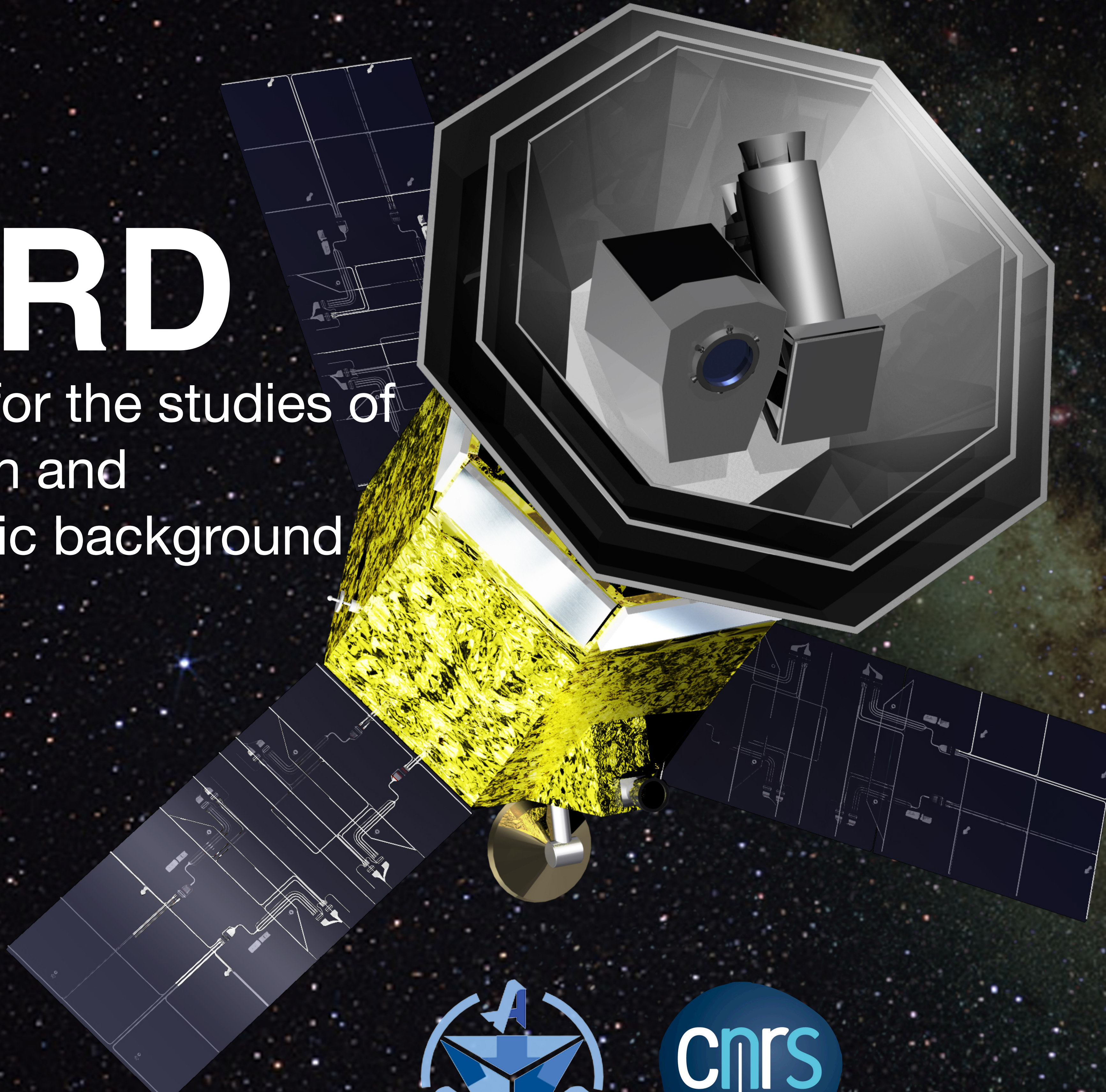
LiteBIRD

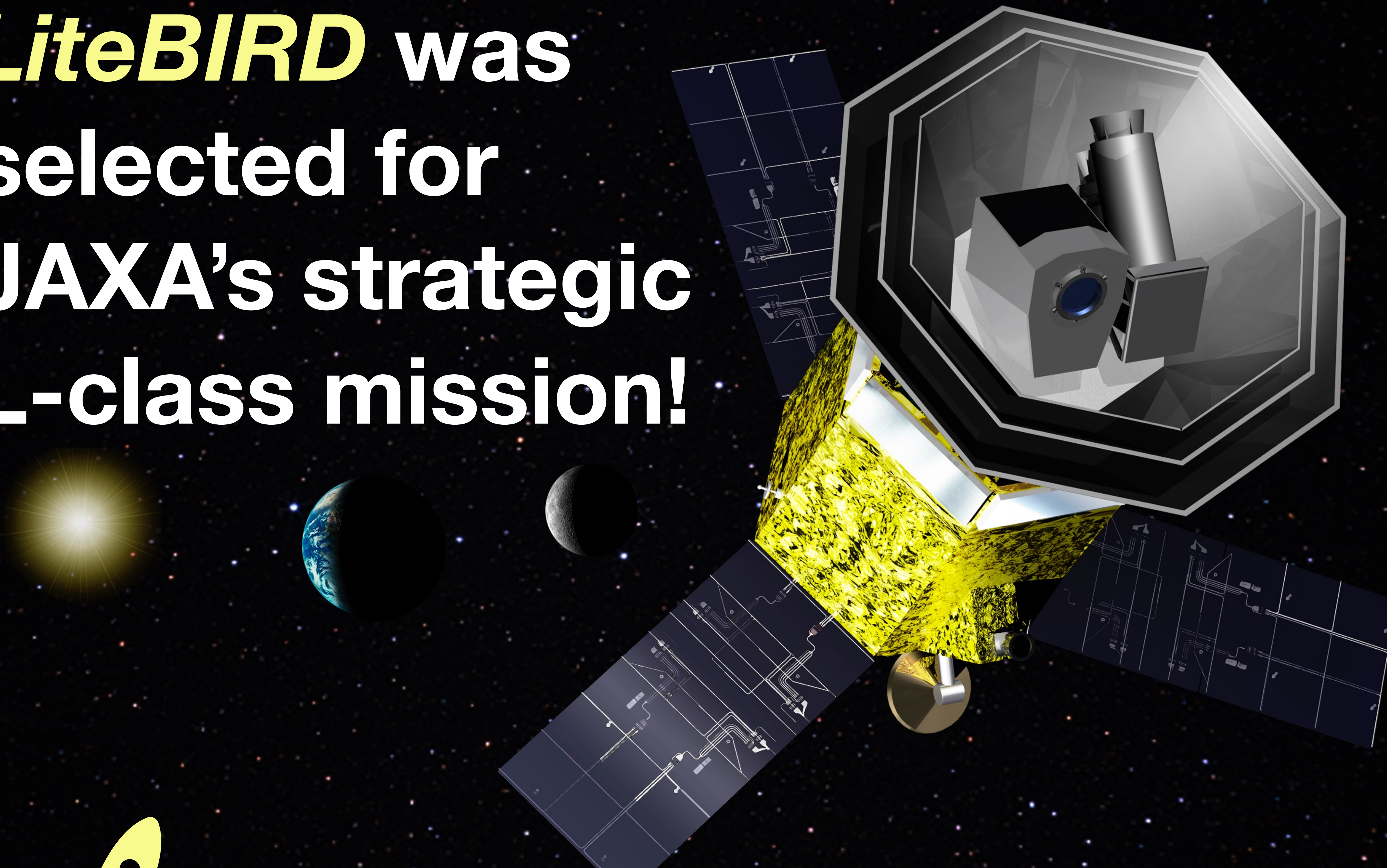
Lite (light) satellite for the studies of
B-mode polarization and
Inflation from cosmic background
Radiation
Detection



Josquin Errard

LPNHE
4th of November, 2019

In May 2019, *LiteBIRD* was selected for JAXA's strategic L-class mission!



launch planned in 2027!

selected history/status

2008 - first LiteBIRD proposal;
Basic concept of a focused mission established;

early 2015 – LiteBIRD US MO proposal submitted and granted (July 2015): extended frequency range (HFT) proposed;

mid-2015 – LiteBIRD selected as one of the two candidate projects for JAXA’s Large mission;
LiteBIRD and SolarSail (more recently known as Okeanos);

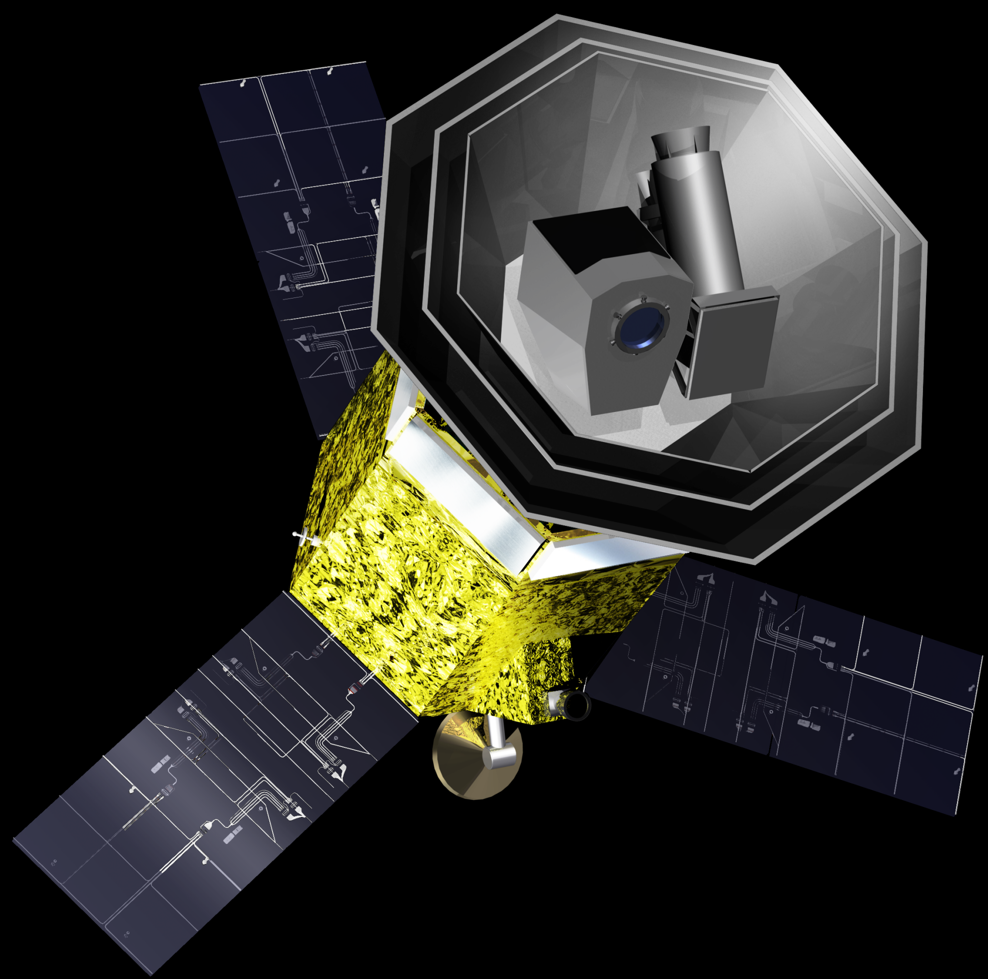
fall 2015 – an ‘invitation’ letter to the European CMB community by Saku Tsuneta (ISAS);

mid-2017 – LiteBIRD-Europe established;
first meeting in Cardiff, UK;

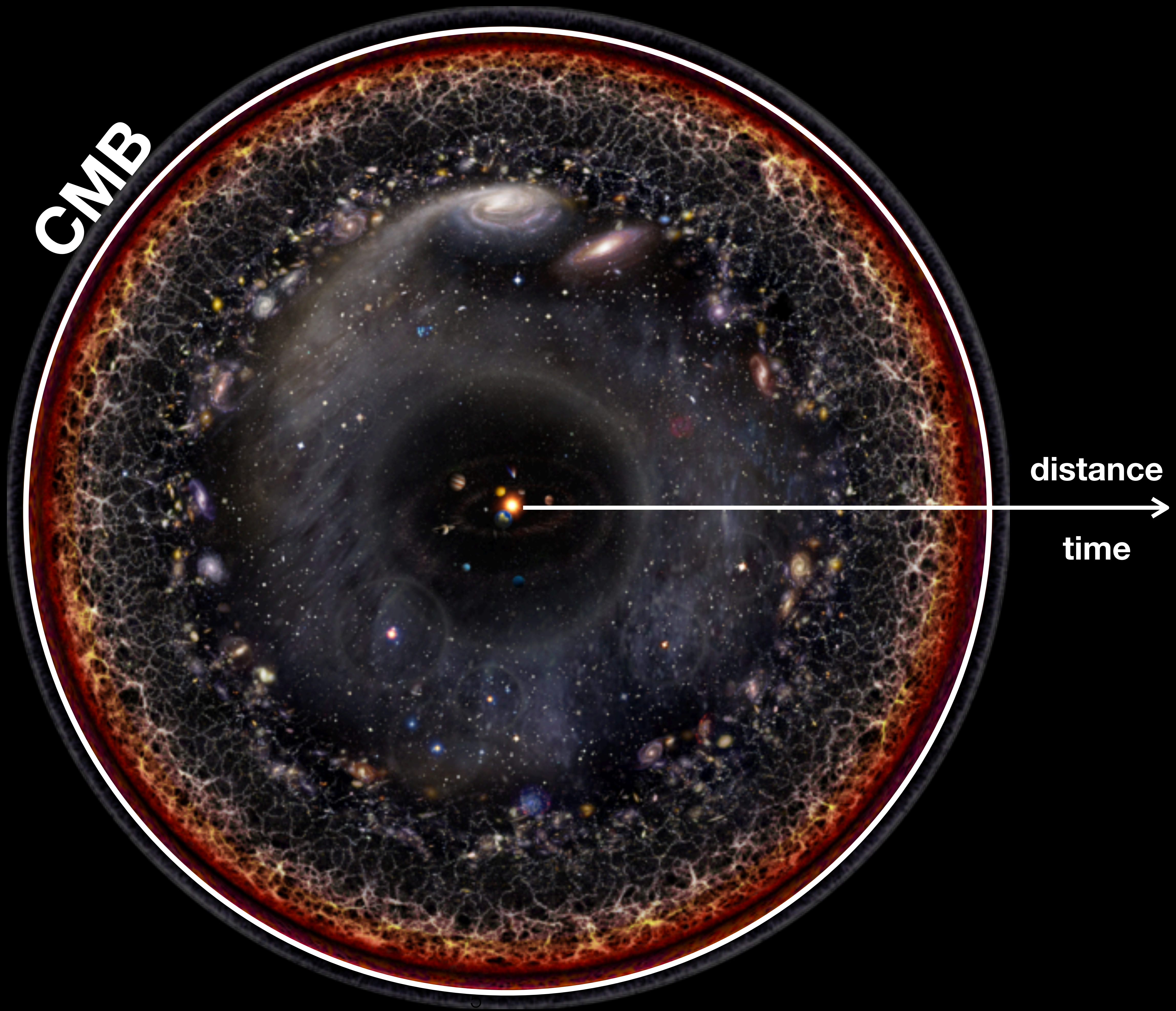
mid-2018 – ESA-JAXA CDF study;
LiteBIRD-Europe collaboration representatives invited;

mid/fall - 2018 – selection for the phase A in Italy and France;

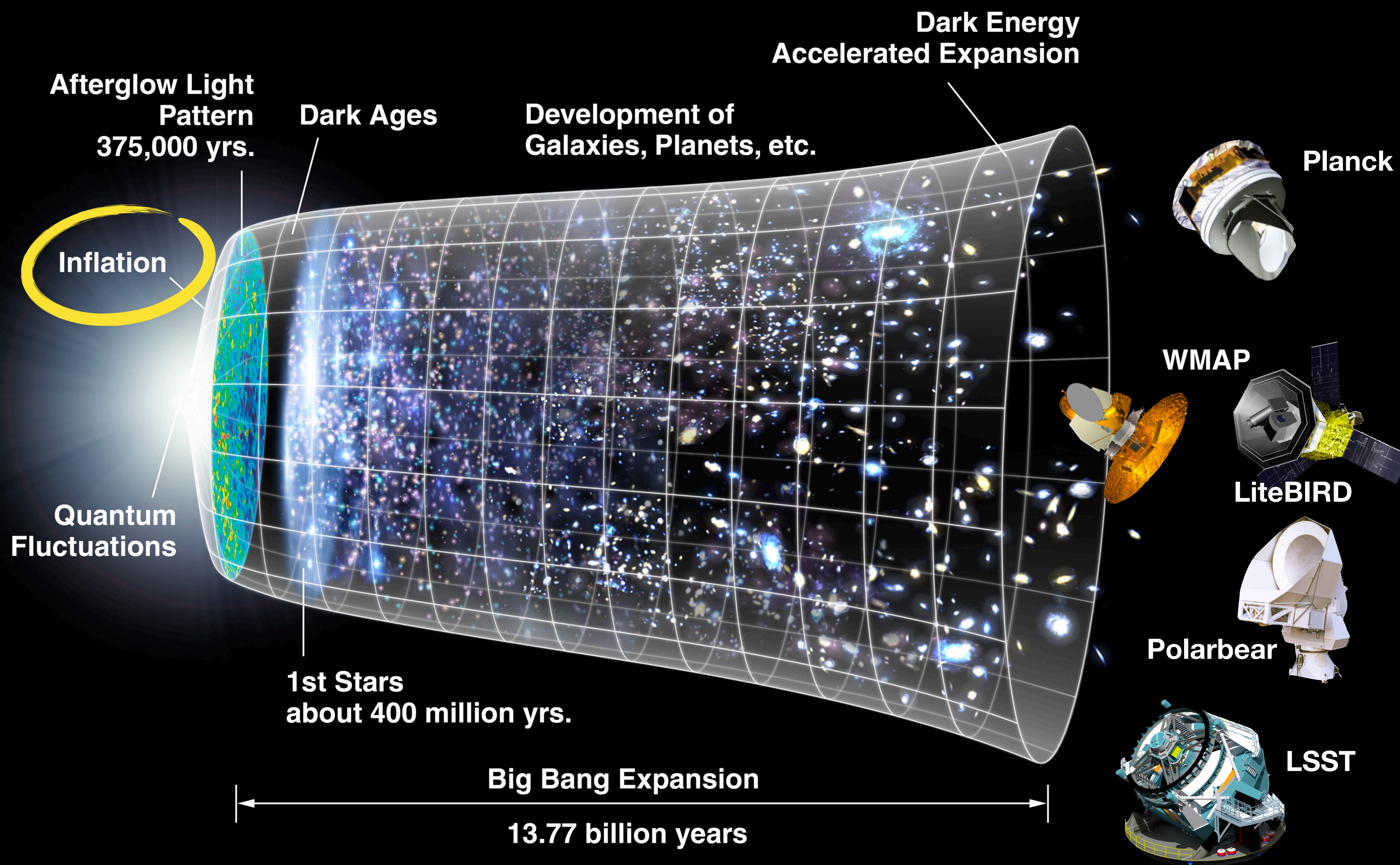
May 2019 – LiteBIRD downselected by JAXA for the L3 large mission with a launch in FY 2027.



Introduction
LiteBIRD design
LiteBIRD science
Challenges
Collaboration


CMB
distance
time

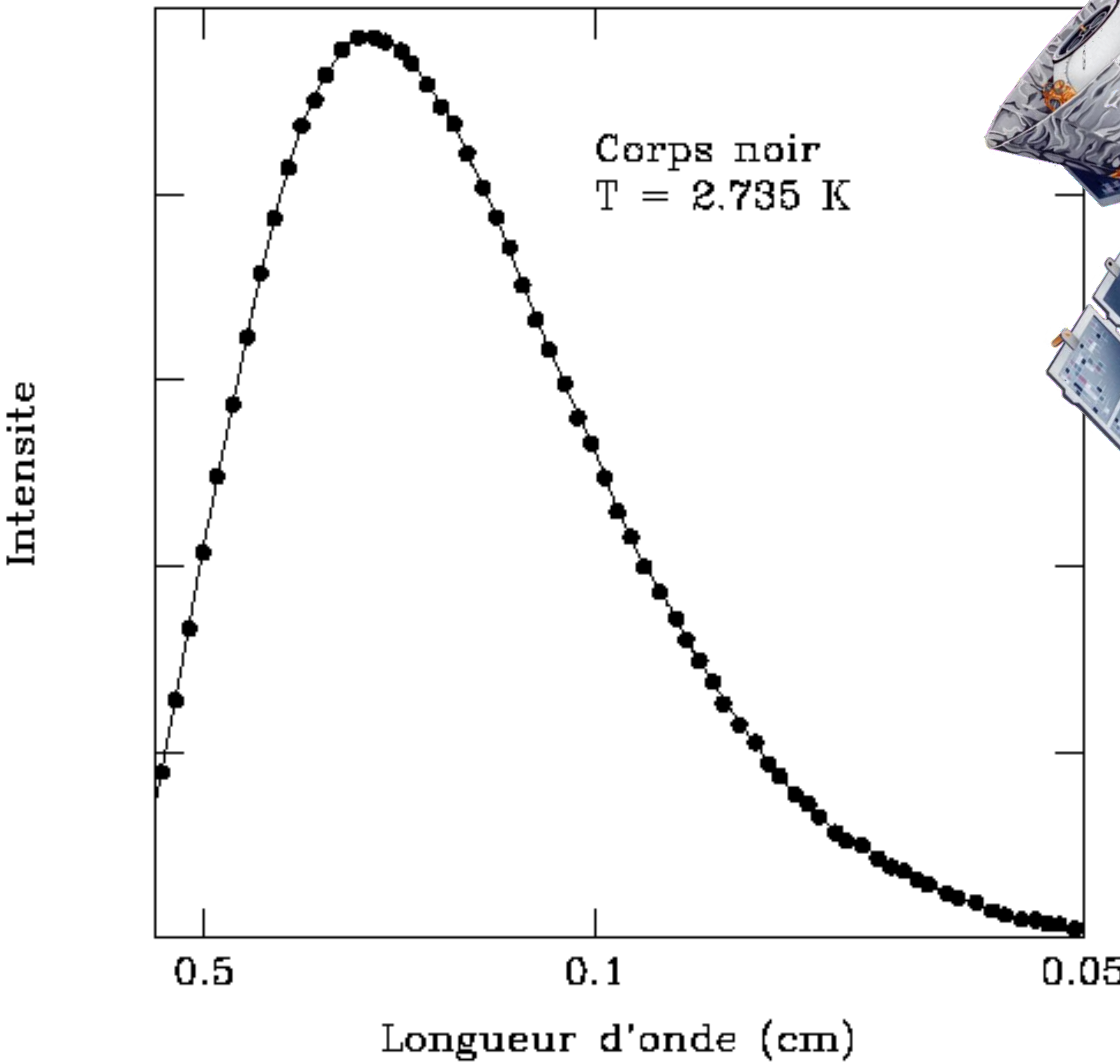
Hot Big Bang scenario




the night sky at optical wavelengths

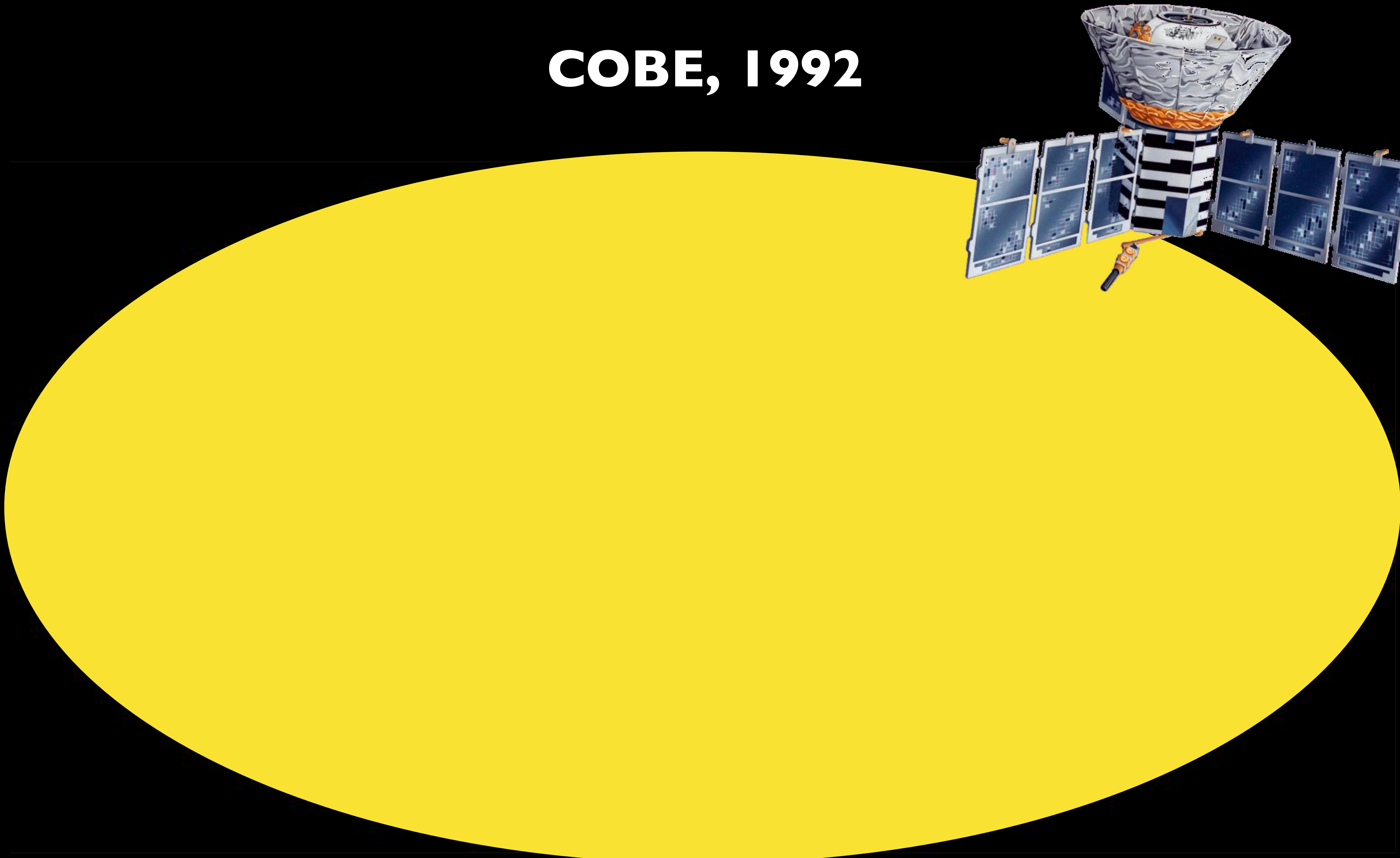
at millimeter wavelengths, we observe the isotropic Cosmic Microwave Background photosphere — with a black body emission at a 2.7K temperature

the Cosmic Microwave Background follows a perfect black body spectrum

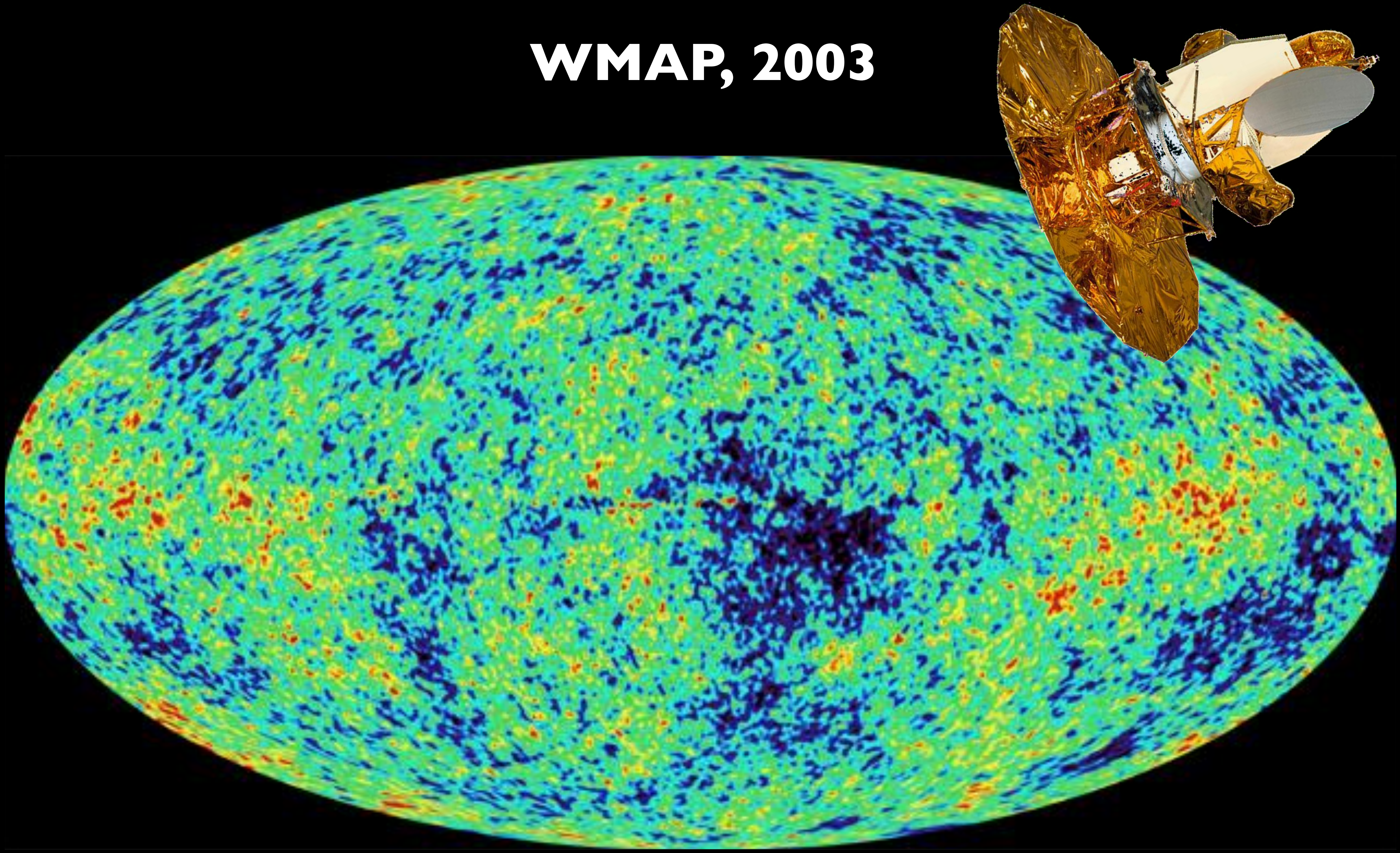


George F. Smoot and John C. Mather Nobel prize 2006 *“for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation*".

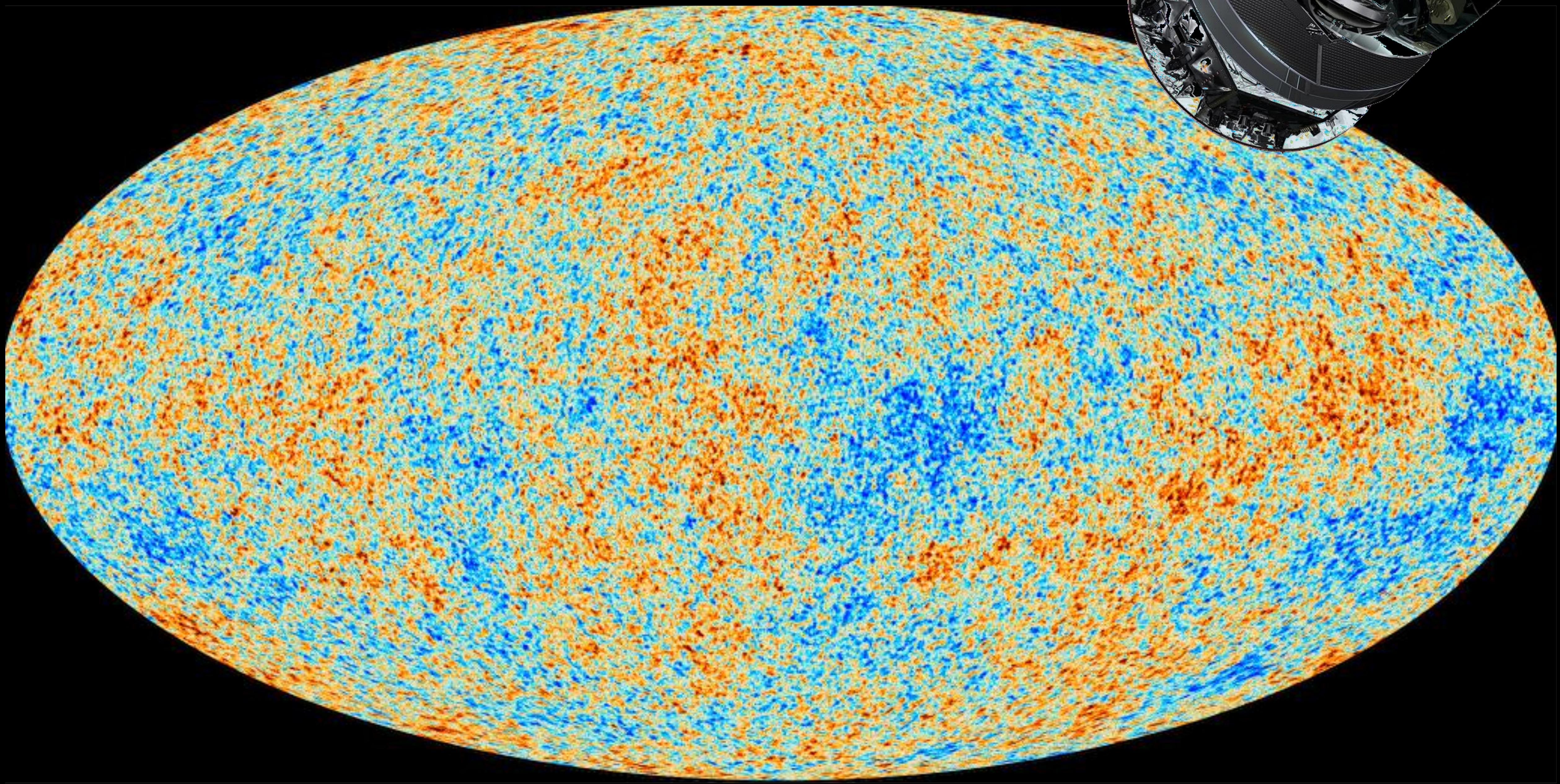
COBE, 1992

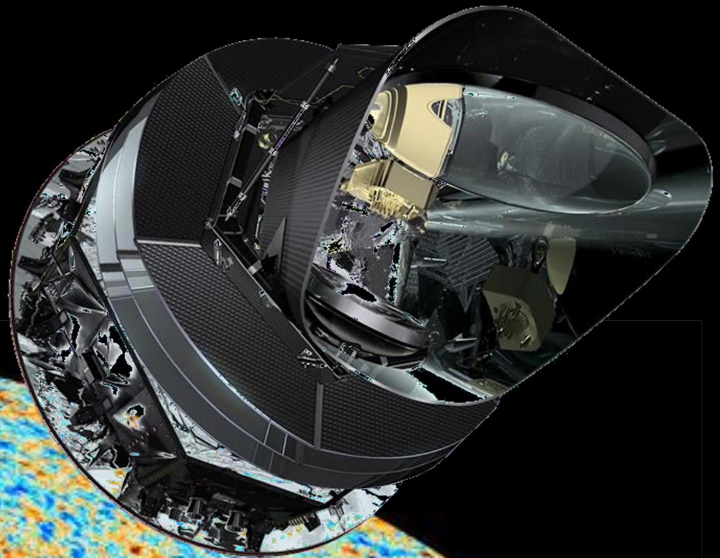


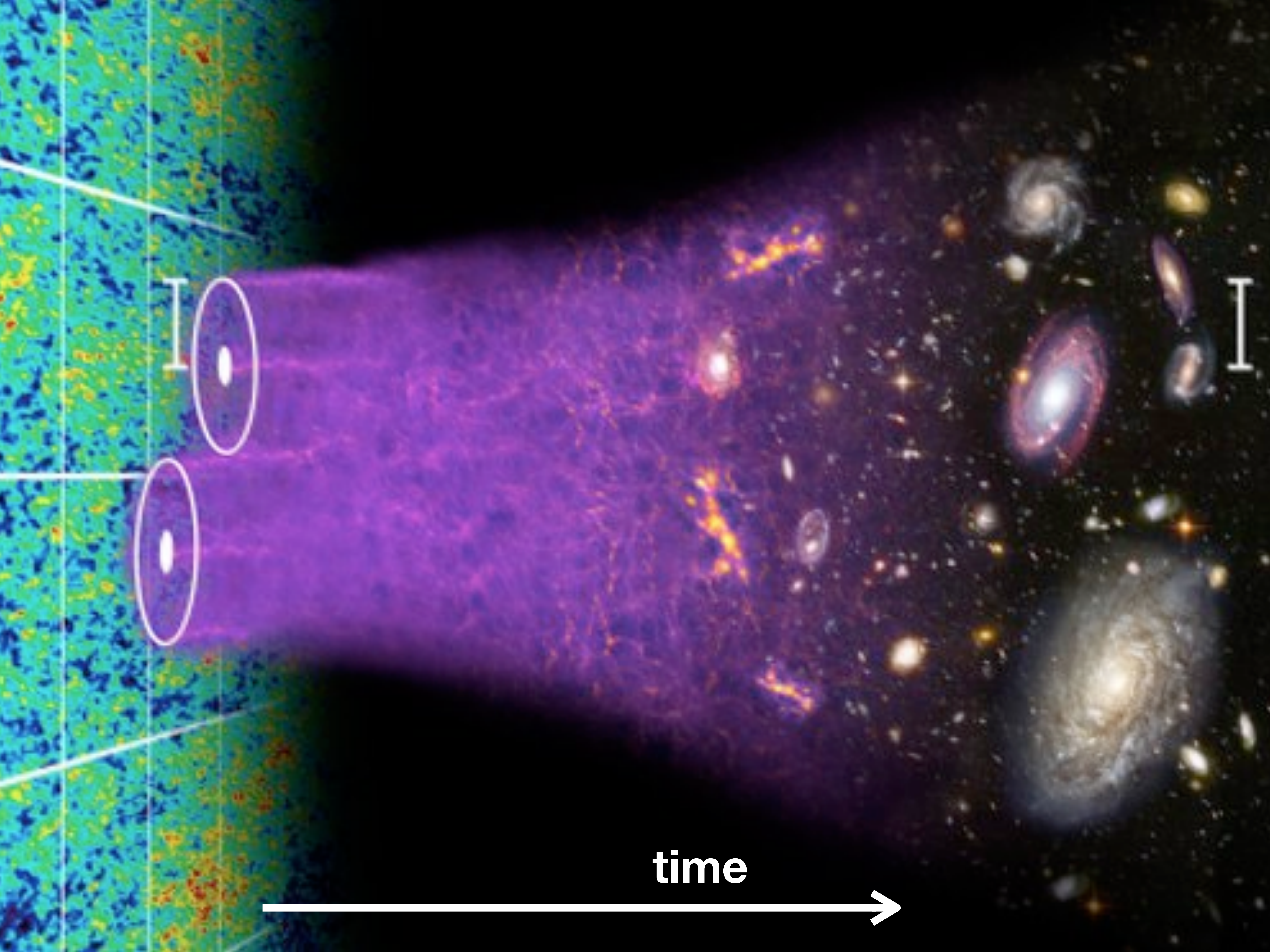
WMAP, 2003

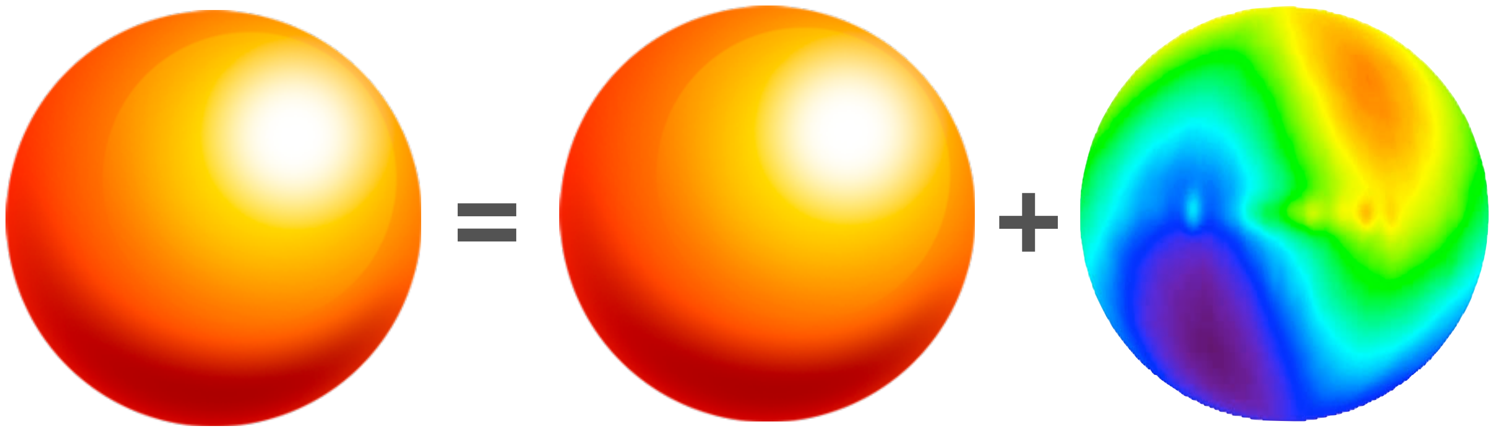


Planck, 2015



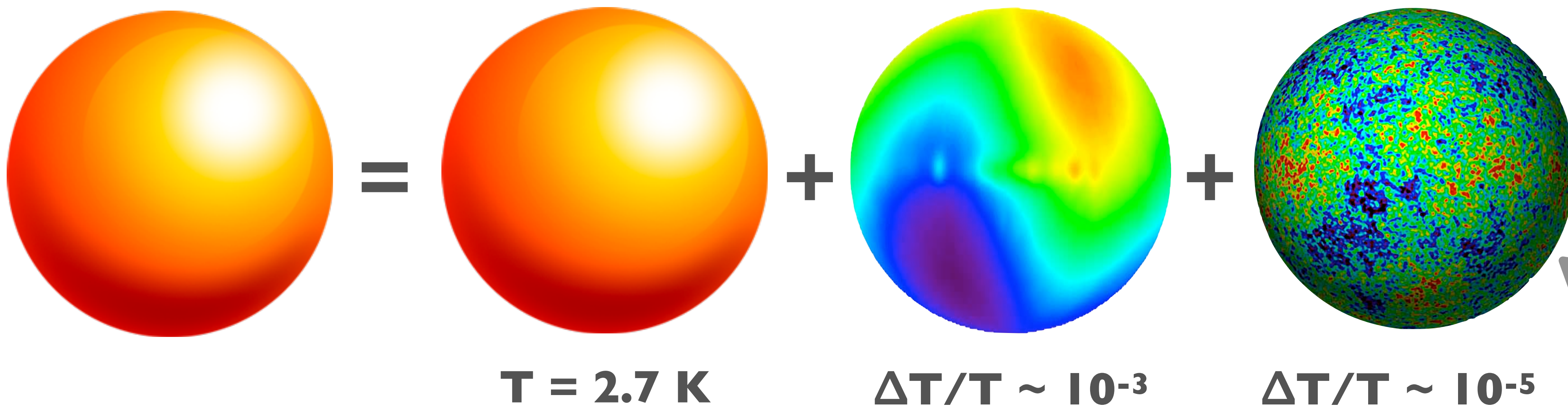



time



$T = 2.7$ K $\qquad \Delta T/T \sim 10^{-3}$

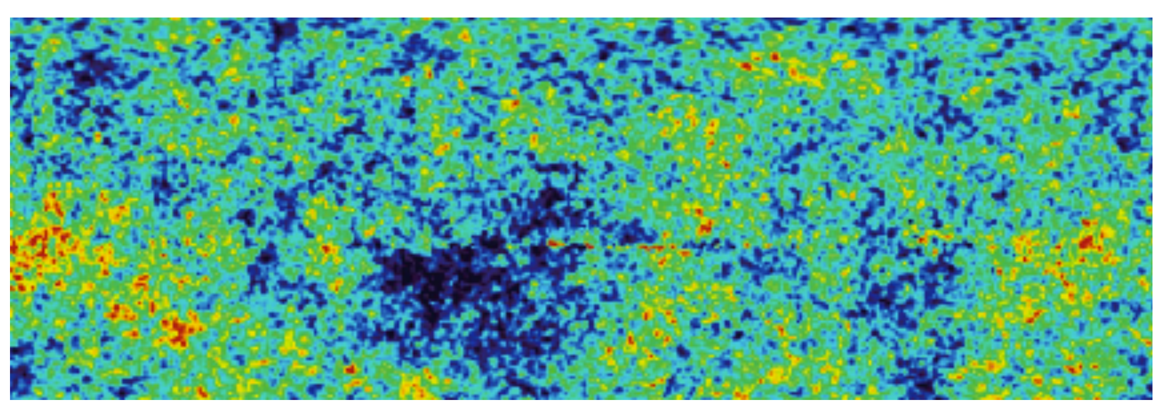
key predictions from cosmic inflation



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

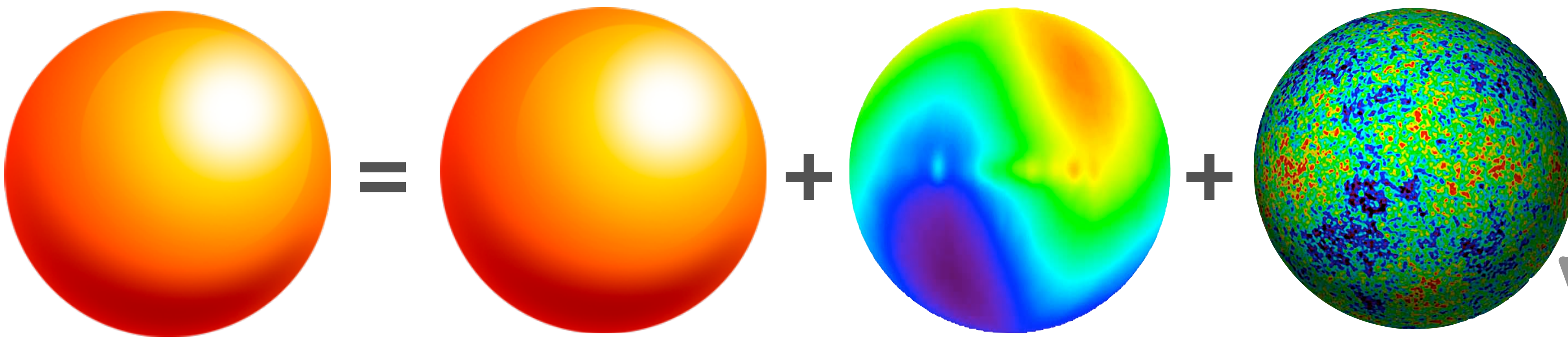
- Fluctuations we observe today in CMB and the matter distribution originate from quantum fluctuations during inflation

$\zeta \longrightarrow$



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

key predictions from cosmic inflation



T = 2.7 K $\Delta T/T \sim 10^{-3}$ $\Delta T/T \sim 10^{-5}$

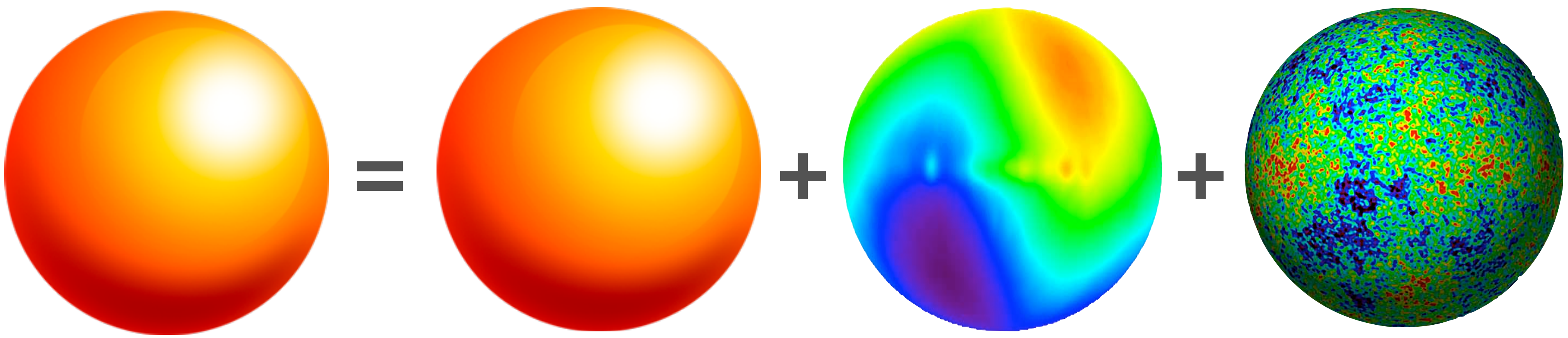
observations are already in remarkable agreement with single-field slow-roll inflation:

- super-horizon fluctuation
- adiabaticity
- gaussianity
- $n_s < 1$

but we want gravitational waves in addition!

e.g. *The Best Inflationary Models After Planck*
J. Martin, C. Ringeval, R. Trotta, V. Vennin, JCAP, 2014
e.g. *Exploring Cosmic Origins with CORE: Inflation*
F. Finelli, M. Bucher et al., JCAP, 2017

key predictions from cosmic inflation



T = 2.7 K $\Delta T/T \sim 10^{-3}$ $\Delta T/T \sim 10^{-5}$

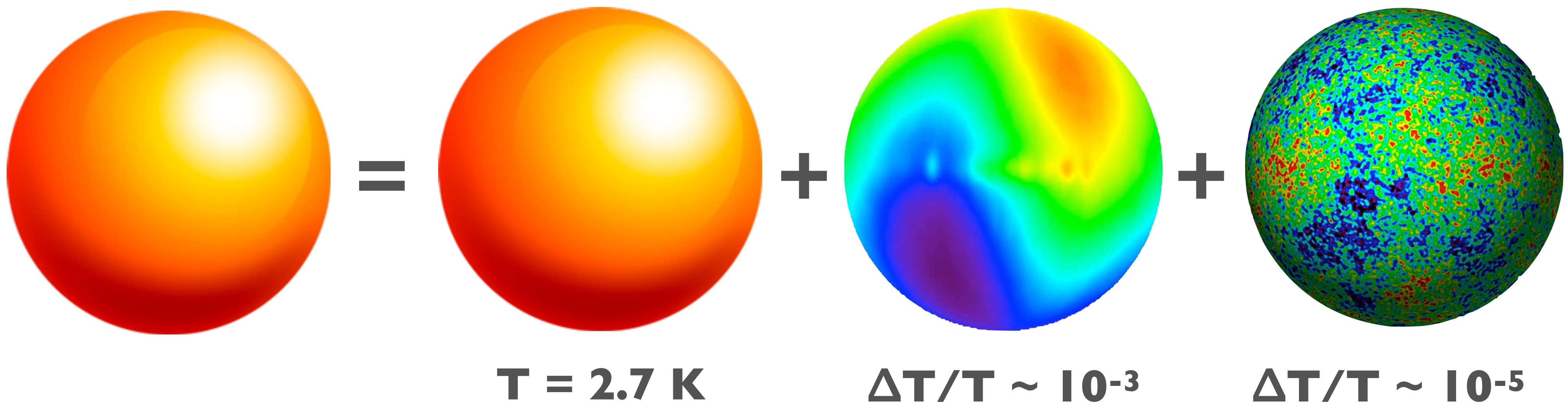
$$d\ell^2 = a^2(t)[1 + 2\zeta(\mathbf{x}, t)][\delta_{ij} + h_{ij}(\mathbf{x}, t)]dx^i dx^j$$

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

$h_{ij} \longrightarrow$

Grishchuk (1974)
Starobinsky (1979)

key predictions from cosmic inflation

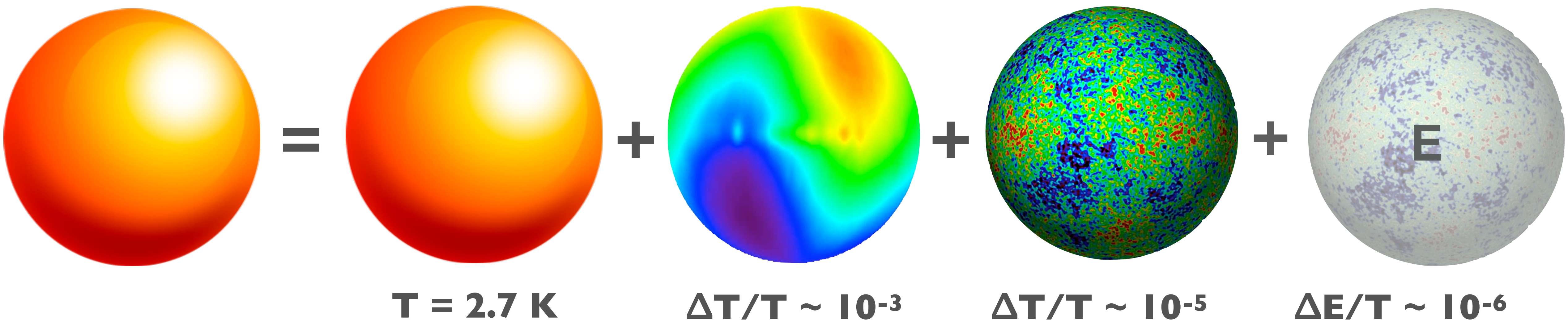


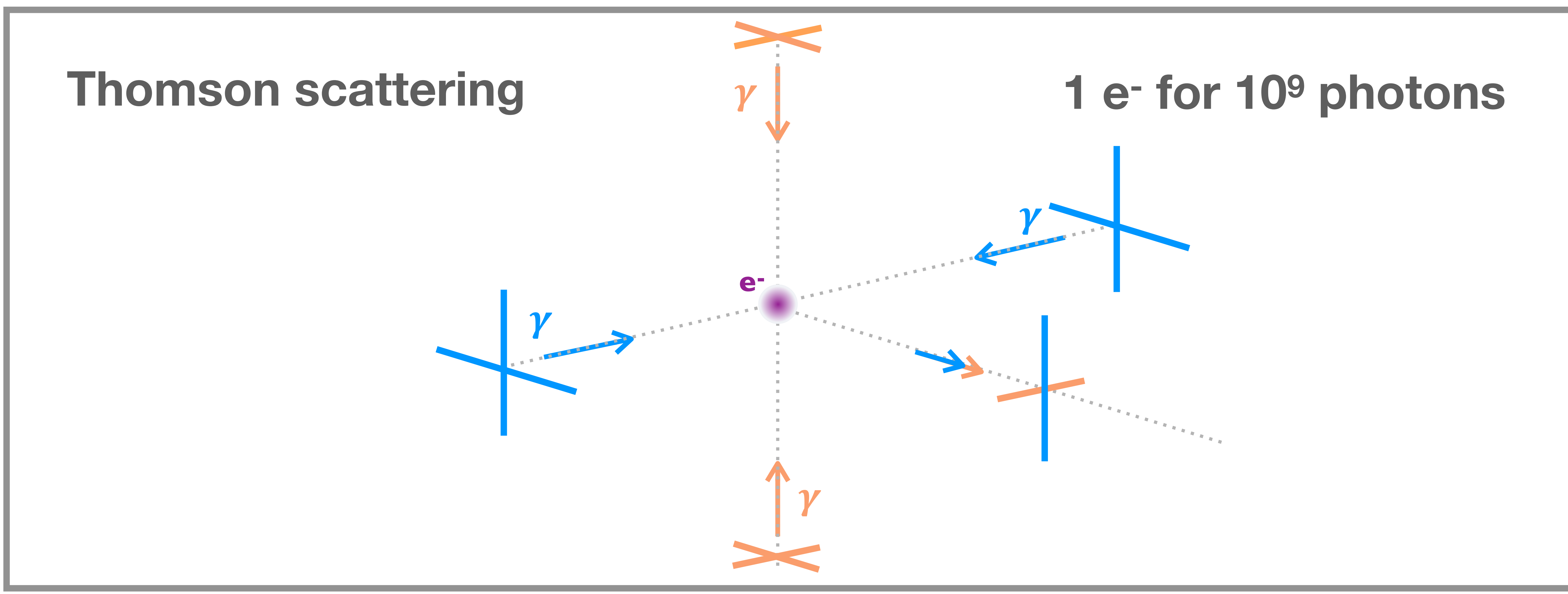
- LIGO/Virgo detected gravitational waves from binary blackholes, with the wavelength of thousands of kilometers
- But the primordial GW affecting the CMB has a wavelength of **billions of light-years**!

how to detect them?

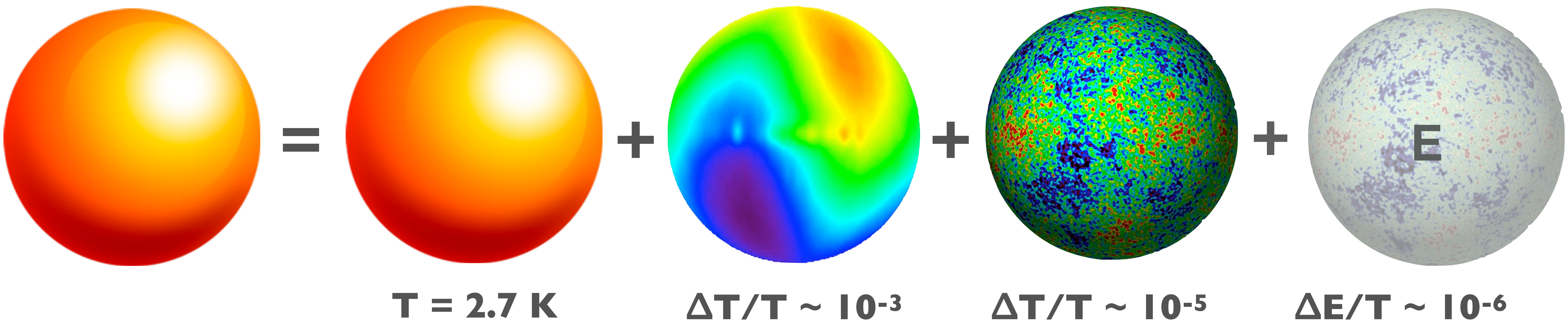
CMB POLARIZATION!

key predictions from cosmic inflation

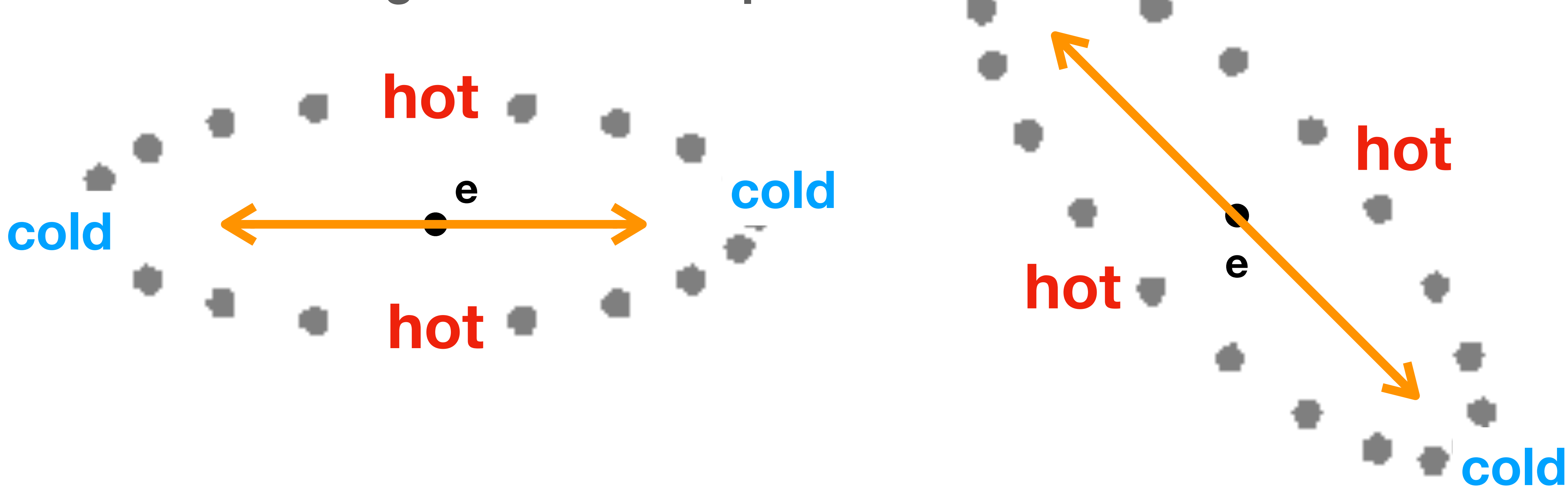




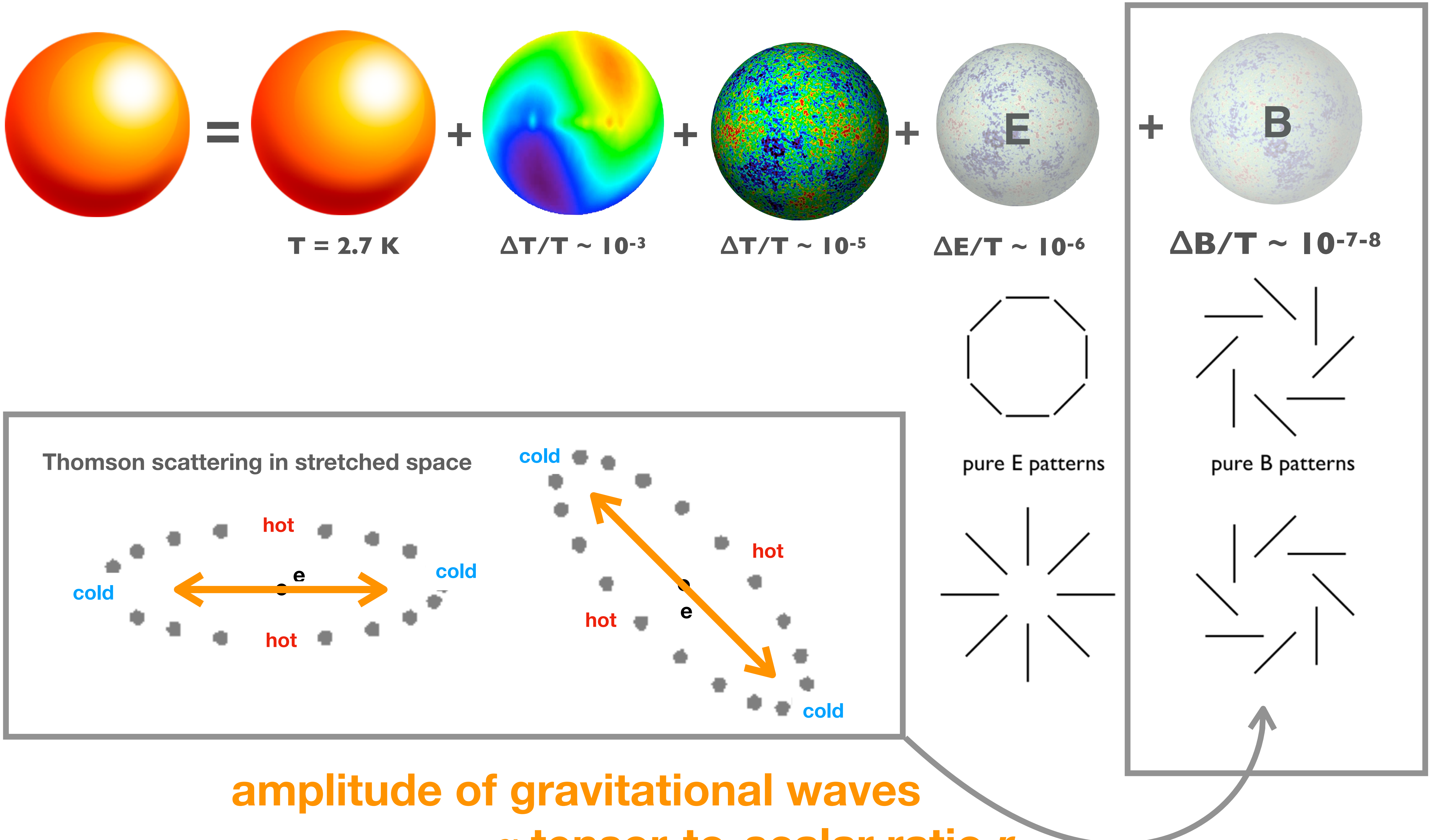
key predictions from cosmic inflation



Thomson scattering in stretched space

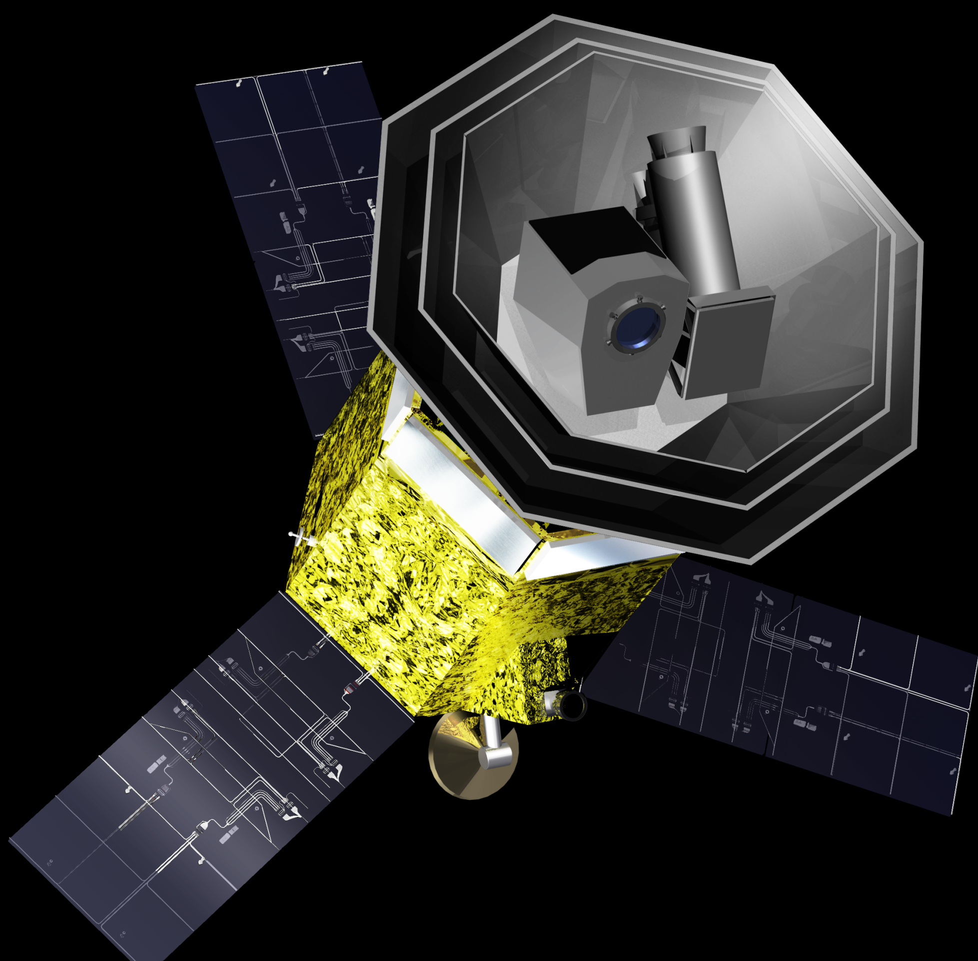


key predictions from cosmic inflation



amplitude of gravitational waves
α tensor-to-scalar ratio *r*


BICEP2 + Keck
WMAP
measurements of *r*
starts being limited
by our own galaxy:
the Milky Way



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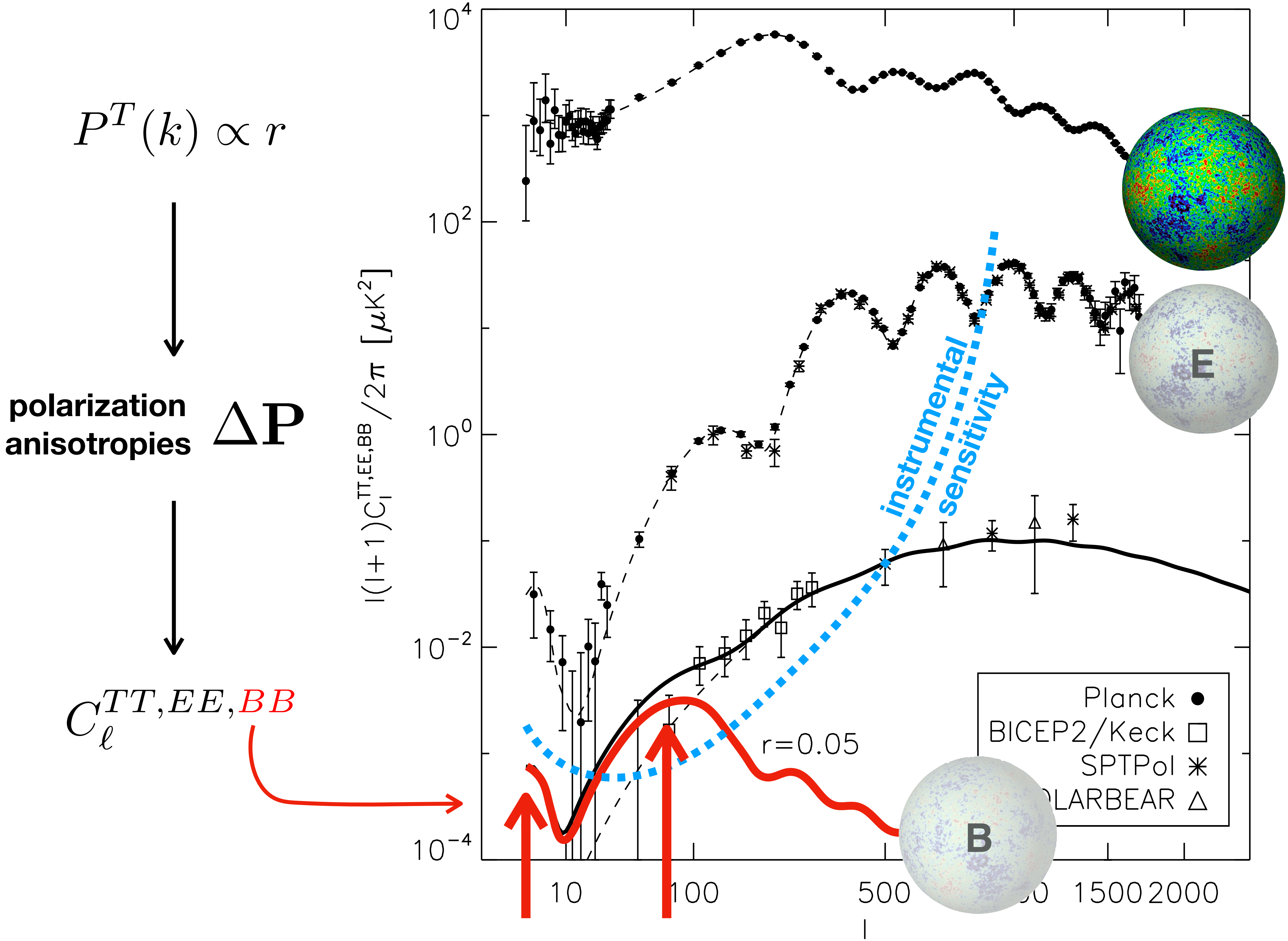
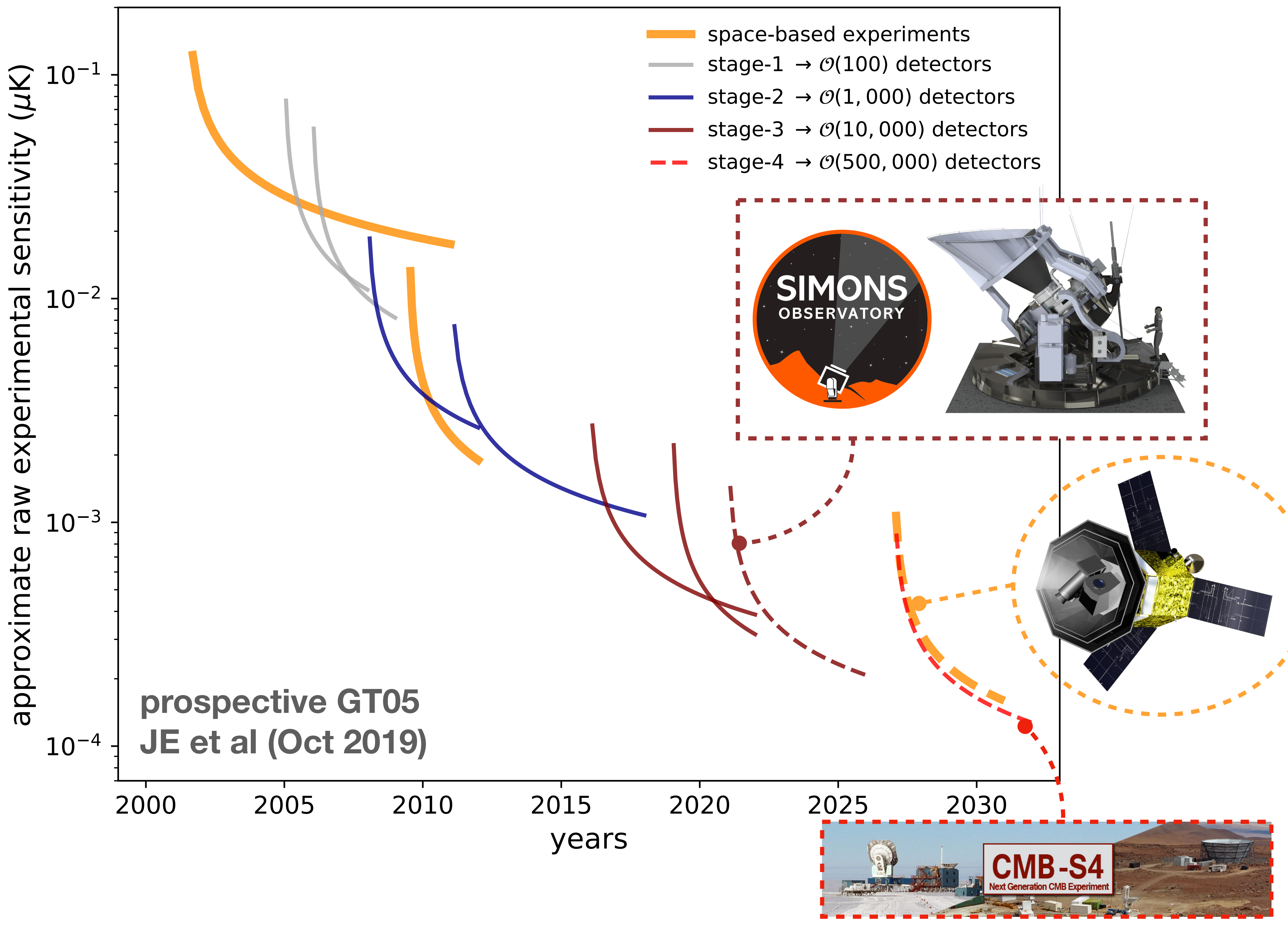
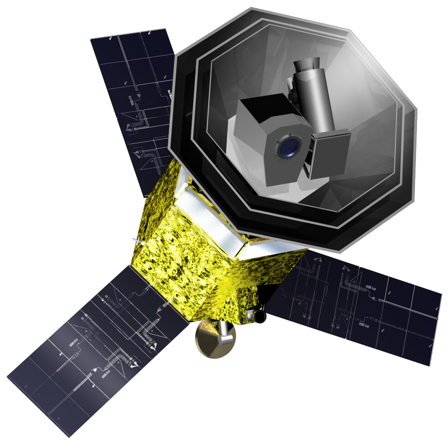


$P^T(k) \propto r$
polarization anisotropies
$\Delta \mathrm{P}$
$C_\ell^{TT,EE,BB}$
$l(l+1)C_l^{TT,EE,BB}/2\pi\ [\mu K^2]$
10^4
10^2
10^0
10^{-2}
10^{-4}
10
100
500
1500
2000
l
instrumental sensitivity
r=0.05
E
B
Planck
BICEP2/Keck
SPTPol
LARBEAR

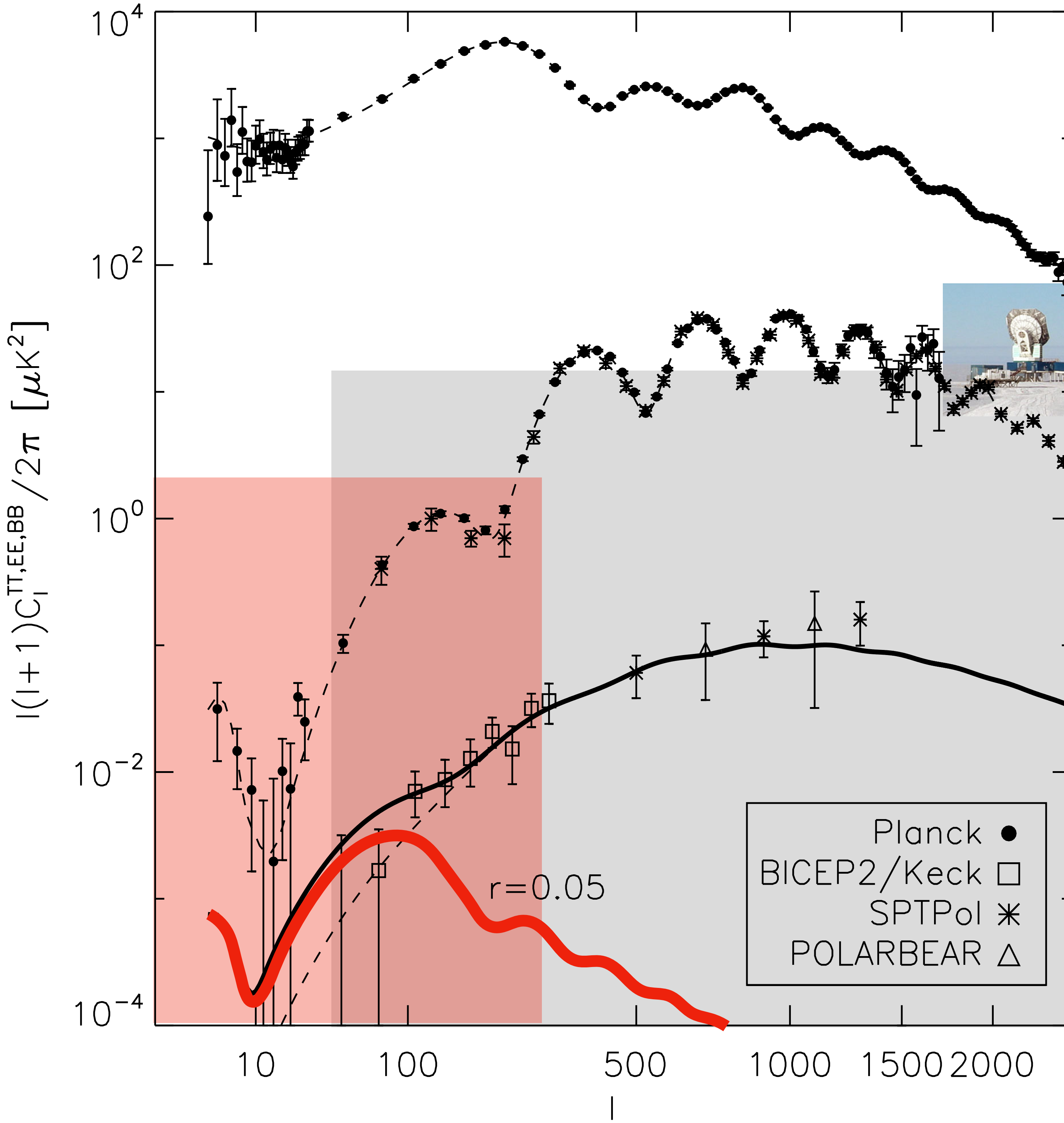
CMB B-modes: race to sensitivity



Space and ground: a powerful duo



<u>LiteBIRD</u>
JAXA-led
focused
mission
σ(r)<0.001
$2 \leq \ell \leq 200$
focused but still with many byproducts



<u>Ground</u>
US-led telescopes on ground
$30 \leq \ell \leq \sim 8000$
e.g. Simons Observatory and CMB-S4

- best cost-effective way to characterize B-modes
- great synergy with two on-going projects

Why space?

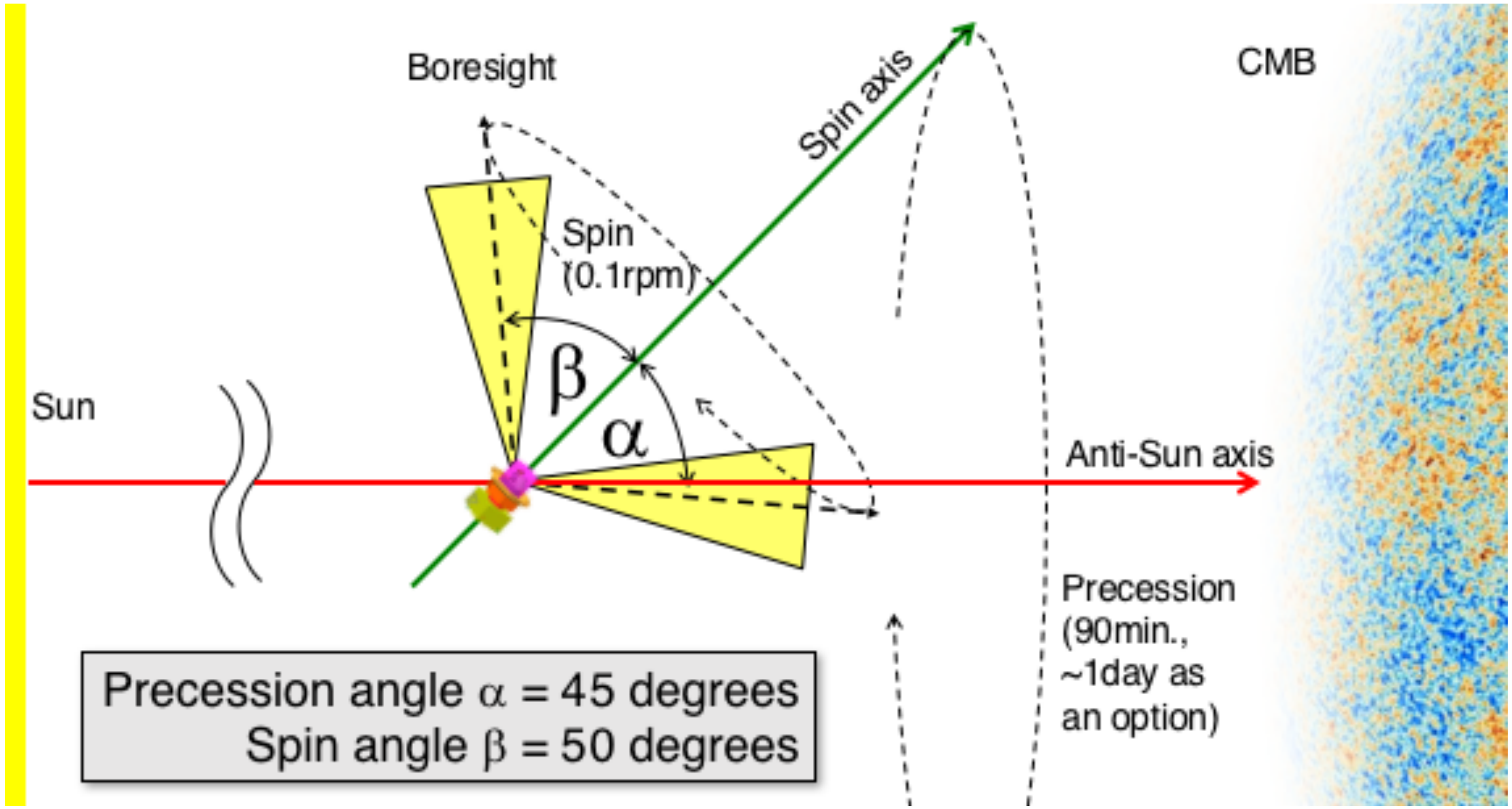
- **Superb environment !**
  - No statistical/systematic uncertainty due to atmosphere
  - No limitation on the choice of observing bands (except CO lines), important for foreground separation
  - No ground pickup

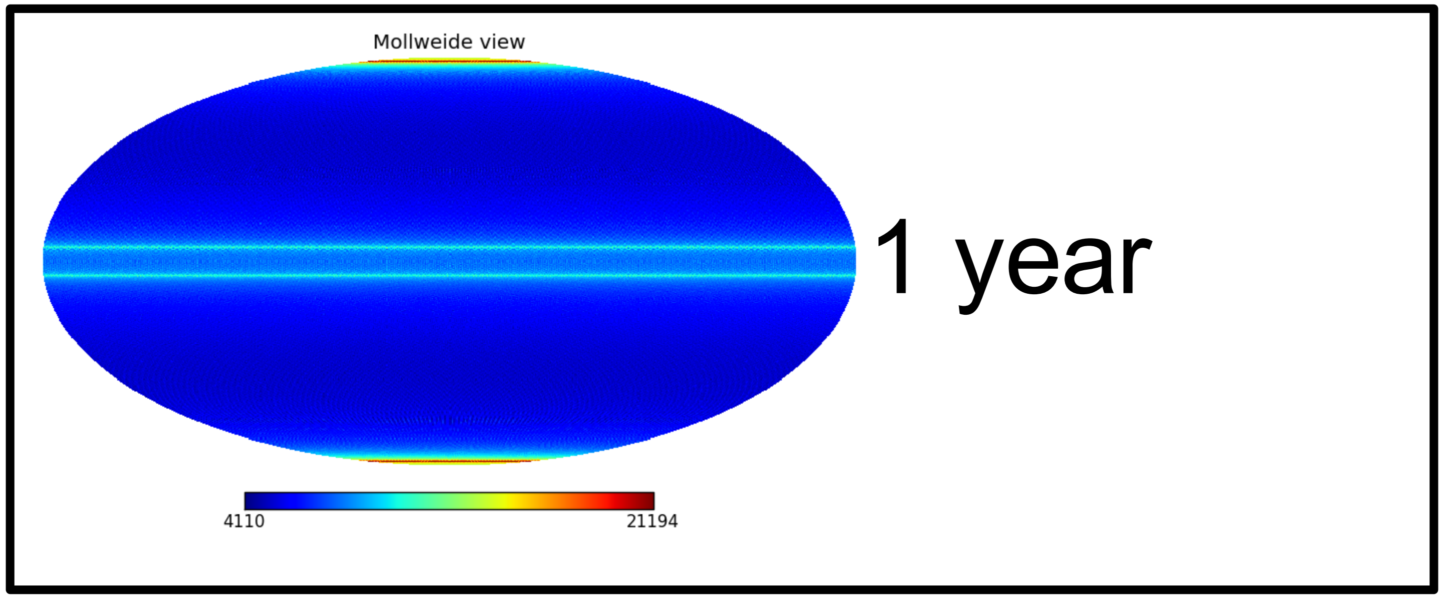
Rule of thumb: 1,000 detectors in space ~ 100,000 detectors on ground

- **Only way to access lowest multipoles w/ $\delta r \sim O(0.001)$**
  - Both B-mode bumps need to be observed for the firm confirmation of Cosmic Inflation → we need measurements from space.
- **Complementarity with ground-based CMB projects**
  - Foreground information from space will help foreground cleaning for ground CMB data
  - High multipole information from ground will help to “delens” space CMB data

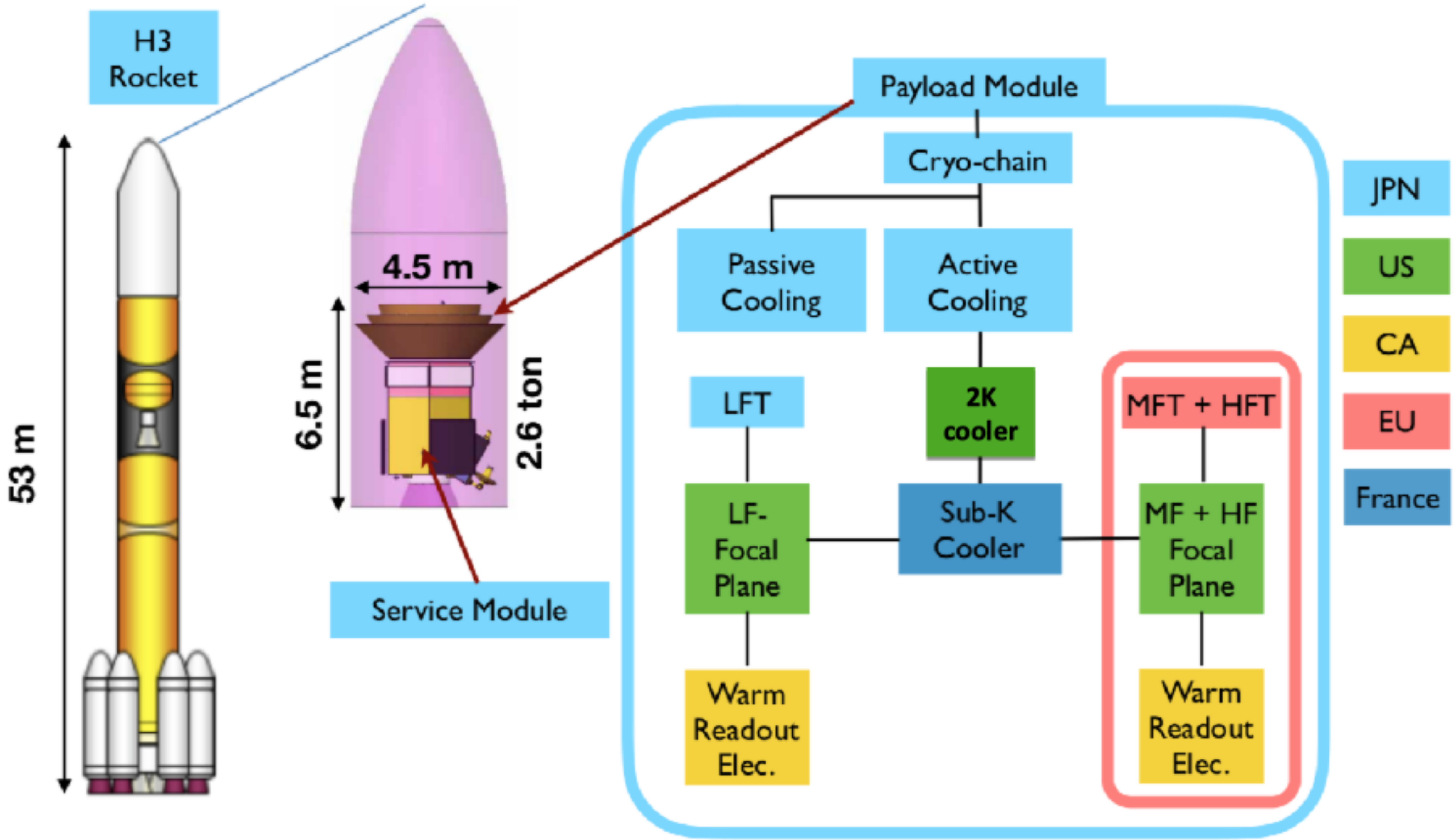
LiteBIRD operation

orbit: Sun-Earth L2 Lissajous





LiteBIRD instruments



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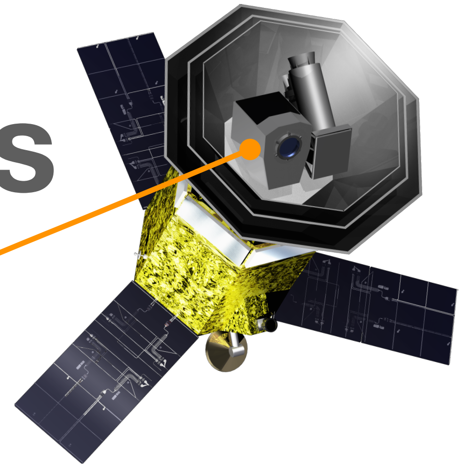
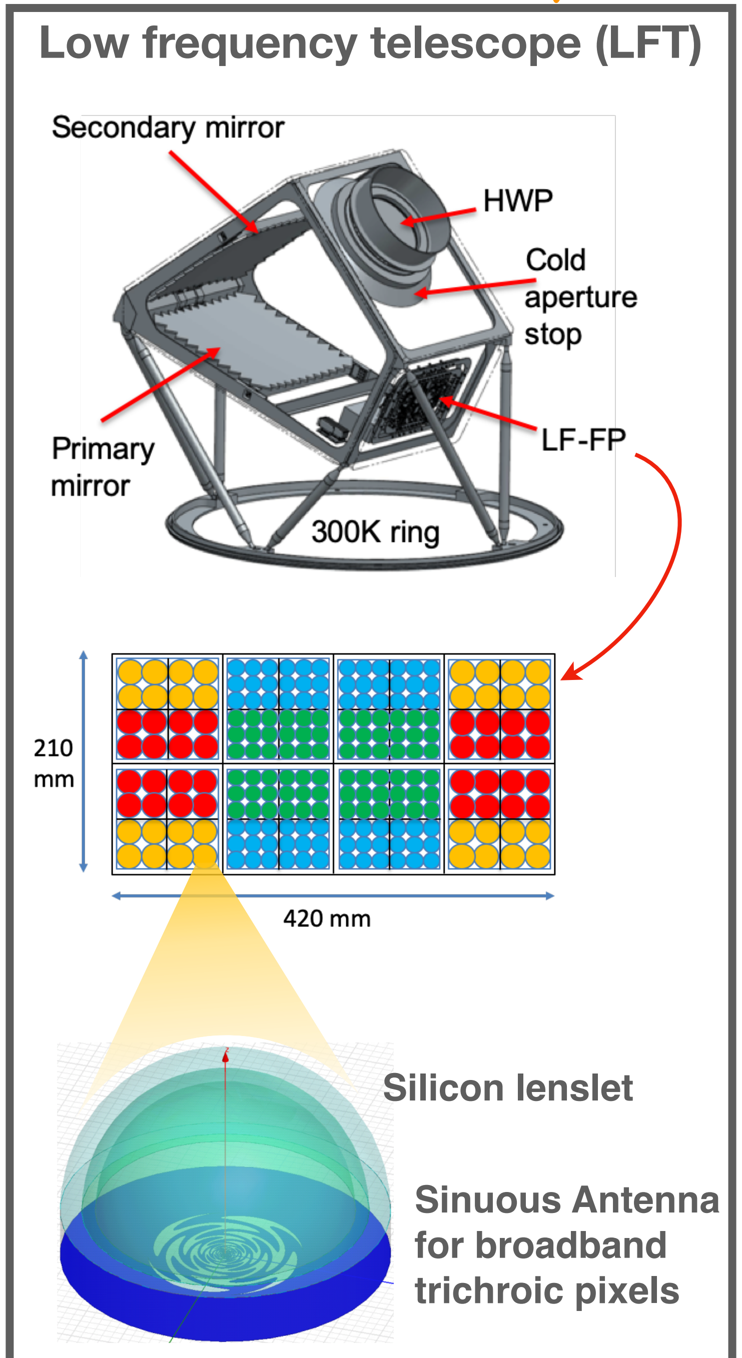
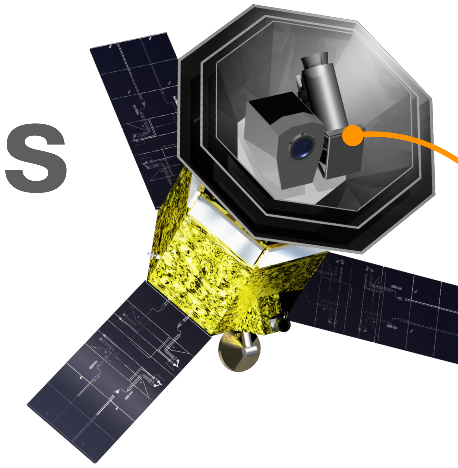


- **Three telescopes with TES arrays**
- Polarization modulator with a rotating half-wave plate (HWP) for 1/f noise & systematics reduction
- Cryogenic system for 0.1K base temperature



- Crossed Dragone
- Aperture diameter: 400 mm
- Angular resolution: 20 -70 arcmin.
- Freq. coverage: 34 - 161GHz
- Field of view: 20 deg x 10 deg
- F#3.0 & crossed angle of 90 degree
- All 5K parts are made of Aluminum ➔ less than 150 kg
- New mirror design (anamorphic aspherical surfaces)

LiteBIRD instruments



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Two F/2.3 refractive telescopes:

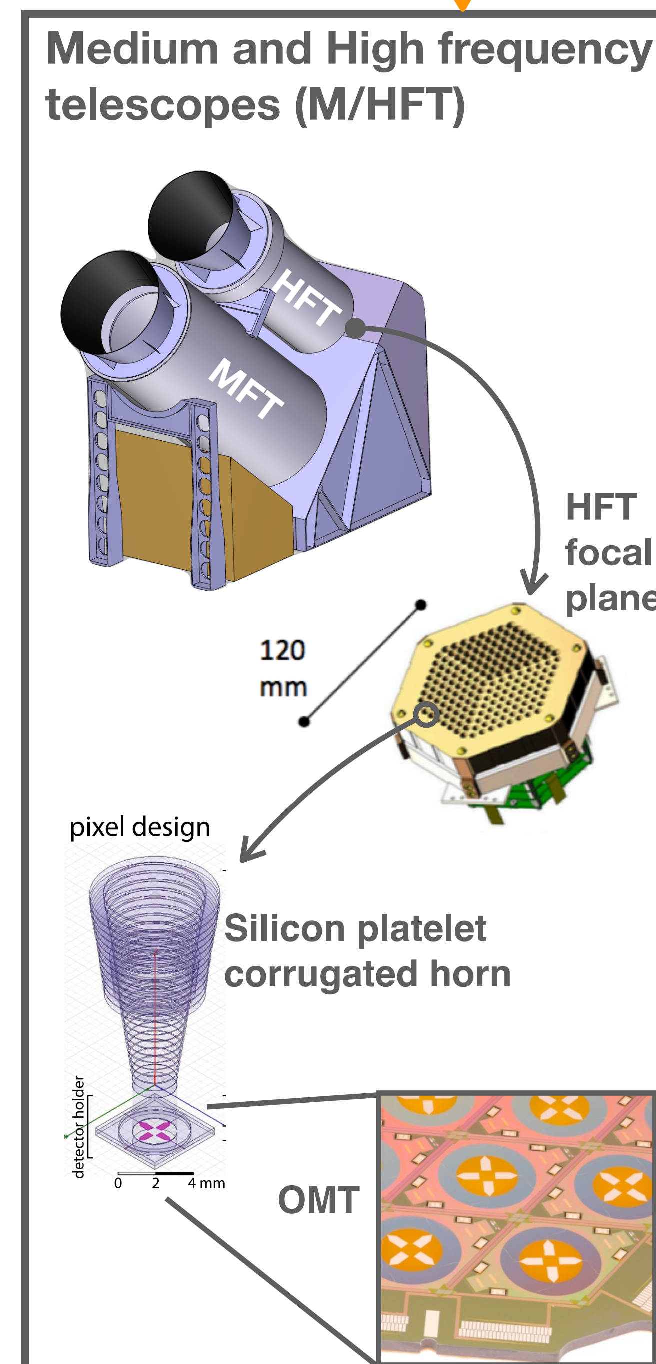
- 89-270 GHz
- 238-448 GHz

Apertures:

- 30mm
- 20mm

FoV: Φ 20mm

- Transmissive metal-mesh HWP
- Silicon lenses



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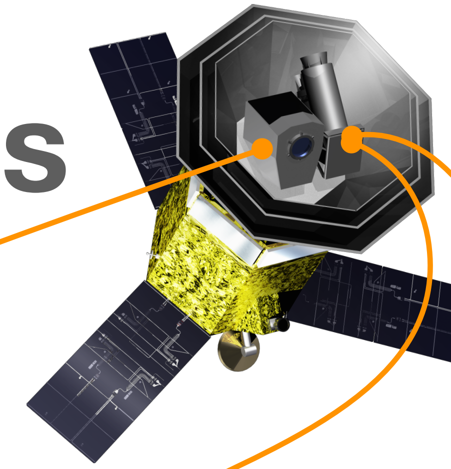

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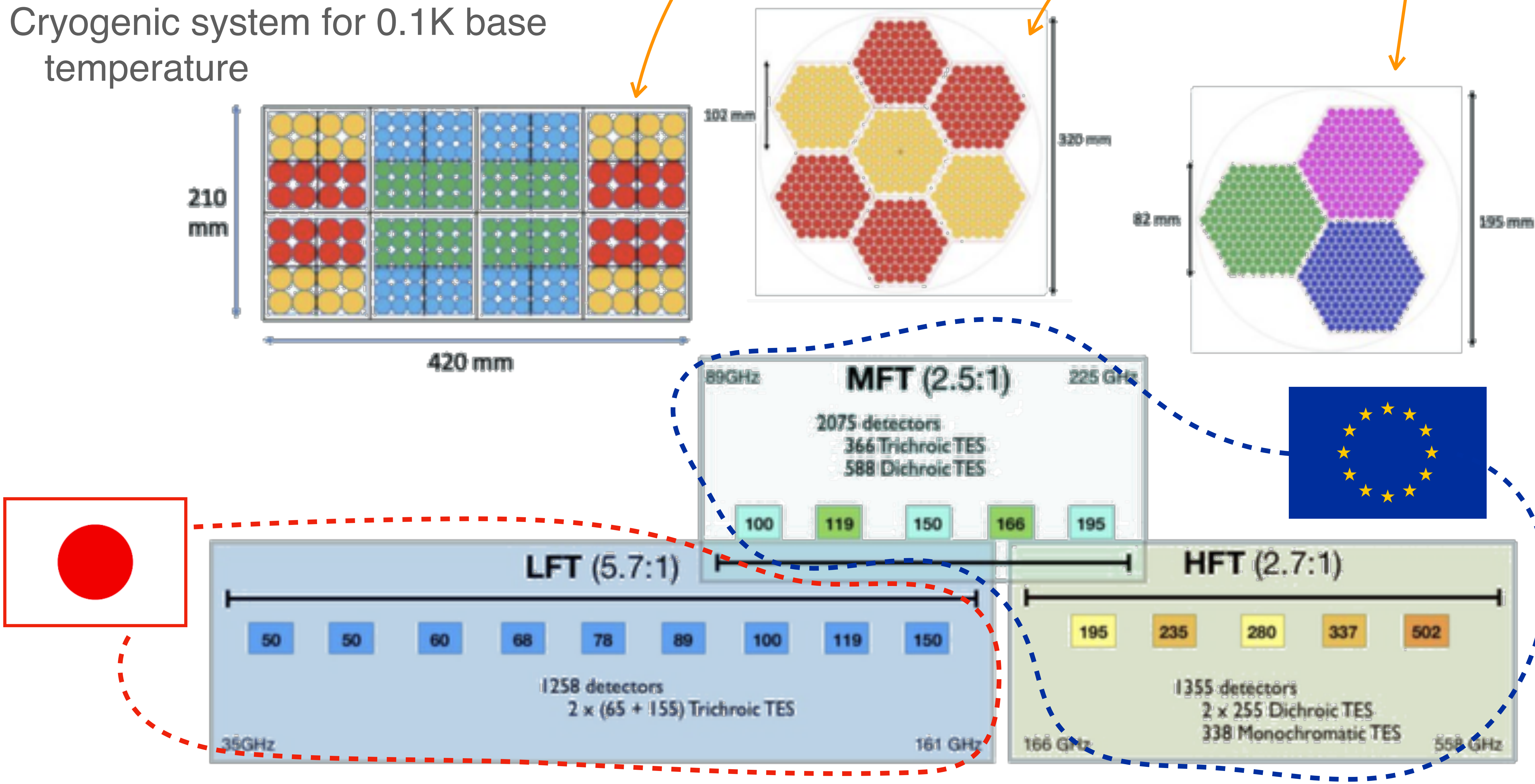

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- **Polarization modulator with a rotating half-wave plate (HWP) for 1/f noise & systematics reduction**
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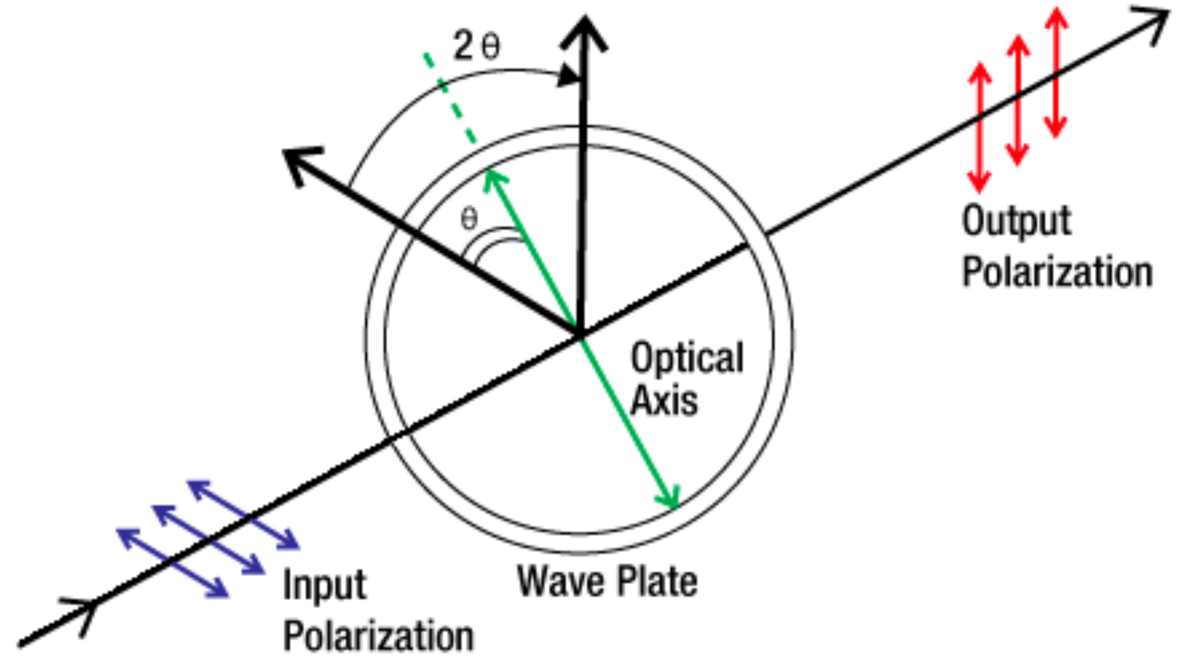
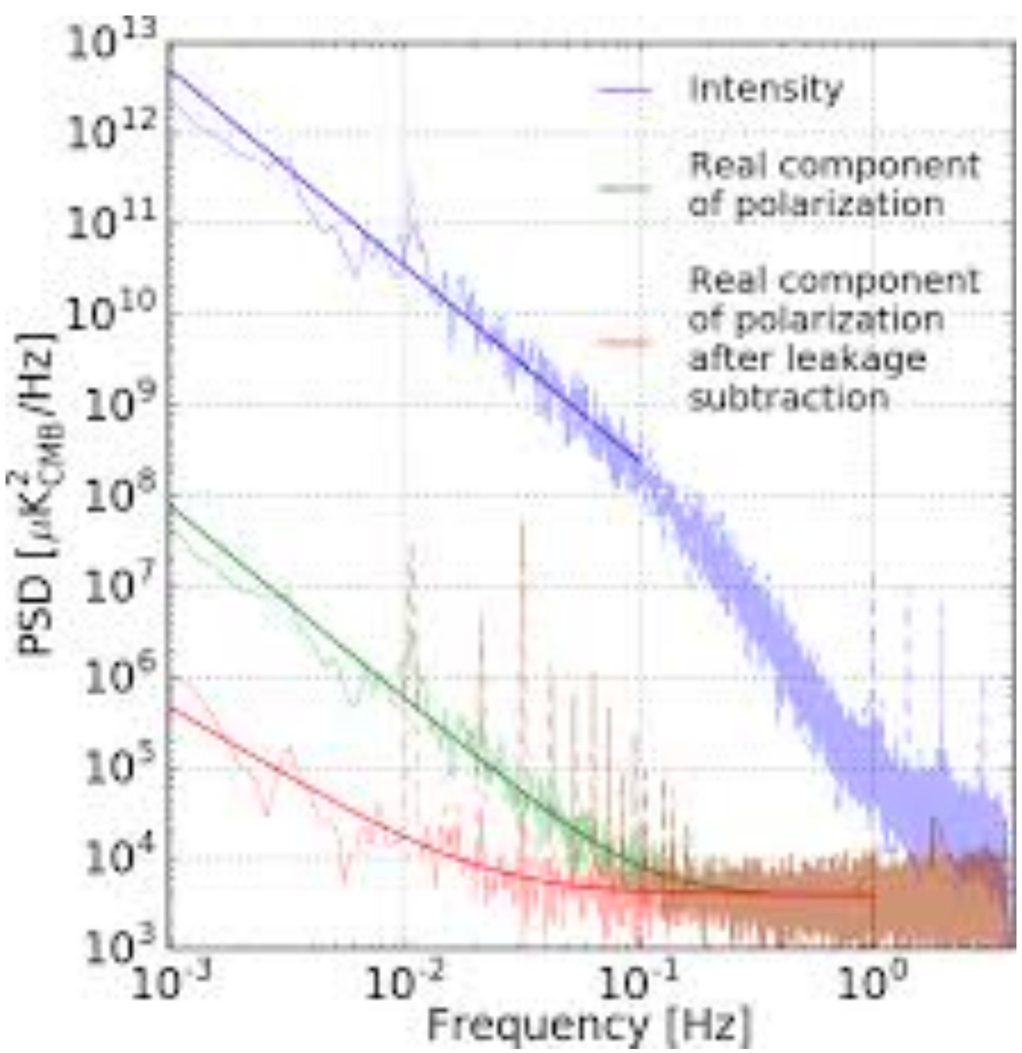
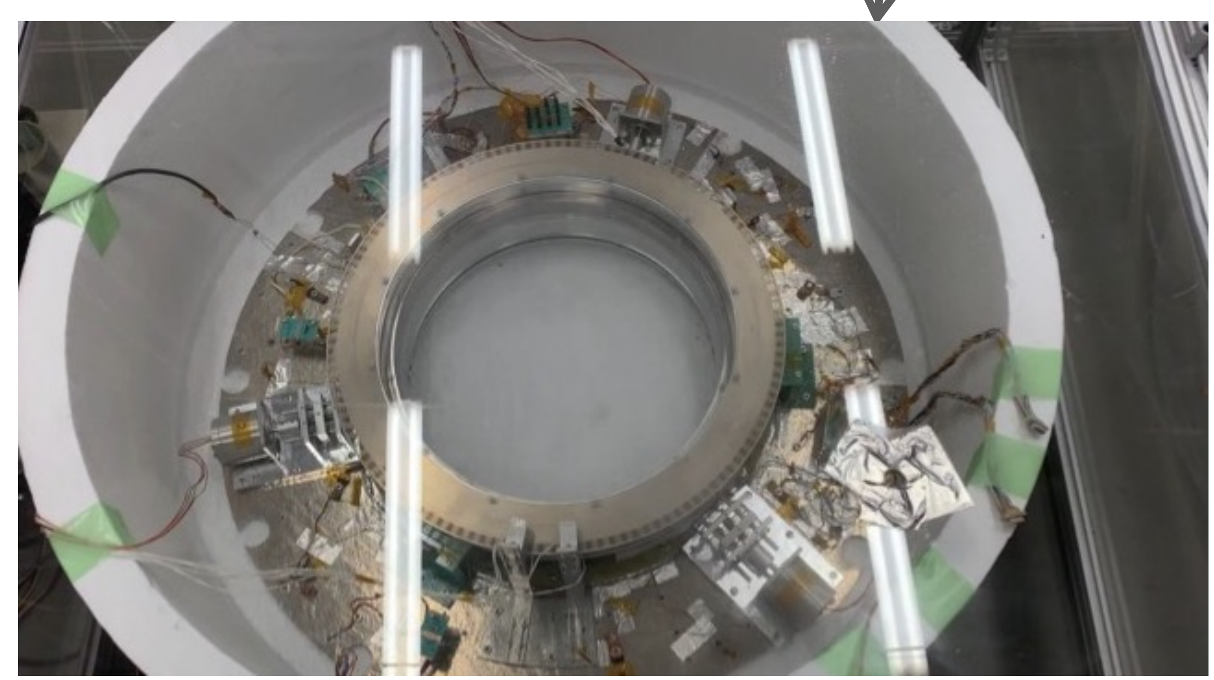




Superconducting magnetic bearing system operational in a 4K cryostat.
We observed the stable rotation at cryogenic temperature (<10K).



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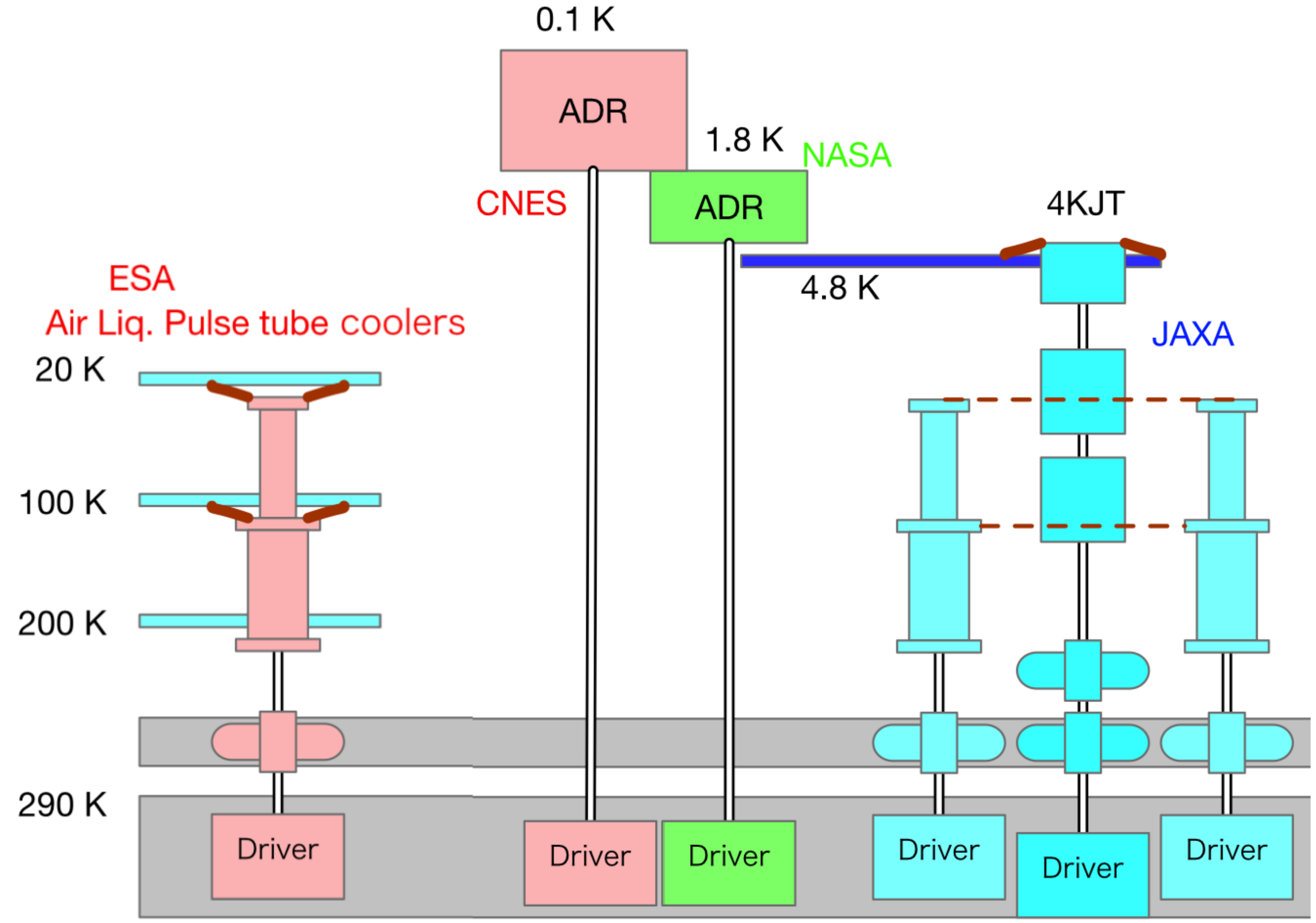

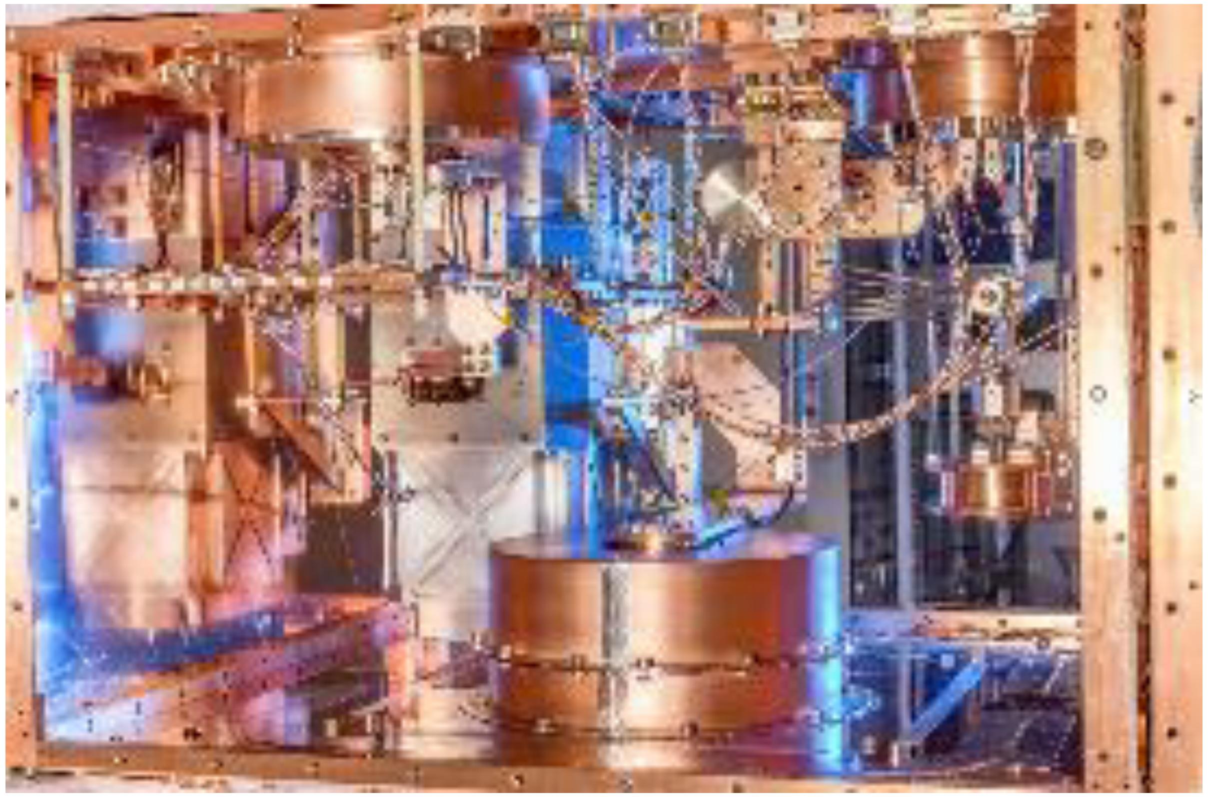

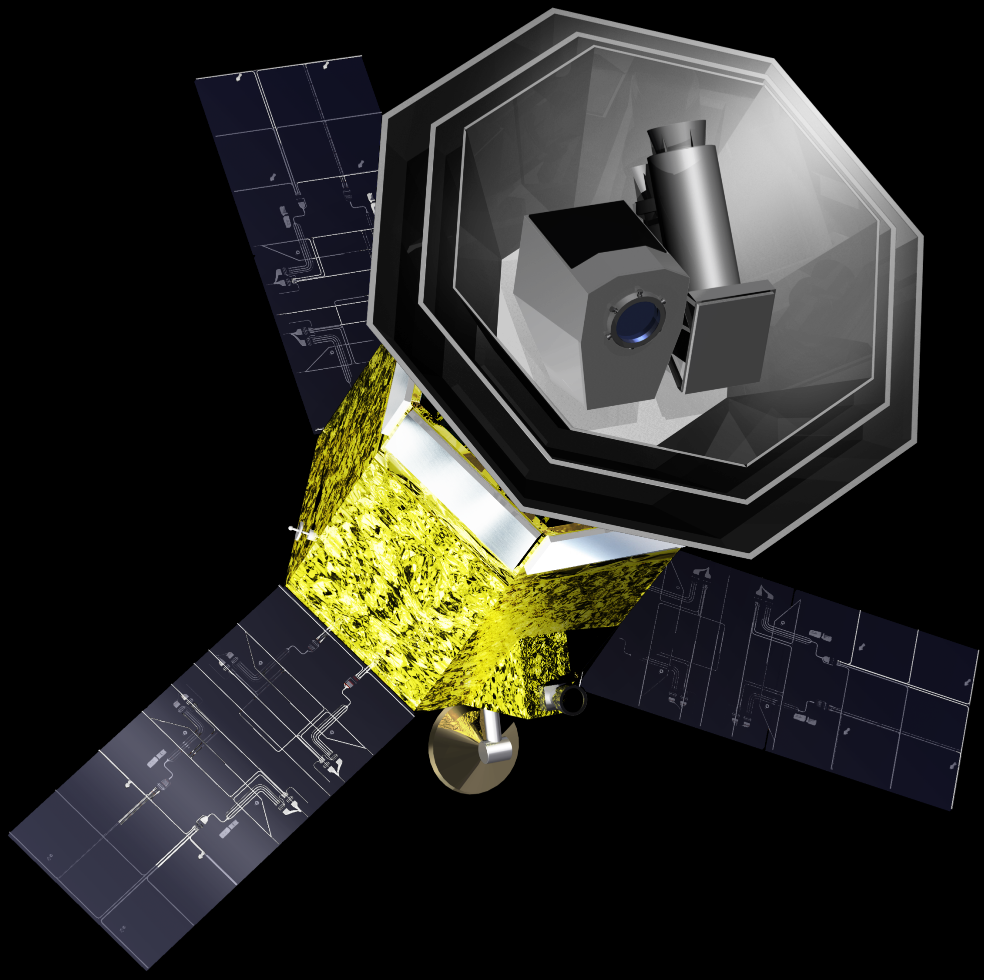

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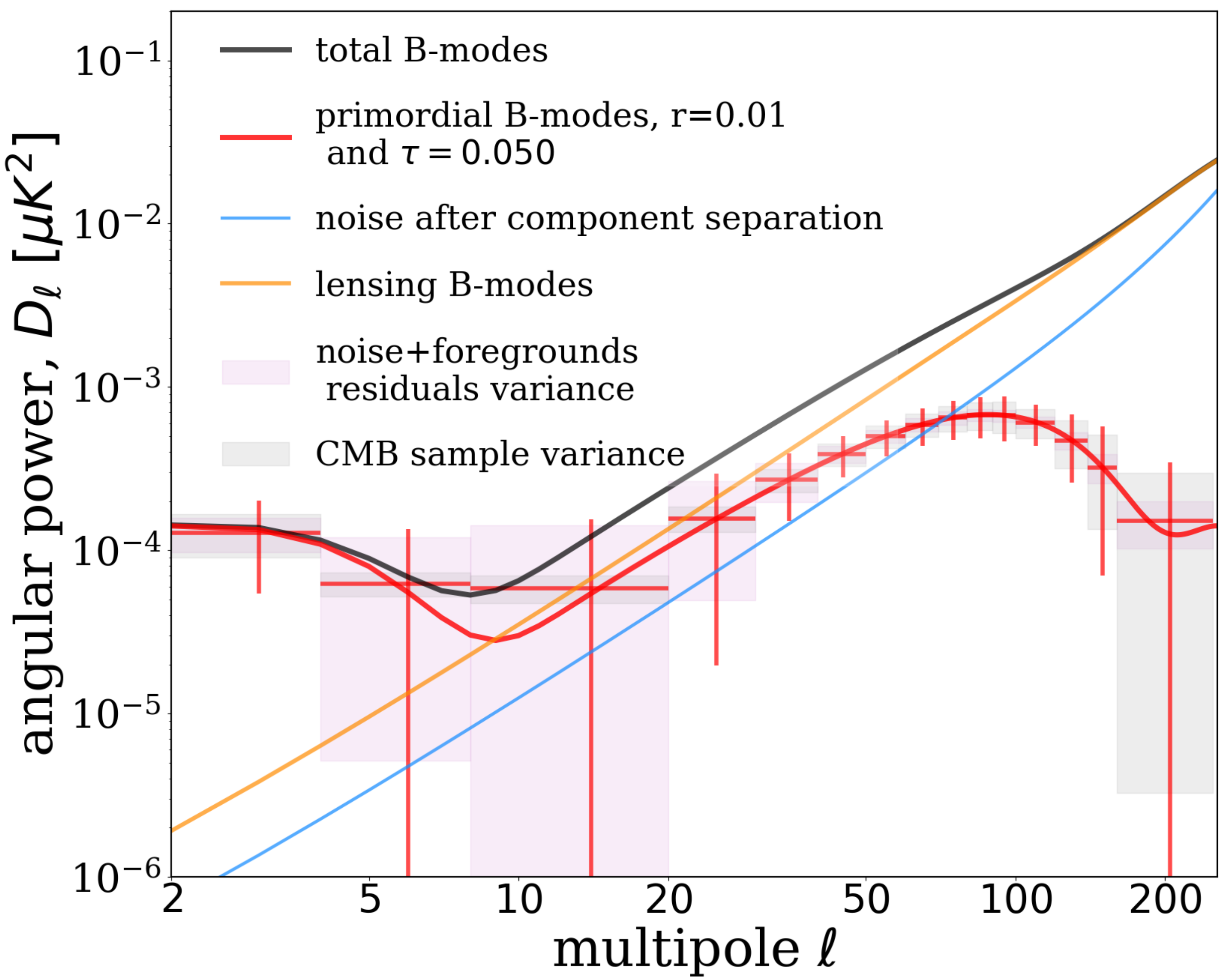
LiteBIRD science goals

Full success:

- **total uncertainty δr < 0.001 (for r=0)**
- **> 5σ observation for each bump (for r ≥ 0.01)**



Rationale

- Large discovery potential for 0.005 < r < 0.05
- Simplest and well-motivated $R+R^2$ "Starobinsky" model will be tested.
- Clean sweep of single-field models with characteristic field variation scale of inflaton potential greater than M_{pl} (A. Linde, JCAP 1702 (2017) no.02, 006

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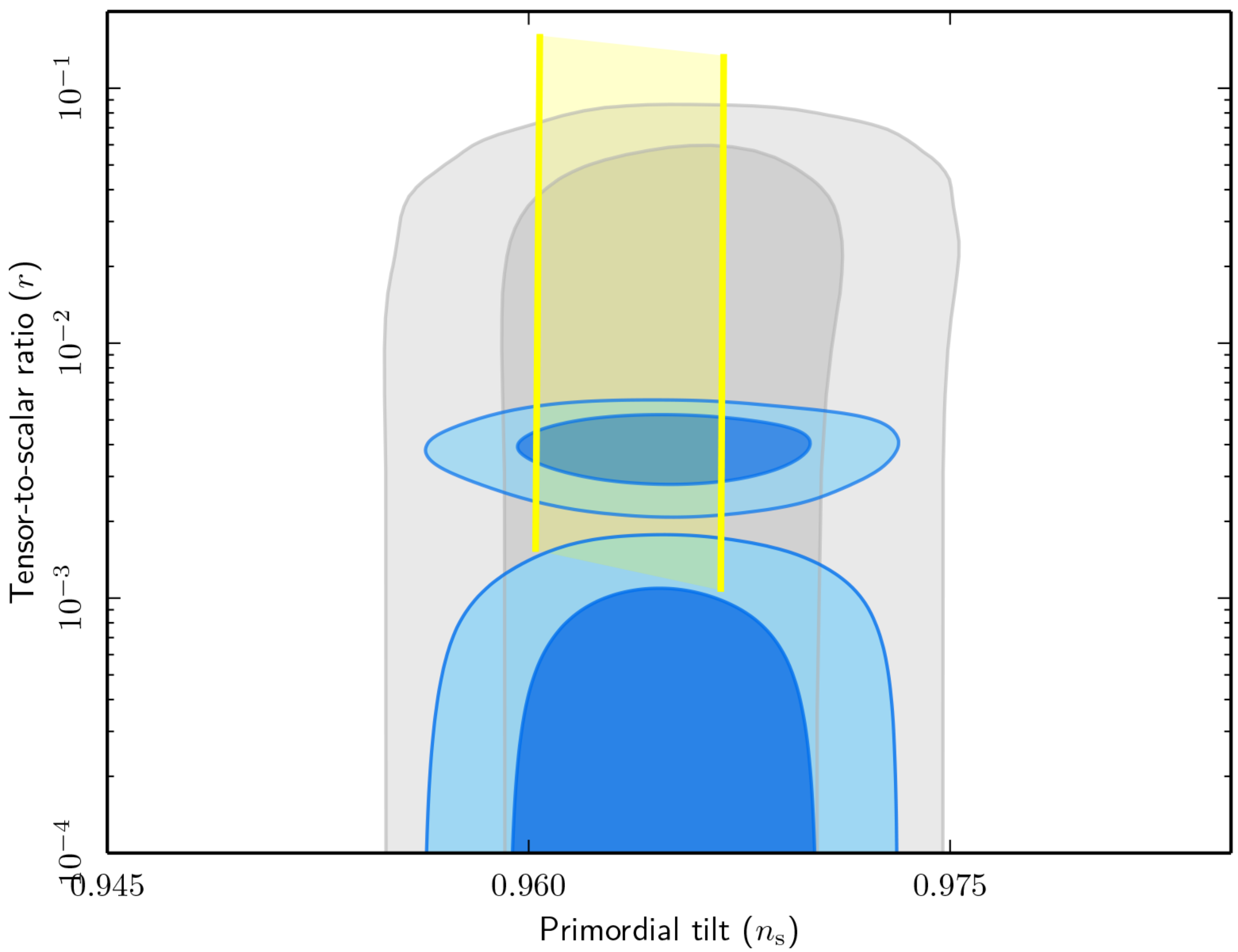

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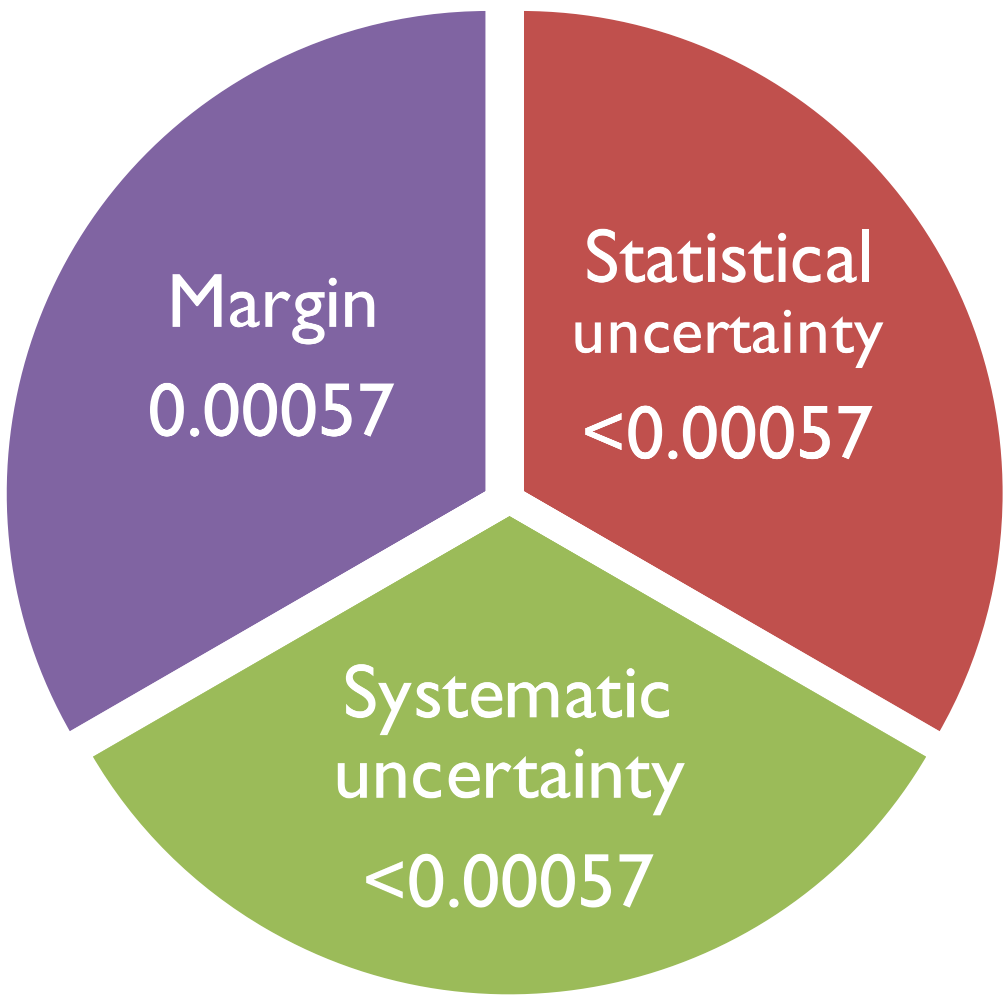
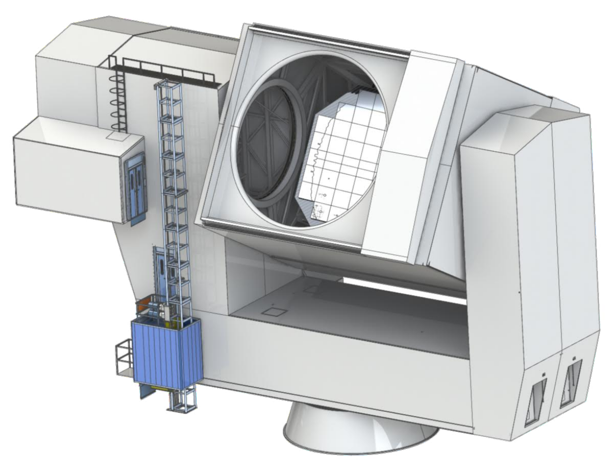


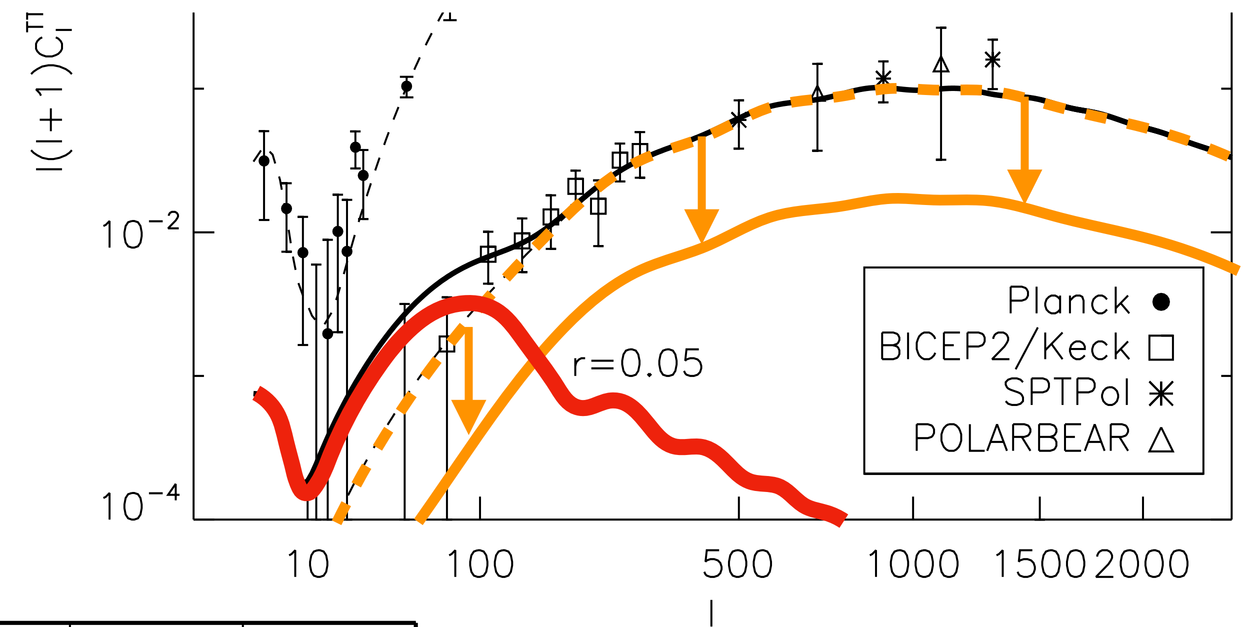
Statistical uncertainty includes
- foreground cleaning residuals
- lensing B-mode power
- 1/f noise

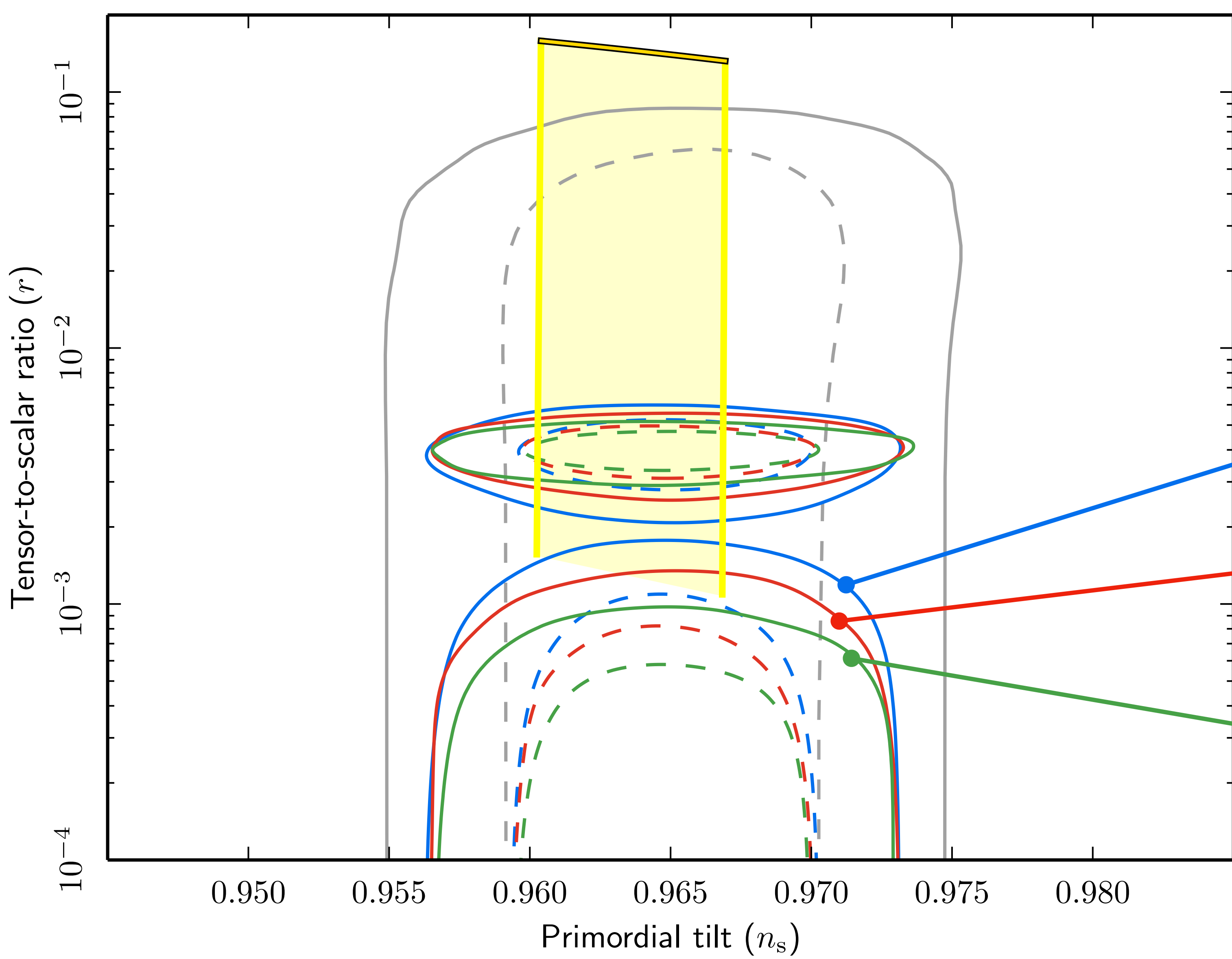
Systematic uncertainty includes
- Bias from 1/f noise
- Polarization efficiency & knowledge
- Disturbance to instrument
- Off-boresight pick up
- Calibration accuracy

LiteBIRD — extra success



delensing





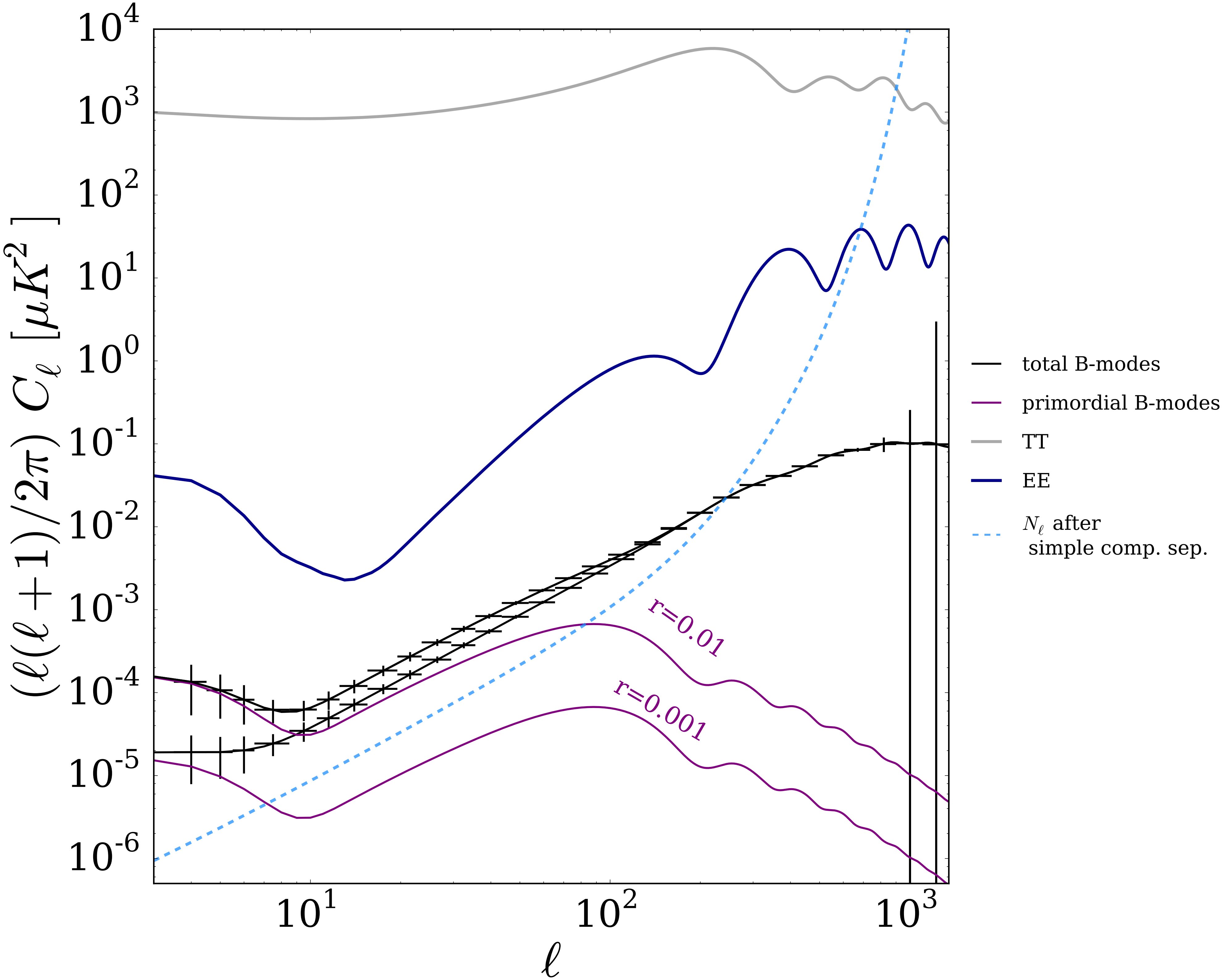
Aiming at detection with >5σ in case of Starobinsky model

1. Baseline

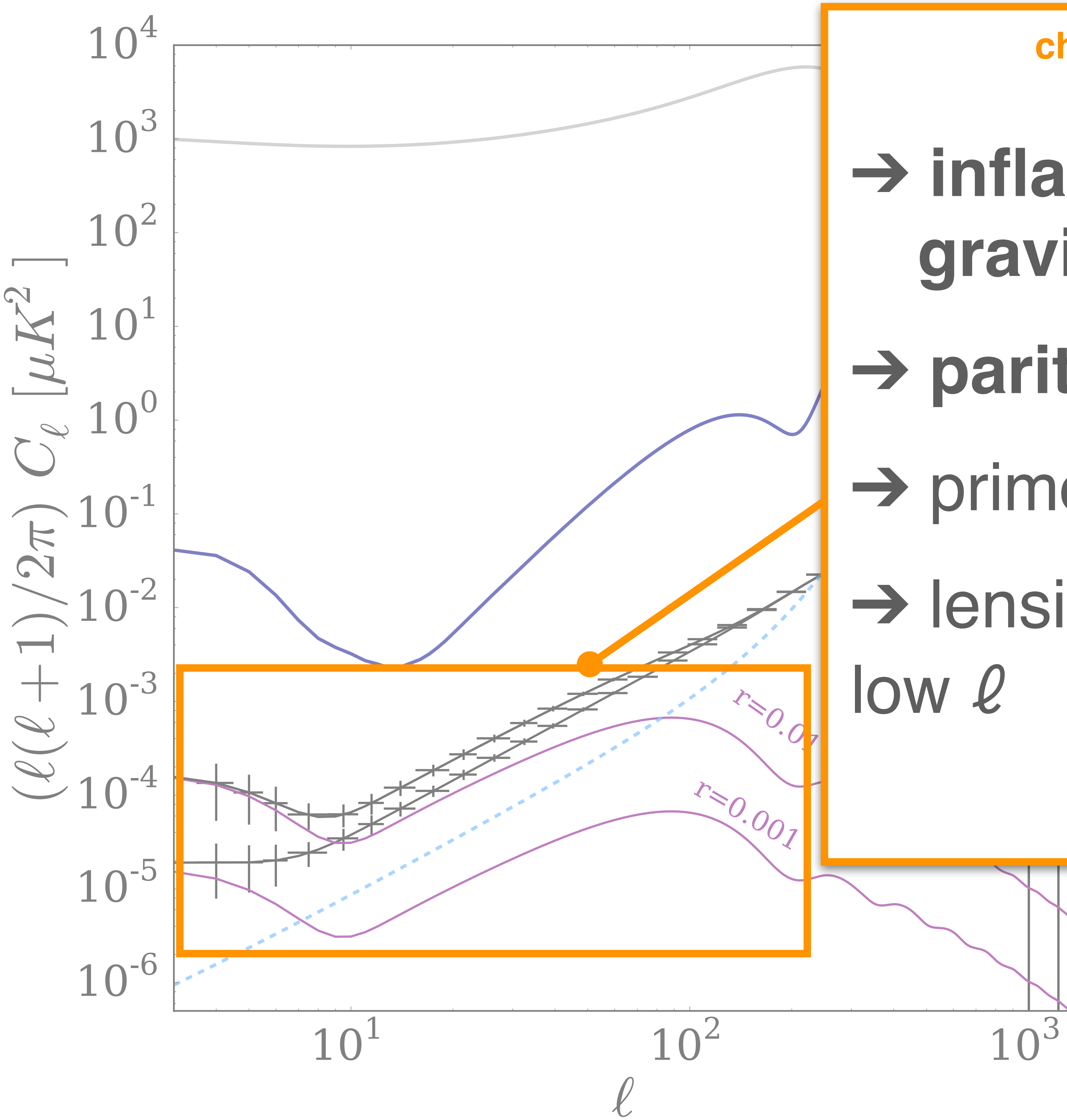
2. Adding delensing w/ Planck CIB & WISE

3. adding 2. and extra foreground cleaning w/ high-resolution ground CMB data

LiteBIRD —science outcomes



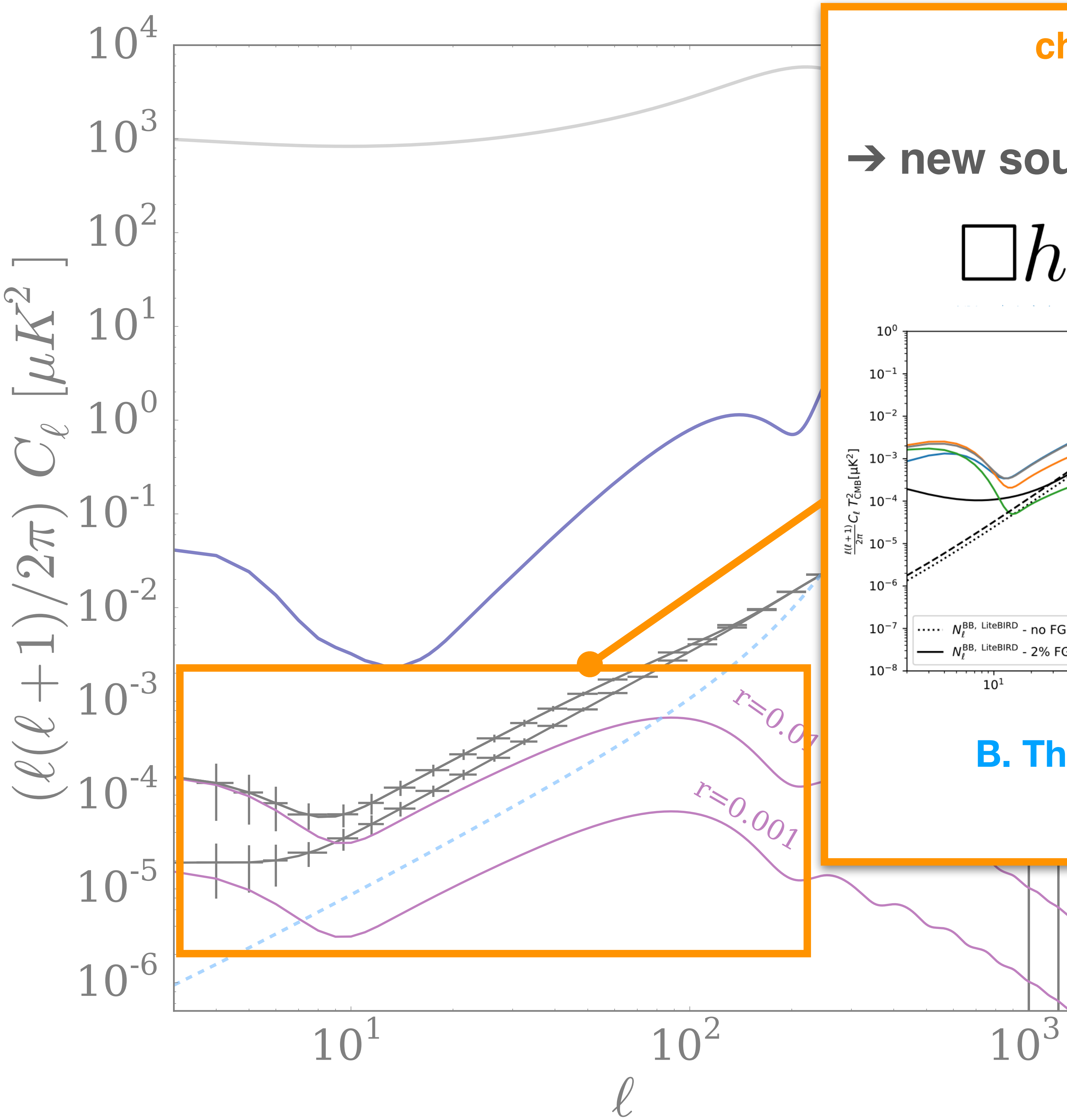
LiteBIRD —science outcomes



characterizing primordial BB

- ➔ **inflation** and **quantum gravity** {r, n_T}
- ➔ **parity violation** in gravity
- ➔ primordial **magnetic field**
- ➔ lensing B-mode to very low ℓ

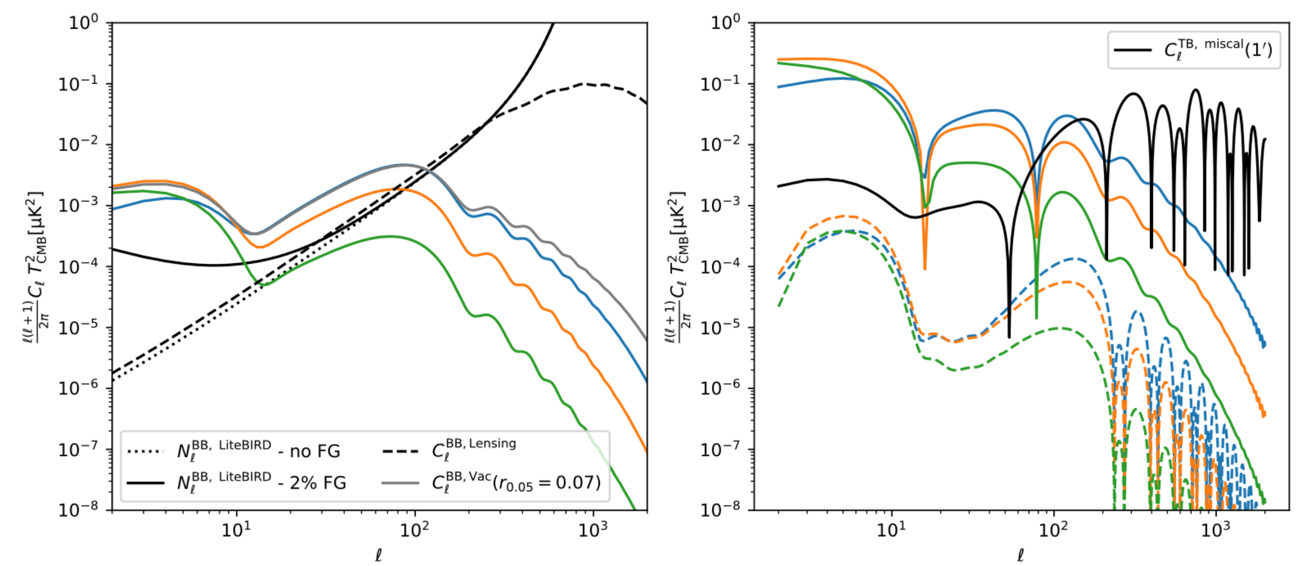
LiteBIRD —science outcomes



characterizing primordial BB

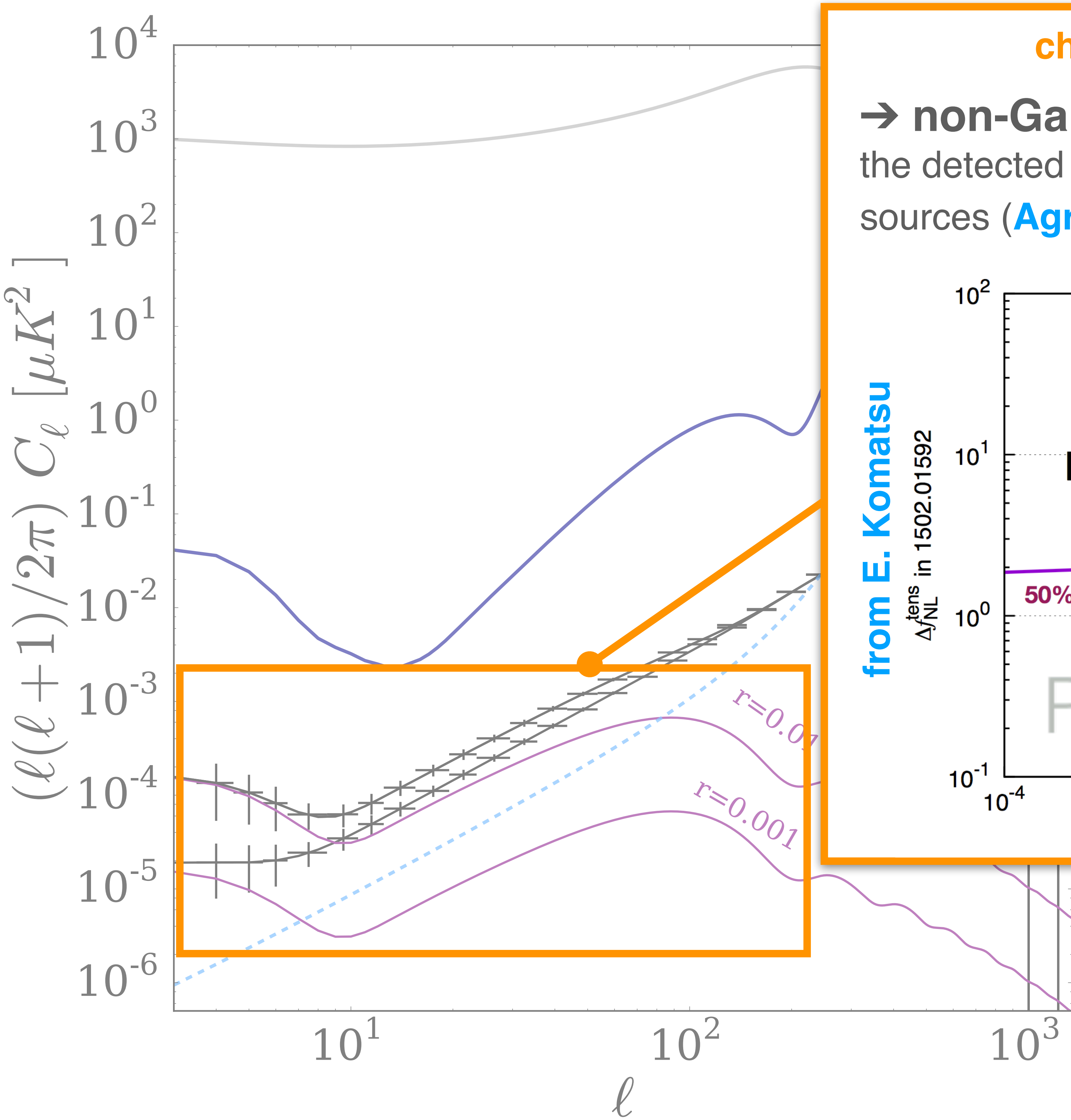
→ **new source** fields for gravitational waves

$$\Box h_{ij} = -16\pi G \pi_{ij}$$



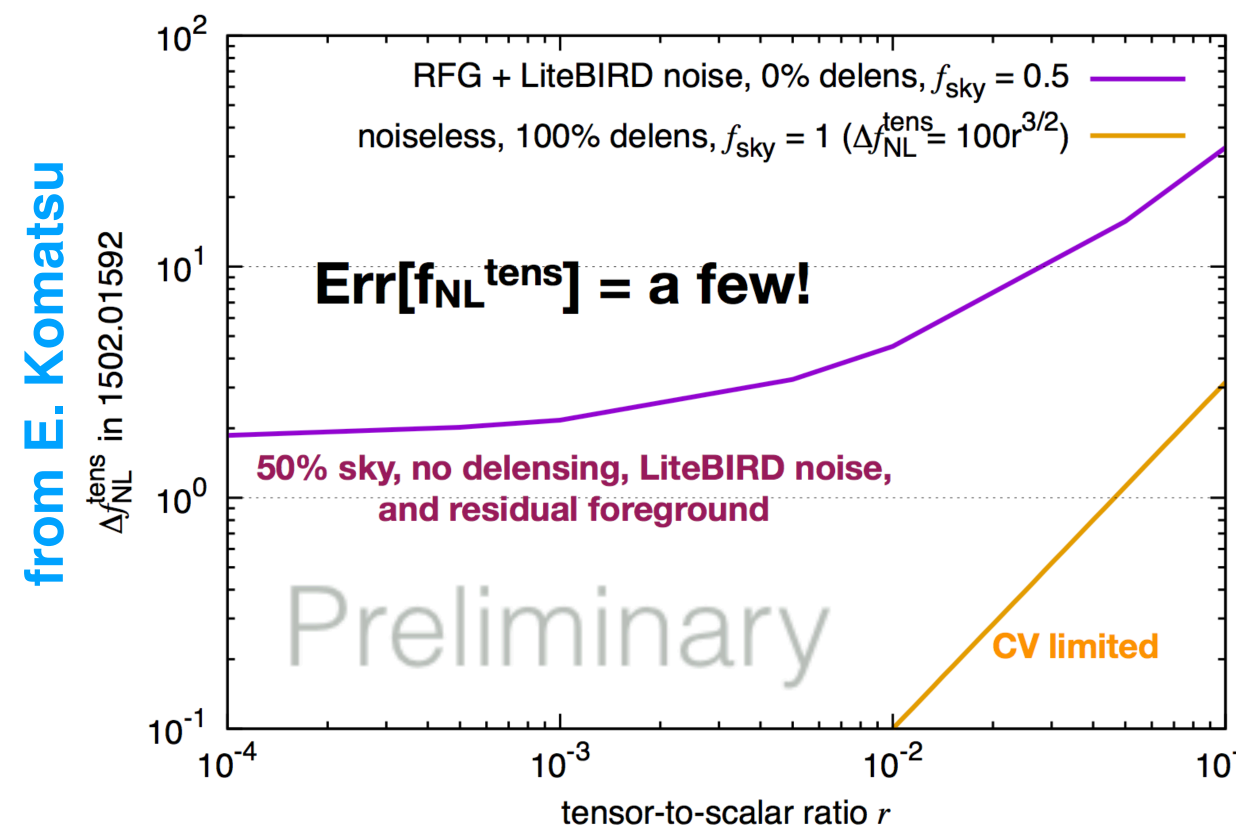
B. Thorne et al (2017) — 1707.03240

LiteBIRD —science outcomes

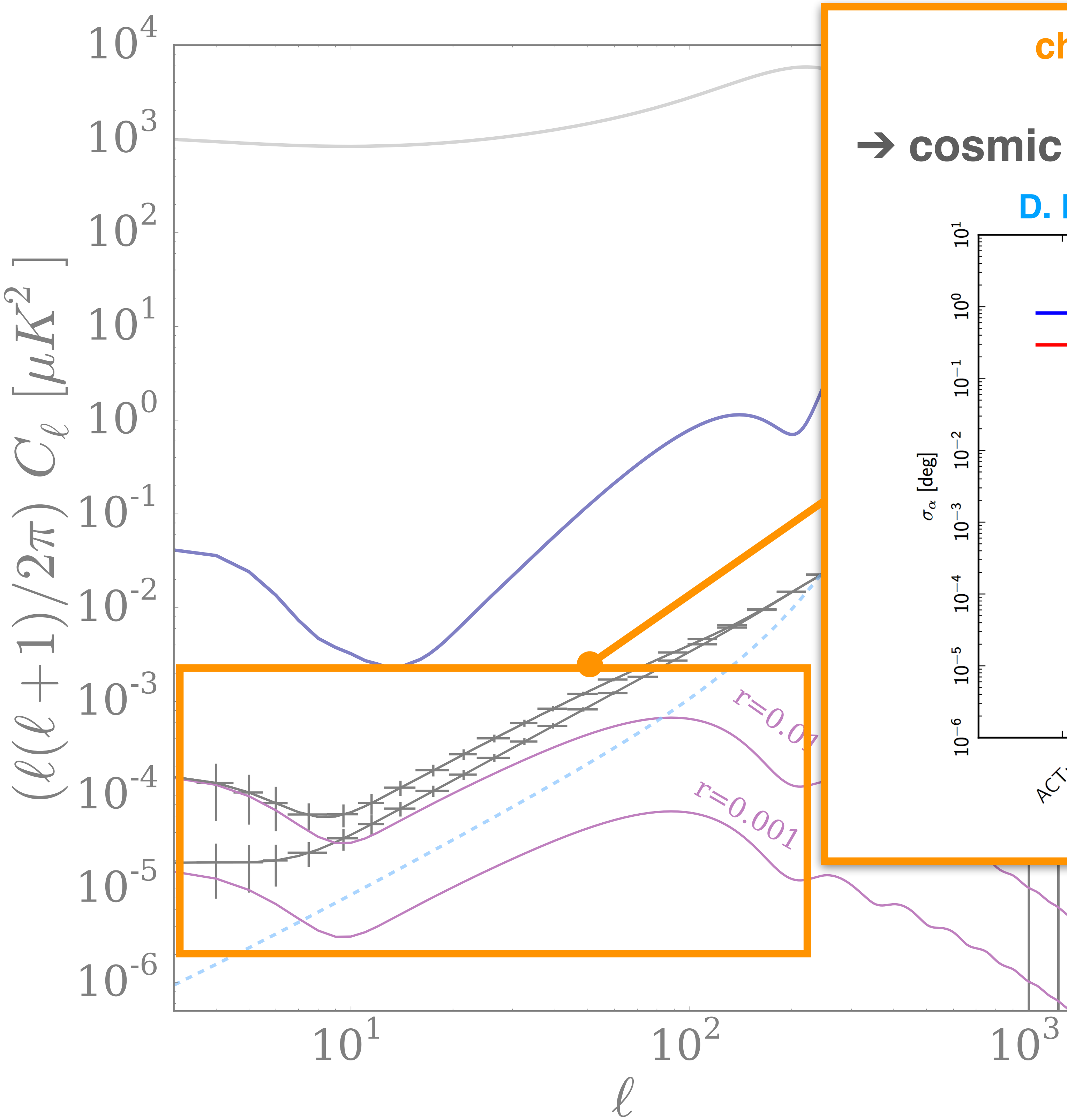


characterizing primordial BB

➔ **non-Gaussianity** — powerful test of whether the detected GW comes from the vacuum or sources (**Agrawal et al —1707.03023**)



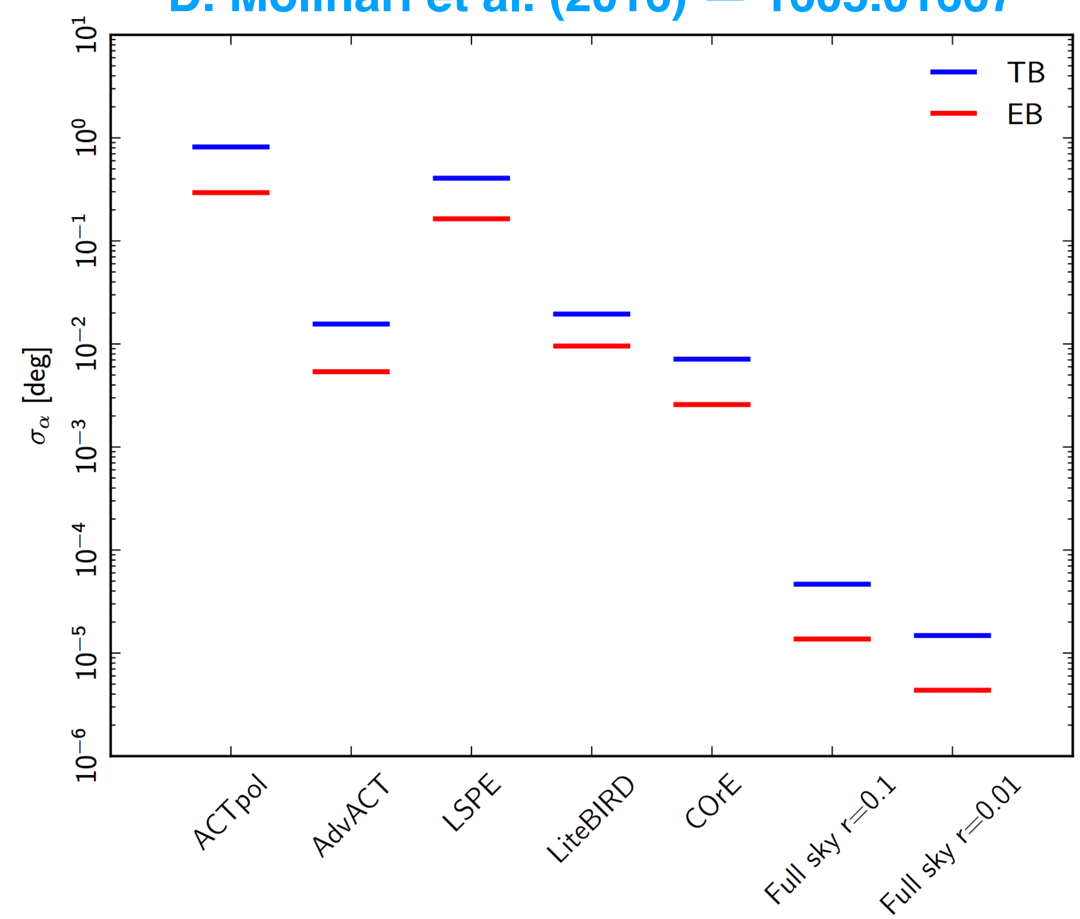
LiteBIRD —science outcomes



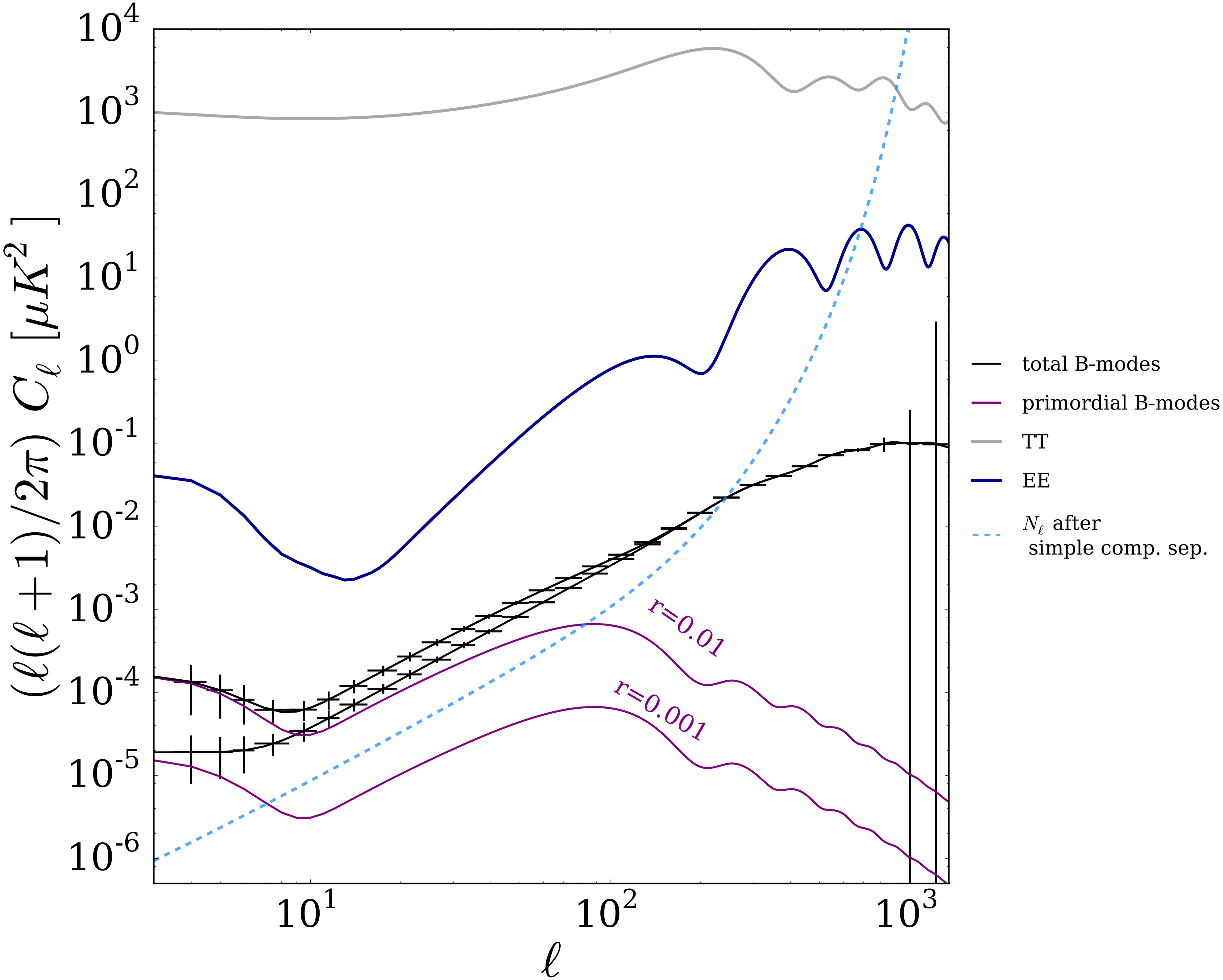
characterizing primordial BB

➔ **cosmic birefringence**

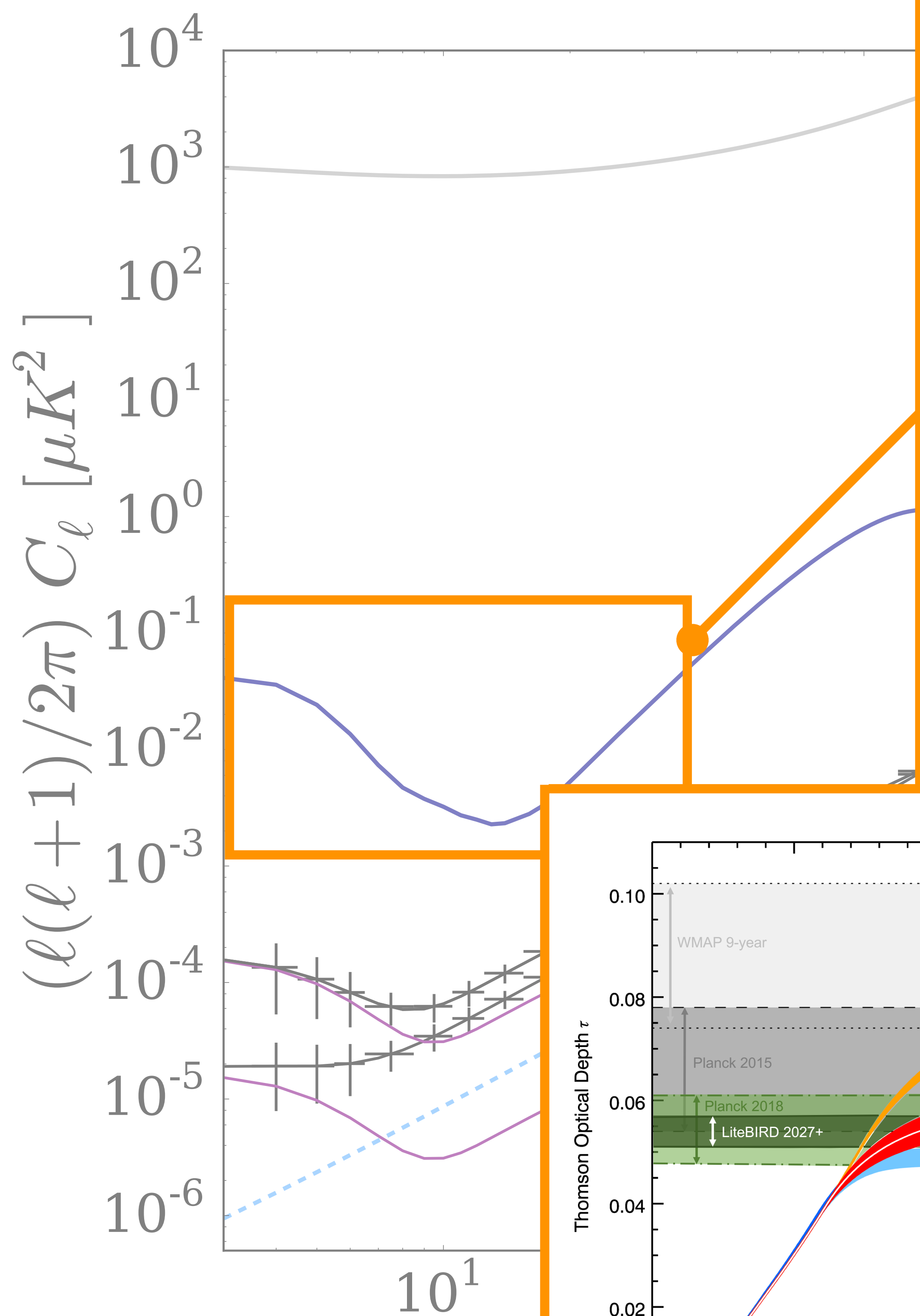
D. Molinari et al. (2016) — 1605.01667



LiteBIRD —science outcomes



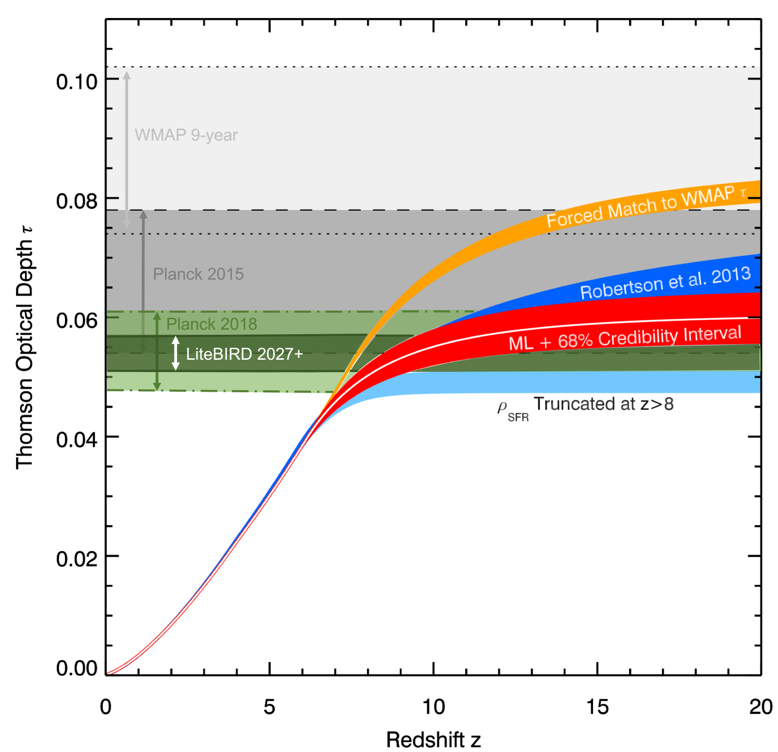
LiteBIRD —science outcomes

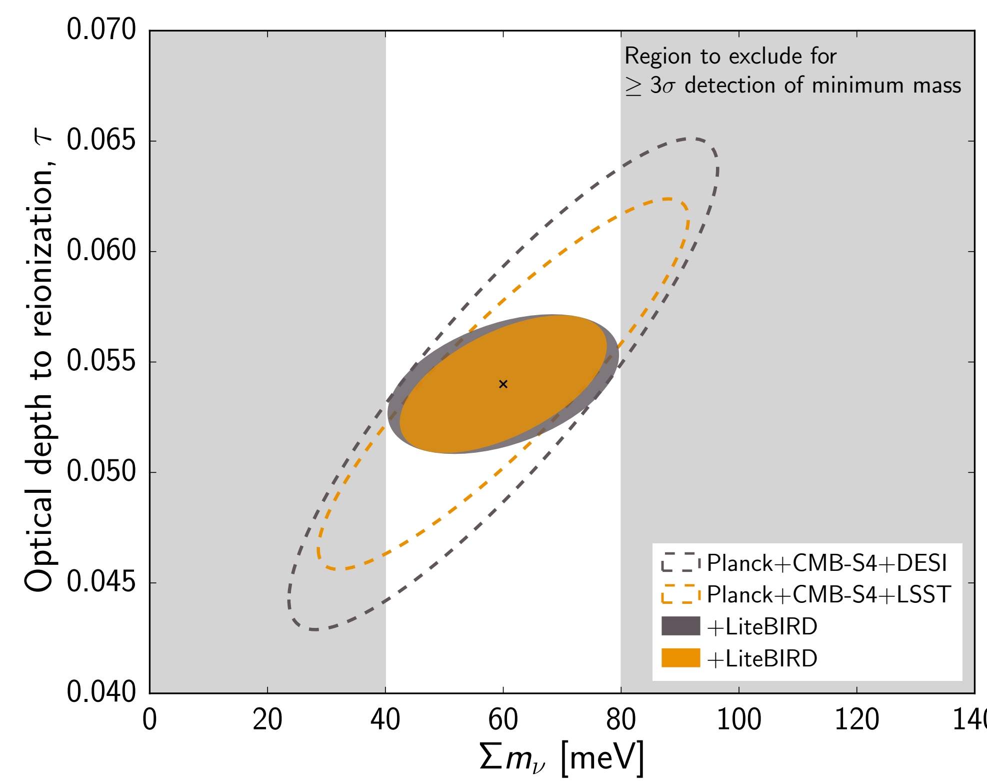


characterize reionization history

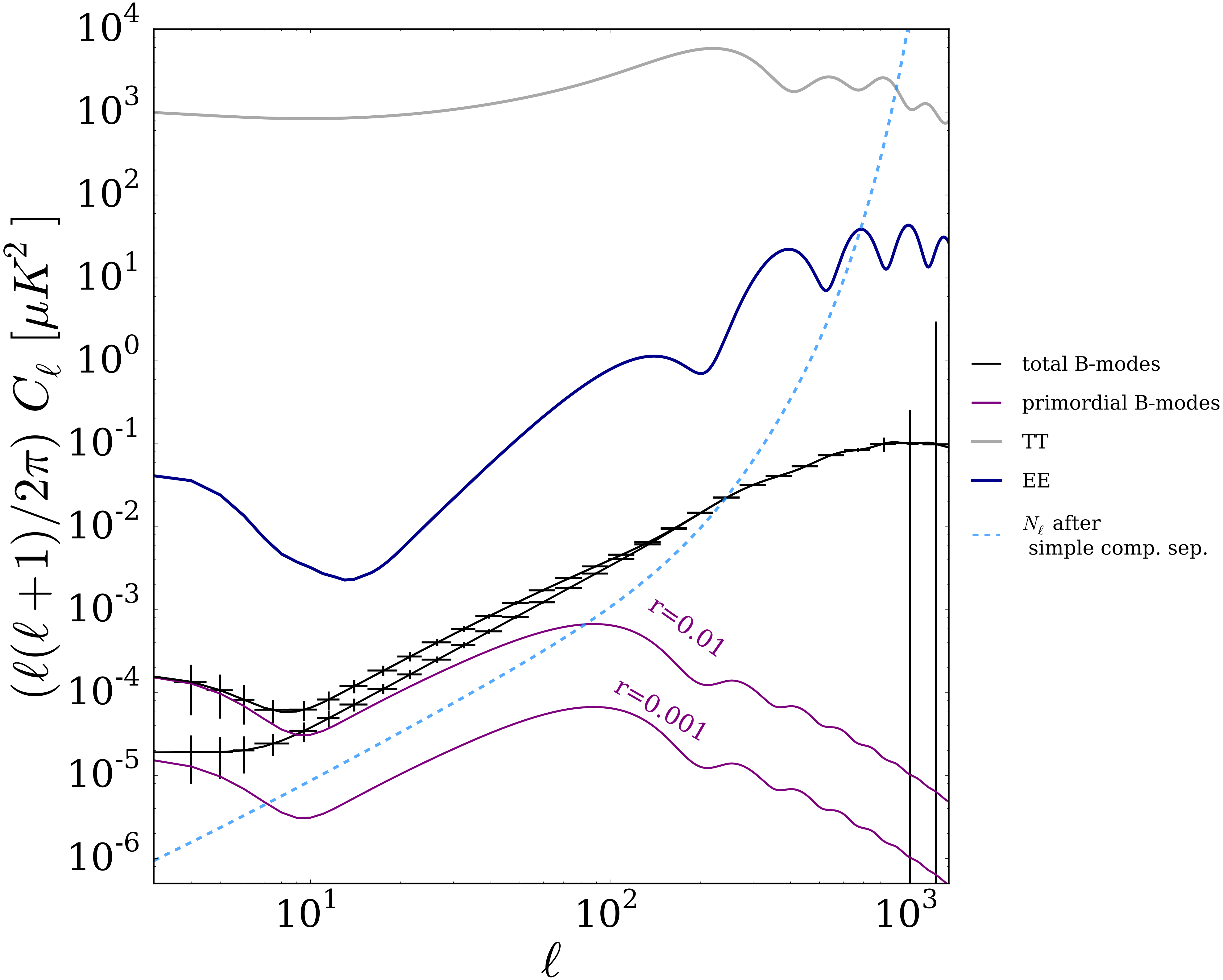
➔ better τ and sum of neutrino masses

➔ crucial information for many other surveys

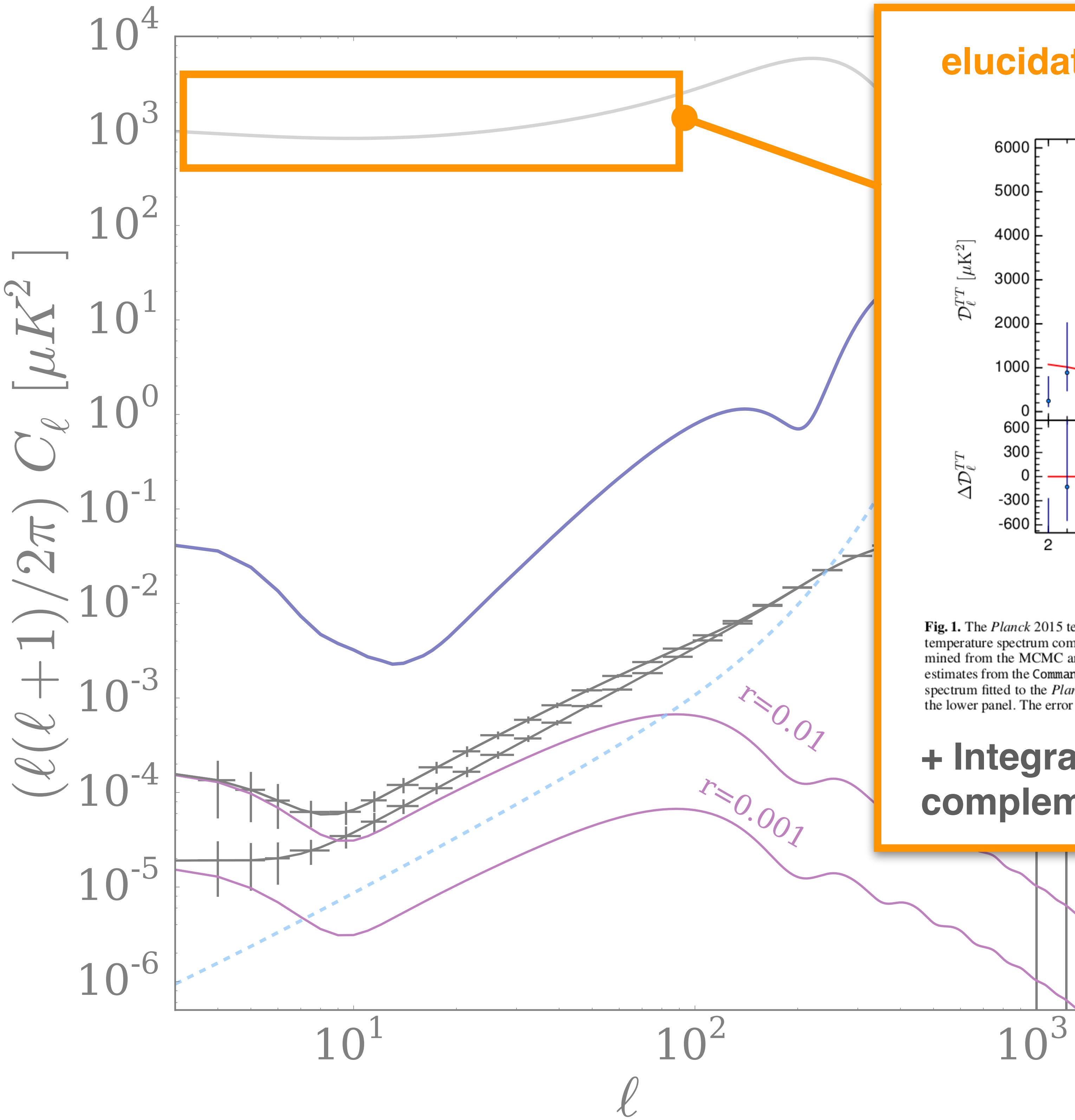




LiteBIRD —science outcomes



LiteBIRD —science outcomes



elucidating anomalies with polarization

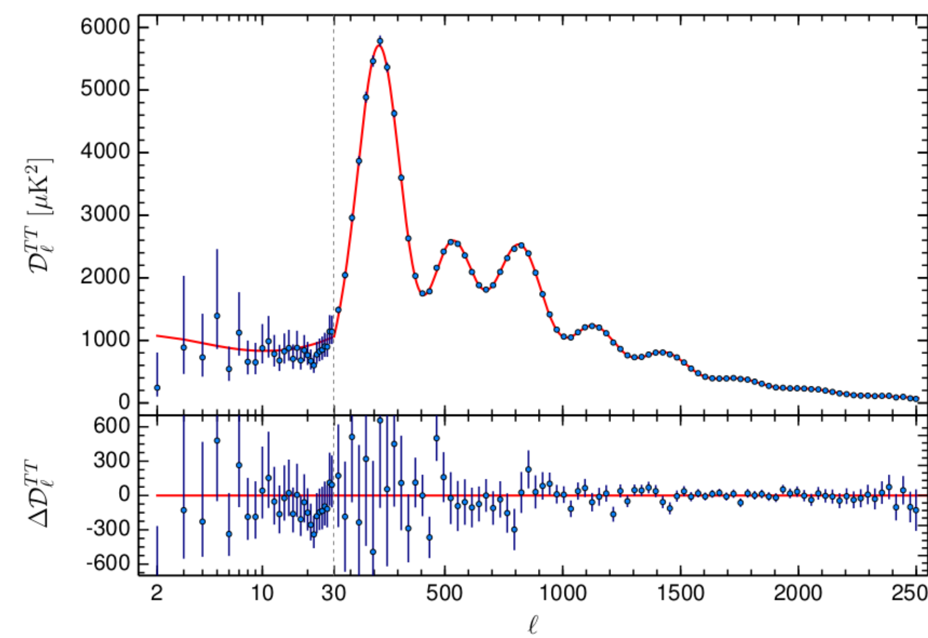
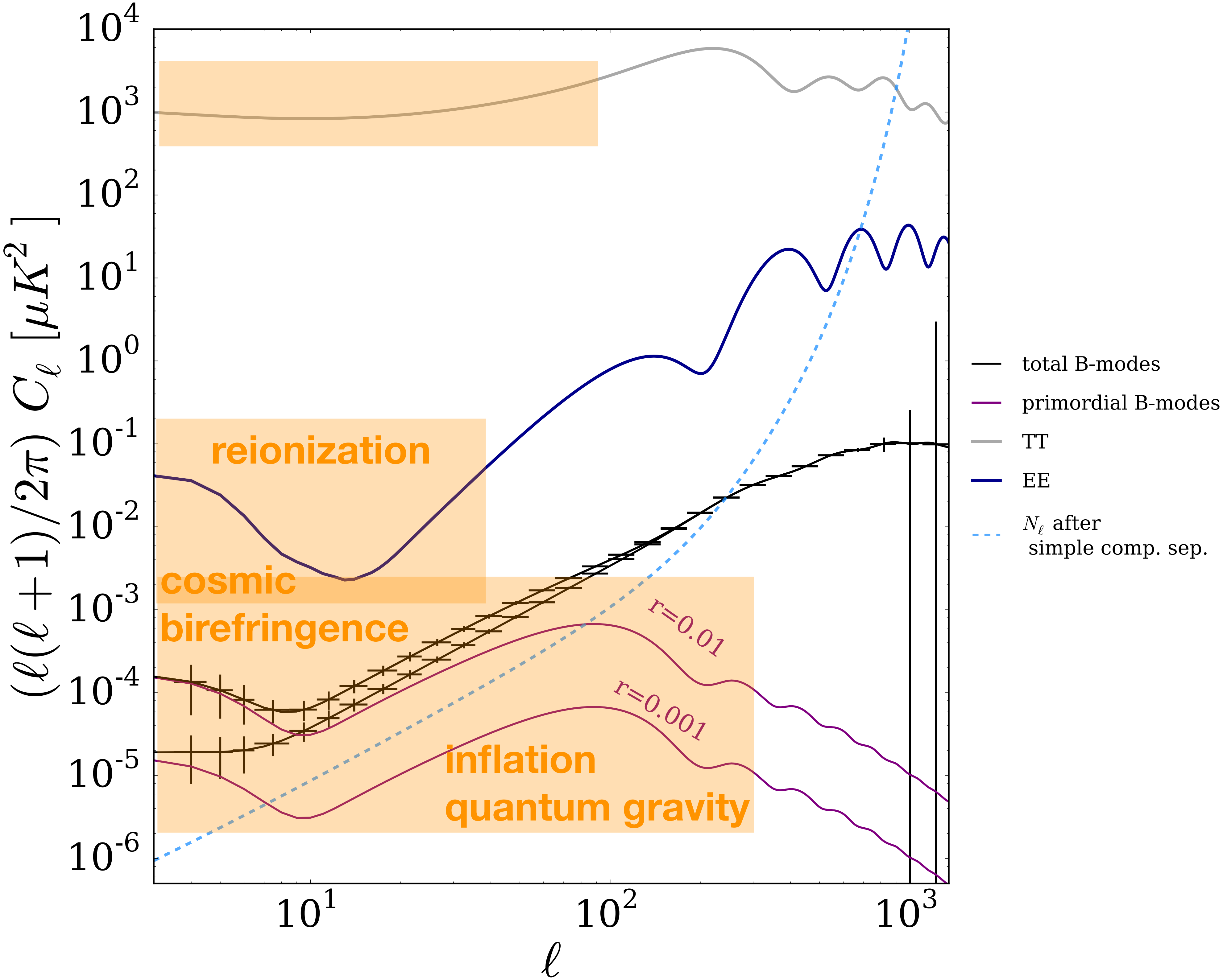


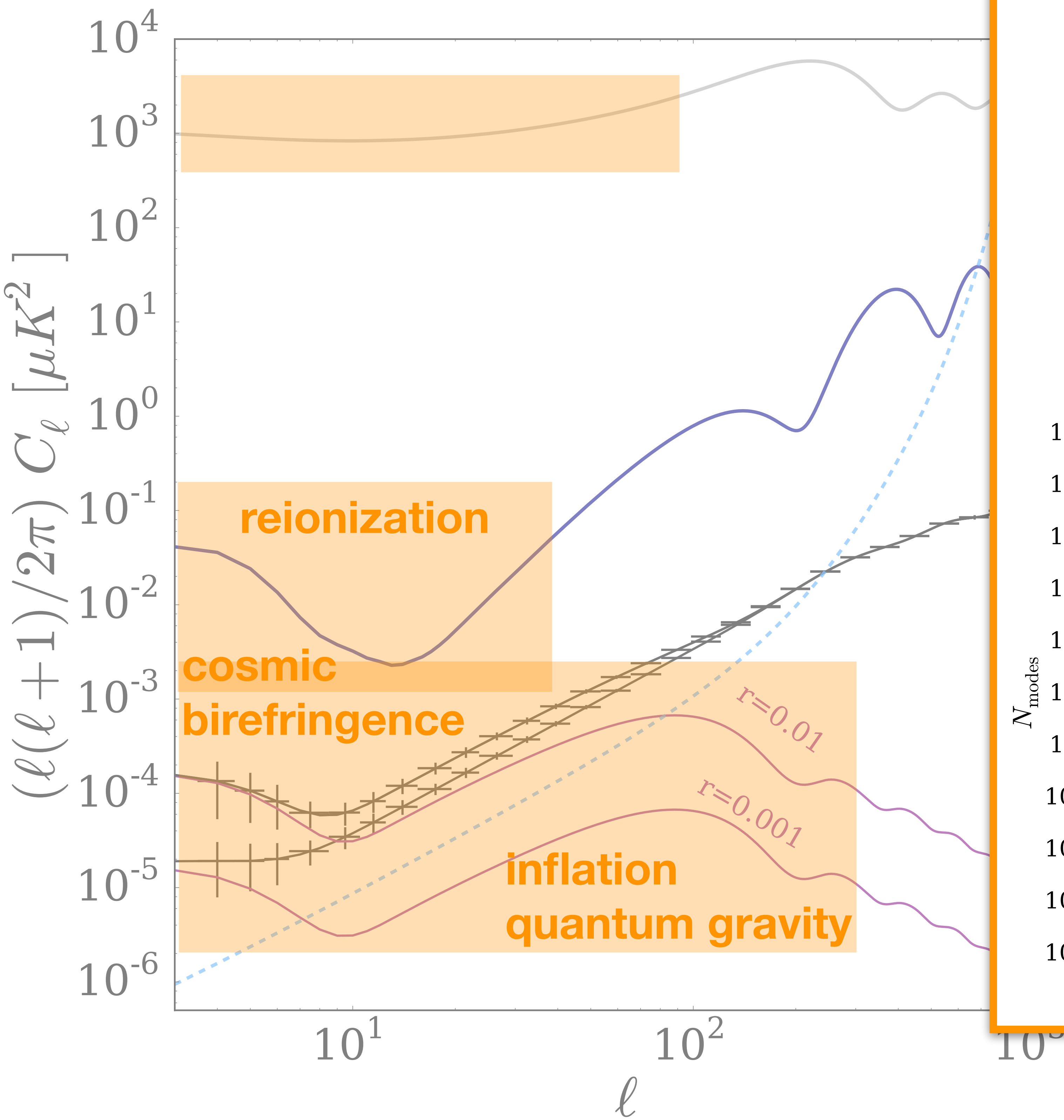
Fig. 1. The *Planck* 2015 temperature power spectrum. At multipoles $\ell \geq 30$ we show the maximum likelihood frequency averaged temperature spectrum computed from the `Plik` cross-half-mission likelihood with foreground and other nuisance parameters determined from the MCMC analysis of the base ΛCDM cosmology. In the multipole range $2 \leq \ell \leq 29$, we plot the power spectrum estimates from the `Commander` component-separation algorithm computed over 94% of the sky. The best-fit base ΛCDM theoretical spectrum fitted to the *Planck* TT+lowP likelihood is plotted in the upper panel. Residuals with respect to this model are shown in the lower panel. The error bars show $\pm 1\,\sigma$ uncertainties.

+ Integrated Sachs Wolfe effect complementary to density measurements

LiteBIRD —science outcomes

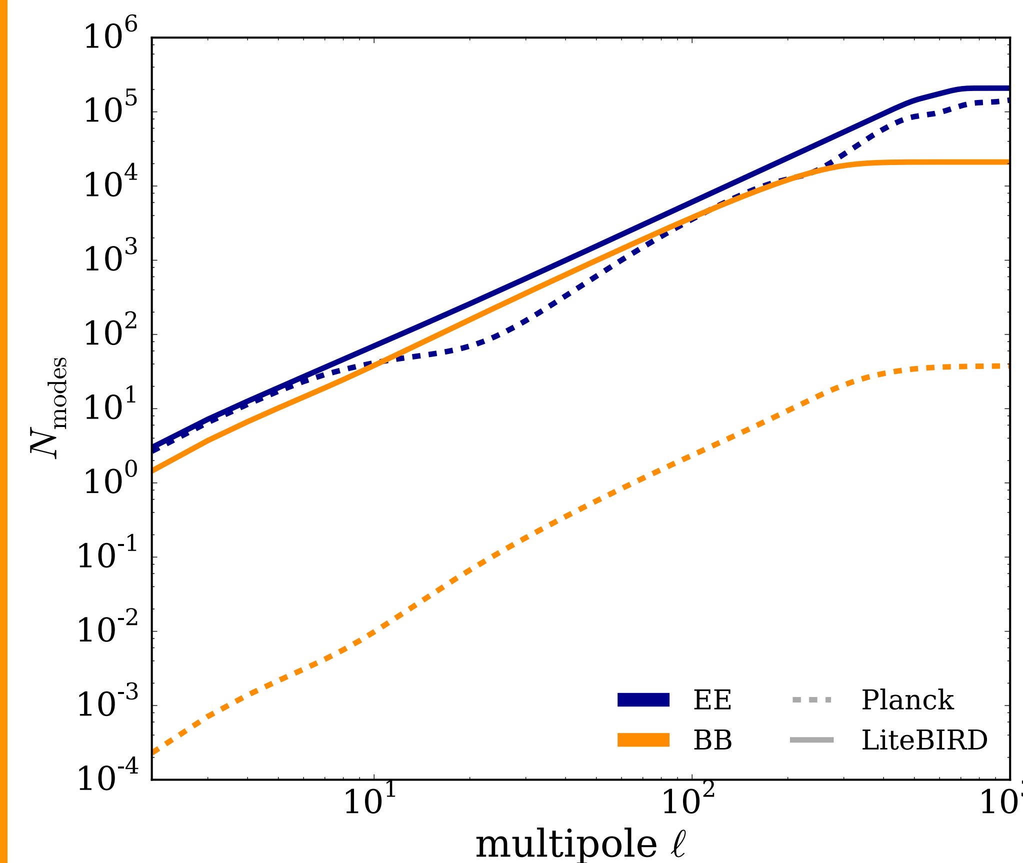


LiteBIRD —science outcomes

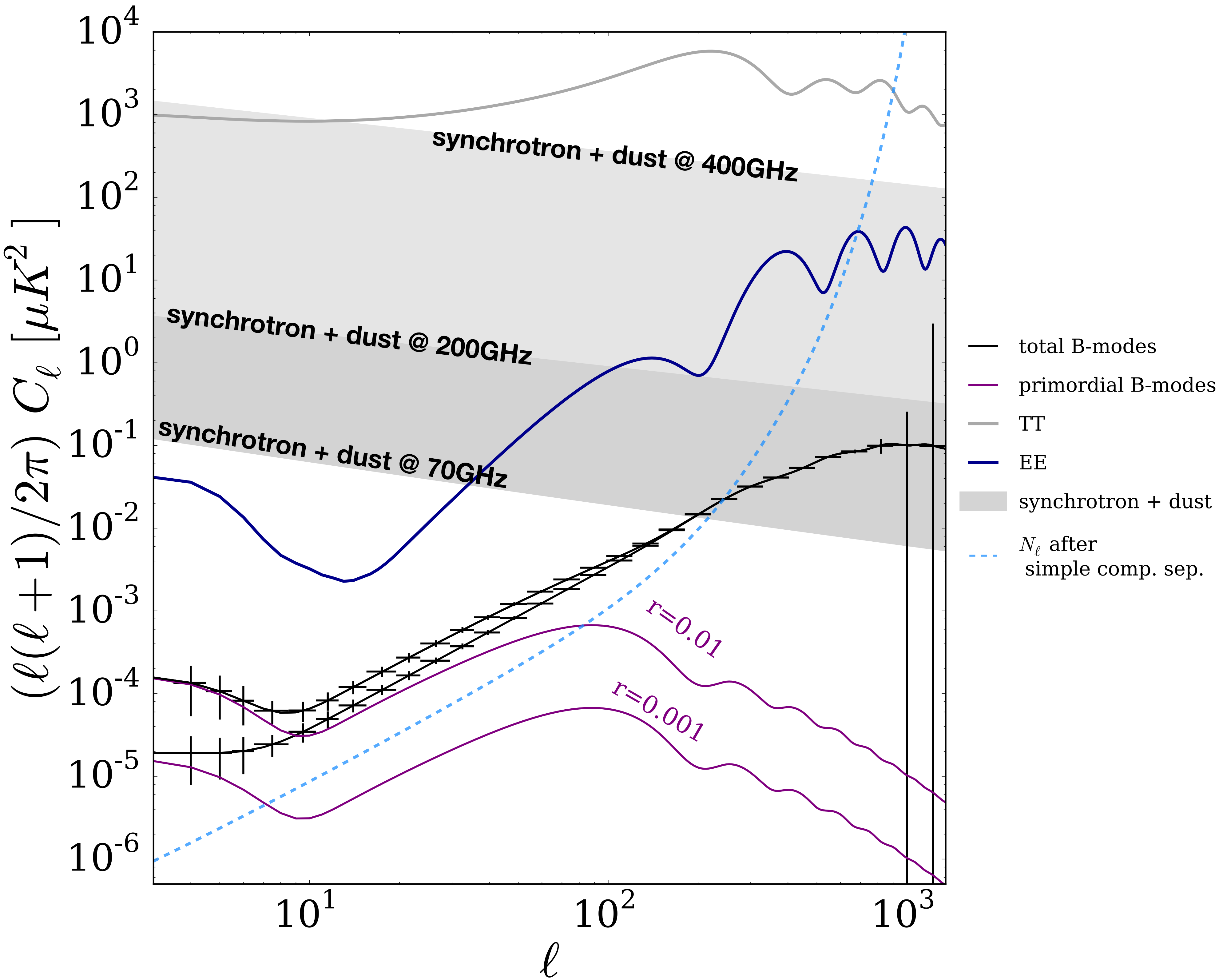


Exploring Cosmic Origins with CORE: Inflation
F. Finelli, M. Bucher et al., JCAP, 2017

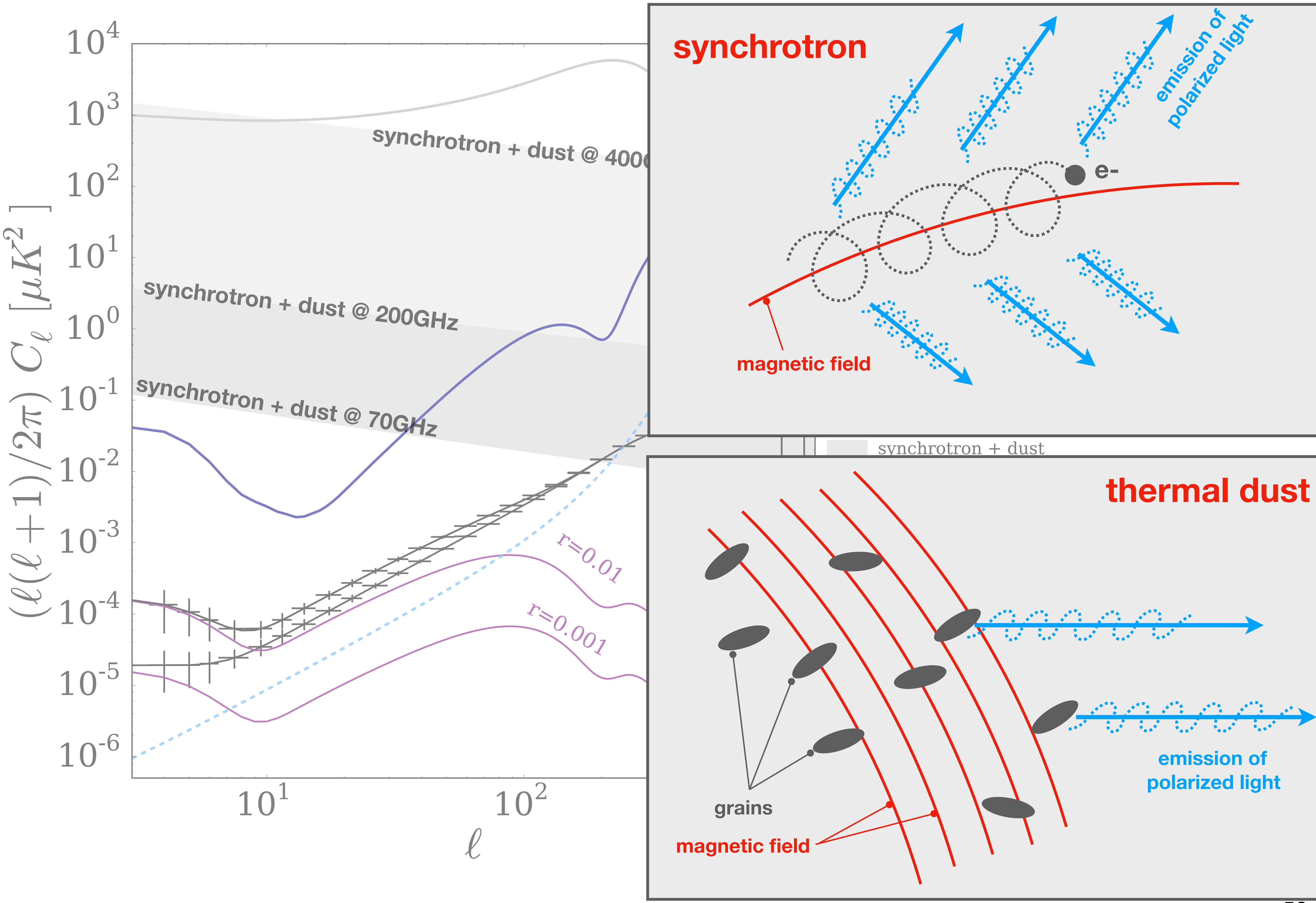
$$N_{\mathrm{modes}} = \sum_{\ell,m} \left(\frac{C_\ell}{C_\ell + N_\ell} \right)^2$$

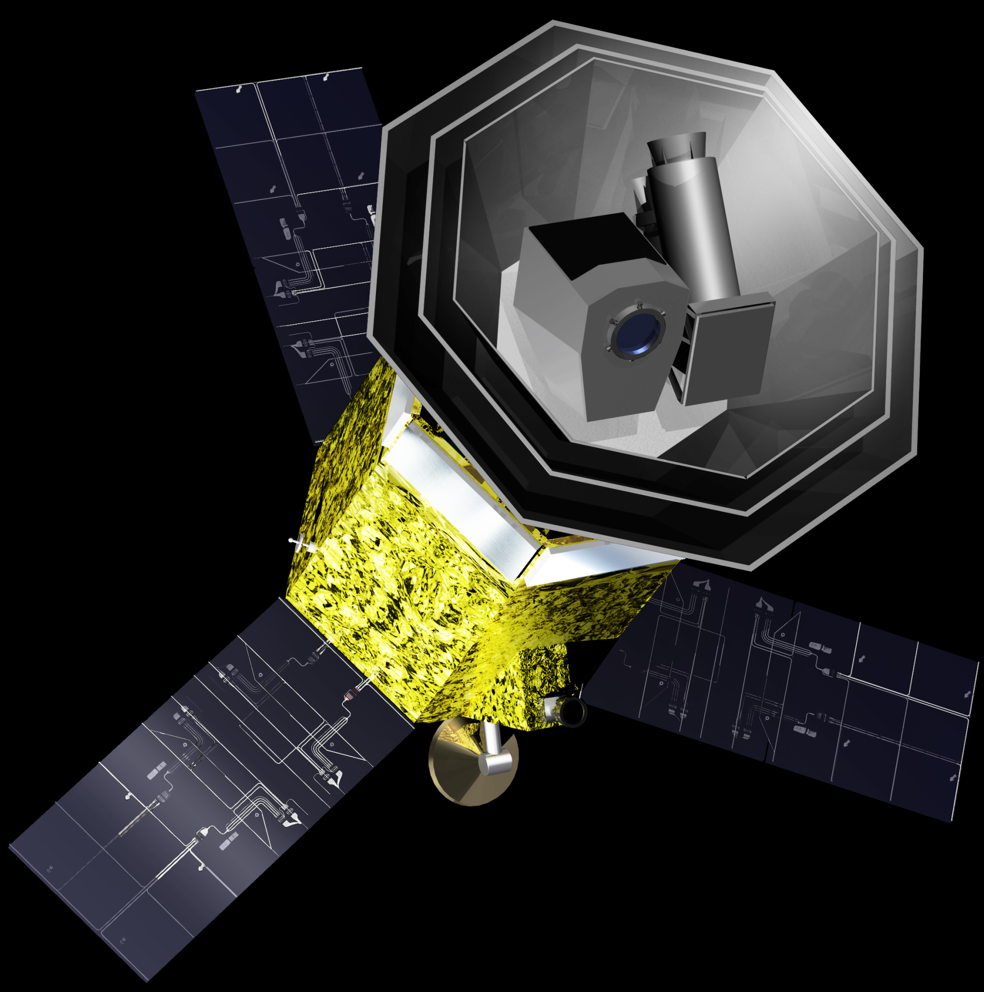


LiteBIRD —science outcomes



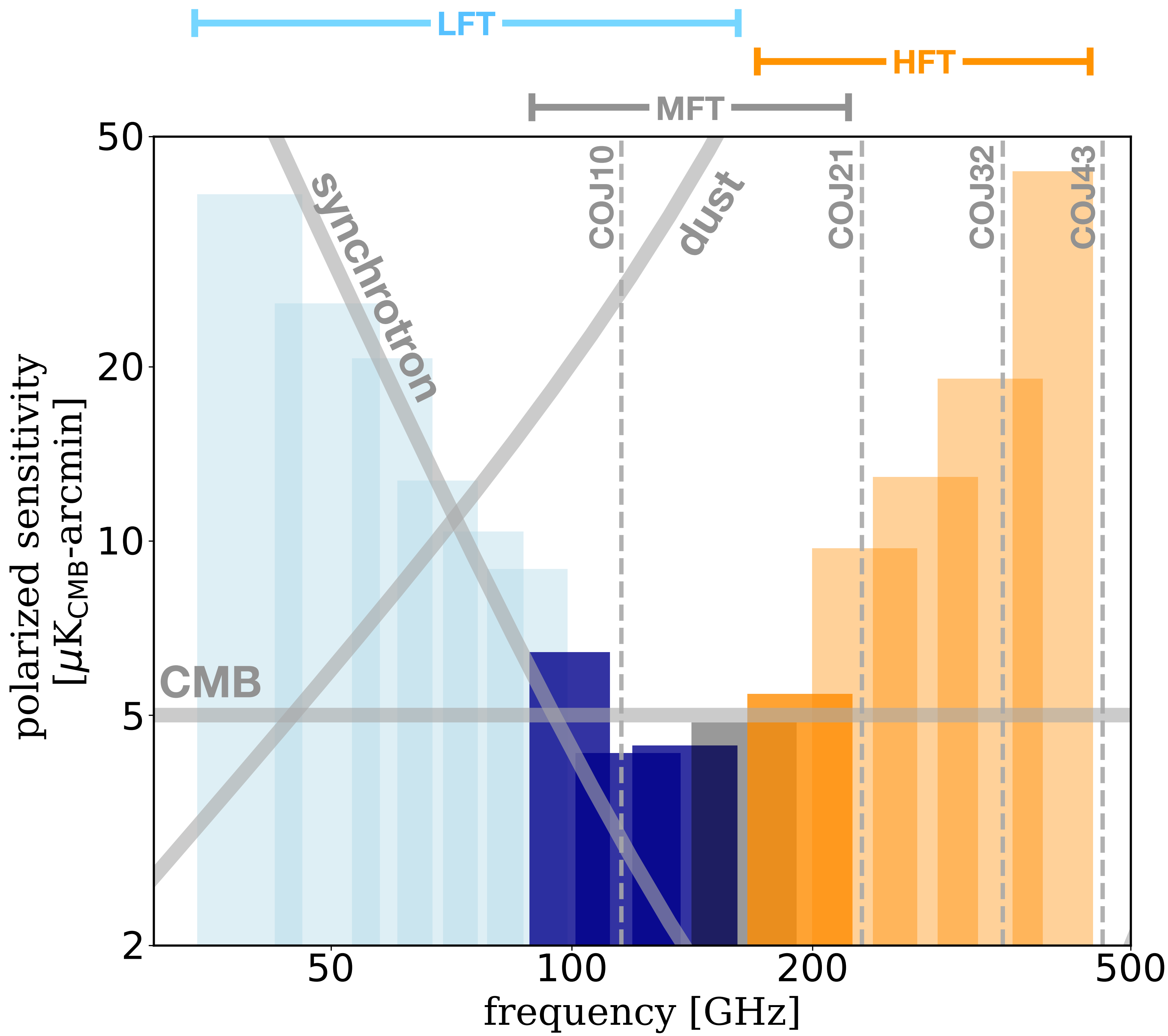
LiteBIRD —science outcomes



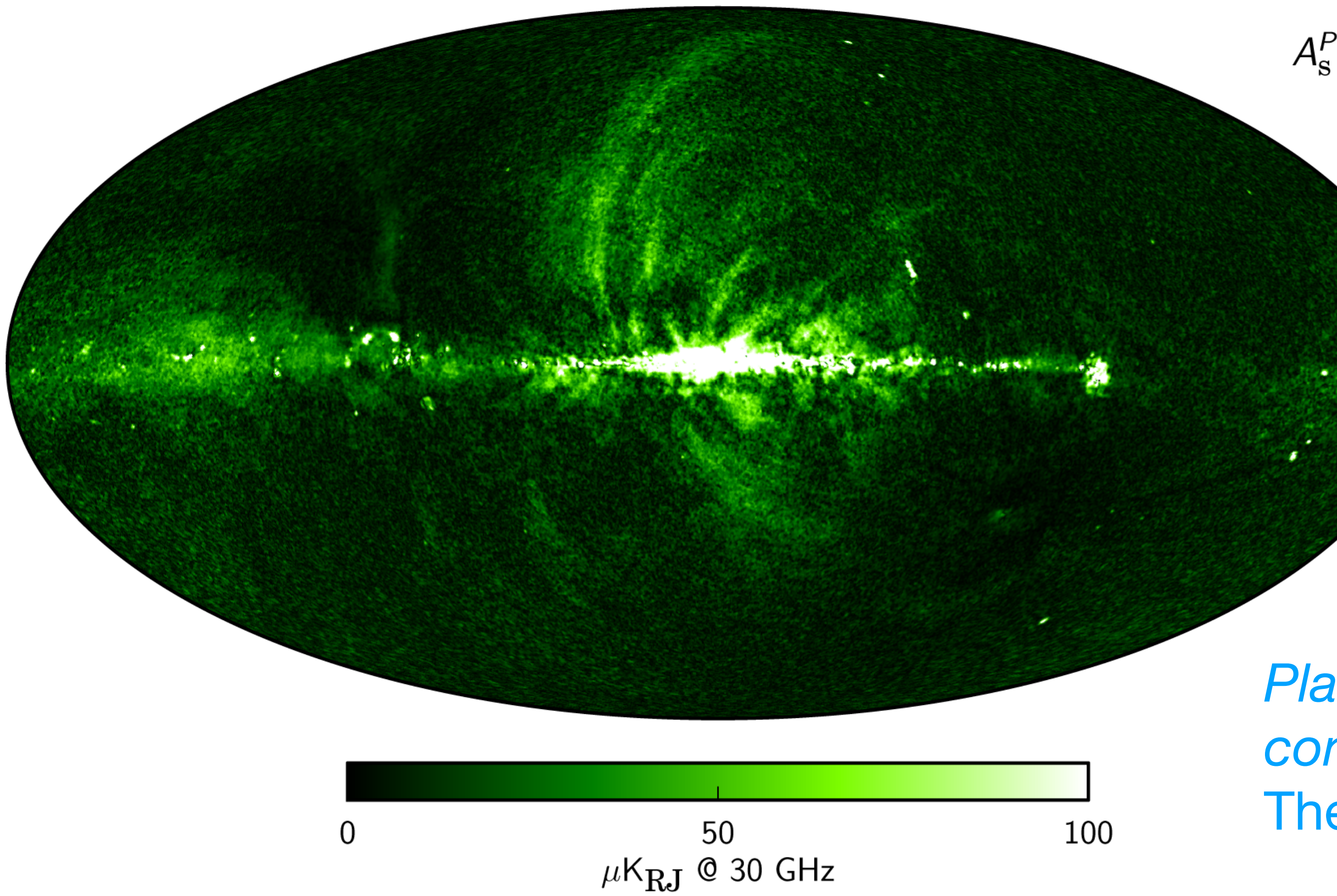


Introduction
LiteBIRD design
LiteBIRD science
Challenges
Collaboration

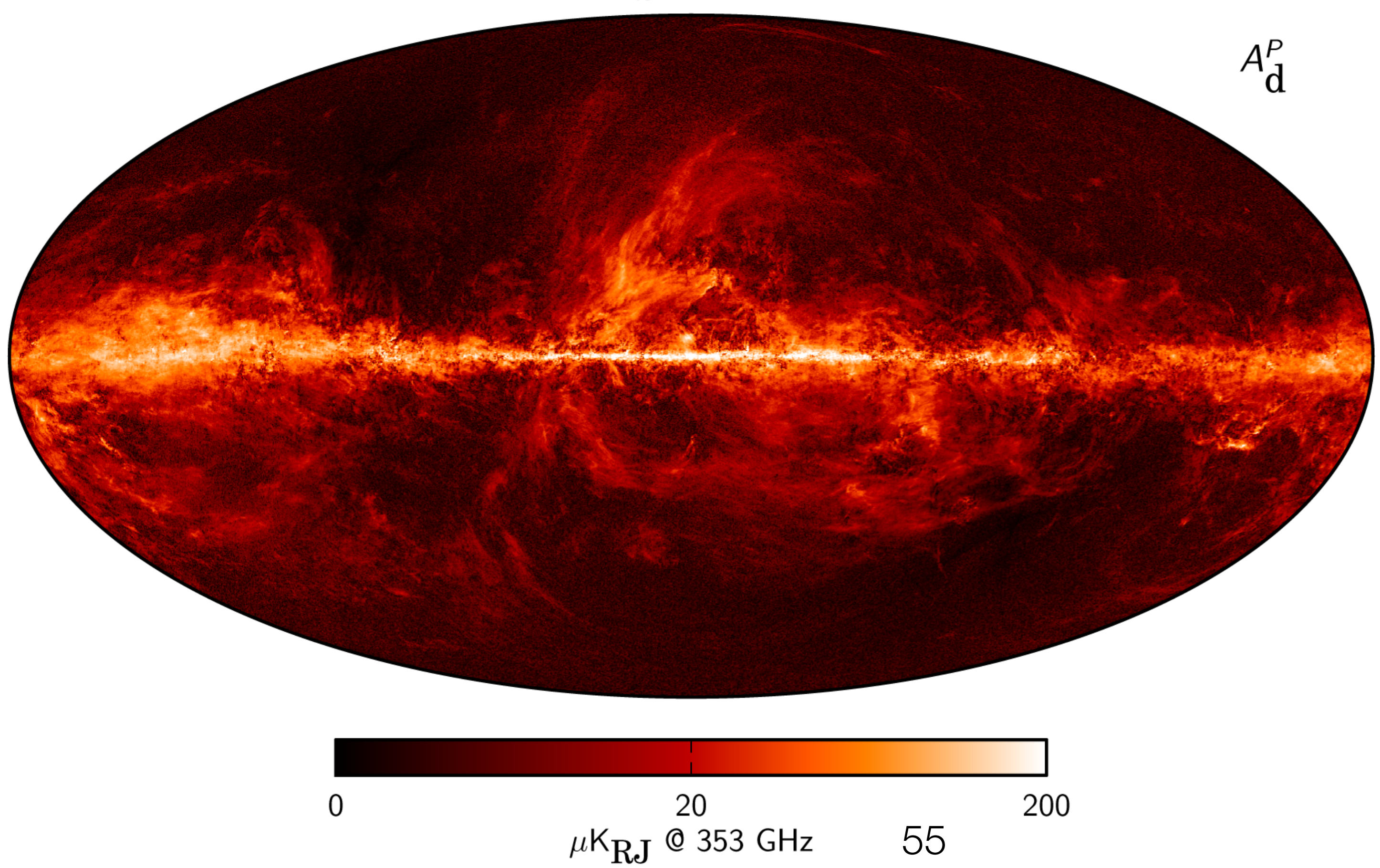
LiteBIRD — foregrounds cleaning



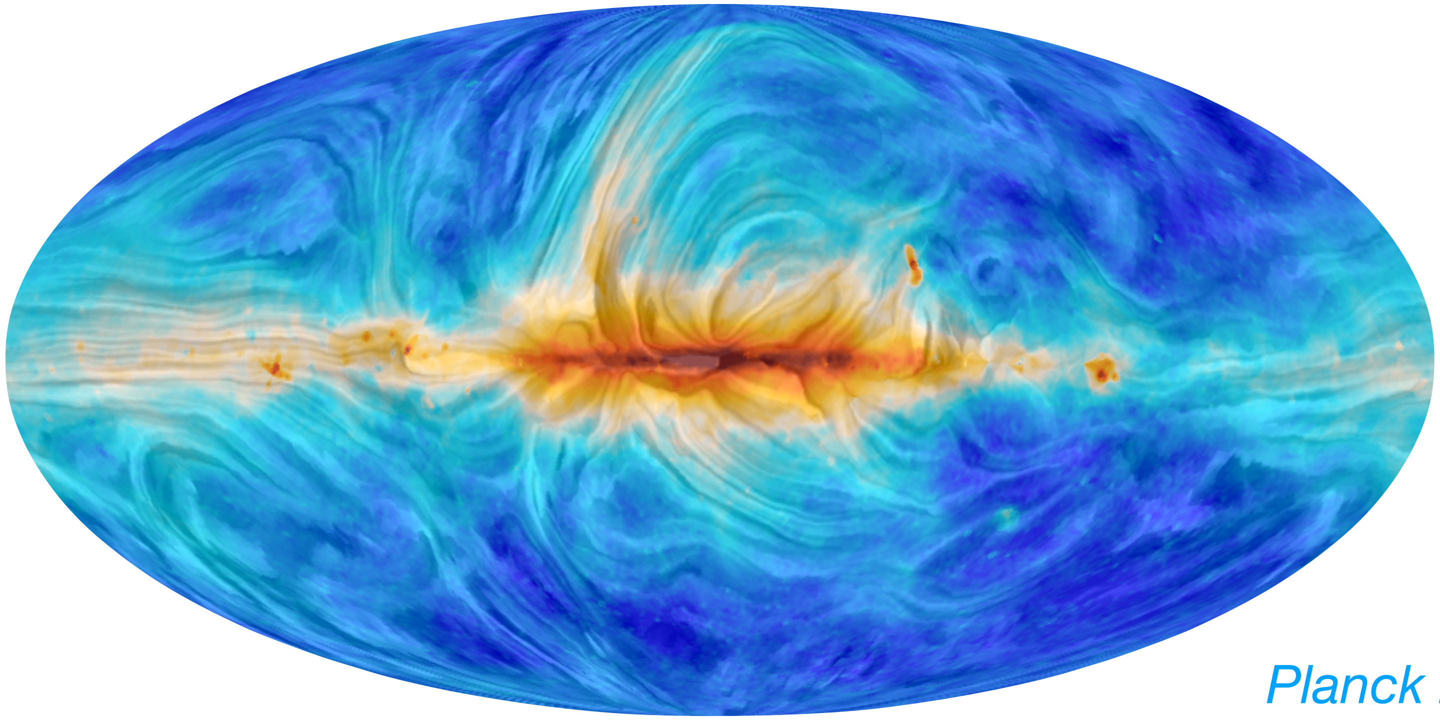
synchrotron and dust polarized emissions follow the galactic magnetic field



Planck 2015 results. X. Diffuse component separation: Foreground maps
The Planck collaboration, A&A, 2015

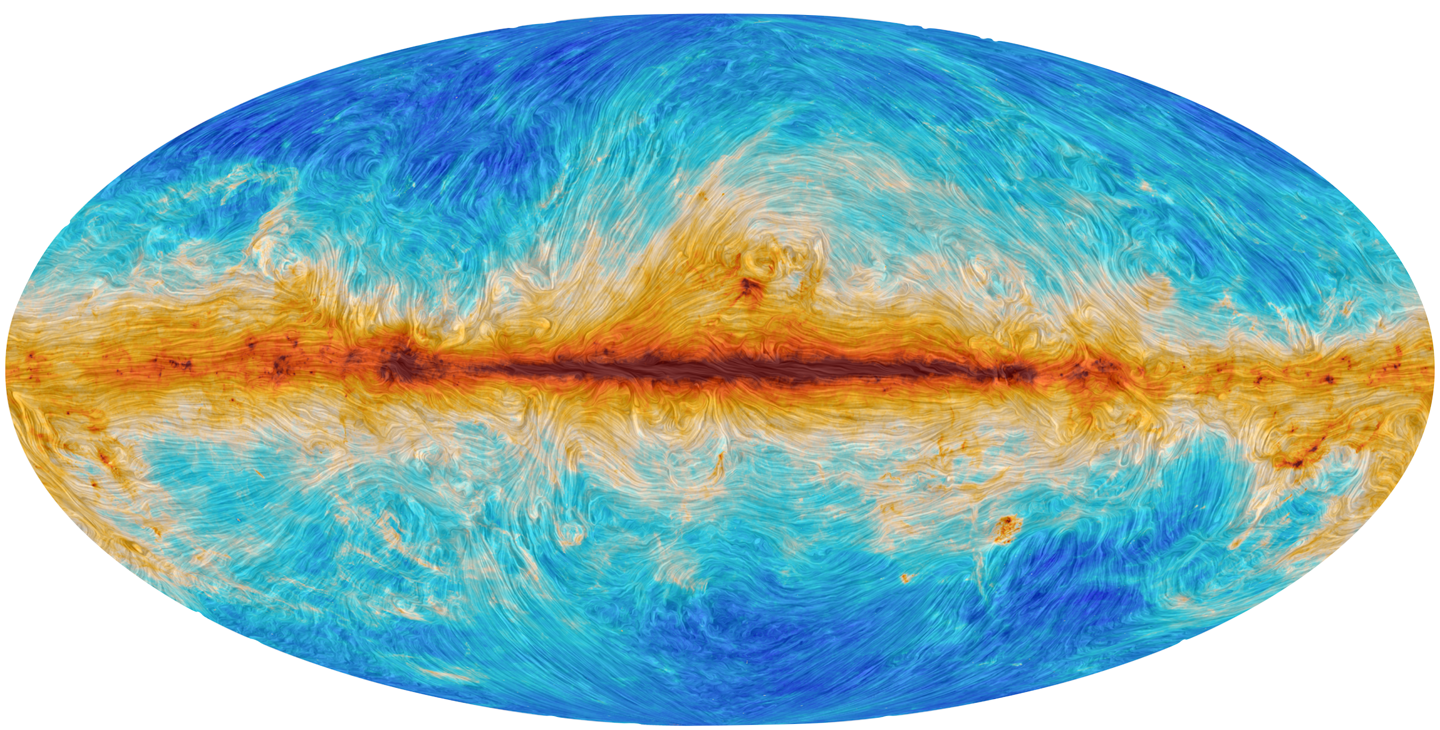


synchrotron and dust polarized emissions follow the galactic magnetic field

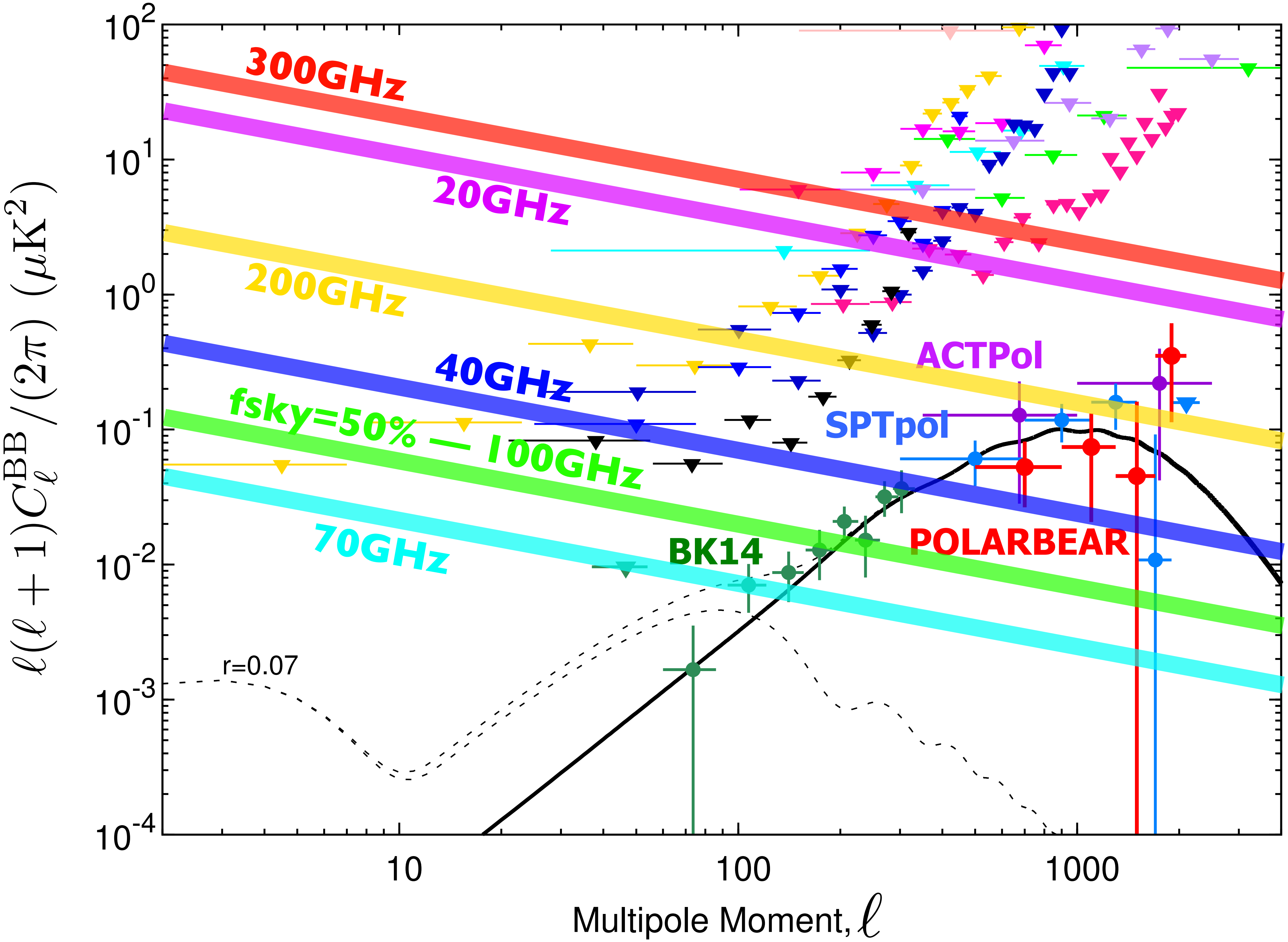


intensity @ 30GHz
+ B-field from polarization

Planck 2015 results. X. Diffuse component separation: Foreground maps
The Planck collaboration, A&A, 2015



amplitude of galactic foregrounds for different frequencies



removing galactic foregrounds

analogy interlude

One or multiple dust components?

CMB

Anomalous Microwave Emission (AME)?

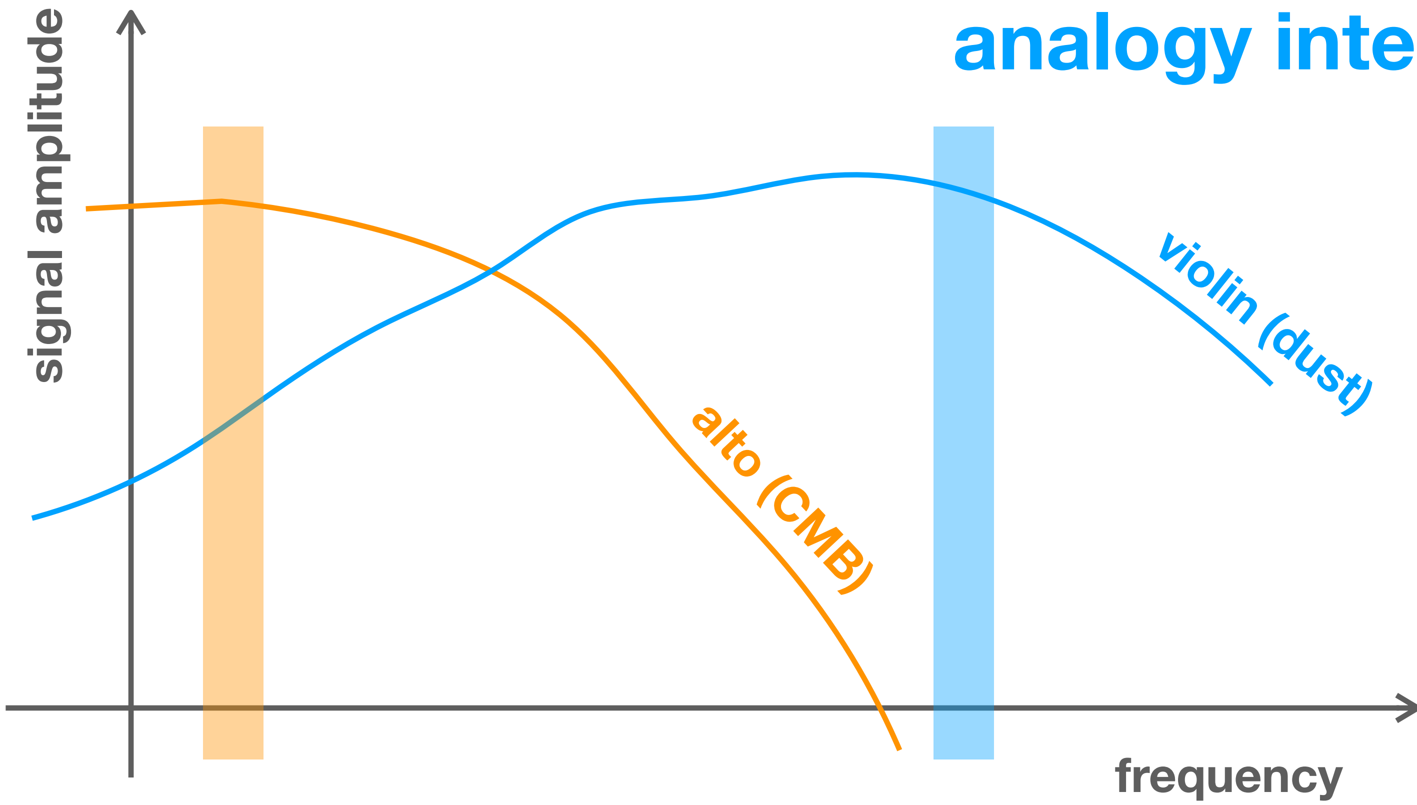
Synchrotron

(black body)

Johannes-Quintett / KV516, Mozart

removing galactic foregrounds

analogy interlude



- removing one or several components increase the noise variance in the final “clean” component
- misestimating a spectrum leaks components to the “clean” component (can be statistical or systematic misestimation)

$$d_{\nu_0} = a_0\,\mathrm{CMB} + b_0\,\mathrm{dust} + n_{\nu_0}$$

$$d_{\nu_1} = a_1\,\mathrm{CMB} + b_1\,\mathrm{dust} + n_{\nu_1}$$

$$d_{\nu_0} b_1 - d_{\nu_1} b_0 = CMB\ (b_1 a_0 - b_0 a_1) + n_{\nu_0} b_1 - n_{\nu_1} b_0$$

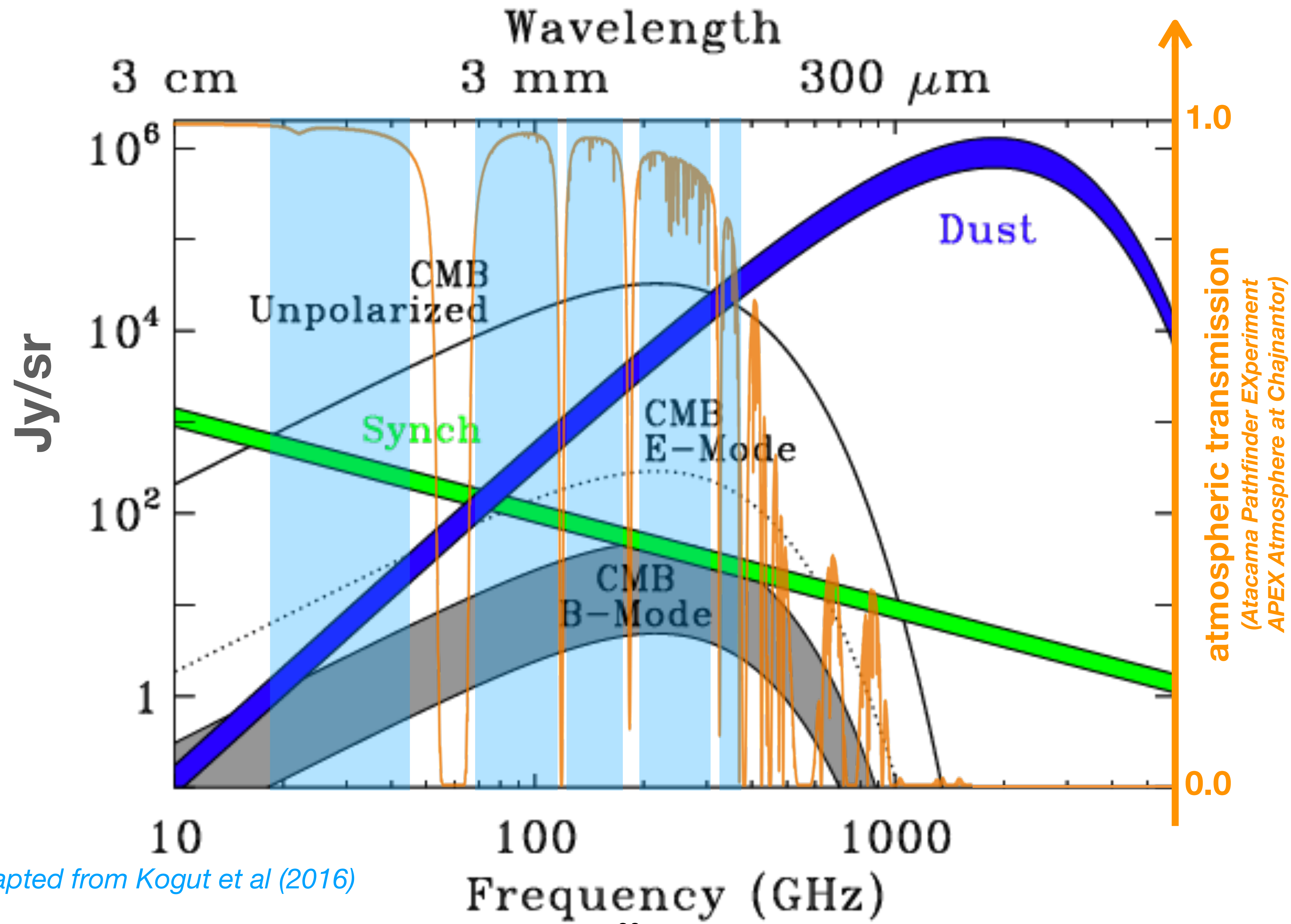
boosted variance

$$\sigma^2_{\mathrm{CMB}} = \frac{\sigma^2_{\nu_0} b_1^2 + \sigma^2_{\nu_1} b_0^2}{(b_1 a_0 - b_0 a_1)^2}$$

statistical/systematic residuals in the cleaned signal

$$\delta\mathrm{CMB} \propto \delta b_1\,(\alpha\, d_{\nu_0} + \beta\, d_{\nu_1})$$

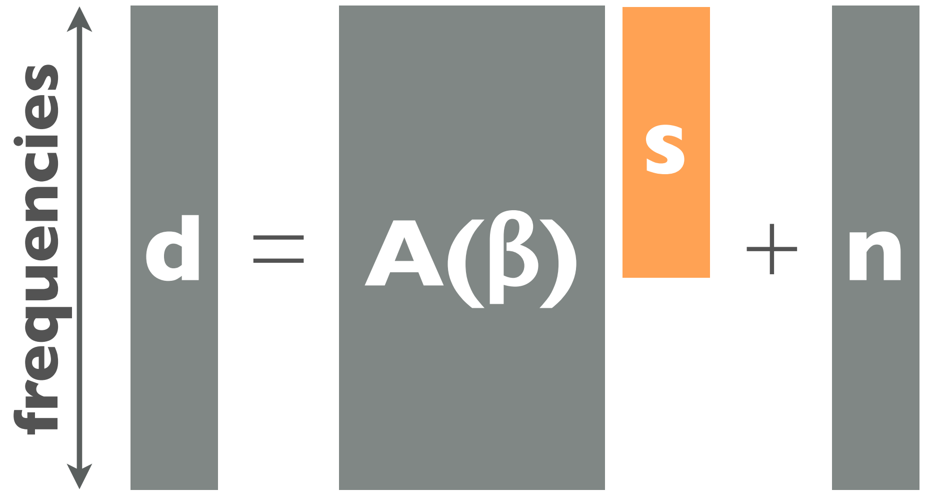
removing galactic foregrounds

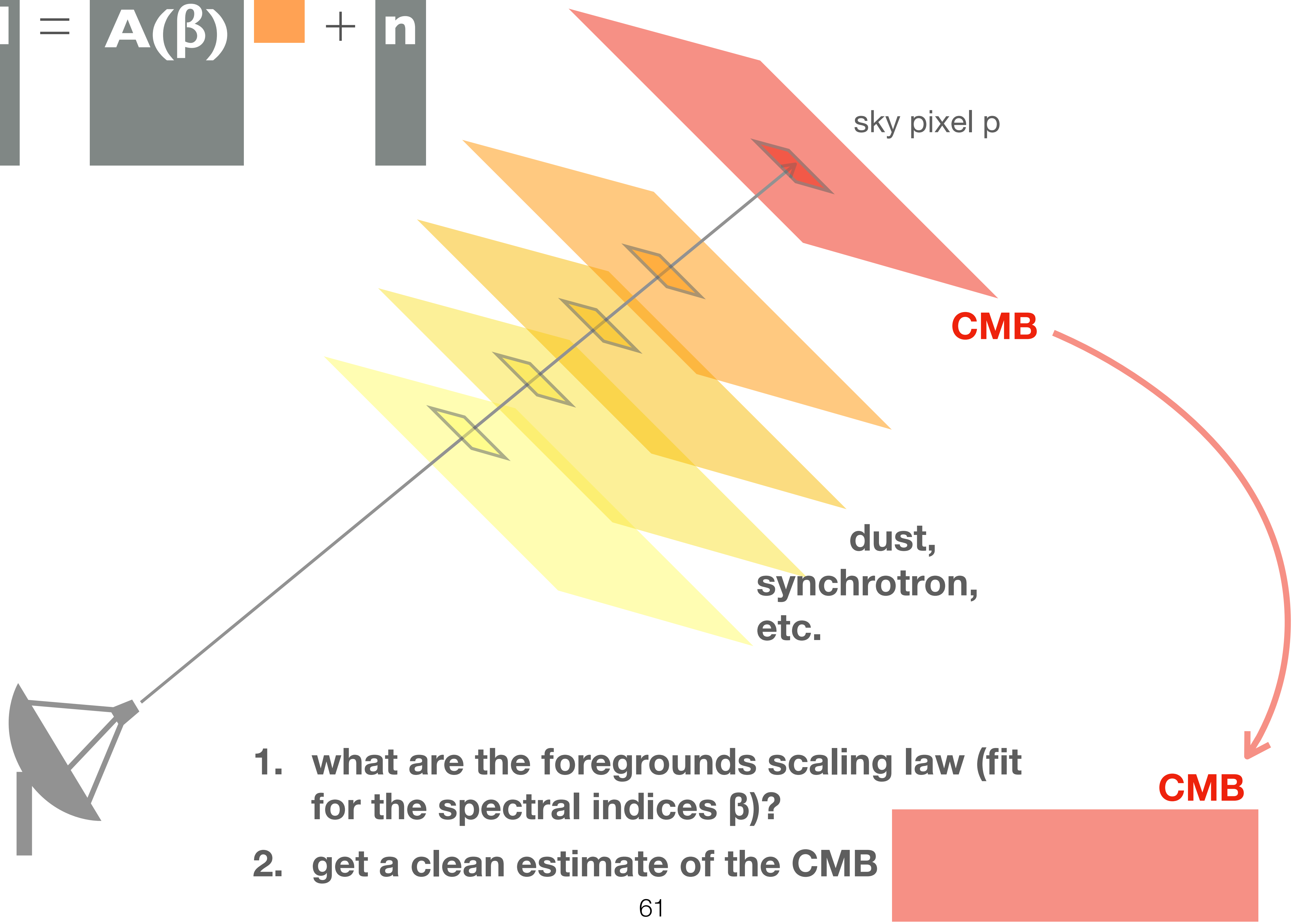


adapted from Kogut et al (2016)

astrophysical foregrounds are one of the biggest challenges (if not the biggest one) for the B-modes quest

$$d_i(p) = A_{ij}\, s_j(p) + n_i(p)$$

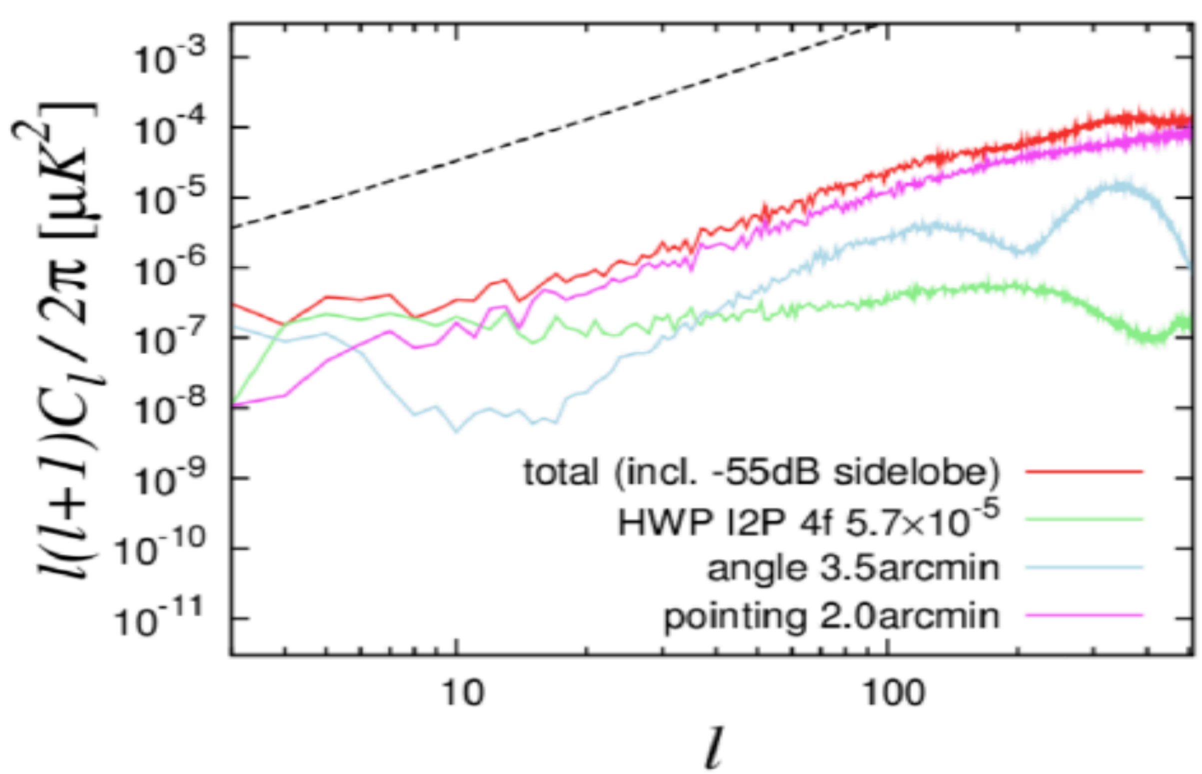


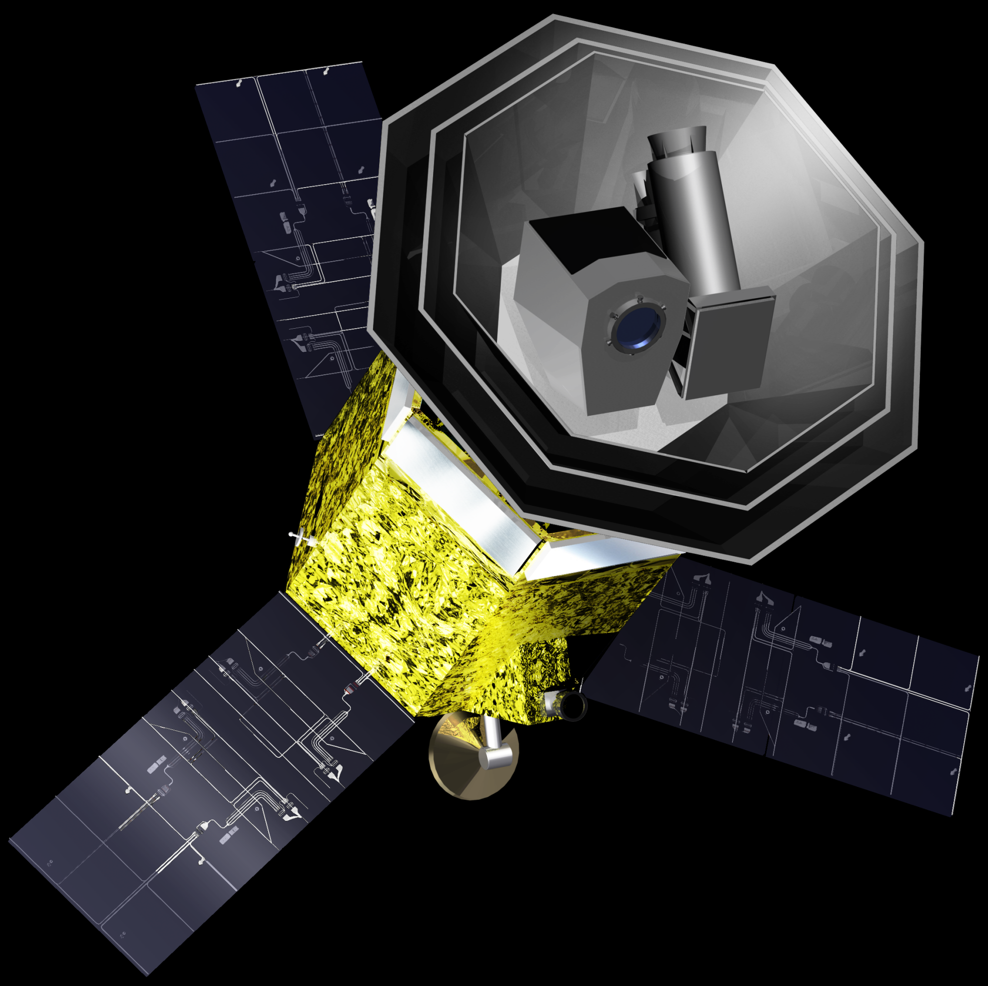


1. what are the foregrounds scaling law (fit for the spectral indices β)?
2. get a clean estimate of the CMB

LiteBIRD — systematics and calibration

- **One of the largest study groups in LiteBIRD**
- **Systematic approach for systematic uncertainties**
  - List systematic error items 14 categories, 70 items listed
  - Assign each item $\sigma(r)_{sys} < 5.7 \times 10^{-6}$ as the budget (1% of total budget for systematic error)
  - Derive a requirement for each item, define method (incl. calibration methods) and estimate $\sigma(r)_{sys}$
  - Assign special budget allocations for outstanding items
  - Sum each contribution at the map level to estimate total $\sigma(r)_{sys}$ (some studies use TOD basis) to take positive correlations into account
  - Iterate procedure
- **Example: studies of systematic errors due to HWP imperfection**
  - Mueller matrix from RCWA simulations of electromagnetic wave propagation through realistic HWP for different frequencies and incident angles
  - 4f component from M_{IQ}, M_{IU} ~10^{-4} in the worst case
  - Obtain leakage maps and BB power to estimate $\sigma(r)_{sys}$





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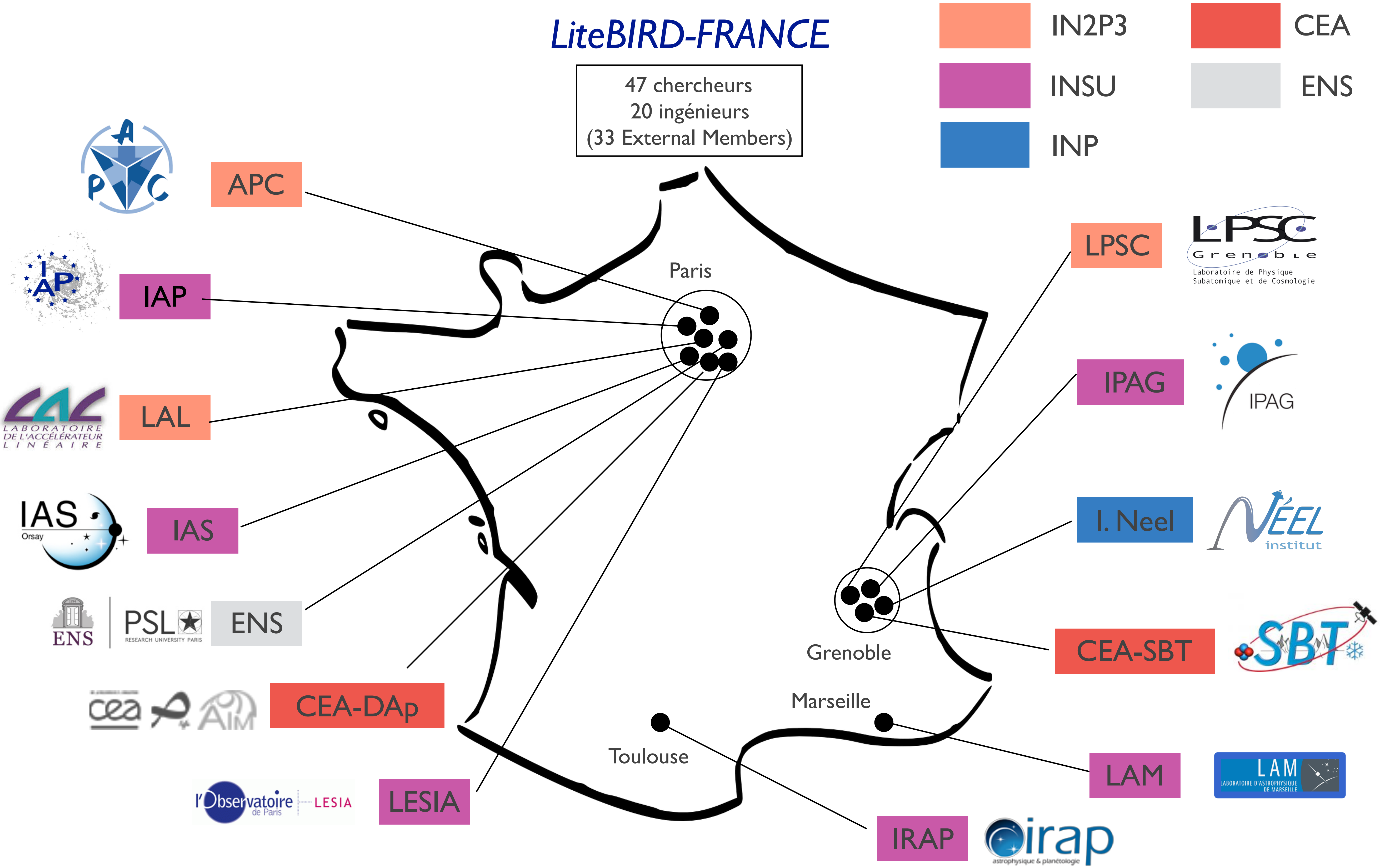
LiteBIRD Joint Study Group

About 200 researchers from Japan, North America & Europe
Team experiences: CMB exp., X-ray satellites, other large proj. (HEP, ALMA etc.)

LiteBIRD Global face-to-face meeting, @ Italian Space Agency, Jan. 2019

LiteBIRD in France



LiteBIRD is the next-generation CMB satellite selected by JAXA as a Strategic Large Mission to be launched in 2027

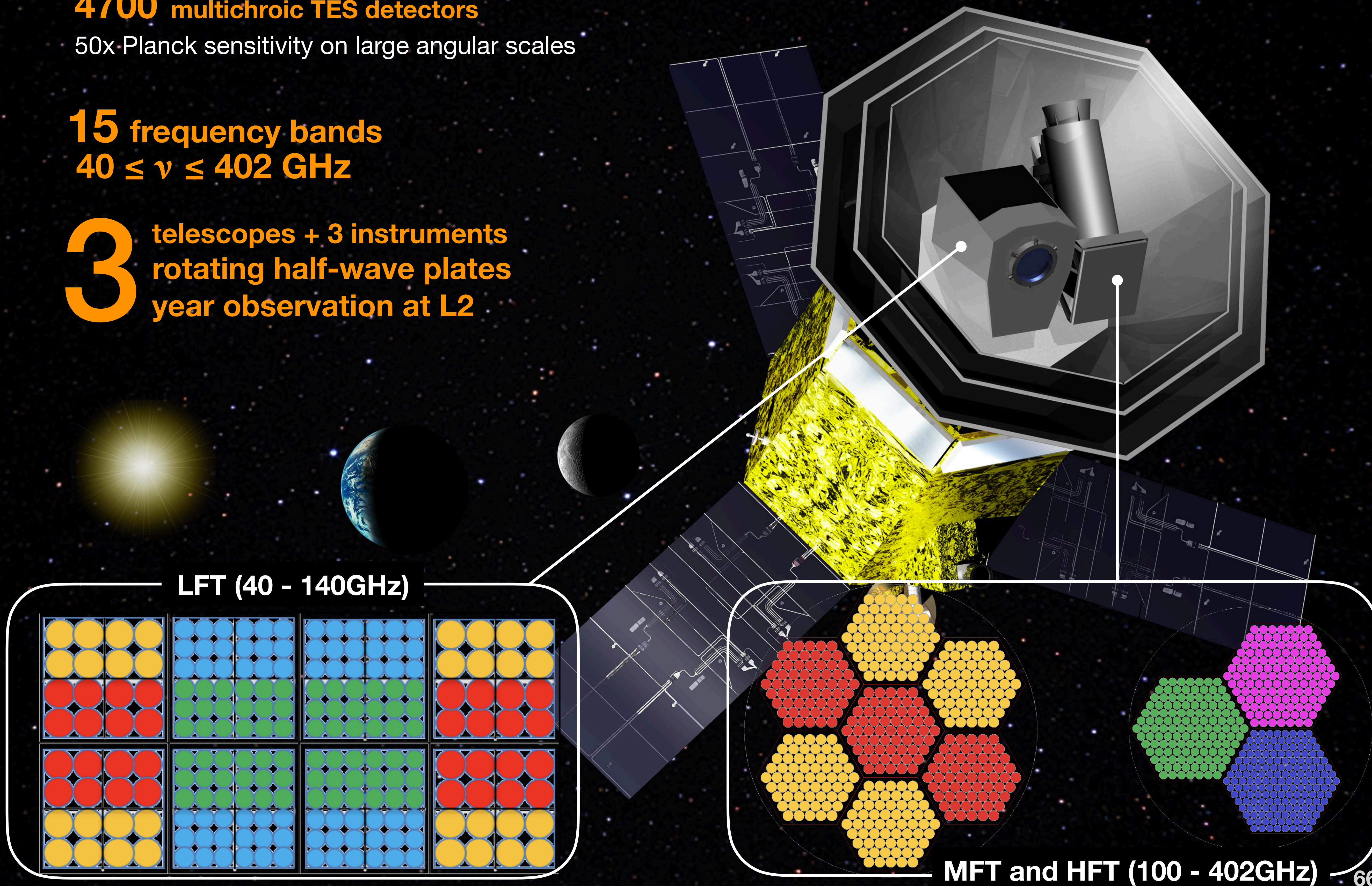
4700 multichroic TES detectors

50x Planck sensitivity on large angular scales

15 frequency bands

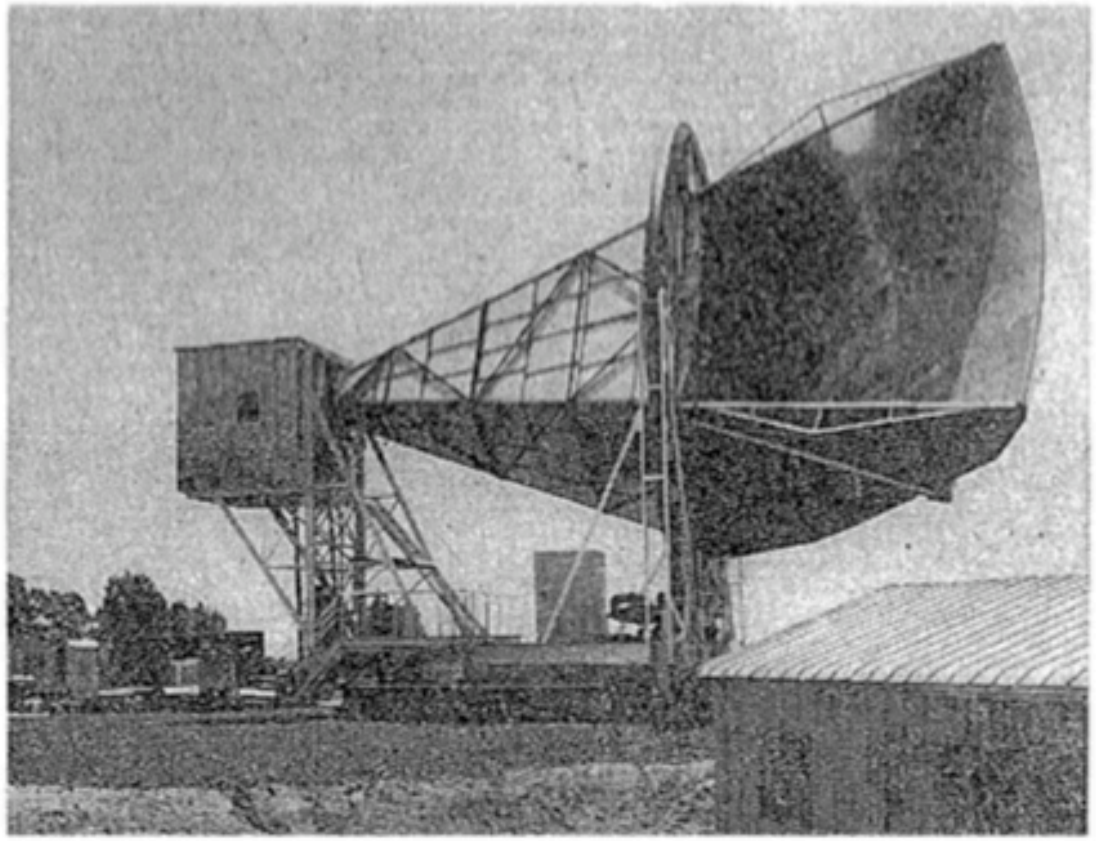
$40 \leq \nu \leq 402$ GHz

3 **telescopes + 3 instruments**
rotating half-wave plates
year observation at L2



BACKUP

Signals Imply a 'Big Bang' Universe



Horn antenna, used in space exploration, at the Bell Laboratories in Holmdel, N. J.

By WALTER SULLIVAN

Scientists at the Bell Telephone Laboratories have observed what a group at Princeton University believes may be remnants of an explosion that gave birth to the universe.

These remnants are thought to have originated in the burst of light from that cataclysmic event.

Such a primordial explosion is embodied in the "big bang" theory of the universe. It seeks to explain the observation that virtually all distant galaxies are flying away from the earth. Their motion implies that they all originated at a single point 10 or 15 billion years ago.

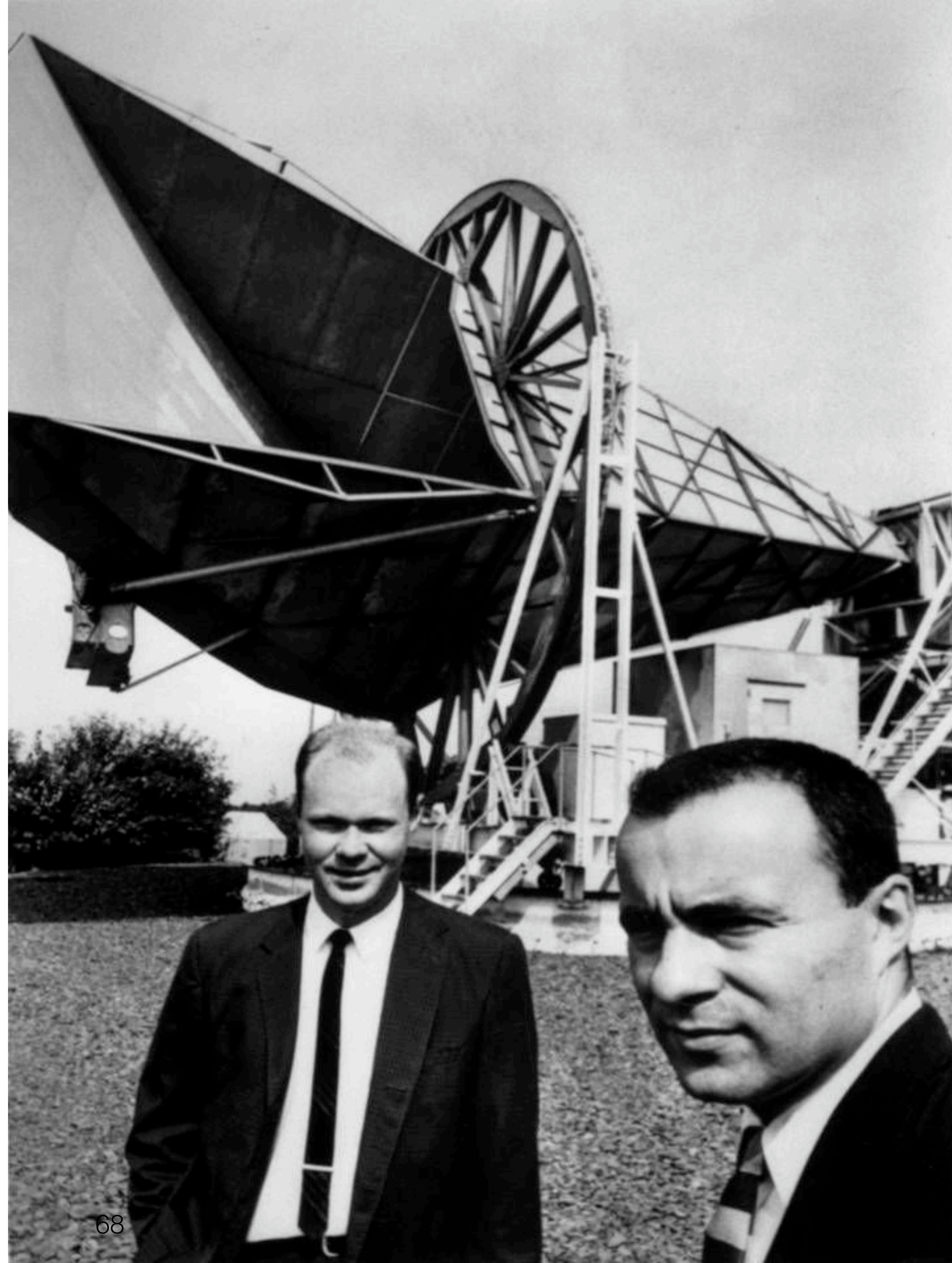
The Bell observations, made by Drs. Arno A. Penzias and Robert W. Wilson from a hilltop in Holmdel, N. J., were of radio waves that appear to be flying in all directions through the universe. Since radio waves and light waves are identical, except for their wavelength, these are thought to be remnants of light waves from the primordial flash.

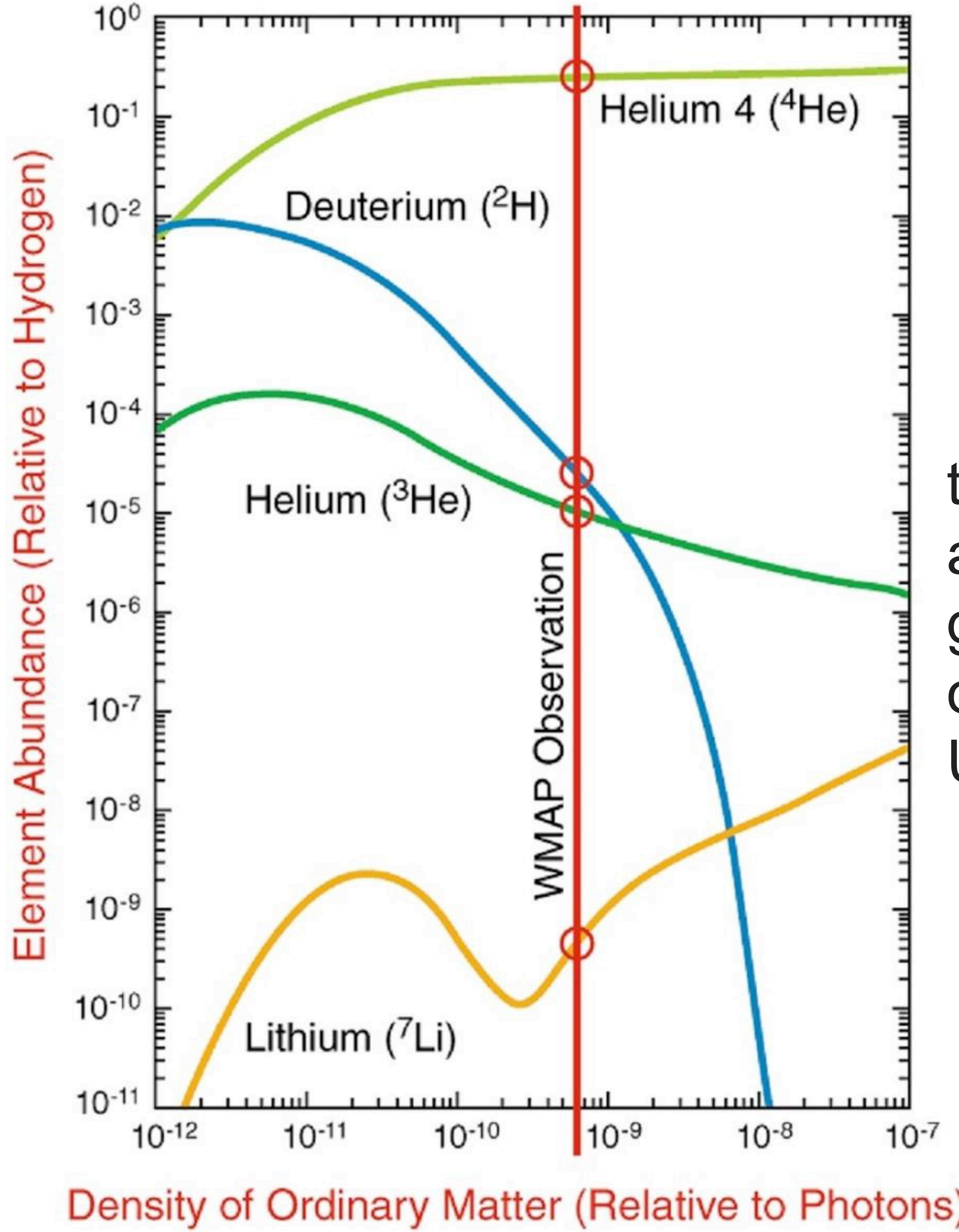
The waves were stretched into radio waves by the vast expansion of the universe that has occurred since the explosion and release of the waves from the expanding gas cloud born of the fireball.

In what may prove to be one of the most remarkable coincidences in scientific history, the existence of such waves was predicted at

Continued on Page 18, Column 1

The New York Times
Published: May 21, 1965

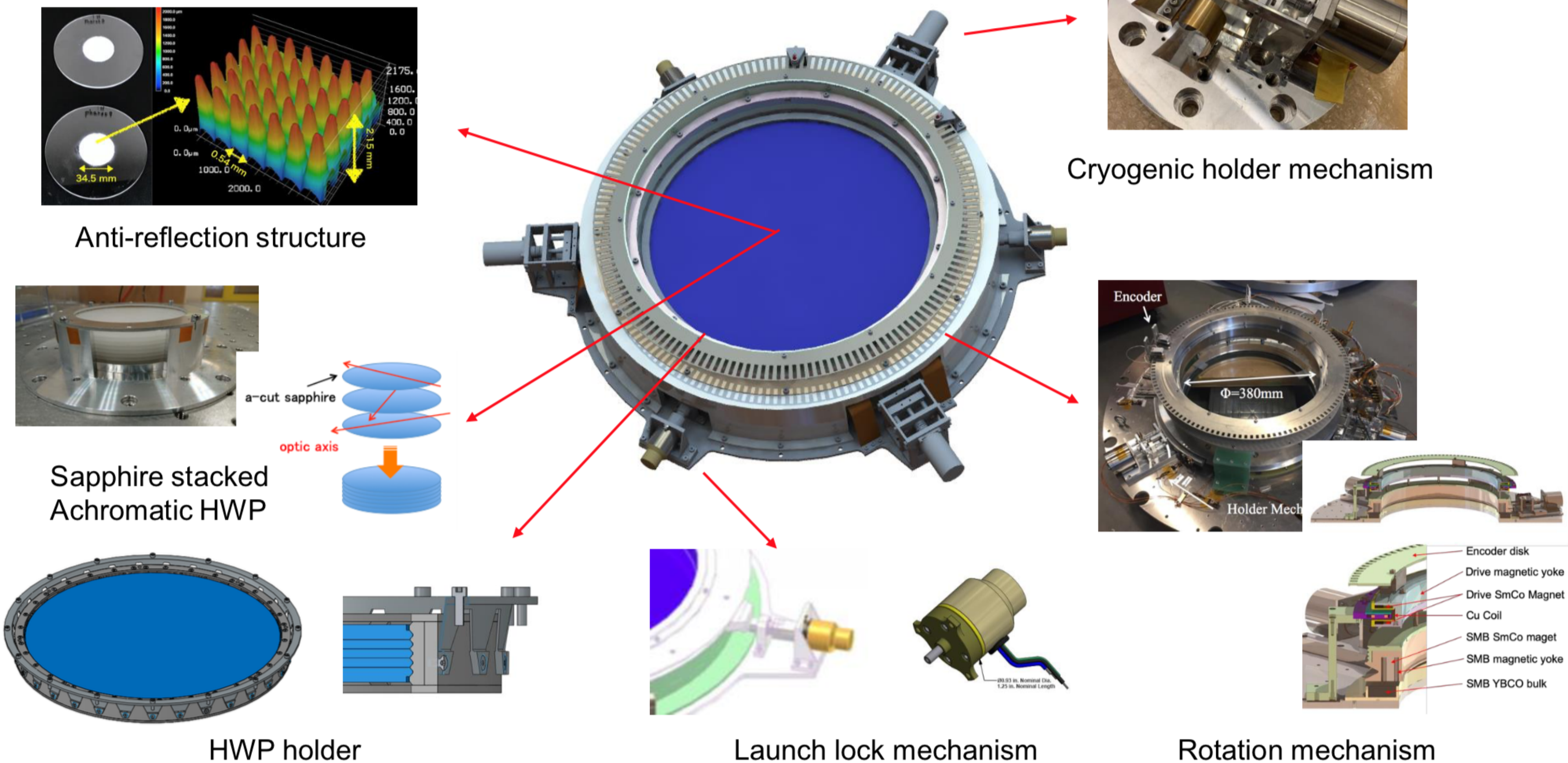




the hot Big Bang also predicts the good proportions of elements in the Universe!

LFT Polarization modulator developments

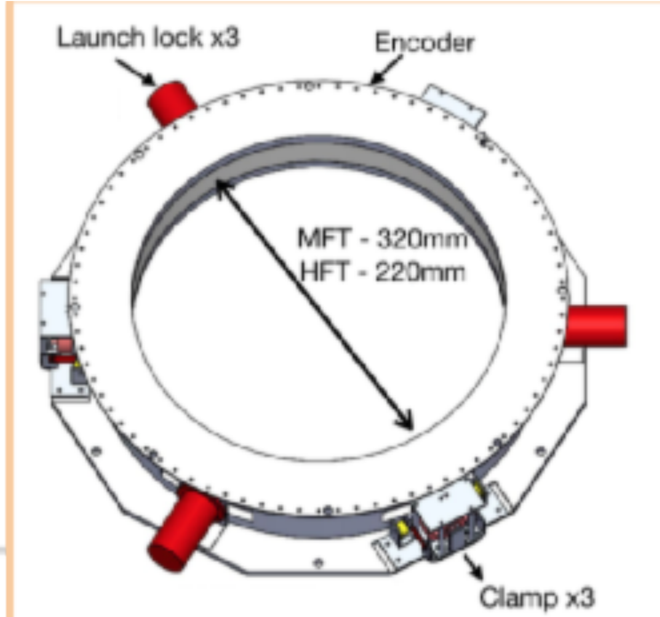
(As for MHFT PM developments, see B. Mot, et al.)

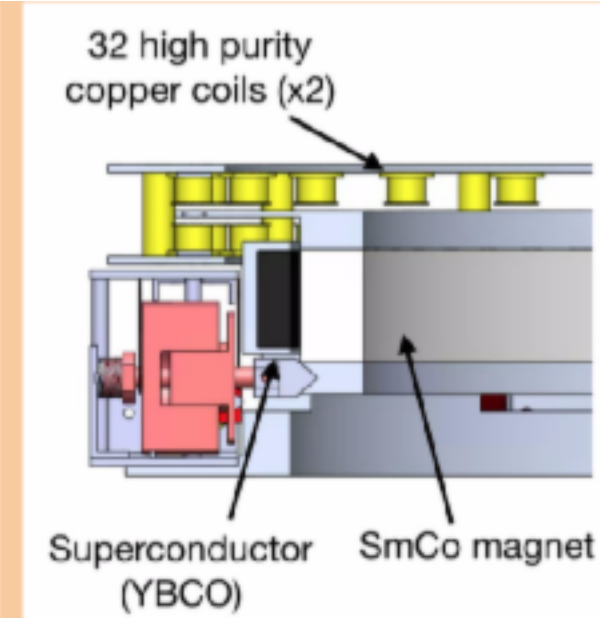


MHFT:

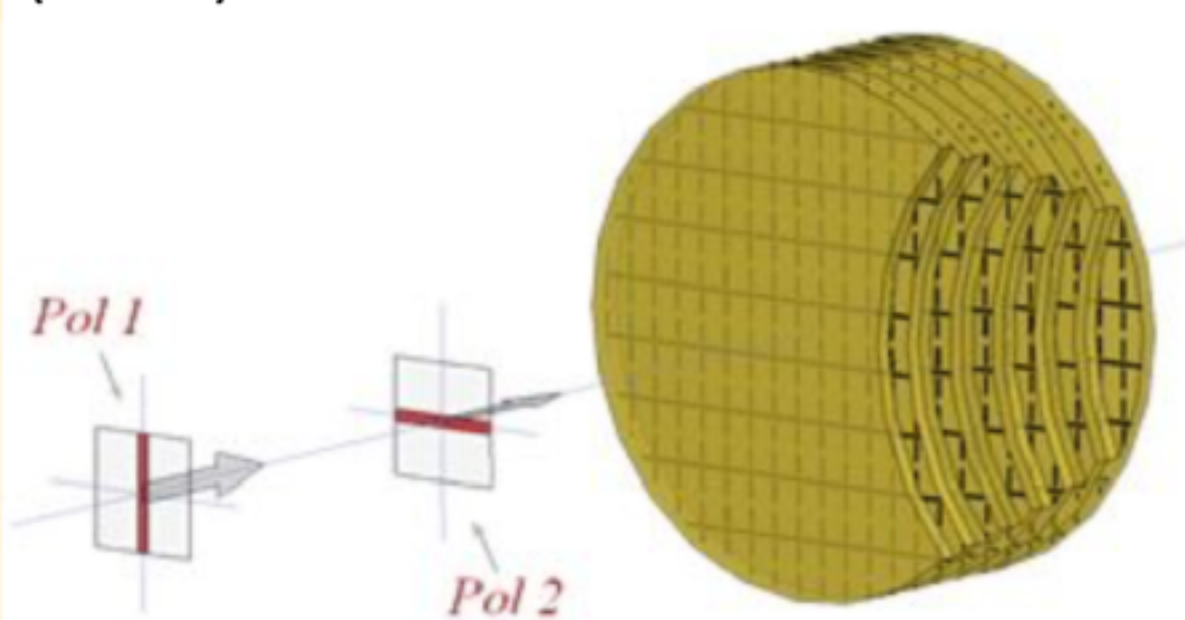
Φ 30 mm and 39-70rpm;

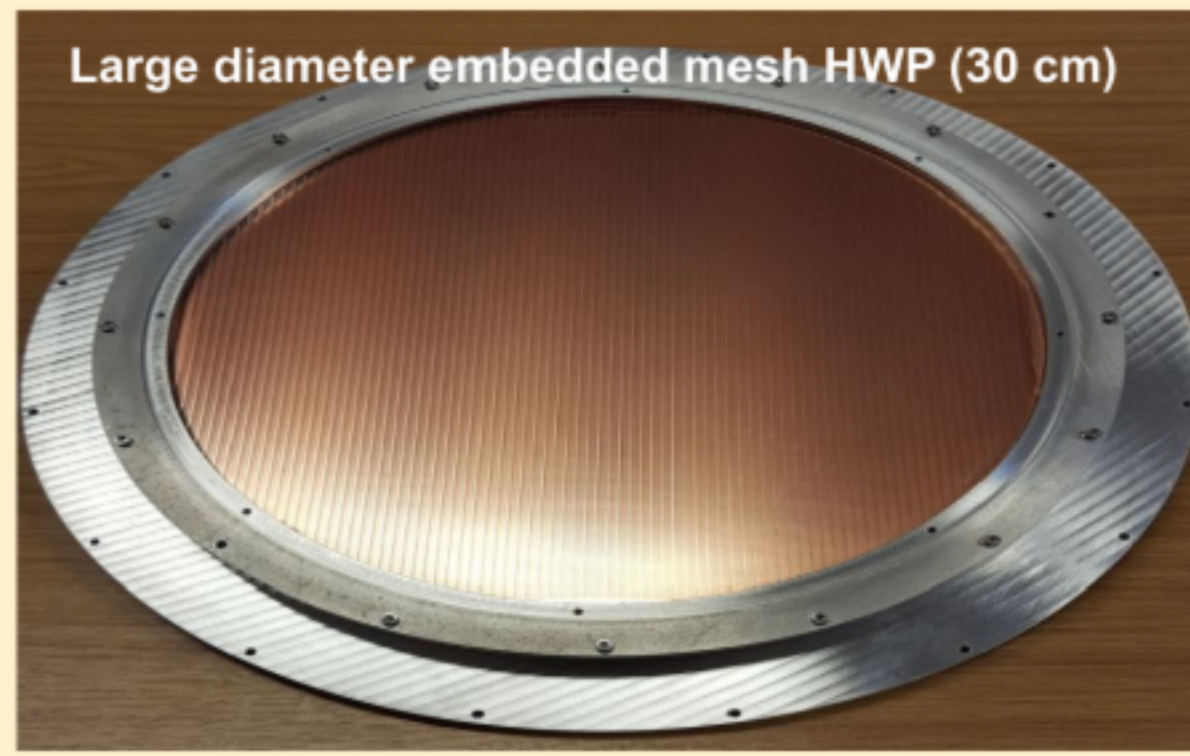
Φ 20 mm and 61-110rpm.





(Cardiff) **Embedded Mesh-HWP**





LiteBIRD —science outcomes

- Full success
- Extra success (see previous page)
- Characterization of B-mode and search for sources fields
  (e.g scale-invariance, non-Gaussianity, parity violation)
- Power spectrum features in polarization
- Large-scale E mode and its implications
  for reionization history and the neutrino mass
- Cosmic birefringence
- SZ effect (thermal and relativistic correction)
- Elucidating anomalies
- Galactic science