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Snowmass2021 - Letter of interest cosmology intertwined I: Perspectives for the next decade

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A B S T R A C T

The standard Λ Cold Dark Matter cosmological model provides an amazing description of a wide range of astrophysical and astronomical data. However, there are a few big open questions, that make the standard model look like a first-order approximation to a more realistic scenario that still needs to be fully understood. In this Letter of Interest we will list a few important goals that need to be addressed in the next decade, also taking into account the current discordances present between the different cosmological probes, as the Hubble constant H_0 value, the $\sigma_8 S_8$ tension, and the anomalies present in the Planck results. Finally, we will give an overview of upgraded experiments and next-generation space-missions and facilities on Earth that will be of crucial importance to address all these questions.

The big questions and goals for the next decade – The standard Λ Cold Dark Matter (ΛCDM) cosmological model provides an amazing description of a wide range of astrophysical and astronomical data. Over the last few years, the parameters governing ΛCDM have been constrained with unprecedented accuracy by precise measurements of the cosmic microwave background (CMB) [1,2]. However, despite its incredible success, ΛCDM still cannot explain key concepts in our understanding of the universe, at the moment based on unknown quantities like Dark Energy (DE), Dark Matter (DM) and Inflation. Therefore, in the next decade the first challenges would be to answer the following questions:

- What is the nature of dark energy and dark matter?
- Did the universe have an inflationary period? How did it happen? What is the level of non-gaussianities?
- Does gravity behave like General Relativity even at horizon size scales? Is there Modified Gravity?
- Do we need quantum gravity, or an unified theory for quantum field theory and General Relativity?
- Is the universe flat, open or closed?
- What is the age of the universe?
- Do we actually need physics beyond the Standard Model (SM) of particle physics?
- For each elementary particle, there is an antiparticle that has exactly the very same properties but opposite charge. Then, why we do not see antimatter in the universe?
- Will the swampland conjectures of string theory help with fine-tuning problems in cosmology? Alternatively, will cosmology help us observationally test conjectures from string theory?

The ΛCDM model can therefore be seen as an approximation of a more realistic scenario that still needs to be fully understood. However, since the ΛCDM model provides an extremely good fit of the data, deviations from the model are not expected to be too drastic from the phenomenological point of view, even if they can be conceptually really different. In particular, discrepancies with different statistical significance between observations at early and late cosmological time may involve the addition of new physics ingredients [3] in the ΛCDM minimal model. For this reason, it is timely to investigate the $> 4\sigma$ Hubble constant tension [4], the $\sim 3\sigma$ tension in the amplitude of mass fluctuations σ_8 (or closely related parameter S_8) [5], as well as several oddities in the Planck results that have to do with the excess of the lensing signal and nonzero spatial curvature [6]. In the next decade we aim to address these discrepancies solving the following key questions:

- What is the origin of the sharpened tension in the observed and inferred values of H_0, $f\sigma_8$, and S_8?
- Is it possible that some portion of the tension may still be systematic errors in the measurements?
- Is the tension a statistical fluke or is it pointing to new physics?
- Is it possible to explain the tension without changing the standard ΛCDM cosmology?
- Is there underlying new physics that can accommodate this tension?

In order to address all the open questions, and to change the ΛCDM from an effective model to a physical model, the goals for the next decade will be to:

- improve our understanding of systematic uncertainties;
- maximize the amount of information that can be extracted from the data by considering new analysis frameworks and exploring alternative connections between the different phenomena;
- improve our understanding of the physics on non-linear scales;
- de-standardize some of the ΛCDM assumptions, or carefully label them in the survey analysis pipelines, to pave the road to the beyond-ΛCDM models tests carried out by different groups.

This agenda is largely achievable in the next decade, thanks to a coordinated effort from the side of theory, data analysis, and observation. In separate LoI's [4–6] we provide a thorough discussion of these challenging questions, showing also the impossibility we have at the moment of solving all the tensions at the same time.

Stepping up to the new challenges – The next decade will provide a compelling and complementary view of the cosmos through a combination of enhanced statistics, refined analyses afforded by upgraded experiments, and next-generation space-missions and facilities on Earth:

- Local distance ladder observations will achieve a precision in the H_0 measurement of 1% [7].
- Gravitational time delays will reach a $\sim 1.5\%$ precision in H_0 without relying on assumption on the radial mass density profiles [8] with resolved stellar kinematics measurement from JWST or the next generation large ground based extremely large telescopes (ELTs).
- CMB-S4 will constrain departures from the thermal history of the universe predicted by the SM [9,10]. The departures are usually conveniently quantified by the contribution of light relics to the effective number of relativistic species in the early Universe, $N_{\rm eff}$ [11]. CMB-S4 will constrain $\Delta N_{\rm eff} \leq 0.06$ at the 95% confidence level allowing detection of, or constraints on, a wide range of light relic particles even if they are too weakly interacting to be detected by lab-based experiments [9].
- The Euclid space-based survey mission [12] will use cosmological probes (gravitational lensing, baryon acoustic oscillations (BAO) and galaxy clustering) to investigate the nature of DE, DM, and gravity [13].
- The Rubin Observatory Legacy Survey of Space and Time (LSST [14]) is planned to undertake a 10-year survey beginning in 2022. LSST will chart 20 billion galaxies, providing multiple simultaneous probes of DE, DM, and ΛCDM [15–17].
- The Roman Space Telescope (formerly known as WFIRST [18]) will be hundreds of times more efficient than the Hubble

Space Telescope, investigating DE, cosmic acceleration, exoplanets, cosmic voids.

- The combination of LSST, Euclid, and WFIRST will improve another factor of ten the cosmological parameter bounds, allowing us to distinguish between models candidates to alleviate the tensions.
- The Square Kilometre Array (SKA) will be a multi-purpose radio-interferometer, with up to 10 times more sensitivity, and 100 times faster survey capabilities than current radio-interferometers, providing leading edge science involving multiple science disciplines. SKA will be able to probe DM properties (interactions, velocities and nature) through the detection of the redshifted 21 cm line in neutral hydrogen (HI), during the so-called Dark Ages, before the period of reionization. SKA will also be able to test the DE properties and the difference between some MG and DE scenarios by detecting the 21 cm HI emission line from around a billion galaxies over 3/4 of the sky, out to a redshift of $z \sim 2$.
- CMB spectral distortions will be an avenue to test a variety of different cosmological models in the next decade [19], with applications ranging from non-standard inflationary scenarios and beyond the SM physics [20] to the H_0 tension [21,22] (see also [23,24] for recent reviews);
- $O(10^5)$ voids will be detected in upcoming surveys; they can constrain the expansion history of the universe [25] following a purely geometric approach, and distinguish different gravity models [26].
- Gravitational wave (GW) coalescence events would provide a precise measurement of H_0 [27,28]. The LIGO-Virgo network operating at design sensitivity is expected to constrain H_0 to a precision of $\sim 2\%$ within 5 years and 1% within a decade [29]. Moreover, in [30] it is shown that even in absence of an electromagnetic counterpart, it is possible to measure H_0 by cross-correlating with a clustering tracer, such as a galaxy survey. Therefore, black hole binaries should provide a competitive H_0 estimate [31].
- CERN's LHC experiments ATLAS and CMS will provide complementary information by searching for the elusive DM particle and hyperweak gauge interactions of light relics [32–35]. In addition, the ForwArd Search ExpeRiment (FASER) will search for light hyperweakly-interacting particles produced in the LHCs high-energy collisions in the far-forward region [36–38].

Concluding, the current tensions and discrepancies among different measurements, in particular the H_0 tension may be offering offer crucial insights in our understanding of the universe. For example, the standard distance ladder result has many steps in common with the discovery of the accelerating universe (which gave cosmology the evidence for DE). So whatever the definite resolution of the tensions happens to be, and whether it involves galaxies and their evolution, DE, or something else, it is going to have far-reaching consequences for cosmology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Planck Collaboration, Y. Akrami, et al., Planck 2018 results. I. Overview and the cosmological legacy of Planck, 1807.06205[astro-ph.CO]
[2] Planck Collaboration, N. Aghanim, et al., Planck 2018 results. VI. Cosmological parameters, 1807.06209 [astro-ph.CO].
[3] L. Verde, T. Treu, A. Riess, Tensions between the early and the late universe, 7, 2019, 1907.10625 [astro-ph.CO]
[4] E.D. Valentino, et al., Cosmology intertwined II: the hubble constant tension, 2008.11284 [astro-ph.CO]
[5] E.D. Valentino, et al., Cosmology intertwined III: $f\sigma_8$ and s_8, 2008.11285 [astro-ph.CO]
[6] E.D. Valentino, et al., Cosmology intertwined IV: the age of the universe and its curvature, 2008.11286 [astro-ph.CO]
[7] A.G. Riess, W. Yuan, S. Casertano, L.M. Macri, D. Scolnic, The accuracy of the hubble constant measurement verified through Cepheid amplitudes, Astrophys. J. 896 (2) (2020) L432005.02445 [astro-ph.CO].
[8] S. Birrer, T. Treu, TDCOSMO v: strategies for precise and accurate measurements of the hubble constant with strong lensing, 2008.06157 [astro-ph.CO].
[9] K. Abazajian, et al., CMB-s4 science case, reference design, and project plan, 1907.04473 [astro-ph.IM].
[10] K. Abazajian, et al., CMB-s4 decadal survey APC white paper, Bull. Am. Astron. Soc. 51 (7) (2019) 2091908.01062 [astro-ph.IM].
[11] G. Steigman, D. Schramm, J. Gunn, Cosmological limits to the number of massive leptons, Phys. Lett. B 66 (1977) 202–204.
[12] Euclid Collaboration, R. Laureijs, et al., Euclid definition study report, 1110.3193 [astro-ph.CO]
[13] S. Capozziello, M. De Laurentis, Extended theories of gravity, Phys. Rept. 509 (2011) 167–3211108.6266 [gr-qc].
[14] v.Z. Ivezić, et al., LSST Collaboration, LSST: from science drivers to reference design and anticipated data products, Astrophys. J. 873 (2) (2019) 1110805.2366 [astro-ph].
[15] LSST Science, LSST Project Collaboration P.A. Abell, et al., LSST science book, version 2.0,. 0912.0201 [astro-ph.IM].
[16] H. Zhan, J.A. Tyson, Cosmology with the large synoptic survey telescope: an overview, Rept. Prog. Phys. 81 (6) (2018) 0669011707.06948 [astro-ph.CO].
[17] V. Sahni, A. Starobinsky, Reconstructing dark energy, Int. J. Mod. Phys. D 15 (2006) 2105–2132astro-ph/0610026.
[18] R. Akeson, et al., The wide field infrared survey telescope: 100 hubbles for the 2020s, 1902.05569 [astro-ph.IM].
[19] J. Chluba, et al., Spectral distortions of the CMB as a probe of inflation, recombination, structure formation and particle physics: Astro2020 science white paper, Bull. Am. Astron. Soc. 51 (3) (2019) 1841903.04218 [astro-ph.CO].
[20] J. Chluba, et al., New horizons in cosmology with spectral distortions of the cosmic microwave background, 1909.01593 [astro-ph.CO].
[21] M.H. Abitbol, J.C. Hill, J. Chluba, Measuring the hubble constant from the cooling of the CMB monopole, 1910.09881 [astro-ph.CO].
[22] M. Lucca, The role of CMB spectral distortions in the hubble tension: a proof of principle, 2008.01115 [astro-ph.CO].
[23] A. Kogut, M. Abitbol, J. Chluba, J. Delabrouille, D. Fixsen, J. Hill, S. Patil, A. Rotti, CMB spectral distortions: Status and prospects, 1907.13195 [astro-ph.CO].
[24] M. Lucca, N. Schöneberg, D.C. Hooper, J. Lesgourgues, J. Chluba, The synergy between CMB spectral distortions and anisotropies, JCAP 02 (2020) 0261910.04619 [astro-ph.CO].
[25] N. Hamaus, A. Pisani, J.-A. Choi, G. Lavaux, B.D. Wandelt, J. Weller, Precision cosmology with voids in the final BOSS data, JCAP 12 (2020) 0232007.07895 [astro-ph.CO].
[26] J. Zhang, B.R. Dinda, M.W. Hossain, A.A. Sen, W. Luo, A study on cubic Galileon gravity using N-body simulations, Phys. Rev. D 102 (4) (2020) 0435102004.12659 [astro-ph.CO].
[27] B.F. Schutz, Determining the hubble constant from gravitational wave observations, Nature 323 (1986) 310–311.
[28] B.P. Abbott, et al., LIGO ScientificVirgo, 1M2H, Dark Energy Camera GW-E, DES, DLT40, Las Cumbres Observatory, VINROUGE, MASTER Collaboration, A gravitational-wave standard siren measurement of the hubble constant, Nature 551 (7678) (2017) 85–881710.05835 [astro-ph.CO].
[29] H.-Y. Chen, M. Fishbach, D.E. Holz, A two per cent hubble constant measurement from standard sirens within five years, Nature 562 (7728) (2018) 545–5471712.06531 [astro-ph.CO].
[30] S. Mukherjee, B.D. Wandelt, Beyond the classical distance-redshift test: cross-correlating redshift-free standard candles and sirens with redshift surveys, 1808.06615 [astro-ph.CO].
[31] S. Mukherjee, B.D. Wandelt, S.M. Nissanke, A. Silvestri, Accurate and precision cosmology with redshift unknown gravitational wave sources, 2007.02943 [astro-ph.CO]
[32] O. Buchmueller, C. Doglioni, L.T. Wang, Search for dark matter at colliders, Nat. Phys. 13 (3) (2017) 217–2231912.12739 [hep-ex].
[33] B. Penning, The pursuit of dark matter at colliders—an overview, J. Phys. G 45 (6) (2018) 0630011712.01391 [hep-ex].
[34] X.C. Vidal, et al., Report from working group 3, Beyond the Standard Model physics at the HL-LHC and HE-LHC 7 (2019) 585–8651812.07831 [hep-ph]. 12
[35] L.A. Anchordoqui, Hubble hullabaloo and string cosmology, 2020, 52005.01217 [astro-ph.CO].
[36] FASER Collaboration A. Ariga, et al., Technical proposal for FASER: forward search experiment at the LHC, 1812.09139 [physics.ins-det].
[37] FASER Collaboration A. Ariga, et al., FASER: forward search experiment at the LHC, 1901.04468 [hep-ex].
[38] J.L. Feng, FASER and the search for light and weakly interacting particles, Astrophys. Space Sci. Proc. 56(2019) 69–75.