Cosmology with CMB

P2I - January 2024

Sophie Henrot-Versillé

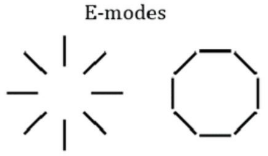
Cosmology with CMB

Where do we stand (biased view & not exhaustive) ?

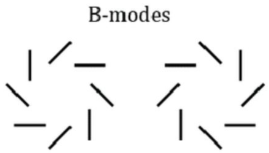
Where do we go and how ?

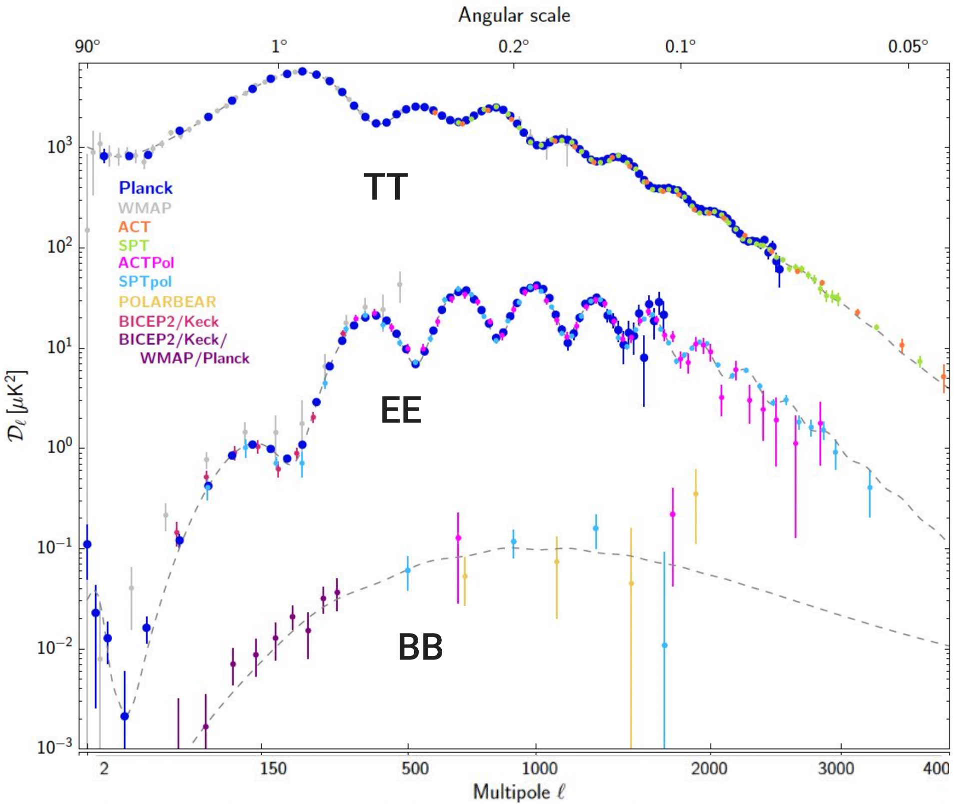
CMB spectra state of the art: Temperature & Polarisation

curl-free even-parity



divergence- free odd-parity

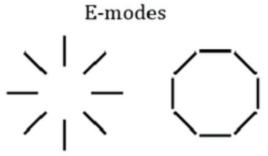




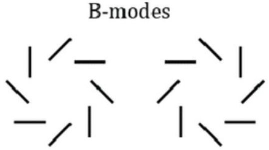
Planck 2018 results. I. Overview and the cosmological legacy of Planck - Planck collaboration

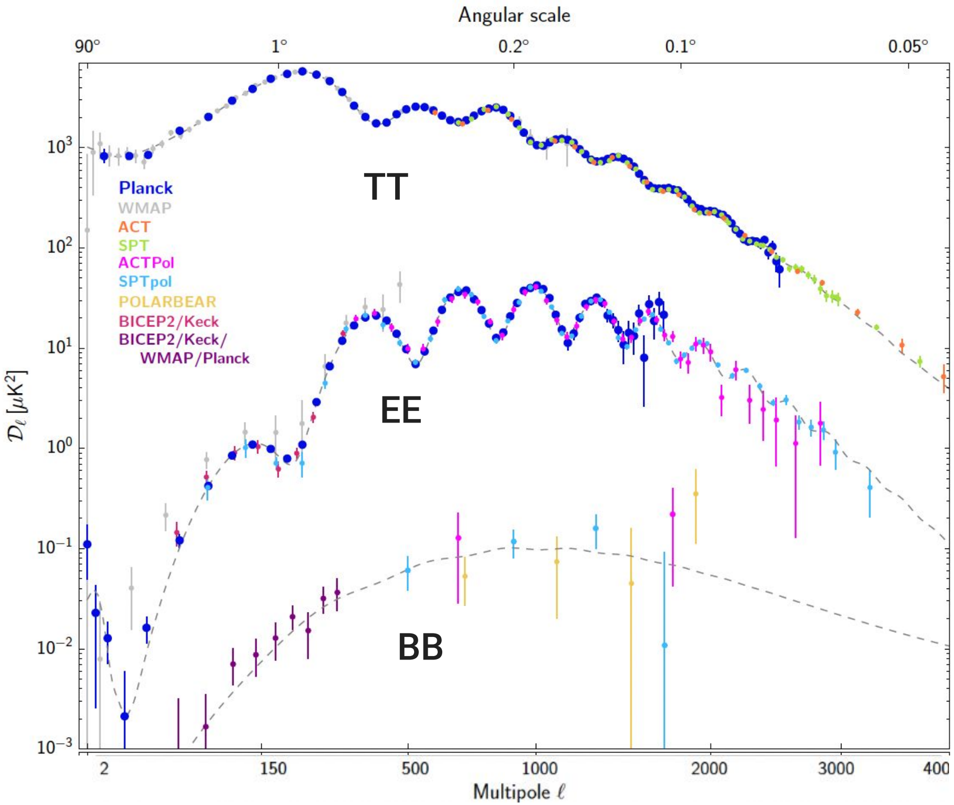
CMB spectra state of the art: Temperature & Polarisation

curl-free even-parity



divergence- free odd-parity

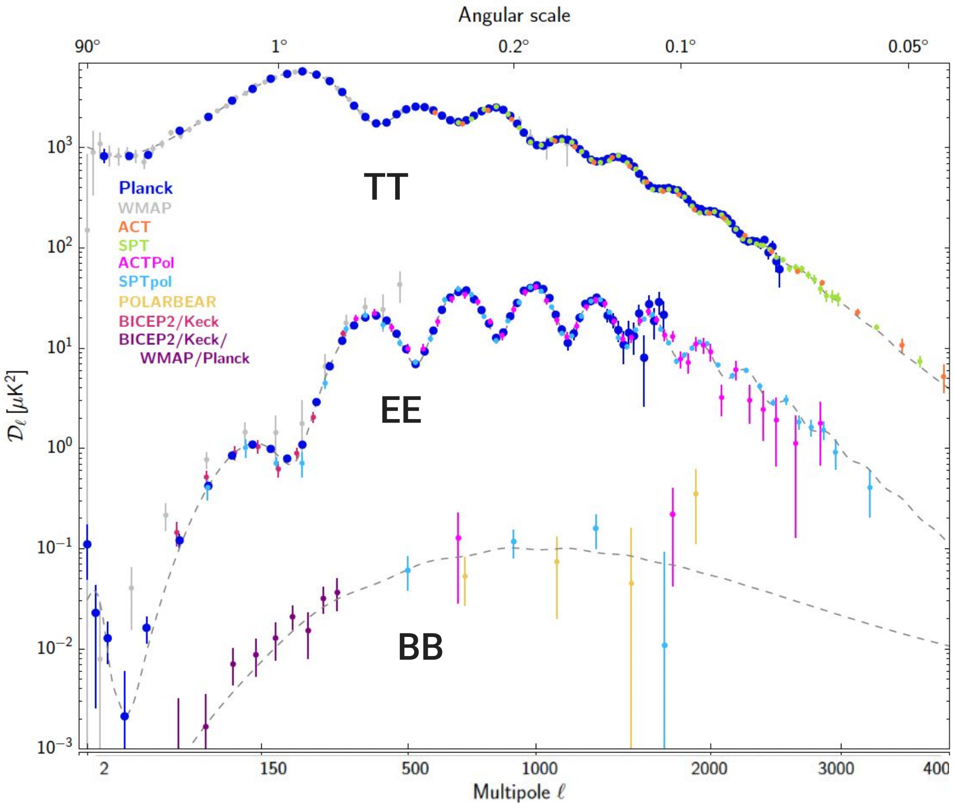




Planck 2018 results. I. Overview and the cosmological legacy of Planck - Planck collaboration

CMB spectra state of the art: Temperature & Polarisation

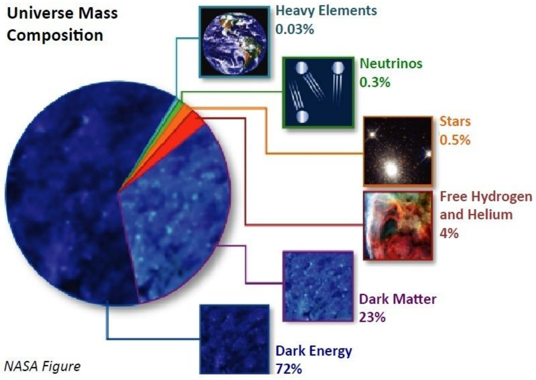
The TT Planck spectrum is cosmic variance limited up to l=1600
It **cannot** be improved !



Planck 2018 results. I. Overview and the cosmological legacy of Planck - Planck collaboration

What do we mean by ΛCDM ?

Minimal ΛCDM ID CARD



$$\rho_\nu = N_{\rm eff}(7/8)(4/11)^{4/3}\rho_\gamma$$

$N_{\rm eff} = 3.046$ 3 neutrinos not fully decoupled before electron-positron annihilation

$m_\nu = 0.06\,{\rm eV}$ and only one massive neutrino (sometimes 3 with equal masses..)

$A_L = 1$, introduced to test the lensing $C_\ell^\Psi \to A_L C_\ell^\Psi$

- Flat universe
- Gaussian, adiabatic fluctuations
- no primordial gravitational waves,
- no running of the spectral index

…

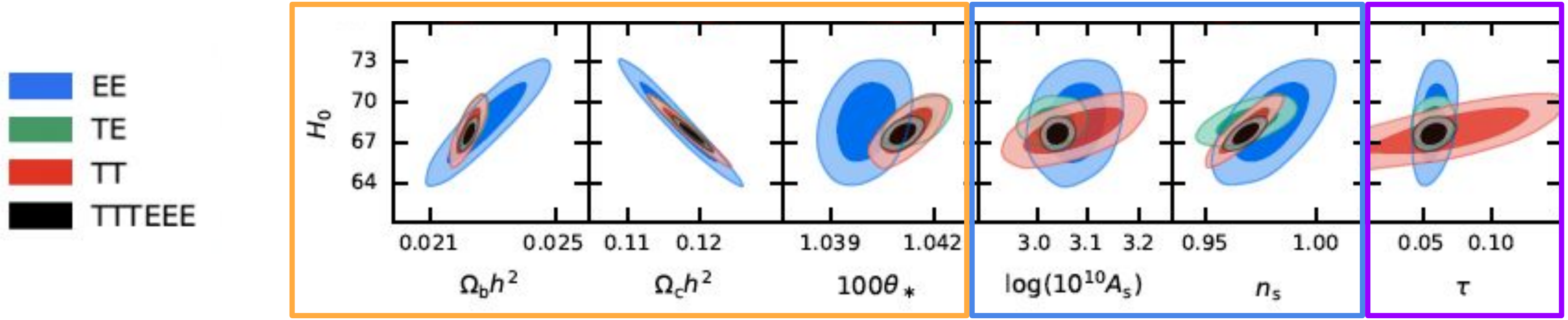
…

ΛCDM: 6 parameters, where do we stand ?

Cosmological parameters derived from the final (PR4) Planck data release

M. Tristram, A.J. Banday, M. Douspis, X. Garrido, K.M. Górski, S. Henrot-Versillé, S. Ilić, R. Keskitalo, G. Lagache, C.R. Lawrence, B. Partridge, D. Scott

NEW RELEASE



Matter & Dark Energy Content, H0

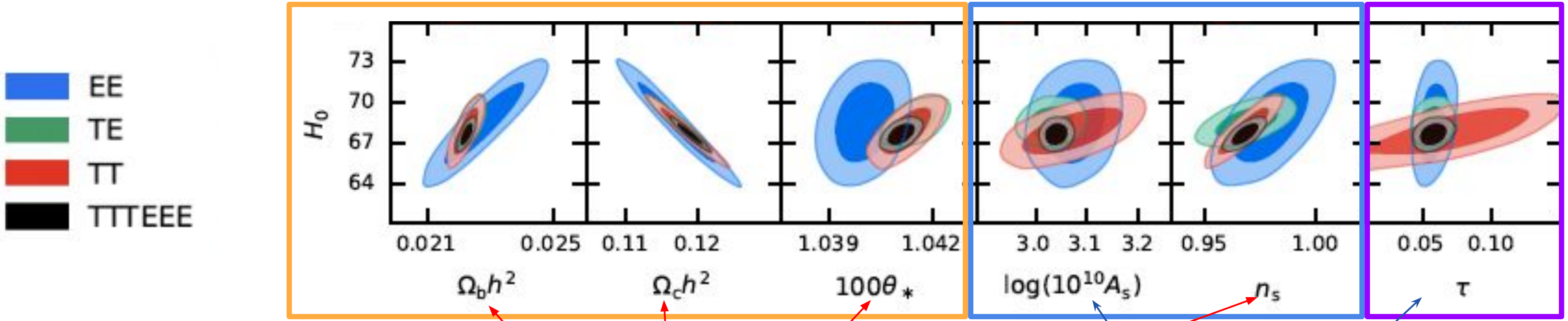
Primordial spectrum parameters

Reionisation optical depth

ΛCDM: where do we stand ?

Cosmological parameters derived from the final (PR4) Planck data release

M. Tristram, A.J. Banday, M. Douspis, X. Garrido, K.M. Górski, S. Henrot-Versillé, S. Ilić, R. Keskitalo, G. Lagache, C.R. Lawrence, B. Partridge, D. Scott



Parameter	TT	TTTEEE
$\Omega_b h^2$	0.02224 ± 0.00025	0.02226 ± 0.00013
$\Omega_c h^2$	0.1183 ± 0.0024	0.1188 ± 0.0012
$100\theta_*$	1.04123 ± 0.00046	1.04108 ± 0.00026
$\log(10^{10}A_s)$	3.073 ± 0.061	3.040 ± 0.014
n_s	0.9678 ± 0.0072	0.9681 ± 0.0039
τ	0.0753 ± 0.0322	0.0580 ± 0.0062
H_0	67.89 ± 1.11	67.64 ± 0.52
σ_8	0.8186 ± 0.0221	0.8070 ± 0.0065
S_8	0.826 ± 0.024	0.819 ± 0.014
Ω_m	0.3059 ± 0.0147	0.3092 ± 0.0070

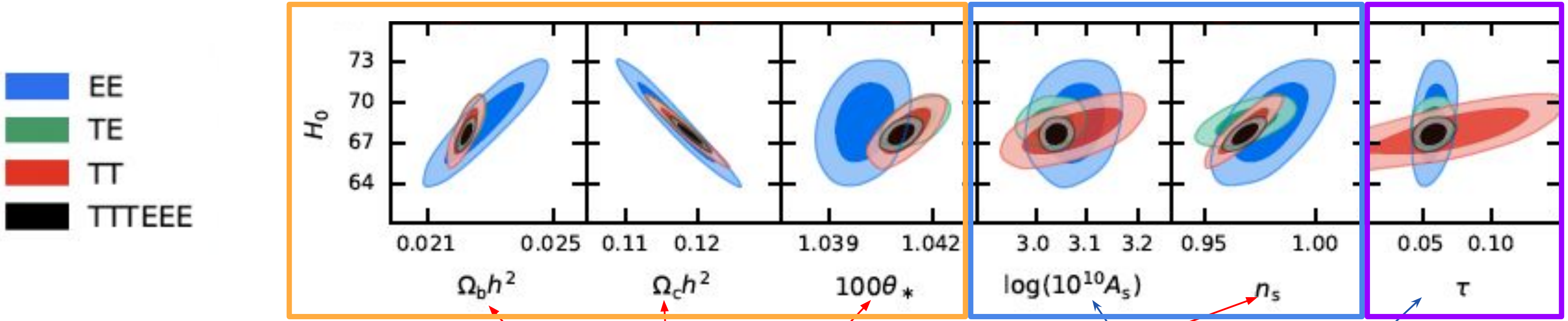
CMB TT data dominate the error bars

TT and EE have ~ same weight in the error budget TODAY !

ΛCDM: where do we stand ?

Cosmological parameters derived from the final (PR4) Planck data release

M. Tristram, A.J. Banday, M. Douspis, X. Garrido, K.M. Górski, S. Henrot-Versillé, S. Ilić, R. Keskitalo, G. Lagache, C.R. Lawrence, B. Partridge, D. Scott



Parameter	TT	TTTEEE
$\Omega_b h^2$	0.02224 ± 0.00025	0.02226 ± 0.00013
$\Omega_c h^2$	0.1183 ± 0.0024	0.1188 ± 0.0012
$100\theta_*$	1.04123 ± 0.00046	1.04108 ± 0.00026
$\log(10^{10}A_s)$	3.073 ± 0.061	3.040 ± 0.014
n_s	0.9678 ± 0.0072	0.9681 ± 0.0039
τ	0.0753 ± 0.0322	0.0580 ± 0.0062
H_0	67.89 ± 1.11	67.64 ± 0.52
σ_8	0.8186 ± 0.0221	0.8070 ± 0.0065
S_8	0.826 ± 0.024	0.819 ± 0.014
Ω_m	0.3059 ± 0.0147	0.3092 ± 0.0070

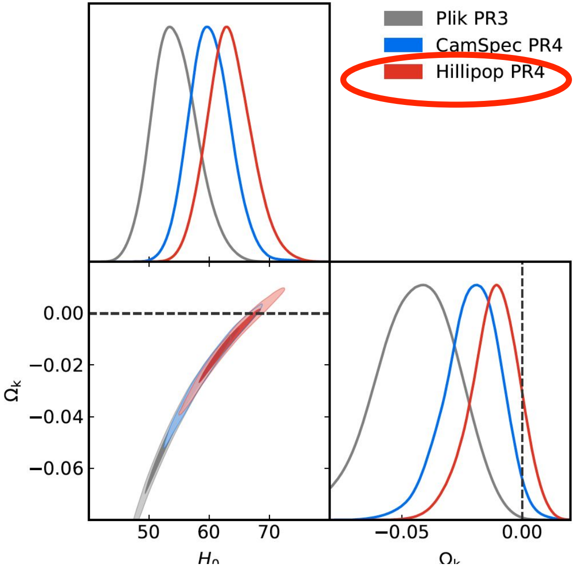
CMB TT data dominate the error bars

TT and EE have ~ same weight in the error budget TODAY !

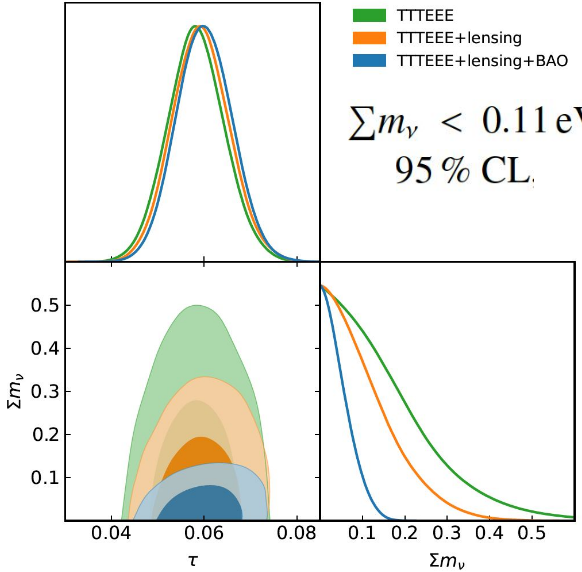
Beyond ΛCDM…curvature, neutrinos, …

Cosmological parameters derived from the final (PR4) Planck data release

M. Tristram, A.J. Banday, M. Douspis, X. Garrido, K.M. Górski, S. Henrot-Versillé, S. Ilić, R. Keskitalo, G. Lagache, C.R. Lawrence, B. Partridge, D. Scott



$$\Omega_K = -0.012 \pm 0.010,$$



$$\sum m_\nu < 0.11\,\text{eV}$$
95 % CL.

$$\sum m_\nu < 0.39\,\text{eV}$$
(95 % CL, TTTEEE).

Beyond ΛCDM…primordial Universe

Inflation predicts the existence of two types of perturbations:

- fluctuations of the scalar inflaton field: scalar perturbations
- fluctuations of the gravitational field: tensor perturbations
  The so-called primordial gravitational waves !

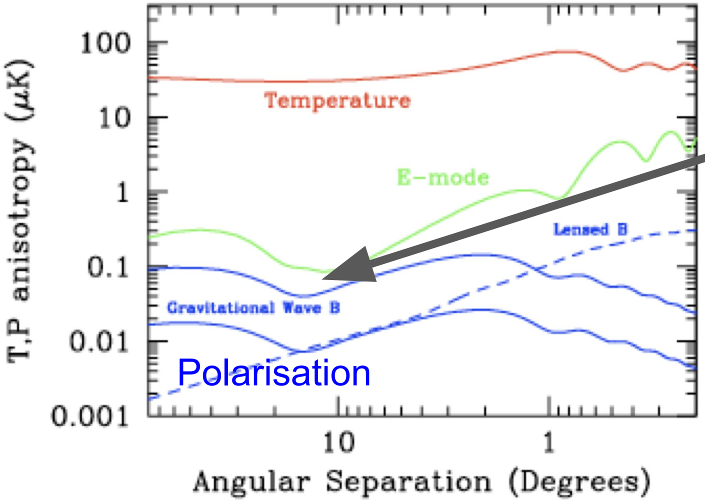
$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1} \quad \text{scalar}$$

$$\mathcal{P}_{\mathcal{T}}(k) = A_t \left(\frac{k}{k_0}\right)^{n_t} \quad \text{tensor}$$

$$r = A_t / A_s$$

"Tensor to scalar ratio"

Amplitude of the CMB Bmode spectrum at large scales



In slow-roll inflation (favored by current data): given it is generated by one scalar field:

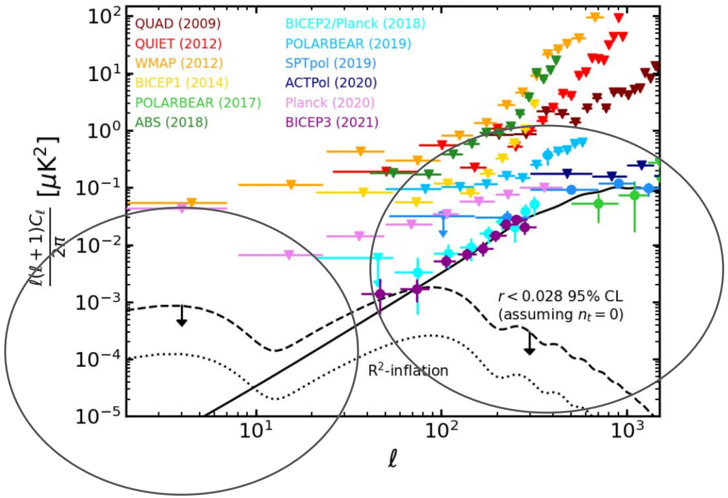
$$r = 8M_{\rm Pl}^2 \left(\frac{V_\phi}{V}\right)^2$$

$$n_s - 1 \equiv \frac{d\ln \mathcal{P}_\zeta}{d\ln k} \simeq -3M_{\rm Pl}^2 \left(\frac{V_\phi}{V}\right)^2 + 2M_{\rm Pl}^2 \frac{V_{\phi\phi}}{V}$$

$$n_t = -r/8$$

First and second derivative of the potential

Beyond ΛCDM…r and nt

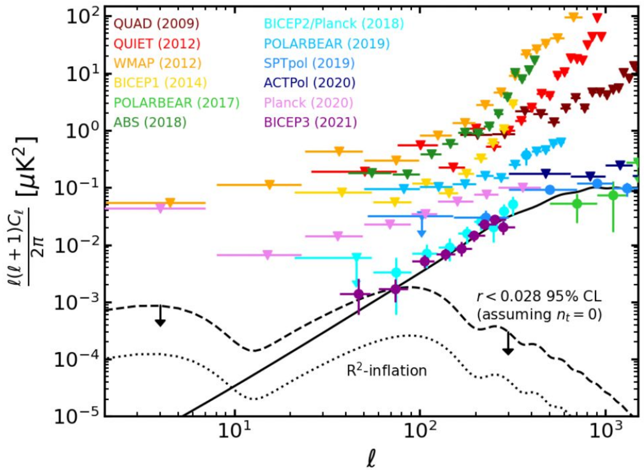


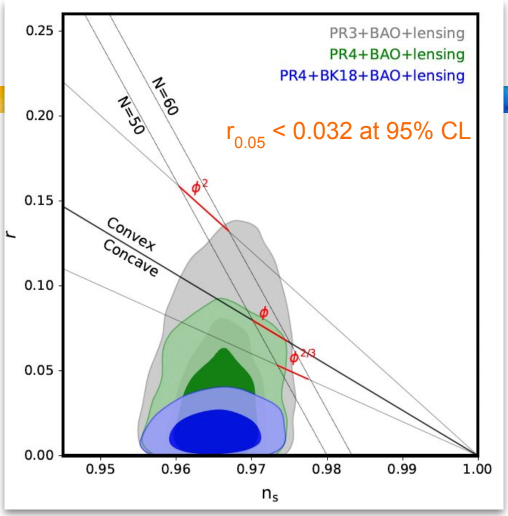
Lensed
B modes

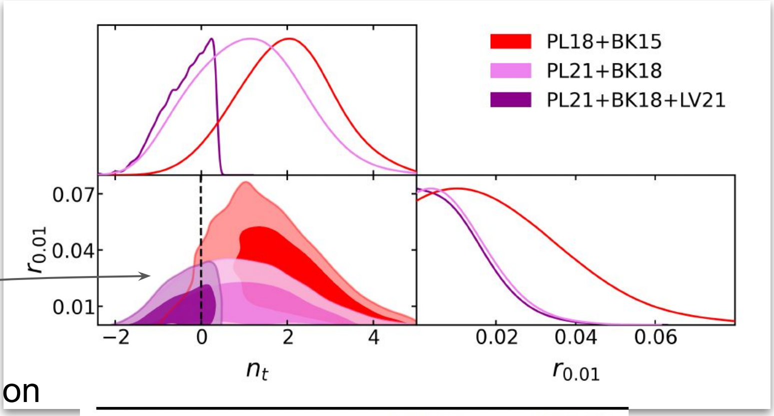
primordial signal

> CMB photons are gravitationally deflected by large scale structures
> The amount of lensing deflection depends on the projected (dark+neutrinos..) matter density in that direction

Beyond ΛCDM…r and nt







Improved limits on the tensor-to-scalar ratio using BICEP and *Planck*

M. Tristram,[1] A. J. Banday,[2] K. M. Górski,[3,4] R. Keskitalo,[5,6] C. R. Lawrence,[3] K. J. Andersen,[7] R. B. Barreiro,[8] J. Borrill,[5,9] L. P. L. Colombo,[10] H. K. Eriksen,[7] R. Fernandez-Cobos,[11] T. S. Kisner,[5,6] E. Martínez-González,[8] B. Partridge,[12] D. Scott,[13] T. L. Svalheim,[7] and I. K. Wehus[7]

Updated constraints on amplitude and tilt of the tensor primordial spectrum

Giacomo Galloni[1,2], Nicola Bartolo[3,4,5], Sabino Matarrese[3,4,5,6], Marina Migliaccio[1,2], Angelo Ricciardone[3,4] and Nicola Vittorio[1,2]

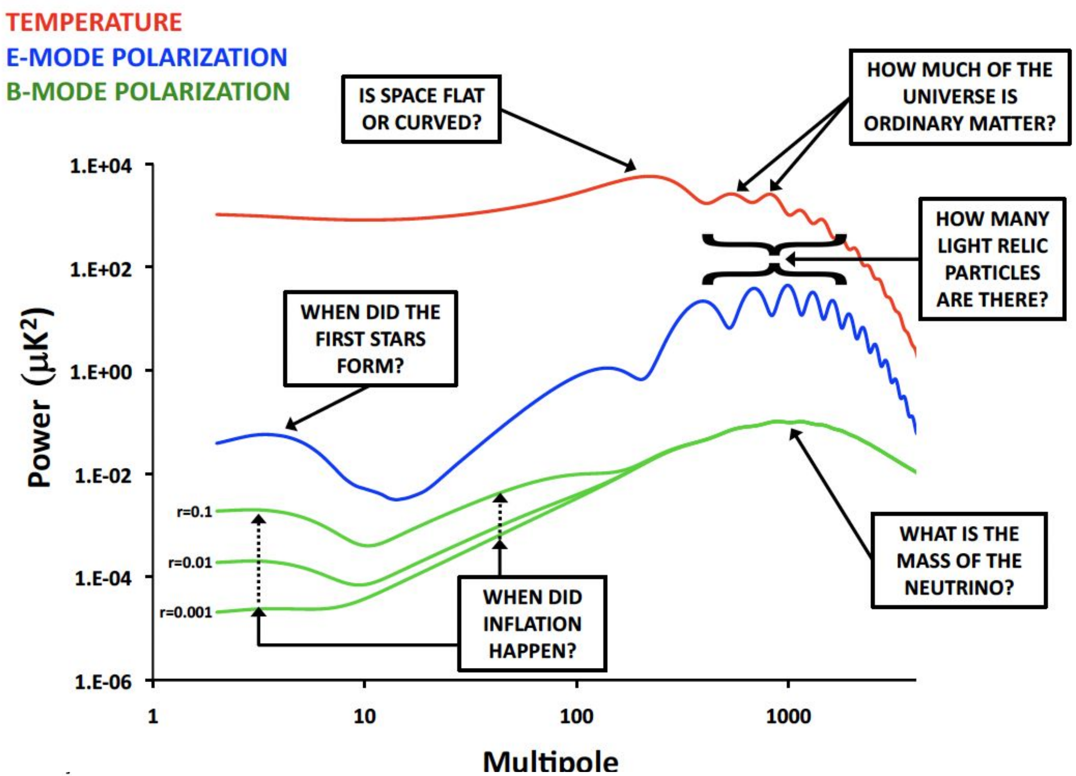
Published 26 April 2023 •

slow-roll single-field prediction

$$n_t = -r/8 = -2\epsilon.$$

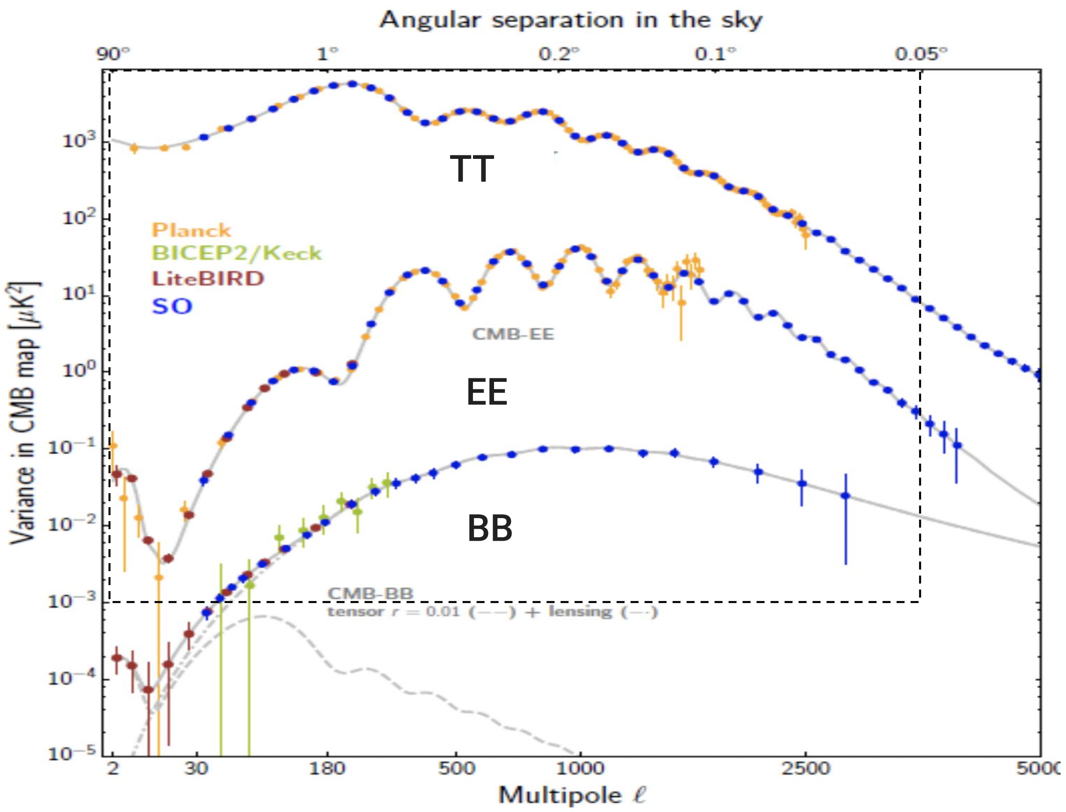
	$r_{0.01}$ 95% CL	n_t 95% CL
PL21+BK18	< 0.029	[−1.21, 3.54]

What are the next steps & what to measure ?



Snowmass2021 Cosmic Frontier: Cosmic Microwave Background Measurements White Paper

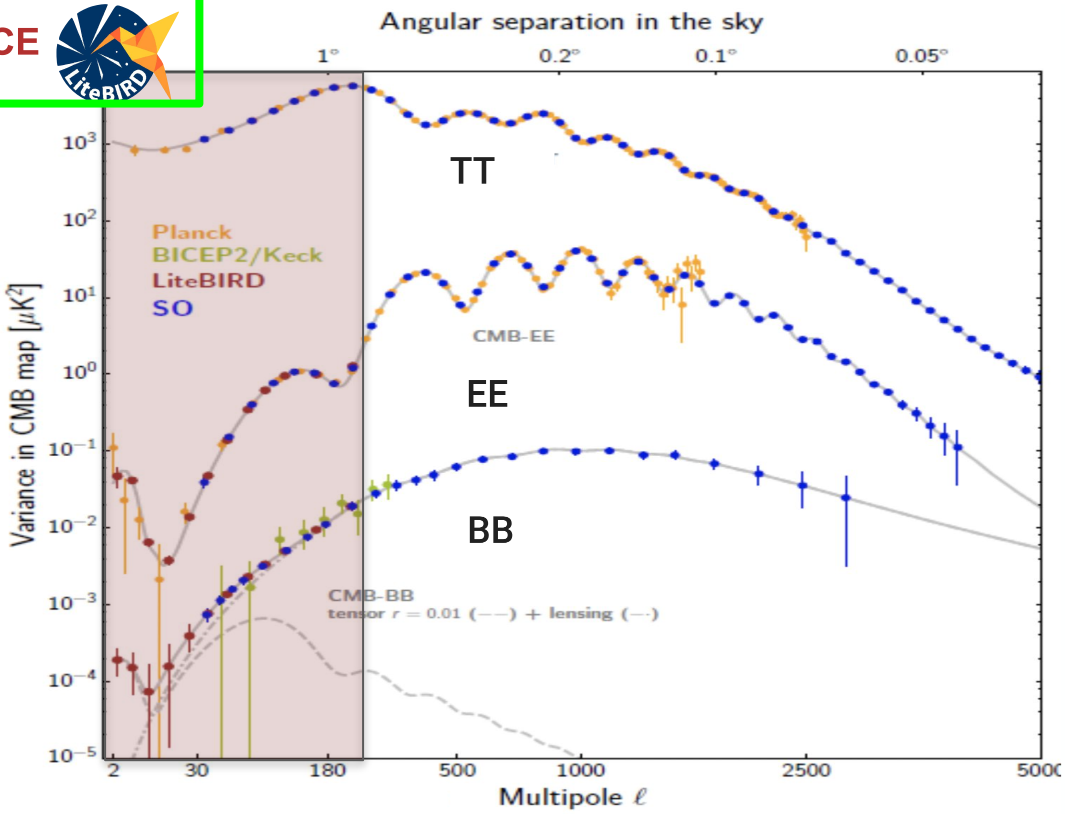
Into the future…



Into the future…

SPACE

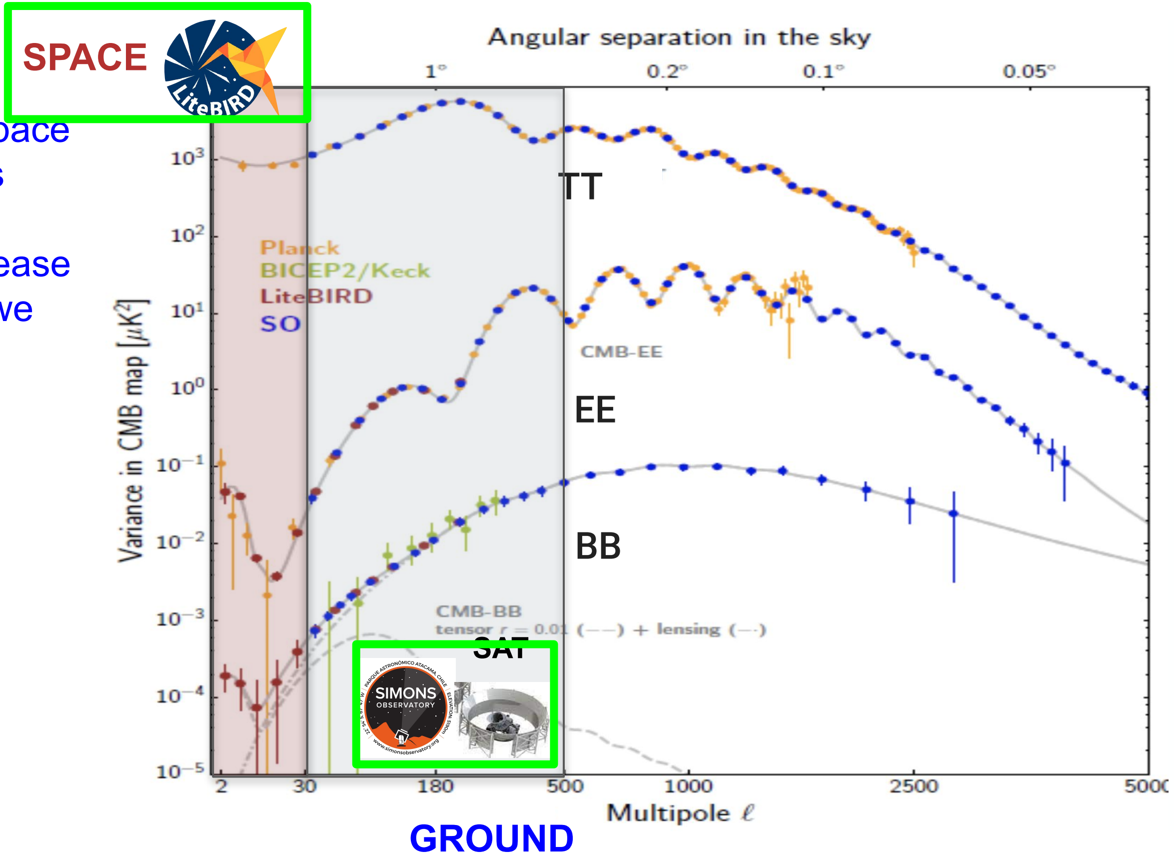
We need to go to space
for the larger scales



Into the future…

We need to go to space for the larger scales

To significantly increase the # of detectors, we need to be on the ground



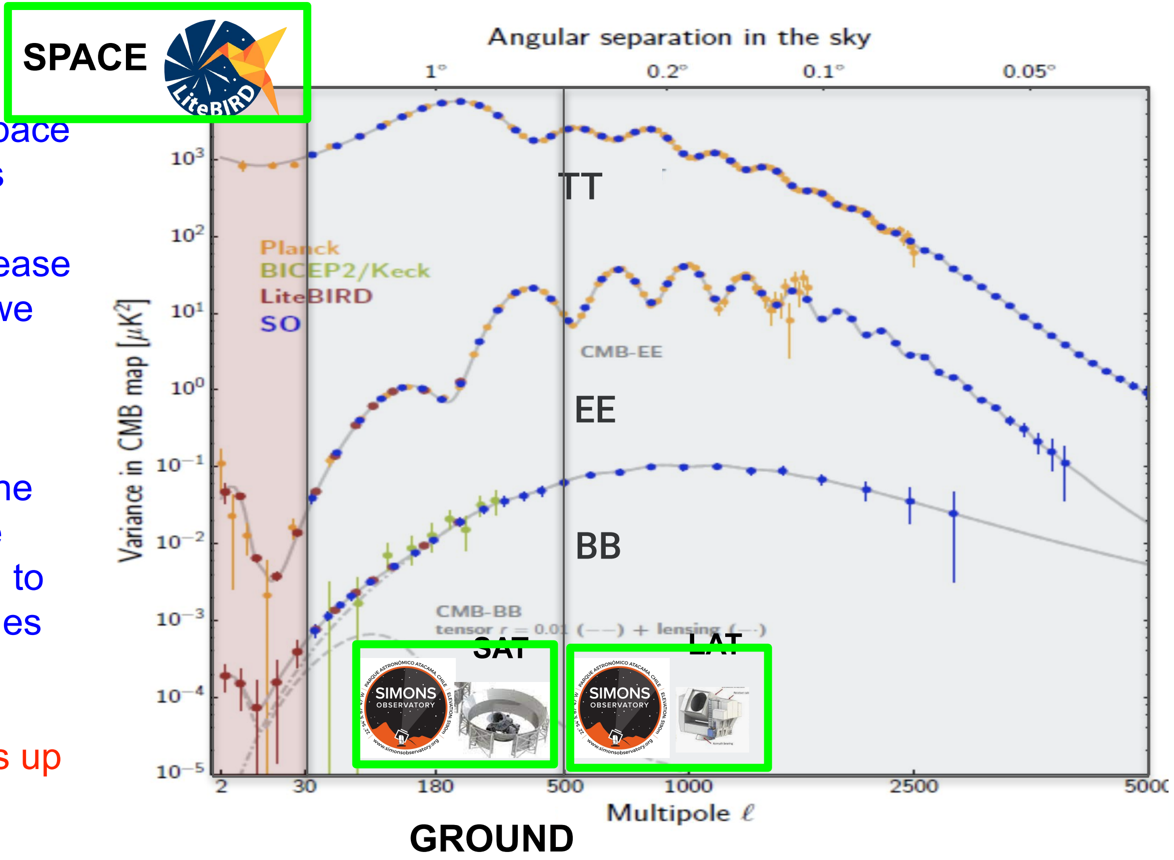
Into the future…

We need to go to space for the larger scales

To significantly increase the # of detectors, we need to be on the ground

We need to be on the ground for the large telescopes required to study the small scales (neutrino mass)

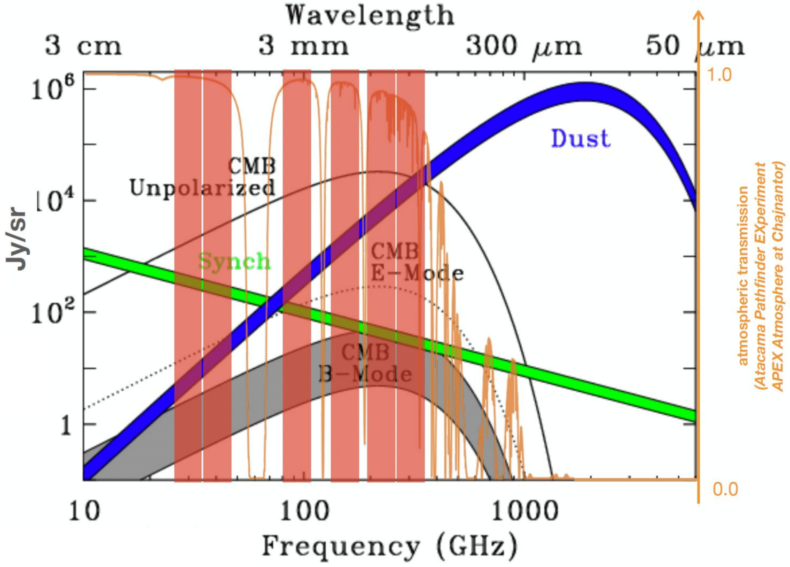
=> Best TradeOff as up now



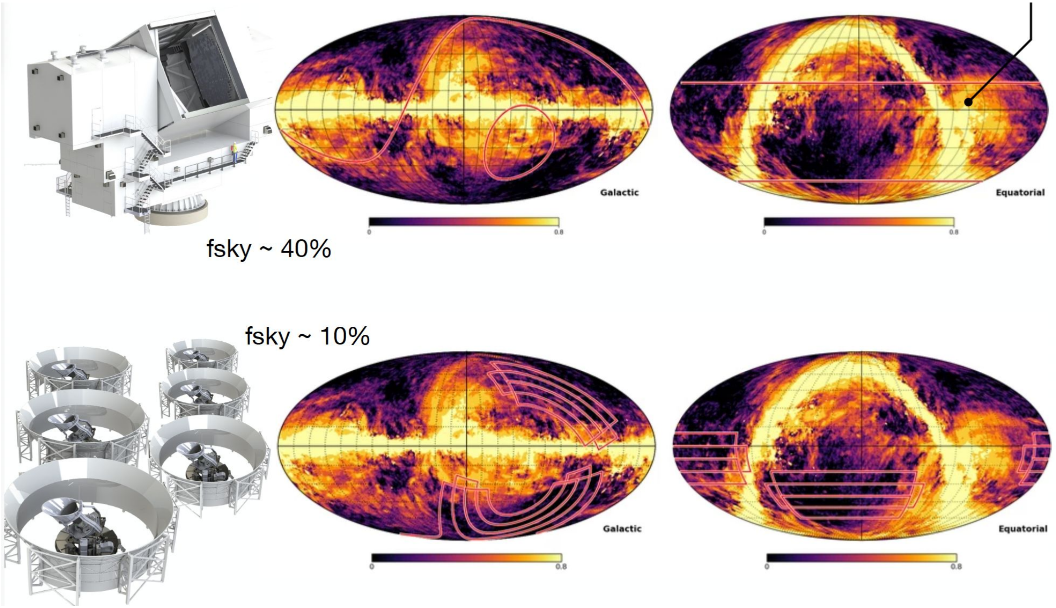
++ CMB-S4

Simons Observatory in a nutshell

6 frequency bands
27-270 GHz

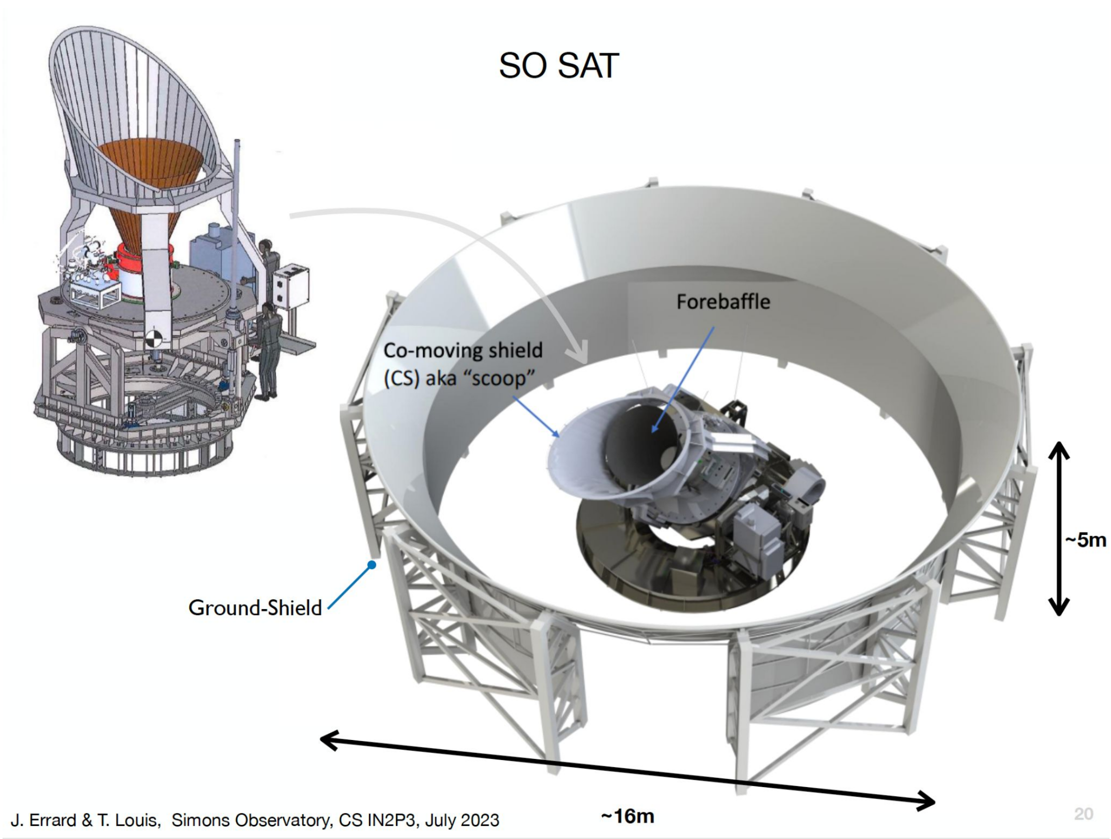


LAT & SAT

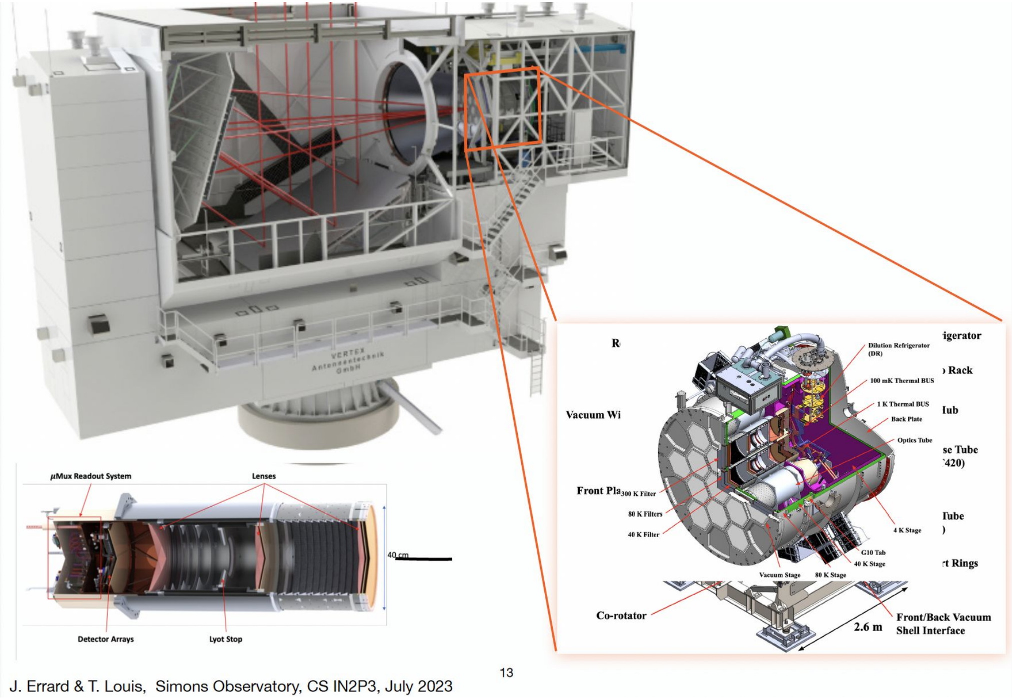


credit: Josquin Errard

Simons Observatory: SAT - baffle and installation

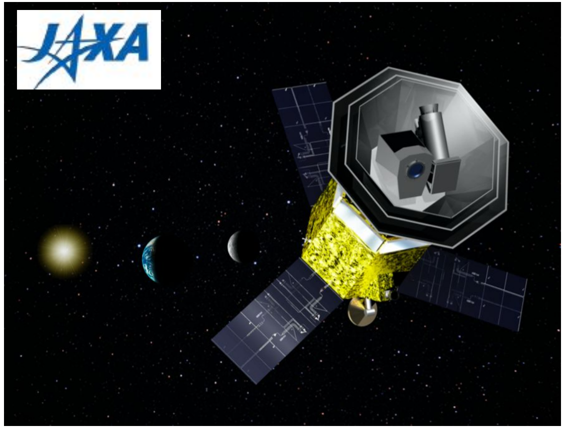


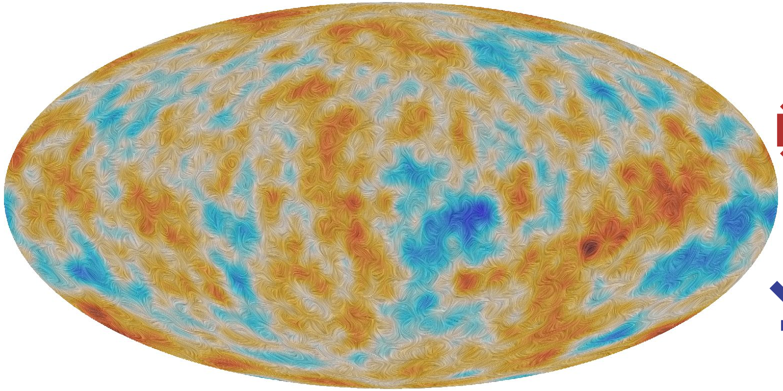
Simons Observatory: LAT - the instrument

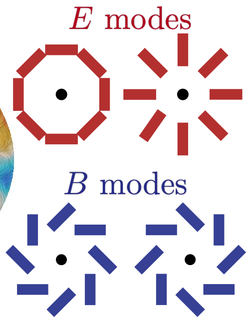


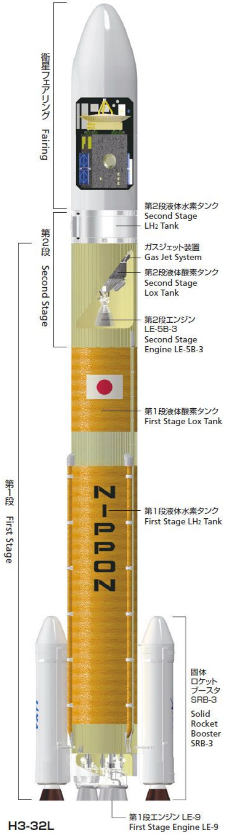
LiteBIRD: overview

- Lite (Light) satellite for the study of *B*-mode polarization and Inflation from cosmic background Radiation Detection
- JAXA's L-class mission selected in May 2019
- Expected launch ~**2032** with 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**, after component separation







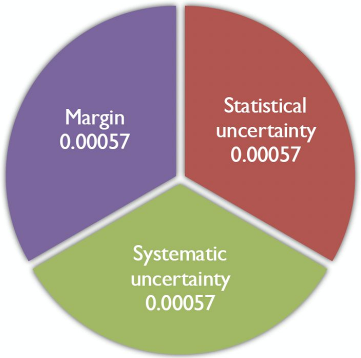


LiteBIRD full success

Full Success

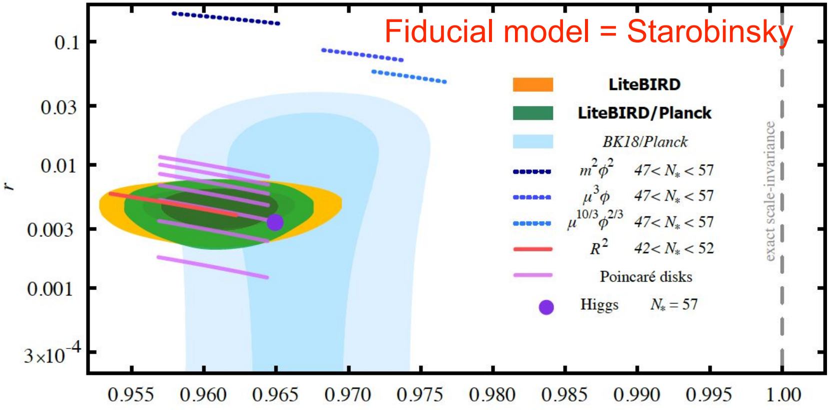
- $\sigma(r) < 10^{-3}$ (for r=0, no delensing)
- $>5\sigma$ observation for each bump (for $r \geq 0.01$)

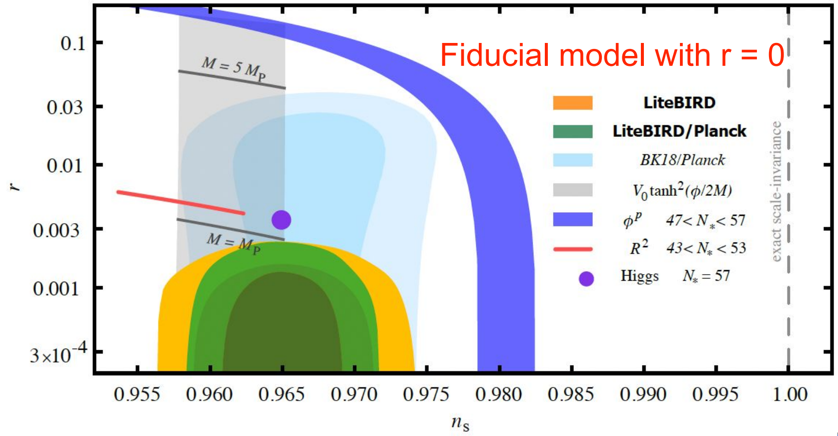
LiteBIRD will also provide a cosmic variance limited measurement of the E modes



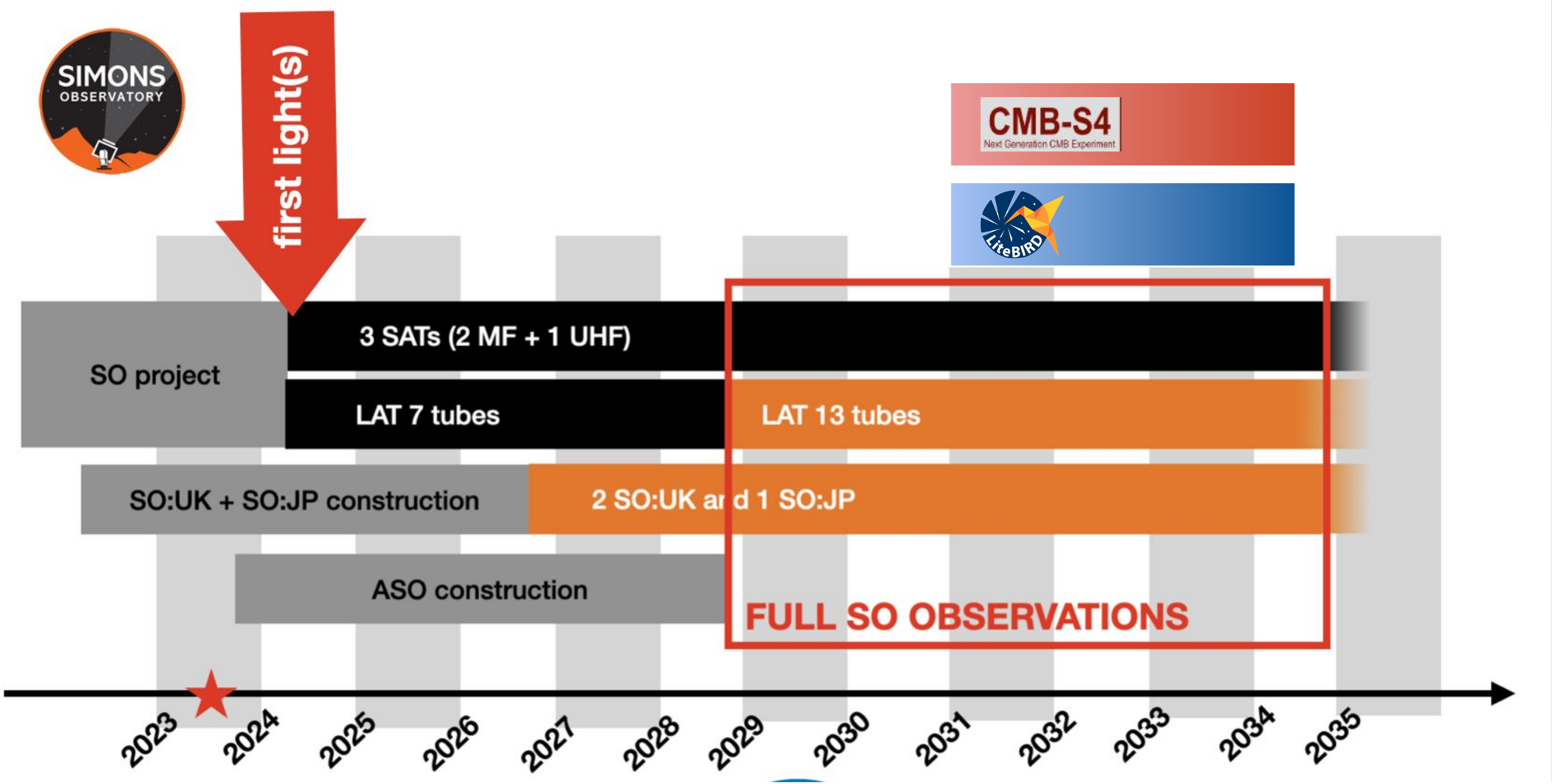
Statistical uncertainty
- foreground cleaning residuals
- lensing B-mode power
- 1/f noise

Systematic uncertainty
- Bias from 1/f noise
- Polarization efficiency & knowledge
- Disturbance to instrument
- Off-boresight pick up
- Calibration accuracy



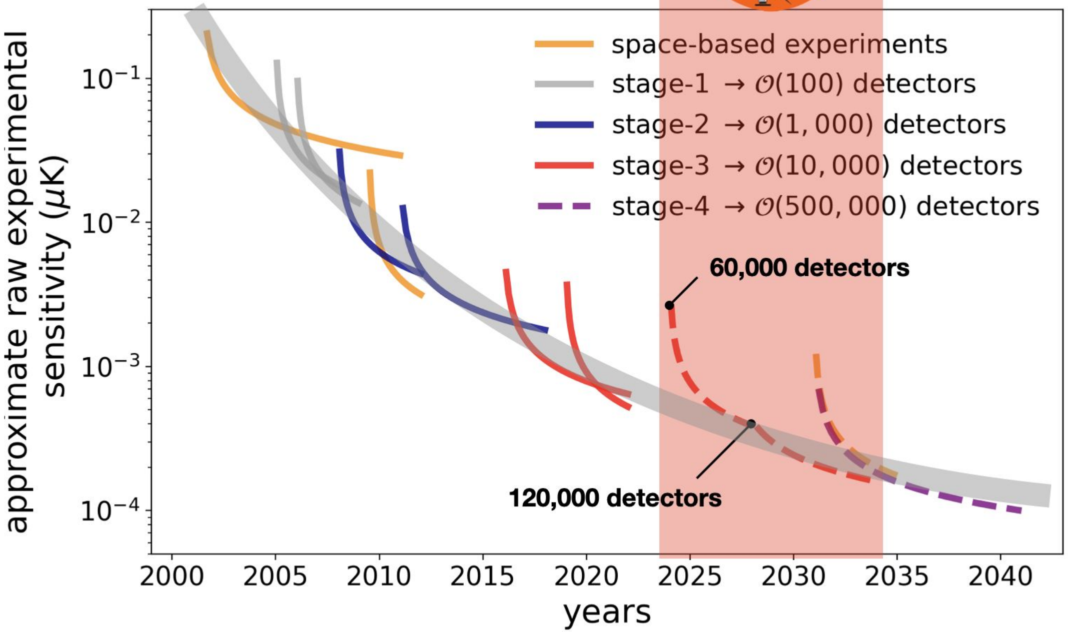


Timescales…


SIMONS OBSERVATORY
first light(s)
CMB-S4
Next Generation CMB Experiment
LiteBIRD
SO project
3 SATs (2 MF + 1 UHF)
LAT 7 tubes
LAT 13 tubes
SO:UK + SO:JP construction
2 SO:UK and 1 SO:JP
ASO construction
FULL SO OBSERVATIONS
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035

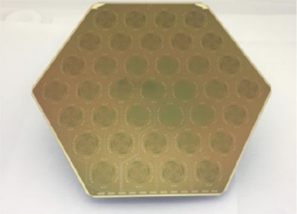
Simons Observatory: detectors

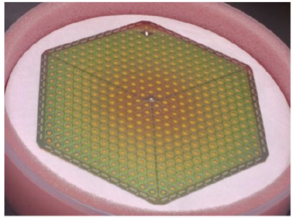
SO sensitivity

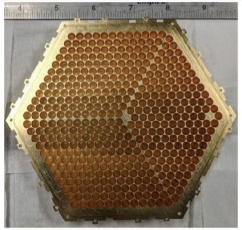


Low frequency (LF) detector arrays & lenslets

Mid frequency (MF) and ultra-high frequency (UHF) detector & horn arrays





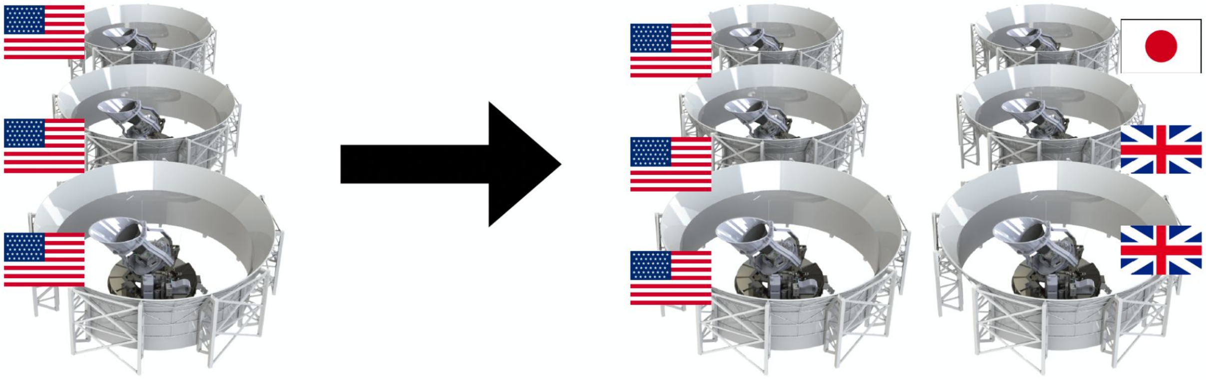


SO will use dual-polarization. dichroic TES bolometer detectors. cooled to 100 mK. The LF detector arrays build on the proven performance of POLARBEAR and the MF and UHF on ACT.

Simons Observatory: SAT - TimeScales

From Josquin Errard, CS IN2P3 July 2023

news #1 SO += SO:UK + SO:JP



~ 2024

~ 2028

3 SATs
30,000 detectors in total
6 frequency bands

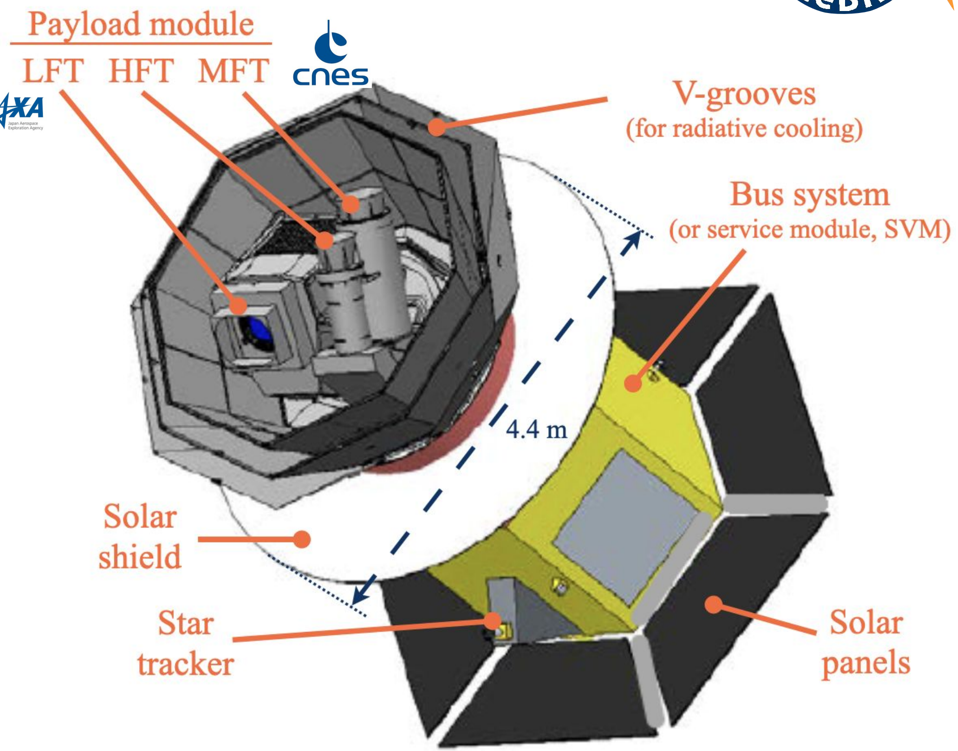
6 SATs
60,000 detectors in total
6 frequency bands

…a French SAT is also discussed

The instruments and the payload

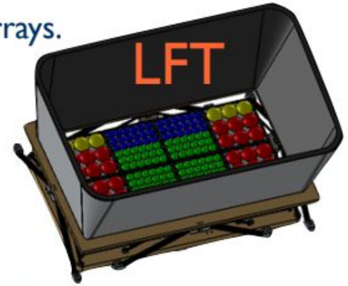
- **3 telescopes** are used to provide the **40-402 GHz** frequency coverage
  1. **LFT** (low frequency telescope)
  2. **MFT** (middle frequency telescope)
  3. **HFT** (high frequency telescope)
- Multi-chroic transition-edge sensor (TES) **bolometer arrays** cooled to **100 mK**
- Polarization modulation unit (PMU) in each telescope with **rotating half-wave plate** (HWP), for $1/f$ noise and systematics reduction
- Optics cooled to **5 K**

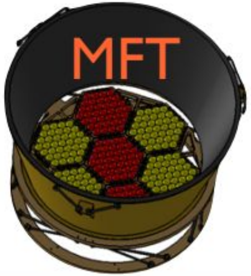
- Mass: 2.6 t
- Power: 3.0 kW
- Data: 17.9 Gb/day



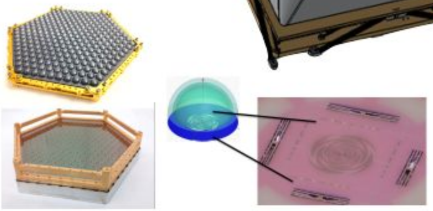
LiteBIRD focal planes

- Transision-Edge Sensor (TES) arrays.
- Multichroic detectors.
- Number of sensors: 4508
- 15 bands including overlap between instruments.

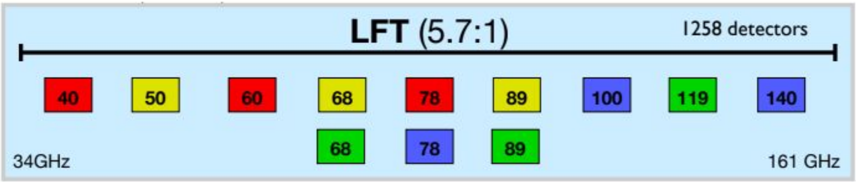


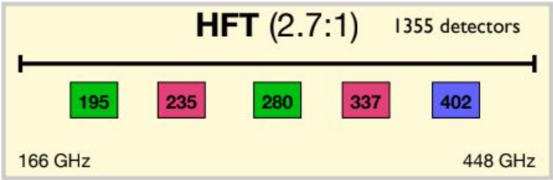


Lensed coupled detectors
Lenslets

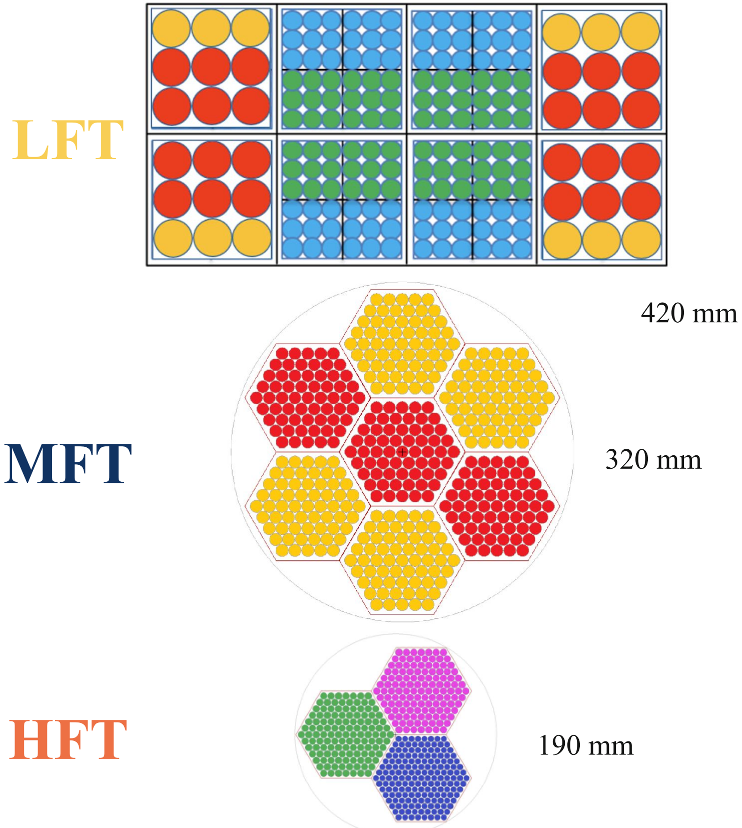


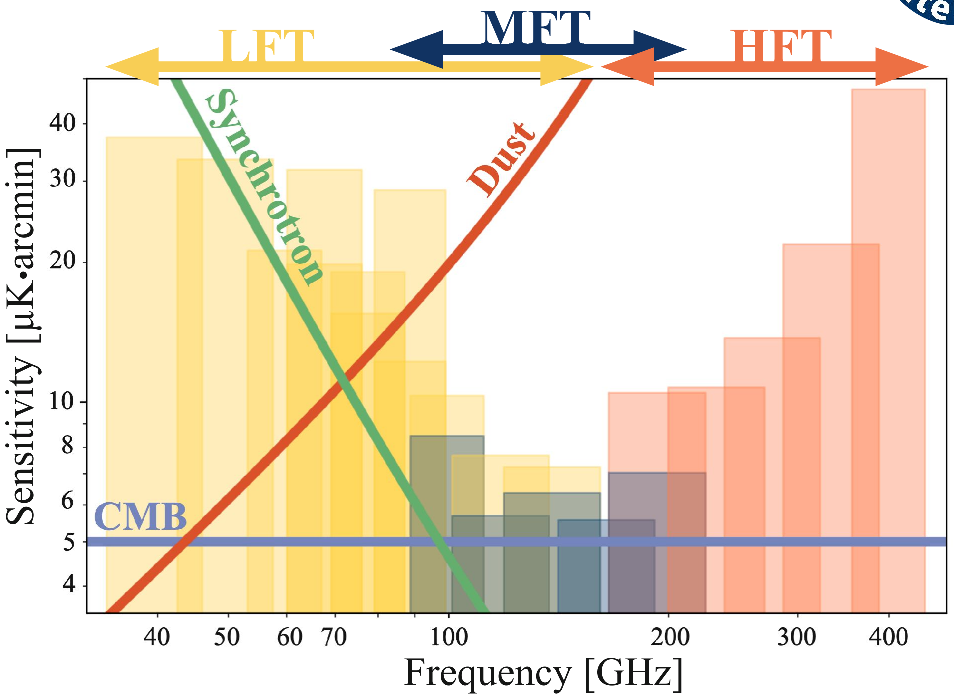
Horn coupled detectors
Platelets





LiteBIRD sensitivity





- Projected **polarization sensitivities** for a **3-year full-sky survey**
- Best of 4.3 μK·arcmin @ 119 GHz (Hazumi+ 2020)
- Combined sensitivity to primordial CMB anisotropies (after foreground removal): **2.2 μK·arcmin**

LiteBIRD full success / extra success

Extra Success

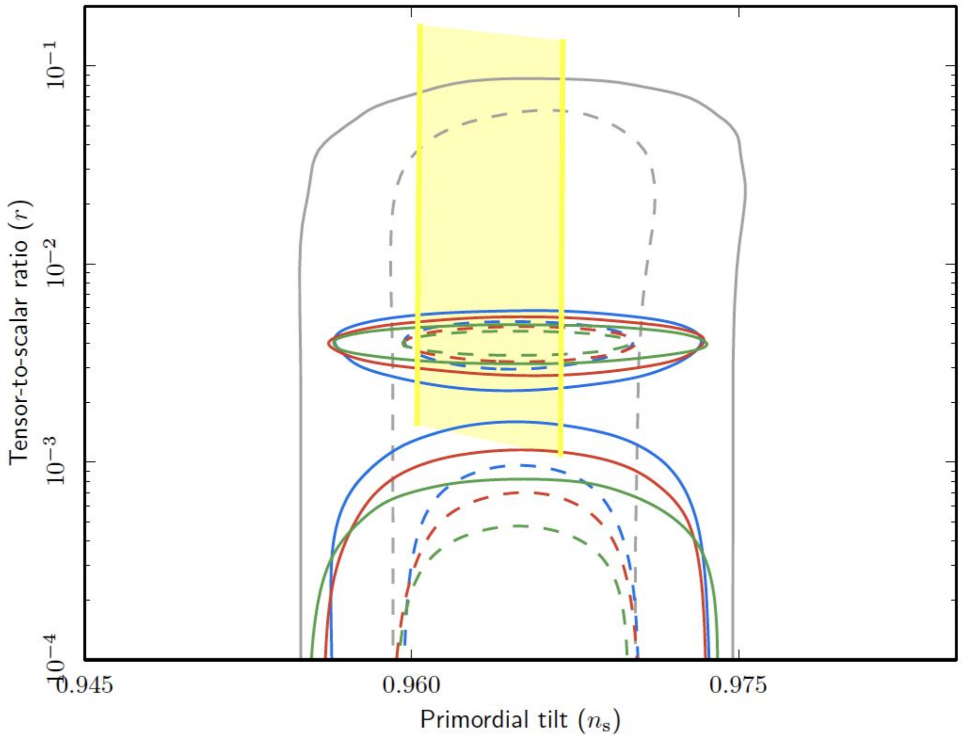
- improve σ(r) with external observations
- delensing improvement to σ(r) can be a factor ≥ 2

Aiming at detection with >5σ in case of Starobinsky model

Baseline

+ delensing w/Planck CIB & WISE

+ extra foreground cleaning w/ high-resolution ground CMB data

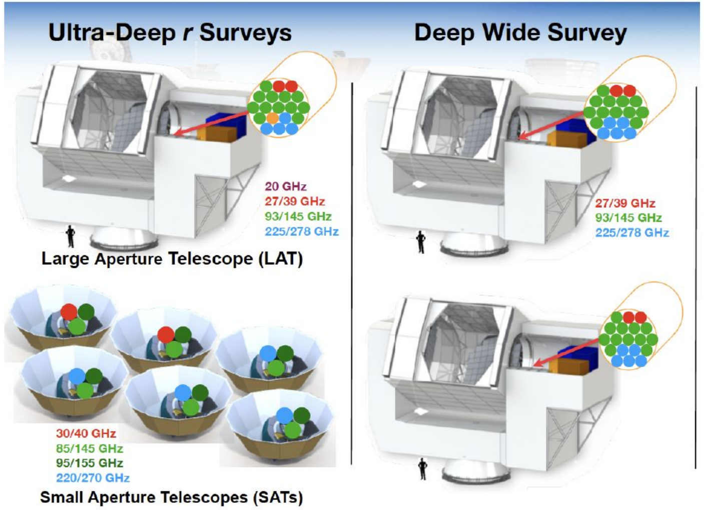


CMB-S4: the ultimate ground based ?

> Last years:
Tremendous effort
on an
Analysis Of Alternatives

> In late 2022 :
a new baseline design and a revised schedule

- South Pole:
  18 x 0.55m small refractor telescopes ~150,000 detectors with 8 bands, a dedicated de-lensing 6m telescope with 120,000 detectors, 7 bands



- Chile
  2x 6m telescope with 120,000 detectors each and 7 bands.

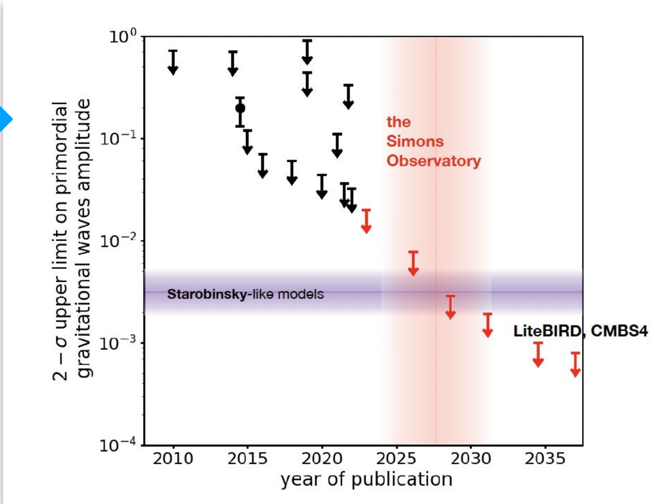
- The instrument will feature kilo-pixel arrays, dichroic, horn-coupled, superconducting TES detectors and time-domain multiplexing.

R. Stompor CS IN2P3 July 2023

Forecasts…

Table 1. Summary of Key Science Goals from Advanced SO[a]

	Current[b]	**Advanced SO 2024-2032**	CMB-S4[c] 2028-2035	Using Rubin, DESI, or *Euclid*
Primordial perturbations				
r $(A_L = 0.3)$	0.03	0.0012 [d]	0.0005	✓
n_s	0.004	0.002	0.002	-
$e^{-2\tau}\mathcal{P}(k = 0.2/\mathrm{Mpc})$	3%	0.4%		-
$f_{\mathrm{NL}}^{\mathrm{local}}$	5	1	0.6	✓
Relativistic species				
N_{eff}	0.2	0.045	0.03	-
Neutrino mass				
m_ν (eV, $\sigma(\tau) = 0.01$)	0.1	0.03	0.03	✓
m_ν (eV, $\sigma(\tau) = 0.002$)		0.015	0.015	✓
Accelerated expansion				
$\sigma_8(z = 1 - 2)$	7%	1%	1%	✓
Galaxy evolution				
η_{feedback}	50-100%	2%		✓
p_{nt}	50-100%	4%		✓
Reionization				
Δz	1.4	0.3	0.25	-
τ	0.007	0.0035	0.003	-
Cluster catalog	4000	33,000	70,000	✓
AGN catalog	2000	100,000	$> 100,000$	-
Galactic science				
Molecular cloud B-fields	10s	> 860		-
$\sigma(\beta_{dust})$	0.02	< 0.01		-
Planet 9				
Distance limit for 5 M_e		900 AU		✓
Transient Detection Distance				
Long GRBs, on-axis		420 Mpc		✓
Low-Luminosity GRBs		60-190 Mpc		✓
Normal SNe		$\gtrsim 4$ Mpc		✓
TDEs, on-axis		2100 Mpc		✓

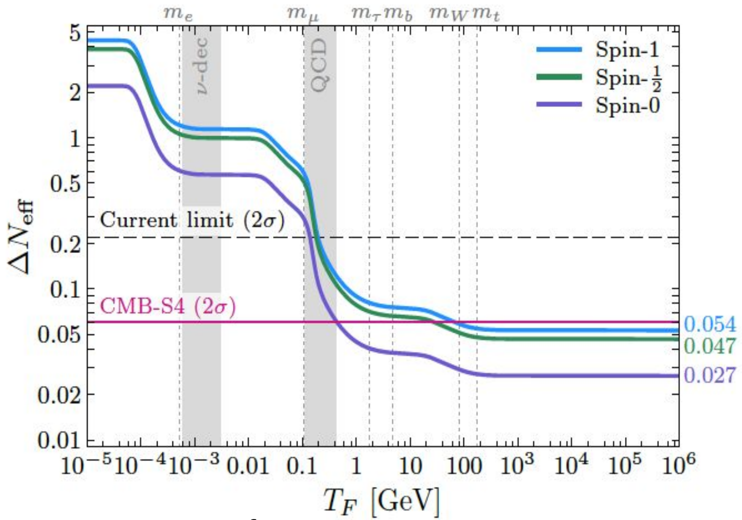


Forecasts…

Table 1. Summary of Key Science Goals from Advanced SO[a]

	Current[b]	**Advanced SO 2024-2032**	CMB-S4[c] 2028-2035	Using Rubin, DESI, or *Euclid*
Primordial perturbations				
r ($A_L = 0.3$)	0.03	0.0012 [d]	0.0005	✓
n_s	0.004	0.002	0.002	-
$e^{-2\tau}\mathcal{P}(k = 0.2/\mathrm{Mpc})$	3%	0.4%		-
$f_{\mathrm{NL}}^{\mathrm{local}}$	5	1	0.6	✓
Relativistic species				
N_{eff}	0.2	0.045	0.03	-
Neutrino mass				
m_ν (eV, $\sigma(\tau) = 0.01$)	0.1	0.03	0.03	✓
m_ν (eV, $\sigma(\tau) = 0.002$)		0.015	0.015	✓
Accelerated expansion				
$\sigma_8(z = 1-2)$	7%	1%	1%	✓
Galaxy evolution				
η_{feedback}	50-100%	2%		✓
p_{nt}	50-100%	4%		✓
Reionization				
Δz	1.4	0.3	0.25	-
τ	0.007	0.0035	0.003	-
Cluster catalog	4000	33,000	70,000	✓
AGN catalog	2000	100,000	$> 100,000$	-
Galactic science				
Molecular cloud B-fields	10s	> 860		-
$\sigma(\beta_{dust})$	0.02	< 0.01		-
Planet 9				
Distance limit for 5 M_e		900 AU		✓
Transient Detection Distance				
Long GRBs, on-axis		420 Mpc		✓
Low-Luminosity GRBs		60-190 Mpc		✓
Normal SNe		$\gtrsim 4$ Mpc		✓
TDEs, on-axis		2100 Mpc		✓

arbitrary single massless particle, which decouples from the SM at a temperature TF



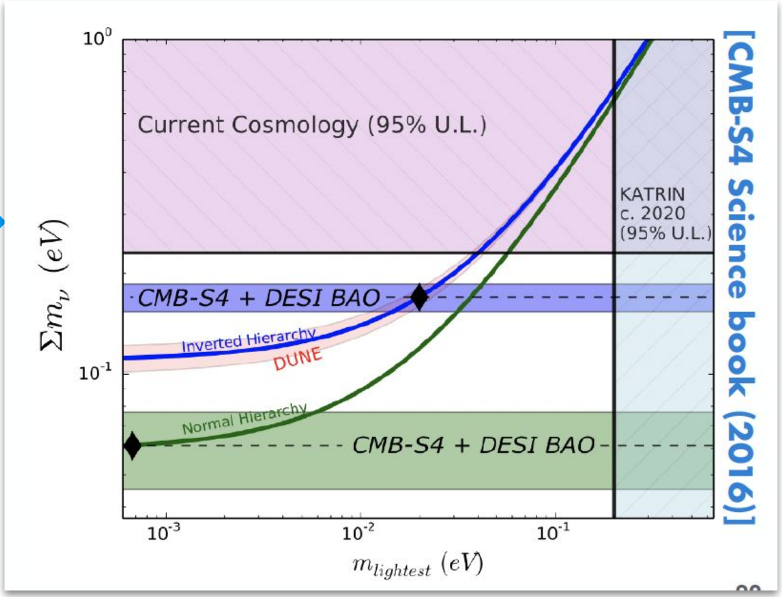
freezeout temperature

CMB-S4 Science Case, Reference Design, and Project Plan

Forecasts…

Table 1. Summary of Key Science Goals from Advanced SO[a]

	Current[b]	**Advanced SO 2024-2032**	CMB-S4[c] 2028-2035	Using Rubin, DESI, or *Euclid*
Primordial perturbations				
r ($A_L = 0.3$)	0.03	0.0012 [d]	0.0005	✓
n_s	0.004	0.002	0.002	-
$e^{-2\tau}\mathcal{P}(k = 0.2/\mathrm{Mpc})$	3%	0.4%		-
$f_{\mathrm{NL}}^{\mathrm{local}}$	5	1	0.6	✓
Relativistic species				
N_{eff}	0.2	0.045	0.03	-
Neutrino mass				
m_ν (eV, $\sigma(\tau) = 0.01$)	0.1	0.03	0.03	✓
m_ν (eV, $\sigma(\tau) = 0.002$)		0.015	0.015	✓
Accelerated expansion				
$\sigma_8(z = 1-2)$	7%	1%	1%	✓
Galaxy evolution				
η_{feedback}	50-100%	2%		✓
p_{nt}	50-100%	4%		✓
Reionization				
Δz	1.4	0.3	0.25	-
τ	0.007	0.0035	0.003	-
Cluster catalog	4000	33,000	70,000	✓
AGN catalog	2000	100,000	$> 100,000$	-
Galactic science				
Molecular cloud B-fields	10s	> 860		-
$\sigma(\beta_{dust})$	0.02	< 0.01		-
Planet 9				
Distance limit for 5 M_e		900 AU		✓
Transient Detection Distance				
Long GRBs, on-axis		420 Mpc		✓
Low-Luminosity GRBs		60-190 Mpc		✓
Normal SNe		$\gtrsim 4$ Mpc		✓
TDEs, on-axis		2100 Mpc		✓



=> will provide a 2 to 4 σ determination of the neutrino mass ordering

Beyond ΛCDM…primordial Universe ?

Prediction	Measurement
A spatially flat universe	$\Omega_K = 0.0007 \pm 0.0019$
with a *nearly* scale-invariant (red)	
spectrum of density perturbations,	$n_s = 0.967 \pm 0.004$
which is almost a power law,	$dn/d\ln k = -0.0042 \pm 0.0067$
dominated by scalar perturbations,	$r_{0.05} < 0.032$ at 95% CL
which are Gaussian	$f_{NL} = -0.9 \pm 5.1$
and adiabatic,	$\alpha_{-1} = 0.00013 \pm 0.00037$
with negligible topological defects	$f < 0.01$
	n_t in [-1.21,3.54] @95%CL

***Planck* 2018 results**

I. Overview and the cosmological legacy of *Planck*

Planck Collaboration

+ updates