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Current status and future prospect of studying the physics of early universe using the measurement of the cosmic microwave background polarization

Tomotake Matsumura, Kavli IPMU

東京大学 THE UNIVERSITY OF TOKYO

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Outline

- What physics can we learn from a CMB experiment?
- Latest results
- What’s the prospect in next 5-10 years.

Cosmic history

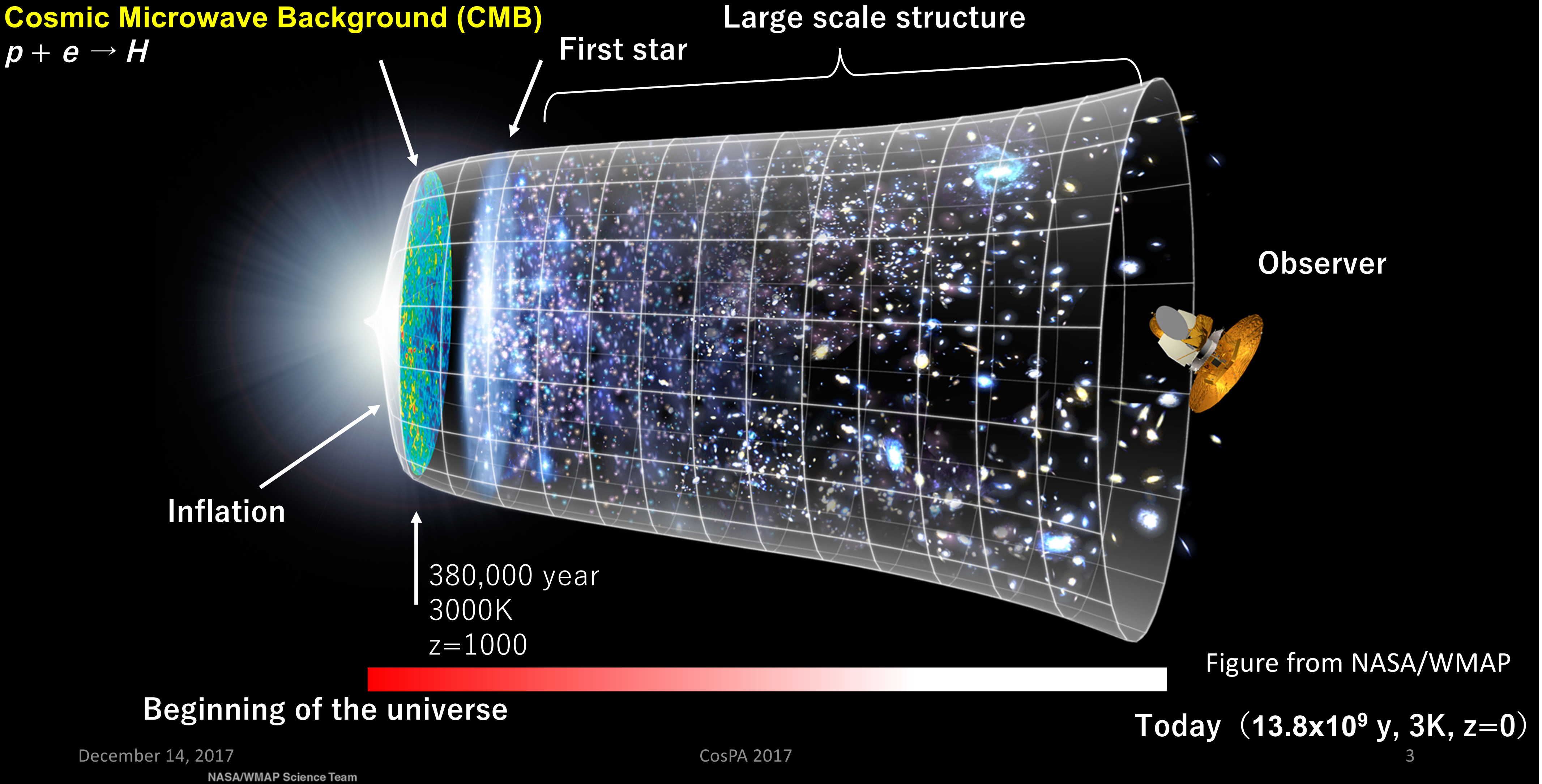


Figure from NASA/WMAP

Cosmic history

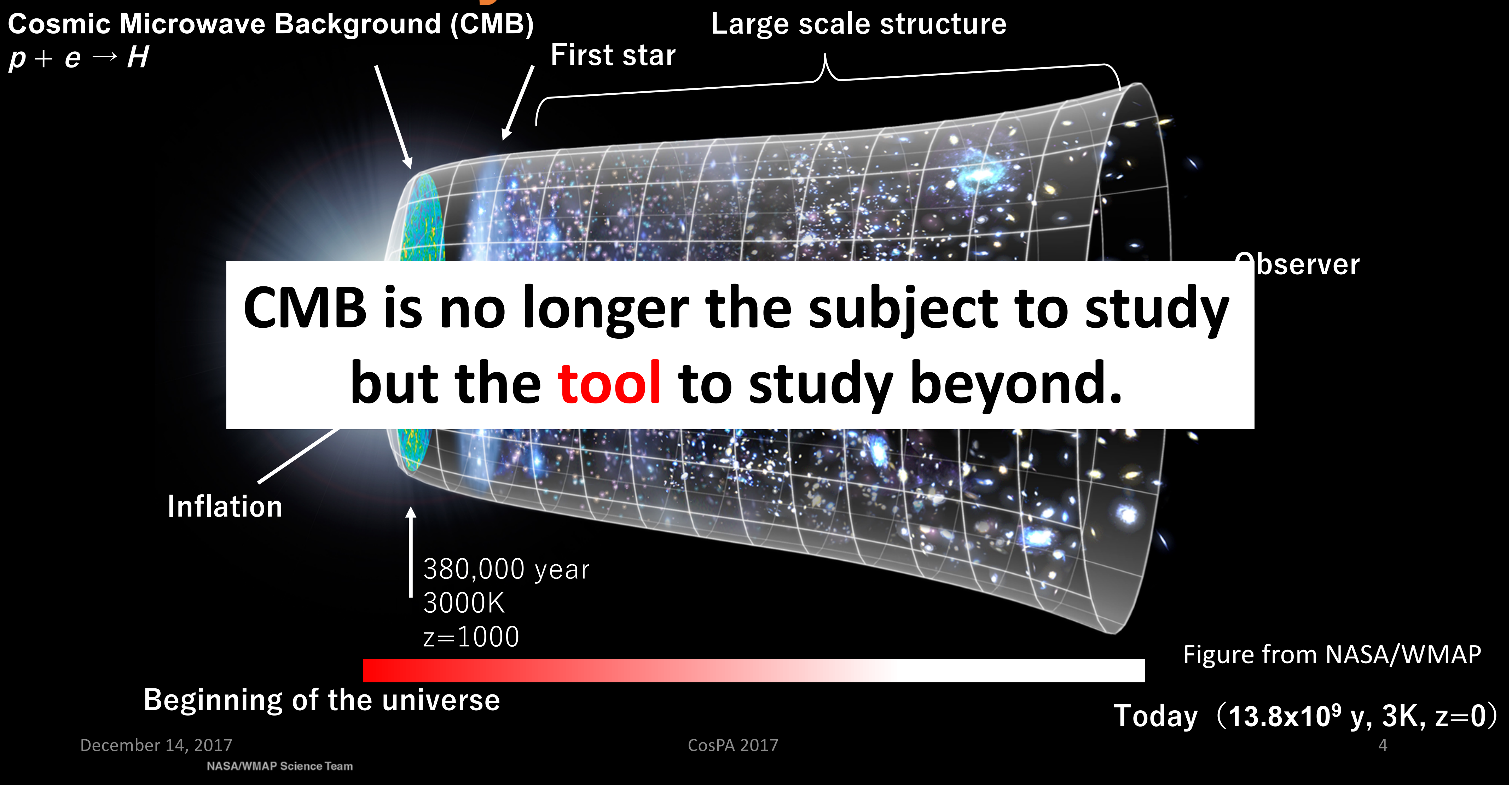
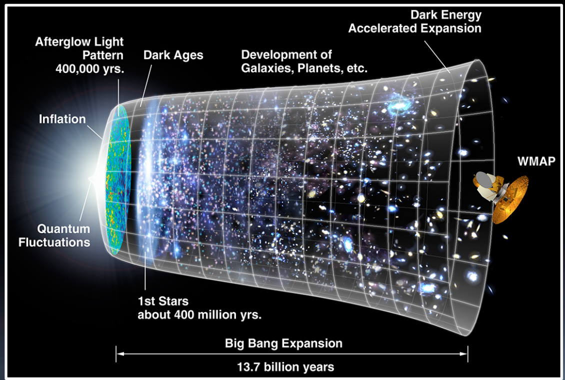


Figure from NASA/WMAP

CMB is no longer the subject to study but the tool to study beyond.

Detecting the cosmic inflation



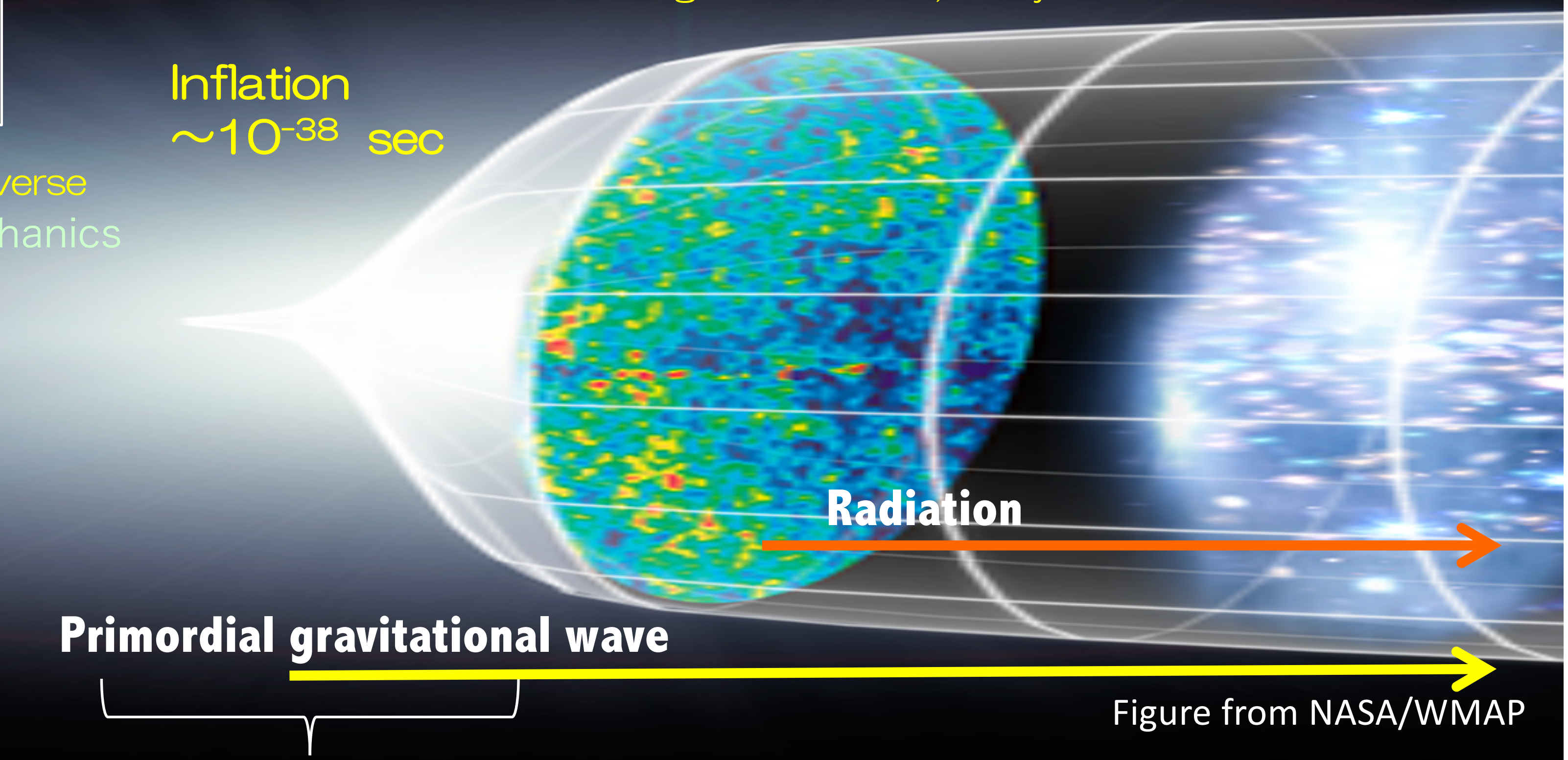
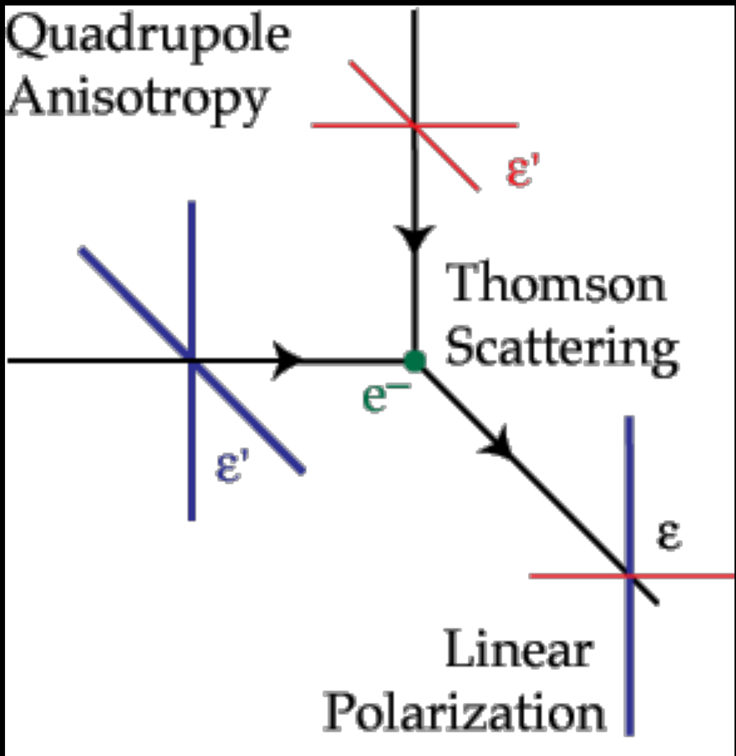


Figure from NASA/WMAP

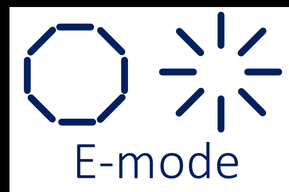
The primordial gravitational wave originated from the cosmic inflation can leave an imprint of the signature in the CMB polarization.

CMB polarization

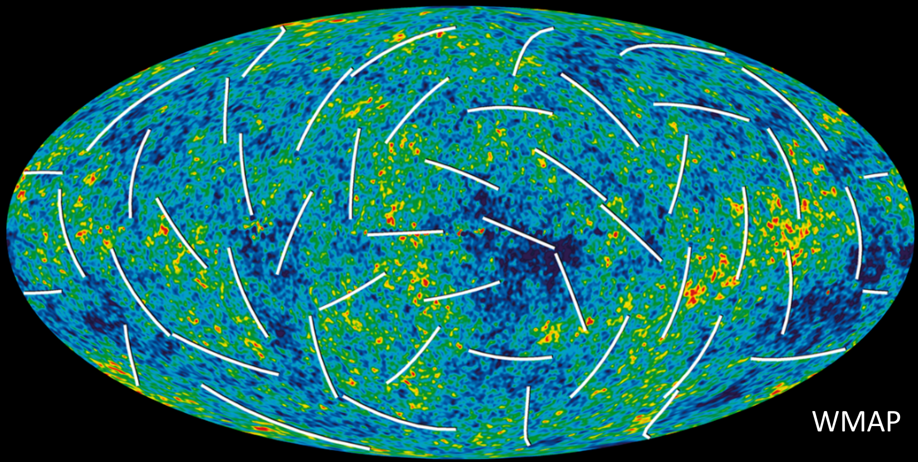


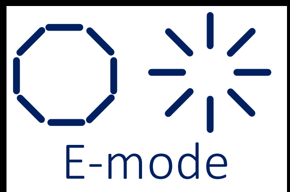
W. Hu (U. of Chicago)

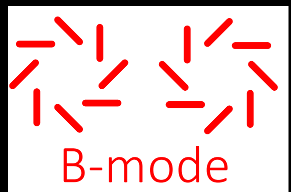
- At the last scattering surface, the CMB photon and electrons are interacting by the Thomson scattering. Once the universe is cooled enough, electron and proton form hydrogen and the leftover photon freestream until it is observed today.
- Quadrupole intensity pattern at the scattering center can result the linear polarization in the scattered radiation. Thus, there exists linear polarization regardless of inflation.
- When the source of the quadrupole pattern is from the density perturbation, this produces E-mode.

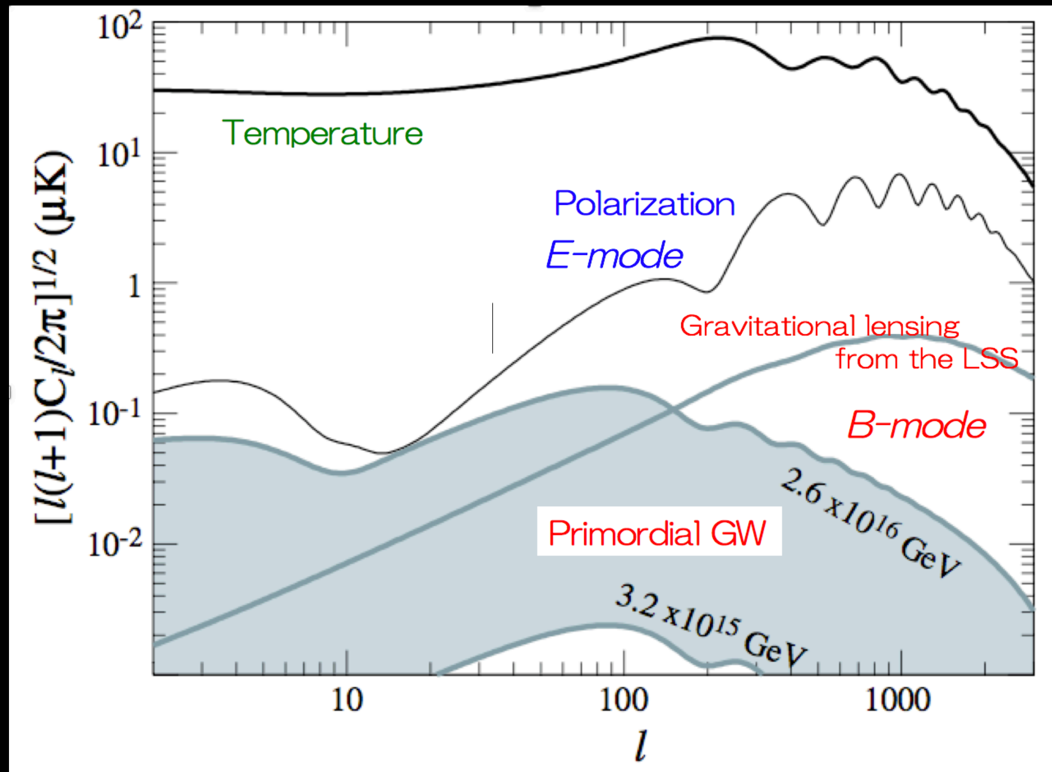


E-mode and B-mode









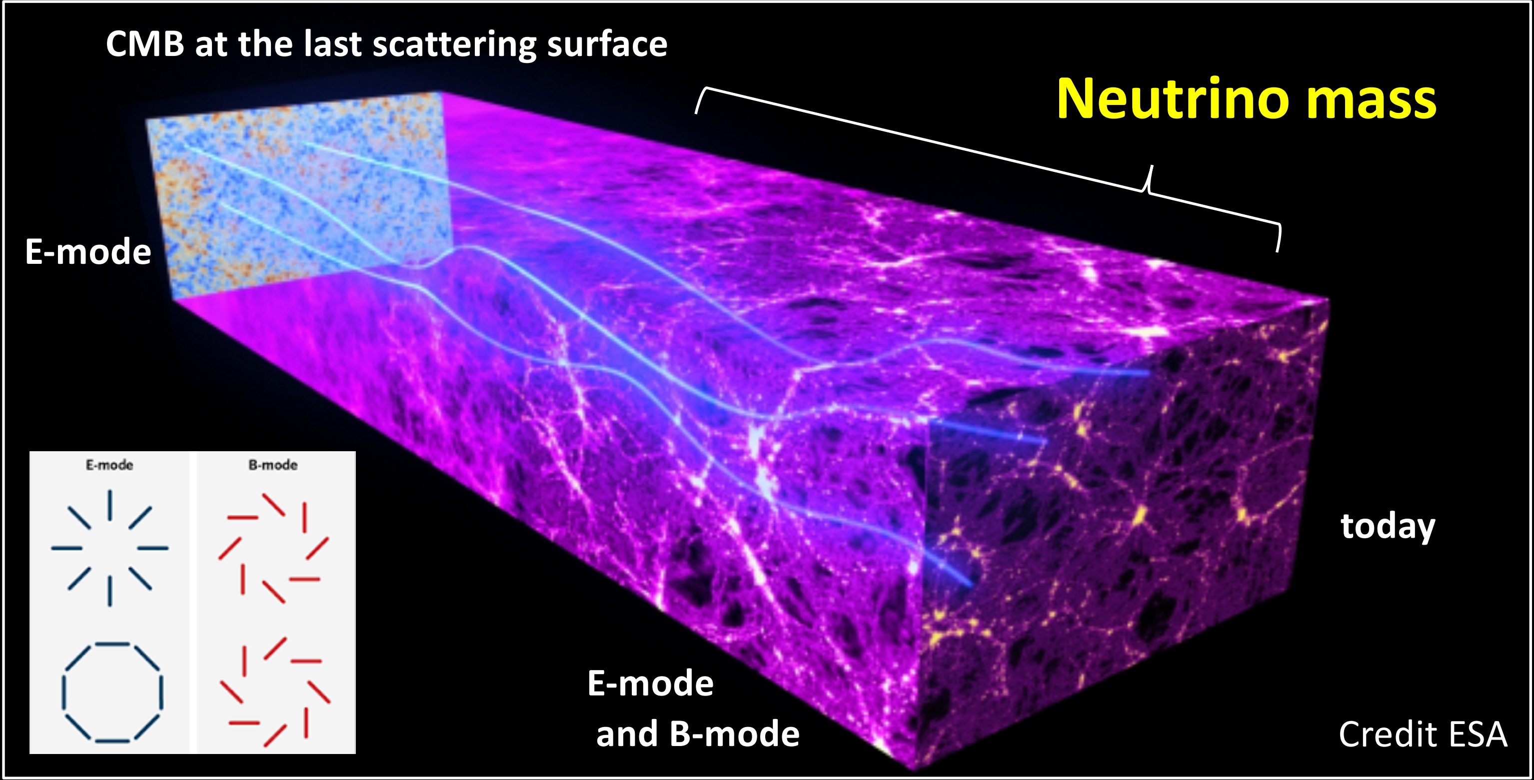
W. Hu (U. of Chicago)

- The primordial gravitational wave propagate from inflation leaves a polarization pattern of E-mode and also **B-mode**.
- In addition to the inflation originated B-mode, there is **the weak gravitational lensing originated B-mode** as well as **the foreground emission originated B-mode**.

Energy scale of inflation V
Tenor-to-scalar ratio r

$$V^{\frac{1}{4}} = 1.06\times10^{16}\left(\frac{r}{0.01}\right)^{\frac{1}{4}}\ [\mathrm{GeV}]$$

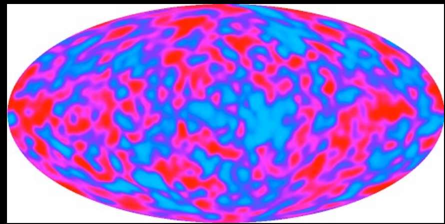
CMB as a probe of the LSS



- The CMB photons travel through the potential of the large scale structure and weak gravitationally lensed.
- The effect is prominent at around $z \sim 2$ while the effect is integrated through out the history of the universe since the last scattering surface.
- Sensitive to the sum of the neutrino mass and dark energy via the LSS potential.

time

1989 NASA **COBE**

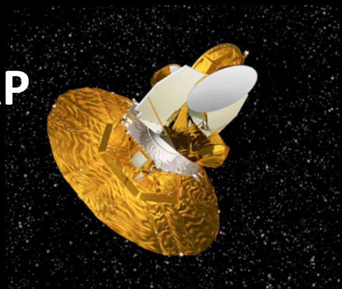


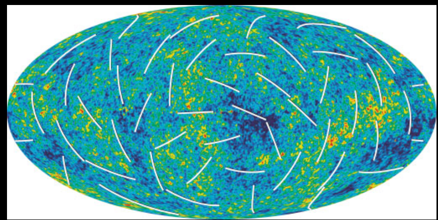
Temperature anisotropy

⇅

Density perturbation

2001 NASA **WMAP**

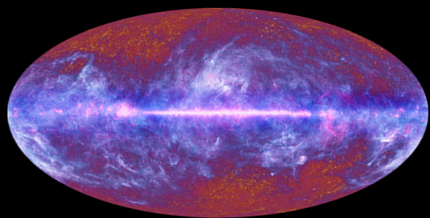




FUNDAMENTAL PHYSICS
BREAKTHROUGH
PRIZE

Discovery of the CMB polarization

2009 ESA **Planck**

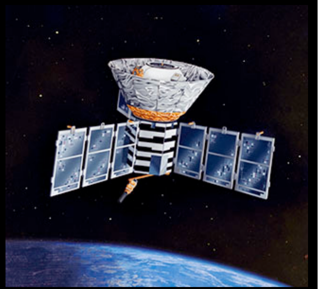


Precision ΛCDM cosmology

Constraining many cosmological parameters, including beyond standard parameters, $r, n_s, \sum m_\nu, N_{eff}$

time

1989 NASA **COBE**



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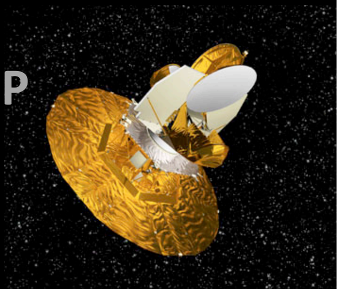

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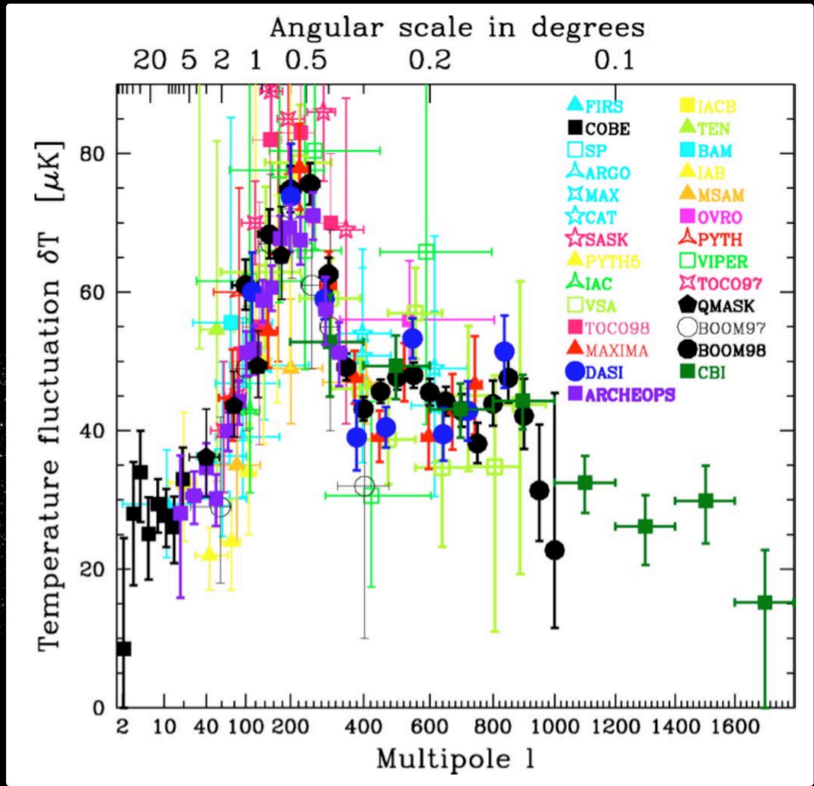
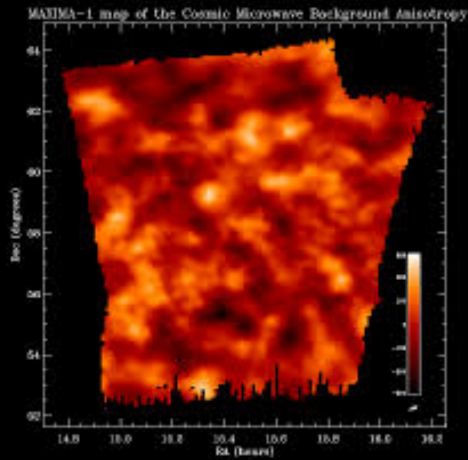


Many ground and balloon projects play key roles to complement the satellite results.



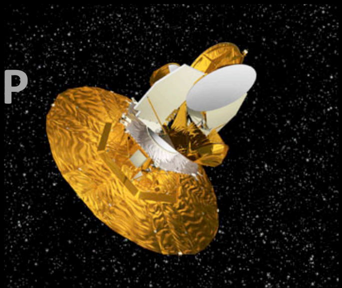
MAXIMA

BOOMERanG

time

1989 NASA **COBE**

2001 NASA **WMAP**



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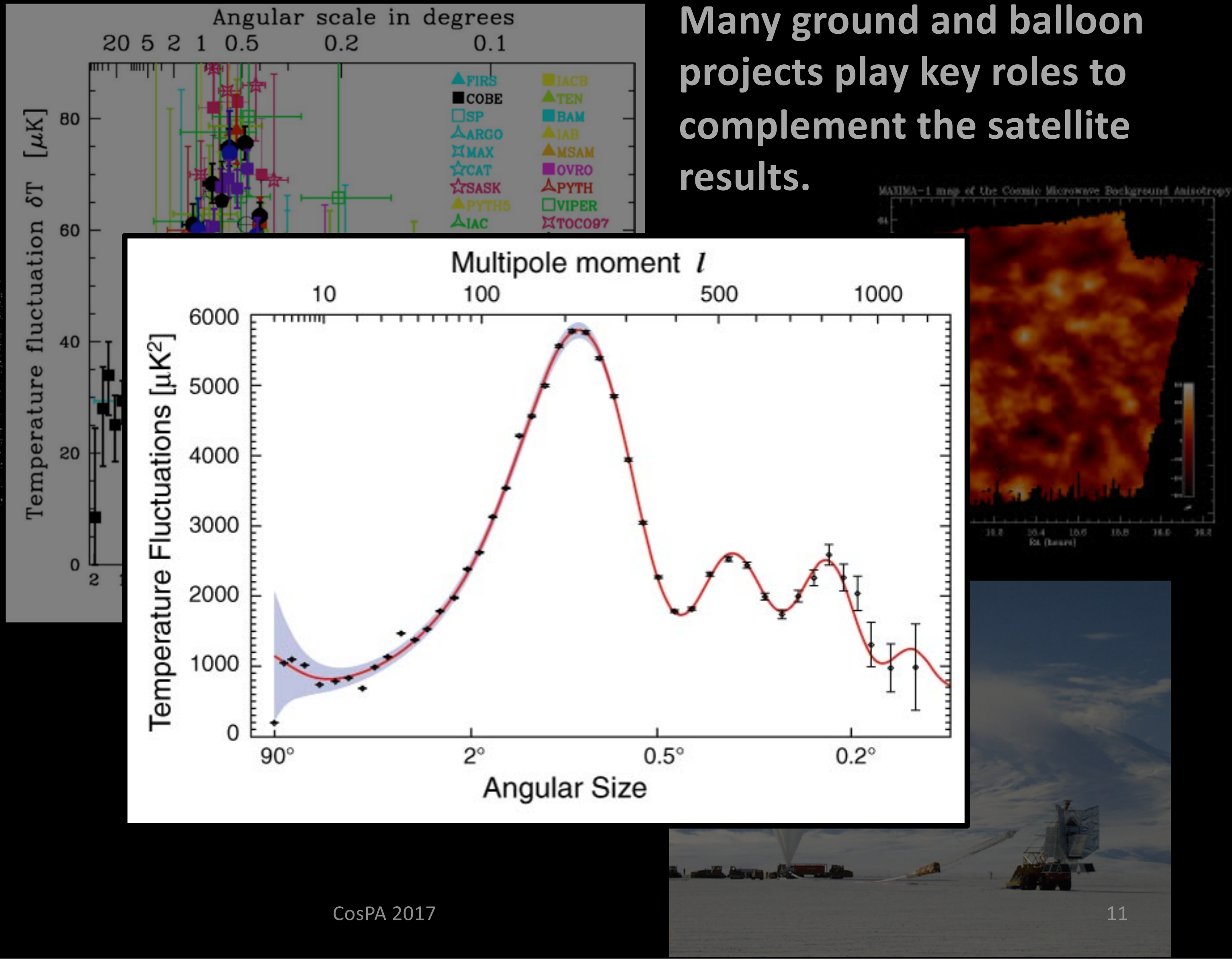

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time

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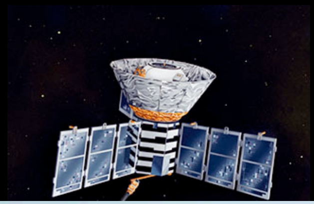
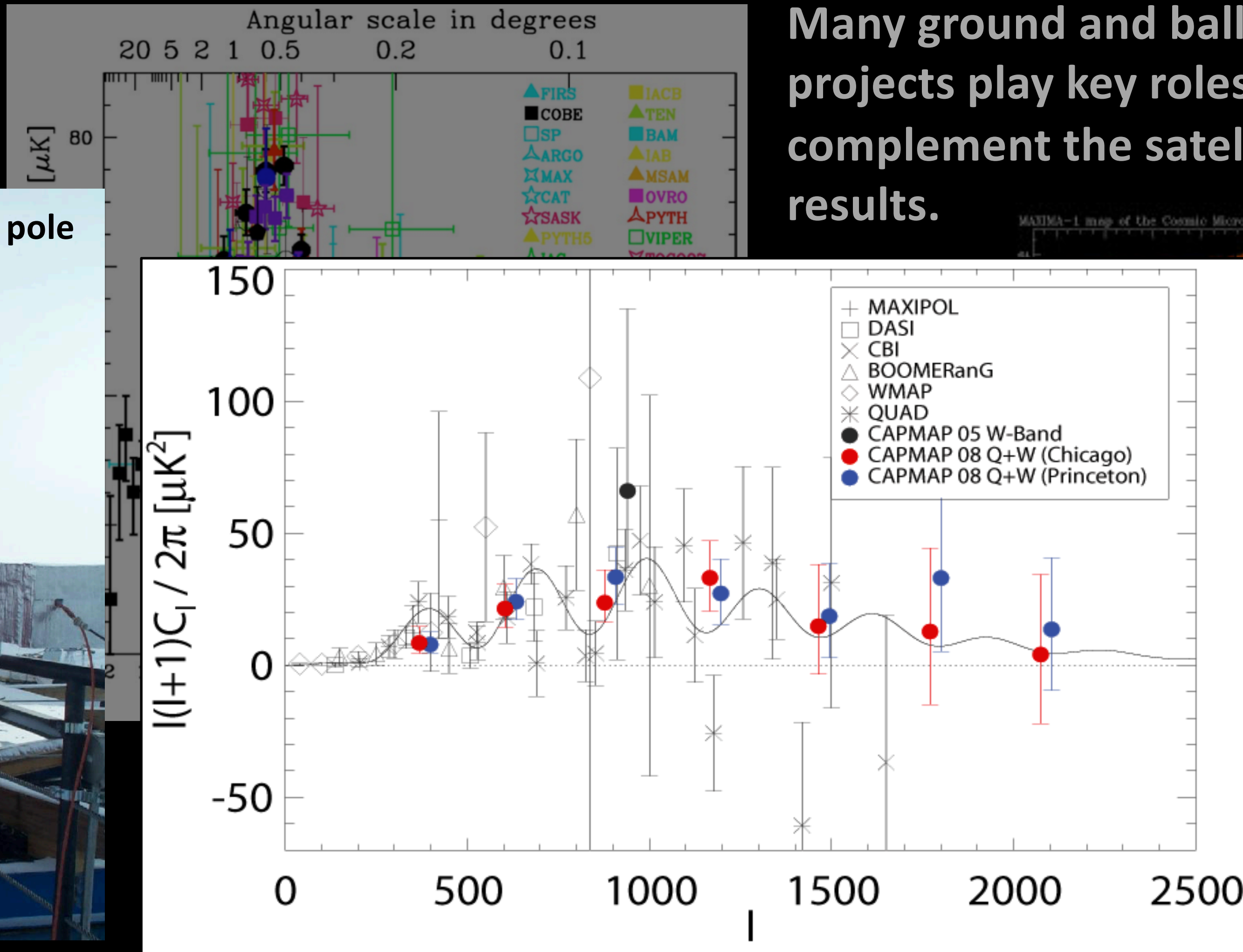
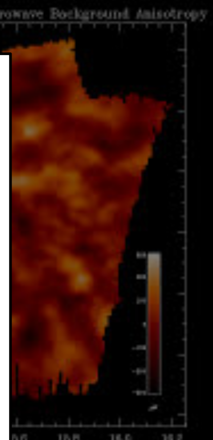


200

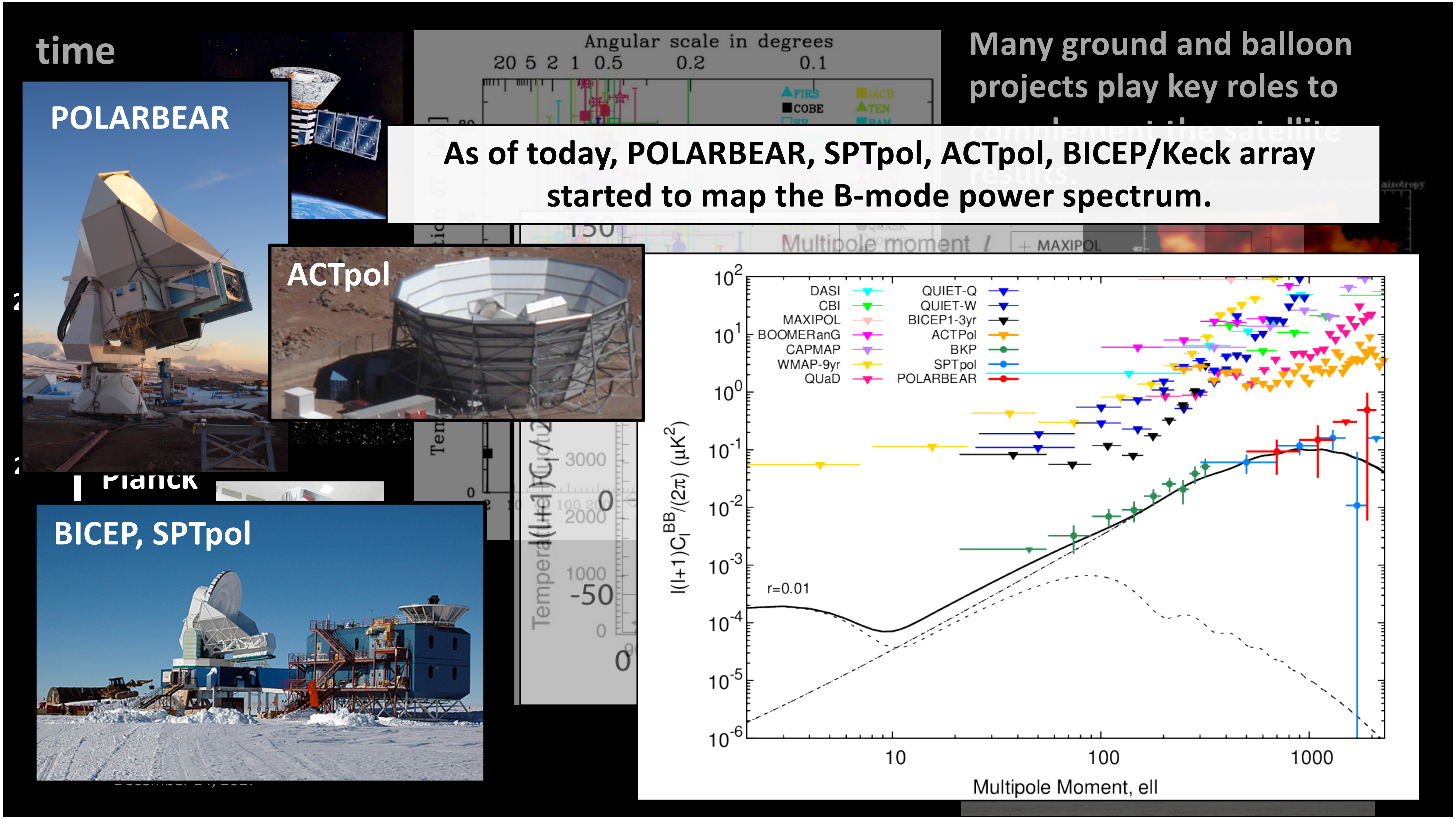
200

Many ground and balloon projects play key roles to complement the satellite results.





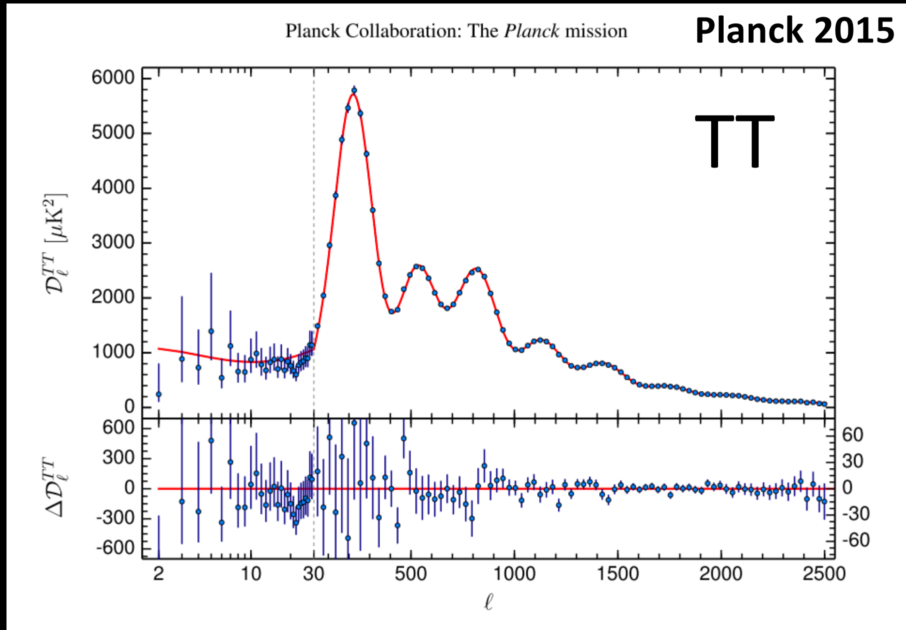
Detection of the CMB E-mode polarization by DASI (2002).


time
Many ground and balloon
projects play key roles to
POLARBEAR
As of today, POLARBEAR, SPTpol, ACTpol, BICEP/Keck array
started to map the B-mode power spectrum.
ACTpol
Planck
BICEP, SPTpol
Angular scale in degrees
20 5 2 1 0.5 0.2 0.1
Multipole moment l
MAXIPOL
DASI
CBI
MAXIPOL
BOOMERanG
CAPMAP
WMAP-9yr
QUaD
QUIET-Q
QUIET-W
BICEP1-3yr
ACTPol
BKP
SPTpol
POLARBEAR
r=0.01
l(l+1)C_l^BB/(2π) (μK^2)
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10
100
1000
Multipole Moment, ell

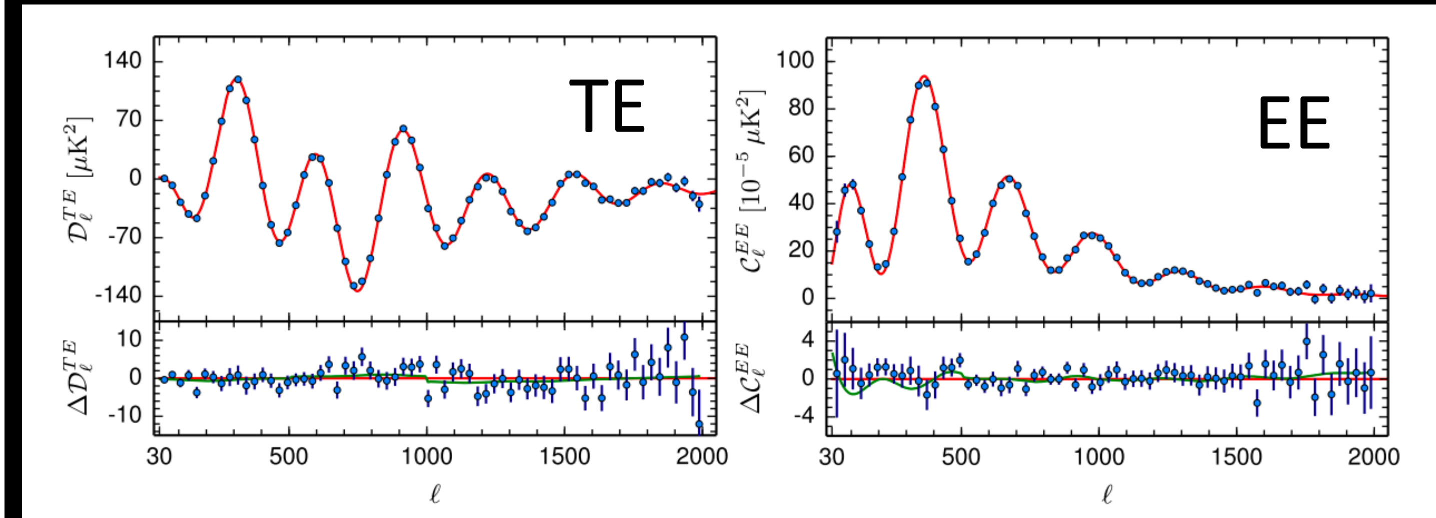
In the post Planck era, inflation is the main driver to all the CMB experiments.

Planck power spectrum

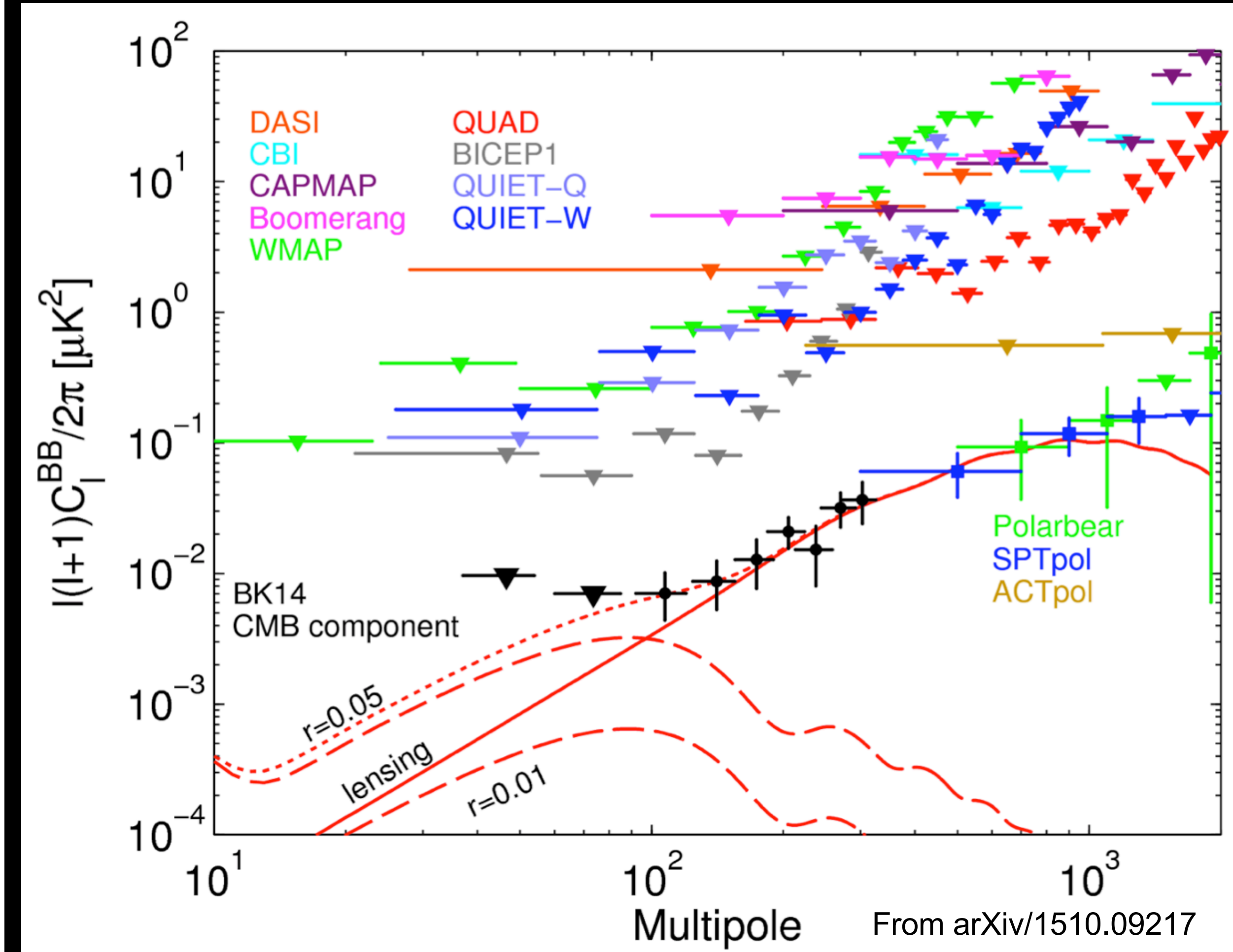
One of the main science deliverables of Planck was n_s given the angular resolutions.



Parameter	*Planck* TT+lowP+lensing
$\Omega_b h^2$	0.02226 ± 0.00023
$\Omega_c h^2$	0.1186 ± 0.0020
$100\theta_{MC}$	1.04103 ± 0.00046
τ	0.066 ± 0.016
$\ln(10^{10} A_s)$	3.062 ± 0.029
n_s	0.9677 ± 0.0060
H_0	67.8 ± 0.9
Ω_m	0.308 ± 0.012
$\Omega_m h^2$	0.1415 ± 0.0019
$\Omega_m h^3$	0.09591 ± 0.00045
σ_8	0.815 ± 0.009
$\sigma_8 \Omega_m^{0.5}$	0.4521 ± 0.0088
Age/Gyr	13.799 ± 0.038
r_{drag}	147.60 ± 0.43
k_{eq}	0.01027 ± 0.00014

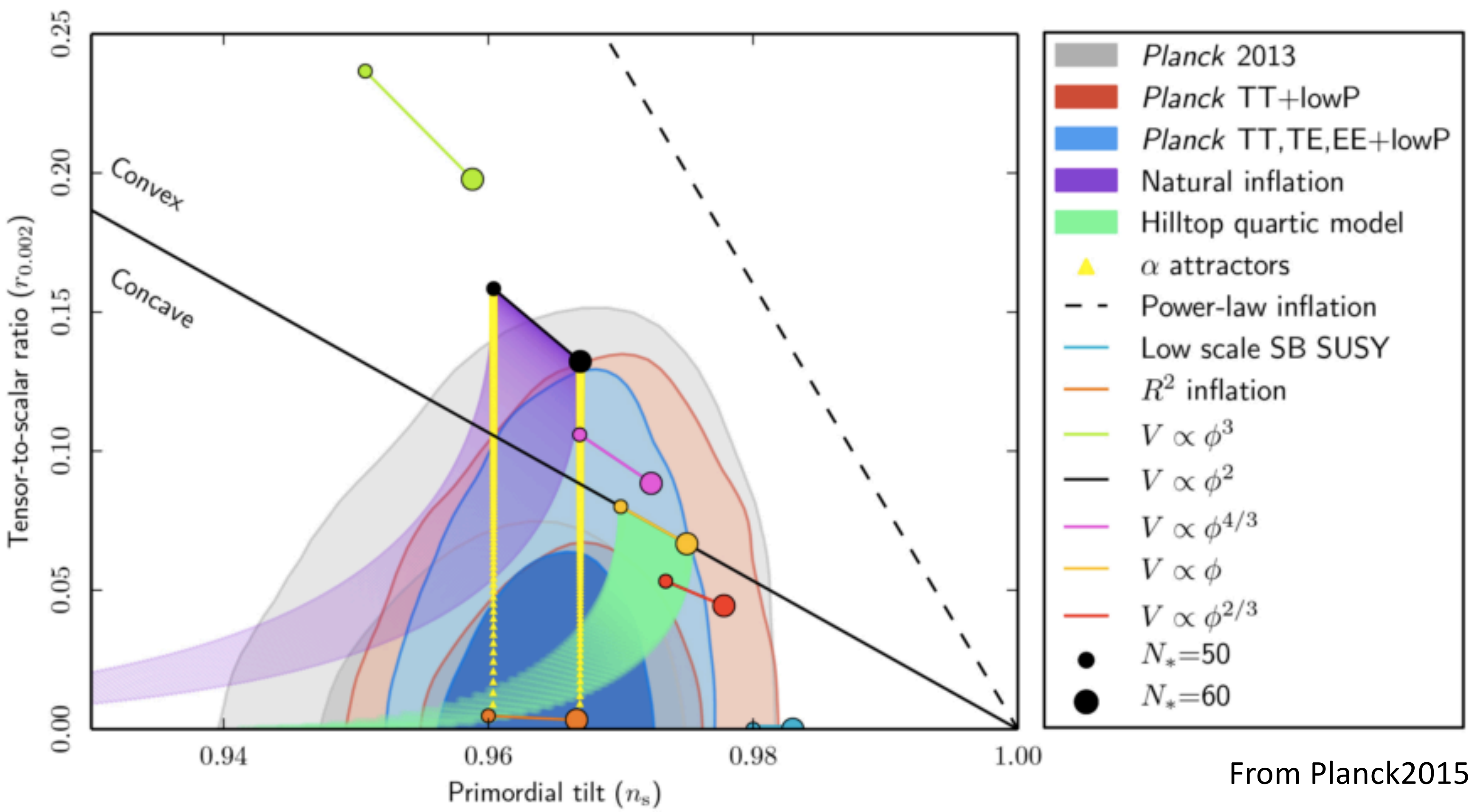


B-mode hunting today



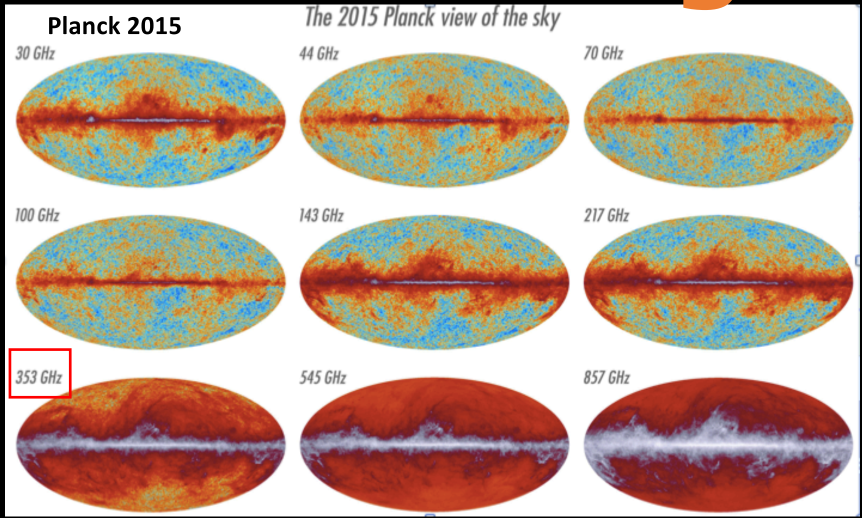
- **Planck Temperature: *r* < 0.12 (95%C.L.)**
- **BICEP-Keck array-Planck, known as BKP, Polarization: *r* < 0.09 (95%C.L.)**
- **Combining all including BAO:**
  ***r* < 0.07 (95%C.L.)**

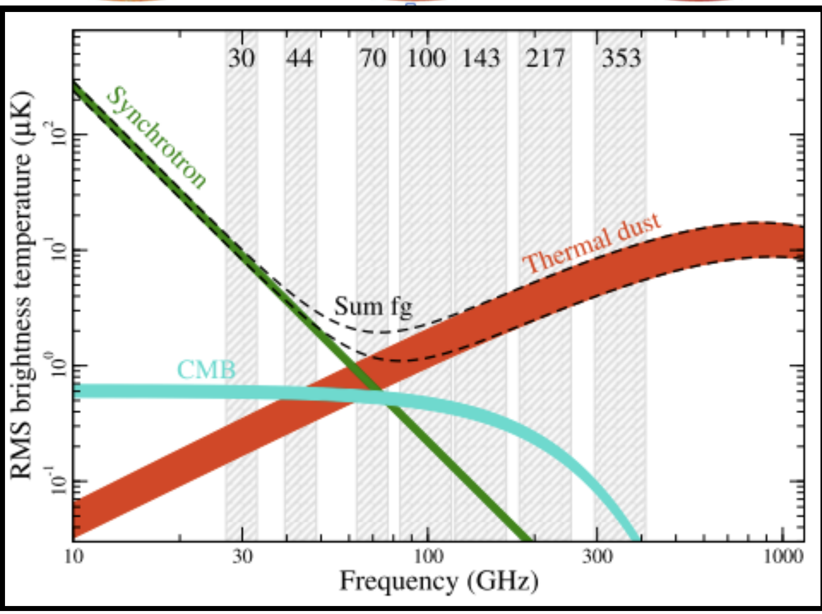
Current constraint in r - n_s plane



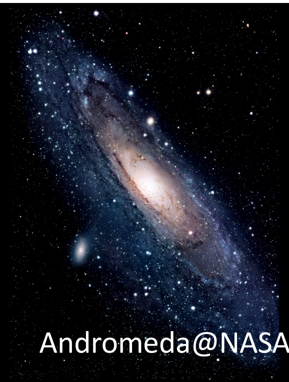
From Planck2015

Foreground challenge

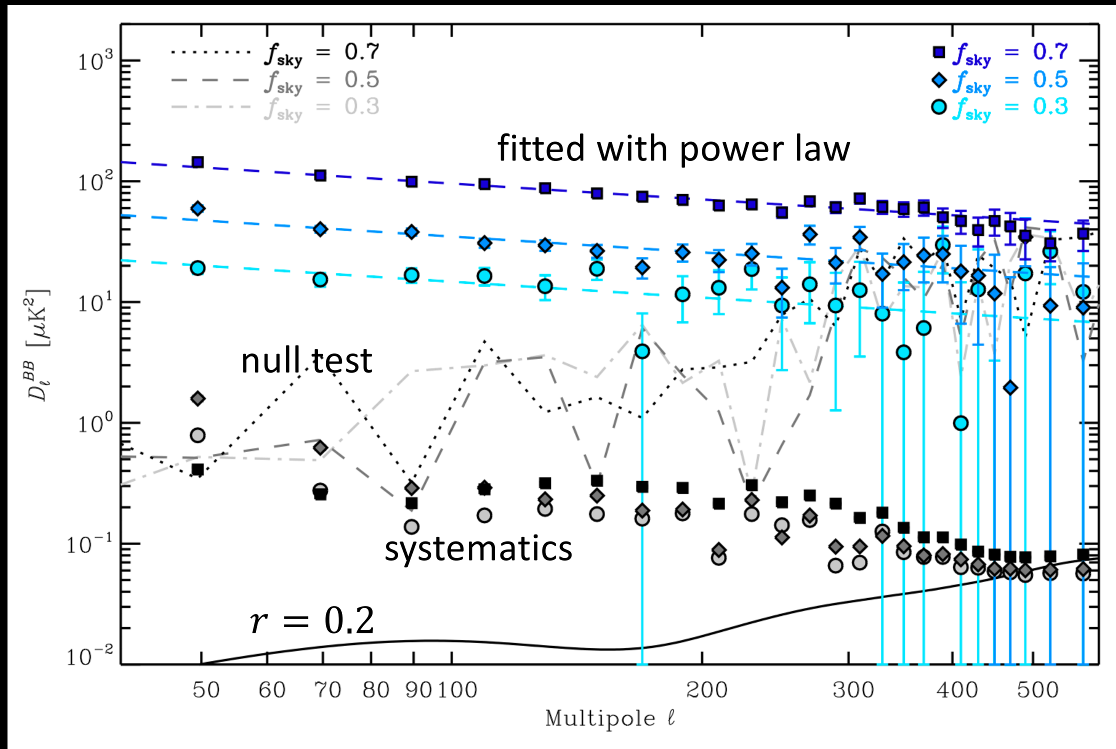




We are living in the Galaxy.



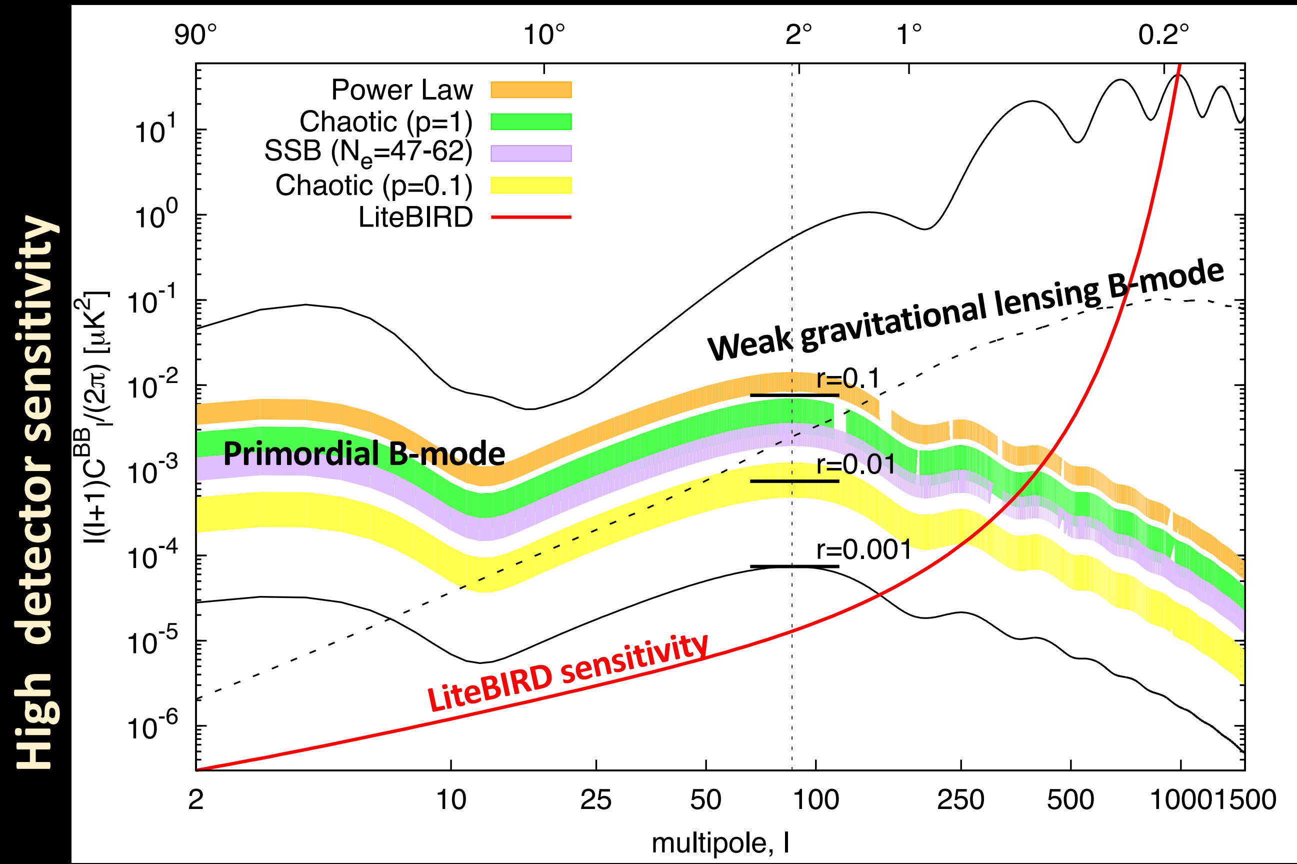
Planck 353 GHz B-mode power spectra with various mask size. The CMB B-mode is the primordial B-mode (r=0.2) and the lensing B-mode.



CMB experiment 101

- **Full sky coverage**
  - Scan strategy
- **Foreground removal**
  - Simultaneous observation over broadband
- **Large angular scale**
  - Beam size
- **High sensitivity**
  - Detector sensitivity
  - Control systematics

Angular resolution



Full sky coverage

M. Hazumi et al. 2012

CMB experiment 101

To be a compelling CMB experiment, we need $\sim 30\ nK$ CMB equivalent noise over 1 degree scale on the sky.

$$Noise = \frac{2 \times NET_s}{\sqrt{\frac{t_{obs}}{4\pi f_{sky}} \times N_{det}}}$$

Single detector noise

The # of detectors

Observational time

- NET_s: For space mission, one can achieve about $50\ \mu K\sqrt{s}$ using a superconducting bolometric detector. On the ground, it's about $300\ \mu K\sqrt{s}$ at a place such as Chile and the South Pole.
- Free to choose t_{obs} and N_{det} to achieve the desired noise level.

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Single detector noise → NET_s

The # of detectors → N_{det}

Observational time → t_{obs}

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Example1)

- **From space, t_{obs} = 3 years and N_{det} >2000 detectors allow to reach the desired sensitivity over the full sky ($f_{sky} = 1$) as a ball park estimate.**

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Example2)

- **Or one might choose t_{obs} = 3 years and N_{det} >10^4 detectors and aiming $f_{sky} \sim 0.4$ from the ground.**


Ongoing and upcoming observations
Space
LiteBIRD
POLARBEAR
& Simons Array
SIMONSOBSERVATORY
CLASS
Chile
ACTpol
Quijote
Spain
GroundBIRD
CMB-S4
Next Generation CMB Experiment
BFORE system design
BFORE
cryostat
asymmetric sun shield
and solar arrays
lightweight gondola
Balloons: EBEX/SPIDER
South pole
/Antarctica
South pole telescope (SPTpol)
BICEP2, BICEP3, Keck array
CosPA 2017


Ongoing and upcoming observations
POLARBEAR
& Simons Array
SIMONSOBSERVATORY
CLASS
Chile
ACTpol
Ali
Tibet
Space
LiteBIRD
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Spain
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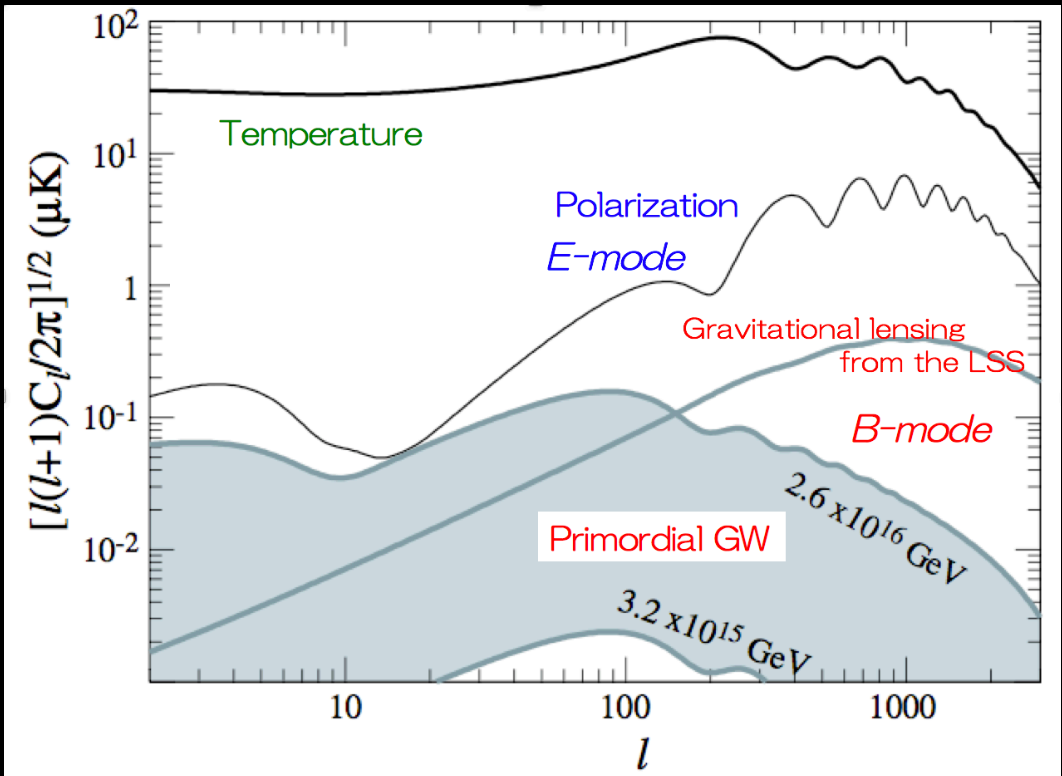
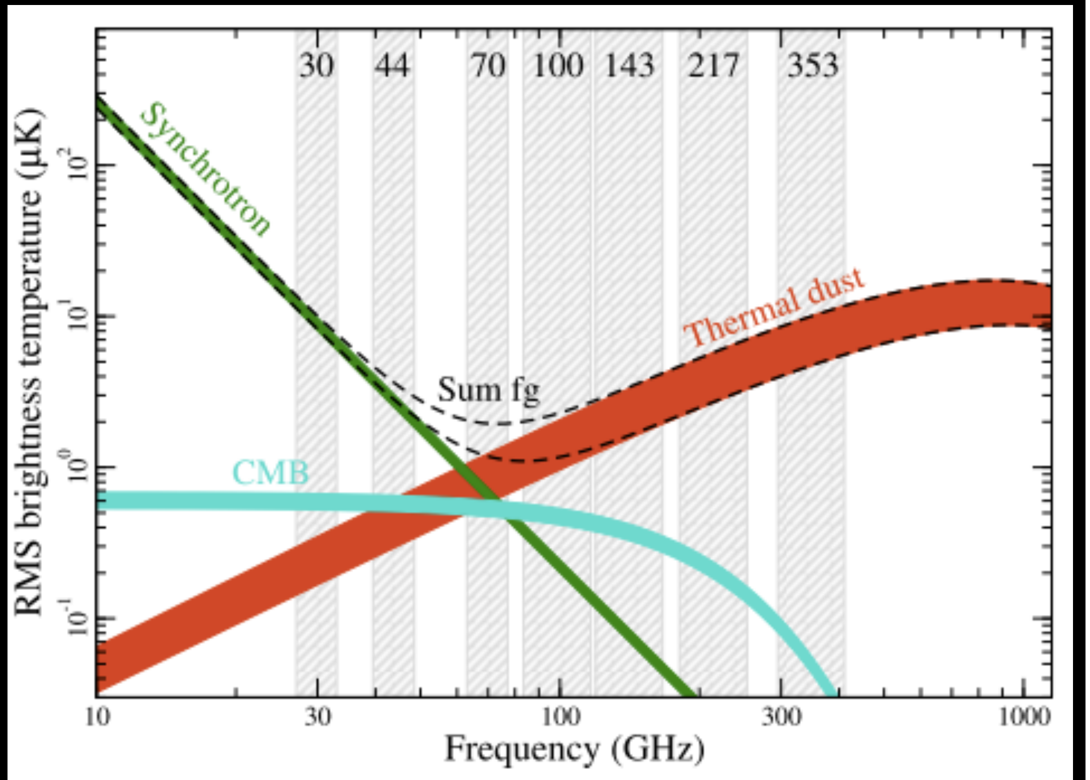
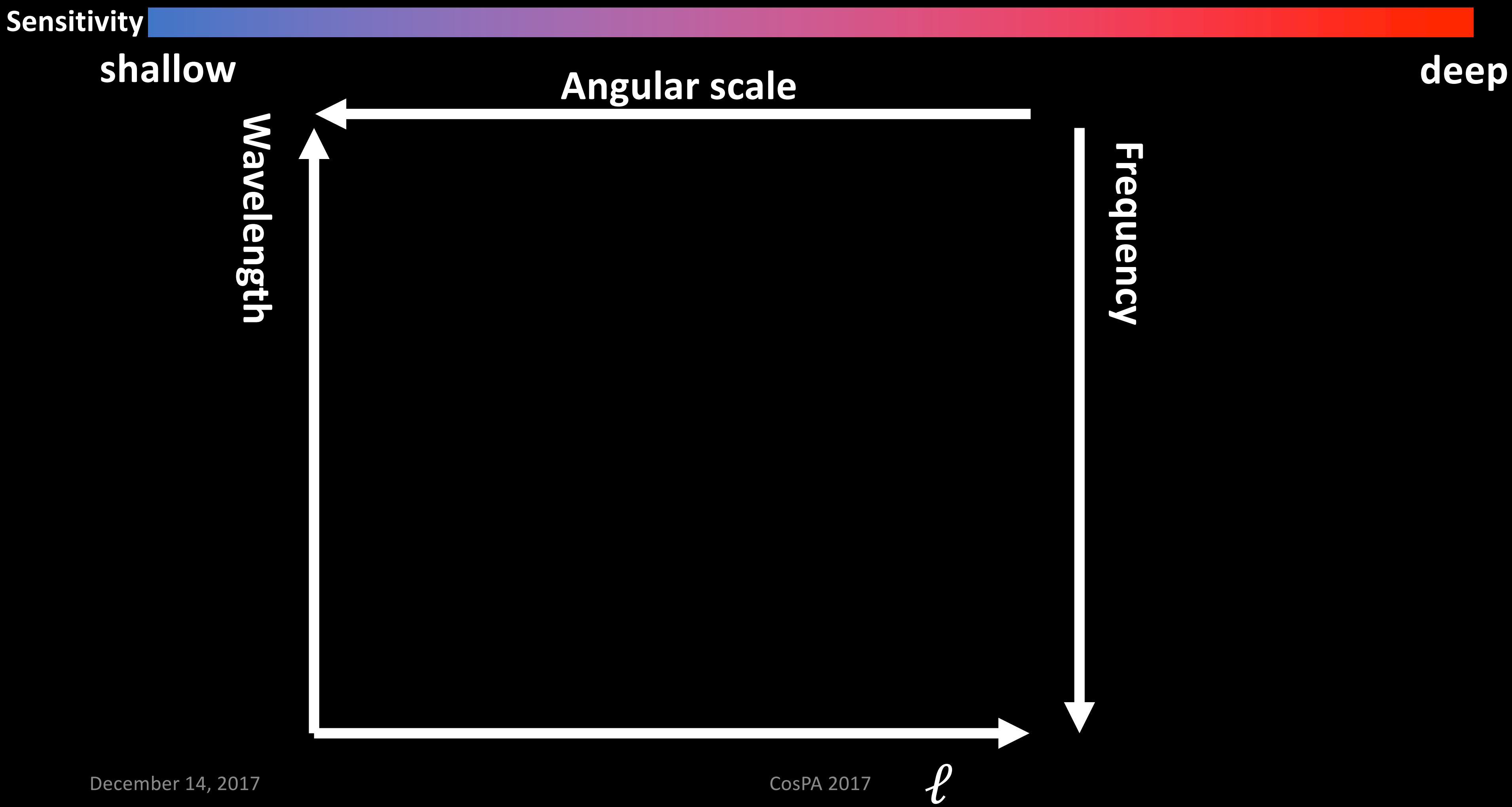
Next Generation CMB Experiment
BFORE system design
BFORE
cryostat
asymmetric sun shield and solar arays
lightweight gondola
Balloons: EBEX/SPIDER
South pole
/Antarctica
South pole telescope (SPTpol)
BICEP2, BICEP3, Keck array
CosPA 2017

small space telescope **small ground telescope** **large ground telescope**



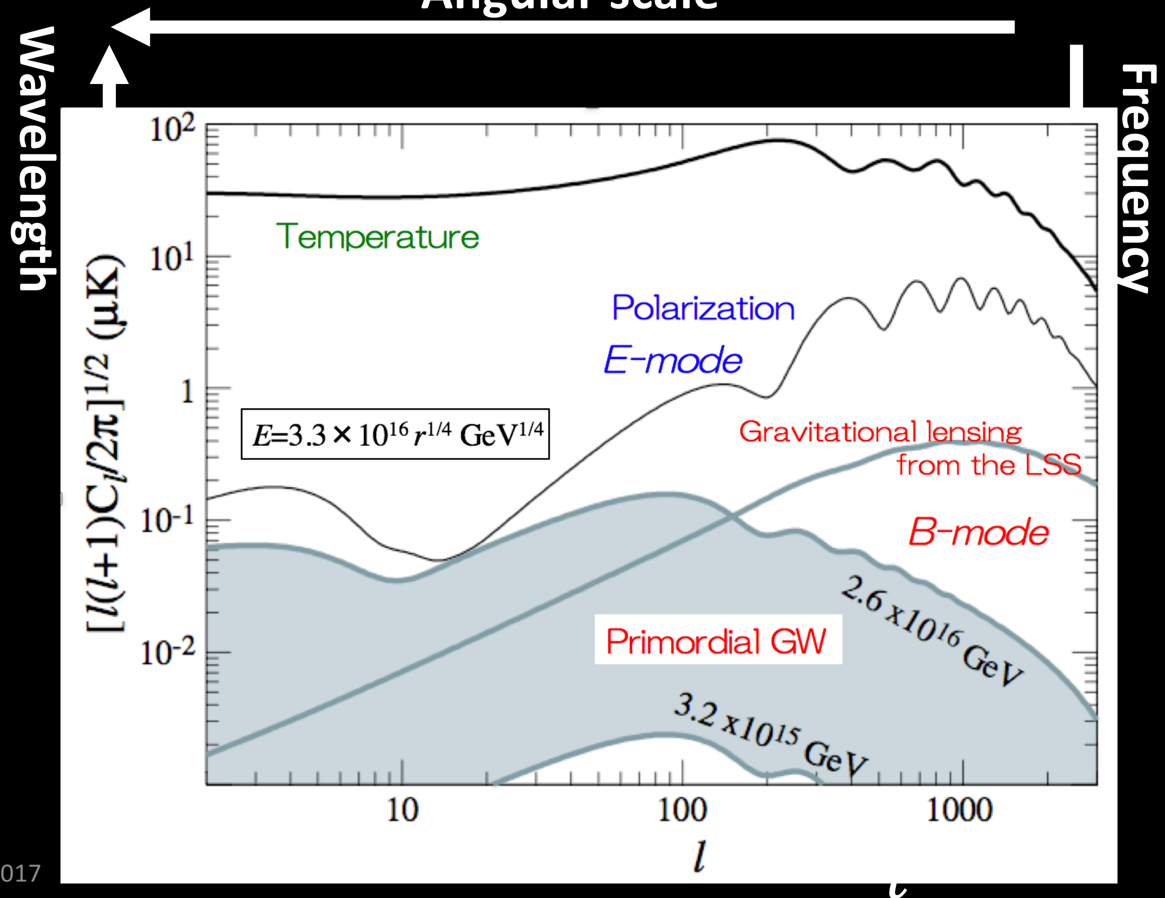


CMB sensitivity conceptual diagram



CMB sensitivity conceptual diagram

Sensitivity
shallow
deep



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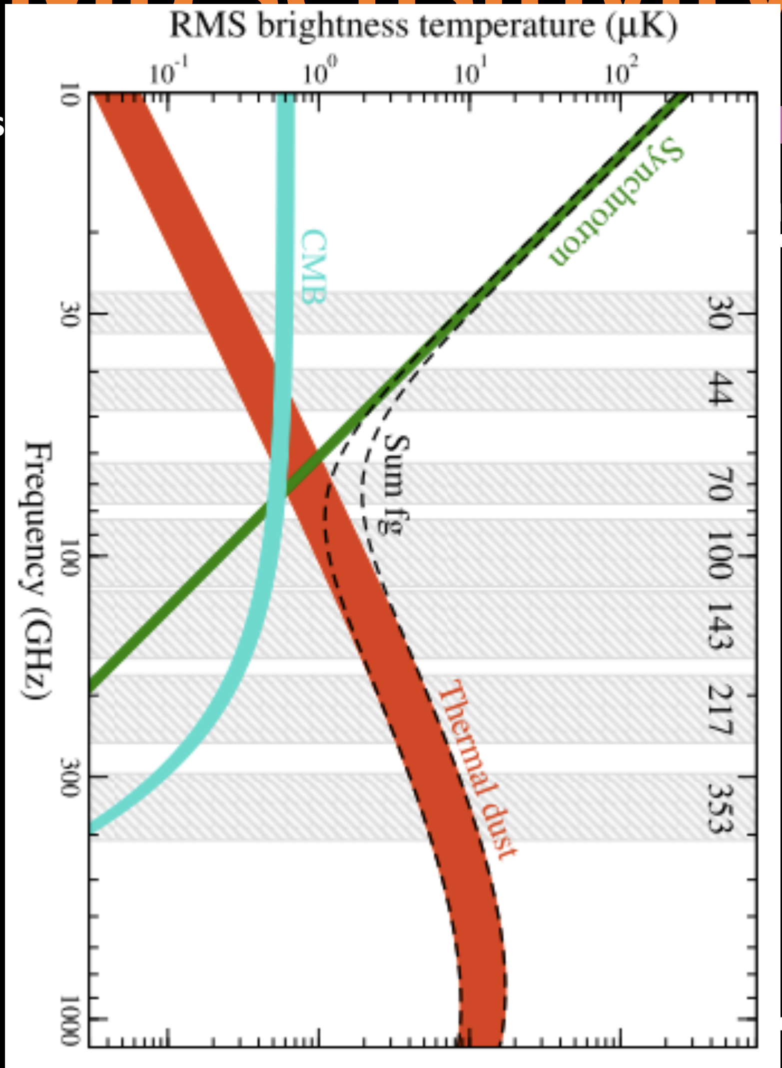


Sens

deep

r scale

Frequency

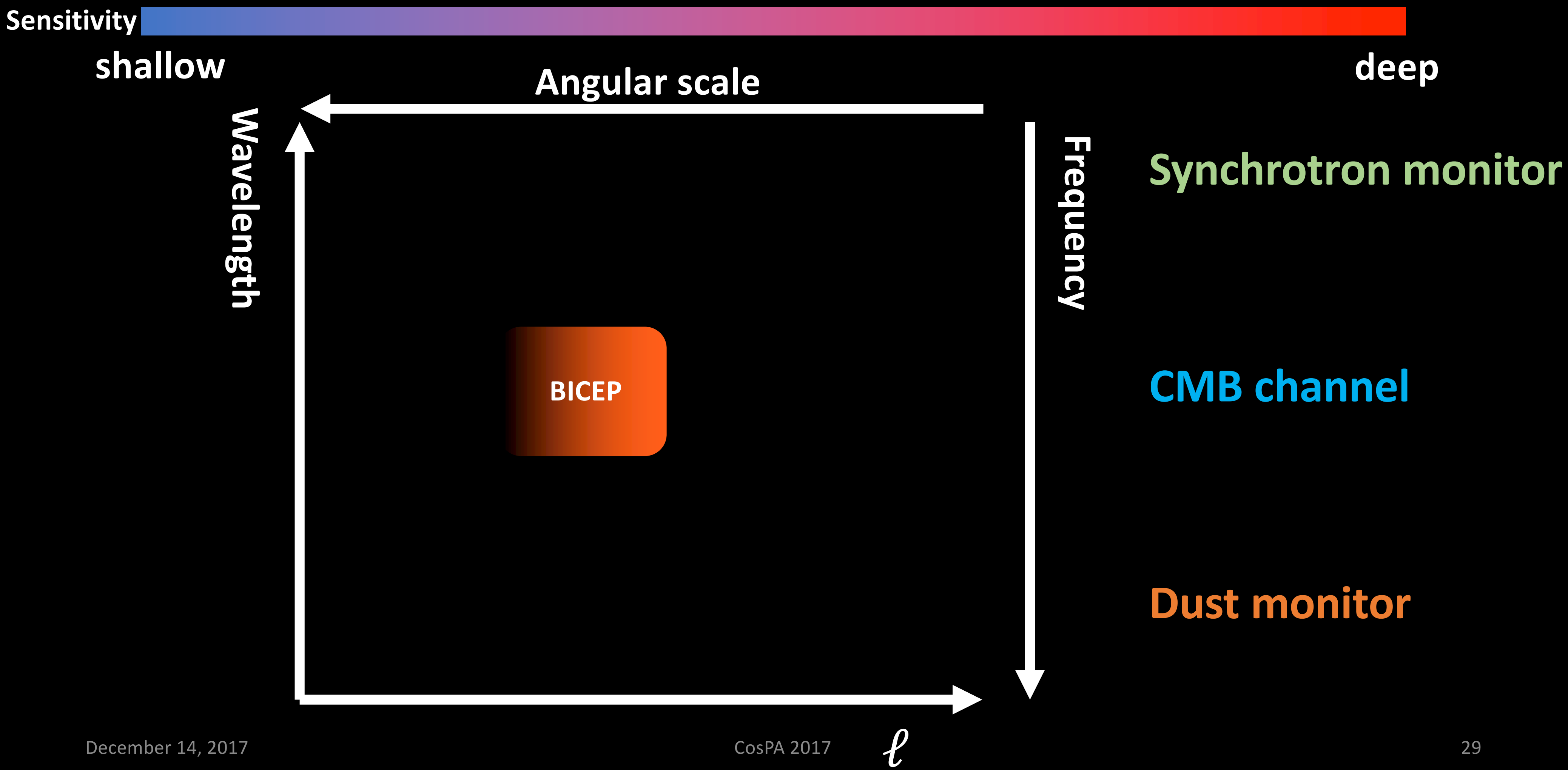
Synchrotron monitor

CMB channel

Dust monitor

ℓ

CMB sensitivity conceptual diagram



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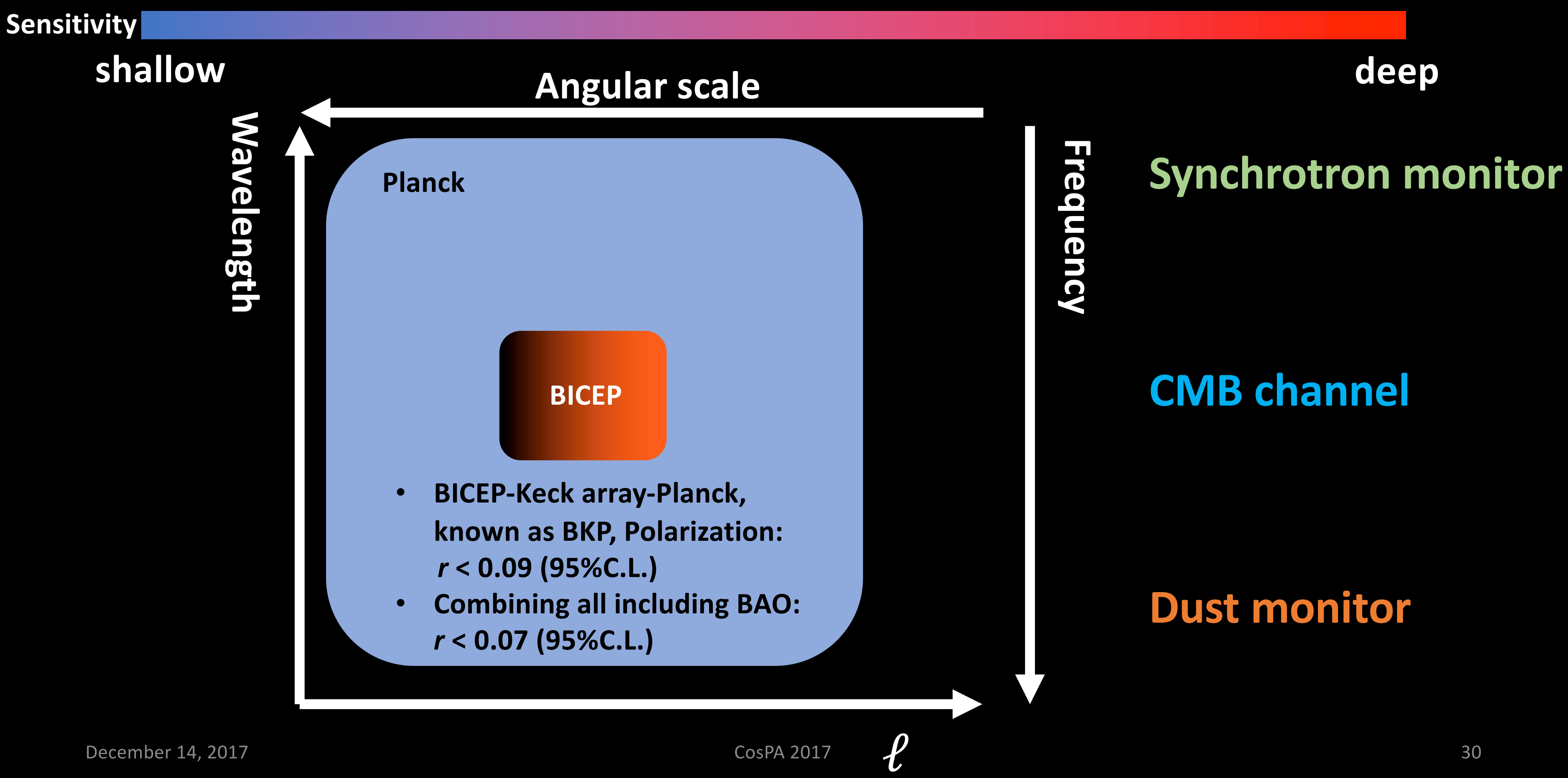

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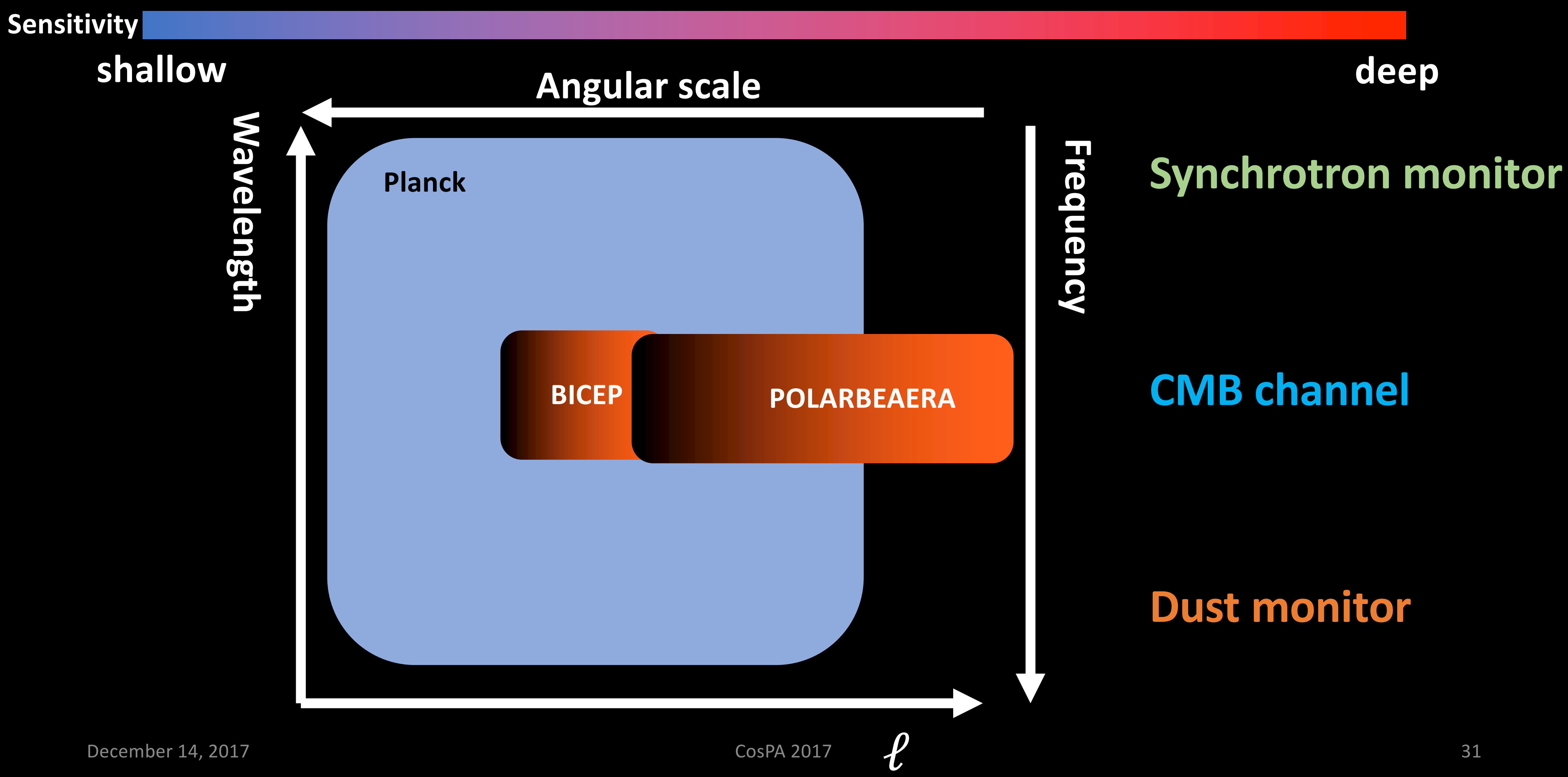

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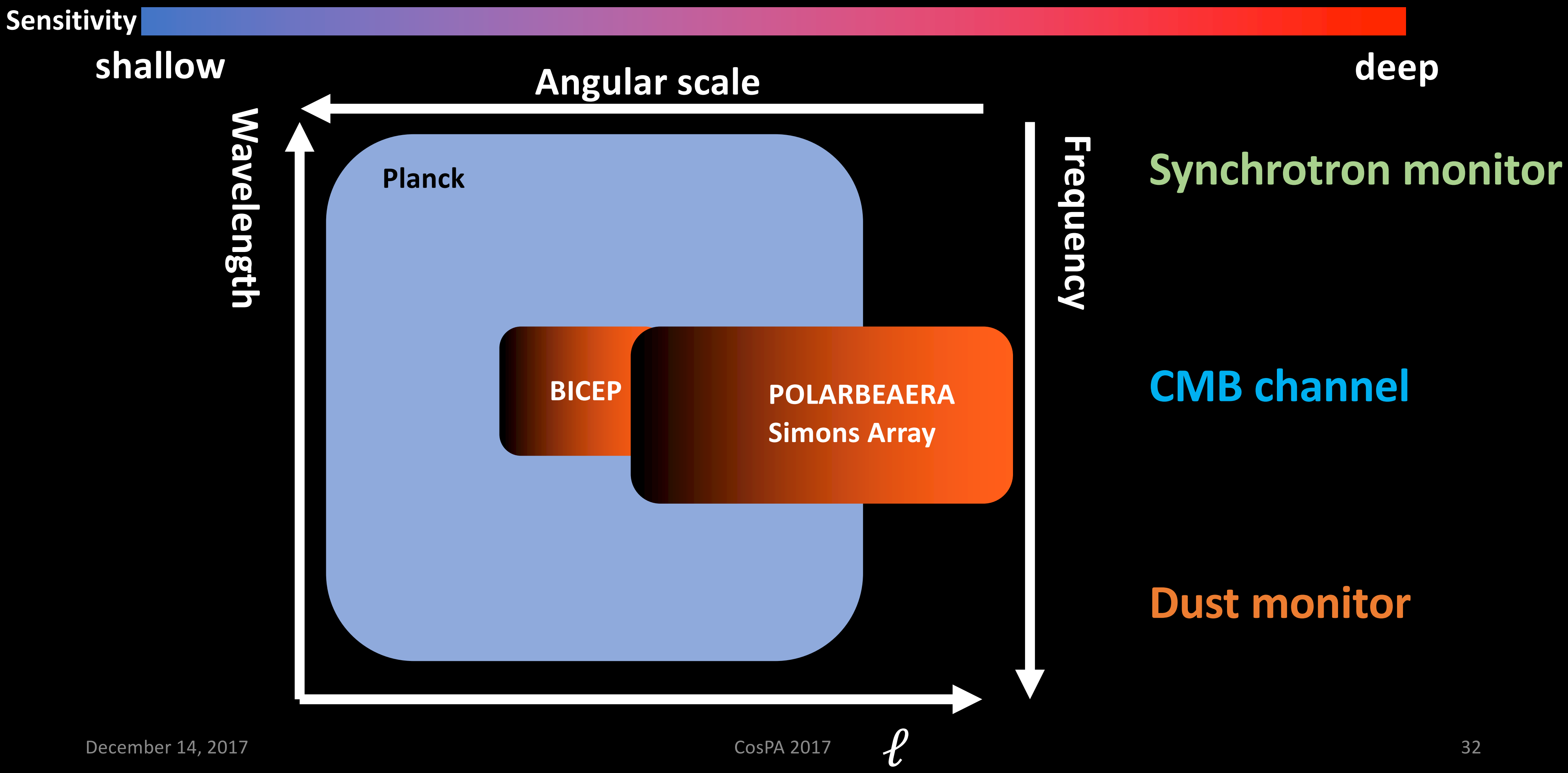

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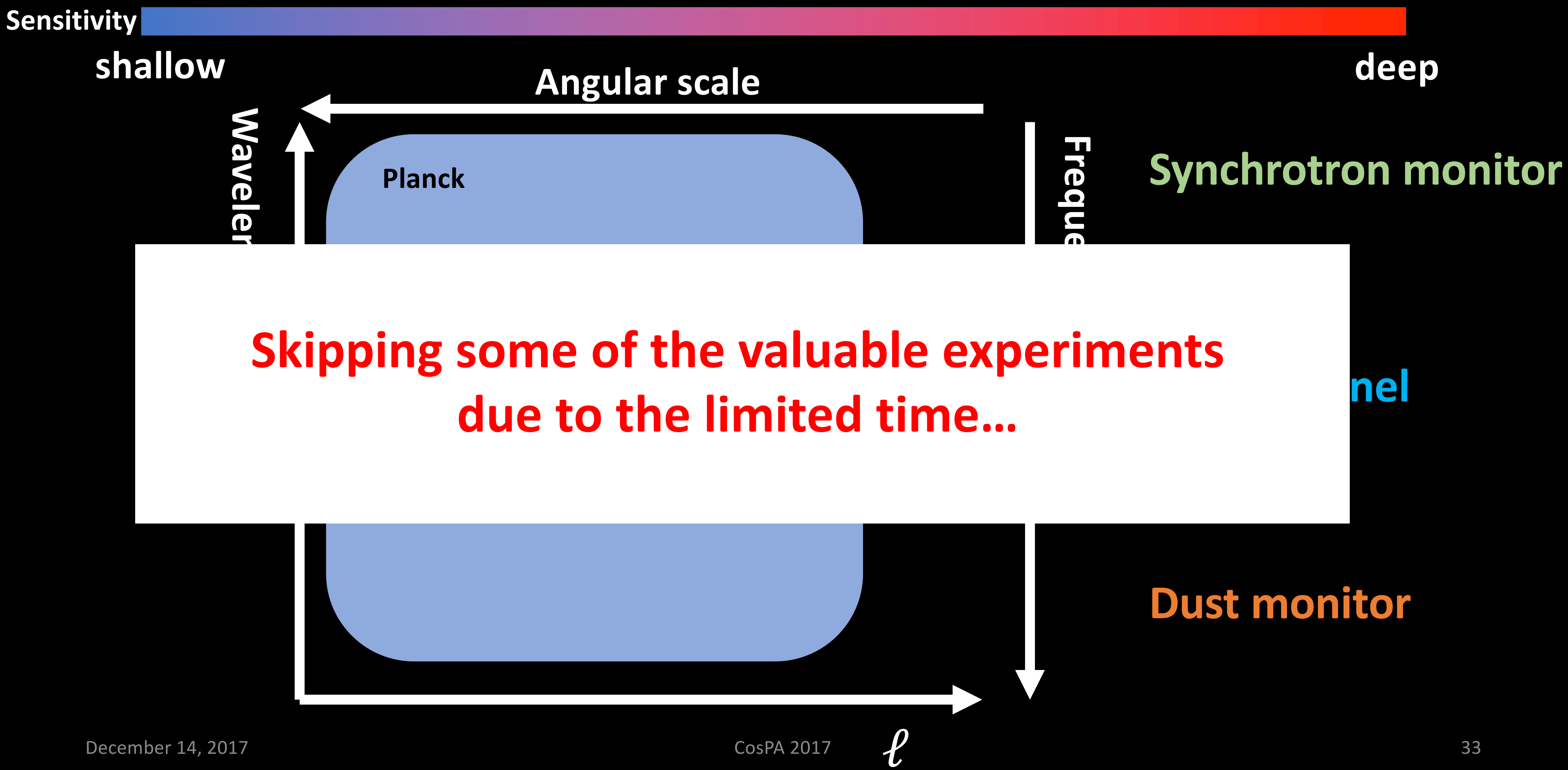
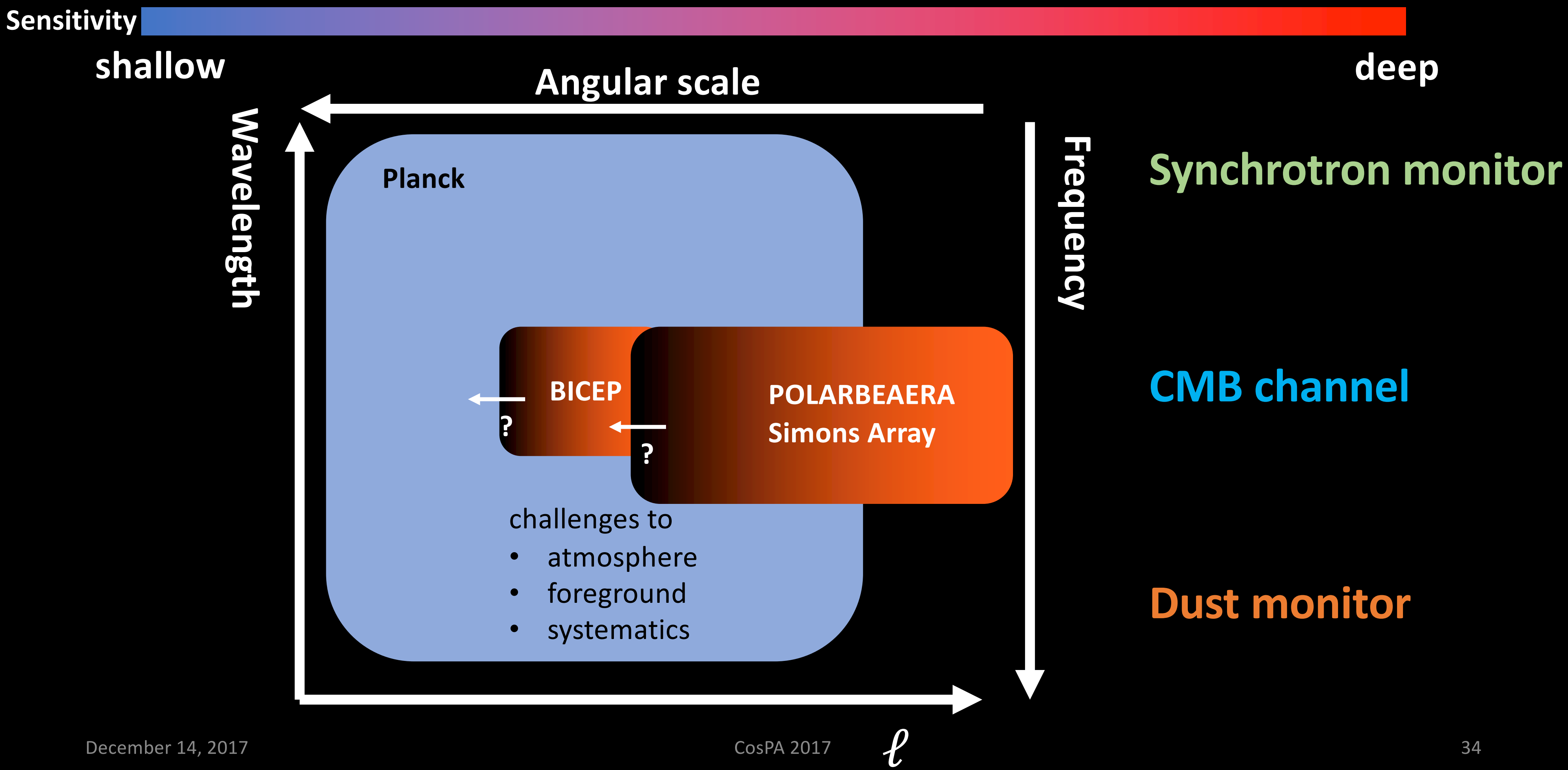


Skipping some of the valuable experiments due to the limited time…

CMB sensitivity conceptual diagram



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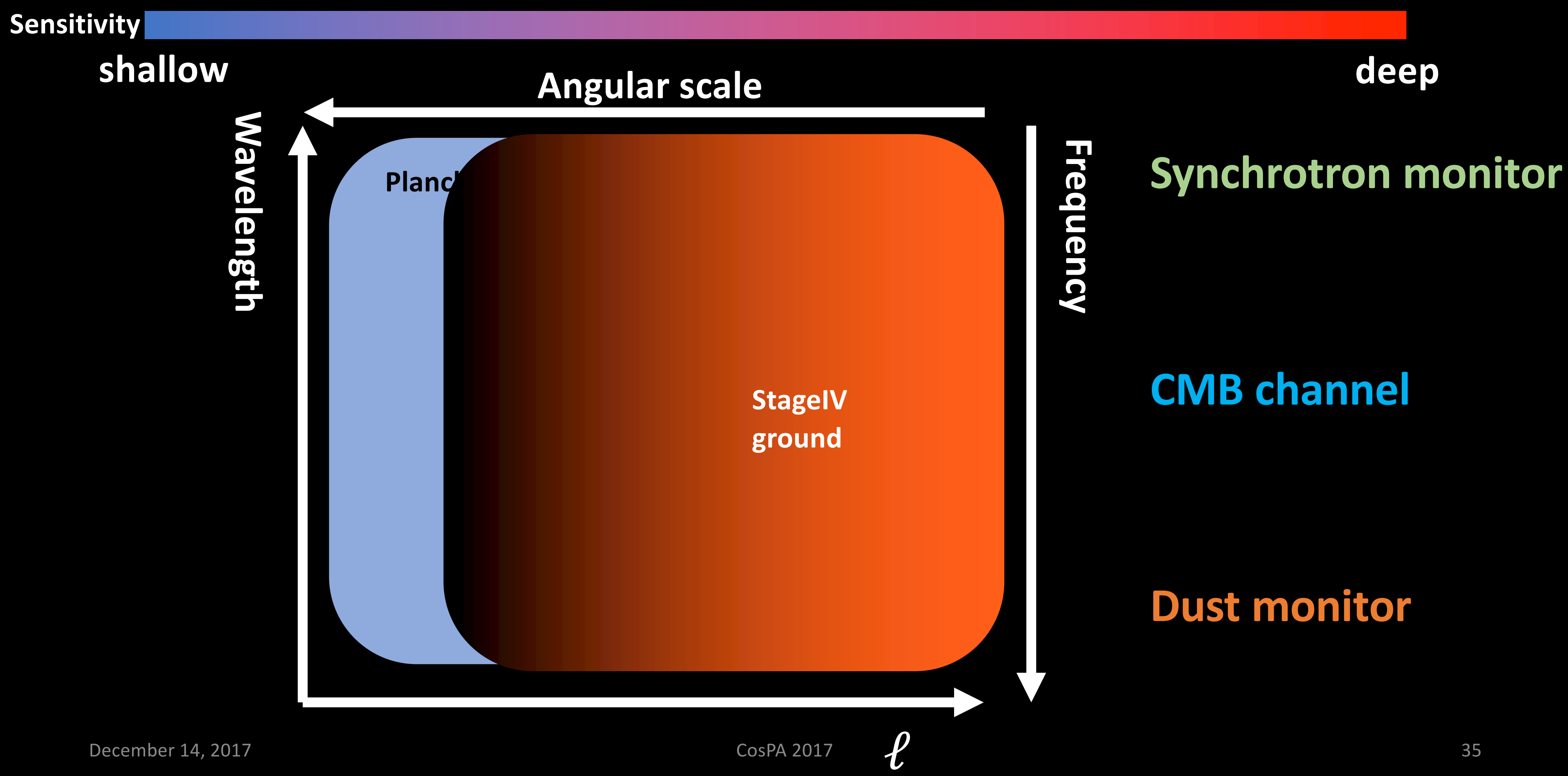

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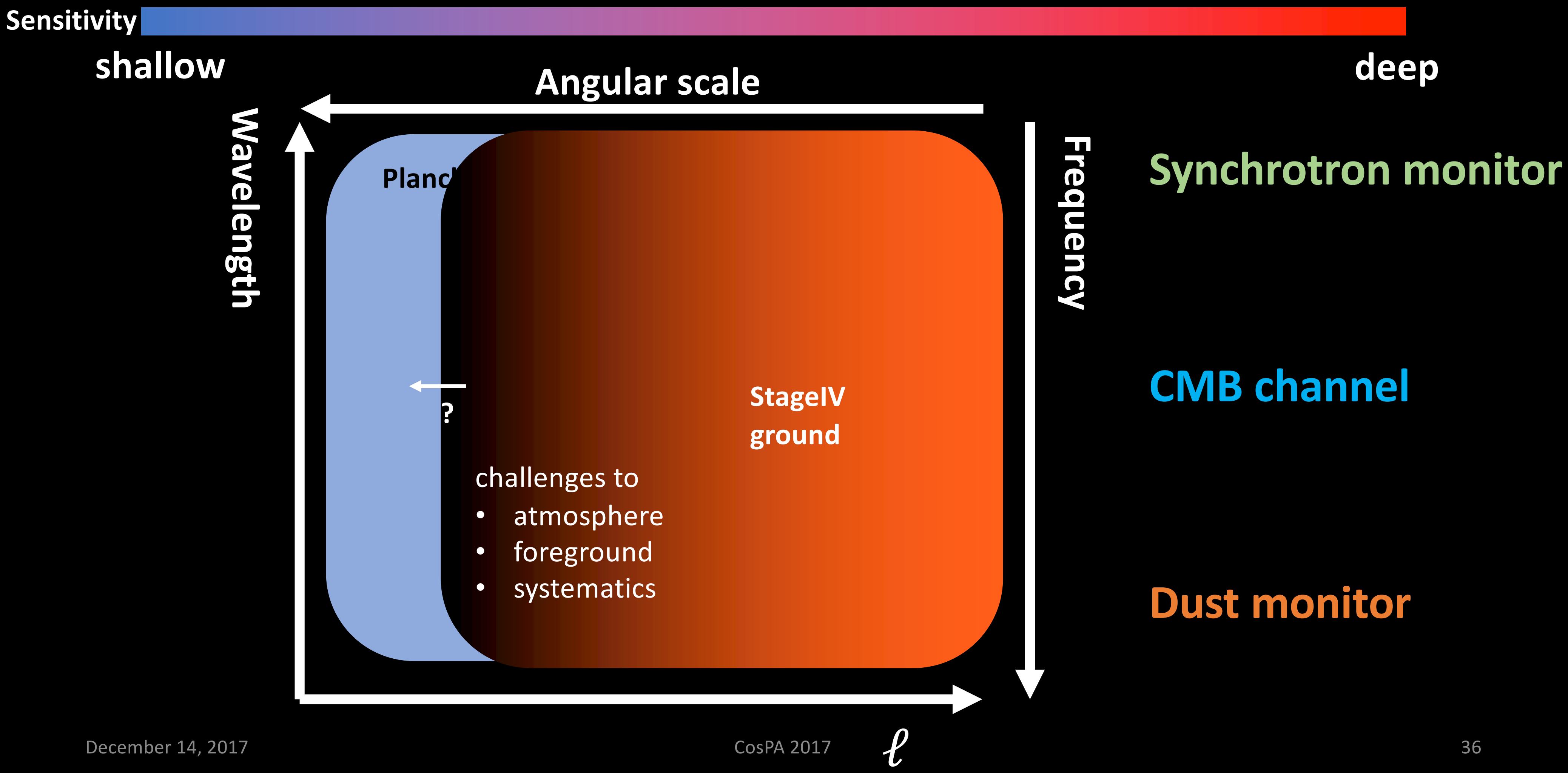

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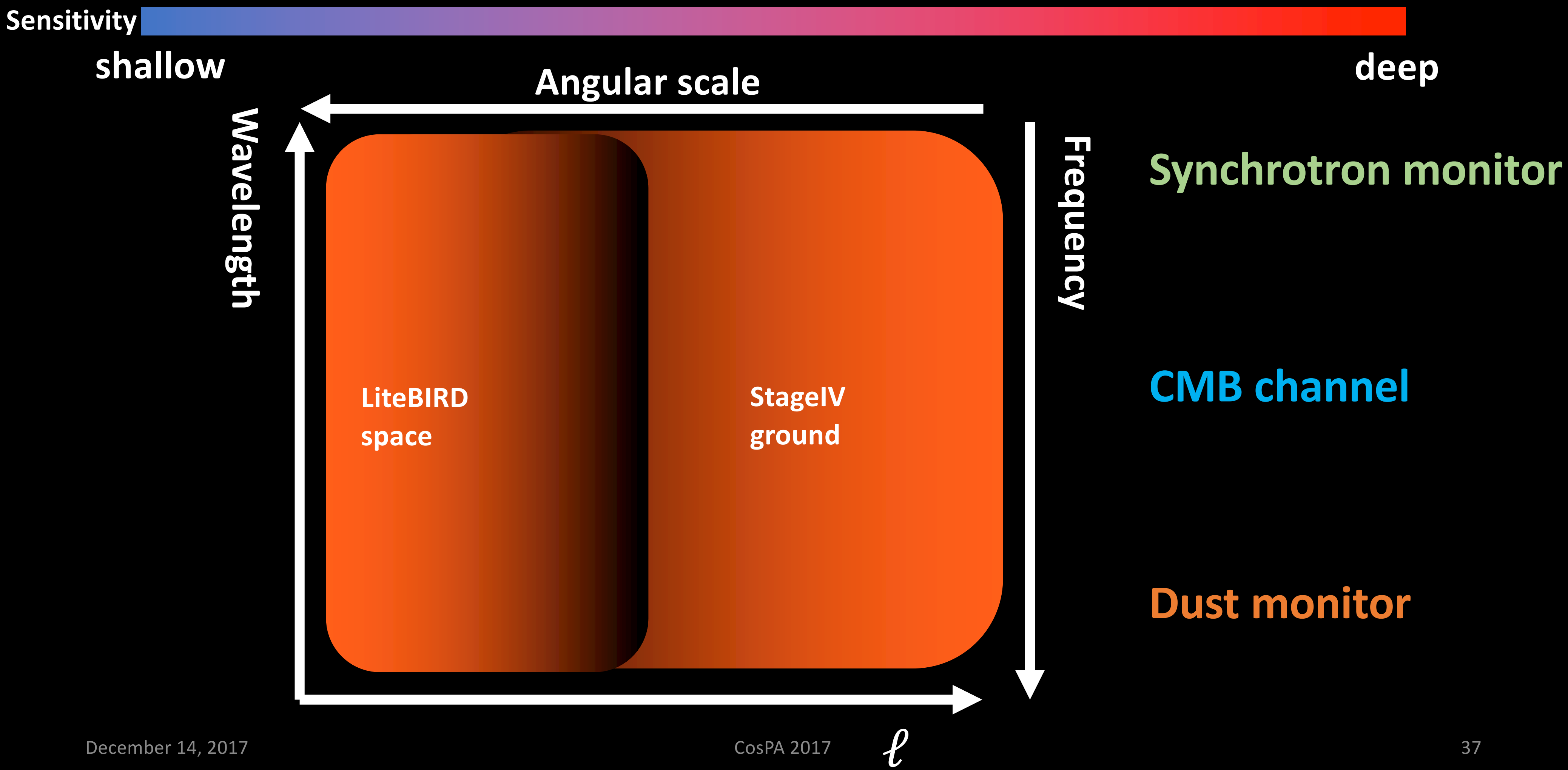
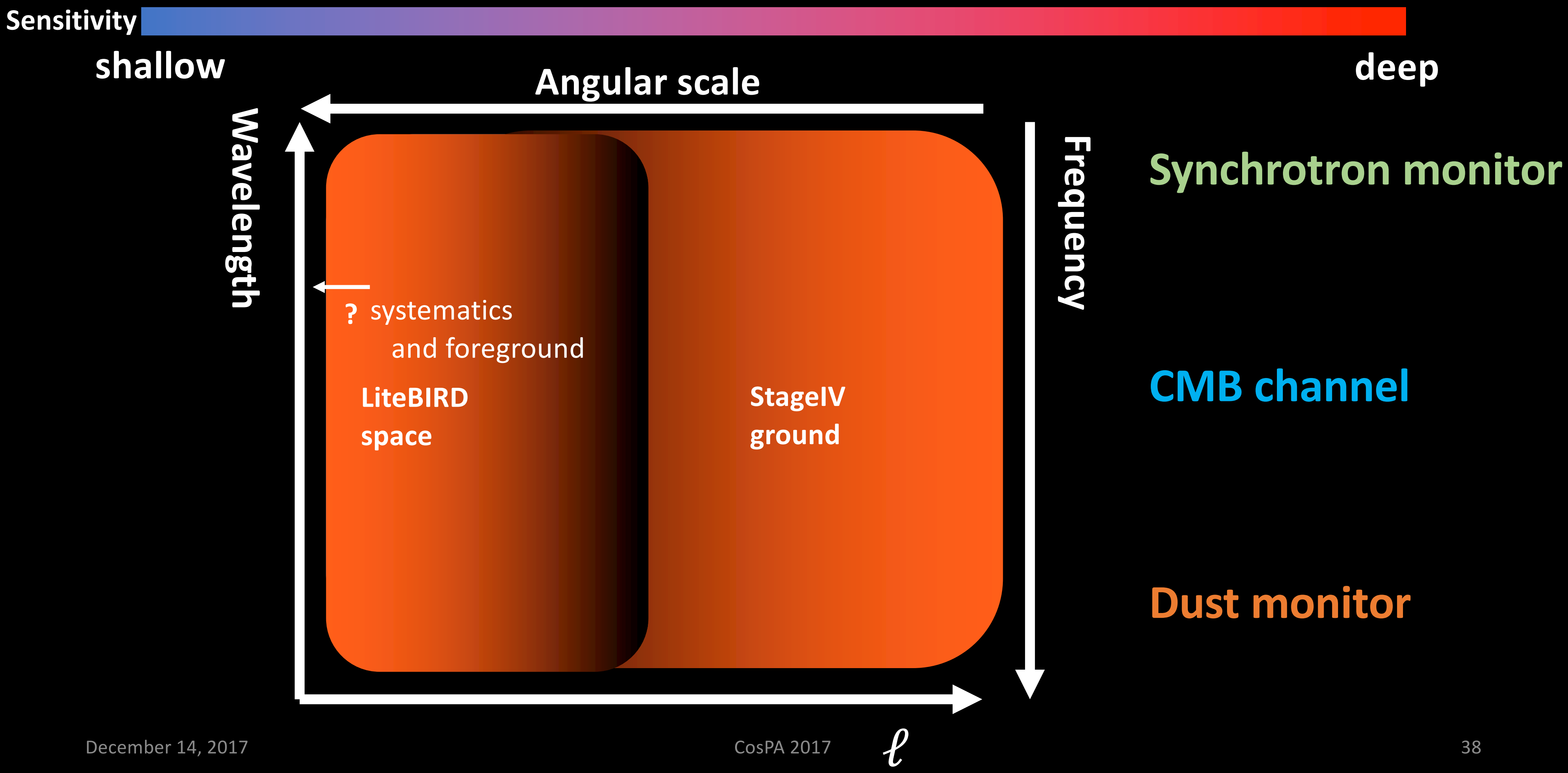


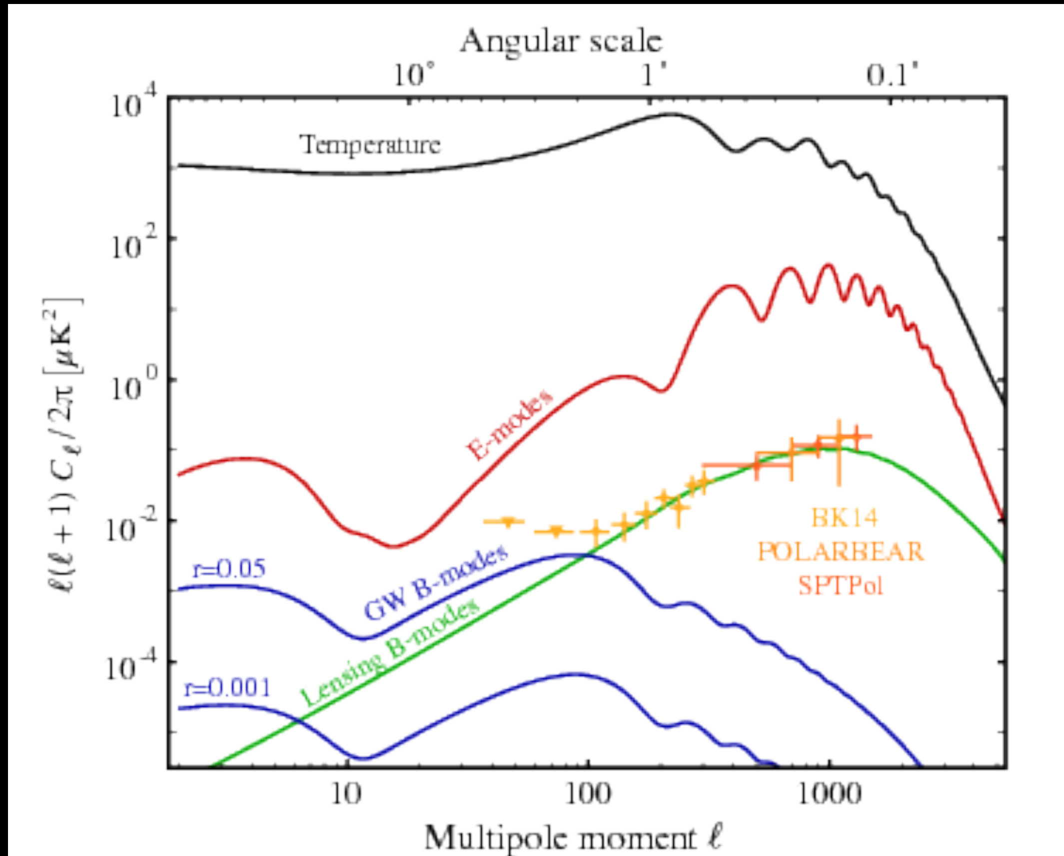
CMB sensitivity conceptual diagram



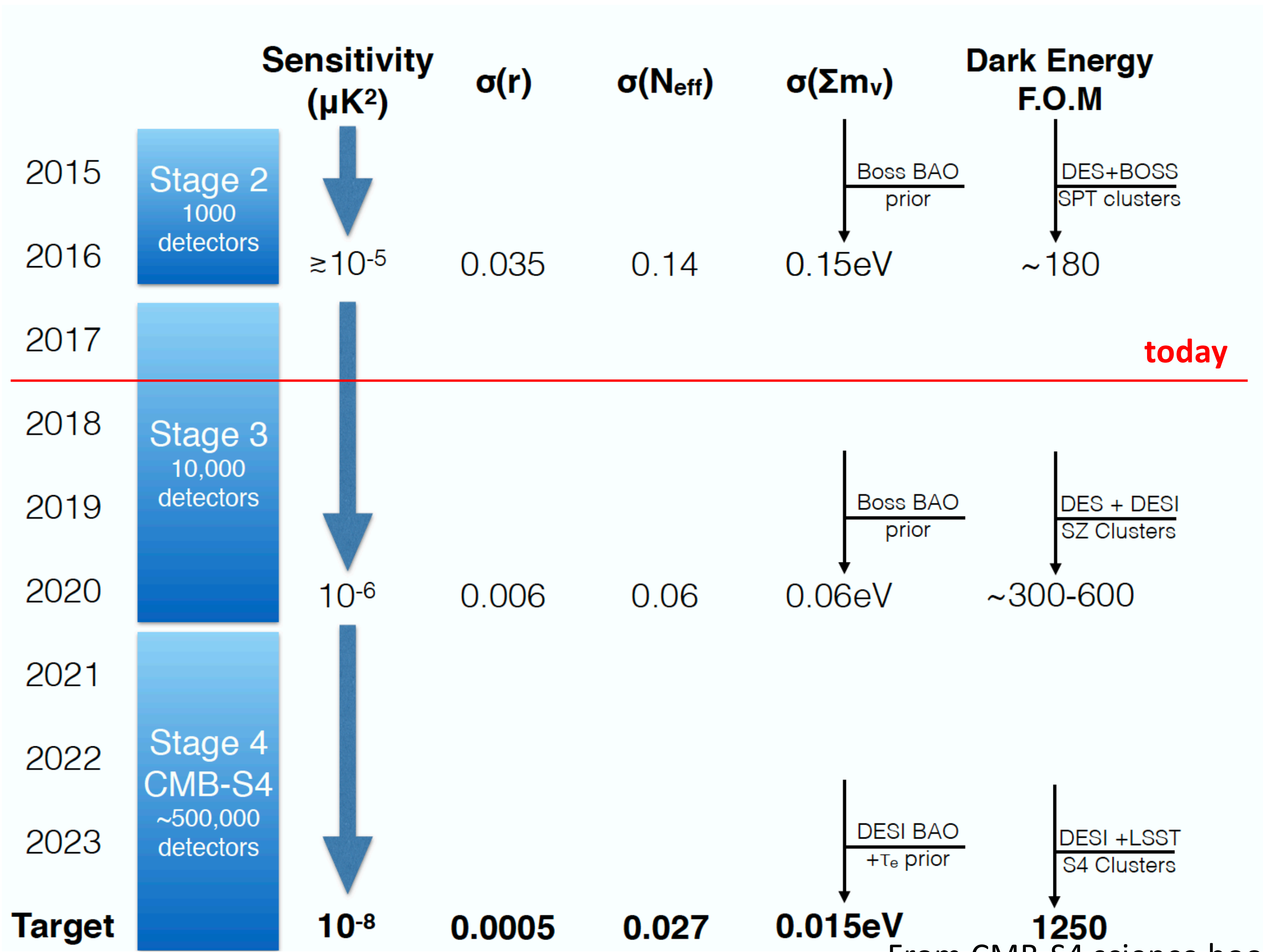
What is the reasonable target of r?

The community is coming to a consensus: "reaching $\sigma(r) \sim 10^{-3}$ within 10 years time scale is a reasonable goal to aim."

- Many inflationary models predict $r > 0.01$ → >10 sigma discovery
- Simple well-motivated inflationary models (single-large-field slow-roll models) have $r > 0.002$ from Lyth relation.

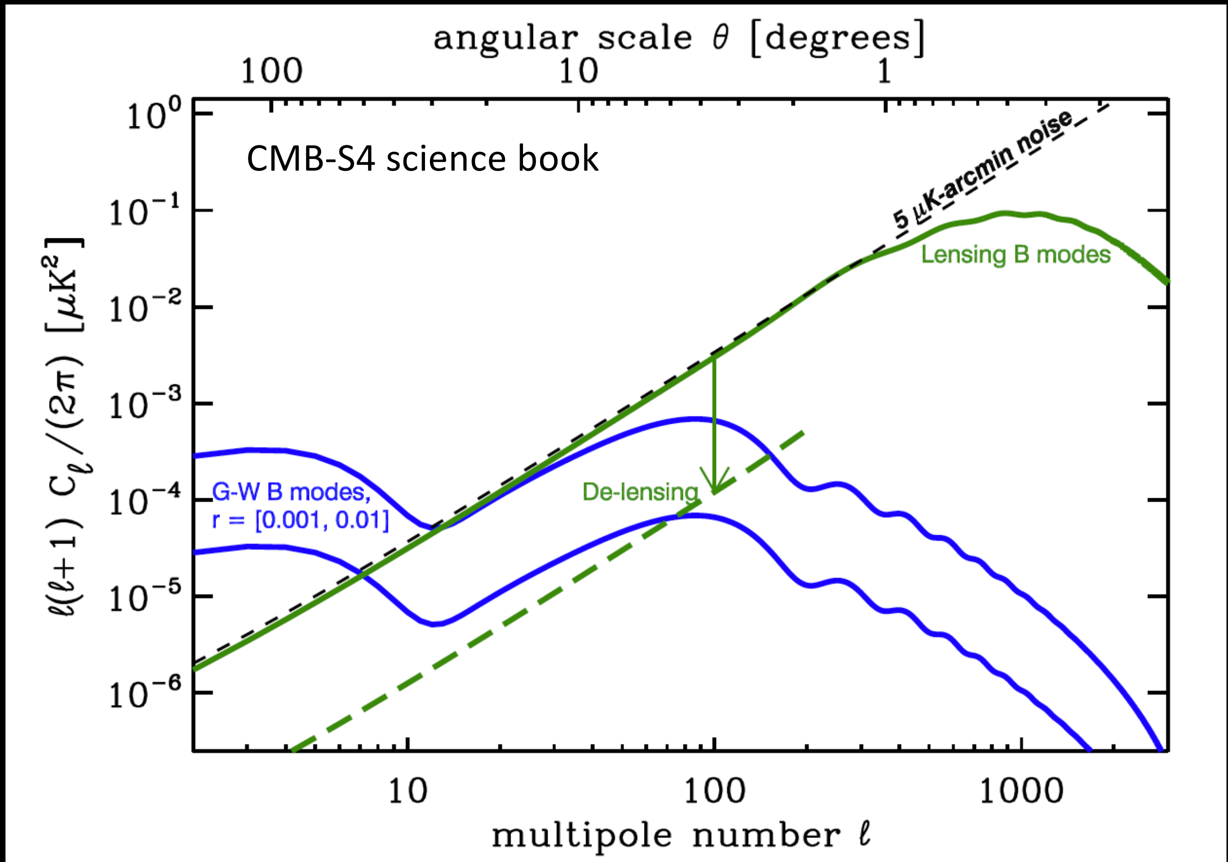


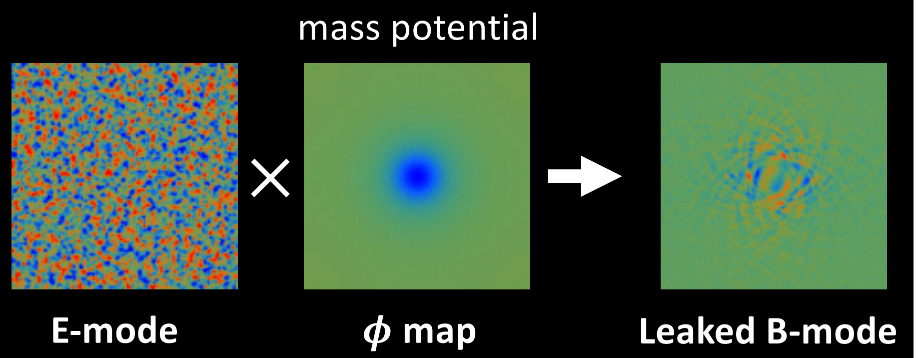
$$r = \frac{1}{N^2}\left(\frac{\Delta\phi}{m_{\rm pl}}\right)^2 \approx 2\cdot 10^{-3}\left(\frac{\Delta\phi}{m_{\rm pl}}\right)^2$$



From CMB-S4 science book

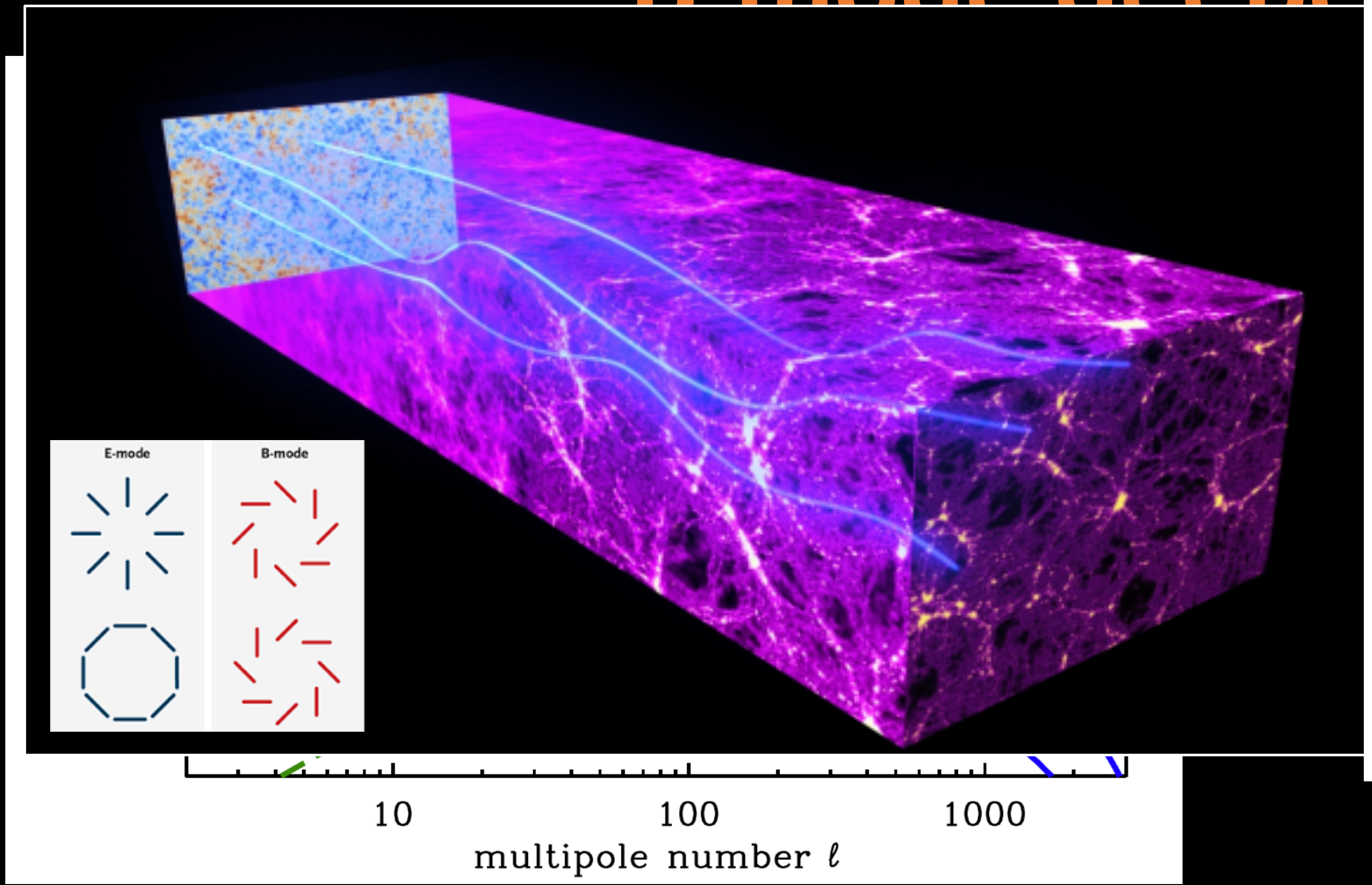
Delensing to probe the primordial B-mode deeper

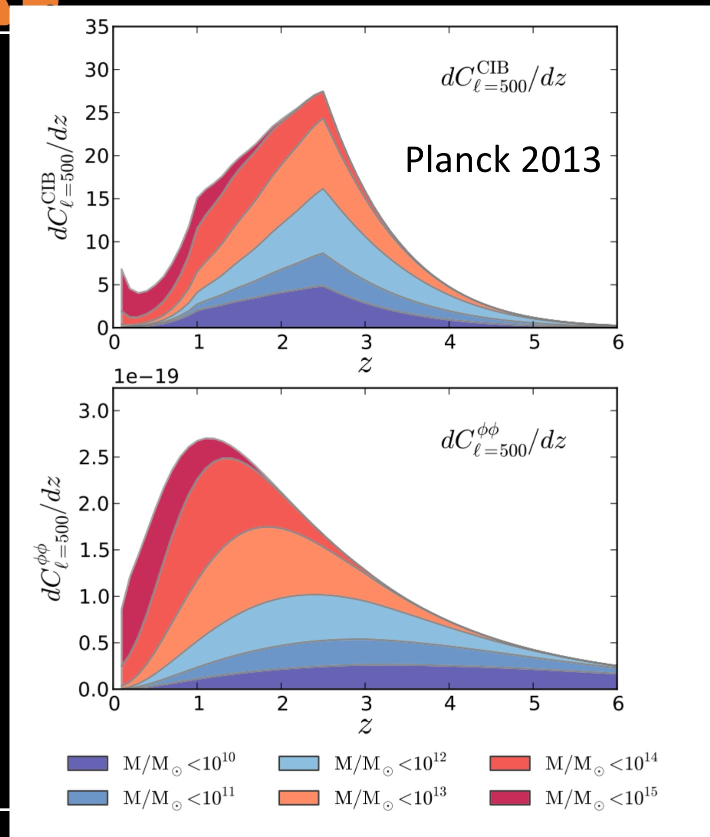




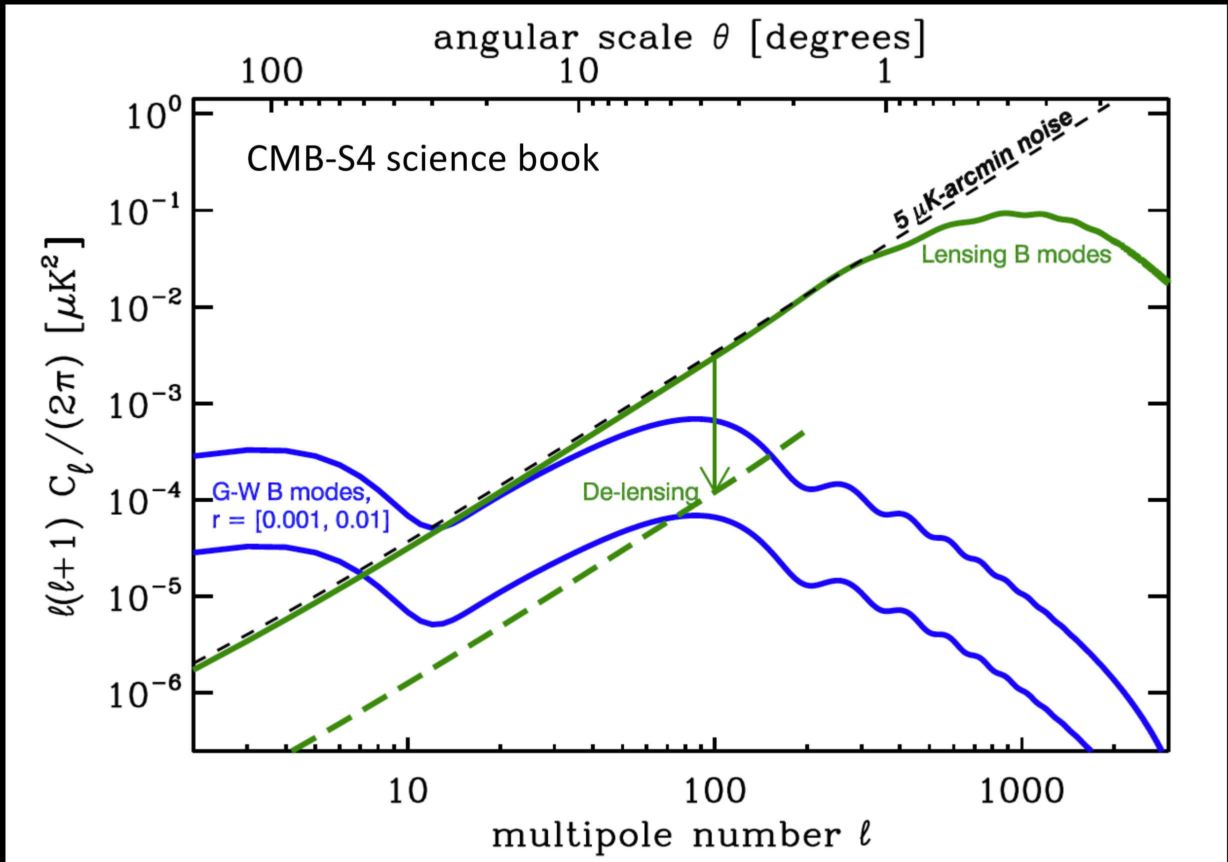
Source as a cosmic noise!

Delensing to probe the primordial B-mode deeper

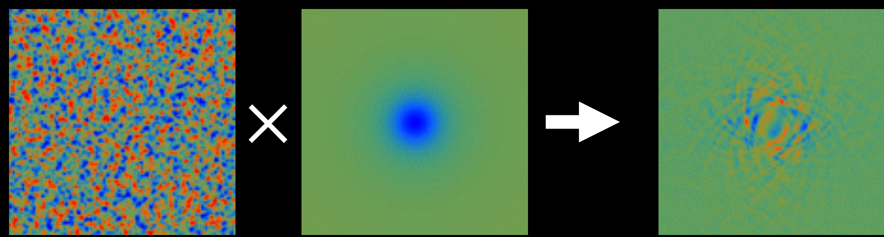




Delensing to probe the primordial B-mode deeper



from CMB T, EB, CIB and more

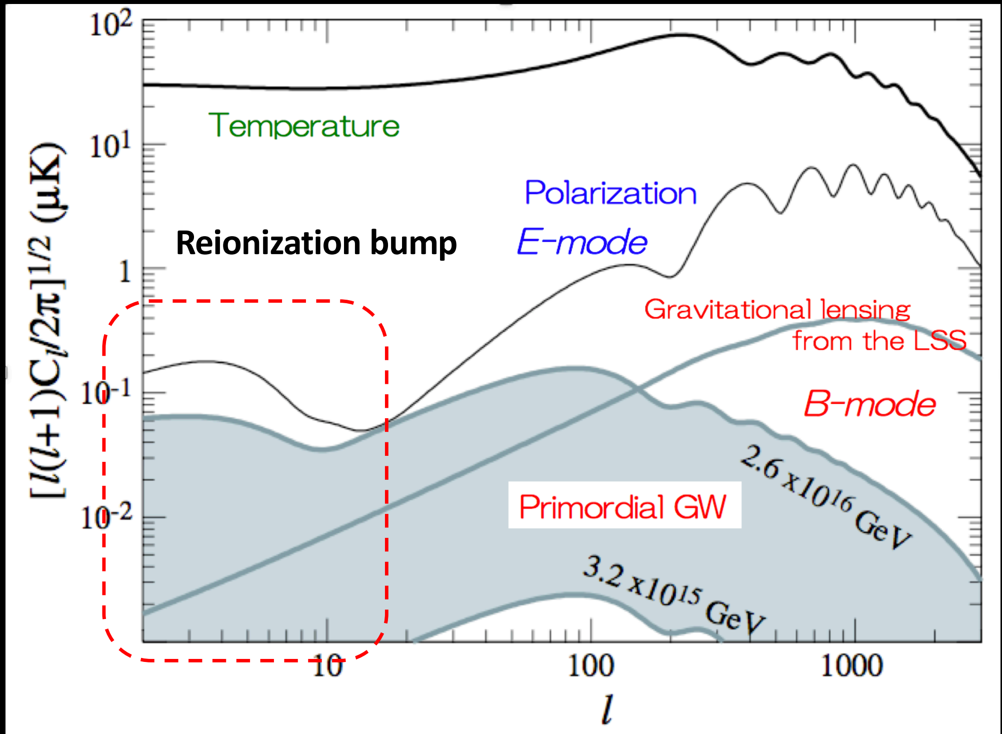


(Observed B) — (Estimated leaked B-mode)

Delensed B-mode

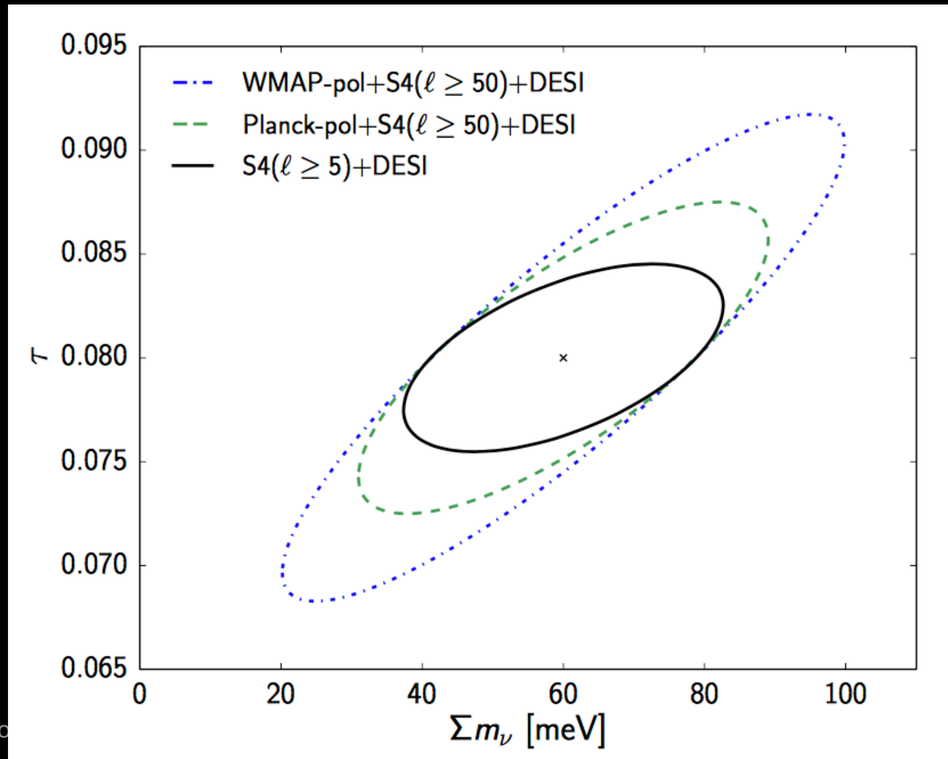
The rapid progress of developing the analysis method and it started to be applied to the real data, e.g. SPTpol x Herschel. arXiv:1701.04396.

Primordial B-mode search and Neutrino



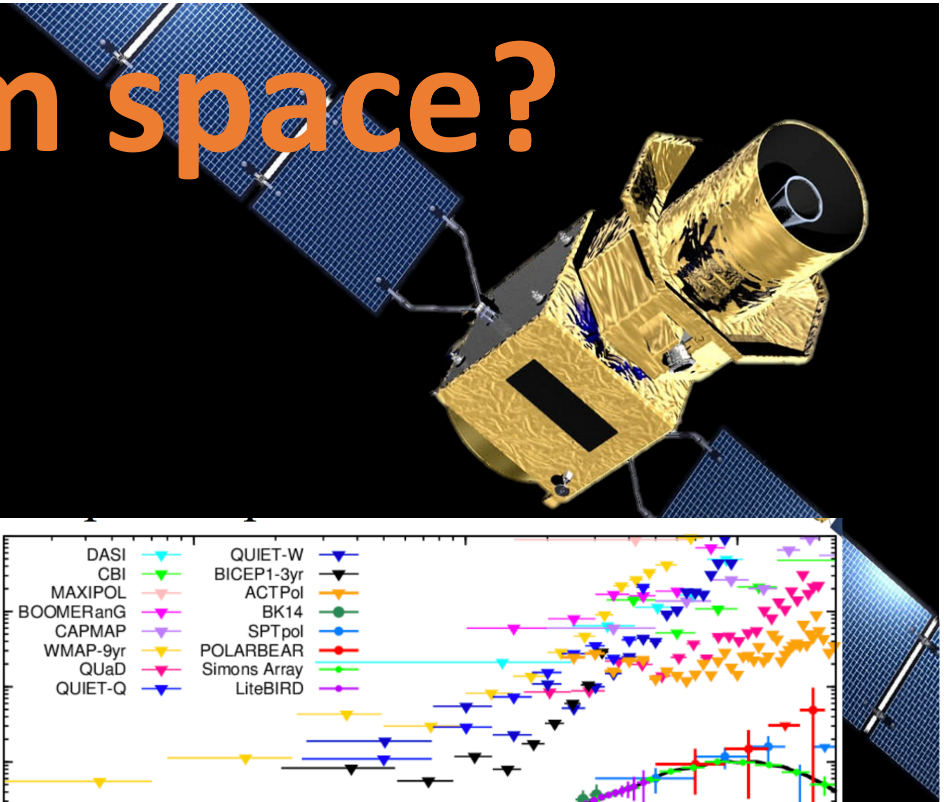
- The sum of the neutrino mass degenerates with τ.
- The primordial B-mode search aiming low ℓ gives you a constraint of reionizaion bump free.

$\tau = 0.055 \pm 0.009,$ lowE. **Planck 2016**



We can measure the signature of reionization of the universe, called reionization bump. The measurement of this bump allows to constrain the optical depth of the universe, τ. This signal appears at low ell range in the polarization power spectrum, E-mod and B-mode. The better E-mode measurements in the multipole $\ell < 20$ will improve τ measurement precision.

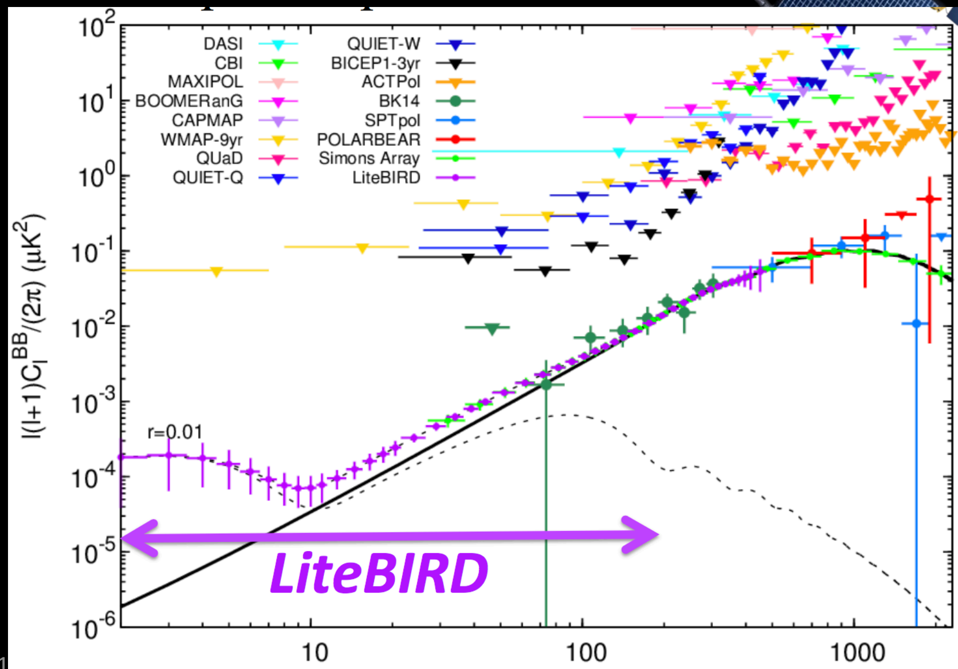
Prospect from space?



ESA Planck finished the observations and there are multiple attempts to the next generation CMB satellite.

- NASA mission concept study EPIC
- Post Planck ESA mission COrE
- NASA PIXIE, spectrometer
- ISAS/JAXA, LiteBIRD

LiteBIRD is the only funded CMB sallite mission as of today. The mission is not fully funded yet, and currently in ISAS/JAXA PhaseA1 for the conceptual design study.



Beyond horizon

- **PICO: Probe Inflation and Cosmic Origin**
- **The concept study for a future CMB space mission**
- **The output of this study is for NASA 2020 decadal survey**

- **Sciences**
  - **inflation**
  - **reionization**
  - **neutrino mass**
  - **Neff**

PICO is an open collaboration
wiki: z.umn.edu/cmbprobe
list: cmbprobe@lists.physics.umn.edu
You are invited to contribute.

- **Broadband imager and spectrometer.**
  - $\boldsymbol{\sigma(r) = 1.5\times10^{-5}}$*
  - $\boldsymbol{\sigma(\tau)} = 0.0019$ (cosmic variance)
  - $\boldsymbol{\sigma(\sum m_\nu) = 15}$ meV
  - $\boldsymbol{\sigma(N_{eff})}$=0.03

* noise only, no foregrounds, no systematics, includes delensing using self measurement of EB

Summary

- CMB is no longer the subject to study but the tool to study beyond.
- In the post Planck era, inflation is the main driver to all the CMB experiments.
- The ground base experiments are moving toward CMB-S4 and the space mission is partially funded for a conceptual study. Both are aiming $\delta r \sim 10^{-3}$.
- Inflation is not the only science to learn from CMB, but also a lot to learn more, e.g. the reionization, neutrino.

Thank you