(some) polarisation aspects of the CMB(*)

(*) Cosmic Microwave Background

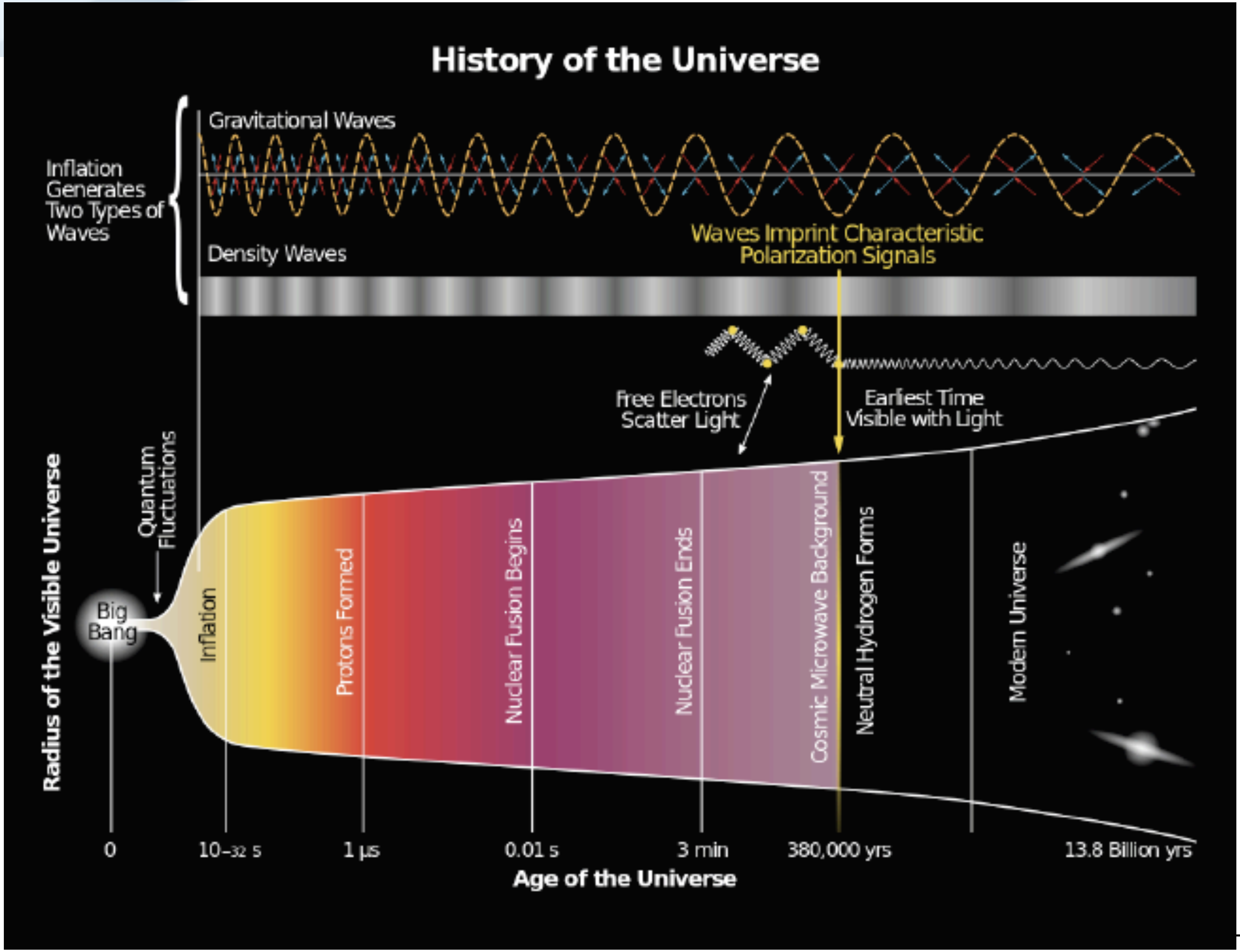
Outline

I will focus on the following questions:

- What is the CMB
- Why do we measure its temperature and polarisation (cosmology oriented)
- What have we already learned with the polarisation of the CMB
- What are the next challenges

The CMB

The Cosmic Microwave Background



When T~ 3000K: this is the recombination era:

electron+nuclei => neutral atoms

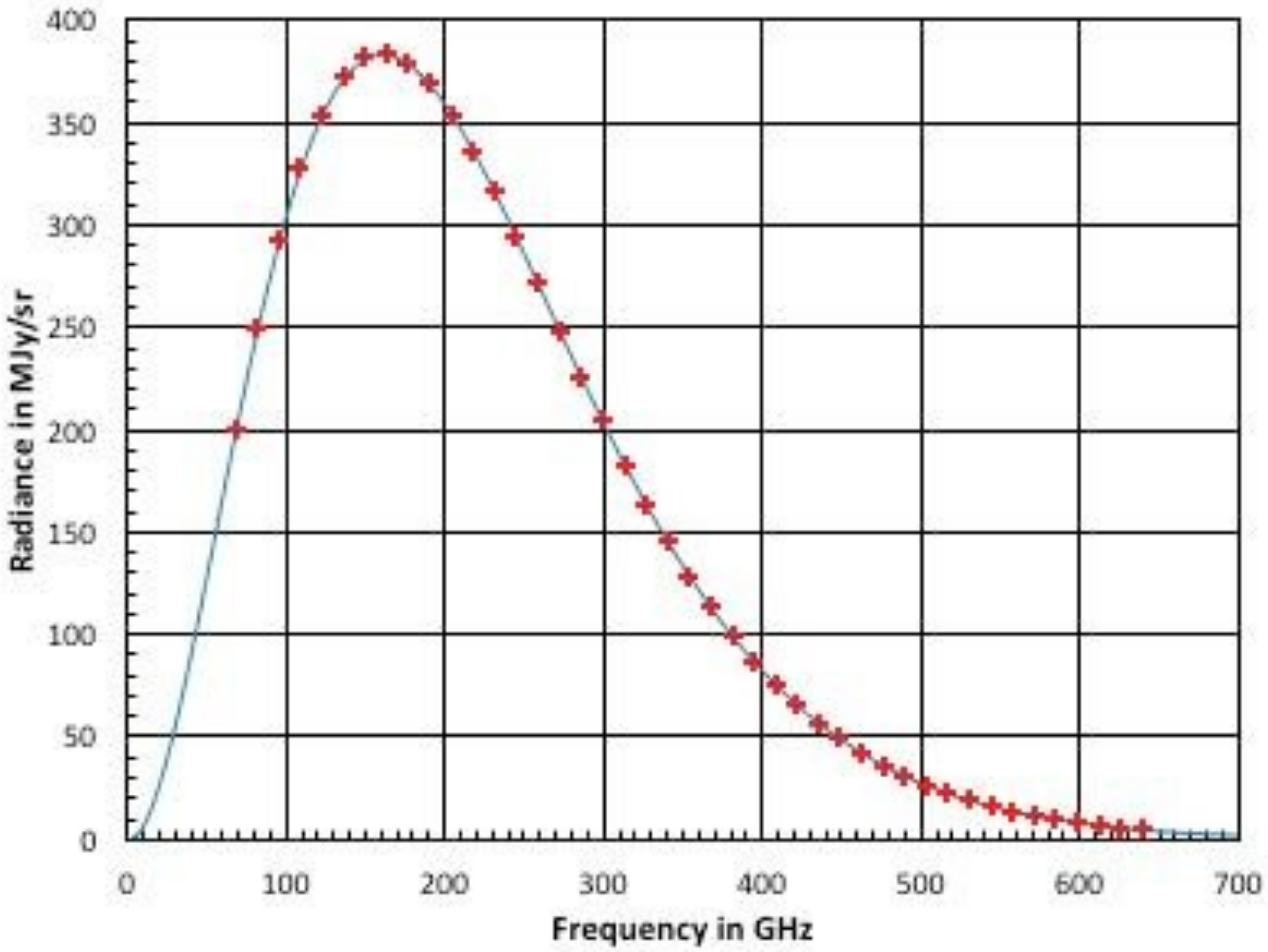
Photons & matter decouple and no longer interact

The Universe becomes transparent.

Photons now travel (almost) uninterrupted across the Universe.
This is the Cosmic Microwave Background

The CMB is linearly polarized at **the 10% level due to Thomson scattering of photons off free electrons in the surface of last scattering**.

The Cosmic Microwave Background (temperature)

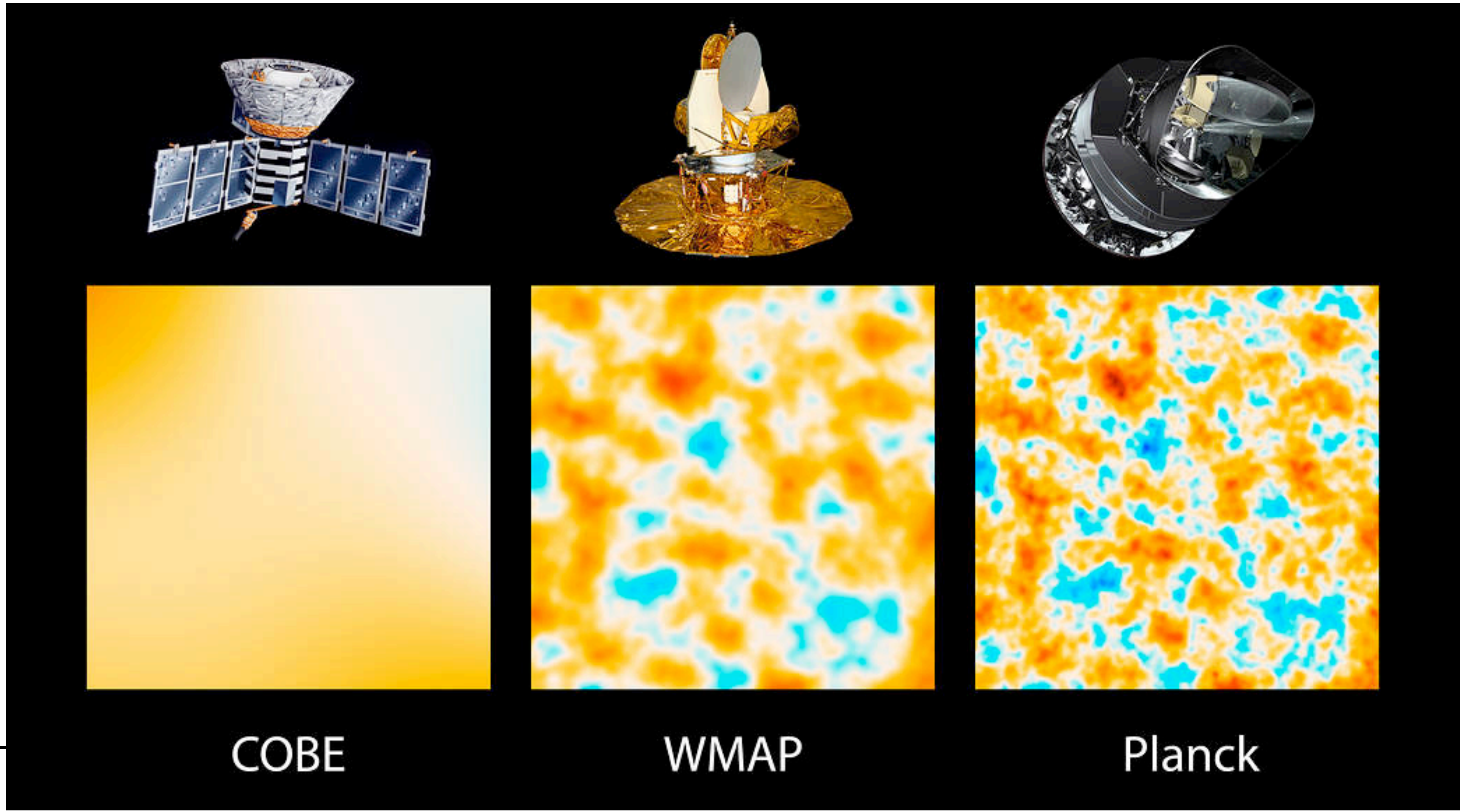


100-200 GHz

A black body spectrum
T = 2.7 K

Almost Isotropic

Anisotropies: $$\frac{\Delta T}{T} \sim 10^{-5}$$



What are the physical parameters ?

the Hubble parameter H_0
(expansion of the Universe)
the baryon density $\Omega_b h^2$
the cold dark matter density $\Omega_c h^2$
the redshift of reionization z_{reio}
and 2 parameters linked to the primordial density spectrum
=> $P_R(k)=A_s(k/k_0)^{ns}$

⇒ The Λ_{CDM} model
With 6 physical parameters

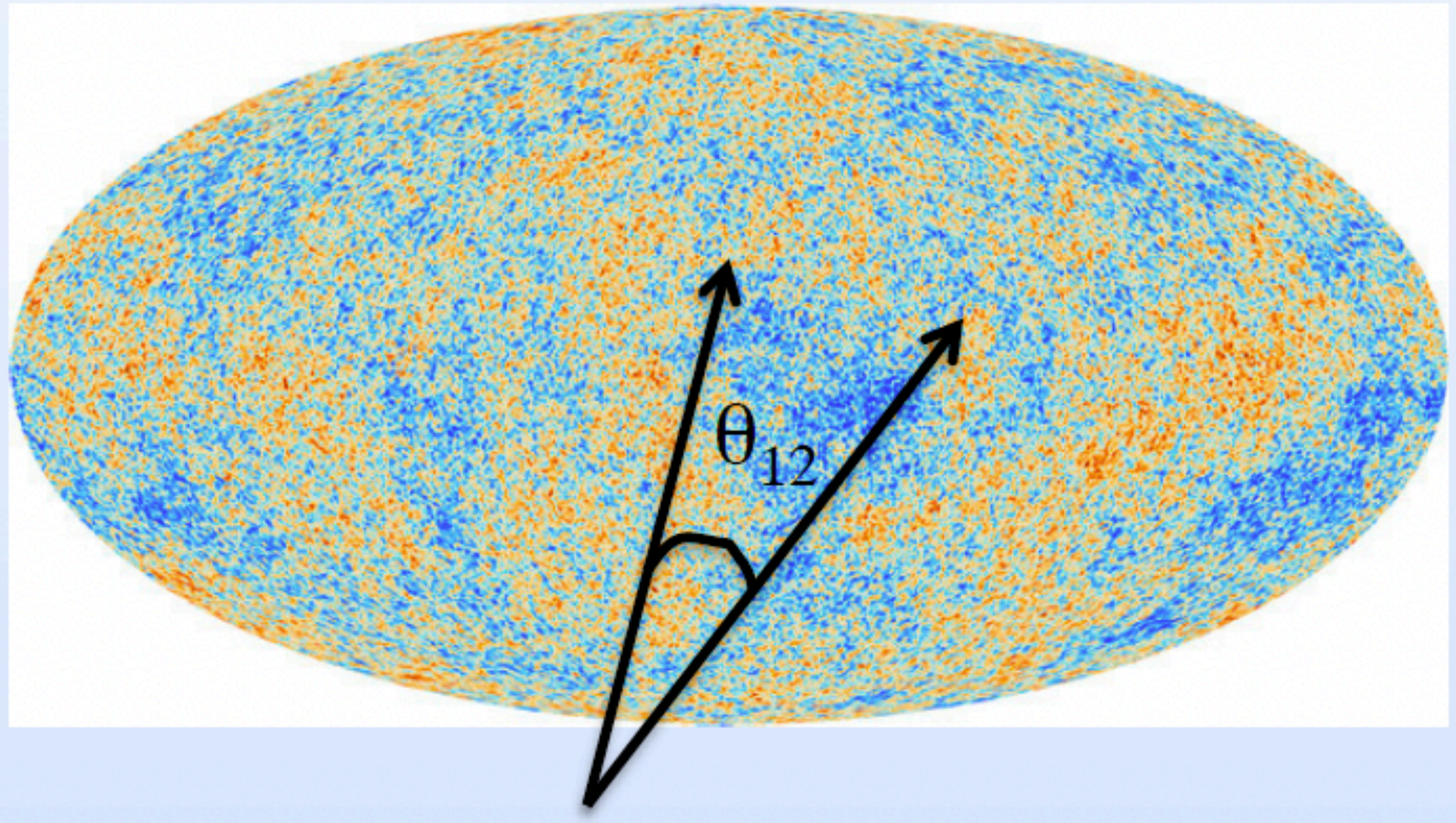
This ..and some General Relativity

And Beyond:

Varying the Σmass(neutrinos)
Varying the Number of relativistic species
Flatness of the Universe (..)

⇒ The so called « extended models »

From anisotropies maps to the 2pt correlation function to the cosmological parameters



Given 2 points on the sky separated by θ_{12}

=> measure T_1 and T_2

Then take all the pairs of points separated by θ_{12} and compute the 2D correlation function:

$$< T_1 T_2 >= c(\theta_{12}) = \sum_l C_l (2l+1) P_l(\cos\theta_{12})$$

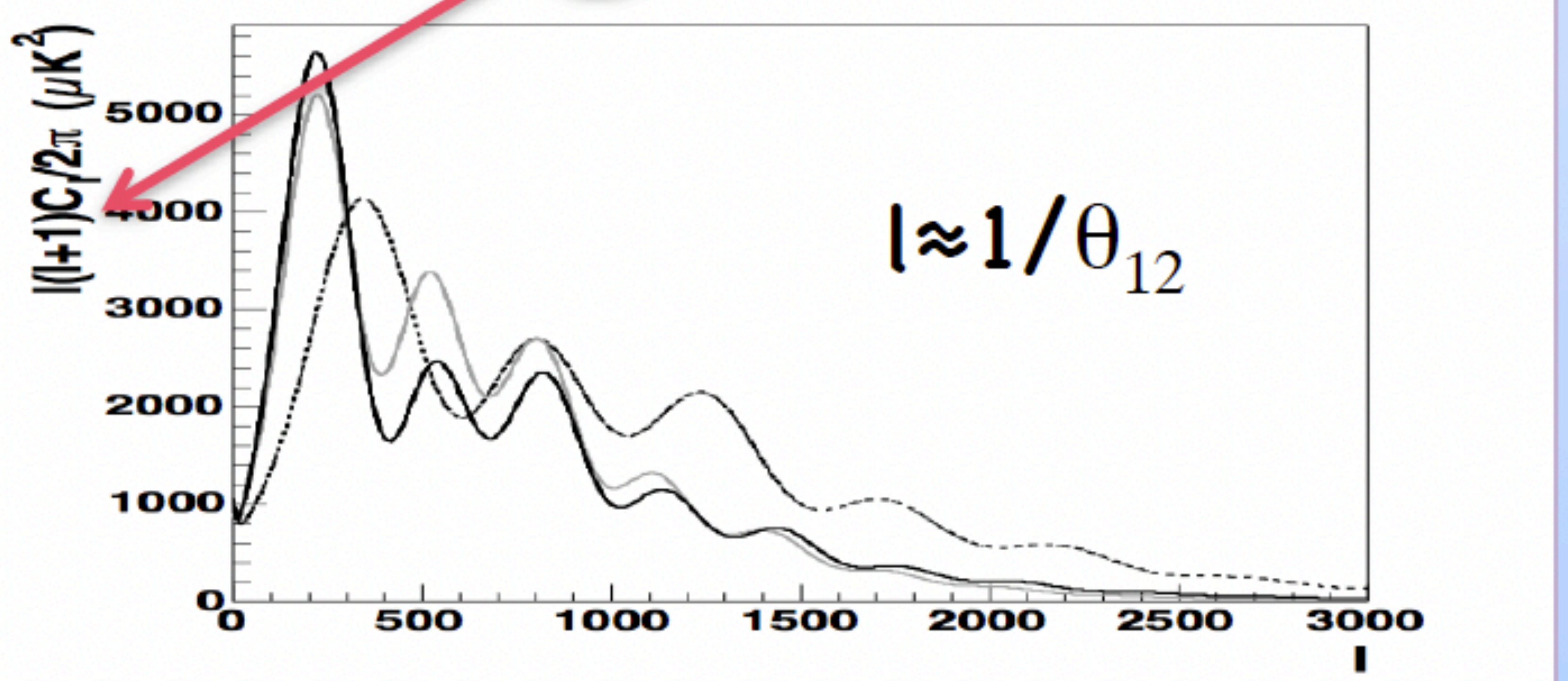
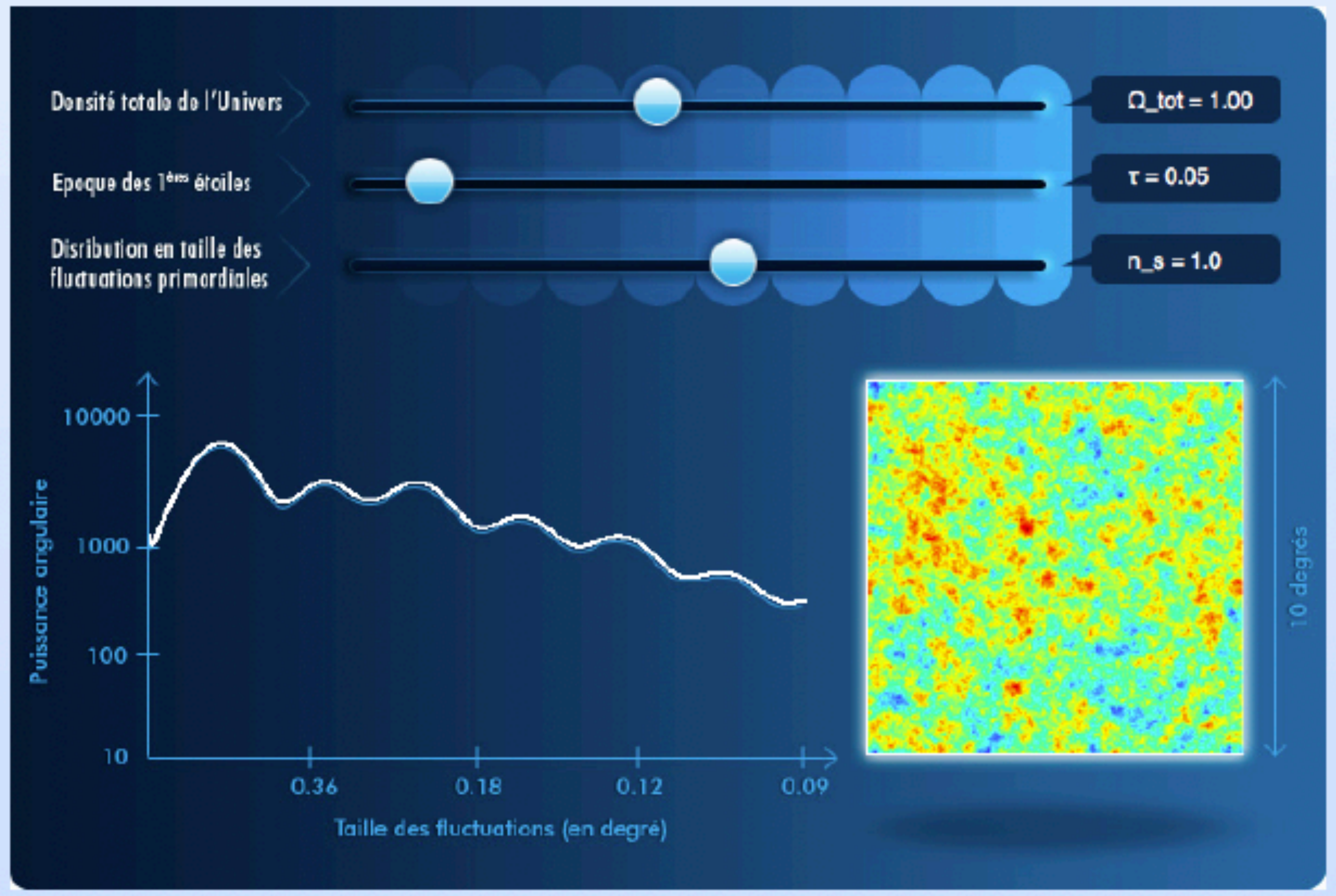
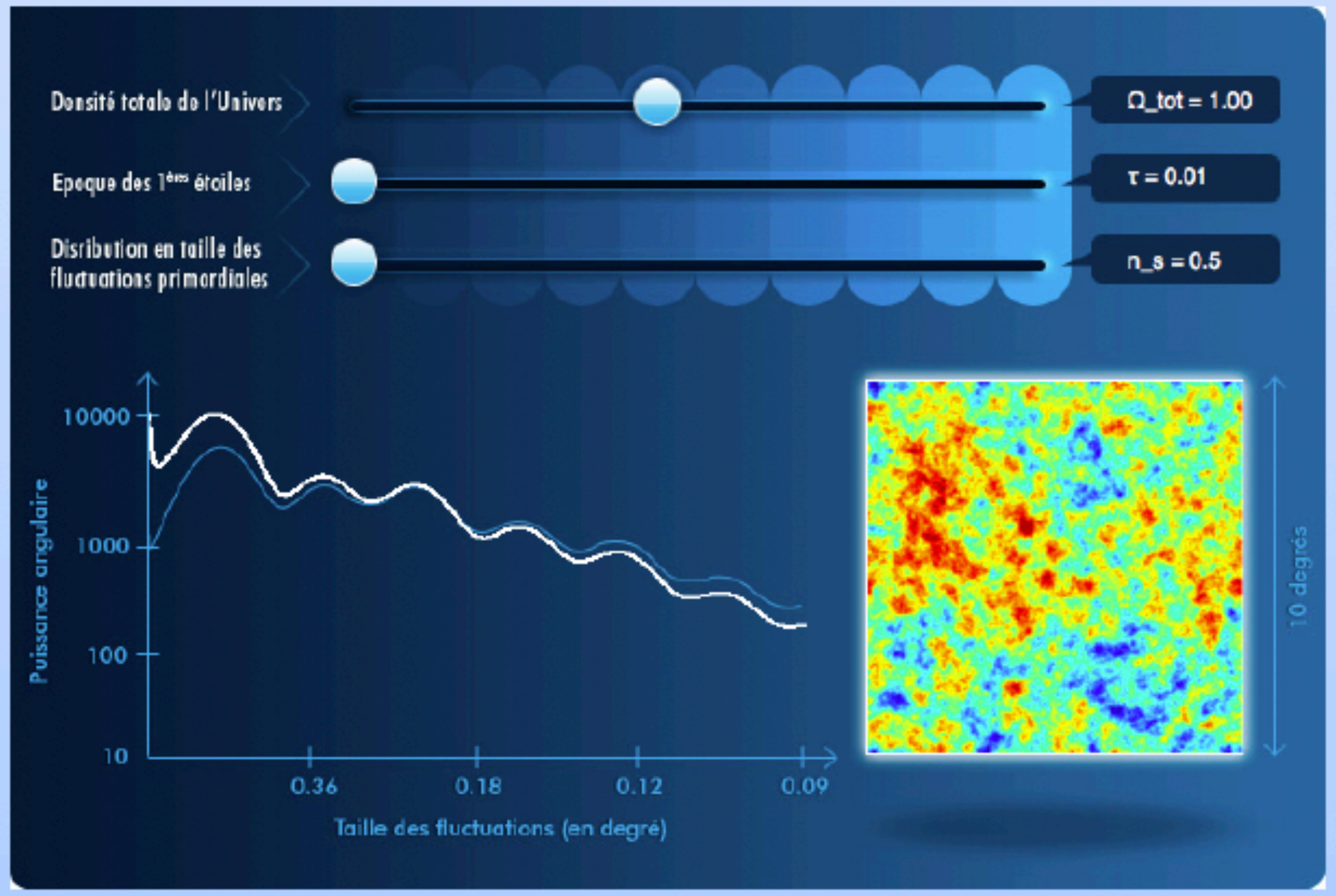


Figure 1. Three different CMB TT power spectra (up to ℓ_{max} = 3000), used as illustrations for the method. The dark full line corresponds to *WMAP* data best fit model.

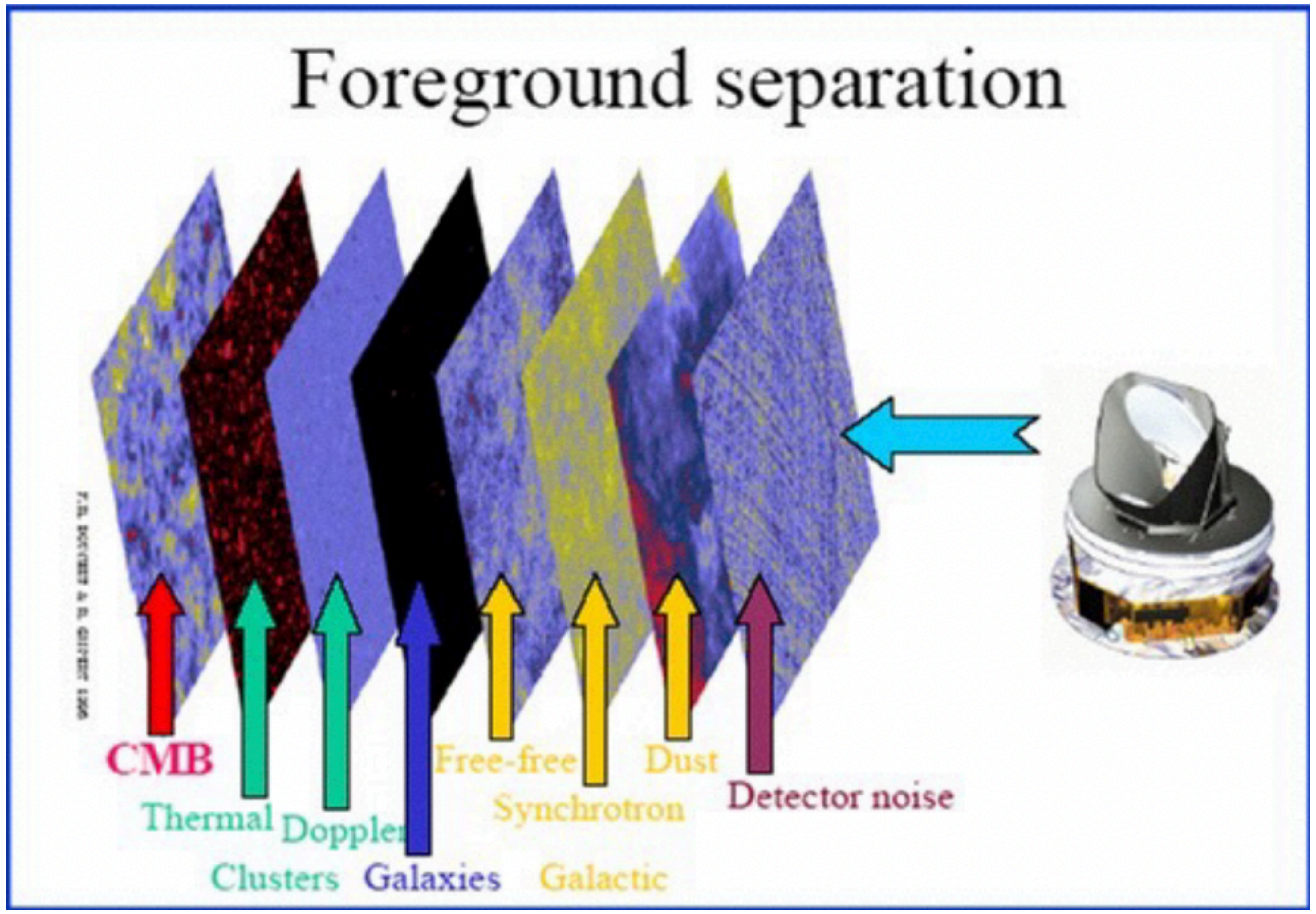
The C_l depend on the value of the cosmological parameters

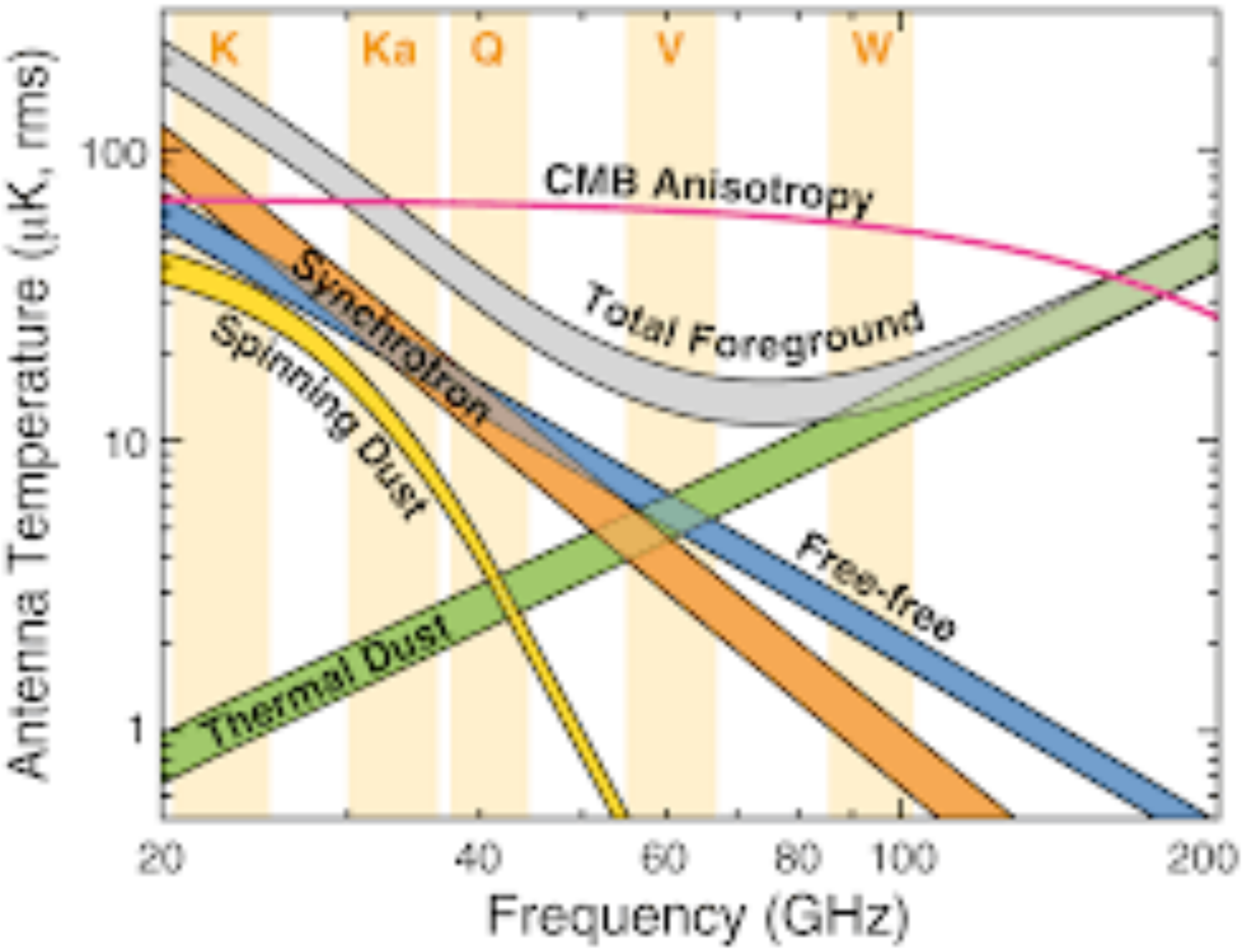




Fit the cosmological parameters from the Cl spectrum

It is not that easy..

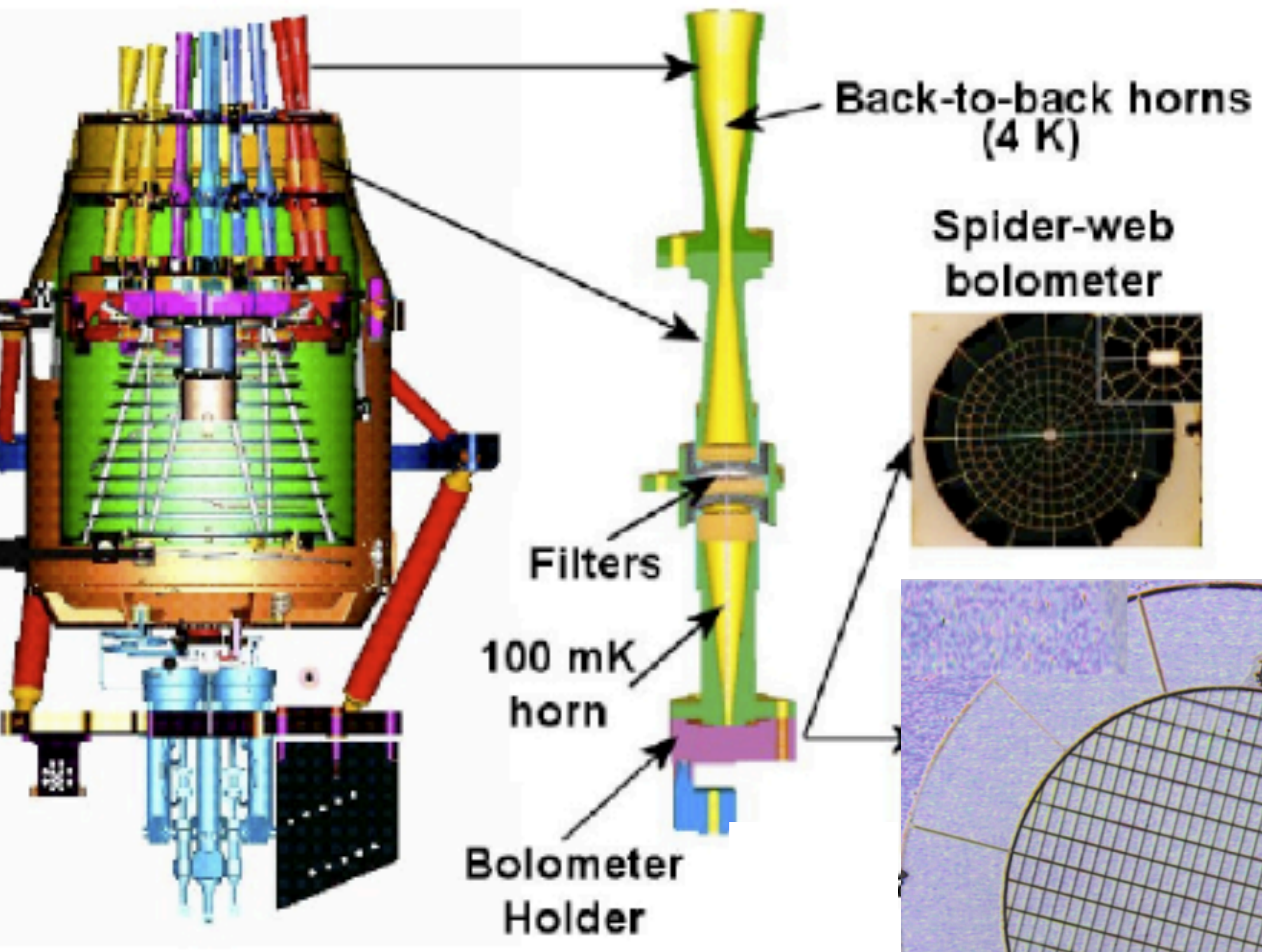


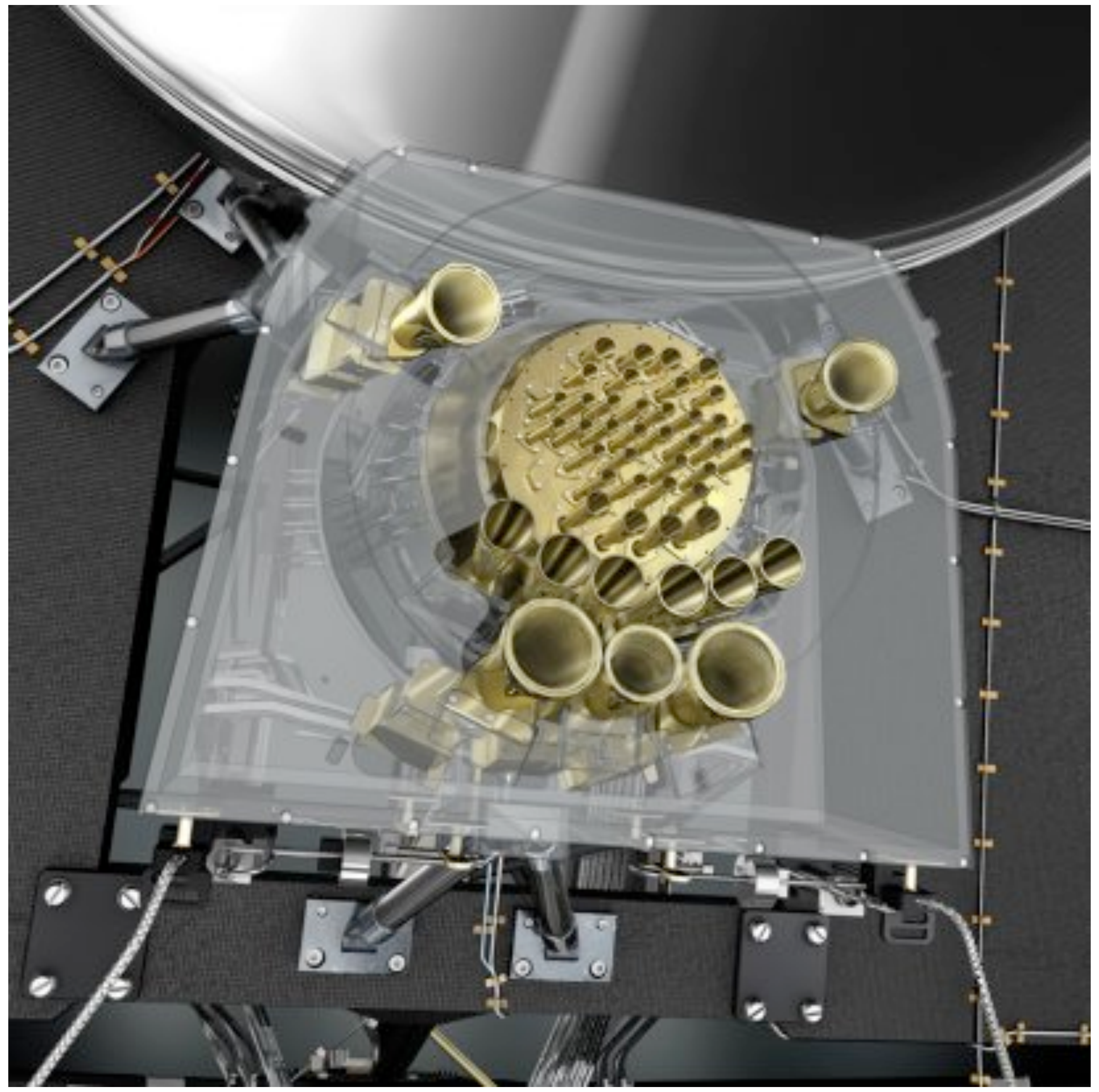


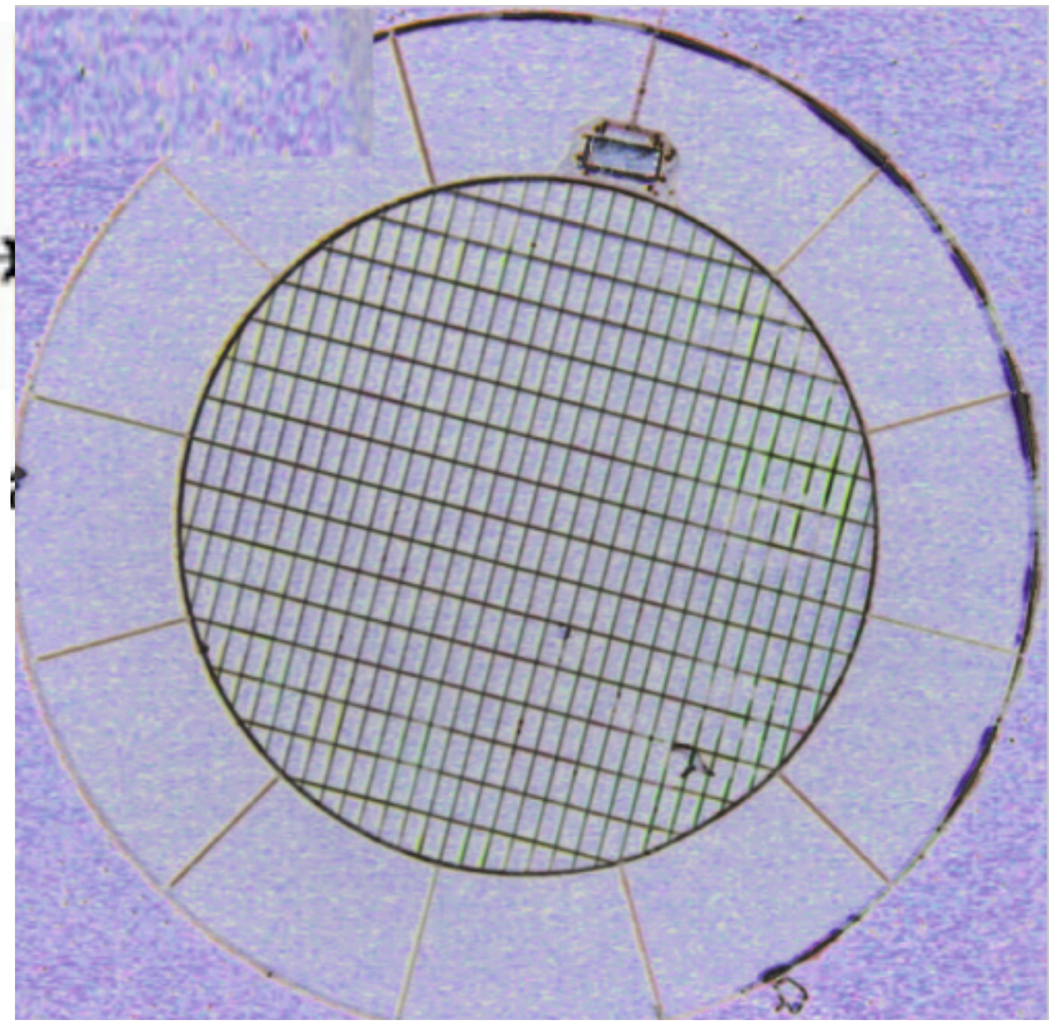
This is true for temperature AND polarisation and the foregrounds are different…
I will not detail this here

What has been done in Planck ?

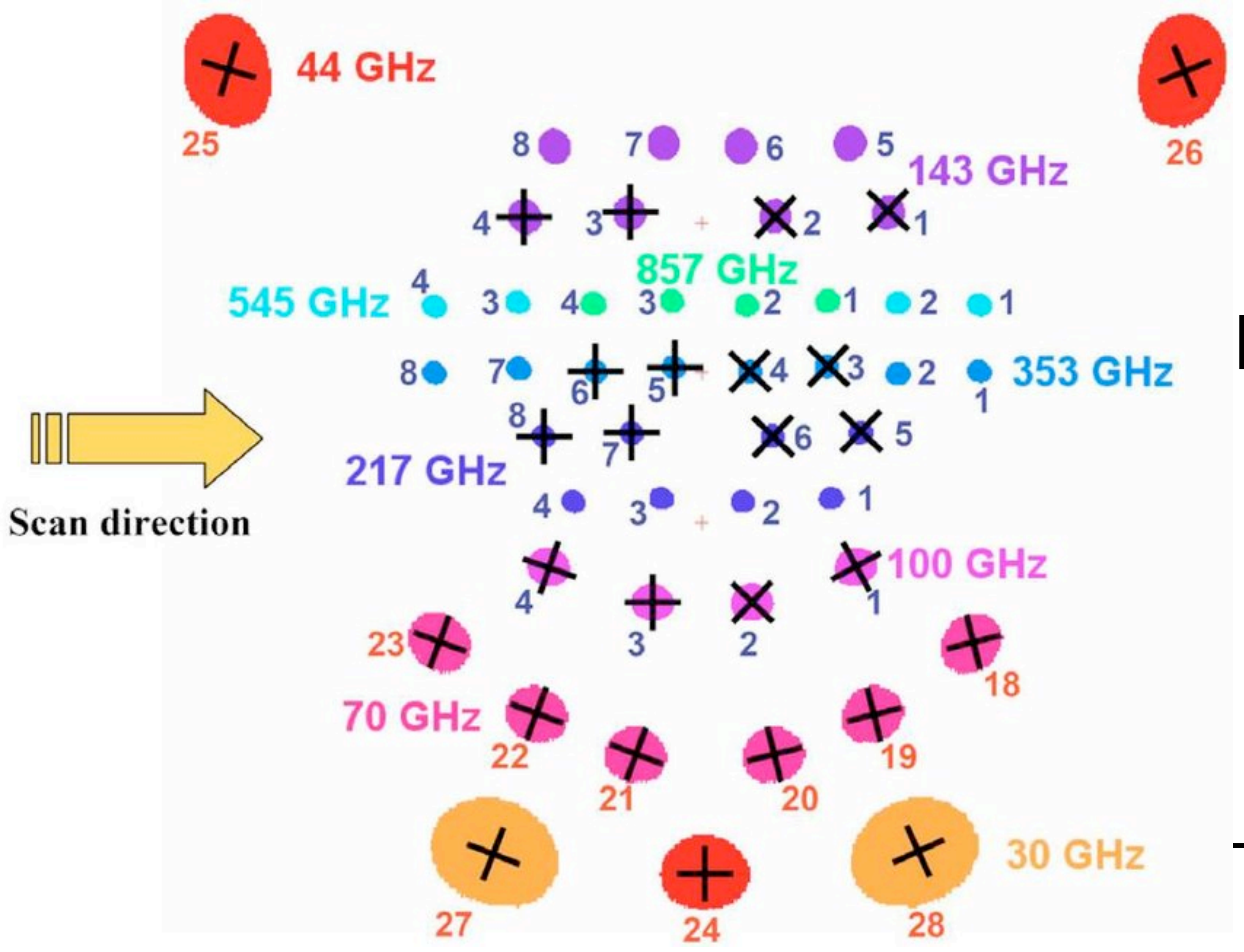
The example of the Planck-HFI detectors







Polarisation sensitive bolometer



- Bolometers (52 channels for HFI)
- Polarisation sensitive: the absorber of PSBs is a rectangular grid with metallization in one direction
- Cooled down at 100mK

(5 to 11 arcmin for the beam)

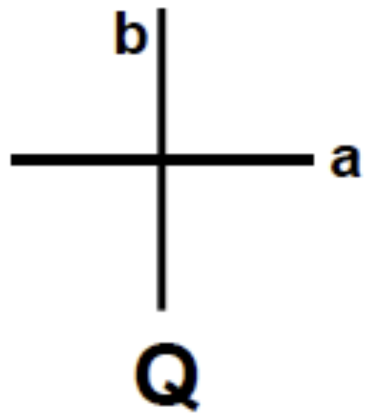
Planck polarisation measurements

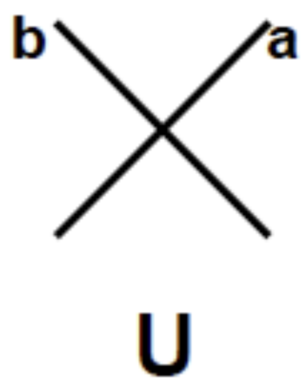
- Planck detectors are sensitive to linear polarisation

$$s = \frac{1}{2}\Big[(1+\epsilon)\,\mathcal{I} + (1-\epsilon)\Big(\mathcal{Q}\;cos(2\psi) + \mathcal{U}\;sin(2\psi)\Big)\Big]$$

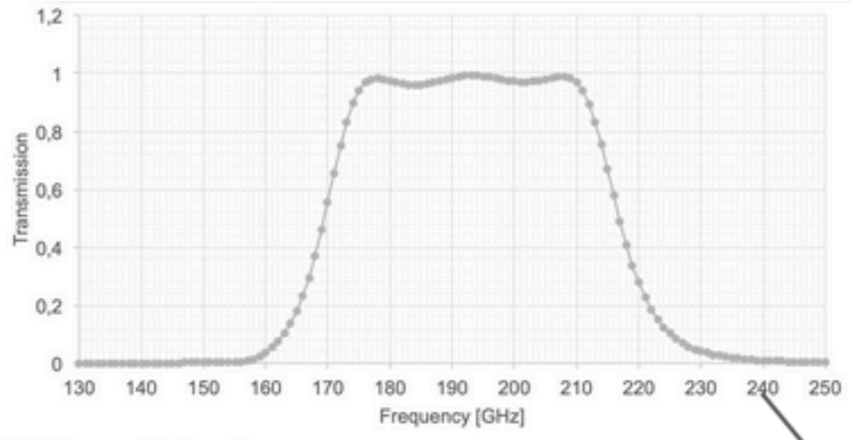
Such measurements are sensitive to any differential calibration error + T to P leakage

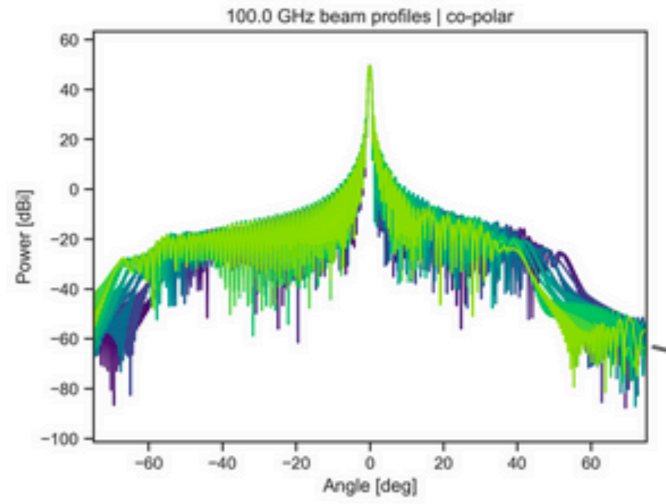
- Planck uses combination of orthogonal detectors to get Q and U :

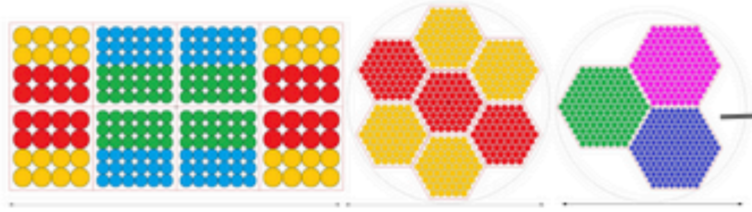


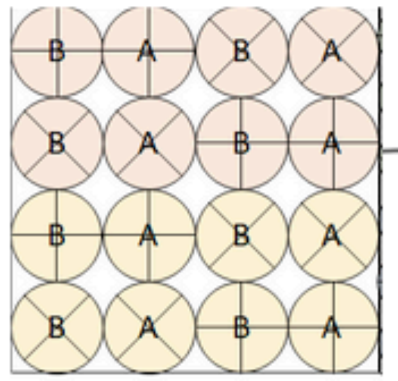


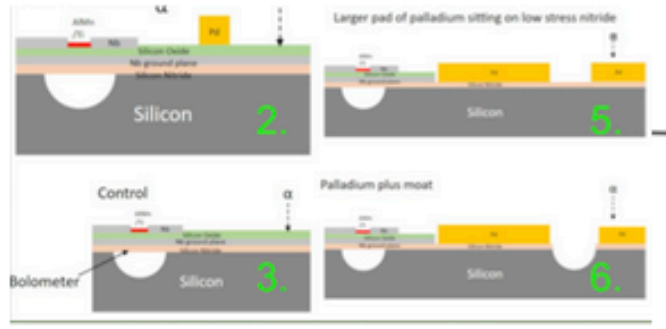
=> **redefine as E and B analogous to electric and magnetic field**











Name	Origin	Description	Major mode of Leakage
Bandpass Mismatch	Spectral Filters	Edges and shape of the spectral filters vary from detector to detector.	I -> P
Beam Mismatch and Asymmetry	Optical beams	Beam shape differs from an ideal Gaussian form.	I -> P E -> B
Pointing Uncertainty	Attitute control, pointing reconstruction	Detector pointing at location different from that given by reconstructed pointing data.	I -> P E -> B
Polarisation Misalignment	Detectors	Uncertainty in polarisation calibration. Polarisation axis misaligned with measured direction.	E -> B
Gain mismatch and stability	Detectors and Calibration	Gain calibration mismatch between detectors. These could also be variable over time	I -> P

B-modes from space -2019

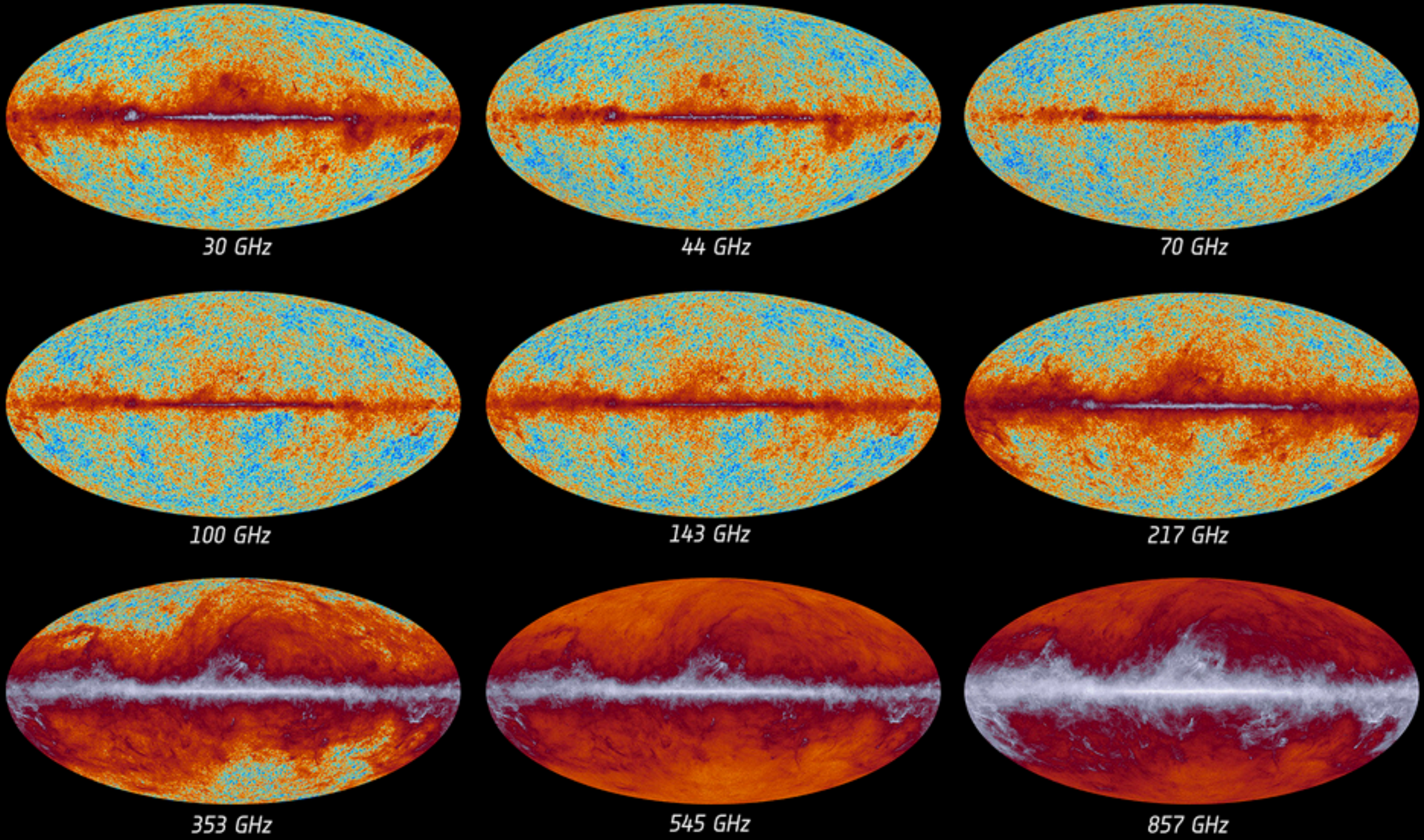
From Ranajoy Banerji

planck

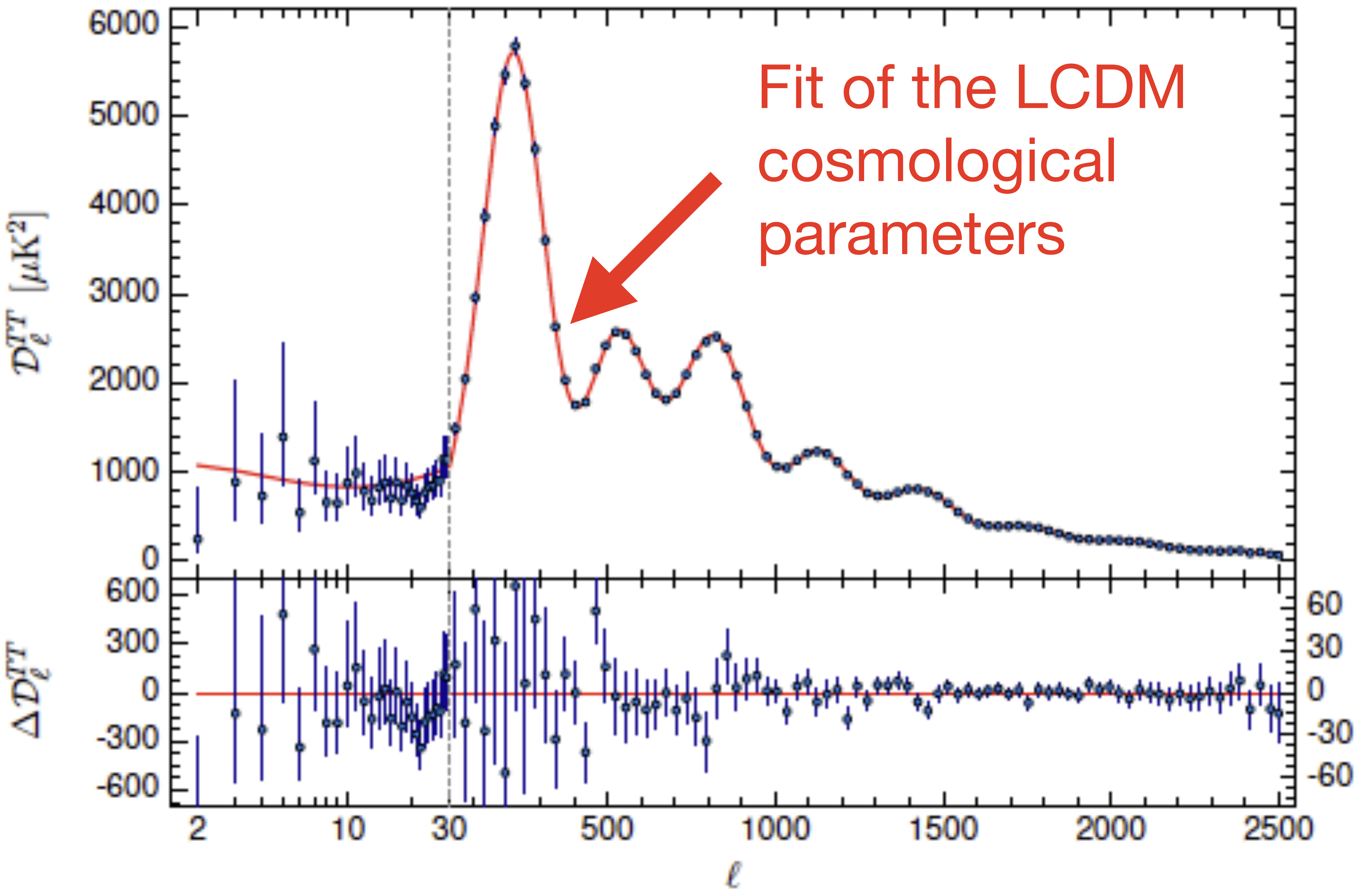
The sky as seen by Planck

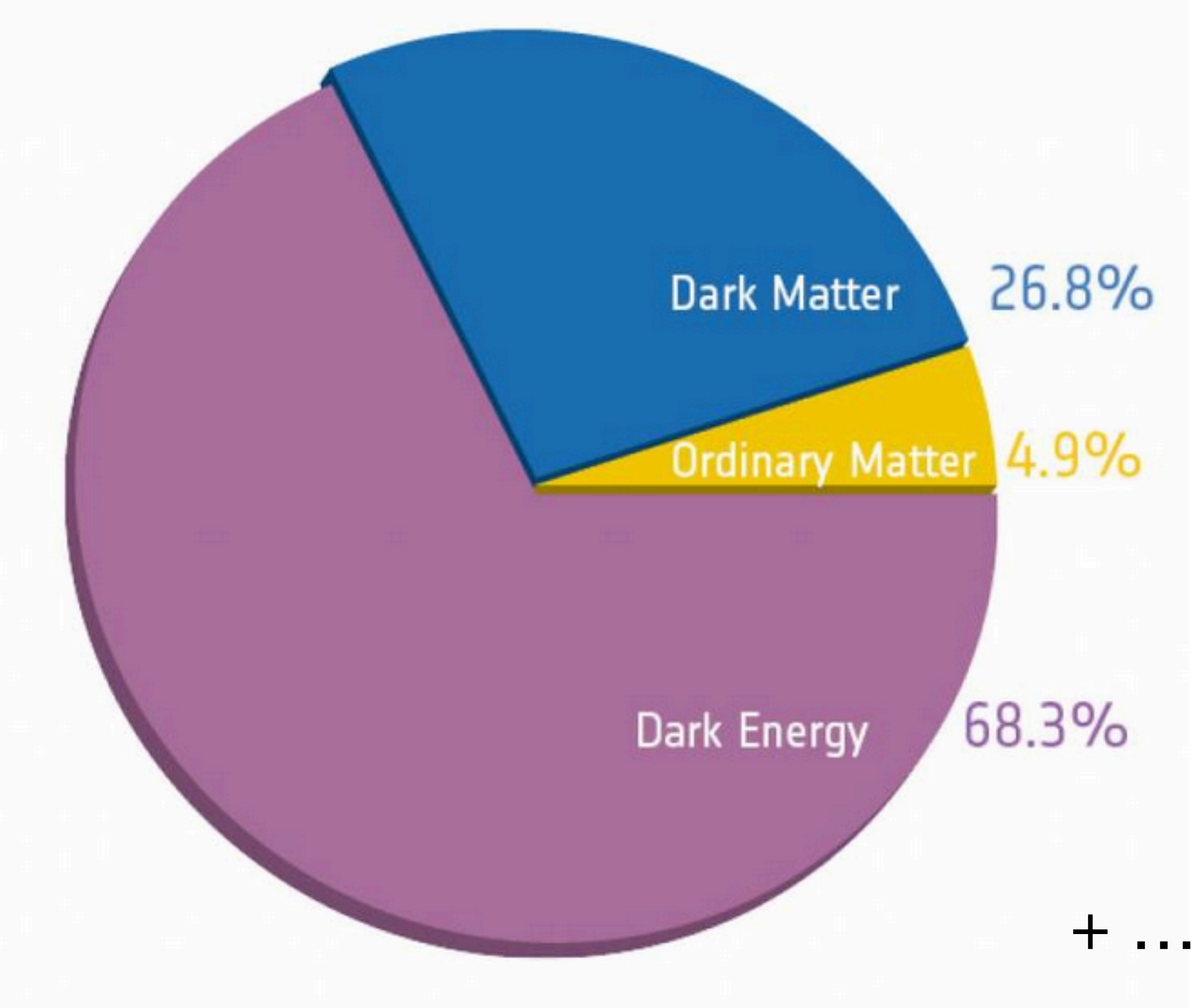
esa

Temperature



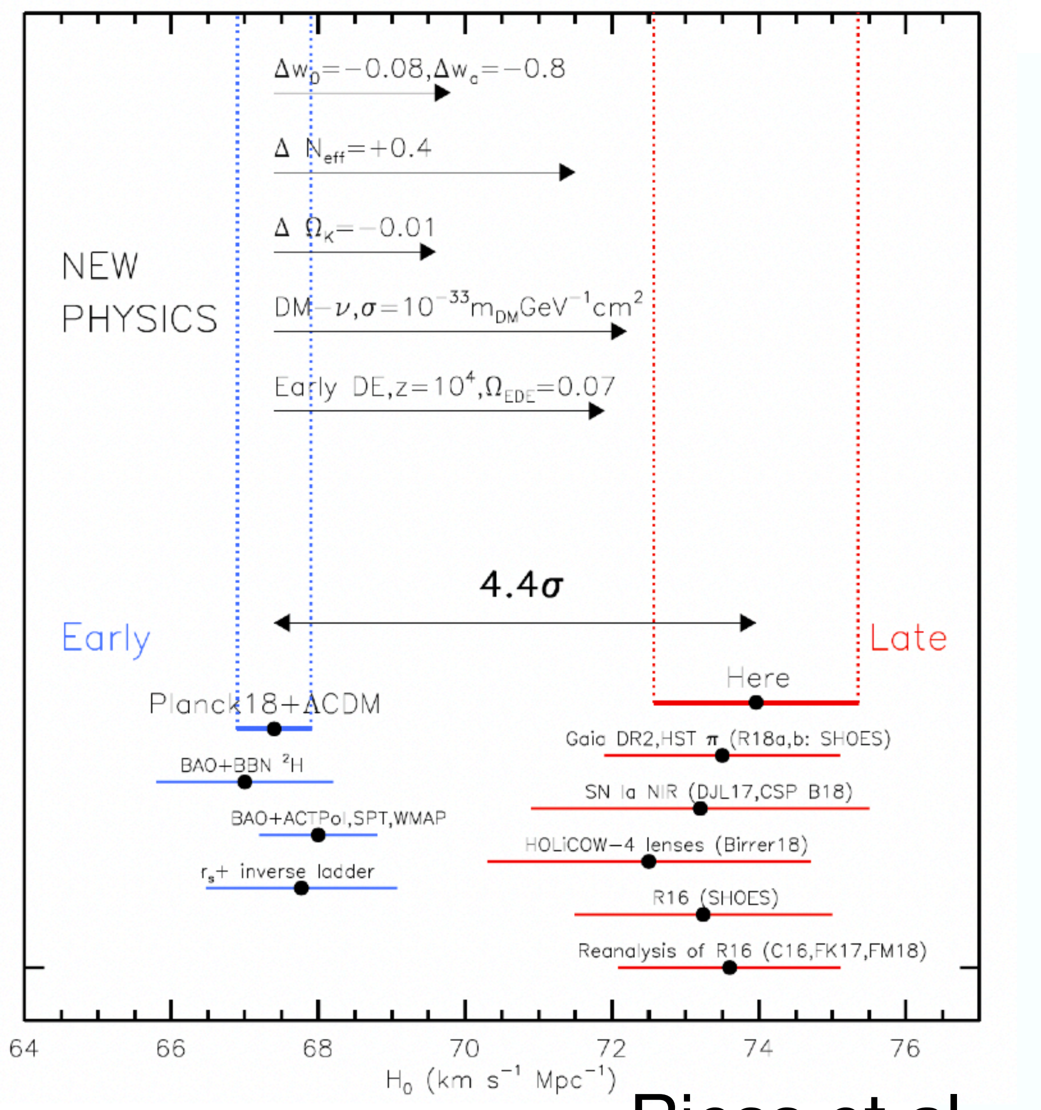
The Planck spectra and the cosmological parameters





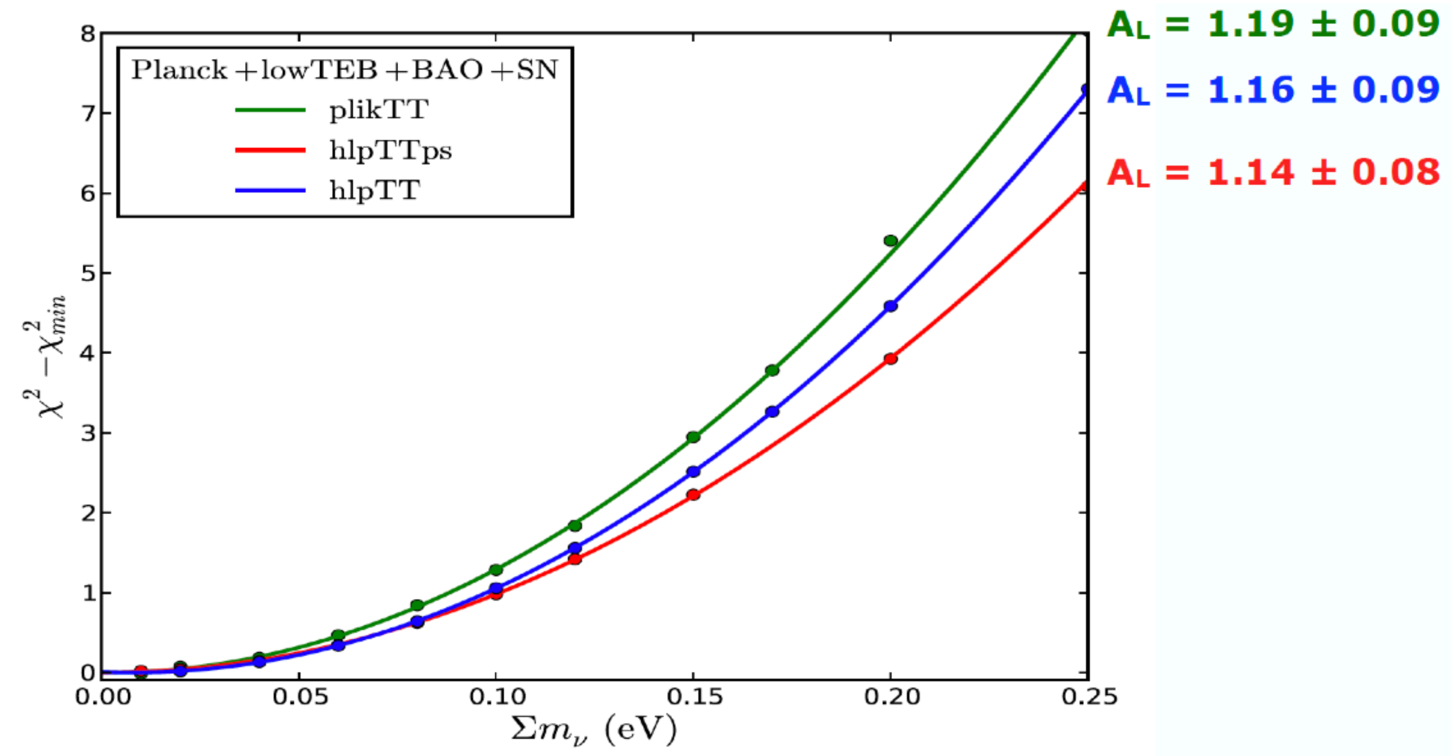
+ ....a lot of results !

H0



Riess et al.

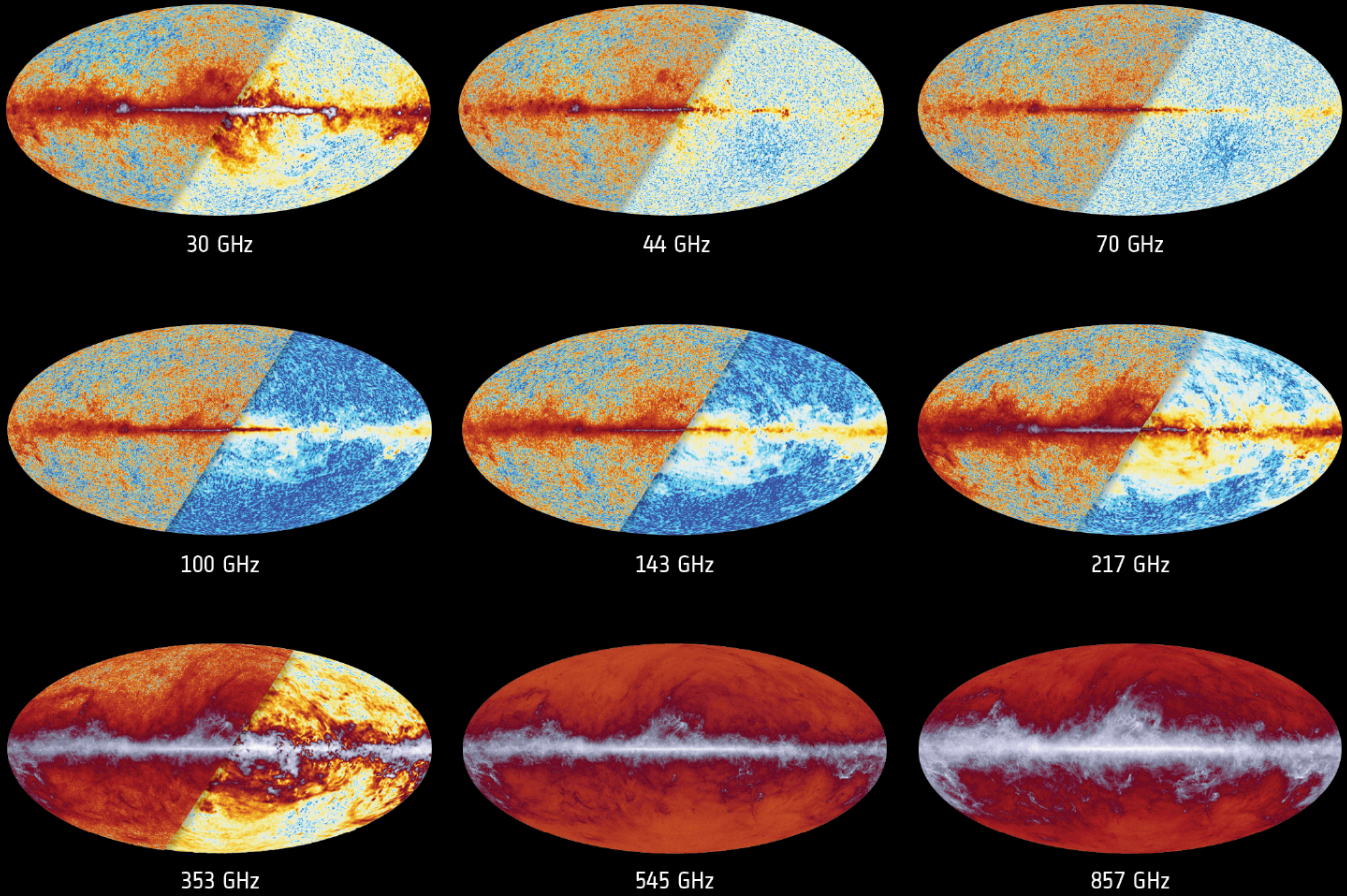
Neutrino mass



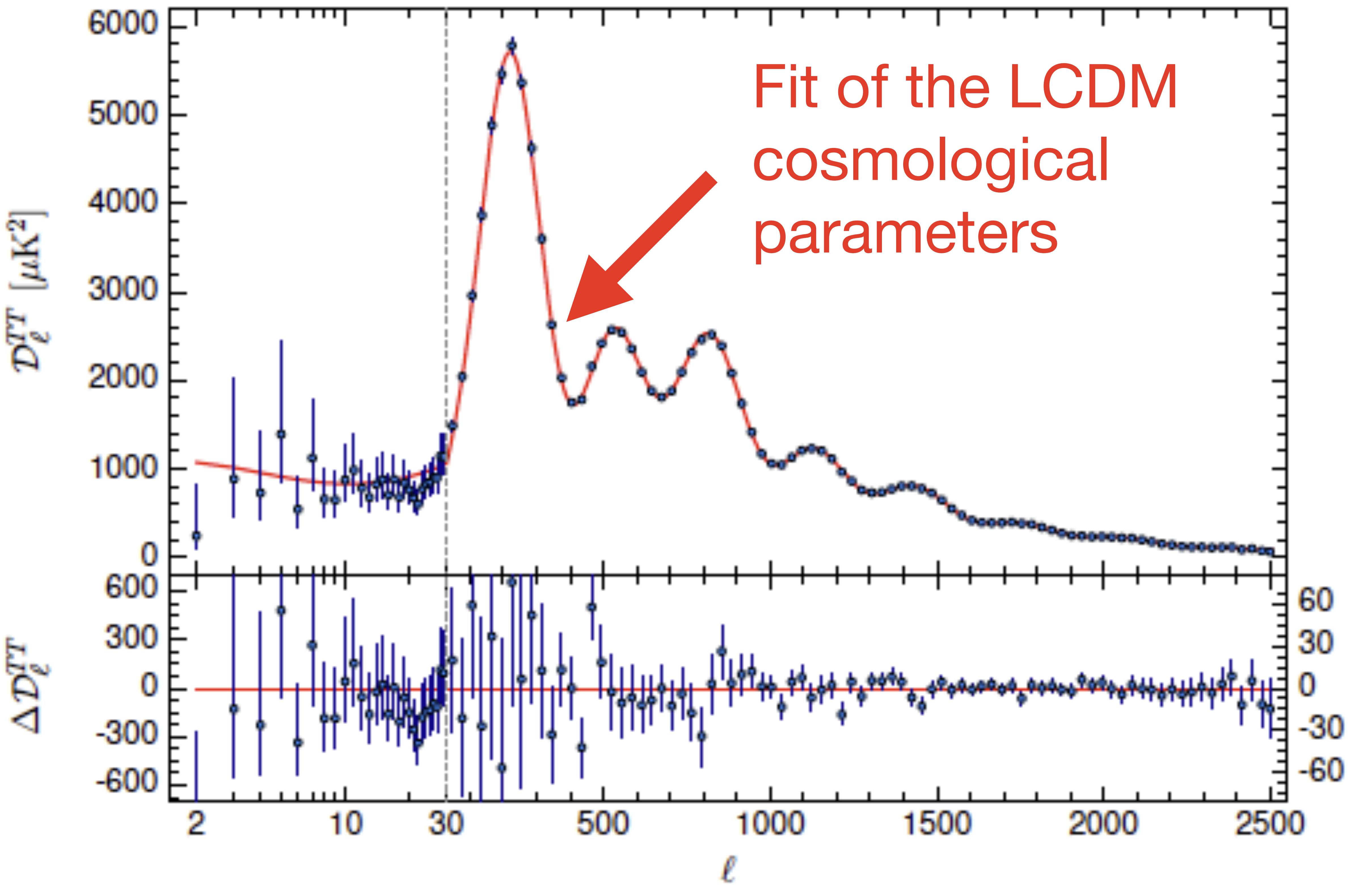
PLANCKTT+lowTEB BAO+SNIa 2015	ΛCDM+ Σm_ν limit (eV)	ΛCDM+ A_L
hlpTT	0.18	1.16±0.09
hlpTTps	0.20	1.14±0.08
PlikTT	0.17	1.19±0.09

SHV et al.

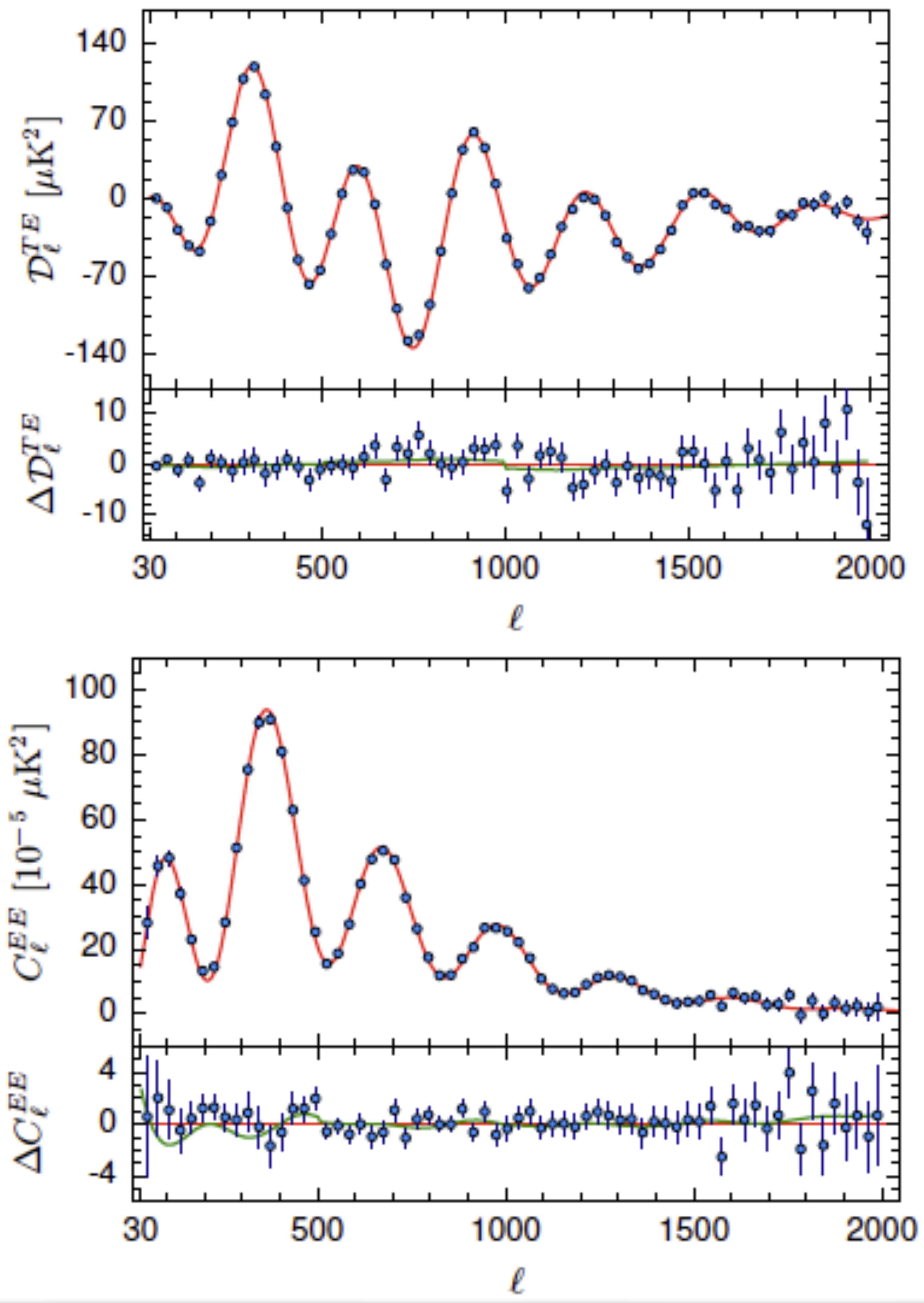
Intensity / Polarization Sky



The Planck spectra



Plot of the theoretical TE and EE spectra computed from the best fit on temperature

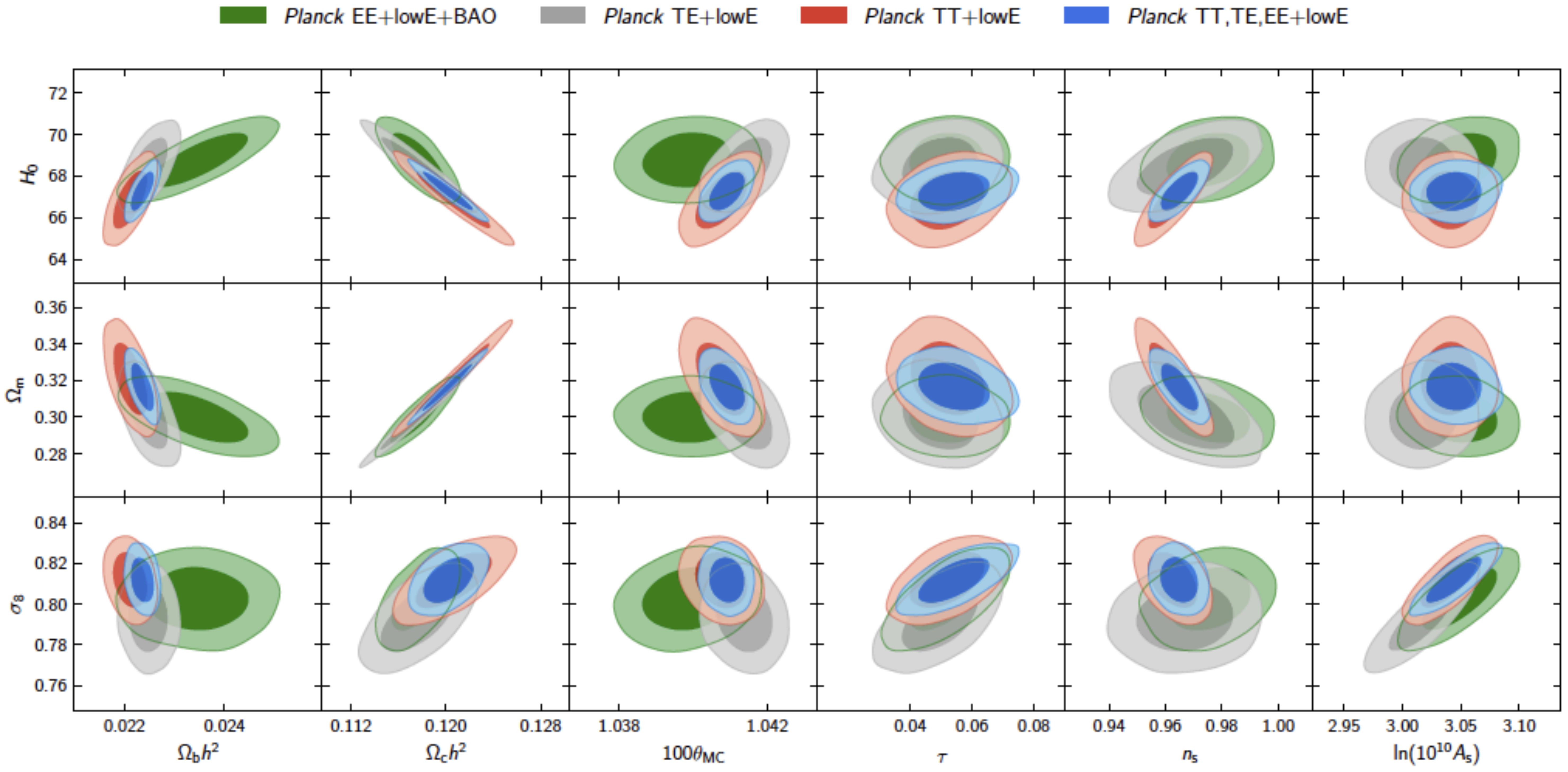


On the cosmological parameters

Parameter	TT+lowE 68% limits	TE+lowE 68% limits	EE+lowE 68% limits	TT,TE,EE+lowE 68% limits
$\Omega_b h^2$	0.02212 ± 0.00022	0.02249 ± 0.00025	0.0240 ± 0.0012	0.02236 ± 0.00015
$\Omega_c h^2$	0.1206 ± 0.0021	0.1177 ± 0.0020	0.1158 ± 0.0046	0.1202 ± 0.0014
H_0 [km s^{-1} Mpc^{-1}] . .	66.88 ± 0.92	68.44 ± 0.91	69.9 ± 2.7	67.27 ± 0.60
τ	0.0522 ± 0.0080	0.0496 ± 0.0085	0.0527 ± 0.0090	$0.0544^{+0.0070}_{-0.0081}$
$\ln(10^{10} A_s)$	3.040 ± 0.016	$3.018^{+0.020}_{-0.018}$	3.052 ± 0.022	3.045 ± 0.016
n_s	0.9626 ± 0.0057	0.967 ± 0.011	0.980 ± 0.015	0.9649 ± 0.0044

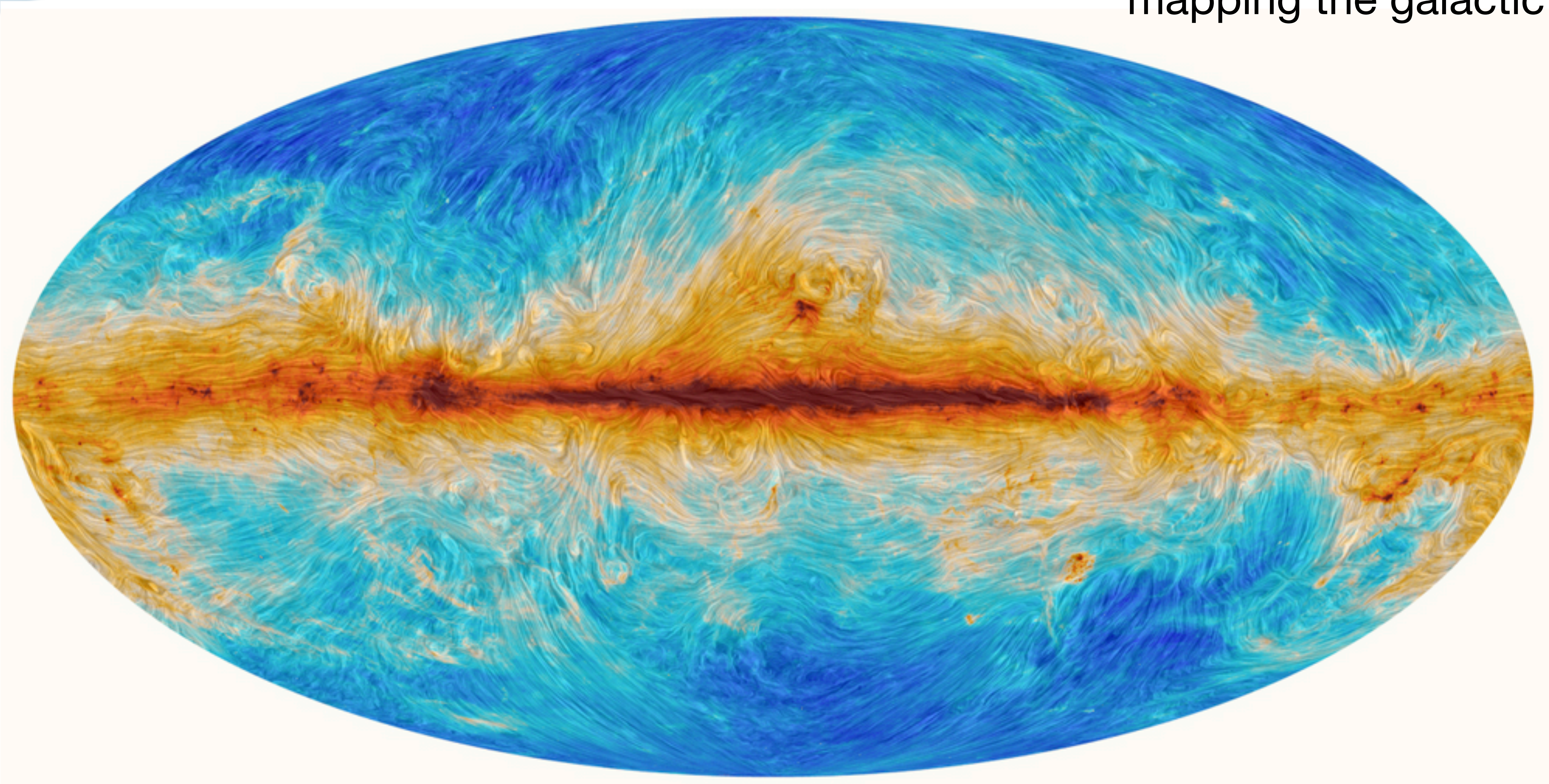
Increase of the accuracy

- Polarisation and temperature data are highly consistent
- Mainly E modes reconstruction for CMB



Beyond Cosmological parameters

mapping the galactic magnetic field

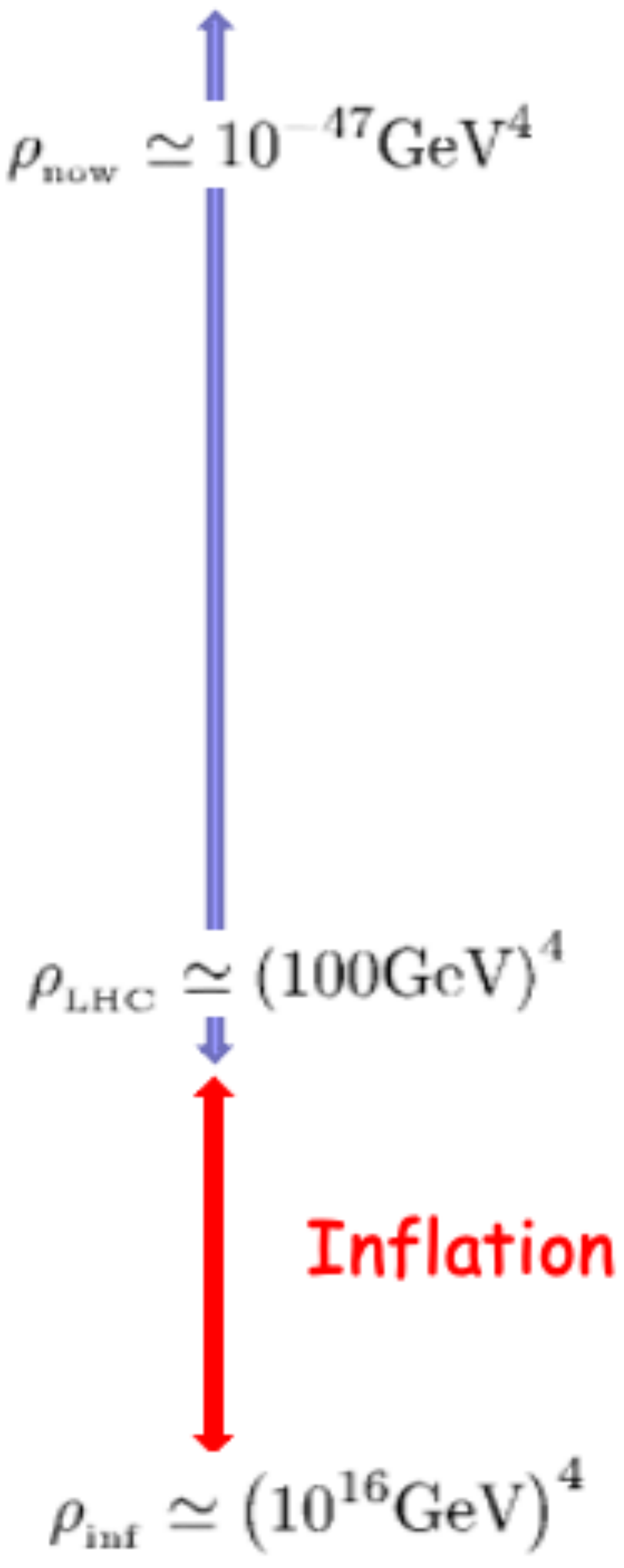


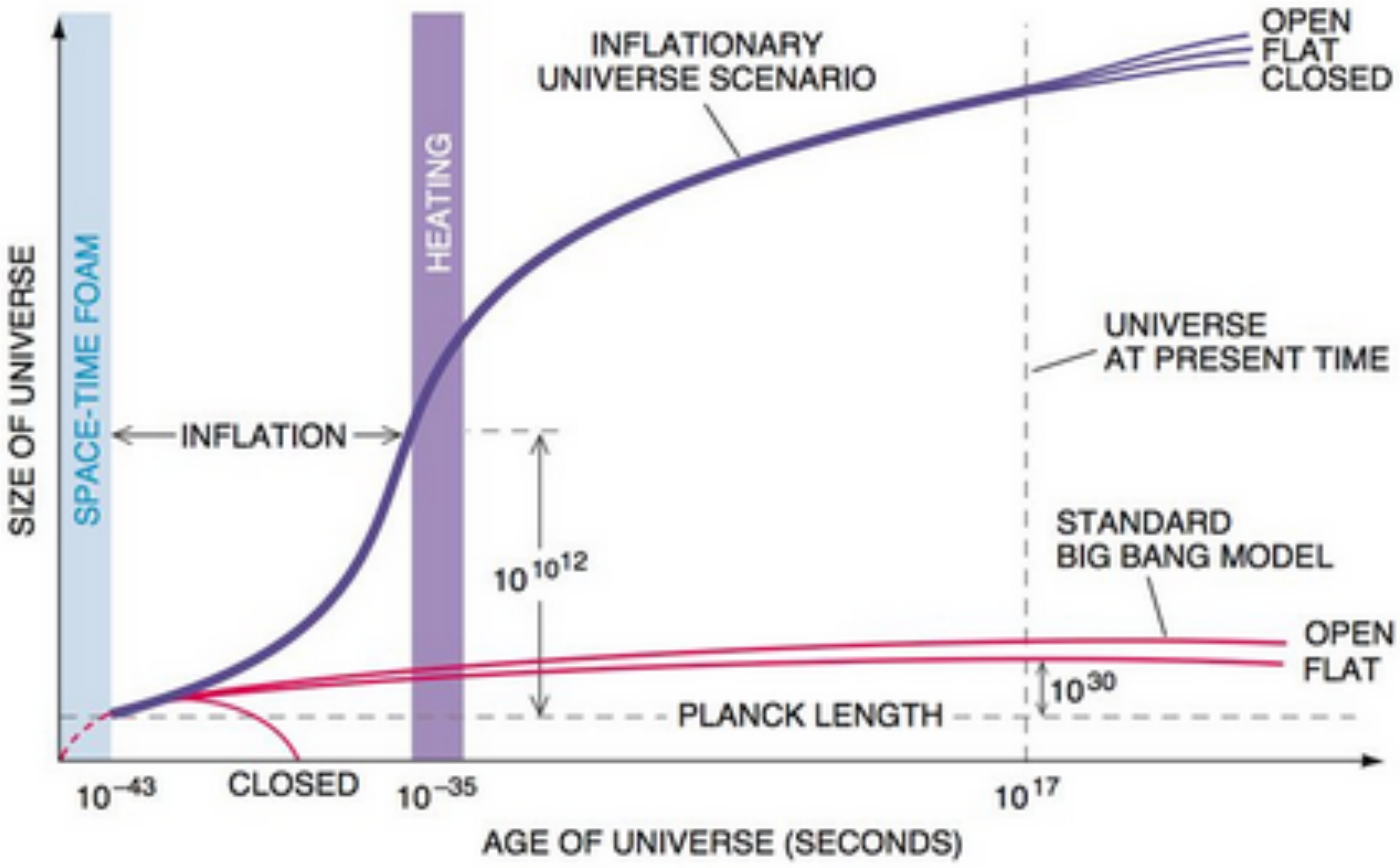
The Galactic magnetic field as revealed by Planck

Very important for B modes searches and foreground fighting

Beyond LCDM: focus on primordial Universe & inflation

Inflation





Inflation is an extremely rapid acceleration in the universe soon after its creation.

The Big questions:

Energy scale of Inflation

Physical processes at the origin of Inflation

Inflation Energy Transfer to the standard model of particle physics

Field content of the early Universe

Quantum origin of cosmological perturbations

The current picture: inflation physics

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 !

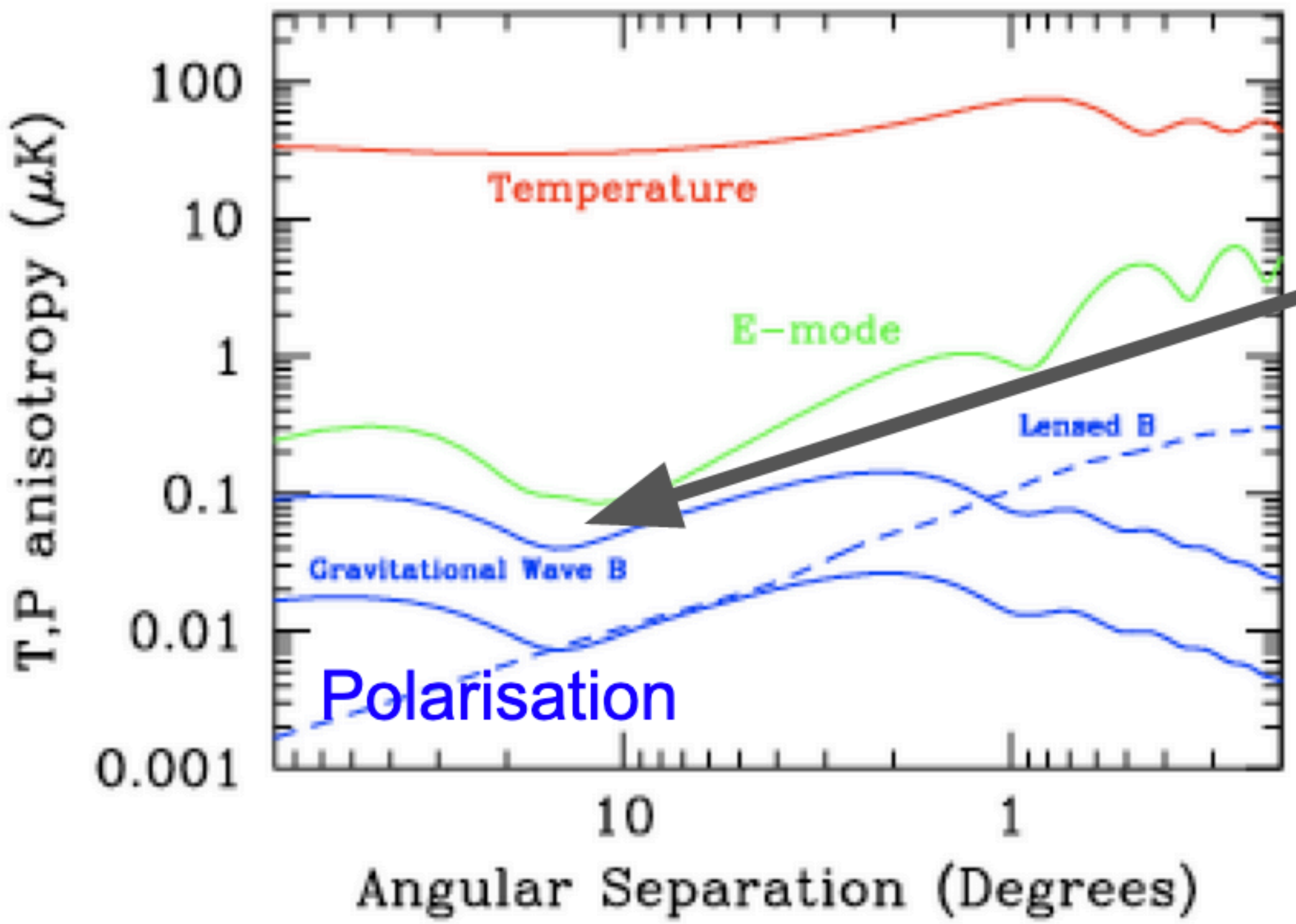
$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1} \quad \text{scalar}$$

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

$$r = A_t / A_s$$

"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:

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

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

First and second derivative of the potential

The unlensed B modes spectrum

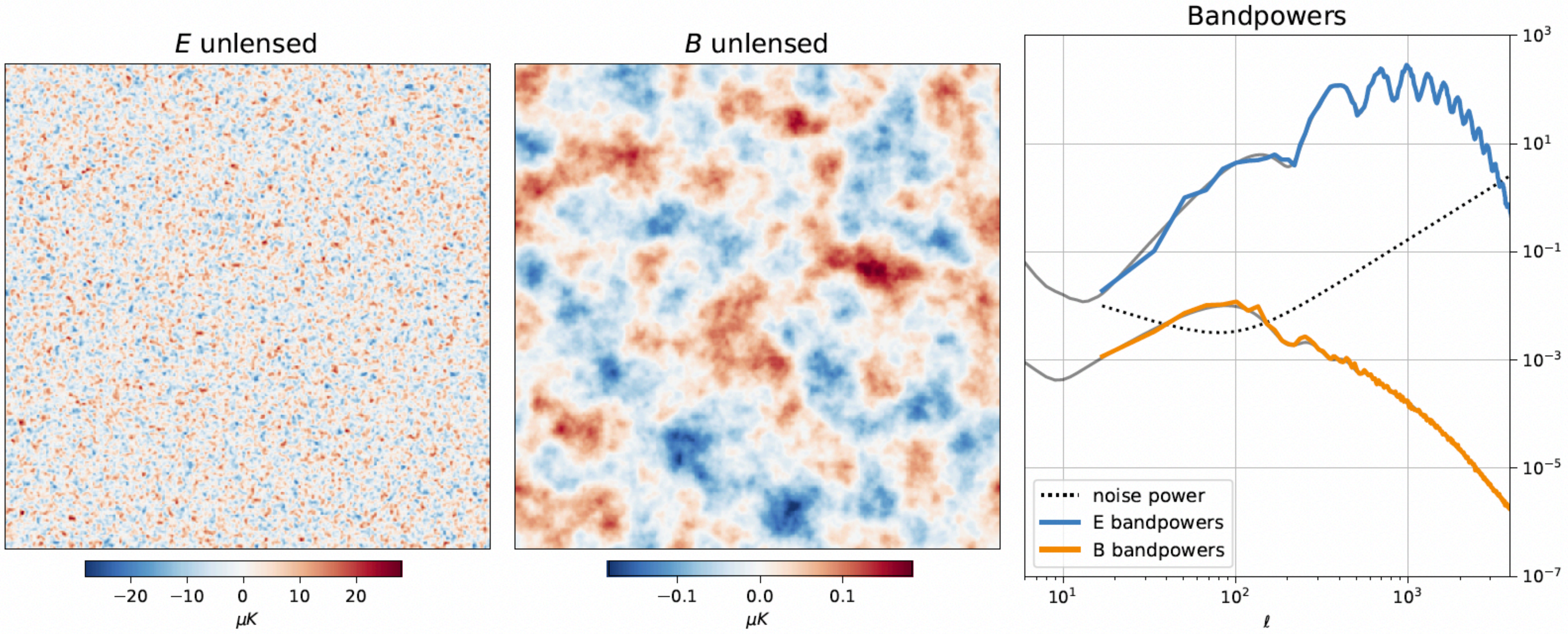
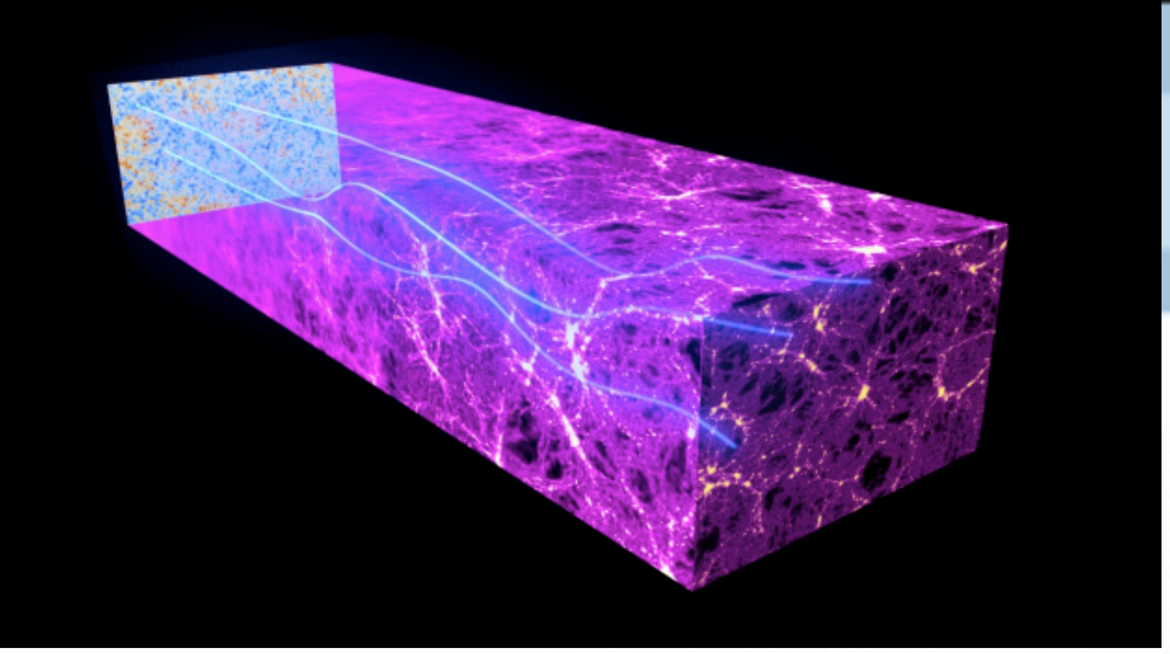


Figure: Unlensed polarization on 455 deg^2 patch of sky with $r = 0.025$. Note: r determines the amplitude of the unlensed B fluctuations. Dashed line on the right corresponds to $\sqrt{2}$ μKarcmin QU noise with a knee at $\ell = 100$



The effect of lensing on the B modes spectrum

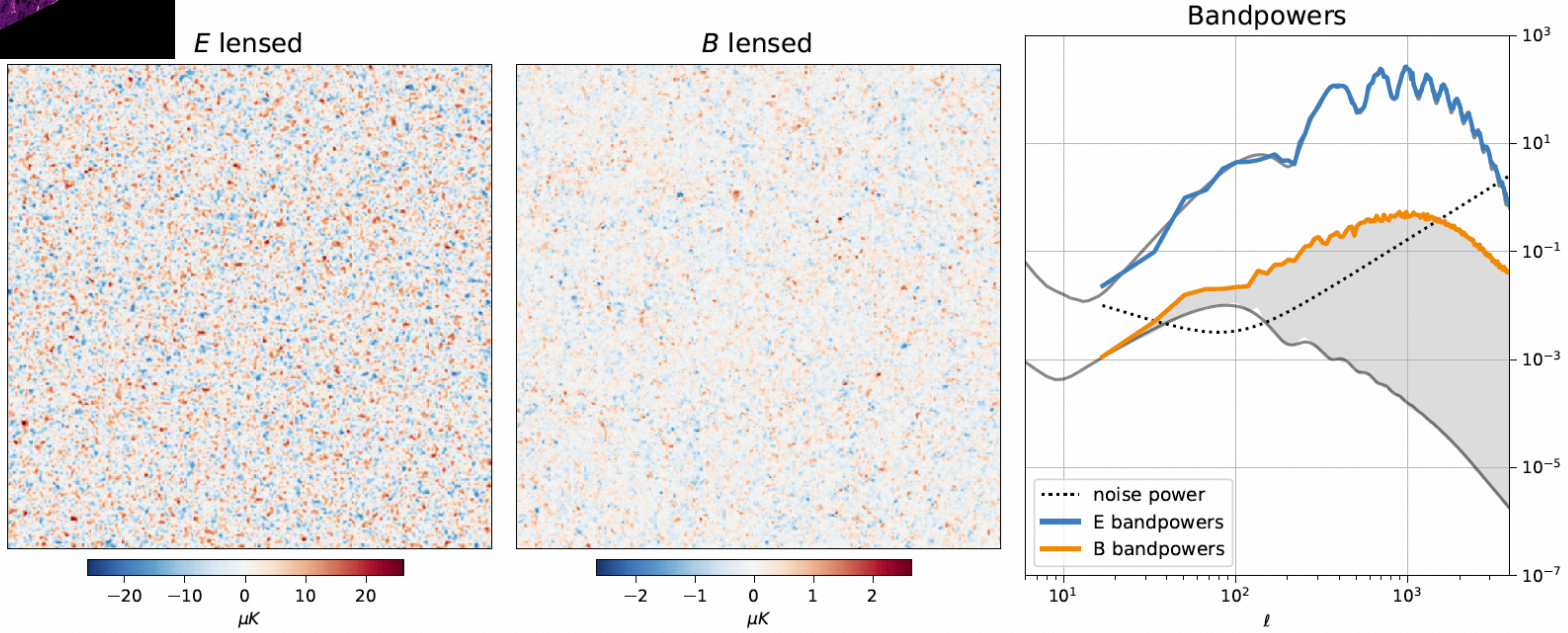
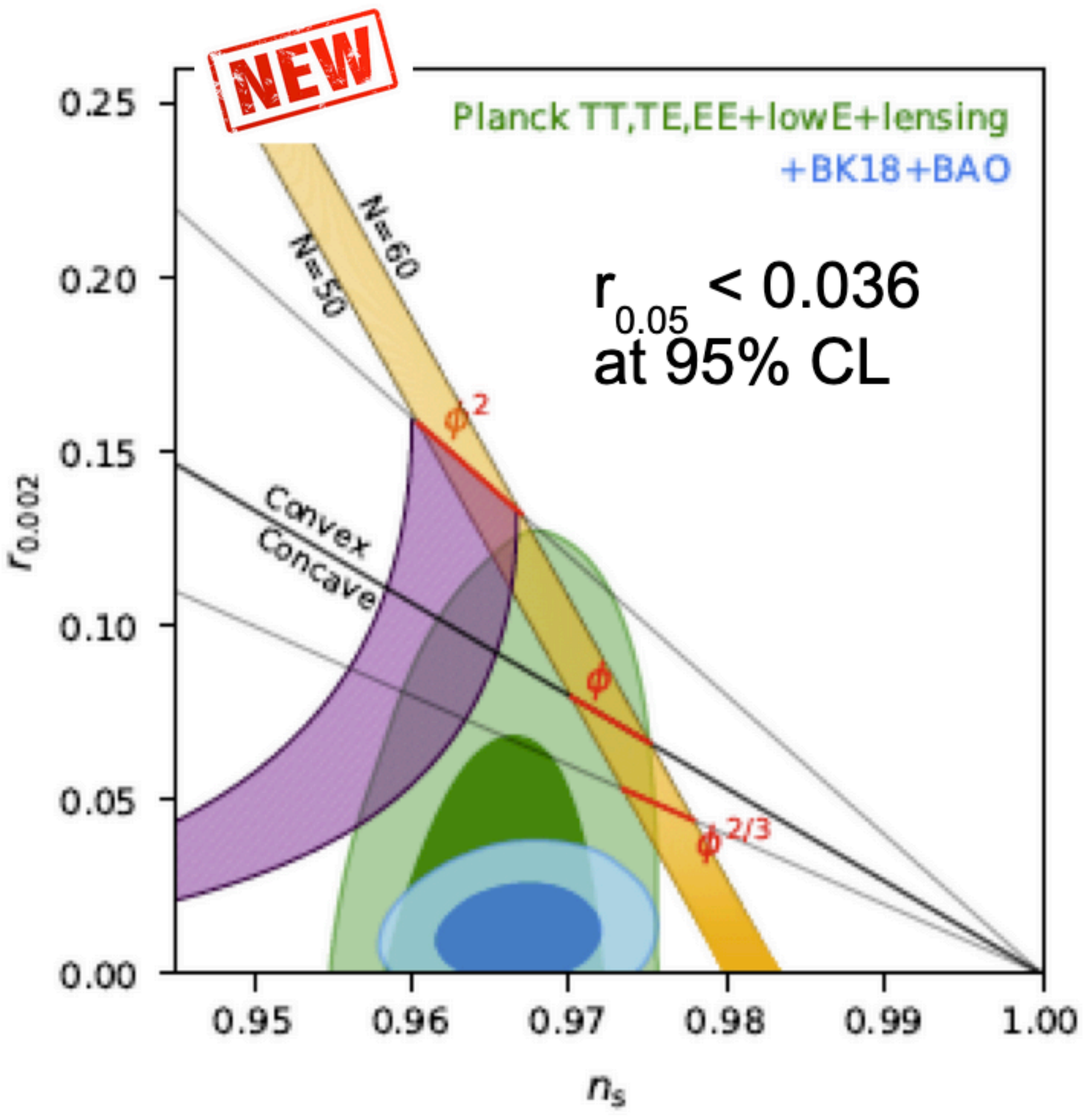


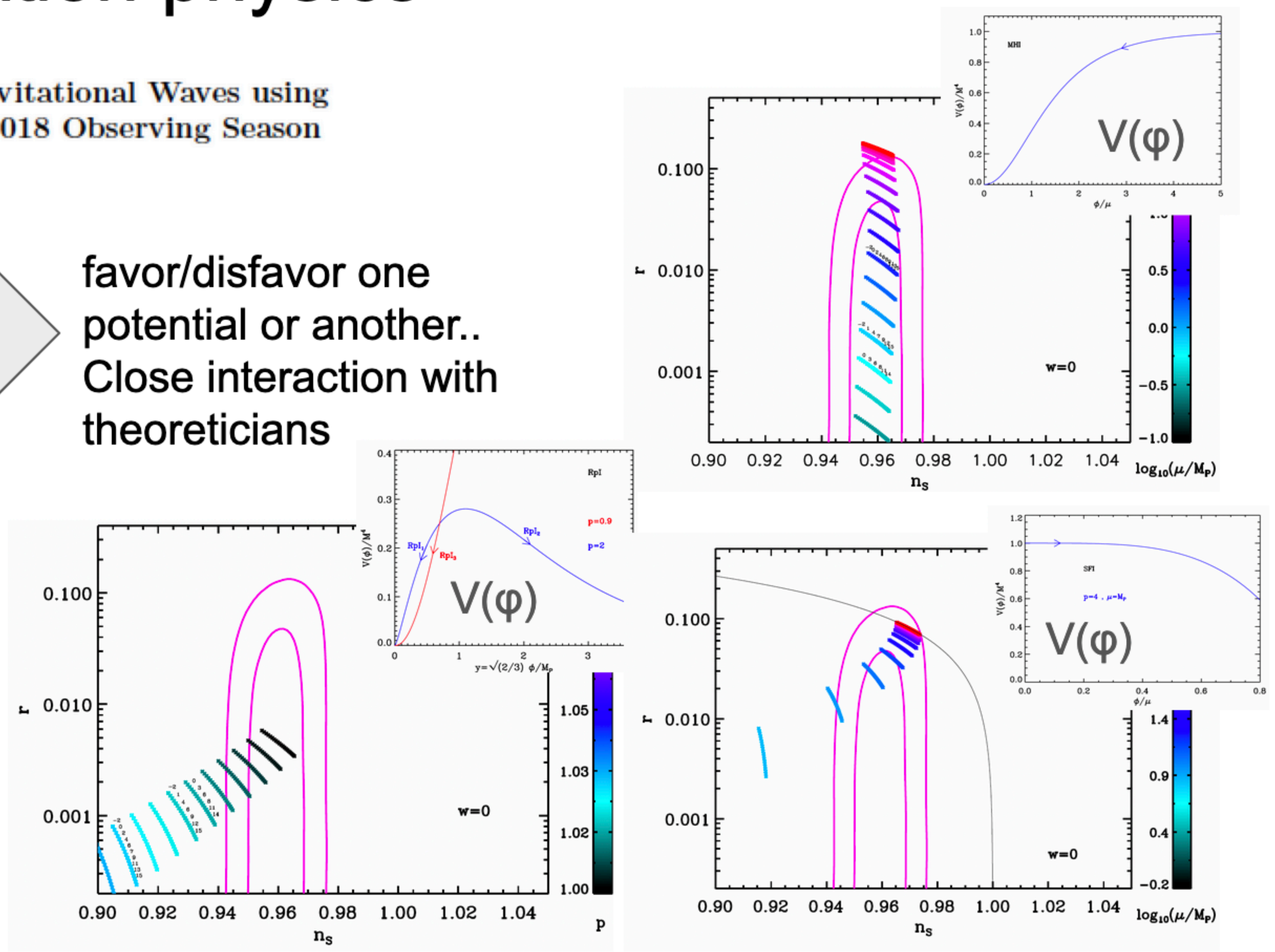
Figure: Lensed polarization. Qualitatively given by a phase distortion of *E* and a high frequency additive foreground corruption of *B* due to *E* fluctuations leaking into B fluctuations.

The current picture: inflation physics

BICEP / *Keck* XIII: Improved Constraints on Primordial Gravitational Waves using *Planck*, WMAP, and BICEP/*Keck* Observations through the 2018 Observing Season



favor/disfavor one potential or another.. Close interaction with theoreticians



arXiv:2110.00483

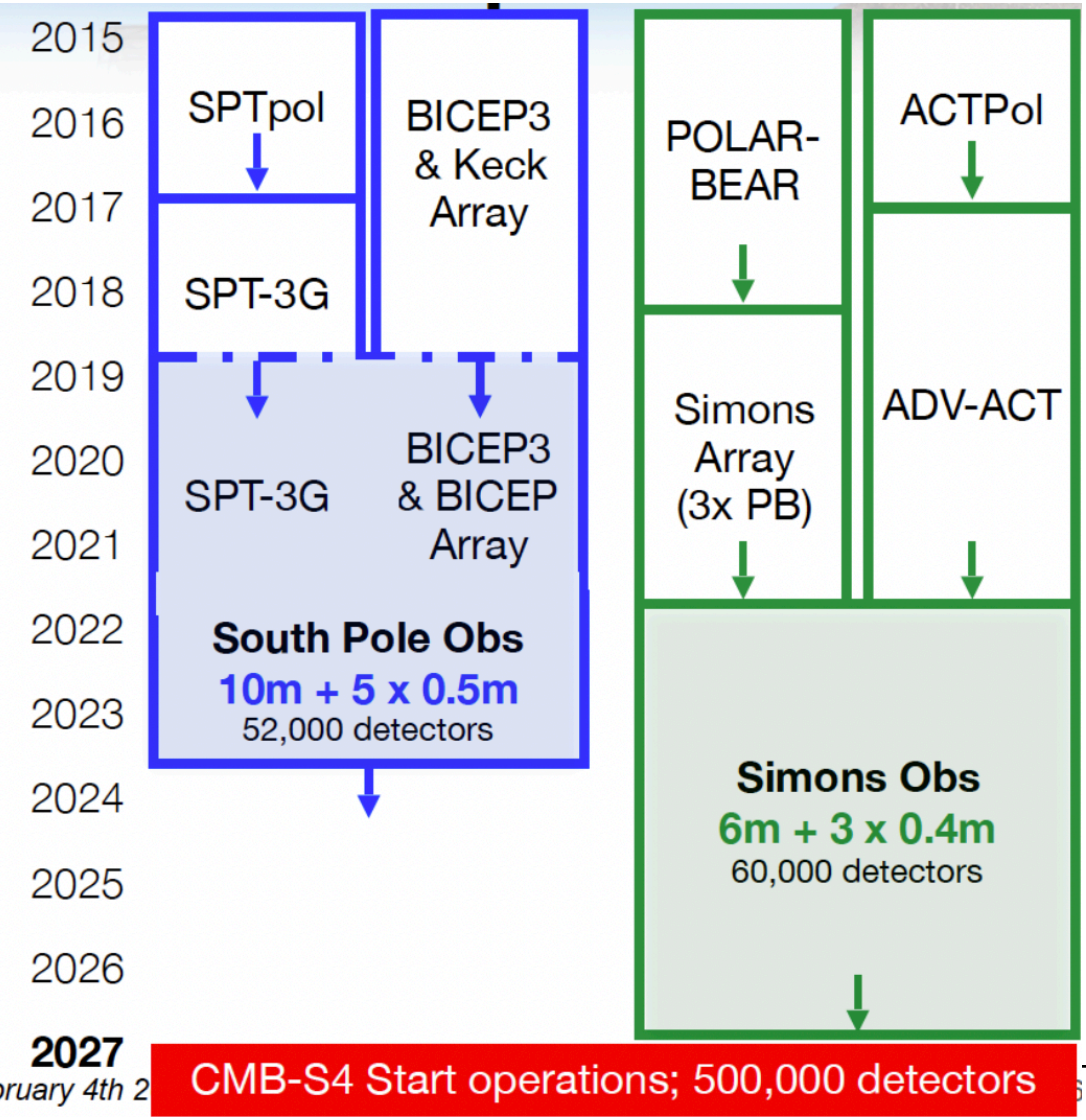
ArXiv 1303.3787

The next generation: ground based and space

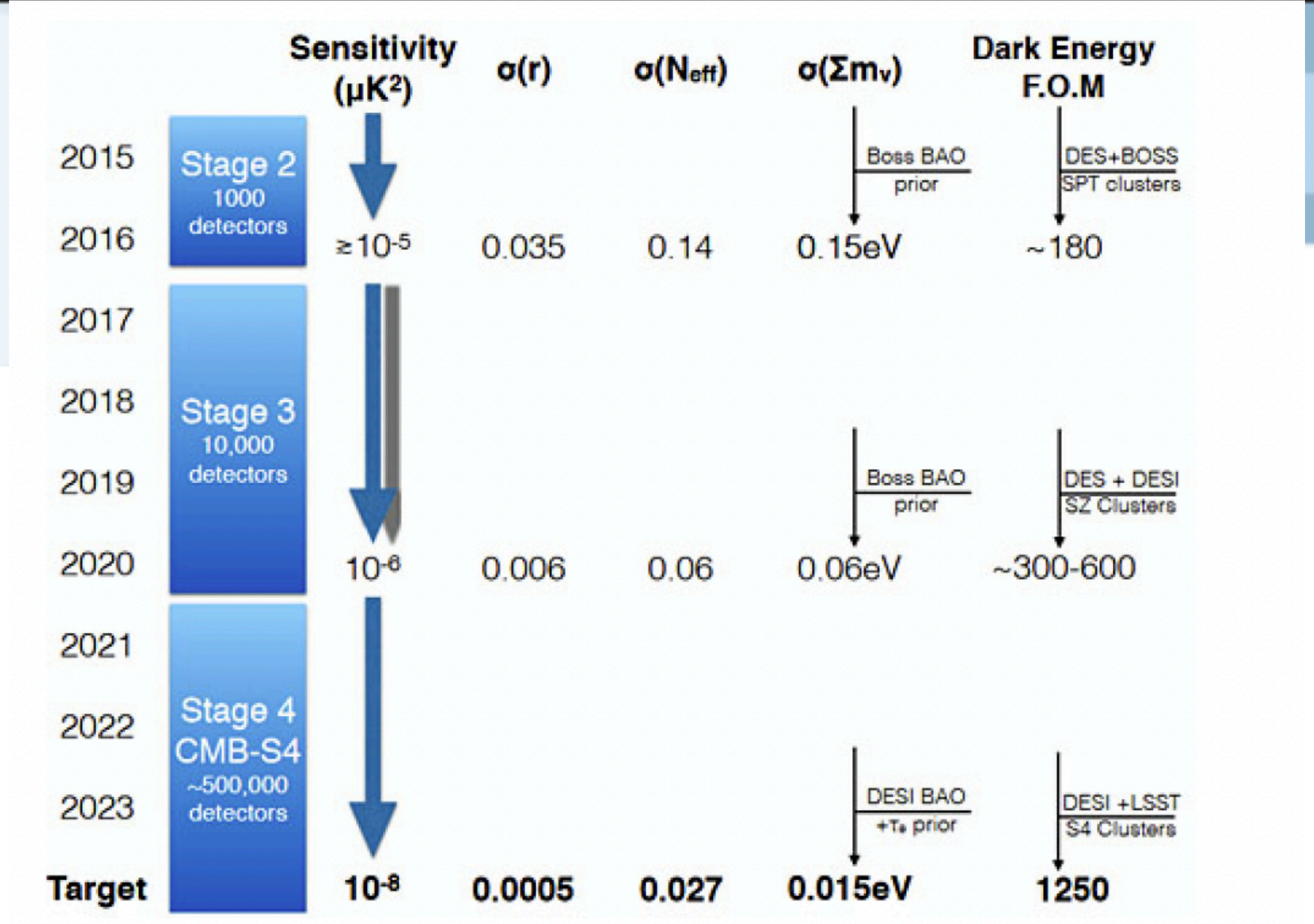
A large effort: South Pole + Atacama plateau

Science-driven expansion of capabilities + cost-driven consolidation of teams

- Late 2010s:
  - single-site, single resolution
  - O(10K) detectors
  - ACT, BICEP/Keck, POLARBEAR, SPT, etc
- Early 2020s:
  - single-site, dual-resolution
  - O(50K) detectors
  - Simons Observatory (SO), South Pole Observatory (SPO)
- Late 2020s:
  - dual-site, dual-resolution
  - O(500K) detectors
  - CMB-S4



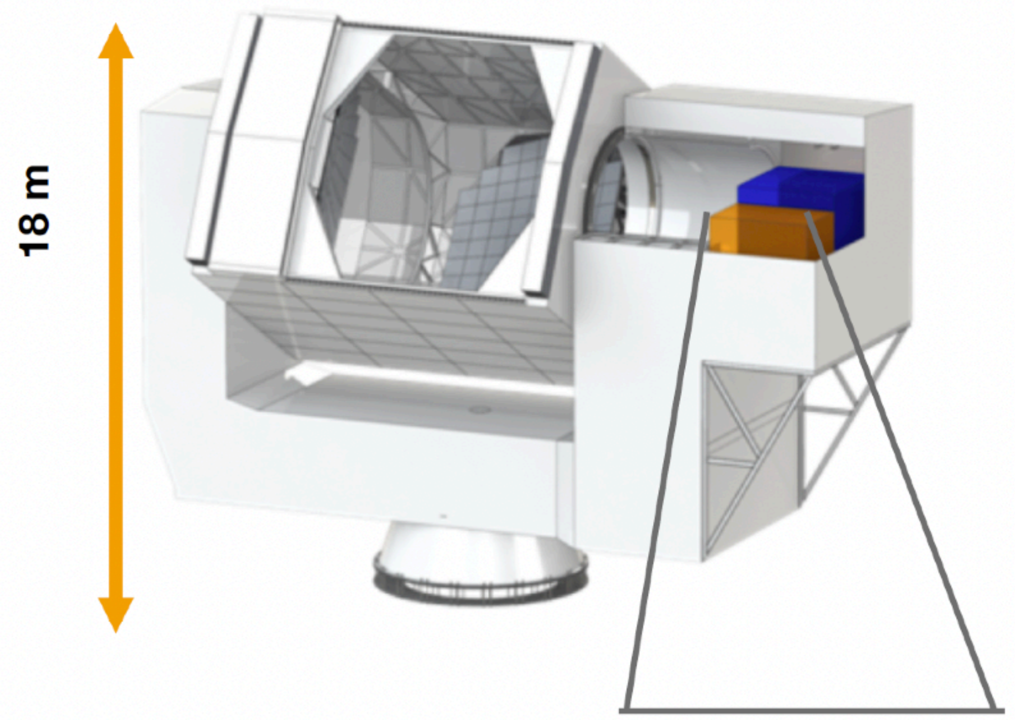
Ground based forecasts

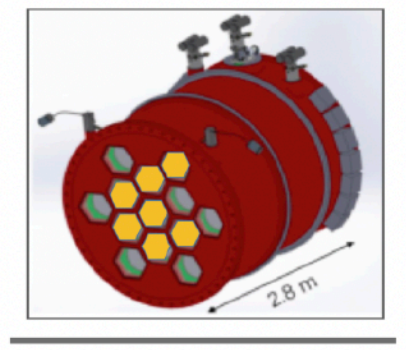


Years	Stage	Sensitivity (μK²)	σ(r)	σ(N_{eff})	σ(Σm_ν)	Dark Energy F.O.M
2015–2016	Stage 2, 1000 detectors	≥10^{-5}	0.035	0.14	0.15eV (Boss BAO prior)	~180 (DES+BOSS SPT clusters)
2017–2020	Stage 3, 10,000 detectors	10^{-6}	0.006	0.06	0.06eV (Boss BAO prior)	~300-600 (DES + DESI SZ Clusters)
2021–2023, Target	Stage 4 CMB-S4, ~500,000 detectors	**10^{-8}**	**0.0005**	**0.027**	**0.015eV** (DESI BAO +τ prior)	**1250** (DESI +LSST S4 Clusters)

Simons Observatory - telescopes

Large Aperture Telescope

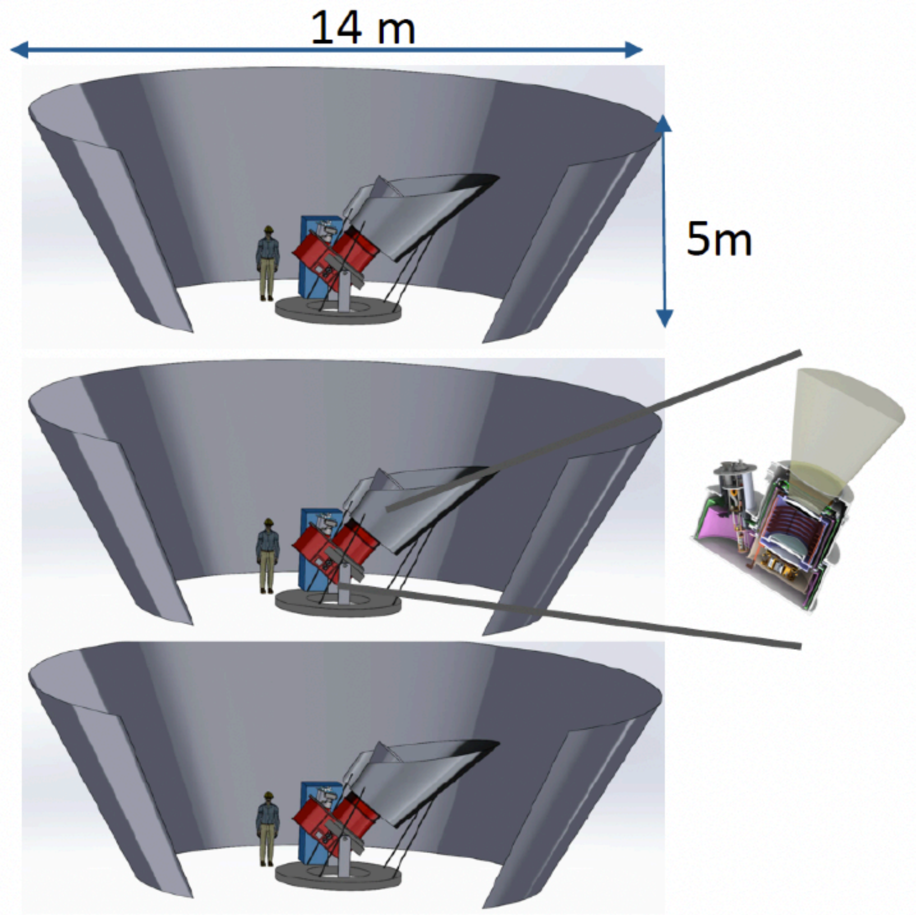




6 m crossed Dragone coupled to 13 optics tubes,

SO-Nominal uses 7 tubes, with dichroic pixels:
- One tube: 30/40 GHz
- Four tubes: 90/150 GHz
- Two tubes: 220/270 GHz

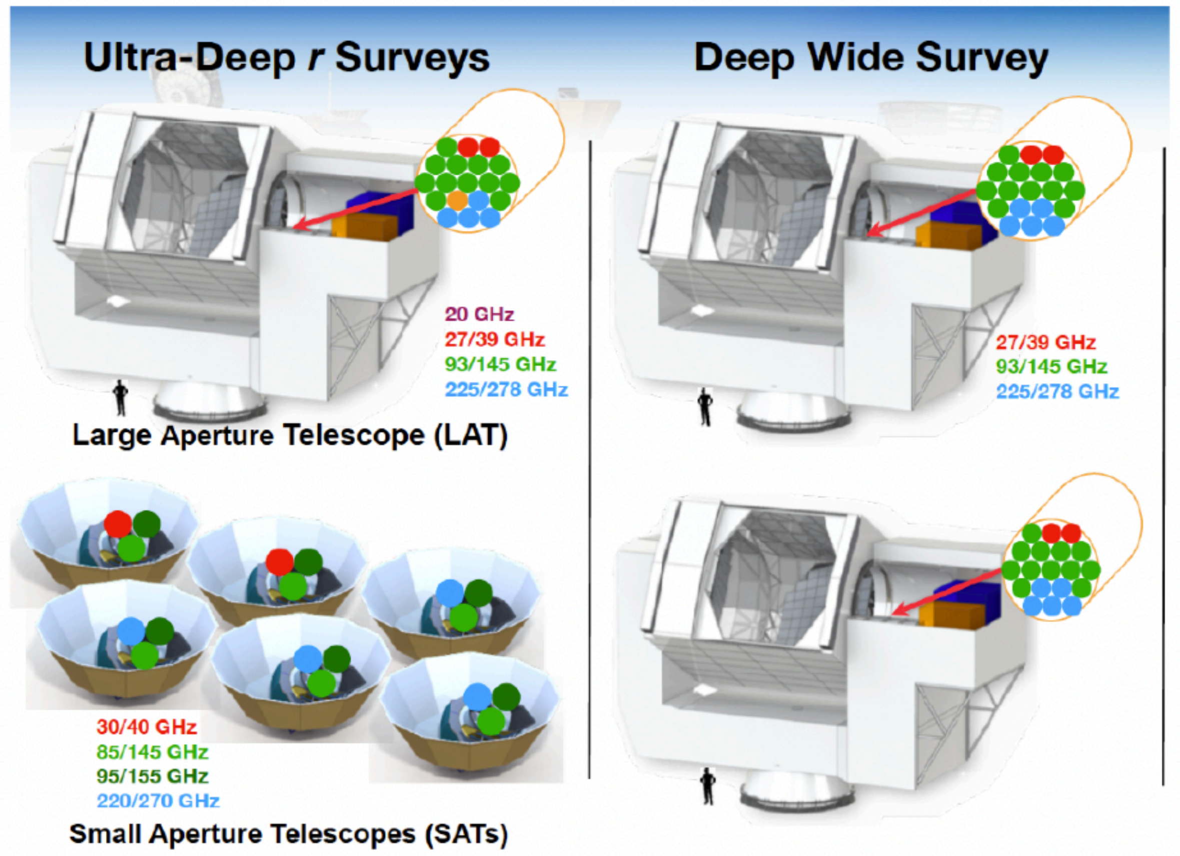
Small Aperture Telescopes



SO-Nominal deploys three refractors 42 cm in diameter, rotating half-wave plate.
Dichroic pixels:
30/40 | 90/150 | 220/270 GHz

CMB-S4 – instruments

- 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

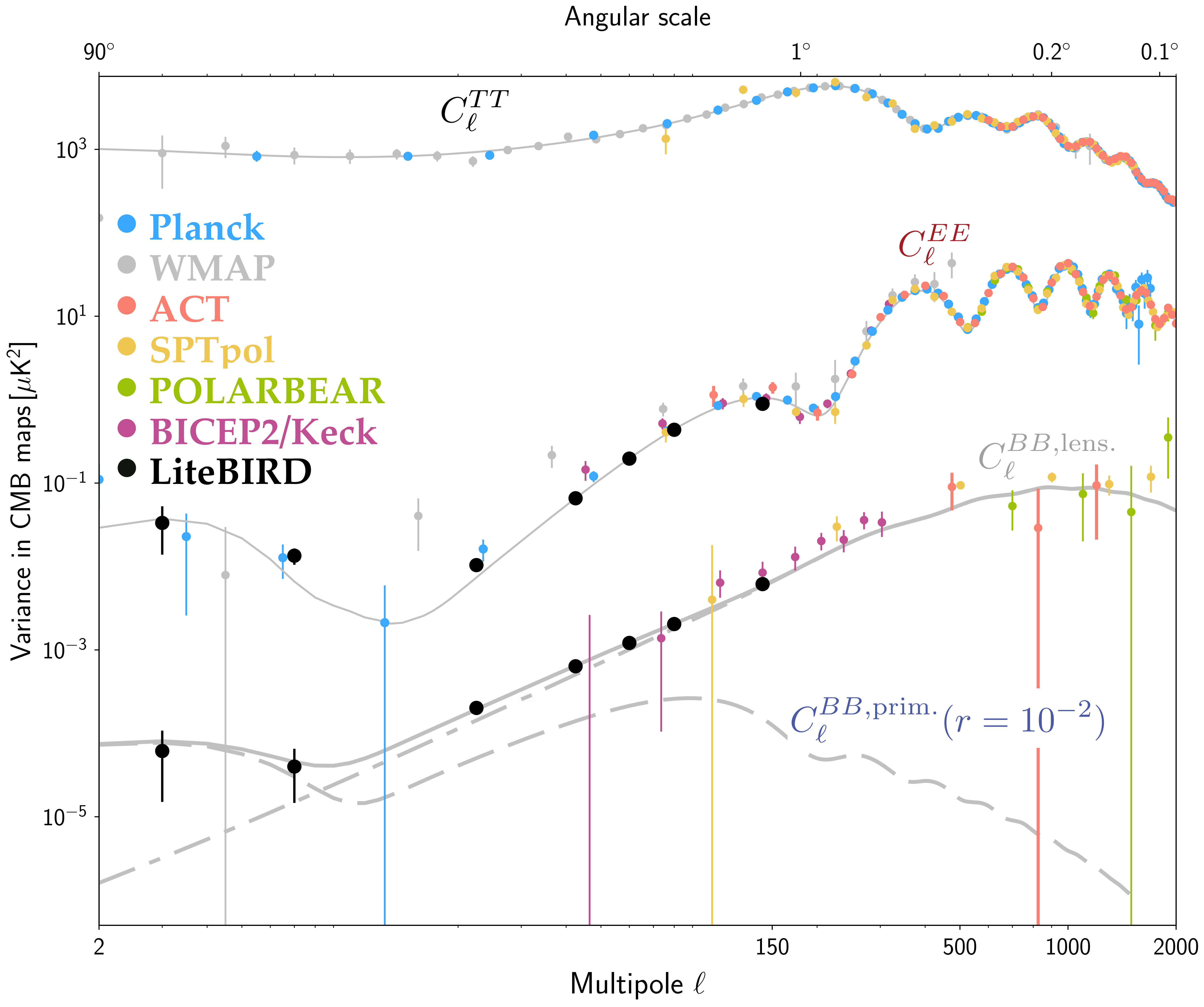


- Chile
  2x 6m telescope with 120,000 detectors each and 7 bands.

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

CMB polarisation from Space: LiteBIRD

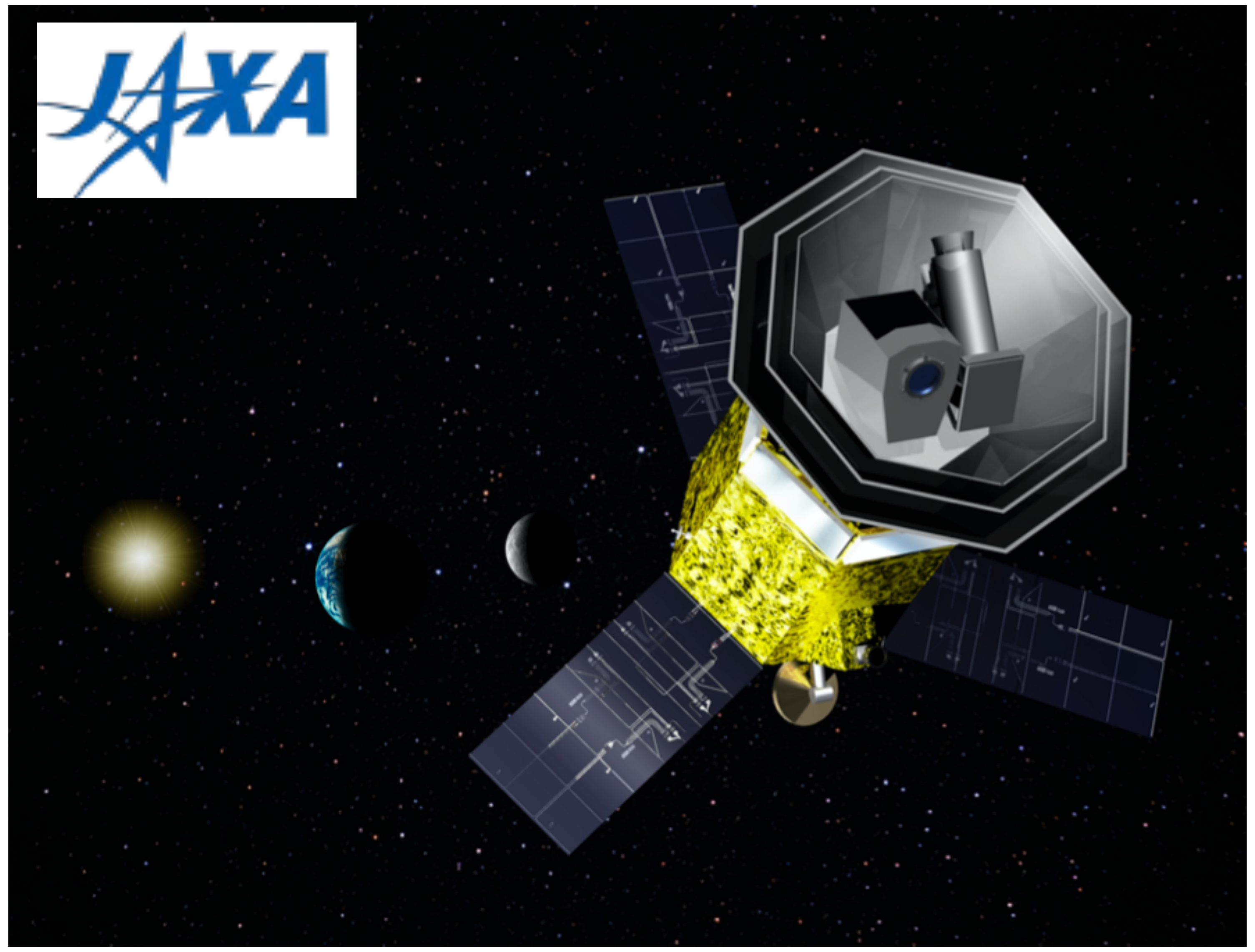
- Definitive search for the ***B*-mode signal** from **cosmic inflation** in the CMB polarization
  - Making a discovery or ruling out well-motivated inflationary models
  - Insight into the quantum nature of gravity
- The inflationary (i.e. primordial) *B*-mode power is proportional to the **tensor-to-scalar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

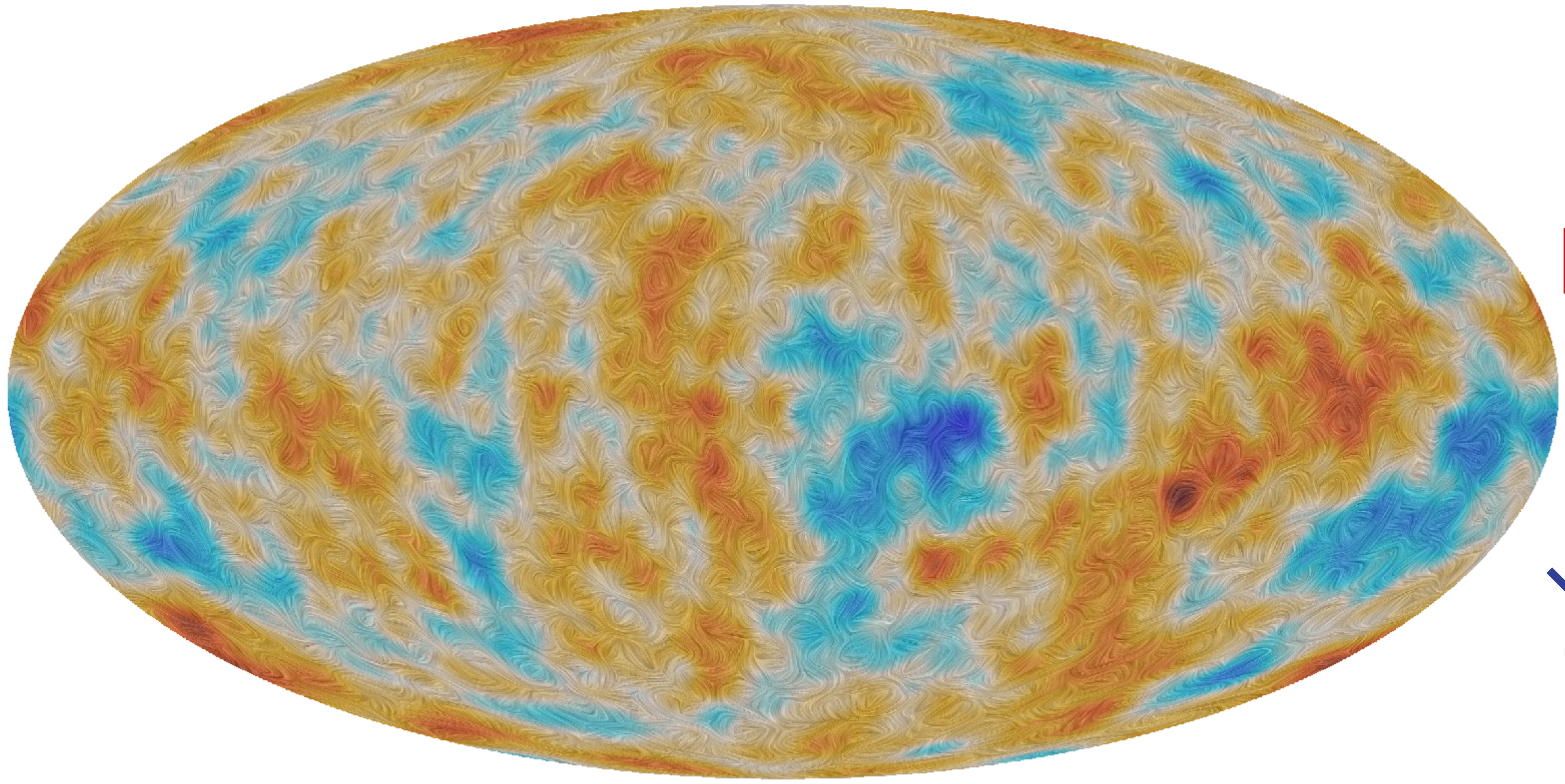


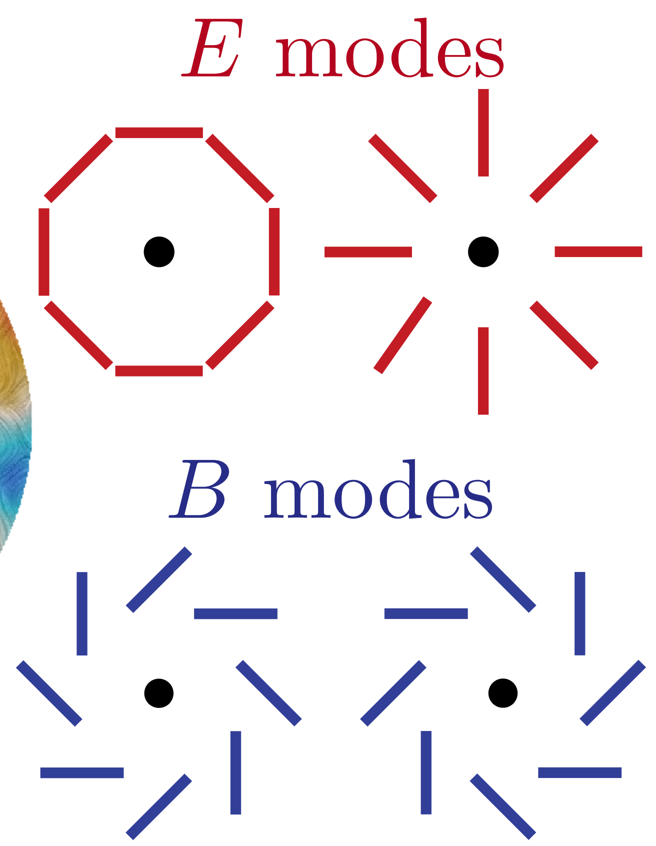
- LiteBIRD will improve current sensitivity on *r* by a factor ~50
- L1-requirements (no external data):
  - For $r = 0$, **total uncertainty of $\delta r < 0.001$**
  - For $r = 0.01$, 5-σ detection of the reionization ($2 < \ell < 10$) and recombination ($11 < \ell < 200$) peaks independently
- Huge discovery impact (evidence for inflation, knowledge of its energy scale, …)

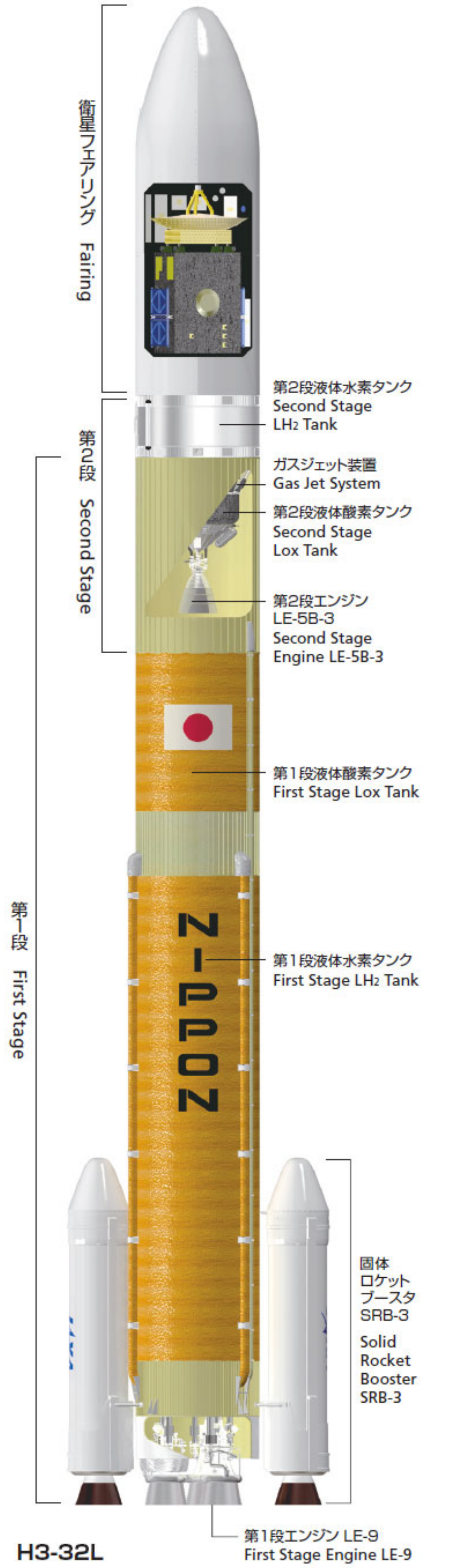
LiteBIRD overview

- 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 in late **2029** 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



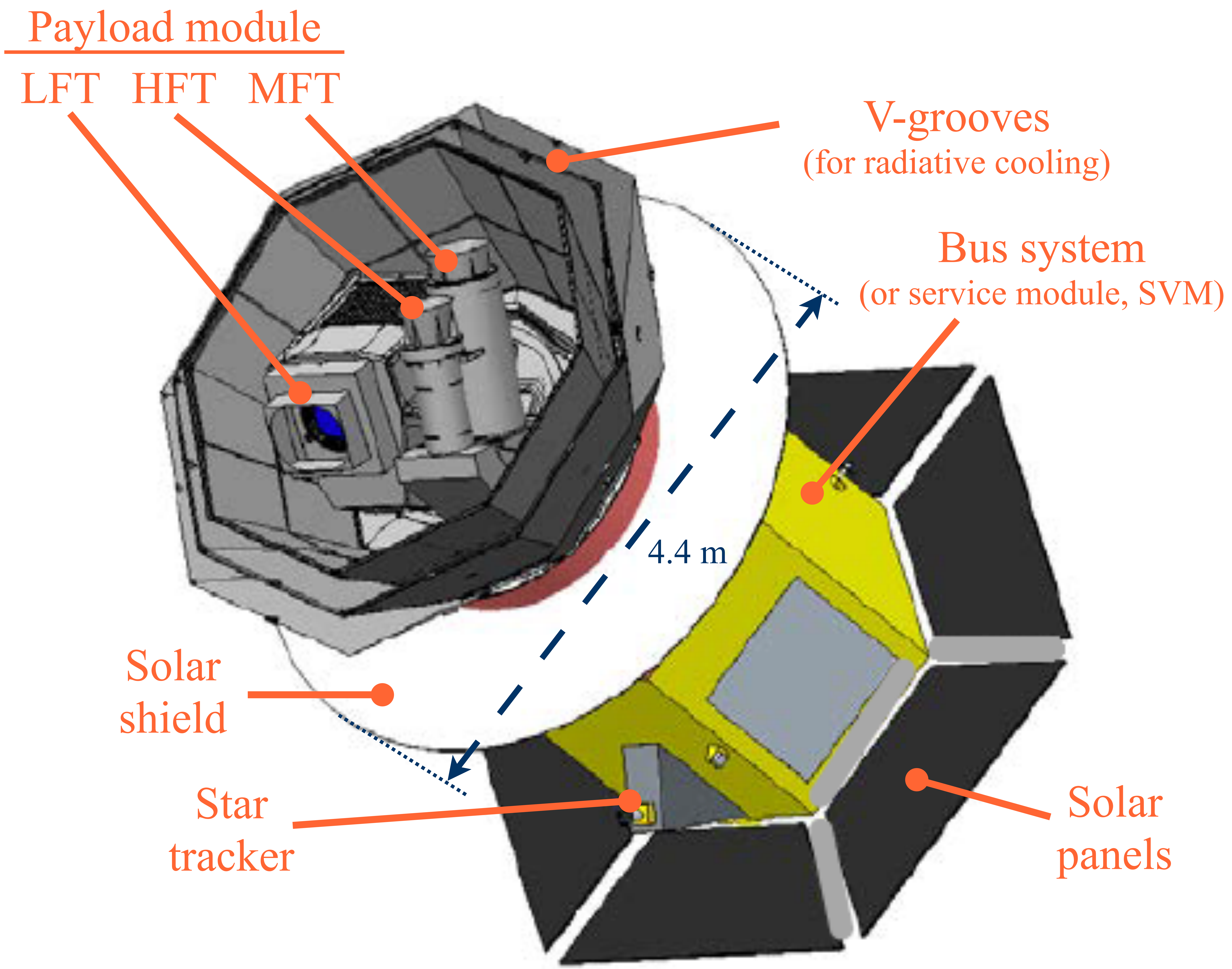






LiteBIRD spacecraft overview

- **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**

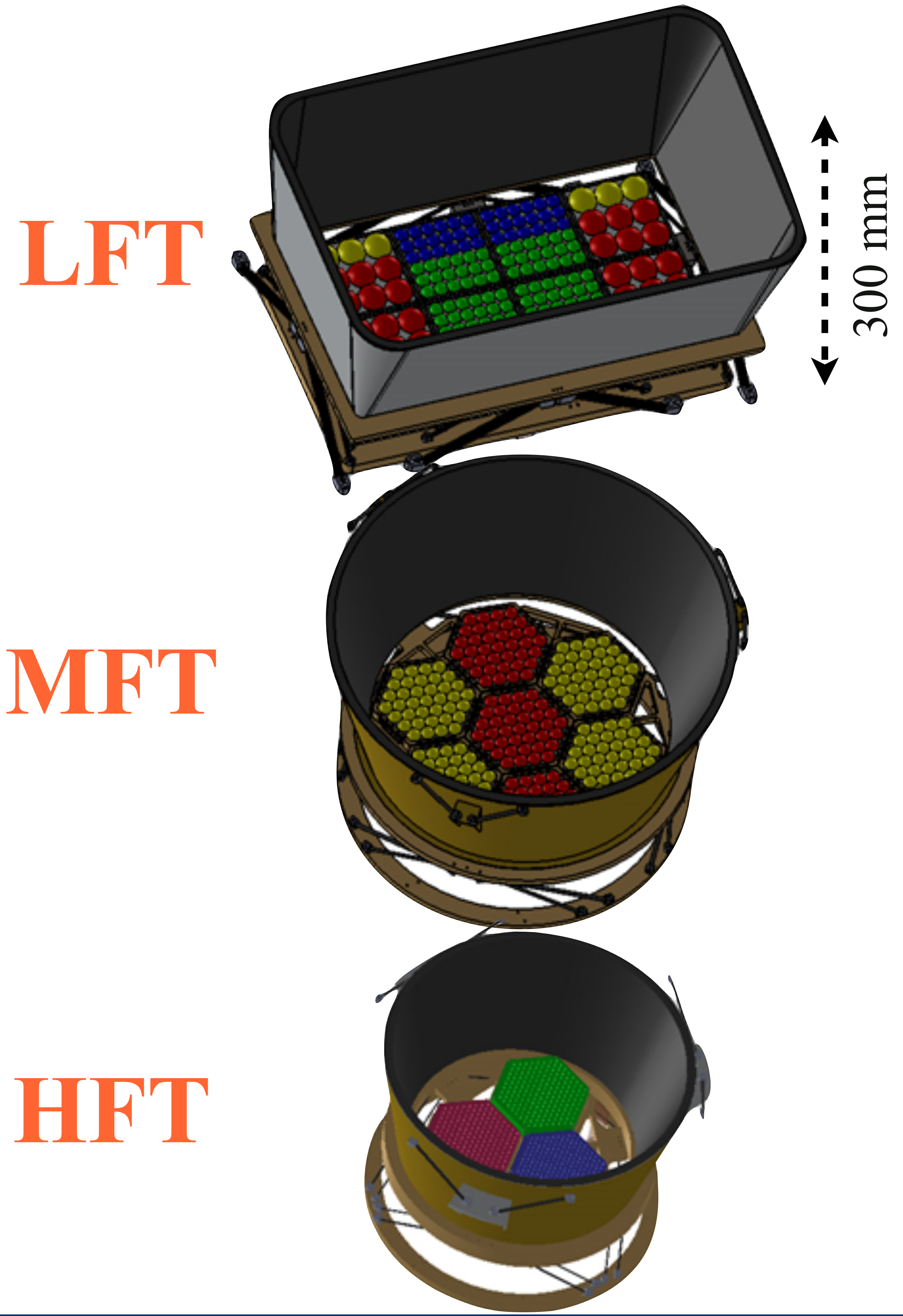


- Mass: 2.6 t
- Power: 3.0 kW
- Data: 17.9 Gb/day

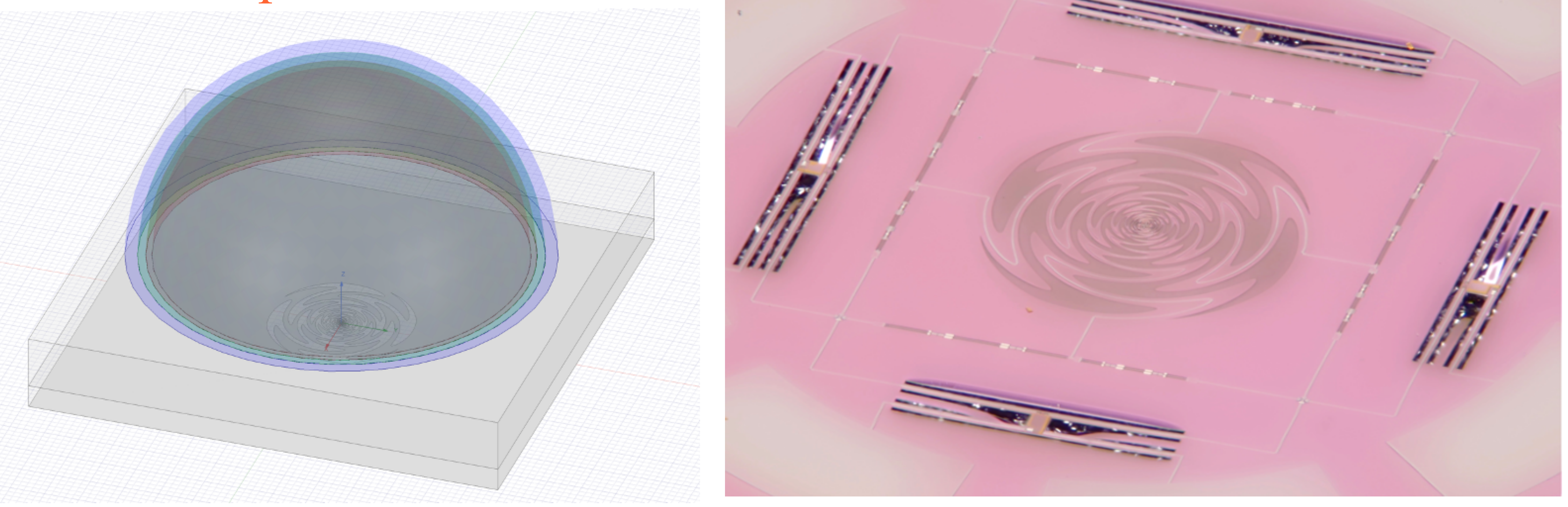
Focal plane configuration

- Transition-Edge Sensor (TES) arrays

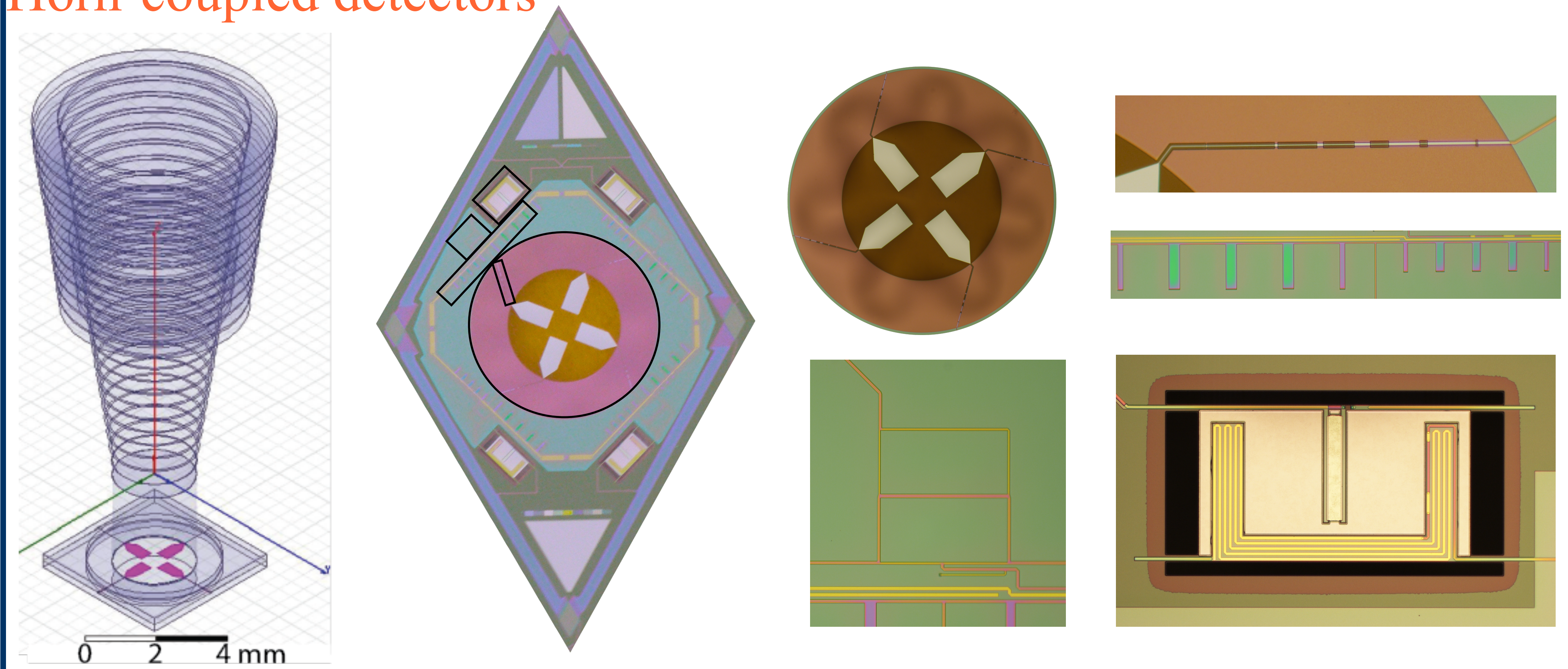
	LFT	MFT	HFT
Detector type	Lenslet/sinous	Lenslet/sinous	Horn/OMT
Nbands	9 (40-140 GHz)	5 (100-195 GHz)	5 (195-402 GHz)
Ndet	1080	2074	1354

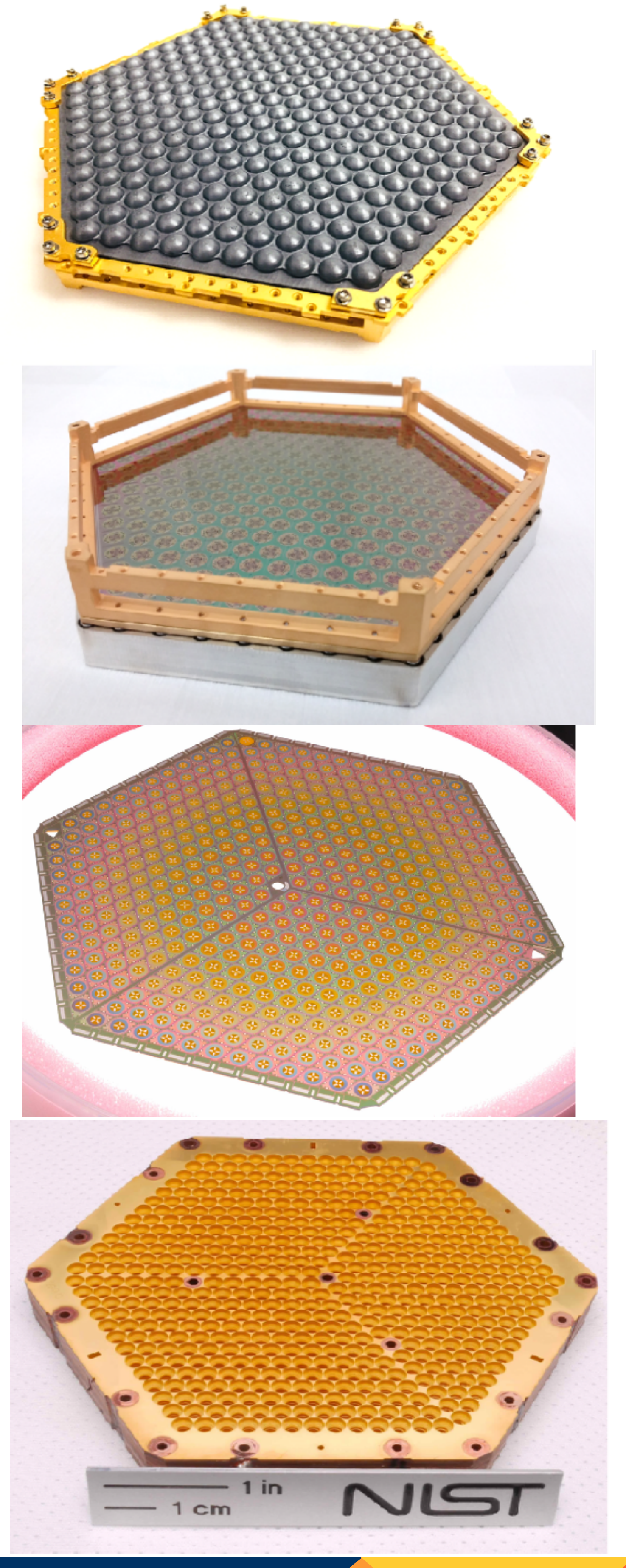


Lensed coupled detectors



Horn-coupled detectors



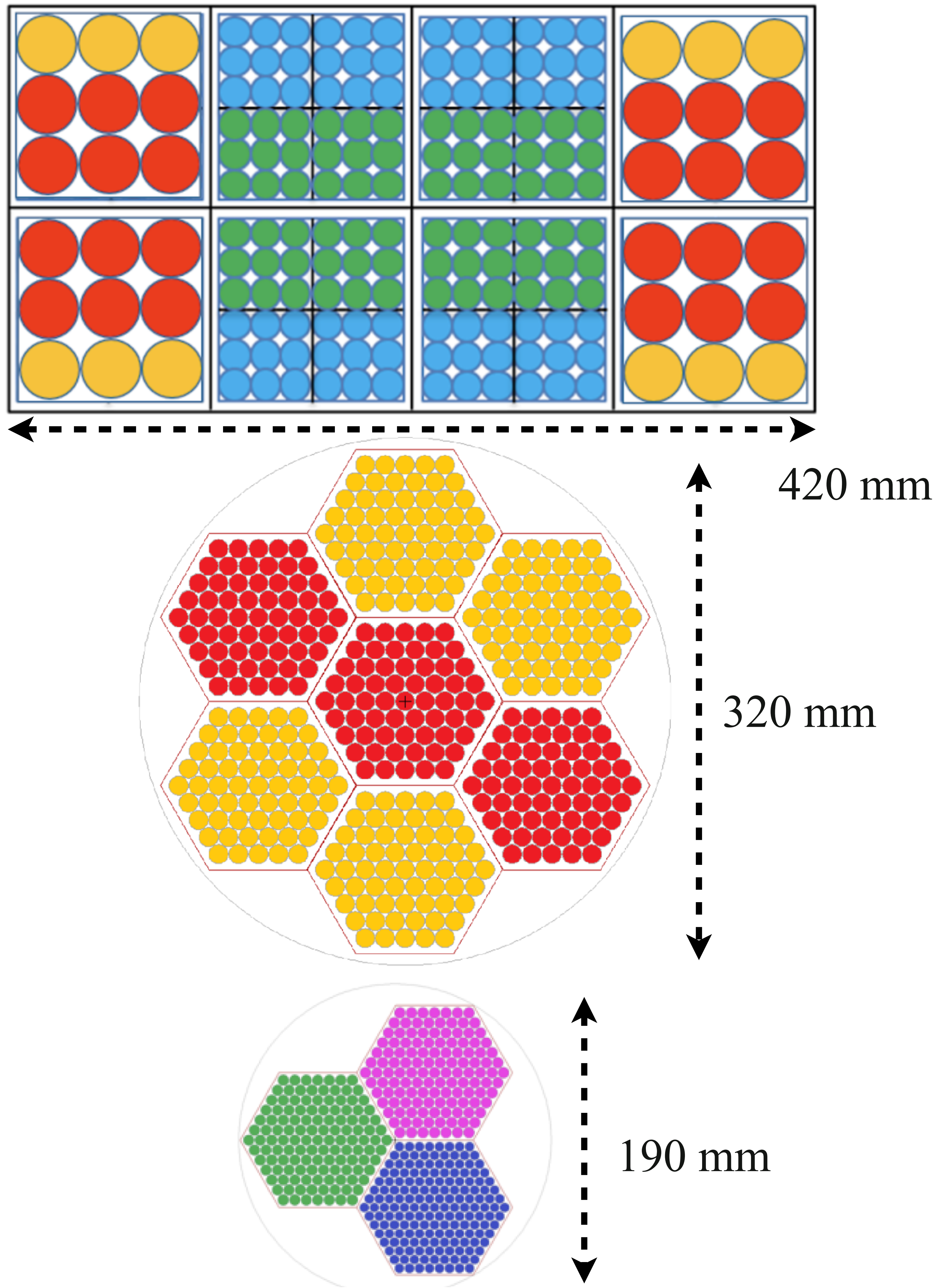


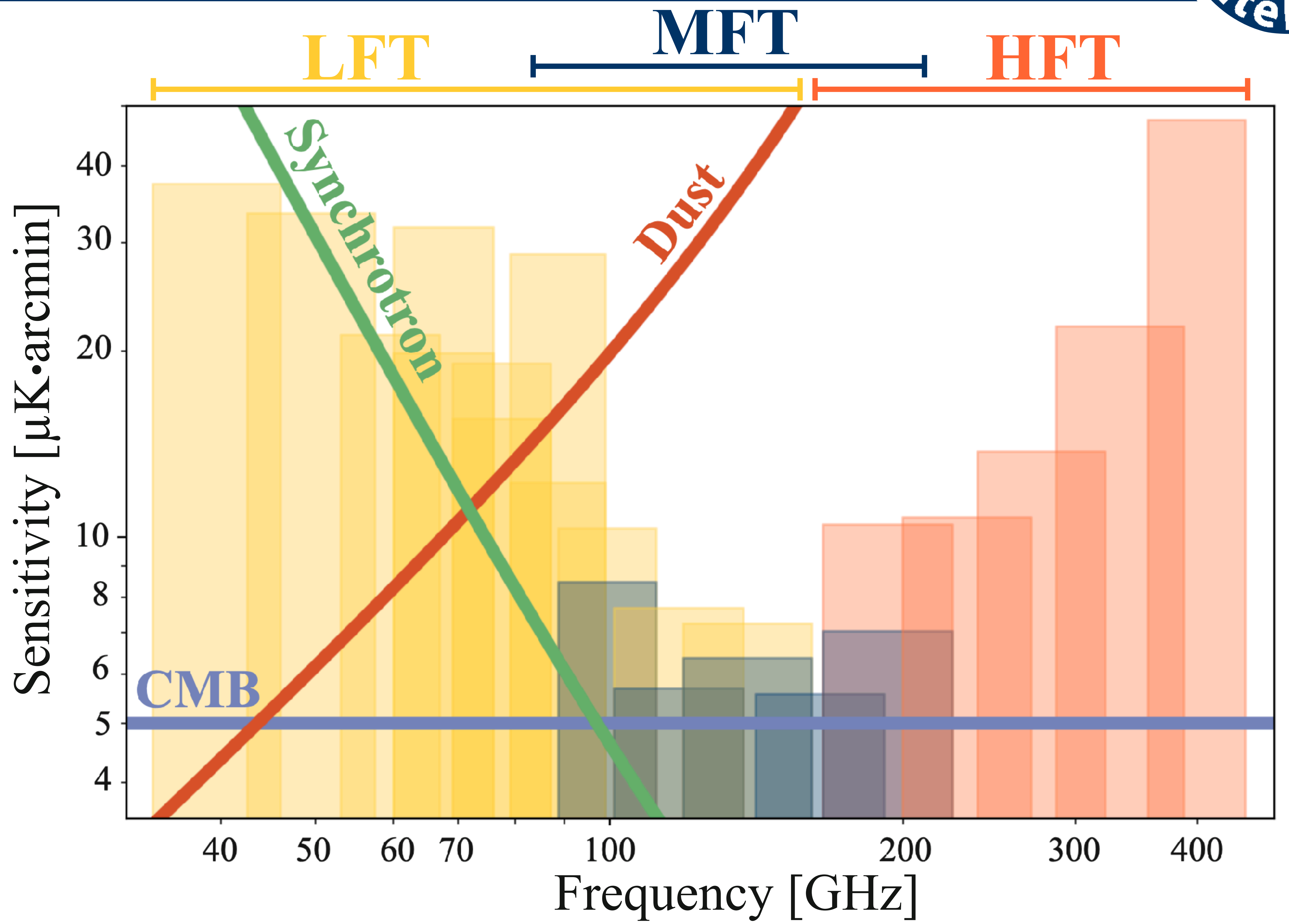
LiteBIRD sensitivities

LFT

MFT

HFT

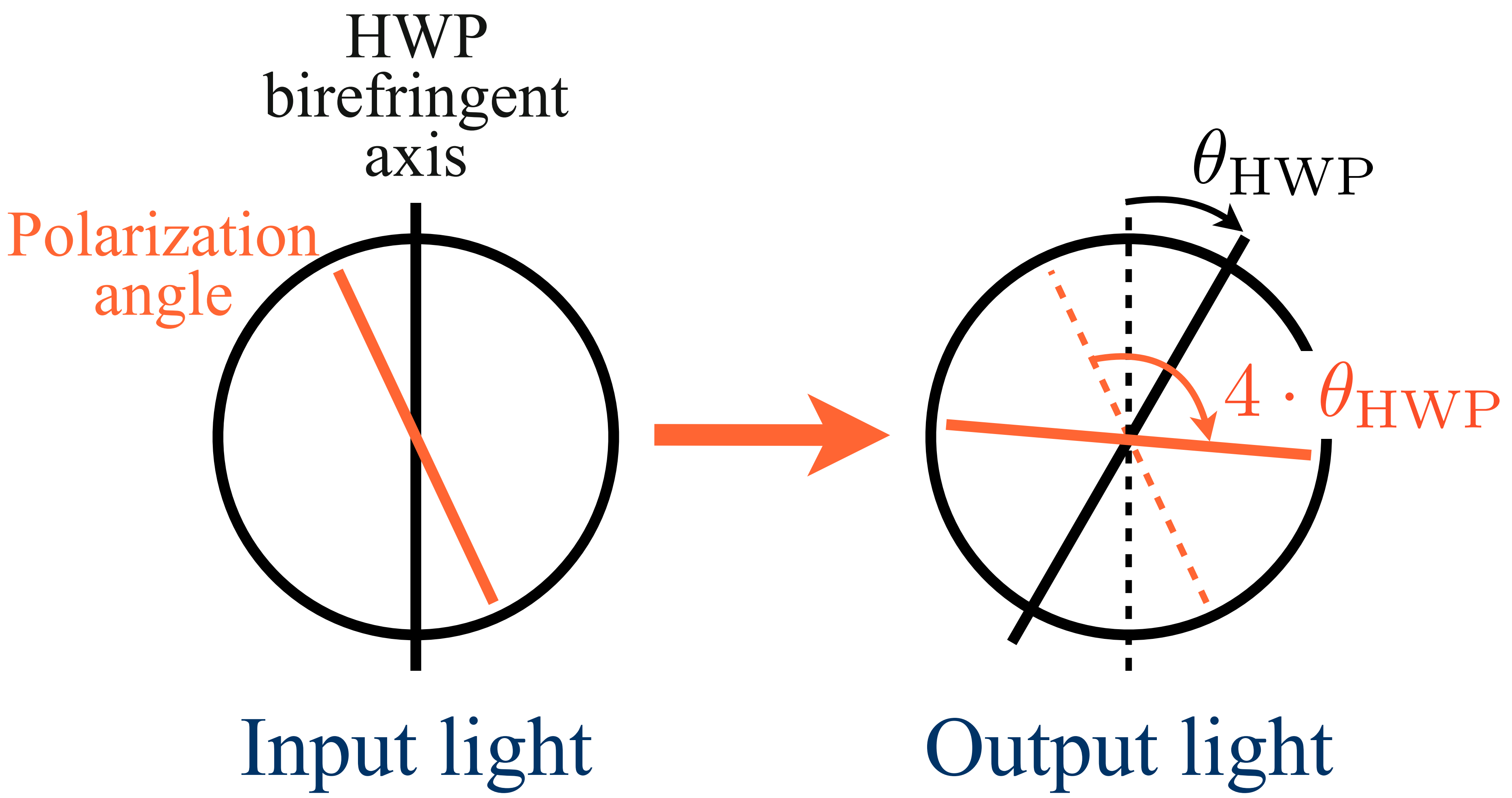


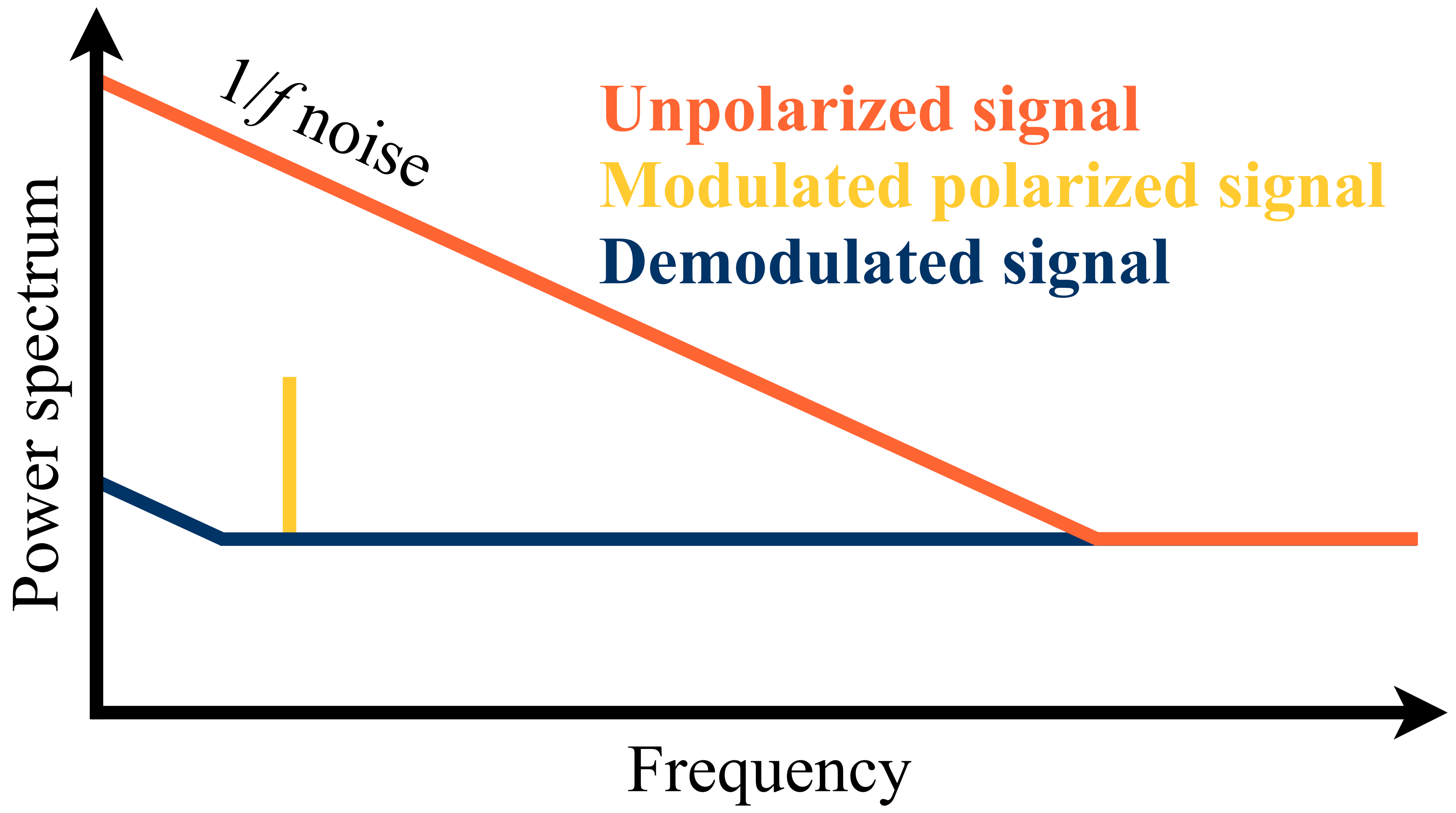


- Projected **polarization sensitivities** for a **3-year full-sky survey**
- Best of 4.3 μK·arcmin @ 119 GHz (Hazumi+ 2020)
- Combined sensitivity to primordial CMB anisotropies (after foreground removal): **2.2 μK·arcmin**

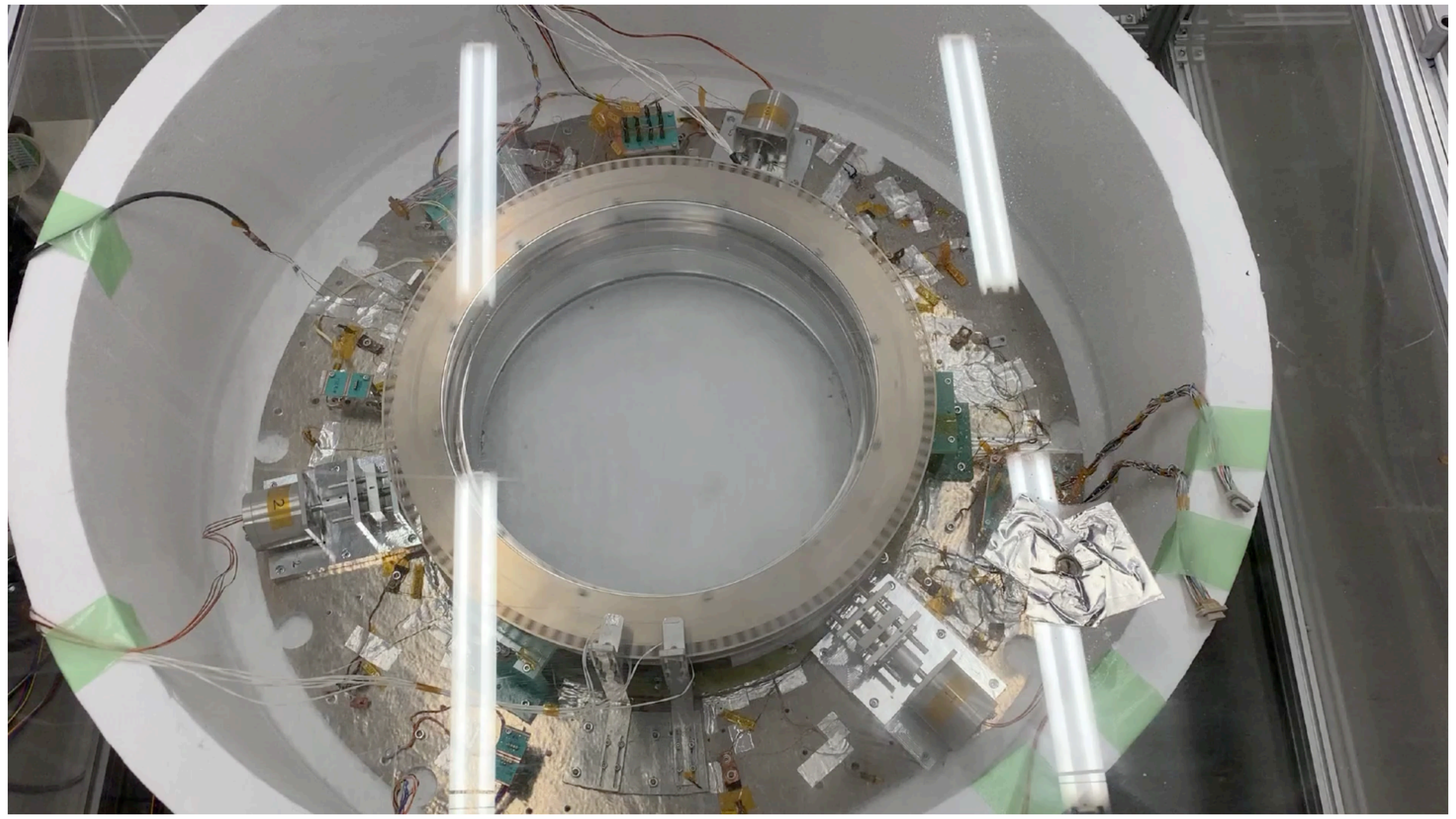
Polarization Modulation Unit (PMU)

- Rotating a birefringent plate to modulate polarization
- The first sky-side optical element





- LFT PMU BBM at Kavli IPMU:



- Rotation test of superconducting magnetic bearing system in the 4K cryostat
- Stable rotation at cryogenic temperature (< 10 K)

Outlook

- I have focused on the polarisation aspects of CMB for our understanding of cosmology and only took the example of the base LCDM and its extension to test for inflation.

- **BUT** a lot more is expected to come out of coming CMB polarisation measurements:
  1. Characterize the *B*-mode power spectrum and search for source source fields (e.g. scale-invariance, non-Gaussianity, parity violation, …)
  2. Power spectrum features in polarization
     - Large-scale ***E*-modes**
     - **Reionization** (for LiteBIRD: improve $\sigma(\tau)$ by a factor of 3)
     - **Neutrino mass** (for LiteBIRD: $\sigma(\sum m_\nu) = 15$ meV)
  3. Constraints on **cosmic birefringence**
  4. **SZ effect** (thermal, diffuse, relativistic corrections)
  5. Elucidating **anomalies**
  6. **Galactic science**
     - Characterizing the foreground SED
     - Large-scale Galactic magnetic field
     - Models of dust polarization

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