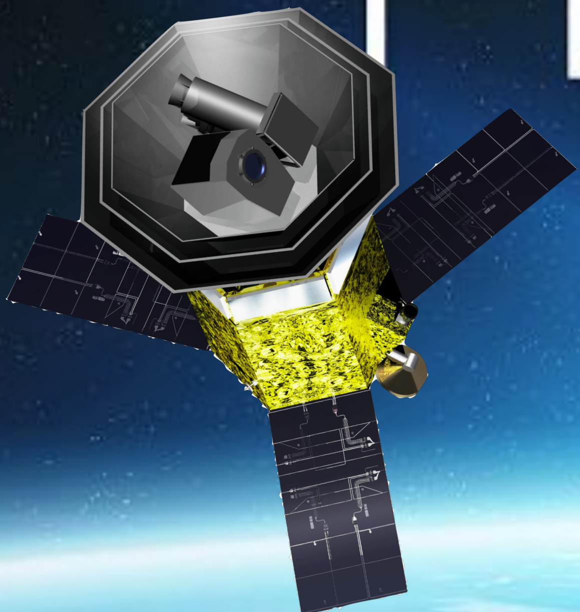
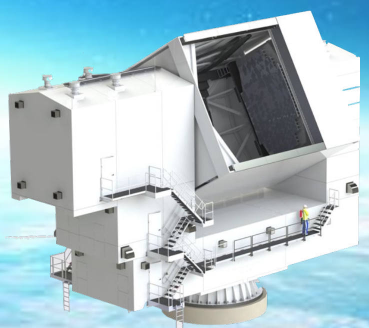
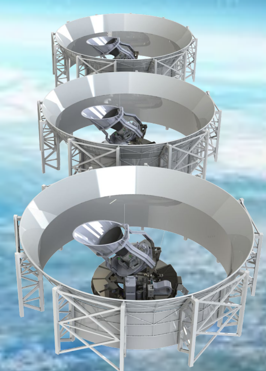


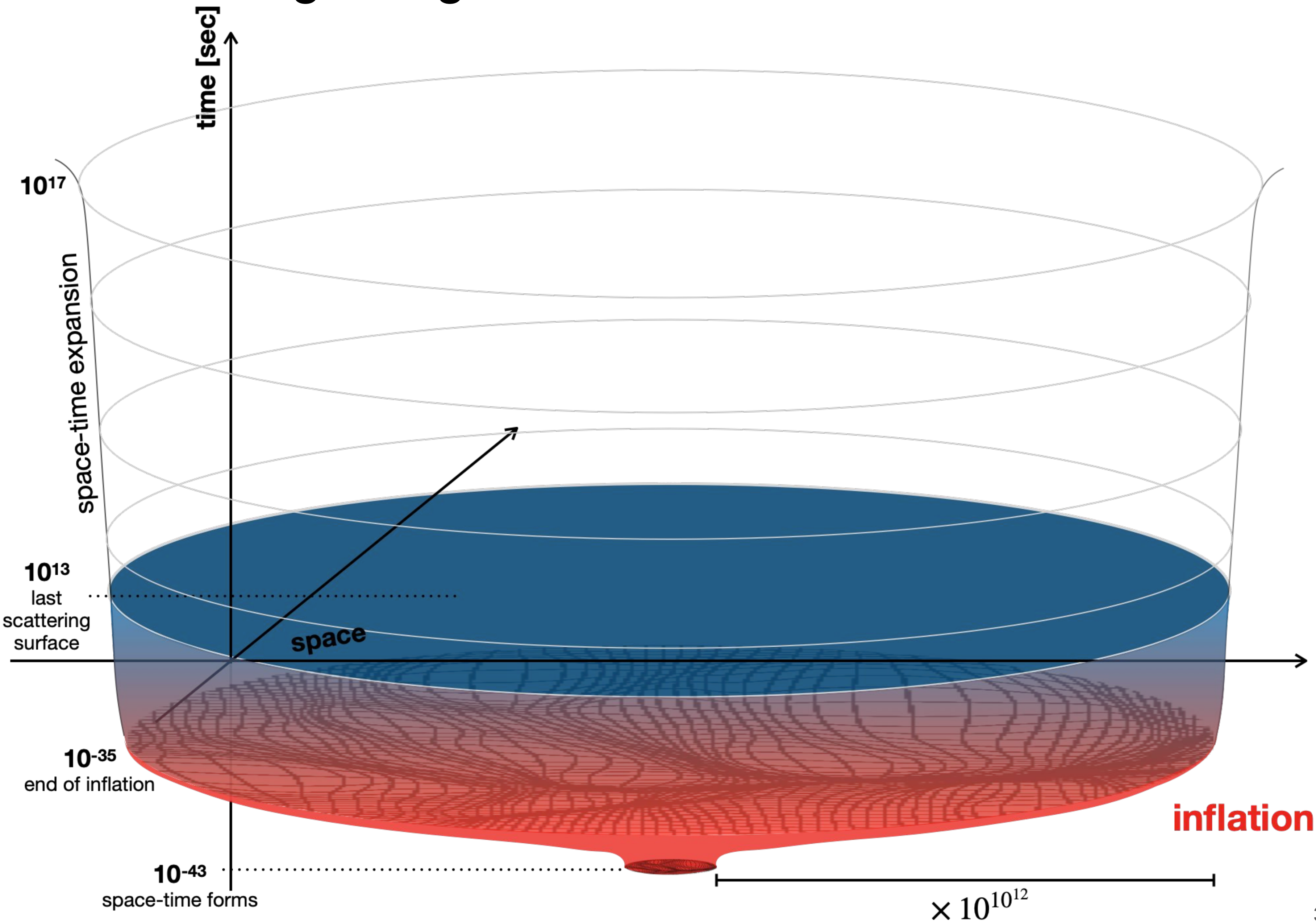
Tomotake Matsumura (Kavli IPMU, U. of Tokyo)
Josquin Errard (APC/IN2P3)

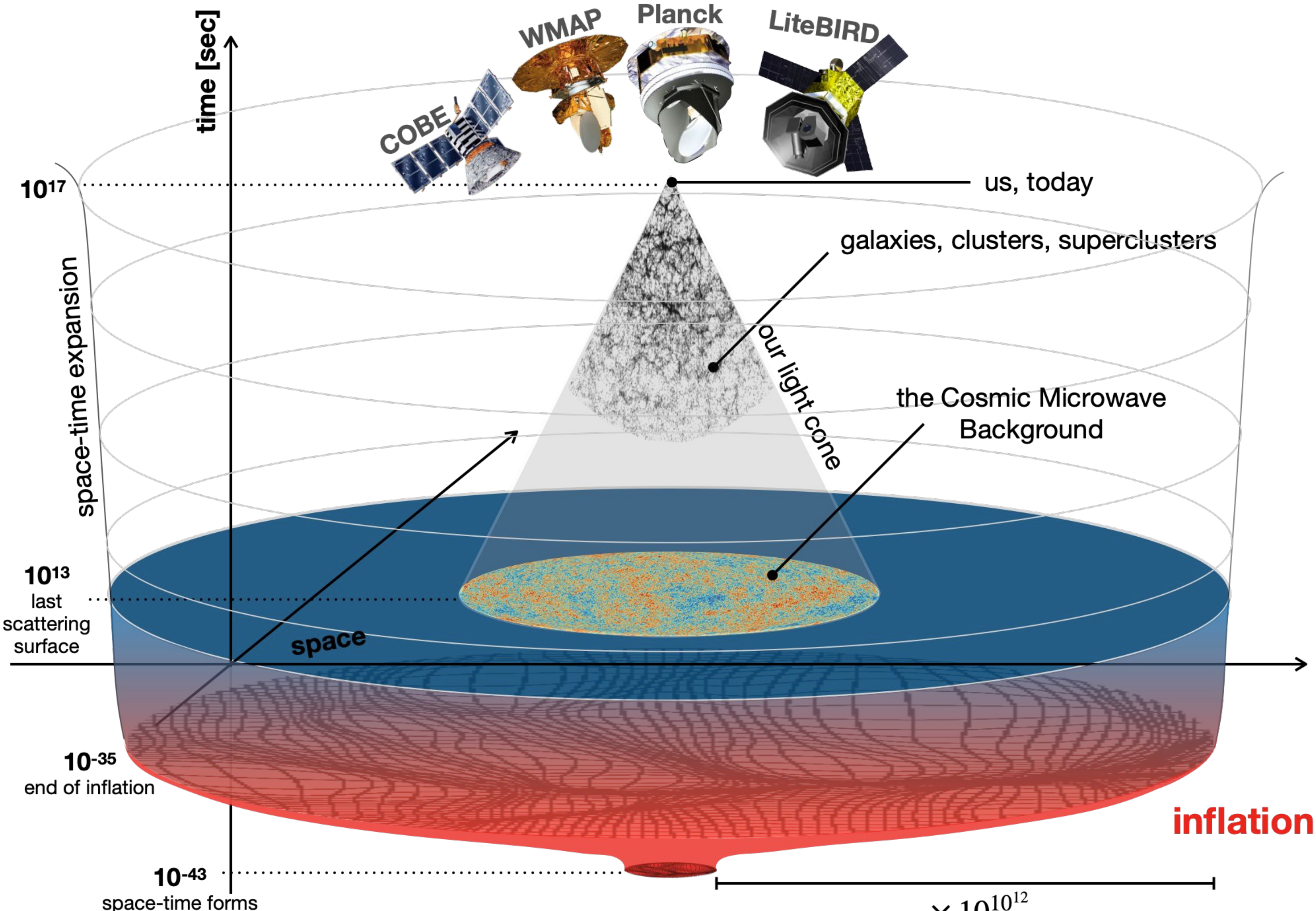




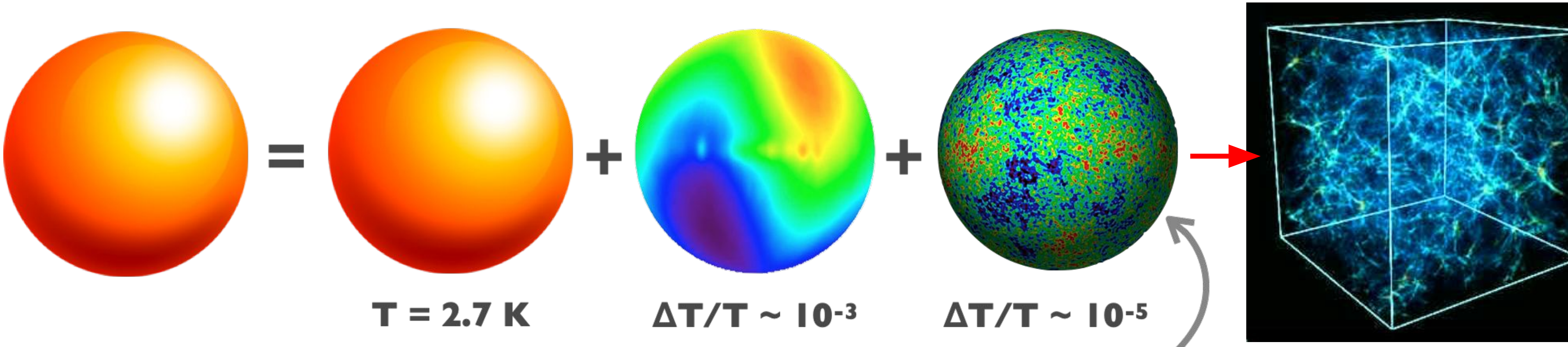

Why is Universe's space-time geometrically flat?
Why is the CMB so isotropic and homogeneous?
How are primordial perturbations generated?

Beginning of the Universe: cosmic inflation




time [sec]
COBE
WMAP
Planck
LiteBIRD
10^{17}
us, today
galaxies, clusters, superclusters
space-time expansion
our light cone
the Cosmic Microwave Background
10^{13}
last scattering surface
space
10^{-35}
end of inflation
inflation
10^{-43}
space-time forms
$\times 10^{10^{12}}$

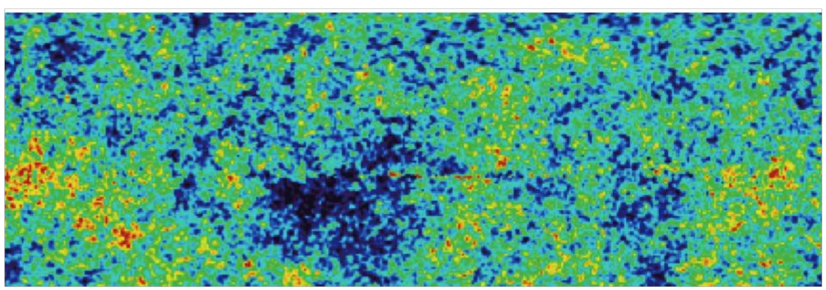
key predictions from cosmic inflation



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

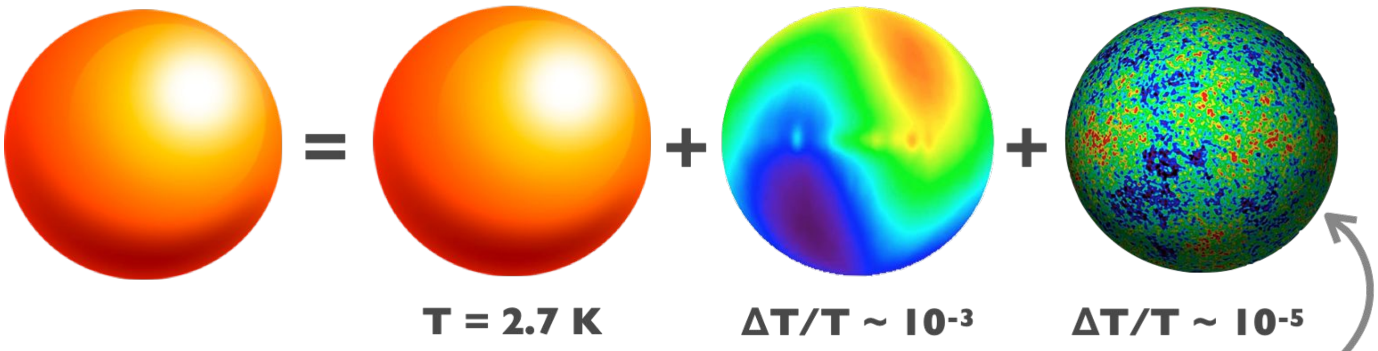
- Fluctuations we observe today in CMB and the matter distribution originate from quantum fluctuations during inflation

$\zeta \longrightarrow$



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

key predictions from cosmic inflation



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

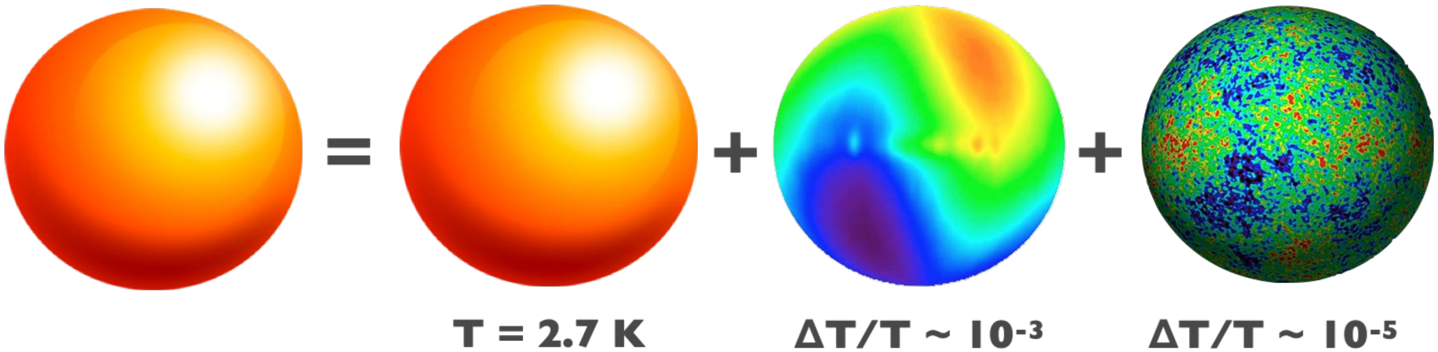
- super-horizon fluctuation
- adiabaticity
- gaussianity
- $n_s < 1$

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

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

key predictions from cosmic inflation



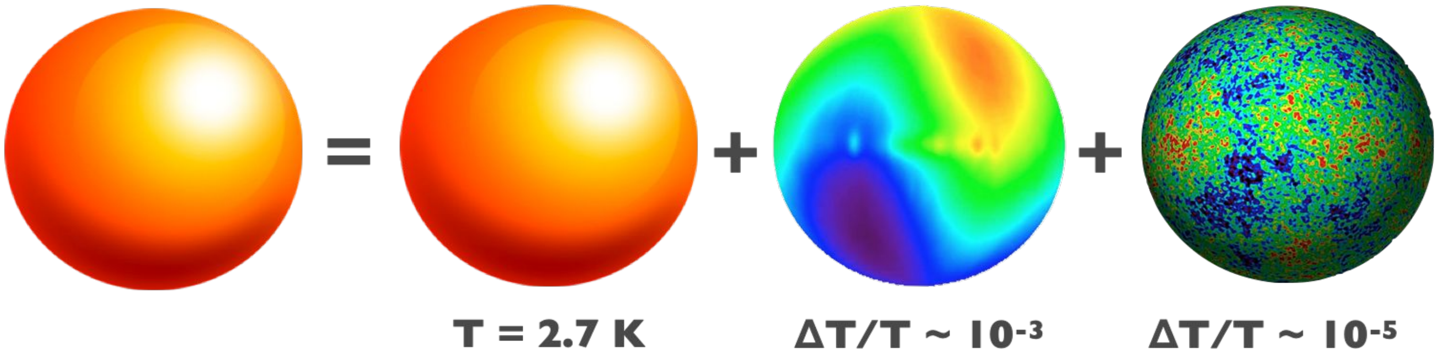
$$d\ell^2 = a^2(t)[1 + 2\zeta(\mathbf{x}, t)][\delta_{ij} + h_{ij}(\mathbf{x}, t)]dx^i dx^j$$

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

h_{ij} ⟶

Grishchuk (1974)
Starobinsky (1979)

key predictions from cosmic inflation

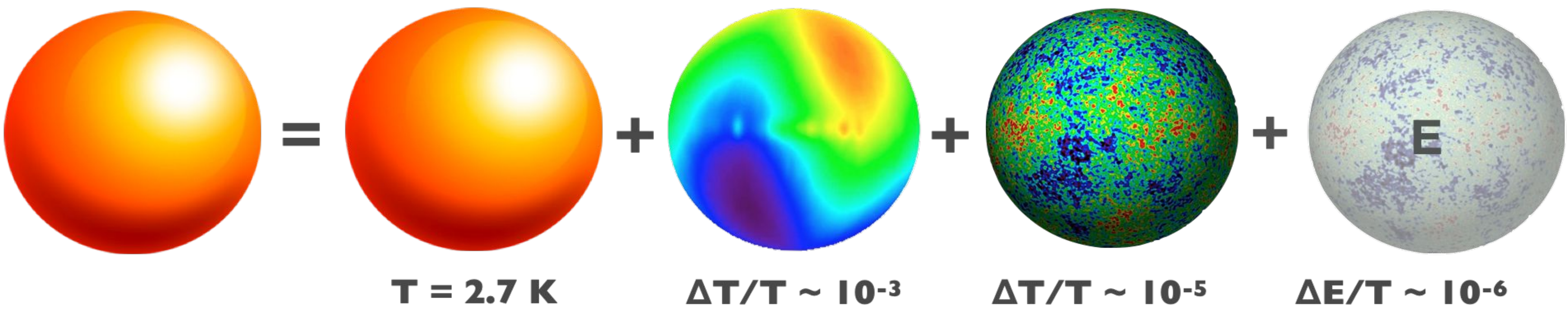


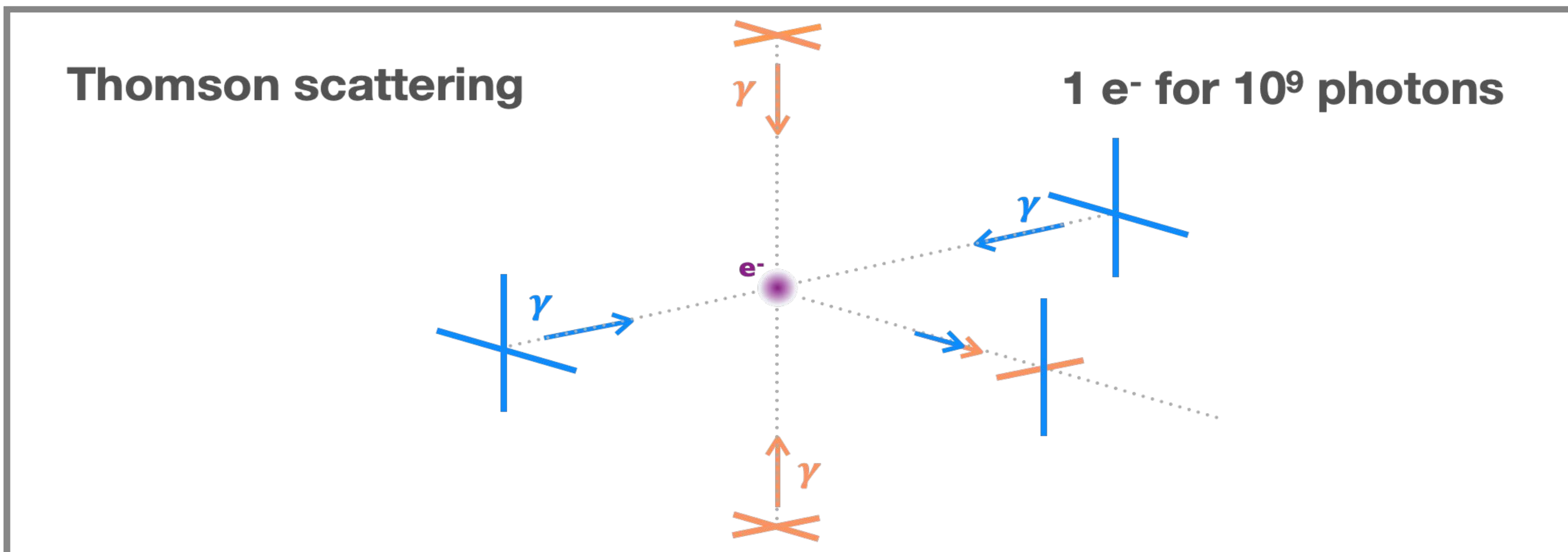
- LIGO/Virgo detected gravitational waves from binary blackholes, with the wavelength of thousands of kilometers
- But the primordial GW affecting the CMB has a wavelength of **billions of light-years**!

how to detect them?

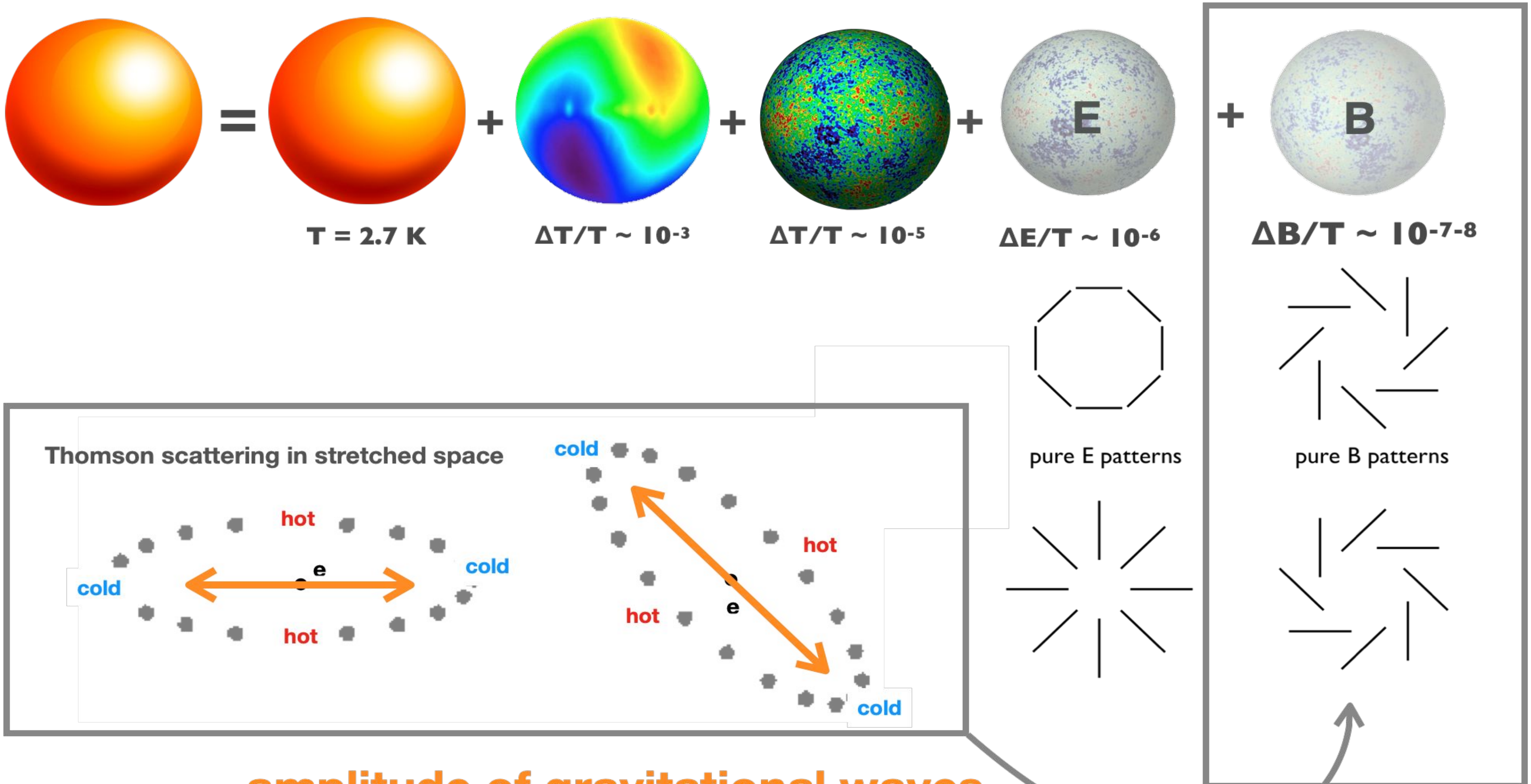
CMB POLARIZATION!

key predictions from cosmic inflation

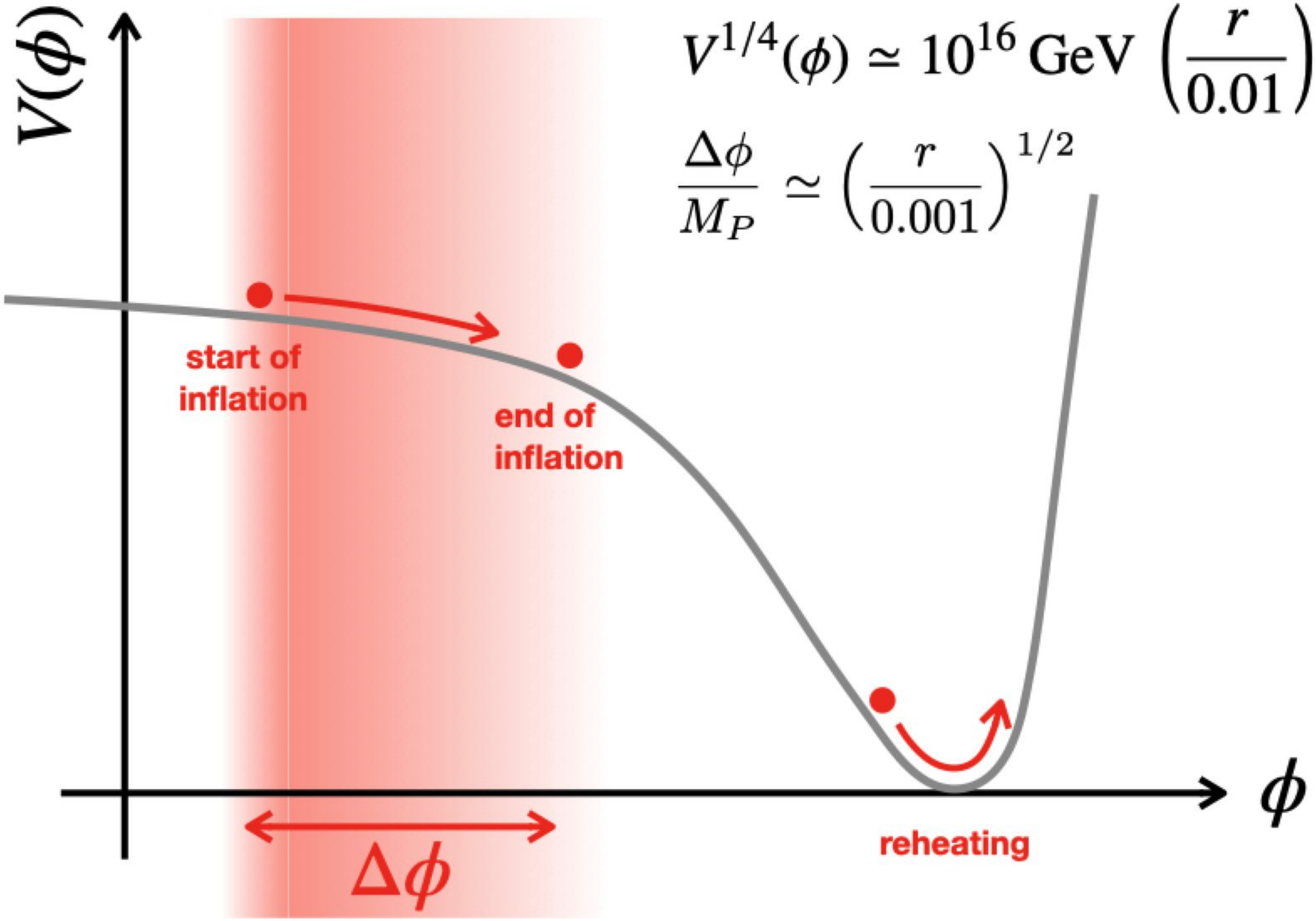




key predictions from cosmic inflation

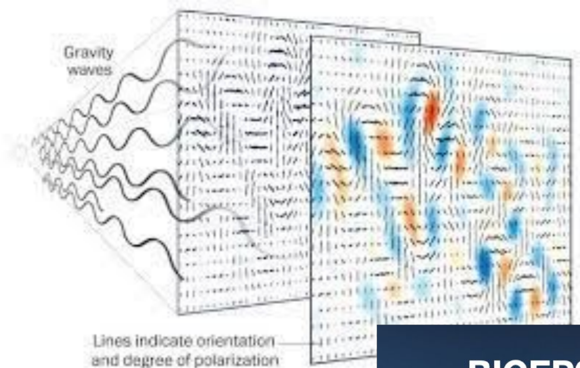


amplitude of gravitational waves
α tensor-to-scalar ratio *r*



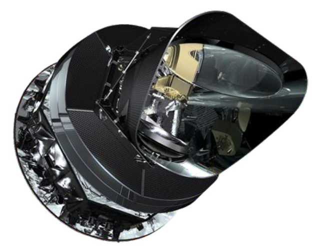
$$V^{1/4}(\phi) \simeq 10^{16}\,\mathrm{GeV}\left(\frac{r}{0.01}\right)^{1/4}$$

$$\frac{\Delta\phi}{M_P} \simeq \left(\frac{r}{0.001}\right)^{1/2}$$



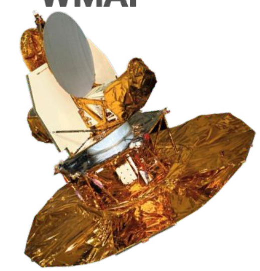
+

Planck



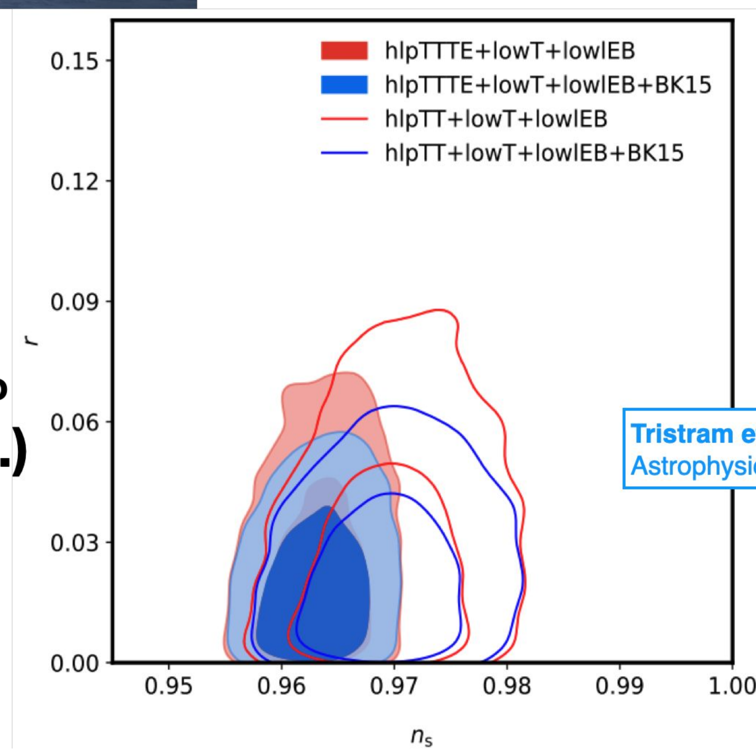
+

WMAP



tensor-to-scalar ratio

$r<0.044$ (95% c.l.)



Tristram et al, Astronomy & Astrophysics, 2020

Simons Array

2010 2015 2020 2025 2030

SIMONS OBSERVATORY

CMB-S4
Next Generation CMB Experiment

A Measurement of the Cosmic Microwave Background B-mode Polarization Power Spectrum at Sub-degree Scales with POLARBEAR, ApJ 2014

Measurement of the Cosmic Microwave Background Polarization Lensing Power Spectrum with the POLARBEAR Experiment, PRL 2014

Evidence for Gravitational Lensing of the Cosmic Microwave Background Polarization from Cross-Correlation with the Cosmic Infrared Background, PRL 2014

POLARBEAR constraints on cosmic birefringence and primordial magnetic fields, PRD 2015

A Measurement of the Cosmic Microwave Background B-mode Polarization Power Spectrum at Subdegree Scales from Two Years of polarbear Data, ApJ 2017

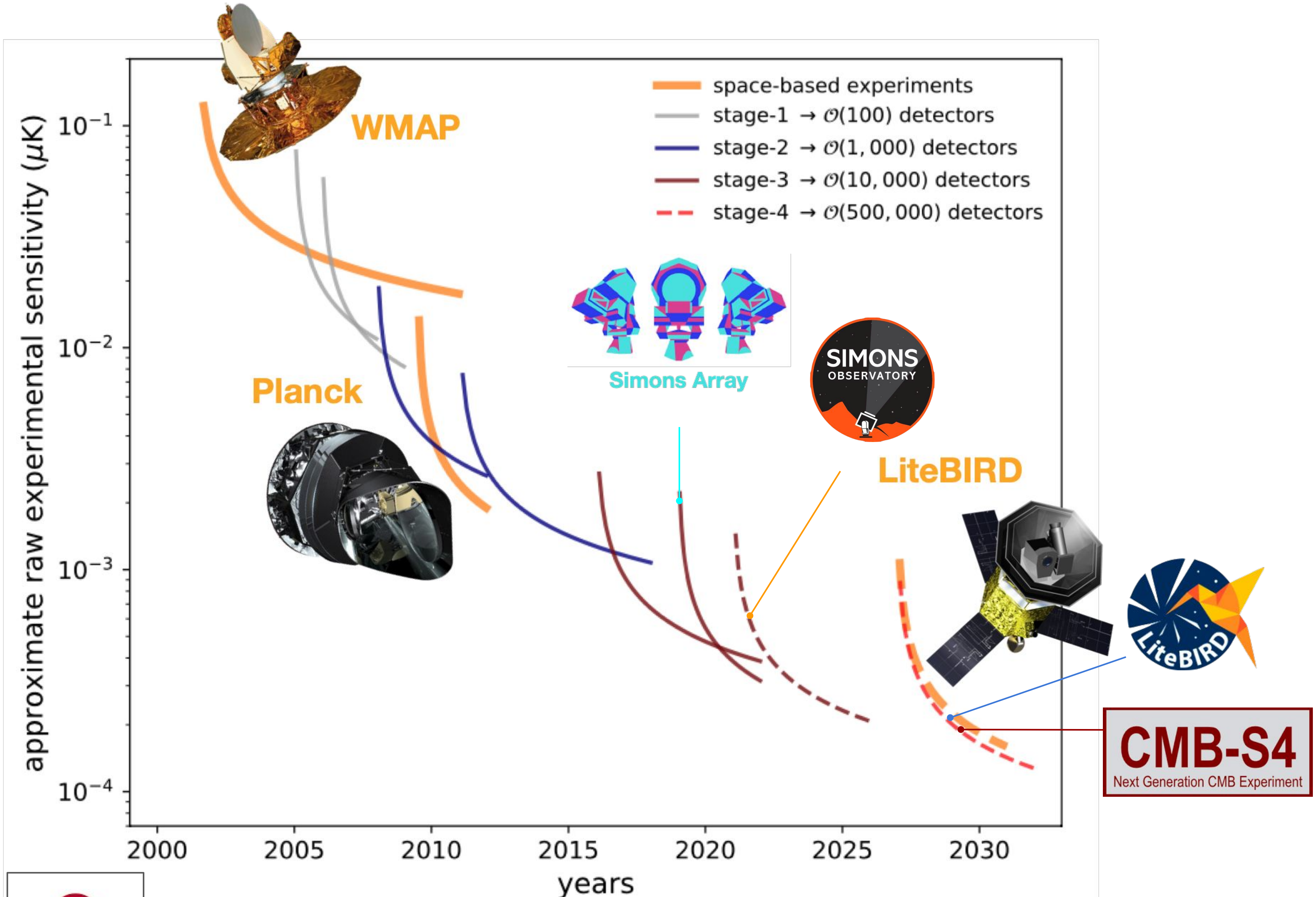
Evidence for the Cross-correlation between Cosmic Microwave Background Polarization Lensing from Polarbear and Cosmic Shear from Subaru Hyper Suprime-Cam, ApJ 2019

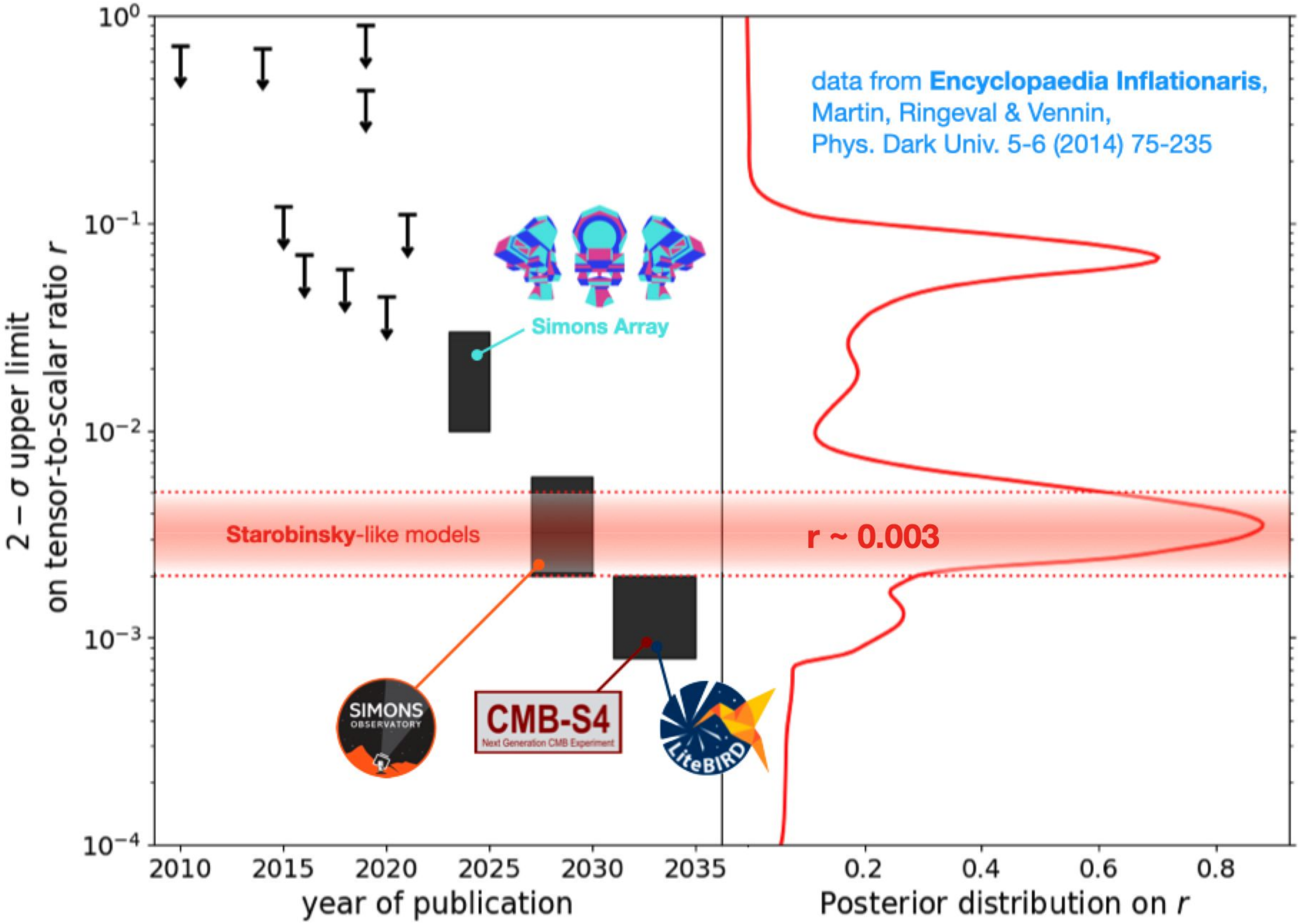
A Measurement of the CMB E-mode Angular Power Spectrum at Subdegree Scales from 670 Square Degrees of POLARBEAR Data, ApJ 2020

A Measurement of the Degree-scale CMB B-mode Angular Power Spectrum with POLARBEAR, ApJ 2020

Internal Delensing of Cosmic Microwave Background Polarization B -Modes with the POLARBEAR Experiment, PRL 2020

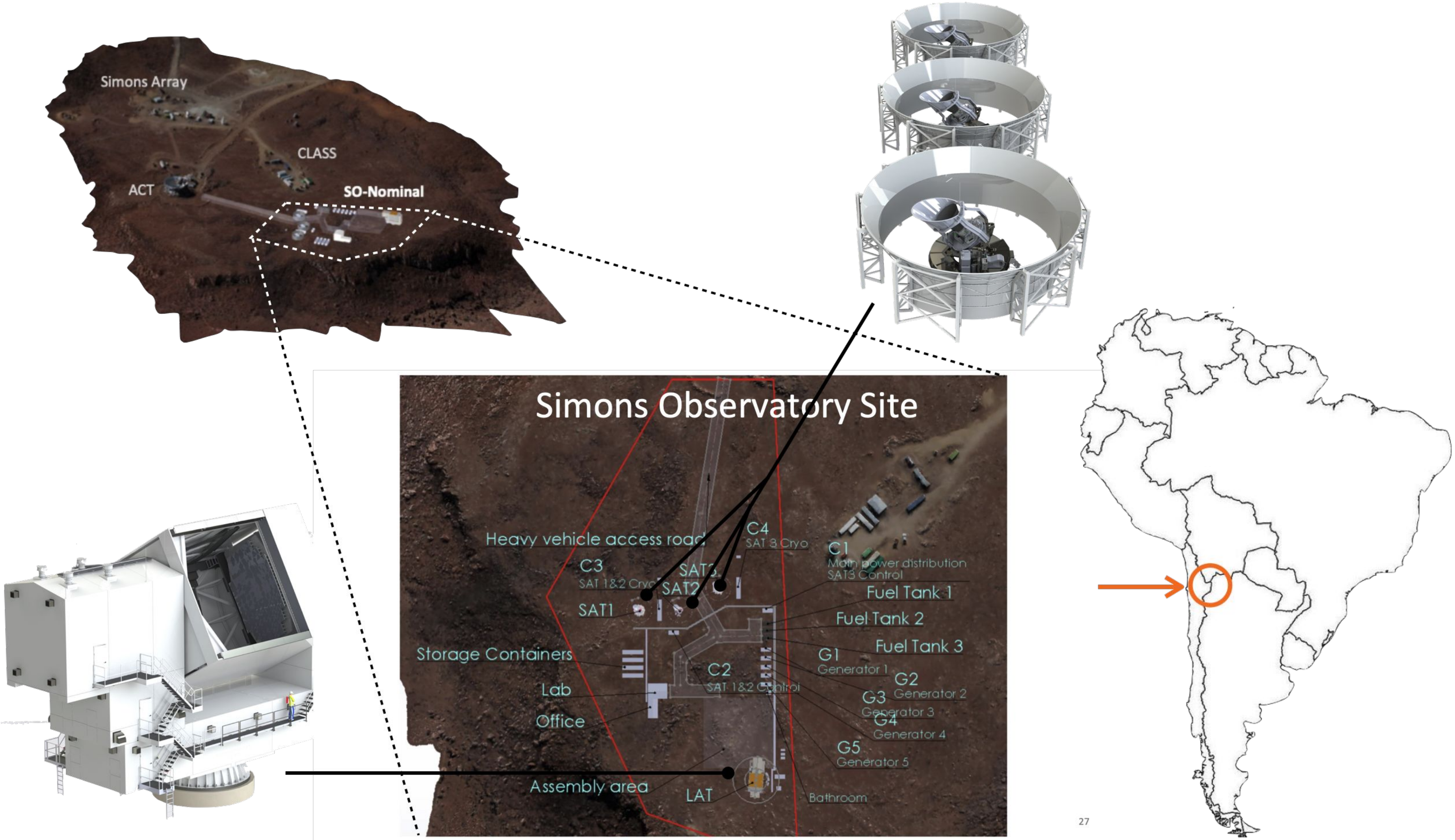
improving the sensitivity of CMB experiments: number of detectors





Current and expected upper 95% confidence level limits on tensor-to-scalar ratio r (left panel) as a function of the (forecasted) year of publication. The right panel shows the posterior distribution on r, averaged over all physical single-field models of inflation as listed in Martin, Ringeval & Vennin [Phys. Dark Univ. 5-6, 75 (2014)] (where each model is weighted by its Bayesian evidence), using the Planck 2013 data and the results of Martin, Ringeval, Trotta & Vennin [JCAP 03, 039 (2014)].

APC and **IJCLab** in France, **U.Tokyo, IPMU** and **KEK** in Japan



- SAT data analysis led by Europe (APC in France + Oxford) and Japan (U. Tokyo)
- LAT data analysis led by IJCLab, France
- SAT hardware development in Japan
- SAT calibration developments at APC, France

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

	Current[b]	**SO 2023-2032**	CMB-S4[c] 2028-2035	Data	Ref.
Primordial perturbations					
r ($A_L = 0.5$)	0.03	0.0012 [d]	0.0005	SO-SAT + external delensing	45
n_s	0.004	0.002	0.002	SO-LAT	45
$e^{-2\tau}\mathcal{P}(k = 0.2/\text{Mpc})$	3%	0.4%		SO-LAT	46
$f_{\text{NL}}^{\text{local}}$	5	1	0.6	SO-LAT+Rubin	36
Relativistic species					
$N_{\text{eff.}}$	0.2	0.045	0.03	SO-LAT	20
Neutrino mass					
m_ν (eV, $\sigma(\tau) = 0.01$)	0.1	0.03	0.03	SO-LAT+DESI	16
m_ν (eV, $\sigma(\tau) = 0.002$)		0.015	0.015	or SO-LAT+Rubin	
Accelerated expansion					
$\sigma_8(z = 1-2)$	7%	1%	1%	SO-LAT+Rubin	47
Galaxy evolution					
η_{feedback}	50-100%	2%		SO-LAT + DESI	6
p_{nt}	50-100%	4%		SO-LAT + DESI	6
Reionization					
Δz	1.4	0.3	0.25	SO-LAT	4
τ	0.007	0.0035	0.003		4
Cluster catalog	4000	33,000	70,000	SO-LAT	
AGN catalog	2000	100,000	$> 100,000$	SO-LAT	

[a] Projected 1σ errors as in[2], scaled to account for the improved noise from this proposed infrastructure. Sec. 2 of[2] describes our methods to account for noise properties and foreground uncertainties. A 20% end-to-end observation efficiency is used, matching what has been typically achieved in Chile. We assume the *Planck* data are included.

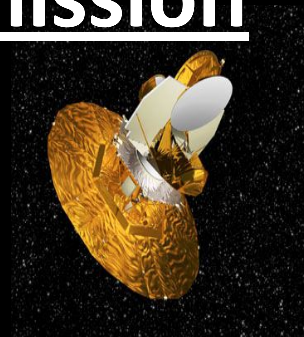
[b] Primarily from[9] and[42]. We anticipate data from existing ground-based data to improve on the 'current' limits by 2023. Constraints are expected to lie between the 'current' and SO levels.

[c] Forecast constraints for CMB-S4[1,5], for comparison. CMB-S4 forecasts use different Galaxy evolution parameters.

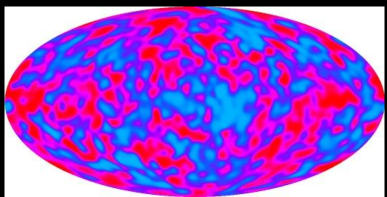
[d] The SO projected uncertainty would drop to 0.0007 if we meet our goal noise level and assume a simpler foreground scenario with spatially homogeneous foreground spectra.

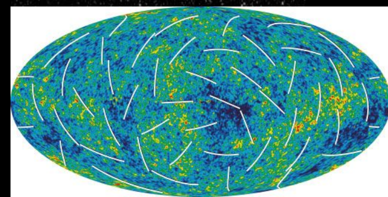
CMB polarization telescopes today

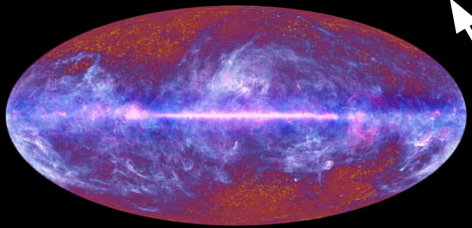
CMB space mission



Next generation CMB satellite



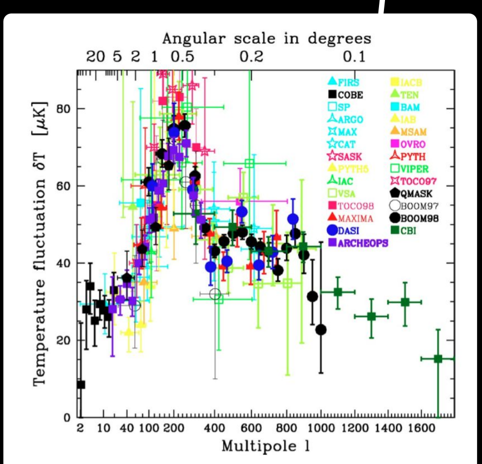


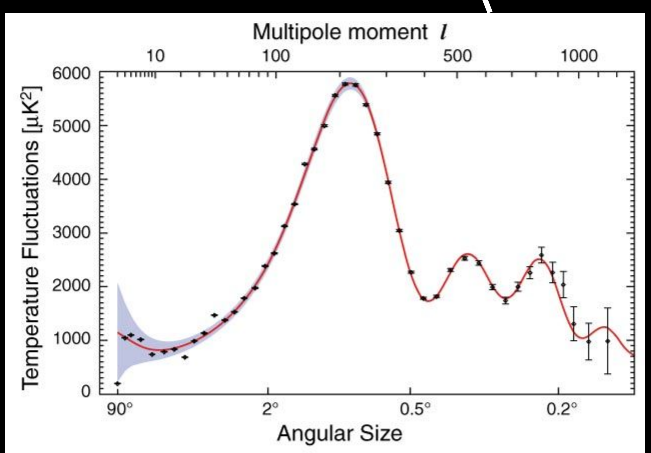


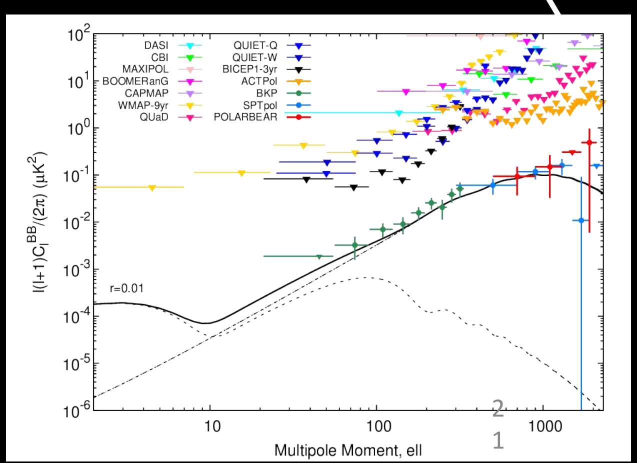
	COBE (1989)
Band	32-90GHz
# det.	6 radiometers
Op. T	140 K
Beam	～7°
Orbit	Sun Synch.

WMAP (2001)
23-94GHz
20 radiometers
90 K
～0.22°
L2

Planck (2009)
30-857GHz (pol. 353GHz)
22 radiometers + 52 bolometers
20K/100 mK
> ～0.1°
L2

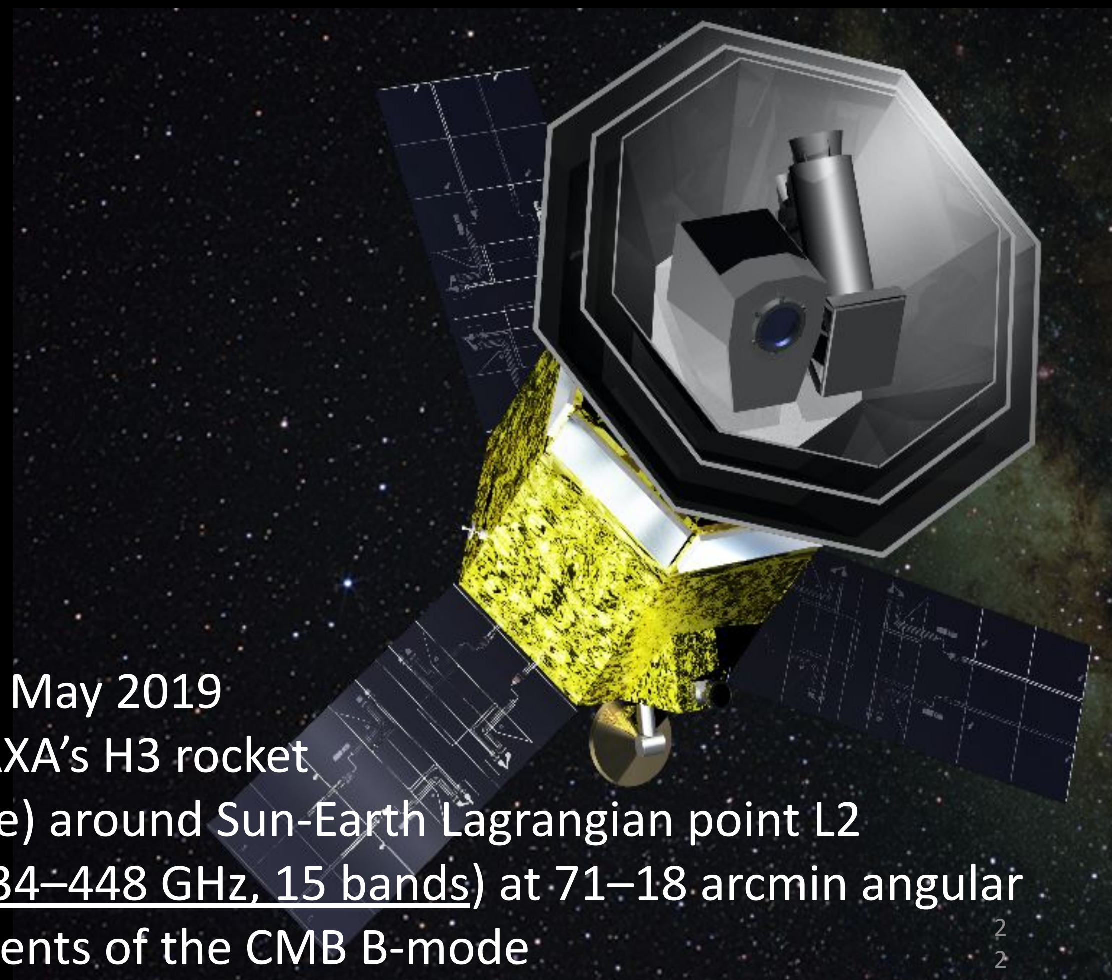






LiteBIRD is a next generation CMB polarization satellite that is dedicated to probe the inflationary B-mode. The science goal of LiteBIRD is to measure the tensor-to-scalar ratio with the sensitivity of $\sigma_r = 0.001$ for $r = 0$, and 5σ detection for $r \geqq 0.01$ for each bump. In this way, we test the major large-single-field slow-roll inflation models.

Full Success



- JAXA’s L-class mission selected in May 2019
- Expected launch in 2020s with JAXA’s H3 rocket
- Observations for 3 years (baseline) around Sun-Earth Lagrangian point L2
- Millimeter-wave all sky surveys (34–448 GHz, 15 bands) at 71–18 arcmin angular resolution for precision measurements of the CMB B-mode

LiteBIRD is a next generation CMB polarization satellite that

Full Success

is dedicat
LiteBIRD
= 0.001 f
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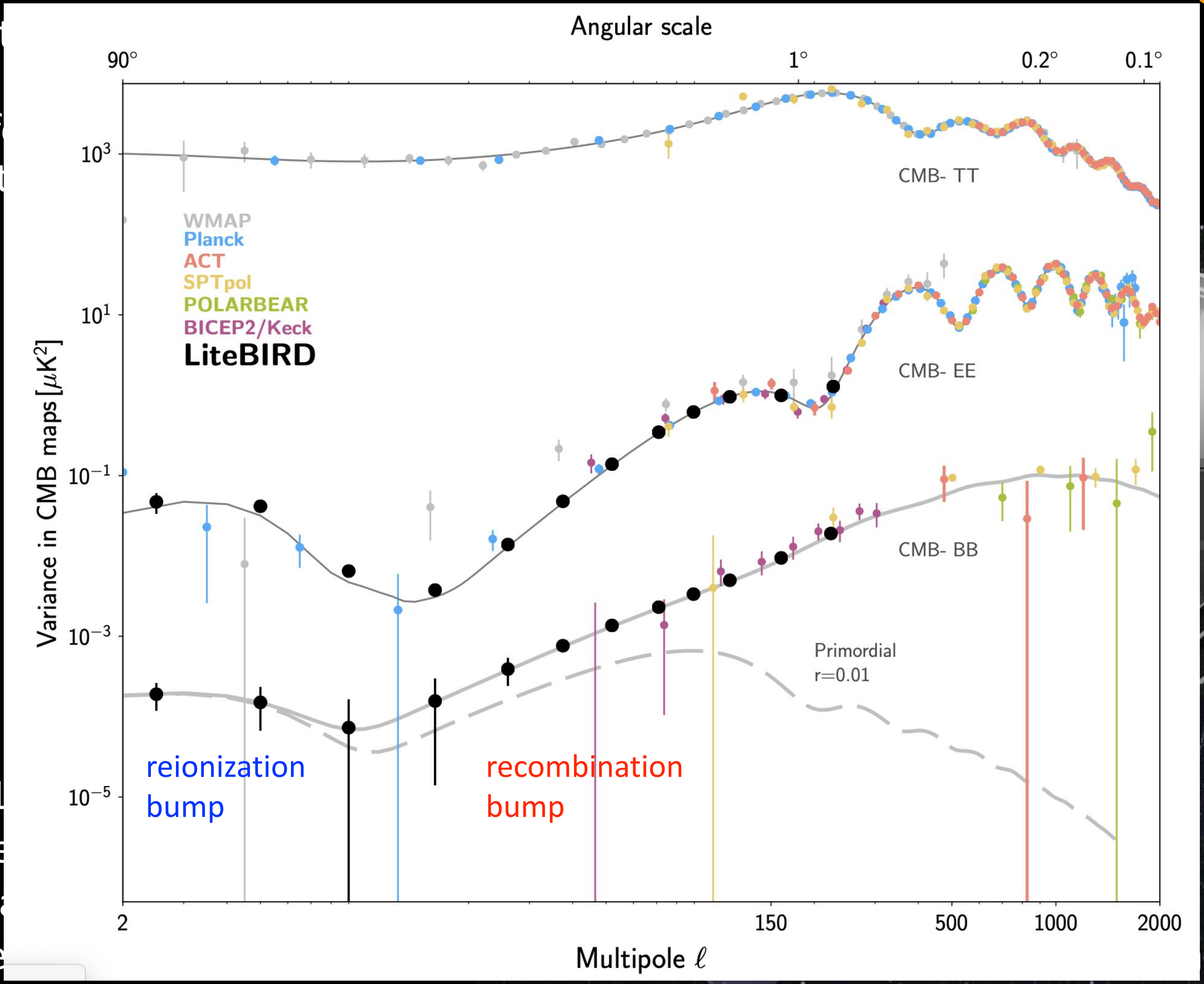

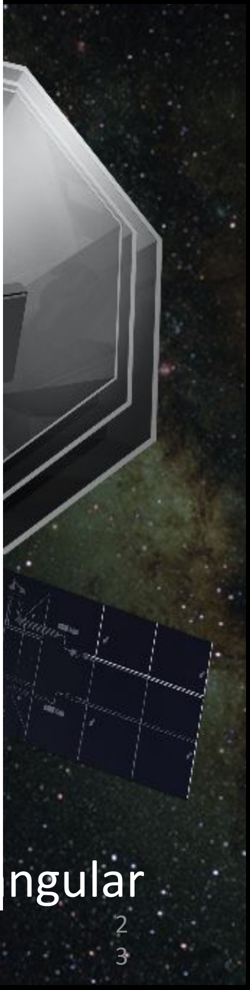

- JAXA's L
- Expecte
- Observ
- Millime ... ngular resolution for precision measurements of the CMB B-mode

LiteB… …hat

Full Success

is dedicat…
LiteBIRD …
= 0.001 f…
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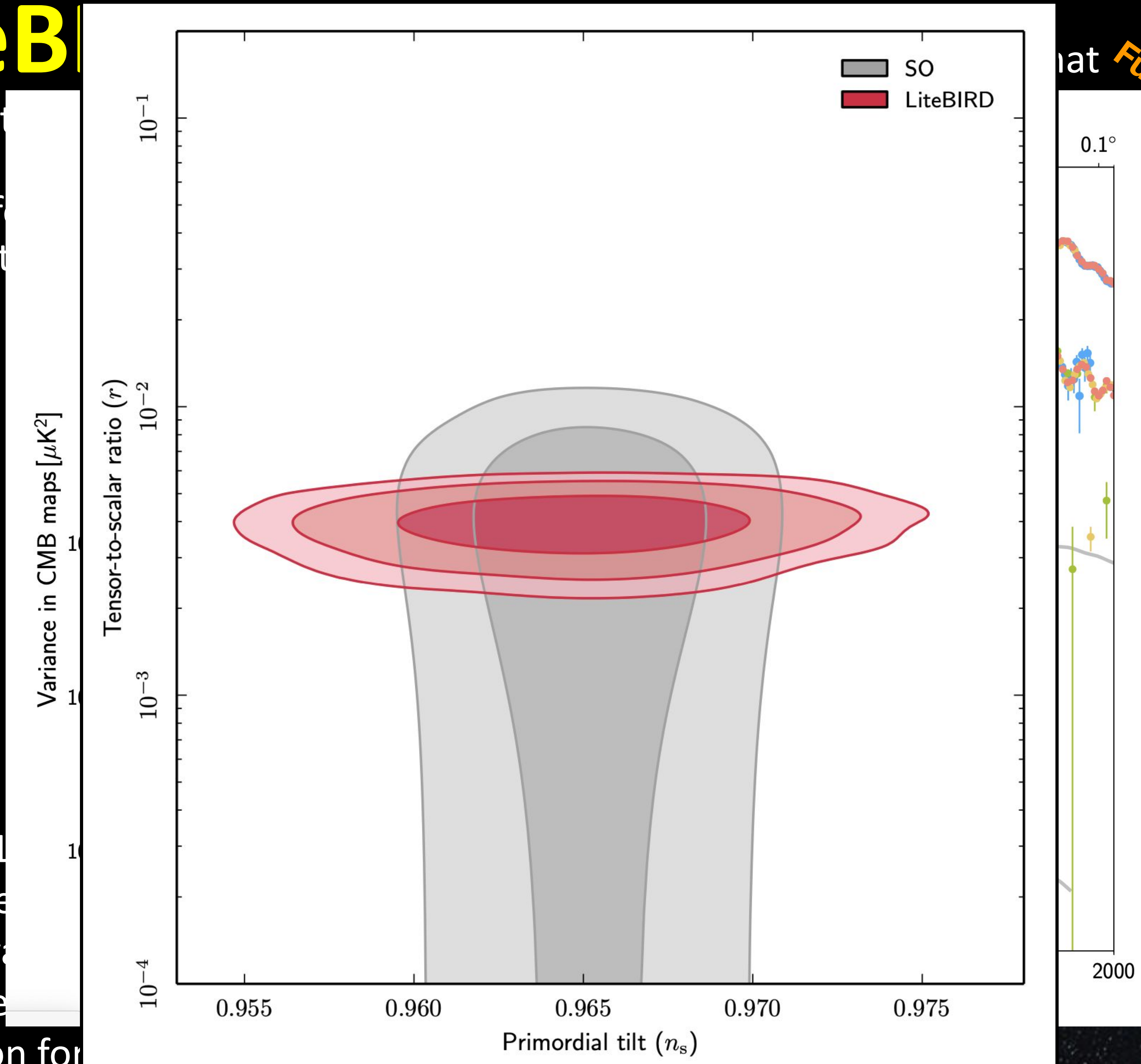


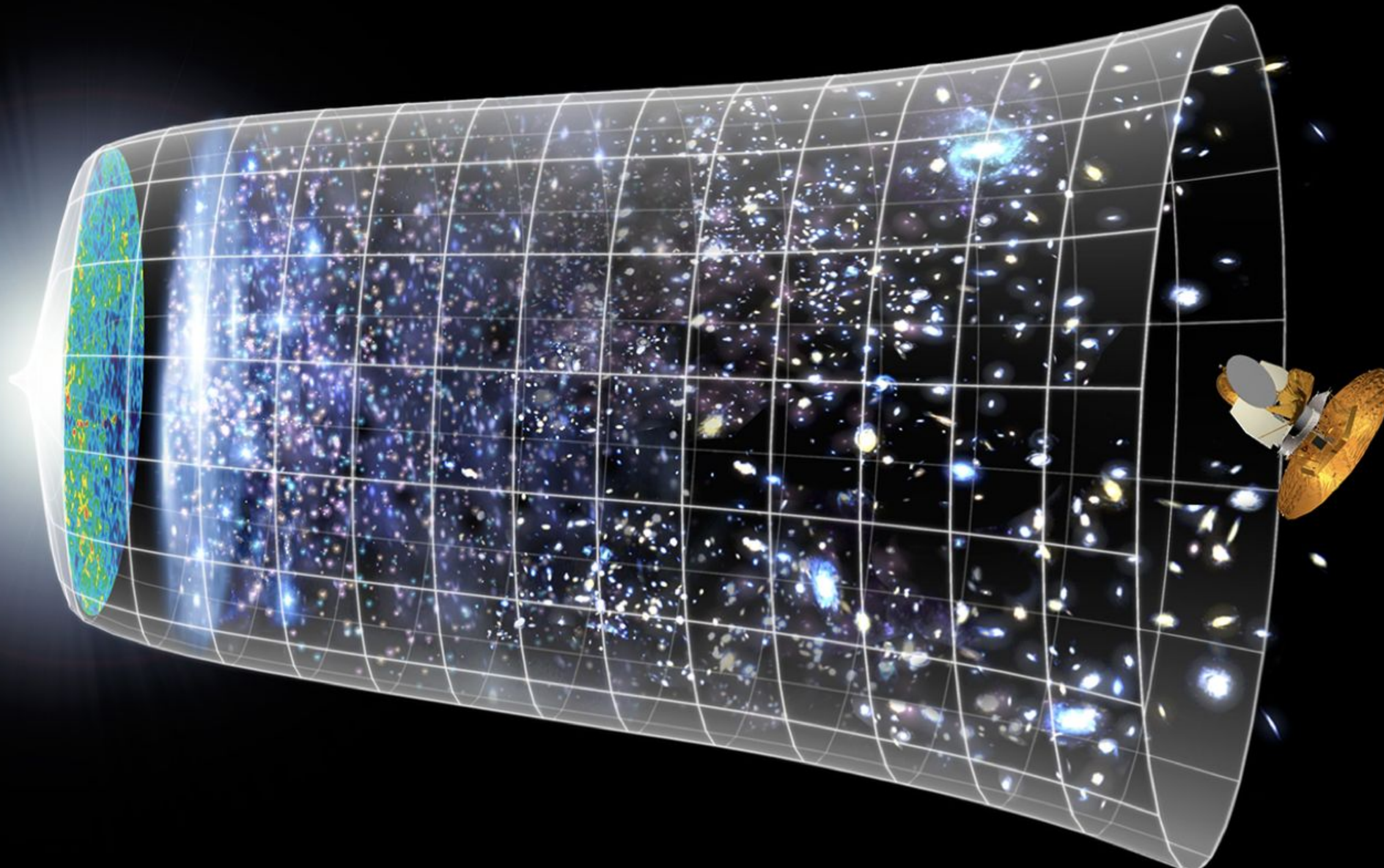
- JAXA's L…
- Expecte…
- Observ…
- Millime… …ngular resolution for…

LiteBIRD
Collaboration meeting at MPA Garching, Munich in 2019-12

- Japan is in charge of launch, satellite system, and low-frequency telescope. In particular, Kavli IPMU is in charge of the polarization modulator and the data analysis.
- France is a lead country in Europe via CNES, and the team in Europe is in charge of the middle and high frequency telescopes with rich Planck experiences.

PI Masashi Hazumi, more detailed info/slide is available from [SPIE2020].

In order to observe the CMB, we have to see through anything between us and CMB.

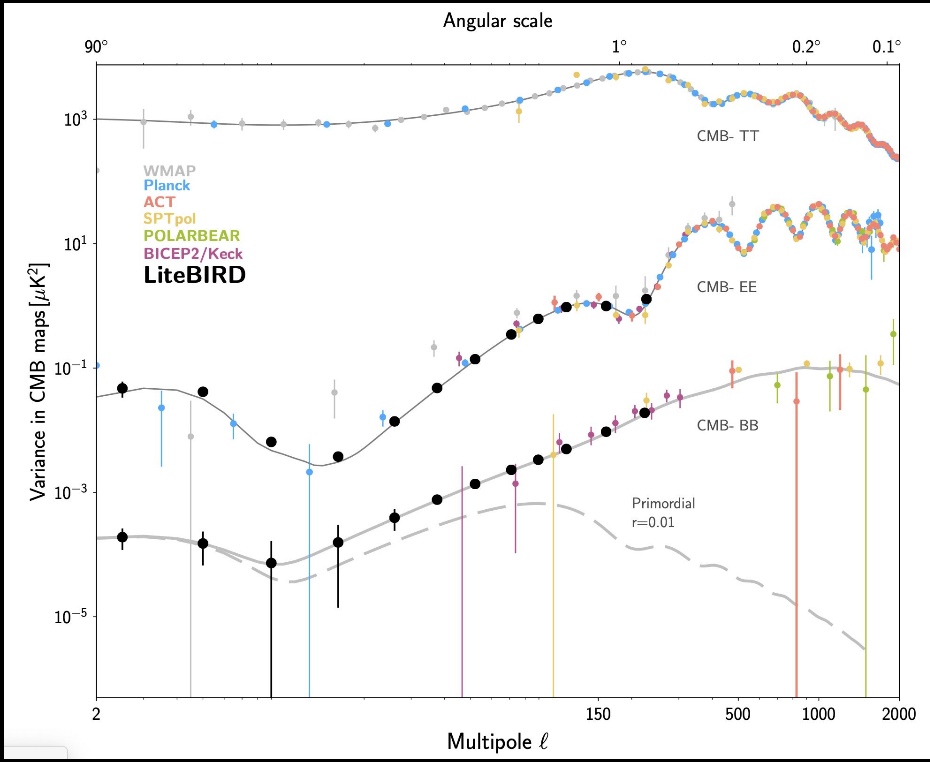


They can be disturbance but we can learn them with great accuracy.

Is CMB pol. experiment, incl. LiteBIRD only after r? Well, yes but no!

E.g. while the design of LiteBIRD is purely driven by the inflationary B-mode signal, LiteBIRD can deliver a number of rich by-products from its measurement.

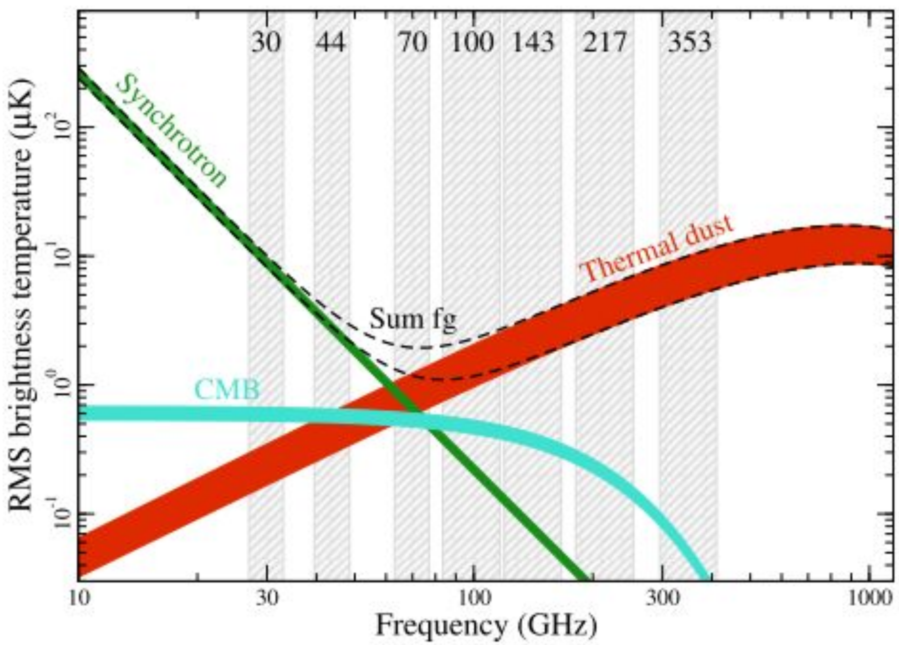
- Characterization of B-mode, e.g. non-Gaussianity
- Reionization history from E-mode and the neutrino mass
- Cosmic birefringence
- CMB polarization power spectrum shape
- SZ effect
- Anomaly
- Cross-correlation science
- Galactic magnetic field
- Galactic science

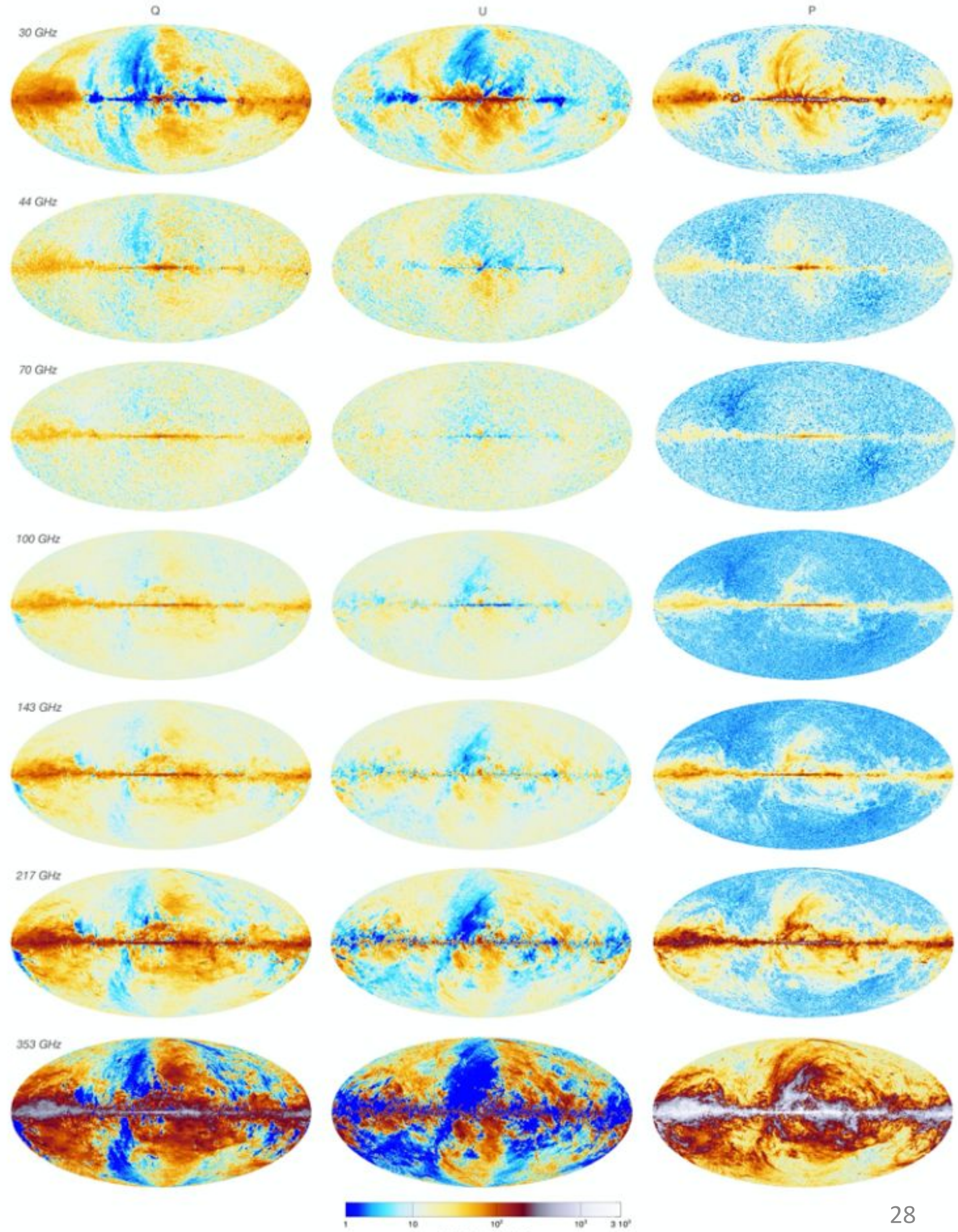


Polarized foreground emissions

Planck 2018 results. IV.
Diffuse component separation

- As we live in our Galaxy, we have to observe the CMB through our polarized galactic emission.
- The main polarized foreground emissions are the synchrotron and thermal dust emissions.
- These emissions do have the difference spectral emission as compared to the CMB.





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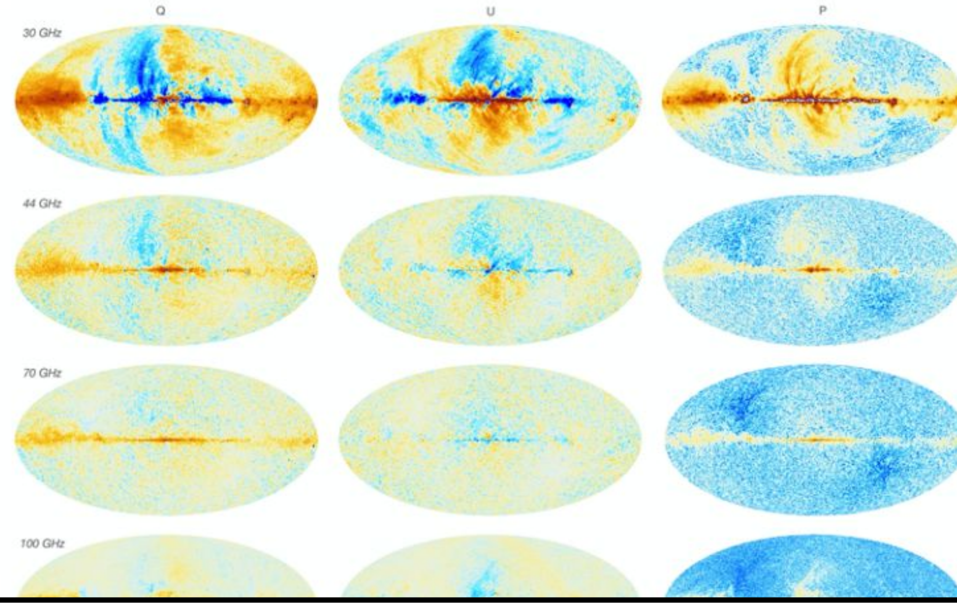
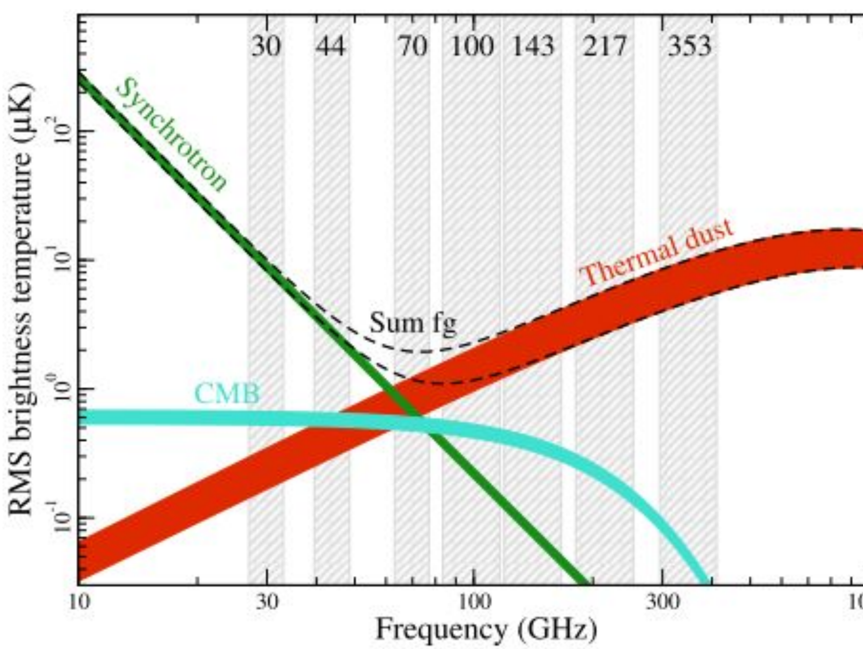
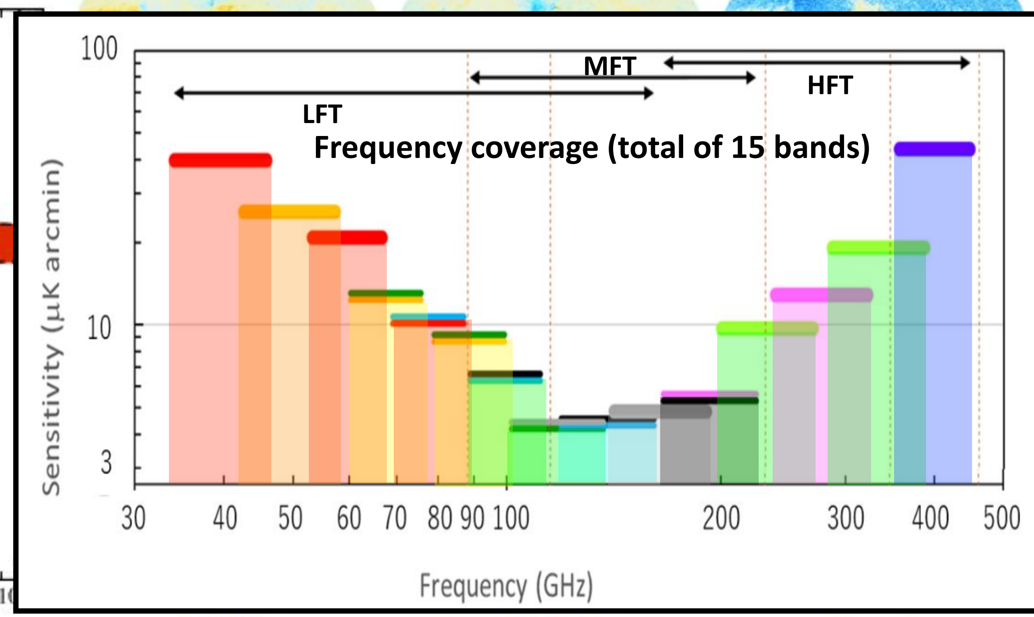
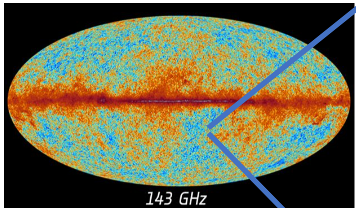






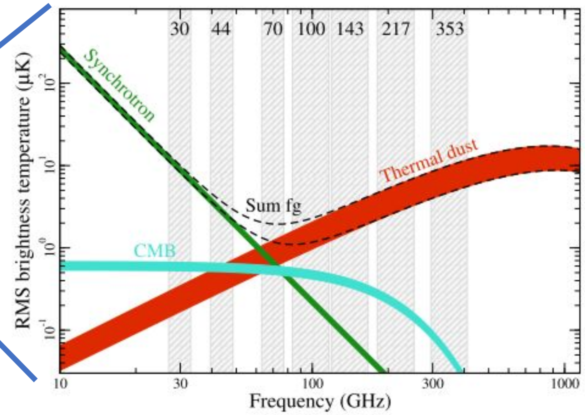
Foreground removal prospect

Errard and Stompor, Phys.Rev. D99 (2019) no.4, 043529



Planck 143GHz map

(*this is a temperature map as an example)



Parametrizing the foreground emissions

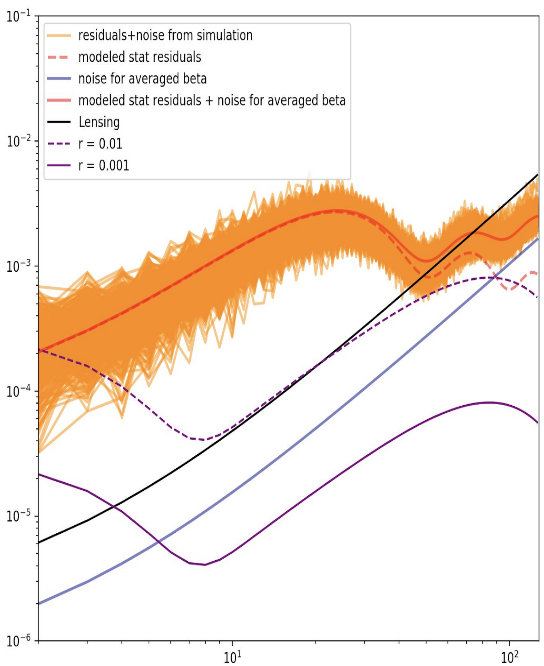
Based on the Planck data, the foreground emissions can be parametrized as

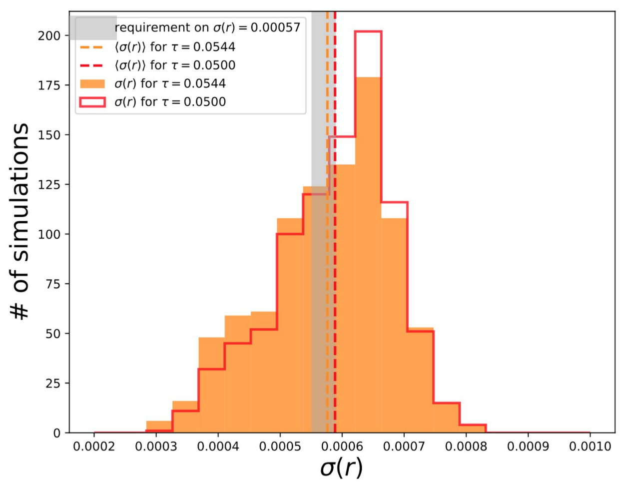
Synchrotron (incl. AME)

$$[Q_s, U_s](\hat{n}, \nu) = [Q_s, U_s](\hat{n}, \nu_*) \left(\frac{\nu}{\nu_s}\right)^{\beta_s(\hat{n}) + C_s(\hat{n}) \ln(\nu/\nu_*^C)}$$

Dust

$$[Q_d, U_d](\hat{n}, \nu) = [Q_d, U_d](\hat{n}, \nu_*) \left(\frac{\nu}{\nu_d}\right)^{\beta_d(\hat{n}) - 2} \frac{B(\nu, T_d(\hat{n}))}{B(\nu_*, T_d(\hat{n}))}$$





8 parameters to model the foreground emissions at each direction of the sky. This corresponds to

(8 parameters at each sky pixel)

(the sky pixel number) = **6144** pars

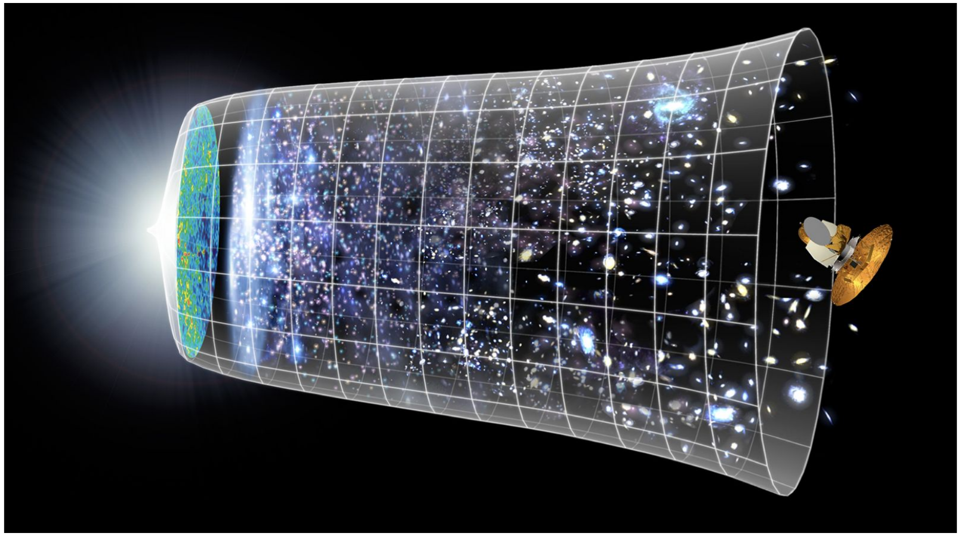
with $N_{side} = 8$

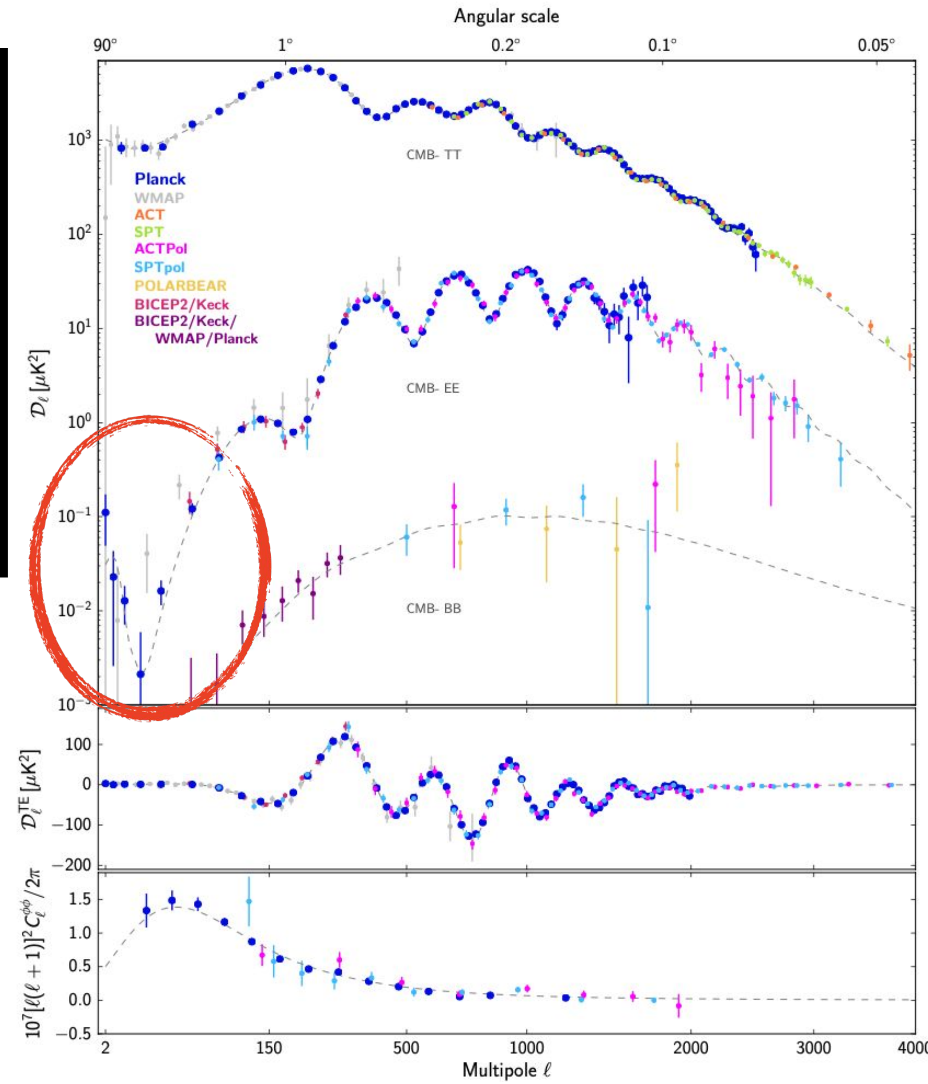
Result

$$\sigma(r) = 0.0006 \ \text{for} \ r_{in} = 0$$

The consistent results from other method too.

Large-scale E-mode





- The CMB can be polarized by the plasma from the reionization.
- Planck is sensitive to the feature originated from reionization.
- The sensitivity of Planck is not sufficient enough to carry out the cosmic variance limited measurement.

$$\tau = 0.0544^{+0.0070}_{-0.0081}$$

68%, TT, TE, EE+lowE

From Planck2018

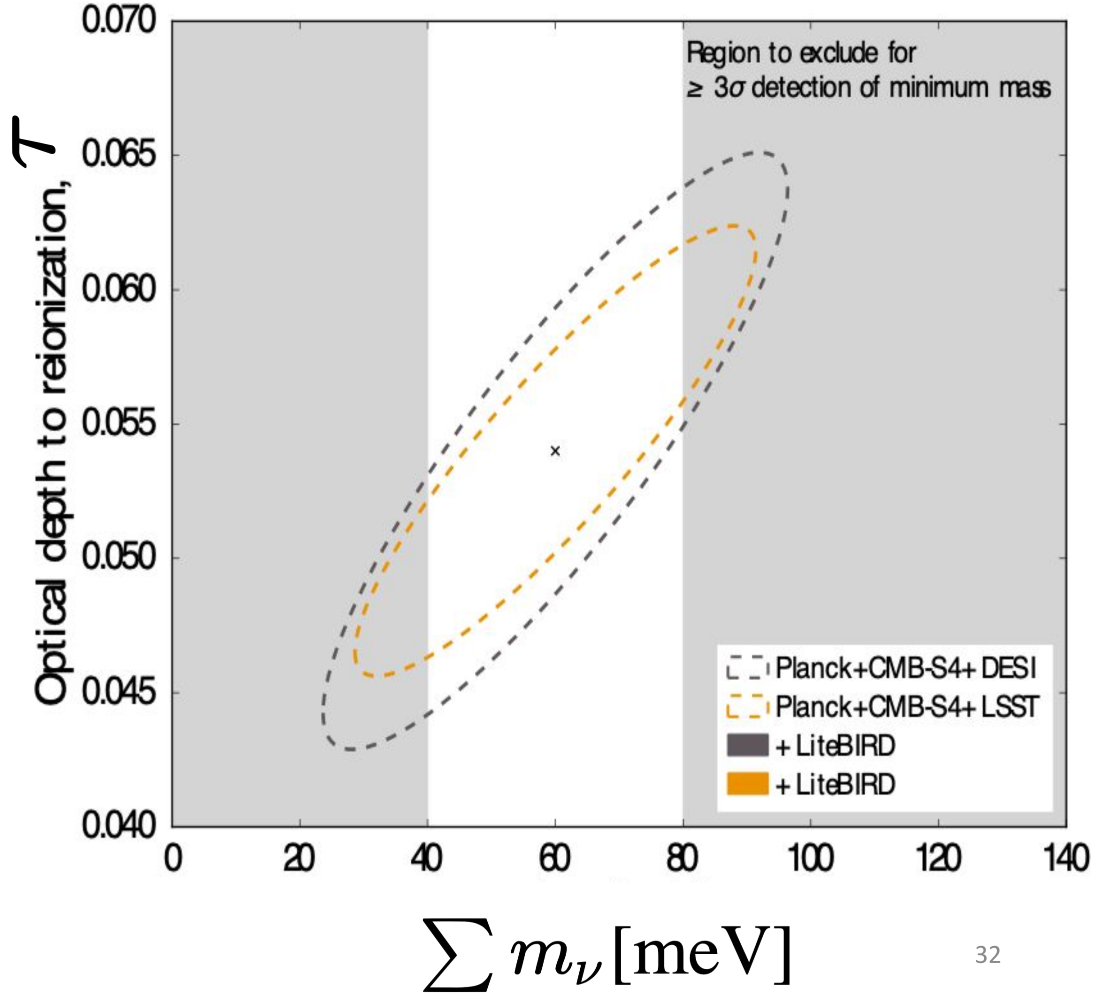
Why do we care?

$\sum m_\nu$ w/ improved τ

The determination of τ helps break the degeneracy in the lensing B-mode between the overall amplitude and the smearing by the neutrino mass.

$$\sigma_{\sum m_\nu} = 15\ \mathrm{meV}$$

- ≧3σ detection of minimum mass for normal hierarchy
- ≧5σ detection of minimum mass for inverted hierarchy



Caveat:
No systematic error included yet.

Simons Array

2010 2015 2020 2025 2030

SIMONS OBSERVATORY

CMB-S4
Next Generation CMB Experiment

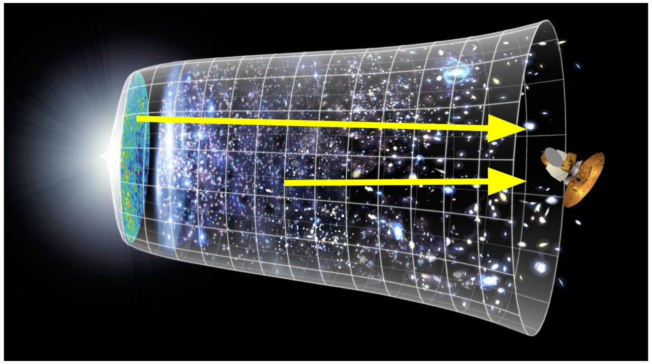
Next 5 years

- We expect to have very close collaborations between France and Japan on multiple CMB polarization experiments to probe inflationary B-mode.
- The nature of the collaboration will span broadly: instrumental, simulation and analysis.
- The rich CMB data can also enlarge the area of synergy beyond the physics of early universe, including the cross-correlation with other data, e.g. CMB x CIB, CMB x Weak lensing, CMB x any other LSS tracer via CMB x Rubin(LSST), x PFS.

We can travel (if allowed)!

Beyond 5 years and more

- LiteBIRD x CMB-S4



Horizon 2020 MSCA-RISE **CMB-INFLATE**, Research and Innovation Staff Exchange program to benefit LiteBIRD research efforts: 1.1M Euro total, **PI: G. Patanchon** (APC, U. Paris)