

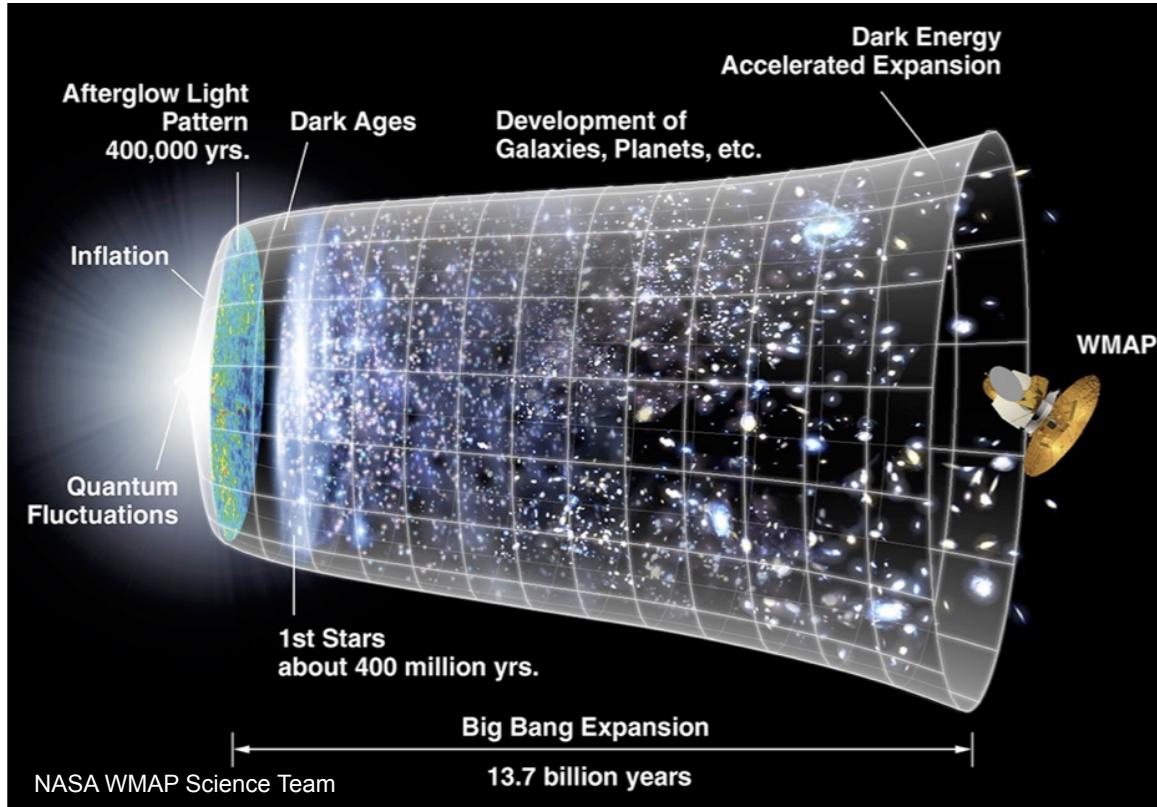
Constraining Cosmic Birefringence with Polarization Angle Calibration

Sara M. Simon
she/her
Fermilab
June 15, 2026



Photo Credit: Nick Galitzki

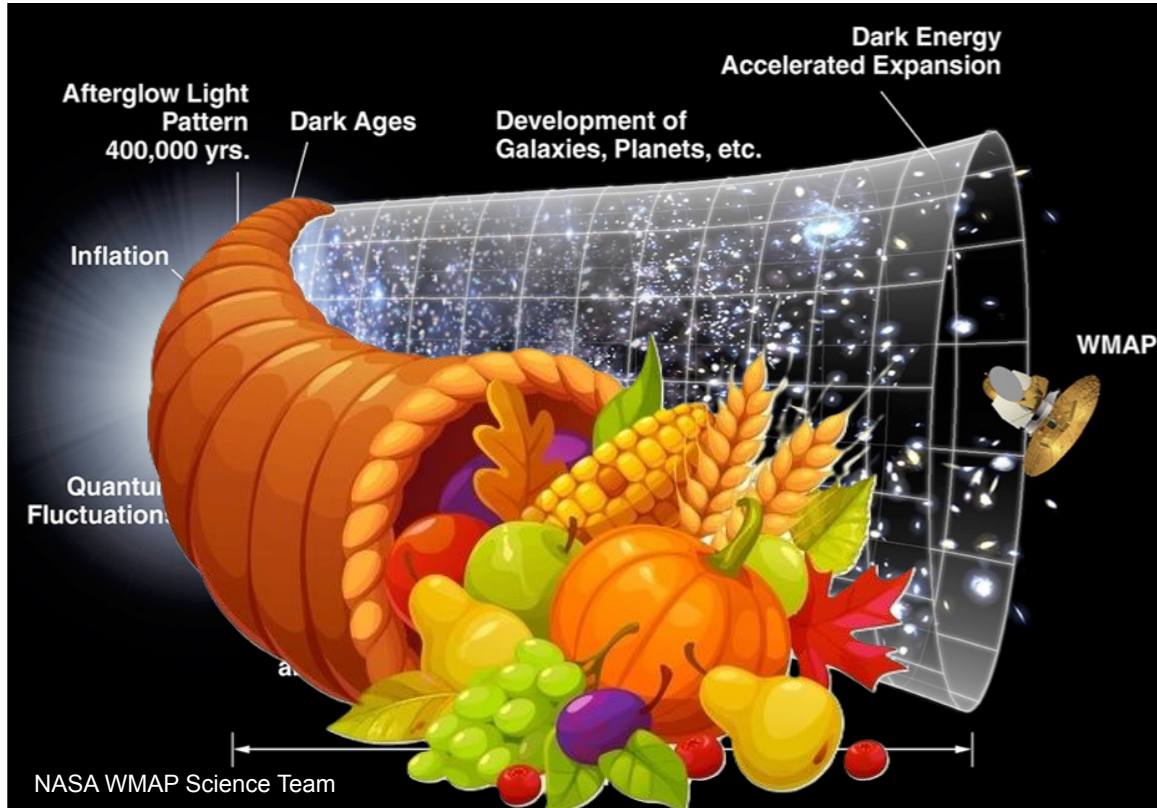
A unique probe of fundamental physics



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 to the formation and evolution of structure

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The CMB answers fundamental questions

- CMB constrains dark matter and dark energy through the growth of structure (σ_8), the expansion rate (H_0), and the amounts of dark matter and dark energy
 - Extremely accurate probe of these mysterious dark components
 - Highly complementary to supernovae and large-scale structure studies

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 - One of the few ways to probe early universe $\sim 10^{-36}$ s after its beginning

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 - One of the few ways to probe early universe $\sim 10^{-36}$ s after its beginning
- CMB can probe for new physics Beyond the Standard Model (BSM)
 - Constrain/probe physical mechanisms of cosmic birefringence

Extracting scientific parameters from CMB observations

CMB Temperature and Polarization Maps



Temperature and Polarization Power Spectra
+
Maps of Lensing and Sources



Science

Formation and evolution of structure

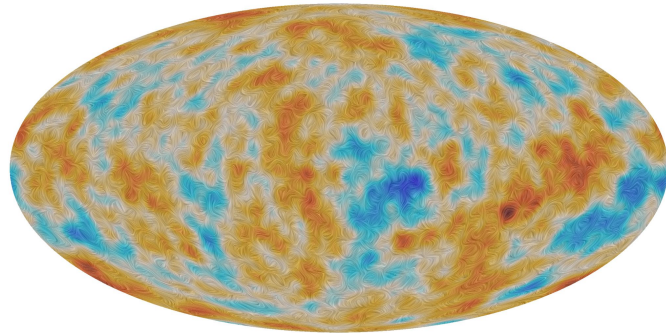
Contents and nature of dark matter and dark energy

N_{eff} and $\sum m_\nu$

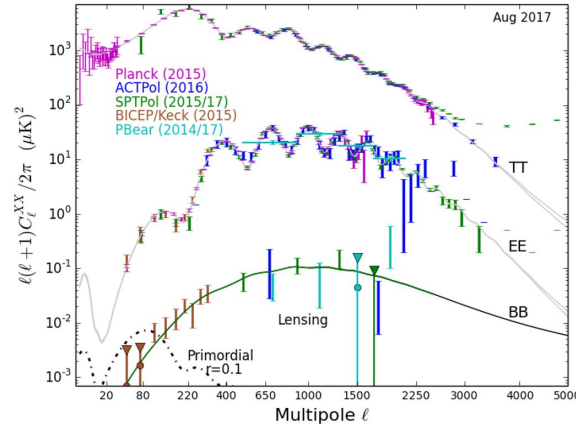
Inflation (r)

BSM Physics

Information about astrophysical processes

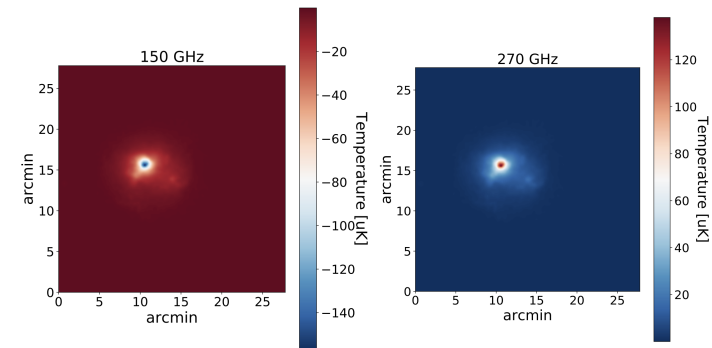
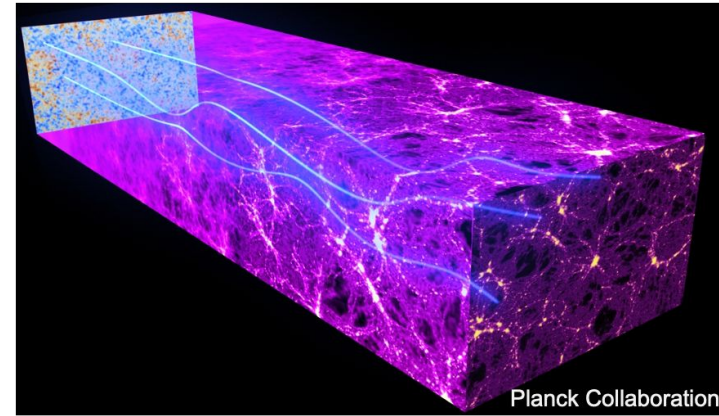


Planck Collaboration 2015



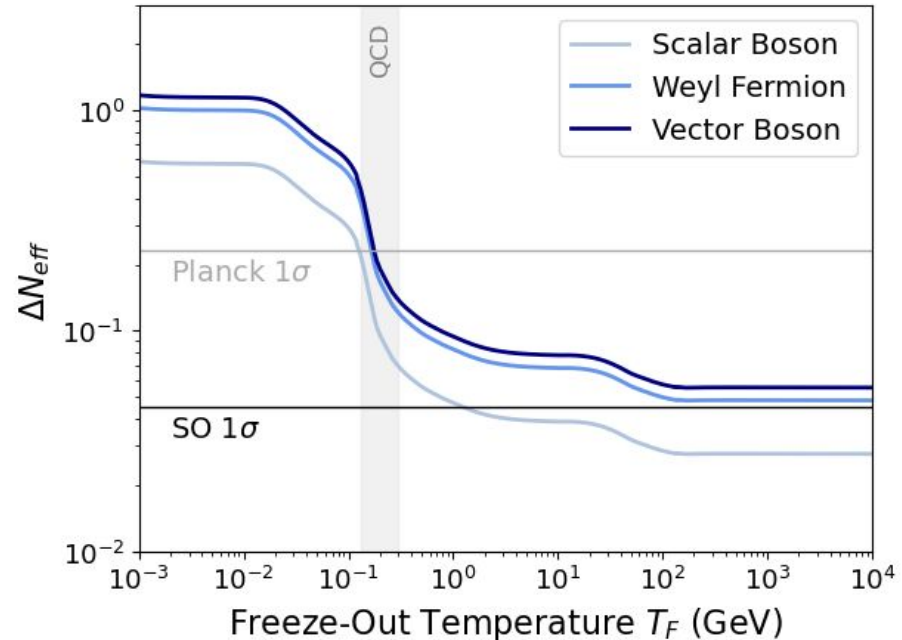
Probing the dark sector through matter mapping

- 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
- Large numbers of high redshift ($z > 2$) galaxy clusters
 - No cosmological dimming + high sensitivity



Searching for new light relics

- Any light relics would modify the radiation density \rightarrow CMB power spectra
- Standard Model: $N_{eff} = 3.046$
- Probe extensions to the Standard Model
 - Axions, sterile neutrinos, dark photons, gravitinos
- Broad, model-independent capability to discover or rule out new light relics that freeze out during and after QCD phase transition

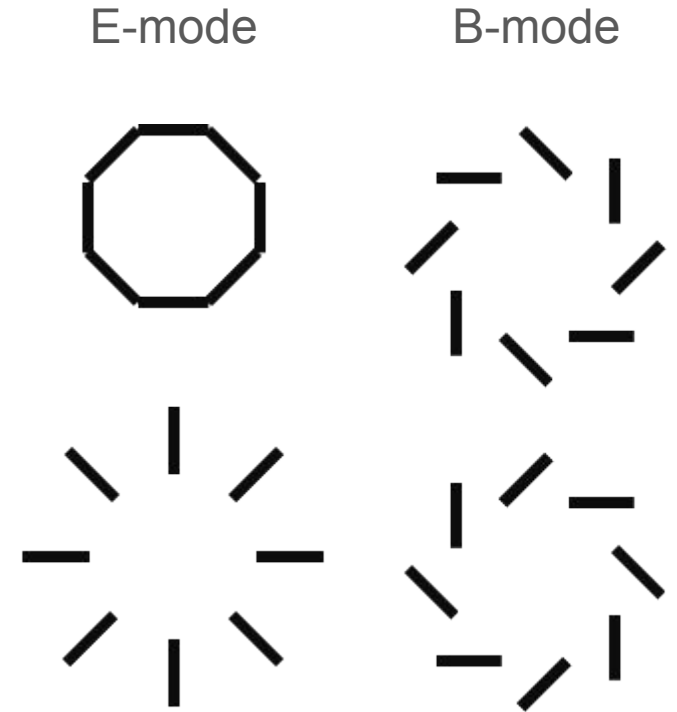


$$\Delta N_{eff} \geq 0.047 \quad \text{Spin } \frac{1}{2}, 1, \frac{3}{2}$$

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

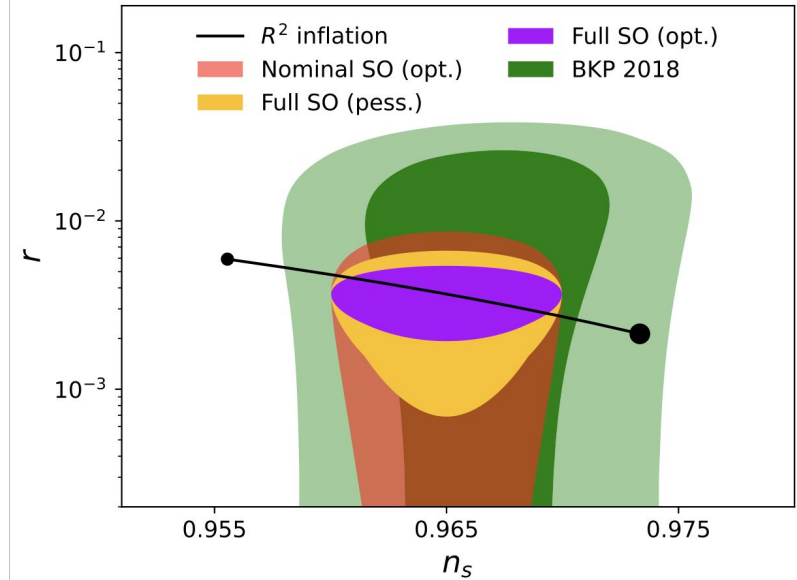
Polarization in the CMB

- CMB linearly polarized at decoupling by Thompson scattering → Mathematically decompose into E-mode (even parity) and B-mode polarization (odd parity)
- Scalar (density) perturbations → E-mode polarization
- Tensor (gravitational wave) perturbations → B-mode polarization & E-mode polarization



Reaching 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
 - r gives energy scale of inflation → insights into mechanisms
 - Probe quantum gravity and fundamental physics $\sim 10^{-36}$ s after the universe began at grand unification theory energy scales (10^{16} GeV)
- Reach inflationary limits in the next 10 years that will discover or rule out the most simple and compelling models of inflation



The Simons Observatory Collaboration, 2025

Cosmic Birefringence as a BSM probe

- Standard Model: No parity symmetry violation → Zero Birefringence → Linearly polarized CMB expected to travel without mixing between polarization states
- BUT... If there is parity symmetry violation → uniform rotation of linear polarization across sky (β)
 - CMB TB and EB spectra have odd parity → sensitive to cosmic birefringence
 - EB spectra expected to be zero → extremely sensitive probe
- Cosmic Birefringence would point to BSM physics
 - Primordial magnetic fields
 - Pseudoscalar or “axion-like” fields coupled to photons via the Chern-Simons effect → favored candidates for dark matter, used in some models to explain dark energy

Key systematics limit this measurement

- Planck polarization data hint at non-zero cosmic birefringence $\beta=0.3 \pm .11^\circ$ (e.g. P. Diego-Palazuelos, et al., 2022)
- Galactic foregrounds are usually assumed not to contribute to EB spectrum → some interpretations of Planck result hint at new physics in foregrounds
 - Example: Misalignment between filamentary dust structures and the on-sky magnetic field → new implications for role of magnetic fields in astrophysical processes like star formation
- Instrumental systematics can rotate polarization angle → absolute polarization angle calibration is challenging!
 - One of key calibration methods for inflation is to null the EB spectra rather than perfectly calibrating the polarization angle of the instrument
- **Need exceptional polarization angle calibration to disentangle these effects**

Simons Observatory

- Located at an elevation of ~ 5200 m in the Atacama Desert in Chile
- Multichroic cameras 30/40 GHz, 90/150 GHz, 220/280 GHz
- 120,000+ detectors at ~ 100 mK

Small Aperture Telescopes (SATs):

- Six ~ 0.5 m refractive telescopes
- Measure/constrain primordial B-mode

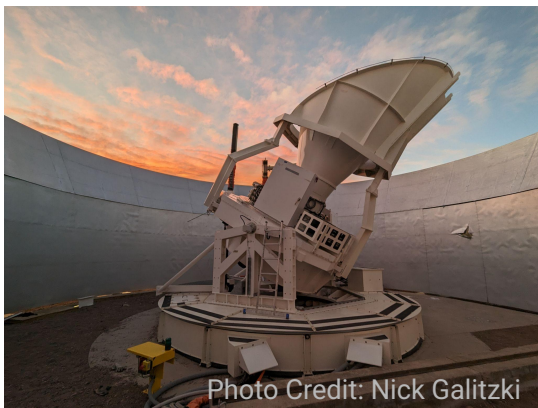


Photo Credit: Nick Galitzki

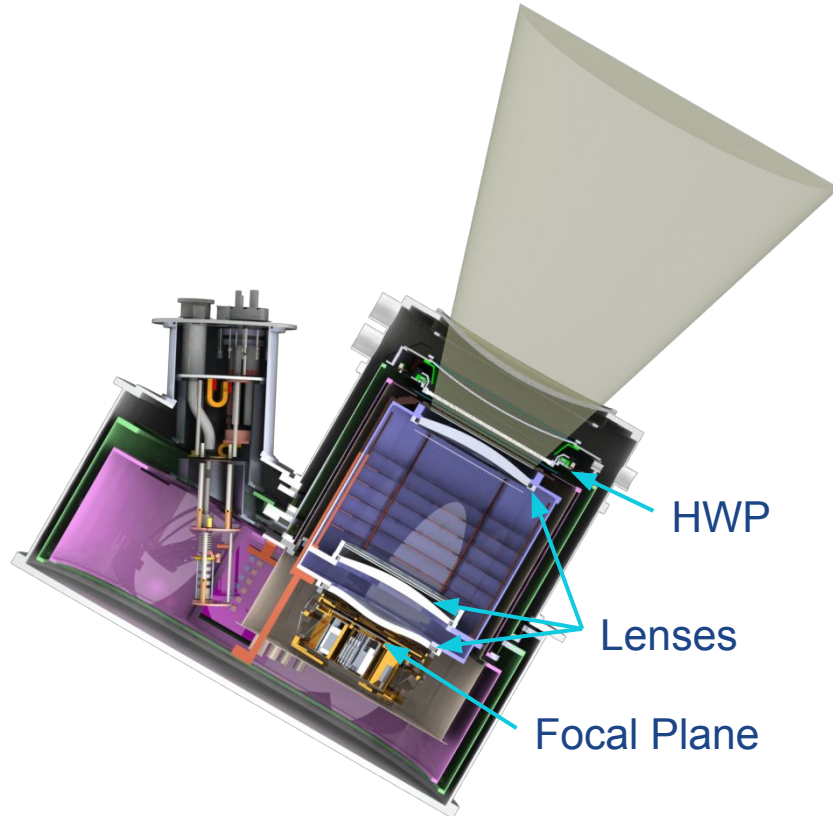
Large Aperture Telescope (LAT):

- One ~ 6 m crossed-Dragone telescope with 13 optics tubes
- Small angular scale science



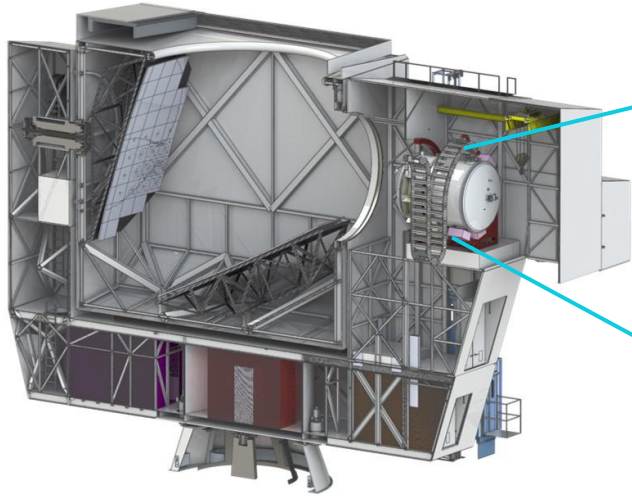
Photo Credit: Nick Galitzki

Small Aperture Telescopes

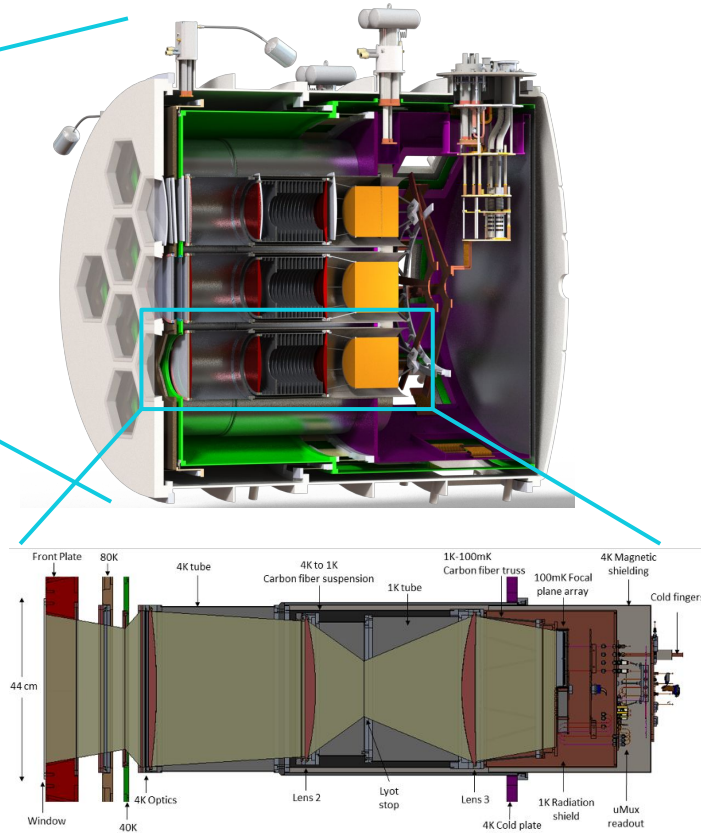


- 3-lens refractive design
- 17 arcmin full width at half maximum (FWHM) at 150 GHz
- Field of view (FOV) 35°
- Polarization modulation with a continuously rotating, cryogenic half-wave plate (HWP)
 - Polarization modulation mitigates atmospheric noise, systematic effects, and instrumental polarization leakage
 - Can be used to calibrate and characterize instrument → time constants, polarization angle, data selection, monitor gain

Large Aperture Telescope



- 6 m Crossed-Dragone
- 1.4 arcmin beam FWHM at 150 GHz
- 1.3° FOV per optics tube, 7.8° FOV total



Detector Modules

- Feedhorn-coupled orthomode transducers (OMTs) for most modules → beam defined by feedhorn
- Transition-edge sensors (TESes) with ~ 160 mK transition
- 4 detectors/pixel: 2 orthogonal polarizations for 2 bands
- Read out with μ MUX ~ 1000 detectors/line

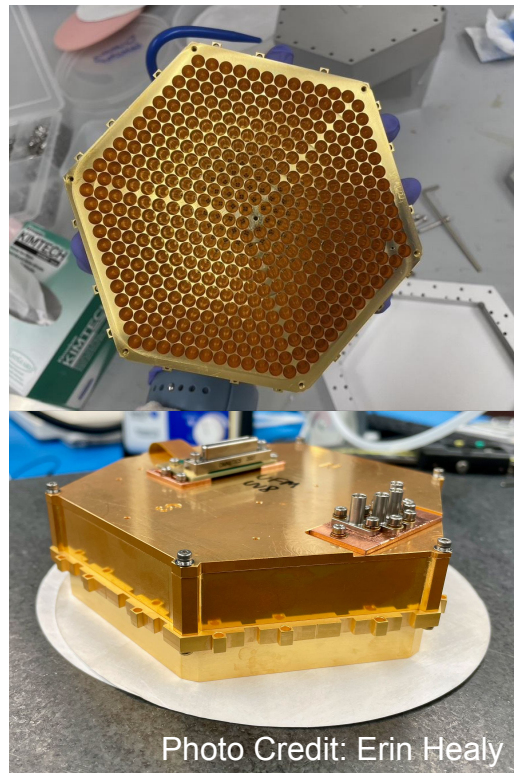
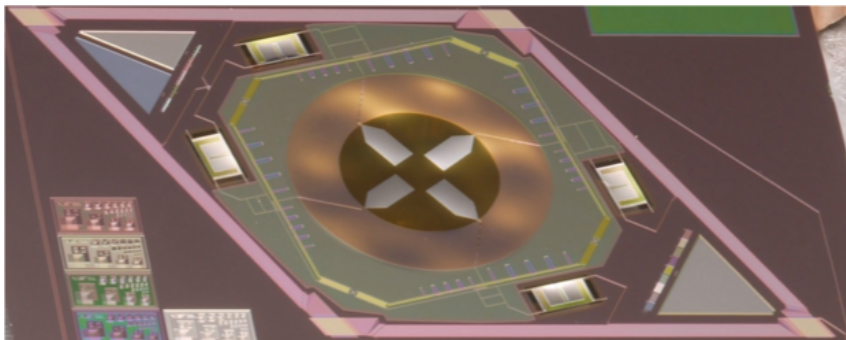
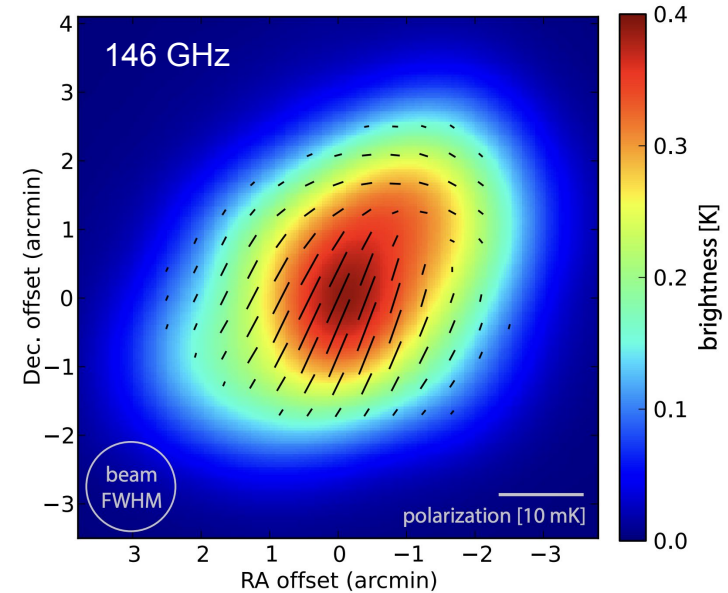


Photo Credit: Erin Healy

Celestial sources do not provide adequate calibration

- Tau A (Crab Nebula) only known to $0.27^\circ \rightarrow$ extended source with polarization angle variability + has frequency dependence [J. Aumont, et al., 2020]

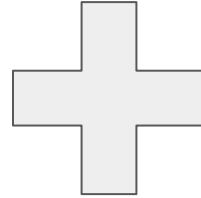
Precision calibration of CMB polarization angles will require dedicated hardware and analytic techniques



Naess, et al., 2014

Instrumental polarization angle calibration

**Relative Detector
Polarization Angles**

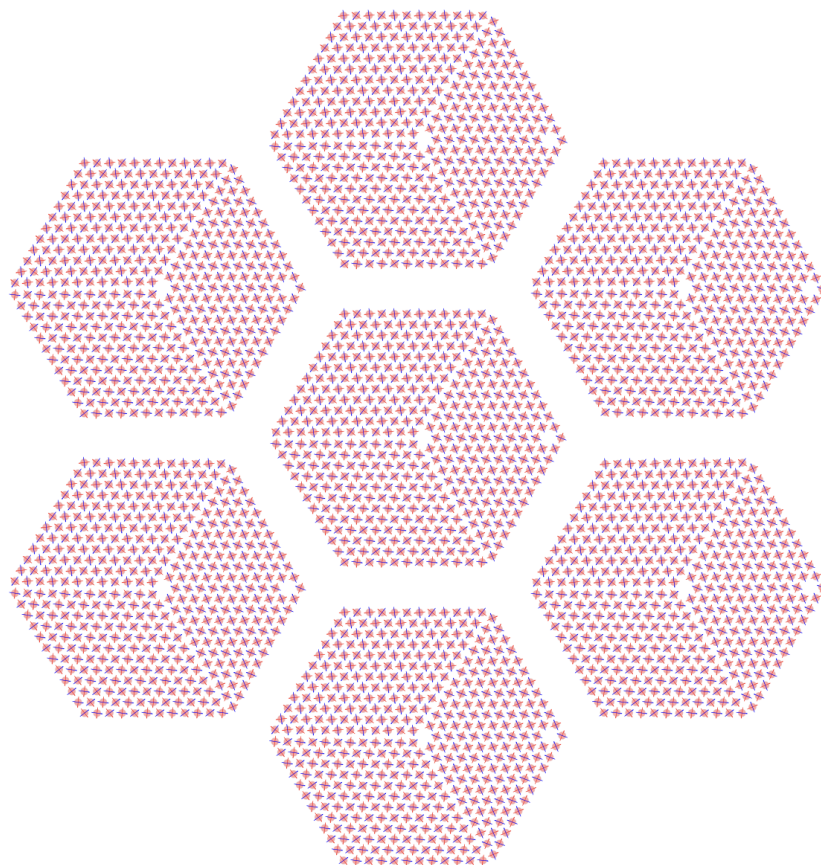


**Absolute Polarization
Calibration on Sky**

Reconstruct relative polarization angles

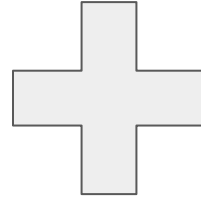
Relative Detector Polarization Angles

- Projected on-sky detector layouts
- Geometric effects
- Simulated optical effects
- Calibrate relative angle with polarized source

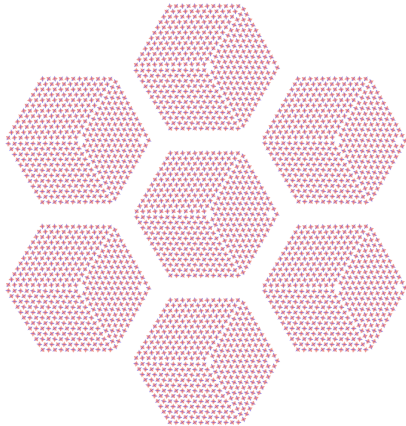


Absolute reference is the key challenge

**Relative Detector
Polarization Angles**



**Absolute Polarization
Calibration on Sky**



Reference polarization angle
to celestial coordinates

- Sky cameras
- Tilt meters
- Photogrammetry

Key challenges in polarization angle calibration

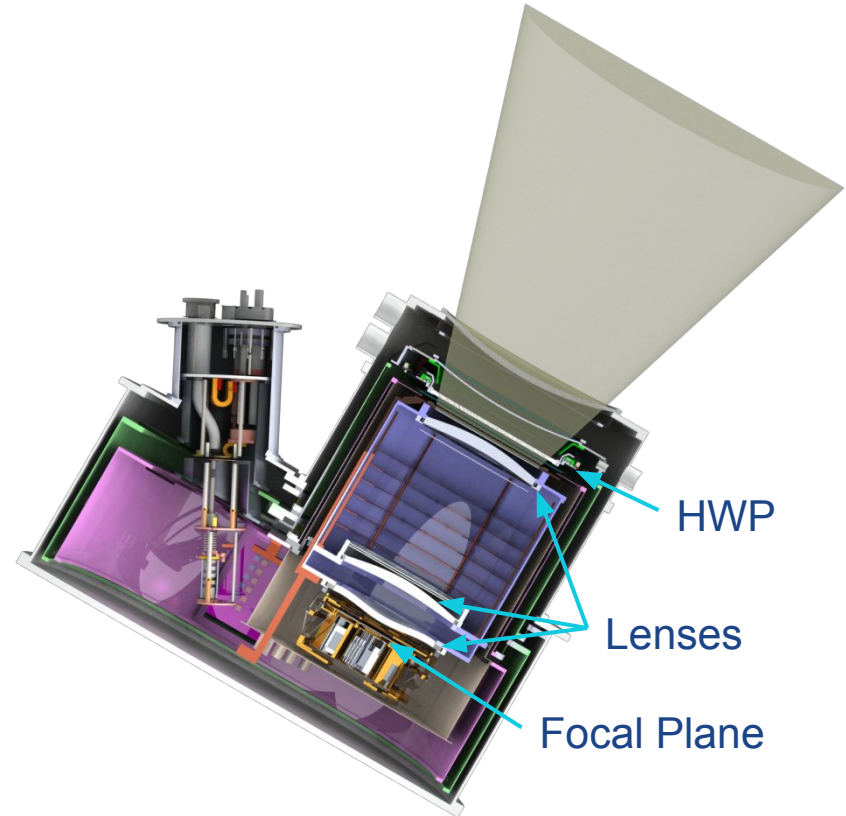
- Absolute polarization angle reference to sky
- Different calibration requirements and methods between SATs and LAT
 - Must calibrate in the far-field of telescope → big difference in instrumental far-fields
- 120k+ detectors → variability
- Balancing calibration time with observation time

Develop multiple methods to reduce risk and cross-check

SO is developing novel techniques in tandem with demonstrated methods

SAT polarization angle calibration overview

- Far-field can be reached with artificial sources (e.g. tower or drone)
- When input polarized signal, phase from the demodulated timestream related to the polarization angle
- HWP phase is frequency-dependent → need to understand bandpass
- Detector time constants add a phase lag → polarization angle rotation

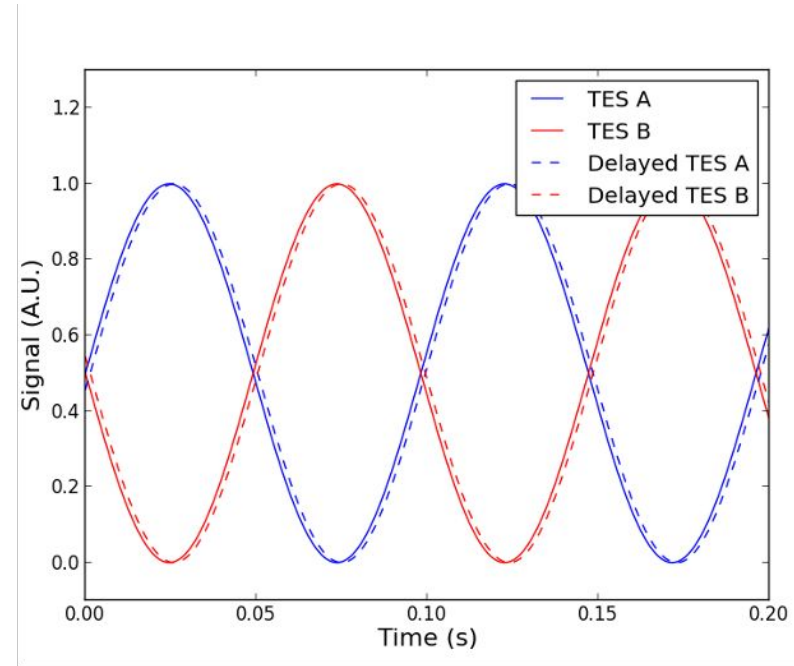


Time constant contributions to the polarization angle

- Time constant contribution depends on time constant and HWP rotation speed:

$$\phi \approx \phi_0 + \frac{4f}{f_{3dB}}$$

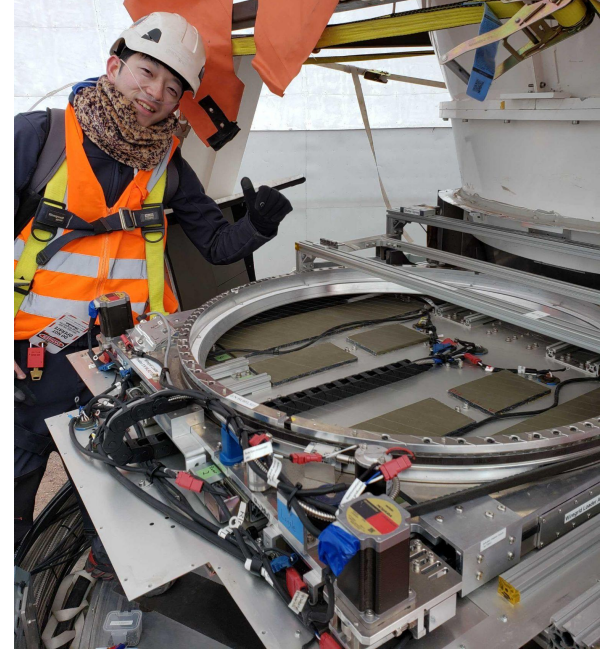
- Effect depends on direction of HWP → change rotation angle of HWP weekly to mitigate in data
- Detector time constants vary with loading → can change if polarization source or atmospheric loading are changing



Order 5° shift for ~1.3 ms time constant

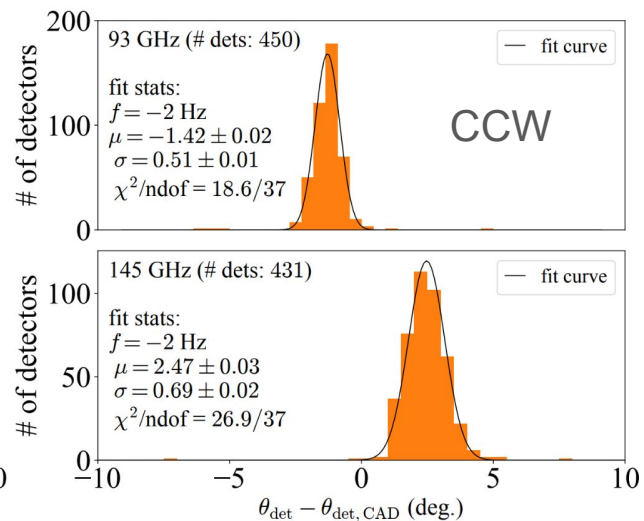
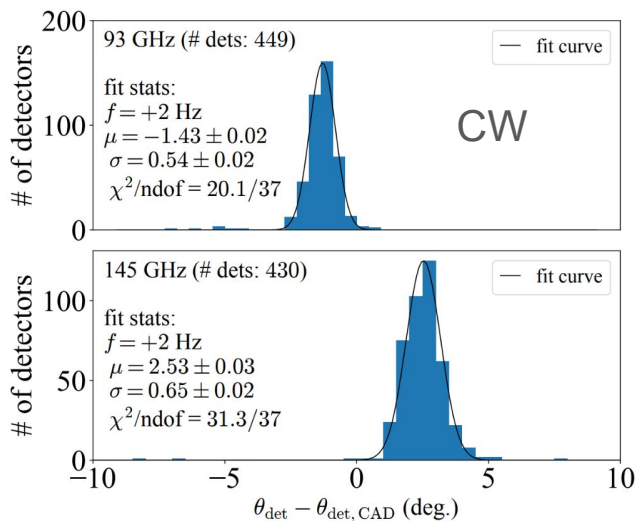
SAT Method 1: Wire Grid

- Wire grid inputs a polarized signal dependent on direction of wires
- Relative polarization angle from wire grid → can rotate grid discretely to sample different angles + determine detector relative responsivity
- Calibration performed weekly when we change HWP directions → HWP spin up/down + wire grid gives time constant calibration
- Absolute reference with integrated tilt sensor



Wire grid progress

- Regular wire grid observations over the last 2 years + dedicated campaigns
- Statistical uncertainty 0.2° at 90 GHz/ 0.3° at 150 GHz
- Systematic uncertainty at 0.08° level
- Working toward absolute angle calibration by incorporating tilt sensor and comparing to Tau A



Nakata, et al., 2025

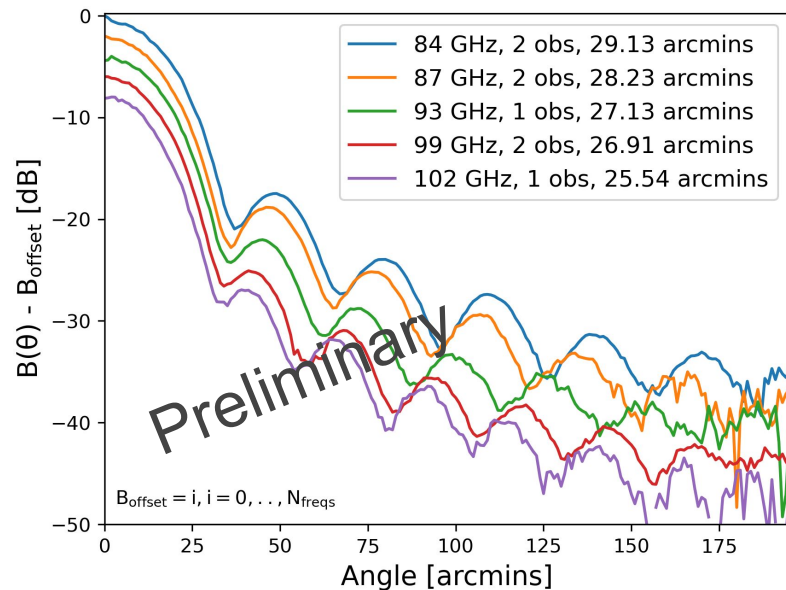
SAT Method 2: Polarized Drone

- Polarized source on drone to reach SAT farfield (POLOCALC) → Polarized beams + polarization angle
- Single frequency source + wire grid gives polarized signal
- Star camera + GPS + Photogrammetry to get pointing
- Star camera alignment with wire grid measured to $\leq 0.1^\circ$ [Coppi, et al., 2022]
- Final target is a polarization angle calibration of 0.01°
- Teams at University of Milano-Bicocca, Pontificia Universidad Católica in Chile, & UT Austin



POLOCALC field tests

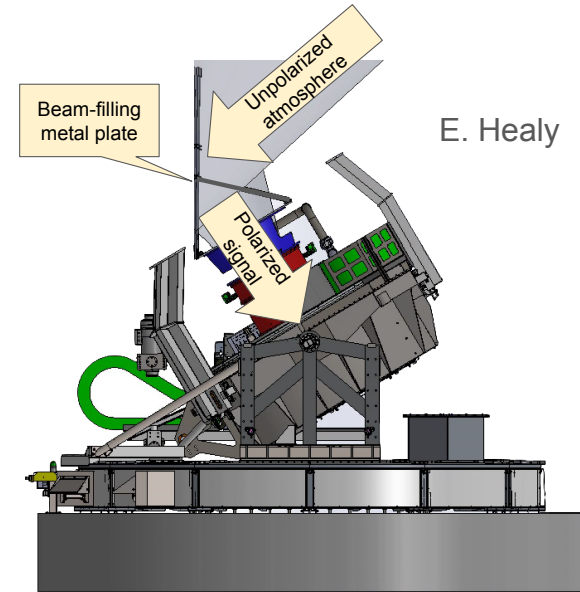
- First flight in May 2022
- Have now completed four campaigns!
 - Over 120 flights in the 90 GHz band
 - Over 80 flights in the 150 GHz band
 - A few high frequency 220/280 GHz band flights
- Excellent measurements of the beams → good agreement with Jupiter observations
- Ongoing work to understand extrapolation from single frequencies to band average
- Ongoing work to improve source gain characterization to realize polarization angle calibration → very promising!



N. Dachlythra

SAT Method 3: Plate Calibrator

- Polarized signal produced by reflection off conductor with finite conductivity (metal plate)
 - Fresnel equations & Kirchoff's laws
 - Order ~100 mK polarization signal!
- HWP enables making a measurement of Q → absolute measurement of polarization angle
- Change HWP direction between measurements to reduce time constant effects
- UChicago team: **Erin Healy**, Maya Atassi, Shreya Sutariya, Jeff McMahon, Tommy Alford, Sara Simon



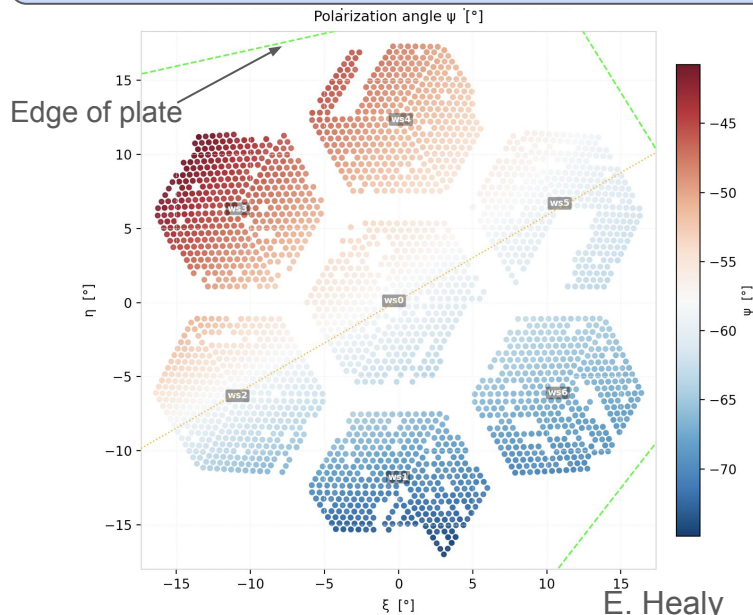
$$Q_{plate} = \frac{2\delta}{\lambda_0} \left(\frac{1}{\cos \beta} - \cos \beta \right) (T_{plate} - T_{atmosphere})$$

β = angle between detector ray and plate normal

δ = skin depth of surface material

Plate calibrator concept

Relative Detector Polarization Angles



Signal level referenced to coordinates of plate axes

Absolute Polarization Calibration on Sky

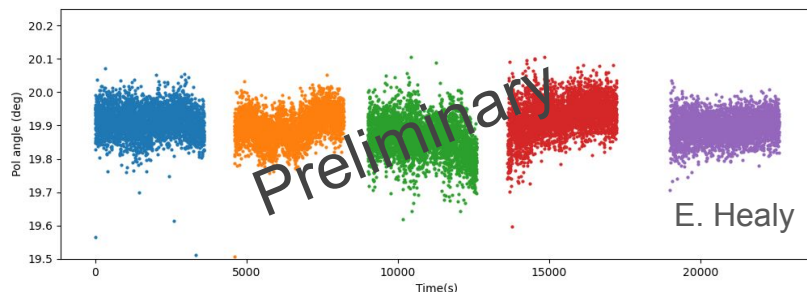


E. Healy

Photogrammetry + Laser Metrology + Plumb bob to characterize geometric effects and direction of local gravity

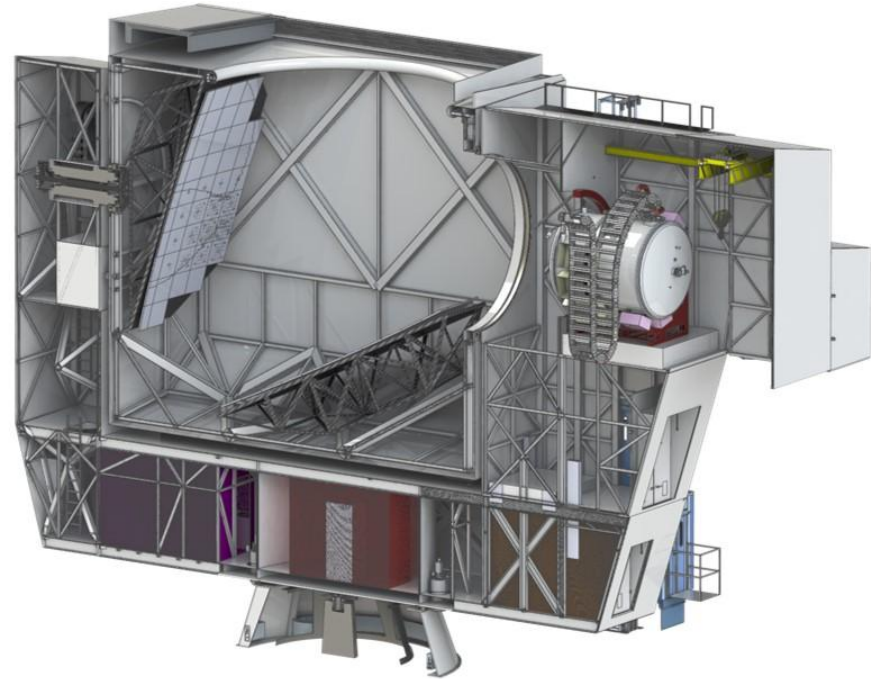
First plate calibrator field test

- 6 hours of data in December 2025
- High S:N in detectors → Statistical error $0.01^\circ/\text{detector}/\text{hour}$
- Photogrammetry of plate $\sigma \sim 0.5 \text{ mm} \rightarrow 0.014^\circ$
- Need to improve systematic performance ($\sim 0.1^\circ$)
 - Plumb bobs affected by wind → alternate references (moon)
 - Account for time constant contributions → include HWP spin up & down in data to characterize
 - Atmospheric effects + HWP frequency dependence



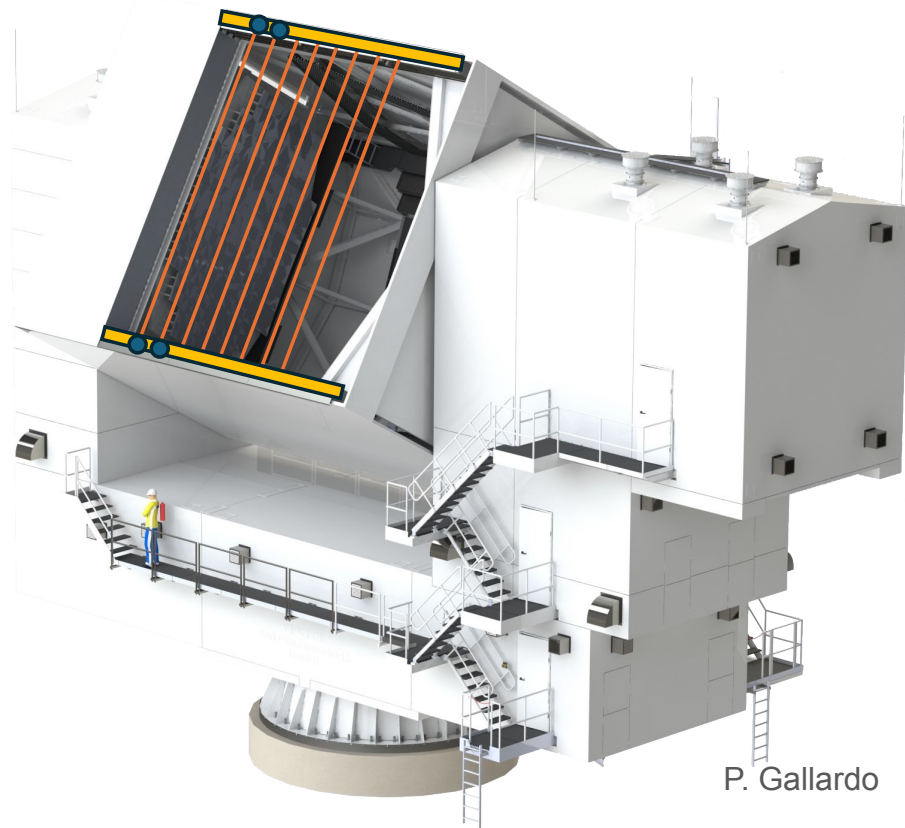
LAT polarization angle calibration overview

- LAT far-field can only be reached by satellite → limits available methods
- Absolute polarization angle can be derived from cross-correlations with SATs
- Ideally calibrate independently to ensure that capture any variation across angular scales



Method 1: Wire Grid

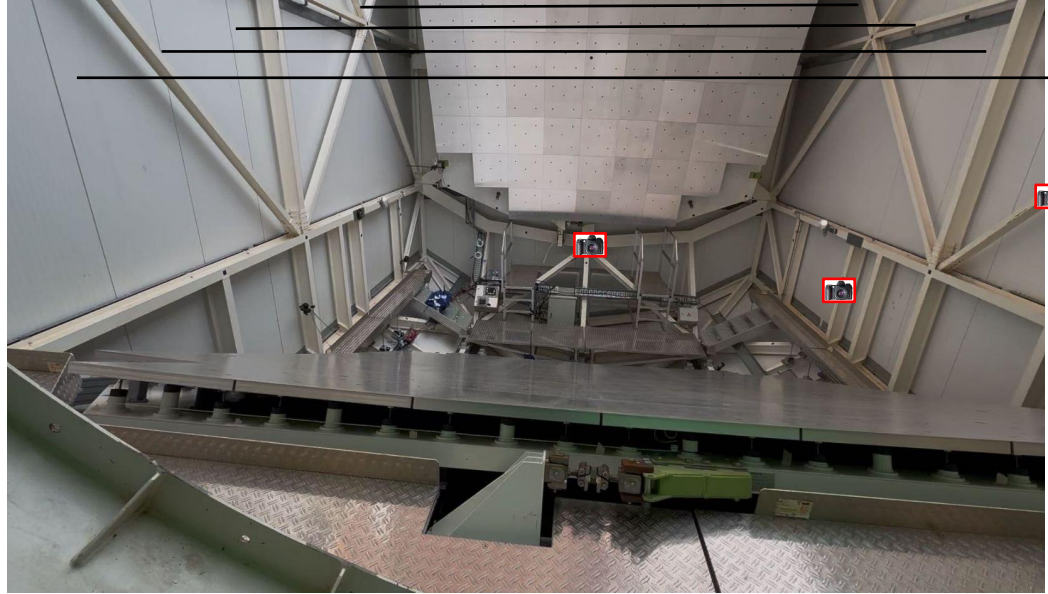
- Absolute polarization angle from wire grid in front of mirrors + on sky orientation from sky cameras $\rightarrow 0.01^\circ$ target
 - Sample different angles by rotating the telescope receiver
 - Nods in elevation to modulate on-sky angle
- Observe polarized sources + small patch of CMB with and without the wire grid
- UPenn team: **Patricio Gallardo**, Declan Baker, Alex Manduca, Mark Devlin, & Sam Grubb



P. Gallardo

Initial wire grid tests

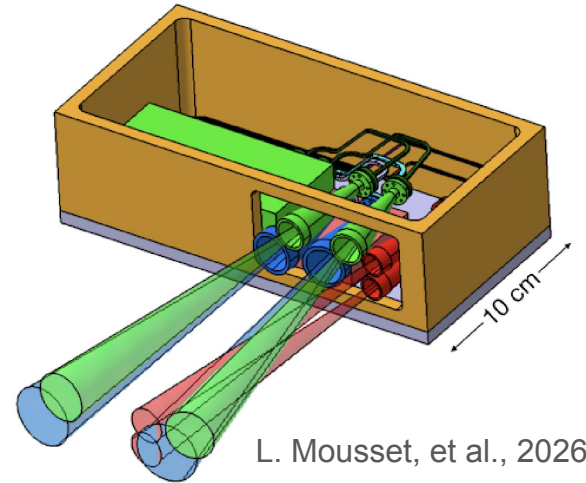
- Initial receiver tests in April/May 2026 → completed observations with/without wire grid for ~20 hours
- Wire orientations referenced to astronomical coordinates measured to $\sim 0.05^\circ$
- Further improvements expected with pipeline refinement → now underway



P. Gallardo

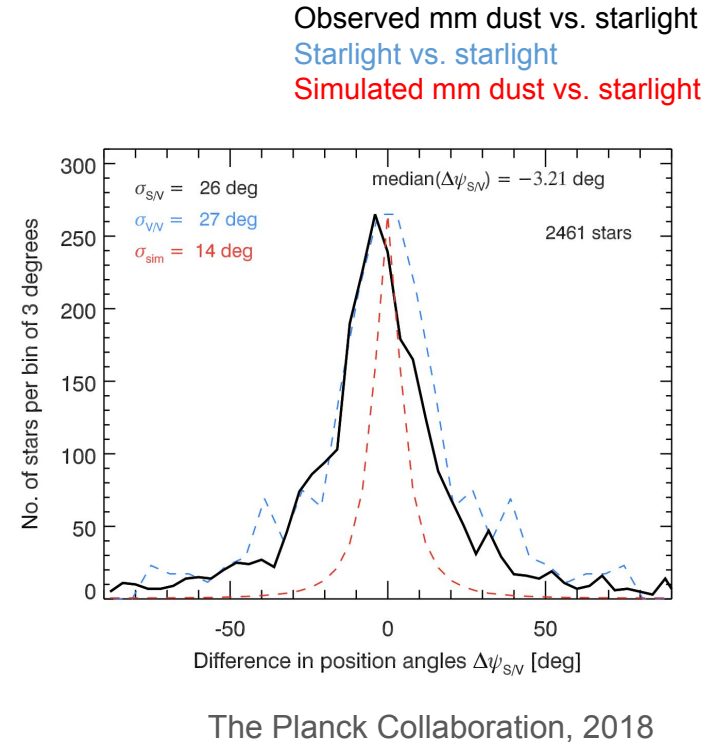
Method 2: Polarized Satellite Source

- Install a polarized source on a satellite for far-field LAT calibration
- Proposed COSMOCal project would install a source on a commercial satellite → polarized beams and polarization angle calibration
 - Visible in Europe and Chile
 - 0.1° absolute polarization angle calibration
 - Potential to launch in 2030



Method 3: Polarized Starlight

- Optical starlight polarized by same galactic dust observed in millimeter wavelengths
- Get polarization angle calibration by comparing LAT polarized intensity vs. maps of starlight polarization
- Near-term optical experiments observing polarized starlight expected to increase sample from $\sim 2.5\text{k}$ to 10^5 \rightarrow could be potential for new constraints with this method if can be well understood



Summary

- CMB is a powerful probe of the dark sector
- Cosmic Birefringence constraints from CMB experiments will rely on absolute polarization angle calibration
- Only way we can improve polarization angle calibration is with dedicated hardware and analysis techniques
- Experimentalists are rising to the challenge through the development of several novel techniques
- Rapid progress expected in the next several years → improved constraints are on the horizon!

Thank You



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