Recent Cosmic Microwave Background Results

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Probing the Cosmic Frontier with CMB

We now have a model that describes the evolution of our Universe from a hot and dense state.

The model has some unusual features

- new physics -
  Dark Matter, Dark Energy, and starts with a period of Inflation.

Most of the model has been learned from measurements of the cosmic microwave background (CMB).
Inflation

Period of accelerating expansion in the early Universe during which the observable Universe shrinks

Favored model - Slow-roll inflation:
Universe’s density is dominated by the potential of a scalar field with ‘flattish’ potential

Open question: Can you use the Higgs for this scalar field? (see last talk)
Cosmic Microwave Background

Predicted in 1948: ~5 K
Seen in 1965: 3.5 K
Current: 2.7 K
Polarization of the CMB

CMB is polarized by Thomson Scattering

from W. Hu's web page
Naked eye

With Polarized Sunglasses

Credit: Talex
The CMB is polarised (~10%)”

• Any polarisation pattern can be decomposed into “E” (grad) and “B” (curl) modes

Smith et al 2008
Why use E&B?
look at what produces each

Density Wave

Gravitational Wave

E-Mode Polarization Pattern
Polarization along/perpendicular to k

B-Mode Polarization Pattern
Polarization +45deg to k
Why use E&B?

*look at what produces each*

Density fluctuations at LSS do not produce “B” modes; Gravitational waves do!

- E-Mode Polarization Pattern
  - Polarization along/perpendicular to \( k \)

- B-Mode Polarization Pattern
  - Polarization +45deg to \( k \)
Why use E&B?

look at what produces each

B-modes are a great place (low background) to look for gravitational waves from inflation
Measurements of CMB Power spectra

Angular scale $\theta$ [degrees]

(from sound waves)

Temperature

(from sound waves)

E modes

(from gravitational lensing)

Lensing B modes

(CMB-S4 Forecast
Planck 2015
ACTPol
BICEP2/Keck
Polarbear
SPT(TT) / SPTpol)

Large Angular Scales

Multipole number $\ell$

Small Angular Scales

(Angular scale)

(Power)

$\ell(\ell+1)/2\pi C_\ell [\mu K^2]$
Measurements of CMB Power spectra

Angular scale $\theta$ [degrees]

Temperature (from sound waves)

E modes (from sound waves)

Lensing B modes (from gravitational lensing)

Six orders of magnitude in 25 years

(from CMB-S4 Science Book 2016)
Six orders of magnitude in 25 years

Goal: Inflationary B-modes (from gravitational lensing)

Measurements of CMB Power spectra

Angular scale $\theta$ [degrees]

$\ell(\ell+1)/2\pi C_\ell [\mu K^2]$ vs Multipole number $\ell$

Small Angular Scales
Chasing inflationary gravitational waves

“smoking gun of inflation”

The power in G. Waves is described by “r” = tensor-to-scalar ratio

Current 95% CL upper limit is $r < 0.06$ (BICEP/Keck + Planck)

Goal: $r < 0.002$ ($\sigma(r)=0.001$)

How do we get the next factor of $\sim30$?
Basic Ingredients

• More detectors
  – Detectors have reached noise floor of photon statistics

• Both large and small angular scales
  – Large scales for IGW signal; small scales to remove lensing power

• Wide frequency coverage
  – Separating CMB and the Milky Way
CMB’s “Moore’s Law”

- WMAP
- Space based experiments
- Stage–I – ≈ 100 detectors
- Stage–II – ≈ 1,000 detectors
- Stage–III – ≈ 10,000 detectors
- Stage–IV – ≈ 100,000 detectors

Approximate raw experimental sensitivity ($\mu K$)

-工作总结：
  - 2013
  - CMB’s “Moore’s Law”
  - SPTpol
  - POLARBEAR
  - ACTpol
  - ~6000 detector-years
  - Simons Observatory (CMB-S4 prototype)
  - SPT-3G
  - Simons Array
  - Adv. ACTpol
  - ~60,000 detector years
  - CMB-S4
  - 2 million detector-years

Takeaway:
Tests of inflation will dramatically improve over next 10 years

Year

Putting New wafers on the South Pole Telescope

Instrument work on right now!
1x Large Aperture Telescope

crossed Dragone design

Key adv:
Allows large focal plane (2m!) for lots of detectors

Simons Observatory

Instrument overview: arxiv:1808.04493

Science overview: arxiv:1808.07445

3x Small Aperture Telescopes

Key advs: 1) Cheap way to get sensitivity, 2) Improved systematics control

No pretty hardware pictures yet, but telescope contract is signed

1.9 m
Simons Observatory

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Importance of Delensing

Figure 5: Left: Reduction in lensing B-mode power through the use of a lensing template constructed from SPT-3G data. At the noise level of the planned SPT-3G 1500 deg$^2$ survey, delensing will remove over 2/3 of the lensing power. The prediction for the B-mode spectrum from inflationary gravitational waves with $r=0.01$ is shown for reference.

Right: Forecasts, courtesy of the BICEP/Keck Collaboration, for $\sigma(r)$ from the BICEP Array as a function of observing date with and without SPT-3G delensing.

The same patch of sky, however, can provide a template of lensing B modes to subtract from BICEP Array data, revealing the potential PGW signature beneath. This delensing process is impossible with BICEP Array data alone, because the $<1\text{m}$ apertures of the BICEP/Keck family of telescopes do not resolve the necessary angular scales. SPT-3G, on the other hand, is optimally positioned to provide such data.

The bulk of the five years of operations funded by this proposal will be devoted to a survey of 1500 deg$^2$ of the sky, matched to the BICEP Array observing region. The high-resolution SPT-3G data is crucial for delensing, because it will provide a high-signal-to-noise measurement of the E-mode sky down to arcminute scales and, for the first time, a high-fidelity reconstruction of the CMB lensing potential at all angular scales necessary for delensing degree-scale B modes (see, e.g., Fig. 9 of this proposal and Fig. 2 of Simard et al. 2015). As shown in Fig. 5, left panel, the full five-year SPT-3G data set will enable the removal of over 2/3 the lensing power in the B-mode map. As shown in Fig. 5, right panel, the removal of this contaminating signal has the potential to improve constraints on $r$ from BICEP Array by more than a factor of two. Furthermore, while the degree-scale information from SPT-3G will not be as deep as full BICEP Array data, it will be deep enough to provide a useful cross-check on any large-scale B-mode excess detected by BICEP Array. As noted above, the scientific potential of joint analyses of SPT-3G and BICEP Array data has been recognized by the NSF through a joint SPT-BICEP/Keck MSIP award, but the data products produced in the work proposed here are a necessary precondition of the MSIP-funded research.

3.2 Cracks in the Cosmological Model?

The six-parameter $\Lambda$CDM cosmological model is a remarkably simple description of the Universe that, until recently, appeared to fit all cosmological data with remarkable fidelity. As cosmological data have become ever more precise, though, certain apparent inconsistencies have begun to arise between best-fit parameters from different sets of data. Are these the result of systematic errors or statistical flukes, or are they pointing us to new physics? SPT-3G data will play a central role in elucidating the nature of these inconsistencies and in possibly establishing the existence of physics beyond $\Lambda$CDM.

As shown in the left panel of Fig. 6, the most statistically significant tension among current cosmological data sets is a $>3\sigma$ discrepancy between the Riess et al. (2018) classical distance-ladder determination of $H_0$ and value derived from the Planck CMB + Planck lensing data assuming $\Lambda$CDM (Planck Collaboration et al., 2018). The right panel of Fig. 6 shows there are also milder tensions in the amplitude of density fluctuations when describing tensions between estimates of single parameters from different data sets, we define $\sigma$ as the quadrature sum of the fully marginalized single-parameter uncertainties from the individual data sets.
New era: delensing crucial to IGW searches

SPT-3G will remove 2/3s of lensing BB power

Figure 5:

Left: Reduction in lensing B-mode power through the use of a lensing template constructed from SPT-3G data. At the noise level of the planned SPT-3G 1500 deg$^2$ survey, delensing will remove over 2/3 of the lensing power. The prediction for the B-mode spectrum from inflationary gravitational waves with $r = 0.01$ is shown for reference.

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As shown in the left panel of Fig. 6, the most statistically significant tension among current cosmological data sets is a $\sigma > 3\sigma$ discrepancy between the Riess et al. (2018) classical distance-ladder determination of $H_0$ and value derived from the Planck CMB + Planck lensing data assuming $\Lambda$CDM (Planck Collaboration et al., 2018). The right panel of Fig. 6 shows there are also milder tensions in the amplitude of density fluctuations.

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Credit: BICEP Array collaboration
also, CMB-S4 *(still in flux)*

Technology overview: arxiv:1706.02464
Science overview: arxiv:1610.02743

For testing inflation, the small telescopes provide the raw sensitivity, and the large telescopes remove the gravitational lensing signal (that would otherwise act as a noise floor)
And many others such as

BICEP Array: receivers being installed now

CLASS: on-sky performance reported last week 1811.08287

also, CMBpol, PIXIE (US) CoRE (EU)

GroundBIRD

LiteBIRD (Japan)
Separating the CMB and Milky Way: A trip from low to high frequencies

Multiple frequency bands can distinguish CMB from the dust and synchrotron emission of the Milky Way.

Note: CMB looks the same in all plots.
Separating the CMB and Milky Way: A trip from low to high frequencies

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Separating the CMB and Milky Way: A trip from low to high frequencies

Takeaway: Foreground cleaning will be crucial. Even at the best frequency, far away from the plane of the Milky Way, galactic signals are much larger than \( r = 0.001 \).
Current state of play
Three years ago

- ACTPol
- BICEP1
- BOOMERanG
- CAPMAP
- CBI
- DASI
- MAXIPOL
- QUaD
- QUIET-Q
- QUIET-W
- WMAP

Large Angular Scales

Small Angular Scales

Only upper limits
Today

Significant detections of B-modes, but only upper limits on grav waves

(B-mode power)

Large Angular Scales

Small Angular Scales

Multipole $l$

(Angular scale)

$r=0.1$

BICEP2+Keck
BICEP2+Keck/Planck
Polarbear
SPTpol
Observational constraints on Inflation Parameters

Planck TT + $\tau$ prior + lensing + BAO + BICEP/Keck

Others: $n_T$ (poorly constrained); running (consistent with zero)

95% CL: $r < 0.06$

$n_{s}$ (power law index of density perturbations)
Figure 4: (Left) The tensor-to-scalar ratio $r$ and the spectral tilt $n_S$ following from the effective potential ($3.12$). The non-minimal coupling $\varpi$ varies between $10^1$ and $10^2$ along the lines of constant $\varpi$, with larger values corresponding to smaller tensor-to-scalar ratios. The star in the lower part of the plot stands for the universal values in Eq. ($2.44$). (Right) The power spectrum $P_R$ as a function of the number of e-folds before the end of inflation and the associated comoving scale $k$ in inverse megaparsecs ($63$). The monotonic curve at the bottom of the plot corresponds to the universal/non-critical Higgs inflation scenario. The upper non-monotonic curves are associated with different realizations of the critical Higgs inflation scenario. The shaded regions stand for the latest 68% and 95% C.L. constraints provided by the Planck collaboration. For small $\varpi$ values, the tensor-to-scalar ratio can become rather large, $r \sim O(10^{1})$ ($56, 60, 61, 139$). Note, however, that although the direct comparison of CMB data with the primordial spectrum at large scales displays a reasonable consistency, the global behavior of the spectrum cannot be accurately described by the simple expansion in ($2.27$), since the running of the spectral tilt $\alpha_s \approx d \ln n_s / d \ln k$ and its running $\alpha_s \approx d^2 \ln n_s / d \ln k^2$ also become considerably large, cf. Fig. 5.

On top of the large-scale modifications, the non-monotonic evolution of the slow-roll parameter $\epsilon$ in the vicinity of the inflection point leads to the enhancement of the spectrum of primordial density fluctuations at small and intermediate scales. It is important to notice at this point that the standard slow-roll condition may break down if the potential becomes extremely flat and the inertial term in the inflaton equation of motion is not negligible with respect to the Hubble friction term ($140–142$). In this regime, even the classical treatment is compromised since stochastic effects cannot longer be ignored ($143–146$). If we restrict ourselves to situation in which the slow-roll approximation is satisfied during the whole inflationary trajectory, the height and width of the generated bump at fixed spectral tilt are correlated with the value of the tensor-to-scalar ratio $r$, cf. Fig. 4. Contrary to some claims in the literature ($102$), the maximum amplitude of the power-spectrum compatible with the 95% C.L Planck $n_s \epsilon$ contours ($63$) is well below the critical threshold $P_{\text{max}} R_10^2 10^3$ needed for primordial black hole formation ($147–149$). This conclusion is unchanged if one.

Note: Swapped colors: Blue is now Planck, Red arrow: Planck+BICEP/Keck limit

NB: Will reach down here in next 5-10 years (Grav Wave power)
Conclusions

• Next decade: 30-fold improvement in searches for inflationary gravitational waves
  – More detectors
  – Careful treatment of galactic foregrounds
  – Removing grav lensing noise

• Also other science: neutrinos, dark energy, dark matter, …
Beyond r/n_s

Higgs inflation produces more complex power spectra

- CMB Spectral distortions can probe smaller scales
- Need a satellite: LiteBIRD; PIXIE

Addition from spectral distortions

Recent discussion of caveats:
Gosenca, Adamek, Byrnes & Hotchkiss, ArXiv:1710.02055

Credit: Rubio 2018

Credit: J. Chluba

CMB constraints so far

Amplitude of power spectrum rather uncertain at k > 3 Mpc^{-1}
Improved limits at smaller scales can rule out many inflationary models


Credit: J. Chluba

CMB et al.

Probe extra \approx 10 e-folds of inflation!
Takeaway: Foreground cleaning will be crucial. Even at the best frequency, far away from the plane of the Milky Way, galactic signals are much larger than $r=0.001$. 