The future of the CMB

Fiera di Primiero, September 2025

Image: CMB polarization from Planck/ESA

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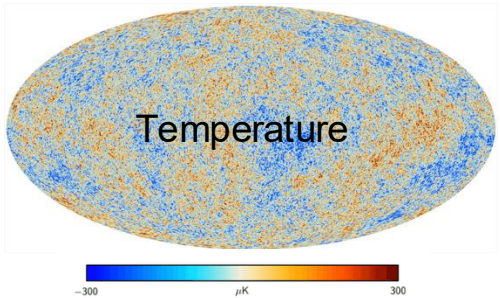
School of Physics and Astronomy

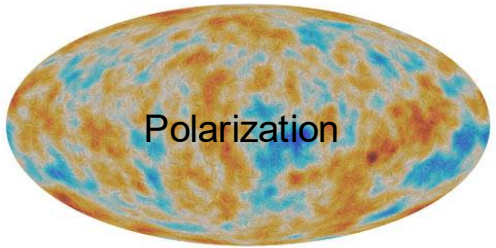
erc European Research Council
UK SPACE AGENCY
UKRI UK Research and Innovation
Science & Technology Facilities Council

Exploring the Universe with the CMB



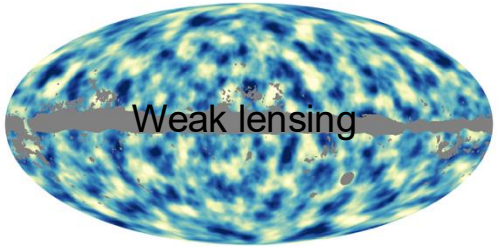
Cold light, 2.7K
Variations in the sky of
1 part in 100000

→ Initial seeds of cosmic structures
Gravitational fields
Make up of the Universe



Polarized light at the 10% level
Variations in the sky of less
than 1 part in 1000000(00)

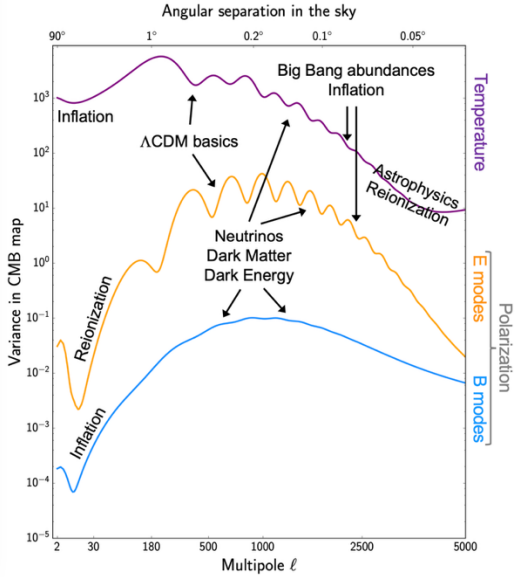
→ Where and how
atoms/molecules/stars are forming
First second of Universe existence

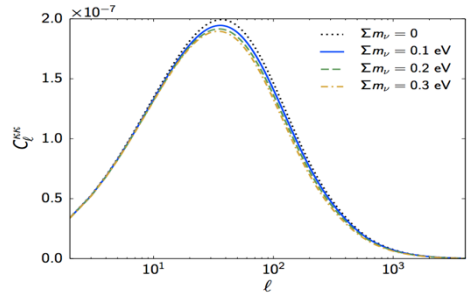


2 arcminute (~1/15 of the Moon)
total deflection over a 13.3
billion-year journey

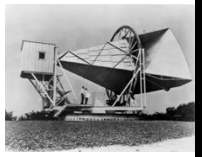
→ Geometry and matter distribution
from early Universe to today

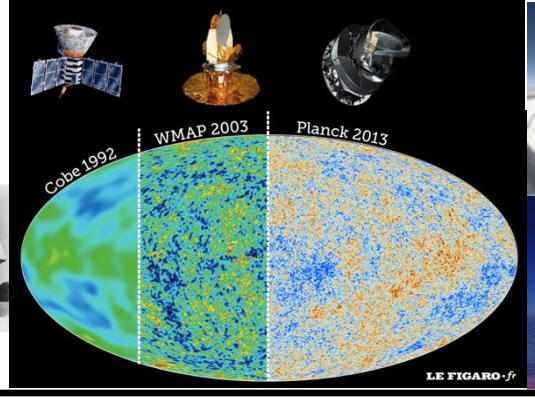
ESA/Planck Collaboration





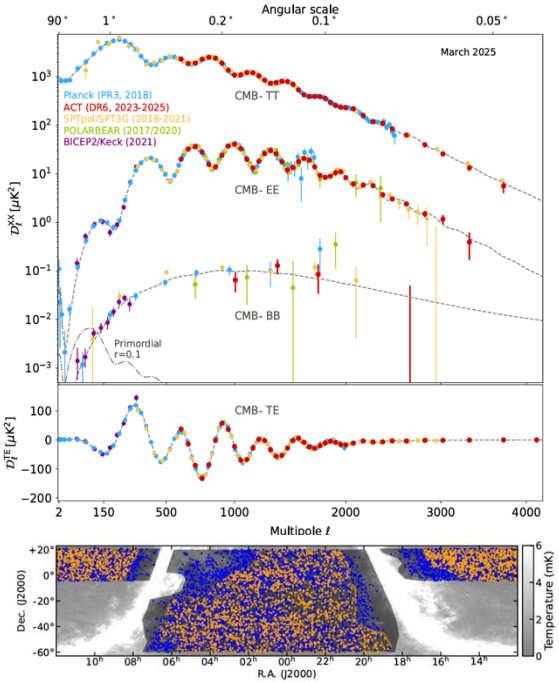
From discovery to physics in the sky

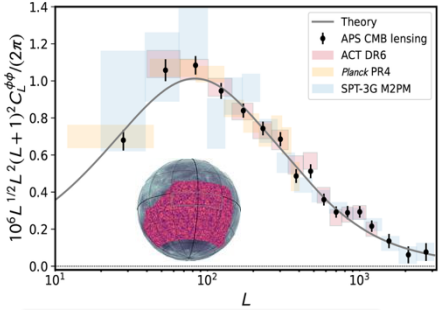


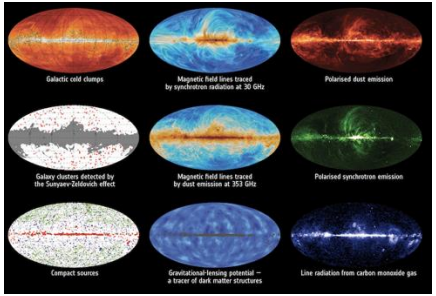


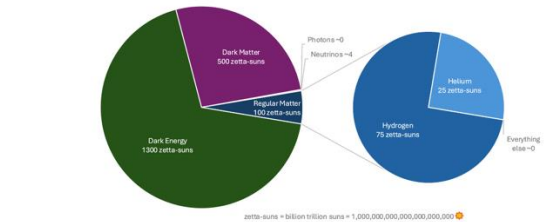
Louis et al 2025
Calabrese et al 2025
Bicep/Keck Collaboration 2021
Qu et al 2024, 2025
Aguena et al 2025
Sherwin et al 2011

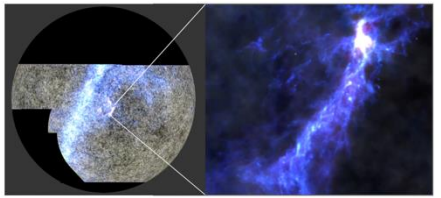
also
Planck Collaboration parameters 2020
Planck Collaboration inflation 2020
Planck Collaboration lensing 2020
Camphuis et al 2025
Naess et al 2025
Madhavacheril et 2024

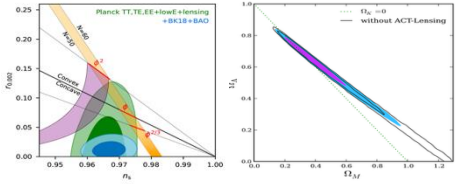


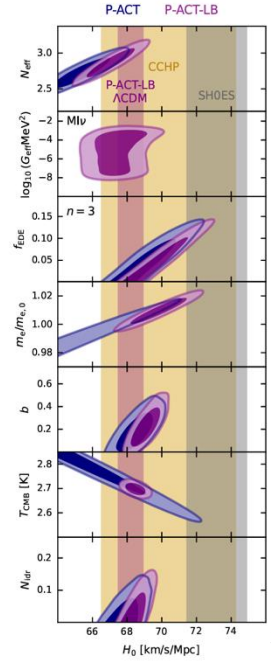






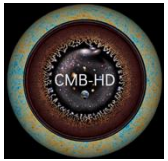






The future

**with some uncertainty in some arrows and dates*

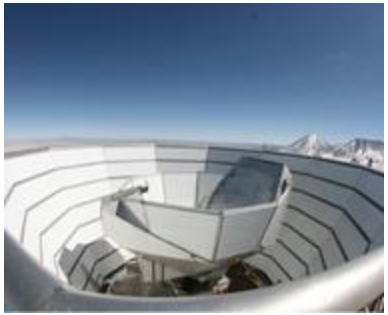


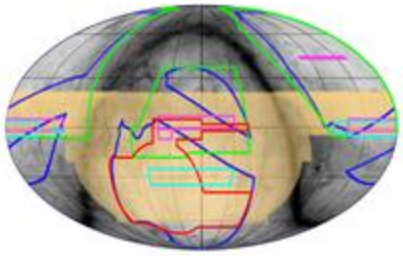
2020 2025 2030

Another satellite

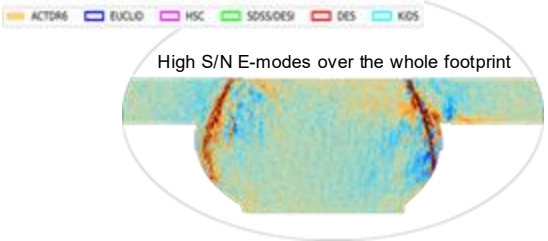
The (near) future

ACT DR6





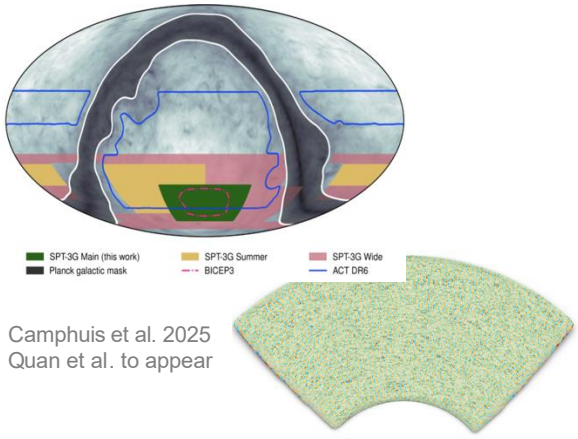
Naess et al. 2025



- 3 broad bands: 90, 150 and 220 GHz
- Combined sensitivity of 6.2 μK√s, and 1.4’ FWHM @ f150
- Deeper than Planck over 19000 square degrees (on small scales)
- On average ⅓ the white noise RMS of Planck

New lensing analysis, cross-correlations and sources

SPT 3G



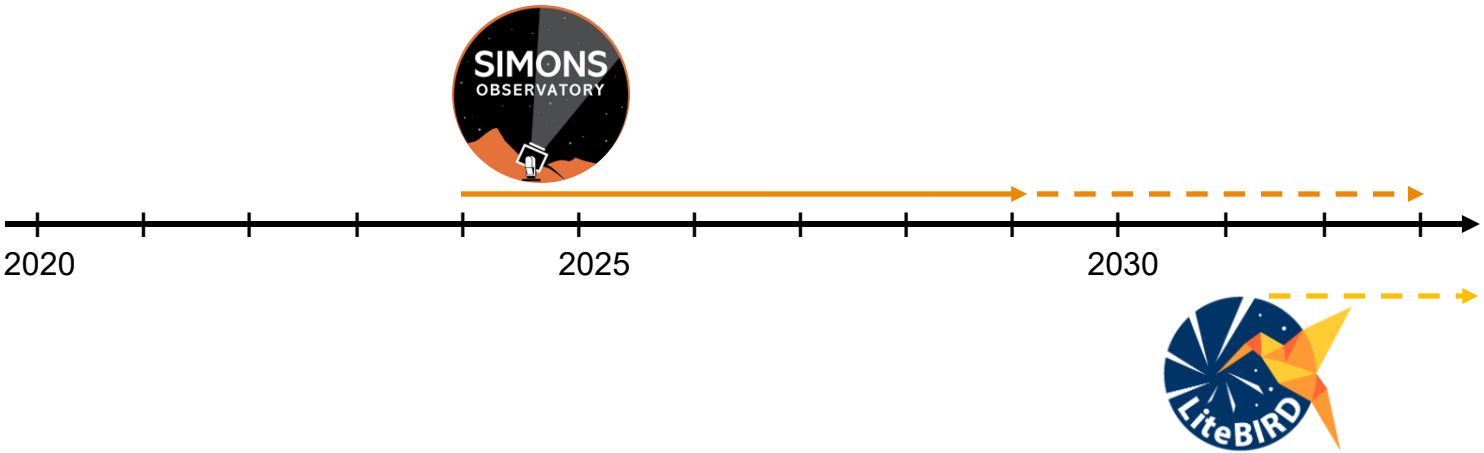
Camphuis et al. 2025
Quan et al. to appear

- D1 dataset from Main field 90, 150, 220 GHz during 2019-2020
- Combined sensitivity of 3.3 μk-arcmin in T and 5.1 in pol, over 4% of sky
- Summer and Wide fields bringing additional 2800/6000 deg2

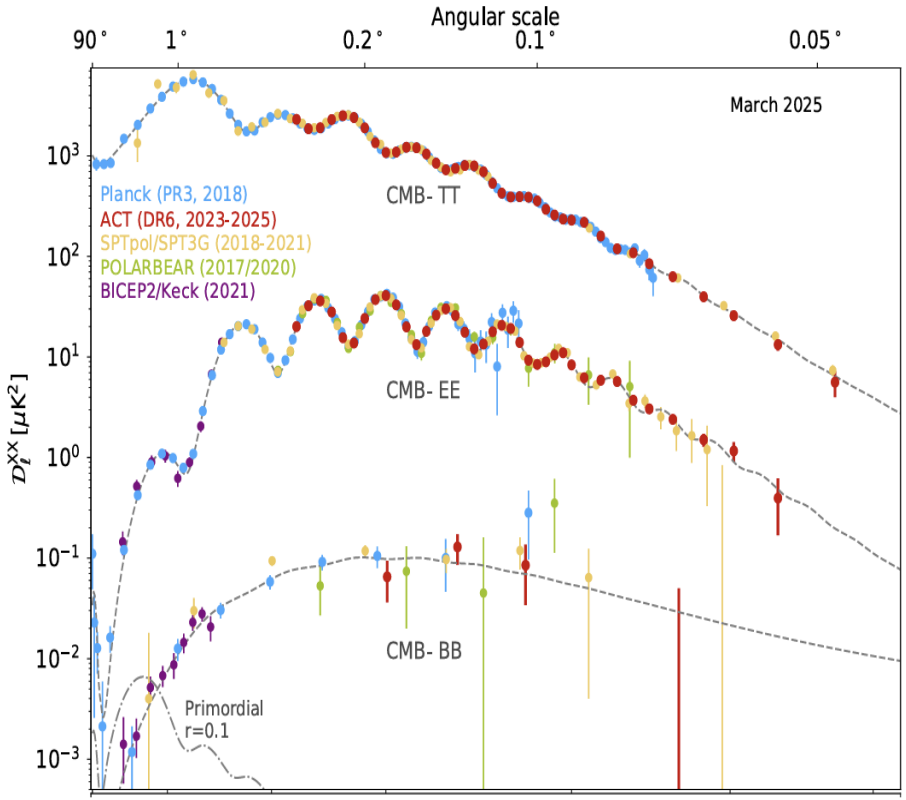
More D1 plus extra field analyses

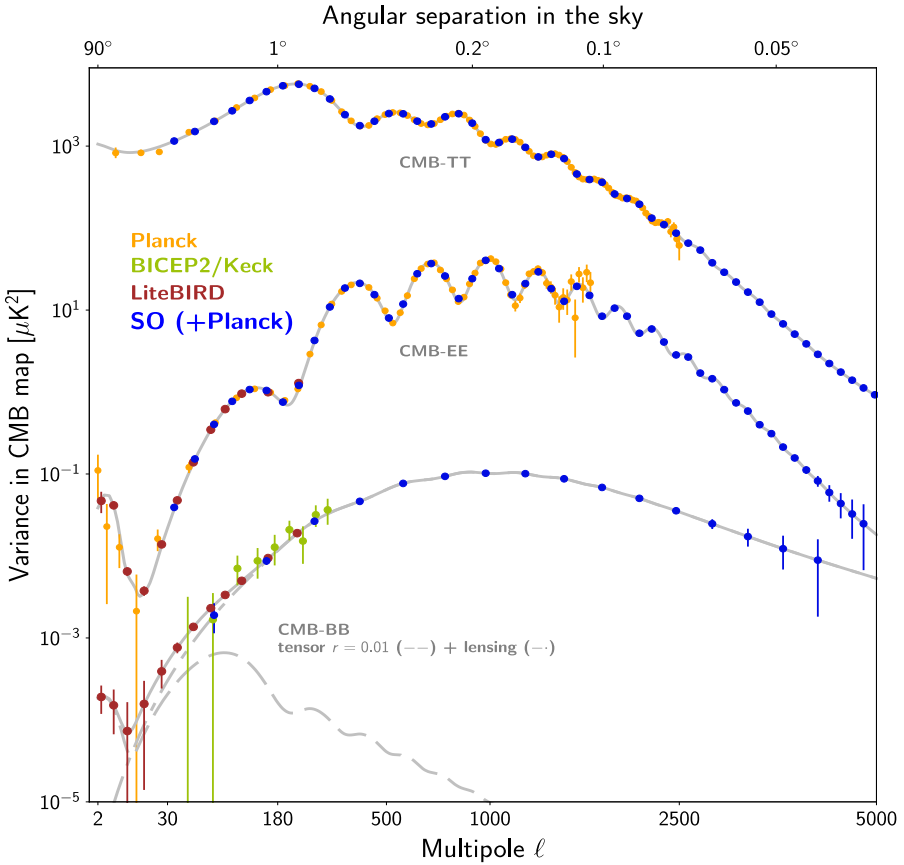
** Also Simons Array, BICEP2/Keck*

The future

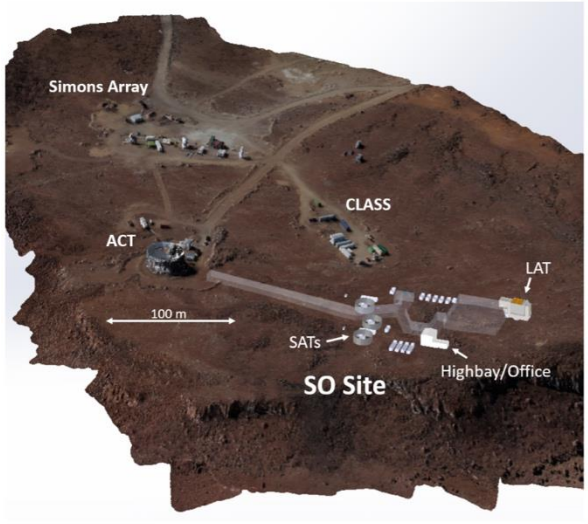


High precision, high sensitivity CMB polarization

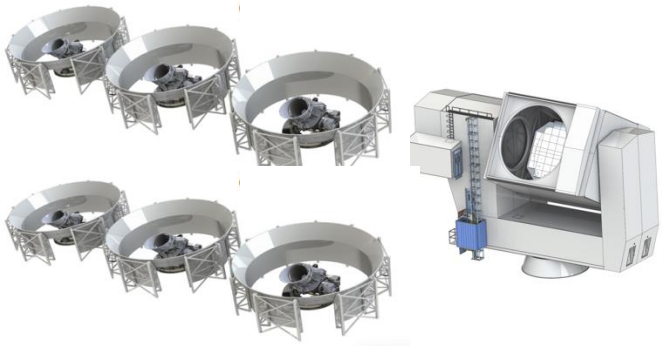




The Simons Observatory



Six 0.5-m Small Aperture Telescopes
One 6-m Large Aperture Telescope fully populated with 13 tubes



a little over 123,000 detectors
6 frequency bands in the mm

Operations started!

Green Observatory, replacing 70% of the power at the site with Solar Energy

Large international collaboration
15+ countries, 60+ institutions
~375 collaborators

https://simonsobservatory.org/

Solar Power (2025)
(courtesy of NSF and UKRI)

SO Nominal

ASO (2028)
(fully populating
the LAT)

SO:JP – One SAT (2026)

SO:UK – Two SATs (2026)

Permissions request underway

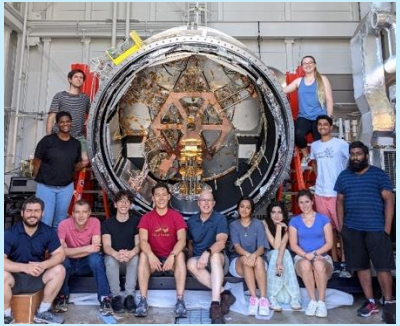
Time Domain Astrophysics

Tidal Disruption Events

Stellar Flares

Variable AGN

Training the Next Generation



Extragalactic Astronomy

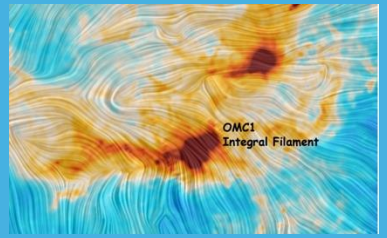
Missing Baryons

Sources

Galaxy Clusters

Galactic Astronomy

Interstellar Dust

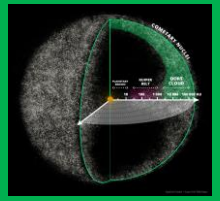


Star Formation, Magnetic Fields and Dust Turbulence

SIMONS OBSERVATORY

PARQUE ASTRONÓMICO ATACAMA, CHILE | ELEVATION: 5190m | 22° 57' 5, 67° 47' W | www.simonsobservatory.org

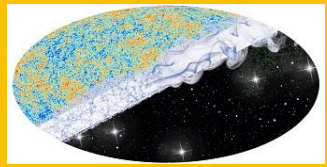
Planetary Science



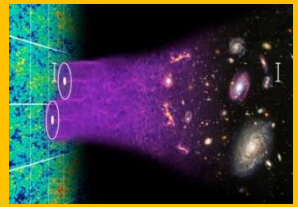
Exo-Oort Clouds

Planet 9

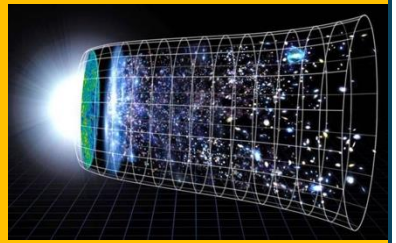
Cosmology and Particle Physics



H_0 Tension and New Physics

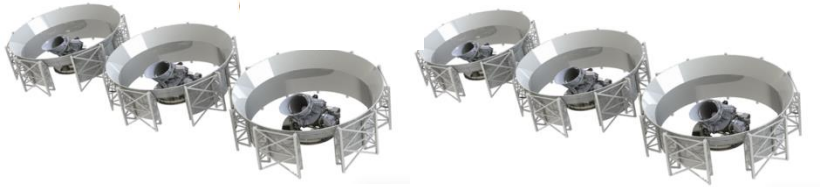


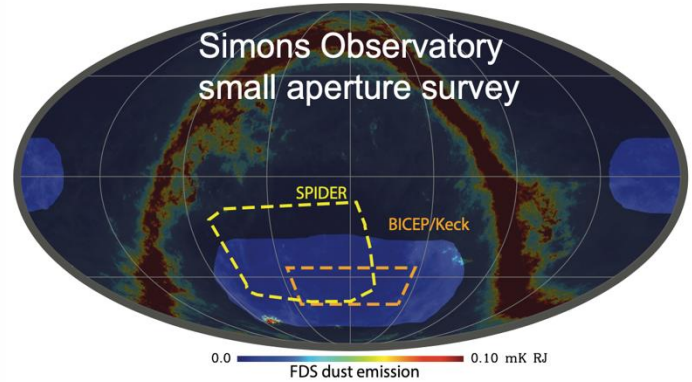
Light Relics and Neutrinos



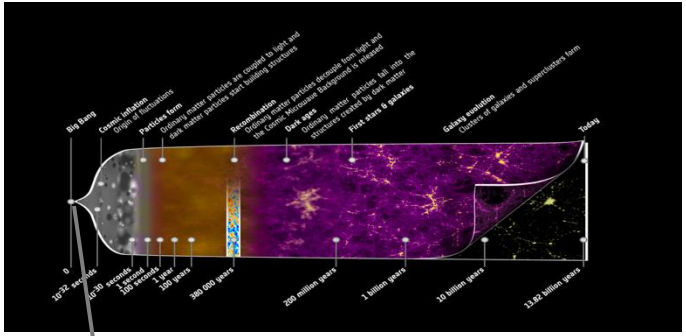
The Evolution of the Universe Over Cosmic Time

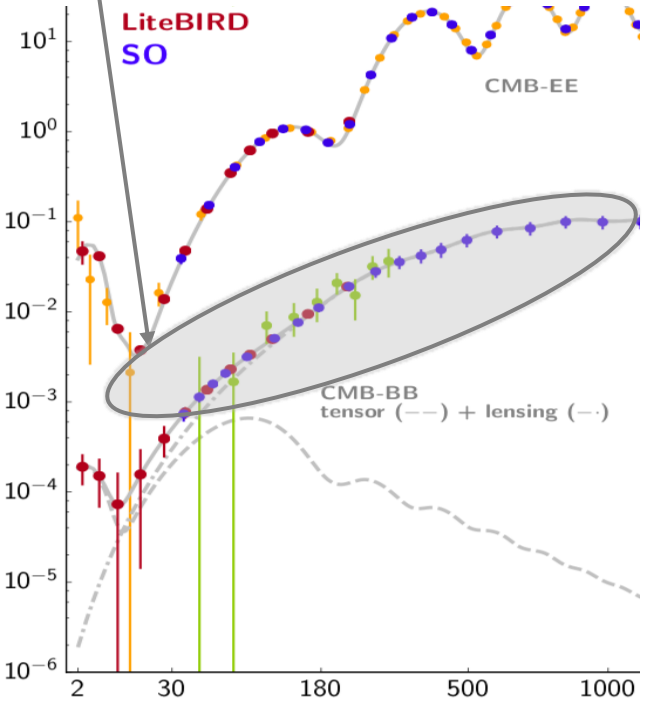
Primordial Perturbations





On sky since 2023!





<u>Small Aperture Survey</u>

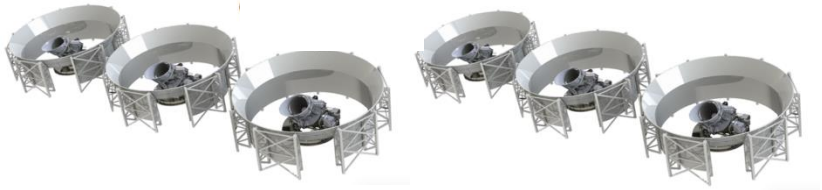
Deep, high sensitivity

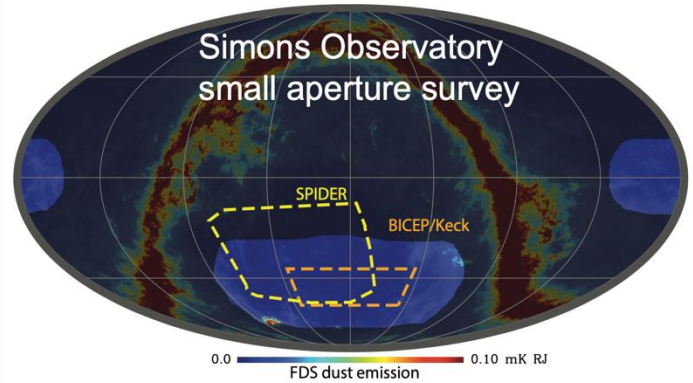
1 μK arcmin (@90/150GHz) over 5000° 2 after 6-SAT 9-year survey covering 6 frequencies (30-280 GHz)

Dedicated to B-mode searches → primordial gravitational waves/primordial perturbations

The Simons Observatory Collaboration 2019

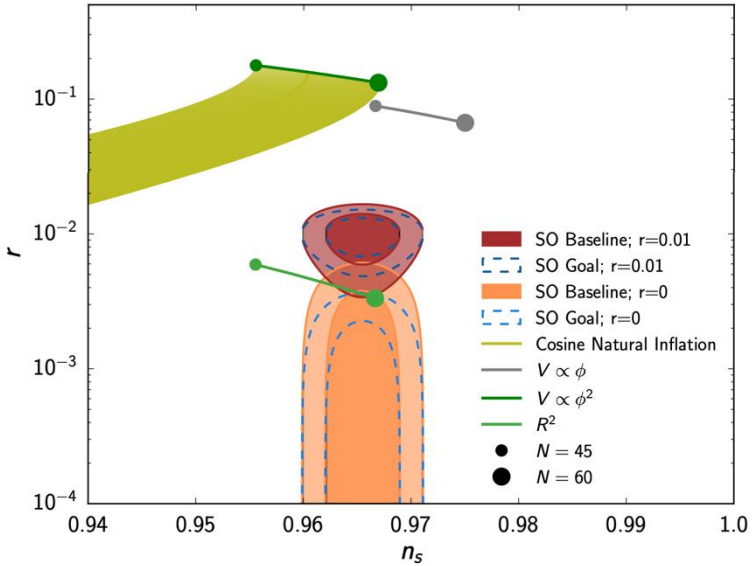
Primordial Perturbations





SO will detect or rule out models with r ≥0.01 **at 3σ or greater**

Goal is σ(r) = 0.002-0.003 with first 3 SATs



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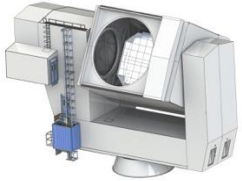
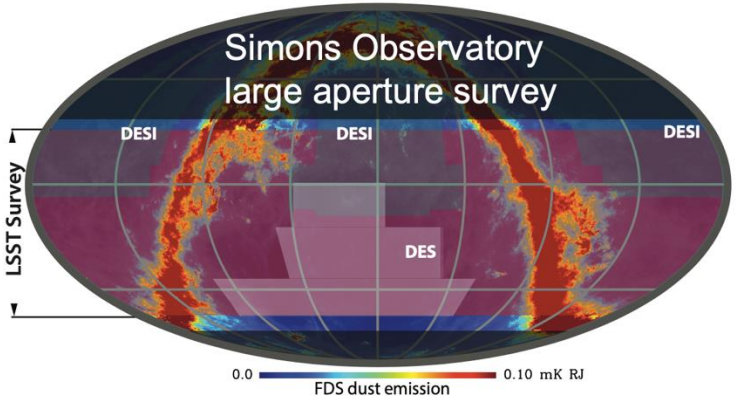
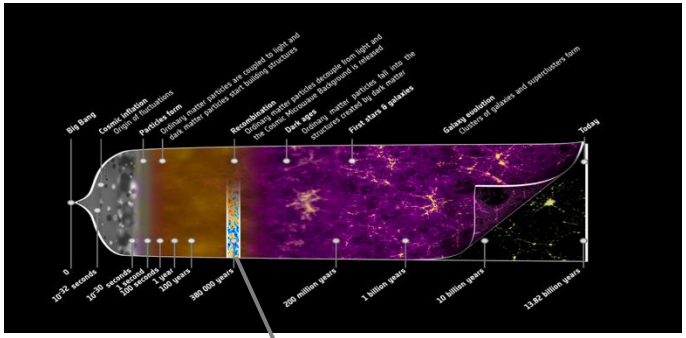
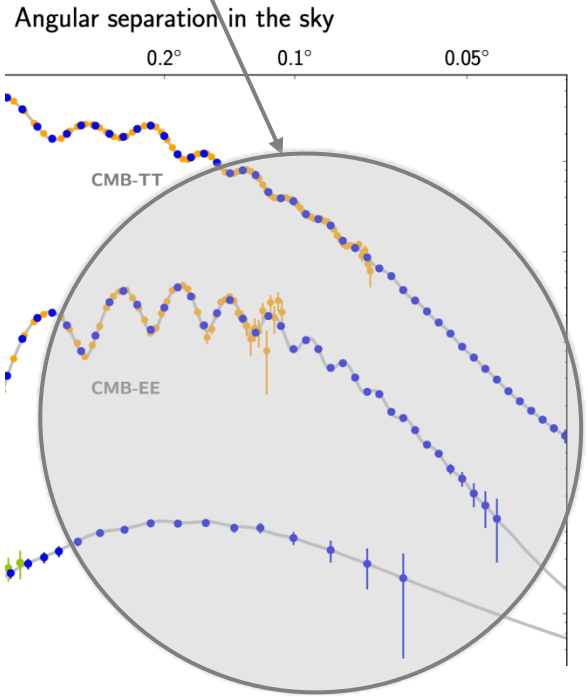
High precision tests of the cosmological model





First light Feb 2025!





Large Aperture Survey

Wide (40-70% of sky), at high resolution (1.4' at 150 GHz) and high sensitivity (6 uK-arcmin in combined 90/150), over 6 frequencies (30-280 GHz)

New results on dark matter and matter distribution, neutrinos, expansion/age of the Universe and much more

The Simons Observatory Collaboration 2019, 2025

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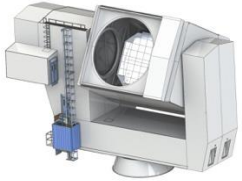

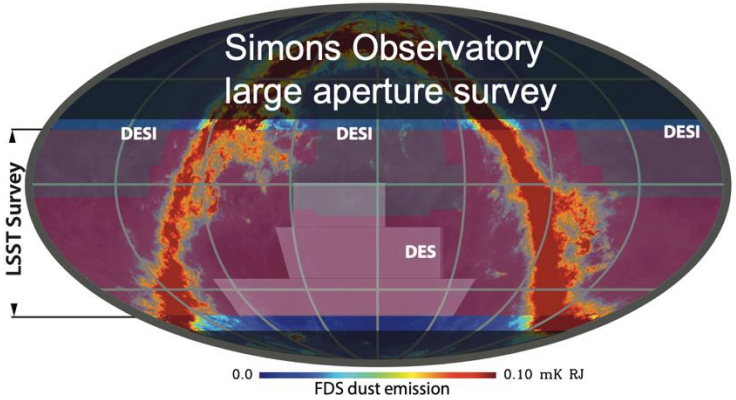

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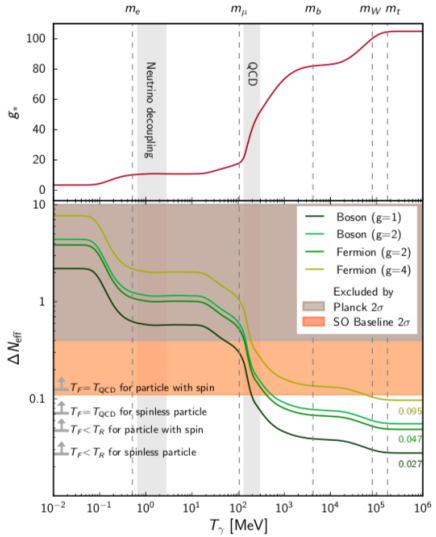
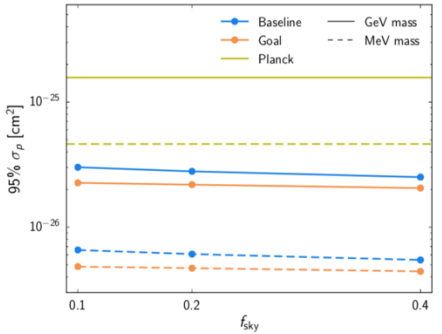
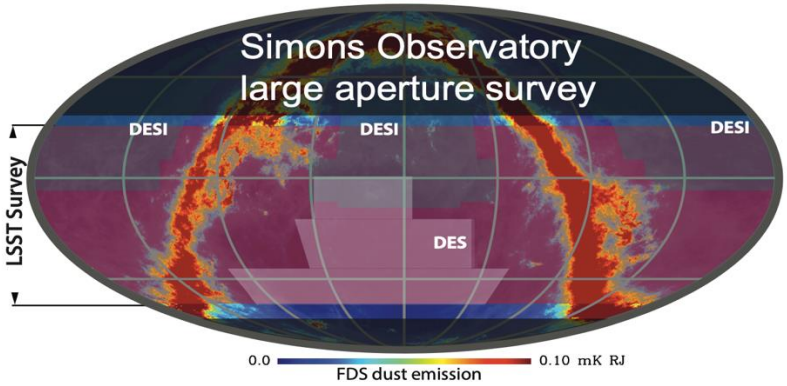
SO can detect any particle with spin that decoupled after the start of the QCD phase transition (at 2σ)



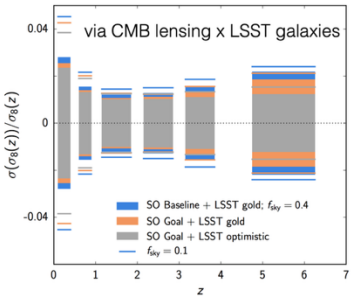
Strong limits on DM-proton elastic scattering;
Better limits and detection at intermediate mass scales of a DM axion fraction of 2%

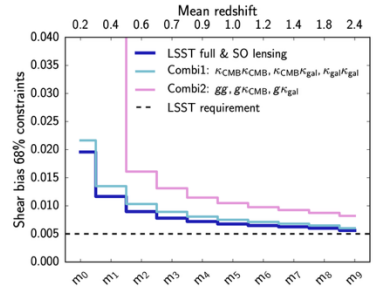


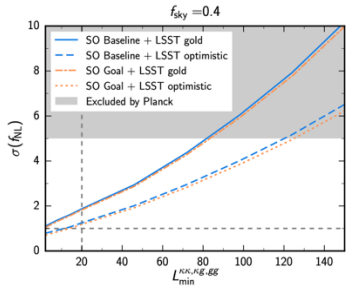
Multi-survey science

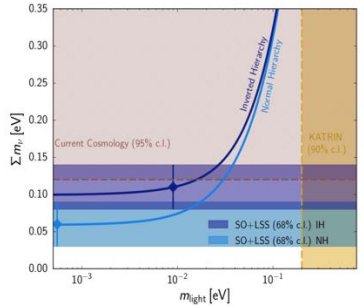


* with some post-pandemic and war updates









- *Enabling joint science from CMB lensing, tSZ, kSZ x Optical galaxy shear, clustering and clusters*
  - Neutrino mass
  - Structure growth: sigma8 at z>1
  - Non-Gaussianity: fnl
  - Cluster mass calibration
  - Shear bias calibration
  - Constraints on baryonic feedback

The Simons Observatory Collaboration 2019, 2025

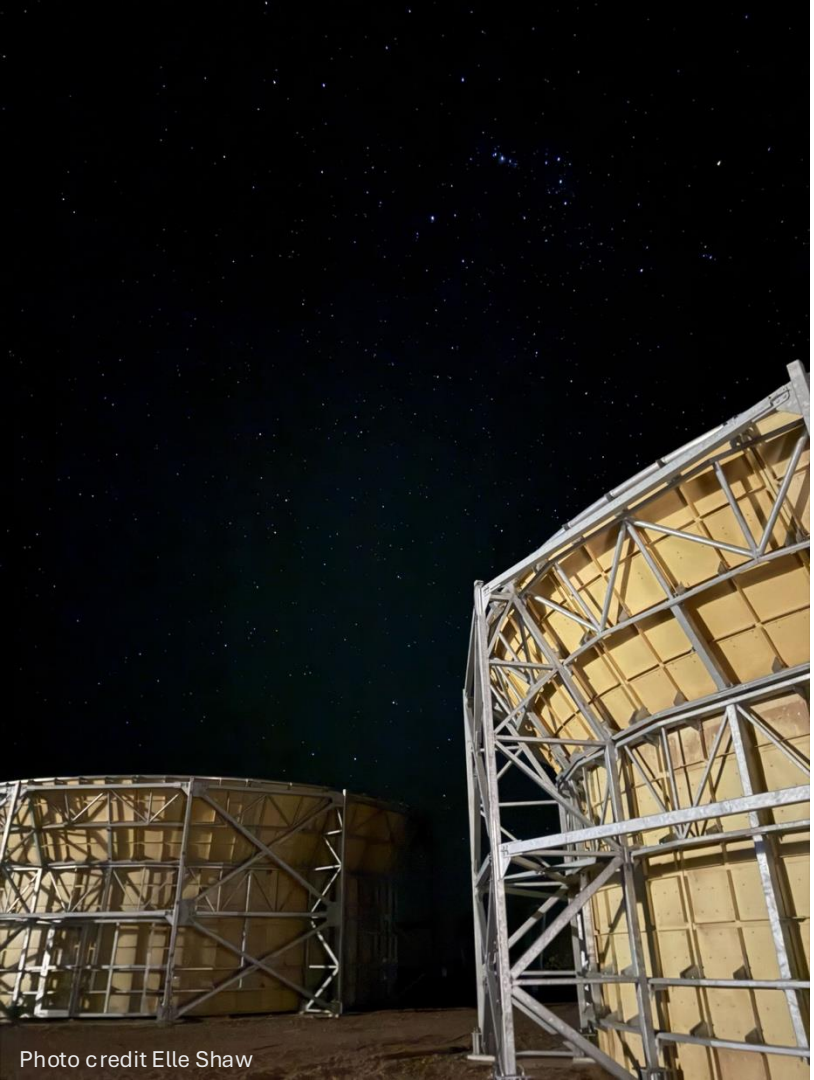


Photo credit Elle Shaw

Preliminary SAT Maps

Q/U maps

Started mapping the sky with two MF (90/150) SATs

Polarization patterns start being visible in the targeted SAT region

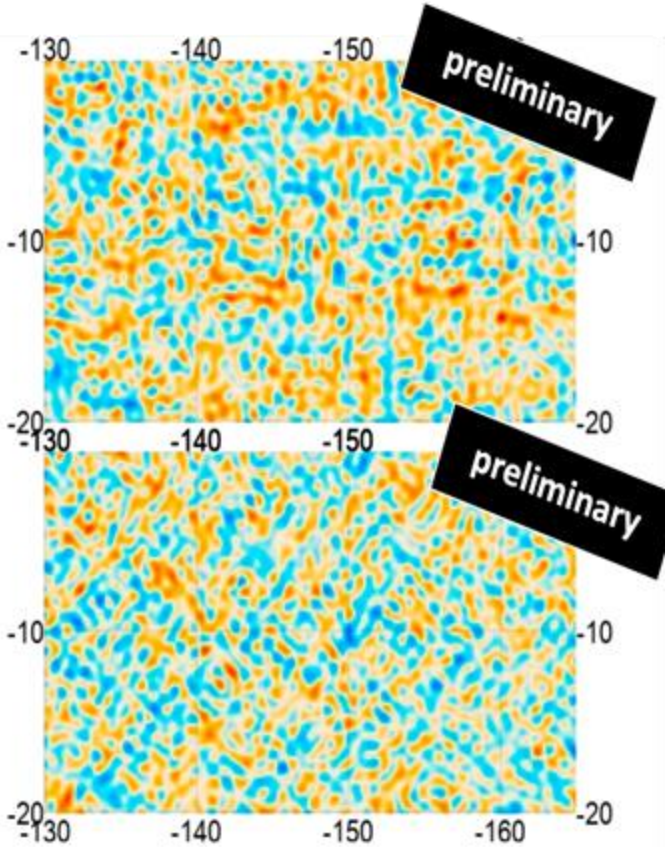
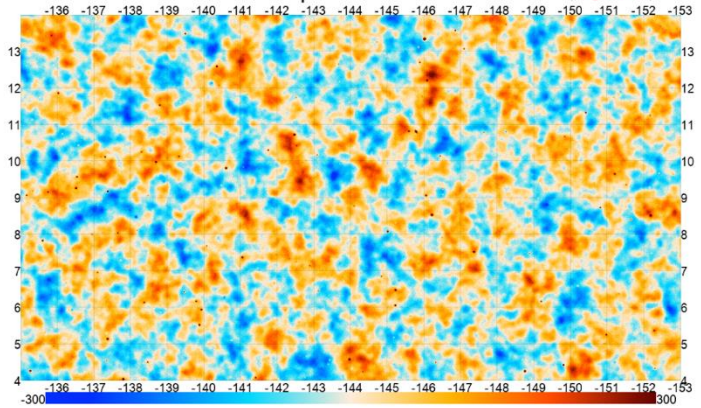


Photo credit Felipe Carrero

Preliminary LAT Maps

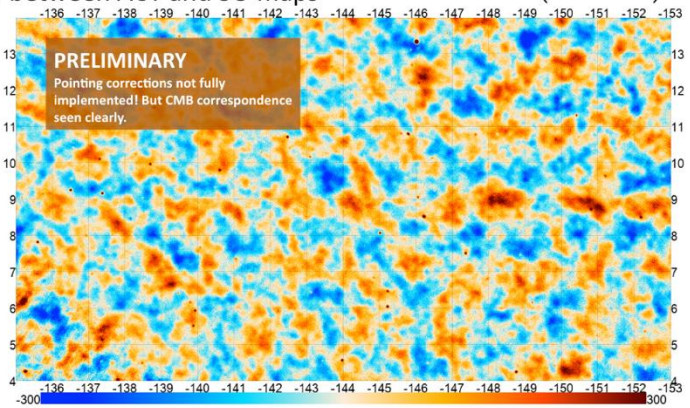
Flip between ACT and SO maps

ACT DR6 at 90 GHz (**5 years**)



Flip between ACT and SO maps

SO LAT at 90 GHz (**144 hours**)

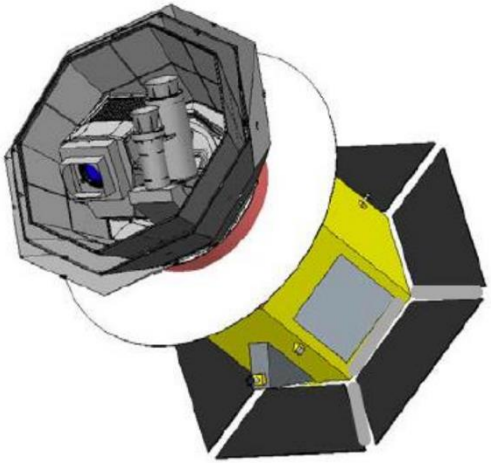


SO Collaboration

JAXA's new strategic L-class mission for all-sky surveys of cosmic microwave background (CMB) polarization

multipole telescopes in a single satellite
observing from L2 for 3 years
in 15 frequency bands in the mm
Goal to get r with $\delta r < 10^{-3}$

Launch early 2030s



LiteBIRD Collaboration PTEP 2023

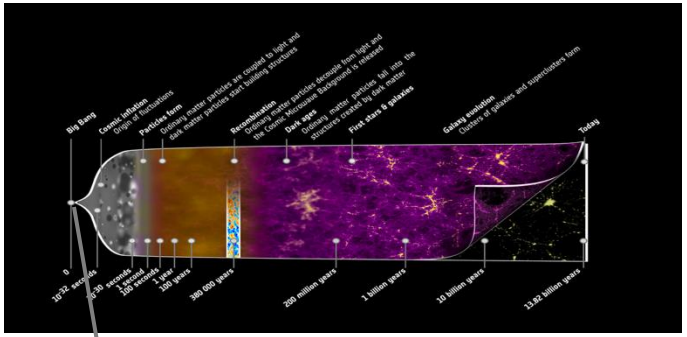
Large international collaboration
~400 Collaborators from Japan, Europe, Canada and US

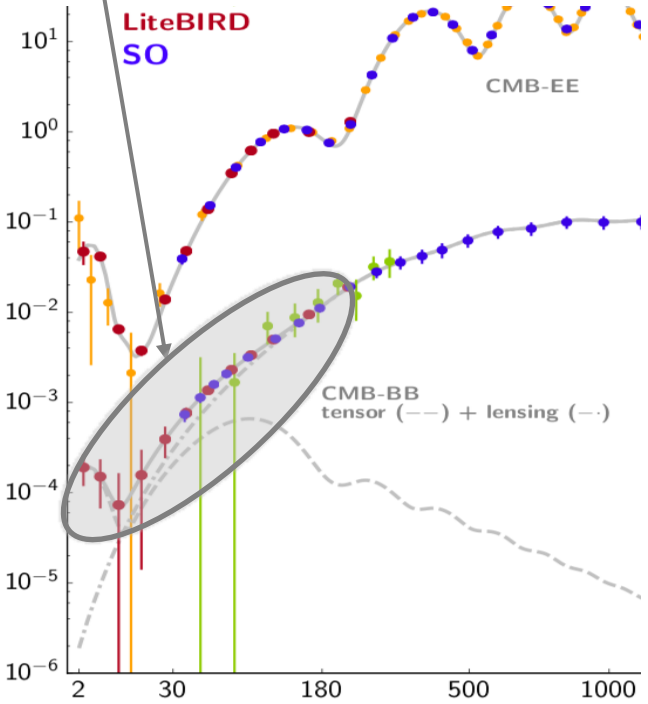
Cosmic Inflation

Current data support cosmic inflation via constraints on the primordial perturbations (no non-Gaussianity, adiabatic, and nearly scale-invariant spectrum, low contribution from tensor modes)

No direct proof through detection of primordial Gravitational Waves → target of LiteBIRD

- High-significance measurement of the B-mode large scale spectrum



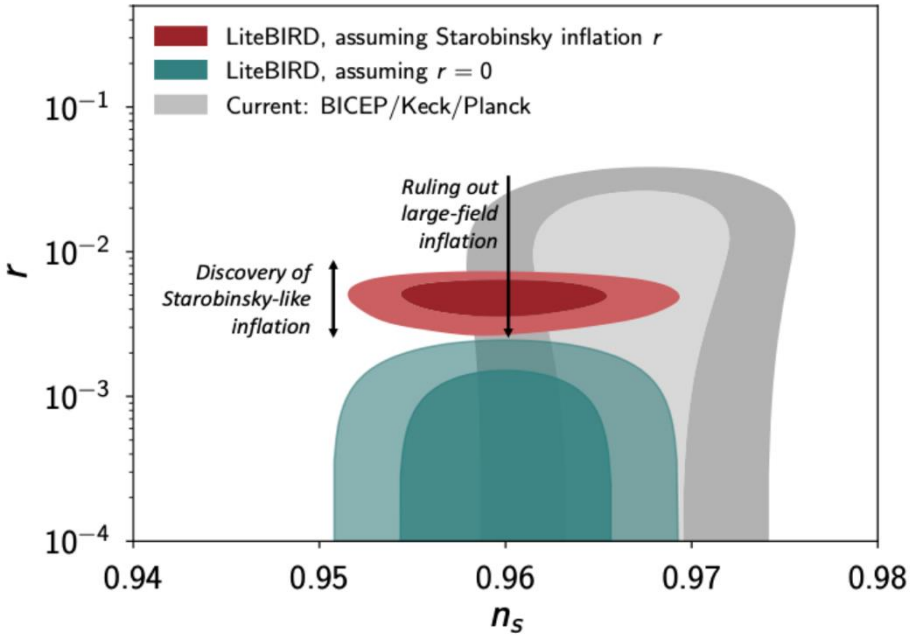


Cosmic Inflation

Current data support cosmic inflation via constraints on the primordial perturbations (no non-Gaussianity, adiabatic, and nearly scale-invariant spectrum, low contribution from tensor modes)

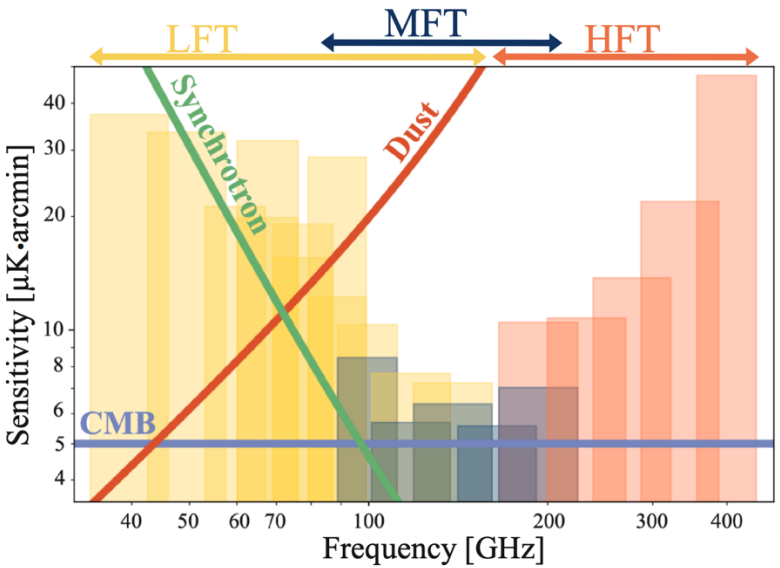
No direct proof through detection of primordial Gravitational Waves → target of LiteBIRD

- A non-zero r measurement from LiteBIRD will result in the detection at high significance of well-motivated inflationary models that predict r>0.01
- In the absence of a detection, robustly constraining r~10^{-3} would falsify large-field models as well as the first inflationary model proposed by Starobinsky

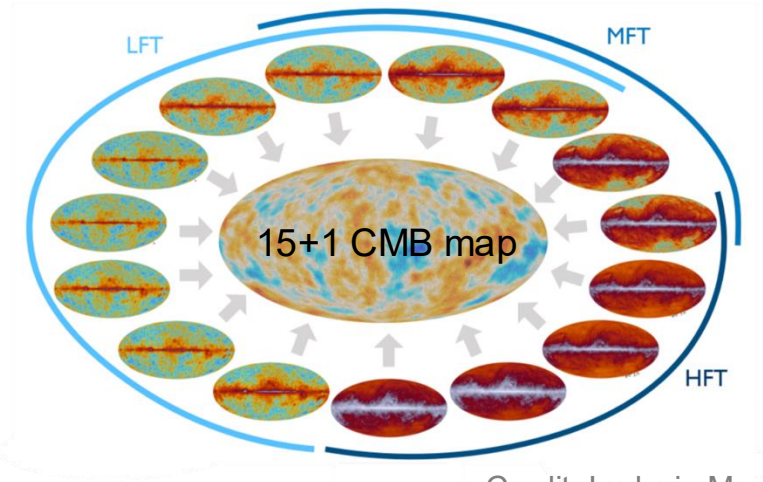


LiteBIRD Collaboration PTEP paper 2023

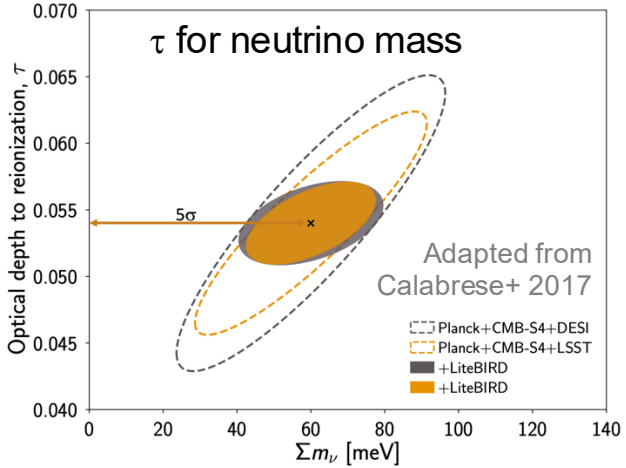
LiteBIRD legacy maps



- Projected polarization sensitivities in 15 bands for a 3-year full-sky survey
- 70-18 arcmin resolution
- Best of 4.3 μK-arcmin @ 119 GHz
- Combined sensitivity to primordial CMB anisotropies: 2.2 μK-arcmin



Credit: Ludovic Montier



CCAT-prime

The Fred Young Submillimeter Telescope

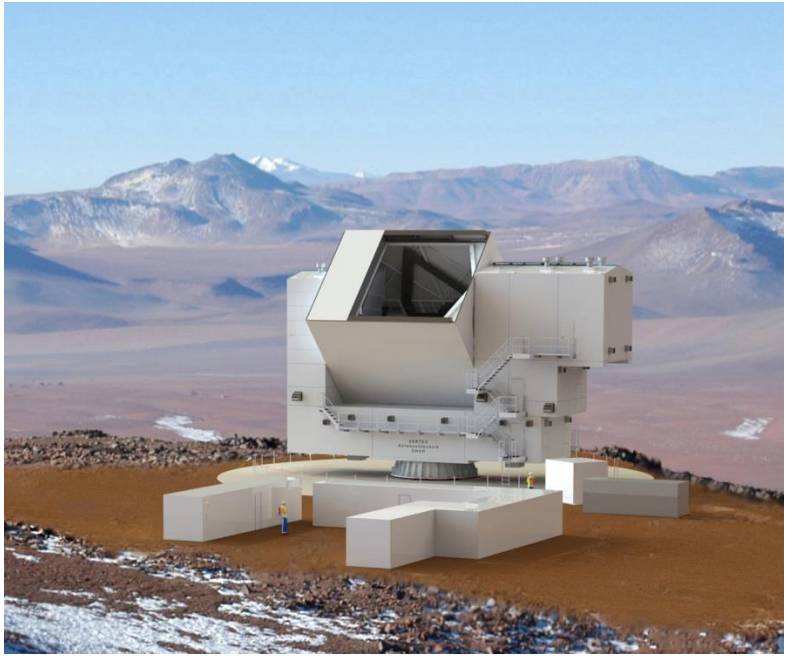
Higher site in Chile allowing to map higher frequencies (compared to SO/S4)

6-meter telescope

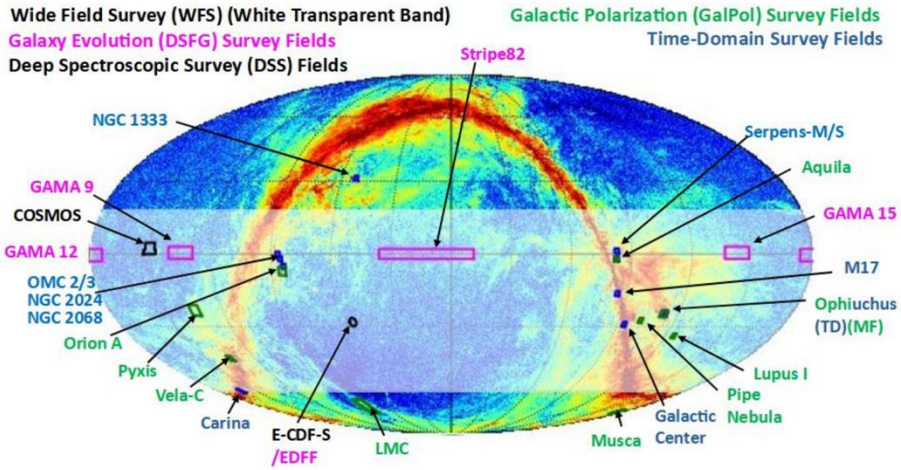
designed to operate at submillimeter to millimeter (200 – 3,000 μm / 100 – 1,500 GHz)

The construction phase is expected to lead to first light in 2024

https://www.ccatobservatory.org/



CCAT-prime

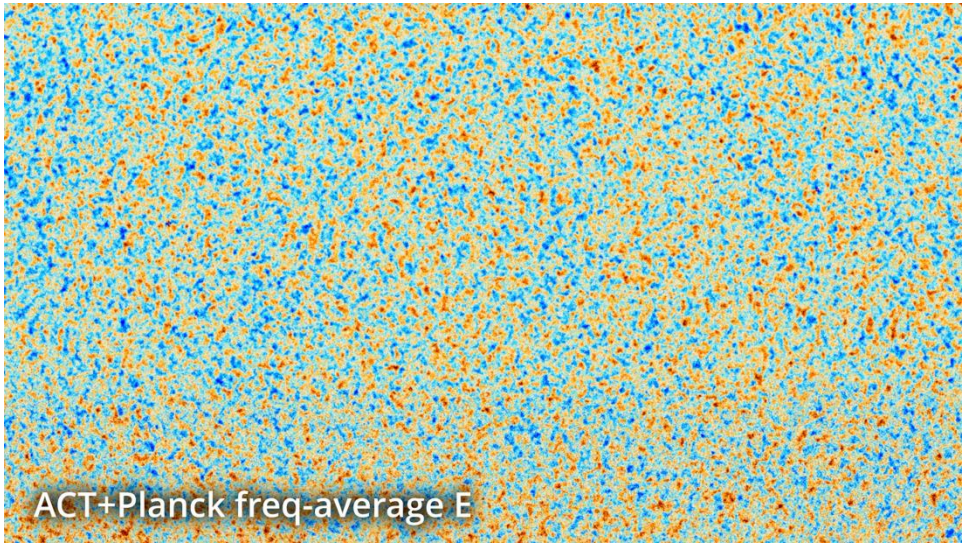


- Wide-field survey for CMB foregrounds, galaxy cluster evolution and Rayleigh scattering science
- Deep intensity mapping/reionization surveys, galaxy evolution survey fields, Galactic polarization science targets, time-domain science fields
- *More frequency coverage for CMB tSZ, kSZ x Optical galaxy shear, clustering and clusters*

Science goals

1. kSZ: kinetic Sunayev-Zel'dovich effect (to characterize the motions and relativistic content of galaxy clusters)
2. IM/EOR: Intensity mapping of [CII] from the EOR (to trace the appearance of the first population of star-forming galaxies)
3. GECO: Galactic ecology of the dynamic ISM (to probe multiple spectral line tracers of the ISM over a range of environments in the Milky Way, Magellanic Clouds and other nearby galaxies)
4. Stage IV CMB platform (Map the CMB at 10x the speed of current telescopes and provide submm coverage for galactic foreground removal for other CMB efforts)

Outlook



ACT Collaboration

- The CMB is our main probe of the early Universe and is the leading dataset for constraining cosmological models
- New fundamental physics constraints starting to appear from polarization
- New experiments built to enable new breakthroughs
- Physical interpretation of the results now requires deeper connections between theory and data across experiments and fields