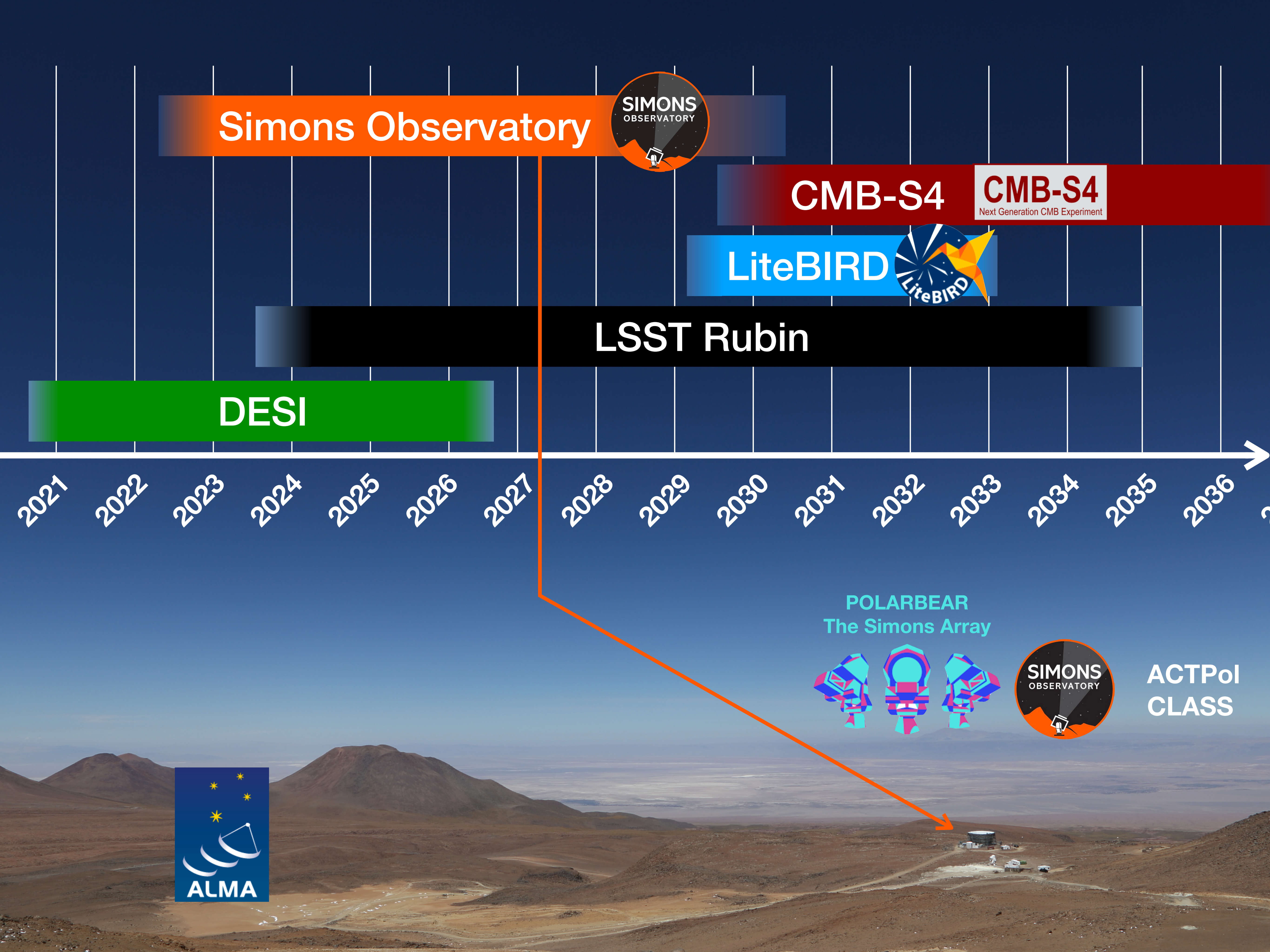
Future observations of the primordial, polarized Cosmic Microwave Background

expected science and challenges

Josquin Errard, online colloquium at CEA, October 4, 2021
josquin@apc.in2p3.fr



Simons Observatory

CMB-S4

LiteBIRD

LSST Rubin

DESI

2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
2036

POLARBEAR
The Simons Array

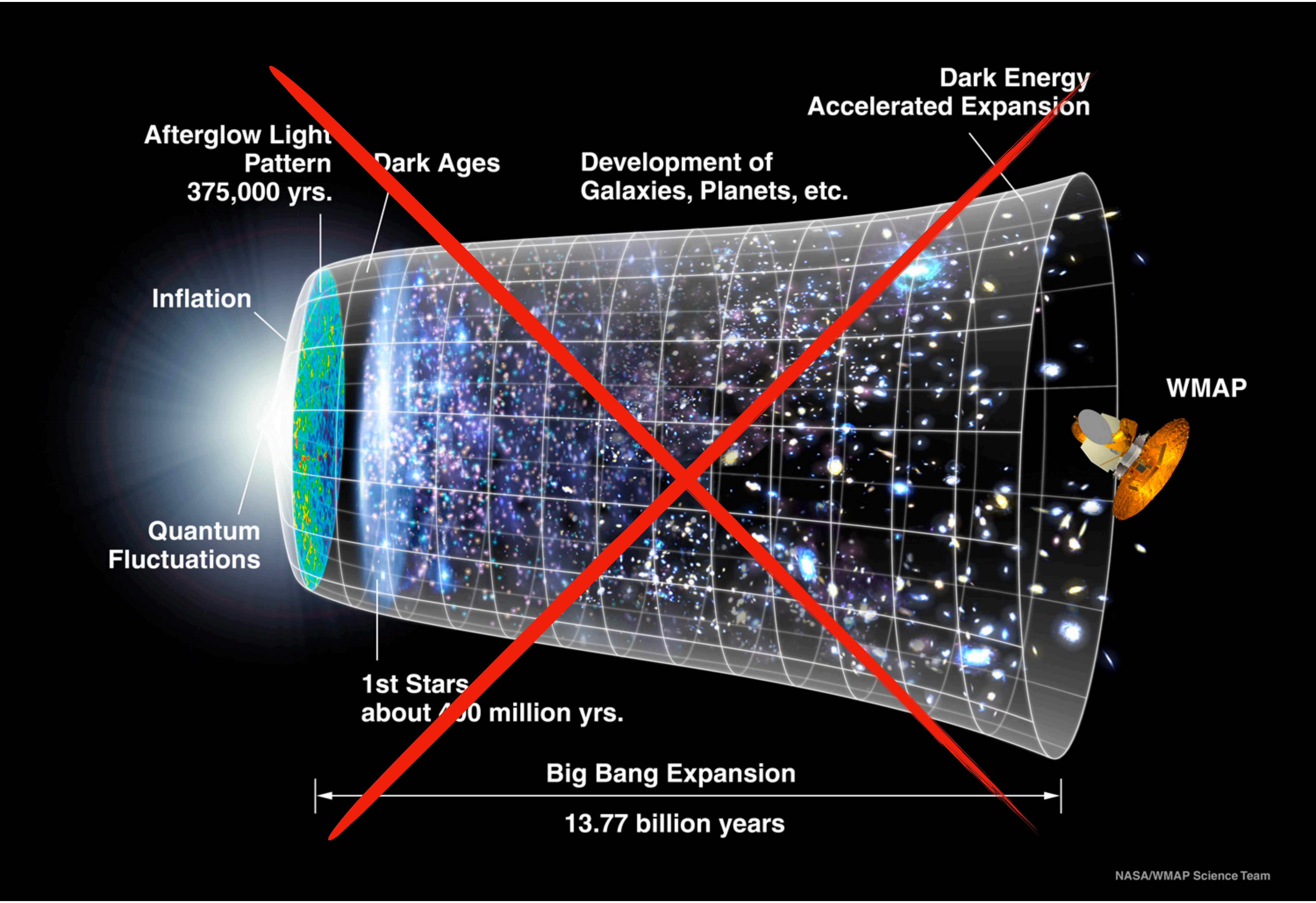
ACTPol
CLASS

Future observations of the primordial, polarized Cosmic Microwave Background **expected science and challenges**

1. Introduction: a brief overview of challenges

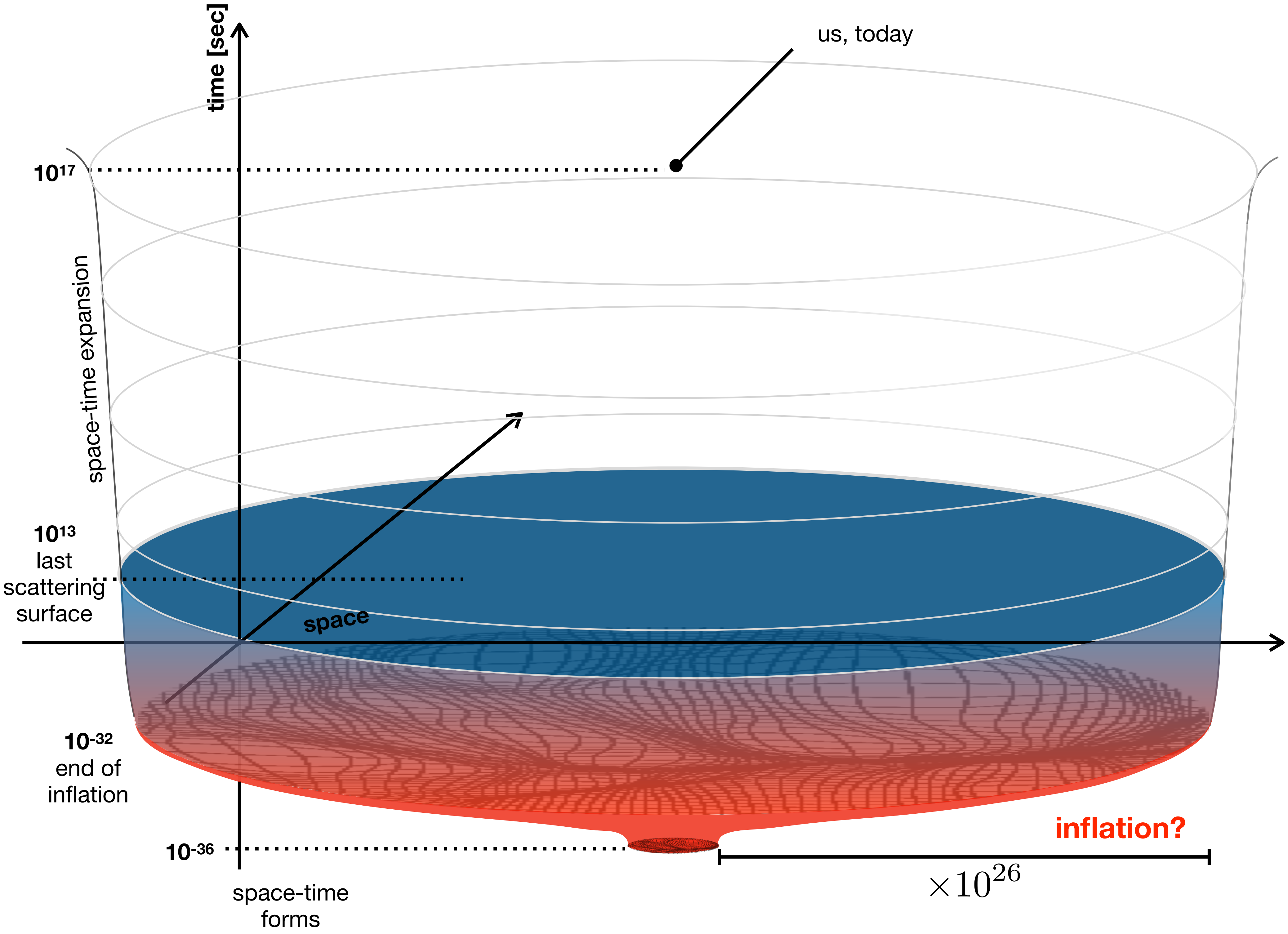
2. Some hardware and software mitigations techniques to reach primordial CMB B-modes

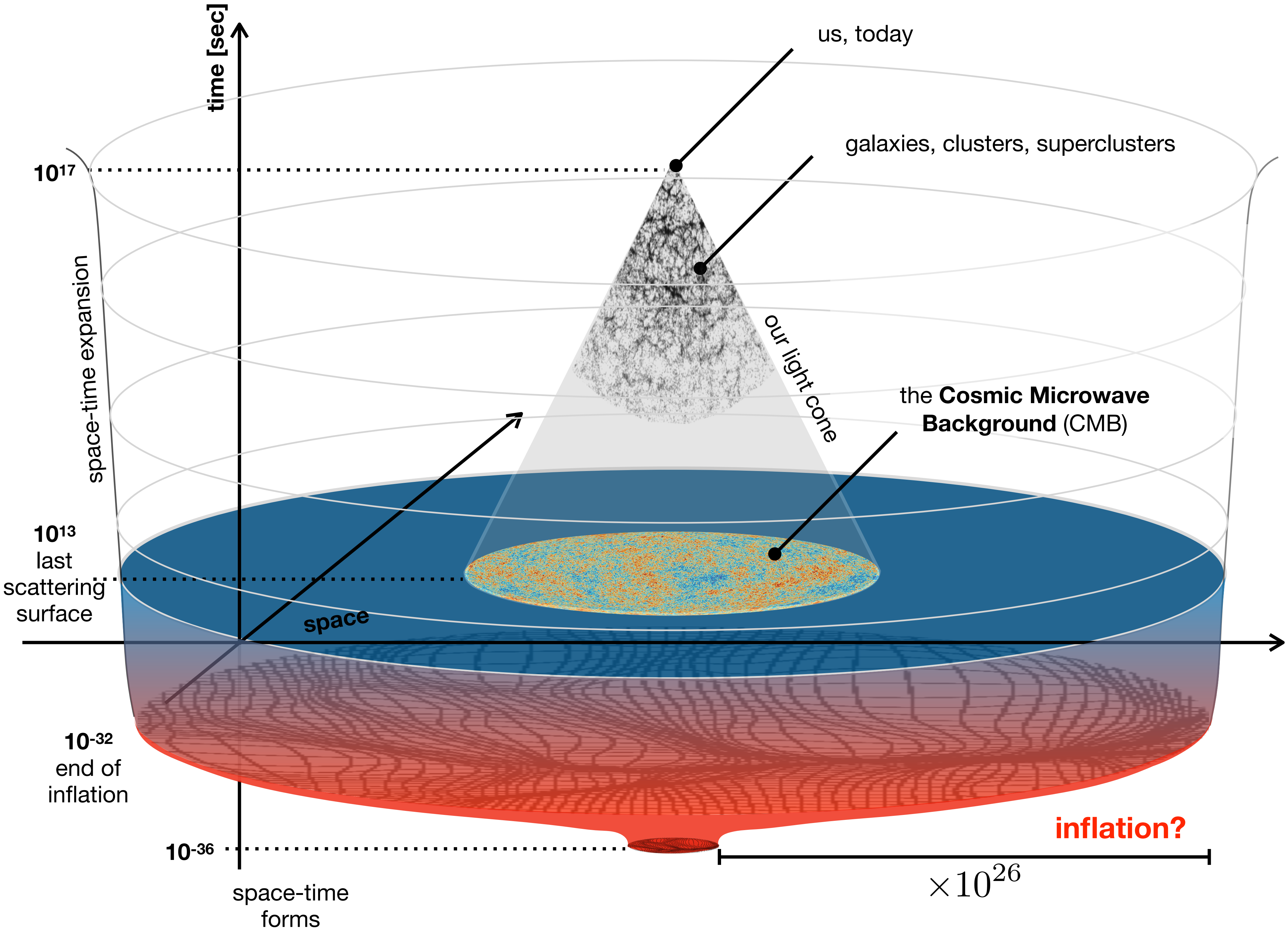
3. The Simons Observatory and LiteBIRD



NASA/WMAP Science Team

a general introduction to ΛCDM+inflation cosmology…

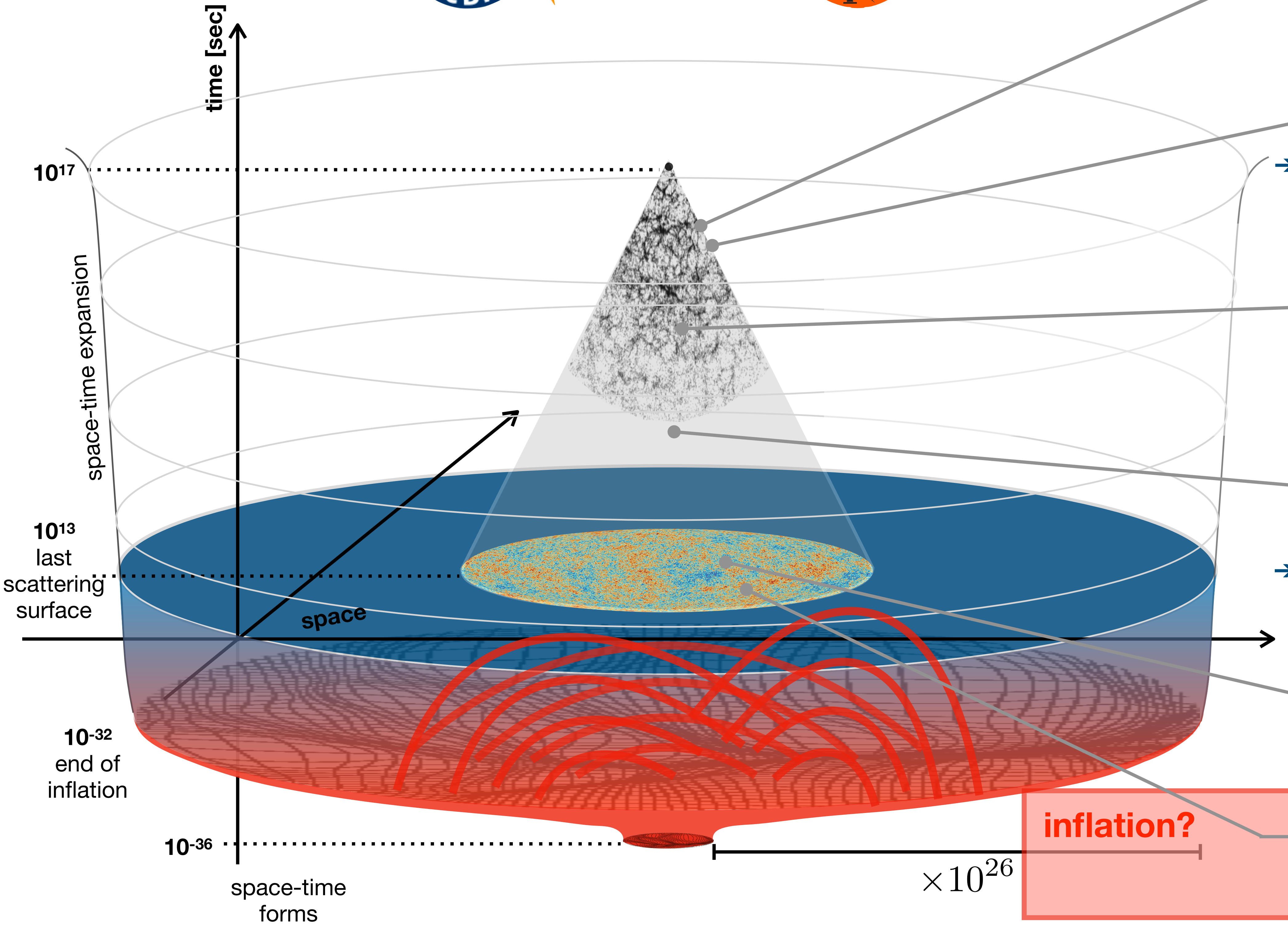



time [sec]
us, today
galaxies, clusters, superclusters
10^{17}
space-time expansion
our light cone
the **Cosmic Microwave Background** (CMB)
10^{13}
last scattering surface
space
10^{-32}
end of inflation
inflation?
10^{-36}
$\times 10^{26}$
space-time forms

LiteBIRD

CMB-S4
Next Generation CMB Experiment

SIMONS OBSERVATORY



dark energy

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

galaxy evolution

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

neutrino mass

lensing potential (TT+EB), tSZ
➔ Σm_ν

reionization

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

relativistic species

damping tail
➔ N_{eff} (TE, TT, EE)

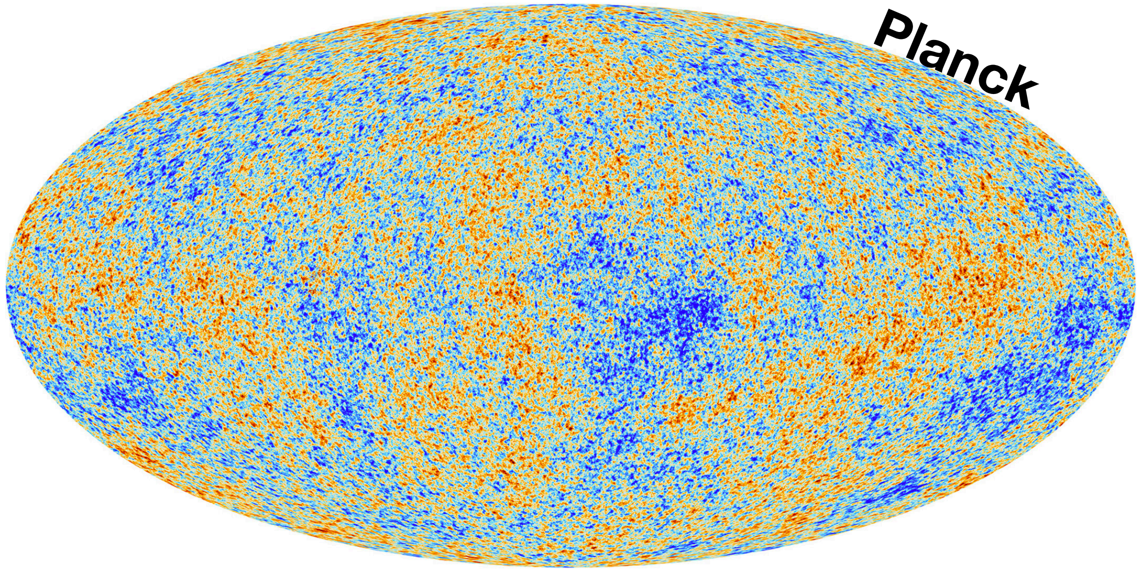
inflation?

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)

inflation ϕ



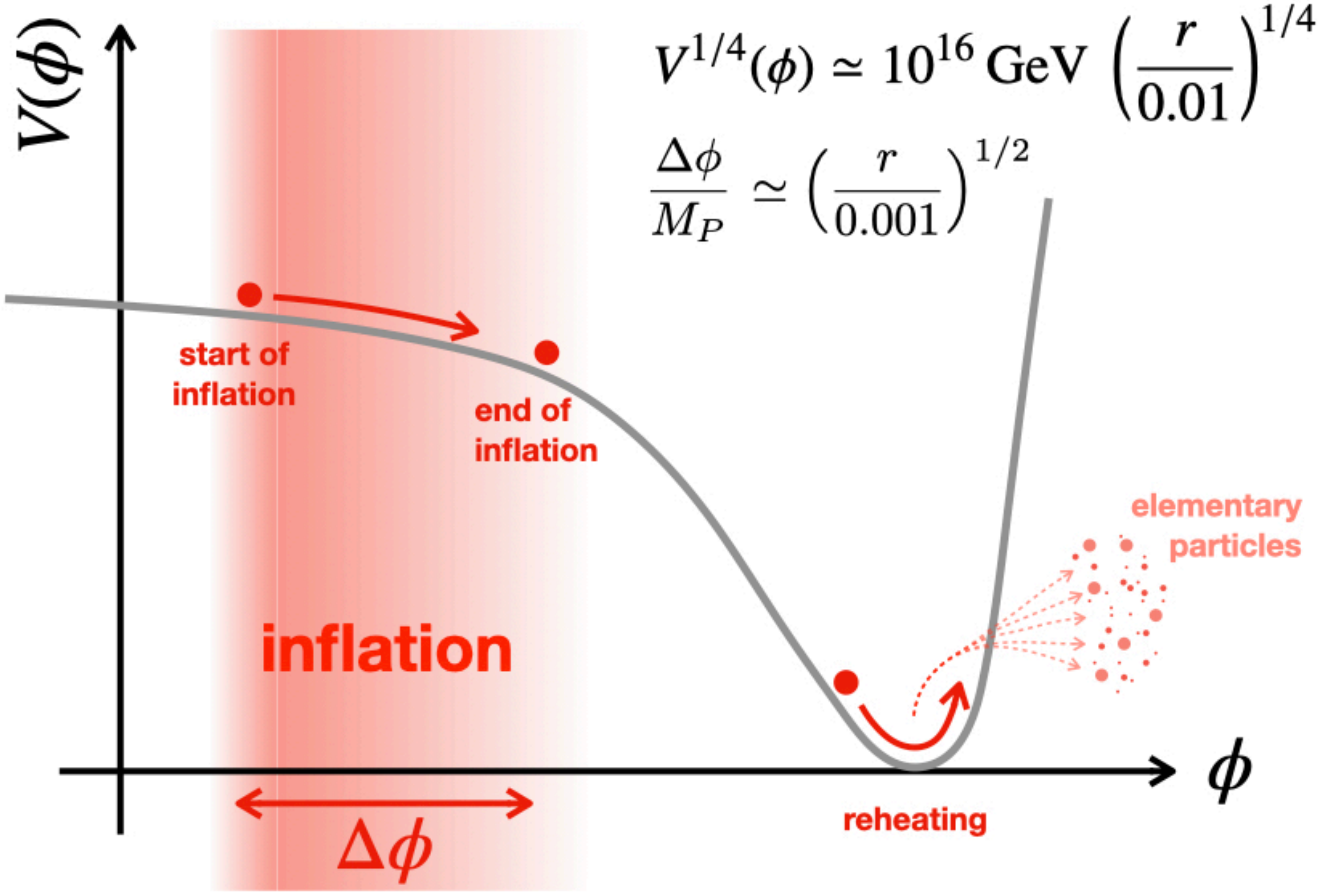
Observations are already in remarkable agreement with single-field slow-roll inflation:

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

- **dynamics of an homogeneous scalar field in a FLRW 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 happens when potential dominates over kinetic energy (slow-roll)**



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

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

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

inflation ϕ

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

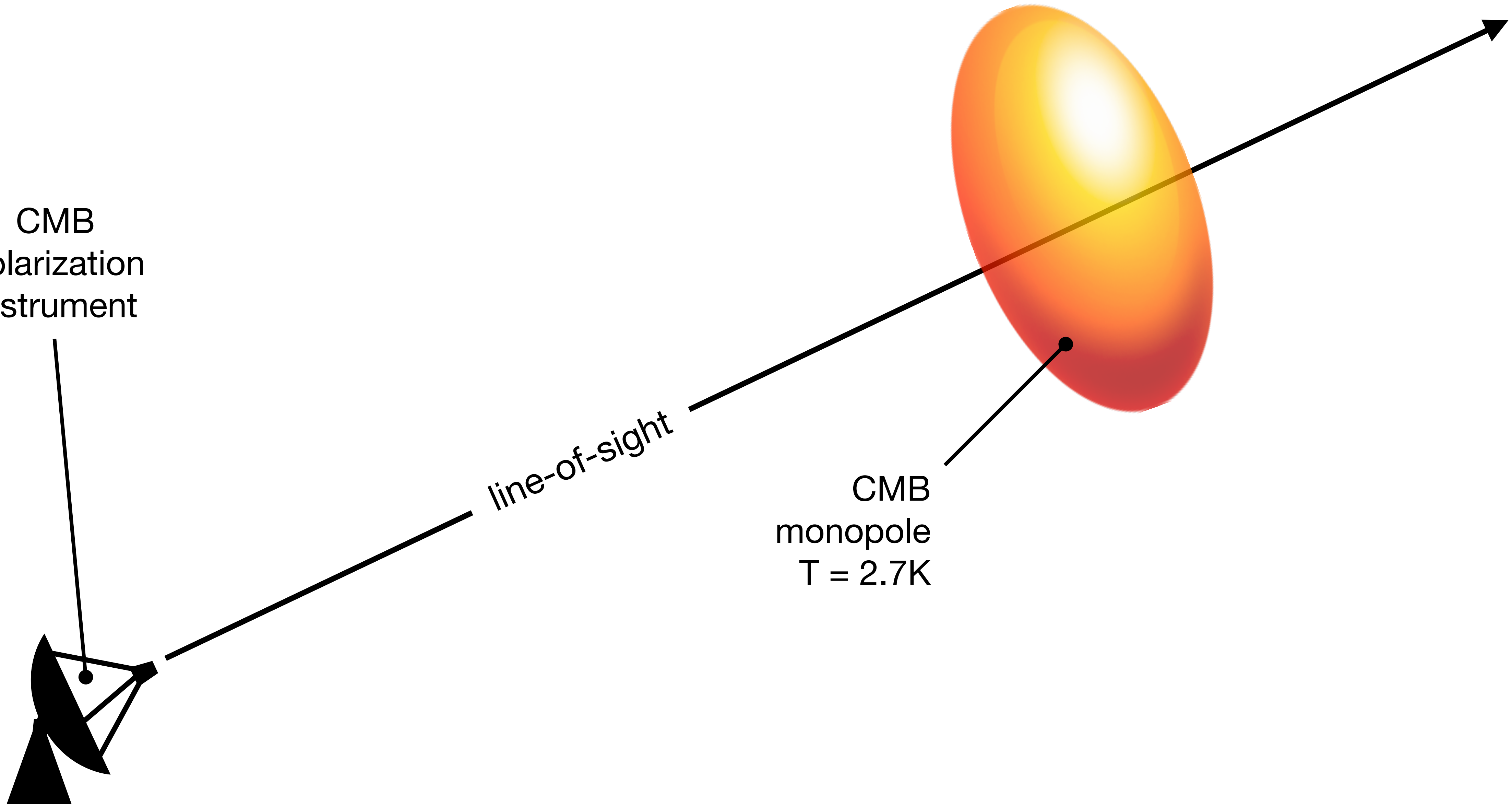
$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0}\right)^{\boxed{n_s}-1}$$ scalar

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

- **With the definition of the tensor-to-scalar ratio "r"** $\boxed{r} = A_t/A_s$ **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 $$r = 8M_{\rm Pl}^2\left(\frac{V_\phi}{V}\right)^2$$ $$n_{\rm s} - 1 \equiv \frac{\mathrm{d}\ln\mathcal{P}_\zeta}{\mathrm{d}\ln k} \simeq -3M_{\rm Pl}^2\left(\frac{V_\phi}{V}\right)^2 + 2M_{\rm Pl}^2\frac{V_{\phi\phi}}{V}$$

credits: Matt Tristram

Back to the observations …



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.

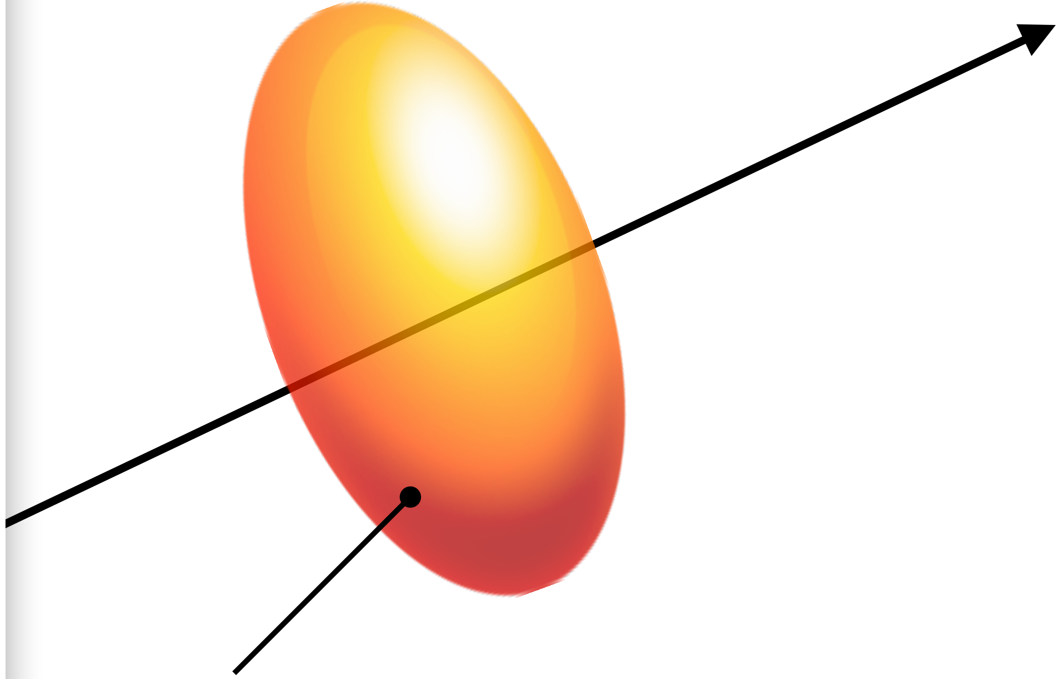
The Bell observations, made by Drs. Arno A. Penzias and Robert W. Wilson from a hilltop in Holmdel, N. J., were of radio waves that appear to be flying in all directions through the universe. Since radio waves and light waves are identical, except for their wavelength, these are thought to be remnants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

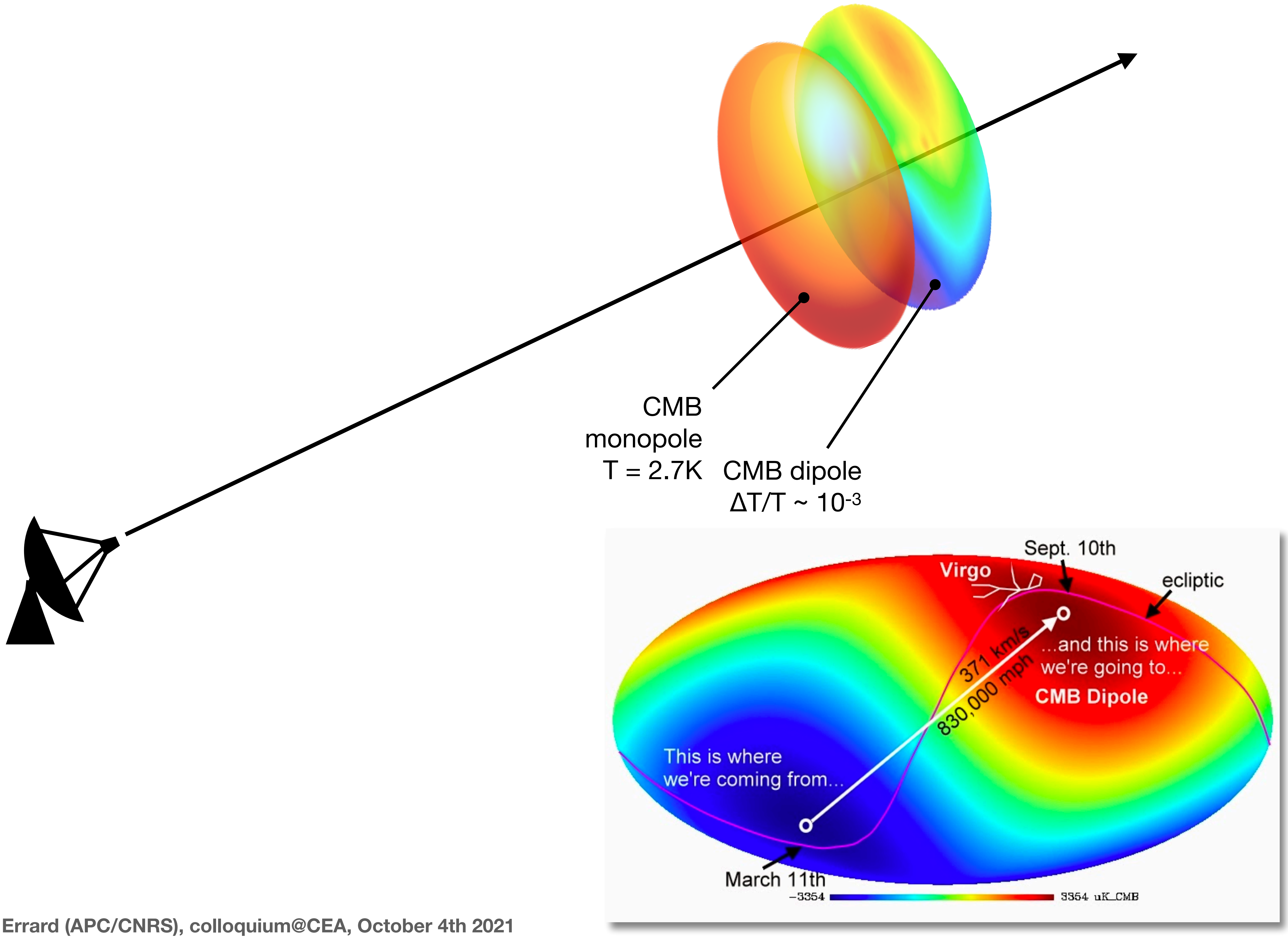
Continued on Page 18, Column 1

The New York Times
Published: May 21, 1965



CMB
monopole
T = 2.7K

at mm wavelengths, we could see an isotropic signal, with an emission following a 2.7K black body spectrum

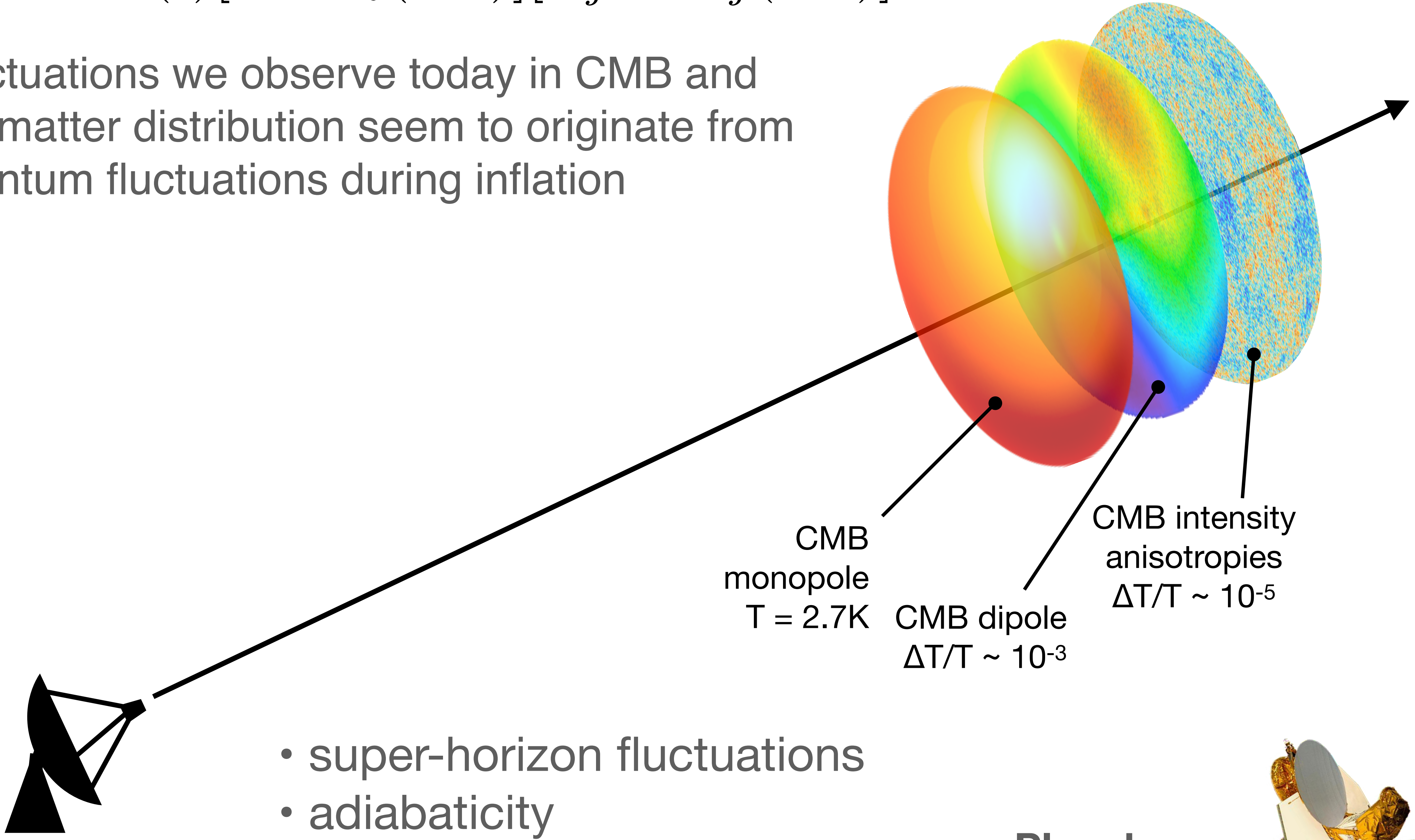


CMB
monopole
T = 2.7K

CMB dipole
$\Delta T/T \sim 10^{-3}$

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

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



CMB monopole
T = 2.7K

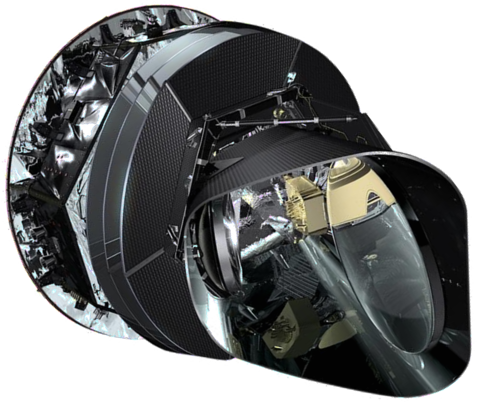
CMB dipole
$\Delta T/T \sim 10^{-3}$

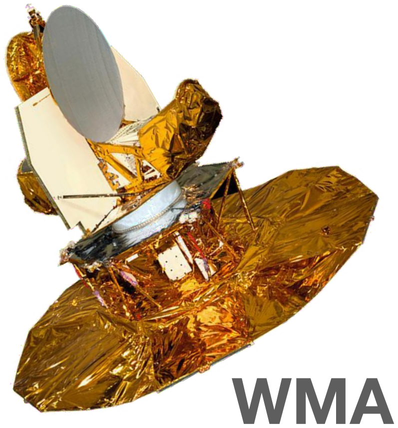
CMB intensity anisotropies
$\Delta T/T \sim 10^{-5}$

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

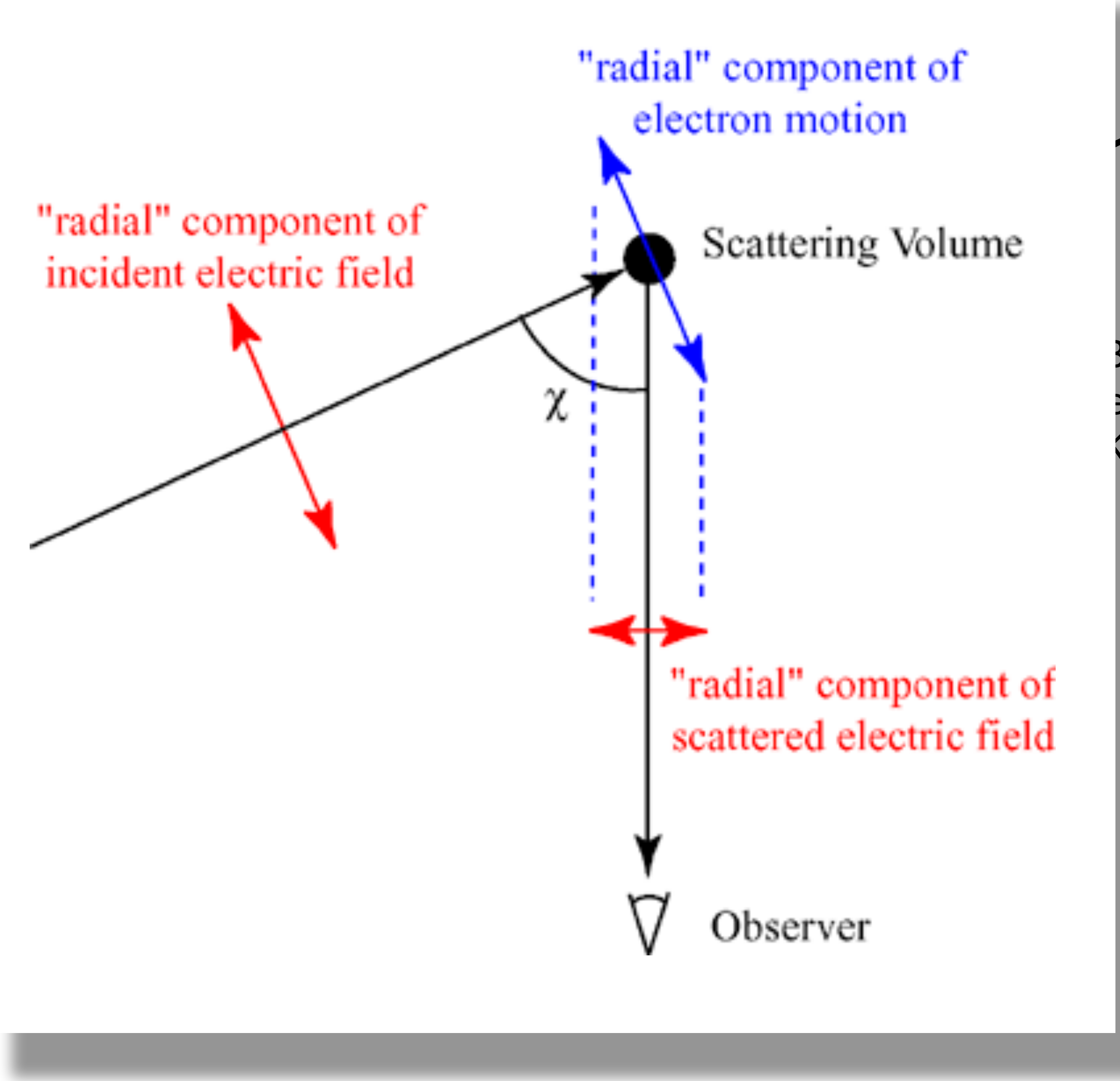
$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$$

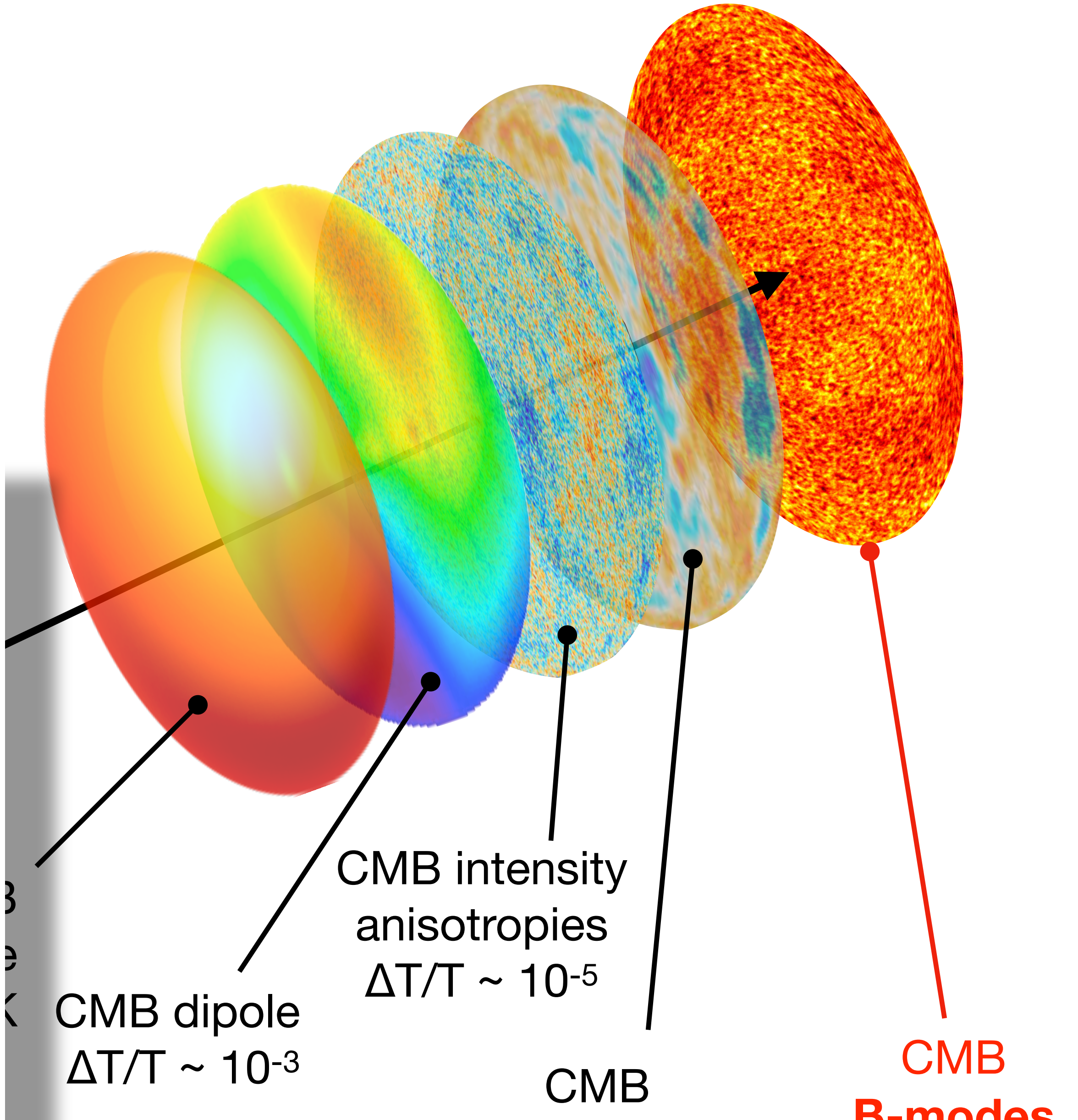
Planck





WMAP



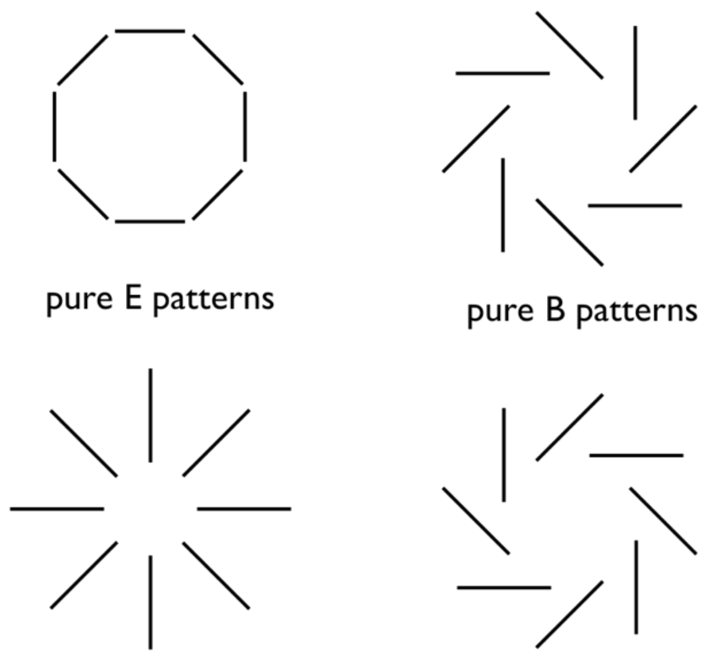


CMB dipole
$\Delta T/T \sim 10^{-3}$

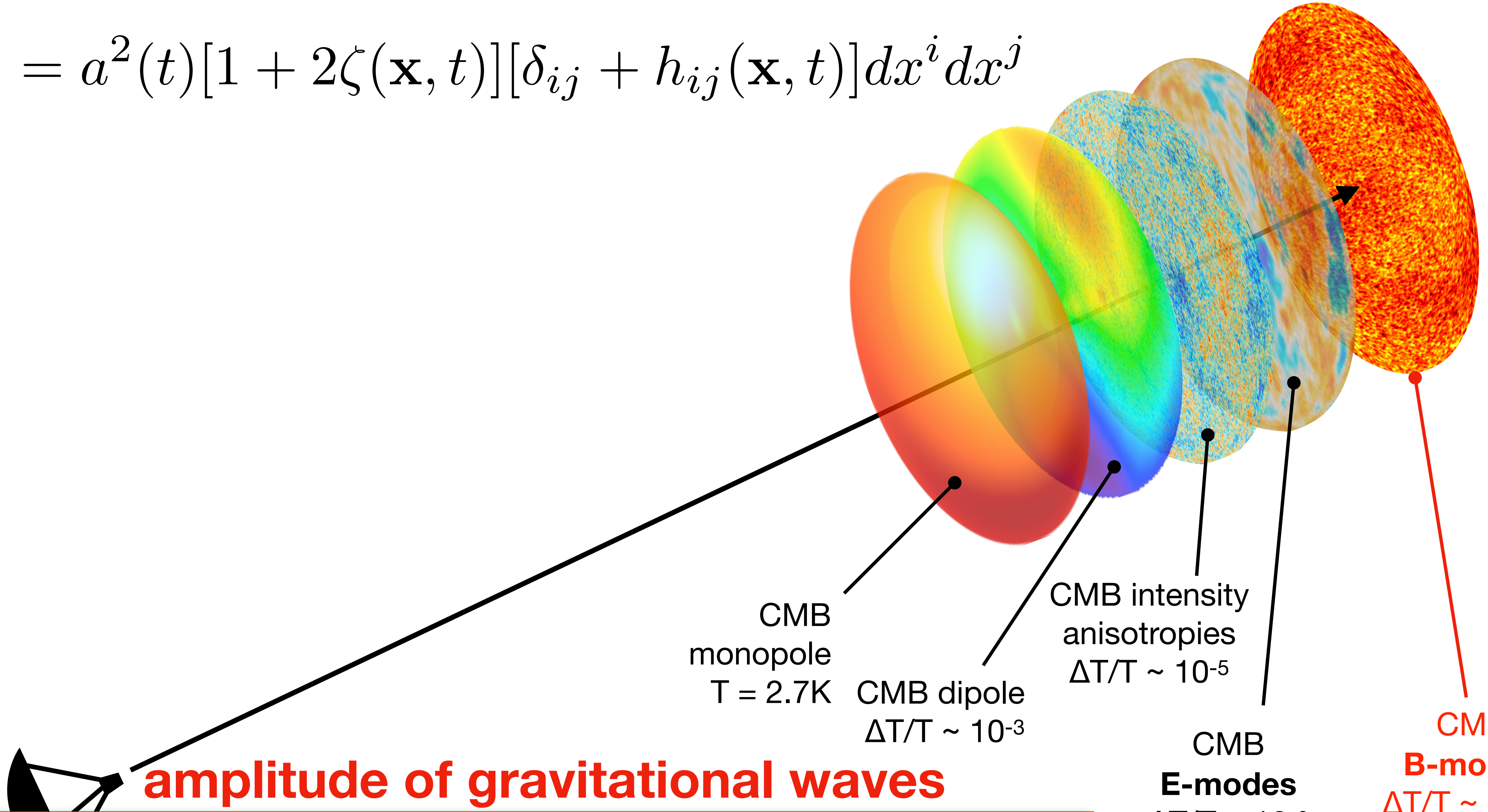
CMB intensity anisotropies
$\Delta T/T \sim 10^{-5}$

CMB
E-modes
$\Delta T/T \sim 10^{-6}$

CMB
B-modes
$\Delta T/T \sim 10^{-7\text{-}8}$



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



CMB monopole
T = 2.7K

CMB dipole
$\Delta T/T \sim 10^{-3}$

CMB intensity anisotropies
$\Delta T/T \sim 10^{-5}$

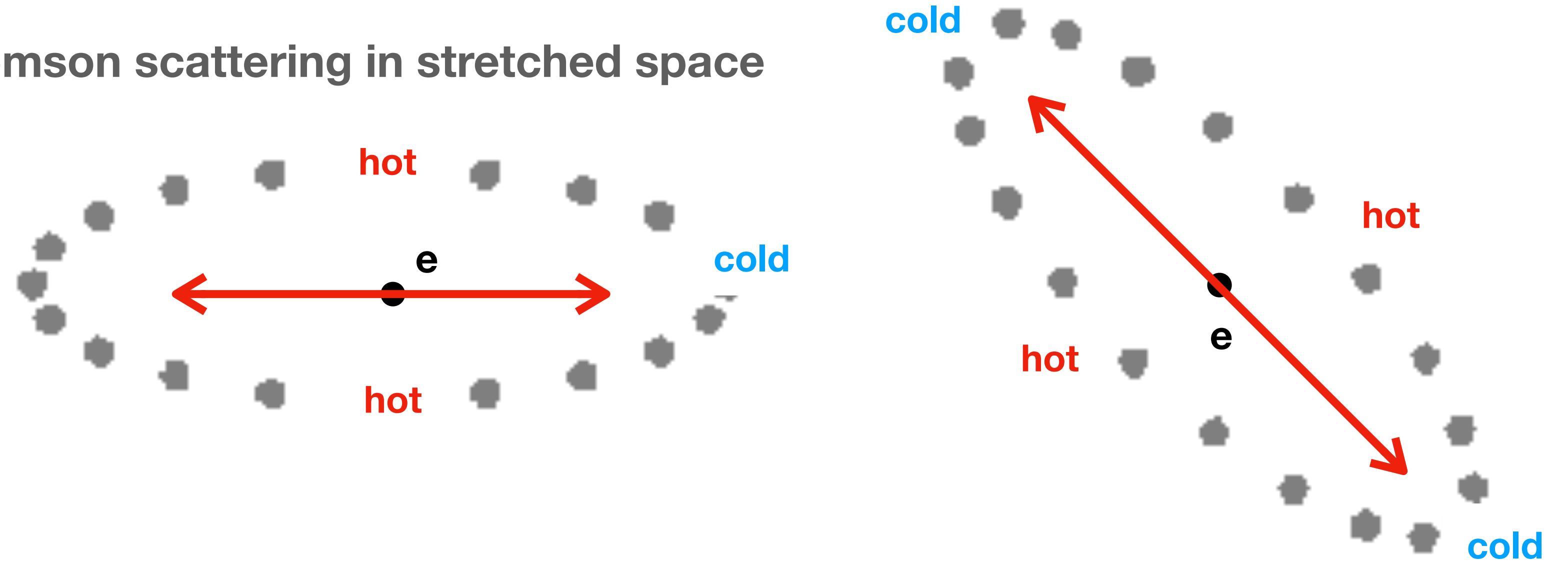
CMB **E-modes**
$\Delta T/T \sim 10^{-6}$

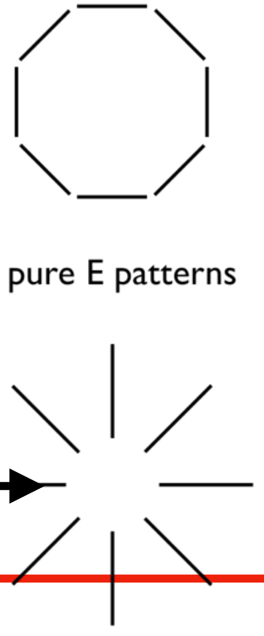
CMB **B-modes**
$\Delta T/T \sim 10^{-7\text{-}8}$

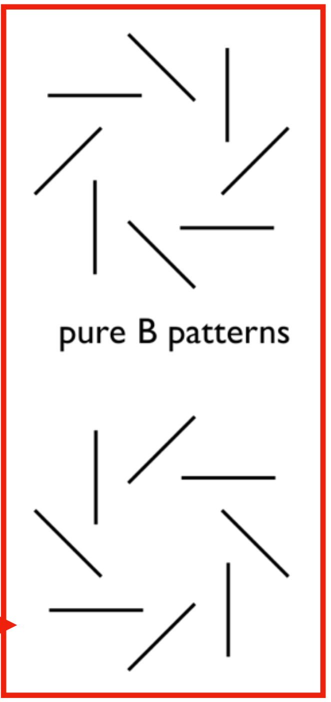
amplitude of gravitational waves

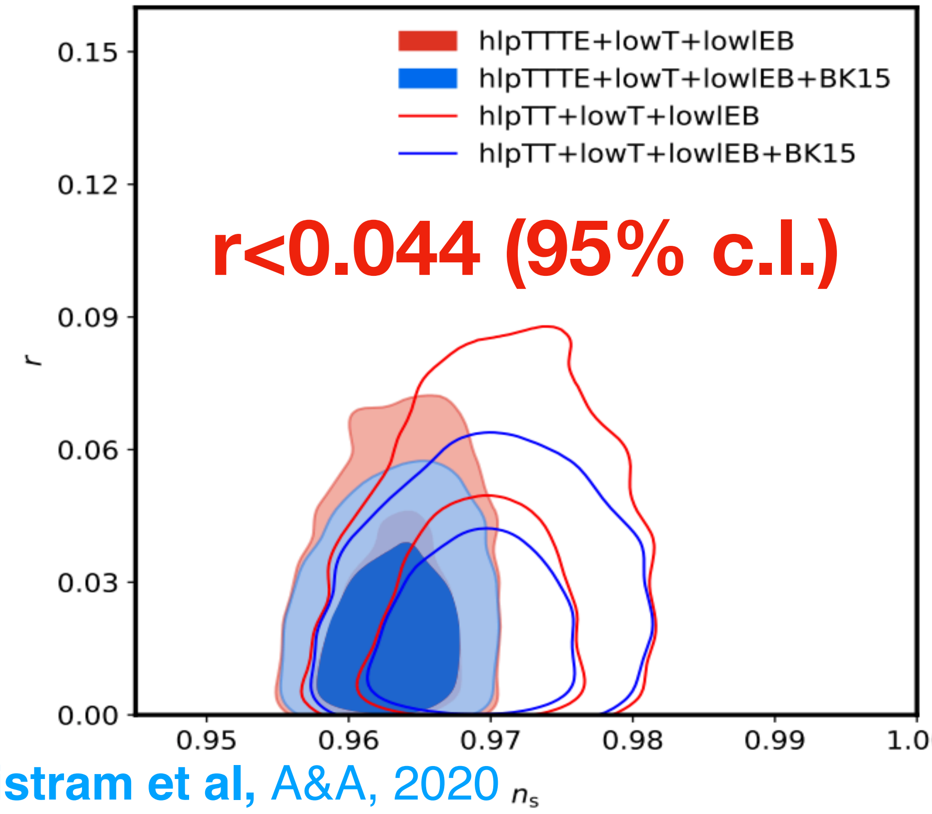
α tensor-to-scalar ratio *r*

Thomson scattering in stretched space



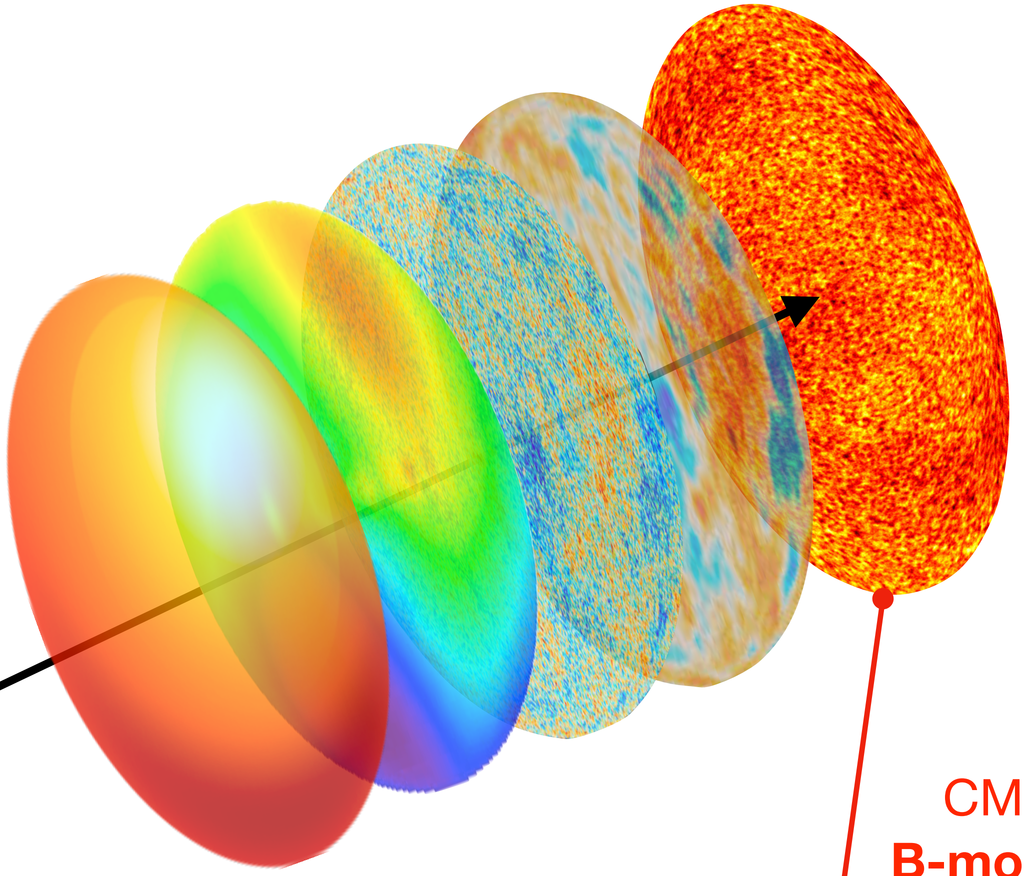






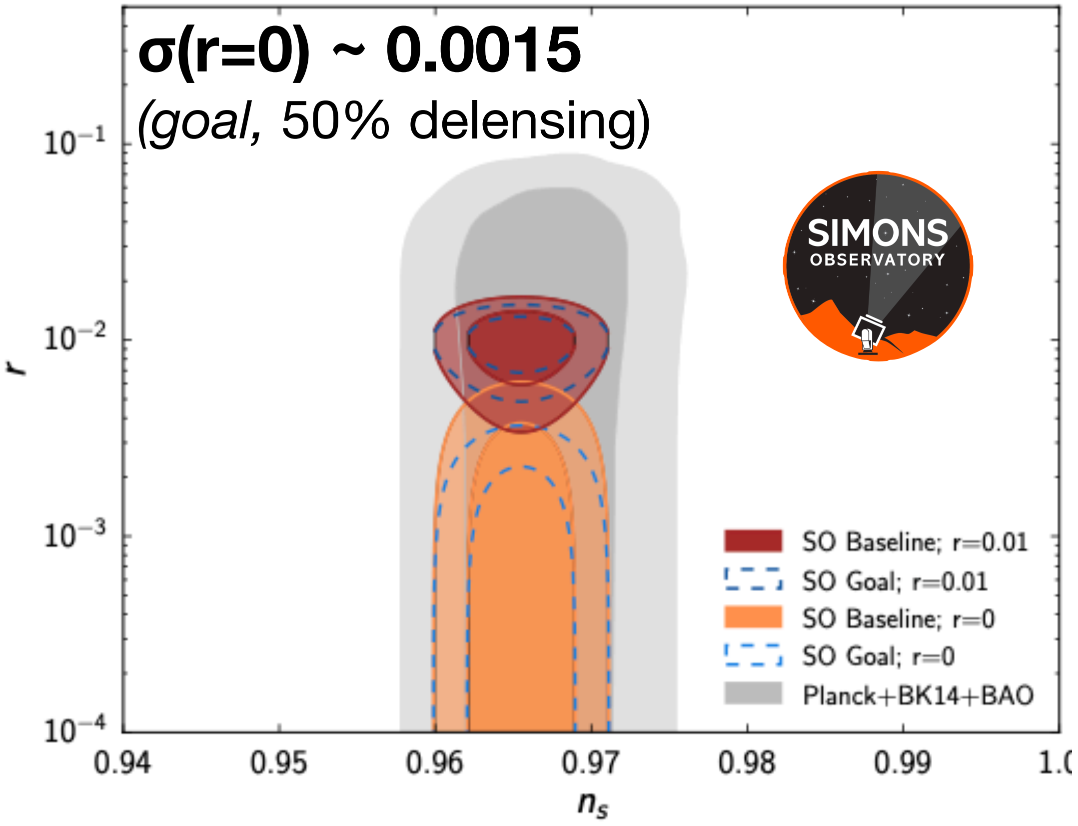
$r<0.044$ (95% c.l.)

Tristram et al, A&A, 2020



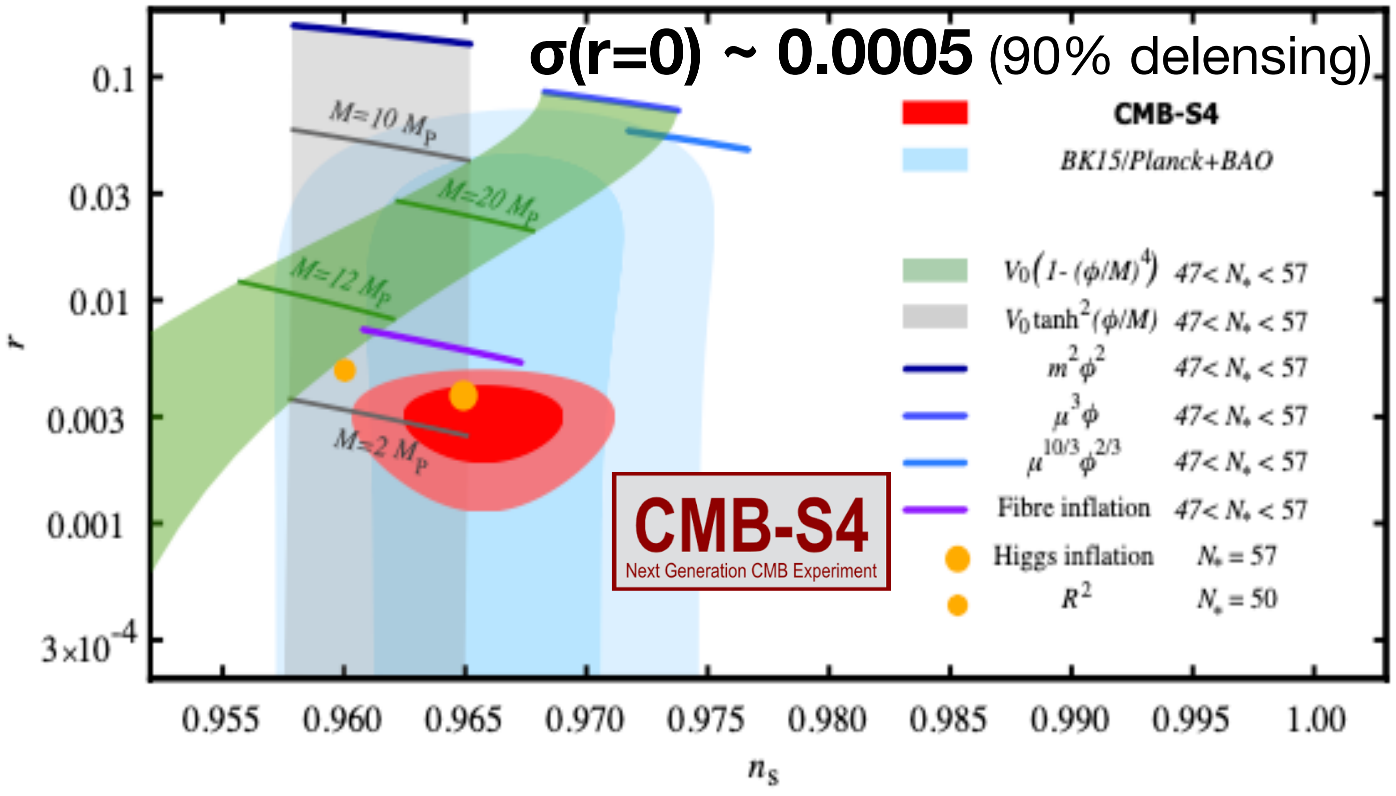
CMB
B-modes
$\Delta T/T \sim 10^{-7-8}$

performance by ~ 2028



σ(r=0) ~ 0.0015
(goal, 50% delensing)

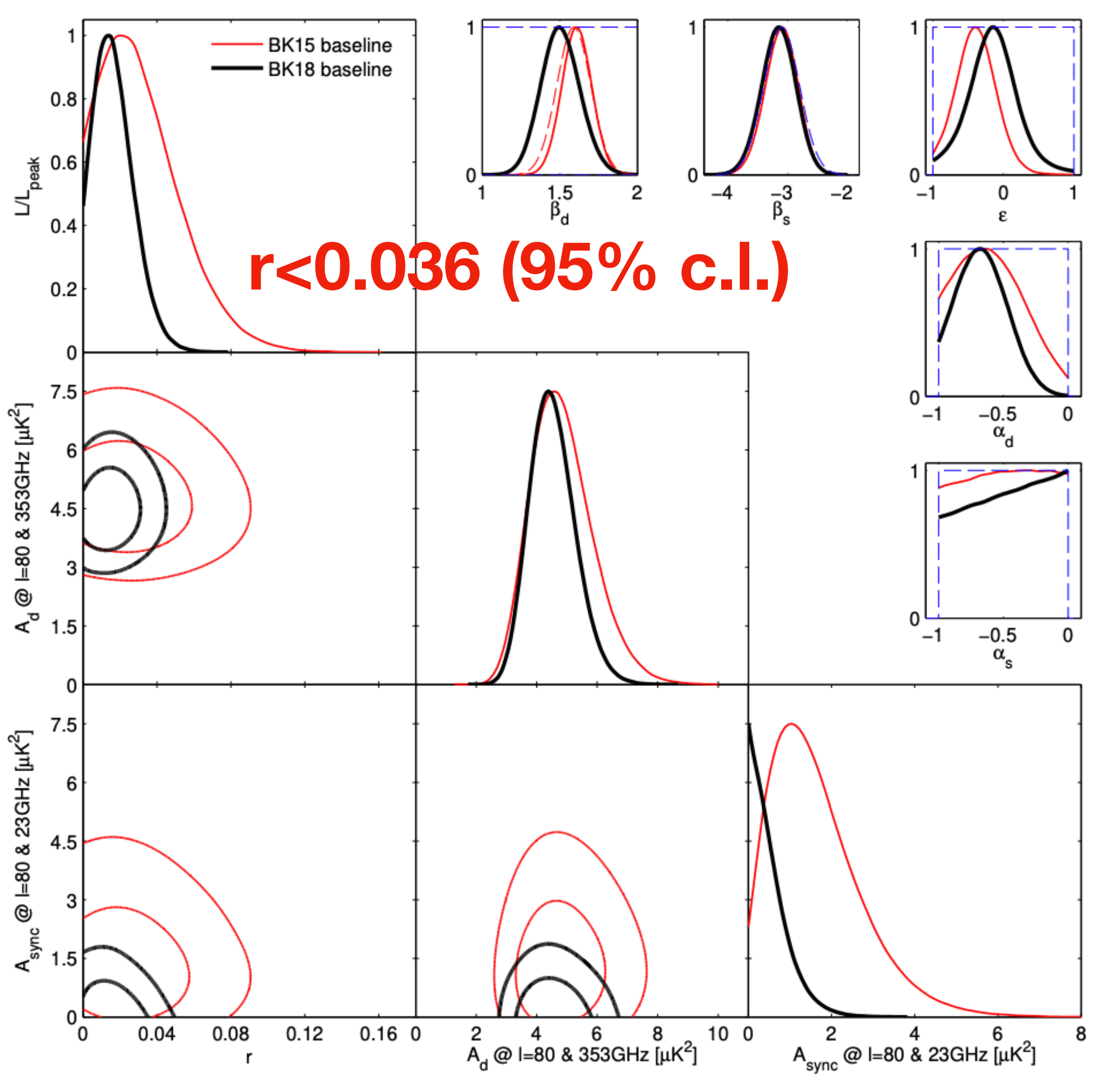
performance by ~ 2035



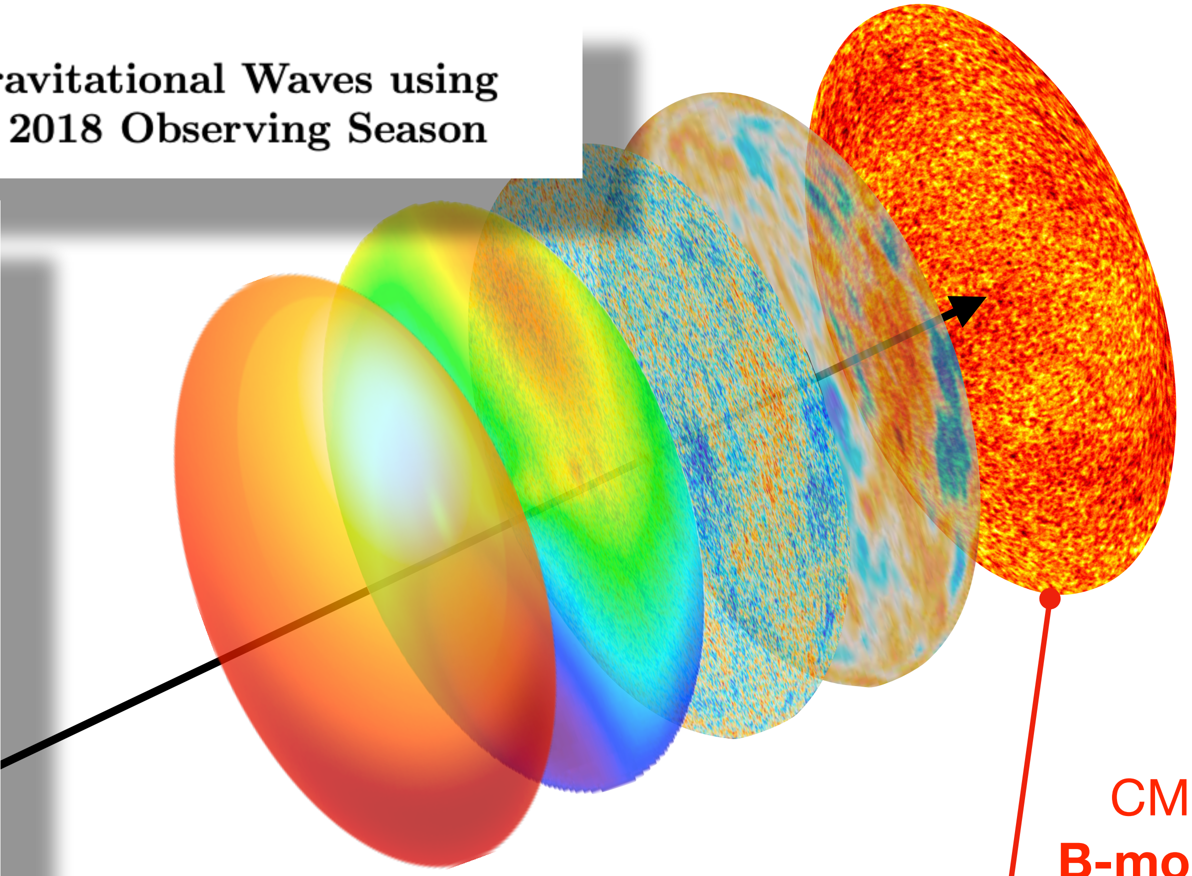
σ(r=0) ~ 0.0005 (90% delensing)

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

2110.00483

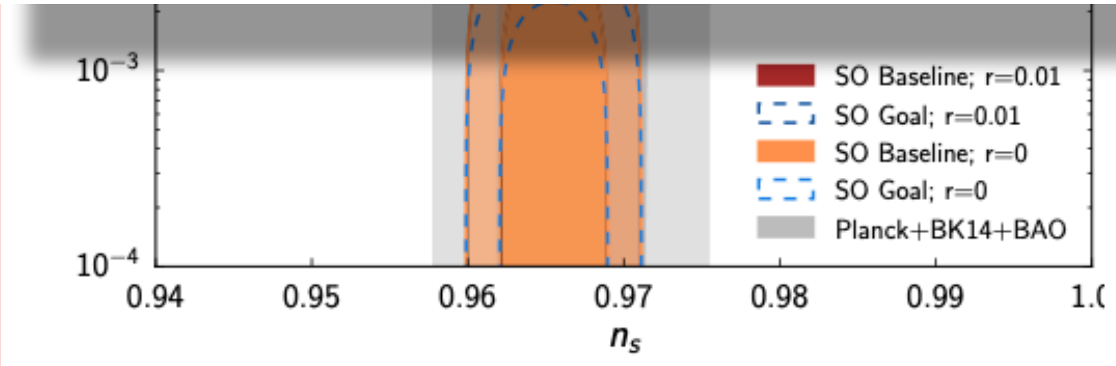


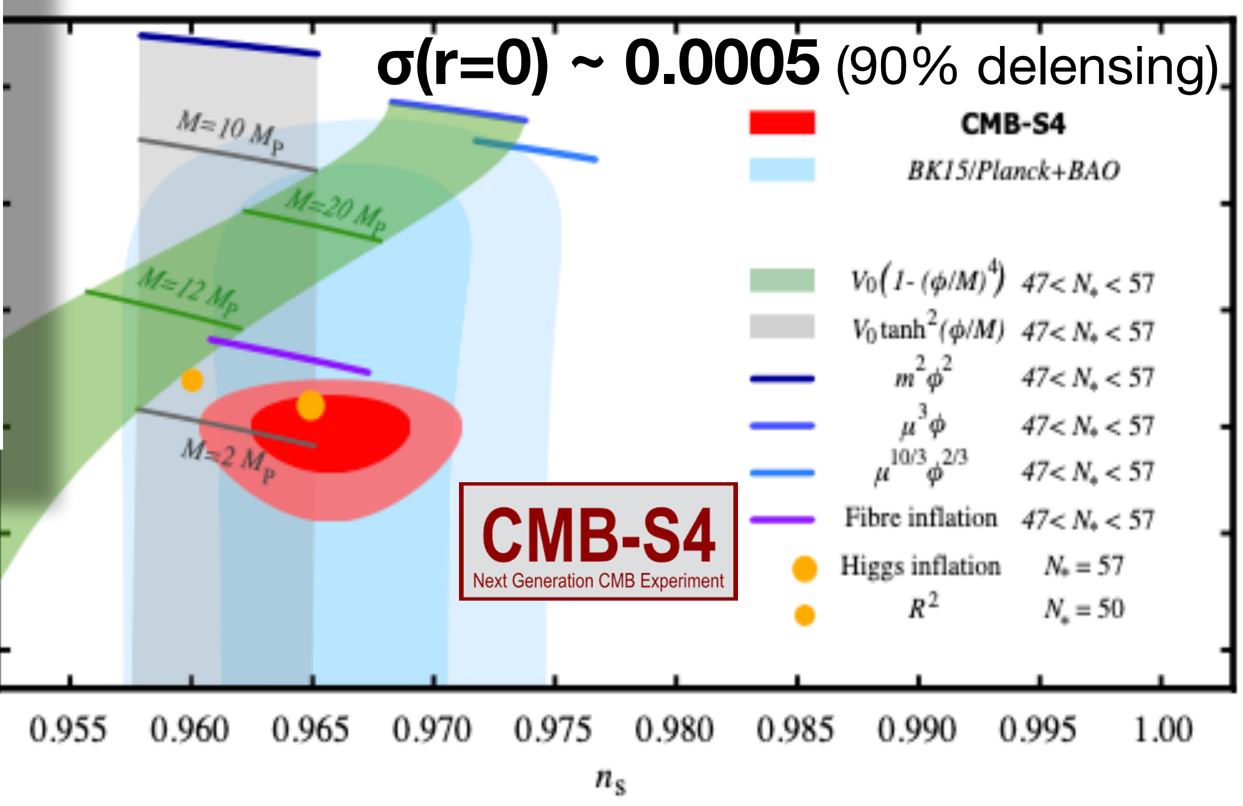
r<0.036 (95% c.l.)



CMB
B-modes
$\Delta T/T \sim 10^{-7-8}$

performance by ~ 2035





σ(r=0) ~ 0.0005 (90% delensing)

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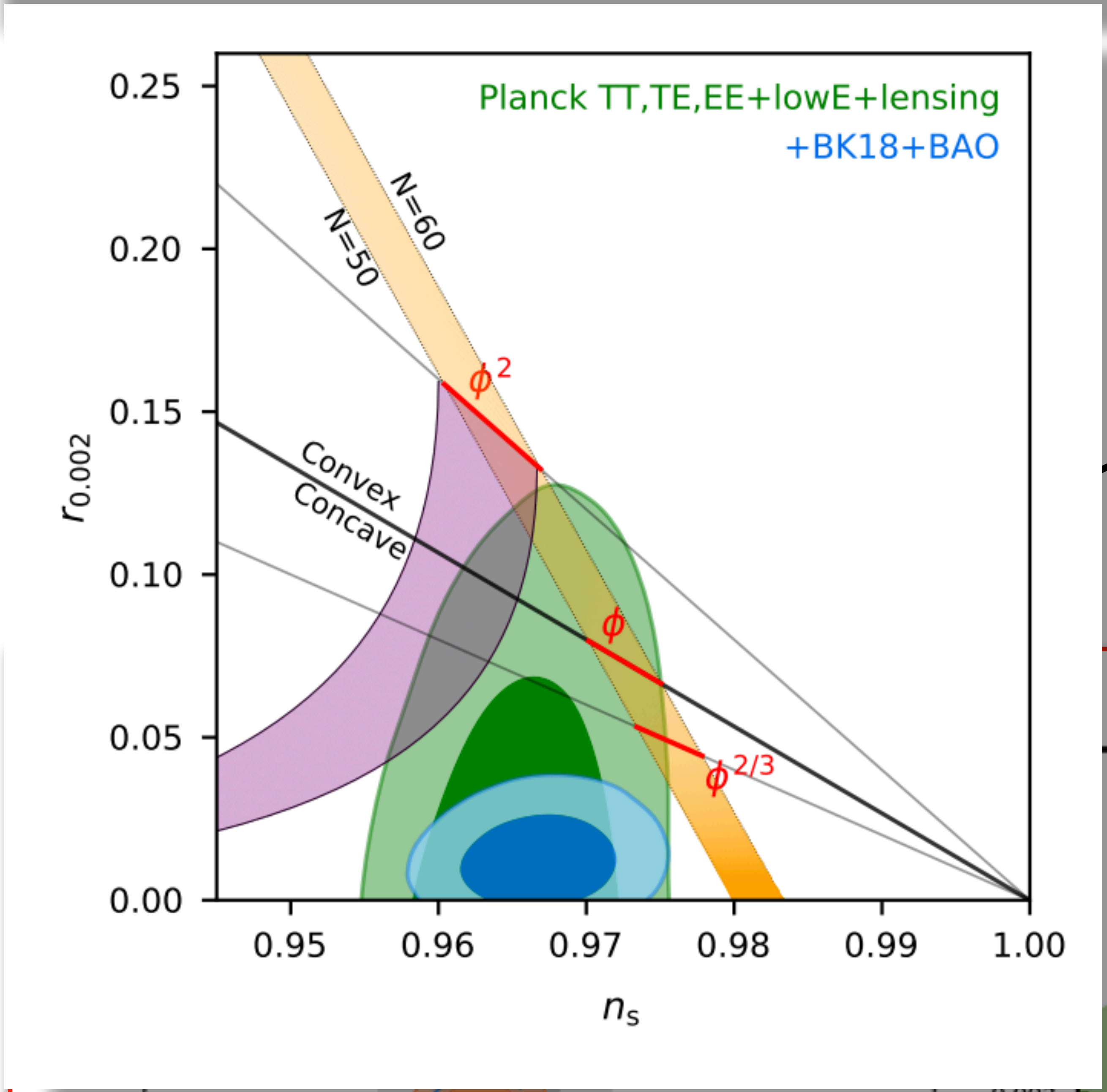
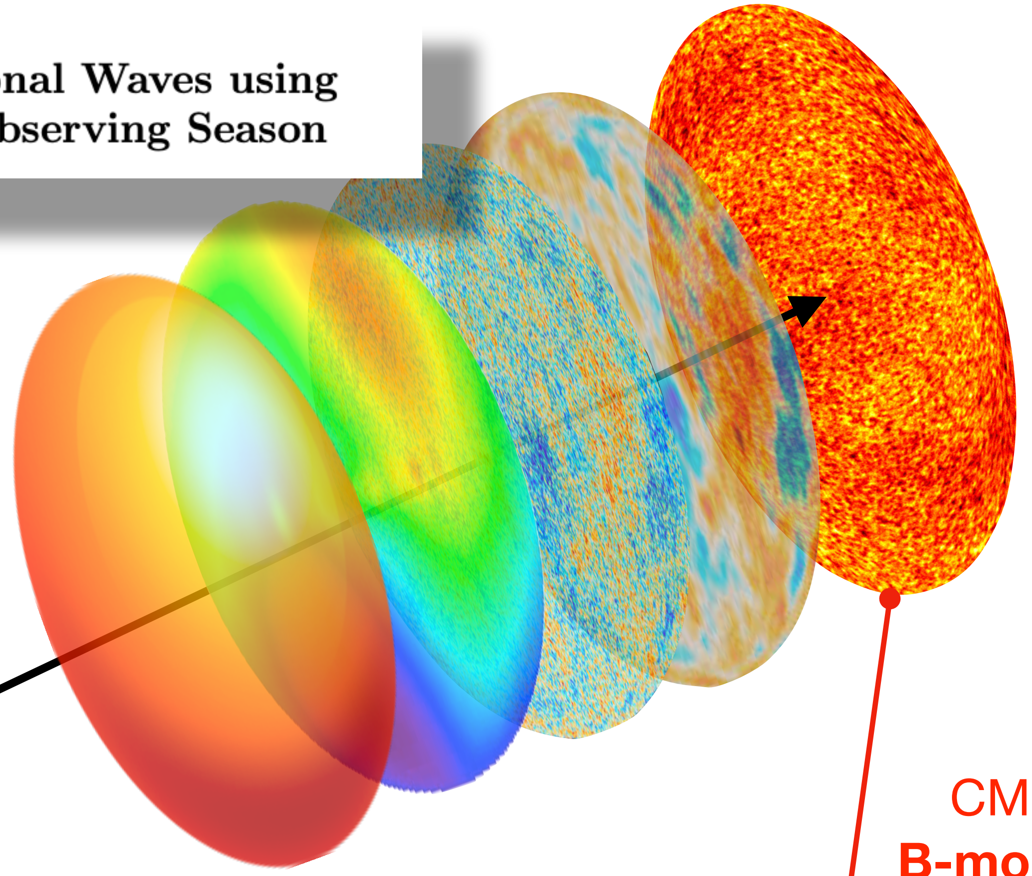
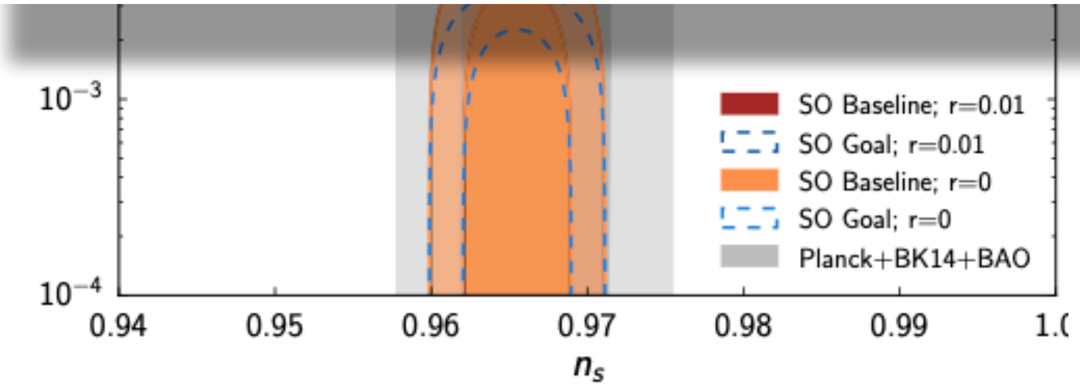


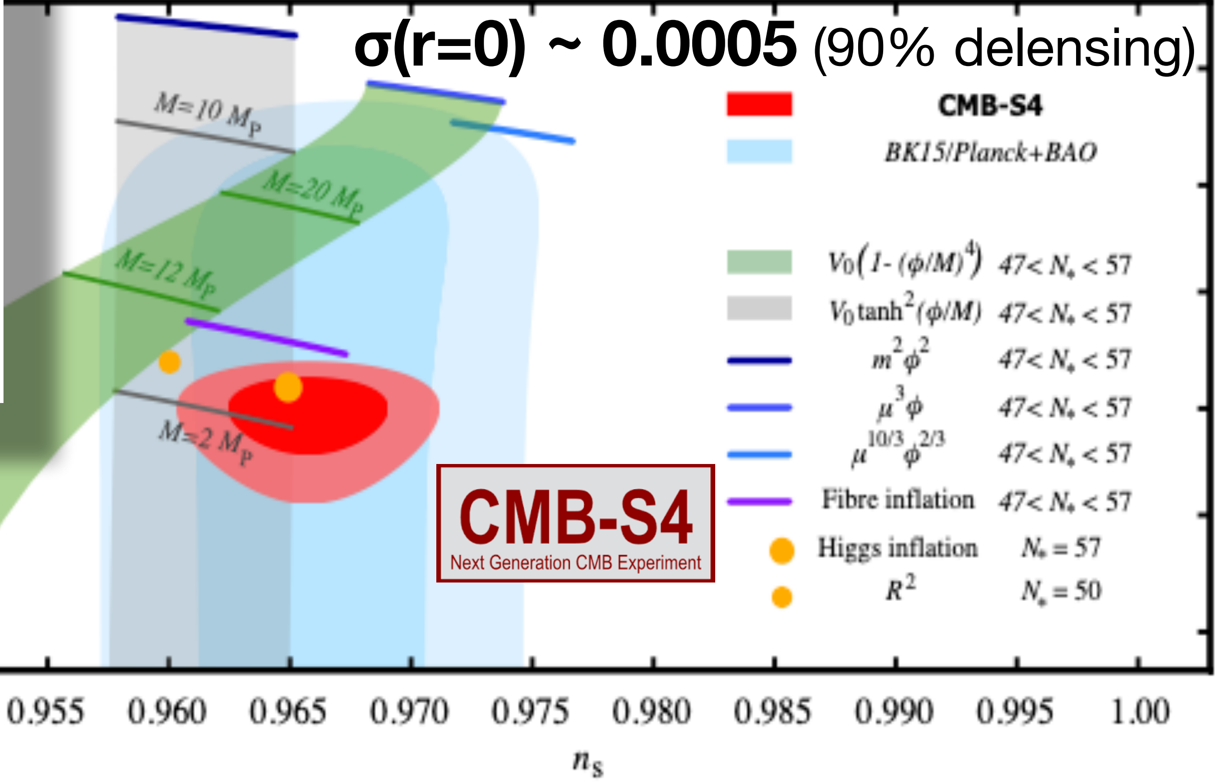


CMB
B-modes
$\Delta T/T \sim 10^{-7-8}$

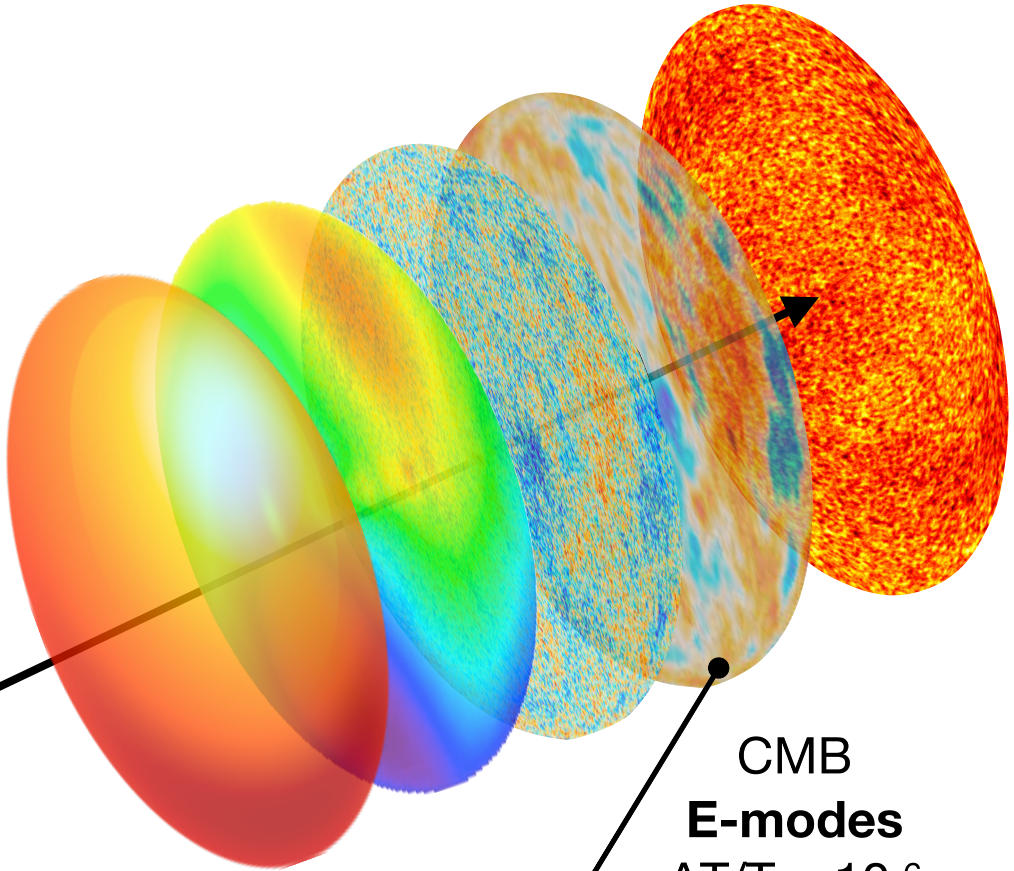
performance by ~ 2035



σ(r=0) ~ 0.0005 (90% delensing)



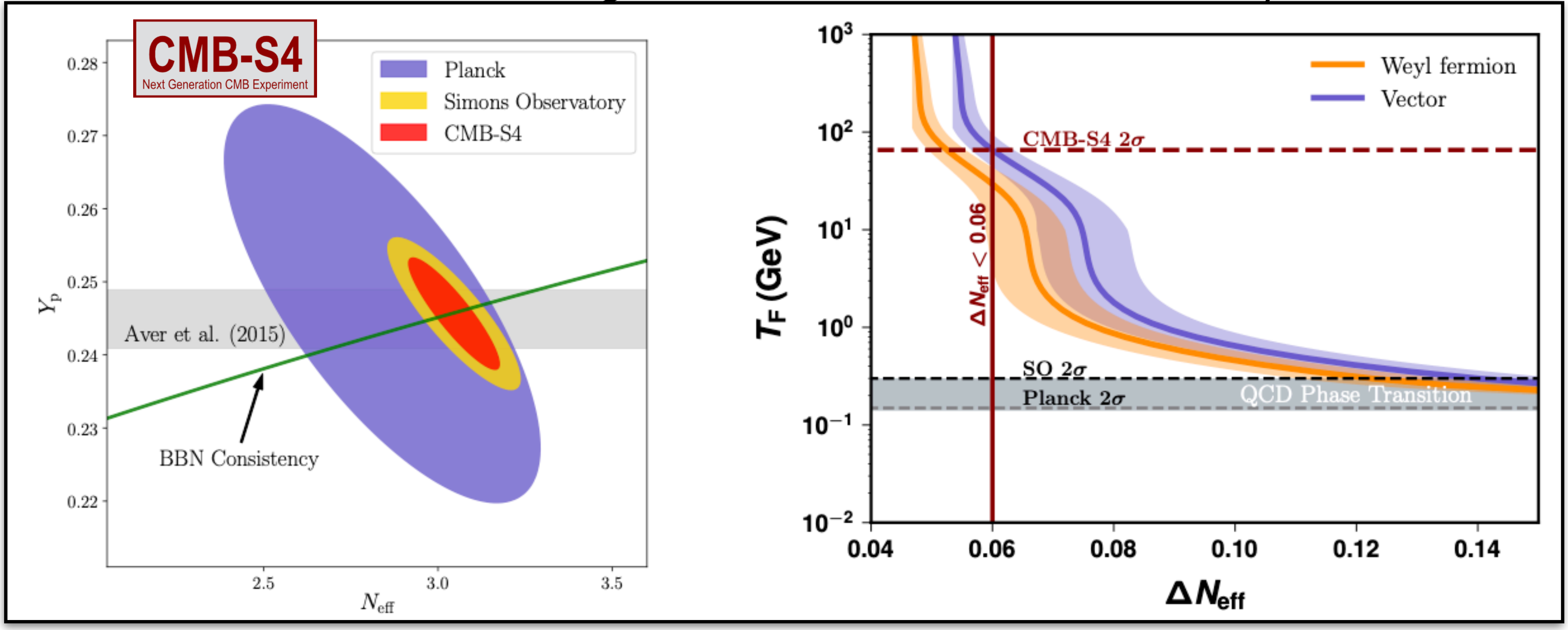
Josquin Errard (APC/CNRS), colloquium@CEA, October 4th 2021

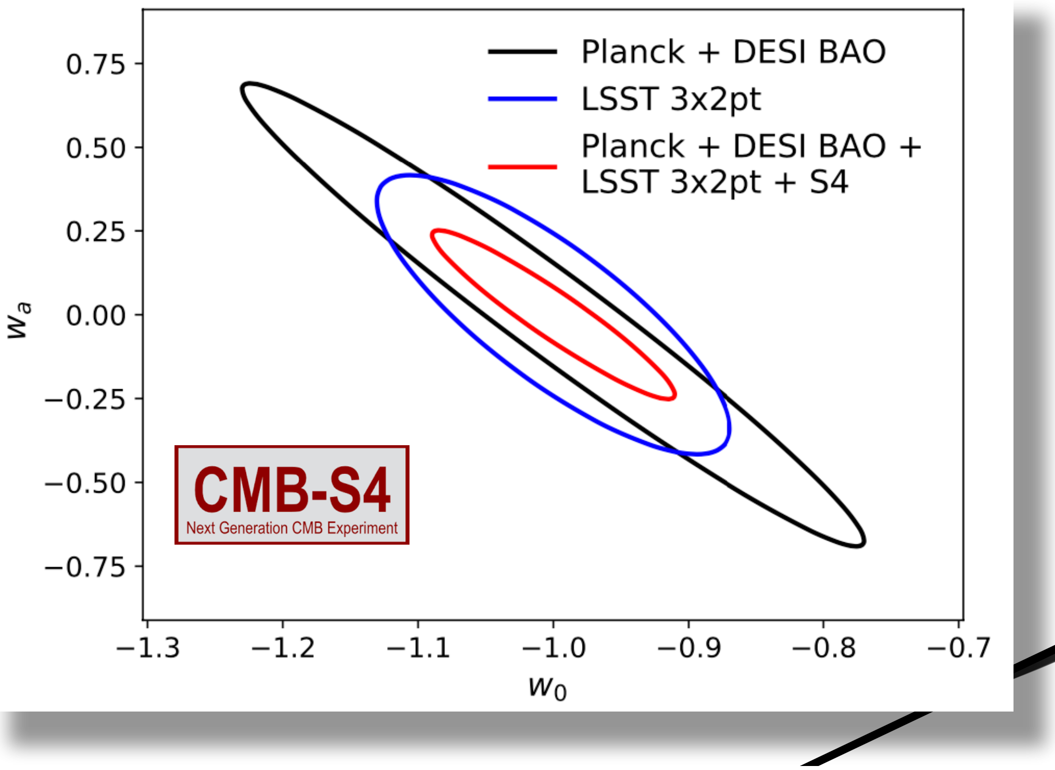


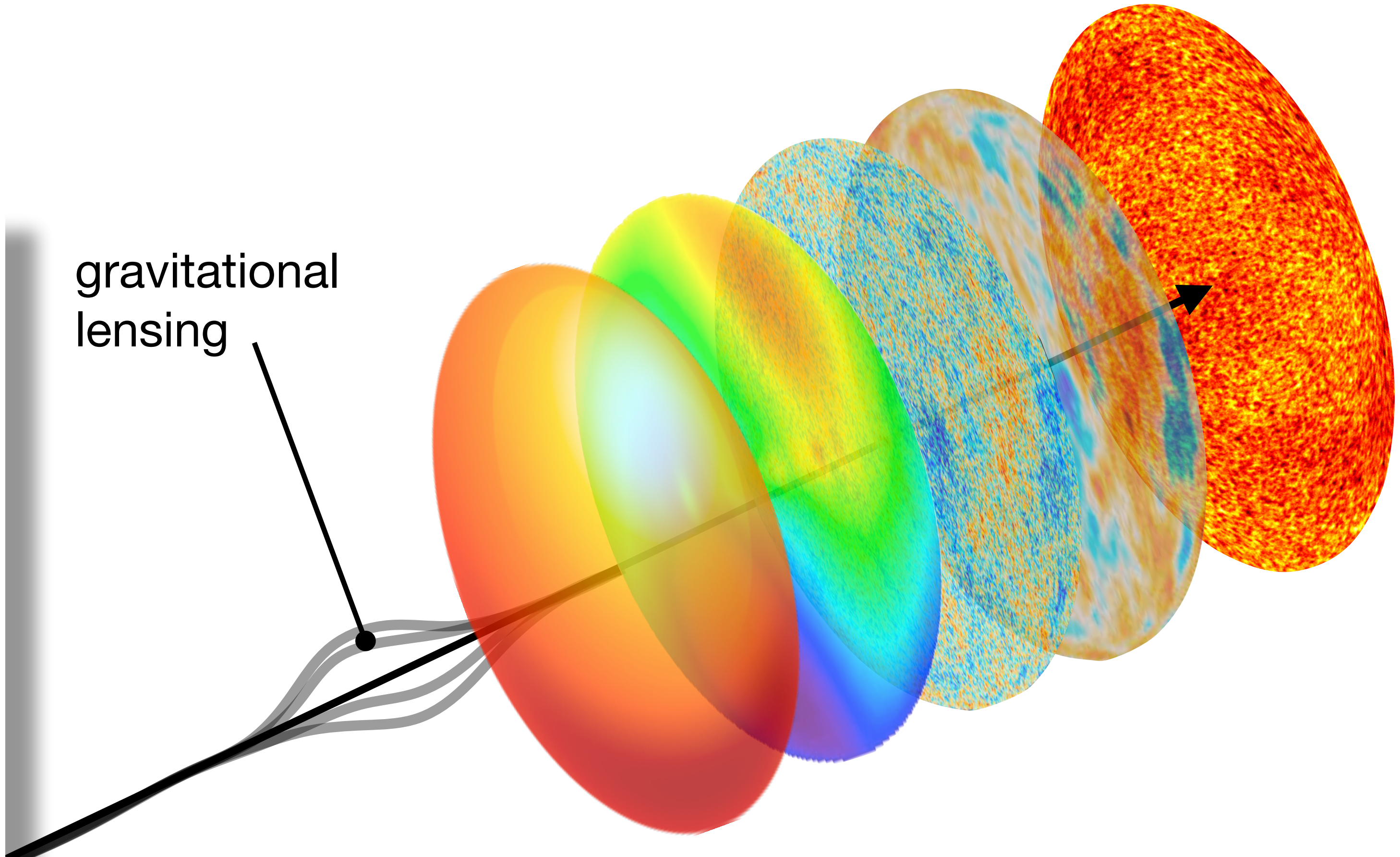
CMB

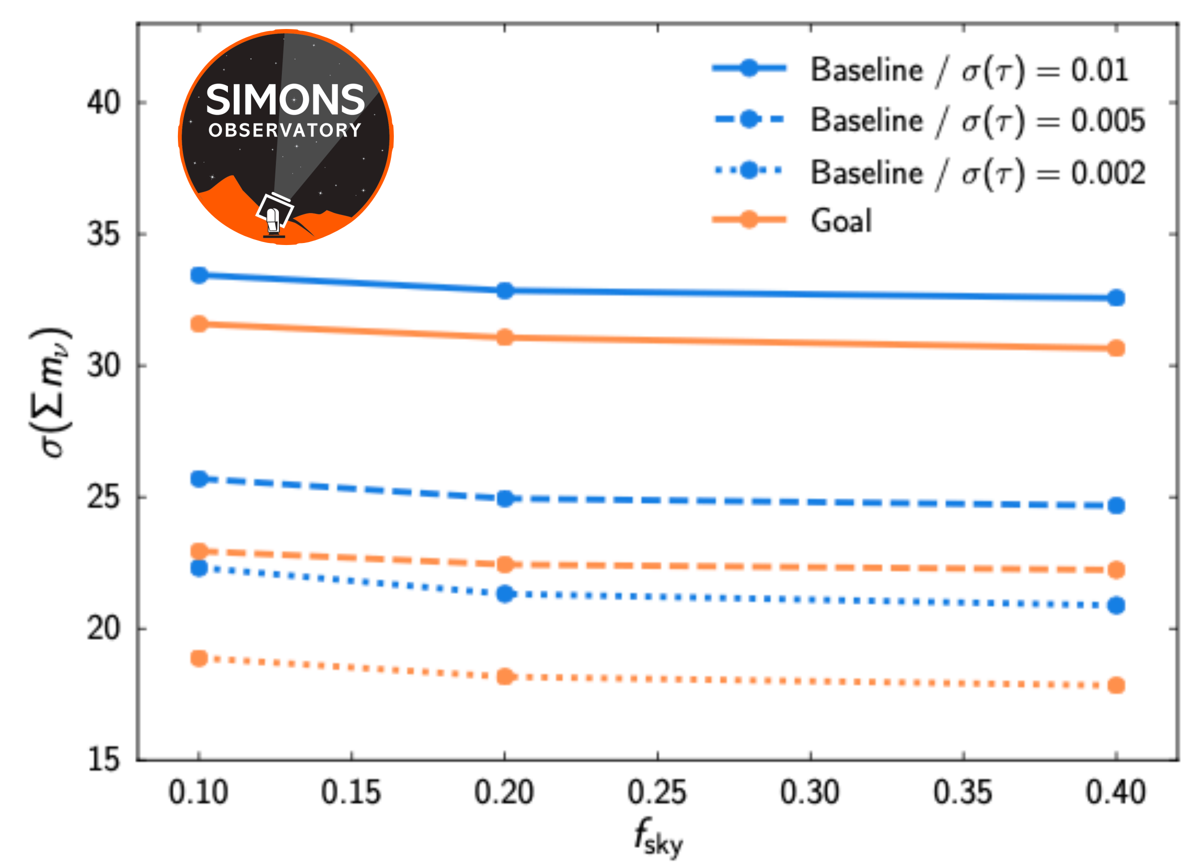
E-modes

$\Delta T/T \sim 10^{-6}$



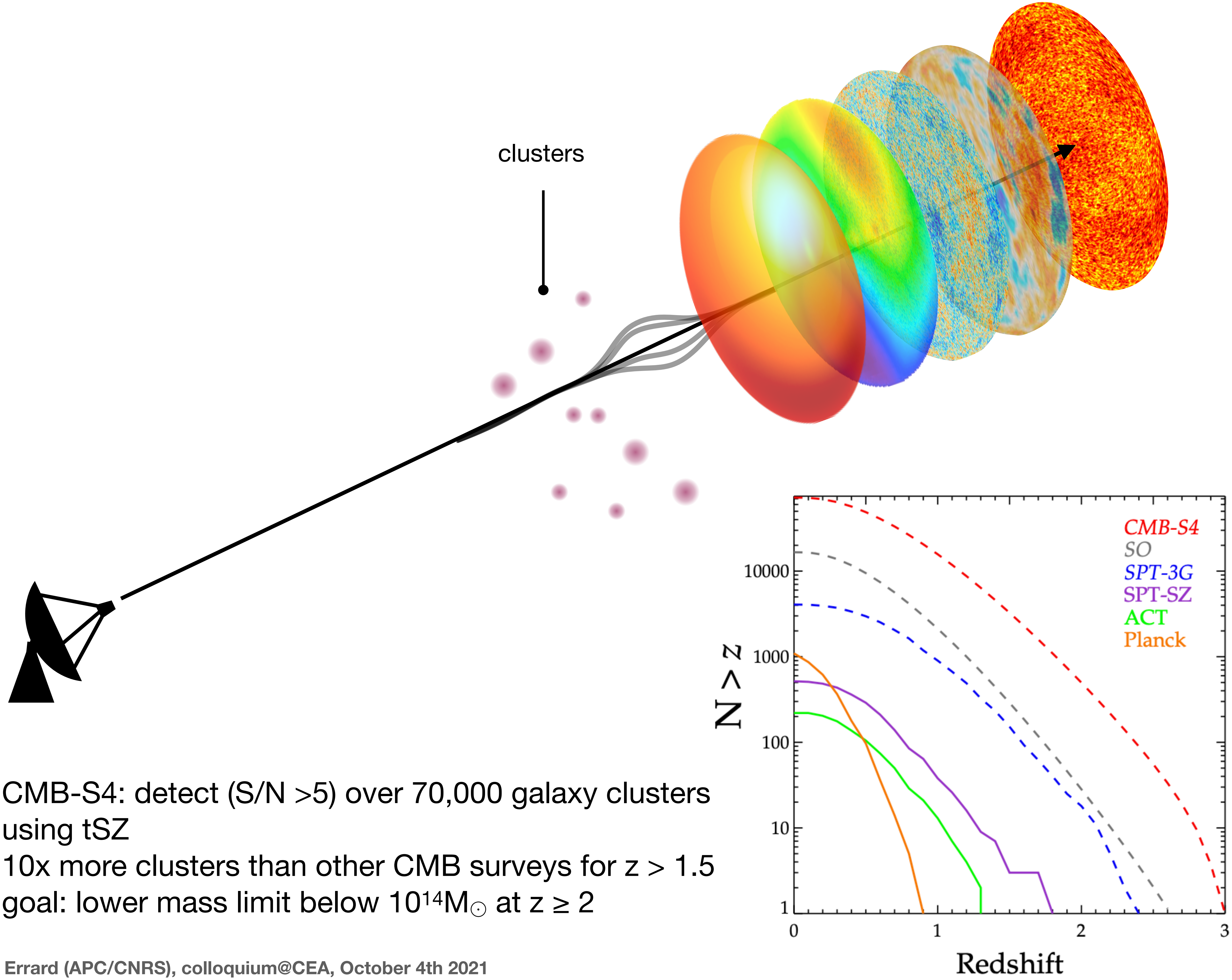






$$\sigma(\Sigma m_\nu) = 33\ \text{meV} \quad \text{SO Baseline} + \text{DESI-BAO}\,,$$
$$\sigma(\Sigma m_\nu) = 31\ \text{meV} \quad \text{SO Goal} + \text{DESI-BAO}\,,$$

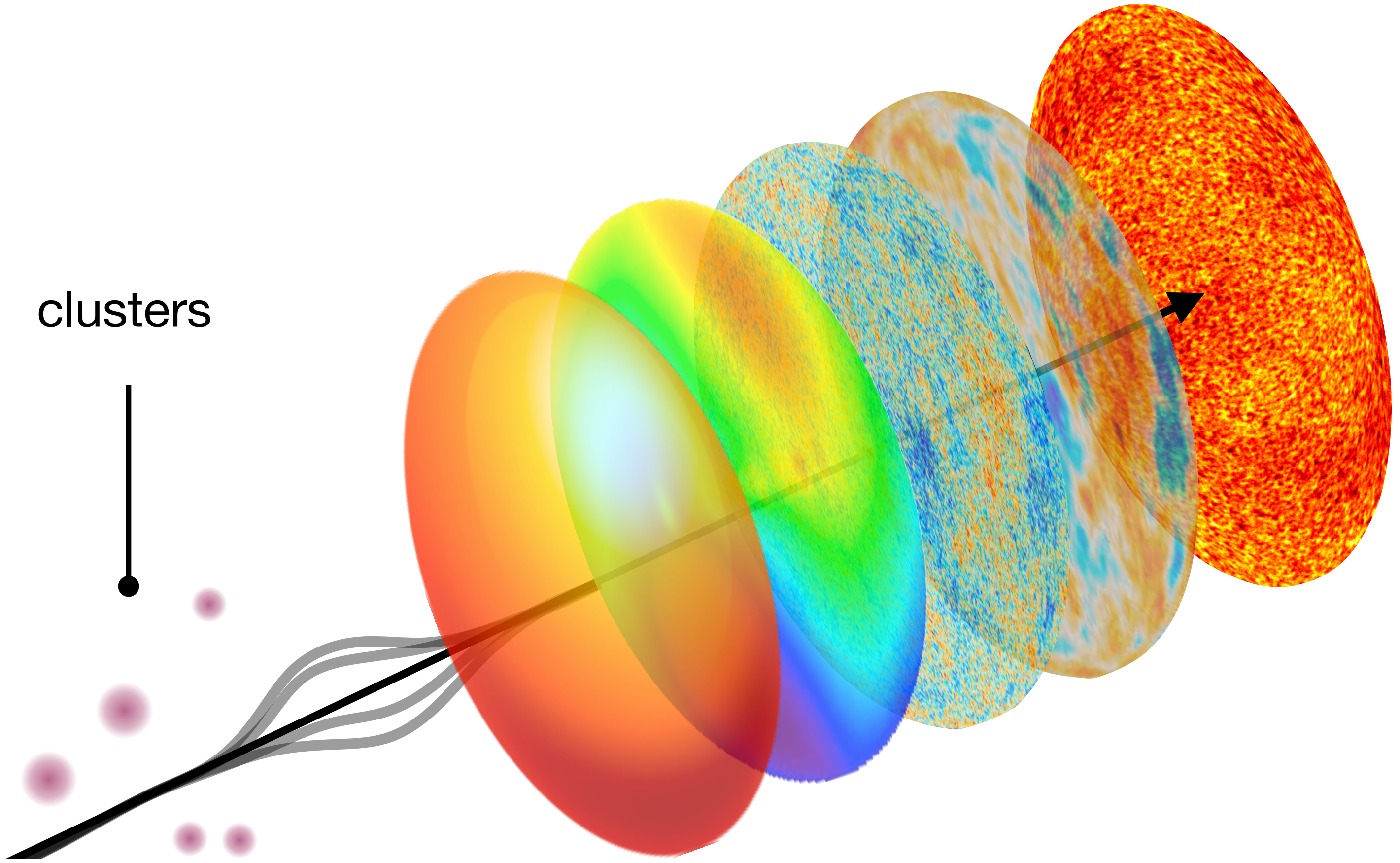
$$\sigma(\Sigma m_\nu) = 22\ \text{meV} \quad \text{SO Baseline} + \text{DESI-BAO} + \tau$$
$$\sigma(\Sigma m_\nu) = 17\ \text{meV} \quad \text{SO Goal} + \text{DESI-BAO} + \tau$$



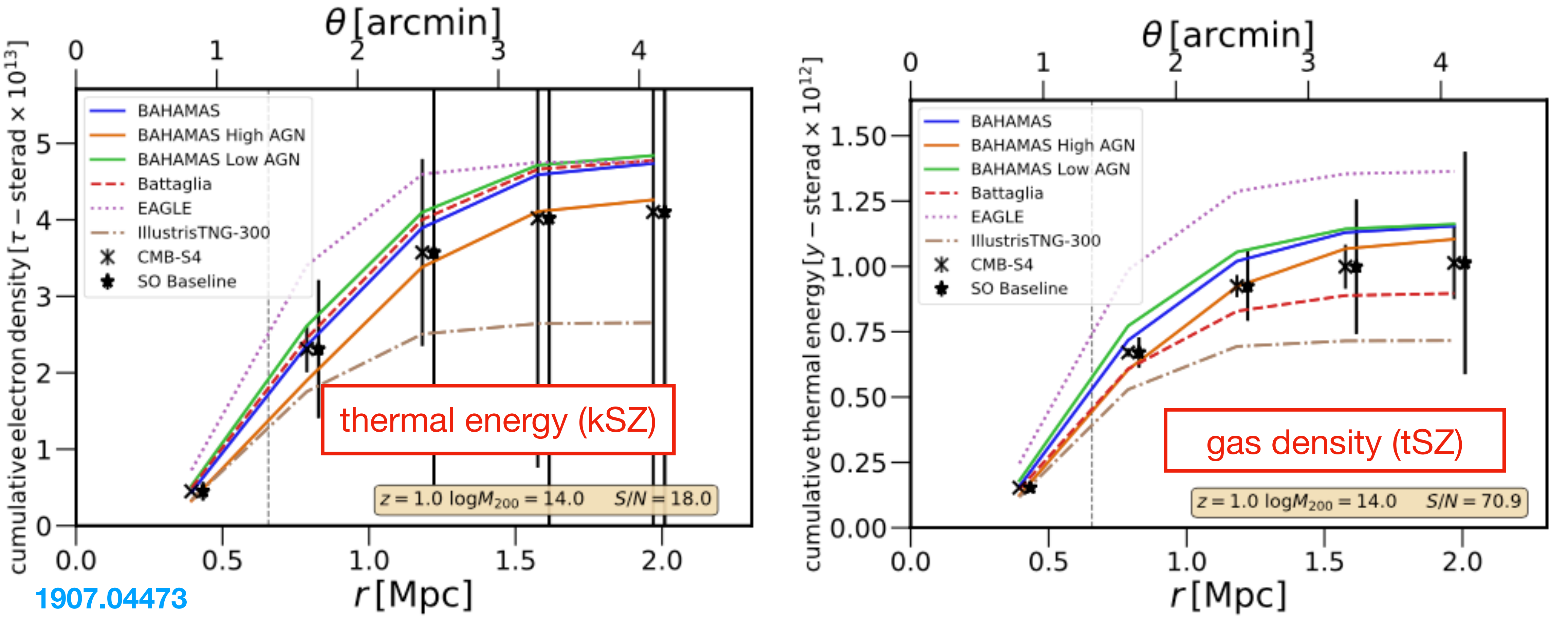
CMB-S4: detect (S/N >5) over 70,000 galaxy clusters using tSZ

10x more clusters than other CMB surveys for z > 1.5

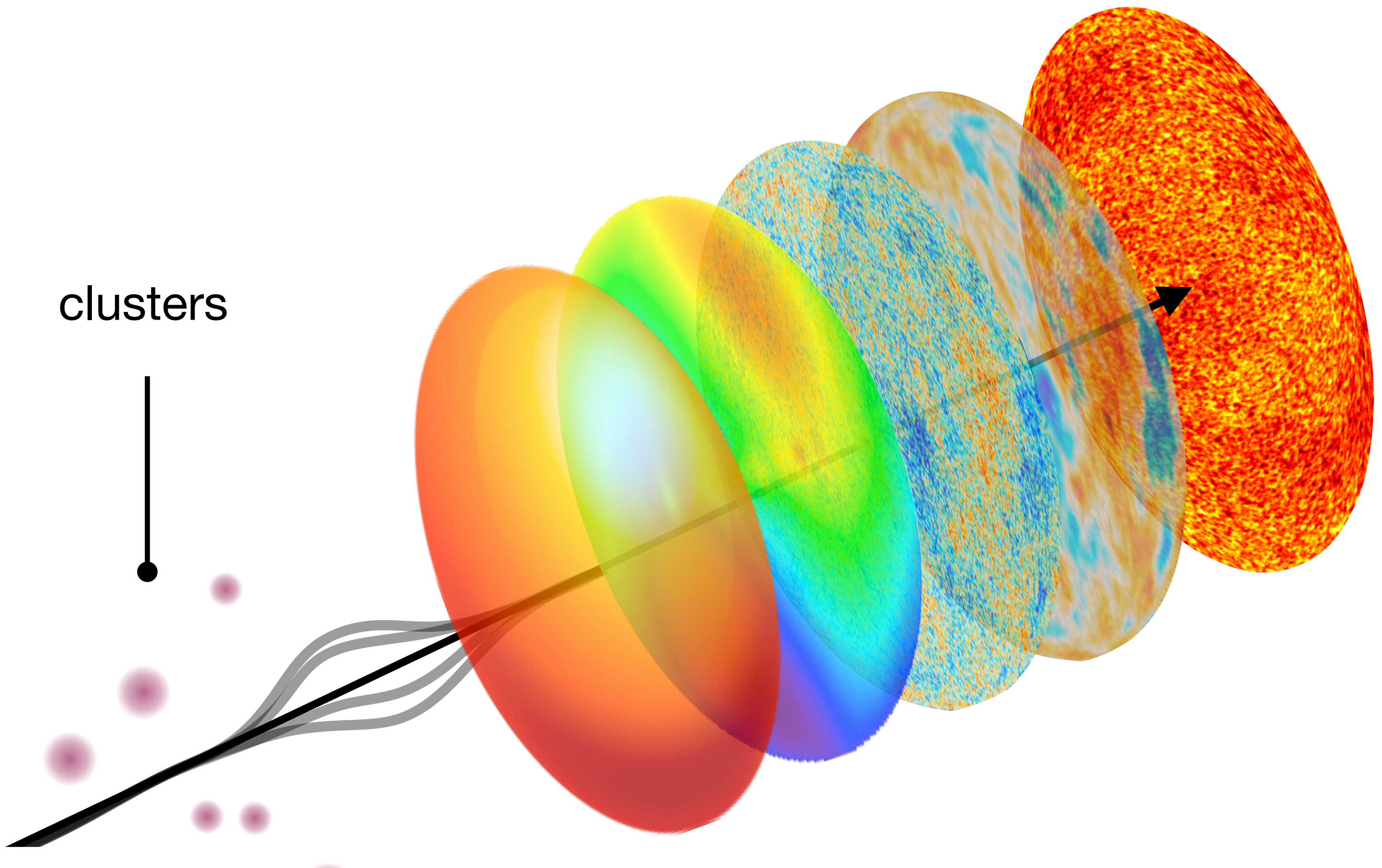
goal: lower mass limit below $10^{14} M_\odot$ at $z \geq 2$

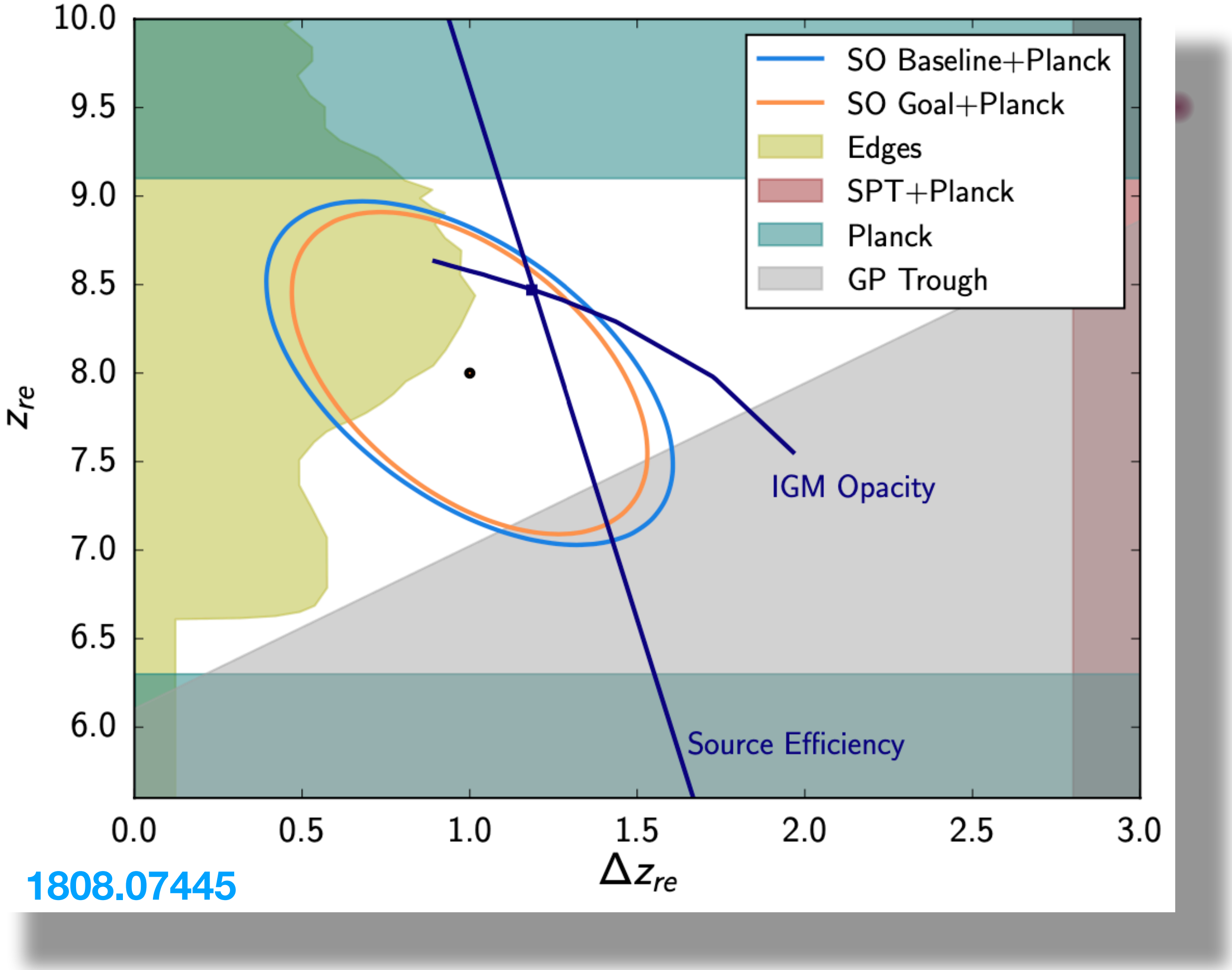


constrain/rule out feedback models ➔ better understanding of the small scale power spectrum + hydrostatic mass bias



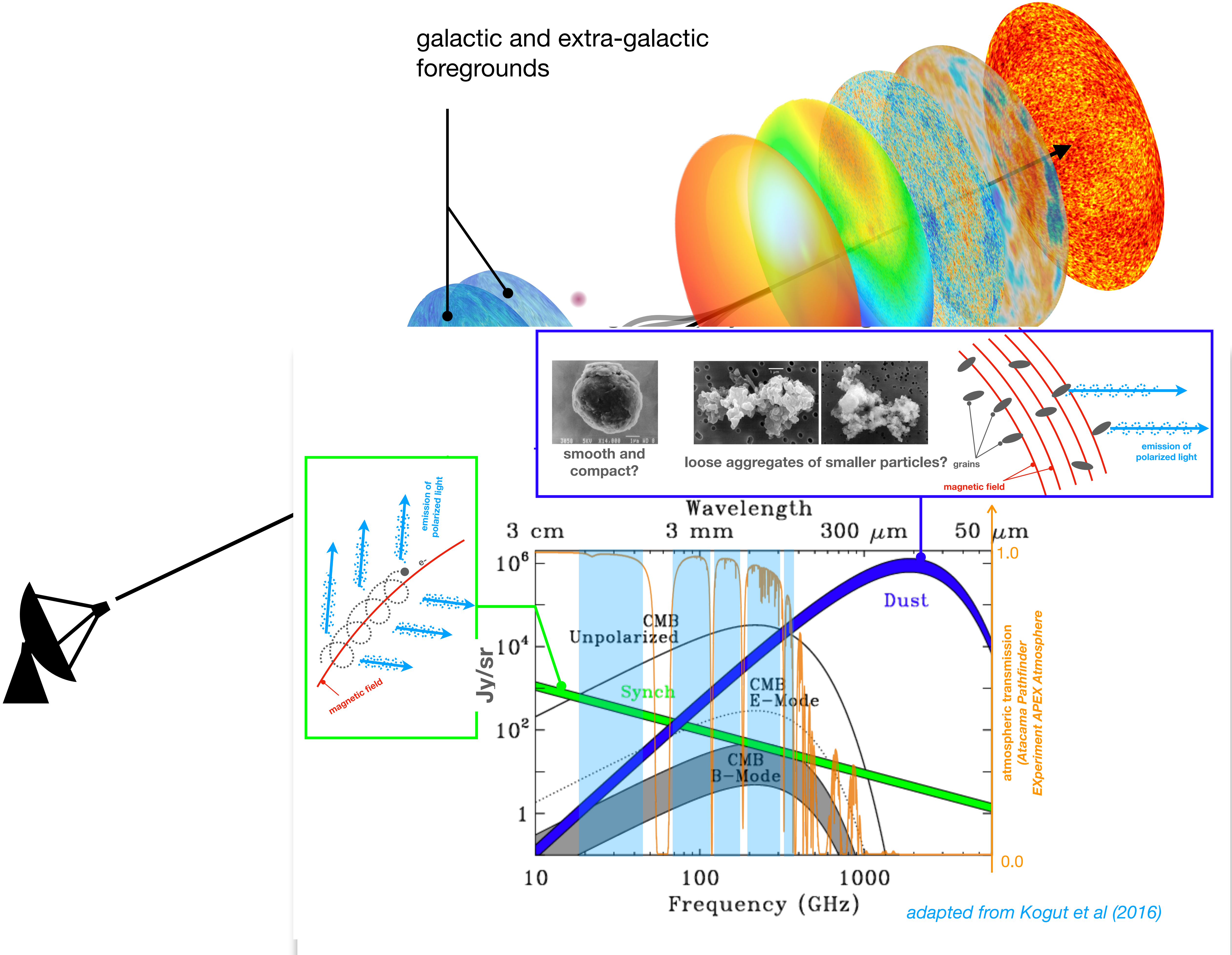
1907.04473


clusters

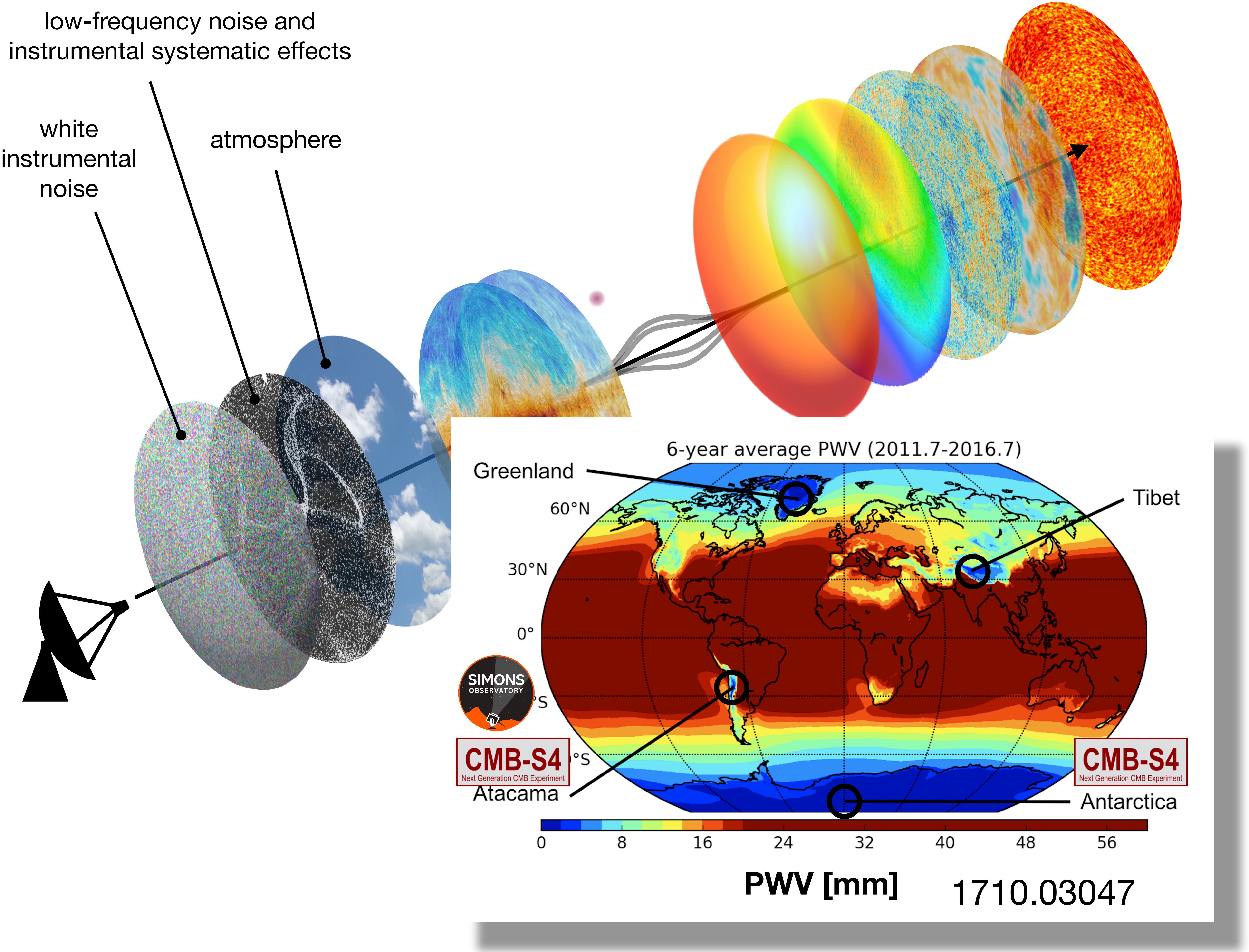

SO Baseline+Planck
SO Goal+Planck
Edges
SPT+Planck
Planck
GP Trough
IGM Opacity
Source Efficiency
z_{re}
Δz_{re}
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0

1808.07445

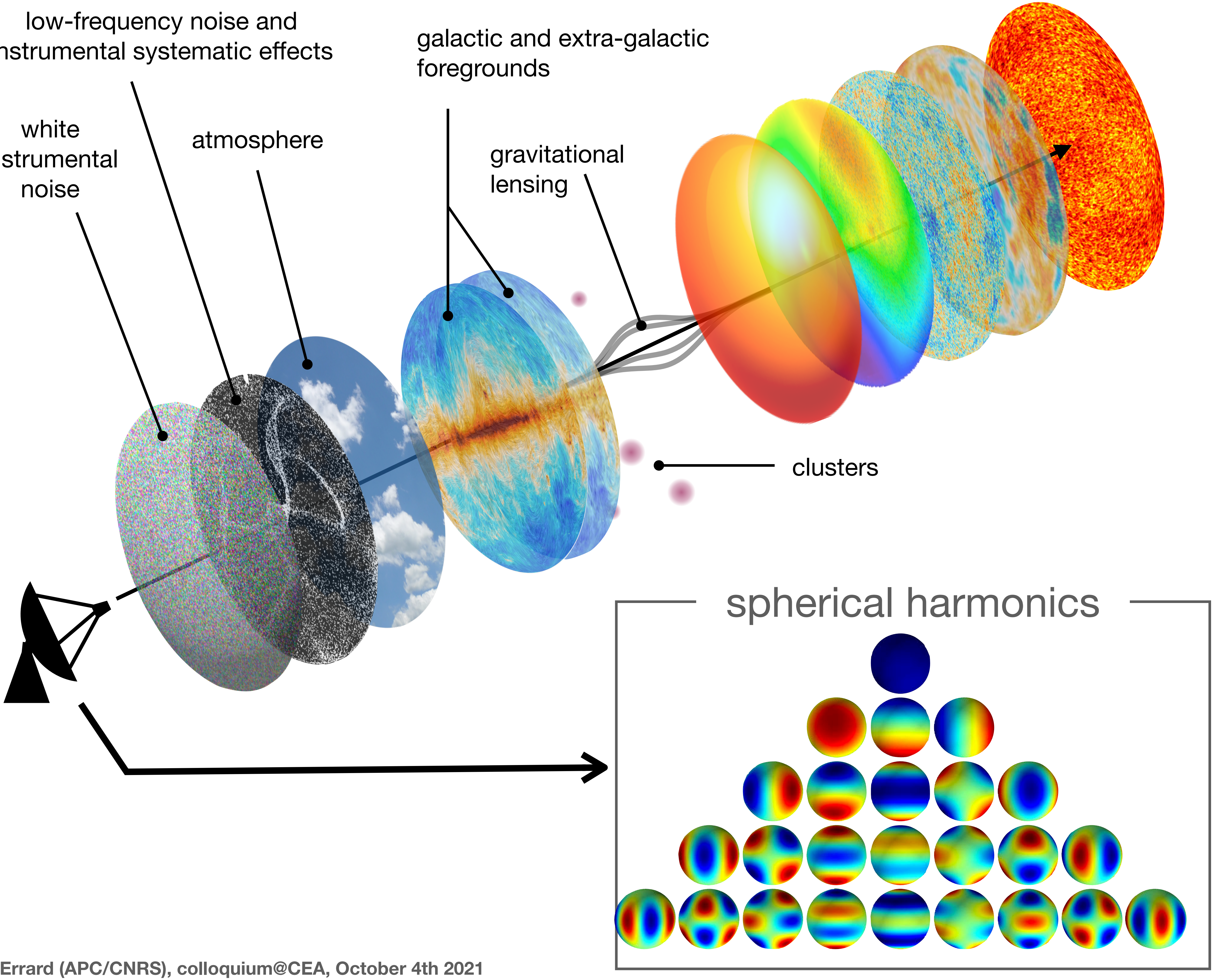
galactic and extra-galactic foregrounds



adapted from Kogut et al (2016)


low-frequency noise and instrumental systematic effects
white instrumental noise
atmosphere
6-year average PWV (2011.7-2016.7)
Greenland
Tibet
60°N
30°N
0°
°S
°S
Atacama
Antarctica
SIMONS OBSERVATORY
CMB-S4 Next Generation CMB Experiment
CMB-S4 Next Generation CMB Experiment
0
8
16
24
32
40
48
56
PWV [mm]

1710.03047



low-frequency noise and instrumental systematic effects

white instrumental noise

atmosphere

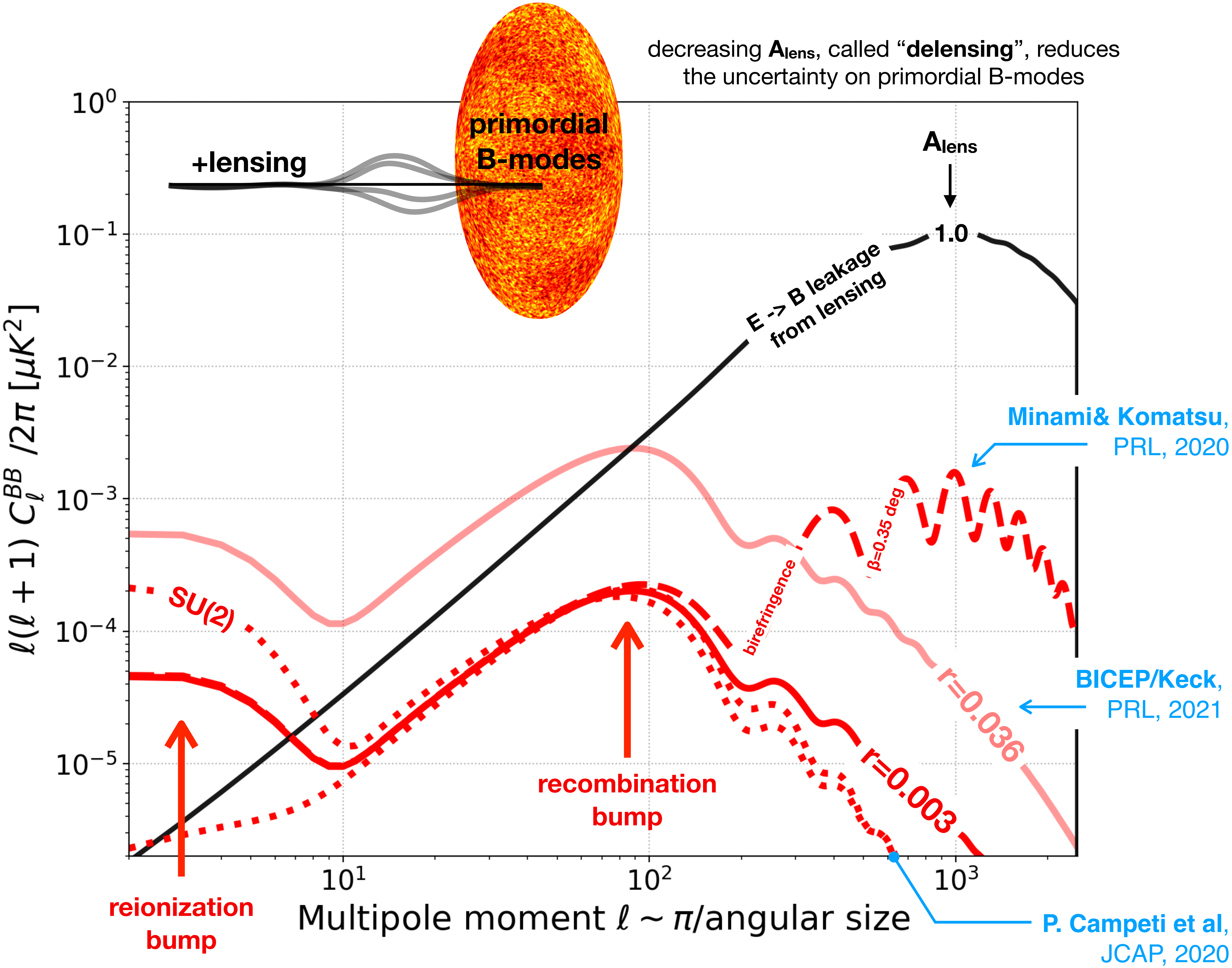
galactic and extra-galactic foregrounds

gravitational lensing

clusters

spherical harmonics

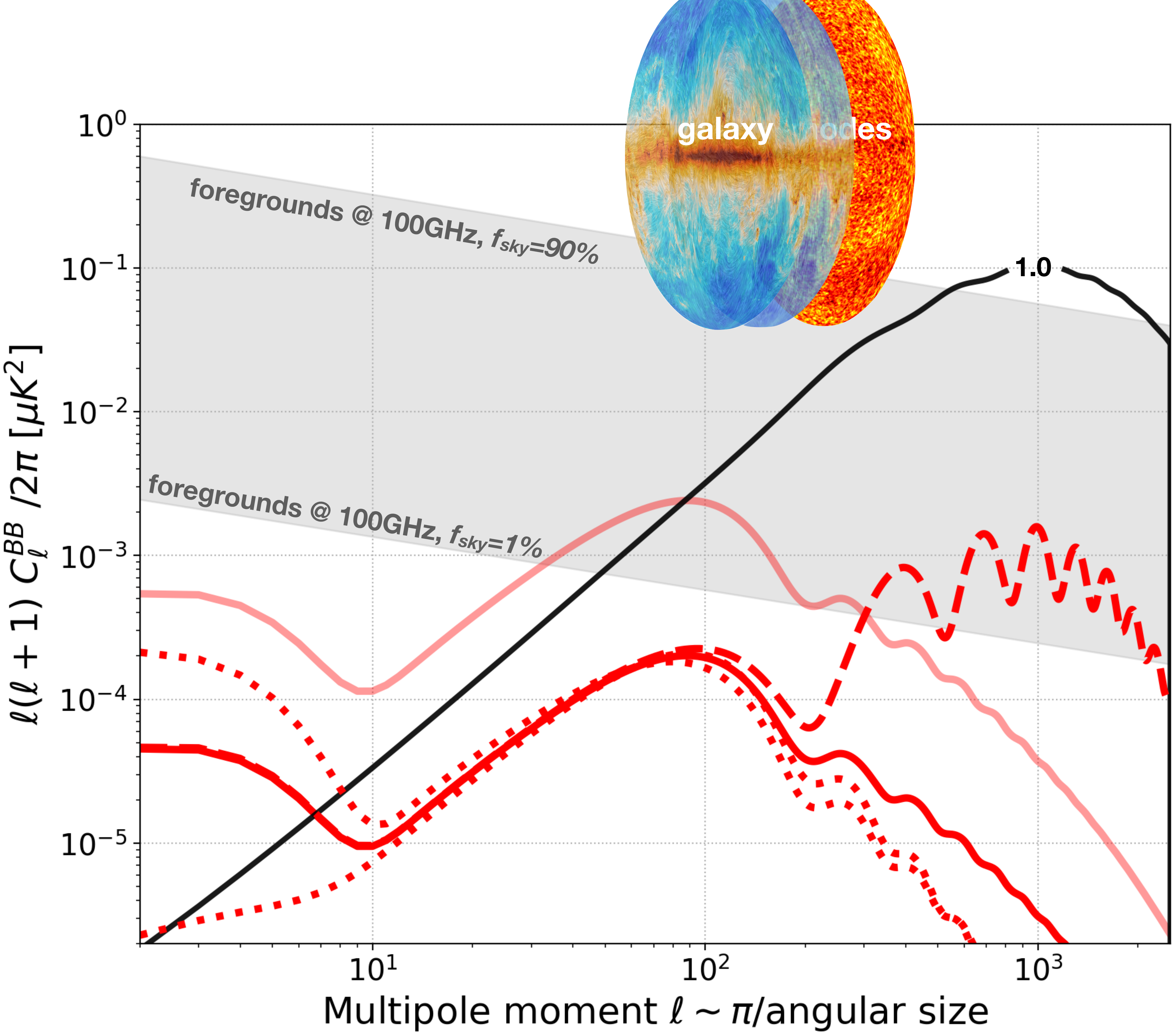
decreasing **A_{lens}**, called “**delensing**”, reduces the uncertainty on primordial B-modes

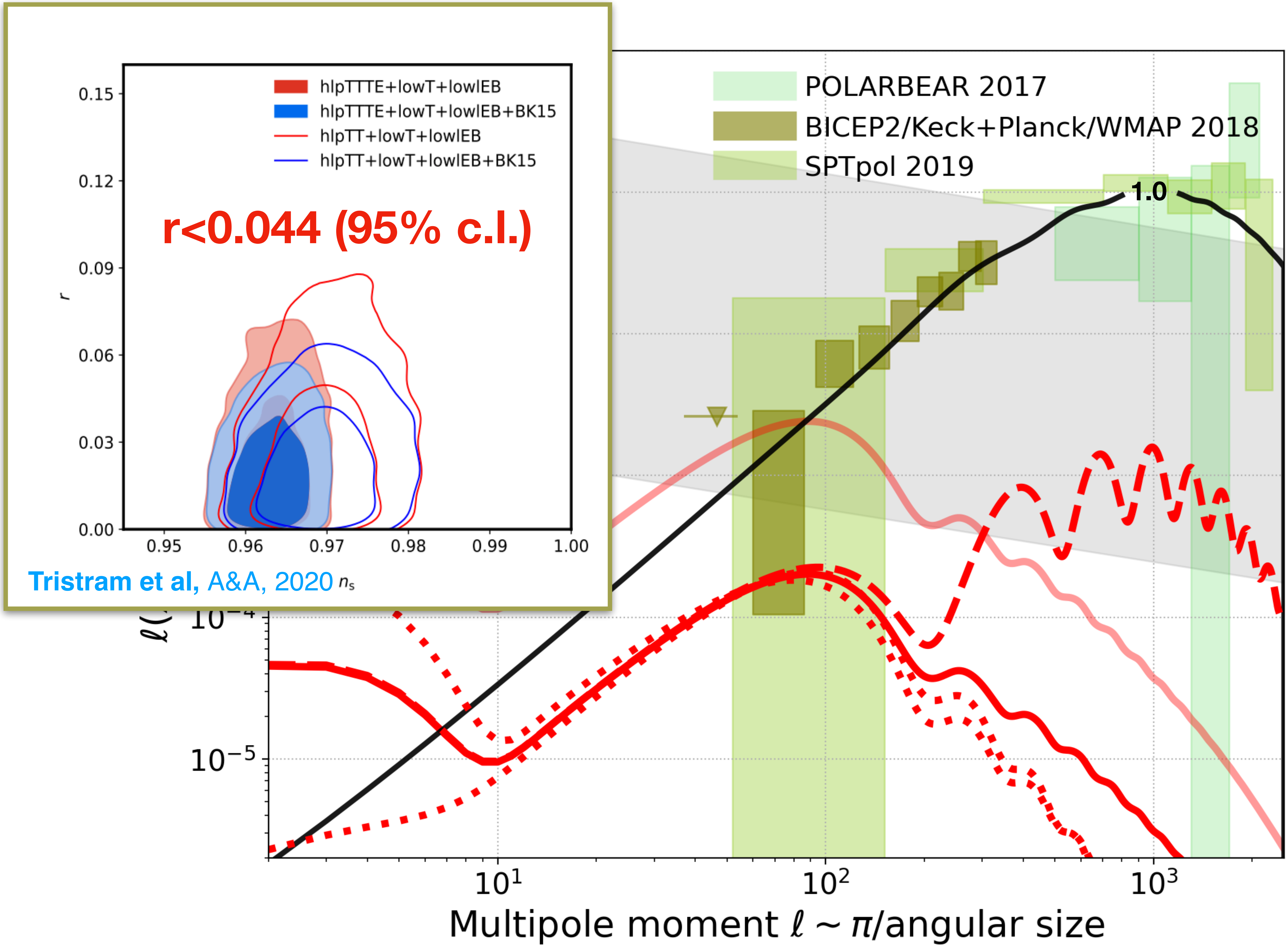


Minami& Komatsu, PRL, 2020

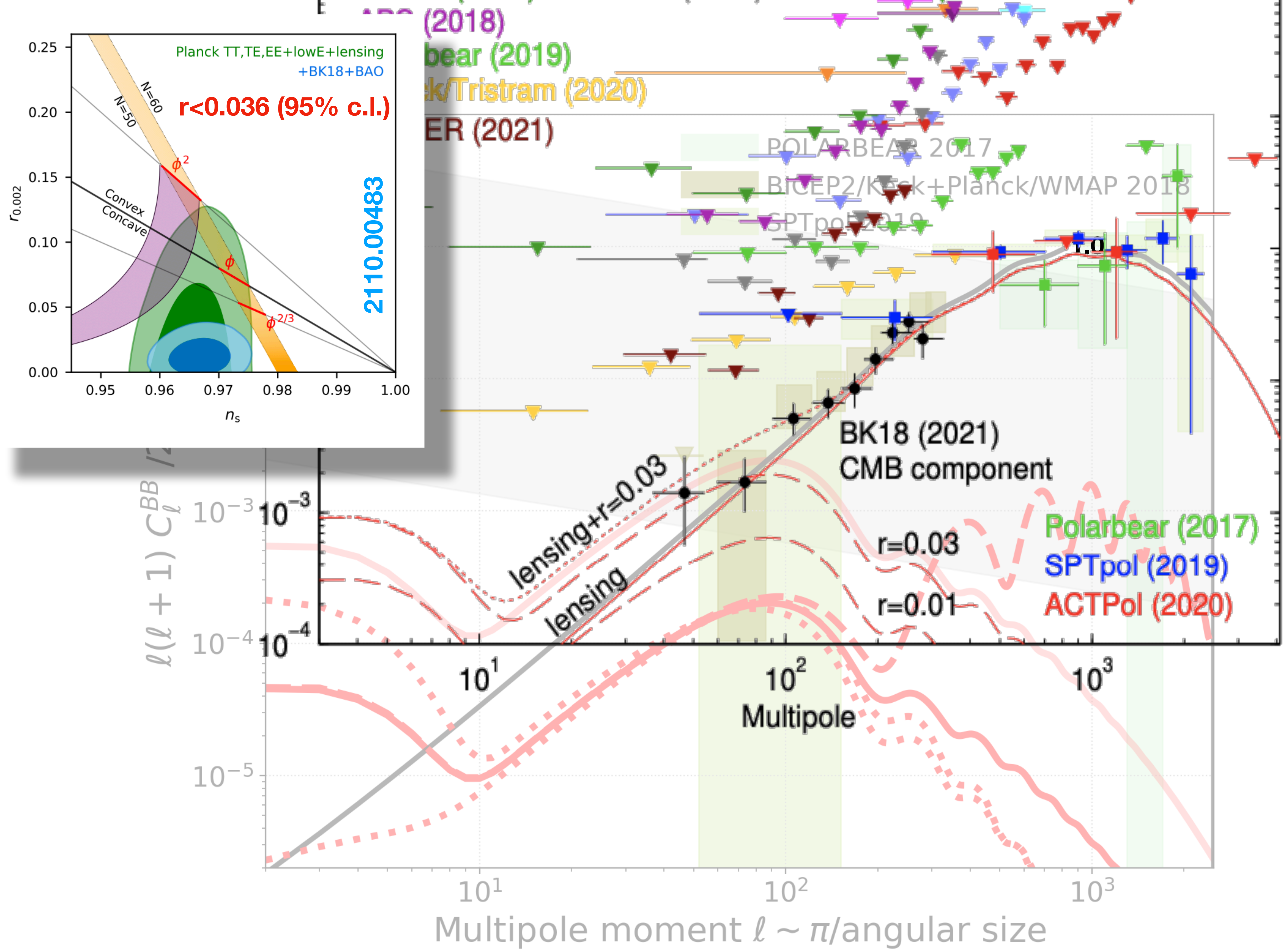
BICEP/Keck, PRL, 2021

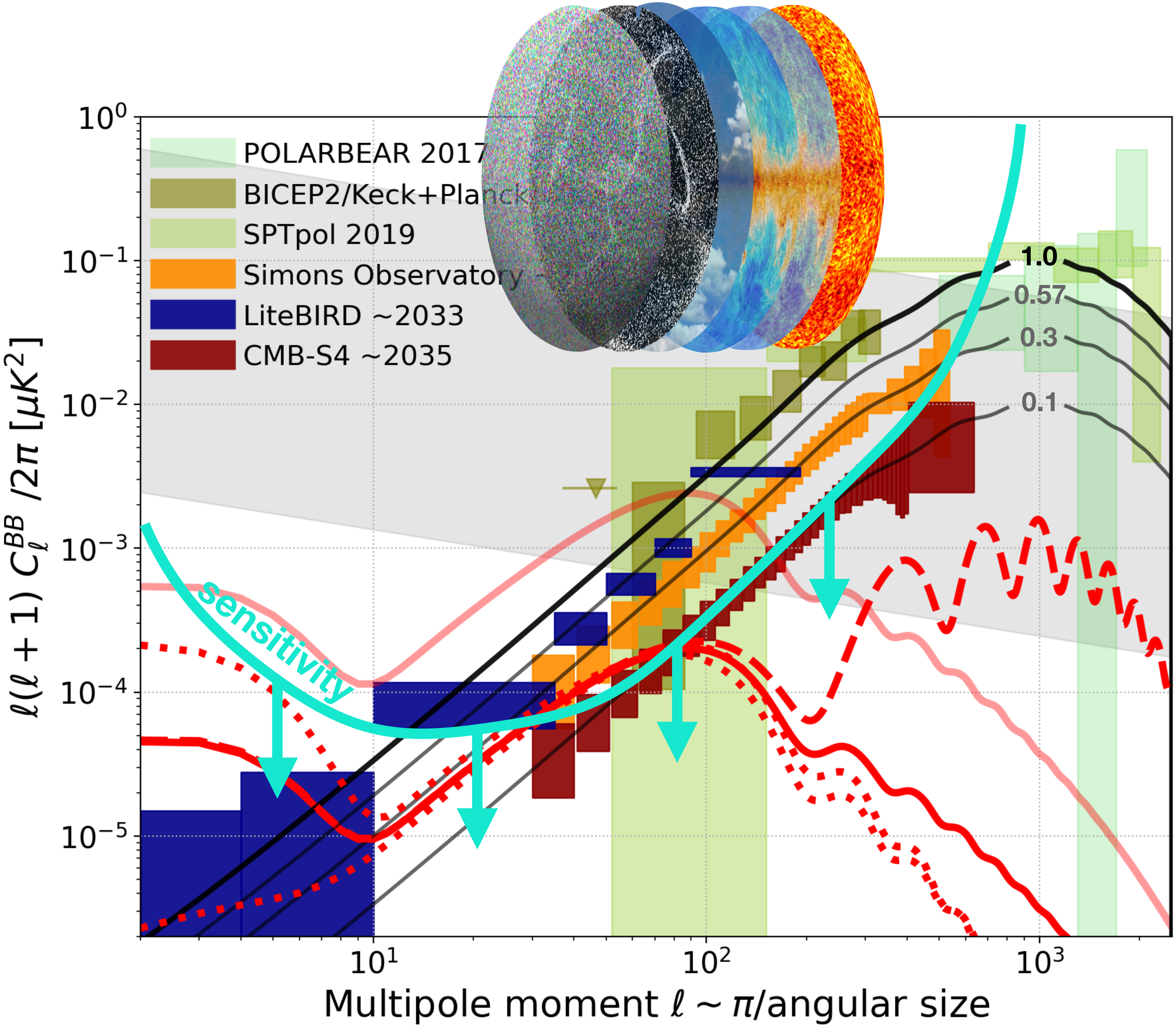
P. Campeti et al, JCAP, 2020


galaxy
odes
foregrounds @ 100GHz, f_{sky}=90%
foregrounds @ 100GHz, f_{sky}=1%
1.0
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$\ell(\ell+1)\ C_\ell^{BB}\ /2\pi\ [\mu K^2]$
10^{1}
10^{2}
10^{3}
Multipole moment $\ell \sim \pi$/angular size



Tristram et al, A&A, 2020

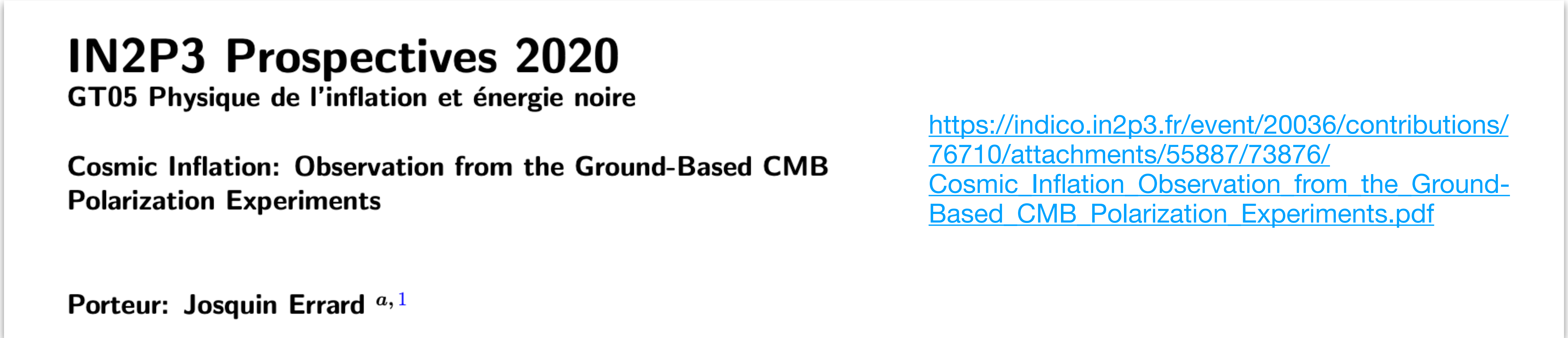

Planck TT,TE,EE+lowE+lensing
+BK18+BAO
r<0.036 (95% c.l.)
2110.00483
N=60
N=50
ϕ^2
ϕ
$\phi^{2/3}$
Convex
Concave
$r_{0.002}$
n_s
0.25
0.20
0.15
0.10
0.05
0.00
0.95
0.96
0.97
0.98
0.99
1.00
(2018)
bear (2019)
k/Tristram (2020)
ER (2021)
POLARBEAR 2017
BICEP2/Keck+Planck/WMAP 2018
SPTpol 2019
BK18 (2021)
CMB component
lensing+r=0.03
lensing
r=0.03
r=0.01
Polarbear (2017)
SPTpol (2019)
ACTPol (2020)
10^{-3}
10^{-4}
10^{-5}
10^1
10^2
10^3
Multipole
$\ell(\ell+1)\,C_\ell^{BB}\,/2$
Multipole moment $\ell \sim \pi$/angular size


POLARBEAR 2017
BICEP2/Keck+Planck
SPTpol 2019
Simons Observatory ~
LiteBIRD ~2033
CMB-S4 ~2035
1.0
0.57
0.3
0.1
sensitivity
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^1
10^2
10^3
$\ell(\ell+1)\ C_\ell^{BB}\ /2\pi\ [\mu K^2]$
Multipole moment $\ell \sim \pi$/angular size

Future observations of the primordial, polarized Cosmic Microwave Background

expected science and challenges

1. Introduction: a brief overview of challenges
2. Some hardware and software mitigations techniques to reach primordial CMB B-modes
3. The Simons Observatory and LiteBIRD



IN2P3 Prospectives 2020

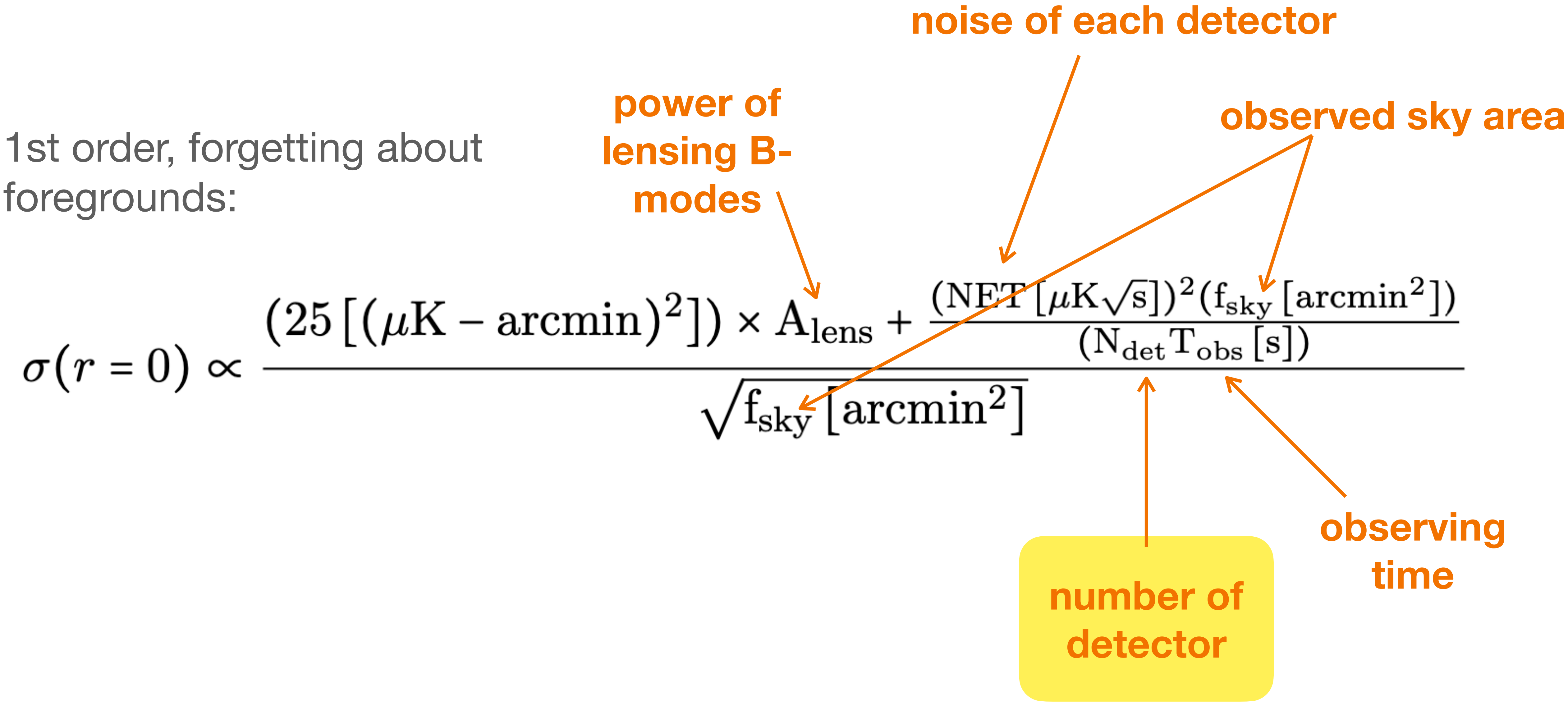
GT05 Physique de l'inflation et énergie noire

Cosmic Inflation: Observation from the Ground-Based CMB Polarization Experiments

Porteur: Josquin Errard [a,1]

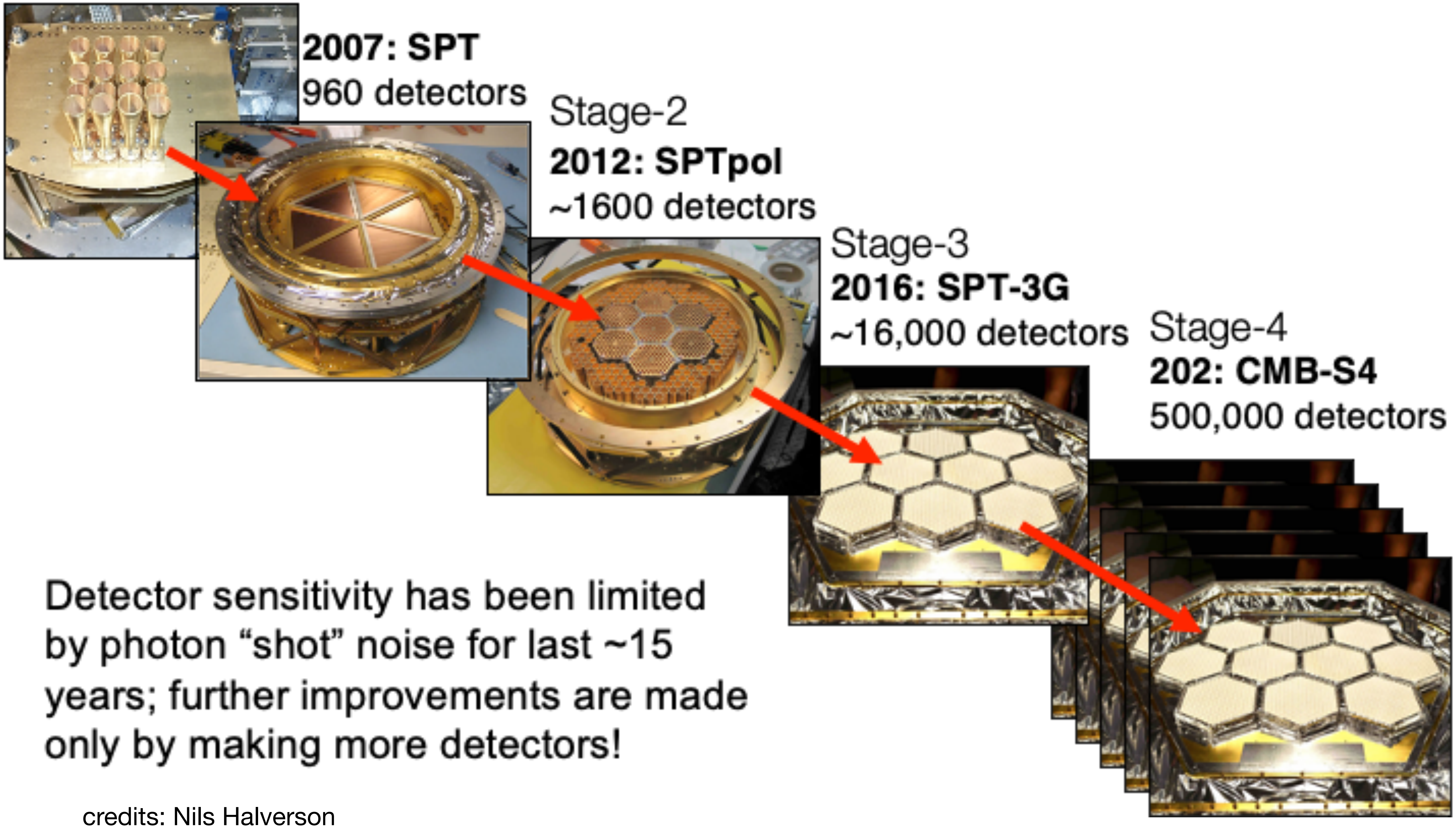
https://indico.in2p3.fr/event/20036/contributions/76710/attachments/55887/73876/Cosmic_Inflation_Observation_from_the_Ground-Based_CMB_Polarization_Experiments.pdf

1st order, forgetting about foregrounds:



$$\sigma(r=0) \propto \frac{(25\,[(\mu\mathrm{K} - \mathrm{arcmin})^2]) \times \mathrm{A}_{\mathrm{lens}} + \frac{(\mathrm{NET}\,[\mu\mathrm{K}\sqrt{\mathrm{s}}])^2 (\mathrm{f}_{\mathrm{sky}}\,[\mathrm{arcmin}^2])}{(\mathrm{N}_{\mathrm{det}}\mathrm{T}_{\mathrm{obs}}\,[\mathrm{s}])}}{\sqrt{\mathrm{f}_{\mathrm{sky}}\,[\mathrm{arcmin}^2]}}$$

improving the sensitivity of CMB experiments: number of detectors



2001: ACBAR
16 detectors

2007: SPT
960 detectors

Stage-2
2012: SPTpol
~1600 detectors

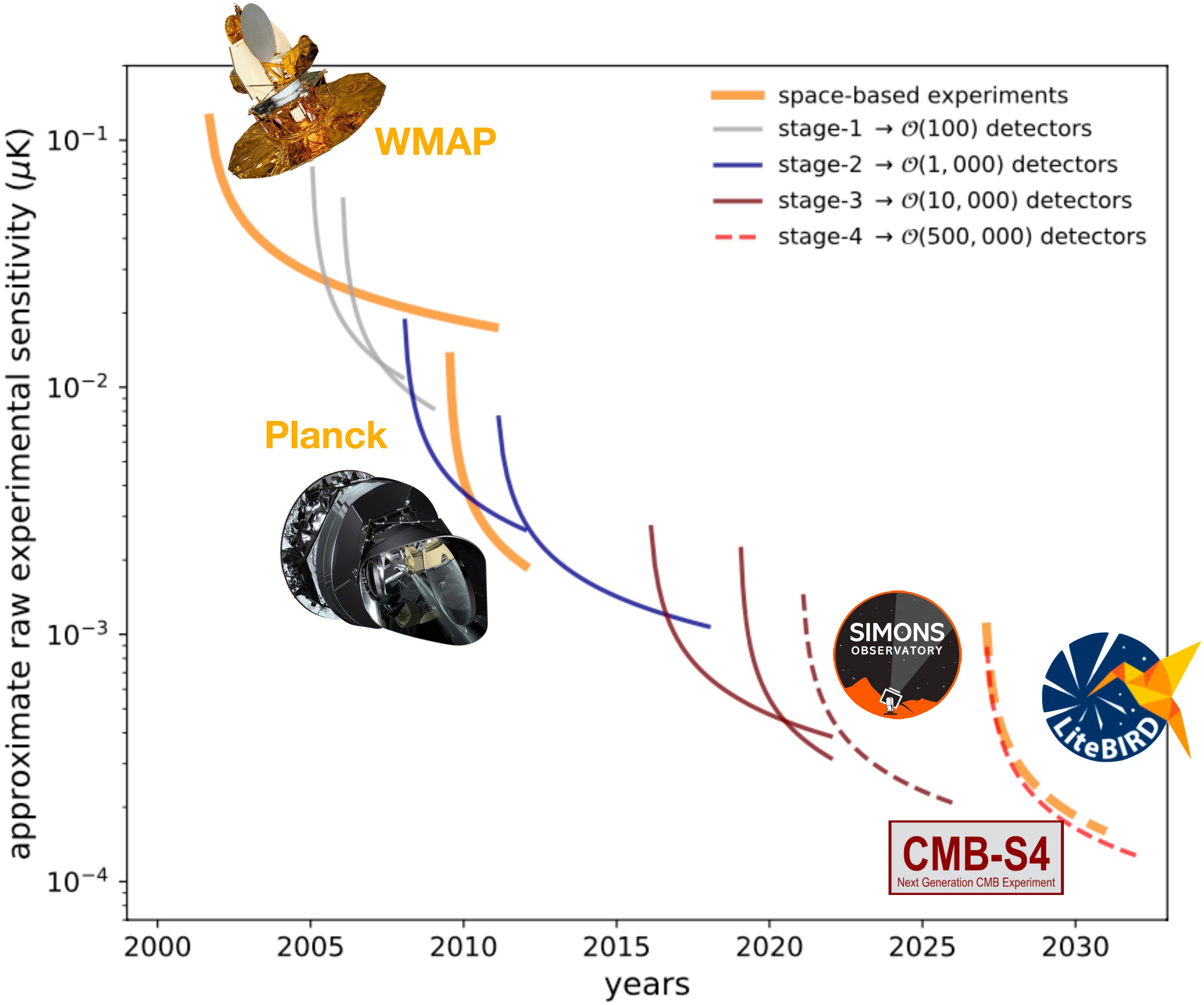
Stage-3
2016: SPT-3G
~16,000 detectors

Stage-4
202: CMB-S4
500,000 detectors

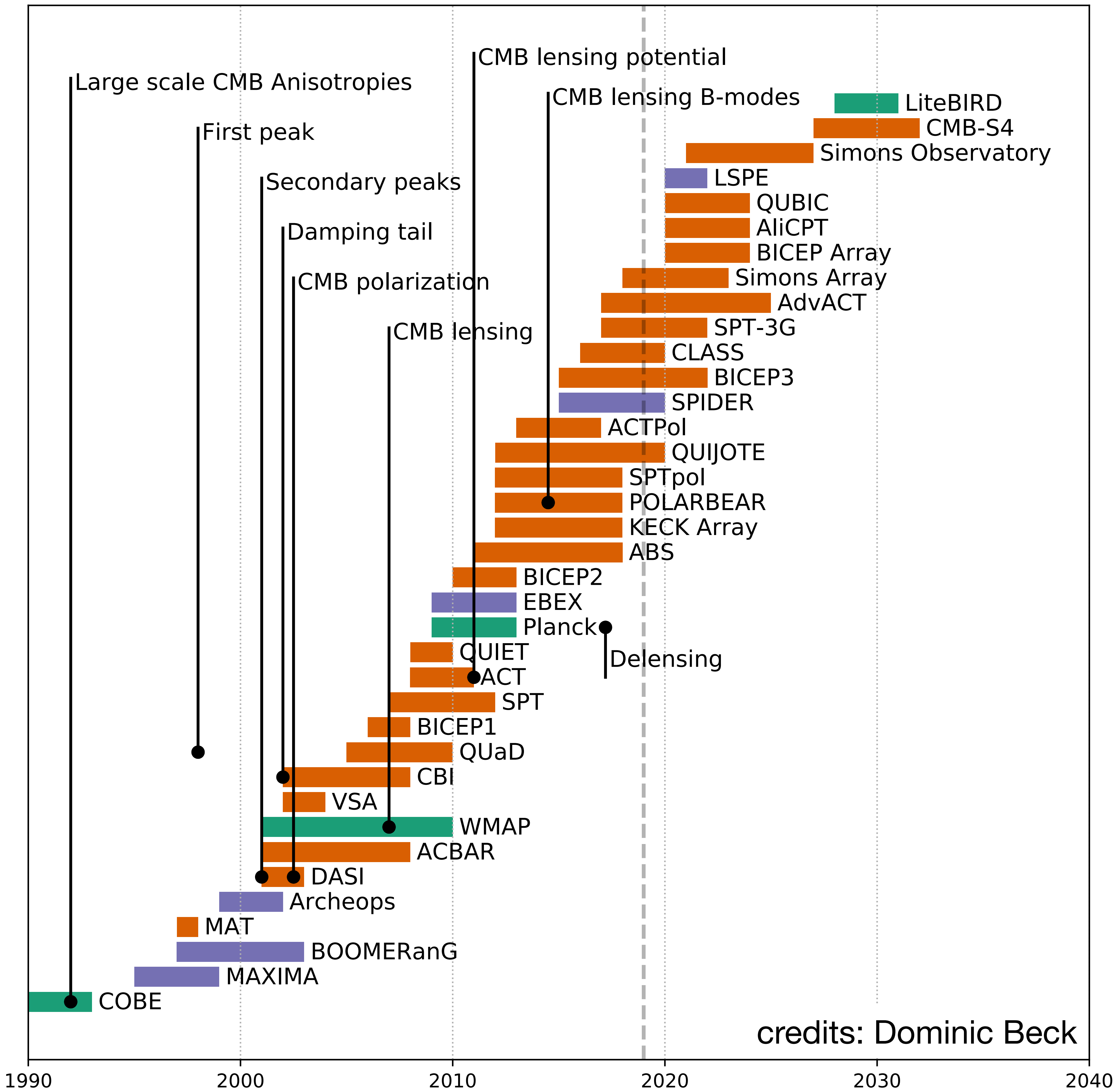
Detector sensitivity has been limited by photon "shot" noise for last ~15 years; further improvements are made only by making more detectors!

credits: Nils Halverson

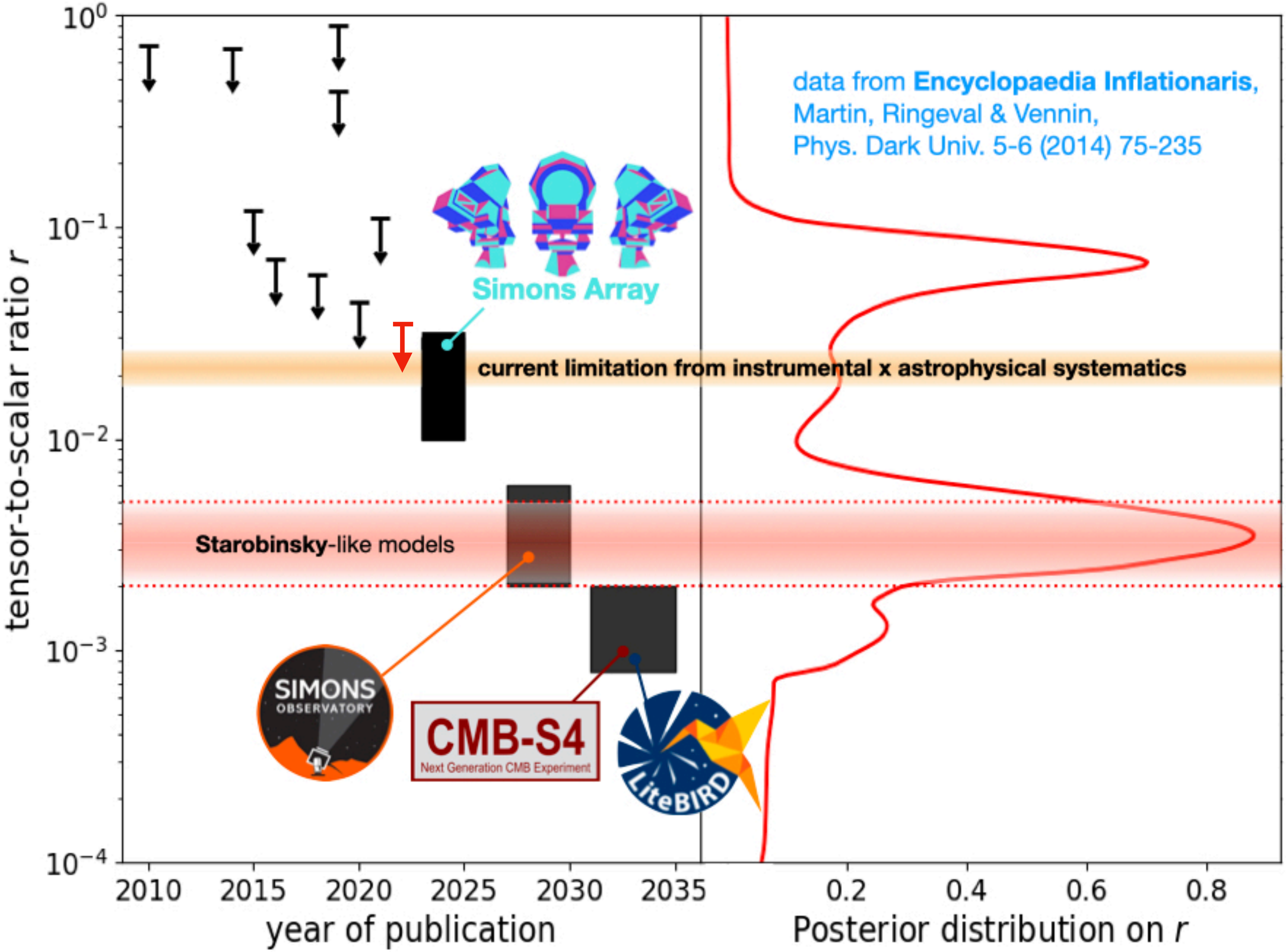
improving the sensitivity of CMB experiments: number of detectors



improving the sensitivity of CMB experiments: number of detectors

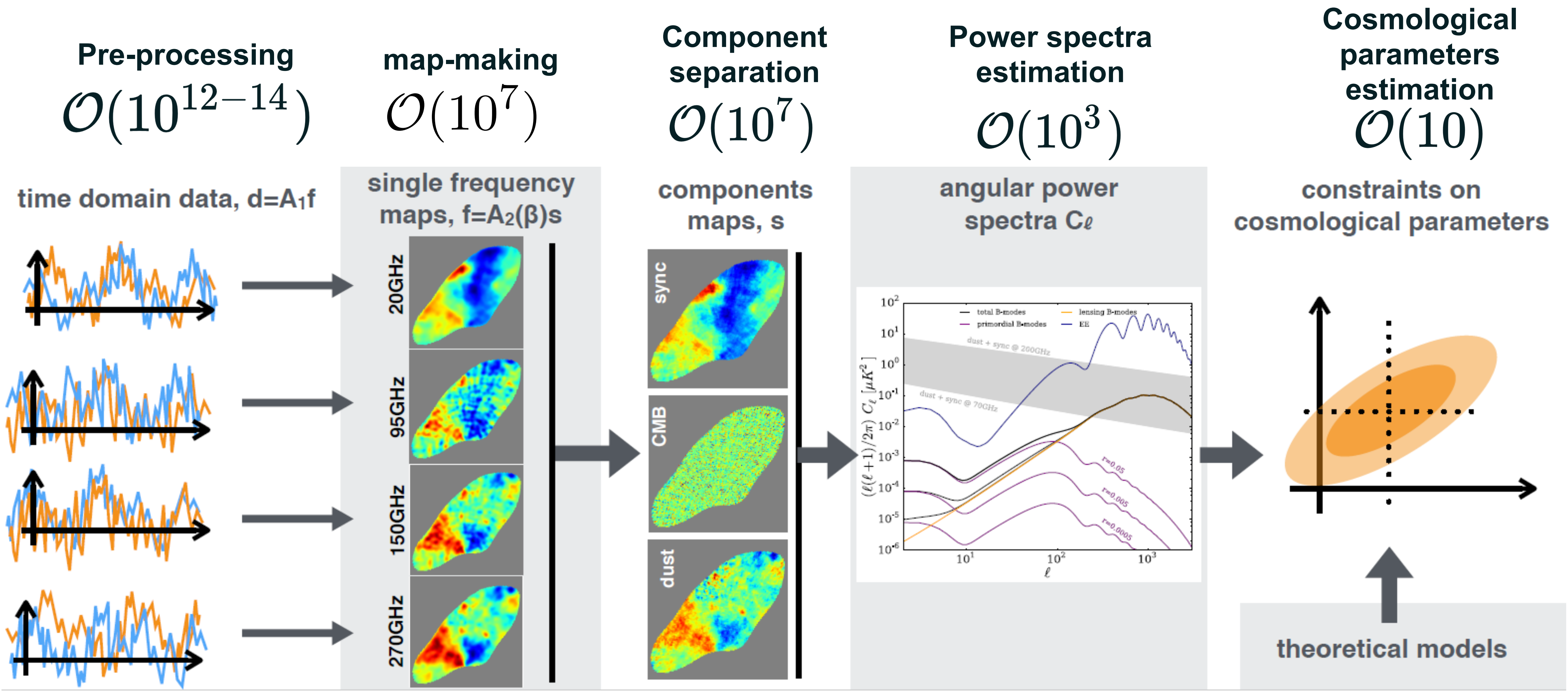


credits: Dominic Beck



Josquin Errard (APC/CNRS), colloquium@CEA, October 4th 2021

This is it? Adding more detectors is enough to reach inflationary gravitational waves?



Pre-processing $\mathcal{O}(10^{12-14})$

time domain data, d=A₁f

map-making $\mathcal{O}(10^{7})$

single frequency maps, f=A₂(β)s

Component separation $\mathcal{O}(10^{7})$

components maps, s

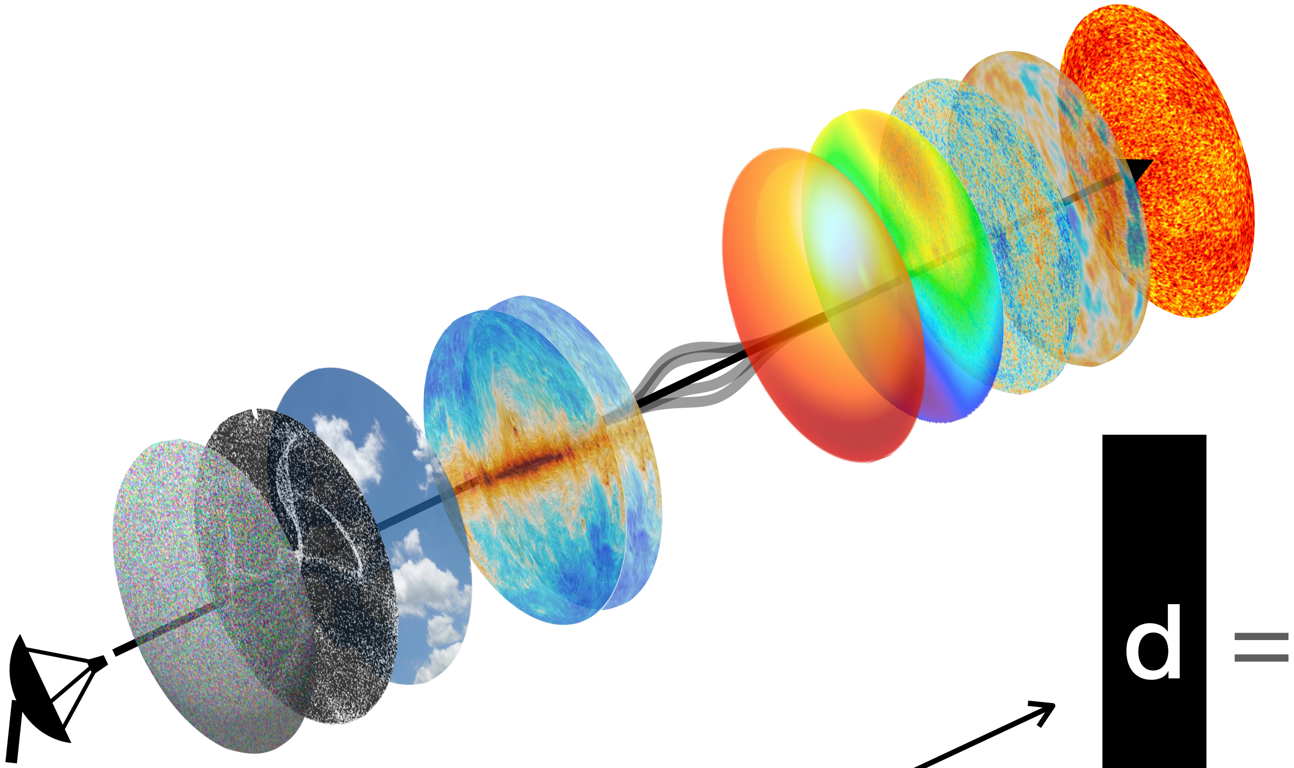
Power spectra estimation $\mathcal{O}(10^{3})$

angular power spectra Cℓ

Cosmological parameters estimation $\mathcal{O}(10)$

constraints on cosmological parameters

theoretical models



$$d = A\,s + n$$

observed data

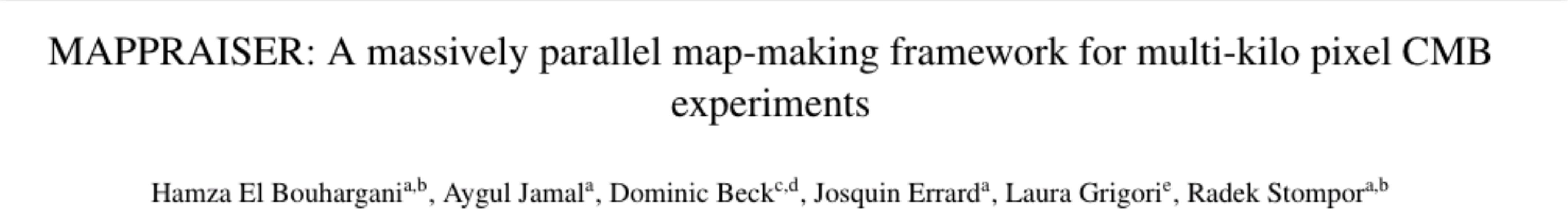
instrument characteristics

CMB signal, function of cosmology (+astrophysical signals)

noise(s)

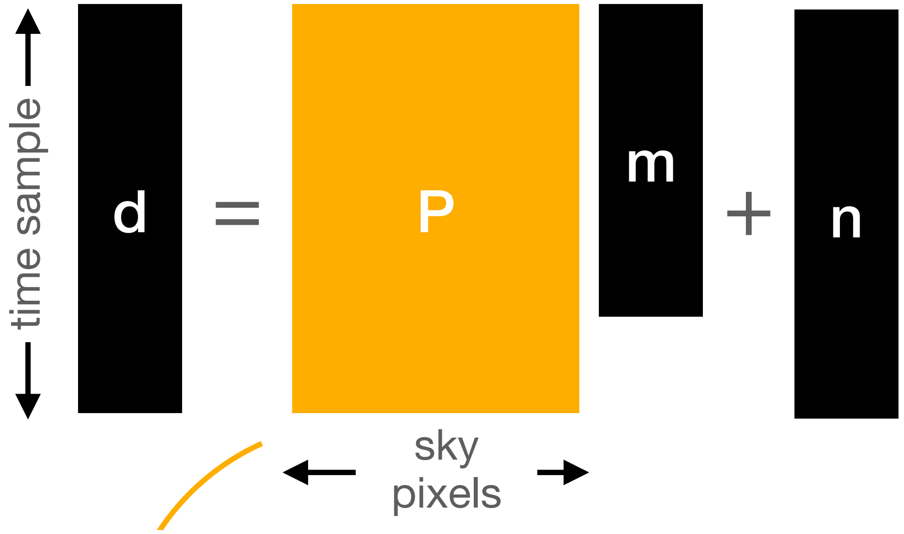
$$s = ?$$

map-making



MAPPRAISER: A massively parallel map-making framework for multi-kilo pixel CMB experiments

Hamza El Bouhargani[a,b], Aygul Jamal[a], Dominic Beck[c,d], Josquin Errard[a], Laura Grigori[e], Radek Stompor[a,b]



GLS

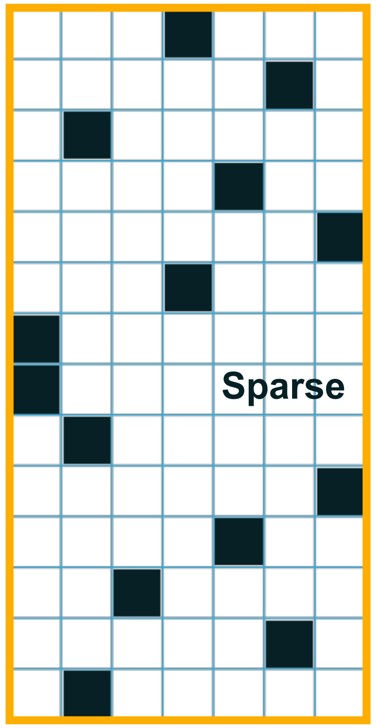
$$\hat{\mathbf{m}} = (\mathbf{P}^{\mathbf{T}}\mathbf{M}\mathbf{P})^{-1}\mathbf{P}^{\mathbf{T}}\mathbf{M}\mathbf{d}$$

time samples = $\mathcal{O}(10^{12-14})$

pixels = $\mathcal{O}(10^{6-8})$

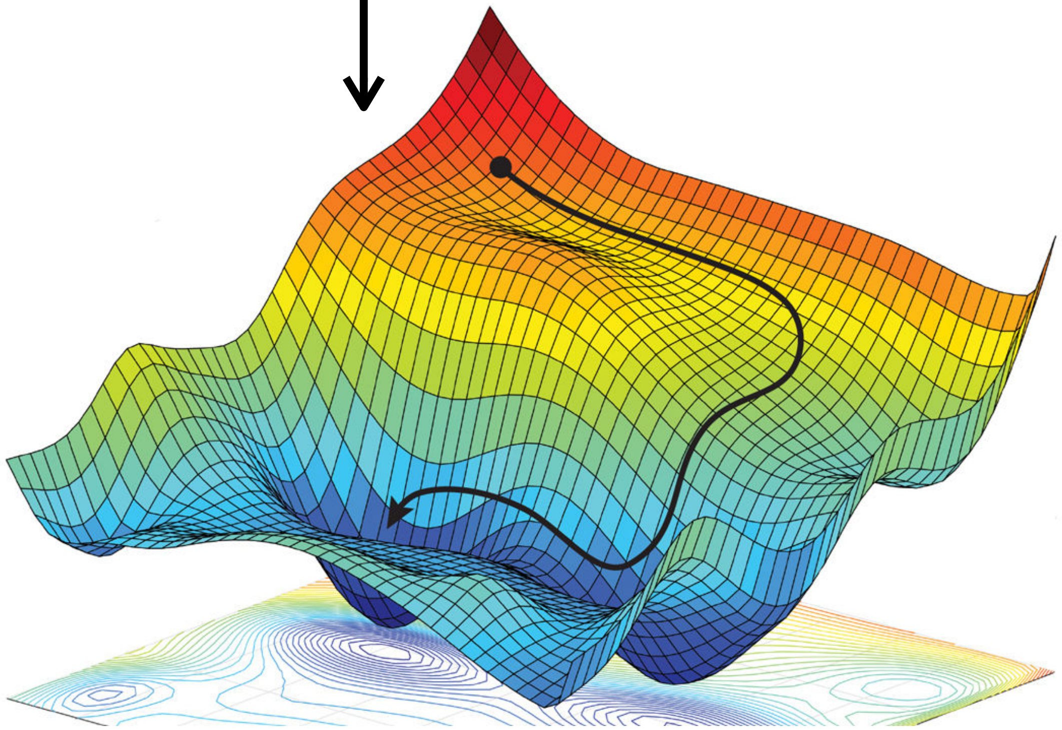
Iterative solver $\mathcal{O}(n_t)$

“Pointing matrix”



Weight model: **M**

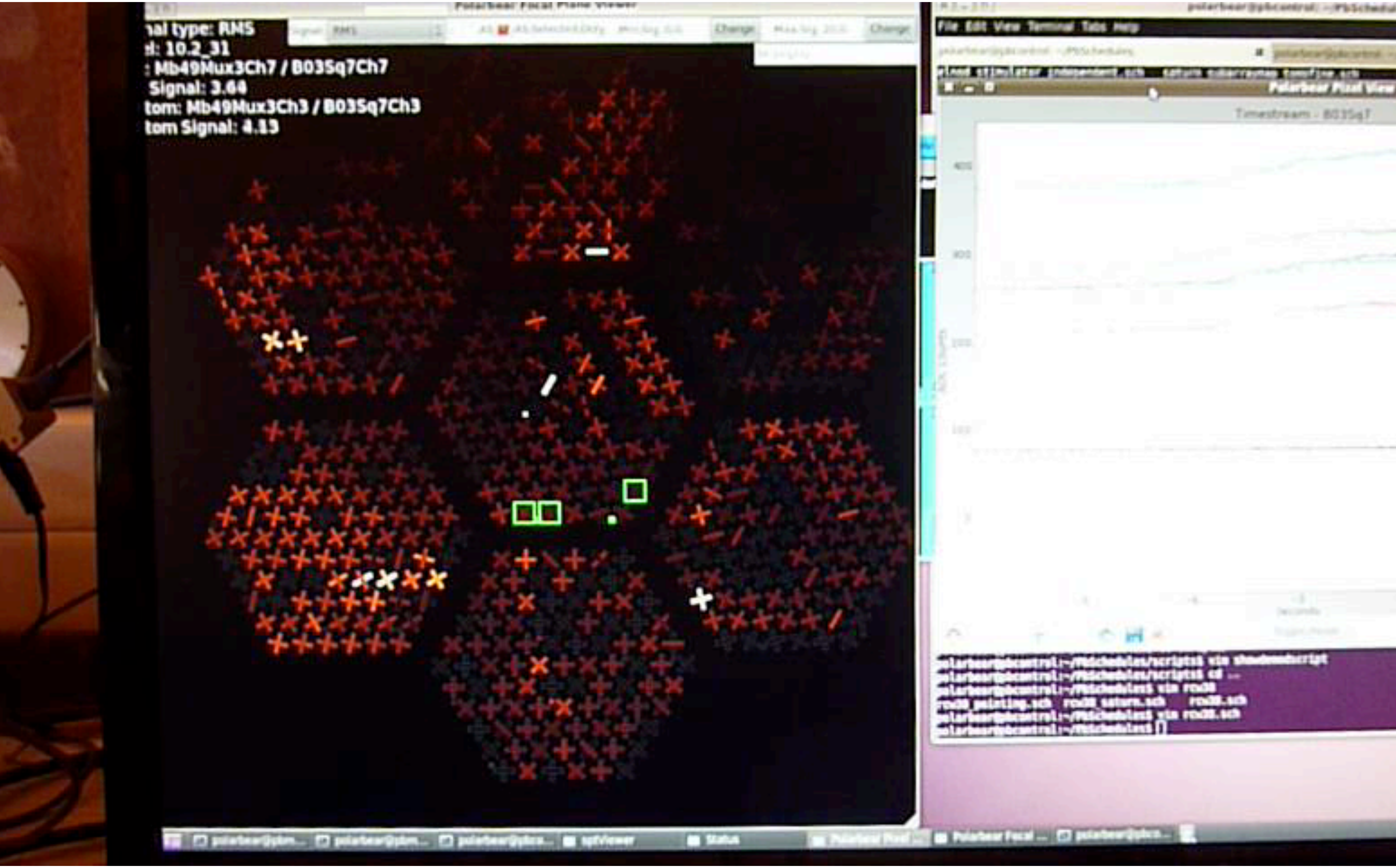
?



Credit: Science Magazine

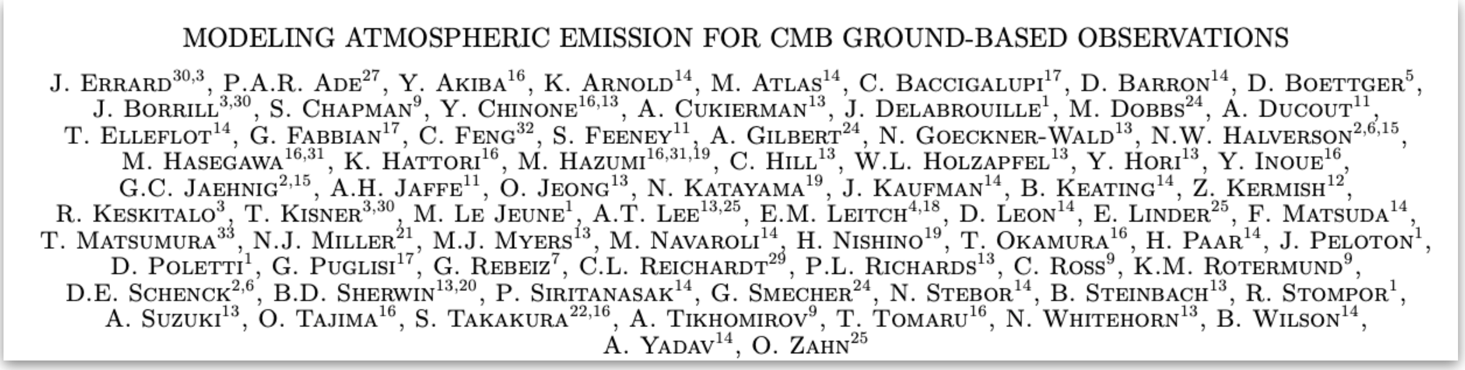
credits: Hamza El Bouhargani

improving the sensitivity of CMB experiments: atmosphere



nal type: RMS
d: 10.2_31
: Mb49Mux3Ch7 / B03Sq7Ch7
Signal: 3.64
tom: Mb49Mux3Ch3 / B03Sq7Ch3
tom Signal: 4.13

improving the sensitivity of CMB experiments: atmosphere



MODELING ATMOSPHERIC EMISSION FOR CMB GROUND-BASED OBSERVATIONS

J. Errard[30,3], P.A.R. Ade[27], Y. Akiba[16], K. Arnold[14], M. Atlas[14], C. Baccigalupi[17], D. Barron[14], D. Boettger[5],
J. Borrill[3,30], S. Chapman[9], Y. Chinone[16,13], A. Cukierman[13], J. Delabrouille[1], M. Dobbs[24], A. Ducout[11],
T. Elleflot[14], G. Fabbian[17], C. Feng[32], S. Feeney[11], A. Gilbert[24], N. Goeckner-Wald[13], N.W. Halverson[2,6,15],
M. Hasegawa[16,31], K. Hattori[16], M. Hazumi[16,31,19], C. Hill[13], W.L. Holzapfel[13], Y. Hori[13], Y. Inoue[16],
G.C. Jaehnig[2,15], A.H. Jaffe[11], O. Jeong[13], N. Katayama[19], J. Kaufman[14], B. Keating[14], Z. Kermish[12],
R. Keskitalo[3], T. Kisner[3,30], M. Le Jeune[1], A.T. Lee[13,25], E.M. Leitch[4,18], D. Leon[14], E. Linder[25], F. Matsuda[14],
T. Matsumura[33], N.J. Miller[21], M.J. Myers[13], M. Navaroli[14], H. Nishino[19], T. Okamura[16], H. Paar[14], J. Peloton[1],
D. Poletti[1], G. Puglisi[17], G. Rebeiz[7], C.L. Reichardt[29], P.L. Richards[13], C. Ross[9], K.M. Rotermund[9],
D.E. Schenck[2,6], B.D. Sherwin[13,20], P. Siritanasak[14], G. Smecher[24], N. Stebor[14], B. Steinbach[13], R. Stompor[1],
A. Suzuki[13], O. Tajima[16], S. Takakura[22,16], A. Tikhomirov[9], T. Tomaru[16], N. Whitehorn[13], B. Wilson[14],
A. Yadav[14], O. Zahn[25]

$$\mathbf{C}_{ij}^{tt'} \equiv \langle T_{\mathrm{ant}}^{\,i}(t)T_{\mathrm{ant}}^{\,j}(t')\rangle \equiv \langle T_{\mathrm{ant}}(\hat{\mathbf{r}}_{\mathbf{s}}{}^{\mathbf{i}}(t))T_{\mathrm{ant}}(\hat{\mathbf{r}}_{\mathbf{s}}{}^{\mathbf{j}}(t'))\rangle = \frac{1}{\lambda^4}\int\frac{d\mathbf{r}}{r^2}\int\frac{d\mathbf{r}'}{r^2}\,B(\hat{\mathbf{r}}_{\mathbf{s}}{}^{\mathbf{i}}(t),\mathbf{r})B(\hat{\mathbf{r}}_{\mathbf{s}}{}^{\mathbf{j}}(t'),\mathbf{r}') \times\langle\alpha(\mathbf{r})\alpha(\mathbf{r}')\rangle\,T_{\mathrm{phys}}(\mathbf{r})T_{\mathrm{phys}}(\mathbf{r}')$$

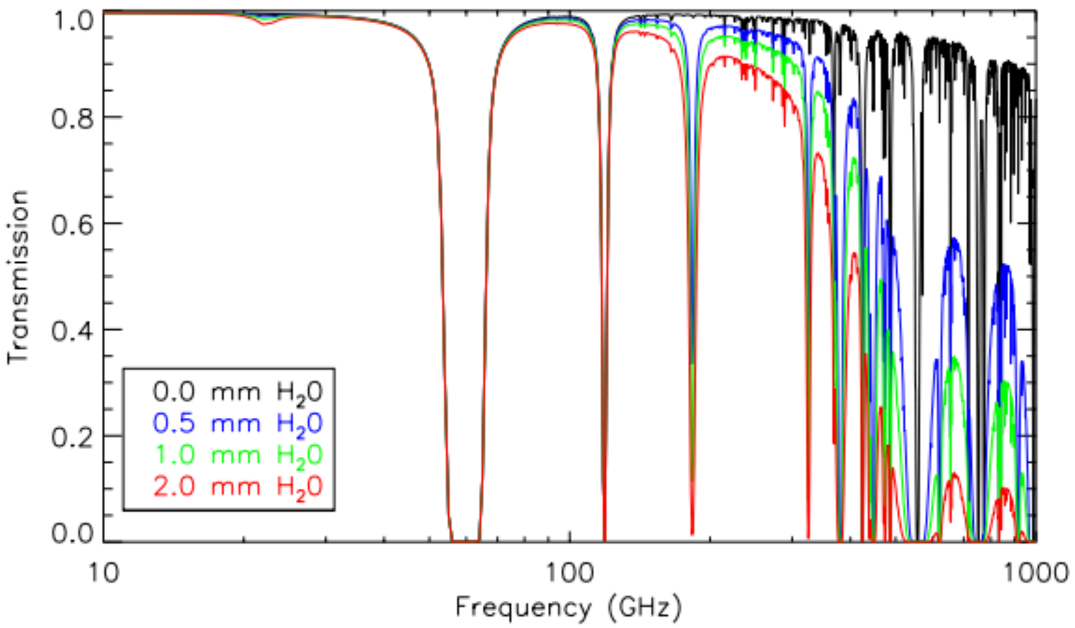
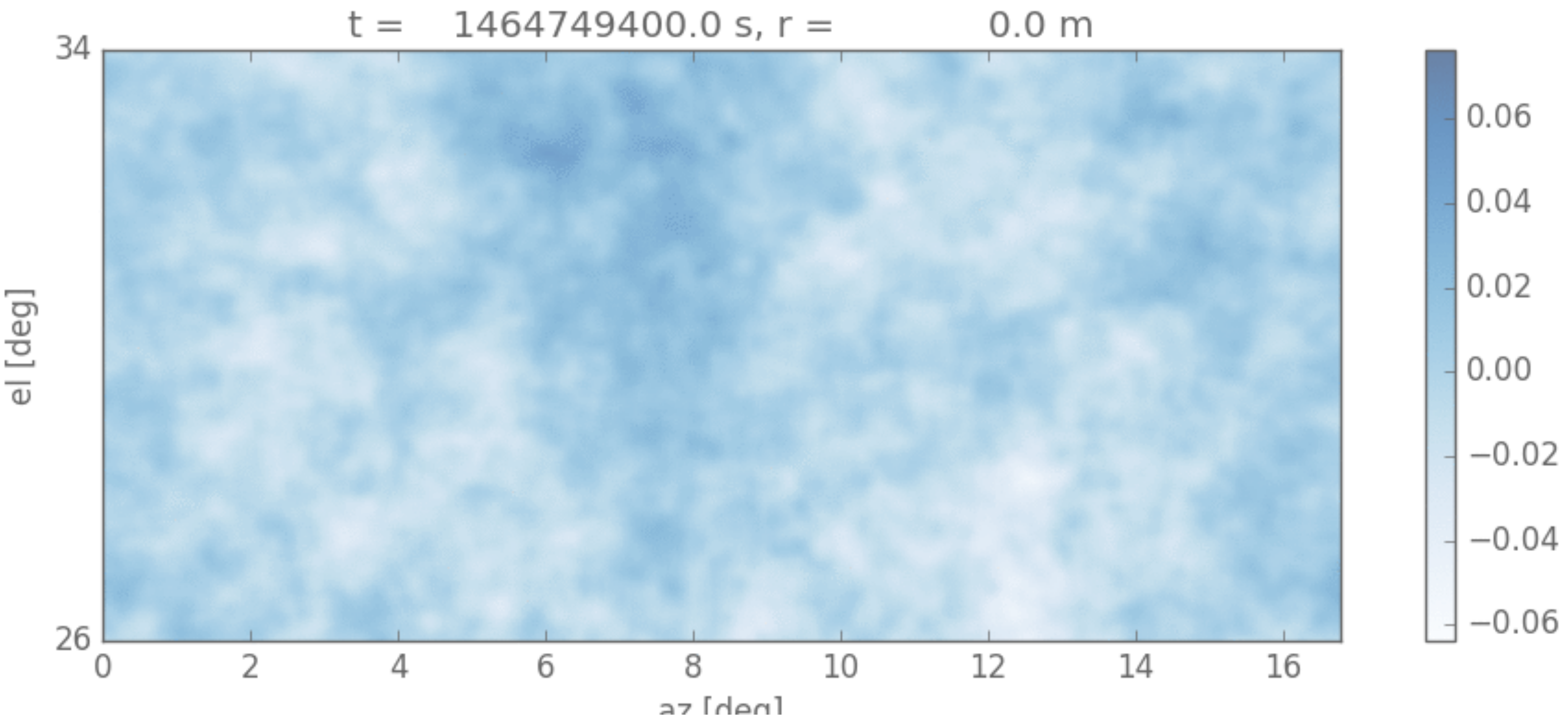


Fig. 1.— Atmospheric transmission from the Atacama plateau at the zenith for different amounts of precipitable water vapor. This is obtained using the ATM code, Pardo et al. (2001).

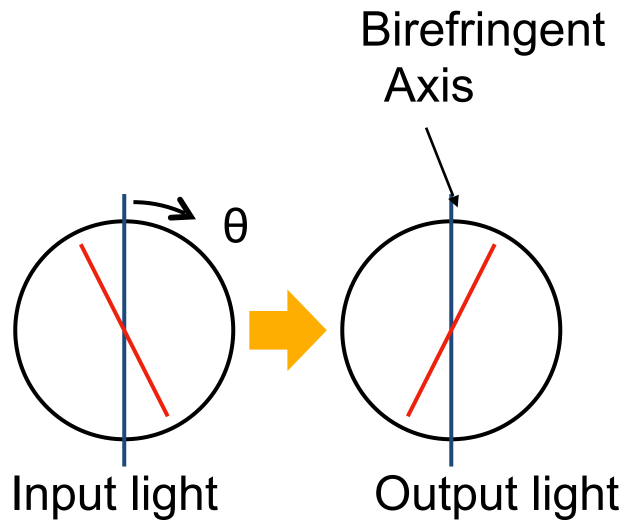


improving the sensitivity of CMB experiments: atmosphere

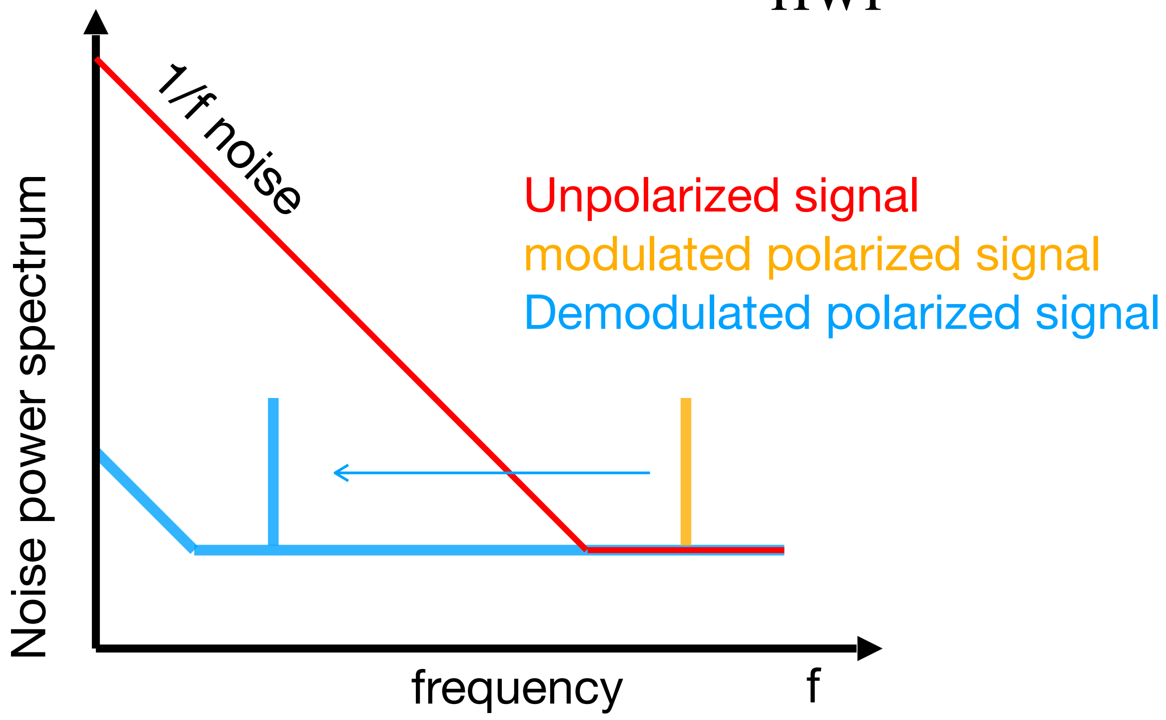
Polarization Modulation Unit (PMU)

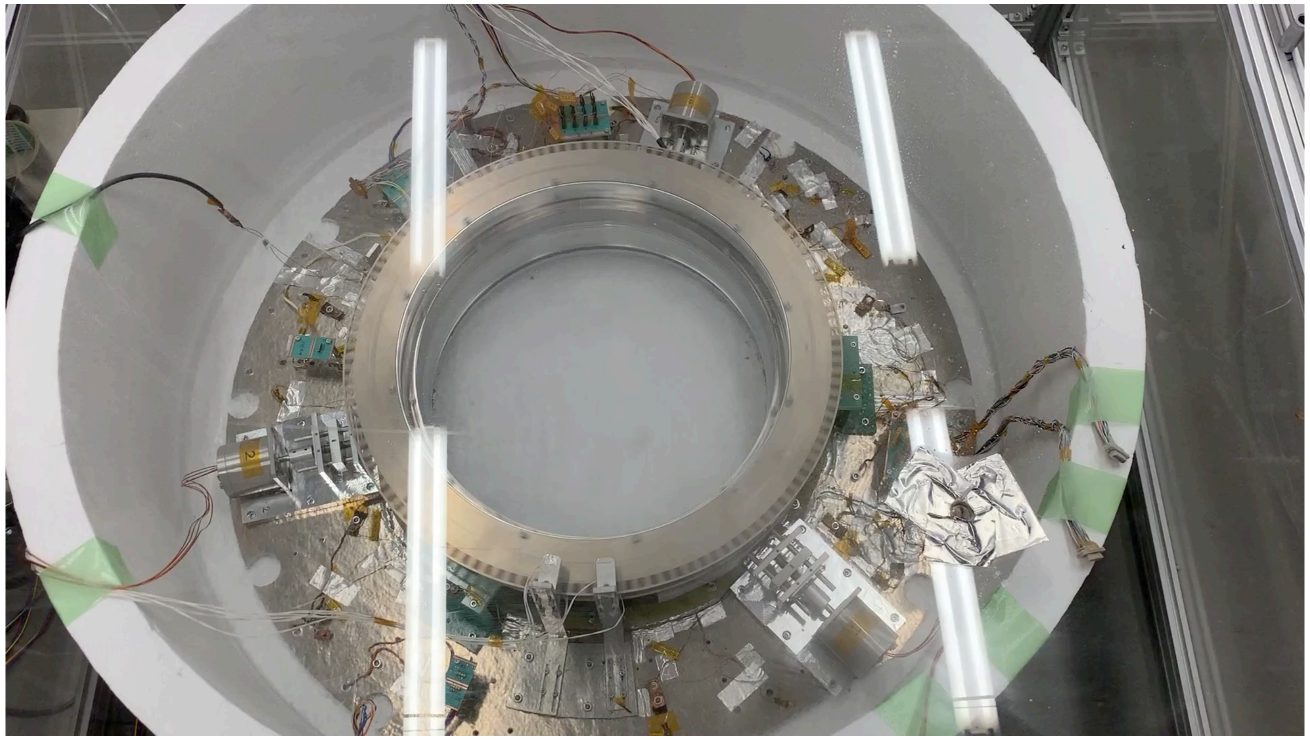
Operation Principle ➔

- Rotating a birefringent plate to modulate polarization
- Placed at the most sky side



$$I + P\cos 4\theta_{\mathrm{HWP}}$$

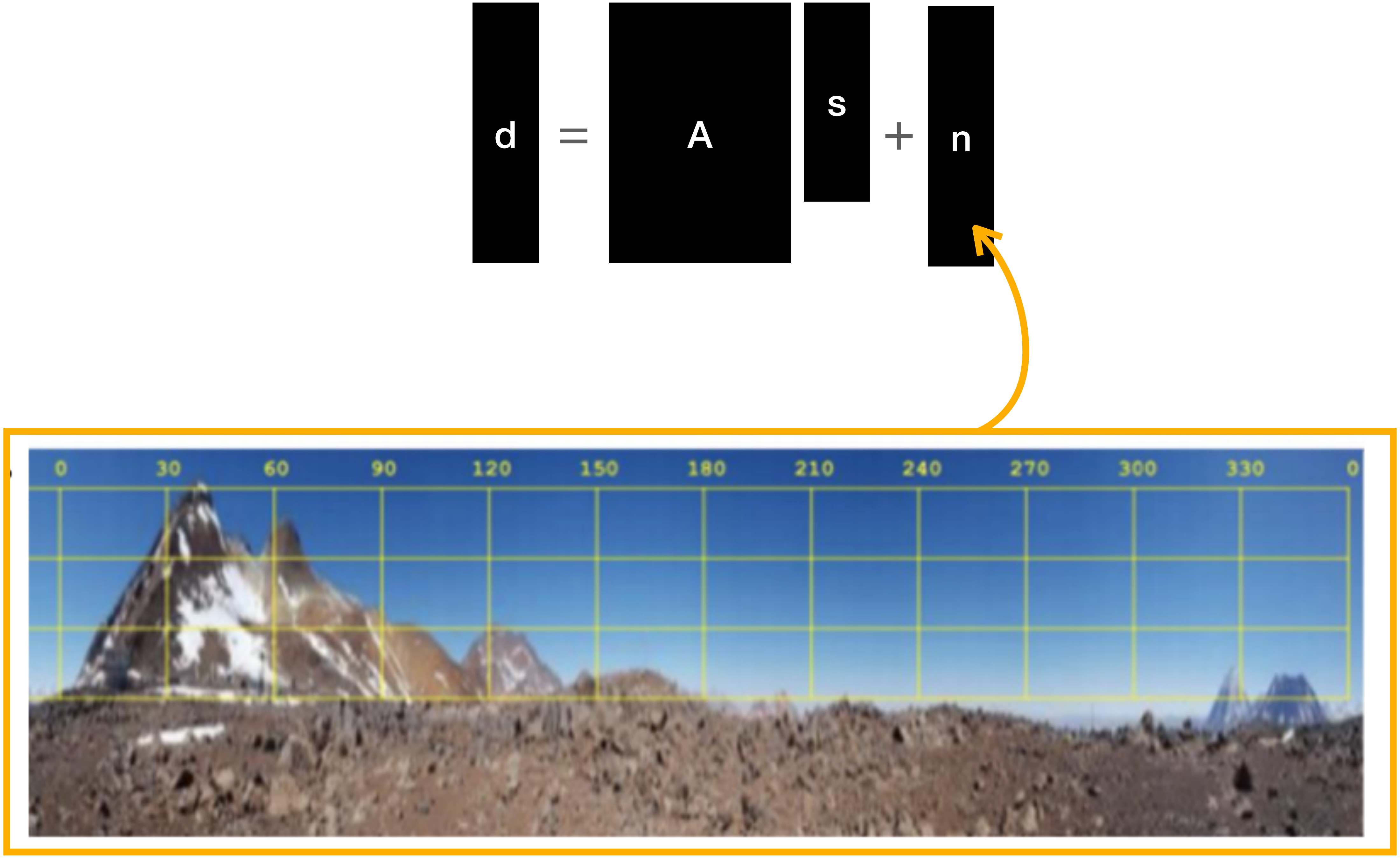




Rotation test of a superconducting magnetic bearing system in the 4K cryostat.

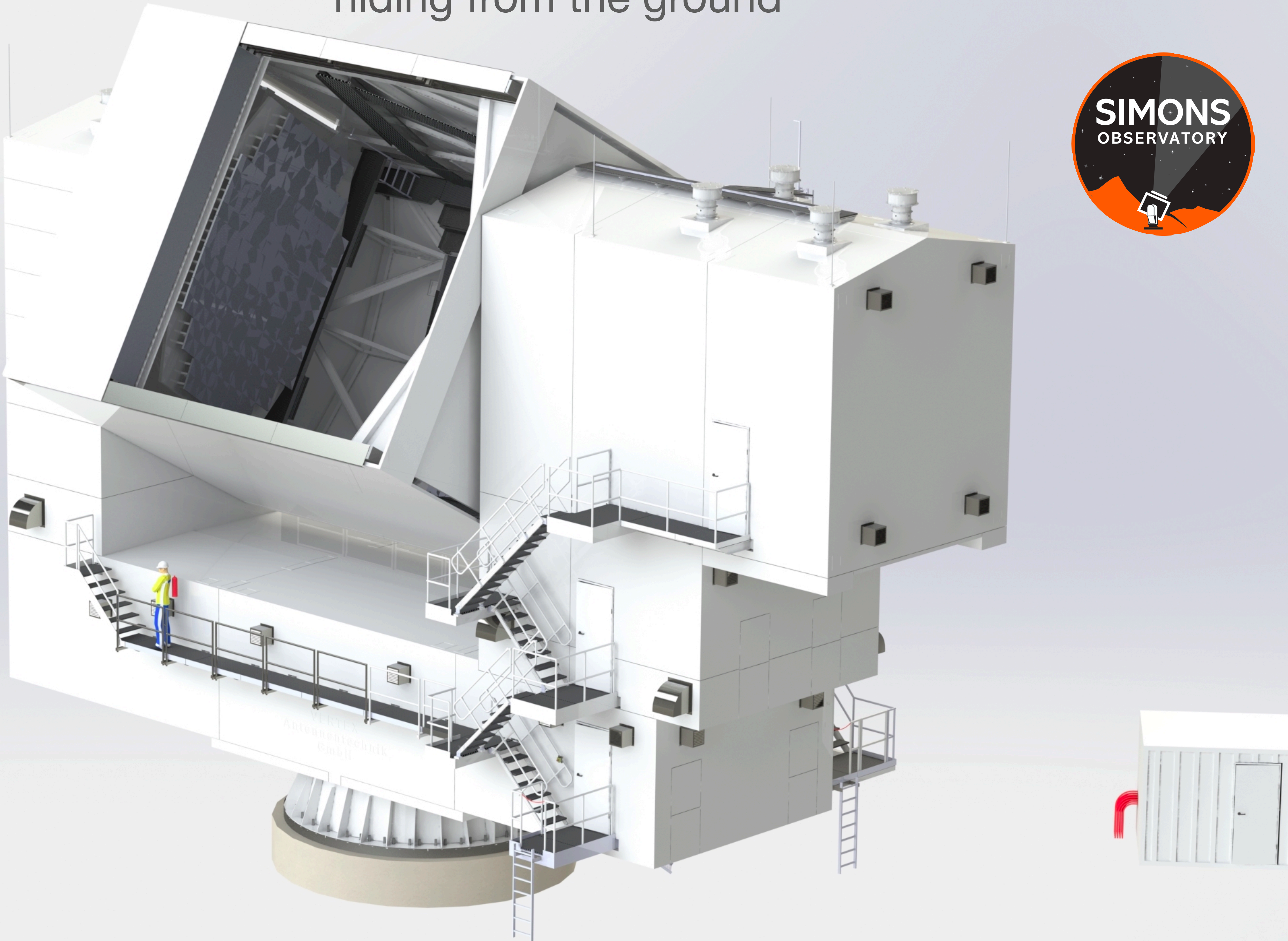
The stable rotation at cryogenic temperature (<10K)

improving the sensitivity of CMB experiments: hiding from the ground

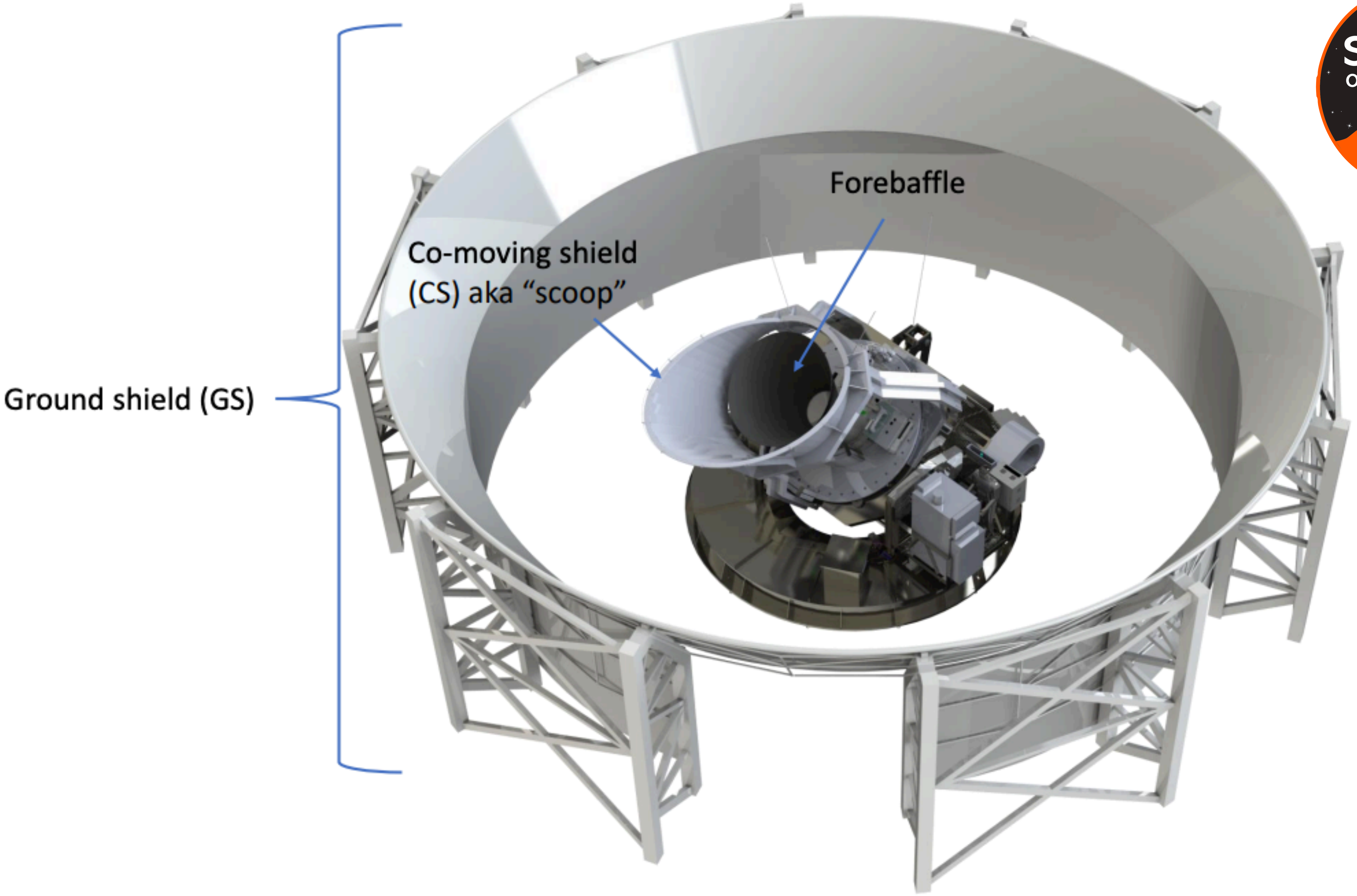


improving the sensitivity of CMB experiments: hiding from the ground

SIMONS OBSERVATORY

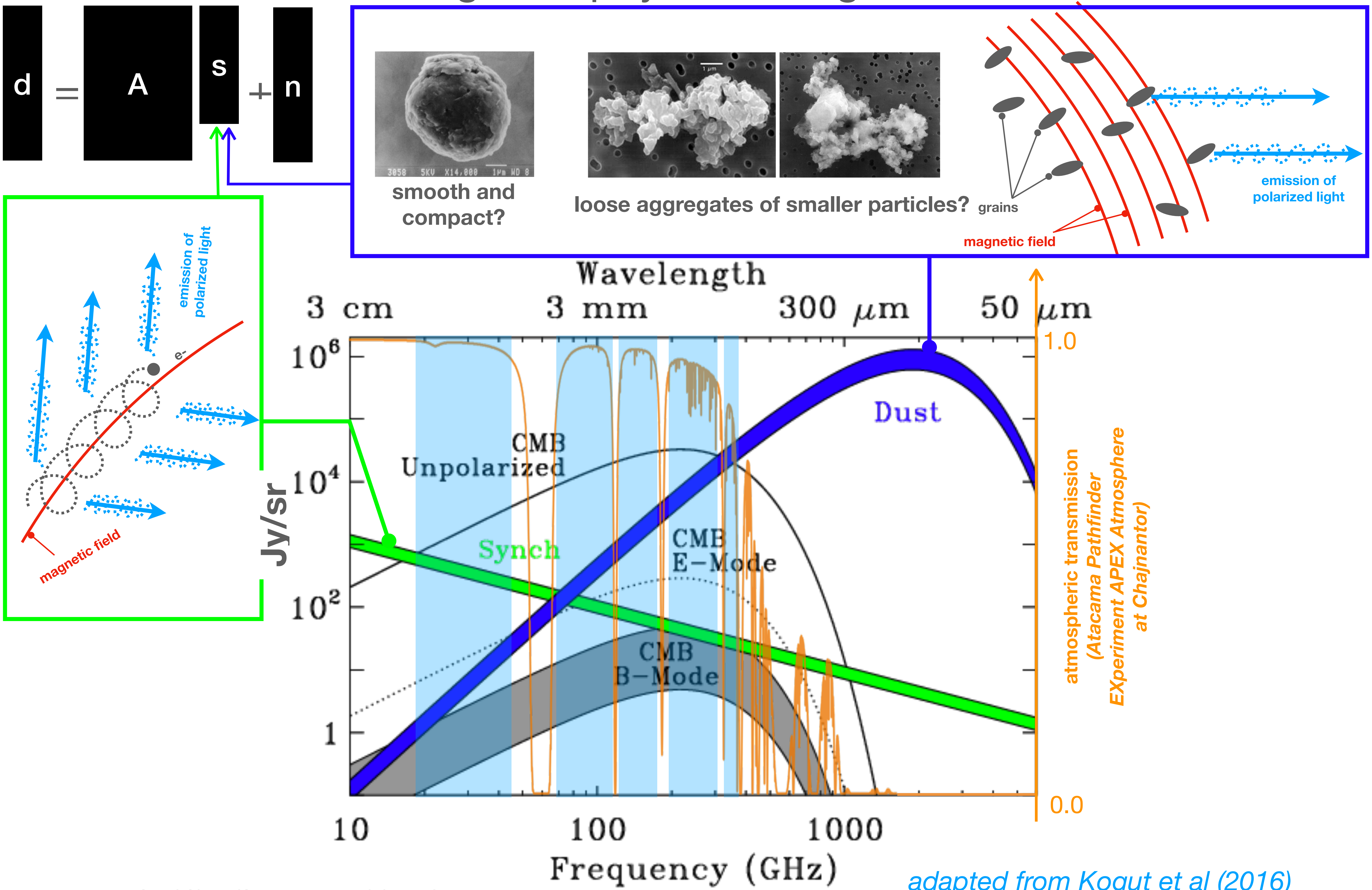


improving the sensitivity of CMB experiments: hiding from the ground

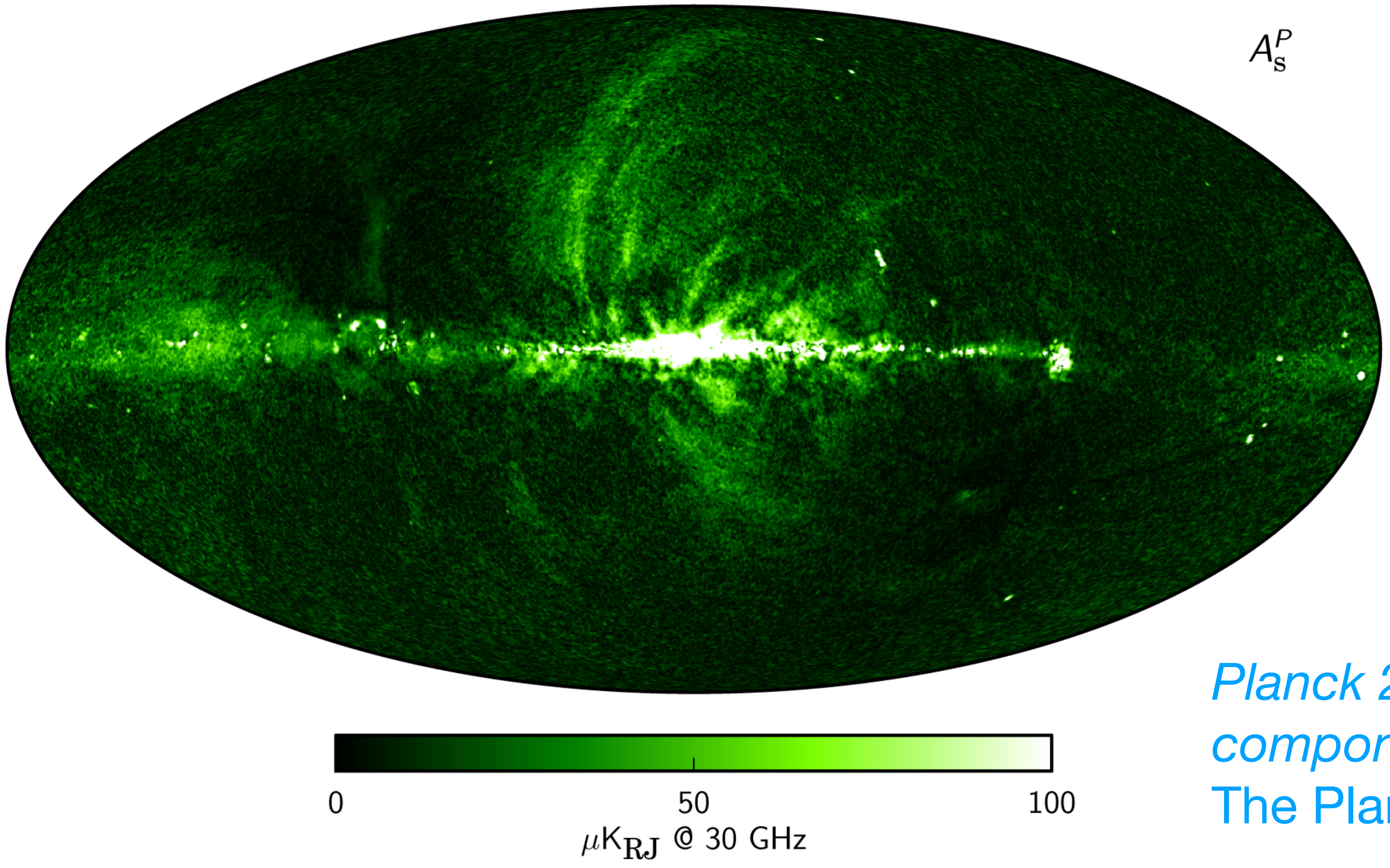


SIMONS OBSERVATORY

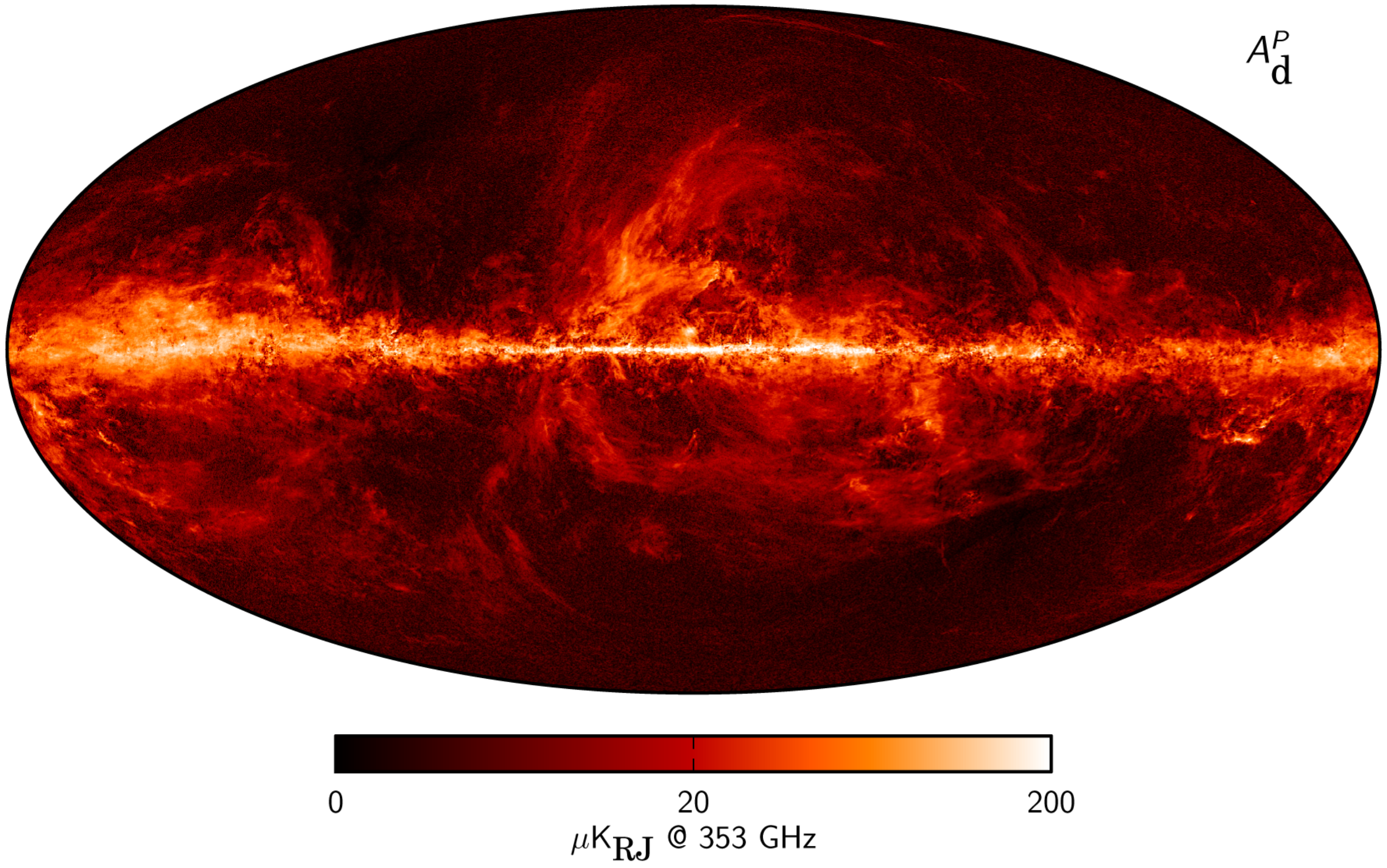
improving the sensitivity of CMB experiments: cleaning astrophysical foregrounds

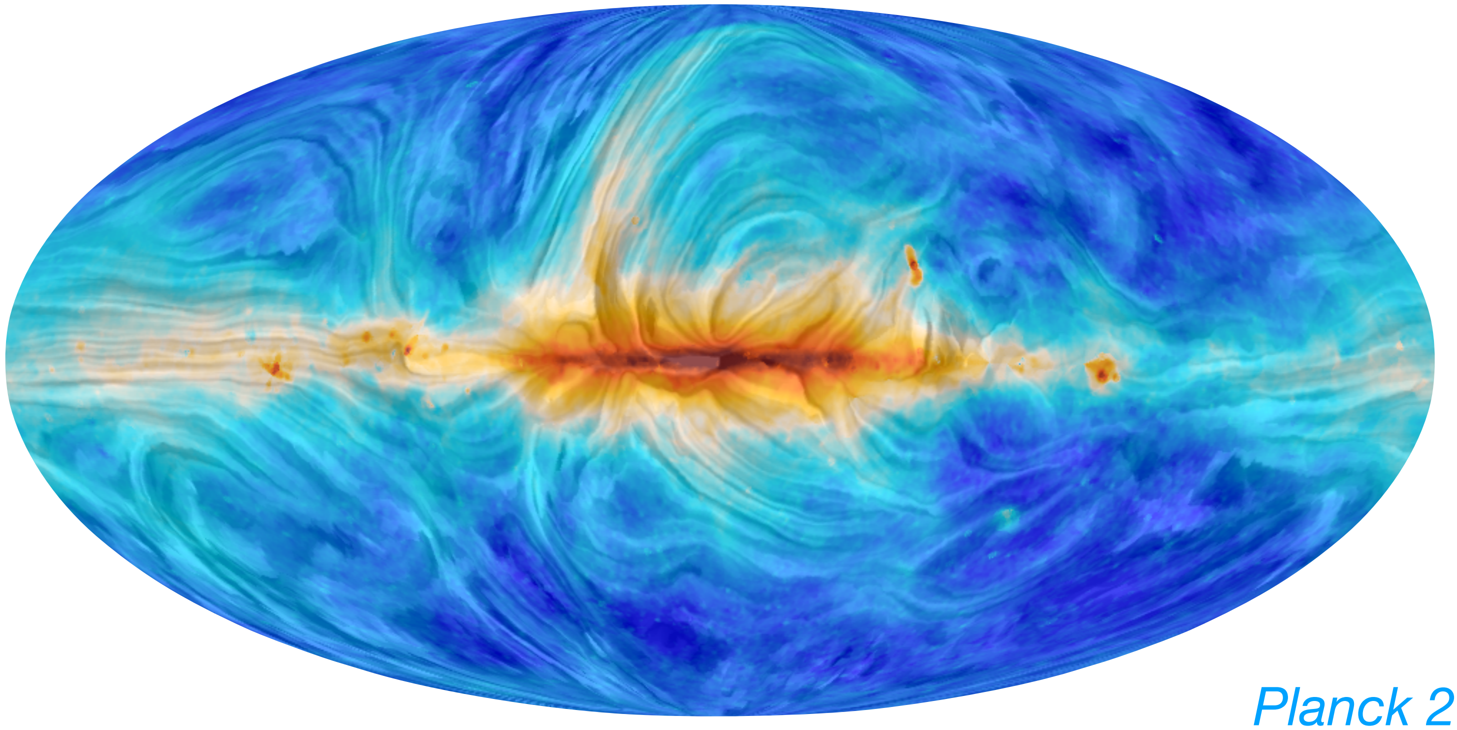


adapted from Kogut et al (2016)



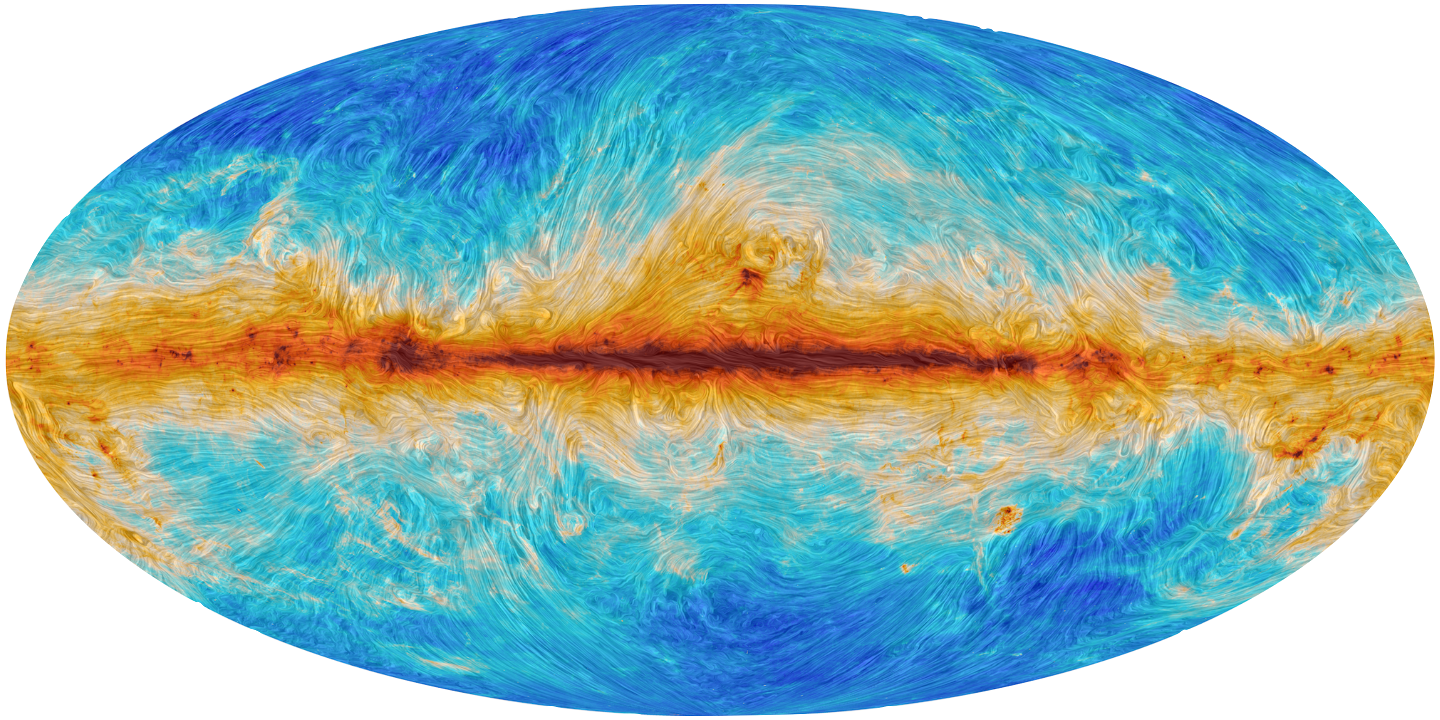
Planck 2015 results. X. Diffuse component separation: Foreground maps
The Planck collaboration, A&A, 2015

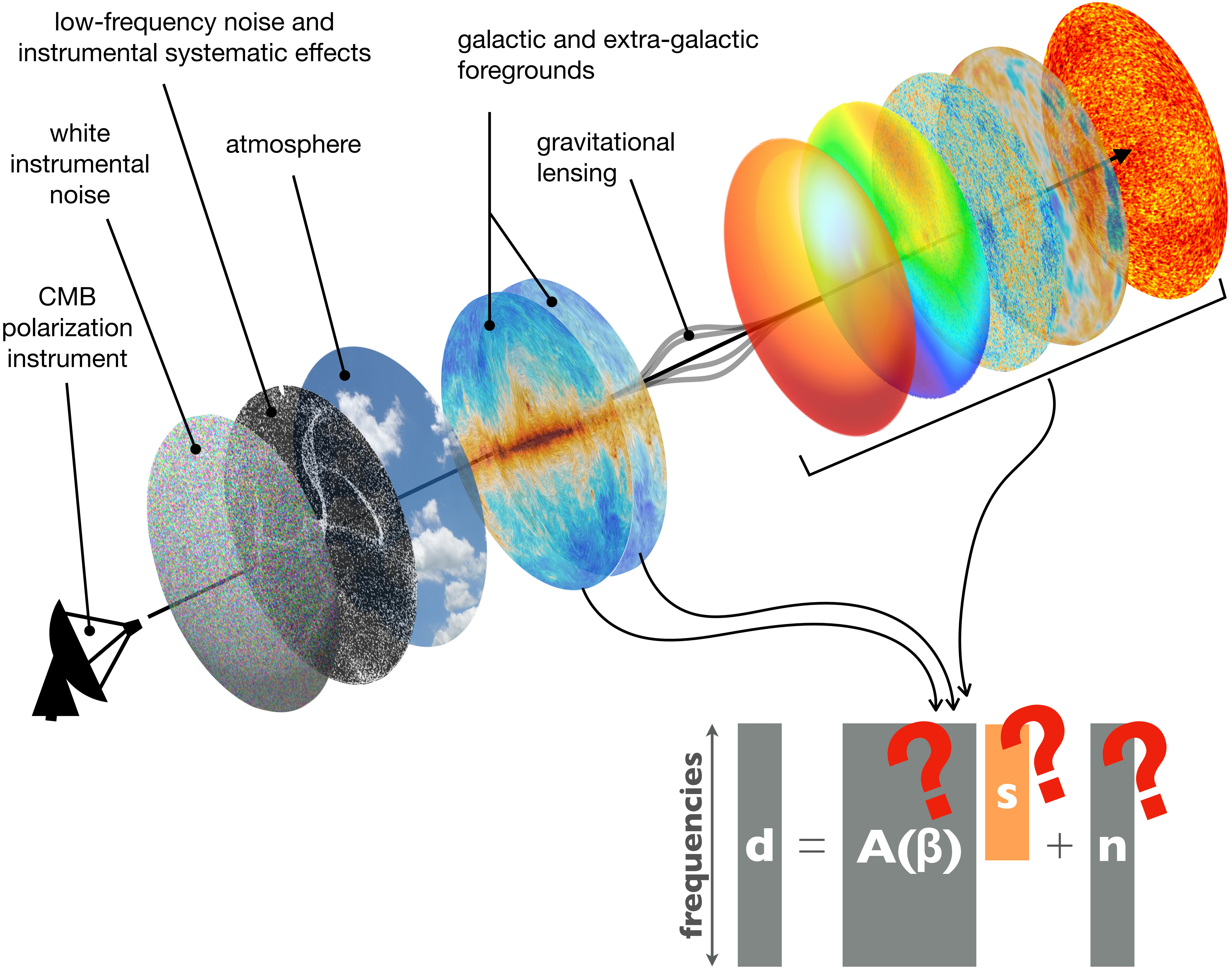




intensity @ 30GHz
+ B-field from polarization

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





low-frequency noise and instrumental systematic effects

galactic and extra-galactic foregrounds

white instrumental noise

atmosphere

gravitational lensing

CMB polarization instrument

frequencies

$$\mathbf{d} = \mathbf{A}(\beta)\,\mathbf{s} + \mathbf{n}$$

improving the sensitivity of CMB experiments: cleaning astrophysical foregrounds

removing galactic foregrounds

analogy interlude

One or multiple dust components?

CMB

Anomalous Microwave Emission (AME)?

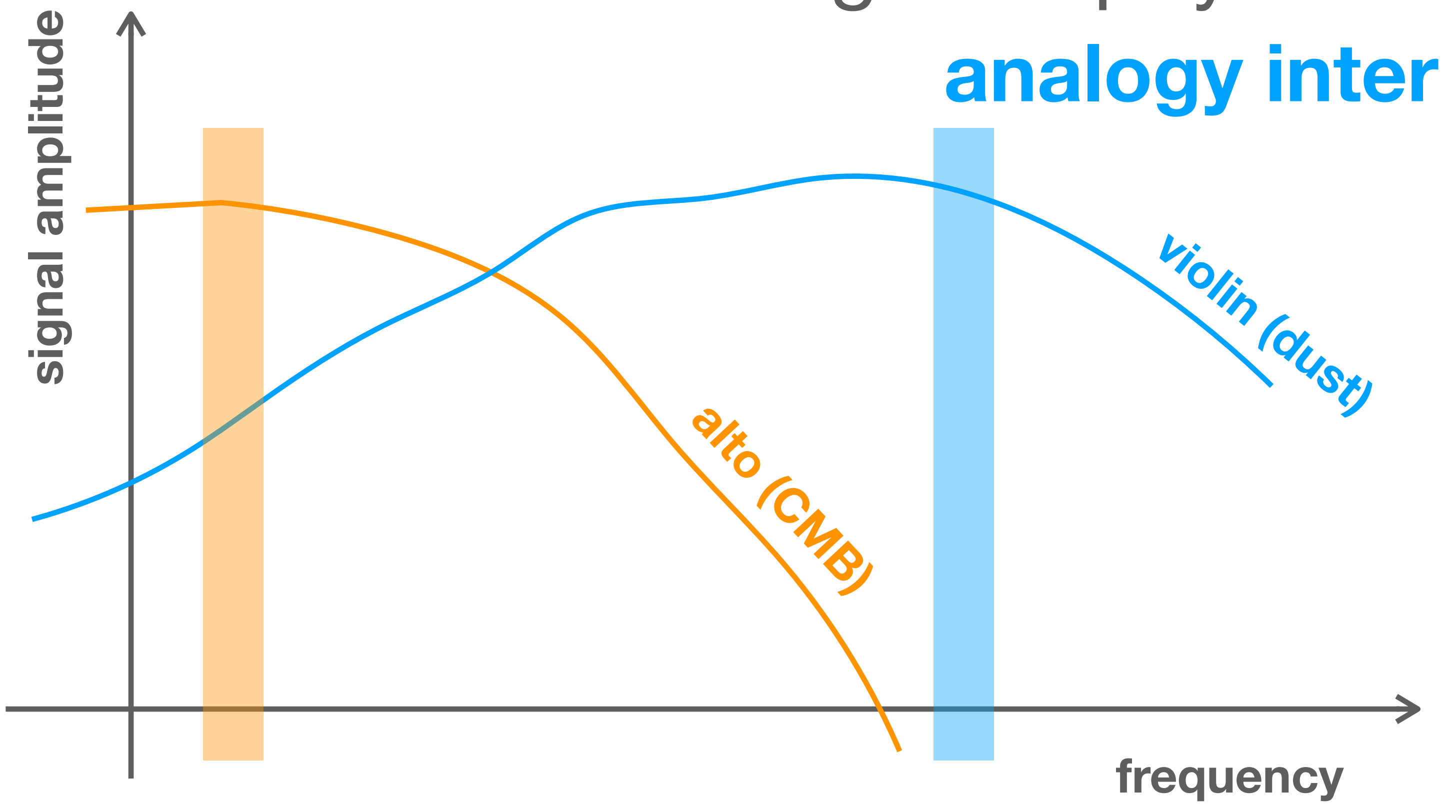
Synchrotron

(black body)

Johannes-Quintett / KV516, Mozart

improving the sensitivity of CMB experiments: cleaning astrophysical 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)

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

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

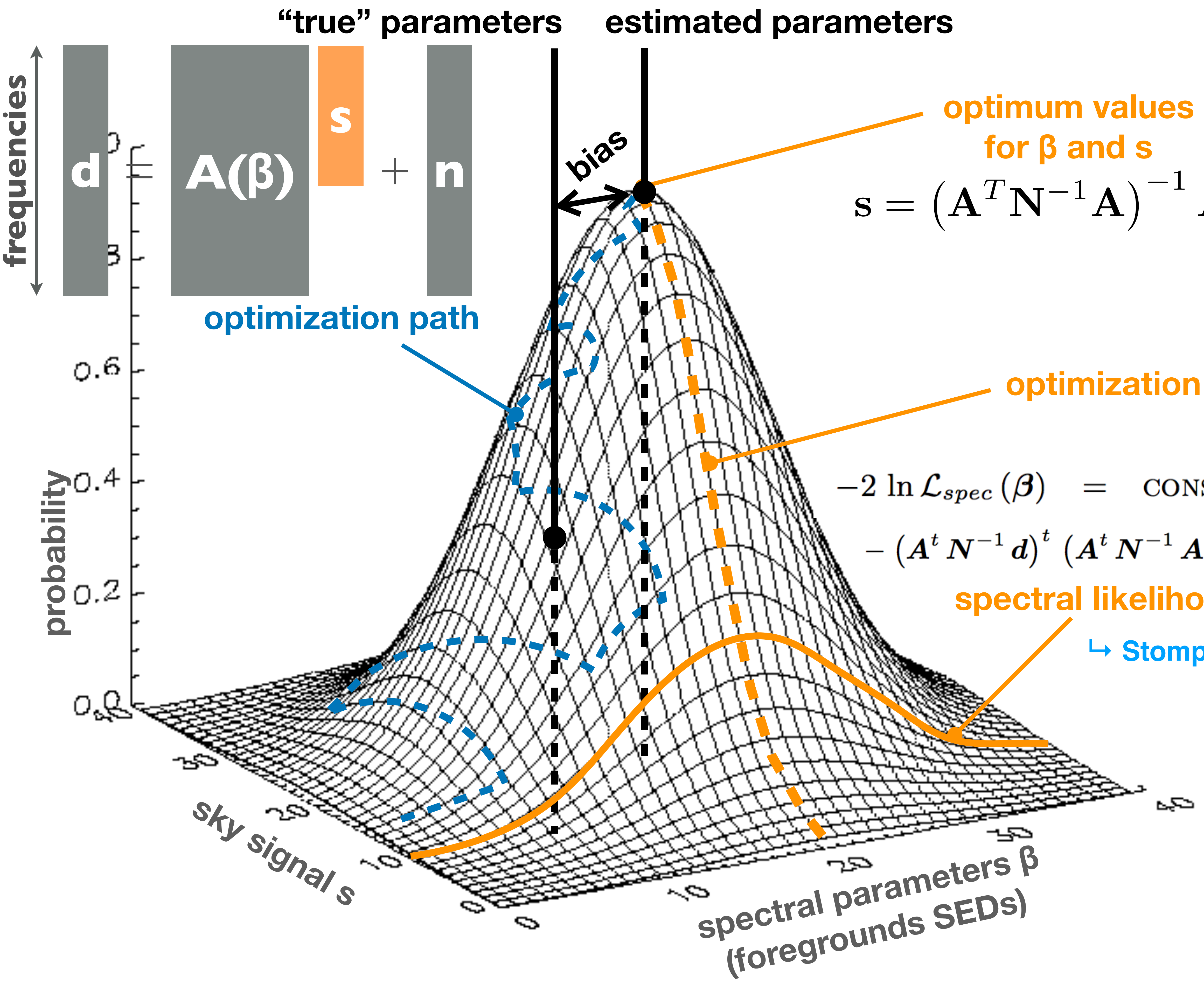
$$d_{\nu_0} b_1 - d_{\nu_1} b_0 = CMB\ (b_1 a_0 - b_0 a_1) + n_{\nu_0} b_1 - n_{\nu_1} b_0$$

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

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



“true” parameters

estimated parameters

frequencies

d = **A(β)** **s** + **n**

bias

optimum values for β and s

$$\mathbf{s} = \left(\mathbf{A}^T\mathbf{N}^{-1}\mathbf{A}\right)^{-1}\mathbf{A}^T\mathbf{N}^{-1}\mathbf{d}$$

optimization path

optimization path

$$-2\,\ln\mathcal{L}_{spec}\left(\boldsymbol{\beta}\right) = \mathrm{CONST} - \left(\boldsymbol{A}^t\,\boldsymbol{N}^{-1}\,\boldsymbol{d}\right)^t\left(\boldsymbol{A}^t\,\boldsymbol{N}^{-1}\,\boldsymbol{A}\right)^{-1}\left(\boldsymbol{A}^t\,\boldsymbol{N}^{-1}\,\boldsymbol{d}\right)$$

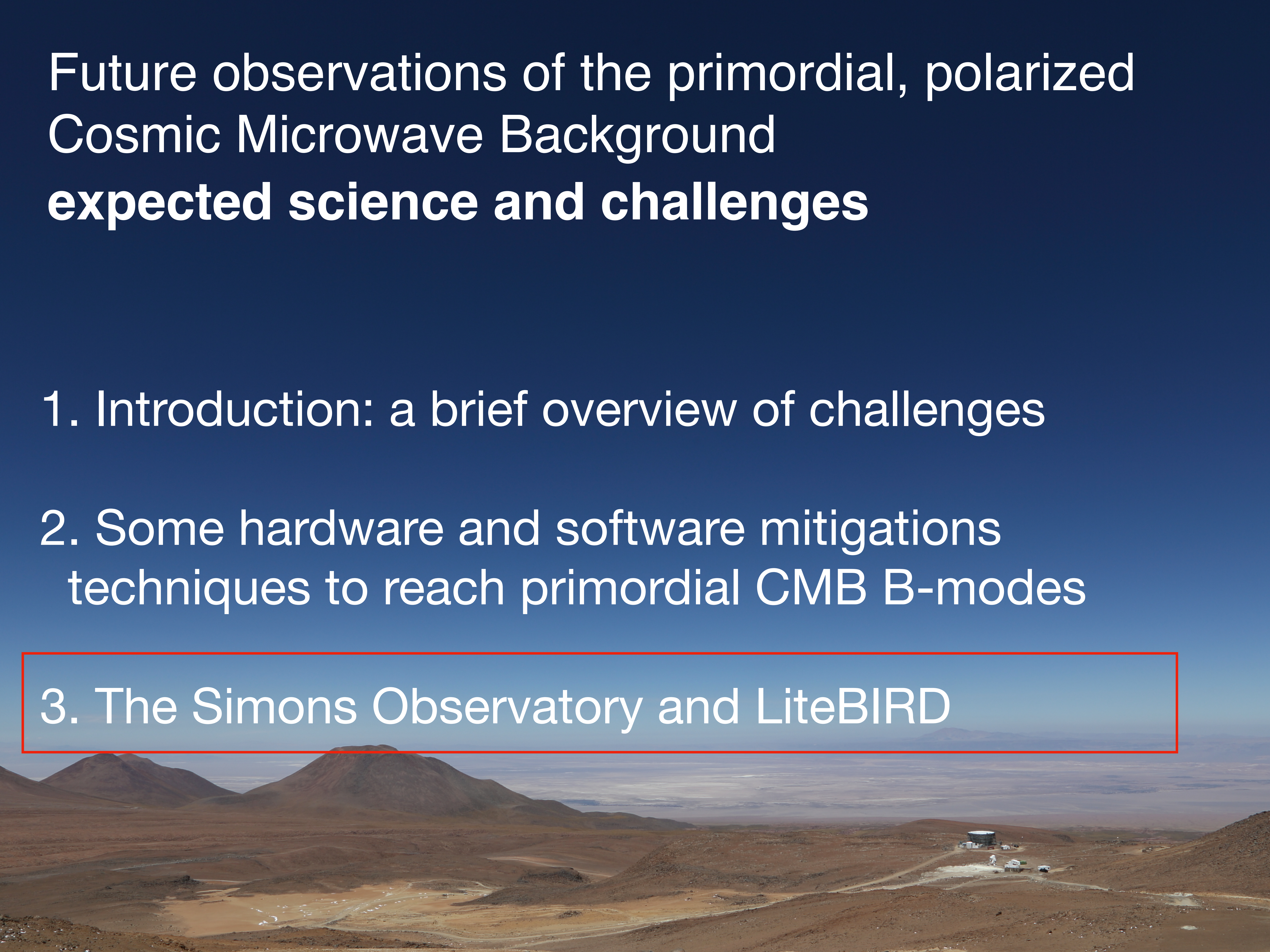
spectral likelihood

↳ **Stompor et al (2009)**

probability

sky signal s

spectral parameters β (foregrounds SEDs)



Future observations of the primordial, polarized Cosmic Microwave Background **expected science and challenges**

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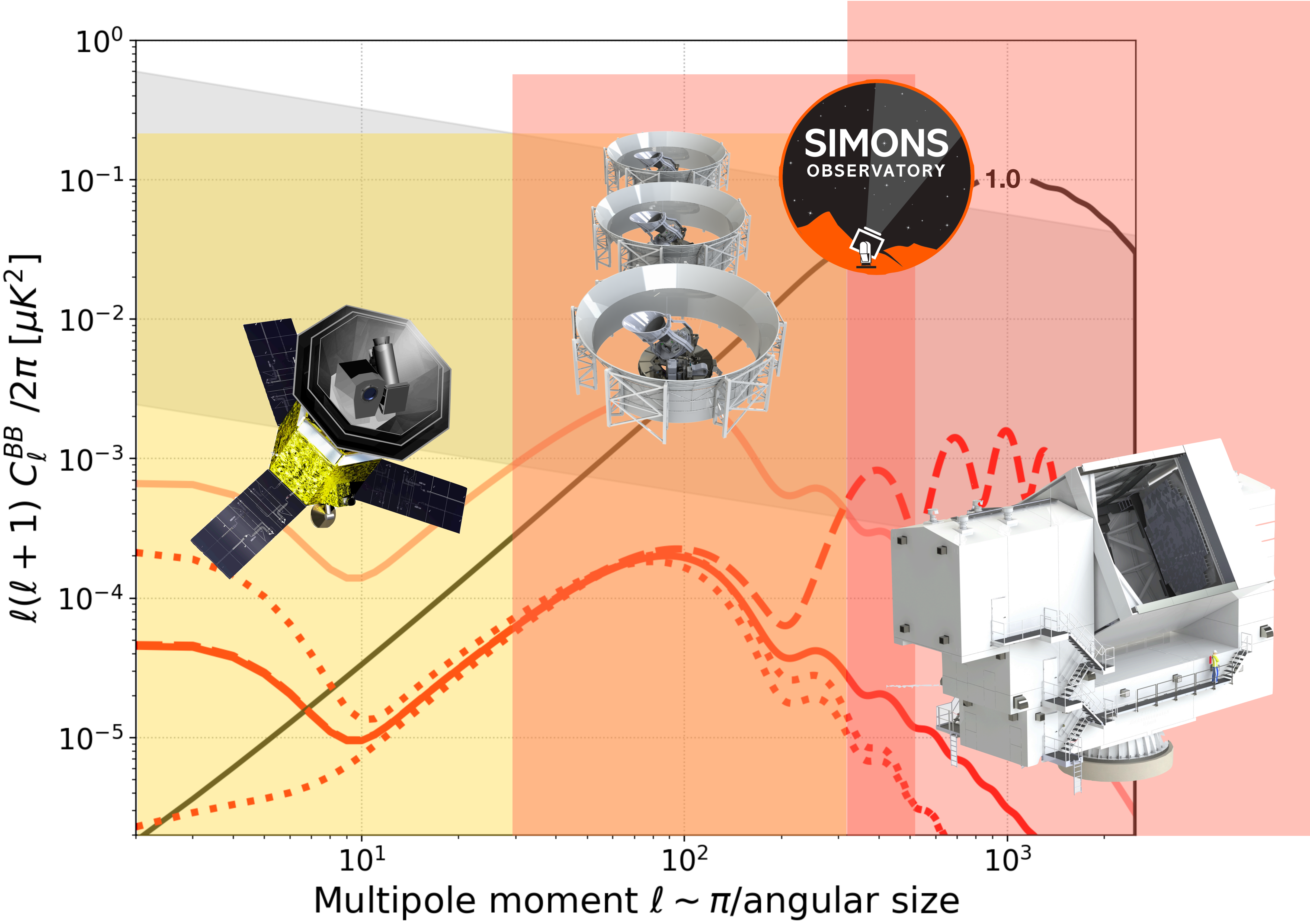
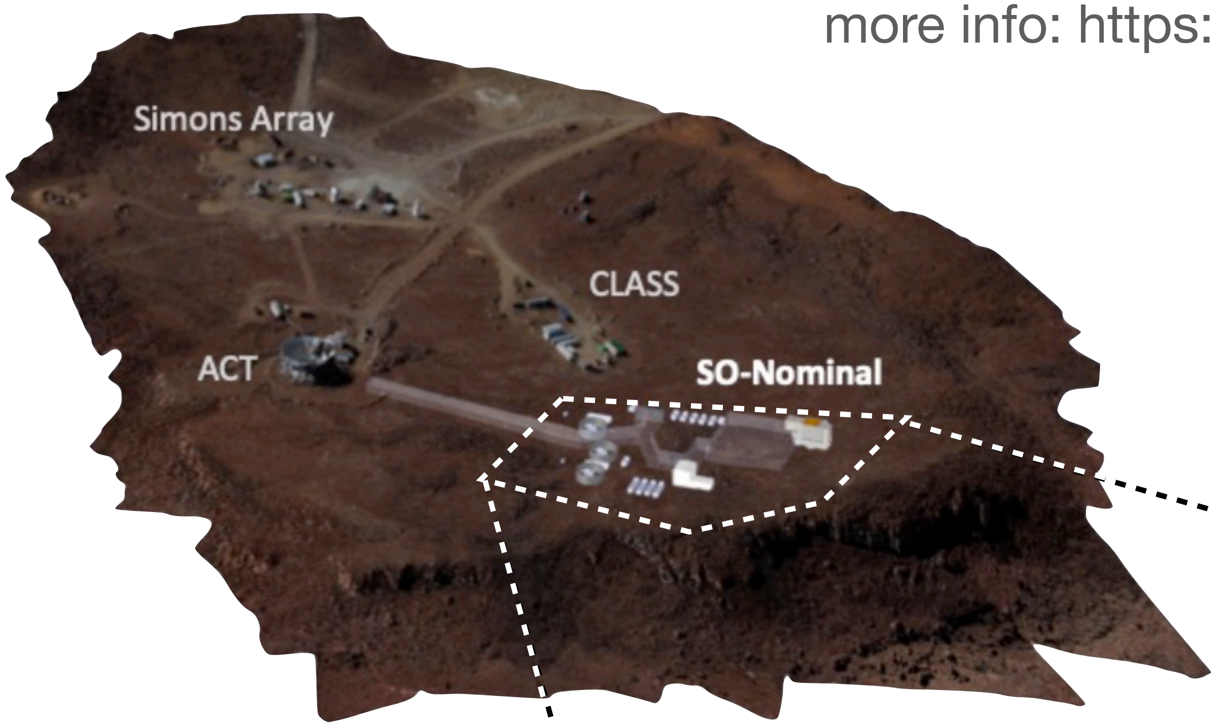
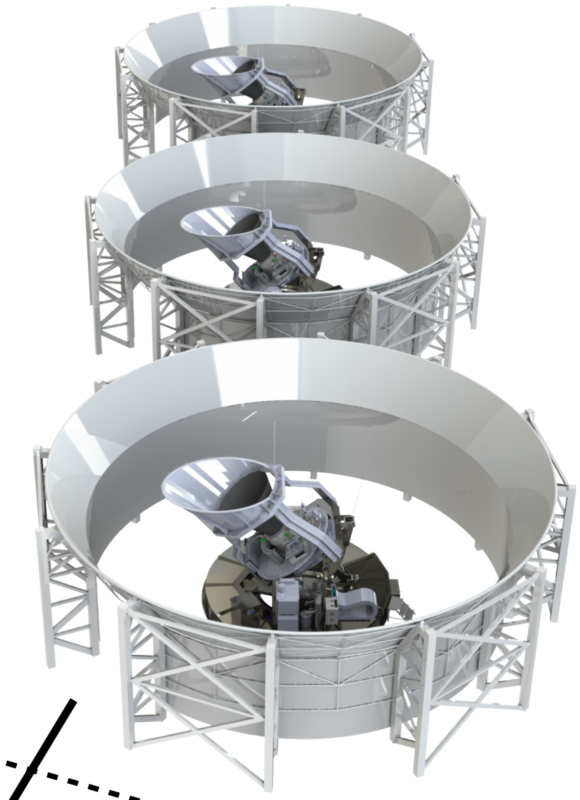
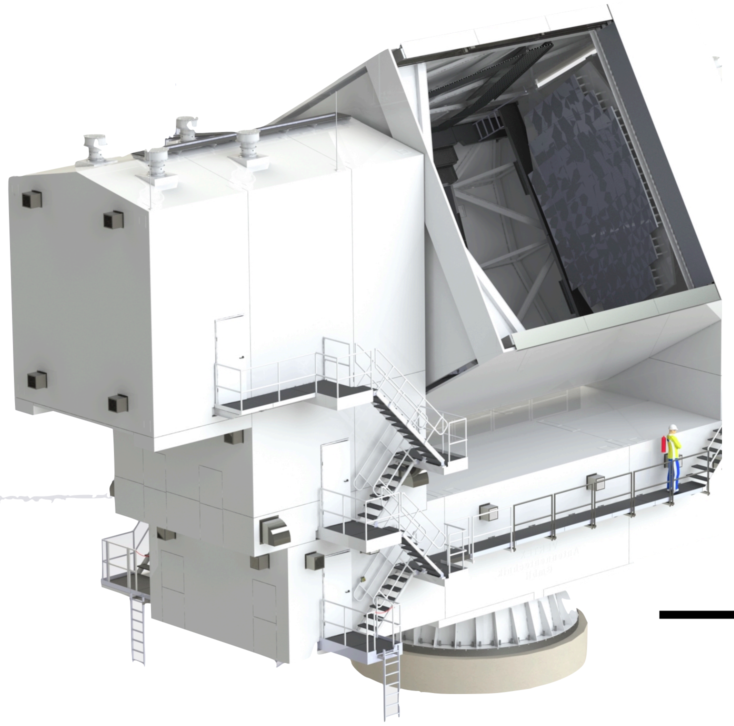
3. The Simons Observatory and LiteBIRD

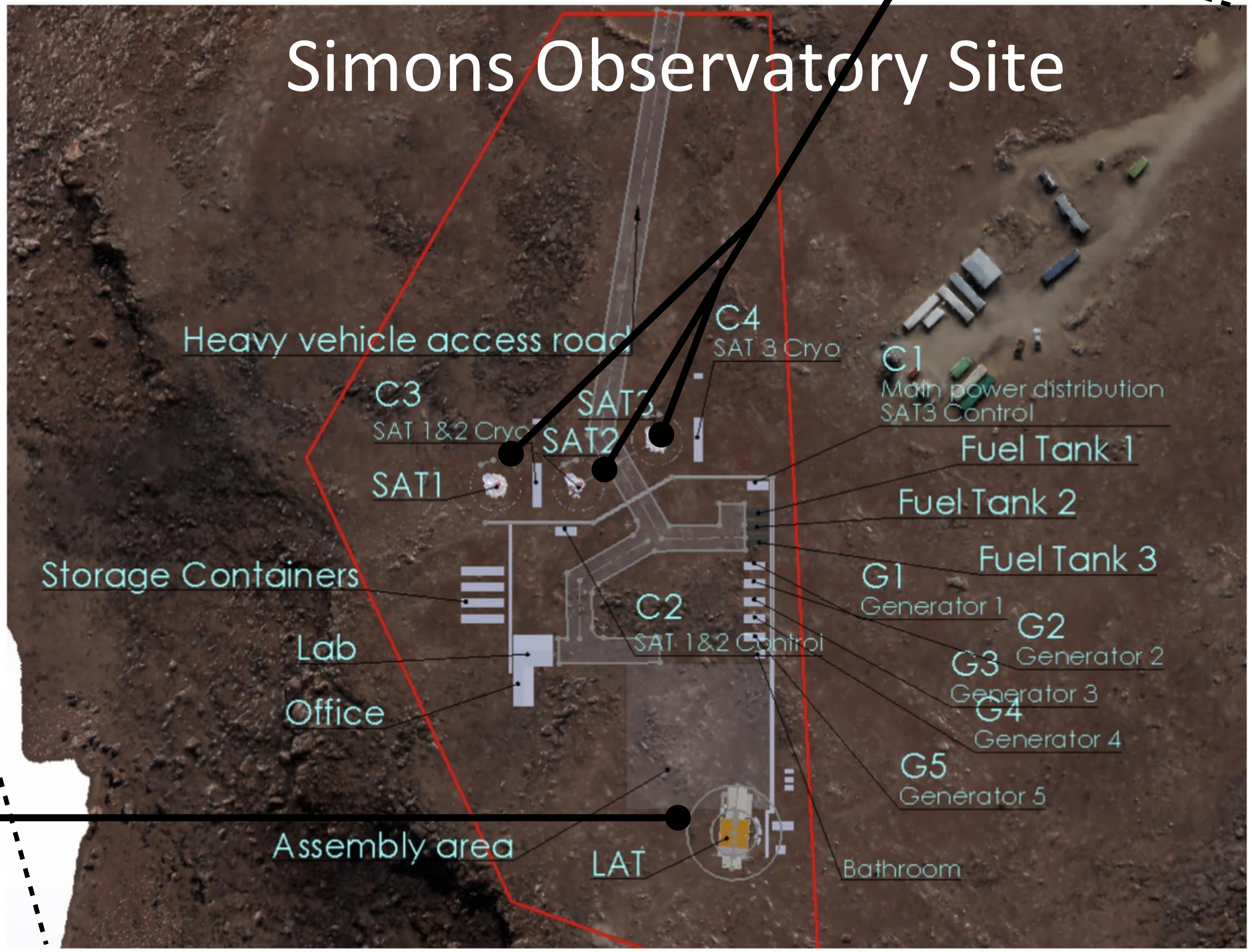

10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$\ell(\ell+1)\ C_\ell^{BB}\ /2\pi\ [\mu K^2]$
10^1
10^2
10^3
Multipole moment $\ell \sim \pi$/angular size
SIMONS
OBSERVATORY
1.0

more info: https://simonsobservatory.org/



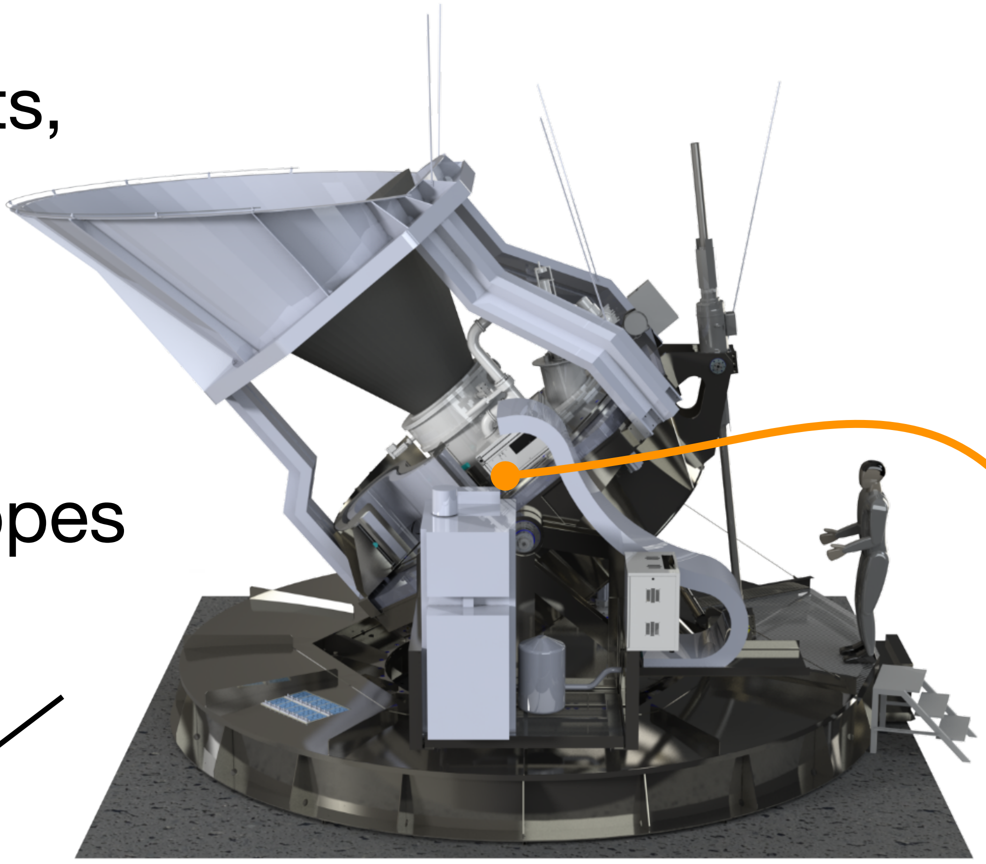


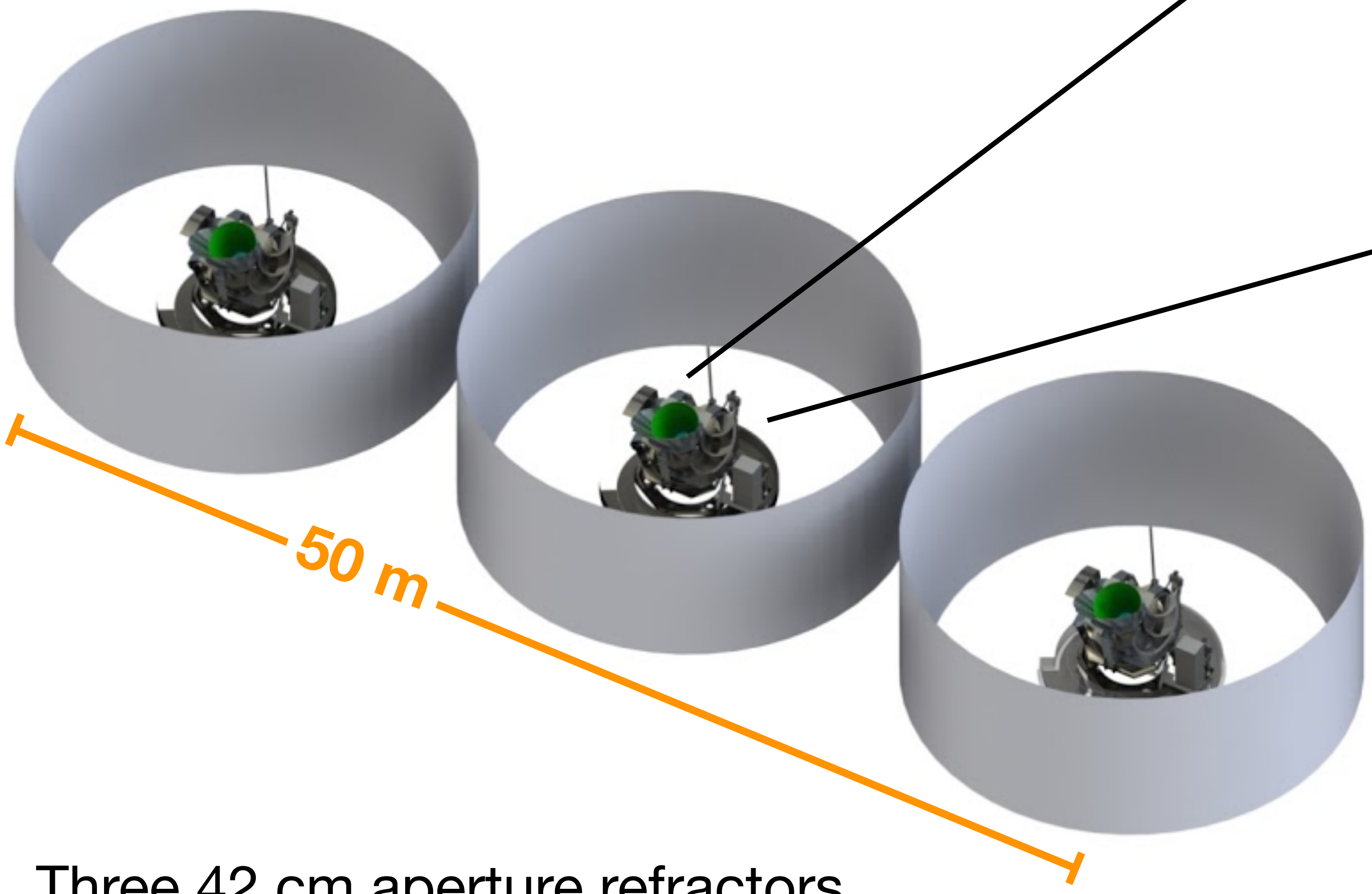




xForecast has been used in many contexts, for example:

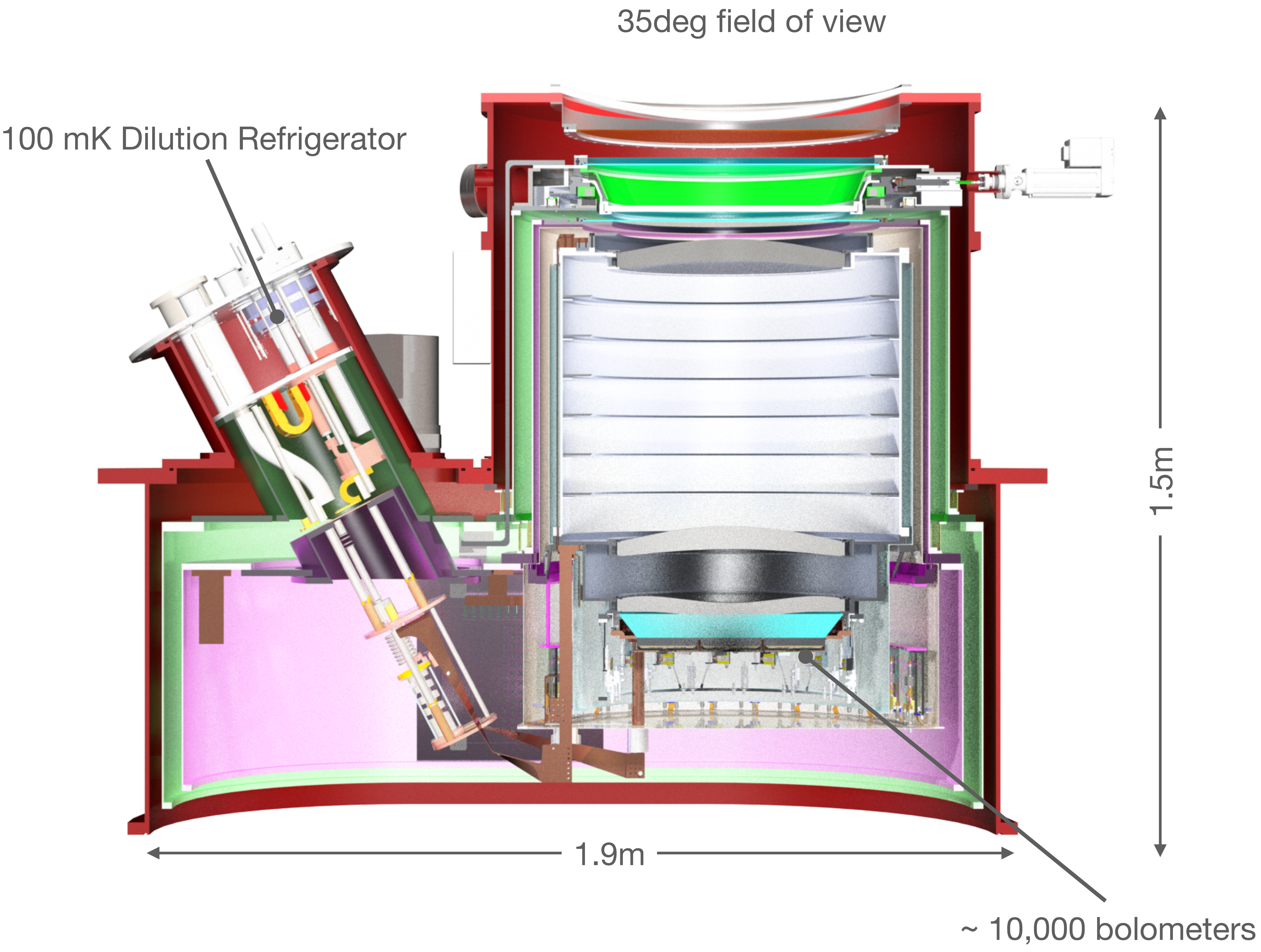
Simons Observatory
Small Aperture Telescopes





Three 42 cm aperture refractors, with dichroic pixels sensitive at:
30/40 | 90/150 | 90/150 | 220/270 GHz

- ~30,000 detectors in total for the 3 SATs
- Dilution-refrigerator-cooled 100-mK focal plane
- Cryogenic half-wave plate
- 1-K cryogenic 3-lens Si optics and 1-K stop


35deg field of view
100 mK Dilution Refrigerator
1.5m
1.9m
~ 10,000 bolometers

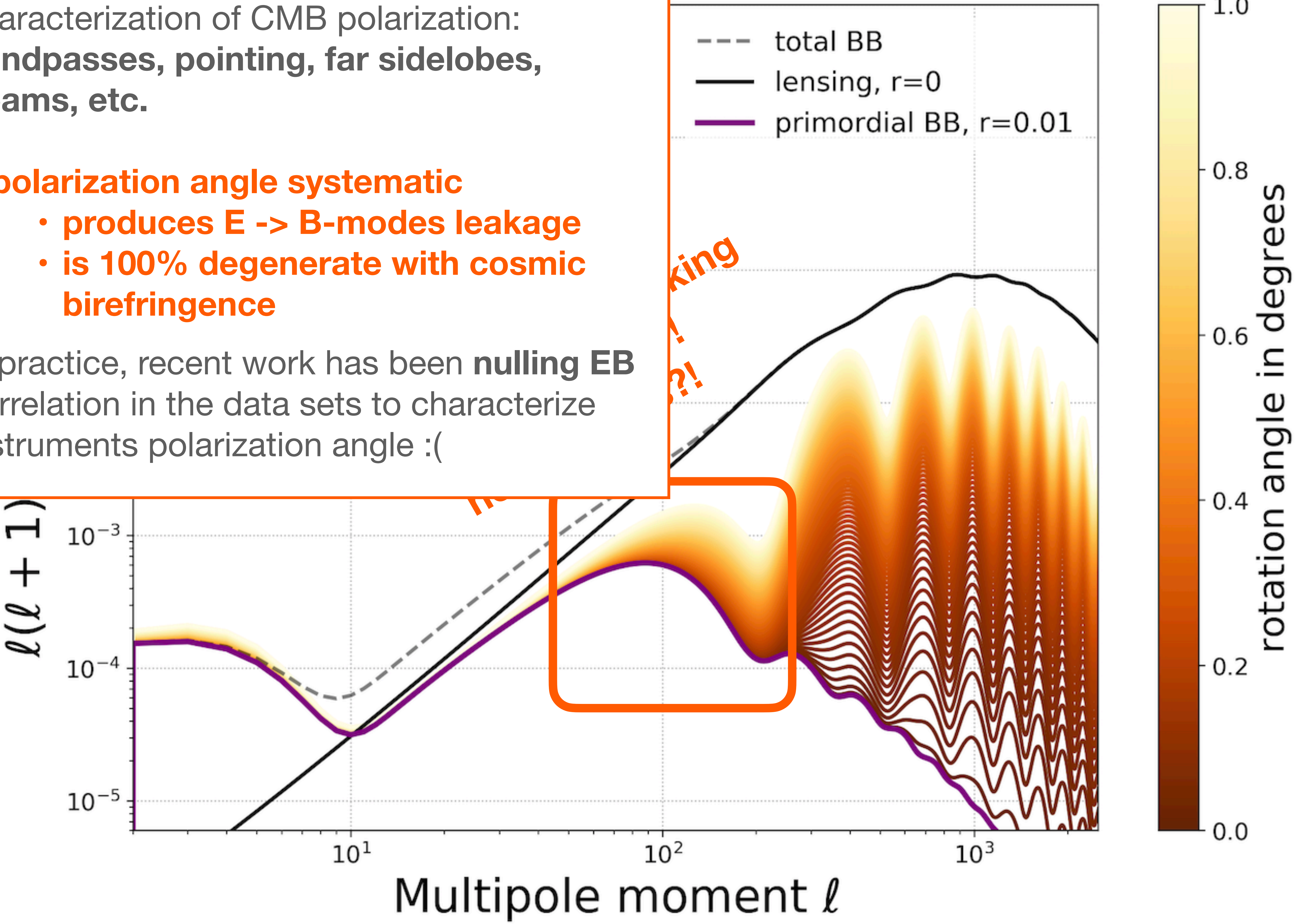
x10 speed

many systematics effects impacting the characterization of CMB polarization: **bandpasses, pointing, far sidelobes, beams, etc.**

+ polarization angle systematic

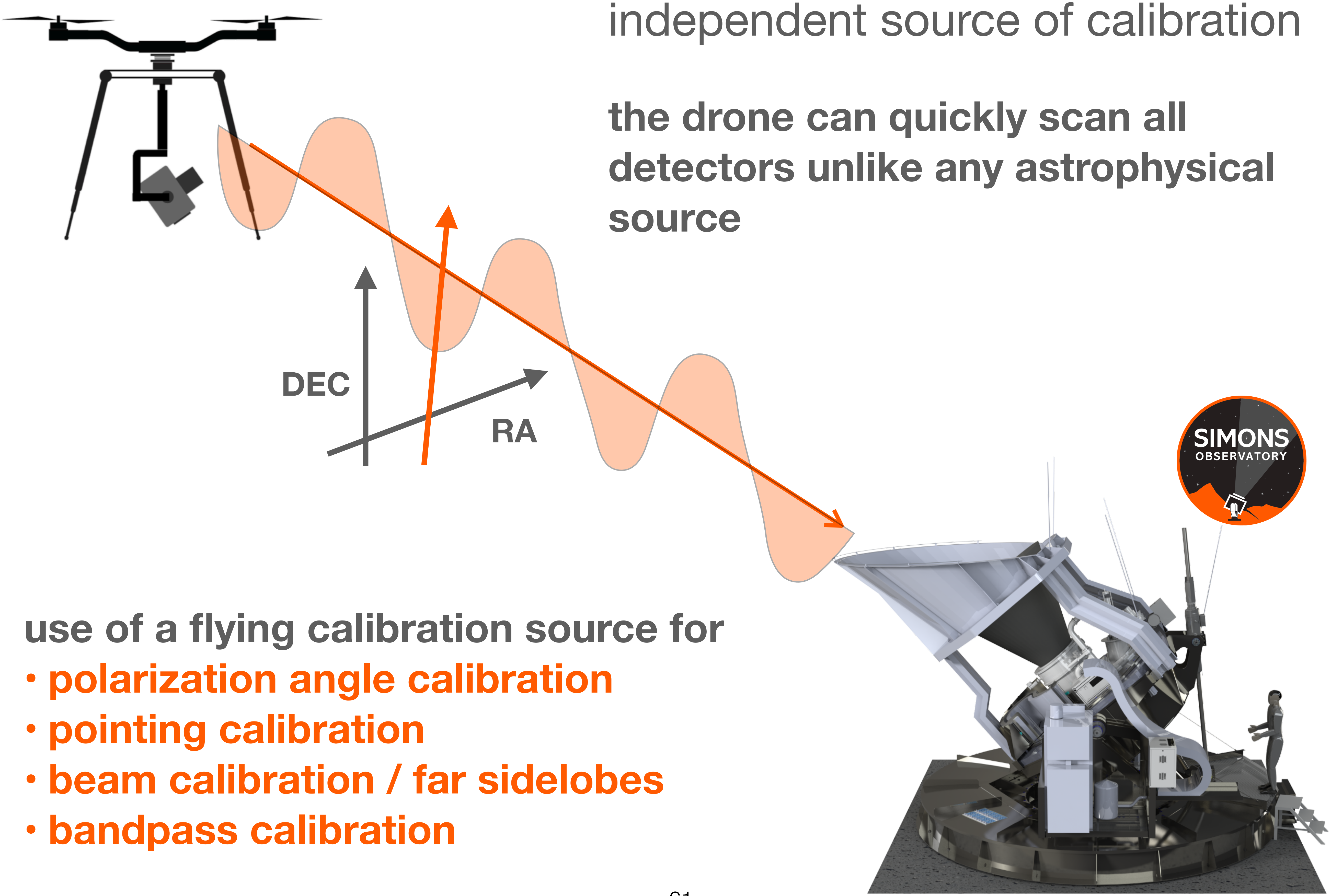
- **produces E -> B-modes leakage**
- **is 100% degenerate with cosmic birefringence**

in practice, recent work has been **nulling EB** correlation in the data sets to characterize instruments polarization angle :(



the idea is to have a cosmology-independent source of calibration

the drone can quickly scan all detectors unlike any astrophysical source



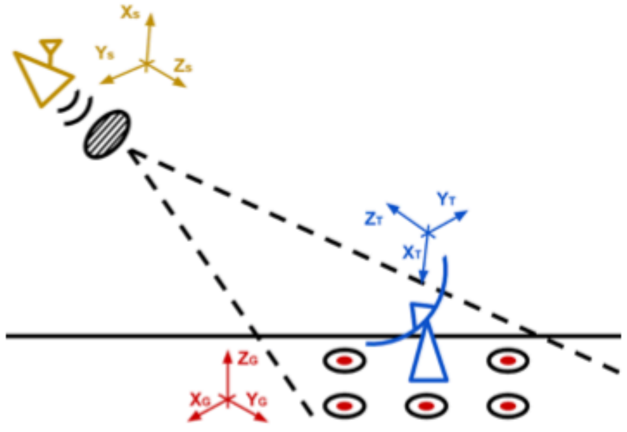
use of a flying calibration source for

- **polarization angle calibration**
- **pointing calibration**
- **beam calibration / far sidelobes**
- **bandpass calibration**

Photogrammetric position reconstruction

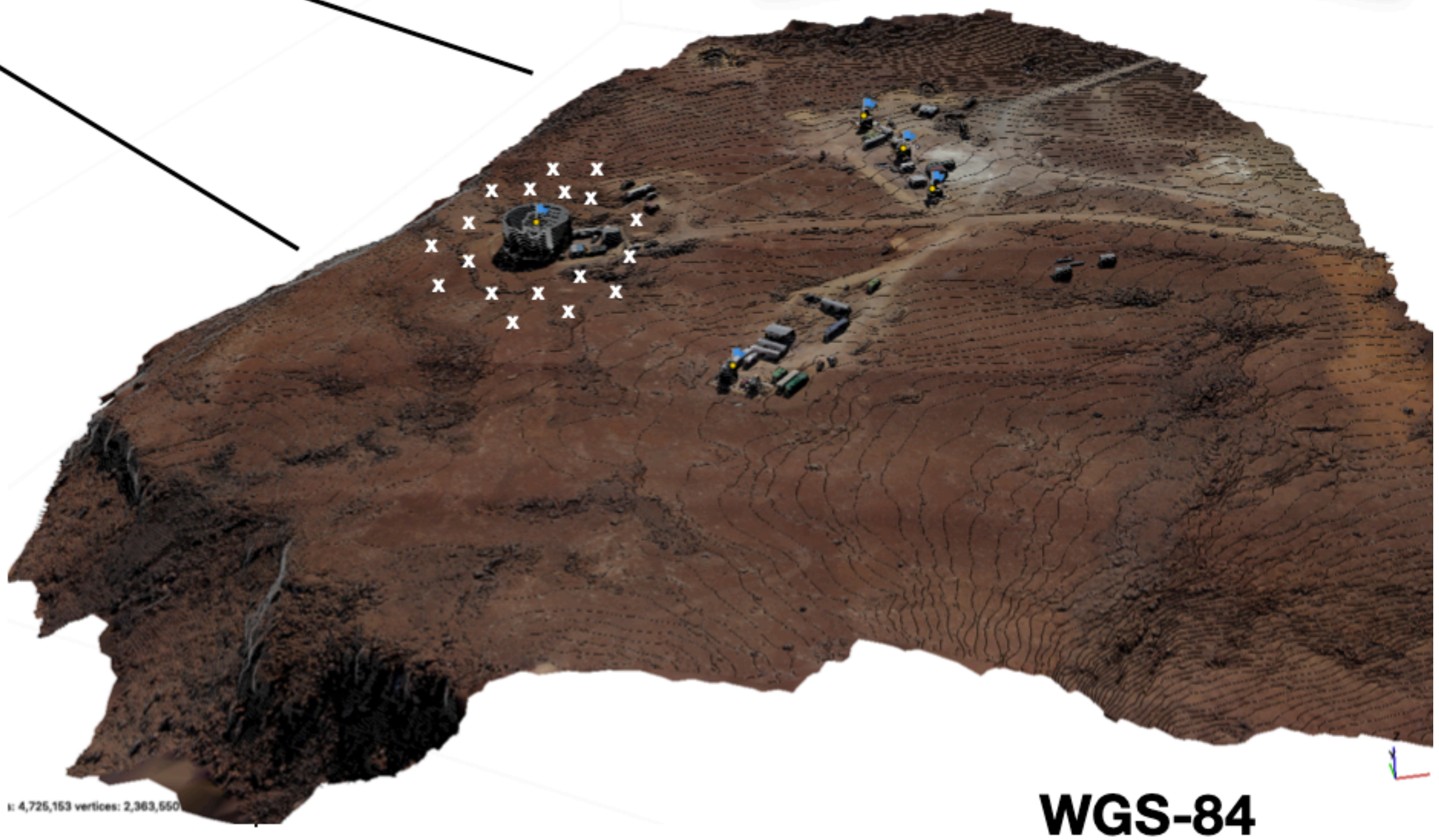
High precision in-time metrology

Determine camera coordinates and angles: (x,y,z,θ,ϕ,ψ)



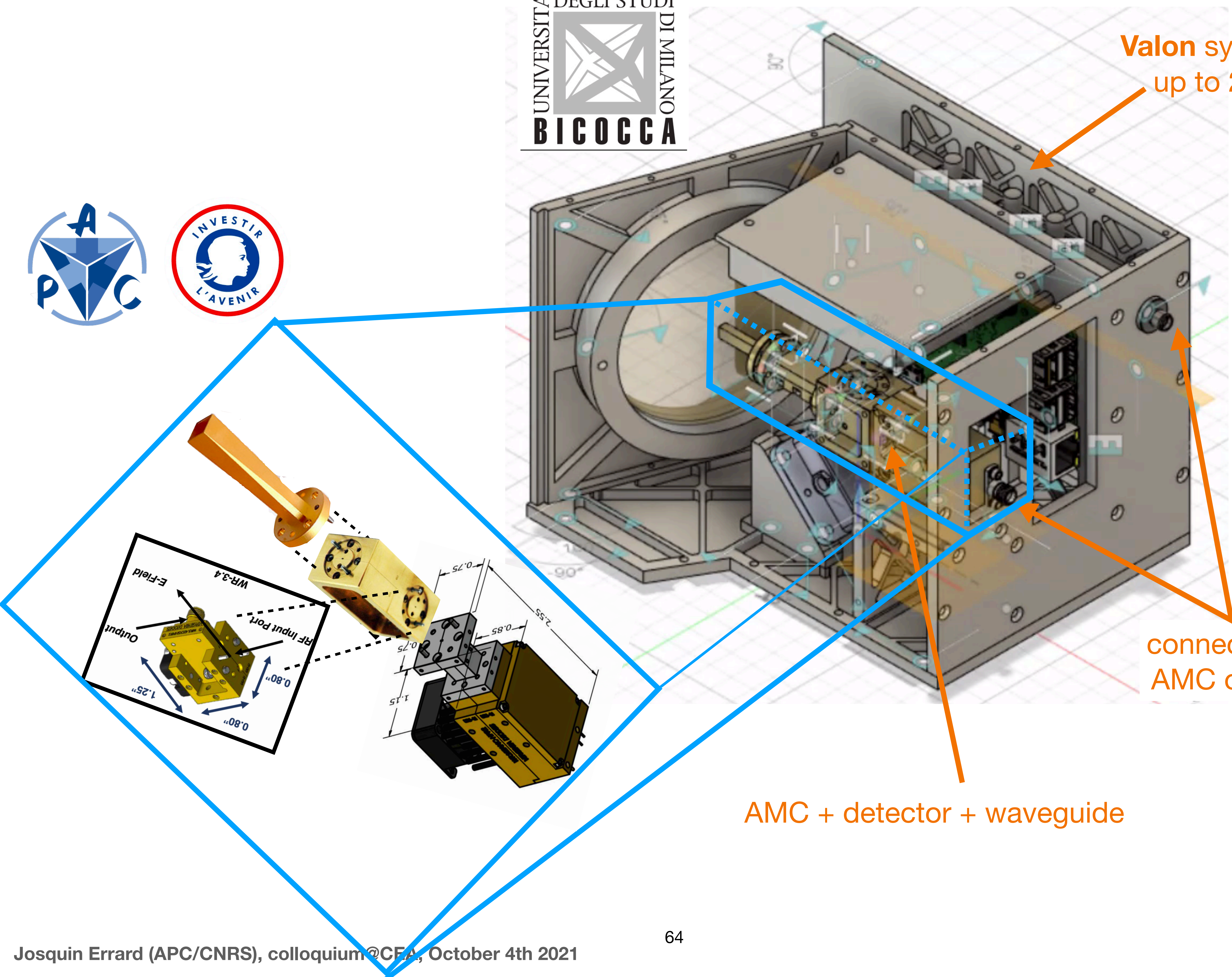
Build a reference coordinate system

- We plan to use photogrammetry to measure the time varying position of the source with high accuracy.
- The camera position and angle can be precisely reconstructed from fiducial marks on the ground.
- The polarization angle of the source will be referenced to the angle of the camera.
- The source and camera will be held on a rigid frame, and their relative angles will be calibrated in the laboratory.



WGS-84

From Rolando Dunner



Valon synthesizer
up to 20GHz

connection to
AMC outside

AMC + detector + waveguide

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

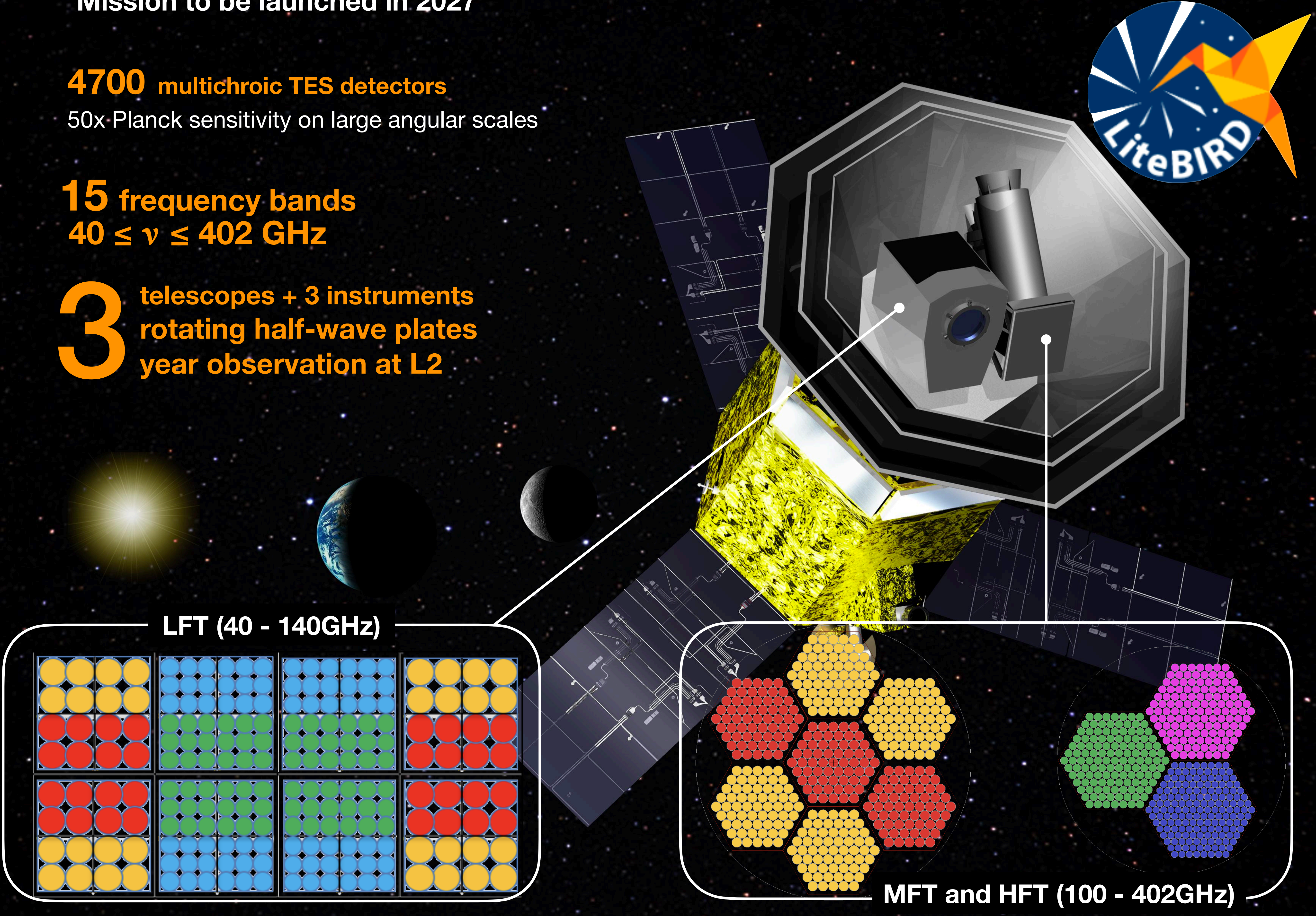
4700 multichroic TES detectors

50x Planck sensitivity on large angular scales

15 frequency bands

$40 \leq \nu \leq 402$ GHz

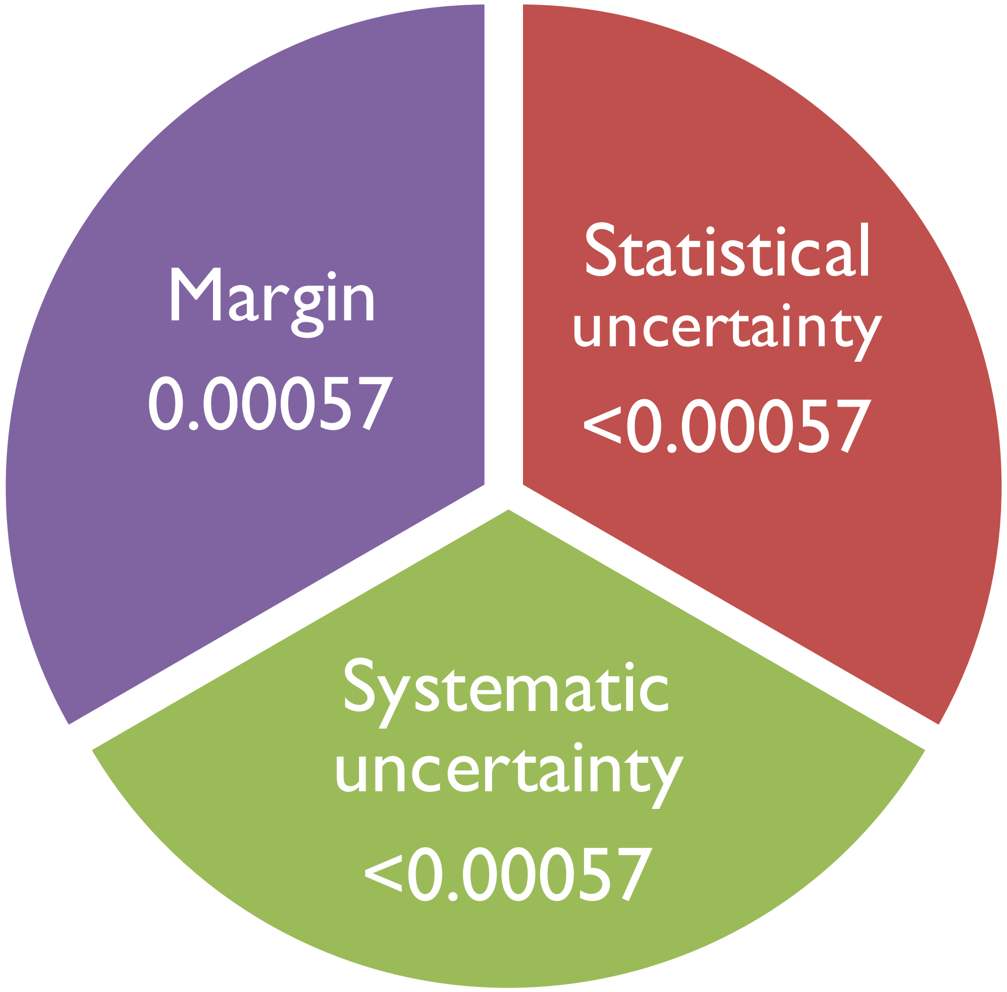
3 **telescopes + 3 instruments**
rotating half-wave plates
year observation at L2



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

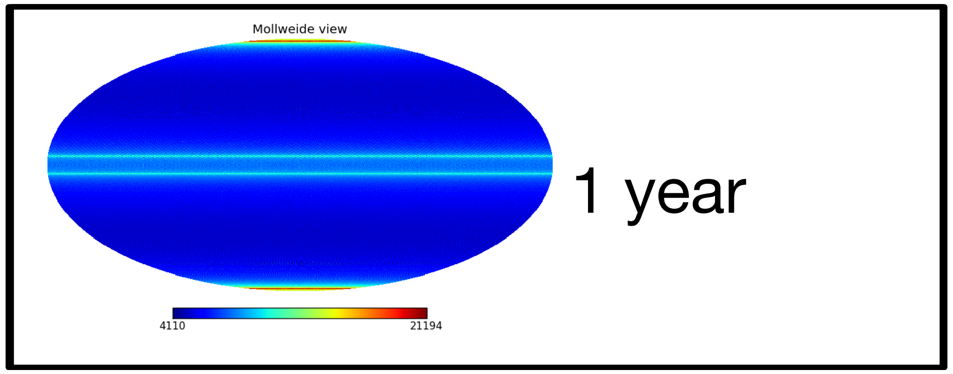
- foreground cleaning residuals
- lensing B-mode power
- 1/f noise

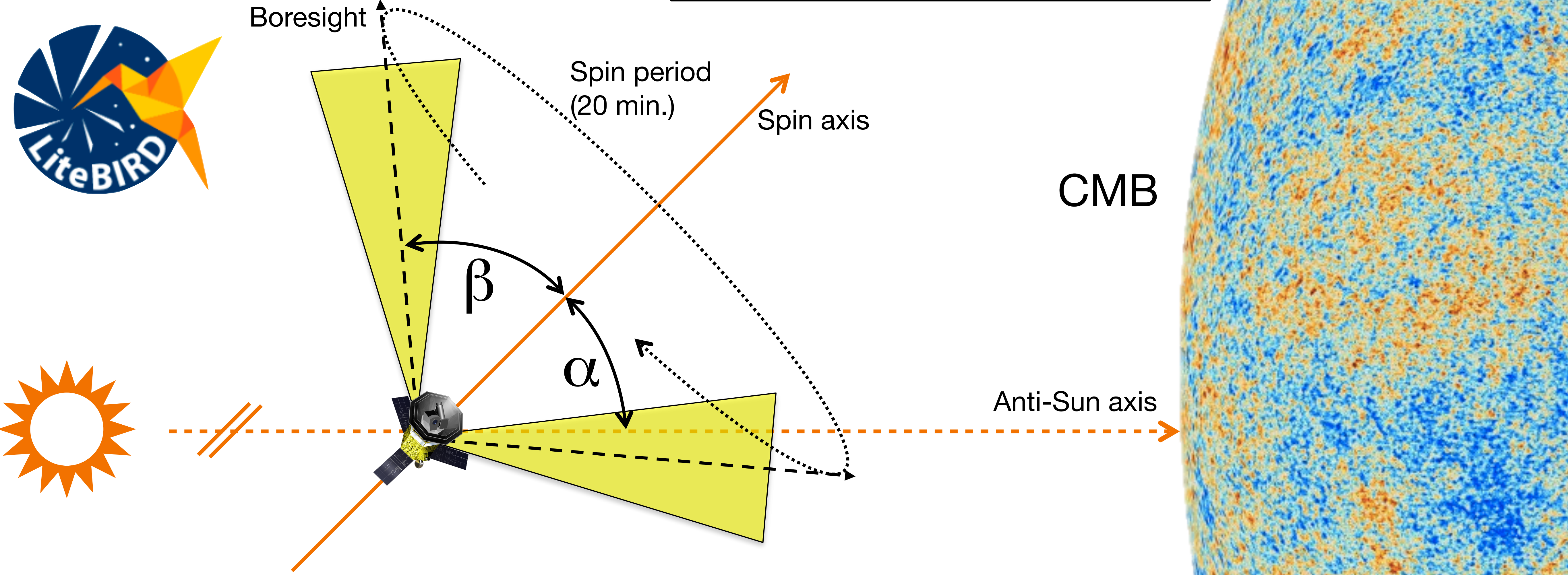
systematic uncertainty includes

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

LiteBIRD Operation

Sun-Earth L2 Lissajous Orbit

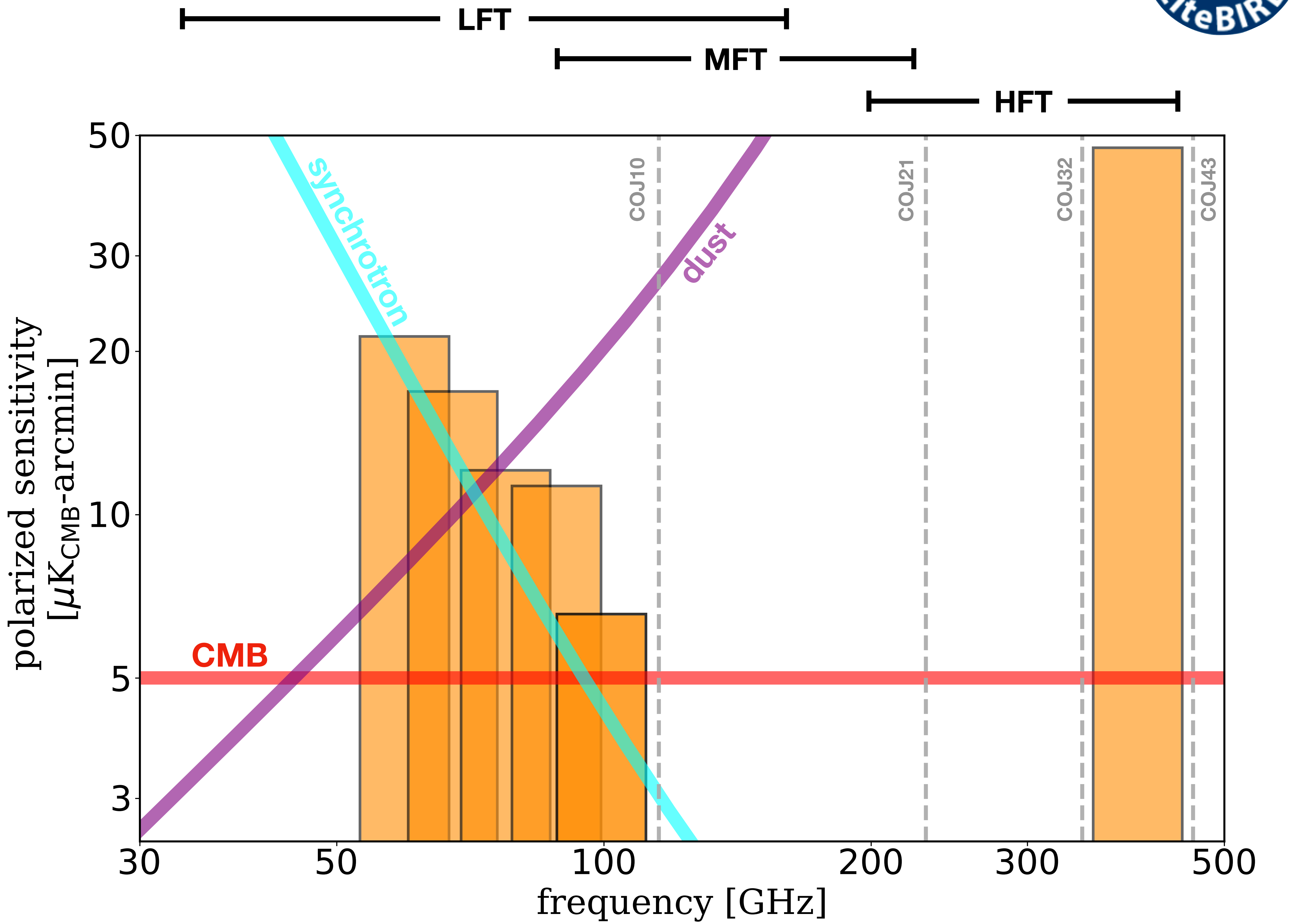




Precession angle α = 45 degrees
Spin angle β = 50 degrees

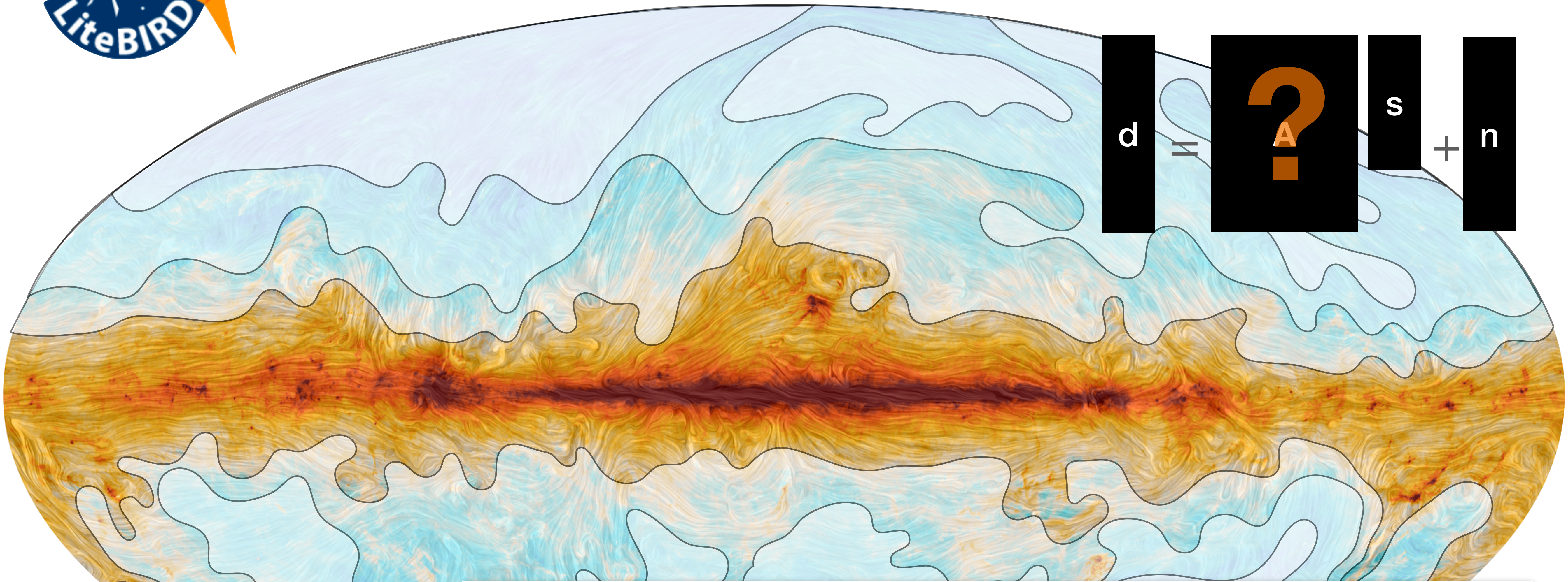
“Precession” period 3.2058 hours

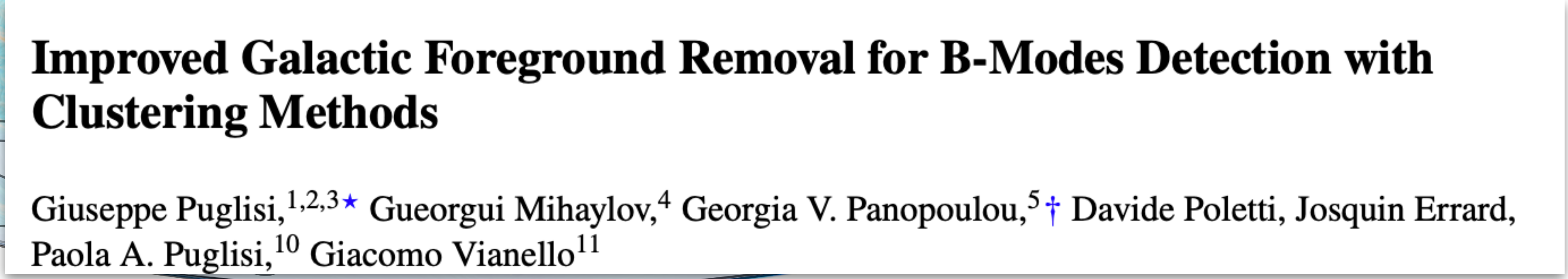
LiteBIRD: 15 frequency bands



Josquin

LiteBIRD component separation





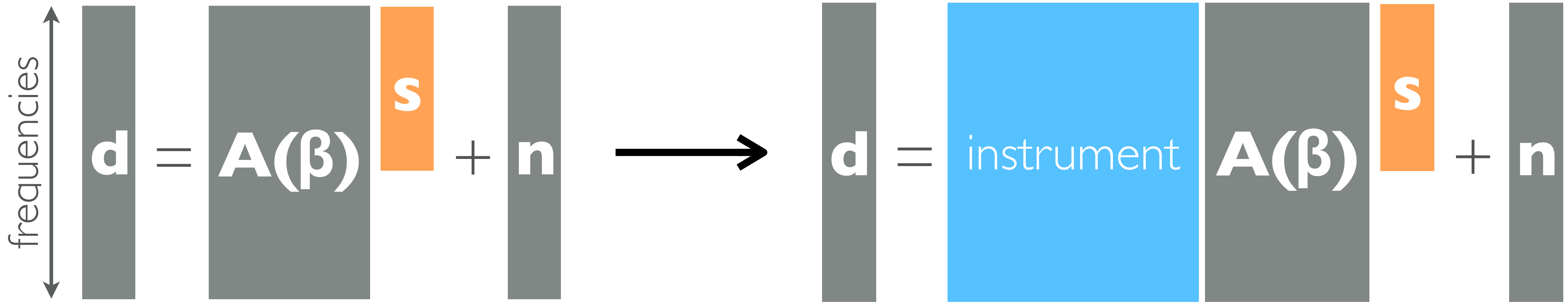
Improved Galactic Foreground Removal for B-Modes Detection with Clustering Methods

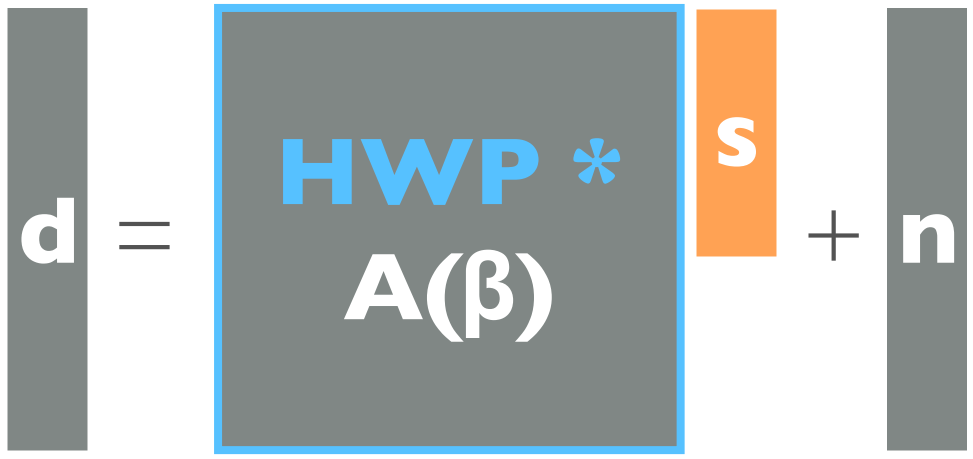
Giuseppe Puglisi,[1,2,3]★ Gueorgui Mihaylov,[4] Georgia V. Panopoulou,[5]† Davide Poletti, Josquin Errard, Paola A. Puglisi,[10] Giacomo Vianello[11]

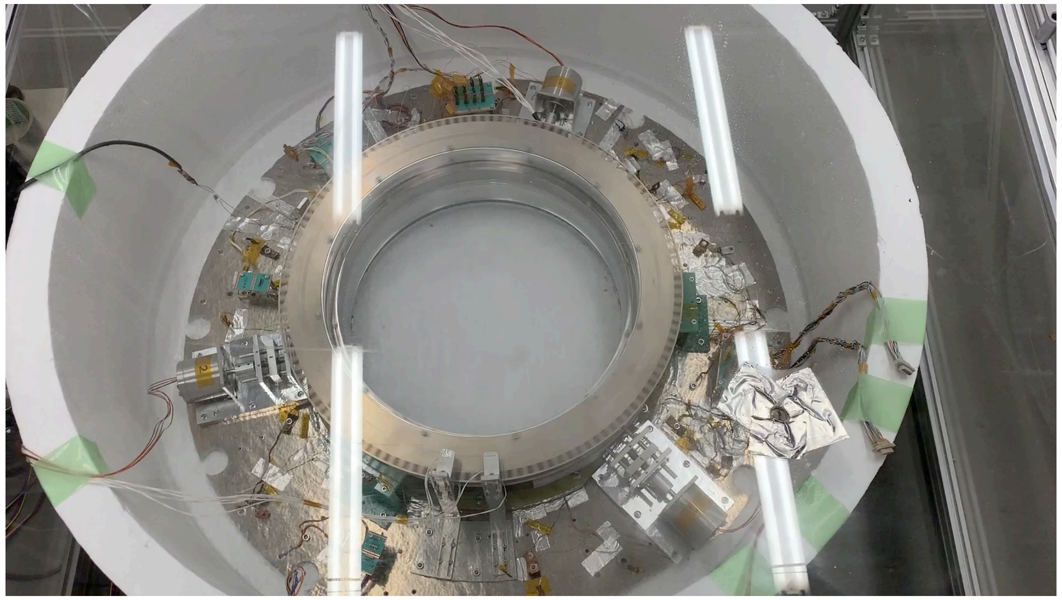
credits: Planck/ESA

we decompose the observed sky in distinct regions where dust / synchrotron are believed to follow significantly different SED
➔ this is an idea developed/tested/validated within LiteBIRD to minimize the statistical uncertainty after component separation

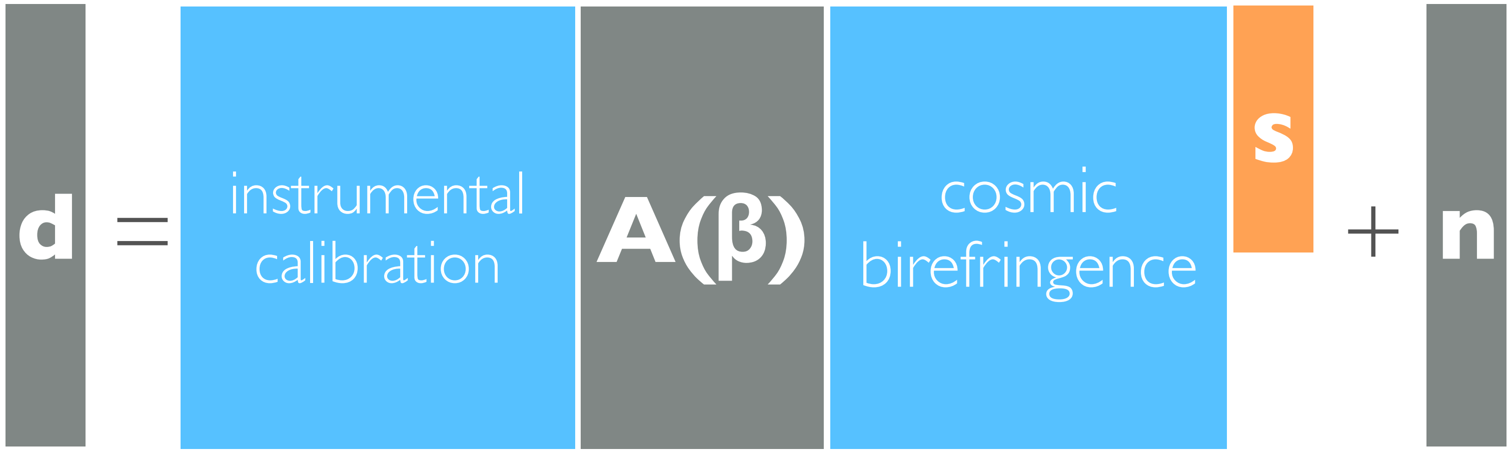
CMB challenges: next steps in “component separation”







Vergès, JE, Stompor (2020)



Jost, JE, Stompor (in prep)

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.)

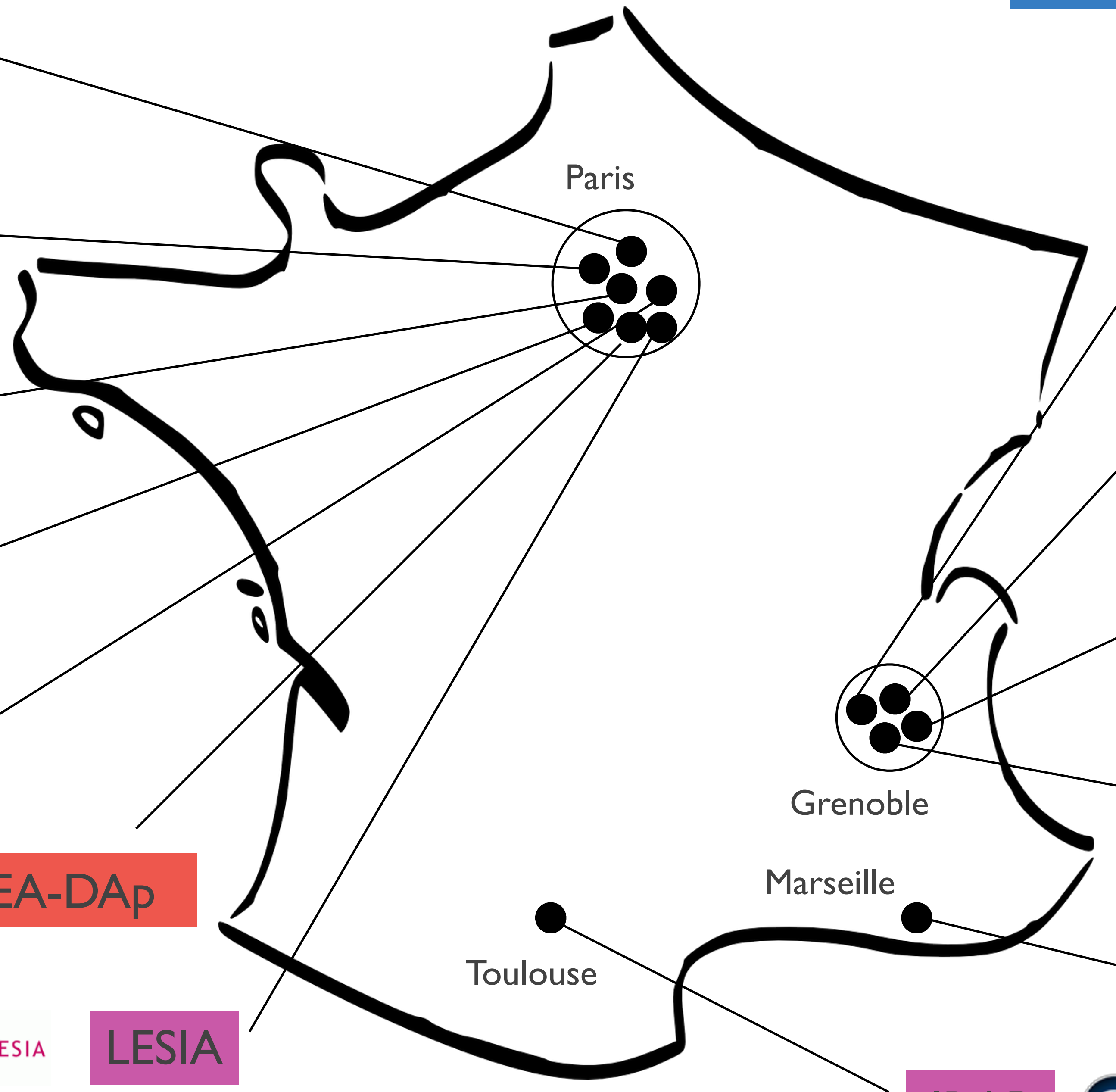
LiteBIRD Global face-to-face meeting,
@ Italian Space Agency, Jan. 2019

LiteBIRD in France

LiteBIRD-FRANCE

47 chercheurs
20 ingénieurs
(33 External Members)

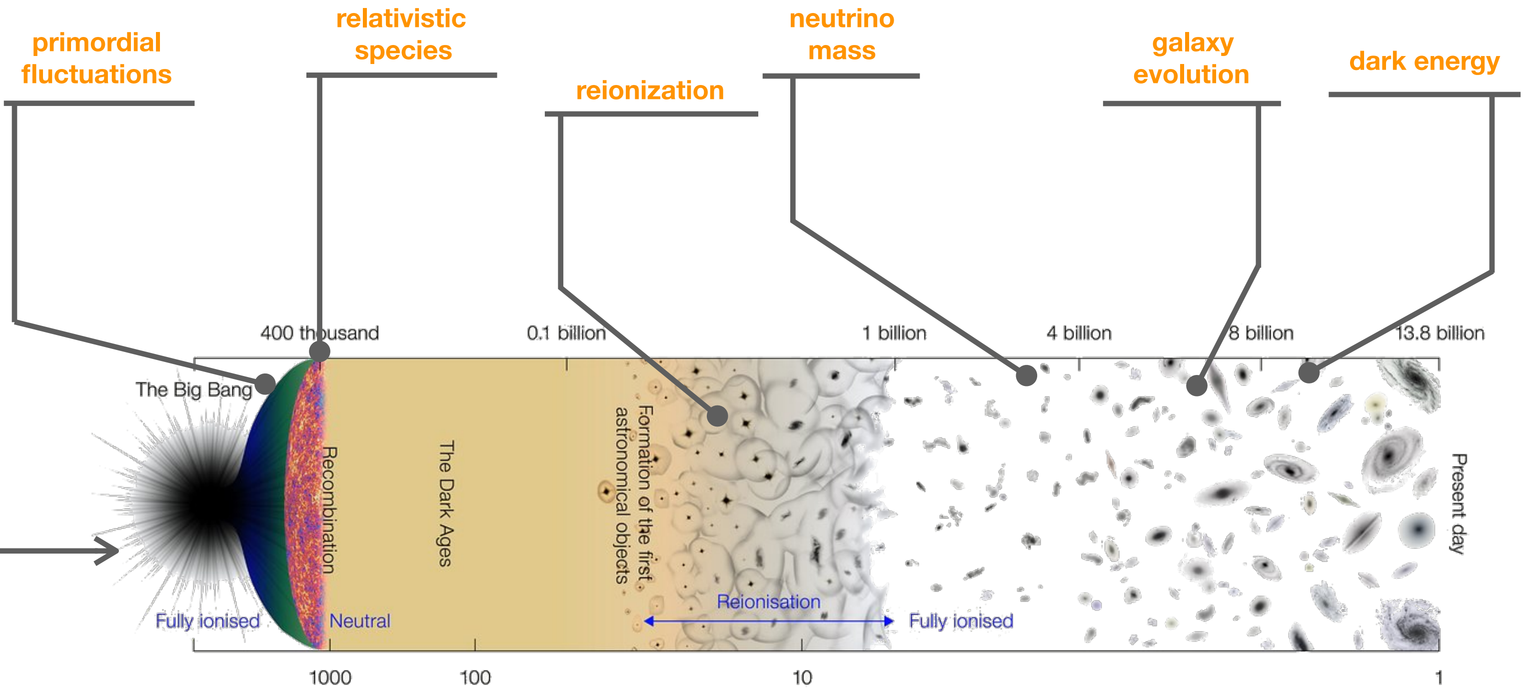
🟧 IN2P3
🟥 CEA
🟪 INSU
⬜ ENS
🟦 INP



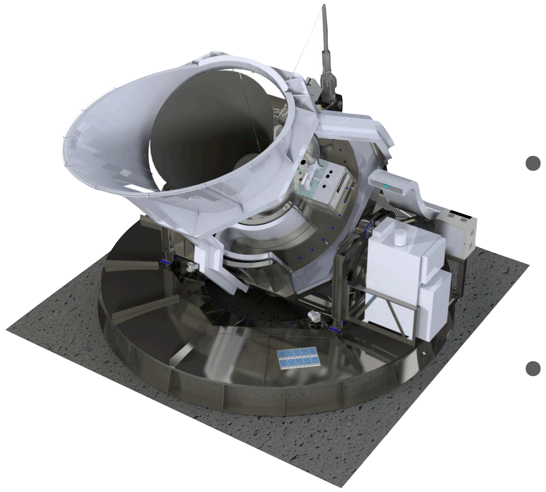
- APC
- IAP
- LAL
- IAS
- ENS
- CEA-DAp
- LESIA
- LPSC
- IPAG
- I. Neel
- CEA-SBT
- LAM
- IRAP

Conclusions

- CMB is an open window onto the physics at the highest energies
- a lot of exciting science to be done looking at the early and late Universe



- detection of primordial CMB B-modes would be a wonderful observational evidence for cosmic inflation



- bigger focal planes and larger observatories are being designed and built
- a lot of challenges ahead, in particular the control of astrophysical and instrumental systematics

- stay tune for the deployment of the **Simons Observatory!** and later, for the launch of **LiteBIRD**!