Cosmic Microwave Background

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CMB measurements probe cosmology and fundamental physics

**Inflation**
- Spectral index of fluctuations, $n_s$
- non-Gaussianity?
- Inflationary gravitational waves?

**Neutrinos**
- Number of relativistic species (Neff or “dark radiation”)
- Sum of the neutrino masses, $\sum m_\nu$ through impact on growth of structure

**Dark Energy**
- Probe growth with SZ clusters, CMB lensing, correlation with galaxy surveys
- Is GR correct on large scales?

➡ requires precision CMB measurements of the temperature and polarization CMB anisotropy from degrees to arc minutes

graphic from NASA website
COBE → WMAP → Planck
COBE → WMAP → Planck
High angular resolution (high-\(\ell\)) CMB measurements

Exceptional high and dry sites for dedicated CMB observations. Exploiting and driving ongoing revolution in low-noise bolometer cameras
Planck
143 GHz
zoom in
50 deg²
Ground based high resolution
50 deg^2

7x finer angular resolution
7x deeper
Ground based high resolution 50 deg²

Point Sources
Active galactic nuclei, and the most distant, star-forming galaxies
Clusters of Galaxies

S-Z effect: “Shadows” in the microwave background from clusters of galaxies

Ground based high resolution 50 deg²
Angular power spectrum of primary CMB anisotropy

Fit by standard $\Lambda$CDM - only six parameters - $\Omega_b h^2$, $\Omega_c h^2$, $\theta_s$, $A_s$, $n_s$, $\tau_e$
So, are we finished with primary CMB Temperature anisotropy measurements?

Fit by standard $\Lambda$CDM - only six parameters -

$\Omega_b h^2, \Omega_c h^2, \theta_s, A_s, n_s, \tau_e$
So, are we finished with primary CMB Temperature anisotropy measurements?

Figure from Planck 2015 Results XI

Angular scale

Cosmic Variance limited

Fit by standard ΛCDM - only six parameters -

$\Omega_b h^2$, $\Omega_c h^2$, $\theta_s$, $A_s$, $n_s$, $\tau_e$
So, are we finished with primary CMB Temperature anisotropy measurements?

Angular power spectrum of primary CMB anisotropy

Figure from Planck 2015 Results XI

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Angular scale

Fit by standard $\Lambda$CDM:
- only six parameters -
  $\Omega_b h^2$  $\Omega_c h^2$  $\theta_s$  $A_s$  $n_s$  $\tau_e$

Figure from Planck 2015 Results XI
Angular Scale

$D_\ell (\mu K^2)$

primary CMB (cosmology)

secondary CMB (cosmology & astrophysics)

Planck
SPT - S13
SPT 150 GHz
SPT 220 GHz
ACT 148 GHz
ACT 220 GHz
SPT 95 GHz

Story et al., 2013
George et al., 2014
Das et al., 2014
Large-Scale Structure Lenses the CMB

- RMS deflection of $\sim 2.5'$
- Lensing efficiency peaks at $z \sim 2$
- Coherent on $\sim$degree ($\sim 300$ Mpc) scales

graphic from ESA website
CMB lensing

Planck lensing potential reconstruction (projected mass map).

Planck XV (2015)
CMB lensing power spectra

Great progress, but still a long way to go.

Planck XV (2015)
What about physics constraints? Can they be improved?

Enormous precision and accuracy:

- Flat universe ($\Omega_k < 0.005$)
- $\Omega_{bh}^2 = 0.02222 \pm 0.00023$
- $\Omega_{ch}^2 = 0.1197 \pm 0.0022$
- (>50σ detection of non-baryonic dark matter)

But extensions to $\Lambda$CDM model are poorly constrained.

Planck Results I 2015
Inflation?

**Inflation checklist:**

- Flat geometry ($\Omega_k < 0.005$)
- Harmonic peaks (9+)
- Gaussian random fields
  
  ($f_{\text{NL}}^{\text{local}} = 0.8 \pm 5.0$, $f_{\text{NL}}^{\text{equil}} = -4 \pm 43$, and $f_{N}^{\text{ortho}} = -26 \pm 21$)

- Departure from scale invariance! ($n_s = 0.968 \pm 0.006$)
- Inflationary gravitational waves (tensors) ($r < 0.07$)

*constraints include CMB polarization data*
Neutrinos

- relativistic at decoupling

Redshift $z$

Energy Density [eV/cm$^3$]

Scale Factor $\alpha$

- Matter/Radiation Equality
- Neutrinos 10%
- Photons 15%
- Atoms 12%
- CDM, baryons
- $\Lambda$ (dark energy)
- neutrinos 0.5 eV
- neutrinos 0.05 eV
- neutrinos 0 eV

13.7 BILLION YEARS AGO
(Universe 380,000 years old)

at decoupling
Neutrinos - transition to part of matter budget today

- Matter/Radiation Equality
- Decoupling
- CDM, baryons
- Dark Matter 23%
- Atoms 4.6%
- Dark Energy 72%
- Neutrinos: 0.5 eV, 0.05 eV, 0 eV
- \( \Lambda \) (dark energy)
Massive neutrinos suppress small scale power

CMB lensing is sensitive to this
The non-gamma relativistic energy density of the Universe is parametrized by $N_{\text{eff}}$, the effective number of relativistic species, where $N_{\text{eff}} = 3.046$ for 3 neutrinos.

$N_{\text{eff}} = 3.15 \pm 0.23$

greater than 10σ detection of cosmic neutrino background!

$\Sigma m_\nu < 0.23$ eV at 95% c.l.

Joint $\Sigma m_\nu$ and $N_{\text{eff}}$ constraints: $N_{\text{eff}} = 3.2 \pm 0.5; \Sigma m_\nu < 0.32$ eV
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$N_{\text{eff}}$ constraints and light relics

$\Delta N_{\text{eff}}$ constraints and light relics

Sets experimental target of $\Delta N_{\text{eff}} = 0.027$ (goal for CMB-S4)
The frontier: CMB Polarization

The frontier is CMB lensing and polarization, and the future of CMB lensing is polarization.
The frontier: CMB Polarization

The frontier is CMB lensing and polarization, and the future of CMB lensing is polarization.

Just like the sky, the CMB must be polarized

from W. Hu’s web pages
CMB Polarization

Temperature

density oscillations

E modes
CMB Polarization

- E modes
- B modes
- Inflationary Gravitational wave oscillations
- density oscillations
- reionization bump
- recombination bump

- Temperature
- Polarization
- T modes
- CMB

Graph showing power spectra for temperature and polarization modes.
Tensor (gravitational) perturbation amplitude
Scalar (density) perturbation amplitude

\[
r \equiv \frac{\text{Tensor (gravitational) perturbation amplitude}}{\text{Scalar (density) perturbation amplitude}}
\]

Energy
\[
\text{energy} = 10^{16} \left( \frac{r}{0.01} \right)^{\frac{1}{4}} \text{ GeV}
\]

Time
\[
\text{time} = 10^{-36} \left( \frac{r}{0.01} \right)^{-\frac{1}{2}} \text{ seconds}
\]
lensing distorts E-mode to B-mode polarization

graphic from ESA website
CMB Polarization

Temperature

E modes

lensing B modes

B modes

r = 0.01

lensing of EE to BB
CMB Polarization

\[ r = 0.01 \]

\[ \sum m_\nu = 0 \]

\[ \sum m_\nu = 1.5 \text{ eV} \]

Temperature

E modes

B modes

lensing of EE to BB

lensing B modes
Polarization with mid to large telescopes

2.5m Huan Tran Telescope
bolo.berkeley.edu/polarbear

6m Atacama Cosmology Telescope
physics.princeton.edu/act/

10m South Pole Telescope
pole.uchicago.edu
Polarization with small aperture CMB telescopes

BICEP2 & 3 and KECK at South pole
bicepkeck.org

Also

Ground: ABS, QUBIC, QUIJOTE, GroundBird
Balloon: EBEX, PIPER, LSPE
Satellite proposals: LiteBIRD, PIXIE, CORE
Rapid progress. All within last 3 years.
Polarization status and future challenge

Inflationary gravity wave B modes

10 nK ➝ reionization bump
CLASS exploring from the ground;
LiteBIRD, PIXIE, & CORE satellites proposals

recombination bump
key target of CMB-S4

E modes
lensing B modes
inflationary gravity wave
B modes

... still a long, long way to go.
The next big steps

![Graph showing the increase in CMB sensitivity over time.](image)

**A Moore’s Law of CMB sensitivity**

- **Today**
- **Increasing sensitivity**

**Approximate raw experimental sensitivity (µK)**

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

**Year**

- 2000
- 2005
- 2010
- 2015
- 2020
### Sensitivity ($\mu K^2$)

<table>
<thead>
<tr>
<th>Year</th>
<th>Stage</th>
<th>Detectors</th>
<th>Sensitivity</th>
<th>$\sigma(r)$</th>
<th>$\sigma(N_{\text{eff}})$</th>
<th>$\sigma(\Sigma m_{\nu})$</th>
<th>Dark Energy F.O.M</th>
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<tbody>
<tr>
<td>2015</td>
<td>Stage 2</td>
<td>1000 detectors</td>
<td>$\approx 10^{-5}$</td>
<td>0.035</td>
<td>0.14</td>
<td>0.15 eV</td>
<td>Boss BAO prior</td>
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<td>2016</td>
<td>Stage 3</td>
<td>10,000 detectors</td>
<td>$10^{-6}$</td>
<td>0.006</td>
<td>0.06</td>
<td>0.06 eV</td>
<td>DES + BOSS SZ Clusters</td>
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<tr>
<td>2017</td>
<td>Stage 4</td>
<td>CMB-S4</td>
<td>$10^{-8}$</td>
<td>0.0005</td>
<td>0.027</td>
<td>0.015 eV</td>
<td>DESI BAO + $\tau_e$ prior</td>
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<td>2018</td>
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**Target** | $10^{-8}$ | 0.0005 | 0.027 | 0.015 eV | 1250

**Dark Energy F.O.M**

- Boss BAO prior
- DES + BOSS SZ Clusters
- DESI BAO + $\tau_e$ prior
- DESI + LSST S4 Clusters
Stage 4 CMB experiment: CMB-S4

- A next generation **ground-based** program to pursue **inflation**, **neutrino properties**, **dark radiation**, **dark energy** and new discoveries.

- Greater than tenfold increase in sensitivity of the combined Stage 3 experiments (>100x current Stage 2) to cross **critical science thresholds**.

- O(500,000) polarization sensitive detectors spanning 30 - 300 GHz using multiple telescopes at South Pole and Chile (and possibly northern sites) to map most of the sky, as well as deep targeted fields.

- Broad participation of the CMB community, including the existing CMB groups, e.g., **ACT, BICEP/KECK, CLASS, Polarbear & SPT**, the National Labs and the High Energy Physics community. International partnerships.

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*Scale of CMB-S4 exceeds capabilities of the University CMB groups.*

→ **Partnership of CMB community and National labs will do it.**
Community workshops to advance CMB-S4

U. Minnesota
Jan 16, 2015

LBNL, Berkeley
March 7-9, 2016

U. Michigan
Sep 21-22, 2015

Next: UChicago Sep 19-21 2016
Please attend - register at
https://kicp-workshops.uchicago.edu/cmb-s4-2016

1st edition Science Book complete!
Next: instrument definition and iterate with science goals
- **Ground**: Angular resolution for CMB lensing (+de-lensing B modes!), damping tail, clusters….

- **Space**: All sky for reionization peak; high frequencies for dust.

- Combined data would provide best constraints.
Polar Sun-Synch Orbit
- 660 km altitude, period = 97 min
- Precess once per orbit for zenith scan
- Full-sky coverage every 6 months

Cryogenic instrument in low-Earth orbit
- 4 multi-mode detectors
- Angular resolution 1.6°
- Spin at 4 RPM to sample Stokes Q/U

LiteBIRD (JAXA, ~2025)

CMB satellite proposals

LiteCORE (ESA M5 ~2026-2030)

All targeting $\sigma(r) \sim \text{few } 10^{-4}$
**Last words**

The CMB is the gift that keeps on giving.

Science is spectacular: we are searching for inflationary gravitational waves and will rigorously test single field slow roll inflation. We will determine the number and masses of the neutrinos, constrain possible new light relic particles, provide precise constraints on the nature of dark energy, test general relativity on large scales, and more…

CMB-S4 will be great leap forward.

- Science Book available at CMB-S4.org and will be posted on the archive soon.
- NSF and DOE are now requesting applications for CMB-S4 concept design team members (see posting at CMB-S4.org).
- Next workshop September 19-21, 2106 at U. Chicago [https://kicp-workshops.uchicago.edu/cmb-s4-2016](https://kicp-workshops.uchicago.edu/cmb-s4-2016)
backup slides
Science Book projection for CMB-S4 strawman configuration

Angular scale $\theta$ [degrees]

Temperature

E modes

Lensing B modes

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

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

Multipole number $\ell$
CMB lensing and optical surveys

CMB-S4 lensing will complement large optical surveys such as DES, DESI, LSST, Euclid, WFIRST, etc.

The combination leads to better shear-bias calibration and more robust constraints on Dark Energy and the properties of neutrinos. (e.g., Das, Errard, and Spergel, 2013)
Cosmology with SZ clusters

Tracing the growth of structure with evolution of massive galaxy clusters.

$\Sigma m_\nu = 0.14 \pm 0.08 \text{ eV}$
CMB-S4 Sunyaev-Zel’dovich (SZ) Cluster Survey:

• Cluster counts will depend on designed beam size, roughly:
  • 1’: 140,000 clusters
  • 2’: 70,000 clusters
  • 3’: 45,000 clusters

• Strong complementarity with LSST cluster survey:
  • Low scatter observable
  • High-redshift: >10,000 clusters at z > 1

CMB-lensing cluster mass scaling!
\[ \sigma(M) \sim 2 \times 10^{13} \] at z > 1 per 1000 clusters

Projection B. Benson
High resolution ground-based measurements excellent for de-lensing.
SPTpol: 1\textsuperscript{st} Detection of CMB B-mode Polarization

SPTpol Measured E-mode polarization + Lensing Potential from Herschel CIB → Predicted B-mode polarization

B-mode template to correlate with SPT B-mode map

SPTpol: 1\textsuperscript{st} Detection of CMB B-mode Polarization

\begin{align*}
\langle \hat{E}^{150} \phi \rangle \times \hat{B}^{150} \\
\langle \hat{E}^{95} \phi \rangle \times \hat{B}^{150} \\
\langle \hat{E}^{150} \phi \rangle \times \hat{B}^{150}_\chi
\end{align*}

null test

Also detected by Polarbear arXiv:1312.6645 & 1312.6646
**Combined Neutrino mass constraints**

Future Cosmology

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

\[ \text{Current Cosmology (95% U.L.)} \]

**Future Cosmology**

Current Cosmology (95% U.L.)

KATRIN c. 2020 (95% U.L.)

\[ \Sigma m_{\nu} \text{ (eV)} \]

\[ m_{\text{lightest}} \text{ (eV)} \]

\[ 10^{-3} \quad 10^{-2} \quad 10^{-1} \]

\[ 10^{0} \quad 10^{1} \quad 10^{2} \]

CMB-S4 + DESI BAO

Inverted Hierarchy

DUNE

Normal Hierarchy

“use cosmology to tighten the noose” Boris Kayser

arXiv:1309.5383
CMB-S4 lensing sensitivity to $\Sigma m_\nu$

Does not well measure curvature, so dependent on $\tau_e$

need $\tau_e$ measurement

Allison et al arXiv:1509.07471
$N_{\text{eff}}$ and CMB damping

fixing $\Omega_b h^2$, $z_{\text{EQ}}$, $\theta_s$

$\ell^2 D_\ell \left[ 10^8 \mu \text{K}^2 \right]$

Planck 2015

SPT-SZ

$N_{\text{eff}} = 1$

$N_{\text{eff}} = 2$

$N_{\text{eff}} = 3$

$N_{\text{eff}} = 4$

$N_{\text{eff}} = 5$
Artificially keep $\theta_d$ constant by increasing helium fraction, $Y_P$

**Helium fraction & $N_{eff}$ degeneracy**

$\ell^2 D_\ell \left[10^8 \mu K^2 \right]$

- Planck 2015
- SPT-SZ

$N_{eff} = 1$
$N_{eff} = 2$
$N_{eff} = 3$
$N_{eff} = 4$
$N_{eff} = 5$
Artificially keep $\theta_d$ constant by increasing helium fraction, $Y_P$.

$N_{\text{eff}}$ causes $\ell$-dependent phase offset that can be measured much more accurately in polarization spectra.

$N_{\text{eff}}$ is the extra relativistic energy density compared to photons. For standard 3 neutrinos, $N_{\text{eff}} = 3.046$. 
$N_{\text{eff}}$ & Helium fraction degeneracy

- Agreement with physics of
  1) Cosmic neutrino background at ~1 sec
  2) Light element production at ~3 min
  3) CMB emitted at ~380,000 years

- But we’d like to do much better!

$N_{\text{eff}} = 3.15 \pm 0.23$ (along BBN consistency curve)
$N_{\text{eff}} = 3.14 \pm 0.44$ (marginalizing over $Y_P$)

Highly significant detection of neutrino background
“Pessimistic” ν degeneracy forecasts
Allison et al., 1509.0747

for CMB-S4 (3 arcmin res, ℓ > 20) + DESI BAO:

\[ \Sigma m_\nu = 19 \, \text{meV} \ (\Lambda CDM + \Sigma m_\nu) \]
\[ = 30 \, \text{meV} \ (\Lambda CDM + \Sigma m_\nu + \Omega_k) \]
\[ = 27 \, \text{meV} \ (\Lambda CDM + \Sigma m_\nu + w_0) \]
\[ = 46 \, \text{meV} \ (\Lambda CDM + \Sigma m_\nu + w_0 + w_a) \]
\[ = 64 \, \text{meV} \ (\Lambda CDM + \Sigma m_\nu + w_0 + w_a + \Omega_k) \]
"Optimistic" v forecasts
Pan & Knox 1506.07493

\[ \Sigma m_\nu = 9 \text{ meV (} \Lambda \text{CDM} + \Sigma m_\nu) \]
for CMB-S4 (\(\ell > 5\)) + DESI BAO + DESI RSD
Complementarity of Neutrino mass constraints

FIG. 1: Projected constraints on neutrino parameters from upcoming cosmic surveys (vertical), neutrino-less double beta decay experiments (horizontal), and all other current measurements (gray) assuming an inverted mass hierarchy and Majorana neutrinos.

FIG. 3: If the mass hierarchy is normal but the sum of the masses is still relatively large, for example at the value indicated by the star, then there will be a lower limit on $m_{\beta\beta}$, a target for ambitious future double beta decay experiments.