Cosmology with CMB in space

Josquin Errard (APC/CNRS)
Grenoble, Dec 9-10

Cosmology with CMB in space

Inflation

with LiteBIRD

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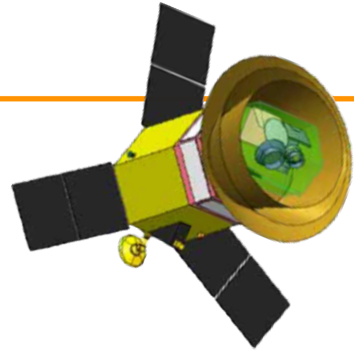

launch in 2028

IN2P3 Prospects 2020

GT05 – Physique de l'inflation et énergie noire

Cosmic inflation and fundamental physics from space
LiteBIRD

Porteur: Matthieu Tristram

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[a]APC, [b]CEA, [c]ENS, [d]IAP, [e]IAS, [f]Institut Néel, [g]IPAG, [h]IRAP, [i]LAL, [j]LPSC, [k]LPT, [l]FORTH (Greece)

LiteBIRD is a space mission selected by JAXA as its Strategic Large Mission scheduled for launch in 2027. LiteBIRD represents the next generation of CMB mission after COBE, WMAP, and Planck. The science goals of LiteBIRD are to detect the primordial gravitational waves through the measure of the tensor-to-scalar ratio, r, and to characterize the CMB B-mode and E-mode spectra down to degree scales with an unprecedented sensitivity. With a sensitivity after component separation which reaches $\sigma(r) = 10^{-4}$ on the tensor-to-scalar ratio, the mission defines "full success" for a final precision better than $\sigma(r) = 10^{-3}$ including the post-cleaning contributions of residual foreground and systematic effect residuals. This will be achieved using LiteBIRD data only, without applying any correction for lensing. A further improvement in the B-mode sensitivity will come from the combination of LiteBIRD and ground-based data (including delensing). This creates the possibility for the first detection of a quantum gravitational wave or, at the very least, will considerably improve the current upper limits by more than one order of magnitude.

In addition, LiteBIRD will provide an ultimate measurement of large scale E-modes polarisation which will allow constraining the reionization models as well as breaking degeneracies in determining other cosmological parameters. LiteBIRD will also give access to unprecedented polarization maps in multiple frequency bands in mm-domain allowing for constraints on possible spectral distortions of the primordial blackbody, testing parity violation in the early Universe as well as constraining the physics of post-inflationary reheating.

This paper is tightly coupled with the proposals "Cosmic inflation - theory" and "Cosmic inflation from ground based CMB polarization experiments".

IN2P3 Prospectives 2020

GT05 - Physique de l'inflation et énergie noire

ESA Voyage 2050 white papers for cosmology with a spectro-polarimetric survey of the microwave sky

Jacques Delabrouille[a] on behalf of the proposers

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and
IRFU, CEA-Saclay, 91190 Gif-sur-Yvette Cedex

voyage 2050

THE THIRD SKY PROGRAMME.

V.K.Dubrovich[1], M.Yu.Khlopov[2,3,4]

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[2] National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), 115409 Moscow, Russia
[3] APC laboratory 10, rue Alice Domon et Leonie Duquet 75205 Paris Cedex 13, France
[4] Institute of Physics, Southern Federal University, Stachki 194 Rostov on Don 344090, Russia

The study of the early universe goes in several directions. One of the most advanced at pr statistical description of the power spectrum of primary temperature fluctuations of the C fluctuations are observed on the last scattering surface in the epoch of recombination of l redshifts of about 1100. In addition, the global characteristics of the CMB spectrum carryi on the global energy release in the epoch of z <10^5 are investigated. However, with all the achievements of these works, there are still directions completely unexplored in the expe

Cosmic Microwave Background

primordial fluctuations

large scale B-modes
➔ tensor-to-scalar ratio (BB)
damping tail
➔ primordial power on small scales (TE, TT, EE)
➔ primordial bispectrum (f_{NL} via TTT,TTE,… + lens/kSZ)

relativistic species

damping tail
➔ N_{eff} (TE, TT, EE)

reionization

sources
➔ duration of reionization (kSZ)
➔ mean free path of photons (kSZ)

neutrino mass

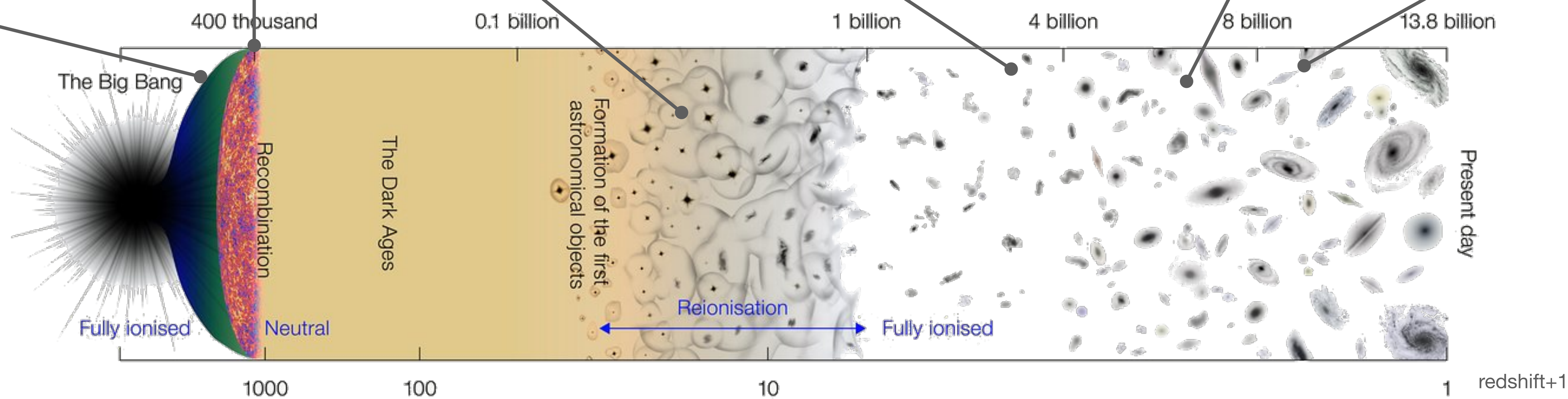
lensing potential (TT+EB), tSZ
➔ Σm_ν

galaxy evolution

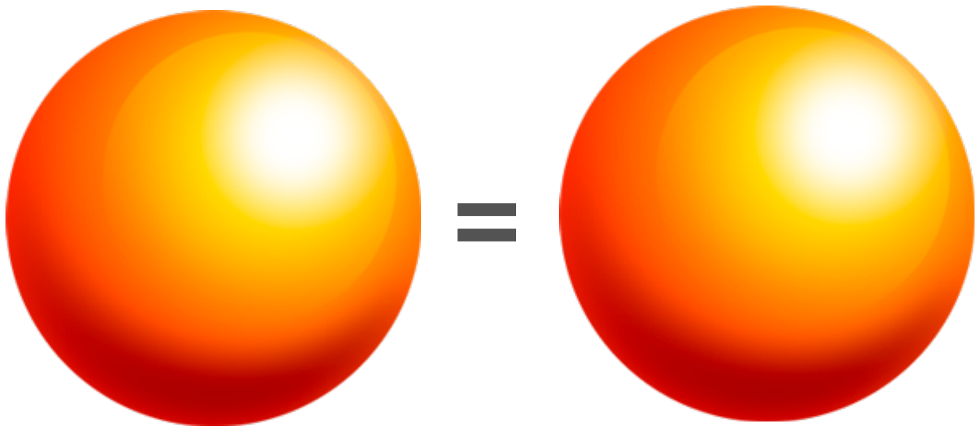
tSZ, kSZ
➔ non-thermal pressure (tSZ+kSZ)
➔ feedback efficiency (tSZ+kSZ)

dark energy

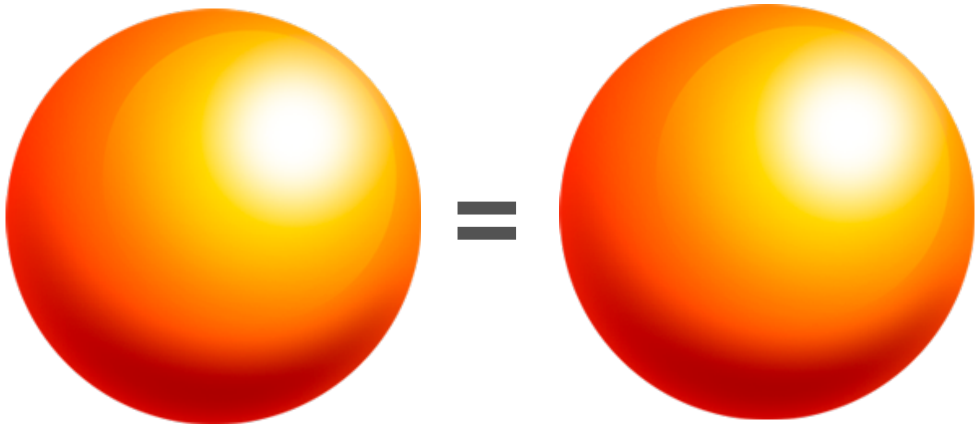
tSZ, lensing
➔ σ_8 at z=2-3 (lensing, tSZ)
➔ growth of structure (kSZ)



credits: ESO



T = 2.7 K



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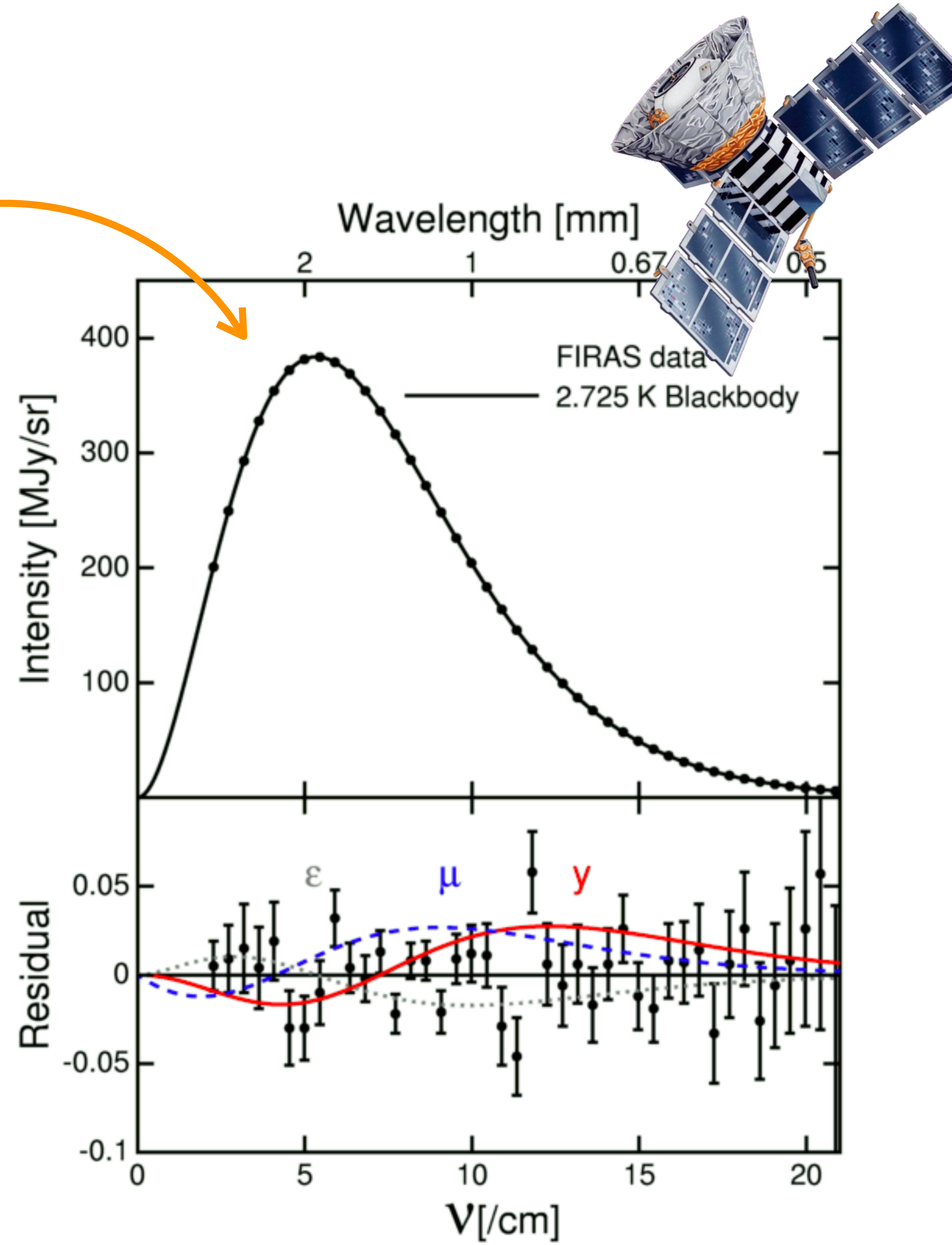
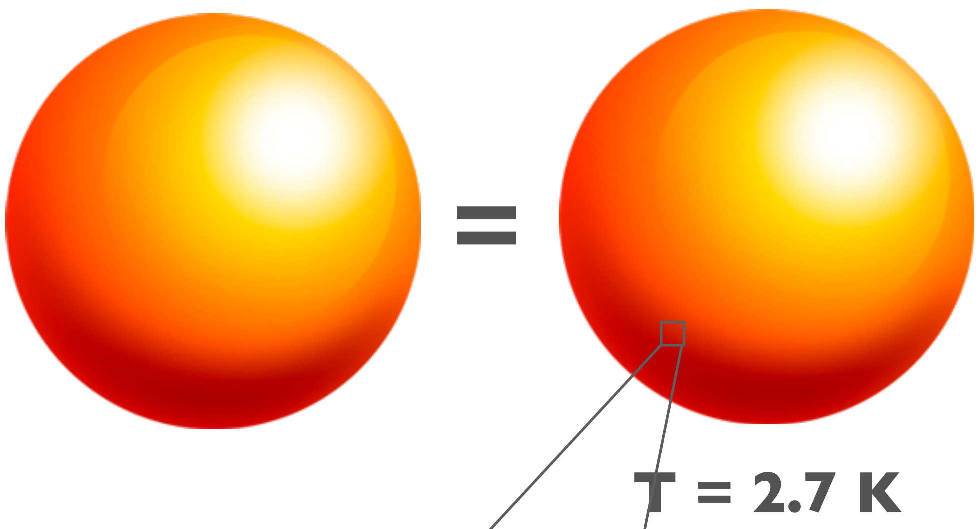
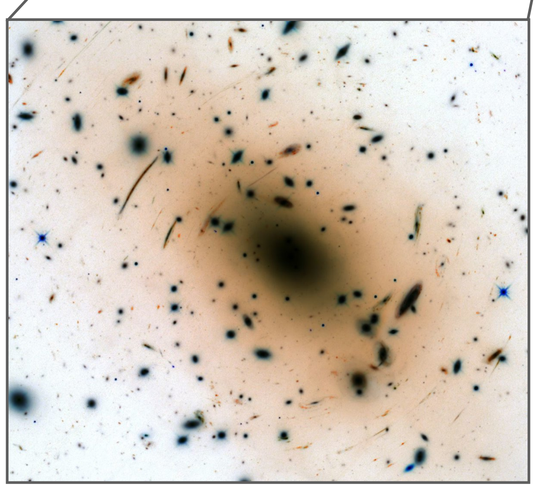
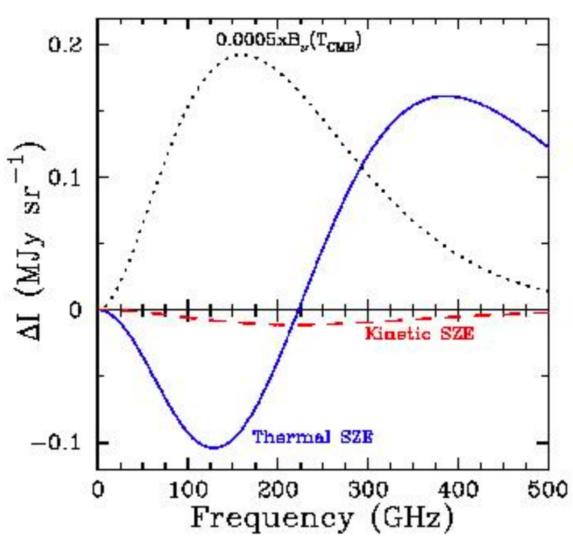
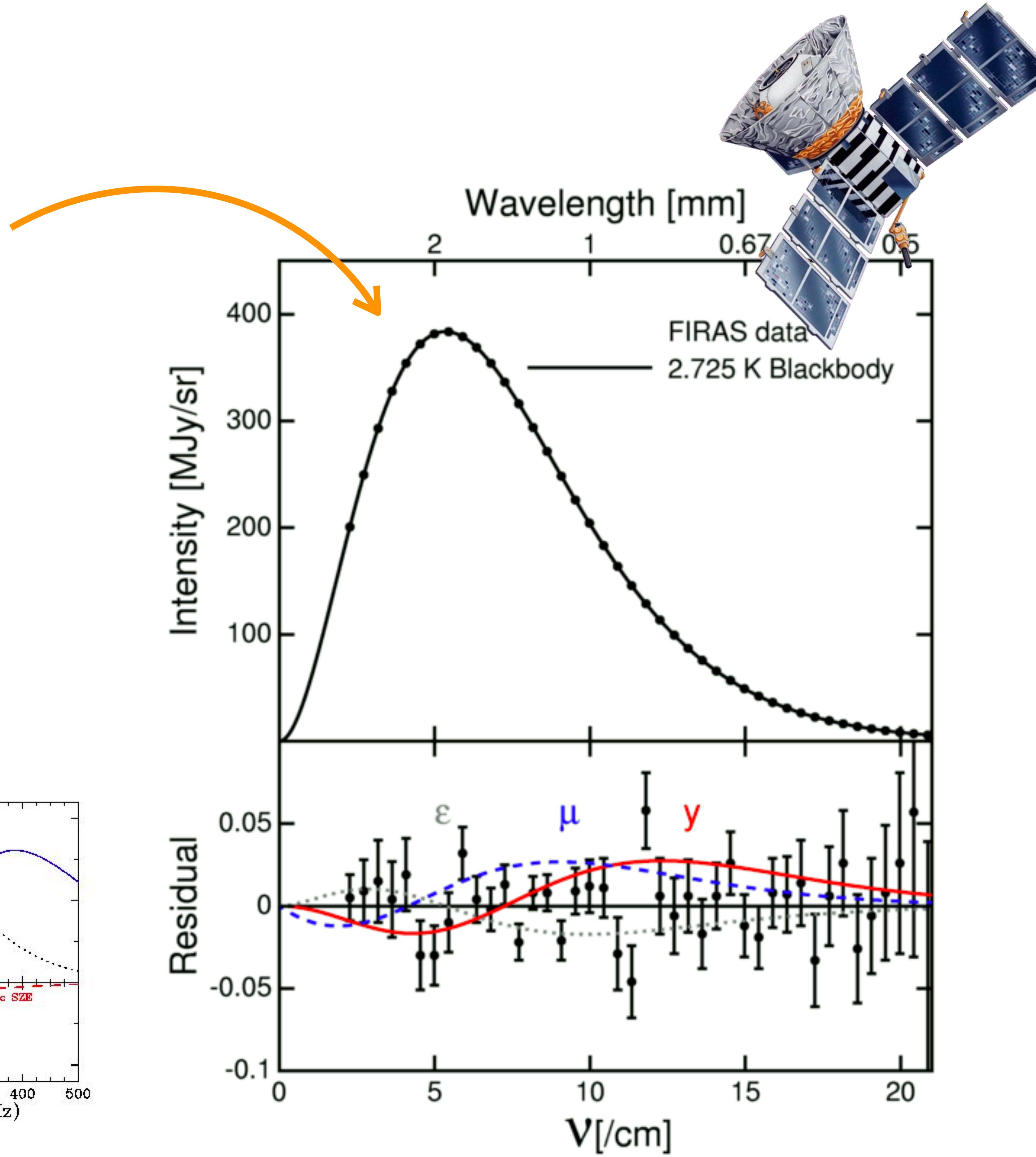

Wavelength [mm]
2
1
0.67
0.5
400
300
200
100
Intensity [MJy/sr]
FIRAS data
2.725 K Blackbody
ε
μ
y
0.05
0
-0.05
-0.1
Residual
0
5
10
15
20
ν[/cm]

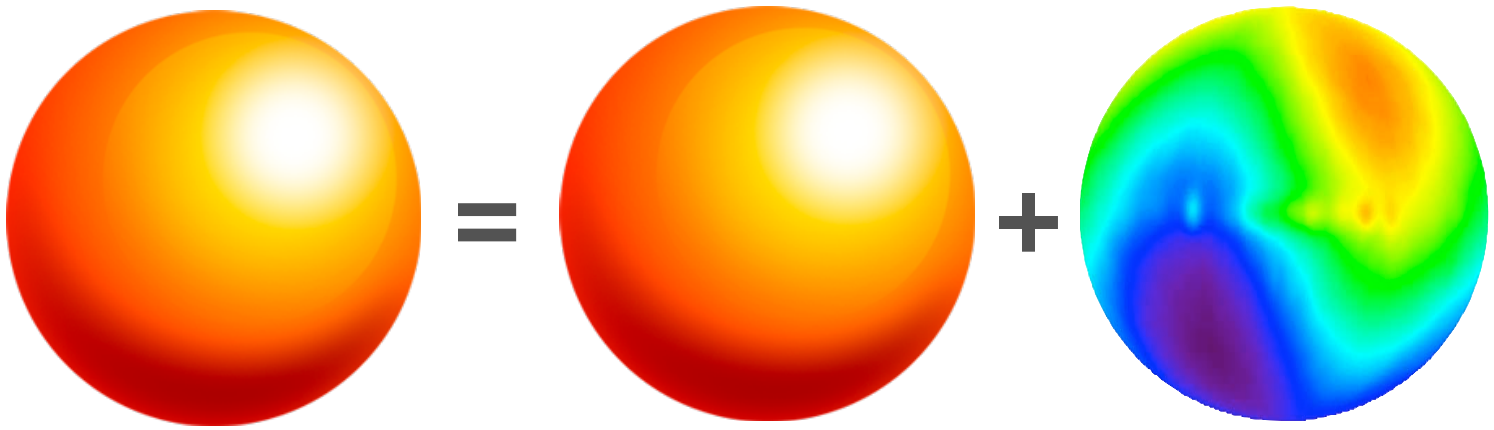






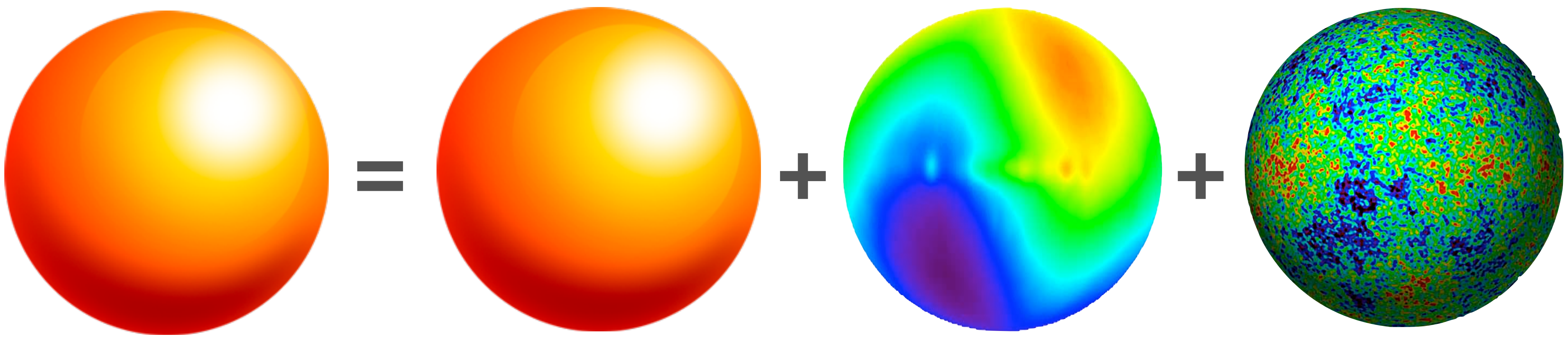


[see talks by Celine Combet and Thibaut Louis]



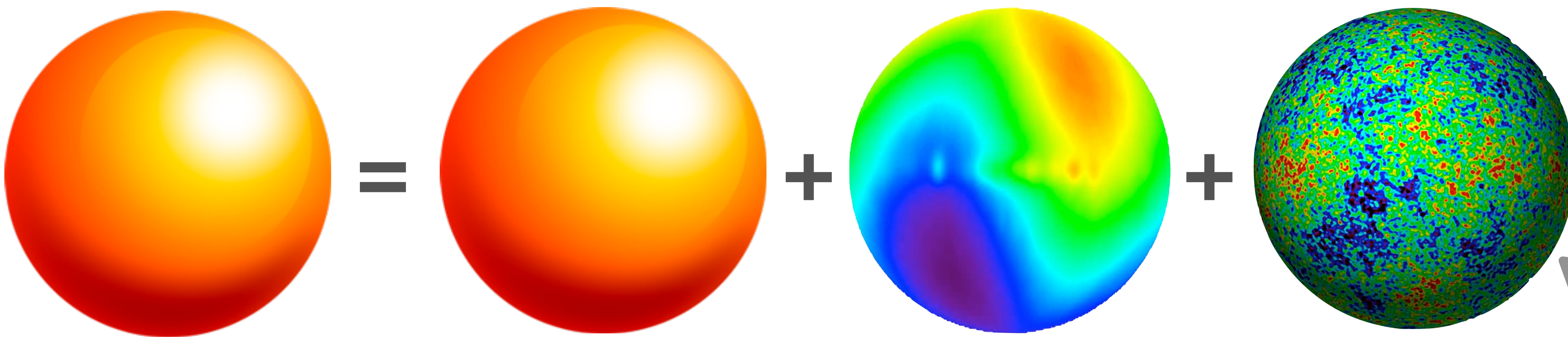
$T = 2.7$ K $\quad \Delta T/T \sim 10^{-3}$

key predictions from cosmic inflation



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

key predictions from cosmic inflation

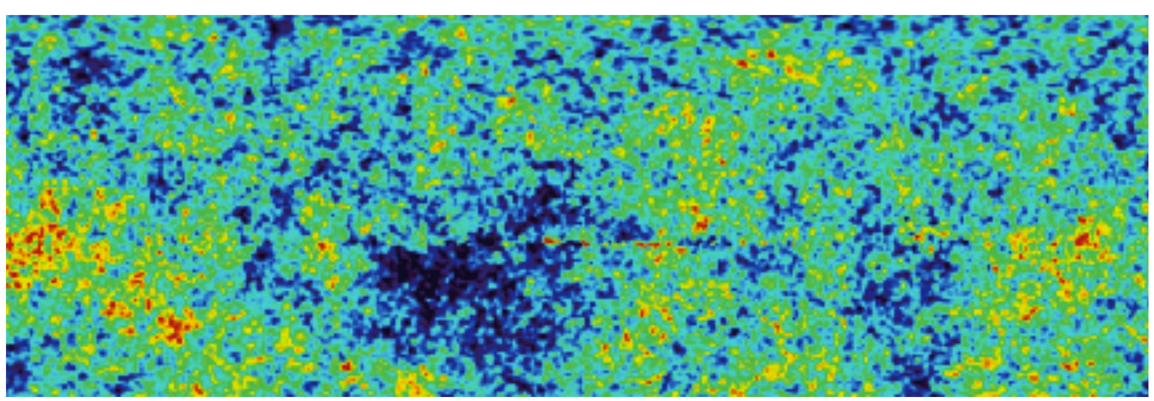


T = 2.7 K $\Delta T/T \sim 10^{-3}$ $\Delta T/T \sim 10^{-5}$

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

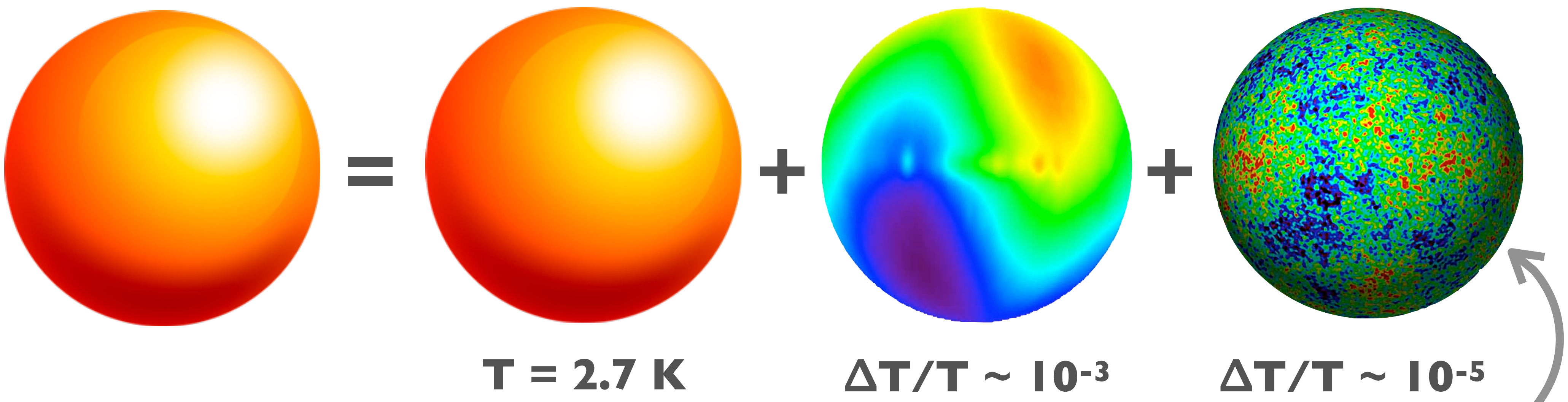
- Fluctuations we observe today in CMB and the matter distribution originate from quantum fluctuations during inflation

$\zeta \longrightarrow$



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

key predictions from cosmic inflation



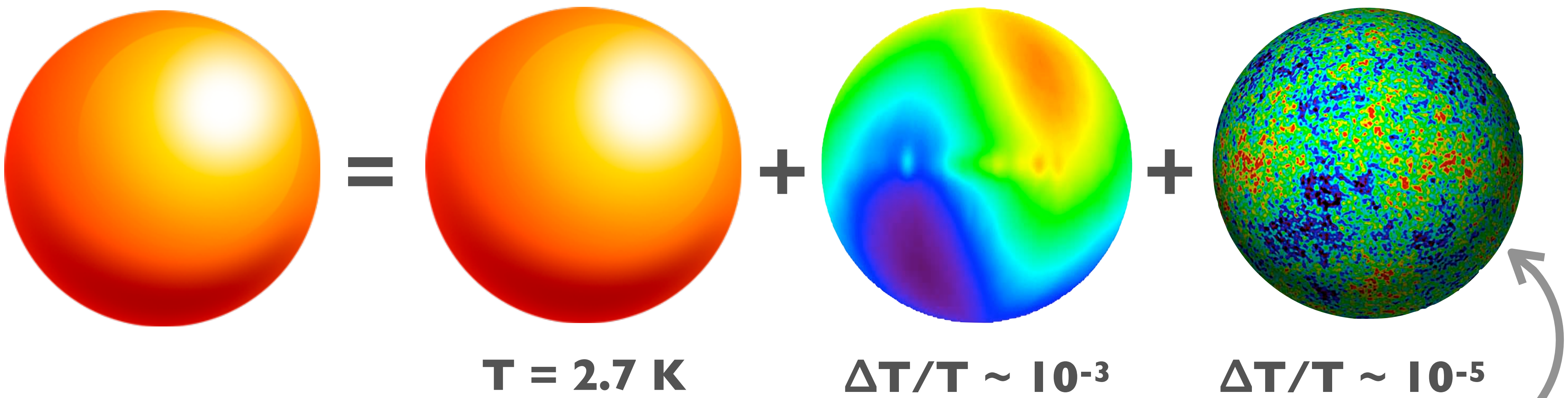
observations are already in remarkable agreement with single-field slow-roll inflation:

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

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



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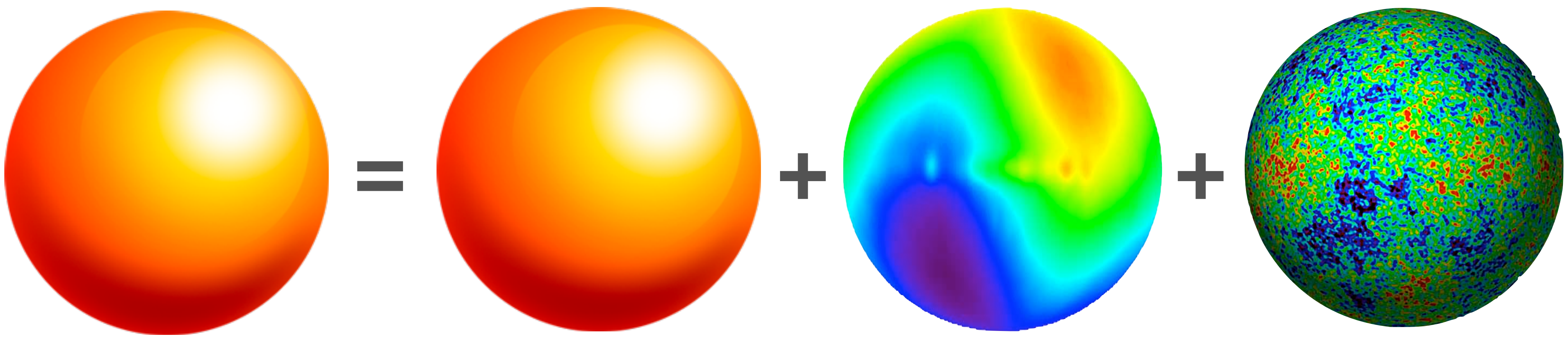
but we want gravitational waves in addition!
“extraordinary claims require extraordinary evidence”

key predictions from cosmic inflation



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

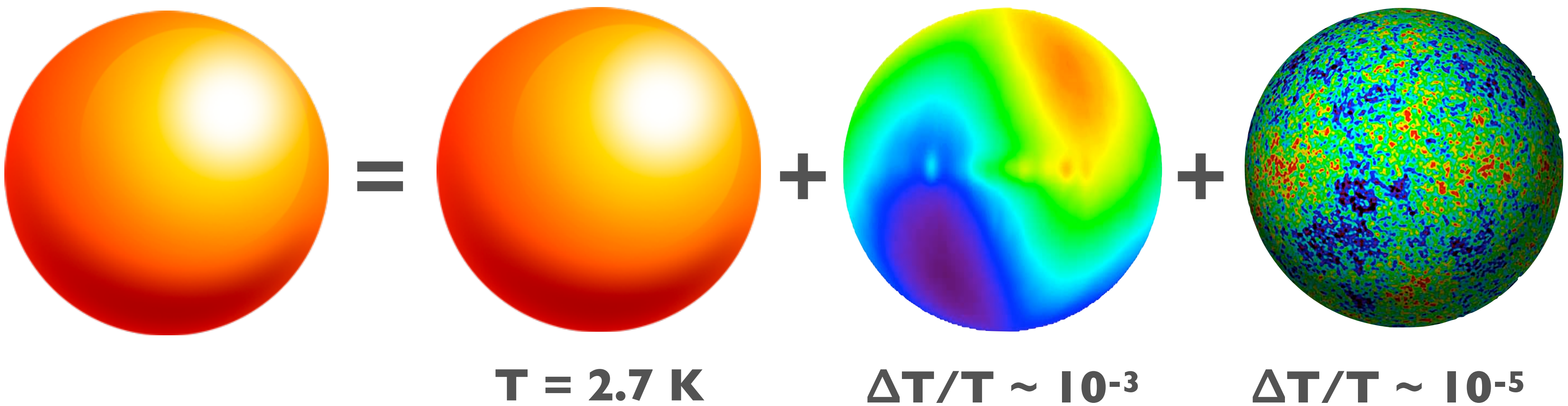
$$d\ell^2 = a^2(t)[1 + 2\zeta(\mathbf{x}, t)][\delta_{ij} + h_{ij}(\mathbf{x}, t)]dx^i dx^j$$

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

h_{ij} ⟶

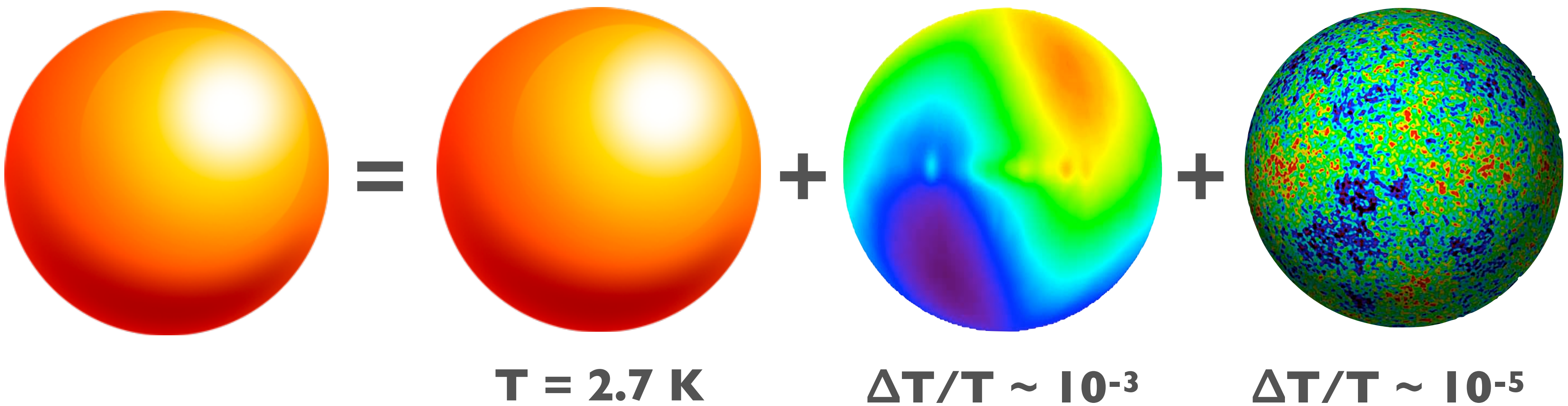
Grishchuk (1974)
Starobinsky (1979)

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**!

key predictions from cosmic inflation



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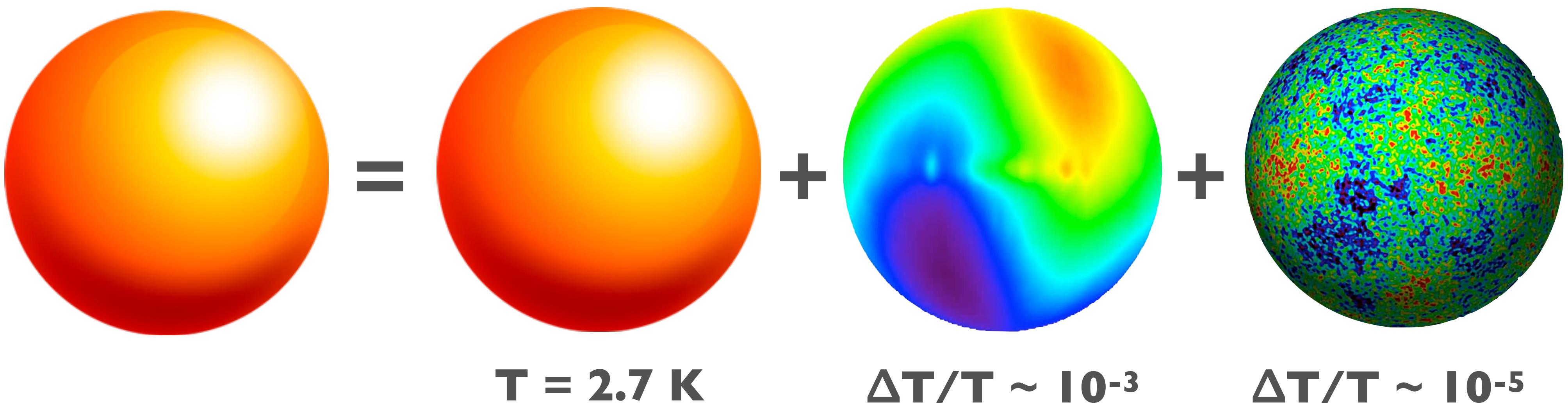
how to detect them?

key predictions from cosmic inflation



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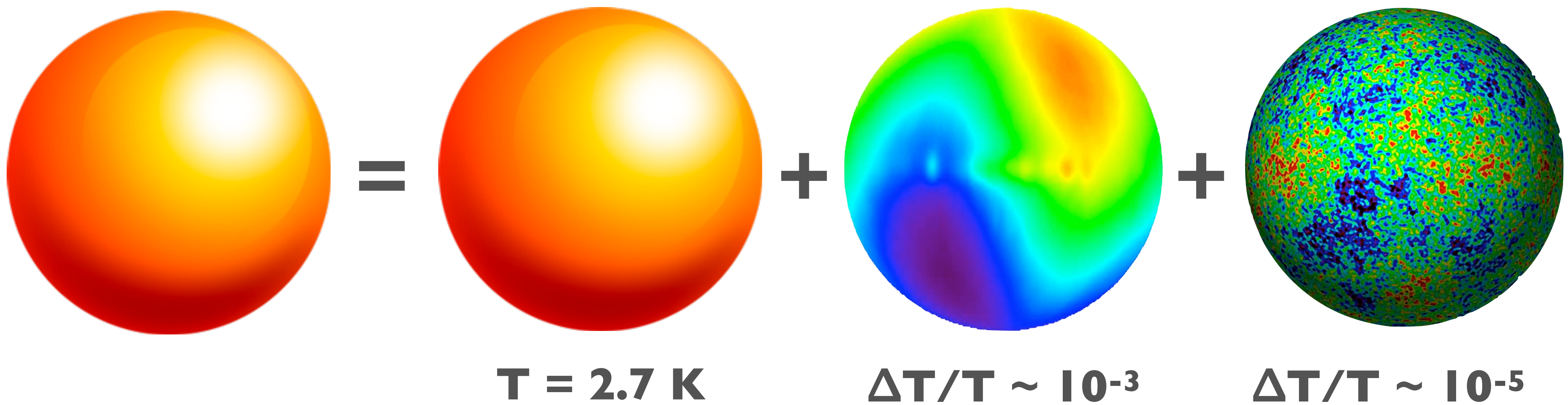
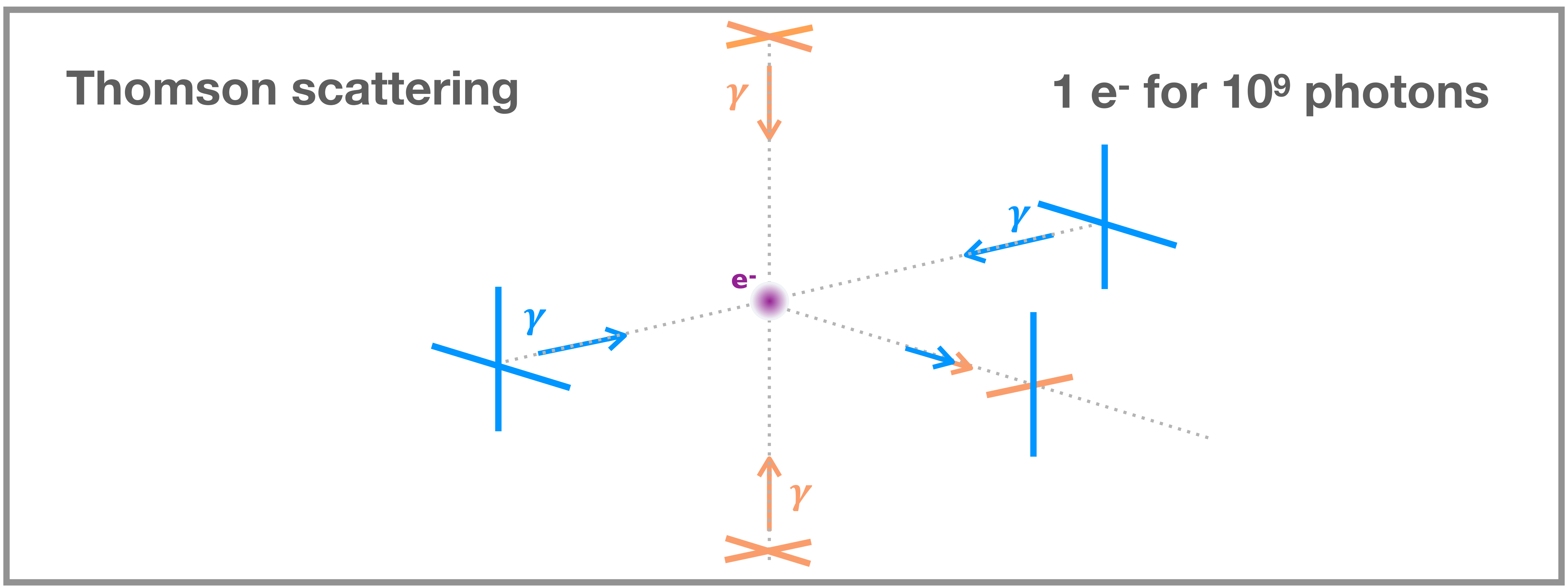
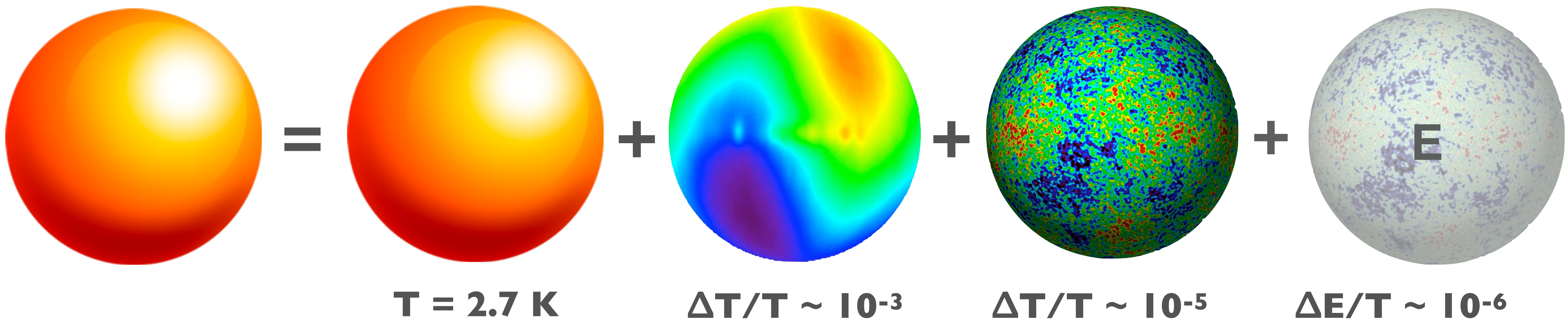
CMB POLARIZATION!

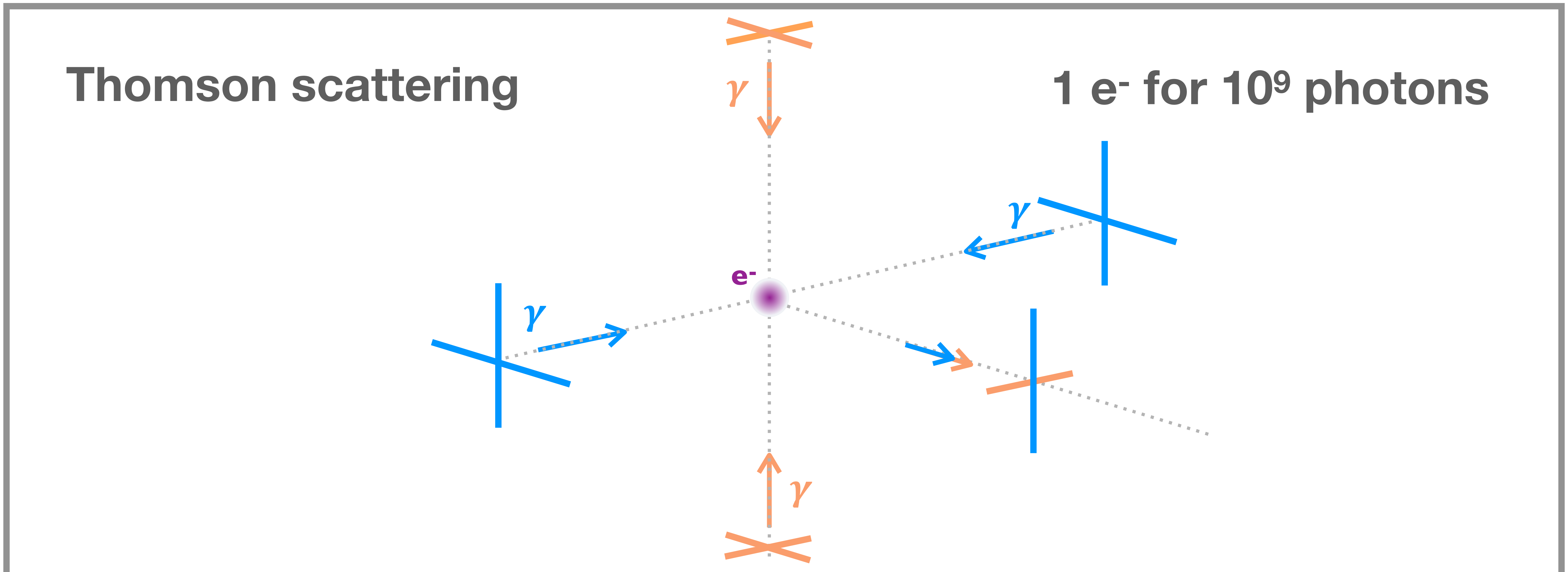
key predictions from cosmic inflation



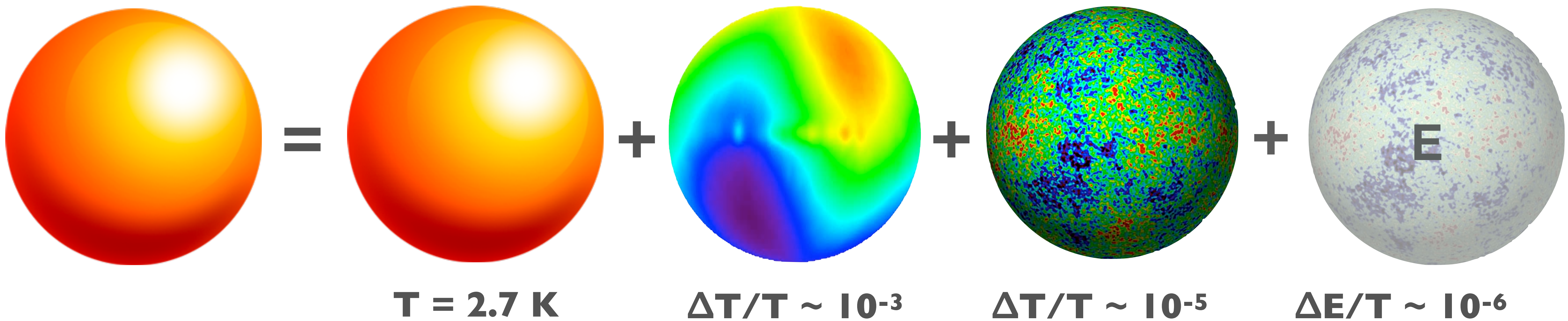


key predictions from cosmic inflation

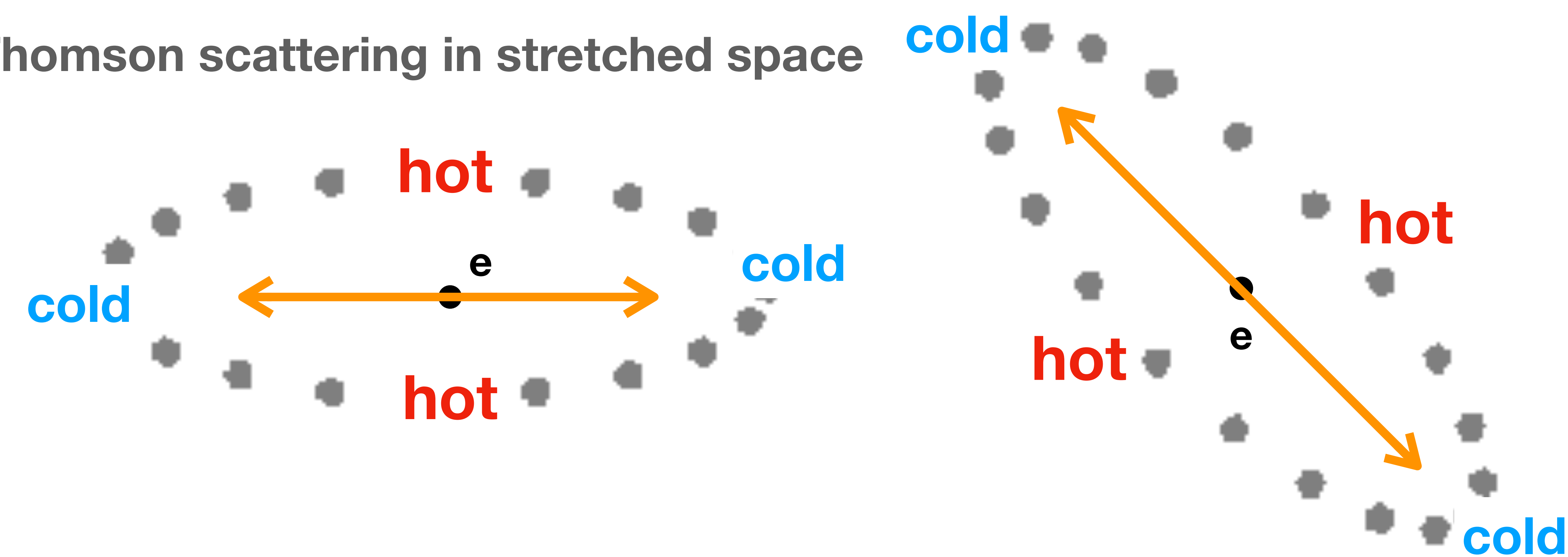




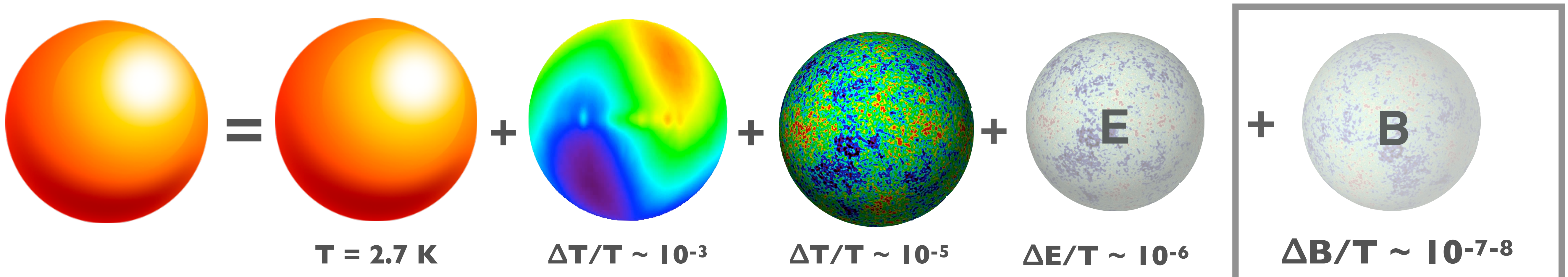
key predictions from cosmic inflation

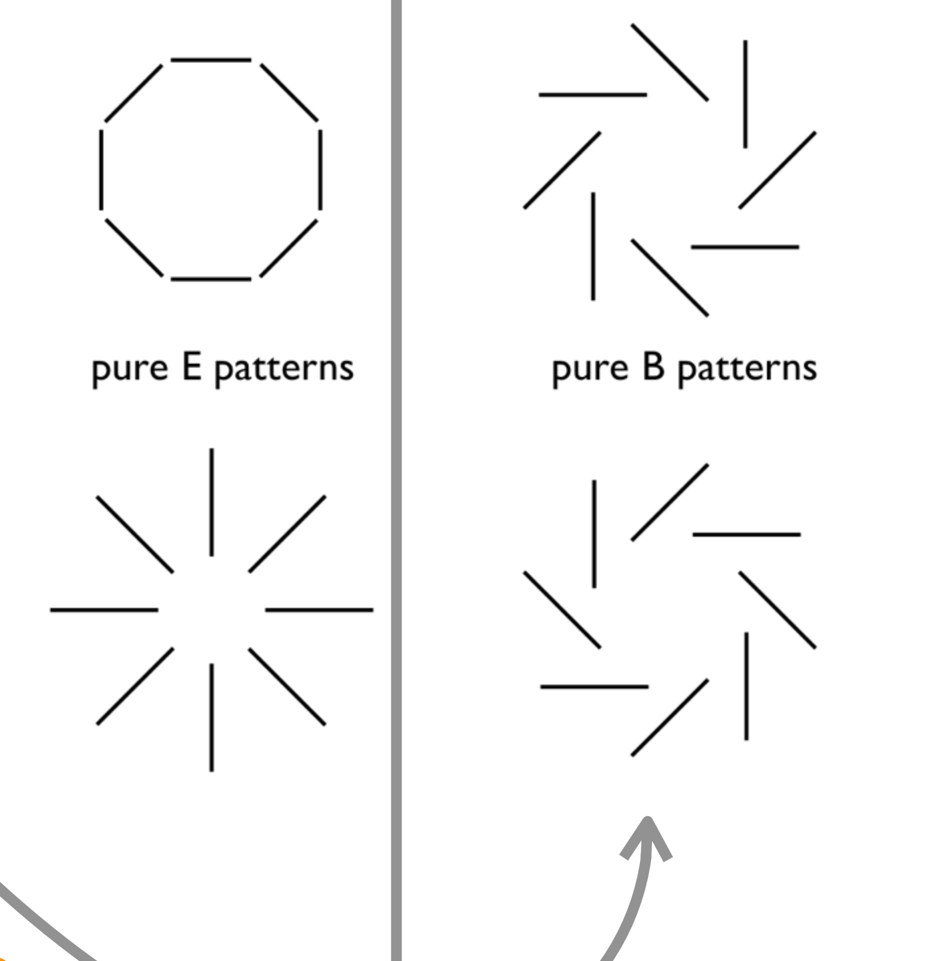


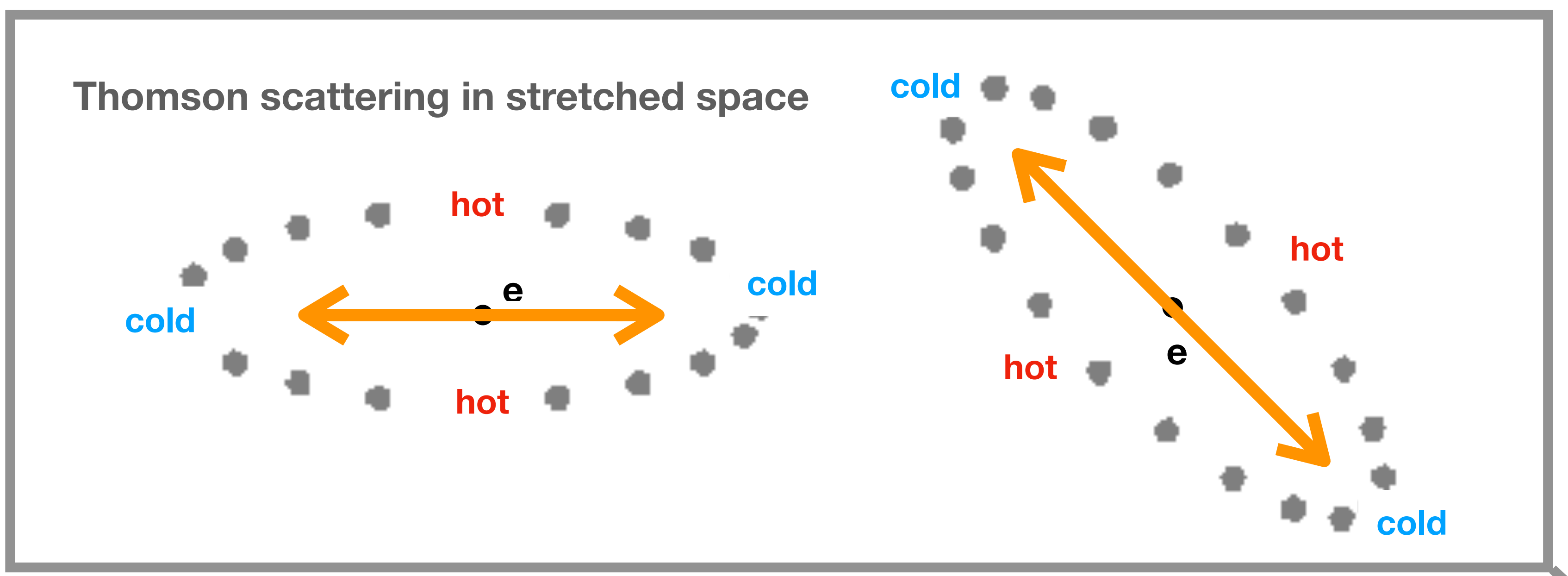
Thomson scattering in stretched space



key predictions from cosmic inflation







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

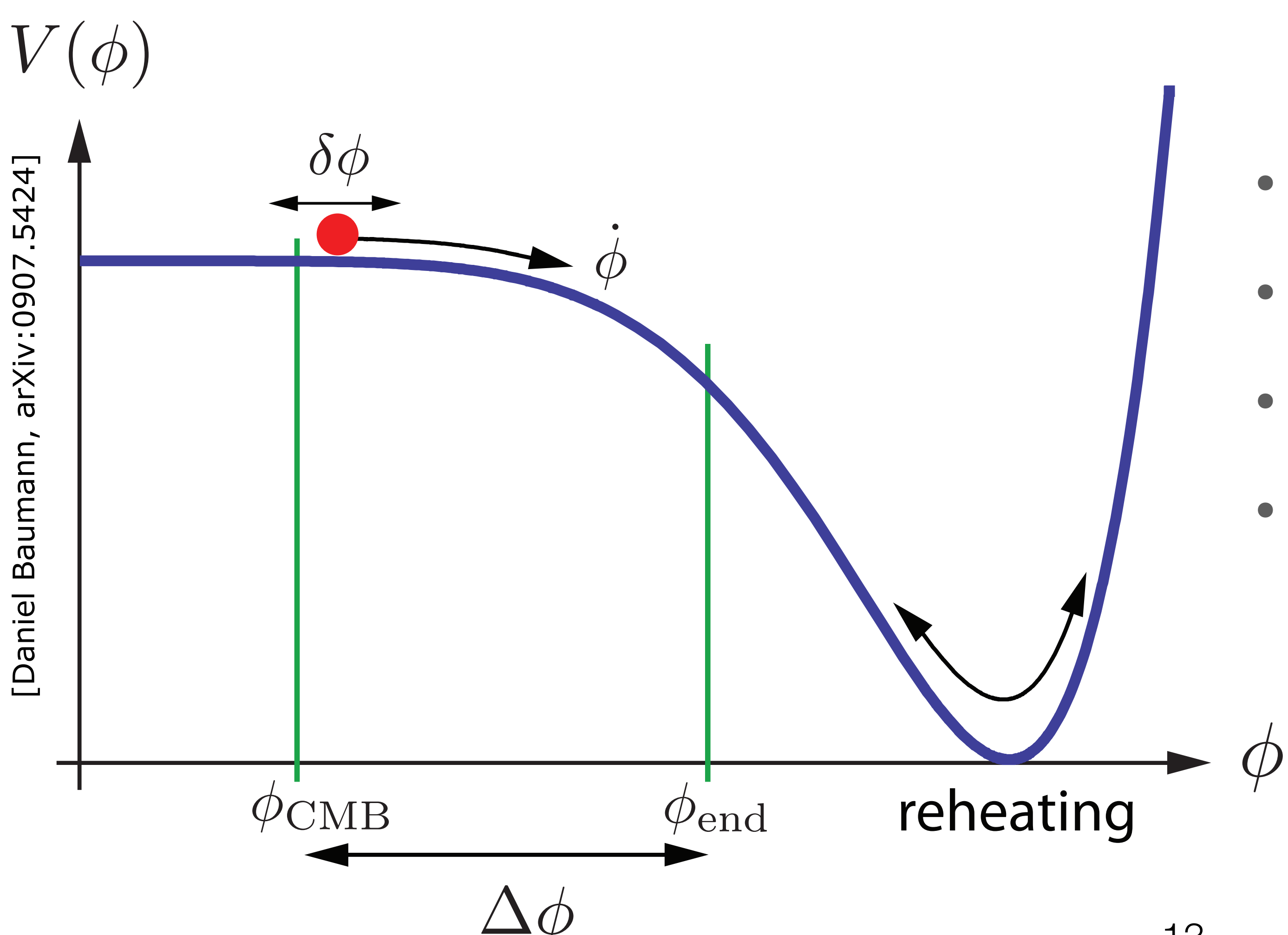
inflation ϕ

[see talk by Elias + Vincent Vennin et al prospective paper]

- dynamics of an homogeneous scalar field in a FRW geometry is given by

$$\ddot{\phi} + 3H\dot{\phi} + V_{,\phi} = 0 \qquad \text{and} \qquad H^2 = \frac{1}{3}\left(\frac{1}{2}\dot{\phi}^2 + V(\phi)\right)$$

- inflation happen when potential dominates over kinetic energy (slow-roll)



- where did **V(Φ) comes from** ?
- why did the field start in **slow-roll** ?
- why is the potential so **flat** ?
- how do we convert the field energy into **particules** ?

credits: Matt Tristram

inflation ϕ

- **According to single field, slow-roll inflationary scenario, quantum vacuum fluctuations excite cosmological scalar and tensor perturbations**

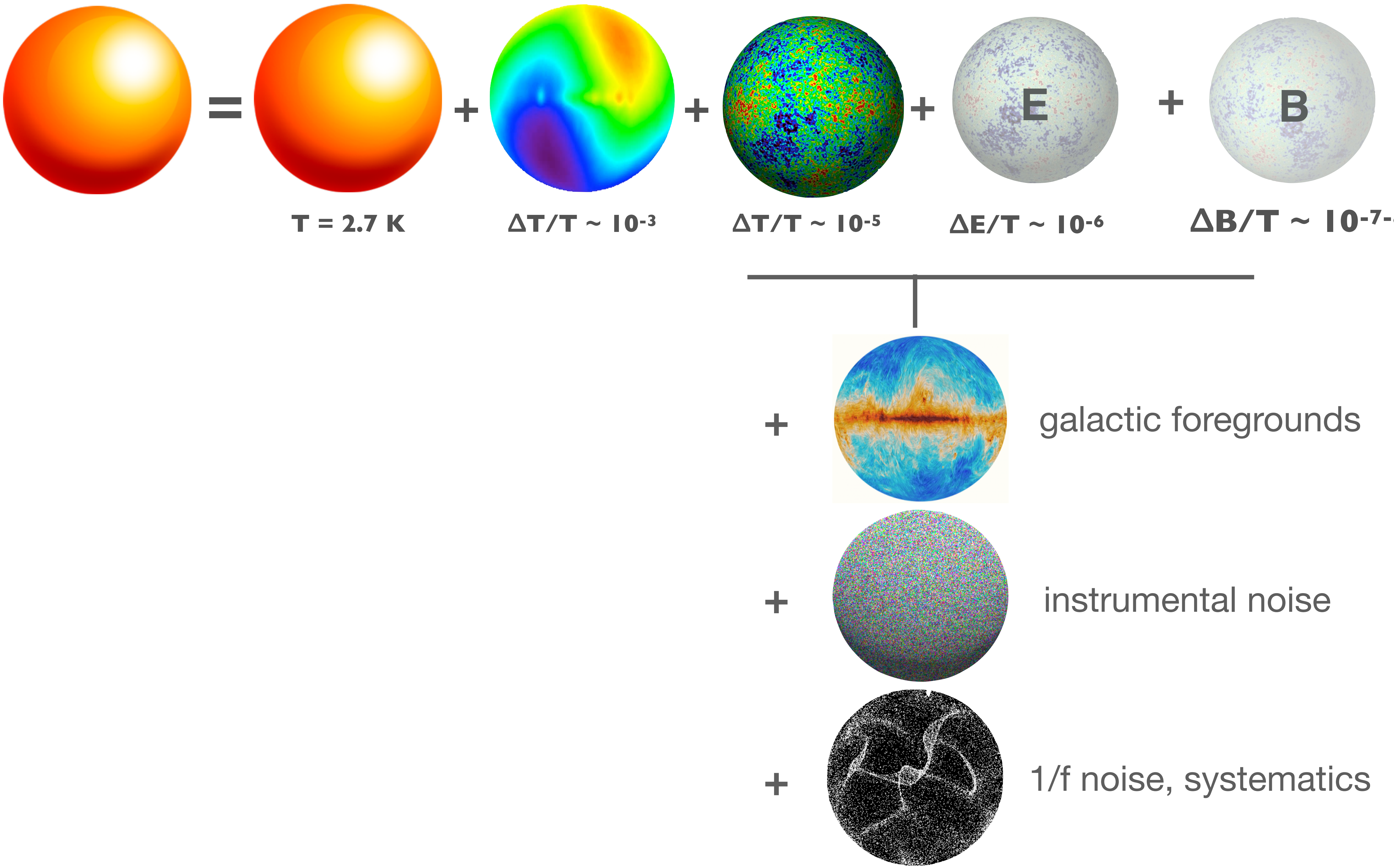
$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1} \quad \text{scalar}$$

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

- **with the definition of the tensor-to-scalar ratio "r"** $r = A_t / A_s$ **which characterizes the amplitude of GW and gives direct constraints on the shape of the potential**
  - energy scale of inflation $$V^{1/4}(\phi) \simeq 10^{16}\,\mathrm{GeV} \left(\frac{r}{0.01}\right)^{1/4}$$
  - inflaton field excursion $$\frac{\Delta\phi}{M_P} \simeq \mathcal{N}_* \left(\frac{r_*}{8}\right)^{1/2} \simeq \left(\frac{r}{0.001}\right)^{1/2}$$
  - derivative of the potential $$r = 8M_{\mathrm{Pl}}^2 \left(\frac{V_\phi}{V}\right)^2$$ $$n_{\mathrm{s}} - 1 \equiv \frac{\mathrm{d}\ln\mathcal{P}_\zeta}{\mathrm{d}\ln k} \simeq -3M_{\mathrm{Pl}}^2 \left(\frac{V_\phi}{V}\right)^2 + 2M_{\mathrm{Pl}}^2 \frac{V_{\phi\phi}}{V}$$

credits: Matt Tristram

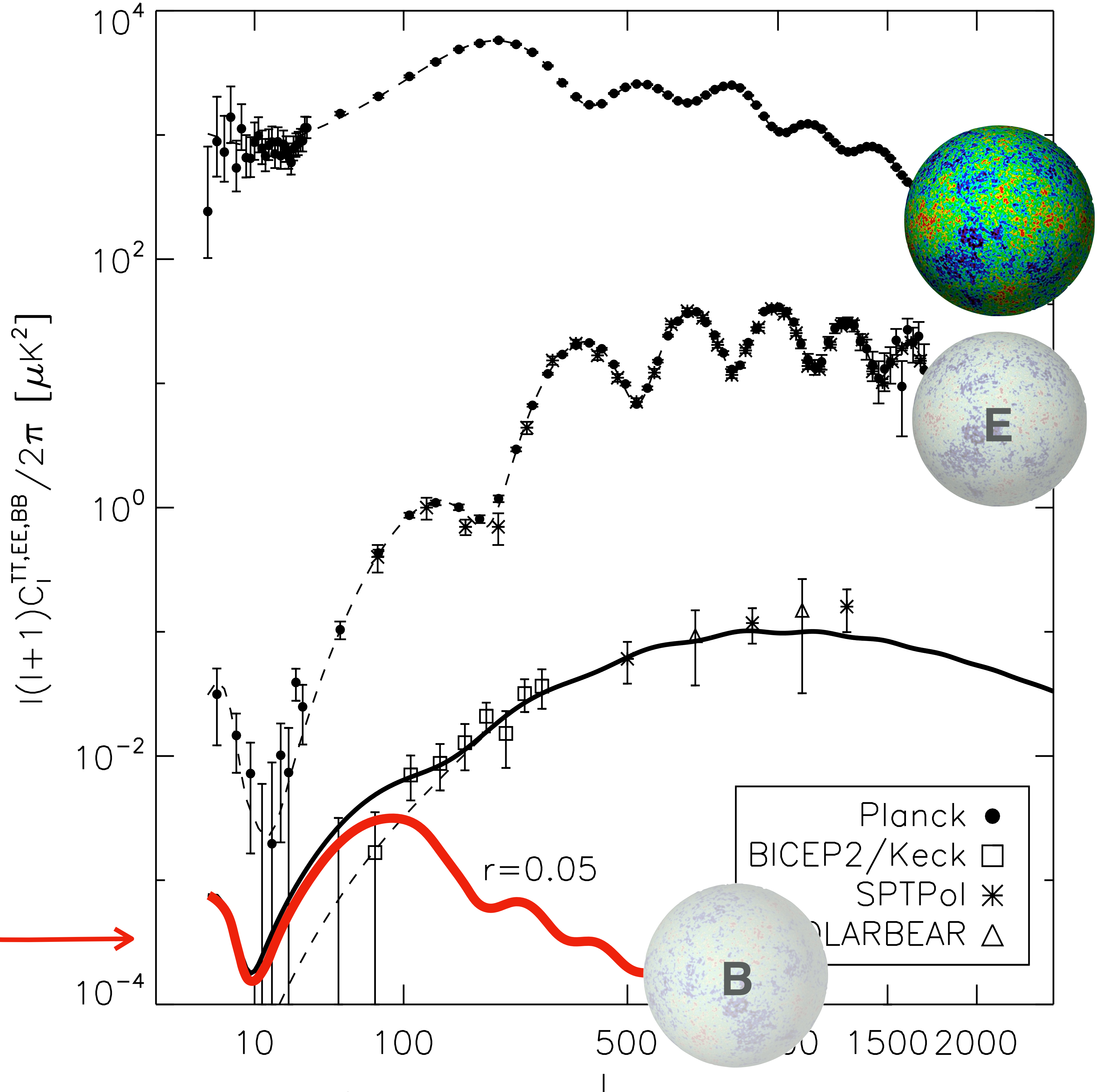
observational challenge



$$P^T(k) \propto r$$

polarization anisotropies $\Delta \mathbf{P}$

$$C_\ell^{TT,EE,{\color{red}BB}}$$



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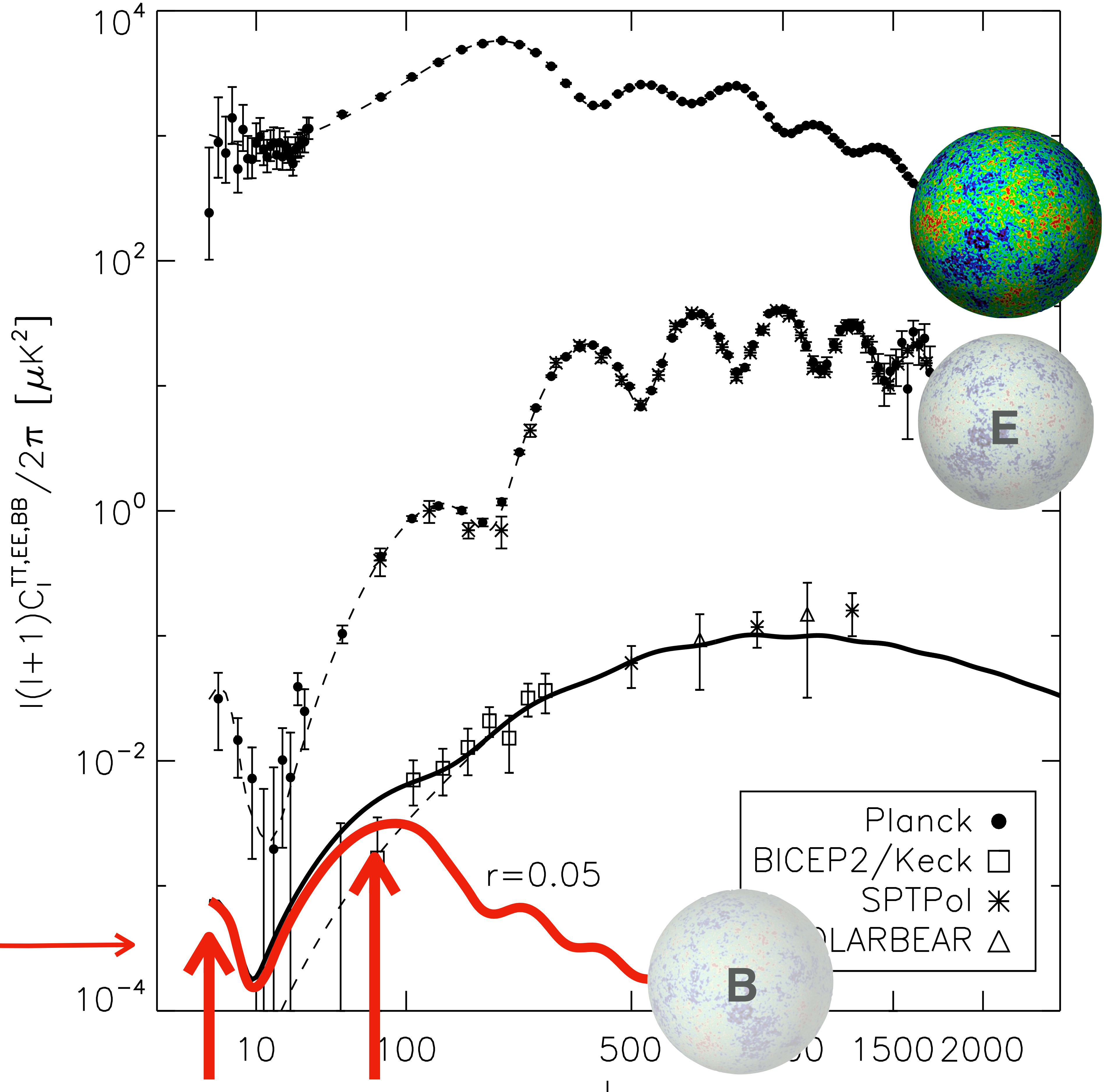
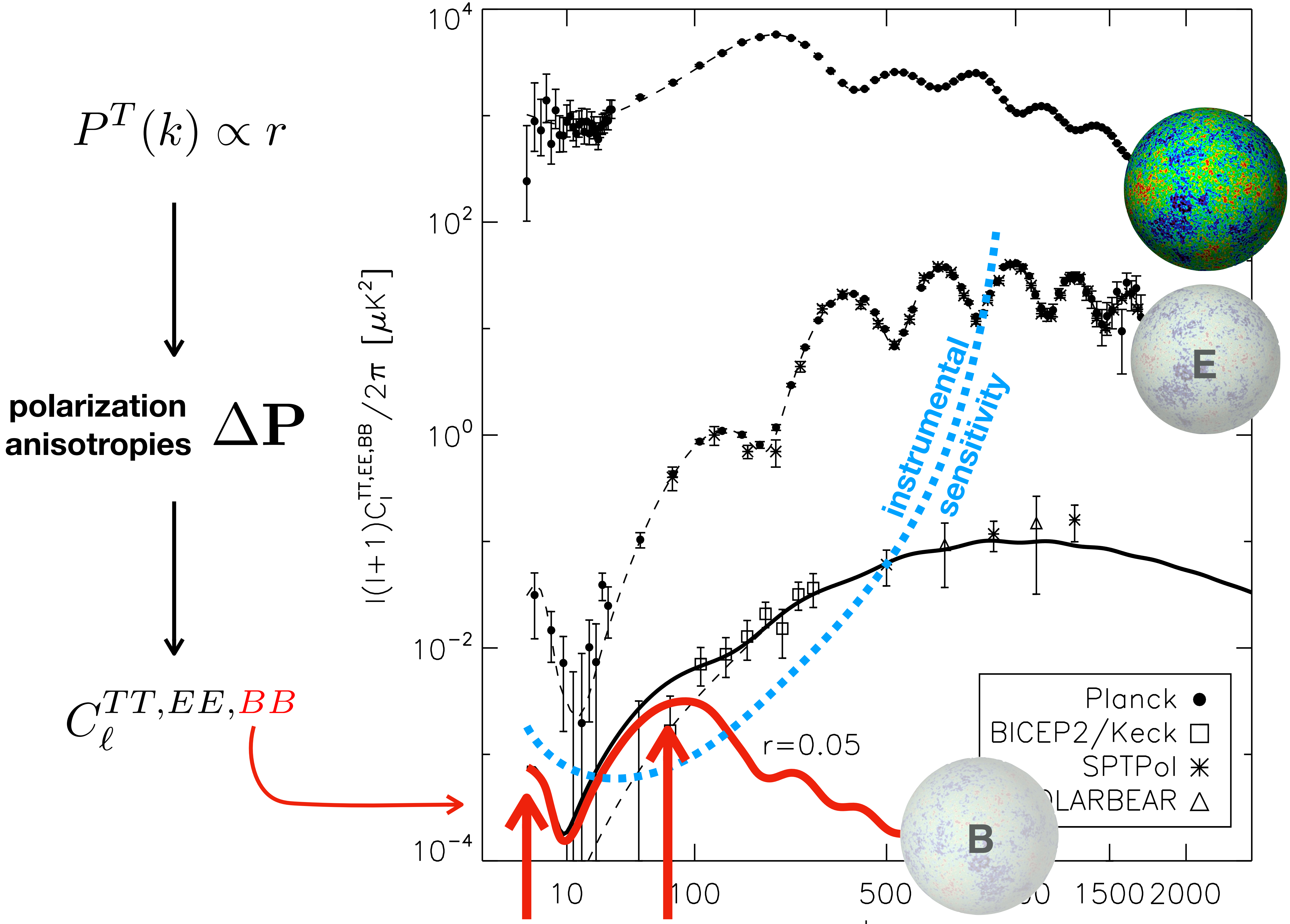


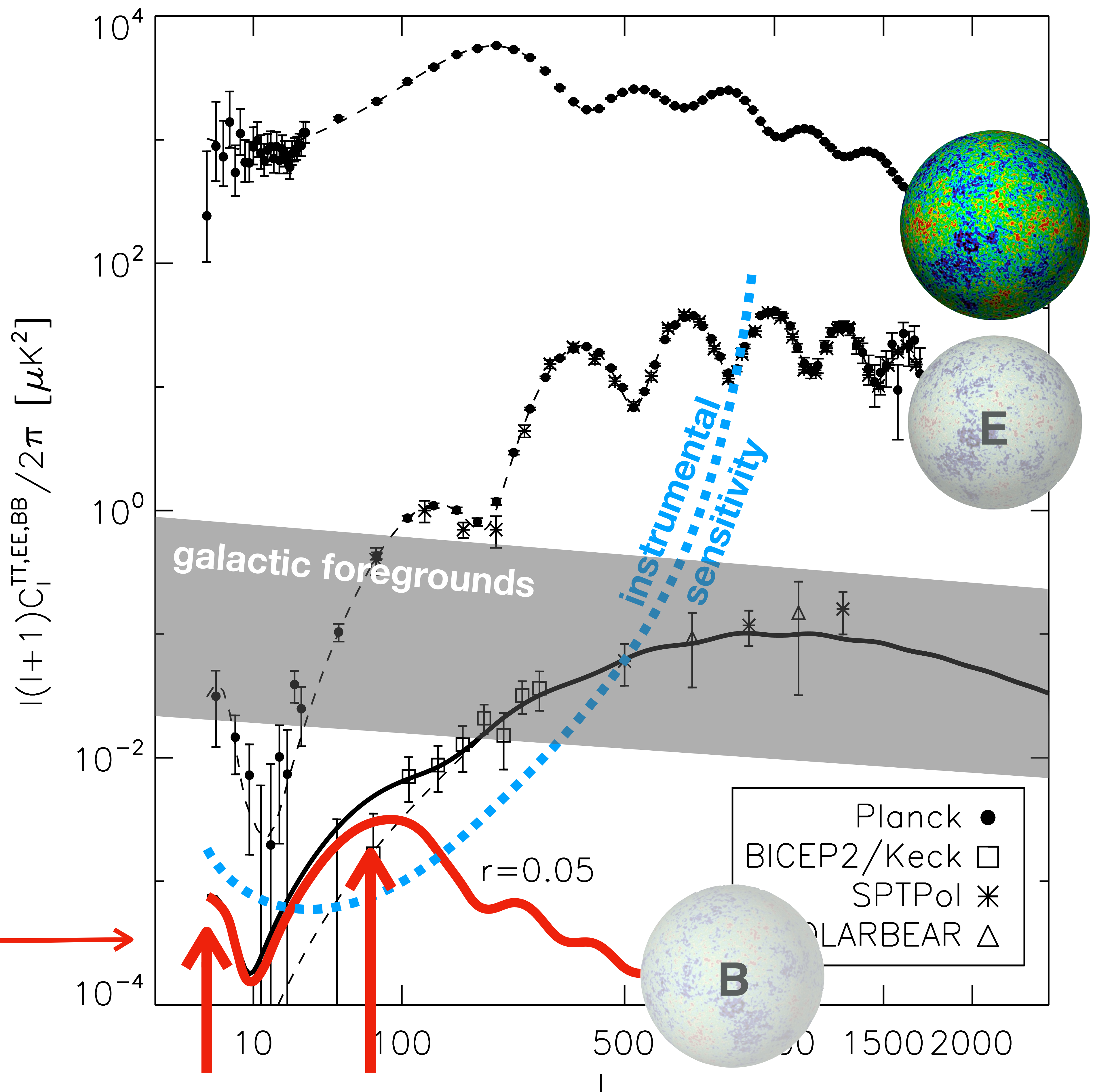


$P^T(k) \propto r$
polarization anisotropies
$\Delta \mathbf{P}$
$C_\ell^{TT,EE,BB}$
$l(l+1)C_l^{TT,EE,BB}/2\pi$ [μK^2]
10^4
10^2
10^0
10^{-2}
10^{-4}
10
100
500
1500
2000
l
instrumental
sensitivity
r=0.05
Planck
BICEP2/Keck
SPTPol
E
B

$P^T(k) \propto r$

polarization anisotropies $\Delta \mathbf{P}$

$C_\ell^{TT,EE,BB}$



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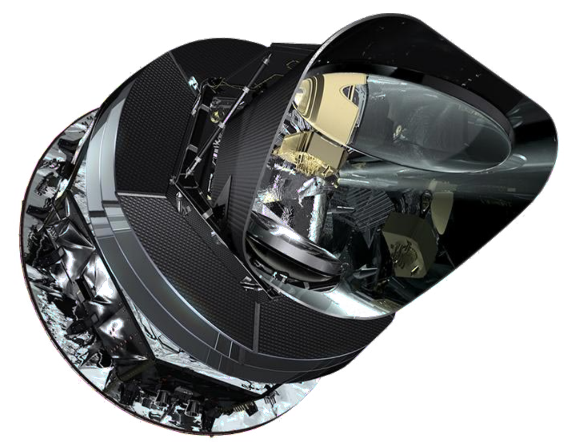
Planck



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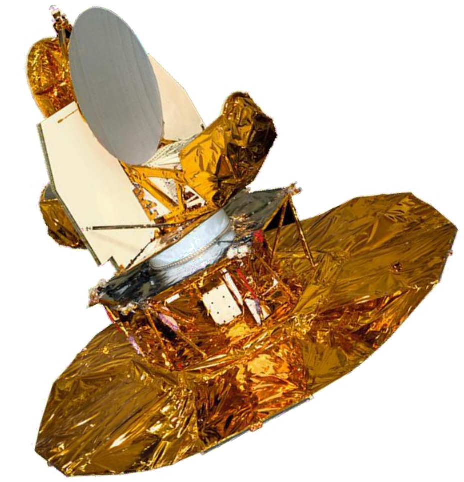
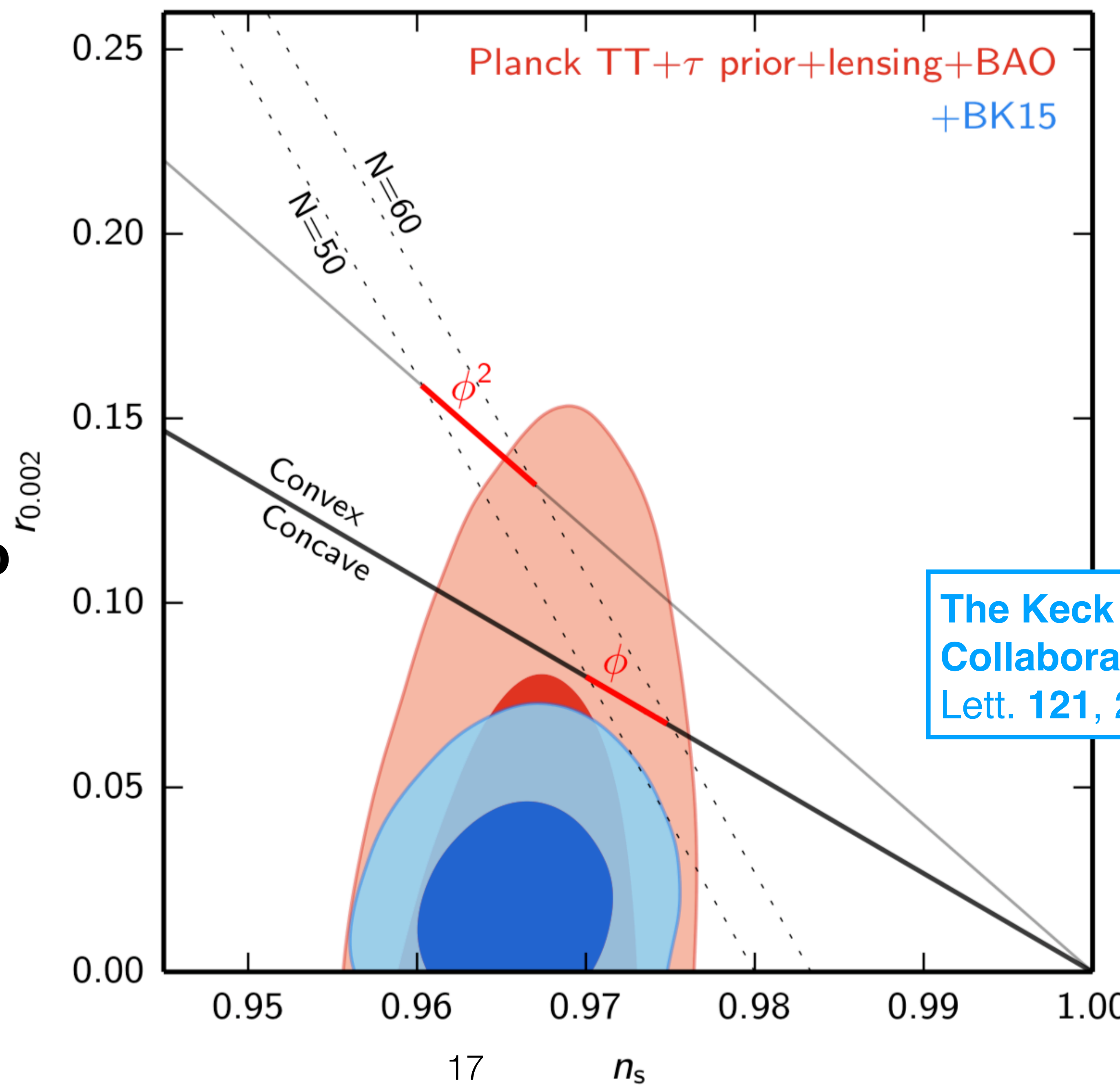
WMAP



tensor-to-scalar ratio

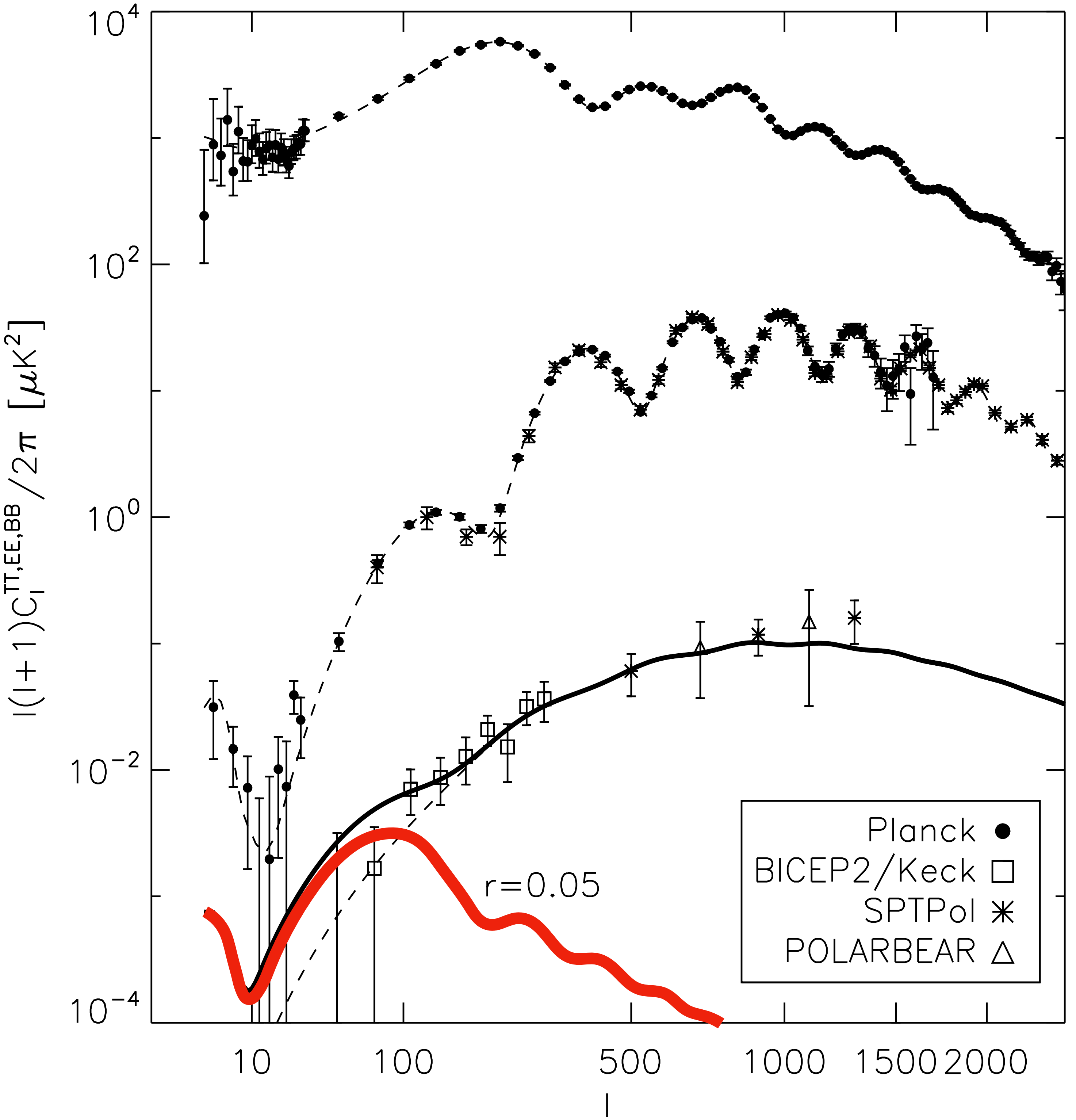
r<0.06 @ 2σ



The Keck Array and BICEP2 Collaborations, Phys. Rev. Lett. **121**, 221301, 2018

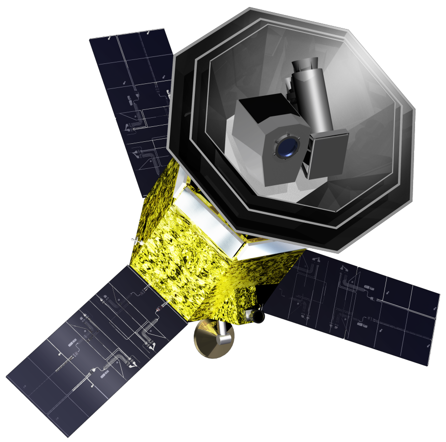

BICEP2 + Keck
WMAP
measurements of r
starts being limited
by our own galaxy:
the Milky Way
tensor
r<0.

Space and ground: a powerful duo

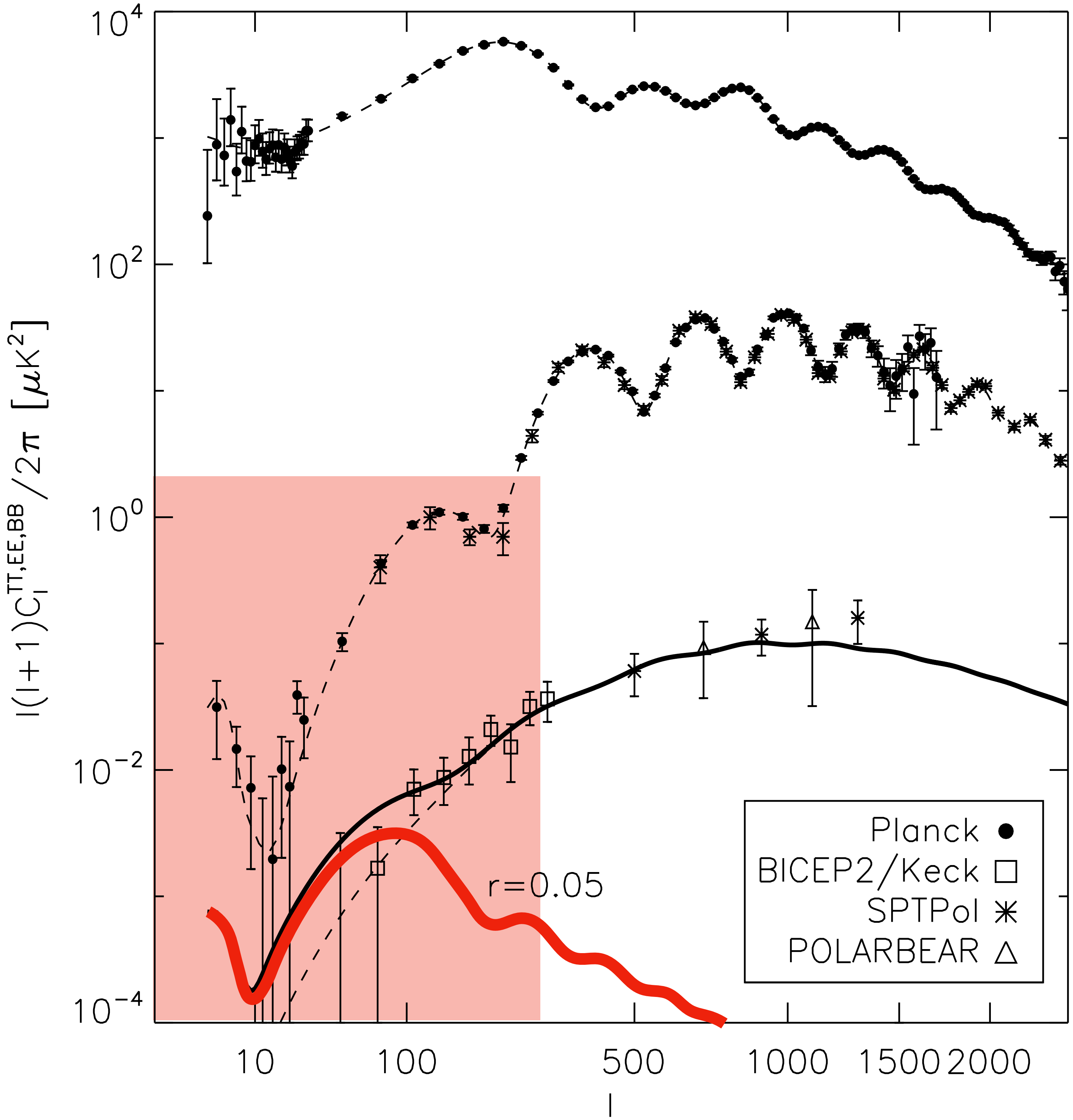


[see Thibaut's upcoming talk]

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



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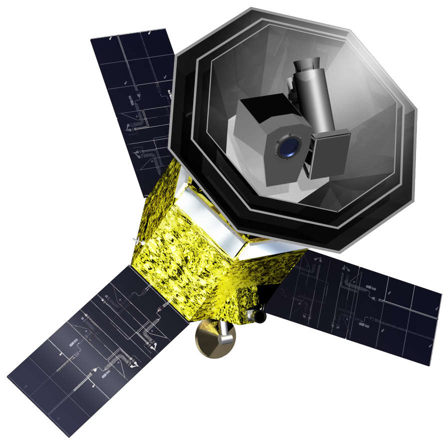

<u>LiteBIRD</u>
JAXA-led
focused
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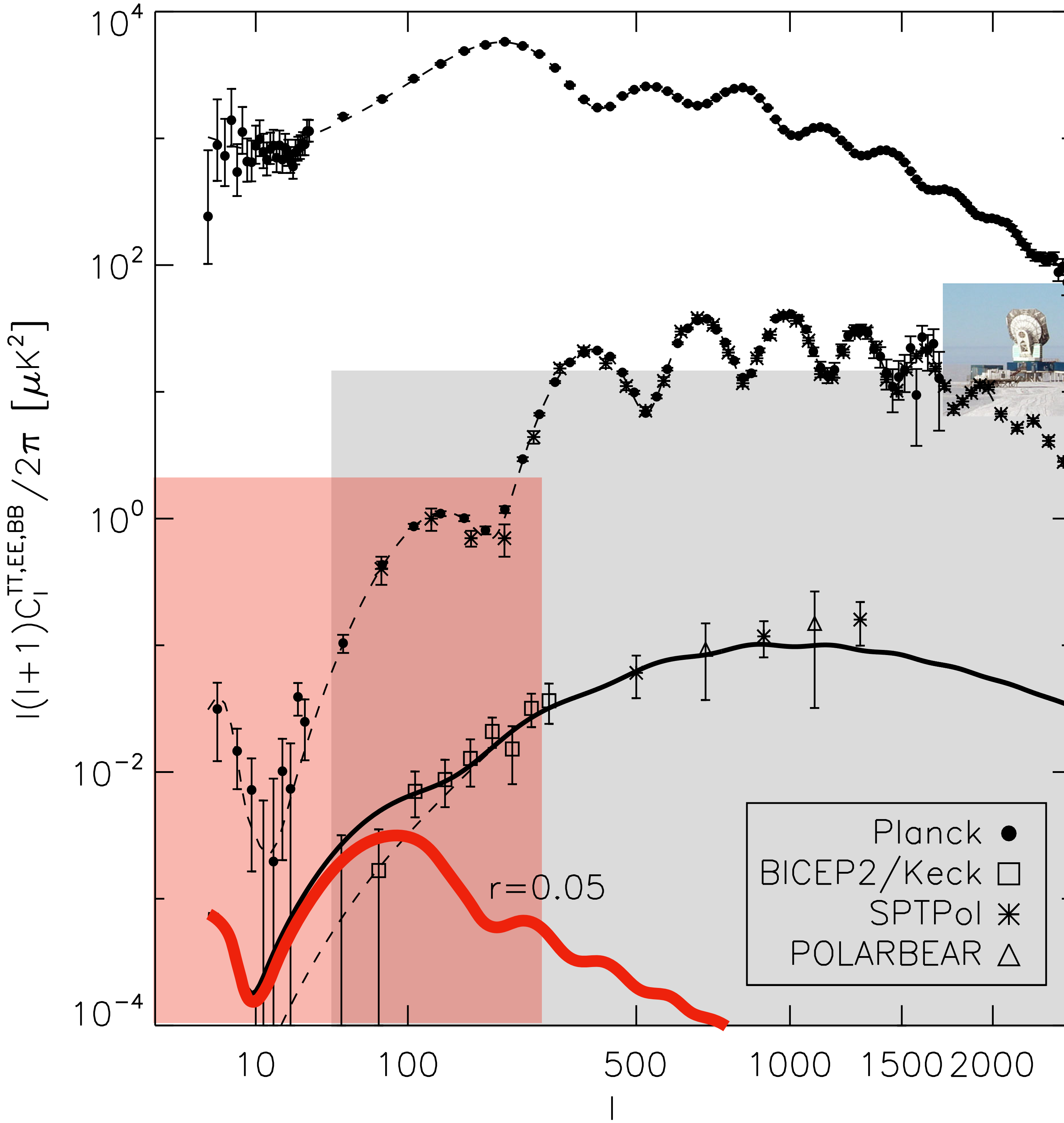
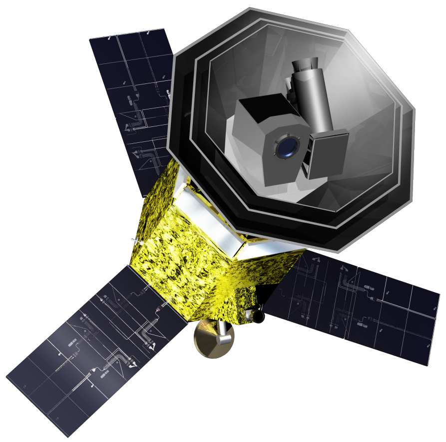
$2 \le \ell \le 200$
focused but still with many byproducts



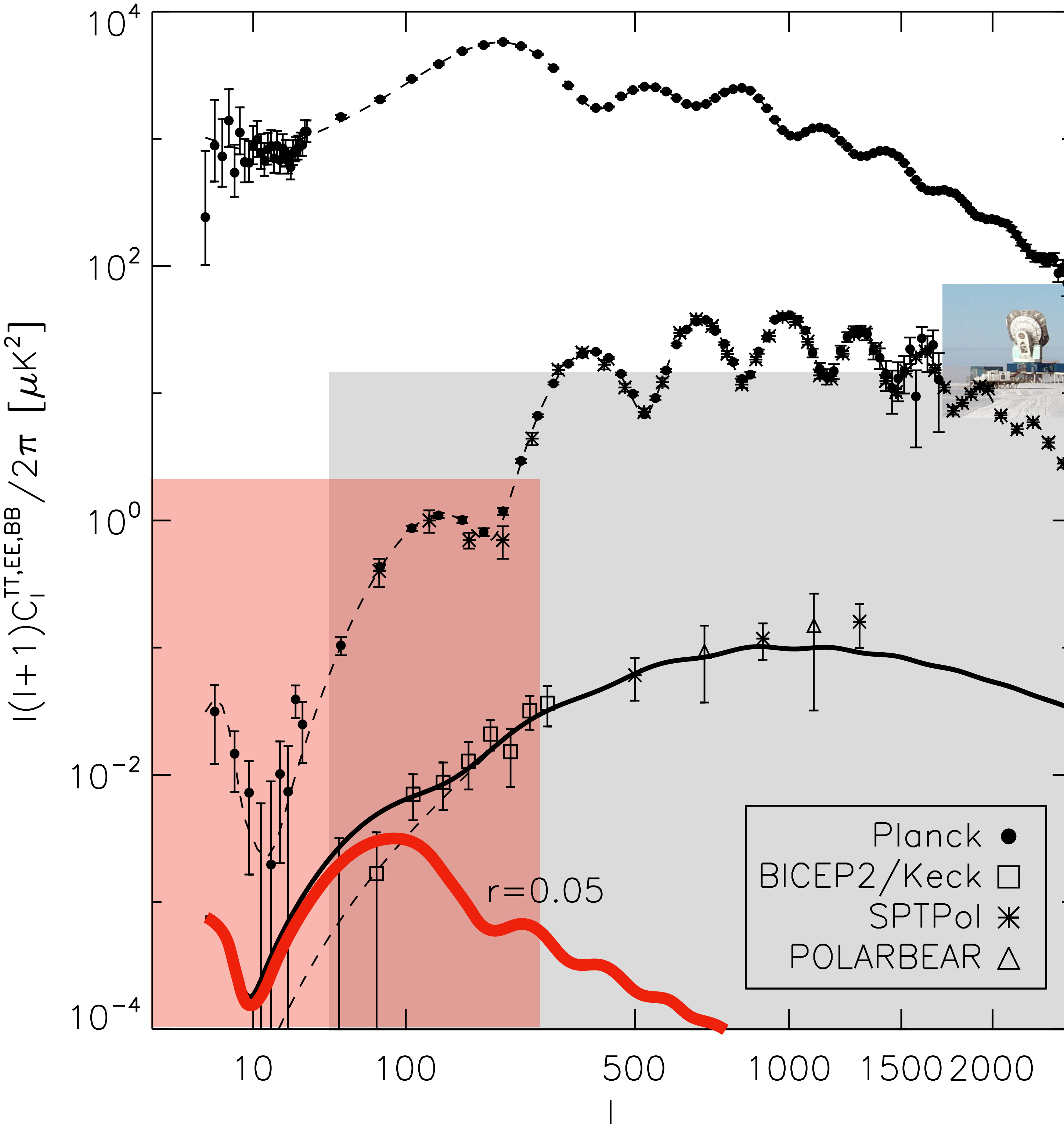
<u>Ground</u>
US-led telescopes on ground
$30 \le \ell \le \sim 8000$
e.g. Simons Observatory and CMB-S4

[**see Thibaut's upcoming talk**]

Space and ground: a powerful duo



<u>LiteBIRD</u>
JAXA-led
focused
mission
$\sigma(r)<0.001$
$2 \leq \ell \leq 200$
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

[see Thibaut's upcoming talk]

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

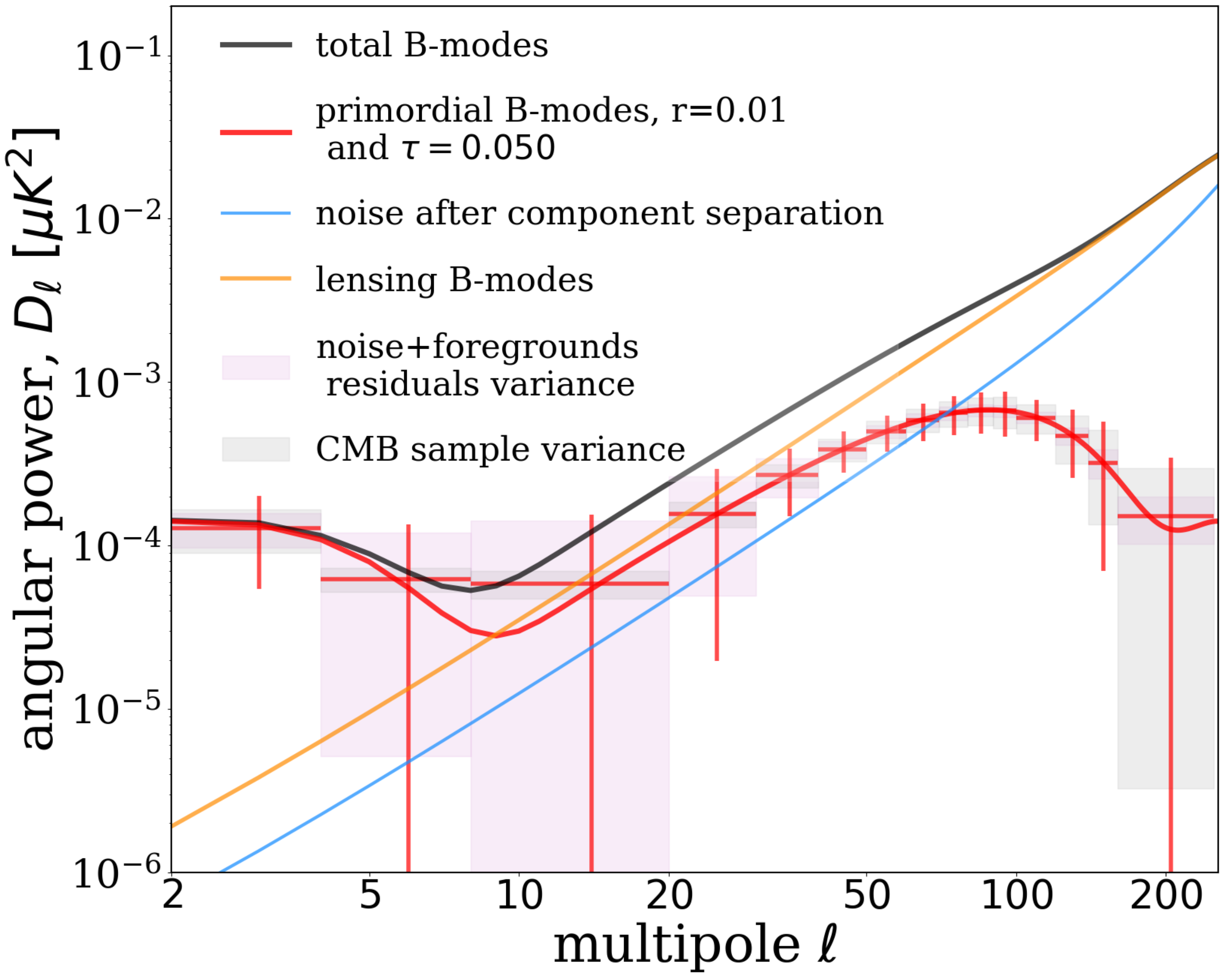
- **Only way to access lowest multipoles w/ δr ~ O(0.001)**
  - Both B-mode bumps need to be observed for the firm confirmation of Cosmic Inflation → we need measurements from space.

- **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 science goals

Full success:

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



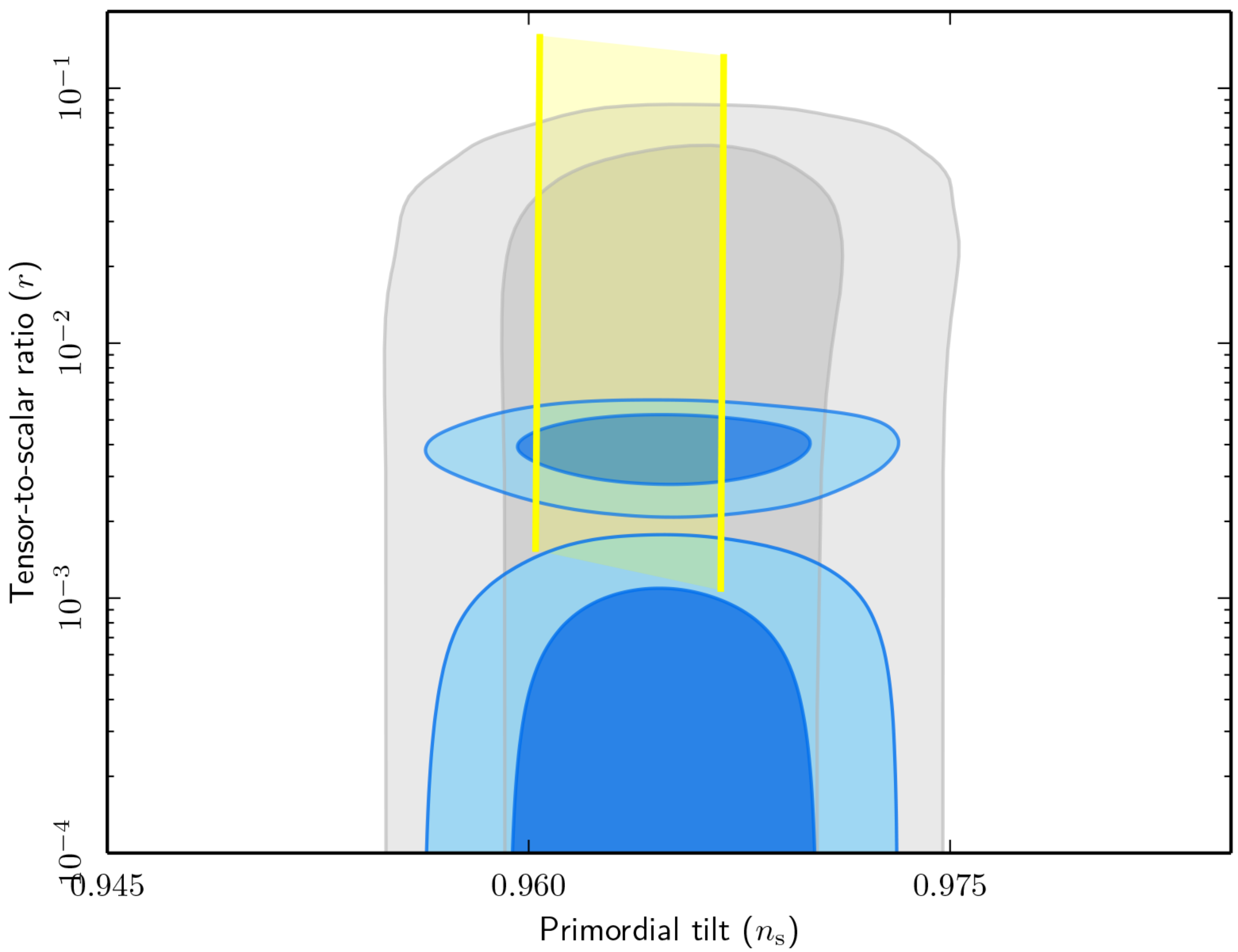
Rationale

- 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)

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
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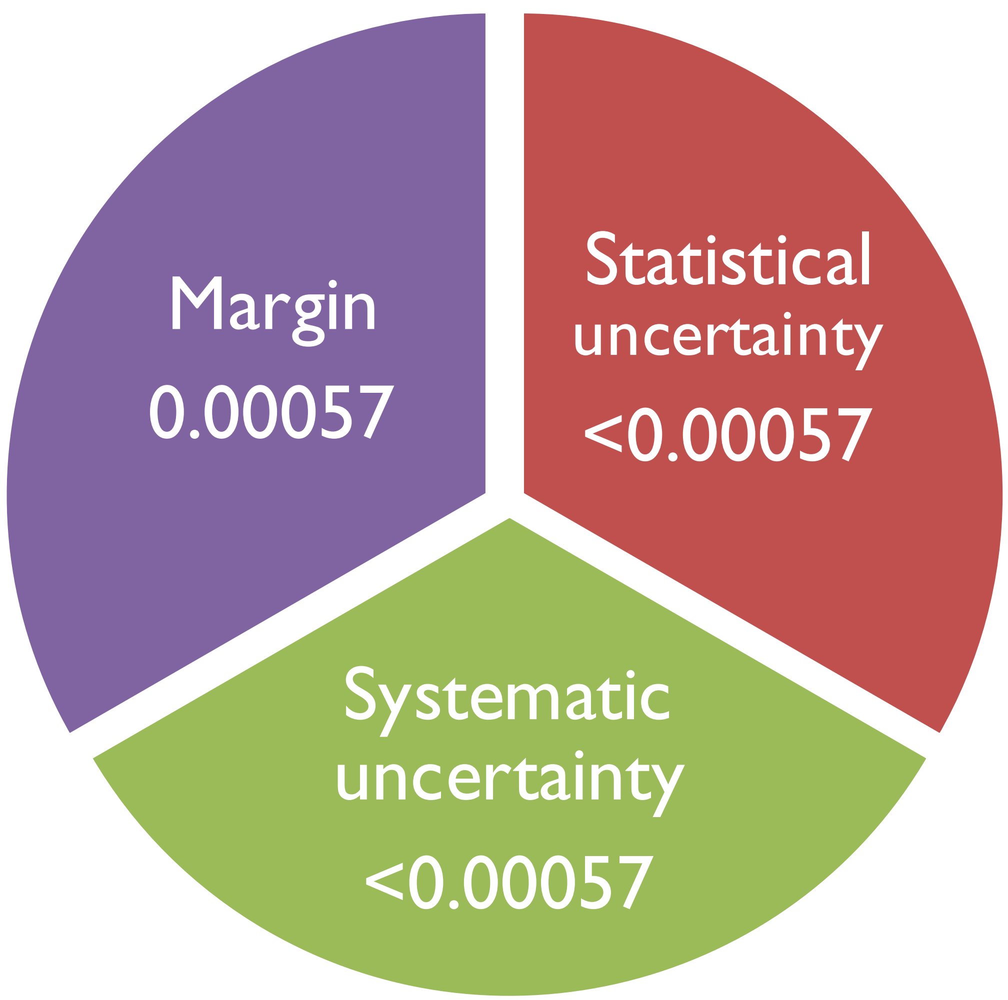
LiteBIRD science goals

Full success:

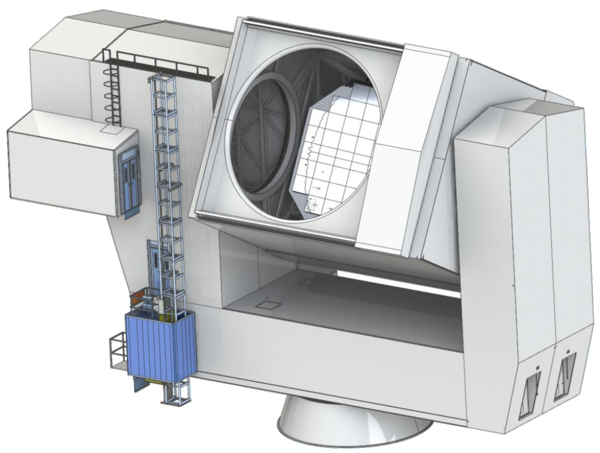
- **total uncertainty $\delta r < 0.001$ (for $r=0$)**
- **$> 5\sigma$ observation for each bump (for $r \geq 0.01$)**



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

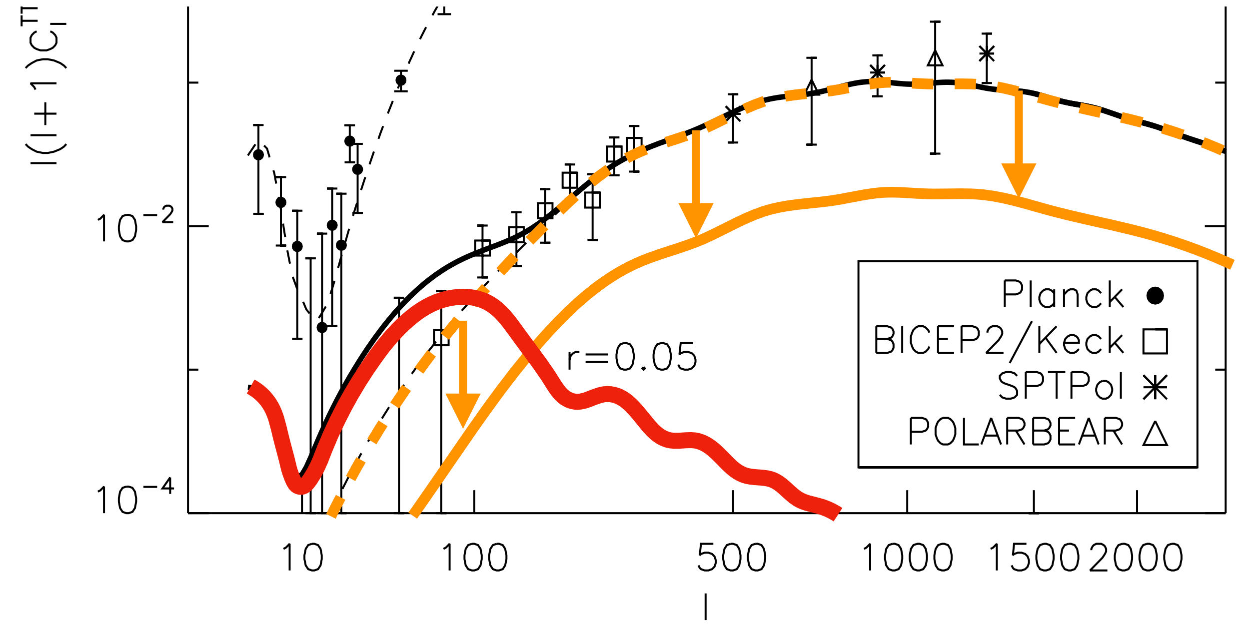
systematic uncertainty includes
- Bias from 1/f noise
- Polarization efficiency & knowledge
- Disturbance to instrument
- Off-boresight pick up
- Calibration accuracy

LiteBIRD — extra success

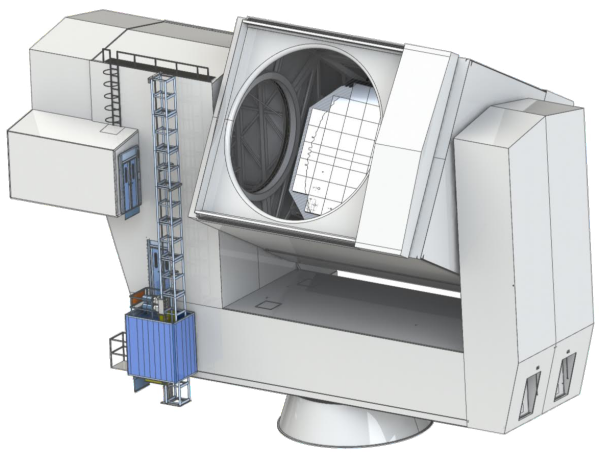


delensing

[see Thibaut's upcoming talk]

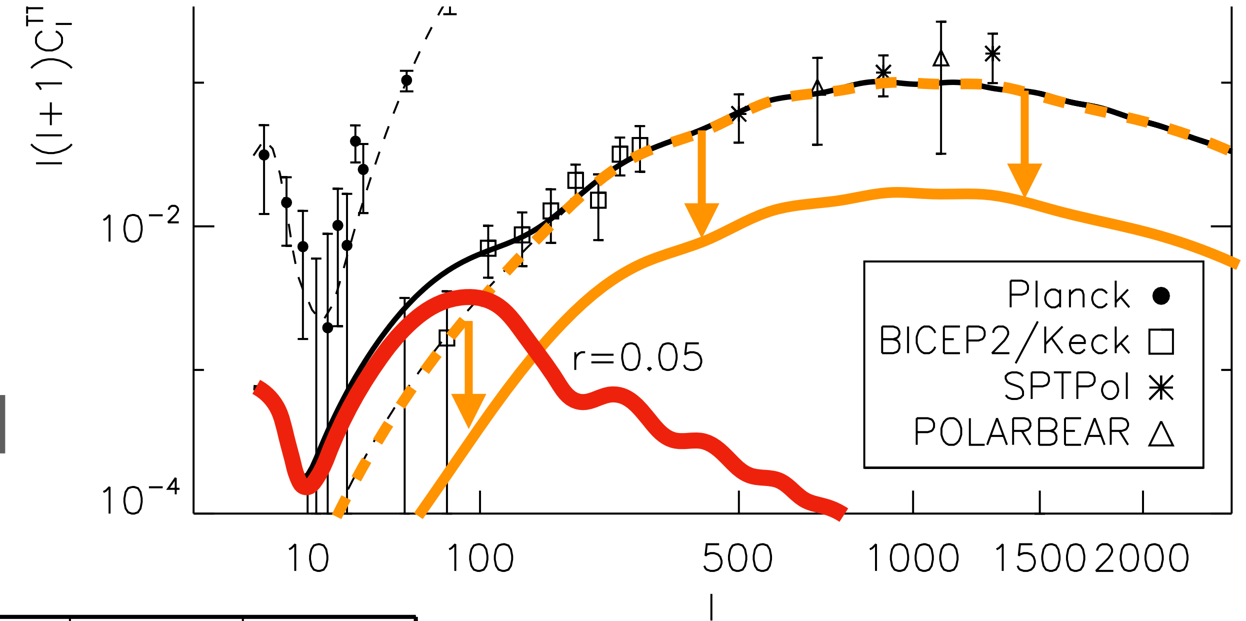


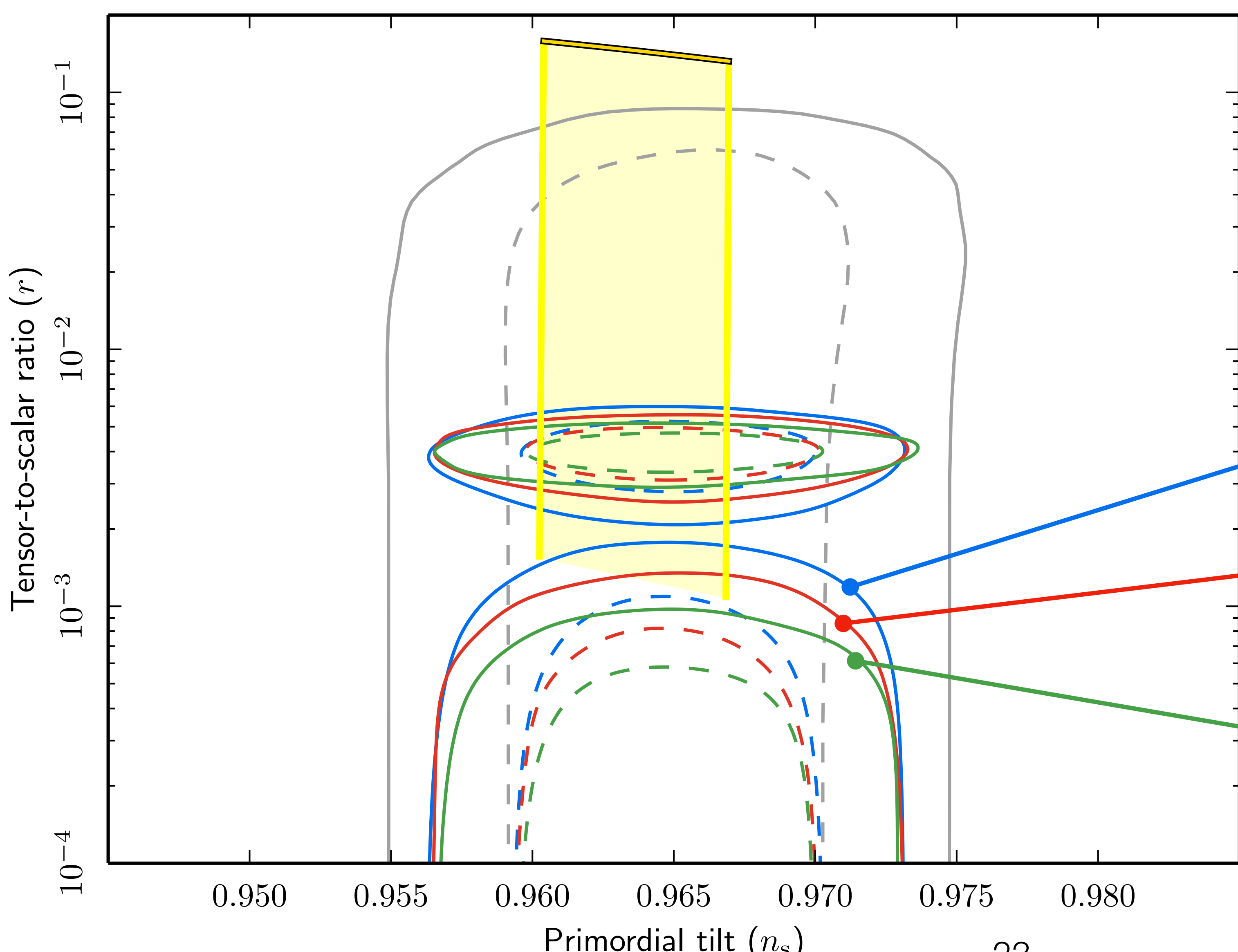
LiteBIRD — extra success



delensing

[see Thibaut's upcoming talk]



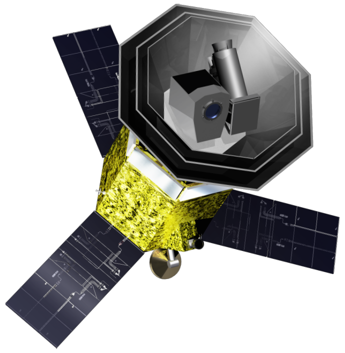


Aiming at detection with >5σ in case of Starobinsky model

1. Baseline

2. Adding delensing w/ Planck CIB & WISE

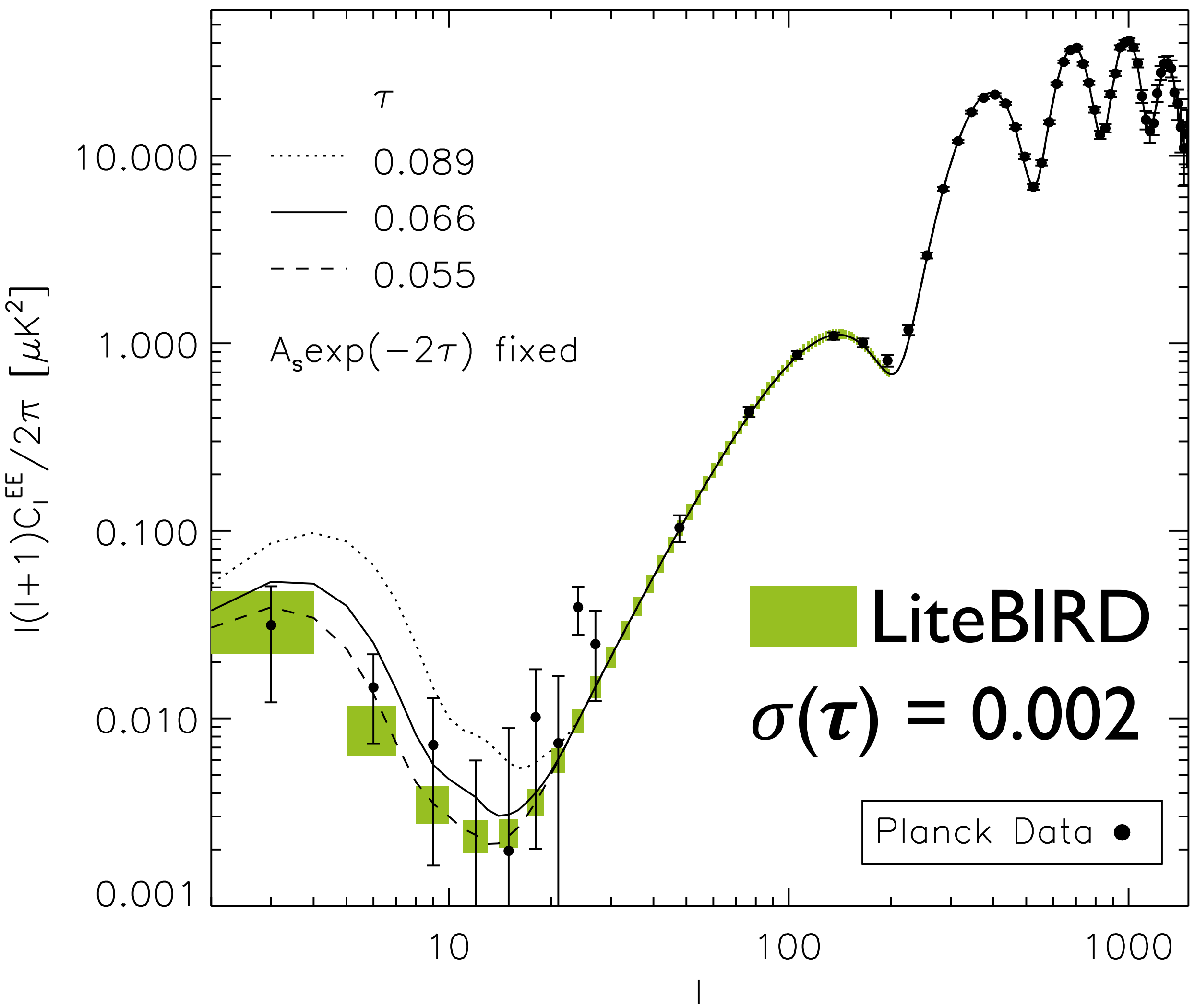
3. adding 2. and extra foreground cleaning w/ high-resolution ground CMB data

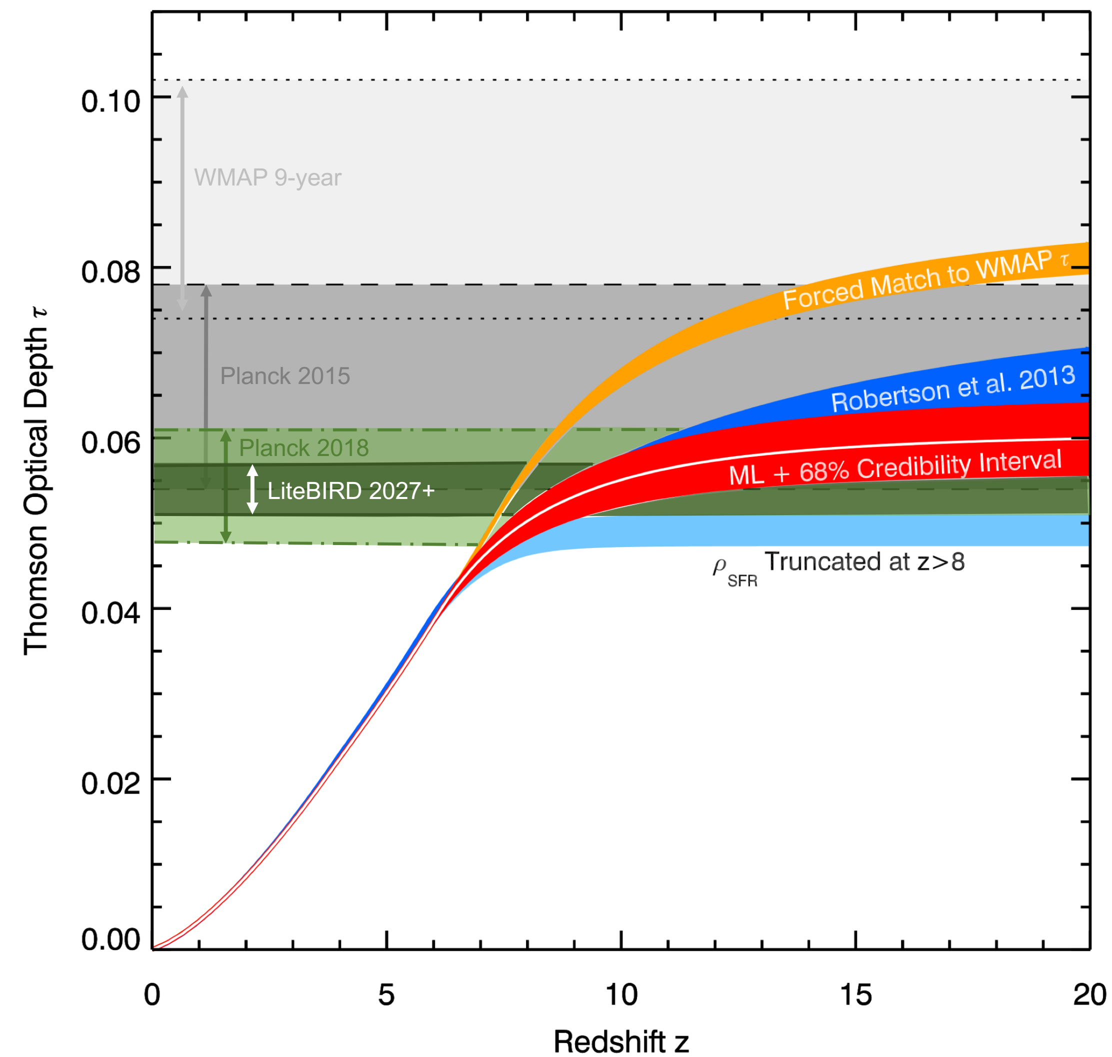


Full success:

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

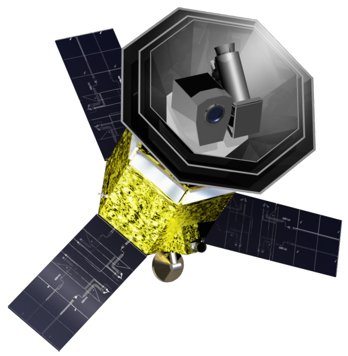
A cosmic variance limited measurement of EE on large angular scales will be an important, and guaranteed, legacy for LiteBIRD





$\sigma(\tau)$ better than current Planck constraints by a factor 2

[LiteBIRD Collaboration, PTEP 2012]

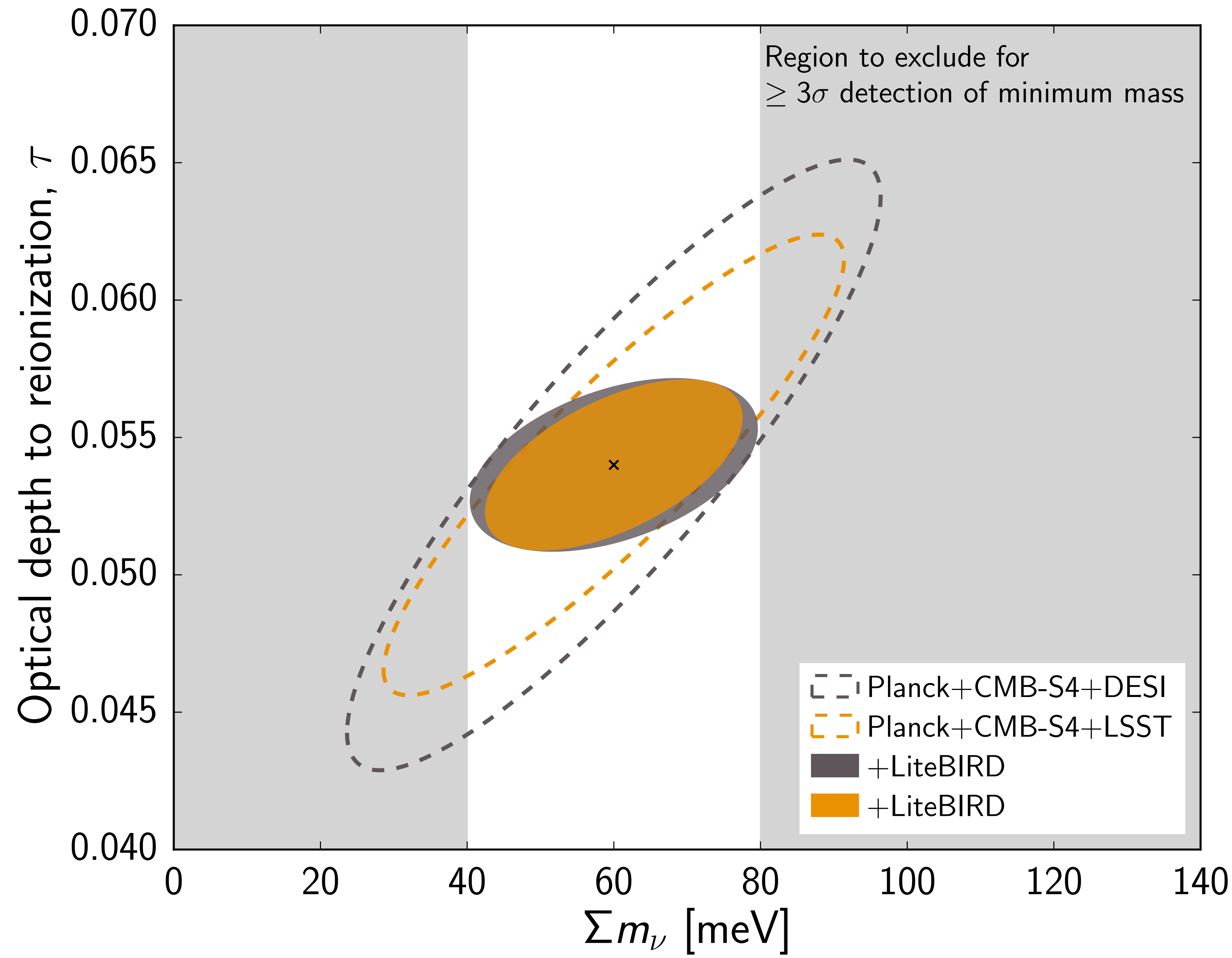


Full success:

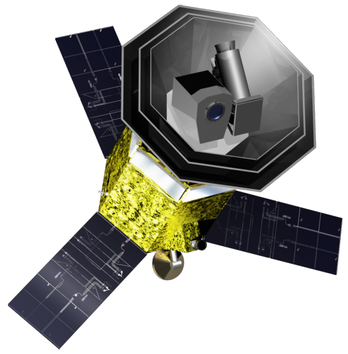
- **total uncertainty δr < 0.001 (for r=0)**
- **> 5σ observation for each bump (for r ≥ 0.01)**

Improvement in reionization optical depth measurement implies:

- $\sigma(\Sigma m_\nu)$ = 15 meV
- determine neutrino hierarchy (normal v.s. inverted)
- measurement of minimum mass (≥ 3σ detection NH, ≥ 5σ detection for IH)



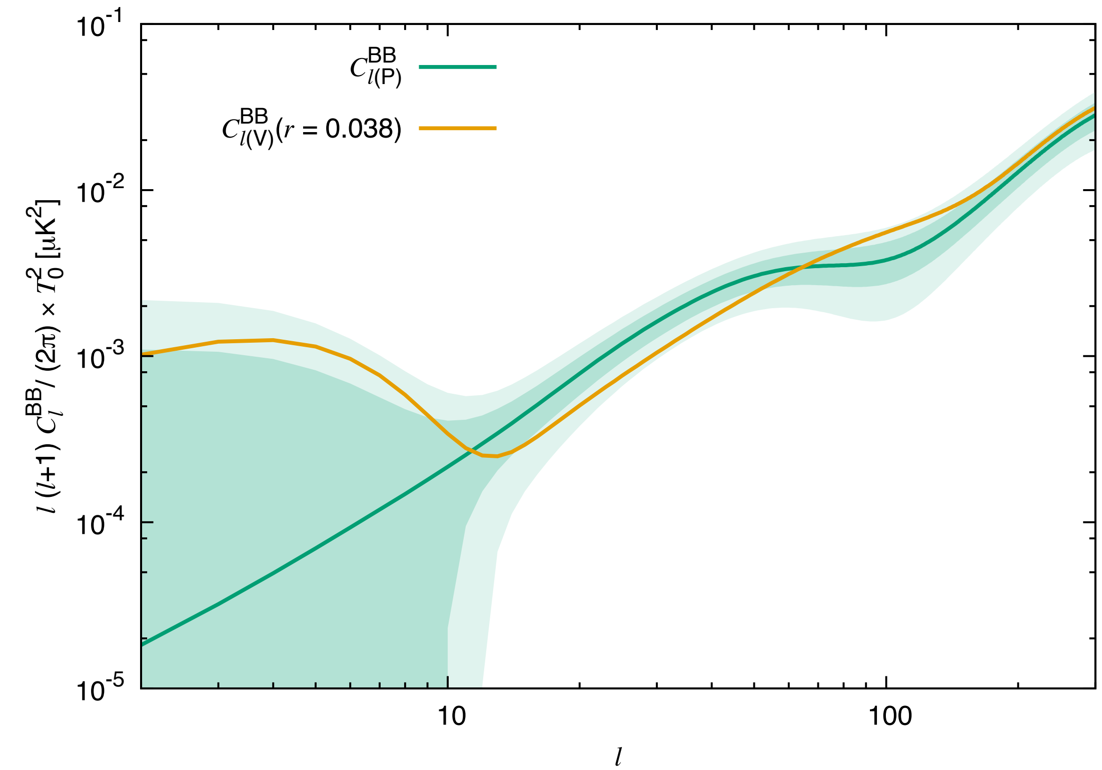
[Calabrese et al arXiv:1611.10269]



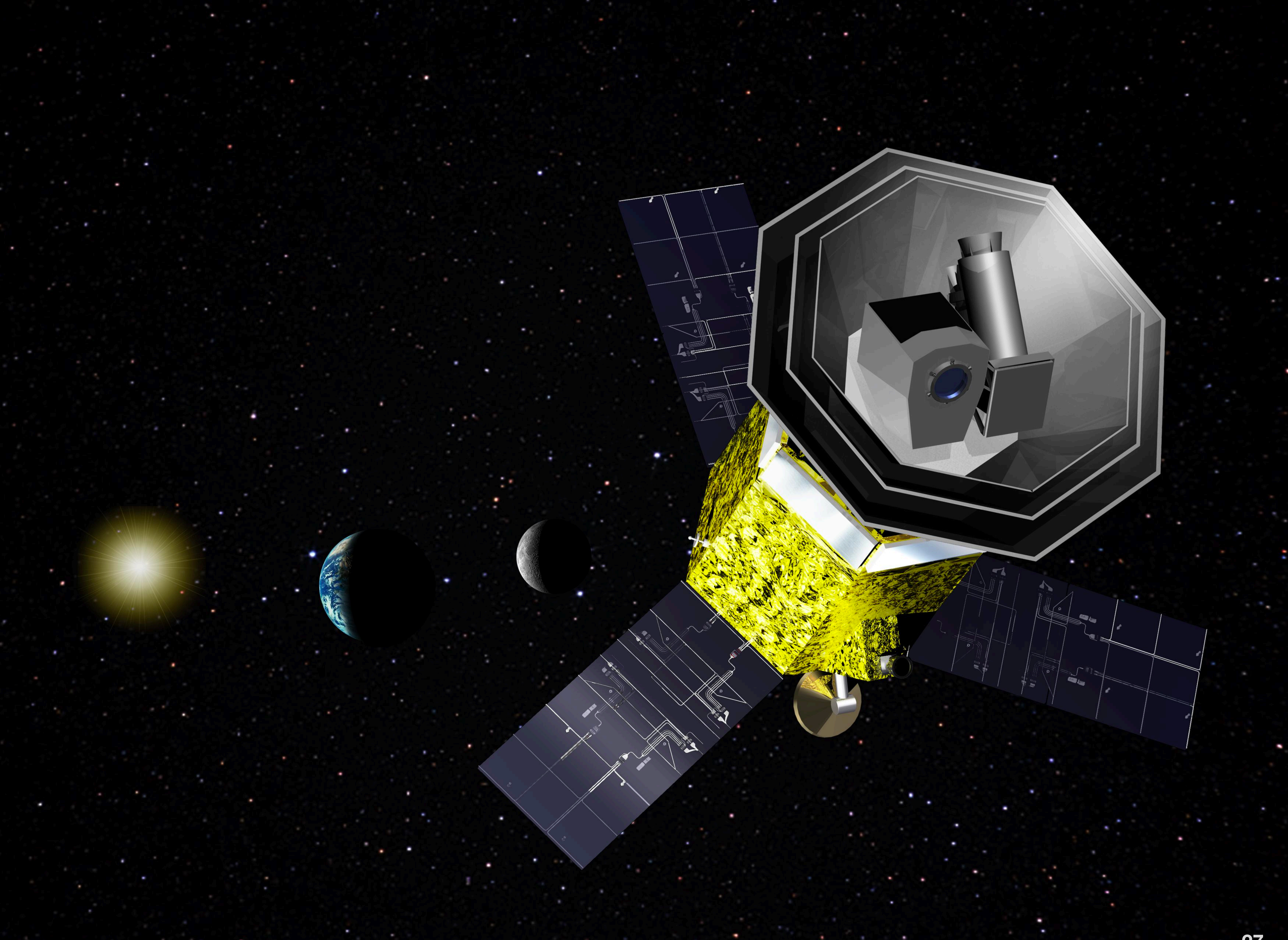
Full success:

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

- **tensor tilt n_t**: constraints on the primordial tensor power spectrum can distinguish between inflation models e.g. Campeti et al. 2019, [arXiv:1905.08200]
- **non-gaussianity** through BBB, → e.g. Namba et al [arXiv1509.07521]



- **parity-violation** = TB and EB non longer zero (constraints on Faraday rotation from primordial magnetic field (with anisotropies of Δα, parity-violating gravitational waves with spectral shape in C_ℓ)
- **galactic science** — with frequency range from 34 to 448 GHz and access to large scales LiteBIRD will characterize to high accuracy the foregrounds SED, constrain the large scale galactic magnetic field, and constrain models of dust polarization grains
- **mapping the hot gas in the Universe** — significant improvement on the SZ y-map in terms of foregrounds residuals thanks to the 15 band
- **anisotropic CMB spectral distortions** could be measured well [Mukherjee-Silk-Wandelt 2018]
- **synergy with other probes** — SZ x 3D galaxy distribution, gravitational lensing, ISW



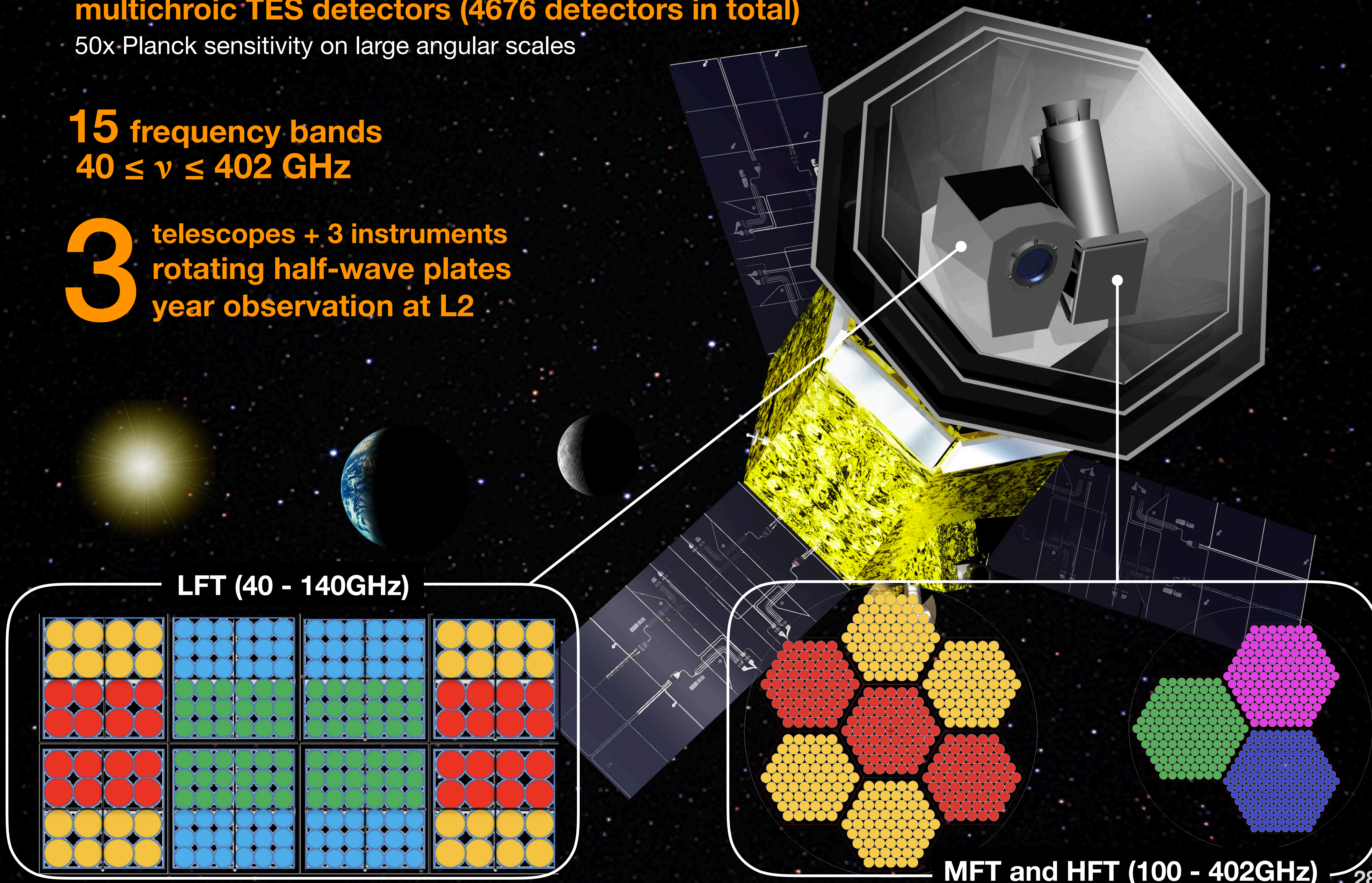
LiteBIRD is the next-generation CMB satellite selected by JAXA as a Strategic Large Mission to be launched in 2028

multichroic TES detectors (4676 detectors in total)

50x Planck sensitivity on large angular scales

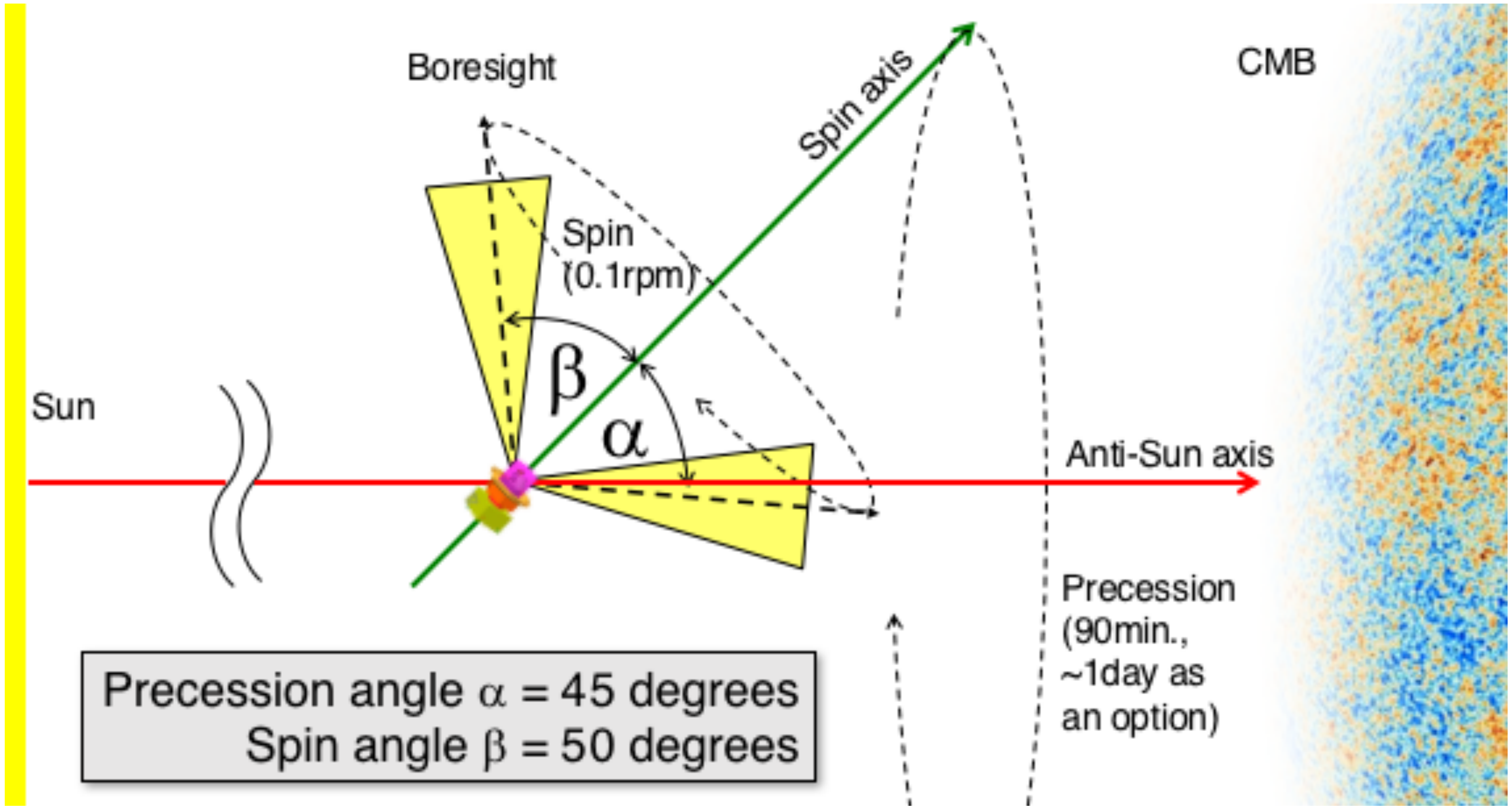
15 frequency bands
$40 \leq \nu \leq 402$ GHz

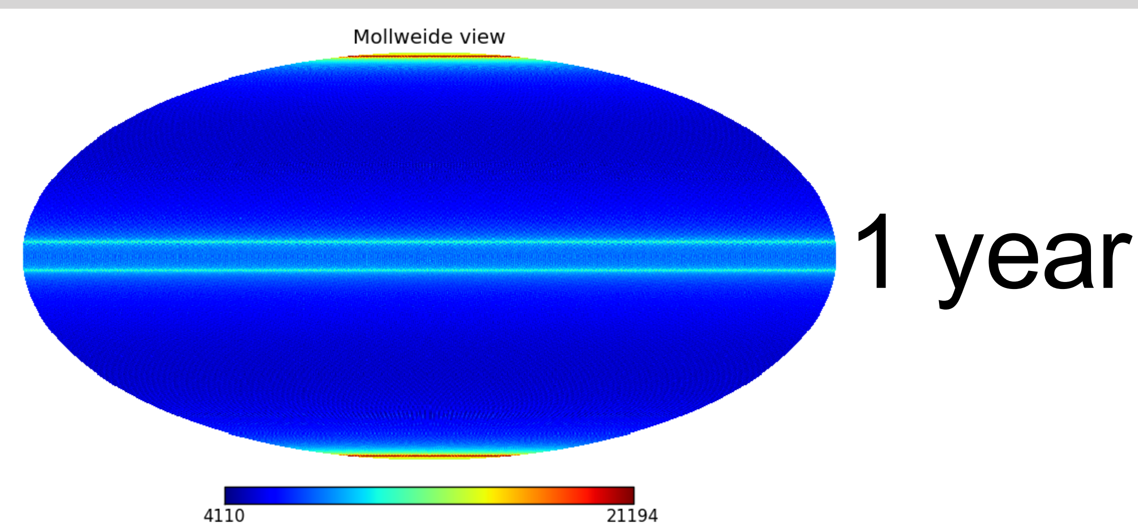
3 **telescopes + 3 instruments**
rotating half-wave plates
year observation at L2



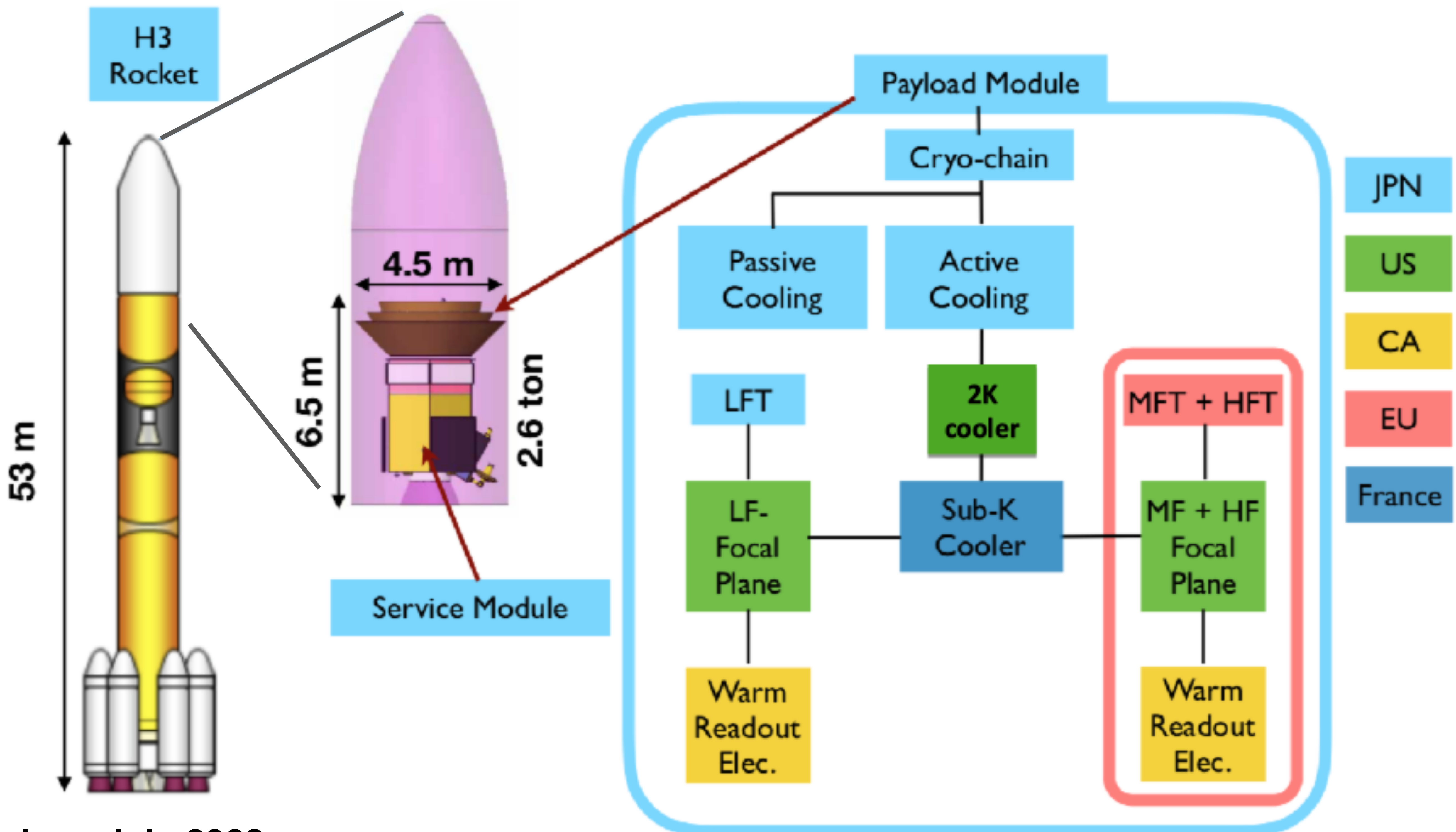
LiteBIRD operation

orbit: Sun-Earth L2 Lissajous



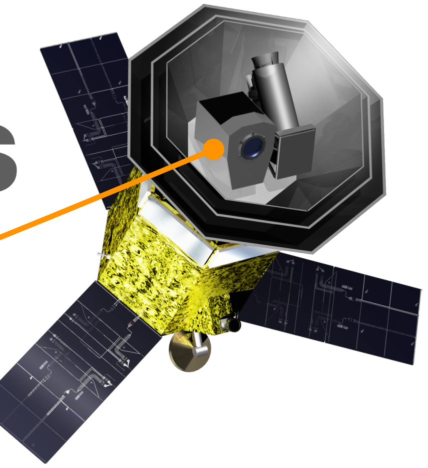


LiteBIRD instruments

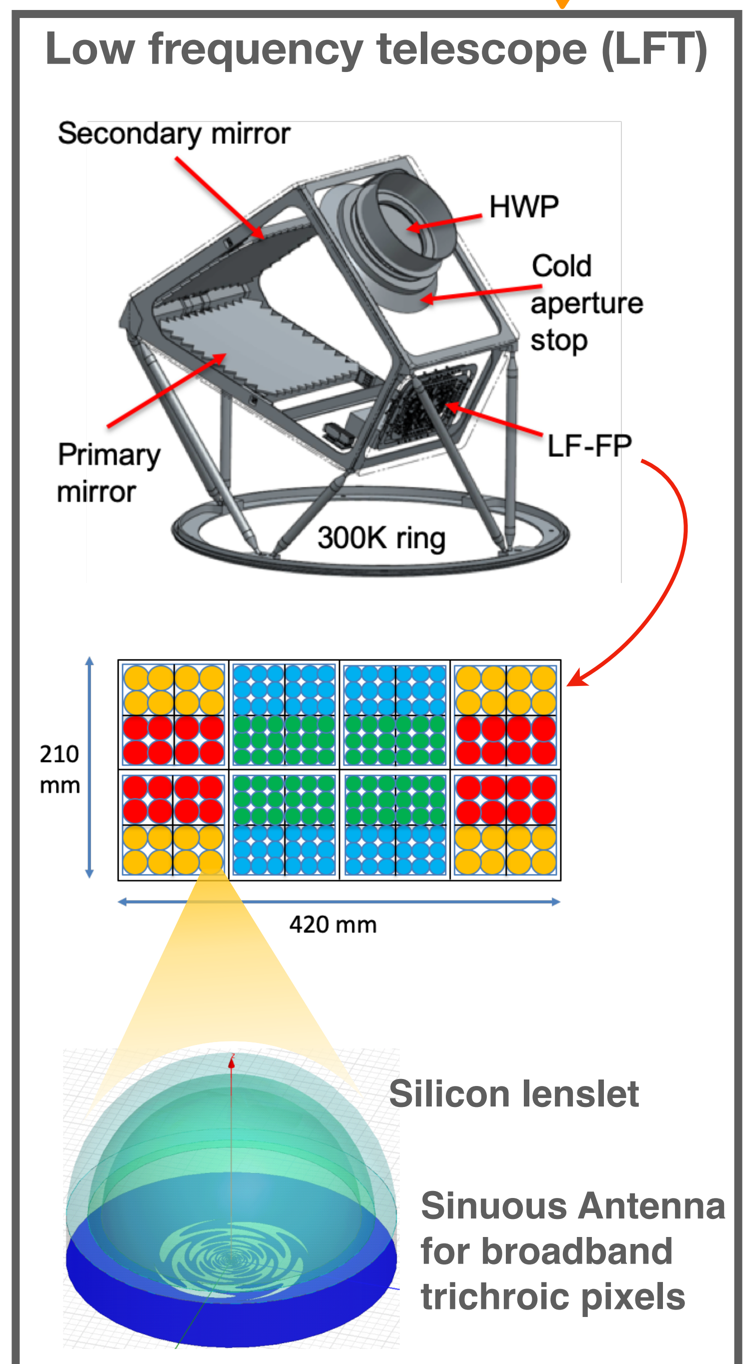


launch in 2028

LiteBIRD instruments

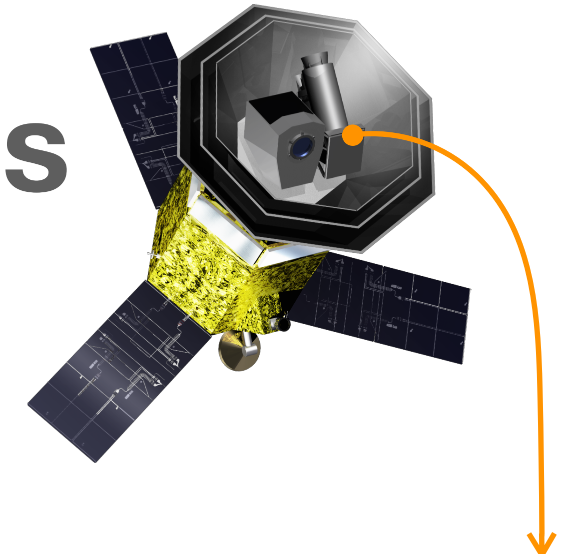


- **Three telescopes with TES arrays**
- Polarization modulator with a rotating half-wave plate (HWP) for 1/f noise & systematics reduction
- Cryogenic system for 0.1K base temperature



- 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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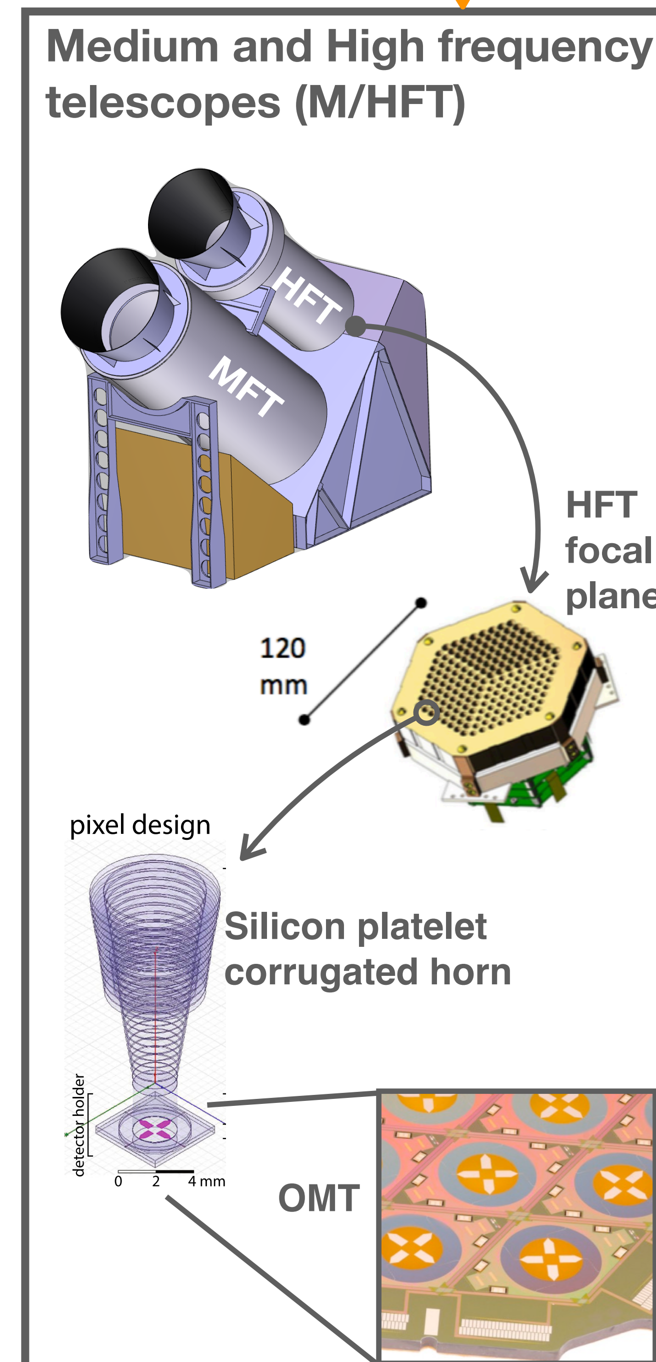
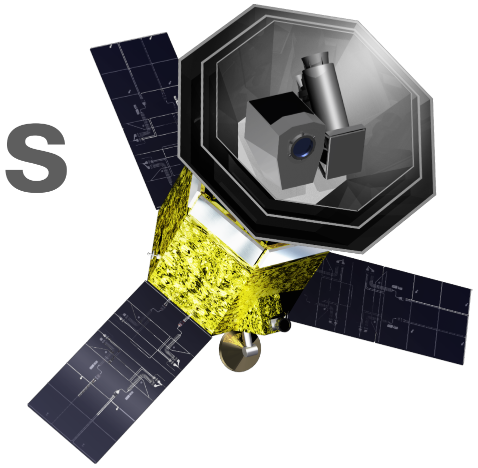


Two F/2.3 refractive telescopes:
- 89-270 GHz
- 238-448 GHz

Apertures:
- 30mm
- 20mm

FoV: 28 deg
- Transmissive metal-mesh HWP
- HDPE lenses

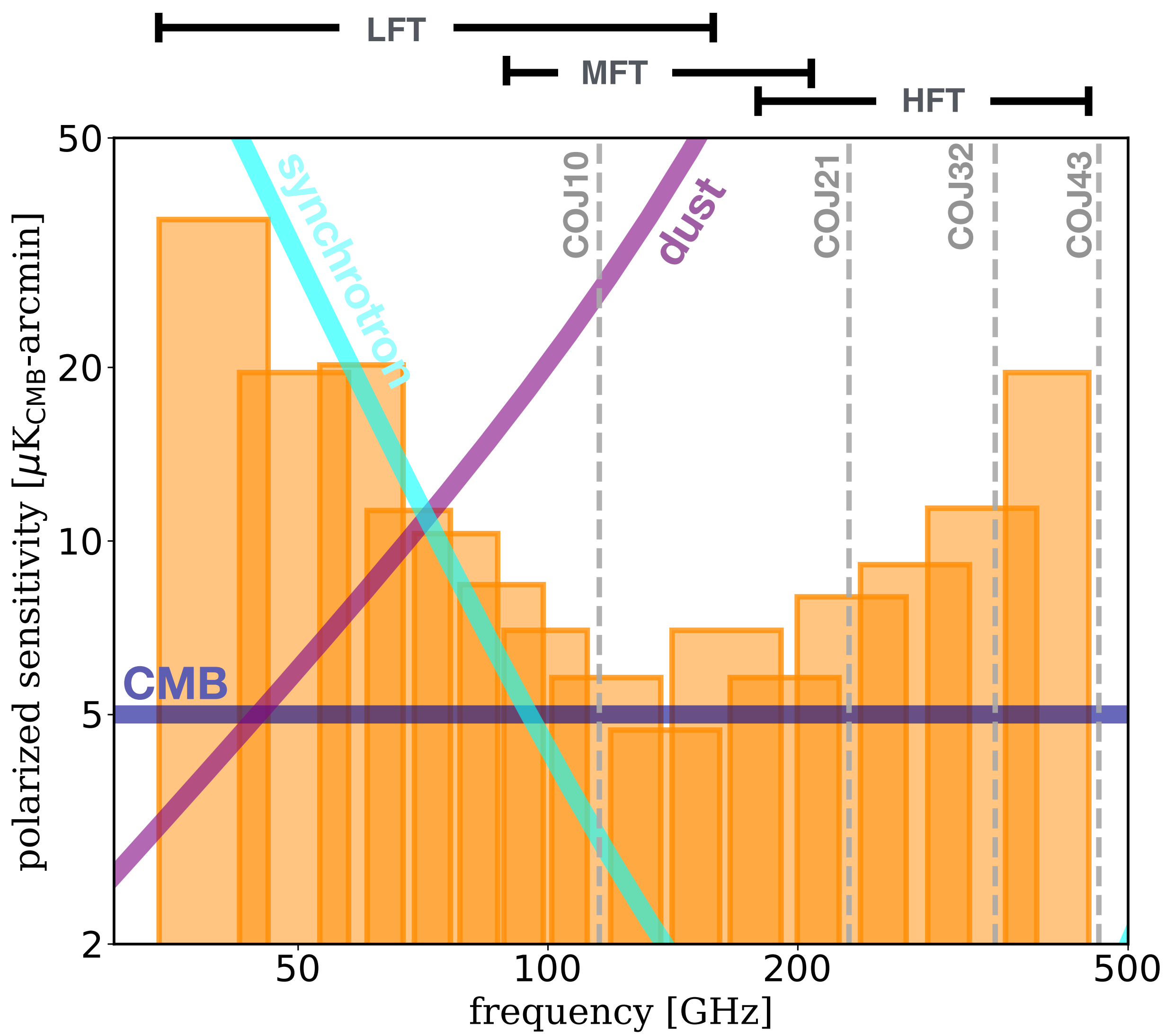
LiteBIRD instruments



- **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

15 bands from 34GHz to 448GHz

4676 detectors

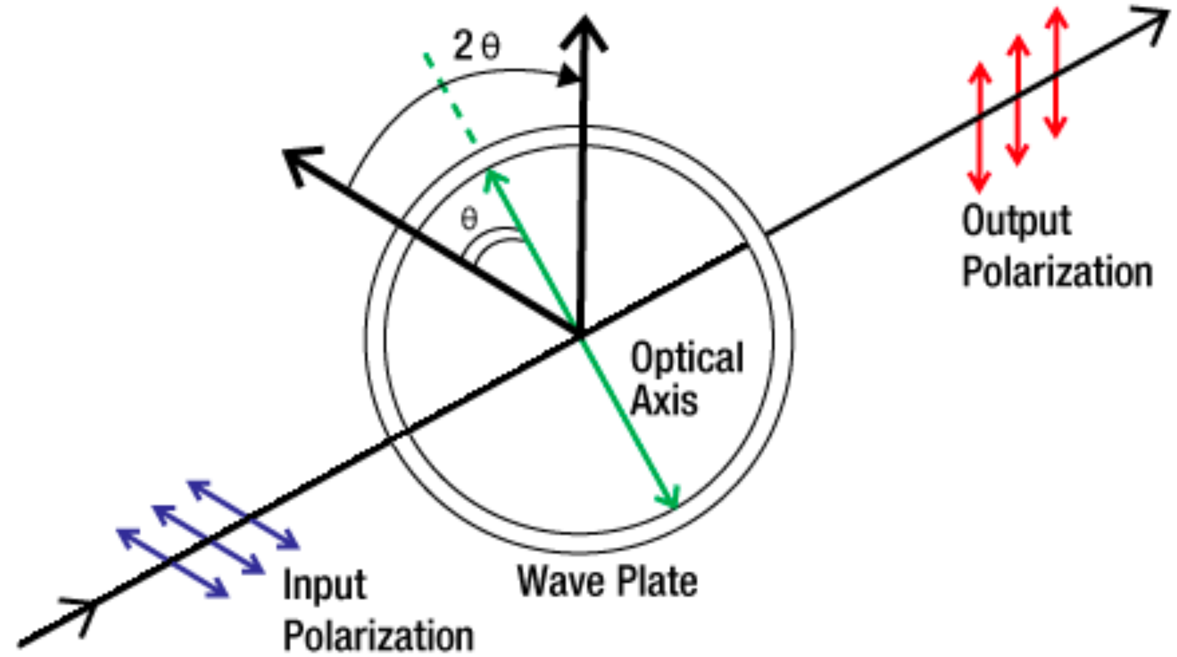


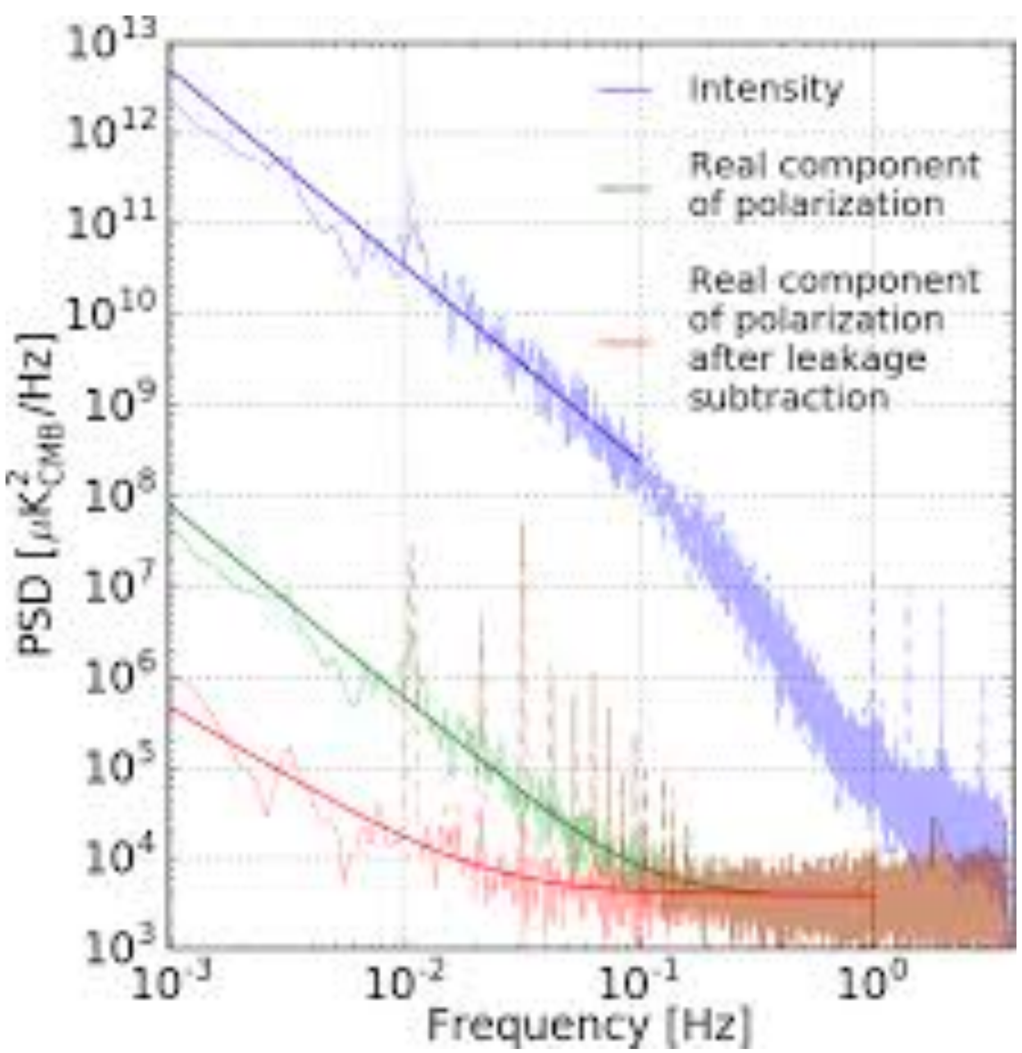
9 bands LFT
5 bands x 2 MHFT

+ 4 bands overlapping

LiteBIRD instruments

- 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

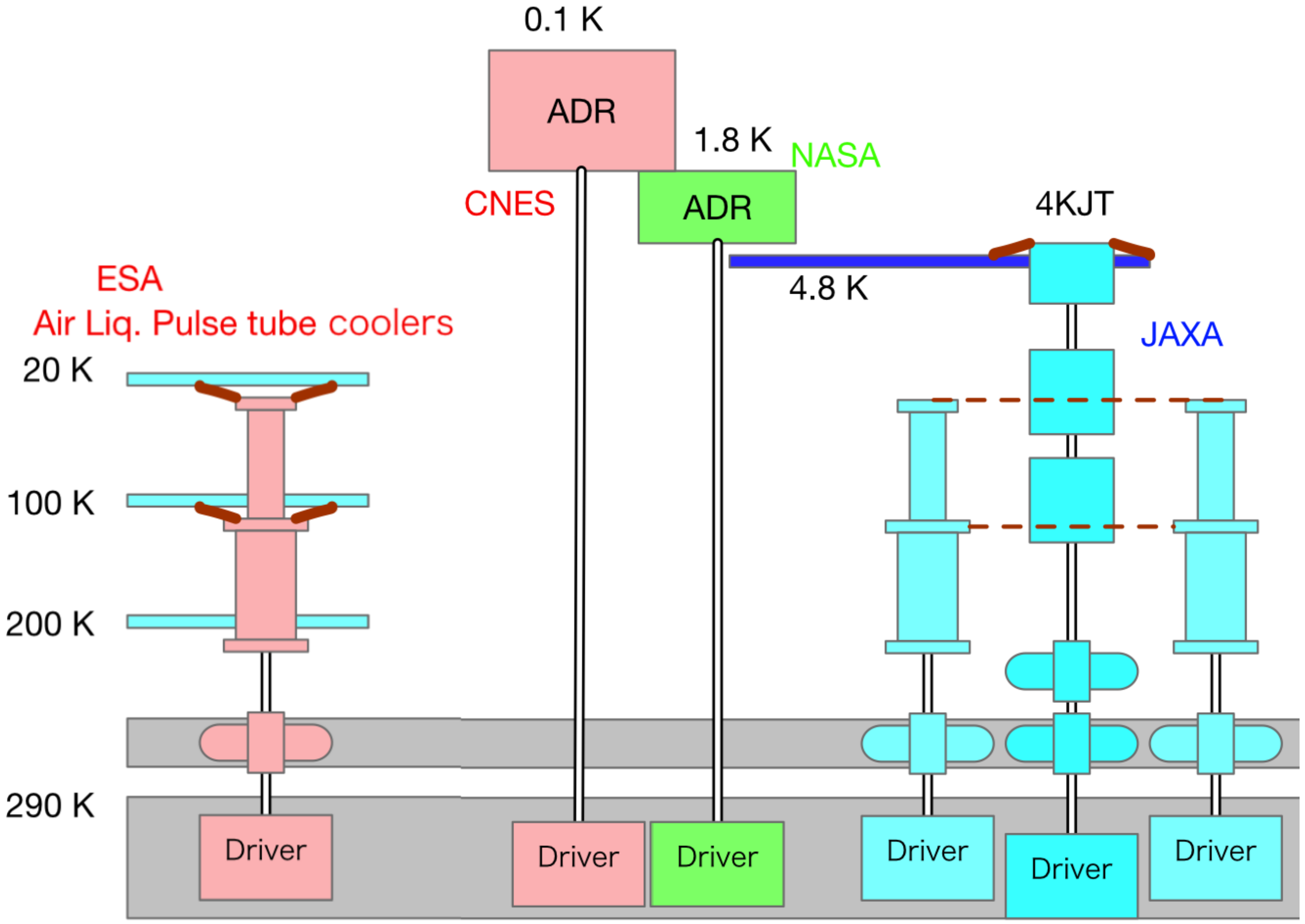


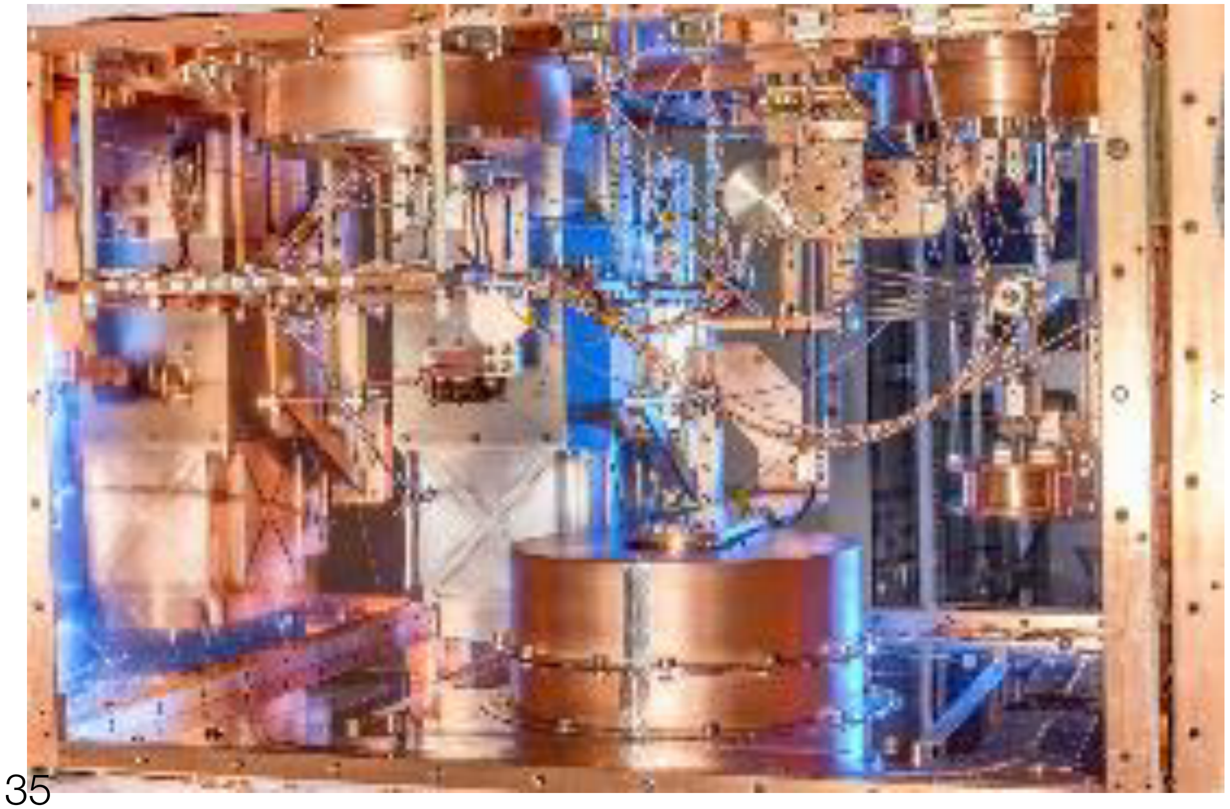


Superconducting magnetic bearing system operational in a 4K cryostat.
We observed the stable rotation at cryogenic temperature (<10K).

LiteBIRD instruments

- 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**



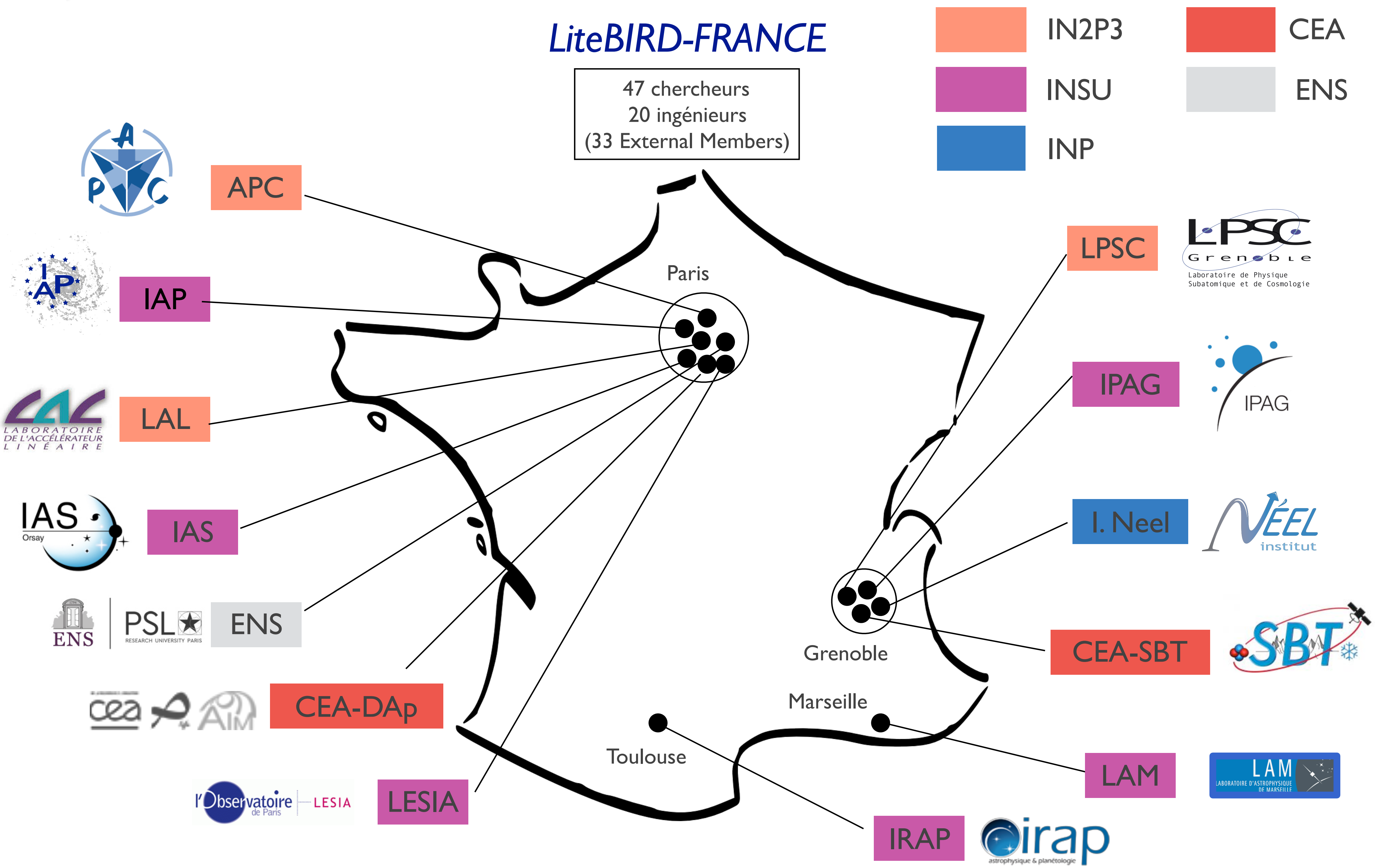


LiteBIRD Joint Study Group

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



+ an endorsement letter has gathered more than **178 signatures** among the French physics community

IN2P3 Prospects 2020

GT05 – Physique de l'inflation et énergie noire

Cosmic inflation and fundamental physics from space
LiteBIRD

Porteur: Matthieu Tristram

[i]D. Auguste, [h]J. Aumont, [h]T. Banday, [h]L. Bautista, [a]D. Beck, [d]K. Benabed, [f]A. Bideaud, [h]A. Blanchard, [i]J. Bonis, [c]F. Boulanger, [j]O. Bourrion, [a]M. Bucher, [f]M. Calvo, [b]J.-F. Cardoso, [j]A. Catalano, [i]F. Couchot, [b]L. Duband, [b]J.-M. Duval, [a]J. Errard, [d]S. Galli, [a]K. Ganga, [a]Y. Giraud-Héraud, [f]J. Goupy, [e]J. Grain, [a]J.Ch. Hamilton, [i]S. Henrot-Versille, [d]E. Hivon, [i]H. Imada, [a]E. Kiritsis, [a]D. Langlois, [d]M. Lilley, [i]T. Louis, [j]J.F. Macias-Perez, [e]B. Maffei, [h]A. Mangilli, [h]R. Mathon, [f]A. Monfardini, [h]L. Montier, [h]B. Mot, [a]F. Nitti, [h]F. Pajot, [a]G. Patanchon, [l]V. Pelgrims, [b]V. Pettorino, [a]M. Piat, [g]N. Ponthieu, [a]D. Prele, [b]T. Prouvé, [h]G. Roudil, [d]J. Silk, [a]R. Stompor, [i]M. Tristram, [d]B. Wandelt, [k]B. van Tent, [a]V. Vennin, [f]G. Vermeulen, [a]F. Voisin

[a]APC, [b]CEA, [c]ENS, [d]IAP, [e]IAS, [f]Institut Néel, [g]IPAG, [h]IRAP, [i]LAL, [j]LPSC, [k]LPT, [l]FORTH (Greece)

LiteBIRD is a space mission selected by JAXA as its Strategic Large Mission scheduled for launch in 2027. LiteBIRD represents the next generation of CMB mission after COBE, WMAP, and Planck. The science goals of LiteBIRD are to detect the primordial gravitational waves through the measure of the tensor-to-scalar ratio, r, and to characterize the CMB B-mode and E-mode spectra down to degree scales with an unprecedented sensitivity. With a sensitivity after component separation which reaches $\sigma(r) = 10^{-4}$ on the tensor-to-scalar ratio, the mission defines "full success" for a final precision better than $\sigma(r) = 10^{-3}$ including the post-cleaning contributions of residual foreground and systematic effect residuals. This will be achieved using LiteBIRD data only, without applying any correction for lensing. A further improvement in the B-mode sensitivity will come from the combination of LiteBIRD and ground-based data (including delensing). This creates the possibility for the first detection of a quantum gravitational wave or, at the very least, will considerably improve the current upper limits by more than one order of magnitude.

In addition, LiteBIRD will provide an ultimate measurement of large scale E-modes polarisation which will allow constraining the reionization models as well as breaking degeneracies in determining other cosmological parameters. LiteBIRD will also give access to unprecedented polarization maps in multiple frequency bands in mm-domain allowing for constraints on possible spectral distortions of the primordial blackbody, testing parity violation in the early Universe as well as constraining the physics of post-inflationary reheating.

This paper is tightly coupled with the proposals "Cosmic inflation - theory" and "Cosmic inflation from ground based CMB polarization experiments".

IN2P3 Prospectives 2020

GT05 - Physique de l'inflation et énergie noire

ESA Voyage 2050 white papers for cosmology with a spectro-polarimetric survey of the microwave sky

Jacques Delabrouille[a] on behalf of the proposers

[a]APC, CNRS/IN2P3, 10 rue A. Domon et L. Duquet, 75013 Paris
and
IRFU, CEA-Saclay, 91190 Gif-sur-Yvette Cedex

THE THIRD SKY PROGRAMME.

V.K.Dubrovich[1], M.Yu.Khlopov[2,3,4]

[1] Special Astrophysical Observatory, St. Petersburg Branch, Russian Academy of Sciences, St. Petersburg, 196140 Russia
[2] National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), 115409 Moscow, Russia
[3] APC laboratory 10, rue Alice Domon et Leonie Duquet 75205 Paris Cedex 13, France
[4] Institute of Physics, Southern Federal University, Stachki 194 Rostov on Don 344090, Russia

"The most obvious and promising is relatively high resolution spectroscopy combined with the study of individual fluctuations - the search and study of spectral-spatial fluctuations of the temperature of the CMB."

primordial fluctuations

large scale B-modes
→ tensor-to-scalar ratio (BB)
damping tail
→ primordial power on small scales (TE, TT, EE)
→ primordial bispectrum (f_{NL} via TTT,TTE,… + lens/kSZ)

relativistic species

damping tail
→ N_{eff} (TE, TT, EE)

reionization

sources
→ duration of reionization (kSZ)
→ mean free path of photons (kSZ)

neutrino mass

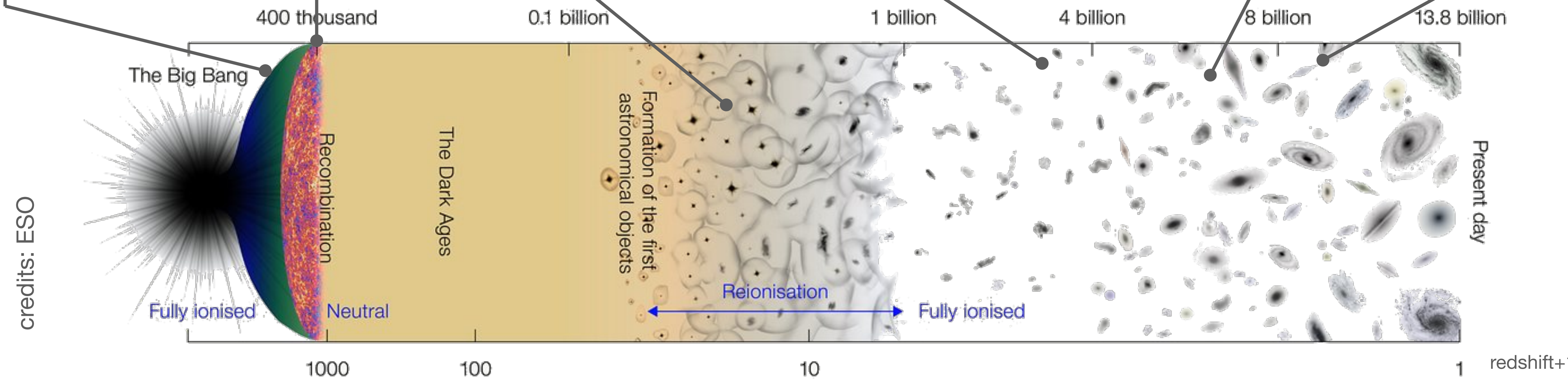
lensing potential (TT+EB), tSZ
→ Σm_ν

galaxy evolution

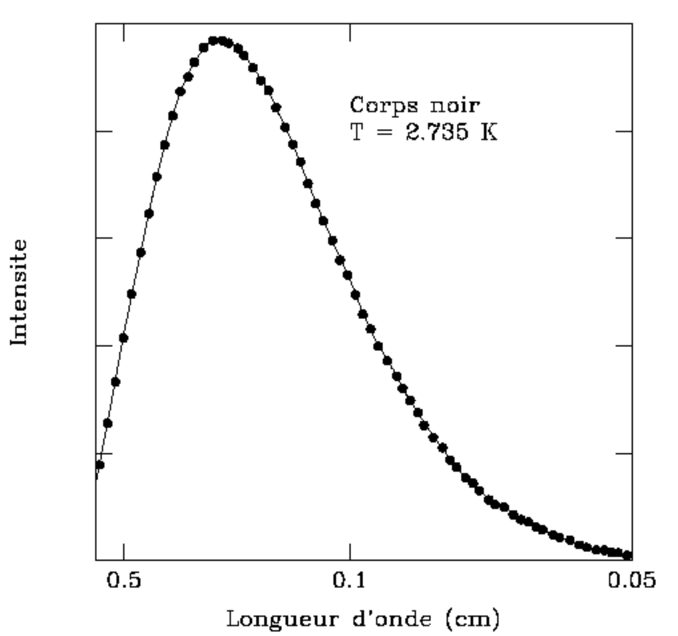
tSZ, kSZ
→ non-thermal pressure (tSZ+kSZ)
→ feedback efficiency (tSZ+kSZ)

dark energy

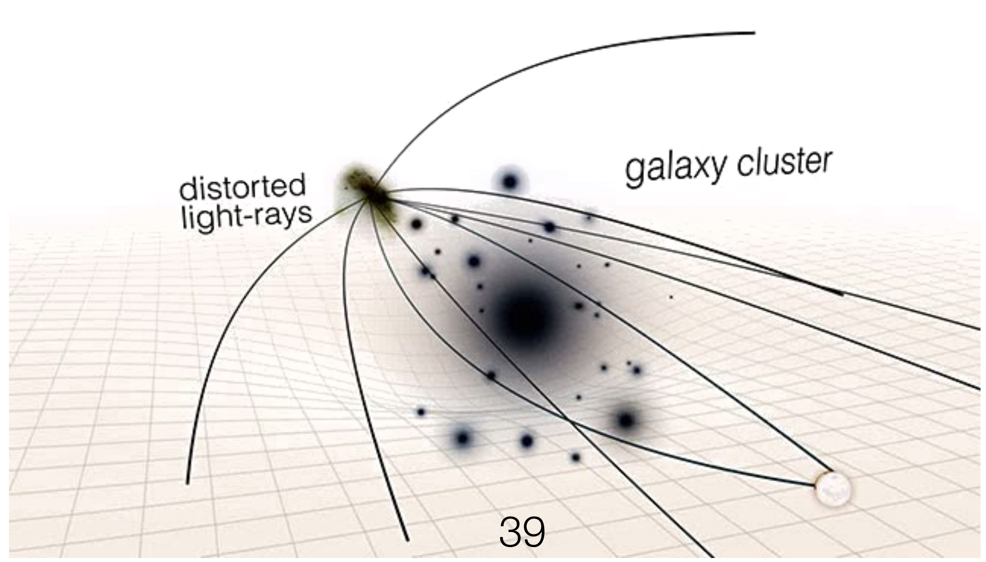
tSZ, lensing
→ σ_8 at z=2-3 (lensing, tSZ)
→ growth of structure (kSZ)



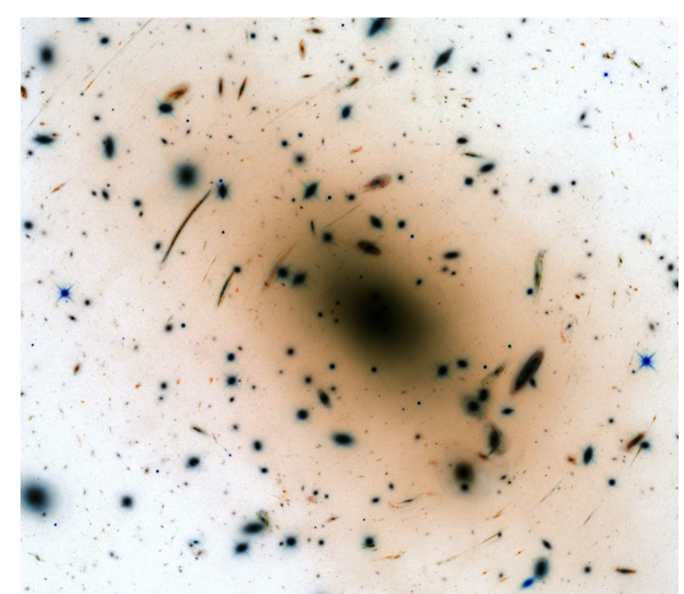
spectroscopy



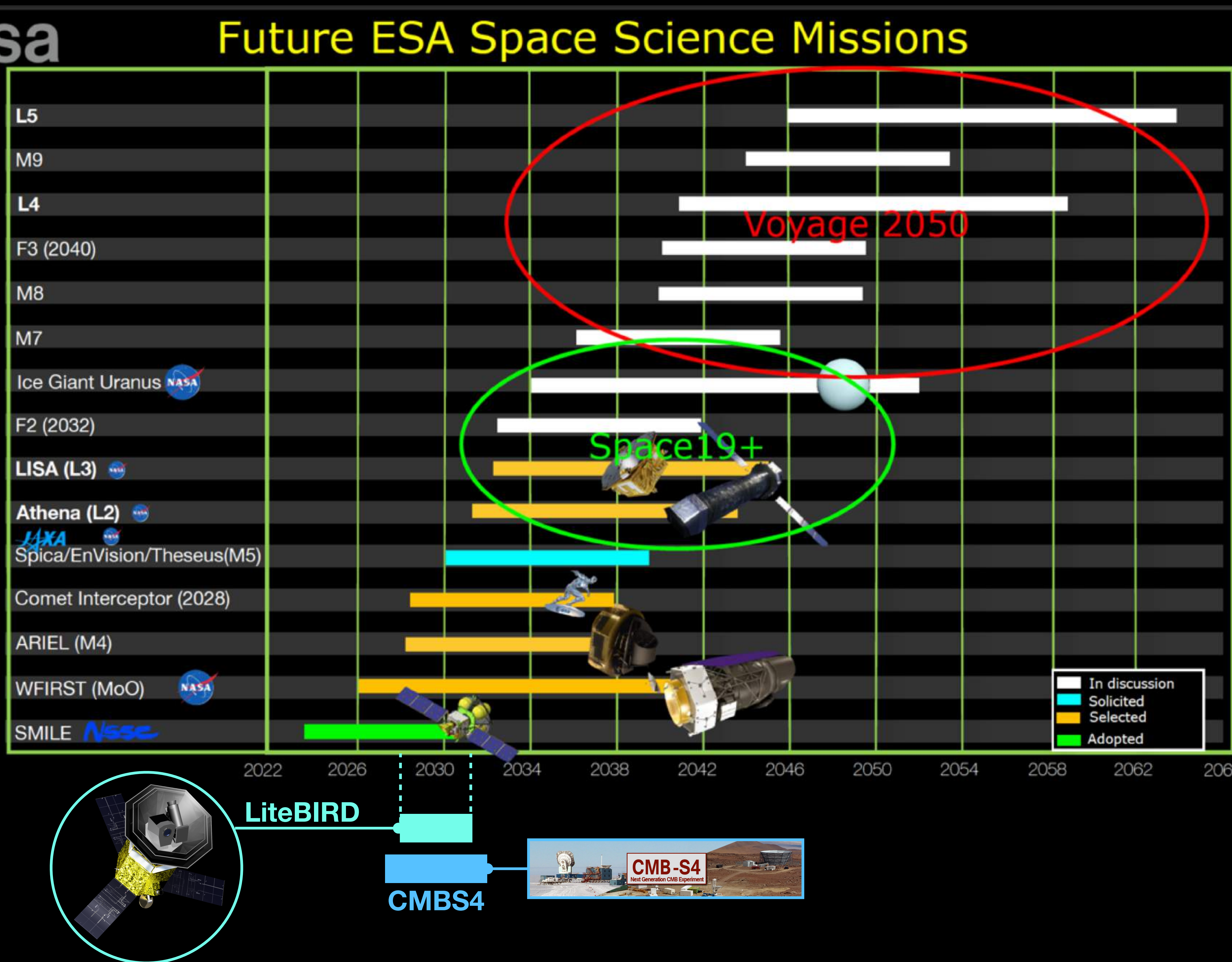
gravitational lensing



galaxy clusters



Slide G. Hasinger



adapted from J. Delabrouille VOYAGE 2050 WORKSHOP, Oct 2019

A space telescope / mission with 3 instruments

Microwave Imaging and Spectroscopy Telescope

1. A broad-band, multi-frequency polarised imager
   - Reference model: PICO instrument at the focus of 3.5m cold telescope
   - 21 bands from ~20 to ~800 GHz

CONTINUUM EMISSION

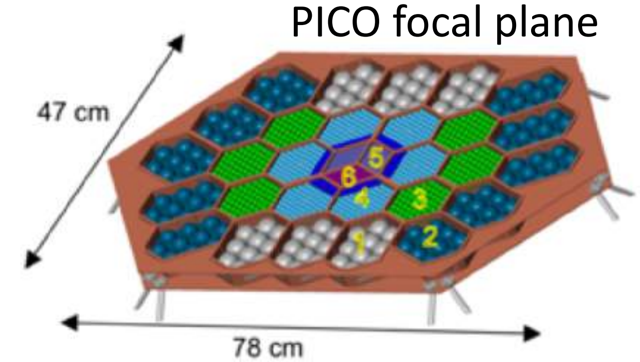
2. A sensitive spectrometer with R ≈ 300
   - Reference model: Extended Deshima at the focus of the same telescope
   - Frequency range ~100-1000 GHz (goal 50-2000 GHz)

LINE EMISSION

3. An absolutely calibrated FTS
   - Reference model: a three-module version of PIXIE / PRISTINE
   - Frequency range ~10-2000 GHz

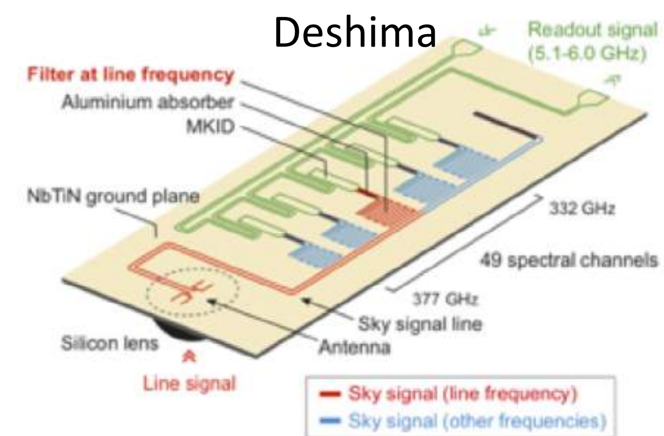
INTEGRATED EMISSION

PICO focal plane

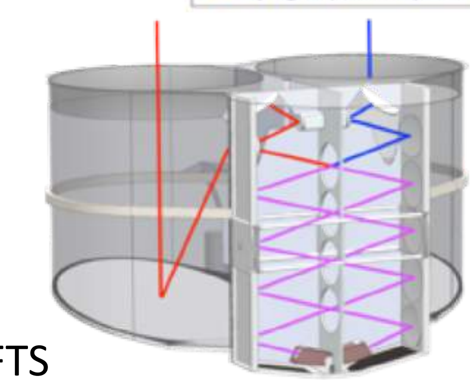


(S. Hanany et al. 2019)

Deshima



(A. Endo et al. 2019)



PIXIE FTS

(A. Kogut et al. 2019)

from J. Delabrouille VOYAGE 2050 WORKSHOP, Oct 2019

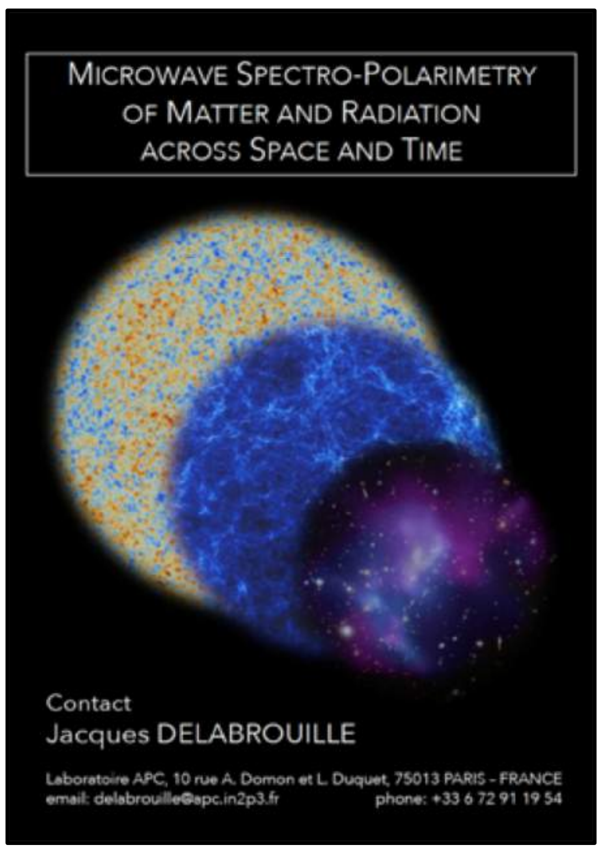
- **Map entire cosmic web**

  ⇓

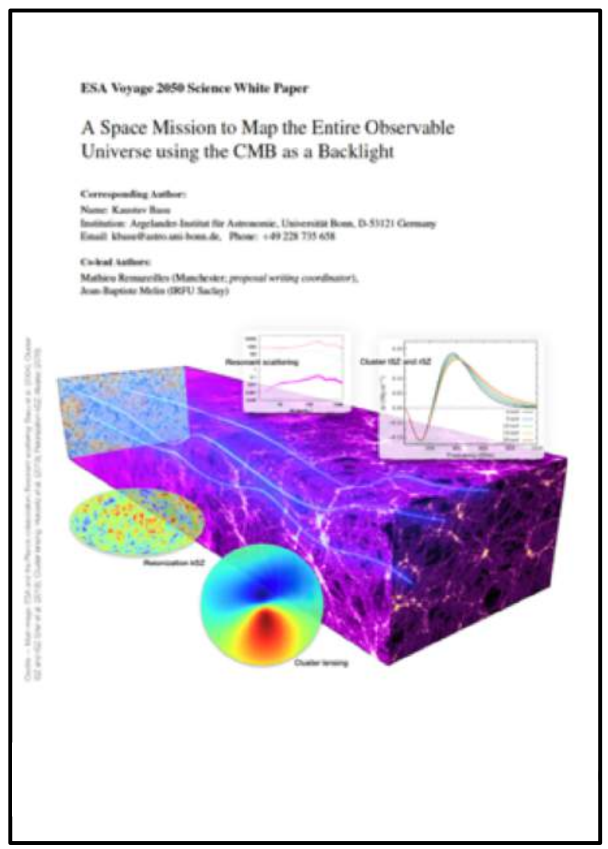
- **Dark Energy**
- **Modified gravity**
- **Distribution of early atoms**
- **Neutrino masses…**

←

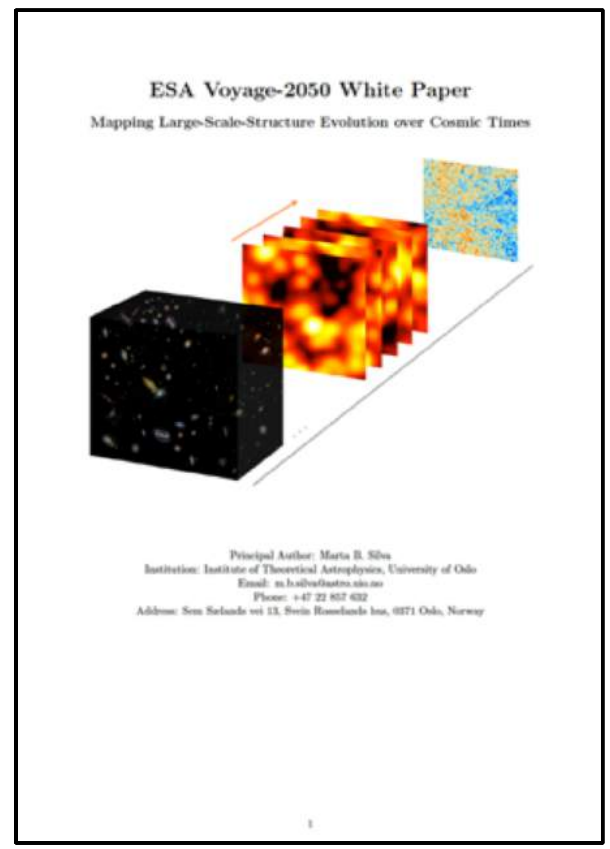
- **10^6 galaxy clusters**
- **Full sky Dark Matter maps**
- **CMB sensitivity ≈ 5000 × Planck ≈ 10 × CMB-S4 (polar.)**
- ***line intensity mapping***



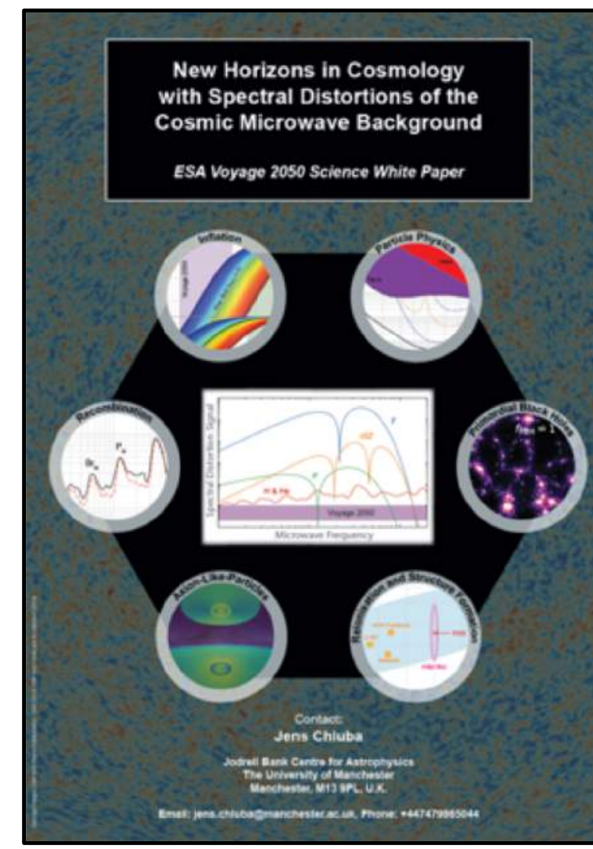
Microwave survey
Jacques Delabrouille et al.



CMB Backlight
Kaustuv Basu et al.



High redshift structures
Marta Silva et al.



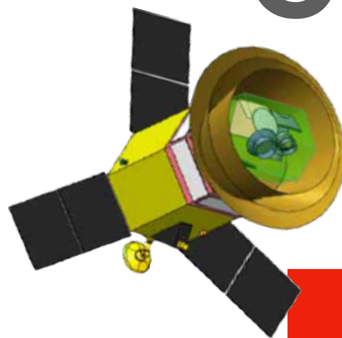
Spectral distortions
Jens Chluba et al.

L-CLASS MISSION

3 SYNERGISTIC DESIGN-DRIVING SCIENCE CASES

from J. Delabrouille VOYAGE 2050 WORKSHOP, Oct 2019

Conclusions



LiteBIRD*

Voyage 2050* (?)

2020 2025 2030 2035 2050

Simons Array*

Simons Observatory*

CMB-S4*

QUBIC*

AliCPT*

BICEP Array

AdvACT

SPT-3G

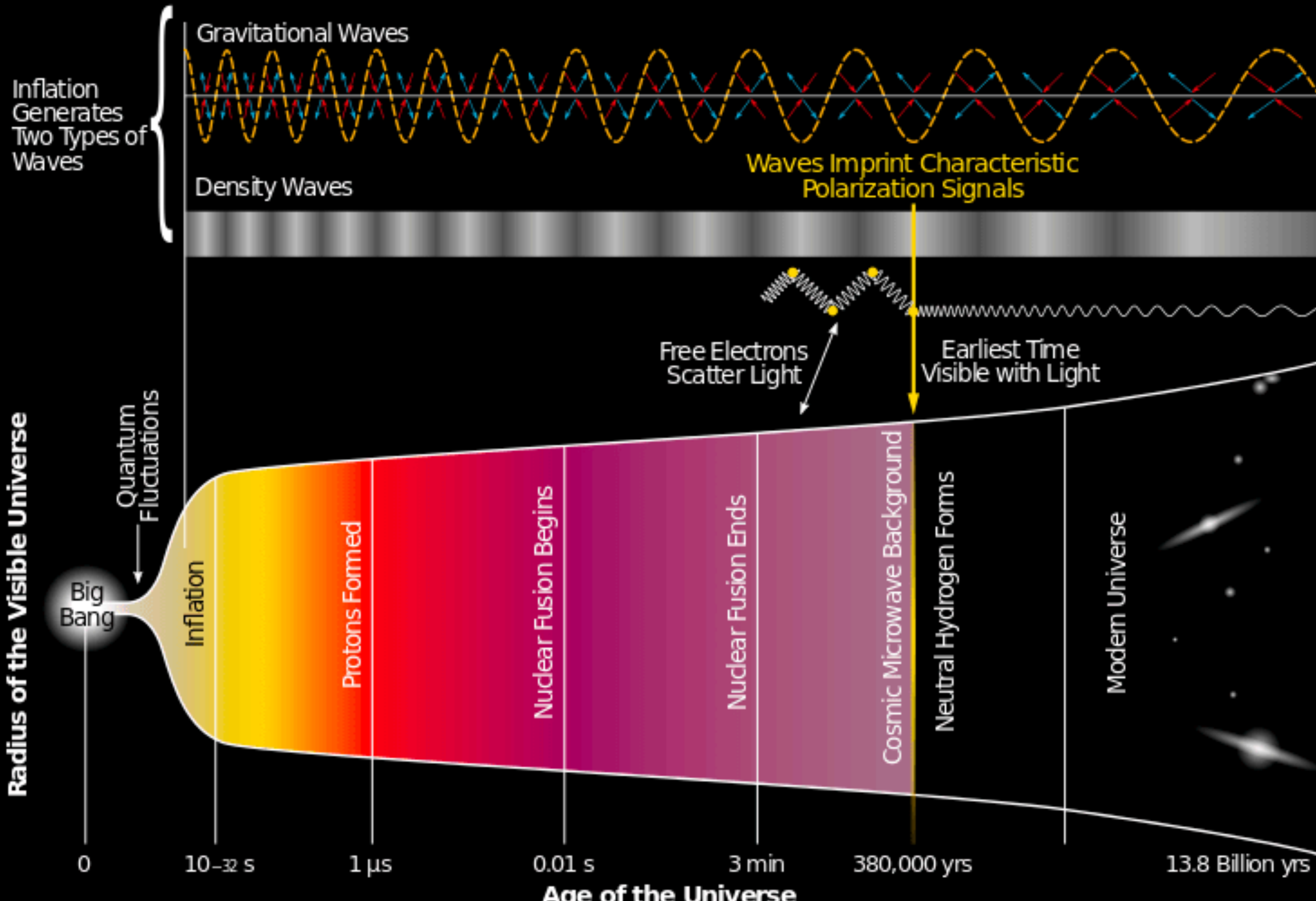
[see talk by Thibaut Louis]

cnrs

(*) IN2P3

BACKUP

History of the Universe



www.universetoday.com

- Planck data do not need convex potentials (n>1), multi-fields models or non-minimal kinetic term
- minimal models of particular interest include
  - the **Starobinsky model** “$R+R^2$” (first model introduced)
  - the **“Higg’s inflation”** with non-minimal coupling from gravity introduced by quantum corrections in a curved space-time (the same shape as R^2)
  - inflaton based on a field appearing in the extensions of the standard model of particle physics (usually extensions based on super-symmetry)
  - …

credits: Matt Tristram

LiteBIRD — beyond the B-mode power spectrum

- within single field slow-roll inflation, the tensor perturbation obey the vacuum equation $\Box h_{ij} = 0$
- inducing the following statistical properties
  1. nearly scale invariant power spectrum $n_t = -r/8$
  2. nearly Gaussian probability distribution
  3. parity-conserving probability distribution

tensor tilt n_t

- current upper-limit on tensor-to-scalar: $r < \sim 0.01$
- better sensitivity expected on tensor tilt: $\sigma(n_t) > \sim 0.003$

impossible to verify the consistency relation !

BUT

other mechanism than single-field slow-roll inflation predict deviations from scale-invariant P_k
(e.g. gravity inflation, open inflation, SU(2)-axion model, multi-field inflation…)

constraints on the primordial tensor power spectrum can distinguish between inflation models

e.g. PCA [Campeti et al. 2019, arXiv:1905.08200]

LiteBIRD — beyond the B-mode power spectrum

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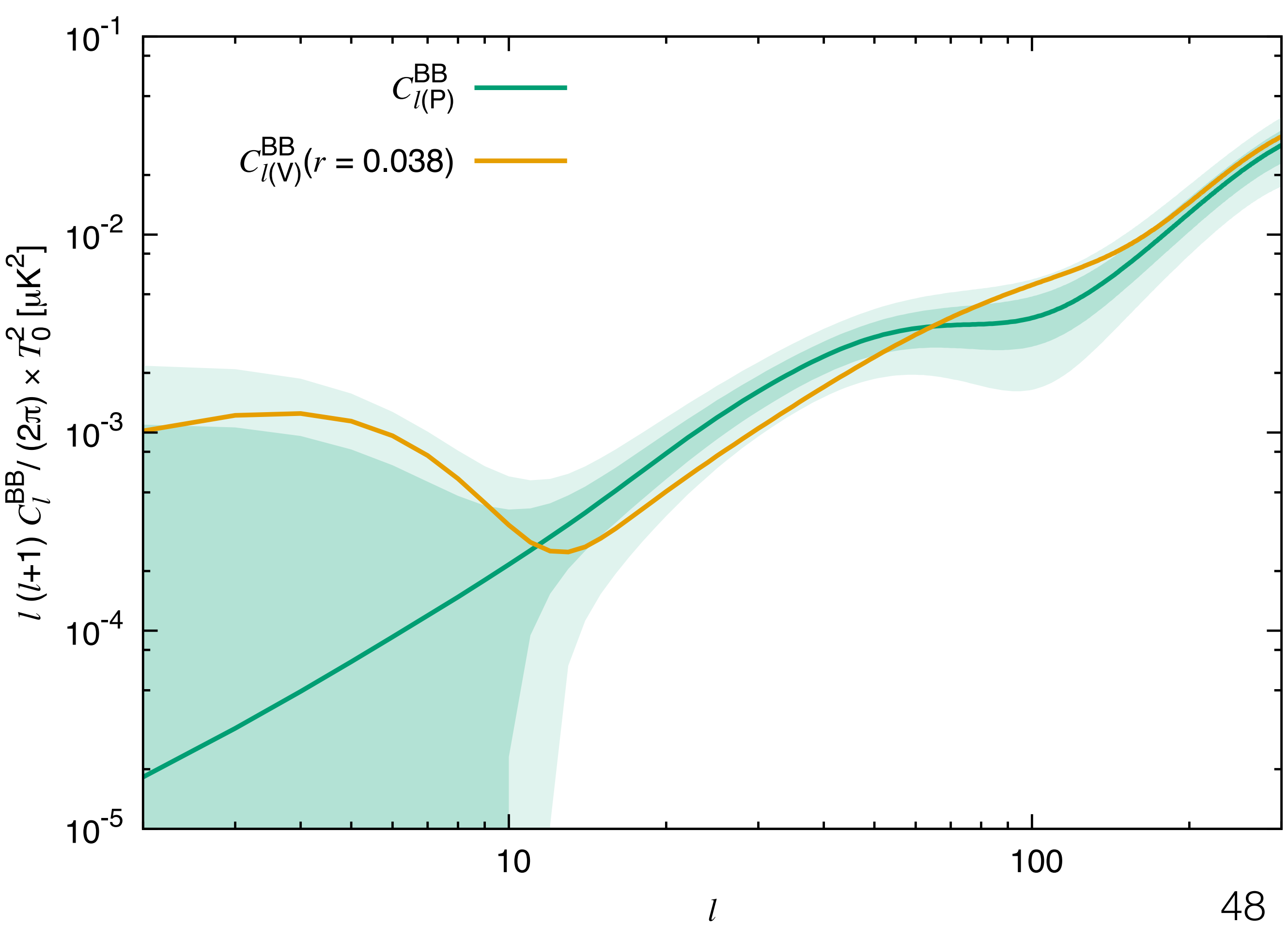
Non-Gaussianity



indistinguishable with BB for ℓ>10 alone

↓

non-Gaussian features using BBB bi-spectrum

Example: "Pseudoscalar model" [Namba, Peloso, Shiraishi, Sorbo, Unal, arXiv1509.07521]

LiteBIRD — beyond the B-mode power spectrum

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Parity-violating

- parity-violating coupling of a scalar field to the electromagnetic tensor induces a rotation of the polarization direction

$$\begin{aligned} C_\ell^{TB,\mathrm{obs}} &= (2\Delta\alpha)\ C_\ell^{TE}, \\ C_\ell^{EB,\mathrm{obs}} &= (2\Delta\alpha)\ C_\ell^{EE}, \\ C_\ell^{BB,\mathrm{obs}} &= (2\Delta\alpha)^2 C_\ell^{EE}. \end{aligned}$$

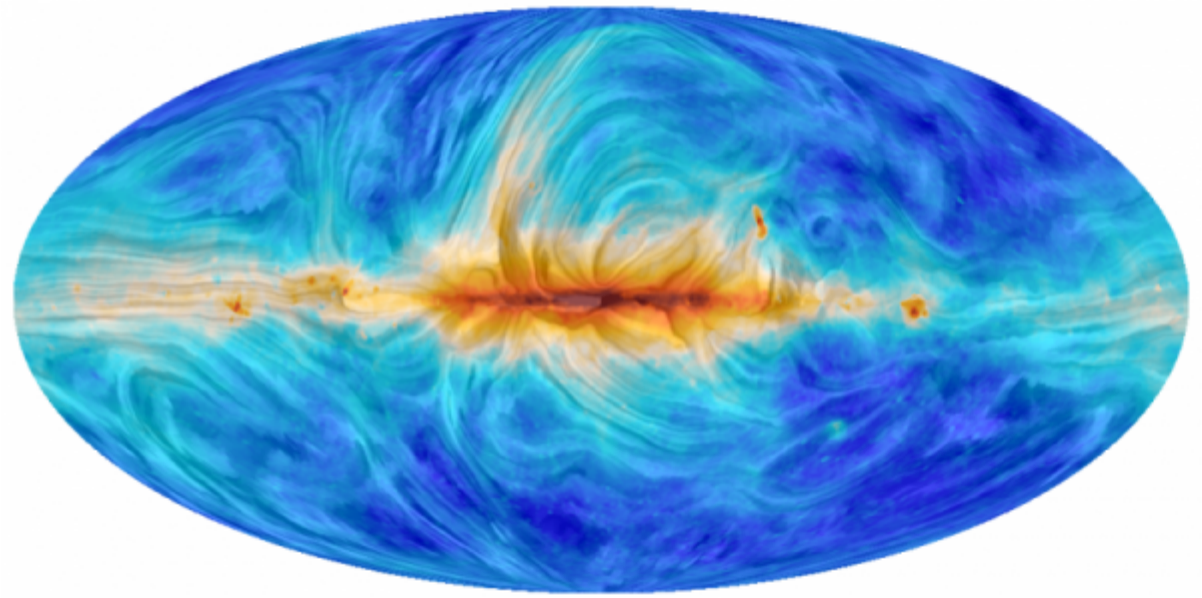
⟶ TB and EB non longer zero

- homogeneous effect **degenerated** with miscalibration of polarization angles
- but
  - constraints on Faraday rotation from primordial magnetic field (with anisotropies of $\Delta\alpha$)
  - parity-violating gravitational waves (with spectral shape in C_ℓ)

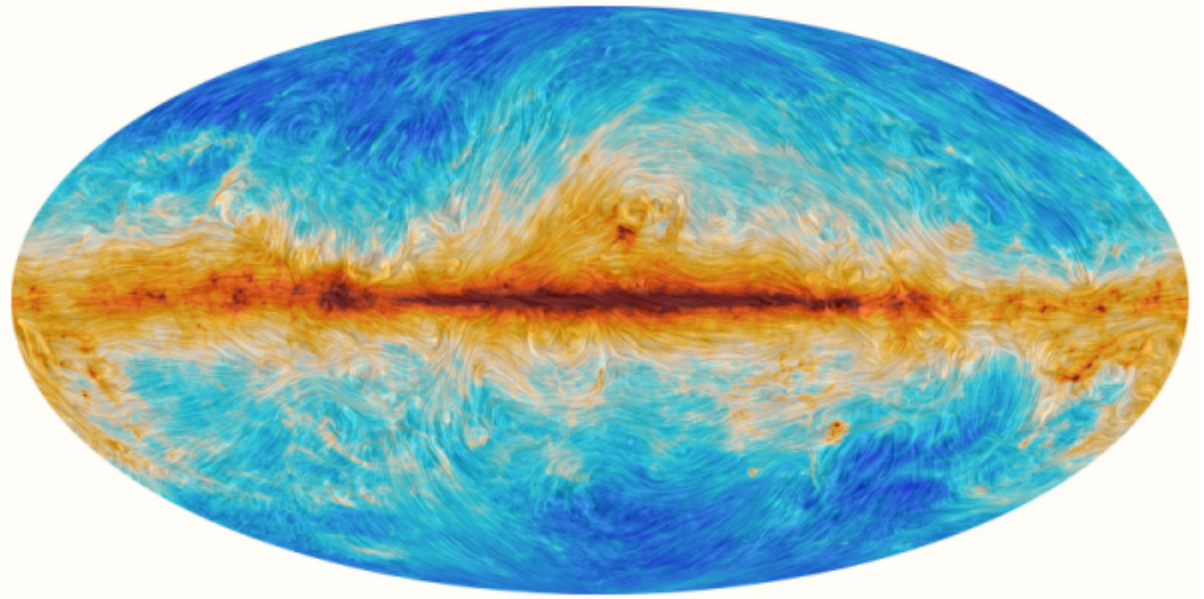
LiteBIRD — galactic science

With frequency range from 34 to 448 GHz and access to large scales LiteBIRD will gives constraints on

- Characterization of the foregrounds SED
- Large scale Galactic magnetic field
- Models of dust polarization grains



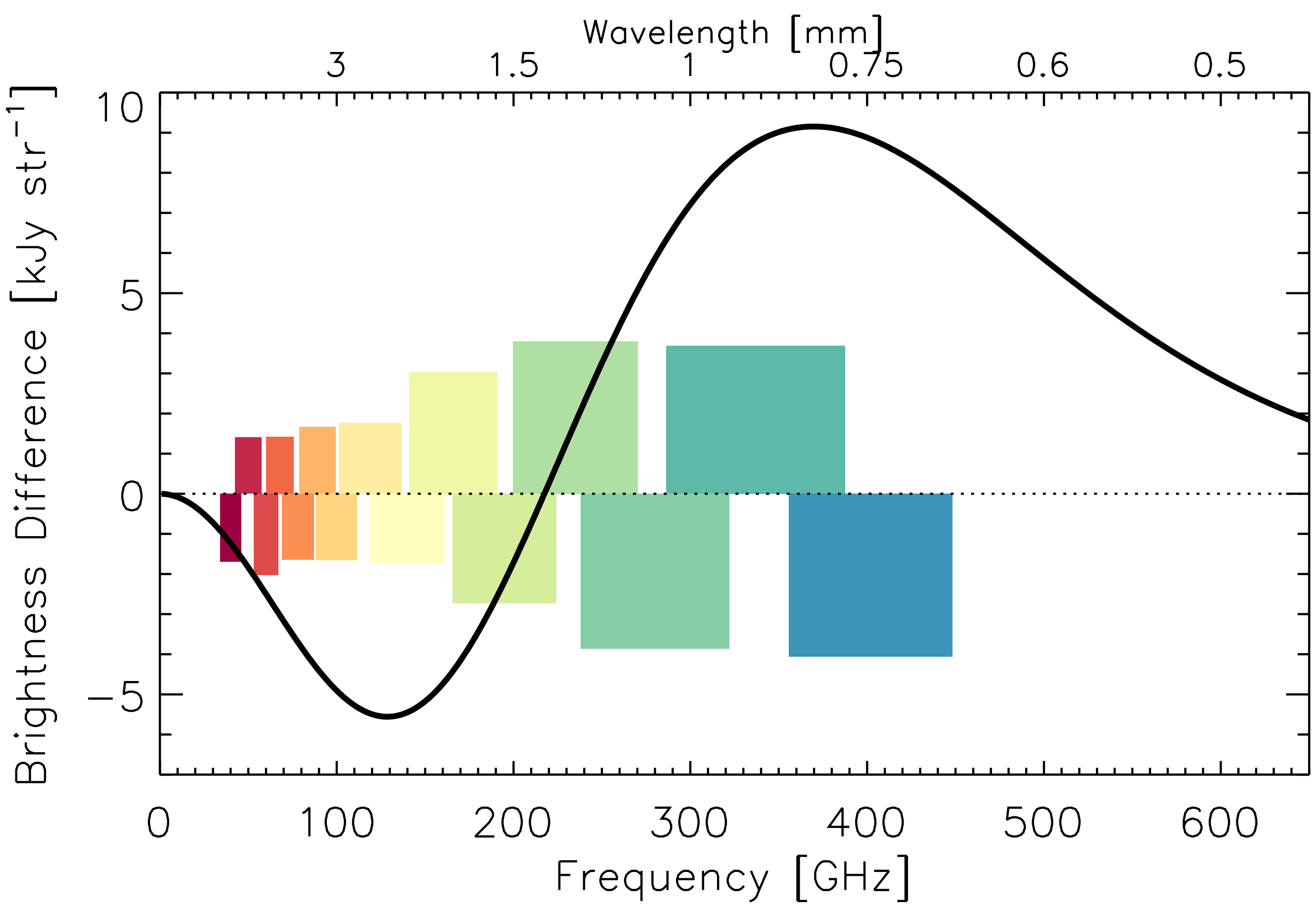
Synchrotron

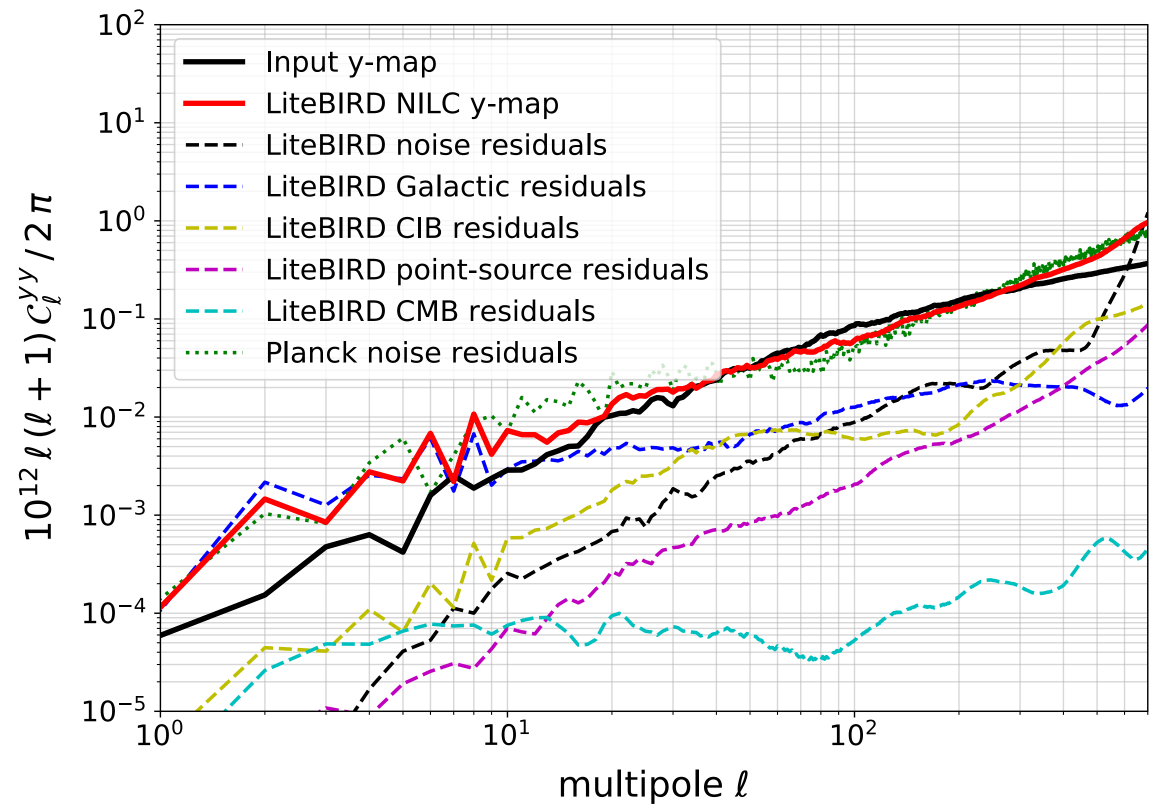


Dust

LiteBIRD — mapping the hot gas in the Universe

significant improvement on the SZ y-map in terms of foregrounds residuals thanks to the 15 bands





LiteBIRD — spectral distortions

- Anisotropic CMB spectral distortions could be measured well
  - Forecasts better than PIXIE ! (15 bands are many)
  - Multi-field effects or non-Bunch-Davies initial conditions
    - spatially-varying chemical potential distributions [Pajer-Zaldarriaga-2012, Ganc-Komatsu-2012]
    - Effects on $C_\ell^{\mu\mu}$, $C_\ell^{\mu T}$
- Frequency Space Differential measurements for detecting any spectral distortion [Mukherjee-Silk-Wandelt 2018]
  - Use inter-frequency differences only

interesting theoretical ideas need experimental assessment:

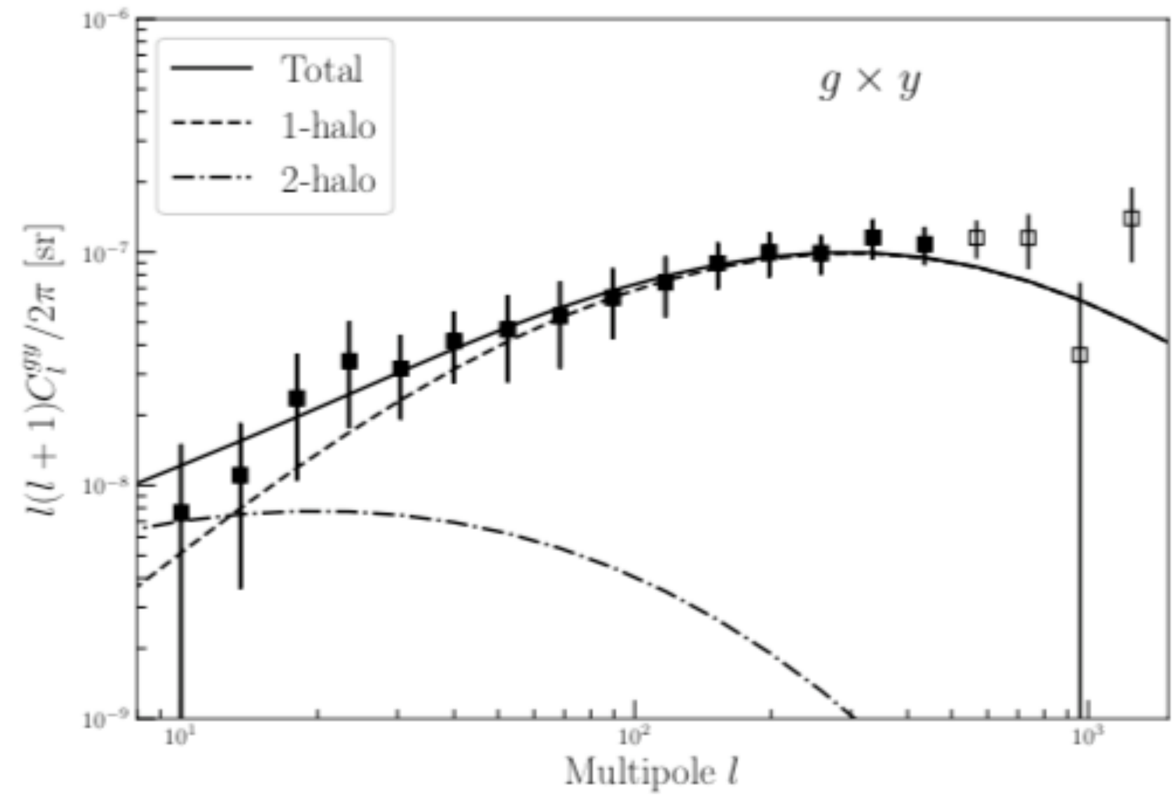
- include 1/f noise, systematic errors, etc…
- use advantages of multi-color detectors
- use “controlled imperfection” of HWP for gain calibration

LiteBIRD — synergy with other probes

- Galaxy surveys

full-sky map of hot gas
(thermal SZ)
⊗
3D distribution of the matter
(galaxy survey)

how gas traces the matter in the Universe



- Integrated Sachs-Wolf effect

improvement on ISW signal (~20%)

- Lensing

LiteBIRD E-modes
+
CMB-S4 high-resolution

→ improve our knowledge of the projected gravitational lensing produced by the large-scale structure

LiteBIRD — science case

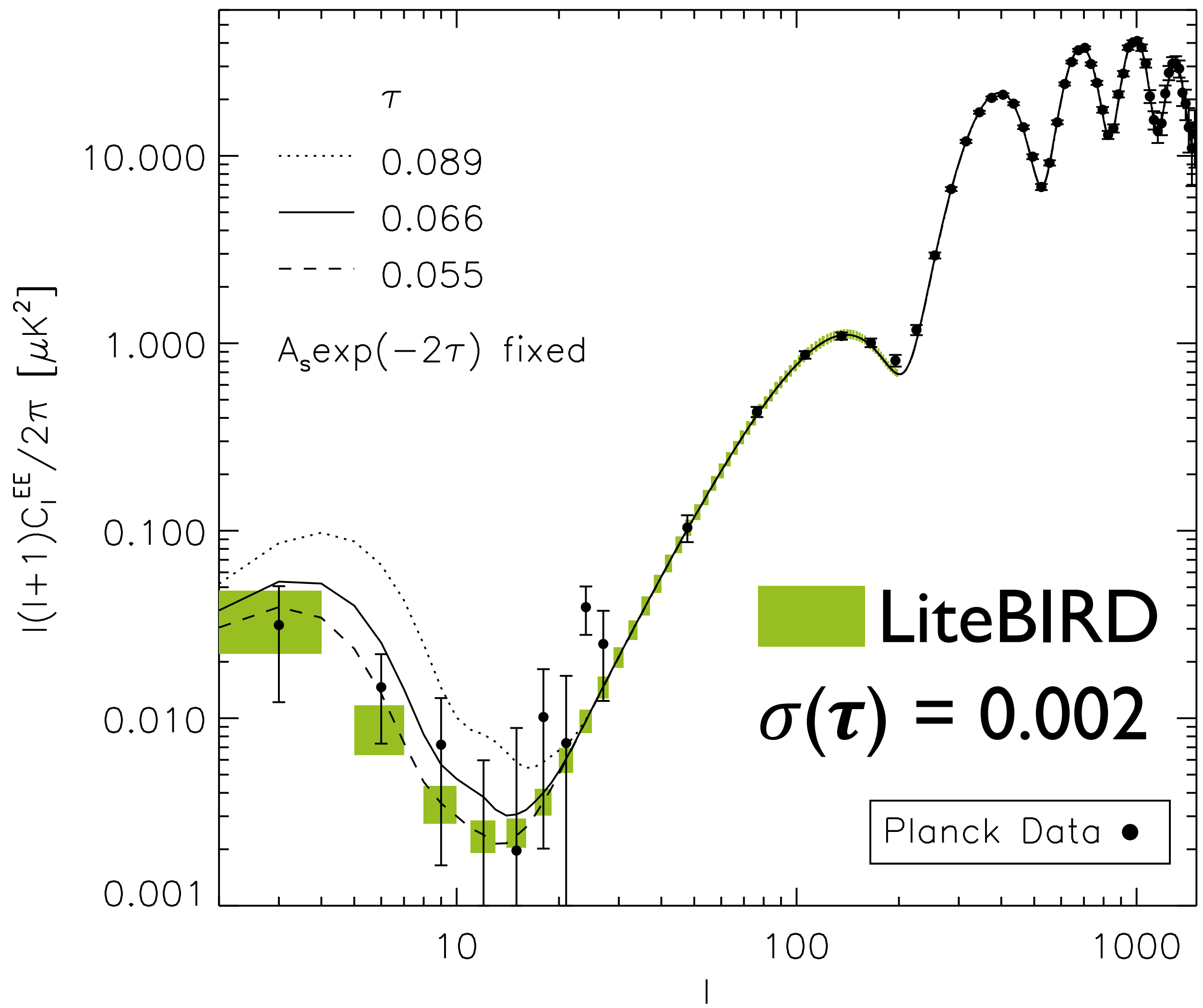
- Primordial gravitational waves from inflation
  - B-mode power spectrum
  - Full success
  - Extra success
  - Beyond the B-mode power spectrum

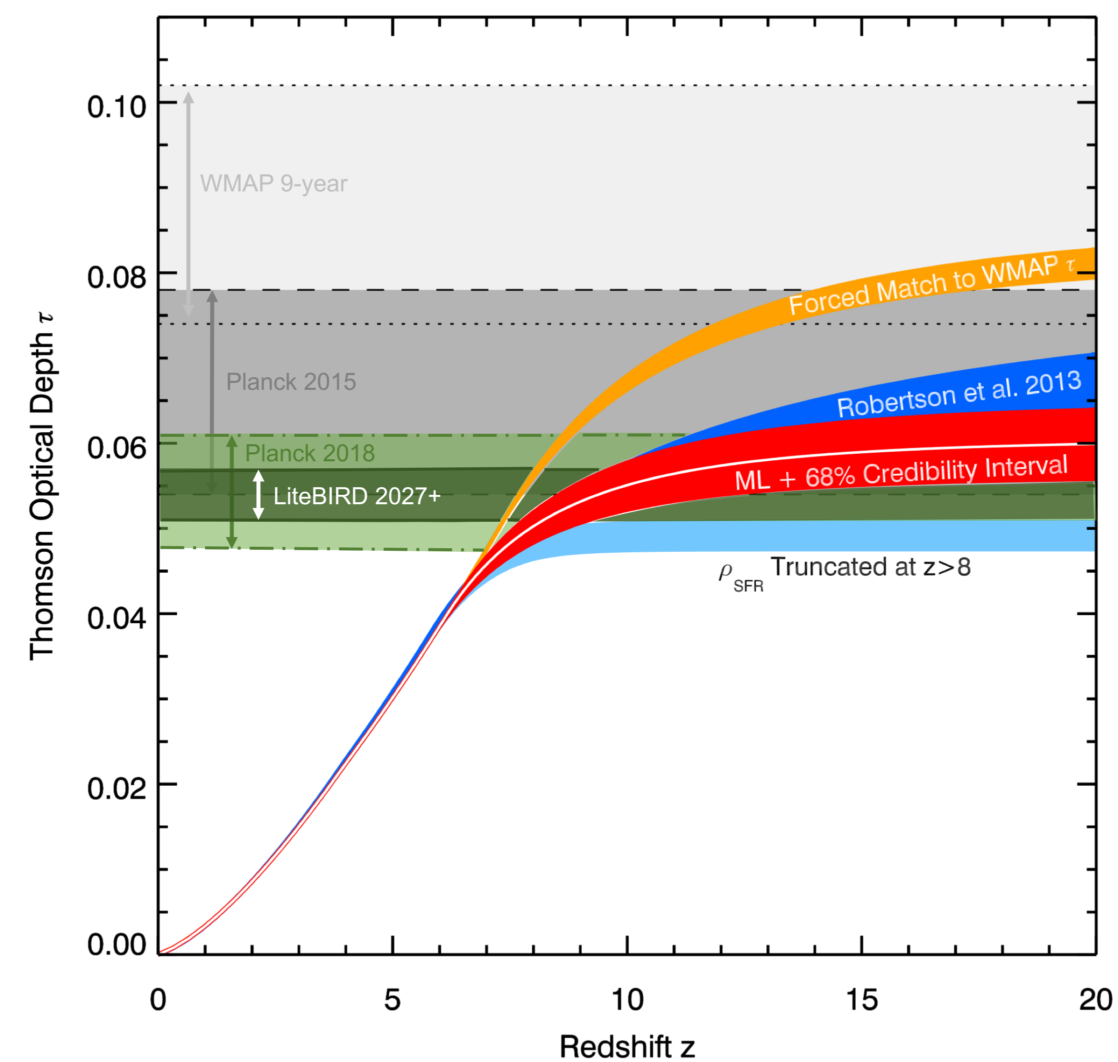
- Galactic science
- Optical depth and reionization of the Universe
- Cosmic birefringence

- Mapping the hot gas in the Universe
- Anisotropic CMB spectral distortions
- Elucidating anomalies with polarization
- Correlation with other data sets

LiteBIRD — reionization

A cosmic variance limited measurement of EE on large angular scales will be an important, and guaranteed, legacy for LiteBIRD





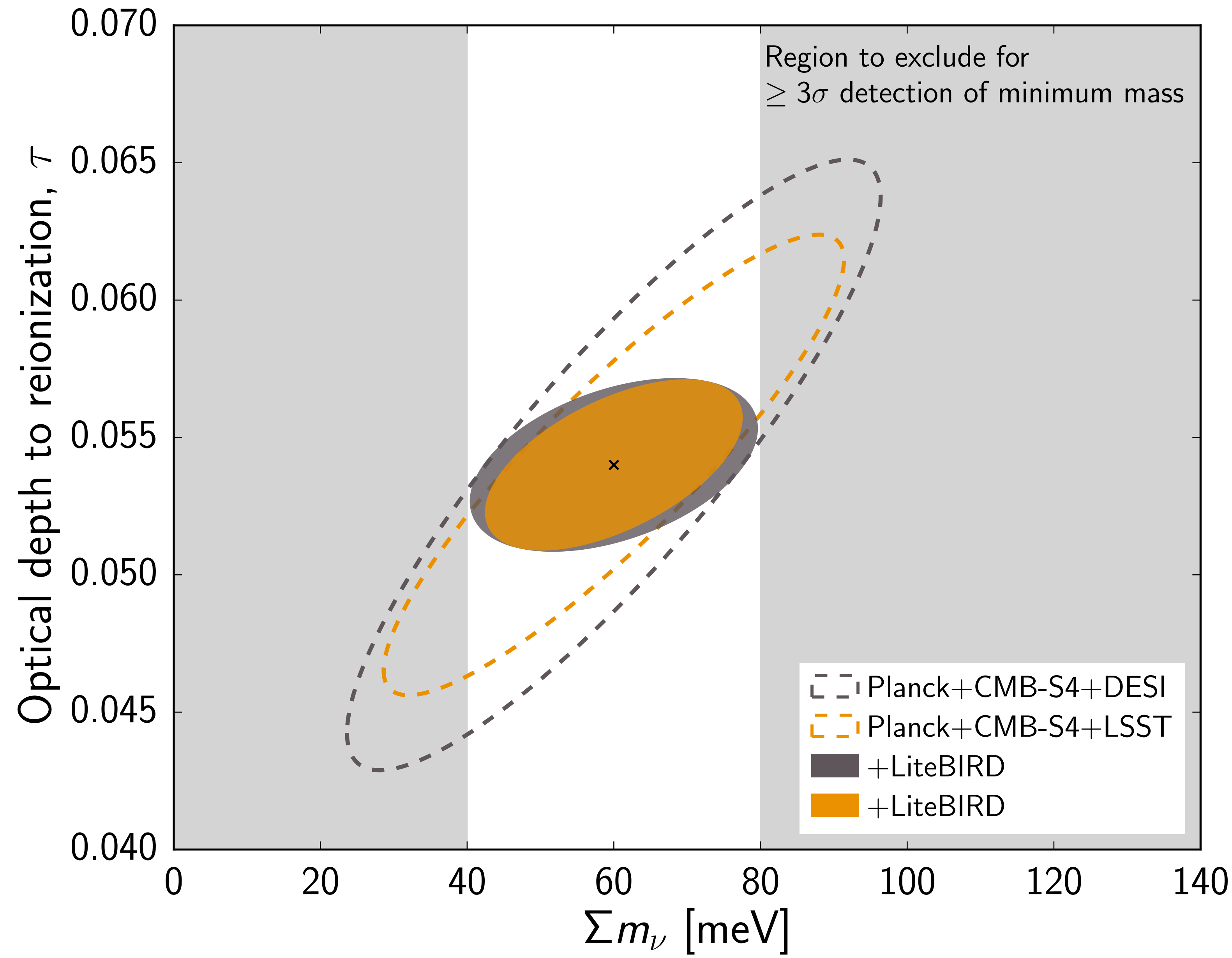
$\sigma(\tau)$ better than current Planck constraints by a factor 2

[LiteBIRD Collaboration, PTEP 2012]

LiteBIRD — reionization and neutrino sector

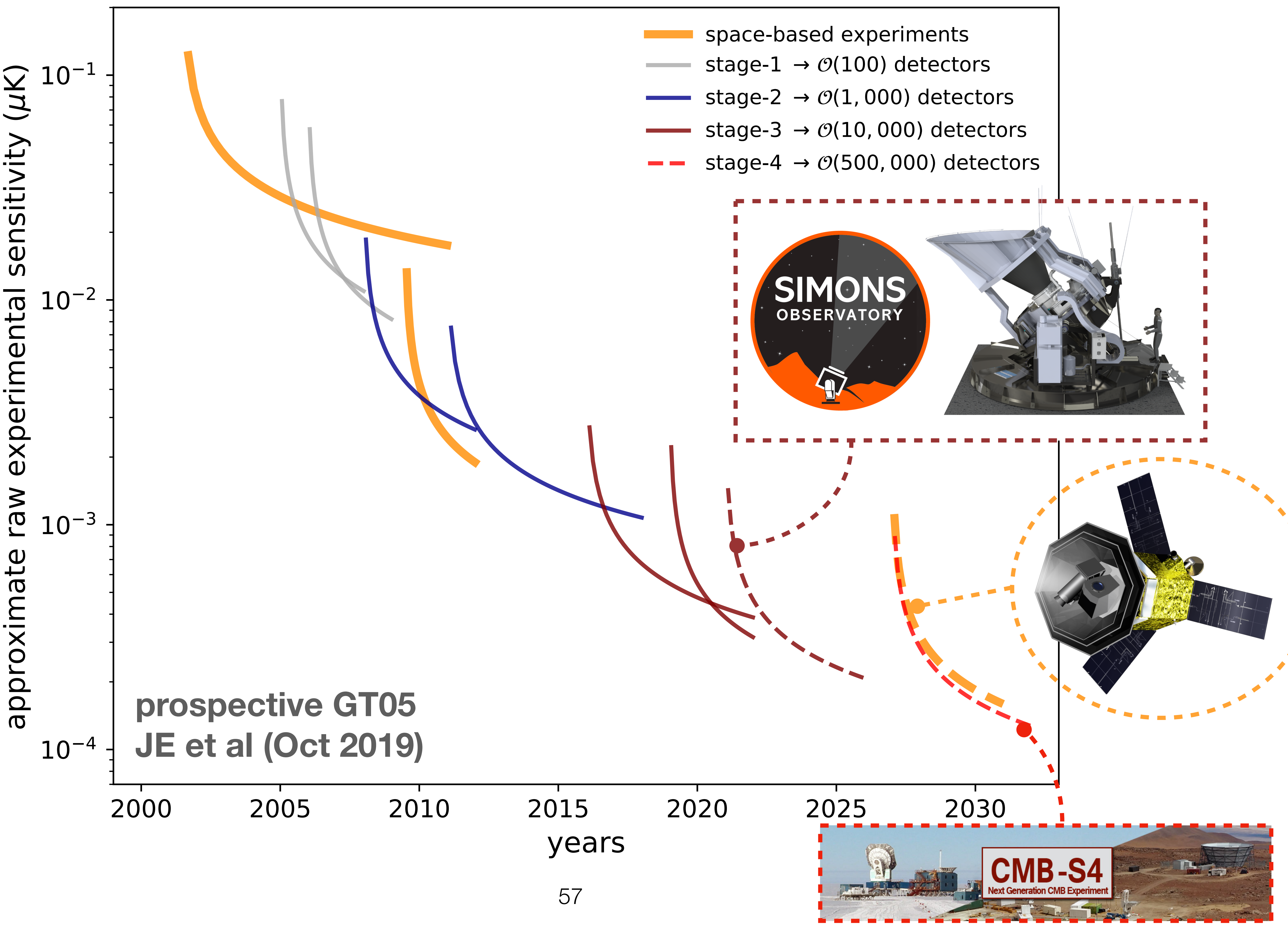
Improvement in reionization optical depth measurement implies:

- $\sigma(\Sigma m_\nu)$ = 15 meV
- determine neutrino hierarchy (normal v.s. inverted)
- measurement of minimum mass (≥ 3σ detection NH, ≥ 5σ detection for IH)

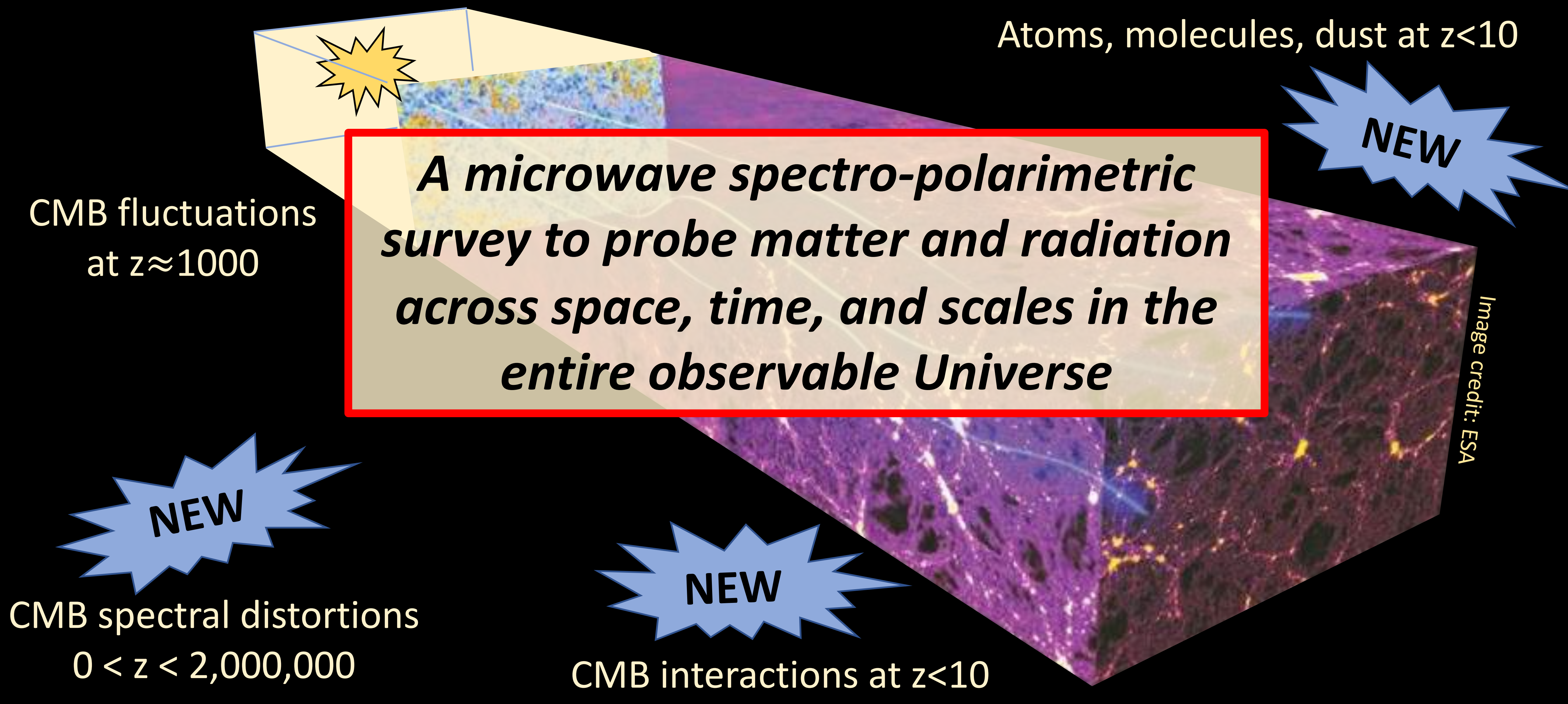


[Calabrese et al arXiv:1611.10269]

CMB B-modes: race to sensitivity



Observe the Universe in the Microwave



from J. Delabrouille VOYAGE 2050 WORKSHOP, Oct 2019