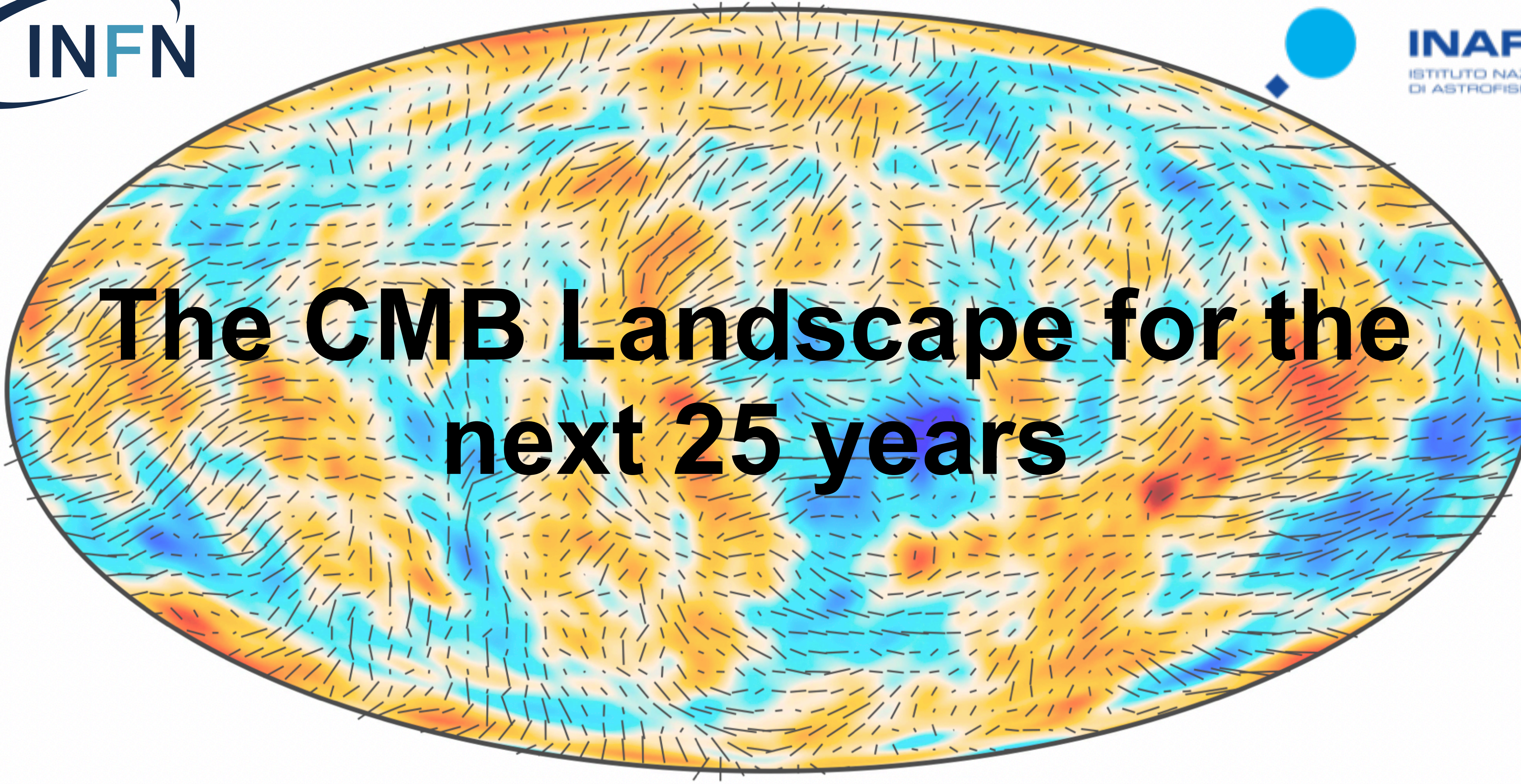
The CMB Landscape for the next 25 years



Paolo Natoli

Università di Ferrara, INFN and INAF

with many thanks to A.Gruppuso and other collaborators

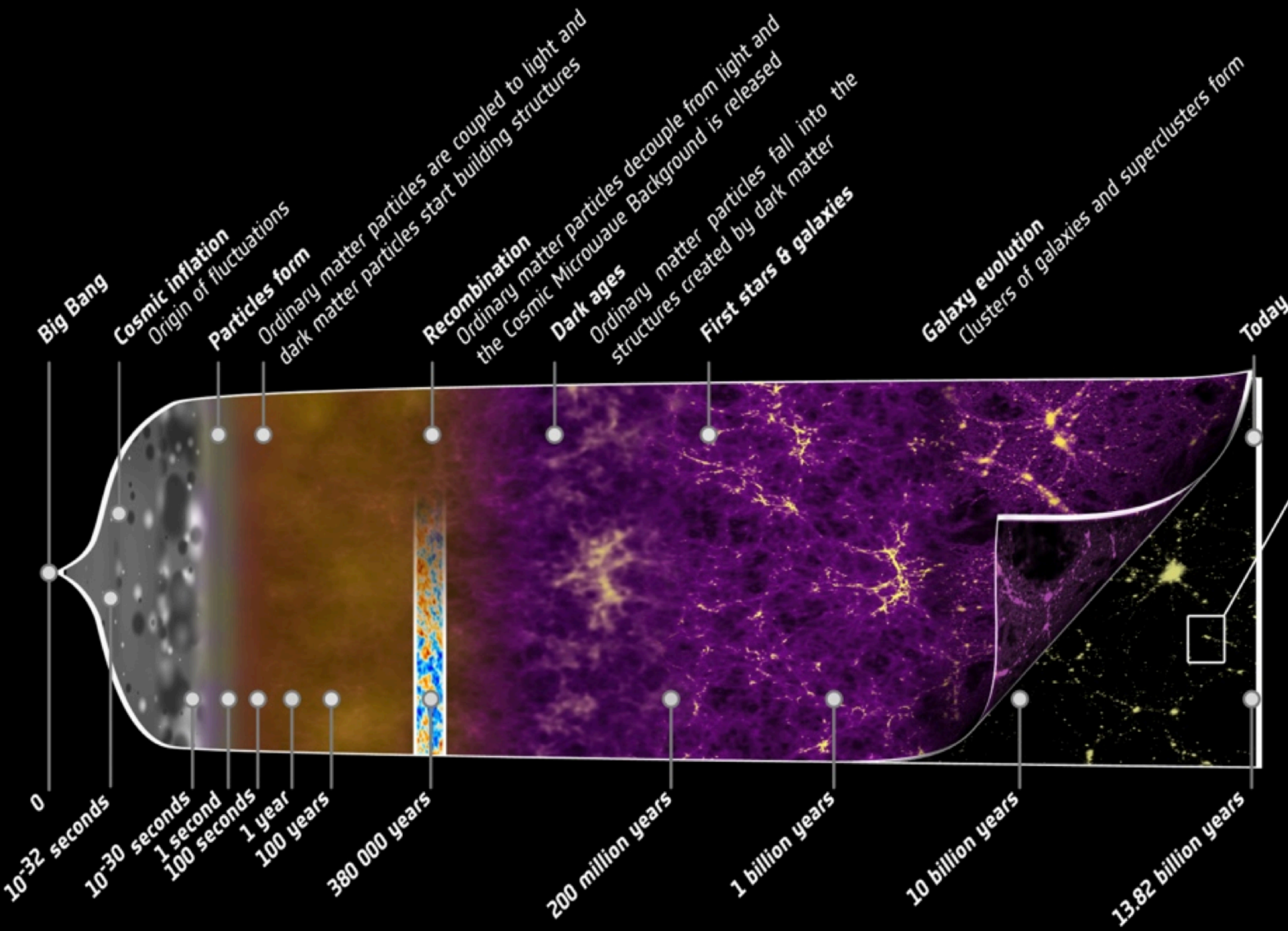
Gravity, Strings and Supersymmetry Breaking

Scuola Normale Superiore, Pisa, 3-5 April 2025

Outline

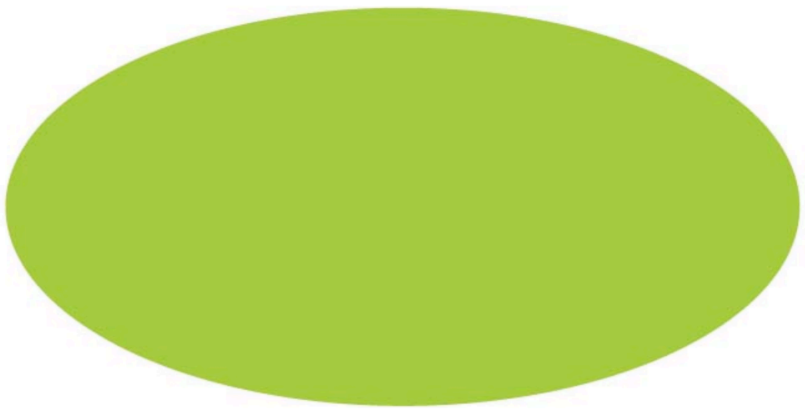
- Physics of the CMB
- Statistics of CMB anisotropies and polarisation
- State-of-the-art of CMB results
- Upcoming and long-term CMB observations
- Conclusions

Cosmic Microwave Background (CMB) photons are released at recombination



CMB – Cosmic Microwave Background

Black Body Spectrum with T=2.726 K



$$I_\nu = \frac{2h\nu/c^2}{e^{h\nu/kT} - 1}$$

$$I_\nu \equiv \frac{2\nu^2 kT_A}{c^2}$$

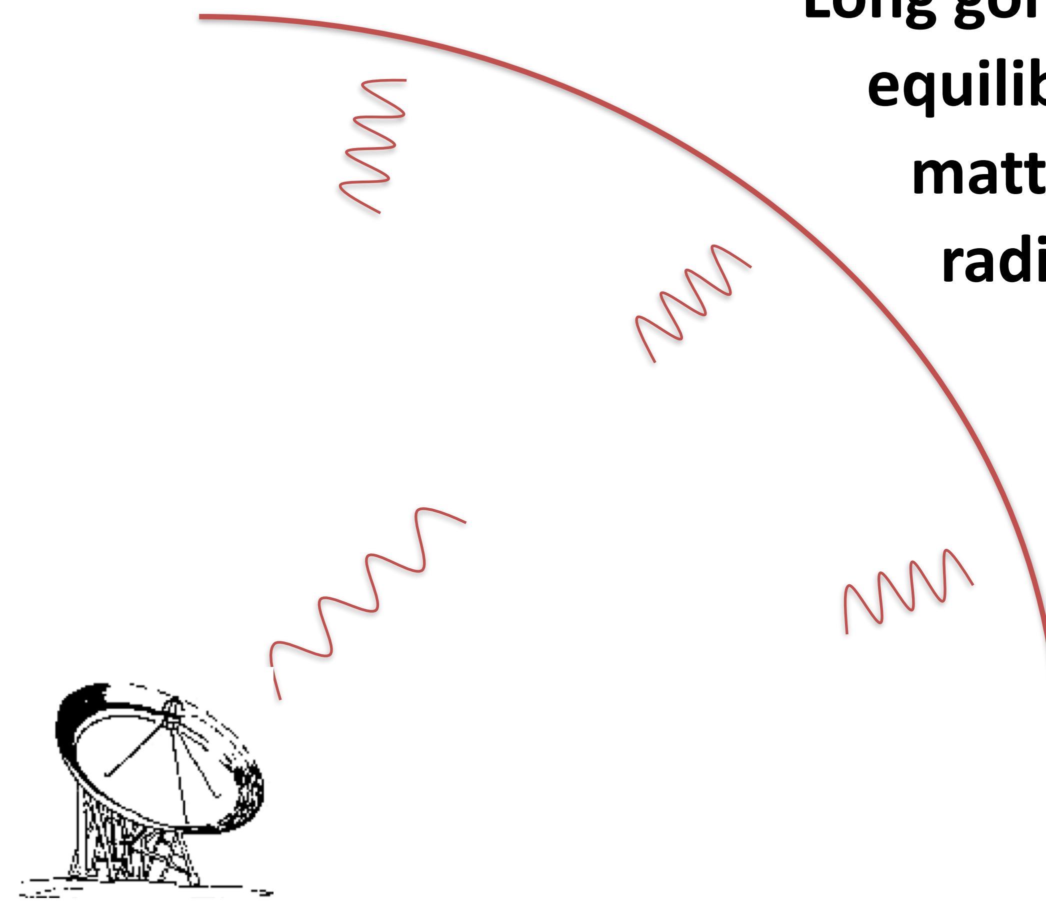
$T \simeq T_A$ when $x \ll 1$

$$x = h\nu/kT$$

$$\frac{\Delta T}{T_0}(\hat{n}) = \frac{\Delta T_A}{T_A}(\hat{n})\left(\frac{e^x - 1}{x\, e^x}\right)$$

CMB anisotropies

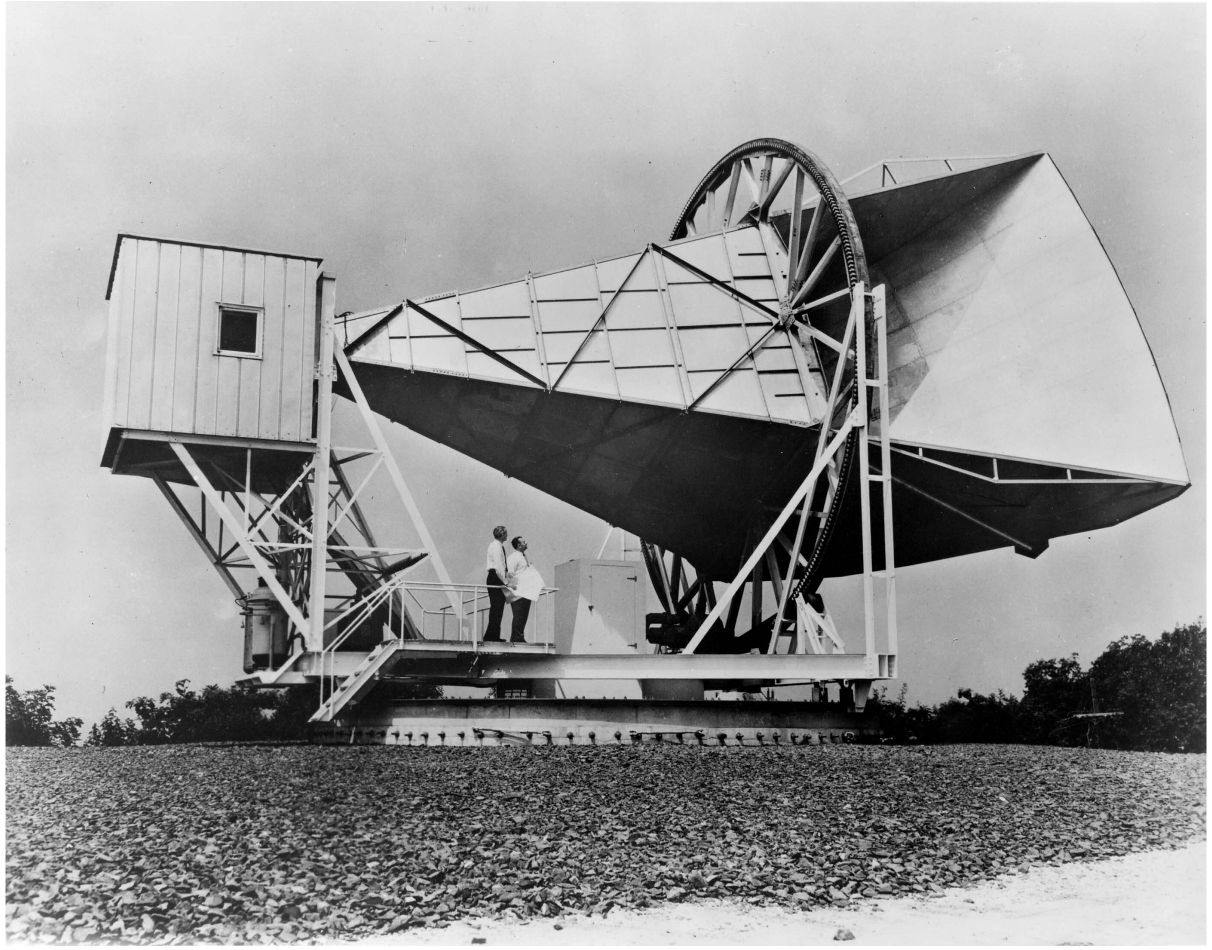
Long gone thermal equilibrium of matter and radiation



3 K ← **3000 K**

13.8 Gyr ← **380000 yr**

3 K → microwave
emission peaks at 150 GHz



Horn antenna
(Holmdel, New Jersey)

The discovery of the CMB (1965)

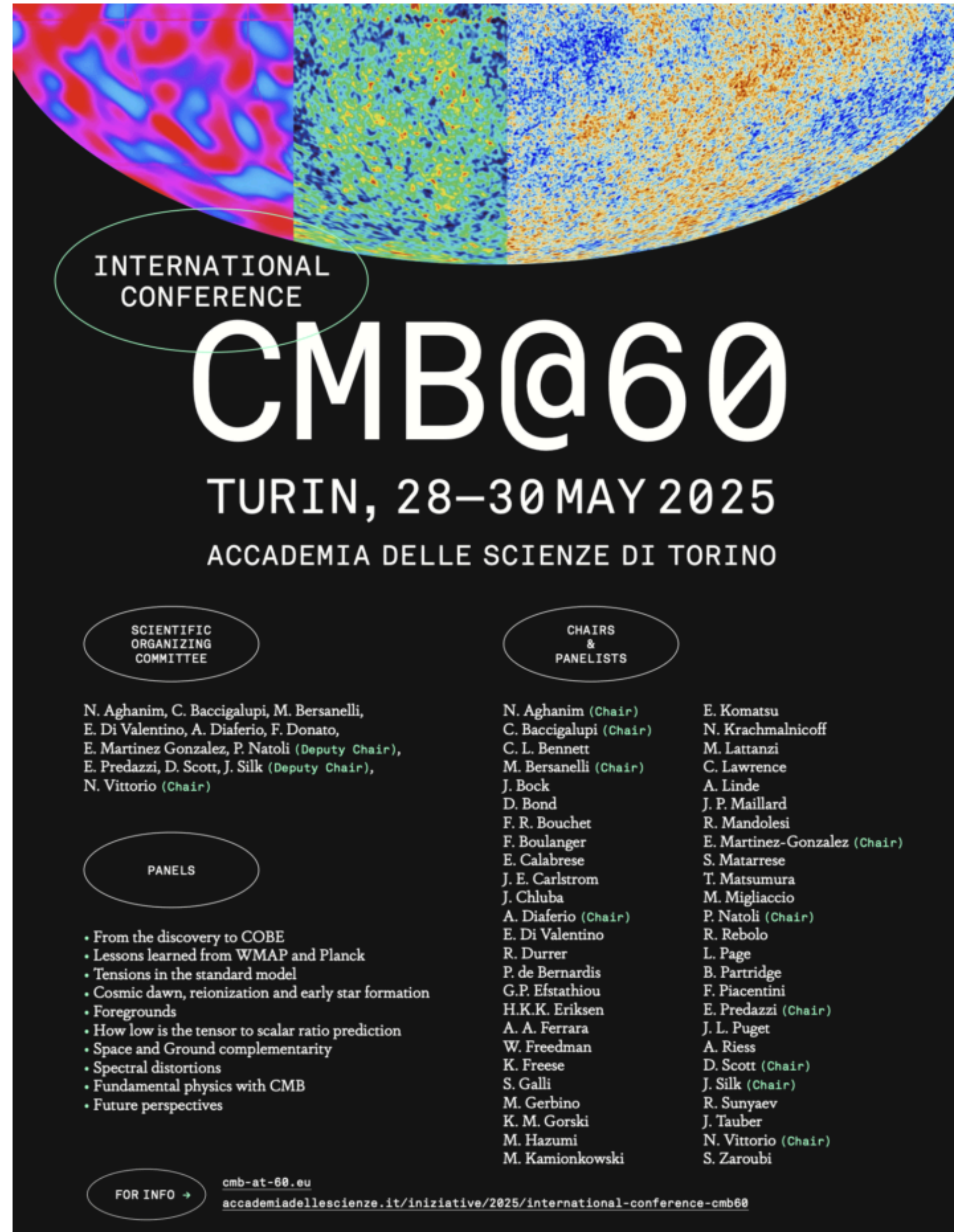
A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE
AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and

First Nobel prize for CMB (1978)

CMB@60: Torino, 28-30 May 2025

Main organizers:
N. Vittorio (chair), P. Natoli, J. Silk



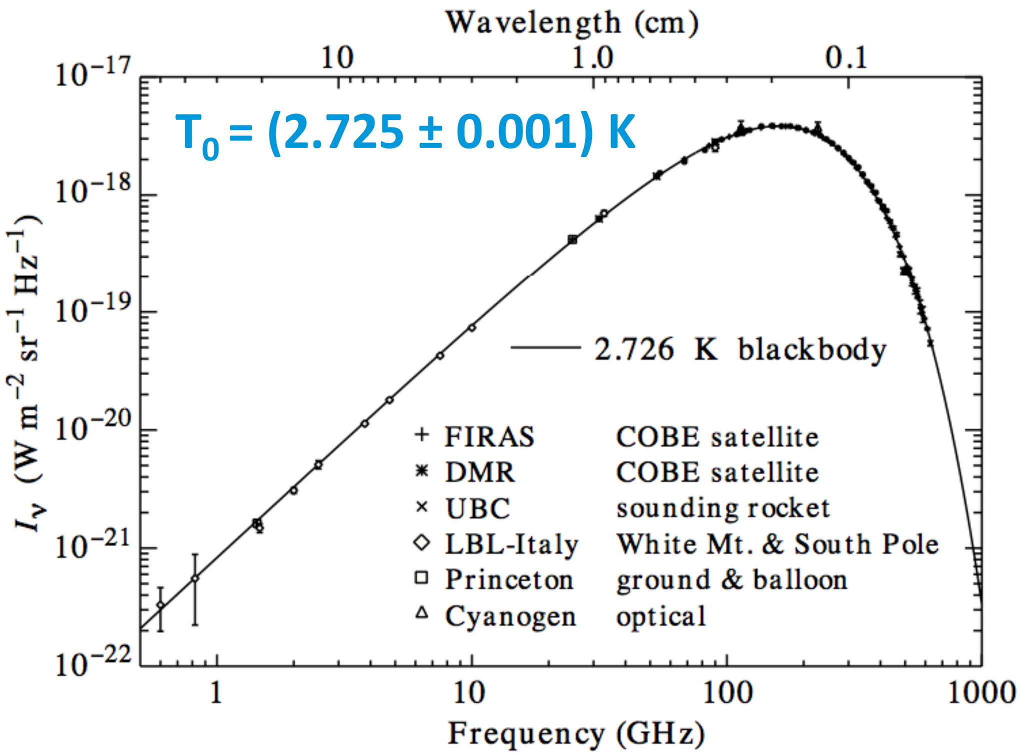
CMB – Cosmic Microwave Background

Second Nobel prize for CMB (2006)

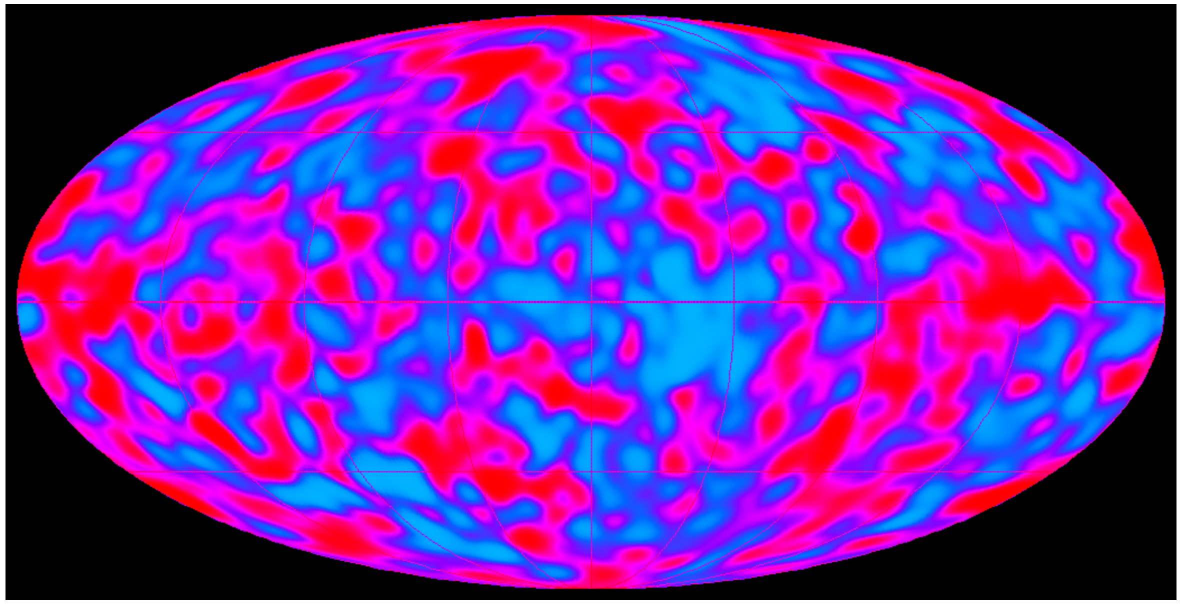
COBE SATELLITE - NASA (1989-1993)
G. Smoot and J. Mather

The CMB has a black body spectrum

The CMB shows anisotropies at 1 part in 10^5

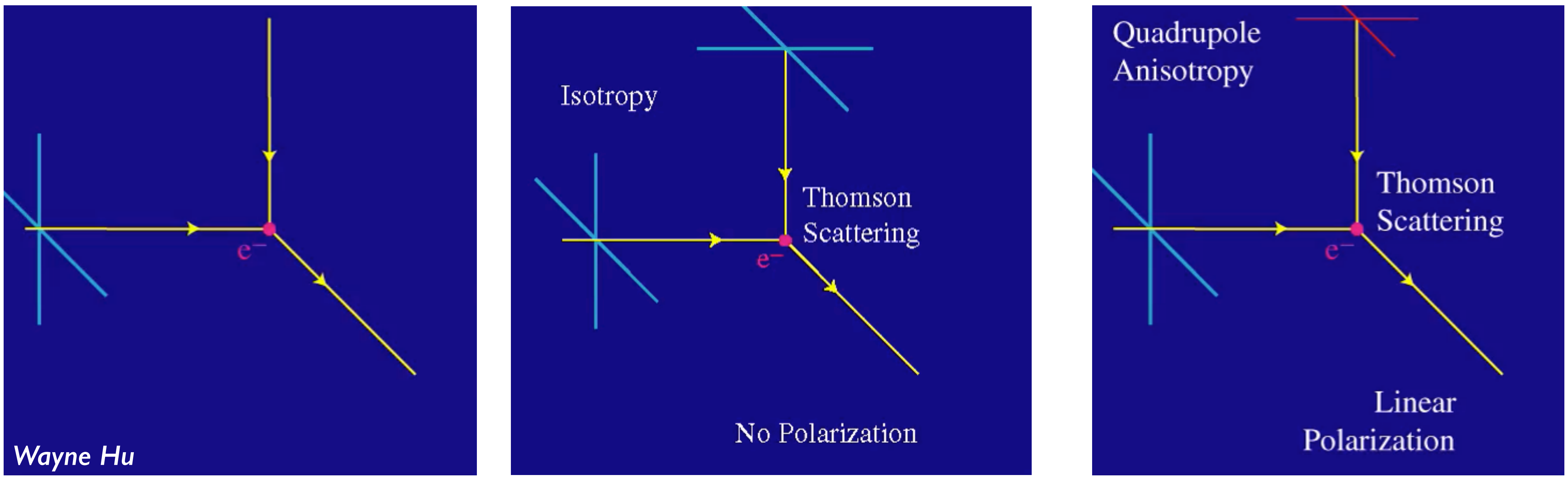


The most accurate black body we know



Anisotropies in T

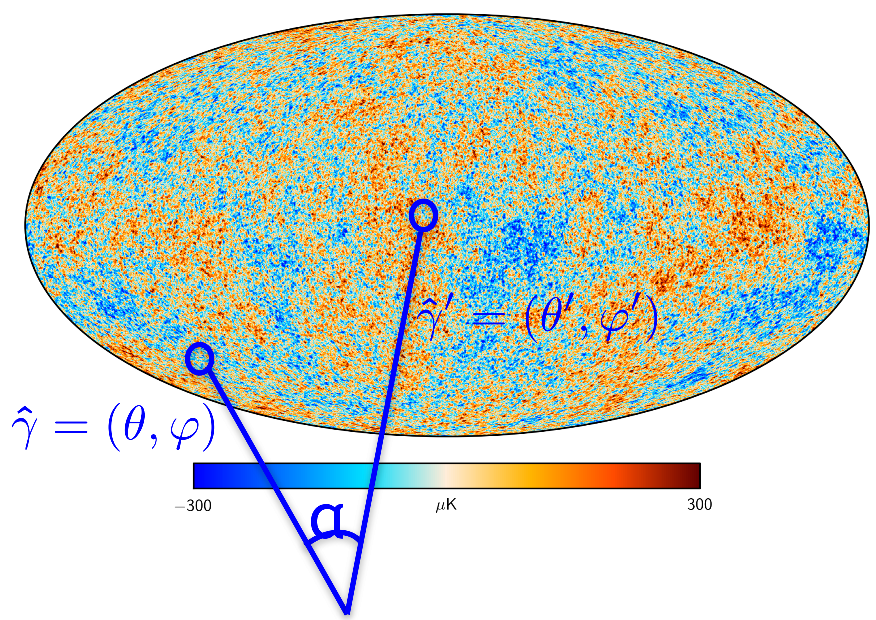
The CMB is linearly polarized



- The **Thomson scattering** cross section depends on photon polarization: $\frac{d\sigma_T}{d\Omega} \propto |\hat{\epsilon} \cdot \hat{\epsilon}'|^2$

- CMB polarization is created only by a **local temperature quadrupole** anisotropy. This is generated only when the photon diffusion length grows enough to reveal higher order moments in the brightness distribution (e.g. at recombination)

STATISTICAL DESCRIPTION



CORRELATION FUNCTIONS

$$\langle \frac{\delta T}{T}(\hat{\gamma}) \frac{\delta T}{T}(\hat{\gamma}') \rangle$$

← from Inflation Gaussian random variables

$$\langle \frac{\delta T}{T}(\hat{\gamma}) \frac{\delta T}{T}(\hat{\gamma}') \frac{\delta T}{T}(\hat{\gamma}'') \rangle$$

$$\langle \frac{\delta T}{T}(\hat{\gamma}) \frac{\delta T}{T}(\hat{\gamma}') \frac{\delta T}{T}(\hat{\gamma}'') \frac{\delta T}{T}(\hat{\gamma}''') \rangle$$

...

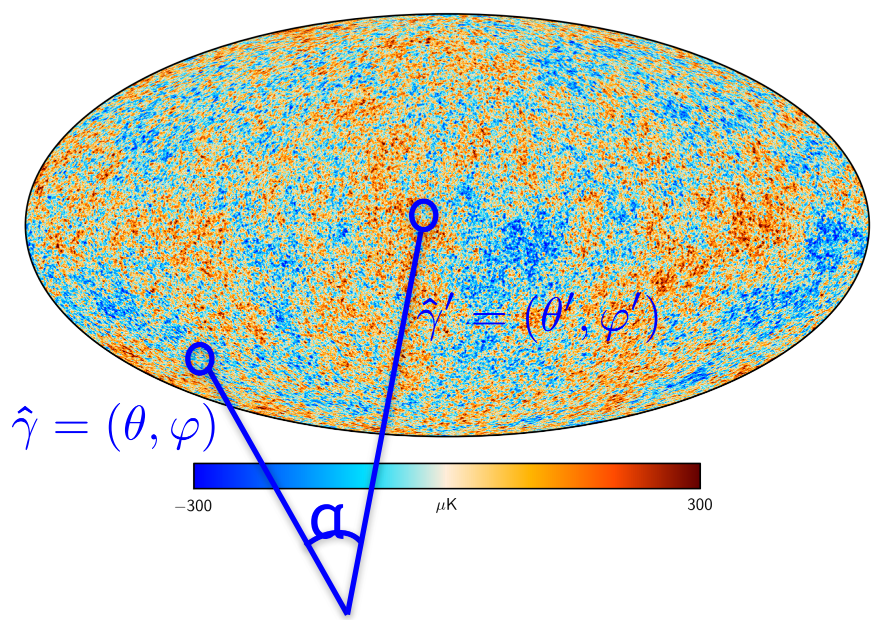
$$\frac{\delta T}{T}(\hat{\gamma}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\hat{\gamma})$$ + isotropy hypothesis

⇓

$$\langle \frac{\delta T}{T}(\hat{\gamma}) \frac{\delta T}{T}(\hat{\gamma}') \rangle = \sum_{\ell} \frac{2\ell+1}{4\pi} C_\ell P_\ell(\hat{\gamma} \cdot \hat{\gamma}')$$

Key-observable for CMB anisotropies (they are used to compare theory-observations)

STATISTICAL DESCRIPTION



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...

$$\frac{\delta T}{T}(\hat{\gamma}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\hat{\gamma})$$

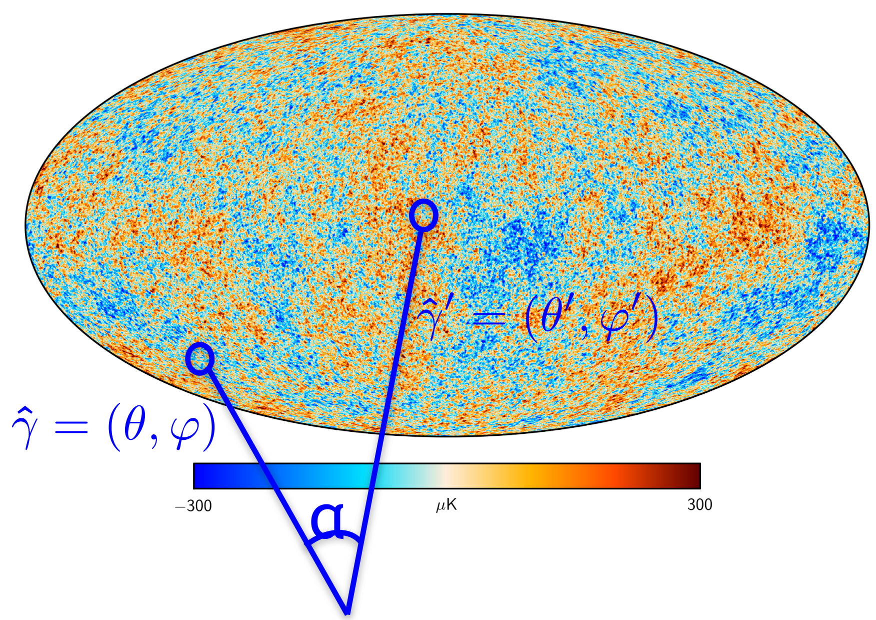
\+ isotropy hypothesis

$$\langle \frac{\delta T}{T}(\hat{\gamma}) \frac{\delta T}{T}(\hat{\gamma}') \rangle = \sum_{\ell} \frac{2\ell + 1}{4\pi} C_\ell P_\ell(\hat{\gamma} \cdot \hat{\gamma}')$$

All the information is contained in these Coefficients

Key-observable for CMB anisotropies (they are used to compare theory-observations)

STATISTICAL DESCRIPTION



CORRELATION FUNCTIONS

$$\langle \frac{\delta T}{T}(\hat{\gamma}) \frac{\delta T}{T}(\hat{\gamma}') \rangle$$ ← from Inflation Gaussian random variables

$$\langle \frac{\delta T}{T}(\hat{\gamma}) \frac{\delta T}{T}(\hat{\gamma}') \frac{\delta T}{T}(\hat{\gamma}'') \rangle$$

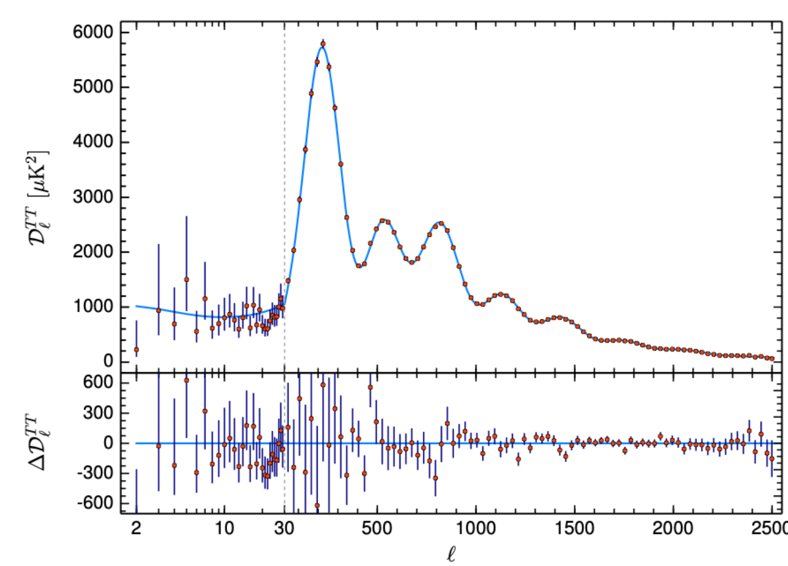
$$\langle \frac{\delta T}{T}(\hat{\gamma}) \frac{\delta T}{T}(\hat{\gamma}') \frac{\delta T}{T}(\hat{\gamma}'') \frac{\delta T}{T}(\hat{\gamma}''') \rangle$$

...

$$\frac{\delta T}{T}(\hat{\gamma}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\hat{\gamma})$$ + isotropy hypothesis

⇩

$$\langle \frac{\delta T}{T}(\hat{\gamma}) \frac{\delta T}{T}(\hat{\gamma}') \rangle = \sum_{\ell} \frac{2\ell + 1}{4\pi} C_\ell P_\ell(\hat{\gamma} \cdot \hat{\gamma}')$$



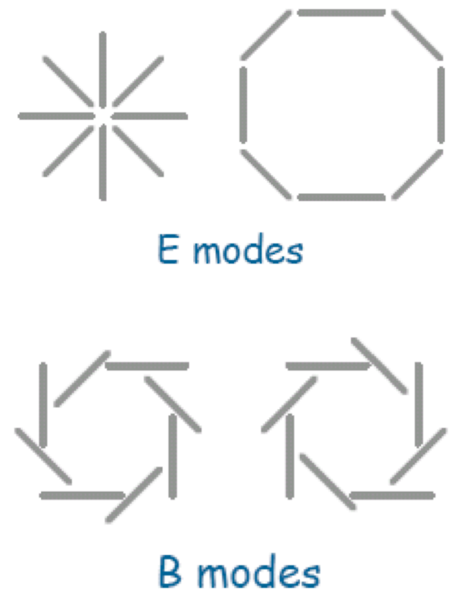
Key-observable for CMB anisotropies (they are used to compare theory-observations)

STATISTICAL DESCRIPTION

Polarisation is a spin 2 tensor.

Polarisation is more complicated to describe

POLARIZATION



Maps of the Stokes parameters

$$Q(\hat{n}) \pm iU(\hat{n}) = \sum_{\ell m} a_{\pm 2,\ell m\ \pm 2}Y_{\ell m}(\hat{n})$$

$$a_{E,\ell m} = -\left(a_{+2,\ell m} + a_{-2,\ell m}\right)/2$$

$$a_{B,\ell m} = i\left(a_{+2,\ell m} - a_{-2,\ell m}\right)/2$$

E-modes: even under parity

B-modes: odd under parity

HP. ISOTROPY:

Angular Power Spectrum

$$\langle a^X_{\ell m} a^{*Y}_{\ell' m'} \rangle = C^{XY}_\ell \delta_{\ell\ell'} \delta_{mm'}$$

ESTIMATOR

$$C_\ell = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} a^X_{\ell m} a^{*Y}_{\ell m}$$

6 spectra: **TT, EE, BB, TE, TB, EB**

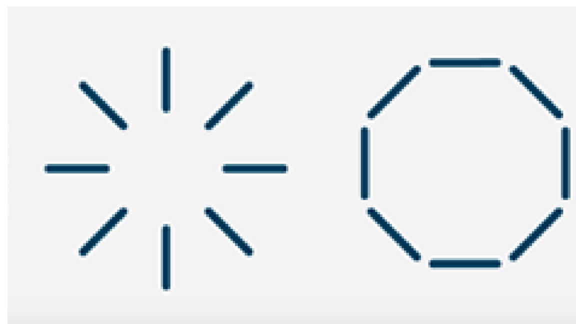
but due to parity conservation

$$C^{TB}_\ell = C^{EB}_\ell = 0$$

CMB polarisation science

The CMB is **linearly polarized** at the level of a few percent
Q and U are usually combined in two fields called E-modes and **B-modes**

E-mode



B-mode

E-modes arise naturally from Thomson scattering in a heterogeneous plasma

- Acoustic peaks
- Re-ionisation → optical depth: τ

B-modes two production mechanisms:

- Gravitational lensing of E-field → Small scales
- Gravitational waves arising from cosmic inflation → Large scales → tensor-to-scalar ratio: r

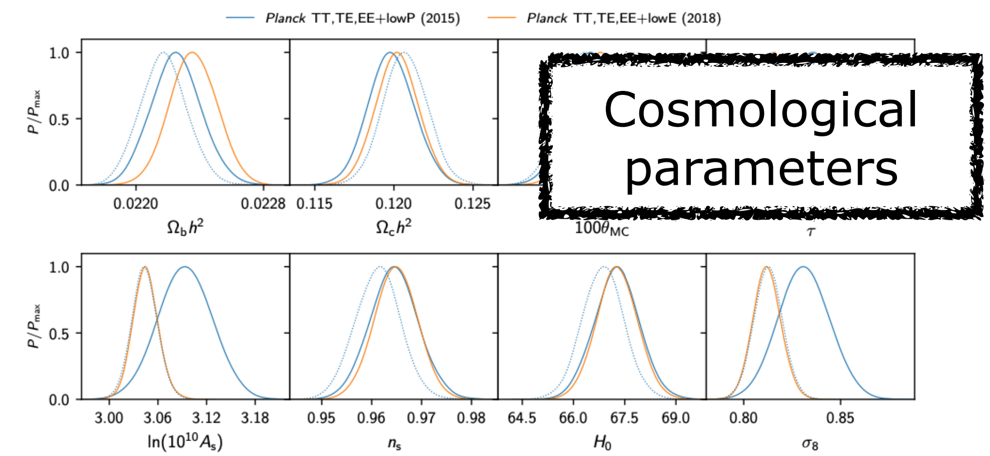
CMB DATA ANALYSIS PIPELINE

Time-ordered data

$\sim 10^{10}$

Huge compression of data

~ 10



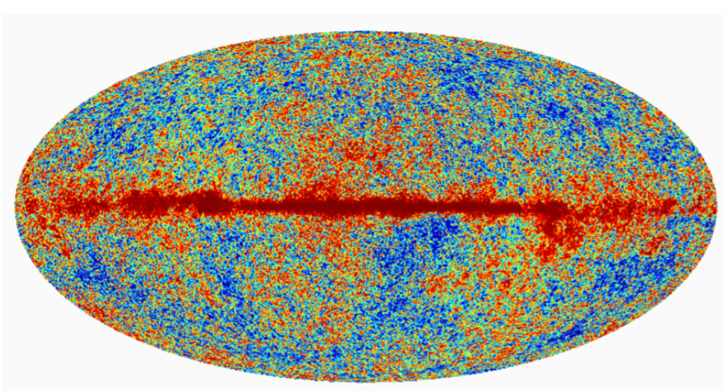
Cosmological parameters

$\sim 10^7$

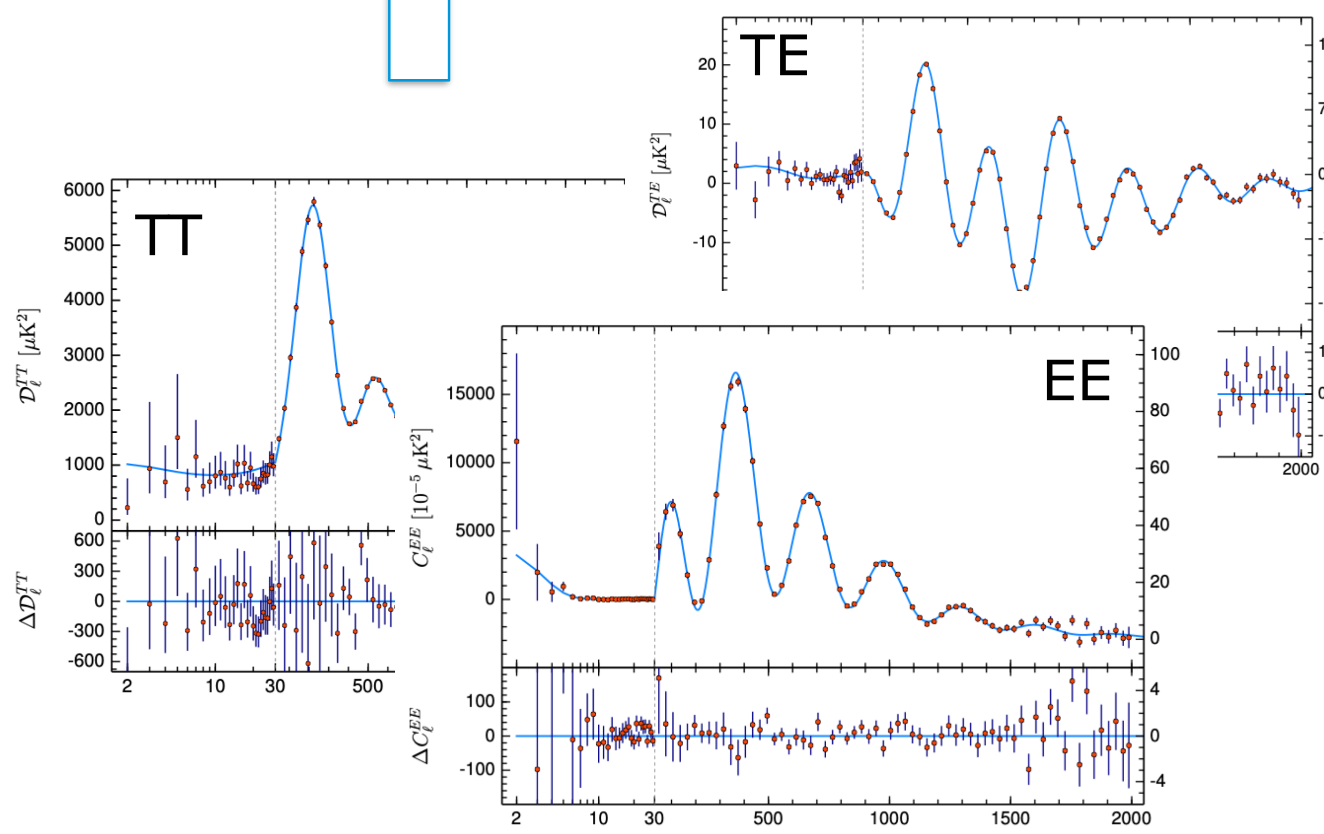
$\sim 10^3$

Likelihood function
+ MCMC techniques

Map Making
(scanning strategy)

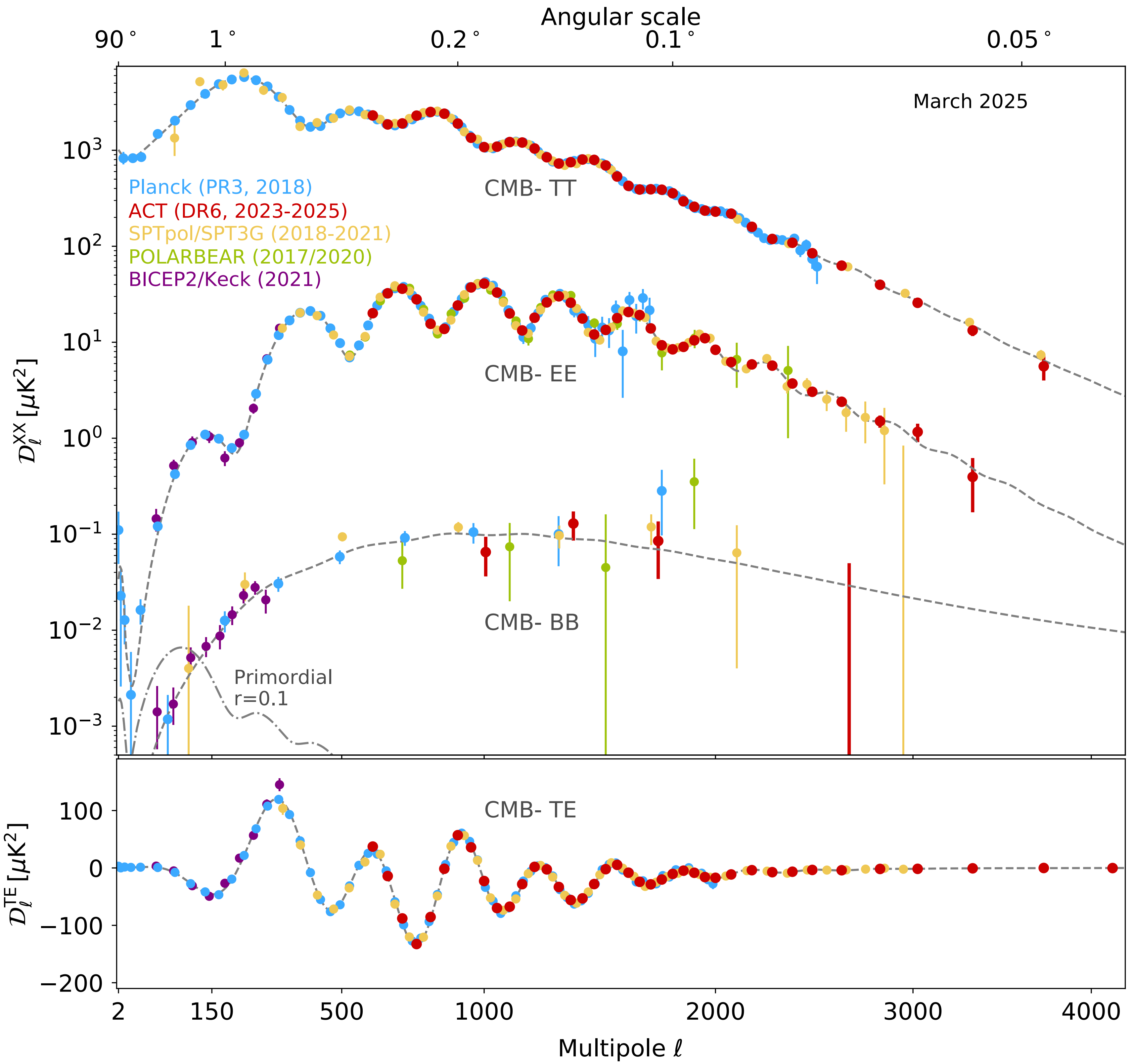


Angular power spectra analysis



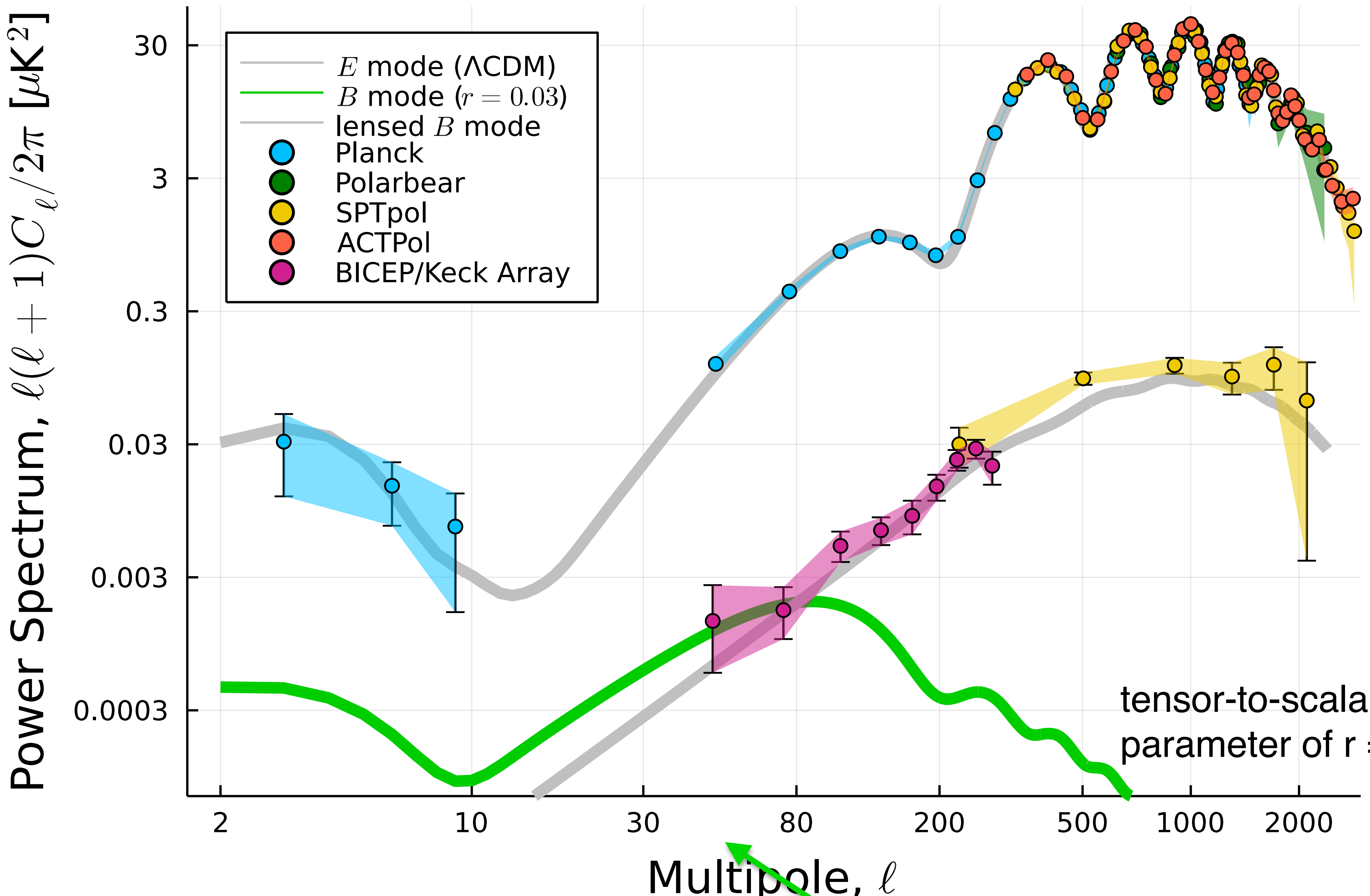
C_ℓ are the key-object to characterise the CMB anisotropies
(they are used to compare theory-observations)

State-of-the-art of CMB observations



T.Louis et al. [ACT], ``The Atacama Cosmology Telescope: DR6 Power Spectra, Likelihoods and ΛCDM Parameters,'' [arXiv:2503.14452 [astro-ph.CO]].

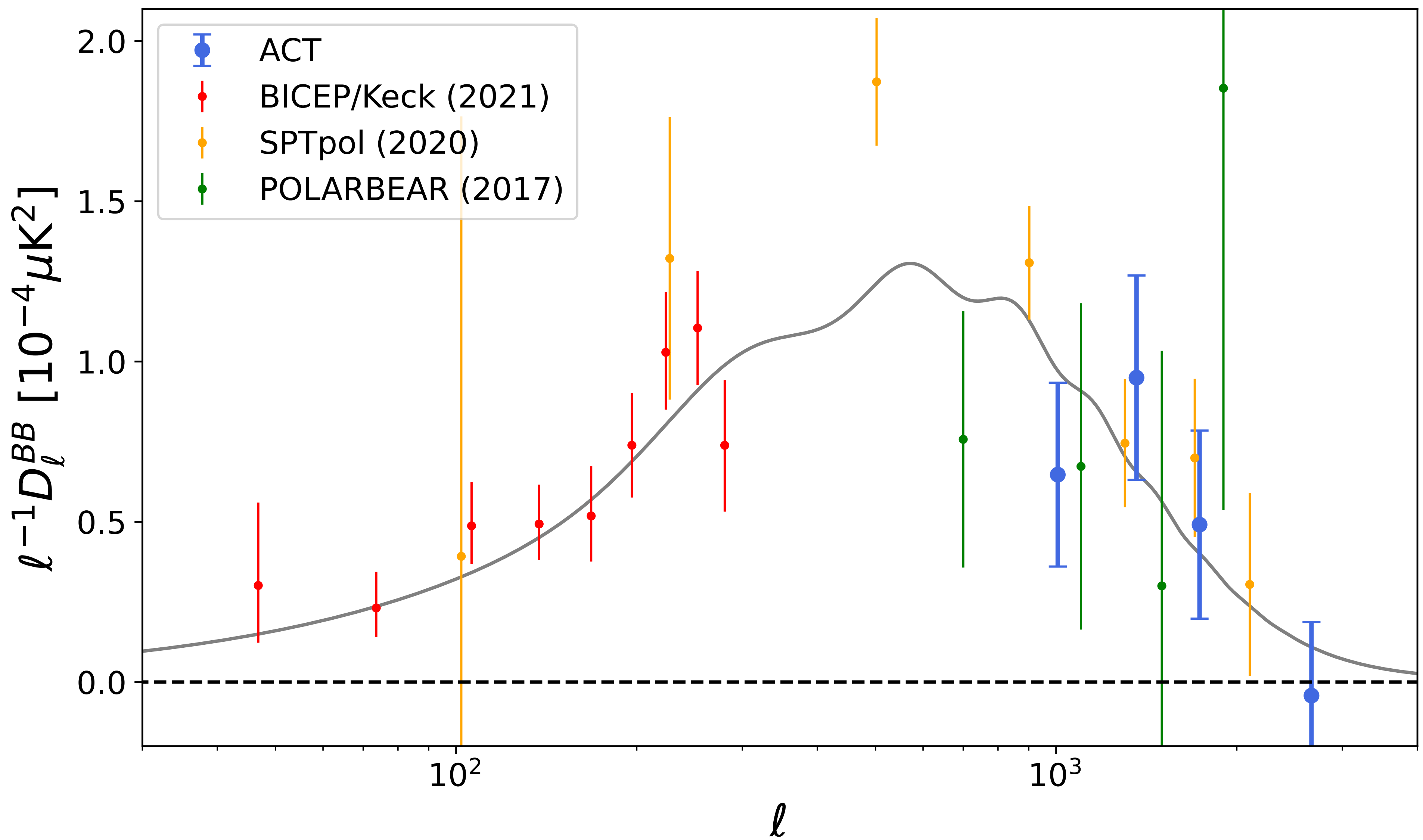
Focus on polarisation (EE and BB)



E.Komatsu, ``New physics from the polarized light of the cosmic microwave background,'' Nature Rev. Phys. \textbf{4} (2022) no.7, 452-469 [arXiv:2202.13919 [astro-ph.CO]].

Primordial B modes still to be detected

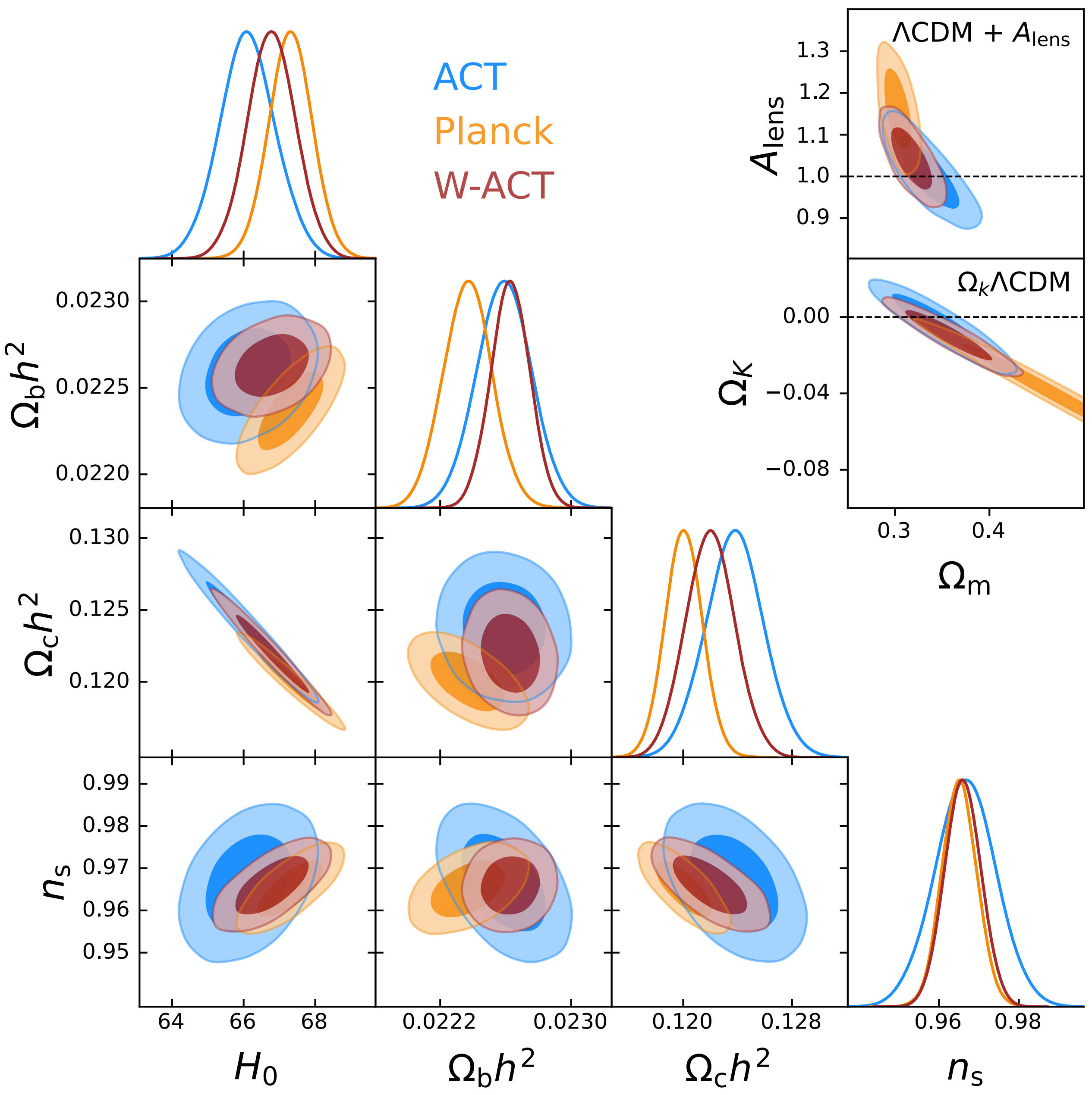
Focus on BB lensing spectrum



Compilation of B-mode power spectra measurements from ACT, BICEP/Keck (Ade et al. 2021), SPTpol (Sayre et al. 2020a) and POLARBEAR (POLARBEAR Collaboration 2017).

T.Louis et al. [ACT], ``The Atacama Cosmology Telescope: DR6 Power Spectra, Likelihoods and ΛCDM Parameters,'' [arXiv:2503.14452 [astro-ph.CO]].

Cosmological parameters

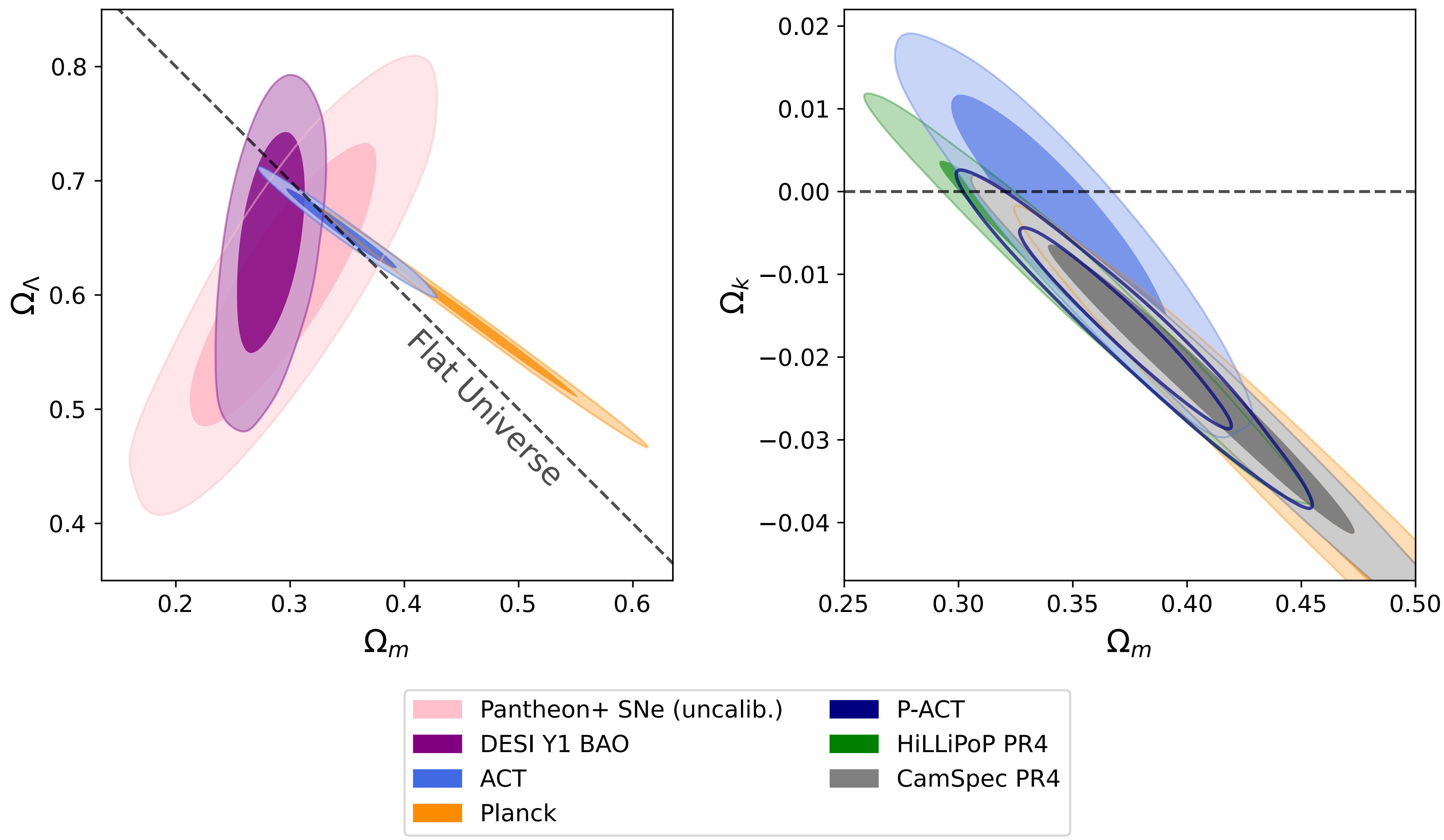


Triangular plot: Subset of the ΛCDM cosmological parameters estimated from ACT, and ACT combined with WMAP large-scale data (W-ACT), compared to results from the Planck PR3 power spectra.

We show the Hubble constant, H_0, the baryon density, $\Omega_b h^2$, the cold dark matter density $\Omega_c h^2$, and the scalar spectral index, n_s. The optical depth is constrained using Planck large-scale polarization data from Sroll2.

Distributions showing the correlation of the matter density, Ω_m, with the lensing parameter, A_{lens}, or the curvature Ω_K, when each are added as extensions to the ΛCDM model; we see no departures from the expected lensing, or from spatial flatness, with ACT or W-ACT.

Cosmological parameters



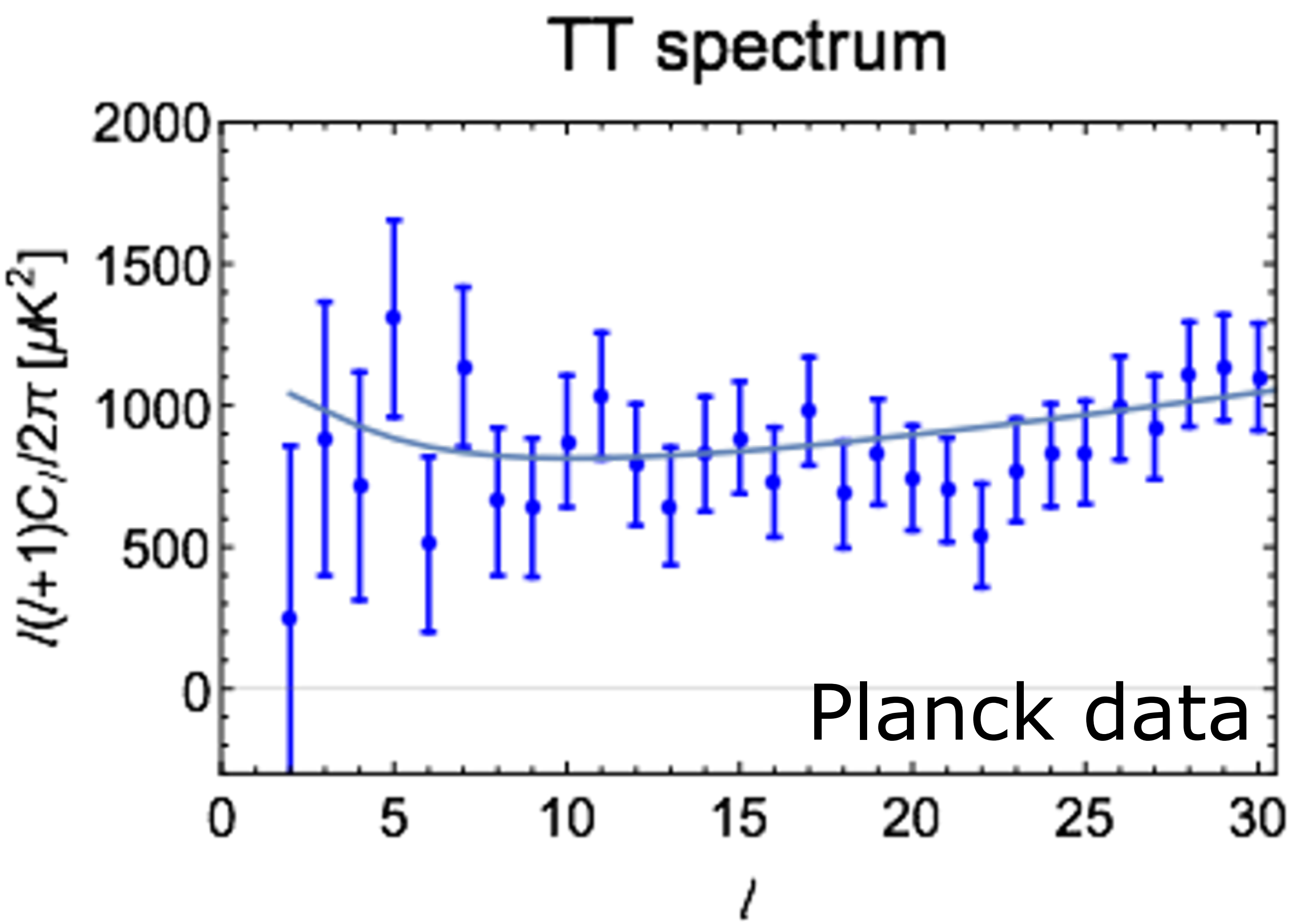
(Left) Measurements of background cosmological parameters, including possible non-zero spatial curvature, from DESI Y1 BAO, Pantheon+ supernovae (SNe), ACT, and Planck PR3.

(Right) Results from ACT, P-ACT, and the Planck NPIPE CamSpec (Rosenberg et al. 2022) and HiLLiPoP likelihoods (Tristram et al. 2024) are consistent with ΛCDM (zero curvature).

Extensions to ΛCDM?

- ΛCDM model is fully characterized by six parameters. Some CMB features at the largest CMB angular scales, however, are not well captured, and for instance "anomalies" occur, although they are often regarded as mere curiosities (stat significance 2-3σ).

- The "lack of power" is one of these anomalies (at large angular scale there is less power than expected in the CMB maps).

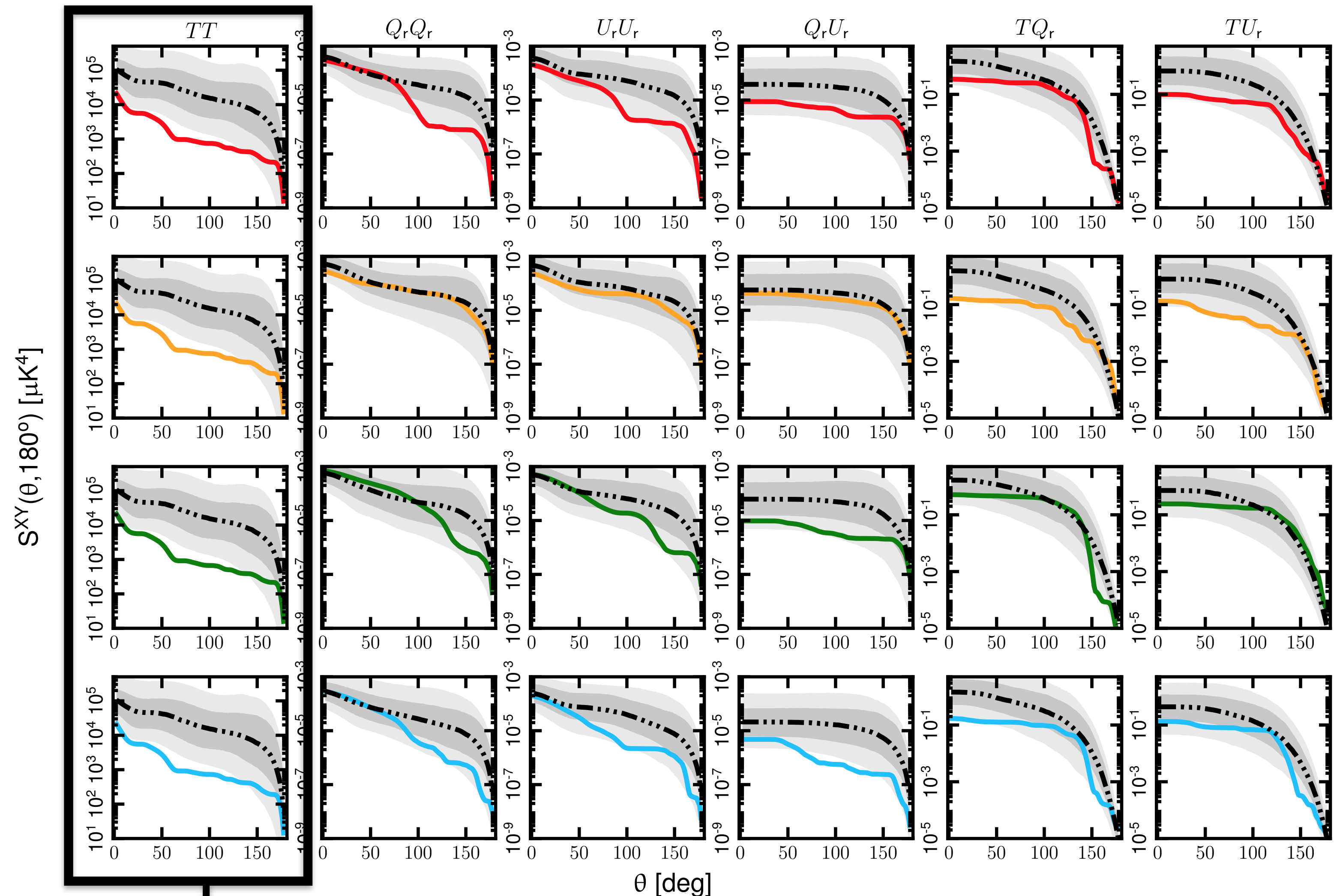


More estimates below the best-fit model than above

Extensions to ΛCDM?

- ΛCDM model is fully characterized by six parameters. Some CMB features at the largest CMB angular scales, however, are not well captured, and for instance “anomalies” occur, although they are often regarded as mere curiosities (stat significance 2-3σ).

- The “lack of power” is one of these anomalies (at large angular scale there is less power than expected in the CMB maps). This is for studied with the 2-point correlation function



Planck collaboration, ``Planck 2018 results. VII. Isotropy and Statistics of the CMB,'' Astron. Astrophys. 641 (2020), A7 doi:10.1051/0004-6361/201935201 [arXiv:1906.02552 [astro-ph.CO]].

$$S^{XY}(\theta,180^\circ) = \int_{-1}^{\cos(\theta)} \left[C_2^{XY}(\theta)\right]^2 \, d(\cos(\theta))$$

$\theta = 60^\circ$ probability to exceed ~99.9%

Extensions to ΛCDM?

- A possible fundamental origin of this effect

$$C_\ell = \frac{4\pi}{9} \int_0^\infty \frac{dk}{k} \mathscr{P}(k)\, j_\ell^2[k(\eta_0 - \eta_{LS})]$$ at large scales

standard ΛCDM

$$\mathscr{P}(k) = A\, k^{n_s - 1}$$

E.Dudas, N.Kitazawa, S.P.Patil and A.Sagnotti (2012)

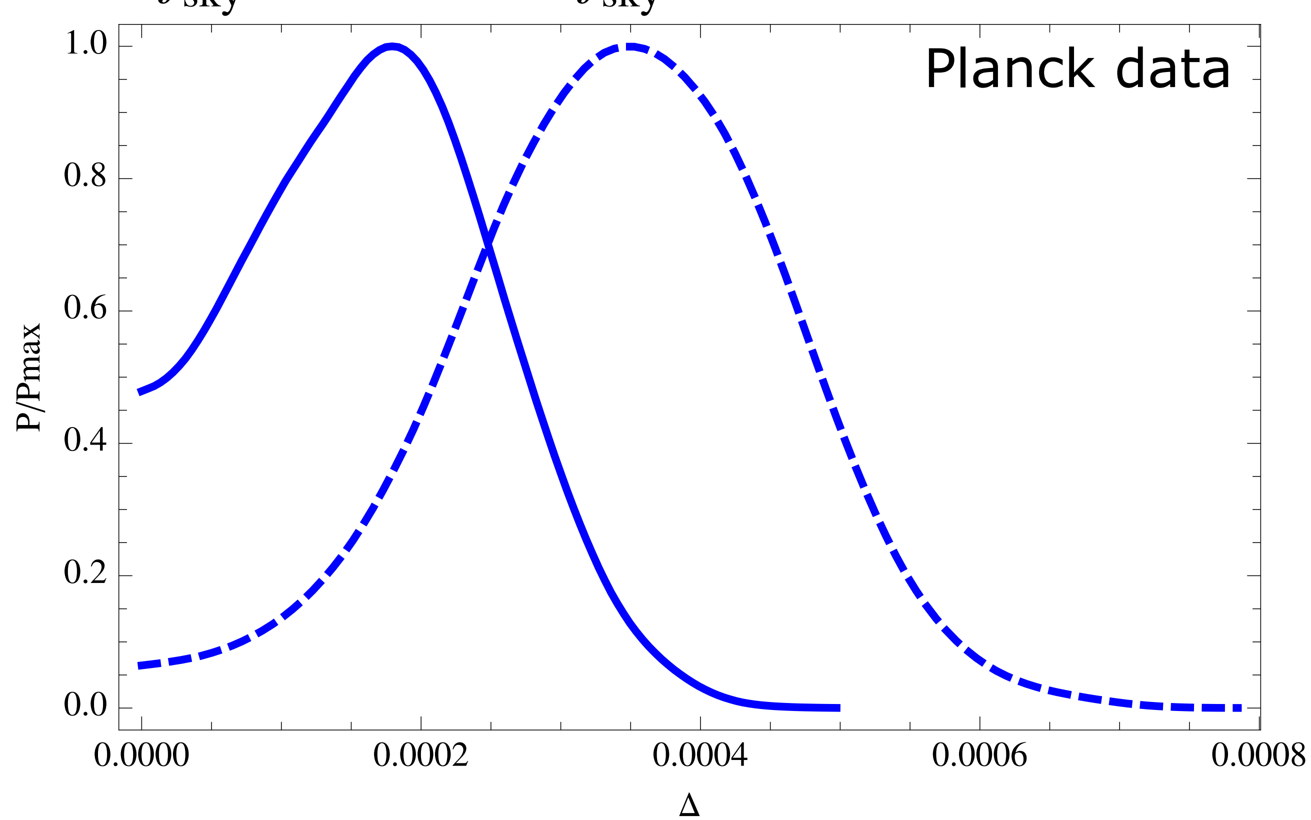
N.Kitazawa and A.Sagnotti (2014),(2015)

$$\mathscr{P}_\Delta(k) = A\, \frac{k^3}{(k^2 + \Delta^2)^{2 - n_s/2}}$$

a new parameter Δ which describes an infrared cut-off

$$\mathscr{P}_\Delta(k) \xrightarrow{\Delta \to 0} \mathscr{P}(k)$$

$f_{\rm sky} \sim 90\,\%$ $\quad$ $f_{\rm sky} \sim 40\,\%$



$$\Delta = (0.351 \pm 0.114) \times 10^{-3}\ \text{Mpc}^{-1}$$

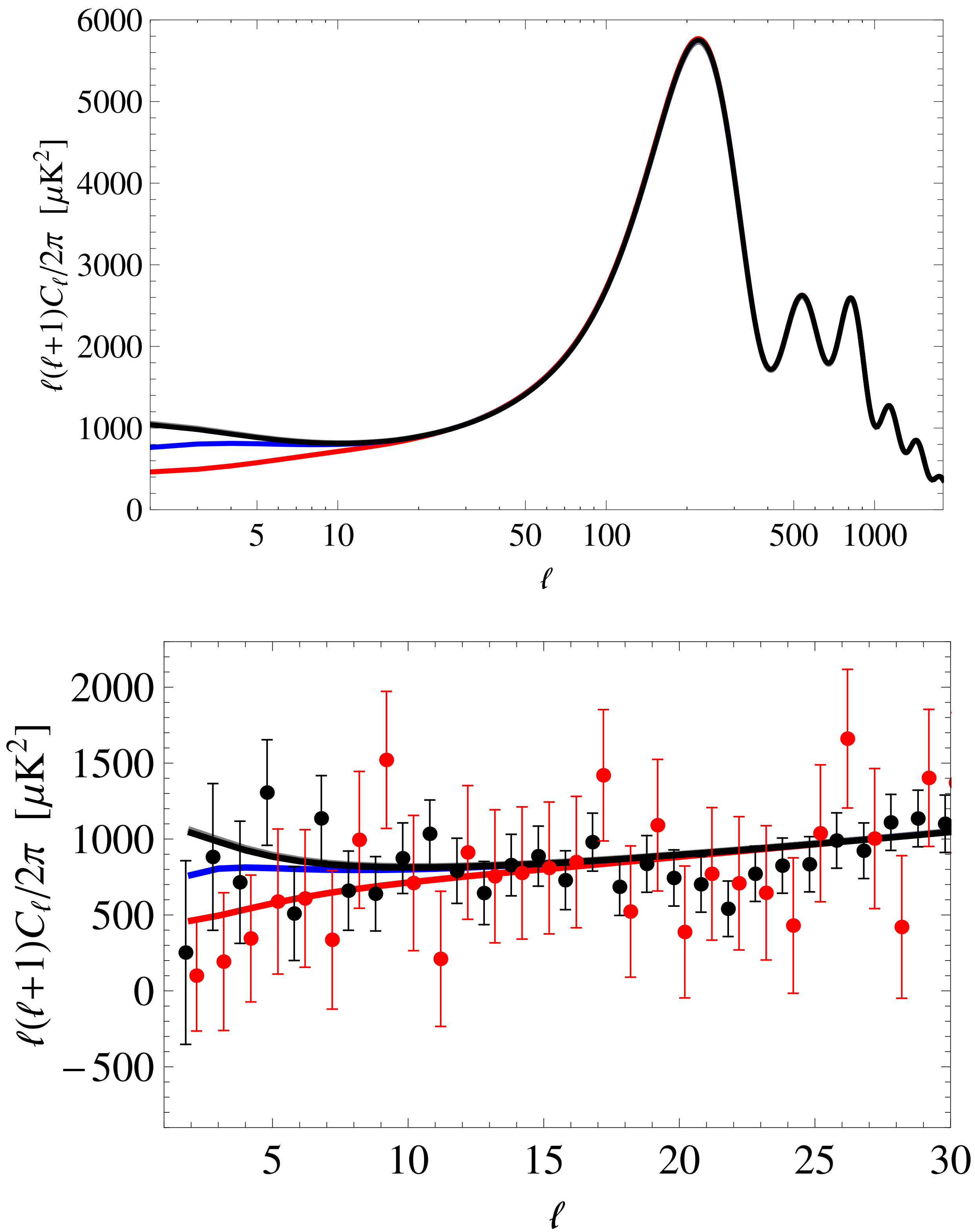
99.4% C.L. detection

A.Gruppuso and A.Sagnotti (2015)

A.Gruppuso, N.Kitazawa, N.Mandolesi, P.Natoli and A.Sagnotti (2015)

A.Gruppuso, N.Kitazawa, M.Lattanzi, N.Mandolesi, P.Natoli and A.Sagnotti (2018)

Extensions to ΛCDM?

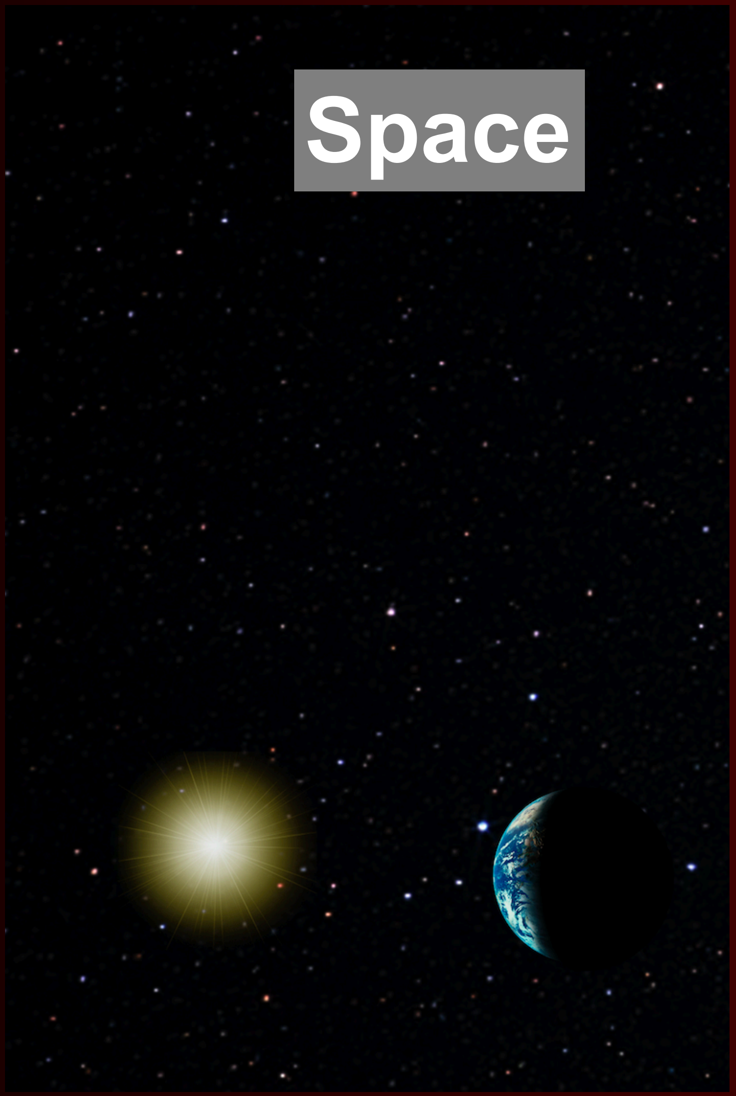


Ongoing and Future Projects

Ground

Balloon

Space



CMB Polarization Projects

Courtesy of Masashi Hazumi

Ground

POLARBEAR → Simons Array

Balloon

Space

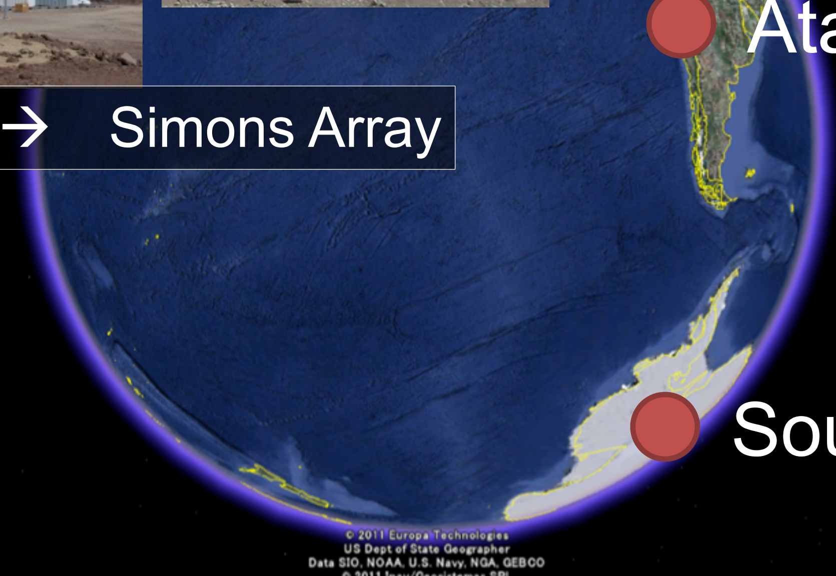
CMB Polarization Projects

Courtesy of Masashi Hazumi

Ground

ACTPol
→ Advanced ACTPol

POLARBEAR → Simons Array



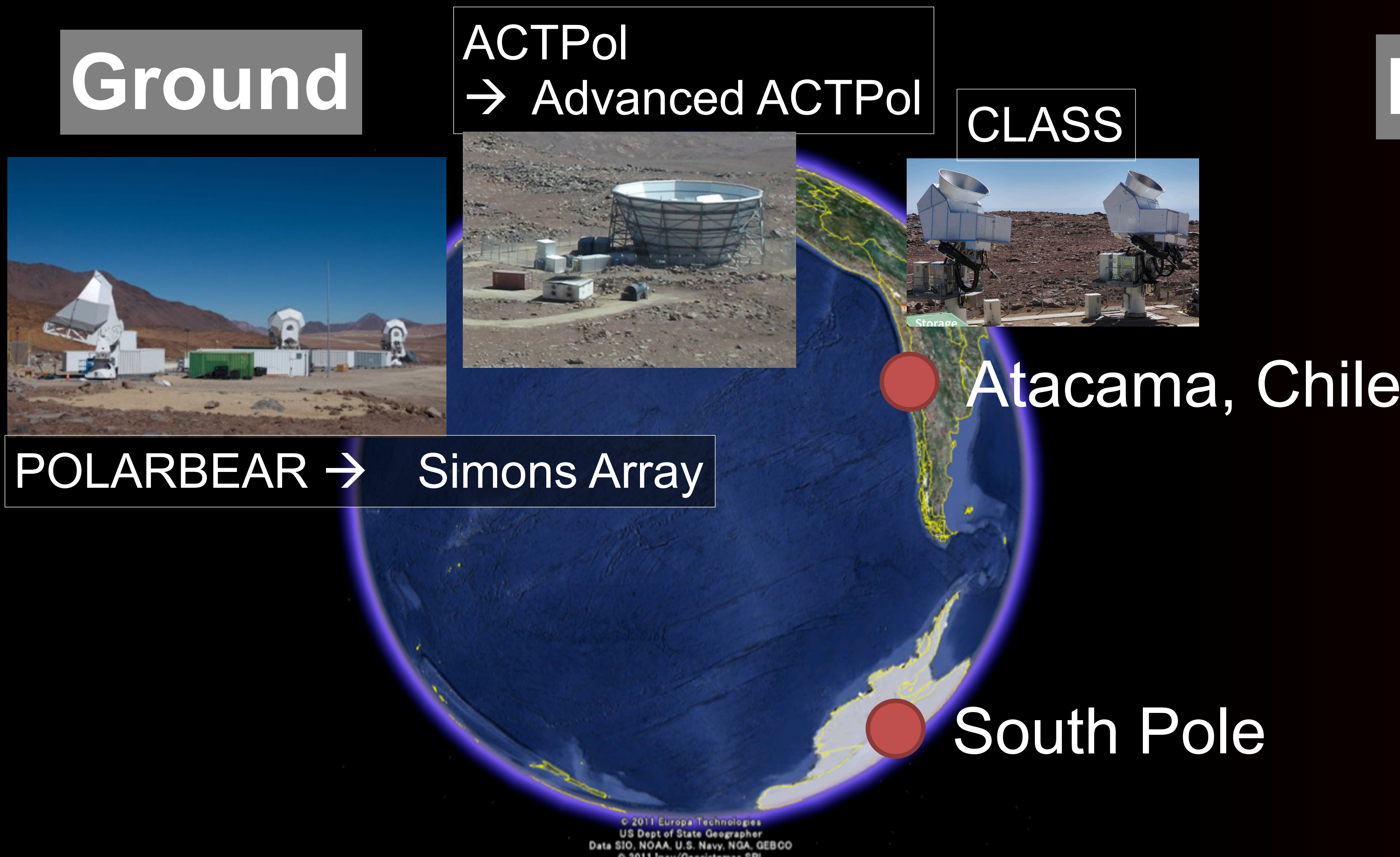
Balloon

Space

CMB Polarization Projects

Courtesy of Masashi Hazumi

Ground

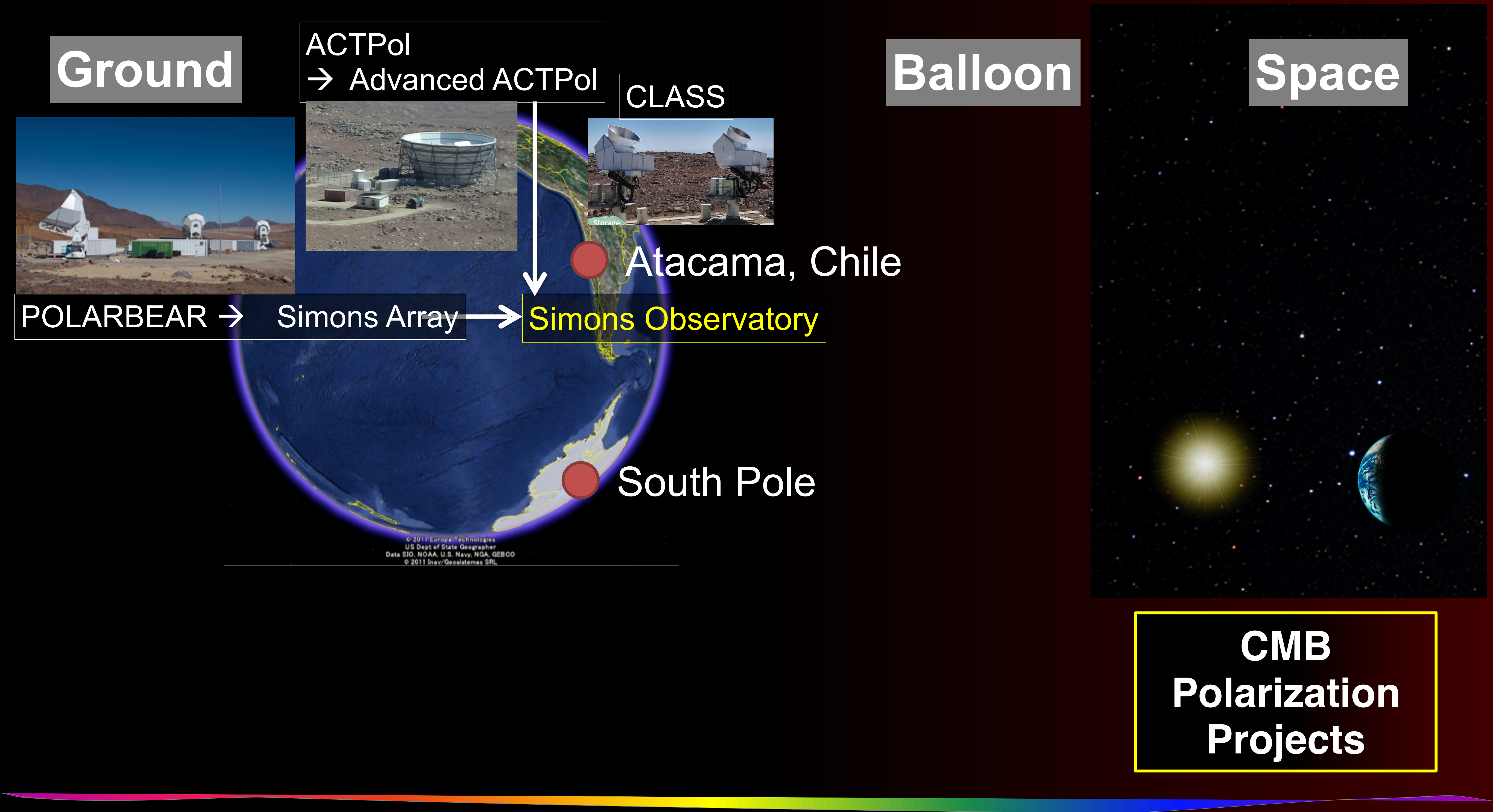


Balloon

Space

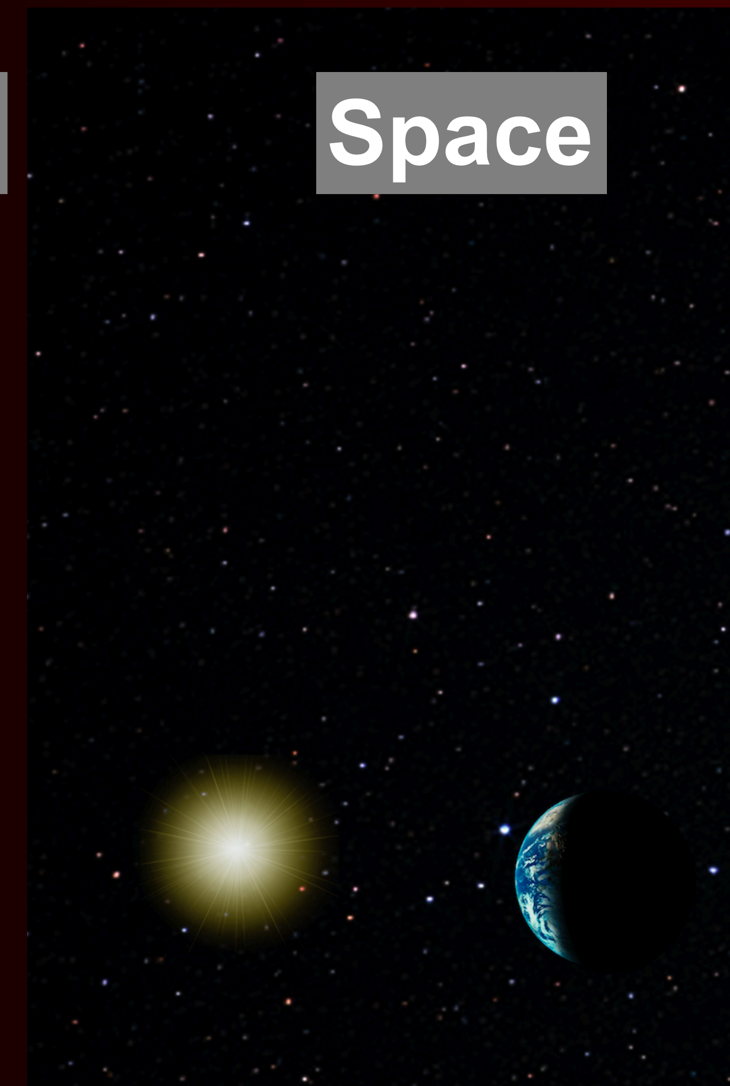
CMB Polarization Projects

Courtesy of Masashi Hazumi



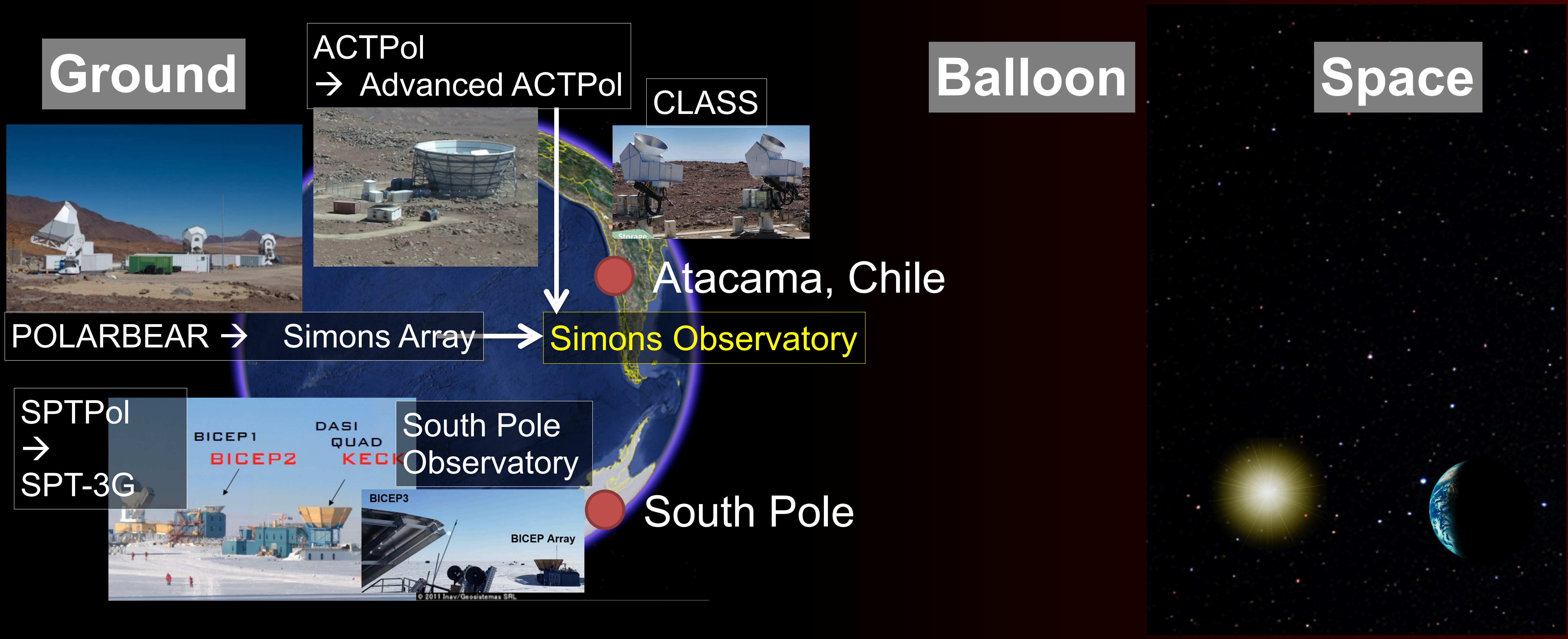
Courtesy of Masashi Hazumi

Balloon



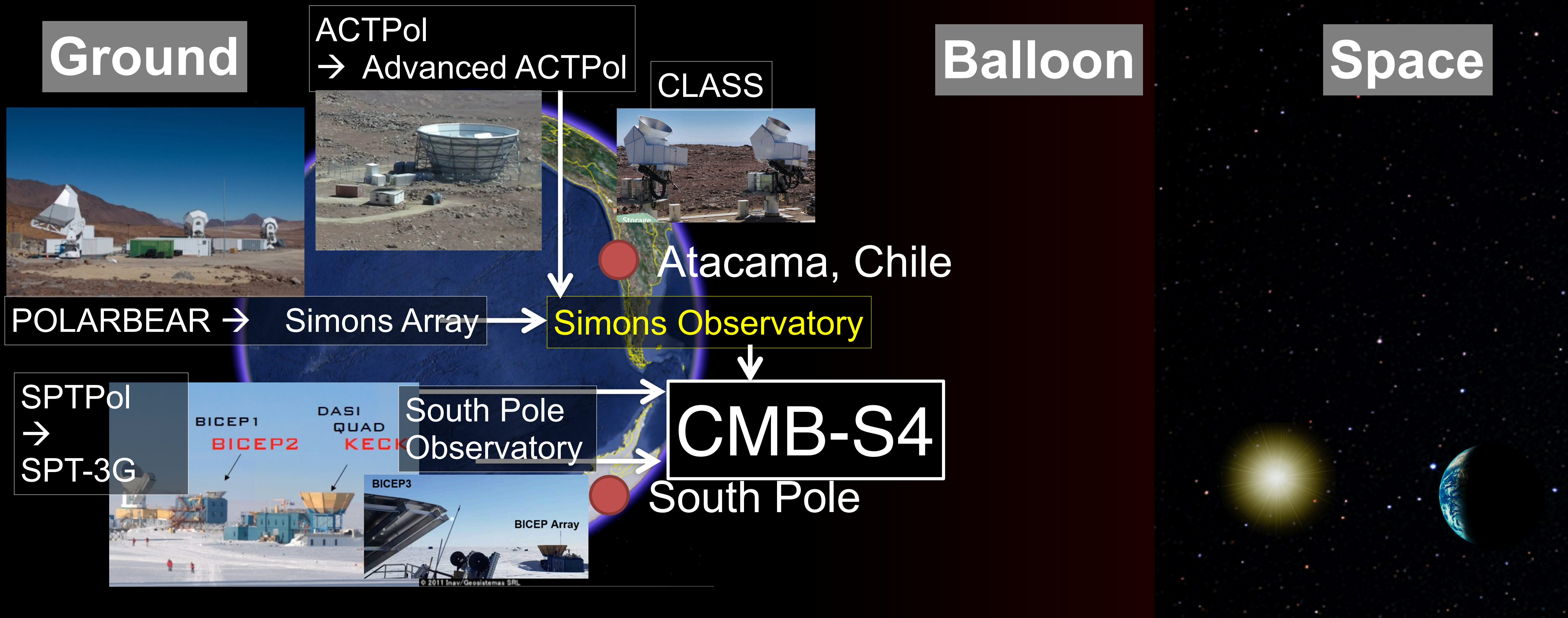
CMB Polarization Projects

Courtesy of Masashi Hazumi



CMB Polarization Projects

Courtesy of Masashi Hazumi



CMB Polarization Projects

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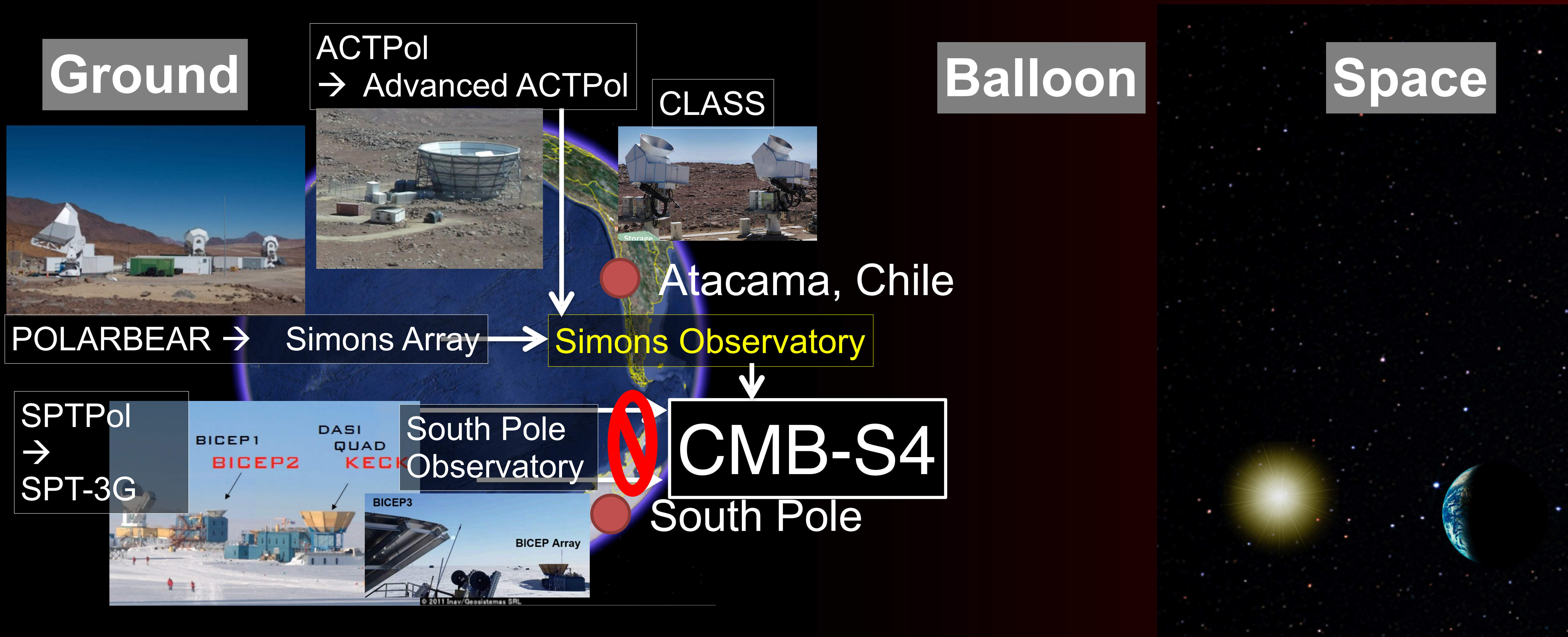
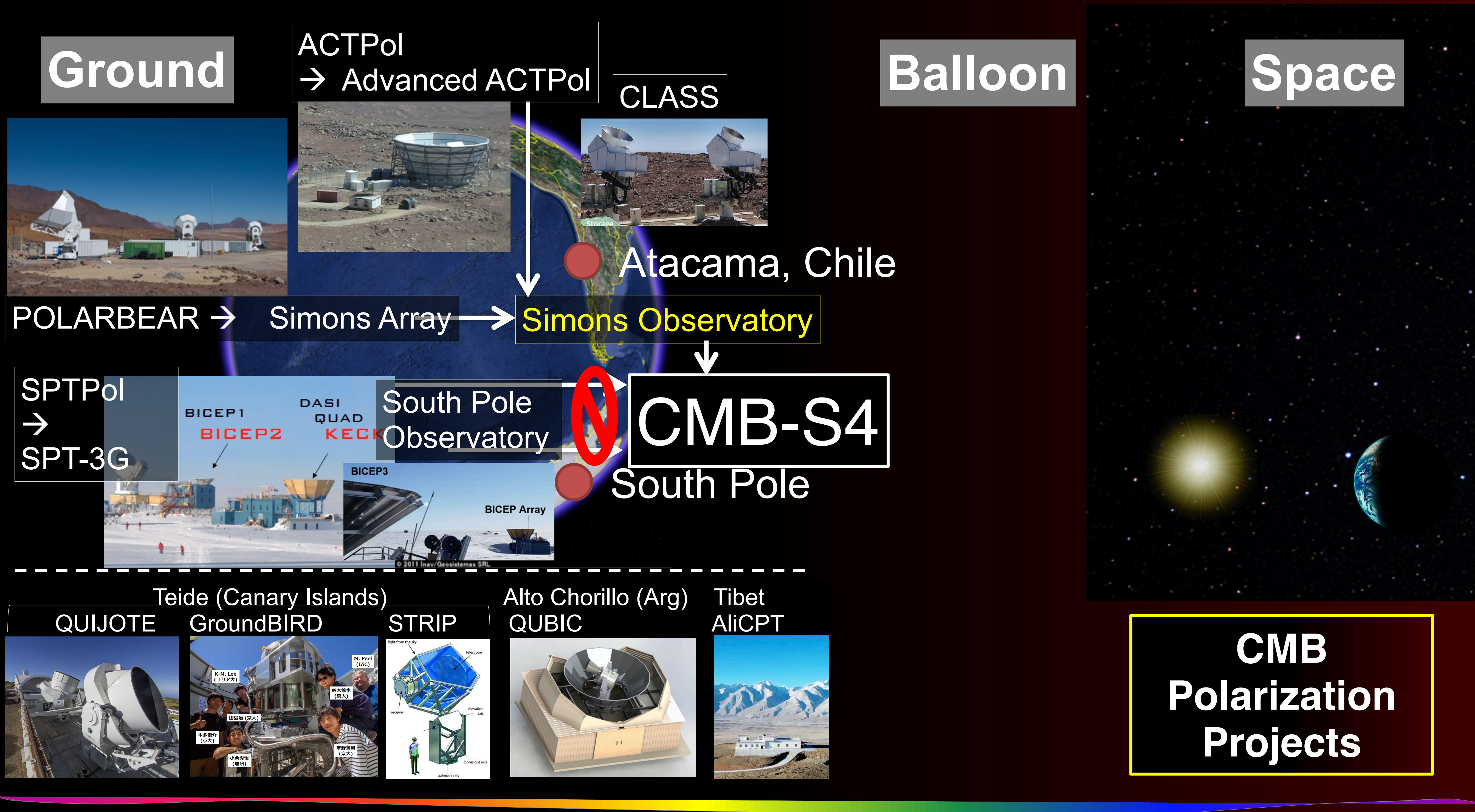
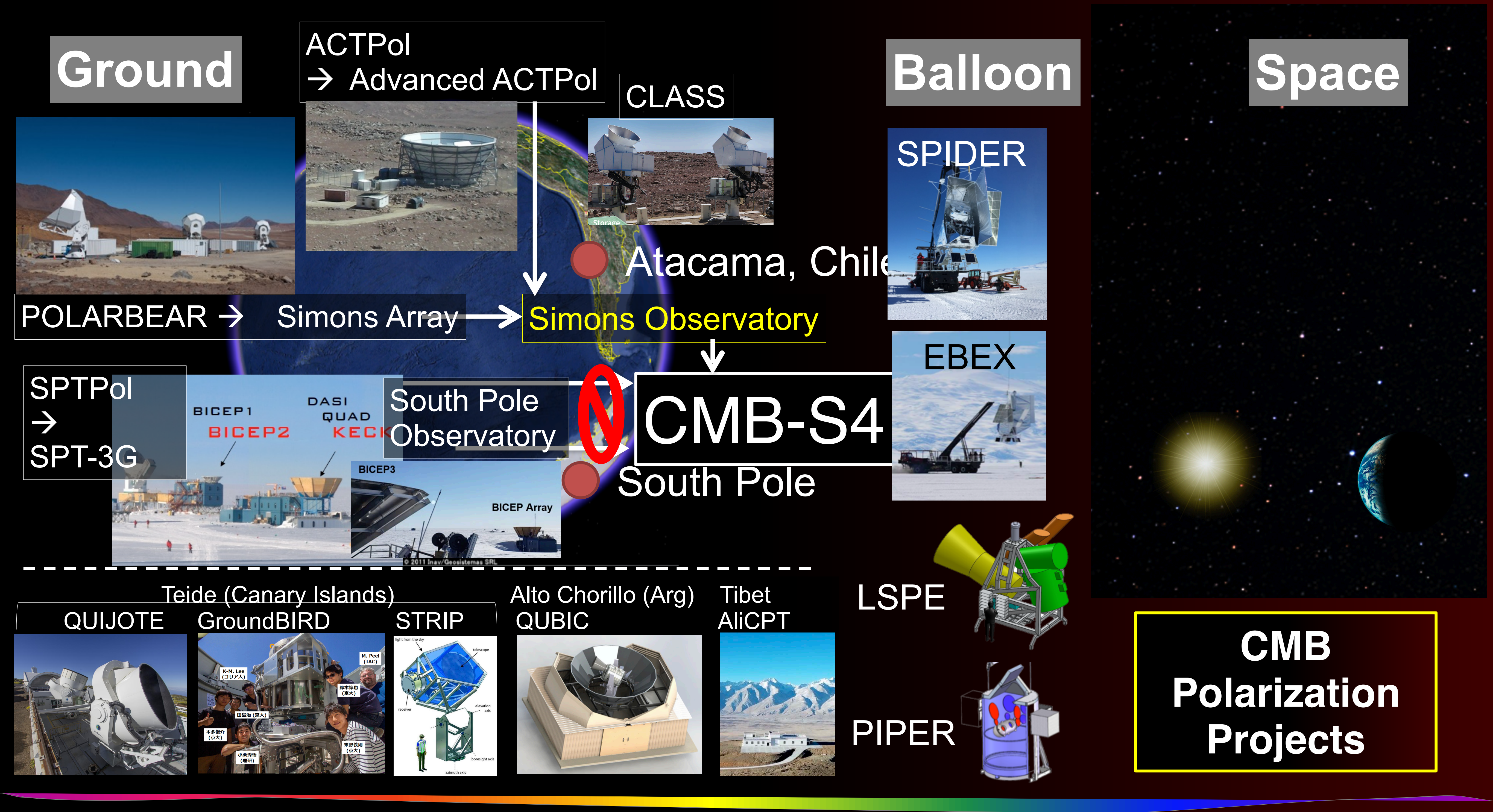


CMB Polarization Projects

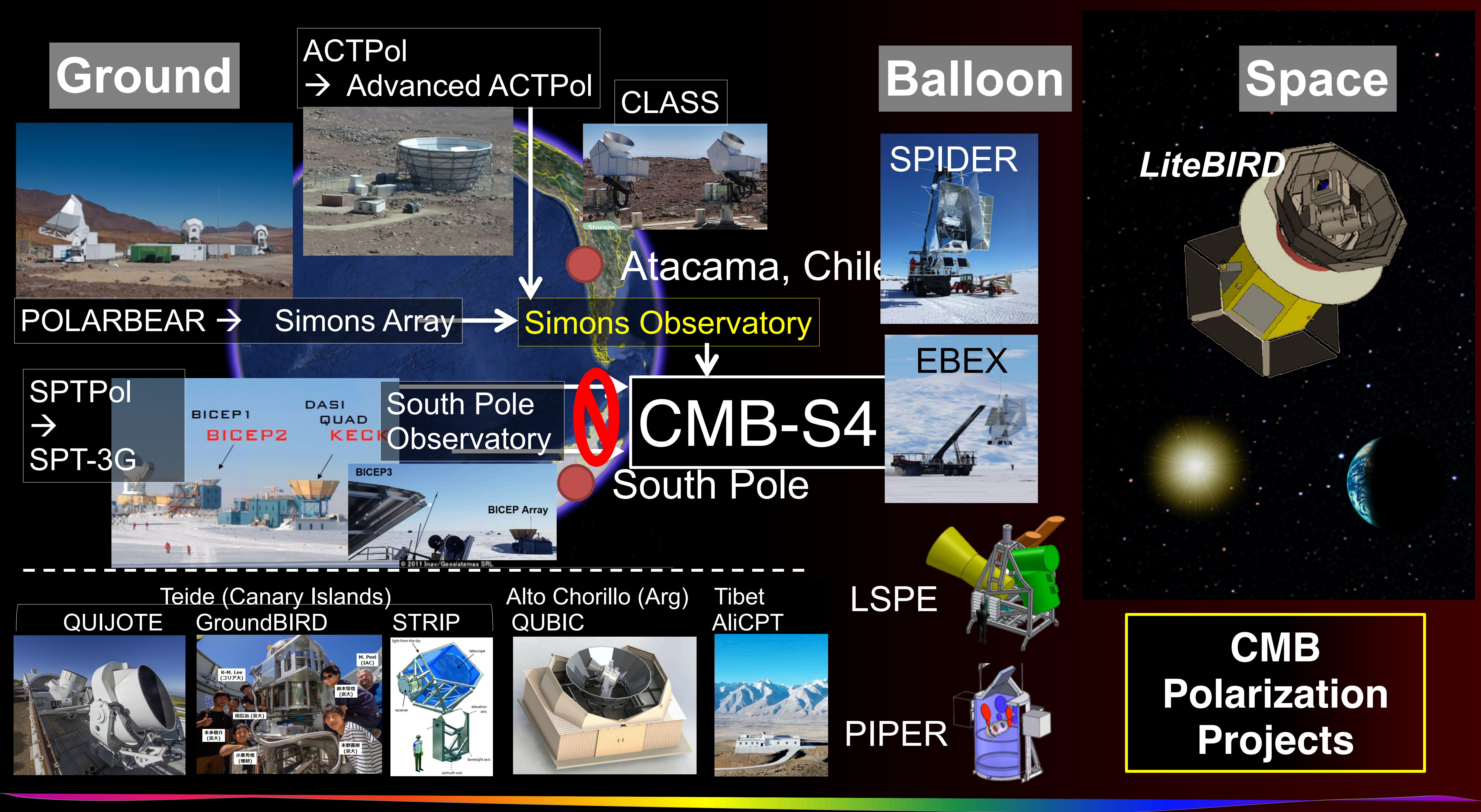
Courtesy of Masashi Hazumi



Courtesy of Masashi Hazumi



Ground
ACTPol
→ Advanced ACTPol
CLASS
Balloon
Space
SPIDER
Atacama, Chile
POLARBEAR → Simons Array
Simons Observatory
SPTPol
→
SPT-3G
BICEP1
BICEP2
DASI
QUAD
KECK
South Pole
Observatory
CMB-S4
EBEX
BICEP3
BICEP Array
South Pole
Teide (Canary Islands)
QUIJOTE
GroundBIRD
STRIP
Alto Chorillo (Arg)
QUBIC
Tibet
AliCPT
LSPE
PIPER
CMB
Polarization
Projects
Courtesy of Masashi Hazumi


Ground
ACTPol
→ Advanced ACTPol
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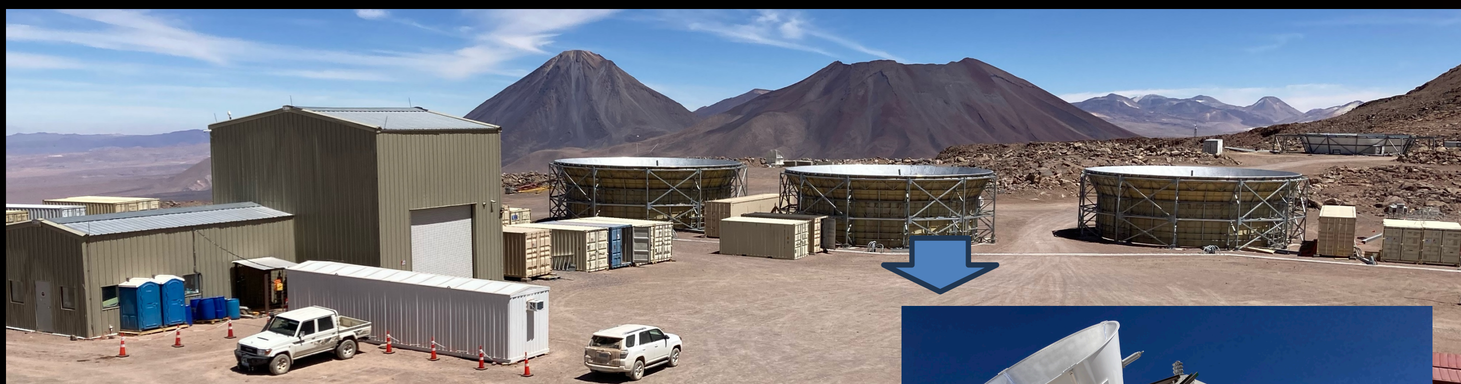
CMB
Polarization
Projects
Courtesy of Masashi Hazumi

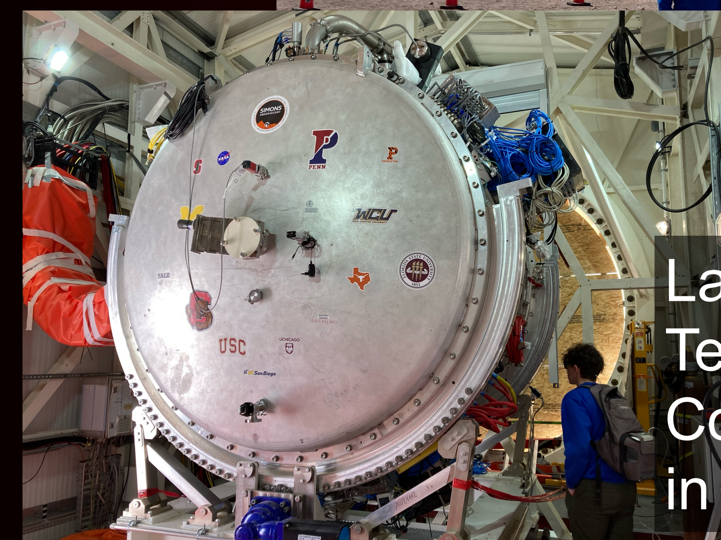
Simons Observatory (SO)



Small Aperture Telescopes (SATs) started taking data in 2024.

Target sensitivity: $\sigma(r) = 0.003$

Photos in Dec 2024



Large Aperture Telescope (LAT) Commissioning in 2025

Rich science

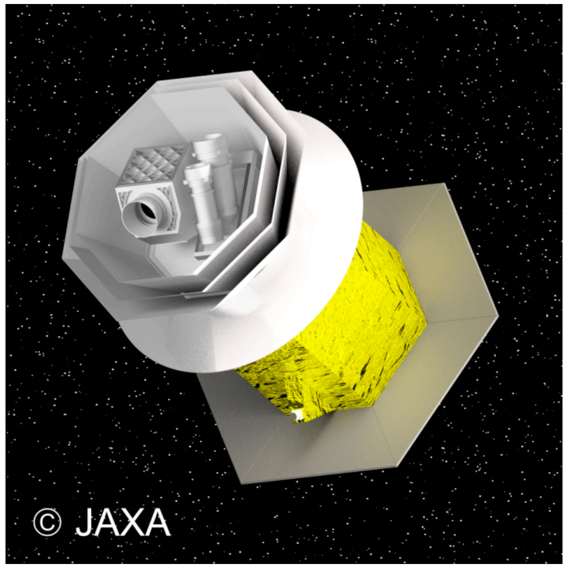
Current limit is $r < 0.032$ (95% C.L.) (M. Tristram et al. 2021, combining Bicep2/Keck 2018 and Planck PR4 data set)

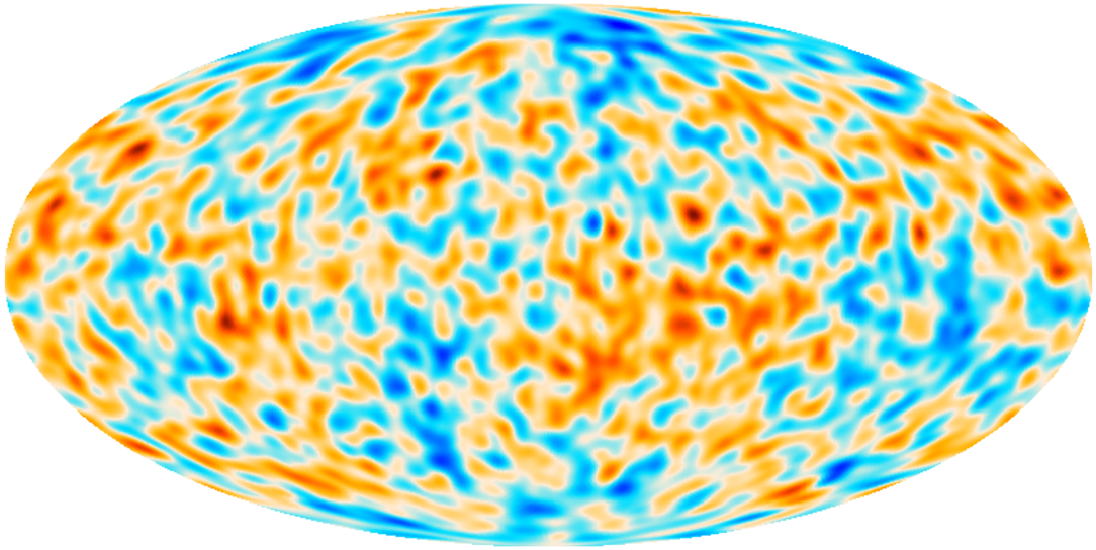
Courtesy of Masashi Hazumi

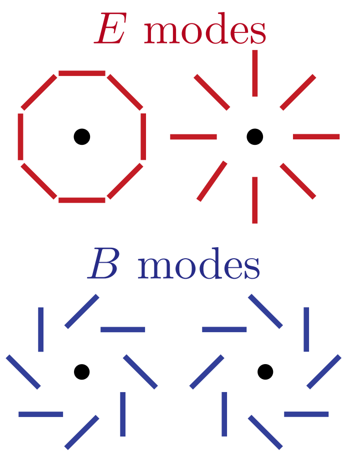
LiteBIRD overview

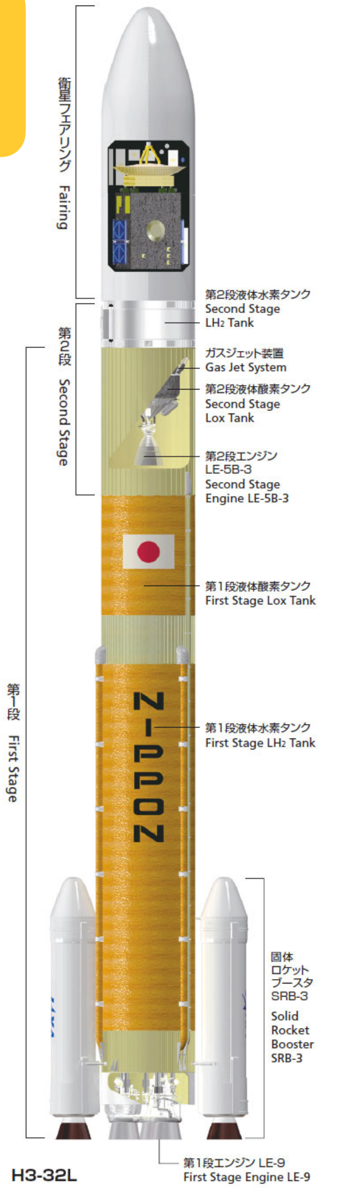
- Lite (Light) spacecraft for the study of *B*-mode polarization and Inflation from cosmic background Radiation Detection
- JAXA's L-class mission was selected in May 2019 to be launched by JAXA's H3 rocket.
- **All-sky 3-year survey**, from Sun-Earth Lagrangian point L2
- Large frequency coverage (**40–402 GHz**, 15 bands) at **70–18 arcmin** angular resolution for precision measurements of the **CMB *B*-modes**
- Final combined sensitivity: **2.2 μK·arcmin**

📖 LiteBIRD collaboration PTEP 2023







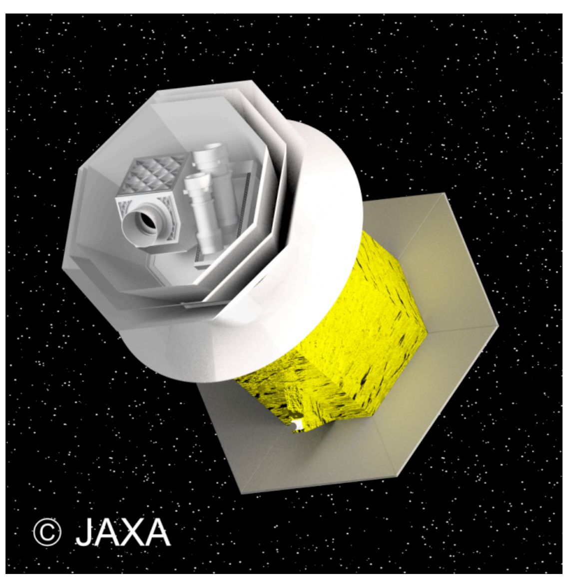


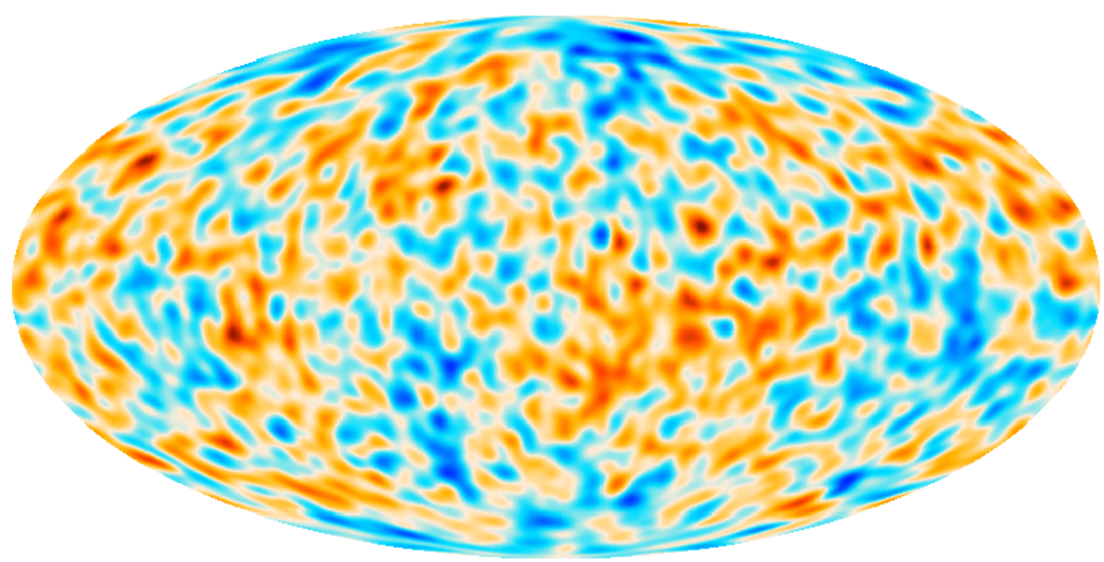
LiteBIRD overview

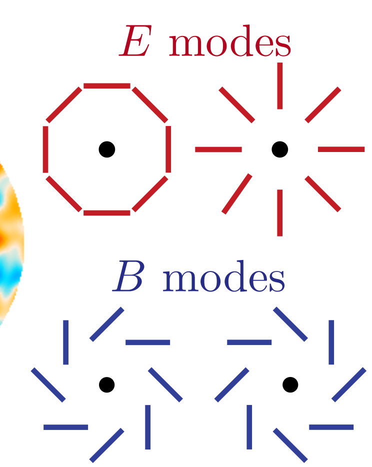
LiteBIRD reformation phase

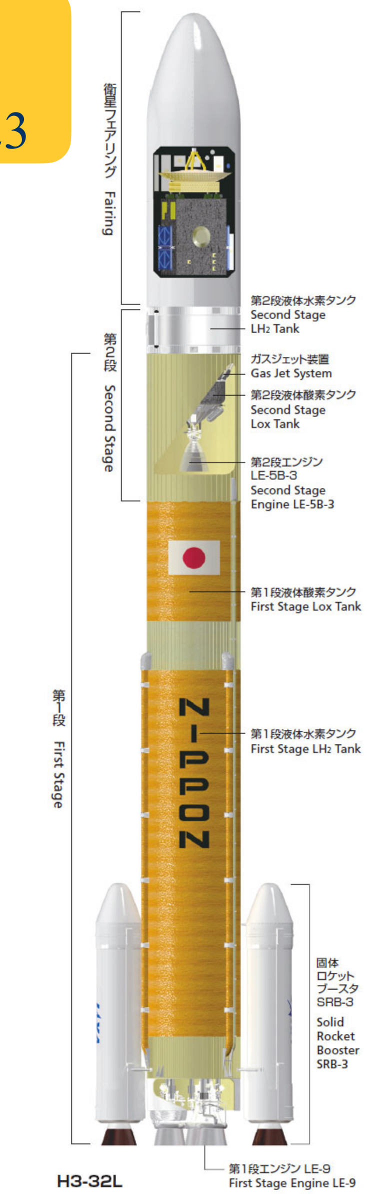
- After the ISAS/JAXA mission definition review, LiteBIRD is under rescope studies to consolidate the mission's feasibility with the same scientific objectives.
- The LiteBIRD collaboration will spend approximately one year (~ late 2025) on the studies of the reformation plan.

📖 LiteBIRD collaboration PTEP 2023









LiteBIRD main scientific objecti

- Definitive search for the ***B*-mode signal** from **cosmic inflation** in the CMB polarization
    - Making a discovery or ruling out well-motivated inflationary models
    - Insight into the quantum nature of gravity
- The inflationary (i.e. primordial) *B*-mode power is proportional to the **tensor-to-scalar ratio, *r***
- Current best constraint: $r < 0.032$ (95% C.L.)

  (📖 Tristram et al. 2022, combining BK18 and Planck PR4)
- LiteBIRD will improve current sensitivity on r by a factor ~50
- L1-requirements (no external data):
    - For $r = 0$, **total uncertainty of $\delta r < 0.001$**
    - For $r = 0.01$, 5-σ detection of the reionization ($2 < \ell < 10$) and recombination ($11 < \ell < 200$) peaks independently
- L2-requirements:
    - $\sigma_{stat} < 6\times10^{-4}$ and $\sigma_{sys} < 6\times10^{-4}$
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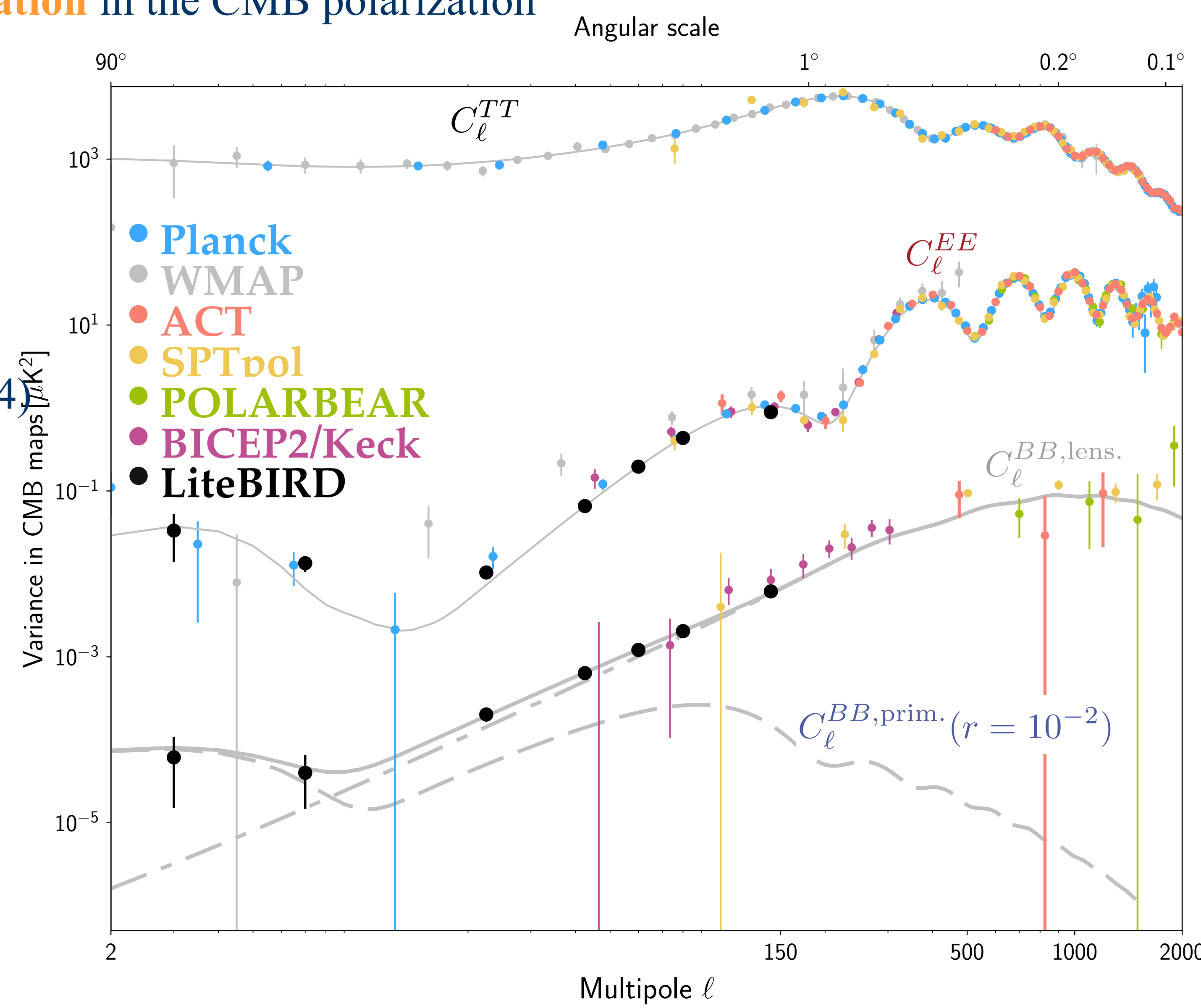

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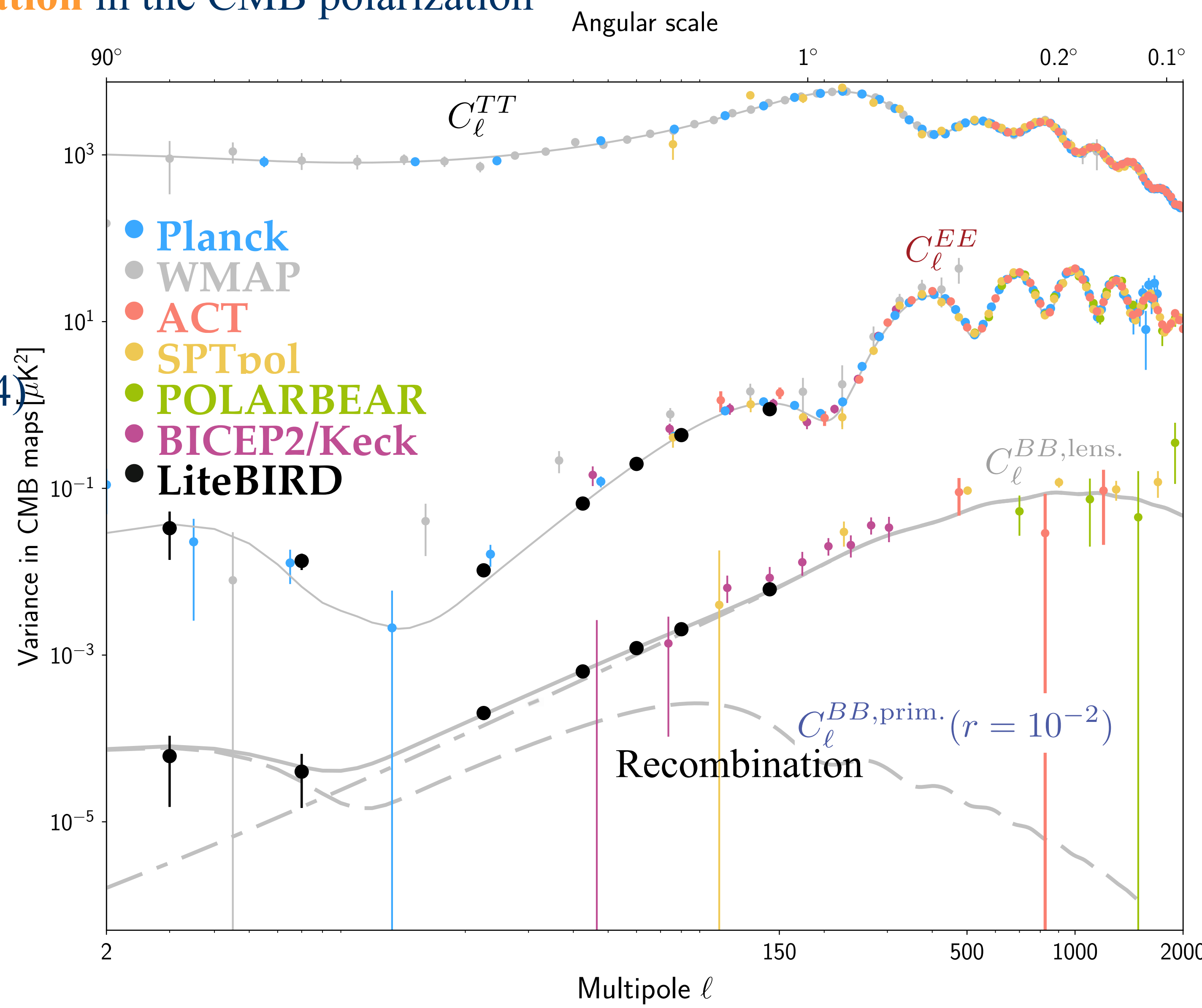

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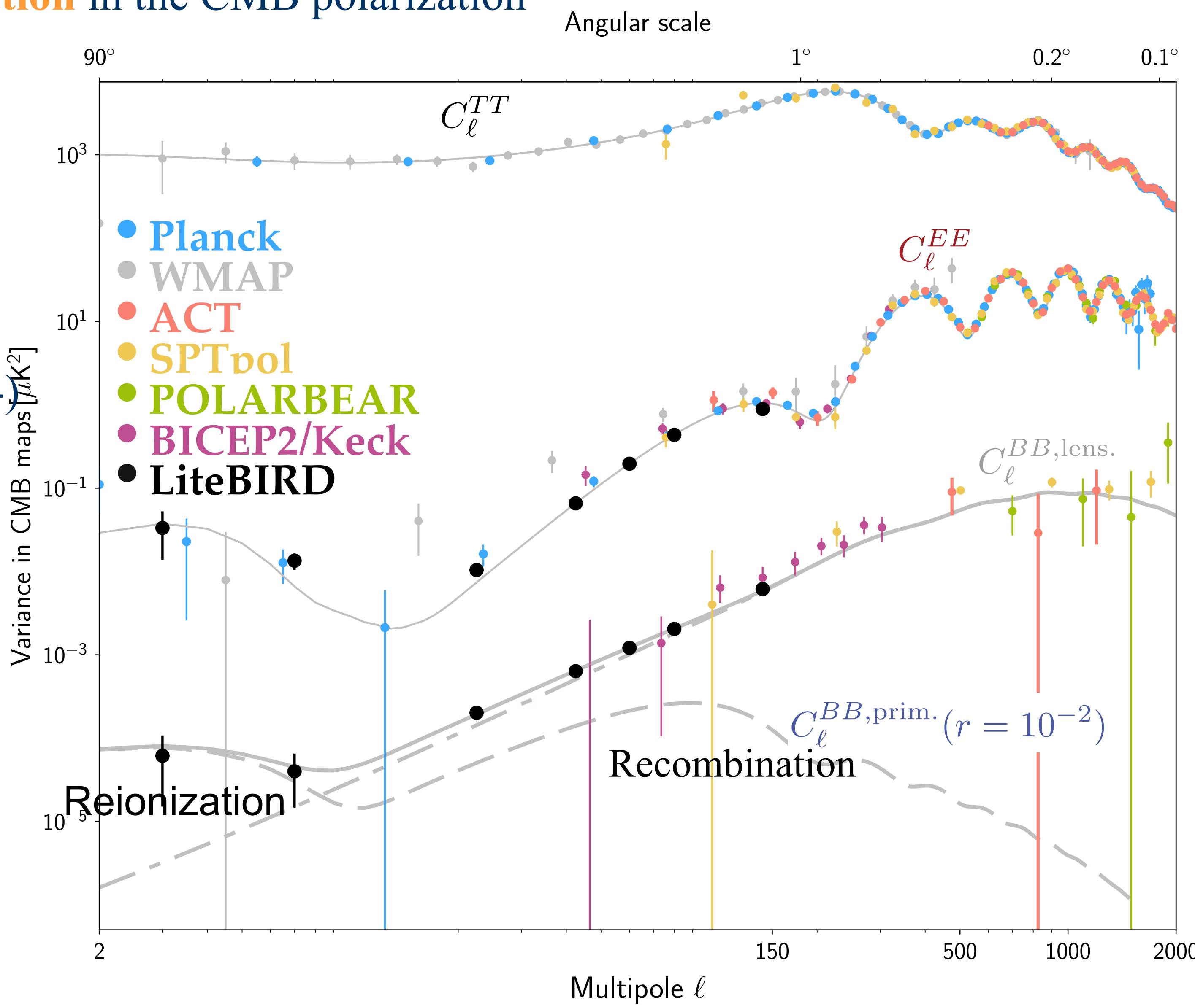

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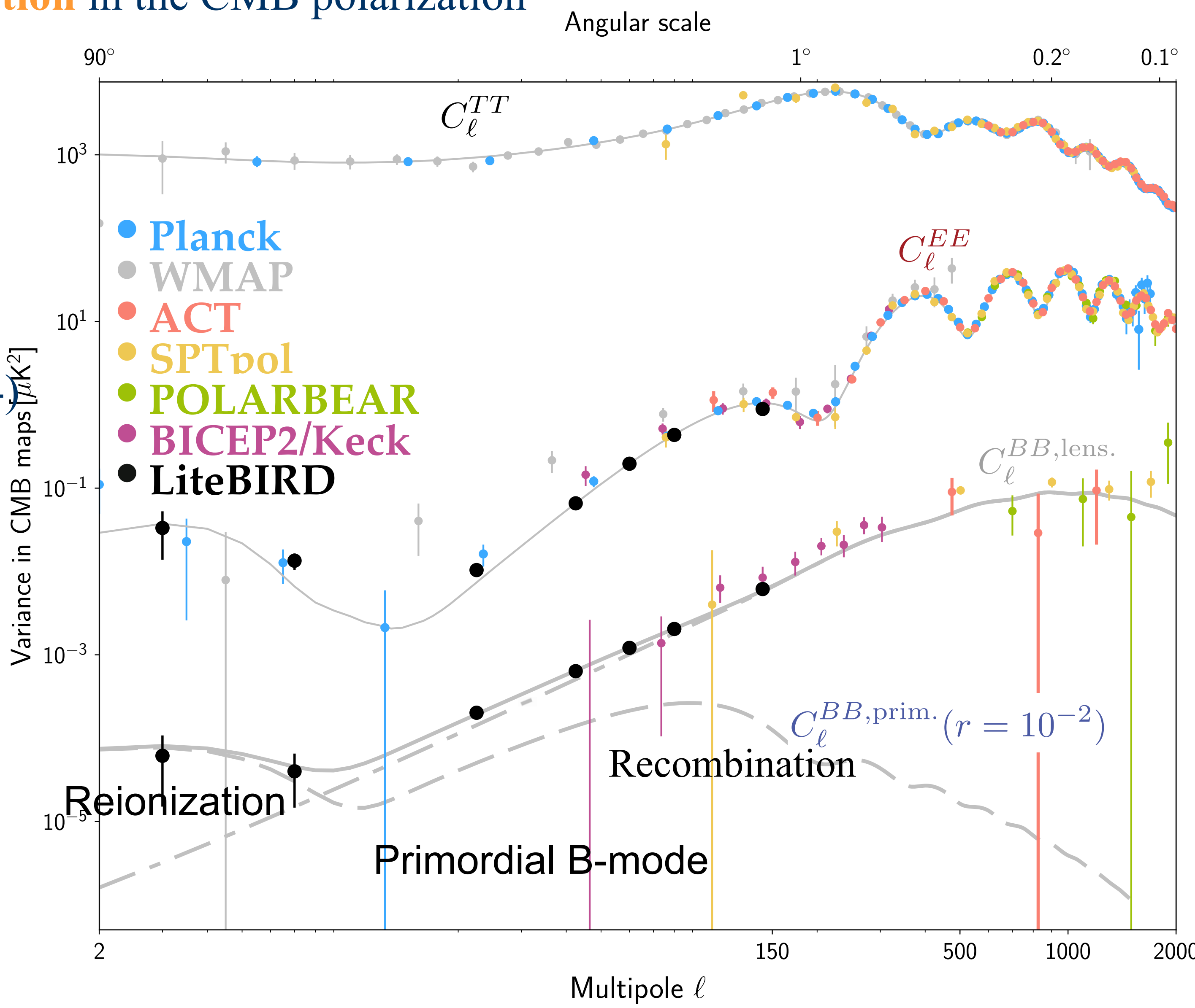

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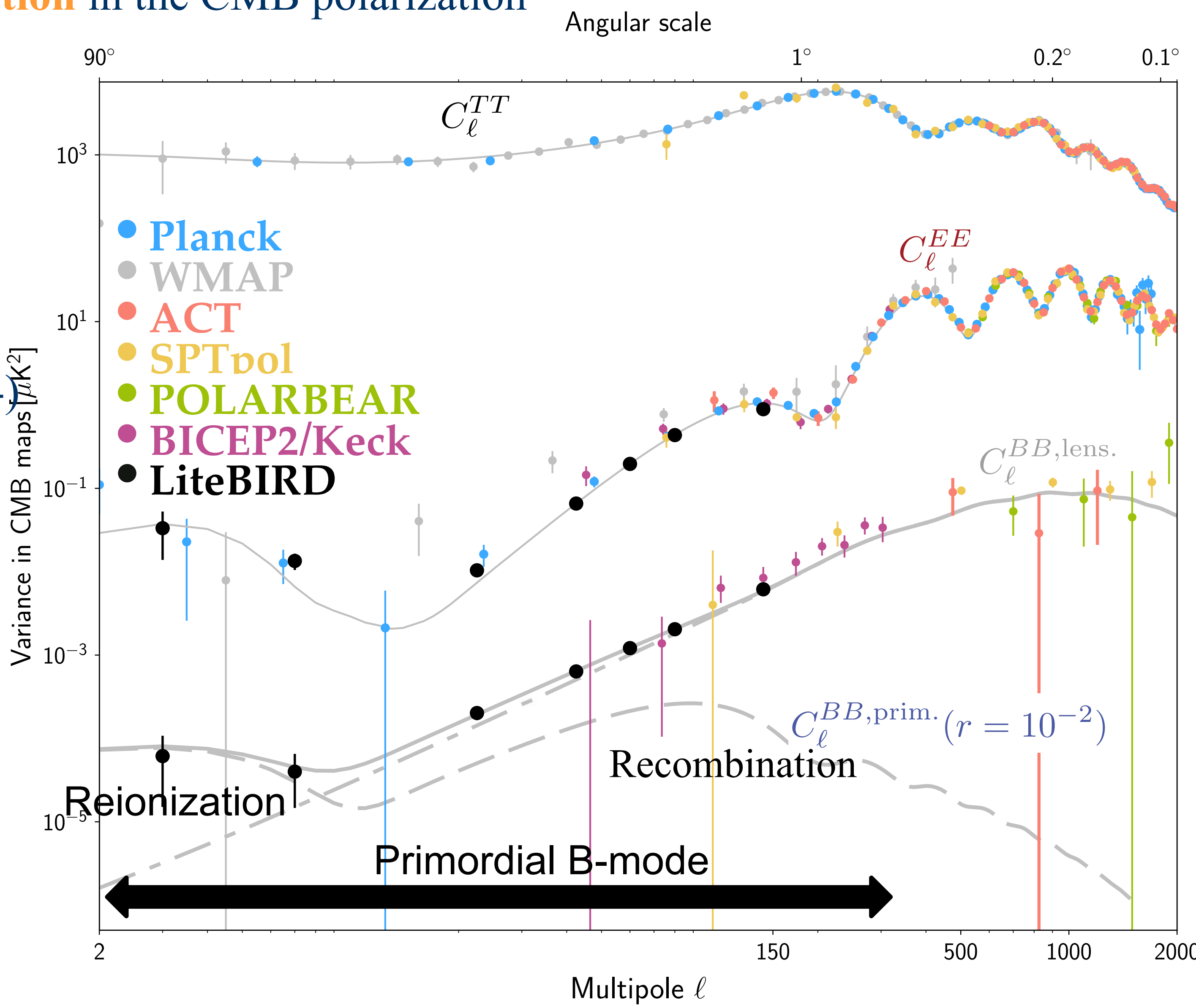

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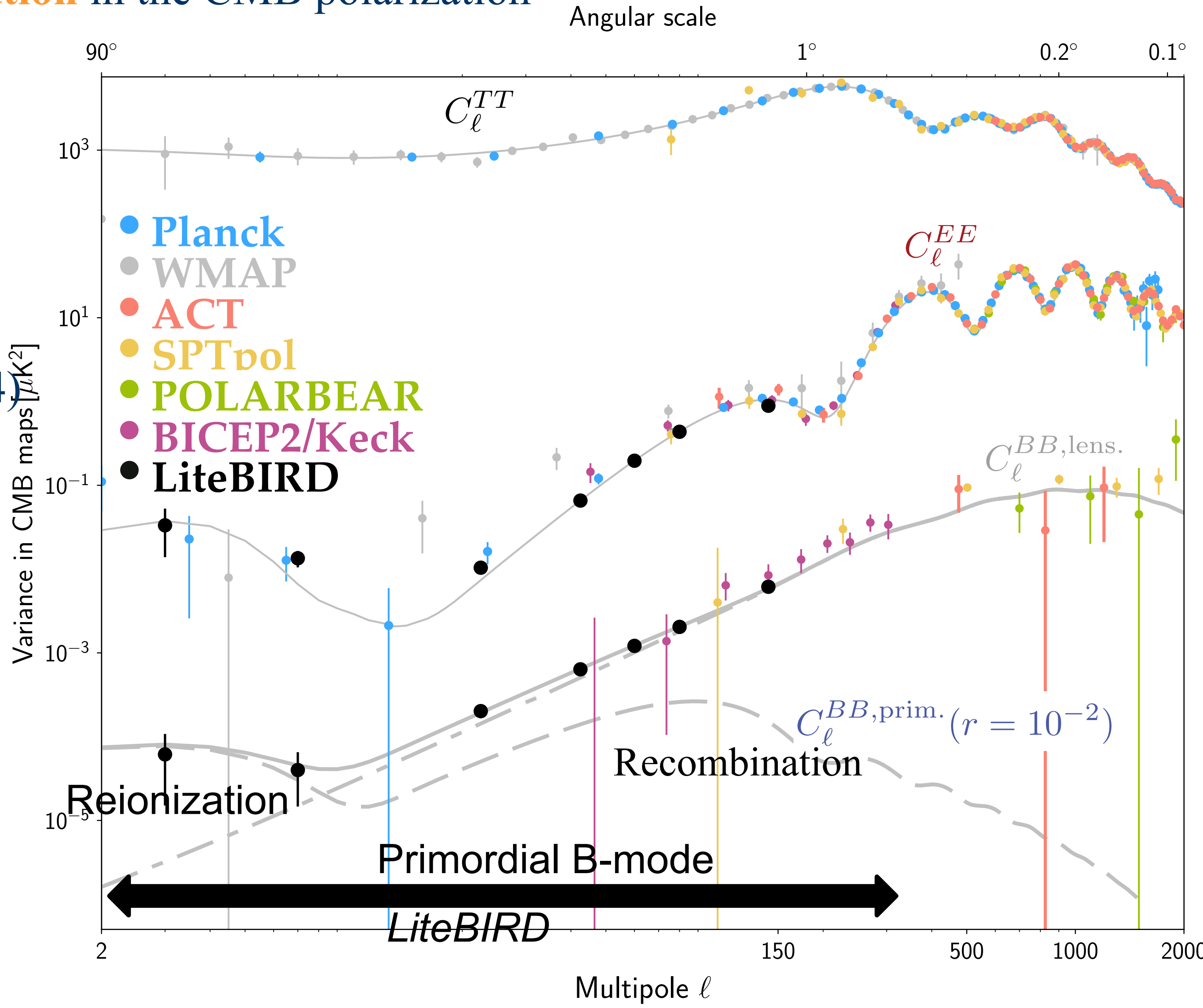

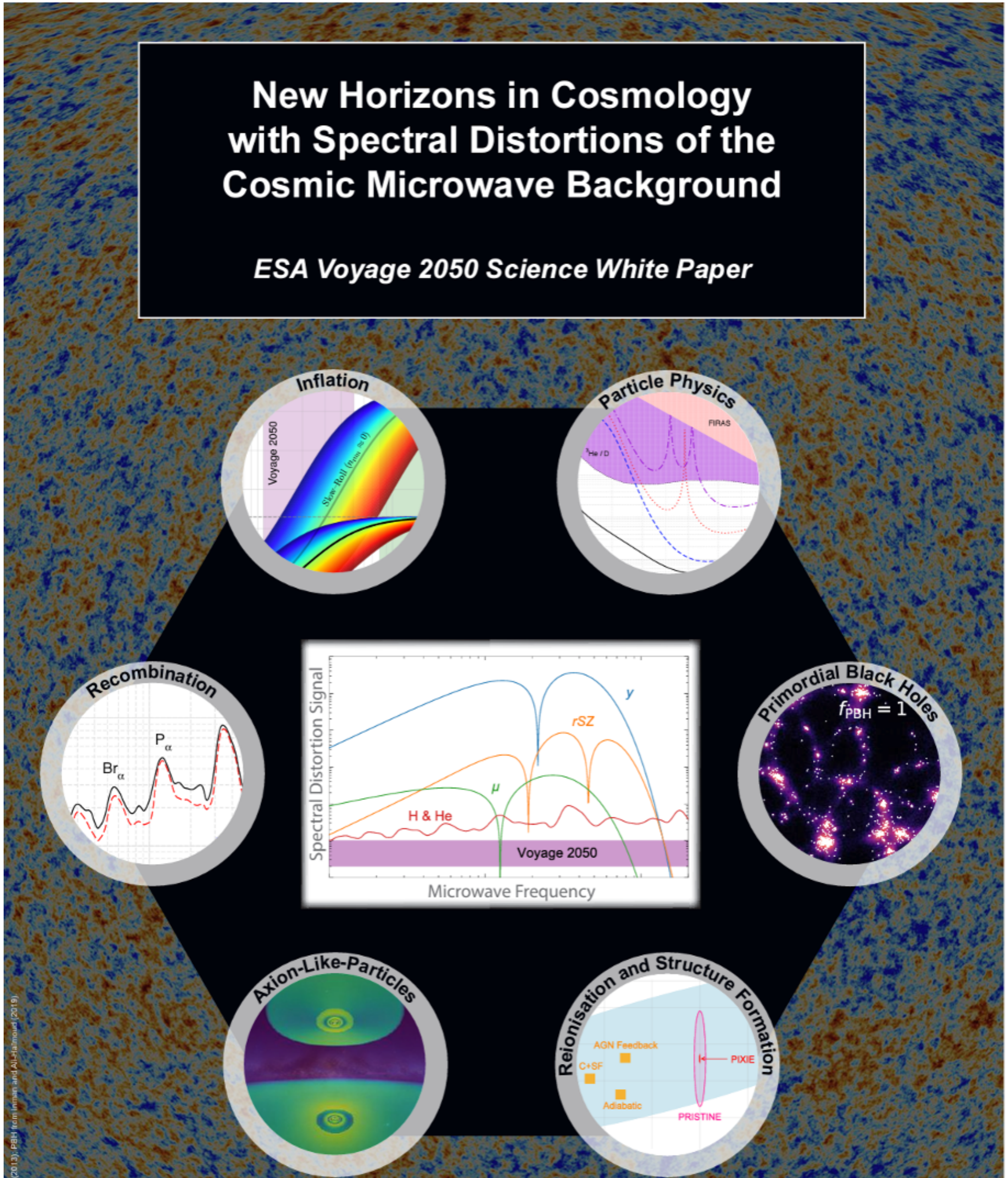
New Horizons in Cosmology
with Spectral Distortions of the
Cosmic Microwave Background
ESA Voyage 2050 Science White Paper
Inflation
Voyage 2050
Slow-Roll
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Br$_\alpha$
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y
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$f_{PBH} = 1$
Axion-Like-Particles
Reionisation and Structure Formation
AGN Feedback
C+SF
Adiabatic
PIXIE
PRISTINE

Conclusions

- We have measured the temperature anisotropies of the CMB up to CV thanks to Planck et al.
- Solid preference for ΛCDM, with some intriguing anomalies.
- The present and even more so the future is polarisation
- Upcoming CMB experiments have B-modes as primary goal.
  - This is a direct connection to Quantum Gravity (GW from vacuum)
- CMB polarisation is challenging: large scales are fundamental for primordial modes
- So far, evidence for new physics is scant. But we try hard.
- The long term future is spectral distortion