Beyond Planck: Neutrino & GUT-Scale Physics from the Cosmos

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for CF5 Inflation and Neutrino topical groups
(See CF5 documents)
Early universe as a HEP lab

$V^{1/4} = 1.06 \times 10^{16} \text{ GeV } \left( \frac{r}{0.01} \right)^{1/4}$

- Inflation
- Cosmic neutrino background
- Cosmic microwave background
Inflation?

Universe expands by $> e^{60}$ solving smoothness problem, flatness and more..

What drove inflation?

What is the energy scale of inflation?

- spectral index of fluctuations, $n_s$
- constrain tensor to scalar fluctuations
- inflationary gravitational wave B-mode polarization
- non-Gaussianity?
Neutrinos?

$N_{\text{eff}}$

Effective number of relativistic species impacts intrinsic CMB power spectrum

graphic from NASA/WMAP
Neutrinos?

\[ \Sigma m_\nu \]

Sum of the neutrino masses impacts growth of large scale structure, i.e., the matter power spectrum.
Neutrinos?

$\Sigma m_\nu > 0$

Sum of the neutrino masses impacts growth of large scale structure, i.e., the matter power spectrum

graphic from NASA/WMAP
Primary CMB anisotropy - 9 harmonics

Fit by vanilla $\Lambda$CDM - just six parameters

Inflation checks: Geometrical flat universe; Superhorizon features; acoustic peaks/adiabatic fluctuations; departure from scale invariance.
Constraining inflationary models
joint r and n_s limits

Spectral Index of primordial fluctuations, n_s,
where \( \Delta^2_R(k) = \Delta^2_R(k_0) \left( \frac{k}{k_0} \right)^{n_s - 1} \)

Inflation evidence
\( n_s \neq 1 \) at over 5\( \sigma \)
Constraining inflationary models
joint $r$ and $n_s$ limits

Spectral Index of primordial fluctuations, $n_s$,
where $\Delta^2_R(k) = \Delta^2_R(k_0) \left( \frac{k}{k_0} \right)^{n_s - 1}$

Inflation evidence $n_s \neq 1$ at over $5\sigma$
Primary CMB anisotropy - 9 harmonics
Improves precision of sound horizon, $\theta_s$, & provides larger lever arm

$\theta_s$ is the angular distance a sound wave could have travelled by recombination

$\sim 1/\theta_s$
And most importantly provides determination of the damping scale, $\theta_d$

$\theta_d$ is the angular diffusion length at recombination.

Photon has a mean free path and diffuses. So, oscillations on small scales are damped exponentially. (Silk damping)

Note $\frac{r_d}{r_s} = \frac{\theta_d}{\theta_s} \propto H^{0.5}$ so ratio is sensitive energy density.
Constraining model extensions: joint $N_{\text{eff}}$ and $\Sigma m_\nu$ constraints

$N_{\text{eff}}$ is the effective number of relativistic species. For standard 3 neutrinos $N_{\text{eff}} = 3.046$. It measures the extra energy relative to the photons.
Lensing of the CMB

17°x17°

lensing potential

unlensed cmb

from Alex van Engelen
Lensing of the CMB

17°x17°

from Alex van Engelen
high resolution and sensitivity map of the CMB covering 1/16 of the sky from SPT

(2500 square degrees)
CMB Lensing Map
reconstruction of the mass projected along the line of sight to the CMB.

Lensing convergence map smoothed to 1 deg resolution from CMB lensing analysis of SPT 2500 deg² survey
CMB Lensing Map
reconstruction of the mass projected along the line of sight to the CMB.

Correlation of matter traced by CMB lensing (contours, SPT) and distribution of high z galaxies (grayscale; Herschel 500 um) [arXiv:1112.5435]

Smoothed to 1 deg resolution from CMB lensing analysis of SPT 2500 deg² survey
Sensitive to the neutrino masses
\( \Sigma m_\nu = 0.1 \text{ eV} \rightarrow 5\% \text{ amplitude of spectrum} \)

Polarization gives additional lensing sensitivity and is a cleaner probe.
\( B_{\text{lens}} \) modes are only sourced by lensing.
Full potential of CMB lensing for $\Sigma m_\nu$ needs to exploit polarization data

**Sensitive to the neutrino masses**

$\sum m_\nu = 0.1 \text{ eV} \rightarrow 5\%$ amplitude of spectrum

Polarization gives additional lensing sensitivity and is a cleaner probe. $B_{lens}$ modes are only sourced by lensing.
CMB polarization: the next frontier for lensing & inflation
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- $r = 0.01$
- lensing of EE to BB
CMB polarization: the next frontier for lensing & inflation

\[ \sum m_\nu = 0 \]

\[ \sum m_\nu = 1.5 \text{ eV} \]
CMB polarization: the next frontier for lensing & inflation

Figure from CF5 inflation document - note expanded scale with $0.001 < r < 0.01$
Status of B-mode experiments

EE: > 2σ detections

BB: 95% C.L. limits

100 nK !
SPTpol Detection of lensing B-modes
(reported last week)

$C_{l}^{BB} [\mu K^2 \times 10^4]$

$(\hat{E}^{150} \phi^{\text{CIB}}) \times \hat{B}^{150}$

$(\hat{E}^{95} \phi^{\text{CIB}}) \times \hat{B}^{150}$

$(\hat{E}^{150} \phi^{\text{CIB}}) \times \hat{B}_\chi^{150}$

null test

$l$

SPTpol: Hanson et al, arXiv:1307.5830
CMB timeline

- **2009**: $r < 0.7$ (BICEP)  Chiang et al, 0906.1181

- **2013**: $r \lesssim 0.1$ from Inflationary B-modes (BICEP 2)?
- **2013**: Stage II experiments detect lensing B-modes
- **2013-2016**: Stage II experiments
  \[ \sigma(r) \sim 0.03, \sigma(N_{\text{eff}}) \sim 0.1, \sigma(\Sigma m_\nu) \sim 0.1 \text{eV} \]
- **2016-2020**: Stage III experiments
  \[ \sigma(r) \sim 0.01, \sigma(N_{\text{eff}}) \sim 0.06, \sigma(\Sigma m_\nu) \sim 0.06 \text{eV}; \]

- **2020-2025**: **Stage IV goal to reach**
  \[ \sigma(r) = 0.001, \sigma(N_{\text{eff}}) = 0.025, \sigma(\Sigma m_\nu) = 16 \text{ meV} \]
The Stage IV experiment: CMB-S4

• Builds on extensive experience from earlier generation experience
  – Technology
  – Systematic Error Control
• Two surveys
  – Inflation Survey (few % of the sky)
  – Neutrino mass Survey (50% of the sky)
• Experiment configuration
  – 500,000 detectors spanning 40 - 220 GHz using HEP invented superconducting Transition-Edge-Sensors (TES)
  – 3’ or better resolution for CMB lensing
  – multiple platforms
• Midscale project: $50M to $100M capital cost
National lab and HEP community involvement in CMB-S4

- CMB-S4 requirements exceed capabilities of University-based experiments
  - Focal-plane Arrays and Readout
    - Improved Production Reliability
    - Increased Production Volume and Throughput
      - 500,000 detectors ~ 300 silicon arrays
    - Multiplexed TES Readout
    - Large Cryogenic Optics
  - Computing Infrastructure and Analysis tools
    - ~10,000 x Planck data size (~ 3 TB/day)
  - Project Organization/Management
Experimental Evolution

Approximate raw experimental sensitivity (µK)

- WMAP
- Planck
- Detection of B-mode polarization

Year

- Space based experiments
- Stage–I $\approx 100$ detectors
- Stage–II $\approx 1,000$ detectors
- Stage–III $\approx 10,000$ detectors
- Stage–IV $\approx 100,000$ detectors

CMB-S4
Inflation projection for CMB-S4

\[ \Delta \phi \lesssim m_{pl} \]

\[ \Delta \phi \gtrsim m_{pl} \]

Current limit (CMB+BAO)

large-field \( \Delta \phi \approx m_{pl} \)

small-field \( \Delta \phi \approx m_{pl} \)

CMB-S4 reach
CMB-S4 Lensing Sensitivity $\Sigma m_\nu$

![Graph showing CMB Lensing power spectrum with sensitivity to $\Sigma m_\nu$ values of 50, 100, and 150 meV.]
Joint projections $N_{\text{eff}} - \Sigma m_\nu$

Our forecasters: J. Errard, P. McDonald, A. Slosar, K. Wu, O. Zahn

- $\sigma(\Sigma m_\nu) = 16$ meV
- $\sigma(N_{\text{eff}}) = 0.020$

*with two probes*
Combined Neutrino mass constraints

\[ \sigma(\Sigma m_\nu) = 16 \text{ meV} \]

"use cosmology to tighten the noose" Boris Kayser
Summary

CMB measurements are at the heart of cosmology and fundamental physics.

Stage IV CMB experiment is needed.
It will be challenging, but achievable, with 100x or more increase in detectors from current Stage II, incredible attention to systematics, and commensurate increase in computing.

It is a HEP multilab-scale project!