

Λ CDM problems

A survey

Beyond Λ CDM: Problems, solutions, and the road ahead

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Abstract

Despite its continued observational successes, there is a persistent (and growing) interest in extending cosmology beyond the standard model, Λ CDM. This is motivated by a range of apparently serious theoretical issues, involving such questions as the cosmological constant problem, the particle nature of dark matter, the validity of general relativity on large scales, the existence of anomalies in the CMB and on small scales, and the predictivity and testability of the inflationary paradigm. In this paper, we summarize the current status of Λ CDM as a physical theory, and review investigations into possible alternatives along a number of different lines, with a particular focus on highlighting the most promising directions. While the fundamental problems are proving reluctant to yield, the study of alternative cosmologies has led to considerable progress, with much more to come if hopes about forthcoming high-precision observations and new theoretical ideas are fulfilled.

exotic components

theoretical issues

anomalies

Challenges for Λ CDM: An update

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A number of challenges to the standard Λ CDM model have been emerging during the past few years as the accuracy of cosmological observations improves. In this review 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 Λ CDM model as specified by the Cosmological Principle, General Relativity and the Planck18 parameter values. In addition to the well-studied 5σ challenge of Λ CDM (the Hubble H_0 tension) and other well known tensions (the growth tension, and the lensing amplitude A_L anomaly), we discuss a wide range of other less discussed less-standard signals which appear at a lower statistical significance level than the H_0 tension some of them known as 'curiosities' in the data) which may also constitute hints towards new physics. For example such signals include cosmic dipoles (the fine structure constant α , velocity and quasar dipoles), CMB asymmetries, BAO $\text{Ly}\alpha$ tension, age of the Universe issues, the Lithium problem, small scale curiosities like the core-cusp and missing satellite problems, quasars Hubble diagram, oscillating short range gravity signals etc. The goal of this pedagogical review is to collectively present the current status (2022 update) of these signals and their level of significance, with emphasis on the Hubble tension and refer to recent resources where more details can be found for each signal. We also briefly discuss theoretical approaches that can potentially explain some of these signals.

exotic components

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tensions

1. What are the biggest problems or shortcomings of the Λ CDM scenario?

- | | |
|--|-----|
| a) Nothing is wrong with Λ CDM | 5% |
| b) The cosmological constant problem | 66% |
| c) The coincidence problem | 13% |
| d) Dark matter | 21% |
| e) The big bang singularity | 10% |
| f) Inflation | 21% |
| g) Λ CDM will remain the best-fit model to the data while not being understood theoretically | 48% |
| h) It cannot explain small-scale structure | 23% |
| i) Baryonic effects are too difficult to model | 18% |
| j) Cosmic variance | 2% |

2. The cosmological constant problem will be solved by...

- | | |
|---|-----|
| a) a dark energy theory | 18% |
| b) a modified gravity theory | 28% |
| c) better understanding of particle physics | 46% |
| d) realising it is not a problem | 20% |

3. Dark energy will turn out to be...

- | | |
|---|-----|
| a) a new scalar field | 15% |
| b) indistinguishable from a cosmological constant | 48% |
| c) related to dark matter | 12% |
| d) a modification to GR | 26% |
| e) something completely different | 33% |

4. Dark matter. We will...

- | | |
|--|-----|
| a) never know what dark matter is | 10% |
| b) show that dark matter is not a particle | 13% |
| c) show that dark matter is modified gravity | 18% |
| d) discover the dark matter particle | 56% |

5. Anomalies

- | | |
|--------------------------------------|-----|
| a) will overturn Λ CDM | 7% |
| b) will remain and must be addressed | 67% |
| c) will go away | 20% |
| d) new anomalies will be found | 84% |

6. Next generation experiments will make discoveries that will...

- | | |
|---|-----|
| a) confirm Λ CDM to higher precision | 39% |
| b) lead to additions to Λ CDM | 39% |
| c) lead to large modifications to Λ CDM | 31% |
| d) overturn Λ CDM | 10% |