Future CMB experiments probing primordial GWs

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irap
astrophysique & planétologie

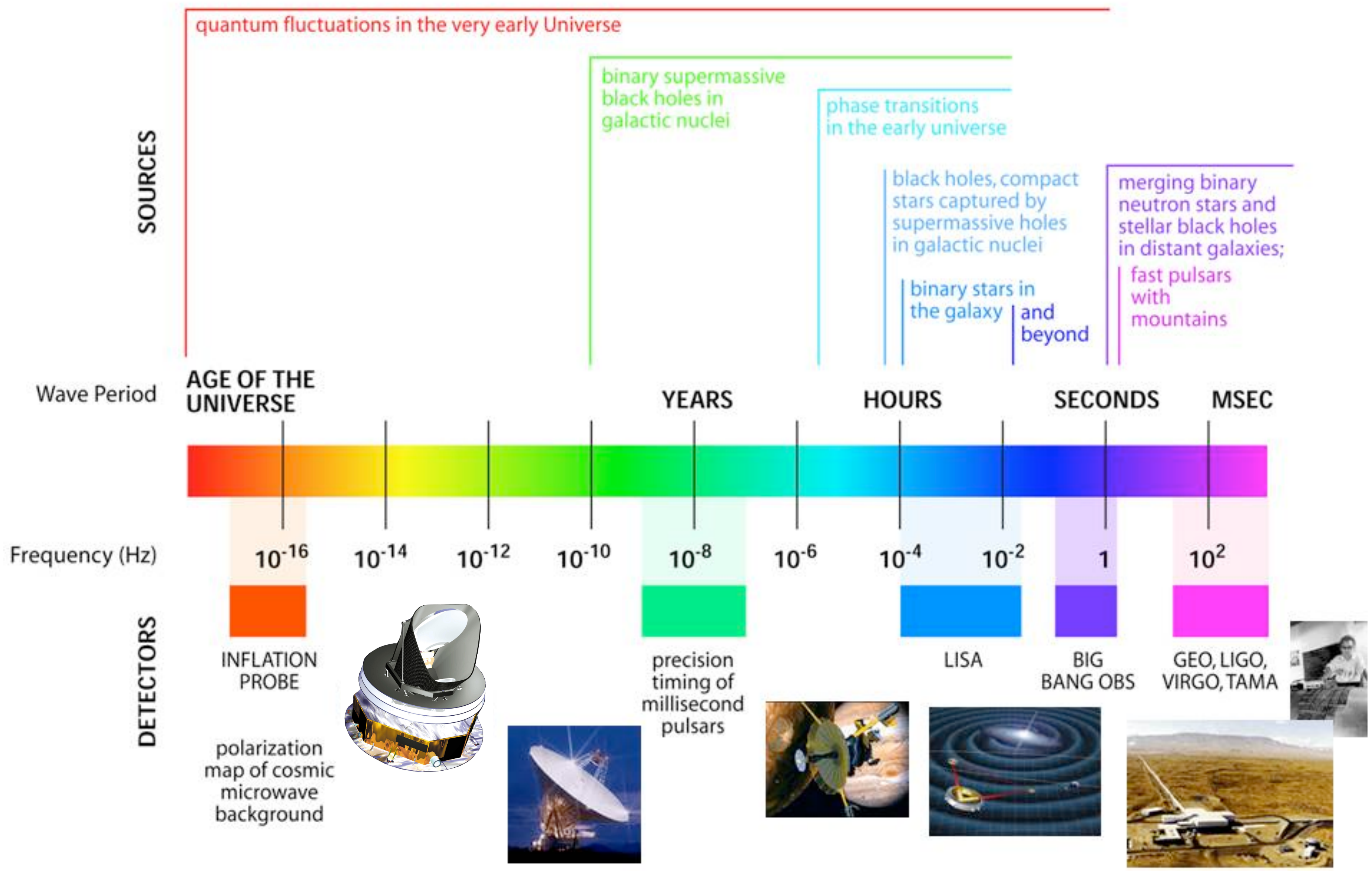
SIMONS OBSERVATORY

CMB-S4
Next Generation CMB Experiment

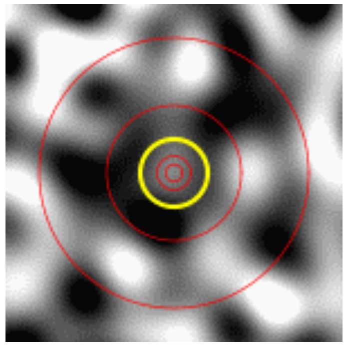
LiteBIRD

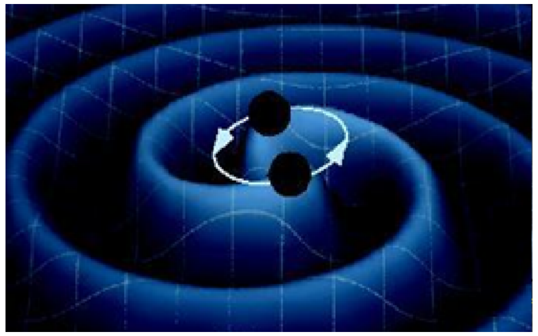
Looking for Primordial Gravitational waves

Big leap between LISA and CMB Probes



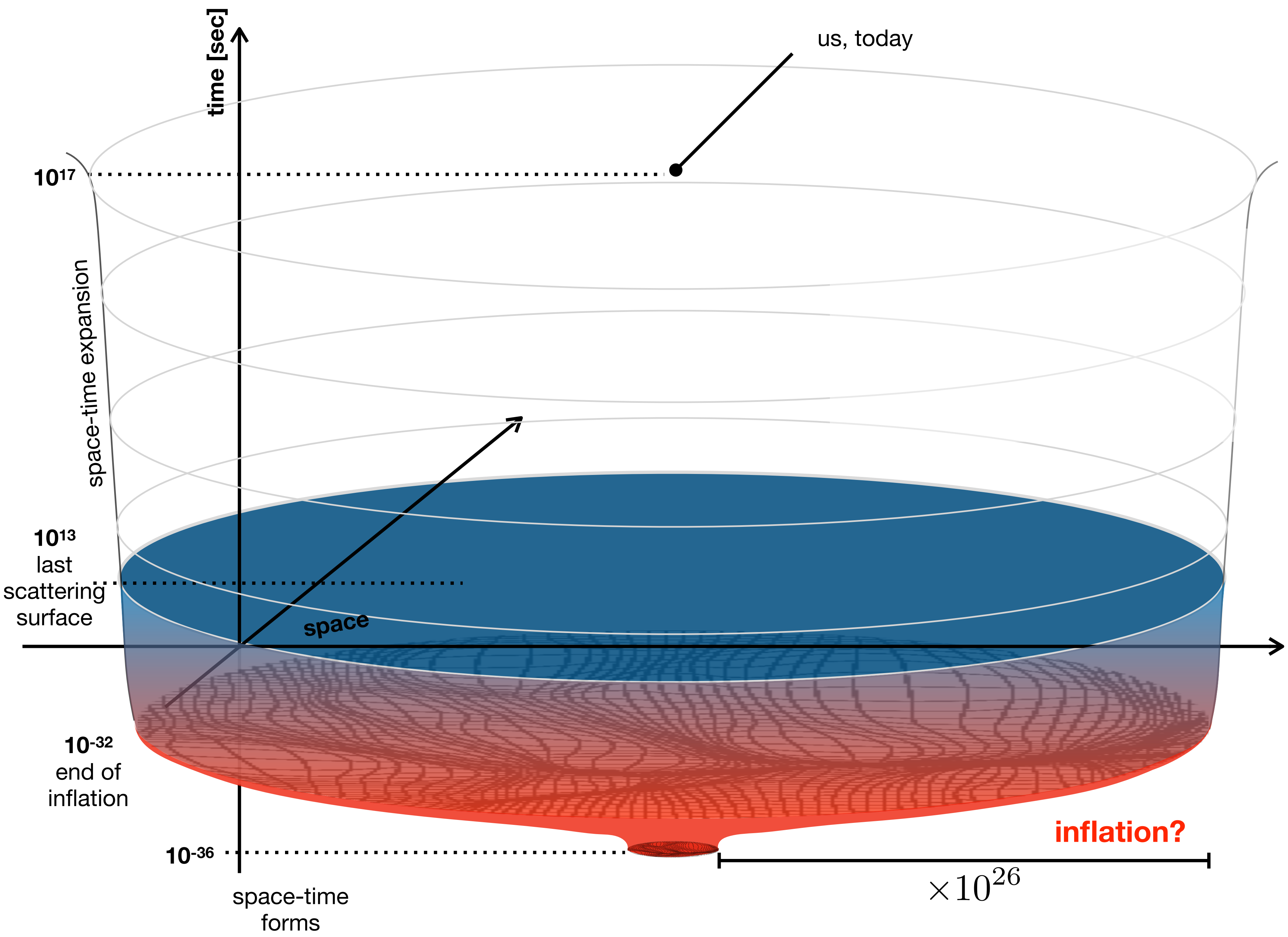
Gravitational waves with quantum origin





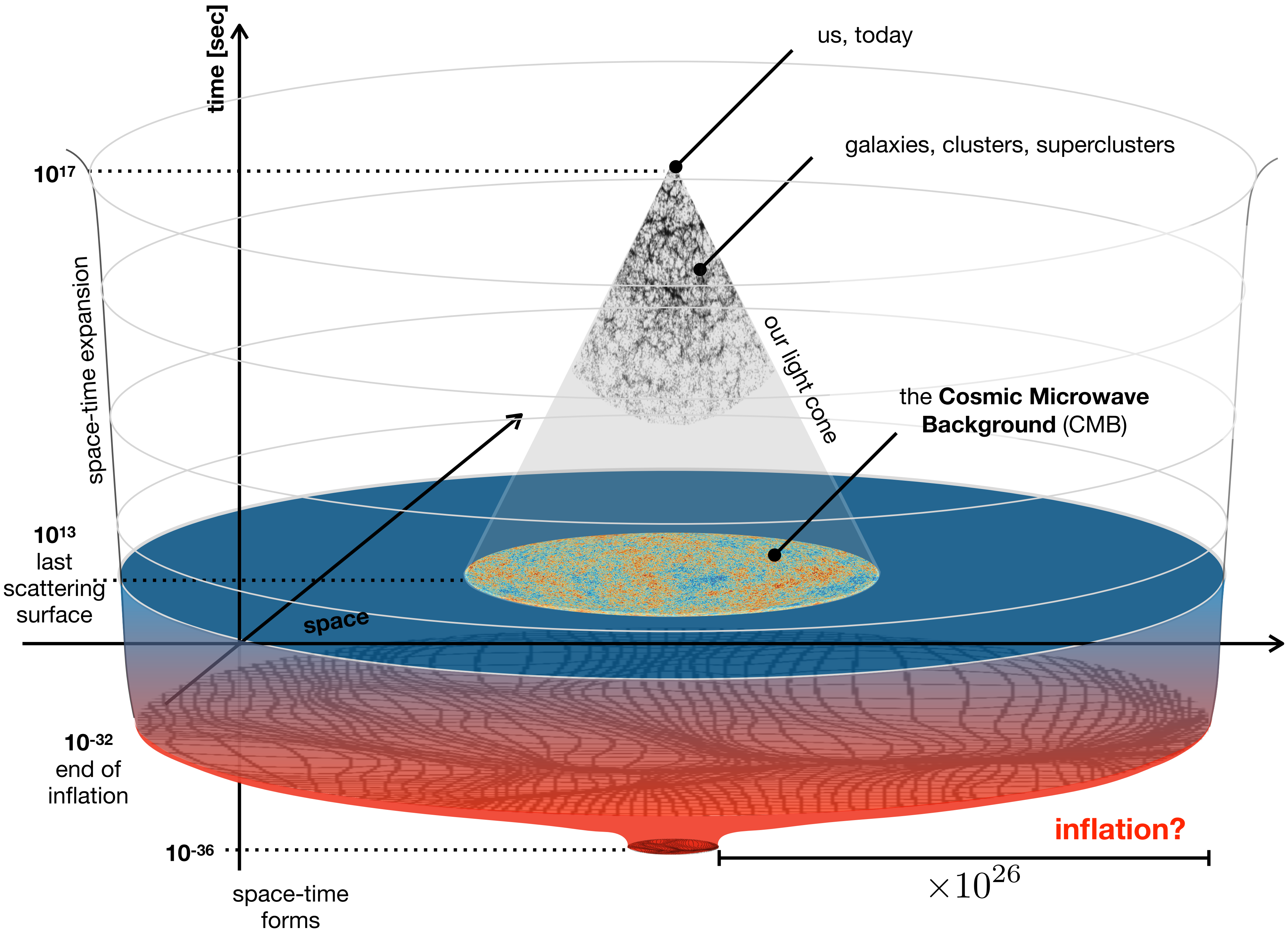
Gravitational waves with classical origin

Looking for Primordial Gravitational waves



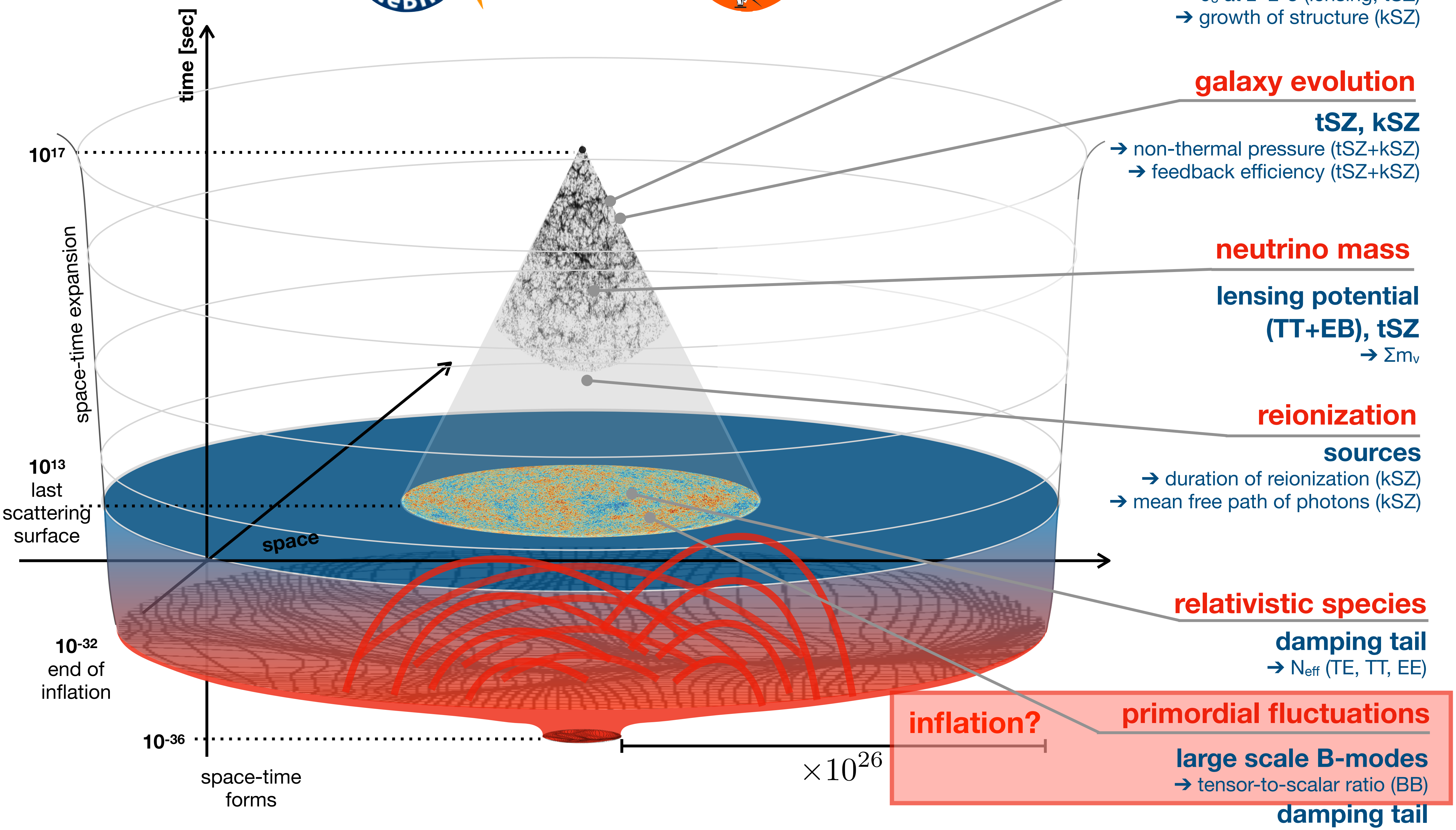
Credits: Josquin Errard

Looking for Primordial Gravitational waves



Credits: Josquin Errard

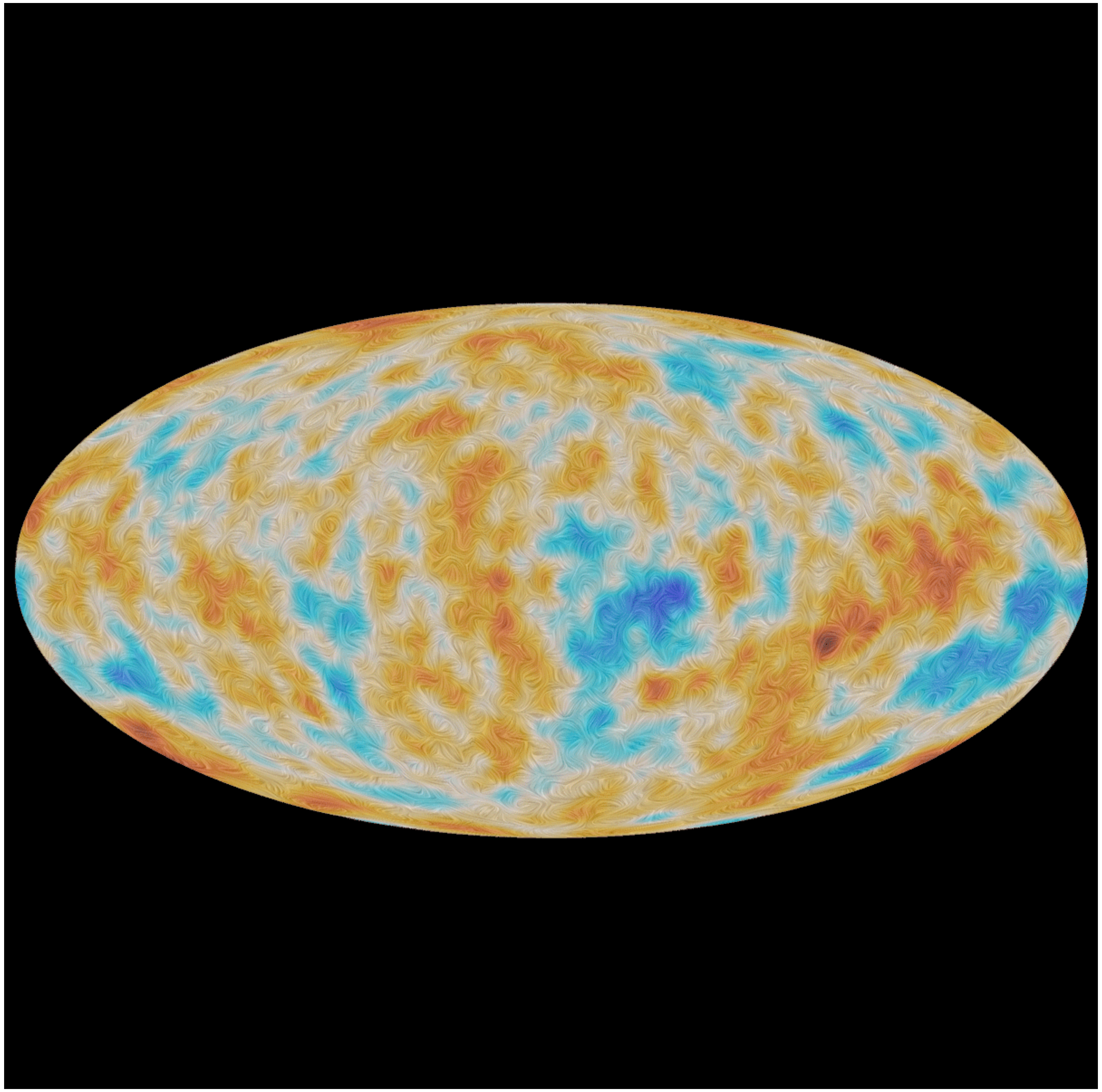
Looking for Primordial Gravitational waves



Credits: Josquin Errard

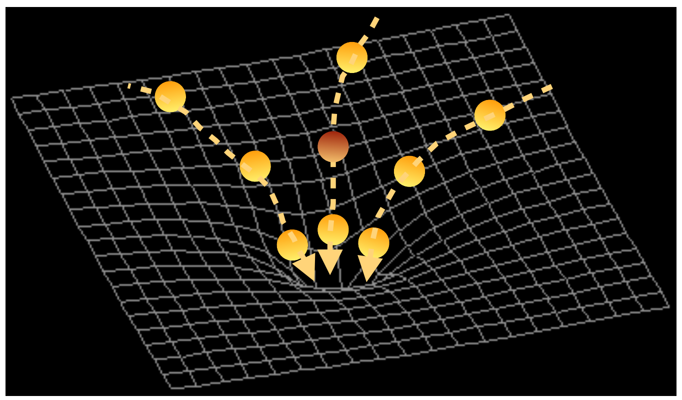
Looking for Primordial Gravitational waves

The imprints of gravitational waves on CMB

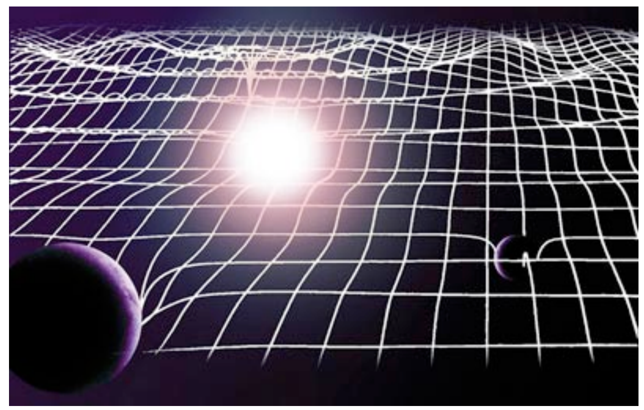


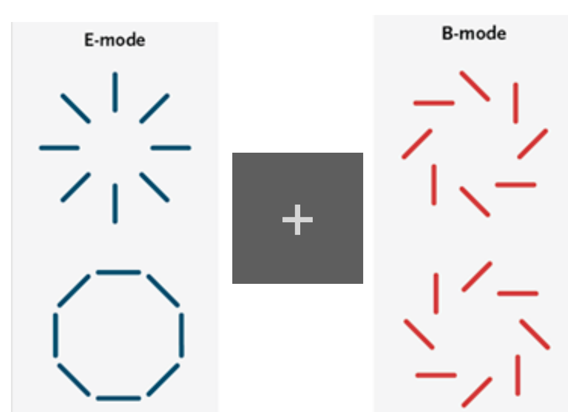
Looking for Primordial Gravitational waves

The imprints of gravitational waves on CMB



Gravitational waves





Inflation

↓

Quantum fluctuation of spacetime

↓

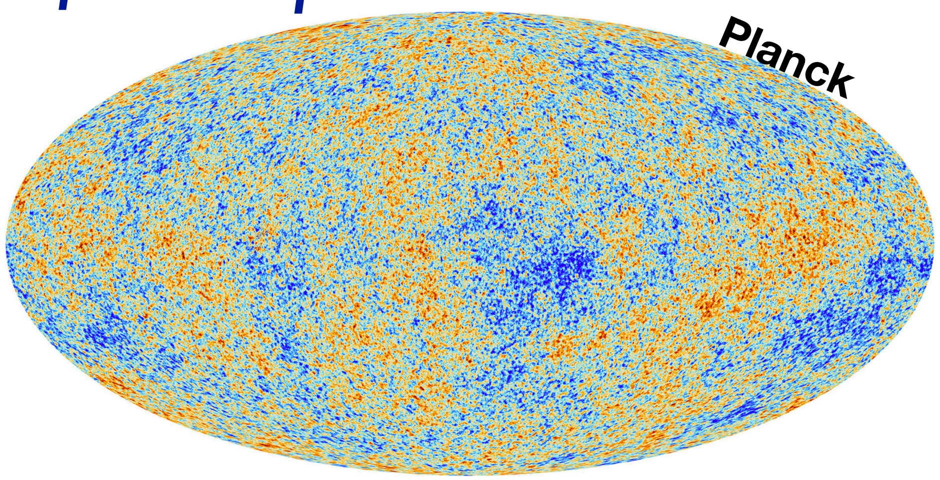
Primordial gravitational waves

↓

“vortex”es in the CMB polarization map (called “B-mode”)

Looking for Primordial Gravitational waves

… as a tracer of Inflation period



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

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

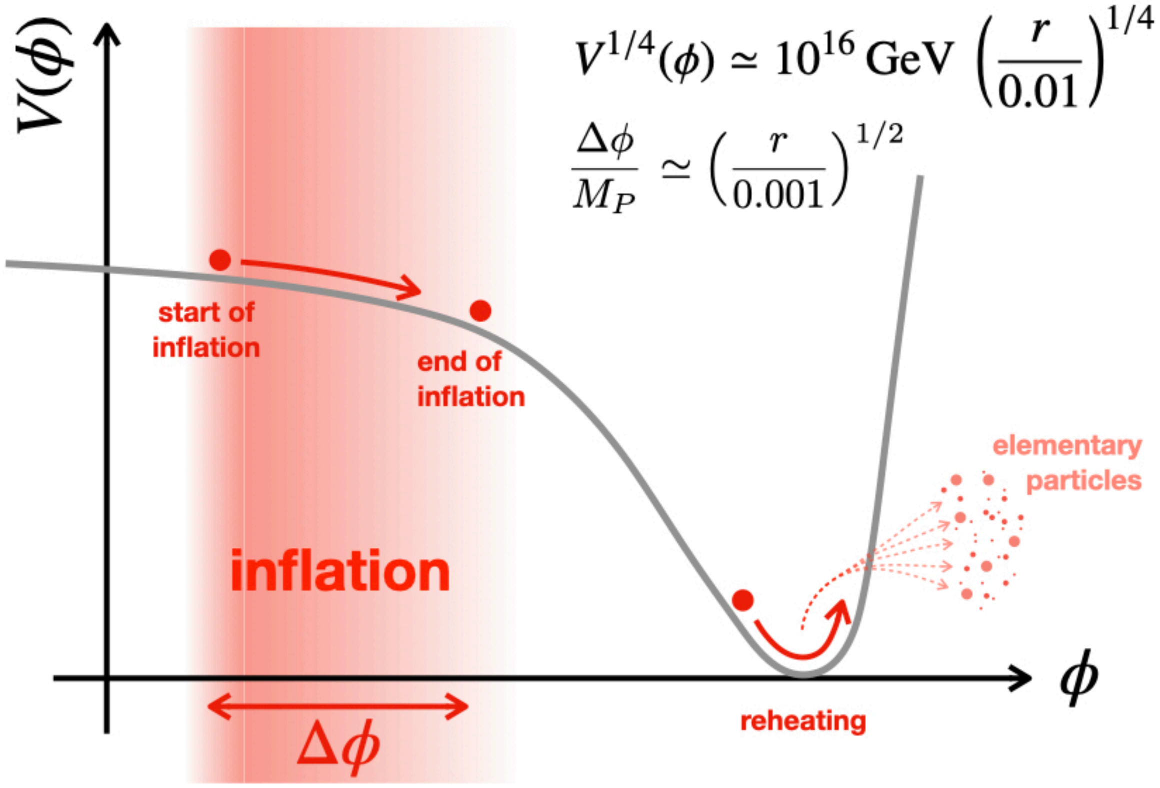
- **dynamics of an homogeneous scalar field in a FLRW geometry is given by**

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

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

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

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



- 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** ?

Looking for Primordial Gravitational waves

... *as a tracer of Inflation period*

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

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

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

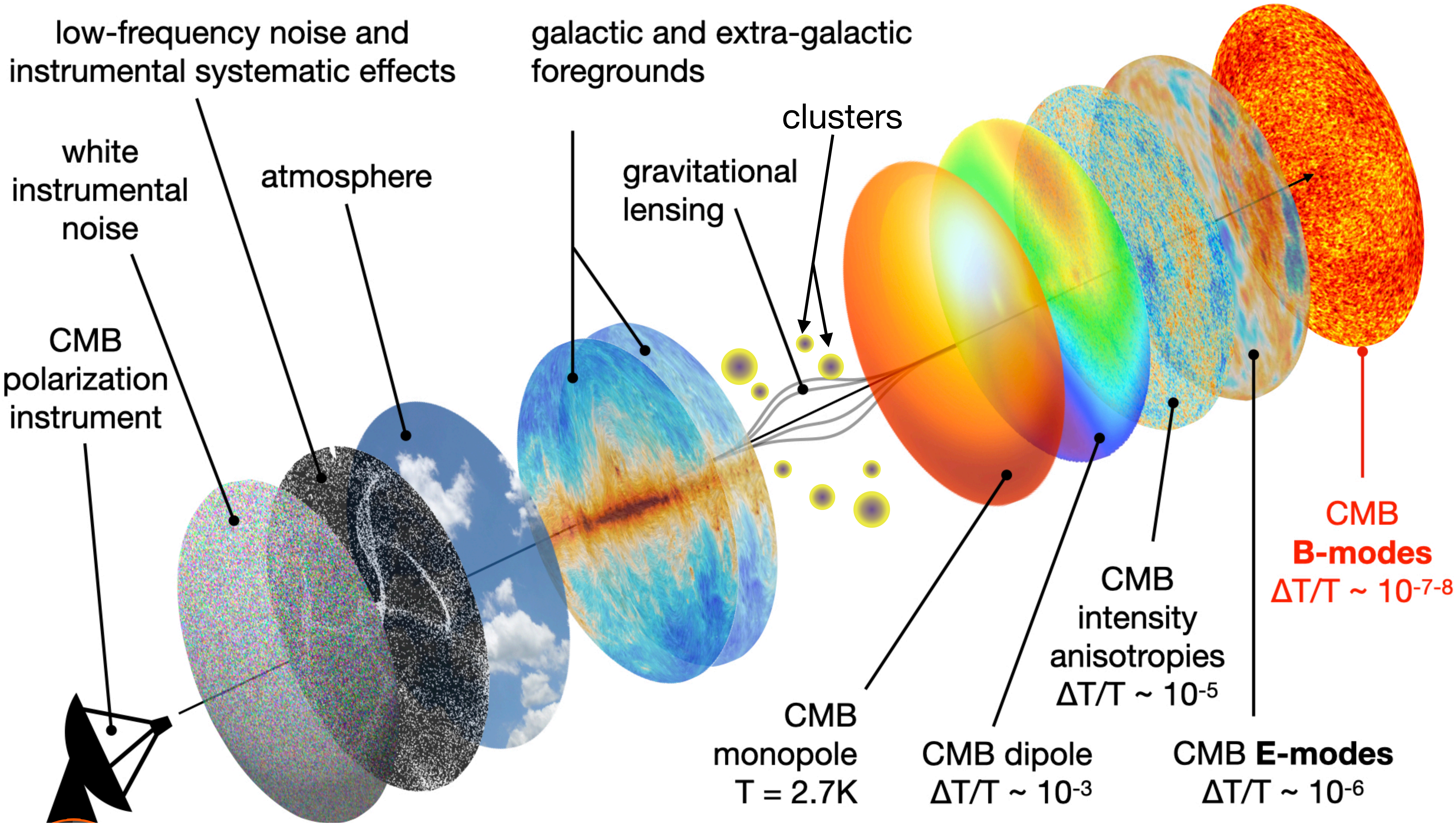
- **With the definition of the tensor-to-scalar ratio "r"** $r = A_t / A_s$ **which characterizes the amplitude of GW and gives direct constraints on the shape of the potential**
  - energy scale of inflation $V^{1/4}(\phi) \simeq 10^{16}\,\mathrm{GeV} \left(\frac{r}{0.01}\right)^{1/4}$
  - inflaton 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

$$r = 8M_{\mathrm{Pl}}^2 \left(\frac{V_\phi}{V}\right)^2$$

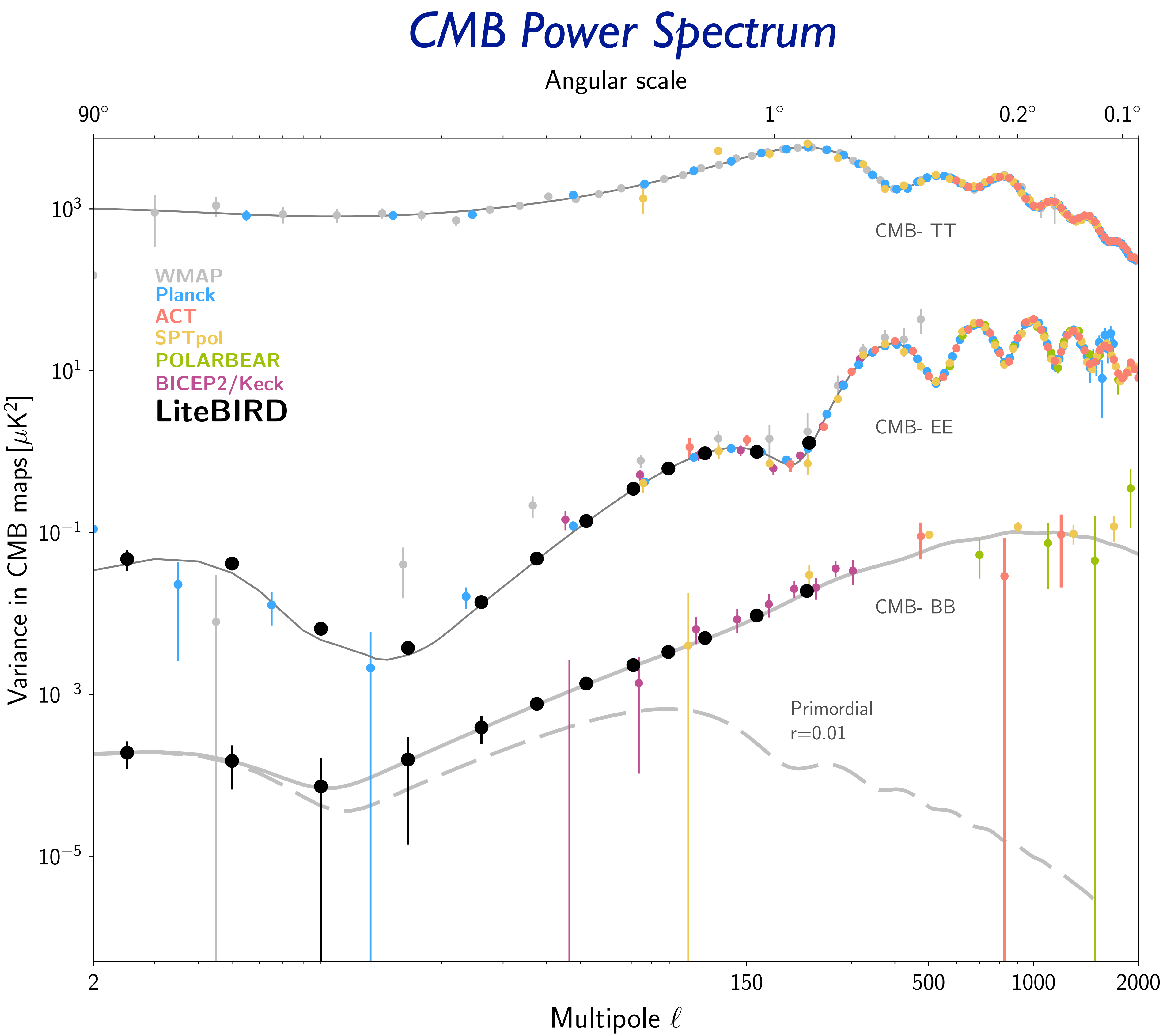
$$n_{\mathrm{s}} - 1 \equiv \frac{\mathrm{d}\ln\mathcal{P}_\zeta}{\mathrm{d}\ln k} \simeq -3M_{\mathrm{Pl}}^2 \left(\frac{V_\phi}{V}\right)^2 + 2M_{\mathrm{Pl}}^2 \frac{V_{\phi\phi}}{V}$$

Future probes of the CMB B-Modes

The challenge of detecting the CMB B-Modes

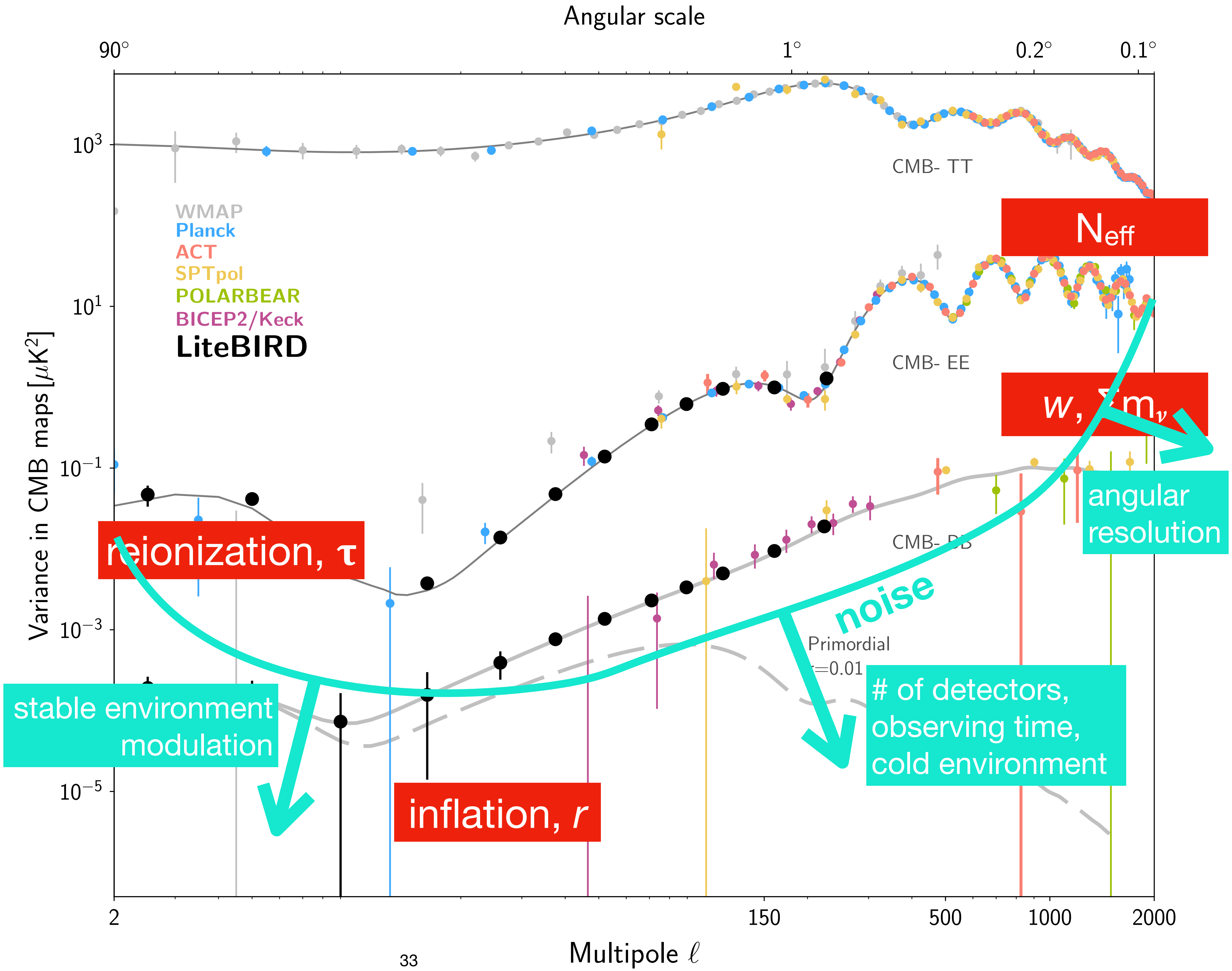


Future probes of the CMB B-Modes



Future probes of the CMB B-Modes

CMB Power Spectrum : Noise Mitigation ?



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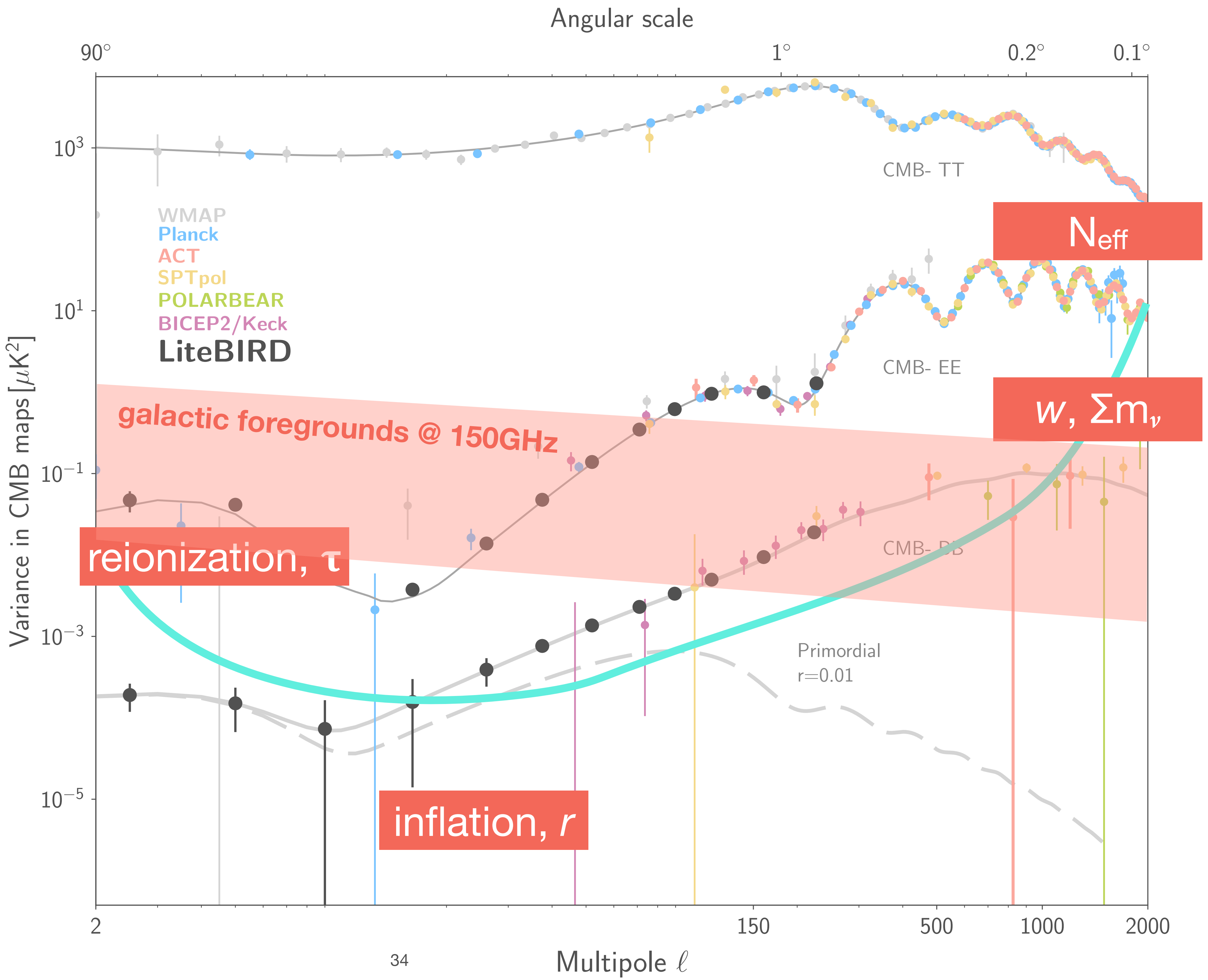
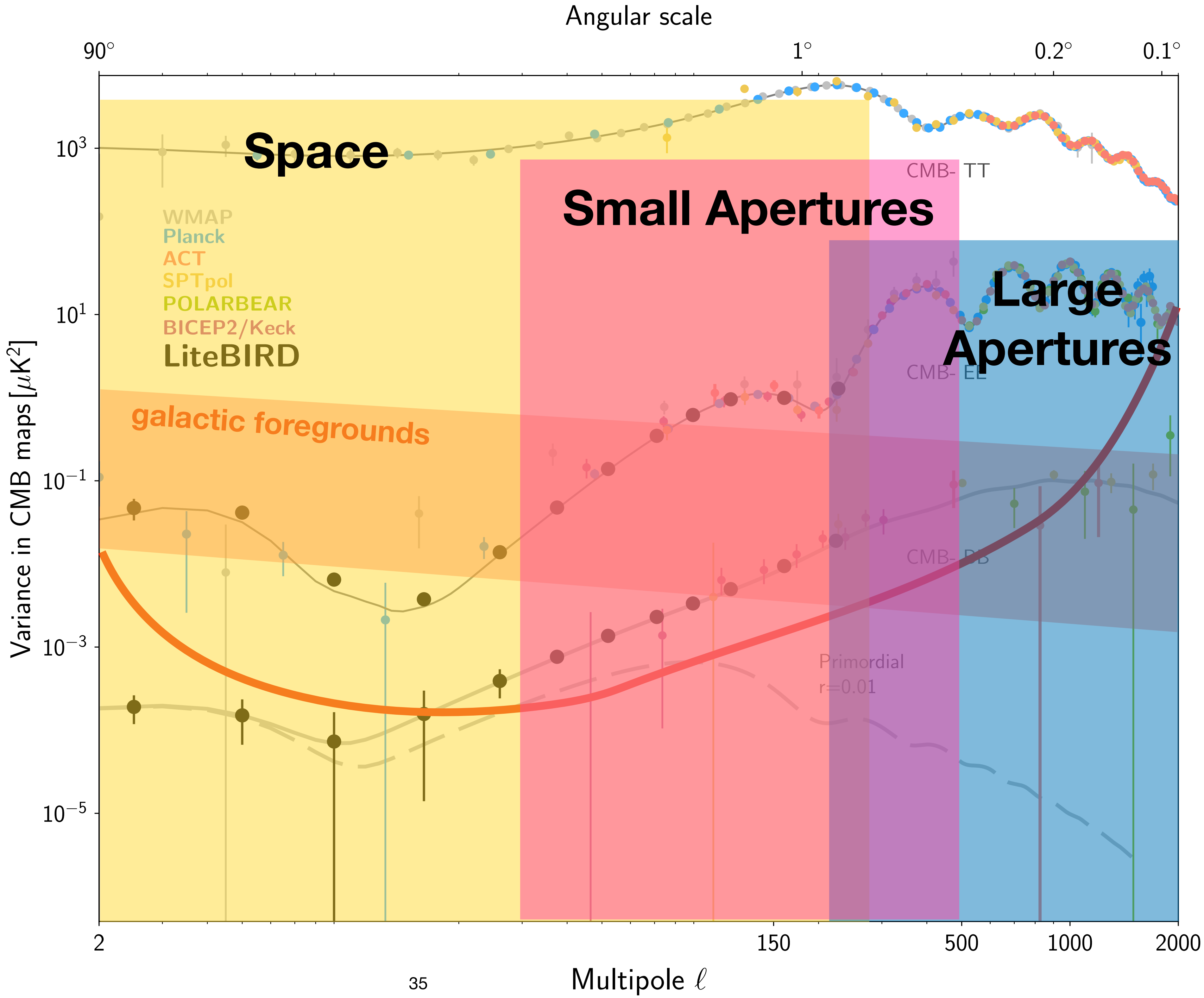
Future probes of the CMB B-Modes

CMB Power Spectrum : Foreground Mitigation ?



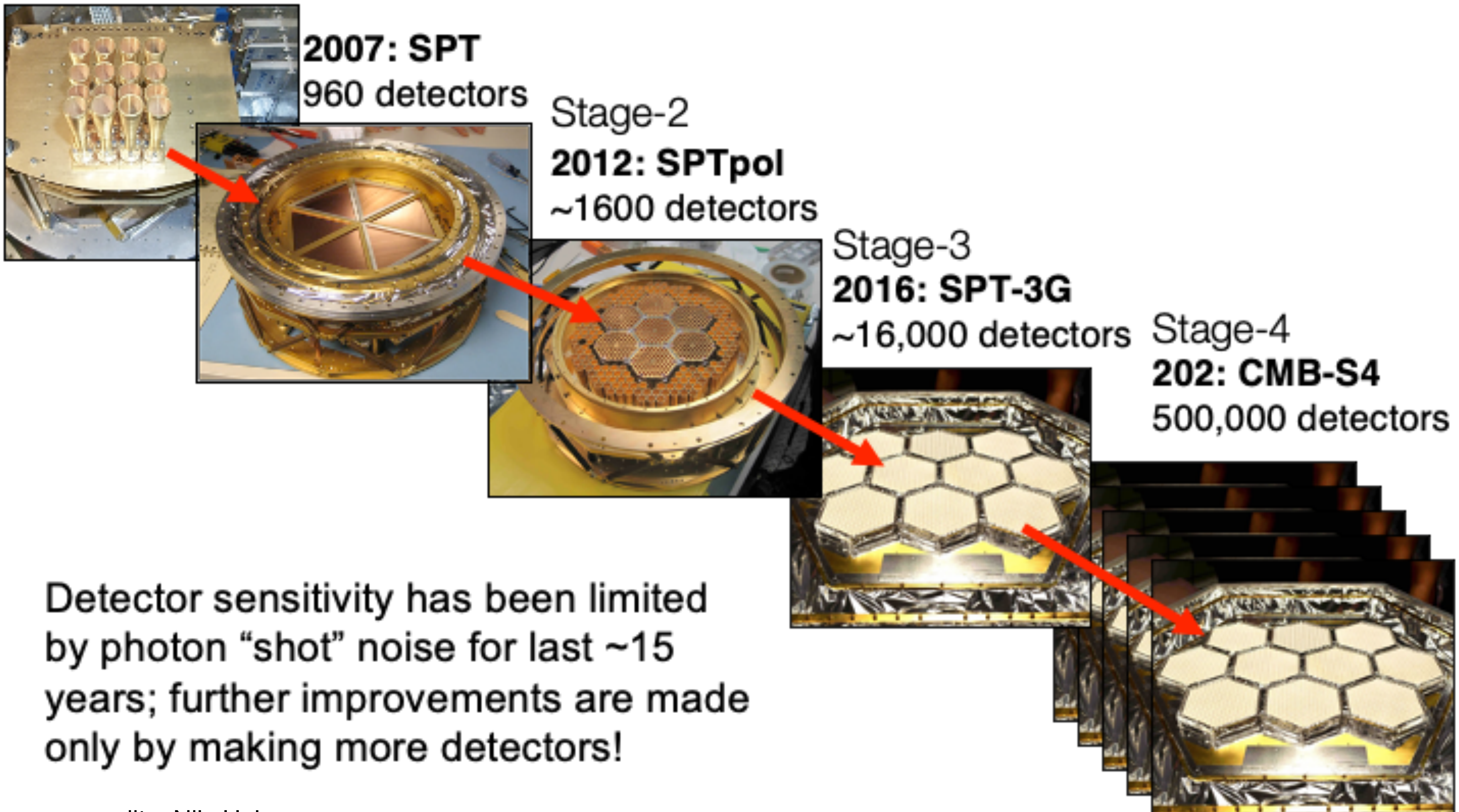
Future probes of the CMB B-Modes

CMB Power Spectrum :



Future probes of the CMB B-Modes

Improving sensitivity of CMB experiments

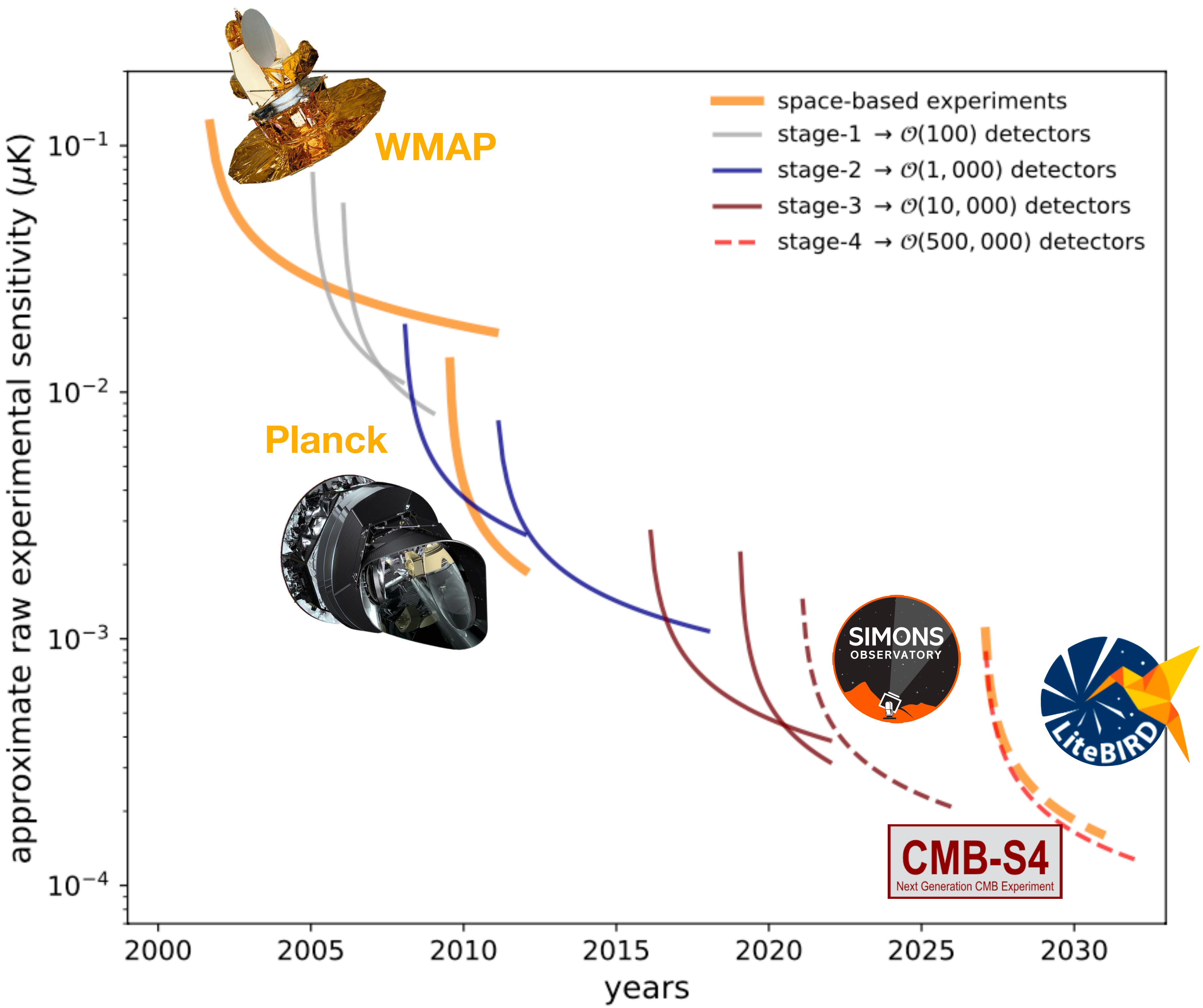


Detector sensitivity has been limited by photon “shot” noise for last ~15 years; further improvements are made only by making more detectors!

credits: Nils Halverson

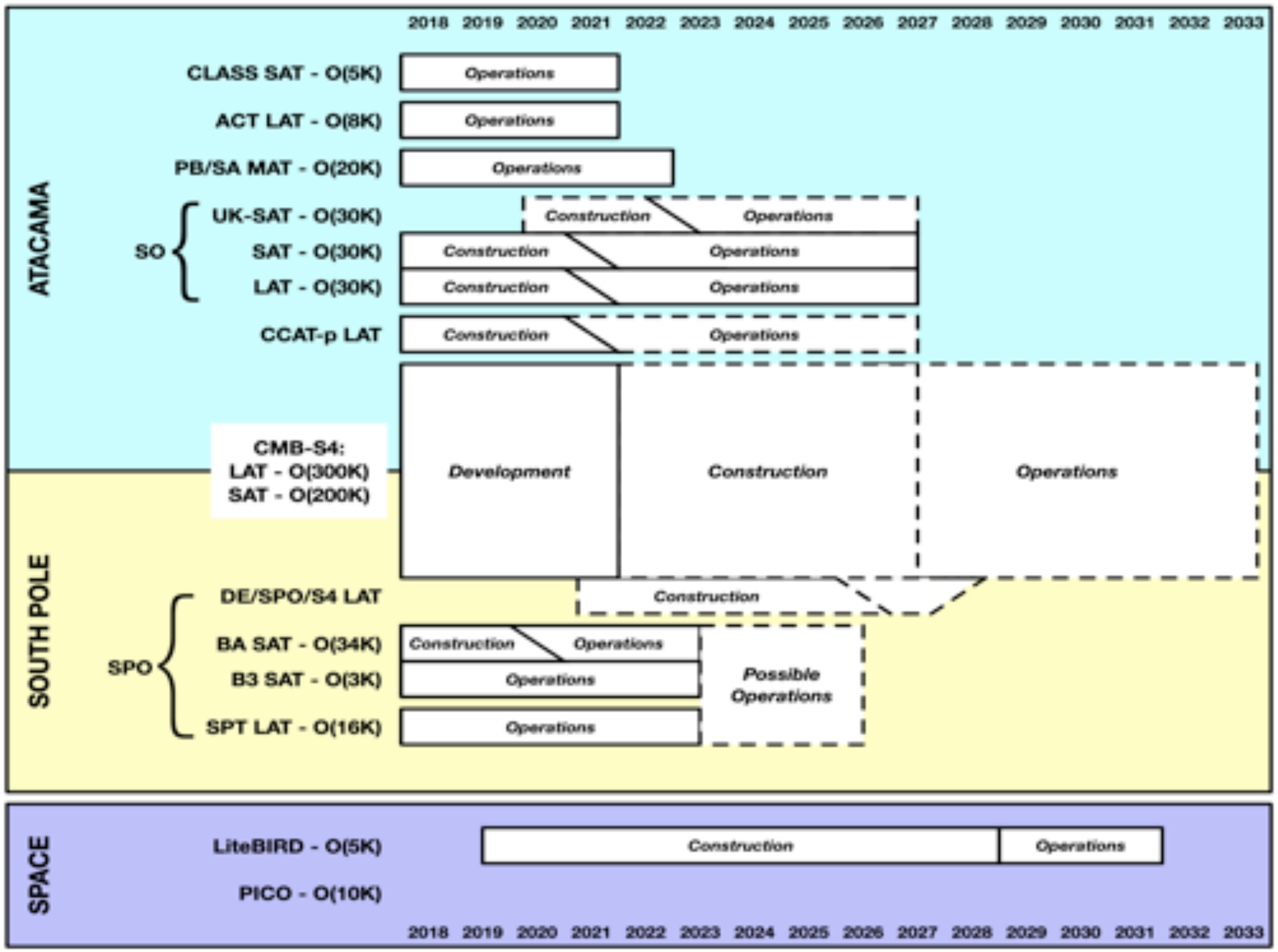
Future probes of the CMB B-Modes

Improving sensitivity of CMB experiments



Future probes of the CMB B-Modes

Global Panorama of CMB experiments



Complementarity Ground / Space:

- large / small angular scales
- High frequency bands from Space
- Delensing capability
- Science targets

3rd Generation experiments targeting sigma(r) around $O(10^{-2})$ to $3x10^{-3}$

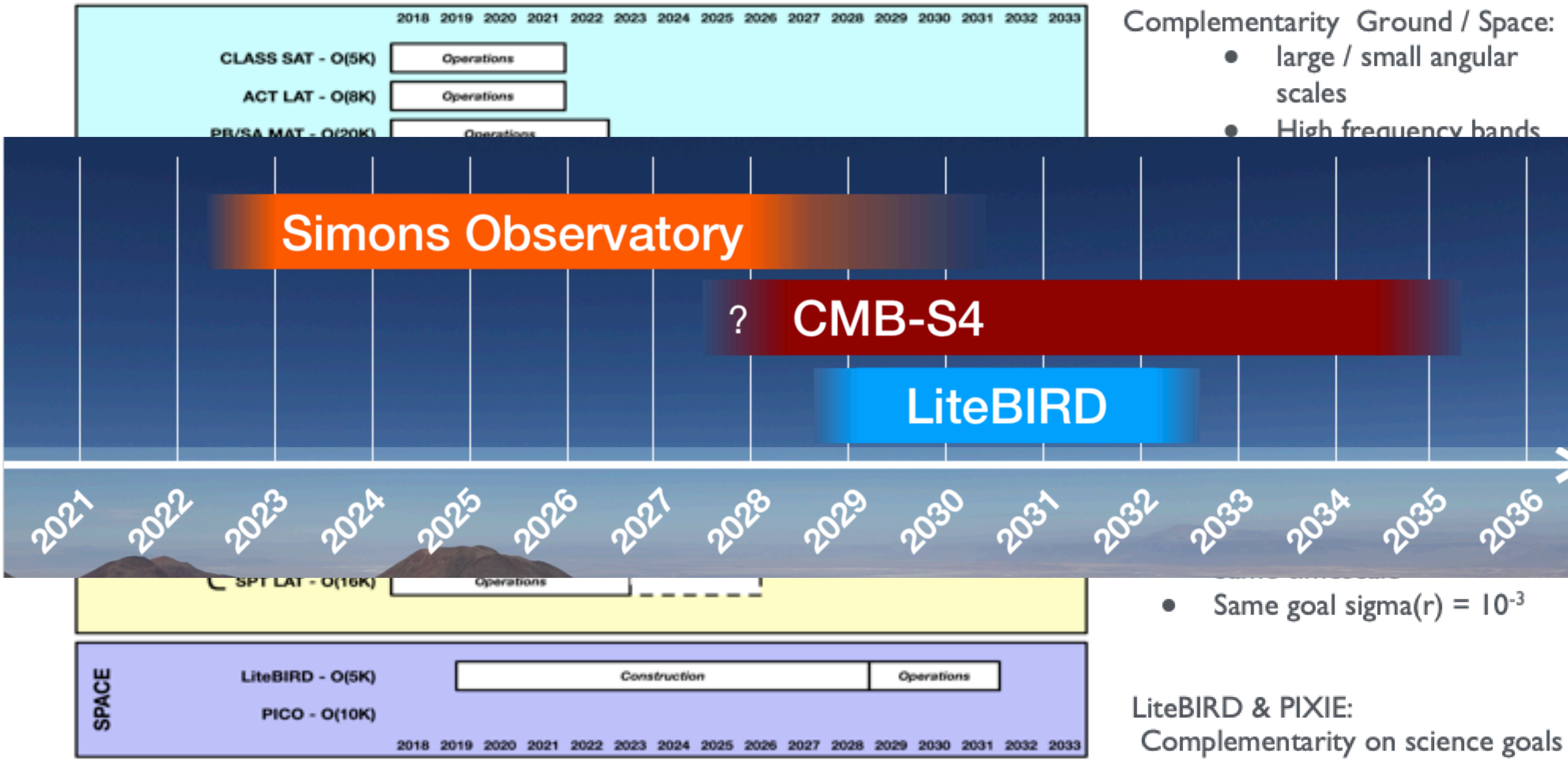
LiteBIRD & CMB-S4 :

- Same timescale
- Same goal sigma(r) = 10^{-3}

LiteBIRD & PIXIE:
Complementarity on science goals

Future probes of the CMB B-Modes

Global Panorama of CMB experiments



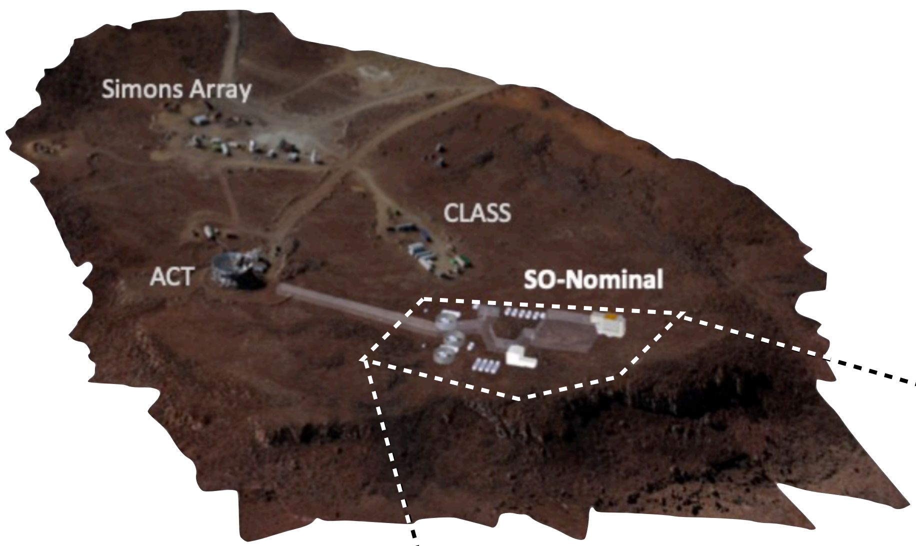
Complementarity Ground / Space:

- large / small angular scales
- High frequency bands

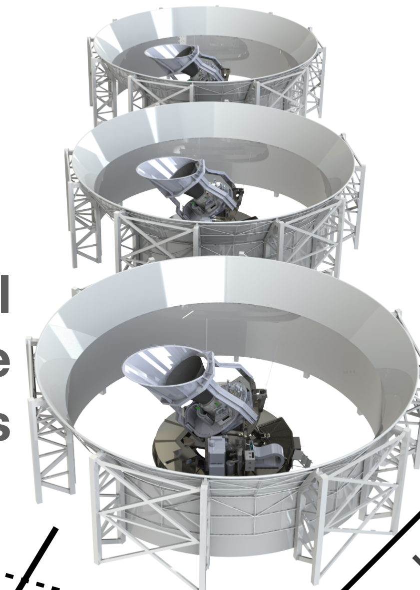
- Same goal sigma(r) = 10^{-3}

LiteBIRD & PIXIE:
Complementarity on science goals

Simons Observatory



3 small aperture telescopes



16m

Survey:
10% of sky

FoV: 35 deg

100mK FP with Half Wave plate

~10 000 detectors each

Sensitivity:
~ 2 μK.arcmin

28GHz - 280GHz

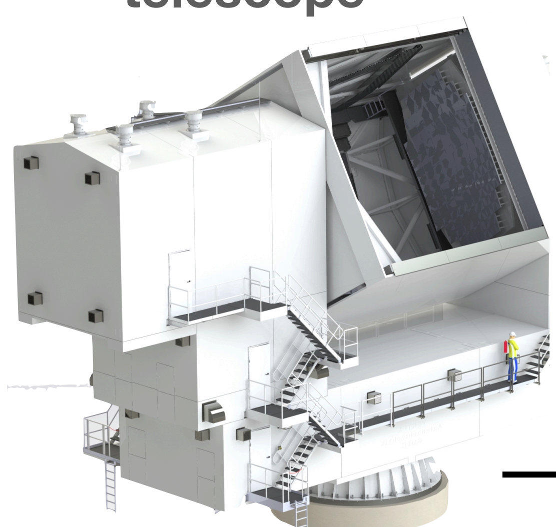
Survey :
40% sky

Sensitivity:
~ 6 μK.arcmin

FoV: 8 deg

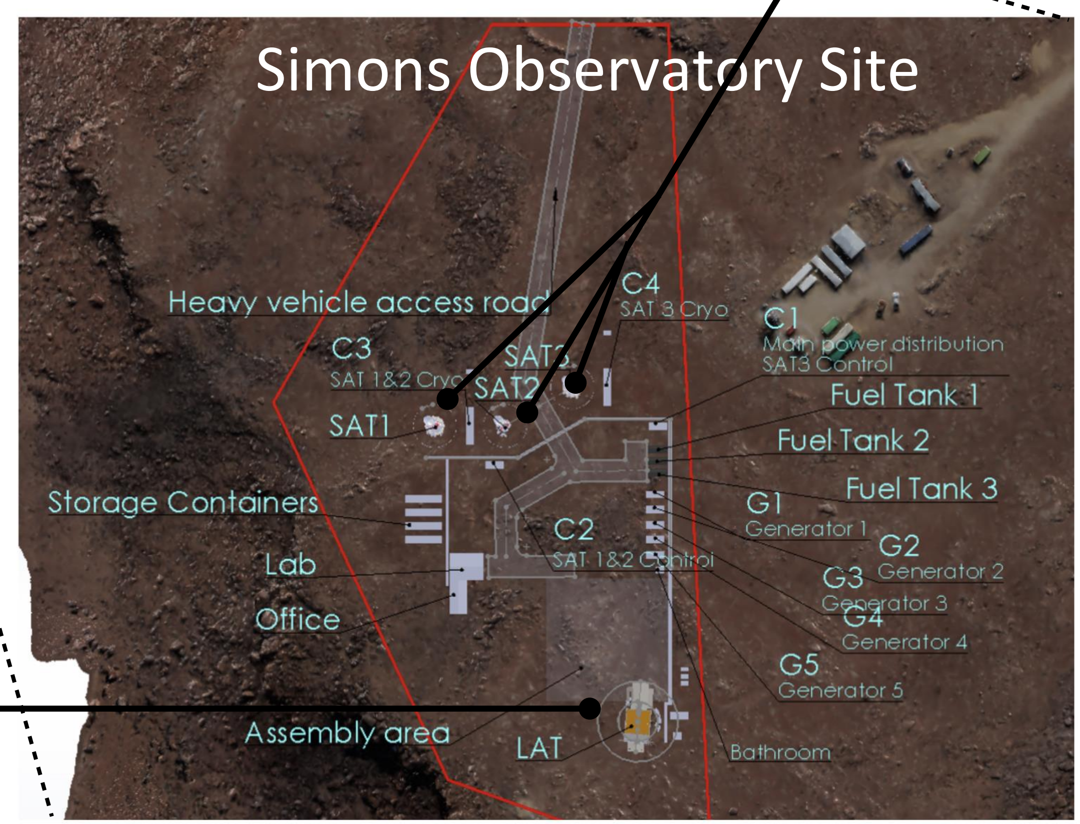
~30 000 detectors

1 large aperture telescope



15m

19m



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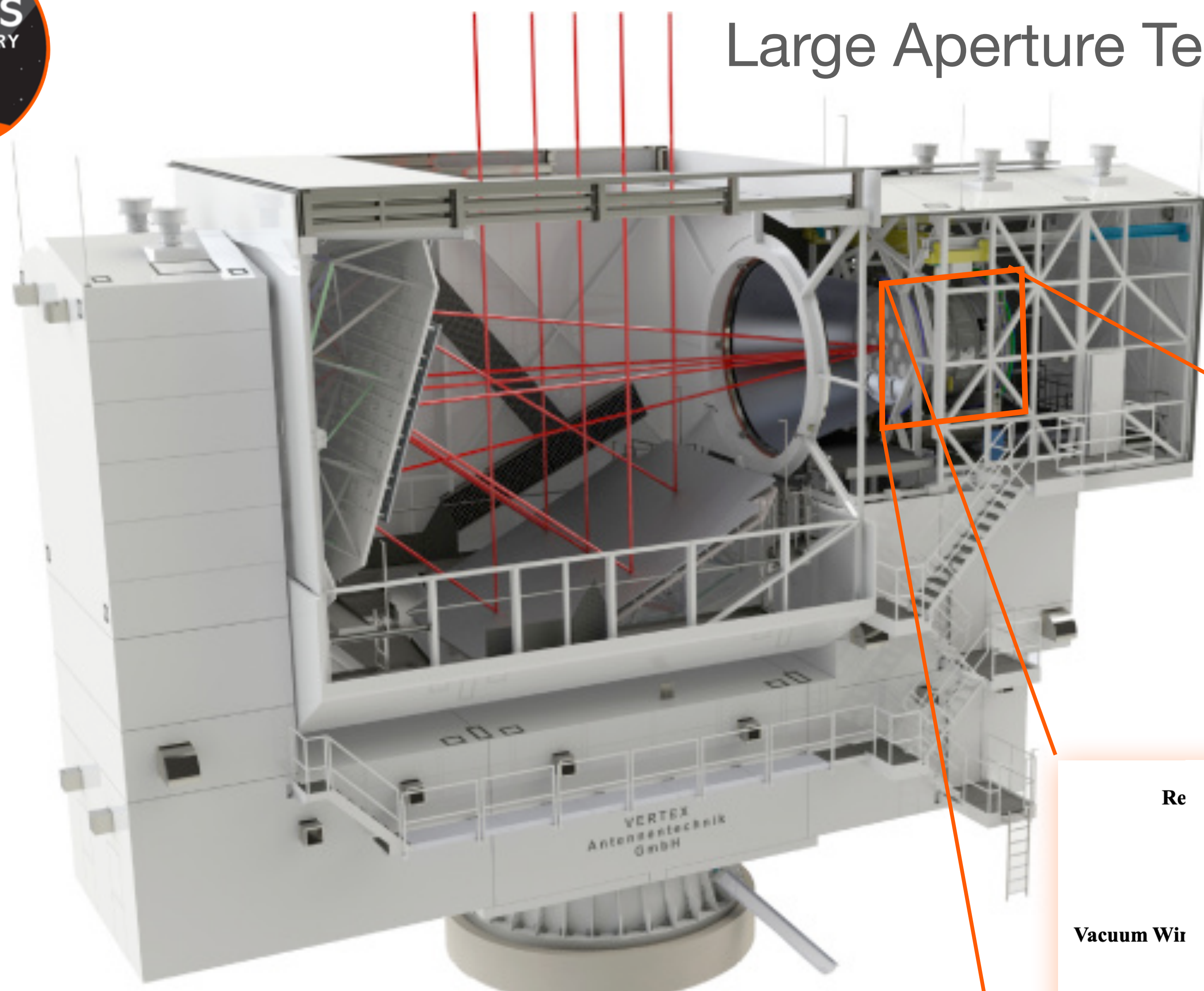
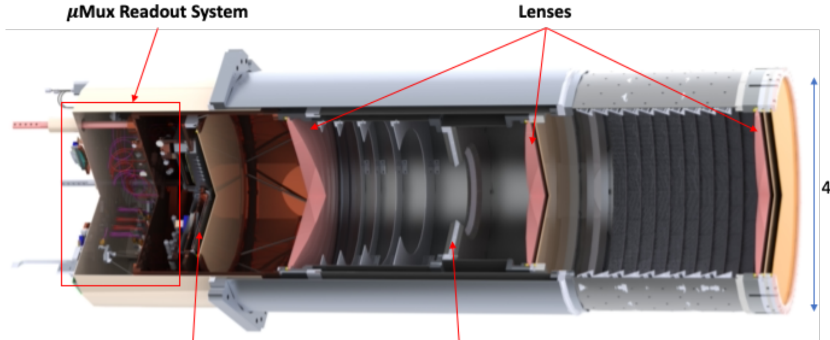
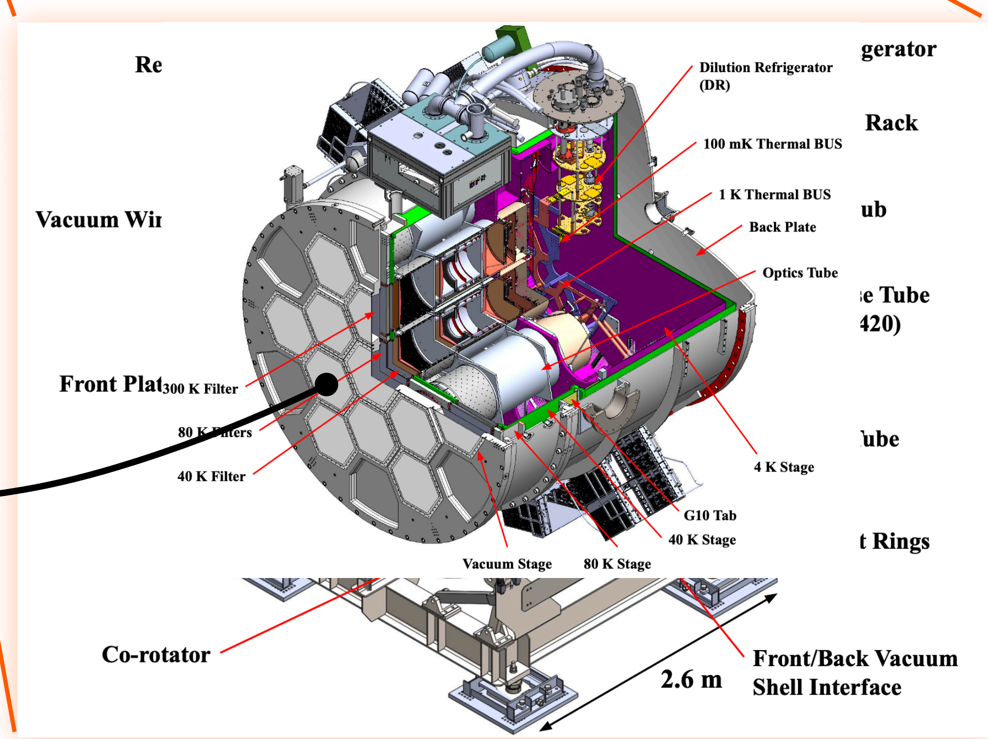
Large Aperture Telescopes

see 2103.02747

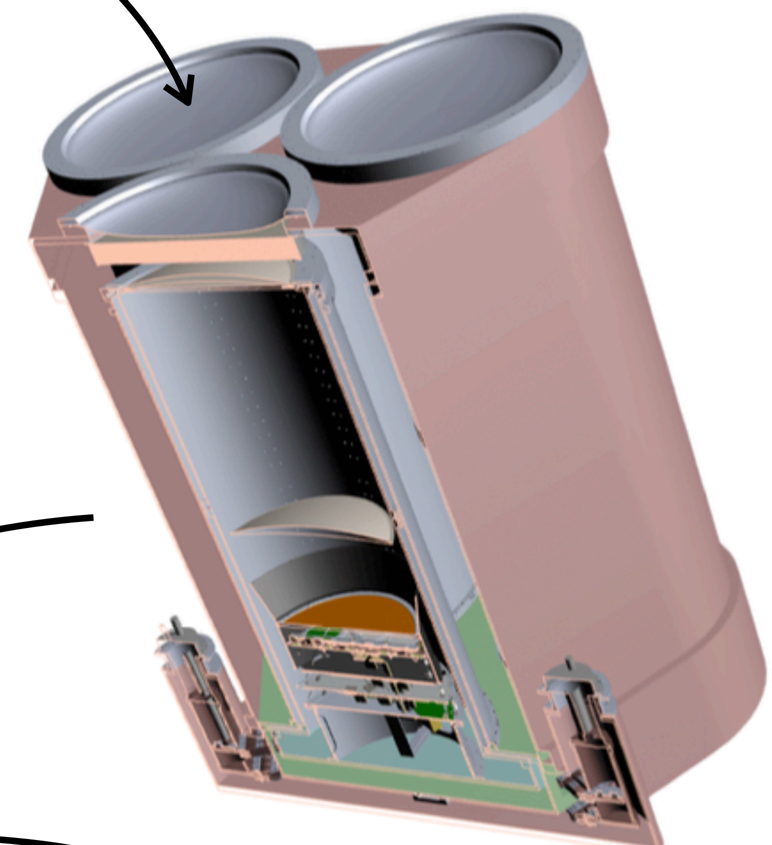




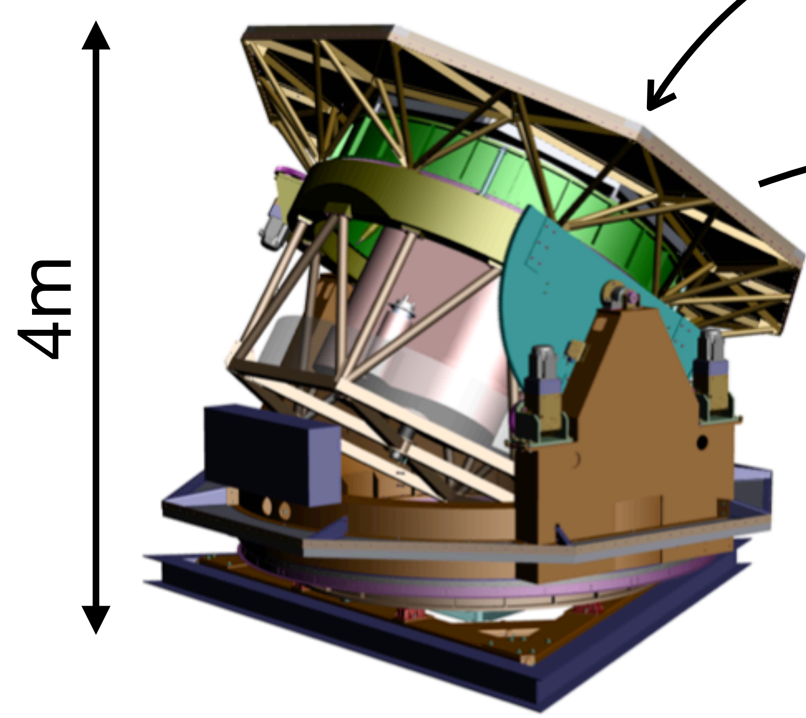


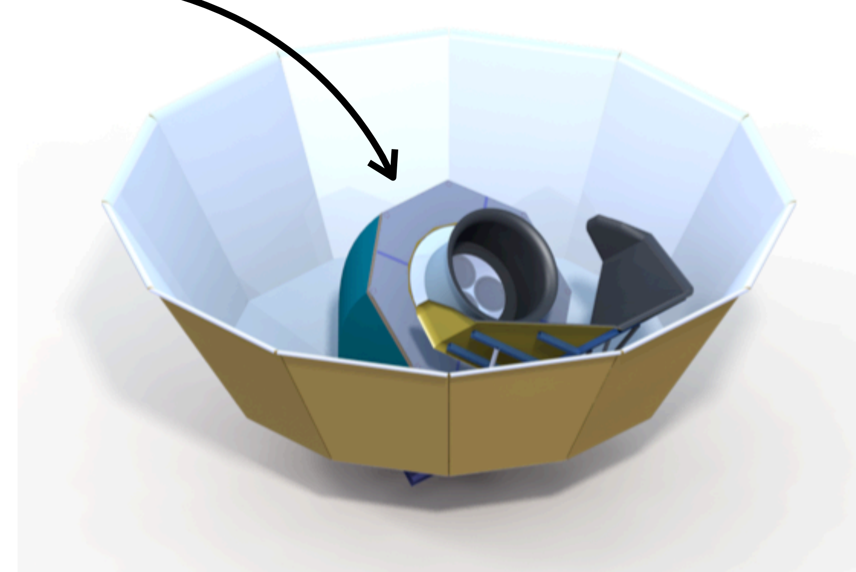
SO / CMB-S4

Small Aperture Telescopes



3 tubes



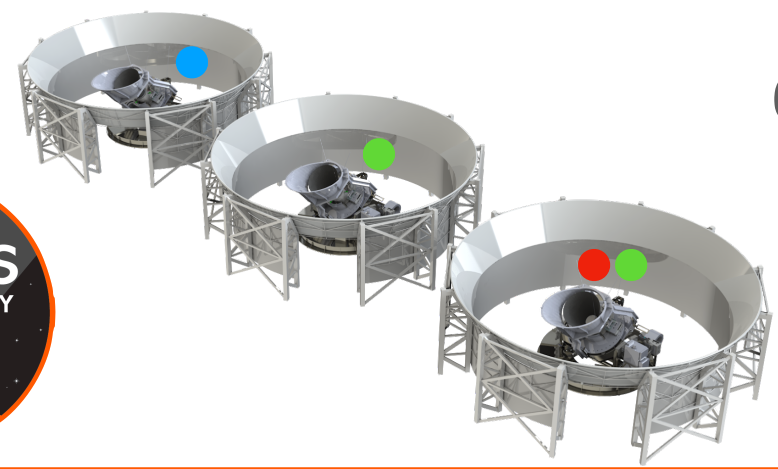


20GHz - 270GHz

Sensitivity:
~ 1 μK.arcmin

SO / CMB-S4

Funded by
Simons Foundation

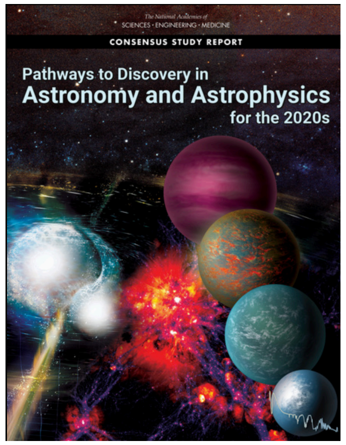


60,000 detectors

27/39GHz
93/145GHz
225/280GHz

Joint DOE/NSF project

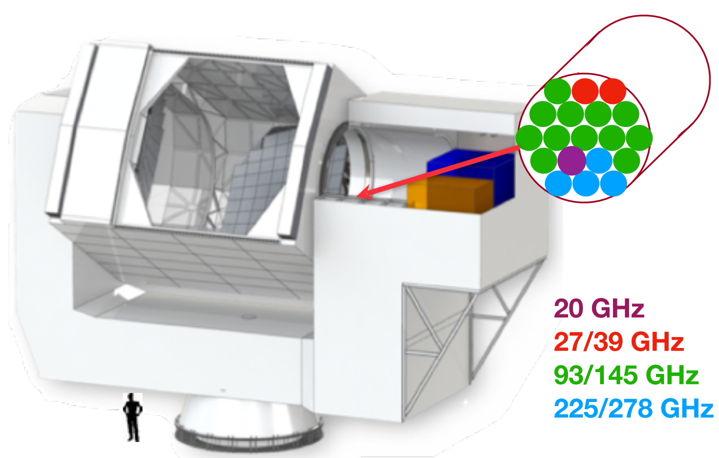
Astro2020 US
Decadal Survey of
Astronomy:



CMB-S4 = Priority #2

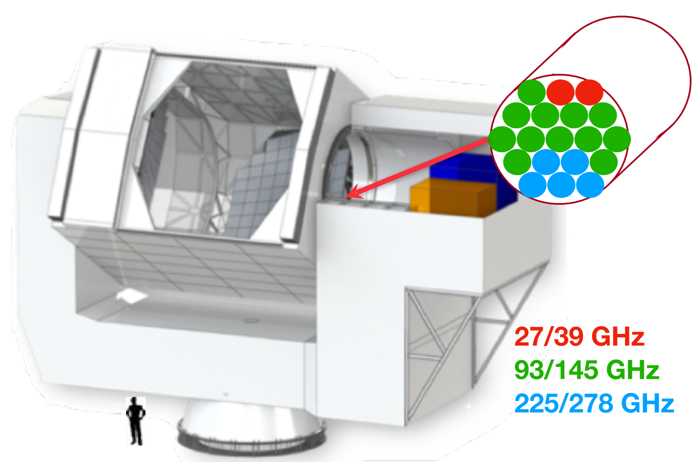
CMB-S4
Next Generation CMB Experiment

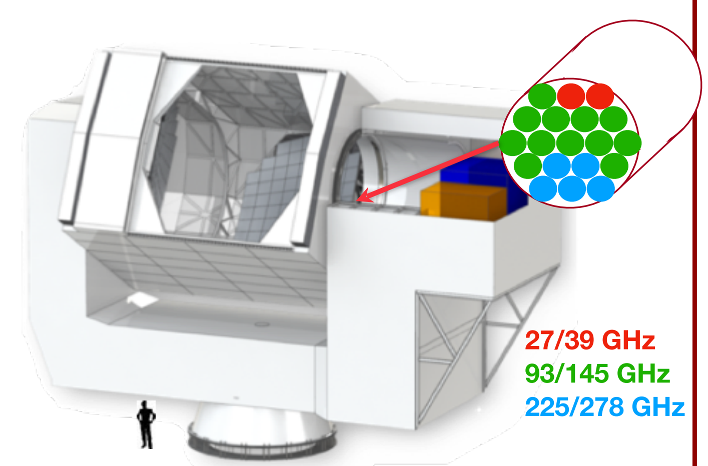
Ultra-deep survey: observe ~3% of the sky with 150,000 detectors in SATs & a de-lensing LAT with 120,000 detectors.



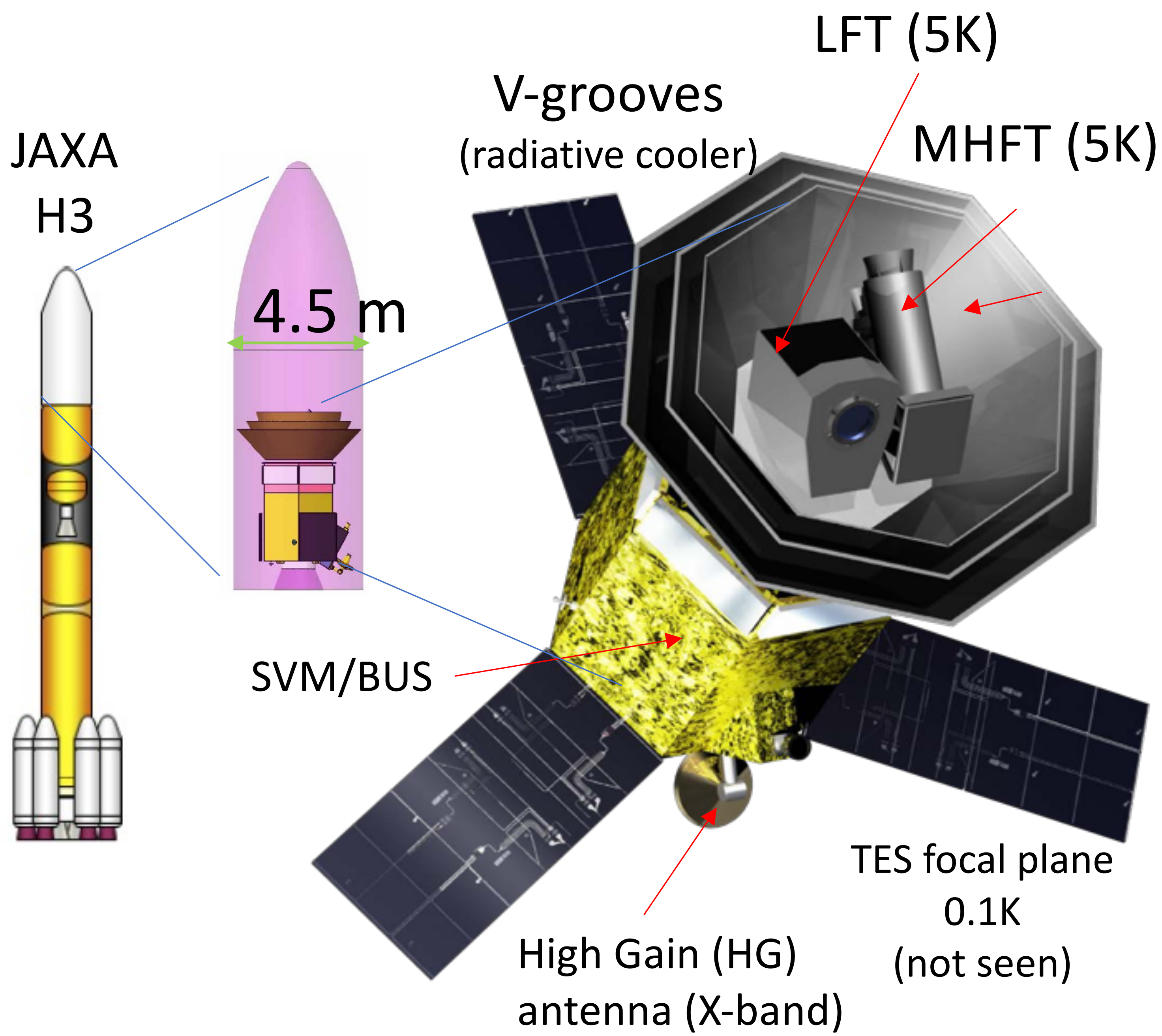
500,000 detectors

Deep-wide survey: Two LATs observing ~60% of the sky with 240,000 detectors.





LiteBIRD Mission



Main Specifications

Hazumi et al SPIE2020 11443-249

L-Class JAXA Mission, selected in 2019

Launch 2029

L2 orbit
All-sky Survey during 3 years

Large frequency coverage
15 bands 34 - 448 GHz

Resolution:

LFT	MFT	HFT
70.5' - 23.7'	37.8' - 28'	28.6' - 17.9'

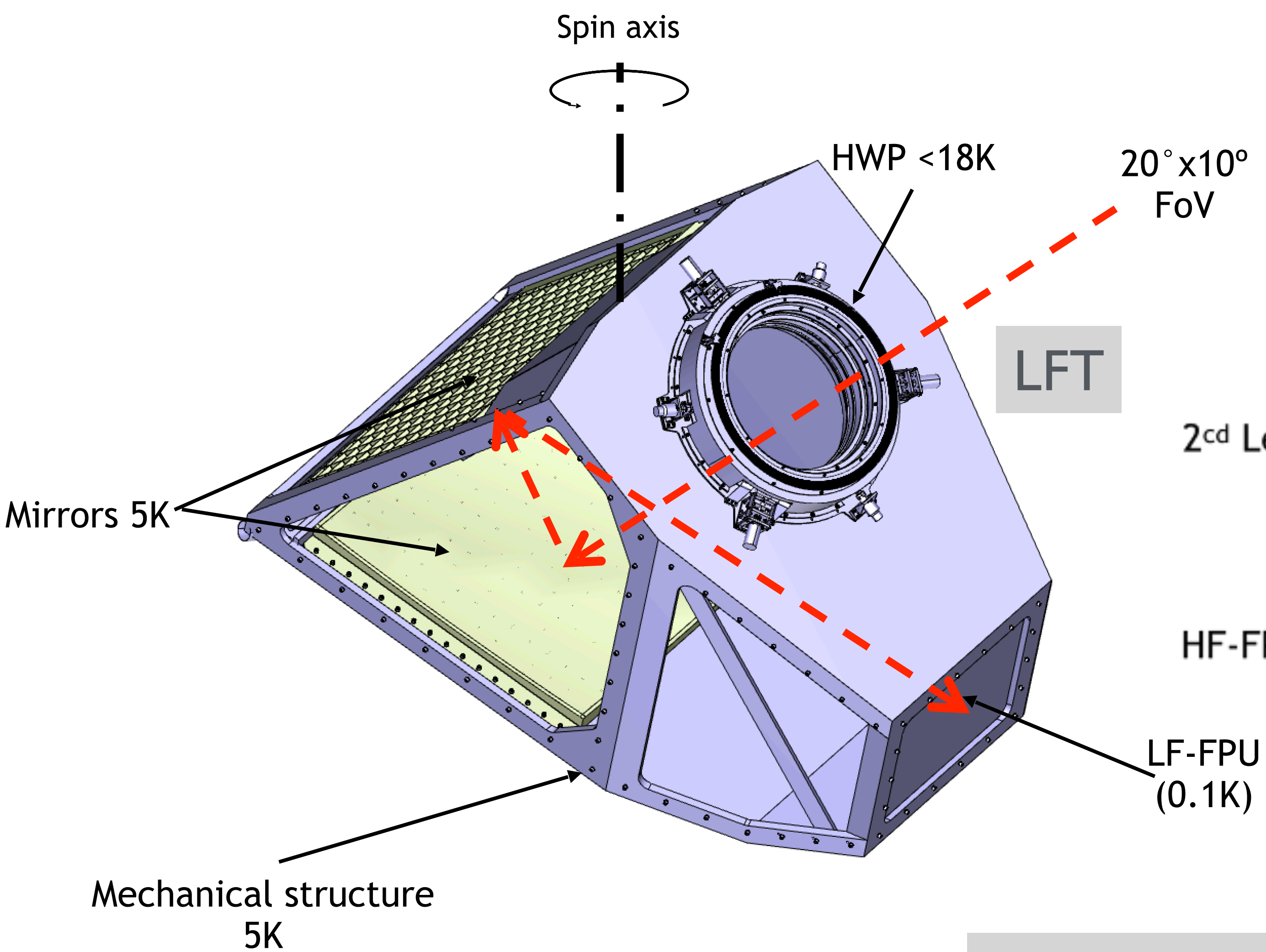
Sensitivity in Polarisation: 2.2 uK.arcmin

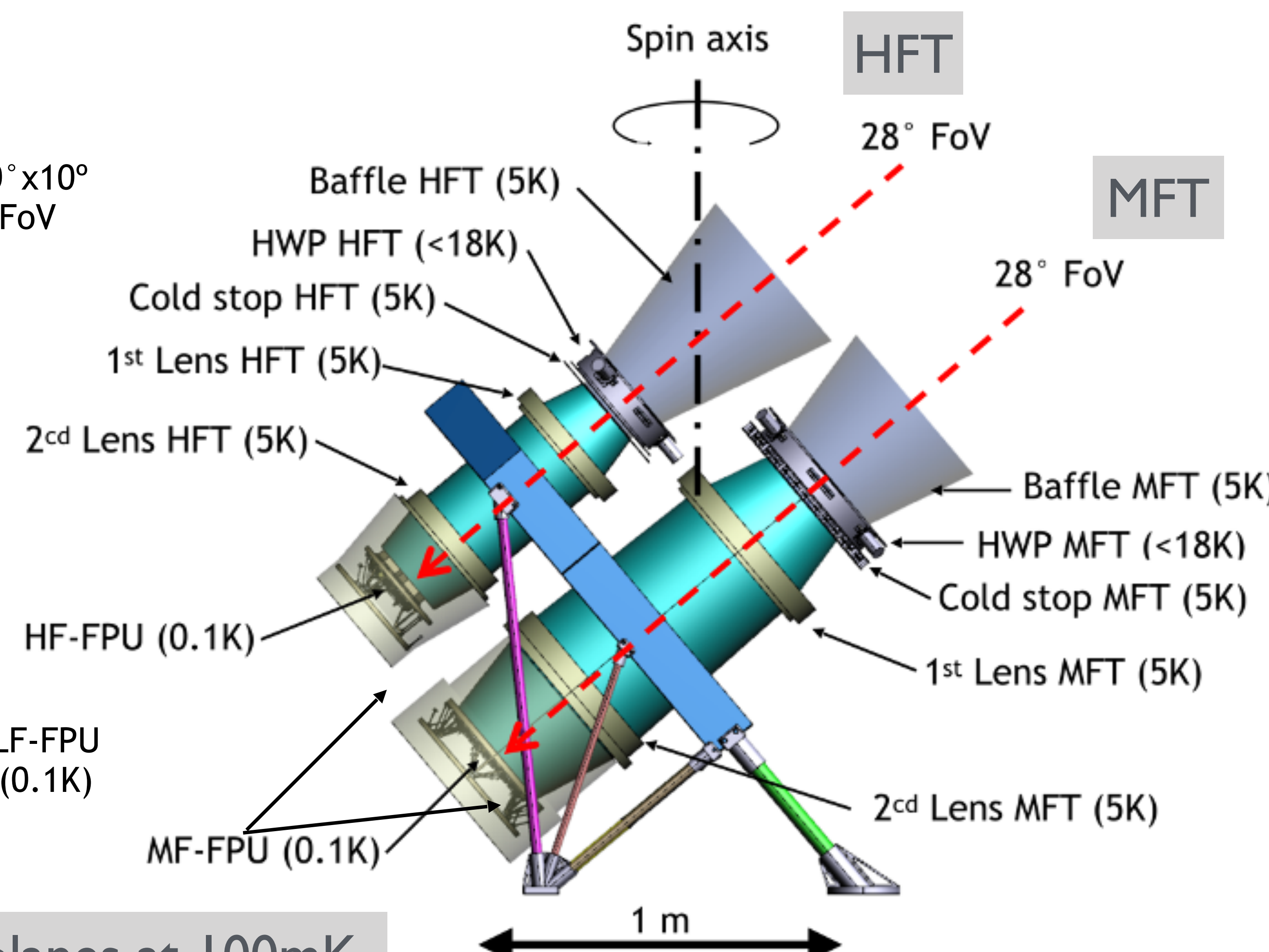
Continuously rotating HWP

4508 TES detectors cooled down at 100mK

Systematics Mitigation

Full instruments and optics at 5K





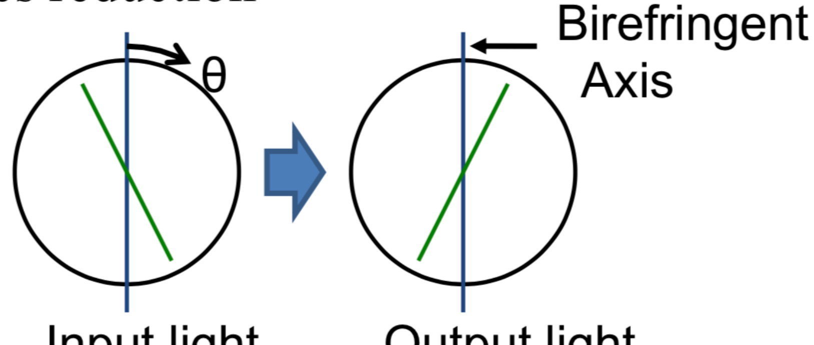
Focal planes at 100mK

Systematics Mitigation

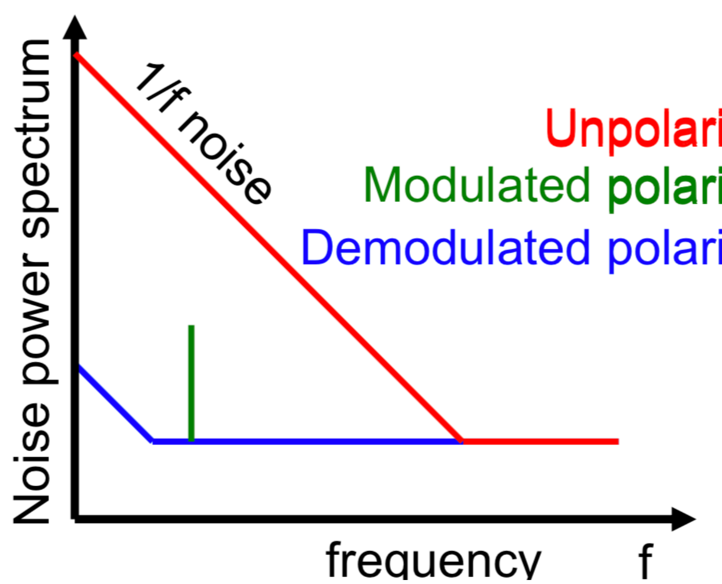
Continuously Rotating Half-Wave Plates

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

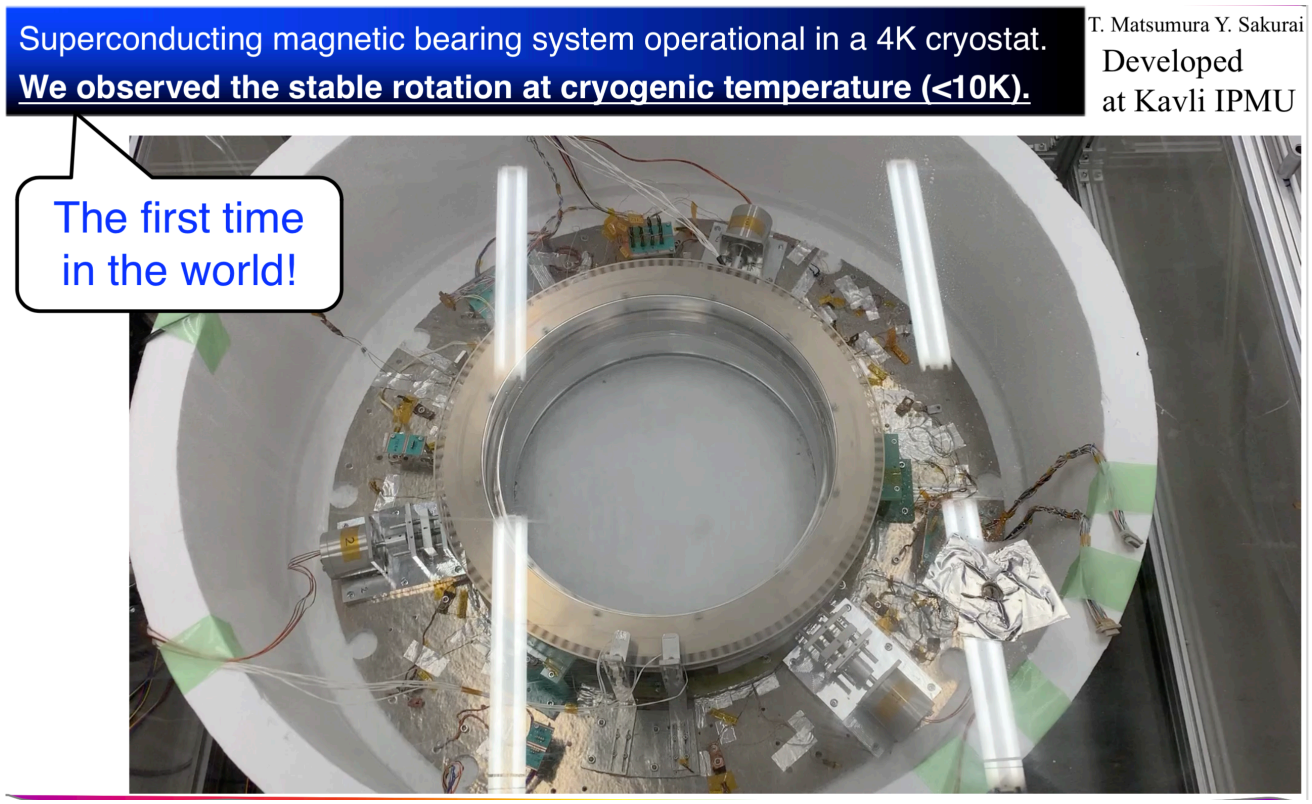
Rotating a birefringent plate at the most sky side



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



Magnetic sustentation
First prototype in the world developed at IPMU (Tokyo)



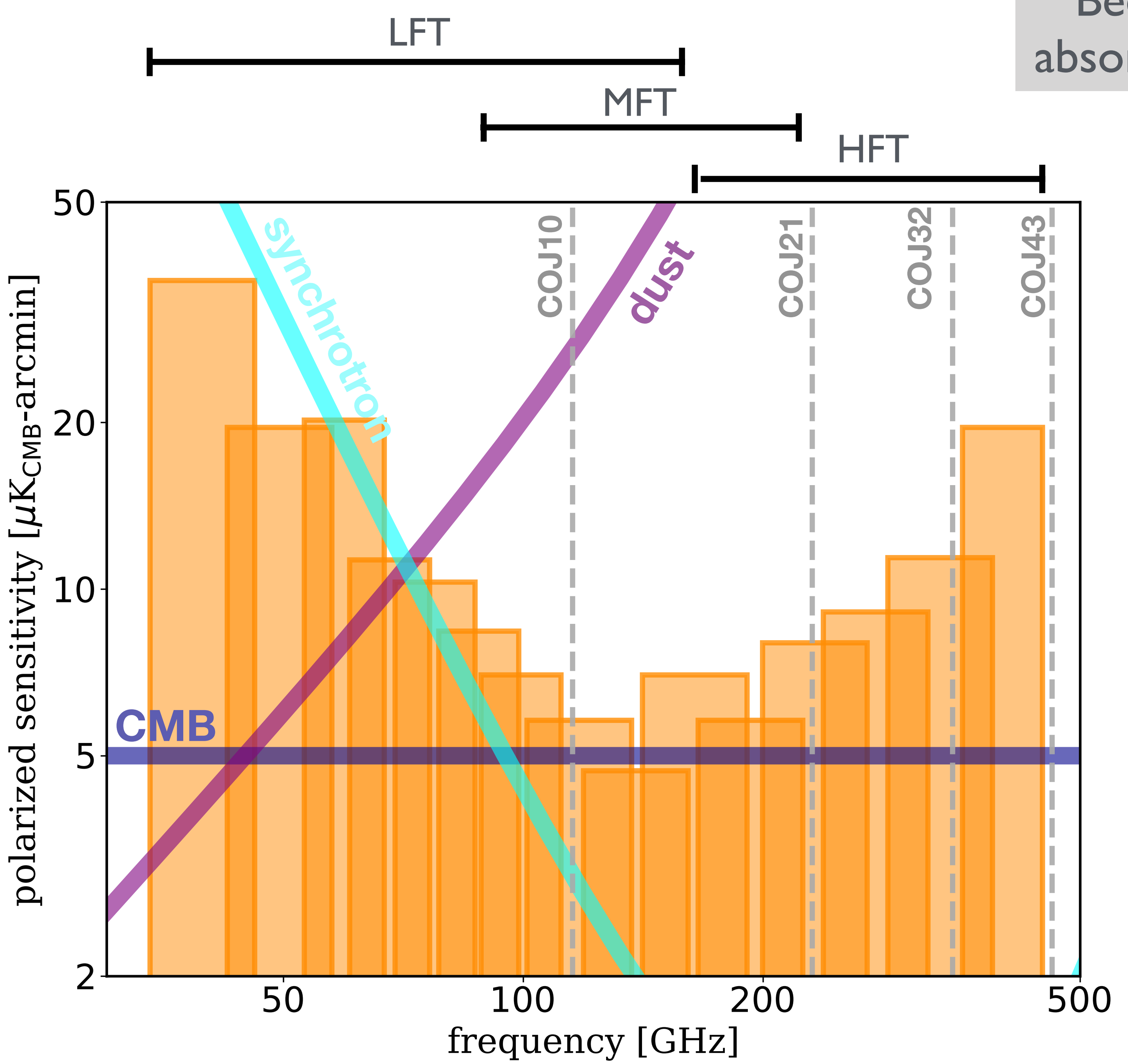
Parallel development in Italy

Foregrounds Mitigation

Possible only from Space !
Because of atmospheric
absorption from the ground

15 bands
from 34GHz
to 448GHz

+4600
detectors

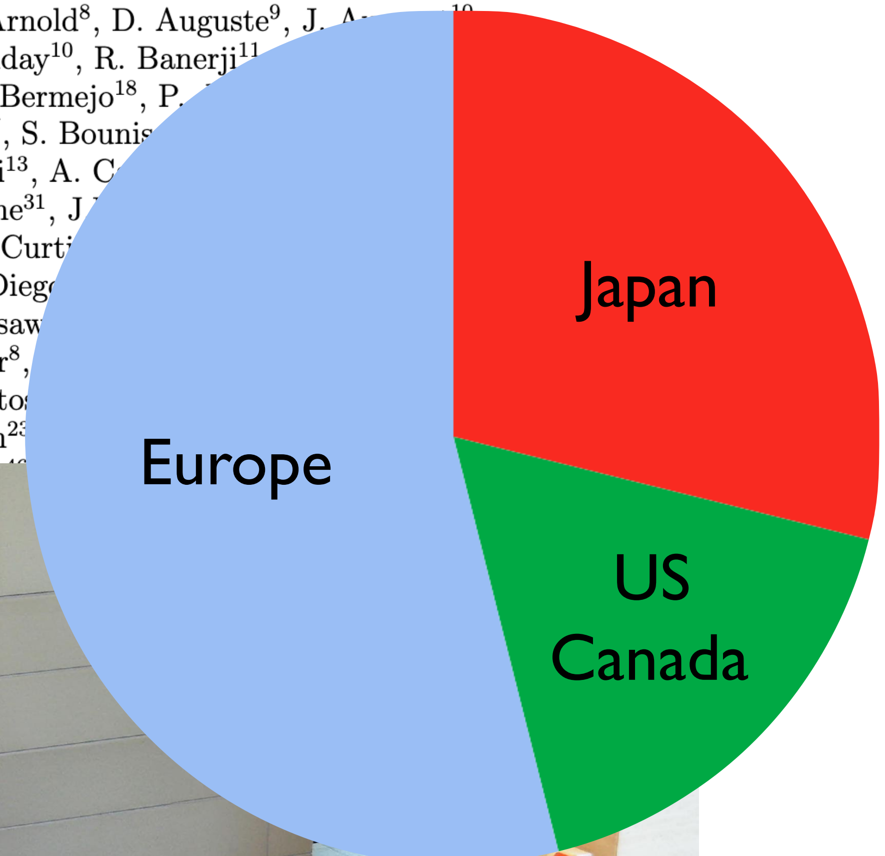


9 bands LFT
5 bands x 2 MHFT
+
4 bands
overlapping

An international collaboration

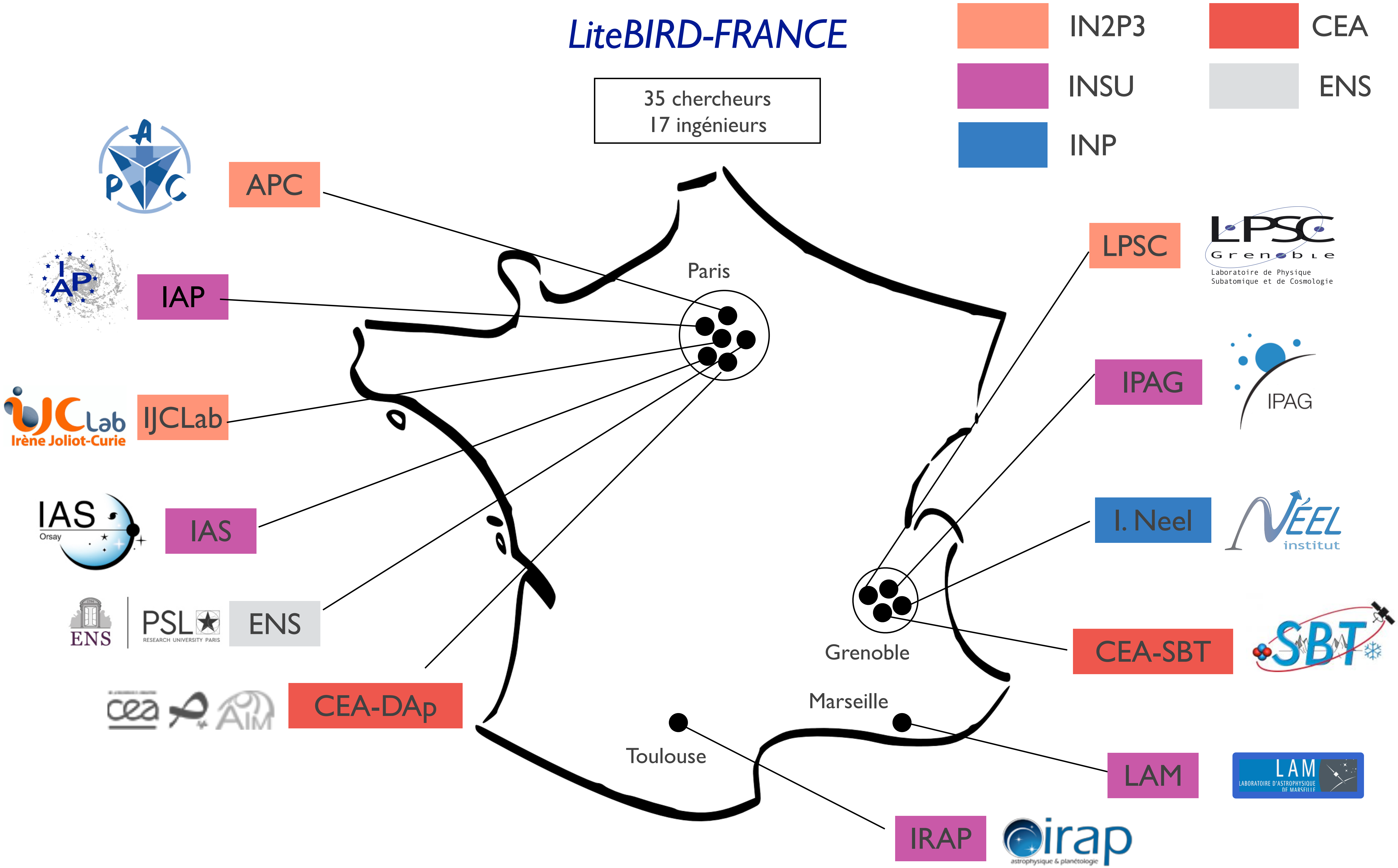
About 300 researchers from Japan, Europe & North America

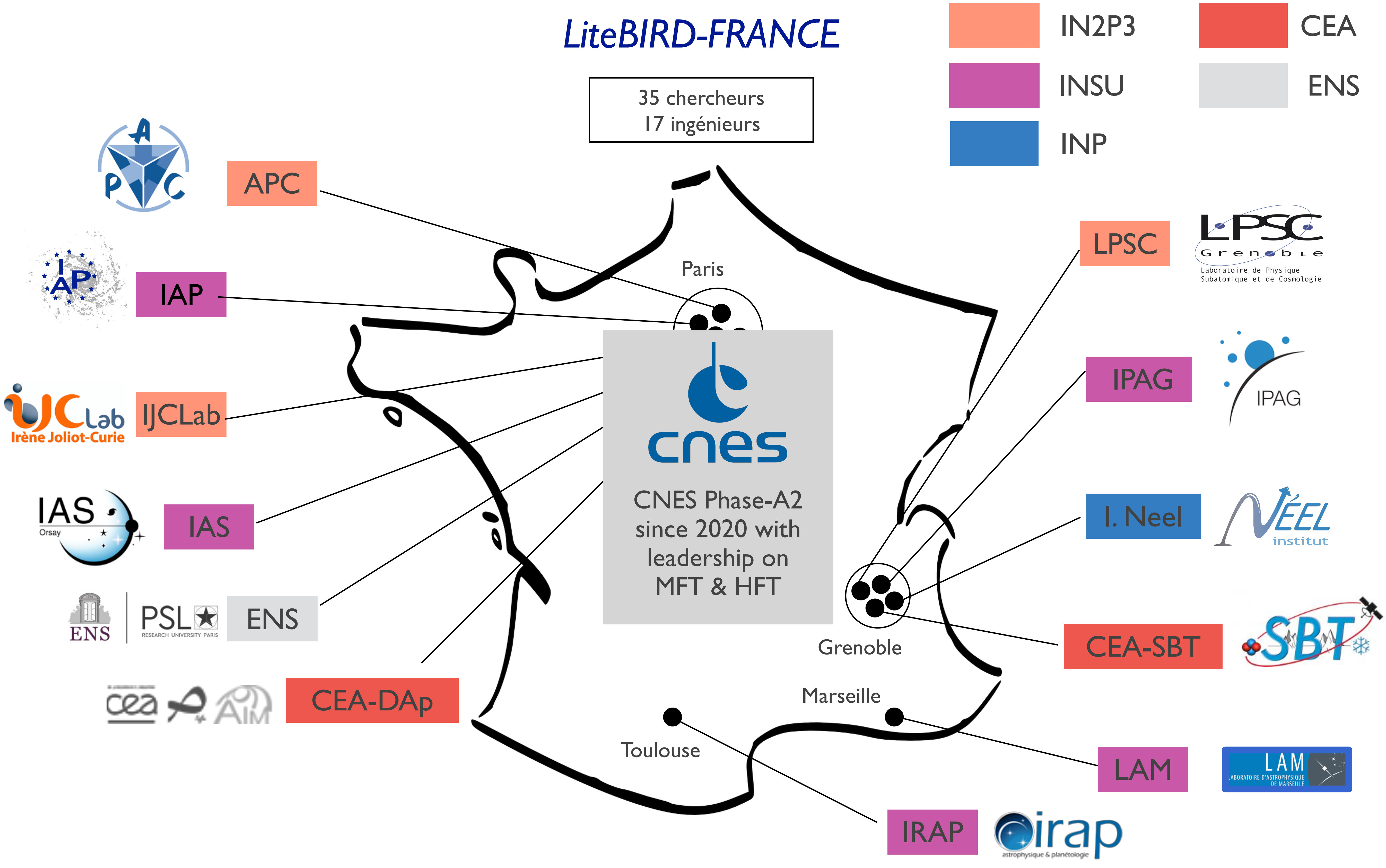
M. Hazumi[1,2,3,4], P.A.R. Ade[5], A. Adler[6], E. Allys[7], K. Arnold[8], D. Auguste[9], J. A...
R. Aurlien[11], J. Austermann[12], C. Baccigalupi[13], A.J. Banday[10], R. Banerji[11]...
S. Basak[15], J. Beall[12], D. Beck[16], S. Beckman[17], J. Bermejo[18], P. ...
M. Bersanelli[20], J. Bonis[9], J. Borrill[21,22], F. Boulanger[7], S. Bounis...
M. Brown[24], M. Bucher[25], E. Calabrese[5], P. Campeti[13], A. C...
A. Challinor[27,28,29], V. Chan[30], K. Cheung[17], Y. Chinone[31], J. ...
F. Columbro[19], J. Cubas[33], A. Cukierman[17,16], D. Curti...
N. Dachlythra[34], M. De Petris[19], C. Dickinson[24], P. Dieg...
T. Dotani[2], L. Duband[35], S. Duff[12], J.M. Duval[35], K. Ebisaw...
J. Errard[25], T. Essinger-Hileman[37], F. Finelli[38], R. Flauger[8], ...
M. Galloway[11], K. Ganga[25], J.R. Gao[39], R. Genova-Santos...
T. Ghigna[3,43], E. Gjerløw[11], M.L. Gradziel[44], J. Grain[23]...



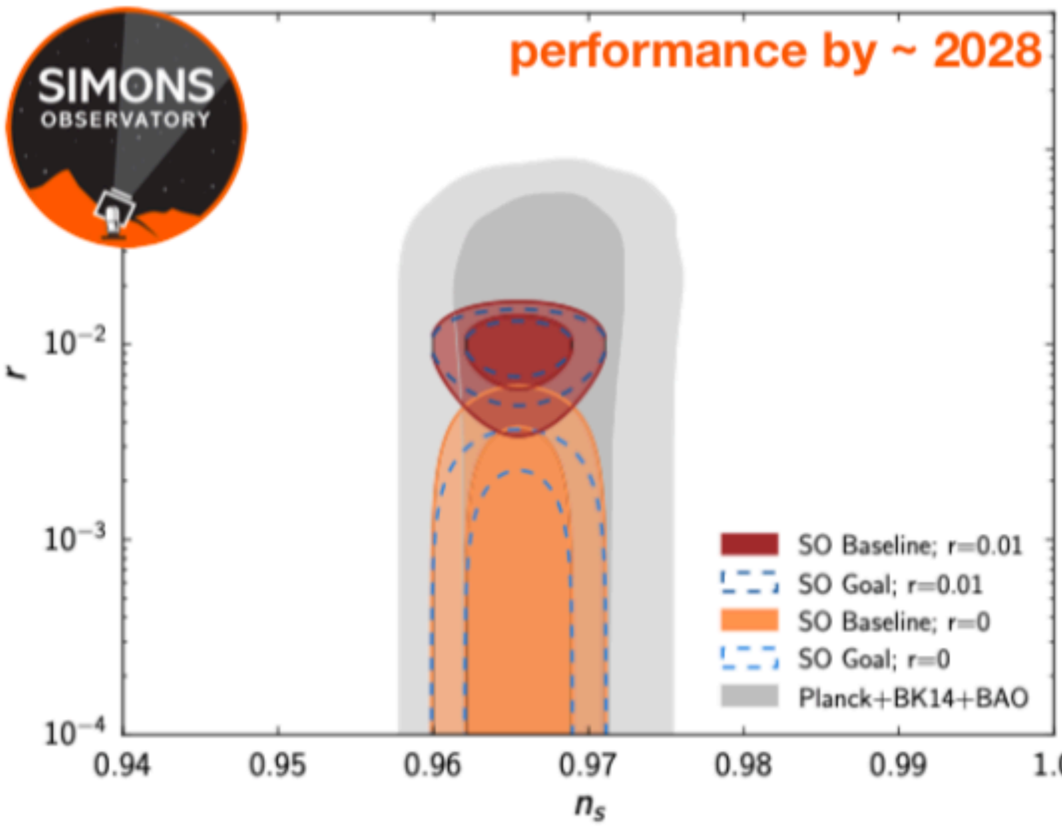
LiteBIRD-FRANCE

35 chercheurs
17 ingénieurs

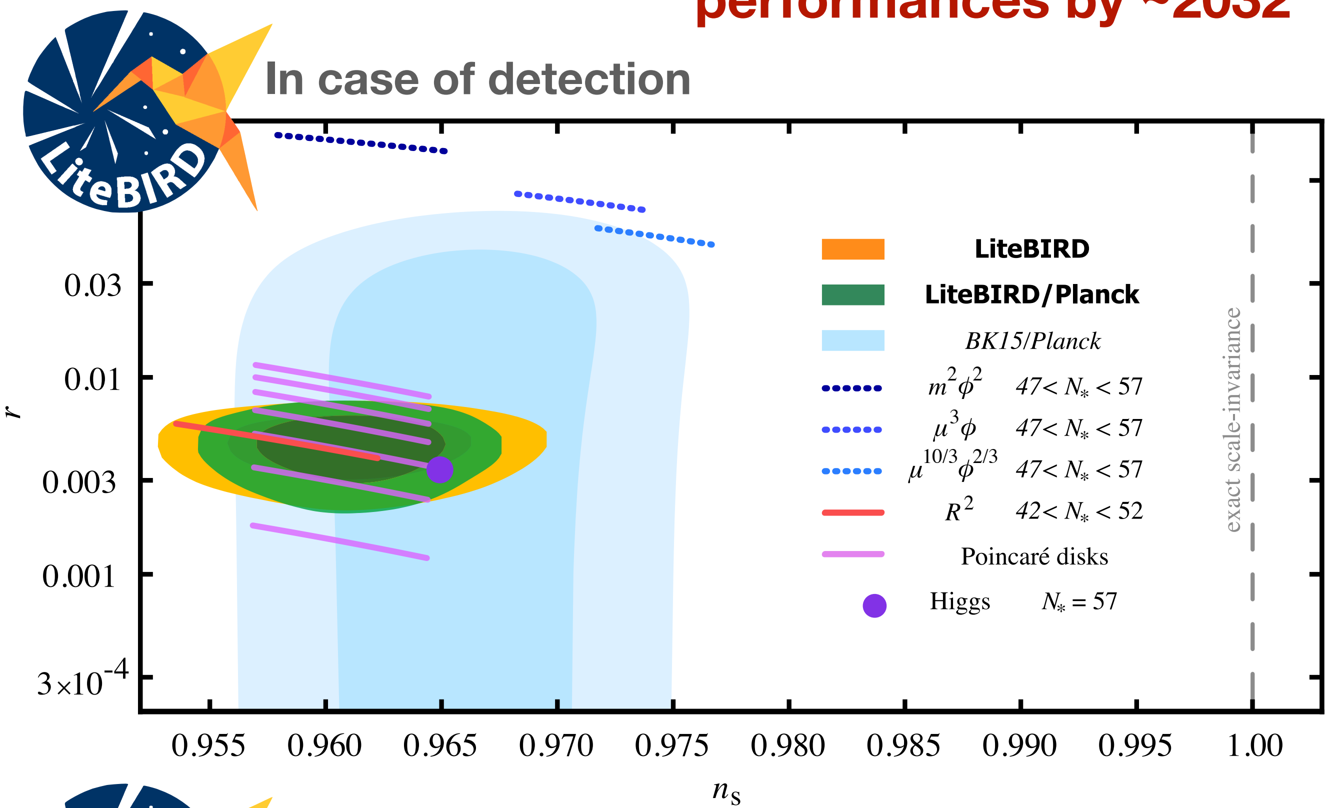


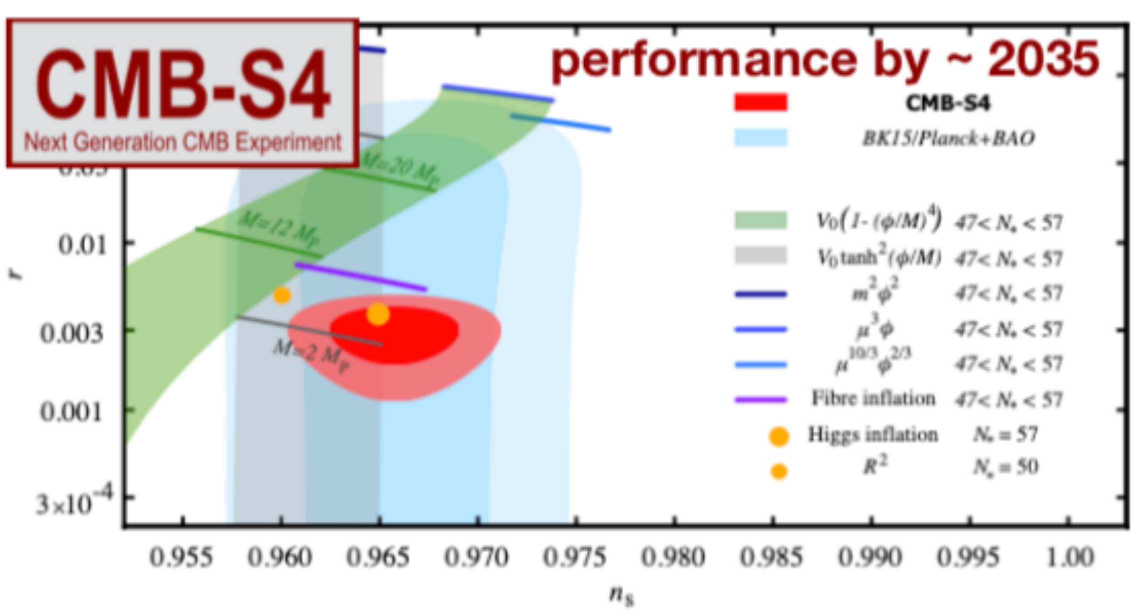

LiteBIRD-FRANCE
35 chercheurs
17 ingénieurs
IN2P3
CEA
INSU
ENS
INP
APC
IAP
IJCLab
IAS
ENS
CEA-DAp
Paris
Toulouse
Marseille
Grenoble
CNES Phase-A2 since 2020 with leadership on MFT & HFT
LPSC
IPAG
I. Neel
CEA-SBT
LAM
IRAP

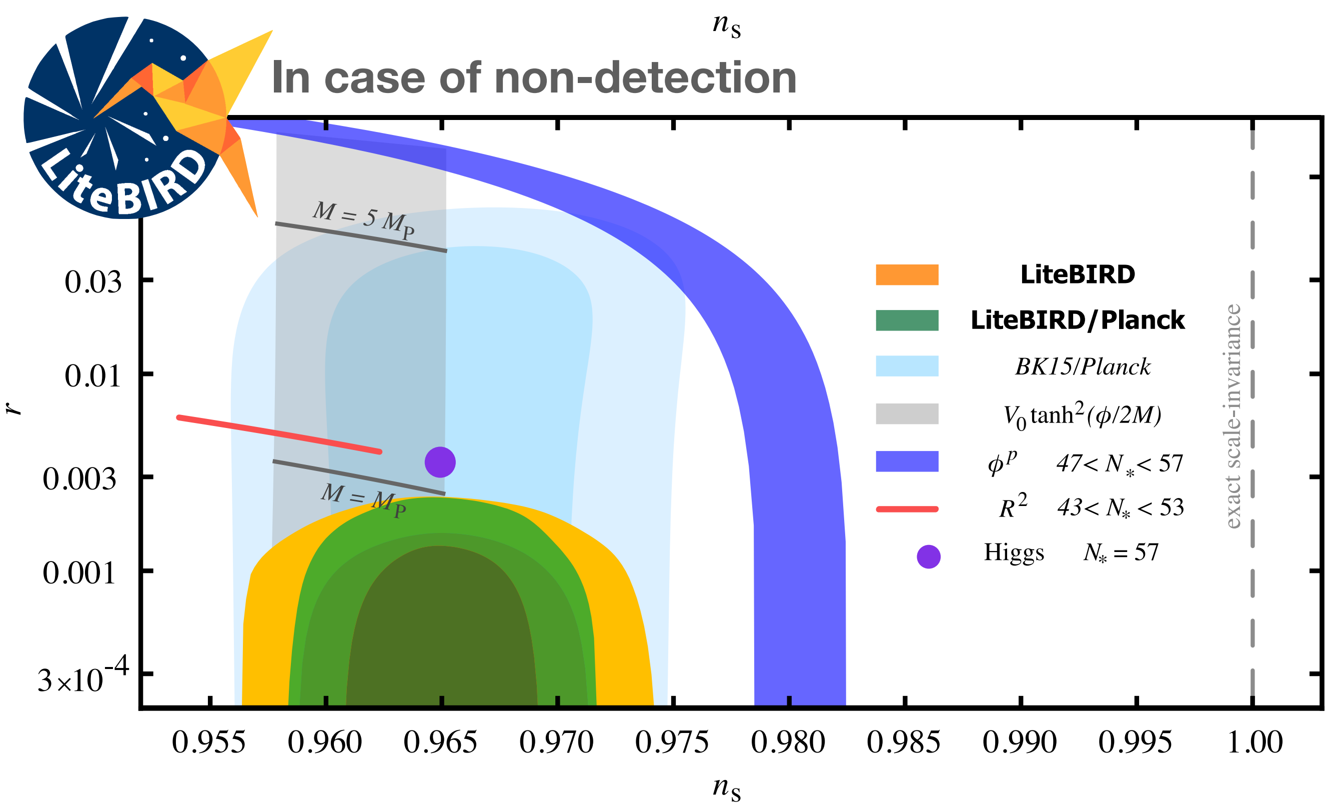
Some Forecasts as a Conclusion / Perspectives



performances by ~2032







Some Forecasts as a Conclusion / Perspectives