Observing the dark sector

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Abstract

Despite the observational success of the standard model of cosmology, present-day observations do not tightly constrain the nature of dark matter and dark energy and modifications to the theory of general relativity. Here, we will discuss some of the ongoing and upcoming surveys that will revolutionize our understanding of the dark sector.

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1 Introduction

Basically all available cosmological observations are successfully explained by the standard model of cosmology, according to which the universe is dominated by cold dark matter and a dark energy in the form of a cosmological constant. However, a satisfactory theoretical explanation of the dark sector is still lacking and the properties of dark matter and dark energy are not yet well constrained by the data. This is the motivation for the large experimental effort that will revolutionize our understanding of the dark sector in the coming years. Here, we will restrict the discussion to galaxy, gravitational-wave and 21-cm surveys.

2 Galaxy surveys

Figure 1 shows the timeline of the ongoing and upcoming galaxy surveys that will be discussed in this section. Surveys have been classified according to their constraining power on the dark energy equation of state [Albrecht et al., 2006]. This is quantified via the so-called Figure of Merit (FoM), which is defined as $\text{FoM} = \det^{-1} F(w_0, w_a)$, where $F$ is the (marginalized) Fisher matrix relative to the dark energy equation of state, parameterized according to $w(a) = w_0 + (1-a)w_a$. Stage-II experiments (previous to DES) feature a FoM less than 50, Stage-III experiments about 50–200 and Stage-IV experiments about 200+. DES and eBOSS are Stage-III level, J-PAS approaches Stage IV and the remaining are all “Stage IV”.

2.1 Extended Baryon Oscillation Spectroscopic Survey

The Extended Baryon Oscillation Spectroscopic Survey (eBOSS) is part of the fourth phase of the Sloan Digital Sky Survey (SDSS-IV) and extends the Baryon Oscillation Spectroscopic Survey (BOSS, part of SDSS-III) to much higher redshifts. The eBOSS survey started on July 2014 and will last 6 years and concentrates its efforts on the observation of galaxies and, in particular, quasars, in a range of redshifts currently left unexplored by other three-dimensional maps of large-scale structure of the universe. In filling this gap, eBOSS will create the largest volume survey to date, see Figure 2.

300,000 luminous red galaxies (LRG) will be observed over 7500 deg$^2$ in the redshift range $0.6 < z < 0.8$, 189,000 emission line galaxies (ELG) over 1000 deg$^2$ in the range $0.6 < z < 1.0$ and 573,000 quasars over 7500 deg$^2$ in the range $0.9 < z < 3.5$. This large catalog will produce 1-2% distance measurements.
from baryon acoustic oscillations between $0.6 < z < 2.5$. At this time, the DR14 of the first 2 years of observations has been publicly released, see Ata et al. [2018] for the first measurement of baryon acoustic oscillations between redshift 0.8 and 2.2. See Blanton et al. [2017] for further information.

2.2 Dark Energy Survey

The Dark Energy Survey (DES)\(^1\) is a project that is mapping 5,000 deg\(^2\) of the sky (approximately 1/8 of the whole sky) using 525 nights of observations in 5 years at the Blanco Telescope in the Cerro Tololo International Observatories in Chile. The project is led by Fermilab, a US national laboratory near Chicago, and its current (third) Director is Rich Kron from the University of Chicago. There are more than 400 scientists from over 25 institutions in the US, Brazil, Spain, UK, Germany, Switzerland and Australia working on the project. The group at Universidade Estadual Paulista is part of DES through the DES-Brazil Consortium, led by Laboratório Interinstitucional de e-Astronomia (LIneA)\(^2\).

A large digital camera with 570 Megapixels in 62 CCD’s was built by the collaboration and installed in the telescope. This so-called DECam takes exposures using 5 filters (grizY) that provide an estimate of the photometric redshift of approximately 300 million objects. This large amount of data is transferred and processed at the National Center of Supercomputing Applications (NCSA) in Urbana-Champaign to generate a value-added catalogue.

The first light of DES was in 2012. There was a 6 months extension in the observation period that should end in January 2019. There are already 234 papers from the DES collaboration in Inspires database. Results from the first year of observations have been published leading to several ground-breaking results, some of which will be mentioned below. Some highlights are:

- Produced the largest contiguous mass map of the Universe;
- Discovered nearly a score of Milky Way dwarf satellites and other Milky Way structures;

\(^1\)www.darkenergysurvey.org
\(^2\)www.linea.gov.br
Measured weak lensing cosmic shear, galaxy clustering, and cross-correlations with CMB lensing and with X-ray and SZ-detected clusters;

- Measured light curves for large numbers of type Ia supernovae and discovered a number of super-luminous supernovae including the highest-redshift SLSN so far;
- Discovered a number of redshift z>6 QSOs;
- Discovered a number of strongly lensed galaxies and QSOs;
- Discovered a number of interesting objects in the outer Solar System;
- Found optical counterparts of GW events – led by a brazilian who studied in UFES - Marcelle Soares-Santos.

DES combines four different observational probes in order to find the best constraints on Dark Energy:

- Distribution of 300 million galaxies, including measurements of the Baryon Acoustic Oscillation;
- Weak gravitational lensing of galaxies;
- Supernovae of type Ia;
- Counts of clusters of galaxies.

The main cosmological result of the first year of observations was published in Abbott et al. [2018d]. It combines measurements of three 2-point correlation functions involving galaxy positions and weak lensing (shear): galaxy-galaxy (galaxy clustering), galaxy-shear and shear-shear. This is what is called a key paper and uses results of other 11 papers. We use 2 galaxy samples:

- “Shape catalogue”: 26M galaxies for cosmic shear measurements (source galaxies) divided into 4 redshift bins;
- “Position catalogue”: 650,000 luminous red galaxies (lens galaxies) for clustering measurements divided into 5 redshift bins.

The photometric redshift distributions for the two samples are shown in Fig. 3.

The data vectors were defined using scale cuts to mitigate non-linear bias effects and it comprises 457 entries (different redshift bins, angular bins, correlation functions). We used a theoretical (halo-model based) covariance matrix (dimension 457×457) computed with the CosmoLike code validated with 800 lognormal mocks.

For the MCMC analysis we had 20 nuisance parameters (related to the redshift uncertainty, galaxy bias, intrinsic alignment and shear calibration) in addition to the usual 6 cosmological parameters for the spatially flat ΛCDM model (7 for wCDM). We concentrate the analysis on the two most sensitive parameters: $S_8$ and $\Omega_m$. We also compare results from DES alone with DES combined with other data, such as CMB, BAO and SNIa. The results are shown in Fig.4.

In Fig. 5 we show the 1 and 2−σ contours for the parameters $S_8$ and $\Omega_m$ obtained from DES, Planck and combined. It’s amazing to see that, for the first time, results from large surveys of galaxies provide bounds on cosmological parameters that are competitive with the ones obtained from CMB. It also shows the consistency of the ΛCDM model from the time of recombination where the CMB was generated to late times after galaxy formation.

We also analyzed the results in the context of a model with a constant equation of state $w$CDM and the results are shown in Fig. 6. The result for the dark energy equation of state when DES is combined with other data provides
Figure 3: Photometric redshift distributions for the galaxy position (lens) catalogue and for the shear (sources) catalogue.

Figure 4: Results for $S_8$ and $\Omega_m$ within $\Lambda$CDM obtained from DES and other experiments.
the state-of-the-art determination of $w$:

$$w = -1.00^{+0.04}_{-0.005}$$ (1)

in perfect agreement with ΛCDM.

Other extensions of the spatially ΛCDM model were studied recently [Abbott et al., 2018e]. Four extensions were analyzed:
1. Spatial curvature;
2. The effective number of neutrinos species;
3. Time-varying equation-of-state of dark energy ($w = w_0 + w_a(1 - a)$ parametrization);
4. Tests of gravity ($\Sigma$ and $\mu$ parametrization).

As an example, in Fig. 7 we show the contour plots for $w_0$ and $w_a$ for DES and other external data. We can see that DES data from the first year of observation is still not competitive with other data.

The group at Universidade Estadual Paulista led the analysis of the BAO signal in harmonic space [Camacho et al., 2018] which was used in the BAO main paper [Abbott et al., 2017i]. The main measurement is what is called the shift parameter $\alpha$ which gives the location of the BAO peak with respect to a reference cosmology. In Fig. 8 we show the measurement of the shift parameter $\alpha$ for 1800 mocks using the angular correlation function $w(\theta)$ and the angular power spectrum $C_l$. The result relative to the data is shown as a star. The measurements are consistent.

In Fig. 9 we show the DES measurement of the angular diameter distance
Figure 6: Results for $S_8$ and $\Omega_m$ within $w$CDM obtained from DES and other experiments.

Figure 7: Contour plots for $w_0$-$w_a$ extension obtained from DES and other experiments.
Figure 8: Measurement of the shift parameter $\alpha$ for 1800 mocks using the angular correlation function $w(\theta)$ and the angular power spectrum $C_l$. The result relative to the data is shown as a star.

Figure 9: DES measurement of the angular diameter distance corresponding to the BAO feature compared to other measurements.
corresponding to BAO feature compared to other measurements at different redshifts.

2.3 Javalambre Physics of the Accelerating Universe Astrophysical Survey

The Javalambre Physics of the Accelerating Universe Astrophysical Survey (J-PAS – Benitez et al., 2014) is a ground-based survey that is expected to begin scientific observations at the beginning of 2019. It features a dedicated 2.5m telescope with an excellent étendue which sports a 1.2 Gigapixel camera with a very large field of view of 4.7 deg\(^2\). The observatory is in the mountain range “Sierra de Javalambre”, at an altitude of 2000 meters, an especially dark region with the very good median seeing of 0.7\(''\).

J-PAS will observe approximately 8500 deg\(^2\) of the northern sky via the revolutionary technique of quasi-spectroscopy: by observing with 54 narrow-band filters plus two medium-band and three broad-band filters in the whole optical range it will produce a pseudo-spectrum \((R \sim 50)\) for every pixel, see Figure 10. Therefore, J-PAS really sits between photometric surveys such as DES and spectroscopic surveys such as DESI, fruitfully combining the advantages of the former (speed and low cost) with the ones of the latter (spectra). In particular, it will be possible to determine the redshift of galaxies with a precision of 0.003\((1 + z)\). In other words, it will be possible to accurately study the large scale structure of the universe using the galaxy and quasar catalogs produced by J-PAS. This makes J-PAS the first survey to approach the “Stage IV” level.
Figure 11: Forecasted constraints on radial and angular BAO from the galaxy catalogs produced by J-PAS (thick solid lines for 8,500 deg$^2$, thin solid lines for 4,000 deg$^2$) as compared with DESI (dashed lines, 14,000 deg$^2$) and Euclid (dotted lines, 20,000 deg$^2$). LRGs in red, ELGs in green and QSOs in blue. Redshift bins of $\Delta z = 0.2$ are used. Fisher forecasts by Raul Abramo.

As far as dark matter, dark energy and modified gravity, the most interesting observables will be galaxy clustering and galaxy cluster number counts. Regarding the former, thanks to the very precise photo-z determinations and the large volume that will be explored, it will be possible to obtain excellent measurements of Baryonic Acoustic Oscillations (BAO) and Redshift Space Distortions (RSD) in a wide redshift range ($0 < z < 3$). About 90 million luminous red galaxies (LRG) and emission line galaxies (ELG) (up to $z \sim 1.2$) and 2 million quasars (up to $z \sim 3$) are expected to be detected. Figures 11 and 12 show the corresponding forecasts. See also Abramo and Leonard [2013], Abramo et al. [2016] where constraints using the multi-tracer method are discussed.

Regarding cluster counts, thanks again to its quasi-spectroscopic photometric redshift, J-PAS will provide near optimal efficiency for separating cluster members from foreground and background galaxies. Indeed, the accuracy of the photometric redshift matches the typical velocity dispersion of massive clusters,
Figure 12: Forecasted constraints on the growth of structure \( (f_s = f\sigma_8) \) from the galaxy catalogs produced by J-PAS (thick solid lines for 8,500 deg\(^2\), thin solid lines for 4,000 deg\(^2\)) as compared with DESI (dashed lines, 14,000 deg\(^2\)). LRGs in mustard and ELGs in green. Redshift bins of \( \Delta z = 0.2 \) are used. Fisher forecasts by Raul Abramo.

allowing to detect clusters above the noise to much lower masses and higher redshifts than wide-field surveys using conventional filters. J-PAS will produce a catalog of about 700 thousand clusters with more than 10 members, down to \( \sim 3 \cdot 10^{13} M_\odot \). See Figure 13 for a forecast. Weak lensing observations will also be carried out and will be used to calibrate the cluster mass determination.

Weak and strong gravitational lensing data will also contain important cosmological information. J-PAS will be a revolutionary observatory also regarding the study of supernovas, galaxy evolution and stellar physics. See Benitez et al. [2014] for the full potential of the J-PAS survey.

2.4 Dark Energy Spectroscopic Instrument

The Dark Energy Spectroscopic Instrument (DESI) is a Stage IV ground-based dark energy experiment that will study the expansion history of the universe through baryon acoustic oscillations and the growth of structure through redshift-space distortions with a wide-area galaxy and quasar redshift survey. DESI is the successor to the successful Stage-III BOSS redshift survey and complements imaging surveys such as the Stage-III Dark Energy Survey and the Stage-IV Large Synoptic Survey Telescope discussed below. In addition to providing Stage IV constraints on dark energy, DESI will provide new measurements that can constrain theories of modified gravity and inflation, and will provide cutting-edge limits on the sum of neutrino masses.

DESI will obtain optical spectra for tens of millions of galaxies and quasars, constructing a 3D map spanning the nearby universe to 11 billion light years. 5,000 pencil-size robots will automatize the positioning of the optical fibers that will catch the light for distant galaxies and transmit it to the spectrographs. The DESI Survey will be conducted on the Mayall 4-meter telescope at Kitt Peak National Observatory in Arizona (USA), starting at the beginning of 2020. See
X-ray and SZ curves have been taken from Weinberg et al. (2013) as a function of redshift that each survey will observe. As in Fig. 12, the cluster selection function for the J-PAS survey is shown to be an increasing mass function within a wider range of masses. The X-ray eROSITA selection function shows an increasing mass function up to redshift 0.7 and ten times superior to those found in the Milky Way. The impact of the previously shown J-PAS selection function can be seen in Fig. 13, where we plot the total number of clusters and groups as the LSST and eROSITA up to redshift 0.7, at least.

According to this figure, the number of bound structures detected at least, up to redshift 0.7, at least. The 'knee' of the curve is starting at $z \sim 0.225$ for J-PAS, $z \sim 0.25$ for DES, and $z \sim 0.2$ for SPTpol, as shown in Fig. 13. While several efforts have been invested for the J-PAS, DES, and SPTpol, Austermann et al. 2009, have been extracted with the LSST, The Dark Energy Survey Collaboration 2012, Euclid Consortium 2010, and SPTpol, Austermann et al. 2012, with different initial values to compute the fit. The best-fitting parameters are free parameters. We choose $\Omega_m = 0.3$, $\Omega_L = 0.7$, and $\sigma_8 = 0.85$. In Fig. 13, we show the density plot of the relation of the two observables. The potentials $\Psi$ and $\Phi$ encode the growth of scalar perturbations which is still poorly constrained and could signal physics beyond the standard model of cosmology such as modifications to general relativity at large cosmological scales.

Figures 11 and 15 show the forecasted error on radial and angular BAO determinations. From Euclid alone it will be possible to obtain a FoM on the dark

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**Figure 13:** Total number of groups/clusters per redshift bin as a function of redshift for different next-generation surveys. From Ascaso et al. [2016].

figures 11 and 12 for forecasts on radial and angular BAO and on the growth of structures. See DES [2016] for further information.

### 2.5 Euclid Consortium

The Euclid spacecraft [Laureijs et al., 2011] is currently under construction and scheduled for launch in the second half of 2021. During its mission, which will last at least 6 years, Euclid will observe approximately $\Omega_{sky} = 15000 \text{deg}^2$ of the extra-galactic sky, which is about half of the total sky facing away from the Milky Way.

Euclid is the combination of two complementary probes. The 1.2-m Korsch telescope will feed, via a beam splitter, the visible band imager (VIS) and the near infrared spectrometer and photometer (NISP) instruments, in step-and-stare mode. Thanks to this unique design it will be possible to produce, at the same time, 40 million spectroscopic redshifts in the range $0.5 < z < 2$ and 2 billion galaxy images with photo-$z$ in the redshift range $0 < z < 3$. In other words, Euclid will allow us to study simultaneously the clustering (the potential $\Psi$) and the lensing (the combination $\Psi - \Phi$) of galaxies. It will so constrain both the potential $\Psi$ and $\Phi$, thus factoring out possible survey-specific systematics which could degrade the results obtained from the combination of the two observables. The potentials $\Psi$ and $\Phi$ encode the growth of scalar perturbations which is still poorly constrained and could signal physics beyond the standard model of cosmology such as modifications to general relativity at large cosmological scales.

Figures 11 and 15 show the forecasted error on radial and angular BAO determinations. From Euclid alone it will be possible to obtain a FoM on the dark
energy equation of state greater than 400 and constrain the growth of perturbations at the level of $\sigma_8 = 0.01$. If Euclid data will be consistent with $\Lambda$CDM, this level of precision will allow us to confirm the standard model of cosmology with a “decisive” statistical evidence (using Jeffreys’ scale terminology).

Also, it will be possible to identify 60 thousand clusters in the redshift range $0.5 < z < 2$, with more than 10 thousand at $z > 1$. See the review Amendola et al. [2018] for the full breadth of the Euclid mission.

2.6 Large Synoptic Survey Telescope

The Large Synoptic Survey Telescope (LSST)\(^3\) is a wide-field, ground-based telescope, designed to image a substantial fraction of the sky in six optical bands (ugrizy, covering the wavelength range 320-1050 nm) every few nights. The 8.4-meter LSST uses a special three-mirror design, creating an exceptionally wide field of view ($9.6 \text{ deg}^2$ field-of-view or roughly 49 times the area of the Moon in a single exposure), and has the ability to survey the entire sky in only three nights. LSST will be equipped with the largest digital camera ever built, with 3.2 billions of pixels tiled by 189 4k x 4k CCD science sensors. The observing strategy for the main survey will be optimized for homogeneity of depth and number of visits. The current baseline design will allow about 20,000 deg$^2$ of sky to be covered using pairs of 15-second exposures in two photometric bands every three nights on average, with typical 5$\sigma$ depth for point sources of $r \sim 24.5$.

The system will yield high image quality as well as superb astrometric and photometric accuracy for a ground-based survey. The coadded data within the main survey footprint will have a depth of $r \sim 27.5$. LSST’s wide and deep coverage of billions of galaxies has the power to test differences in fundamental models that describe the Universe.

The LSST is currently being built on the Cerro Pachón ridge at CTIO, Chile. Construction has started in 2014, first light is expected for 2019, Science Verification is scheduled for 2020 and Science Operations should start in 2023. It is planned to operate for a decade allowing the stacked images to detect galaxies to redshifts well beyond unity. The LSST and the survey are designed to meet the requirements of a broad range of science goals in astronomy, astrophysics and cosmology, including the study of dark energy. Much of that power comes from the fact that the measurements will be obtained from the same basic set of observations, using a powerful facility that is optimized for the purpose.

The Science case for the LSST is described in the LSST Science book.\(^4\) In 2008, eleven separate quasi-independent science collaborations were formed to focus on a broad range of topics in astronomy and cosmology that the LSST could address. The one directly involved with the study of Dark Energy is the Dark Energy Science Collaboration (DESC). Within the DESC there are several working groups:
1. Weak Lensing,
2. Large Scale Structure,
3. Supernovae,
4. Strong Lensing,
5. Theory and Joint Probes,
6. Photometric Redshifts.

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\(^3\text{lsst.org.}\)
\(^4\text{lsst.org/scientists/scibook.}\)
The Dark Energy science goals of LSST are:

1. Weak gravitational lensing: the detection of light from distant sources that is distorted due to the bending of space-time from baryonic and dark matter along the line of sight. Tomographic measurements of weak lensing will provide percent-level constraints on cosmological parameters.

2. Large-scale structure: the large-scale power spectrum for the spatial distribution of galaxies as a function of redshift. This includes the Baryonic Acoustic Oscillations and the measurement of the distance-redshift relation. With the enormous number of galaxies detected by LSST, the co-moving distance will be measured with percent-level precision.

3. Type Ia Supernovae: luminosity distance as a function of redshift measured with Type Ia SNe as standardizable candles. LSST will discover and measure at least 500 SNe Ia per season, giving tens of thousands of well-measured SNe Ia light curves up to $z \sim 1$ over the full ten-year survey.

4. Galaxy clusters: the spatial density, distribution, and masses of galaxy clusters as a function of redshift. LSST will be able to measure the masses of $\sim 20,000$ clusters to a precision of 10%.

5. Strong gravitational lensing: the angular displacement, morphological distortion, and time delay for the multiple images of a source object due to a massive foreground object. LSST will give a sample of $\sim 2600$ time-delayed lensing systems, an increase of a factor of 100 compared to the sample available today.

LSST is a natural evolution of the Dark Energy Survey (DES). Both are photometric surveys using digital cameras. DES is now finishing its 5.5 years of observations. However, the dark energy constraining power of LSST could be several orders of magnitude greater than that of the DES. In Fig. 14 it is shown the Fisher matrix forecast for the LSST sensitivity on the parameters $w_0$ and $w_a$ that parametrize a time evolution of dark energy. It is clear the importance of combining different probes in order to obtain better constraints.

LSST will go much further than any of its predecessors in its ability to measure growth of structure, and will provide a stringent test of theories of modified gravity. While these projections for LSST statistical significance are compelling, they probably do not capture the true nature of the revolution that LSST will enable. The sheer statistical power of the LSST dataset will allow for an all-out attack on systematics, using a combination of null tests and hundreds of nuisance parameters and by combining probes. Beyond tests of systematics, there is a growing sense in the community that the old, neatly separated categories of dark energy probes will not be appropriate for next generation surveys. For example, instead of obtaining constraints on dark energy from cluster counts and cosmic shear separately, LSST may use clusters and galaxy-galaxy lensing simultaneously to mitigate the twin systematics of photometric redshift error and mass calibration. A homogeneous and carefully calibrated dataset such as LSST’s will be essential for such joint analyses.

The Brazilian participation in the LSST was the result of a negotiation led by LIneA and LNA that resulted in ten PI positions (with 4 posdocs/students for each PI). A Brazilian Participation Group for the LSST was organized and all the information is available at bpg-lsst.linea.gov.br.
Another revolutionary future survey is the Square Kilometer Array (SKA), which will become the world’s largest radio telescope. It will be built in two phases: phase 1 split into SKA1-SUR in Australia and SKA1-MID in South Africa and SKA2 which will be at least 10 times as sensitive. The first stage is expected to end observations around 2023 and the second phase is scheduled for 2030 [see Yahya et al., 2015, Santos et al., 2015, Raccanelli et al., 2015, Bull et al., 2015].

The first phase SKA1 will be able to measure in an area of 5000 deg$^2$ of the sky and a redshift range up to $z = 0.8$ approximately 5 million galaxies; SKA2 is expected to cover a much larger fraction of the sky (30000 deg$^2$) reaching much deeper redshifts (up to $z = 2.5$) and is expected to detect about 1 billion galaxies with spectroscopic redshifts [Santos et al., 2015]. See Figure 15 for the forecasted constraints on radial and angular BAO and the growth of structures from SKA as compared with other surveys.

The SKA survey will allow us to address important questions on fundamental physics, in areas such as cosmic dawn and reionization, gravity and gravitational radiation, dark energy and dark matter, and astroparticle physics. SKA will also shed light on the nature of neutrinos, cosmic inflation (early universe) and foundations of cosmology. See [Bull et al., 2018, and references therein] for a review of the fundamental physics that can be studied with the Square Kilometer Array.
Figure 15: Forecasted constraints on radial and angular BAO and the growth of structures from SKA as compared with other surveys. “GS” stands for galaxy survey while “IM” for intensity mapping survey (Hα survey is a Euclid-like survey). Forecasts from Bull [2016] where more information can be found.
4 Gravitational wave surveys

The detection of GW170817 [Abbott et al., 2017f], the coincident Gamma Ray Burst (GRB) [Abbott et al., 2017e], and the other electro-magnetic counterparts in a wide region of the spectrum from X to radio frequencies [Abbott et al., 2017d] marked the historical debut of Gravitational Waves (GWs) on the stage of Multi-messenger Astronomy in the first month of joint activity of the Advanced LIGO [Harry, 2010], located in the US, and Advanced Virgo detector [Acernese et al., 2015], located in Italy.

Advanced LIGO and Advanced Virgo GW detectors are Michelson interferometer with Fabry-Perot cavities which represent the most precise ruler ever made: by measuring the differential variation of the interferometer’s arms they can monitor the passage of a GWs in the frequency range from few tens of Hz to roughly 1 kHz. Because of the frequency range, interferometric GW detectors are sensitive only to binary coalescence of compact objects, thus small enough (∼ 10−100 km) that can achieve such high orbital frequencies. Interferometers respond linearly to the GW strain by measuring the difference in optical path with the result of being mild directional detectors, as they can detect only GWs that do not alter symmetrically the two end mirrors.

The cryogenic Japanese detector KAGRA [Somiya, 2012, Aso et al., 2013], with comparable design sensitivity, is planning to join the GW detection effort before the end of third Observation Run (O3) of LIGO and Virgo, which is due to start in April 2019 and to last for at least one year, and the Indian INDIGO [Ind] by the start of the next decade.

GWs have 2 polarizations, conventionally called $h_+$ and $h_\times$ and each detector is sensitive to only one linear combination of them, the coefficients of proportionality between detector output and $h_+, \times$ being the pattern functions $F_+, \times$, see fig. 16 for the values of the LIGO and Virgo pattern functions at the time of GW170817.

For un-modeled events LIGO and Virgo search for excess noise but for coalescing binaries accurate theoretical models exist enabling to correlate observational data with pre-computed templates.

One important quantitative detail is that because of the quadrupolar nature of the source the two polarizations are affected in a specific way by the relative orientation of the binary orbital plane and the observation direction. Denoting such angle by $\iota$ one has

\[
\begin{align*}
\frac{h_+}{h_\times} &\propto \frac{(1 + \cos^2 \iota)}{2}, \\
\frac{h_+}{h_\times} &\propto \cos \iota,
\end{align*}
\]

introducing a degeneracy between $\iota$ and the source-observer distance to which the GW amplitude is inversely proportional: unless the two polarizations are independently measured there is a strong degeneracy between distance and inclination. Stronger signals could equally well be closer and misaligned or farther and better aligned, with the latter possibility favored a priori because at a larger distance more volume is available, hence more sources are possibly present (until a red-shift $z \sim 2$, see discussion below, see Schutz [2011]).

Note that LIGO is composed of 2 detectors and they are almost aligned, to have similar pattern functions so no event that is detected by one of the two can fall into the blind region of the other.
Figure 16: Pattern functions of the LIGO Hanford (first line), LIGO Livingston (second line) and Virgo detector (third line) as a function of right ascension and declination at the time of GW170817: August 17th 2017, 12:41:53 UTC. The first and second column represent respectively $F_+^2$ and $F_\times^2$, the position of the GW170817 source being right ascension= 13h 09' 48'', declination= -23° 22' 53''. Pattern function values range from 1 (dark red) to -1 (dark blue). The values of $\sqrt{F_+^2 + F_\times^2}$ for LIGO Hanford, LIGO Livingston and Virgo are respectively 0.89, 0.75, 0.30 at the location and time of GW170817.

GWs can be localized with reasonable accuracy, e.g. the 90% credible region of GW170817 which happened at 40 Mpc from Earth ($z \sim 0.01$) and was observed by 3 detectors (though very little signal was present in Virgo), measured 28 degree squared, with lower precision expected for fainter objects. The localization is obtained by short-circuiting the information of the time of arrival (triangulation) and the information from the signal amplitudes and phases across the detector network [Abbott et al., 2018a], with the result shown in Figure 17 for GW170817, where the GRB [Abbott et al., 2017d] and optical [Coulter et al., 2017] localizations are also shown.

The almost coincident detection of GWs and GRB also enabled to constrain the velocity of light and of GWs to be almost exactly equal to each other, up to one part in $10^{-15}$ [Abbott et al., 2017e], setting non-trivial constraint on practically all non-General Relativity gravity model modifying the radiative sector of General Relativity [Creminelli and Vernizzi, 2017].

On the top of the GW event sourced by a binary neutron star, 10 more events have been detected, 3 in the first Observation run O1 (lasted from September 2015 to January 2016) and the remaining ones in O2 (spanning the period between December 2016 and August 2017, only the last month of which with both LIGOs and Virgo on), see Figure 18, Abbott et al. [2016a,b, 2017g,a,b, 2018c].

The events detected are compatible with an event rate of $\sim 100$ merger
events per Gpc$^3$ per year for binary black holes [Abbott et al., 2016c] and $\sim 10^4$ merger events per Gpc$^3$ per year for binary neutron stars [Abbott et al., 2017f]. For comparison, the average density of galaxies is $\sim 10^8$/Gpc$^3$.

With a distance reach, at design sensitivity, of $\sim 200$ Mpc for binary neutron stars, and few Gpc for a black hole binary with a total mass of $\sim 100 M_\odot$, one can realistically infer that up to one event per week will be detected in O3.

On the fundamental physics side GW detections enabled the first ever constraint on high order post-Newtonian parameters describing the 2 body dynamics. The frequency $f$ of a signal changes as the binary distance shrinks and at leading order the rate of change of $f$ is given by

$$\dot{f} = \frac{96}{5} \pi^{8/3} \left( \frac{G_N M_c}{M_\odot} \right)^{5/3} f^{11/3} \approx 10 \text{sec}^{-2} \left( \frac{M_c}{M_\odot} \right)^{5/3} \left( \frac{f}{100 \text{Hz}} \right)^{11/3},$$

where we have introduced the chirp mass $M_c \equiv \eta^{3/5} M$, with $\eta \equiv m_1 m_2 / M^2$, being $m_i$ the individual constituent mass and $M \equiv m_1 + m_2$. It is possible to parametrize the observed GW phase $\phi$ in an expansion in terms of the relativistic parameter $v \equiv (G_N M f)^{1/3}$, being $G_N$ the Newton’s constant:

$$\phi(t) = \frac{5}{16 \eta} \int_{v_0}^{v(t)} \left( 1 + \phi_1 v^2 + \ldots + \phi_3 v^6 + \ldots \right) \frac{dv}{v^6},$$

where both fundamental gravity theory and astrophysical parameters of the source concur to determine the post-Newtonian coefficients $\phi_i$. The most recent bounds are reported in Abbott et al. [2018b], see Figure 19 relative to GW170817.

On the cosmology side the coincident measure of luminosity distance via GWs and red-shift via electromagnetic radiation enabled the measure of the Hubble-Lemaître constant, but with the nuisance of the correlation of luminosity distance with the un-measured inclination angle $\iota$, giving the result in Figure 20.
Figure 18: Spectrum of the 3 detected gravitational wave events in O1 and of GW170817 compared to the real O1 and O2 noise (of the LIGO Livingstone detector) and the Advanced LIGO design sensitivity.

Note that the GW signal does not allow to determine the red-shift, since it is degenerate with the total mass of the binary. E.g. in the phase \( \phi(t) \) the main dependencies are on the individual masses via the combination \( \phi(t_s/M_c, \eta) \) (it has additional, sub-leading dependence on the dimension-less spins \( \chi_{1,2}, S_{1,2}/m_1^2 \) and orbital angular momentum unit vector \( \hat{L} \)), but substituting the source time \( t_s \) for the observer time \( t_o \) one gets \( \phi(t_o/((1 + z)M_c), \eta) \), thus introducing the dependence on the the red-shifted mass \( M \equiv M(1 + z) \). E.g. for the + polarization, denoting by \( D \) the coordinate distance, we have

\[
\begin{align*}
    h_+ &= \frac{1 + \cos^2 \iota}{2} \frac{M u^2}{D} \cos \phi \left( t_s/M_c, \eta, \hat{L}/m_i^2, \chi_{1,i} \cdot \chi_{2,i}, \ldots \right) \\
    &= \frac{1 + \cos^2 \iota}{2} \frac{M(1 + z) v^2}{D(1 + z)} \cos \phi \left( t_o/(M_c(1 + z)), \eta, \hat{L}/m_i^2, \chi_{1,i} \cdot \chi_{2,i}, \ldots \right) \\
    &= \frac{1 + \cos \iota}{2} \frac{M v^2}{d_L} \cos \left[ \phi \left( t_o/M, \eta, \hat{L}/m_i^2, \chi_{1,i} \cdot \chi_{2,i}, \ldots \right) \right],
\end{align*}
\]

where the final result is expressed in terms of the luminosity distance \( d_L = (1 + z)D \). The cross polarization has a similar expression, with a different prefactor, hence, beside not being able to disentangle \( M \) and \( z \) dependence, with only one measure of \( F_+ h_+ + F_\times h_\times \) it is also impossible to disentangle \( d_L \) and \( \iota \), see figure 20.

Red-shift can be either measured electromagnetically or inferred from the luminosity distance assuming a cosmological model, in the latter case at the price of not being able to check the cosmological model. GW170817 represented the first standard siren event with electromagnetic counterpart, and many more are expected in O3 at design sensitivity: \( \sim O(1)/\text{month} \).

Note that as suggested in the original paper [Schutz, 1986], a determination
Figure 19: Bounds on deviation from phasing post-Newtonian coefficients from the analysis of the GW170817 signal [Abbott et al., 2018b]. Note that the −1 and the 0.5PN coefficients are identically zero in GR. Results for two different phenomenological approximants IMRPhenomP [Husa et al., 2016] and SEOBNR [Bohé et al., 2017] are reported. Different approximants are obtained by resumming the PN approximation in different ways.

Figure 20: Two-dimensional probability distribution function of \( \cos \iota \) vs. \( H_0 \) for the GW170817 event [Abbott et al., 2017c]. Reported also the Hubble constant determination from Cepheid variable stars [Riess et al., 2016] and CMB Planck data [Ade et al., 2016].
of $H_0$ is also possible without an electromagnetic counterpart by correlating the distance measure and sky-localization from GW detectors with galaxy catalogs and associating to the GW events the red-shift of all of the galaxies present in the localized region. In Del Pozzo [2012] it was shown that it will be possible to determine the Hubble-Lemaître constant with a precision of few % after 50 dark sirens detections, i.e. GW events without the concurrent presence of electromagnetic transient, see figure 21. In a region of 10 degrees squared, say, $\sim 10^4$ galaxies are expected to be present within a distance up to $\sim 500$ Mpc, and even if galaxy catalogs can encompass most of the stellar mass present in the localized region, and photometric redshift determinations are available (see Soares-Santos et al. [2019] for an implementation of the idea with a recent binary black hole detection), the number of candidate galaxies will induce a large error in the final measurement which be counteracted only by combining large numbers of dark sirens.

4.1 Future detectors

Beyond the existent LIGOs and Virgo observatories, which are in their advanced phase, there are plans to build third generation detectors, with the advantage to be able to push their frequency reach down to the $Hz$, allowing to accumulate much more signals, since the GW amplitude in the frequency domain $\tilde{h}(f) \propto v^2(f)f^{-1/2} \sim f^{-7/6}$.

With the third generation detectors Einstein Telescope (ET) [Punturo et al., 2010] and Cosmic Explorer (CE) [Abbott et al., 2017b] sources at $z \sim 2$ for binary neutron star signals, and even larger for binary black holes will be accessible, enabling to accumulate much more statistics to improve the precision on post-Newtonian and cosmological parameters, with $O(1000)$ events per month expected.

ET is planned to consist of a three 10-Km long Michelson interferometers arranged in an equilateral triangle to be built underground to minimize seismic and Newtonian noise. CE has a similar design, but a L-shape with longer (40
km) arms, offering, like ET an order of magnitude increase in sensitivity and a wider band extending down to a few Hertz.

On the astrophysics side it is worth noticing that the number of detectable sources increases with the observable volume and at low red-shift an increase by a factor $x$ in distance reach implies an $x^3$ enhancement of the number of sources, but in cosmology the volume stops increasing with the cube of the distance for large distances, which has important consequences for the rate of detections.

On general grounds the rate of detected mergers $R_m$ per red-shift can be expressed in terms of the comoving density of mergers

$$R_m(z_m) = \frac{dN_m}{dt_o dV_c} = \frac{dN_m}{dt_o} \frac{dV_c}{dz} \frac{1}{1 + z_m} = \frac{1}{1 + z_m} \frac{dV_c}{dz} R_m(z_m), \quad (6)$$

where in the last passage we have defined the comoving volume density rate $R_m$ of mergers and in the previous one we have used that $\frac{dt_o}{dt_m} = (1 + z_m)$. The comoving density of mergers $R_m$ is not constant in time and its modelization is an active and difficult field of research, however the main dependence on red-shift of $R_m$ is actually given by the volume differential factor $\frac{dV_c}{dz} = 4\pi D_c^2 dD_c/dz_c$,

with $D_c(z) = \int_0^z H^{-1}(z')dz'$.

In fig. 22 we take the rate of star formation $R_{sfr}$ from Madau and Dickinson [2014]:

$$R_{sfr}(z) = K \left( \frac{1 + z}{C} \right)^{\alpha} \left( \frac{1 + z}{C} \right)^{\beta} \quad (7)$$

(with $\alpha = 2.7$, $\beta = 5.6$, $C = 2.9$) and by making the very crude approximation of equating it to the compact object density merge rate at the same red-shift one can show how it affects the detectable merger rates, see fig. 22.

Despite some qualitative change by the inclusion of the star formation rate, one can see that the volume density peaks at around $z \sim 2$ and we expect the detectable merge rate also peak around $z \sim 2$. By collecting $O(10^4)$ it will
be indeed possible to measure the star formation/merger rate [Vitale and Farr, 2018].

Another GW detector planned for the future is the space interferometer LISA, which is expected to widen the detection up to $z \sim 15$ [Klein et al., 2016, eli]. The space detector LISA, planned to observe GWs starting from the decade of 2030, will not be limited in the low frequency region by terrestrial noise and will have a sensitive frequency band in the region $10^{-3} - 10^{-1}$ Hz, complementing earth-based detectors. Signals will be much longer, e.g. from eq. (3) it results that the time $\Delta t(f)$ for the GW signal to evolve from an instantaneous frequency $f$ to coalescence is given by

$$\Delta t(f) = \frac{5M_c}{256} \left( \pi G N M_c f \right)^{-8/3}$$

thus showing that LISA will have many overlapping sources of GWs. Another consequence of the opening a low frequency window (a factor $10^4$ lower than LIGO) is the possibility to observe systems up to a mass of $\sim 10^6 M_\odot$ (i.e. $10^4$ higher than LIGO) hence starting to access the realm of supermassive black holes.

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