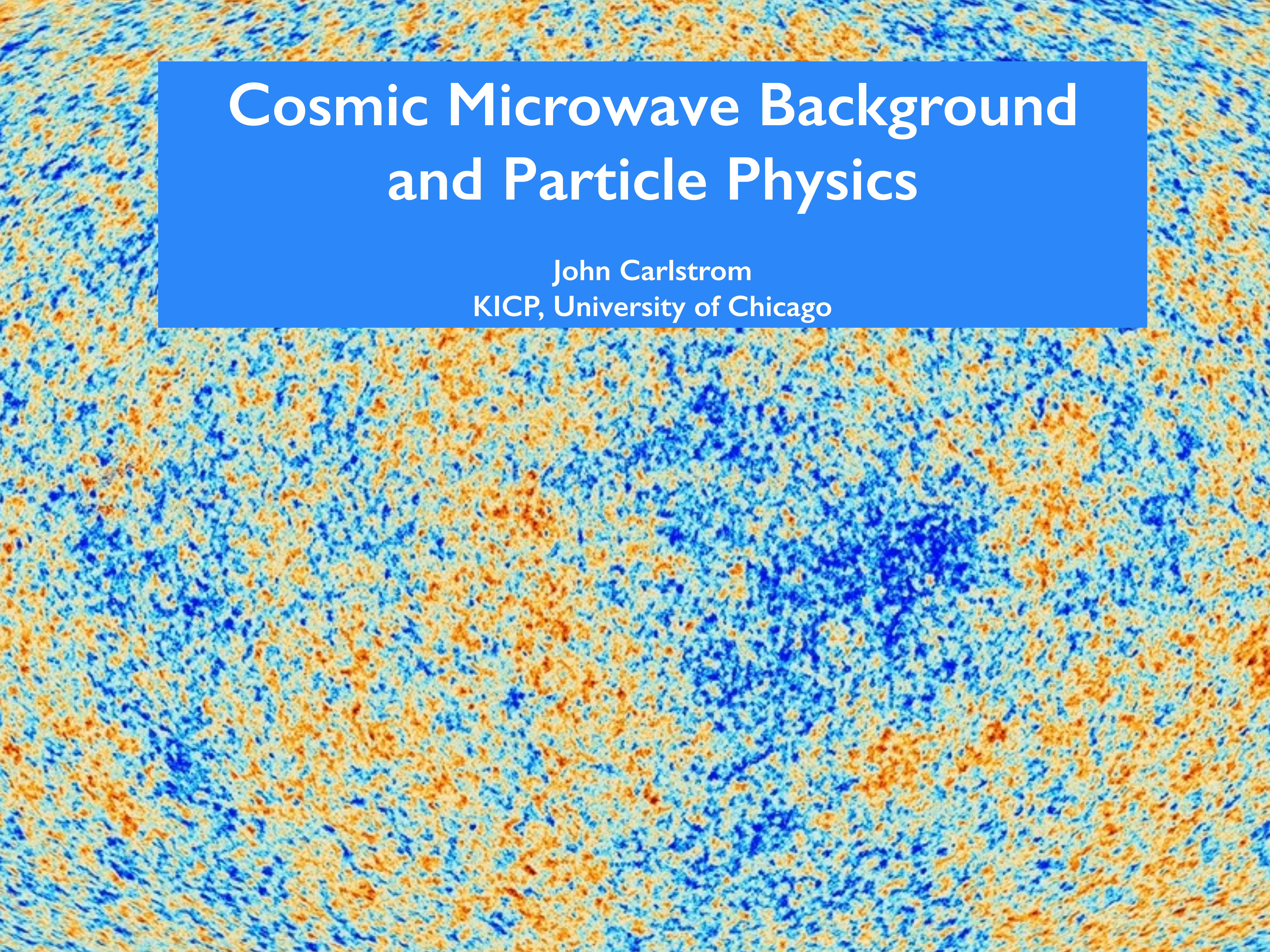
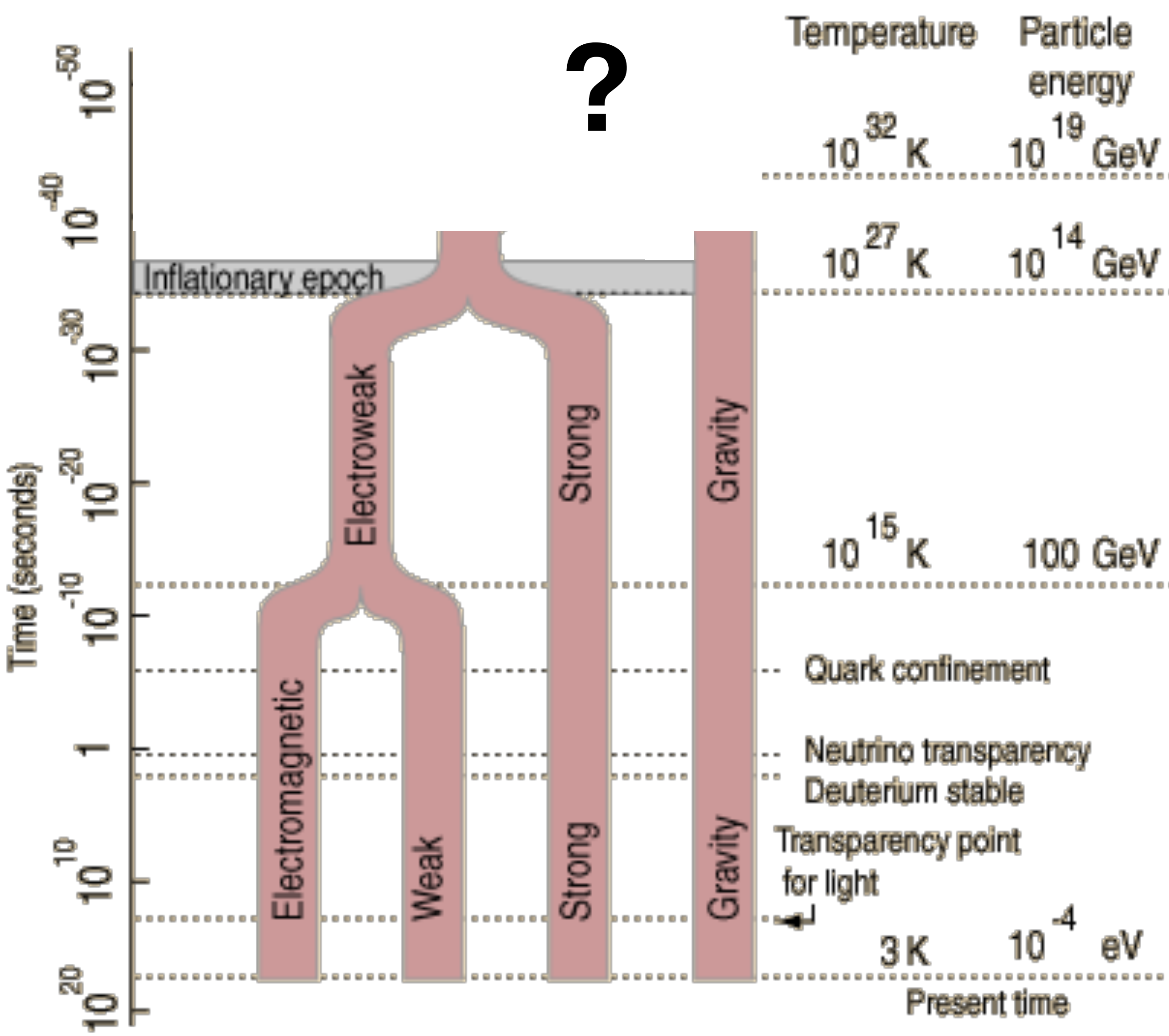
Cosmic Microwave Background and Particle Physics

John Carlstrom
KICP, University of Chicago



The Universe as a Physics Lab



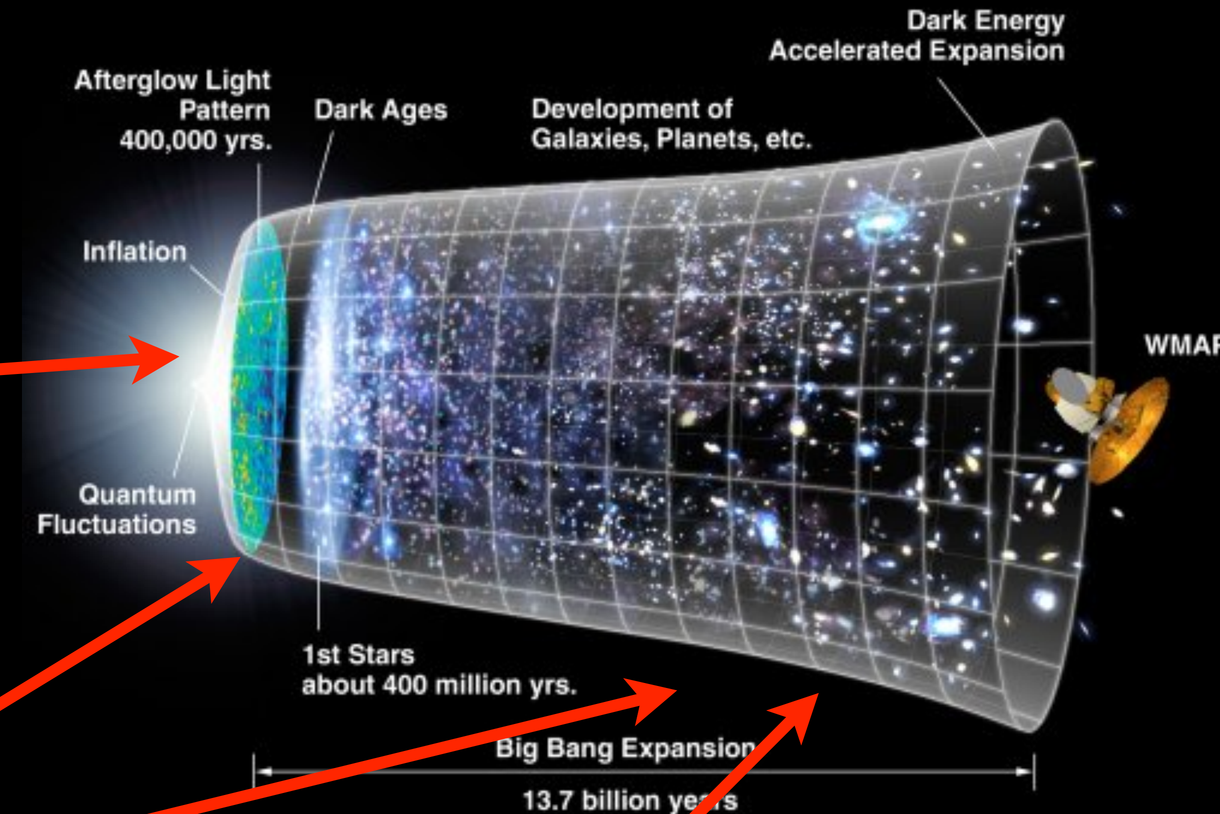
Inflation?

period of accelerated expansion at ~10^{-36} seconds, ~10^{16} GeV

Cosmic neutrino background

Cosmic microwave background

CMB measurements probe cosmology and fundamental physics



Inflation

- Spectral index of fluctuations, n_s
- non-Gaussianity?
- Inflationary gravitational waves?

Neutrinos / Light relics

- Number of relativistic species (Neff or "dark radiation")
- Sum of the neutrino masses, ($\sum m_\nu$) through impact on growth of structure

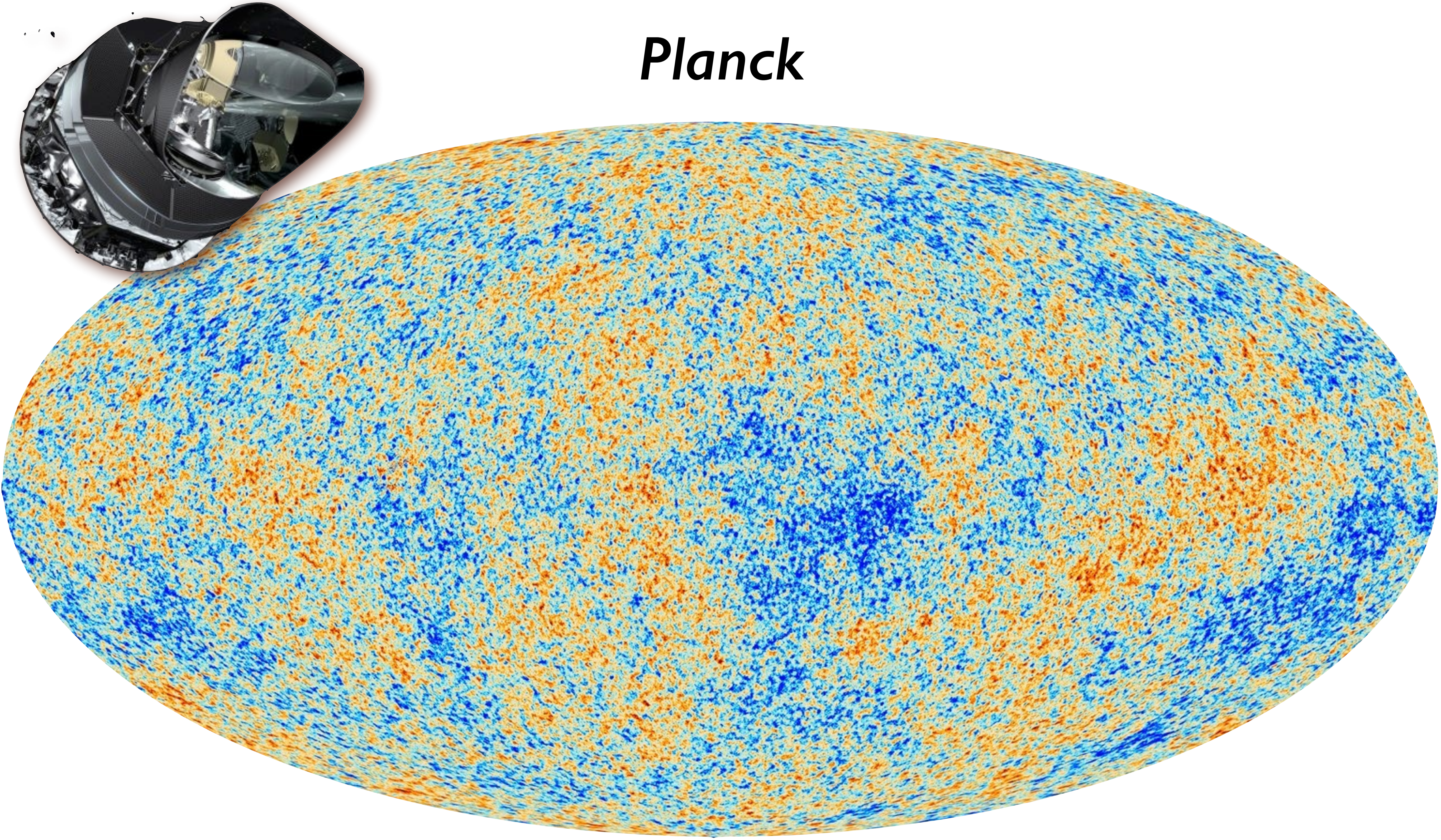
Dark Energy

- Probe growth with SZ clusters, CMB lensing, correlation with galaxy surveys
- Is GR correct on large scales?

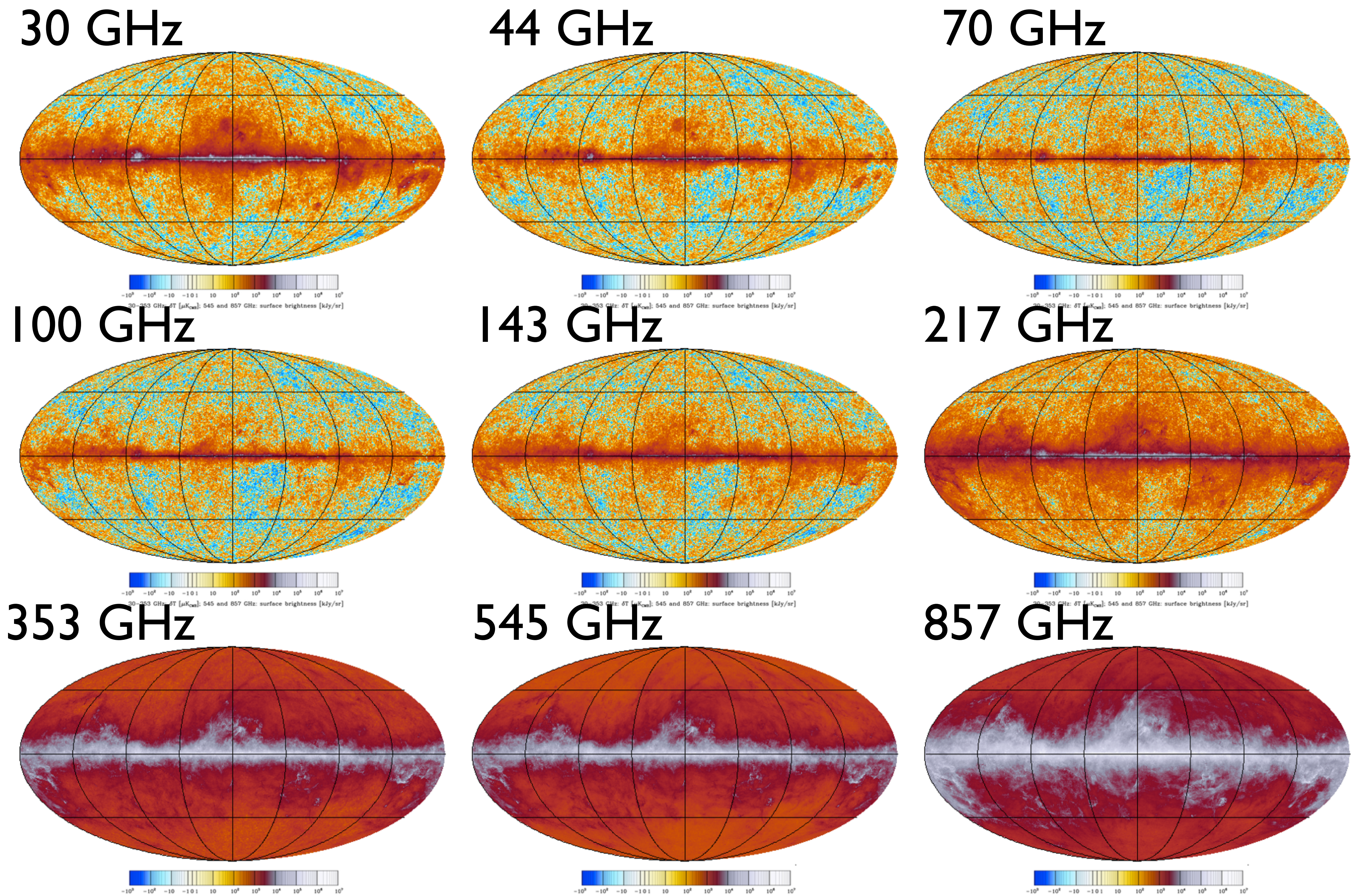
➡ *requires precision CMB measurements of the temperature and polarization CMB anisotropy from degrees to arc minutes*

graphic from NASA website

Planck



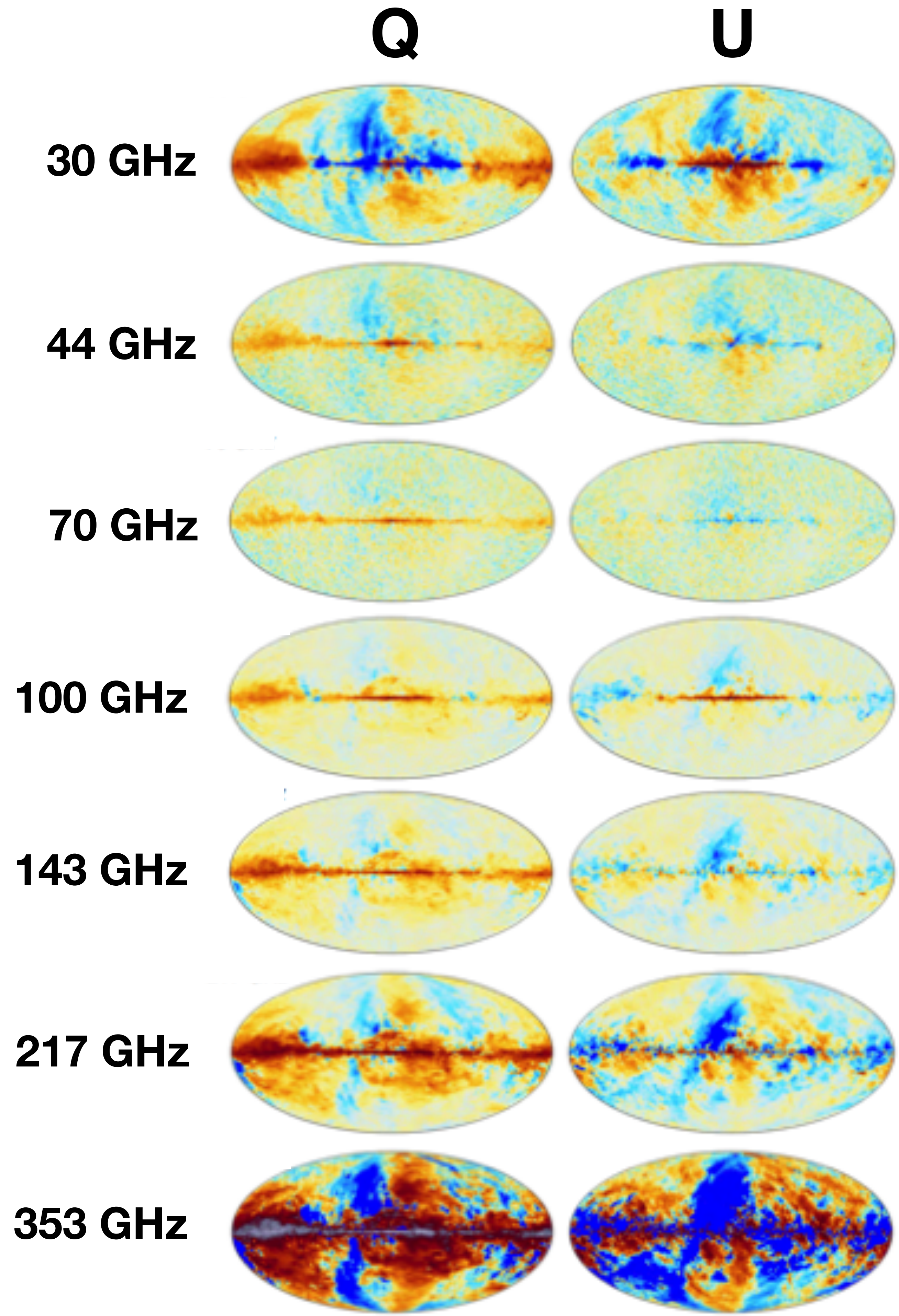
Planck Intensity (CMB and foregrounds)



ESA/Planck

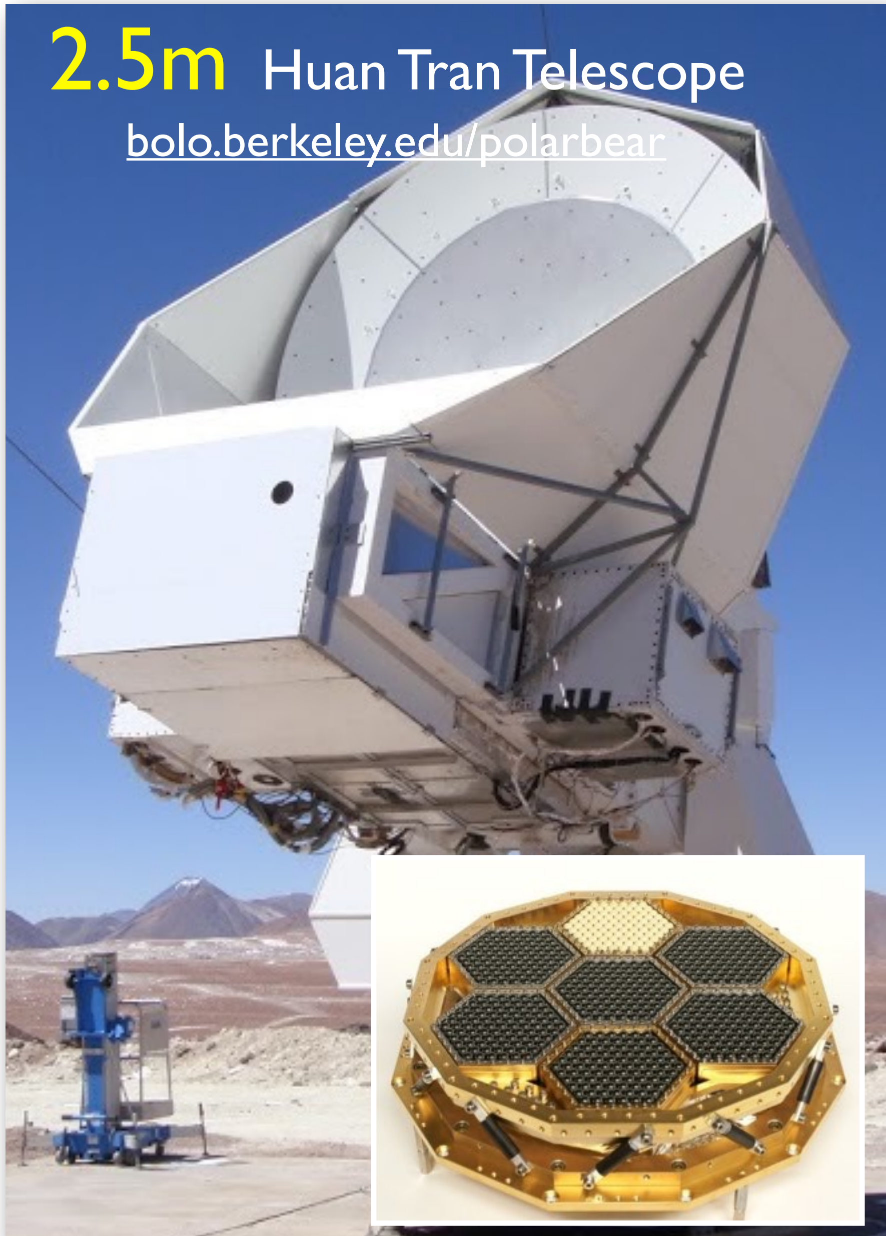
Polarized galactic **synchrotron** dominates at low frequencies

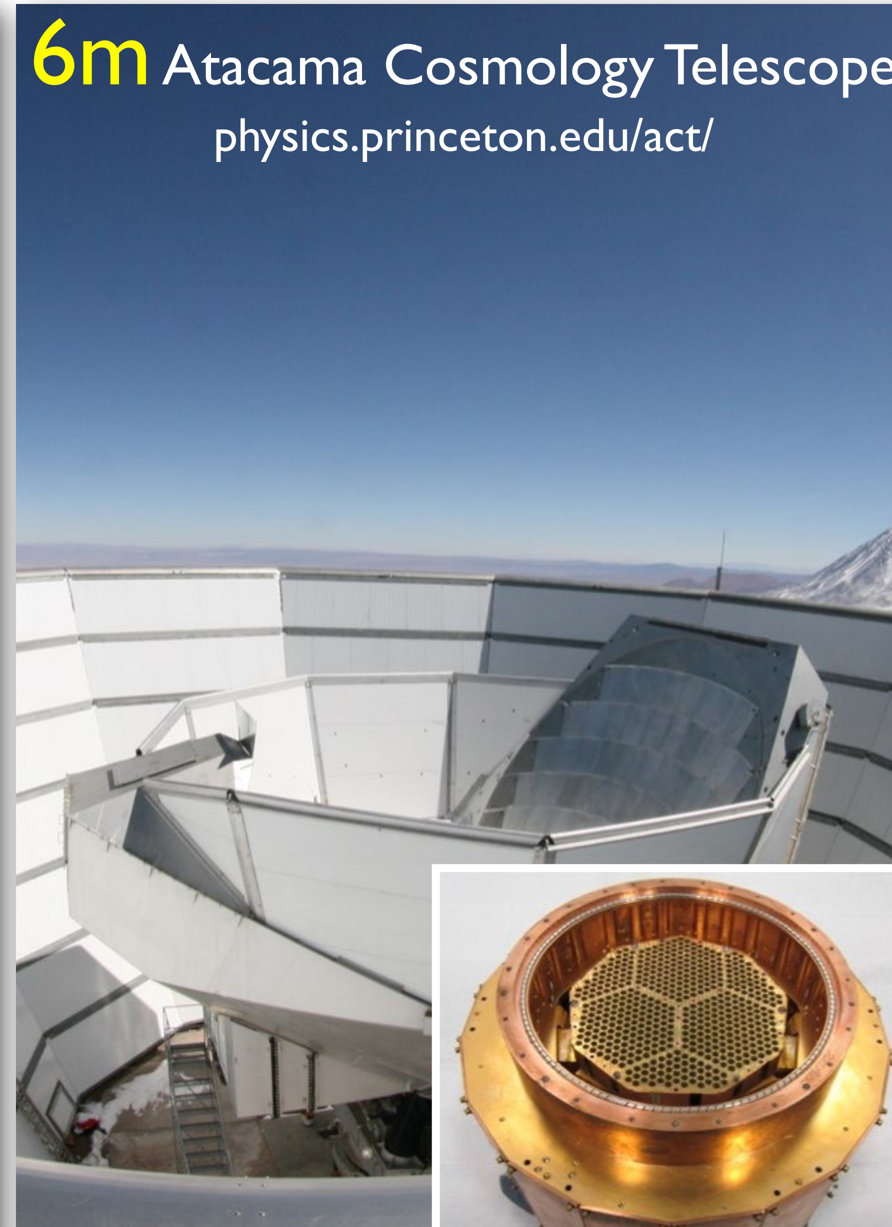
Planck provides ***polarized*** *maps at 7 frequencies*

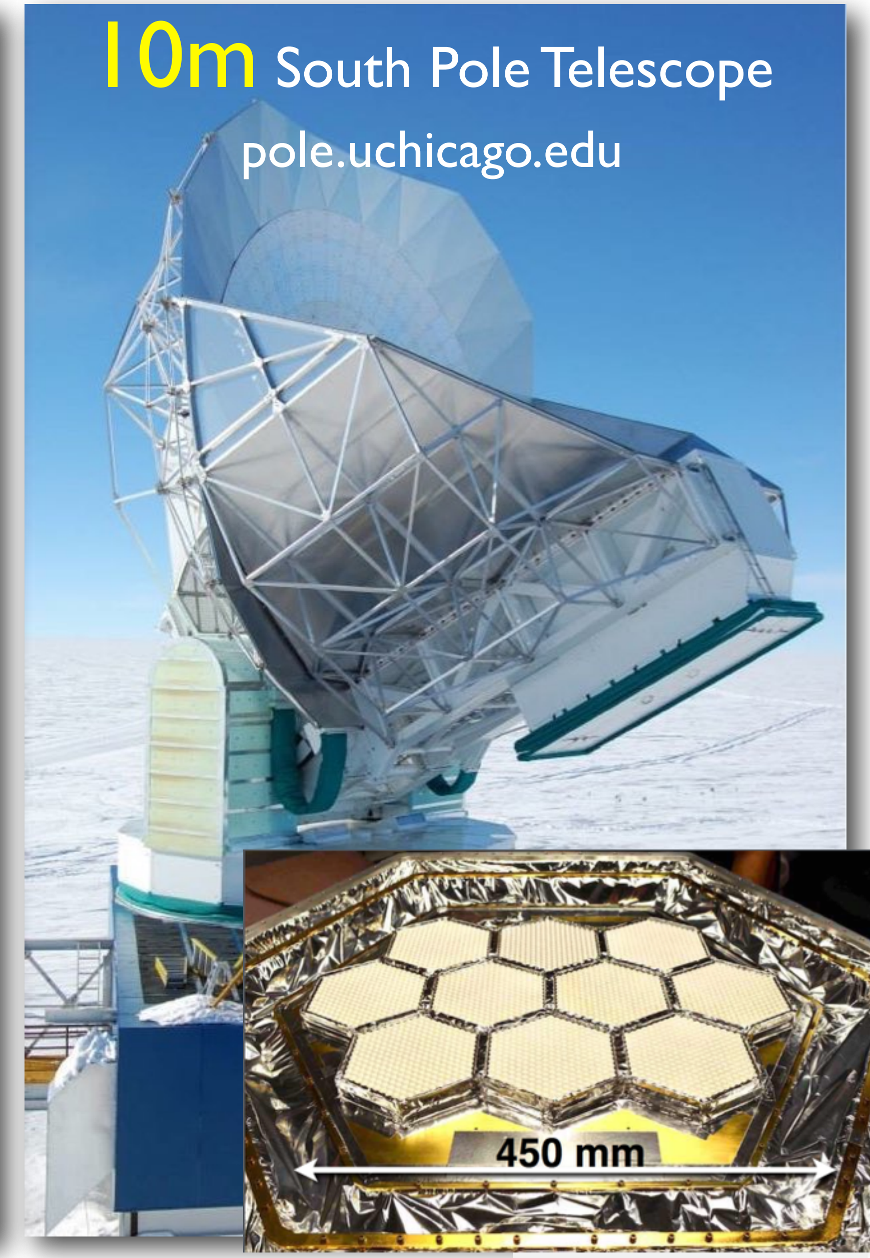


Polarized thermal emission (~20K) from galactic **dust** aligned in magnetic fields dominates at high frequencies

High resolution CMB experiments



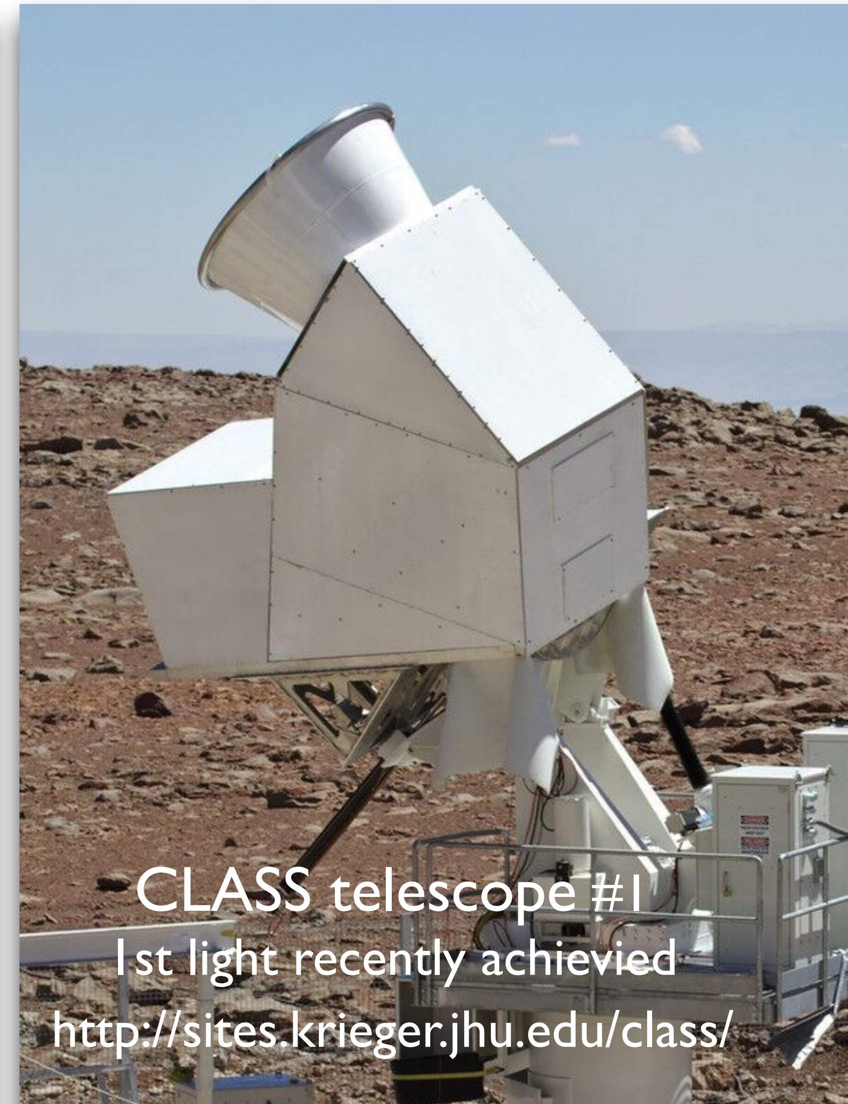


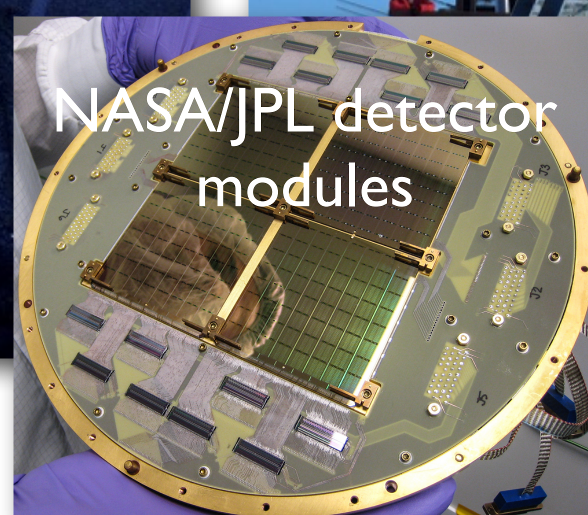


Exceptional high and dry sites for dedicated CMB observations.

Exploiting and driving ongoing revolution in low-noise bolometer cameras

Small aperture (big beam) CMB telescopes



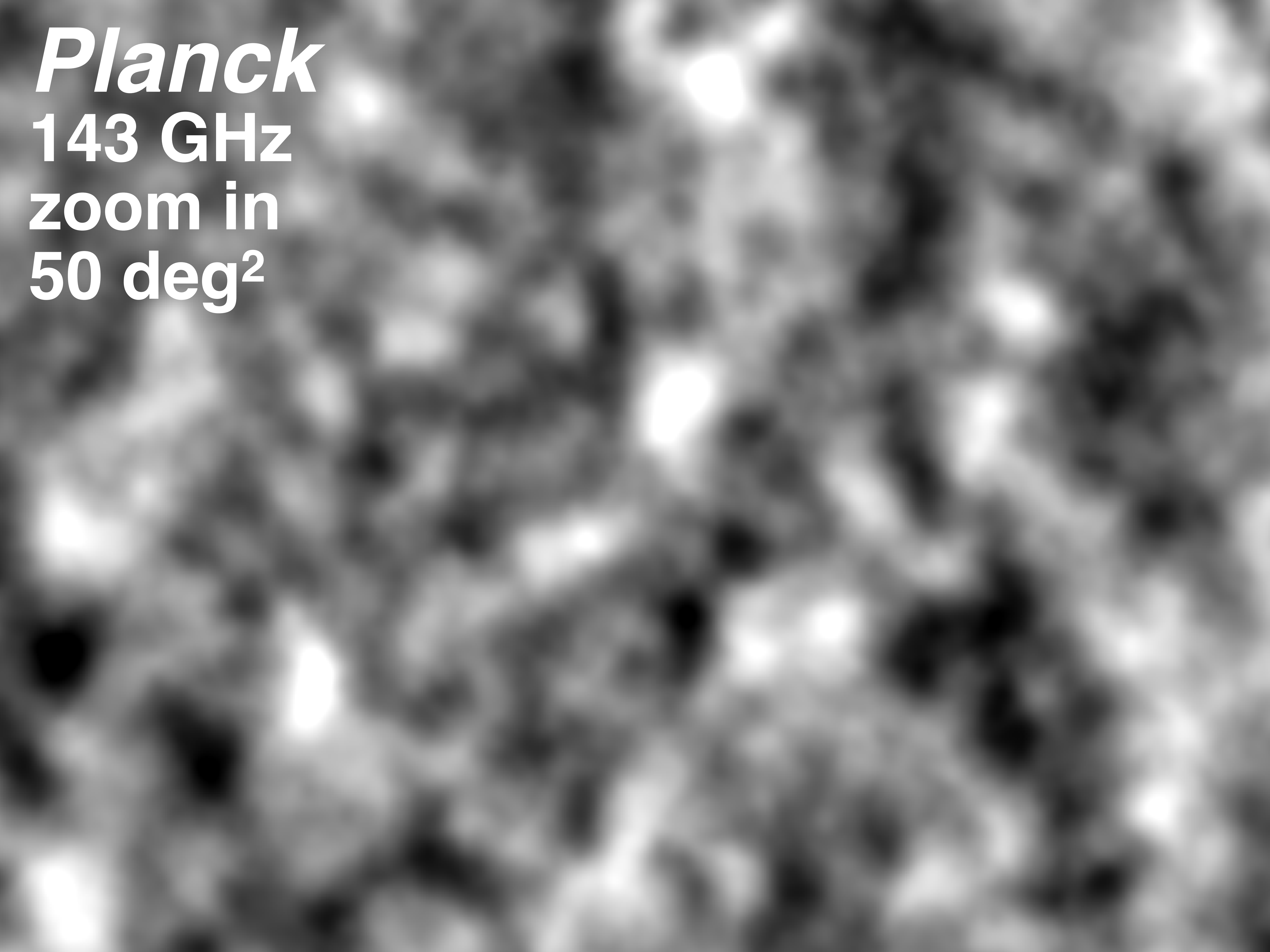


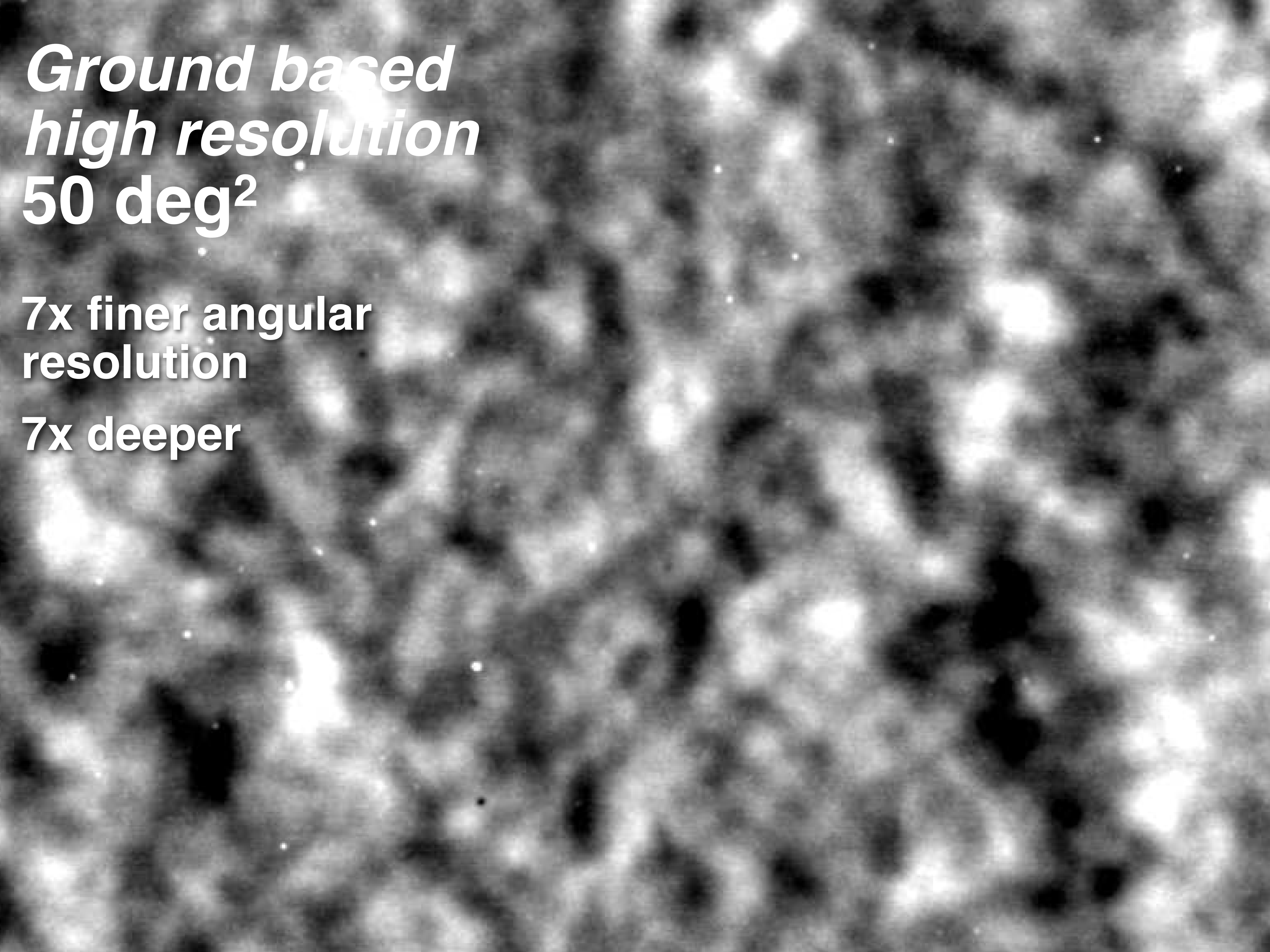
Also

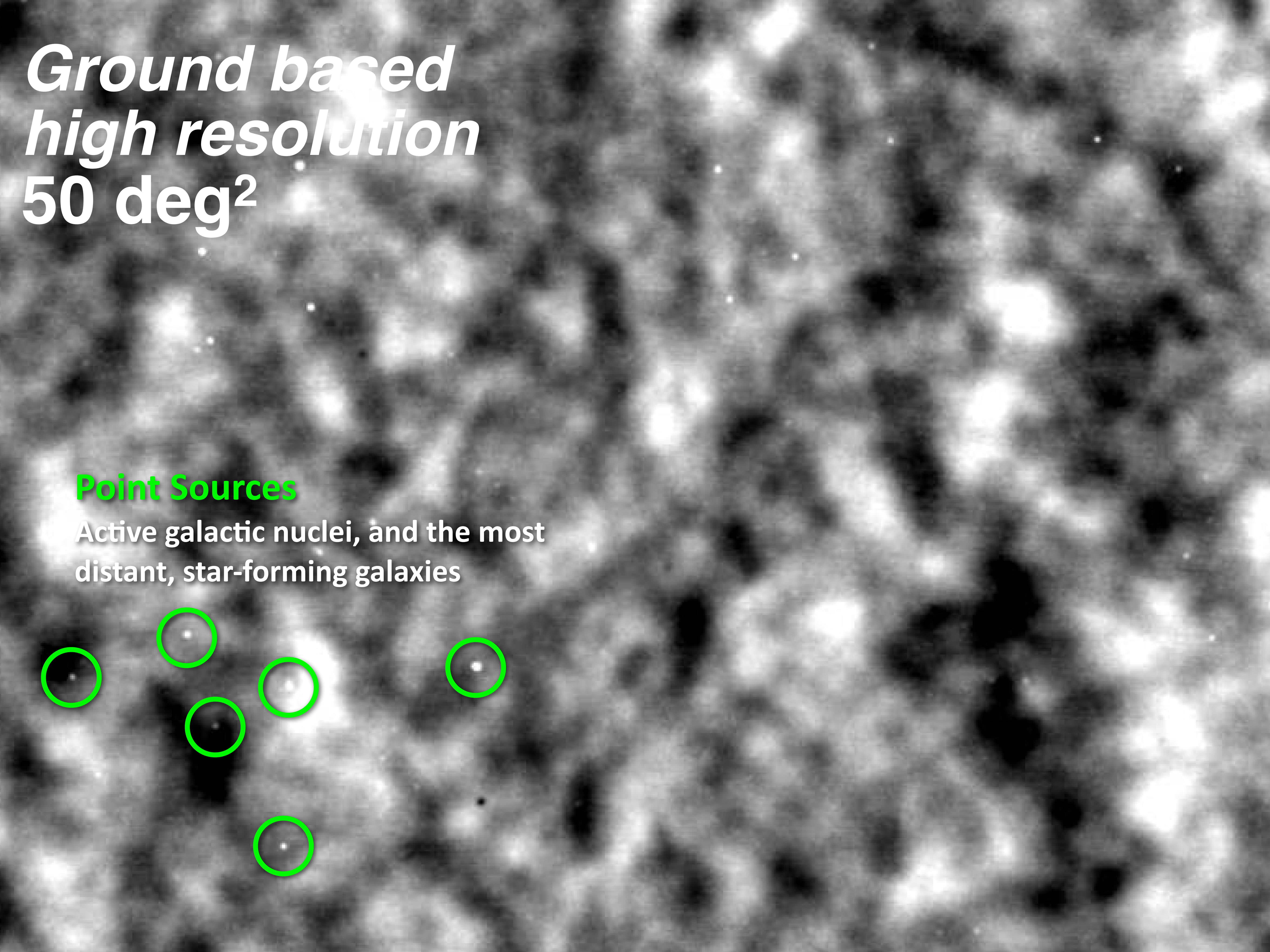
Ground: CBASS (5 GHz), QUIJOTE (11-40GHz),
QUBIC 150/220 GHz upcoming

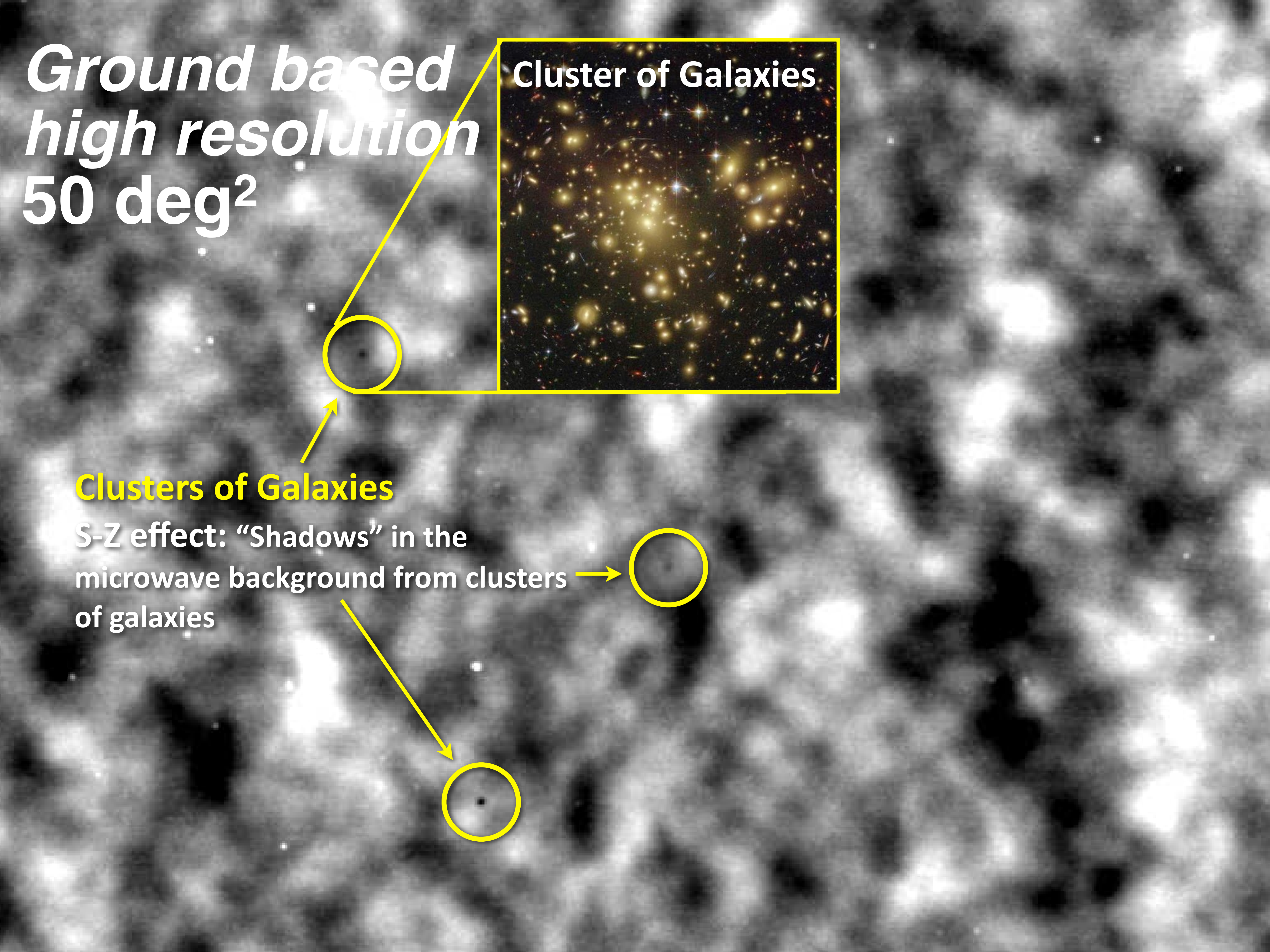
Balloon: PIPER & LSPE upcoming, (EBEX, BFORE pending)

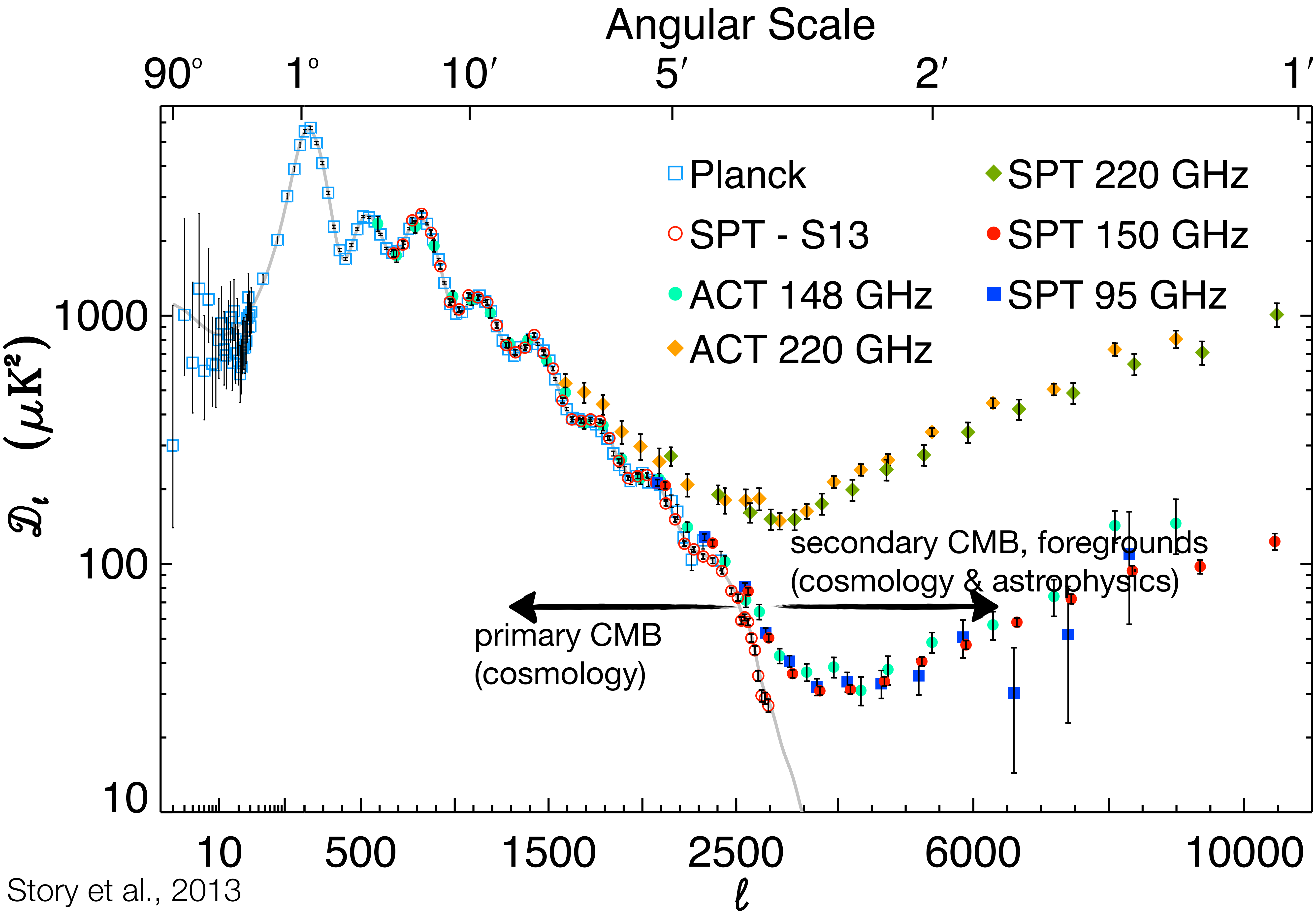
Satellite proposals: LiteBIRD, PIXIE


Planck
143 GHz
zoom in
50 deg^2


Ground based
high resolution
50 deg^2
7x finer angular resolution
7x deeper


Ground based
high resolution
50 deg^2
Point Sources
Active galactic nuclei, and the most
distant, star-forming galaxies


Ground based high resolution
50 deg²
Cluster of Galaxies
Clusters of Galaxies
S-Z effect: "Shadows" in the microwave background from clusters of galaxies



Story et al., 2013
George et al., 2014
Das et al., 2014

Status of primary CMB TT measurements

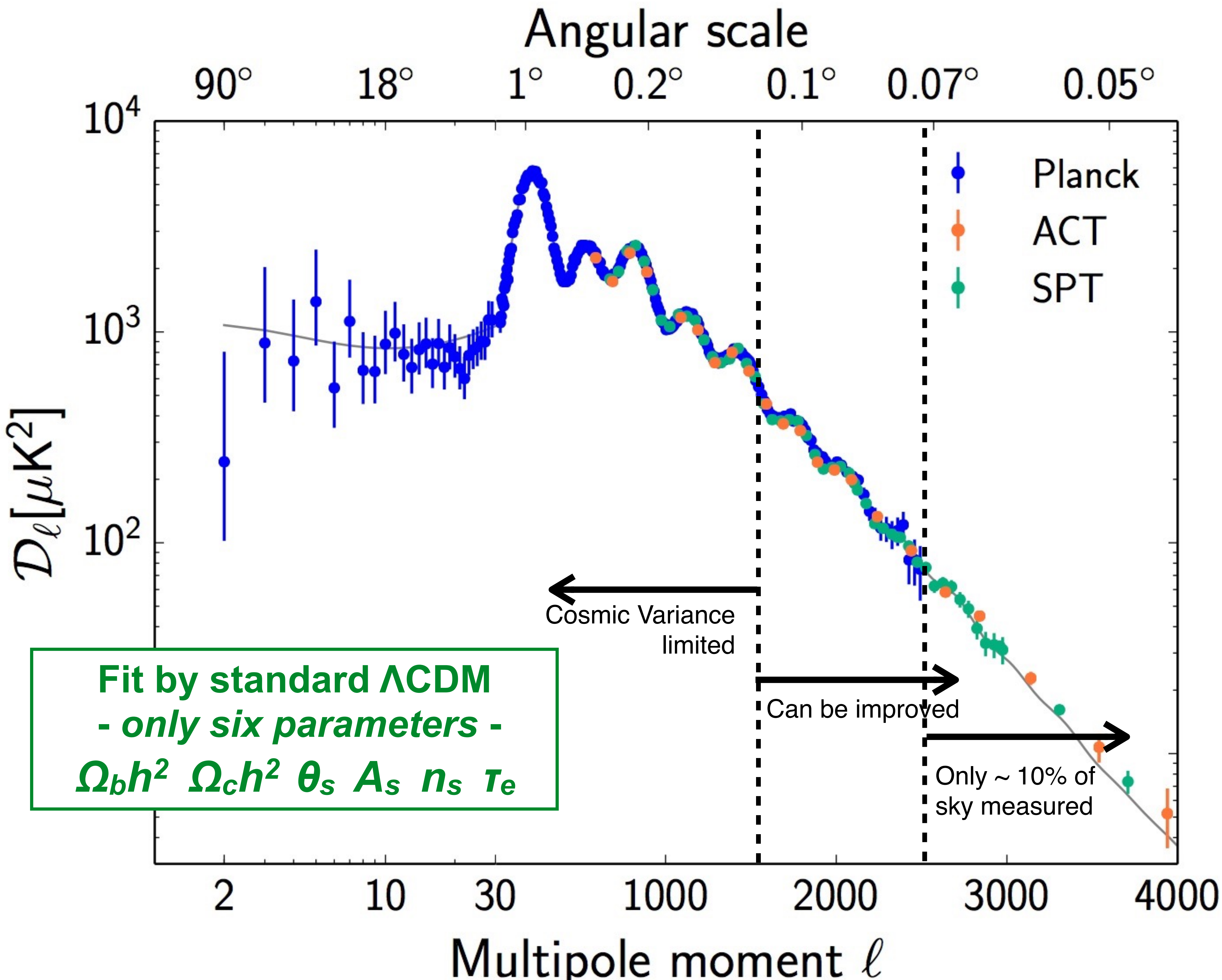
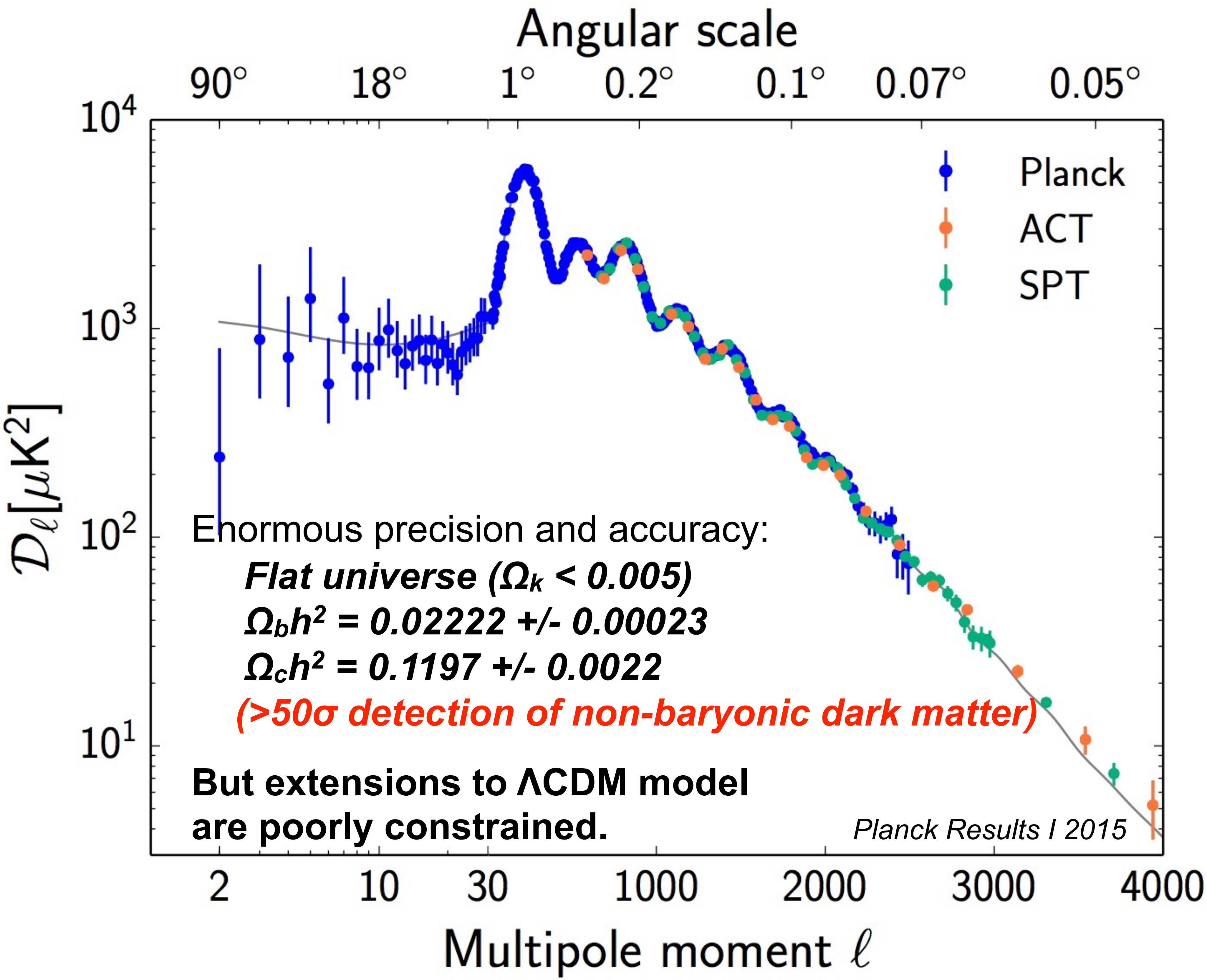


Figure from Planck 2015 Results XI

Constraints on cosmological parameters



Enormous precision and accuracy:

Flat universe (Ω_k < 0.005)

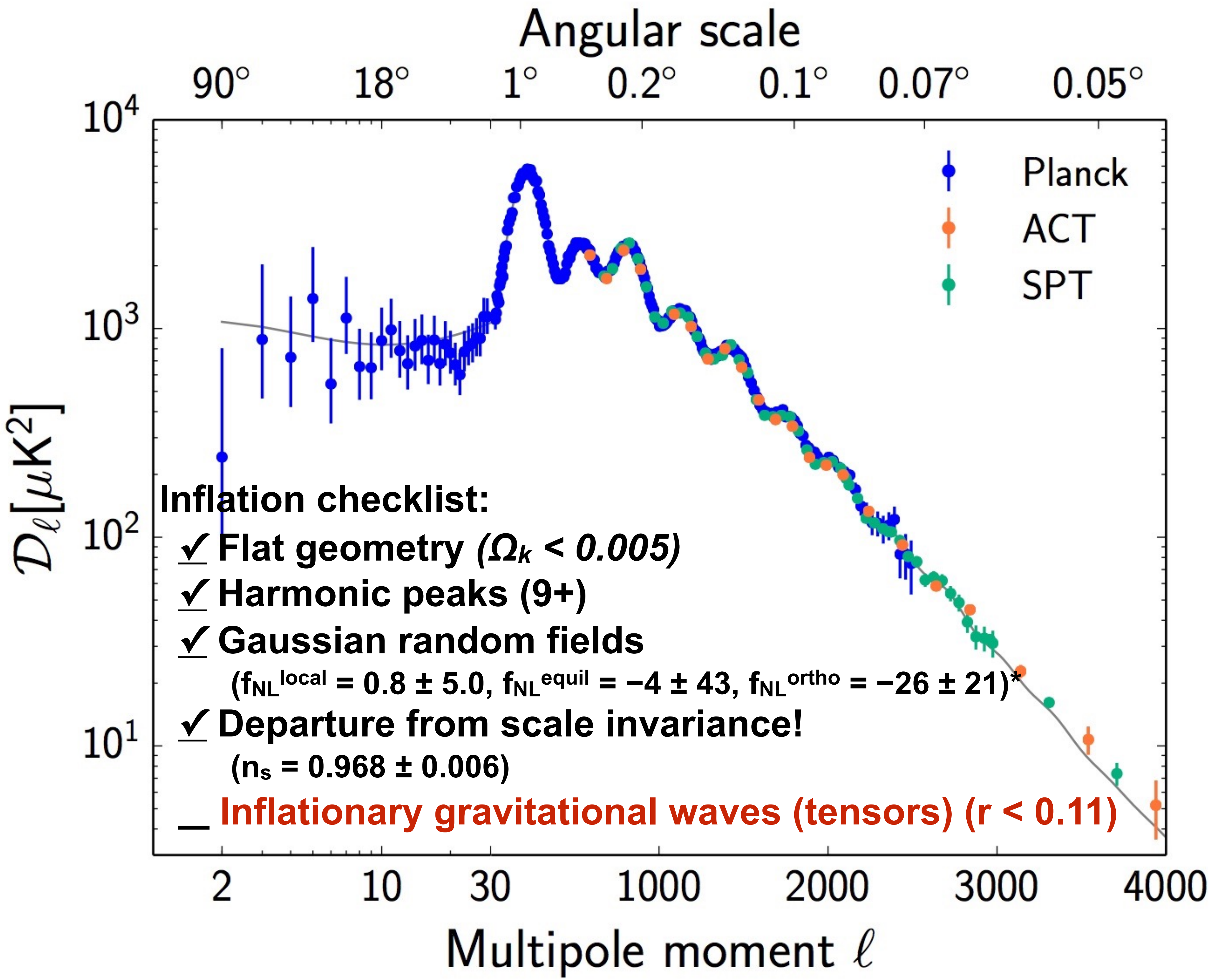
$\Omega_b h^2$ = 0.02222 +/- 0.00023

$\Omega_c h^2$ = 0.1197 +/- 0.0022

(>50σ detection of non-baryonic dark matter)

But extensions to ΛCDM model are poorly constrained.

Constraints on cosmological parameters



Inflation checklist:

✓ **Flat geometry *(Ω_k < 0.005)***

✓ **Harmonic peaks (9+)**

✓ **Gaussian random fields**

(f_{NL}^{local} = 0.8 ± 5.0, f_{NL}^{equil} = −4 ± 43, f_{NL}^{ortho} = −26 ± 21)*

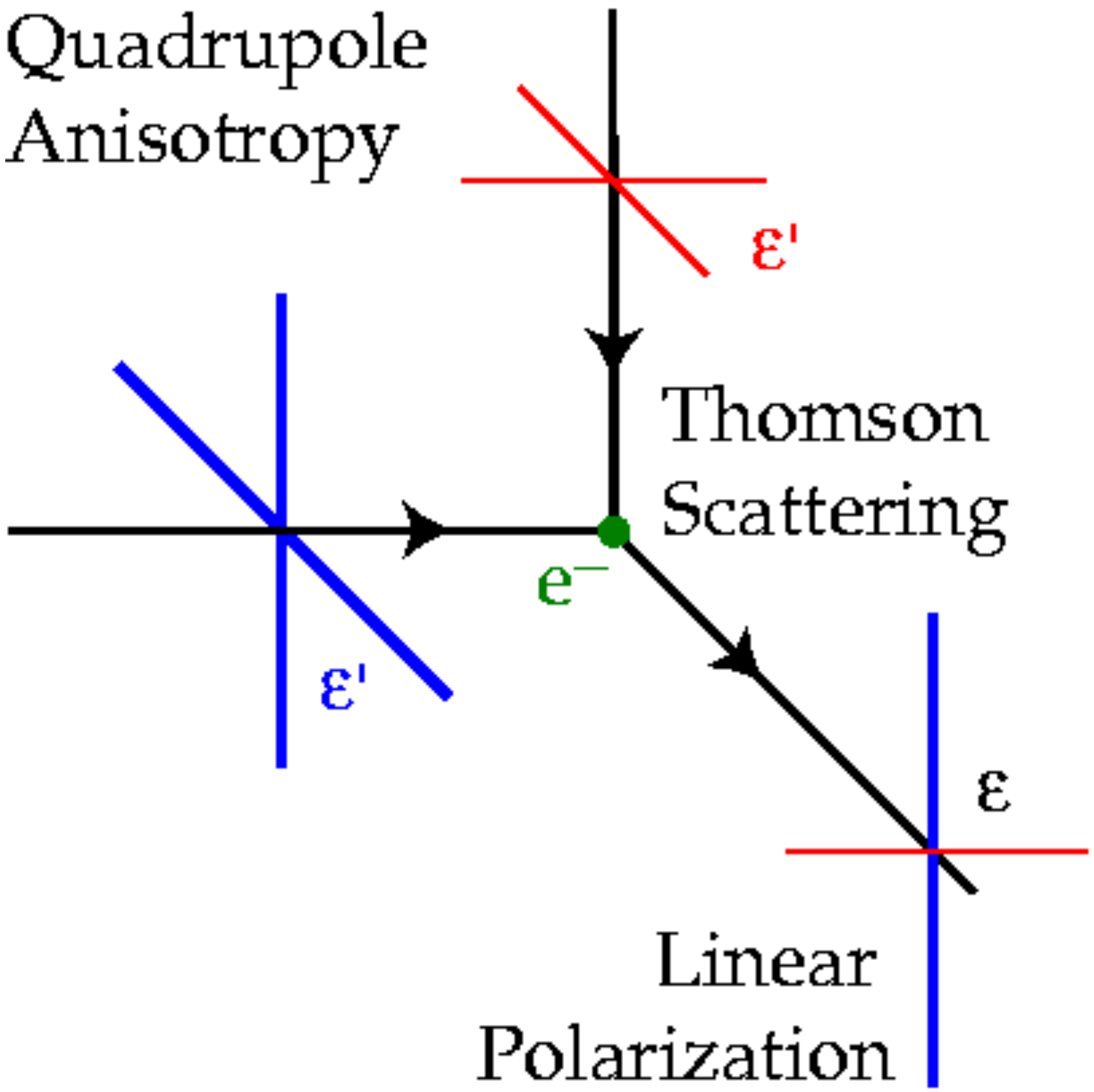
✓ **Departure from scale invariance!**

(n_s = 0.968 ± 0.006)

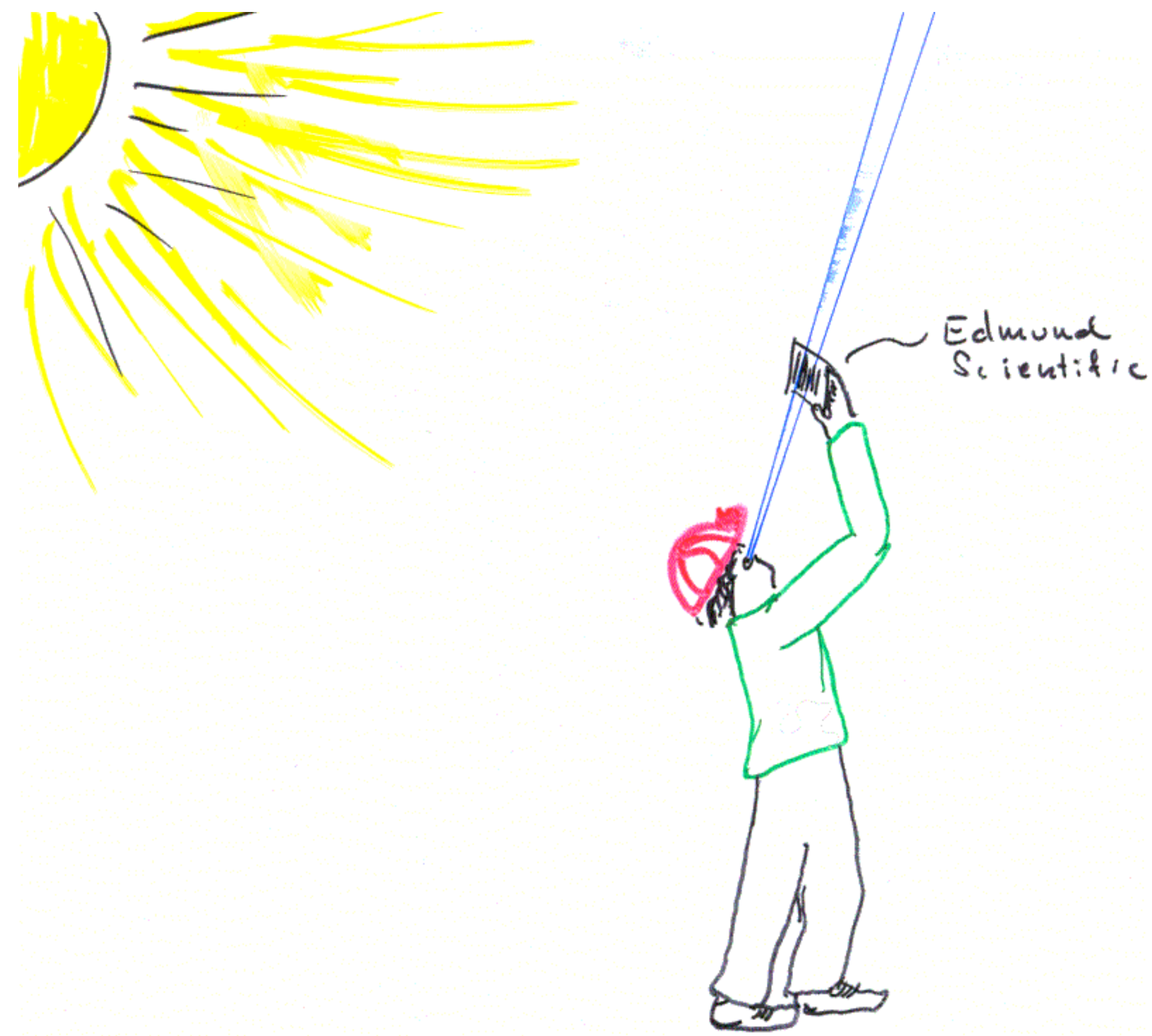
_ **Inflationary gravitational waves (tensors) (r < 0.11)**

Polarization of the CMB

Owing to Thomson scattering –
CMB must be polarized



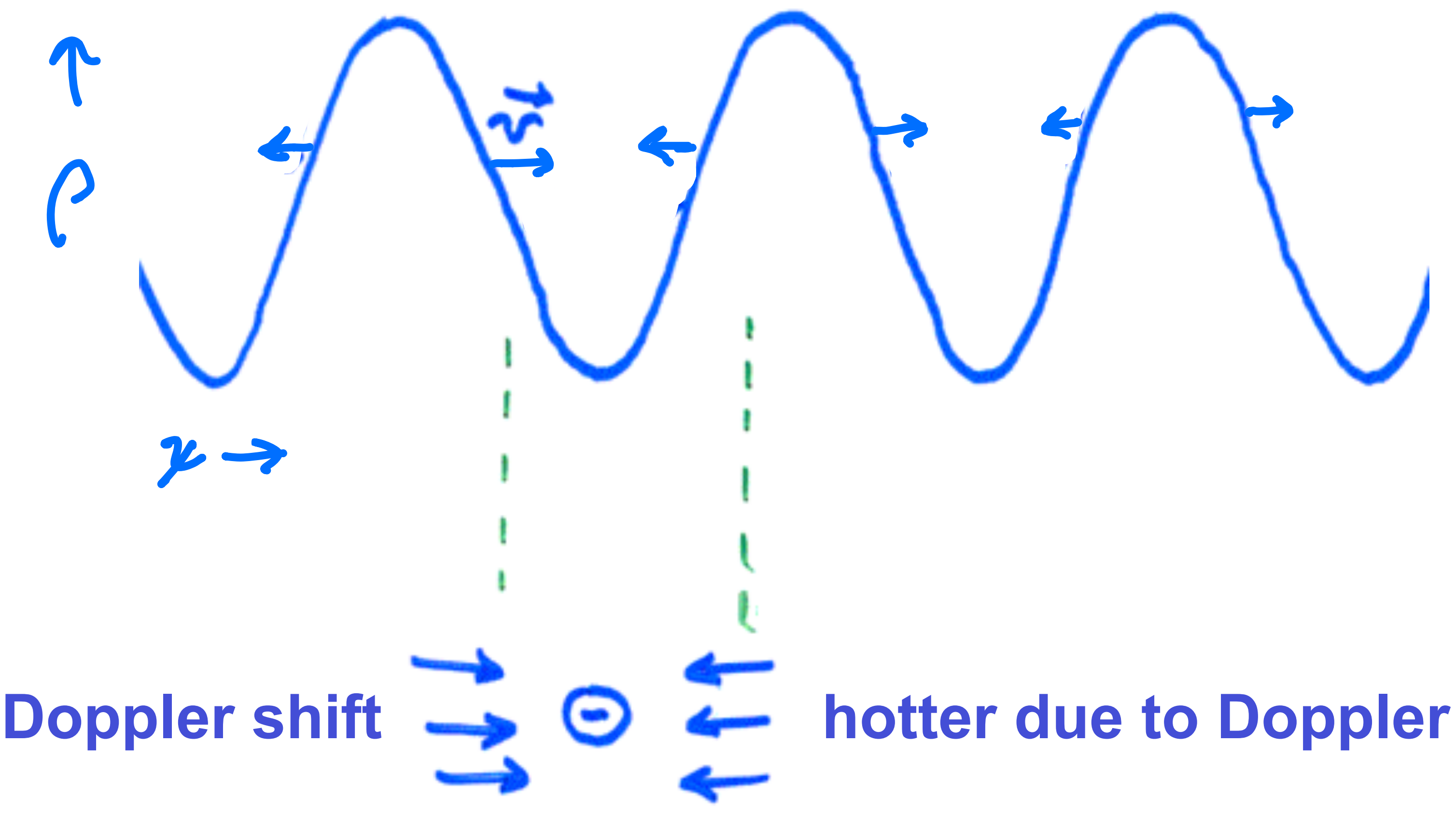
from W. Hu's web pages



Just like the sky,
the *CMB must be polarized*

Generating CMB polarization

Density mode

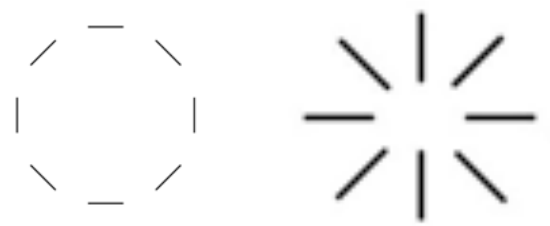


hotter due to Doppler shift **hotter due to Doppler shift**

At decoupling mean free path increases and electron ‘sees’ quadrupole → scattered light is polarized

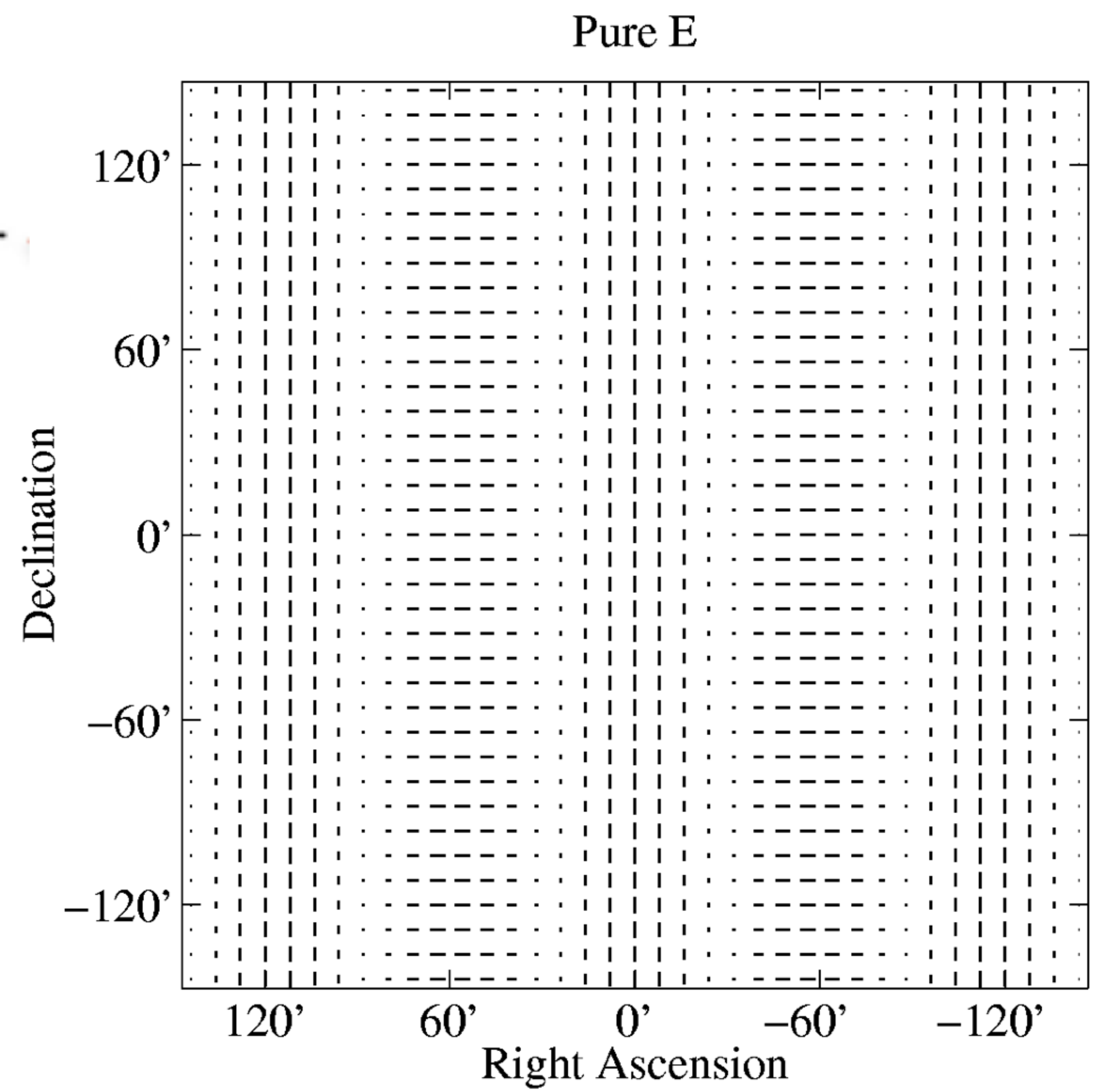
E-mode Polarization (Curl free)

Polarization parallel & perpendicular to wave vector



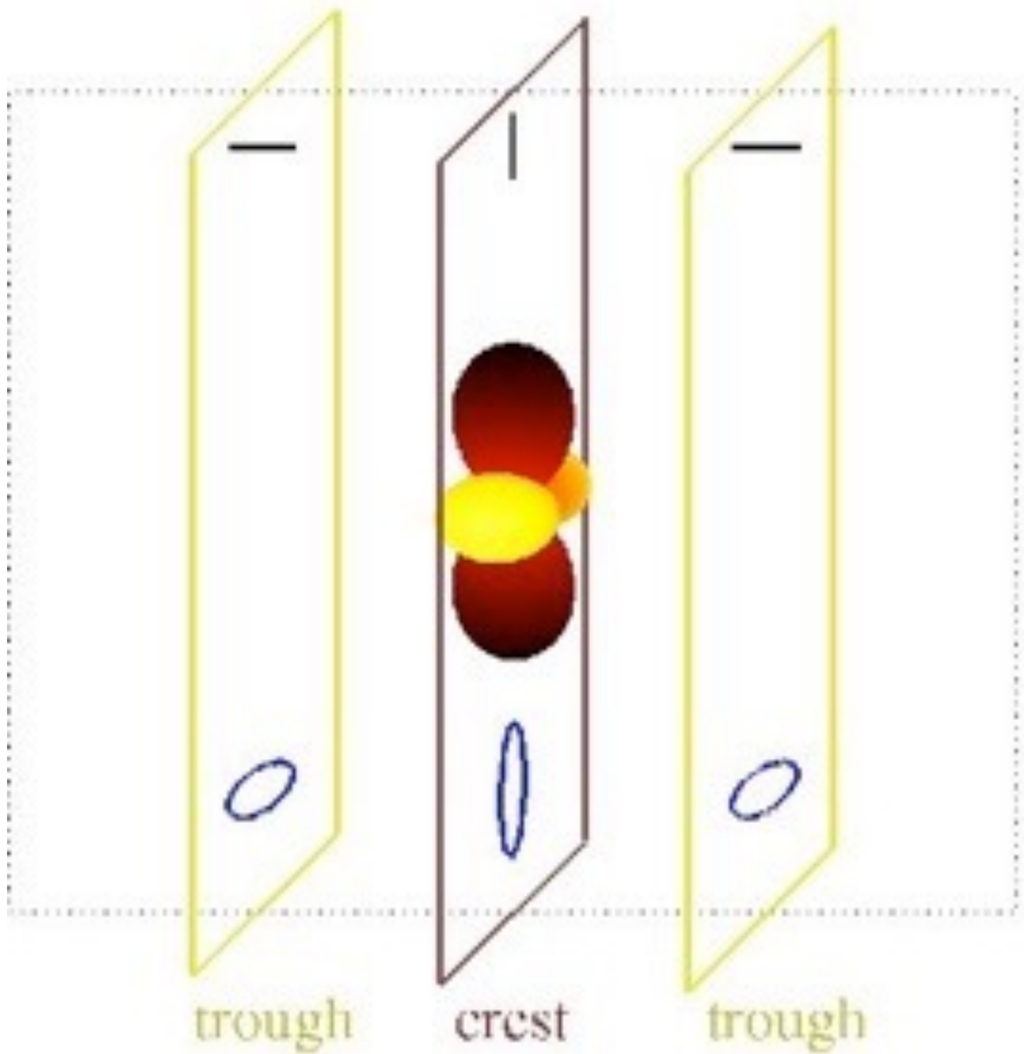
Even parity, curl-free

Density (scalar) fluctuations generate only E-Polarization



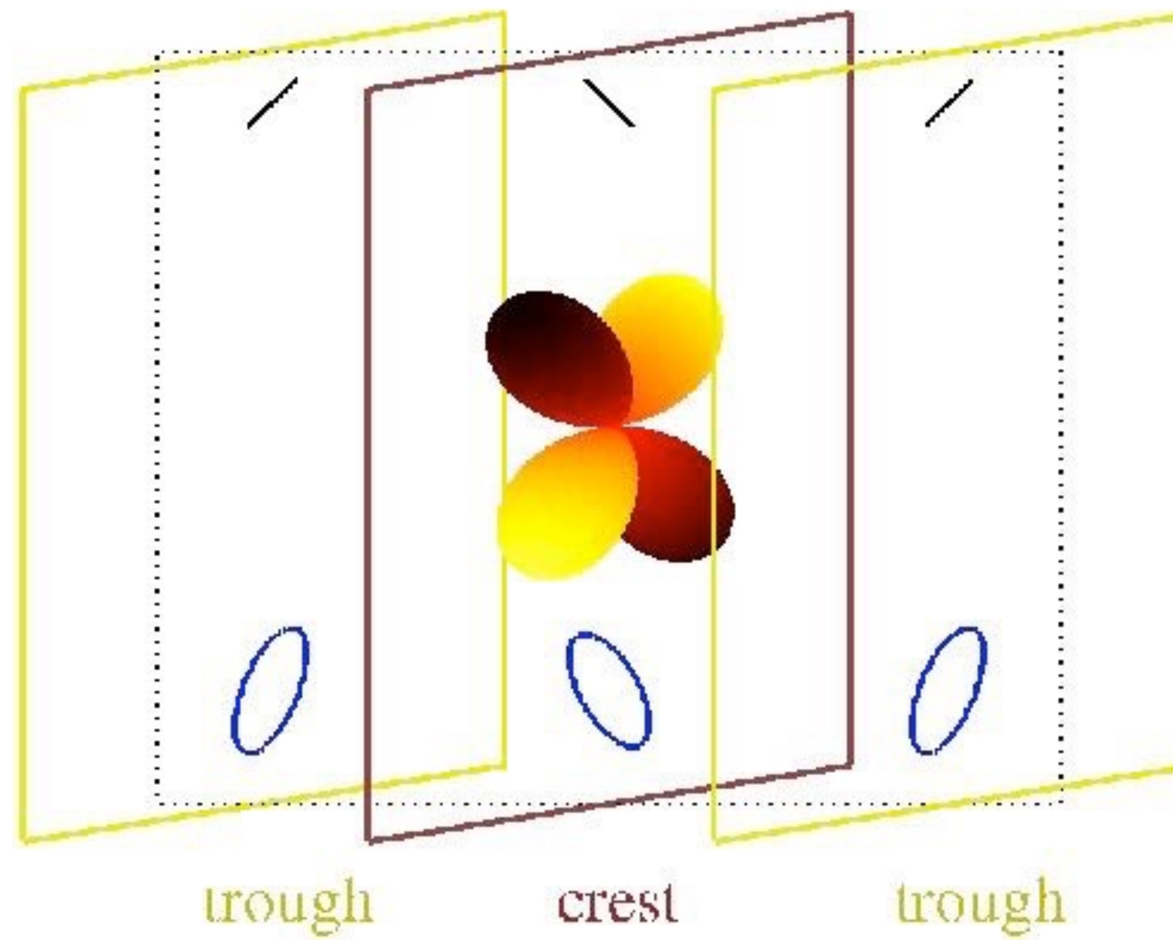
Gravitational wave induced CMB polarization

'+' mode, $\vec{k}$ parallel



E-mode

'×' mode, $\vec{k}$ not parallel



B-mode
(Inflationary GW B-modes)

Figure from John Kovac's thesis

B-mode Polarization (div free)

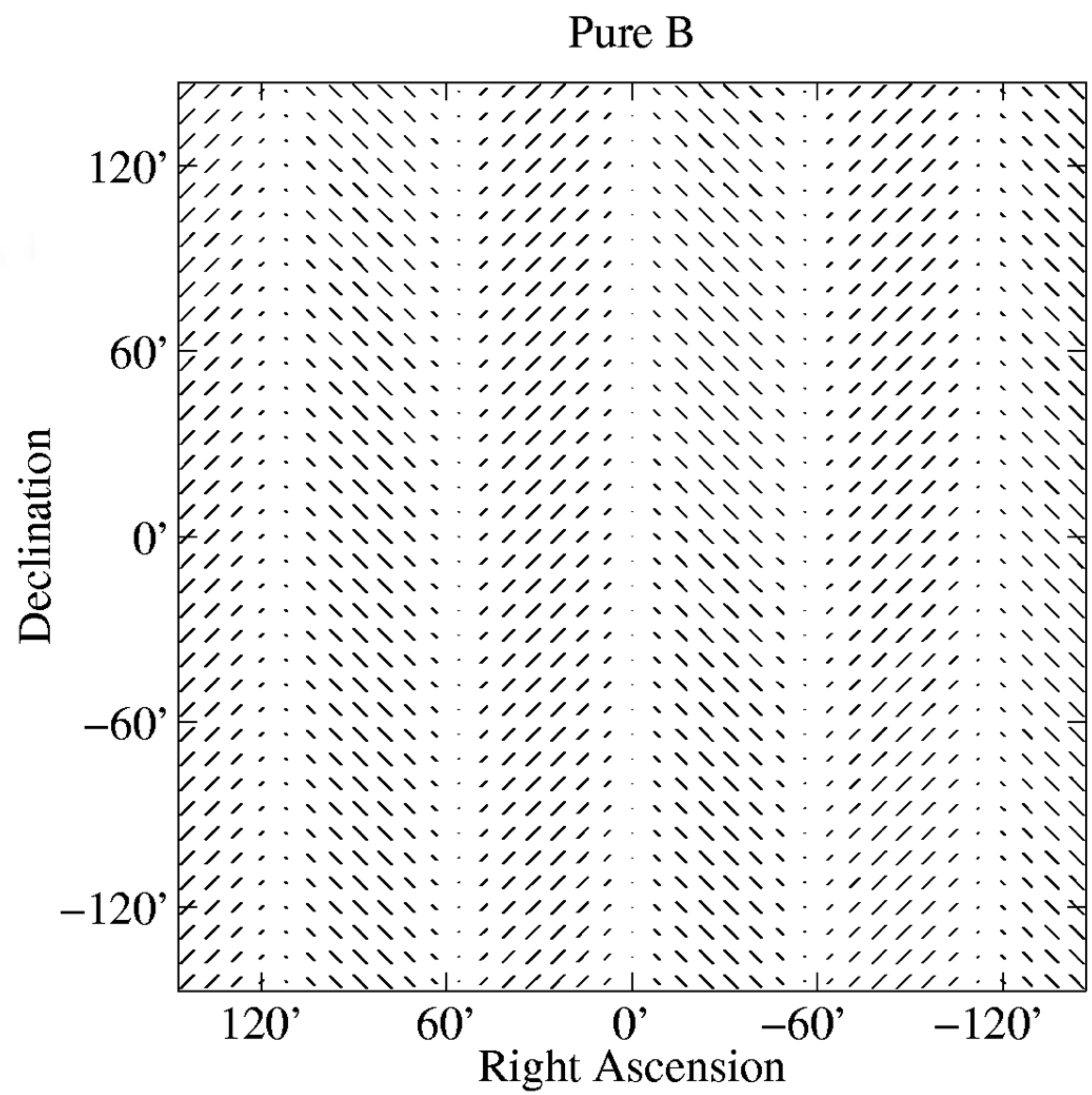
Polarization oriented ±45 degrees
to wave vector

Odd parity, div free

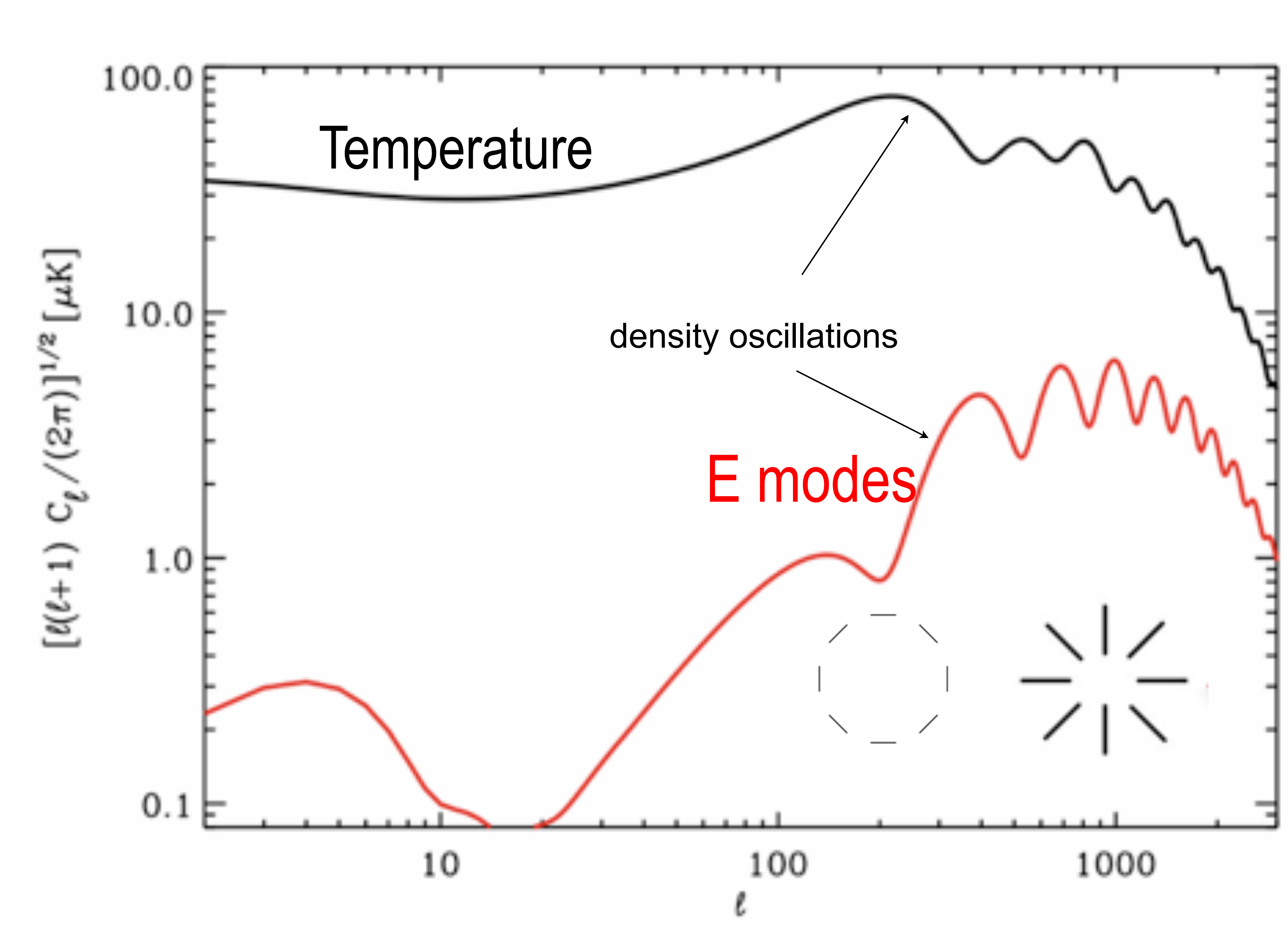
NOT generated by density fluctuations

Would be generated by **inflationary gravitational waves** present at recombination.

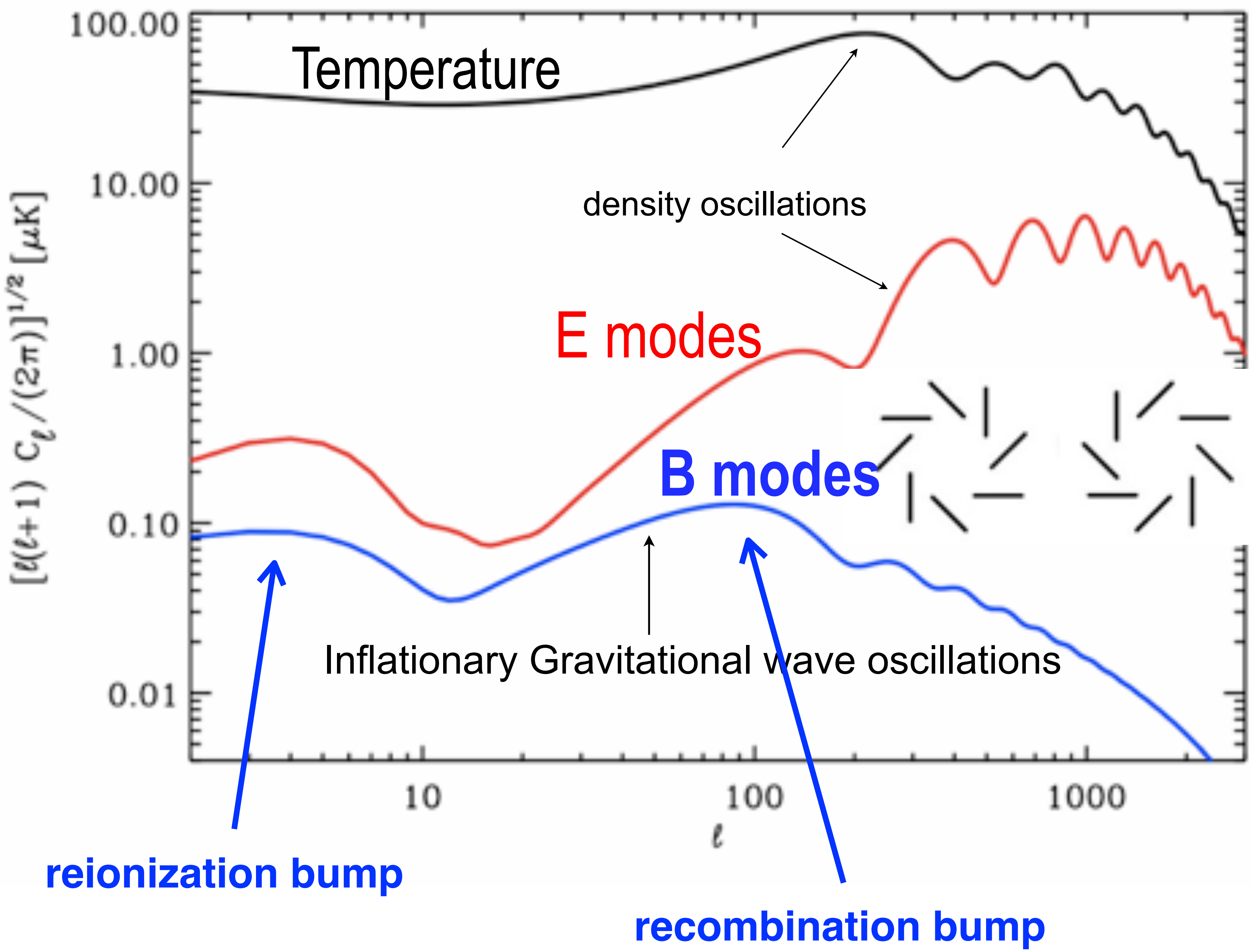
Key probe of Inflation and a direct measure of its energy scale



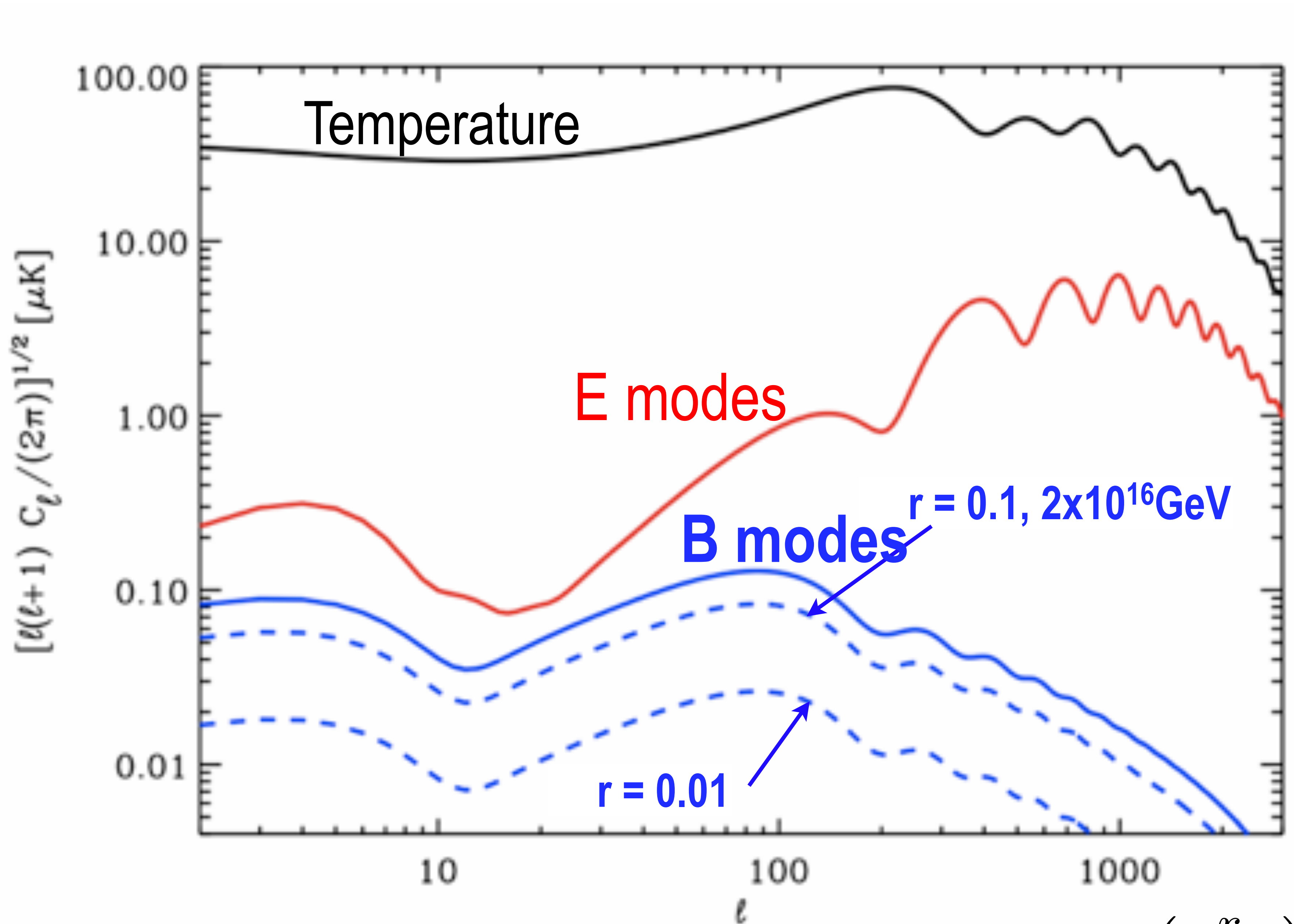
CMB Polarization



CMB Polarization



CMB Polarization

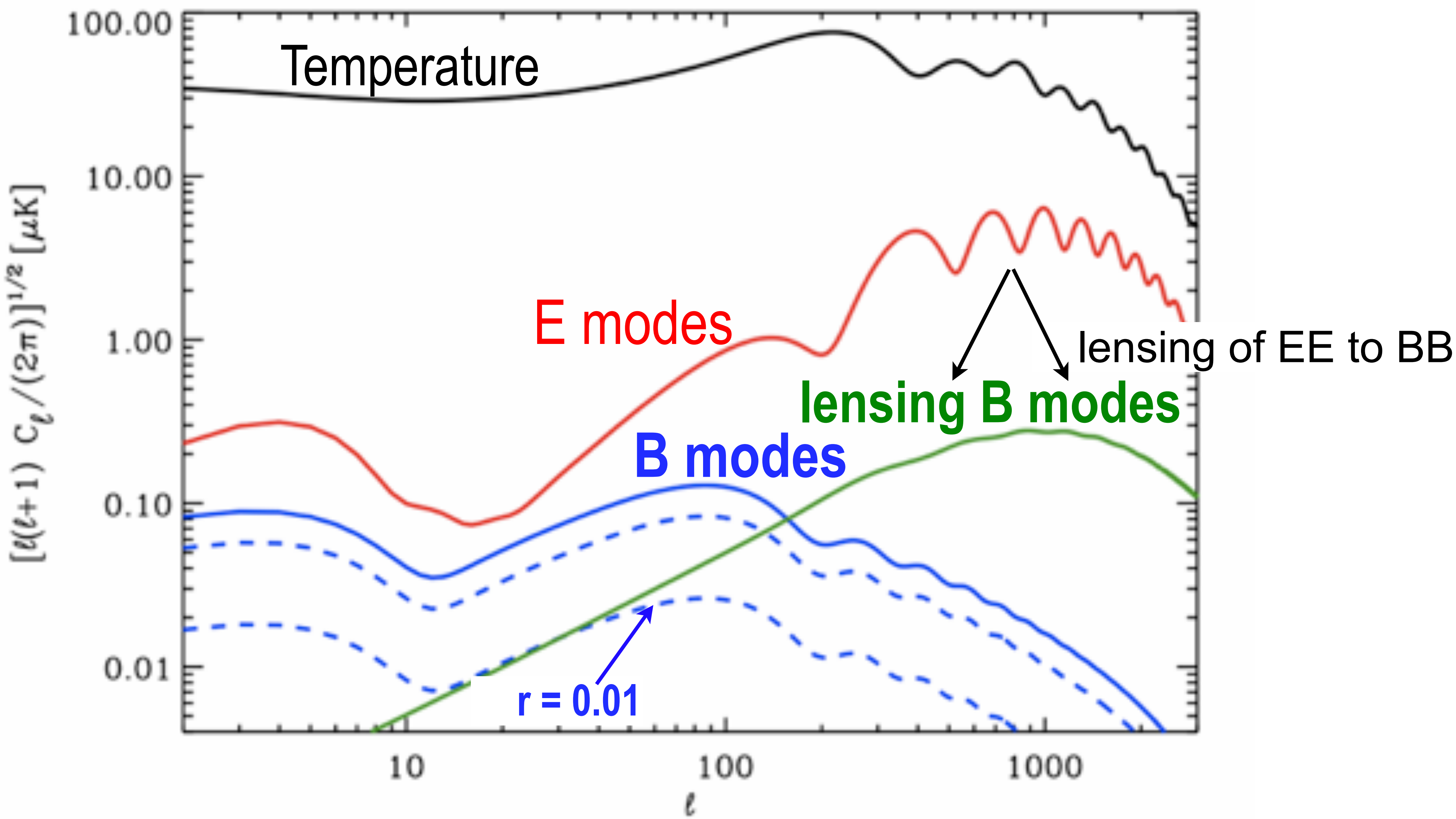


$$r \equiv \frac{\text{Tensor (gravitational) perturbation amplitude}}{\text{Scalar (density) perturbation amplitude}}$$

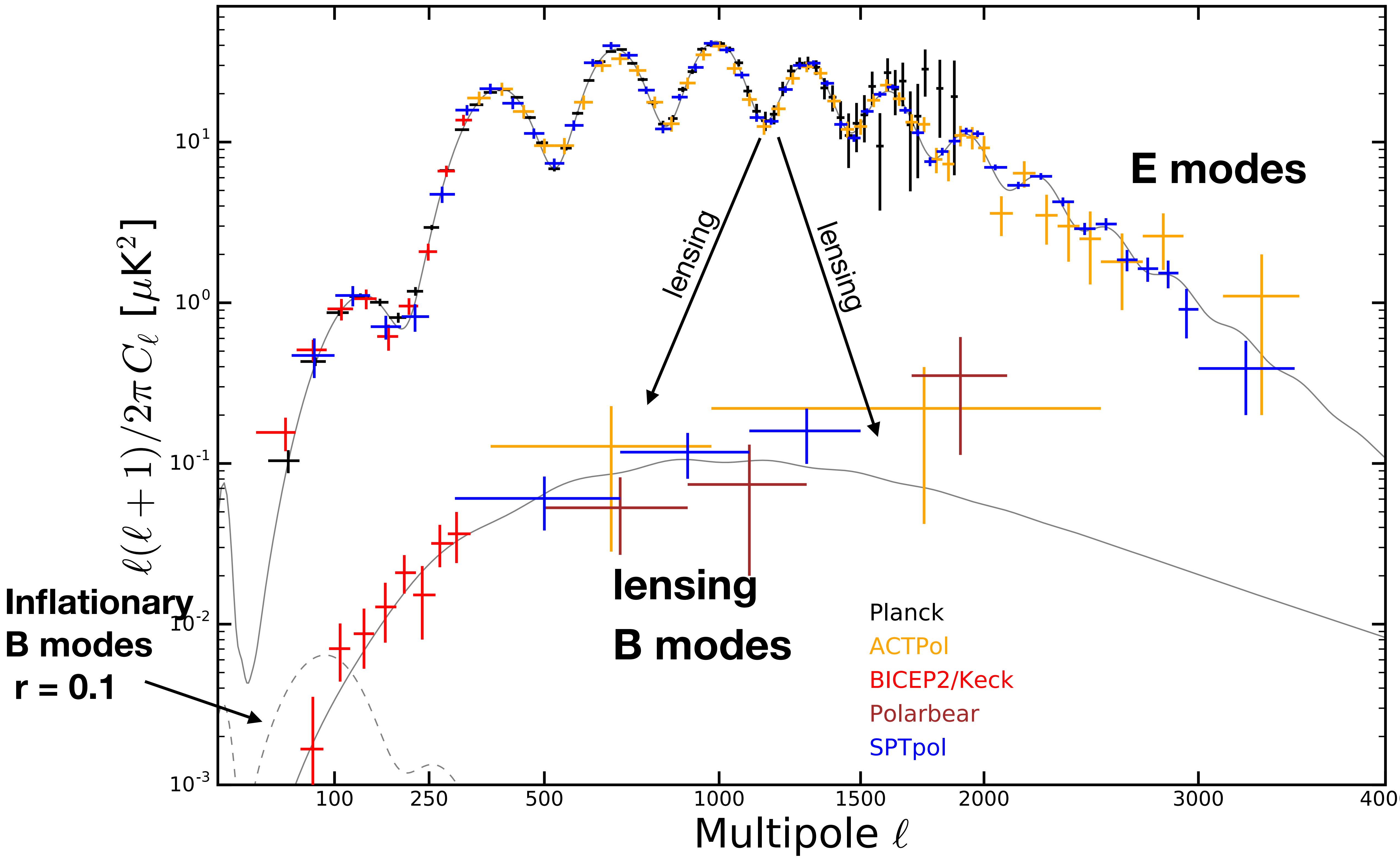
$$\text{energy} = 10^{16}\left(\frac{r}{0.01}\right)^{\frac{1}{4}}\ \text{GeV}$$

$$\text{time} = 10^{-36}\left(\frac{r}{0.01}\right)^{-\frac{1}{2}}\ \text{seconds}$$

CMB Polarization

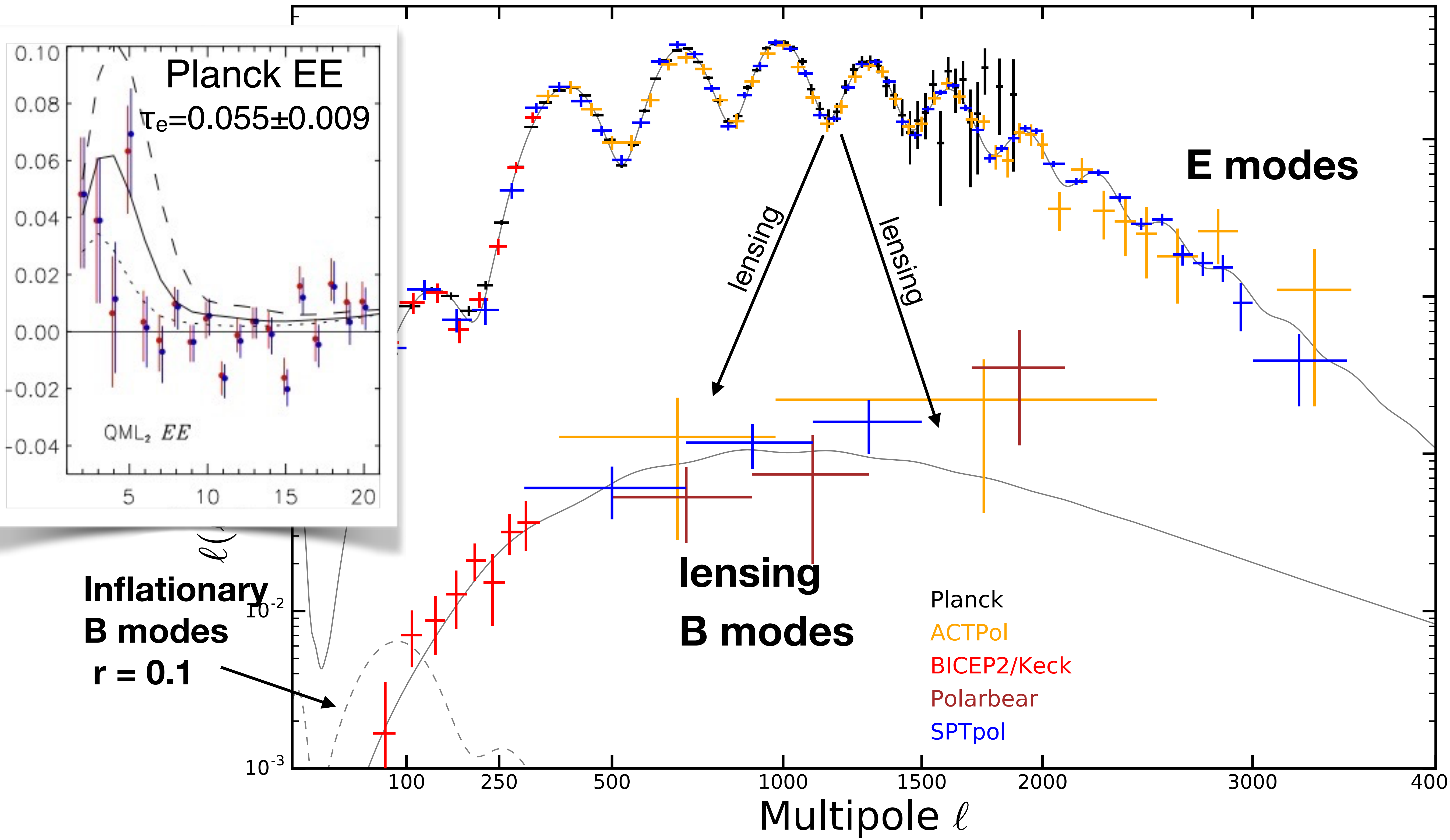


Status of CMB polarization measurements



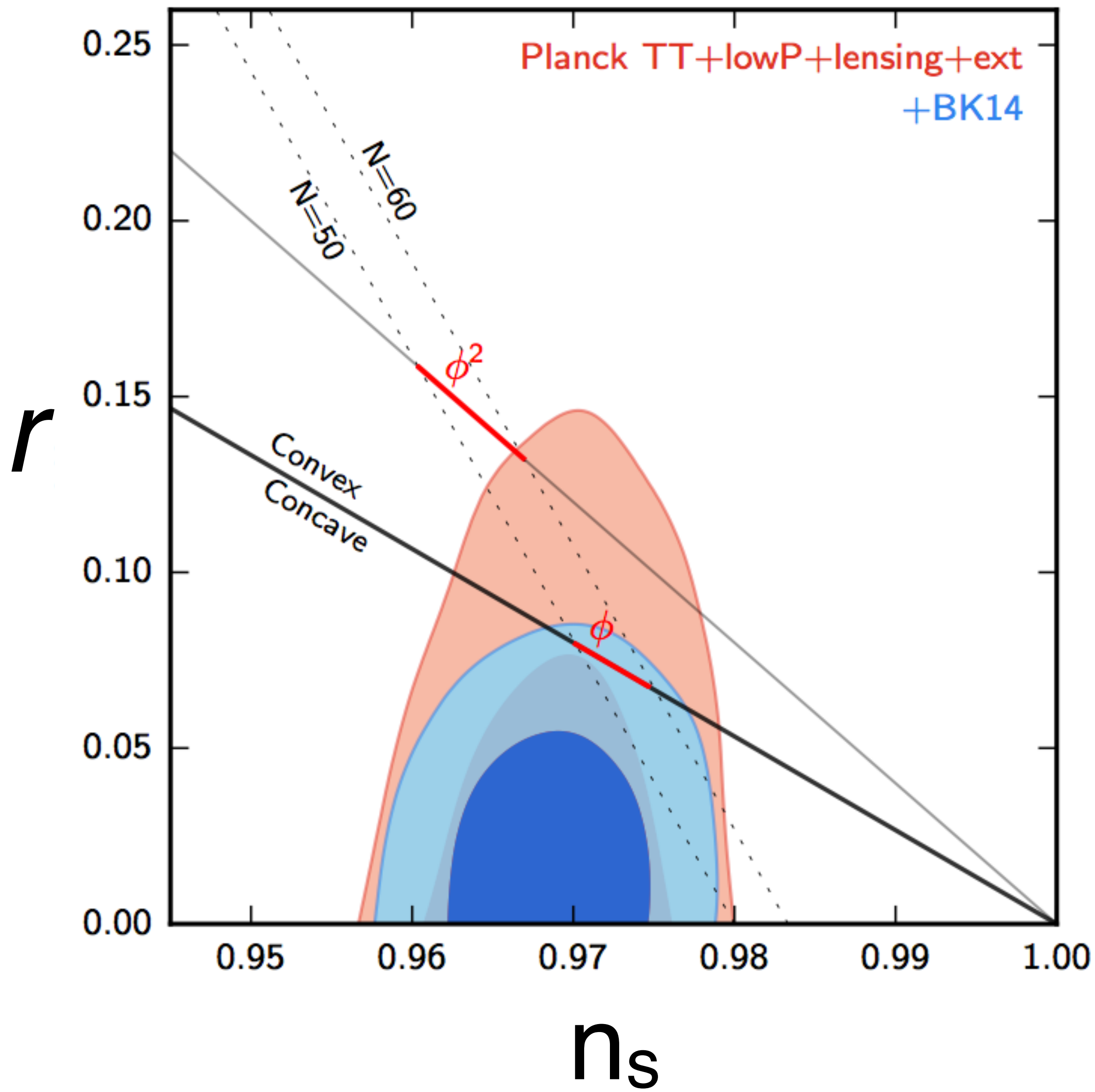
Rapid progress. All within last few years.

Status of CMB polarization measurements



Rapid progress. All within last few years.

arXiv:1510.09217



The tensor to scalar ratio, r, is now constrained by B-mode polarization measurements

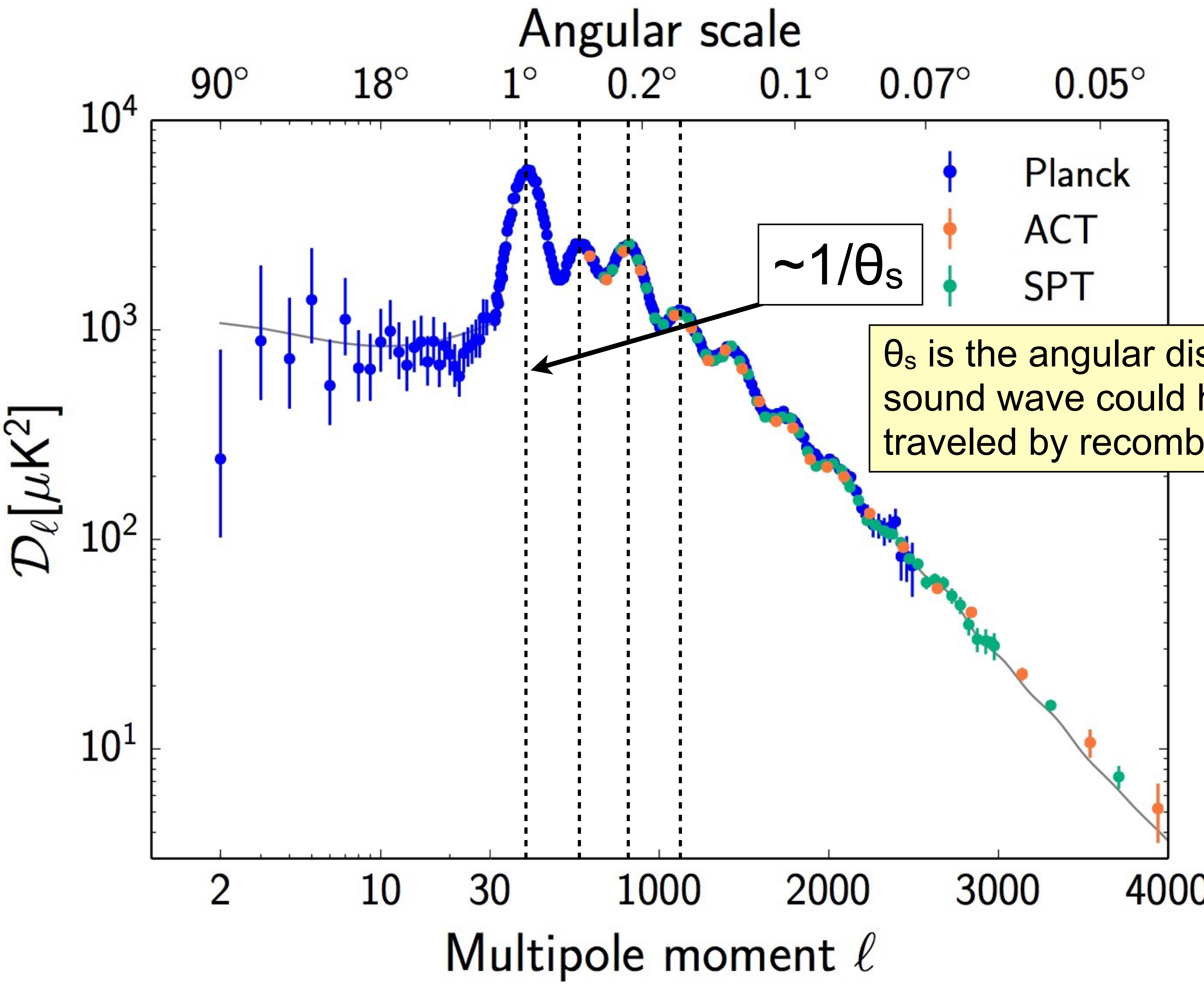
BICEP/Keck & Planck result:

r < 0.07 at 95% C.L.

Raw sensitivity σ(r) = 0.006

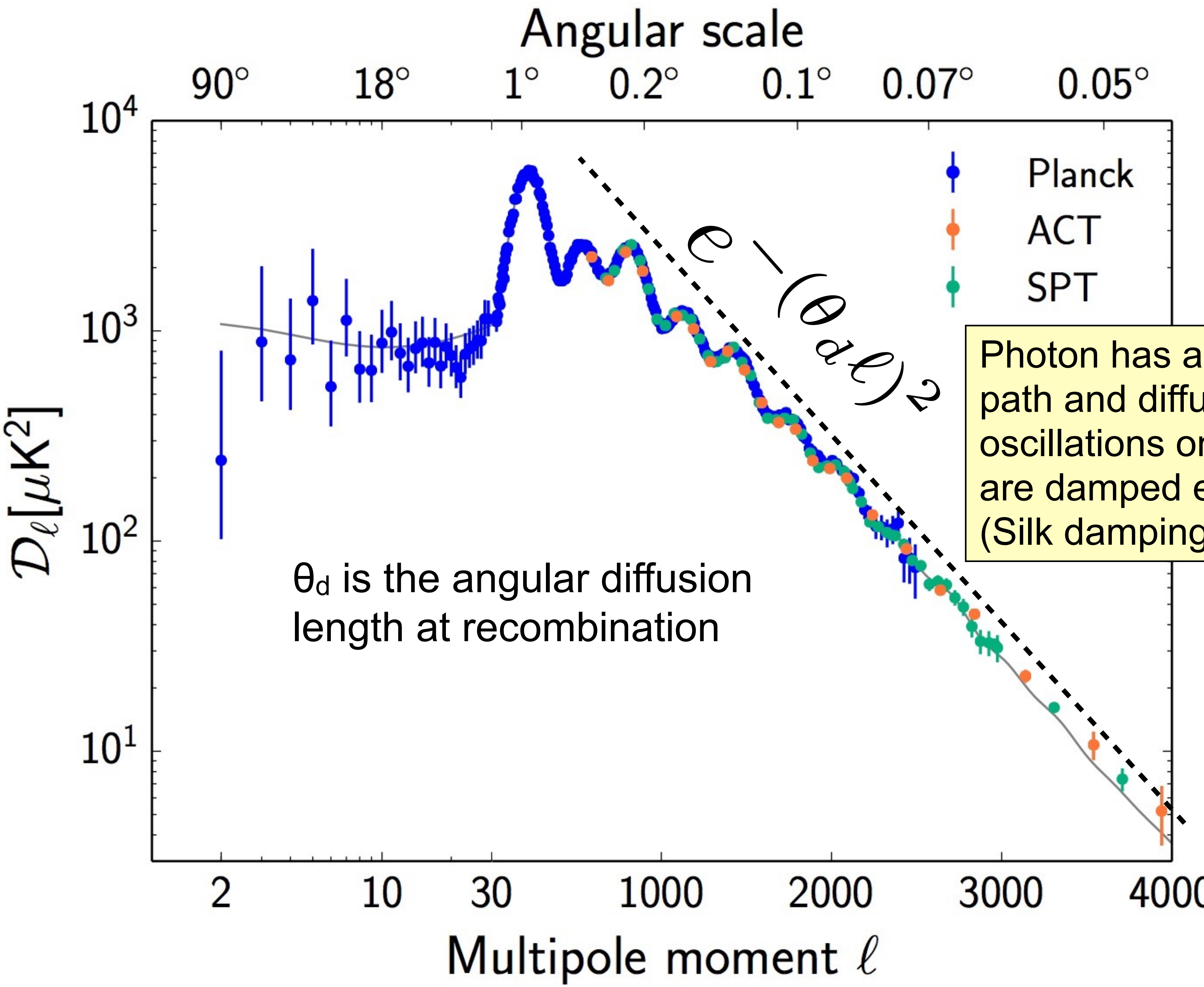
→ *limited by foreground component separation and soon by gravitational lensing distortions of the CMB*

Two scales: sound horizon, θ_s



θ_s is the angular distance a sound wave could have traveled by recombination

and the damping scale, θ_d



θ_d is the angular diffusion length at recombination

Photon has a mean free path and diffuses. So, oscillations on small scales are damped exponentially. (Silk damping)

Sensitivity to Neutrinos

How would an extra neutrino affect the CMB observables, the sound horizon θ_s and the damping scale θ_d?

An extra neutrino species **increases the expansion rate** during this radiation-dominated era via the Friedmann Eq.

$$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2 \propto (\rho_\gamma + \rho_\nu + \rho_{matter} + ...)$$

More neutrinos → higher density → faster expansion

Neff slides adapted from Ryan Keisler

Sensitivity to Neutrinos

Consider how the real space equivalents, $\mathbf{r_s}$ and $\mathbf{r_d}$, depend on the expansion rate, H:

Sound Scale

$$r_s \propto \mathrm{time} \propto H^{-1}$$

Damping Scale

$$r_d \propto \sqrt{\mathrm{time}} \propto H^{-0.5}$$

(diffusion process. random walk.)

$$\frac{r_d}{r_s} = \frac{\theta_d}{\theta_s} \propto H^{0.5}$$

see e.g. 1104.2333, Z. Hou et al.

Sensitivity to Neutrinos

$$\frac{\theta_d}{\theta_s} \propto H^{0.5} \propto (\rho_\gamma + \rho_\nu + \rho_m + \ldots)^{0.25}$$

- The ratio $\frac{\theta_d}{\theta_s}$ is measured well using the CMB.
- The photon density ρ_γ is well known from 3K temperature of CMB.
- The ratio $\frac{\rho_m}{\rho_\gamma + \rho_\nu} = 1 + z_{EQ}$ is also measured well using the CMB.

We can solve for the neutrino density ρ_ν.

see e.g. 1104.2333, Z. Hou et al.

Sensitivity to Neutrinos

We express ρ_ν as the effective number of neutrino-like particles,

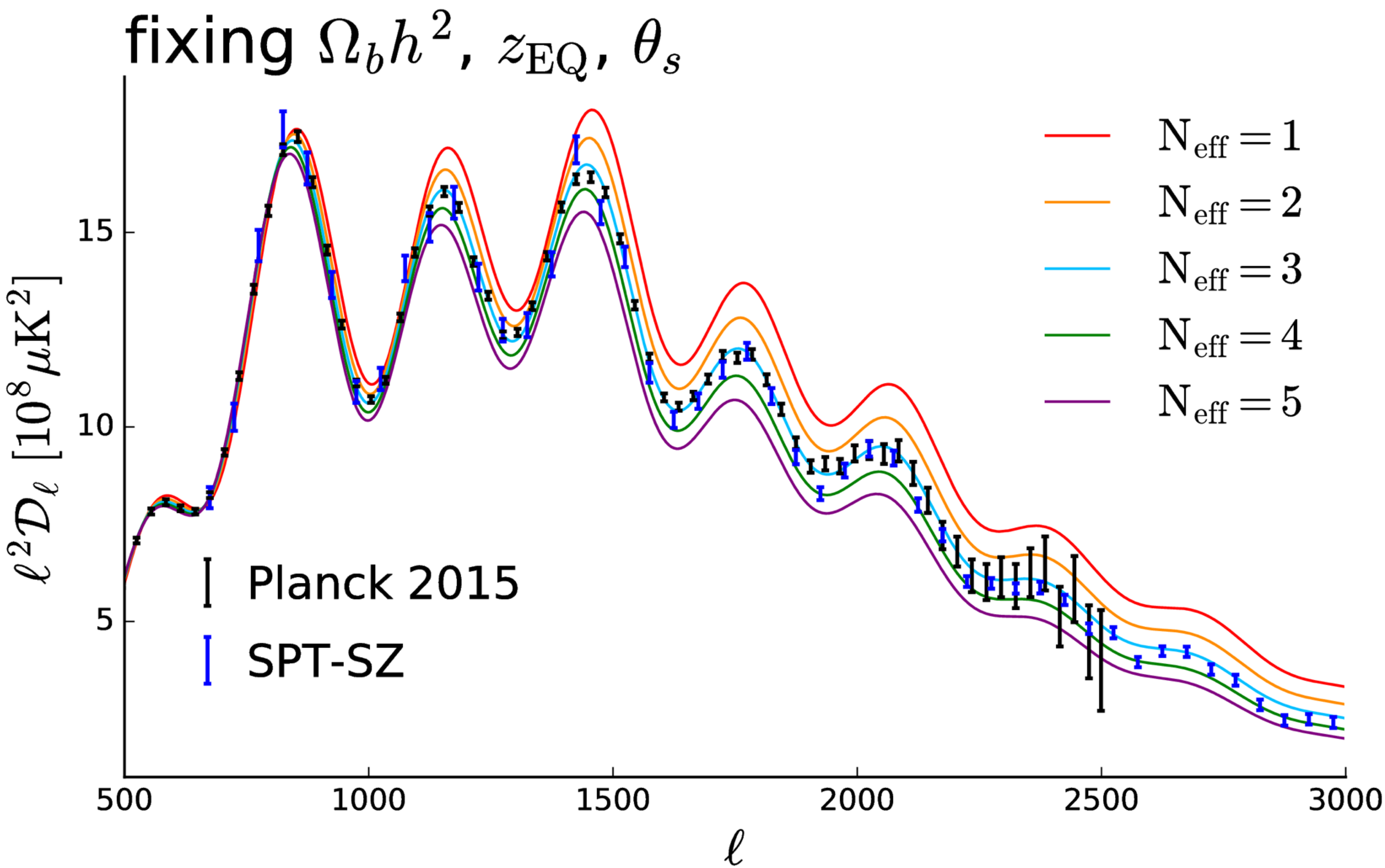
$$N_{eff} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_\nu}{\rho_\gamma}$$

If perfect decoupling and 3 neutrinos, then $N_{eff} = 3.00$.

Imperfect decoupling and effects of e^+e^- annihilation give

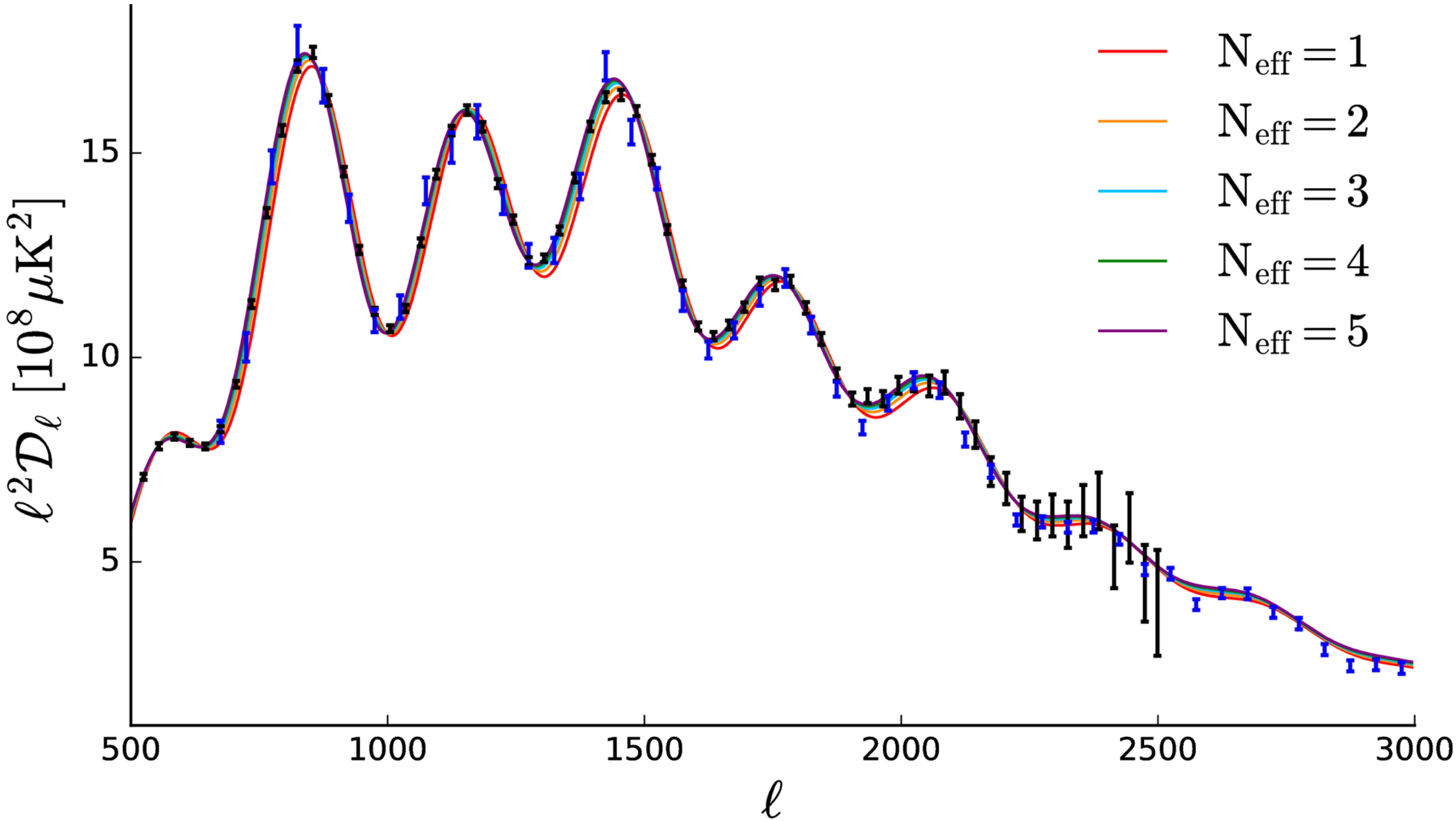
$N_{eff} = 3.046$

N_{eff} and CMB damping



Helium fraction & N_{eff} degeneracy

Keep θ_d constant with N_{eff} by increasing helium fraction, Y_P



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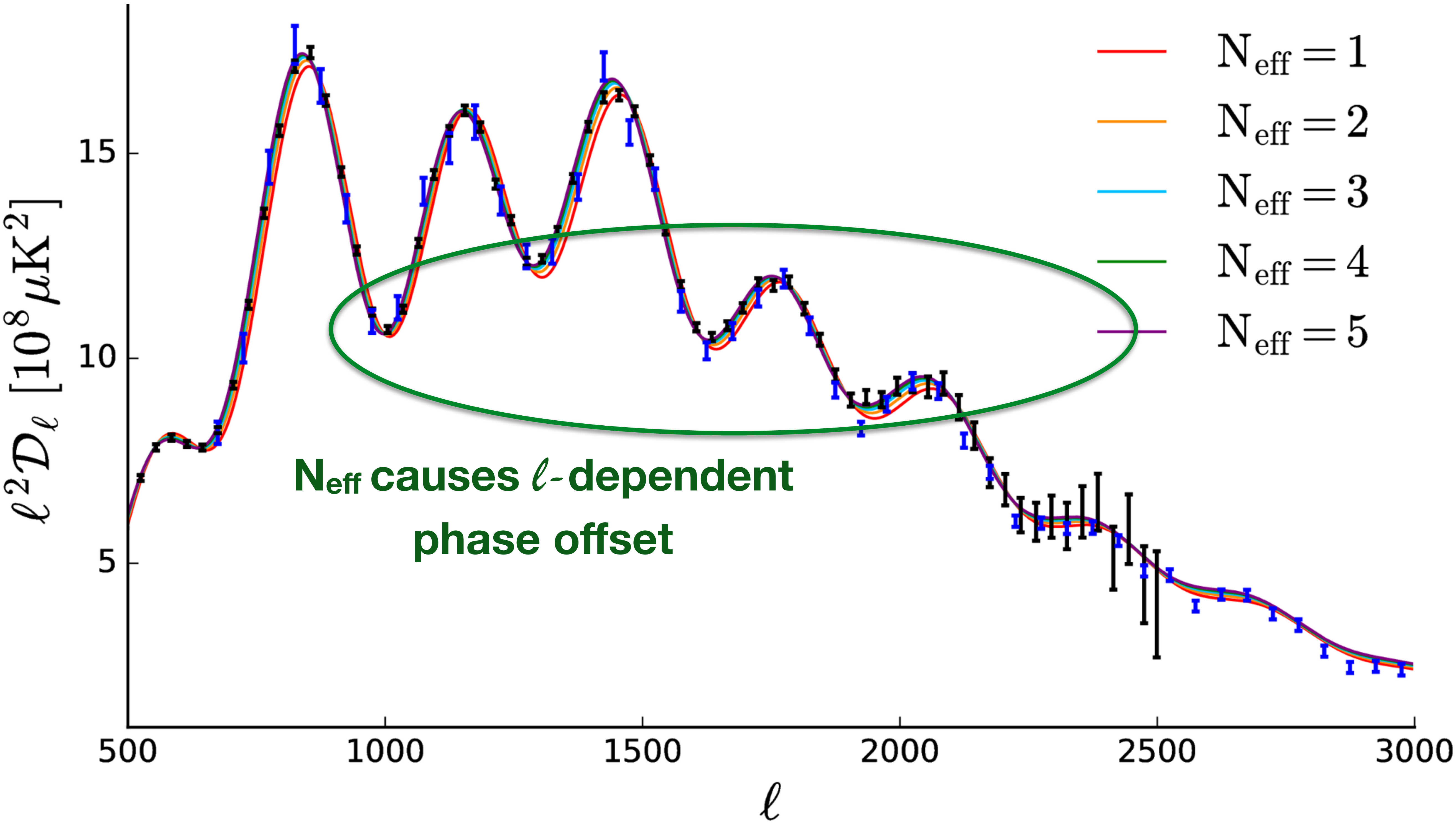
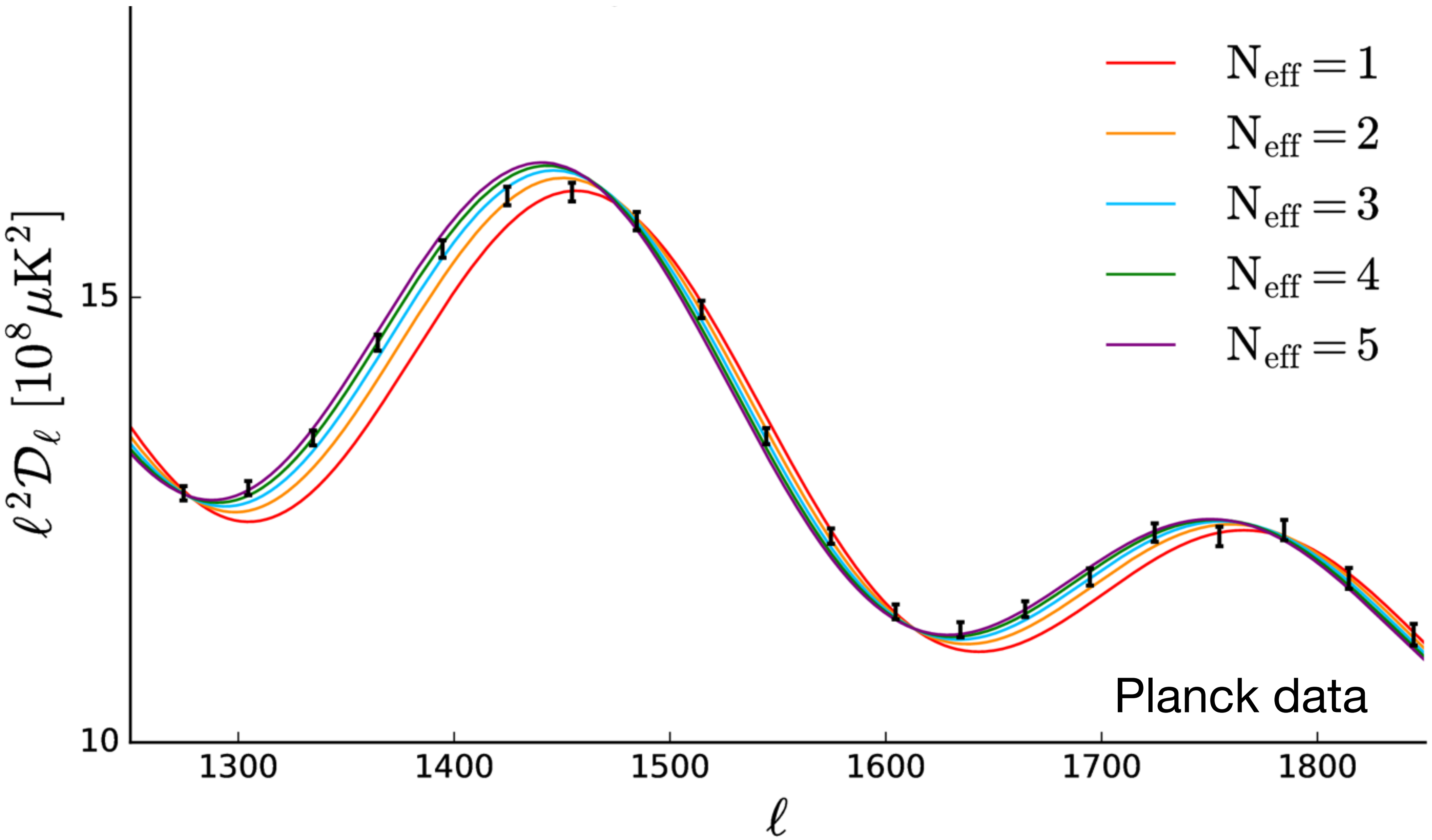


Phasing of peaks breaks helium fraction & N_{eff} degeneracy

Keep θ_d constant with N_{eff} by increasing helium fraction, Y_P



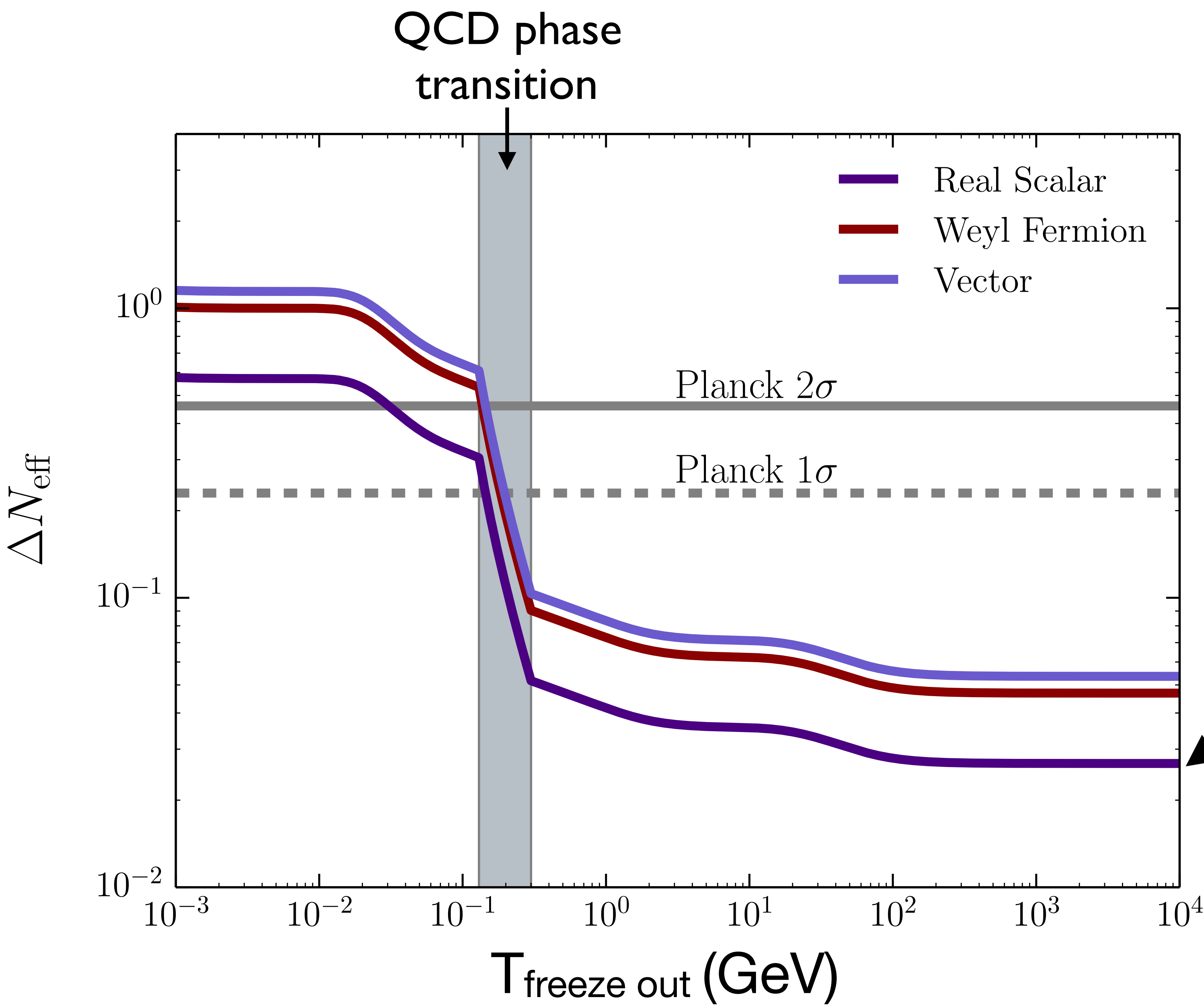
N_{eff} causes ℓ-dependent phase offset

$N_{eff} = 3.15 \pm 0.23$ (along BBN consistency curve)

$N_{eff} = 3.14 \pm 0.44$ (marginalizing over Y_P)

Highly significant detection of neutrino background

N_{eff} constraints and light thermal relics

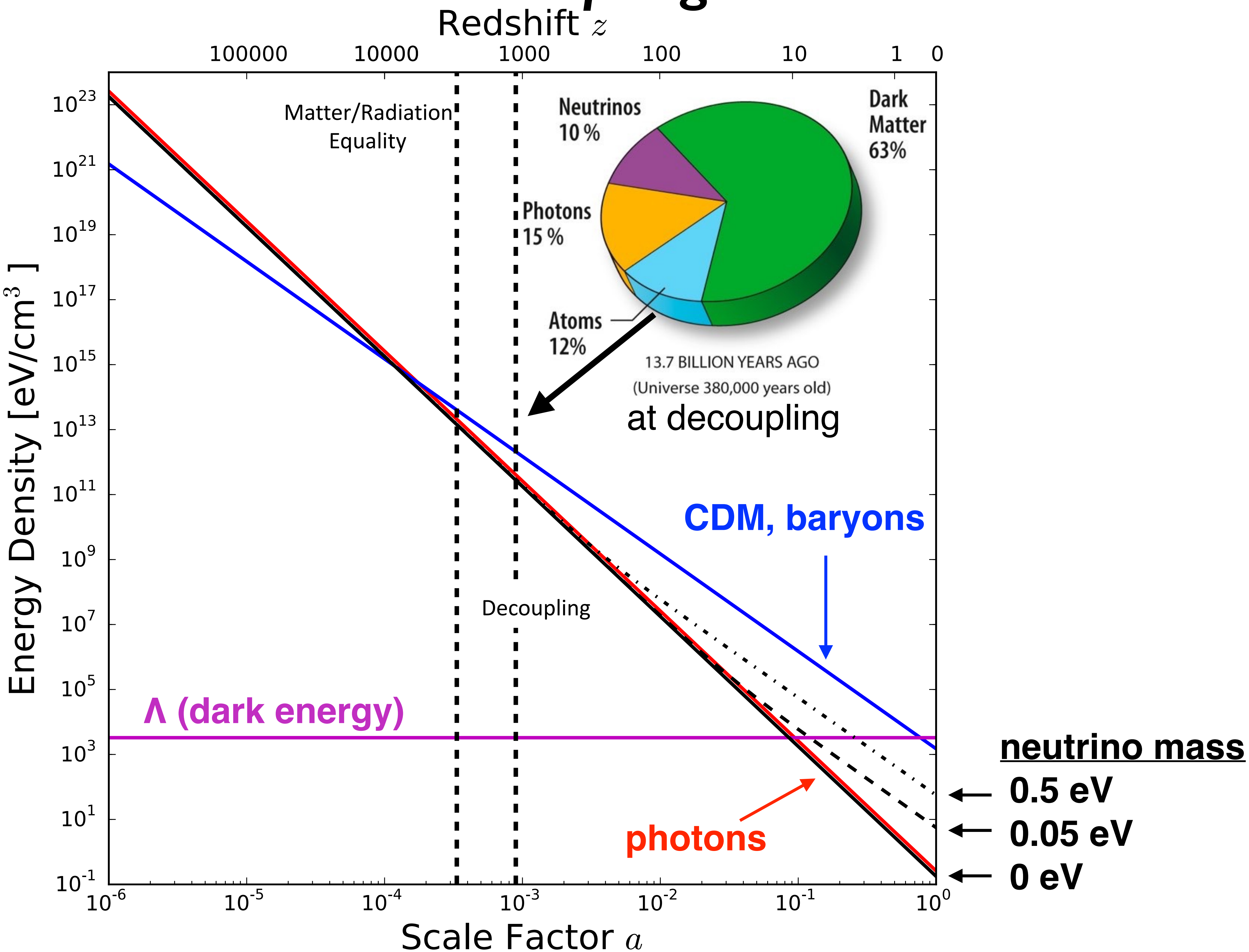


N_{eff} measurements constrain light thermal relics

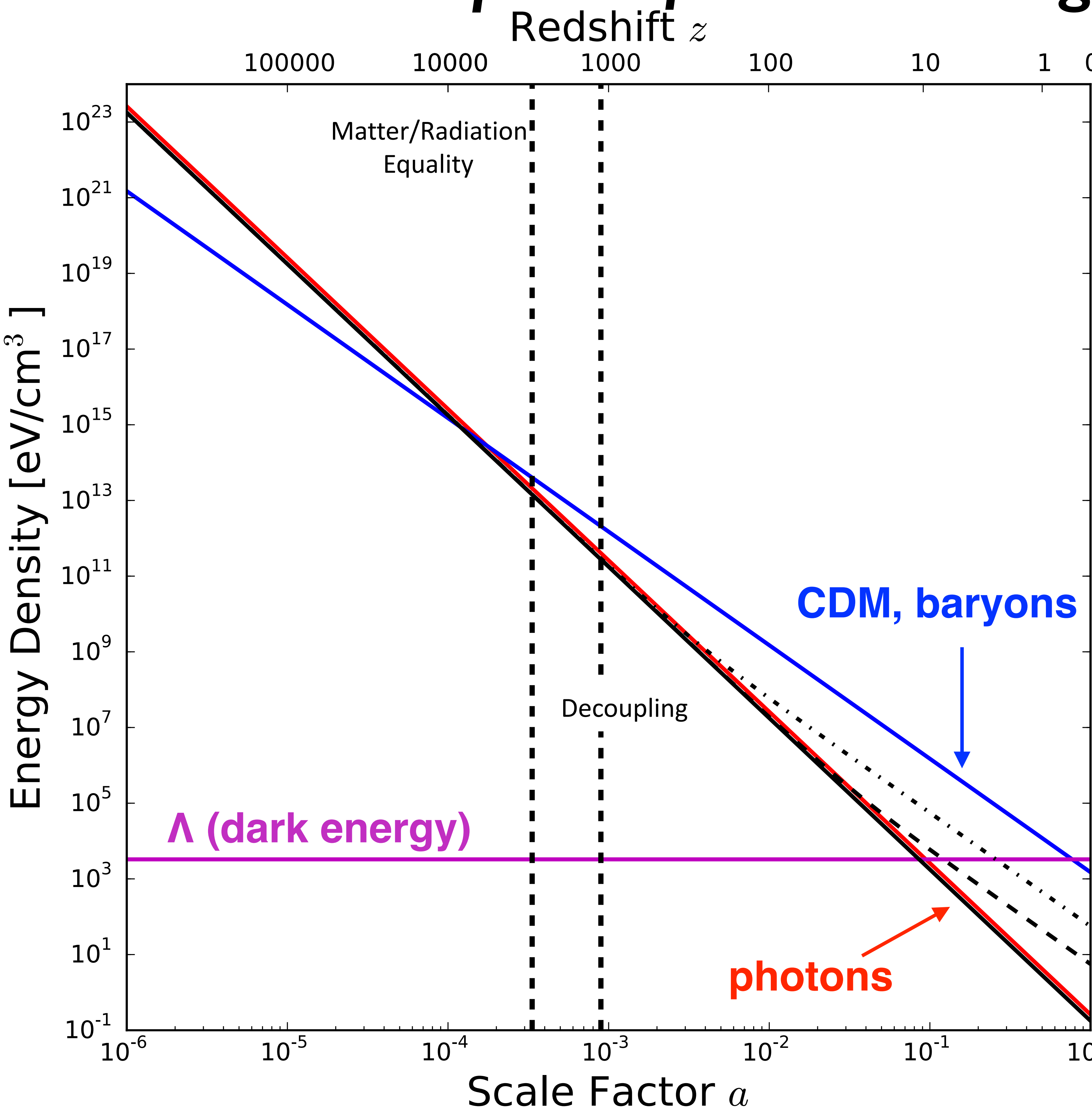
Sets natural, and exceedingly challenging, target of $\Delta N_{eff} = 0.027$ for a relic scalar, 0.054 for a vector.

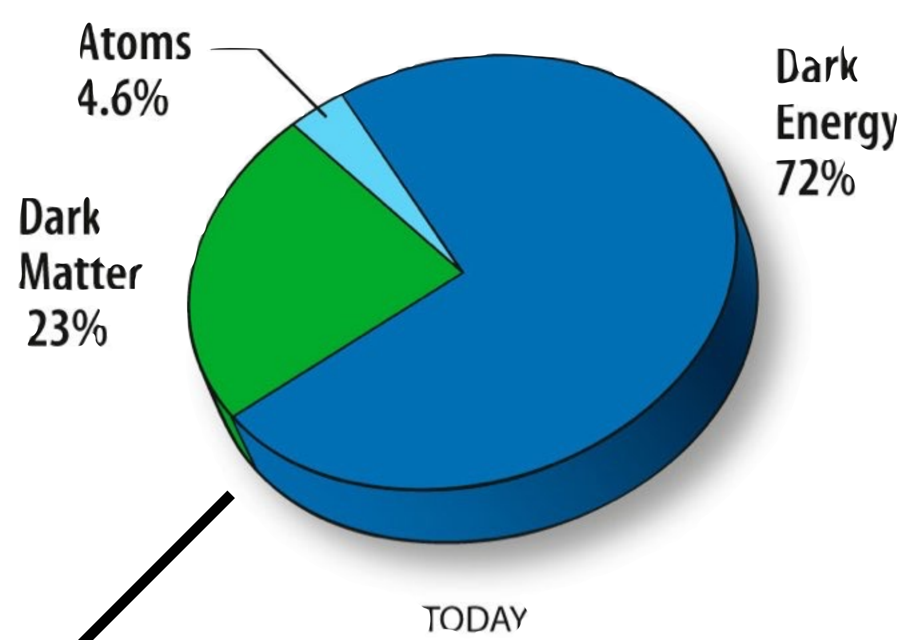
Green, Meyers in CMB-S4 Science Book (http://CMB-S4.org)
also see Baumann, Green, Wallisch "A New Target for Cosmic Axion Searches" arXiv:1604.08614

Neutrinos
- relativistic at decoupling



Neutrinos
- transition to part of matter budget today





Matter power spectrum

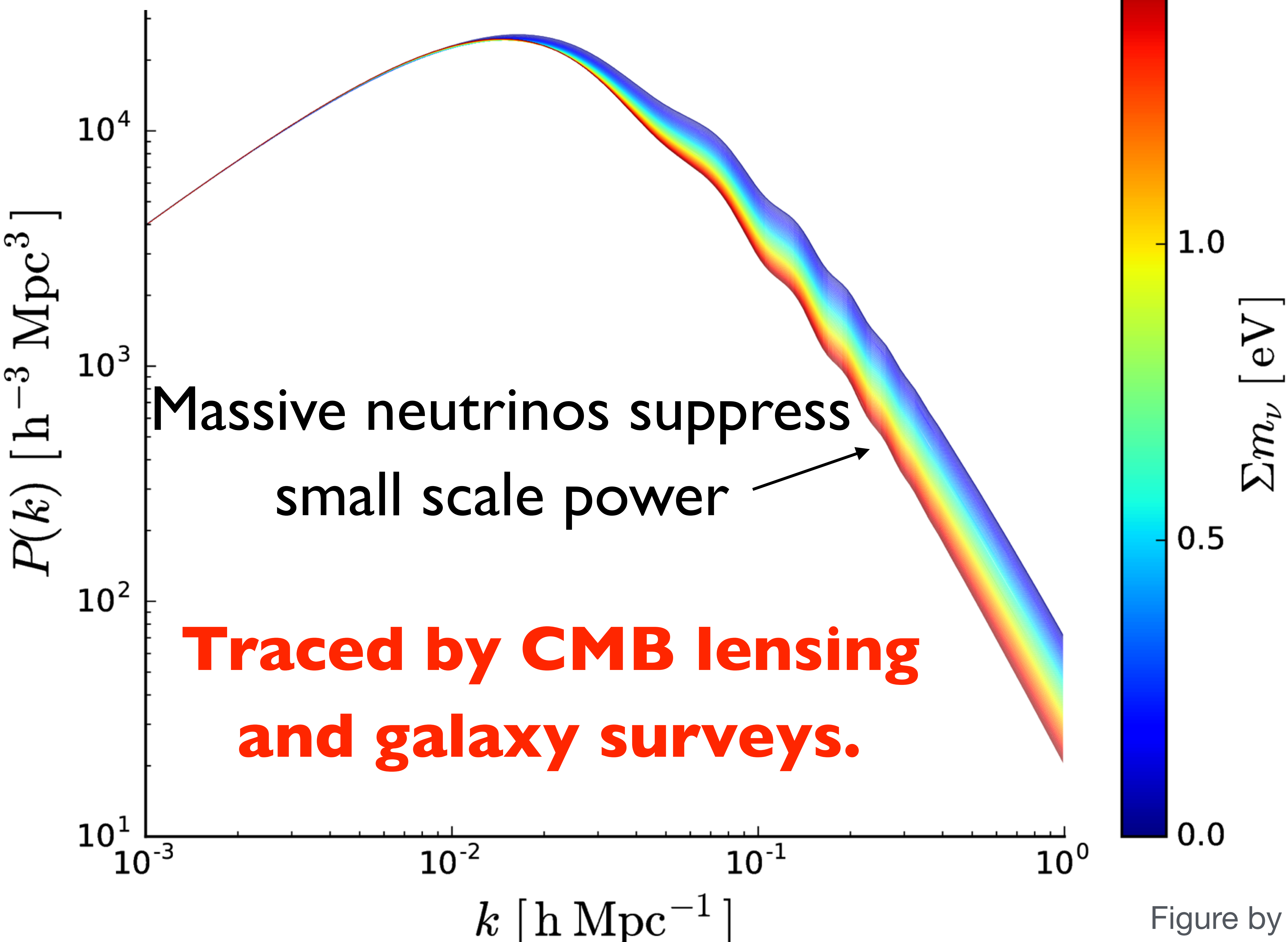
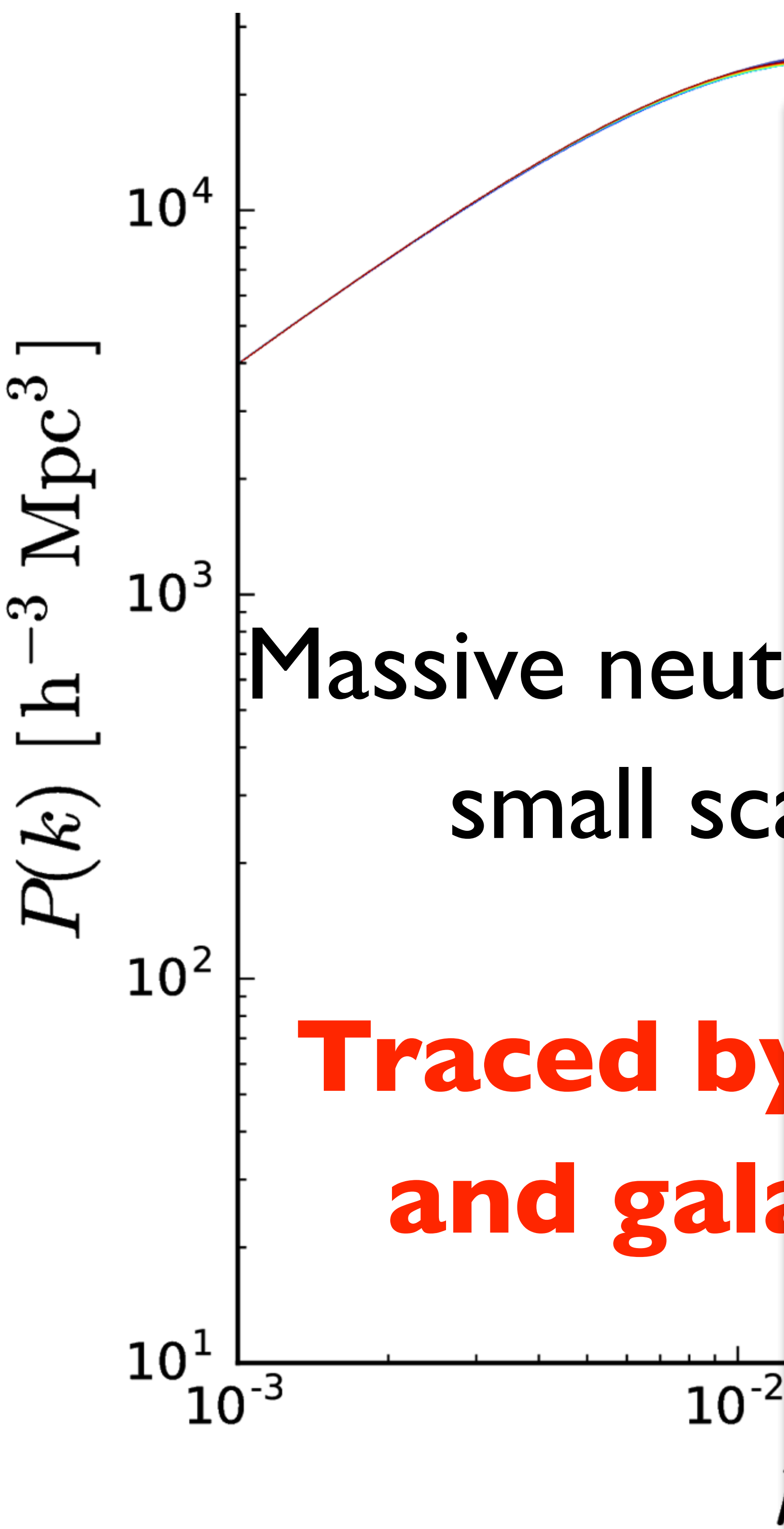


Figure by Zhen Hou

Matter power spectrum

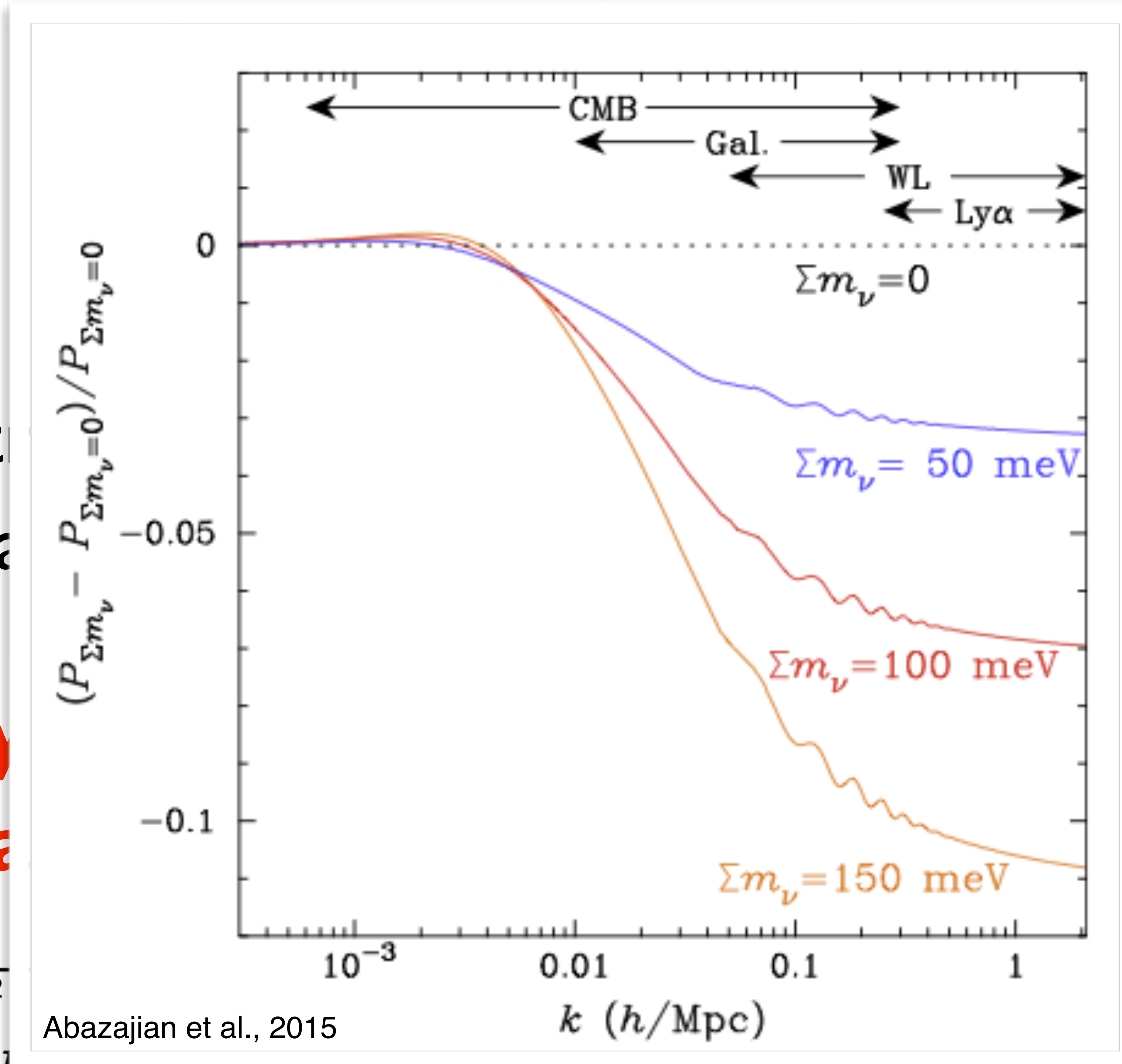


Massive neut

small sca

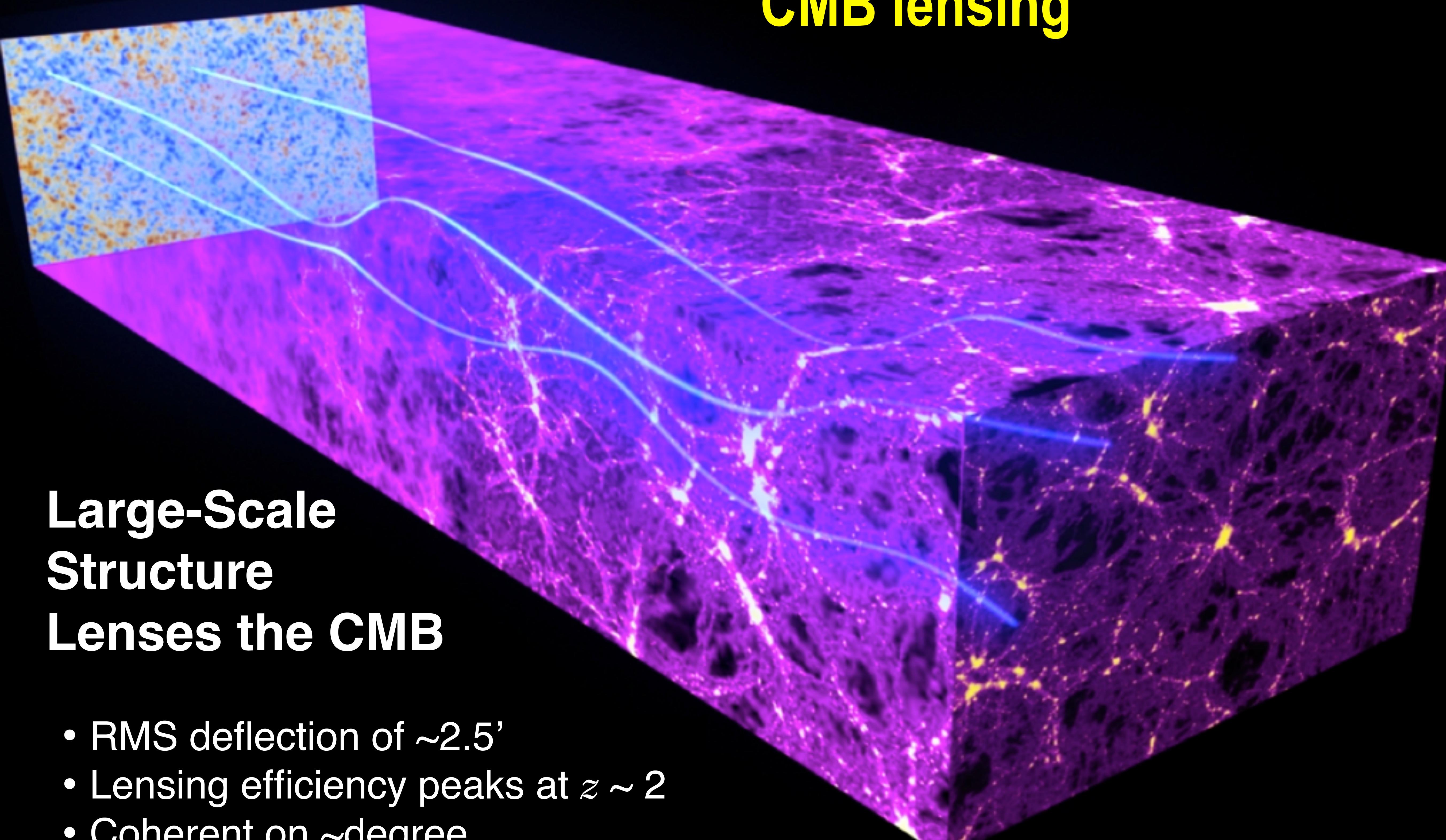
Traced by

and gala



Abazajian et al., 2015

CMB lensing



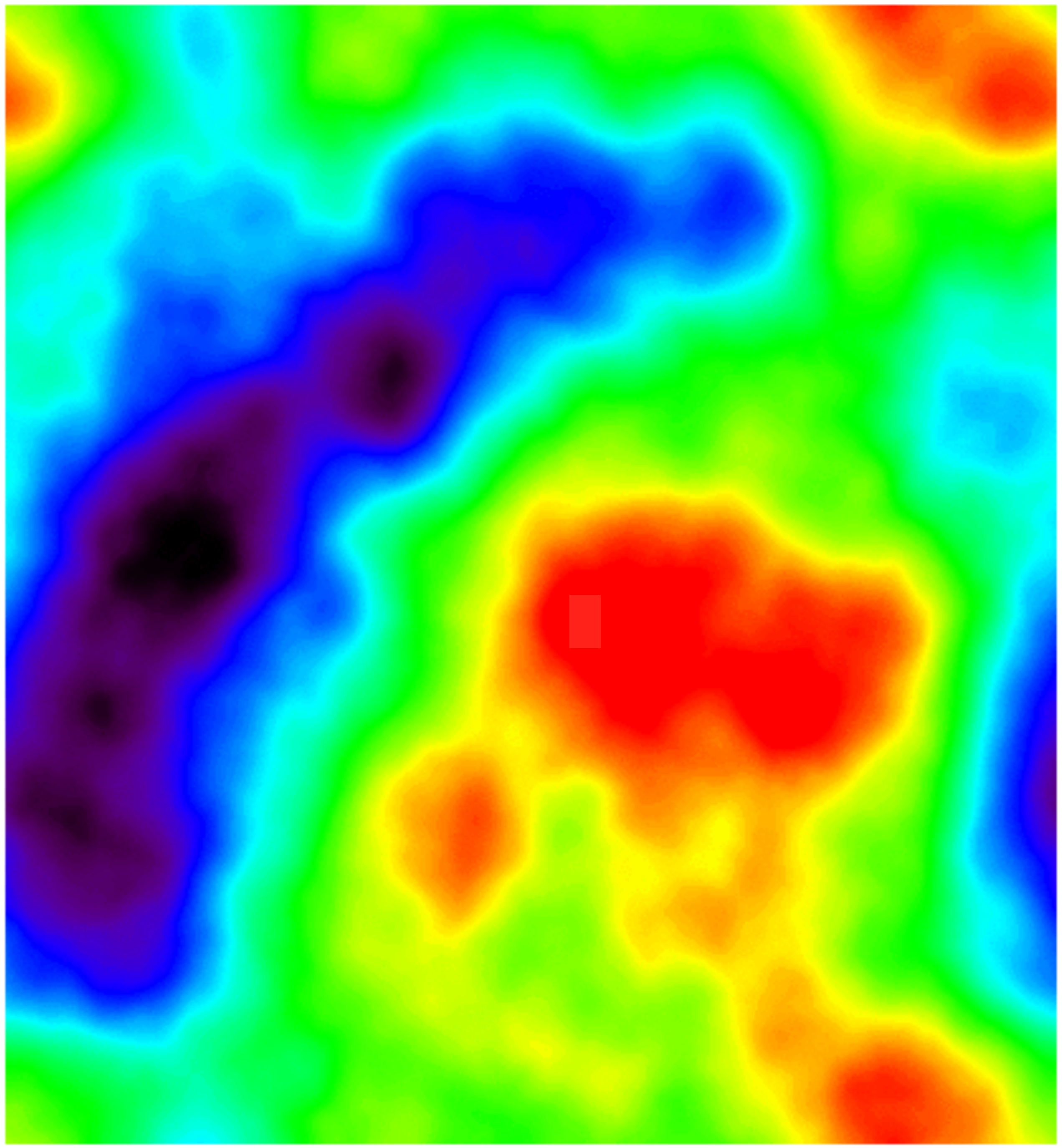
Large-Scale Structure Lenses the CMB

- RMS deflection of ~2.5’
- Lensing efficiency peaks at $z \sim 2$
- Coherent on ~degree (~300 Mpc) scales

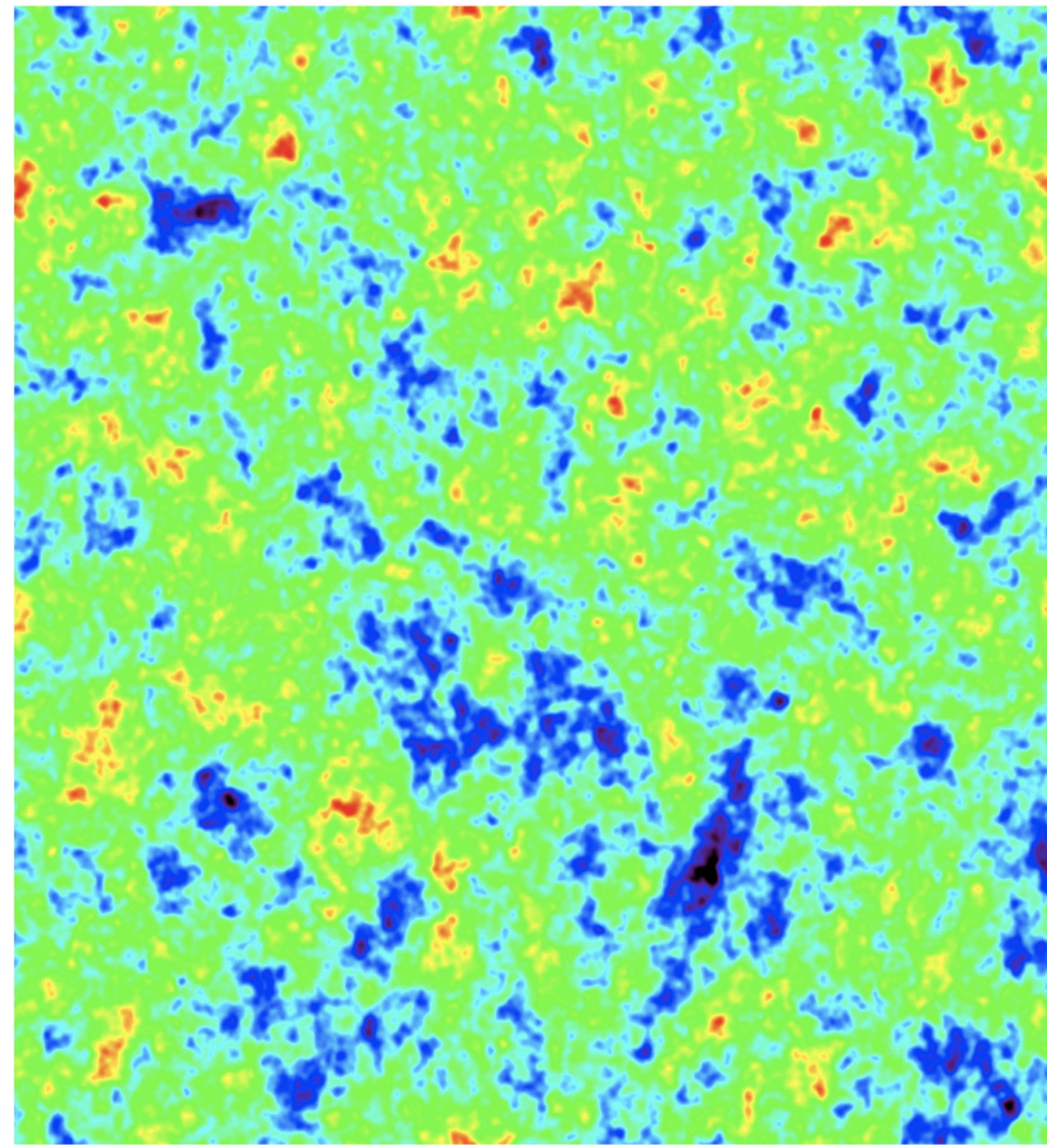
graphic from ESA website

Lensing of the CMB

17°x17°



lensing potential

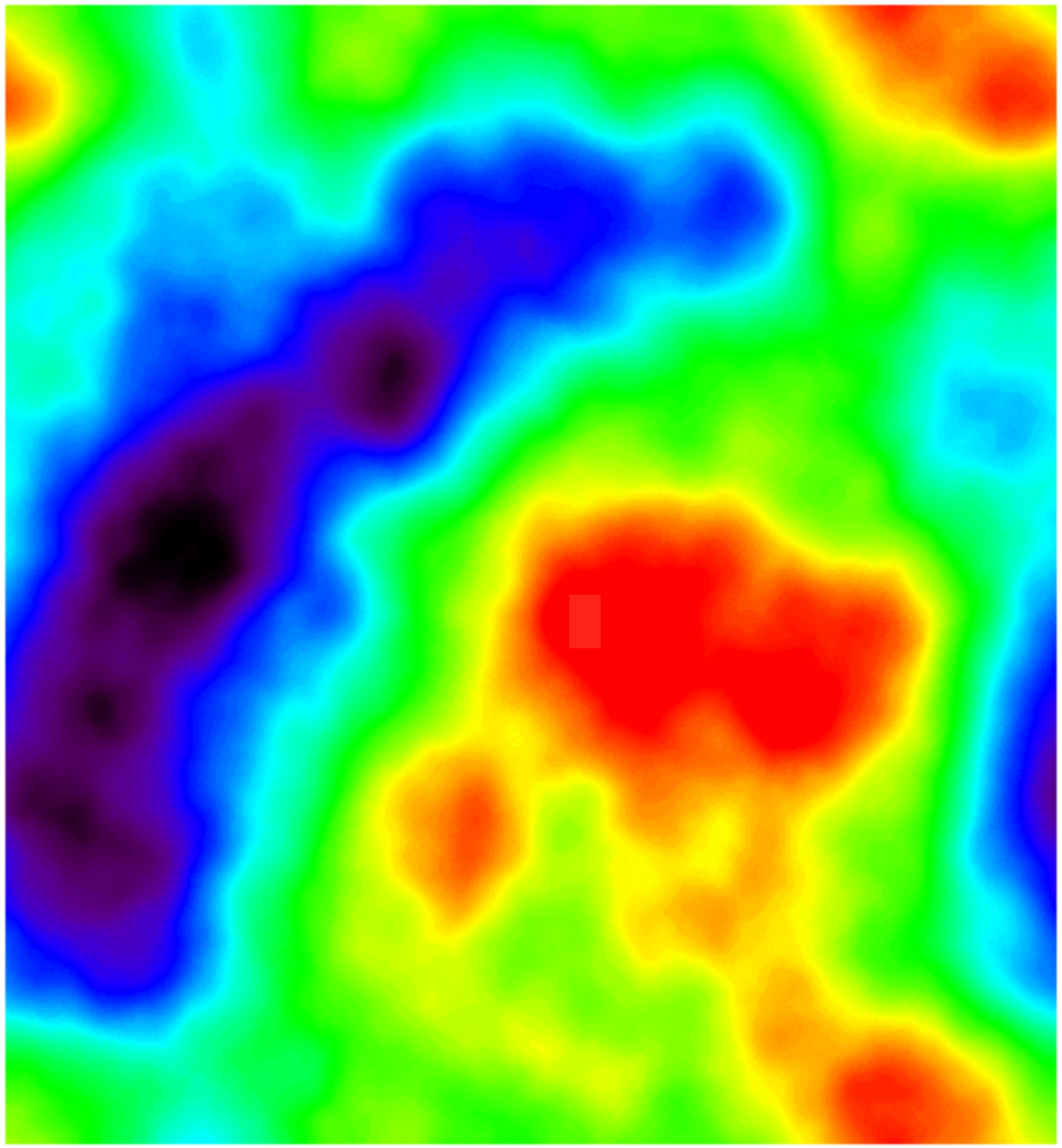


unlensed cmb

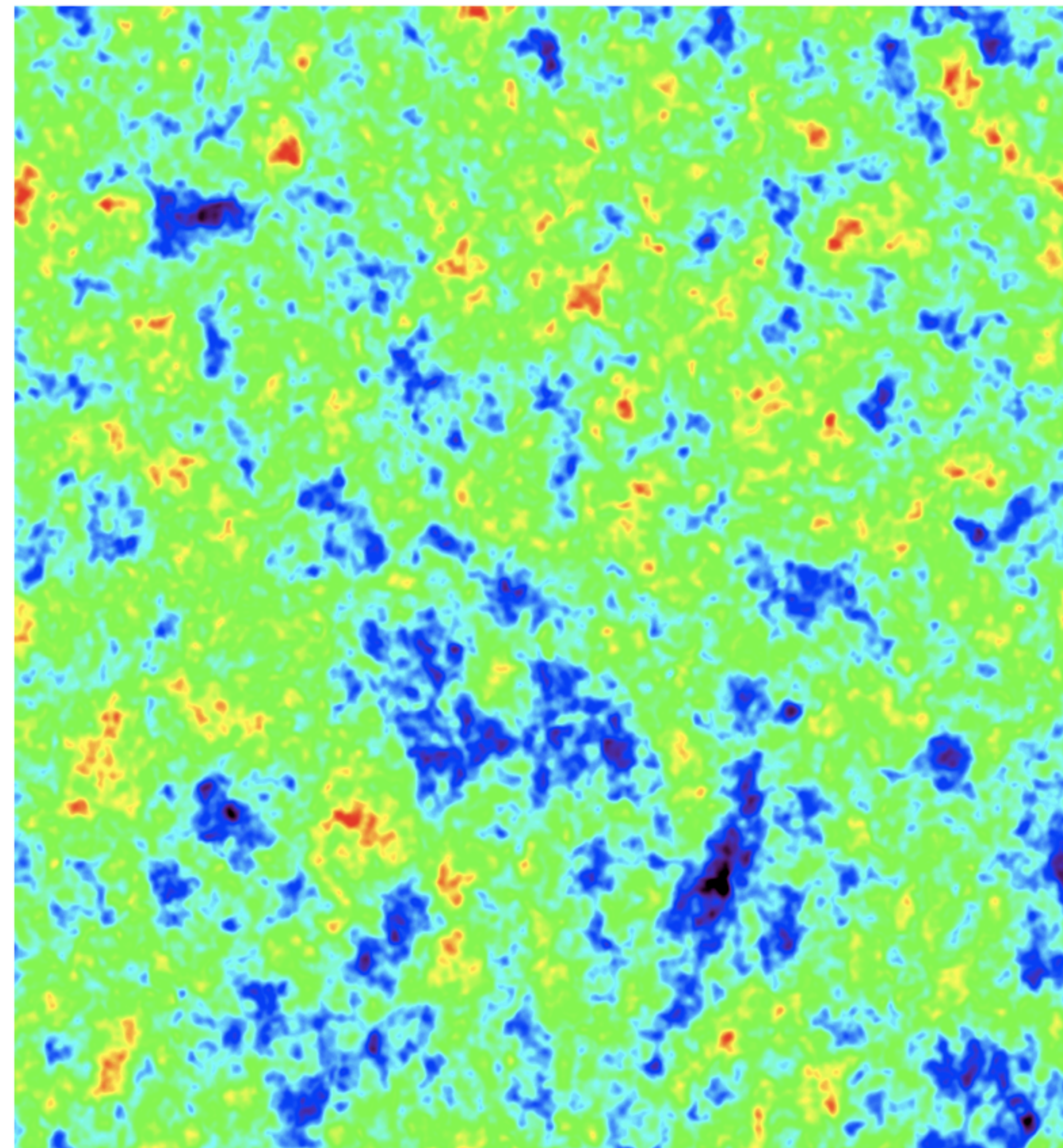
from Alex van Engelen

Lensing of the CMB

17°x17°



lensing potential

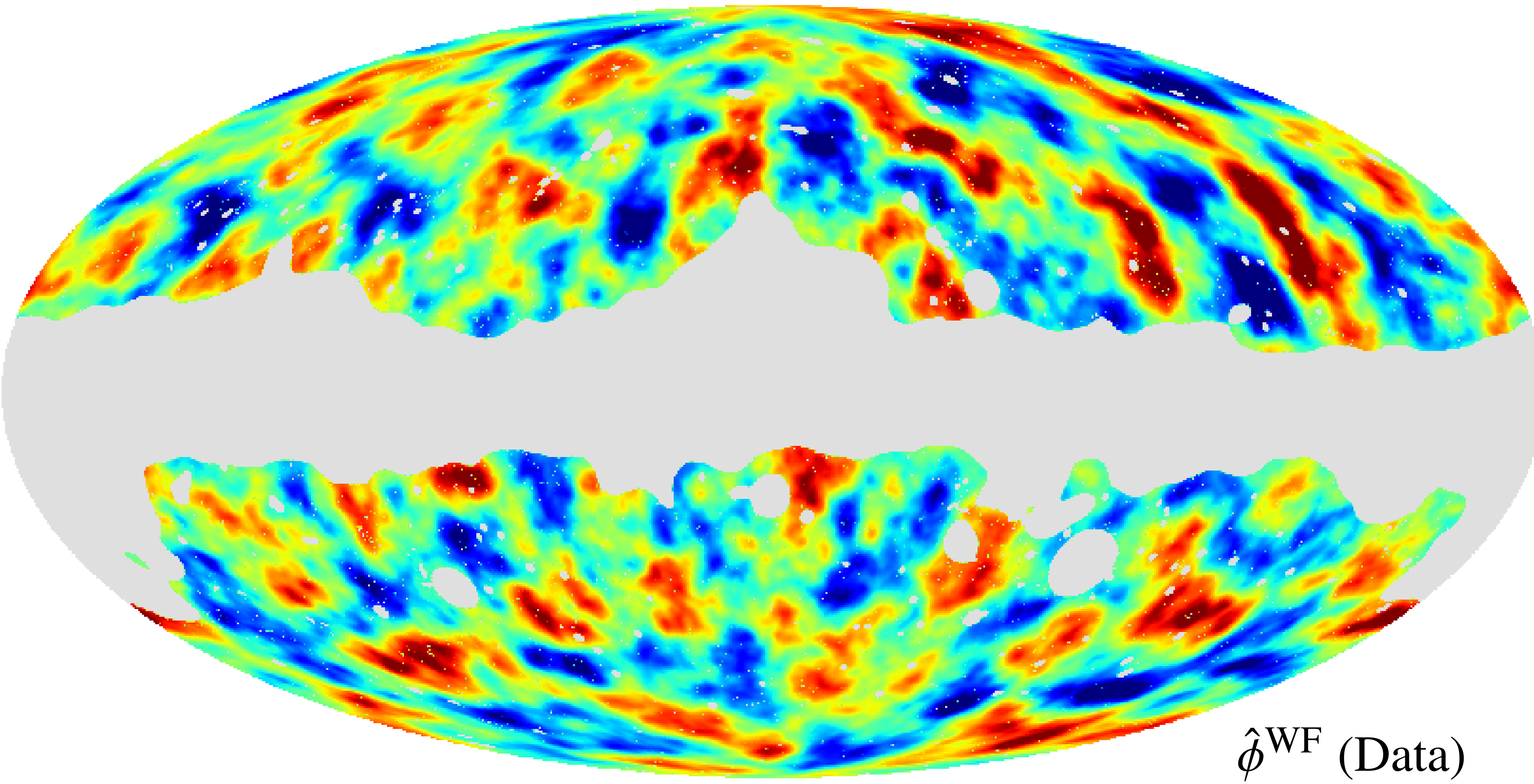


lensed cmb

from Alex van Engelen

CMB lensing

Planck lensing potential reconstruction (projected mass map).



Planck XV arXiv:1502.01591

CMB lensing

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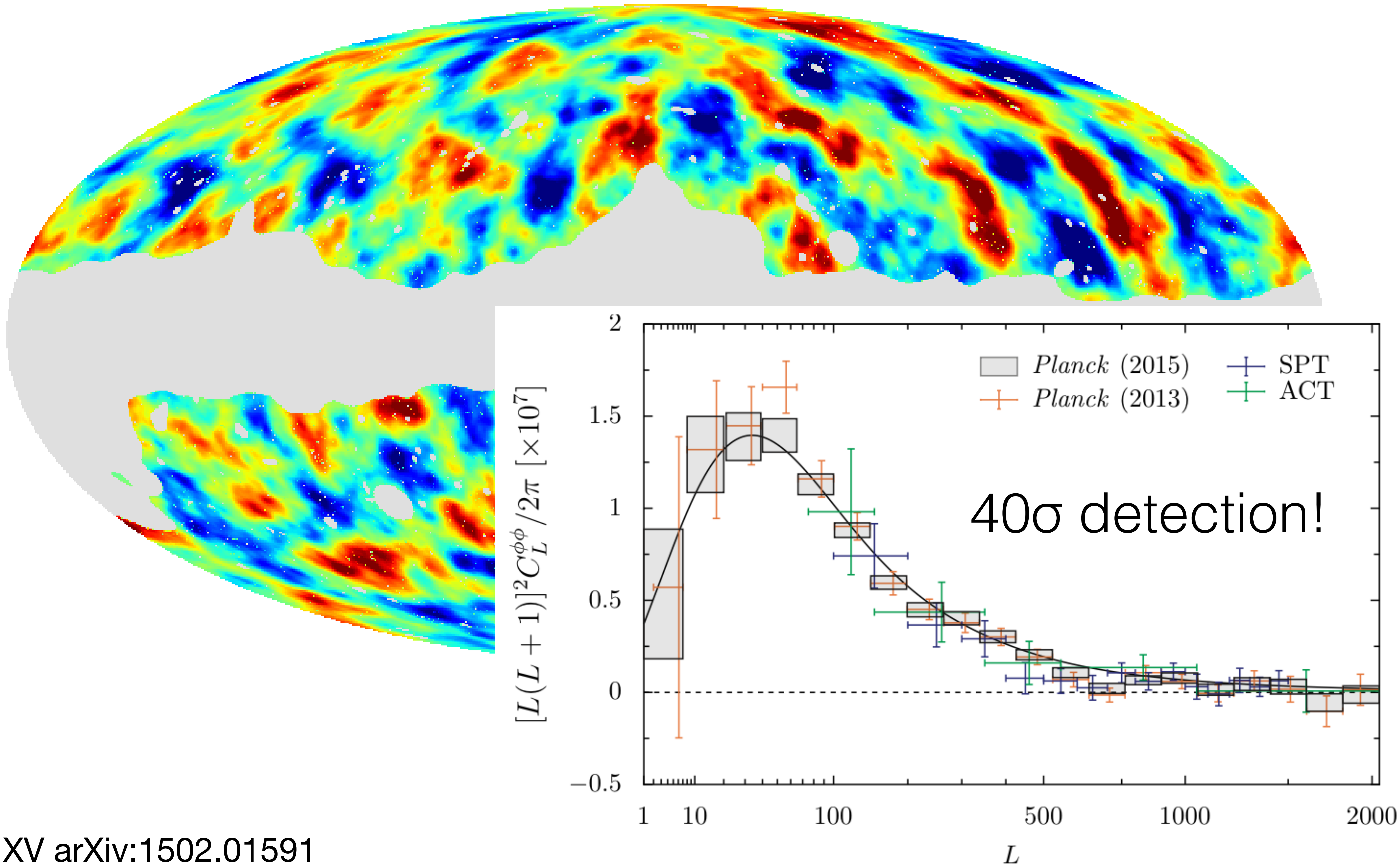
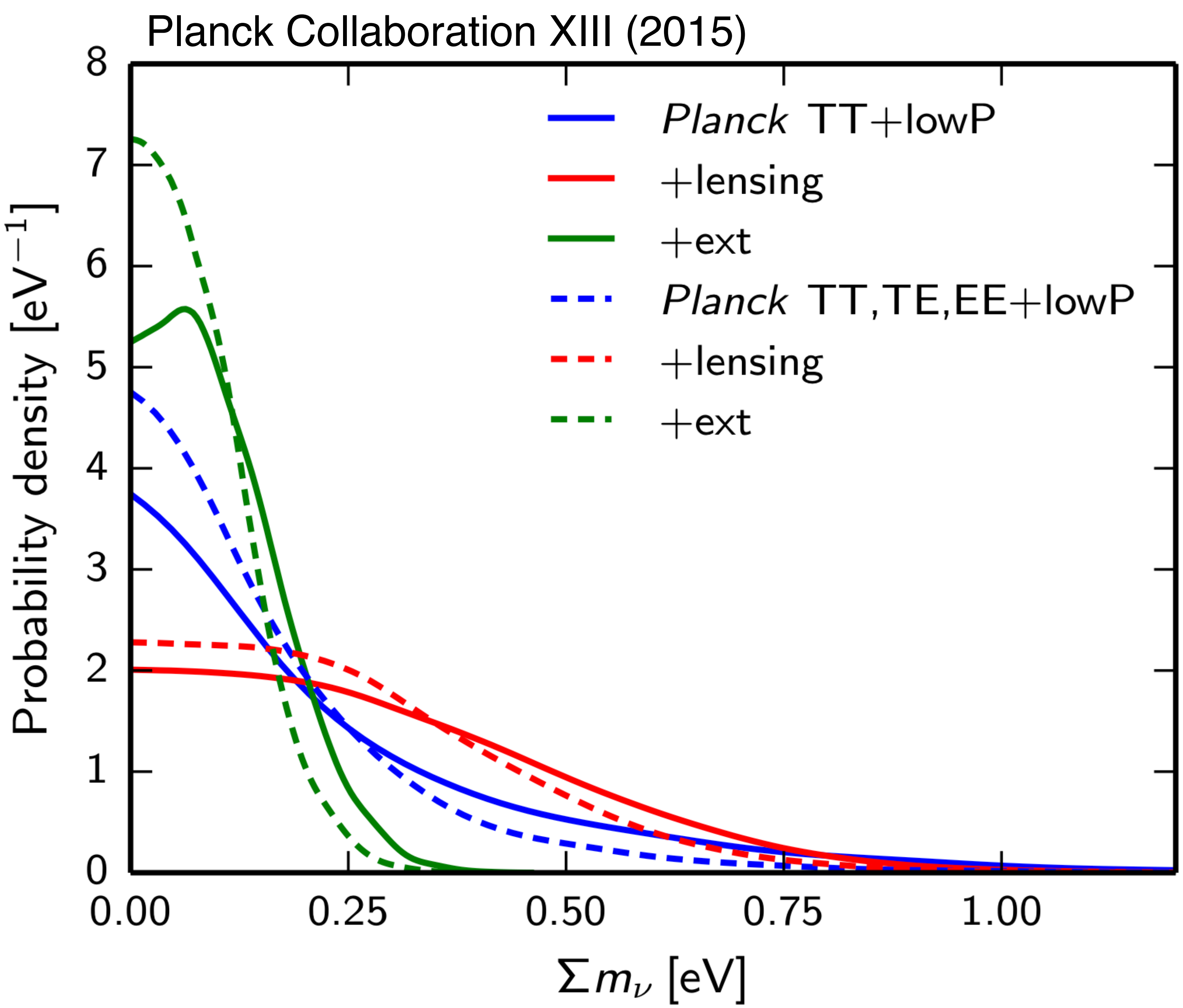


Planck XV arXiv:1502.01591

Cosmological Neutrino Mass Constraints



CMB alone:

$\Sigma m_\nu < 0.59$ eV at 95% c.l.

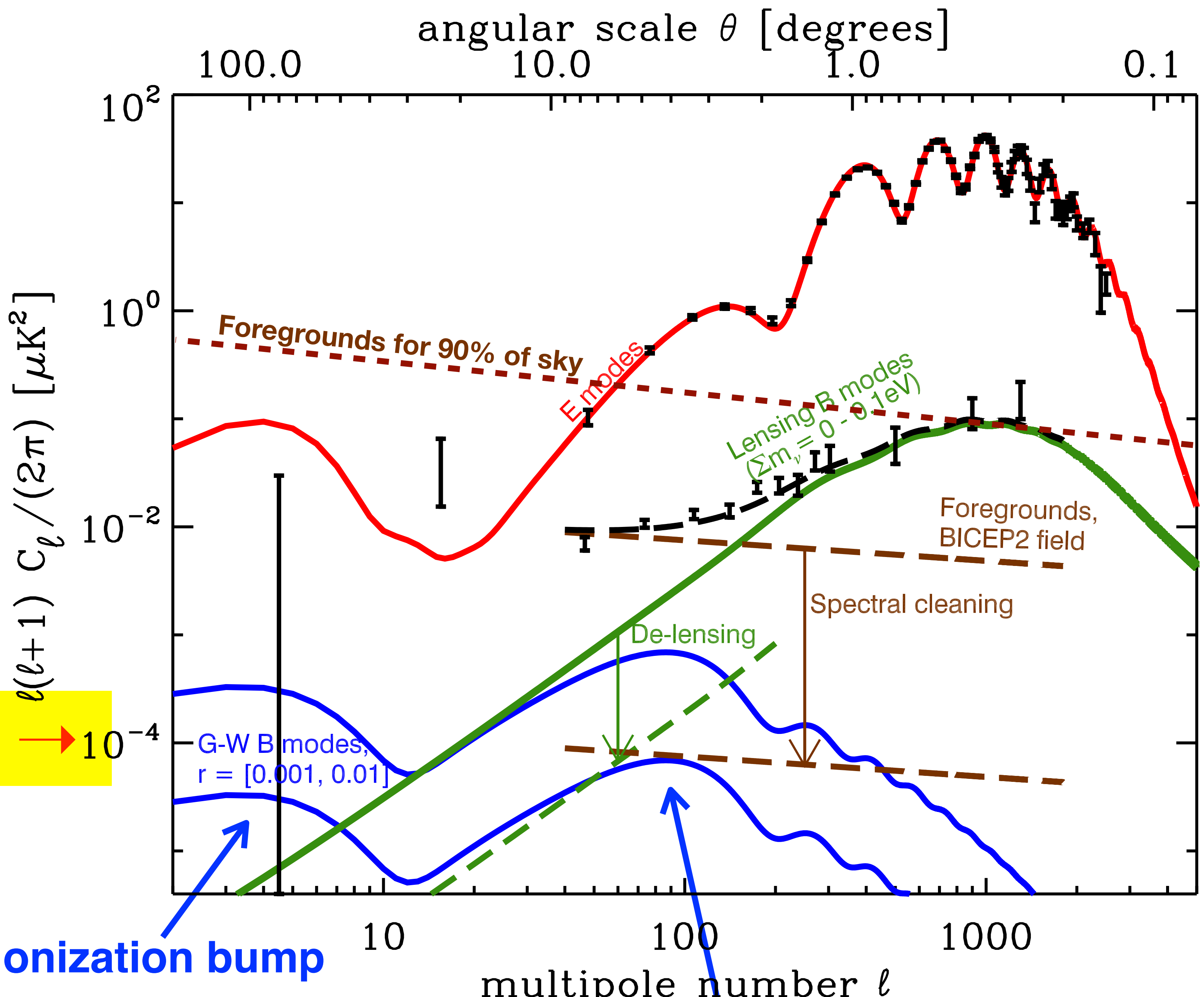
Including other cosmological data:

$\Sigma m_\nu < 0.23$ eV at 95% c.l.

Joint Σm_ν and N_{eff} fit:

$$\left.\begin{array}{l} N_{eff} = 3.2 \pm 0.5 \\ \Sigma m_\nu < 0.32 \text{ eV} \end{array}\right\} 95\% \text{ c.l.}$$

The path forward is through much more sensitive polarization measurements!



E modes

lensing B modes

inflationary gravity wave B modes

10 nK →

reionization bump

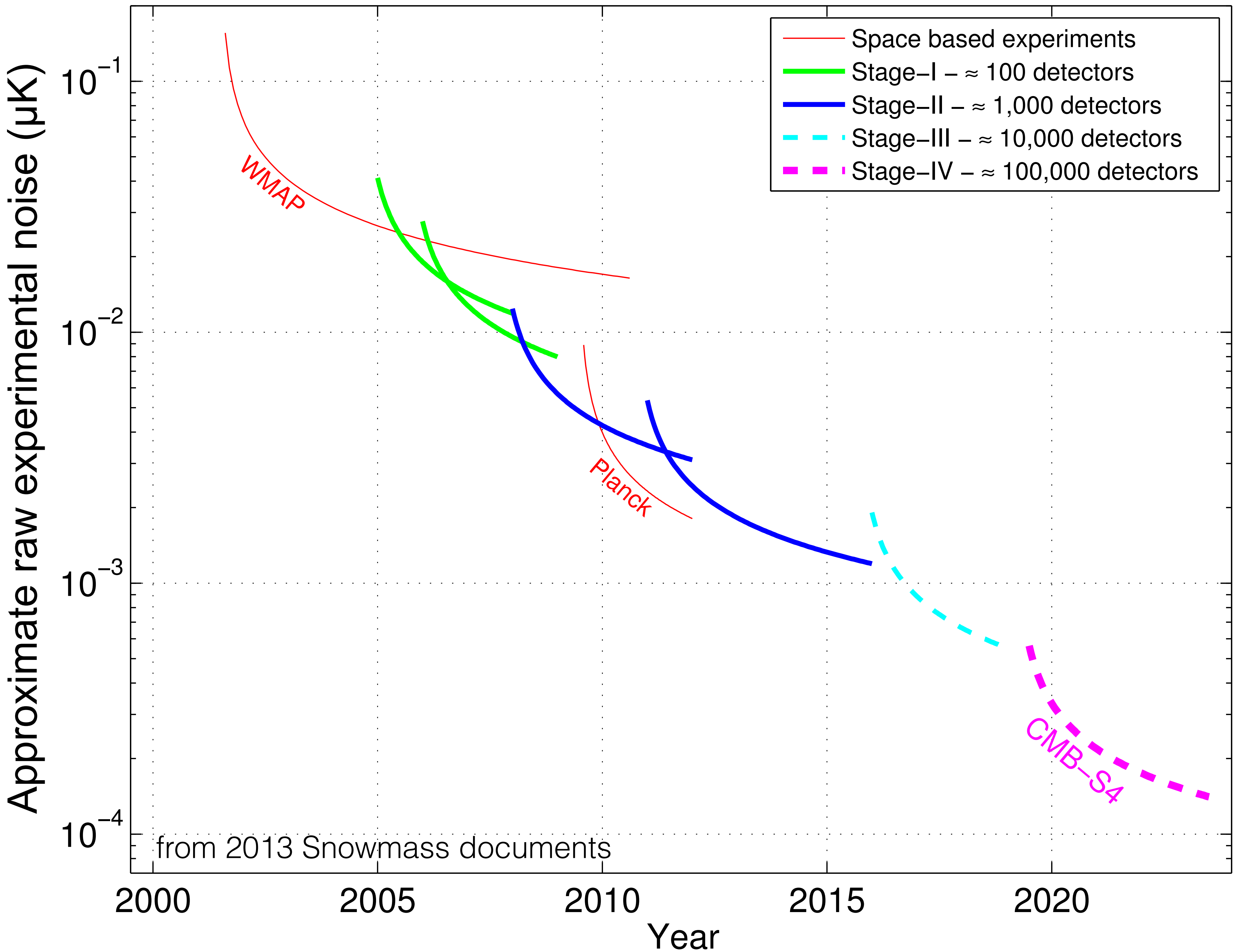
CLASS exploring from the ground;

target of LiteBIRD, PIXIE , CORE satellites proposals

recombination bump

key target of ground experiments, incl. CMB-S4

Detectors are a big challenge,

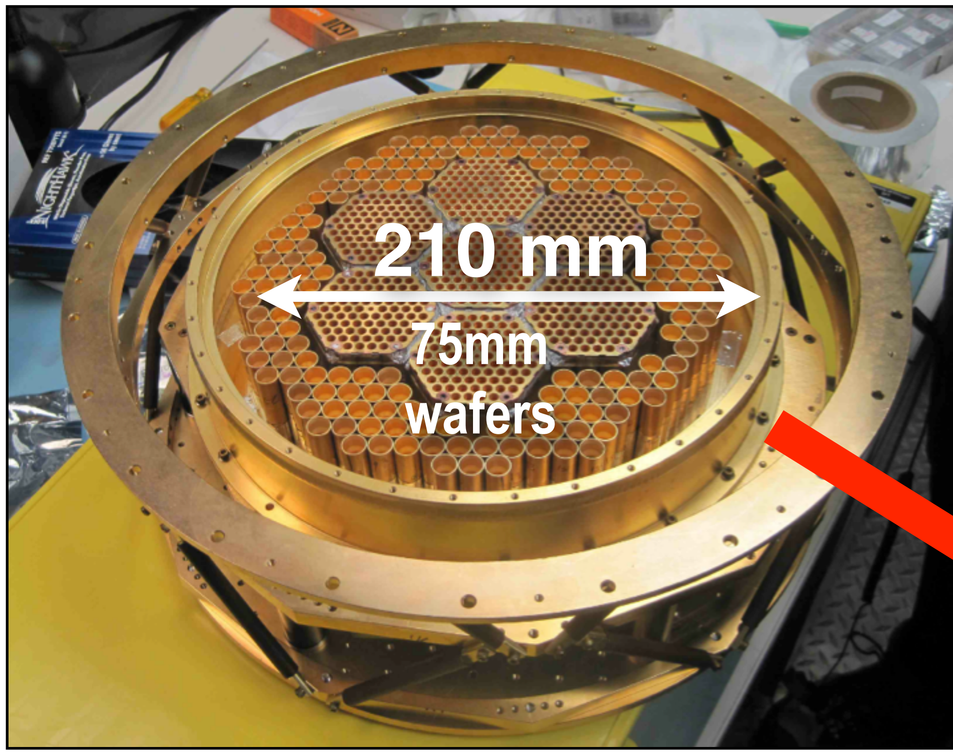


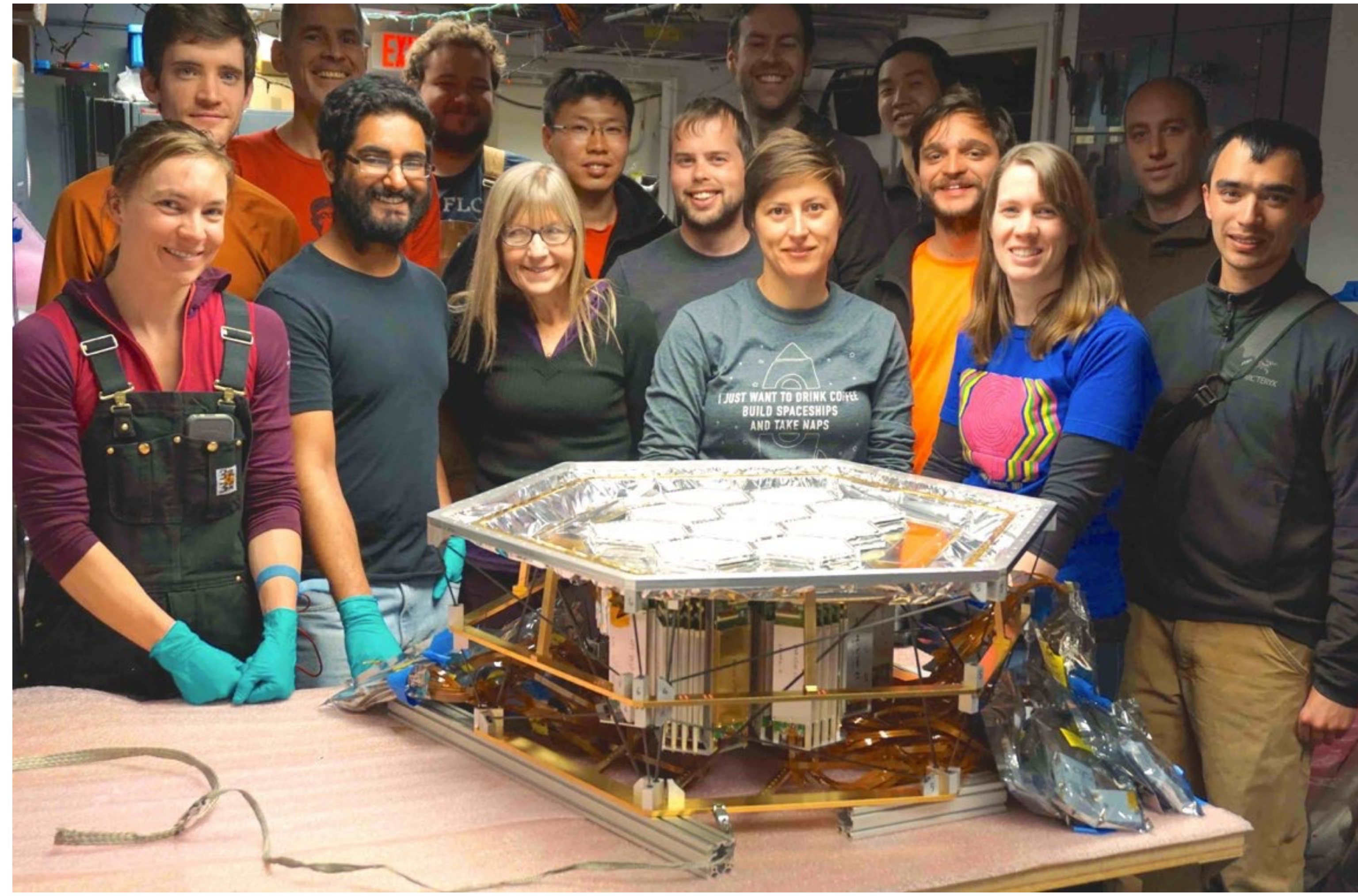
<u>but it will take much more to achieve our goals.</u>

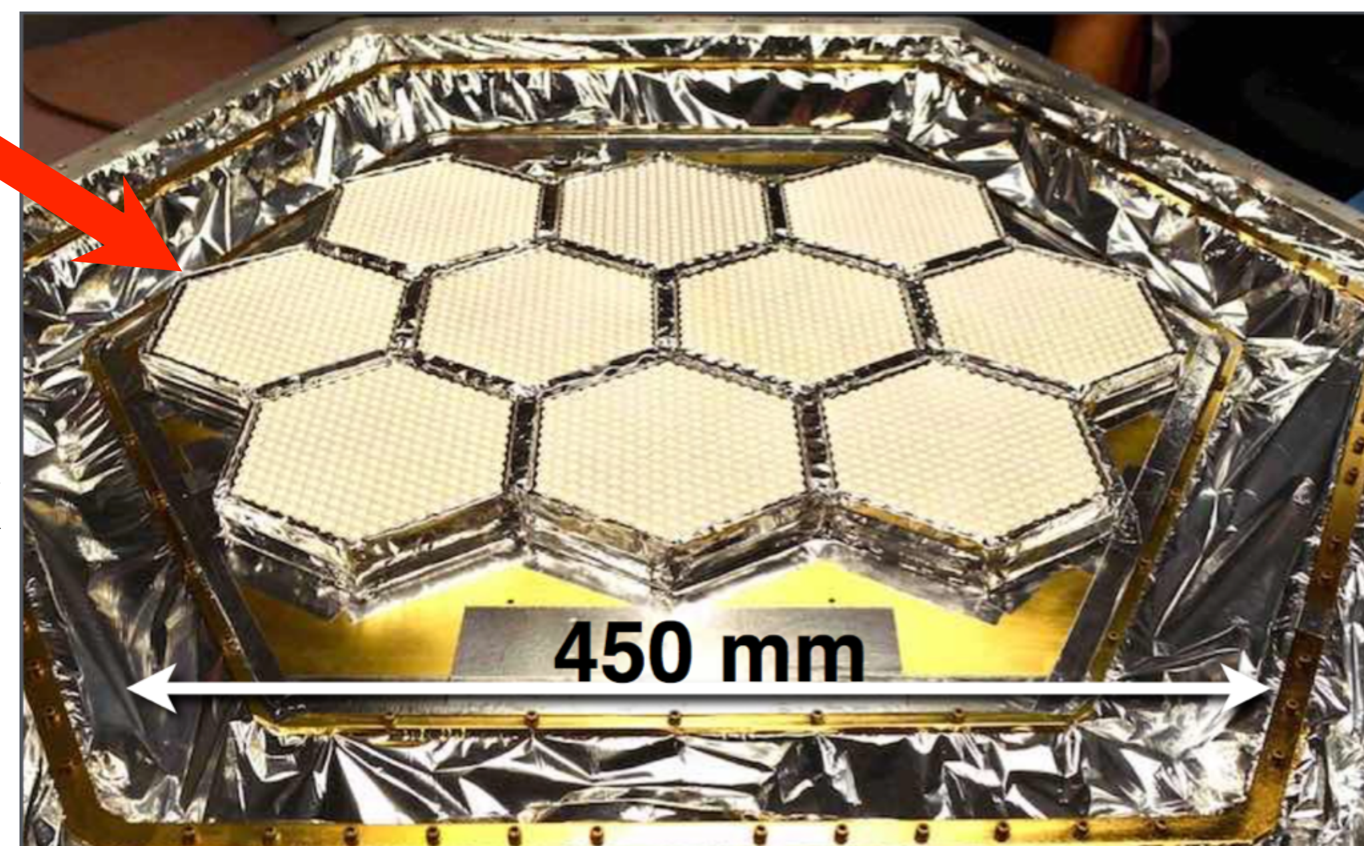
example Stage 2 to Stage 3:

SPTpol → SPT-3G

2012: SPTpol Stage 2
1600 detectors (ANL/NIST)

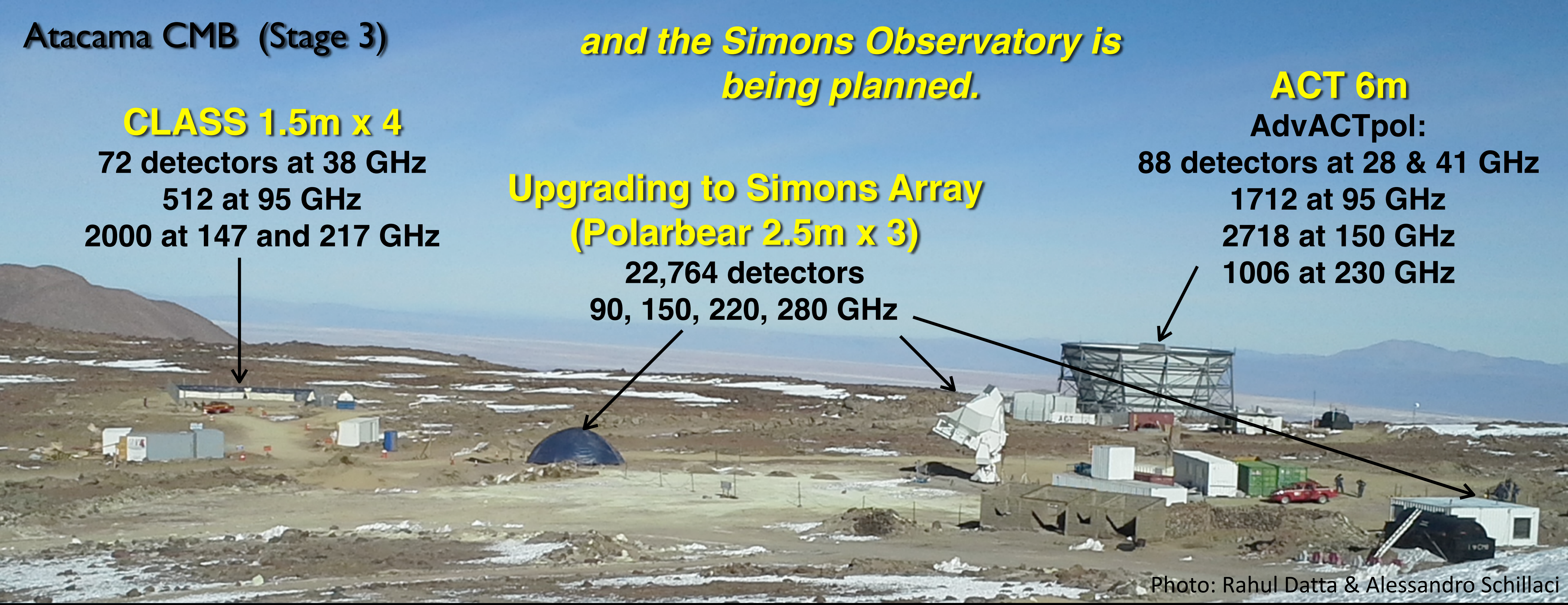




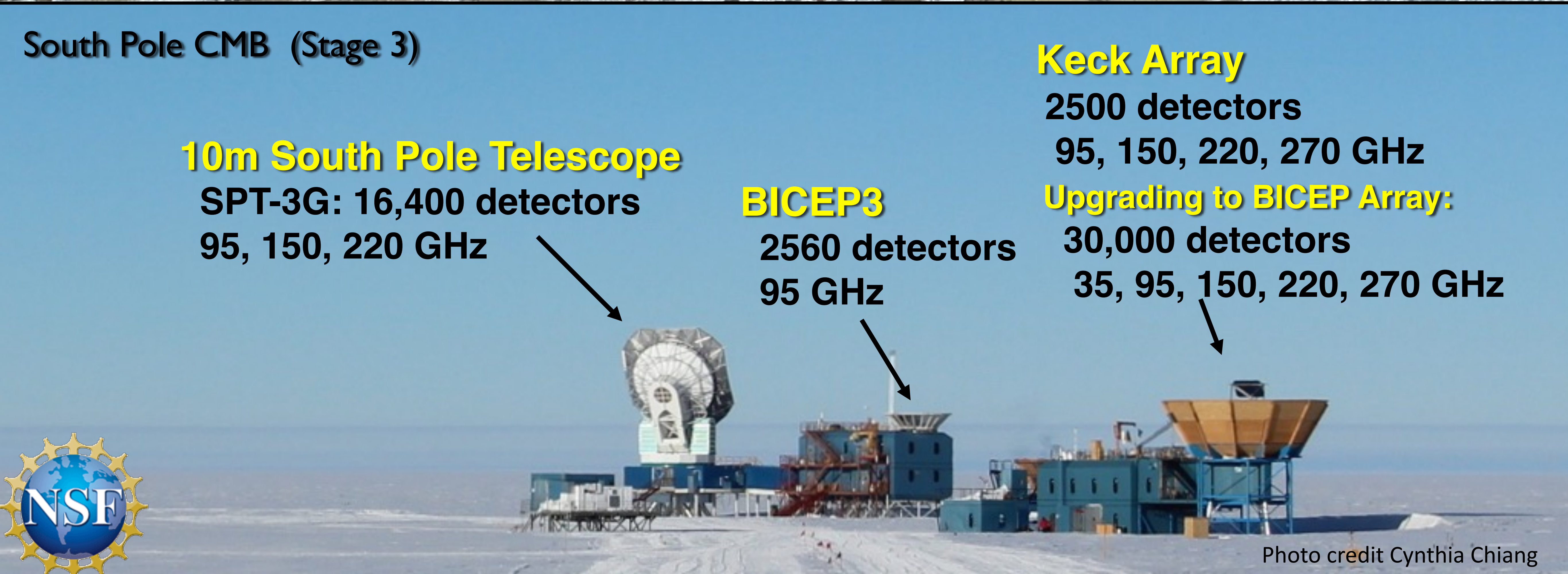


2017: SPT-3G Stage 3 4x larger area
16,000 detectors at T = 250mK

NSF U.S. DEPARTMENT OF ENERGY KAVLI GORDON AND BETTY MOORE FOUNDATION



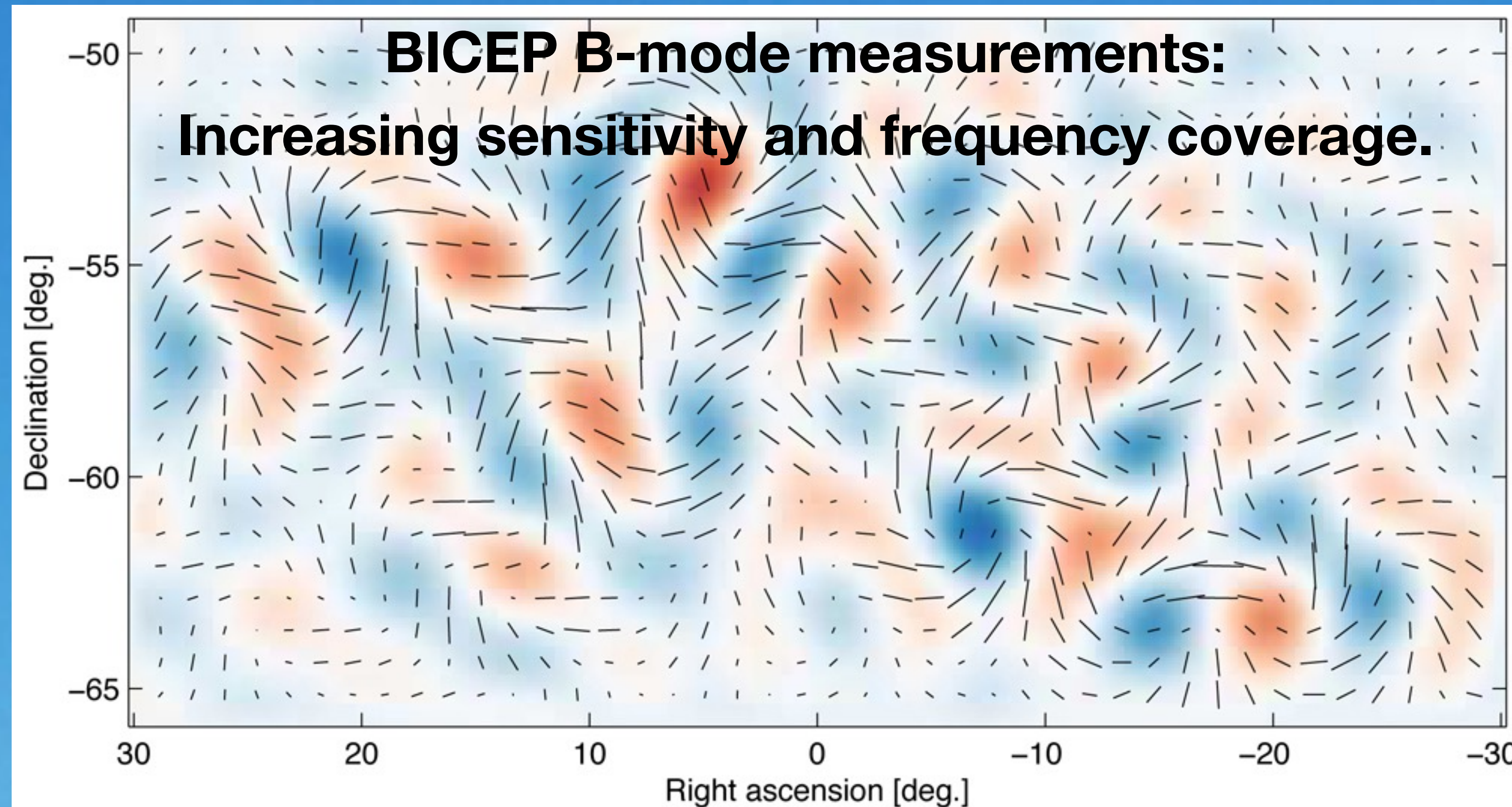
Atacama CMB (Stage 3)
and the Simons Observatory is being planned.
CLASS 1.5m x 4
72 detectors at 38 GHz
512 at 95 GHz
2000 at 147 and 217 GHz
Upgrading to Simons Array
(Polarbear 2.5m x 3)
22,764 detectors
90, 150, 220, 280 GHz
ACT 6m
AdvACTpol:
88 detectors at 28 & 41 GHz
1712 at 95 GHz
2718 at 150 GHz
1006 at 230 GHz
Photo: Rahul Datta & Alessandro Schillaci



South Pole CMB (Stage 3)
Keck Array
2500 detectors
95, 150, 220, 270 GHz
Upgrading to BICEP Array:
30,000 detectors
35, 95, 150, 220, 270 GHz
10m South Pole Telescope
SPT-3G: 16,400 detectors
95, 150, 220 GHz
BICEP3
2560 detectors
95 GHz
Photo credit Cynthia Chiang

		Sensitivity (μK^2)	$\sigma(r)$	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$	Dark Energy F.O.M
2015	Stage 2 1000 detectors				Boss BAO prior	DES+BOSS SPT clusters
2016		$\gtrsim 10^{-5}$	0.035	0.14	0.15eV	~180
2017	Stage 3 10,000 detectors					
2018						
2019					Boss BAO prior	DES + DESI SZ Clusters
2020		10^{-6}	**0.006**	**0.06**	**0.06eV**	~300-600

Stage 3 example: BICEP and SPT



10m South Pole Telescope
SPT-3G: 16,400 detectors
95, 150, 220 GHz

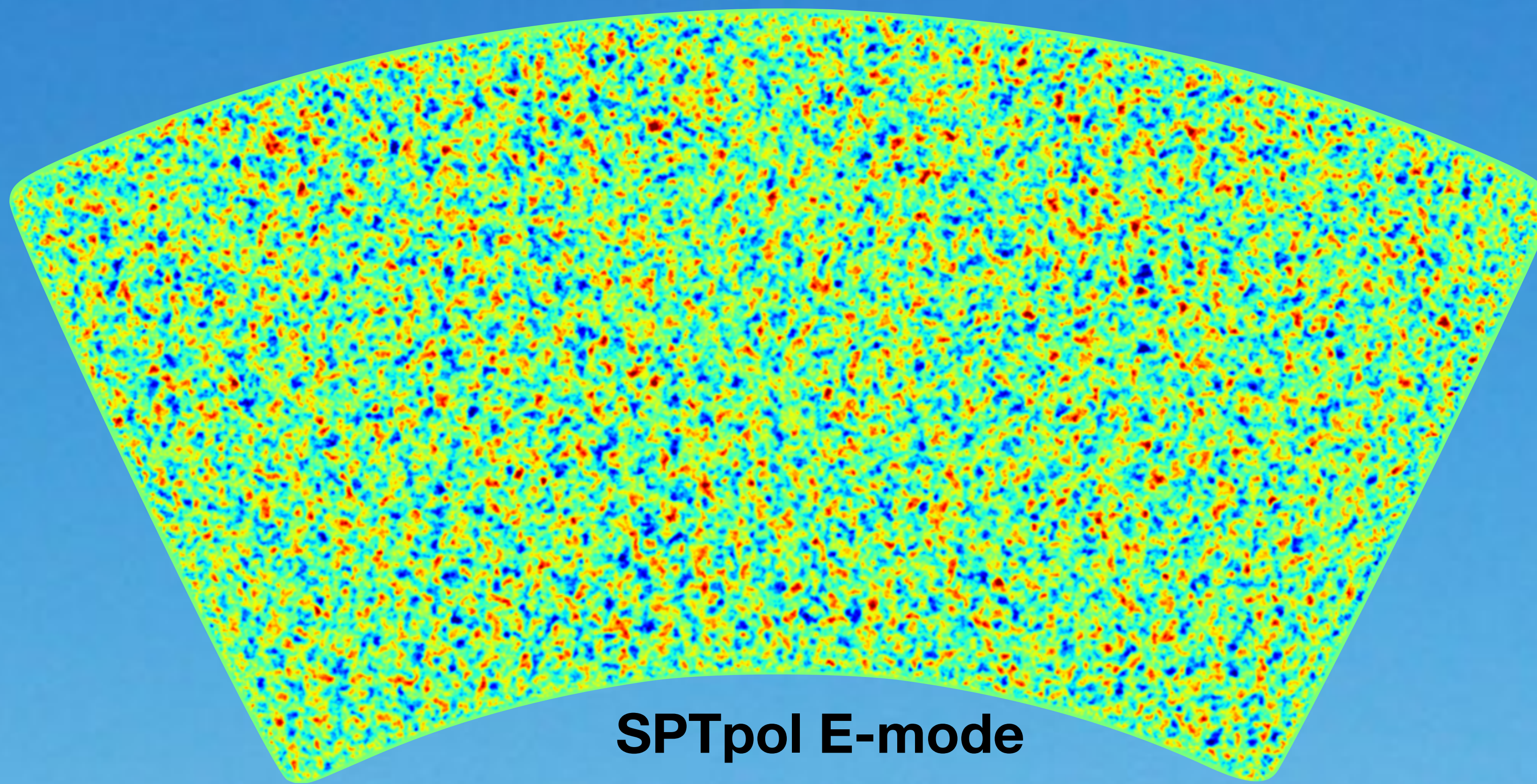
BICEP3
2560 detectors
95 GHz

Keck Array
2500 detectors
95, 150, 220, 270 GHz

Upgrading to BICEP Array:
30,000 detectors
35, 95, 150, 220, 270 GHz

Photo credit Cynthia Chiang

Stage 3 example: BICEP and SPT



SPTpol E-mode

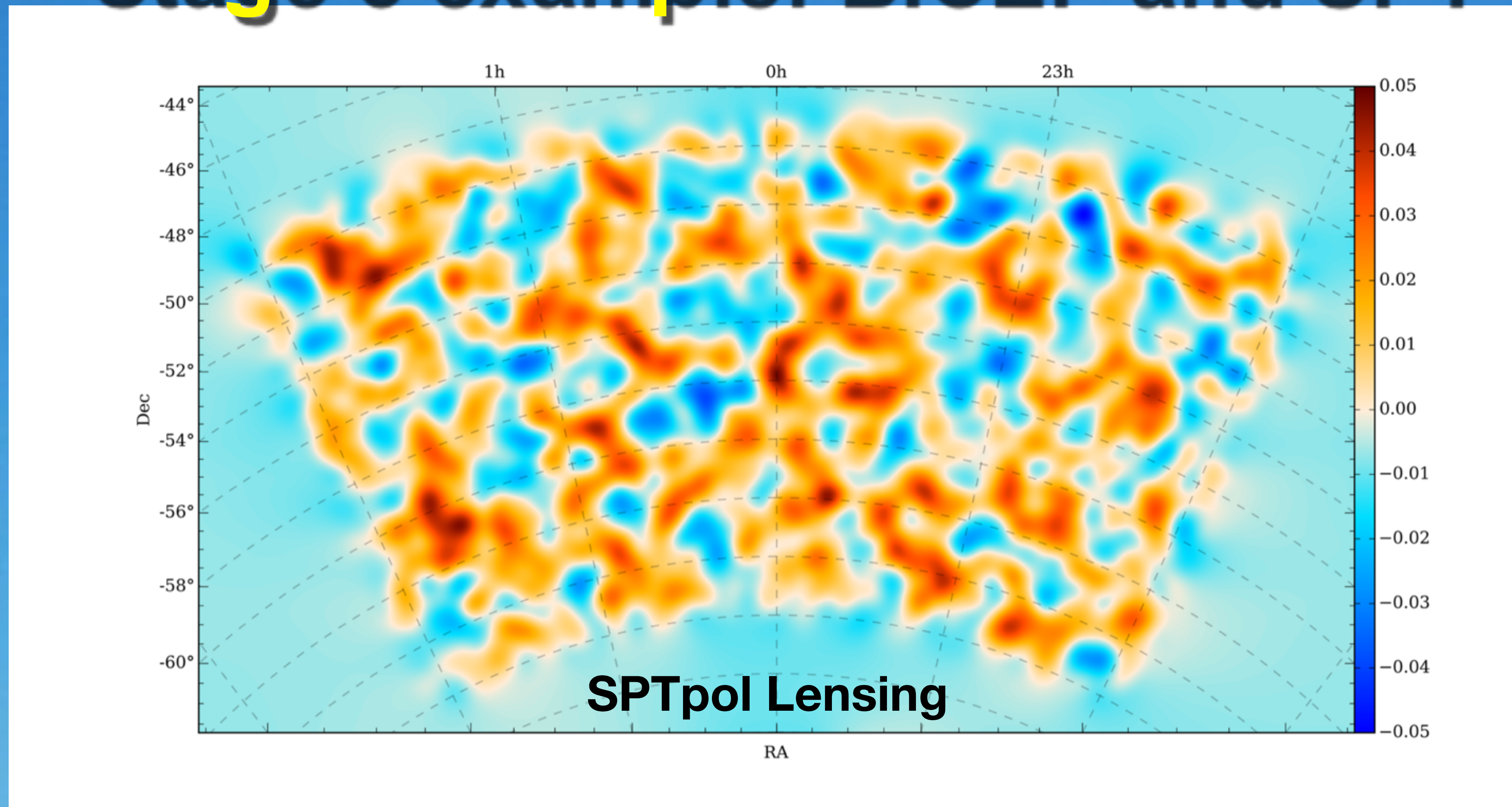
10m South Pole Telescope
SPT-3G: 16,400 detectors
95, 150, 220 GHz

BICEP3
2560 detectors
95 GHz

Keck Array
2500 detectors
95, 150, 220, 270 GHz
Upgrading to BICEP Array:
30,000 detectors
35, 95, 150, 220, 270 GHz

Photo credit Cynthia Chiang

Stage 3 example: BICEP and SPT

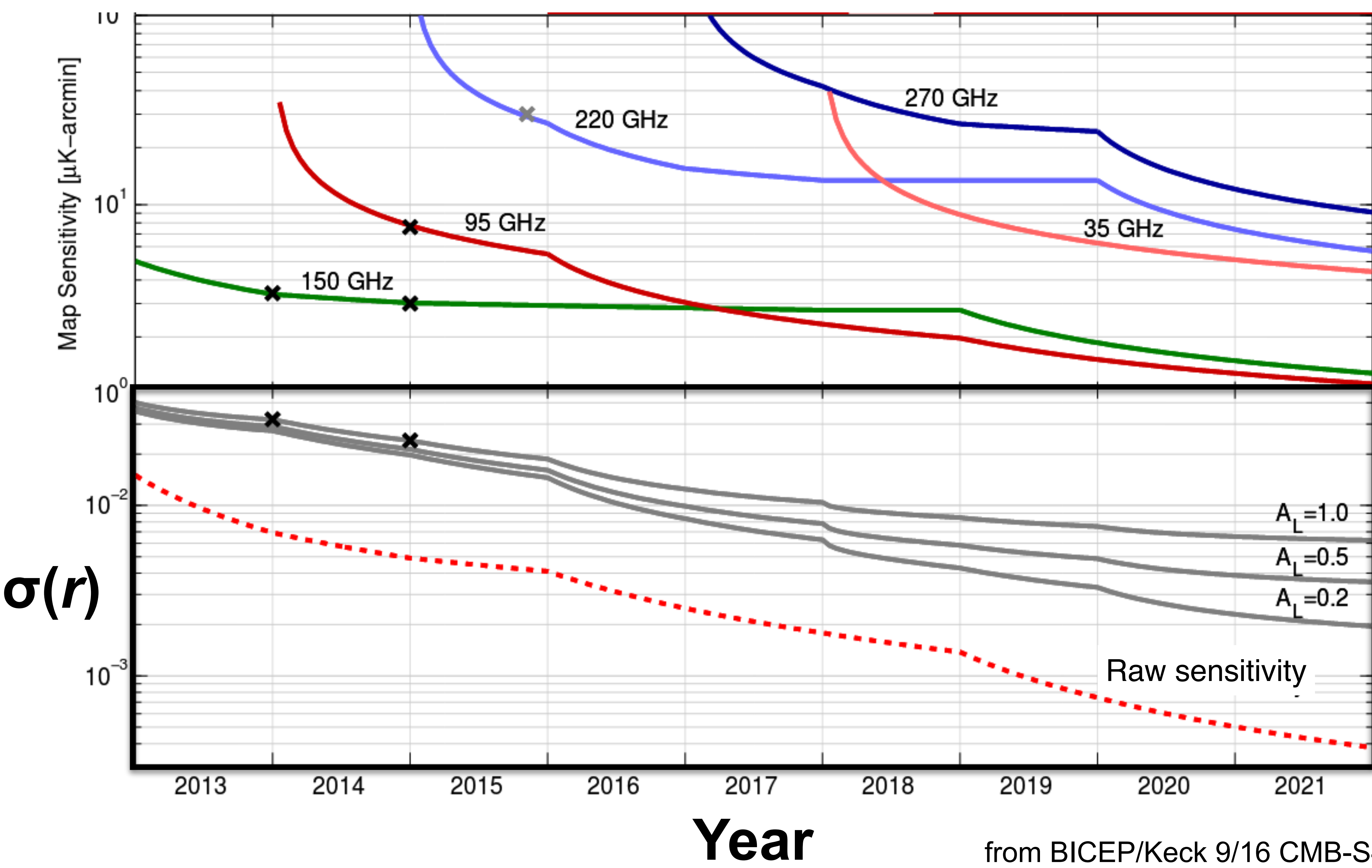


Keck Array
2500 detectors
95, 150, 220, 270 GHz
Upgrading to BICEP Array:
30,000 detectors
35, 95, 150, 220, 270 GHz

10m South Pole Telescope
SPT-3G: 16,400 detectors
95, 150, 220 GHz

BICEP3
2560 detectors
95 GHz

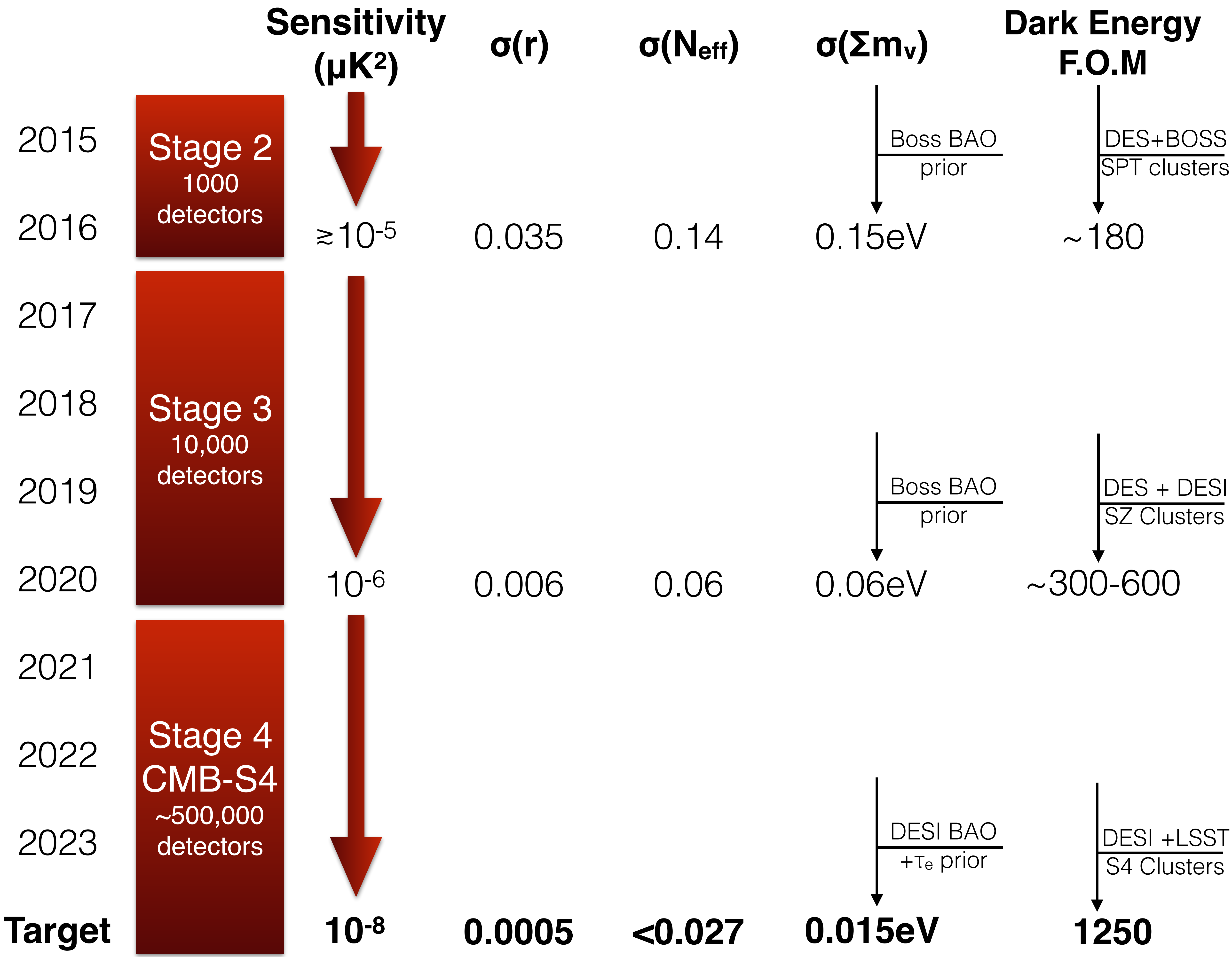
Stage 3 σ(r) as BICEP Array receivers deployed with SPT-3G de-lensing



with SPT-3G de-lensing **σ(r)~0.003**

from BICEP/Keck 9/16 CMB-S4 workshop

Photo credit Cynthia Chiang



Sensitivity (μK²)
σ(r)
σ(N_eff)
σ(Σm_ν)
Dark Energy F.O.M
2015
2016
2017
2018
2019
2020
2021
2022
2023
Target
Stage 2
1000 detectors
Stage 3
10,000 detectors
Stage 4
CMB-S4
~500,000 detectors
Boss BAO
prior
DES+BOSS
SPT clusters
≳10-5
0.035
0.14
0.15eV
~180
Boss BAO
prior
DES + DESI
SZ Clusters
10-6
0.006
0.06
0.06eV
~300-600
DESI BAO
+τe prior
DESI +LSST
S4 Clusters
10-8
0.0005
<0.027
0.015eV
1250

CMB-S4
Next Generation CMB Experiment

Stage 4 CMB experiment: CMB-S4

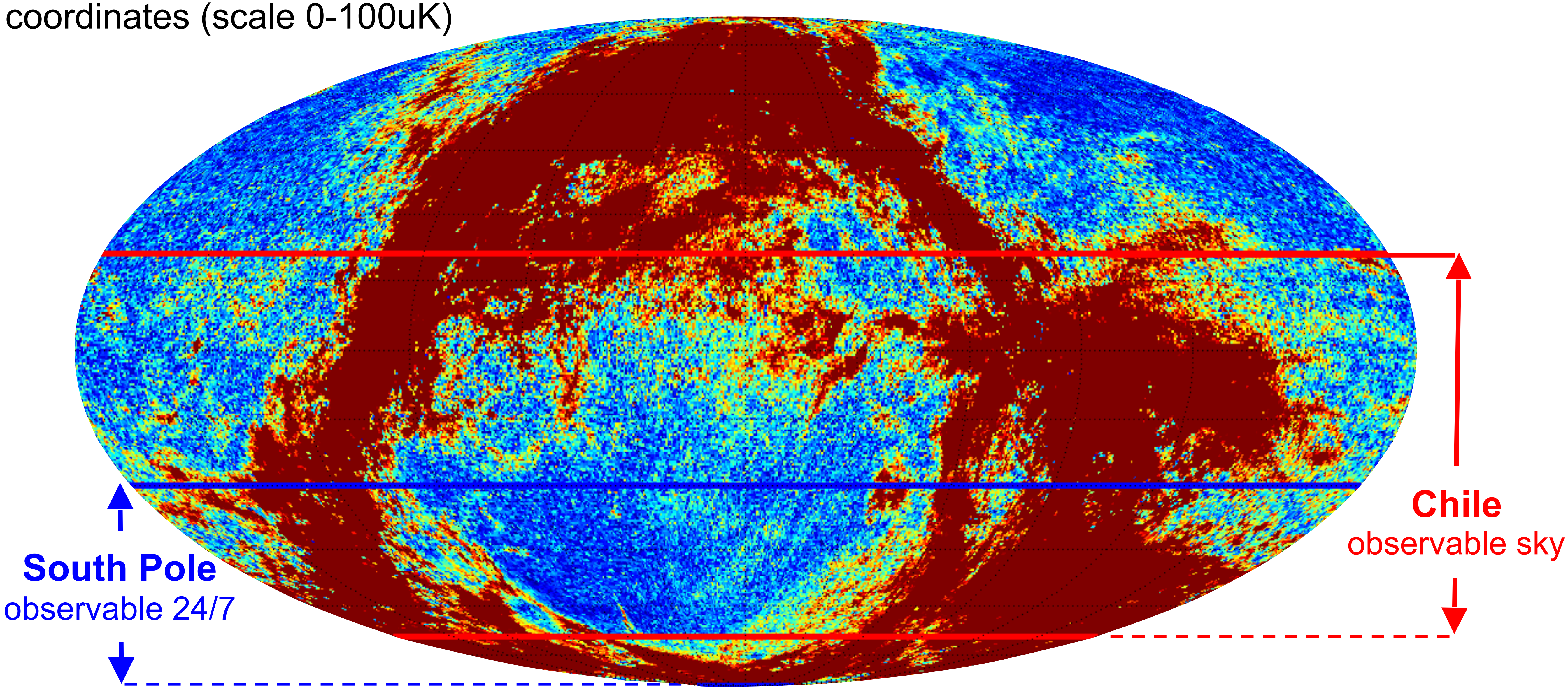
- A next generation ground-based program to pursue inflation, neutrino properties, dark radiation, dark energy and new discoveries.
- Greater than tenfold increase in sensitivity of the combined Stage 3 experiments (>100x current Stage 2) to cross critical science thresholds.
- O(500,000) detectors spanning 30 - 300 GHz using multiple telescopes, large and small, at South Pole and Chile to map most of the sky, as well as deep targeted fields.
- Broad participation of the CMB community, including the existing CMB experiments (e.g., ACT, BICEP/Keck, CLASS, POLARBEAR/Simons Array, Simons Obs & SPT), National Labs and the High Energy Physics community.
- International partnerships expected and desired.

Recommended by P5

CMB-S4
Next Generation CMB Experiment

Telescopes at Chile and South Pole (established and proven CMB sites)

Planck 353 GHz polarized intensity map in celestial coordinates (scale 0-100uK)



open to adding northern site, e.g., Tibet, Greenland

Figure from Clem Pryke

Continuing series of community workshops to advance CMB-S4

U. Minnesota
Jan 16, 2015

U. Michigan
Sep 21-22, 2015

LBNL, Berkeley
March 7-9, 2016

U. Chicago
Sep 19-20, 2016

SLAC, Stanford
Feb 27-28, 2017

Next: August 24-25 Harvard

CMB-S4

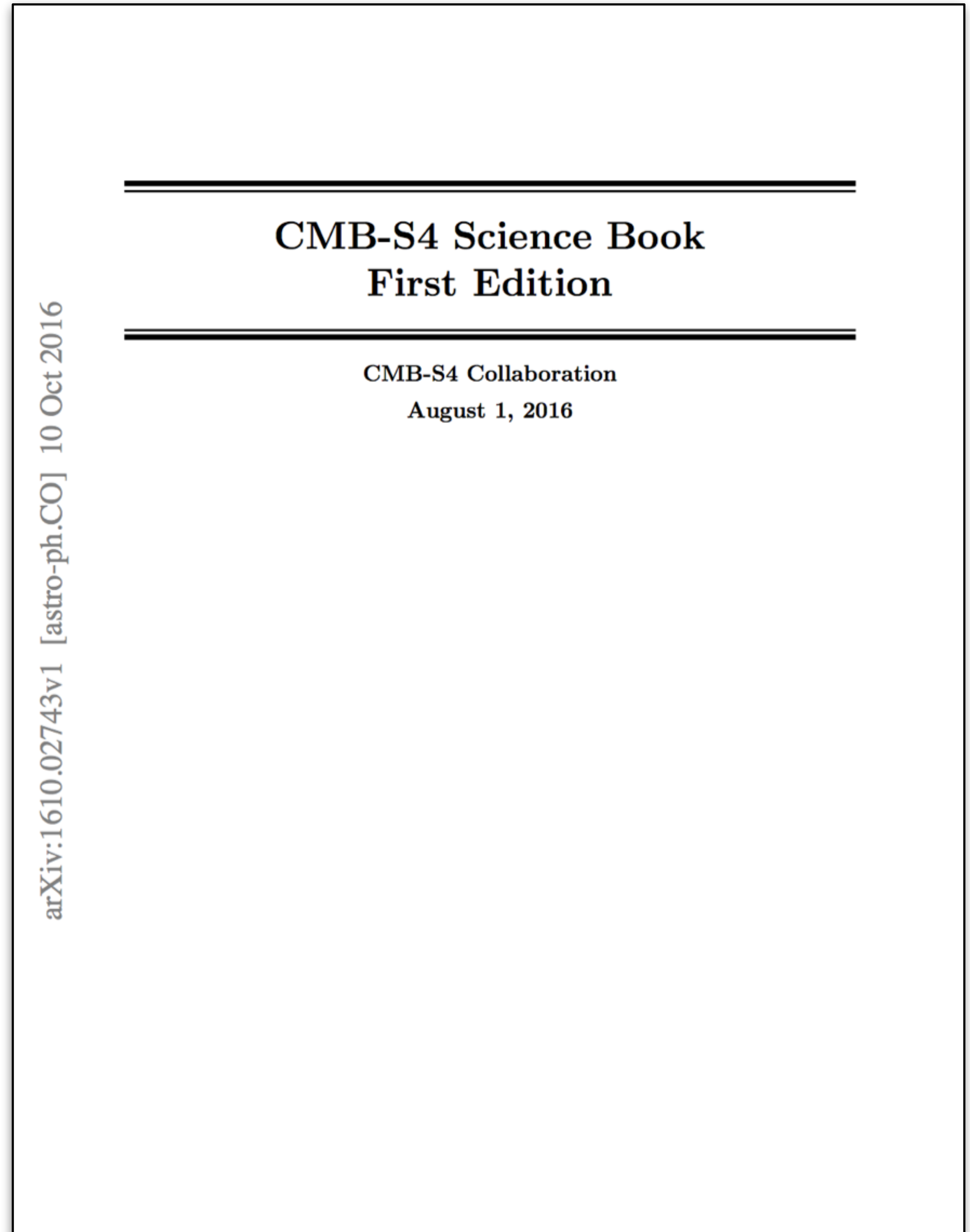
Next Generation CMB Experiment

CMB-S4 Science Book

CMB-S4 Science Book
and Technology Book
available at web site
http://cmb-s4.org

Science Book: 8 chapters (220 pages):

1) Exhortations
2) Inflation
3) Neutrinos
4) Light Relics
5) Dark Matter
6) Dark Energy
7) CMB lensing
8) Data Analysis, Simulations & Forecasting



arXiv:1610.02743v1 [astro-ph.CO] 10 Oct 2016

CMB-S4 Science Book
First Edition

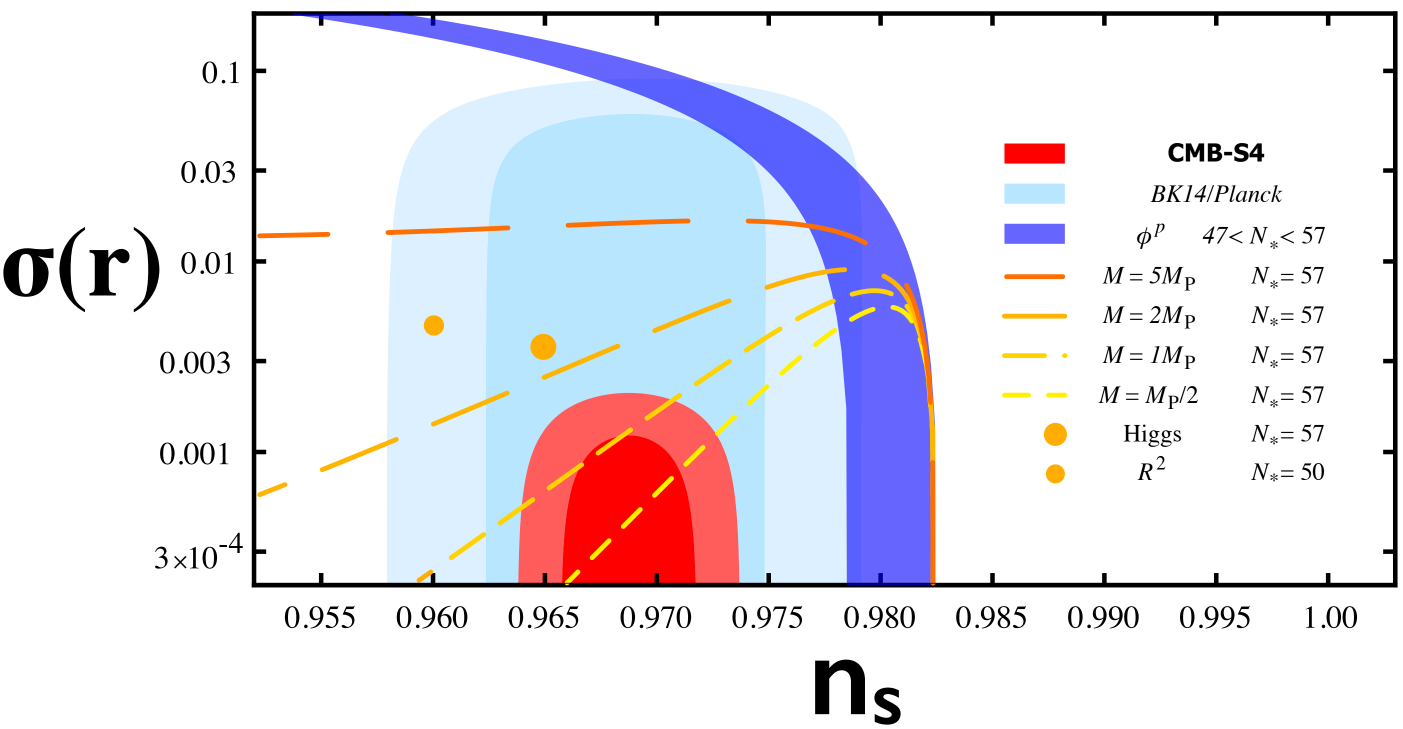
CMB-S4 Collaboration
August 1, 2016

CMB-S4
Next Generation CMB Experiment

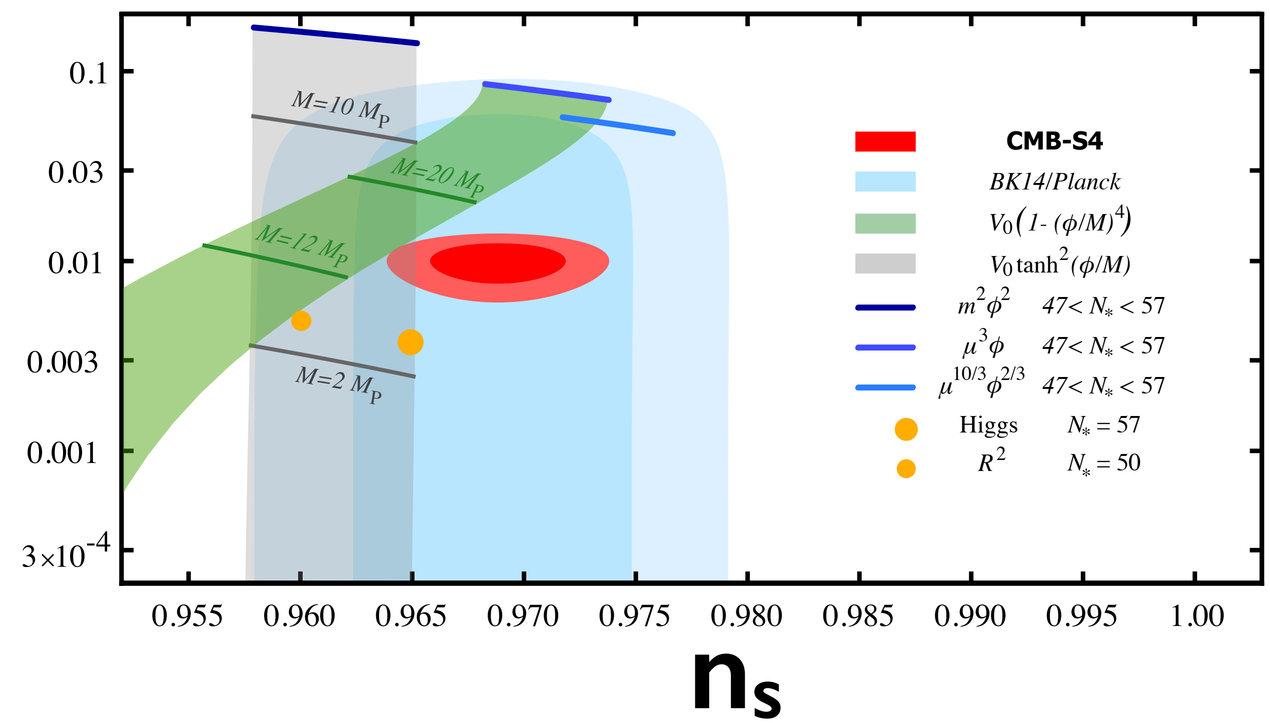
Example of optimization / projection of inflation reach of CMB-S4

for nominal 3% f_{sky} and 10^6 detector years

r = 0



r = 0.01



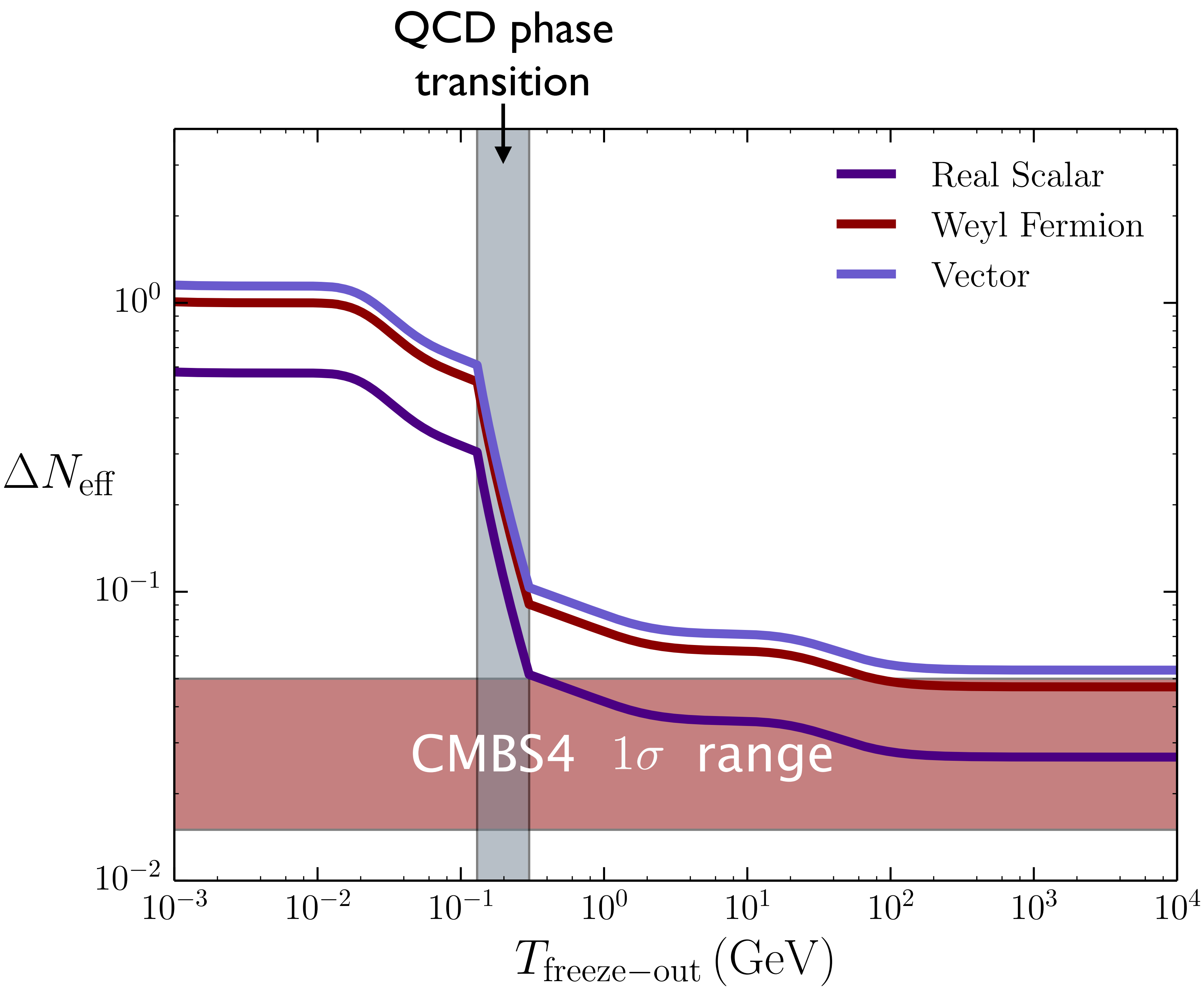
A detection of primordial B modes with CMB-S4 would provide evidence that the theory of quantum gravity must accommodate a Planckian field range for the inflaton.

Conversely a non-detection of B modes with CMB-S4 will mean that a large field range is not required.

CMB-S4

Next Generation CMB Experiment

N_{eff}: thermal relics

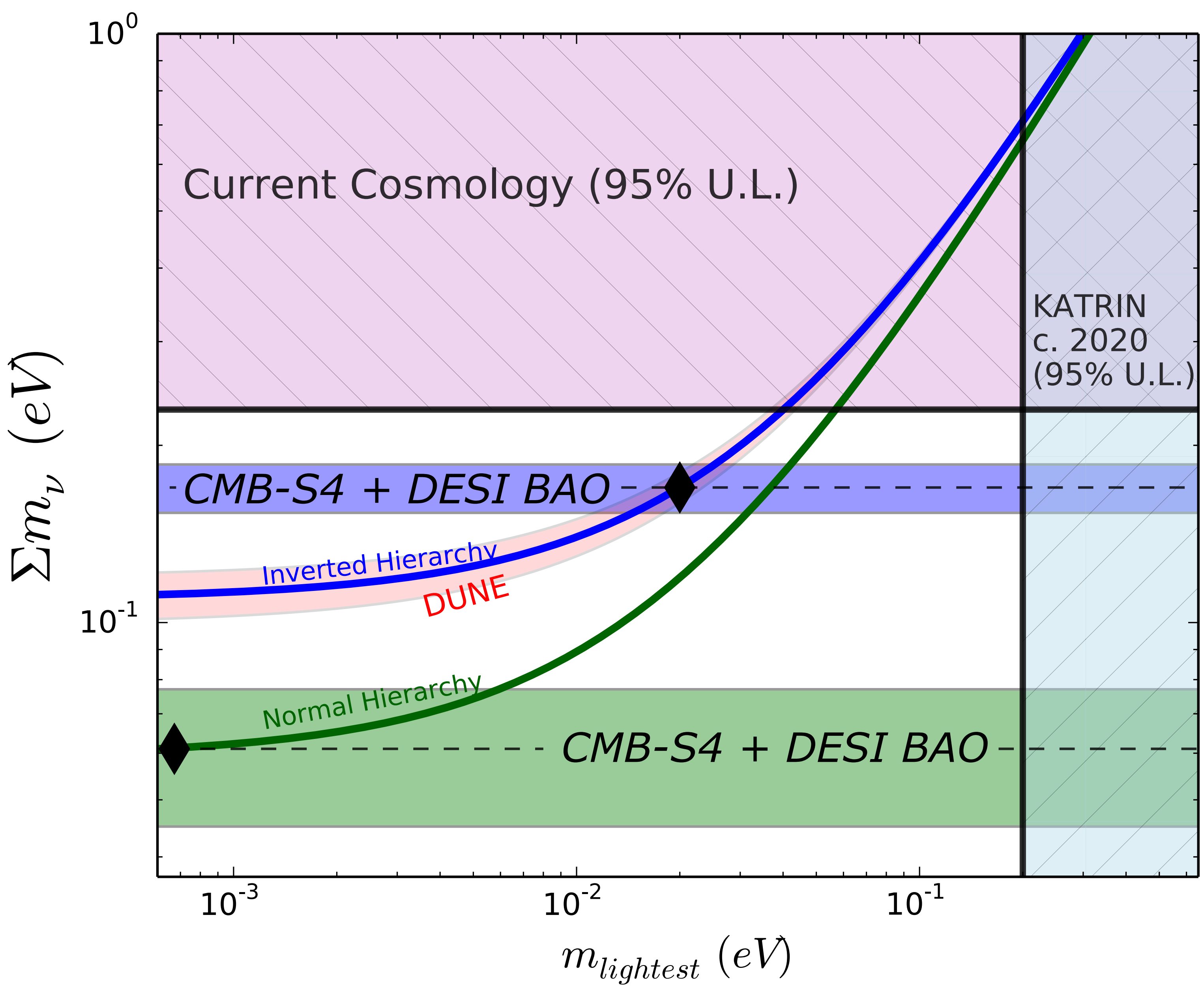


- $\sigma(N_{eff})$ constraint leads to orders of magnitude improvement of constraint on the freeze-out temperature for any thermal relic
- Natural target:
  $\Delta N_{eff} < 0.027$ limits axion SM couplings for $T_{freeze\text{-}out} < T_{reheat}$ (very challenging spec for CMB-S4)

Green, Meyers CMB-S4 Science Book draft (https://cosmo.uchicago.edu/CMB-S4workshops)
Also Baumann, Green & Wallisch, "A New Target for Cosmic Axion Searches" arXiv:1604.08614

CMB-S4
Next Generation CMB Experiment

Neutrino mass scale, Σm_ν



Caveats:

- Need DESI BAO or H_0 to break Σm_ν - Ω_m degeneracy
- Need improved measurement of optical depth to reionization (from CLASS? Balloons? Satellite? 21cm?)

Snowmass arXiv:1309.5383

CMB ν degeneracy forecasts

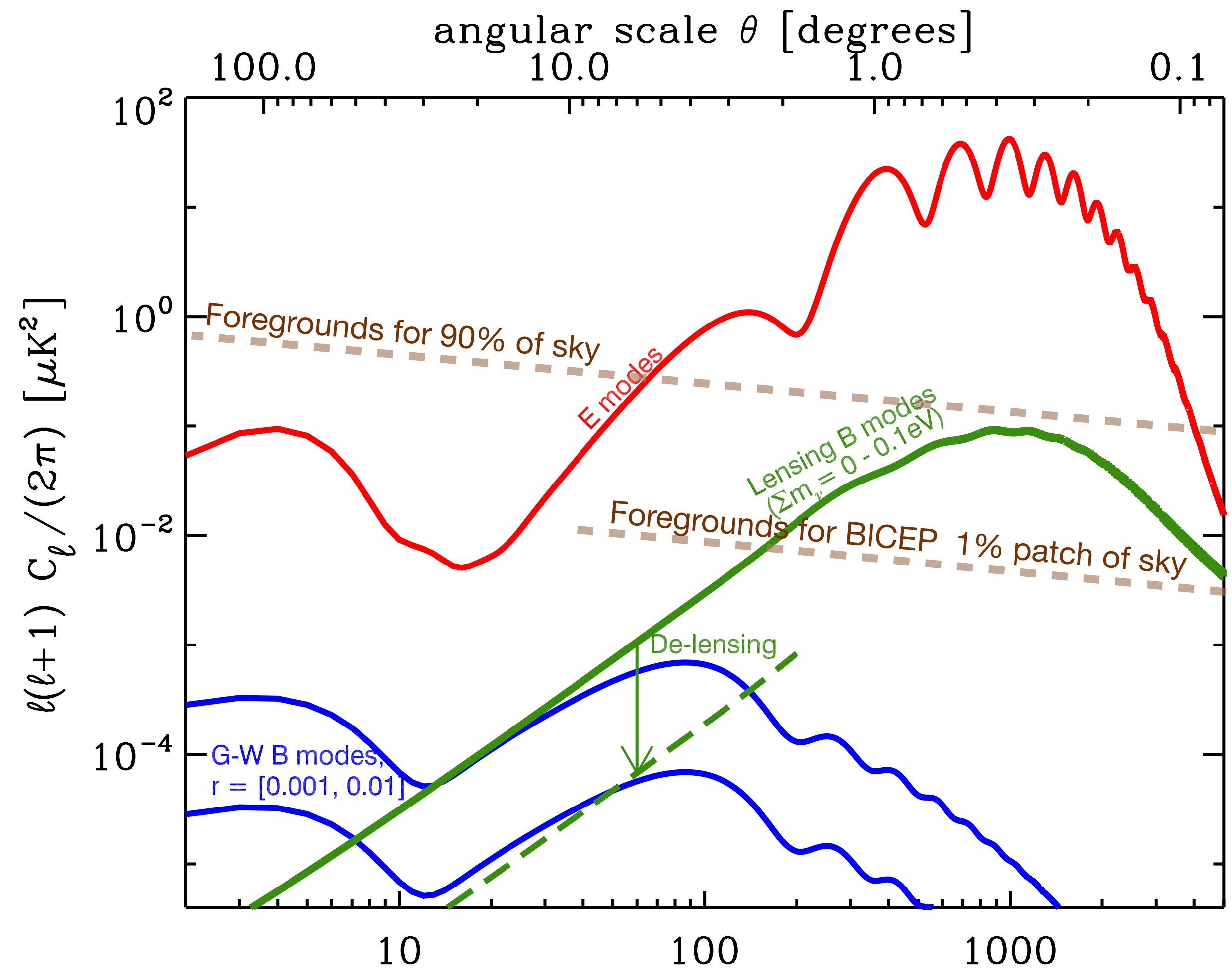
Allison et al., 1509.07471

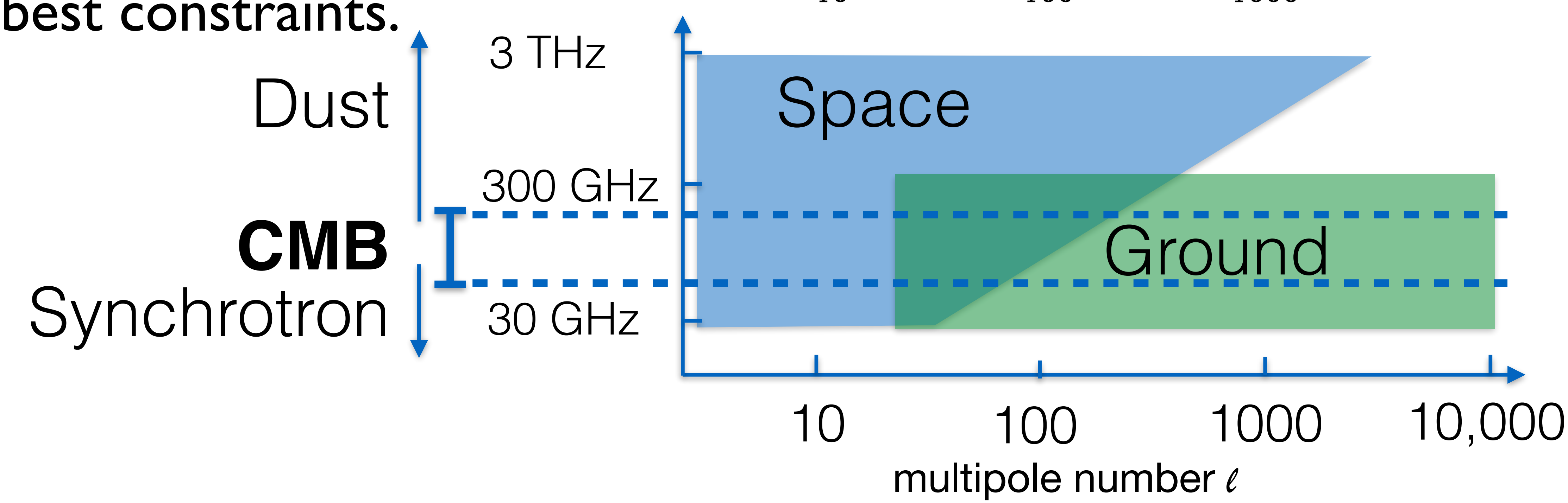
for CMB-S4 (3 arcm res, $\ell > 20$) + DESI BAO:

$$
\begin{aligned}
\Sigma m_\nu &= 19 \text{ meV} \quad (\Lambda CDM + \Sigma m_\nu) \\
&= 30 \text{ meV} \quad (\Lambda CDM + \Sigma m_\nu + \Omega_k) \\
&= 27 \text{ meV} \quad (\Lambda CDM + \Sigma m_\nu + w_0) \\
&= 46 \text{ meV} \quad (\Lambda CDM + \Sigma m_\nu + w_0 + w_a) \\
&= 64 \text{ meV} \quad (\Lambda CDM + \Sigma m_\nu + w_0 + w_a + \Omega_k)
\end{aligned}
$$

Complementary strengths of ground and space

- **Ground:** Resolution required for CMB lensing (+de-lensing!), damping tail, clusters….
- **Space:** All sky for reionization peak; high frequencies for dust.
- Combined data will provide best constraints.

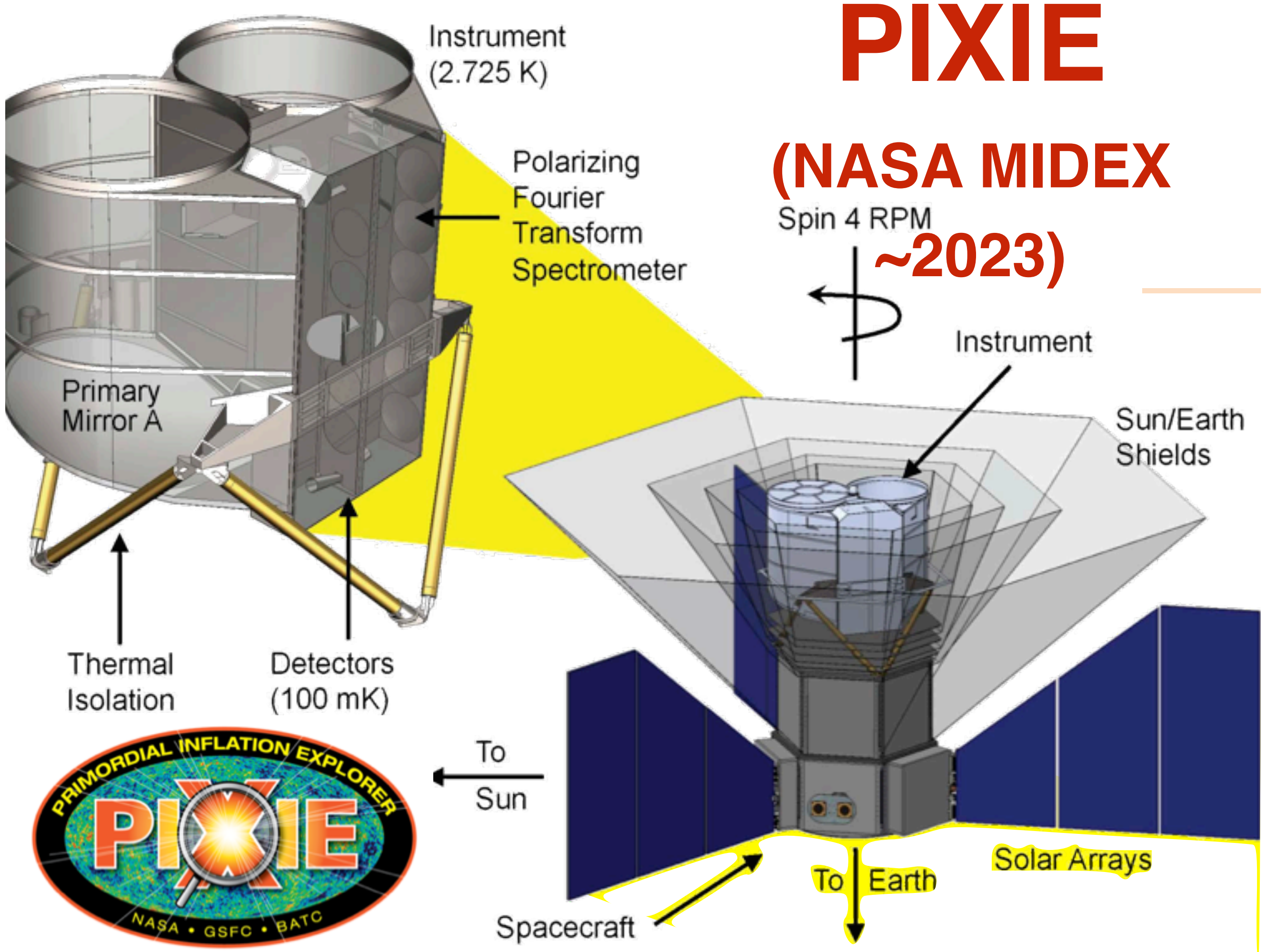




CMB satellite proposals

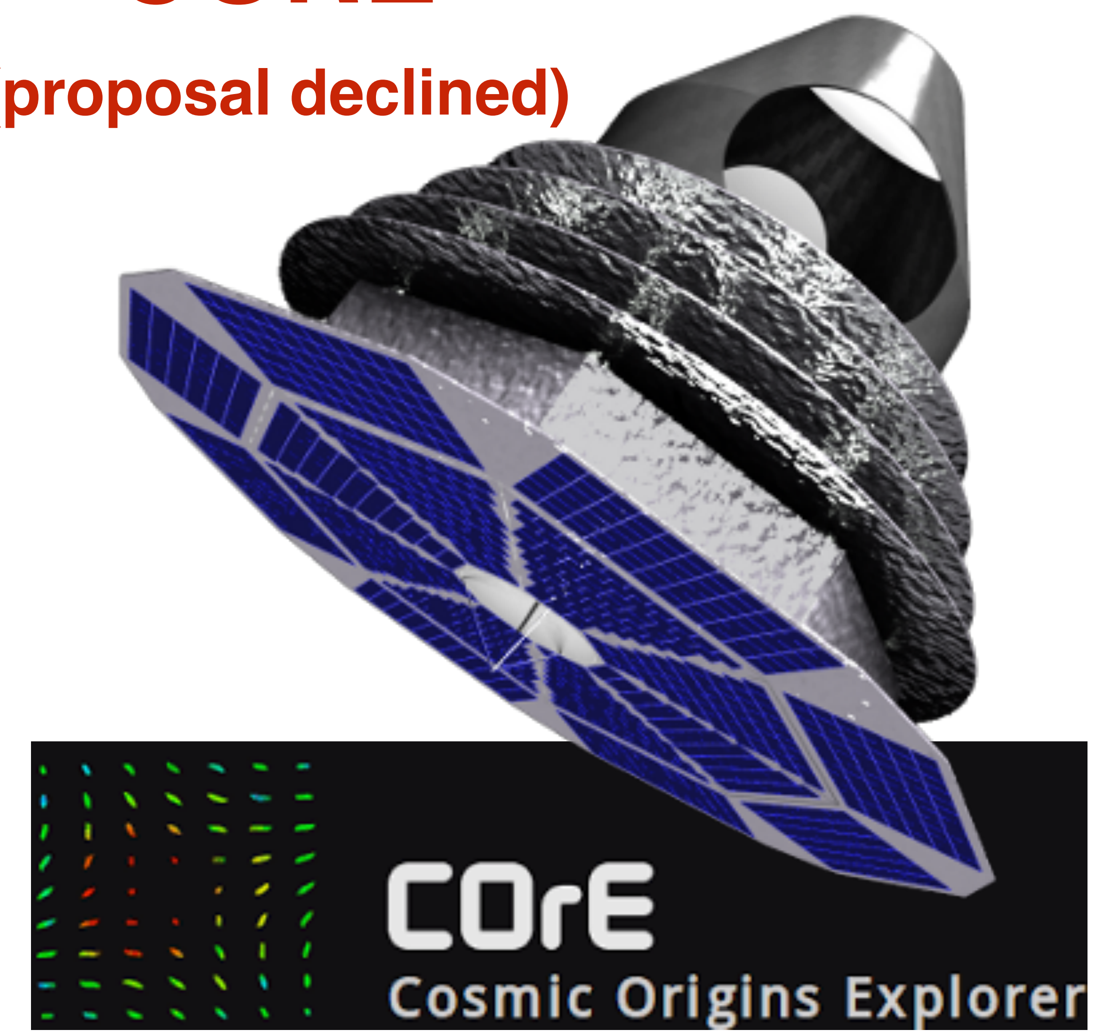
PIXIE

(NASA MIDEX ~2023)



CORE

(proposal declined)



LiteBIRD (JAXA, ~2027)

Lite (Light) Satellite for the Studies of B-mode Polarization and Inflation from Cosmic Background Radiation Detection

All targeting $\sigma(r)$ ~ few 10^{-4}

Last words

CMB is the gift that keeps on giving. CMB-S4 will be a great leap forward.

The science is spectacular. We will be searching for primordial gravitational waves and testing single field slow roll inflation, determining the neutrino masses, searching for new relics, mapping the universe in momentum, investigating dark energy, testing general relativity and more.