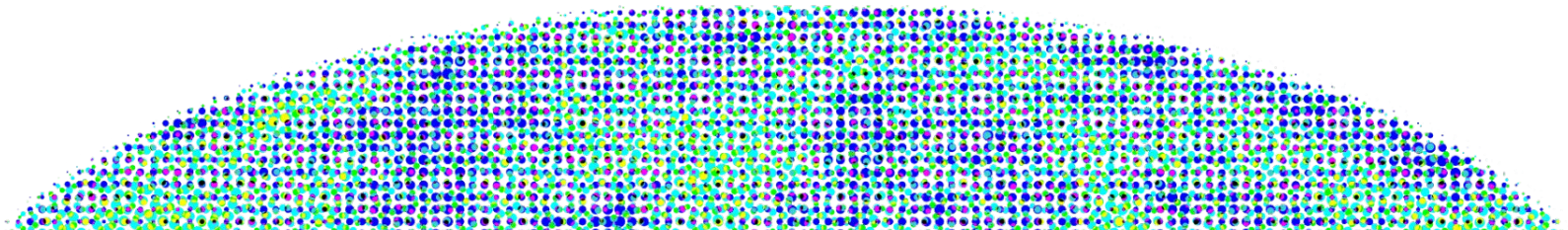
CMB S4

The Millimeter Universe with CMB-S4

Sara M. Simon (she/her)
for the CMB-S4 Collaboration
06/27/25

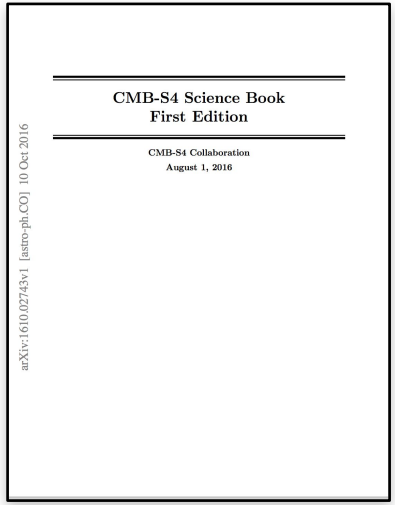


An Extremely Broad Science Reach

Primary CMB Anisotropy: Inflationary gravitational waves • Inflation energy scale • Quantum Gravity • Light relics • BSM particles • Inflationary non-gaussianity • Primordial power spectrum • Cosmic census (baryons-dark matter-dark energy) …

Secondary Anisotropy and using the CMB as a backlight: Neutrino mass • Dark Energy • Cosmic birefringence • Axion dark matter • Dark matter-baryon scattering • Sunyaev-Zeldovich scattering effects • Galaxy clusters • Galaxy evolution and feedback • Gravitational lensing • Cross-correlations with gas/mass/galaxies • Cosmological momentum field • Reionization/1st stars…

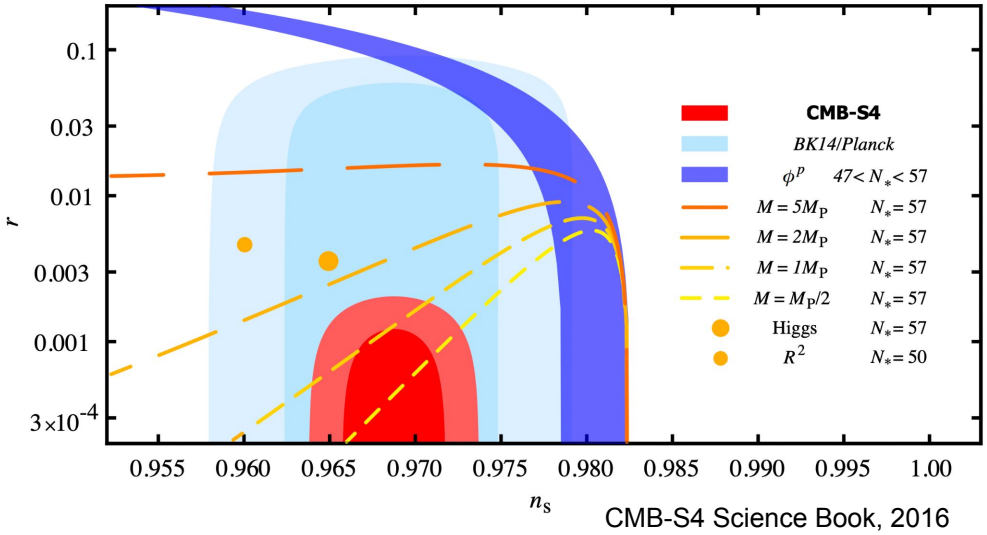
Time-domain, Deep, Wide-area, Millimeter-wave Surveys: Gamma ray bursts • Tidal disruption events • Fast blue optical transients • Supernovae • Time-variable active galactic nuclei • Multi-messenger correlations with time-domain observatories • Dusty star-forming galaxies • Stellar flares • Galactic black hole flares • Fast radio bursts • Interstellar medium • Galactic magnetic field • Exo-Oort Clouds • Planet 9 • Asteroids…



CMB-S4 Science Book First Edition (2016)
200 pages, >1250 citations
available at http://cmb-s4.org
arXiv:1610.02743

Critical Thresholds on Inflation

- Inflation would have left a unique imprint in the polarization of the CMB (B-modes)
  - Quantified by 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 $\sigma(r)<5\times10^{-4}$**
- Discover or rule out the most simple and compelling models of inflation

Probing Light Relics

- Any light relics would modify the radiation density → CMB power spectra
- Probe extensions to the Standard Model
  - Axions, sterile neutrinos, dark photons, gravitinos
- CMB-S4 will reach $\sigma(N_{eff}) \sim 0.03$
- **Broad, model-independent** capability to discover or rule out new light relics that freeze out during and after QCD phase transition

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

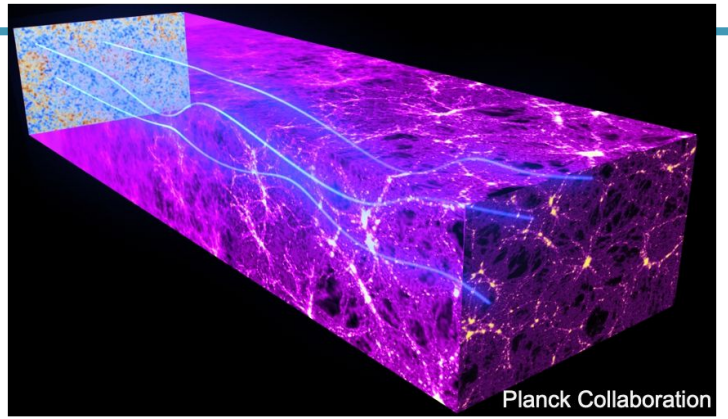
$$N_{eff} = 3.046$$

$$\Delta N_{eff} \geq 0.047 \text{ Spin } \tfrac{1}{2}, 1, \tfrac{3}{2}$$

$$\Delta N_{eff} \geq 0.027 \text{ Spin } 0$$

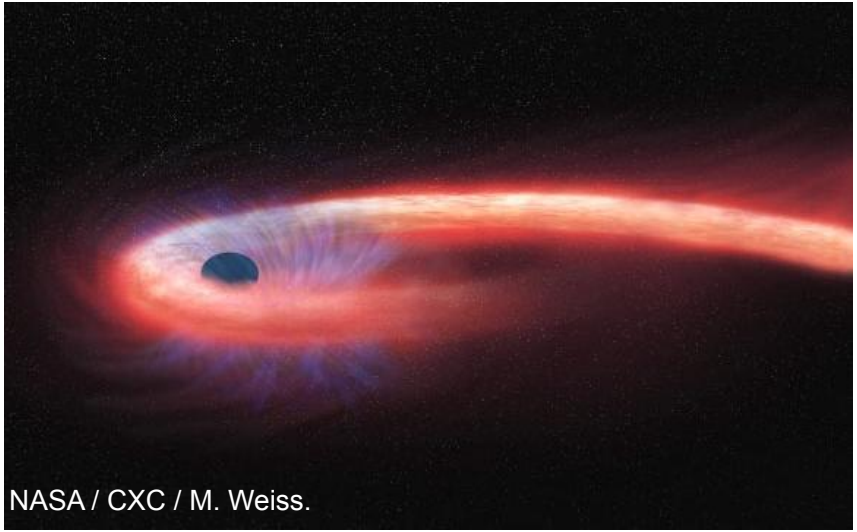
Matter Mapping

- Map matter through gravitational lensing and galaxy clusters detected 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 measuring the difference in masses
    - Highly complementary to supernovae and large-scale structure surveys
- Detect > 95% of high-redshift ($z \geq 1.5$) galaxy clusters above $1.0 \times 10^{14} M_\odot$ ($0.7 \times 10^{14} M_\odot$) over 50% (3%) of the sky→ critical legacy dataset for cosmological and astrophysical studies with clusters



The Time-Variable Millimeter-Wave Sky

- Detect and measure a large number of transients → population statistics + long-term high cadence monitoring
    - Significant number of gamma-ray bursts (GRBs)
- 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 will enable follow-up at other wavelengths
- Open a new window on the dynamic universe→ Potential for new discoveries!


NASA / CXC / M. Weiss.

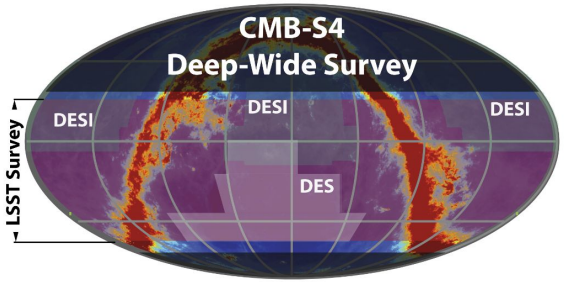
CMB-S4 Science Goals

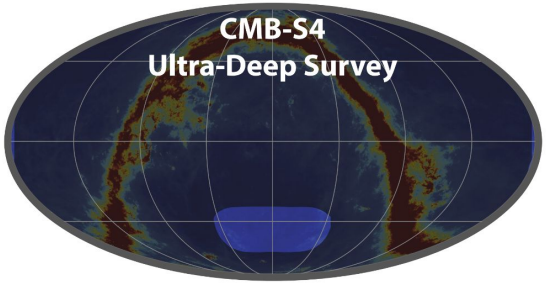
The science goals and quantitative science requirements that must be met to achieve those goals have been developed over many years and form the basis for the strong endorsements of CMB-S4 by P5, Astro 2020, and many other science advisory bodies:

- Test models of inflation by measuring or putting upper limits on the imprint of primordial gravitational waves on the CMB
- Determine the role of light relic particles in fundamental physics and in the structure and evolution of the Universe
- Measure the emergence of clusters of galaxies as we know them today
- Explore the millimeter-wave transient sky

CMB-S4

Original CMB-S4 concept was split between the Atacama desert in Chile and the South Pole to leverage the unique advantages of both sites





CMB-S4 Redesign

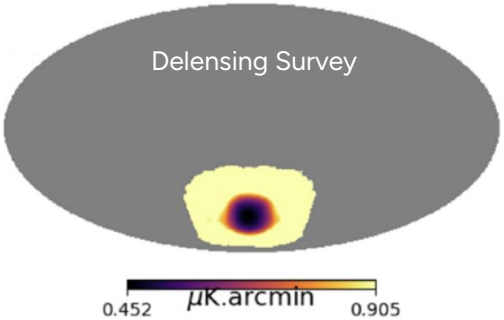
- Funding agency constraints on deploying new experiments to the South Pole
- Developed a revised project plan to meet our science goals given this new constraint
- Developed two reports for the funding agencies
    - Chile-based CMB-S4 configuration
    - Survey of current and near-term CMB experiments
- The revised project plan builds on these reports to combine current and near-term projects with additional instrumentation to reach our science goals

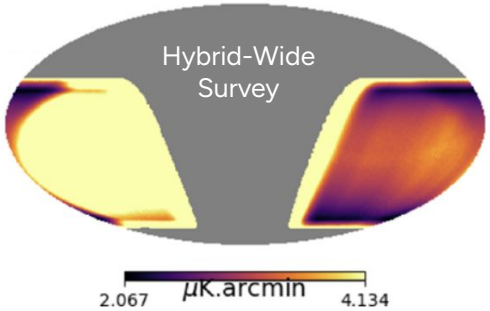
Updated CMB-S4 Design

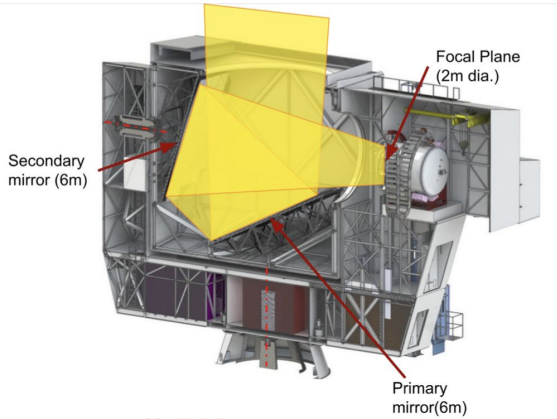
- Continued operations with **Simons Observatory (SO)**
- Continued operations with the **South Pole Observatory (SPO)** with the proposed SPT-3G+ camera and upgrades to BICEP/Keck
- **CMB-S4** hardware in Chile→ more than doubling the mapping speed of SO
  - 1 Large-Aperture Telescope (LAT)
  - 6 Small Aperture Telescopes (SATs), 3/mount
- Resources to enable combining these data sets
- Potential for an additional phase of future hardware depending on project needs
  - Systematic limitations
  - Foreground limitations
  - Limitations from a lack of delensing power
  - Integrate down on *r* detection
  - Leveraging South Pole if it becomes available

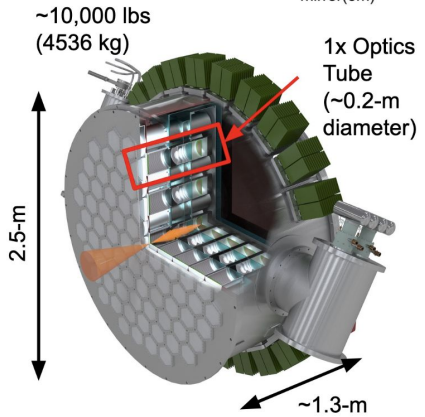
Large Aperture Telescope

- 6 m Crossed-Dragone Telescope using same design as SO and CCAT
- Next-generation receiver with 85 optics tubes → ~2x mapping speed of ASO receiver
- Preform two surveys
  - Delensing survey to extend delensing from SPT-3G+
  - Hybrid-Wide survey to complement SO wide survey



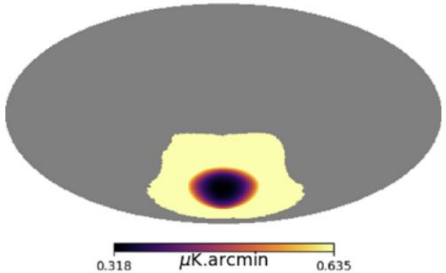


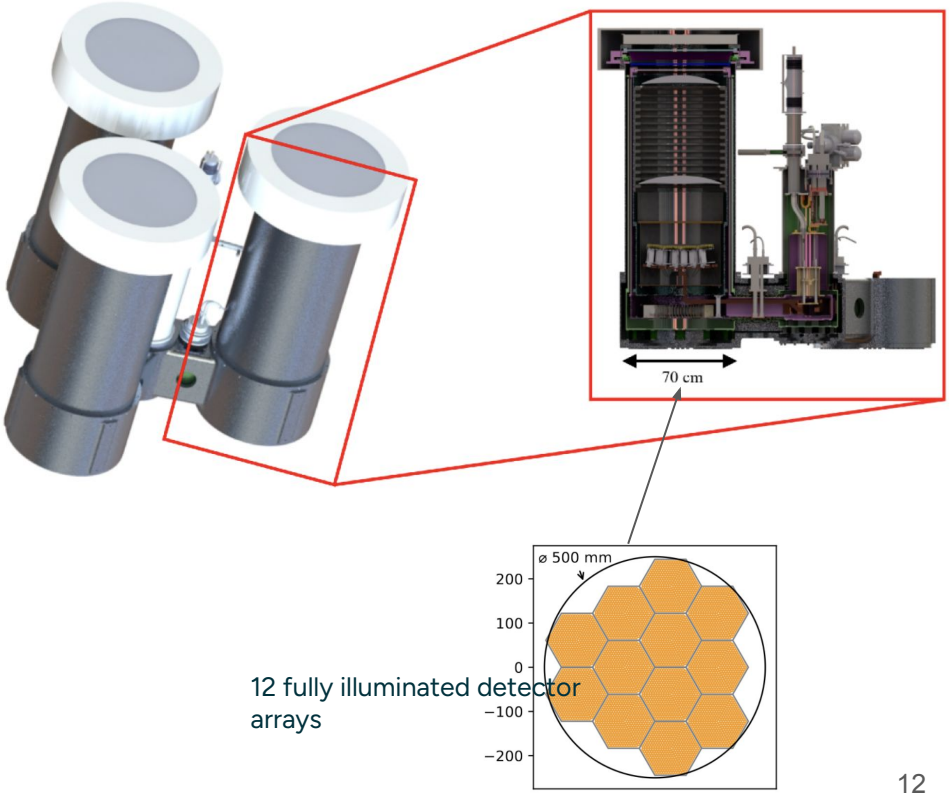




Small Aperture Telescopes

- Six 560 mm refractive SATs
- 12 detector arrays/telescope with densely packed pixels
- Polarization modulation with a continuously-rotating half-wave plate
- Each SAT ~2x mapping speed of SO SAT
- Integrate deeply on small Southern patch





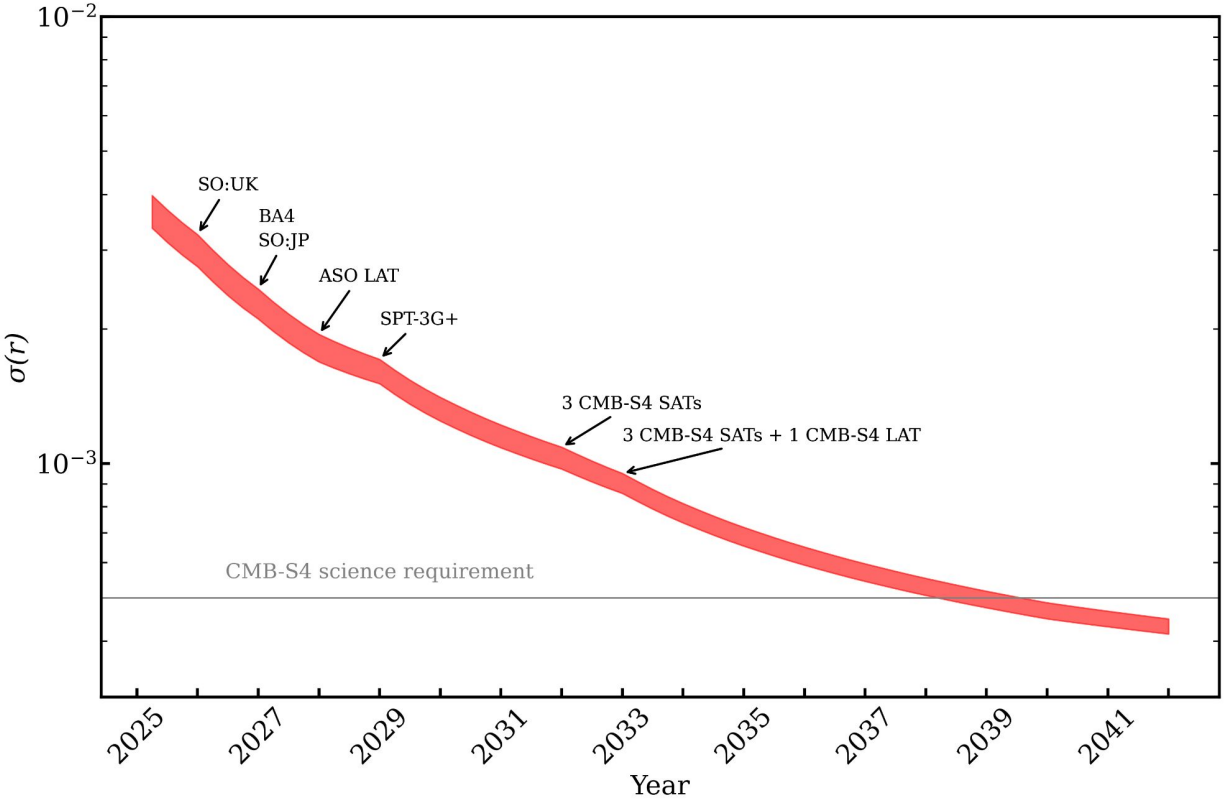
12 fully illuminated detector arrays

Inflation Science as a Function of Time

Forecasted $\sigma(r)$ constraints for combined observations with:

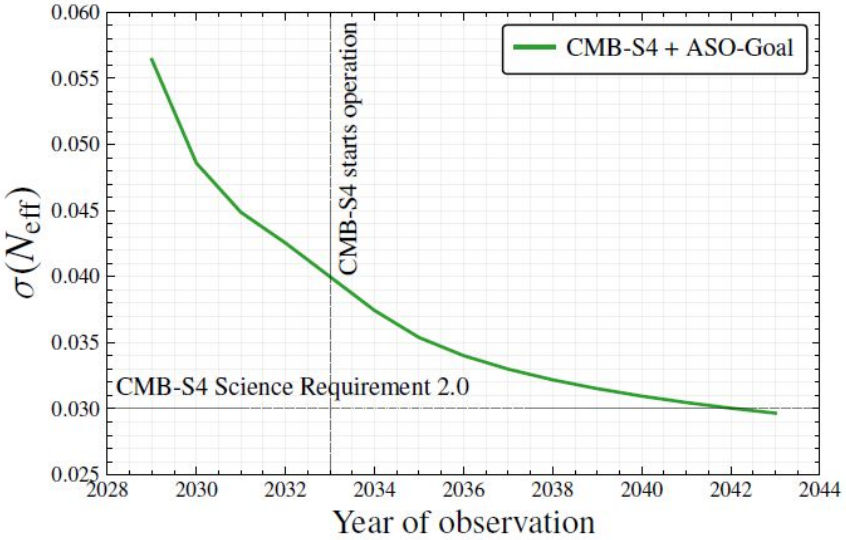
- SO
- SPO
- CMB-S4 (6 SATs+1 LAT)

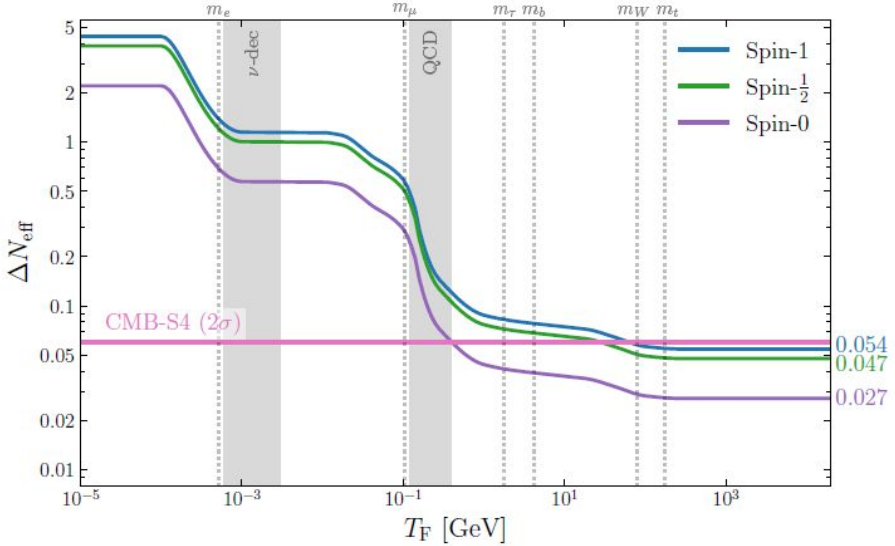
Arrows indicate when assume additional instrumentation brought online



$\sigma(N_{eff})$ as a Function of Time

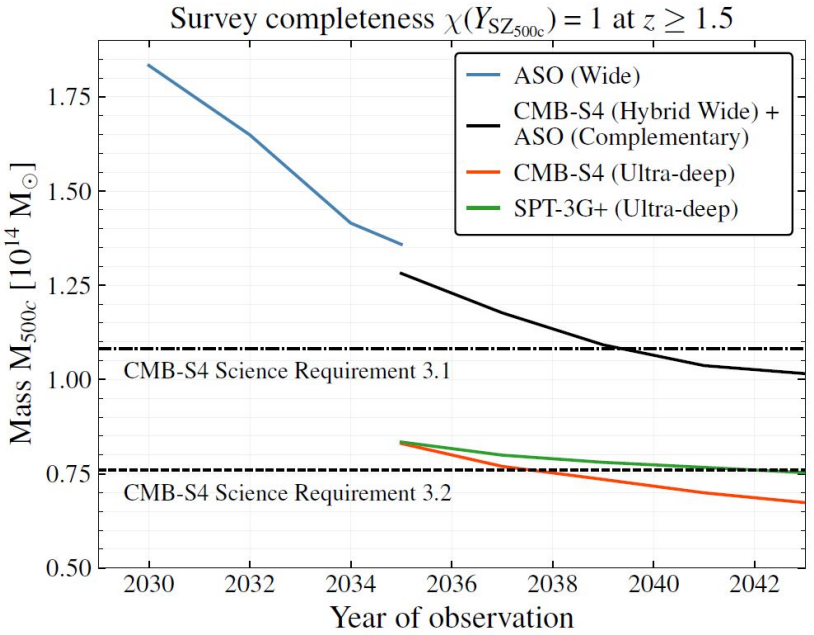
Forecasts for $\sigma(N_{eff})$ from CMB-S4 Hybrid Wide LAT survey + CMB-S4 Ultra Deep Survey + ASO Survey





High Redshift Galaxy Clusters

- Minimum detectable cluster mass with 100% completeness at $z \geq 1.5$
- CMB-S4 Hybrid Wide LAT Survey + ASO meets requirement to detect $1.0 \times 10^{14} M_\odot$ clusters over 50% of sky
- CMB-S4 Delensing LAT Survey + SPT-3G+ surpasses requirement to measure $0.7 \times 10^{14} M_\odot$ over 3% of sky in 3 years (SPT-3G+ alone in 7 years)



Transient mm-Wave Sky

- Transient performance is tightly tied to survey strategy
- Expect to detect ~3.5x the number of GRBs as current/near-term experiments → improve our understanding of the driving physics of these events
- CMB-S4 Delensing LAT Survey + SPT-3G+ reach 3 mJy noise levels over 3% of the sky
- Combined CMB-S4 Hybrid Wide LAT Survey + ASO hit 35% of sky at 30 mJy noise levels on consecutive days → rich sample of transient events

Conclusion

- The CMB-S4 science program is broad and inspiring
- SO and SPO are making rapid progress and will be essential to our field
- CMB-S4 gives us a clear path to realizing the scientific goals our community has developed over the last ten years including:
  - Precise measurements of inflation
  - Light relativistic species
  - Mapping the matter in our universe
  - Opening a new window into millimeter wave transients

CMB S4

Thank you for listening to our presentation.

Learn more at **https://cmb-s4.org/**