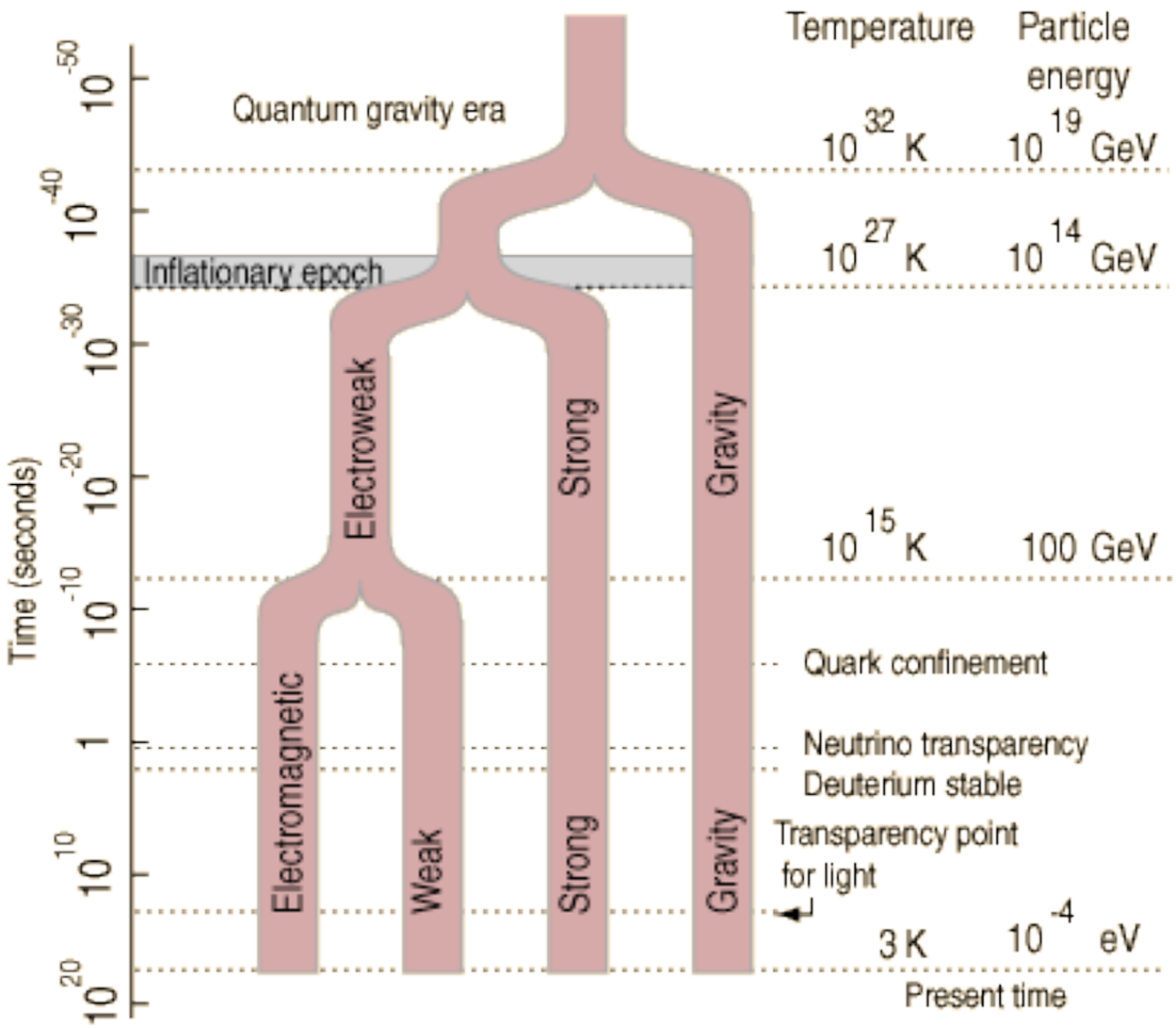
Beyond Planck:
Neutrino & GUT-Scale Physics from the Cosmos

John Carlstrom
for CF5 Inflation and Neutrino topical groups
(See CF5 documents)

Early universe as a HEP lab



Inflation

$$V^{1/4} = 1.06 \times 10^{16}\ \mathrm{GeV} \left(\frac{r}{.01}\right)^{1/4}$$

Cosmic neutrino background

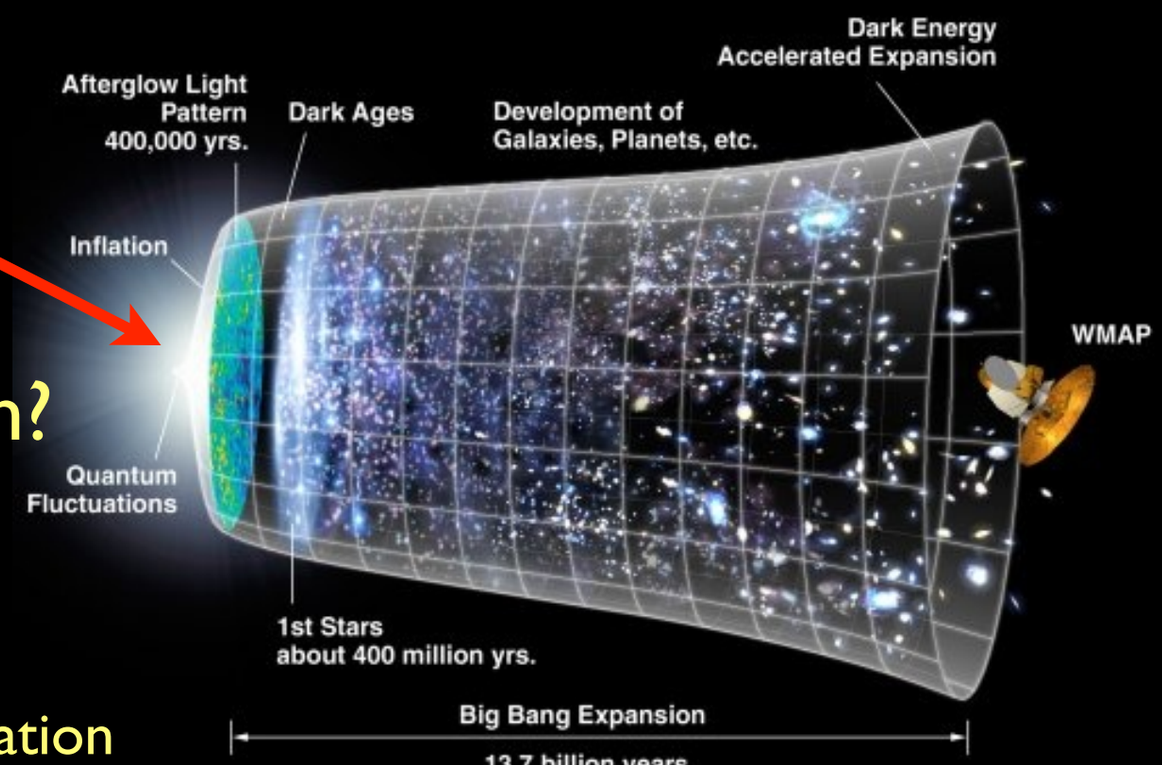
Cosmic microwave background

Inflation?

Universe expands by $>e^{60}$
solving smoothness problem,
flatness and more..

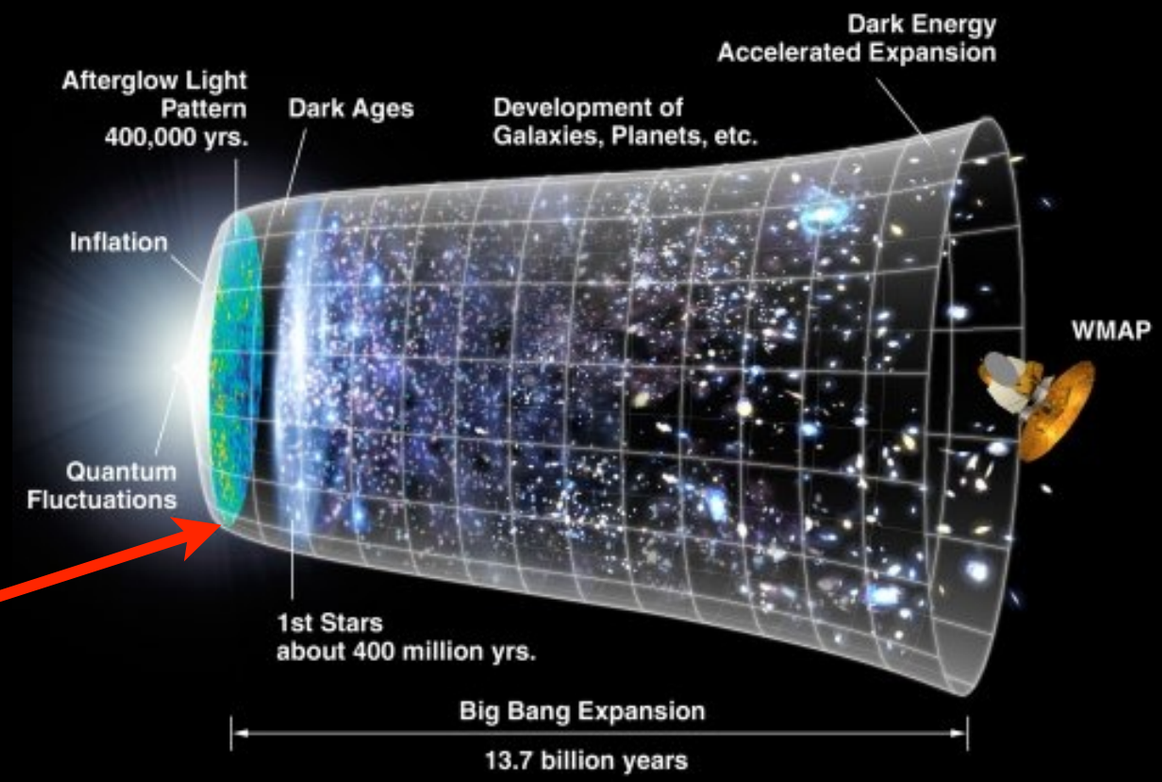
What drove inflation?
What is the energy scale of inflation?

- spectral index of fluctuations, n_s
- constrain tensor to scalar fluctuations
- inflationary gravitational wave B-mode polarization
- non-Gaussianity?



graphic from NASA/WMAP

Neutrinos?

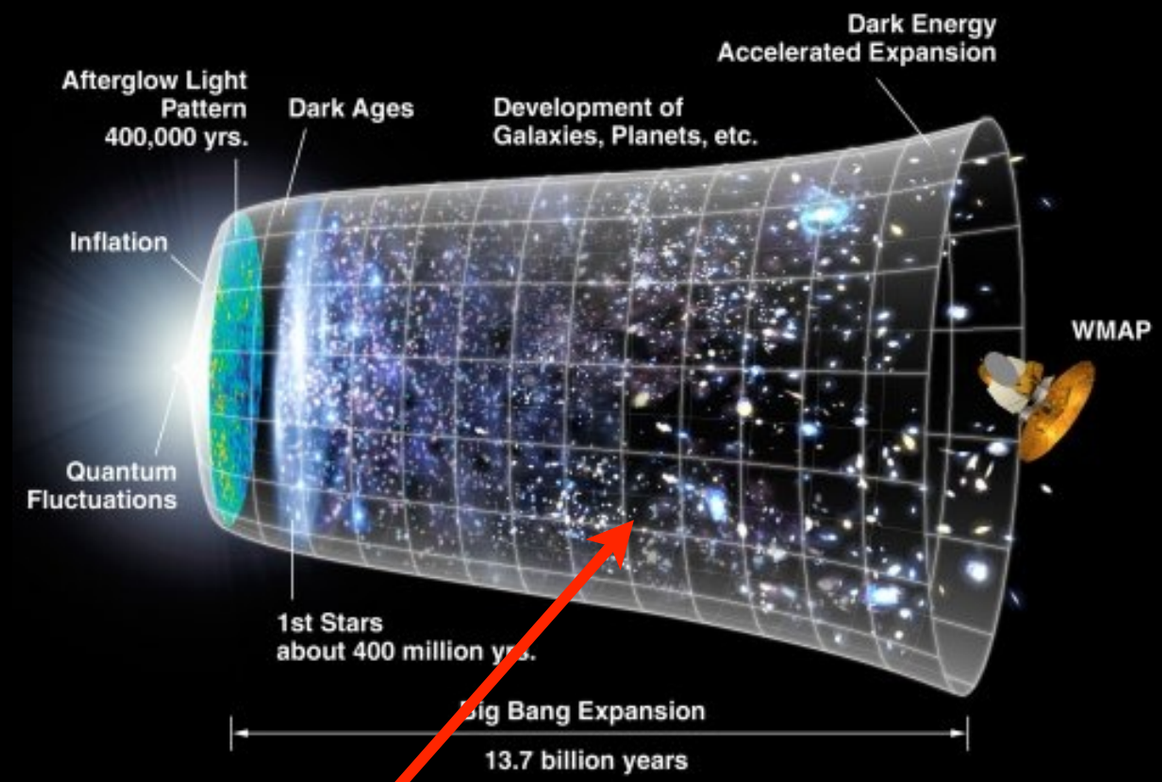


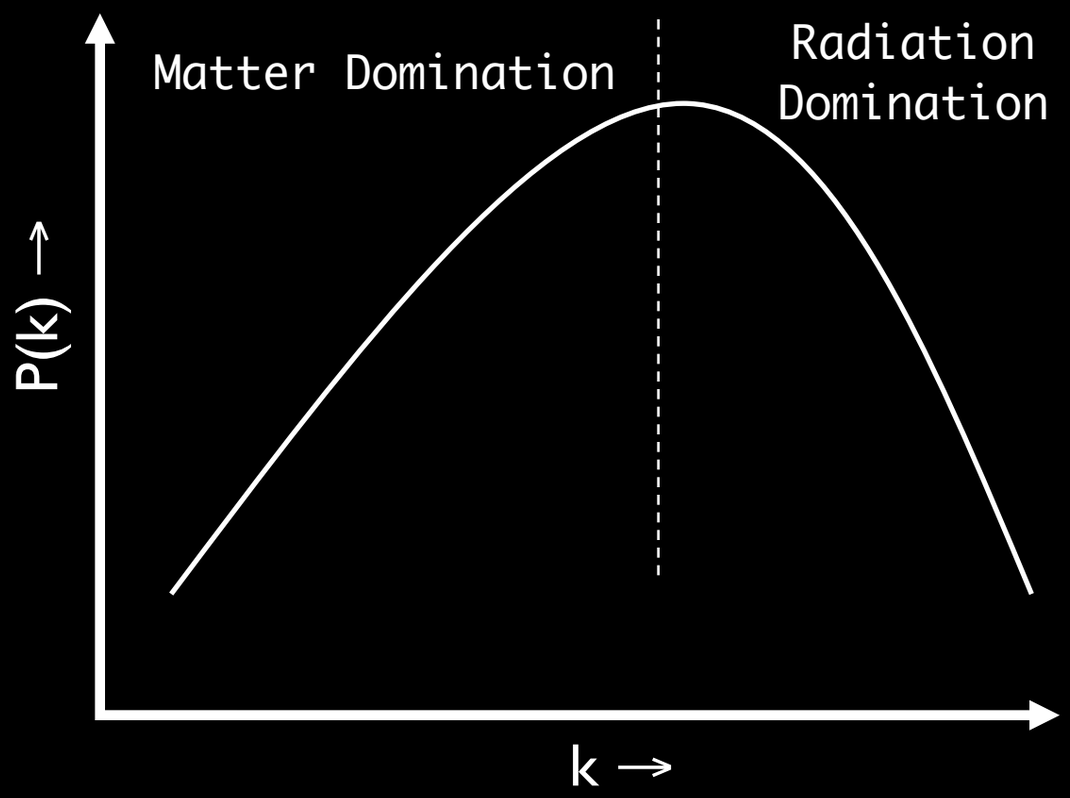
N_{eff}

Effective number of relativistic species
impacts intrinsic CMB power spectrum

graphic from NASA/WMAP

Neutrinos?



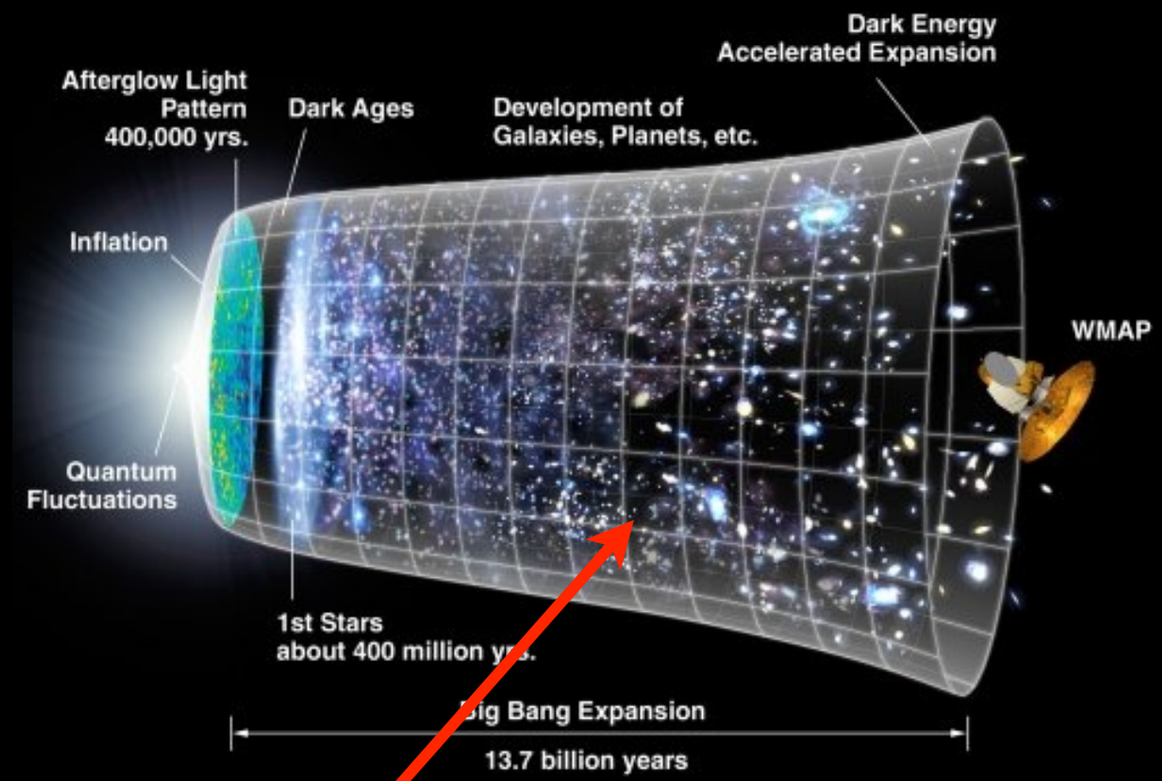


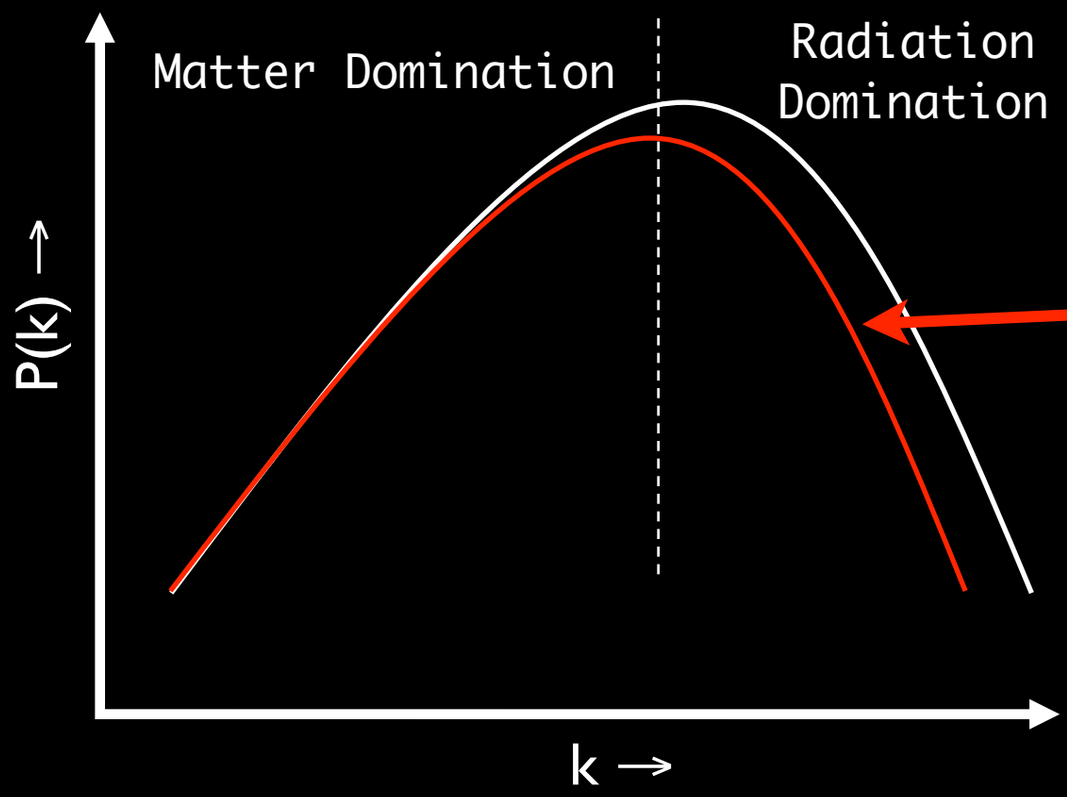
Σm_ν

Sum of the neutrino masses
impacts growth of large scale structure,
i.e., the matter power spectrum

graphic from NASA/WMAP

Neutrinos?



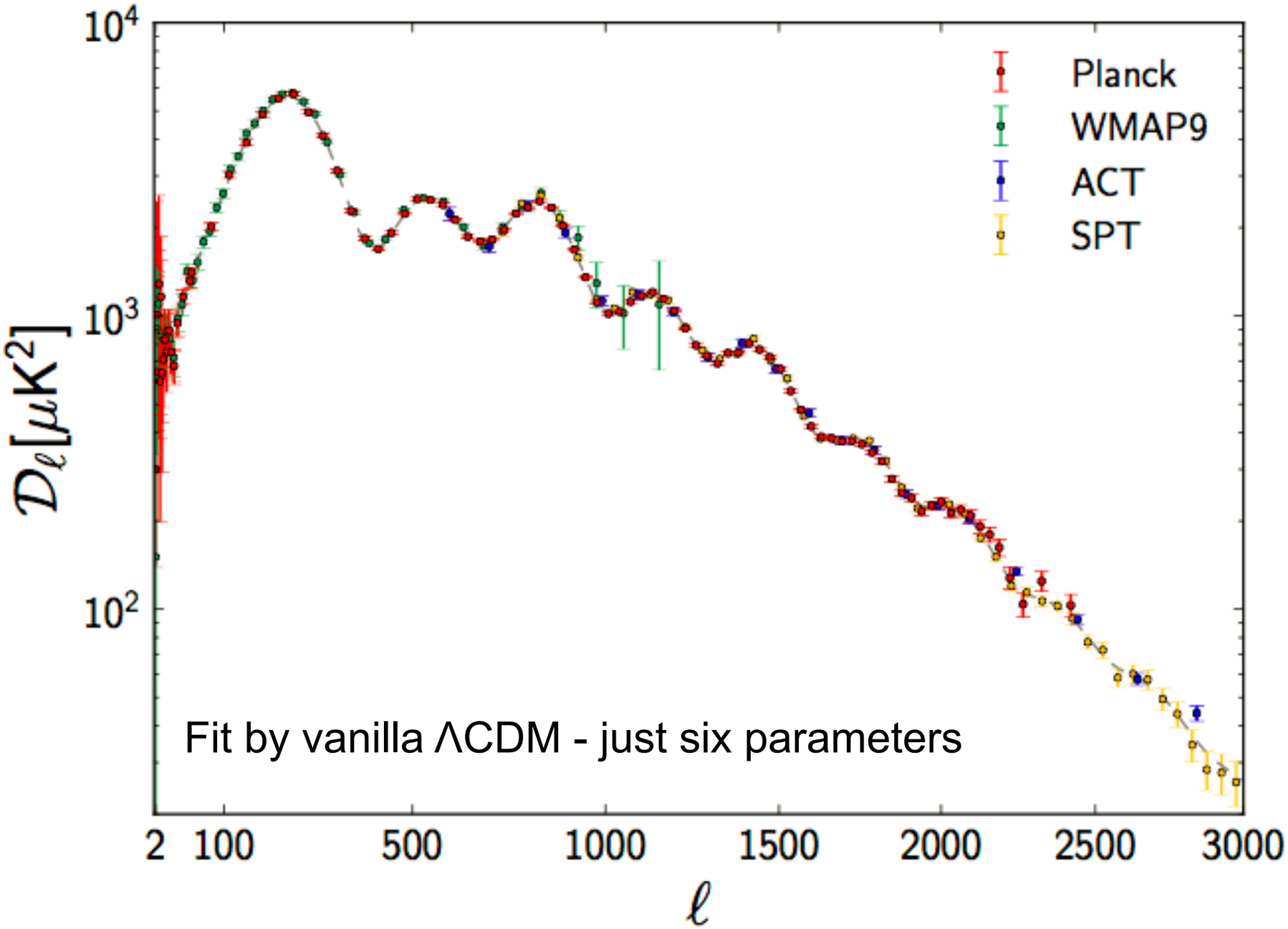


$\Sigma m_\nu > 0$

Sum of the neutrino masses
impacts growth of large scale structure,
i.e., the matter power spectrum

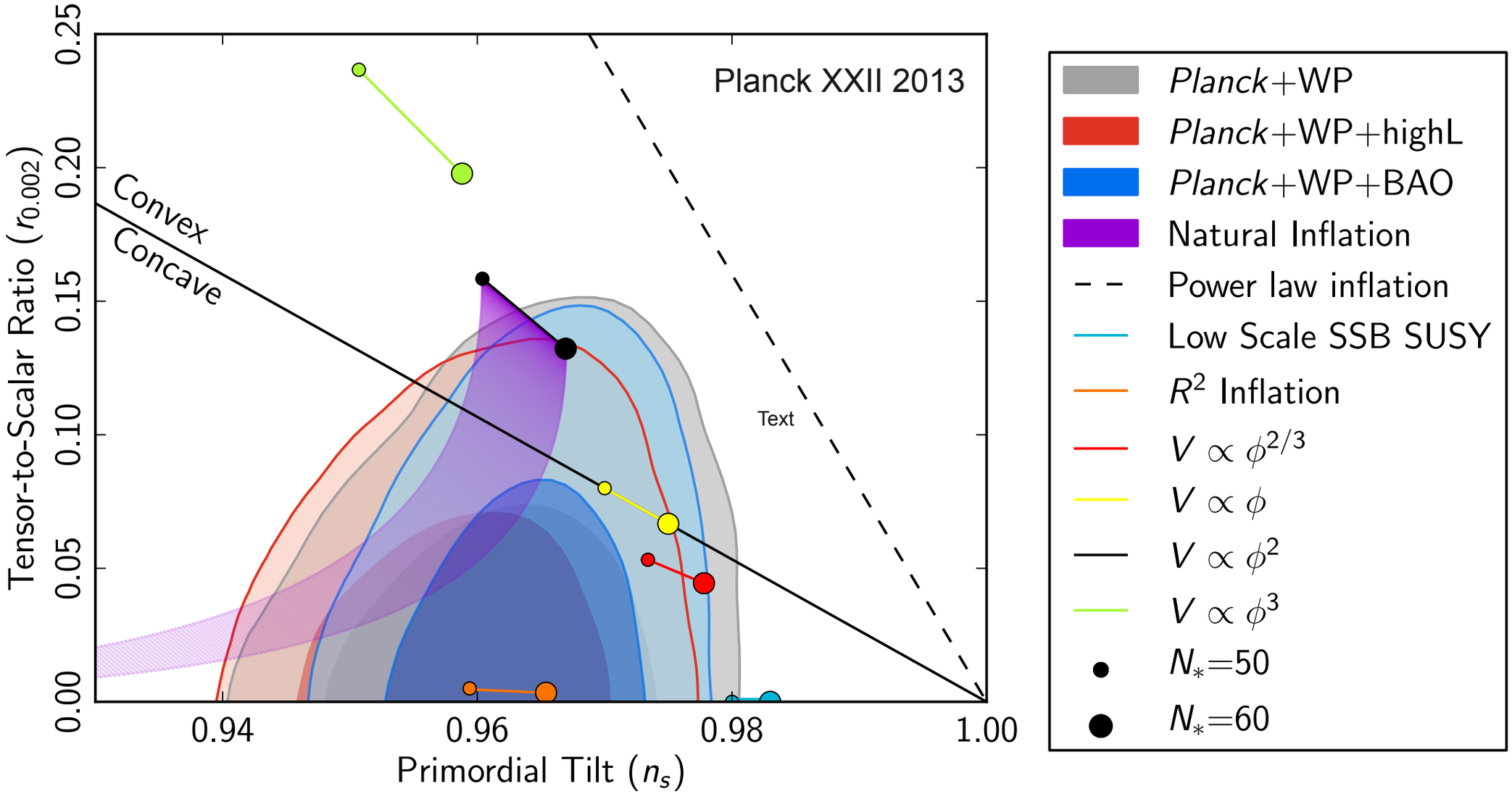
graphic from NASA/WMAP

Primary CMB anisotropy - 9 harmonics



Inflation checks: Geometrical flat universe; Superhorizon features; acoustic peaks/adiabatic fluctuations; departure from scale invariance.

Constraining inflationary models
joint r and n_s limits

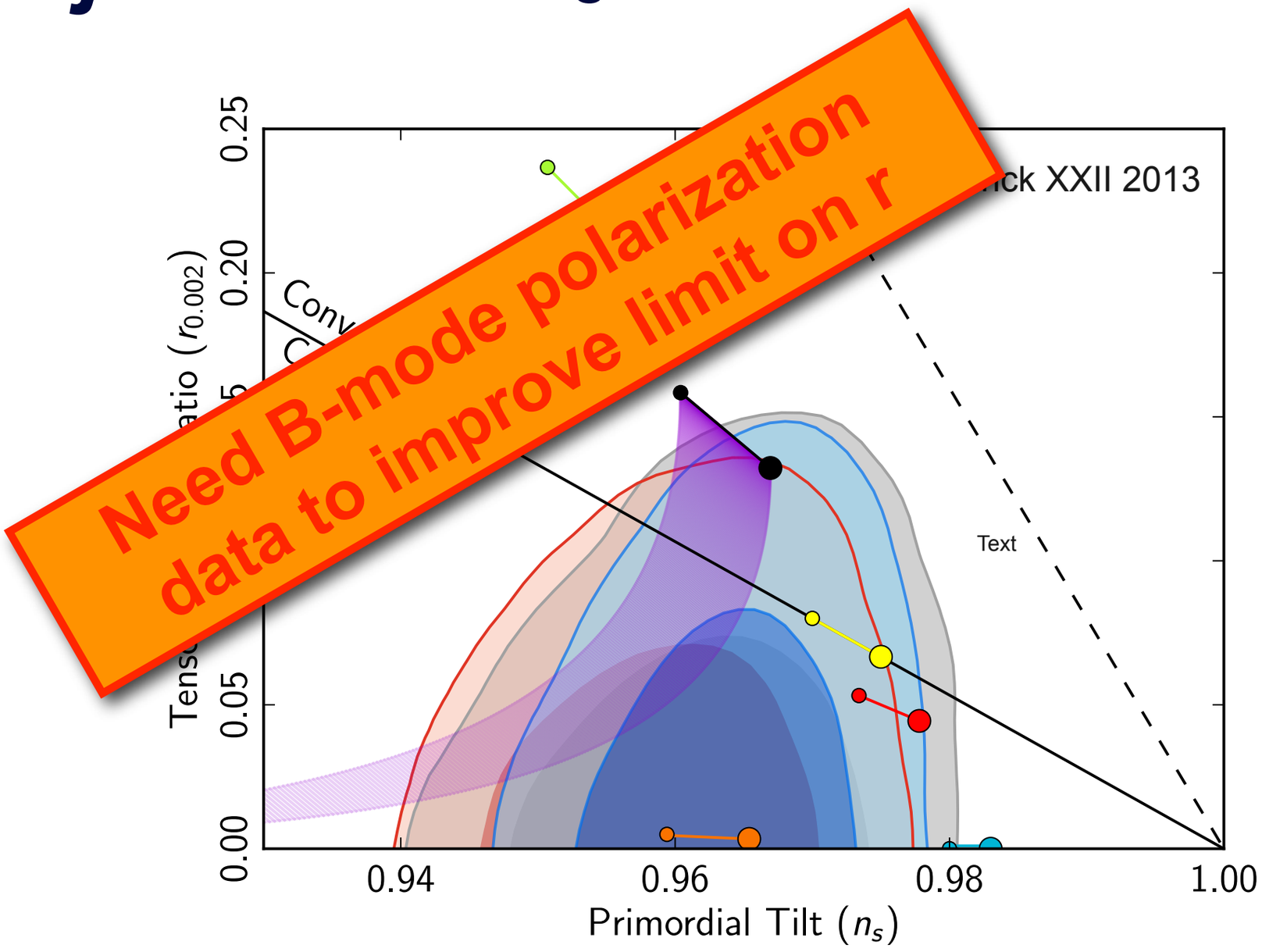


Spectral Index of primordial fluctuations, n_s,

where $\Delta^2_R(k) = \Delta^2_R(k_0)\left(\frac{k}{k_0}\right)^{n_s-1}$

Inflation evidence $n_s \neq 1$ at over 5σ

Constraining inflationary models
joint r and n_s limits



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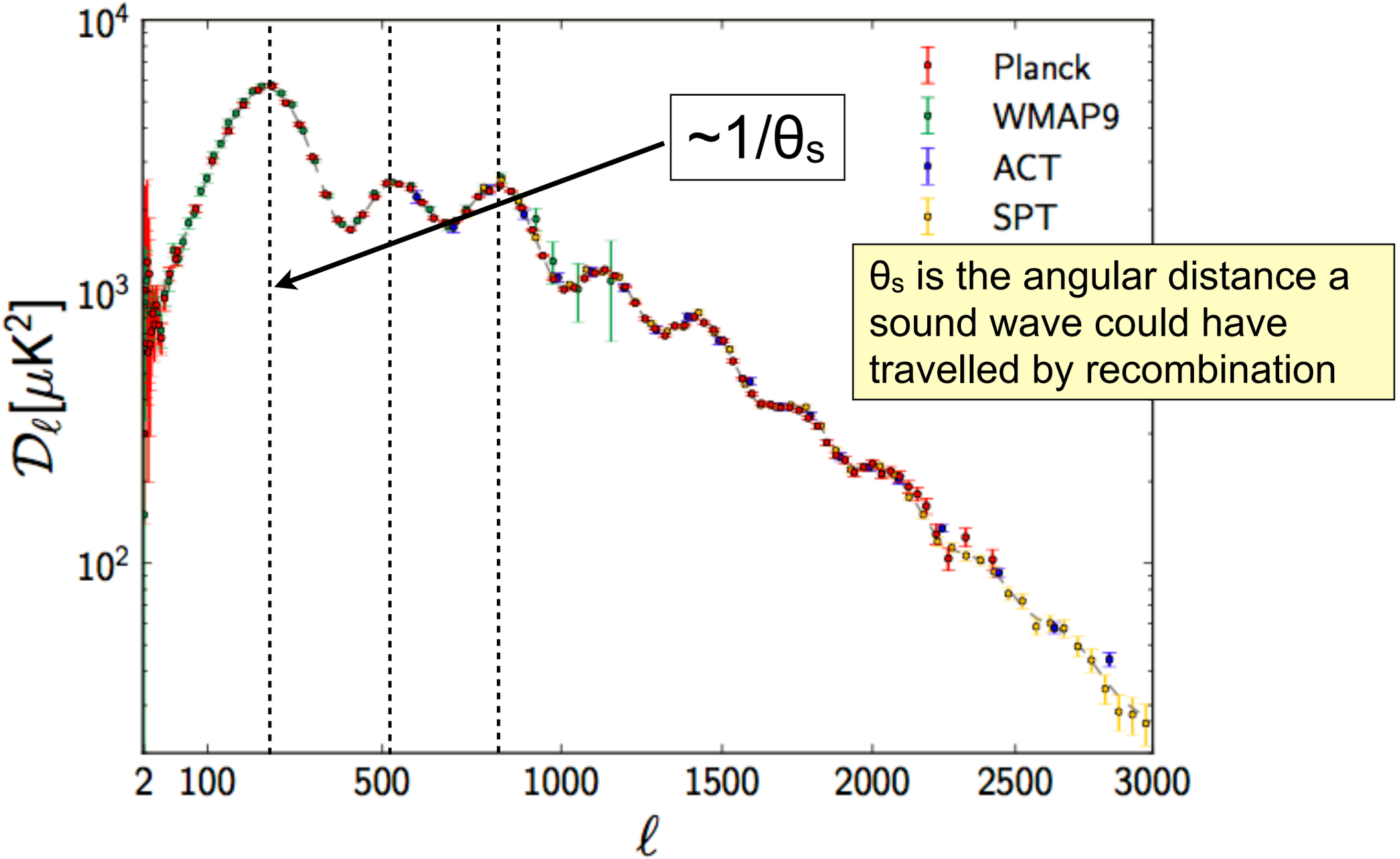
Inflation evidence $n_s \neq 1$ at over 5σ

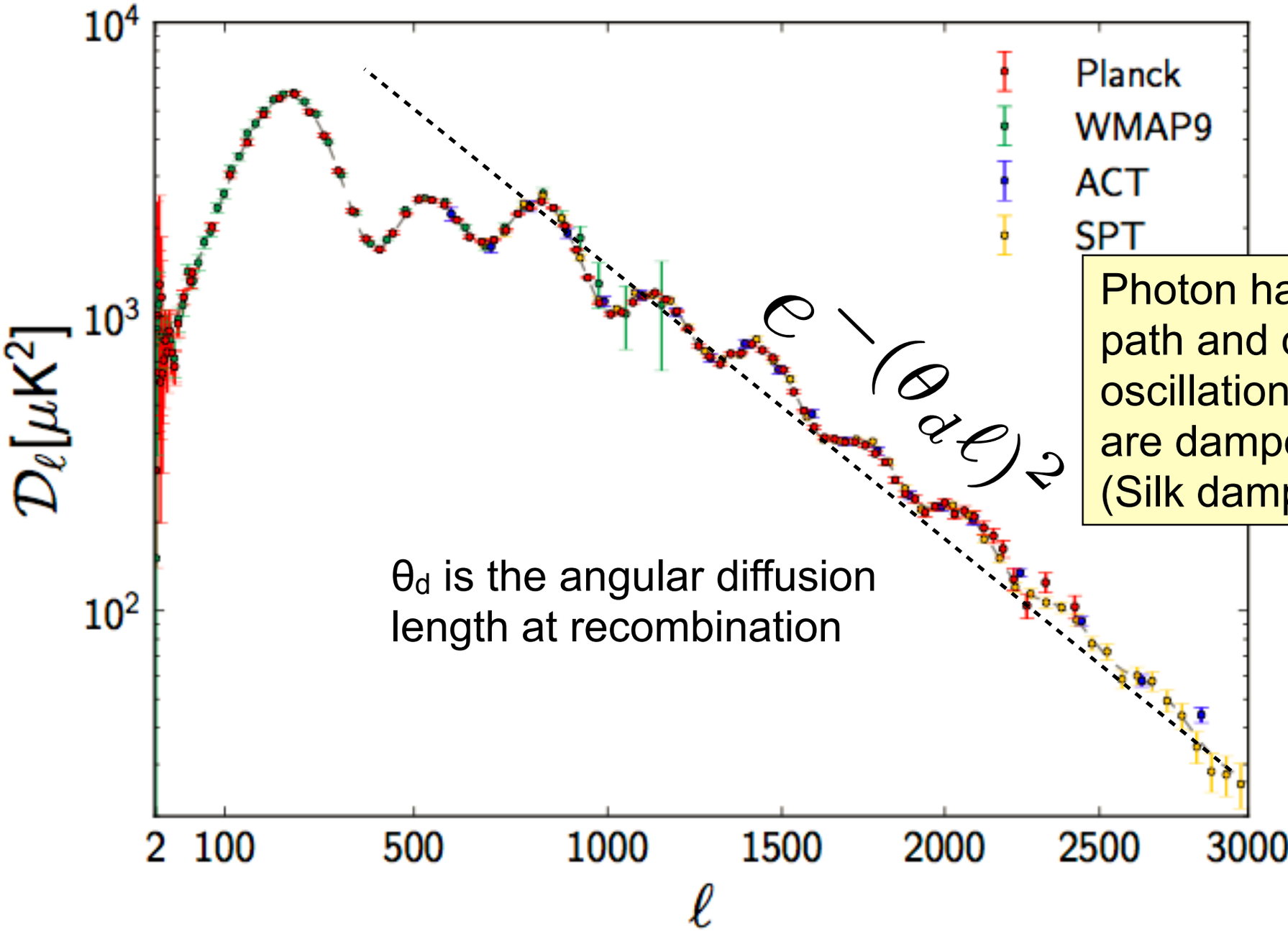
Primary CMB anisotropy - 9 harmonics

Improves precision of sound horizon, θ_s, & provides larger lever arm



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

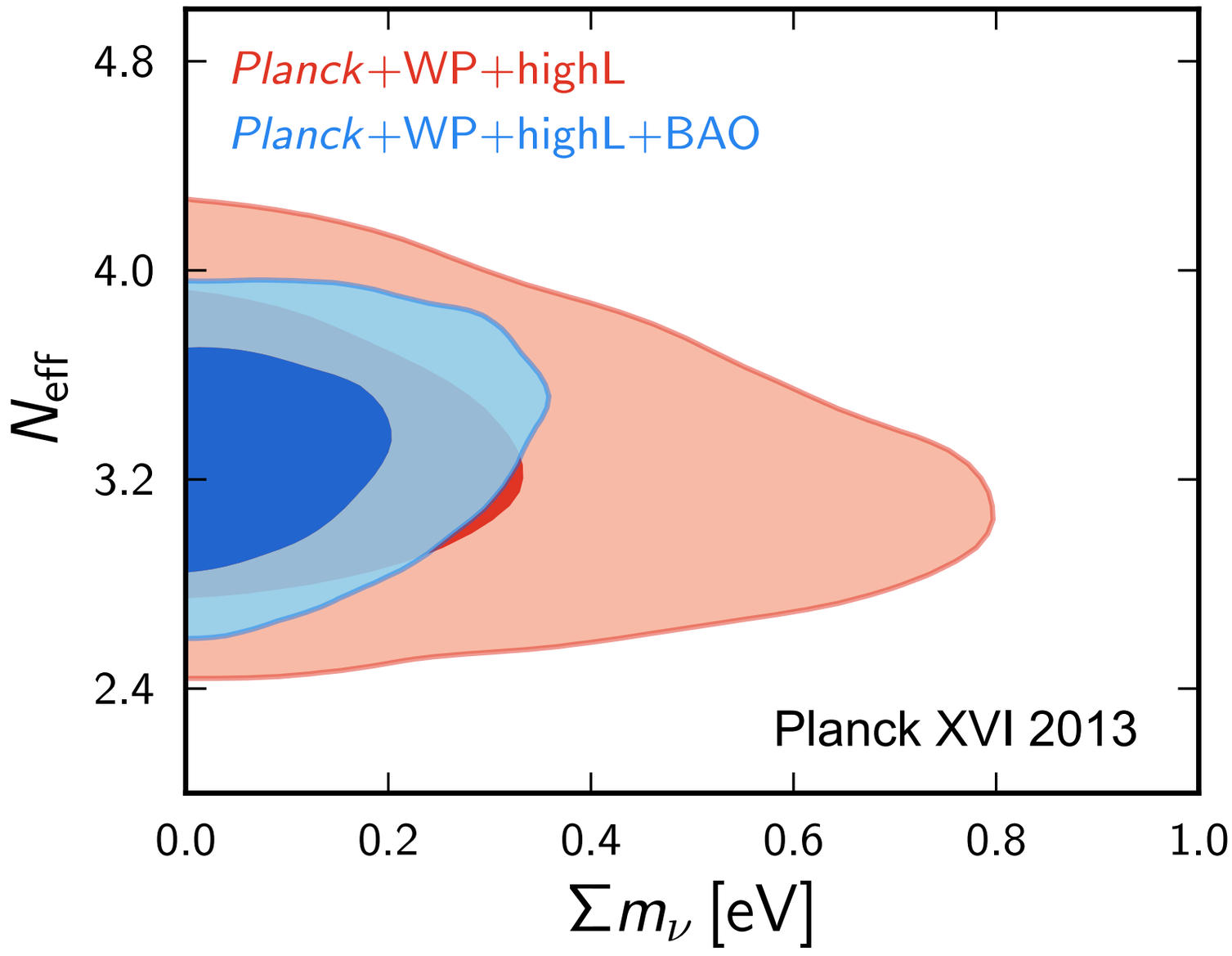
And most importantly provides determination of the damping scale, θ_d



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

Note $\dfrac{r_d}{r_s} = \dfrac{\theta_d}{\theta_s} \propto H,^{0.5}$ so ratio is sensitive energy density.

Constraining model extensions:
joint N_{eff} and Σm_ν constraints



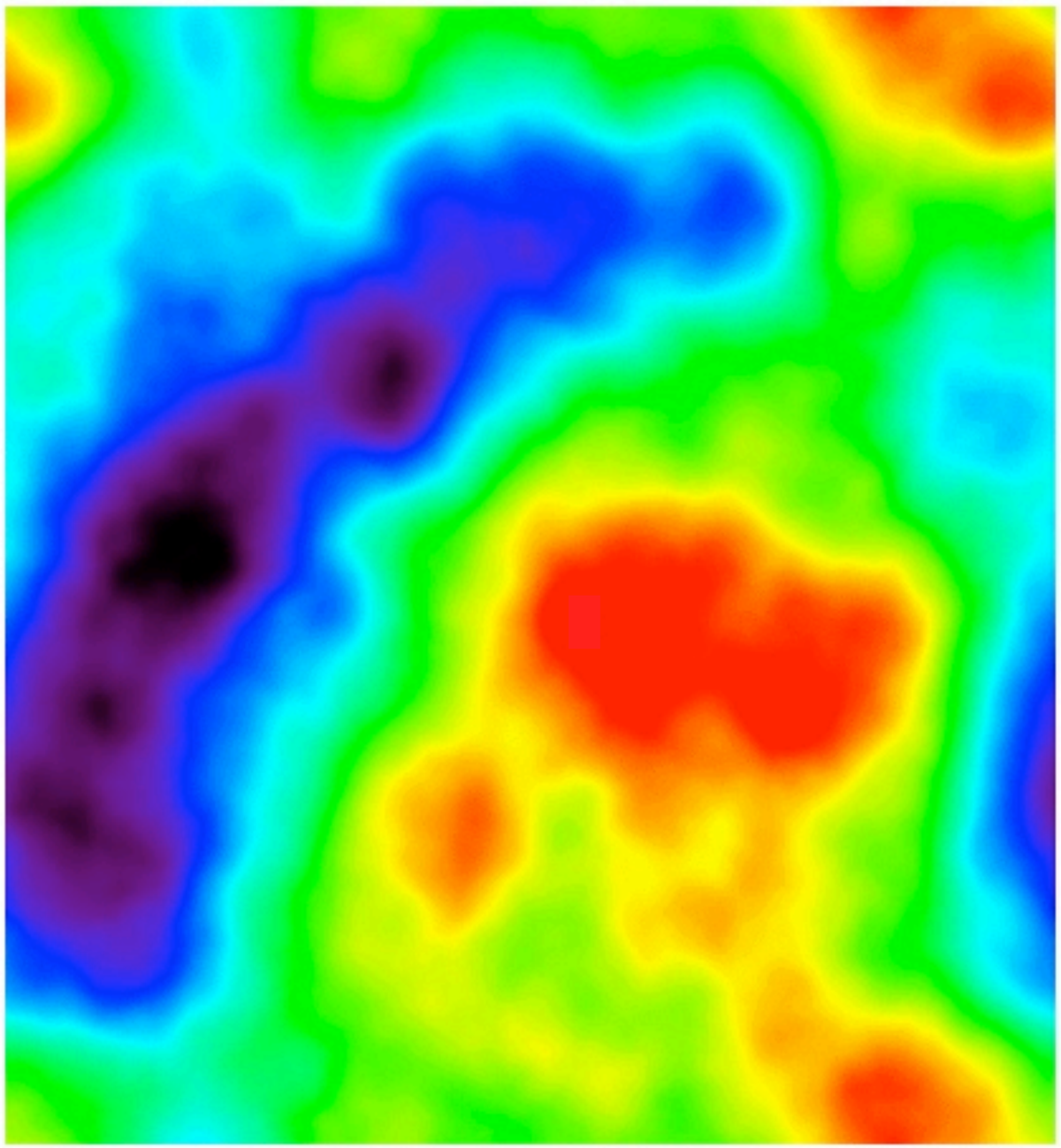
$\sigma(N_{eff}) = 3.30 \pm 0.27$

$\sigma(\Sigma m_\nu) < 0.23$eV at 95% C.L.

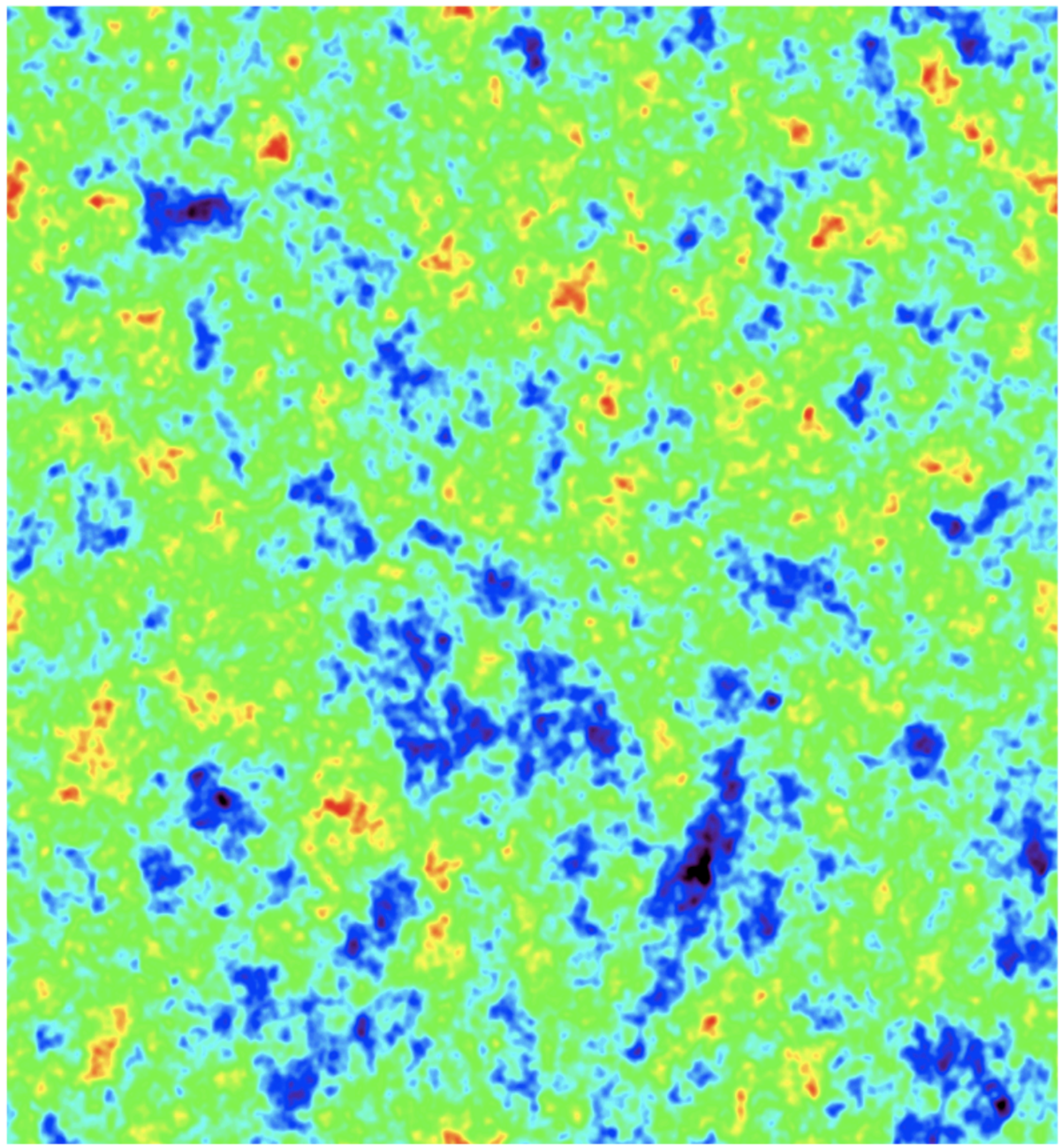
N_{eff} is the effective number of relativistic species.
For standard 3 neutrinos N_{eff} =3.046.
It measures the extra energy relative to the photons.

Lensing of the CMB

17°x17°



lensing potential

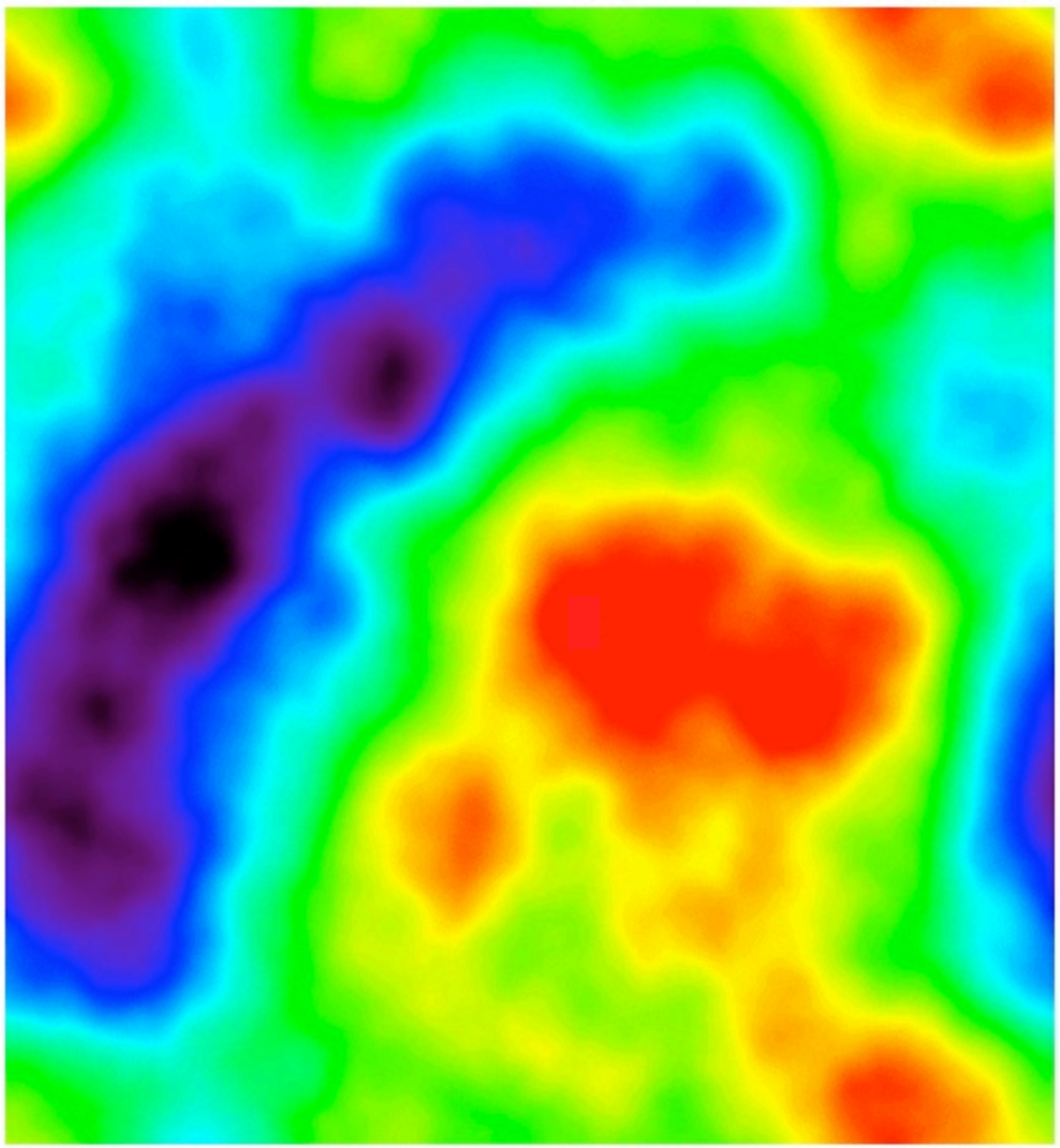


unlensed cmb

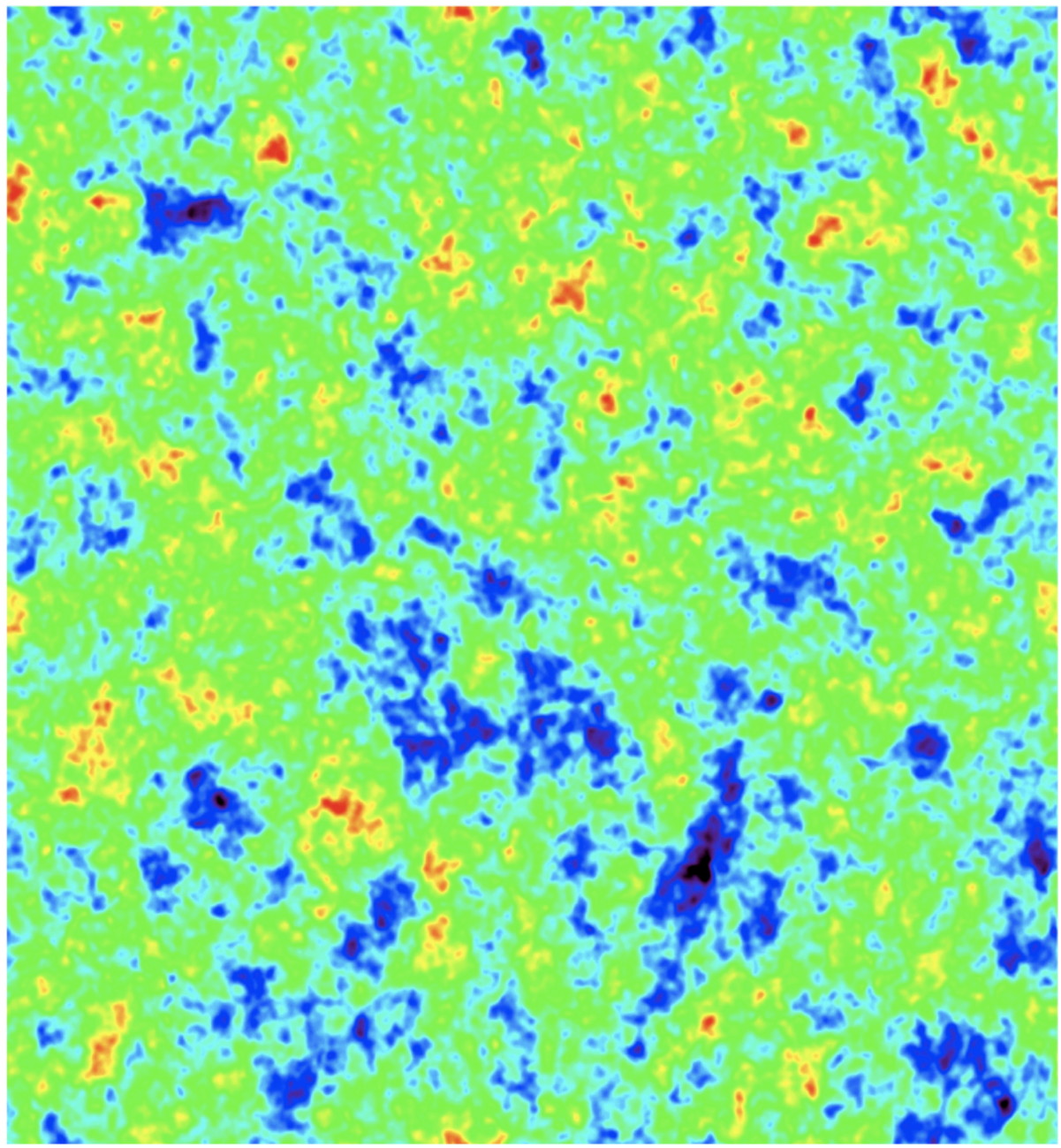
from Alex van Engelen

Lensing of the CMB

17°x17°



lensing potential

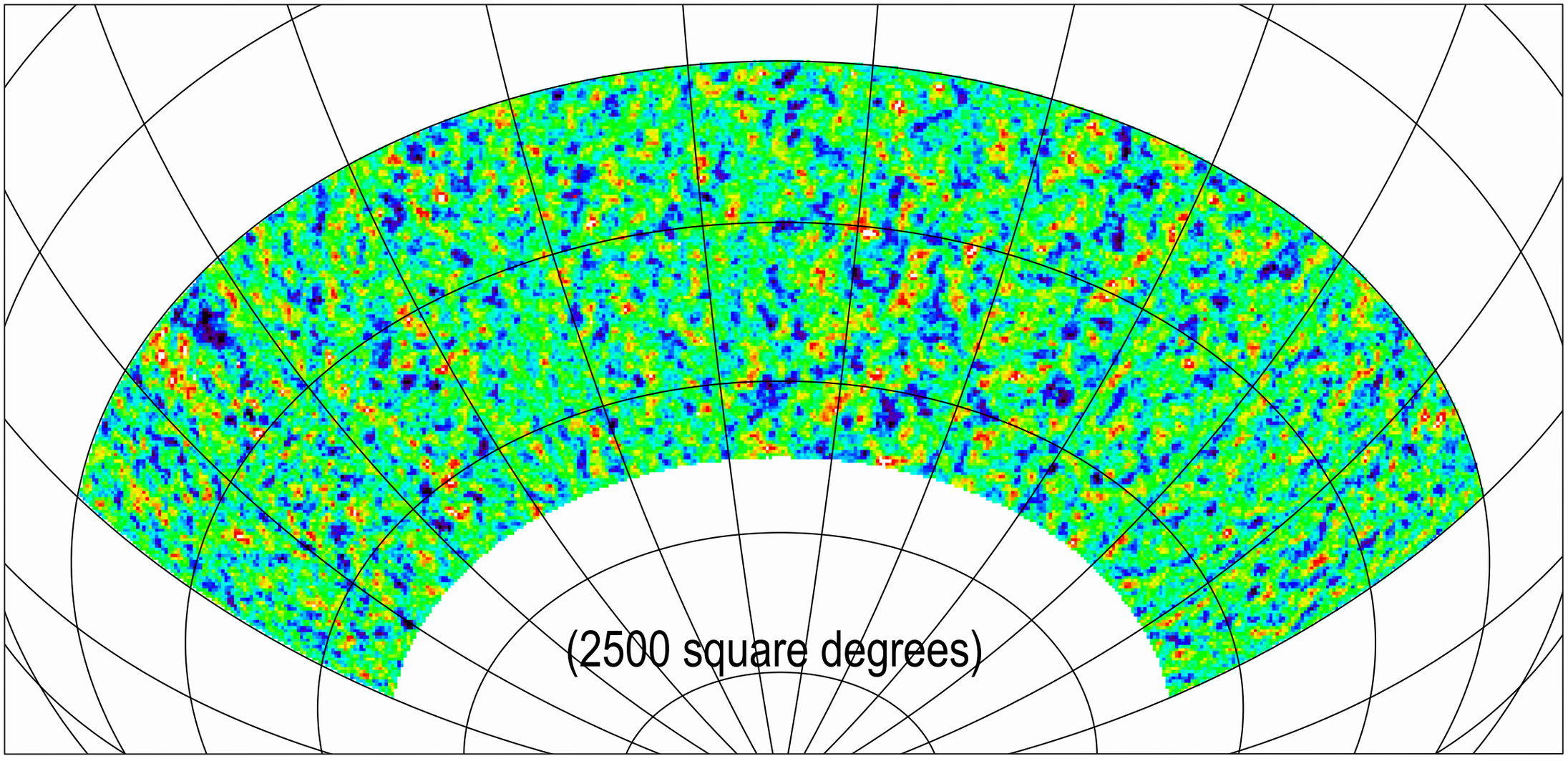


lensed cmb

from Alex van Engelen

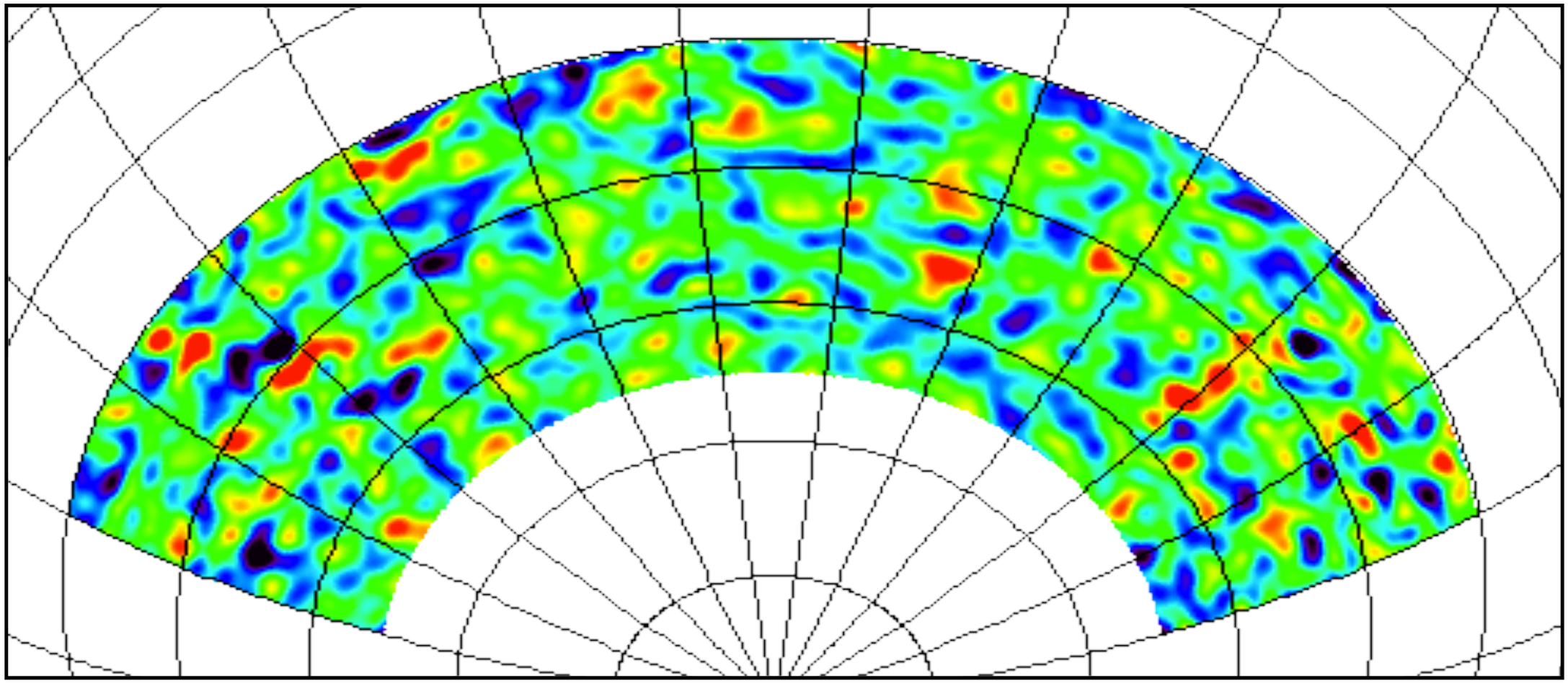
high resolution and sensitivity map of the CMB

covering 1/16 of the sky from SPT



CMB Lensing Map

reconstruction of the mass projected along the line of sight to the CMB.



Lensing convergence map smoothed to 1 deg resolution
from CMB lensing analysis of SPT 2500 deg^2 survey

CMB Lensing Map

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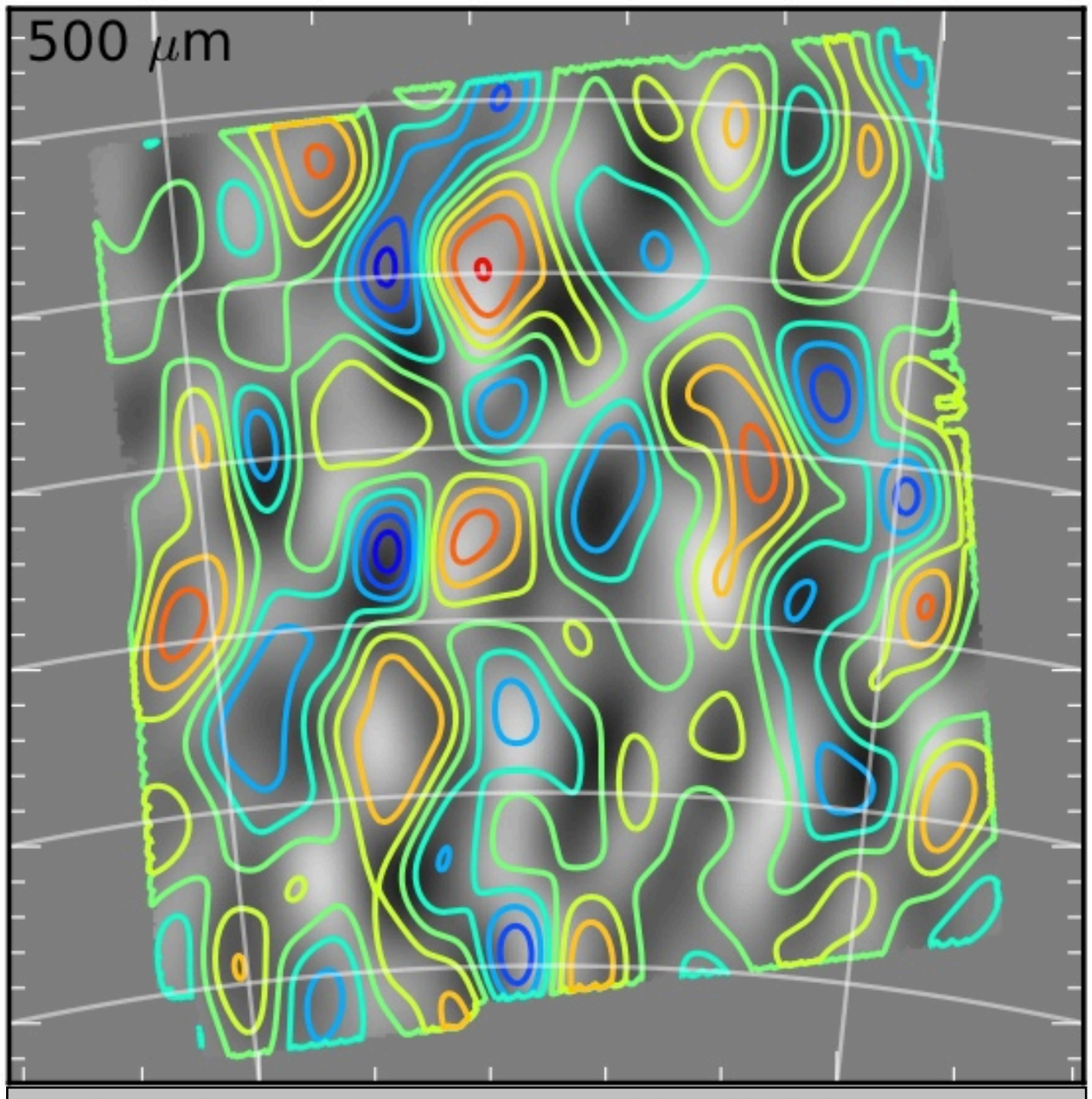
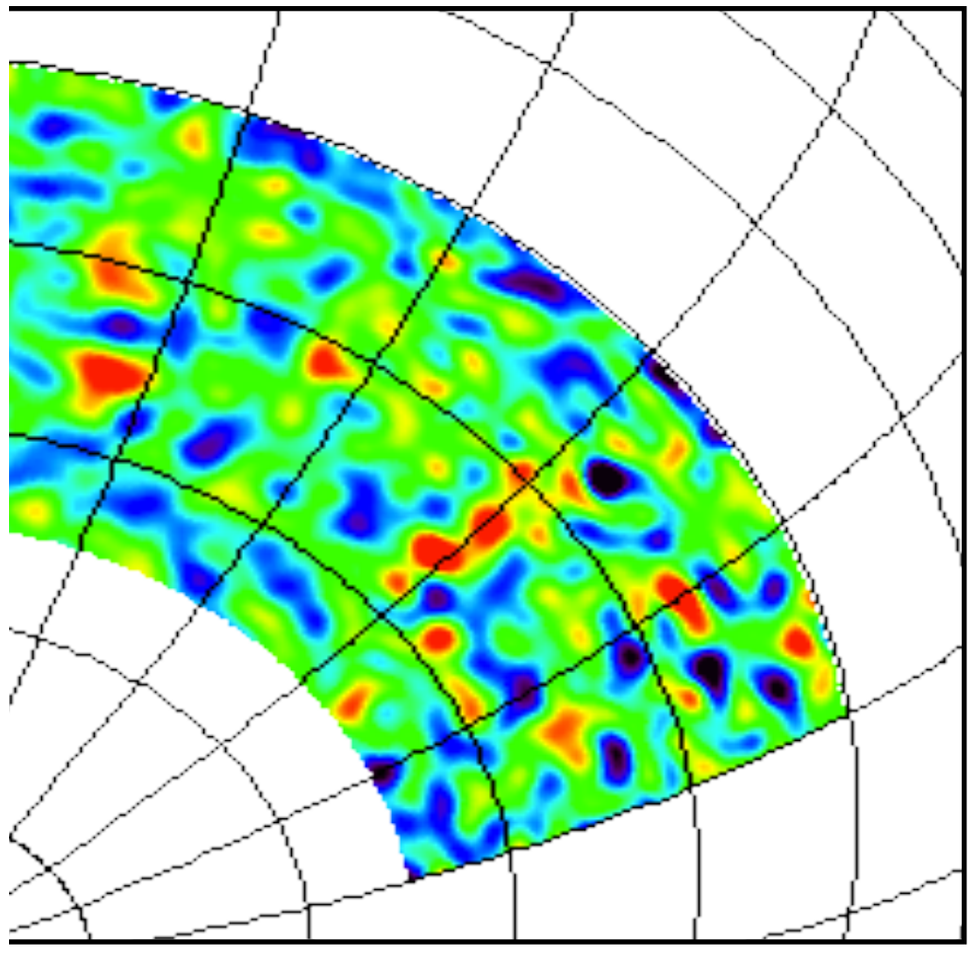


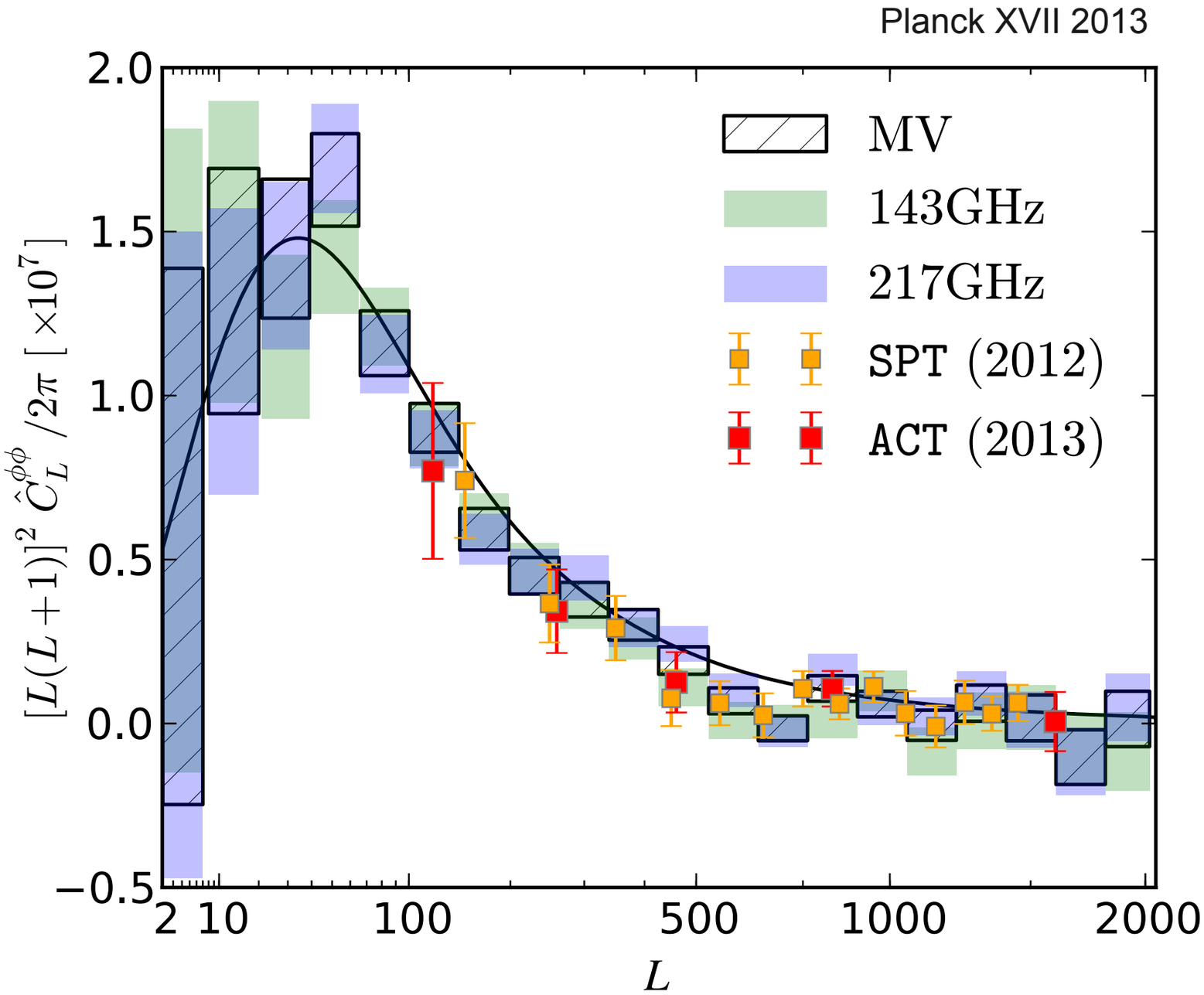


Correlation of matter traced by CMB lensing (contours, SPT) and distribution of high z galaxies (grayscale; Herschel 500 um) [arXiv:1112.5435]

othed to 1 deg resolution

from CMB lensing analysis of SPT 2500 deg^2 survey

CMB lensing power spectrum



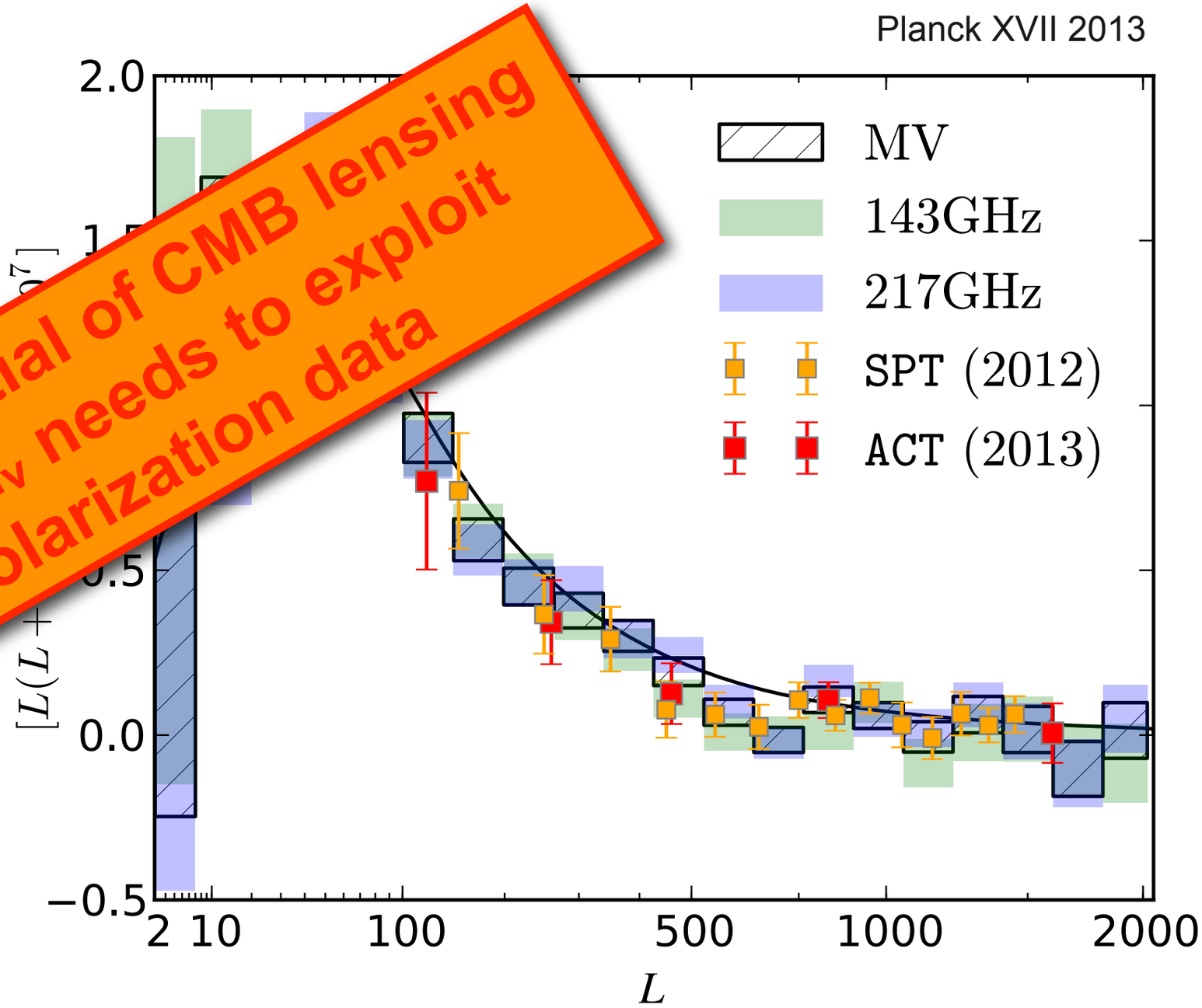
Sensitive to the neutrino masses

$\sum m_\nu$ = 0.1 eV → 5% amplitude of spectrum

Polarization gives additional lensing sensitivity and is a cleaner probe.

B_{lens} modes are only sourced by lensing.

CMB lensing power spectrum



Full potential of CMB lensing for Σm_ν needs to exploit polarization data

Sensitive to the neutrino masses

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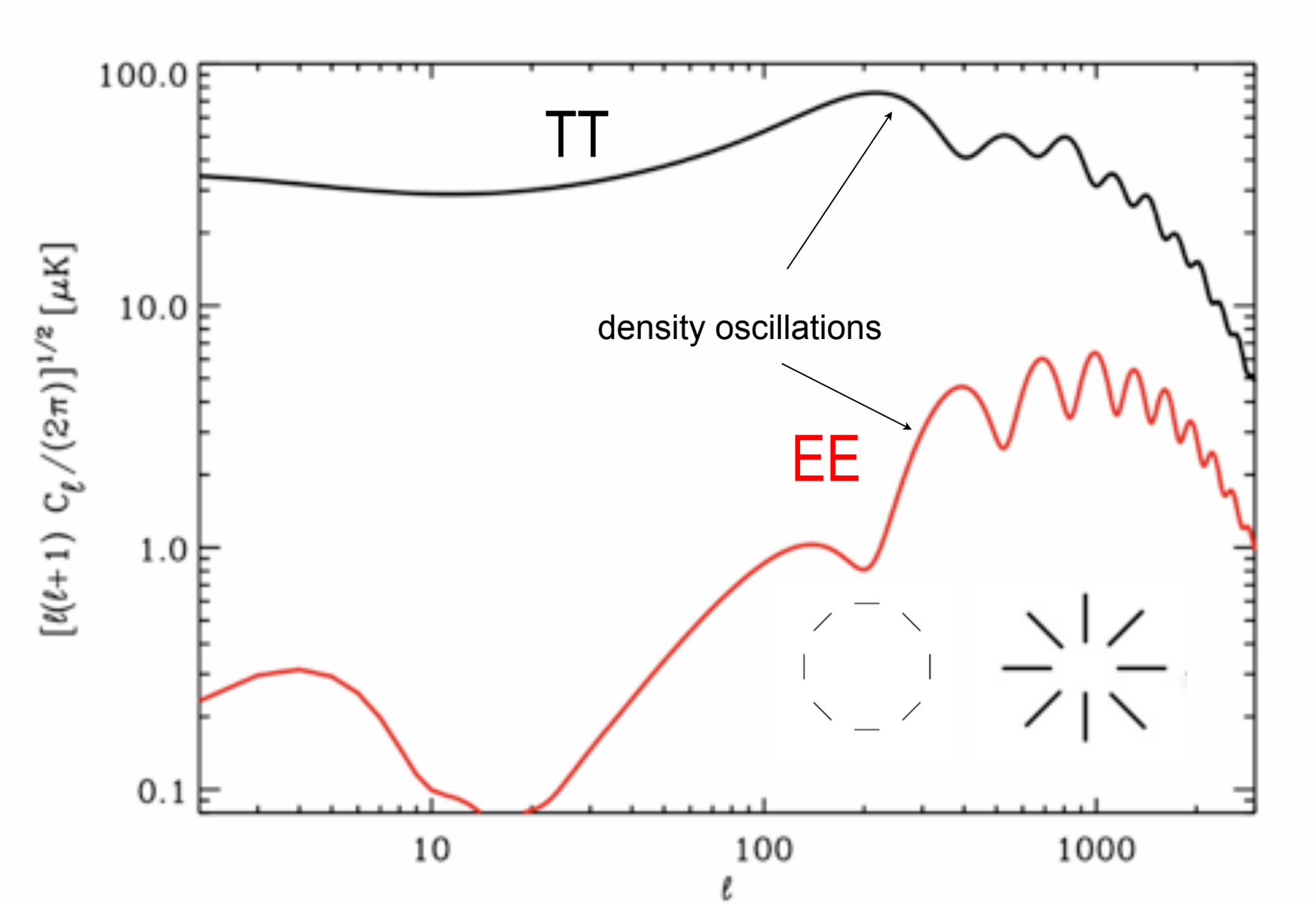
CMB polarization:
the next frontier for lensing & inflation



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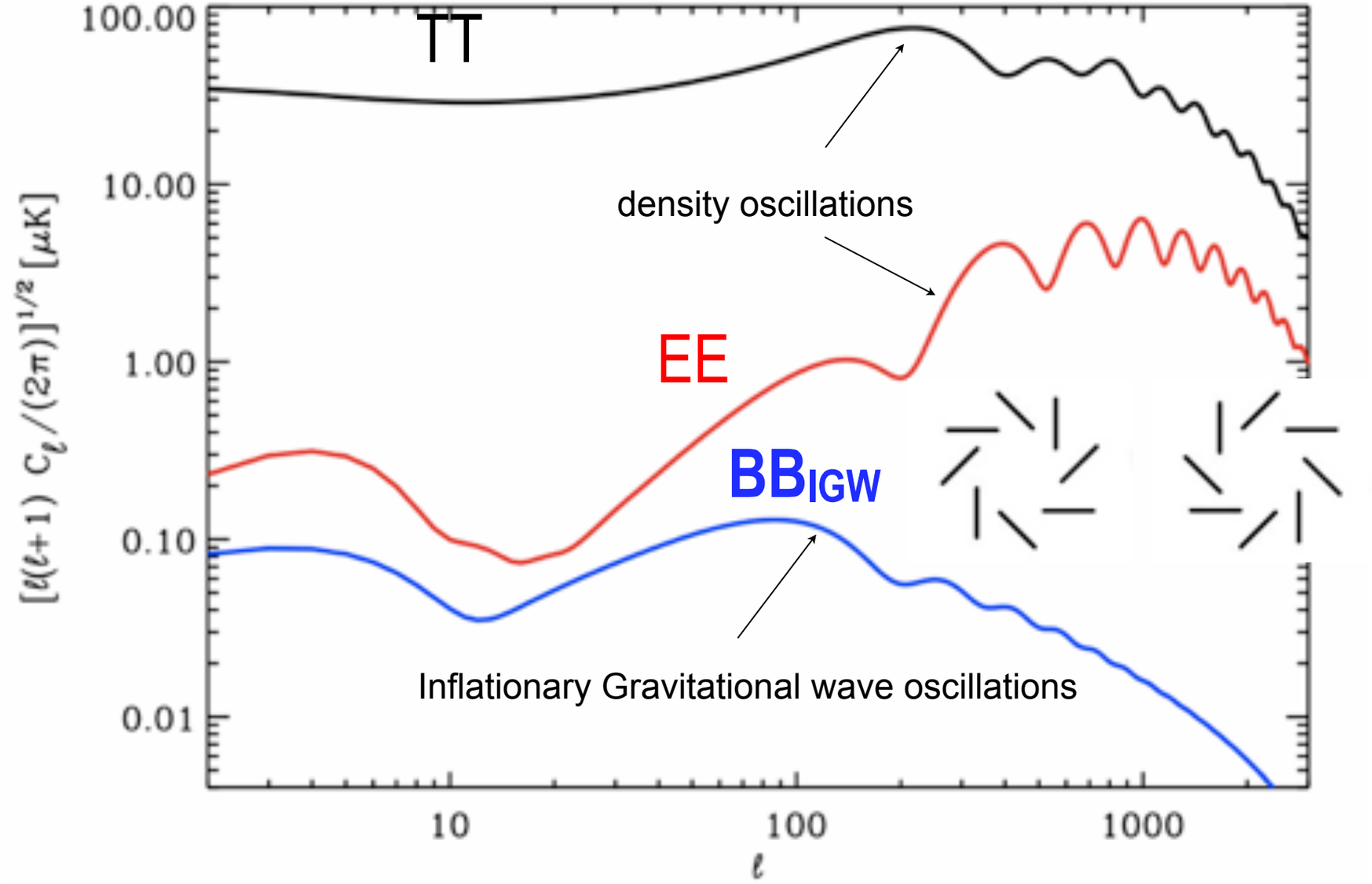

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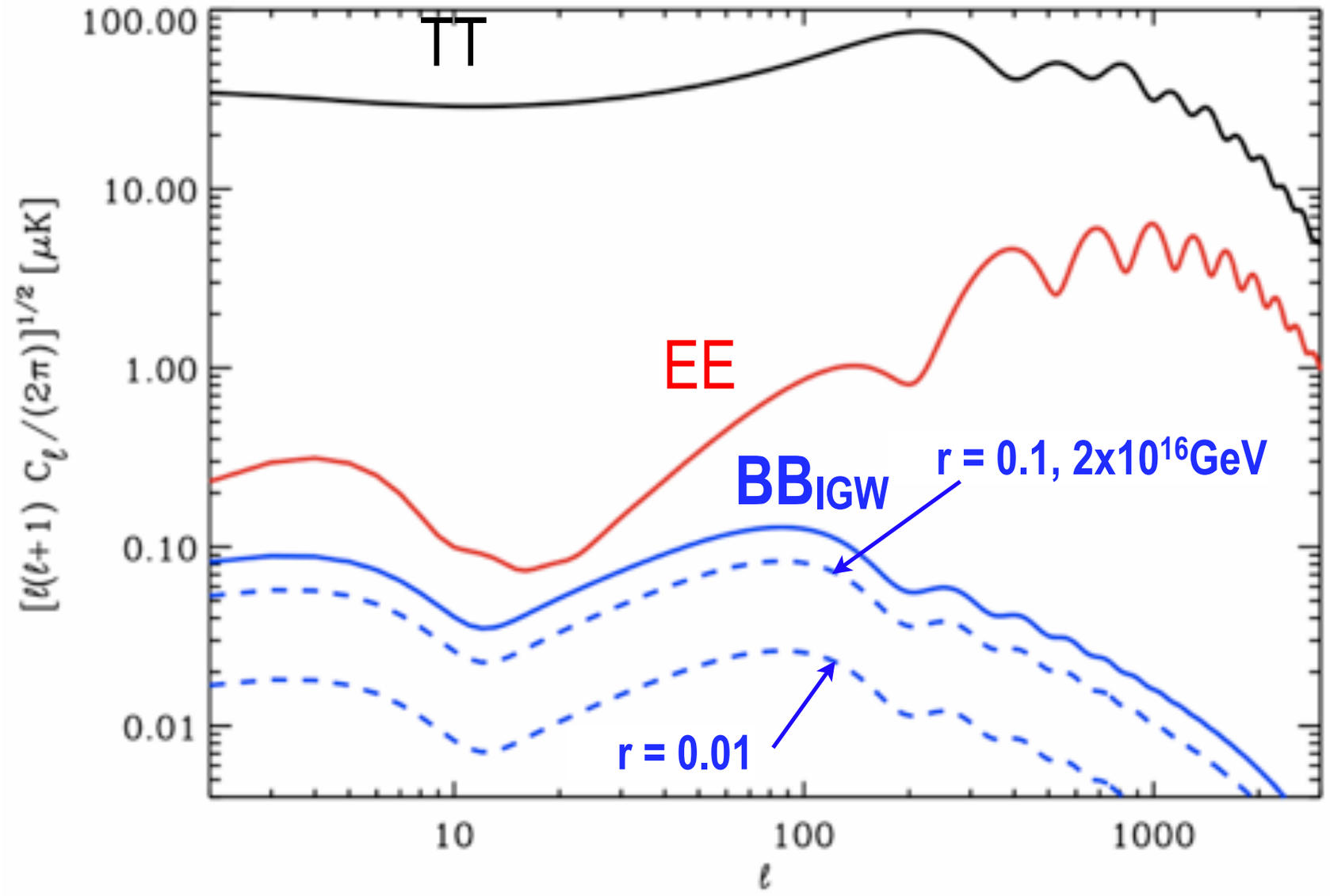

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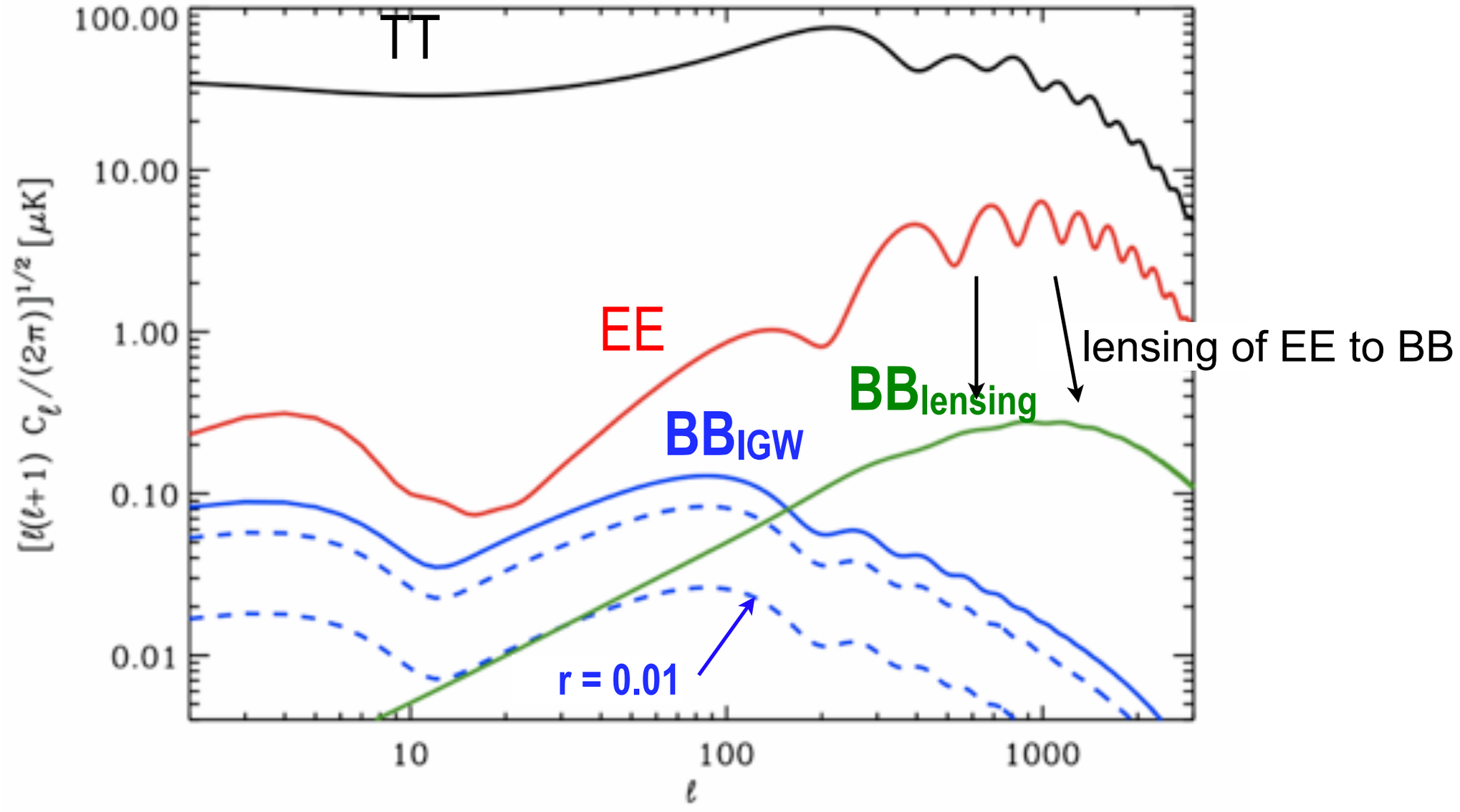

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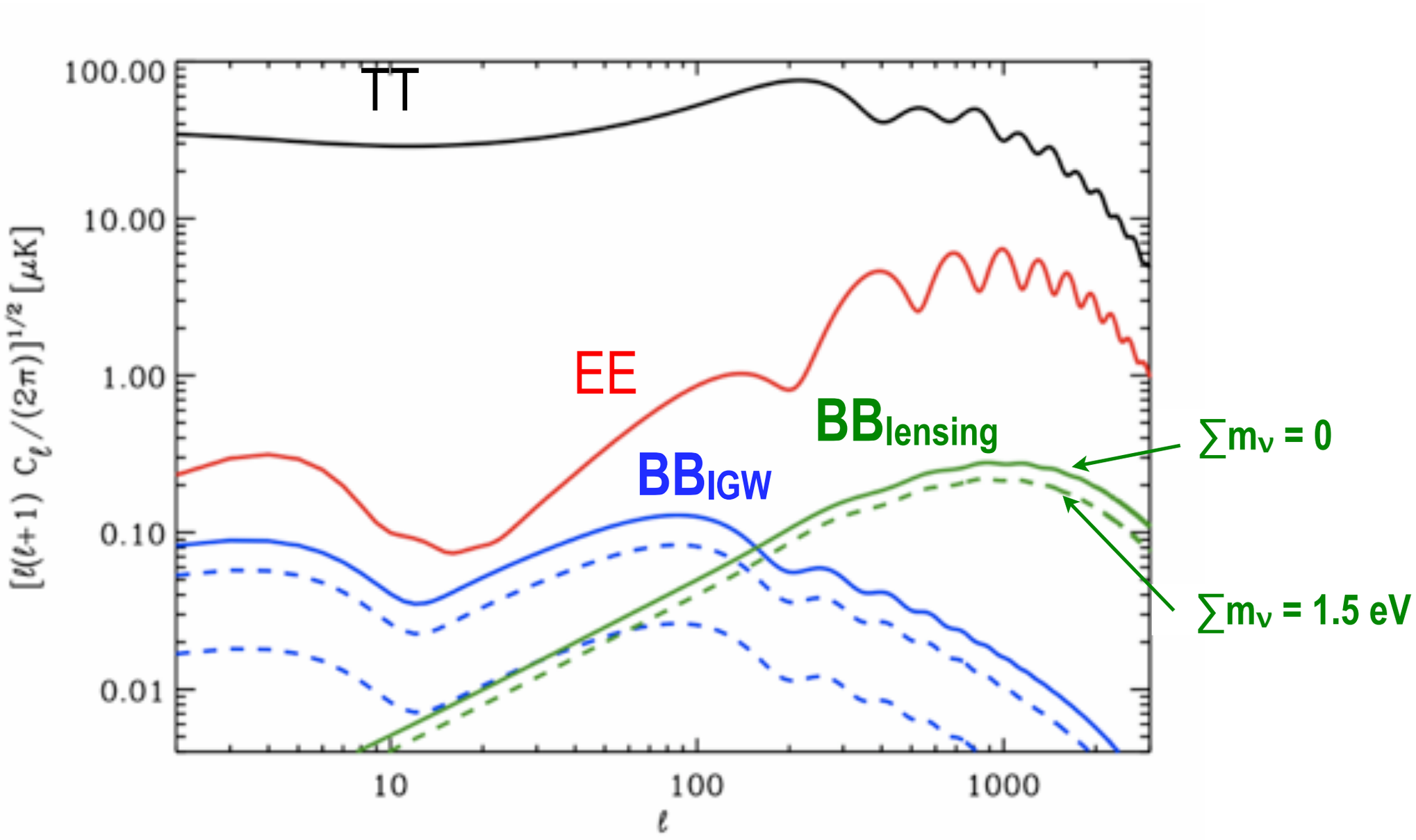

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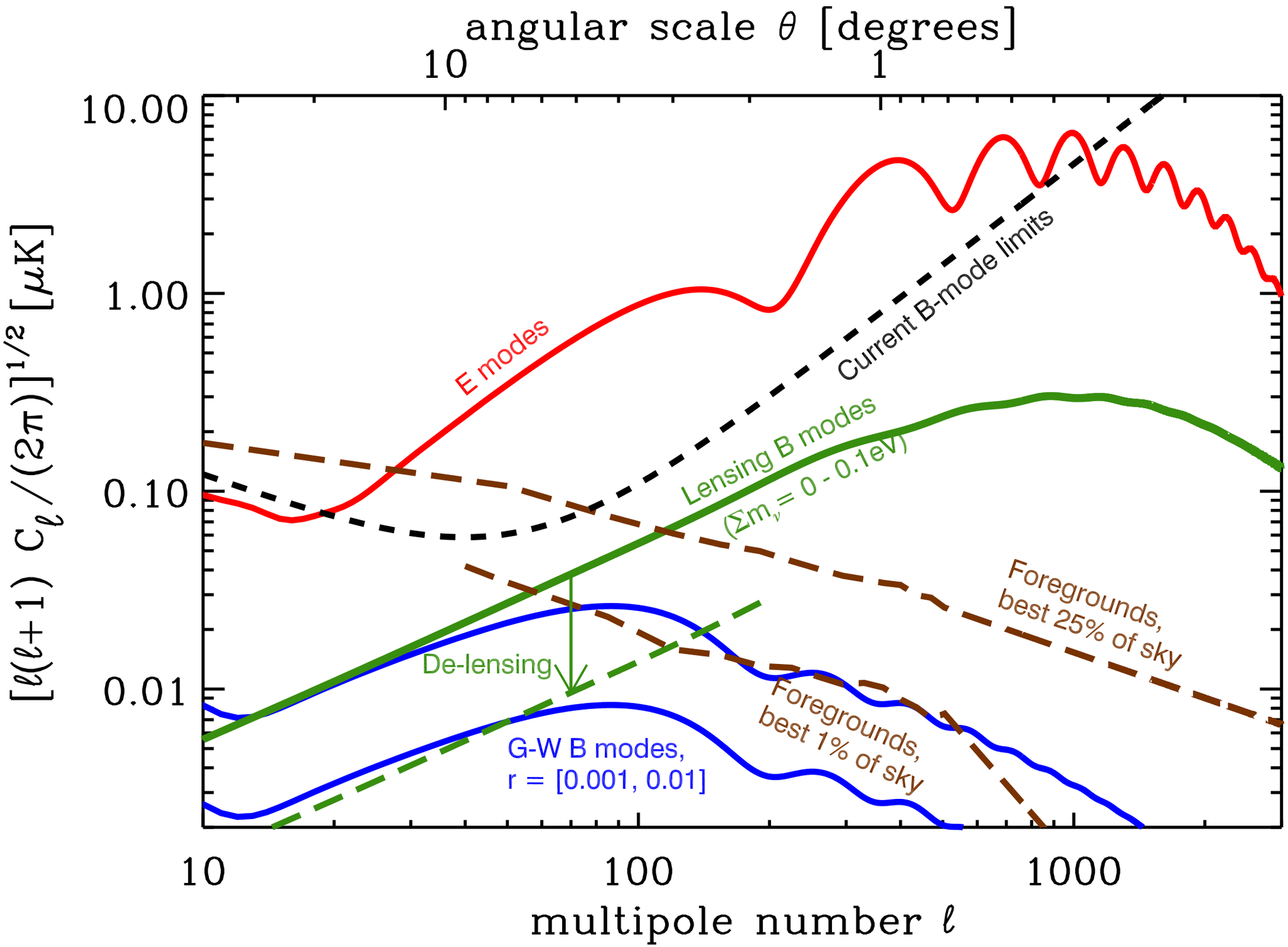
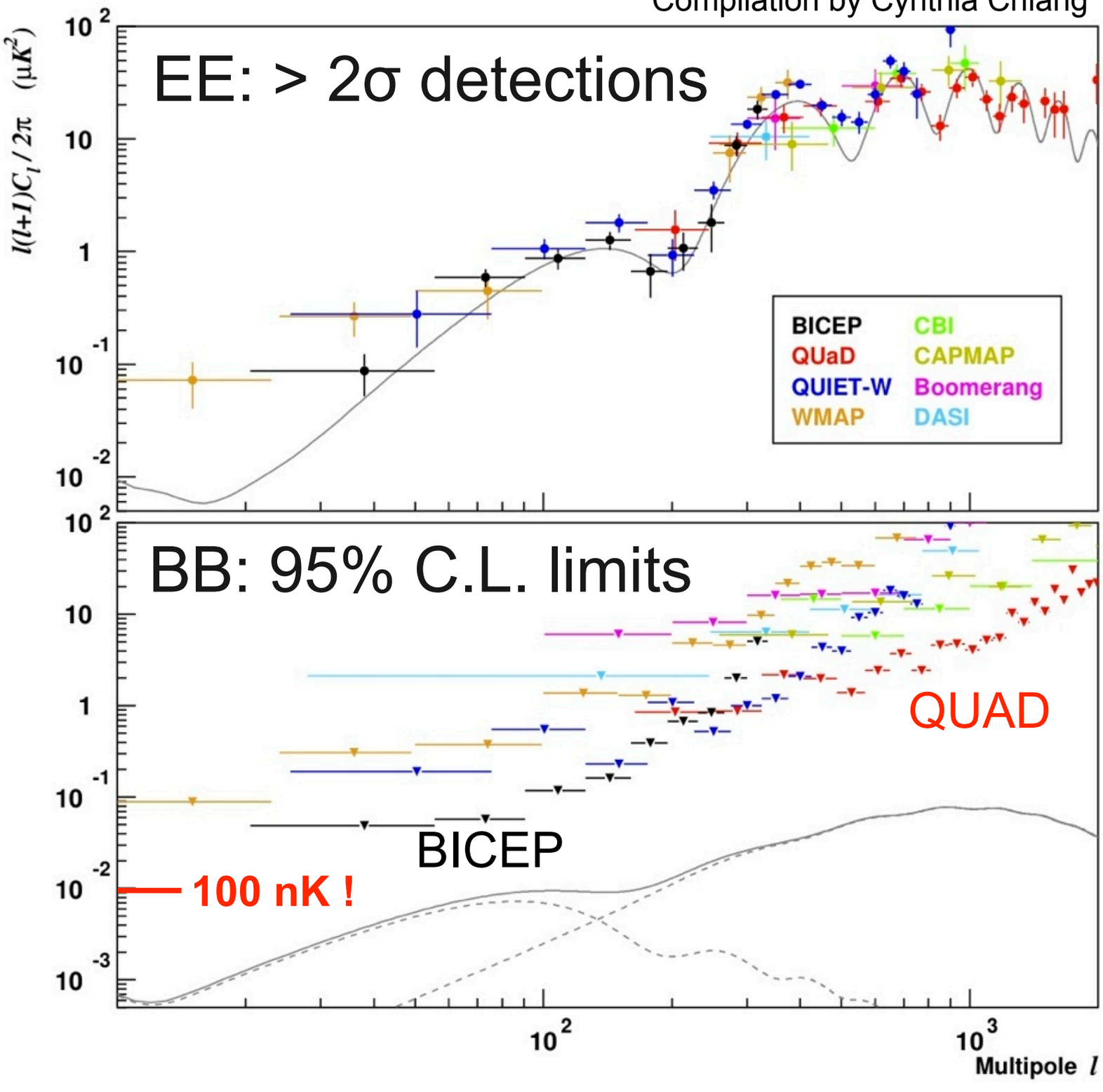
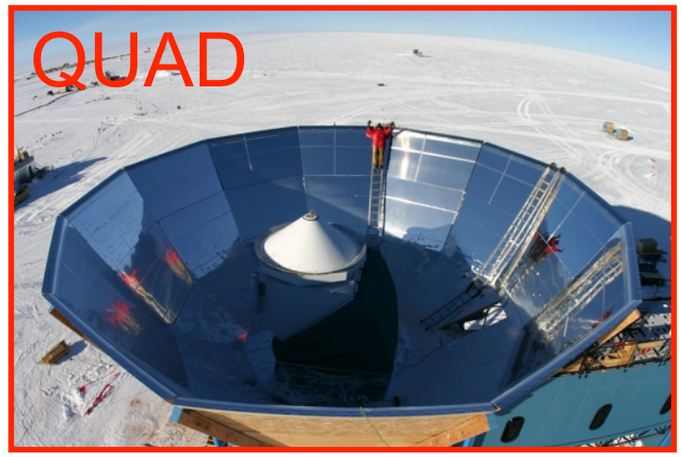


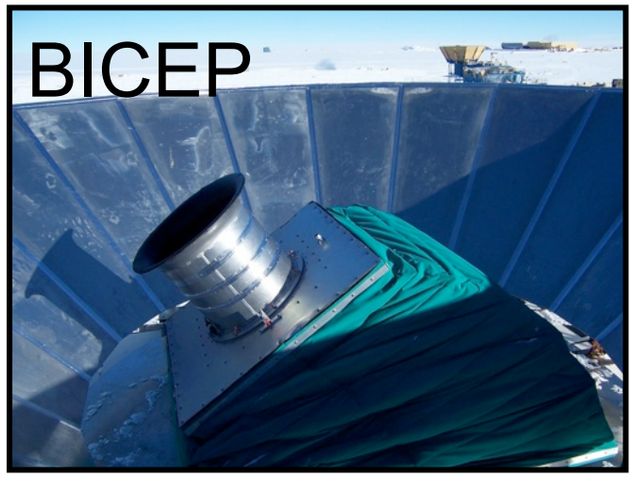
Figure from CF5 inflation document - note expanded scale with 0.001 < r < 0.01

Status of B-mode experiments

Compilation by Cynthia Chiang

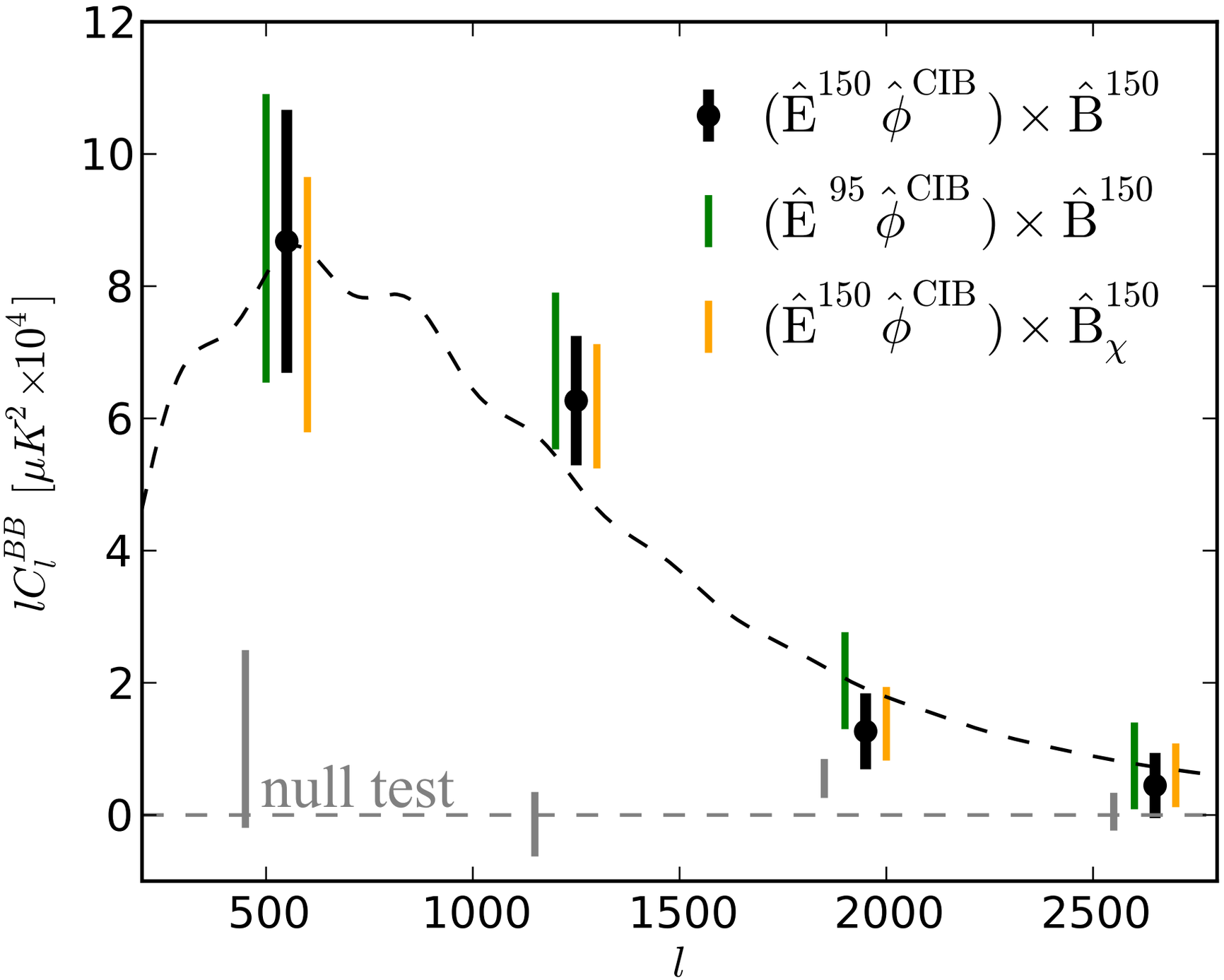


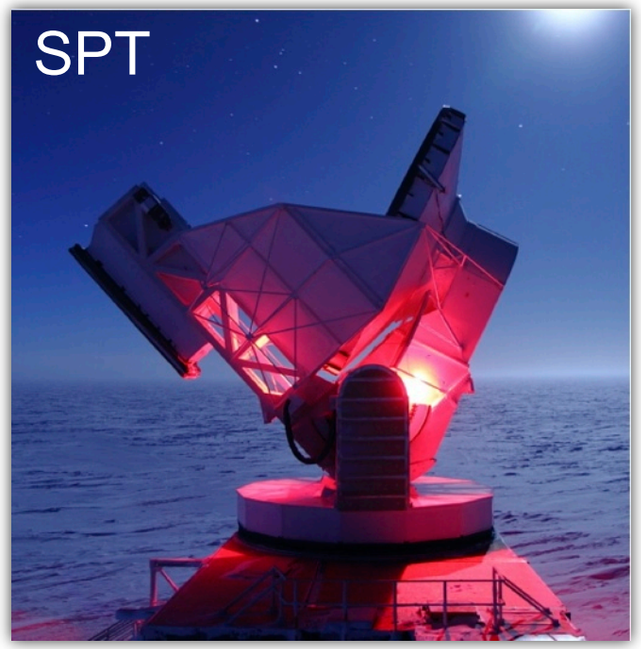


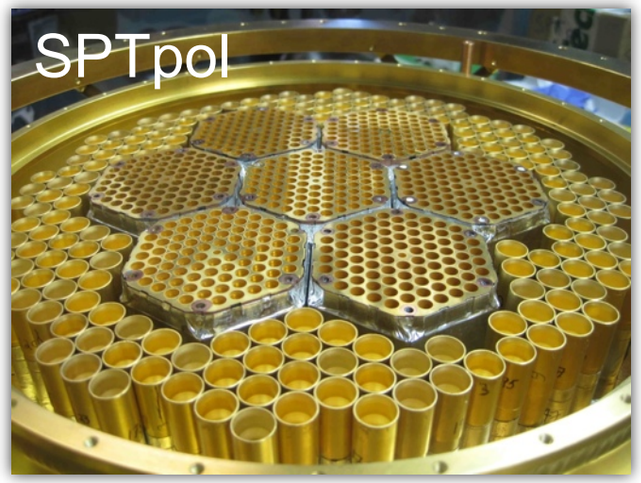


SPTpol Detection of lensing B-modes

(reported last week)







SPTpol: Hanson et al, arXiv:1307.5830

CMB timeline

- 2009: r < 0.7 (BICEP) Chiang et al, 0906.1181

- 2013: r ≲ 0.1 from Inflationary B-modes (BICEP 2) ?
- 2013: Stage II experiments detect lensing B-modes
- 2013-2016: Stage II experiments
  $\sigma(r)\sim0.03$, $\sigma(N_{eff})\sim0.1$, $\sigma(\Sigma m_\nu)\sim0.1$eV
- 2016-2020: Stage III experiments
  $\sigma(r)\sim0.01$, $\sigma(N_{eff})\sim0.06$, $\sigma(\Sigma m_\nu)\sim0.06$eV;

- 2020-2025: **Stage IV goal to reach**
  $\sigma(r) = 0.001$, $\sigma(N_{eff}) = 0.025$, $\sigma(\Sigma m_\nu) = 16$ meV

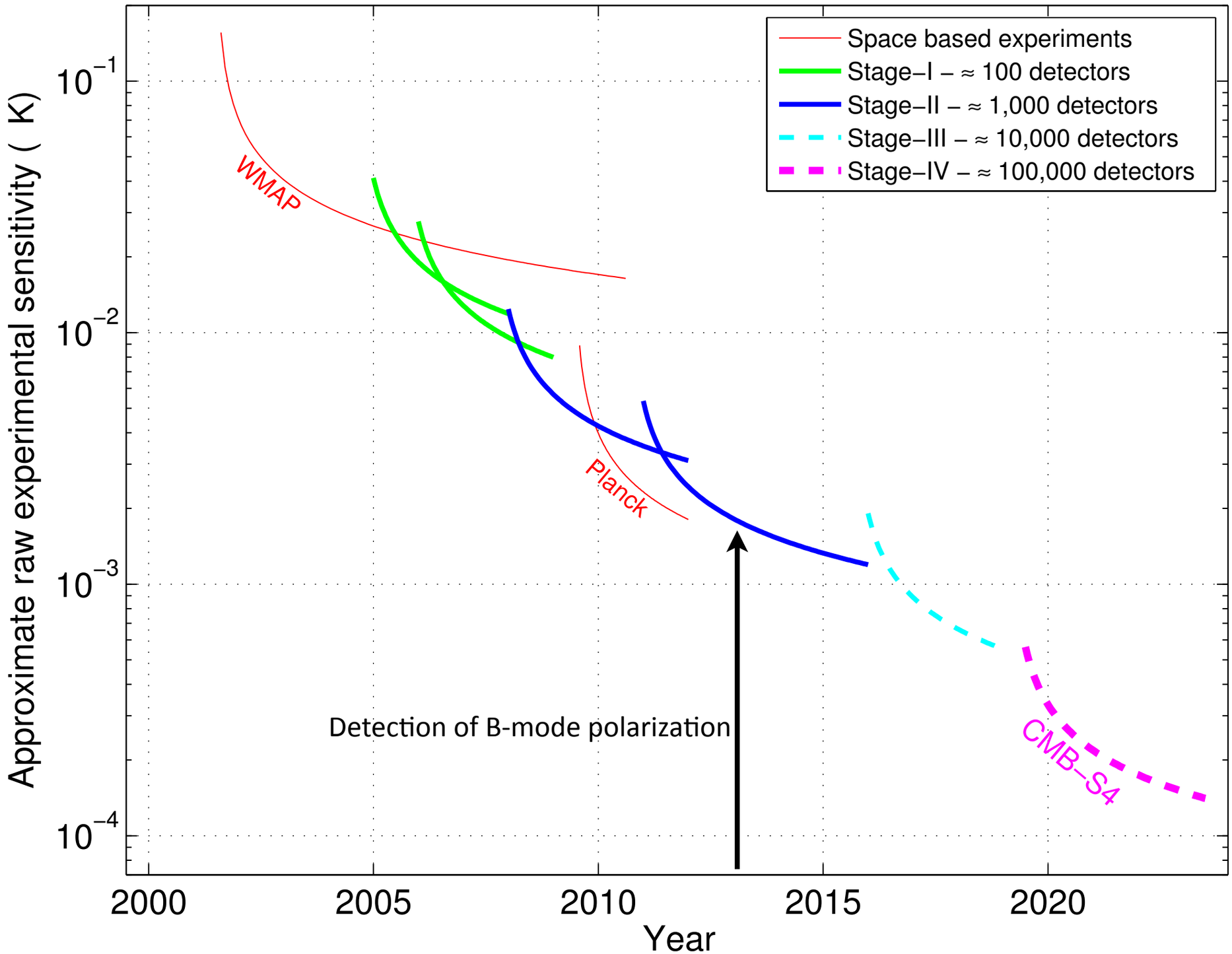
The Stage IV experiment: CMB-S4

- Builds on extensive experience from earlier generation experience
  - Technology
  - Systematic Error Control
- Two surveys
  - Inflation Survey (few % of the sky)
  - Neutrino mass Survey (50% of the sky)
- Experiment configuration
  - 500,000 detectors spanning 40 - 220 GHz using HEP invented superconducting Transition-Edge-Sensors (TES)
  - 3’ or better resolution for CMB lensing
  - multiple platforms
- Midscale project: $50M to $100M capital cost

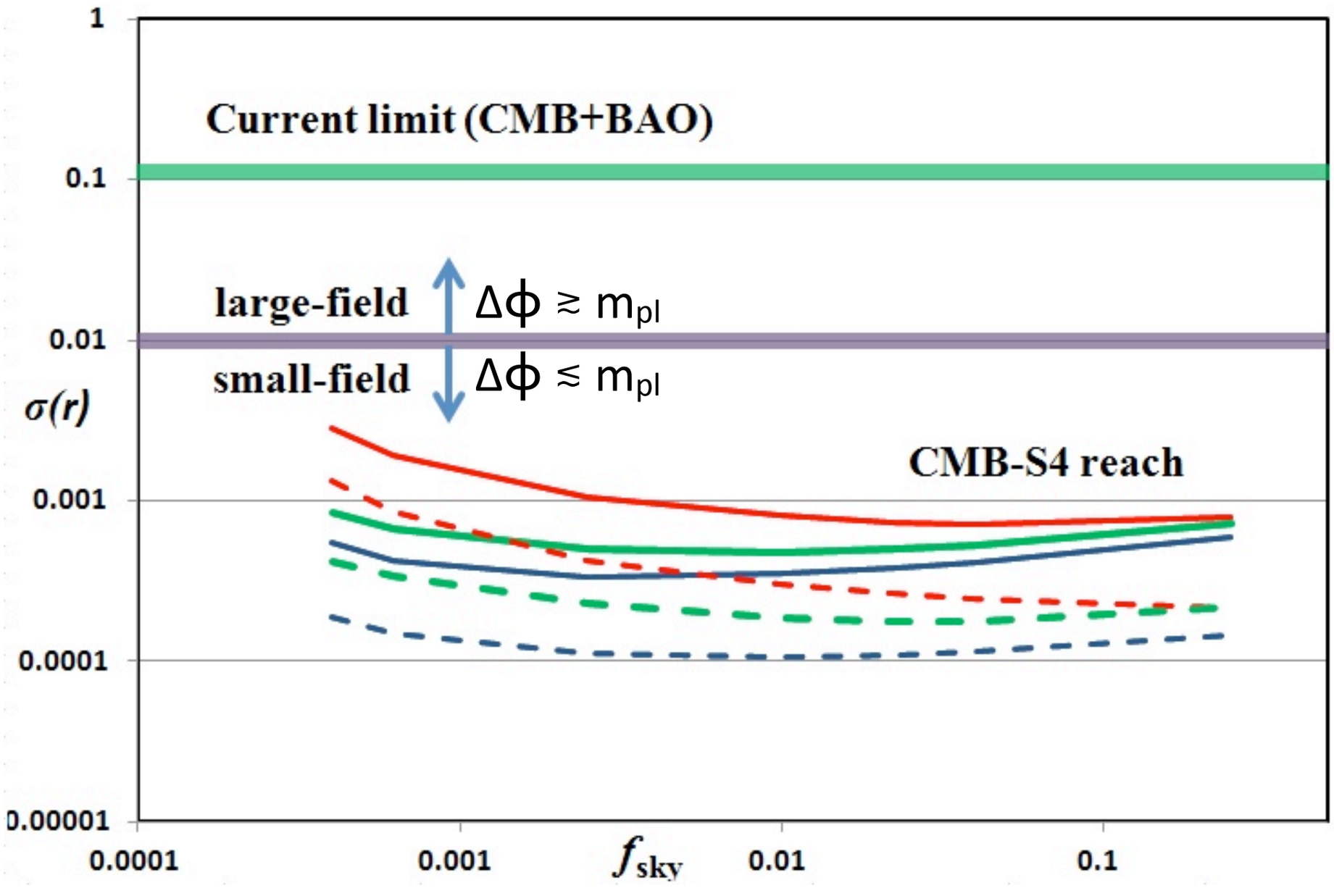
National lab and HEP community involvement in CMB-S4

- **CMB-S4 requirements exceed capabilities of University-based experiments**
  - Focal-plane Arrays and Readout
    - Improved Production Reliability
    - Increased Production Volume and Throughput
      - 500,000 detectors ~ 300 silicon arrays
    - Multiplexed TES Readout
    - Large Cryogenic Optics
  - Computing Infrastructure and Analysis tools
    - ~10,000 x *Planck* data size (~ 3 TB/day)
  - Project Organization/Management

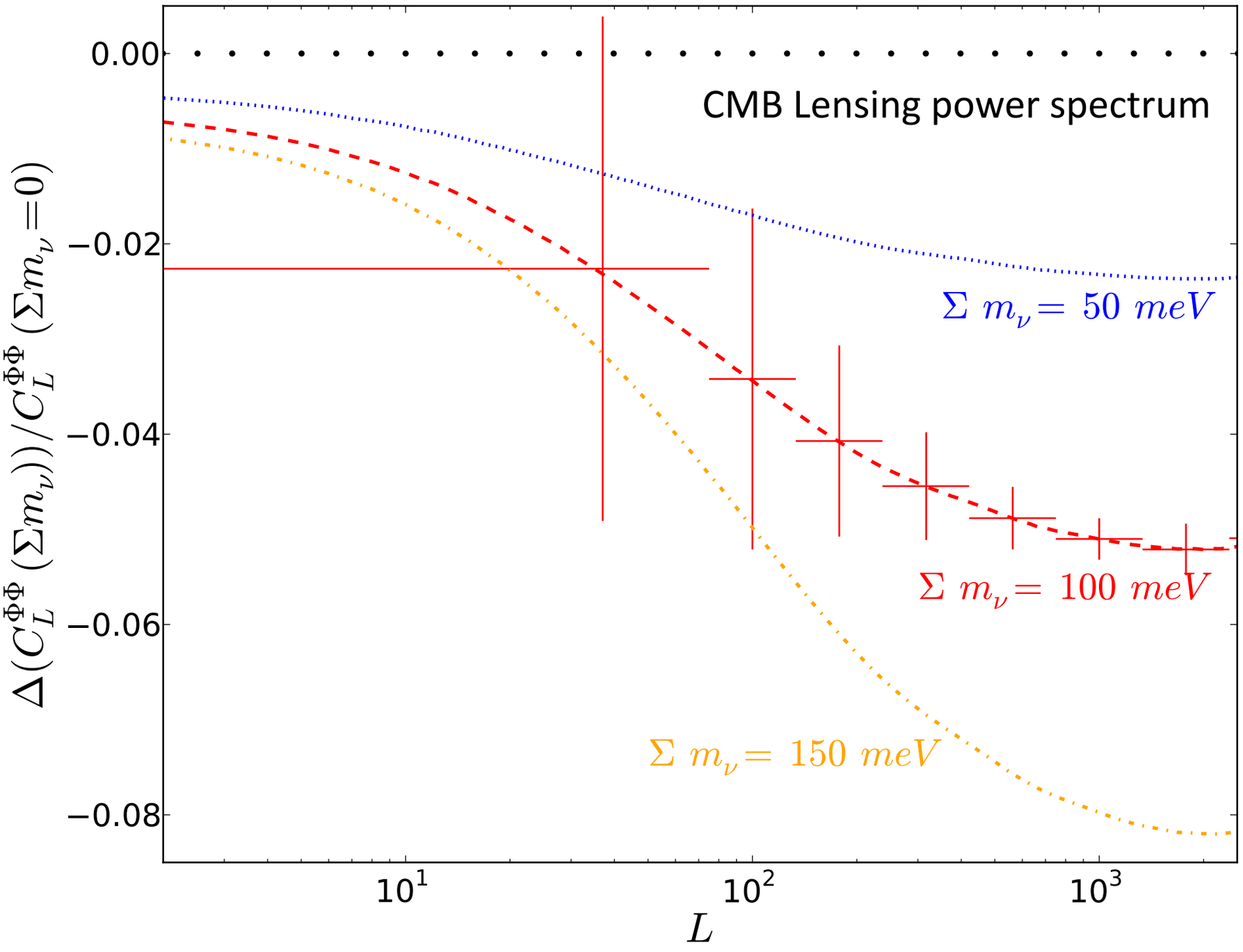
Experimental Evolution



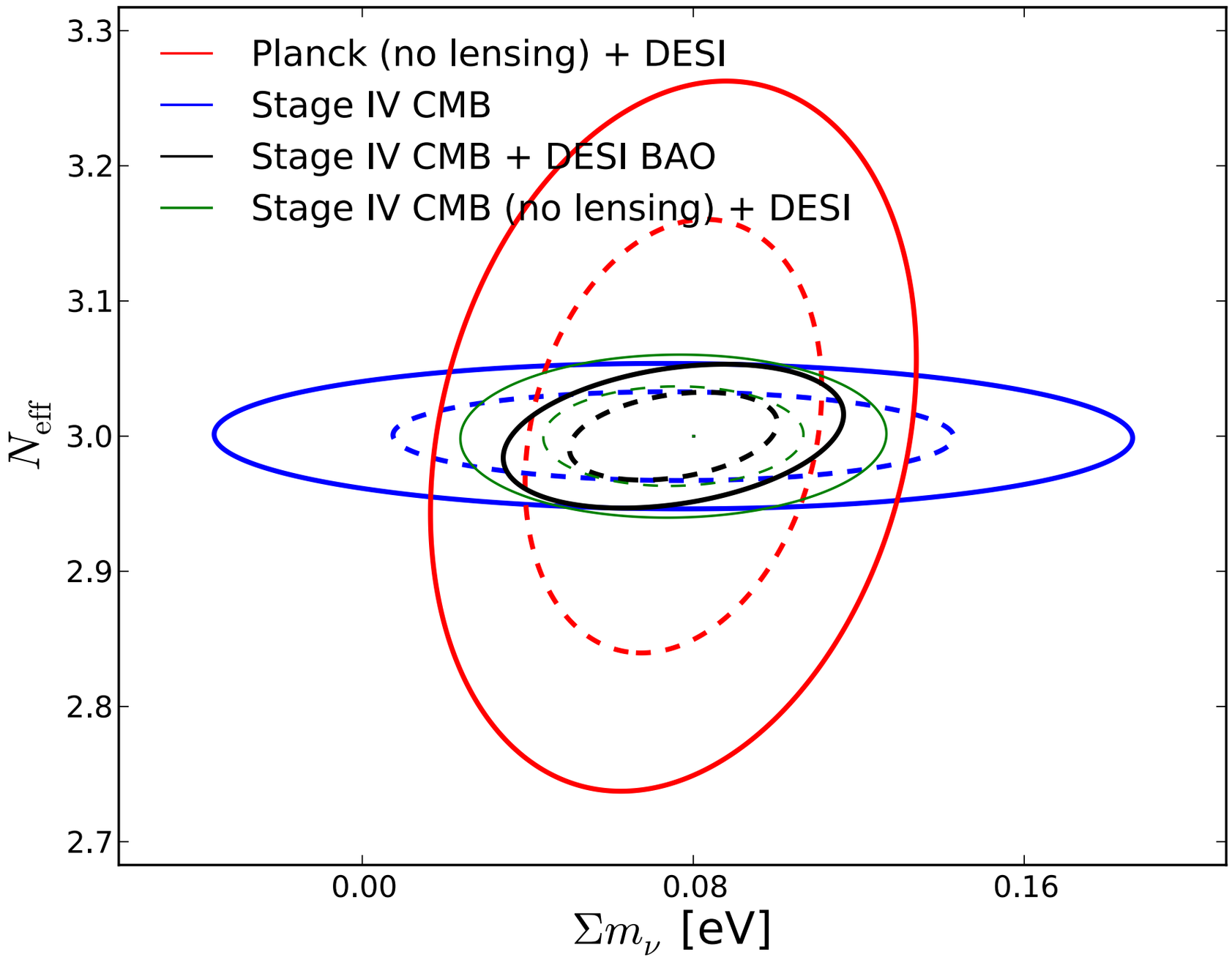
Inflation projection for CMB-S4



CMB-S4 Lensing Sensitivity Σm_ν



Joint projections N_{eff} - Σm_ν



$\sigma(\Sigma m_\nu)$ = 16 meV

$\sigma(N_{eff})$ = 0.020

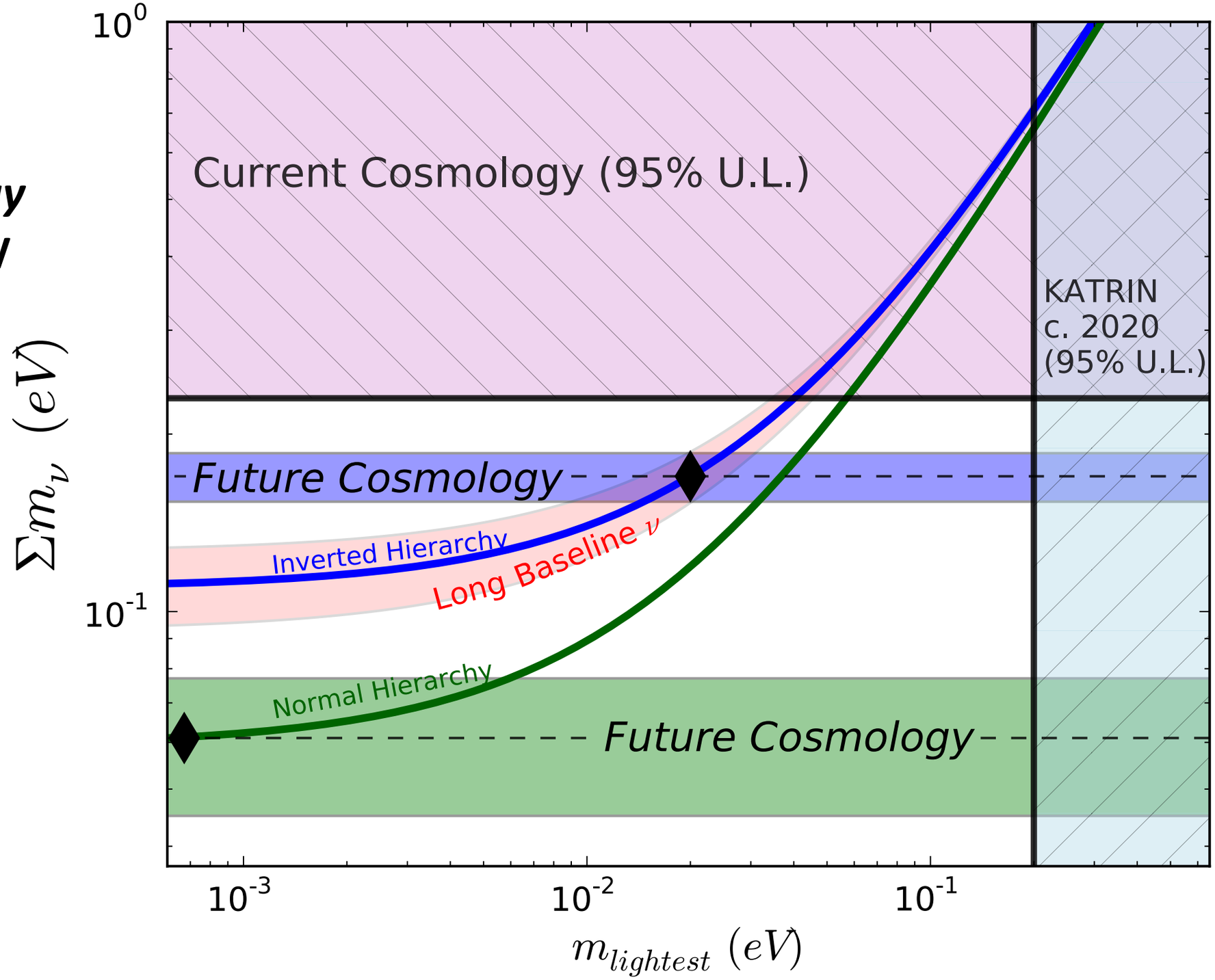
with two probes

Our forecasters: J. Errard, P. McDonald, A. Slosar K. Wu, O. Zahn

Combined Neutrino mass constraints

Future Cosmology

$\sigma(\Sigma m_\nu) = 16$ meV



"use cosmology to tighten the noose" Boris Kayser

Summary

CMB measurements are at the heart of cosmology and fundamental physics.

Stage IV CMB experiment is needed.

It will be challenging, but achievable, with 100x or more increase in detectors from current Stage II, incredible attention to systematics, and commensurate increase in computing.

It is a HEP multilab-scale project!