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, $(\Sigma m_\nu)$ 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
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High angular resolution (high-\(\ell\)) CMB measurements

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

10m South Pole Telescope
pole.uchicago.edu

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 deg$^2$
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

Ground based high resolution
50 deg²

Clusters of Galaxies

S-Z effect: “Shadows” in the microwave background from clusters of galaxies
Angular power spectrum of primary CMB anisotropy

Figure from Planck 2015 Results XI

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?

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Angular power spectrum of primary CMB anisotropy

Fit by standard ΛCDM - only six parameters - $\Omega_\text{b}h^2$, $\Omega_\text{c}h^2$, $\theta_s$, $A_s$, $n_s$, $\tau_e$

Cosmic Variance limited

Can be improved

Only ~ 10% of sky measured

Figure from Planck 2015 Results XI
Angular Scale

$D_i (\mu K^2)$

$\ell$

primary CMB (cosmology)

secondary CMB (cosmology & astrophysics)

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

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

- RMS deflection of ~2.5’
- Lensing efficiency peaks at $z \sim 2$
- Coherent on ~degree (~300 Mpc) scales
Planck lensing potential reconstruction (projected mass map).
Great progress, but still a long, way to go.
What about physics constraints? Can they be improved?

Enormous precision and accuracy:

Flat universe ($\Omega_k < 0.005$)

$\Omega_b h^2 = 0.02222 \pm 0.00023$

$\Omega_c h^2 = 0.1197 \pm 0.0022$

($>50\sigma$ detection of non-baryonic dark matter)

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

Inflation checklist:

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

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

at decoupling

0.5 eV
0.05 eV
0 eV
Neutrinos
- transition to part of matter budget today

Matter/Radiation Equality
Decoupling

Λ (dark energy)

CDM, baryons

Energy Density [eV/cm$^3$]

Redshift $z$

Scale Factor $\alpha$

Atoms 4.6%
Dark Matter 23%
Dark Energy 72%

neutrinos
- 0.5 eV
- 0.05 eV
- 0 eV
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!

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

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

$N_{\text{eff}}$ measurements can constrain light thermal relics

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

Baumann, Green, Wallisch arXiv:1604.08614
CMB-S4 Science Book (http://CMB-S4.org)
CMB Polarization

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

- Temperature
- E modes
- B modes
- Inflationary Gravitational wave oscillations
- reionization bump
- recombination bump
- density oscillations
Tensor (gravitational) perturbation amplitude
Scalar (density) perturbation amplitude

\[ r = 0.1, 2 \times 10^{16} \text{GeV} \]

\[ r = 0.01 \]

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

\[ \text{time} = 10^{-36} \left( \frac{r}{0.01} \right)^{-\frac{1}{2}} \text{seconds} \]
CMB Polarization

Temperature

E modes

B modes

lensing B modes

lensing of EE to BB

$\ell$-dependence of $C_\ell$ for CMB polarization modes. The $E$-modes are shown in red, the $B$-modes in green, and the temperature component in black. The parameter $r = 0.01$ indicates the level of primordial gravitational waves. The graph displays the angular power spectrum $C_\ell$ normalized by $(2\pi)^2$ in units of $\mu$K^2.
CMB Polarization

Temperature

E modes
B modes

lensing of EE to BB

$\sum m_\nu = 0$
$\sum m_\nu = 1.5 \text{ eV}$

$r = 0.01$
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

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

10 nK

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

angular scale $\theta$ [degrees]

100.0 10.0 1.0 0.1

$10^0$ $10^{-2}$ $10^{-4}$

E modes
lensing B modes
inflationary gravity wave B modes

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

recombination bump
key target of CMB-S4

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

A Moore’s Law of CMB sensitivity
<table>
<thead>
<tr>
<th>Year</th>
<th>Stage</th>
<th>Detectors</th>
<th>Sensitivity ($\mu K^2$)</th>
<th>$\sigma(r)$</th>
<th>$\sigma(N_{\text{eff}})$</th>
<th>$\sigma(\Sigma m_\nu)$</th>
<th>Dark Energy F.O.M</th>
</tr>
</thead>
<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>~180</td>
</tr>
<tr>
<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>~300-600</td>
</tr>
<tr>
<td>2017</td>
<td>Stage 4 CMB-S4</td>
<td>~500,000 detectors</td>
<td>$10^{-8}$</td>
<td>0.0005</td>
<td>0.027</td>
<td>0.015 eV</td>
<td>1250</td>
</tr>
</tbody>
</table>

**Target:**

- **Sensitivity ($\mu K^2$)**: $10^{-8}$
- **$\sigma(r)$**: 0.0005
- **$\sigma(N_{\text{eff}})$**: 0.027
- **$\sigma(\Sigma m_\nu)$**: 0.015 eV
- **Dark Energy F.O.M**: 1250

**Note:**

- Boss BAO prior
- DES + BOSS SPT clusters
- DES + DESI SZ Clusters
- 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/Simons Array & SPT, the National Labs and the HEP community. International partnerships.

*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.
Instrument and Observatory

**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-moded detectors
- Angular resolution 1.6°
- Spin at 4 RPM to sample Stokes Q/U

CMB satellite proposals

**LiteBIRD** (JAXA, ~2025)

**LiteCORE** (ESA M5 ~2026-2030)

**PIXIE** (NASA MIDEX ~2023)

Lite (Light) Satellite for the Studies of B-mode Polarization and Inflation from Cosmic Background Radiation Detection

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
backup slides
Science Book projection for CMB-S4 strawman configuration
Cosmology with SZ clusters

Tracing the growth of structure with evolution of massive galaxy clusters.
CMB-S4 SZ cluster projections

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:
\[ \sigma(M) \sim 2 \times 10^{13} \text{ at } z > 1 \text{ per 1000 clusters} \]
High resolution ground-based measurements excellent for de-lensing.
SPTpol: 1st Detection of CMB B-mode Polarization

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

100 deg^2 survey

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

SPTpol: 1st Detection of CMB B-mode Polarization

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

Null test

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

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

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


Also detected by Polarbear arXiv:1312.6645 & 1312.6646
\[ \sum m_\nu \geq 58 \text{ meV} \]

Diagram illustrating the normal hierarchy (NH) and inverted hierarchy (IH) with mass-squared differences \( \Delta m^2_{\text{atm}} \) and \( \Delta m^2_{\text{sol}} \).

- **Normal Hierarchy (NH):**
  - \( \nu_1, \nu_2, \nu_3 \) with \( \nu_e, \nu_\mu, \nu_\tau \) below.
  - \( \Delta m^2_{\text{atm}} \) and \( \Delta m^2_{\text{sol}} \) differences.

- **Inverted Hierarchy (IH):**
  - \( \nu_1, \nu_2, \nu_3 \) with \( \nu_e, \nu_\mu, \nu_\tau \) above.
  - \( \Delta m^2_{\text{atm}} \) and \( \Delta m^2_{\text{sol}} \) differences.

\[ \sum m_\nu \geq 100 \text{ meV} \]
Combined Neutrino mass constraints

Future Cosmology
σ(Σm_ν) = 16 meV

“use cosmology to tighten the noose” Boris Kayser
CMB-S4 lensing sensitivity to $\Sigma m_\nu$

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

need $\tau_e$ measurement
$N_{\text{eff}}$ and CMB damping

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

Planck 2015
SPT-SZ
Artificially keep $\theta_d$ constant by increasing helium fraction, $Y_P$.
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.

$N_{\text{eff}}$ 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” $\nu$ degeneracy forecasts
Allison et al., 1509.0747

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

$$\Sigma m_\nu = 19 \text{ meV} \ (\Lambda CDM + \Sigma m_\nu)$$
$$= 30 \text{ meV} \ (\Lambda CDM + \Sigma m_\nu + \Omega_k)$$
$$= 27 \text{ meV} \ (\Lambda CDM + \Sigma m_\nu + w_0)$$
$$= 46 \text{ meV} \ (\Lambda CDM + \Sigma m_\nu + w_0 + w_a)$$
$$= 64 \text{ meV} \ (\Lambda CDM + \Sigma m_\nu + w_0 + w_a + \Omega_k)$$
\[ \sum m_\nu = 9 \text{ meV} \text{ (} \Lambda CDM + \sum m_\nu \text{)} \]

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.