Challenges in Cosmology from the Big Bang to Dark Energy, Dark Matter and Galaxy Formation

Joseph Silk$^{1,2,3}$

$^1$Institut d’Astrophysique de Paris, Sorbonne Université, UPMC Univ. Paris 6 & CNRS, UMR 7095, 98 bis Boulevard Arago, F-75014 Paris, France
$^2$Department of Physics and Astronomy, 3701 San Martin Drive, The Johns Hopkins University, Baltimore MD 21218, USA
$^3$BIPAC, 1 Keble Road, University of Oxford, Oxford OX1 3RH, UK
E-mail: silk@iap.fr

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I review the current status of Big Bang Cosmology, with emphasis on current issues in dark matter, dark energy, and galaxy formation. These topics motivate many of the current goals of experimental cosmology which range from targeting the nature of dark energy and dark matter to probing the epoch of the first stars and galaxies.

**KEYWORDS:** cosmology, dark energy, dark matter, galaxy formation

1. Introduction

Cosmology has entered a new era in the twenty-first century. It has become a precision science. Nevertheless, big questions remain. I will attempt to address some key issues in this talk, focussing on these topics:

- The Big Bang
- Dark Energy
- Dark Matter
- Galaxy Formation

Modern cosmology began with Alexander Friedmann in 1922 and especially with Georges Lemaitre, who in 1928 sketched the current suite of cosmological models and realized that there was indeed tantalizing evidence for expansion of space from Vesto Slipher’s measurements of galaxy redshifts. In 1929, Edwin Hubble, indeed unaware of the earlier work, announced his discovery of the law that relates redshift linearly to increasing distances of the galaxies, and the expanding universe was born. Lemaitre himself was aware of the problems of formally following his equations back to the singular state $t = 0$, and advocated the ”primeval atom” as a more physical starting point. The Lemaitre-Eddington solution, motivated to avoid the initial singularity, starts from a static configuration but was later found to be unstable. This set the scene for inflation along with other possibly less-inspiring alternatives. After nearly 90 years of progress in observational cosmology, all that has really changed on the theory side is the addition of inflationary cosmology to our cosmic toolbox, allowing the extension of physical cosmology back to the Planck time, some $10^{-43}$ seconds into the Big Bang.
2. History of physical cosmology 1933-2000

2.1 The standard model

Little new happened in our understanding of cosmology for the first two decades following Hub-
ble’s announcement of the recession of the galaxies, and its rapid incorporation into evidence for the
expansion of space. It was to take the entry into cosmology of nuclear physicists to allow the next
giant step forward. This was a consequence of the realization that the Big Bang was an ideal labora-
tory to study nuclear physics, and in particular the awareness that the high density and temperature
achievable in the first minutes might facilitate the nucleosynthesis of the chemical elements.

George Gamow dreamt that all of the chemical elements could be synthesized primordially, but he
eventually realized that the lack of a stable element of atomic mass 8 made it impossible to go beyond
lithium (mass 7). With Alpher and Herman, he did however succeed in generating helium, the second
most abundant element in the universe, in the Big Bang. This was a major accomplishment, as it was
realized in the 1950s that ordinary stars could not generate enough helium as observed in nearby stars
[1]. Nor could stars account for what we now know to be its uniformity in abundance throughout the
observable universe. It was soon shown in a classic paper by Burbidge, Burbidge, Fowler and Hoyle,
that the ejecta of massive stars exploding as supernovae, as well as red giant mass loss, could account
for the bulk of the heavy elements [2].

Modern calculations of primordial nucleosynthesis also account for the abundance of deuterium,
an isotope of hydrogen which is only destroyed in stars. Lithium is also produced, but the amount pre-
dicted is about 3 times more than observed in the oldest stars [3]. The cosmological origin of lithium
is one of the very few serious questions that are as yet unresolved in cosmology. Another important
consequence of helium and deuterium synthesis is that the bulk of the universe is nonbaryonic. If the
bulk of the matter in the universe were baryonic, the nuclear reactions in the first few minutes would
have been so efficient as to overproduce helium by a large amount. However a quantitative baryon
budget was to require Hubble Space Telescope observations of intergalactic and circumgalactic gas
in order to measure the total density of matter with high accuracy, e.g. [4].

On the observational side, the cosmic microwave background radiation was to provide a basis for
undertaking the first precise measurements of the different components of the universe. In fact, pre-
cision cosmology emerged after 2000 as a consequence of several generations of cosmic microwave
background experiments, following its detection by Penzias and Wilson in 1964 [5], and the mea-
surement of its blackbody spectrum by COBE in 1990 [6].

The major theoretical development in cosmology, following the glory days of Lemaitre, de Sitter,
Einstein and Eddington in the 1930s, was the invention of inflationary cosmology, attributed to
Starobinsky, Guth and Linde [7–9] although others played important roles, e.g. [10, 11]. Inflation
accounted for the flat geometry of the universe, its size and for the presence of infinitesimal density
fluctuations. The latter were initially found to be too large in the early inflationary models, but a
consistent theory was first developed by Mukhanov [12]. The inflationary density fluctuations were
predicted to be adiabatic, gaussian, and nearly scale-invariant. All of these properties were later con-
firmed to a high degree of approximation by the WMAP and Planck satellites.

2.2 Dark matter

The case for dark matter in galaxies was effectively made quite early, with optical studies of M31
by Rubin & Ford in 1970 [13], and especially with the first deep 21cm observations of M31 and other
nearby galaxies by Roberts and others in 1972 [14], although the argument for the prevalence of dark
matter in clusters of galaxies was made decades earlier by Zwicky in 1933 [15].

Far more matter is needed than is allowed in the form of baryons, by a factor of about 6. A higher
baryon density would have generated excessive helium and too little deuterium. There was another
mini-revolution in cosmology following the discovery of inflation in 1981, when it also became clear
that the early universe was a fertile hunting ground for novel dark matter-related ideas in high energy particle physics. Within two or three years, a number of particle physics candidates emerged for nonbaryonic dark matter. Now there are hundreds of candidates, but there are still no detections.

Two preferred candidates attracted most attention. One was the lightest neutralino, a left-over particle from the epoch when supersymmetry (SUSY) prevailed, proposed by Pagels & Primack in 1982 [16]. Neutralinos are an attractive candidate because if the natural scale for the breaking of SUSY is that of the W and Z bosons, around 100 GeV, one naturally obtains the observed relic density of dark matter.

Many experiments were launched to search for neutralinos in the form of weakly interacting massive particles (WIMPs), inspired by the possibilities of direct detection via elastic or even inelastic scattering [17] and of indirect detection, via the annihilation products that include high energy antiprotons, positrons and gamma rays [18] and neutrinos [19]. Sadly, accelerator experiments have frustrated this dream by failing to find evidence for SUSY below a TeV.

A second candidate came to be dubbed the invisible axion. Axions were invented to solve an outstanding issue in QCD, the strong CP problem, by Wilczek & Weinberg in 1978 [20,21]. Neutralinos and axions are intrinsically cold dark matter (CDM), that is, dark matter which can respond to the pull of gravity on all mass scales as advocated by Blumenthal et al. in 1984 [22].

Cold dark matter was shown to account for large-scale structure by Davis et al. in 1985 [23], in a way that hot dark matter (HDM), could not accomplish. This was epitomized by massive neutrinos and effectively nonbaryonic matter created late in the universe with a significant velocity dispersion, hence said to initially be hot, could not accomplish. Warm dark matter, perhaps in the form of sterile neutrinos, remains a possible option that does not affect large-scale structure, unlike HDM, but improves predictions at dwarf galaxy scales via enhanced free-streaming relative to CDM [24].

2.3 Acceleration

The case for acceleration of the universe from Type 1a supernovae was first presented in 1998 by Perlmutter, Riess, Schmidt and colleagues [25,26]. These results are interpreted as strong evidence for the cosmological constant, itself considered to be evidence for the presence of a dominant component of dark energy. The flatness of the universe, measured by CMB experiments such as BOOMERANG, was a notable factor in establishing the need for dark energy as well as for dark matter [27]. It was not until 2000 that scientists decisively showed that the universe contained a near-critical density of mass-energy by measuring the curvature of space via the CMB. It became clear that the dominant energy-density component was not predominantly dark matter. Had it been, galaxy peculiar velocities would have been excessive because of the clustering effects of dark matter. Dark energy dominates as a scalar field, and remains nearly uniform, acting like antigravity on the very largest scales.

2.4 Galaxy formation

After robustly developing the framework for the Big Bang, the next challenge was to understand how galaxies, and more generally large-scale structure, formed. The seed fluctuations needed to form structure by gravitational instability in the expanding universe were first predicted in 1967 as temperature anisotropies in the cosmic microwave background [28] that damped out towards smaller scales [29,30]. In fact the first rigorous calculations of density irregularities in a coupled matter-radiation fluid [31] identified what were later recognised as the baryon acoustic oscillations [32]. The early calculations were later improved by incorporating the growth-boosting effects of dark matter, leading to smaller fluctuations [33,34]. It was to take more than another decade for the detection of these elusive temperature fluctuations. The first indications came from the COBE satellite in 1992, but the measured temperature anisotropies were only on 7 degree angular scales. These are super-horizon at last scattering and demonstrate the imprint of quantum fluctuations arising at inflation.

However much finer angular scales needed to be studied in order to seek the direct traces of
the seeds of the largest self-gravitating structures such as clusters of galaxies. These seeds produce cosmic microwave background fluctuations on angular scales of a few arc-minutes. These fluctuations were only accurately measured a decade later, as the unique features of the predicted acoustic sound wave damping peaks, detected by the WMAP satellite. Indeed this telescope detected the first three peaks, and after another decade, the SPT and ACT telescopes measured a total of seven damping wiggles in 2011 [35, 36]. There was no longer any doubt that we were seeing the seeds of structure formation imprinted on the microwave sky.

Observational surveys soon became the preferred tool for low redshift cosmology, that is cosmology over look-back times of up to ten billion years. Million galaxy surveys, notably 2DF (1997) and SDSS (2000), set out the observational basis for a cold dark matter-dominated universe. The next step towards connecting primordial fluctuations with galaxies required detection of the acoustic imprint of the primordial seed fluctuations on the matter distribution [37]. Improved, more accurate, spectroscopically calibrated surveys, were needed for detection, which eventually came with the next generation of galaxy redshift surveys, that would be aimed towards a redshift of order unity.

Growth from seeds to structure formation involved the operation of gravitational instability. This operated once the radiation decoupled from the matter as the universe recombined 380,000 years after the Big Bang. Structure formation was greatly aided by the self-gravity of the dark matter. The case for cold dark matter driving galaxy formation with the aid of baryonic dissipation was made by White & Rees in 1978 [38].

It also rapidly became apparent that complex baryonic physics was needed in addition to the effects of gravity to result in structures that resembled the observed distribution of galaxies. For one thing, the intergalactic gas had to condense and cool in order to make the dense cold clouds that can fragment and form stars. It soon became evident that the physics of supernova feedback was required to avoid excessive formation of large numbers of dwarf galaxies [39]. A similar problem for massive galaxies was avoided by the presence of supermassive black holes, releasing prolific amounts of energy in a quasar phase contemporaneously with the formation of the oldest stars, that left its imprint on the relation between black hole mass and spheroid velocity dispersion [40].

3. Modern cosmology

Theory has progressed enormously in the past decade, especially in the area of simulations of large volumes of the universe. While massive large-volume, large-scale structure simulations provide an impressive match to survey data, real issues remain however with regard to small-scale cosmology, namely galaxy formation. Of course to explain the late universe requires a lot of dirty physics. It is a bit like predicting the weather. But the early universe is much simpler. Let me first summarize the current status of precision cosmology from the CMB.

3.1 Cosmic microwave background radiation

All-sky mapping of the CMB has proven to be crucial in evaluating the parameters of cosmology with high precision. This has been the important contribution of the WMAP and especially the Planck experiments [41]. Seven numbers characterize the CMB fluctuations (if one does not assume a spatially flat universe). Apart from the densities of dark energy $\Omega_{\Lambda}$, dark matter $\Omega_{m}$ and baryons $\Omega_{b}$, one has the scalar spectral index $n_s$ and normalization $\sigma_8$ of the density fluctuations, the (revised) optical depth $\tau$ [42] and the Hubble constant $H_0$ (Table I). The inferred age of the universe is 13.799 $\pm$ 0.021 Gyr.

There is general consistency with other probes, notably baryon acoustic oscillations (BAO) and weak gravitational lensing, with some slight tension remaining in the latter case. A slight tension remains at the $2\sigma$ level with the slightly higher Planck 2015 determination of the fluctuation amplitude parameter $\sigma_8$ [43]. There is somewhat more tension with the Hubble constant measurements, found
locally to be slightly higher than the Planck 2015-preferred value: 73.24 ± 1.74 km/sec/Mpc [44].

These differences are possibly due to systematics between the very different distance scales probed, although more profound explanations cannot be excluded. It is already quite remarkable how well the very early universe as mapped by Planck matches the local universe, as charted via weak lensing, BAOs and supernovae, in the context of the standard model of cosmology, ΛCDM.

B-mode polarization is predicted to be a unique probe of the gravitational wave background imprinted by inflation [45, 46]. Many experiments are underway to address this goal. Most notably, spectral distortions in the blackbody spectrum arising from the standard model of structure formation due to dissipative processes are predicted to be in the form of a negative chemical potential distortion at a level of a part in 10^8 [47]. Detection of µ-distortions at this level would probe fluctuation damping and primordial non-gaussianity on dwarf galaxy scales [48]. However such values of µ are four orders of magnitude below the COBE FIRAS limits, and only detectable with a dedicated future space experiment [49].

Table I. Cosmological parameters: 2016 [41, 42]

| Parameter |
|-----------|
| Ω_b       |
| Ω_m       |
| Ω_Λ       |
| σ_8       |
| n_s       |
| H_0       |
| τ         |

3.2 Baryon acoustic oscillations and weak gravitational lensing

The large-scale structure of the galaxy distribution is a fertile hunting ground for evaluating both the geometry of the universe and its rate of expansion [50]. The baryonic acoustic oscillation (BAO) scale ≈ 150 Mpc is a standard ruler for cosmology. It is the precise analogue of the photon oscillations at z = 1080 on the last scattering surface but is observable in the large-scale distribution of the galaxies at the present epoch and out to z ≈ 1 [51]. Its remarkable power is that measurement requires no knowledge of the type of tracer. Comparison of the two length scales constrains the angular diameter distance and Hubble parameter at different redshifts. Hence deviations in dark energy due to possible variations in the cosmological constant assumption can be inferred.

The angular diameter distance measurements are especially sensitive to the geometry of the universe. Weak gravitational lensing, galaxy clustering and redshift space distortions all measure the dark matter content of the universe to high precision, and at different redshifts constrain the growth rate of density fluctuations and its dependence on dark energy. Supernova measurements constrain the expansion rate of the universe. Degeneracies persist between cosmological parameters, leaving scope for dynamical dark energy or modified gravity, to be probed by missions such as EUCLID [52].

3.3 Dark energy

No deviations with look-back time are detected from the cosmological constant Λ in the standard model to < 5%. The small value measured for Λ represents what has been called the greatest problem in physics. There are two key questions: why is Λ so small, by ∼120 powers of 10 as compared to the vacuum density at the scale of grand unification? And why is it just becoming dominant today, at ∼10^{17} second rather than at grand unification some 10^{-36} second after the Big Bang? Is the explanation due to particle physics or due to astrophysics? Or do we need to wait for a fundamental theory of quantum gravity to emerge?
There is a particle physics “explanation”, or rather, the indication of a possible route to be further explored. Consider a topological classification of all Calabi-Yau manifolds. This idea seems promising, in reducing more than \(10^{500}\) manifolds predicted by string theory to a much smaller number, those with small Hodge number, but needs further exploitation in terms of phenomenological string theory to be a useful guide [53]. Nevertheless, this approach may provide a hint as to an eventual possible selection principle for a universe congenial to both the standard model of particle physics and a low value of the cosmological constant.

And there is an astrophysics “explanation”, or again, more realistically, a hint of a promising direction that merits an in-depth study. Consider a universe with a few very large voids. Putting us near the center of a huge Gpc-scale void could explain our apparent acceleration, but at the price of producing excessive peculiar velocities and excessive kSZ signals [54]. A more controversial approach is to postulate a universe with many large voids whose cumulative effect via back reaction may arguably contribute towards global acceleration, albeit probably not at a sufficient level to account for dark energy [55].

### 3.4 What is dark matter?

Dark matter is not baryonic. This is a canonical result, emanating from nucleosynthesis considerations in the first minutes of the Big Bang. Confirmation comes from the observed abundances of helium and deuterium, as well as the inferred effective number of neutrino species, \(N_{\text{eff}} = 3.15 \pm 0.23\), versus the predicted value of 3.046. This differs from a pure integer because neutrino decoupling precedes electron-positron pair annihilation and is close enough so that neutrino flavour oscillations generate neutrino spectral distortions that slightly enhance the number density of relic neutrinos [56].

Primordial nucleosynthesis is highly successful in accounting for light element abundances, albeit with a question mark over Li overproduction. The matter fraction (including dark matter) is \(\Omega_m = 0.3089 \pm 0.0062\), whereas the baryon fraction, with \(h = H_0/100\) km s\(^{-1}\) Mpc\(^{-1}\), is \(\Omega_b h^2 = 0.02230 \pm 0.00014\). Hence 84\% of the dark matter is not made of baryons.

Nor is it made of standard model neutrinos. The sum of neutrino masses required to account for dark matter is \(\Omega_\nu h^2 = \sum m_\nu/93\text{eV}\), whereas from the Planck data \(\sum m_\nu < 0.23\text{eV}\). Including limits from the Lyman-\(\alpha\) forest of intergalactic hydrogen clouds extends the scales probed to smaller comoving mass scales, albeit at the risk of introducing systematics associated with hydrodynamic modeling of the intergalactic medium, to set a limit of \(\sum m_\nu < 0.12\text{eV}\) [57]. The measured contribution from neutrino oscillations is about 58meV, so that \(\Omega_\nu h^2 > 0.0006\). The maximum value is \(\Omega_\nu h^2 < 0.0025\).

The mystery of dark matter is that despite intensive searches, both indirect [58] and direct [59], its nature has not been identified. There is little question as to its observational dominance on scales from tens of kpc up to horizon scales, assuming Einstein gravity. It most likely consists of massive weakly interacting particles. The most attractive ansatz for the WIMP particle has long been provided by supersymmetry, which motivates the so-called WIMP miracle. If the lightest stable SUSY particle was once in thermal equilibrium, \(<\sigma v>_{\chi} \sim 3.10^{-26}\text{cm}^3\text{s}^{-1}\), with the consequence that thermal WIMPs generically account for the dark matter if the cross-section is typical of weak interactions. There is a wide range of SUSY models that give scatter in the cross-section at fixed WIMP mass by several orders of magnitude while still giving the correct dark matter density. The 100 or more free parameters in SUSY have led theorists to explore minimal models [60], which are highly predictive and invaluable for guiding indirect detection experiments, but at the price of restrictions on the full range of dark matter candidate masses and annihilation channels.

Fermi satellite observations of an excess, relative to standard templates, diffuse gamma ray flux in the galactic center region have motivated a mini-industry of dark matter interpretations, usually involving WIMP self-annihilations. The preferred WIMP mass is around 40-50 GeV, although this depends on the adopted annihilation channels [61]. The dark matter interpretation requires a thermal
cross-section, as favored by WIMP freeze-out in the very early universe. An alternative interpretation involving gamma rays from an old population of millisecond pulsars has received much attention, and is even favored by recent studies of evidence via fluctuation analyses for a faint discrete source population [62].

High energy positron and antiproton measurements by, most recently, the AMS-02 space experiment have also been claimed to provide evidence for dark matter particles of mass near a TeV. There is a new component of positrons beyond expectations from secondary cosmic ray production. However, the interpretation of the rising positron/electron ratio with increasing energy as a dark matter signal requires an implausibly high annihilation signal, and an astrophysical interpretation in terms of $e^+e^-$ pairs produced by nearby pulsar winds seems more likely, cf. [63]. The observed antiproton flux is consistent with secondary production [64].

As the WIMP mass is increased, the scaling $<\sigma v>_x \sim \alpha^2 W/m^2_x$ indicates that there is a maximum WIMP mass to avoid overclosing the universe, the so-called unitarity limit, of around 50 or 100 TeV [65]. The possibility of exploring such a large mass range, being near the limit of most acceptable SUSY models, is a prime reason for encouraging the construction of a future 100 TeV collider [66].

Candidates for cold dark matter include neutralinos, axions, and primordial black holes. Warm dark matter is another viable option, characterized most recently by 7 keV sterile neutrinos as motivated by controversial claims of a 3.5 keV x-ray line in the Perseus cluster and elsewhere. This particular candidate, just the most recent of a long series, seems to have been largely abandoned as of 2016 [67, 68].

The large-scale structure of the universe is well reproduced by cold or warm dark matter. The progress in surveys and in numerical simulations has been noteworthy. The first galaxy redshift survey (the CfA survey) in 1981 was of around 1000 galaxies, and was modeled with simulations of 32K particles [69]. Surveys and simulations advanced rapidly. After two decades, both large data surveys (the 2dF and Sloan digital galaxy redshift surveys of $\sim 10^6$ galaxies) and simulations with $\sim 10^8$ N-body masses were accomplished. Current simulations can cope with a trillion particles (as of 2016).

However addition of baryonic physics is crucial if we are to go beyond using mass points as tracers of large-scale structure. This remains a controversial subject in view of the differing prescriptions for the necessary subgrid physics.

4. Advances in Galaxy Formation

Some 380000 years after the Big Bang, temperature fluctuations imprinted on the last scattering surface provide evidence for the spectrum of primordial adiabatic fluctuations that seeded galaxy formation about a billion years later. Gravitational instability of weakly interacting cold (or warm) dark matter enables the growth of structure in the form of galactic halos that culminates in the formation of the first dwarf galaxies. Gas accretion triggers star formation, and the subhalos merge together as gravitational instability relentlessly continues until the full range of galaxy masses has developed.

But this grand scenario hides the ad hoc subgrid physics. The evolution of massive gas clouds is controlled by the competition between self-gravity and atomic cooling. The building blocks of galaxies are clouds of $\sim 10^6$ solar masses, since these form at a redshift of order 20 and are the smallest self-gravitating clouds that are warm enough to excite trace amounts of $H_2$ cooling and allow the first stars to form [70].

The largest galaxies weigh in at about $\sim 10^{13} M_\odot$ in the cold dark matter theory, and form as the dwarf galaxies merge together hierarchically in a bottom-up fashion, as dictated by the approximate scale-invariance (measured via the CMB) in Fourier space of the primordial spectrum of density fluctuations. One success is that simple scaling physics can explain the characteristic mass of a galaxy $\sim 10^{12} M_\odot$, as this is the largest halo that can effectively dissipate gas energy and form stars [71, 72].

Numerical simulations are used to explore the detailed process of galaxy formation, from that
of the first stars to massive galaxies. However we cannot resolve star formation or AGN feedback in cosmological zoom-in simulations. The best one can do is to resolve parsec scales, in state-of-the-art trillion particle simulations. However feedback physics is set on microparsec scales. The usual compromise is to model sub-grid physics by local observational phenomenology. The current generation of simulations includes both supernova and AGN/quasar feedback, using jets and/or mechanical outflows. Many aspects of the observed galaxy population can be explained. But some cannot. No model yet accounts for all aspects of galaxy formation.

For example, an exploration of various supernova feedback recipes found that no current prescription was able to reconcile the observed star formation efficiency per unit of cold gas in star-forming Milky Way-type galaxies with the mass-loading observed for galactic outflows in a wide range of models [73]. Improvements might include, among others, more sophisticated turbulence prescriptions [74], AGN-loaded superbubbles [75] or cosmic ray pressure-induced cooling delays [76].

More globally, dwarf galaxy issues, including their predicted numbers, the question of cores versus cusps, and the ”too big to fail” problem, have been largely resolved by improved baryonic physics and high resolution simulations [77]. However even here, not all studies agree on whether supernova feedback is sufficiently effective in a multi-phase interstellar medium in generating the low stellar content of the ultrafaint dwarfs [78] or in producing the recently discovered population of ultradiffuse galaxies in both cluster and group environments [79,80]. Nor is it obvious how to reconcile the history of inefficient star formation and baryonic mass loss with the efficient chemical seeding observed of r-process elements [81] observed in at least one ultrafaint dwarf galaxy. Moreover, the AGN/high star formation rate connection at high redshift continues to be an enigma, if galaxy mergers are indeed not a general panacea for this correlation [82]. More complex feedback physics, both negative and positive, may be needed than has hitherto been incorporated into the simulations.

Some authors are sufficiently desperate that they favor warm [83], fuzzy [84, 85] or even self-interacting [86] dark matter as a general panacea for dwarfs, although these particle physics solutions are highly debated. For example, removing small-scale power has negative consequences at high redshift, especially for early galaxy formation [87,88] and reionization of the universe [89].

As observational facilities are built to probe ever higher redshifts, doubts persist on the physics of galaxy formation. The state-of-the-art numerical simulations of galaxy formation are beautiful, but are they reliable, and more specifically, are they predictive? The simulations are becoming increasingly complex, in terms of input physics. One can easily imagine that they will soon be as difficult to analyze as the observational data, in terms of extracting any fundamental understanding of how galaxies actually formed.

5. The Future for Cosmology

The CMB temperature fluctuations have ushered in the modern age of precision cosmology. The low optical depth measured by Planck means that understanding reionization is much less of a challenge for theoretical models. The current goal that dominates most proposed experiments is to probe inflation via its gravitational wave imprint. Neutrino mass measurements are an important corollary, but will never replace direct experiments. Polarization searches for the B-mode imprint of inflation are confused by the foreground B signal, most notably from galactic dust. The immediate goal is to increase the sensitivity. The Planck satellite was good for microKelvin sensitivity.

To achieve B-mode polarization detection, one needs to reach the nanoKelvin level. Several ground-based experiments are underway using thousands or eventually tens of thousands of bolometers, or being planned in the CMB Stage IV effort [90] with hundreds of thousands of pixels, in contrast to the 32 bolometers on the Planck HFI instrument. Space has other advantages, with regard to overcoming systematic errors and foregrounds, especially at large angular scales, and successors to Planck are also being designed.
One can expect the best CMB measurements to probe \( N \sim \ell^2 \sim 10^6 \) independent Fourier modes on the sky. These independent samples to \( \ell \sim 1000 \) allow one to achieve \( N^{-1/2} \sim 0.1\% \) precision on large scales, corresponding to the precursors of galaxy clusters, before damping of the primordial fluctuations sets in and eliminates any smaller scales from detectability on the last scattering surface.

Galaxy surveys allow one to approach smaller scales and increase the independent sample number, and hence precision. Moreover, one gains by working in 3-D, with redshift information. Future surveys should allow \( N \sim 10^8 \) independent samples. This could provide an order of magnitude increase in precision over CMB measurements for cosmology. However galaxies are messy and biased. Larger numbers are surely needed per independent sample. Hence their advantage over the relatively clean CMB is limited by bias and systematics.

There is only one option to truly enhance the accuracy of future cosmology experiments. 21 cm probes of the dark ages provide the ultimate precision by sampling Jeans mass HI gas clouds at \( z \sim 30 \) that are still in the linear regime [91]. These clouds are colder than the CMB, as long as we observe them before galaxies or quasars, or even the first stars, have formed, that is at very high redshift.

Using 21 cm absorption against the CMB allows one to approach a very large number of independent modes, perhaps \( N \sim 10^{10} \). This would allow 100 times better precision than attainable with the CMB. One can now imagine trying to measure a guaranteed prediction of inflation, namely primordial non-gaussianity. This is generically expected in inflation, and is measured by nonvanishing higher order correlations. With sufficiently high precision, one could attempt to measure the fluctuation bispectrum. Primordial non-gaussianity on all scales is a more generic but more challenging and elusive prediction of inflation. This would be an important probe of inflation, and indeed is actually guaranteed, albeit at only a low level (the usual measure of second-order nongaussianity \( f_{NL} \sim 1-n_s \sim 0.02 \)) in single-field slow roll inflation [92].

There are many inflationary models, involving multiple inflation fields or inflationary features in the primordial power spectrum of density fluctuations [93], where effects of scale-dependent non-gaussianity could be substantial, especially if enhanced small-scale power is present that would not be constrained by the Planck limits \( f_{NL} \sim O(\pm 10) \) [94] on larger scales.

To attain such a large number of modes at high redshifts, ideally in the redshift range 30-60, one would need to use 21cm measurements at low radio frequencies, below 100 MHz, combined with high angular resolution. These requirements necessitate a large array of dipoles in a telescope site in an area with low radio interference. For example, a dipole array would need to be of size \( \ell \lambda / 2\pi \sim 300 \) km in order to resolve Fourier modes \( \ell \sim 10^5 \) or a few arc-seconds corresponding to a cloud size of order 1 Mpc and a corresponding bandwidth of 0.1 MHz [95]. Perhaps only the far side of the Moon would provide a suitable site. This would be a project to consider for the next century.

6. Summary

There has been remarkable progress in cosmology over the past 2 decades, and it is now a precision science. However there are still important questions to be addressed. Here is a personal subset.

6.1 Theory

I begin with theoretical questions

- Dark matter is here to stay but what is it? Should we change our theory if we fail to detect dark matter within a decade, or two?
- Does the low value of dark energy requires fine-tuning? And does this justify appeal to the multiverse with so many free parameters and little prospect of verifiability?
- Does dark energy vary with epoch? This might be the simplest way to avoid appeal to anthropic arguments to understand its low value at the present epoch.
- Is galaxy formation more of the same at early gas-rich epochs? Or is something radically new
needed? Does the frequency, structure and chemistry of dwarf galaxies require a more radical ingredient such as feedback from intermediate mass black holes?

• How are supermassive black holes formed in the early universe? Are intermediate mass black hole seeds needed? Will gravity waves eventually probe their formation directly?

• CMB: should we prioritize, if funding constraints require this, B mode polarization or spectral distortions as the next new frontier of the very early universe? Or is the guarantee of primordial non-gaussianity a more fundamental and realistic goal?

• Exploring the dark ages with 21cm at \( z > 20 \) is the most promising but also the most challenging new frontier: is this feasible even at the most radio-quiet site known, on the far side of the moon?

• Is inflation the correct description of the early universe?

• Is the cosmological principle valid? This certainly motivated Einstein, Friedmann and Lemaître. We should soon be able to test its validity, for example via all-sky surveys with the SKA.

• Our cosmological model, and in particular our assessment of its contents such as dark matter and dark energy, assumes general relativity. Is general relativity valid?

6.2 Observations and experiment

Finally I turn to a complementary wish list of observational questions. Cosmology is a field where observations of the natural phenomena, so sparse for millennia, are now far ahead of theory. Here what one might expect observations to provide, someday.

• Spatially resolved spectroscopic mapping of molecular gas and star forming regions in galaxies near the peak of cosmic star formation at \( z \sim 2 \). One could thereby attack the weakest link in galaxy formation theory, and understand the differences between early universe star formation, when galaxies are youthful and gas-rich, with the present epoch that is witnessing the inevitable fading of the bright lights of the universe.

• Overcoming cosmic variance by targeting the scattering of cosmic microwave background photons by hot gas in millions of galaxy clusters as probes of the local CMB quadrupole at redshifts up to redshifts \( z \sim 2 \). One could then meaningfully address the large angular-scale anomalies in the cosmic microwave background, which are potential witnesses of a pre-inflationary past.

• With sufficiently high precision measurement of CMB temperature fluctuations, determination of the spatial curvature of the universe on horizon scales becomes feasible. One could then address one of the most fundamental questions in cosmology: how big is the universe?

• Direct measurement of the expansion and acceleration of the universe by spectroscopy of distant objects at a resolving power of \( 10^6 \) or greater. The second generation EELT CODEX spectrograph will be a first step, but one could do better with even larger telescopes in the future.

• Resolution of Jeans mass neutral hydrogen scales in the dark ages, before the first stars formed. These are the ultimate building blocks of galaxies. Detection in absorption against the CMB requires a low frequency radio interferometer on the far side of the moon with milliKelvin sensitivity at 50 MHz.

• Extraction of a primordial non-gaussianity signal from the seed fluctuations that generated large-scale structure. Even the simplest, single-field inflation models predict such a signal at a level about 100 times below current limits. Our best bet here again may be a low frequency radio interferometer on the far side of the moon.

• Resolution of the central engine in quasars and active galactic nuclei by microarc-second microwave imaging. This also may require development of a lunar observatory in combination with a lunar satellite.
As for identification of dark matter, I see one promising strategy for exploring the final frontier of massive particle candidates. Let us assume the dark matter consists of a weakly interacting particle. The problem currently with all astrophysics searches via indirect detection signatures is the lamp-post strategy: use of model predictions about electromagnetic signals for looking in the dark. Any Bayesian would admit that given any reasonable model priors, the probability of finding a signal would be low. History tells us that extending the energy frontier is a more fruitful approach towards discovering new phenomena. No guarantees of course, but I opt for a future 100 TeV proton collider as the next step towards exploring a promising regime where heavy dark matter particles may be hiding. One may not even need to seek much higher energies as general unitarity arguments limit the mass range to about 50 TeV that one needs to search for hints of any new dark-matter related physics.
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