SPT, SPO & S4

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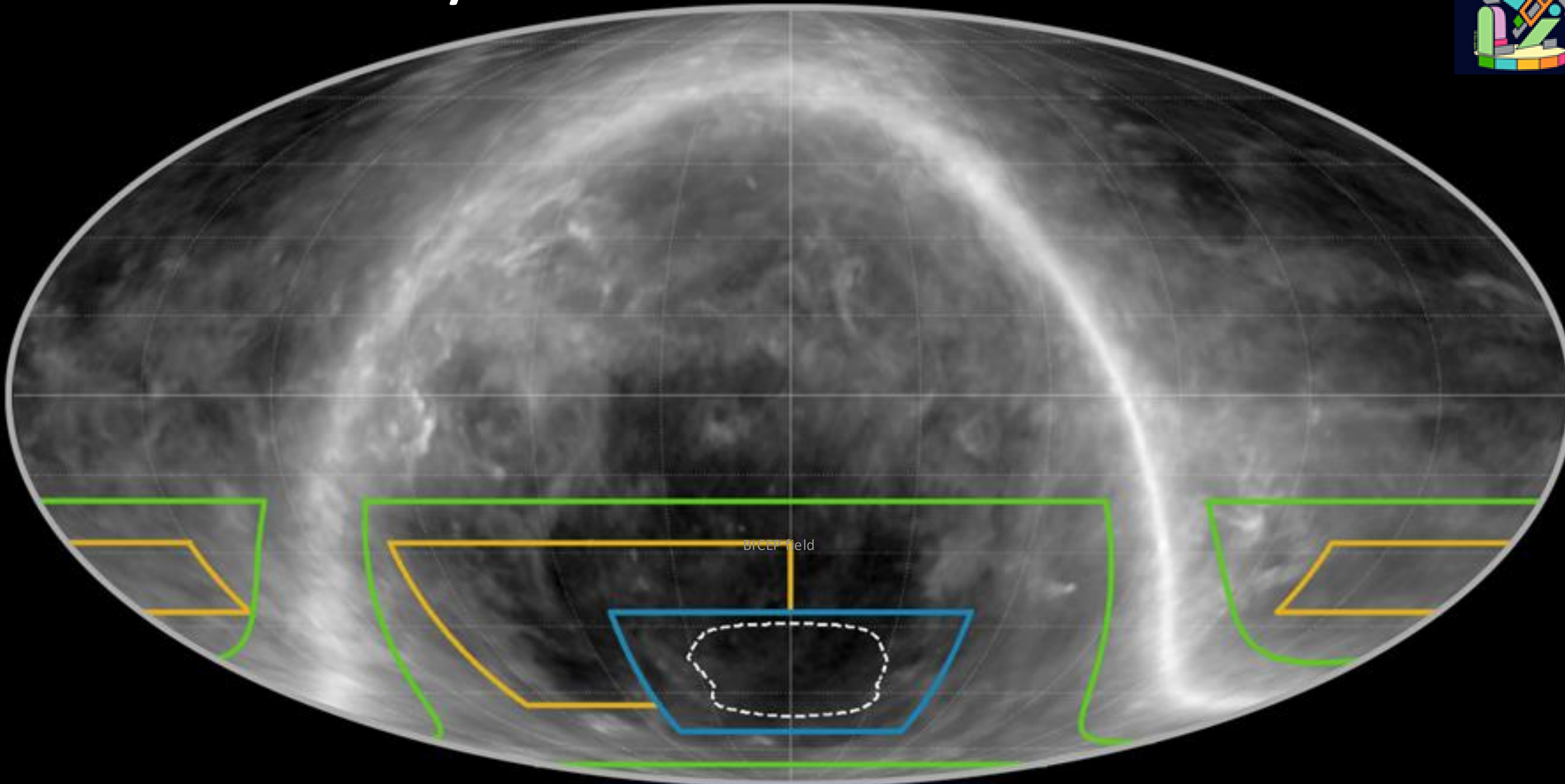
South Pole Telescope - SPT

- **10 m** primary mirror telescope
- Location: Amundsen-Scott station, South Pole
- Frequency bands: **95, 150, 220 GHz**
- FWHM : **1.70, 1.40, 1.20 arcmin** @ nu above
- SPT-3G = Third survey camera installed on SPT, after SPT-SZ and SPT-pol
    - deployed in early **2017**
    - field of view **2.8 deg2**
    - diameter of the focal plane **0.43 m** (**3.5** times larger area than before)
    - ~**16 000** transition-edge sensor (**TES**) bolometers operating at **300 mK**.
    - Sobrin+2022 ([arXiv:2106.11202](https://arxiv.org/abs/2106.11202), design and performance)
    - 1500 + 8600 sq. deg

Photo Aman Chokshi, May 2022

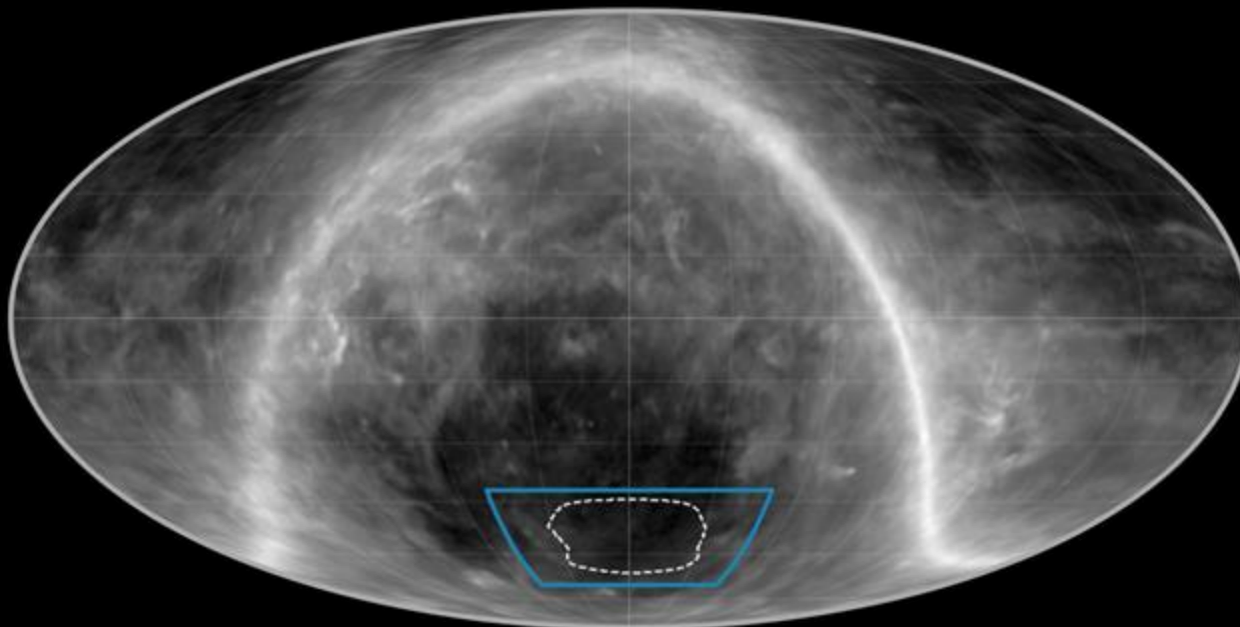

The SPT Collaboration
~150 collaborators from 33 institutions
NSF
erc
European Research Council
U.S. DEPARTMENT of ENERGY

SPT-3G Surveys



Survey	Area [deg^2]	Years observed	Noise level (T) [μK$-$arcmin]			
			90 GHz	150 GHz	220 GHz	Coadd
SPT-3G Main	1500	2019-2023, 2025-2026	2.5	2.1	7.6	1.6
SPT-3G Summer	2600	2019-2023	8.5	9.0	31	6.1
SPT-3G Wide	6000	2019-2024	14	12	42	8.8

Recent and Upcoming 2019-2020 SPT-3G Results



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*** CMB power spectra and lensing reconstruction results from 2 years (2019-2020) of the SPT-3G 1500d Main Survey (so noise levels ~2.5x higher than in this table).**

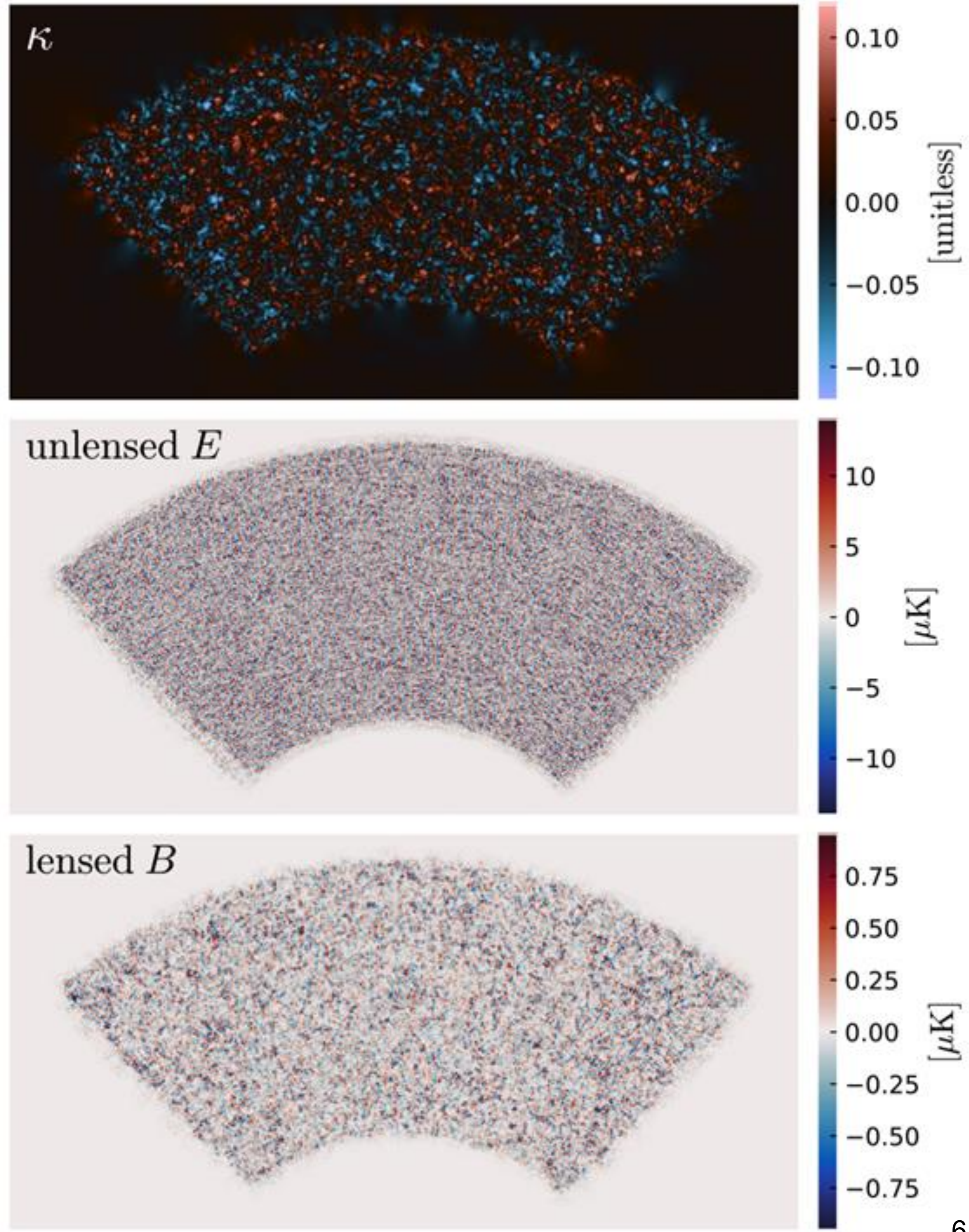
MUSE @ SPT

- MUSE is a novel algorithm for optimally and simultaneously estimating the CMB lensing power spectrum, the unlensed CMB E-mode polarization power spectrum (EE), and systematics parameters.
- This algorithm, the Marginal Unbiased Score Expansion (developed by Millea & Seljak PhysRevD.105.103531, and Millea arXiv.2209.10512), has just been applied to real data for the first time.
- The data is the polarization ONLY from SPT/SPT-3G observations, taken in 2019 and 2020 covering 1500 deg^2 at 95, 150, and 220 GHz with arcminute resolution and roughly 4.5 μK-arcmin coadded noise in polarization.
- The E-mode spectrum at ℓ > 2000 and lensing spectrum at L > 350 are the most precise to date.

Ge et al., arXiv:2411.06000, Cosmology From CMB Lensing and Delensed EE Power Spectra Using 2019-2020 SPT-3G Polarization Data

Fei Ge

Marius Millea



MUSE @ SPT

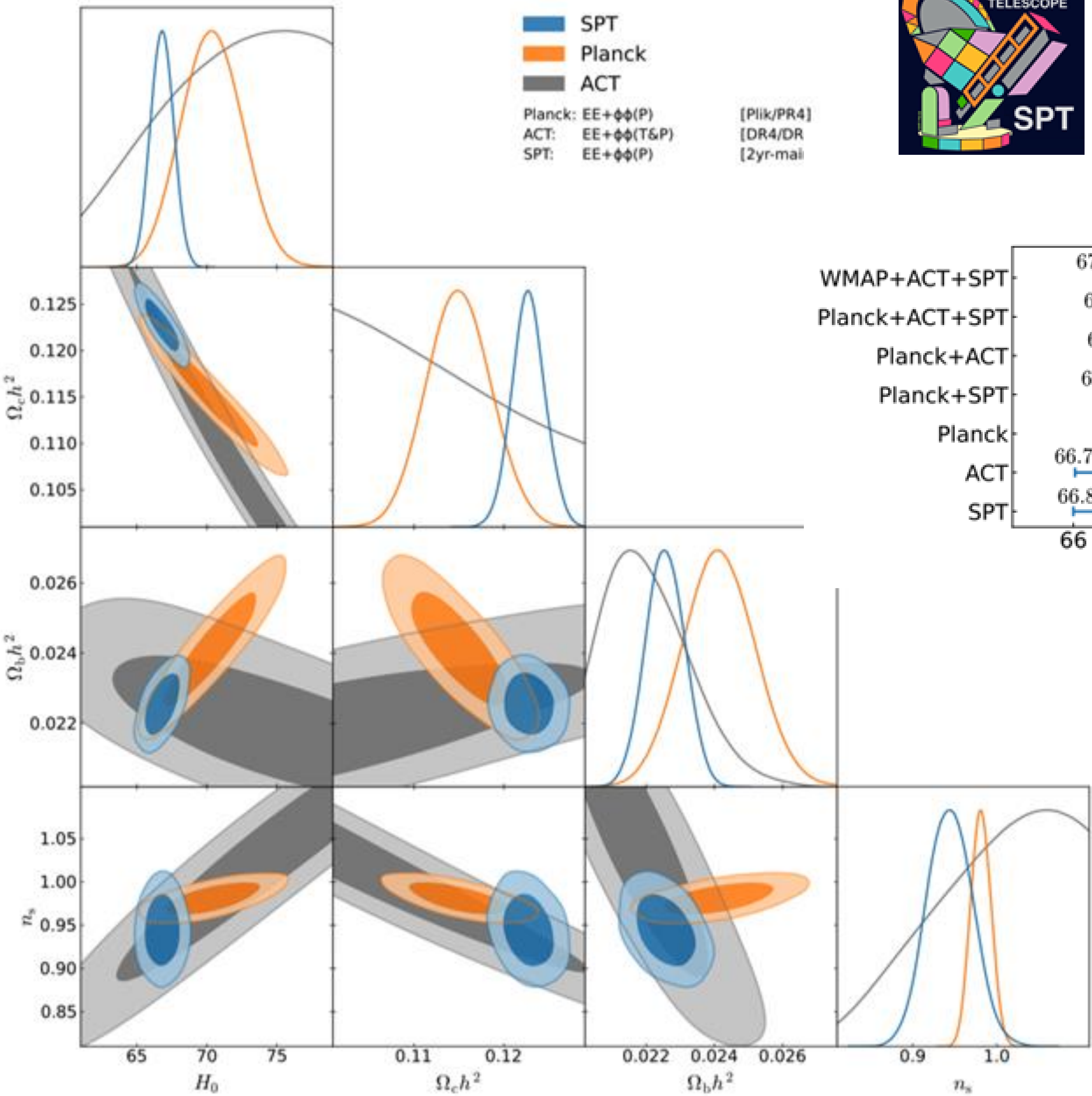
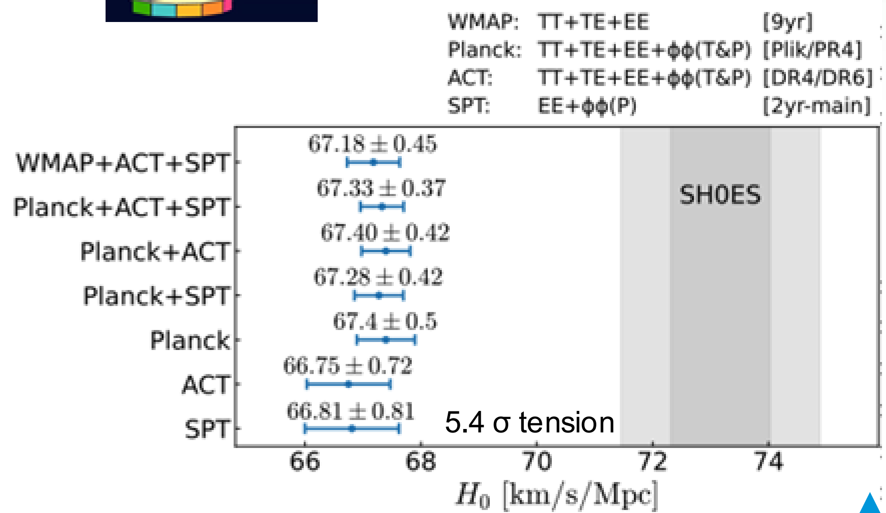


FIG. 13. Posterior distributions of ΛCDM cosmological parameters derived from CMB polarization data alone (Planck and SPT), or from a CMB EE spectrum and a CMB lensing spectrum inferred from both temperature and polarization data (ACT). The details of the datasets are listed in Tab. I. We see that the tightest constraints on $\Omega_b h^2$, $\Omega_c h^2$, and H_0 come from the SPT data.



SPT and ACT confirm (*quasi independently*) the low H value within LCDM first announced by Planck

The contours demonstrate the great power of SPT polarization data (versus that of Planck without T or current ACT)

ACT+SPT+Planck combined CMB lensing

"Unified and consistent structure growth measurements from joint ACT, SPT and Planck CMB lensing"

Combines lensing from the two experiments to put the tightest constraints on the growth of structure and sound-horizon-independent estimate of Ho

$$\sigma_8 = 0.829 \pm 0.009$$
$$\mathrm{H}_0 = 66.4 \pm 2.5\mathrm{kms}^{-1}\mathrm{Mpc}^{-1}$$

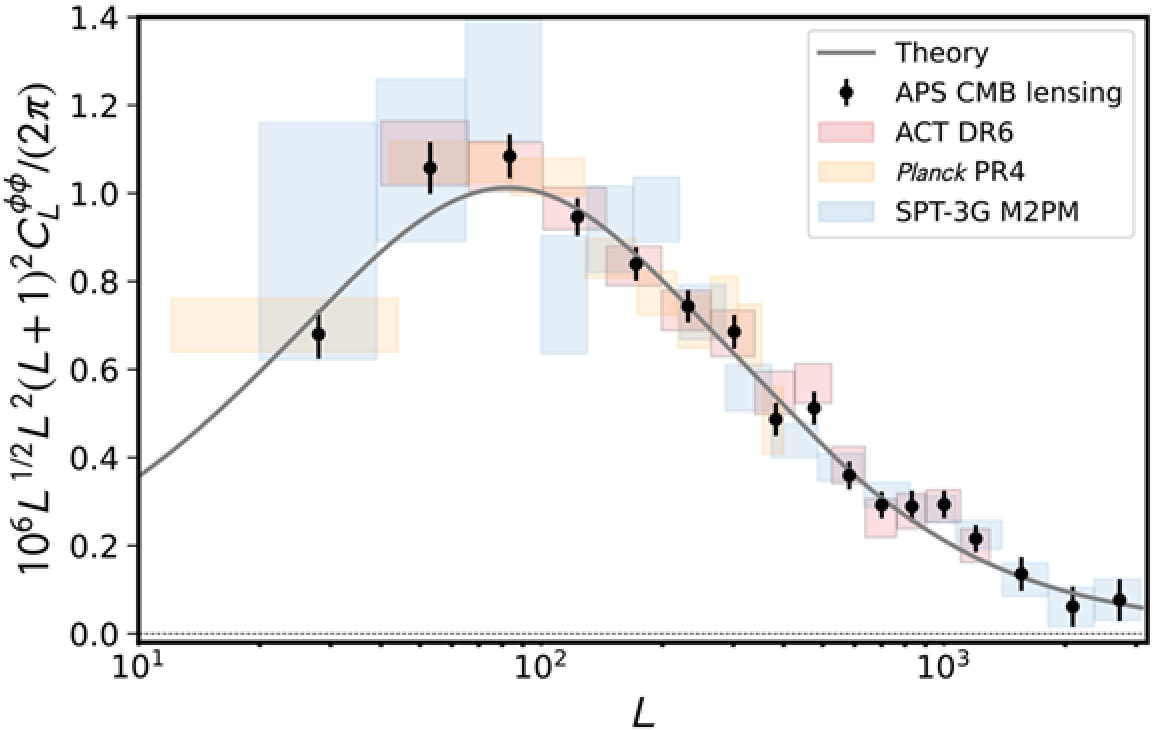


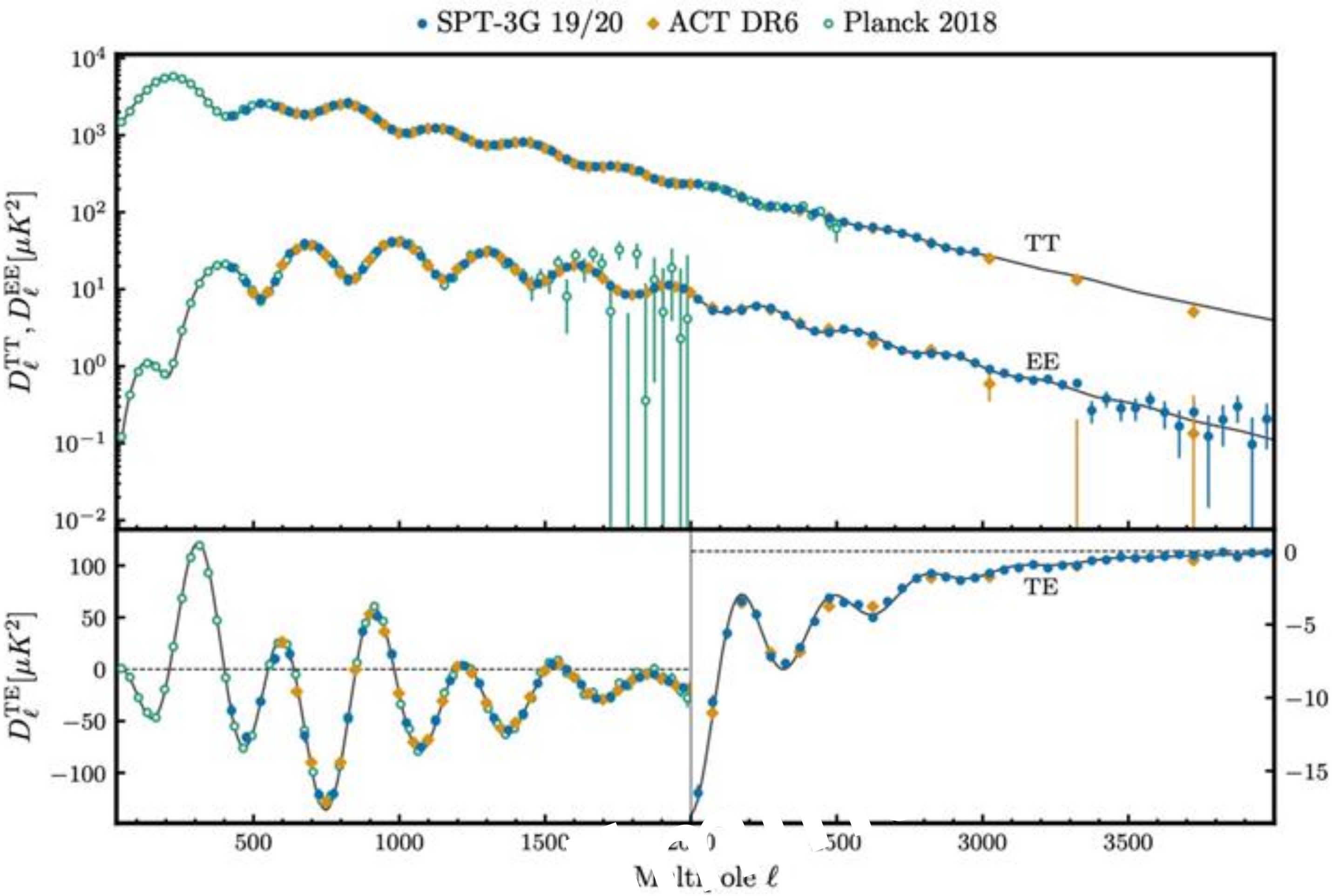
FIG. 2. We present the combined lensing bandpowers from the three surveys in black. In the background we show the *Planck* lensing bandpowers from PR4 NPIPE analysis in orange, the ACT DR6 lensing potential power spectrum bandpowers in red, and the lensing bandpowers from SPT-3G M2PM in blue. The gray line shows the theory prediction from the best-fit cosmology of the CMB likelihood. Note that we have applied an additional $L^{1/2}$ scaling over that usually used to display bandpowers to enhance visually the small scales.

Qu, Ge, et al., arXiv:2504.20038

Imminent SPT-3G 2019-2020 results: MASTER-style CMB power spectra and parameters

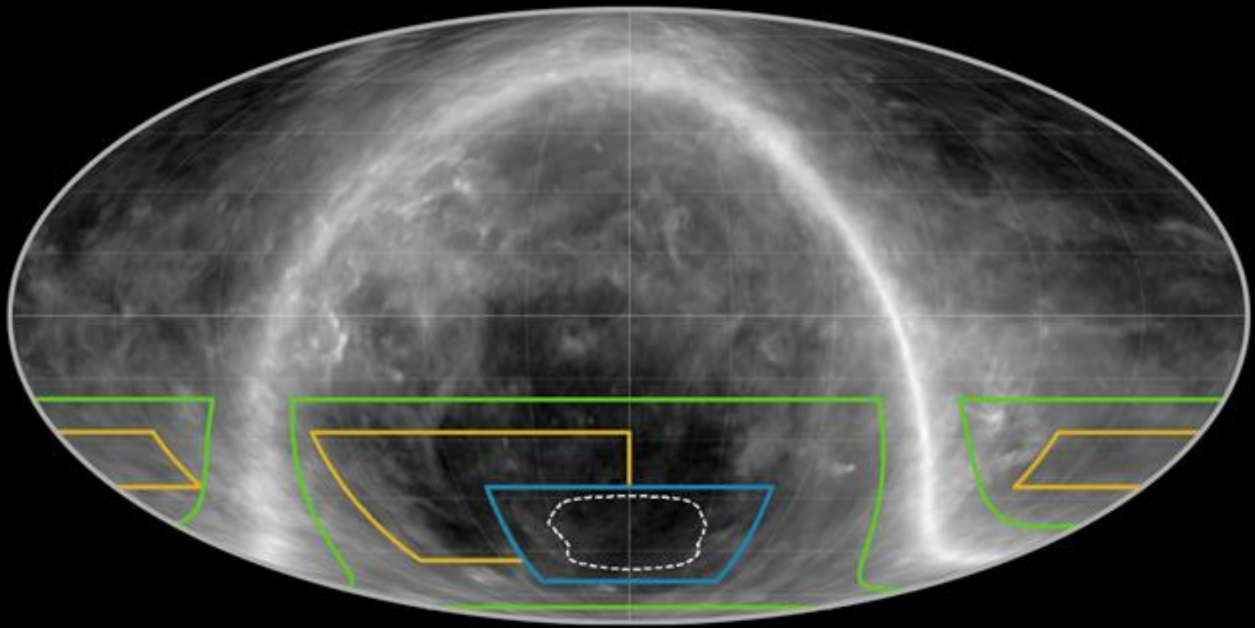
Etienne Camphuis

Wei Quan



Parameter	Planck	SPT-3G 19/20 from TT/TE/EE only
H0	67.36 ± 0.54	± 0.91
ombh2	0.02237 ± 0.00015	± 0.00018
omch2	0.1200 ± 0.0012	± 0.0024
ns	0.9649 ± 0.0042	± 0.010
logA	3.044 ± 0.014	± 0.016
tau	0.0544 ± 0.0073	± 0.0073

Projected Power Spectrum and Lensing Constraints From the Ext-10k Survey *completed in 2024*



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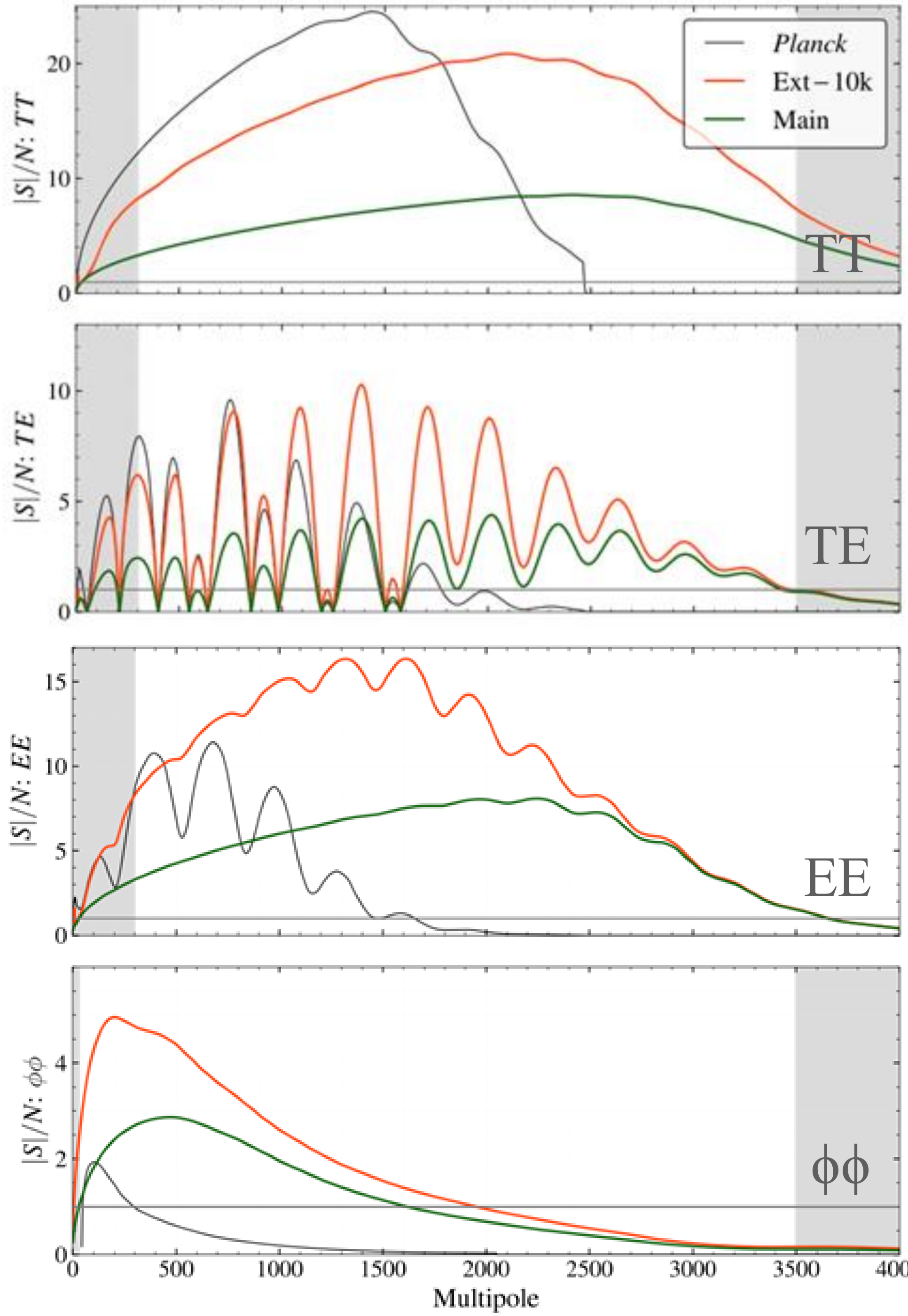
SPT-3G Wide	6000	2019-2024	14	12	42	8.8

Together these make up the SPT-3G Ext-10k 10,000 deg^2 survey

Expected S/N per multipole

SPT-3G Ext-10k survey has higher S/N than Planck at basically all scales in EE and φφ



Prabhu et al. arXiv:2403.17925v3

Future SPT constraints

The full SPT-3G dataset is expected to achieve an improvement in the ΛCDM FoM of 130; i.e., SPT-3G will reduce the allowed six-dimensional parameter volume by a factor of 130 compared to Planck.

This reduction in volume is comparable to what is expected from the first two years of the SO-Baseline dataset (which comes next).

This similarity in constraining power, plus the substantial amount of overlap in sky coverage, will provide an opportunity for significant map-level consistency tests. These can be used to detect, or limit, sources of systematic error, increasing the robustness of the parameter determinations from both SO and SPT3G.

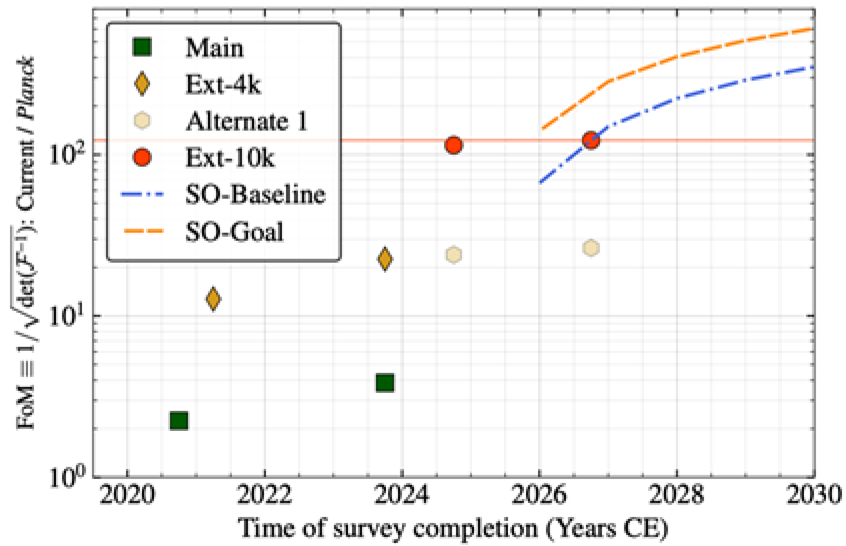


Figure 7. Figure of merit (FoM) for ΛCDM compared to *Planck*: We present the FoM for SPT-3G Main (green), Ext-4k (yellow), and Ext-10k (red). The transparent yellow circle represents the improvement in Ext-4k, if we were to continue the SPT-3G Main survey during 2024 as opposed to conducting the SPT-3G Wide survey. The evident increase in FoM with the new strategy emphasizes its potential efficacy over continuing the SPT-3G Main survey for cosmological parameter constraints. For reference, we also show the FoM expected for the two SO configurations (Baseline in blue and Goal in orange) under the assumption that the observations will begin in early 2025.

Prabhu et al. arXiv:2403.17925v3

Future SPT constraints

Improvements vs Planck only On 1-parameter extensions (>X2 for 4)

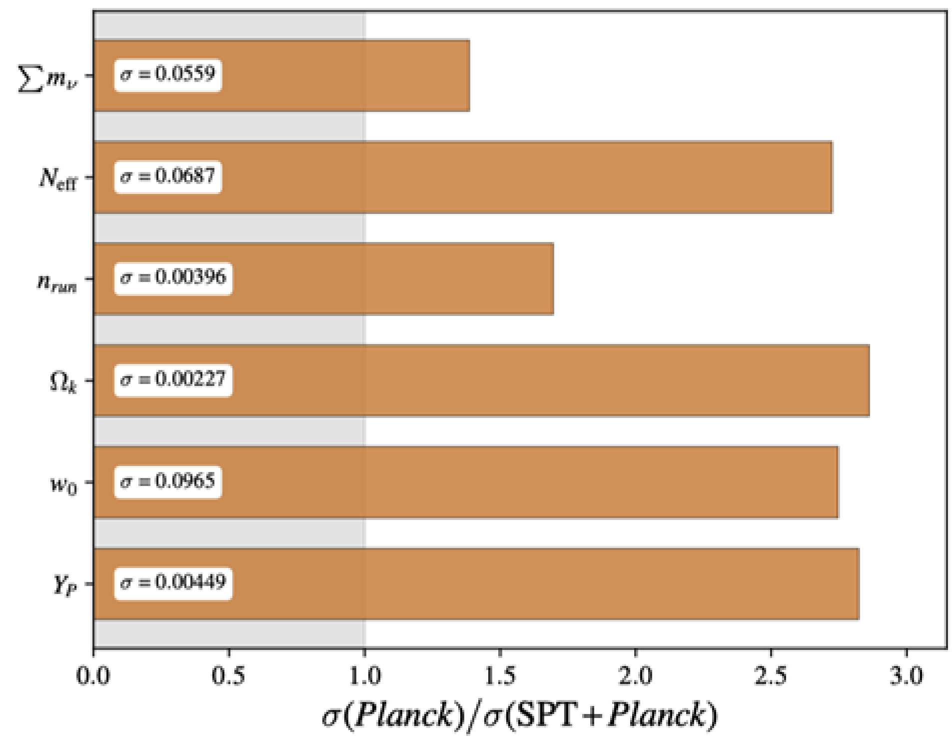


Figure 9. Ratio of 1σ constraints on single-parameter extensions from *Planck* to those forecasted from the combination of Ext-10k and *Planck*. The gray shaded region corresponds to the current best constraints from *Planck* alone. The actual errors are expressed in the text boxes.

Improvements vs Planck only On 2-parameters extensions

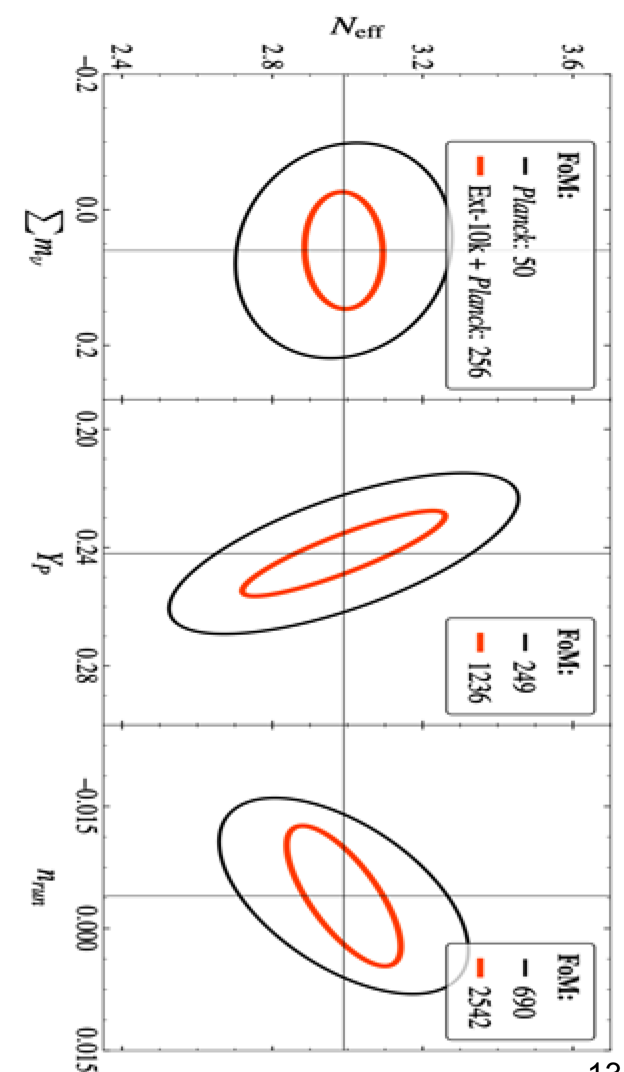
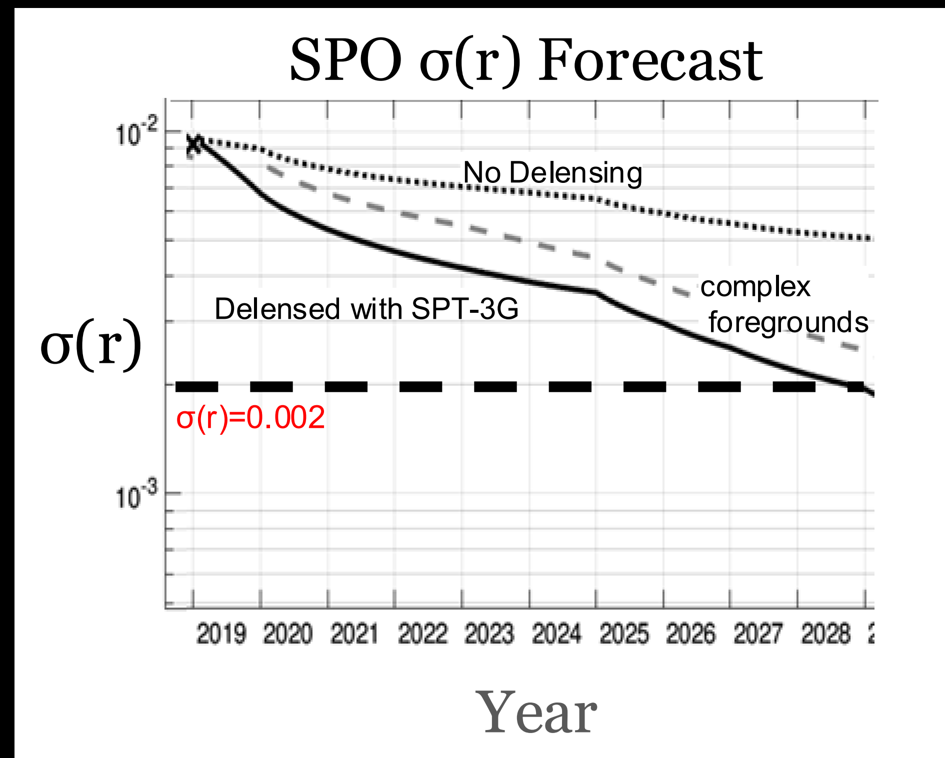


Figure 11. Marginalized two-dimensional parameter contours for the three pairs of double-parameter extensions to ΛCDM considered in this work. The red contours represent the joint constraints from the Ext-10k+*Planck*, and the black contours show the constraints from *Planck* alone. The inverse of the allowed volume of the two-dimensional parameter space (FoM) are given in the legend. Compared to the constraints from *Planck* alone, we find reductions in individual parameter errors that approach or exceed a factor of two except for $n_{\rm run}$, where we obtain ×1.3 reduction.


South Pole Observatory


BICEP3


BICEP Array

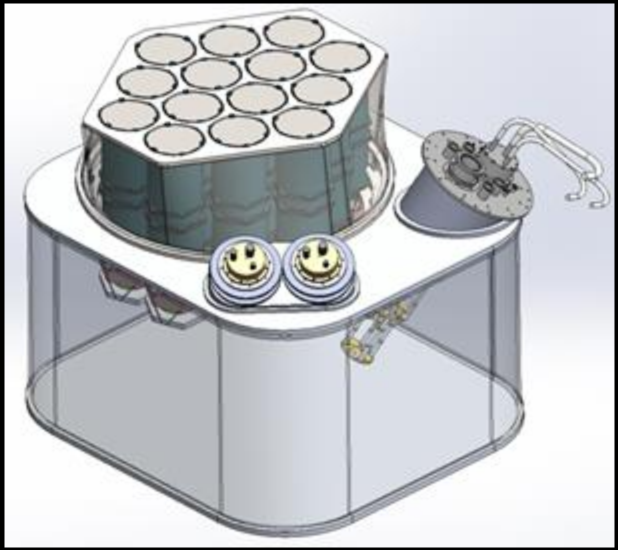

SPO σ(r) Forecast
σ(r)
Year
No Delensing
complex
foregrounds
Delensed with SPT-3G
σ(r)=0.002
10^-2
10^-3
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028

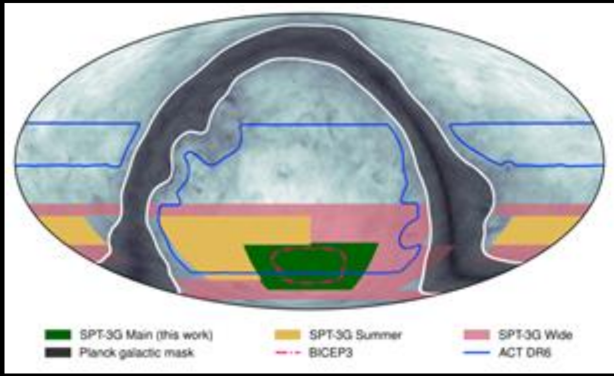
to deploy in 2029

7 times higher mapping speed than SPT-3G

➞ combined 0.49 uK-arcm !

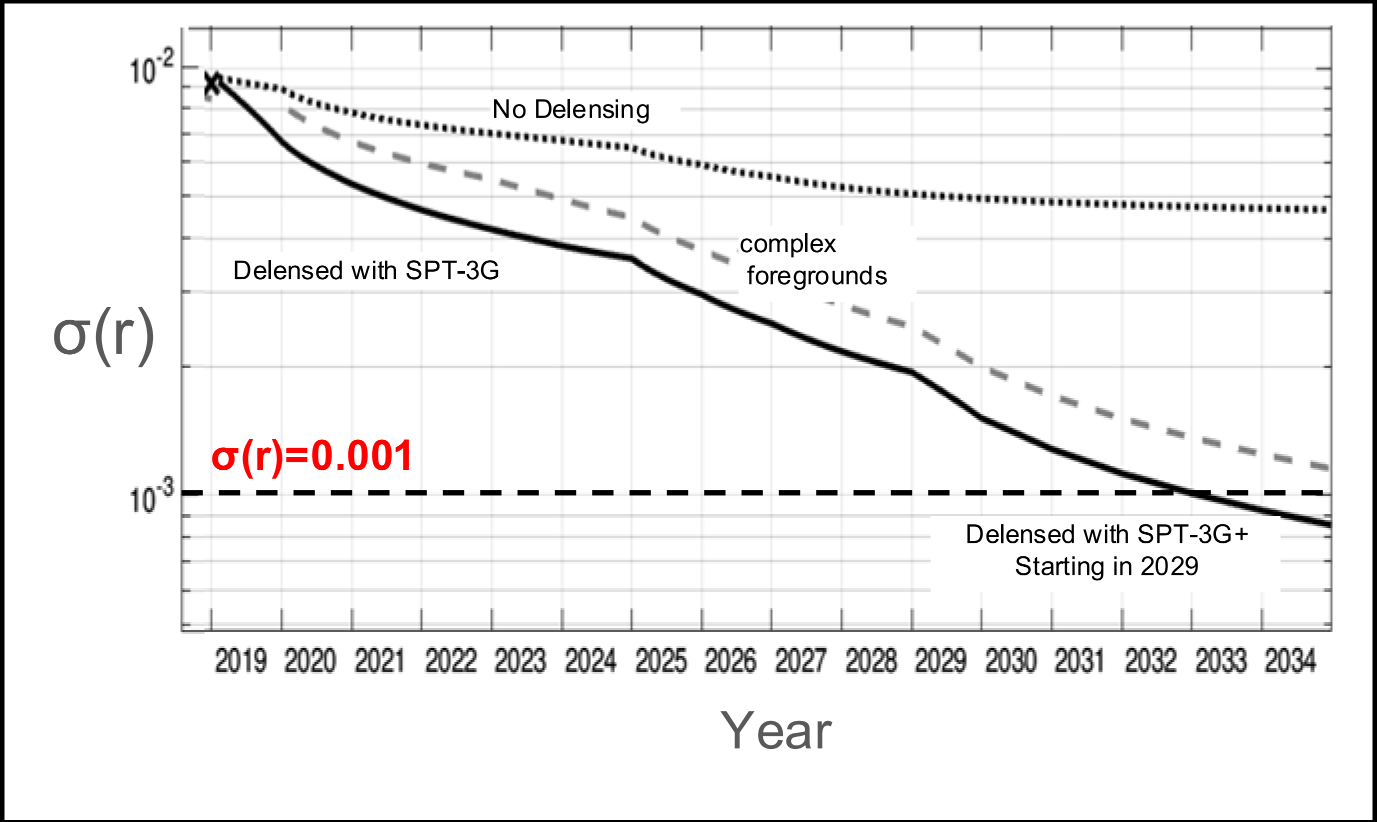
σ(r) ~ 0.001





SPO w/SPT-3G+

σ(r) reach of SPO with SPT-3G+



These forecasts are anchored on the demonstrated performance of BICEP and SPT measurements over the last decade

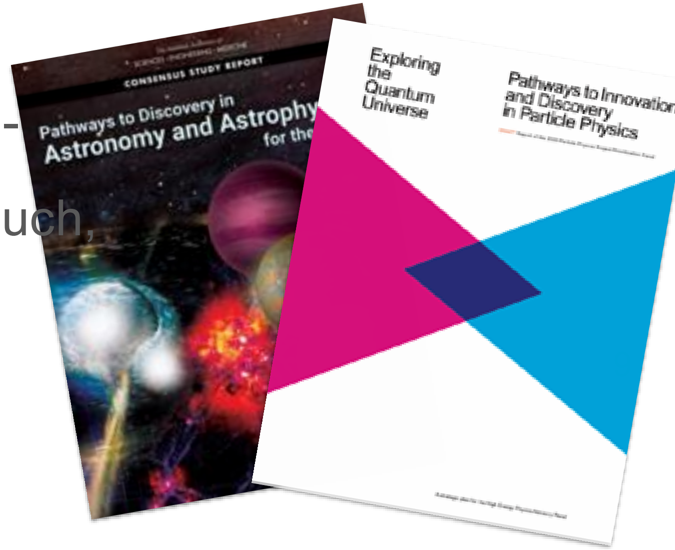
CMB S4 Genesis and Design

Developed over a decade by a broad community process and endorsed by numerous reports [e.g. Astro2020 *(2nd priority, tied with ngVLA)*, 2023 P5 *(highest priority new major project)*].

CMB-S4's key science goals drive the need for two complementary surveys, which will also enable a variety of other science goals.

- A **ultra-deep (~3% of the sky) survey** with both arcminute and degree-scale sensitivity, to search for the signal from primordial gravitational waves generated by Inflation, goal $\sigma(r) \lesssim 5 \times 10^{-4}$

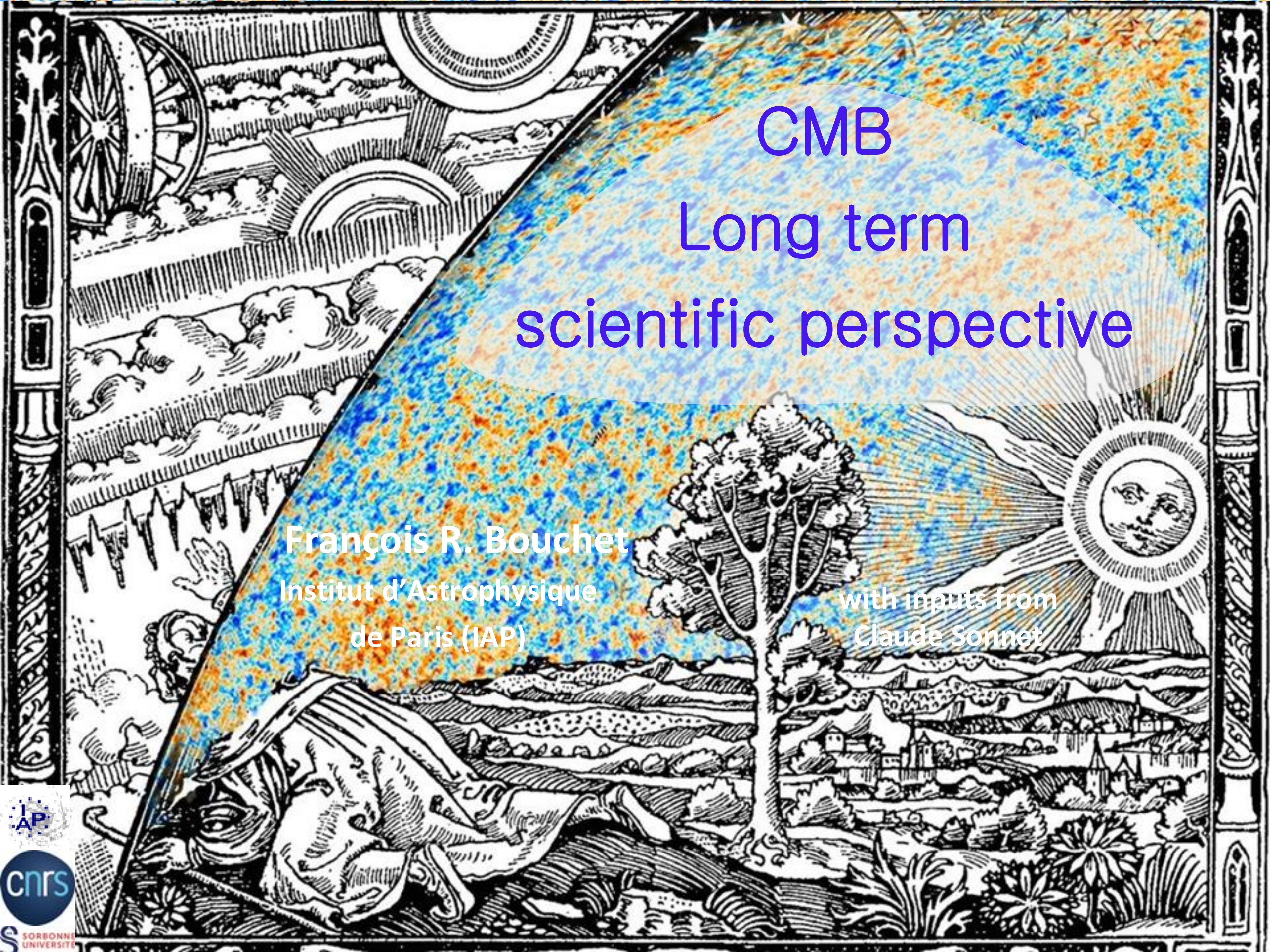
- A **deep-wide (~60% of the sky) survey** with arcm-scale sensitivity, to search for signatures from new particles, galaxy clusters, transient sources, and much, much more



U.S. DEPARTMENT OF ENERGY

CMB S4 Current Status

- May 2024: NSF declined to enter CMB-S4 into the Major Facilities Design Stage.
    - Driven by major South Pole infrastructure redevelopment needs.
    - Agencies requested a revised conceptual design **"that does not include substantial new instrumentation or facilities at the South Pole."** And to **"Include data and information from existing and planned experiments, including those that are continuing at South Pole with support from both NSF and DOE"**
    - More recently the US agencies are facing severe fiscal challenges.
- The project is working toward a revised project concept for CMB-S4 that, together with tight coordination with SO and SPO, could accomplish all of CMB-S4's science goals for a fraction of the cost of a "stand-alone" CMB-S4 configuration.



CMB Long term scientific perspective

François R. Bouchet

Institut d'Astrophysique de Paris (IAP)

with inputs from Claude Sonnet

LT Goals (license to dream)

1. Extract all the information that CMB data contains, which is very rich, fundamental and often unique about the Universe, providing a major contribution to the overall goals of Cosmology; and because yes, we can ! (track record !)

Instrumental goals:

- Cosmic Variance limited measurements at all scales (initially the primary δt)
- Spectral distortions measurements (mu, y, recombination lines, NG)
- Temporal monitoring

Challenges:

- Instrumental
- Data analysis
- Theoretical

Cosmic Variance-Limited CMB Science

1. Power spectra
   - Model parameters constraints. Fisher Matrix Analysis: Information scaling $\propto \ell_{max}^{2.5}$ (Tegmark et al. (1997), ApJ, 480, 22). See next for what's left. Then go 3D/to the moon.
   - Reconstruction / features: breaks, oscillations, possibly not even monochromatic

Higher-order statistics at $\ell < 3000$ (bi-spectrum, tri-spectrum). Very rich Pheno.

Isocurvature modes

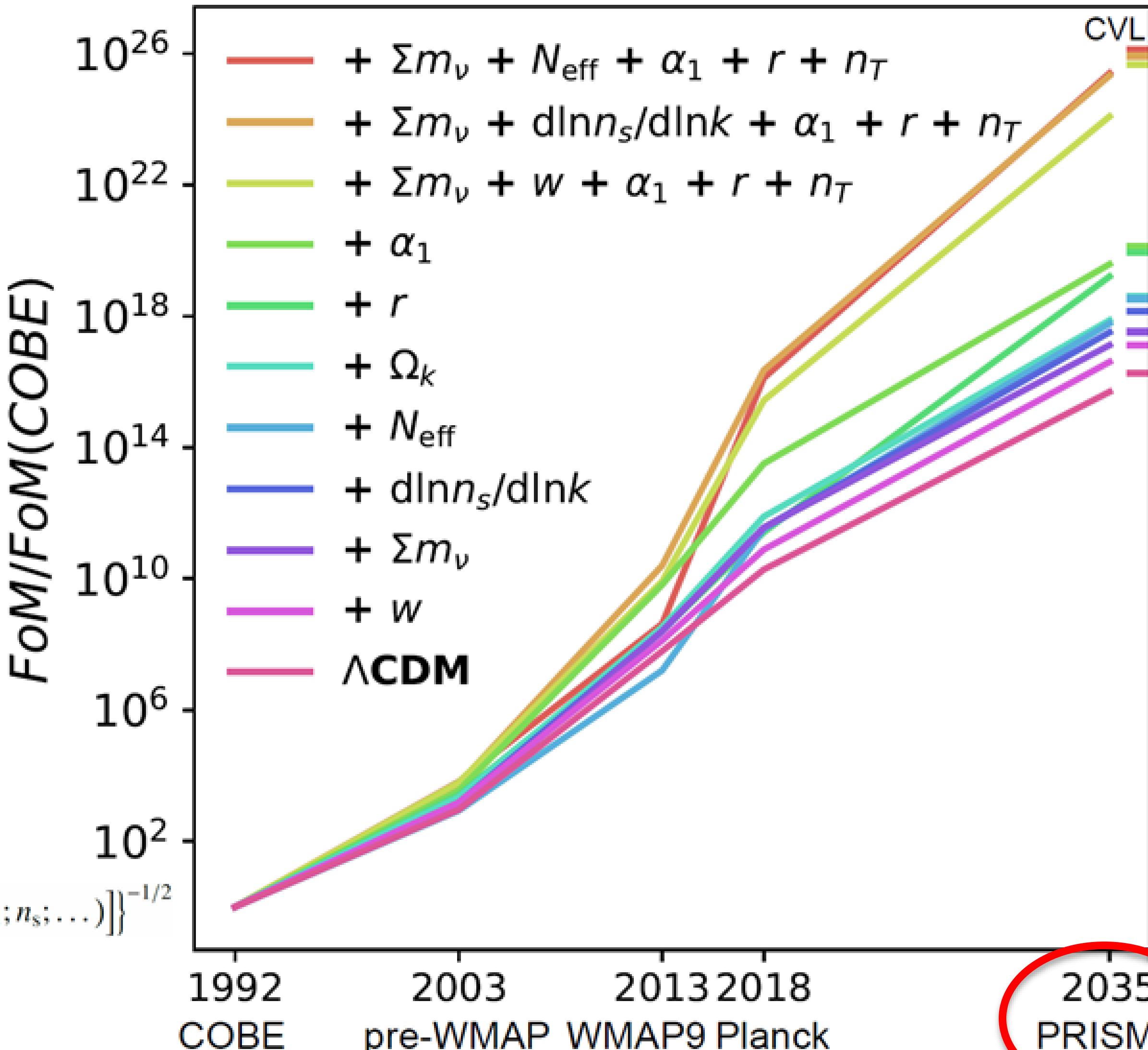
Curiosities (Hole, hemispheric asymmetry, etc.)

Reionisation constraints on optical depth ($\sigma(\tau)$ ~ 0.001 fundamental limit) & history ($x_e(z)$ with δz ~ 0.2 resolution)

Secondaries (tSZ, kSZ, FG science, etc.)

LSS data Cross-correlation and Co-analysis

The CMB treasure trove…
has still very much to give



+P18 τ

Another factor of 10^9 is in reach

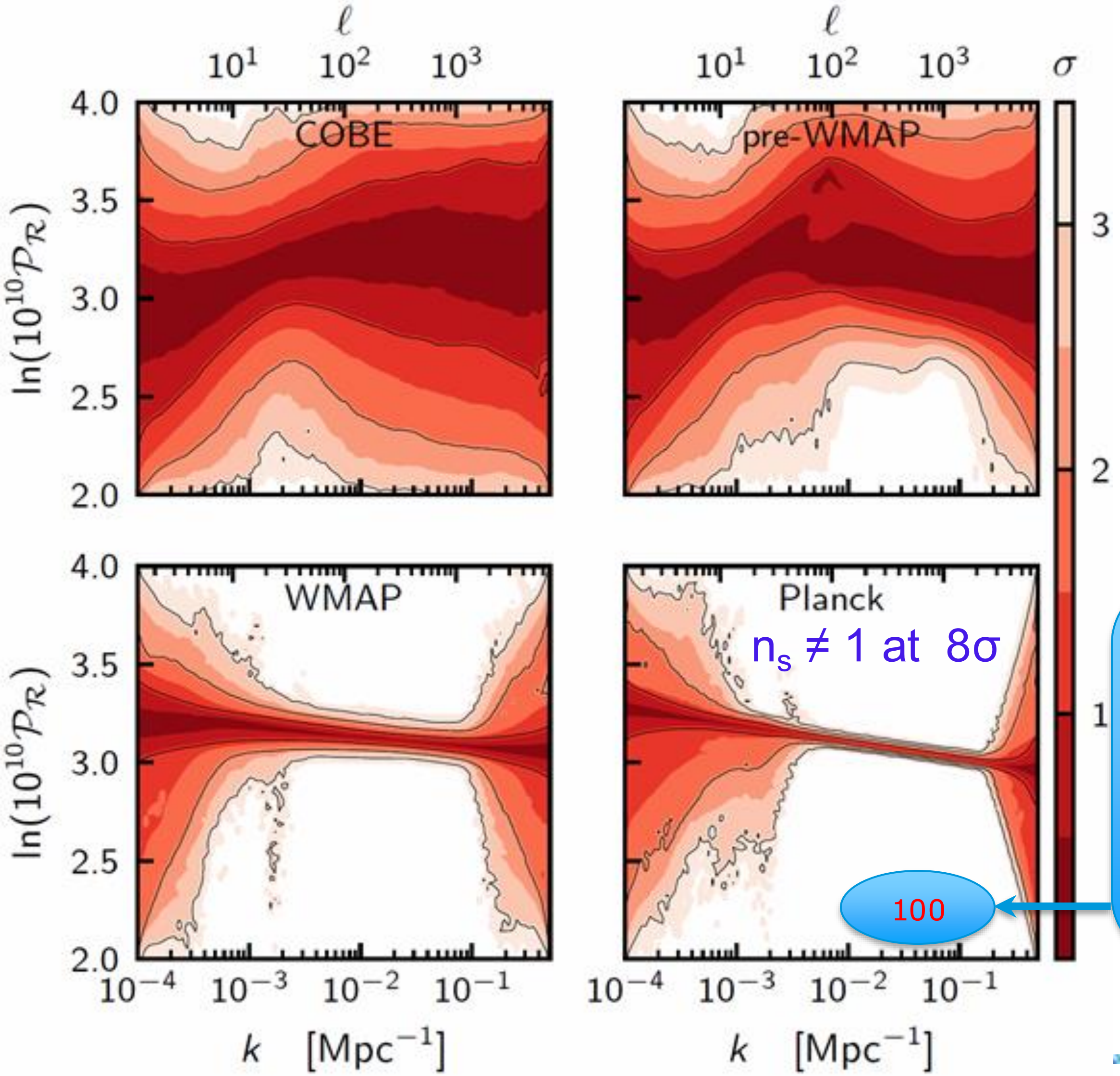
This FOM ratio indicates the progressive compression factor in the volume of the allowed parameter space (at 1σ)

This is measured through

$$\left\{\det\left[\mathrm{Cov}(\Omega_b h^2; \Omega_c h^2; \tau, A_s; n_s; \ldots)\right]\right\}^{-1/2}$$

Because Planck measured 1 430 000 TT modes but only 109 000 EE modes, and only few B modes are known so far

Primordial Power Spectrum reconstruction, versus time

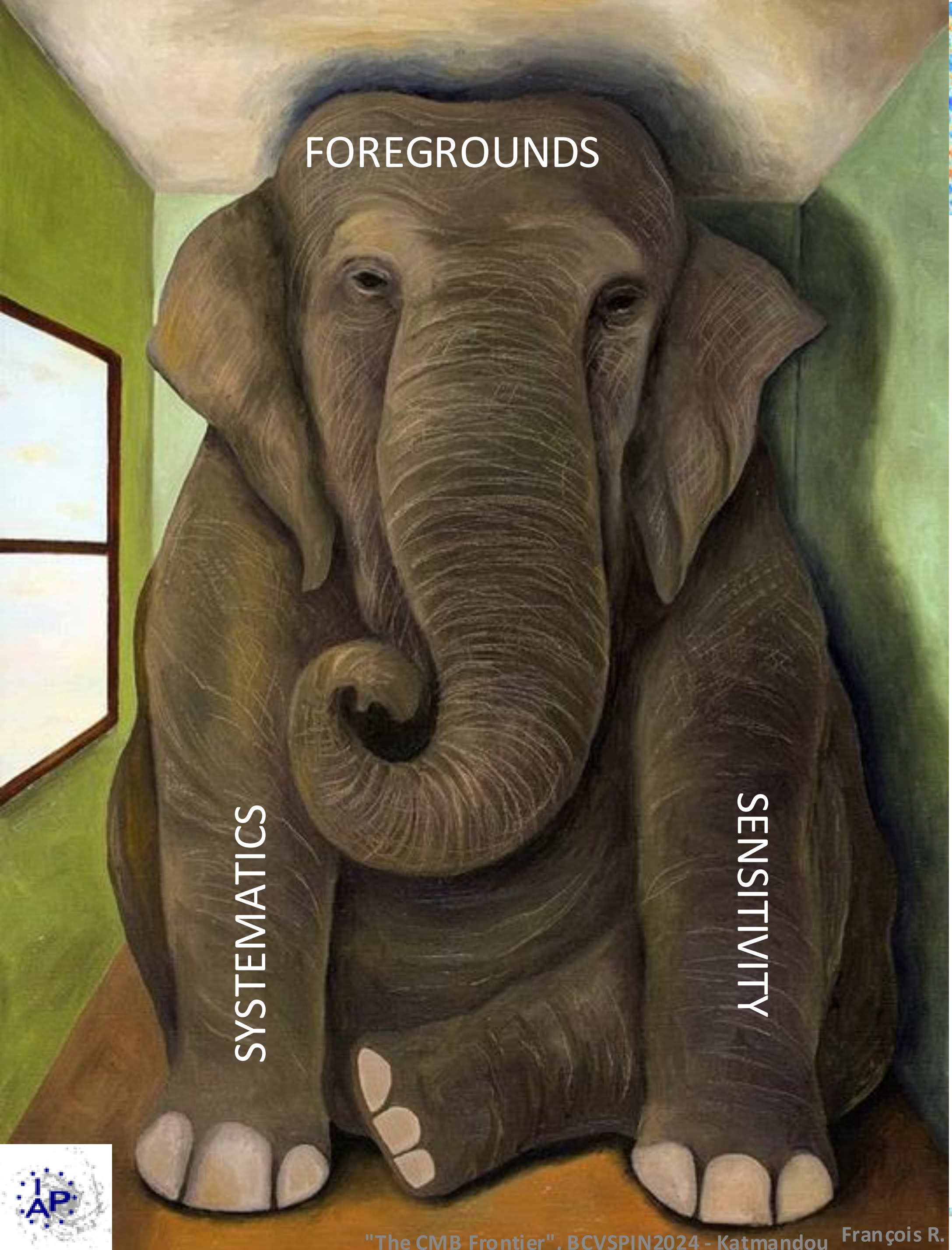


Featureless and tilted ?

YES!

This pictorial denotes a hundred fold improvement in precision since (at most) COBE

(Planck 2018 I)



CHALLENGES

- **SENSITIVITY**: low loading, high optical throughput, Det #, multichroic…
- **BEAMS**: in situ measurement of beams, esp. sidelobes (ν & pol dependence, stability)
- **BANDPASSES:** in situ characterization, pol dependence, avoid CO
- **FAR SIDE LOBE PICKUP**: shielding, sufficient suppression of scan synchronous pickup, stability
- **I □ Q/U LEAKAGE**: ν dependence, polarization dependence, stability, spatial dependence
- **CALIBRATION**: stability, dynamic range, ν dependence, pointing jitter
- **POLARIZATION ANGLES**: in situ measurement, ν dependence
- **STRIPING**: minimize 1/f (modulation)
- **FOREGROUNDS:** Spectral range, atmosphere monitoring…

Other (Data Analysis) challenges

- Extract the most from this expensive data flow
    a. Improved algorithms (speed, robustness, accuracy…) for Component Separation, Optimal Power Spectrum Estimation, Non-linear Effects in Parameter Inference, Lensing & Reionization (tomography), multi-data reconstruction, etc.
    b. Improved theoretical framework (new model, fewer assumptions, new regime,…) for Testing predictions Beyond GR, Beyond Inflation Paradigm, Quantum Gravity, Multiverse Signatures…
    c. Simulations will become even more challenging (and so will be the size of the analysis groups?) but needed for precision science (and even more for accurate science).
    d. Taming future computing architectures (Moore's law on cpus unlikely to be enough (smaller final uncertainties tend to increase algorithmic complexity)
- Sharing the data efficiently
    a. at TOI level? (e.g., to surround pixelization issues); data size
    b. X-correlations need a lot of detailed knowledge on both sides (e.g., Planck x Bicep/Keck)
    c. Flexible/efficient formats, computing architecture, etc
    d. Overall human organisation… (we need large integrated teams with varied cultural backgrounds in scattered sites)

Beyond CMB-S4… (On the ground)

Massive Detector Arrays: 10^6+ detector elements across 30-350 GHz

- Multiple observatory sites: Chile, South Pole, Northern hemisphere
- Noise levels: ~0.1 μK-arcmin polarization sensitivity
- Systematics control: far below statistical uncertainty across all scales

Novel Telescope Designs: Ultra-wide field (>30°) mm-wave telescopes

- Multi-chroic pixels with 5+ frequency bands simultaneously
- Background-limited operation from 20-1000 GHz
- Systematic error reduction: -60dB polarization leakage

Atmospheric Limitation Mitigation: Site optimization: highest/driest locations globally

- Novel observation strategies: atmosphere modeling and subtraction
- Advanced filtering: time-stream domain atmospheric template removal
- Pushing to lower frequencies: 10-30 GHz ground-based polarimetry

Integration with Radio/Sub-mm Facilities: Complementarity with ngVLA, ALMA-2, AtLAST

- Multi-wavelength observations: radio sources to CMB to dust continuum
- Joint analysis frameworks: consistent atmospheric modeling
- Common calibration standards: sub-percent absolute calibration

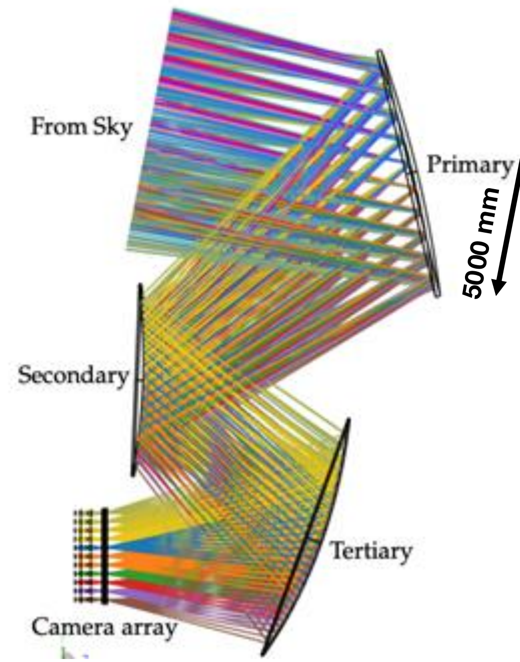
Space-Based (Ultimate?) CMB Observatory

PICO/CMB-Bharat/COrE+/PRISM Successors:
- Do both the degree angular scale B-mode measurements and the arcminute lensing measurements.
- Sensitivity: sub-µK-arcmin across full sky
- Full frequency coverage: 10 GHz - 1 THz in 20+ bands
- Ultra-stable L2 orbit operation: multi-decade observations (?)
- Absolute calibration: <0.001% reference against cosmological dipole

Technical Requirements:
- Cooling: sub-100 mK continuous operation for 10+ years
- Mirror size: 3-5m primary, for sub-arcminute resolution at high nu & Low nu FGs
- Polarization systematics: <10 nK equivalent systematic error
- Data transmission…

Beyond Single-Spacecraft Limitations (for enhanced resolution):
- Formation flying concepts: sparse aperture interferometry
- CMB gravitational lensing tomography with ~10" resolution
- Direct SZ imaging of individual galaxy clusters at z > 3
- Pushing to higher frequencies: dust polarization science to 2 THz

Synergy with Other Space Missions:
- Joint analysis with Cosmic Explorer/Einstein Telescope GW data
- Cross-correlation with all-sky X-ray (Athena/Lynx successors)
- Ultimate galaxy surveys beyond LSST/Euclid/Roman
- Multi-messenger cosmology: CMB × GW × neutrinos × UHECRs



A TMA, like sphereX
(but MUCH larger)

Spectral Distortions: Responsible Physical mechanisms

Pre-recombination

• Cooling by adiabatically expanding ordinary matter (JC, 2005; JC & Sunyaev 2011; Khatri, Sunyaev & JC, 2011)

• Heating by decaying or annihilating relic particles (Kawasaki et al., 1987; Hu & Silk, 1993; McDonald et al., 2001; JC, 2005; JC & Sunyaev, 2011; JC, 2013; JC & Jeong, 2013)

• Evaporation of primordial black holes & superconducting strings (Carr et al. 2010; Ostriker & Thompson, 1987; Tashiro et al. 2012; Pani & Loeb, 2013)

• Dissipation of primordial acoustic modes & magnetic fields (Sunyaev & Zeldovich, 1970; Daly 1991; Hu et al. 1994; JC & Sunyaev, 2011; JC et al. 2012 - Jedamzik et al. 2000; Kunze & Komatsu, 2013)

• Cosmological recombination radiation (Zeldovich et al., 1968; Peebles, 1968; Dubrovich, 1977; Rubino-Martin et al., 2006; JC & Sunyaev, 2006; Sunyaev & JC, 2009) „high“ redshifts

Post-recombination

• Signatures due to first supernovae and their remnants (Oh, Cooray & Kamionkowski, 2003)

• Shock waves arising due to large-scale structure formation (Sunyaev & Zeldovich, 1972; Cen & Ostriker, 1999)

• SZ-effect from clusters; effects of reionization (Refregier et al., 2003; Zhang et al. 2004; Trac et al. 2008) • Additional exotic processes (Lochan et al. 2012; Bull & Kamionkowski, 2013; Brax et al., 2013; Tashiro et al. 2013)

(photon injection effects are in blue)

 Another treasure trove still mostly untouched

Spectral Distortion Science Goals

PIXIE-like Mission Successors:

1.
- Sensitivity threshold: $\delta I/I \sim 10^{-9}$ across 30-600 GHz (2030s ?)
- Ultimate goal: $\delta I/I \sim 10^{-10}$ (2040s+)
- Frequency resolution: $\delta\nu/\nu \sim 0.001$ with ~1000 channels
- Spatial resolution: mapping spectral distortions at degree scales

μ-type Distortion Science:

- Ultra-small scale primordial power spectrum constraints: $10 < k/\mathrm{Mpc}^{-1} < 10^4$ [Chluba+2023
- Expected signal amplitude: $\mu \sim 2 \times 10^{-8}$ [Lucca & Schöneberg 2023]
- Sensitivity to running of running of scalar spectral index: $d^2n_s/d\ln k^2$ [Cabass+ 2023]
- Implications for primordial black hole formation scenarios
- Pre-recombination energy injection from exotic particle decay signatures [Bolliet+ 2023; Hill+ 2023]

y-type Distortion Applications:

- Late-time structure formation contributions: $y \sim 1.8 \times 10^{-6}$
- Cross-correlation with large-scale structure as LSS probe
- Isolating contributions from different density-temperature regimes
- Constraints on AGN feedback models: energy partition functions

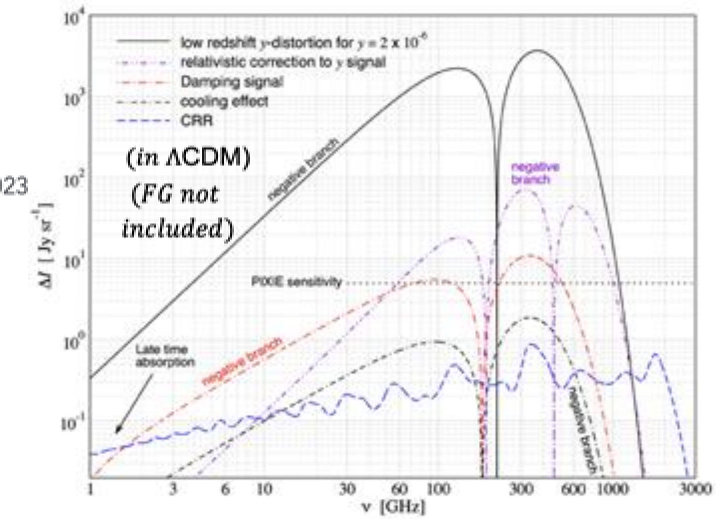
Beyond μ and y Parameters:

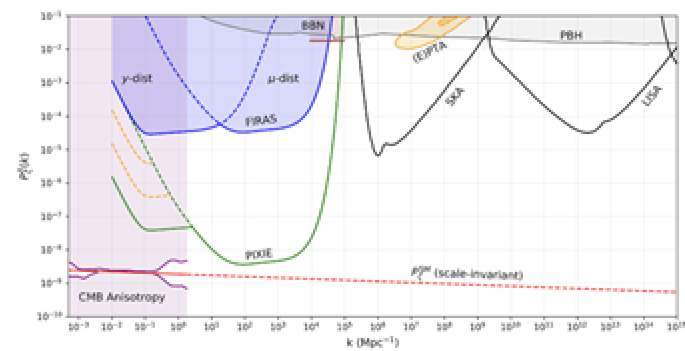
- Detecting relativistic corrections to y-distortion: $\sigma(kT_e) \sim 0.2$ keV
- Measuring recombination line spectral distortions: Lyα, Hα, Pα
- Residual distortions from dark matter-baryon scattering
- Exotic energy injection scenarios: complete characterization

Beyond Standard Physics:

- Decay of long-lived particles: lifetime $\tau > 10^{10}$ s constraints
- Primordial black hole evaporation signatures: $M_{PBH} \sim 10^{13}$-10^{15} g
- Axion-photon conversion in magnetic fields: $g_{a\gamma} \sim 10^{-11}$ GeV^{-1}
- Testing energy conservation: constraining photon-axion oscillations

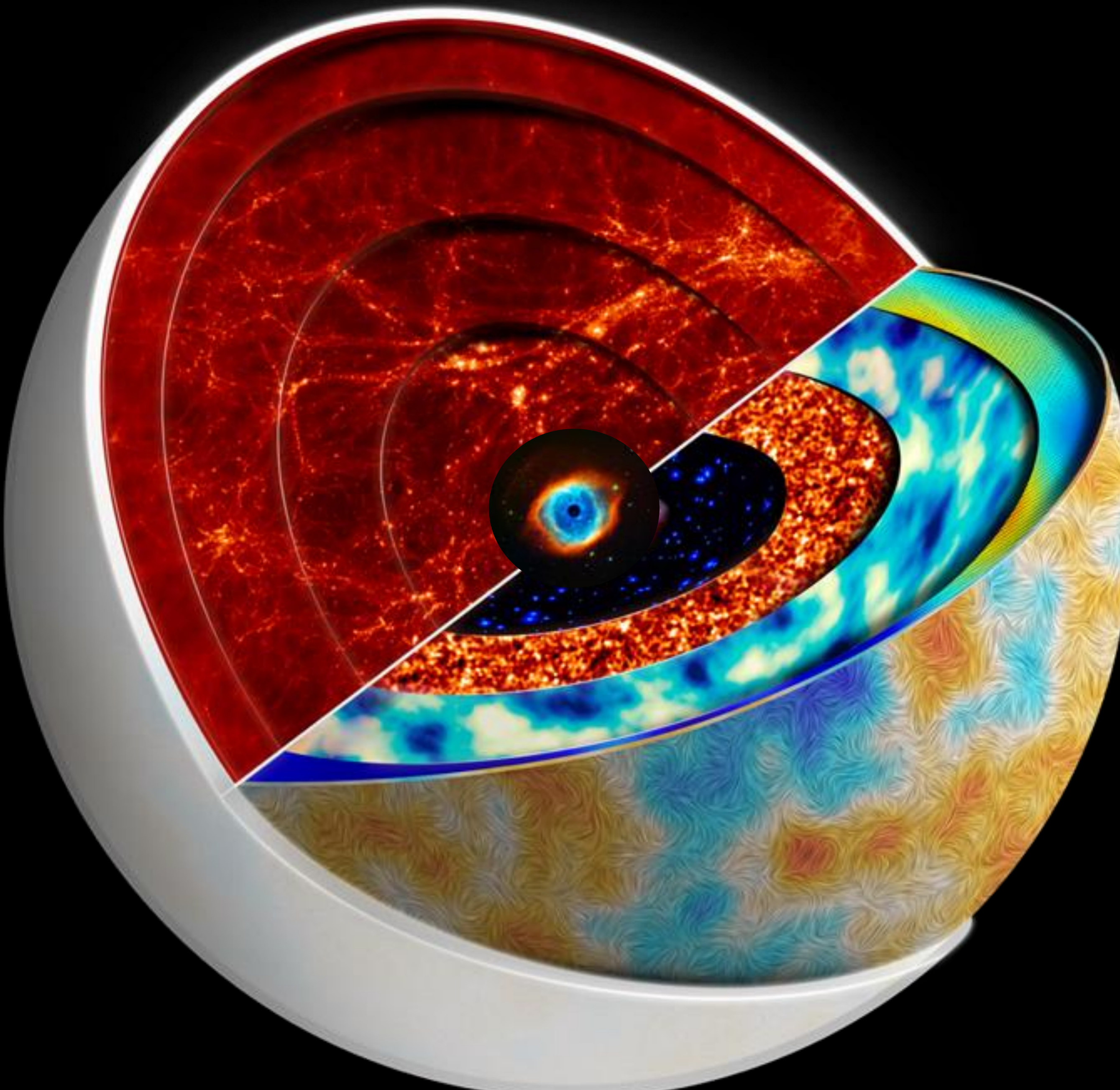
(for now, FOSSIL just submitted to ESA M8 call)





Predicting is hard, especially the future ☺, but

The CMB will surely remain a cornerstone of cosmological research, with plenty of exciting future directions



And we shall continue creating (& condemning) new avenues

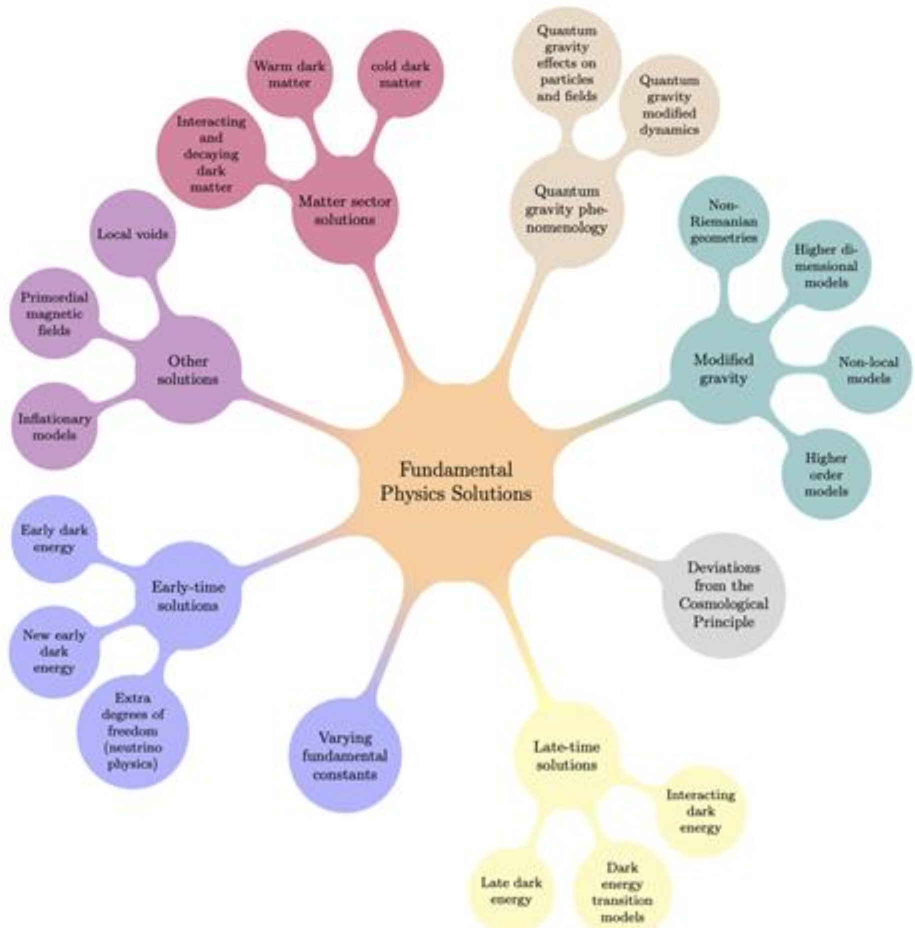


FIG. 6: Fundamental physics provides a number of potential solutions to address the challenge of tensions in cosmology.

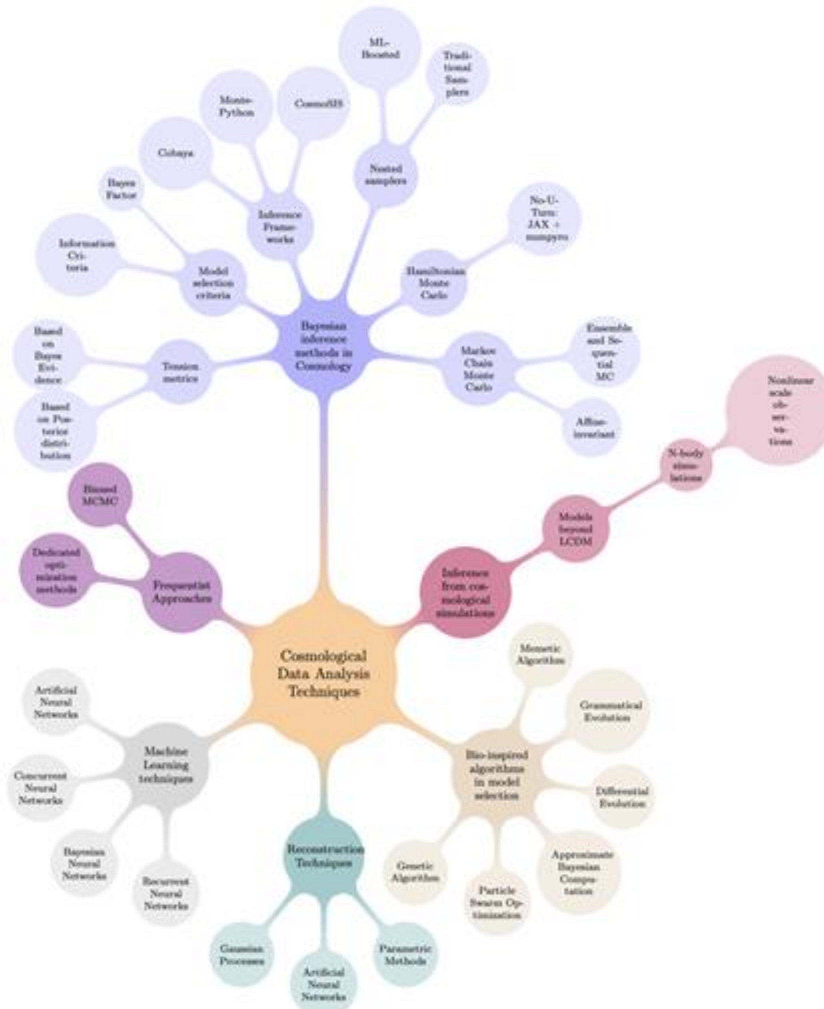


FIG. 7: Schematic of the different data analysis approaches used in the cosmology community.

Di Valentino+ 2504.01669v2

ANNEX

Possibly for detailed discussions

If any

(depending on previous talks content)

ITEMS FOR FURTHER DISCUSSION ?

1. Primordial Non-Gaussianity & Inflation
2. Trans-Planckian Modulation Signals
3. Beyond ΛCDM: Exotic Scenario Constraints
4. Dark Energy and Modified Gravity Signatures
5. Thermal and Kinetic SZ
6. Reionization Epoch Tomography
7. Computational and Analysis Revolution ?
8. CMB Data as Permanent Cosmic Archive
9. …

Lots to chew on

Primordial Non-Gaussianity & Inflation

1.
Local Non-Gaussianity:
- Current bounds: $f_{NL}^{local} = -0.9 \pm 5.1$ (68% CL) [Planck Collab. 2023]
- Next-gen projections: $\sigma(f_{NL}^{local}) \sim 0.8$ (LiteBIRD) [Hazumi+ 2023]; ~ 0.2 (CMB+LSS optimal) [Achúcarro+ 2023]
- Multifield inflation implications: detecting $f_{NL}^{local} > 0.5$ [Braglia+ 2023]
- NB: Ultra-large scale survey effects: scale-dependent bias enhancements [Barreira+ 2023; Dizgah+ 2023]; Spherex

Equilateral and Orthogonal Templates: (& Modal decomposition)
- Sound speed of inflaton fluctuations: $c_s \geq [100\, \sigma(f_{NL}^{equil})]^{(-1/2)}$
- Projection: $\sigma(f_{NL}^{equil}) \sim 10$ (CMB-S4+PICO)
- Differentiating higher-derivative operators in EFT of inflation
- Non-Bunch-Davies vacuum state signatures

Higher-Order Statistics:
- Trispectrum: probing g_{NL} and τ_{NL} with optimal estimators
- Testing Suyama-Yamaguchi inequality: $\tau_{NL} \geq (6f_{NL}^{local}/5)^2$
- Modal coupling approaches to general bispectrum shapes
- Non-perturbative effects: CMB skew-spectra approach

Machine Learning Applications:
- Neural networks for non-Gaussian feature extraction
- Simulation-based inference for model-independent constraints
- Anomaly detection: searching for localized non-Gaussian features
- Optimal compression of higher-order statistics

Trans-Planckian Modulation Signals

Primordial Oscillatory Features:

- Logarithmic oscillation templates: scale-invariant vs. localized modes [Palma et al. 2023]
- Sharp features in inflaton potential: constraining phase transitions [Braglia et al. 2023b]
- Clock signals: resonant non-Gaussianity from heavy fields [Sohn & Fergusson 2023]
- Challenging modified initial states: Bogoliubov coefficient constraints [Green & Wu 2023]

Detecting and Characterizing Oscillations:

- Template-based matched filtering: linear vs. logarithmic oscillations
- Blind feature searches: wavelet decomposition approaches
- Optimal binning strategies for high-frequency oscillations
- Cross-validation between CMB and LSS oscillatory features

Theoretical Implications:

- Testing trans-Planckian censorship conjecture
- Implications for de Sitter quantum gravity
- New physics at the highest energy scales: stringy signatures
- Multiverse scenario tests: bubble collision signatures

Statistical Challenges:

- Look-elsewhere effect correction methods
- Global vs. local significance assessment
- Bayesian evidence calculations for oscillatory models
- Distinguishing instrumental effects from physical signals

Beyond ΛCDM: Exotic Scenario Constraints

1. Cosmic Birefringence:
- Uniform rotation angle β: current constraint $|\beta| < 0.3°$ (95% CL) [Eskilt et al. 2023]
- Next-gen. sensitivity: $\sigma(\beta) \sim 0.002°$ [Namikawa et al. 2023]
- Axionic dark matter constraints: coupling constant $g_{\gamma a} < 10^{-15}$ GeV^{-1} [Fujita+2023; Jain+2023]

Primordial Magnetic Fields: Faraday rotation of CMB polarization: B_1Mpc $< 10^{-9}$ Gauss
- Vector and tensor mode generation: distinctive B-mode signatures
- Scale-dependent PMF spectrum constraints: spectral index n_B
- Origin scenarios: inflation vs. phase transition discrimination

Cosmic Strings and Defects: Current constraint: $G\mu < 1.1 \times 10^{-7}$ (95% CL)
- Projected sensitivity: $G\mu \sim 10^{-8}$ (CMB-S4)
- String network evolution: scaling solution vs. transient effects
- Distinguishing cosmic strings from primordial GW B-modes

Isocurvature Modes:
- Current constraints: $\beta_{iso} < 0.038$ (95% CL, CDM); $\beta_{iso} < 0.025$ (neutrino)
- Correlation with adiabatic modes: measuring α parameter
- Testing multi-field inflation: curvaton vs. axion scenarios
- Implications for QCD axion dark matter: fa constraints

Dark Energy and Modified Gravity Signatures

1. Integrated Sachs-Wolfe Effect:

- Cross-correlation with eROSITA and Euclid galaxy catalogs: $\sigma(A_{ISW}) \sim 0.05$ [Kovács+ 2023; Euclid Collab. 2023]
- Redshift tomography: w(z) constraint improvements [Hang+ 2023]
- Modified gravity screening effects: scale-dependent ISW enhancement [Frusciante+ 2023]
- Testing Copernican principle: off-diagonal correlations as isotropy probe [Ghosh+ 2023]

CMB Lensing with Modified Gravity: Distinguishing MG from massive ν: breaking the σ_8-Σm_ν degeneracy

- Horndeski gravity parameter constraints: running of effective Planck mass
- Testing screening mechanisms: chameleon vs. Vainshtein signatures
- Scale-dependent growth rate: optimal binning for MG discrimination

Beyond w(z) Parametrization: Early dark energy constraints from recombination physics

- Sound horizon shifts: addressing the H_0 tension
- Model-independent reconstruction: Gaussian process approaches
- Constraining phase transitions in dark energy sector

Joint CMB-Gravitational Wave Analysis: Modified GW propagation: amplitude vs. phase effects

- Cross-correlation between CMB lensing and stochastic GW background
- Ultra-large scale consistency tests: c_T/c constraints
- Primordial vs. late-time screening effects differentiation

Thermal and Kinetic SZ

1. Relativistic Corrections to tSZ Effect:

- Direct measurement of ICM temperature distributions: kT_e > 5 keV [Remazeilles & Chluba 2023]
- Multi-frequency separation of relativistic signatures [Lee+ 2023; Raghunathan+ 2023]
- Constraints on non-thermal electron populations [Basu+ 2023]
- Testing cluster temperature-mass scaling relation evolution to z ~ 2 [Mroczkowski+ 2024]

Kinetic SZ Tomography: Velocity reconstruction accuracy: $\sigma(v)$ ~ 150 km/s with next-gen surveys

- Peculiar velocity field as growth rate probe: $f(z)\,\sigma_8(z)$ to 2% precision
- Pairwise kSZ as direct probe of baryonic acoustic oscillations
- Separating primary CMB and kSZ: projected reconstruction methods

Cluster Cosmology Applications: Mass calibration: hydrostatic bias constraints to 2% precision

- Blind SZ catalog completeness and purity functions
- Testing cluster pressure profiles to $3r_{500}$
- Cluster counts: σ_8-Ω_m degeneracy breaking with improved mass calibration

Beyond Clusters: Diffuse Gas Physics: WHIM detection via stacked filament analysis

- Missing baryon census: cross-correlation with galaxy and QSO samples
- Constraints on AGN feedback models from stacked SZ profiles
- Characterizing ICM turbulence via tSZ - kSZ cross-correlation

Reionization Epoch Tomography

1. E-mode Polarization at $\ell < 30$:

- Model-independent optical depth constraints: $\sigma(\tau) \sim 0.002$ [Watts+ 2023]
- Large-scale E-mode cosmic variance: mitigation strategies [Roy+ 2021]
- Extended vs. instantaneous reionization scenarios differentiation [Heinrich & Hu 2023]
- Joint analysis with kSZ 4-point function and 21cm observations [La Plante et al. 2023; Beane & Lidz 2023]

Patchy Reionization Signatures:

- Remote quadrupole scattering: distinctive B-mode contribution
- Small-scale kSZ power: reionization duration constraints
- Bubble size distribution probes: multi-frequency cross-spectra analysis
- Sensitivity to ionization history asymmetry and topology

First Star Formation Constraints:

- Population III star formation efficiency from reionization onset
- Constraints on escape fraction evolution from τ measurement
- X-ray binary contributions to early heating
- Feedback mechanisms and implications for high-z galaxy observations

Beyond Standard Reionization Models:

- Exotic energy injection signatures (dark matter annihilation)
- Testing accelerated reionization from primordial black holes
- Implications for alternative dark matter models (WDM, SIDM)
- Lyman-α constraints and complementarity with Hubble frontier fields

Computational and Analysis Revolution ?

- **Quantum Computing Applications**:
  - Non-Gaussian likelihood evaluation: exponential speedup
  - Quantum machine learning for foreground separation
  - Quantum annealing for optimal observation strategy
  - Quantum simulation of early universe processes
- **Exascale+ Analysis Frameworks**:
  - Full end-to-end simulation: timestreams to cosmological parameters
  - Joint likelihood analysis: all cosmological probes simultaneously
  - Bayesian neural networks: posterior approximation beyond MCMC
  - Real-time analysis: immediate parameter constraints from raw data
- **Optimal Information Extraction**:
  - Modal decomposition techniques beyond power spectra
  - Hybrid classical-ML analysis: physical constraints + neural flexibility
  - Field-level likelihood approaches: constraining $\phi(x)$ directly
  - Simulation-based inference: likelihood-free parameter estimation
- **Advanced Statistical Methods**:
  - Differentiable programming pipelines end-to-end
  - Model uncertainty quantification: marginalization over theoretical errors
  - Active learning: targeted observation strategy optimization
  - Anomaly detection algorithms: searching for new physics signatures

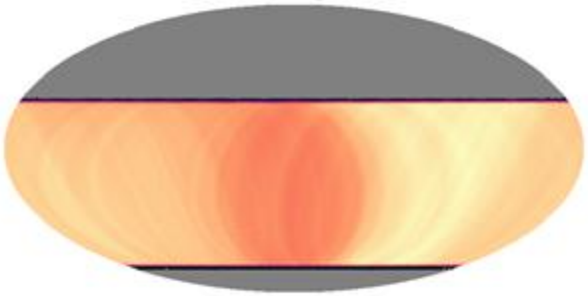
CMB Data as Permanent Cosmic Archive

1. Constraints on Time-Varying Constants:
   - Fine structure constant: $\Delta\alpha/\alpha < 10^{-6}$ across recombination
   - Gravitational constant: $\Delta G/G < 10^{-5}$ from BBN to recombination
   - Standard model coupling constants: comprehensive joint constraints
   - Electron-proton mass ratio: $\mu = m_e/m_p$ variations at $z\sim1100$
- Ultra-Long Baseline Reobservations:
   - Searching for time-dependent effects over 50-100 year timescales
   - Ultimate calibration of astronomical standards against CMB dipole
   - Proper motion of CMB acoustic features: 10^{-10} effects with century baseline
   - Testing Copernican principle: all-sky isotropy evolution monitoring
- Reference Frame Establishment:
   - CMB dipole as ultimate reference frame for astronomy
   - Absolute calibration for all future microwave/mm-wave astronomy
   - Temperature stability: monitoring $T_{CMB}(z=0)$ to 10^{-6} precision
   - Cross-calibration of future astronomical facilities against CMB
- Data Preservation for Multi-Century Science:
   - Permanent archival of time-ordered, map, and spectral data
   - Documentation for millennium-scale scientific utility
   - Platform-independent formats and analysis tools
   - Knowledge transfer to future generations of cosmologists

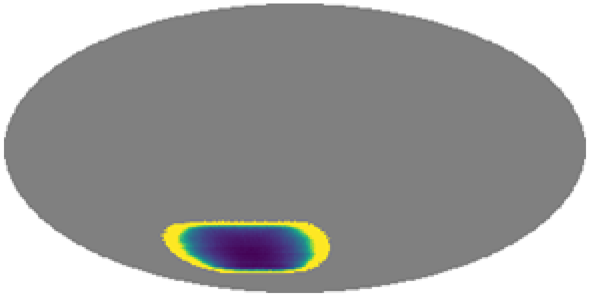
CMB S4 Early 2024 Design Status

After long consideration of possible configurations, primarily in the premier millimeter-wave sites of Atacama Chile and the South Pole, the project arrived at a baseline design to conduct the surveys:

Deep-Wide Survey from Chile
with two 6m telescopes



Ultra-deep Survey from South Pole
24/7 targeted observations with one 5m telescope & nine 0.6m telescopes



CMB-S4 to exploit the unique features of each site

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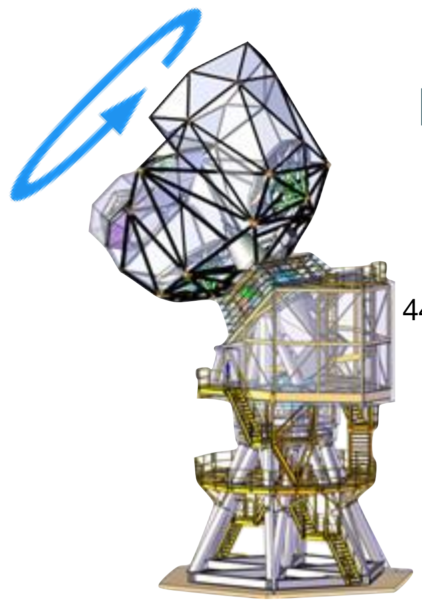
Chile

Two 6m Telescopes

CCAT and SO Design

South Pole

One 5m Telescope,
Nine 0.6m telescopes



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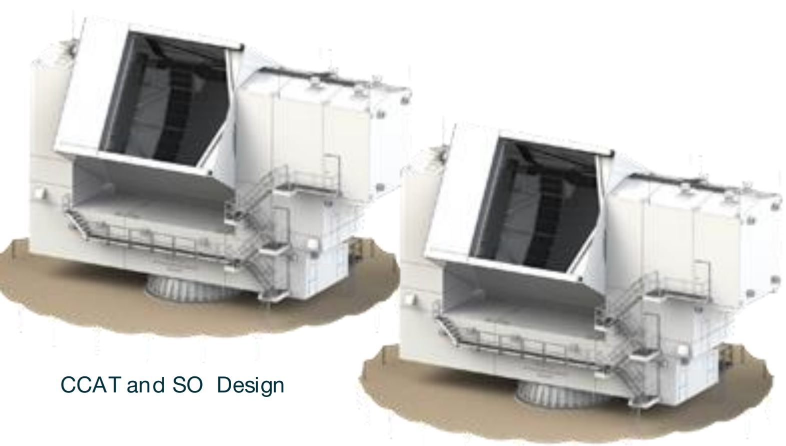
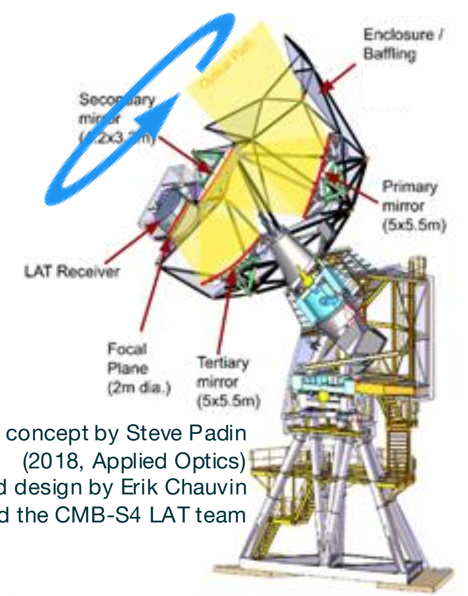


CCAT and SO Design



Design concept by Steve Padin (2018, Applied Optics)
Detailed design by Erik Chauvin and the CMB-S4 LAT team

Three Mirror Anastigmat (TMA)

Enormous FOV and optimized for control of systematics for degree angular scale B-mode and for arcminute CMB lensing measurements

CMB-S4 to exploit the unique features of each site

Goals of Modern Cosmology

To develop and test theoretical models that can explain astronomical observations and particle physics measurements to build a coherent understanding of the cosmos.

Research Areas

- **Origin**: Uncover the mechanisms of cosmic genesis and constrain inflation models
- **Evolution**: Characterize the universe's expansion history with precision
- **Structure Formation**: Explain the emergence of cosmic structure across scales
- **Composition Analysis**: Determine the exact nature of dark matter and dark energy
- **(Ultimate Fate**: Model long-term cosmic evolution scenarios)

The CMB will remain a cornerstone of cosmological research, with several exciting future directions. (ou alors dans les conclusions)