Polarization/Inflation Measurements at the Chile Site

High Energy Physics Advisory Panel

Dec 6, 2024

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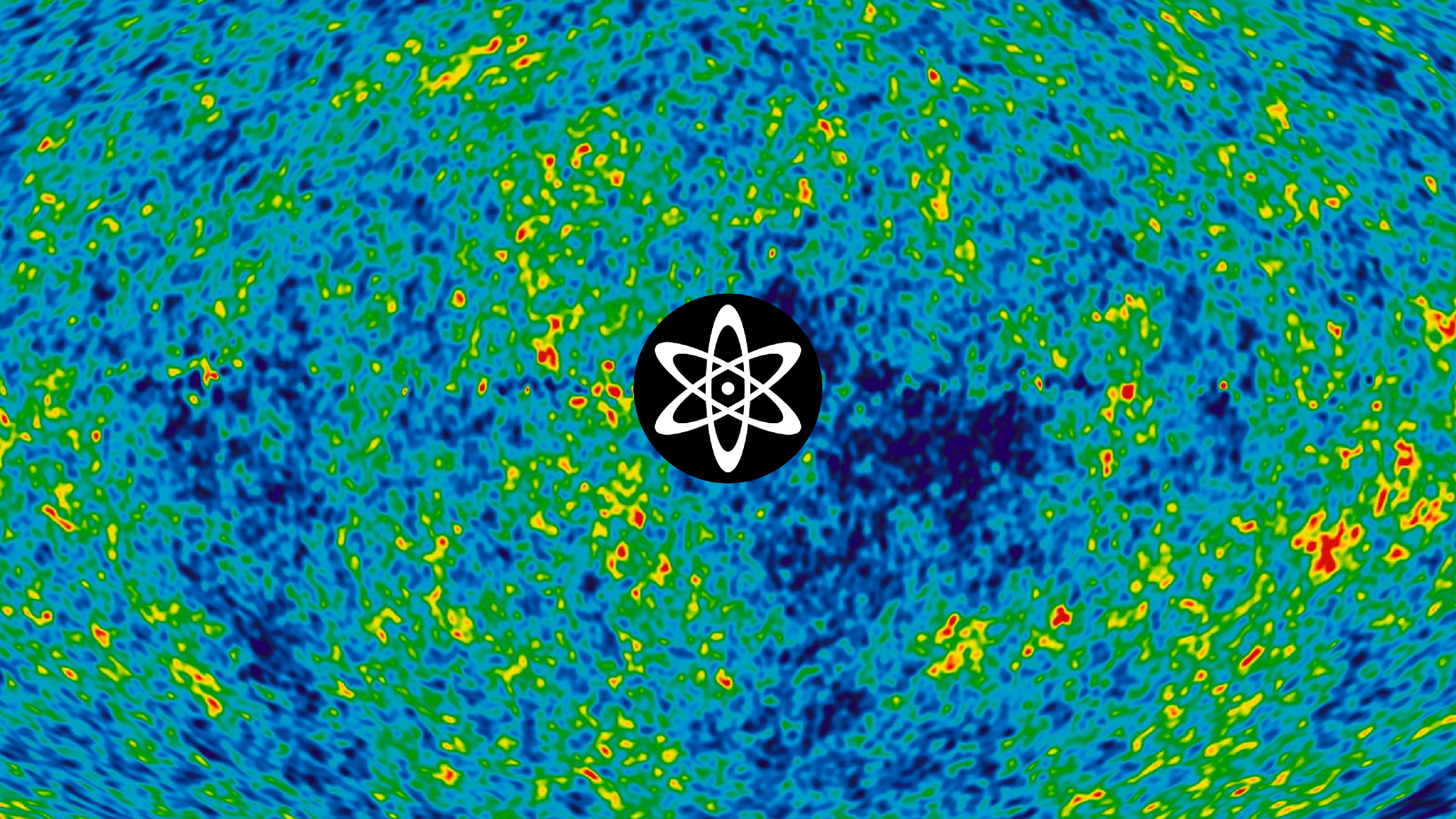
Johns Hopkins University

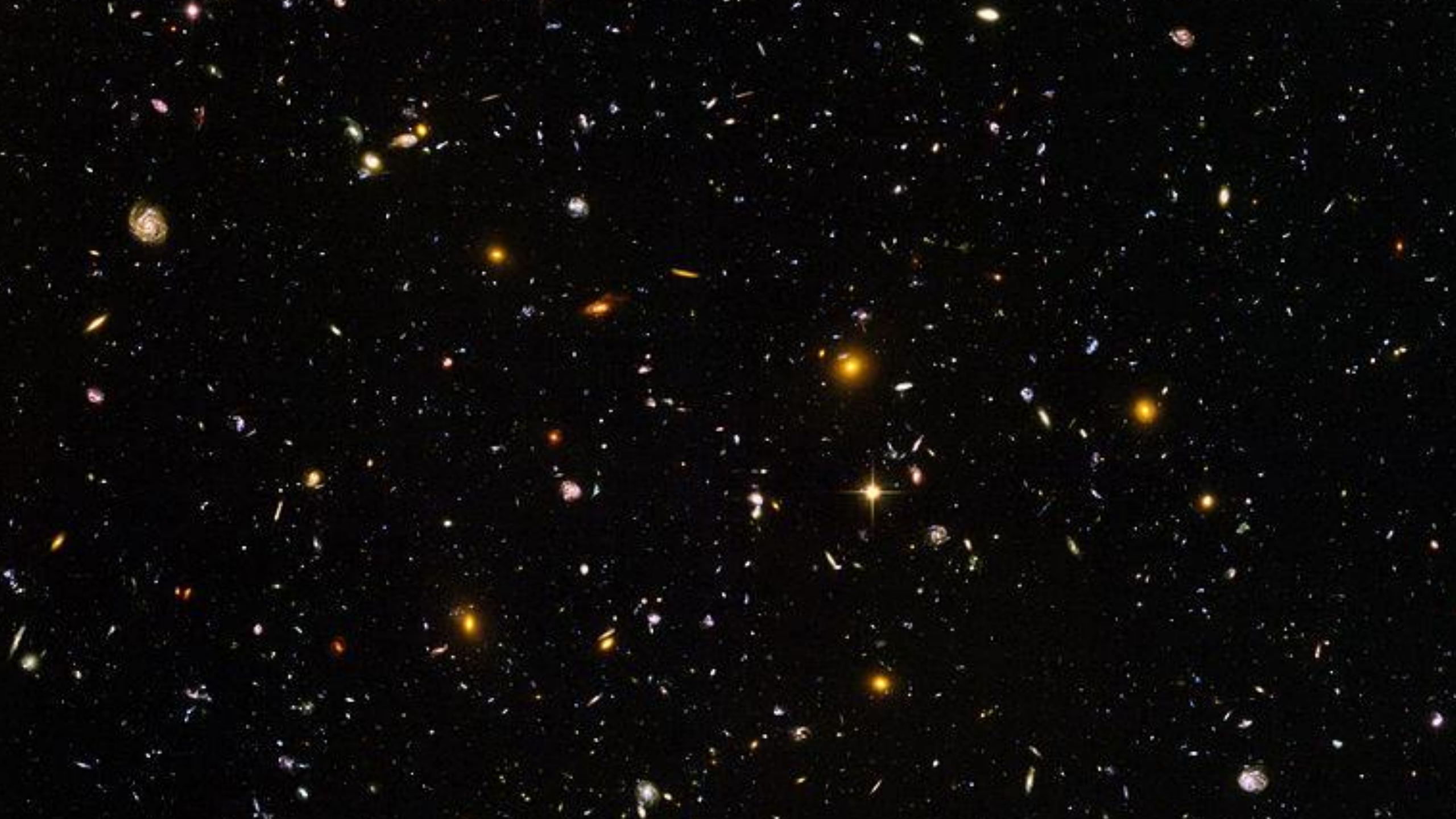
Take Aways

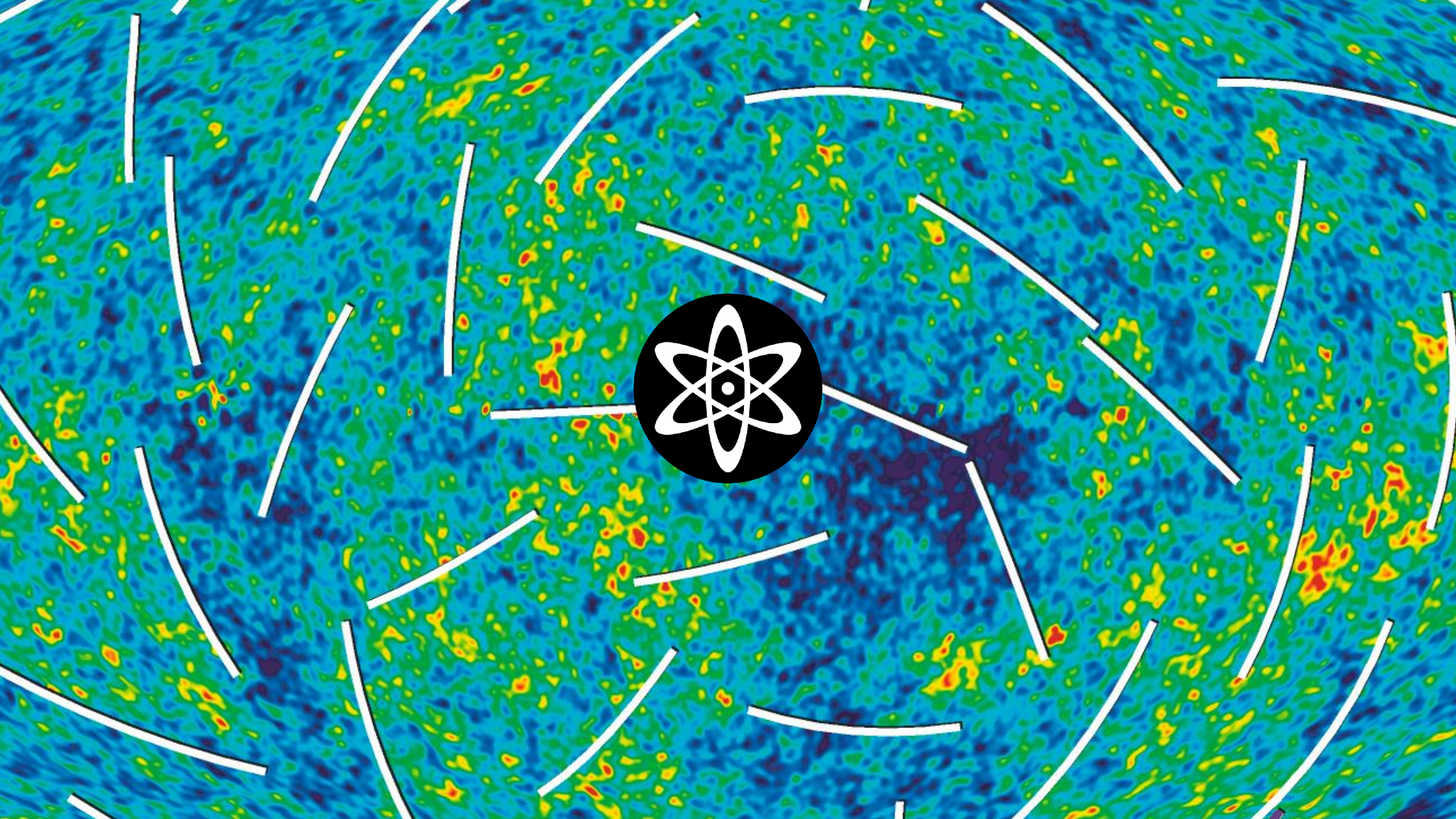
- The Chile Site is a world-class location for millimeter-wave astronomy, including CMB inflationary polarization measurements.
- Technologies and strategies exist to grapple with the unique challenges of the Atacama.
- A merged effort of CMB-S4 and Simons Observatory (SO) will be stronger: more expertise and resources for the hardest measurement. The leadership of both CMB-S4 and SO are eager to discuss partnership.
- The best strategy is a phased deployment of SATs and additional LAT for delensing as the survey sensitivity grows towards the $\sigma(r) \leq 5 \times 10^{-4}$ goal.
- The phased project structure allows for improvements made to instrumentation and lessons learned from data to greatly enhance future observations. It is the only way CMB studies have succeeded in the past.

Why me?

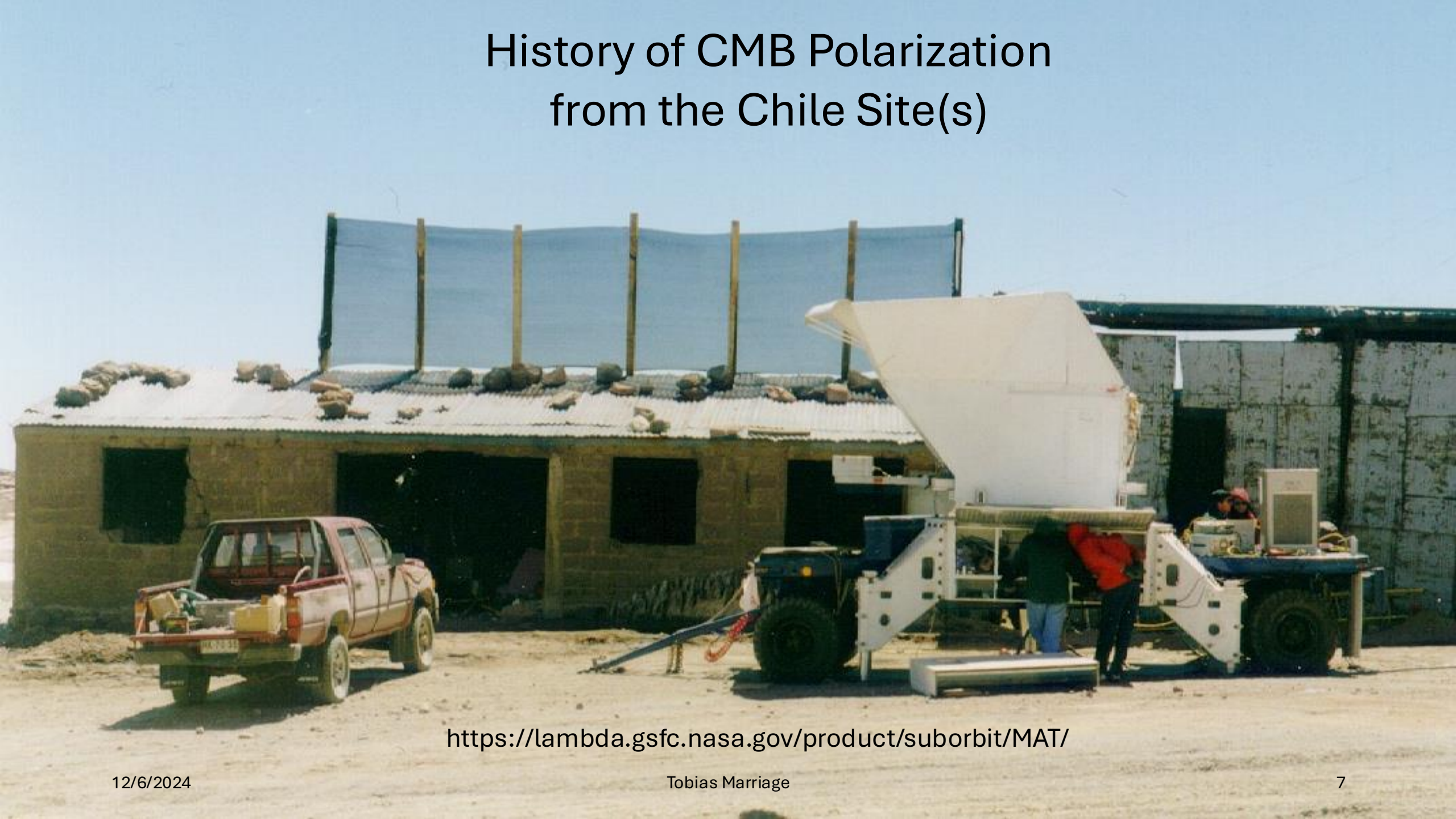
- Expertise: 24 years designing, building, commissioning, analyzing, and publishing CMB experiments based at the Chile Site
- Distance: One of the few in the CMB field who is neither a member of CMB-S4 nor Simons Observatory. (I am currently saturated as one of two Co-PIs of the CLASS CMB experiment.)
- Familiarity: CLASS is a neighbor of SO, and I have collaborated closely with SO members in the past. I have served on multiple CMB-S4 reviews, attended select meetings, and am currently an external member of a CMB-S4 committee to compare experiments.





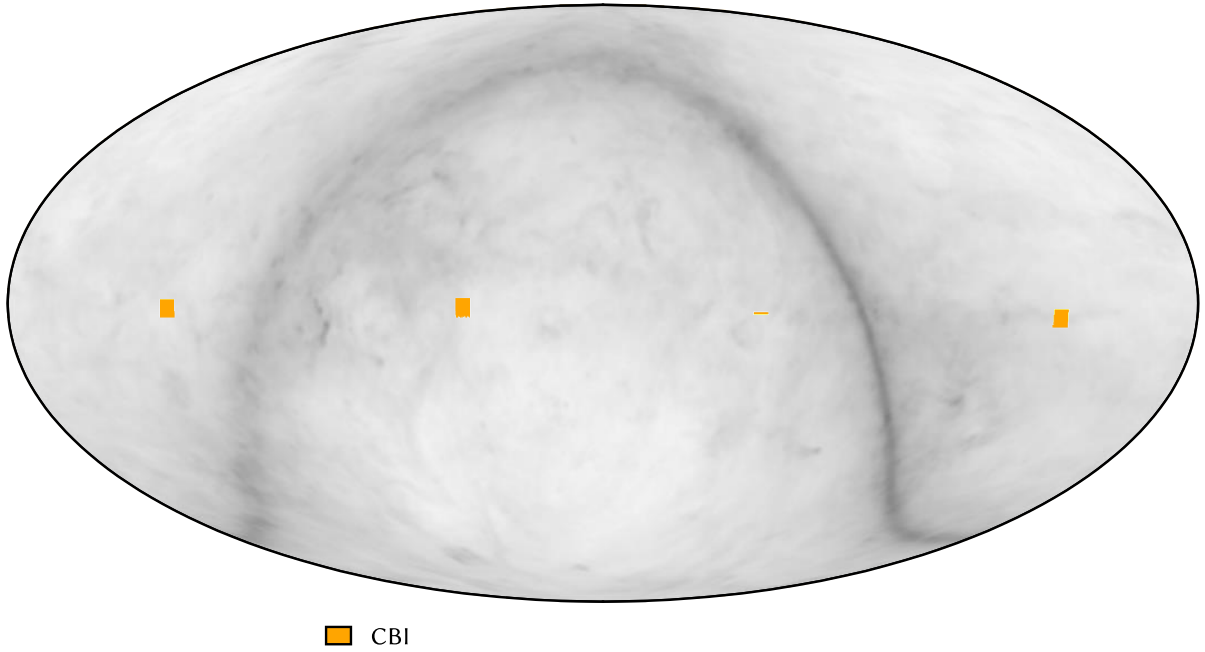


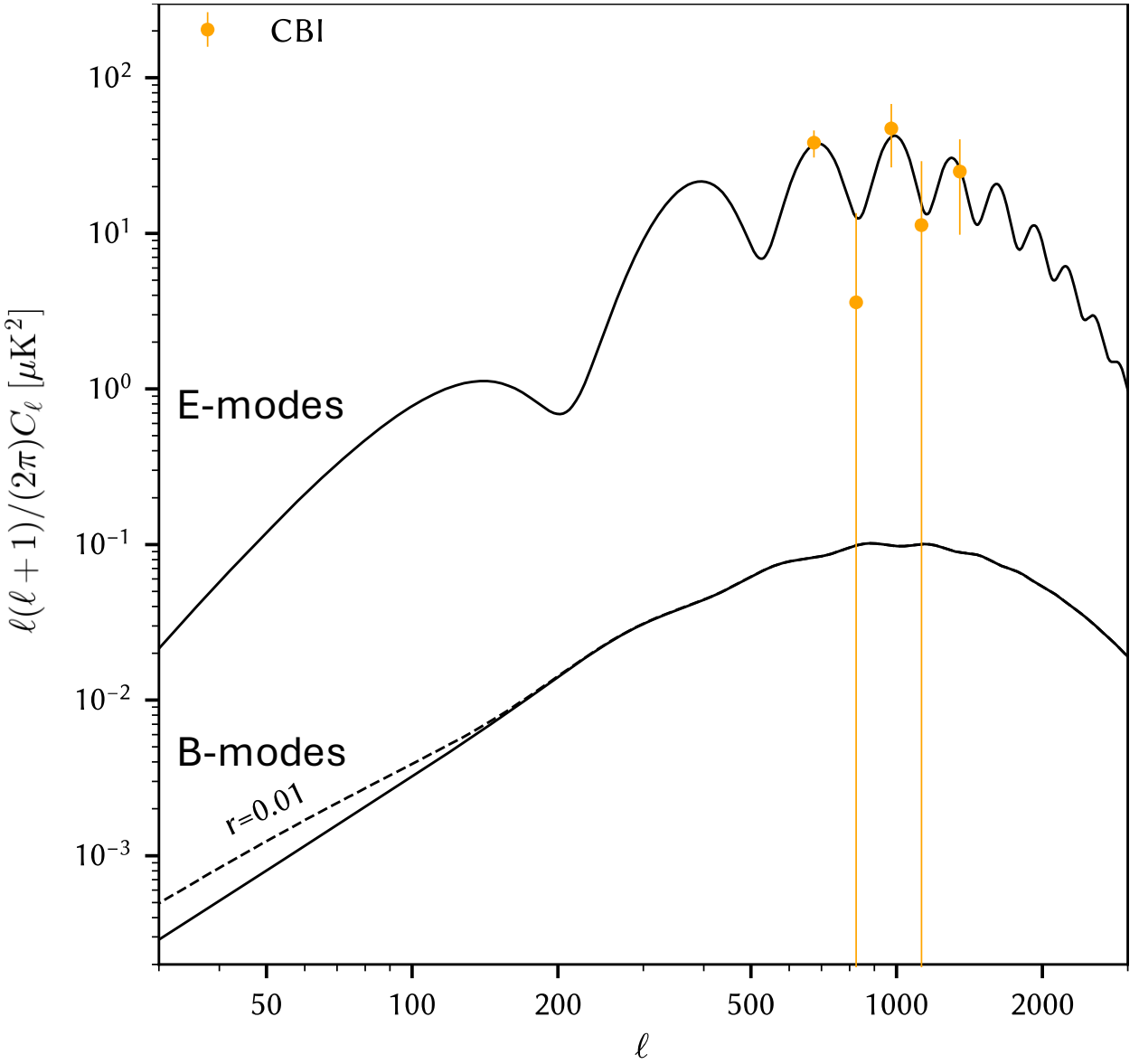
History of CMB Polarization from the Chile Site(s)



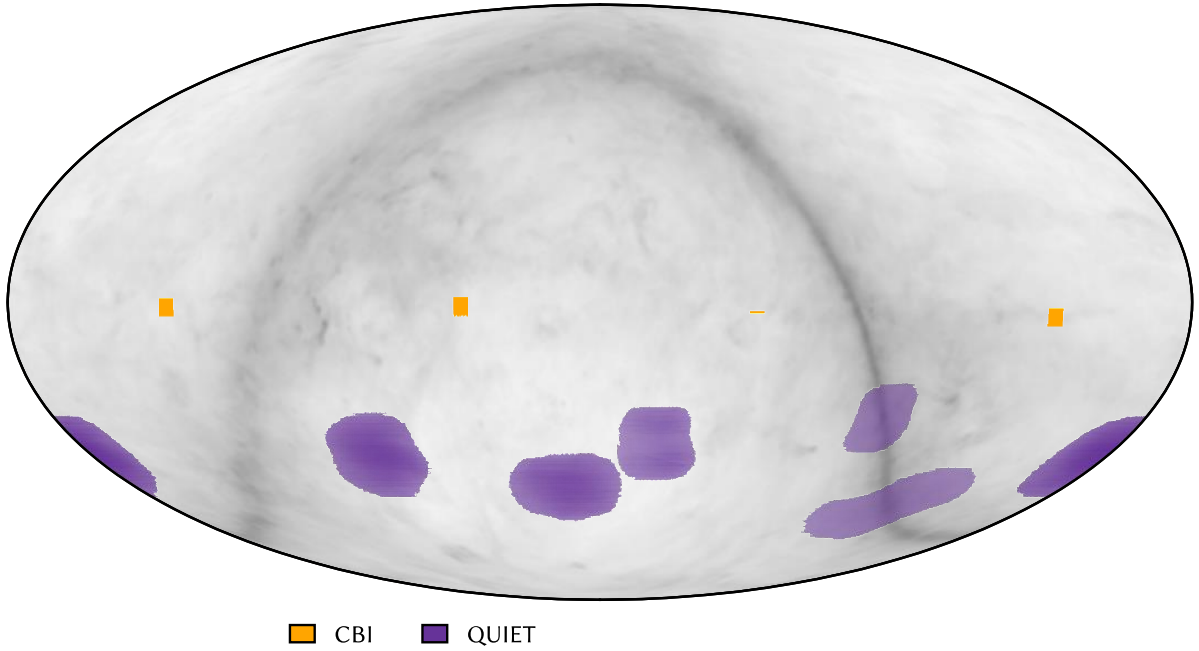
https://lambda.gsfc.nasa.gov/product/suborbit/MAT/

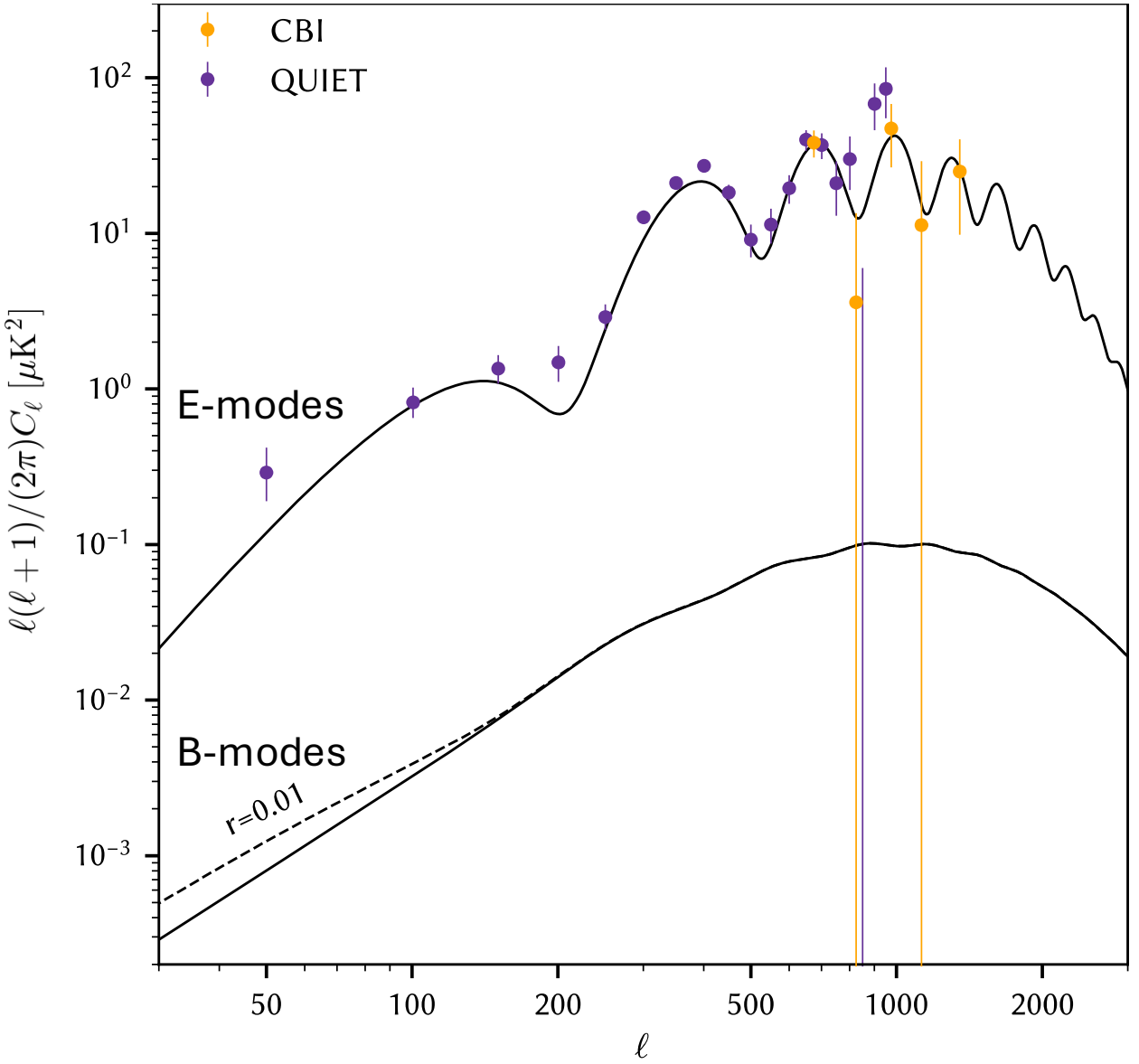
Cosmic Background Interferometer (CBI, 1999-2008)



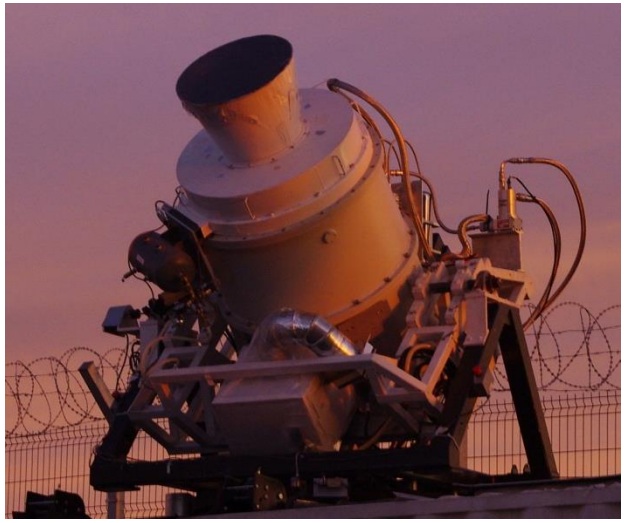


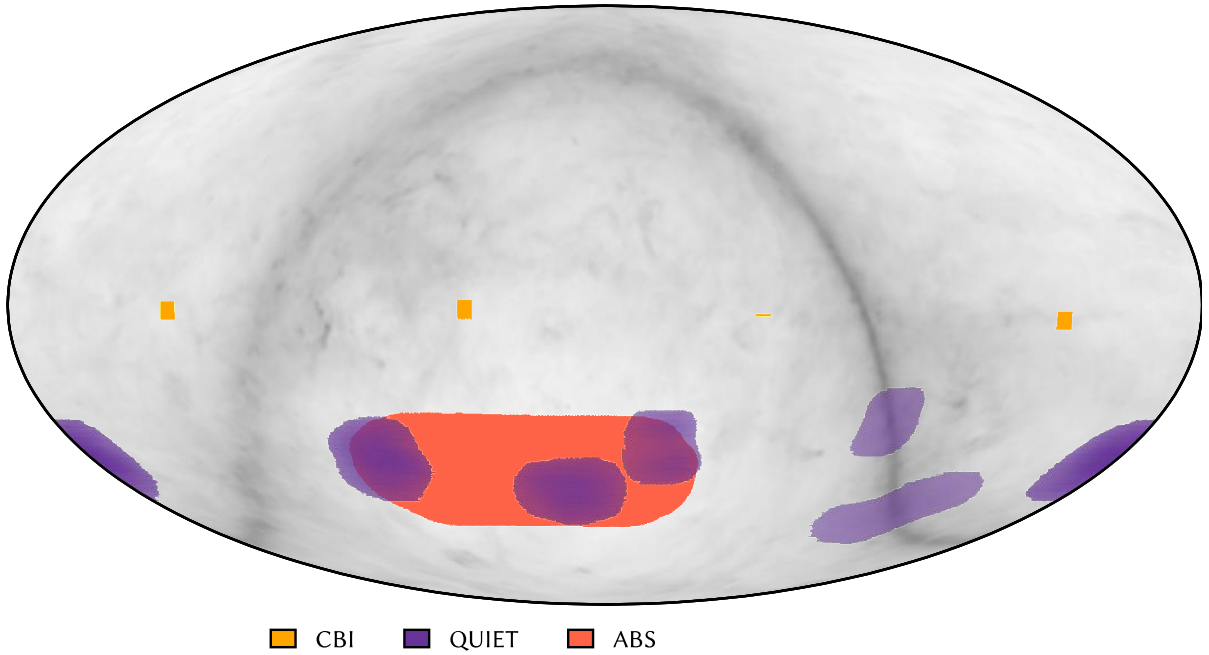
Q/U Imaging Experiment (QUIET, 2008-2010)

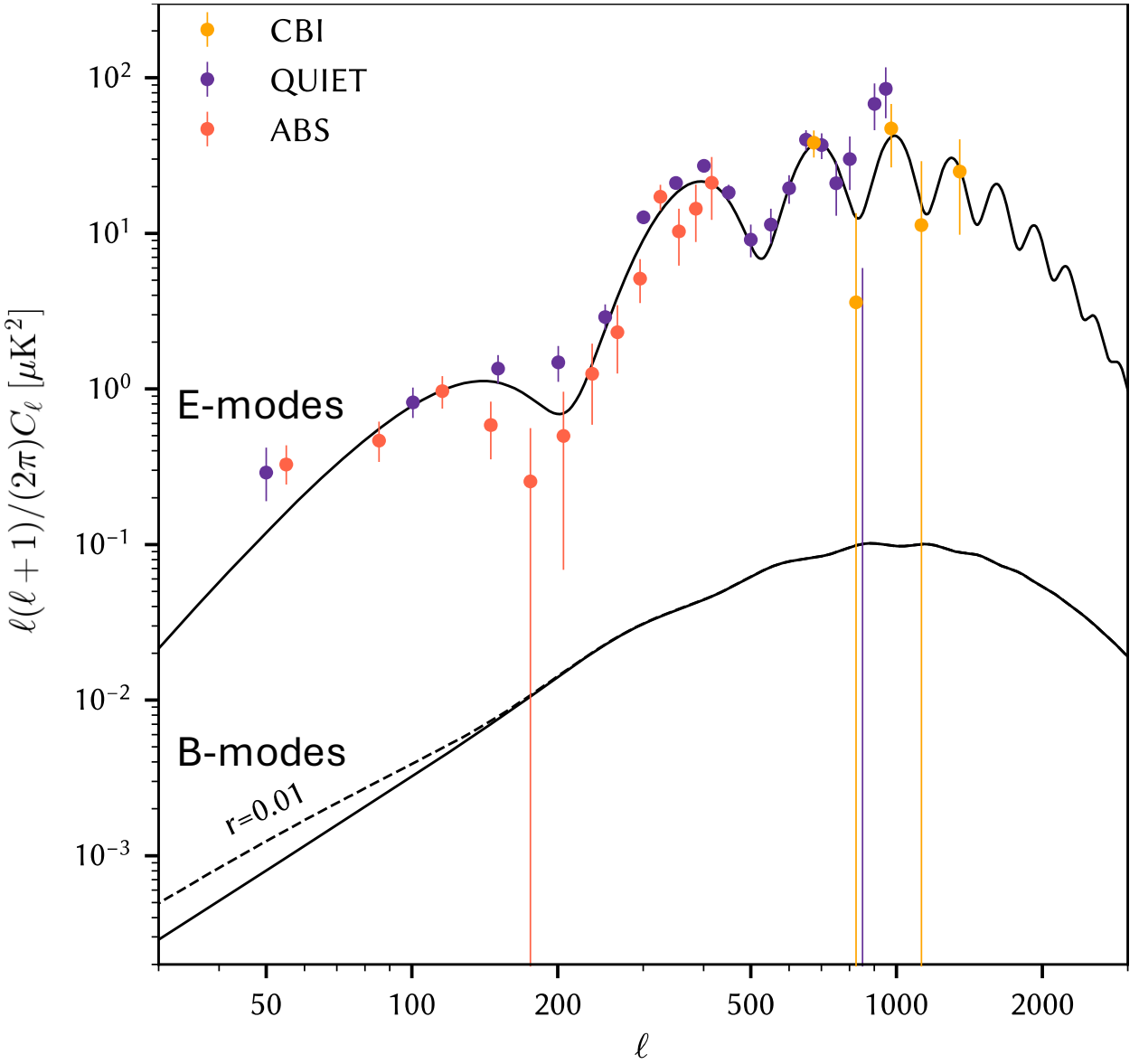




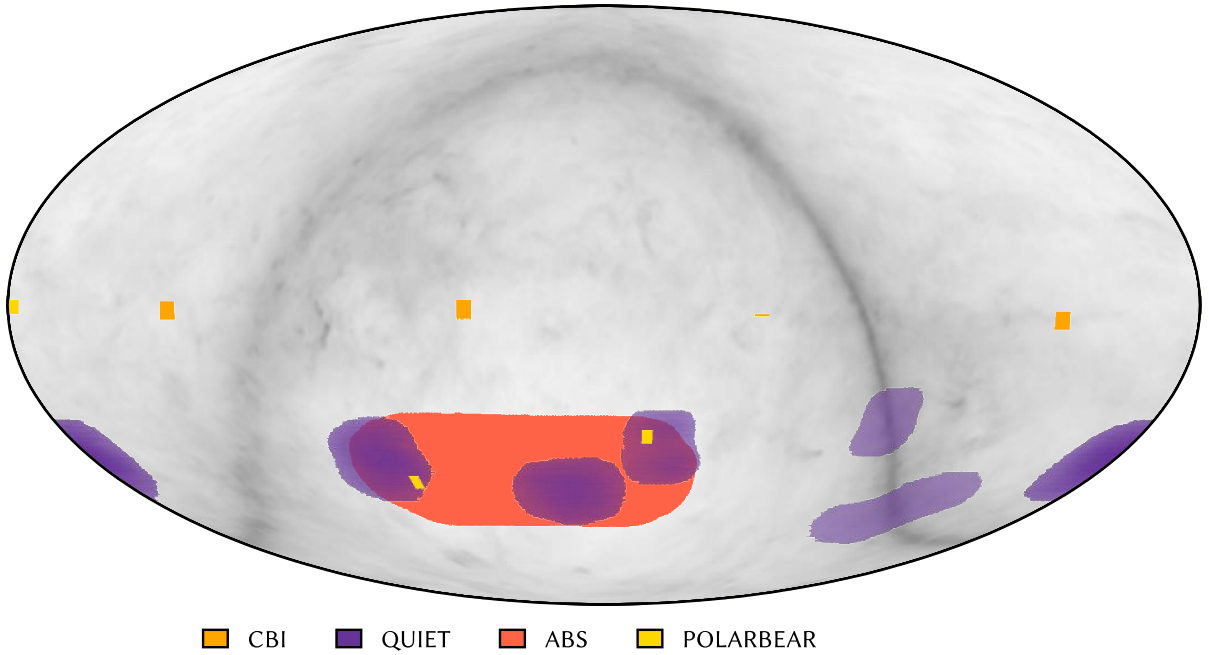
Atacama B-mode Search (ABS, 2012-2014)

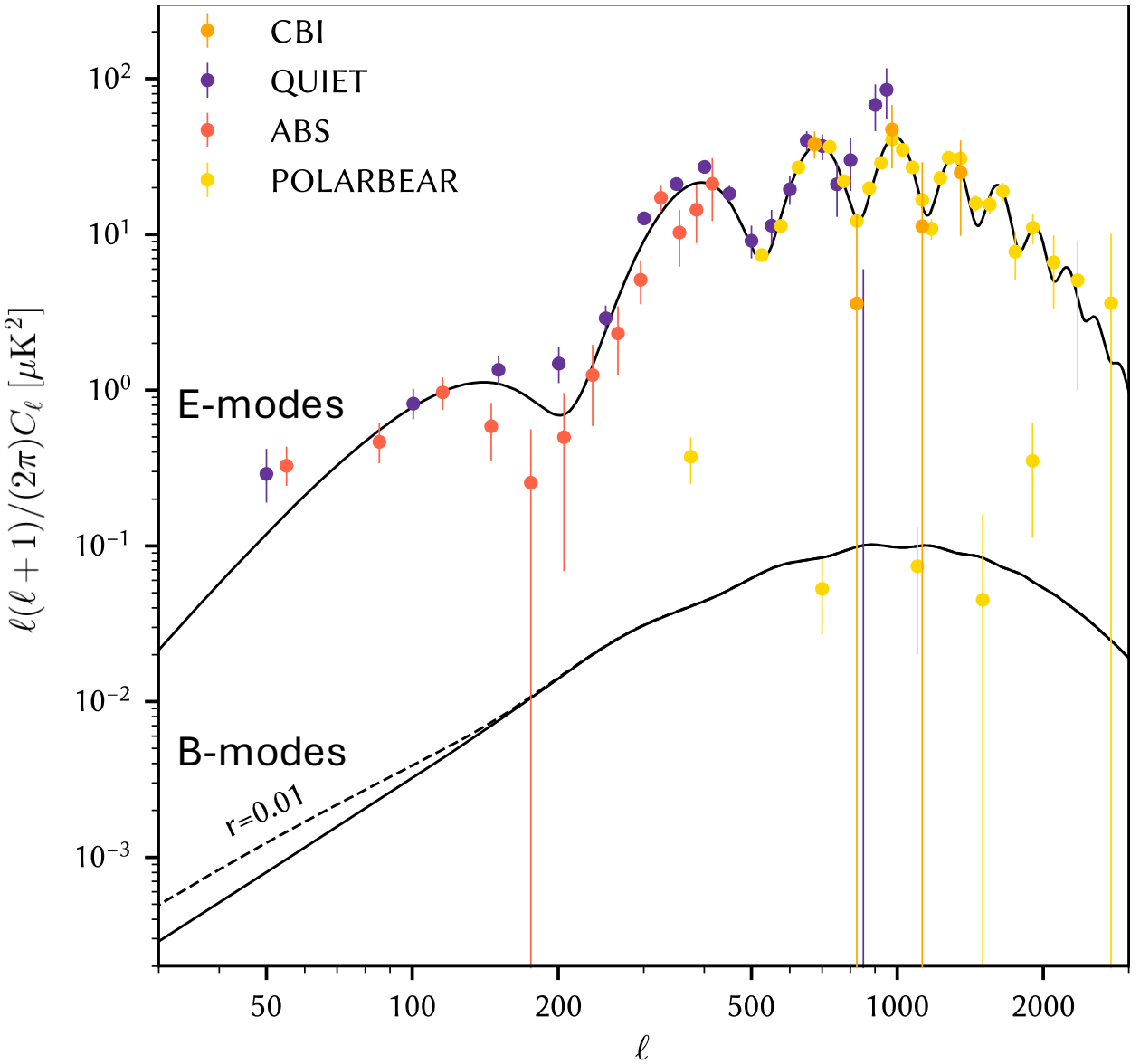




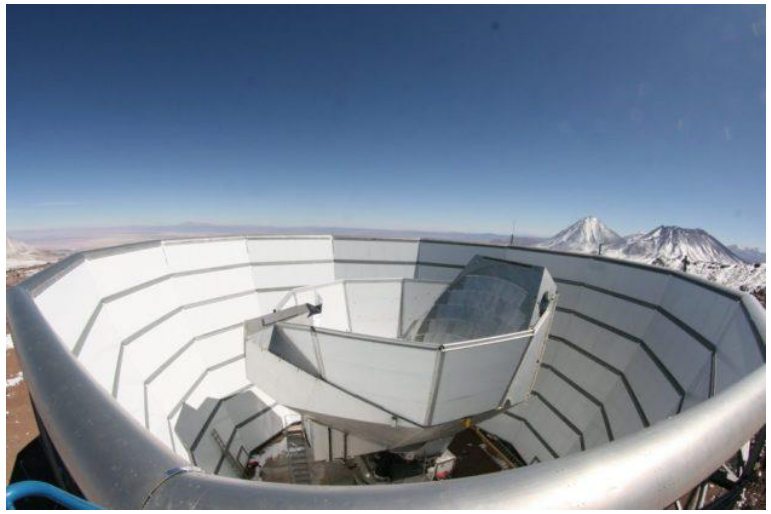


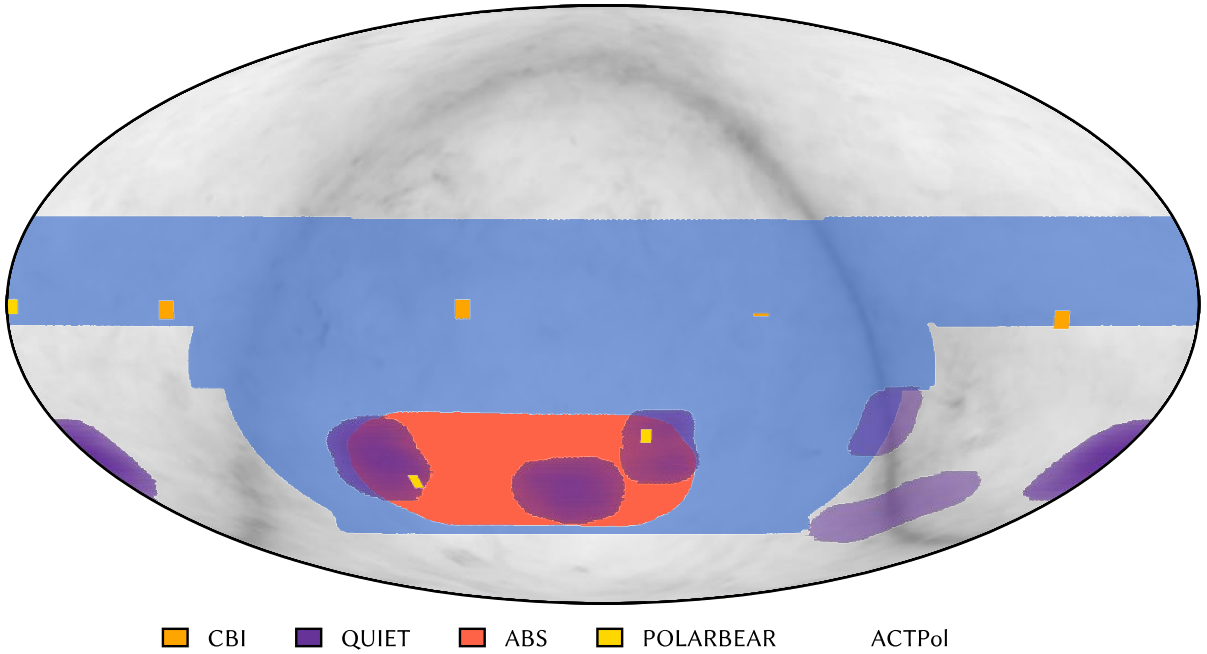
Polarbear/Simons Array (2012-2024)

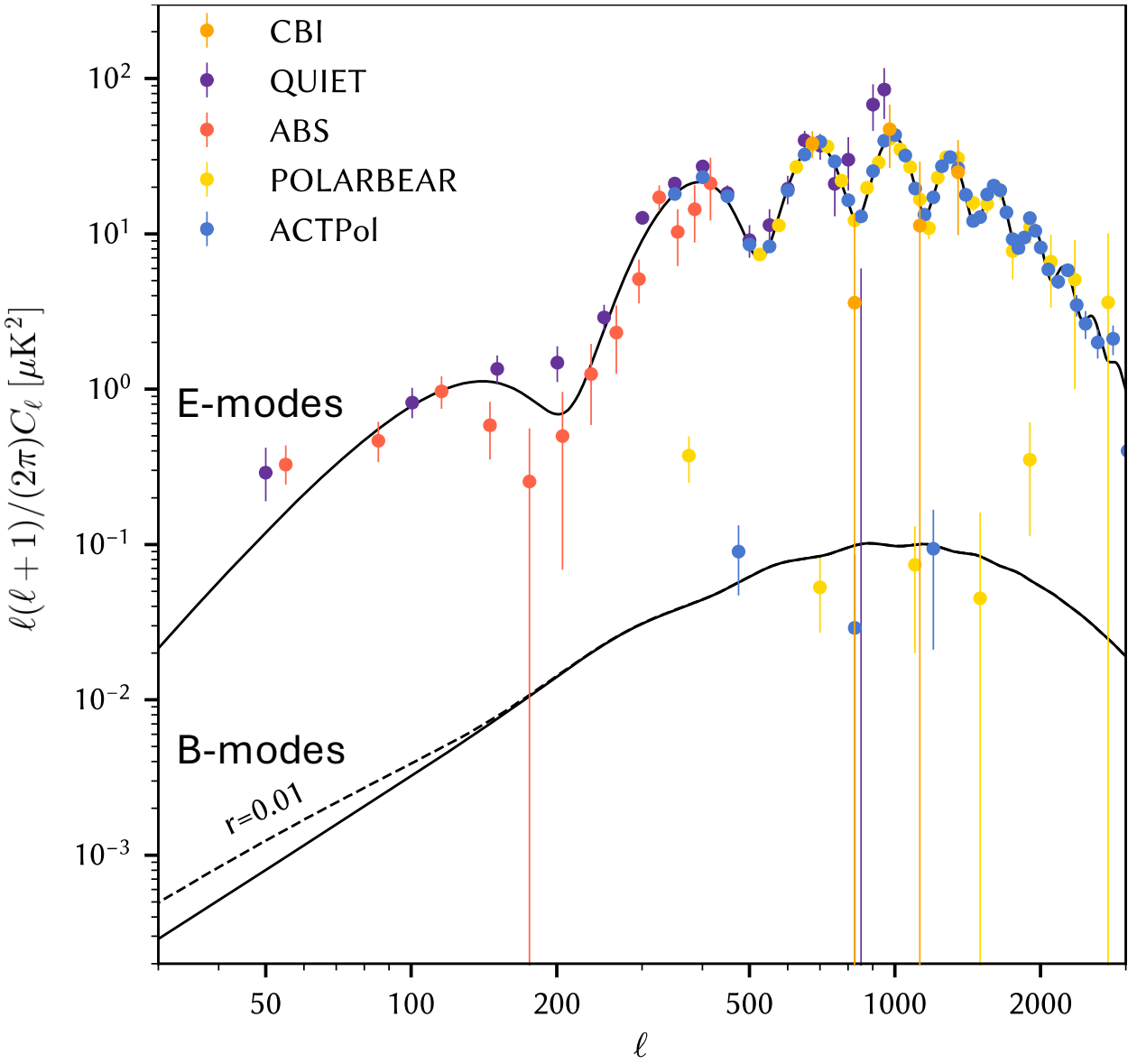




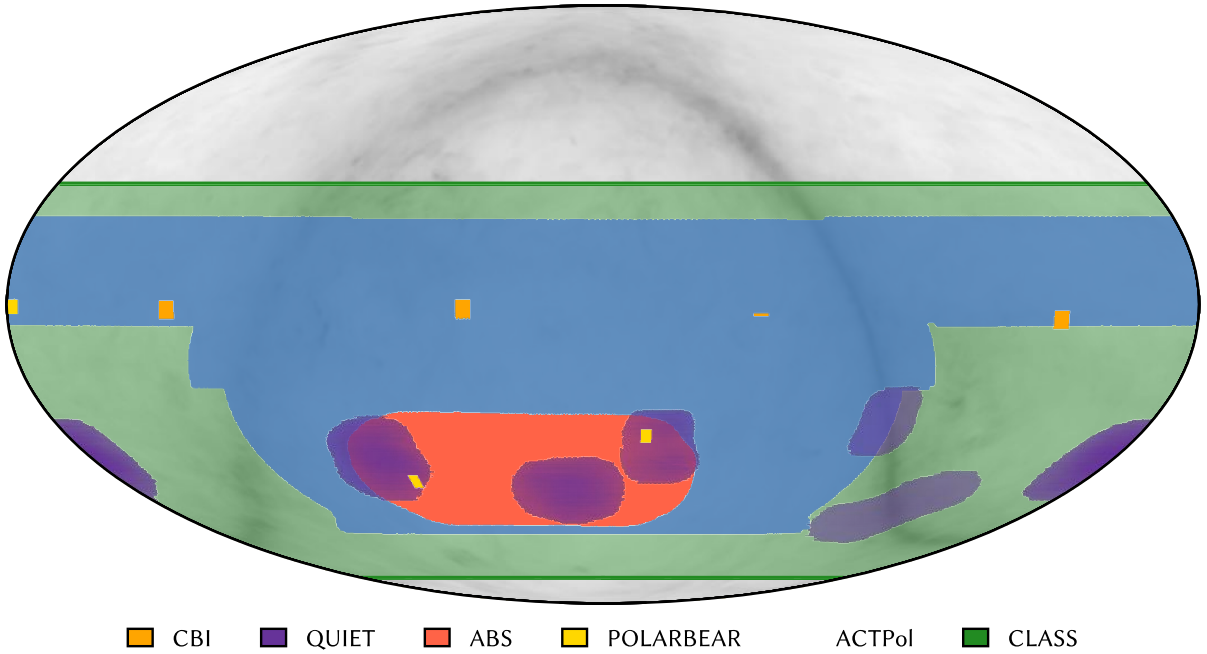
Atacama Cosmology Telescope Polarization (ACTPol, 2013-2022)

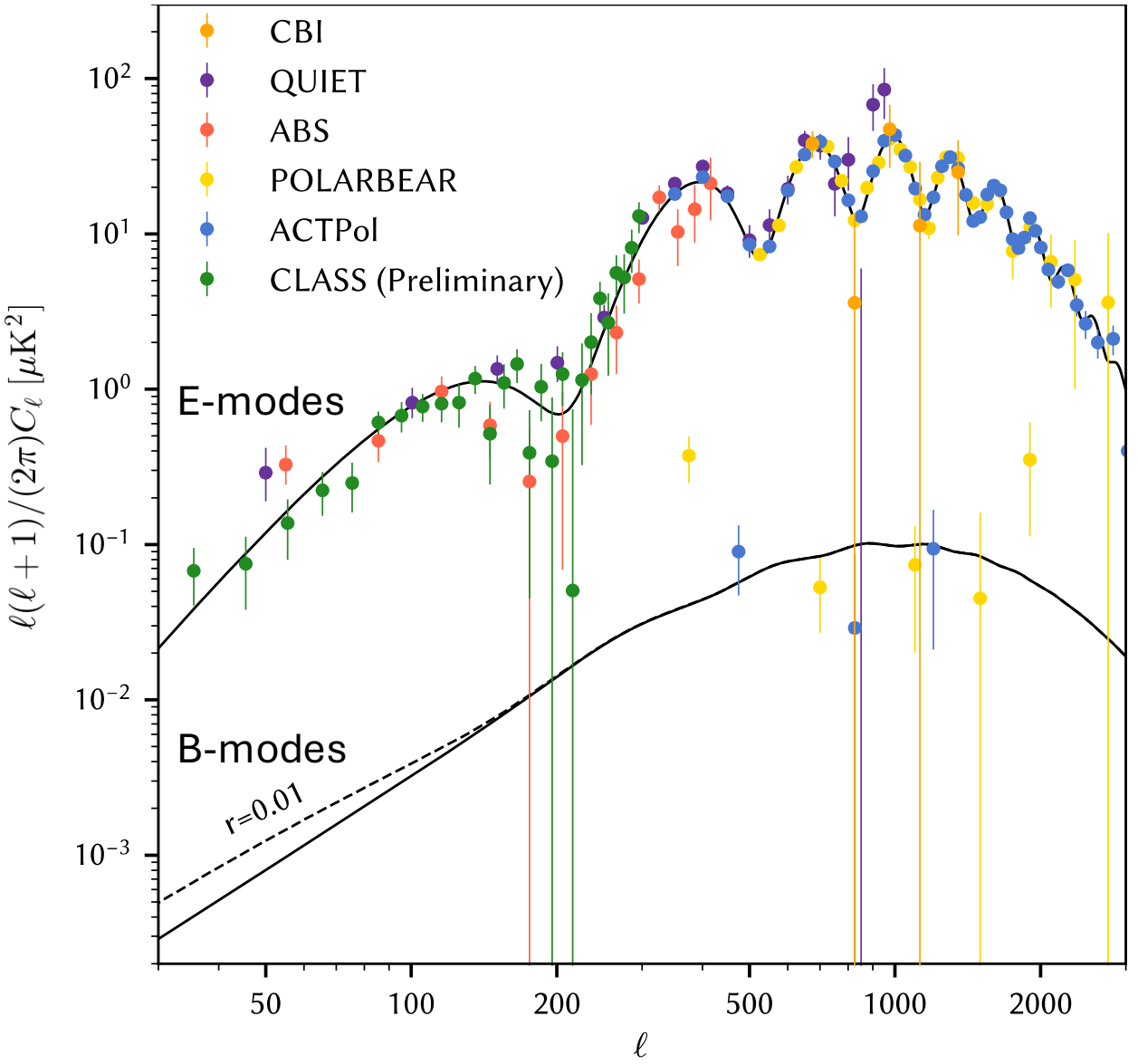


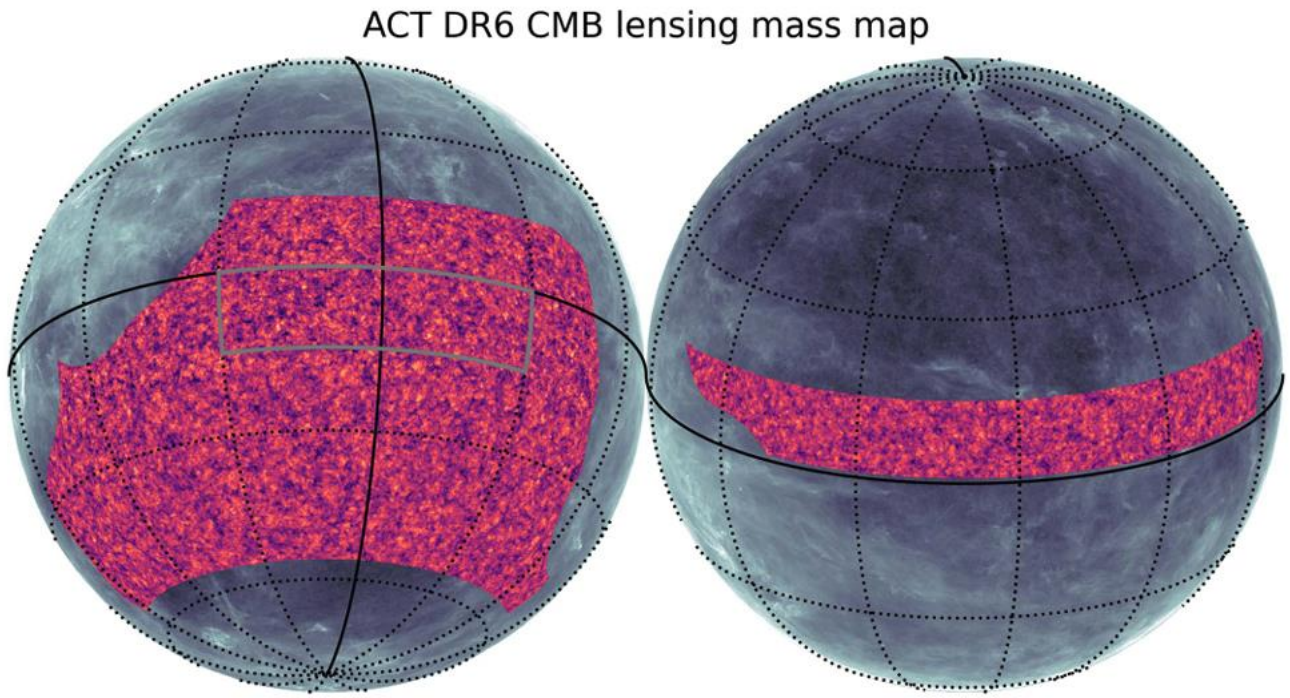




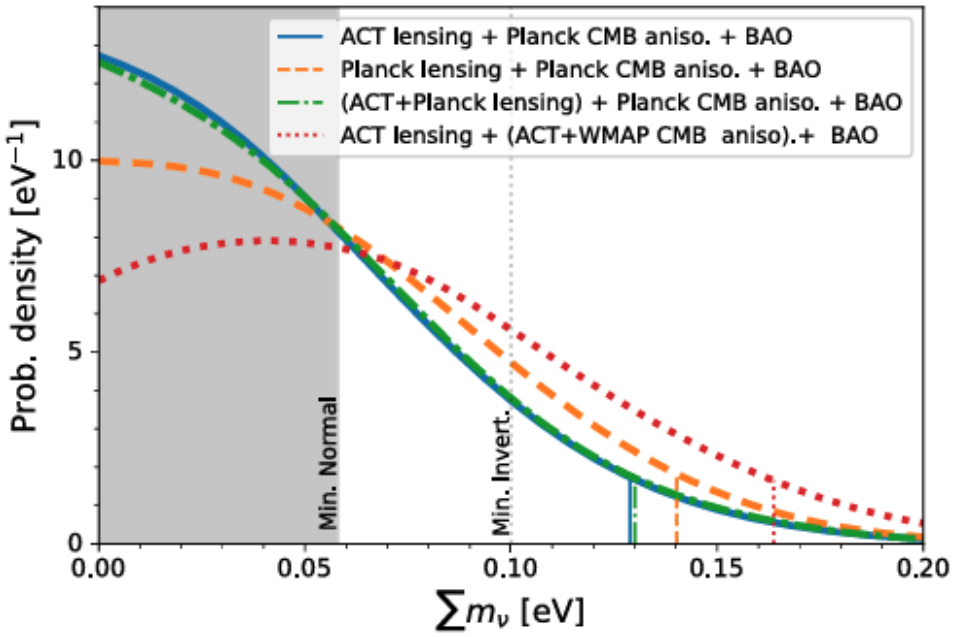
Cosmology Large Angular Scale Surveyor (CLASS, 2016-Present)

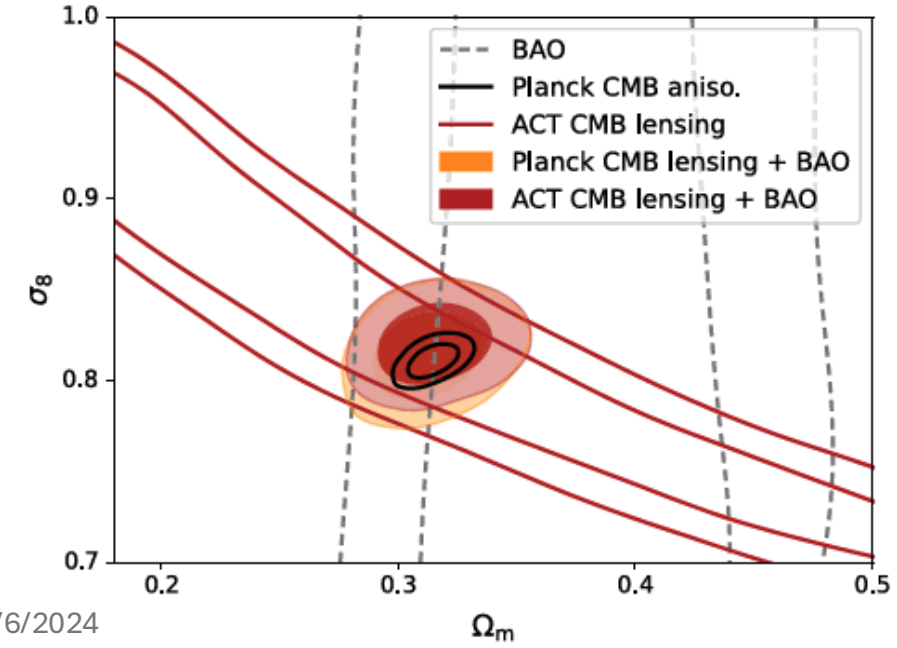




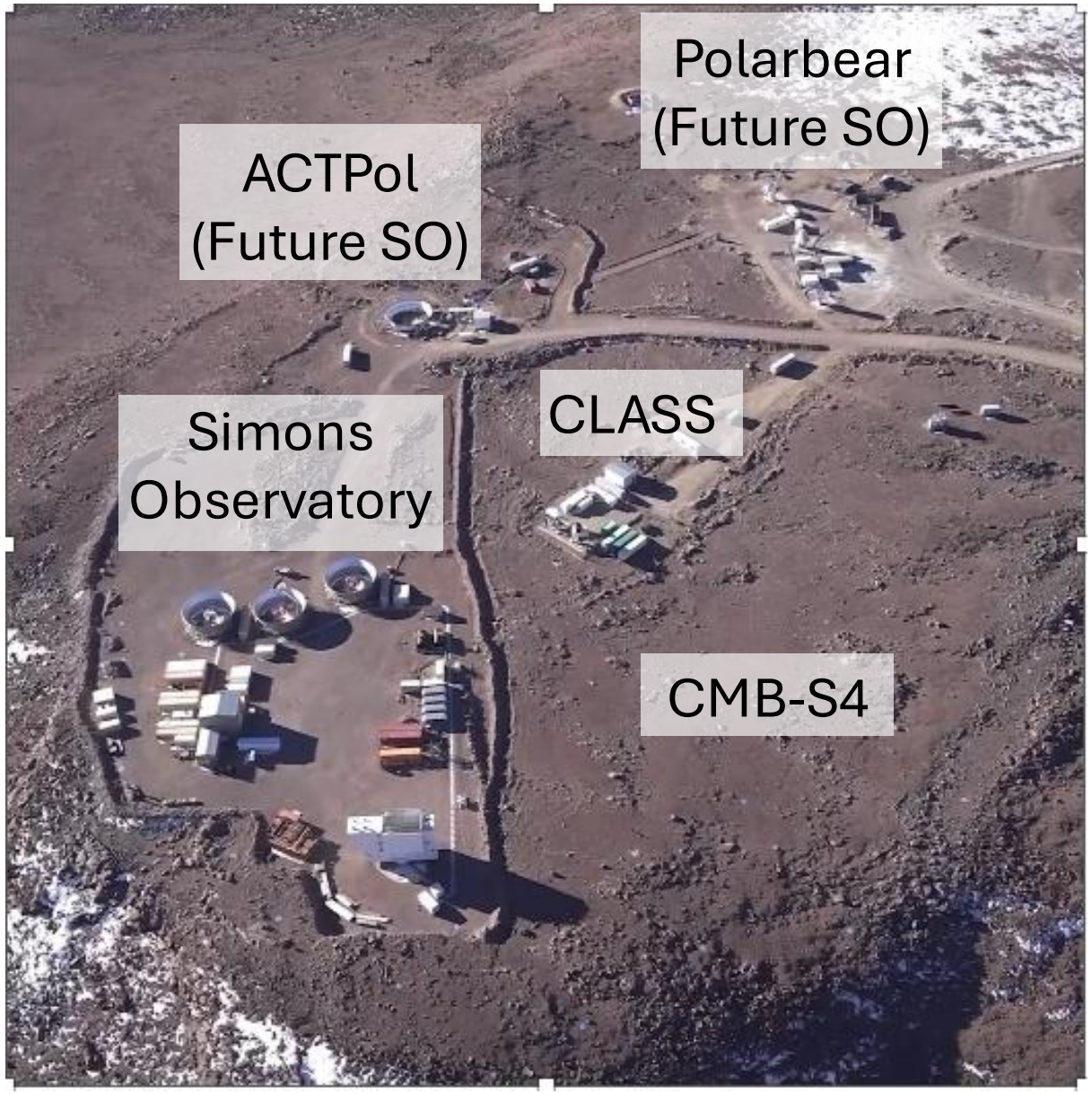


Madhavacheril et al. 2023





- "Final" CMB Lensing result from ACTPol
- Constraining power on the cosmic matter distribution and sum of neutrino masses comparable to the Planck space telescope
- Results being used in cosmological analyses of other premier datasets, such as DESI.

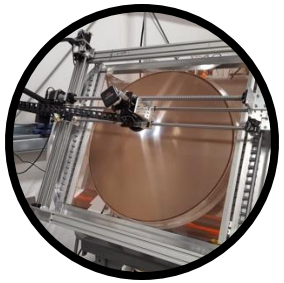


Dünner et al 2020

Chile Site Facts

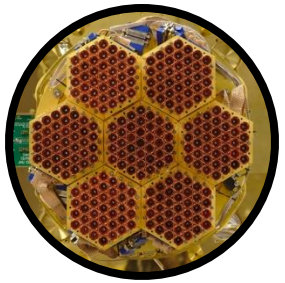
- The Chile Site has a world class atmosphere for microwave observations (50% <1 mm PWV).
- The site is highly accessible with 24-hour connections to North America.
- 75% of sky is accessible.
- For these reasons, over 25 years, the site has attracted a broad range of CMB experiments led by different teams testing technologies and developing the logistical knowhow to run large projects.
- The teams are producing results that are pushing the limits of cosmology.
- And now for B-modes.

Challenge Management (CLASS example)

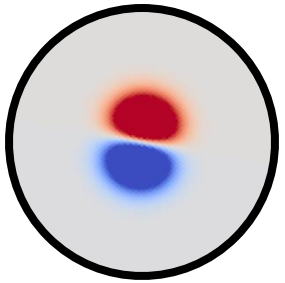


Modulator systematics

Wind signal



Internal reflections

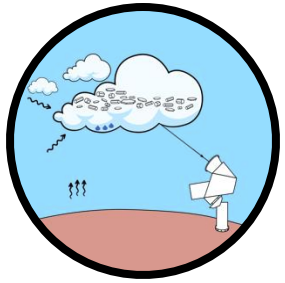


Polarization leakage

Ground emission

Radio frequency interference

Atmospheric turbulent emission



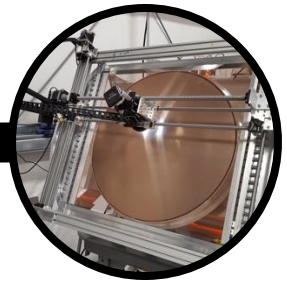
Cloud polarization

Challenge Management

Remove instrument source of systematic signal.

Simulations and pipeline enhancement.
Evolution of modulator technology and receiver optics.

Modeling and pipeline enhancements.
Modulator tech experimentation.



Modulator systematics

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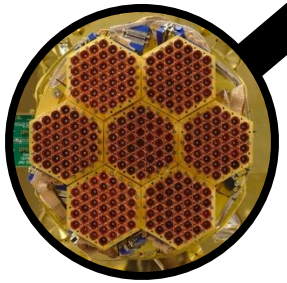

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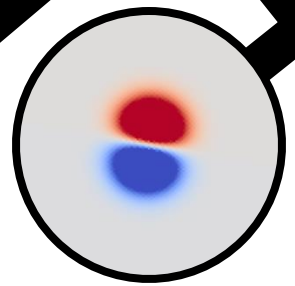

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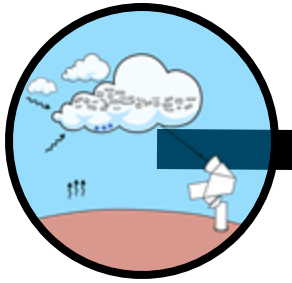


Cloud polarization

Improved data selection.
Spectral discrimination.

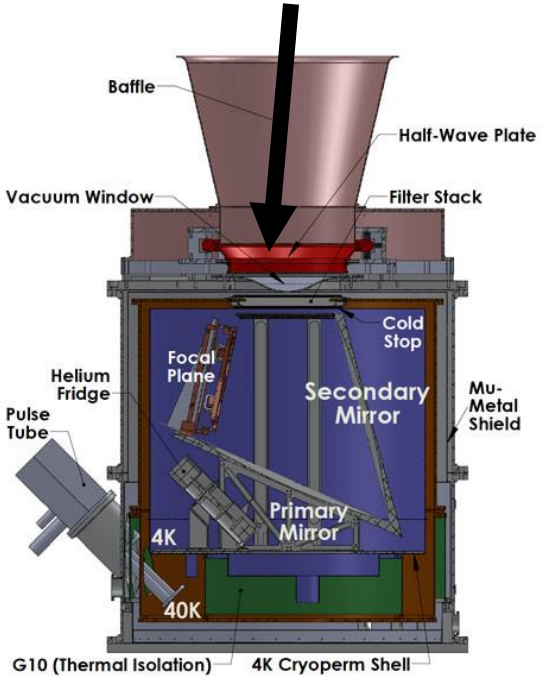
Modulation mitigation.
Shielding experimentation.
Scan experimentation.

RF filter on receiver.
Data selection.
Astro Park facilitated negotiations.

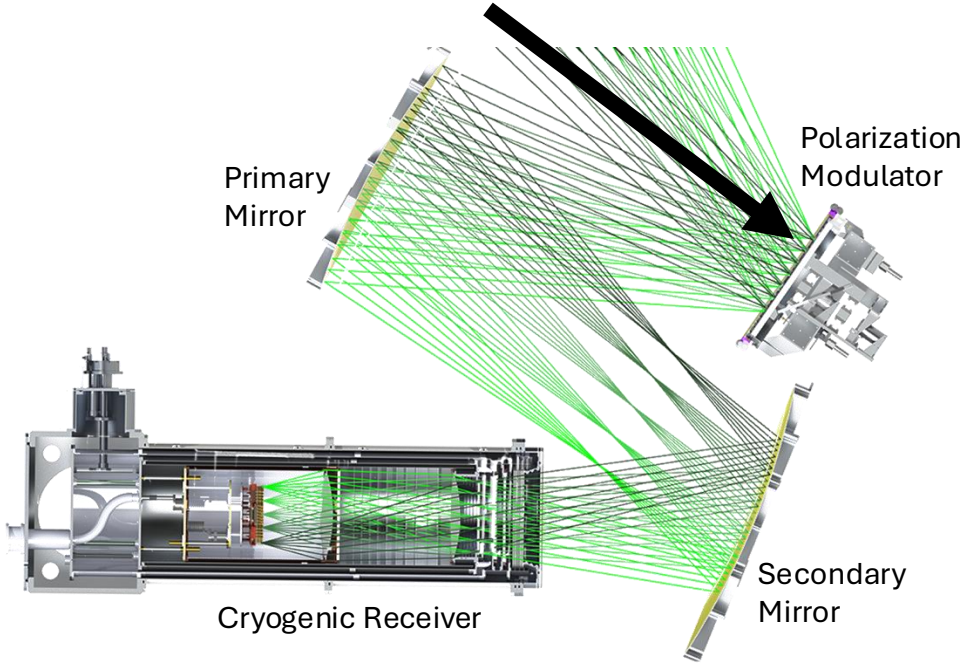
Modulation mitigation.

Rapid Front-end Polarization Modulation

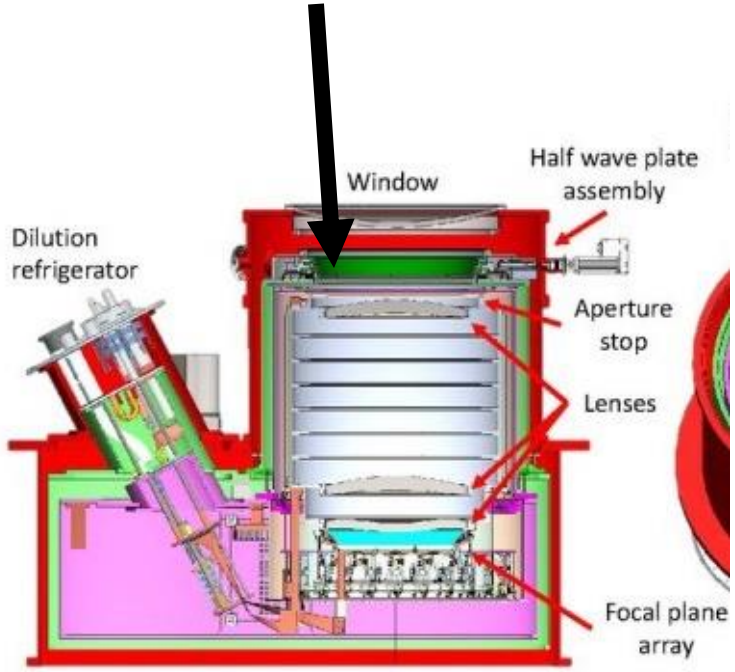
ABS
Half Wave Plate



CLASS
Variable Delay Polarization Modulator
Reflective Half Wave Plate



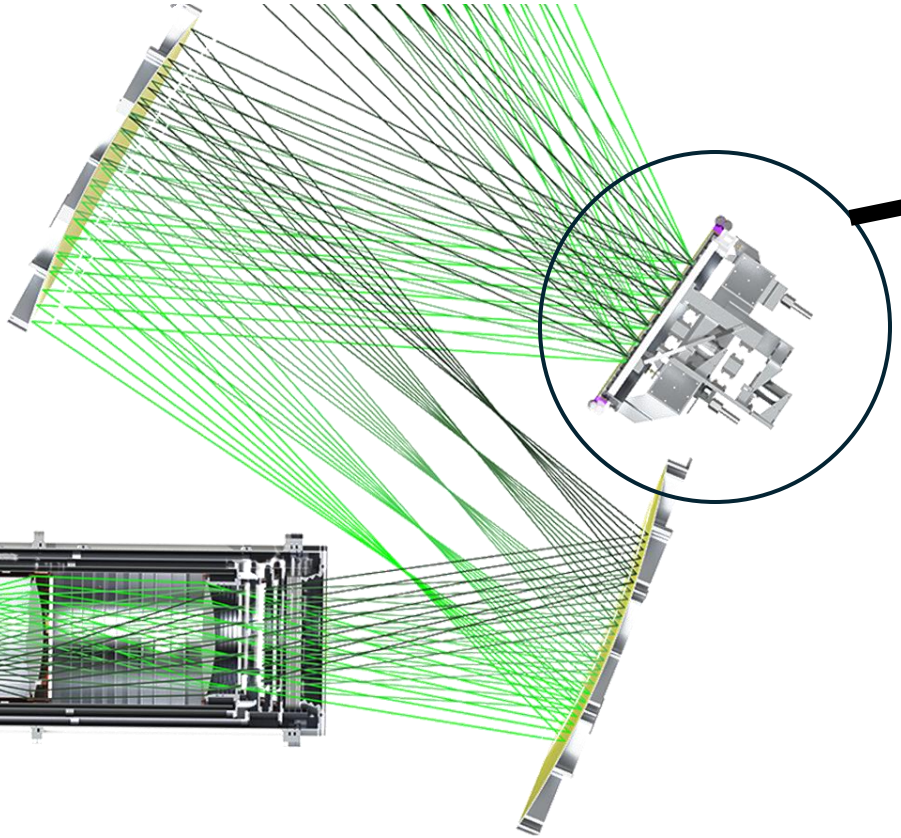
SO Small Aperture Telescope
Cryogenic Half Wave Plate



Polarbear/Simons Array also adopted a half-wave plate modulator, and QUIET had modulation built into its signal chain.

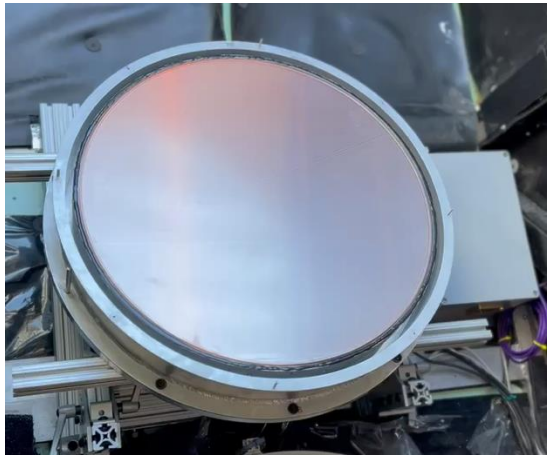
CLASS Example

Testing multiple modulation approaches

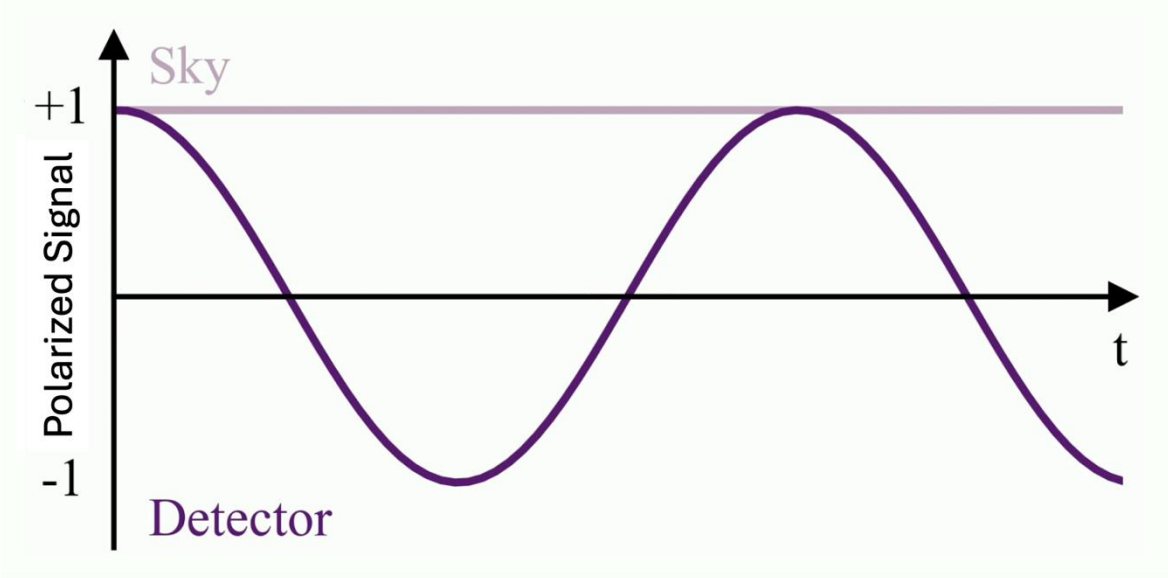


Variable Delay Polarization Modulator

Reflective Half Wave Plate



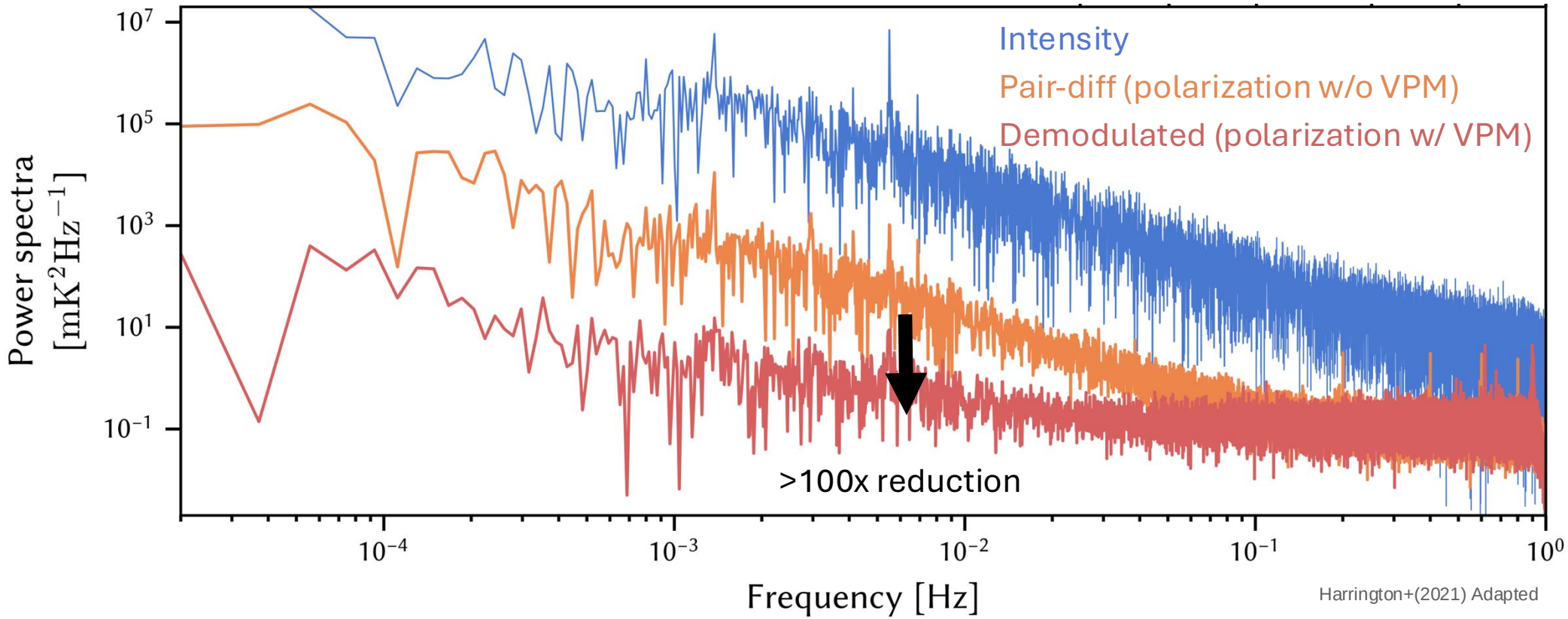
Amplitude Modulation of Polarized Signal



In the data, we can then "lock in" to the modulated signal's frequency and phase, separating it from spurious polarization.

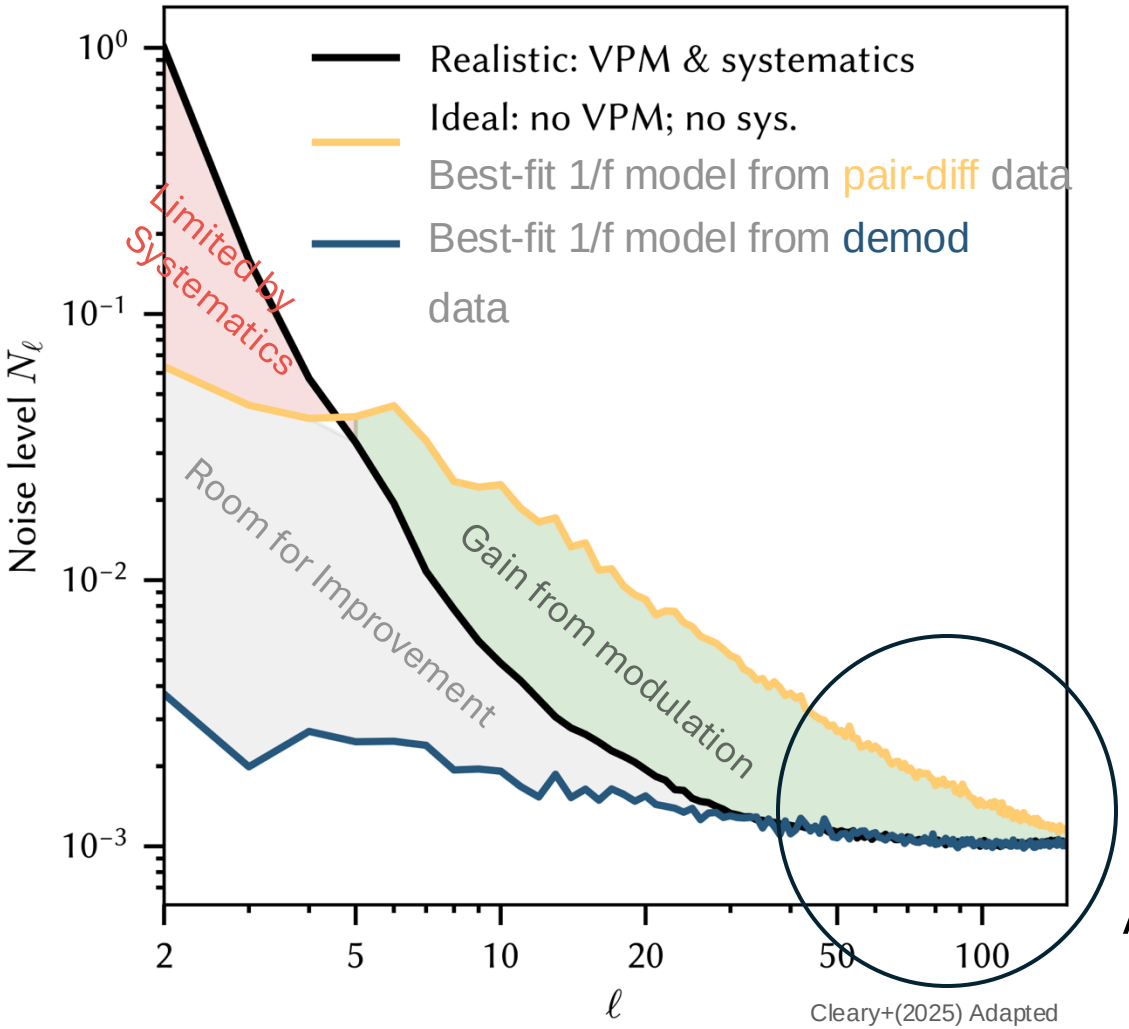
Modulation Results (CLASS Example)

Modulation reduces noise power at <10 mHz, where largest-scale B-mode signal lives, by over *two orders of magnitude* compared to pair-differencing unmodulated detectors.



Harrington+(2021) Adapted

Modulation Results (CLASS Example)



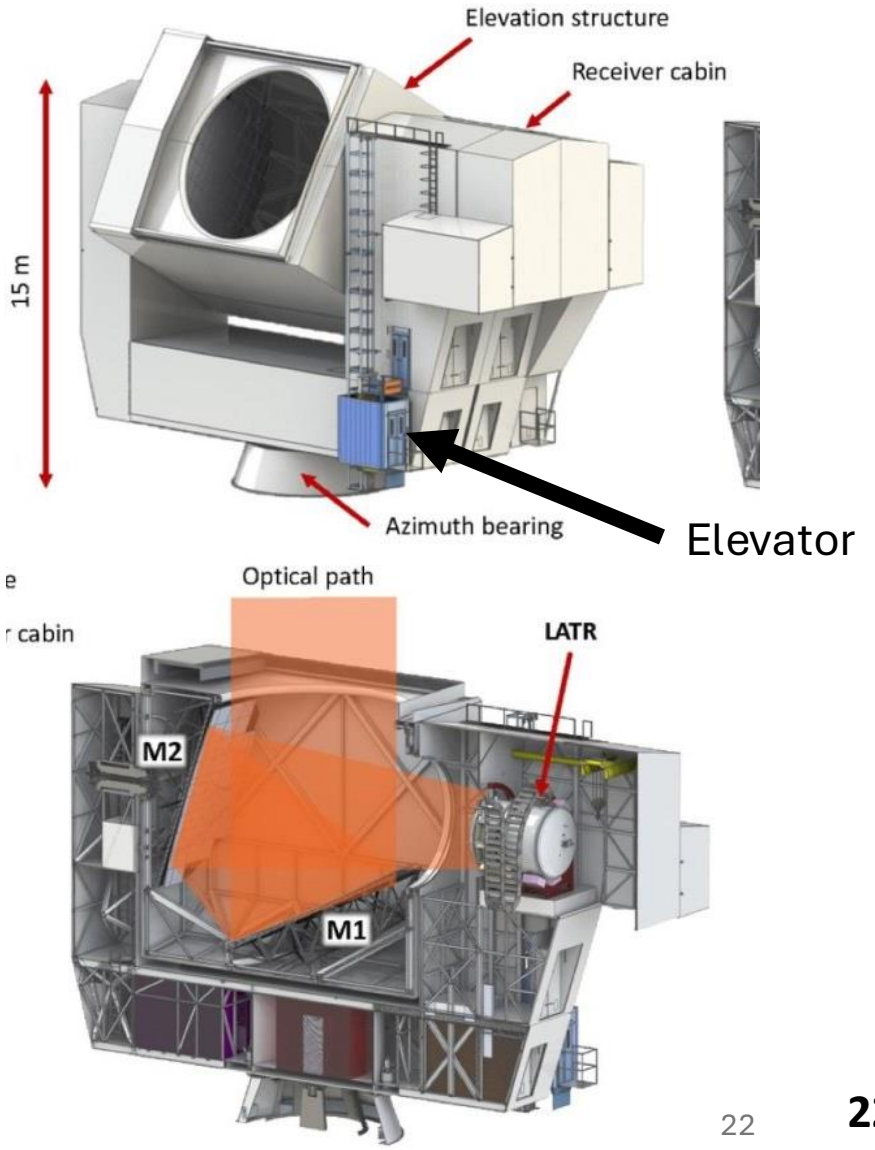
- Modulation significantly improves the map level $1/\ell$ noise up to $\ell < 150$.
- More systematic effects will present themselves as noise level goes down, but so far things look promising with significant progress already on understanding systematic effects.

Area targeted by SO and CMB-S4

Simons Observatory Today

(SO is projected to be Fully Operational mid-2025)

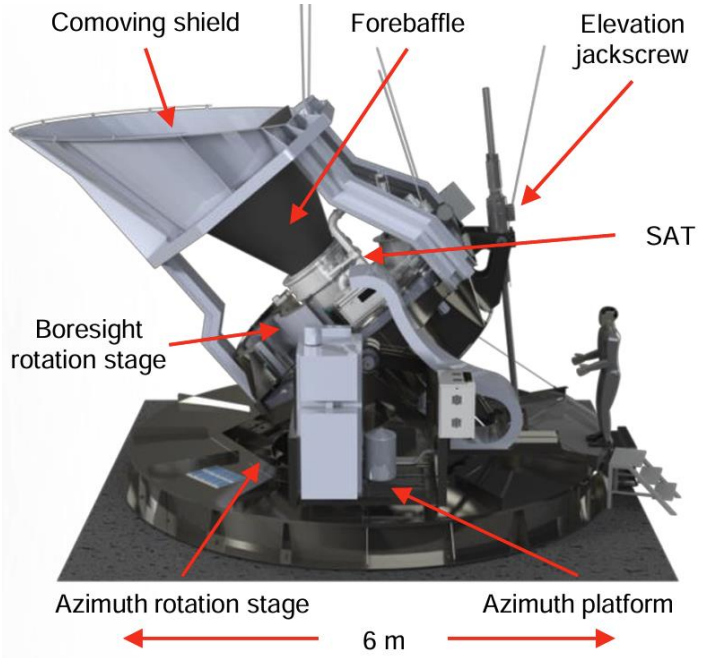
Large Aperture Telescope (LAT)



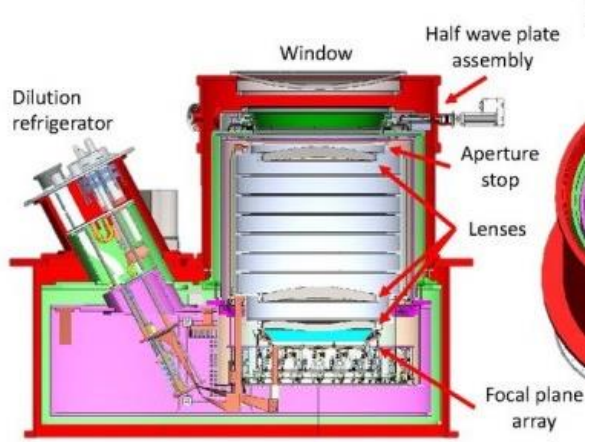
Simons Observatory Today

(SO is projected to be Fully Operational mid-2025)

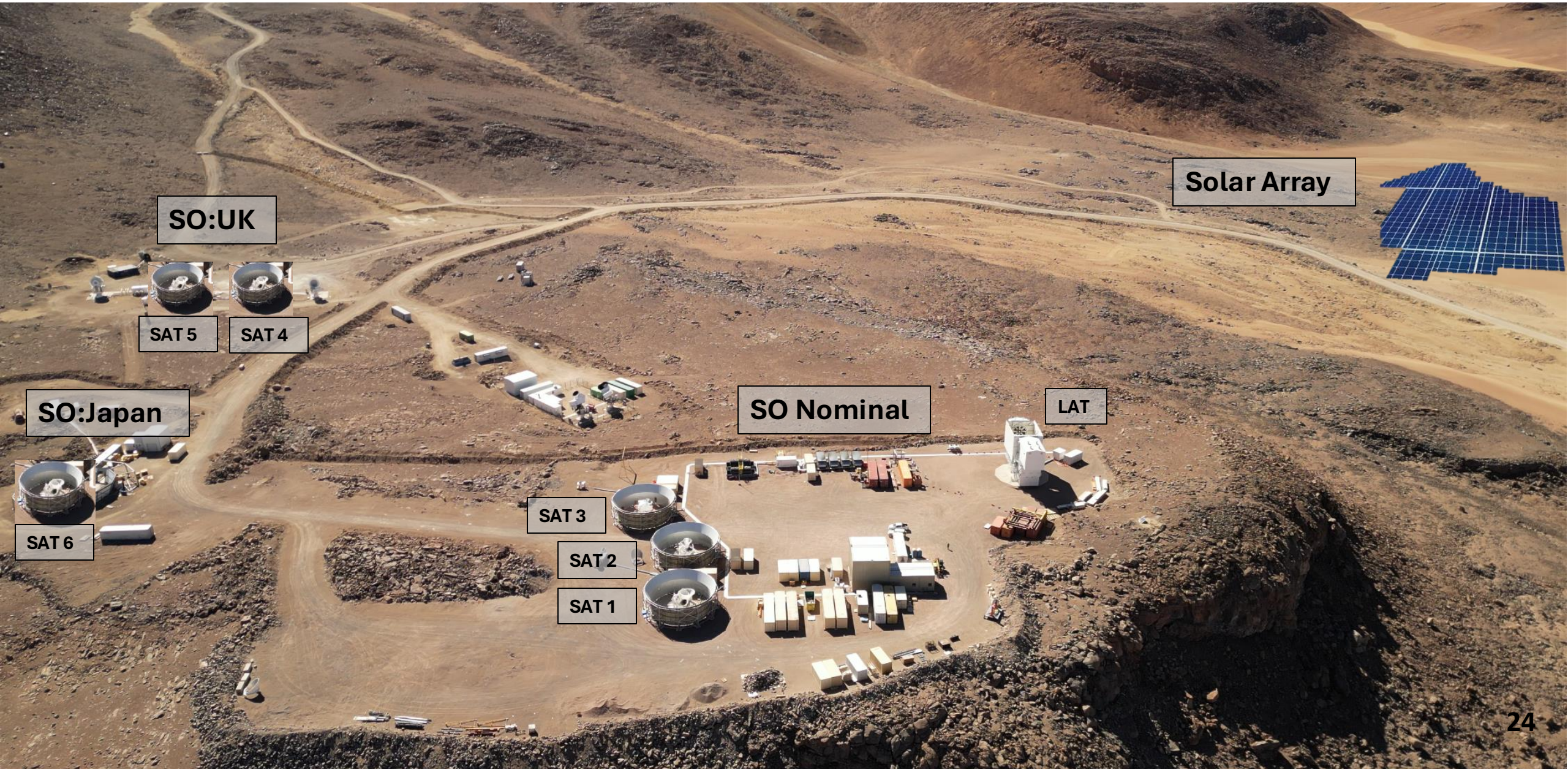
Small Aperture Telescope (SAT)



Galitzki+ 2024

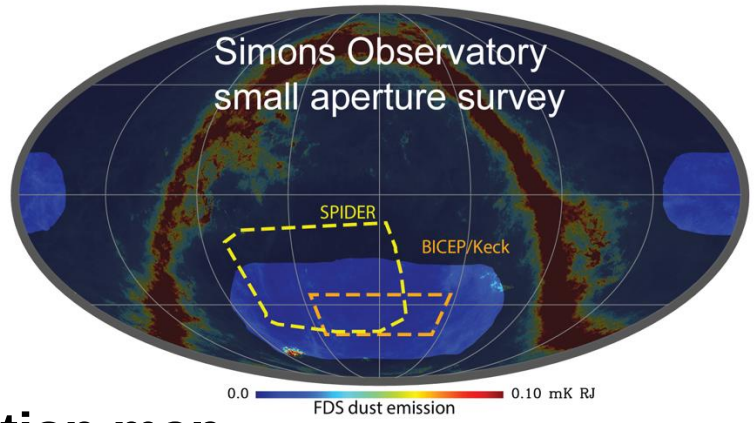


Simons Observatory 2026

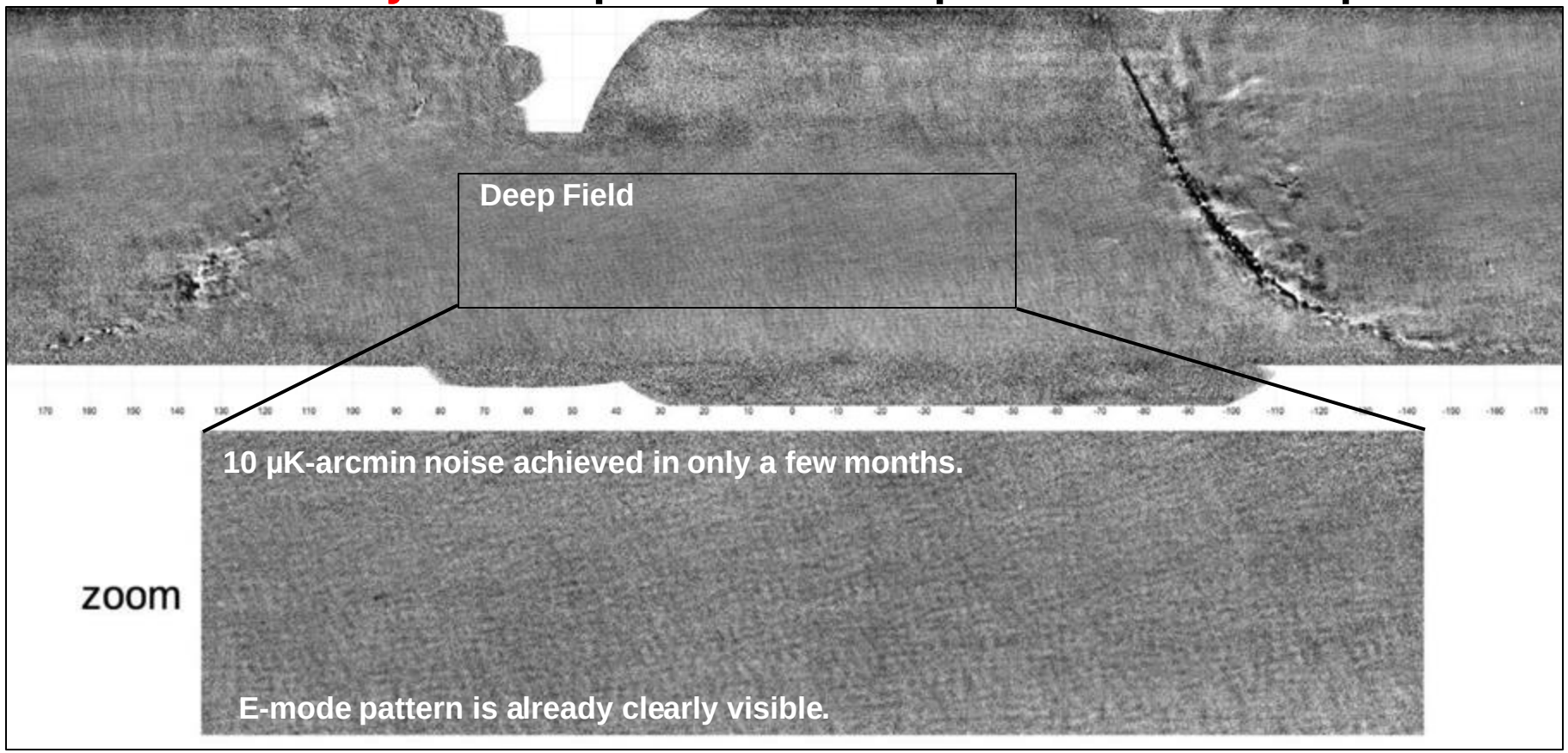


SATs Operating and Exceeding Requirements

- Measured Noise and Observations show Chile SATs are **on track to deliver high signal to noise maps of CMB polarization.**
- **Beam systematic effects are approaching 10x smaller** than what is seen in other experiments. This will greatly simplify its analysis.

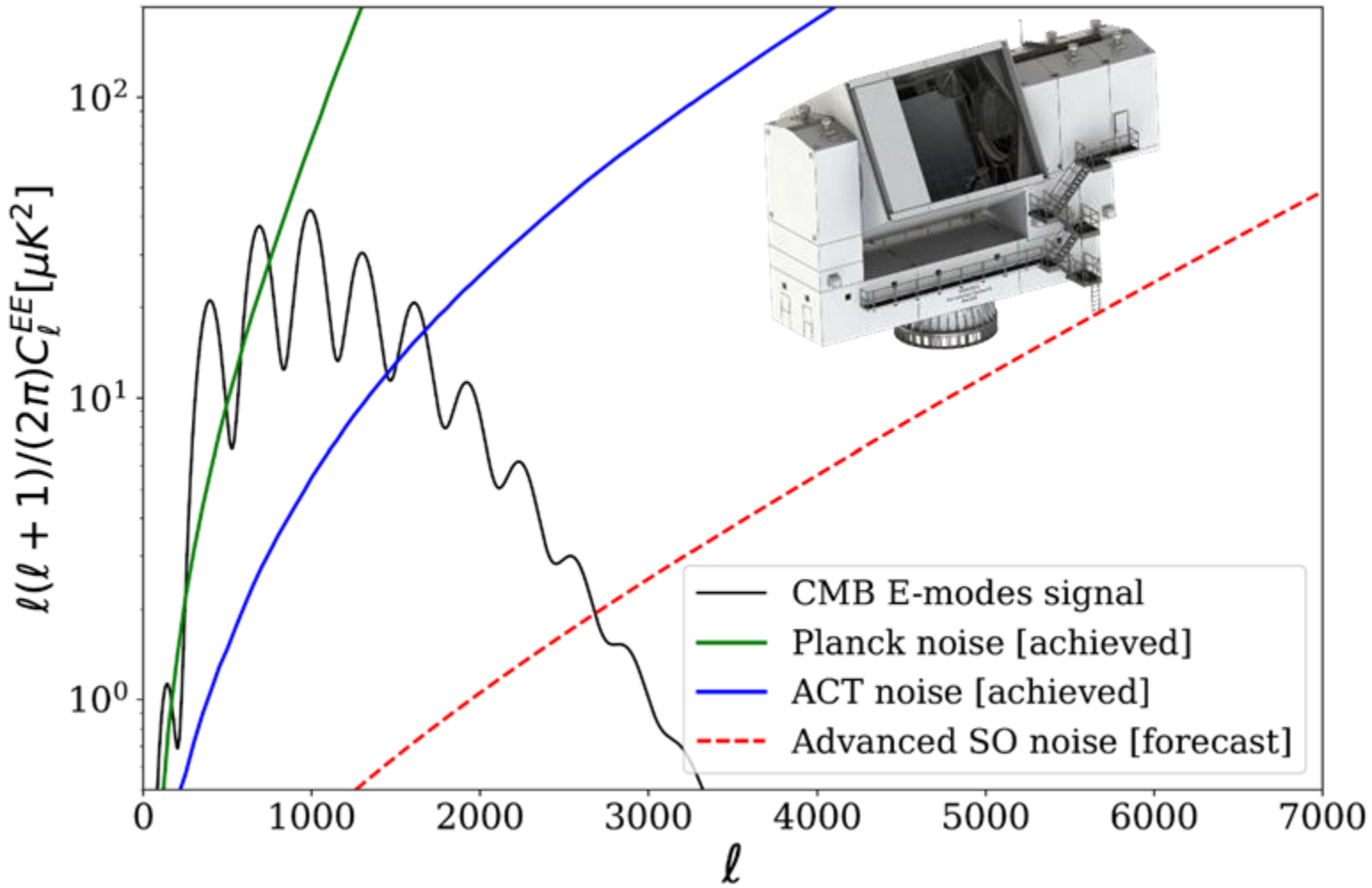


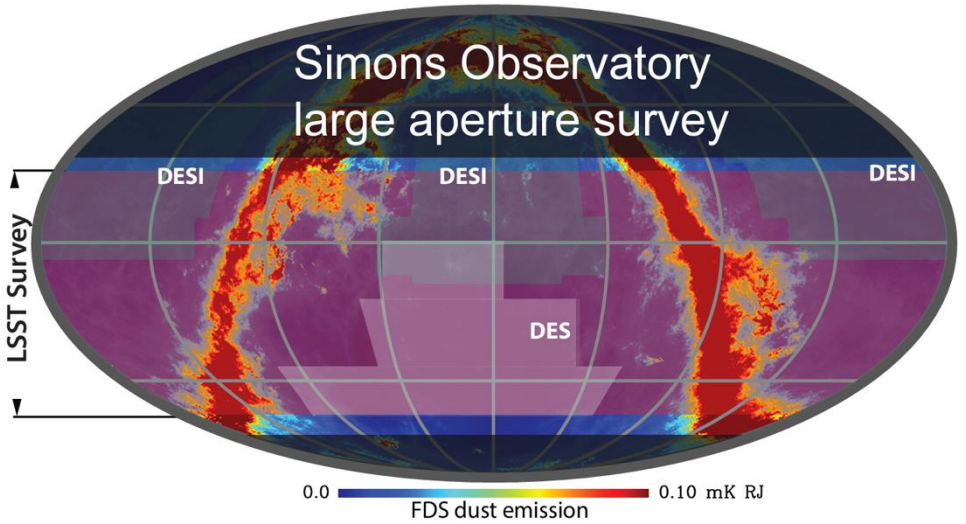
Preliminary Small Aperture Telescope Polarization map



Large Aperture Telescope Science

High-resolution, 20,000 deg^2 Legacy Maps of the Millimeter-wave Sky to 2.5 μK-arcmin





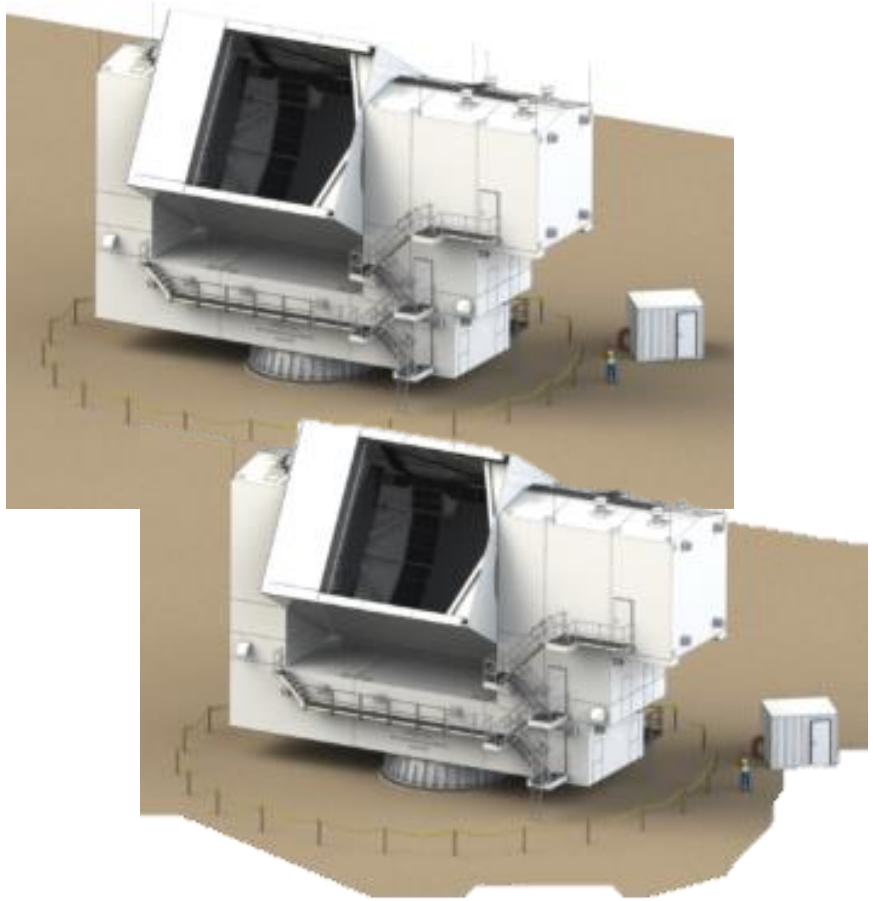
- Neutrino mass (Σm_ν)
- Effective Number of Relativistic Species (N_{eff})
- Tilt of the Primordial Scalar Spectrum (n_s)
- Large Scale Structure (σ_8)
- Non-Gaussianity (f_{NL})
- 10,000s of SZ galaxy clusters
- Galactic science
- Transients
- And more!

Focus of LAT on Legacy Survey leaves need for additional LAT for delensing B-modes for S4-like primordial gravitational wave goals.

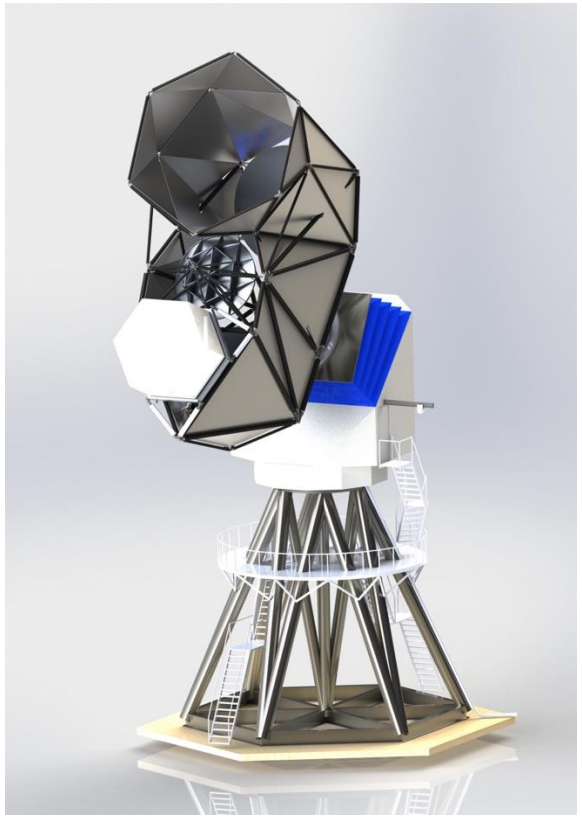
CMB Stage 4

Chile Legacy Survey LATs

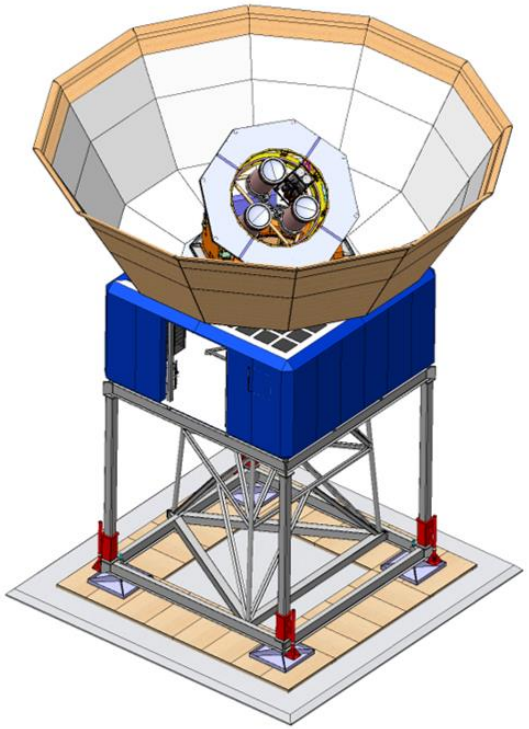
Each with ~1.5 more detectors/mapping speed compared to the SO LAT.



South Pole LAT, Candidate for delensing in Chile



Three-Shooter SATs. Each tube approximates an SO SAT.



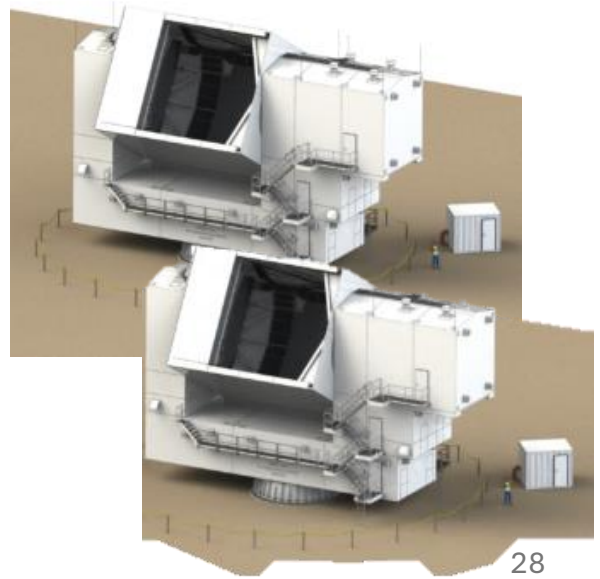
Developing a Revised CMB-S4 Configuration

The Funding Agencies have charged CMB-S4 to develop an all-Chile configuration that is able to address all of the CMB-S4 science goals, and can meet the inflation science goal of $\sigma(r) \leq 5\times10^{-4}$ within a reasonable survey duration ($\lesssim$ 10 years). *A report is to be submitted in Spring 2025*.

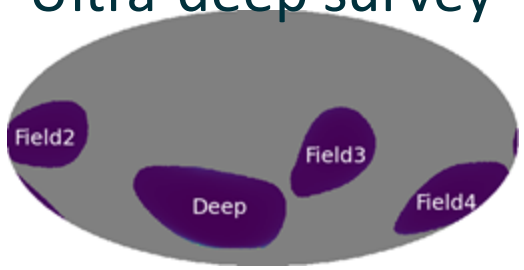
CMB-S4 will conduct:

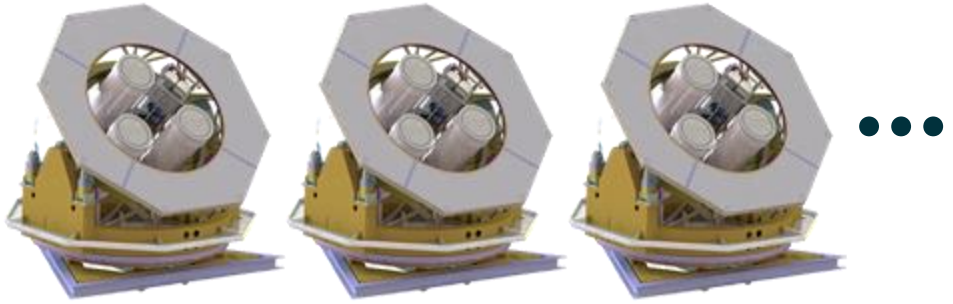
- An ultra-deep survey for inflation science with multiple SATs covering the 4 cleanest patches of sky visible from Chile;
- A de-lensing survey to support the B-mode search using one or more 6-m LATs viewing the same sky patches as the SATs;
- A wide-deep "legacy" survey to address many other science topics using two 6-m LATs over 7 years as in the previous 2-site configuration.

Wide-deep survey



Ultra-deep survey





CMB-S4 Chile Configuration Optimization

Optimization studies are organized in five main areas:

- Simulations and Forecasting
- Small-Aperture Telescope Design
- Large-Aperture Telescope Design
- Site Design
- Cost Modeling

The current focus is on simulations and forecasting and on optimizing the SAT design.

- CMB-S4 simulations and forecasts are by intent conservative, to ensure that CMB-S4 will be able to achieve the science goals with high confidence.
- Design studies concentrate on larger aperture SATs than used by SO, taking advantage of larger diameter sapphire disks for half-wave plates that are now becoming available.
- Lessons learned by SO in designing and initial operations of their SATs are being incorporated to the extent possible.

CMB-S4 plans to be ready for CD-1 and CDR by the end of FY 2026, if funding permits.

Looking Ahead

The importance of a phased approach.

- As discussed on previous slides, careful design studies and forecasts are being undertaken by the S4 collaboration and will be available soon.
- SO is participating through members who are in both collaborations, especially in terms of understanding assumptions that enter forecasts.
- A general picture is emerging that to reach the CMB-S4 inflation goals by the early-mid 2040s, one needs
  - The delensing LAT and
  - ~20 additional SATs (where an S4 3-shooter is three SATs) beyond the original 6 SO SATs.

Chile Site Phased Project

Take Aways

- The Chile Site is a world-class location for millimeter-wave astronomy, including CMB inflationary polarization measurements.
- Technologies and strategies exist to grapple with the unique challenges of the Atacama.
- A merged effort of CMB-S4 and Simons Observatory (SO) will be stronger: more expertise and resources for the hardest measurement. The leadership of both CMB-S4 and SO are eager to discuss partnership.
- The best strategy is a phased deployment of SATs and additional LAT for delensing as the survey sensitivity grows towards the $\sigma_r \leq 5 \times 10^{-4}$ goal.
- The phased project structure allows for improvements made to instrumentation and lessons learned from data to greatly enhance future observations. It is the only way CMB studies have succeeded in the past.

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