CMB-S4

Next Generation CMB Experiment

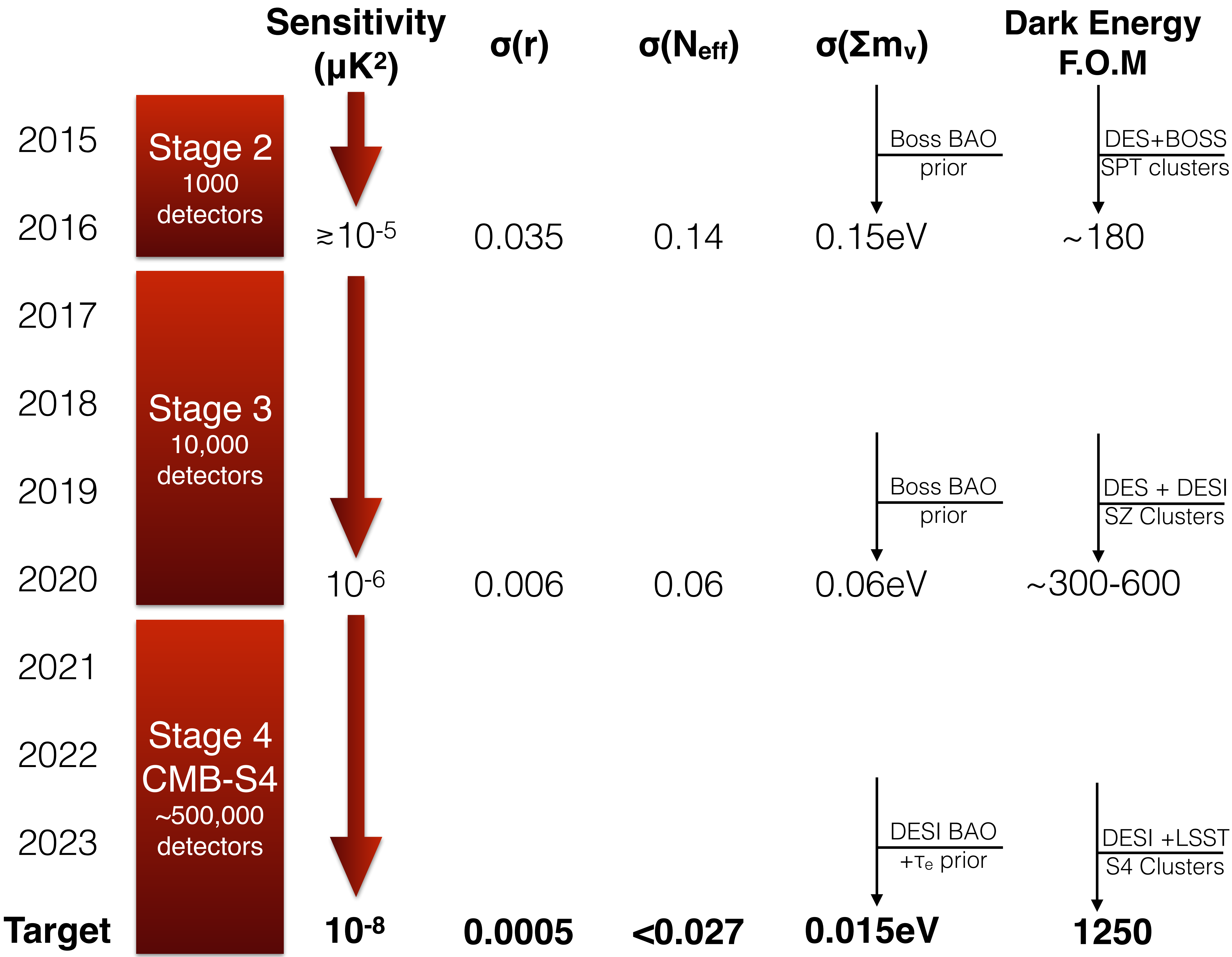
John Carlstrom
on behalf of CMB-S4 collaboration

CMB-S4
Next Generation CMB Experiment

Stage 4 CMB experiment: CMB-S4

- **A next generation ground-based program to pursue <u>inflation</u>, <u>neutrino properties</u>, <u>dark radiation</u>, <u>dark energy</u> and new discoveries.**
- **Greater than tenfold increase in sensitivity of the combined Stage 3 experiments (>100x current Stage 2) to cross <u>critical science thresholds.</u>**
- **O(500,000) detectors spanning 30 - 300 GHz using multiple telescopes and sites 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 & SPT), National Labs and the High Energy Physics community. <u>International partnerships expected and desired.</u>**

Recommended by P5 & NRC Antarctic reports



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

Status of primary CMB TT measurements

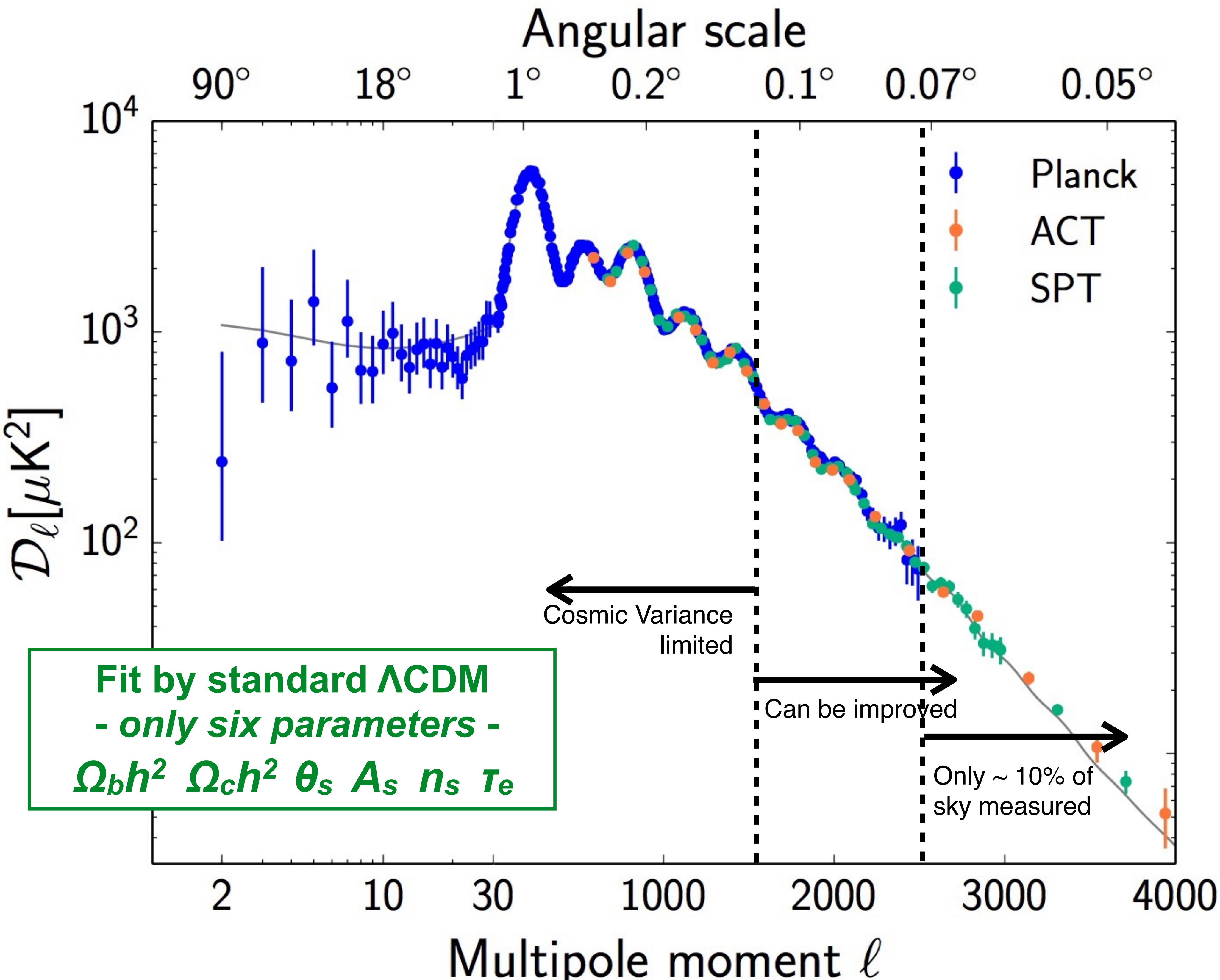
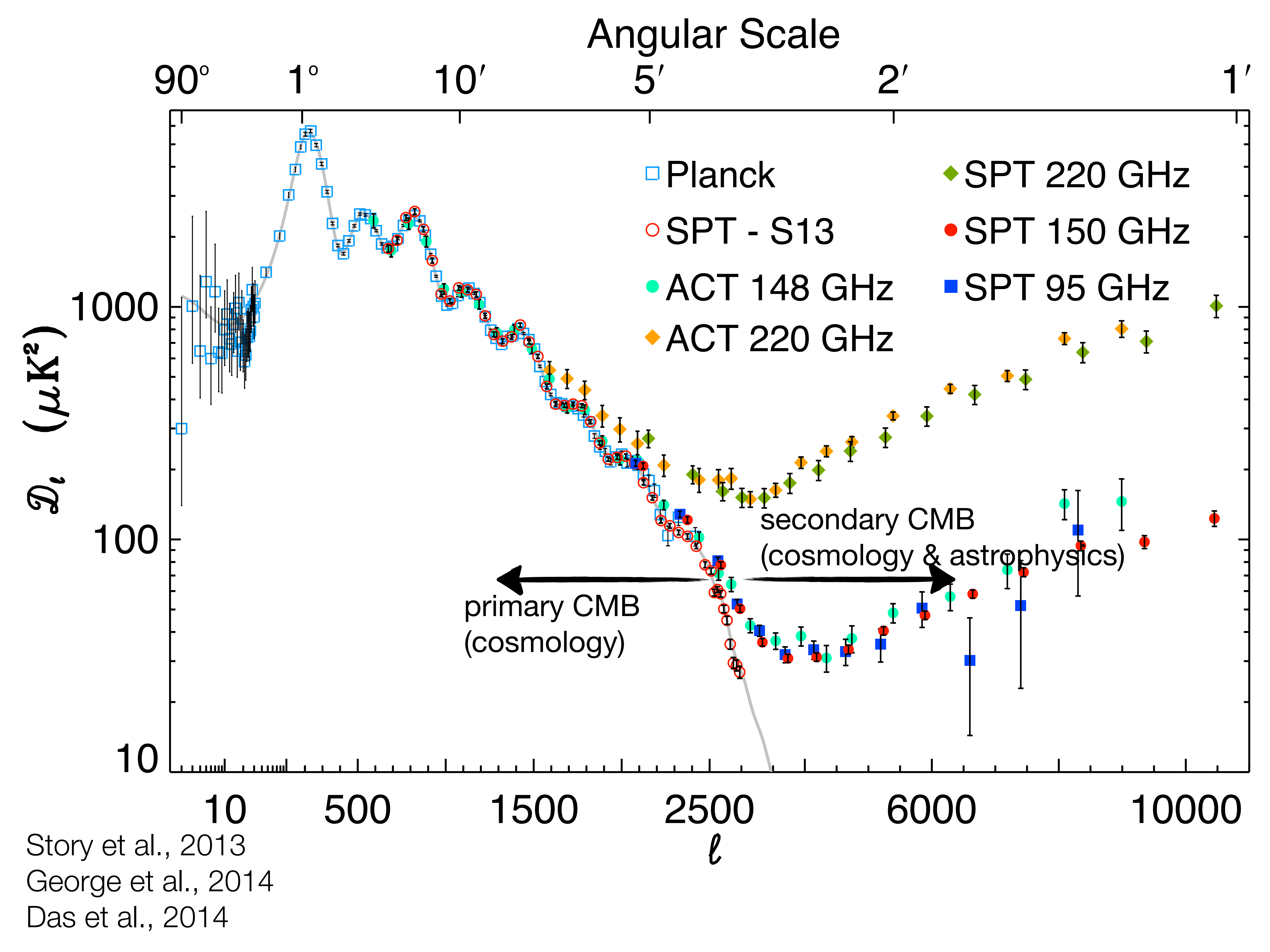
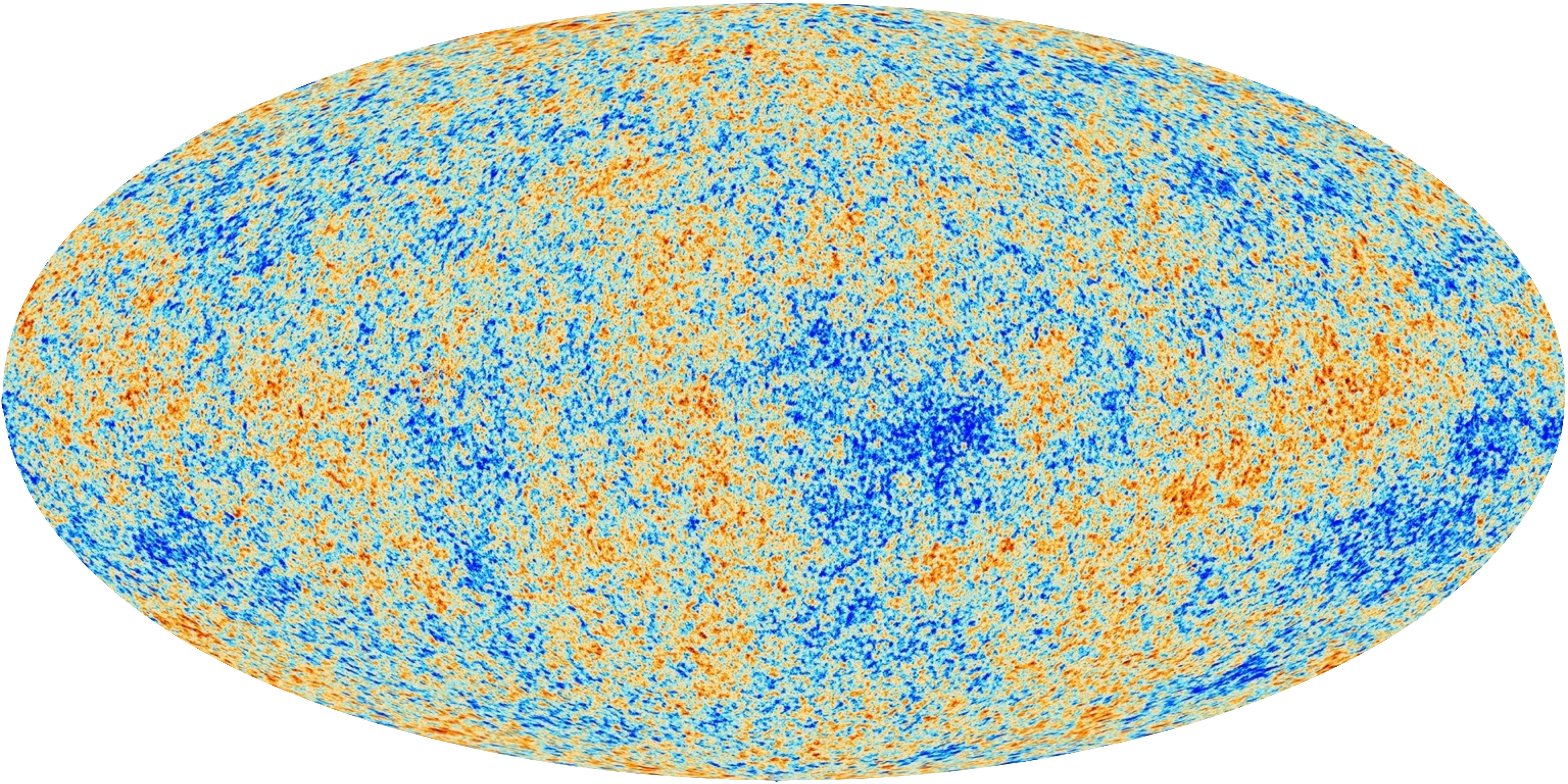


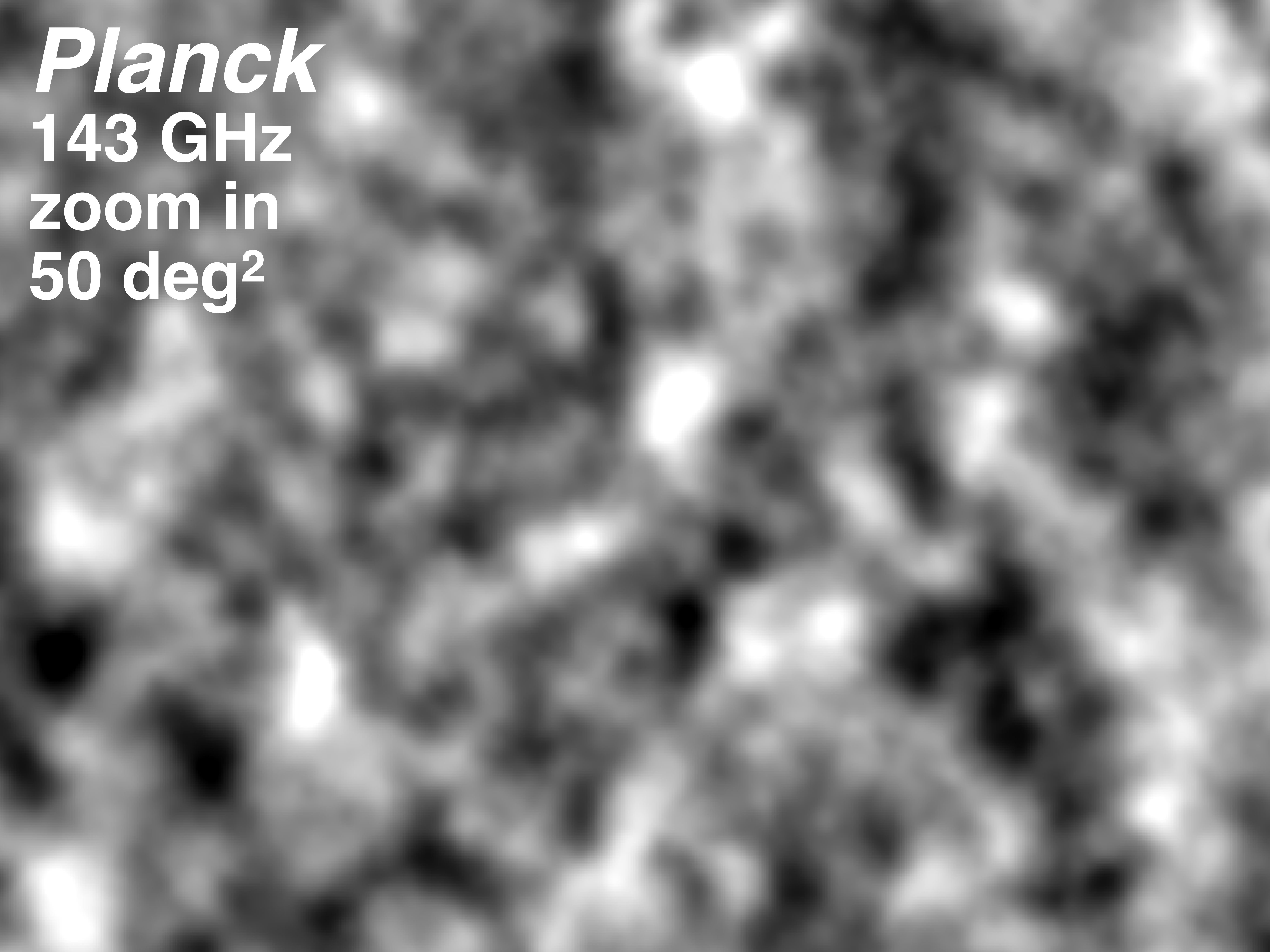
Figure from Planck 2015 Results XI

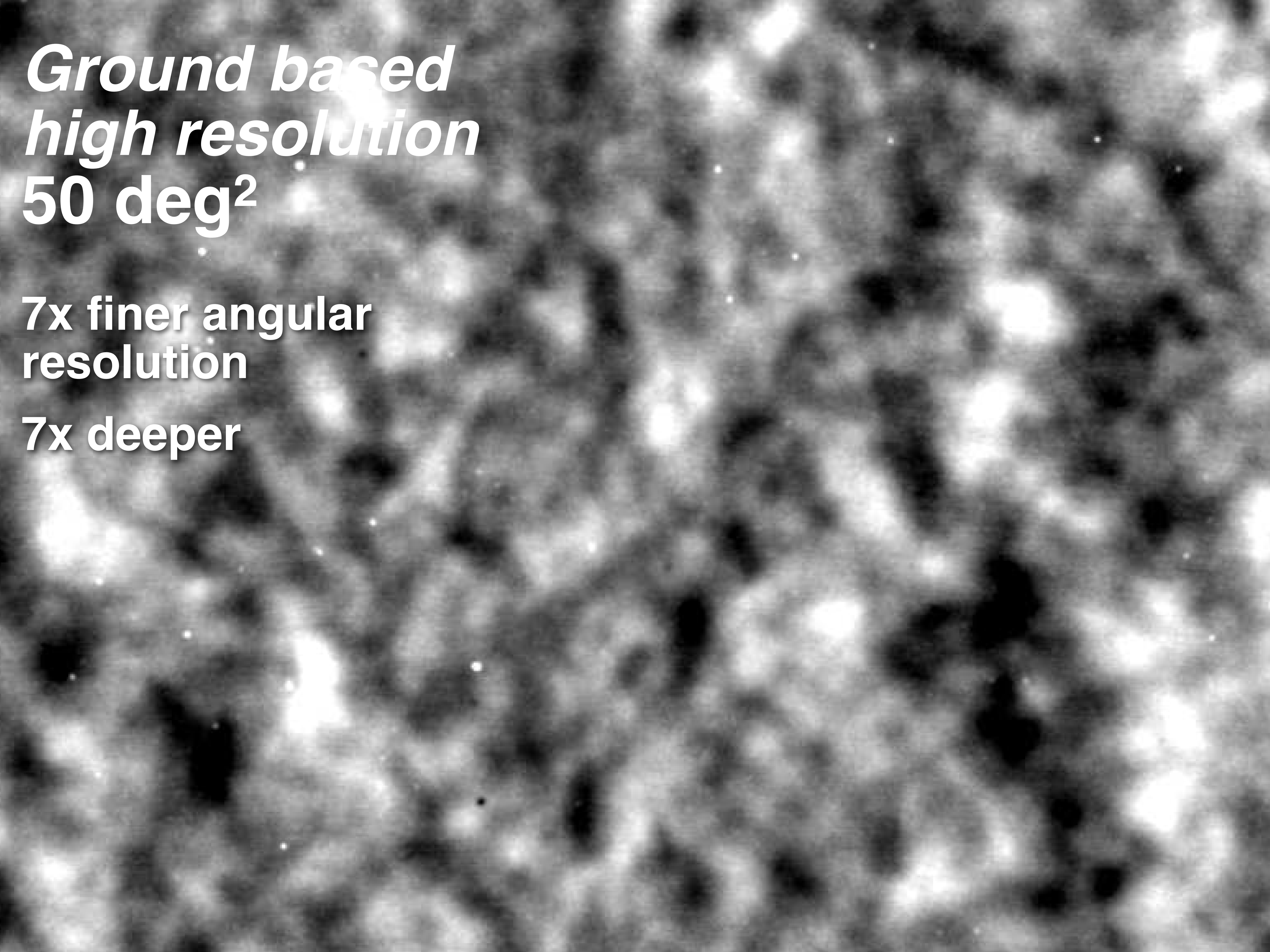


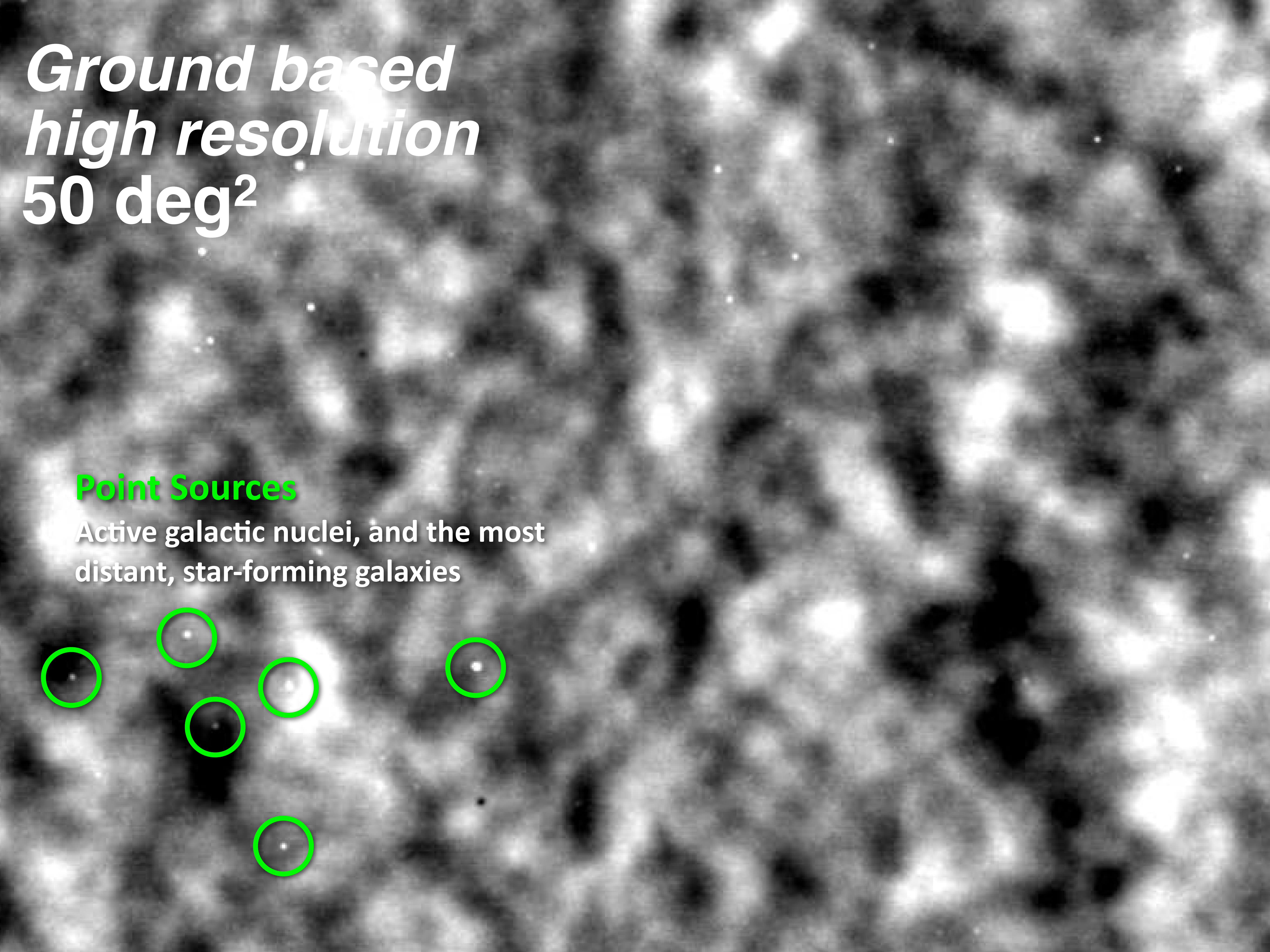
Angular Scale
90°
1°
10′
5′
2′
1′
Planck
SPT - S13
ACT 148 GHz
ACT 220 GHz
SPT 220 GHz
SPT 150 GHz
SPT 95 GHz
$\mathcal{D}_\ell$ (μK^2)
1000
100
10
secondary CMB
(cosmology & astrophysics)
primary CMB
(cosmology)
10
500
1500
2500
6000
10000
ℓ
Story et al., 2013
George et al., 2014
Das et al., 2014

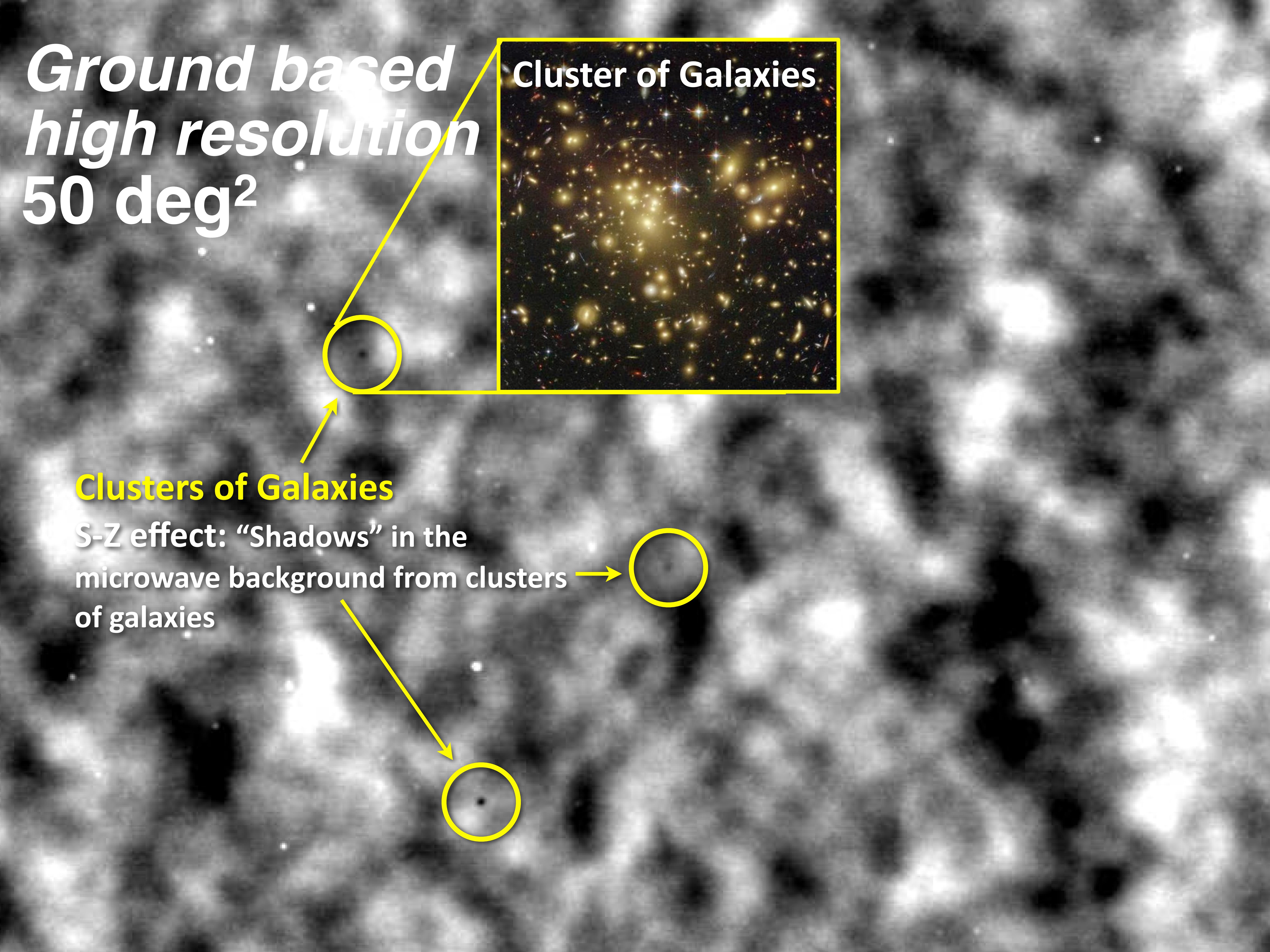
Planck



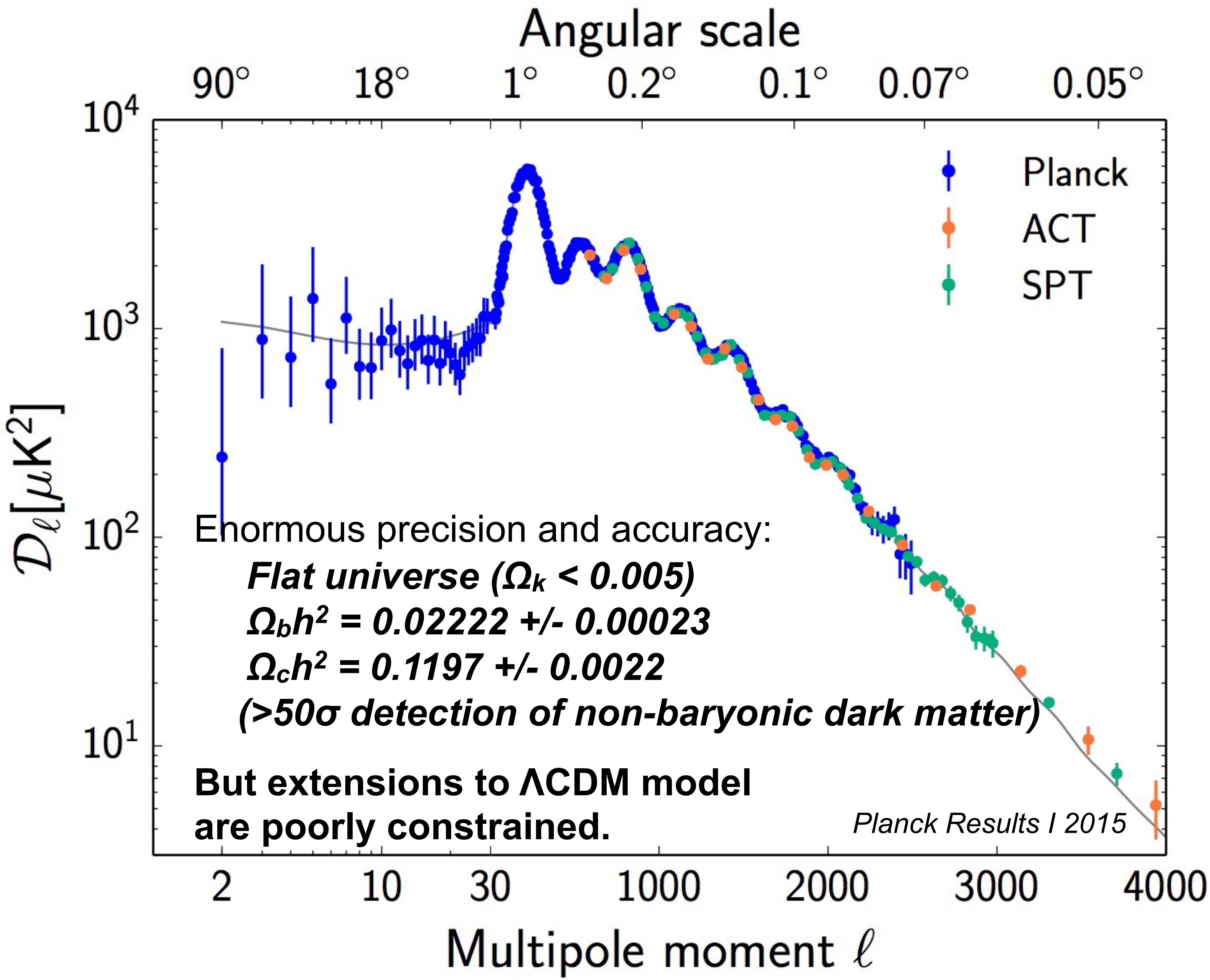

Planck
143 GHz
zoom in
50 deg^2


Ground based
high resolution
50 deg²
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 deg^2
Cluster of Galaxies
Clusters of Galaxies
S-Z effect: "Shadows" in the
microwave background from clusters
of galaxies

Status of primary CMB TT measurements



Enormous precision and accuracy:

Flat universe (Ω_k < 0.005)

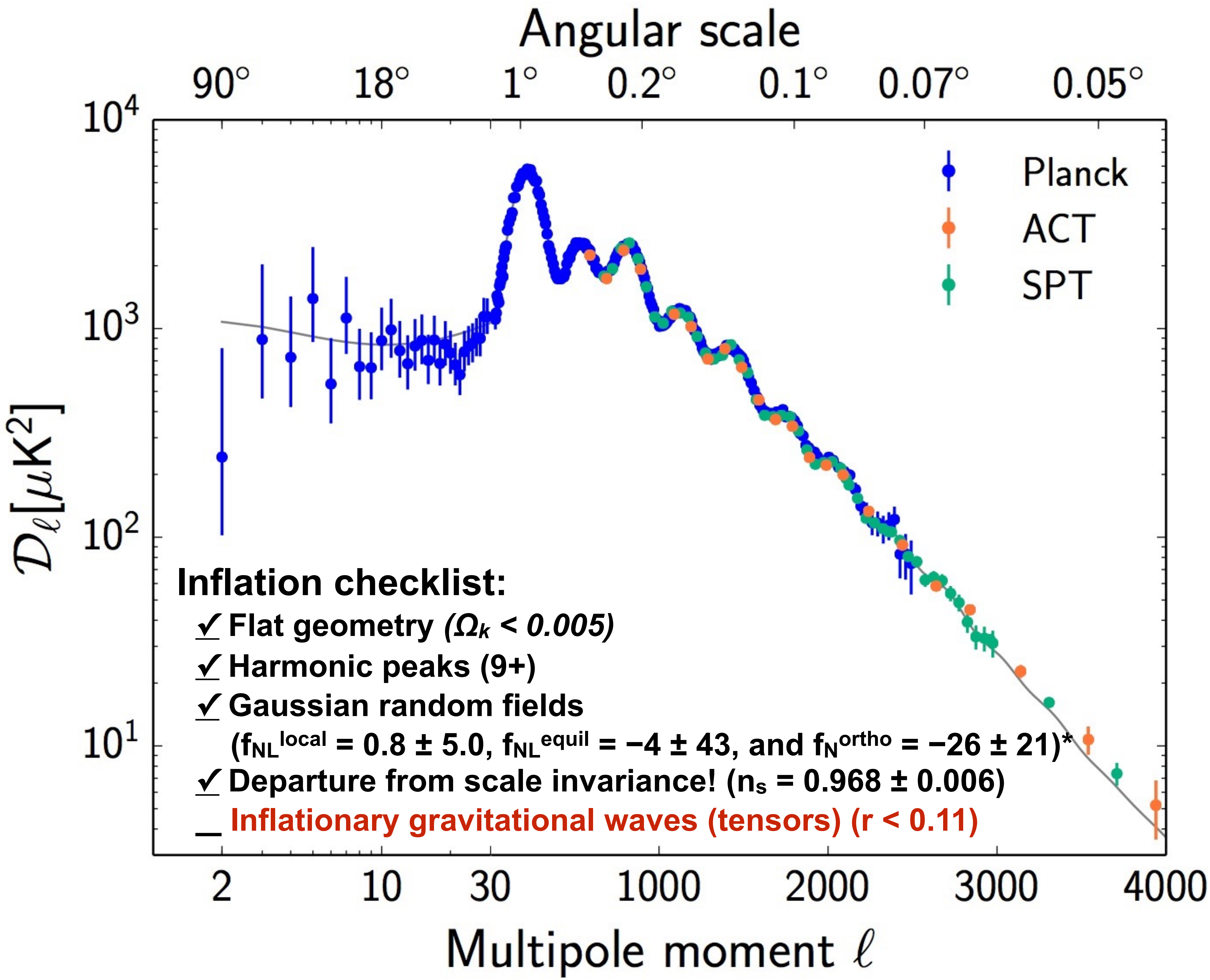
$\Omega_b h^2$ = 0.02222 +/- 0.00023

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

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

But extensions to ΛCDM model are poorly constrained.

Status of primary CMB TT measurements



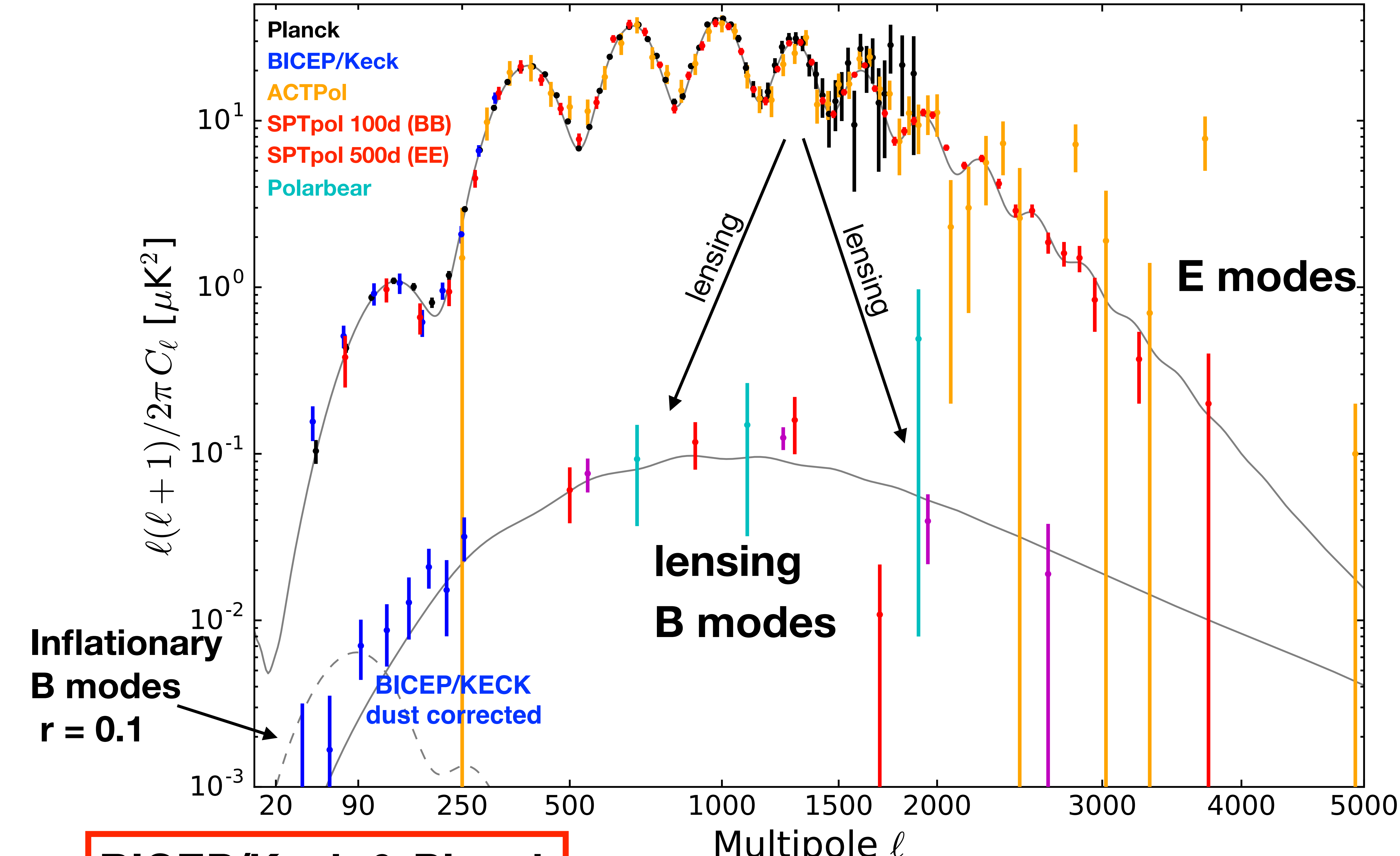
Inflation checklist:

- ✓ **Flat geometry** ***(Ω_k < 0.005)***
- ✓ **Harmonic peaks (9+)**
- ✓ **Gaussian random fields**
  (f_{NL}^{local} = 0.8 ± 5.0, f_{NL}^{equil} = −4 ± 43, and f_N^{ortho} = −26 ± 21)*
- ✓ **Departure from scale invariance! (n_s = 0.968 ± 0.006)**
- __ **Inflationary gravitational waves (tensors) (r < 0.11)**

*constraints include CMB polarization data

Status of CMB polarization measurements

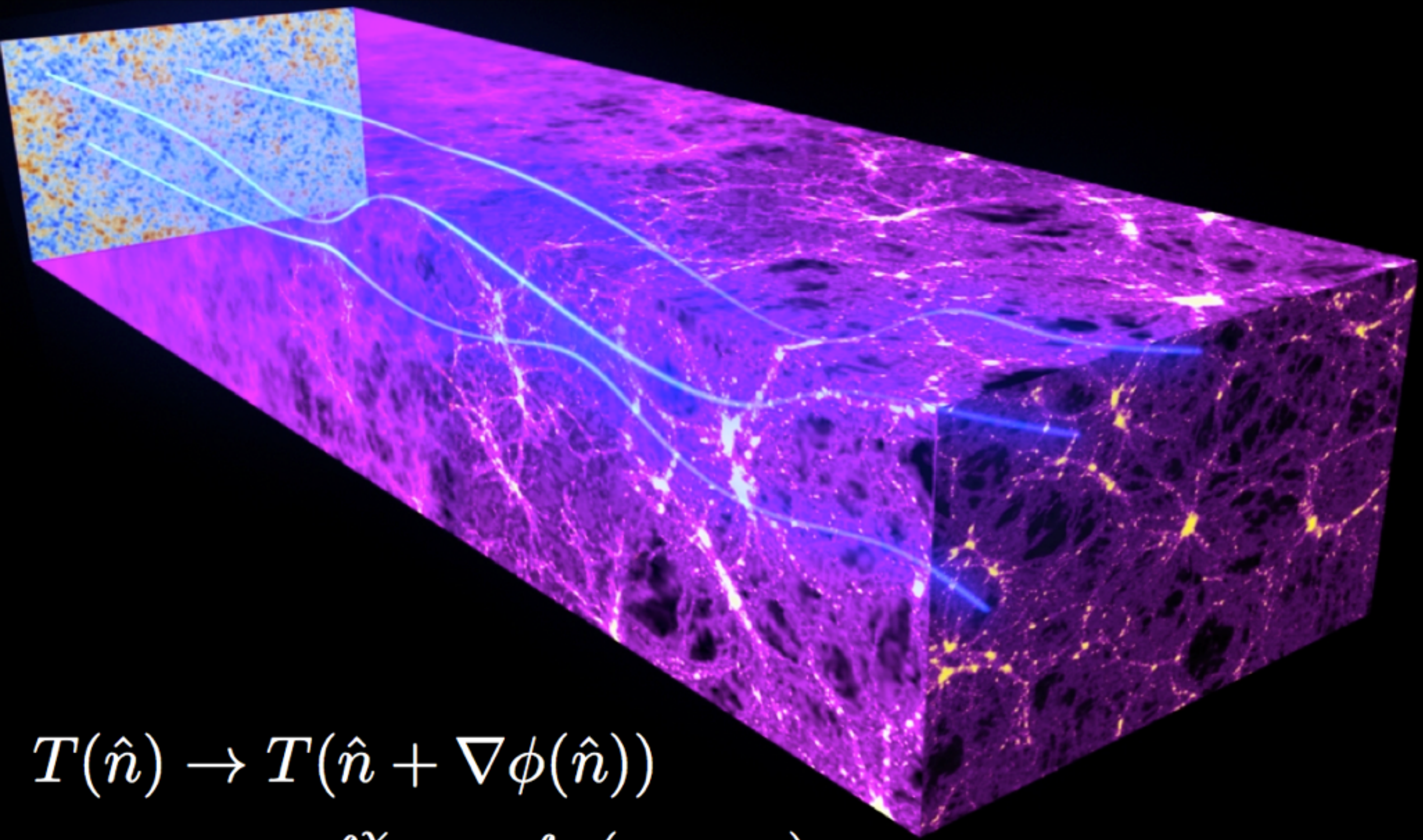
Rapid progress. All within last 3 years.



BICEP/Keck & Planck

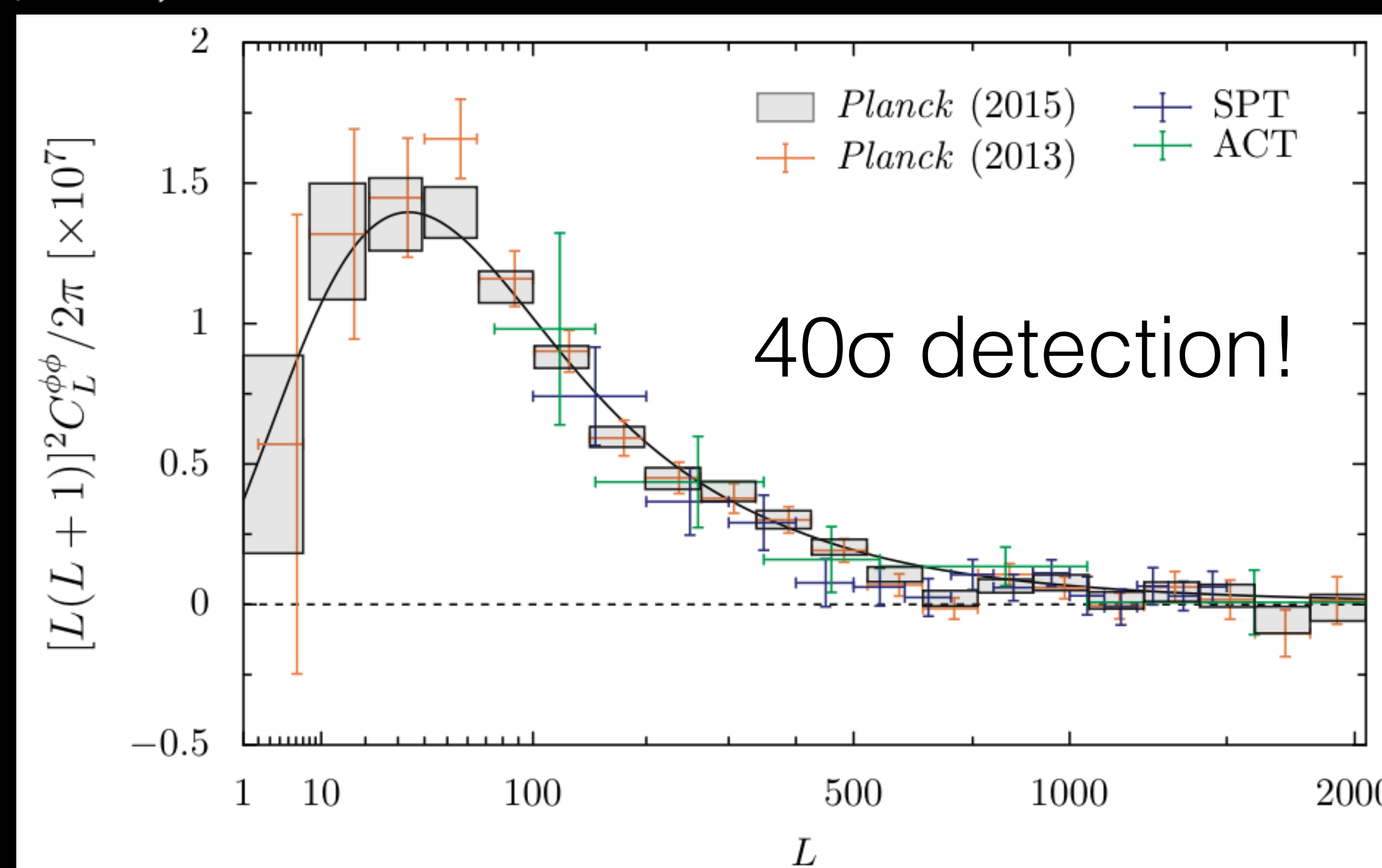
***r* < 0.07 at 95% C.L.**

CMB lensing - great progress, but a long, long way to go



$$T(\hat{n}) \rightarrow T(\hat{n} + \nabla\phi(\hat{n}))$$

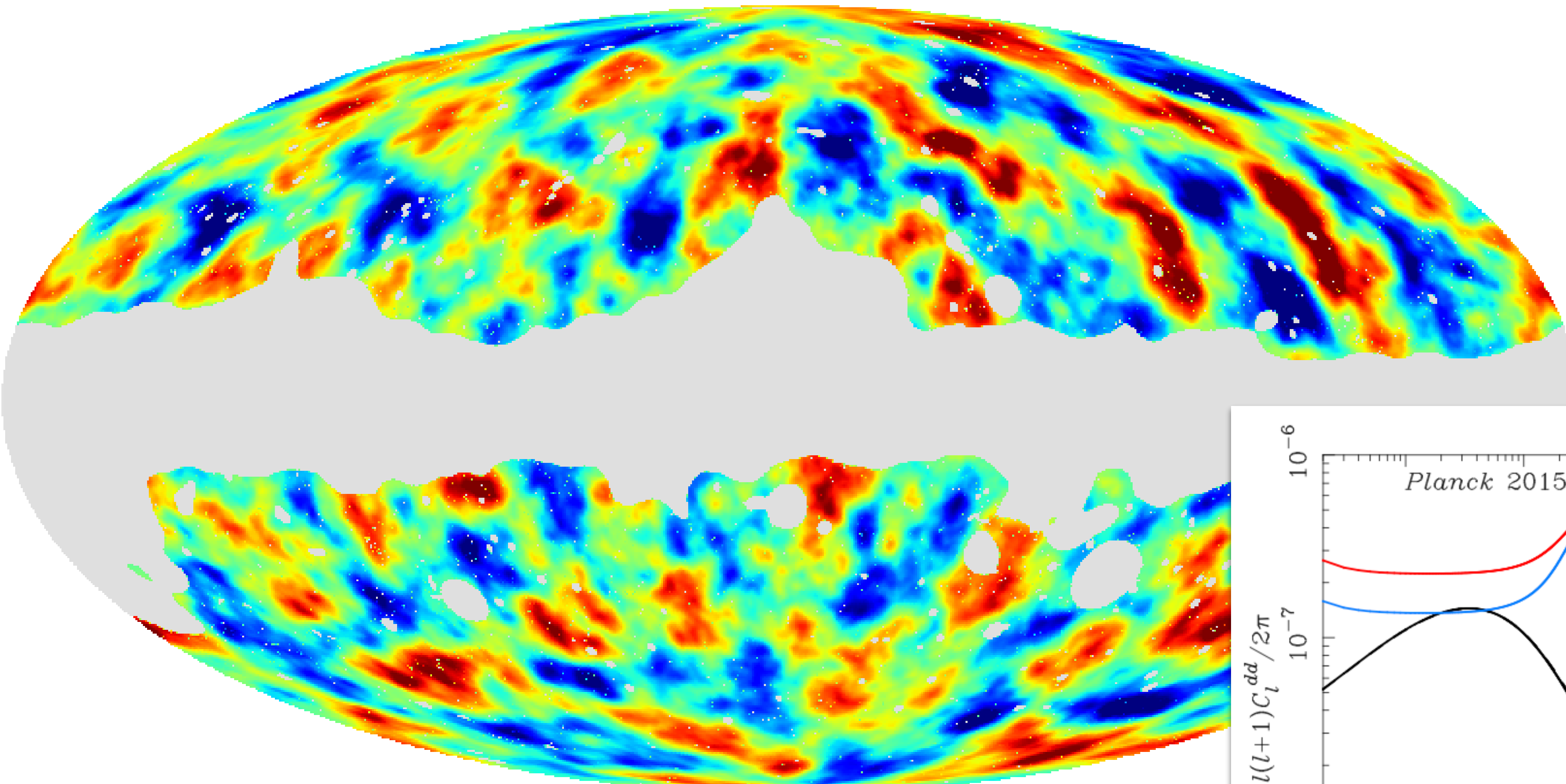
$$\phi(\hat{n}) = -2\int_0^{\chi_*} d\chi \frac{f_K(\chi_* - \chi)}{f_K(\chi_*)f_K(\chi)} \Psi(\chi\hat{n}; \eta_0 - \chi)$$

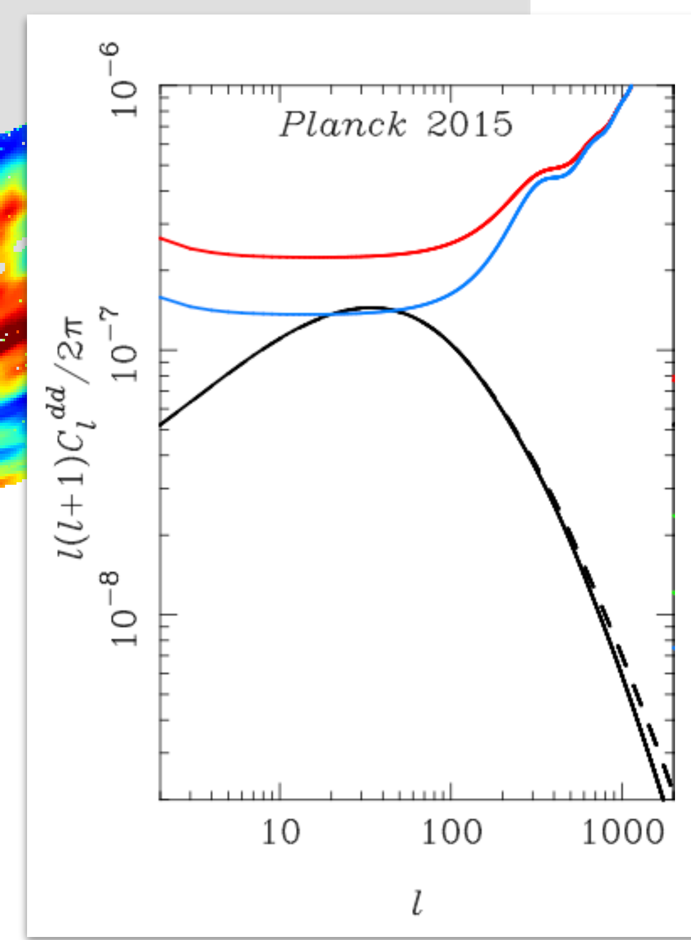


graphic from ESA Website

CMB lensing

Planck lensing potential reconstruction (projected mass map).



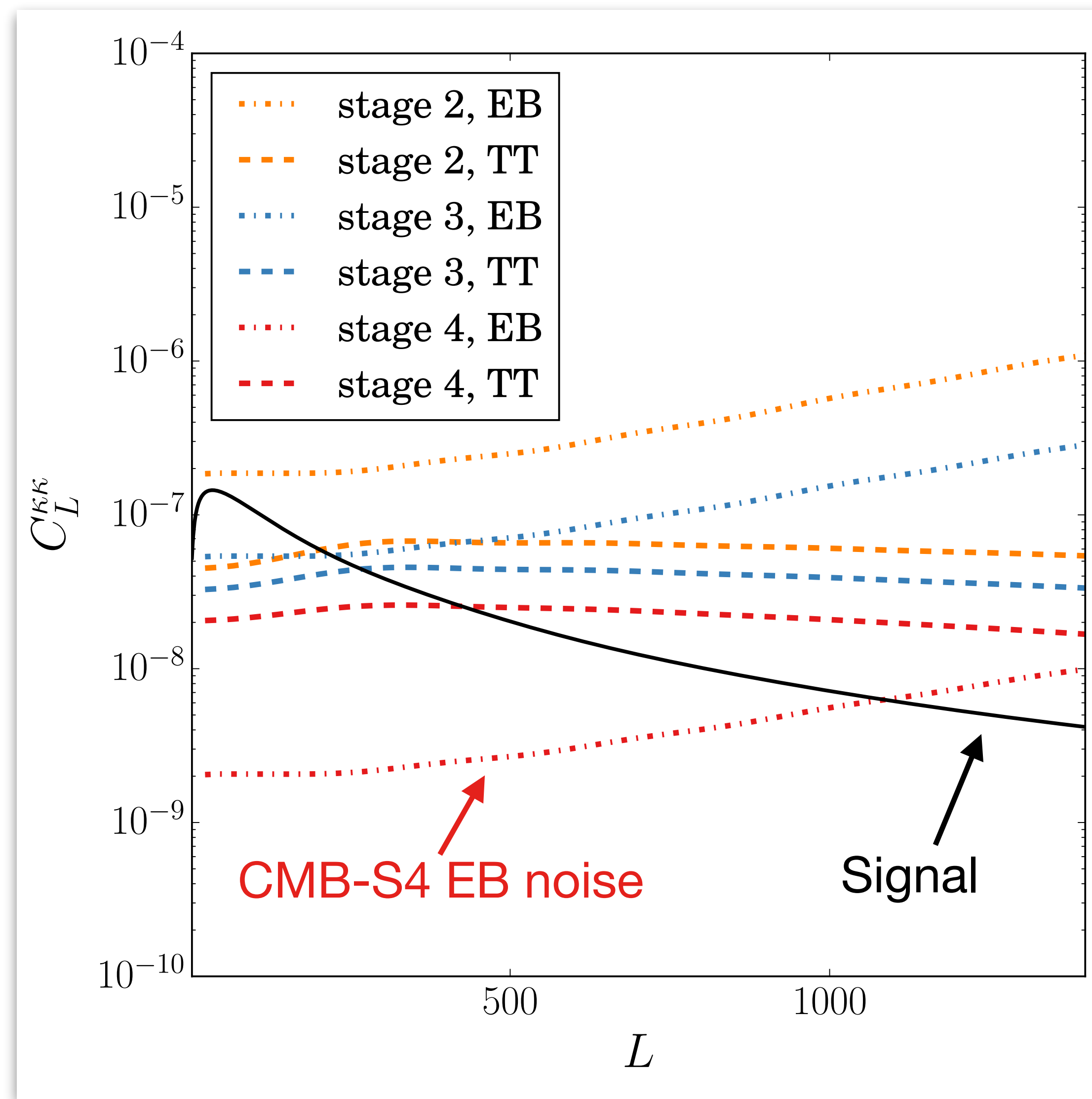


Planck XV (2015)

CMB lensing

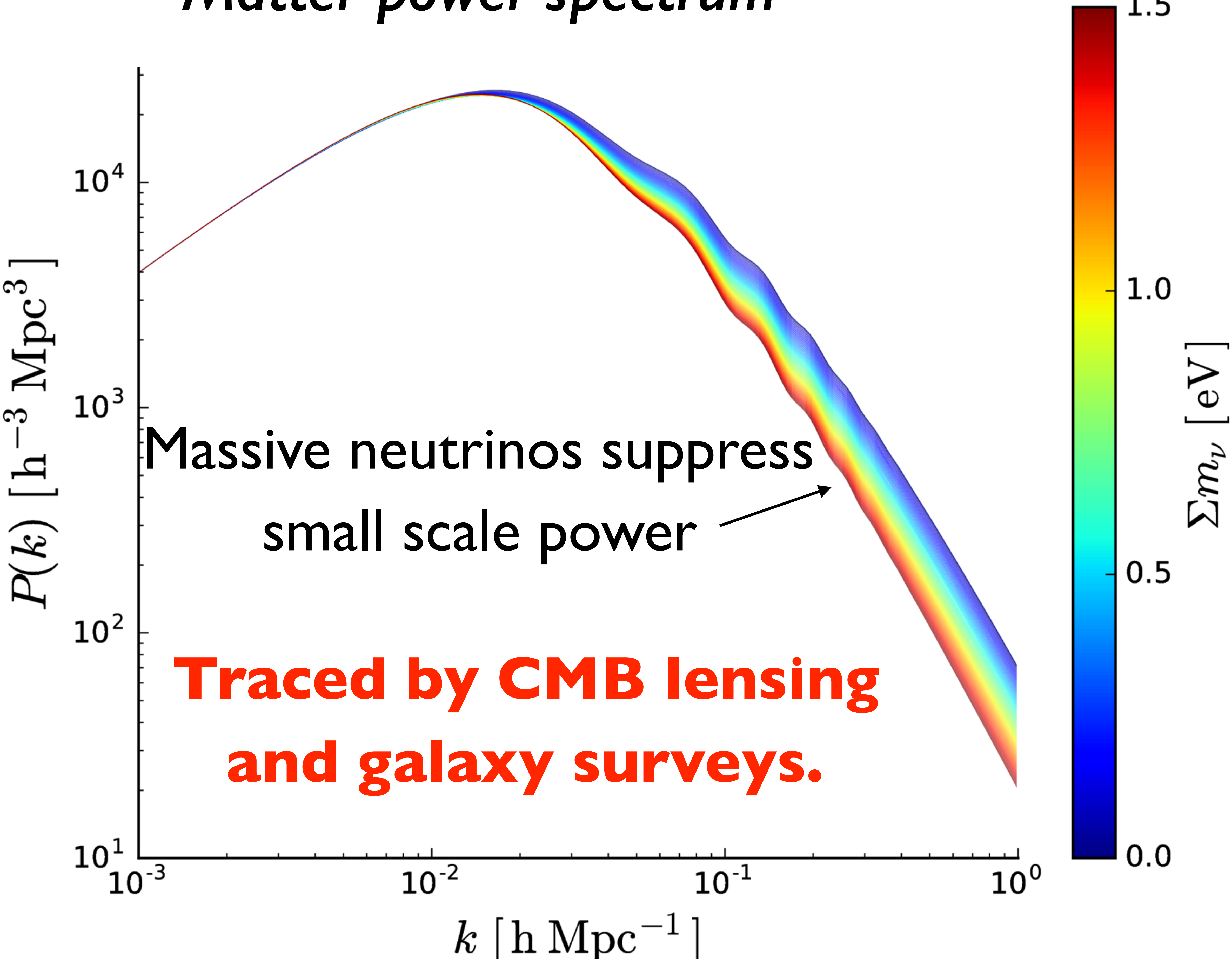
SPTpol 500d lensing potential reconstruction of BICEP field,
L < 250 imaged with s/n > 1.

preliminary
(removed for posting)

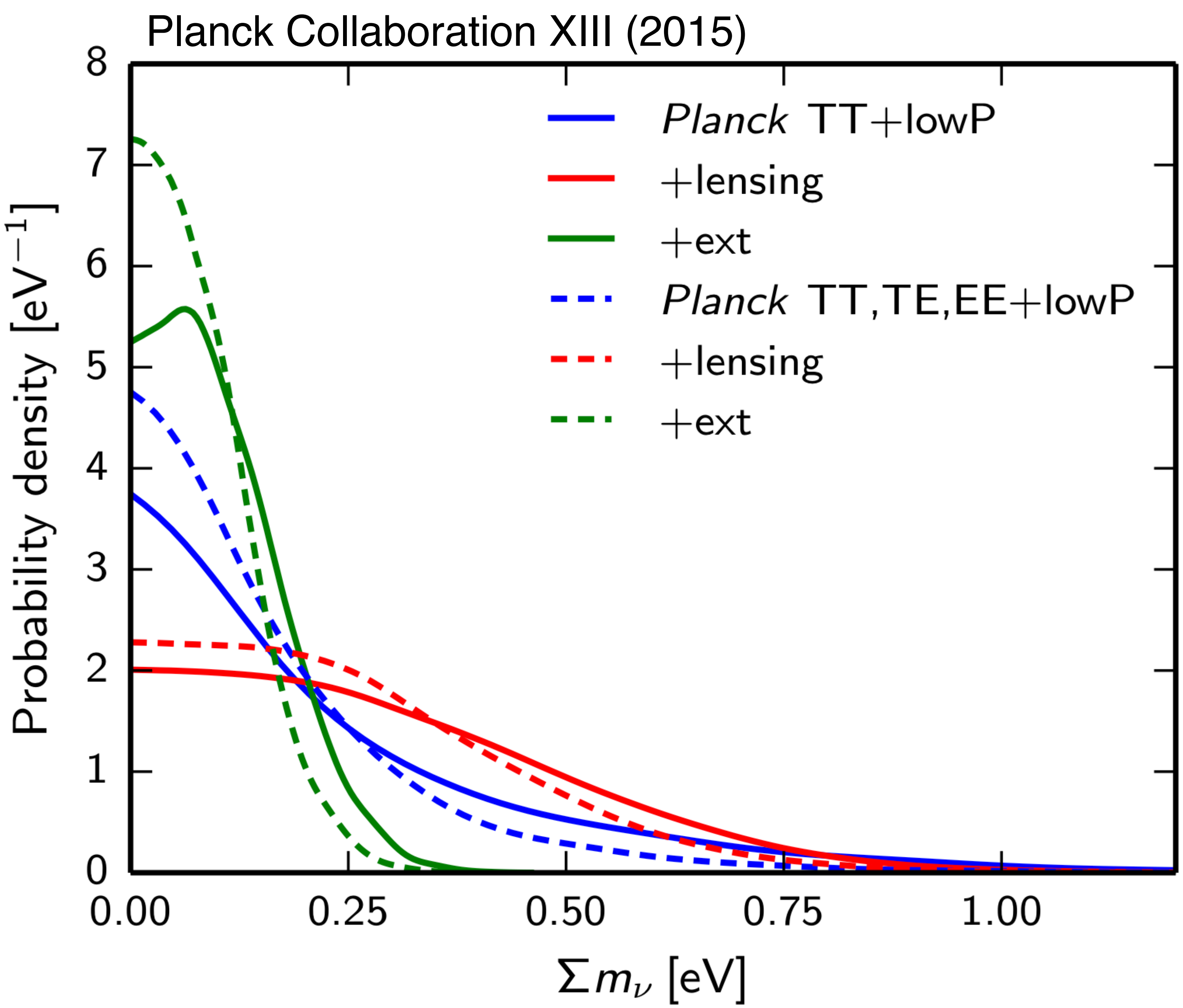


CMB-S4 will measure modes with s/n > 1 to L ~ 1100 over most of the sky.

Matter power spectrum



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:

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

N_{eff} is the extra relativistic energy density compared to photons.
For standard 3 neutrinos, N_{eff} = 3.046.

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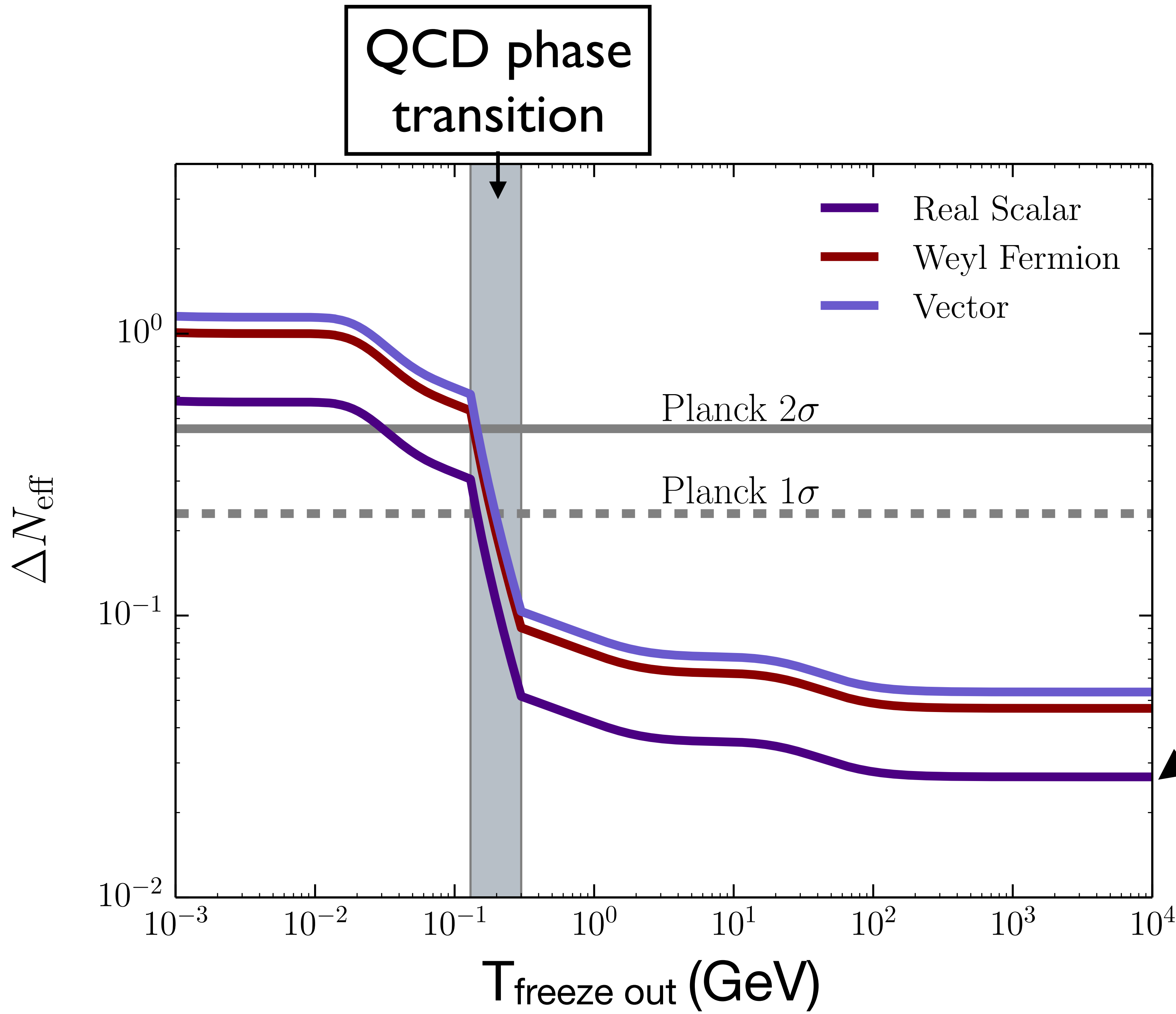
Next Generation CMB Experiment

N_{eff} constraints and light thermal relics



N_{eff} measurements can constrain light thermal relics

Sets natural, and exceedingly challenging, target of $\Delta N_{eff} = 0.027$

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

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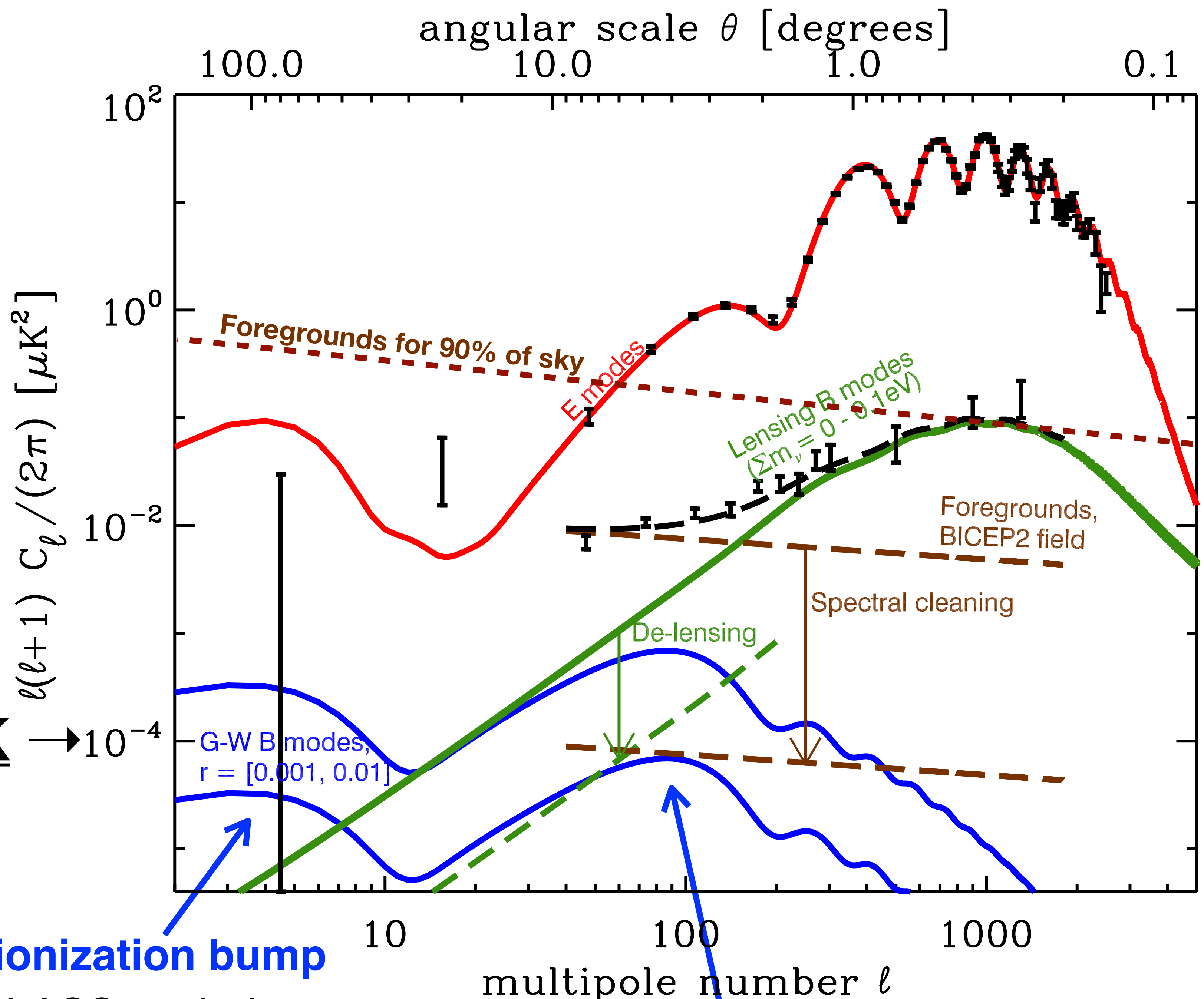
The path forward

- CMB science goals require ***much improved CMB polarization and CMB-lensing:***
  - Inflation: B-mode polarization and de-lensing
  - Neutrinos: N_{eff} or "dark radiation" requires de-lensed polarization spectra; $\sum m_\nu$ requires CMB-lensing (and τ_e).
  - Dark Energy: CMB-lensing correlations with galaxy surveys; CMB-lensing cluster calibration for SZ cosmology

and ***CMB-lensing requires much improved CMB polarization.***

→ we need CMB polarization!

Polarization future challenge



E modes

lensing
B modes

inflationary
gravity wave
B modes

10 nK

reionization bump
CLASS exploring
from the ground;
LiteBIRD, PIXIE, &
CORE satellites proposals

recombination bump
key target of CMB-S4

… still a long,
long way to go.

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Next Generation CMB Experiment

What's needed to realize CMB-S4

- **Scaling up:**
  - detectors, focal planes
  - sky area and frequency coverage
  - multiple telescopes; new designs
  - computation, data analysis, simulations
  - project organization, management
- **Systematics:**
  - improved control, especially of foreground mitigation
- **Theory/phenomenology:**
  - Increased precision for analysis; new methods

Scale of CMB-S4 exceeds capabilities of the University CMB groups.

→ Partnership of CMB community and National labs will do it.

Community workshops to advance CMB-S4

U. Minnesota
Jan 16, 2015

U. Michigan
Sep 21-22, 2015

LBNL, Berkeley
March 7-9, 2016

Next: UChicago Sep19-21 2016
Please attend - register at
https://kicp-workshops.uchicago.edu/cmb-s4-2016

1st edition Science Book complete
http://cmb-s4.org
Next: conceptual design and iterate with science goals

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CMB-S4 Science Book

download Science Book
and sign up as "endorser"
at http://cmb-s4.org

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

CMB-S4 Science Book
First Edition

CMB-S4 Collaboration

August 1, 2016

This advanced copy is being provided prior to posting with the list of contributors on the public archive.

Strawman CMB-S4 specifications

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- **Surveys:**

  - Inflation, Neutrino, and Dark Energy science requires optimized surveys using a range of resolution and sky coverage from deep to wide

- **Sensitivity:**

  - ~1 uK-arcmin for $f_{sky} \gtrsim 40\%$ and considerably deeper on targeted fields (access to ≳70% of total sky, including galaxy)

- **Configuration:**

  - *O*(500,000) detectors on multiple telescopes,
  - **spanning ~ 30 - 300 GHz for foreground mitigation**

- **Resolution:**

  - exquisite **low-ℓ and high-ℓ** sensitivity for inflationary B modes with delensing
  - arc minute for CMB lensing & neutrino science
  - higher resolution improves sensitivity to dark energy, gravity tests, mapping the universe in momentum with SZ effects, and ancillary science.

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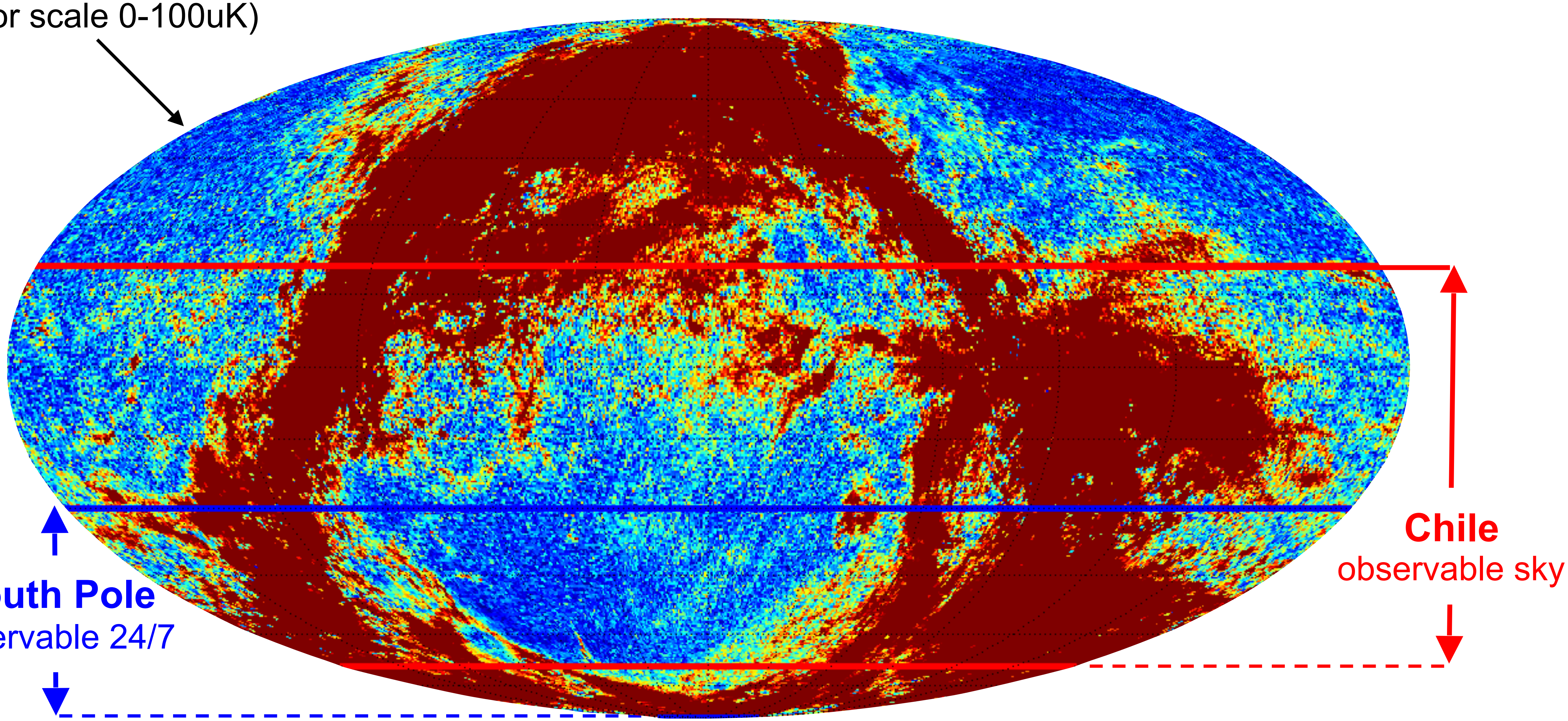
Telescopes at Chile and South Pole (established and proven CMB sites)

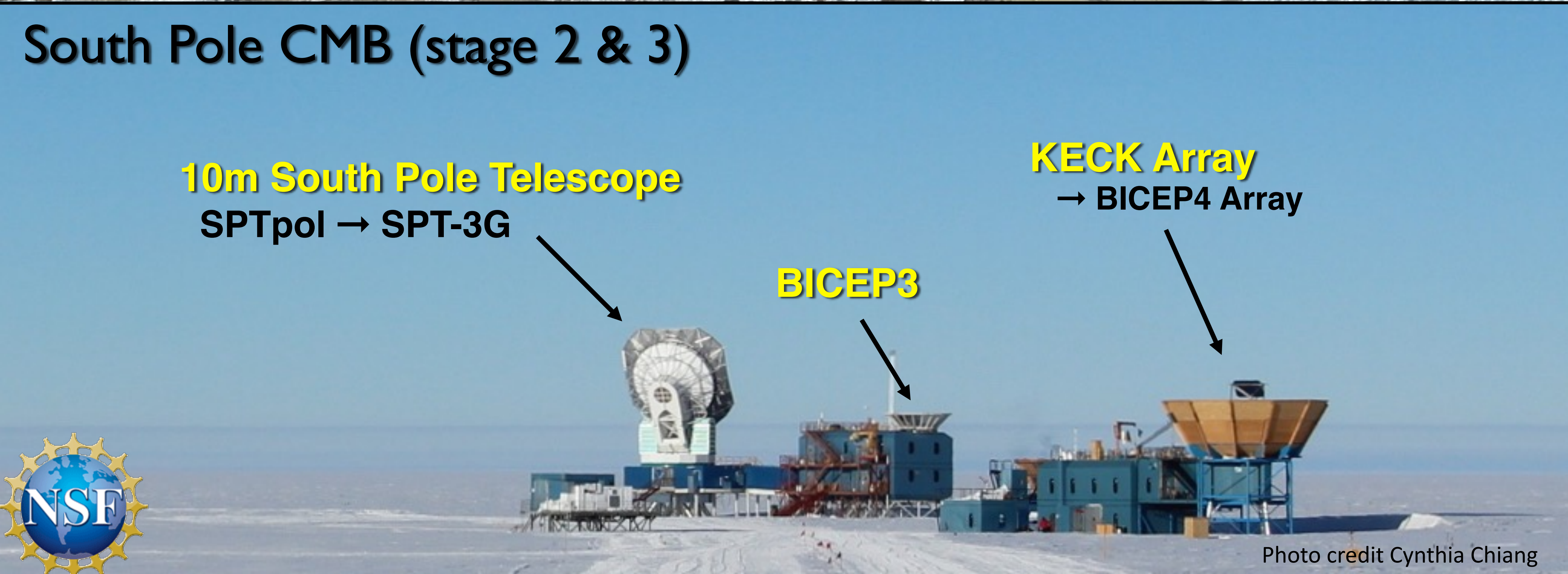
Planck 353GHz polarized intensity map in celestial coordinates (color scale 0-100uK)



possibly add new northern site, e.g., Tibet, Greenland

Figure from Clem Pryke


Atacama CMB (stage 2 & 3)
Stage-2 ~ 1000 detectors
Stage-3 ~10,000 detectors
CLASS 1.5m x 4
Simons Array
(Polarbear 2.5m x 3)
ACT 6m
ACTPol → AdvACTpol
Photo: Rahul Datta & Alessandro Schillaci


South Pole CMB (stage 2 & 3)
10m South Pole Telescope
SPTpol → SPT-3G
BICEP3
KECK Array
→ BICEP4 Array
Photo credit Cynthia Chiang

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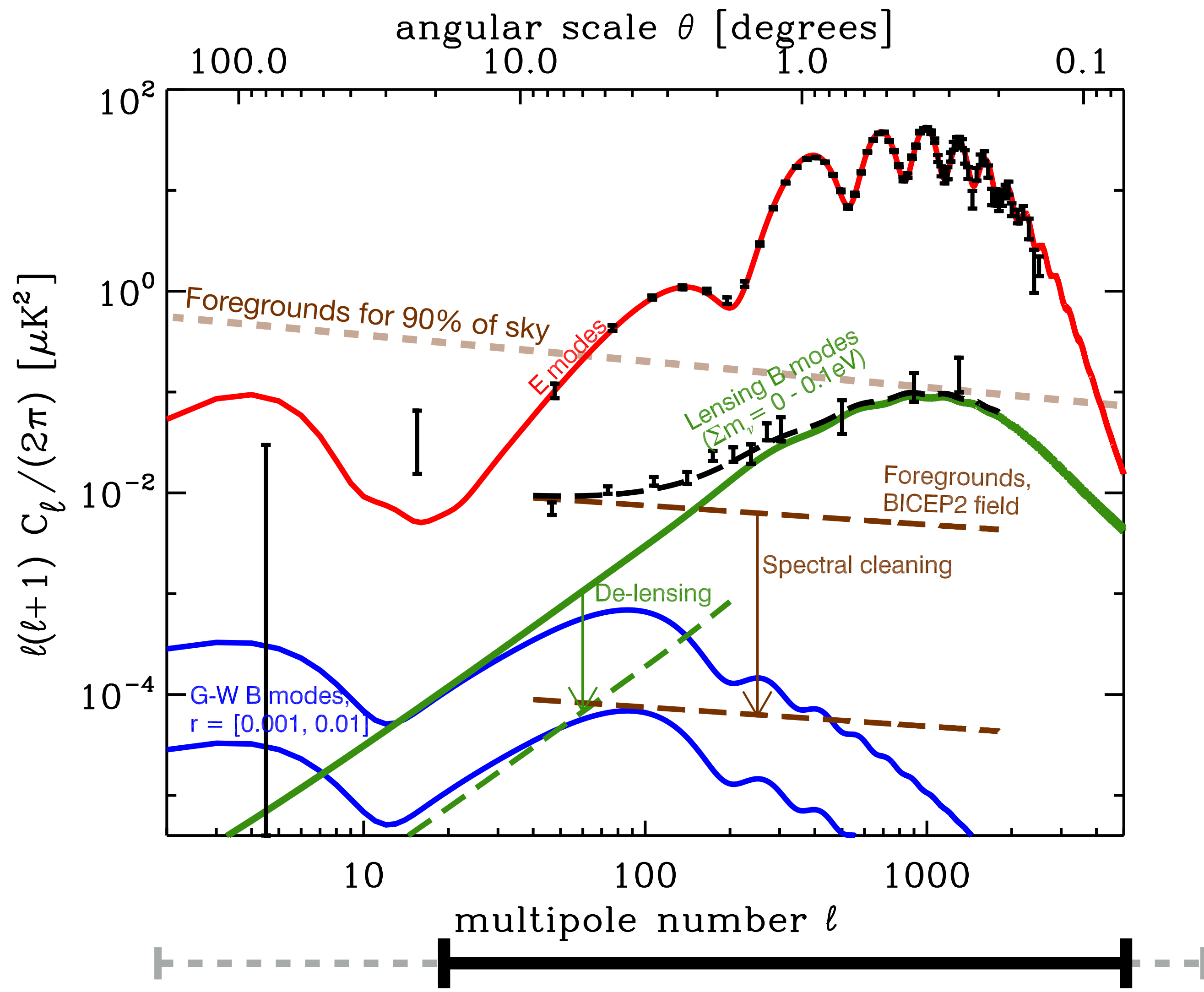
Angular range of CMB-S4

- Inflationary B modes search requires exquisite sensitivity at recombination bump ($\ell \sim 100$) and high-ℓ for de-lensing.
- High-ℓ and large area for CMB lensing cosmic variance limited constraints on neutrino mass and N_{eff}
- Higher-ℓ for dark energy, gravity tests and to probe reionization, via SZ effects



ℓ range of CMB-S4

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Next Generation CMB Experiment

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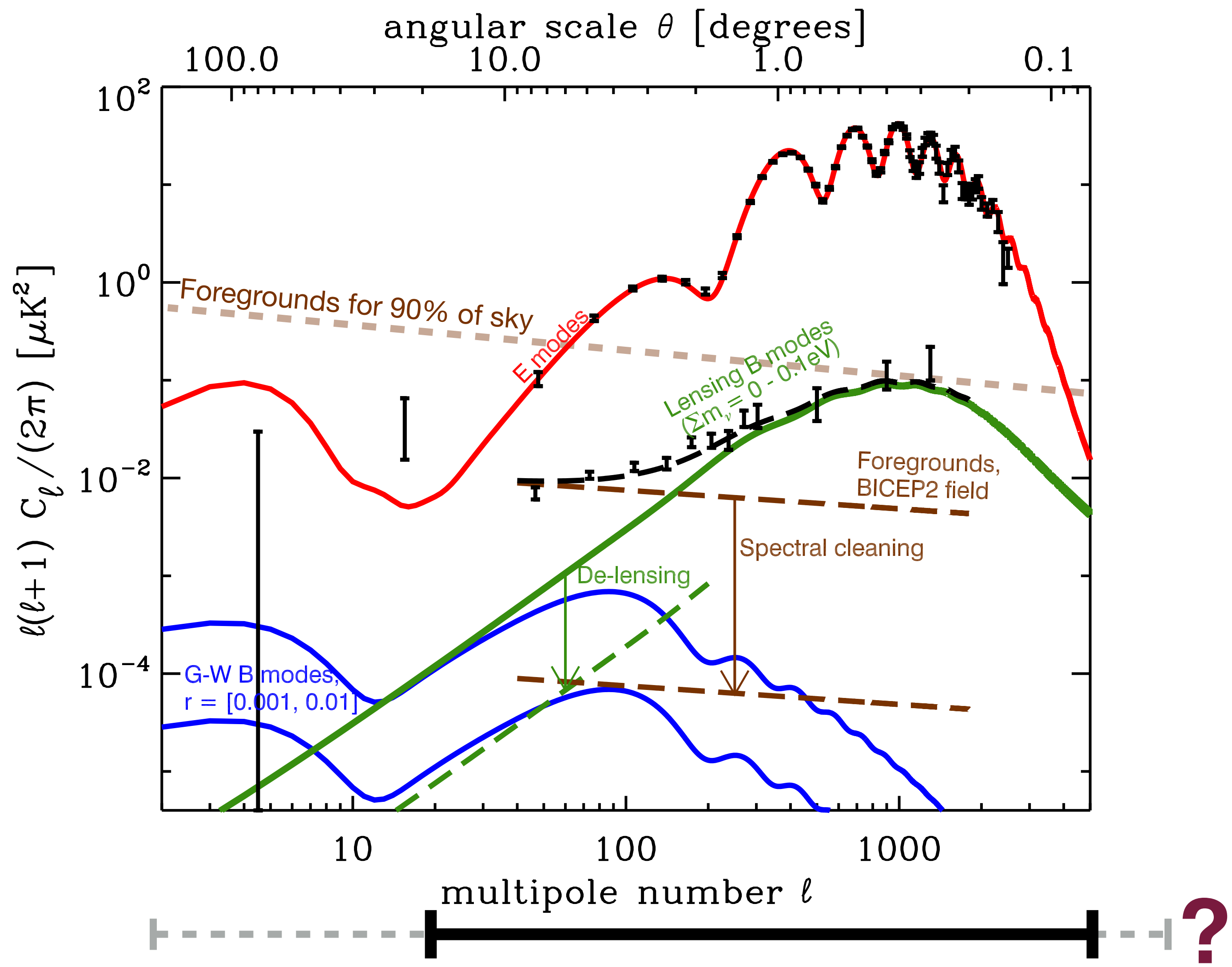

ℓ range of CMB-S4

There will be dedicated high-ℓ science session at the upcoming Chicago CMB-S4 workshop.

Angular range of CMB-S4

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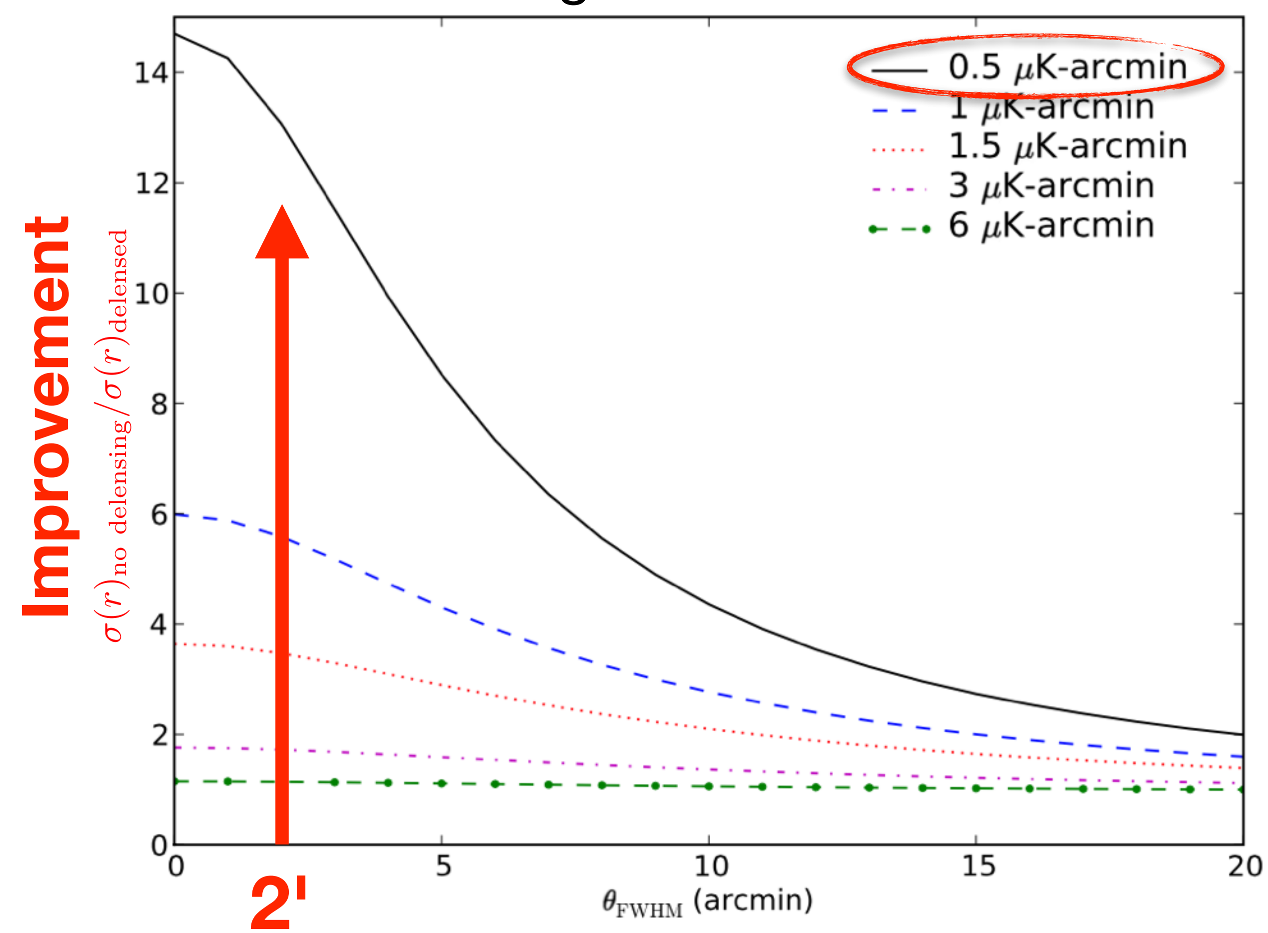
De-lensing Improvement on σ(r)
vs Angular Resolution



Angular resolution (arcmin)

from Smith et al., CMBpol Mission Study arXiv:0811.2916

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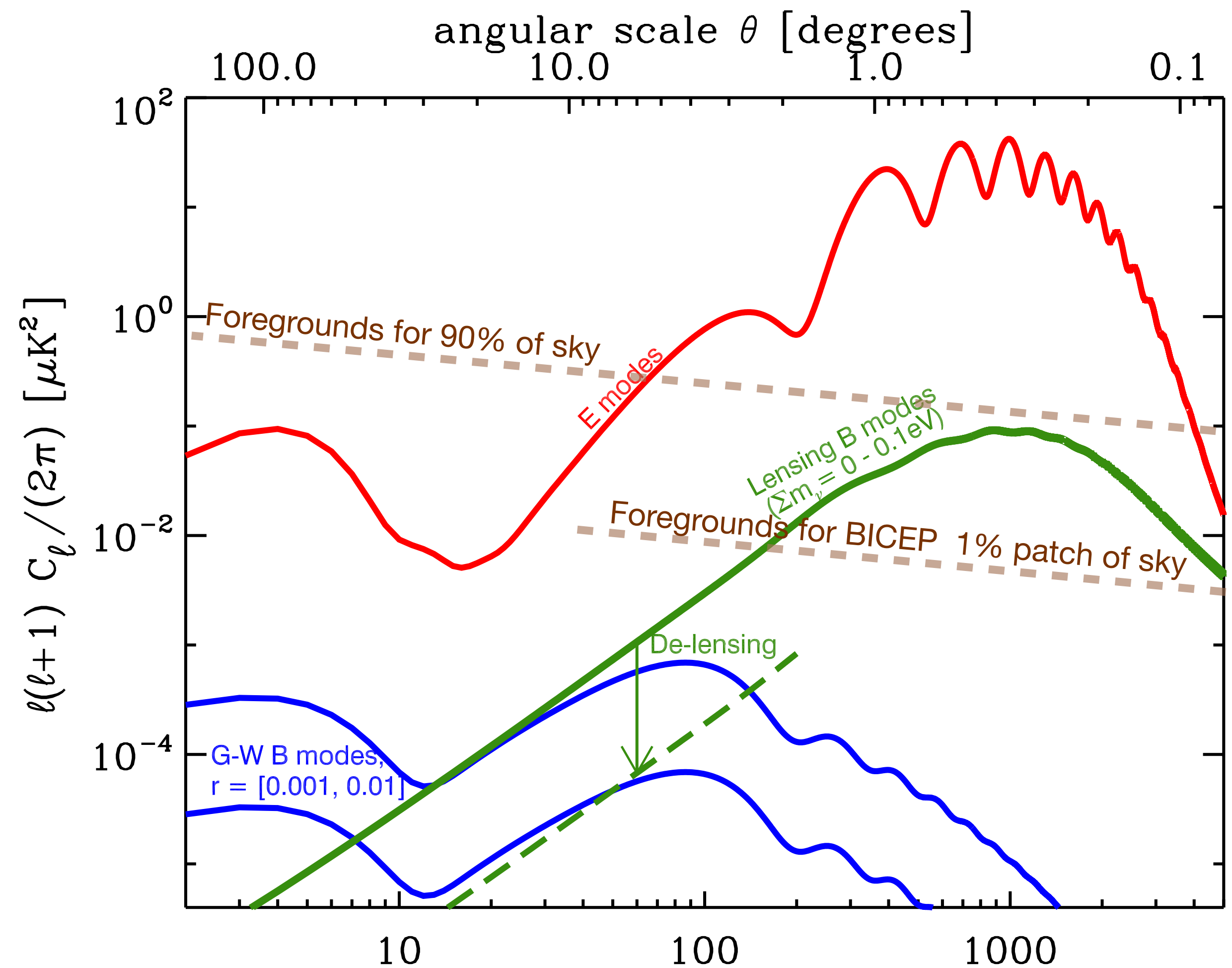
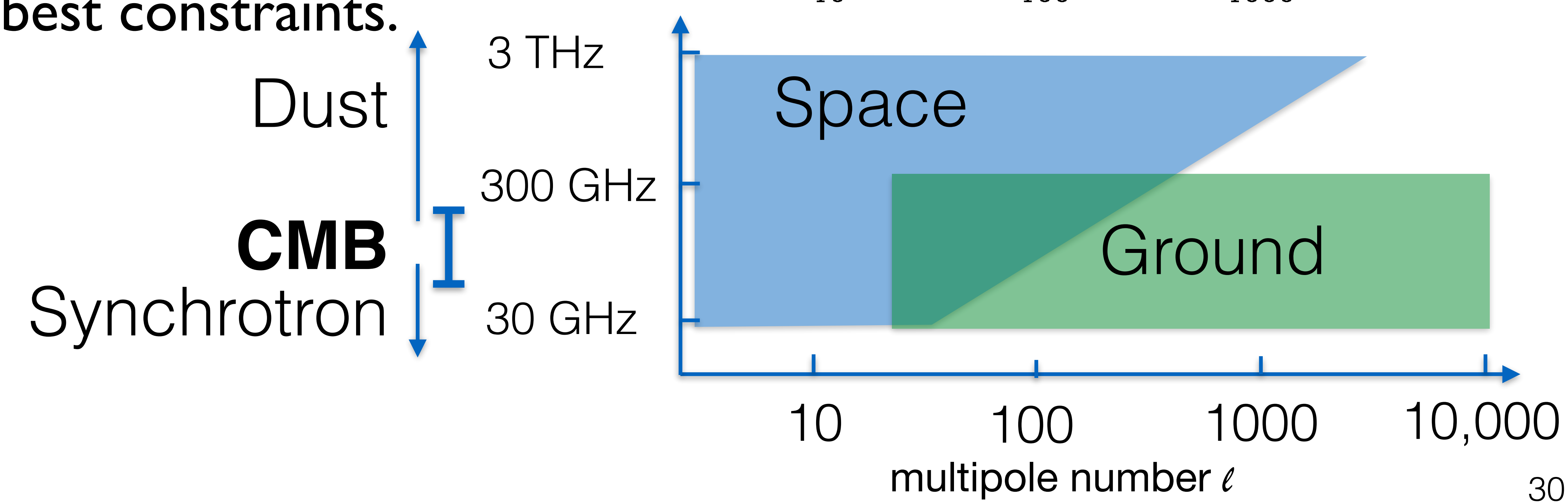
Complementary strengths of ground and space

- **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.





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"starting point" for Science Book forecasting

• Survey to target r

- Array of small-aperture (~1m) telescopes, and separate large-aperture telescopes for de-lensing
- 250,000 detectors x 4 years → 10^6 detector years split over as many as 8 frequency bands (2 per atmospheric window)
- real-world inefficiencies included

→ ***investigate split of small and large telescopes effort, sky area, residual lensing noise, detector count, band selection for foreground mitigation***

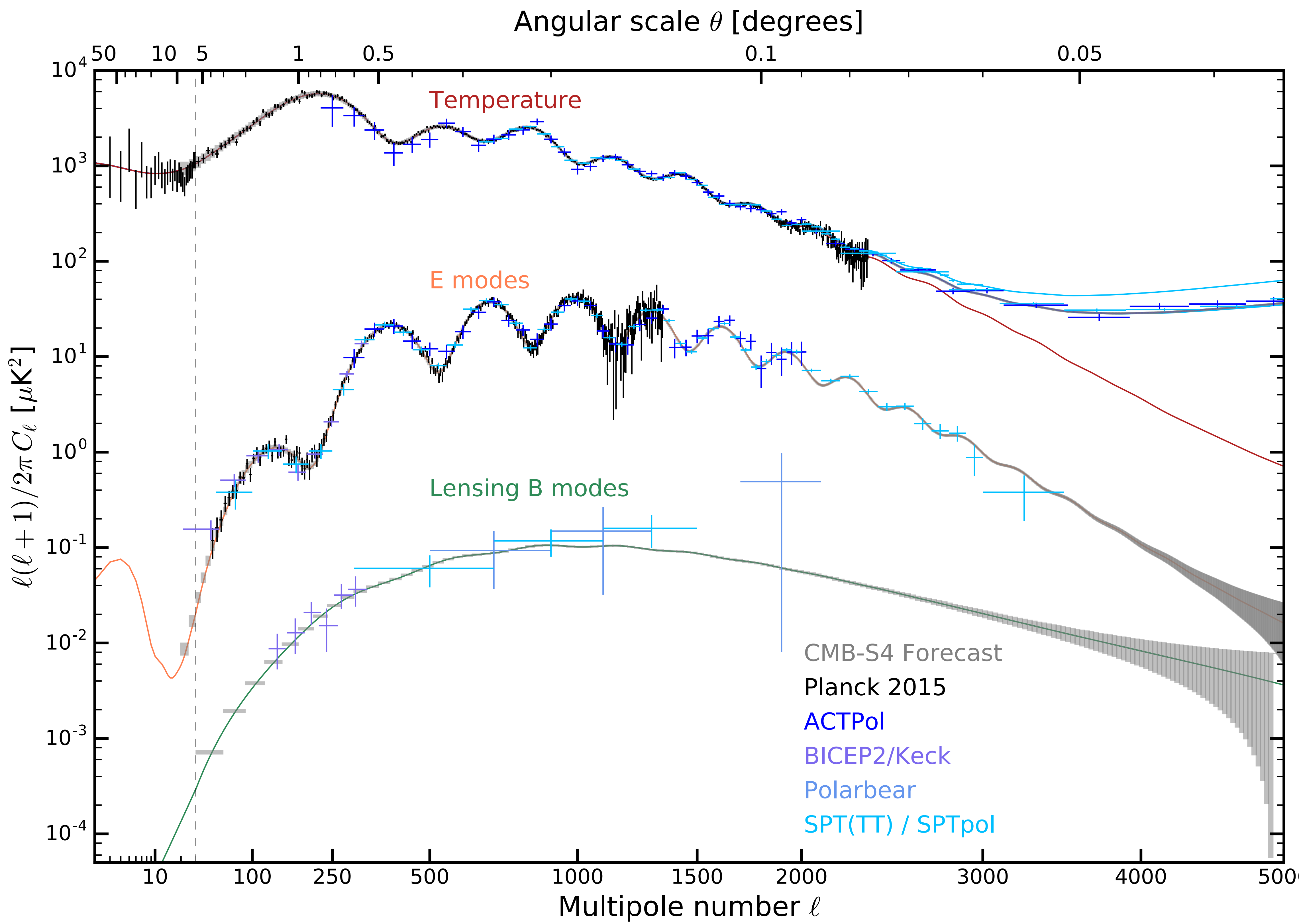
• Survey to target non-r

- Array of large-aperture telescopes, with 10^6 detector years with few frequency bands
- useable sky fraction, f_{sky} = 40%

→ ***investigate angular resolution, sky coverage, and detector count on neutrino, light-relic, and dark energy science goals***

CMB-S4
Next Generation CMB Experiment

Science Book projection for nominal CMB-S4 configuration



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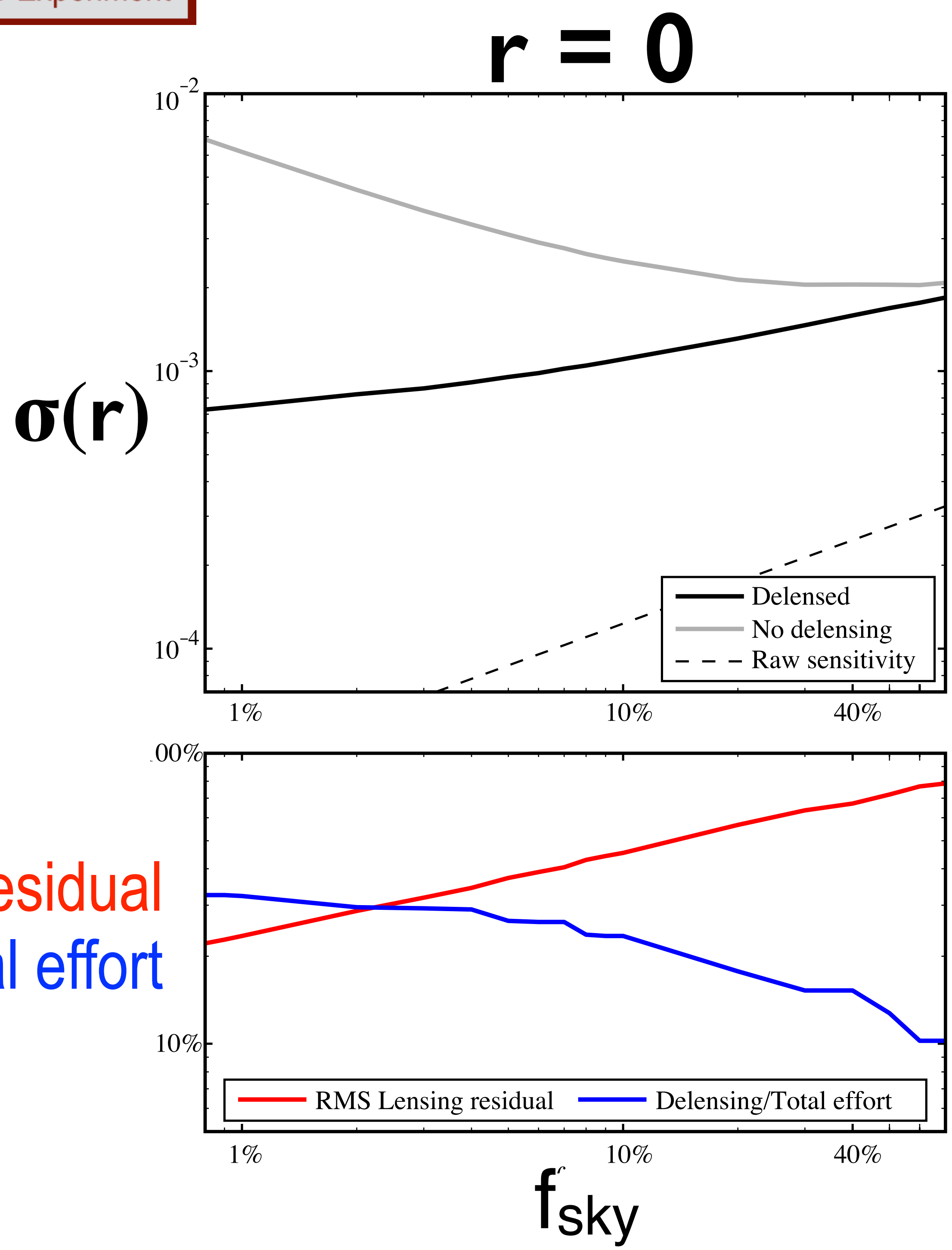
Next Generation CMB Experiment

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



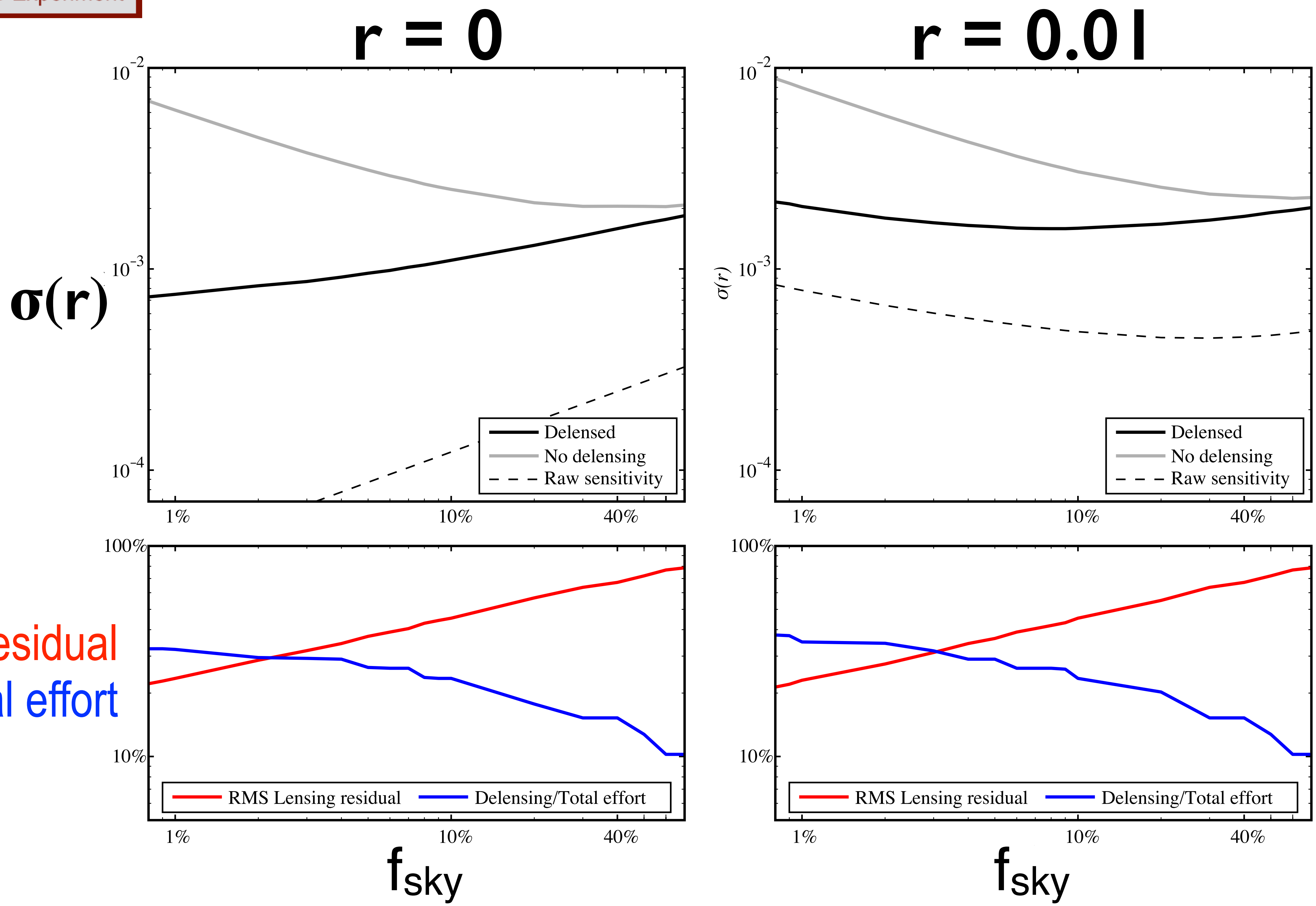
Caveat: assumes best foreground regions, so don’t trust $f_{sky} > 0.1$

BPCM (Bandpower Covariance Matrix) optimization of

- 8 CMB-S4 frequency bands: 30, 40, 85, 95, 145, 155, 215 & 270GHz
- 13 model parameters (including FG correlations and dust spectral power law index scatter)
- fraction of effort with arc minute telescopes and degree scale telescopes

by V. Buza, C. Bischoff & J. Kovac

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



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- fraction of effort with arc minute telescopes and degree scale telescopes

SB: V. Buza, C. Bischoff & J. Kovac

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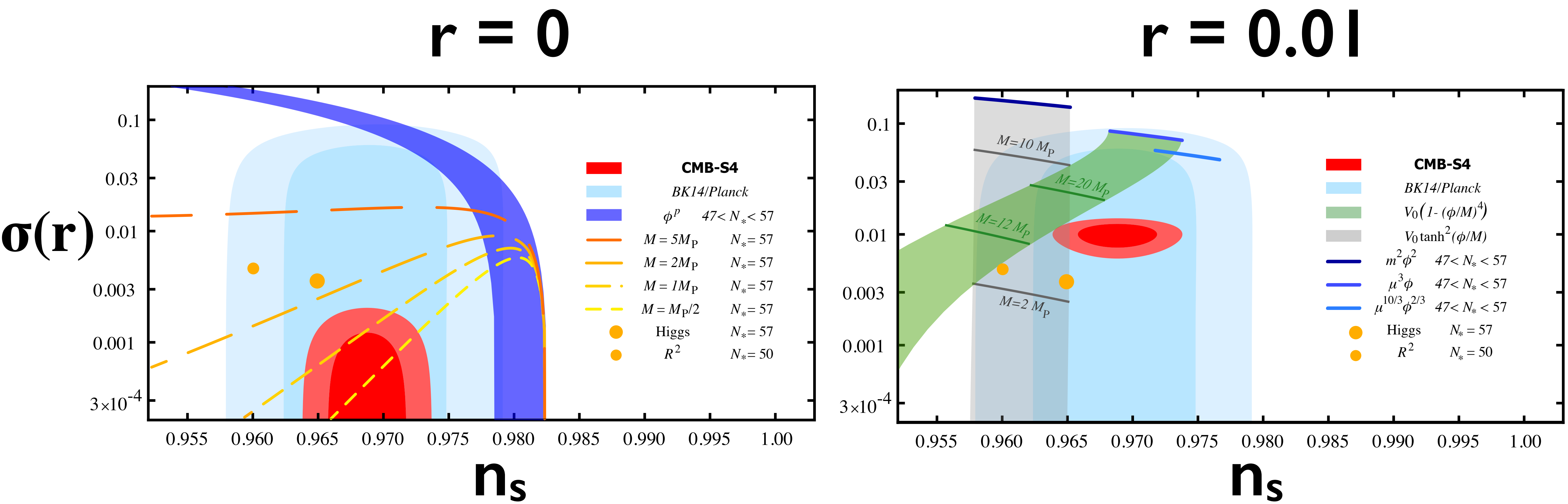
Example of optimization / projection of inflation reach of CMB-S4

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



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.

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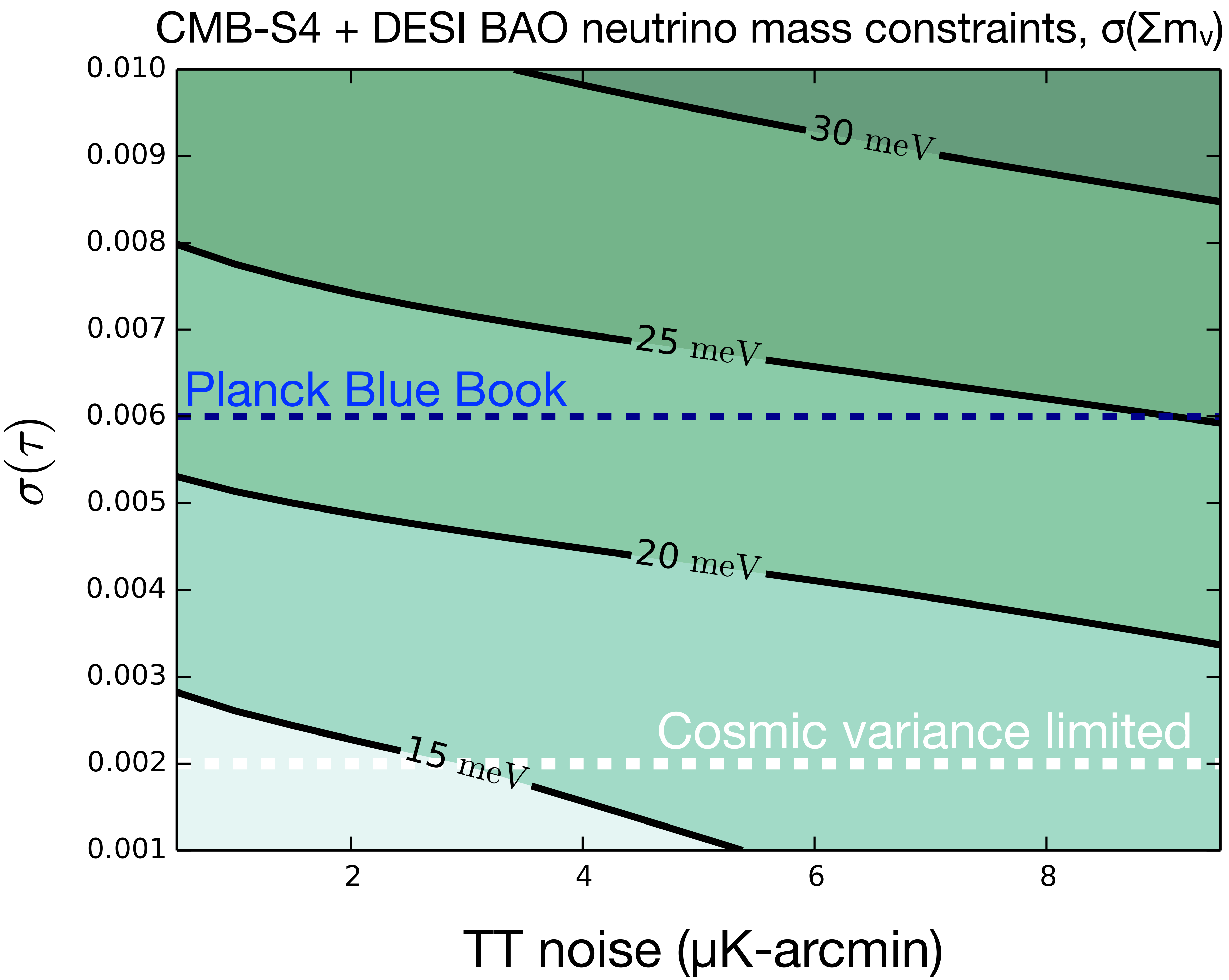
CMB-S4 projections for σ(Σm_ν)



σ(Σm_ν) limited primarily by uncertainty in τ_e

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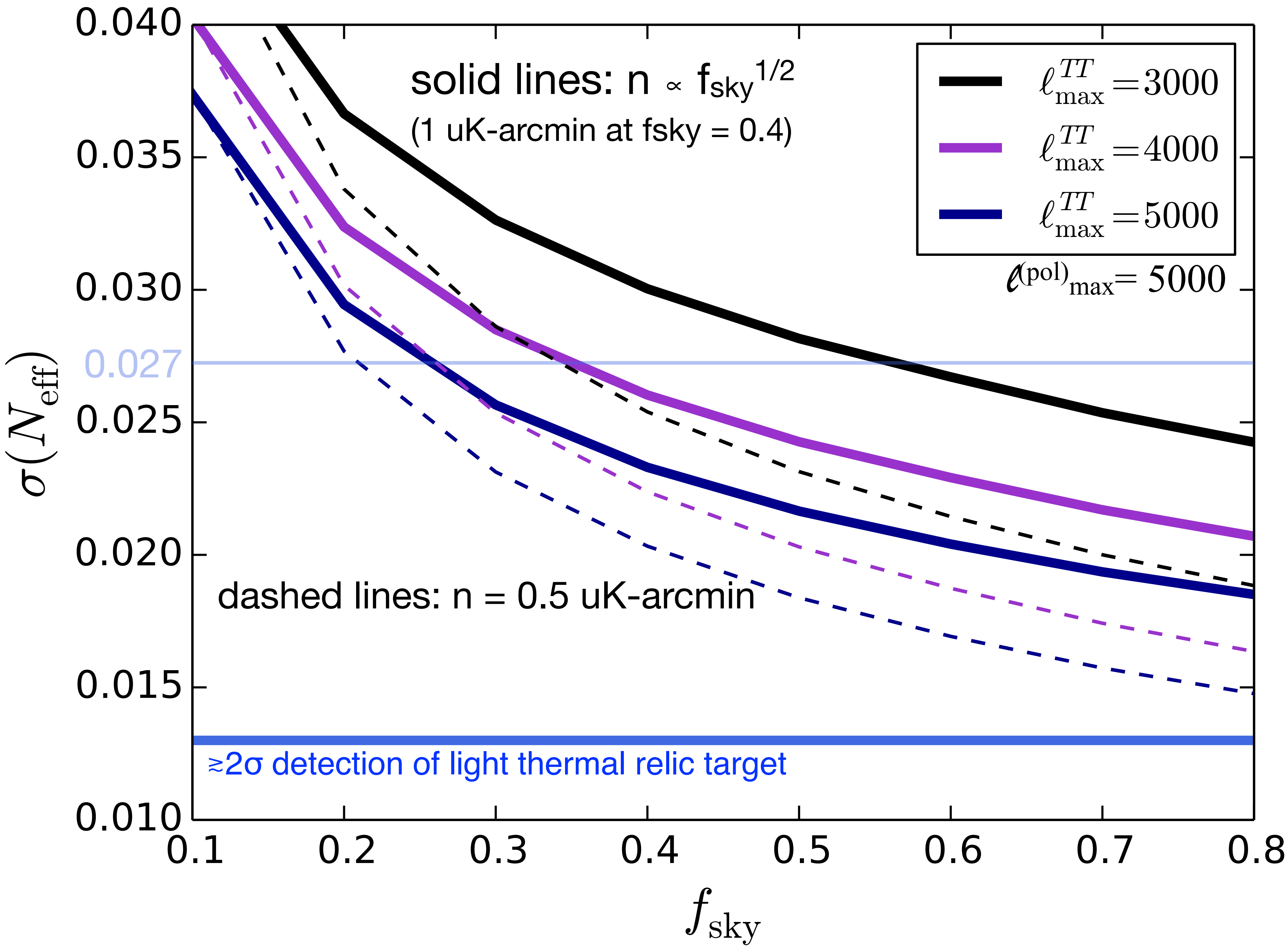
CMB-S4 projections for N_{eff}



$\sigma(N_{eff})$ target very challenging

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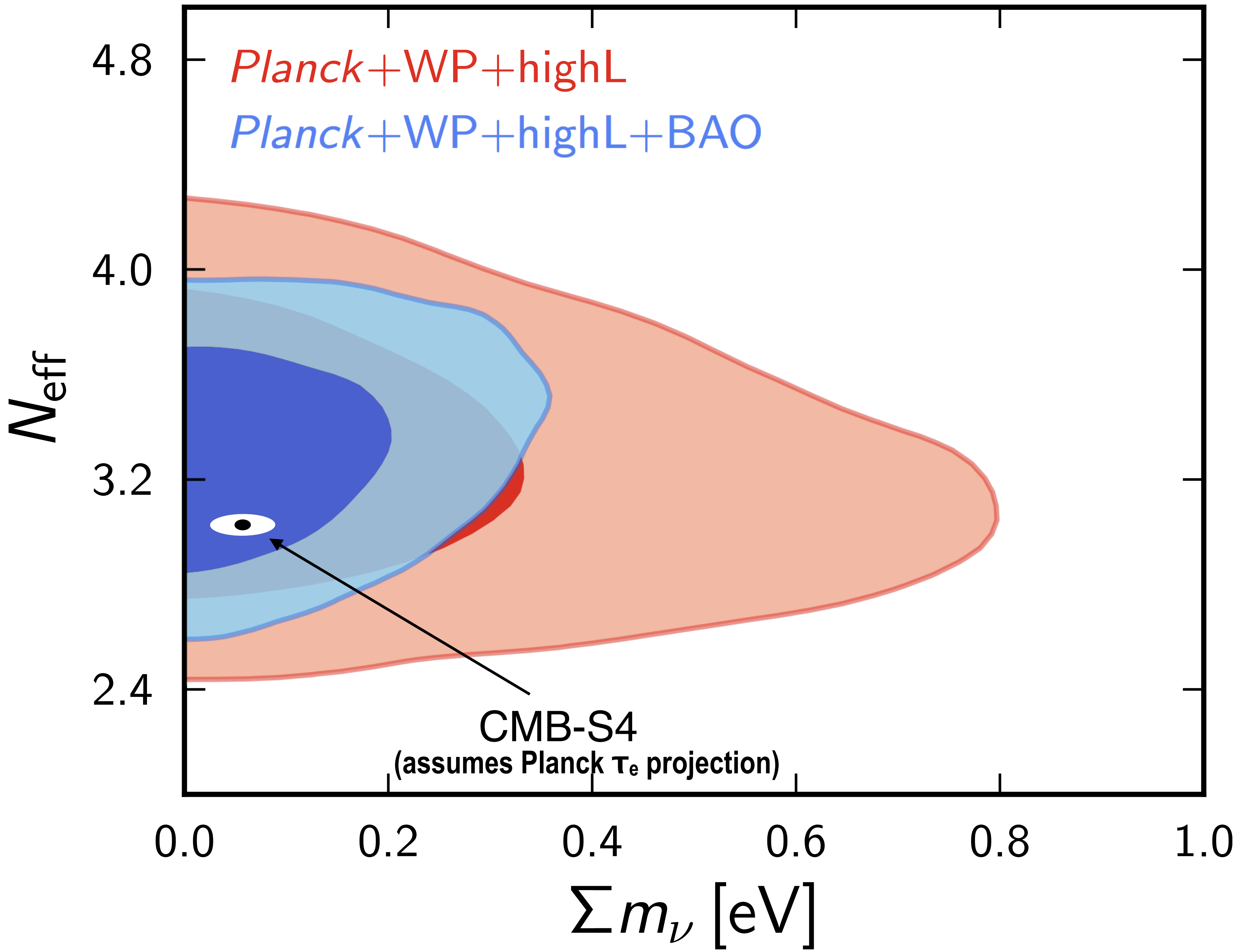
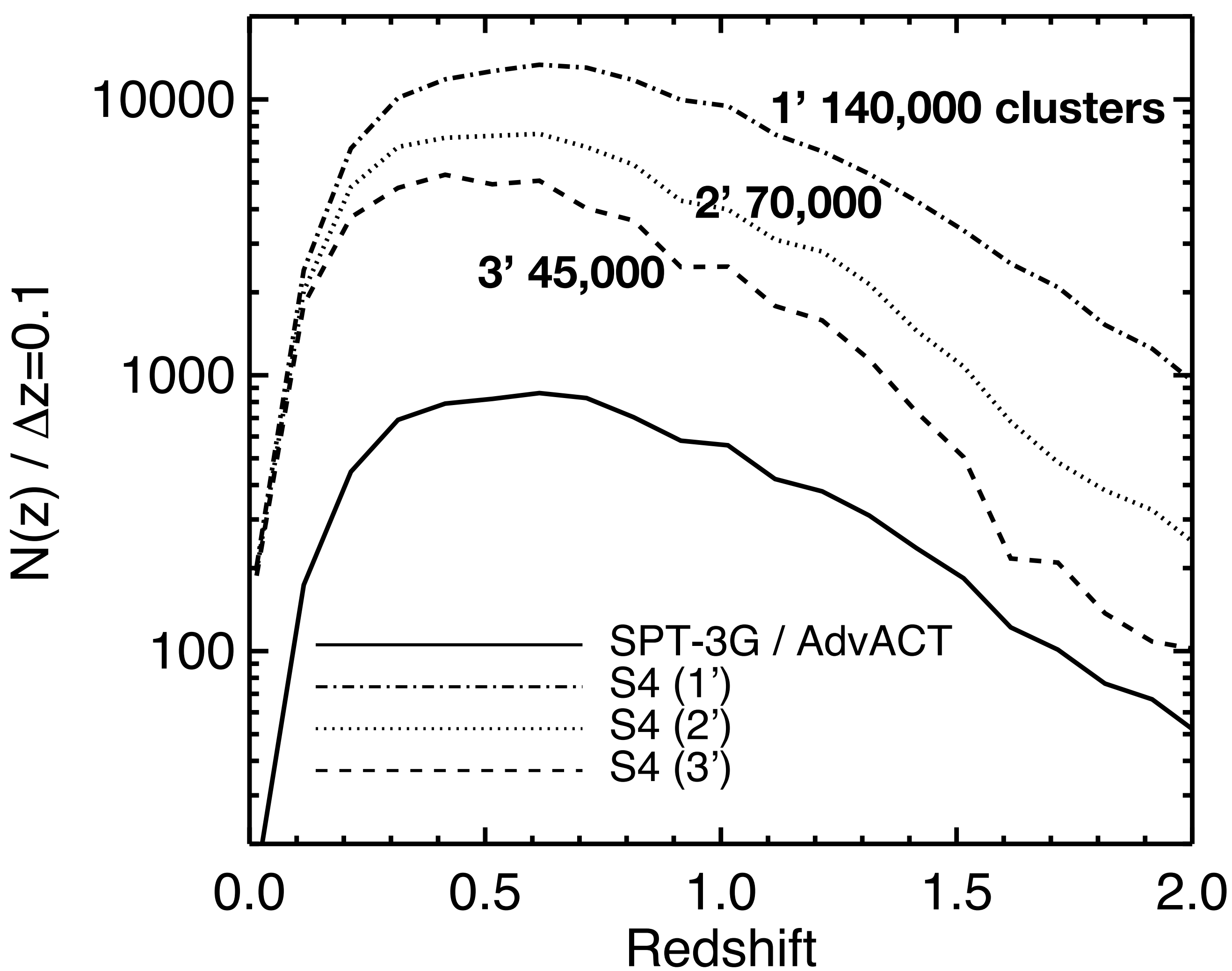
Projected CMB-S4 N_{eff} - Σm_ν constraints



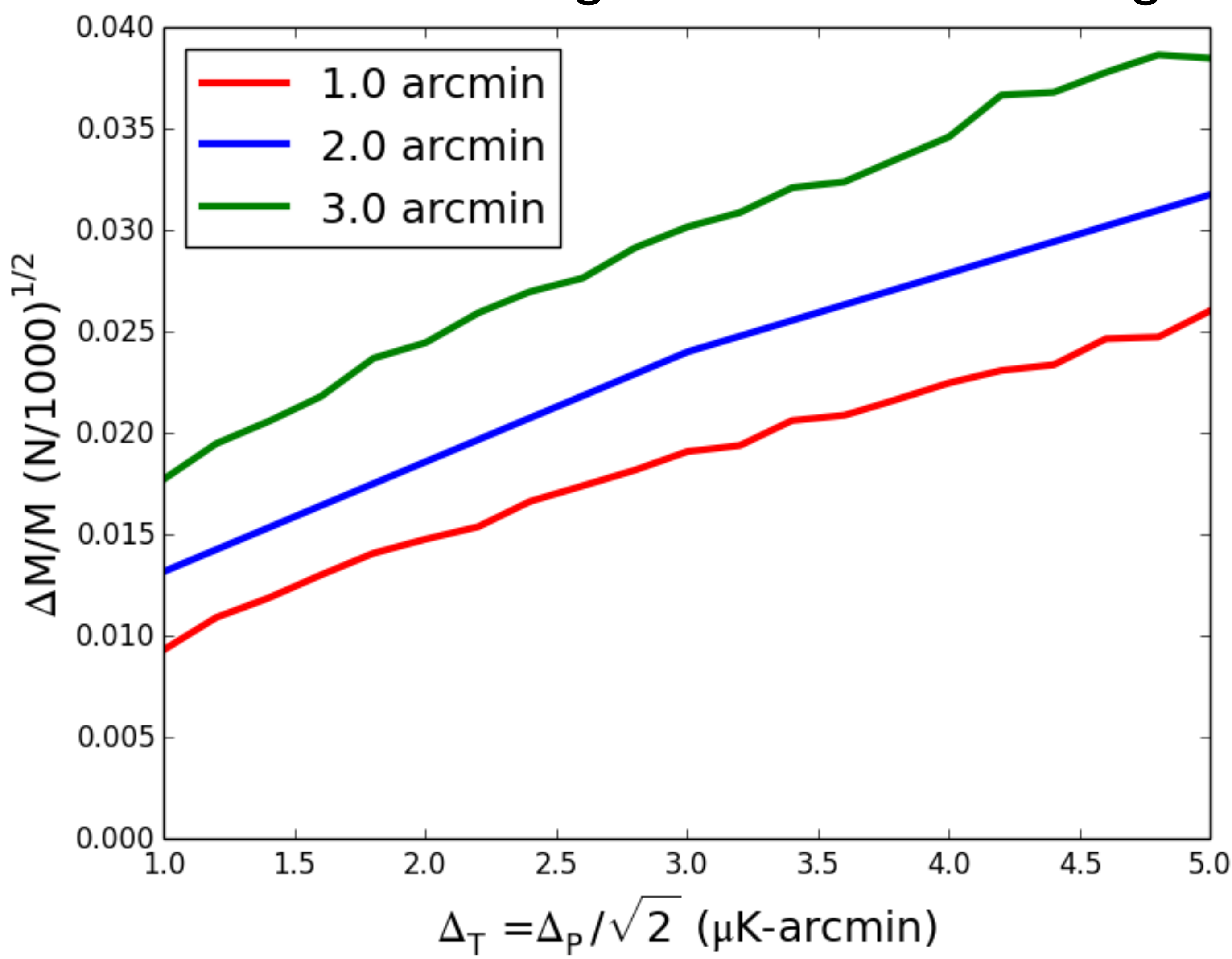
CMB-S4 forecast: arXiv:1309.5383; see also Wu et al, ApJ 788,138 (2014)*

CMB-S4 SZ cluster projections and lensing mass calibration for dark energy via growth of structure

CMB-S4 cluster count vs redshift



CMB-S4 lensing cluster mass scaling



Cluster sample and mass calibration strong functions of beam size

Especially important at z > 1.

Collaboration

- Community— university and labs —have delivered the Science Book.
- Now working on instrumentation white papers and conceptual designs (focus of upcoming workshops)
- NSF and DOE joint call for applications for a CMB-S4 Concept Definition Team (CDT).
- Starting to address project organization, including coordination of sites and partnerships.
- Target date for baseline design (CD2) 2020

CMB-S4
Next Generation CMB Experiment

Last words

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

The science is spectacular. We will be searching for inflationary gravitational waves and rigorously 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.