CMB Stage 4 Update

John Carlstrom for CMB-S4 collaboration
AAAC January 28, 2016
Stage IV CMB experiment: CMB-S4

• CMB-S4: a next generation ground-based program building on CMB stage 2 & 3 projects to pursue inflation, neutrino properties, dark energy and new discoveries.

• Targeting to deploy $O(500,000)$ detectors spanning 30 - 300 GHz using multiple telescopes and sites to map most of the sky to provide sensitivity to cross critical science thresholds.

• Multi-agency effort (DOE & NSF). Complementary with balloon and space-based instruments.

• Broad participation of the US CMB community, including the existing NSF CMB groups, DOE National Labs and the High Energy Physics community.

• U.S. led program; international partnerships expected.

A science driven program combining the deep CMB experience of the university groups with the expertise and resources at the national labs.
Stage IV CMB experiment: CMB-S4

The future enabled by CMB-S4:
- Detect or rule out generic slow roll inflation, $E \sim 10^{16}$ GeV
- Measure the sum of the neutrino masses
- Cosmological test of neutrino interactions and additional light species.
- Greatly improve Dark Energy constraints and test General Relativity on large scales.
- More fundamental discoveries?

Path Forward is clear. Required Technologies are in the pipeline. Next Steps: Scaling to $O(500,000)$ detectors.
The Universe as a Physics Laboratory

Inflation?
period of accelerated expansion at \( \sim 10^{-35} \) seconds generates gravitational wave background

Cosmic neutrino background at 1 second

Cosmic microwave background

The CMB gains us access to energy scales of order \( 10^{16} \) GeV
Inflation? accelerated expansion
Universe expands by $> e^{60}$

- Measure primordial fluctuations
- non-Gaussianity?
- constrain tensor to scalar fluctuations, inflationary gravitational waves?

→ through precision temperature and ultra-sensitive polarization measurements of the primary CMB anisotropy
Physics at recombination

Universe cools enough to form neutral H. Photons start free-streaming

- Measure dynamics; inventory stuff in the universe
- Number of relativistic species, helium abundance
- Recombination history; energy injection

➡ through precision measurement of CMB power spectrum to fine angular scales, i.e., covering the “damping” tail
➡ eventually through spectral distortions and recombination lines
Reionization “Cosmic Dawn”

When and how did it proceed?

- through measurement of polarization on large angular scales
- through measurements of the diffuse kinematic SZ effect on small angular scales
Structure Formation
- Gravitational collapse creates increasingly large structures
  - Properties of dark matter
  - Masses of the neutrinos

Cosmic Acceleration
- Dark energy begins accelerating the expansion of the Universe.
  - Is dark energy dynamic or a cosmological constant?
  - Is GR correct on large scales?

- structure formation through lensing of the CMB and kinematic SZ effect
- measure evolution of Galaxy Clusters through thermal SZ effect
Planck
50 deg$^2$

2x finer angular resolution
7x deeper
Ground based high resolution
50 deg²

13x finer angular resolution

50x deeper
Ground based high resolution 50 deg$^2$

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 deg$^2$
Everything cosmology & astrophysics

need more and better T and Pol high ell data

primary CMB (cosmology)

Story et al., 2013
George et al., 2014
Das et al., 2014
Angular Power Spectrum

Fit by standard $\Lambda$CDM - only six parameters -
$\Omega_b h^2$ $\Omega_c h^2$ $\Omega_\Lambda$ $\Delta^2_R$ $n_s$ $\tau_e$

Figure from Planck 2015 Results XI
Are we finished with primary CMB Temperature anisotropy measurements?

Fit by standard $\Lambda$CDM - only six parameters - $\Omega_b h^2 \Omega_c h^2 \Omega_{\Lambda} \Delta^2 R \, n_s \, \tau_e$

Angular scale

Figure from Planck 2015 Results XI
What about physics constraints? Can they be improved?

Enormous precision and accuracy:

- Flat universe \( (\Omega_k < 0.005) \)
  - \( \Omega_b h^2 = 0.0226 \pm 0.00023 \)
  - \( \Omega_c h^2 = 0.1186 \pm 0.0026 \)  
  (>40σ difference of \( \Omega_c \) & \( \Omega_b \))

But extensions to ΛCDM model are poorly constrained.

especially need polarization
What about physics constraints?

Inflation?

Inflation checklist:

- ✓ Flat geometry
- ✓ Super horizon features
- ✓ Harmonic peaks
- ✓ Adiabatic fluctuations
- ✓ Gaussian random fields
- ✓ Departure from scale invariance!
- Inflationary gravitational waves (tensors)!

Requires CMB B-mode polarization data
What about physics constraints? Neutrinos?

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

> 10σ detection of cosmic neutrino background!

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

Can do much better!
- Determine the masses
- Show $N_{\text{eff}} = 3.046$ or point the way to new physics

$N_{\text{eff}}$ is the effective number of light relativistic species, for std model $N_{\text{eff}} = 3.046$
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
- Introduces correlations in CMB multipoles
CMB lensing and optical surveys

CMB lensing reconstruction of mass maps sensitive to growth of structure, probe neutrino mass

CMB lensing will complement large optical surveys such as DES, eBOSS, LSST, DESI, 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)
Polarization of the CMB

![Graph showing polarization spectra](image)

- **TT**: Smooth curve indicating temperature temperature anisotropies.
- **EE**: Oscillating curve indicating polarization anisotropies.

Density oscillations are evident in the EE spectrum.
Polarization of the CMB

- Density oscillations
- Inflationary Gravitational wave oscillations
- Polarization of the CMB
- Reionization bump
- Recombination bump
- EE
- BB_{IGW}
Polarization of the CMB

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

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

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

![Graph showing polarization of the CMB with labels for TT, EE, BB\textsubscript{IGW}, and BB\textsubscript{lensing}, along with a notable feature at r = 0.01.](image)
Polarization with large aperture CMB 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

Spider balloon experiment spider.princeton.edu

Deploying: CLASS large angular scale experiment in Chile sites.krieger.jhu.edu/class/

Also

Ground: ABS, QUBIC, QUIJOTE, GroundBird

Balloon: EBEX, PIPER, LSPE

Satellite proposals: LiteBird, PIXIE
Polarization of the CMB

Rapid progress! All in last ~2 years.
Polarization of the CMB

Incredible progress but a still a long, long way to go... Need CMB-S4

Key targets of CMB-S4:
- **Recombination bump** for $r > 0.001$
- **Entropy bump**
- **De-lensing**
- **Spectral cleaning**

**Ground-based exploration**
- **Reionization bump**
- **Inflationary gravity wave B modes**

- 10 nK
Strawman CMB-S4 specifications

• **Survey(s):**
  - Inflation, Neutrino, and Dark Energy science requires an optimized survey(s) using a range of resolution and sky coverage from deep to wide.

• **Sensitivity:**
  - polarization sensitivity of $\sim 1$ uK-arcmin over $\geq 70\%$ of the sky, and better on deep field(s).

• **Resolution:**
  - exquisite low-$\ell$ and high-$\ell$ coverage for inflationary B modes
  - $\ell_{\text{max}} \sim 5000$ for CMB lensing & neutrino science (arc minutes)
  - higher-$\ell$ improves dark energy constraints, gravity tests on large scales via the $\Sigma Z$ effects, mapping the universe in momentum, $n_s$, and ancillary science.

• **Configuration:**
  - $O(500,000)$ detectors on multiple telescopes (small and large aperture)
  - spanning $\sim 30 - 300$ GHz for foreground mitigation
Angular range of CMB-S4

- High-\(\ell\) for dark energy and gravity
- High-\(\ell\) and large area for cosmic variance limited constraints on neutrino mass and \(N_{\text{eff}}\)
- Inflationary B modes search requires exquisite sensitivity at both low-\(\ell\) and high-\(\ell\) because of need for de-lensing.
Angular range of CMB-S4

- High-$\ell$ for dark energy and gravity
- High-$\ell$ and large area for cosmic variance limited constraints on neutrino mass and $N_{\text{eff}}$
- Inflationary B modes search requires exquisite sensitivity at both low-$\ell$ and high-$\ell$ because of need for de-lensing.

High resolution ground-based measurements excellent for de-lensing, especially for deep fields.

from Smith et al., CMBpol Mission Study arXiv:0811.2916
Inflation reach of CMB-S4

Single Field Slow Roll models

CMB polarization provides the only probe for $r < 0.1$
Snowmass CMB-S4 forecasters: J. Errard, P. McDonald, A. Slosar, K. Wu, O. Zahn
Expectations for SZ Cluster Surveys

<table>
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<th>Stage</th>
<th>$N_{\text{clust}}$</th>
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<td>$\sim 1,000$</td>
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<td>Stage 3</td>
<td>$\sim 10,000$</td>
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<tr>
<td>CMB-S4</td>
<td>$\sim 100,000$</td>
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</table>

CMB lensing will directly calibrate cluster mass SZ scaling:

**CMB-S4:** $\sigma(M) \sim 0.1\%$

for an extremely powerful probe of structure formation and dark energy.

Also kSZ measurements of momentum and tests of gravity on large scales.
What’s needed to realize CMB-S4

- **Scaling up:**
  - detectors, focal planes
  - sky area and frequency coverage
  - multiple telescopes; new designs
  - computation, data analysis, simulations
  - project management

- **Systematics:**
  - improved control, especially of foreground mitigation

- **Theory/phenomenology:**
  - Increased precision for analysis; new methods

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

→ Partnership of CMB community and DOE labs will do it.
Scalable background limited, broadband bolometric detectors.

NIST/Truce collab

Caltech/JPL

UCB/Polarbear

ANL/SPT-3G
Maintaining Moore's Law: focal planes are saturated so must use parallel processing and multiple telescopes.

Stage 2
Now
~1000 detectors

Stage 3
ramping up
~10,000 detectors

Stage 4
CMB-S4
~500,000 detectors

increasing detector count
Greatly enhance DES, DESI and LSST science by overlapping sky

Coverage from Chile and South Pole
70% of the sky, overlapping the large optical surveys

Possibly add northern site for full sky coverage: Tibet? Greenland?
May provide opportunity for international partner.
Recent South Pole CMB experiments at NSF’s Amundsen-Scott Research Station
Recent & upcoming Atacama CMB experiments

- CLASS 1.5m
- Polarbear 2.5m
- Simons 2.5m
- ACT 6m
- Simons 2.5m

Site access arranged by MOU with CONICYT

Photo: Rahul Datta & Alessandro Schillaci
Moving CMB-S4 forward

"Cosmology with CMB-S4" workshop at U. Michigan Sep 21-22, 2015
Community driven progress

• 2013: Community came together to produce and endorse Snowmass documents and need for stage 4 ground based project.

Includes appendix on:
“A Stage-IV CMB experiment, CMB-S4”
arXiv:1309.5383

arXiv:1309.5381
Community driven progress

- 2013/2014: Major US ground based CMB groups and DOE lab representatives came together to provide input on CMB-S4 to the Particle Physics Project Prioritization Panel (P5).


- 2015: CMB-S4 one of only three priorities identified in the NRC report “A Strategic Vision for NSF Investments in Antarctic and Southern Ocean Research.”

- 2015 - Ongoing DOE Cosmic Visions CMB group made up of representatives from the DOE CMB scientists, management and from the major ground-based CMB projects.

C-V group provides DOE with link to CMB community and input for DOE planning (monthly telecons with K. Turner and E. Linder). Produced three “planning” documents on CMB-S4: Science; Technical; and Programmatic.
Community driven progress

- **2015 - CMB-S4 Community workshops** every ~six months.
  - “Cosmology with the CMB and its Polarization” at UMN January 16, 2015. Day dedicated to CMB-S4 discussion.
  - “Cosmology with CMB-S4 Collaboration Workshop” at the LBNL, Berkeley, March 7-8, 2016.
  - “CMB-S4” at the University of Chicago ~Sep 2016.
Community driven progress

• Now: Initial writing teams producing first draft of the Science Book “science” chapters based on output of Michigan workshop. Will distribute to entire CMB-S4 community for feedback prior to March Berkeley workshop.

Inflation:
- R. Flauger
- J. Dunkley
- J. Kovac
- L. Knox*
- C-L Kuo
- M. Peloso
- S. Shandera
- E. Silverstein
- L. Sorbo
- K. Wu
  (building on SnowMass)

Neutrinos:
- K. Abazajian
- G. Fuller
- A. Friedland
- D. Green*
- A. Kusaka
- M. Loverde
- A. Slosar
  (building on SnowMass)

D.E. & Gravity
- B. Benson
- J. Barlett
- F. de Bernardis
- R. Caldwell
- C. Dvorkin
- S. Dodelson
- B. Holzapfel
- W. Hu*
- M. Raveri
- S. Staggs

CMB-lensing
- A. van Engelen
- S. Dodelson
- G. Holder
- Madhavacheril
- N. Seghal*
- B. Sherwin
- K. Story

Analysis & Sims
- N. Battaglia
- J. Borrill
- T. Crawford*
- J. Delabrouille
- J. Dunkley
- J. Kovac
- C. Pryke
Agency roles in CMB-S4

NSF
- Funds the world leading ground based CMB efforts (AST, PHY & PLR).
- Leads Stage 2 and 3 efforts, with small but key contributions from DOE
- Critical role in sustaining university efforts into CMB-S4
  - possibly capital investment from NSF in new CMB telescopes

DOE
- Key contributions to Stage 2 & 3 efforts
  - Detectors, Readout, Computing, large cryogenic components
- Critical role for DOE in scaling up for CMB-S4

NSF and DOE activities will need to be carefully coordinated for CMB-S4.
Agency roles in CMB-S4

NASA

- Independent of planned CMB-S4 effort, but fundamentally complementary:
  - Complementary detector technology (JPL, GSFC)
  - Ballooning program $\rightarrow$ high-$\nu$, low-$\ell$: foregrounds, possibly reionization bump
  - Involvement in possible Japanese (JAXA) satellite Litebird
    $\rightarrow$ high-$\nu$, low-$\ell$; foregrounds, reionization bump, $\tau_e$
  - PIXIE satellite possibility $\rightarrow$ spectral coverage, low-$\ell$; foregrounds, reionization bump, $\tau_e$
Complementarity strengths of ground and space

- **Ground**: Resolution required for CMB lensing (+delensing!), damping tail, clusters….

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

- Combined CMB-S4 and NASA mission data would improve constraints.
Last words

CMB-S4 will be a great leap for CMB measurements, cosmology and astrophysics.

The community is behind it and we are moving forward. The biggest challenge is scaling up.

The CMB is the gift that keeps on giving. With the next generation CMB measurements we will be searching for inflationary gravitational waves and rigorously testing single field slow roll inflation, determining the neutrino masses, mapping the universe in momentum, investigating dark energy, testing general relativity and more.
backup slides
CMB-S4 FAQs

1. Why not do it all from space?
   - CMB-S4 is the next logical step for U.S. ground-based CMB. All the pieces are in place.
   - CMB-S4 program could flow seamlessly from Stage 3, continuing science output.
   - It would take an extremely ambitious and expensive mission to do it all from space. CMB-S4 can obtain its goals from the ground much sooner and cheaper.
   - CMB-S4 could inform a future space mission.
CMB-S4 FAQs

2. Why not wait to see what Stage 3 does (and downselect technology)?

- The Stage 3 groups and the extended community are planning CMB-S4 and developing the technology. They will optimize the technology, especially for scaling up, but no major downselects are expected. The basic technologies are in place, and so are the people.

- CMB-S4 goals are beyond the reach of Stage 3 experiments (but not the aspirations of the Stage 3 groups!).

- Information learned from Stage 3 (e.g., foregrounds, $r$) can be easily incorporated into CMB-S4 (see planning flow chart).

- CMB-S4 is timely because it will enhance the science return from other cosmic surveys (e.g., LSST, DESI).
3. Why not have another CMB task force report?

- P5 has endorsed CMB and CMB-S4. The NRC report “A Strategic Vision for NSF Investments in Antarctic and Southern Ocean Research” chose CMB-S4 as one its three priorities.

- CMB-S4 is the natural next step. We do not feel another review of the field is necessary for planning the future ground-based program.

- The U.S. leaders and practitioners of the field are working to optimize the science and the technology of CMB-S4. It is an open community effort. It will undergo a more exhaustive examination and optimization than can be achieved by a task force.

- The people who would serve on a task force for ground based CMB are a subset of the people already involved in CMB-S4.
Plan optimum multi-band, ground-based survey to target inflation, neutrino properties and dark energy. Degree (recombination bump) to arcminute (CMB lensing, D.E.) resolution over $\approx 70\%$ of sky

- **r $\geq 0.05$?**
  - Re-optimize B-mode and de-lensing survey to constrain $n_T$

- **Improved knowledge of foregrounds?**
  - Re-optimize bands at the focal plane level

- **r $\geq 0.01$?**
  - Optimize survey for cosmic variance limited $r$ measurement

- **r $< 0.01$?**
  - Optimize survey for highest $r$ sensitivity, $\sigma(r) < 10^{-4}$

- **Exploit synergy of satellite frequency coverage at low ell (reionization bump) with CMB-S4 at higher ell (recombination bump and de-lensing) for B-mode science. No change to neutrino & DE plan.**

- **Adapt low-ell strategy to target reionization bump B-modes?**

- **Maintain CMB-S4 strategy for precision mass determination.**

- **Litebird satellite decision?**

- **PIXIE satellite decision?**

- **Stage 3 demonstration of low ell feasibility?**

- **Evidence for high neutrino mass?**

**CMB-S4 Ops**
Scheduling considerations for CMB-S4

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Steady stream of science on way to CMB-S4 achieving critical thresholds in inflation and neutrinos.
# CMBR participants

## Directorship

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<tr>
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<th>Institution</th>
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<tr>
<td>Carlstrom, John</td>
<td>U. Chicago</td>
<td>Director</td>
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<tr>
<td>Page, Lyman</td>
<td>Princeton</td>
<td>Co-Director</td>
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<td>Meyer, Stephan</td>
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<tr>
<td>Basri, Gibor</td>
<td>U.C. Berkeley</td>
<td>Diversity Officer</td>
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<tr>
<td>TBD</td>
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## Internal Guiding Board

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<td>U. Penn</td>
<td>Harvard U.</td>
</tr>
<tr>
<td>Holzapfel, Bill</td>
<td>U.C. Berkeley</td>
<td>U.C. Berkeley</td>
</tr>
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</table>

## Coordinators

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
<th>Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stassun, Keivan</td>
<td>Fisk</td>
<td>Education, Diversity and Outreach (EDO)</td>
</tr>
<tr>
<td>TBD</td>
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<td>EDO Executive Coordinator</td>
</tr>
<tr>
<td>Lloyd Knox</td>
<td>U.C. Davis</td>
<td>Physics &amp; Cosmology</td>
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<tr>
<td>Padin, Steve</td>
<td>Caltech</td>
<td>Technology and Methods</td>
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## Center Council

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
<th>Role</th>
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<tbody>
<tr>
<td>Arnold, Kam</td>
<td>UCSD</td>
<td>Hu, Wayne</td>
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<td>Bean, Rachel</td>
<td>Cornell</td>
<td>Johnson, Bradley</td>
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<td>Bennett, Charles</td>
<td>JHU</td>
<td>Jones, Bill</td>
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<td>Benson, Bradford</td>
<td>FNAL</td>
<td>Kamionkowski, Marc</td>
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<td>Bock, Jamie</td>
<td>Caltech</td>
<td>Keating, Brian</td>
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<td>Burger, Arnold</td>
<td>Fisk U.</td>
<td>Kosowsky, Arthur</td>
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<tr>
<td>Chang, Clarence</td>
<td>ANL</td>
<td>Kuo, Chao-Lin</td>
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<td>Crawford, Tom</td>
<td>U. Chicago</td>
<td>Kusaka, Akito</td>
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<td>Dodelson, Scott</td>
<td>FNAL</td>
<td>Landsberg, Randy</td>
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<td>Filippini, Jeff</td>
<td>UIUC</td>
<td>Leitch, Erik</td>
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<td>Flauger, Raphael</td>
<td>CMU</td>
<td>LoVerde, Marilena</td>
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<td>Halverson, Nils</td>
<td>CU Boulder</td>
<td>Lubin, Phil</td>
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<td>Hanany, Shaul</td>
<td>UMN</td>
<td>Marriage, Toby</td>
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<td>Heitmann, Katrin</td>
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<td>Mauskopf, Phil</td>
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<td>Hirata, Chris</td>
<td>OSU</td>
<td>McMahon, Jeff</td>
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<tr>
<td>Ho, Shirley</td>
<td>CMU</td>
<td>Meinhold, Peter</td>
</tr>
</tbody>
</table>

## Other Institutions

- Columbia
- Case Western
- Caltech
- OSU
- Haverford
- Penn State
- U.C. Berkeley
- U.W Madison
- IUUC
- U. Chicago
- IAS
# Technology Status, Next Steps & Needs

<table>
<thead>
<tr>
<th>Technology area</th>
<th>Critical next steps</th>
<th>Ongoing lab efforts</th>
<th>Needs</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Performance Computing (HPC)</td>
<td>Scale current CMB mission simulation &amp; analysis capability to:</td>
<td>LBNL is simulating &amp; mapping full CMB mission data sets;</td>
<td>Invest in computational science (transitioning from Planck).</td>
</tr>
<tr>
<td></td>
<td>- 1000x data volume</td>
<td>ANL, FNL, LBNL &amp; SLAC (and many university groups) are performing various S3 analyses.</td>
<td>Continue to provide significant HPC resources.</td>
</tr>
<tr>
<td></td>
<td>- next-generation HPC architectures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Detectors</td>
<td>Develop plans for increasing fab throughput to ~100 wafers/yr (requires multiple fab facilities)</td>
<td>SLAC, LBNL &amp; ANL are building fab facilities;</td>
<td>Major investment in fab resources</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ANL is fabricating detectors for SPT-3G</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>FNAL, SLAC, LBNL &amp; ANL are testing materials and building detector test facilities;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(several university groups can each test ~2 wafers/month)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>FNAL, SLAC, LBNL &amp; ANL are working on detector designs;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(ongoing effort in several university groups)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Invest in test facilities</td>
</tr>
<tr>
<td></td>
<td>Demonstration of new bands (for foreground removal)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Invest in detector design work</td>
</tr>
<tr>
<td>Optics</td>
<td>Demonstration of large lenses with broadband anti-reflection coatings</td>
<td>SLAC is making lenses for SPT-3G;</td>
<td>Invest in lens development</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SLAC &amp; LBNL are working on AR coatings;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(ongoing effort in several university groups)</td>
<td></td>
</tr>
<tr>
<td>Platforms, shields, pol modulation, camera configuration, cryogenics, detector readout electronics, camera integration, control architecture</td>
<td>Choose candidate technologies from S2 &amp; S3 experiments</td>
<td>LBNL is developing pol modulators;</td>
<td>Continue LDRD &amp; Start DOE HEP office support</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FNAL is integrating the SPT-3G camera;</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>LBNL is working detector module integration;</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>(ongoing effort in several university groups)</td>
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</tbody>
</table>
“use cosmology to tighten the noose”  Boris Kayser
Snowmass joint projections $N_{\text{eff}} - \Sigma m_\nu$

$\sigma(N_{\text{eff}}) = 0.020$

CMB uniquely probes $N_{\text{eff}}$

$\sigma(\Sigma m_\nu) = 16 \text{ meV}$
(with DESI BAO)
## P5 Summary of Scenarios

<table>
<thead>
<tr>
<th>Project/Activity</th>
<th>Scenario A</th>
<th>Scenario B</th>
<th>Scenario C</th>
<th>Science Drivers</th>
<th>Technique (Frontier)</th>
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<tbody>
<tr>
<td><strong>Medium Projects</strong></td>
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<tr>
<td>LSST</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>✓</td>
<td>C</td>
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<tr>
<td>DM G2</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>✓</td>
<td>C</td>
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<tr>
<td>Small Projects Portfolio</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>✓</td>
<td>All</td>
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<tr>
<td>Accelerator R&amp;D and Test Facilities</td>
<td>Y, reduced</td>
<td>Y, some reductions with redirection to PIP-II development</td>
<td>Y, enhanced</td>
<td>✓</td>
<td>E, I</td>
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<tr>
<td>CMB-S4</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>✓</td>
<td>?</td>
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<tr>
<td>DM G3</td>
<td>Y, reduced</td>
<td>Y</td>
<td>Y</td>
<td>✓</td>
<td>C</td>
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<tr>
<td>PINGU</td>
<td>Further development of concept encouraged</td>
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<td>ORKA</td>
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<td>LAr1</td>
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### P5’s Timelines

<table>
<thead>
<tr>
<th>Project</th>
<th>2015</th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
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<tr>
<td>Currently operating</td>
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<td>Large Projects</td>
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<tr>
<td>Mu2e</td>
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<tr>
<td>LHC: Phase 1 upgrade</td>
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<td>HL-LHC</td>
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<td>LBNF</td>
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<tr>
<td>CMB S4</td>
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</table>

CMB-S4 ramps up as LSST ramps down.
Neutrinos - fully relativistic at decoupling

Redshift $z$

Energy Density [eV/cm$^3$]

Scale Factor $\alpha$

CDM, baryons

Neutrinos $0.5$ eV

Photons $0.05$ eV

Atoms $0$ eV

Dark Matter $63\%$

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

at decoupling

$\Lambda$ (dark energy)

neutrinos

$0$ eV
Neutrinos - transition to become part of matter budget today.

The graph illustrates the energy density of different components over the scale factor and redshift. Atoms dominate at high redshift, while neutrinos transition to become part of the matter budget today. The pie chart on the right shows the distribution of energy components, with dark energy accounting for 72%, dark matter for 23%, and atoms for 4.6%. The energy densities are marked as 0 eV, 0.05 eV, and 0.5 eV, respectively.
CMB lensing power spectrum

Sensitive to the neutrino masses, $\Sigma m_\nu$