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Cosmological probes of the dark sector

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Abstract

Cosmology has entered a precision era, revealing a rather mysterious universe dominated by dark energy and dark matter. With the plethora of forthcoming observations, novel probes of this dark sector (notably, dark matter) will become accessible, and currently proposed ideas will be probed and constrained. This contribution aims at describing some of the most promising way to progress on the theory/phenomenology side, highlighting the interplay with existing IN2P3 engagements as well as new windows of opportunity.

1 Introduction

The accelerated expansion of the universe is attributed to a dark energy (DE), *tentatively* identified with the cosmological constant, Λ, accounting for about 2/3 of the energy budget of the current universe. About 85% of the remaining energy content is in the form of a cold, non-interacting form of matter dubbed dark matter (DM). Albeit its existence is by now well established on a wide variety of astrophysical scales, its true nature remains unknown despite decades of extensive theoretical and experimental efforts. Cosmological probes typically consist of (but are not limited to) the cosmic microwave background (CMB) temperature and polarization anisotropies, large scale surveys of galaxies (LSS) also including the baryonic acoustic oscillations (BAO), Ly-α forest from quasars light absorption by neutral hydrogen clouds, supernovae of type Ia (SN1a) and measurements of light elements produced during the big bang nucleosynthesis (BBN). If we limit ourselves to the DM, a remarkable example of the power of the cosmological probes is provided by the most accurate measurement of its relic density[1] $\omega_{\rm cdm} = 0.11933 \pm 0.00091$ (*Planck* 2018 TT,TE,EE+Lensing+BAO [1]). Although all DM "detections" are limited to its gravitational interaction, cosmology is also constraining a number of its "particle" properties, such as its mass (e.g. [2, 3]), its annihilation rate (e.g. [4, 5, 6, 7, 8, 9, 10, 1]), its decay rate (e.g. [11, 12]) and its scattering rate with baryons (e.g. [13, 14, 15, 16, 17, 18]).

The standard cosmological model, which includes Λ, cold DM, along with baryons, photons, and neutrinos (known as the ΛCDM model), is incredibly powerful at describing cosmological observables up to a very high degree of precision. However, the next decade will see it subject to tightened tests, with a higher potential to shed light on its dark components. This hope is particularly motivated by a number of "tensions" which have emerged over the recent years. Above all, the Hubble tension is a mismatch between the Hubble constant measured using low redshift data (e.g. SN Ia) and high redshift

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[1]Hereafter, error bars on measurements are given at the 68% C.L. while constraints are given at the 95% C.L.

data (e.g. CMB) [19]. This tension is best expressed in terms of the SH0ES low-z determination of the Hubble constant, $H_0 = 74.03 \pm 1.42$ km/s/Mpc [20], and the CMB determination from *Planck*, $H_0 = 67.4 \pm 0.5$ km/s/Mpc [1]– two estimates which are $\sim 4.4\,\sigma$ apart. Additionally, the value of a quantity measuring the power spectrum normalization of density inhomogeneitiesinferred from CMB is about 2.5σ larger than what deduced from weak lensing surveys. As a final example, we mention that the Experiment to Detect the Global Epoch of Reionization Signature (EDGES) [21], which targets the global 21cm signal from hyperfine transitions of neutral hydrogen in the "Dark Ages" ($10 < z < 200$), announced a detection of an absorption profile centered at 78 MHz (corresponding to redshift $z\sim17$), with a best-fit amplitude more than twice the maximum allowed in the standard cosmological model (ΛCDM). There has been numerous proposition to resolve these tensions, often involving some type of DM interaction, with baryons [22, 23], an additional component of dark radiation [24, 25, 26, 27] or dark energy [28]), or DM decay [29, 30, 31].

The IN2P3, whose primary research mission includes shedding light on the nature of DM and DE, must keep its involvement in theoretical and experimental program of searches via cosmological probes. This is almost the only option for DE, but also a crucial one for DM: especially given the lack of detection at colliders and direct detection experiments, cosmological probes probably provide the main room for improvements, besides being the only way to test the evolution of DM properties over cosmic time and scales. Robustly identifying the nature of DM *will* require detection and consistency checks between various data sets at hands.

2 Current situation

In the following, based on Ref. [32], we review cosmological searches involving the dark sector (with an emphasis on DM) and present promising area of developments for the next decade, highlighting fields IN2P3 and its researchers are currently involved in, as well as possible windows of opportunity for an involvement in the near future.

2.1 Electromagnetic energy injection

Injection of electromagnetic (e.m.) energy is a characteristic feature of many "dark relics", which may be the DM or only part of it. Examples include but are not limited to particle annihilation and decay [4, 5, 6, 7, 8, 9, 10, 1, 11, 12] or primordial black holes evaporation and accretion of surrounding matter [33, 34, 35, 10]. Electromagnetic particles injected in the cosmological baryon-photon plasma (or baryon gas after hydrogen recombination) can generically heat and ionize the surrounding medium. Cosmological searches have a number of advantages over other indirect probes. First and foremost, they do not suffer from poorly known astrophysical backgrounds, propagation modeling and spatial distribution uncertainties. Second, by combining different probes, they allow to test particle properties at very different redshifts, from the very early Universe to the current epoch. This is illustrated in the context of decaying particles in Fig. 1, right panel, where we show the constraints on the fraction of decaying dark matter as a function of the lifetime of the decaying component from a variety of cosmological probes that we describe below.

BBN has been used since decades to derive constraints on exotic energy injection, in particular from e.m. particle decay as considered here. Energy injection could modify the yields of light nuclei (in particular ^{2}H and ^{3}He), whose observations match pretty well the predictions of the ΛCDM model (see e.g. Refs [36, 37] for reviews). The abundance of Lithium-7 could offer a complementary probe of e.m. energy injection in the early universe. However, the relation between its observed 'quasi-plateau' abundance in metal-poor halo stars and its cosmological abundance is still disputed. Assuming that the two are equals, it has been recently shown that a purely e.m. injection of energy may reconcile observations with theoretical predictions [38] (see also [39] for an update).

Spectral distortions of the CMB have been studied as a way to probe electromagnetic energy injection since seminal papers [40, 41, 42]. Lots of efforts have been paid towards a better treatment of these distortions (see e.g. [43] for a recent review), including applications to early decaying massive particles (e.g. [44, 45, 46, 47]) and primordial black holes [48, 49]. It has been found that the distortions are (mostly) of two types, depending on the energy injection time. At very early times, no spectral

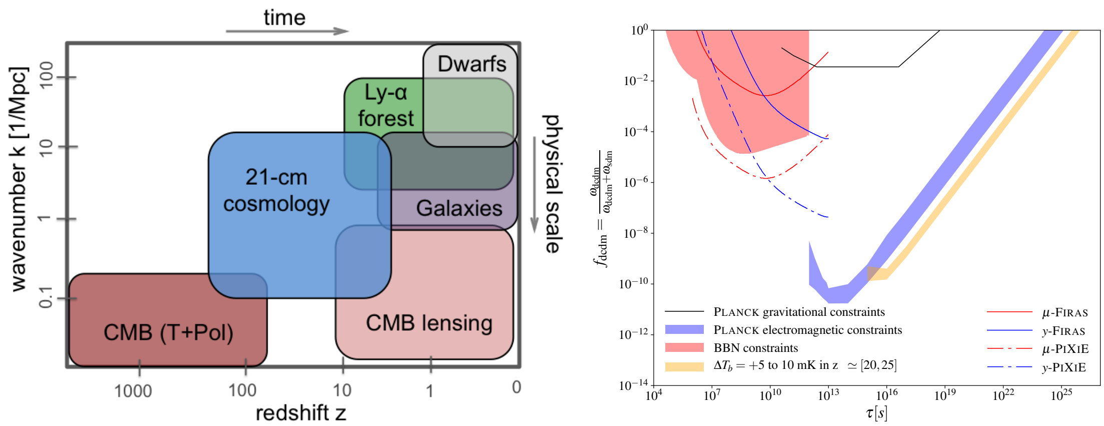

Figure 1: Left panel − Approximate cosmological epochs and physical scales corresponding to different observables (spectral distortions are omitted for compactness of presentation; their origin lies to the left of the plot). From Ref. [32]. Right panel − Constraints on the fraction of decaying dark matter as a function of the lifetime of the decaying component from a variety of cosmological probes From Ref. [12].

distortion can survive, since it would simply result in a shift of the blackbody temperature. Below $z \sim 2 \times 10^6$, the CMB spectrum starts acquiring an effective chemical potential μ, while at later time, the CMB is mostly sensitive to a modification of the so-called comptonization $y-$parameter, quantifying the amount of energy transfer via Compton scattering. Spectral distortions are of major interest for e.m. energy injection happening before recombination, which are loosely constrained by the CMB angular spectra discussed further on (see also Ref. [47] for a detailed analysis of sensitivity prospects as a function of the particle lifetime).

CMB anisotropies are remarkably sensitive to e.m. energy injection through its impact on the free-electron fraction x_e and the temperature of the intergalactic medium (IGM) T_{IGM}. The accurate computation of the effect of electromagnetic energy injection onto the thermal history of the universe requires the use of numerical recipes such as monte-carlo methods [7, 50]. *Planck* measurements of CMB temperature and polarization anisotropy on degree angular scales provide some of the strongest and most robust bounds on annihilations and decays of sub-GeV DM, complementing indirect searches that probe heavier DM candidates [1, 11].

Additionally, cosmology is currently the only way to probe decays into invisible channels, such as neutrinos or other dark particles [51, 52], providing robust and model-independent bound on the lifetime of dark matter. Such constraints are extremely important in the context of the afore-mentioned cosmological tensions, which according to some proposal may indicate that (a part of) DM is unstable on cosmological time-scales [29, 30, 31]. However, CMB lensing and BAO measurements provide strong constraints on such tentative resolutions, excluding the relevant parameter space [53, 52]. These constraints are represented in fig. 1.

2.2 Interactions with Baryons

On top of e.m. energy injection through annihilation and decay, there are many models (including the famous WIMP framework) in which (a fraction of) DM can exchange heat and momentum with baryonic matter. The so-called direct detection experiments constitute a large part of the search program for dark matter through potential elastic scattering between Galactic-halo DM and nuclei in underground targets. In a cosmological context, such scattering can affect both the thermal history and the evolution of cosmological perturbations [13, 14, 15, 16, 17, 18, 54, 55, 56, 57]. Hence, cosmological observables can be considered a direct-detection experiment over cosmic times and scales, as illustrated in Fig. 1, left panel.

As is the case with e.m. energy injection, the CMB is a pristine probe of such interactions through distortions of its blackbody spectrum and temperature/polarization anisotropies. By scattering with either protons, electrons, or photons in the early Universe, DM can drain heat from the primordial plasma [58], leading to spectral distortions of the CMB. The CMB frequency spectrum is most sensitive to light particles that thermally decouple as early as $z \sim 2 \times 10^6$ and DM masses lower than ~ 0.1 MeV with current data. Moreover, DM-baryon scattering prior to recombination ($z \sim 1100$) induces a drag force between the DM and baryon fluids, smoothing density fluctuations more prominently at progressively smaller scales and for stronger interactions. *Planck* measurements of the CMB temperature anisotropy currently provide the strongest cosmological bound on the DM-proton scattering cross section [13, 14, 15, 16, 17, 18]. They already sensitively probe DM particles with masses outside the detection limits of most existing direct detection experiments (> 1 keV) [14], through their interactions with baryons when the Universe was only a thousand years old.

However, the CMB has a limited sensitivity to small spatial scales, where the effects of the interactions are more prominent. Small scales are accessible to other observables, but are more prone to systematic modeling and measurement uncertainties. For example, SDSS Lyman-α forest measurements trace the matter power spectrum on comoving scale of about 1 Mpc; their analysis set some of the most stringent to-date cosmological bounds on DM-baryon interactions [16, 59]. These bounds imply that a proton residing in a Milky-Way-like galaxy does *not* scatter with DM over the age of the galaxy.

2.3 Interactions with Dark Radiation

There is nowadays a strong interest for complex dark sector, which naturally contains dark radiation component (DR) that can interact with DM particles (see Ref. [60] for a review). Such models are ubiquitous in theories proposed to explain the hierarchy problem of the Standard Model of particles [61, 62]. But recently, their investigation has been additionally motivated by their role in mitigating cosmological tensions [24, 25, 26, 27], while some models have been built to explain the putative anomalies in DM structure on sub-galactic scales [63, 64, 65, 66].

Cosmology offers a unique way to probe DM-DR interactions, especially if DM resides in a secluded sector that only weakly couples to known particles. The typical effect of DM interacting with DR in the early Universe is to suppress the growth of structure, as compared to a scenario with no interaction. The resulting suppression of power is captured in the CMB anisotropy and all tracers of large-scale structure (similar to the case of DM-baryon interactions): galaxy clustering, galaxy weak lensing, the Lyman-α forest, and the cosmological 21-cm signal [67, 68, 69]. Interestingly, on top of the suppressed structure growth rate, there are signatures associated to an interacting DR component that can be disentangled from that of relativistic particles that do not couple to DM, such as the standard free-streaming neutrinos [70, 71, 72]. Current CMB, BAO and Ly-α data allow to probe models that have been suggested to solve cosmological tensions, potentially excluding a large part of the parameter space depending on the scaling of the interaction rate with redshift [26, 73, 74].

3 Expected improvements

The next decade will see the development of an extensive experimental program to improve over current observations of the CMB and LSS that we will discuss below. The IN2P3 should continue taking part in these efforts, and support the theoretical development necessary to interpret the data and perform searches for new physics.

3.1 Improving known probes: CMB and LSS in the next decade

With the end of *Planck*, CMB observations are going to move from space to ground-based experiments. In particular, the privately funded Simons Observatory[2] will improve over observations from the ACT project and BICEP/Keck array, to probe many aspects of cosmology, from inflation to properties of the dark matter. Meanwhile, the CMB-S4 [3], an even more ambitious effort, has been proposed to NSF [75]. Ground-based experiment are extremely useful to improve over current small scale measurements of CMB anisotropies, in particular polarization anisotropies and lensing of the

[2] https://simonsobservatory.org
[3] https://cmb-s4.org

CMB. In a more distant future, the Japanese satellite LiteBird[4], recently accepted by JAXA, will be built to improve over the large-scale polarization measurement provided by *Planck*. A space mission is extremely complementary to ground-based one by helping with polarized foreground removal and adding cosmological information on large-scale. In the search for DM, small-scales measurement are especially interesting to probe the damping tail of the CMB power spectrum, which provides us with strong constraints on the effective number of relativistic species $N_{\rm eff}$. Additionally, an accurate measurement of the peaks position from polarization does not only constrain $N_{\rm eff}$, but also the interacting properties of the relativistic species [70, 71, 72]. In fact, species affecting the expansion rate and the evolution of perturbations in the pre-recombination era—including possible solutions to the Hubble tension [76, 77]—can be better probed by polarization than temperature, at equal signal-to-noise ratio [78]. Finally, large-scale polarization measurements are the cleanest way to probe gravitational waves imprint on CMB B-modes from a non-zero tensor-to-scalar ratio r, because small-scales measurement rely on a good knowledge of the dust and E-mode lensing contribution. Moreover, E-mode measurements on large-scales are able to better constrain e.m. energy injection and therefore the DM annihilation or decay rate [12]. For instance, a satellite like CoRE, proposed to ESA in 2017 [79, 80], could improve over current constraints by up to an order of magnitude. On the other hand, the first high-signal-to-noise measurements of CMB polarization and lensing on ∼arcmin angular scales—to be delivered by the next-generation CMB experiments—enable a leap in sensitivity to DM scattering cross sections by up to *several orders of magnitude* beyond *Planck* [81, 82, 83, 84]. Spectral distortions in conjunction with power suppression in CMB anisotropy in future data could yield robust evidence for DM physics, in particular DM-baryon scattering, taking place in the very early Universe. Future measurements that can detect a fractional distortion of order $\sim 10^{-8}$ would be sensitive to interacting DM particles as massive as ~ 1 GeV [58]. For all these reasons, it is essential that IN2P3 joins the international efforts for improvement of CMB observations.

The IN2P3 is already involved in the next-generation surveys of galaxy, namely the LSST project and EUCLID satellite, which have both DE and DM studies among their key science cases. While we address the reader to the dedicated contribution for more details [. . .], we emphasize that most of these efforts rely on improved modeling of non-linear evolution of small scales [85]. It is therefore essential to support theoretical developments in these fields, especially in the context of non-standard cosmologies, which are largely unexplored. Future joint analyses with high-precision CMB measurements and probes that have orthogonal systematic uncertainties will help mitigating associated uncertainties.

3.2 A new probe: the 21 cm window

The next decade will also see the beginning of a new era in cosmology through measurements of the hyperfine 21-cm line in atomic hydrogen. First, the 21 cm signal will allow to probe the cosmic era from the Dark Ages to Reionization, i.e. $200 > z > 10$, far beyond galaxy surveys. Second, together with other line-intensity mapping (LIM) technique, it can be used to measure the BAO as far back as the epoch of reionization and test the nature of the dark sector [86, 87, 88].

The intensity of the 21-cm signal is proportional to the difference between the temperature of the gas (i.e., baryons) and of the CMB, as well as proportional to the neutral hydrogen fraction, therefore capturing the thermal history at these redshifts. As we have discussed, new physics in the dark sector can alter the temperature of baryons and the ionization level of the gas. The sky-averaged signal and its fluctuations are both sensitive to this effect. In fact, it is known since more than a decade that 21 cm is affected by any new energy injection in the post-recombination Universe, likely surpassing the sensitivity of the CMB anisotropy to the same processes [89, 90, 91, 92, 12, 93]. This is illustrated in the context of decaying particles in fig. 1. Recently, the EDGES experiment [21] announced the first detection the cosmological global 21 cm signal, in the form of an absorption profile centered at 78 MHz (i.e., $z \sim 17$). Surprisingly, the claimed best-fit amplitude is more than twice the maximum allowed in ΛCDM, possibly indicating the presence of an interaction between one component of DM and baryons [94, 22, 95, 23, 96]. Such a late-time scattering scenario arises, for example, in a simple model where some DM particles carry a small electric charge and exhibit Coulomb-like interactions ("millicharged" DM) [97, 98]. This is an excellent example of the complementarity between various

[4] http://litebird.jp/eng/

detection techniques, since this scenario is challenging to test in direct detection experiments [99], while being subject to tight CMB and astrophysical bounds [22, 100, 101].

Regardless of the validity of EDGES detection, numerous experiments such as HERA [5] and SKA [6] are (or will be) attempting at measuring the 21 cm signal. The difficulty for DM searches consist in accurately modeling the impact of astrophysical sources on the 21 cm signal. Indeed, the first generation of cosmological 21 cm signal measurement will focus on the redshift window $10 < z < 30$, corresponding to the era of reionization, for which our current understanding is very poor. Fortunately, the 21 cm signal is so sensitive to the gas thermal history that, despite the strong existing constraints, there exists a certain number of "smoking-gun" effect that could unambiguously tell us about DM properties, such as a signal observed "in emission" rather than "in absorption". If no unambiguous signals are detected, advances will require a sufficiently accurate treatment of the interplay of stellar and exotic sources. This is a complicated task and a long term goal, but certainly deserves further investigations. In that respect, theoretical efforts will be essential to fully exploit the tremendous capacities of the 21 cm window, for instance through refined numerical simulation (such as 21cmFAST [102, 103, 104]), or development of tools for multi-messenger analysis (e.g. with CMB data or Quasars Ly-α forest). Additionally, LIM surveys such as SphereX [7] and Tianlai [8] will provide very precise measurements of the BAO after reionization, allowing to independently test the nature of the dark sector. We recommend that the IN2P3 takes part in this effort, at least providing support to the required theoretical and simulation studies.

4 Conclusion and recommendations

The next decade of observations is going to be crucial for searches of new physics in the dark sector, which over the last decades has been discovered to dominate cosmological evolution. If the past generation of instruments have brought the evidences for DE and DM on solid basis, the next-generation of CMB and galaxy surveys will reach sufficient sensitivity to potentially uncover DE departures from a simple cosmological constant, or DM effects below present-day searches, possibly involved in the resolution of some of the existing tensions. Moreover, the 21 cm signal will open a window still unexplored on the cosmic history. The combination of all cosmological probes at hand will be essential to make use of the full potential of each dataset and robustly ensure the detection of non-trivial properties of the dark sector. On the observational side, we recommend that IN2P3 promotes the next-generation measurements of CMB polarization anisotropy and lensing, keeps its involvement in next-generation surveys of large-scale structure and near-field cosmology (Galaxy surveys and Lyman-α forest), and does not miss the opening frontier of the cosmological 21cm measurements. On the theoretical side, we believe that IN2P3 should support effort for high-accuracy theoretical predictions, in particular through simulation and modeling of non-linearities in cosmologies beyond ΛCDM. Additionally, understanding baryonic systematic uncertainties in DM-related inference will be essential to exploiting the full capacities of the surveys. Last but not least, we think that our best shot to shed light on the nature of the dark sector is to support the development of frameworks for joint analyses of cosmological and other probes, in particular those off the most beaten paths.

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