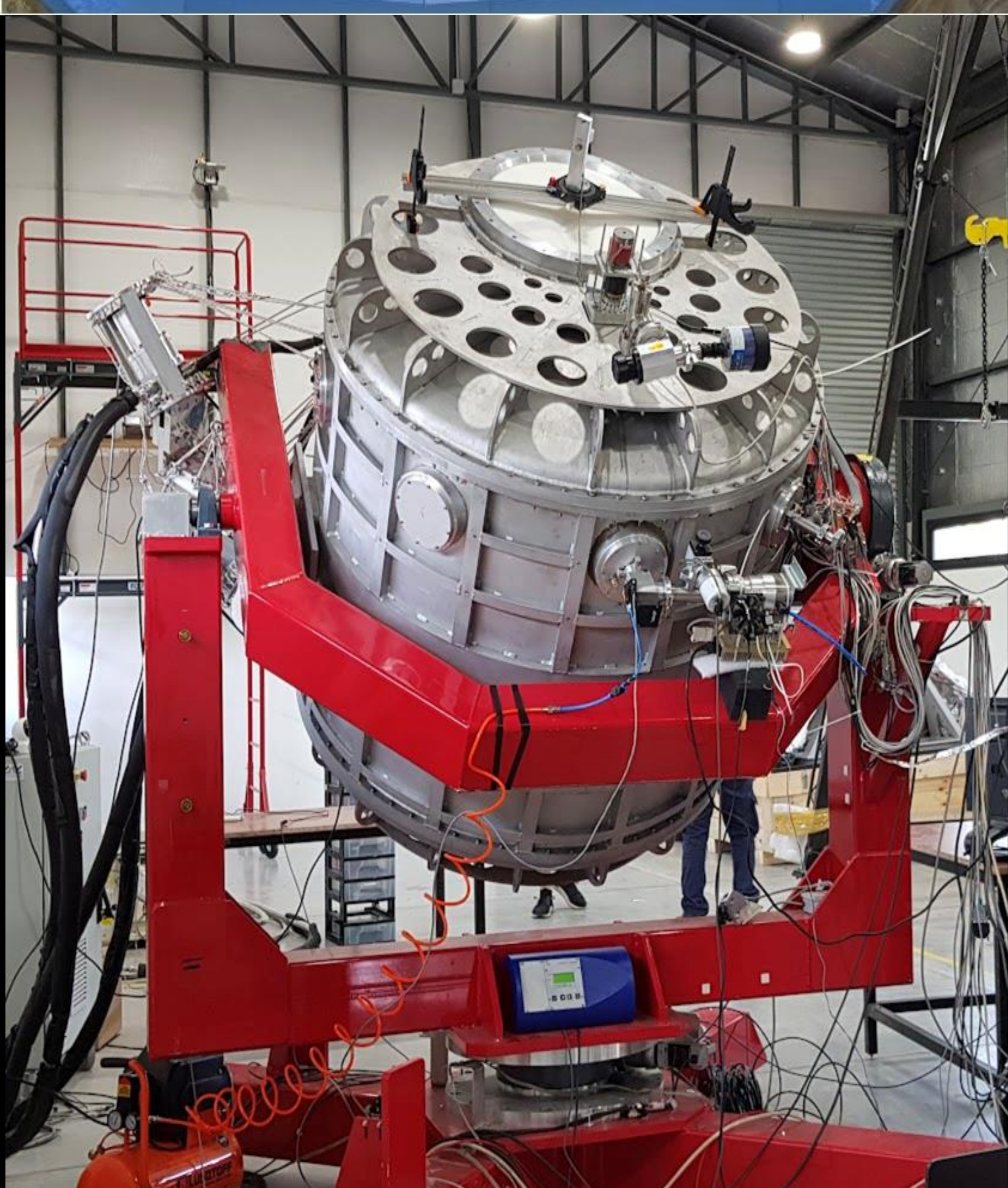
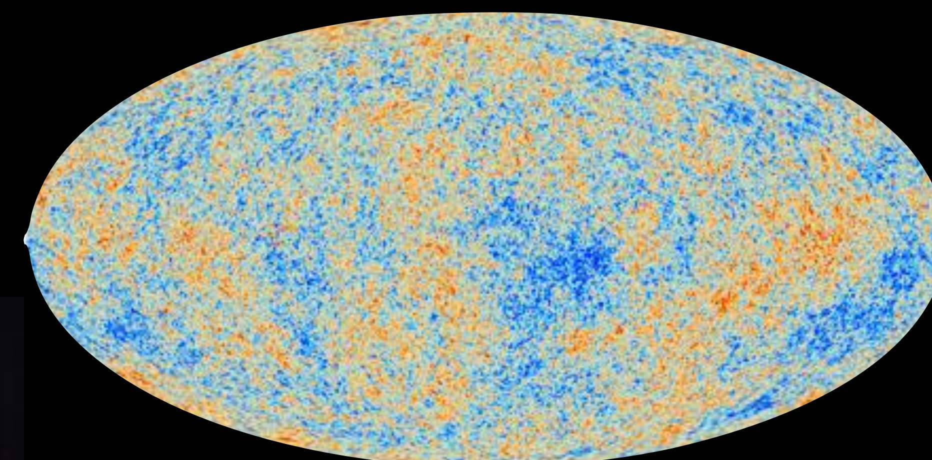
CMB measurements with mm-telescopes

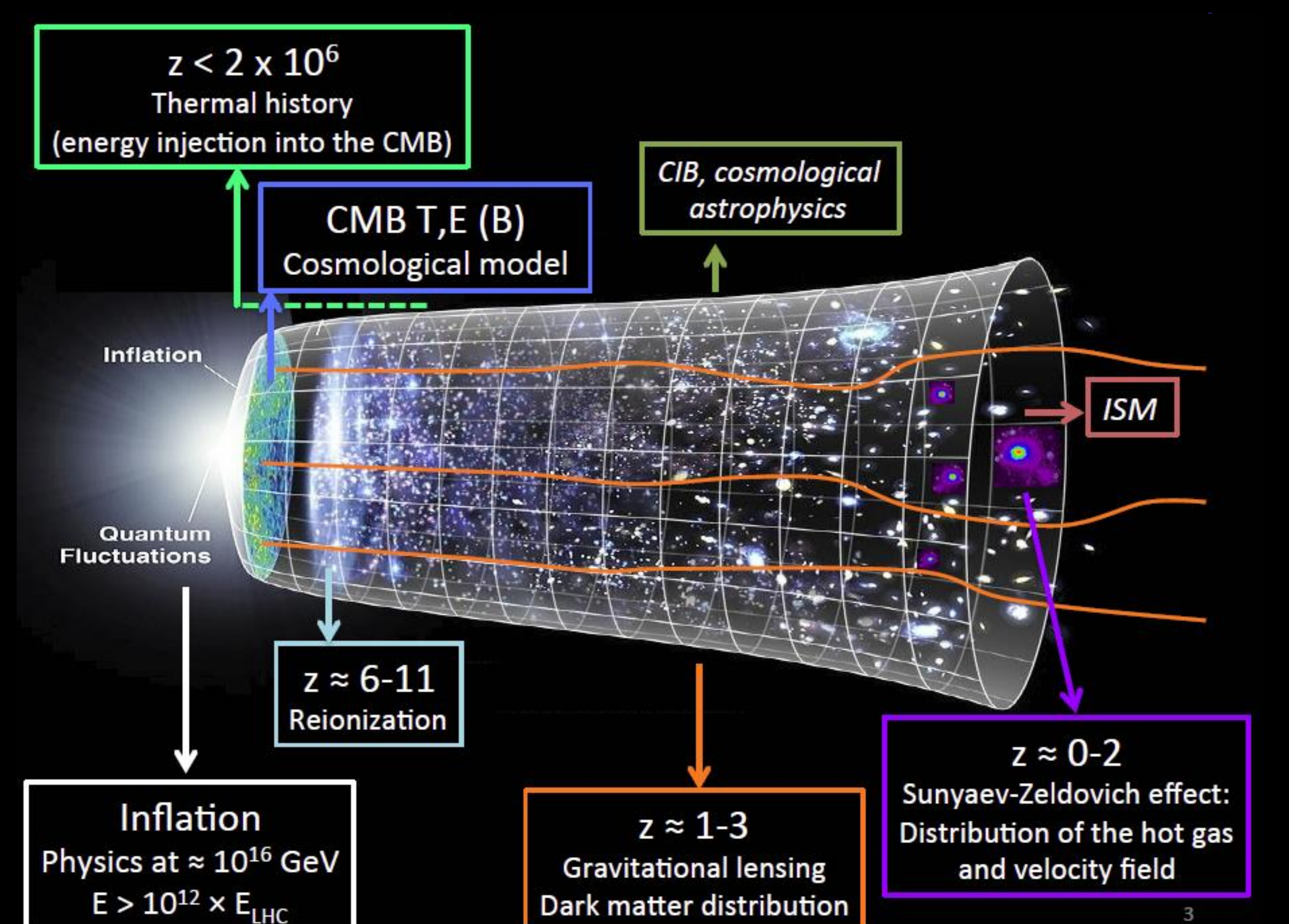




**no published errata*

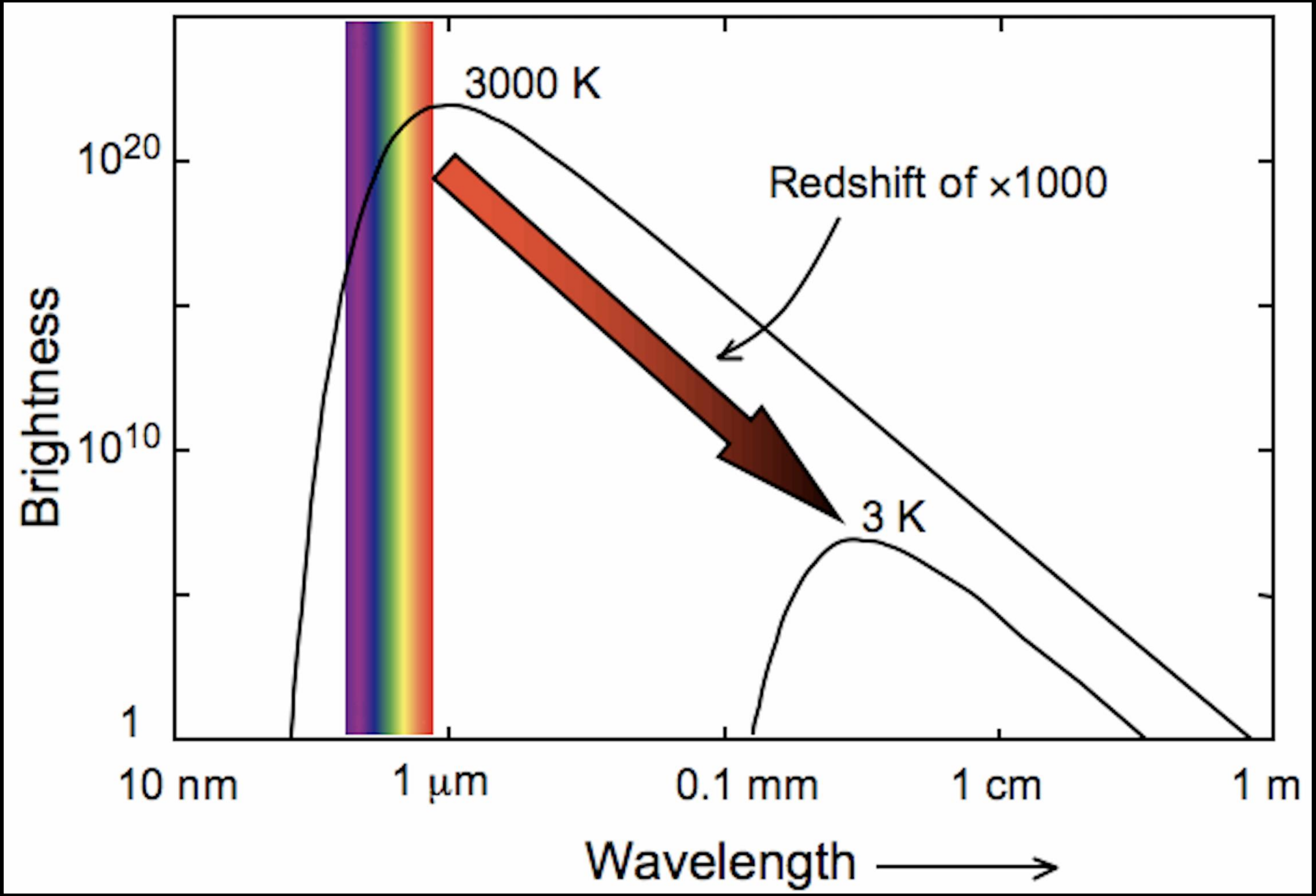
S. Loucatos
Irfu CEA-Saclay and APC Paris

HEP Thessaloniki 2022

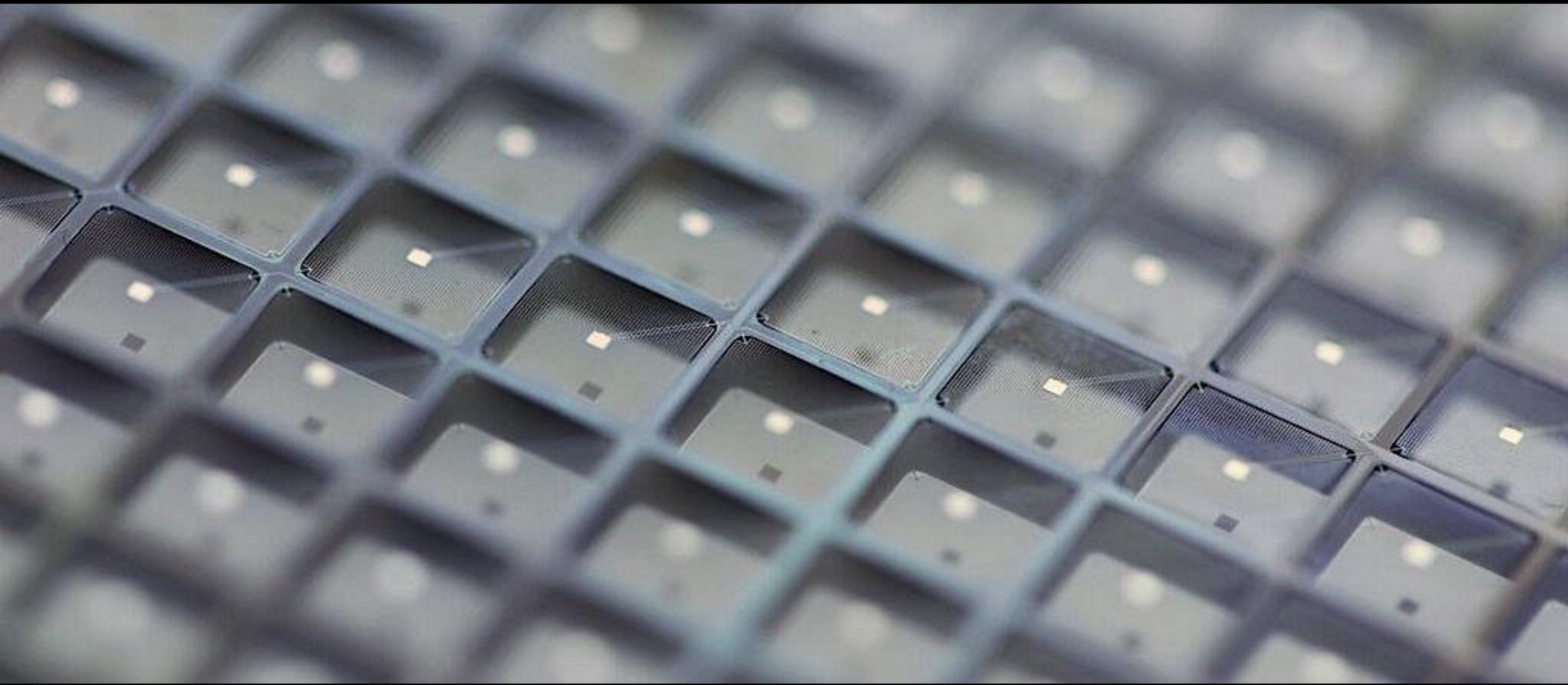


$z < 2 \times 10^6$
Thermal history
(energy injection into the CMB)
CMB T,E (B)
Cosmological model
CIB, cosmological astrophysics
Inflation
Quantum Fluctuations
ISM
$z \approx 6\text{-}11$
Reionization
$z \approx 0\text{-}2$
Sunyaev-Zeldovich effect:
Distribution of the hot gas and velocity field
Inflation
Physics at $\approx 10^{16}$ GeV
$E > 10^{12} \times E_{LHC}$
$z \approx 1\text{-}3$
Gravitational lensing
Dark matter distribution

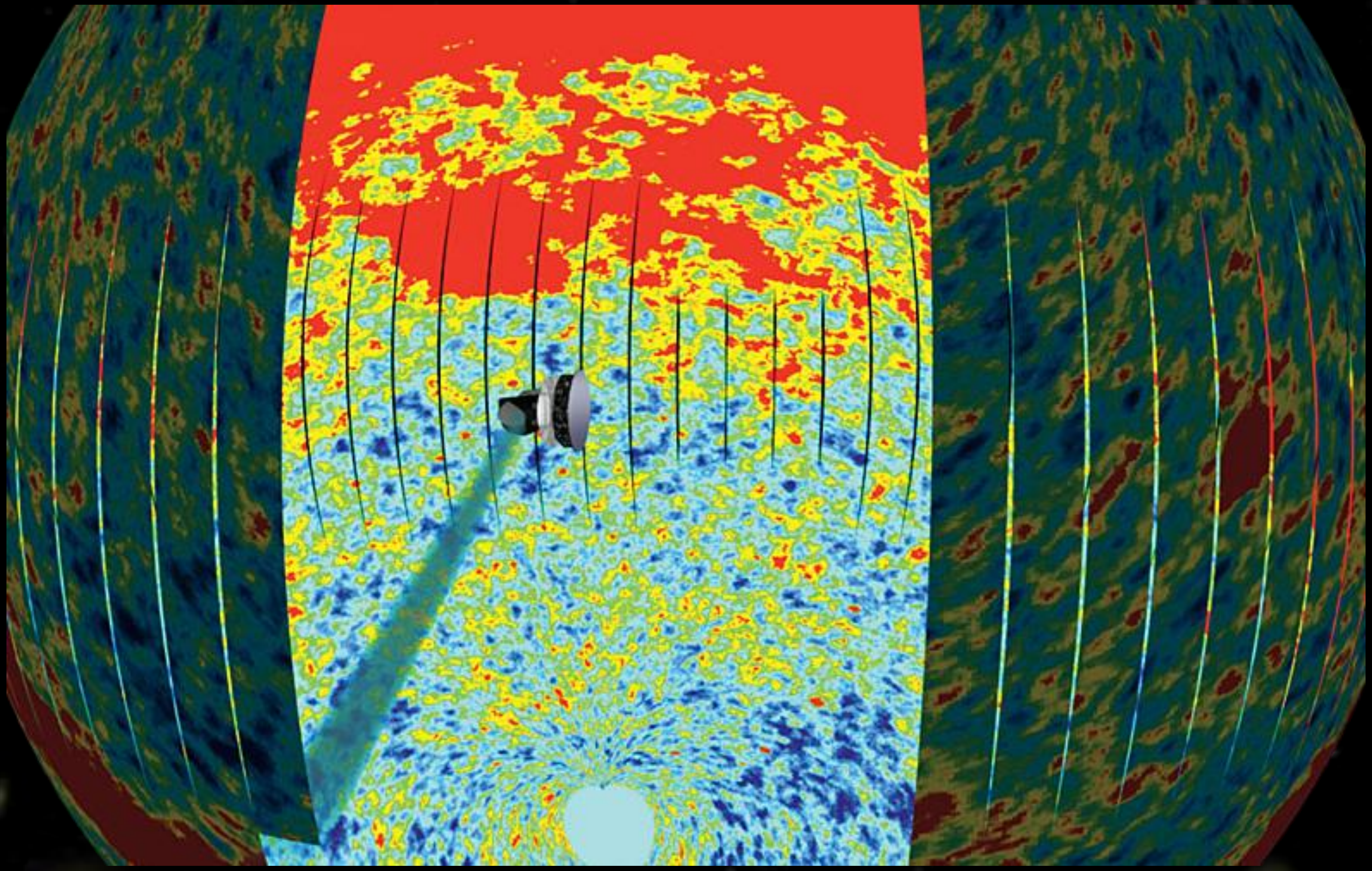
Radiation emitted at 3000K → cooled by universe expansion to 2.77 K



Environmet of the detectors < T_{CMB}
Thermometers (bolometers) cooled at 100 -300 mK
→ minimize the thermal noise (phonons)

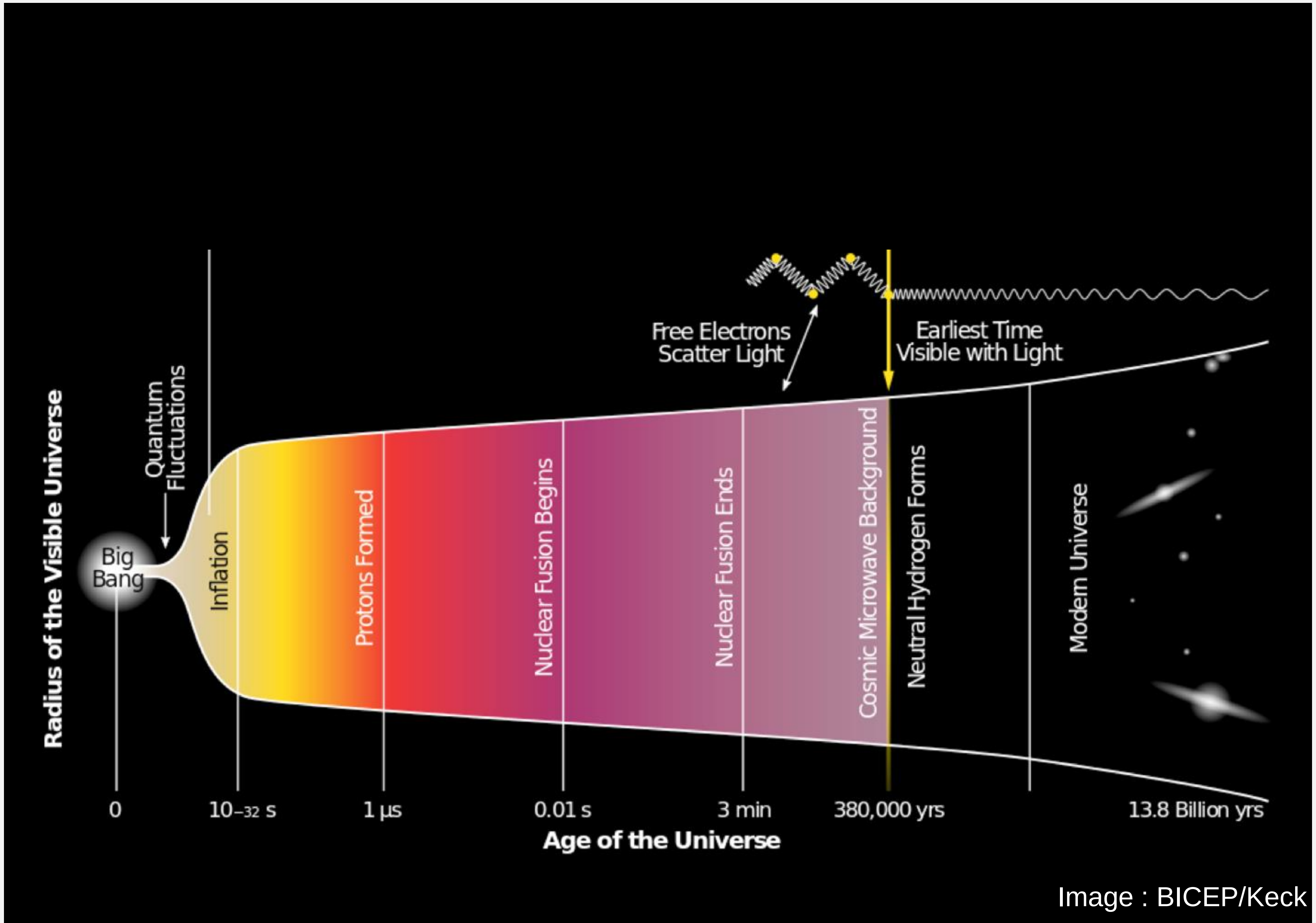


Many pixels = imager



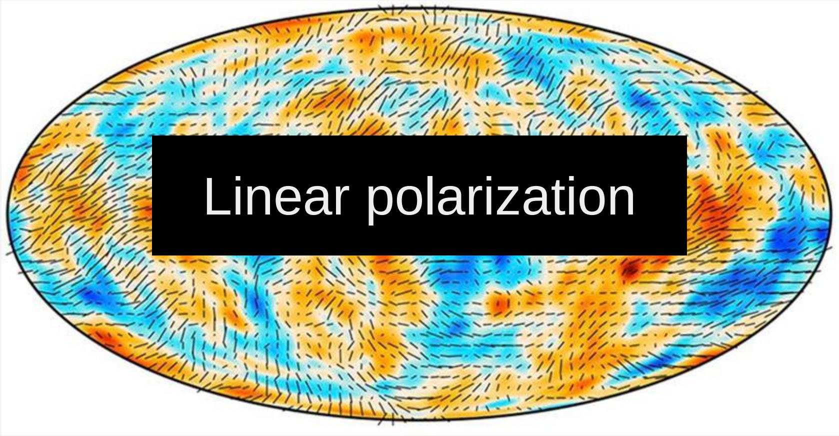
Planck sky scan

The CMB as a window to study cosmic inflation



L. Mousset Blois 2022

The CMB as a window to study cosmic inflation



E modes

B modes

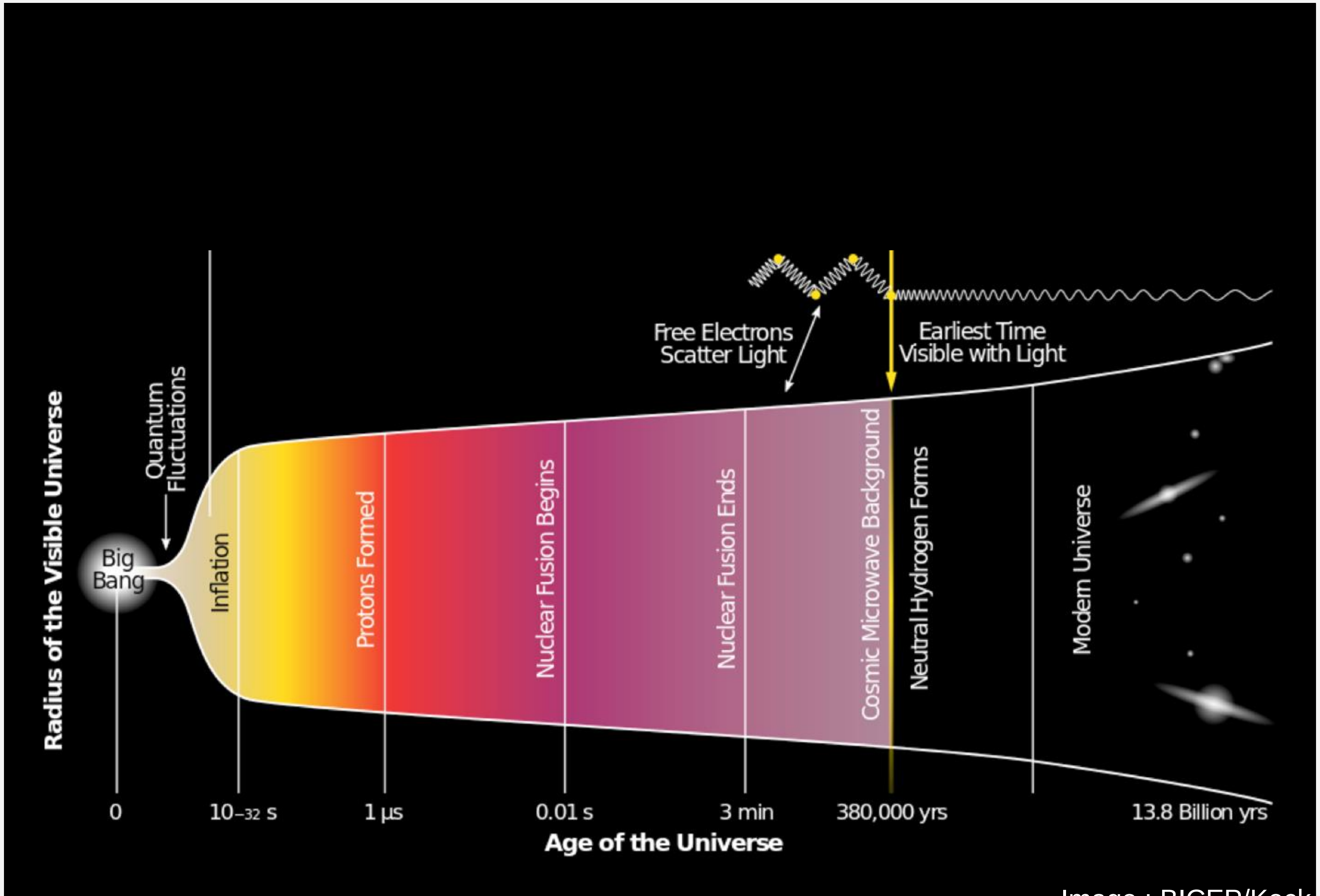
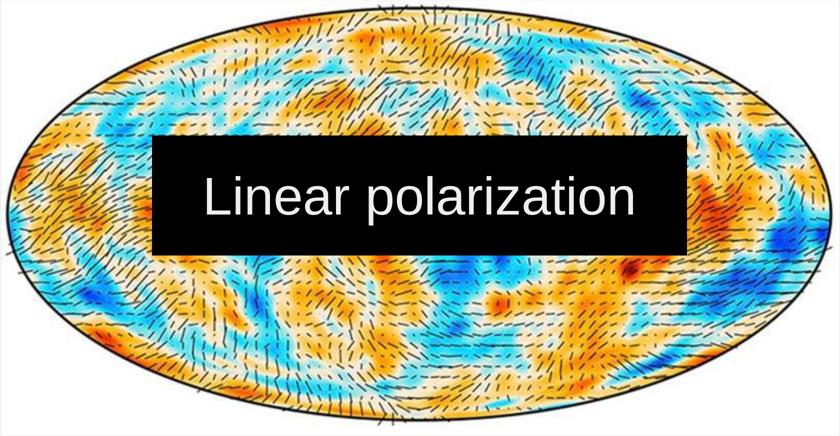


Image : BICEP/Keck

The CMB as a window to study cosmic inflation



E modes

B modes

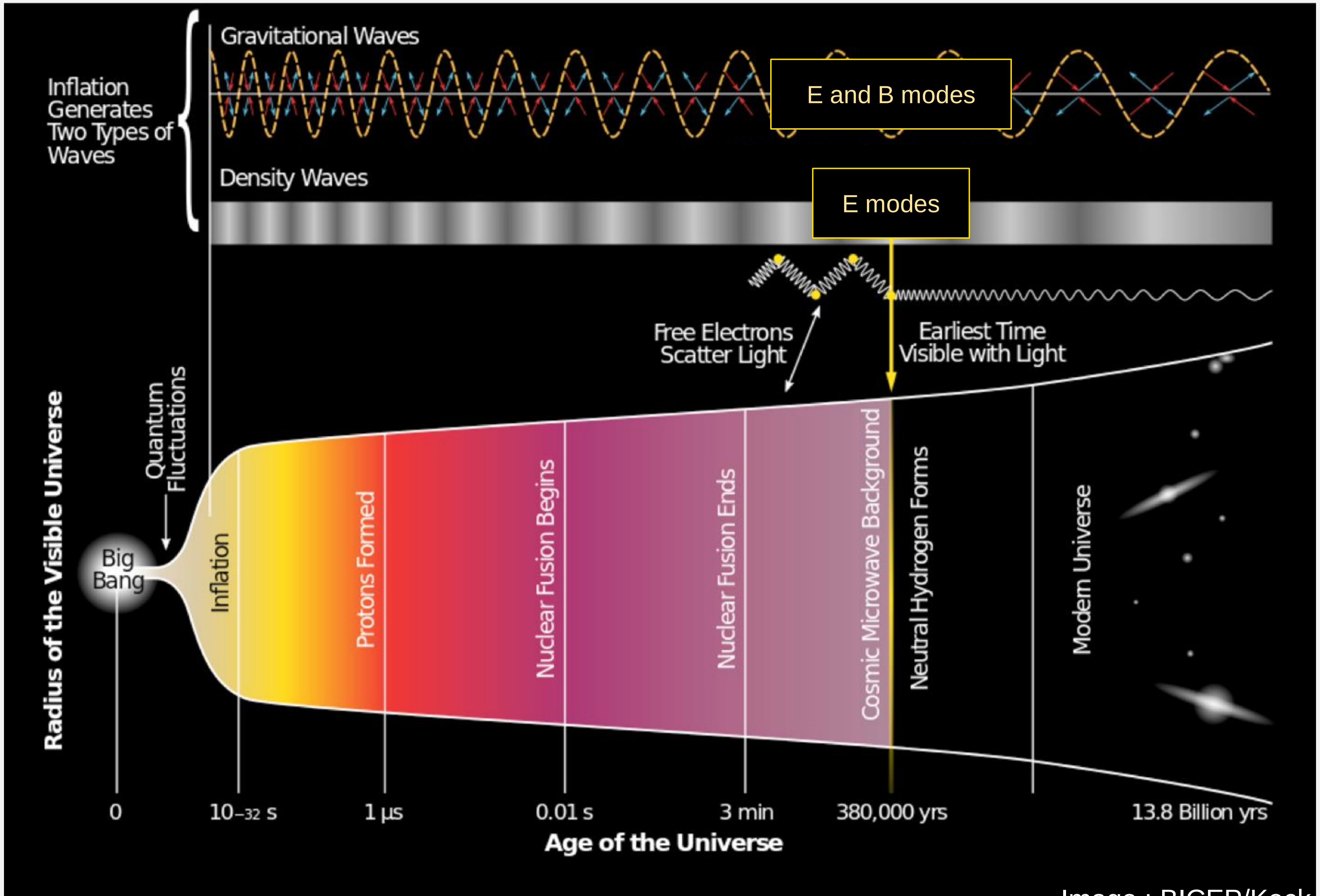
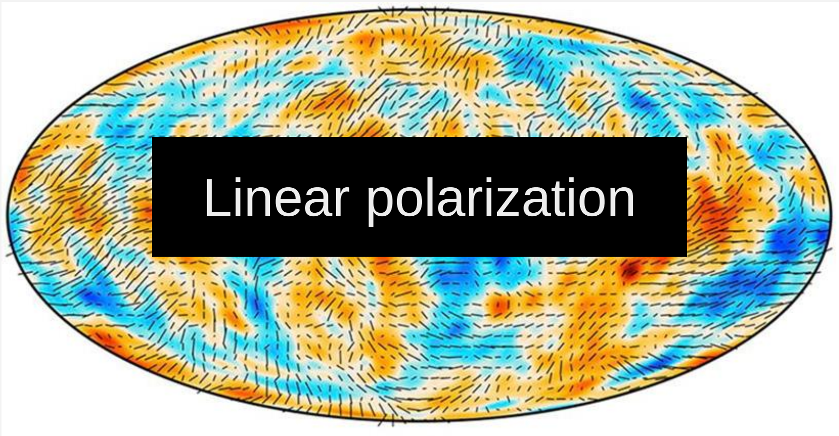
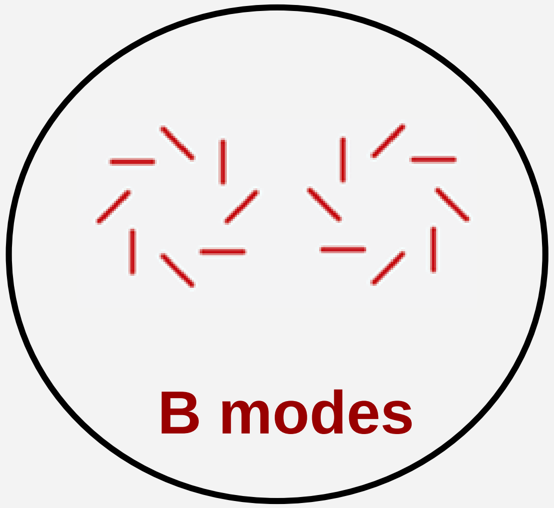


Image : BICEP/Keck

The CMB as a window to study cosmic inflation



E modes

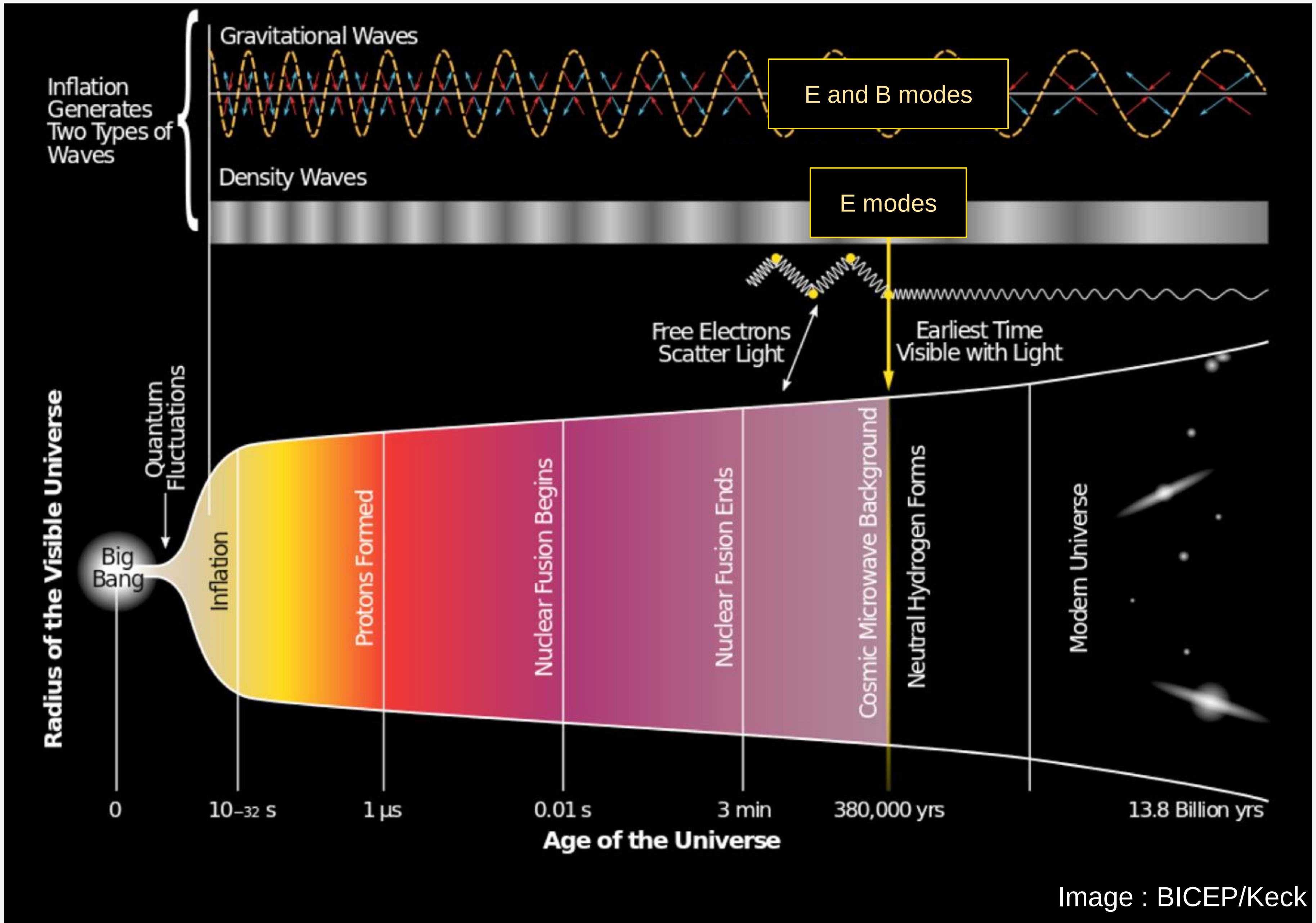


The amplitude is parametrized by **the tensor to scalar ratio r.**

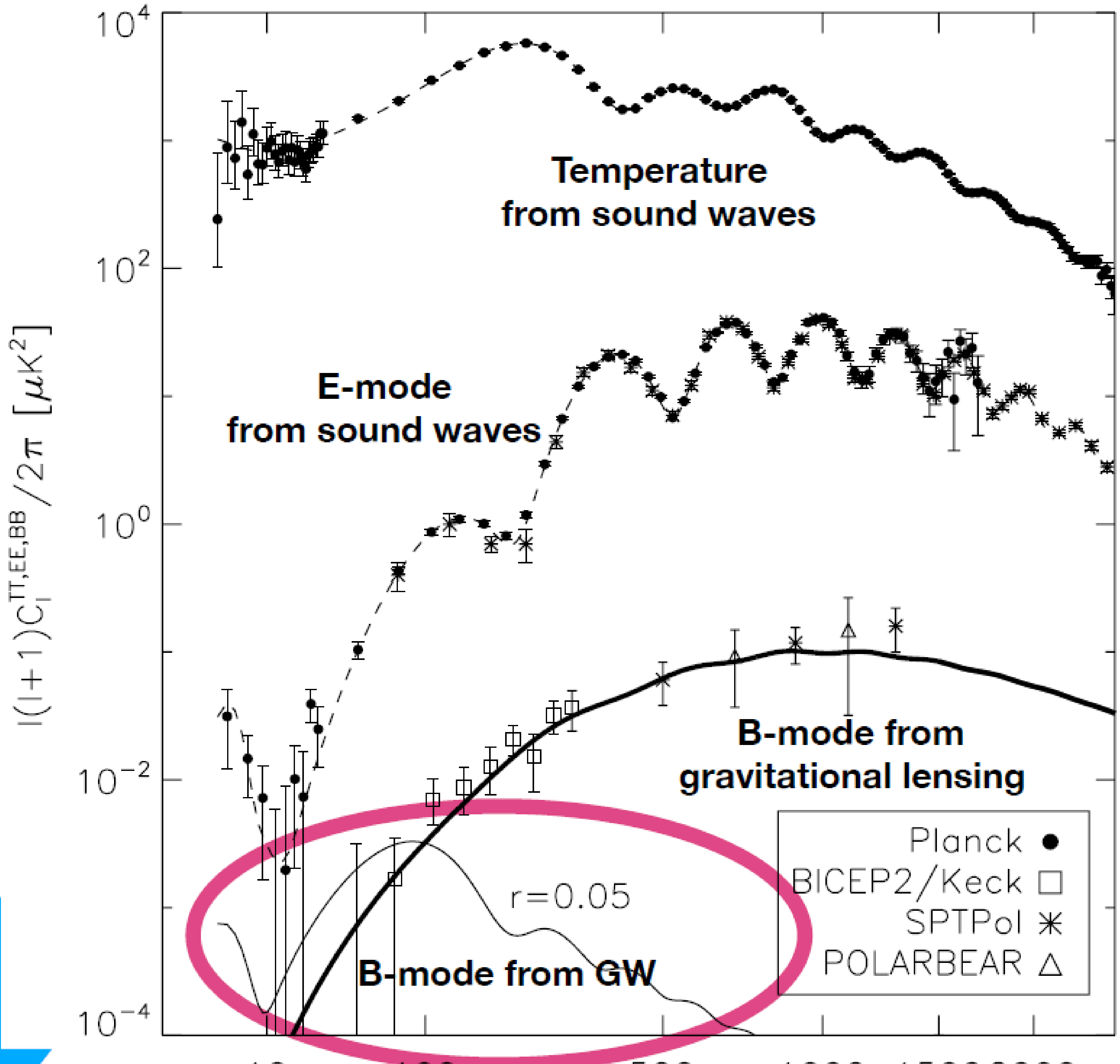
Current upper limit:

$r < 0.032$ à 95% C.L.

[Tristram et al., 2022, BICEP/Keck]



Another two orders of magnitude in the next 10–15 years



We want this!!

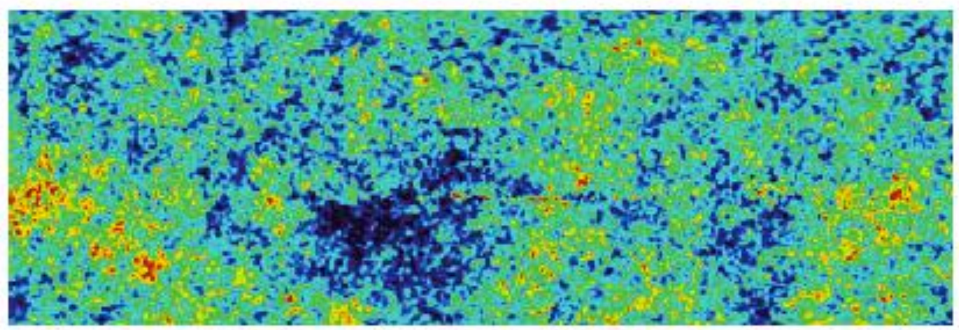
E. Komatsu "*European Coordination of the CMB Programme*", Florence 20/9/18

Key Predictions

ζ

scalar mode

- Fluctuations we observe today in CMB and the matter distribution originate from quantum fluctuations during inflation

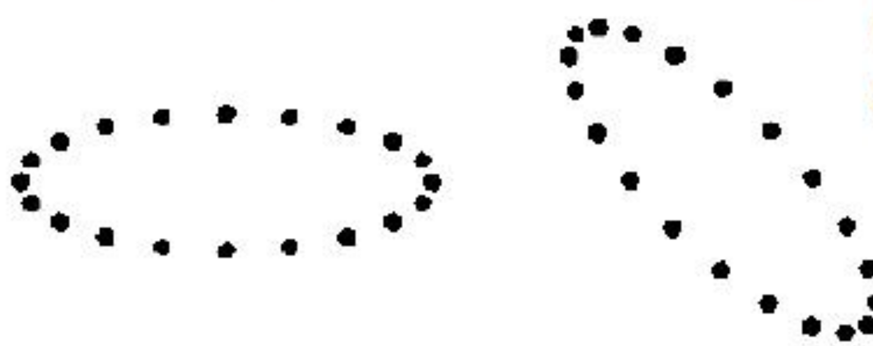


Mukhanov&Chibisov (1981)
Guth & Pi (1982)
Hawking (1982)
Starobinsky (1982)
Bardeen, Steinhardt&Turner (1983)

h_{ij}

tensor mode

- There should also be *ultra long-wavelength* gravitational waves generated during inflation



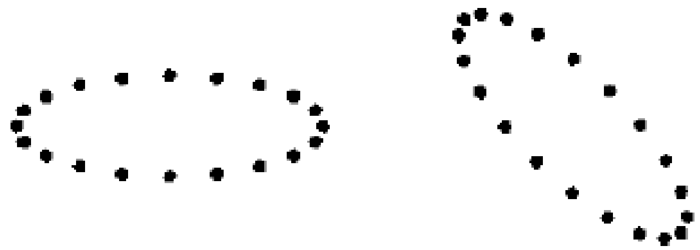
Grishchuk (1974)
Starobinsky (1979)

We measure distortions in space

- A distance between two points in space

$$d\ell^2 = a^2(t)[1+2\zeta(\mathbf{x},t)][\delta_{ij}+h_{ij}(\mathbf{x},t)]dx^i dx^j$$

- **ζ** : “curvature perturbation” (scalar mode)
  - Perturbation to the determinant of the spatial metric
- $\mathbf{h_{ij}}$: “gravitational waves” (tensor mode)
  - Perturbation that does not alter the determinant



$$\sum_i h_{ii} = 0$$

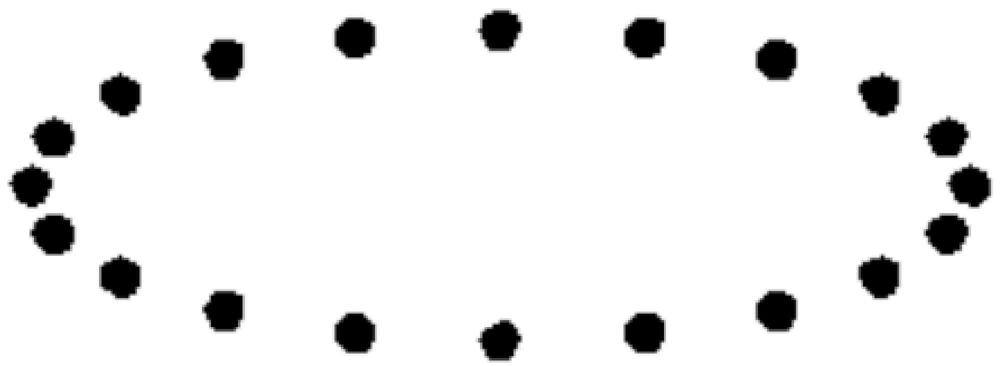
Measuring GW

- GW changes distances between two points

$$d\ell^2 = d\mathbf{x}^2 = \sum_{ij} \delta_{ij} dx^i dx^j$$

$$\Downarrow$$

$$d\ell^2 = \sum_{ij} (\delta_{ij} + \underline{h_{ij}}) dx^i dx^j$$



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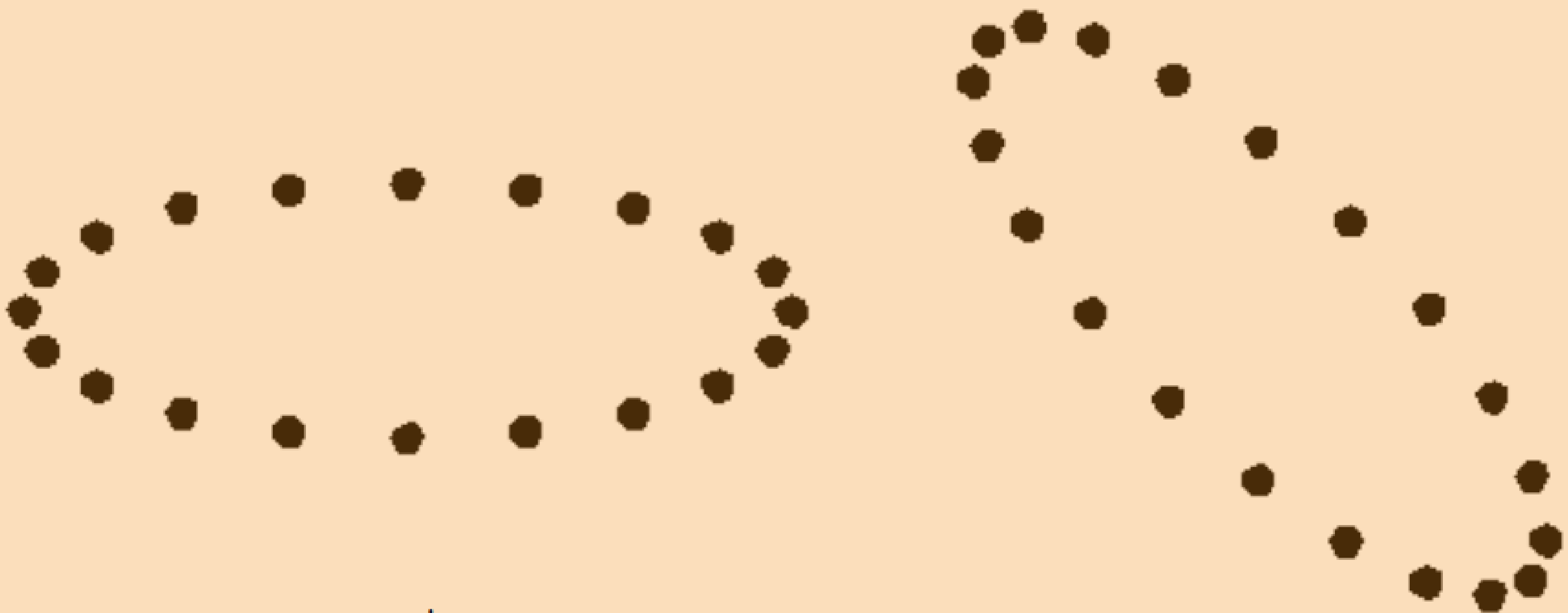
Laser interferometers LIGO and VIRGO detected GW from binary Blackholes and NS, with the wavelength
of thousands of kilometres
But, the primordial GW affecting the CMB has a wavelength of **billions of light-years**!! How do we find it?

Detecting GW by CMB

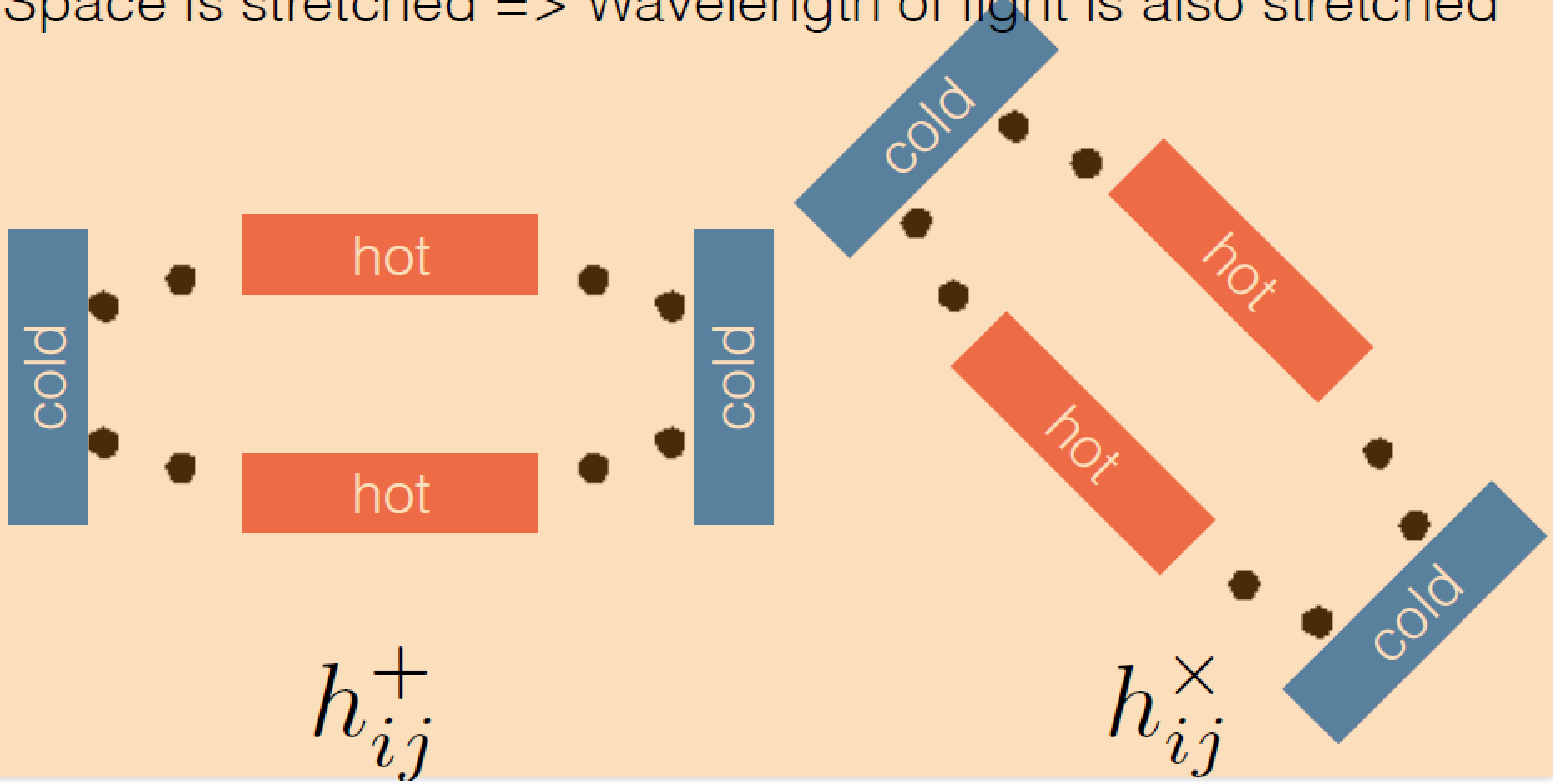
GW propagating in isotropic electro-magnetic fields



$$h_{ij}^{+} \qquad h_{ij}^{\times}$$

Detecting GW by CMB

Space is stretched => Wavelength of light is also stretched



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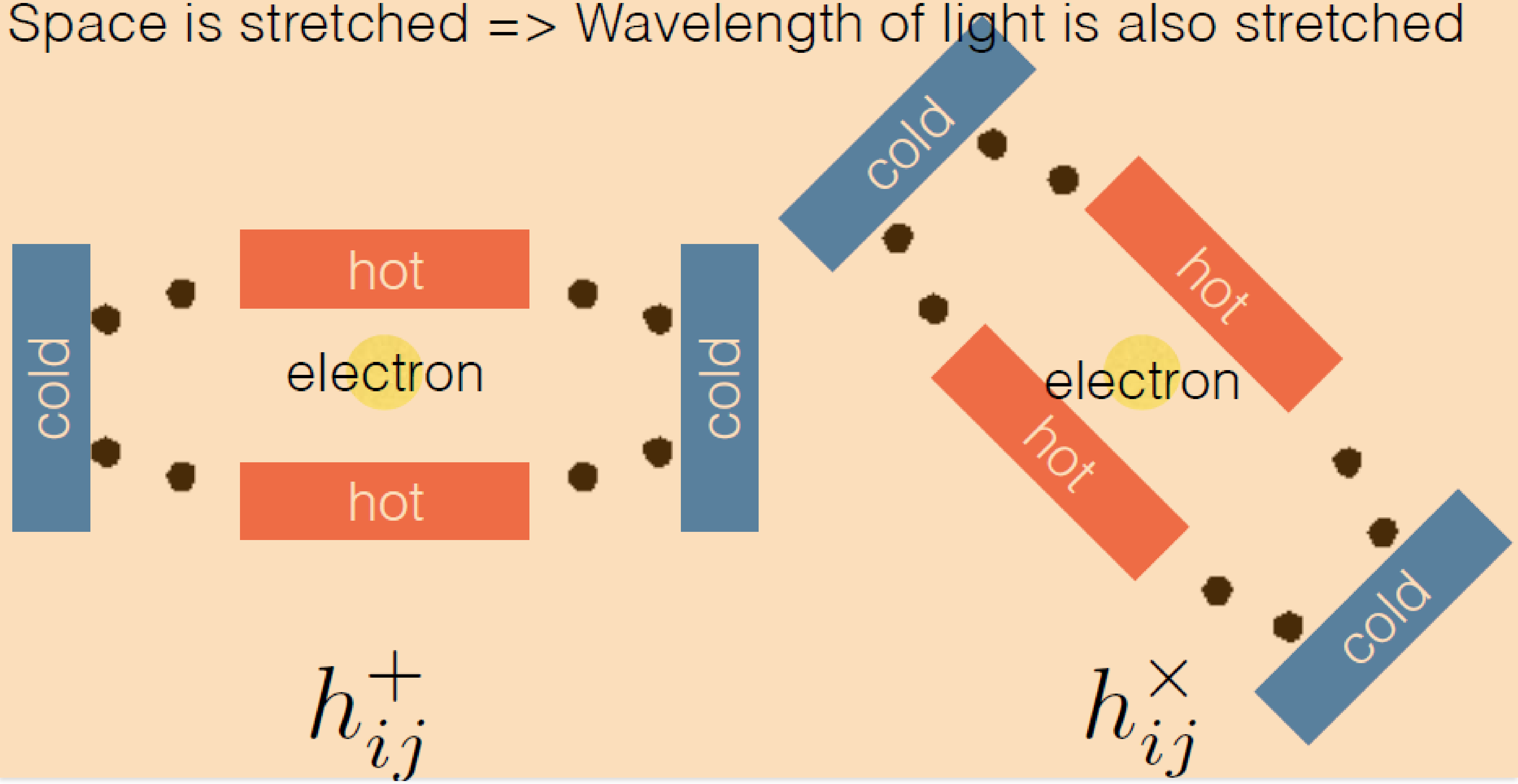
Detecting GW by CMB **Polarisation**

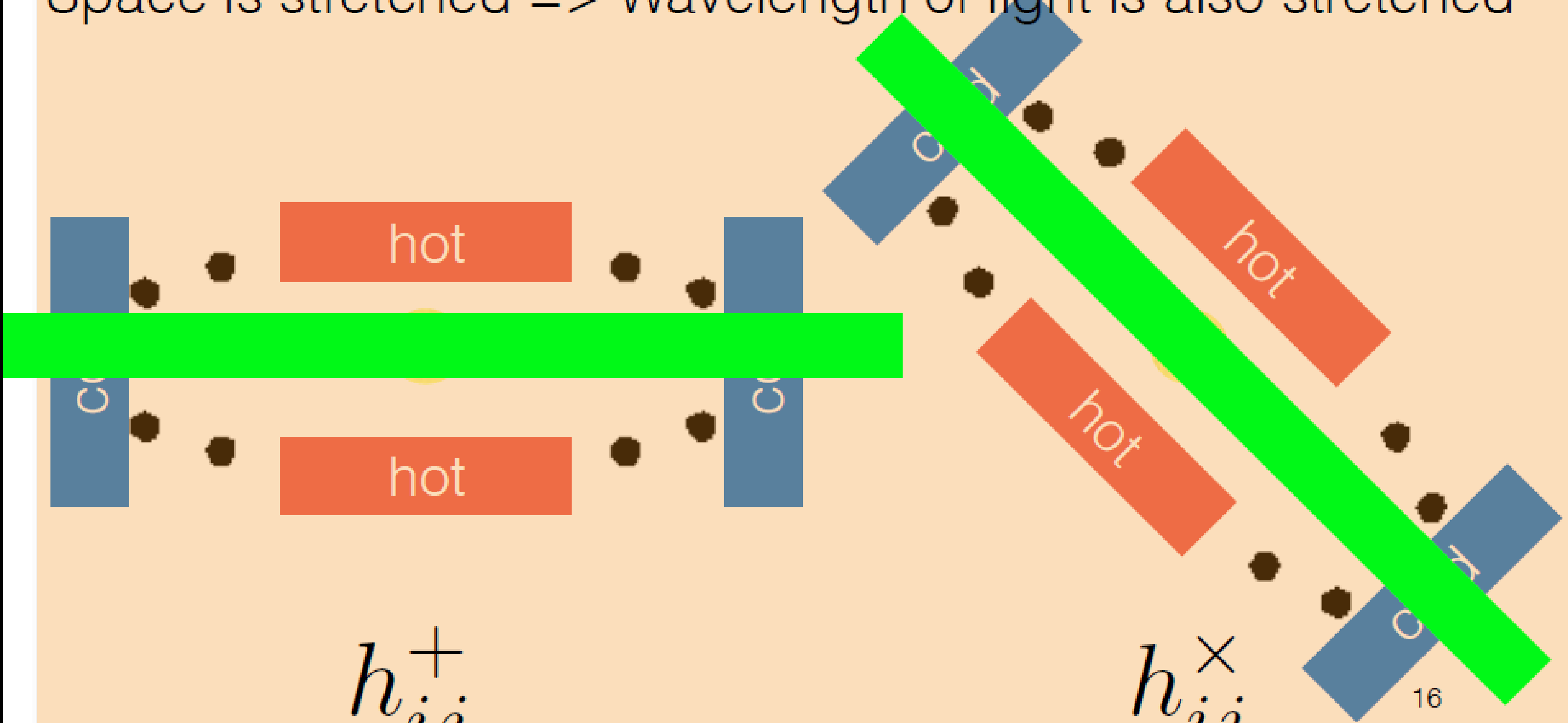
Space is stretched => Wavelength of light is also stretched



E. Komatsu "*European Coordination of the CMB Programme*", Florence 20/9/18

Detecting GW by CMB
Polarisation

Space is stretched => Wavelength of light is also stretched

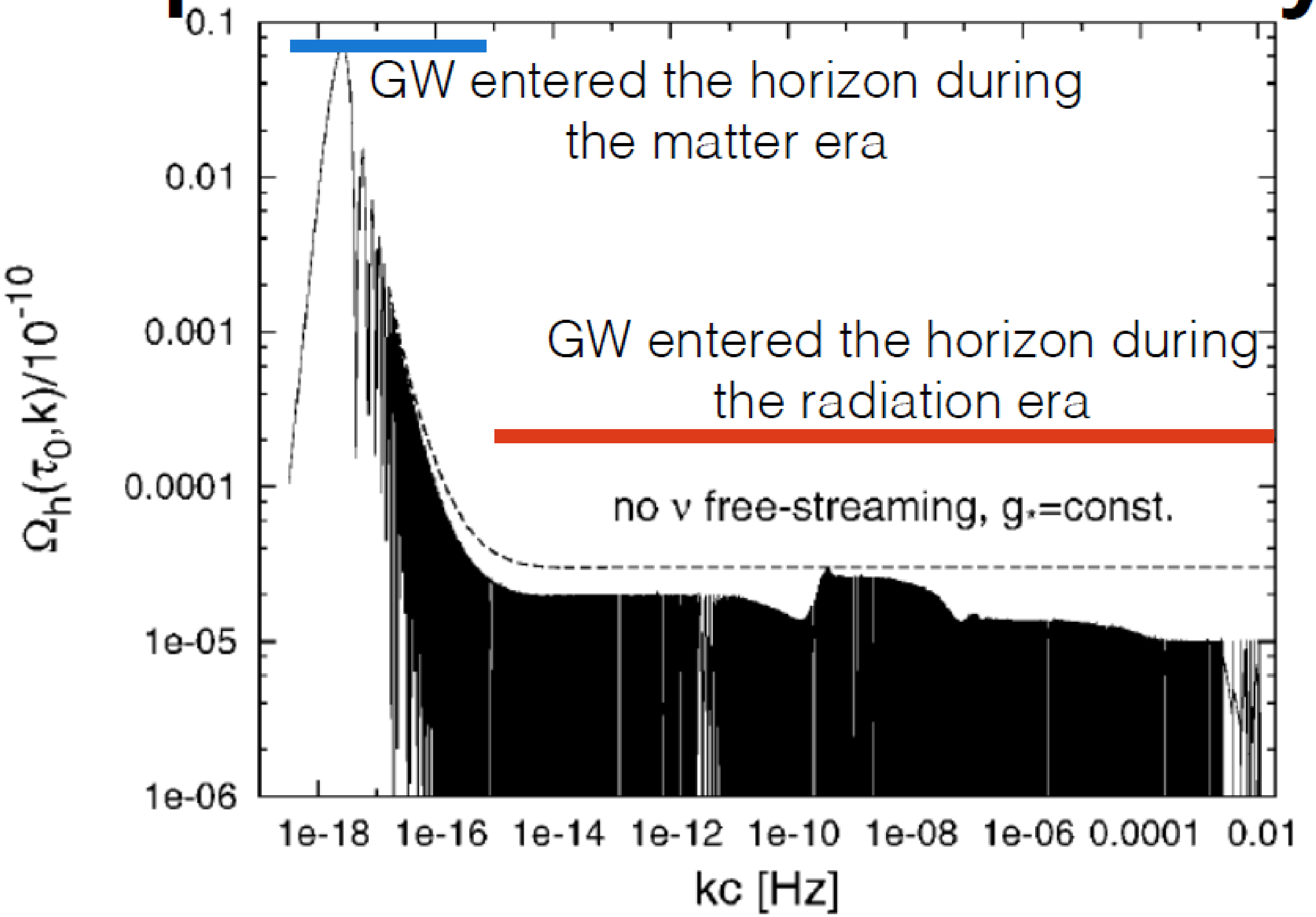


h^{+}_{ij} $\qquad$ $h^{\times}_{ij}$

Theoretical energy density

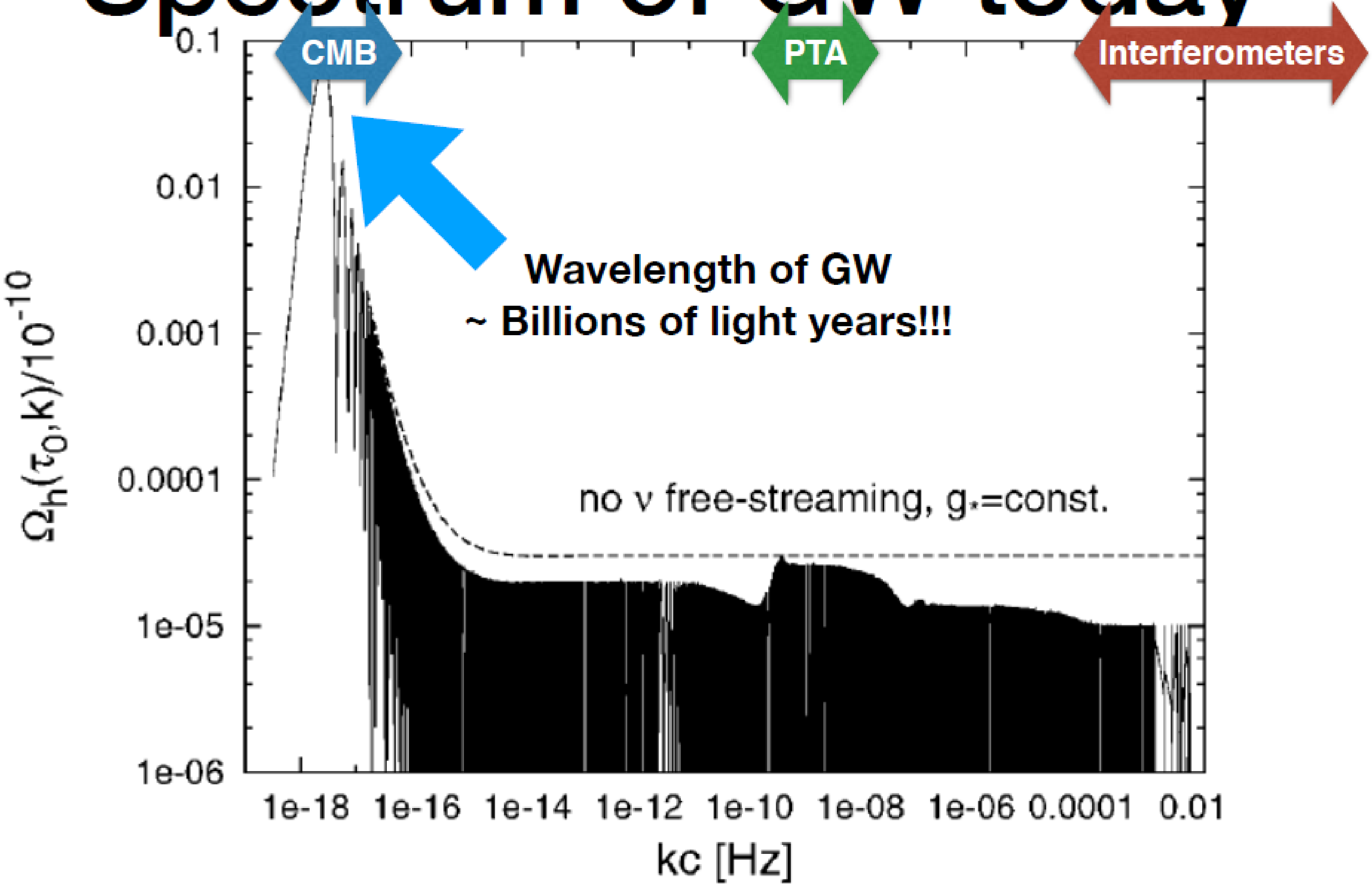
Watanabe & EK (2006)

Spectrum of GW today



Watanabe & EK (2006)

Theoretical energy density
Spectrum of GW today



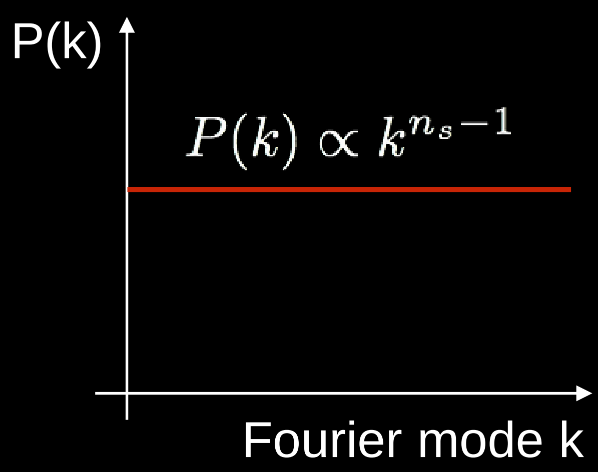
Density Field Transfer Function

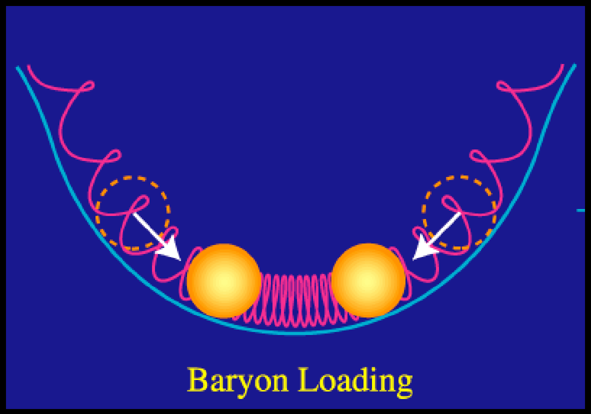
Early Universe Primordial Density Fluctuations

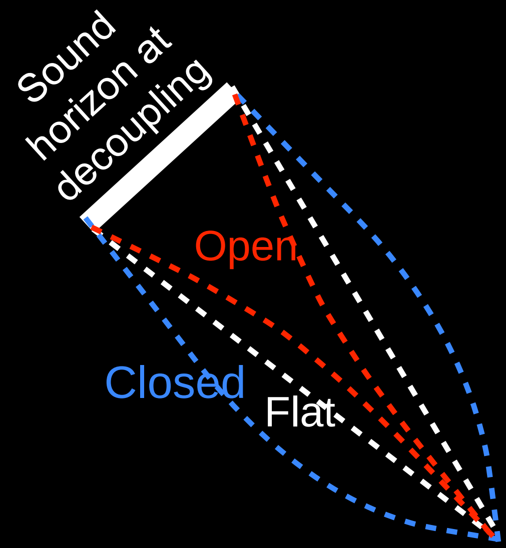
Acoustic Oscillations

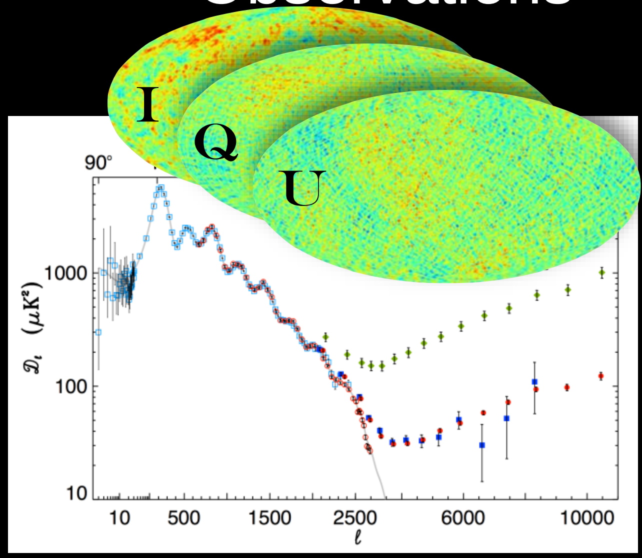
Geometry

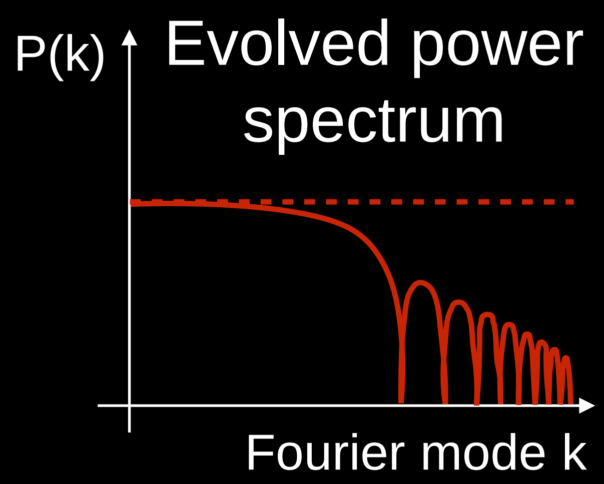
CMB Observations









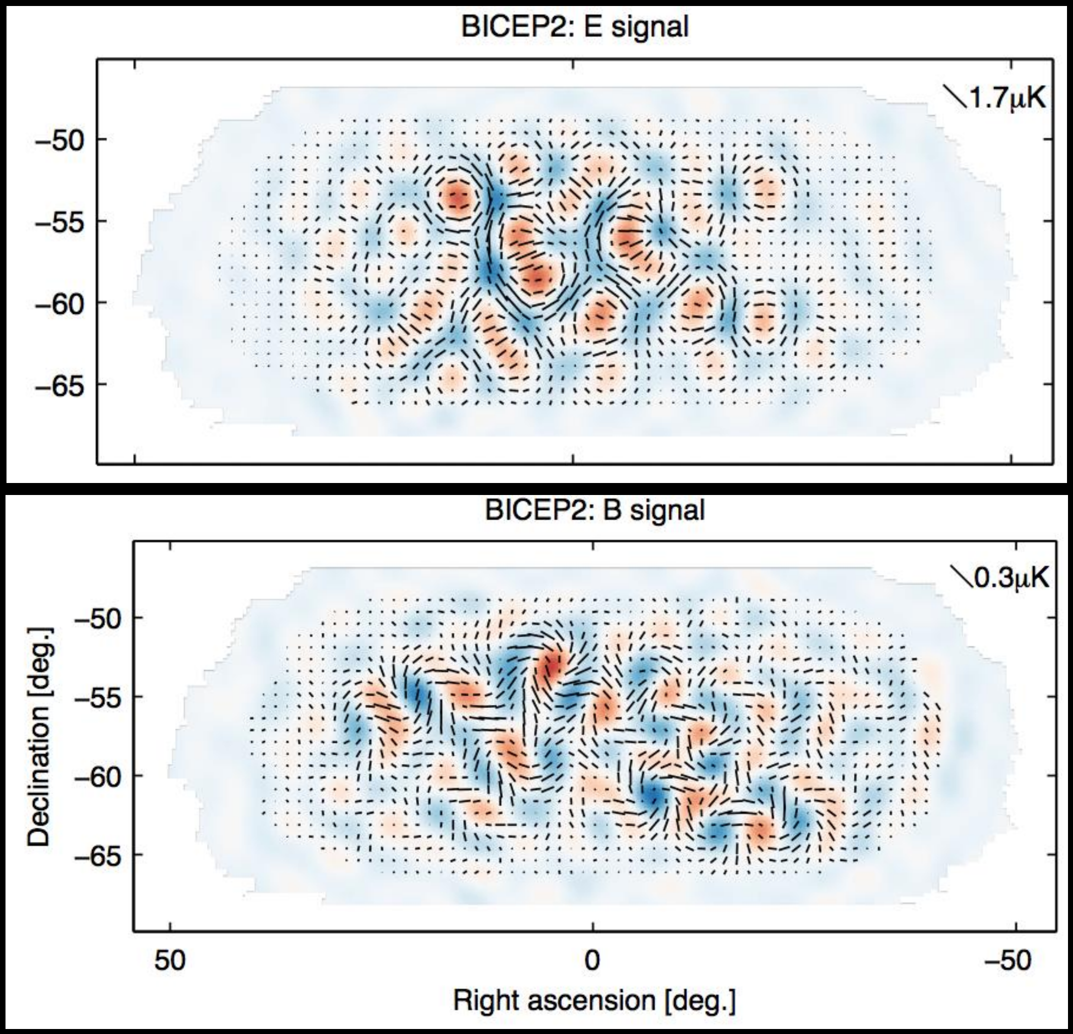


- Perturbations evolve from end of inflation to decoupling due to matter-radiation oscillations.
- The <u>transfer function</u> depends upon « simple physics » and cosmological parameters
- Allows to fit both cosmology and primordial spectra (including inflationary physics)

Scalar and tensor modes - E & B polarization

- Scalar perturbations: $P_s(k) = A_s \left(\frac{k}{k_0}\right)^{n_s-1}$
  - Density fluctuations
    - Temperature
    - E polarization
    - No B polarization

- Tensor perturbations: $P_t(k) = A_t \left(\frac{k}{k_0}\right)^{n_t}$
  - Specific prediction from inflation!
  - = Primordial gravitational waves
    - Temperature
    - E polarization
    - B Polarization



⇒ detecting primordial B-modes: $r = \frac{P_t(k_0)}{P_s(k_0)}$

~ ratio between B and E modes

- Direct detection of tensor modes
- «smoking gun» for inflation
- Measurement of its energy scale $V^{1/4} = 1.06 \times 10^{16}\mathrm{GeV} \left(\frac{r_{\mathrm{CMB}}}{0.01}\right)^{1/4}$

BICEP, Keck

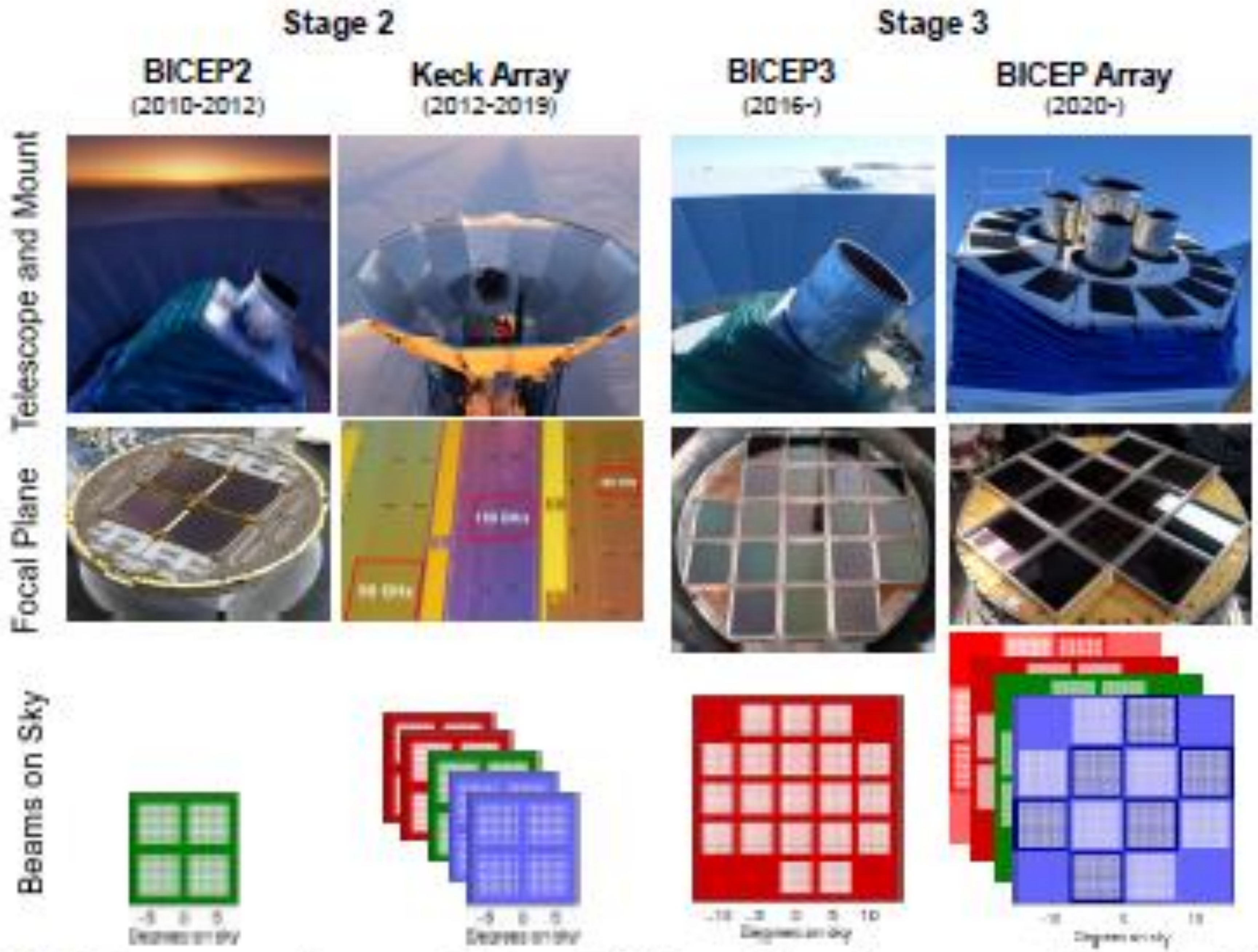


Figure 1. The BICEP/*Keck* telescopes are Stage-2 and Stage-3 CMB ground-based experiments characterized by $\approx 10^3$ and $\approx 10^4$ detectors respectively. The top two panels show the telescopes (and their physical focal planes) operating since 2010. In the bottom panel, each plane stands for a receiver. The white dots represent the detectors and the beam size as projected on the sky, while the color of a plane denotes the observing frequency. The first receiver (30/40 GHz) of BICEP Array started running in 2020, and it will be fully upgraded to have the other three receivers shown in the figure by 2023.

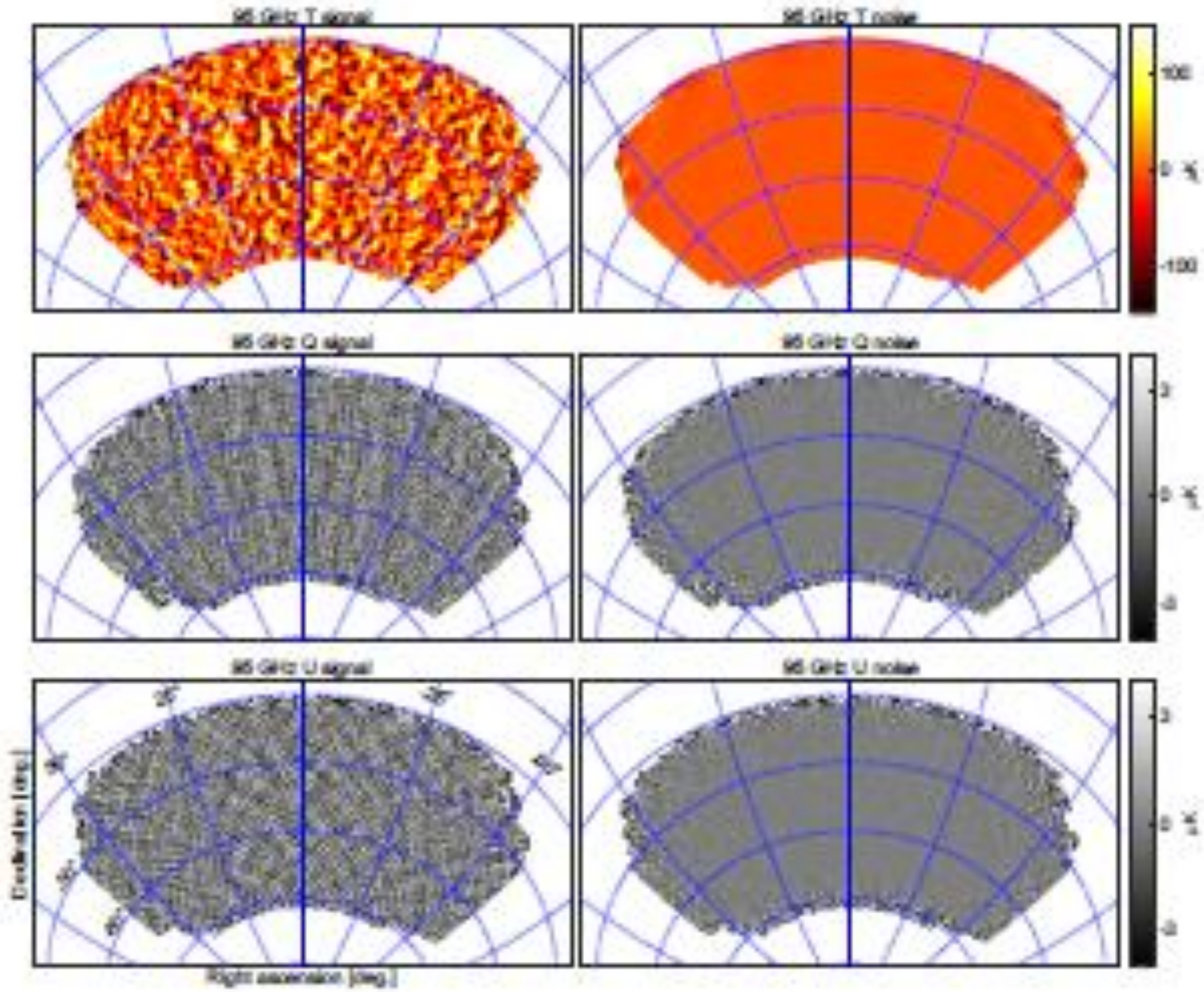
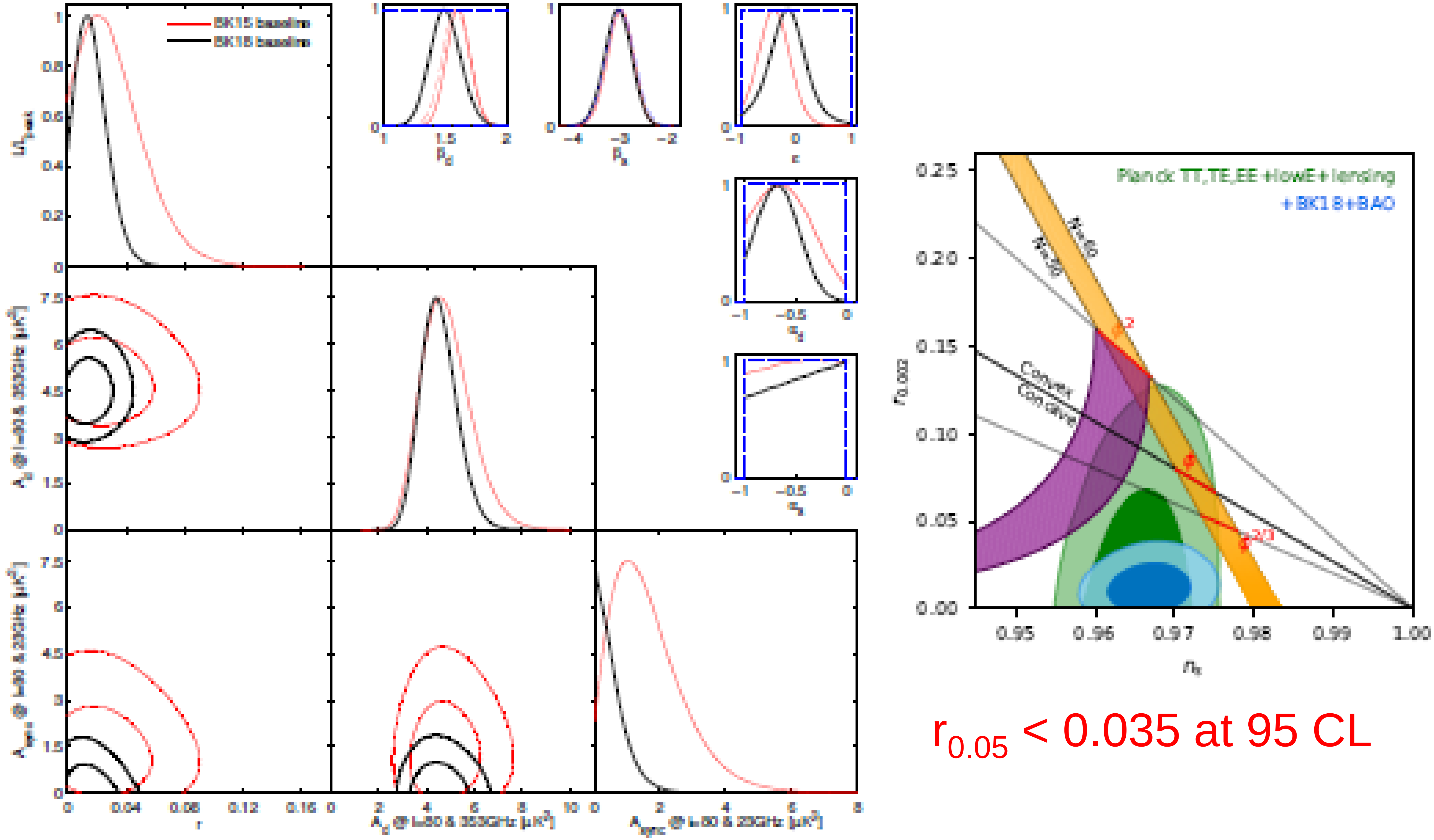


Figure 2. The BICEP3 95 GHz T, Q, U maps from the BK18 paper are displayed in the left column. These signal maps are made using BICEP3 data from the 2016-2018 observing seasons. The right column shows maps of a noise realization produced by randomly and evenly flipping the sign of scan sets during the map coadding process. Note that the signal maps in general appear different from the full-sky measurement of the same sky patch since they are heavily filtered by beam smoothing, timestream processing and deprojection.



$r_{0.05} < 0.035$ at 95 CL

Figure 5. *Left*: CosmoMC likelihood results for the BICEP/*Keck* baseline model. Selected 1D and 2D marginalized posteriors are shown. The red faint curves are the results from BK15 while the black solid curves are the results of BK18. The dashed blue and red lines show priors on foreground parameters. The analysis method is the same as in BK15, except the β_d prior based on *Planck* data from other regions of the sky is removed this time due to the improved sensitivity of BK18. *Right*: Constraints in the r vs. n_s plane. The purple and orange bands are natural inflation and monomial inflation respectively. The blue contour shows the updated constraint after adding BK18 and BAO data to the *Planck* baseline analysis. The r posterior is tightened from $r_{0.05} < 0.11$ to $r_{0.05} < 0.035$ at 95% confidence.

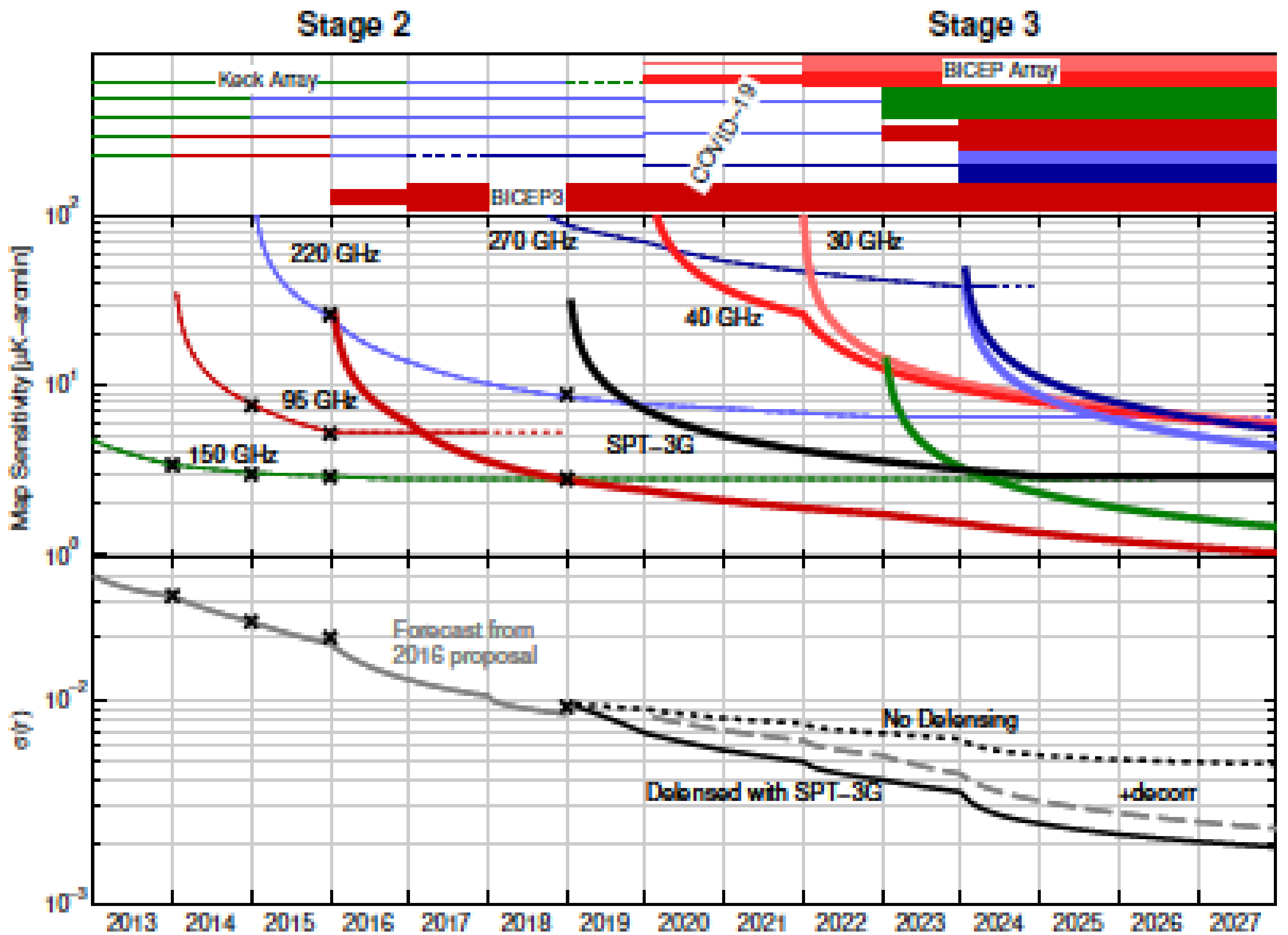


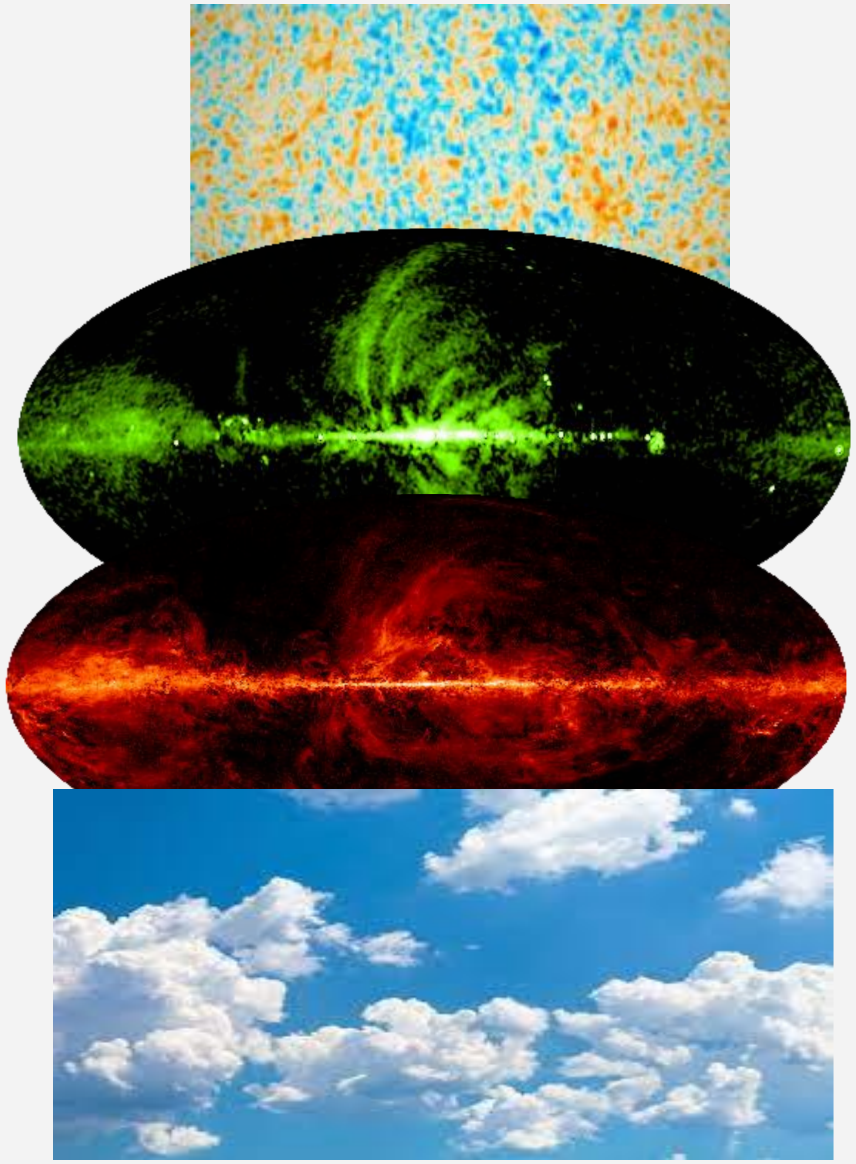
Figure 6. The forecasts for the BICEP/*Keck* program. The top panel shows the plan of observation. The thickness of each line represents the detector number in a single receiver while its color represents the center frequency labeled in the next panel; the middle panel shows the corresponding map depth over time as lines. The cross marks are published values including those in BK15 and BK18. The sensitivity beyond 2018 is predicted by scaling based on achieved performance. The black SPT-3G line is the combined 95/150 GHz map depth projected from the achieved sensitivity in the 2019 and 2020 seasons; the bottom panel transforms map depth into $\sigma(r)$. Cross marks are again the published values. The good agreement between these cross marks and projection lines indicates that the forecasting method is realistic. Two independent forecasts (solid and dotted lines) highlight the significance of delensing. Including dust decorrelation in the delensing case (the dashed line) results in slightly higher $\sigma(r)$.

BICEP/Keck collaboration arXiv:2203.16556

M. Tristram et al Phys Rev D 105, 083524 (2022)

P. Campet, E. Komatsu arXiv:2205.05617

Problematic of foregrounds



CMB

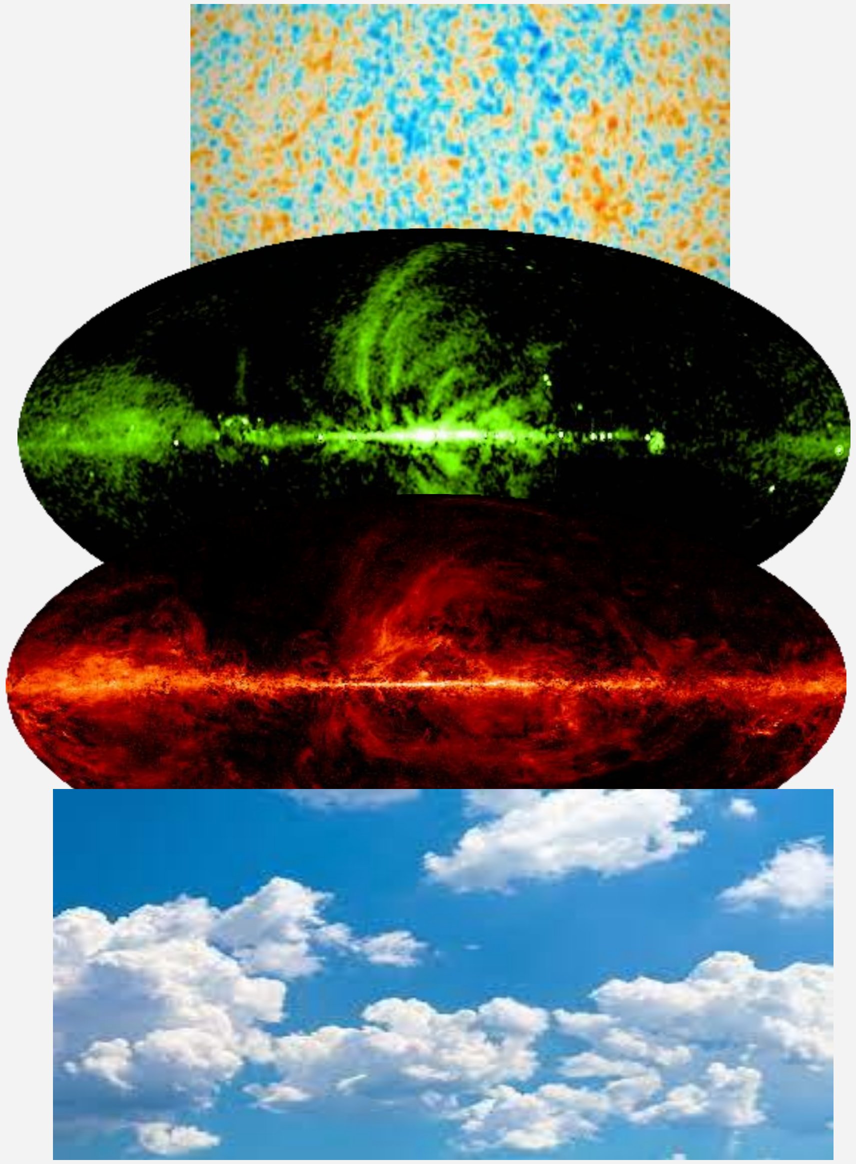
Synchrotron

Dust

Atmosphere

Sum of several emissions

Problematic of foregrounds



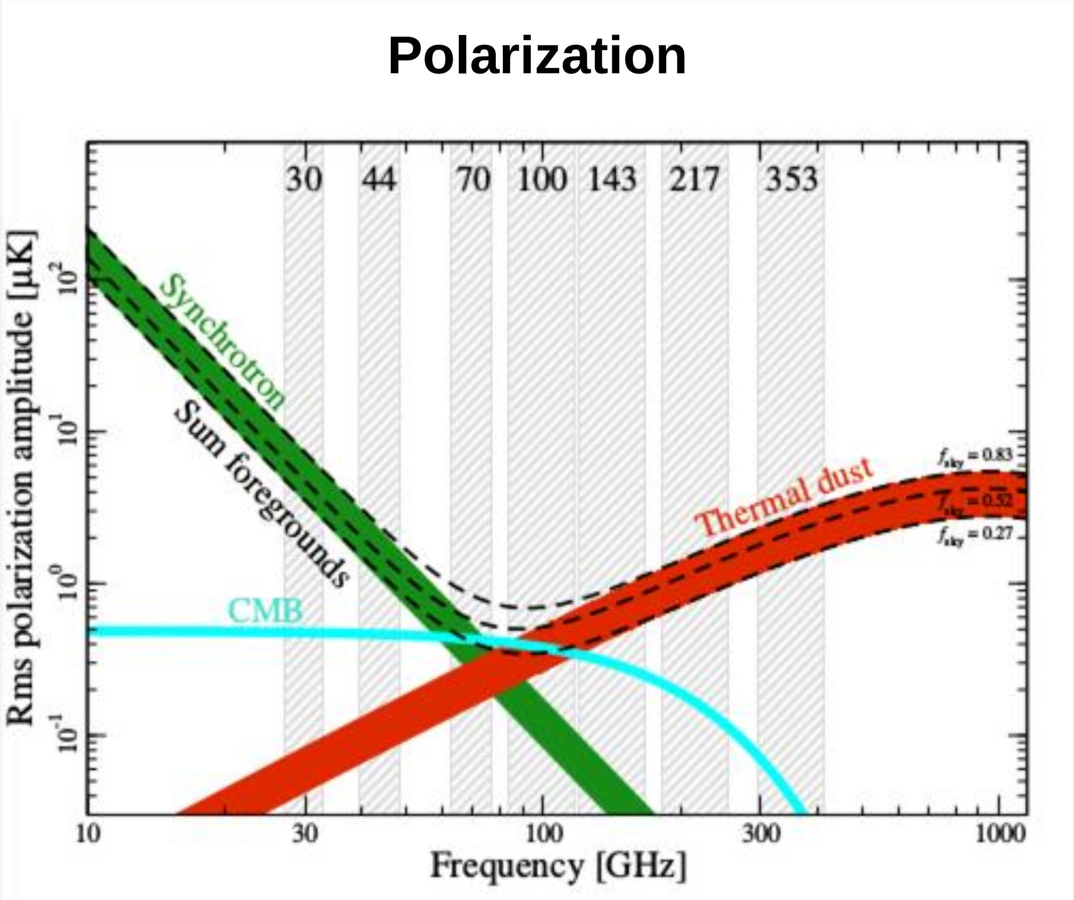
CMB

Synchrotron

Dust

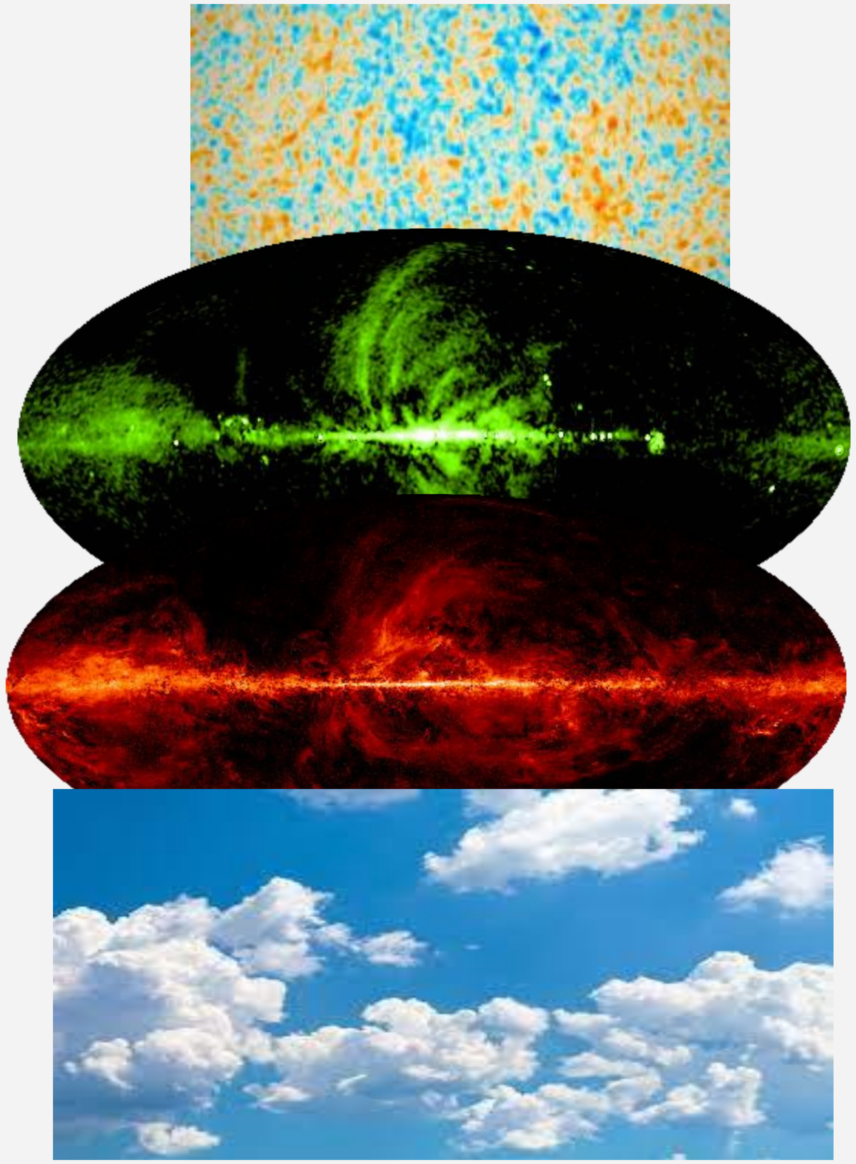
Atmosphere

Sum of several emissions



Credit : Planck

Problematic of foregrounds



CMB

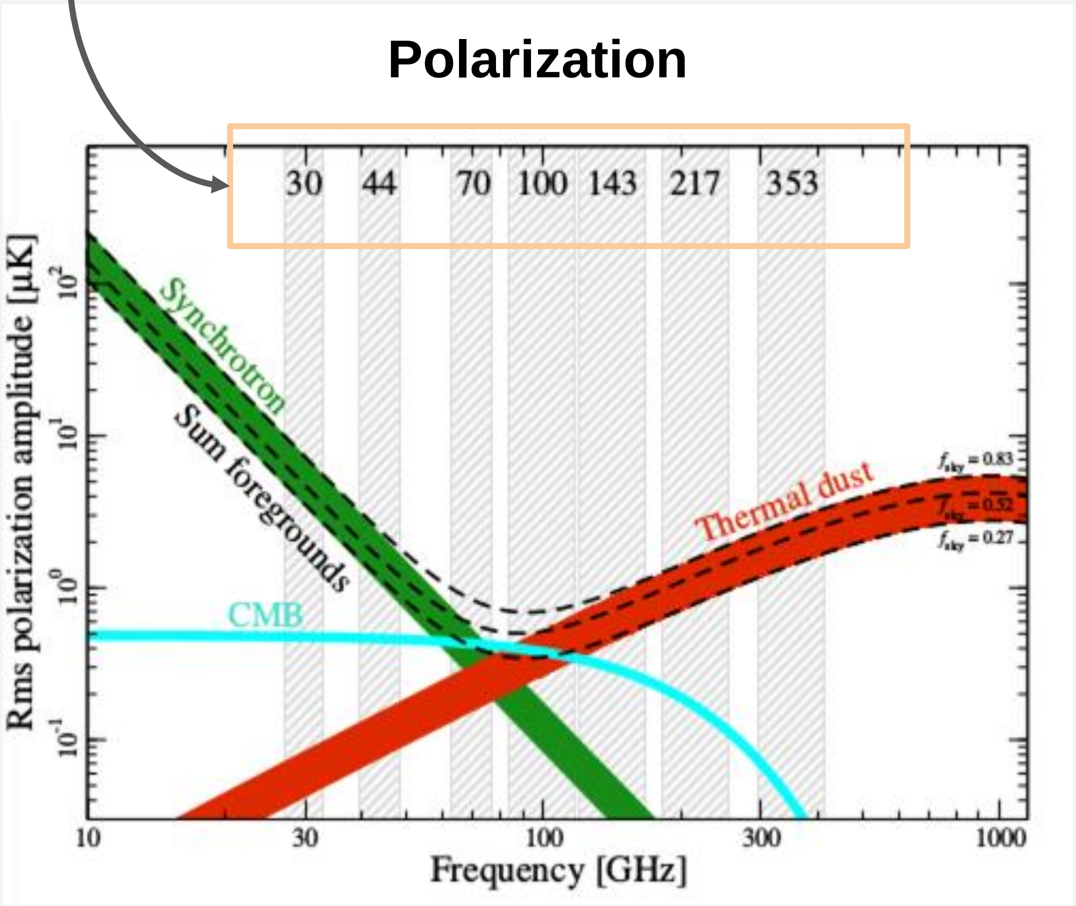
Synchrotron

Dust

Atmosphere

Sum of several emissions

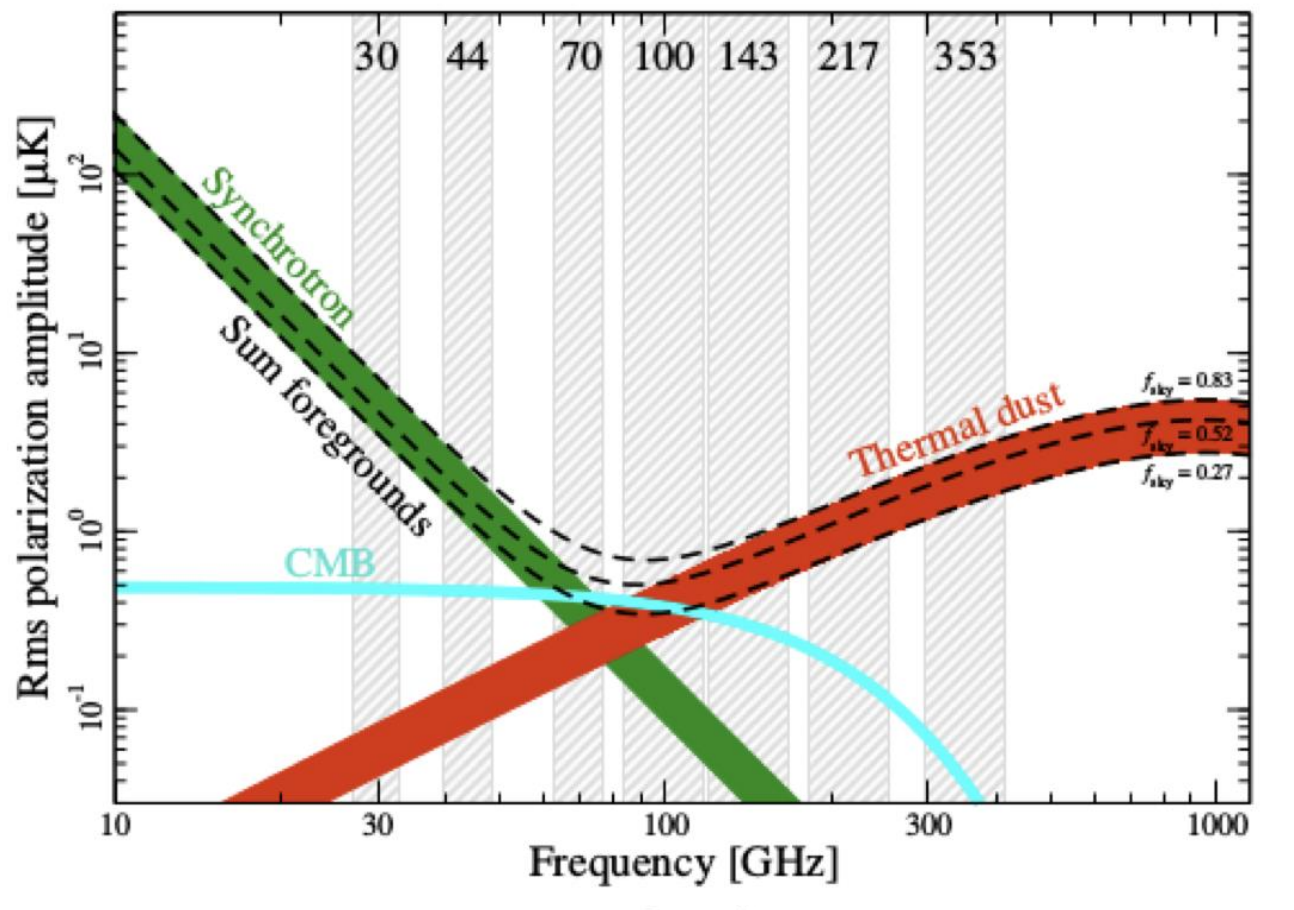
Observation at distinct frequencies is needed



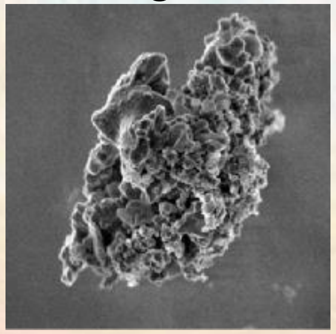
Credit : Planck

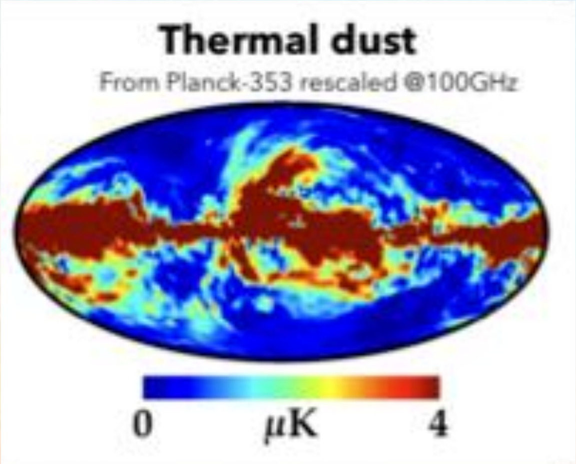
Galactic Foregrounds

Polarization

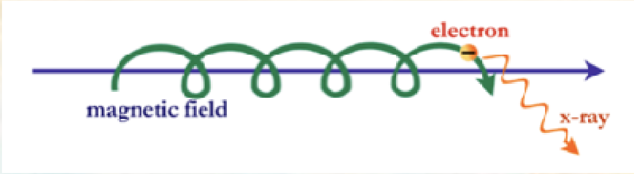


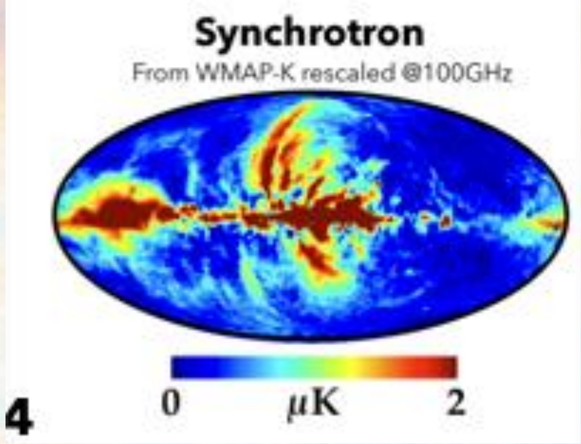
Dust grains





Synchrotron



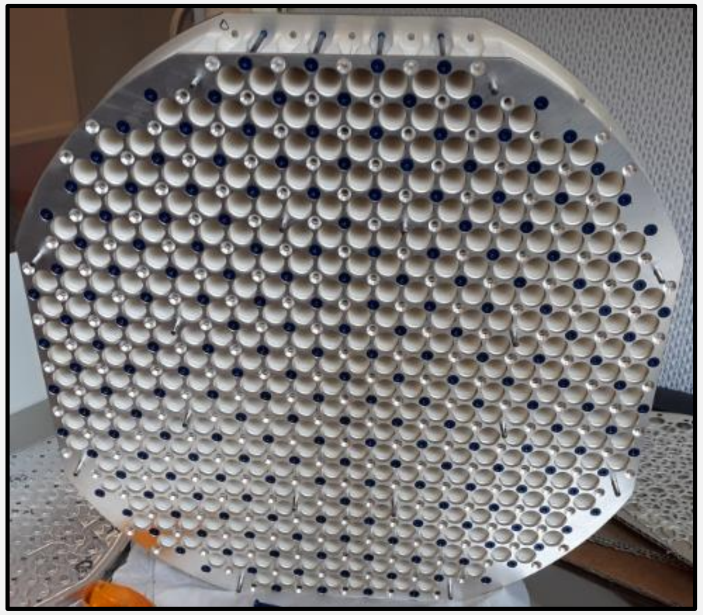


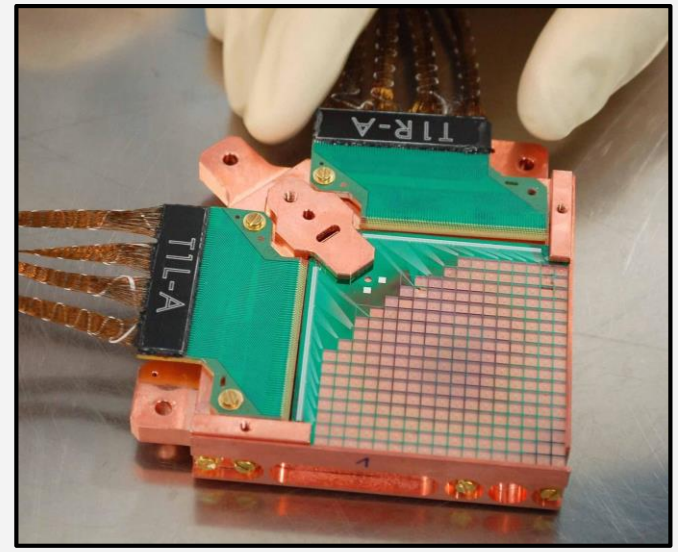
[N. Krachmalnicoff]

Many efficient foreground cleaning techniques exist. They rely on multiwavelength observations.
But they usually assume “smoothness” of the foreground EM spectrum...

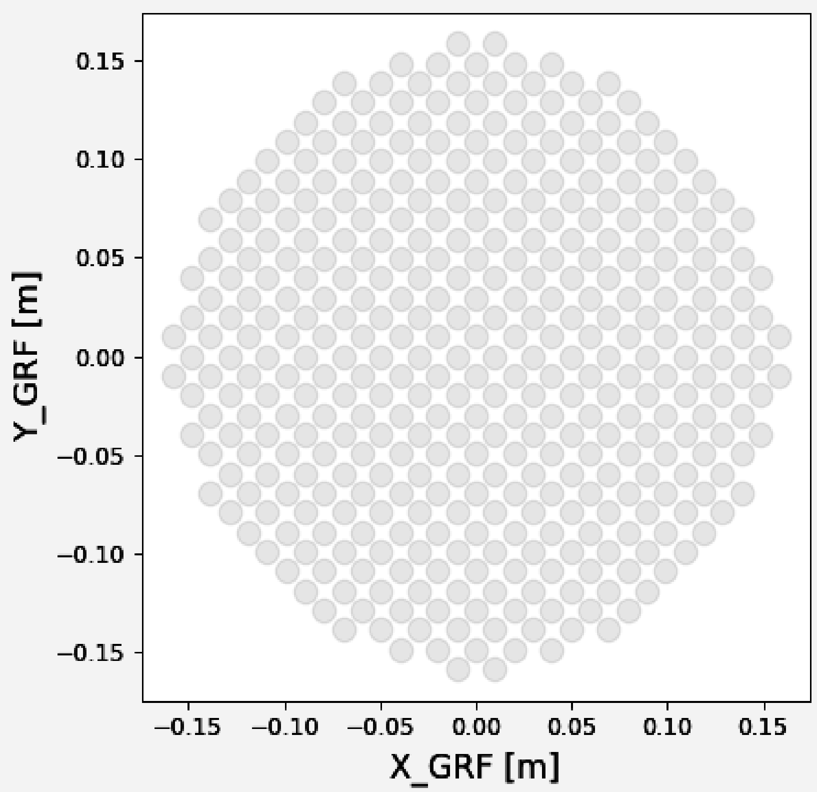
Back to Index

QUBIC, the bolometric interferometer

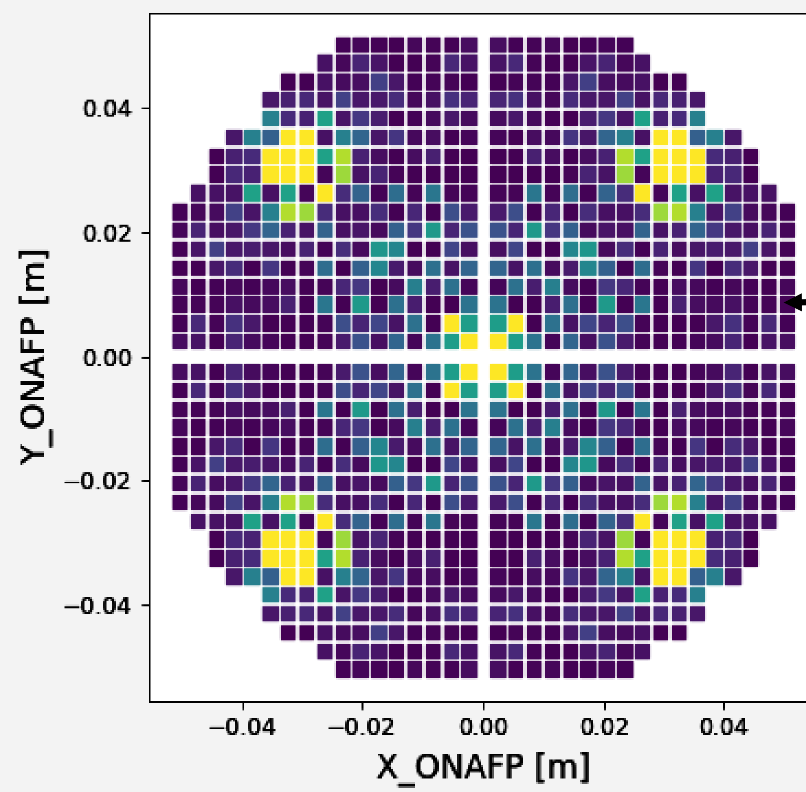




Horn array



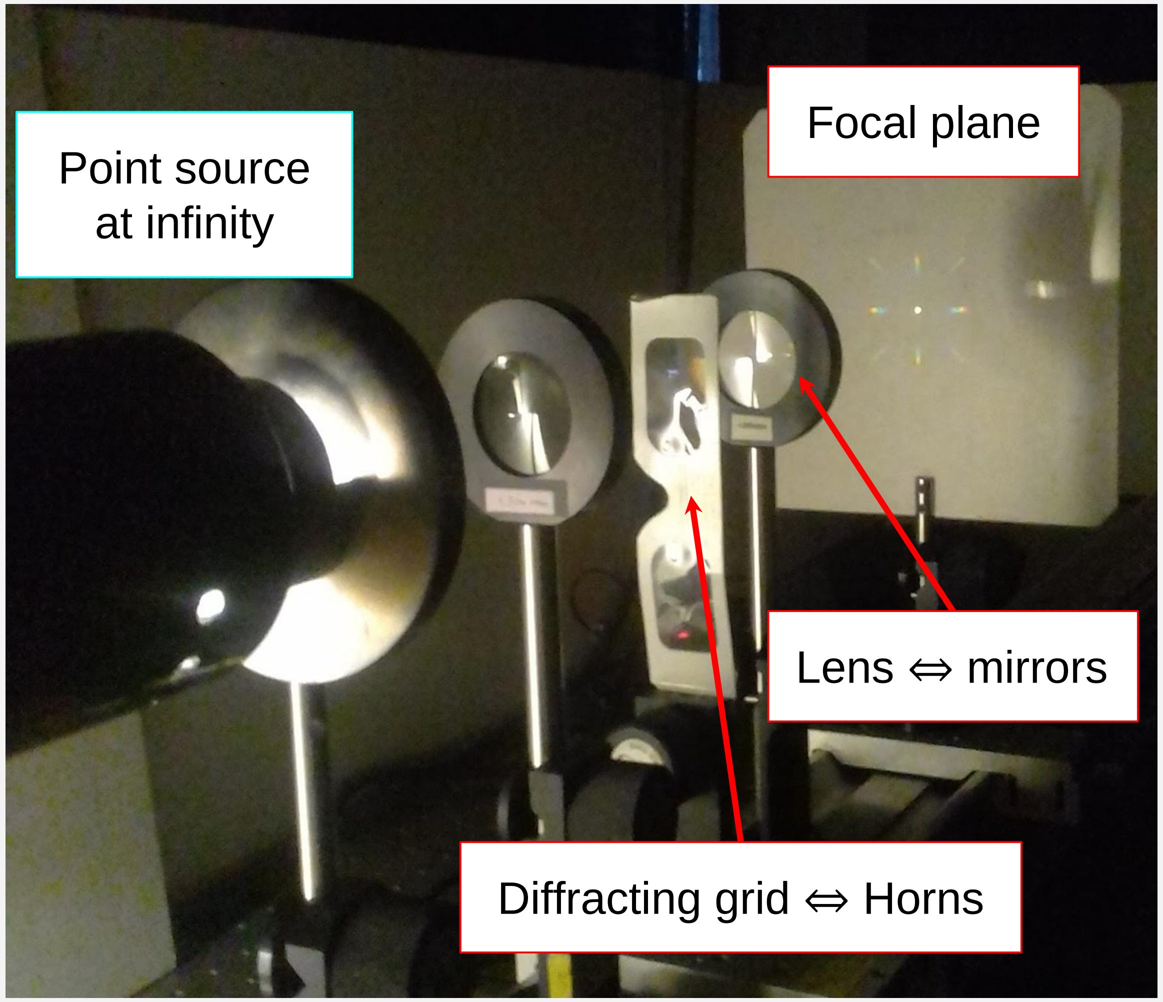
Focal plane : bolometers (TES)

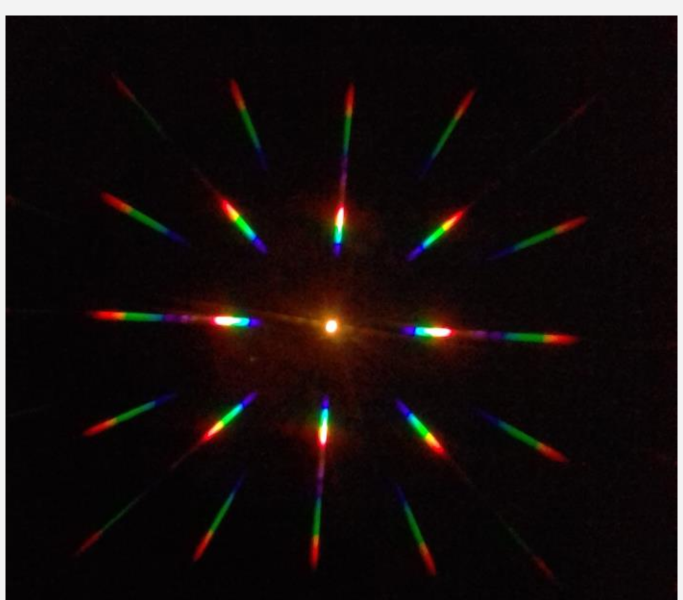


PSF : Response of the instrument on th
focal plane for one
direction on the sky,
at one wavelength.

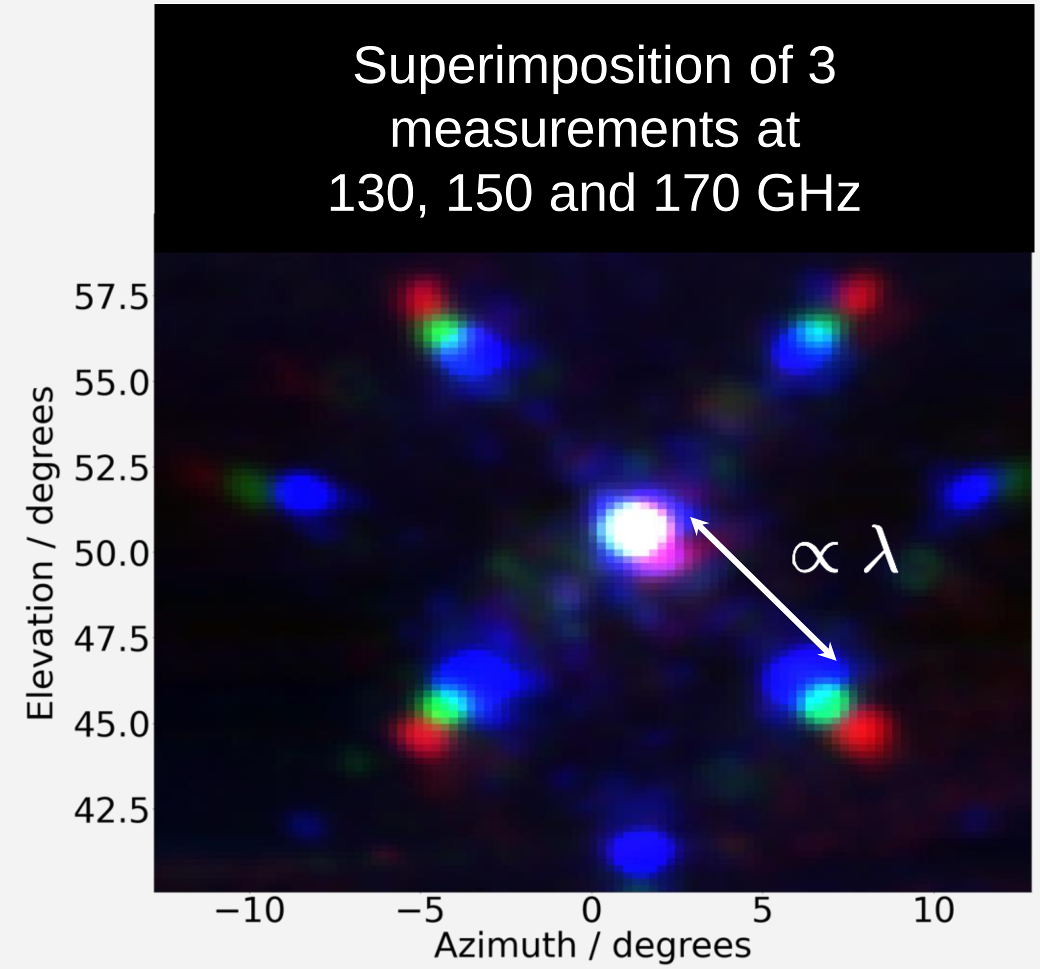
Spectral imaging

[Mousset, Gamboa et al, QUBIC II, JCAP]

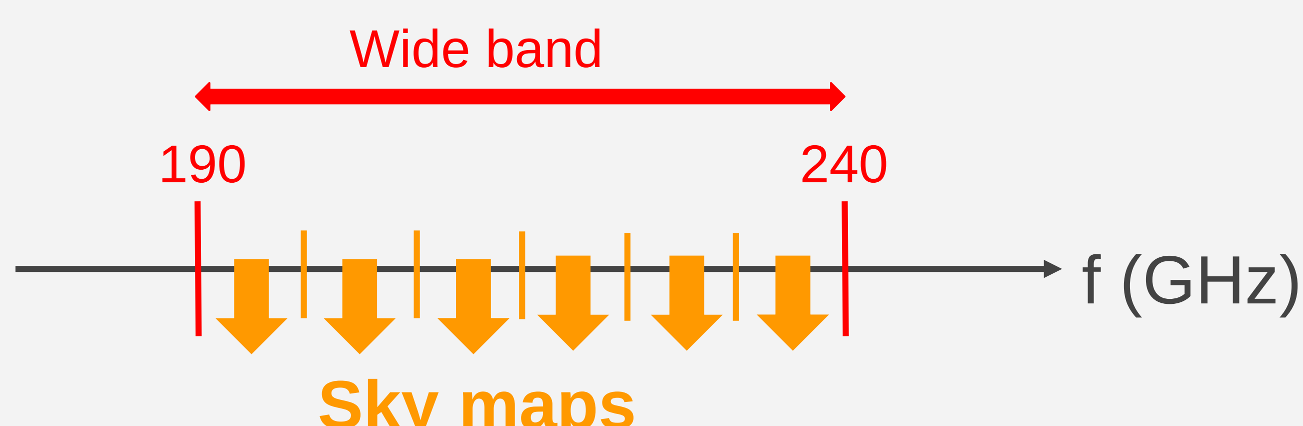




Spectrale information is spatially encoded

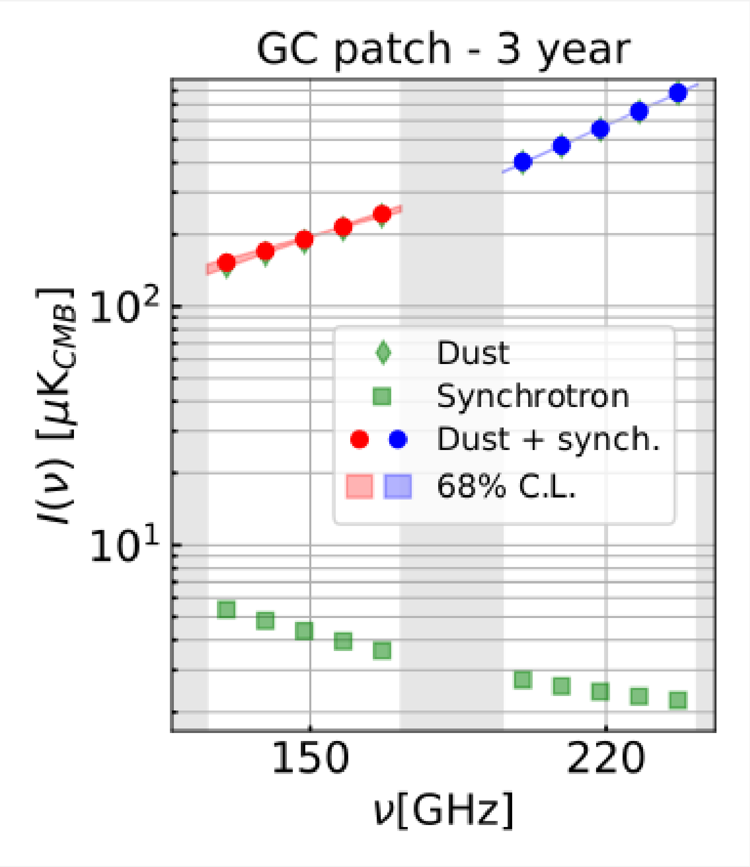


Bolometers **integrate the signal** in a wide frequency band. Spectral imaging allows to split the band in **sub-bands** during the **post-processing.**

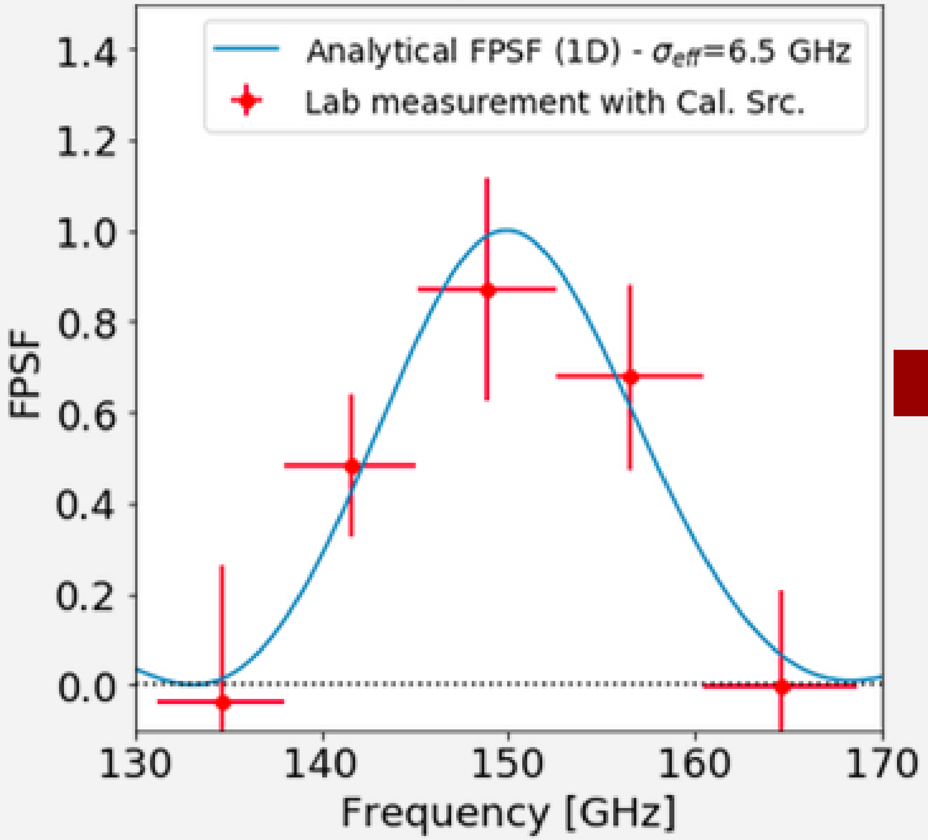


A potential lever arm to control foregrounds

Work in progress



Constrain complex Spectral Energy Density (SED) models



Detect monochromatic emissions (for example CO lines)

Installation in Argentina

Mai 2021

Observation of the sky from Salta in October

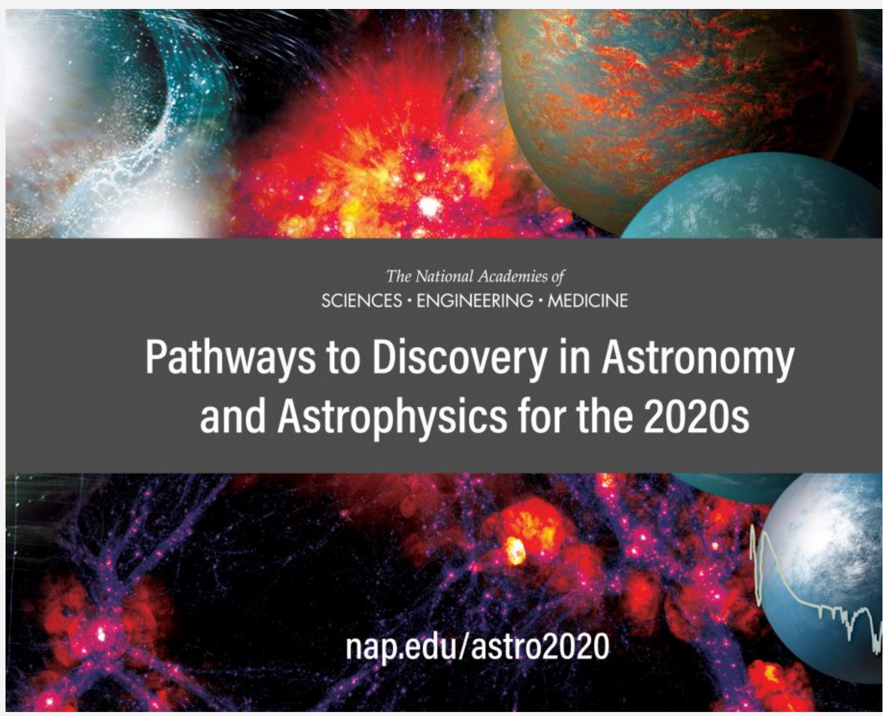
Re-assembling in Salta

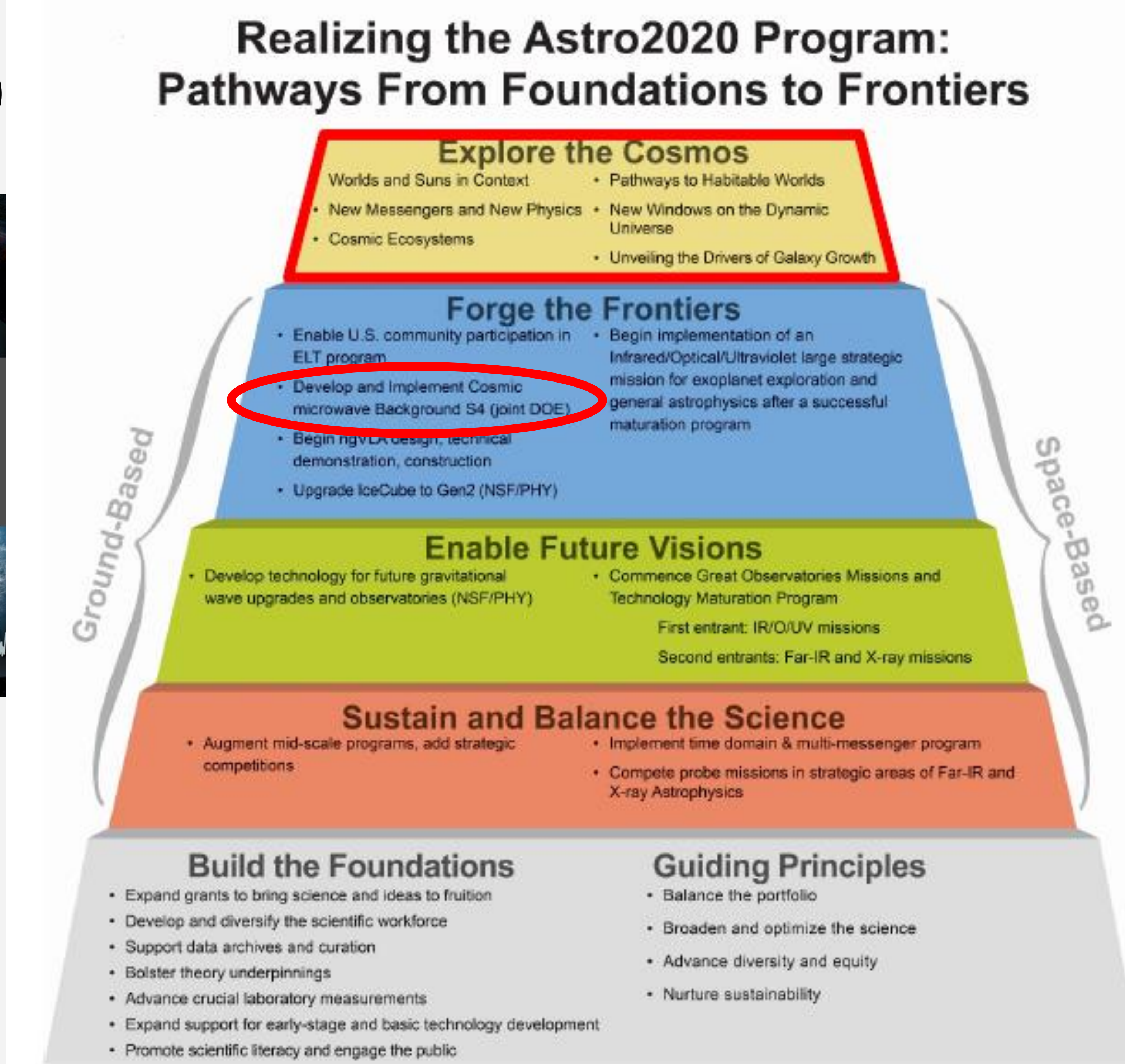
May 2022

Observation site:
San Antonio de Los Cobres, ~5000 m

US Decadal Survey

nap.edu/astro2020



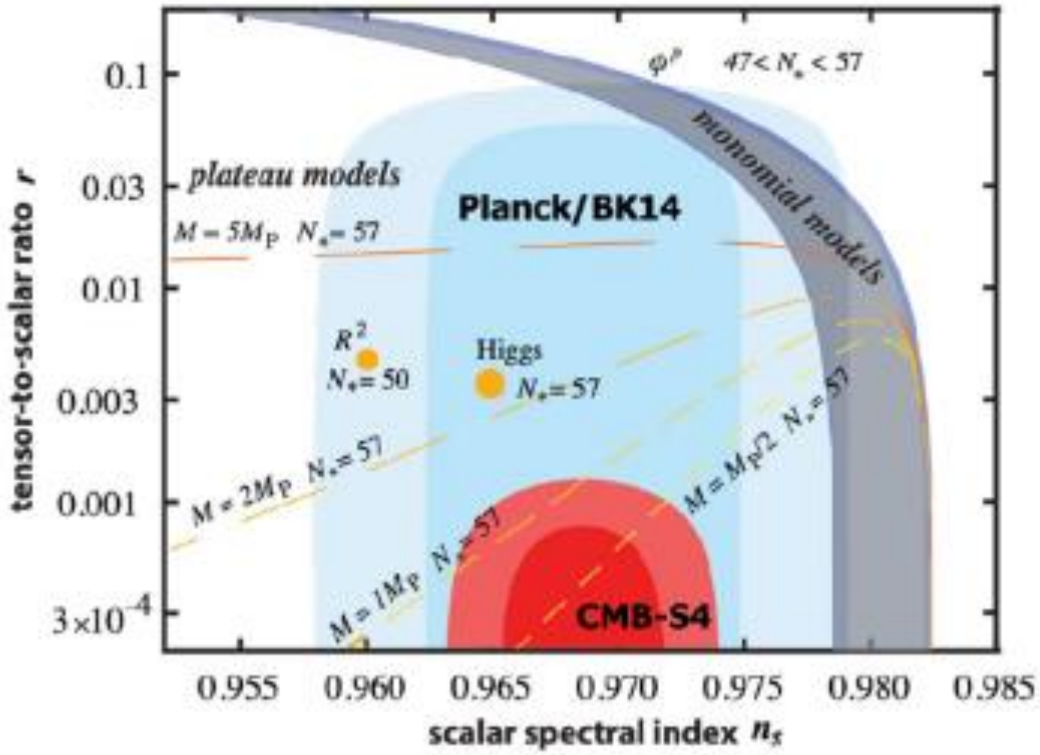


The Cosmic Microwave Background Stage 4 Observatory

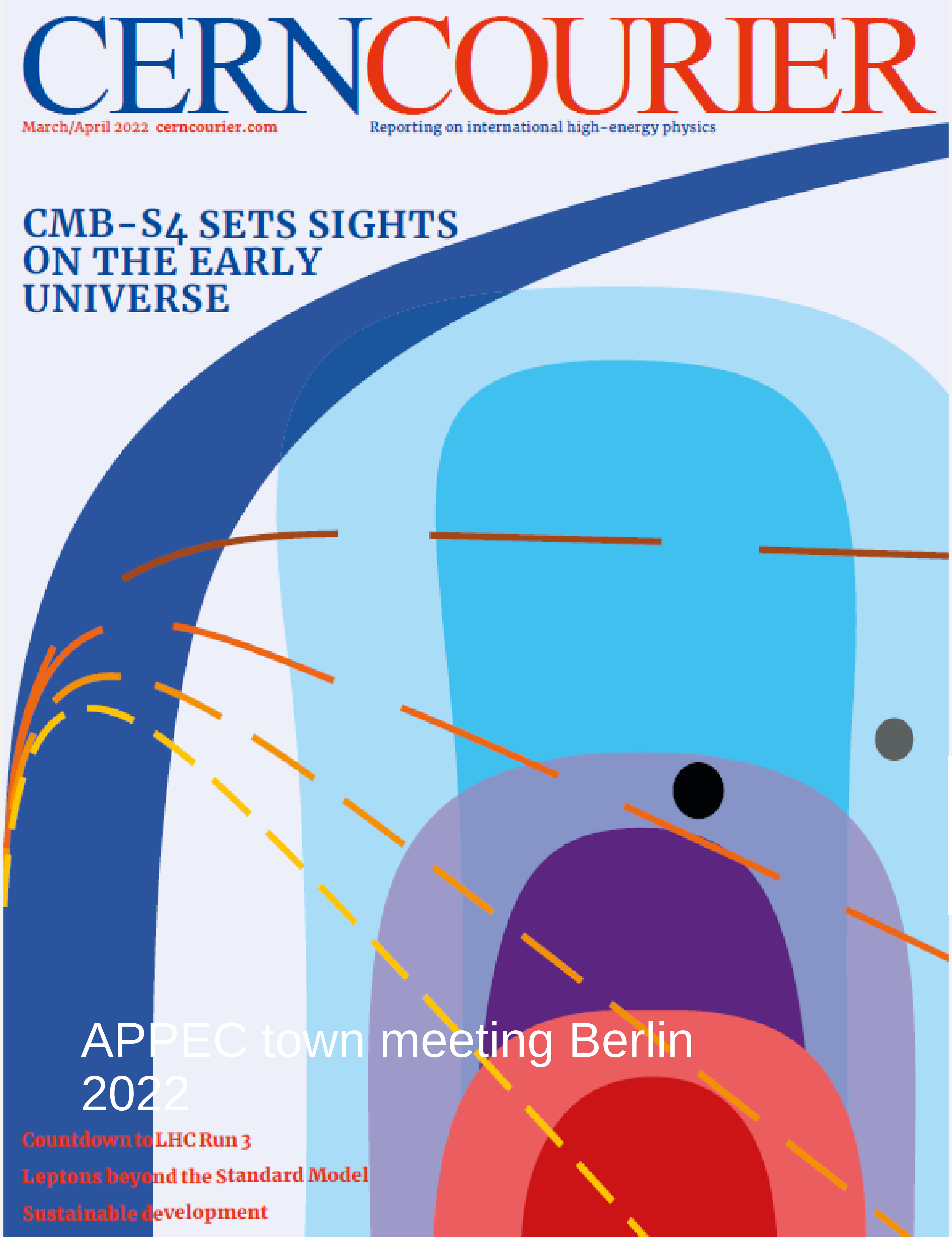
CMB-S4 builds on the foundation of decades of CMB measurements to take a major leap, pushing CMB science to the next level

Scientific goals

- B-mode CMB polarization signatures of primordial gravitational waves and inflation
- Maps 50% sky, every other day from 0.1- 1 cm with unprecedented sensitivity
- Broad science including systematic time domain science

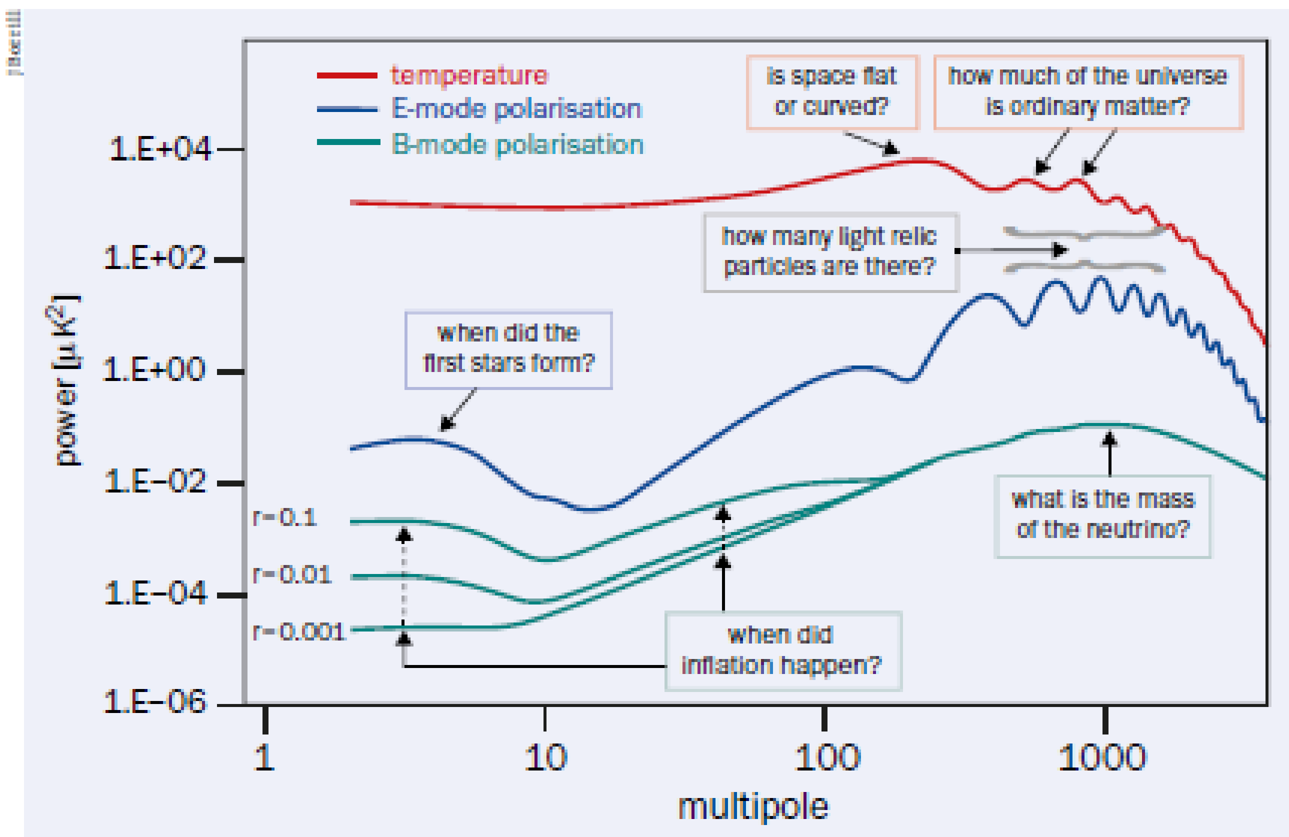


CMB-S4 consists of a systematically planned suite of facilities in Antarctica and Chile designed to sample a wide range of independent frequencies, and probe a combination of large and small angular scales

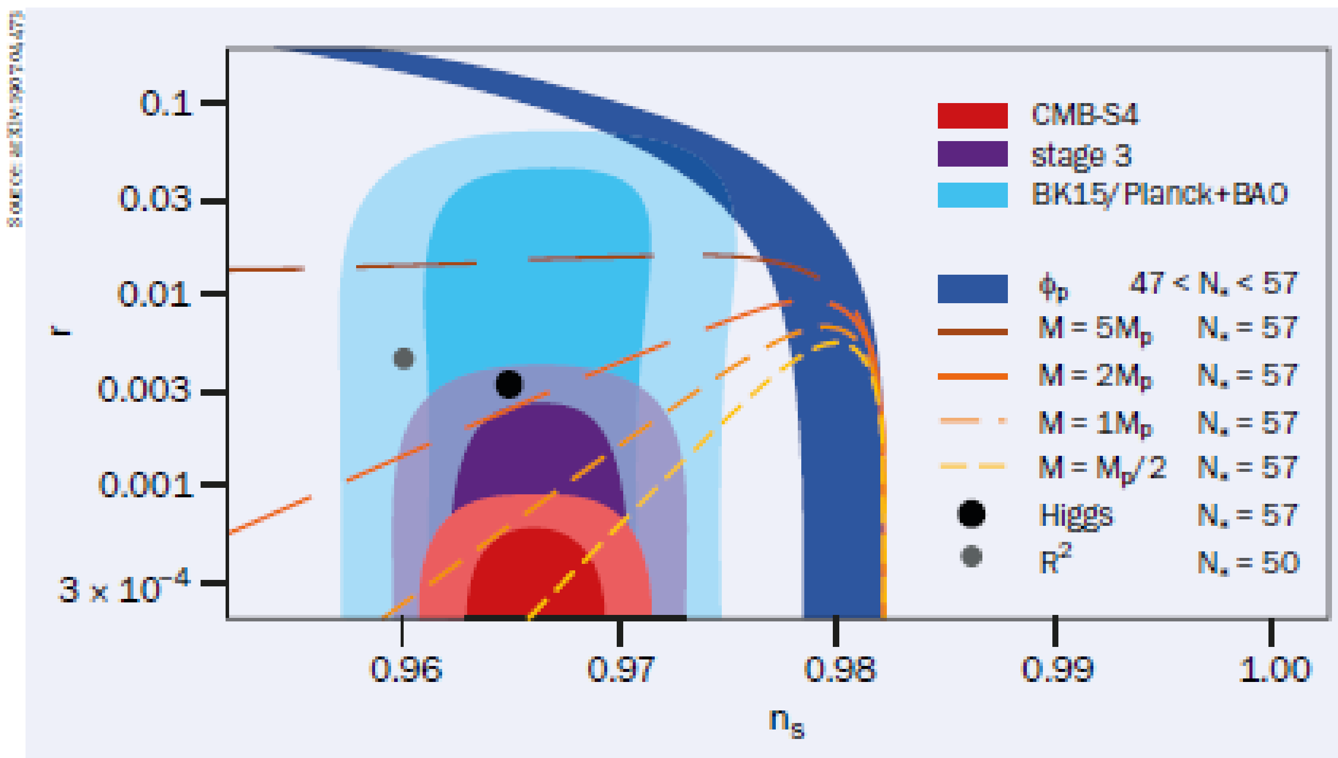


APPEC town meeting Berlin 2022

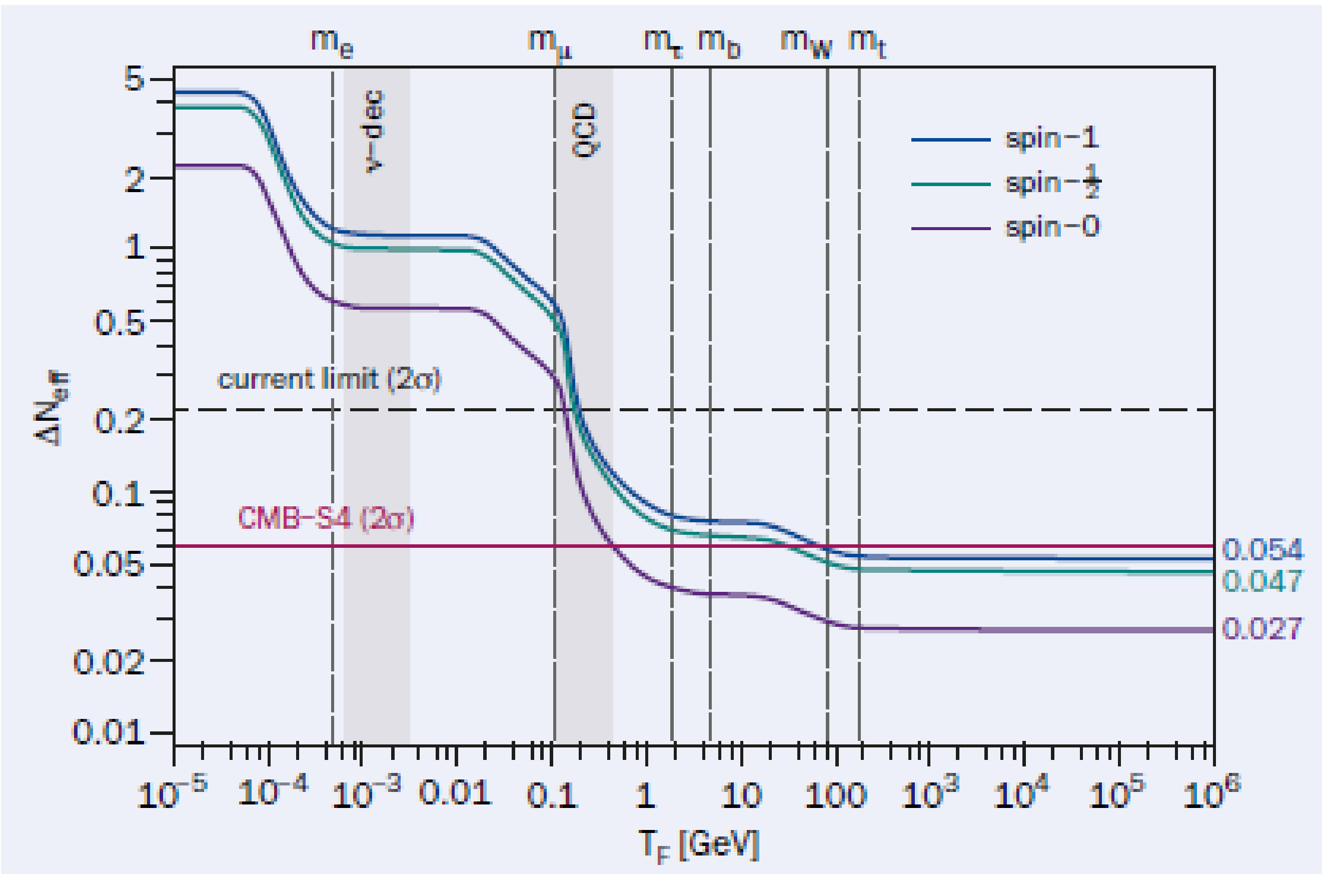
On the cover: *CMB-S4 constraints on inflation, flipped for presentation purposes.* **36**



Power spectra *The temperature and polarisation power spectra of the CMB, illustrating features that can answer key questions in cosmology and fundamental physics. The CMB polarisation is decomposed into a curl-free E-mode and divergence-free B-mode by analogy with electromagnetism, with r quantifying the scalar-to-tensor ratio (the size of the B-modes relative to that of the temperature power spectrum).*



Constraining inflation *Current (light blue and purple) and anticipated (red) CMB-S4 constraints on the scalar-to-tensor ratio r compared with the predictions of various inflationary models that naturally explain the observed value of the spectral "tilt" of the power spectrum, $n_s = 0.965$. The popular Starobinsky and Higgs inflation models are shown as grey and black circles. The lines show models with different masses of the inflaton in units of the Planck mass M_P and N_* is the number of e-folds. The corresponding inflation potentials ϕ_P all either polynomially or exponentially approach a plateau.*



Light relics *Current (black) and anticipated (magenta) CMB-S4 constraints on the effective number of light-relic species* $N_{eff} = N_{SMeff} + \Delta N_{eff}$*, with* $N_{SMeff} = 3.045$ *from neutrinos. The plot shows the contributions of a single massless particle (which decoupled from the SM at freeze-out temperature* T_F*) to* N_{eff}*, with the displayed values on the right indicating observational thresholds for particles with different spins.*

Looking up *The full facility will employ 18 0.5 m small-aperture telescopes (top left), three per mount, fielding 150,000 detectors; one 5 m large-aperture telescope (right) fielding 130,000 detectors; and two 6 m large-aperture telescopes fielding 275,000 detectors (bottom left).*