The CMB-S4 Experiment
Science and Instruments

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for the CMB-S4 Collaboration
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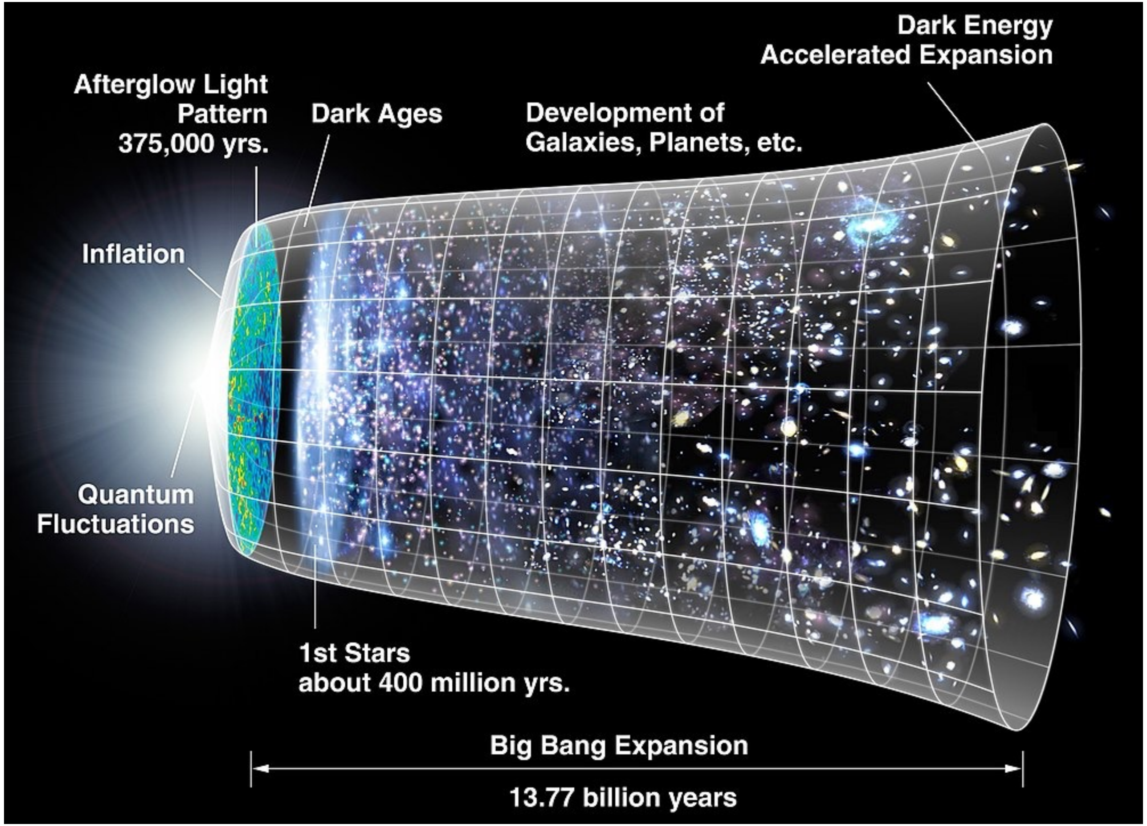
NSF
CMB-S4
U.S. DEPARTMENT OF ENERGY | Office of Science

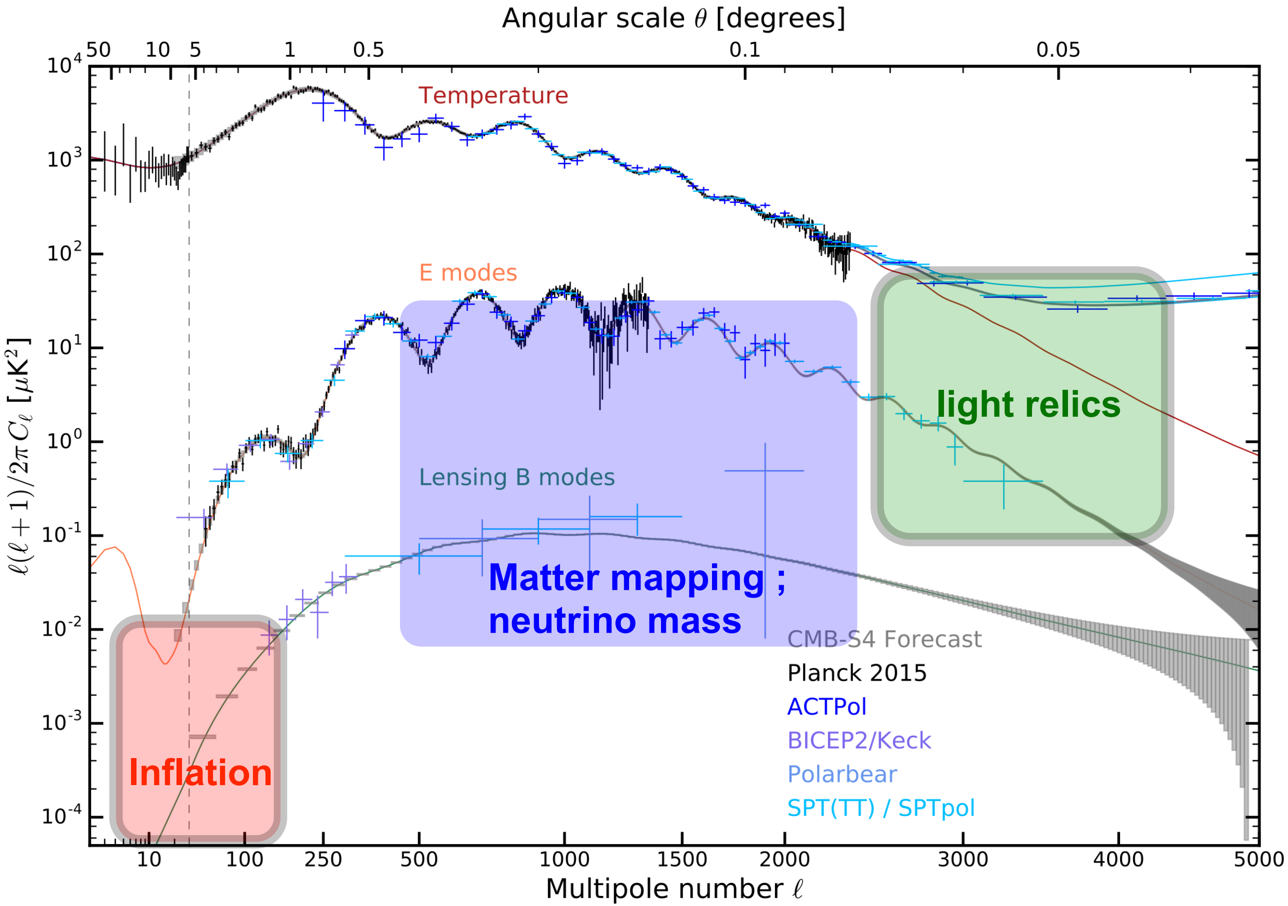
A Unique Probe of Fundamental Physics



The cosmic microwave background (CMB) probes the fundamental physics of the universe in two ways:

- Snapshot of the high energy physics of the early universe
- Backlight through the full formation and evolution of structure

CMB-S4 Science Themes

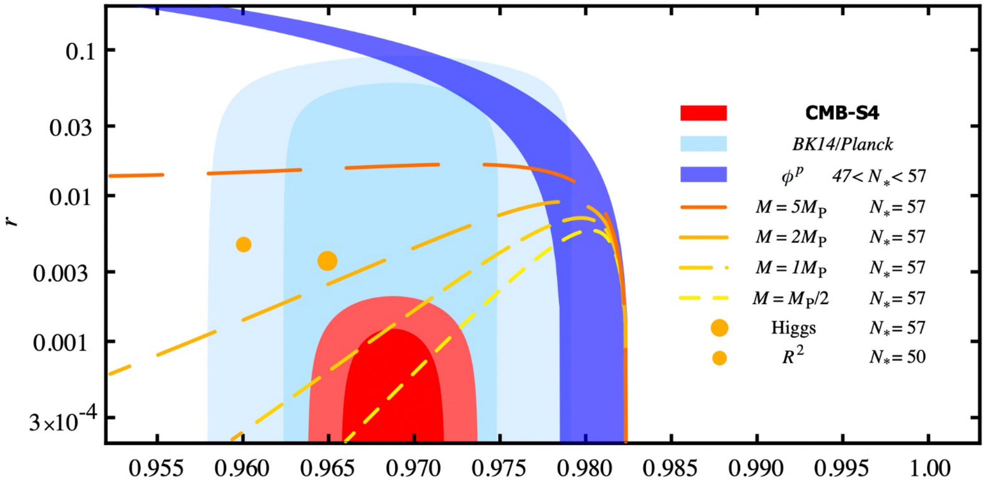


Time-variable millimeter-wave sky

Deepest mm map of our Galaxy – with polarization

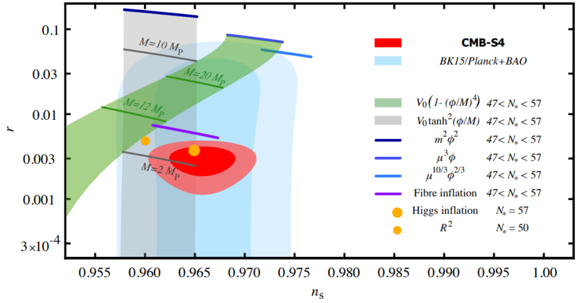
Critical Thresholds on Inflation

- Inflation would have left a unique imprint in the polarization of the CMB (B-modes)
  - Tensor-to-scalar ratio r gives energy scale of inflation
  - Probe quantum gravity and fundamental physics ~10^{-36} s after the universe began, at grand unification theory energy scales (10^{16} GeV)



CMB-S4 Science Book, 2016

- CMB-S4 will reach $\sigma(r)<0.0005$ → Two orders of magnitude lower than current constraints!
- Discover or rule out the most simple and compelling models of inflation



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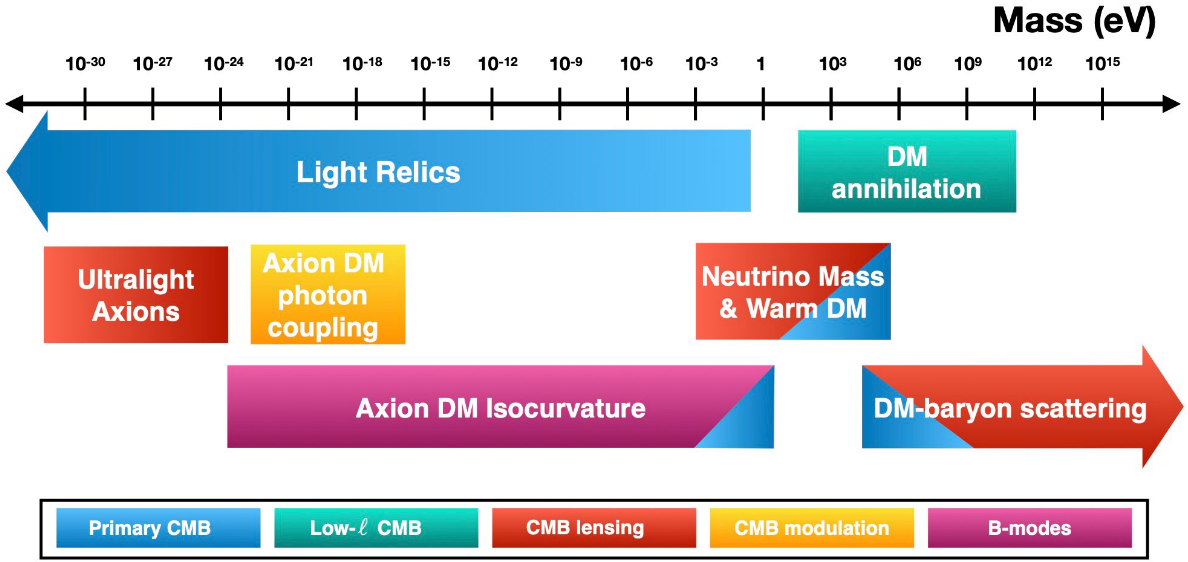
Probing Light Relics

- Any light relics would modify the radiation density → CMB power spectra
- CMB gives insights to the dark sector across the mass spectrum

$$\rho_{rad} = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\right]\rho_\gamma$$

Planck (current): $\sigma(N_{eff}) \sim 0.2$

CMB-S4: $\sigma(N_{eff}) \sim 0.027$



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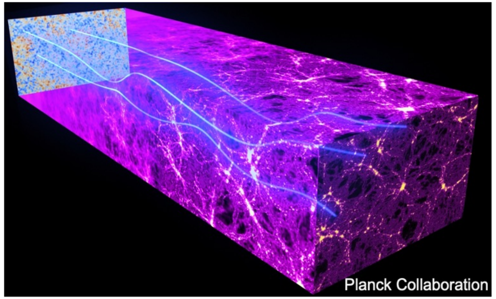
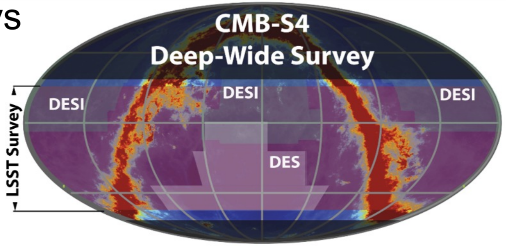
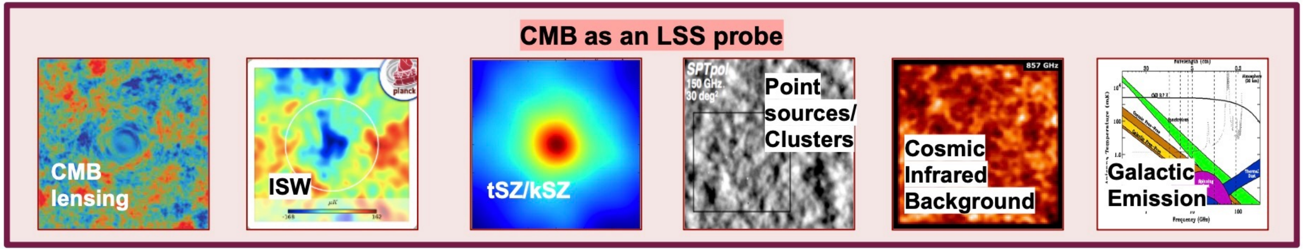
Matter Mapping

- Map matter through gravitational lensing, map galaxy clusters via the Sunyaev-Zel'dovich effect
- Information about the growth of structure → dark matter, dark energy, sum of the neutrino masses
  - Complementary to neutrino oscillation experiments Δm_ν
  - Highly complementary to supernovae and large-scale structure surveys
  - Cross-correlations remove systematics, give crosscheck
  - Baryon pressure, velocity, feedback
- Galaxy clusters to higher z, lower M

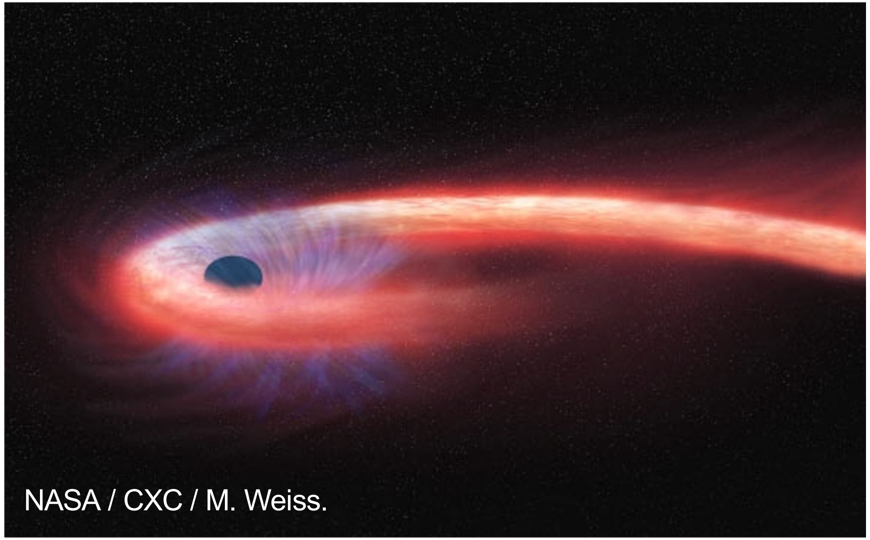




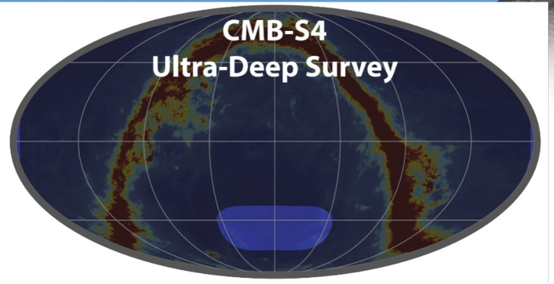


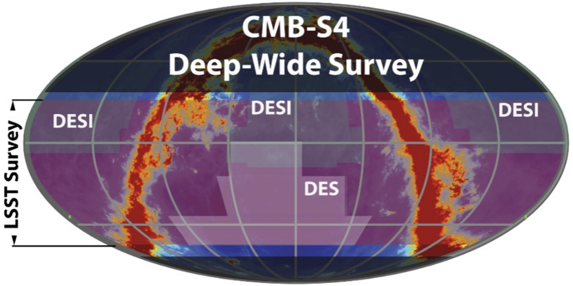
The Time-Variable Millimeter-Wave Sky

- First millimeter-wave survey expected to routinely detect transients → population statistics + long-term high cadence monitoring
- Many transient events evolve from low frequency to high frequency in time → CMB-S4 will issue maps of ~hourly observations on few hour timescales
  - Early detection
  - Follow up at other wavelengths → moving into age of multi-messenger astronomy
- Potential for new discoveries!


NASA / CXC / M. Weiss.

CMB-S4 Design





Ultra-Deep Survey from the South Pole and **Deep-Wide Survey** from Chile with arcmin angular resolution

7 frequency bands (20-300 GHz) for foreground subtraction

Uses mature technology successfully demonstrated in current experiments (ACT, PolarBear, SPT, BK Array, etc.)

Exceeds current generation by ~10x in channel count

SAT=Small Aperture Telescope ; LAT=Large Aperture Telescope

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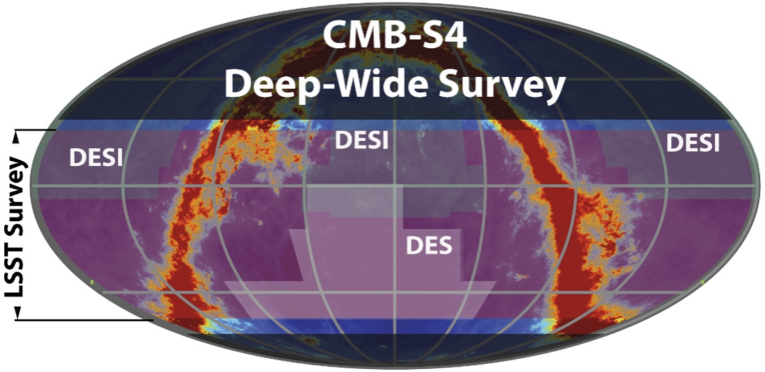
Two Large Aperture Telescopes in Chile

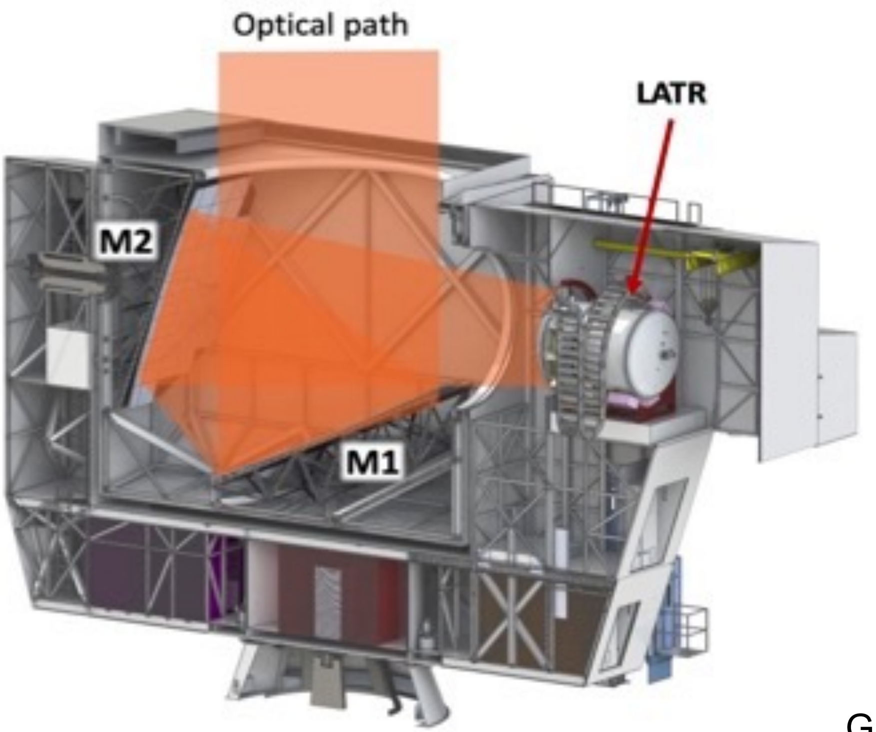
Two 6-m Large Aperture Telescopes (LAT)



Deep and Wide field survey optimized for matter mapping via CMB lensing, neutrino mass, light relics, and transient mm-wave phenomenon.

Overlaps with other optical surveys (DES, DESI, LSST) for cross-correlation

Two Large Aperture Telescopes in Chile



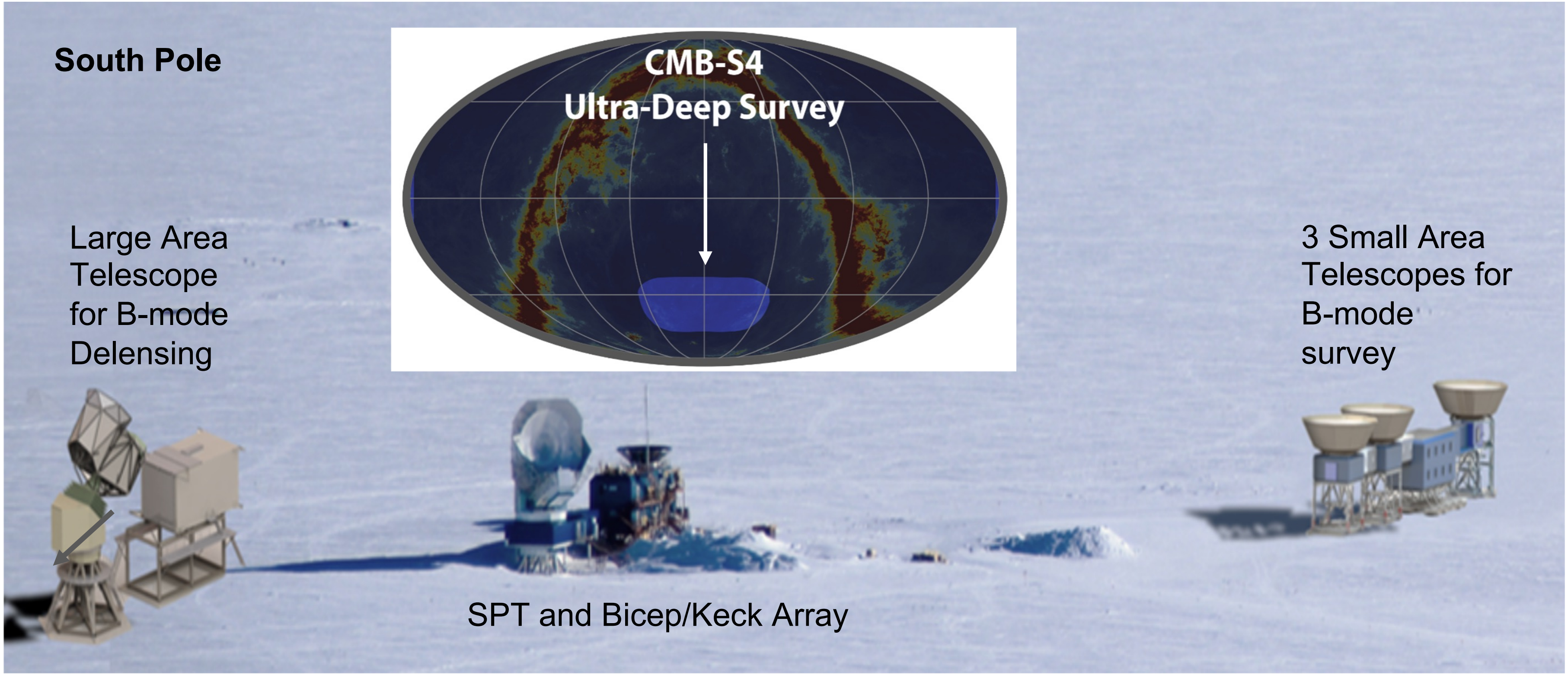
6-meter primary diameter
Crossed-Dragone Design

1.4’ angular resolution at 150 GHz

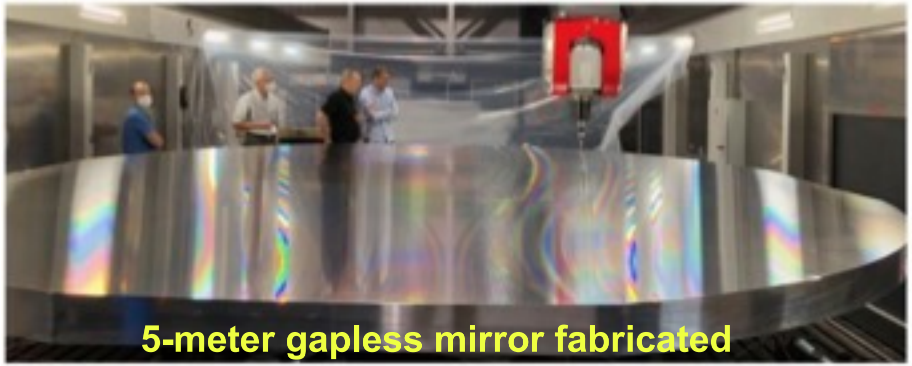
Design based on experience from CCAT-Prime (FYST) and the Simons Observatory

Gallardo et. al.
https://arxiv.org/abs/2207.10012

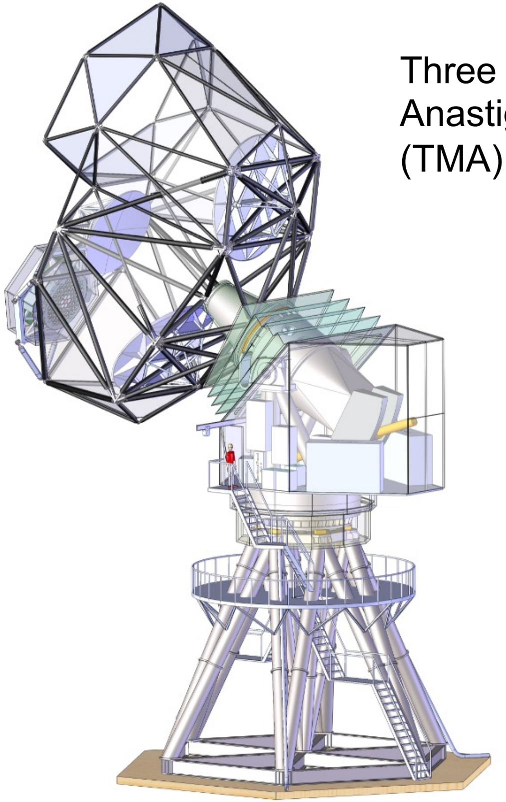
South Pole Large and Small Area Telescopes

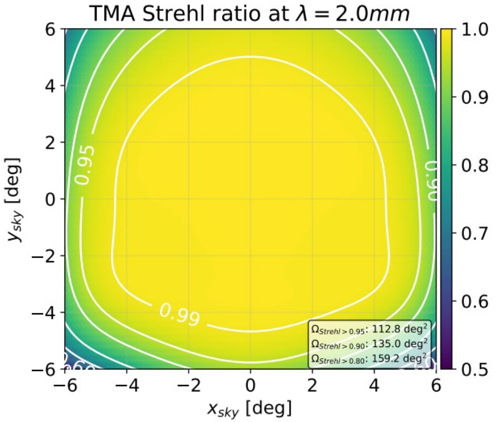


South Pole Large Aperture Telescope



Three Mirror Anastigmat (TMA) Design





Optimized for the B-mode Delensing Survey

- Optimal beam over FOV
- Gapless mirrors to prevent B-mode contamination
- Boresight rotation to cancel polarization systematics

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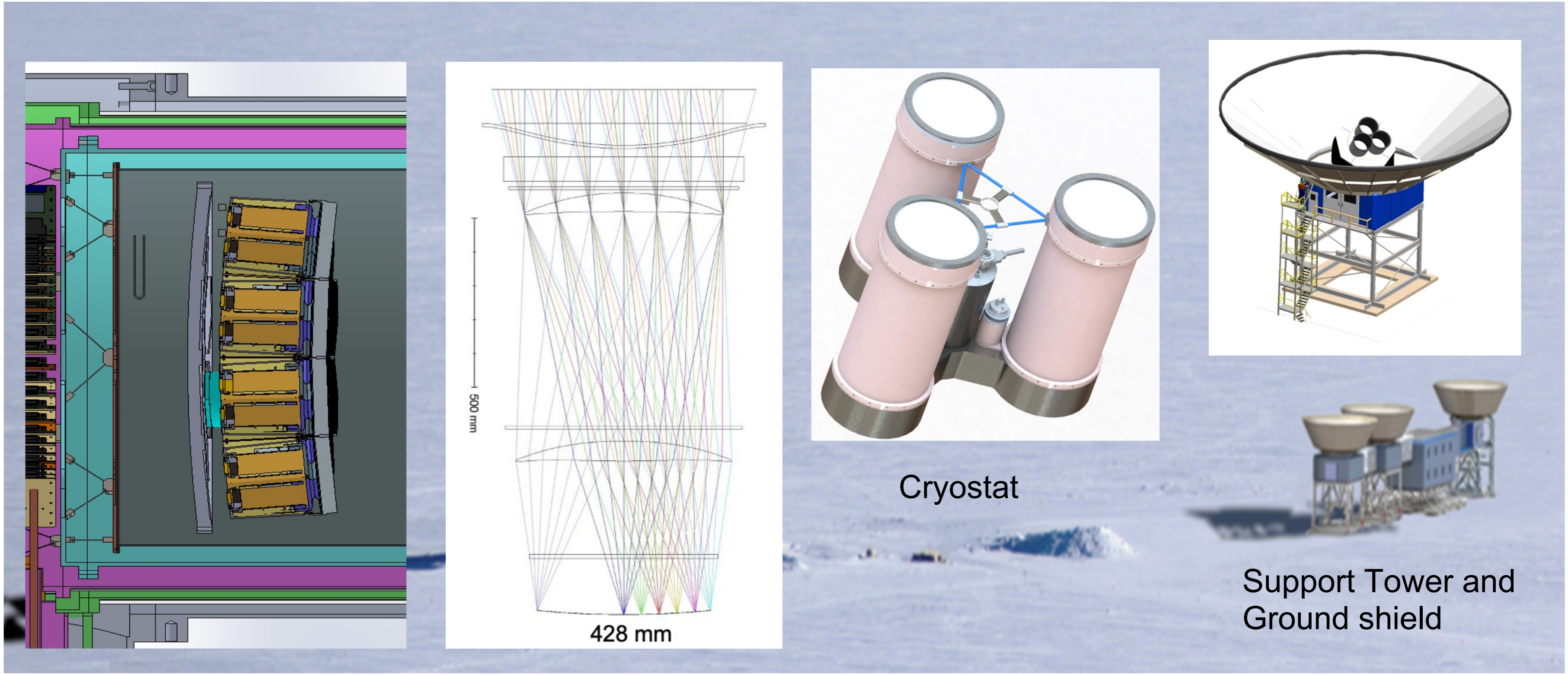
South Pole Small Area Telescopes

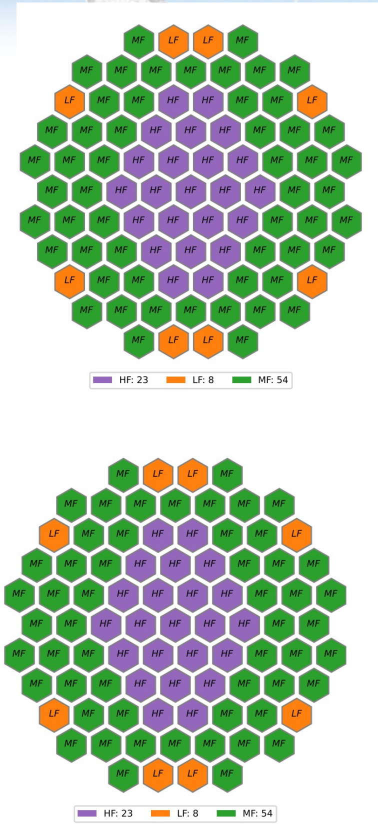


Focal Plane

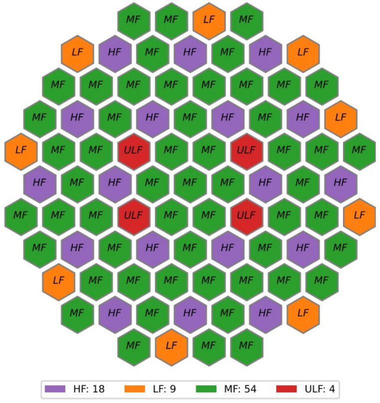
Cold Refractor Optics

Builds upon proven Bicep/Keck Array Design

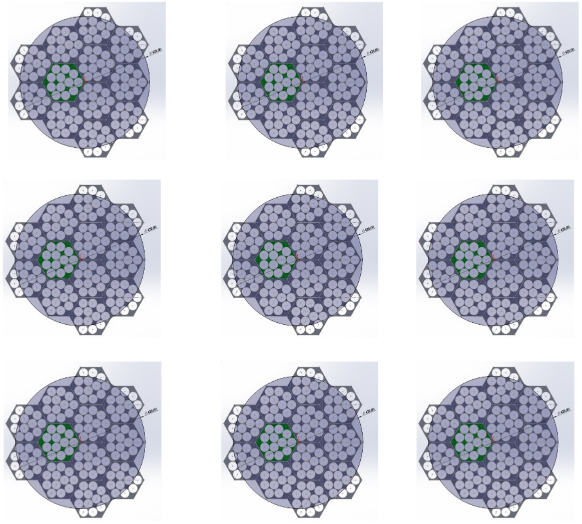
Telescope Focal Plane



Chilean LAT Focal Plane
~ 270,000 detectors



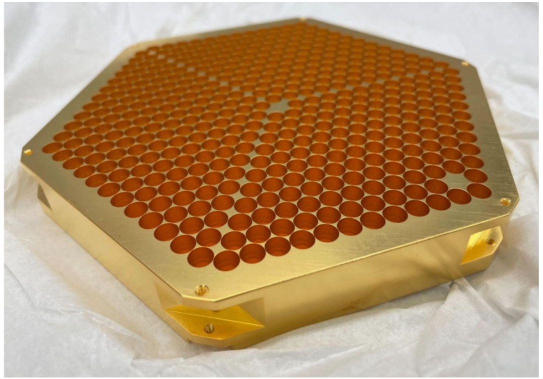
South Pole LAT
Focal Plane
~ 130,000 detectors



South Pole SAT Focal Plane
~ 100,000 detectors
(low frequency detectors shown for illustration)

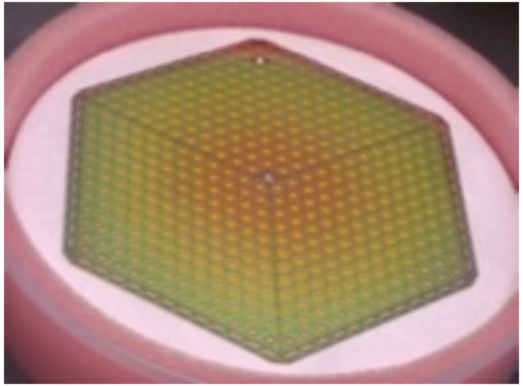
7 frequency bands (20-300 GHz)

CMB-S4 will be the most sensitive CMB experiment to date

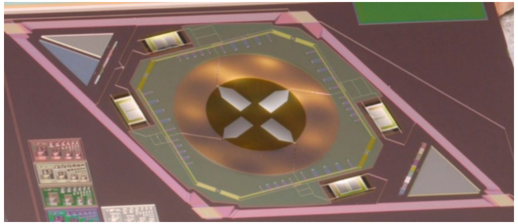


Horn antenna array for best beam optics

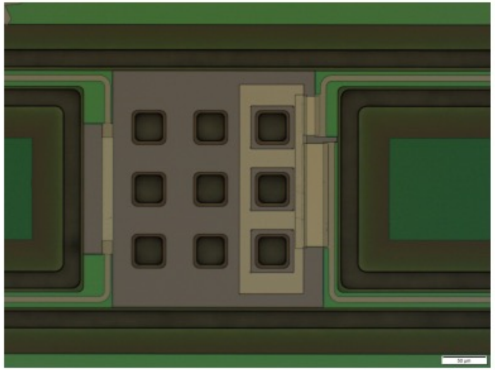
(90 GHz design shown for illustration)



100 mK Super conducting Circuits on 6” Nb Si wafers



Polarization-sensitive orthomode transducers



Transition Edge Sensors read out with 80-to-1 multiplexing in the time domain (i.e. sequential readout).

- **Detector Noise practically limited only by photon statistics**
- **Mature technology used by ~all ground-based experiments**

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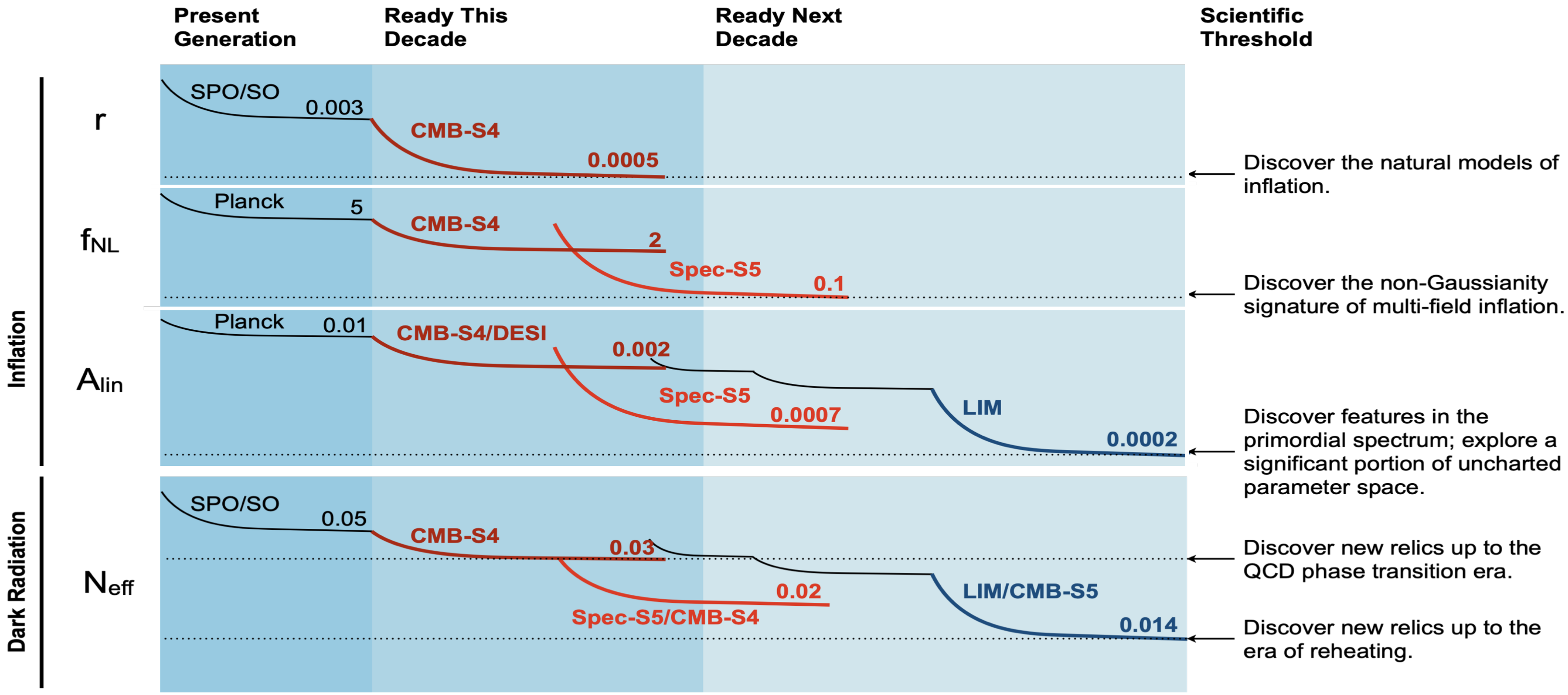
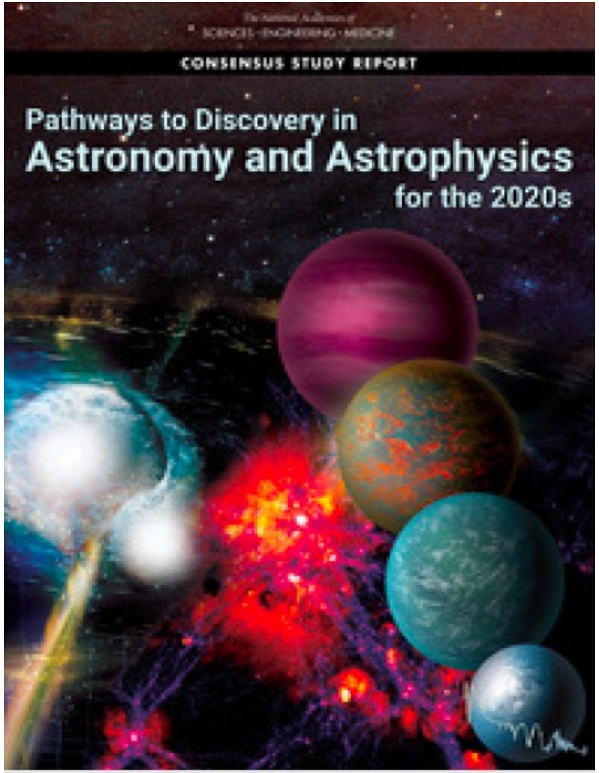
CMB-S4 Science Goals in 7-9 years



US Snowmass Cosmic Frontier 5 report

CMB-S4 Concept Endorsement by US Community

- CMB community has united around “Stage 4” experiment concept, ***CMB-S4:***
  - Designed to make transformational discoveries in fundamental physics, cosmology, astrophysics & astronomy
  - Recommended by 2014 P5 under all budget scenarios
  - Recommended by 2015 NAS report A Strategic Vision for NSF Investments in Antarctic and Southern Ocean Research
  - ***Strongly recommended by Astro2020: “NSF & DOE should jointly pursue the design and implementation of CMB-S4”***
  - Prominently featured in recent Snowmass process / ongoing 2023 P5: Snowmass Cosmic Frontier report “Our top project priority is to complete construction of CMB-S4”.



CMB-S4 has members from 26 US institutions and 19 countries

enthusiasm from the international community!

Summary

- The next generation of CMB observations are poised to make tremendous discoveries
  - *r* : Observe gravity operating on quantum scales
  - N_{eff} : Probe for light particles beyond the standard model
  - $\sum m_{\nu}$: Constrain the masses of neutrinos
  - New insights into dark energy, dark matter, structure formation
  - New discovery space for transients in the millimeter sky
- CMB-S4 offers a unique opportunity to study fundamental physics of the universe scaling up mature technology
- CMB-S4 will impact many fields: HEP, Cosmology, and Traditional Astronomy

Thank you!