Proceedings

An overview of nonstandard signals in cosmological data

George Alestas [1,†], George V. Kraniotis [2,†] and Leandros Perivolaropoulos [3,†]

[1] g.alestas@uoi.gr
[2] gkraniotis@uoi.gr
[3] leandros@uoi.gr
† Current address: Department of Physics, University of Ioannina, 45110 Ioannina, Greece

Version January 29, 2021 submitted to Proceedings

Abstract: We discuss in a unified manner many existing signals in cosmological and astrophysical data that appear to be in some tension (2σ or larger) with the standard ΛCDM as defined by the Planck18 parameter values. The well known tensions of ΛCDM include the H_0 tension the S_8 tension and the lensing (A_{lens}) CMB anomaly, There is however, a wide range of other, less standard signals towards new physics. Such signals include, hints for a closed universe in the CMB, the cold spot anomaly indicating non-Gaussian fluctuations in the CMB, the hemispherical temperature variance assymetry and other CMB anomalies, cosmic dipoles challenging the cosmological principle, the Lyman-α forest Baryon Accoustic Oscillation anomaly, the cosmic birefringence in the CMB, the Lithium problem, oscillating force signals in short range gravity experiments etc. In this contribution present the current status of many such signals emphasizing their level of significance and referring to recent resources where more details can be found for each signal. We also briefly mention some possible generic theoretical approaches that can collectively explain the non-standard nature of these signals. In many cases the signals presented are controversial and there is currently debate in the literature on the possible systematic origin of some of these signals. However, for completeness we refer to all the signals we could identify in the literature citing also references that dispute their physical origin.

Keywords: cosmological data; anomalies; cosmic dipoles; lithium problem; cosmic birefrigence; CMB anomalies; H_0 problem; growth tension; LCDM standard model; S_8 tension;

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1. Introduction

We are experiencing an era where a single cosmological model is heralded by experts as the gold standard in explaining the way the universe behaves at a large scale. This model is ΛCDM and contains cold dark matter as well as a cosmological constant associated with dark energy. Despite the huge improvements of the cosmological observations that have been made over the last years, ΛCDM seems to still be very consistent with most of the data produced [1–12]. However, this has been the case only for the majority and not the entirety of these data. There is arguably significant evidence, now more than ever, that the originally thought negligible imperfections of ΛCDM are actually deep cracks that indicate underlying pathologies of the model.

In this light, we attempt to discuss in a unified manner many existing signals in cosmological and astrophysical data that appear to be in some tension (2σ or larger) with the standard ΛCDM model as defined by the Planck18 parameter values. In addition to the well known tensions (H_0 tension, S_8 tension and A_{lens} anomaly), there is a wide range of other less discussed, less-standard signals at a lower statistical significance level than the H_0 tension which may also constitute hints towards new physics. The goal of this manuscript is to collectively present the current status of these signals and their level of significance, refer to recent sources where more details can be found for each signal and discuss possible generic theoretical approaches that can collectively explain their non-standard nature.

In order to access the significance of each non-standard signal as well as the possibility that it can lead to new physics one must answer the following questions/points of study:

- What are the current cosmological and astrophysical datasets that include such non-standard signals?
- What is the statistical significance of each signal?
- Is there a common theoretical framework that may explain these non-standard signals if they are of physical origin?

There have been previous similar studies [13,14] collecting and discussing signals in data that are at some statistical level in tension with the standard ΛCDM model, but these are by now outdated. This manuscript serves as an attempt to provide an updated collection of these non-standard signals with emphasis to more recent measurements which may prove to be a useful resource for the community.

2. A Collection of Non-Standard Signals

In this section, we attempt to provide an extensive list of the non-standard cosmological signals in cosmological data. In many cases the signals are controversial and there is currently debate in the literature on their possible systematic origin. However, for completeness we refer to all signals we could identify in the literature including also references that dispute their physical origin.

2.1. Signals in SnIa data

Arguably the best known tension of ΛCDM is the difference in the value of the Hubble constant H_0 measured from two independent robust sources: local measurements using standard candles and the distance ladder and measurements using the sound horizon at recombination as a standard ruler calibrated using the CMB anisotropy spectrum or the Big Bang Nucleosynthesis (BBN). The locally measured value of H_0 was found to be in approximately $4-5\sigma$ tension with the Planck18 CMB value[2,15–19]. This could be an indication of early dark energy [20] or late phantom dark energy [21,22].

Another non-standard signal that seems to exist within the SnIa data (*e.g.* Pantheon) is the abnormal oscillations of the $H(z)$ best fit parameter values (*e.g.* Ω_{0m}) obtained from redshift bins of the data, with respect to the corresponding best fit values of the complete dataset. This oscillating behaviour approaches the 2σ level for low z redshift bins [23–27].

This type of behaviour could be evidence of a dark energy parametrization with a similarly oscillating density, induced by a scalar field potential with a local minimum. The presence of undetected large scale inhomogeneities at low redshifts such as superclusters or voids [28,29] could also provide a viable physical explanation of this phenomenon.

2.2. Signals in the CMB data

A plethora of such signals, that could be either effects of systematics or indications of physical extensions of the ΛCDM model, have been dicovered in the CMB data. The most significant of these signals are the following:

- The Planck CMB anisotropy power spectrum data appear to favor a universe with mildly positive curvature (a closed universe) at a $2-3\sigma$ level. This trend is connected with the lensing anomaly and the high-low l tension discussed below and may represent a particular interpretation of the same signal in the CMB data[30–32].
- An anomalously strong ISW effect on scales larger than $100h^{-1}Mpc$ has been identified in the CMB data [33,34]. Specifically a combination with BOSS data shows a large ISW signal of supervoids with $A_{ISW} \approx 5.2 \pm 1.6$. This is in 2.6σ tension with ΛCDM .

- The CMB Cold Spot is a region of the CMB sky with scale of about 5° which is unexpectedly large and cold relative in the context of the expected Gaussian CMB fluctuations. The Cold spot is approximately $70\mu K$ colder than the average CMB temperature, while the typical rms temperature variation is only $18\mu K$ [35].
- The hemispherical temperature variance asymmetry[36–38]:The CMB full-sky temperature pixels manifest a hemispherical asymmetry in power with pole axis nearly aligned with the Ecliptic. The northern ecliptic hemisphere is has abnormaly low variance compared to the predictions of Gaussian ΛCDM fluctuations while the southern hemisphere is well consistent with the expected level of variance. The possible extension of this effect in polarization pixels is expected to be tested by the CMB-S4 mission[39].
- The lack of large-angle CMB temperature correlations[40]: the magnitude of the two-point angular-correlation function of the CMB temperature anisotropies is anomalously low for angular scales larger than about 60 degrees. Physical mechanisms operating close to the time of recombination are expected to play a role in the explanation of this observed lack of large-angle CMB temperature correlations.
- The lensing anomaly[41]: Oscillatory residuals between the Planck temperature power spectra and the best-fit ΛCDM model in the multipole range $l \in [900, 1700]$ in opposite phase compared to the CMB and thus phenomenologically similar to the effects of gravitational lensing. This smoothing of the acoustic peaks in the temperature power spectrum could be induced by an oscillatory feature, generated during inflation[42].
- The preference for odd parity correlations[43,44]: There is an anomalous power excess of odd l multipoles compared to even l multipoles in the CMB anisotropy spectrum. The odd-parity preference at low multipoles could be a phenomenological origin of the lack of large-scale CMB temperature correlation.
- The high-low l tension[45]. The ΛCDM parameter values derived by the high l part of the CMB anisotropy spectrum ($l > 1000$) are in $2-3\sigma$ tension with the corresponding values of these parameters derived from the low l part of the spectrum ($l < 1000$). This anomaly is probably related to the lensing anomaly and the indications for a closed universe discussed above.

2.3. Signal in the Weak Leansing - RSD data

The low $\Omega_{0m} - \sigma_8$ tension (S_8 or growth tension.[46–53]): The value of $S_8 \equiv \sigma_8(\Omega_{0m}/0.3)^{0.5}$ is found by weak lensing and redshift space distortion (RSD) data to be lower compared to the Planck18 value at a level of about 3σ. This indicates that dynamical cosmological probes favor lower values of Ω_{0m} than geometric probes which could be a signal of weaker gravity than the predictions of General Relativity in the context of a ΛCDM background.

2.4. Age of the Universe

The oldest stars in our vicinity were created as close to the Big Bang as possible and therefore are of a similar age with the Universe. This characteristic makes them powerful assets in determining that age. Most significantly, even a single old enough star is able to provide us with an accurate measurement. The determination of the ages of the oldest stars in our galaxy is made by using their distances by direct parallax measurements [54], as well as spectroscopic determinations of their chemical composition.

The age of the universe as obtained from local measurements using the ages of oldest stars in the Milky Way appears to be larger, and in some tension with the corresponding age obtained using the CMB Planck data in the context of ΛCDM [55].

2.5. Cosmic dipoles

There have been claims for signals indicating the violation of the cosmological principle. A physical mechanism for producing such violation on Hubble scales is studied in Ref. [56]. Such signals include the following:

- The fine structure constant α dipole. Spectra from quasars indicate a spatially dependent value of the fine structure constant at a 4σ level of significance. This signal indicates both the violation of the cosmological principle and variation of the fundamental constants[57,58]. This dipole is also anomalously aligned with others [59,60].
- The large scale velocity flow dipole [61,62].
- The quasar density dipole, which is a statistically significant (4σ) dipole in the density of quasars with direction close to the CMB dipole. [63]

2.6. Signal in BAO data

The Lyman-α forest BAO anomaly (galaxy vs $Ly - \alpha$ BAO) [64,65] refers to a $2.5 - 3\sigma$ discrepancy between the BAO peak in the Ly-α forest at an effective redshift of $z \sim 2.34$ and the best fit Planck18 ΛCDM cosmology. This abnormality was found to be present in the data even in the case where it is assumed that the BAO scale is a standard ruler independent of the sound horizon.

Since the anomaly was first reported studying the Ly-α forest at a redshsift of $z \sim 2.34$ it could imply evolution of the dark energy equation of state $w(z)$ in the range $0.57 < z < 2.34$.

2.7. Parity violating rotation of CMB linear polarization

A parity violating axion-like scalar field, which can play the role of dark matter and dark energy, could rotate the plane of linear polarization of CMB photons as they travel from the last scattering surface to the present by a non-zero angle β (cosmic birefringence angle). A non-zero value of β was recently detected the Planck18 polarization data at a 2.4σ statistical significance level [66].

This study provides a non-zero estimate for β with a confidence of 99.2% C.L. If proven to be correct this would be a very significant result which would hint towards new physics beyond ΛCDM , sensitive to parity violation.

2.8. The Lithium problem

Big Bang Nucleosynthesis (BBN) is very useful tool in cosmology since it has the rare quality of connecting the early Universe with present day observations. However, despite of the great success that the theory of BBN has in explaining the creation and abundancy of the elements observed in our Universe, it fails while trying to explain the observed quantity of Lithium. Specificaly, the observed value of Lithium is $\simeq 3.5$ smaller than that predicted by BBN [67,68]. In particular measurements of old, metal-poor stars in the Milky Way's halo find 5 times less lithium that BBN predicts

2.9. Quasar Hubble diagram

A possible deviation from the ΛCDM cosmology hinting towards phantom dark energy has been documented when constructing a Hubble diagram using quasars as distance indicators, in the redshift range of $0.5 < z < 5.5$ [69,70]. The observed tension between the best fit cosmographic parameters and ΛCDM could reach 4σ, even when combining the quasar data with the usual SnIa datasets.

This deviation from ΛCDM seems at first glance to be a genuine tension, however, a strong case can be made towards the opposite [71]. Specifically, it could be argued that the log-polynomial expansion of the luminosity distance relation,

$$d_L(z) = \frac{cln(10)}{H_0}[log_{10}(1+z) + a_2 log_{10}^2(1+z) + a_3 log_{10}^3(1+z) + ...] \tag{1}$$

where $H_0, a_2, a_3, ...$ are free parameters, used to construct the aforementioned diagram is not valid for redshifts larger than 2, a fact that points towards the observed tension being an artifact.

2.10. Oscillating force signals in short range gravity experiments

A re-analysis of short range gravity experiments has indicated the presence of an oscillating force signal with sub-mm wavelength at a 2σ level [72,73]. This type of signal seems to hold some statistical significance and could be hint towards several possible physical effects, amongst them an indication for a short distance modification of GR.

This oscillating behaviour could be seen as evidence for emerging signatures of non-local behaviour in experimental data. It could also provide a motivation for re-examining the stability of $f(R)$ gravity with negative squared mass which are thought to be unstable at the perturbative level.

3. Conclusion-Discussion

The signals discussed in this contribution, as well as others not covered, could be interpreted as telltale signs of the need to incorporate a model more complex than ΛCDM as the new standard model of Cosmology. There arises, therefore, the need to investigate new fundamental physics with the aim to reconcile the emerging tensions.

Such interesting new physics, is most likely to affect four basic observable parameters: The Hubble parameter $H(z, w)$, the effective Newton constants for growth of perturbations $\mu \equiv \frac{G_{eff}}{G_N}$ and lensing $\Sigma \equiv \frac{G_L}{G_N}$, as well as the fine structure constant α (w is the dark energy equation of state parameter and G_N is the locally measured value of the Newton's constant). According to ΛCDM $H(z) = H(z, w = -1)$, $\mu = 1$, $\Sigma = 1$. The fine structure constant α is also assumed constant and uniform in the standard model.

Generic extensions of ΛCDM may allow for a redshift dependence of the parameters w, μ, Σ and α as well as a possible large scale spatial dependence which could violate the cosmological principle. *Varying fundamental constants* can potentially address the fine structure constant α dipole, the lithium problem, growth tension, SnIa signals (variation of the SnIa absolute magnitude $\mathcal{M}$), quasar signals and the ISW CMB signal.

The identification of the new physics that can explain the nonstandard signals detected in the data can be realized in an effective manner through the following strategy:

- Tuning of current missions towards the verification or rejection of non-standard signals.
- Identification of favored parametrizations of $H(z, w(z), r)$, $\mu(z, r)$, $\Sigma(z, r)$, $\alpha(z, r)$ assuming that at least some of the non-standard signals are physical.
- Identification of the theoretical models (field Lagrangians) that are consistent with these parametrizations. Interestingly, for example only a small subset of modified gravity models is consistent with the weak gravity in the context of a ΛCDM background [74–77] suggested in the context of the S_8 tension.

In view of the upcoming volume of emerging new cosmological data in the next decade it is likely that the observed nonstandard cosmological signal will be translated into exciting new physical theories.

Funding: This research is co-financed by Greece and the European Union (European Social Fund - ESF) through the Operational Programme "Human Resources Development, Education and Lifelong Learning 2014-2020" in the context of the project "Scalar fields in Curved Spacetimes: Soliton Solutions, Observational Results and Gravitational Waves" (MIS 5047648).

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