Observations of Lyα Emitters at High Redshift

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Abstract In this series of lectures, I review our observational understanding of high-
$z$ Lyα emitters (LAEs) and relevant scientific topics. Since the discovery of LAEs
in the late 1990s, significant progresses in LAE studies have been made over the
past two decades by deep multi-wavelength observations. More than ten (one) thou-
sand(s) of LAEs have been identified photometrically (spectroscopically) in optical
and near-infrared data, and the redshifts of these LAEs range from $z \sim 0$ to $z \sim 10$.
These large samples of LAEs are useful to address two major astrophysical issues,
galaxy formation and cosmic reionization. Statistical studies have revealed the gen-
eral picture of LAEs’ physical properties: young stellar populations, remarkable
luminosity function evolutions, compact morphologies, highly ionized inter-stellar
media (ISM) with low metal/dust contents, low masses of dark-matter halos. Typical
LAEs represent low-mass high-$z$ galaxies, high-$z$ analogs of dwarf galaxies, some of
which are thought to be candidates of population III galaxies. These observational
studies have also pinpointed rare bright Lyα sources extended over $\sim 10 - 100$
kpc, dubbed Lyα blobs, whose physical origins are under debate. LAEs are used
as probes of cosmic reionization history through the Lyα damping wing absorption
given by the neutral hydrogen of the inter-galactic medium (IGM), which comple-
ment the cosmic microwave background radiation and 21cm observations targeting
the epoch of reionization. The low-mass and highly-ionized population of LAEs can
be major sources of cosmic reionization, and physical parameters including the ion-
izing photon escape fraction have been extensively investigated. The budget of ion-
izing photons for cosmic reionization has been constrained, although there remain
large observational uncertainties in the parameters. Beyond these two established
topics of LAEs, galaxy formation and cosmic reionization, several new usages of
LAEs for science frontiers have been suggested such as the distribution of H1 gas in
the circum-galactic medium and filaments of large-scale structures. On-going 10 m-
class optical telescope programs and future telescope projects, such as JWST, ELTs,
and SKA, will address the remaining open questions related to LAEs, and push the horizons of the science frontiers.

1 Introduction

About two decades have passed since the observational discovery of Lyα emitters (LAEs) at high redshift. Before then, early theoretical studies focused on discussing young primordial galaxies with strong Lyα emission. However, after the discovery, observations have revealed a number of exciting characteristics of LAEs, some of which are beyond the theoretical predictions. In this section, I show the growing importance of LAE studies, overviewing the LAE observation history through the early theoretical predictions, the discovery, and new problems in this observational field. Throughout this lecture, magnitudes are in the AB system, if not otherwise specified. All physical values are calculated with the concordance cosmology of \( H_0 = 100h \text{ km s}^{-1} \text{ Mpc}^{-1} \) with \( h \simeq 0.7, \Omega_m \simeq 0.3, \Omega_\Lambda \simeq 0.7, \Omega_b h^2 \simeq 0.02, \sigma_8 \simeq 0.8, \) and \( n_s \simeq 1.0 \) that are consistent with the latest Planck2016 cosmology (Planck Collaboration et al., 2016).

1.1 Predawn of the LAE Observation History

1.1.1 Theoretical Predictions

Partridge & Peebles (1967a) is the first well-known study that discusses galaxies emitting strong Lyα at high redshift, which are called LAEs today. Partridge & Peebles (1967a) predict that an early galaxy emits a strong hydrogen Lyα line through the recombination process in the inter-stellar medium (ISM) that is heated by young massive stars (Figure 1). As much as 6-7% of the total galaxy luminosity can be converted to Lyα luminosity in a Milky Way mass halo. Assuming a high star-formation rate that converts 2% of hydrogen to metal within \( 3 \times 10^7 \text{ yr} \) in a Milky Way mass halo, Partridge & Peebles (1967a) suggest that such galaxies would have an extremely bright Lyα luminosity of \( \sim 2 \times 10^{45} \text{ erg s}^{-1} \) at \( z \sim 10 - 30 \). Interestingly, Partridge & Peebles (1967a) discuss the observability of those young Lyα emitting galaxies, taking the effects of cosmic reionization into account (see also a companion paper, Partridge & Peebles 1967b). Here, Partridge & Peebles (1967a) introduce a possible strong free-electron scattering in the ionized IGM that smears the radiation from the young galaxies, which is an argument that differs from today’s major discussion on the absorption of Lyα emission by the neutral IGM. Although their discussion of young galaxies’ Lyα luminosities and reionization effects on the Lyα observability is very different from the present-day one, it is interesting to notice that the two major cosmological topics discussed today in relation with
LAEs, namely galaxy formation and cosmic reionization, had already been studied theoretically in the 1960s.

![Expected spectrum of a young galaxy](image)

**Fig. 1** Expected spectrum of a young galaxy (Partridge & Peebles, 1967a). Here, $\Delta \nu = 0.002\nu$ is assumed for the line width. This figure is reproduced by permission of the AAS.

### 1.1.2 Early Searches for LAEs

Since the theoretical predictions of Partridge & Peebles (1967a) were published, a number of observational projects searched for young LAEs at $z \sim 2 - 6$ (e.g. Koo & Kron 1980; Pritchet & Hartwick 1987, 1990; Djorgovski & Thompson 1992; Thompson et al. 1995). These observational searches were conducted in the 1980s and 1990s with 4m-class optical telescopes including the Palomar 200-inch Hale telescope that was the largest aperture telescope used for researches before the 10m Keck I telescope became available. Although many candidates were pinpointed by narrowband imaging and slitless spectroscopy in these searches, no real young LAEs at $z \gtrsim 2$ were confirmed by spectroscopy. However, these null-detection results placed meaningful upper limits on the luminosity function of LAEs (Figure 2).
Fig. 2  One sigma upper limits of Ly\(\alpha\) luminosity functions at \(z = 2 - 9\) (black solid and dashed lines). The black arrow indicates the offset value between one and three sigma levels that can allow us to convert the one to three sigma upper limits. The red curve is the approximate Ly\(\alpha\) luminosity function of LAEs at \(z = 2 - 5\) obtained thus far (e.g. Gronwall et al. 2007; Ouchi et al. 2008; Cassata et al. 2011). The black curve is the model Ly\(\alpha\) luminosity function. The blue (green) line represents a typical observational limit of a narrow-field (wide-field) imager mounted on an 8m (4m) class telescope. All numbers quoted in this figure hold for a cosmological model with \(H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_m = 0.2, \) and \(\Omega_\Lambda = 0.0\). This figure is adopted from Figure 13 of Thompson et al. (1995), and reproduced by permission of the AAS.

1.1.3 Discovery

Since 1996, LAE observations have entered a new era. [Hu & McMahon (1996)] have identified two LAEs at \(z = 4.55\) around the QSO BR2237-0607 using the Keck LRIS spectrograph (Figure 3), after having detected them using deep UH88 imaging through a narrow band filter with the central wavelength tuned to the wavelength of Ly\(\alpha\) emission at \(z = 4.55\). At the same time, [Pascarelle et al. (1996a)] discovered 5 LAEs, including a weak AGN, around the radio galaxy 53W002 at \(z = 2.39\) using...
Fig. 3  Top: Images of three LAE candidates in the QSO field of BR2237-0607 at $z = 4.55$ marked with the small circles (Hu & McMahon, 1996). The QSO is indicated with the large circle. The left and right panels present narrowband and broadband images, respectively, that cover the redshifted Ly$\alpha$ emission and the rest-frame UV continua of the LAEs. Bottom: Two-dimensional spectra of the three LAE candidates (Hu & McMahon, 1996). Clear Ly$\alpha$ signals of the LAE candidates are found in the wavelength between 6500 and 7000 Å. The two objects in the two lower panels are LAEs, while the object in the top panel is classified as a low-$z$ [OII] emitter. This figure is reproduced by permission of the Nature Publishing Group.
the Hubble Space Telescope (HST) for broadband imaging, a ground based telescope for narrowband imaging, and the MMT for spectroscopy. Pascarelle et al. (1996b) claim that such LAEs form a galaxy group in the 53W002 region. These discovered LAEs have Ly\(\alpha\) luminosities of a few times \(10^{42}\) erg s\(^{-1}\) that is about 1/100 of the young galaxies predicted by Partridge & Peebles (1967a).

These early studies found LAEs in the vicinity of AGNs that are thought to be signposts of high-\(z\) galaxy overdensities. LAEs in blank fields were first identified by Cowie & Hu (1998) and Hu et al. (1998) who carried out Keck LRIS narrowband imaging and spectroscopy in the SSA22 and Hubble Deep Field (HDF). Such deep field observations started to identify LAEs at \(z \gtrsim 2\) in blank fields routinely with the high sensitivities of 8m class telescopes and the large-area survey capabilities of 4-8m class telescopes around the year 2000. These deep field observation programs include the Hawaii Survey (Cowie & Hu 1998), the Large Area Lyman Alpha Survey (LALA; Rhoads et al. 2000), the Subaru Surveys (e.g. Ouchi et al. 2003), and the Multiwavelength Survey by Yale-Chile (MUSYC; Gawiser et al. 2007), and recently an LAE search with a new technology has been demonstrated by the HETDEX Pilot Survey (HPS; Adams et al. 2011). Recent space based observations even find LAEs at \(z \sim 0\) whose Ly\(\alpha\) emission lines fall in the far UV wavelength range. There is an HST survey program, the so-called Lyman-Alpha Reference Sample (LARS; Östlin et al. 2014) that investigates the Ly\(\alpha\) properties of star-forming galaxies originally selected as H\(\alpha\) emitters at \(z \sim 0\). Moreover, far and near UV grism data from the Galaxy Evolution Explorer (GALEX) are used to detect LAEs at \(z \sim 0 - 1\) and to build Ly\(\alpha\) flux limited samples for studies of Ly\(\alpha\) luminosity functions (Section 3.2; Deharveng et al. 2008; Cowie et al. 2010, 2011). For more details about \(z \sim 0\) LAE observations, see M. Hayes’ lectures in this course.

There is a question why no single LAE at high-\(z\) could be identified by the observations until 1996, about two decades after the predictions of Partridge & Peebles (1967a). As shown in Figure 2, the blank field surveys conducted until 1995 found no LAEs at \(z > 2\) down to number densities of \(\sim 10^{-4}\) Mpc\(^{-3}\) at \(L(\text{Ly}\alpha) = 10^{43}\) erg s\(^{-1}\) and \(\sim 10^{-3}\) Mpc\(^{-3}\) at \(L(\text{Ly}\alpha) = 10^{42}\) erg s\(^{-1}\). These number-density limits just touch the Ly\(\alpha\) luminosity functions at \(z \sim 3 - 5\) that have been determined to date (see Section 3.2). In other words, one could have found LAEs in a blank field before 1996, if there was a one-more push of sensitivity or survey volume. However, such a one-more push was not made until 1996. In reality, there are two important approaches leading to these successful detections of LAEs. The first approach is to focus on AGN regions. The first LAE detections (Hu & McMahon 1996; Pascarelle et al. 1996a) were accomplished in AGN regions, whose galaxy overdensities enhance the probability of bright LAEs existing in the survey area, resulting in successful selections and spectroscopic confirmations even with 2-4 m class telescopes. The second approach is to exploit the great sensitivity of 8m-class telescopes newly available since the 1990s. In fact, the Keck deep narrowband observations by Cowie

\footnote{In the early days of LAE observational studies, many names and abbreviations were used for LAEs, such as Ly\(\alpha\) emitting galaxies, Ly\(\alpha\) galaxies, LEGOs etc. The present-day established name, Ly\(\alpha\) emitter, can be found in the early study of Hu & McMahon (1996), and the abbreviation, LAE, was first suggested in Ouchi et al. (2003).}
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Kong & Hu (1998) successfully identified LAEs in blank fields. Interestingly, these two approaches provided successful detections almost at the same time in the late 1990s. Around the year 2000, wide-field optical imagers started operation in 4m-class telescopes (e.g. KPNO/MOSAIC), allowing the observers to detect LAEs in blank fields even with the moderately low sensitivity of 4m-class telescopes (Rhoads et al. 2000; Gawiser et al. 2007; Figure 2). Moreover, after the first light of the wide-field optical imager Suprime-Cam on the 8m-Subaru telescope in 1999, large LAE surveys cover wider sensitivity and volume ranges, in contrast with the previous narrow-field 8m-class observations (Figure 2). The deep spectroscopic capabilities of the Keck, VLT, and Subaru telescopes are also key for confirmation of faint LAE candidates that are found in blank fields.

1.1.4 Definition of LAEs

Here I introduce the definition of LAEs, although it should be noted that some detailed definitions depend on the study considered. Nowadays, the widely accepted definition of LAEs is: LAEs are galaxies with a Ly$\alpha$ rest-frame equivalent width (EW$_0$) greater than \( \sim 20 \, \text{\AA} \). The criterion of Ly$\alpha$ EW$_0 > 20 \, \text{\AA}$ is historically determined by the realistic selection limit of narrowband imaging surveys for Ly$\alpha$ emitting galaxies at \( z \sim 3 \). By this definition, the main contribution to the LAE population consists of star-forming galaxies, some of which have AGN activity.

1.1.5 LAE Search Techniques

There are two popular techniques to search for LAEs. One is narrowband imaging. Figure 4 illustrates the idea. The redshifted Ly$\alpha$ emission of LAEs is identified by a flux excess in a narrowband image over other wavelength images (Figure 4). The central wavelength of the narrowband filter, \( \lambda_c \), determines the redshift of the target LAEs that is roughly given by \( \lambda_c / 1216 - 1 \). The \( \lambda_c \) value of a narrowband filter is chosen by a scientific requirement (i.e., redshift of target LAEs) and/or observational constraints (e.g. avoiding weak night-sky OH emission lines). In most cases, \( \lambda_c \) is placed in an OH emission window (bottom panel of Figure 4) to realize a high sensitivity.

The other technique is blind spectroscopy, including slitless spectroscopy. Figure 5 shows one example that uses a VLT/FORS grism targeting a blank sky field with no prior positional information of a LAE candidate (Kurk et al. 2004). The LAE candidate is found as a single-line emitter in the grism image. Although this technique provides positions and spectra of LAEs at the same time, the background sky level is high in the slitless data. Thus, HST grism observations are popular to perform slitless spectroscopic searches for LAEs, exploiting the low sky background in space (Pirzkal et al. 2004). The blind spectroscopy technique also includes slit spectroscopy such as long-slit spectroscopy conducted on positions of critical lines of lensing clusters searching for lensed LAEs (Santos et al. 2004). Moreover, the
recent advancement of integral field spectrographs (IFSs) allows blind spectroscopic searches for LAEs in reasonably large areas, keeping the background sky sufficiently low (van Breukelen et al. 2005, Bacon et al. 2015).

Fig. 4 Illustration of the narrowband selection for an LAE at $z = 6.6$ (NB921-C-106098). The top panel presents images of this LAE observed with broadbands ($B$, $V$, $R$, $i'$, and $z'$) and a narrowband ($NB$) whose central wavelength is $\sim 9200$ Å. The second top panel is a spectrum of this LAE in the wavelength range of 9050 – 9275 Å. The third top panel shows the model spectrum of a LAE redshifted to $z \sim 6.6$. The second bottom panel exhibits the transmission curves of the broadbands and the narrowband. The bottom panel presents the atmospheric OH lines. Some images of this figure are taken from Ouchi et al. (2010). This figure is reproduced by permission of the AAS.
Fig. 5 An LAE candidate found in VLT/FORS grism data in a blank field (Kurk et al., 2004), labeled on the image. An [OIII]5007 emitter is also found at the upper right of this image. This figure is reproduced by permission of A&A.

Although these two techniques are major ones for identifying LAEs, recent deep spectroscopy has found continuum-selected galaxies (e.g. dropouts or Lyman break galaxies; LBGs) with a spectroscopic measurement of Lyα $EW_0 > 20\,\AA$ that are also classified as LAEs (e.g. Erb et al., 2014). In this series of lectures, LAEs include continuum-selected galaxies with Lyα $EW_0 > 20\,\AA$.

1.2 Progresses in LAE Observational Studies After the Discovery

Large survey programs have so far identified a total of more than $10^4$ LAEs up to $z \sim 8$ photometrically (e.g. Yamada et al., 2012a; Konno et al., 2016), out of which about $10^3$ have been spectroscopically confirmed (e.g. Hu et al., 2010; Kashikawa et al., 2011). Due to the high abundance (i.e. number density) of LAEs, $10^{-3} \, Mpc^{-3}$ at $L_{Ly\alpha} \sim 10^{42} - 10^{43} \, erg \, s^{-1}$, LAEs are thought to constitute one of the major populations of high-$z$ galaxies. Below, I highlight progresses in LAE observations that are detailed in Sections 3.6.

Deep photometric studies reveal the average spectral energy distribution (SED) of LAEs with deep optical and NIR photometric data. From comparisons with stellar population synthesis models, stellar population, one of the basic properties of galaxies, is studied (e.g. Gawiser et al., 2007; Finkelstein et al., 2007; Ono et al., 2010a,b; Quaita et al., 2011; Hagen et al., 2014, 2016). Figure 6 compares LAEs’ average stellar masses ($M_*$) and specific star-formation rates (sSFRs), defined as the star-formation rate (SFR) divided by stellar mass, with those of other galaxy populations: LBGs, distant-red galaxies (DRGs), and sub-millimeter galaxies (SMGs) at $z \sim 3$. The average $M_*$ of LAEs is $10^8 - 10^9 M_\odot$, which falls in the lowest mass range among the high-$z$ galaxy populations (Section 3.1). The low stellar masses of the LAEs suggest that LAEs are high-$z$ analogs of local star-forming dwarf galaxies. The sSFR values of LAEs are comparable to or slightly higher than those of the other high-$z$ galaxies, although the distribution of LAEs at the low-mass limit of Figure 6 is biased by the observational selection limits.
Fig. 6 SFR as a function of stellar mass for typical LAEs (blue symbols), LBGs/dropouts (black open squares), DRGs (black open circles), and SMGs (star marks) at $z = 3$ (Ono et al., 2010a). The thick ovals indicate the approximated distributions of LAEs (blue), LBGs/dropouts (orange), DRGs (magenta), and SMGs (red). The red squares and circles with error bars denote peculiar LAEs with bright NIR-band fluxes. This figure is reproduced by permission of the Royal Astronomical Society.

A narrowband imaging search for LAEs has serendipitously identified remarkable objects like Ly$\alpha$ blobs (LABs), many of which show no clear AGN signatures (Section 4.1), that were first found in the LBG overdensity region SSA22 (Figure 7; Steidel et al. 2000). LABs consist of a large Ly$\alpha$ nebula with a spatial extent of $\sim 10 - 200$ kpc and a bright total Ly$\alpha$ luminosity $L_{\text{Ly}\alpha} \sim 10^{43} - 10^{44}$ erg s$^{-1}$ (Matsuda et al., 2004). So far, a few tens of LABs are identified at $z \sim 2 - 7$ (Yang et al., 2009; Scarlata et al., 2009; Ouchi et al., 2009a). There are various models of LABs including HI scattering clouds and cooling radiation. However, the physical origins of the large Ly$\alpha$ nebulae are under debate.
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Fig. 7 Color composite images of LABs at $z = 3.1$ in the SSA22 field (Matsuda et al., 2004). The green color indicates Lyα emission, while the blue and red colors are the continua bluer and redder than Lyα for $z \sim 3$ objects, respectively. The top left (second-left) panel shows LAB1 (LAB2), the first LAB in star-forming galaxies discovered by Steidel et al. (2000). Note that the Lyα emission nebula of LAB1 extends over $\sim 200$ kpc. The size of each image is about $200$ kpc $\times$ $200$ kpc. This figure is adopted from http://www.naoj.org/Pressrelease/2006/07/26/index.html by permission of the National Astronomical Observatory of Japan.

Since the late 1990s when the early observations detected LAEs, LAEs have remained the most distant galaxies known to date (Figure 8; Hu et al., 1999, 2002; Kodaira et al., 2003; Iye et al., 2006; Vanzella et al., 2011; Ono et al., 2012; Shibuya et al., 2012; Finkelstein et al., 2013; Oesch et al., 2015; Zitrin et al., 2015), except for some examples of high-$z$ dropouts whose redshifts are estimated with the Lyα continuum break with an accuracy $\Delta z = 0.1 - 0.2$ (Watson et al., 2015; Oesch et al., 2016). Most of the highest redshift galaxies confirmed by spectroscopy are LAEs, because strong Lyα emission can be efficiently detected in a very faint source at high redshift. Some of the high-$z$ galaxies show intrinsically large Lyα $EW_0$ val-
ues, suggestive of very young, population III (popIII)-like starbursts such as those predicted by Partridge & Peebles (1967a) (Section 1.1.1).

![Figure 8](image.png)

**Fig. 8** Spectroscopically identified LAEs at $z = 7.73$ (left; Oesch et al. 2015) and $z = 8.68$ (right; Zitrin et al. 2015). The top and bottom panels present the two- and one-dimensional spectra, respectively. A clear asymmetric line typical for high-$z$ LAEs is identified in the $z = 7.73$ LAE (left). This figure is reproduced by permission of the AAS.

A number of LAEs have been spectroscopically identified at the epoch of reionization (EoR) at $z \gtrsim 6$ (Section 5). Because Ly$\alpha$ photons from LAEs are scattered by neutral hydrogen HI that exists in the IGM at EoR, the detectability of Ly$\alpha$ from LAEs depends on the fraction of HI in the IGM. In a statistical sense, weak Ly$\alpha$ emission of LAEs suggests more Ly$\alpha$ scattering in the IGM or lower Ly$\alpha$ production rates. Exploiting this dependence, LAEs are used as probes of cosmic reionization as well as galaxy formation (Figure 9).

Cosmic reionization has been extensively investigated using LAEs, after isolating the effects of galaxy formation, namely the evolution of the Ly$\alpha$ luminosity, in conjunction with complementary observational constraints (Sections 5, Malhotra & Rhoads 2004, Kashikawa et al. 2006, 2011, Ouchi et al. 2010, Pentericci et al. 2011, Ono et al. 2012, Schenker et al. 2012, Treu et al. 2013, Schenker et al. 2014).
1.3 Goals of This Lecture Series

The goal of this lecture series is to make the readers understand not only the established picture of LAEs, but also the cutting-edge results obtained from observations spanning the redshift range $z \sim 0 - 10$ covered to date. As shown in Section 1.2, today’s major LAE studies address questions about the physical properties of high-$z$ low mass galaxies, including popIII-like galaxies, sources of reionization, and the cosmic reionization history. In other words, most LAE observational studies discuss either galaxy formation or cosmic reionization. This lecture series thus covers

1) Galaxy formation (Sections 2-4) and
2) Cosmic reionization (Sections 5-6).

Note that there are several promising studies of LAEs that are growing in this field. One is the Ly$\alpha$ emission distribution that traces the circum-galactic medium (CGM) extending along filaments of large-scale structures (Cantalupo et al., 2014). Because Ly$\alpha$ is a resonance line, it is used as a probe of the HI distribution of the underlying cosmological structures. The extended Ly$\alpha$ emission studies are detailed in Section 4, together with topics of Ly$\alpha$ blobs, diffuse Ly$\alpha$ halos, Ly$\alpha$ fluorescence,
proto-clusters, and large-scale structures (LSSs), all of which are closely related to galaxy formation. Another important use of LAEs consists in probing properties of dark energy with accurate measurements of cosmic expansion history on the basis of baryon acoustic oscillations (BAO). Because no LAE studies have, so far, successfully detected BAO, an on-going LAE BAO cosmology study project is briefly touched in the section of future studies (Section 7).

2 Galaxy Formation I: Basic Theoretical Framework

One of the major scientific drivers of LAE studies is galaxy formation. In this section, I show the basic theoretical framework of galaxy formation and associated Lyα emission, and identify both established ideas and unresolved difficult issues. This section mainly targets first-year graduate students working on observations and those who know little about the modern picture of galaxy formation.

2.1 Basic Picture of Galaxy Formation

Figure 10 illustrates the basic picture of galaxy formation that is believed in modern astronomy. Generally, galaxy formation is made of two major processes, dark-matter (DM) halo formation and star formation (Mo et al., 2010). First, DM halos are created from the initial density fluctuations, and then star formation takes place in the cold dense gas clouds made by radiative cooling in the DM halos. These two processes are detailed in the following subsections.

Fig. 10  Conceptual diagram of the galaxy-formation processes.
2.1.1 DM Halo Formation

The standard cosmological model of $\Lambda$ cold dark matter ($\Lambda$CDM) suggests that the initial density fluctuations in the early universe grow by gravity and produce cosmic structures (Peebles, 1993). DM halos, virialized systems of DM, with baryon gas are created by gravitational collapses. Low-mass DM halos are first made, and subsequently these low-mass DM halos increase their masses by merger and accretion processes. Because DM dominates the cosmic matter density, this sequence of the cosmological structure formation is governed by DM. DM physically interacts only by gravity, and the formation of cosmic structures including DM halos can be basically predicted with no serious systematics.

Exploiting the great performance of computers today, numerical simulations reproduce DM halos under the assumption that DM is composed of collisionless particles that follow Newton’s law of gravitation. Figure 11 presents the DM-halo mass functions calculated by large cosmological simulations (Springel et al., 2005). The state-of-the-art cosmological simulations (with a box size of a few-10 Mpc$^3$) have a good mass resolution, and already make DM halos with a mass of $\sim 10^7 M_\odot$ (Figure 12; Ishiyama et al. 2013, 2015) that is much smaller than those of most of the local dwarf galaxies and any high-$z$ galaxies observed, to date. In other words, DM halos of galaxies are mostly recovered over cosmic time in numerical simulations.

It is true that the physical origin of DM is poorly understood. However, under the collisionless DM particle assumption, the DM-halo formation is established today.

![Fig. 11](image-url)  
DM-halo mass function as a function of mass and redshift obtained by numerical simulations (Springel et al. 2005). The ordinate is the differential number density $(dn/dM)$ multiplied by $M^2 \rho^{-1}$ where $\rho$ is the mean density of the universe. The solid lines are the best-fit functions to the mass functions with the analytical functional form of Jenkins et al. (2001) (see also Sheth & Tormen 1999). The blue dashed lines are the Press-Schechter functions at $z = 10.07$ and 0 from left to right. This figure is reproduced by permission of the Nature Publishing Group.
Fig. 12 Cosmic structures including DM halos reproduced by the state-of-the-art simulations [Ishiyama et al. 2015]. From top to bottom, cosmic structures at $z = 7, 3, 1,$ and $0$ are shown. The left, center, and right panels represent the simulation results with three different DM-particle masses (box sizes), $2.2 \times 10^8 M_\odot (1120 h^{-1} \text{ Mpc})$, $2.8 \times 10^7 M_\odot (140 h^{-1} \text{ Mpc})$, and $3.4 \times 10^6 M_\odot (70 h^{-1} \text{ Mpc})$, respectively. This figure is reproduced by permission of the ASJ.

The DM halo formation is understood not only by numerical simulations, but also by analytic calculations. Starting from the Gaussian initial density fluctuations, one can derive an approximation of the DM-halo mass function based on linear structure growth and spherical collapse. The analytic form is referred to as the Press-Schechter function [Press & Schechter 1974] that is,
where $M^*$ is the characteristic mass, $a$ is a power-law index of the mass fluctuations, and $\rho_0$ is the mean density of the universe. Figure 11 compares Press-Schechter functions (blue dashed lines) with numerical results (red points). The Press-Schechter functions reasonably approximate the numerical results, while there exist small departures. Note that theorists modify the analytic form of eq. (1), with a few additional free parameters (e.g. Sheth & Tormen 1999), and obtain 'modified' Press-Schechter functions with the best-fit parameters determined by fitting the numerical results (solid lines in Figure 11). A number of galaxy formation studies (including LAE modeling) exploit such modified Press-Schechter functions that are useful to reproduce DM-halo mass functions (mass vs. abundance) at any redshifts and cosmological parameter sets (Mao et al. 2007; Samui et al. 2009). It should be also noted that these analytic formalisms can also provide reliable predictions in clustering of DM halos. In other words, once a redshift, mass, and cosmological parameter set are given, the abundance and clustering of DM halos are predicted by these formalisms based on the $\Lambda$CDM structure formation scenario.

Because galaxies form in DM halos, galaxy luminosity functions and stellar-mass functions should have a functional shape similar to DM halo mass functions. Indeed, galaxy luminosity functions determined by observations can be fit well with the Schechter function (Schechter 1976),

$$
\phi(L) dL = \phi^* \left( \frac{L}{L^*} \right)^{\alpha} \exp \left( - \frac{L}{L^*} \right) d \left( \frac{L}{L^*} \right)
$$

where $\phi(L)$ is the number density of galaxies at luminosity $L$. The Schechter function includes three free parameters, $\phi^*$, $L^*$, and $\alpha$, that correspond to the characteristic number density, the characteristic luminosity, and the faint-end slope, respectively. Similarly, stellar mass functions are expressed with stellar mass $M_*$ and the characteristic stellar mass $M^*$ that are in place of $L$ and $L^*$, respectively, in Equation (2) (Figure 14).

It should be noted that Equation (2) has a functional form of the product of an exponential cut-off and a power law for luminosity, which is the same as Equation (1) where halo mass is replaced with luminosity.

The three free parameters of the Schechter function reflect differences from the DM-halo mass function, which depend on the baryonic processes of star-formation and feedback in galaxy formation (Section 2.1.2). In LAE studies, the Schechter function is used to approximate the Ly$\alpha$ luminosity function and the continuum luminosity function.

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2 This is the Schechter function on the luminosity basis. The magnitude-based Schechter function is shown in, e.g., Equation 8 of Ouchi et al. (2004).
2.1.2 Star Formation

Star formation involves complicated physical processes of gas cooling and feedback as detailed below. Moreover, star-formation is induced by objects and matter outside of the galaxy by mergers and gas accretion. I choose gas cooling, feedback, and cold accretion that are key for understanding LAEs in the context of galaxy formation, and introduce these physical processes below.

Gas Cooling:

Star formation requires a reservoir of cold dense gas in a DM halo. However, such cold dense gas cannot be easily produced in a DM halo. If an adiabatic gas contraction takes place in the DM halo, gas temperature increases. Then, the gas contraction stops by the thermal pressure, and dense gas cannot be produced. In this way, adiabatic contractions do not make dense gas that is necessary for star formation. Star-formation thus requires a gas contraction associated with radiative cooling that reduces thermal energy in the gas cloud (Figure 10). By the radiative cooling, gas temperature should decrease from the virial temperature $T$ of the DM halo ($\sim 10^4$ K) to the temperature of molecular hydrogen H$_2$ clouds ($\leq 10^2$ K).

State-of-the-art simulations calculate the gas cooling processes numerically under realistic physical conditions, although these calculations cannot be described with simple analytical forms. Instead, I introduce a classic picture of gas cooling with the free-fall time of the spherical model (Silk & Wyse 1993) that helps the readers understand the idea of gas cooling.

The cooling function, $\Lambda(T)$, is defined by

$$|\dot{E}_{\text{cool}}| = n^2 \Lambda(T),$$  \hspace{1cm} (3)$$

where $\dot{E}_{\text{cool}}$ and $n$ are the cooling rate (energy density divided by time) and the number density of particles, respectively. The cooling function is calculated based on quantum physics, and displayed in Figure 13. It is clear that metal rich gas has a higher $\Lambda(T)$, because various atomic electron transitions are allowed for heavy elements that enhance the efficiency of radiative cooling. In zero-metal gas, there are two peaks in $\Lambda(T)$ near $10^4$ and $10^5$ K that correspond to hydrogen and helium recombinations, respectively. The upturn of $\Lambda(T)$ from $10^6$ to $10^8$ K is explained by the cooling processes of Bremsstrahlung and Compton scattering.
Fig. 13  Cooling function (top) and gas density (bottom) as a function of virial temperature in a spherical halo [Silk & Wyse, 1993]. Top: The curves represent cooling functions with various metal abundances from zero to one solar metallicities that are indicated by the labels. Bottom: The solid curves denote $t_{\text{cool}} = t_{\text{ff}}$ for the metal abundances from zero to one solar metallicities (same labels as in the top panel). Beyond these curves, the cooling time is shorter than the free-fall time, and gas collapses with a negligible thermal pressure. The dashed curve (the horizontal line) indicates that the cooling time (free-fall time) is equal to the present Hubble time. Above the curve and the horizontal line, the gas contraction completes in the cosmic time. The diagonal lines show the density and virial temperature that correspond to the virial masses of the system, $10^{10}$, $10^{12}$, and $10^{14}M_\odot$. This figure is reproduced by permission of the Physics Reports.
In a virialized system, the kinetic energy $E_K$ of gas is given by $E_K = 3nk_B T/2$, where $k_B$ is the Boltzmann constant. Thus, the cooling time $t_{\text{cool}}$ is given by

$$t_{\text{cool}} = \frac{E_K}{|\dot{E}_{\text{cool}}|} = \frac{3}{2} \frac{k_B T}{n \Lambda(T)}. \quad (4)$$

In the spherical model, the free-fall time $t_{\text{ff}}$, a simple dynamical time, is

$$t_{\text{ff}} = \sqrt{\frac{3\pi}{32G\rho_m}}, \quad (5)$$

where $\rho_m$ is the mass density that is proportional to $n$. If the radiative cooling is very efficient, the cooling time is shorter than the free-fall time, $t_{\text{cool}} < t_{\text{ff}}$. In this case, gas collapse takes place with a negligible thermal pressure, and cold dense gas necessary for star formation is produced. This condition of $t_{\text{cool}} < t_{\text{ff}}$ for gas collapse is presented in the $T$ and $n$ plot of Figure 13 (bottom). Halo masses of $\sim 10^{12} M_\odot$ allow gas collapse down to the low gas densities, indicating an efficient gas cooling. It should be noted that the halo mass of $10^{12} M_\odot$ coincides with the mass of the Milky Way as well as the mass where the stellar-to-halo mass ratio is highest (Behroozi et al., 2013). Metals ease the conditions of gas collapse in a massive halo with $> 10^{12} M_\odot$. In Figure 13, gas halos with $t_{\text{cool}} > t_{\text{ff}}$ cannot collapse but cause a quasi-static contraction due to inefficient cooling, which can take time longer than the Hubble time. As shown in Section 3.8, typical LAEs have halo masses of $10^{10} - 10^{12} M_\odot$ and sub-solar metallicities. Figure 13 indicates that LAEs have physical parameters reasonably good for gas collapse, which enables subsequent star formation.

**Feedback:**

Feedback is known as one of the most important physical processes involved in star formation. Figure 14 compares an observed galaxy stellar-mass function (filled squares) with a DM halo mass function from numerical simulations (dashed line). Because the cosmic baryon fraction $f_b$ is $f_b \equiv \Omega_b/\Omega_m \simeq 0.16$ (Planck Collaboration et al., 2015), the DM-halo mass function should be at least about an order of magnitude higher than the stellar-mass function, which can be clearly seen at $\sim 10^{11} M_\odot$ in Figure 14 (see the mass values at a constant number density of $\log N/[\text{Mpc}^3 M_\odot] \sim -14$). However, in Figure 14, the stellar-mass function is flatter at the low-mass end and steeper at the massive end than the DM-halo mass function. These shape differences are thought to be made by feedback effects that suppress star-formation by gas heating and outflow associated with star-formation and AGN activities in a galaxy (Bower et al., 2006).
Theoretical studies assume two feedback mechanisms in the low and high mass regimes, energy- and momentum-driven feedback effects, respectively (Figure 15; Muratov et al. 2015). The energy-driven feedback for low-mass galaxies is caused by thermal energy inputs from supernova (SN) explosions and stellar radiation. The momentum-driven feedback for high-mass galaxies is activated by kinetic energy inputs from stellar winds, radiative pressure, and AGN jets. Defining the mass-loading factor $\eta \equiv \dot{M}_{\text{out}}/SFR$ where $\dot{M}_{\text{out}}$ is the outflow rate, numerical simulations show

$$\eta \propto V_{\text{circ}}^{-2}$$  \hspace{1cm} (6)

$$\eta \propto V_{\text{circ}}^{-1}$$  \hspace{1cm} (7)

for the energy and momentum driven feedbacks, respectively. Here, $V_{\text{circ}}$ is the circular velocity given by

$$V_{\text{circ}} = \sqrt{\frac{GM_h}{r_{\text{vir}}}},$$

where $M_h$ and $r_{\text{vir}}$ are the DM-halo mass and the virial radius, respectively. In Figure 15, the energy and momentum driven feedbacks are seen at $M_h \lesssim 10^{10} M_\odot$ and $\gtrsim M_h \sim 10^{10} M_\odot$, respectively. From observations of local galaxies, the relation of Equation (7) is confirmed (Heckman et al. 2015), while no observations reach $\lesssim M_h \sim 10^{11} M_\odot$ to test the relation of the energy-driven feedback (Equation 6). Because the average DM-halo mass of LAEs is estimated to be $M_h \sim 10^{11} M_\odot$ by clustering analysis (Section 3.8), feedbacks in typical LAEs are probably dominated by the momentum-driven feedback.
Note that some theoretical studies claim the existence of positive feedback effects that induce star-forming activities by, e.g., the shock cooling of AGN jets, radiation pressure, etc. (Silk 2013; Vitale et al. 2015).

**Fig. 15** Mass loading factor as a function of $V_c$ (left) and DM-halo mass (right) predicted by numerical simulations (Muratov et al., 2015). The red, blue, and black symbols represent galaxies at $z = 0 - 0.5$ ($z_{med} = 0.25$), $0.5 - 2$ ($1.25$), and $2 - 4$ ($3$), respectively, produced in the simulations. The red, blue, and black dotted lines indicate a broken-power law fit to the simulated galaxies at corresponding redshifts that roughly corresponds to the energy- and momentum-driven feedbacks (Equations 6 and 7), although the slope of the energy-driven feedback is slightly steeper than Equation 6. This figure is reproduced by permission of the the Royal Astronomical Society.

**Cold Accretion:**

Another important mechanism for star-formation is cold accretion. In the standard picture of galaxy growth, gas infalling in a DM halo is heated to a virial temperature by shocks at around the DM-halo virial radius, and then reaches a quasi-hydrostatic equilibrium with $T \sim 10^6 (V_{circ}/167 \text{ km s}^{-1})^2 \text{ K}$. The hot virialized gas cools by cooling radiation, and forms a cold gas disk that produces stars at the DM-halo center (Rees & Ostriker, 1977; White & Rees, 1978; Fall & Efstathiou, 1980). Recent theoretical studies suggest that, in this galaxy growth process, the infalling gas can penetrate into the DM halo center through the diffuse shock-heated medium, if the infalling gas is dense ($\sim 1 \text{ cm}^{-3}$) and cold (a few $10^4 \text{ K}$; Fardal et al. 2001; Kravtsov 2003; Kereš et al. 2005), which is referred to as cold accretion, cold mode accretion, or cold stream. The theoretical studies predict that, beyond the virial radius of DM halos, there exist multiple cold dense gas streams to the DM-halo center through filaments of LSSs (Figure 16). These cold dense gas streams collide at the DM-halo center, and cool very efficiently, which triggers intense star formation (Dekel et al., 2009). Such cold accretion is important, because about two-thirds of gas accretion in mass has a form of smooth gas flows, in contrast with the rest of the gas accretion taking place in a form of mergers with a $> 1/10$-mass ratio (Katz et al. 2003; Kereš et al. 2009; Dekel et al. 2009). This theoretical picture would explain high SFR galaxies with no merger signatures, such as bright LBGs.
and SMGs with an SFR of \( \gtrsim 100 \text{M}_\odot \text{yr}^{-1} \), and could be an answer to the question why the number density of high SFR galaxies at \( z \sim 2 \) is significantly larger than those expected from merger events. Note that cold gas accretion is allowed in a massive halo only at \( z \gtrsim 2 \) (Figure 16), when the accretion gas is sufficiently cold.

Because the cold accretion is a theoretical picture, in the past decade observers have searched for a signature of cold accretion in their observational data. In LBGs at \( z \sim 2 \), velocities of low ionization metal absorption lines are mostly blueshifted from the galaxy systemic velocities, indicating gas outflow associated with star-forming activities (Steidel et al., 2010). Although there are several reports of cold accretion object candidates in deep observational studies (e.g. Nilsson et al., 2006; Rauch et al., 2011), no definitive observational evidence for cold accretion has been found so far. Because the cold accretion gas infalls along with filaments of LSSs, the covering fraction of cold accretion gas is very small, \(\sim 1-2\% \) (Faucher-Giguère & Kereš, 2011). A large number of sightlines (i.e. a large sample of galaxies) would be needed to prove or disprove the existence of cold accretion.

**Fig. 16** Left: Radial flux of cold gas accretion into the center of a DM-halo predicted by numerical simulations (Dekel et al., 2009). The color scale indicates the inflow rate per solid angle. The box size is 320 kpc. The dotted line represents the virial radius of the DM halo. There are three cold accretion streams clearly found in this figure, two of which include gas clumps with a mass ten times lower than that of the central galaxy. Right: DM-halo mass as a function of redshift (Dekel et al., 2009). The red horizontal curve indicates the threshold mass above which infalling gas is shock-heated around the DM-halo virial radius. The blue line represents the limit of cold accretion of gas whose density (temperature) is high (low) enough to penetrate into the DM halo center through the diffuse shock-heated medium. The dashed line denotes the characteristic DM-halo mass of the Press-Schechter mass function (eq. 1) at a given redshift. This figure is reproduced by permission of the Nature Publishing Group.
2.1.3 Role of Observations

As introduced in Section 2.1, the basic process of galaxy formation is DM-halo formation and star formation (Figure 10). DM-halo formation is well understood with no large systematics by simple numerical simulations and analytic approximations (Section 2.1.1), while star-formation is poorly understood due to the complicated baryonic processes: gas cooling, feedback, and cold accretion as well as merger induced star-formation. The star-formation process involves a number of unknown parameters, such as gas metallicity, density, temperature, outflow, and inflow. Observations can obtain these key parameters tightly connected to star formation, and constrain free parameters of galaxy formation models. On the other hand, many cosmological simulations including those for LAEs assume a simple relation between halo-mass and galaxy luminosity (e.g. McQuinn et al. 2007) as well as an empirical relation between gas and star-formation density such as the Kennicutt-Schmidt (KS) law (Figure 17). Such models with empirical relations can derive the star-formation surface density $\Sigma_{\text{SFR}}$ from the gas surface density $\Sigma_{\text{gas}}$ that is predicted by numerical simulations and semi-analytic models, and aim to explain other various observational quantities of galaxies (e.g. Garel et al. 2012). In this way, key observational parameters and empirical relations are important to understand star-formation in galaxies. Thus, the goal of observations is to determine star-formation key parameters and empirical relations to develop a self-consistent physical picture of galaxy formation.
2.2 Origins of Ly\(\alpha\) Emission from LAEs

Once a galaxy formation model is developed, Ly\(\alpha\) emission of galaxies can be modeled. Theoretical studies suggest that in galaxies, Ly\(\alpha\) emission can have five major origins, which probably explain the diversity of the spatial distribution of Ly\(\alpha\) emission revealed by observations (Figure 18).
Ly$\alpha$ emission following hydrogen recombination in the ISM near the center of a galaxy can result from two origins of ionizing sources: i) star formation that makes HII regions and ii) nuclear activities (i.e. AGN), if any, producing highly ionized broad and narrow-line regions in the galaxy center.

The remaining three origins are dominated by Ly$\alpha$ emission from the CGM to the outer halo: iii) outflowing gas that collisionally excites hydrogen whose Ly$\alpha$ to H$\alpha$ flux ratio is higher than the one of the optically thick case B recombination $f_{\text{Ly}\alpha}/f_{\text{H}\alpha} > 8.7$ (Nakajima et al., 2013). iv) cooling radiation in the hot halo gas (Section 2.1.2), and v) fluorescence emission produced by the halo and IGM neutral hydrogen gas photo-ionized by UV background radiation supplied, e.g., by QSOs (Kollmeier et al., 2010).

Although Ly$\alpha$ emission can be made by these five photo-ionization and collisional excitation processes i)-v), Ly$\alpha$ photons experience resonance scattering in the H I gas of the ISM, the CGM, and the IGM, due to the large Ly$\alpha$ cross section of H I. Ly$\alpha$ photons are re-distributed in space and wavelength by the resonance scattering. For this reason, scattered Ly$\alpha$ emission would dominate in the CGM, where the Ly$\alpha$ intensity of photo-ionization is relatively weak. It should be noted that observations identify Ly$\alpha$ photons last scattered by H I gas, and largely miss the original Ly$\alpha$ source position and gas dynamics information. However, this resonance nature of Ly$\alpha$ is also useful to probe the distribution and the kinematics of H I gas by observations via theoretical modeling (Section 3.3).

![False-color images of local Ly$\alpha$ emitters obtained by the LARS survey (Hayes et al., 2013). The blue, red, and green colors indicate Ly$\alpha$ emission, H$\alpha$ emission, and far-UV continuum, respectively. The scales in units of kpc are shown in the vertical and horizontal axes. This figure is reproduced by permission of the AAS.](image)
2.3 Summary of Galaxy Formation I

This section overviews the basic theoretical framework of galaxy formation and Ly$\alpha$ production, targeting young observers with a limited theoretical background. This section explains that galaxy formation is made of two physical processes of DM-halo formation and star formation. DM-halo formation is well understood with a simple robust model of cosmic structure formation consistent with observations. However, star formation involves complicated baryonic processes of gas cooling, feedback, and cold accretion as well as mergers that include many physical parameters difficult to determine. It is concluded that observations should constrain important physical parameters and empirical relations that are key for filling in the missing piece of the picture of galaxy formation. To understand LAEs in the context of galaxy formation, one also needs physical models of Ly$\alpha$ emission. Five Ly$\alpha$ emission origins in theoretical models are introduced. Two origins are in ISM regions: i) star formation (HII regions) and ii) AGN (highly-ionized gas in a galaxy center). The other three dominate in the CGM and outer halo regions: iii) outflowing gas, iv) cooling radiation, and v) fluorescence of UV background radiation. LAE observations should also reveal the origins of Ly$\alpha$ photons in parallel with the efforts to address the general galaxy formation issues.

3 Galaxy Formation II: LAEs Uncovered by Deep Observations

Since the discovery of LAEs in the late 1990s, various physical properties of LAEs have been revealed by exploiting deep optical to mid-infrared (MIR) imaging and spectroscopic capabilities of 8m-class ground based telescopes, HST, and Spitzer Space Telescope (Spitzer) in conjunction with observations at other wavelengths using the Chandra X-ray observatory (Chandra), GALEX, Herschel Space Observatory (Herschel), Atacama Large Millimeter / submillimeter Array (ALMA), and Very Large Array (VLA). In this section, I review key physical properties of LAEs uncovered by those observations: stellar population, luminosity function, morphology, ISM properties (metallicity, ionization parameter, dust), AGN activity, and clustering.

3.1 Stellar Population

The stellar population of galaxies is described by stellar mass, age, dust extinction, and some other parameters, and these parameters can be estimated by fitting broadband spectral energy distributions (SEDs) with stellar population synthesis models such as Bruzual & Charlot 2003. It is, however, difficult to investigate stellar populations of LAEs because most LAEs do not have detectable continuum emission even in deep images, although there do exist remarkably bright LAEs (Lai et al.).
Making a composite (average) SED of a number of continuum-faint LAEs by image stacking, early studies have revealed that they have faint and blue SEDs on average. An example SED is shown in the left panel of Figure 19 (Gawiser et al., 2007), which is explained by a model with a low stellar mass of $\sim 10^9 M_\odot$, a young stellar age of $\sim 20$ Myr, and a negligibly small dust extinction.

Because LAEs are young dust-poor star-forming galaxies, they often have strong nebular lines, such as H$\alpha$, H$\beta$, [OIII]5007, and [OII]3727, which contaminate continuum fluxes estimated from broadband photometry. Because the observed-frame equivalent width $EW_{\text{obs}}$ of nebular lines increases with redshift as $EW_{\text{obs}} \propto (1 + z)$, nebular lines of high-$z$ LAEs can cause serious systematic errors in broadband SEDs and hence in the calculation of stellar population parameters. Strong [OIII], H$\beta$, and [OII] lines near 4000Å mimic a Balmer break that is an indicator of stellar age, and an over/underestimated age leads to an over/underestimated stellar mass. Schaerer & de Barros (2009) introduce self-consistent population synthesis models with nebular lines where line ratios (as a function of metallicity) are fixed to the values of Galactic HII regions. Using a sample of $z \sim 6$ LBGs as an example, they claim that models without nebular lines overestimate stellar ages and masses by a factor of 3. Thus, considering nebular lines is critical to obtain stellar population parameters of high-$z$ young star-forming galaxies including LAEs. It should also be noted that there is another important source of contamination, nebular continuum, that is the...
free-free/bound-free emission of hydrogen and helium and two photon continuum emission of hydrogen. Because nebular continuum emission significantly changes UV-continuum colors for very young stellar populations with a stellar age of $\lesssim 10$ Myr for instantaneous starbursts (see Figures 3 and 4 of Bouwens et al. 2010), it is usually included in nebular emission modeling.

The right panel of Figure 19 presents an average SED of $z = 2$ LAEs and its best-fit stellar population synthesis model with nebular emission. Table 1 summarizes the typical ranges of stellar population parameters of $z = 2−7$ LAEs that are obtained under the assumptions of constant star-formation history, a Salpeter IMF (Salpeter 1955), and Calzetti extinction law (Calzetti et al. 2000; see Gawiser et al. 2007; Ono et al. 2010a,b; Guaita et al. 2011; Hagen et al. 2014, 2016). Although different samples give different parameter values, Table 1 shows that LAEs are low-stellar mass galaxies with a low dust extinction, a medium-low SFR, and a young stellar age.

Figure 20 compares LAEs (blue circles) with other galaxies in the stellar mass vs. SFR plane. At $M_\star \gtrsim 10^{10}$ $M_\odot$ in Figure 20, there is a star-formation (SF) main sequence, a tight positive correlation between $M_\star$ and SFR (Daddi et al. 2007; Elbaz et al. 2007). LAEs fall in the low mass regime of $M_\star \sim 10^7 − 10^{10}$ $M_\odot$ slightly above an extrapolation of the SF main sequence found at $M \gtrsim 10^{10}$ $M_\odot$ (Hagen et al. 2014, 2016), suggesting that typical LAEs are high-$z$ dwarf galaxies in a weak burst mode.

LAEs are located in a similar area in the stellar mass vs. SFR plane to other emission line galaxies, i.e., [OII], H$\beta$, and [OIII] emitters, at $z \sim 2$ (green dots).

| Stellar Mass $[M_\odot]$ | $E(B-V)_s$ | SFR $[M_\odot$ yr$^{-1}$] | Stellar Age [Myr] | Metallicity $Z_\odot$ |
|--------------------------|-------------|---------------------------|------------------|------------------|
| $10^7 − 10^{10}$ | 0 − 0.2 | 1 − 100 | 1 − 100 | 0.1 − 0.5 |

$^a$ Color excess due to stellar extinction. The color excess due to nebular extinction, $E(B-V)_{\text{neb}}$, falls in the same range as $E(B-V)_s$ (Section 3.4.3). Calzetti’s extinction law (Calzetti et al. 2000) is assumed. $^\dagger$ LAEs at $z \sim 2−3$ with a Ly$\alpha$ luminosity near $L_{\text{Ly}\alpha} \sim 10^{42} − 10^{43}$ erg s$^{-1}$.
Fig. 20  LAEs compared with the star-formation main sequence on the SFR vs. stellar mass plot (Hagen et al., 2016). The blue circles represent LAEs, while the green circles denote optical emission galaxies (oELGs). The gray and magenta circles indicate BzK and Herschel/PACS-detected galaxies, respectively (Rodighiero et al., 2011). The dotted and dashed lines show the star-formation main sequences at $z = 2$ obtained by Speagle et al. (2014) and Whitaker et al. (2014), respectively. This figure is reproduced by permission of the AAS.

3.2 Luminosity Function

The luminosity function and its evolution over time is one of the most fundamental properties for any galaxy population. The Ly$\alpha$ luminosity function of LAEs has been derived at $z \sim 0 - 8$ by large survey programs (Section 1.1.3) since the discovery of LAEs in the late 1990s. The bottom and top panels of Figure 21 present Ly$\alpha$ luminosity functions and their best-fit Schechter function parameters, respectively, from $z \sim 0$ to 6, where the Schechter function parameters are the characteristic Ly$\alpha$ luminosity $L_{\text{Ly}\alpha}^*$ and the normalization $\phi_{\text{Ly}\alpha}^*$ that determines the abundance $^3$ Two evolutionary trends are seen in Figure 21: a monotonic increase in the normalization from $z \sim 0$ to 3 and no evolution in either the normalization or the shape over $z \sim 3 - 6$. I explain details of these two trends in the following paragraphs.

$^3$ Ly$\alpha$ luminosity functions above $z \sim 6$ are discussed in the cosmic reionization section (Section 5).
Fig. 21  Top: Best-fit Schechter parameters and the error contours of Ly$\alpha$ luminosity functions at $z \sim 0 - 6$ (Konno et al. 2016). The pluses represent the best-fit values while the contours indicate their 68% and 90% confidence levels. Redshift is coded by color: orange, $z = 0.3$; magenta, 0.9; red, 2.2; blue, 3.1; cyan, 3.7; green, 5.7. Bottom: Ly$\alpha$ luminosity functions at $z \sim 0 - 6$ (Konno et al. 2016). The curves indicate the best-fit Ly$\alpha$ luminosity functions, with the same color code as the top panel. The red and blue circles show the data points of the Ly$\alpha$ luminosity functions at $z = 2.2$ and 3.1, respectively. This figure is reproduced by permission of the AAS.
The first evolutionary trend is an increase found at \( z \approx 0 - 3 \) (Deharveng et al. 2008; Cowie et al. 2010). It is notable that the abundance of \( z = 0.3 \) LAEs is very low with \( \phi_{\text{Ly}^\alpha}^* = 1 \times 10^{-14} \text{ Mpc}^{-3} \), about 50 times lower than that of \( z \approx 0 \) SDSS optical-continuum selected galaxies, \( \phi^* = 5 \times 10^{-3} \text{ Mpc}^{-3} \) (Blanton et al. 2001), meaning that LAEs are very rare in the local universe (Deharveng et al. 2008). The top panel of Figure 21 suggests that over \( z = 0.3 \) and \( z = 2.2 \) the increase is statistically more significant in Ly\( \alpha \) luminosity \( (L_{\text{Ly}^\alpha}) \) than in the normalization \( (\phi_{\text{Ly}^\alpha}^*) \). The evolution of the Ly\( \alpha \) luminosity function is also quantified with the Ly\( \alpha \) luminosity density,

\[
\rho_{\text{Ly}^\alpha} = \int_{L_{\text{Ly}^\alpha}^\text{lim}}^\infty L_{\text{Ly}^\alpha} \phi_{\text{Ly}^\alpha}(L_{\text{Ly}^\alpha}) dL_{\text{Ly}^\alpha},
\]

where \( L_{\text{Ly}^\alpha} \) and \( L_{\text{Ly}^\alpha}^\text{lim} \) are the Ly\( \alpha \) luminosity and the limiting Ly\( \alpha \) luminosity, respectively. For reference, the UV continuum luminosity density \( \rho_{\text{UV}} \) is defined by

\[
\rho_{\text{UV}} = \int_{L_{\text{UV}}^\text{lim}}^\infty L_{\text{UV}} \phi_{\text{UV}}(L_{\text{UV}}) dL_{\text{UV}},
\]

where \( \phi_{\text{UV}}(L_{\text{UV}}) \), \( L_{\text{UV}} \), and \( L_{\text{UV}}^\text{lim} \) are the UV-continuum luminosity function, the UV-continuum luminosity, and the limiting UV-continuum luminosity, respectively. Figure 22 compares the evolutions of Ly\( \alpha \) and UV-continuum luminosity densities, where the latter is derived with UV-continuum selected galaxies (Tresse et al. 2007). Figure 22 clearly shows that, from \( z \approx 0 \) to 3, the Ly\( \alpha \) luminosity density increases by a factor of \( \sim 20 - 30 \), which is significantly faster than the UV-continuum luminosity density evolution (a factor of \( \sim 5 - 7 \); Deharveng et al. 2008; Cowie et al. 2010). Similarly, in the same redshift range, the Ly\( \alpha \) luminosity density increases even faster than the cosmic SFR density (a factor of \( \sim 10 \)) on the Madau-Lilly plot (Madau & Dickinson 2014), indicating that the Ly\( \alpha \) luminosity density evolution cannot be explained by the cosmic SFR density evolution alone.

The second evolutionary trend is that the Ly\( \alpha \) luminosity function is nearly constant over \( z \approx 3 - 6 \) (Ouchi et al. 2008). In contrast, the UV-continuum luminosity function of UV continuum-selected LBGs decreases from \( z \approx 3 \) to 6 and beyond, indicating that Ly\( \alpha \) emitting galaxies dominate in number more at \( z \approx 6 \) than at \( z \approx 3 \) (Ouchi et al. 2008). Indeed, deep spectroscopic surveys for UV-continuum selected LBGs suggest that the Ly\( \alpha \) emitting galaxy fraction increases from \( x_{\text{Ly}^\alpha} \approx 0.3 \) to 0.5 over \( z = 4 - 6 \) for galaxies with an absolute UV magnitude \( M_{\text{UV}} \) range of \( -20.25 < M_{\text{UV}} < -18.75 \) corresponding to \( < L_{\text{Ly}^\alpha}^\text{lim} \) (the left panel of

---

4 In this panel, the data for \( z = 0.9 \) has a very low \( \phi_{\text{Ly}^\alpha}^* \) value that does not fall in the interpolation of the best-fit \( \phi_{\text{Ly}^\alpha}^* \) values between \( z = 0.3 \) and \( z = 2 - 3 \). Although the Ly\( \alpha \) luminosity function may have a truly very low \( \phi_{\text{Ly}^\alpha}^* \) value at \( z \approx 1 \), there remains a possibility that the \( z = 0.9 \) Ly\( \alpha \) luminosity function could be biased toward a high \( L_{\text{Ly}^\alpha}^\text{lim} \), which gives a low \( \phi_{\text{Ly}^\alpha}^* \) value. In fact, this \( z = 0.9 \) Ly\( \alpha \) luminosity function is derived only with bright LAEs (Barger et al. 2012). The result of the Ly\( \alpha \) luminosity function at \( z \approx 1 \) is still under debate.

5 The wavelength of the UV continuum is often chosen at the far UV wavelength of \( \sim 1500 \text{Å} \) in the rest frame that is longer than the Ly\( \alpha \)-line wavelength.
Figure 22. Lyα-luminosity density (red triangles) and UV-continuum luminosity density (blue diamonds) as a function of redshift (Cowie et al., 2010). This figure is reproduced by permission of the AAS.

In other words, about a half of $L_{\text{UV}}$-LBGs at $z \sim 6$ are LAEs with $EW_0 > 25$ Å. This $x_{\text{Ly} \alpha}$ evolution result indicates an increase with redshift in either the fraction of Lyα emitting galaxies or the Lyα luminosity of galaxies or both. Allowing both $\phi_{\text{Ly} \alpha}$ and $L_{\text{Ly} \alpha}$ to evolve, one can derive the number- and luminosity-weighted average Lyα escape fraction $\langle f_{\text{esc}}^{\text{Ly} \alpha} \rangle$ from the Lyα luminosity density (Equation 9) as:

$$\langle f_{\text{esc}}^{\text{Ly} \alpha} \rangle = \frac{\rho_{\text{Ly} \alpha}}{\rho_{\text{int}}}$$

where $\rho_{\text{Ly} \alpha}$ is the intrinsic Lyα luminosity density expected from the cosmic SFR density $\Psi_{\text{SFR}}$ (e.g., Madau & Dickinson 2014). The intrinsic Lyα luminosity density can be estimated by $\rho_{\text{Ly} \alpha}^\text{int} [\text{erg s}^{-1}\text{Mpc}^{-3}] = 1.1 \times 10^{42} \Psi_{\text{SFR}} [\text{M}_\odot\text{yr}^{-1}\text{Mpc}^{-3}]$ under the assumption of the case B recombination ($L_{\text{Ly} \alpha}/L_{\text{H} \alpha} = 8.7$; Brocklehurst 1971) and the Hα luminosity $L_{\text{H} \alpha}$-SFR relation of Kennicutt (1998a). Figure 24 presents $\langle f_{\text{esc}}^{\text{Ly} \alpha} \rangle$ as a function of redshift (Hayes et al. 2011a), and indicates a monotonic increase in $\langle f_{\text{esc}}^{\text{Ly} \alpha} \rangle$ from $z \sim 0$ to 6.

Here I address the issue whether all of these observational results at $z \sim 3 - 6$ are self-consistent. Observations of UV-continuum selected galaxies show that faint UV-continuum galaxies have a higher chance of emitting strong Lyα in this redshift range (right panel of Figure 23; Ando et al. 2006; Stark et al. 2011). In other words, a majority of LAEs are faint UV-continuum galaxies. Although the abundance of bright ($> L^*$) UV-continuum galaxies drops significantly, the abundance of faint UV-continuum galaxies does not largely decrease towards high-$z$, due to a steepening of the luminosity function slope $\alpha$ (Bouwens et al. 2015). Because the abundance of LAEs is linked to the one of faint UV-continuum galaxies, the Lyα luminosity function of LAEs does not evolve largely over $z \sim 3 - 6$. In this way, all observational results suggest a self-consistent physical picture.
Because LAEs become a more dominant population at $z \sim 6$ than at $z \sim 3$, LAEs contribute much to the cosmic SFR density at $z \sim 6$. Figure 25 presents the evolution of the cosmic SFR density (Ciardullo et al. 2012). The contribution of LAEs is only 1/10 of the total cosmic SFR density at $z \sim 3$ while it becomes the whole of it at $z \sim 6$. If this trend continues at $z \gtrsim 6$ (i.e. the EoR), LAEs may be a major population that emit ionizing photons for cosmic reionization. Thus, it is probably important to study LAEs to understand the physical properties of ionizing sources for cosmic reionization, although a large fraction of Ly$\alpha$ photons from LAEs (galaxies with intrinsically strong Ly$\alpha$ emission) may not reach observers due to absorption by neutral hydrogen in the IGM at the EoR (see Section 6 for details of reionization sources).

An interesting approach to estimate the cosmic SFR density has been proposed by Croft et al. (2016). It is based on the so-called intensity mapping technique, and consists in determining the power spectrum of diffuse Ly$\alpha$ emission from star-forming galaxies that are too faint to be detected individually, but numerous enough to yield a significant signal in a statistical sense. Croft et al. (2016) have found that...
Fig. 24  Average Ly\(\alpha\) escape fraction as a function of redshift (Hayes et al., 2011a). The black symbols indicate average Ly\(\alpha\) escape fraction estimates based on various observational results while the red line is the best-fit power law function to them. This figure is reproduced by permission of the AAS.

Fig. 25  Cosmic SFR density as a function of redshift (Ciardullo et al., 2012). The data points with error bars represent the LAEs’ contribution to the cosmic SFR density, while the gray region indicates the total cosmic SFR density estimated with LBGs corrected for dust extinction. This figure is reproduced by permission of the AAS.

The cosmic SFR density at \(z = 2 - 3.5\) estimated from diffuse Ly\(\alpha\) emission is about 30 times higher than those by Ciardullo et al. (2012) and comparable to (or higher than) the dust-extinction corrected total cosmic SFR density. Because some amount of Ly\(\alpha\) emission should be absorbed by dust, this result may be overestimating the true cosmic SFR density. Although being a powerful important technique, intensity mapping requires a very careful evaluation of systematics. Recently, Croft et al.
Masami Ouchi (2018) have updated the analysis with the systematics removals, reducing the intensity measurement of the diffuse Ly\(\alpha\) emission by a factor of 2. [Croft et al. (2018)] find that there is no correlation between the diffuse Ly\(\alpha\) emission and the Ly\(\alpha\) forest, and show that the diffuse Ly\(\alpha\) emission is not explained by faint star-forming galaxies, but fluorescence Ly\(\alpha\) emission around QSOs in a scale up to \(15h^{-1}\) Mpc.

### 3.3 Morphology

It has been known that LAEs are generally very compact since first revealed by HST in the mid 90’s ([Pascarelle et al. 1996a,b] Figure 26). Deep HST images reveal small effective radii, \(r_e\), in rest-frame UV and optical continua, \(\sim 1\) kpc on average ([Malhotra et al. 2012] [Paulino-Afonso et al. 2018] [Shibuya et al. 2018c]). The radial profiles of the rest-frame UV and optical continua typically show a disk morphology with a Sérsic index \(n\) of \(n \sim 1\), and follow the \(r_e\)-magnitude relation similar to the one of LBGs, indicating that faint continuum LAEs have a small size in \(r_e\) (Figure 27) [Paulino-Afonso et al. 2018] [Shibuya et al. 2018c]. Because a majority of LAEs have a faint continuum, the \(r_e\)-magnitude relation can explain the compact morphologies of LAEs.

Although previous HST studies claim no redshift evolution of \(r_e\) on average, a recent HST study ([Shibuya et al. 2018c]) finds that the no-redshift evolution results may be produced by the sample selection bias. If a sample selection is not controlled, one can identify more LAEs with a faint continuum at low redshift. Because LAEs with a faint continuum have a \(r_e\) value smaller than LAEs with a bright continuum due to the \(r_e\)-magnitude relation, \(r_e\) measurements of low-redshift LAEs are typically small, diminishing the trend of the redshift evolution. Figure 28 shows the median \(r_e\) value as a function of redshift that is obtained with the controlled samples whose LAEs fall in the same continuum luminosity range ([Shibuya et al. 2018c]). The median \(r_e\) value monotonically decreases as \(\sim (1 + z)^{-1}\) for a given continuum luminosity ([Shibuya et al. 2018c]). This evolutionary trend of LAEs is similar to the one of LBGs (e.g. [Shibuya et al. 2015]).

The compact morphology of LAEs is not only found in continua, but also in Ly\(\alpha\) emission by HST narrowband imaging studies ([Bond et al. 2010] [Finkelstein et al. 2011b]). It should be noted that deeper narrowband-imaging and spectroscopic observations identify very diffuse extended (\(\gtrsim 10\) kpc) Ly\(\alpha\) halos around LAEs that are detailed in Section 4 ([Hayashino et al. 2004] [Steidel et al. 2011] [Patrício et al. 2016] [Wisotzki et al. 2016]). A combination of these observational studies indicates that the spatial structure of Ly\(\alpha\) emission of LAEs is composed of a peaky Ly\(\alpha\) core and a diffuse Ly\(\alpha\) halo (see also [Leclercq et al. 2017]).
Fig. 26  HST images of three LAEs dubbed CHa-2, CH8-1, and CH8-2 at $z = 4.4$ (Finkelstein et al. (2011b)); from left to right, narrowband $F658N$, narrowband $F658N$ corrected for the charge-transfer effect, $B_{435}$, $V_{606}$, and $i_{775}$. The $F658N$ band includes the redshifted Ly$\alpha$ emission of the LAEs. The centers of the black circles indicate the centroids of the LAEs in the $F658N$ band. See Finkelstein et al. (2011b) for more details. This figure is reproduced by permission of the AAS.
Fig. 27  Left: Radial profile of UV-continuum surface brightness obtained with the HST images [Shibuya et al. 2018c]. The red shade represents the radial profile of the composite LAE with the 1σ uncertainty. The composite LAE consists of LAEs with $0.12 - 1L_{z=3}^*$ at $z = 0 - 7$, where $L_{z=3}^*$ is the characteristic luminosity of the Schechter function for the UV luminosity function at $z = 3$. The black solid and dashed lines indicate the Sérsic profiles with $n = 1$ and 4, respectively. The gray line denotes the radial profile of the point-spread function (PSF). Right: Size-magnitude ($r_e$-magnitude) relation [Shibuya et al. 2018c]. The top two panels show the size-magnitude relations in the rest-frame optical wavelength, while the bottom two panels present those in the rest-frame UV wavelength. The red and cyan circles represent LAEs and continuum-selected star-forming galaxies, respectively, where the error bars indicate the 16th- and 84th-percentiles of the $r_e$ distribution. The red dots indicate the size and magnitude measurements of individual LAEs. The cyan dotted lines are the power law functions best fit to the data points of the cyan circles. The gray symbols represent the measurements for LAEs obtained in the other studies. This figure is reproduced by permission of the AAS.
3.4 ISM Properties

Hydrogen in the ISM has three gas phases: H$^+$ ions, H atoms, and H$_2$ molecules. Corresponding to these three phases, the ISM is classified into three regions: HII regions (H$^+$), photodissociation regions (PDR; H), and molecular regions (H$_2$) whose gas temperatures are $\sim 10^4$, $10^2 - 10^3$, and $10^1 - 10^2$ K, respectively (Figure 29).
In local galaxies, most of the ISM is in PDRs, where UV radiation from stars photodissociates molecules. However, PDRs have large spatial variations of temperature and density (Figure 29), making it difficult to understand PDR properties by simple modeling. Moreover, there are many atomic and molecular transitions in PDRs as well as in molecular regions. In contrast, HII regions are moderately homogeneous media with a small number of ionization transitions, and thus can be modeled more simply than PDRs and molecular regions. It should also be noted that HII regions radiate emission lines falling in optical wavelengths where ground-based deep spectroscopy is possible. These emission lines enable us to constrain
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physical parameters of HII regions such as gas-phase metallicity, electron temperature $T_e$, ionization parameter $q_{ion}$, and electron density $n_e$.

Although it is difficult to characterize ISM properties of LAEs that are generally faint, recent LAE observations have constrained the gas-phase metallicity and ionization parameter in HII regions. Moreover, there are some useful observations to constrain parameters of atomic gas and dust mainly found in PDRs and molecular regions. Below I explain observational results as well as the methods used to probe the ISM properties.

3.4.1 Gas-Phase Metallicity

One of the most important ISM quantities that characterize galaxies is the gas-phase metallicity of HII regions. The metallicity of a galaxy is estimated from the ratio of appropriate lines using photoionization models. Depending on the strength of the lines used, there are two methods: the direct $T_e$ method and the strong emission line method. Note that all of the line ratios discussed below are corrected for dust extinction.

Direct $T_e$ Method

The direct $T_e$ method mainly uses weak lines sensitive to electron temperature, OIII]1661,1666, [OIII]4363, [Nii]5755, and [Oii]7320,7330 etc. Because the most popular line among these is the auroral [OIII]4363 line, below I explain the direct $T_e$ method with this line.

One can estimate $T_e$ from $f_{[OIII]4959} + f_{[OIII]5007}$ and $f_{[OIII]4363}$ using the following equation:

$$\frac{f_{[OIII]4959} + f_{[OIII]5007}}{f_{[OIII]4363}} = \frac{7.90 \times 3.29 \times 10^4 / T_e}{1 + 4.5 \times 10^{-4} n_e / T_e^{1/2}},$$

(12)

with a small uncertainty depending on $n_e$ (left panel of Figure 30; Osterbrock 1989). The $T_e$ value is determined by the ratio $(f_{[OIII]4959} + f_{[OIII]5007})/f_{[OIII]4363}$, because the [Oii]4363 ([OIII]4959,5007) flux increases (decreases) when the rate of collisional excitation (de-excitation) from $^1D_2$ to $^1S_0$ (from $^1D_2$ to $^3P$) increases with $T_e$ (right panel of Figure 30). Because metals are major coolants of the gas in HII regions, $T_e$ is primarily determined by metallicity. Therefore, if $T_e$ is estimated, one can reliably derive the metallicity based on photoionization models (Izotov et al., 2006).

$$12 + \log \frac{O^+}{H^+} = \log \frac{f_{[OIII]3727}}{f_{H\beta}} + 5.961 + \frac{1.676}{t_2} - 0.40 \log t_2 - 0.034 t_2 + \log(1 + 1.35 x),$$

(13)

Note that electrons stay at $^1D_2$ significantly longer than $^3P$. 

---

Note: This text is a summary and does not include all the details of the original document. It focuses on the key points related to the gas-phase metallicity and the direct $T_e$ method.
Fig. 30  Left: Line ratios as a function of electron temperature (Osterbrock, 1989). The second top curve indicates the line ratio \( \frac{f_{\text{OIII\,4959}} + f_{\text{OIII\,5007}}}{f_{\text{OIII\,4363}}} \), while the other curves show line ratios that are not discussed in the text. Right: Schematic diagram presenting the quantum states \( ^1S_0, \, ^1D_2, \) and \( ^3P \) of an \( \text{O}^{2+} \) ion and emission lines produced by transitions between two states (Osterbrock, 1989). The solid and dashed-line arrows represent permitted and forbidden lines, respectively. This figure is reproduced by permission of the University Science Books.

\[
12 + \log \frac{\text{O}^{2+}}{\text{H}^+} = \log \frac{f_{\text{OIII\,4959}} + f_{\text{OIII\,5007}}}{f_{\text{H}\beta}} + 6.200 + \frac{1.251}{t_3} - 0.55 \log t_3 - 0.014 t_3, \tag{14}
\]

where

\[
t_2 = 10^{-4} T_e [\text{OII}], \tag{15}
\]
\[
t_3 = 10^{-4} T_e [\text{OIII}], \tag{16}
\]
\[
x = 10^{-4} n_e t_2^{-0.5}, \tag{17}
\]

and \( \text{O}^+, \, \text{O}^{2+}, \) and \( \text{H}^+ \) are the abundances of singly-ionized oxygen, doubly-ionized oxygen, and ionized hydrogen, respectively; \( T_e [\text{OII}] \) and \( T_e [\text{OIII}] \) are the electron temperatures in \( \text{O}^+ \) and \( \text{O}^{2+} \) ion gas. For simplicity, one can assume the relation (Campbell et al., 1986; Garnett, 1992)

\[
t_2 = 0.7 t_3 + 0.3 \tag{18}
\]

that generally does not change the metallicity estimate. Because the last term of eq. \((13)\), \( \log (1 + 1.35x) \), is negligibly small, this term can be practically omitted.

The oxygen abundance is calculated with

\[
\frac{\text{O}}{\text{H}} = \frac{\text{O}^+}{\text{H}^+} + \frac{\text{O}^{2+}}{\text{H}^+}. \tag{19}
\]
It should be noted that the contribution of O$^{3+}$ and higher-order ionized oxygen is negligibly small, only < 1%, in HII regions heated by stars.

**Strong Emission Line Method**

The strong emission line method uses flux ratios of major emission lines of star-forming galaxies that include [OII]3727, Hβ4861, [OIII]5007, Hα6563, and [NII]6584. One of the most frequently used line ratios is the $R_{23}$ index defined by:

$$R_{23} = \frac{f_{\text{[OII]}3727} + f_{\text{[OIII]}4959} + f_{\text{[OIII]}5007}}{f_{\text{H}^\beta}}. \quad (20)$$

The top panel of Figure 31 presents $R_{23}$ as a function of oxygen abundance. The solid lines in this panel show $R_{23}$-oxygen abundance relations calculated by photoionization models with different ionization parameter ($q_{\text{ion}}$) values. Here, $q_{\text{ion}}$ is defined by

$$q_{\text{ion}} = \frac{Q_{\text{H}_0}}{4\pi R_s^2 n_H}, \quad (21)$$

where $Q_{\text{H}_0}$ is the number of hydrogen ionizing photons produced per unit time, $R_s$ is the Strömgren radius, and $n_H$ is the hydrogen density. Because $R_{23}$ strongly depends on $q_{\text{ion}}$ (see the top panel of Figure 31), one needs to empirically calibrate the $R_{23}$-oxygen abundance relation with local galaxies that have $R_{23}$ and oxygen abundance measurements from the direct $T_e$ method. In the top panel of Figure 31 the star marks with error bars denote the average values of the local galaxies, and the dashed line is an empirical relation that fits the star marks. In this way, a locally calibrated empirical relation is used to derive oxygen abundances from $R_{23}$ measurements. However, it should be noted that the oxygen abundances of high-z galaxies estimated in this manner have systematic errors because ISM properties of high-z galaxies including $q_{\text{ion}}$ are different from those of local galaxies (Nakajima & Ouchi, 2014).

The top panel of Figure 31 shows a degeneracy in all $R_{23}$-oxygen abundance relations because there are basically two possible oxygen abundances for a given $R_{23}$ measurement. This is because $R_{23}$ increases with increasing metallicity up to $\sim 1Z_{\odot}$, while at higher metallicities fine-structure cooling emission in far-infrared (FIR) wavelengths dominates and reduces the collisionally excited line fluxes of [OII] and [OIII] that are the numerators of $R_{23}$. To resolve this degeneracy, one can use the $N2$ index defined by:

$$N2 = \frac{f_{\text{[NII]}6584}}{f_{\text{H}^\alpha}}. \quad (22)$$

The bottom panel of Figure 31 displays photoionization model calculations (solid lines), local galaxy averages (star marks), and an empirical $N2$-oxygen abundance relation that fits the local galaxy averages (dashed line). Since the $N2$ index does not include oxygen line measurements i.e. only $f_{\text{[NII]}6584}$ and $f_{\text{H}^\alpha}$, oxygen abundances from the $N2$ index have a systematic uncertainty due to a possible variation of the nitrogen-to-oxygen abundance ratio, implying that the $N2$ index alone is not a good
Fig. 31 $R_{23}$ ($N_2$) index as a function of oxygen abundance presented in the top (bottom) panel [Nagao et al. 2006]. The star marks denote local galaxy averages obtained by the direct $T_e$ method, and the dashed line represents an empirical fit to them. The solid lines show photoionization model calculation results with the normalized ionization parameter, $U \equiv q_{ion}/c$, of $\log U = -3.8, -3.5, -3.2, -2.9, -2.6, -2.3,$ and $-2.0$ from bottom to top (top to bottom) in the top (bottom) panel. The dotted lines indicate solar metallicity. This figure is reproduced by permission of the Astronomy & Astrophysics journal.

estimator of oxygen abundance. However, one can obtain a coarse oxygen abundance estimate from an $N_2$ index (eq. [22]) measurement that is useful to resolve the degeneracy of the $R_{23}$-oxygen abundance relation discussed above. Once the degeneracy is resolved by the $N_2$ index, a single solution of oxygen abundance can be obtained from the $R_{23}$ index.

Because the strong emission line method does not use weak lines such as the [OIII]4363 auroral line whose flux intensity is only $\sim 1/70$ of [OIII]5007 [Izotov...
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et al., 2006), it can efficiently estimate the metallicities of faint galaxies including LAEs. However, as described above, one should keep in mind that abundances based on the strong emission line method would be biased if the ISM properties of galaxies in question are different from those of local calibrators.

Metallicity Estimates of LAEs

Although it is difficult to determine the metallicity of LAEs due to their faintness, some constraints have been obtained for a small number of LAEs. Finkelstein et al. (2011a) have obtained upper limits of $Z < 0.17Z_\odot$ and $< 0.28Z_\odot$ for two LAEs with the spectroscopic $N2$ index (see also Guaita et al., 2013), while Nakajima et al. (2012) have placed a lower limit of $Z > 0.09Z_\odot$ for a stack of 105 LAE narrow-band images that cover $[OII]3727$, $[NII]6584$, and H$\alpha$ lines based on a combination of two strong line methods, the $N2$ index and the $[OII]/H\beta$ index (Nagao et al., 2006). Nakajima & Ouchi (2014) have examined the metallicities of 6 LAEs at $z = 2 - 3$ with the $R23$ index and the ratio of $[OIII]5007$ to $[OII]3727$ fluxes, and found that they fall in the range of $12 + \log(O/H) = 7.98 - 8.81$, with an average of $Z \sim 0.5Z_\odot$. These metallicity constraints generally agree with the mass metallicity relation (Finkelstein et al., 2011a) and an extrapolation of the SFR-mass metallicity relation to low mass of star-forming galaxies at similar redshifts (Nakajima et al., 2012).

More recently, Kojima et al. (2017) have measured the oxygen abundances of LAEs by the direct $T_e$ method (left panel of Figure 32), to show that one LAE (and five lensed LAEs) has (have) a metallicity (metallicity range) of $Z = 0.26^{+0.08}_{-0.07}Z_\odot$ ($Z = 0.1 - 0.3Z_\odot$). The right panel of Figure 32 presents oxygen abundance and ionization parameter measurements for the one LAE and four lensed LAEs, after carefully removing one lensed LAE (ID 6) whose value, $Z = 0.1Z_\odot$, is based on unreliable flux estimates. These results by the direct $T_e$ method and the strong line method suggest that the gas-phase metallicity of LAEs at $z \sim 2 - 3$ is typically $Z \sim 0.1 - 0.5Z_\odot$ (Table 1). So far, no extremely metal poor LAEs with $Z \lesssim 0.01Z_\odot$ have been identified. However, because most of the LAEs with metallicity estimates are moderately bright, there remains a possibility that very metal poor LAEs are found in future studies targeting faint objects.

7 Here, a solar metallicity of $\log(Z/Z_\odot) = 12 + \log(O/H) - 8.69$ is assumed (Asplund et al., 2009).
3.4.2 Ionization State

The ionization state of typical LAEs’ H\textsc{ii} regions is clearly different from those of other types of high-$z$ galaxies. Recent optical-NIR spectroscopy has revealed that the $O_{32}$ ratios of $z \sim 2–3$ LBGs and LAEs are significantly higher than those of local SDSS galaxies (left panel of Figure 33; Nakajima et al. 2013; Nakajima & Ouchi 2014), where the $O_{32}$ ratio is defined by

$$O_{32} = \frac{f(\text{[OIII]}5007)}{f(\text{[OII]}3727)}.$$  \hspace{1cm} (23)

Specifically, LAEs have extremely large values of $O_{32} \sim 10$, being about $10–100$ times higher than those of the local SDSS galaxies and even higher than those of the LBGs on average. In the left panel of Figure 33, photoionization models with various metallicity and $q_{\text{ion}}$ values are compared with LAEs. Although the models predict that $O_{32}$ increases with decreasing metallicity, the high $O_{32}$ values of LAEs cannot be explained by models that reproduce the local SDSS galaxies with $q_{\text{ion}} = 0.1 – 1 \times 10^8$ cm s$^{-1}$. The $z \sim 2–3$ LAEs are found to have $q_{\text{ion}} = 1 – 9 \times 10^8$ cm s$^{-1}$, about an order of magnitude larger than those of the local SDSS galaxies (Nakajima & Ouchi 2014). The left panel of Figure 33 also shows that there exist
local counterparts to LAEs, green pea galaxies (GPs; Cardamone et al. 2009; Jaskot & Oey 2014), whose $O_{32}$ and $R_{23}$ values are comparable with those of LAEs.

The physical origin of the high $q_{\text{ion}}$ values of LAEs is not well understood. The ionization parameter defined by eq. (21) is rewritten as

$$q_{\text{ion}}^3 \propto Q_{H_0} n_H \varepsilon^2$$ \hspace{1cm} (24)

by the substitution of the Strömgren radius. Here, the Strömgren radius $R_s$ is defined as

$$Q_{H_0} = \frac{4}{3} \pi R_s^3 n_H \alpha_B \varepsilon$$ \hspace{1cm} (25)

with the coefficient of the total hydrogen recombination to the $n > 1$ levels $\alpha_B$, where $\varepsilon$ is the volume filling factor of the Strömgren sphere. Eq. (24) indicates that either $Q_{H_0}$, $n_H$, or $\varepsilon$ needs to increase by a factor of $10^3$, $10^3$, or 30, respectively, to explain the high $q_{\text{ion}}$ values of LAEs. With a moderately high SFR and metal-poor young stellar population, LAEs produce ionizing photons more efficiently than the local SDSS galaxies. However, it may not be possible that the $Q_{H_0}$ of LAEs are $\sim 10^3$ times higher than those of the local SDSS galaxies. Some studies have reported an increase in the electron density from $\sim 25$ cm$^{-3}$ ($z \sim 0$) to $\sim 250$ cm$^{-3}$ ($z \sim 2$; Steidel et al. 2014; Shimakawa et al. 2015; Sanders et al. 2016), but these increase rates are not as high as $10^3$ times. It is also unlikely that the average $\varepsilon$
increases by a factor of 30 from $z \sim 0$ to 2. I discuss the issue of high $q_{\text{ion}}$ at the end of this subsection.

Some other observations also suggest that LAEs have high $q_{\text{ion}}$ values. LAEs with a large Ly$\alpha$ $EW_0$ tend to have high-ionization metal lines in rest-frame UV spectra. Stark et al. (2014) have identified moderately strong C$\text{II}\lambda 1901,1909$ lines in lensed LAEs at $z \sim 2$ by deep spectroscopy, and revealed a positive correlation between Ly$\alpha$ and C$\text{III}\lambda 1901,1909$ $EW_0$. The left panel of Figure 34 suggests that high-ionization lines C$\text{II}\lambda 1901,1909$ are strong for large-Ly$\alpha$ $EW_0$ galaxies such as LAEs. Highly ionized gas containing C$^2+$ is probably more abundant in LAEs compared to other types of galaxies. Subsequently, Stark et al. (2015a) and Stark et al. (2015b) have reported the detections of moderately strong lines of C$\text{III}\lambda 1907,1909$ lines in two LAEs at $z = 6 - 7$ and C$\text{IV}\lambda 1548$ line in an LAE at $z = 7$, respectively. Although there still remains the possibility that the C$\text{IV}\lambda 1548$ line is produced by a hidden AGN, not by young, massive stars (e.g. detection of N$\text{V}\lambda 1239$ for the definitive AGN identification; Laporte et al. 2017), these spectroscopic results suggest that ionization state of LAEs at $z = 2 - 7$ is very high.

Most of the ALMA studies of LAEs have targeted the [C$\text{II}$$\lambda 158\mu\text{m}$ fine structure line that originates from low-ionization C$^+$ gas. Because C has a lower ionization potential than H, it is thought that the majority of [C$\text{II}$$\lambda 158\mu\text{m}$ photons are produced in PDRs that extend beyond H$\text{II}$ regions. These ALMA studies have found that LAEs have significantly fainter [C$\text{II}$$\lambda 158\mu\text{m}$ luminosities $L_{\text{CII}}$ than local galaxies with similar SFRs (right panel of Figure 34; Ouchi et al. 2013; Ota et al. 2014; Knudsen et al. 2016).
Fig. 35  Left: Observed SED of EGS-zs8-2 at \( z = 7.48 \) (red circles: Roberts-Borsani et al. 2016). The blue line denotes the best-fit SED model with nebular emission lines. The open diamonds are the expected photometry in the photometric bands for the best-fit SED. The vertical dashed lines mark the wavelengths of major nebular emission lines. The observed flux density at 4.5 \( \mu \text{m} \) shows an excess that is probably made by strong \([\text{O}\text{III}]\)4959,5007 and \( \text{H} \beta \) line emission. Right: \([\text{O}\text{III}]\)88\( \mu \text{m} \) (top) and \( \text{Ly}\alpha \) lines of SXDF-NB1006-2 (Inoue et al., 2016). The dotted line denotes the 1\( \sigma \) noise level. The blue and purple dashed lines represent the line-peak velocities of \([\text{O}\text{III}]\)88\( \mu \text{m} \) and \( \text{Ly}\alpha \), respectively. The red curve in the top panel indicates the best-fit Gaussian function to the \([\text{O}\text{III}]\)88\( \mu \text{m} \) line. The gray regions in the bottom panel show the wavelength range with large sky subtraction systematics. This figure is reproduced by permission of the AAS and Science.
of a density-bounded nebula, compared with an ionization-bounded nebula that is the standard picture of HII regions. In the standard picture, the size of an ionized nebula is determined by the number of ionizing photons, which corresponds to the radius of the Stromgren sphere (eq. [25]). On the other hand, the size of a density-bounded nebula is determined by the amount of atomic gas around the ionizing source. In contrast with an ionization-bounded nebula, a density-bounded nebula does not have an outer shell of ionized hydrogen gas emitting low-ionization lines such as [OII]3727, but an inner shell of ionized hydrogen gas producing high-ionization lines such as CIII]1907,1909, [OIII]5007, and [OIII]88m. Moreover, PDRs, major sources of [CII]158m emission, are not well developed. The density-bounded nebula scenario explains the high O32 ratio (i.e. high qion) and the weak [CII]158m emission. If this scenario applies to LAEs, ionizing photons escape easily from the ISM of LAEs. Such ionizing photons can be major sources of cosmic reionization (Nakajima & Ouchi 2014; Jaskot & Oey 2014, Section 6.3.2). Although this scenario should be tested by theoretical models and more observations, it is interesting that the ISM state of LAEs may be important for the understanding of cosmic reionization.

3.4.3 Dust and Extinction

Stellar population analyses of LAEs suggest that the dust extinction of stellar continuum emission is as low as $E(B-V)_s \simeq 0 - 0.2$ on average under the assumption of Calzetti’s extinction law (Calzetti et al. 2000, Section 3.1). One can also estimate the color excess of nebular lines, $E(B-V)_{neb}$, with the Balmer decrement. Note that $E(B-V)_{neb}$ is not necessarily the same as $E(B-V)_s$, because nebular lines originate from star-forming regions that are generally dustier than other regions in the galaxy. Calzetti et al. (2000) claim that local starbursts have $E(B-V)_{neb} = E(B-V)_s / 0.44$, although the relation between $E(B-V)_{neb}$ and $E(B-V)_s$ for high-z galaxies is poorly understood.

With a Balmer decrement measurement, Hα/Hβ, the dust extinction of nebular lines is estimated with

$$E(B-V)_{neb} = \frac{2.5}{k_{H\beta} - k_{H\alpha}} \log\left(\frac{H\alpha/H\beta}{2.86}\right),$$

(26)

where $k_{H\alpha}$ and $k_{H\beta}$ are coefficients depending on the dust extinction law. The Calzetti extinction law gives $k_{H\alpha} = 3.325$ and $k_{H\beta} = 4.598$ (Momcheva et al. 2013, Kashino et al. 2013). Here, $H\alpha/H\beta = 2.86$ is an intrinsic (i.e., dust-free) line ratio at $T_e = 10^4$ K and $n_e = 10^2$ cm$^{-3}$ for the case B recombination (Osterbrock & Ferland 2006). Since the Hβ fluxes of LAEs are generally too faint to detect (e.g. Guaita et al. 2013), only a small number of LAEs have $E(B-V)_{neb}$ measurements; they fall in the range of $E(B-V)_{neb} = 0 - 0.2$ (Kojima et al. 2017). So far, there are no studies of $E(B-V)_{neb}$ statistics nor of the relation between $E(B-V)_{neb}$ and
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$E(B-V)$ for LAEs (cf. Erb et al. 2016). A statistical study addressing these issues of $E(B-V)_{\text{neb}}$ should be conducted for LAEs in the near future.

The dust extinction of high-$z$ galaxies is characterized with the UV-continuum slope, $\beta$, defined by

$$f_{\lambda} = \lambda^{-\beta},$$

where $f_{\lambda}$ is the UV-continuum spectrum of the galaxy in the wavelength range $\simeq 1300 - 3000 \, \text{Å}$ (Calzetti 2001). The $\beta$ value is used as an indicator of the amount of dust extinction for moderately young star-forming galaxies such as LBGs and LAEs whose intrinsic UV-continuum slope is $\beta \simeq -2.2$.

Figure 36 presents the average $\beta$ values of LAEs with high Lyα equivalent widths $EW_0 > 50 \, \text{Å}$, and compares them with those of LBGs. The LAEs have $\beta \simeq -2$ that is significantly smaller than those of the LBGs at the same UV luminosity, suggesting that LAEs are generally dust poor. Figure 36 also indicates that UV-continuum faint LAEs and LBGs with $M_{UV} \sim -20$ have similar $\beta$ values, and probably similar extinction properties, supporting the idea that a high fraction of faint LBGs are LAEs (Section 3.2).

Fig. 36  Top: $\beta$ as a function of UV magnitude (Stark et al. 2010). The red triangles denote LAEs with $EW_0 > 50 \, \text{Å}$, while the purple circles indicate dropout galaxies at $z \sim 4$ with $EW < 50 \, \text{Å}$. The green squares and blue squares represent dropout galaxies at $z \sim 4$. Bottom: Typical uncertainties in $\beta$ measurements. This figure is reproduced by permission of the AAS.
To evaluate the dust extinction law of a galaxy, one can use the $IRX$ ratio,

$$IRX = \frac{L_{IR}}{L_{UV}},$$

(28)

where $L_{IR}$ and $L_{UV}$ are the total infrared (IR; $3 - 1000\mu m$) and UV ($\sim 1500\AA$) luminosities, respectively. The values of $L_{IR}$ can be estimated from, e.g., Spitzer/MIPS, Herschel/SPIRE, APEX/LABOCA, and ALMA photometry (Wardlow et al., 2014; Kusakabe et al., 2015; Capak et al., 2015). Figure 37 presents the $IRX$-$\beta$ relation for LAEs and LBGs at $z \sim 2$ and $5 - 6$, together with the model curves of Calzetti and SMC dust extinction. It is clear that LAEs have low $IRX$ values at a given $\beta$ on average. The left panel of Figure 37 indicates that LAEs at $z \sim 2$ have an extinction curve similar to that of the SMC and different from those of Calzetti’s local starbursts. There are three LAEs at $z = 5 - 6$ with $IRX$-$\beta$ measurements shown in the right panel of Figure 37. This panel suggests that these three LAEs have $IRX$ values which fall close to or even below the SMC curve, although these extremely low $IRX$ estimates are still under debate. However, there is a consensus based on deep ALMA observations that LAEs at $z > 5$ have faint $\sim 1$mm flux densities (Ouchi et al., 2013; Ota et al., 2014; Maiolino et al., 2015; Capak et al., 2015; Knudsen et al., 2016).

Fig. 37 $IRX$ as a function of the UV slope $\beta$ for LAEs at $z \sim 2$ (left; Kusakabe et al., 2015) and at $z \sim 5 - 6$ (right; Capak et al., 2015). Left: The red filled and open circles indicate, respectively, the upper limits of $IRX$ estimated by the stack of Spitzer/MIPS and PACS images centered at the sky positions of 213 LAEs at $z = 2.2$. The gray thin-solid, dashed, and thick-solid lines denote, respectively, the dust extinction relations of Calzetti, Takeuchi (Takeuchi et al., 2012), and the SMC. The squares (inverse-triangle) represent UV-continuum bright (and young) galaxies at $z \sim 2$. Right: The red, orange, and blue circles show the detections, the upper limits, and the average of the no-detection data for galaxies (including 3 LAEs) at $z \sim 5 - 6$. The solid and dashed lines are the $IRX$-$\beta$ relations of Calzetti and the SMC. This figure is reproduced by permission of the AAS and the Nature Publishing Group.
On average, LAEs have low extinction and low dust masses. However, there exists a rare population of dusty LAEs with red stellar SEDs and bright submm luminosities. Figure [38] shows the SEDs of two spectroscopically-confirmed LAEs (dubbed R1 and R2) at $z = 3 - 4$ which have red SEDs and strong Ly$\alpha$ emission (Ono et al. 2010a). It should be noted that some SMGs have strong Ly$\alpha$ emission that can be used for redshift determination (Chapman et al. 2005; Capak et al. 2011). How Ly$\alpha$ photons can escape from those dusty starbursts without significant extinction is an open question. Dusty LAEs might have dust-poor star-forming regions that are spatially separated from usual dust-rich star-forming regions.

![Fig. 38 SEDs of two red LAEs, R1 and R2, at $z = 3.142$ and $3.684$, respectively (Ono et al., 2010a). The squares denote photometric data obtained by deep optical and near-infrared observations. The red and blue curves represent the best-fit SED models of exponentially-decaying and constant star-formation histories, respectively; data shown by open squares are not used for the fitting because they are contaminated by either strong Ly$\alpha$ emission or the IGM Ly$\alpha$ forest absorption. This figure is reproduced by permission of MNRAS.](image)

### 3.5 Outflow and Ly$\alpha$ Profile

Using deep optical and near-infrared spectra, many researchers have investigated the velocities of the Ly$\alpha$ line, the low-ionization UV metal absorption lines, and the nebular emission lines in LAEs. The average outflow velocity $V_{\text{out}}$ of LAEs at $z \sim 2$ is estimated to be $V_{\text{out}} \simeq 200$ km s$^{-1}$ with low-ionization UV metal absorption.

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*In the Saas Fee lectures, the topics of this subsection were originally included in Section 4.2. For the readers' convenience, I have moved these topics here.*
lines blueshifted from the systemic velocity (left panel of Figure 39; Hashimoto et al. 2013; Shibuya et al. 2014b). Here, the systemic velocity is determined by strong nebular lines such as Hα that originate from HII regions. Blueshifted absorption lines are thought to form in the outflowing gas. Another important feature in line velocities is that the Lyα line peak is generally redshifted from the systemic velocity (right panel of Figure 39). The Lyα line offset \( \Delta V_{\text{Ly}\alpha} \) is defined as the offset velocity of the Lyα line peak with respect to the systemic velocity. The average Lyα line offset of \( z \sim 2 - 3 \) LAEs is \( \Delta V_{\text{Ly}\alpha} \simeq 200 \text{ km s}^{-1} \) (Mclinden et al. 2011; Hashimoto et al. 2013; Shibuya et al. 2014b; Erb et al. 2014). This average Lyα offset velocity is comparable with the average outflow velocity, \( \Delta V_{\text{Ly}\alpha} \simeq V_{\text{out}} \).

Interestingly, typical LBGs (\( L_{\text{UV}} \gtrsim L_* \)) at \( z \sim 2 - 3 \) have \( V_{\text{out}} \simeq 200 \text{ km s}^{-1} \) on average (Pettini et al. 2001; Steidel et al. 2010), being comparable with that of LAEs. However, the average Lyα offset velocity of LBGs is \( \Delta V_{\text{Ly}\alpha} \simeq 400 \text{ km s}^{-1} \), about twice as large as LAEs’ \( \Delta V_{\text{Ly}\alpha} \) (Figure 40). Note that there is a negative correlation between \( \Delta V_{\text{Ly}\alpha} \) and Lyα EW \( \text{0} \) (e.g. Figure 7 of Hashimoto et al. 2013). In contrast with LAEs, LBGs show \( \Delta V_{\text{Ly}\alpha} \simeq 2V_{\text{out}} \). The \( \Delta V_{\text{Ly}\alpha} - V_{\text{out}} \) relation is key to understanding the physical differences in LAEs and LBGs via theoretical modeling as discussed below.

![Fig. 39 Left: Average UV low ionization absorption lines for four LAEs (Shibuya et al. 2014b) obtained by stacking the Si ii1260, Cii1334, and Si ii1526 lines. The systemic velocity is determined with nebular emission lines. Right: Line profiles of Lyα (red solid line) and [OIII]5007 (black solid line) observed by McLinden et al. 2011. The red and black dotted lines represent the best-fit model profiles for the Lyα and [OIII] lines, respectively. This figure is reproduced by permission of the AAS.](image-url)
Fig. 40 Ly$\alpha$ offset velocity $\Delta v_{\text{Ly}\alpha}$ for LAEs (red histograms) and LBGs (blue histograms) (Shibuya et al. 2014b). This figure is reproduced by permission of the AAS.

Detailed Ly$\alpha$ profiles of LAEs at $z \sim 2 - 3$ are investigated by medium-high resolution spectroscopy. Such spectroscopic efforts have revealed that LAEs have a variety of Ly$\alpha$ profiles (Tapken et al. 2007; Yamada et al. 2012b; Hashimoto et al. 2015). Among those, three typical profiles are a single asymmetric/symmetric line, an asymmetric line with a weak blue peak, and a double-peak line, as presented in Figure 41.

Fig. 41 Ly$\alpha$ profiles obtained by observations (black lines) and ES modeling (blue and red lines) for three LAEs (Verhamme et al. 2008). The blue and red lines represent the best-fit spectra and the intrinsic spectra predicted by the ES models, respectively. This figure is reproduced by permission of the A&A.
Ly\(\alpha\) profiles depend on physical parameters relating to H\(\text{I}\) resonance scattering of Ly\(\alpha\), such as the H\(\text{I}\) density, gas dynamics (including outflows), and dust extinction, and are quantitatively investigated by modeling. One of the most popular models for Ly\(\alpha\) profiles is the expanding shell (ES) model (Ahn 2004; Verhamme et al. 2006). This model assumes a galaxy-scale spherical shell of outflowing gas around the Ly\(\alpha\) source that is described with four parameters: the H\(\text{I}\) column density \(N_{\text{HI}}\), the expansion (outflow) velocity corresponding to \(V_{\text{out}}\), the doppler (thermal) velocity of gas in the shell \(b\), and the optical depth of dust extinction \(\tau_{\alpha}\). The assumption that LAEs have an ES is supported by the fact that nearby starbursts have a galaxy-scale supershell made by multiple SNe in star-forming regions (Marlowe et al. 1995; Martin 1998; Kothes & Kerton 2002).

Figure 42 illustrates the ES model and predicted profiles of Ly\(\alpha\) emission escaping to the observer. The physical origins of the individual Ly\(\alpha\) profiles are explained below. The light path "3" produces the profile "3", where Ly\(\alpha\) photons travel straight to the observer. Note, however, that the profile is slightly redshifted because the blue side of the Ly\(\alpha\) emission is efficiently scattered off by the H\(\text{I}\) gas of the ES. The light path "1b" is back-scattered once by the ES, providing a strong, redshifted peak in the predicted profile. The velocity of the peak, \(\sim 2V_{\text{out}}\), is accomplished by two effects: (i) Ly\(\alpha\) photons are scattered by the gas receding with \(V_{\text{out}}\) and hence their wavelengths are redshifted by \(V_{\text{out}}\) as seen from the gas, and (ii) the gas is receding from the observer by \(V_{\text{out}}\). The light path "1c" indicates multiple scattering of Ly\(\alpha\) photons that gives the highly redshifted Ly\(\alpha\) profile, but its contribution to the total flux is small in the reasonable range of H\(\text{I}\) column density.

Fig. 42  Left: Ly\(\alpha\) profile predicted by the ES model (Verhamme et al. 2006). Here, the abscissa axis is in units of the normalized velocity of the shell defined by \(x = -2V_{\text{out}}/b\) (see text). A negative \(x\) value indicates a wavelength longer than the systemic velocity \((x = 0)\). The black line shows the total Ly\(\alpha\) line profile that can be observed. The blue, red, green, and cyan lines indicate the spectral components corresponding to the number of scattering events of none, once, twice, and 3 times. The labels 1, 3, and 2 below the spectra represent the regimes of long, systemic, and short wavelengths. Right: Illustration of the ES model (Verhamme et al. 2006). The central dot indicates the Ly\(\alpha\) source position, while the annulus made of the two black circles represents the H\(\text{I}\) gas shell. The solid, dashed, and dotted line arrows show examples of Ly\(\alpha\) photon light paths (towards the observer) that produce the spectral components whose labels correspond to those in the left panel. This figure is reproduced by permission of the A&A.
Back-scattered light dominates the total Ly$\alpha$ flux when the H$\text{i}$ column density is higher than $N_{\text{HI}} \sim 10^{20}$ cm$^{-2}$. Therefore, the velocity offset of the total flux, $\Delta V_{\text{Ly} \alpha}$, changes with $N_{\text{HI}}$ from $\Delta V_{\text{Ly} \alpha} \sim 0$ to $\sim 2V_{\text{out}}$. The value of $\Delta V_{\text{Ly} \alpha} \sim 0$ is found in low $N_{\text{HI}}$ where the majority of Ly$\alpha$ photons take the path "3", while $\Delta V_{\text{Ly} \alpha}$ has $\sim 2V_{\text{out}}$ for $N_{\text{HI}} \gtrsim 10^{20}$ cm$^{-2}$.

As demonstrated in Figure 41, the best-fit ES models reproduce the variety of Ly$\alpha$ profiles with the only four physical parameters.

The ES models also explain the $\Delta V_{\text{Ly} \alpha}$-$V_{\text{out}}$ relations of LAEs and LBGs. Because LAEs have the relation of $\Delta V_{\text{Ly} \alpha} \simeq V_{\text{out}}$, the ES models suggest that their H$\text{i}$ column density is low, $N_{\text{HI}} \lesssim 10^{20}$ cm$^{-2}$, which produces weak back-scattered Ly$\alpha$ emission (Hashimoto et al., 2013; Shibuya et al., 2014b; Hashimoto et al., 2015). In contrast, LBGs have the relation of $\Delta V_{\text{Ly} \alpha} \simeq 2V_{\text{out}}$. The ES models indicate that back-scattered Ly$\alpha$ emission dominates in LBGs, and that their H$\text{i}$ column density is $N_{\text{HI}} \sim >10^{20}$ cm$^{-2}$ on average that is higher than those of LAEs.

The low H$\text{i}$ column densities of LAEs may explain the large increase in the average Ly$\alpha$ escape fraction from $z \sim 0$ to 6 shown in Figure 24, because the fraction of LAEs in the entire galaxy population increases with redshift (Figure 23). There are six possible mechanisms that control the Ly$\alpha$ escape fraction: 1) IGM absorption, 2) stellar population, 3) outflow velocity, 4) gas-cloud clumpiness (Neufeld effect), 5) simple dust extinction, and 6) H$\text{i}$ gas resonance scattering in the ISM with dust. Because the IGM absorption is stronger at higher $z$, mechanism 1) cannot explain the increase in Ly$\alpha$ escape fraction towards high $z$. The stellar population and outflow velocity of the mechanisms 2) and 3) evolve little for LAEs in the range $z \sim 3 - 6$ (Sections 3.1 and 3.5), which are not large enough to explain the evolution of two orders of magnitude of the Ly$\alpha$ escape fraction in the range $z \sim 0 - 6$ (Figure 24). The mechanism 4) has been ruled out by recent theoretical studies (Section 4.2; Laursen et al., 2013; Duval et al., 2014).

The top left panel of Figure 43 presents the evolution of the Ly$\alpha$ escape fraction corrected for dust extinction with a simple screen model (eq. 34). This simple dust extinction evolution of the mechanism 5) is found to predict only one order of magnitude evolution of the Ly$\alpha$ escape fraction. Instead, the large evolution of the Ly$\alpha$ escape fraction can be probably explained by the mechanism 6). The mechanism 6) involves H$\text{i}$ gas evolution with the effect of dust extinction in the ISM via Ly$\alpha$ resonance scattering. To reproduce the large Ly$\alpha$ escape fraction evolution based on the ES models, it is suggested that the H$\text{i}$ column density should decrease by 1-2 orders of magnitude (Figure 43) from $z \sim 0$ to 6 that reduces the effect of selective Ly$\alpha$ absorption for LAEs towards $z \sim 6$. In this way, the H$\text{i}$ column density evolution is a major parameter of LAEs that determines not only $\Delta V_{\text{Ly} \alpha}$, but also the Ly$\alpha$ escape fraction.
Fig. 43  Top left: Evolution of the Lyα and UV luminosity densities whose absolute values are presented in the labels in the left and right ordinate axes, respectively. The red symbols and line indicate the Lyα luminosity density. The blue and orange symbols/shades represent the observed and dust-corrected UV luminosity densities, respectively. For comparison, the gray shade denotes the dust-corrected UV luminosity density scaled to the position of the Lyα luminosity density at $z \sim 3$. Bottom left: Evolution of the Lyα escape fraction derived from the observed Lyα and dust-corrected luminosity densities (red filled symbols). The best-fit function to the Lyα escape fraction evolution is shown with the magenta and the black-dashed lines obtained by Konno et al. (2016) and Hayes et al. (2011a), respectively. The blue symbols represent the Lyα escape fraction corrected for dust extinction under the simple assumption of no Lyα resonance scattering. Right: Evolution of the average HI column density of galaxies inferred from the Lyα escape fraction and the ES models (red circles). The black solid line and gray shade are the best-fit function with the outflow velocity of 150 km s$^{-1}$ and the uncertainty raised by the different assumptions of the outflow velocity ranging from 50 to 200 km s$^{-1}$. The black open circle shows the average HI column density obtained by radio observations. All of these plots are taken from Konno et al. (2016). This figure is reproduced by permission of the AAS.

3.6 AGN Activity

LAE searches often find AGNs with strong Lyα emission from the presence of broad ($\gtrsim 500$ km s$^{-1}$) emission lines and high ionization lines such as CIV1548 and NV1240 as well as strong X-ray, far-UV, radio, and short-wavelength IR emission (Figure 44). Diagnostics with nebular line ratios such as the BPT (Baldwin et al. 1981) diagram are also used (Finkelstein et al. 2011a, Nakajima et al. 2013, Guaita et al. 2013). AGNs with strong Lyα emission are referred to as AGN-LAEs.
Early studies claim that about 1% of narrowband-selected LAEs at $z \sim 2 - 3$ are AGN-LAEs, and that the AGN-LAE fraction increases with the Ly$\alpha$ luminosity (Gawiser et al. 2007; Ouchi et al. 2008). Recently, Konno et al. (2016) have obtained statistical results on AGN-LAEs at $z = 2$ based on a narrowband survey (see also Matthee et al. 2017a). The top panel of Figure 45 presents the Ly$\alpha$ luminosity function of LAEs that clearly shows an excess over the best-fit Schechter function at $\log L_{\text{Ly}\alpha} > 43.4$ erg s$^{-1}$. Almost all objects in this luminosity range are bright in either X-ray, far-UV, or radio, thus being classified as AGN-LAEs. The bottom panel of Figure 45 is the AGN UV luminosity function derived with these AGN-LAEs, where the moderately large error bars include the systematic uncertainty raised by the incompleteness of AGN missed from the LAE selection because of weak or no Ly$\alpha$ emission. The AGN UV luminosity function estimated from the AGN-LAE sample agrees well with the faint-end UV luminosity function given by the SDSS study. In summary, the bright end of the Ly$\alpha$ luminosity function ($\log L_{\text{Ly}\alpha} > 43.4$ erg s$^{-1}$) is dominated by AGN-LAEs, and AGN-LAEs may be used to estimate the AGN UV luminosity function at the faint end.
Top: Lyα luminosity function at $z = 2$. The blue and magenta (orange) circles (squares) represent Lyα luminosity functions derived by three different studies. The black circles are the same as the blue circles, but based on LAEs with no AGN signature, i.e., with neither strong X-ray, far-UV, nor radio emission. The blue and black curves are the best-fit Schechter functions with the blue and black circle data points, respectively. 

Bottom: UV luminosity function of AGN at $z = 2$. The red circles indicate the AGN UV luminosity function estimated with the LAE-AGN whose errors include the systematic uncertainty raised by the incompleteness of AGN missed from the LAE selection because of weak or no Lyα emission. The blue and green circles represent the AGN UV luminosity functions derived with the SDSS and 2dF-SDSS LRG data, respectively. The red curve shows the best-fit Schechter function. The cyan circles and curve denote the UV luminosity function of LBGs. These two plots are taken from Konno et al. (2016). This figure is reproduced by permission of the AAS.
3.7 Overdensity and Large-Scale Structure

As explained in Section 1.1.3, early LAE searches targeted fields centered on an AGN, especially a massive radio galaxy, that is thought to be a signpost of a high-z galaxy overdensity. I present one of the LAE overdensity examples in Figure 46 that

![Overdensity of LAEs around the radio galaxy TN J1338 1942. Top: VLT narrowband image centered at TN J1338 1942. The green box and the blue circles indicate the positions of TN J1338 1942 and LAEs, respectively. The image is taken from https://www.eso.org/public/news/eso0212/. Bottom: Histogram of velocity differences $\Delta v$ between LAEs and TN J1338 1942 (Venemans et al., 2002). This figure is reproduced by permission of the A&A.](image)
shows narrowband selected LAEs around a luminous radio galaxy, TN J1338 1942, at $z \sim 4.1$ (Venemans et al., 2002). The number density of LAEs in this overdense region is about 15 times higher than the one in the average blank field. The number-density peak is clearly found at the redshift of TN J1338 1942, while the narrowband is capable to detect LAEs in a moderately broad redshift range (bottom panel of Figure 46). Such an overdensity of high-$z$ galaxies is often refereed to as a 'proto-cluster' (Steidel et al., 2000). There are about 30 overdensities of high-$z$ galaxies in the range $z \sim 2 - 8$ reported to date (see Table 5 of Chiang et al., 2013). About a half of them are LAE overdensities like the one around TN J1338 1942.

Some systematic narrowband surveys of LAEs have covered a contiguous field with a size of $> 100$ comoving Mpc, and discovered filamentary LSSs in a flanking field of a 'proto-cluster' at $z \sim 3$ (Figure 47; Yamada et al., 2012a) and in a blank field at $z \sim 6$ (Ouchi et al., 2005a). It is interesting that narrowband surveys can efficiently map out a high-$z$ galaxy distribution in a large scale. Specifically, a mapping observation in an unbiased blank field allows to obtain average features of LAE clustering that can be used to constrain properties of the dark-matter halos hosting LAEs, with structure formation models (Section 3.8).

**Fig. 47** Large-scale ($> 100$ Mpc) sky distribution of LAEs in and around the SSA22 overdensity of galaxies at $z = 3.1$ (Yamada et al., 2012a). The dots indicate LAEs, while the green contours represent the surface density of LAEs. This figure is reproduced by permission of the AAS.
Properties of galaxy-hosting DM halos are key to understanding galaxy formation (Figure 10; Section 2.1). Invisible DM halos are not directly observed, but there are various indirect methods to estimate their masses, $M_h$. One promising approach is to use gravitational lensing that provides reliable estimates of $M_h$. Other approaches include abundance matching and clustering. The abundance matching and clustering methods statistically estimate an average $M_h$ for a given galaxy population, by comparing the abundance and the clustering amplitude, respectively, between galaxies and DM halos. The abundance and the clustering amplitude are chosen as an indicator of $M_h$ because they are reliably calculated as a function of $M_h$ using the standard ΛCDM structure formation model (abundance: Figure 12; clustering: Figure 48) at any redshifts (Section 2.1.1). The basic idea of the abundance matching (clustering) method is to identify the ensemble of model dark-matter halos whose number density (clustering amplitude) is equal to that of observed galaxies. Modern abundance matching methods take account of the contribution of sub-halos to explain satellite galaxies as well as star-formation and merger histories, and increase the reliability of $M_h$ estimates (e.g. Behroozi et al. 2013). Similarly, for the clustering method, it is popular to use clustering predictions of the halo occupation distribution (HOD) of central and satellite galaxies (e.g. Zheng et al. 2005). Figure 49 compares $M_h$ of local galaxies estimated by various techniques, and indicates that the results of the three techniques, lensing, clustering, and abundance matching, agree very well in the galaxy DM halo mass scale up to $M_h \sim 10^{13} M_\odot$. Table 2 summarizes the three techniques.

Table 2 DM-Halo Mass Estimate Techniques

| Technique          | Key Quantity          | Advantage                                      | Disadvantage (Requirement)                              | Redshift Range$^a$ |
|--------------------|-----------------------|------------------------------------------------|--------------------------------------------------------|-------------------|
| Lensing            | Background object shear | Moderately simple gravity model                | Large galaxy sample of high spatial resolution imaging data | 0 – 1             |
| Clustering         | Correlation function   | Virtually free from duty-cycle systematics     | Large galaxy sample                                     | 0 – 7             |
| Abundance Matching | Luminosity function    | Small galaxy sample                           | Many parameters constrained by star-formation/merger histories | 0 – 8             |

$^a$ Redshift range that is covered by observations, to date.

There are a number of methods to characterize hosting DM halos: e.g., satellite kinematics, X-ray luminosities, and Sunyaev-Zel’dovich effects. Here, I highlight only lensing, abundance matching, and clustering that require optical and NIR imaging data alone.
Fig. 48 Angular correlation function (top three panels) and clustering bias (bottom panel) as a function of angular distance for z ~ 4 LBGs (Ouchi et al., 2005b). The open squares denote the angular correlation function of objects with $i' < 27.5$, while the filled circles are those for different magnitude limits indicated by labels. The solid lines are the best-fit HOD models, while the dashed lines indicate their breakdowns into one-halo and two-halo terms that are the correlations of galaxies in single halos and two different halos, respectively. The dotted lines represent the DM angular correlation function (bias = 1). This figure is reproduced by permission of the AAS.
Fig. 49. DM-halo masses estimated by five methods plotted as a function of stellar mass (Harikane [2016a]). The red diamonds represent estimates by the reliable lensing technique. The blue circles, green open circles, and gray squares denote DM-halo masses estimated from clustering, X-ray luminosity, and satellite kinematics. The green line with a green shade indicate the DM-halo mass estimated by the abundance matching technique. This figure is reproduced by permission of the University of Tokyo.

Figure 50 presents the stellar to DM-halo mass ratio (SHMR) as a function of $M_h$ for $z \sim 0$ galaxies. This result is obtained by the combination of these three techniques that enhances the reliability of $M_h$ estimates. In Figure 50 the SHMR has a peak at $M_h \sim 10^{12} M_\odot$, meaning that stars are most efficiently formed in DM halos whose present-day mass is $M_h \sim 10^{12} M_\odot$. The shape of the SHMR plot reflects $M_h$-dependent gas cooling and feedback and thus is essential to understand star-formation processes in DM halos (Section 2.1.2). Properties of galaxy-hosting DM halos are investigated by a combination of these three techniques up to $z \sim 1$ in, e.g., the COSMOS field where wide and deep HST data are available (Leauthaud).
However, for more distant galaxies at $z \gtrsim 2$, it is difficult to apply the lensing technique that requires shear measurements of a large number of background objects in high-sensitivity and high-spatial resolution images. In contrast, the clustering and abundance matching techniques can still be used at $z \gtrsim 2$. Figure 51 presents the evolution of the SHMR obtained with HST and Subaru data by these two techniques. Although the DM-halo mass range is limited, a clear evolution of the SHMR is identified at $M_\text{h} \sim 10^{11} M_\odot$. Beyond $z \sim 7$, there are no clustering measurements obtained to date, because clustering analyses require a large number of galaxies. Only requiring the number density of galaxies, the abundance matching technique has been applied up to $z \sim 8$ to date (Behroozi et al., 2013). Figure 51 compares DM-halo masses estimated by the abundance matching alone to those from the clustering+abundance matching, and suggests that the abundance matching provides good estimates of $M_\text{h}$ at $z \gtrsim 4$ within an uncertainty of a factor of $\sim 3$ (Harikane et al., 2016b).
Observations of Ly\(\alpha\) Emitters at High Redshift

DM-halo masses of LAEs have not been estimated by either lensing or abundance matching. Lensing analyses cannot be performed for high-\(z\) LAEs at \(z \gtrsim 2\) due to the limited quality and amount of imaging data. Moreover, abundance matching does not work because LAEs have a very small duty cycle of strong Ly\(\alpha\) emission and hence have a significantly smaller abundance than DM halos (Section 3.9). Thus, only the clustering method has been used for LAEs.
The clustering amplitude of a given galaxy sample can be evaluated with the angular correlation function (ACF), $\omega_{\text{obs}}(\theta)$, defined as the excess probability of finding galaxies in two solid angles $d\Omega_1$ and $d\Omega_2$ separated by the angular distance $\theta$,

$$
dP = N^2[1 + \omega_{\text{obs}}(\theta)]d\Omega_1 d\Omega_2,
$$

where $dP$ is the probability finding galaxies and $N$ the mean galaxy density per steradian (Groth & Peebles, 1977). Large-area surveys have derived ACFs of LAEs with the Landy & Szalay (1993) estimator (Ouchi et al., 2003; Gawiser et al., 2007; Kovač et al., 2007). As an example, Figure 52 presents ACF measurements for $z = 3.1$ LAEs. Although the statistics is not very good due to moderately small sample sizes, it is well known that the clustering of LAEs is weak, $b_g \sim 2$, at $z \sim 2 - 3$. Here, $b_g$ is the large scale galaxy bias defined by

$$
b_g^2 = \frac{\omega_{\text{obs}}}{\omega_{\text{DM}}},
$$

where $\omega_{\text{DM}}$ is the dark-matter ACF predicted by the structure formation model (e.g. Peacock & Dodds, 1996). ACFs and $b_g$ have been derived for LAEs up to $z = 6.6$. Figure 53 summarizes the bias of $z \simeq 2 - 7$ LAEs with $L_{\text{Ly}\alpha} > \text{a few } \times 10^{42} \text{ erg s}^{-1}$. Including the moderately large errors, the estimated halo masses of LAEs are typically $M_h = 10^{11.3 \pm 1} M_\odot$ over $z \simeq 2 - 7$ (Ouchi et al., 2010). In Figure 53, $b_g$ increases with redshift, suggesting that LAEs in earlier universes ($z \sim 5 - 7$) form from higher density fluctuation peaks and are progenitors of present-day massive...
Fig. 53  Bias of clustering $b_g$ as a function of redshift (Ouchi et al., 2010). The star marks represent $b_g$ measurements of LAEs with $L_{\text{Ly}\alpha}\gtrsim 10^{13} \text{L}_\odot$ in the range $z = 2 - 7$. The solid lines represent $b_g$ for DM halos with a mass of $10^8$, $10^9$, $10^{10}$, $10^{11}$, and $10^{12} \text{M}_\odot$ predicted by the model of Sheth & Tormen (1999), while the gray area indicates the DM halo mass range of $10^{10} - 10^{12} \text{M}_\odot$ corresponding to the typical DM halos of LAEs. The dotted lines denote the evolutionary tracks of $b_g$ for the galaxy-number conserving model. This figure is reproduced by permission of the AAS.

elliptical galaxies (Ouchi et al., 2010). On the other hand, the small $b_g$ of LAEs at $z \sim 2 - 3$ indicate that LAEs at $z \sim 2 - 3$ may be progenitors of today’s Milky-Way like galaxies based on the average evolution of $b_g$ (Figure 53) (Gawiser et al., 2007; Ouchi et al., 2010). Note that, due to the relatively small samples, the ACF measurements of LAEs still include large statistical errors as found from a comparison of Figure 52 and the bottom right panel of Figure 48. So far, no studies of LAE clustering have identified the one-halo term made by LAEs residing in single halos (see Figure 48 and the caption). There remains an open question whether LAEs have
a moderately strong one-halo term similar to continuum-selected galaxies (Figure 48).

3.9 Lyα Duty Cycle

Although stars can be formed in all DM halos (except in the least massive ones), not all halos with stars can be observed as LAEs for the following two reasons. First, if galaxies tend to have an intermittent star-formation history as suggested by theoretical models, they can produce strong Lyα emission only over a limited fraction of cosmic time. Second, it is not easy for Lyα photons produced in a galaxy to escape from it because of their resonant nature. To quantify the first effect, let us introduce the duty cycle of strong Lyα emission, $DC_{\text{Ly} \alpha}$:

$$DC_{\text{Ly} \alpha}(M_h) = \frac{n_{\text{Ly} \alpha}^{\text{model}}}{n_{\text{All}}^{\text{model}}},$$

where $n_{\text{Ly} \alpha}^{\text{model}}$ is the number density of DM halos with $M_h$ which are producing strong enough Lyα emission to be observed as LAEs if all Lyα photons escape, and $n_{\text{All}}^{\text{model}}$ is the number density of all DM halos with the same mass calculated from the DM halo mass function.

Nagamine et al. (2010) have used cosmological numerical simulations to study the effects of $DC_{\text{Ly} \alpha}$ on the Lyα luminosity function (Figure 54) and the ACF. In the simulated luminosity functions, one can find two trends due to changing $DC_{\text{Ly} \alpha}$ and $\langle f_{\text{esc}} \rangle$ (Section 3.2). Lowering $DC_{\text{Ly} \alpha}$ decreases the number density of LAEs irrespective of their luminosity, thus uniformly lowering the luminosity function. On the other hand, the number density of LAEs also decreases by reducing $\langle f_{\text{esc}} \rangle$ because of a uniform reduction of Lyα luminosities. These results mean that the luminosity function alone cannot distinguish a change in $DC_{\text{Ly} \alpha}$ from a change in $\langle f_{\text{esc}} \rangle$. However, this degeneracy can be resolved with clustering measurements. In a galaxy-formation model, LAEs are populated from the most-massive DM halos to low-mass DM halos until the LAE number density becomes as large as the one given by observations. If a $DC_{\text{Ly} \alpha}$ value is high (low), LAEs are hosted by high-mass (low-mass) DM halos on average for a given LAE number density, which show a strong (weak) LAE clustering signal. Although various combinations of $\langle f_{\text{esc}} \rangle$ and $DC_{\text{Ly} \alpha}$ can explain the LAE number density (or Lyα luminosity function), the choice of $DC_{\text{Ly} \alpha}$ changes the LAE clustering signal that can be tested with observational results. Nagamine et al. (2010) have made two competing LAE models: a high $DC_{\text{Ly} \alpha}$ ($= 1$) and a low $\langle f_{\text{esc}} \rangle = 0.1$ (left panel of Figure 54) and a low $DC_{\text{Ly} \alpha}$ ($= 0.07$) and a high $\langle f_{\text{esc}} \rangle = 1$ (right panel of Figure 54), both of which
well reproduce the observed Ly$\alpha$ luminosity function. They find that the LAEs in the former model are clustered much more strongly than observed ones (Section 3.8), while those in the latter model reproduce the observed weak clustering. These models suggest that $D_{C_{Ly\alpha}}$ is an important parameter less than unity. With the same idea, the value of $D_{C_{Ly\alpha}}$ can be estimated by a simple comparison of number density and $b_g$ (i.e. the clustering strength). Figure 55 shows that the number density of observed LAEs $n_{Ly\alpha}^{obs}$ is smaller than $n_{Ly\alpha}^{model}$ with the same $b_g$ by two orders of magnitude. This is a sharp contrast to LBGs at the same redshift (Figure 55). Based on results of the kind shown in Figure 55, Gawiser et al. (2007) and Ouchi et al. (2010) estimate $D_{C_{Ly\alpha}}$ to be about 1%, replacing $n_{Ly\alpha}^{model}$ with $n_{Ly\alpha}^{obs}$ in eq. (31).

Fig. 54 Ly$\alpha$ luminosity functions at $z = 3$ obtained by observations (triangles) and cosmological simulations (curves, color-coded by mass resolution and simulation box size: Nagamine et al. 2010). Left: The model Ly$\alpha$ luminosity functions are calculated by converting SFRs into Ly$\alpha$ luminosities with the Ly$\alpha$ escape fraction $f_{Ly\alpha} = 0.1$ and the duty cycle of strong Ly$\alpha$ emission $D_{C_{Ly\alpha}} = 1$. Right: Same as the left panel, but with $f_{Ly\alpha} = 1$ and $D_{C_{Ly\alpha}} = 0.07$. It should be noted that the simulation results shown in the two panels are indistinguishable despite very different $f_{Ly\alpha}$ and $D_{C_{Ly\alpha}}$ values. In other words, the observed Ly$\alpha$ luminosity function (triangles) can be explained by adjusting only one of these two parameters. This figure is reproduced by permission of the PASJ.

Nagamine et al. (2010) refer to the Ly$\alpha$ duty cycle as the stochasticity of LAEs.
Masami Ouchi

3.10 Summary of Galaxy Formation II

Section 3 has reviewed the basic physical properties of LAEs characterized by observations. Observed SEDs indicate that typical LAEs have a low stellar mass ($\sim 10^7 - 10^{10} M_\odot$) and a moderately low SFR ($\sim 1 - 10 M_\odot$). They are thus distributed in the lowest mass regime of the star-formation main sequence (Section 3.1). The Ly$\alpha$ luminosity function of LAEs rapidly increases from $z \sim 0$ to 3, but shows no significant evolution over $z \sim 3 - 6$. On the other hand, the UV luminosity function of UV-continuum selected galaxies (i.e. dropouts) shows a moderate increase from $z \sim 0$ to 3, followed by a decrease to $z \sim 6$ and beyond. These Ly$\alpha$ and UV luminosity function evolution results suggest a monotonic increase in the Ly$\alpha$ escape fraction $f_{esc}^{Ly\alpha}$ from $z \sim 0$ to 6 (Section 3.2). The morphology of LAEs is very compact on average, with $r_e \sim 1$ (Section 3.3). Showing strong high ionization lines such as [OIII]5007 and CIII]1907,1909, typical LAEs are metal-poor ($\sim 0.3 Z_\odot$) and highly ionized ($\log q_{/\text{cm}} \simeq 8 - 9$) star-forming galaxies with negligibly small dust extinction ($A_V \sim 0$; Section 3.4). Deep spectra of LAEs show a sig-
nature of an outflow that is as strong as that of LBGs. Through theoretical modeling, Lyα profiles and luminosities are useful to constrain the outflow velocity, hydrogen column density, dust extinction, and the spatial distribution of gas clouds (Section 3.5). Multi-wavelength data suggest that an AGN is found in about 1% of LAEs in a given unbiased sample, while a majority of bright LAEs with $\log L_{\text{Ly}\alpha} \gtrsim 43.5$ erg s$^{-1}$ host an AGN at $z \sim 2 - 3$ (Section 3.6). Various studies use LAEs as low-mass galaxies associated with proto-clusters and LSSs to probe the high-z galaxy distribution. Clustering analyses of LAEs suggest that LAEs are more weakly clustered than typical LBGs. The masses of LAE-hosting DM halos are estimated to be $M_h \sim 10^{11+1} M_\odot$, about an order of magnitude smaller than for typical LBGs. Because LAEs are $\sim 10^2$ times less abundant than DM halos with the same bias value (or the same halo mass), the duty cycle of the LAE phase (i.e. the phase when a galaxy is observed as a dust-poor star-forming galaxy with strong Lyα) is only $\sim 1\%$ (Sections 3.7, 3.9).

4 Galaxy Formation III: Challenges of LAE Observations

There exist many open questions about the observational properties and the physical origins of LAEs. In this section, I highlight three important questions about LAEs that are being actively discussed: extended Lyα halos, Lyα escape mechanisms, and the connection between LAEs and pop III star formation. I explain major observational and theoretical progresses achieved to date about these issues.

4.1 Extended Lyα Halos

Deep observations in the 2000s (1980s-1990s) discovered $\sim 10 - 100$-kpc large Lyα nebulae associated with star-forming galaxies (and AGNs) at $z \gtrsim 2$ that spatially extend beyond the stellar components. These nebulae are categorized into two classes, Lyα blobs (LABs) and diffuse Lyα halos (LAHs), according to their size and luminosity, with the former being larger and brighter.

4.1.1 Lyα Blobs

The first LABs discovered are Blob1 and Blob2 (dubbed LAB1 and LAB2) in a LBG overdensity field at $z = 3$ in the SSA22 field (Steidel et al. 2000, Section 1.2). LAB1 and LAB2 are each a huge (> 100 kpc in physical length), bright (10$^{-15}$ erg s$^{-1}$) Lyα nebula belonging to the largest class of LABs. Although similar extended Lyα emission has been found around high-z radio-loud galaxies since the 1980s (e.g. McCarthy et al. 1987, van Ojik et al. 1997), these two LABs are accompanied...
only by star-forming galaxies with no clear AGN signature (see below for more details about the connection between LABs and AGNs). The sizes and luminosities of these two LABs are, respectively, two and one order(s) of magnitude larger than those of $L^*$ LAEs at $z \sim 3$, $\sim 1$ kpc and $\sim 10^{13}$ erg s$^{-1}$ (Figures 28 and 21 respectively). Now a few tens of LABs are known (e.g. Matsuda et al. 2004, Figure 7). The definition of LABs has not been quantitatively determined yet, but galaxies with a spatially extended Ly$\alpha$ halo with a size of $>10$ kpc are usually referred to as LABs in high-$z$ galaxy studies. The LABs found so far have large diversities in Ly$\alpha$ size and luminosity. Moreover, it should be noted that the Ly$\alpha$ sizes and luminosities follow a continuous distribution extending from regular LAEs to the largest LABs such as LAB1 and LAB2 (Figure 7). Although LABs are so far identified at $z \sim 2-7$ (Figure 56), their physical origins are under debate. Three possible physical origins are suggested; AGN photoionization (Section 3.6), cooling radiation (Section 2.1.2), and Ly$\alpha$ scattering HI clouds (Section 3.5).

Fig. 56  Left: Abundance of LABs identified at $z \sim 2-7$ (Shibuya et al., 2018a). The inverse triangle is for LABs in the overdensity region SSA22, and the other symbols for those in field regions. The grey curve illustrates a possible abundance evolution of LABs. Because the selection criteria of LABs are heterogeneous, this evolutionary trend is not conclusive. Right: Color composite image of an LAB at $z = 6.6$ dubbed Himiko (Ouchi et al., 2013). The red color shows a Ly$\alpha$ nebula extending over 17kpc, while the blue and green colors represent rest-frame UV continua observed in the HST J and H bands, respectively. The labels A, B, and C, indicate the three continuum clumps in Himiko. This figure is reproduced by permission of the AAS.

It is known that some AGNs are surrounded by an extended Ly$\alpha$ nebula, but the question is whether all LABs owe their luminosity to an AGN. Deep X-ray follow-up observations find that a number of LABs host an AGN, and that about $\sim 20\%$ of LABs show AGN activities (Basu-Zych & Scharf, 2004, Geach et al., 2009). Conversely, a large fraction of LABs including LAB1 have no AGN signature. Although bright AGNs would contribute to making large extended Ly$\alpha$ nebulae in some cases, there should exist other physical mechanisms to create LABs without an AGN.
Observations of Lyα Emitters at High Redshift

Theoretical studies claim that cooling radiation can be the origin of LABs (Fardal et al., 2001; Dijkstra & Loeb, 2009; Goerdt et al., 2010). Although the Lyα luminosity of cooling radiation around a galaxy is usually fainter than the one of young stars in it, these two luminosities are comparable in massive galaxies. Moreover, cooling radiation would dominate in the outer region of a galaxy, because it is produced primarily in the outer DM halo where Lyα photons are not absorbed by dust (Fardal et al., 2001). Goerdt et al. (2010) suggest that the luminosity and morphology of LABs are reproduced by models that produce Lyα by collisional excitation in cold accretion gas. Although theoretical studies reproduce the characteristics of LABs with cooling radiation, so far there is no observational evidence that clearly supports the cooling radiation scenario. Yang et al. (2006) claim that the HeII 1640 line is useful to test if LABs at z ~ 2−3 originate from cooling radiation, because narrow-line (< 400 km s^-1) HeII 1640 emission can be produced neither by strong galactic outflow nor by population-II star photoionization, but only by cooling radiation. However, HeII 1640 emission alone is not sufficient to distinguish cooling radiation from a narrow-line (type II) AGN and population-III star formation (Section 4.3).

Recent observations have advanced the understanding of LABs. Hayes et al. (2011b) have detected a tangential polarization signal of 0-20% in the Lyα emission of LAB1 (Figure 57). Because it is predicted that resonance scattering of Lyα in HI clouds makes a tangential polarization (Dijkstra & Loeb, 2008), the polarization signal in LAB1 suggests that extended Lyα nebulae are produced by Lyα resonance scattering in HI clouds around galaxies. However, there remains a question about the source of Lyα photons. The HI cloud scattering scenario usually assumes that Lyα photons are produced in the central galaxy of the LABs (Hayes et al., 2011b), but HI cloud scattering also takes place for Lyα photons produced in situ by gas cooling. Trebitsch et al. (2016) have performed radiative hydrodynamics simulations for Lyα photons from the central galaxy and gas cooling, and calculated the polarization and surface brightness (SB) of Lyα emission that are shown in Figure 58. If LAB1 is made by the HI scattering of Lyα photons from the central galaxy, the polarization signal is larger than 20% at > 40 kpc, which is significantly larger than the observational results. Moreover, Trebitsch et al. (2016) find that Lyα photons from the cooling radiation are also scattered and polarized to a level of 10−15%. To explain the moderately small polarization and the large SB values, Trebitsch et al. (2016) suggest that a significant contribution from cooling radiation is necessary. In a way like this, the origins of LABs are still being actively discussed.
Moreover, there is an interesting problem not only about the origin of LABs without AGN signatures, but also of LABs harboring an AGN. Cantalupo et al. (2014) report the discovery of a gigantic LAB around a radio-quiet QSO, UM287, at $z = 2.3$ (Figure 59). This Ly$\alpha$ halo is 460 kpc in size that is larger than the virial diameter, $\sim 280$ kpc, of the DM halo hosting this QSO, and may even extend to a filament of the LSS. If this Ly$\alpha$ nebula is produced by Ly$\alpha$ photons from the recombination of a large cloud that was initially ionized by the QSO, and subsequent scattering in the now neutral cloud, then a very high gas mass or clumping factor is required to explain its high Ly$\alpha$ SB. It is, however, not clear whether this object truly has such a very high gas mass or clumping factor. Thus, the physical origin of this gigantic LAB is also under debate. There is also a report of the identification of large LABs with intermediate sizes of 100 – 300 kpc around radio quiet QSOs (Borisova et al. 2016). These large LABs fill the gap between small and gigantic LABs and may facilitate our understanding of the whole LAB zoo.
**Fig. 58**  Lyα photon polarization as a function of the distance from the central galaxy (Trebitsch et al., 2016). The orange lines represent polarization values along various line of sights in the simulation box. In each panel, the red line denotes the median of the orange lines, while the red region and the red-dashed lines indicate the 1σ dispersion and the first/third quartiles, respectively. The green data points are the observational measurements of Hayes et al. (2011b). The left and central panels present polarization profiles for Lyα photons produced in the extragalactic gas and the galaxy, respectively, while the right panel shows the sum of these two components. This figure is reproduced by permission of the A&A.

**Fig. 59**  Left: Large Lyα nebula around the radio-quiet quasar UM287 that is dubbed Slug nebula (Cantalupo et al., 2014). This is the continuum-subtracted Lyα image, presenting the Lyα surface brightness. The bottom-left scale bar represents 10″ (~80 kpc). Right: Projected maximum sizes of the Lyα nebulae as a function of Lyα luminosity (Cantalupo et al., 2014). The size and luminosity of the Slug nebula is indicated with the red star mark. The black circles and the blue squares are radio galaxies and QSOs, respectively. The green triangles denote LABs with or without AGN mainly identified by narrowband imaging. This figure is reproduced by permission of the Nature Publishing Group.
4.1.2 Diffuse Lyα Halos

Hayashino et al. (2004) and Steidel et al. (2011) have identified diffuse Lyα halos (LAHs) around star-forming galaxies at $z \sim 2 - 3$ by deep spectroscopy and narrowband-image stacking analyses (Figure 60). To date, LAHs are found in star-forming galaxies including LAEs in a wide-redshift range, $z \sim 2 - 7$ (Matsuda et al., 2012; Feldmeier et al., 2013; Momose et al., 2014). LAHs extend to a scale of

![Figure 60](image_url)

Fig. 60 Left six panels: Images, Lyα spectrum, and radial profiles of a galaxy, MUSE#82, at $z = 3.61$ (Leclercq et al., 2017). The top left and right panels present continuum images, an HST $F814W$ image and a MUSE white-light image, respectively. The middle left and right panels show a Lyα spectrum of the central part of this galaxy, and a Lyα image, respectively. The bottom left panel displays a Lyα SB radial profile (blue circles) and a UV continuum profile (green line) together with the PSF (red line). The bottom right panel presents the best-fit model (red line) and its decomposition to core (green line) and LAH (blue line) components, to compare with the observed profile (black circles). Here the core component is modeled with an exponential profile. Right panel: Stacked SB radial profiles of galaxies at $z \sim 2.7$ (Steidel et al., 2011). The red and blue solid lines denote Lyα and UV-continuum SB radial profiles, respectively. The green solid line indicates an estimated Lyα SB radial profile for no LAH case that is calculated with the UV-continuum SB radial profile under the assumption of the Case B recombination. The dashed lines are the best-fit exponential functions of these profiles. This figure is reproduced by permission of the A&A and the AAS.
a few $\times 10$ kpc with a Ly$\alpha$ SB of $\lesssim 1 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ that is about 10–100 times fainter than that of LABs. Their Ly$\alpha$ SB profiles roughly follow a power law (Figure 60) with the LAH scale length $r_n$,

$$S(r) = C_n \exp(-r/r_n),$$

where $S(r)$, $r$, and $C_n$ are the Ly$\alpha$ SB, radius, and normalization factor, respectively.

The parameter $r_n$ characterizes the size of an LAH. Figure 61 presents the relations between $r_n$ and several physical properties of LAEs. Matsuda et al. (2012) claim that $r_n$ positively correlates with the local LAE surface density $\delta_{\text{LAE}}$. The result of Matsuda et al. (2012) would imply that galaxies in a dense environment have a large Ly$\alpha$ halo (cf. Xue et al. 2017). Momose et al. (2016) find that $r_n$ negatively correlates with the Ly$\alpha$ luminosity of the main body of galaxies, $L_{\text{Ly}\alpha}^{\text{cent}}$, at $r < 8$ kpc ($r < 1''$). Because $L_{\text{Ly}\alpha}^{\text{cent}}$ depends on H$\text{I}$ column density through resonant scattering, galaxies with the ISM rich in H$\text{I}$ would have a faint $L_{\text{Ly}\alpha}^{\text{cent}}$ and a large extended Ly$\alpha$ halo. It is suggestive that LAEs (galaxies with a bright $L_{\text{Ly}\alpha}^{\text{cent}}$) have the ISM whose H$\text{I}$ column density is lower than that of LBGs (galaxies with a faint $L_{\text{Ly}\alpha}^{\text{cent}}$).

Fig. 61  Left: LAH scale length as a function of the LAE sky overdensity at $z = 3$ in the SSA22 region (Matsuda et al., 2012). The star mark denotes the median LAH scale length of LBGs in the galaxy overdense region, while the other symbols represent those of LAEs. The dashed line is the best-fit quadratic function to all data points. (Note the non-regular scale on the y-axis.) Right: LAH scale length as a function of Ly$\alpha$ luminosity for LAEs at $z = 2$ (Momose et al., 2016). The star marks are measurements by Momose et al. (2014) and Momose et al. (2016), and the solid line is the best-fit linear function to them. This figure is reproduced by permission of MNRAS.
Because \( r_n \) depends on some galaxy properties, the evolution of \( r_n \) should be investigated carefully with uniformly selected samples at different redshifts. The red star marks in Figure 62 indicate the \( r_n \) values of field (\( \delta_{\text{LAE}} \lesssim 1 \)) LAEs with \( L_{\text{Ly}\alpha} \gtrsim 2 \times 10^{42} \text{ erg s}^{-1} \) at \( z = 2.2 - 6.6 \). It is found that \( r_n \) is nearly constant over \( z = 2.2 - 5.7 \), falling in the range \( r_n = 5 - 10 \text{ kpc} \) (Momose et al., 2014). There is a hint of an increase in \( r_n \) from \( z = 5.7 \) to 6.6 that could be relevant to cosmic reionization, but the error bars are too large to conclude whether this is a real signature.

![Fig. 62 Redshift evolution of the LAH scale length (Momose et al., 2014). The red star marks represent the median LAH scale lengths of LAEs with \( L_{\text{Ly}\alpha} \gtrsim 2 \times 10^{42} \text{ erg s}^{-1} \) at \( z = 2.2 - 6.6 \). The gray region indicates the range of 5 - 10 kpc where the LAH scale lengths of LAEs at the post reionization epoch (\( z = 2.2 - 5.7 \)) fall. The blue squares and the orange and blue circles denote the LAH scale lengths of LAEs in the overdense region of SSA 22. The orange crosses are the measurements of bright LAEs. The open triangles show \( \text{Ly}\alpha \) Petrosian radii of local LAEs. This figure is reproduced by permission of MNRAS.](image)

The physical origin of LAHs is not well understood yet. There are four possible scenarios, i) CGM’s \( \text{HI} \) gas scattering \( \text{Ly}\alpha \) photons that originate from star-forming regions, ii) cooling radiation, iii) unresolved dwarf satellite galaxies, and iv) fluorescence. Lake et al. (2015) perform radiative transfer calculations in hydrodynamical simulations (Figure 63), and find that the scenario i) cannot explain high \( \text{Ly}\alpha \) SB at large radii found by observations (red line in the left panel of Figure 63). The high \( \text{Ly}\alpha \) SB at large radii requires either the mechanism ii) or iii) (right panel of Figure 63). To distinguish the contributions of ii) and iii), UV-continuum SB profiles in stacked broadband images are useful. This is because the mechanism iii) produces stellar UV-continuum emission, while the mechanism ii) creates only negligible UV-continuum emission. It is, however, difficult to investigate UV-continuum SB pro-
files in the stacked images due to systematic errors in sky subtraction (Momose et al., 2016). Recent deep spectroscopic observations with VLT/MUSE find a diffuse LAH on an individual basis with no use of stacking data (Figure 60; Wisotzki et al., 2016; Leclercq et al., 2017). This discovery rules out the possibility that moderately large unresolved dwarf satellite galaxies mimic a diffuse LAH in the scenario iii). Studies of LAHs are proceeding rapidly, and much progress can be expected in the coming few years.

![Average Lyα SB profiles of nine model LAEs at z = 3 obtained by numerical simulations (Lake et al., 2015).](image)

**Fig. 63** Average Lyα SB profiles of nine model LAEs at z = 3 obtained by numerical simulations (Lake et al., 2015). Left: The black curve represents the total Lyα SB profile, while the red, blue, and green curves denote a decomposition into Lyα photons originating from the central star-forming regions, surrounding knotty star-forming regions, and background regions, respectively. The purple filled circles show the observational data of Momose et al. (2014). The open circles are the same as the filled circles, but for data points potentially with large systematic errors. The purple line simply connects all data points. Right: Same as the left panel, but for a decomposition into cooling radiation (red line) and star-formation radiation (blue line) in the top panel. The fractional contributions of these two radiation components (to the total Lyα SB profile) are shown in the bottom panel. This figure is reproduced by permission of the AAS.

### 4.2 Lyα Escape Fraction

One of the most important questions about LAEs is how they emit strong Lyα light. To discuss this question, let us introduce the Lyα escape fraction, \( f_{\text{esc Lyα}} \), defined by

\[
 f_{\text{esc Lyα}} = \frac{L_{\text{obs Lyα}}}{L_{\text{int Lyα}}} \tag{33}
\]

[11] In the Saas Fee lecture, this subsection dealt with outflows and Lyα profiles as well. For the readers' convenience, I have moved these topics to Section 3.5.
Fig. 64 Lyα escape fraction $f_{\text{Ly} \alpha_{\text{esc}}}$ as a function of color excess E(B-V). Left: The data points are all measured at $z = 0 - 0.3$ (Atek et al., 2014a). The black line with a yellow shade indicates the best-fit linear function with the 1σ fitting error. The red dashed line represents a simple attenuation with the Cardelli et al. (1989) extinction law. Right: The black circles and the green triangles denote LAEs at $z \sim 2 - 4$ and 0.3, respectively (Blanc et al., 2011). The black lines present correlations suggested from eq. 35 with various $q$ values, with a solid one corresponding to $q = 1$. The red line is the best-fit linear function to LBGs at $z \sim 2$. This figure is reproduced by permission of the A&A and the AAS.

where $L_{\text{Ly} \alpha}^{\text{obs}}$ and $L_{\text{Ly} \alpha}^{\text{int}}$ are observed and intrinsic Lyα luminosities, respectively. Intrinsic Lyα luminosities can be estimated from a UV continuum or an Hα line luminosity. Note that $f_{\text{Ly} \alpha_{\text{esc}}}$ is similar to the number/luminosity average Lyα escape fraction, $\langle f_{\text{Ly} \alpha_{\text{esc}}} \rangle$ (Equation 11), but that $f_{\text{Ly} \alpha_{\text{esc}}}$ is defined for one individual galaxy. The left panel of Figure 64 presents the Lyα escape fraction as a function of color excess for LAEs at $z \sim 0$ and 2 – 4. There is a clear anti-correlation between these two quantities, suggesting that a certain fraction of Lyα photons are absorbed by dust in the ISM. In the left panel of Figure 64 the $f_{\text{Ly} \alpha_{\text{esc}}}$ values of LAEs are compared with the amount of dust extinction predicted by a simple screen model that includes no Lyα resonance scattering effects,

$$f_{\text{Ly} \alpha_{\text{esc}}, \text{screen}} = 10^{-0.4k_{1216}E(B-V)_{\text{neb}}},$$

where $k_{1216}$ is the extinction coefficient at 1216Å. Calzetti’s law provides $k_{1216} = 12.0$ (Konno et al., 2016). There is a hint of an excess of $f_{\text{Ly} \alpha_{\text{esc}}}$ beyond the dust screen model for some LAEs, albeit with large measurement errors. The right panel of Figure 64 shows various model lines with different $q$ values (Finkelstein et al., 2008) defined as

$$q = \frac{\tau(\text{Ly} \alpha)}{\tau_{1216}},$$
where $\tau(\text{Ly}\alpha)$ and $\tau_{1216}$ are the optical depths for the Ly$\alpha$ line and 1216Å UV-continuum emission. In the right panel of Figure 64, the $q = 1$ model line corresponds to Equation (34).

LAEs with a $f_{\text{esc}}^{\text{Ly}\alpha}$ excess have $q < 1$. A selectively large Ly$\alpha$ extinction ($q > 1$) is simply explained, if Ly$\alpha$ photons cross a long effective distance in a dusty ISM due to a number of Ly$\alpha$ resonance scatterings, which enhances the probability of absorption by dust.

![Fig. 65 Illustration of Neufeld's clumpy cloud model (Neufeld, 1991). In this model, the ISM is made of gas clumps whose central regions contain dust (in cold molecular gas) that can absorb UV-continuum photons. The solid-line arrows indicate the light path of a Ly$\alpha$ (resonance) photon from the source. The Ly$\alpha$ photon is scattered on the surfaces of gas clumps with negligible dust absorptions. The dashed-line arrow represents the light path of an UV-continuum (non-resonance) photon that penetrates clumps. This figure is reproduced by permission of the AAS.](image)

However, a selectively small Ly$\alpha$ extinction ($q < 1$) is difficult to understand. Clumpy gas clouds in the ISM may explain $q < 1$, as has been originally suggested by Neufeld (1991). Figure 65 illustrates this idea. If the ISM is made of clumpy gas clouds, Ly$\alpha$ (resonance) photons that encounter clumpy clouds are scattered on their surface with a negligible dust absorption. On the other hand, UV-continuum (non-resonance) photons can go into the clouds and are eventually absorbed by dust.
inside them. Through these scattering and absorption processes, Lyα photons are absorbed less than UV-continuum photons, resulting in a very high Lyα EW_0. The clumpy cloud model is sometime referred to as Neufeld’s effect. This model predicts narrow Lyα line widths because Lyα photons experience only a small number of resonant scattering before escaping from galaxies (Neufeld, 1991; Hansen & Oh, 2006).

Although Neufeld (1991) investigated this model only in a simple case of static and very clumpy/dusty media, recent studies have used radiative transfer simulations to test this model in realistic ISM conditions (Laursen et al., 2013; Duval et al., 2014; cf. Hansen & Oh, 2006). These simulations have found that Neufeld’s effect is seen (Figure 66) only under special conditions: a low outflow velocity (< 200 km s^{-1}), very high extinction (E(B-V) > 0.3), and an extremely clumpy gas distribution with a density contrast larger than 10^7 (i.e. most gas is locked up in clumps), many of which do not meet the observed properties of LAEs (Table 1). Moreover, under these special conditions, observed Lyα lines can have neither a velocity shift nor an asymmetric profile. Laursen et al. (2013) and Duval et al. (2014) have concluded that while it is true that Neufeld’s effect is working to some degree, this effect cannot explain the fact that a large fraction of LAEs have high f_{Lyα}^{Esc} values (i.e. q < 1). In summary, the physical origin of the high f_{Lyα}^{Esc} values found for LAEs is still under debate (see Section 4.3 for more discussion).

Fig. 66  Left: ISM gas geometry of 500 clumpy clouds with a radius of 350 pc produced in the simulations by Laursen et al. (2013). Right: Ratio of Lyα to UV-continuum photon escape fractions, f_{Lyα}^{Esc} / f_{UV}^{Esc}, as a function of color excess E(B-V) for models of the clumpy cloud ISM (Duval et al., 2014). The cyan circles, gray inverse-triangles, and black triangles represent models with outflow velocities of V_{exp} = 0 – 200 km s^{-1} and H_1 column densities of N_{HI} = 10^{19} – 2 \times 10^{20} cm^{-2} indicated in the legend. An enhancement of Lyα photon escape, f_{Lyα}^{Esc} / f_{UV}^{Esc} > 1, is achieved only with V_{exp} = 0–100 km s^{-1} and E(B – V) \geq 0.3. This figure is reproduced by permission of the A&A.
Observations of Ly$\alpha$ Emitters at High Redshift

4.3 Large Ly$\alpha$ and He II Equivalent Widths: Pop III in LAEs?

LAEs with large Ly$\alpha$ EW$^0$ values are potentially important objects that have excessive Ly$\alpha$ emission at a given stellar continuum. Malhotra & Rhoads (2002) claim the existence of LAEs with Ly$\alpha$ EW$^0 > 240$ Å that cannot be explained by young star formation with the solar metallicity and a Salpeter IMF (Salpeter, 1955). Figure 67 presents a Ly$\alpha$ EW$^0$ histogram of $z = 4.5$ LAEs. Although observational EW estimates include large uncertainties and systematics due to weak or undetected continua (see, e.g., Figure 14 of Shimasaku et al. 2006), LAE studies have shown that $\sim 10 - 30\%$ of LAEs in a narrowband-selected sample have large ($\sim 200 - 300$ Å) Ly$\alpha$ EW$^0$ at $z \sim 2 - 7$ (Dawson et al. 2007; Shimasaku et al. 2006; Ouchi et al. 2008; Kashikawa et al. 2012). The physical origins of the large Ly$\alpha$ EW$^0$ objects are not well understood. These LAE studies discuss the possibilities of the Neufeld effect (Section 4.2), cooling radiation (Section 4.1.1), and pop III star formation. The relation between large Ly$\alpha$ EW$^0$ and pop III star formation is presented in the left panel of Figure 68. This panel shows theoretically calculated Ly$\alpha$ EW$^0$ as a function of stellar age for various stellar populations. For a star-formation history of an instantaneous burst with solar metallicity, Salpeter IMF, and a mass range of $1 - 100$ $M_\odot$, the Ly$\alpha$ EW$^0$ does not exceed $\sim 200 - 300$ Å even at the birth time. A stellar population with a larger number of massive young stars that produce more
ionizing photons has a higher Lyα $EW_0$. Lyα $EW_0$ is thus sensitive to the shape of the IMF and metallicity as well as stellar age. It is predicted that a top heavy IMF is realized in metal poor gas clouds because they contain only a small amount of coolants that are needed for low-mass gas clumps to collapse. Moreover, metal poor stars efficiently produce ionizing photons, because ionizing photons are not absorbed by metals in the stellar atmosphere. The left panel of Figure 68 indicates that Lyα $EW_0$ can reach $\sim 500 - 1500$ Å for galaxies having metal poor instantaneous star-formation with top heavy IMFs. As demonstrated in this panel, LAEs with large Lyα $EW_0$ values can be candidates of pop III galaxies, although not definitive ones (e.g. Yang et al. 2006). Moreover, the production rate of ionizing photons is sensitive not only to IMF, metallicity, and stellar age, but also to the binary fraction of massive stars and many other physical conditions such found in the BPASS model (Eldridge et al. 2017).

Fig. 68  Lyα (left) and HeII (right) $EW_0$ as a function of stellar age for an instantaneous burst of star-formation predicted by the stellar evolution and photoionization models of Schaerer (2003). The three blue dashed lines represent metallicity $Z = 0$ models with a Salpeter IMF and mass ranges of 50 – 500, 1 – 500, and 1 – 100 $M_\odot$ from top to bottom. The blue solid and dotted lines are the same as the blue dashed lines, but for $Z = 10^{-7}$ and $10^{-5}$. The cyan dashed lines denote models with $Z = 0.0004, 0.001, 0.004, 0.008, 0.020,$ and 0.040 from top to bottom. The three squares show constant SFR models with a 50 – 500 $M_\odot$ Salpeter IMF for $Z = 0, 10^{-7},$ and $10^{-5}$ from top to bottom. The red triangles and green circles are the same as the squares, but for the mass ranges 1 – 500 and 1 – 100 $M_\odot$, respectively. The green short lines are the same as the green circles but with metallicities of $Z = 0.0004, 0.001, 0.004, 0.008, 0.020,$ and 0.040 from top to bottom. Note that, in the right panel, HeII $EW_0 \geq 5$Å is reached only for models with very low metallicities of $Z \leq 10^{-7}$, except for the mass range 1 – 100 $M_\odot$. This figure is reproduced by permission of the A&A.
Thus, another test is necessary to isolate pop III star formation from the candidates. HeII1640 is an ideal emission line for such a test. Because He$^+$ has a high ionization potential of 54.4 eV, He$^+$ can be ionized by hard spectra of very massive young stars that can be found in HII regions of pop III star formation. The right panel of Figure 68 presents HeII1640 $EW_0$ as a function of stellar age for instantaneous star-formation, and suggests that a large HeII1640 $EW_0 (>10\text{\AA})$ is indicative of pop III. Although the hot outflowing gas from a WR star and the broad-line region of an AGN can also produce HeII1640 emission with $EW_0 \gtrsim 10\text{\AA}$, both lines are predicted to be much broader, with a line-width velocity of $\sim 1000 \text{ km s}^{-1}$, than those from HII regions of pop III star formation (a few hundred km s$^{-1}$). However, the HeII1640 emission of narrow-line (type II) AGNs has similarly small line widths. To isolate pop III stars from such AGNs, one needs to investigate high ionization lines such as Nv, Ovi, and strong X-ray emission that cannot be produced by the photoionization by very massive stars (cf. fast radiative shocks; Thuan & Izotov 2005).

A strong narrow HeII line is found in a $z=2$ LAE with an extended Ly$\alpha$ halo, named PRG1 (Figure 69; Prescott et al. 2009). The HeII line of PRG1 is strong, HeII $EW_0 = 37 \pm 10\text{\AA}$, and the ratio of HeII to Ly$\alpha$ fluxes is HeII/Ly$\alpha = 0.12$. Metal lines are not detected with upper limits of CIV1548/Ly$\alpha$ and CIII]1909/Ly$\alpha \lesssim$.

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The HeII1640 line corresponds to HeII H$\alpha$. Note that the HeII304 line corresponding to HeII Ly$\alpha$ cannot be easily observed.
These properties of a strong narrow HeII and very weak (or no) metal lines are suggestive of pop III star formation. However, the subsequent deep spectroscopy of Prescott et al. (2015) has clearly detected CIV and CIII] lines with a line ratio of CIV/HeII, CIII]/HeII $\sim 0.5$, indicating that PRG1 is photoionized by an AGN, not by pop III stars.

Fig. 70 Left: The SED (main panel) and a thumbnail image (inset panel) of CR7 (Sobral et al., 2015). The thumbnail image is an HST NIR image that resolves the three continuum components of CR7 named clumps A, B, and C, where clump A is the candidate of pop III star formation reported by Sobral et al. (2015). In the main panel, the black circles represent total flux densities, while the magenta triangles denote HST NIR photometry of clumps B+C. The black and magenta lines are the pop III and $Z = 0.2Z_\odot$ SED models best-fit to the 1–2 $\mu$m data points of the black circles and the magenta triangles, respectively, and the green line indicates the sum of these two model SEDs. The red crosses are the photometry predicted by the best-fit pop III model. Right: Two-dimensional (top) and one-dimensional (bottom) spectra of CR7 reported by Sobral et al. (2015) (cf. Shibuya et al. 2018b; Sobral et al. 2018). The black and blue lines represent X-Shooter spectra with and without a spectrum smoothing process, respectively. The green line denotes a stack of the X-Shooter and VLT/SINFONI spectra. The red line indicates the sky background spectrum. This figure is reproduced by permission of the AAS.

More recently, Sobral et al. (2015) have reported a detection of a strong narrow HeII emission in an LAE at $z = 6.6$ that is dubbed CR7. The left and right panels of Figure 70 present the SED and the HeII spectrum of CR7. This object is made of three stellar components whose total SED exhibits a mature stellar population with a Balmer break. Although the SEDs of the three stellar components are not clearly distinguished, there is a possibility that one component, A, (Figure 70) would have a very young population with a blue SED. Sobral et al. (2015) report that CR7 has a very large HeII equivalent width of $EW_0 = 80 \pm 20 \AA$ as well as a large Ly$\alpha$ equivalent width of $EW_0 = 211 \pm 20 \AA$. The reported line ratio of HeII/Ly$\alpha = 0.22$ is about twice as large as the one of PRG1. No metal lines are detected in VLT/X-Shooter spectra covering the entire NIR wavelength range accessible from the ground. Some theoretical studies suggest that CR7 is a candidate of a direct collapse black hole be-
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cause of a strong He$\text{II}$ line without detection of metal lines from moderately-massive stellar components [Pallottini et al., 2015; Dijkstra et al., 2016]. Recently, Shibuya et al. (2018b) present reanalysis results of the CR7 X-Shooter spectra, and find no He$\text{II}$ line, placing only an upper limit. A similar upper limit is also reported by Sobral et al. (2018). Moreover, ALMA observations reveal the metal [C$\text{II}$] line (Matthee et al., 2017b). To summarize, although CR7 was a promising candidate of pop III star formation or a direct collapse black hole, subsequent studies find no such evidence.

Spectral hardness measurements are useful to diagnose the presence of pop III star formation in a galaxy. Figure 71 shows theoretical predictions of the spectral hardness $Q_{\text{He}^+}/Q_H$ as a function of metallicity [Schaerer, 2003], where $Q_{\text{He}^+}$ and $Q_H$ are the fluxes of ionizing photons for He$^+ (> 54.4 \text{ eV})$ and H ($> 13.6 \text{ eV}$), respectively. This spectral hardness can be estimated from observed He$\text{II}$ and Ly$\alpha$ fluxes, $f_{\text{HeII}1640}$ and $f_{\text{Ly}\alpha}$:

$$f_{\text{HeII}1640}/f_{\text{Ly}\alpha} \sim 0.55 \frac{Q_{\text{He}^+}}{Q_H}.$$  \hspace{1cm} (36)

Reported $f_{\text{HeII}1640}/f_{\text{Ly}\alpha}$ measurements give $Q_{\text{He}^+}/Q_H \sim 0.22$ for PRG1 [Prescott et al., 2009] and $\sim 0.42$ for CR7 [Sobral et al., 2015]. In Figure 71, the estimated $Q_{\text{He}^+}/Q_H$ values are larger than the predictions for pop III star formation by an order of magnitude even for a top heavy IMF with a mass range of $50 - 500 M_\odot$. The large $Q_{\text{He}^+}/Q_H$ value of PRG1 is explained by the existence of an AGN, while that of CR7 is probably explained by the recent reanalysis results of no He$\text{II}$ line detection [Shibuya et al., 2018b; Sobral et al., 2018]. In addition to analyses on an individual basis, one can also measure an average $f_{\text{HeII}1640}/f_{\text{Ly}\alpha}$ from stacked LAE spectra. Composite spectra using large LAE samples show no clear detection of He$\text{II}$ emission, placing upper limits of $f_{\text{HeII}1640}/f_{\text{Ly}\alpha} < 2\%$ and 20\% at $z = 3$ and 5, respectively [Dawson et al., 2004; Ouchi et al., 2008]. Although the upper limit for $z = 5$ LAEs is not strong enough to give a meaningful constraint ($Q_{\text{He}^+}/Q_H \lesssim 0.1$), the one for $z = 3$ LAEs ($Q_{\text{He}^+}/Q_H \lesssim 0.01$) indicates that on average $z = 3$ LAEs do not have star-formation dominated by pop III with a top heavy IMF with a mass cut of $50 - 500$ or $1 - 500 M_\odot$. 
Fig. 71  Spectral hardness $Q_{\text{He}^+}/Q_H$ as a function of metallicity (Schaerer, 2003). The red, blue, and green filled triangles are the spectral hardness values for three very metal poor cases with mass cuts of $1 - 100$, $1 - 500$, and $50 - 500 M_\odot$, respectively, predicted with the stellar evolution and photoionization models of (Schaerer, 2003). The red, blue, and green lines indicate the linear functions in the log-log plot that are best fit to the red, blue, and green filled triangles, respectively. The red crosses are the same as the red filled triangles, but for metal rich cases. The blue open circles and open triangles are other model predictions (see Schaerer 2003). The shaded region and the upper limit denote the spectral hardness of HII regions estimated with observational data. This figure is reproduced by permission of the A&A.

4.4 Summary of Galaxy Formation III

Section 4 has presented three important questions about LAEs: extended Lyα halos, Lyα escape mechanisms, and the connection between LAEs and pop III star formation. Deep observations have revealed largely extended Lyα nebulae, dubbed LABs, Lyα filaments, and LAHs, with a size of about a few 10 kpc to 500 kpc
around high-z star-forming galaxies and AGNs. Because tangential polarization signals are detected in the Lyα blob LAB1, H I gas scattering of Lyα photons should exist in LABs. However, it is not clear what is the major source(s) of the Lyα photons. Proposed candidate sources are H II regions in the ISM, cooling radiation, and unresolved dwarf satellite galaxies. There exist LAEs with a Lyα EW₀ as large as a few 100Å. Recent theoretical calculations suggest that a clumpy ISM made of discrete clouds would boost Lyα EW₀, but that the boosting is only found in physical conditions (high extinction and low outflow velocities) that are clearly different from those seen in typical LAEs. The mechanism producing large EW₀ values is still unknown. Several observational studies have reported LAEs with narrow and strong He II emission lines. These LAEs may be candidates of galaxies with pop III star formation whose young massive stars emit moderately high energy photons ionizing He⁺. However, these pop III star-formation candidates can also be narrow-line AGNs or may include erroneous He II emission measurements. The spectral hardness Qₜₚₜ/Qₜₜ is useful to diagnose pop III star formation and AGNs, although, to date, Qₜᵣ is often estimated from a Lyα flux that includes a large uncertainty in the Lyα escape fraction.

5 Cosmic Reionization I: Reionization History

There are two major questions about cosmic reionization: reionization history and reionization sources. This section addresses the first question with an emphasis on LAE studies, starting with a brief introduction to cosmic reionization. The second question, reionization sources, is discussed in Section 6.

5.1 What is Cosmic Reionization?

Cosmic reionization is a cosmic event that took place at a high redshift (Figure 72). By the recombination of hydrogen at z ~ 10³, the early universe with hot plasma gas evolved into one filled with neutral gas (i.e. atomic hydrogen gas); the last photon scattering surface made by this transition is observed as the cosmic microwave background (CMB). On the other hand, today’s universe does not contain abundant neutral gas, but harbors fully ionized gas in the inter-galactic space that makes no Lyα absorption lines at z ~ 0 in UV spectra of QSOs (Bahcall et al., 1991). These two pieces of evidence suggest that hydrogen atoms that became neutral at z ~ 10³ were ionized again by today. This event is known as cosmic reionization (see the review of Fan et al., 2006b). In this lecture, I focus on hydrogen reionization that is deeply related to LAEs and galaxy formation. See, e.g., Worseck et al., 2014 for observational progresses in helium reionization studies. Hereafter, ‘reionization’ indicates hydrogen reionization, if not otherwise specified.
Cosmic reionization is driven by ionizing photon radiation, $\gamma$, the origin of which being stellar or non-stellar or both:

$$H + \gamma \rightarrow H^+ + e^-,$$

where $H^+$ is an ionized hydrogen atom (proton) and $e^-$ is an electron.

Although the cosmic reionization process and reionization sources are not well understood, many theoretical studies suggest a picture where massive stars in galaxies provide the majority of ionizing photons and first ionize the IGM in the vicinity of galaxies (Figure 73). Ionized regions made around galaxies are called ionized
bubbles or cosmic H II regions. Ionized bubbles grow by time and merge, eventually making the universe fully ionized. In this process, star-formation in low-mass galaxies is suppressed by heating of their cold gas by background ionizing photons (UV background radiation) if they are located in ionized bubbles (e.g. Susa & Umemura 2004, Wyithe & Loeb 2006). This physical picture indicates that galaxies drive cosmic reionization by supplying ionizing photons, while star-formation in galaxies is strongly influenced by the UV background radiation. Thus, cosmic reionization and galaxy formation have a tight physical relation. Because the UV background radiation in ionized bubbles is originally produced by galaxies, one can also find that cosmic reionization is a cosmological-scale feedback process for galaxies. In reionization studies, one of the observational goals is to test this physical picture.

The key quantity for describing cosmic reionization is the neutral hydrogen fraction,

\[ x_{\text{HI}} = \frac{n_{\text{HI}}}{n_{\text{H}}} \]  \hspace{1cm} (38)

where \( n_{\text{HI}} \) is the neutral hydrogen density and \( n_{\text{H}} \) the neutral+ionized hydrogen density. The evolution of the IGM ionization, i.e., the history of reionization, is described by \( x_{\text{HI}} \) as a function of redshift. Note that the ionized hydrogen fraction

\[ Q_{\text{HII}} = 1 - x_{\text{HI}} \]  \hspace{1cm} (39)

is often used in place of \( x_{\text{HI}} \).

It is not easy to estimate \( x_{\text{HI}} \) (or \( Q_{\text{HII}} \)). Emission from ionized gas (e.g. Ly\( \alpha \)) and neutral gas (e.g. 21 cm line) in the IGM is too diffuse to be directly detected even with today’s technology. Instead, one needs to detect an absorption or scattering signal by neutral gas imprint in spectra of bright background sources such as QSOs, CMB, LAEs, and gamma ray bursts (GRBs). The following subsections summarize \( x_{\text{HI}} \) estimates obtained with this method.

### 5.2 Probing Reionization History I: Gunn Peterson Effect

The classic method for estimating \( x_{\text{HI}} \) is to use H I Ly\( \alpha \) absorption lines in high-z QSO spectra, where QSOs play the role of bright background light. Before the end of reionization, neutral hydrogen of the IGM makes a complete absorption trough in QSO spectra at wavelengths shorter than Ly\( \alpha \), which is called the Gunn Peterson effect (Gunn & Peterson 1965, see also Field 1959, Shklovskii 1964, Bahcall & Salpeter 1965). The strength of this effect for a given QSO spectrum is evaluated with the Gunn-Peterson optical depth \( \tau_{\text{GP}} \).

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13 This is the volume-averaged fraction. There is another definition of the neutral hydrogen fraction, the mass-averaged neutral hydrogen fraction, that is sometime used. Because the mass-averaged neutral hydrogen fraction is difficult to evaluate, the volume-averaged fraction is referred to as the neutral hydrogen fraction in most observational studies.
\[ \frac{I}{I_0} = e^{-\tau_{\text{GP}}}, \quad (40) \]

where \( I \) and \( I_0 \) are the observed and intrinsic QSO continuum flux densities at the wavelength of the Ly\( \alpha \) absorption of the redshifted IGM neutral hydrogen. Here, \( I_0 \) is estimated by a power-law extrapolation of the observed QSO continuum at \( > 1216 \text{Å} \). The relation between \( \tau_{\text{GP}} \) and \( x_{\text{HI}} \) is written as

\[ \tau_{\text{GP}}(z) = 4.9 \times 10^8 \left( \frac{\Omega_m h^2}{0.13} \right)^{-1/2} \left( \frac{\Omega_b h^2}{0.02} \right) \left( \frac{1+z}{7} \right)^{3/2} x_{\text{HI}}(z) \quad (41) \]

(Fan et al., 2006b). One can use this equation to estimate \( x_{\text{HI}} \) from \( \tau_{\text{GP}} \). Figure 74 presents optical spectra of QSOs at \( z = 5.7 - 6.4 \). In this figure, QSO residual fluxes escaping from the IGM absorption are found at \( \lesssim 8000 \text{Å} \), while no significant continuum fluxes remain at \( \gtrsim 8000 \text{Å} \) up to rest-frame 1216Å (i.e. Ly\( \alpha \)). These QSO spectra indicate large \( \tau_{\text{GP}} \) values at \( \gtrsim 8000 \text{Å} \), or at \( z \gtrsim 6 \). Figure 75 shows \( \tau_{\text{GP}} \)-based \( x_{\text{HI}} \) measurements over \( z \sim 5-6.5 \), indicating that \( x_{\text{HI}} \) rapidly increases at \( z \gtrsim 5.7 \). This rapid increase in \( x_{\text{HI}} \) suggests that cosmic reionization is completing at \( z \sim 6 \).

In this figure, only lower limits of \( x_{\text{HI}} \) are obtained at \( z \gtrsim 5.7 \). This is because this method can estimate \( x_{\text{HI}} \) only when the IGM is highly ionized with \( x_{\text{HI}} \lesssim 10^{-4} \). Since Ly\( \alpha \) is a resonance line, \( \tau_{\text{GP}} \) cannot be accurately measured for the IGM even with moderately small neutral fractions of \( x_{\text{HI}} \sim 10^{-4} - 1 \), owing to the saturation of Ly\( \alpha \) absorption. In other words, this method is useful only at the final stage of cosmic reionization, i.e., \( z \lesssim 6 \). To probe \( x_{\text{HI}} \) higher than \( \sim 10^{-4} \), one can use Ly\( \beta \) and Ly\( \gamma \) lines whose absorption is weaker than that of Ly\( \alpha \) by factors of 3 and 5, respectively. With Ly\( \alpha \) absorption lines in QSO spectra, there is another technique to evaluate \( x_{\text{HI}} \), which measures the wavelength range over which the spectrum is completely absorbed. This measurement is called the dark gap (Fan et al., 2006b). However, this additional technique extends the redshift range of \( x_{\text{HI}} \) measurements only up to \( z \sim 6.5 \).

\[ ^{14} \text{Except at wavelengths very close to the QSO Ly}\alpha. These wavelengths correspond to the proximity region where hydrogen is completely ionized by strong UV radiation from the QSO. \]
Fig. 74  Optical spectra of QSOs at $z = 5.7 – 6.4$ (Fan et al. 2006a). This figure is reproduced by permission of the AAS.
5.3 Probing Reionization History II: Thomson Scattering of the Cosmic Microwave Background

The CMB is another background light useful for probing the reionization history. Because CMB photons are Thomson-scattered by free electrons existing between $z = 0$ and $z = 1100$ (the redshift when CMB photons are created), one can identify signatures of the scattering in E-mode polarization and temperature fluctuation smearing seen in the CMB. These signatures allow us to estimate the column density of free electrons that is quantitatively expressed with the optical depth of Thomson scattering $\tau_e$.

Here, $\tau_e$ is particularly sensitive to large-scale (low multipole $\ell < 10$) anisotropies of CMB polarization. The top panel of Figure 76 presents auto-power spectra of CMB E-mode polarization anisotropies with various $\tau_e$ values, demonstrating that...
measurements of CMB polarization can constrain $\tau_e$. The auto-power spectra of CMB polarization depend not only on $\tau_e$ but also on the cosmic reionization history, i.e., redshift evolution of $\chi_{\text{HI}}$. However, the dependence on the latter is much smaller than the uncertainties in $\tau_e$ measurements to date (Planck Collaboration et al., 2016). Thus, when deriving $\tau_e$, one can safely assume that the universe is instantaneously ionized at a redshift that is referred to as $z_{re}$. The bottom panel of Figure 76 shows posterior probability distributions of $\tau_e$ given by Planck 2016 observations. The best-estimate $\tau_e$ from the Planck 2016 study is $\tau_e = 0.058 \pm 0.012$.

The Thomson scattering optical depth up to a given redshift is expressed as:

$$\tau_e(z) = \sigma_T \int_0^z n_e(z') \frac{dl(z')}{dz'} dz',$$

(42)

where $\sigma_T$ is the cross section of Thomson scattering and $n$ the number density of free electrons. Setting $z$ to 1100 gives the total optical depth between today and the time when CMB photons are created. In the standard picture, there is a negligible contribution to $\tau_e$ before the formation of the first stars ($z \gtrsim 20$).

In the case of instantaneous reionization, Equation (42) is simplified to

$$\tau_e(z_{re}) \simeq 0.07 \left( \frac{h}{0.7} \right) \left( \frac{\Omega_b}{0.04} \right) \left( \frac{\Omega_m}{0.3} \right)^{-1/2} \left( \frac{1 + z_{re}}{10} \right)^{3/2}.$$  

(43)

Based on the $\tau_e$ estimate above, Planck Collaboration et al. (2016) obtain the instantaneous reionization redshift to be $z_{re} \simeq 7.8 - 8.8$ that is a moderately late epoch. However, note again that the cosmic reionization history cannot be constrained well by this method because the power spectra of CMB polarization are not sensitively dependent on it.\(^{15}\)

\(^{15}\) There is another probe for the cosmic reionization history that uses Kinetic Sunyaev-Zeldovich effects of the CMB temperature anisotropies made by the bulk motion of free electrons at the EoR. However, the constraints on the cosmic history, so far obtained, are not strong (see the summary of Planck Collaboration et al. 2016).
Fig. 76  Top: E-mode polarization auto-power spectrum [Planck Collaboration et al., 2016]. The colored curves represent power spectra for $\tau_e$ values indicated with the color code on the right hand side, while the gray region denotes the cosmic variance for full sky observations in the case of $\tau_e = 0.06$. Bottom: Posterior distributions of $\tau_e$ for various combinations of Planck data [Planck Collaboration et al., 2016]. The gray region indicates the range of $\tau_e$ that is ruled out by observational constraints from the QSO Gunn-Peterson effect. This figure is reproduced by permission of the A&A.
5.4 Probing Reionization History III: Lyα Damping Wing

Sections 5.2 and 5.3 have reviewed two methods to probe the cosmic reionization history. The method using the Gunn Peterson effect can pinpoint the completion epoch of cosmic reionization at $z \sim 6$, but it cannot probe $z \gtrsim 6$ due to the saturation of Lyα absorptions. The method using CMB Thomson scattering, on the other hand, can probe the entire cosmic history with free electrons between $z = 0$ and the CMB epoch, but it has not been able to clearly distinguish different cosmic reionization histories.

![Graph showing Lyα scattering cross section as a function of wavelength (or velocity).](image)

**Fig. 77** Lyα scattering cross section as a function of wavelength (or velocity). The cross section profile consists of two components: an exponential profile made by thermal motions and a power-law tail by natural broadening.

To probe $x_{HI}$ at the missing epoch of $z \gtrsim 6$, one can use HI Lyα damping wing (DW) absorptions seen in LAE, GRB, and QSO spectra. Briefly, Lyα DW is the tail of Lyα absorption. Figure 77 presents the profile of Lyα cross section. The Lyα absorption profile consists of two components. One is the main component with an exponential profile produced by thermal motions, and the other a weak, power-law component due to natural broadening (i.e., quantum mechanics’s uncertainty principle in energy and time). Lyα DW corresponds to the latter. The Lyα DW absorption is more than 5 orders of magnitude weaker than the peak of the main absorption component. Moreover, since the DW absorption has a power-law shape...
(σ ∝ Δλ^−2), it can extend to much redder wavelengths beyond 1216Å than the main component. Because the Lyα DW absorption is significantly weaker than that by the Gunn-Peterson effect, the DW absorption allows us to investigate the IGM with a moderately high neutral hydrogen fraction, x_HI ~ 0.1 – 1.0. Moreover, the extended profile of the DW absorption is useful to study continua at > 1216Å free from the Gunn-Peterson effect. Below, I detail x_HI constraints from the Lyα DW absorption so far obtained with GRB, QSO, and LAE spectra.

Fig. 78  GRB 050904 afterglow spectrum (Totani et al., 2006). Top: Two dimensional spectrum. Middle: One dimensional spectrum. The solid curve represents the best-fit model of the absorption by the neutral hydrogen of the host galaxy in the case of no IGM absorption. The dotted line is an intrinsic power-law spectrum determined from the observed continuum in the wavelength ranges indicated by the horizontal lines at F_λ ≃ 1.35 x 10^-18 erg cm^−2 s^−1 Å^−1. The dashed line denotes a model spectrum when only the IGM absorption shortward of Lyα is taken into account; a very low neutral fraction of x_HI = 10^-3 is assumed here. Bottom: One sigma errors in the observed spectrum. This figure is reproduced by permission of the PASJ.

5.4.1 GRBs

To date, four GRBs at z ~ 6 – 7 have been used to constrain x_HI: GRB 050904 at z = 6.3 (Totani et al., 2006), GRB 080913 at z = 6.7 (Patel et al., 2010), GRB 130606A at z = 5.9 (Chornock et al., 2013, Totani et al., 2014, 2016), and GRB 140515A at z = 6.3 (Chornock et al., 2014). Figure 78 presents an observed spectrum of GRB 050904 and the best-fit continuum model with the Lyα DW absorption. Here, the intrinsic spectrum shortward of Lyα is an extrapolation of a power-law function fitted to the observed continuum longward of Lyα. Note that Lyα DW absorption modeling should consider not only IGM neutral hydrogen but also that in the GRB host galaxy. The Lyβ line is also used to resolve the degeneracy between the IGM and host-galaxy components (Totani et al., 2006). Among the four GRBs, one gives an estimate of x_HI of a few percent, while the others only place an upper or lower
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limit of $x_{HI} \lesssim 0.1 - 0.7$ at $z \sim 6 - 7$. Although there are many GRBs found at the EoR, $z \geq 6$, that include GRB 090423 at $z = 8.2$, the most distant GRB confirmed to date (Tanvir et al., 2009), all of them are too faint to identify the Ly$\alpha$ DW absorption.

Fig. 79 Spectra of QSO ULAS J1342+0928 at $z = 7.5$ and $x_{HI}$ estimation (Bañados et al., 2018). Top: Observed spectrum of ULAS J1342+0928 (black line) and the best-matched SDSS QSO composite spectrum (red line). The gray line represents the $1\sigma$ error. Bottom left: Same as the top panel, but for a close-up view around the Ly$\alpha$ wavelength. The thick blue line represents the best-matched composite spectrum with the DW absorption by the IGM whose neutral fraction is set to the average value over the redshift range between $z = 7$ and the end of the QSO proximity zone (blue dashed lines). The green dotted line denotes a spectrum with a single absorber, such as a foreground galaxy, that appears different from the observed spectrum. Bottom right: Probability density distribution (blue histogram) of $x_{HI}$ values that are obtained by a fitting of the composite spectrum with DW absorptions. The 1 and 2$\sigma$ ranges of $x_{HI}$ are indicated with vertical dashed and dotted lines, respectively. This figure is reproduced by permission of the Nature Publishing Group.

5.4.2 QSOs

DW absorptions in QSO spectra also provide constraints on $x_{HI}$. As in the GRB DW absorption analyses, one needs to assume an intrinsic spectrum for the QSO in question. While the major uncertainty in GRB analyses is the DW absorption by HI gas in the host galaxy, QSO analyses include potential systematic uncertainties in the Ly$\alpha$ emission profile and the QSO near-zone size that impact on the shape of the intrinsic QSO spectrum before IGM absorption. To mitigate these systematic uncertainties, one can use a low-$z$ QSO spectrum template to estimate the intrinsic spectrum. Figure 79 presents the spectrum of QSO ULAS J1342+0928 at $z = 7.5$. The bottom left panel of Figure 79 is a close-up around the Ly$\alpha$ wavelength of this object, overplotted with the best-estimate intrinsic spectrum that is a composite of
SDSS QSO spectra (thick red line). The spectrum with the DW absorption by neutral hydrogen is presented with a thick blue line. The bottom right panel of Figure 79 indicates the obtained probability density function of the IGM neutral hydrogen fraction, from which the best-estimate IGM neutral hydrogen fraction is found to be $x_{\text{HI}} = 0.56^{+0.21}_{-0.18}$ at $z = 7.5$ (Bañados et al., 2018). With a lower-redshift QSO than this object, ULAS J112010641 at $z = 7.1$, Mortlock et al. (2011) obtain $x_{\text{HI}} > 0.1$. This neutral hydrogen constraint at $z = 7.1$ is a lower limit because of an uncertain contribution by a damped Ly$\alpha$ (DLA) system associated with this object. Subsequently, Greig et al. (2016) carefully reconstruct the intrinsic spectrum of this QSO from SDSS BOSS data, and obtain $x_{\text{HI}} = 0.40^{+0.21}_{-0.19}$ at $z = 7.1$ in conjunction with patchy reionization modeling.

5.4.3 LAEs

LAEs play a unique role in estimating $x_{\text{HI}}$. In contrast with bright continuum sources, i.e., GRBs and QSOs, DW absorptions in the Ly$\alpha$ emission lines of LAEs are used to quantify $x_{\text{HI}}$ (e.g. Malhotra & Rhoads 2004; Kashikawa et al. 2006, 2011; Ouchi et al. 2010). Although spectra of LAEs are too faint to be modeled with a comparable accuracy as those of GRBs and QSOs, the abundance of LAEs is orders of magnitude higher than those of GRBs and QSOs. Thus, LAEs can probe the $\text{HI}$ of the IGM with a large number of sightlines, which reduces the field variance systematics. Moreover, one can evaluate the IGM absorption amount of Ly$\alpha$ DW with simple comparisons of Ly$\alpha$ statistics, exploiting the large statistics given by abundant LAEs.

Figure 80 shows the evolution of the Ly$\alpha$ luminosity function and $\rho_{\text{Ly}\alpha}$ over $z = 5.7 - 7.3$ obtained by deep narrowband imaging and spectroscopic surveys. Both the Ly$\alpha$ luminosity function and $\rho_{\text{Ly}\alpha}$ decrease from $z = 5.7$ towards higher $z$. Moreover, it is also suggested that $\rho_{\text{Ly}\alpha}$ evolution is accelerated at $z \gtrsim 7$, and that the decrease in $\rho_{\text{Ly}\alpha}$ at $z > 7$ is clearly faster than that in $\rho_{\text{UV}}$ that represents the star-formation rate density evolution. This accelerated evolution of $\rho_{\text{Ly}\alpha}$, which cannot be explained by any observed evolutionary trends in the star-formation properties of LAEs, suggests high neutral hydrogen fractions of $x_{\text{HI}} = 0.2 \pm 0.2$ ($z = 6.6$), $x_{\text{HI}} = 0.25 \pm 0.25$ ($z = 7.0$), and $x_{\text{HI}} = 0.55 \pm 0.25$ ($z = 7.3$) from comparisons of various reionization models, where the errors include model variances (Ouchi et al. 2010, Konno et al. 2014, Itoh et al. 2018). To estimate $x_{\text{HI}}$, the Ly$\alpha$ emitting galaxy fraction $X_{\text{Ly}\alpha}$ is also measured by deep follow-up spectroscopy of dropout galaxies. Here, $X_{\text{Ly}\alpha}$ is defined by the ratio of galaxies with Ly$\alpha$ emission to all galaxies down to a given UV-continuum magnitude limit. In contrast to the LAE selection, the UV-continuum selection does not depend on cosmic reionization (i.e., the value of $x_{\text{HI}}$).
Fig. 80  Left: Evolution of the Ly\(\alpha\) luminosity function over \(z = 5.7 - 7.3\) ([Itoh et al. 2018]). The cyan, blue, red, and magenta data points (curves) present Ly\(\alpha\) luminosity functions (the best-fit Schechter functions) at \(z = 5.7, 6.6, 7.0,\) and 7.3, respectively. The inset panel presents the error contours of the Schechter parameters \(\phi^*\) and \(L^*_{\text{Ly}\alpha}\) at the 68 and 90% confidence levels. Right: Redshift evolution of the Ly\(\alpha\) luminosity density (red symbols and lines) and the UV luminosity density (blue symbols and lines) ([Itoh et al. 2018]). The Ly\(\alpha\) luminosity density drops at \(z \gtrsim 7\) faster than the UV continuum density, suggestive of strong Ly\(\alpha\) absorption by the IGM with a moderately high \(x_{\text{HI}}\) at \(z \gtrsim 7\). The left and right ordinate axes indicate the Ly\(\alpha\) and UV-continuum luminosity densities, respectively. This figure is reproduced by permission of the AAS.

Fig. 81  Ly\(\alpha\) emitting galaxy fraction \(X_{\text{Ly}\alpha}\) as a function of redshift ([Schenker et al. 2014]). Ly\(\alpha\) emitting galaxies are defined as those with Ly\(\alpha\) \(EW \geq 25\)\(\AA\). The red and blue data points represent \(X_{\text{Ly}\alpha}\) for UV-continuum faint \((M_{\text{UV}} > -20.25)\) and bright \((M_{\text{UV}} < -20.25)\) dropout galaxies, respectively. This figure is reproduced by permission of the AAS.
Figure 81 indicates that $X_{\text{Ly}\alpha}$ peaks at $z \sim 6$ and decreases towards higher $z$ (Stark et al., 2011; Pentericci et al., 2011, 2014; Ono et al., 2012; Schenker et al., 2012, 2014; Treu et al., 2013). The $x_{\text{HI}}$ value is estimated to be $x_{\text{HI}} = 0.39^{+0.08}_{-0.09}$ ($z \sim 7$) and $x_{\text{HI}} > 0.64$ ($z \sim 8$; Schenker et al., 2014). All of these Lyα emission observations suggest that the Lyα emissivity of galaxies decreases from $z \sim 6$ towards higher $z$, and that the neutral hydrogen fraction is moderately high at $z \sim 7 - 8$.

5.5 Reionization History

Figure 82 summarizes $x_{\text{HI}}$ estimates given by the Gunn Peterson effect, Thomson scattering of the CMB, and Lyα DW absorptions of GRBs, QSOs, and LAEs. This figure clarifies that the measurements of the Gunn Peterson effect reveal the completion epoch of cosmic reionization at $z \sim 6$ (Section 5.2). The Lyα DW absorption measurements suggest a moderately high $x_{\text{HI}}$ at $z \sim 6 - 8$, indicative of late reionization, albeit with large uncertainties (Section 5.4). Although the CMB Thomson scattering results have no time resolution, they also imply a moderately late reionization epoch of $z_{\text{re}} \simeq 7.8 - 8.8$ for the case of instantaneous reionization (Section 5.3). However, because all the $x_{\text{HI}}(z)$ data plotted here have large uncertainties, the duration of cosmic reionization, by which the reionization process is characterized, e.g., as being sharp or extended, remains to be determined (Ishigaki et al., 2018).

Fig. 82 Redshift evolution of $x_{\text{HI}}$ (Itoh et al., 2018). The left and right panels are the same, but with linear and log-scale ordinate axes, respectively. The green squares represent estimates from QSO Gunn Peterson optical depths, while the other green symbols indicate results of QSO DW measurements. The magenta and red data points denote $x_{\text{HI}}$ estimated from LAE DW absorptions. The cyan symbols are given by Lyα emitting galaxy fractions. The blue symbols show the results of GRB DW measurements. The orange pentagon presents an estimate obtained with the Lyα EW distribution of dropout galaxies. The black triangle with an arrow indicates the 1σ lower limit of $z_{\text{re}}$ obtained by Planck Collaboration et al. (2016). The black curve and gray shade show $x_{\text{HI}}$ and its uncertainty suggested from the evolution of the UV luminosity function (Ishigaki et al., 2018). This figure is reproduced by permission of the AAS.
5.6 H\text{I} 21 cm Observations: Direct Emission from the IGM

Sections 5.2-5.4 introduce studies of cosmic reionization probed with bright background radiation. Although it is difficult to directly detect emission from the diffuse IGM at the EoR with the technology today, there are many efforts to find such a signal. The most important direct signal is the H\text{I} hyperfine structure line of 21 cm wavelength that is produced when the spins of the proton and electron in a neutral hydrogen atom flip from antiparallel to parallel. Catching this emission produced at the EoR ($z \sim 10$) needs a low frequency radio observation because it is redshifted to $\sim 100$ MHz. Future 21 cm emission data will allow us to study the cosmic reionization history $x_{\text{HI}}(z)$ and the topology of H\text{I} distribution that depends on ionizing sources (i.e., galaxies vs. AGNs; ionizing photons from these two populations have different mean-free paths against neutral hydrogen gas because of different spectral shapes).

5.6.1 Basic Picture of EoR H\text{I} 21 cm Emission

The strength of the 21 cm emission depends on the spin temperature $T_s$ (from Maxwell-Boltzmann equation) that is defined by

$$\frac{n_{\uparrow\uparrow}}{n_{\uparrow\downarrow}} = 3 \exp\left(-\frac{h\nu_{21\text{cm}}}{kT_s}\right),$$

where $n_{\uparrow\uparrow}$ and $n_{\uparrow\downarrow}$ are the number densities of parallel and antiparallel hydrogen atoms, $h$ the Planck constant, $k$ the Boltzmann constant, and $\nu_{21\text{cm}}$ the frequency of 21 cm wavelength. When $T_s$ is lower (higher) than the CMB temperature $T_{\text{CMB}}$, the 21 cm line is observed as absorption (emission) in the CMB spectrum. The observable is thus an increment of brightness temperature relative to the CMB, $\delta T_B$, that is described as

$$\delta T_B \simeq \frac{T_s - T_{\text{CMB}}}{1 + z} \tau_{21\text{cm}}$$

$$\simeq 7(1 + \delta) x_{\text{HI}} \left(1 - \frac{T_{\text{CMB}}}{T_s}\right) (1 + z)^{1/2} \text{ mK},$$

where $\delta$ is the baryon overdensity and $\tau_{21\text{cm}}$ the H\text{I} optical depth at 21 cm (Fan et al. 2006b, Pritchard & Loeb 2010a). Figure 83 presents a theoretical prediction of the brightness temperature increment evolution, together with an H\text{I} map illustration. At $z \sim 150$, baryons and CMB decouple because collisions and cooling dominate in baryon gas. After $z \sim 80$, the cosmic baryon density is sufficiently low that the collisional cooling is inefficient. After the first stars and QSOs, i.e. galaxies, form at $z \sim 20 - 30$, Ly$\alpha$ photons from galaxies are scattered by H\text{I} gas in the IGM. This process redistributes the two spin states of H\text{I}, and enlarges the difference between the spin and CMB temperatures (Ly$\alpha$ cooling aka Wouthuysen-Field effect). Then,
the H\textsc{i} of the IGM is heated by X-ray emission from objects. At $z \sim 15$, the reionization begins, and the brightness temperature increment becomes small, due to an increase in ionized regions in the IGM. In this way, the evolution of $\delta T_B$ is predicted. The spatial fluctuations of $\delta T_B$ also vary with evolutionary phase due to differences in heating and cooling sources.

![Fig. 83. Evolution of brightness temperature from $z = 200$ to 6 suggested by a theoretical model (Pritchard & Loeb, 2010b). Top: Brightness temperature with spatial fluctuations as a function of redshift (cosmic age). The brightness temperature is color-coded following the color bar on the right hand side. Bottom: Sky-averaged brightness temperature as a function of redshift (observed frequency). Also indicated are the epochs of several major cosmic events that change the brightness temperature of the 21cm line. This figure is reproduced by permission of the Nature Publishing Group.]

### 5.6.2 Early H\textsc{i} 21cm Observation Results and Expectations

Measuring the brightness temperature of the IGM at the EOR requires radio observations in low frequencies ($\sim 100$ MHz) (see Figure 83), and several programs have conducted such observations: Giant Metrewave Radio Telescope (GMRT; Paciga et al. 2011), Precision Array for Probing the Epoch of Reionization (PAPER; Parsons et al. 2014; Ali et al. 2015), LOw Frequency ARray (LOFAR; Yatawatta et al. 2013; Jelcic et al. 2014), and Murchison Widefield Array (MWA; Dillon et al. 2014). The left panel of Figure 84 summarizes 21-cm power spectrum ($z \sim 8 - 9$) results from these programs. So far, no programs have identified a signal of the 21-cm emission from the EoR, and only upper limits have been obtained. The left panel of Figure 84 indicates that the $2\sigma$ upper limits are about 2 orders of magnitude higher than predicted signals. Although some programs have expected sensitivities high enough to detect the EoR 21 cm emission, in practice the expected sensitivities cannot be reached due to difficulties in subtraction of bright foreground emission. There are many Galactic and telluric foreground sources. One of the most challenging foregrounds is ionospheric radio emission that varies with sky position and time. Thus,
the most important challenge in detecting 21 cm signals from the EOR is to properly model the foreground emission that is a few orders of magnitude brighter. Because such foreground emission dominates in specific Fourier spaces and wavelengths, it would be possible to isolate the EoR 21 cm emission in the parameter space that is referred to as the “EoR window” (DeBoer et al., 2016), free from the foreground emission.

![Fig. 84](image)

**Fig. 84** Left: Observed and predicted power spectra of 21 cm emission (Ali et al., 2015). All observational data points are upper limits. The yellow, magenta, and green triangles show 2σ upper limits at $z = 8.6, 9.5, \text{ and } 7.7$ that are given by GMRT, MWA, and PAPER experiments, respectively. The magenta curve represents the model 21 cm power spectrum for the 50% reionization case predicted by Lidz et al. (2008). The black dots, the cyan dashed line, and the black dashed vertical line indicate the results of the PAPER experiment shown in Ali et al. (2015), while these results are negated by Ali et al. (2018) due to the underestimations of the signal uncertainties. This figure is reproduced by permission of the AAS. Right: 21 cm absorption profiles at $z = 17$ best-fitted to the EDGES data (Bowman et al., 2018). The eight lines with different colors indicate absorption profiles for different observational set-up data, among which the thick black line corresponding to the highest signal-to-noise ratio case. This figure is reproduced by permission of the Nature Publishing Group.

Although EoR 21-cm emission signals have not been detected yet, there is a report of EoR 21-cm absorption detection. Bowman et al. (2018) have conducted low-frequency radio observations with the Experiment to Detect the Global Epoch of Reionization Signature (EDGES) low-band instruments, and found an absorption at 78 MHz corresponding to $z = 17$ (right panel of Figure 84). This absorption may be a signature of first stars and QSOs whose Lyα photons lower the brightness temperature by the Wouthuysen-Field effect. However, the observed absorption is significantly stronger than model predictions. In other words, the hydrogen gas at $z \sim 17$ is suggested to be colder than the gas kinetic temperature as well as the CMB temperature. Barkana (2018) claims that cold hydrogen gas can be produced by
the interaction of hydrogen gas with dark matter whose temperature is low enough
to explain the low brightness temperature suggested by the EDGES observations.
Because the detection of an absorption by the EDGES, if true, will have a great
impact on our understanding of the thermal history of the universe, it should be
confirmed by independent projects.

Fig. 85  Spatial distributions of ionized gas (top panels), all LAEs (middle panels), and observed
LAEs (bottom panels) over a cosmological volume ($94 \times 94 \times 35$ Mpc$^3$) with average ionized
fractions of 0.3 ($x_{HI} = 0.7$; left column), 0.5 (middle column), and 0.7 ($x_{HI} = 0.3$; right column)
predicted by numerical simulations (McQuinn et al., 2007). In the top panels, ionized regions are
indicated in white. In the middle and bottom panels, LAEs are shown with white dots. This figure
is reproduced by permission of MNRAS.

Theoretical models predict that the cross-correlation function between H$\alpha$ 21 cm
emission and LAEs is key for understanding the reionization process. If cosmic
reionization proceeds from high to low density regions, so called in the inside-out
manner, star-forming galaxies including LAEs exist preferentially in cosmic ionized
bubbles. Moreover, cosmic ionized bubbles allow Ly$\alpha$ photons escaping from LAEs
to survive, thus enhancing the observed overdensity of LAEs in ionized bubbles
(Figure 85, McQuinn et al., 2007). It is thus expected that H$\alpha$ 21 cm emission and
LAEs anti-correlate strongly. Figure 86 presents theoretical predictions of the cross-power spectrum between HI 21 cm emission and LAEs (Lidz et al., 2009). The distance scale where the sign of the correlation changes can be used to constrain the typical size of ionized bubbles. The distance scale becomes large towards the end of reionization (i.e. small $x_{\text{HI}}$; Figure 86).

Fig. 86  Top: Galaxy-21 cm cross-power spectra predicted by Lidz et al. (2009). The solid and dashed lines denote the 21 cm cross-power spectra for all galaxies and LAEs, respectively. The black, red, and blue colors mean the ionized fraction of 0.21, 0.54, and 0.82 (corresponding to $x_{\text{HI}} = 0.79, 0.46,$ and 0.18) at $z = 8.3, 7.3,$ and 6.9, respectively. Bottom: Same as the top panel, but for the cross-correlation coefficients between 21 cm radiation and galaxies. This figure is reproduced by permission of the AAS.

5.7 Summary of Cosmic Reionization I

This section has introduced the basic physical picture of cosmic reionization, and showcased various techniques to probe the cosmic reionization history, discussing constraints obtained by those techniques on the neutral hydrogen fraction $x_{\text{HI}}$ (or ionized hydrogen fraction $Q_{\text{HII}}$) as a function of redshift. There are three major
techniques to estimate $x_{\text{HI}}$ that require bright background light. One uses the Gunn-Peterson effect of background QSO spectra, while the other two measure, respectively, the Thomson optical depth of the CMB and Ly$\alpha$ DW absorptions seen in background GRB, QSO, and LAE spectra. The measurements of the Gunn Peterson effect suggest that cosmic reionization ended at $z \sim 6$ (Section 5.2). The Thomson scattering optical depth of the CMB obtained from the recent Planck2016 data is small ($\tau_e \sim 0.06$) (Section 5.3), and the Ly$\alpha$ DW absorption strengths indicate a moderately high $x_{\text{HI}}$ at $z \sim 6 - 8$ (Section 5.4). These two pieces of information support late reionization. Since the CMB Thomson scattering results available to date have no time resolution and the Ly$\alpha$ DW constraints on $x_{\text{HI}}$ are not very strong, the duration of cosmic reionization (i.e. sharp or extended reionization) has been constrained only weakly.

6 Cosmic Reionization II: Sources of Reionization

This section presents progresses in observations for understanding sources of reionization that is one of the two major questions of cosmic reionization (see the first paragraph of Section 5).

6.1 What are the Major Sources Responsible for Reionization?

There are several candidates for sources of cosmic reionization that supply ionizing photons at the EoR. These candidates include galaxies, AGNs, high-mass X-ray binaries (HMXBs), primordial blackholes (PBHs), and dark-matter annihilation.

Although it is obvious that galaxies and AGNs should contribute to cosmic reionization because they are bright in UV, the question is the relative contributions of individual candidate populations. AGNs produce not only UV ionizing photons, but also X-ray photons whose mean-free paths in the H$\text{I}$ IGM are as large as the sizes of LSSs. If the X-ray emission of AGNs dominates in reionizing the universe, the structures of ionized regions should be smooth. HMXBs can also contribute via X-ray radiation, but it is not yet clear whether they play a major role because the observed X-ray background is mostly explained by known AGNs at redshifts up to $z \sim 6$ (Hickox & Markevitch 2007). PBHs would emit Hawking radiation that would heat the IGM, but observational studies place moderately tight upper limits on the fraction of the total mass of PBHs to dark matter that is less than $\sim 10\%$ over the PBH masses of $\sim 10^{20}$ to $1 M_\odot$ (Niikura et al. 2017). It is predicted that dark-matter particles annihilate into high energy particles including neutrinos and gamma rays that produce X-ray radiation. However, this happens only if dark matter is made of supersymmetric particles such like axions.

In this lecture, I only consider reionization by UV ionizing photons and discuss two promising reionization sources, galaxies and AGNs.
6.2 Ionization Equation for Cosmic Reionization

The key quantity for sources of reionization is the production rate of ionizing photons $\dot{n}_{\text{ion}}$ that is defined by the number of ionizing photons per volume and time. The $\dot{n}_{\text{ion}}$ values should be estimated by observations for galaxies and AGNs. The $\dot{n}_{\text{ion}}$ value is related with the ionized hydrogen fraction of the IGM $Q_{\text{HII}}$ (eq. 39) via the simple one zone model of the ionization equation (Madau et al., 1999; Robertson et al., 2013; Ishigaki et al., 2015; Robertson et al., 2015),

$$\dot{Q}_{\text{HII}} = \frac{\dot{n}_{\text{ion}}}{\langle n_{\text{H}} \rangle} - \frac{Q_{\text{HII}}}{t_{\text{rec}}},$$  

(47)

where $\langle n_{\text{H}} \rangle$ and $t_{\text{rec}}$ are the average hydrogen number density and the recombination time, respectively, given by

$$\langle n_{\text{H}} \rangle = \frac{X_{p} \Omega_{0} \rho_{c}}{m_{\text{H}}}$$  

(48)

$$t_{\text{rec}} = \frac{1}{C_{\text{HII}} \alpha_{B}(T)(1 + Y_{p}/4X_{p}) \langle n_{\text{H}} \rangle (1+z)^{3}}.$$

(49)

Here, $X_{p}$ ($Y_{p}$), $\rho_{c}$, and $m_{\text{H}}$ are the primordial mass fraction of hydrogen (helium), the critical density, and the mass of the hydrogen atom, respectively. In eq. (49), $\alpha_{B}(T)$ is the case B hydrogen recombination coefficient for the IGM temperature $T$ at a mean density. The value of $C_{\text{HII}}$ is the clumping factor,

$$C_{\text{HII}} = \frac{\langle n_{\text{HII}}^{2} \rangle}{\langle n_{\text{HII}} \rangle^{2}},$$

(50)

where $n_{\text{HII}}$ is the density of ionized hydrogen gas in the IGM. With the brackets, $\langle n_{\text{HII}}^{2} \rangle$ and $\langle n_{\text{HII}} \rangle^{2}$ are the spatially averaged values. One can derive the evolution of $Q_{\text{HII}}$ with the observational estimates of $\dot{n}_{\text{ion}}$ via eq. (47), where most of the parameters are determined by physics and cosmology. By this technique, the budget of ionizing photons is evaluated (see Section 6.3).

For the specific case of ionization equilibrium, one can substitute $\dot{Q}_{\text{HII}} = 0$ and $Q_{\text{HII}} = 1$ in eq. (47), and obtain

$$\dot{n}_{\text{ion}} = \frac{\langle n_{\text{H}} \rangle}{t_{\text{rec}}}$$  

(51)

$$= 10^{50.0} C_{\text{HII}} \left( \frac{1+z}{7} \right)^{3} \text{s}^{-1} \text{Mpc}^{-3}.$$  

(52)

This condition of $\dot{n}_{\text{ion}}$ gives the lower limit of the ionizing photon production rate that can keep the ionized universe (e.g. Bolton & Haehnelt 2007; Ouchi et al. 2009b).

One of the free parameters in the ionization equation (eq. 47) is the clumping factor $C_{\text{HII}}$ (eq. 50) that determines the recombination rate of ionized hydrogen in
the IGM. Based on the ionizing photon emissivity measurements from QSO absorption line data, the clumping factor is estimated to be as low as $C_{\text{HII}} \sim 3$ at $z \sim 6$ (Bolton & Haehnelt, 2007). Because the universe becomes homogeneous $C_{\text{HII}} = 1$ with negligibly small fluctuations at the Big Bang epoch, the clumping factor is low, $C_{\text{HII}} \sim 1 - 3$, over the EoR ($z > 6$). In fact, cosmological numerical simulations with the QSO UV background radiation predict monotonically decreasing values of $C_{\text{HII}}$ towards high-$z$ with $C_{\text{HII}} \sim 1 - 3$ (Figure 87; Shull et al., 2012, see also Pawlik et al., 2009). The numerical simulation results of Figure 87 are approximated by the power law,

$$C_{\text{HII}}(z) = 2.9 \left( \frac{1+z}{6} \right)^{-1.1}$$

at $z = 5 - 9$ (Shull et al., 2012). Although there remain systematic uncertainties related with the mass resolution and the radiative transfer implementation, the majority of theoretical models agree with these small clumping factors ($C_{\text{HII}} \sim 1 - 3$) at the EoR. If it is true, the uncertainties of clumping factors are not as large as those of the other free parameters (see Section 6.3).

Fig. 87 Evolution of clumping factor predicted by the numerical simulations (Shull et al., 2012). The black solid line indicates the results of the simulations with 1536$^3$ cells in the $50h^{-1}$ Mpc box, which are approximated with the function of equation (53) at $z = 5 - 9$. The rest of the solid lines are the same as the black solid lines, but for 768$^3$-cell sub-volumes. The dotted line represents the 512$^3$-cell simulations. This figure is reproduced by permission of the AAS.
To evaluate the ionizing photon contribution of galaxies to the cosmic reionization with eq. (47), one needs to estimate \( \dot{n}_{\text{ion}} \) of galaxies. The value of \( \dot{n}_{\text{ion}} \) is calculated by

\[
\dot{n}_{\text{ion}} = \int_{-\infty}^{M_{\text{trunc}}} f_{\text{esc}}(M_{\text{UV}}) \xi_{\text{ion}}(M_{\text{UV}}) \phi(M_{\text{UV}}) L(M_{\text{UV}}) dM_{\text{UV}}
\]

where \( f_{\text{esc}} \) and \( \xi_{\text{ion}} \) are the ionizing photon escape fraction (eq. 56; Section 6.3.2) and the ionizing photon production efficiency (eq. 60; Section 6.3.3), respectively. Here, for simplicity, it is assumed that \( f_{\text{esc}} \) and \( \xi_{\text{ion}} \) do not depend on \( M_{\text{UV}} \). It should be noted that \( f_{\text{esc}} \) is the escape fraction of ionizing photons that is different from the escape fraction of Ly\( \alpha \) photons (eq. 33). The value of \( \rho_{\text{UV}}(M_{\text{trunc}}) \) is the UV luminosity density defined with eq. (10), where \( M_{\text{trunc}} \) is the limiting magnitude for the integration, a.k.a. the truncation magnitude (Ishigaki et al., 2015). The truncation magnitude indicates how faint galaxies can exist, which depends on the gas cooling and feedback efficiencies in a faint (i.e. low-mass) galaxy.

There are three major parameters for \( \dot{n}_{\text{ion}} \), i.e. \( \rho_{\text{UV}}(M_{\text{trunc}}) \), \( f_{\text{esc}} \), and \( \xi_{\text{ion}} \). These three parameters are constrained by observations. In the following sections (Sections 6.3.1-6.3.3), I introduce constraints on the parameters obtained by observations, to date.

### 6.3.1 UV Luminosity Density

A number of deep optical and NIR imaging surveys have derived luminosity functions of UV continuum at \( \sim 1500\,\text{Å} \) at the EoR, and estimated \( \rho_{\text{UV}} \) (e.g. McLure et al. 2013, Schenker et al. 2013, Oesch et al. 2015, Bouwens et al. 2015). These surveys provide good measurements of UV luminosity functions at \( z = 6-10 \), and reveal that the faint-end slopes of the UV luminosity functions are as steep as \( \alpha \approx 2 \) (Bouwens et al., 2015). The steep faint-end slopes imply that the \( \rho_{\text{UV}} \) value is significantly contributed by faint galaxies \( (M_{\text{UV}} \geq -15) \) that are not luminous but abundant (see, e.g., Robertson et al., 2010). Because these conventional deep surveys only reach the moderately bright magnitude limit of \( M_{\text{UV}} \sim -17 \) at \( z \sim 7 \) even in the Hubble Ultra Deep Field (HUDF) program, a \( \rho_{\text{UV}} \) value estimate requires an extrapolation of the UV luminosity function from \( M_{\text{UV}} \sim -17 \) to \( M_{\text{UV}} > -15 \) to obtain \( \rho_{\text{UV}} \) via eq. (10). Moreover, the limiting magnitude of \( M_{\text{trunc}} \) is unknown, requiring an assumption such as \( M_{\text{trunc}} = -13 \) (Robertson et al., 2013). The major uncertainty

\[16\] To understand the sources of reionization, one needs to solve the equation (47). In this case, there are four major parameters, the three parameters \( \rho_{\text{UV}}, f_{\text{esc}}, \xi_{\text{ion}} \) for \( \dot{n}_{\text{ion}} \) and one parameter \( (C_{\text{HII}}) \) for \( t_{\text{rec}} \).
in the $\rho_{\text{UV}}$ determination is the extrapolation of the UV luminosity function at the faint end below the detection limit.

To determine $\rho_{\text{UV}}$ at the EoR with the measurements of the faint-end UV luminosity function, the Hubble Frontier Fields (HFF) project is conducted (Lotz et al. 2017). The HFF project has performed ultra-deep optical and NIR imaging with HST/ACS and WFC3-IR, respectively, in six massive galaxy clusters at $z \sim 0.3 - 0.5$, and targeted intrinsically very faint background galaxies lensed by the clusters. Exploiting the lensing magnifications, one can probe the UV luminosity functions down to the detection limit deeper than the one of the HUDF program by a few magnitudes (e.g. Atek et al. 2014b, 2015, Ishigaki et al. 2015, 2018, Coe et al, 2015, Oesch et al., 2015, 2018, McLeod et al., 2015, 2016, Livermore et al., 2017). The left panel of Figure 88 presents the UV luminosity function at $z \sim 7$ thus obtained. Although it reaches $M_{\text{UV}} \sim -14$ mag, no signature of the truncation of the luminosity function is found. The truncation magnitudes would exist at even fainter magnitudes. Nevertheless, the HFF project has revealed the UV luminosity function up to $M_{\text{UV}} \sim -14$ mag without any extrapolations, thereby imposing the constraint on the truncation magnitude, that it must be fainter than $M_{\text{UV}} \sim -14$ mag at $z \sim 7$.

The results of the HFF project significantly reduce the uncertainty on $\rho_{\text{UV}}$ estimates that is given by the extrapolation and the assumed $M_{\text{trunc}}$ value. The right panel of Figure 88 shows the redshift evolution of $\rho_{\text{UV}}$ calculated from these UV luminosity functions under the assumption of $M_{\text{trunc}} = -15$. In this panel, $\rho_{\text{UV}}$ monotonically decreases from $z \sim 2$ towards high-$z$. The values of $\rho_{\text{UV}}$ at $z \sim 9 - 10$ still include moderately large statistical uncertainties due to the small number of galaxies identified at these redshifts.

Fig. 88  Left: UV luminosity function up to $M_{\text{UV}} \sim -14$ (Ishigaki et al., 2018). The red circles (and the black open diamonds and crosses) are the luminosity functions derived from the HFF data. The other symbols including blue circles are the luminosity functions obtained without HFF data, which reach up to $M_{\text{UV}} \sim -17$. The black line and the gray shade denote the best-fit Schechter function and the fitting error, respectively. Right: Evolution of UV luminosity density that is derived under the assumption of $M_{\text{trunc}} = -15$ (Ishigaki et al., 2018). The ordinate axis on the right-hand side indicates the cosmic SFR density. The red and black symbols represent the observational data points calculated with UV luminosity functions. The orange circles show the cosmic SFR density estimated from the sum of the UV and FIR luminosity densities. This figure is reproduced by permission of the AAS.
6.3.2 Escape Fraction of Ionizing Photon

The ionizing photon escape fraction is measured at $\sim 900\,\text{Å}$ with the ratio of the observed flux $f_{\text{obs}}^{900}$ to intrinsic Lyman-continuum (LyC) flux ($f_{\text{int}}^{900}$):

$$f_{\text{esc}}^{\text{ion}} = \left( \frac{f_{\text{obs}}^{900}}{f_{\text{int}}^{900}} \right) e^{\tau_{900}},$$

(56)

where $e^{\tau_{900}}$ is the line-of-sight average IGM opacity to the LyC photons that is determined by QSO absorption line observations [Steidel et al., 2001]. Because the estimate of $f_{\text{int}}^{900}$ includes large uncertainties with assumptions, observers introduce the relative escape fraction

$$f_{\text{esc},\text{rel}}^{\text{ion}} = \left( \frac{f_{\text{obs}}^{900}}{f_{\text{obs}}^{1500}} \right) e^{\tau_{900}},$$

(57)

where $f_{\text{obs}}^{1500}$ is the observed 1500Å UV continuum flux [Steidel et al., 2001; Inoue et al., 2006; Shapley et al., 2006]. Because the observation study papers discuss $f_{\text{esc}}^{\text{ion}}$ (i.e. the absolute escape fraction) and $f_{\text{esc},\text{rel}}^{\text{ion}}$ (i.e. the relative escape fraction), one needs to carefully check the definition of the ionizing photon escape fraction. Hereafter, the absolute escape fraction $f_{\text{esc}}^{\text{ion}}$ is discussed, unless otherwise specified.

A determination of $f_{\text{esc}}^{\text{ion}}$ requires very deep observations of galaxies for LyC detections. There are two observational approaches to detect LyC of galaxies, extremely deep spectroscopy and narrowband imaging for star-forming galaxies. The left and right panels of Figure 89 present LyC emission of $z \sim 3$ galaxies found in the spectrum and the narrowband image, respectively. With the spectra and narrowband images, the average $f_{\text{esc},\text{rel}}^{\text{ion}}$ value is estimated to be $\sim 5\%$ for LBGs and $\sim 20\%$ for LAEs at $z \sim 3$ [Shapley et al., 2006; Iwata et al., 2009; Nestor et al., 2013]. Interestingly, the average $f_{\text{esc}}^{\text{ion}}$ of LAEs is higher than the one of LBGs, suggesting a positive correlation between $f_{\text{esc}}^{\text{ion}}$ and Ly$\alpha$ EW in the moderately low Ly$\alpha$ EW regime (left panel of Figure 90). Moreover, the average $f_{\text{esc}}^{\text{ion}}$ of $z \sim 3$ galaxies is significantly higher than that of most well known star-forming galaxies ($f_{\text{esc}}^{\text{ion}} < 3\%$) such as Haro11 and Tol 1247-232 [Leitet et al., 2011, 2013]. In addition to the high estimated value of $f_{\text{esc}}^{\text{ion}}$ at $z \sim 3$, the LyC emission in narrowband images show a spatial offset from the intensity peak of the UV ($\sim 1500\,\text{Å}$) continuum (right panel of Figure 89). Although the spatial offset of the LyC emission may indicate that the major LyC emitting region is different from the UV-continuum emitting region, there is a possibility that the spatial offset would be a signature of the chance alignment of a foreground (low-$z$) object whose rest-frame UV continuum can mimic the LyC. However, the probability for such chance alignments is estimated to be only $2 - 3\%$ [Iwata et al., 2009]. With this small probability, one cannot explain all of the LyC emitting galaxy candidates by chance alignments of foreground objects.

Although foreground contamination objects may not be the reason for the high observational value of $f_{\text{esc}}^{\text{ion}}$ at $z \sim 3$, there remains the question why observations do not find star-forming galaxies at $z \sim 0$ with $f_{\text{esc}}^{\text{ion}} \approx 5 - 20\%$ that is as high as that of $z \sim 3$ LBGs and LAEs. Recent HST/COS observations identify a total of 5
star-forming galaxies at $z \sim 0$ with a high escape fraction, $f_{\text{esc}}^{\text{ion}} \sim 6 - 13\%$ (Izotov et al., 2016a,b), which is the definitive evidence that there exist local galaxies with a high $f_{\text{esc}}^{\text{ion}}$ value comparable with those of high-$z$ galaxies (right panel of Figure 90). These 5 star-forming galaxies are selected with the criterion of $O_{32} > 5$ (Izotov et al., 2016b). Because there is a possibility that such a high $O_{32}$ value indicates a high ionization parameter and perhaps a density-bounded nebula, there would exist a positive correlation between $f_{\text{esc}}^{\text{ion}}$ and $O_{32}$ (Nakajima & Ouchi, 2014). In this case, one can easily understand that high-$z$ galaxies, especially LAEs, have the high escape fraction of $\sim 5 - 20\%$, because high-$z$ galaxies have a large value of $O_{32} \sim 10$ that is significantly larger than the average $O_{32}$ value of local galaxies (Figure 33, Section 3.4.2). The question of the high $f_{\text{esc}}^{\text{ion}}$ value for high-$z$ galaxies is being answered by recent studies.

Fig. 89  Left: LyC spectra of a galaxy at $z = 3$ (Shapley et al., 2006). The two- and one-dimensional spectra are shown in the top and bottom panels, respectively. LyC emission is found at wavelengths shorter than the Lyman limit corresponding to the label "Ly Lim" on the left-hand side. Right: Ground-based imaging data of three galaxies at $z = 3$ taken with a narrowband covering the LyC wavelengths (left panels: Iwata et al., 2009). The central panels are the same as the left panels, but with the broadband ($R$ band) images. The right panels display the HST broadband $I_{814}$ images. The contours indicate the LyC emission detected in the narrowband data. This figure is reproduced by permission of the AAS and PASJ.

17 It should be noted that Borthakur et al. (2014) have identified a local star-forming galaxy with an absolute escape fraction of $f_{\text{esc}}^{\text{ion}} \approx 1\%$. This absolute escape fraction corresponds to 21\%, if one does not include dust extinction effects.
6.3.3 Ionizing Photon Production Efficiency

The ionizing photon production efficiency is defined as

$$\xi_{\text{ion}} = \frac{\dot{n}_{\text{ion}}^0}{L_{\text{UV}}}$$

(58)

where $\dot{n}_{\text{ion}}^0$ and $L_{\text{UV}}$ are the intrinsic ionizing photon production rate (before the escape from the ISM) and the UV ($\sim 1500\,\text{Å}$) continuum luminosity, respectively. The left pane of Figure 91 presents $\xi_{\text{ion}}$ as a function of UV spectral slope predicted by stellar synthesis models with various metallicities and IMFs (Robertson et al., 2013). In this way, $\xi_{\text{ion}}$ depends on stellar populations. Although many parameters of stellar populations are constrained with galaxy SEDs in UV ($> 1216\,\text{Å}$), optical, and NIR bands including the UV spectral slope, there remain large differences of $\xi_{\text{ion}}$ for a given SED shape (see Figure 91 for a given UV slope). This is because $\xi_{\text{ion}}$ is very sensitive to the metallicity, IMF, and star-formation history that are key parameters for ionizing photon production, while the observable galaxy SED at $> 1216\,\text{Å}$ does not change. Moreover, there is another large uncertainty in the choice of stellar synthesis models for ionizing production rates that depend on the physical properties of massive binary stars (Eldridge et al., 2017). Nevertheless, the galaxy SED approach can suggest a value of $\log \xi_{\text{ion}} [\text{erg}^{-1}\text{Hz}] \sim 25.2$ that should include systematic uncertainties by a factor of a few (Robertson et al., 2013, Figure 91). To determine $\xi_{\text{ion}}$ with no such systematics, one needs other approaches. A promising method to estimate $\xi_{\text{ion}}$ is to use hydrogen Balmer lines such as H$\alpha$ and H$\beta$. Because Balmer lines are produced in HII regions via photoionization, one can estimate intrinsic ionizing
photons production rates with Balmer line fluxes with the simple analytical relation,

\[ n_{\text{ion}}^0 = 2.1 \times 10^{12} (1 - f_{\text{esc}}^{\text{ion}})^{-1} L_{\text{H} \beta}, \]  
\[ \log(\xi_{\text{ion}}) = \log(n_{\text{ion}}^0) + 0.4 M_{\text{UV}} - 20.64, \]  
(59)  
(60)

where \( L_{\text{H} \beta} \) and \( M_{\text{UV}} \) are the extinction-corrected H\( \beta \) luminosity (erg s\(^{-1}\)) and the extinction-corrected UV continuum magnitude, respectively (Schaerer et al. 2016; Storey & Hummer 1995). In eq. (59), the term of \((1 - f_{\text{esc}}^{\text{ion}})\) subtracts the ionizing photons escaping from the galaxy to the IGM. The right panel of Figure 91 shows \( \xi_{\text{ion}} \) as a function of UV magnitude or UV slope that is obtained by the Balmer line method. The right panel of Figure 91 indicates \( \log(\xi_{\text{ion}}) \approx 25.2 - 25.4 \) for \( z = 4 - 5 \) LBGs (Bouwens et al. 2015) and \( z \sim 0 \) Lyman-continuum leaking galaxies of Izotov et al. (2016a,b) that are similar to (or slightly higher than) the value determined by the galaxy SED study (Schaerer et al. 2016). There would be a trend of increasing \( \xi_{\text{ion}} \) towards small UV slopes (i.e. blue UV continuum; Bouwens et al. 2015). Hereafter, the value of \( \log(\xi_{\text{ion}}) \approx 25.2 - 25.4 \) is referred to as the fiducial value.

Fig. 91 Left: Model predictions for \( \xi_{\text{ion}} \) as a function of \( \beta \) (Robertson et al. 2013). The solid and dashed curves represent dust-free and dusty (\( A_V \sim 0.1 \)) galaxies, respectively, that are calculated with the stellar population synthesis model of Bruzual & Charlot (2003) under the assumptions of the Chabrier (2003) IMF and constant star-formation history. The red, orange, blue, and purple colors of the curves indicate the metallicities of \( Z = 0.004, 0.008, 0.02, \) and 0.05, respectively. The dotted curves are the same as the solid curves, but for the Salpeter (1955) IMF. The calculations stop at \( 7.8 \times 10^8 \) yr corresponding to the cosmic age at \( z \sim 7 \). The gray shade denotes the \( \beta \) range for the average \( z \sim 7 \) galaxy that is obtained by observations. Right: \( \xi_{\text{ion}} \) as a function of \( M_{\text{UV}} \) (top) and \( \beta \) (bottom; Schaerer et al. 2016). The red circles (blue triangles) show \( \xi_{\text{ion}} \) with (without) a dust attenuation correction of the UV continuum for five star-forming galaxies at \( z \sim 0.3 \). Note that two blue triangles are indistinguishable in this plot. The black and magenta circles represent LBGs at \( z = 3.8 - 5 \) and \( 5.1 - 5.4 \), respectively. The cyan region indicates the canonical value for the dust-extinction corrected \( \xi_{\text{ion}} \). This figure is reproduced by permission of the AAS and A&A.
6.3.4 Galaxy Contribution to Reionization: Comparisons of $Q_{\text{HII}}(z)$ and $\tau_e$

Because the observational studies have constrained the three major parameters of galaxies, i.e. $\rho_{\text{UV}}(M_{\text{trunc}})$, $f_{\text{esc}}^{\text{ion}}$, and $\xi_{\text{ion}}$ (Sections 6.3.1 and 6.3.3), one can determine $\dot{n}_{\text{ion}}$ via eq. (55) that is the amount of the ionizing photon contribution of galaxies. The $\dot{n}_{\text{ion}}$ value is used in the ionization equation, eq. (47). In eq. (47), $\dot{n}_{\text{ion}}$ should include not only the ionizing photons from galaxies but also those from the other ionizing sources such as AGNs. However, $\dot{n}_{\text{ion}}$ values of AGNs are poorly determined as discussed in Section 6.4. Here, one can first assume that the contribution to $\dot{n}_{\text{ion}}$ from the other ionizing sources is negligible (i.e. galaxies’ $\dot{n}_{\text{ion}}$ is dominant), and obtain the evolution of the ionized fraction $Q_{\text{HII}}(z)$ and the inferred $\tau_e$ with the equations (47) and (42) via (39). Comparing these $Q_{\text{HII}}(z)$ and $\tau_e$ values with those from the direct measurements shown in Section 5, one can test whether galaxies can reionize the universe or the other sources of reionization are necessary. Below, I discuss the galaxy contribution to reionization based on these arguments.

The $\dot{n}_{\text{ion}}$ value of galaxies is estimated with the three parameters, $\rho_{\text{UV}}$ shown in Figure 88 (Section 6.3.1), $f_{\text{esc}}^{\text{ion}} \simeq 20\%$ (Section 6.3.2), and $\log \xi_{\text{ion}} \left[ \text{erg}^{-1} \text{Hz}^{-1} \right] \sim 25.2$ (Section 6.3.3), where no redshift evolutions of $f_{\text{esc}}^{\text{ion}}$ and $\xi_{\text{ion}}$ are included. Assuming the value of $C_{\text{HII}} = 3$ (cf. eq. 53), one can derive $Q_{\text{HII}}(z)$ with eq. (47). The left panel of Figure 92 presents $Q_{\text{HII}}(z)$ calculated with the galaxies’ $\dot{n}_{\text{ion}}$ thus obtained. Although the direct measurements of $Q_{\text{HII}}(z)$ have large uncertainties, the inferred $Q_{\text{HII}}(z)$ is consistent with the existing direct measurements. The right panel of Figure 92 shows $\tau_e$ as a function of redshift. Again, the inferred $\tau_e$ value agrees with the direct CMB measurement of $\tau_e$ given by Planck Collaboration et al. (2015)\footnote{The up-to-date best measurement of $\tau_e$ is systematically smaller than the value of Planck Collaboration et al. (2015) beyond the 1 sigma error level, $\tau_e = 0.058 \pm 0.012$ (Planck Collaboration et al., 2016). The value is even smaller in the latest Planck result, $\tau_e = 0.0561 \pm 0.0071$ (Planck Collaboration et al., 2018).} Although the direct measurements have large statistical errors in $Q_{\text{HII}}(z)$ and potentially significant systematic errors in $\tau_e$, the $\dot{n}_{\text{ion}}$ value of galaxies alone explain both the direct measurements of $Q_{\text{HII}}(z)$ and $\tau_e$. These results may suggest that galaxies are major sources of cosmic reionization.

However, it should be noted that there are a factor of $\gtrsim 2$ uncertainties in the relatively poor determinations of the three parameters as well as the direct measurements. There remain possibilities that these large errors would not allow us to identify an inconsistency between the inferred value and the direct measurement of $Q_{\text{HII}}(z)$ or $\tau_e$. One can conclude whether galaxies are major sources of cosmic reionization or not, after the errors on these parameters and the direct measurements become considerably small.
Neutral hydrogen fraction \((1 - Q_{\text{HI}})\) as a function of redshift (left) and Thomson scattering optical depth integrated over redshift (right; Robertson et al. 2015). The red region indicates the best estimates obtained from the cosmic star-formation history determined by observations in the case of \(f_{\text{ion}} = 0\). The blue, orange, and cyan regions are the results of the previous study (Robertson et al., 2013), the forced-match to the WMAP data (Hinshaw et al., 2013), and a different cosmic star-formation history with a rapid decrease at \(z \sim 8\), respectively. In the left panel, the data points and the arrows represent the neutral hydrogen fraction estimates obtained from the Gunn-Peterson effect and \(\text{Ly} \alpha\) damping wing measurements. In the right panel, the dark and light-gray shades denote the Thomson scattering optical depth measurements given by Planck 2015 (Planck Collaboration et al., 2015) and the nine-year WMAP (Hinshaw et al.) 2013. This figure is reproduced by permission of the AAS.

### 6.4 AGN Contribution

Recent galaxy studies suggest that a majority of ionizing photons for reionization would be supplied by galaxies (Section 6.3). However, these study results still include large systematic uncertainties. One needs to test whether the other sources can contribute to cosmic reionization. AGNs are prominent sources supplying ionizing photons, because a large amount of ionizing photons are efficiently produced in AGNs and escape from them.

The top panel of Figure 93 presents the number density evolution of QSOs, where QSOs are defined as AGNs brighter than \(-27.6\) magnitude. The number density of QSOs peaks at \(z \sim 2 - 3\), and decreases towards high-\(z\). At \(z \sim 6\), the QSO number density is only \(10^{-9}\) \(\text{Mpc}^{-3}\) (Fan et al. 2004; Richards et al. 2006). Similarly, UV luminosity functions of QSOs decrease very rapidly towards \(z \sim 6\). Based on the UV luminosity functions, the production rate of ionizing photons of QSOs are estimated in the same manner as those of galaxies (Section 6.3). Although it is assumed that QSO spectra have an ionizing photon escape fraction of unity, and that QSOs have a power law spectrum, these assumptions are plausible for QSOs whose LyC escape and production are well understood in contrast with galaxies (Section...
The QSO contribution is estimated to be only \( \sim 1 - 10\% \) of ionizing photons at \( z \sim 6 \) (Srbinovsky & Wyithe 2007). The ionizing photon production rate of QSOs is negligibly small, due to the very small number density of QSOs at \( z \sim 6 \). A further decrease of QSO number density is suggested from \( z \sim 6 \) to \( z \sim 7 \) (Venemans et al. 2013). These results indicate that the ionizing photon production rate of QSOs becomes smaller towards high-\( z \).

Although QSOs (i.e. bright AGNs) do not significantly contribute to cosmic reionization, there remains the possibility that faint AGNs could be major contributors of cosmic reionization. As shown in the bottom four panels of Figure 93, the number density of faint AGNs is larger than QSOs by orders of magnitudes. Given the efficient ionizing photon production with the power-law continuum of AGNs, faint AGNs would be important in cosmic reionization. Moreover, the number density of faint AGNs does not drop as steeply as those of bright AGNs towards the epoch of reionization.

Properties of faint AGNs at the EoR are not well understood, due to the difficulties in identifying faint AGNs at such a high redshift. Treister et al. (2011) report the > 5\( \sigma \) detections in the stacked X-ray spectra of dropout galaxies at \( z \sim 6 \), suggesting the existence of faint AGNs in dropout galaxies. However, subsequent studies identify no X-ray emission in a similar stacked X-ray data of \( z \sim 6 \) dropout galaxies (Willott 2011; Fiore et al. 2012; Cowie et al. 2012) argue that the background subtraction of the X-ray data would produce wrong detections, and that there are no signatures of faint AGNs in dropout galaxies at \( z \sim 6 \) on average. Nevertheless, the contribution of faint AGNs is still under debate.

Giallongo et al. (2015) show a number of dropouts at \( z \sim 4 - 6 \) with X-ray detections on the individual basis, and claim a steep faint-end slope of AGN UV luminosity functions (left panel of Figure 94). If this steep faint-end slope is true, ionizing photons are mostly originated from faint AGNs at \( z \sim 6 \) (Giallongo et al. 2015, right panel of 94). However, the faint-end slope value of the AGN UV luminosity function at \( z \sim 4 - 6 \) remains an open question. Although the UV magnitude range of the Giallongo et al.'s luminosity function has only a small overlap with the one of the previous study at \( M_{UV} \sim -22 \) (McGreer et al. 2013), the AGN number density of Giallongo et al. (2015) is about an order of magnitude higher than that of McGreer et al. (2013) (left panel of Figure 94). Moreover, the ionizing photon escape fraction of faint AGNs is not well understood (Grazian et al. 2018), while QSOs have an escape fraction as high as unity that is indicated by QSO proximity effects. In this way, the contribution of faint AGNs is not clearly understood yet.

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19 Because these faint AGNs are not identified in UV but X-ray, Treister et al. (2011) claim that these faint AGNs do not contribute to cosmic reionization due to the obscuration of UV photons.
Fig. 93  Top panel: Evolution of the QSO number density [Richards et al. 2006]. The red squares and the black circle are the number densities integrated up to $i = -27.6$ mag in QSO luminosity functions obtained from the SDSS data. The lines indicate the fitting results of these number densities and previous studies. Bottom four panels: Evolution of number densities for AGNs with different luminosities (Hopkins et al. 2007). The top left, top right, bottom left, and bottom right panels present the redshift evolution of AGNs for a given luminosity interval of bolometric luminosity, hard X-ray (2 – 10 keV), soft X-ray (0.5 – 2 keV), and $B$ band (0.44 µm), respectively, where the luminosity intervals are indicated with the labels. The lines represent the results of the best-fit evolving double power-law models. This figure is reproduced by permission of the AAS.
Fig. 94  Left: UV luminosity function of AGN at $z \sim 5$. The triangles, circles, and square are the AGN luminosity functions obtained by Giallongo et al. (2015), McGreer et al. (2013), Ikeda et al. (2012), respectively. The solid and dashed lines are the double-power laws best-fit to the data of Giallongo et al. (2015) and McGreer et al. (2013), respectively. Right: Redshift evolution of the cosmic photoionization rate $\Gamma_{-12}$ in units of $10^{-12} \text{s}^{-1}$ (Giallongo et al., 2015). The black squares are the AGN contribution to $\Gamma_{-12}$ (connected to $n_{\text{ion}}$ of AGNs), which are obtained by Giallongo et al. (2015), while the red data points denote the total $\Gamma_{-12}$ estimated from QSO Ly$\alpha$ absorption line systems. This figure is reproduced by permission of the A&A.

6.5 Summary of Cosmic Reionization II

This section has discussed what are the major sources that reionize the universe with the latest observational progresses, explaining the procedures to quantify the budget of ionizing photons. Starting with the galaxy contribution to cosmic reionization, I clarify three major parameters, $\rho_{\text{UV}}(M_{\text{trunc}})$, $f_{\text{ion}}$, and $\xi_{\text{ion}}$, to evaluate the production rate of ionizing photons, i.e. $\dot{n}_{\text{ion}}$. There is another parameter, the clumping factor of the ionized hydrogen IGM ($C_{\text{HII}}$). With the latest observational results for these parameters, the ionizing photon production rate of galaxies alone agrees with the direct observational measurements of $Q_{\text{HII}}(z)$ and $\tau_e$ obtained with high-$z$ objects and CMB (Section 5), respectively. These results may indicate that galaxies are major sources of cosmic reionization, although the agreements are not strong, due to the large errors on these parameters. Because the number density of bright AGNs, i.e. QSOs, is very small at the EoR, the ionizing photon contribution of QSOs is negligibly small. However, there is a possibility that ionizing photons of faint AGNs may significantly contribute to cosmic reionization. The number density as well as the escape fraction of the faint AGNs is not clearly understood by observations, to date, and various observational studies are trying to determine these AGN properties.
7 On-Going and Future Projects

This section summarizes the open questions about LAEs discussed in the previous sections, and introduces on-going and future projects potentially answering them.

7.1 Open Questions

Major open questions about LAEs discussed in this lecture are listed below.

**Galaxy Formation:**

− What are the physical reasons for the LAE’s star-formation and ISM characteristics that distinguish LAEs from the other galaxy populations? For example, are the high-ionization parameters of LAEs due to high ionization production rate, to high electron density, or to density-bounded ISM?

− What are the Lyα blobs and diffuse halos? Are they related to cold accretion? Where is the cold accretion that produces Lyα emission?

− What makes the large Lyα EWs (≥ 200Å) of LAEs? What is the major physical reason for the $f_{\text{esc}}^{\text{Ly} \alpha}$ increase from $z \sim 0$ to 6?

− Have we already identified real popIII star-formation in $z \lesssim 7$ LAEs with strong HeII emission and no detectable metal lines?

**Cosmic Reionization:**

− How did cosmic reionization proceed? Is it true that the reionization occurred late, as suggested by the LAEs and recent CMB studies? Is the evolution of $Q_{\text{HII}}$ extended or sharp? How can some Lyα photons escape from $z > 8$ where the IGM is highly neutral (see Section 7.2.2)?

− Are star-forming galaxies major sources of reionization, especially for low-mass galaxies most of which have intrinsically strong Lyα emission? Do faint AGNs play an important role in supplying ionizing photons? Can we conclude what are the major sources of cosmic reionization, given the large uncertainties on the parameters, $\rho_{\text{UV}}(M_{\text{trunc}})$, $f_{\text{esc}}^{\text{ion}}$, and $\xi_{\text{ion}}$ and $C_{\text{HII}}$?
7.2 New Projects Addressing the Open Questions

7.2.1 On-Going Projects

There are three major on-going projects that can study LAEs up to \( z \lesssim 7 \), Subaru/Hyper Suprime-Cam (HSC; Miyazaki et al. 2018) + Prime-Focus Spectrograph (PFS; Tamura et al. 2016), Hobby-Eberly Telescope Dark Energy Experiment (HETDEX; Hill et al. 2012a), and VLT/Multi-Unit Spectroscopic Explorer (MUSE; Bacon et al. 2010). These three projects can target LAEs, covering the complementary parameter space of LAEs in depth and redshift (Figure 95). Moreover, these three projects are complementary in the covering areas. Subaru/HSC+PFS and HETDEX cover large areas of a few \( 10 - 100 \) deg\(^2\), while VLT/MUSE will observe small fields with an area up to a few 10 arcmin\(^2\).

Fig. 95 Parameter space of Ly\(\alpha\) luminosity vs. redshift that is covered by HSC+PFS (red), HETDEX (blue), and MUSE (green) surveys. The HSC+PFS observations will cover \( z \sim 2 \) and \( z \sim 5 - 7 \).

Subaru/HSC+PFS:

Subaru/HSC is a wide-field optical imager with a field-of-view (FoV) of 1.5 deg-diameter circle (Figure 96). The FoV of HSC is seven times larger than that of its wide-field imager predecessor at Subaru, Suprime-Cam. The HSC large program,
which is the Subaru Strategic Program (SSP) survey, has started in March 2014; it is a collaborative project involving Japanese institutes, Princeton, and Taiwanese institutes. A total of 300 nights are allocated to the HSC SSP survey that will be completed around 2019. The HSC SSP survey has the wedding cake type survey design: it is planned to obtain $g$, $r$, $i$, $z$, and $y$ band imaging data down to the 5 sigma limiting magnitudes $i \sim 26$ in the wide layer (1400 deg$^2$), $i \sim 27$ in the deep layer (30 deg$^2$), and $i \sim 28$ in the ultra-deep layer (3 deg$^2$). The deep and ultra-deep layers are covered by narrowband images with 5 sigma limiting magnitudes of 25–26. With these imaging data, the HSC SSP survey has a wide variety of scientific goals from cosmology to solar-system objects. For LAE studies, the HSC SSP survey will uncover about 20,000 LAEs and 1,000 Ly$\alpha$ blobs down to $L_{\text{Ly}\alpha} \sim 3 \times 10^{42}$ erg s$^{-1}$ at $z = 5.7$ and 6.6. Additional samples of $z = 2.2$ and 7.3 LAEs will be gathered in the deep and ultra-deep layers, respectively. It should be noted that the $z = 5.7$ and 6.6 LAEs are found in a total area nearing 1 comoving Gpc$^2$, allowing studies of $z \sim 6$–7 LAEs in a cosmological large scale. These LAE samples will allow the researchers to address a number of issues of galaxy formation and cosmic reionization by analyses with Ly$\alpha$ luminosity functions and LAE clustering measurements. Some of the early HSC SSP survey results on LAEs have been published. For examples, the evolution of Ly$\alpha$ blobs is determined on the basis of an unprecedentedly large sample (e.g. Shibuya et al. 2018a), and the constraints on $x_{\text{HI}}$ are being obtained with the goal of an $x_{\text{HI}}$ determination accuracy comparable to the model uncertainty of 10% for the reionization history (Ouchi et al. 2018; Konno et al. 2018).

Fig. 96 Left: Subaru/HSC mounted on the Subaru telescope (Courtesy: Y. Utsumi). Right: Subaru/PFS conceptual design (Takada et al. 2014). The PFS instrument with its 2400 fibers will be installed at the Subaru prime focus, just like the HSC instrument. The massive spectrographs fed by the fibers are placed on the floor of the Subaru dome. This figure is reproduced by permission of the PASJ.
The wide-field spectrograph Subaru/PFS complements the wide-field imaging capability of Subaru/HSC (Figure 96). PFS is a multi-object fiber spectrograph that is being developed by a consortium including Japan, Princeton, JHU, Caltech/JPL, LAM, Brazil, ASIAA, and many other contributors. PFS accommodates 2400 fibers with a diameter of 1.0′′ – 1.1′′ that cover a FoV of 1.3 deg², sharing the Subaru wide-field optical corrector with HSC. There are three arms for blue, red, and NIR bands that take spectra at 0.38 – 0.65, 0.63 – 0.97, and 0.94 – 1.26 µm, respectively, with spectral resolutions of \( R = 2400 – 4200 \). The first light of PFS is planned around 2020. There is a plan of large galaxy survey with PFS, and the strategy of the galaxy survey is being built. Follow-up spectroscopy for the LAEs detected by the Subaru/HSC SSP survey is envisaged; it will provide unique data sets that will significantly enhance our understanding of galaxy formation and cosmic reionization.

HETDEX:

HETDEX is a survey with the Hobby Eberly Telescope (HET) and its visible integral-field replicable unit spectrograph (VIRUS) [Hill et al., 2012]. The schematic view of HET and VIRUS is shown in Figure 97. The VIRUS instrument on HET accommodates 78 integral-field units (IFUs) each of which holds 448 fibers. The total number of the VIRUS fibers is over 30 thousands. Because HET/VIRUS is optimized to target redshifted Ly\( \alpha \) emission at \( z = 1.9 – 3.5 \) very efficiently to detect BAO and to constrain the equation of state of dark energy, HET/VIRUS has the narrow wavelength coverage of 3500 – 5500 Å and the low spectral resolution of
The VIRUS instrument in part saw the first light in the middle of 2016. The VIRUS instrument is being built, while the HETDEX survey is conducted. The HETDEX survey will identify 0.8 million LAEs at $z = 1.9 - 3.5$ in a total area of 434 deg$^2$ ($\sim 20\%$ filling area) down to $\sim 4 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$. Although the major scientific goal of HETDEX is understanding the state of equation of dark energy by BAO analysis with the LAEs, a number of statistical studies are being planned with the HETDEX LAEs; for examples, the LAE luminosity function evolution and environment effect in conjunction with clustering analysis. Because the HETDEX LAE data are large and unique, the HETDEX survey will impact many areas of LAE studies.

It should be noted that galaxy-LSS connections can be investigated by such large-volume spectroscopic surveys with HETDEX as well as Subaru/PFS (e.g. Adelberger et al. 2003; Rudie et al. 2012; Rakic et al. 2012; Lee et al. 2014; Mawatari et al. 2017; Mukae et al. 2017). Deep spectroscopy with Subaru/PFS would reveal the IGM HI and metal gas distribution of LSS with Ly$\alpha$ and metal absorption lines found in spectra of background bright AGNs and galaxies. The dense IFU spectroscopy of HETDEX will give the spatial distribution of LAEs. The combination of these surveys may provide the three-dimensional maps of the IGM gas and LAEs addressing the question where LAEs form in the LSSs.

**VLT/MUSE:**

VLT/MUSE is an IFS with a contiguous field coverage of 1 arcmin$^2$ that is orders of magnitude larger than those of the other existing IFSs (top panel of Figure 98). MUSE has a reasonably wide range of wavelength coverage (4650 – 9300 Å) and a medium high spectral resolution ($R \sim 3000$). The image slicers of MUSE keep the total throughputs high, allowing high sensitivity observations. A number of exciting MUSE observation results have been reported since 2015. One of the early MUSE observations consists in a 27-hour integration in the central 1 arcmin$^2$ area of the Hubble Deep Field South (HDF-S). The MUSE HDF-S observations reach the 5$\sigma$ detection limit of $\sim 5 \times 10^{-19}$ erg s$^{-1}$ cm$^{-2}$, and increase the number of the spectroscopically identified galaxies by an order of magnitude (bottom panel of Figure 98; Bacon et al. 2015). Moreover, there are 26 MUSE-identified LAEs whose continuum is not detected in the HST HDF-S images with the detection limit of $I \sim 29.5$. Further deep and wide surveys are being conducted in HUDF (Bacon et al. 2017) and Chandra Deep Field South (Herenz et al. 2017). As stated in Sections 4.1.1 and 4.1.2, MUSE observations are playing important roles in various Ly$\alpha$ studies, e.g. diffuse Ly$\alpha$ emitters in blank fields and Ly$\alpha$ emission around QSOs.

It should be noted that there is a counterpart IFS that is developed for Keck telescopes, Keck Cosmic Web Imager (KCWI; Martin et al. 2010) that is moved from the Palomar 5m telescope (Martin et al. 2010). The uniqueness of KCWI is the blue-band coverage below 4650 Å that is not covered by VLT/MUSE. The blue-band coverage will allow the studies of the LAEs-IGM relation (see above) at $z \sim 2$ that is an optimal redshift for IGM HI detections with a high S/N from the ground.
Fig. 98  Top: Picture of the MUSE instrument that is installed at the Nasmyth platform (Courtesy: ESO). Bottom: HST $I_{814}$-band continuum magnitude as a function of redshift (left) and source number/completeness (right) for LAEs identified by the deep MUSE observations in the HDF-S [Bacon et al. 2015]. Left: The brown circles indicate the spectroscopically confirmed objects newly identified by the MUSE observations. The green circles are the same as the brown circles, but for objects confirmed by previous spectroscopy. The sizes of the circles represent the continuum size obtained with the HST $I_{814}$-band image. The red triangles show the MUSE spectroscopically-confirmed objects with no HST counterparts. The dashed horizontal line presents the $3\sigma$ detection limit in the HST $I_{814}$-band image. Right: The gray histogram denotes the magnitude distribution for all of the HST $I_{814}$-band detected objects. The light-blue histogram (with the shade at $I_{814} = 29.5 - 30.0$ mag) indicates the magnitude distribution of the MUSE spectroscopically-confirmed objects with (no) HST counterparts. The blue curve represents the completeness of the MUSE spectroscopic confirmation. The dashed vertical line marks 50% of completeness. This figure is reproduced by permission of the A&A.
7.2.2 Future Projects

Although the three major LAE surveys of Subaru/HSC+PFS, HETDEX, and VLT/MUSE cover a wide range of parameter space, these LAE surveys only target redshifts up to $z \sim 7$ (Figure 95), due to the limited wavelength coverages of optical bands (Section 7.2.1). There remains the unexplored redshift of $z \gtrsim 8$ for LAE studies. Recent deep HST imaging and Keck/MOSFIRE NIR spectroscopy have pushed the redshift frontier of spectroscopically-identified galaxies from $z \sim 7$ to $8-9$ with Ly$\alpha$ emission (Figure 8; Finkelstein et al. 2013; Schenker et al. 2014; Oesch et al. 2015; Zitrin et al. 2015). These observations find galaxies in the range of the highest redshift confirmed by spectroscopy with a strong Ly$\alpha$ line as a signpost (left panel of Figure 99). Moreover, there is an interesting and puzzling report of the significantly blueshifted Ly$\alpha$ emission associated with a galaxy at a spectroscopic redshift of $z = 9.1$ confirmed with an [OIII]88\,$\mu$m line (right panel of Figure 99; Hashimoto et al. 2018).

To date, only a few LAEs are spectroscopically identified up to $z \sim 8-9$. The small number of the $z \sim 8-9$ LAE identifications would be partly explained by the limits of the sensitivities of the existing observation facilities. Moreover, there is an important effect that Ly$\alpha$ emission of LAEs at $z > 6$ is weakened by the damping wing absorption of the IGM HI at the EoR. In fact, the Ly$\alpha$ luminosity function
Observations of Lyα Emitters at High Redshift

Observations of Lyα emitters at high redshift suggest strong dimming of Lyα luminosity from \( z \sim 6 \) to 7.3 (Figure 80). If one assumes that both the IGM and the LAEs are uniformly distributed and static, Lyα emission of LAEs cannot escape from the universe as early as the epoch of first galaxies. However, clustering and peculiar motions of LAEs would help Lyα photons escape from the highly neutral hydrogen IGM. Theoretical models suggest that up to 10% of Lyα fluxes can escape from an LAE in galaxy-clustered regions at the highly neutral epoch (Figure 100; Gnedin & Prada 2004). To understand LAEs’ physical properties as well as the evolution of \( \chi_{\text{HI}} \), it is important to know how much fraction of high-redshift galaxies show Lyα emission escaping from the highly neutral hydrogen IGM. In other words, at what redshift LAEs disappear in the observations, while continuum-selected star-forming galaxies are still seen at the same redshift in sufficiently deep observations.

![Figure 100](image-url) Bottom: Fraction of observed to intrinsic Lyα fluxes as a function of central galaxy SFR that is predicted by numerical simulations (Gnedin & Prada 2004). The black (gray) solid and dashed lines indicate the top 3 and 10% Lyα flux survival, respectively, in all galaxies at \( z = 9 \), for the case of the Lyα offset velocity of 150 (200) km s\(^{-1}\). The short-dashed and dotted lines are the same as the dashed lines, but for galaxies with no companion galaxy within a distance of 100 and 300 physical kpc, respectively. Top: Number of galaxies in each SFR bin that are used for the predictions shown in the bottom panel. This figure is reproduced by permission of the AAS.

Next generation large telescopes useful for observations of LAEs at \( z \gtrsim 8 - 9 \) are being built (Figure 101). In space, James Webb Space Telescope (JWST) is planned...
to be launched in or after 2021. JWST is a successor of HST that covers optical to IR bands (0.6 − 28µm) with a large 6.5m segmented primary mirror. On the ground, there are three projects of extremely large telescopes for optical-IR observations; the European Extremely Large Telescope (E-ELT), the Giant Magellan Telescope (GMT), and the Thirty Meter Telescope (TMT) that have segmented primary mirrors with 39, 24, and 30m effective diameters, respectively. The E-ELT and the GMT are being constructed in Cerro Armazones and Las Campanas Chile, respectively, in the southern hemisphere, while the TMT is planned to be placed in Mauna Kea, Hawaii in the northern hemisphere. These three projects will cover both the northern and southern hemispheres. There exists a possibility that the TMT may move out from Mauna Kea to La Palma on the Canary Islands, Spain, due to difficult issues of the construction site permission in the Hawaii Island. All three projects plan first light in the middle/late 2020s.

It is expected that the first-light of JWST comes earlier than these three ground-based next generation telescopes. Here I introduce two JWST science cases for LAEs.

The first JWST science case is to probe rest-frame optical nebular lines of LAEs at $z \gtrsim 5$ that are redshifted beyond the $K$ band, which require a space telescope for deep observations. For the test of popIII star-formation (Figure 7, Section 4.3), one can measure the spectral hardness of $Q_{\text{He}^+}/Q_{\text{H}}$ for popIII LAE candidates with flux measurements of an HeII line and a Balmer line such as Hα and/or Hβ. The Balmer lines fall in the JWST’s Near-Infrared Spectrograph (NIRSpec) wavelength window.
of 1 – 5µm for high sensitivity spectroscopy. As discussed in Section 4.3, $Q_H$ estimated from Ly$\alpha$-line measurements have large systematic uncertainties raised by the Ly$\alpha$ escape fraction. If one can constrain the nebular extinction with a Balmer decrement of H$\alpha$/H$\beta$ (or H$\beta$/H$\gamma$ for high-$z$ sources), the Balmer-line method provides a reliable $Q_{\text{He}^+}/Q_H$ value that is critical for popIII star-formation tests. It should be noted that the other JWST LAE studies will be also conducted with rest-frame optical nebular lines including [OII]3727 and [OIII]5007, indicators of metallicity and ionization parameter (Sections 3.4.1-3.4.2), and that systemic velocities from the nebular lines are key for understanding the relation between Ly$\alpha$ photon escape and reionization (Hashimoto et al., 2013).

Fig. 102  Simulation results of JWST/NIRISS observations (Dixon et al., 2015). Bottom: Simulated grism GR150R image with the F200W filter for MACS J0647+7015. The assumed integration time is 10 hours. Top: One-dimensional spectrum of a galaxy at $z = 9.3$ retrieved from the simulated grism image. The black symbols and the red line represent the simulated data points and the error, respectively. The blue curve denotes the best-fit model with a Ly$\alpha$ emission line.
The second JWST science case is to conduct an unbiased search for LAEs at a very high redshift. Such an LAE search can be performed with JWST/Near Infrared Imager and Slitless Spectrograph (NIRISS) that is packaged with the guide camera. NIRISS offers the wide-field slitless spectroscopy (WFSS) with grisms whose FoV and spectral resolution are 4 arcmin$^2$ and $R \sim 150$, respectively, at 0.8 – 2.2$\mu$m. The deep slitless spectroscopy can target Ly$\alpha$ emission redshifted to $z \sim 6 – 17$. Figure 102 presents simulations of deep (10-hour integration) NIRISS/WFSS grism spectroscopy in the lensing galaxy cluster MACS J0647+7015 (Dixon et al., 2015). This simulation predicts the detections of 180 LBGs and LAEs with $F_{200W} = 26 – 28$ mag at $z \sim 6 – 15$ with the help of gravitational lensing magnification, assuming a uniform random redshift distribution of LAEs. Investigating the number of detected LAEs as a function of redshift, one can address the problem of Ly$\alpha$ emission escaping from the highly neutral hydrogen IGM (Figure 100).

In addition to these next generation projects for optical-IR observations, there are many multiwavelength projects useful for LAE studies. Programs of 21cm observations are especially important for understanding a reionization-LAE connection. There are two major projects for next generation 21 cm observations, Hydrogen Epoch of Reionization Array (HERA; Pober et al. 2014) and Square Kilometer Array (SKA). HERA will be a 350-element interferometer that is composed of 14-m parabolic dishes covering 50 – 250 MHz. HERA is under construction. In 2016, a few percent of the dishes are already built on the site of South Africa (DeBoer et al. 2016). HERA is not an interferometer that is significantly larger than the existing 21 cm instruments. However, HERA aims to accomplish detections of the weak EoR signals, improving calibration and foreground isolation accuracies with redundant baselines for the “EoR window” (Section 5.6.2) that are designed with the experiences of PAPER and MWA. HERA expects a 21 cm power spectrum detection with an S/N of $\sim 20$ at $z \sim 9$.

SKA will consist in radio interferometers whose total photon collecting area covers one square kilometer. Towards the completion of the interferometers, SKA has the two-phase approach: Phase 1 for the initial deployment starting in 2018 and Phase 2 for the full operation in the mid 2020s. In the Phase 1, SKA integrates two precursor telescopes of MeerKAT in Karoo, South Africa and Australian Square Kilometre Array Pathfinder (ASKAP) in Murchison, Australia. The SKA Phase 1 instrument consists of three elements of SKA1-Mid (Karoo), SKA1-Survey, and SKA1-Low (Murchison; Figure 103). Among the three elements, SKA1-Low is a low frequency array consisting of more than 100 thousand antennas covering 50-350 MHz corresponding to the wavelength of the redshifted EoR 21 cm emission. Before the full SKA construction, it is expected that SKA1-Low would provide 21 cm data useful for the cross-correlation analysis with LAEs (Sobacchi et al., 2016; Hutter et al., 2016; Kubota et al., 2018). Figure 103 presents the LAE-21cm
brightness temperature cross correlation functions predicted with reionization models \citep{Sobacchi2016}. The models assume LAEs from the Subaru/HSC survey and 100−1000 hour SKA1-Low observations, and suggest that the two different cases with $x_{\text{HI}} = 0$ and 0.5 will be clearly distinguished over the uncertainties. Although the large systematic uncertainties (such as foreground subtraction errors) are serious, as discussed in Section 5.6.2, there is a possibility that a new probe of LAE-21 cm cross correlation (Section 5.6.2) may be powerful, due to the capability for removing the systematics in the cross correlation analysis.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure103.png}
\caption{Left: Artist impression image of SKA low frequency array (courtesy: SKA 2018). Right: LAE-21cm cross correlation functions for the average neutral hydrogen fractions of $x_{\text{HI}} = 0$ (blue dot-dashed lines), 0.10 (red long-dashed lines), 0.25 (orange dashed lines), and 0.50 (green short-dashed lines) that are predicted by numerical simulations \citep{Sobacchi2016}. The shades indicate the total uncertainties of theoretical models and observations including foreground effects. These calculations assume SKA1-Low 1000 hour observations for the 21cm data and the HSC survey for the LAE data \citep{Ouchi2018}. The top and bottom panels present the results of LAEs’ host halo masses of $2 \times 10^{10}$ and $3 \times 10^{9} M_{\odot}$, respectively. This figure is reproduced by permission of the MNRAS.}
\end{figure}

7.2.3 Trying Other Approaches

In Sections 7.2.1 and 7.2.2 I have introduced the next-generation powerful instruments in the on-going and future programs. These next-generation instruments cover the unexplored parameter space, and are useful for resolving the issues of the open questions. However, even with no next-generation instruments, one can make a breakthrough with the present-generation instruments by a new approach. There are two observation examples in such breakthrough studies. One is the polarization observations for LABs conducted by \cite{Hayes2011b} and \cite{Prescott2011}.
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Hayes et al. (2011b) have performed the polarization observations with VLT/FORS for a bright LAB, and detected the tangential polarization indicating the Ly\(\alpha\) photon scattering in the LAB (Section 4.1.1). Another example is the identifications of luminous SNe (SNe IIb) hosted by high-z galaxies, \(z \sim 2 - 4\) LBGs and LAEs (Cooke et al., 2012). Cooke et al. (2012) have investigated variables in these high-z galaxies selected in the CFHT Legacy Survey data. Although it was well known that the popular bright SNe, SNe Ia, at \(z \sim 2 - 4\) were too faint to be detected with the present data, Cooke et al. (2012) successfully found luminous SNe in the \(z \sim 2 - 4\) galaxies. These are two good examples of making a breakthrough discovery with the existing facilities and data. I would suggest young astronomers not to simply wait for next-generation instruments, but to try new observational approaches with existing telescopes and data.

7.3 Summary of On-Going and Future Projects

I have showcased the five major open questions related to LAEs about galaxy formation and cosmic reionization. For galaxy formation, there are four questions about i) the LAE’s distinguishing characteristics of star-formation and ISM, ii) physical origins of LABs and diffuse halos, iii) physical reasons for the large Ly\(\alpha\) EW + Ly\(\alpha\) escape fraction, and iv) the LAE-popIII connection. For cosmic reionization, two questions are presented: a) reionization history (late or early / sharp or extended reionization?) and b) major sources of reionization (star-forming galaxies and/or faint AGN?). These open questions are being addressed by on-going observations with the three new instruments, Subaru/HSC(+PFS), HETDEX, and VLT/MUSE. Although the observing programs of these three new instruments cover the complementary survey parameter space in redshift and depth, these programs can investigate LAEs only at \(z \sim 2 - 7\). Beyond \(z \sim 7 - 8\), one needs next generation large telescopes with great sensitivities, JWST, E-ELT, GMT, and TMT in the optical-IR wavelength range. Among these next generation projects, forthcoming JWST projects will probe rest-frame optical nebular lines of LAEs at \(z \gtrsim 5\) for testing popIII, and conduct the unbiased search for LAEs at \(z \sim 6 - 17\). Beyond the optical-IR wavelength range, 21cm observations with HERA and SKA will provide important results. Theoretical studies suggest that the early-phase low-frequency array of SKA1-Low and Subaru/HSC will identify a signal of spatial anti-correlation between 21 cm emission and LAEs. Although these new facilities are key for exciting discoveries, there exist examples that new observational approaches with existing facilities can also make a breakthrough. With these examples in hand, I encourage young astronomers not to simply wait for next-generation instruments, but try new observational approaches for LAE studies with the existing facilities.
8 Grand Summary for this Series of Lectures

Observations of high-z LAEs and the related scientific subjects are detailed in this series of lectures. After I explain the background of LAE discoveries, I clarify that LAEs are important objects for studying galaxy formation and cosmic reionization (Section 1). This is because LAEs are unique probes for high-z/low-mass (popIII-like) galaxies and the IGM H I gas via resonance scattering and damping wing absorptions. I then overview the basic theoretical ideas of galaxy formation including structure formation, gas cooling/feedback, and the five Lyα emission mechanisms (Section 2). In Section 3, I summarize the physical properties of LAEs, known to date, stellar populations, luminosity functions, morphologies, ISM state, LAE-AGN connection, and hosting halos. Section 4 discusses the observational challenges of LAE properties; extended Lyα halos, Lyα escape fraction, and LAE-popIII connection. This series of lectures moves to cosmic reionization science in Section 5. Evolution of neutral hydrogen fraction (i.e. cosmic reionization history) is constrained by the estimates of the IGM Lyα absorption including the Lyα damping wing absorption. The combination of the Lyα absorption, CMB, and H I 21 cm data provides the rough picture of reionization history. In Section 6 I explain simple analytic formulae to evaluate sources of reionization with three parameters for the ionizing photon production rate and one parameter for the IGM spatial distribution, and discuss whether star-forming galaxies can be major sources of reionization. The observational results suggest that star-forming galaxies alone can explain cosmic reionization, although the contribution of faint AGNs and the other sources are poorly understood, to date. Section 7 lists up the five open questions about LAEs, and explains three on-going projects for LAEs at z ∼ 2−7 (Subaru/HSC+PFS, HETDEX, and VLT/MUSE) and various future optical-IR telescope projects for LAEs at z ∼ 7−8 (JWST and ground-based extremely large telescopes), together with low-frequency 21-cm observations (HERA and SKA), including some examples of science cases.

In the past two decades, I find that high-z LAE studies are one of the most important driving forces for the state-of-the-art observational facilities. The importance of Lyα emission is undoubted, due to the fact that Lyα is the strongest emission for the most abundant element in the universe, namely hydrogen. Moreover, the resonance nature of Lyα photons allows us to probe the distribution and kinematics of neutral hydrogen in any cosmic structures of galaxies and LSSs, from the ISM to the CGM and the IGM. In the coming decade, Lyα observations will continue leading the field of high-z observations with the on-going and future facilities. I hope that some of the readers will conduct new Lyα studies inspired by this series of lectures, and produce exciting results very soon.

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