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Reaching the boundaries of general relativity: Tensions in Cosmology

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The standard concordance model has successfully explained all cosmological survey data for over two decades with unprecedented precision. However, our understanding of cosmology appears to be at a turning point in that predictions from the standard cosmological model from different surveys seem to give best-fit cosmological parameters that are in tension with each other. This may be due to systematics in our understanding of the underlying astrophysics for particular sectors. However, it may also be an indication of new physics in one or more cosmological sectors.

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1. Introduction

Cosmology is currently in an era of unique importance where the volume of observational data and the level of foundational development has brought the prospect of a turning point in the standard model of cosmology and with it potential novel explanations of critical components in our description of the Universe. The abundance of observational measurements, coupled with the depth of these observations and the precision of the information that comes with this opens the way for new and more in-depth explanations of the cosmos, together with its structure, evolution, and composition. On the other hand, these advancements have also brought new questions with significant new tensions between parameter inferences using measurements from the early- and late-Universe, which has led to new challenges for the concordance model. Beyond possible systematic errors, these observational measurements indicate the need for possible new physics beyond the standard model of cosmology, and with this, new insights into the fundamental evolution of the Universe.

The standard model of cosmology describes the Universe through a cosmological constant Λ, cold dark matter (CDM), and gravitational through Einstein's general theory of relativity (GR), or ΛCDM. This has provided decades of agreement between a large range of cosmological datasets, including multiple probes of the cosmic microwave background (CMB), large-scale structure, and other astrophysical observations. In recent years, the statistical tension between ΛCDM parameter inference using CMB, and other early-time measurements, and large-scale structure or astrophysical, and other late-time measurements, has become a significant challenge to explain. The most prominent of these is the Hubble constant tension (H_0), while differences in the amplitude of matter fluctuations (through the S_8 parameter, and others) have also been significant, as well as differences in inferred values of the sound horizon at the epoch of baryonic acoustic oscillations (BAO).

Important questions about the foundations of ΛCDM and our understanding of the Universe are raised by the increasingly robust nature of some of these tensions, including our explanations of the evolution of the Universe, its history of structure formation, and the fundamental nature of dark matter (DM) and dark energy (DE). Provided systematic errors do not dampen these tensions, they may indicate the necessity to go beyond the standard model of cosmology and establish a new concordance model of the Universe. This will entail the careful consideration of both observational data through multiple cosmological probes and the development of new theoretical explanations through these exhaustive statistical treatments.

2. Cosmological tensions

The most robust cosmological tension emerges in recent measurements of H_0 where the expansion rate measured by direct methods and those inferred from early-time observations have continually grown distinct from one another with a statistically significant discrepancy in their values. These challenges to the ΛCDM model motivate the need for new physics. Here, early-time measurements started to more concretely diverge from local measurements with the *Planck* satellite where CMB anisotropy maps have provided precise inferences of the Hubble constant with $H_0 = 67.4 \pm 0.5\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$[4]. Principally, the result assumes a flat ΛCDM cosmology which allows angular scale of the acoustic peak measurements in the CMB power spectra to be used to infer this value of H_0. More recently, the Atacama Cosmology Telescope (ACT) has confirmed this lower value of the Hubble constant giving $H_0 = 68.22 \pm 0.36\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$[59] which comes from the sixth data release of the collaboration and its largest map of the sky. Another important ground-based detector is the South Pole Telescope (SPT) which also infers a similar value of the Hubble constant using partial sky maps giving $H_0 = 66.66 \pm 0.60\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$[23]. Collectively, the robustness of this lower value of H_0 inferred from CMB experiments assuming the concordance model appears to be as a consensus measurement.

These low values of H_0 partially depend on inferred value of the sound horizon based on a ΛCDM cosmology. Another key probe with the same underlying dependency are BAOs which depend intrinsically on the characteristic scale imprinted by sound waves in the early Universe and their transfer to the evolution of the large scale structure of the Universe later on. This anchor enables precise measurements of distance at various redshifts based on this standard ruler. Numerous surveys have inferred BAO constraints on H_0 consistent with CMB values including BOSS, eBOSS and DESI. In fact the latest DESI results give a constraint of $H_0 = 68.17 \pm 0.28\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$when calibrated with *Planck* on the sound horizon [2].

In the local Universe, late-time measurements of the Hubble constant prefer a much higher value of H_0 as compared with the early Universe together with a flat ΛCDM cosmology. This is the core tension in the cosmic tensions paradigm. One of the best direct measurement of the Hubble constant relies on building a distance ladder based on three consecutive distance-based parts, namely: (1) calibrating the luminosities of Cepheid variable stars using *geometric* distance measurements based on Gaia parallaxes, detached eclipsing binaries, and water masers; (2) building standard candle type 1a supernovae (SNIa) measurements using calibrated Cepheid variables with the Hubble Space Telescope (HST); and (3) measuring H_0 using SNIa deep in the Hubble flow where cosmic expansion dominates over peculiar effects.

The precision of constraints on H_0 based on this distance ladder are only possible due to the Period-luminosity relation, or Leavitt law, which establishes a proportionality of the pulsation period and apparent brightness. Following years of work, systematic uncertainties including metallicity, crowding effects, and dust extinction are mitigated through near-infrared photometry. The SH0ES team gives a constraint of $H_0 = 73.17 \pm 0.86\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$[21] using this method, giving an approximately 5.8σ tension with *Planck* CMB estimates. Observations of Cepheids based on James Webb Space Telescope (JWST) appear to validate Cepheid observations with further refinements on crowding effects, while also validating the robustness of the Hubble tension.

SNIa measurements give the strongest far field rung of the distance ladder stretching deep into the Hubble flow. The Pantheon+ dataset gives a consistent picture of this setting which estimates $H_0 = 73.5 \pm 1.1\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$[22] when anchored using local distance measurements from SH0ES. Another important recent analysis of SNIa data is the Dark Energy Survey (DES) 5-year sample which was recently reanalyzed with further improvements on systematics, called the DES-Dovekie, which when combined with *Planck* CMB (assuming a flat ΛCDM cosmology) gives a value of $H_0 = 67.29 \pm 0.34\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$[73]. Besides confirming the presence of cosmic tensions, this validates a broad segment of the analysis pipeline for SNIa.

Beyond SNIa, new standard candles have been studied including tip of the red giant (TRGB), Mira variables, J-region asymptotic giant branch (JAGB), type 2 supernovae (SNe II), surface brightness fluctuations (SBF), and baryonic Tully-Fisher relation methods, and others. These independent methods provide new avenues to establish standard candles and cross-check SNIa estimates. Indeed, these methods individually show consistency with the higher value of H_0 reported by the SH0ES team and others. Recently, these methods have been interwoven to provide a consensus measurement of $H_0 = 73.50 \pm 0.81\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$which is now in 7.1σ tension with CMB estimates (Planck+SPT+ACT) assuming flat ΛCDM. Removing the dependence on any singular measurement of the Hubble constant, speaks to the robustness of the final result.

On the individual methods that establish a standard candle, TRBG is based on an abrupt turning point in the luminosity of red giant branch stars where they start to ignite helium. These standard candles are calibrated with near galaxies such as the Magellanic Clouds and NGC 4258 in order to provide accurate measurements of distance, while they are minimally exposed to possible metallicity systematics. This method has been reported to produce $H_0 = 75.3 \pm 2.9\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$[68] where the Zwicky Transient Facility was used.

Another important method for accurately measuring the Hubble constant is through the use of Mira variable stars which are long period pulsating stars. This makes their period to luminosity relation particularly reliable. Mira variables are similarly calibrated using the Large Magellanic Cloud and NGC 4258, and also are not very sensitive to metallicity or crowing effects. By replacing Cepheids, Mira variables can produce an estimate of $H_0 = 72.37 \pm 2.97\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$when combined with SNIa [49].

The asymptotic giant branch provides a reliable J-region through JAGBs which can be used as a standard candle due to their narrow luminosity range in the near-infrared. These carbon-rich stars provide robust distance measurements due to their stage of stellar development. By first calibrating their distances using near galaxies such as NGC 4258, JAGB can give constraints of $H_0 = 73.3 \pm 2.4\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$when combined with SNIa.

Alternatively, the SBF method does not rely on Cepheids or SNIa at all and instead establishes an estimate of the Hubble constant using luminosity variations for elliptical galaxies. Recent constraints using JWST data give $H_0 = 73.8 \pm 2.4\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$[52]. A method that bypasses the distance ladder altogether uses SNe II where their luminosity and decline rate are correlated during their plateau phase to get constraints on the Hubble constant. Recent studies report a value of $H_0 = 74.9 \pm 1.9\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$[86].

On the distance ladder, Baryonic Tully-Fisher relation (BTFR) where the rotational curve velocities and baryonic mass are related together is a method that has been used to estimate the Hubble constant with high accuracy. This is particularly the case at low redshift where zero-point errors can have be overly impactful. Recent measurements have produced $H_0 = 76.3 \pm 2.6\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$using Cepheid and TRGB calibration techniques [78]. Going beyond distance ladder approaches, masers give an intriguing way to bypass the distance ladder where the technique relies on using H_2O maser emissions from disks rotating about supermassive black holes in order to directly measure distances. The Megamaser Cosmology Project has used this approach to establish the constraint $H_0 = 73.9 \pm 3.0\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.

Supermassive black holes are also the drivers of quasars which have recently been used competitively to estimate values of the Hubble constant using strong lensing effects. By comparing multiple images of a source being lensed by a foreground galaxy, the time delay between these images propagating through different paths can be used to estimate the source distance and therefore a value of the Hubble constant. The H0LiCOW and TDCOSMO collaborations have used this method, giving recent measurements of $H_0 = 75.7^{+8.1}_{-5.5}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$[70]. Along similar lines, gravitational waves (GWs) provide a way to estimate the Hubble constant independent of other methods. In this scenario, GWs produce standard sirens by estimating the luminosity distance to compact object merger events. For instances where an electromagnetic counterpart is also measured, the redshift of these events can be measured directly. This method continues to be developed and currently gives constraints in the range of $H_0 = 75.46^{+5.34}_{-5.39}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$[69].

Alternatively, fast radio burst (FRB) signals are extragalactic while also having a large dispersion measure that increases with redshift. This allows FRBs to be used to probe cosmological parameters. The method can give constraints in the range of $H_0 = 76.16^{+2.48}_{-2.89}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$[53].

On the other hand, by comparing the differential aging of passively evolving galaxies, cosmic chronometers can be used to infer a value of the Hubble constant without relying on standard candles at all. These estimates instead rely on the modelling of stellar populations including their metallicity and star formation history. This method is more exposed to astrophysical systematics. Indeed, recently measurements have achieved constraints of $H_0 = 71.5 \pm 3.1\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$[34]. Staying with purely astrophysical measures of the Hubble constant, HII galaxies have bright ionized hydrogen regions that can be used as standard candles in order to establish estimates of their distance. This depends on the correlation between their luminosity and emission line flux from young massive stars in this region. Estimates from this method give $H_0 = 71.0 \pm 3.5\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$[37].

Finally, the Dark Energy Spectroscopic Instrument (DESI) has resulted in new ways to measure the Hubble constant with different ways in which to calibrate the underlying BAO data based on 14 million galaxies and quasar data. An interesting method in which to anchor the BAOs is to use the fundamental plane relation of early-type galaxies and calibrate their distances using the Coma cluster. By using a distance to the Coma cluster of 98.5 ± 2.2 Mpc, which is based on SNIa, DESI data can achieve constraints in the range $H_0 = 76.5 \pm 2.2\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$[79]. This estimate highlights the significant tension between estimates of H_0 where *Planck* measurements would place the Coma cluster at a distance in excess of 110 Mpc whereas historically this has been < 100 Mpc.

Great efforts have gone into the development of different and distinct methodologies to confront the problem of the Hubble tension. Despite these efforts, the statistical robustness of early- and late-time measurements of H_0 persist at over 5σ significance. As more methods mature and the precision of present methods grows, the possibility of new physics becomes more of a reality where elements of ΛCDM cosmology may need to be revised.

The Hubble tension is the statistically strongest expression of observational tensions in ΛCDM. Another related parameter is the sound horizon which also appears to have a discrepancy in reported values from different data sets. The comoving sound horizon tension refers to the radius of this scale at the end of the drag epoch, r_s^{drag}, as inferred from early- and late-time data sets. This parameter provides a crucial standard ruler for distance calibration in the Universe. In the early Universe, this determines the way in which acoustic oscillations in the photon-baryon plasma relate to each other before recombination. In the early Universe, this is primarily inferred from CMB power spectra where *Planck* gives a measure of $r_s^{\mathrm{drag}} \approx 147.09 \pm 0.26$ Mpc [4]. Late-time measurements where BAO data is anchored with local distance ladder measurements suggest lower values of the sound horizon with tensions in the range of $2-3\sigma$ significance.

The comoving sound horizon is directly related to the expansion rate at recombination and the angular scale of peaks in the CMB. This means that any changes in early Universe physics will effect the value of $r_s^{\rm drag}$. Many solutions based on modifying early Universe include different recombination histories and modified comoving sound horizons. These enhanced cosmologies mostly reduce the value of $r_s^{\rm drag}$ as compared with ΛCDM. On the other hand, possible effects from these cosmologies are dampened by CMB observations. Local Universe based estimates of $r_s^{\rm drag}$ rely on BAOs that are calibrated with late-time methodologies such as distance ladder techniques based on SNIa data sets. The tension present between these estimates of $r_s^{\rm drag}$ provide an additional check on constraints from early- and late-time probes while also highlighting the potential need for new physics that modify not only the present expansion rate but also produce a broader evolution that is consistent with the spectrum of parameters that describe the Universe.

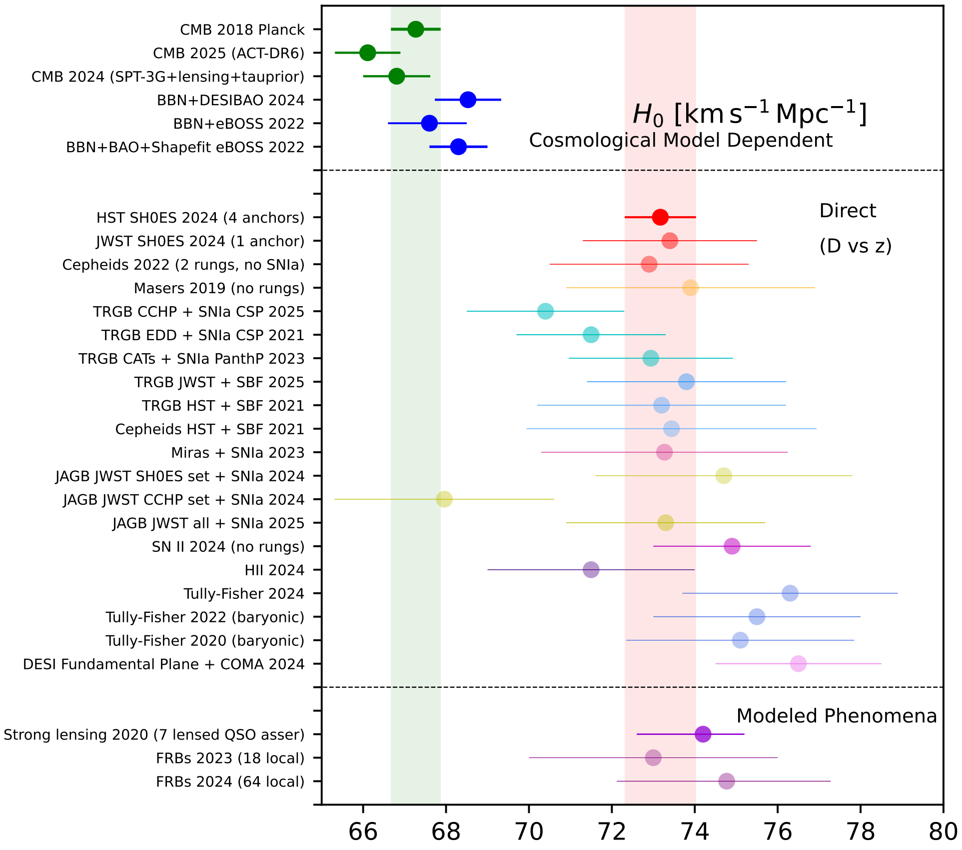

Figure 1: CosmoVerse Whisker plot showing the most precise measurements on H_0 [27].

The tension in the Hubble constant resulting from this range of different measuring techniques and approaches shows a diverse but consistent tension in the form of early- and late-time measurements, which is nuanced by those methods that involve some form of modeling in terms of the underlying astrophysics. These are represented in Fig. 1, which was produced by the CosmoVerse network as part of a consensus effort within the community [27].

The comoving sound horizon is intrinsically connected to the seeds of large scale structures initially formed in the early Universe. An interrelated but entirely separate parameter that has been reported to have a similar tension is S_8 which encapsulates the amplitude of matter perturbations on scales of $8\,h^{-1}$ Mpc. The value of this parameter appears to vary between certain surveys when measured using early- and late-time observational measurements. This parameter is defined as $S_8 := \sigma_8\sqrt{\Omega_m/0.3}$ where Ω_m is the background matter density parameter at present while σ_8 represents the clustering amplitude of matter on these scales. The S_8 cosmological parameter provides a key tool to characterize the growth of large scale structures, and is a critical parameter in the ΛCDM model.

At present, CMB based constraints on S_8 give a consistently relatively high value with *Planck* temperature and anisotropies yielding an early-time value of $S_8 = 0.834 \pm 0.016$ assuming the ΛCDM model [4] while ACT and SPT give respective constraints of $S_8 = 0.875 \pm 0.023$ [59] and $S_8 = 0.8359 \pm 0.0005$ [23]. S_8 constraints can be obtained in the local Universe by estimates on large scale structures through a variety of means including weak lensing measurements and galaxy clustering surveys. For instance, the Dark Energy Survey (DES) reports a value of $S_8 = 0.776 \pm 0.017$ for their year 3 release [1] and $S_8 = 0.776^{+0.032}_{-0.033}$ [26] for the Hyper Suprime-Cam (HSC) Year 3 Results. The Kilo-Degree Survey (KiDS) has produced intriguing results which initially agreed with lower local values of S_8 but which has reported a constraint of $S_8 = 0.815^{+0.016}_{-0.021}$ [89] in their legacy release. While lower than the H_0 tension, the S_8 tension persists at a $2-3\sigma$ statistical level across different data sets.

Unlike the tension in the Hubble constant, the S_8 tension may be driven by a variety of factors including systematics on the one hand or physics beyond ΛCDM in terms of the evolution of structure formation on the other hand. Weak lensing surveys suffer from far more complex processes making systematic uncertainties a serious concern which includes biases in shear calibration, photometric redshift estimate uncertainties, baryonic feedback effects in the suppression of the small-scale power spectrum, and others. Extensive efforts have gone into modeling these effects making the potential of physics beyond the ΛCDM model a realistic possible direction. One likely scenario here is that the equation of state parameter may be required to be time-dependent so that the growth rates changes at different cosmological epochs in time. This may be realized by modifications in the underlying description of gravity, scalar-tensor descriptions of the early Universe, among many others. Another interesting possibility is the presence of massive neutrinos which would suppress structure formation in the late Universe due to their free-streaming behavior. This would produce a lower value of the S_8 parameter.

Unlike the H_0 tension, weak lensing, CMB lensing and galaxy clustering measurements show consistency in cross-corelation measurements for both early- and late-time measurements. Similarly, varying the power spectrum normalization of the intrinsic cosmological parameters similarly does not remove the statistical tension in the measurements. Altogether, this makes the S_8 tension problem both complex and more nuanced to confront. Estimates from these probes have been collated by the CosmoVerse network as part of a consensus effort within the community [27], which are shown in Fig. 2. A resolution to the H_0, S_8 and $r_s^{\rm drag}$ tensions remains an open question that may point to the need of new physics, while also requiring more robust analysis of any and all possible underlying systematics.

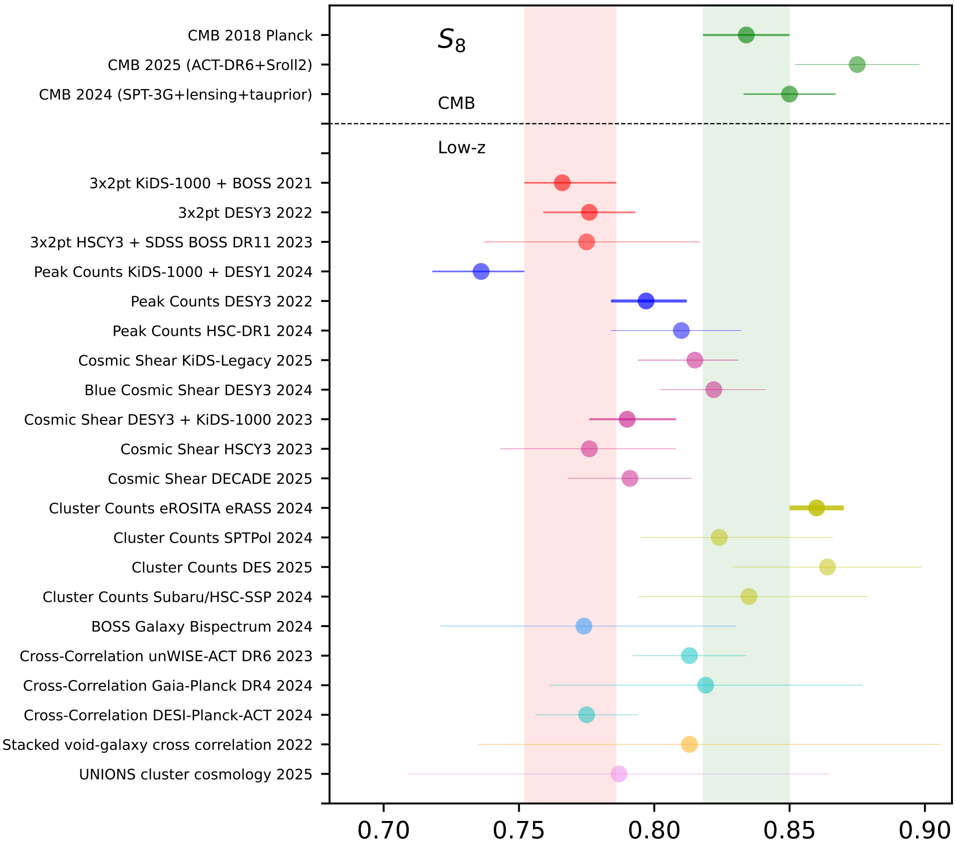

Figure 2: CosmoVerse Whisker plot showing the most precise measurements on S_8 [27].

3. Efforts at possible solutions

As the various expressions of cosmological tensions between early- and late-time surveys continues to be exposed through different data sets, the need for extensions to the standard cosmological model is becoming more pressing. There is a wide spectrum of proposed theoretical models which each take apart different aspects of the ΛCDM model with the aim of resolving the discrepancy between early- and late-time cosmological measurements. At a high level these can be categorized into disparate proposals each exploring different possible new physics scenarios, as depicted in Fig. 3.

These different branches of potential new physics scenarios can be divided into several distinct areas which have themselves been subdivided into a spectrum of various realizations of these extensions to the standard cosmological model. In keeping with the early- and late-time dichotomy, *early dark energy* (EDE) models [54, 63, 74] incorporate an additional cosmological component that dominates for a short period of time the energy budget of the Universe. This transitory epoch

Figure 3: Map of different fundamental physics scenarios beyond the ΛCDM model (reproduced from the CosmoVerse White Paper [27]).

is situated before recombination and acts to reduce the sound horizon and thus allows for a higher value of H_0. The physics of EDE involves a scalar field which activates its potential during this time and which dilutes quickly toward the end of the peak EDE era which limits the action of EDE to the early Universe. A number of different potentials and scalar field combinations have appeared in the literature where distinct evolution profiles have emerged in the field. Prominent examples include oscillatory models where scalar fields oscillate around the recombination epoch whereby energy is used to boost the cosmic expansion rate at this time [44]. Nuancing this general scheme, new early dark energy introduces a phase transition through which the scalar field quick decays physically. On the other end of the spectrum, adiabatic fluctuation EDE models moderate early-and late-time influences to better reflect the underlying data, which also introduces degeneracies of its own. Generally, EDE models provide an interesting approach to increasing the value of the Hubble constant by boosting the physics beyond the recombination epoch. However, these also introduce seemingly insurmountable challenges where the evolution of the large scale structure of the Universe is dampened creating worse tensions in the S_8 parameter. On its own, this general class of models appears to be disfavored by recent data sets, particularly when early- and late-time joint analyses are considered.

On the other end of the spectrum, there are a plethora of late-time models which attempt to augment the growing question of cosmological tensions by modifying late-time cosmic evolution [33, 40, 67]. At these low redshifts, these models by and large modify the equation of state parameter away from a cosmological constant value with an equation of state of -1. Several of these models involve a fairly rapid transition in some cosmological parameters [5–9, 42, 43, 90], while others simply inject new physics that slightly raises the value of H_0 without impacting any early-time physics. These models are frequently dampened when confronted with observational measurements due to the rich volume of data in this region.

Another interesting development in the description of the dark sector is the possible interaction of dark matter and dark energy (IDE) models [20, 30, 87] where an interaction term between dark matter and dark energy is introduced. This has an effect on the cosmological evolution of the Universe, and can allow for the exchange of energy between these sectors, which occurs through a coupling function. This can both increase or decrease the cosmic expansion rate. Interestingly, IDE can increase the value of H_0 while also modifying the growth of structure in a way that decreases the S_8 tension simultaneously. Constraints from CMB and BAO limit the strength of this coupling term and frequently need fine-tuning, but this branch remains an interesting description of possible extensions of the standard model of cosmology. IDE models are grounded in phenomenology while some attempts have been made to develop fundamental models with a robust physical basis.

Alternatively, modified gravity (MG) models [3, 10, 13, 17, 24, 88] are intrinsically foundational in nature wherein extensions to general relativity in the Einstein-Hilbert action are explored. These can introduce additional fields with extra degrees of freedom, or alter the dimensionality of spacetime, among other possibilities. MG models can effect the lensing potential, structure formation, and expansion rates of cosmological profiles which will have an impact on inferred values of H_0 and S_8. These models are most extensively studied and continue to be confronted with observational data both in the early- and late Universe. The most popular of these is $f(R)$ gravity which generalizes the Ricci scalar to an arbitrary function thereof. This can be mapped to a scalar-tensor theory so that the scalar potential becomes the unknown contribution. Scalar-tensor theories can be further generalized to Horndeski gravity models which constitute the most general second order formalism involving a singular scalar field. However, multimessenger signals have drastically limited the applicability of these models which has resulted in further explorations of this model space [16, 55, 81]. CMB and late-time data sets have also placed constraints on these classes of models. Massive and bimetric gravity models also suffer from these constraints limiting their possible expressions in terms of graviton properties. Recent developments of non-Riemannian and metric-affine gravity framework have offers entirely new platforms on which to build cosmological models which have been shown to have actions both in the early and late physics of cosmic evolution. There are a plethora of other intriguing possible MG scenarios where the emphasis remains on the development of mature and robust specific models that meet the growing demands of observational constraints.

Keeping with the idea of modifying the basic constituents of the ΛCDM model, exotic scenarios where non-standard dark matter have seen a resurgence in recent years with extensions to the standard cosmological model through non-standard physics in the dark sector experiencing renewed interest [19, 46, 58]. This includes possible decaying dark matter models, where dark species decay into lighter ones. For particles that decay about the recombination epoch, the expansion profile may be effects through the sound horizon giving higher H_0 inferred values. As in many of the other scenarios, CMB data appears to drastically limit possible models in this branch forcing these fields to be very light in nature. Along the same lines, classes of cosmological models involving extra relativistic species with neutrino physics offer another avenue at meeting the problem of cosmic tensions [14, 15, 38, 80]. A higher number of relativistic species in the early Universe correlates with a higher expansion rate and a reduced sound horizon. Light particles such as sterile neutrinos or dark radiation can produce these settings. In the case of sterile neutrinos, these can act as additional relativistic species in settings where they decoupled from standard model neutrinos early enough. These prospects remains tenuous given the wealth of CMB and other early Universe data sets.

Beyond fundamental physics, other possible explanations of the mismatch between early- and late-time measurements of some cosmological parameters may be that the Galaxy resides in a local void [64, 65, 75, 91] wherein a large underdense region of the Universe biases the constraints on several cosmological parameters. This would indeed produce larger values of H_0 while giving lower values on cosmological scales. On the other hand, the size of this volume would need to be quite large and would thus be inconsistent with present observations. Exotic explanations of this nature also include primordial magnetic fields (PMF) which would be produced before recombination and which would influence the expansion and large scale structure formation of the Universe early in the evolution of the Universe [50, 51]. This would modify the photon-baryon dynamics during recombination and thus the CMB acoustic peaks. PMFs remain limited in their possible scope when confronted with observational data.

Far earlier in the evolution of the Universe is cosmic inflation [11, 41, 41, 42, 61, 62] where a rapid expansion is undergone to tackle the horizon and flatness problems, among others, and which may take on several scenarios. Some of these inflationary scenarios may indirectly effects the late-time cosmological parameters through the initial conditions they produce. This would leave an imprint on the CMB. Saying that, the majority of inflationary models encounter challenges in changing drastically the value of the Hubble constant.

Other possible ideas include the variation of fundamental constants across the evolution profile of the Universe [60, 83, 84]. This includes the fine structure constant α, the electron mass m_e as well as the proton-to-electron mass ratio μ. The variation of these constants would directly effect estimates of key cosmological observables while also altering the sound horizon and recombination physics. These scenarios can be realized by coupling a scalar field to the electromagnetic field which would produce a varying α. Early Universe and high redshift observables have limited these possibilities but they remain impactful in their ability to alter cosmological parameter values.

Solutions have also been suggested as being expressed through some modified local physics effects which would impact the low redshift cosmology without effecting the global evolution [71].

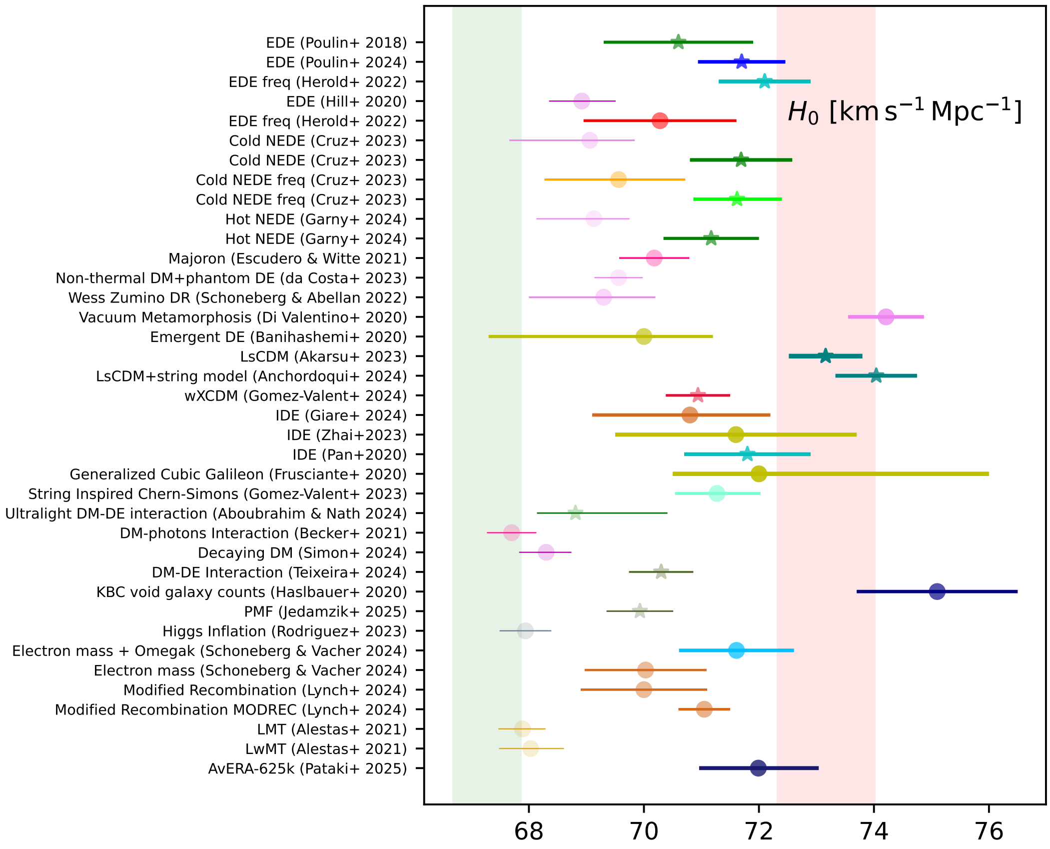

Figure 4: H_0 reported values for different modified cosmological models (reproduced from the CosmoVerse White Paper [27]).

This would impact $G_{\rm eff}$ altering the calibration of standard candles in the local Universe. Constraints from observational measurements generally fail to give a complete resolution to the cosmic tensions issue. Predictions of models from these differences branches of new physics scenaios for H_0 and S_8 values are shown in Fig. 4 and Fig. 5, respectively. It remains an open question where a specific model can be determined which predicts late-time Universe values using early-time data sets. A significant portion of the community remain engaged in probing the effect of possible systematics and other uncertainties in order to make the various realizations of cosmic tensions more robust.

4. Open questions beyond cosmic tensions

Over the decades and in recent years, a number of other questions have arisen as potential challenges to the concordance model. These anomalies and curiosities remain at a mild tension while also spanning a wide range of phenomenology and physics. The most prominent anomaly in the CMB in recent years has been the $A_{\rm lens}$ parameter which was originally introduced as phenomenological parameter to quantify extensions to the standard cosmological model. The

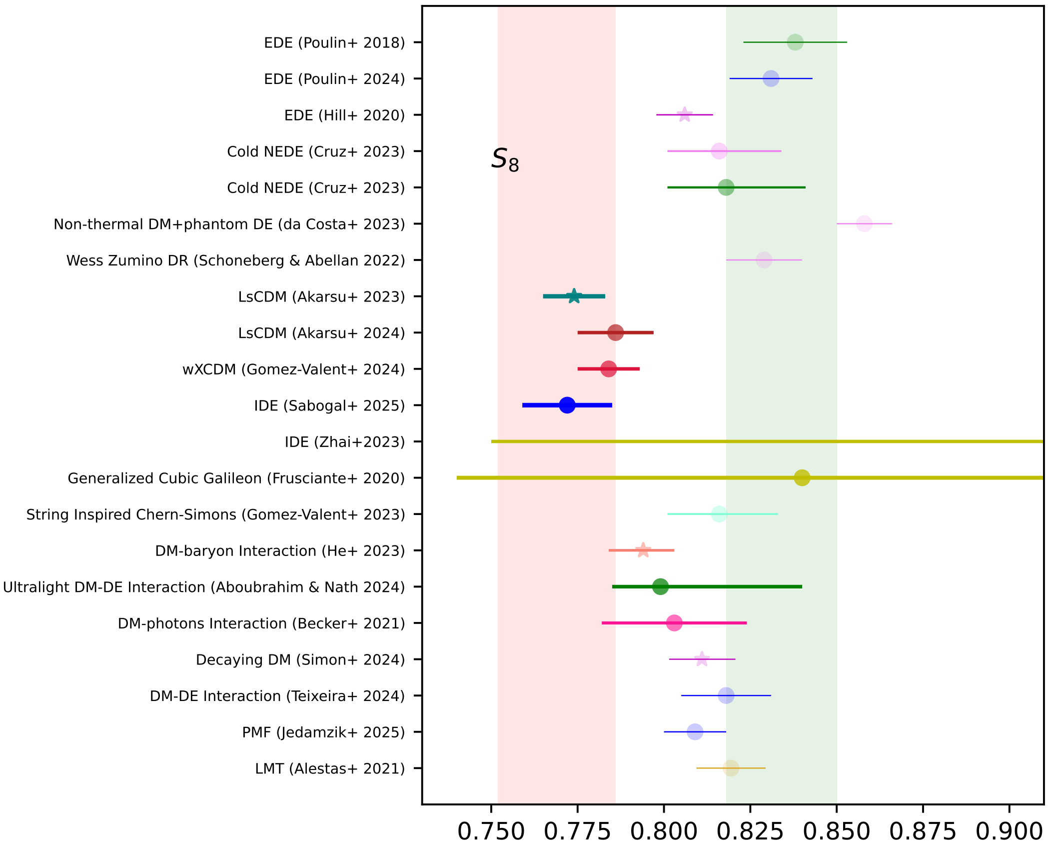

Figure 5: S_8 reported values for different modified cosmological models (reproduced from the CosmoVerse White Paper [27]).

action of $A_{\rm lens}$ is to smoothen the amplitude of lensing-induced acoustic peaks in the CMB power spectrum. *Planck* data points to a higher value than predicted by ΛCDM exposing a $2-3\sigma$ tension within the data set [4, 76]. This points to the need of new physics, or possibly further reanalysis of the underlying data set.

Probing *Planck* data further, the concordance assumption of a flat ΛCDM cosmology appears less favorable than a slightly closed Universe [4, 29]. Studies show a mild preference for $\Omega_k < 0$. This remains an open question and a disputed claim. At a similarly mild statistical level, anomalies in the anisotropy of the CMB have been reported. This includes hemispherical power symmetry, low multipoles alignment, and the cold spot anomaly, among others [72]. Cosmic variance, that is the statistical nature of measurements, may be partially responsible for this, but its persistence in multiple CMB experiments points to some new physics or common systematics.

In the late Universe, equation of state functions that parametrize potential deviations from a cosmological constant, namely $w_0 w_a$CDM already point to possible dynamical dark energy [2]. Barring a systematic, as these studies progress, the statistical robustness of the tension may go beyond

3σ in the next data release of DESI. BAO observations in the late Universe can also used to infer bounds on the sum of neutrino masses which appear to be in tension with lower bounds established by terrestrial neutrino oscillation experiments [28, 39]. These point to possible deviations from the neutrino mass hierarchy with some analyses pointing to negative neutrino masses [45]. While systematics may account for this, the possibility of new physics remains open with the neutrino sector being one of the least understood parts of the standard model of particle physics.

The CMB continues to provide a rich area where new questions may arise in a variety of ways. In fact the cosmic dipole inferred from the CMB exists in tension in that from other phenomenological probes, particularly extended QSOs [57]. This is compounded by slight variations in cosmological parameters across the sky pointing to the possibility of bulk flow anomalies or extensions to the large scale structure of the Universe. Similar points have been highlighted in the measurement of the integrated Sachs-Wolfe effect and it is connected to cosmic superstructure [66]. In the era shortly after the Big Bang, primordial nuclei began to form during Big Bang nucleosynthesis (BBN). The abundances that were produced during BBN can be probed by measuring the abundances of these elements in the earliest stars observable. Coupled with the baryon density ratio predicted by the CMB, this puts extremely accurate estimates on BBN abundances. In recent years the well known Lithium problem has exacerbated while the primordial ratio of Helium has also come into question [77]. These growing tensions point to the possible need of extensions in the concordance model during this era.

Beyond the early Universe, the intermediate, but high redshift, phase of cosmic evolution shows a mild tension in Lyman-α forest measurements when compared jointly with low redshift constraints on the matter power spectrum showing a possible indication of a mismatch in the evolution of large scale structures in the history of the Universe which would implicate differences in the thermal cosmic development [36]. On the growth of cosmic structures, cosmic voids appear to have physical properties that may contribute non-trivially to the integrated Sachs–Wolfe effect possibly indicating deviations from standard cosmology [56].

In terms of other curious observations, recent measurements of the radio background have reported an additional or excess radio background which may be linked to low flux radio sources, PMFs, some form of exotic particle decays, or some unknown systematic [25]. On a similar level, galaxy catalogs appear to infer some bulk flow anomalies possibly pointing to structures not accounted for in the standard model of cosmology [82].

The questions that these anomalies and curiosities point to require more observational data to either confirm their presence or understand the underlying systematics is causing them. The next generation of surveys from Euclid, the Rubin Observatory's Large Synoptic Survey Telescope (LSST), the Roman Space Telescope, and others will play a critical role in understanding these aspects of the standard cosmological model. This will be essential to refining which aspects of the ΛCDM model require extensions or modifications.

5. Emerging data analysis approaches

The growing plethora of cosmological models and the observational data sets on which their parameters can be estimated is growing at an unprecedented rate, pointing to the need for new approaches that are either more efficient than traditional techniques or more agnostic in their assessment of the underlying models under study. The vast majority of analyses of cosmological models involves the interface of cosmological simulators and Markov chain Monte Carlo (MCMC) techniques which are foundational tools for exploring the parameter space of these models. However, as cosmological models continue to increase in terms of their parameter space dimensionality, more sophisticated approaches are required. The appearance of parameter degeneracies and volumetric effects necessitates special treatment in some instances [48]. There have also been advances in nested sampling regimes [12] and Hamiltonian Monte Carlo approaches [47], which have improved the overall precision of parameter estimation approaches.

In recent years, there has been a growing effort to utilize the increasingly robust toolkits emerging based on machine learning (ML). This includes neural networks, Gaussian processes, decision trees and others which have either accelerated data analysis processes or refined selection criteria for physical models [32]. These methods have also been applied in a hybrid format in which MCMC is complemented by ML techniques. In these cases, the aim is to improve the performance of traditional approaches, while other approaches include novel techniques such as the reconstruction of underlying physics using observational data. This inverts the traditional approach of inferring model parameters and rather infers the nature of different physical models. This approach has been applied to the reconstruction of the expansion and growth profiles of the Universe, as well as to the growth of cosmological large scale structures [31, 85].

An interesting approach that has been introduced centers on the use of bio-inspired algorithms such as genetic algorithms (GAs), which have increased potential avenues for model selection techniques and parameter estimation [18, 35]. These methods come with their own nuances, which are inspired by evolutionary processes such as selection, mutation, and crossover mechanisms between generations. By iterating over multiple generations and adjusting these method parameters, the traditional challenges of processing higher-dimensional models or degeneracies are overcome using these methods. On the other hand, this approach produces a preference for more complex scenarios that may not be the simplest explanation of certain evolutionary scenarios. GAs have been applied in addressing cosmological tensions by optimizing model formulations in EDE, IDE scenarios, and MG theory scenarios. Their flexibility allows for the precise searching of complex model spaces.

GAs have a particular attractiveness due to the range of their applicability such as in setting initial conditions for simulations where GA algorithms can ascertain the best initial setups that can reproduce observed structures in the present Universe, which offers new insights into the early Universe that are difficult to obtain using traditional methods. In general, GAs enable powerful toolkits that can be used to explore complex model spaces as well as simulation setups that would be insurmountable otherwise.

The development of these and other statistical tools will be critical to overcoming the challenges of cosmological tensions as well as the development of extensions to the standard cosmological model. These are shown in Fig. 6 where the nuances between data analysis methods are depicted. While they are shown in a decoupled, as already discussed, they are often applied in combination, which shows the strengthening interface between theoretical, computational, and observational domains of cosmology.

The development of new strategies and methods in the analysis of observational data, and their inference on underlying physics will be critical to meeting the challenges of the next generation of

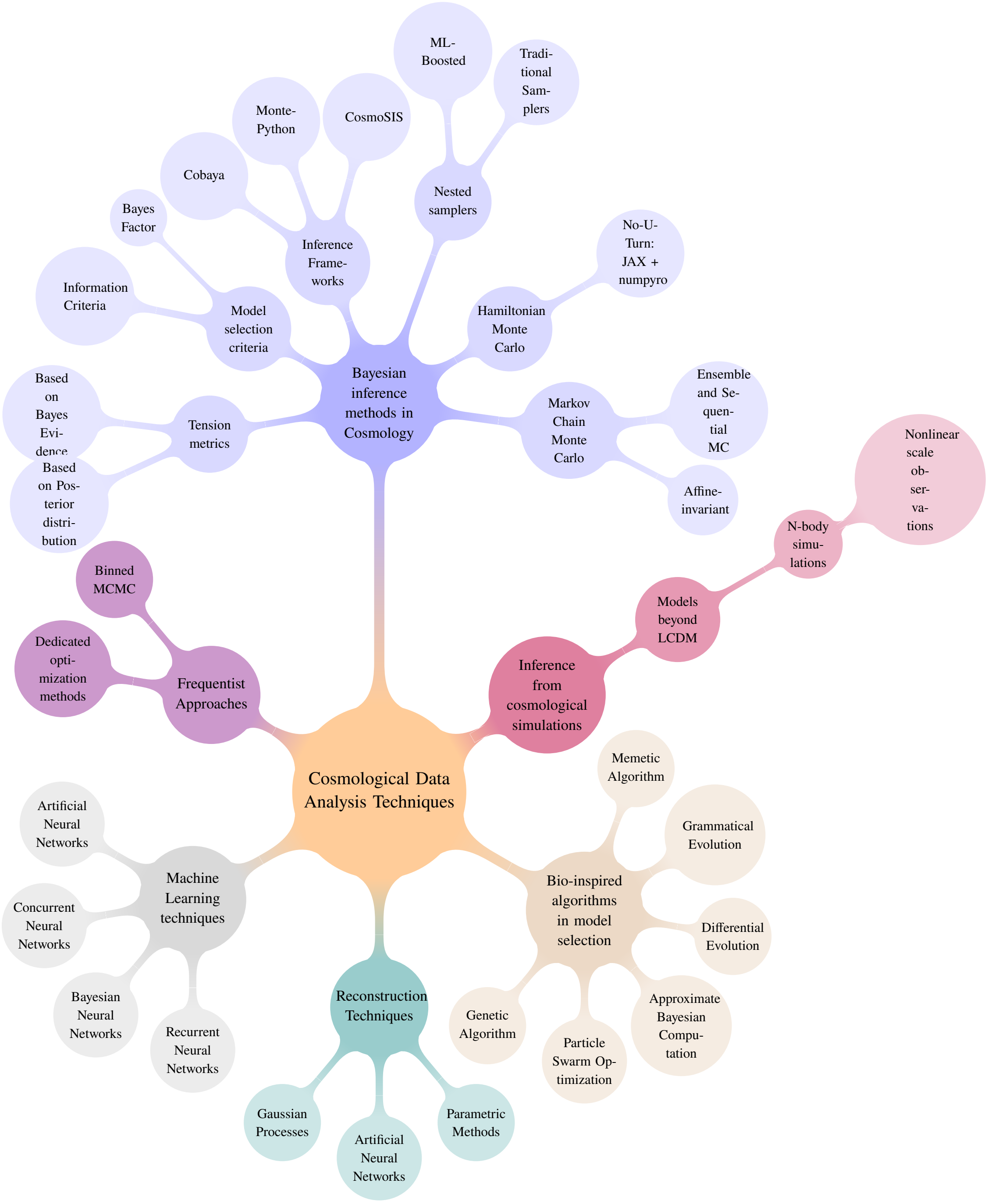

Figure 6: Different data analysis tools being used and developed in the cosmology community (reproduced from the CosmoVerse White Paper [27]).

science experiments including the Simons Observatory, Euclid, and the Roman Space Telescope as well as others. By maturing the growing plethora of cosmological model and confronting them with observational data through the new and emerging data analysis techniques being developed, realistic extensions to the standard cosmological model may be obtained.

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