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Cosmological Experiments

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We review the status of cosmological experiments probing the early universe through the abundnance of elements and the formation and evolution of structures, describing how they leaded to the estabilishment of the cosmological concordance model and mentioning the most important future expectations from them. We focus on the information derived from the observations of the Cosmic Microwave Background (CMB) anisotropies, describing how the traces of processes occurred in the early universe are stored, and pointing out those which still evade our knowledge, as well as the most important forthcoming experiments.

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1. introduction

The term “precision cosmology" has finally come to a common use among cosmologists and theoretical physicists in general, meaning that observations have being progressing so much in the recent years to allow the measure of the main cosmological observables with percent precision. As we will review briefly here, those observations concern the abundance of primordial elements in the early universe, as well as the early and late stage of the evolution of cosmological structures, as seen in the image brought to us by the Cosmic Microwave Background (CMB) and in the present distrubution of large scale structures, respectively. The technology, data acquisition, reduction and interpretation in modern cosmology are without any doubt one of the main achievements of this century for physics as a whole. On the other hand, still it has to be remembered that the extraction of physical information from cosmological measurements is extremely complex even in the sort of easy context provided by the linearization of general relativity, i.e. small deviations around the homogeneous and isotropic picture, known as Friedmann Robertson Wolker (FRW) spacetime. Thus, the interpretation of a given experiment in cosmology relies on a variety of hypotheses and assumptions, and often does depend on complementary data, so that practically any claim in cosmology is possible only by combining different datasets. On the other hand, the variety and independence of the main cosmological observables make us confident that the picture we have reached is solid, to the point of being called “cosmological concordance model", although from the point of view of its theoretical understanding it poses unanswered and outstanding questions for physics as a whole. Here we review the basic properties of the cosmological concordance model, and the most important observations which leaded to its estabilishment, and which are also currently testing it, focusing on the case of CMB anisotropies. The text is organized as follows. In section 2 we describe the concordance model in cosmology. In section 3 we review the main observations supporting it. In section 4 we focus on one of those, namely the CMB, and in section 5 we make some concluding remarks.

2. cosmological concordance model

From the point of view of a pure description, i.e. giving up our ambition to understand it theoretically, the present cosmological picture is relatively simple. The expansion is described by assuming an highly symmetric spacetime on large scales, isotropic and homogeneous as described by the FRW metric, say larger than the biggest cosmological structures, galaxy clusters, extending over tens of Mpc. Other than that, the cosmological concordance model is specified by three main characters: perturbations, components and geometry.

The description of perturbations is supported and simplified by the evidence of small perturbations with respect to the mean temperature of the CMB photons; as it is well known, fluctuations are of the order of one part over 10^5 with respect to the mean 2.7 K, over the whole sky and at all the angular scales. This evidence supports the assumption that in their mathematical description only small deviations from homogeneity and isotropy are allowed [7]. Those perturbations are supposed to originate in a phase of exponential expansion in the very early universe, the inflation, driven by a non-zero vacuum energy similar to a cosmological constant provided by the potential energy of one or more fundamental fields: quantum vacuum states on microscopic scales are stretched by the expansion itself, approaching the scale corresponding to the Hubble expansion rate, where they appear as perturbations, via a mechanism which is simular to the Hawking process for black hole evaporation, and related to the non-invariance of the vacuum for quantum field in curved space-times [2]. Other than that, linear cosmological perturbations are specified by a distribution, which the quantum nature within the inflationary picture predicts to be Gaussian, i.e. specified only by the two points correlation function, which is conveniently described in terms of their power spectrum in the Fourier domain. Since inflation is essentially specified by a single scale which sets the amount of vacuum energy responsible for the expansion itself, it predicts a sort of white spectrum, also known as scale invariant or Harrison Zel'dovich, i.e. with the same power on all scales; more precisely, the perturbation variance in the energy density on a given scale when the latter equals the Hubble expansion rate is a constant [9].

At least three different cosmological components are required. Relativistic matter is made by photons and neutrinos, while non-relativistic species, forming galaxies and their clusters is fundamentally divided into two sub-classes. The matter belonging to the standard model of particle physics, dominated in mass by baryons and constituting the luminous part of cosmological structures, and the Cold Dark Matter (CDM), interacting at most weakly with the rest, and characterized by a kinetic energy which is negligible with respect to the mass, forming the dark haloes around galaxies and galaxy clusters. Recently, a third, and actually dominant cosmological component has been discovered and added to the picture, as some kind of vacuum or dark energy similar to the one driving inflation and imprinting an acceleration to the cosmic expansion during the last couple of billion years. The simplest description, also consistent with the present data, is the cosmological constant; this is not the first time that such a term was considered and studied: it was actually appearing and disappearing from the Einstein equations several times in this century, initially introduced by Einstein himself, wrongly asking for stationarity of the universe, and later by quantum mechanical arguments, predicting it to correspond to the value obtained combining fundamental constants, which is about 123 orders of magnitude larger than the cosmological density today; caused by our incapability of explaining this discrepancy, this issue is known since tens of years as the cosmological constant problem, probably related to our ignorance in describing the vacuum in physics. Although the cosmological constant is a viable candidate for the dark energy, it cannot be for inflation, as the latter has to finish and decay in order to allow structures to form and grow, and therefore cannot be constant; this brought cosmologists to guess that the dark energy responsible for the acceleration today may be similarly dynamical, and most of the cosmological probes today are oriented to constrain such a dynamics. In terms of relative weight, baryons and leptons constitute about 4% of the total cosmological density, dark matter about 20%, while the dark energy is at the level of 76%.

Let us come to geometry now. That is also most simple, in the sense that inflation predicts it to be zero within errors, and indeed so far that is the case in the cosmological observations. Simply, the curvature term in the Friedmann equation describing the expansion gets more and more irrelevant as the inflationary expansion proceeds, as it happens in any physical system being stretched in size. As there is no reason to consider a particularly short amount of inflation, the generic prediction is that the expansion lasts enough to make the curvature irrelevant.

Before moving to the next section, we stress again that this almost elementary description is achieved at the expenses of a real theoretical understanding, which motivates the effort to proceed

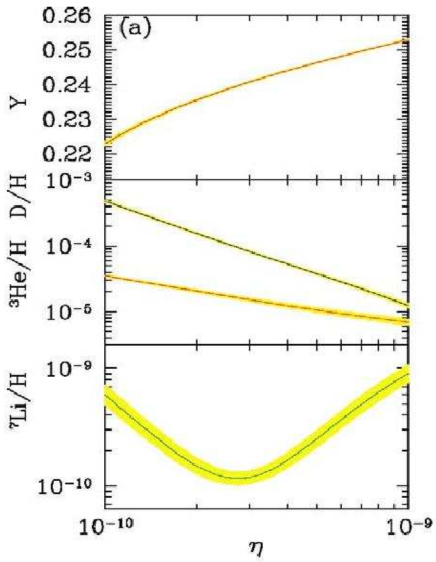

Figure 1: Predicted abundances concerning primordial elements from Nucleosynthesis. The image was taken from [5].

on the way traced by the same cosmological experiments which allowed to build up the picture above, and outlined in the next sections.

3. observational pillars

The cosmological concordance model was built combining the information coming from different datasets. Abundance of light elements, probing the Nucleosynthesis epoch, CMB anisotropies, large scale structure, probed by direct three dimensional mapping of galaxies as well as the weak lensing distortion caused by forming structures, and the observation of standard candles, type Ia supernovae, probing the cosmological geometry through light propagation and redshift. The details of those observations, combining them in order to constrain the cosmological concordance model and focusing on the CMB observations from the Wilkinson Microwave Anisotropy (WMAP) probe, may be found in [15] and references therein. The reactions to form nuclei are rather well known, and occur on sufficiently small scales allowing to treat the cosmological expansion as a separate process running in the background. Assuming thermal equilibrion and knowing the abundances of the components involved, nucleosynthesis predicts the formation of hydrigen and helium essentially, plus tiny fractions of slightly heavier elements. These abundances are measured in the emission light from red giant stars, the so called population II stars, which are supposed to keep the primordial abundances of elements unchanged. Figure 1 shows the predicted abundance of nucleosynthesis elements as a function of the ratio between baryons and photons, η, see [5] and references therein. Remarkably, the measured abundances of elements agrees with the totally independent measure coming from the observations of the CMB anisotropies, which probe the baryon content of the universe through the Thomson scattering of photons onto charged particles at last scattering, as we will see in the next section.

The pattern of cosmological perturbations at present is reconstructed by large redshift surveys. Three dimensional maps of millions of galaxies have been constructed, extending over several hundreds of Mpc [12, 3]. From those, assuming a recipe for relating the distribution of luminous objects to the underlying dark matter, one can take the Fourier transform and measure the power spectrum of density fluctuations directly. Figure 2 shows the measured power spectrum $P(k) = |\delta(k)|^2$, where δ represents the Fourier transform of the density constrast, while h is the value of the Hubble expansion rate today in units of 100 km/sec/Mpc, used for expressing values of wavenumbers in the plot. The bell shape of the spectrum is due to the different growth histories of perturbations in the epochs dominated by radiation and matter, see [9] for details: scales smaller than the one corresponding to the Hubble expansion rate at the epoch of equivalence between matter and radiation, i.e. high wavenumbers in the figure, undergo a suppression. The lines in the plot show best fits cosmological models characterized by different matter densities, increasing from about 20% to 30% of the total density as the curves go up at large wavenumbers; the difference in the best fits and data points reflect the fact that the data are taken from different surveys and even at different times for the same one [12]. Through the perturbations in their thermodynamical temperature, related to the underlying density fluctuations, the CMB anisotropies provide measurements of the power spectrum as well, on very large scales, i.e. small wavenumbers in the figure. The CMB data, not shown in the plot, remarkably agree in amplitude with the ones which is indicated by the surveys of galaxies. The barely visible oscillations on the right of the peak are one of the most promising features for the future of large scale structure measurements. Indeed, those are the scars of CMB acoustic oscillations occurring at the epoch of origin of the CMB, which we will describe in the next section, leaving an imprint in the dark matter, too, commonly known as baryon acoustic oscillations. Since they are related to processes when the cosmic acceleration was absent, they behave as a standard ruler, i.e. their wavelength and the distance at which they are observed are used to probe the recent cosmological expansion, constraining acceleration [4].
A large part of the future of large scale structure studies is represented by the weak distortion that background light undergoes due to the lensing generated by forming cosmological structures [1]. From the knowledge of their power spectrum, one can predict the lensing shear, i.e. ellipticity, induced on background galaxies placed at different redshifts via gravitational lensing. The latter was observed recently for the first time with remarkable agreement by several different groups, as figure 3 shows. For now, the lensing yields an independent measure of the overall perturbation power, essentially the normalization of the primordial power spectrum, often given in terms of the σ_8 quantity, i.e. the matter perturbation variance on spheres with radius of $8h^{-1}$ Mpc. The future promises to bring a differential measurement of the same quantity, i.e. at different redshifts, realizing a tomography of the structure formation process thanks to the unique lensing property of possessing a non-zero cross section which peaks half way between the observer and the source. As the onset of cosmic acceleration occurs on the same epochs, the latter investigations are crucial for studying the underlying dark energy component [13].

Type Ia supernovae, originated in a star binary system in which the actual explosion threshold of the supernova is reached gradually due to the accretion from the companion star, are known to possess an almost constant luminosity, regardless of the enviroment or epoch in which they explode. If so, the redshift we observe today on their light probes the cosmological geometry on their way toward us. These observations indicate that the cosmological expansion is actually

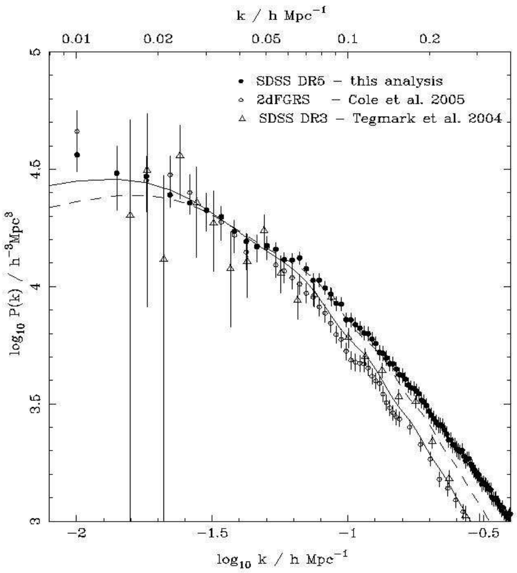

Figure 2: The measured primordial power spectrum with the latest data from the modern redshift surveys, the figure is from [12].

accelerating, see [14] and references therein. If this evidence is combined with the data from CMB and large scale structure, indicating that the cosmological geometry is flat, the introduction of a new cosmological component is required, which is known as dark energy and in the simplest case is represented by a cosmological constant. As for the lensing, in principle dividing supernovae in redshift shells allows to investigate the differential behavior of the onset of acceleration, trying to discriminate a cosmological constant from something else, together with the other cosmological measurements. For this reason, the research in this field is proceeding in a sort of parallel way. Large satellite projects are being planned for surveying large areas of the sky in order to detect the deformation of galaxies due to gravitational lensing, as well as collecting the redshift of exploding supernovae up to the epoch of the onset of cosmic acceleration[1].

The CMB has remained out of the present discussion, as we will be reviewing it in some detail in the next section It is of course a pillar of the cosmological concordance model as well, and one of the main observables to perform further tests and investigations on it. Before concluding, it is worth mentioning another potentially powerful cosmological probe. The 21 cm emission line of hydrogen atoms in the cosmic medium, if foreground emission and instrumental systematics may be controlled at the level of accuracy comparable to the modern observations of the CMB anisotropies in the microwave band, would bring to us an image of the cosmological fluctuations at the reionization epoch, i.e. the age in which the first luminous objects re-ionize the cosmic medium. Theoretical forecasts, see [10] and references therein, as well as large observations campaigns[2] are being studied in order assess the potentiality of this observable.

[1]snap.lbl.gov,www.dune-mission.net
[2]www.lofar.org

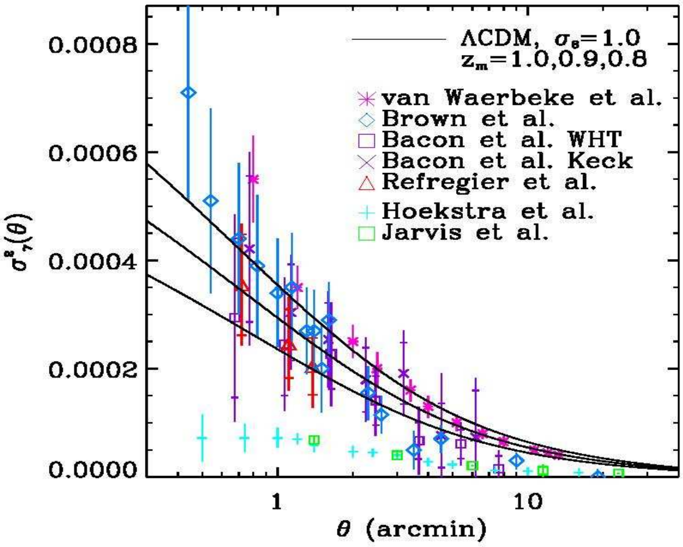

Figure 3: The predicted measure of the ellipticity induced by weak lensing from different redshift of the background galaxies (z_m), also called shear, as a function of the angular scale at which it is measured, together with the data from different experiments. The figure is from [13].

4. the CMB case

Photons decouple from the rest of the system at a temperature of about 3000 K, corresponding to an age of the universe of about 300,000 years. They bring to us the records of cosmological perturbations at that epoch, in the form of anisotropies in their black body distribution. The latter possess temperature fluctuations, as well as linear polarization, since the Thomson scattering onto free electrons at the decoupling epoch is able to transform an anisotropic incident radiation into an outgoing lineary polarized wave, characterized by its total intensity T and Stokes parameters Q and U, function of the direction in the sky. Anisotropies are sensitive to all kinds of cosmological perturbations, which according to general relativity may be scalar, like density perturbations, vector, like vorticity, and tensor, equivalent to gravitational waves [7]. The Stokes parameters may be combined together into a gradient or E component, affected by all kinds like the intensity T, and a curl one, also labeled as B, sensitive to vectors and tensors only [16, 6]. Since the growth of vectors is suppressed by the cosmological expansion, detecting a B component would be a strong indication of the existence of gravitational waves of cosmological origin. The cosmological information from the CMB are usually extracted in the harmonic domain, i.e. considering the coefficients of harmonic expansion on the sphere, $a_{lm}^{T,E,B}$, and compressing them in order to reduce the effects of noise and systematics, in the quantities

$$C_l^{XY} = \frac{1}{2l+1}\sum_m a_{lm}^X (a_{lm}^Y)^* \ , \ X,Y = T,E,B \ . \qquad (4.1)$$

The multipole l is conveniently expressed in terms of the angular scale θ at which it probes the anisotropy power, i.e. $\theta \simeq 200/l$ degrees. In figure 4 the prediction of the C_l distribution from the cosmological concordance model is shown, together with the main cosmological processes activating the different parts of the spectrum. From top to bottom, the curves represent C_l^{TT}, C_l^{TE}, C_l^{EE} and C_l^{BB}; the correlation between T and E is so strong because the E polarization modes are activated by the same density fluctuations at decoupling, which dominate the T modes. On large angular scales, the TT spectrum is dominated essentially by the unperturbed perturbations generated in the early universe, generating the long plateau on $l \leq 100$. On sub-degree angular scales, corresponding to scales lower than the sound speed for photons at decoupling, a series of oscillations is observed, the so called acoustic peaks; those are activated by photons tightly coupled to charged particles via Thomson scattering falling into the potential wells provided by the dark matter, and bouncing back due to their own pressure; therefore, they are most sensitive to the amount of baryonic matter and their observation, limited for now at the first two peaks, leads to the measure represented by the highlighted area in figure 1. The angular scales corresponding to the transition between the plateau and the acoustic oscillations, marked by the peak at $l \simeq 200$ is one of the most important standard ruler in cosmology; its physical scale corresponds to the CMB sound horizon at decoupling, when the effects of curvature or dark energy are negligible; the angle it subtends depends therefore on the distance from last scattering, which is sensitive precisely to curvature or dark energy effects on the cosmic expansion at low redshifts. The angular scales at which the first peak is observed, together with the type Ia supernovae and large scale structure data, is the basis of the evidence for the acceleration in the cosmic expansion. Acoustic oscillations also occur in the component of the polarization which is correlated with T, i.e. the EE and TE spectra, because of the strong correlation between the two processes. Since polarization is caused by CMB photons hitting a last scatterer electron with anisotropic intensity, the polarization exists only on scales corresponding to the mean free path at last scattering, i.e. less than one degree in the sky. On the other hand, large bumps are visible on the EE and BB spectra on multipoles corresponding to tens of degrees in the sky; the reason is the re-scattering process of CMB photons onto electrons coming from the rionization process occurring at redshift of about 10. The induced polarization peaks on the scales subtended by the photon free path at the corresponding epoch, which is sensibly larger, explaining why the reionization bump occurs at such small multipoles. A leakage of EE modes in BB due to gravitational lensing is well apparent in the broad peak in the latter spectra, resembling the EE with smaller amplitude; indeed, even a pure E mode pattern of CMB anisotropy, passing through forming cosmological structures and getting deflected via gravitational lensing, get distorted acquiring a B component, as a result of the incoherence of the underlying lensing structures, see [8] and references therein. Finally, a tensor component with 10% amplitude with respect to the scalar one has been added and manifests as peak at a multipole of about 100 in the BB spectrum. This is the imprint of the polarization anisotropies caused by the corresponding gravitational waves at last scattering; the latter are massless, diffusing as radiation on sub-degree angular scales, as their oscillations are not supported by interaction with any other component.

At the present, the main cosmological consequences are derived from the knowledge of the TT and TE spectrum up to about $\ell \simeq 500$, plus other data from sub-orbital experiments on EE on smaller angular scales, see [15] and references therein. Almost half of the spectrum, including the EE and BB modes, remains hidden to our knowledge. In addition, almost nothing is known about the remaining statistical moments of the distribution of CMB anisotropies. Forthcoming probes

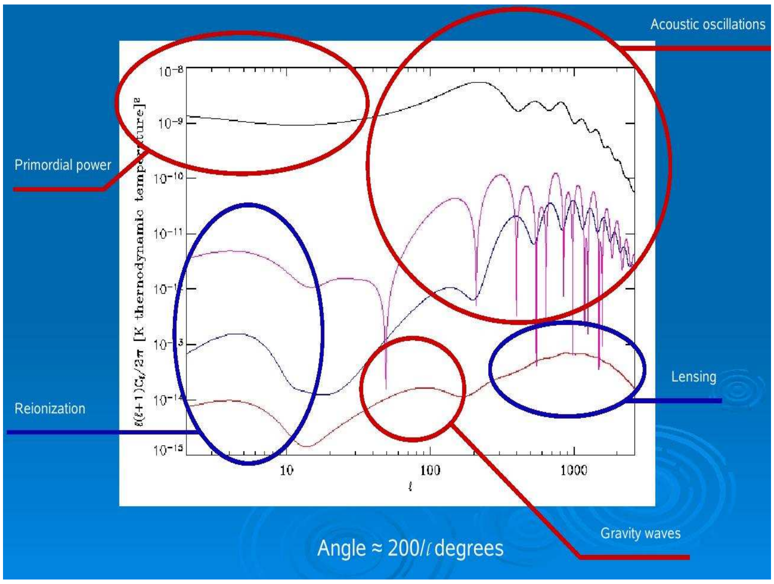

Figure 4: A representation of the angular power spectrum of CMB anisotropies as predicted by the cosmological concordance model, as a function of the angular scale at which it is measured. Also, the main processes activating the different regions of the spectrum are highlighted.

promise to reduce our lack of knowledge on CMB anisotropies. The Planck satellite[3] will be launched in late 2008, and will produce all sky maps at 9 frequency channels, with unprecedented angular sensitivity and resolution, reaching a signal to noise ratio of a few on angular scales of a few arcminutes. A glimpse of the progress which is expected from Planck concerning the observation of the pattern of CMB anisotropies is shown in figure 5. In addition, a number of sub-orbital probes[4] are ongoing or planned to look for polarization CMB anisotropies on sub-degree angular scales and on low foreground regions of the sky, targeting the E modes as well as having the potential sensitivity to detect the B modes from cosmological gravitational waves if they are at least a few percent of the scalar amplitude [11]. If these observations are successful, in the control of instrumental systematics as well as the removal of the foreground emission, a way toward a post-Planck CMB satellite may open.

5. concluding remarks

We made a very brief outline of the ongoing and planned cosmological experiments, focusing on those which allowed to construct the so called cosmological concordance model. The latter is at odd with known physics within the standard model of particle physics, and requires substantial extensions. Known particles make only 4% of the total density; the remaining part is in some form of pressureless dark matter, about 20% of the total density, forming dark haloes around galaxies and clusters of them, and about 76% of a dark energy component which is causing the expansion to accelerate, like a cosmological constant in its simplest form, although no hint about how to relate

[3] www.rssd.esa.int/Planck

[4] lambda.gsfc.nasa.gov

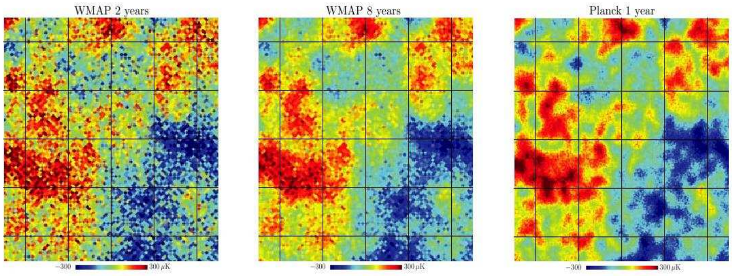

Figure 5: A representation of the improvement expected from Planck with respect to WMAP over limited regions of the sky, in terms of instrumental sensitivity. The image is taken from the Planck blue book available at www.rssd.esa.int/Planck.

its energy scales with the fundamental ones exists. Primordial perturbations are Gaussian and with almost equal power on all scales, seeded by some form of accelerated expansion occurring in the early universe as well, which we describe semi-classically by means of a scalar field, the inflaton, driving and inflationary expansion with its potential energy, eventually decaying in matter and radiation. The cosmological concordance model is made credible and trusted by the community due to the marked independence of the observations leading to its estabilishment. Those are the measured abundances of primordial elements, microwave background radiaton, large scale distribution of galaxies, light coming from distant supernovae traveling cosmological distances. Most of these observables are still far from revealing their full potentiality. We focused on the case of the cosmological fossil radiation, where plenty of experiments with markedly different strategies are trying to catch the tiniest imprints of the cosmological perturbations which are coded in those. This aspect, together with the compelling evidence that the cosmological concordance model, if correct, is pointing to a entirely new world for physics as a whole, puts us roughly in the middle of the road toward the understanding of the messages which are stored in the cosmological observables. Those are likely to unveil at least a fraction of their hidden signatures in the forthcoming decades, the most spectacular ones coming probably in just a few years from the next generation of satellite and sub-orbital missions for the study of the cosmic microwave background anisotropies.

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