Class 25: Inflation

- This class
  - The idea of inflation
  - Solving the four initial condition problems
  - The physics of inflation
  - Predictions/tests of inflation

O: Recap

- The flatness problem
  - Why is the Universe so flat, despite the fact that the flat solution is unstable?

- The horizon problem
  - Why is the CMB so isotropic, despite the fact that patches separated by >degree had never been in casual contact?

- The relic problem
  - Why is the Universe not full of exotic “left over” relics from the GUT era

- The structure problem
  - Where did the initial perturbations come from?
If we close our eyes to physics before the end of the GUT epoch, each of these problems can be phrased as an “initial” condition problem... if the Universe looked “just right” $t \sim 10^{-34}$ s, we can explain how it looks today.

I : Inflation

- Basic idea
  - Universe underwent tremendous period of accelerated expansion at very early times
  - Most natural time for inflation is towards the end of the GUT era ($t \sim 10^{-35}$ s)
  - Overall expansion by a huge factor $\sim 10^{40}$ - $10^{100}$

- Basic dynamics is like dark energy on steroids
  - Universe pervaded by enormous "vacuum energy"
  - Friedmann equation gives

$$a = a_0 \exp \left( t \sqrt{\frac{8\pi G \rho_0}{3}} \right)$$
II : Solution to the initial condition problems

- The Flatness Problem
  - Inflation drives the Universe to flatness
  - Mathematically,
    \[
    |\Omega - 1| = |k|(aH)^{-2}
    \]
    \[
    |\Omega - 1| \propto \exp \left( -2t\sqrt{\frac{8\pi G \rho_0}{3}} \right)
    \]
  - Geometrically, even a highly curved surface will look flat once its expanded by a factor of $10^{40}$-$10^{100}$
The horizon problem

- Before inflation \((t<10^{-35}\text{s})\), particle horizon is at 
  \(r_0 = 2ct \approx 6 \times 10^{-27}\text{m}\)
- Inflation then expands this region by a factor of 
  \(10^{40}-10^{100}\) ... so causally connected region is now 
  \(10^{14}-10^{74}\text{m}\)
- From inflation to present day, there's another factor of \(10^{25}\) “regular” expansion
- Causally connected region of the Universe today is 
  \(>10^{39}\text{m}\) (much greater than the observable Universe today).
The Relic Problem
- Inflation dilutes away any exotic relics that may have been around before inflation
- Probability that there is a relic in our observable Universe is extremely small
- CAVEAT: Once we fully understand inflation, we’d better make sure that inflation itself (especially the exit from inflation) does not create relics of its own!

Structure problem
- Quantum fluctuations during inflation are the original seeds for the structure that we see around us today
- Prolonged exponential expansion would produce a “scale-invariant” spectrum of perturbations

Demonstration of scale-invariant perturbations
III : The physics of inflation

- See discussion on board

IV : Testing inflation

- How do we test/constrain inflation models?
- Possibilities... we can search for...
  - Deviations from flatness
    - HARD TO TOLERATE FOR ANY INFLATION MODEL
  - Deviations from scale-invariant perturbations
    - SMALL DEVIATIONS EXPECTED
  - Gravitational waves from inflation
    - EXPECTED, BUT AMPLITUDE HIGHLY UNCERTAIN
- Status...
  - No deviation from flatness found
  - Planck requires small deviation from scale invariance
  - Gravitational wave searches ongoing
    - Look for gravitational wave signature in CMB
    - In future, look directly for gravitational wave background
Planck 2013 results. XXII. Constraints on inflation

Ade et al. (2013)

Abstract

To analyze the implications of the Planck data for cosmic inflation, the Planck team took a unique temperature anisotropy measurement, combined with the WMAP large-angle polarization data, and provided the scalar potential index, n_s, at a = 0.008 at 187 GHz, ruling out exact scale invariance at or near the Planck scale. The data favored the simplest model of inflation, the tachyon model, with a scalar potential index of n_s = 0.81 ± 0.03. The data also favored the simplest model of inflation, the tachyon model, with a scalar potential index of n_s = 0.81 ± 0.03. The data also favored the simplest model of inflation, the tachyon model, with a scalar potential index of n_s = 0.81 ± 0.03.

Diagram

The diagram shows the tensor-to-scalar ratio (r) as a function of the primordial tilt (n_s). The gray line represents the best-fit values from Planck, while the red and blue lines represent the best-fit values from Planck with and without high-L data, respectively. The black points represent the best-fit values from Planck with and without BAO data, respectively. The green points represent the best-fit values from Planck with and without low-scale SUSY data, respectively. The purple line represents the best-fit values from Planck with and without R^2 inflation, respectively. The black line represents the best-fit values from Planck with and without V < 0, respectively.
Inflationary paradigm in trouble after Planck2013

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Abstract

The recent Planck satellite combined with earlier results eliminate a wide spectrum of more complex inflationary models and favor models with a single scalar field, as reported in the analysis of the collaboration. More important, though, is that all the simplest inflation models are disfavored by the data while the surviving models—namely, those with plateau-like potentials—are problematic. We discuss how the restriction to plateau-like models leads to three independent problems: it exacerbates both the initial conditions problem and the multiverse-unpredictability problem and it creates a new difficulty which we call the inflationary "weakness" problem. Finally, we comment on problems reconciling inflation with a standard model Higgs, as suggested by recent LHC results. In sum, we find that recent experimental data disfavors all the best-motivated inflationary scenarios and introduces new, serious difficulties that cut to the core of the inflationary paradigm. Forthcoming searches for B-modes, non-Gaussianity and new particles should be decisive.

The Planck satellite data reported in 2013 shows with high precision that we live in a remarkably simple universe. The measured spatial curvature is small; the spectrum of fluctuations is nearly scale-invariant; there is a small spectral tilt, consistent with there having been a simple-dynamical mechanism that caused the smoothing and flattening; and the fluctu-