Inflation-era High Energy Physics and neutrino constraints via CMB measurements

Gearing up for a Stage IV CMB polarization experiment

WARNING

Read before opening

1) This is a quickly assembled talk. Many of the future projections are gross estimates of work in progress, or from someone in the audience during one the sessions, or rumors from experiments.
2) The momentum and excitement of the field is very real and highly addictive.

What stages?

- **Stage II: (>1K detector elements)**
  - e.g: EBEX, SPTpol, BICEP2/Keck, Polarbear, ACTpol...
  - already observing (or about to)

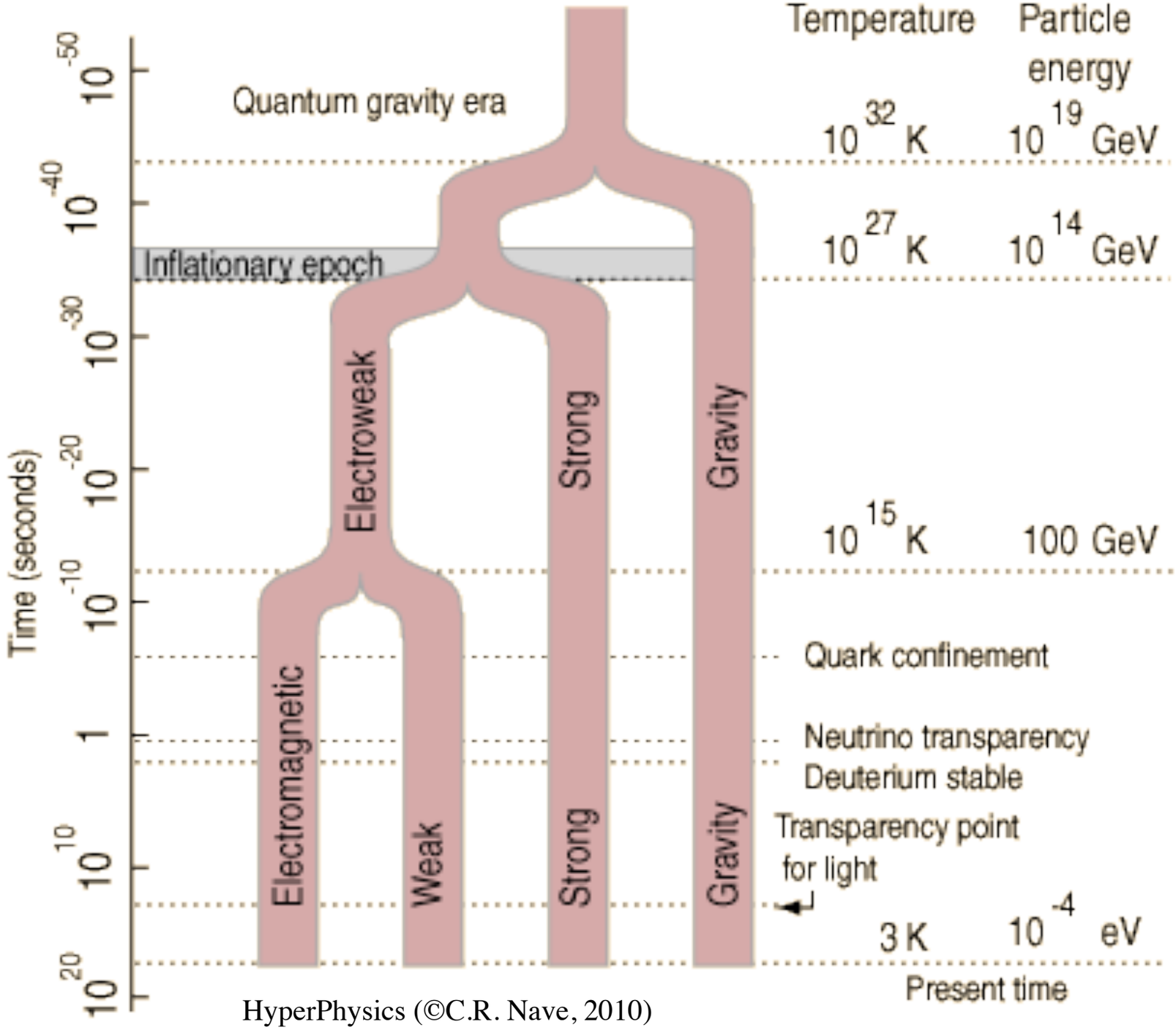
- **Stage III: (>10K detector elements)**
  - 10x mapping speed over Stage II (a few in the works, 2015+)

- **Stage IV: (>100K detector elements)**
  - 100x mapping speed over Stage II
  - Baseline: deploy ~2020, observe ~ 5 years

VERY CHALLENGING! – Requires 100k to 500k detectors;
Incredible attention to systematics.
Commensurate increases or more in HPC.

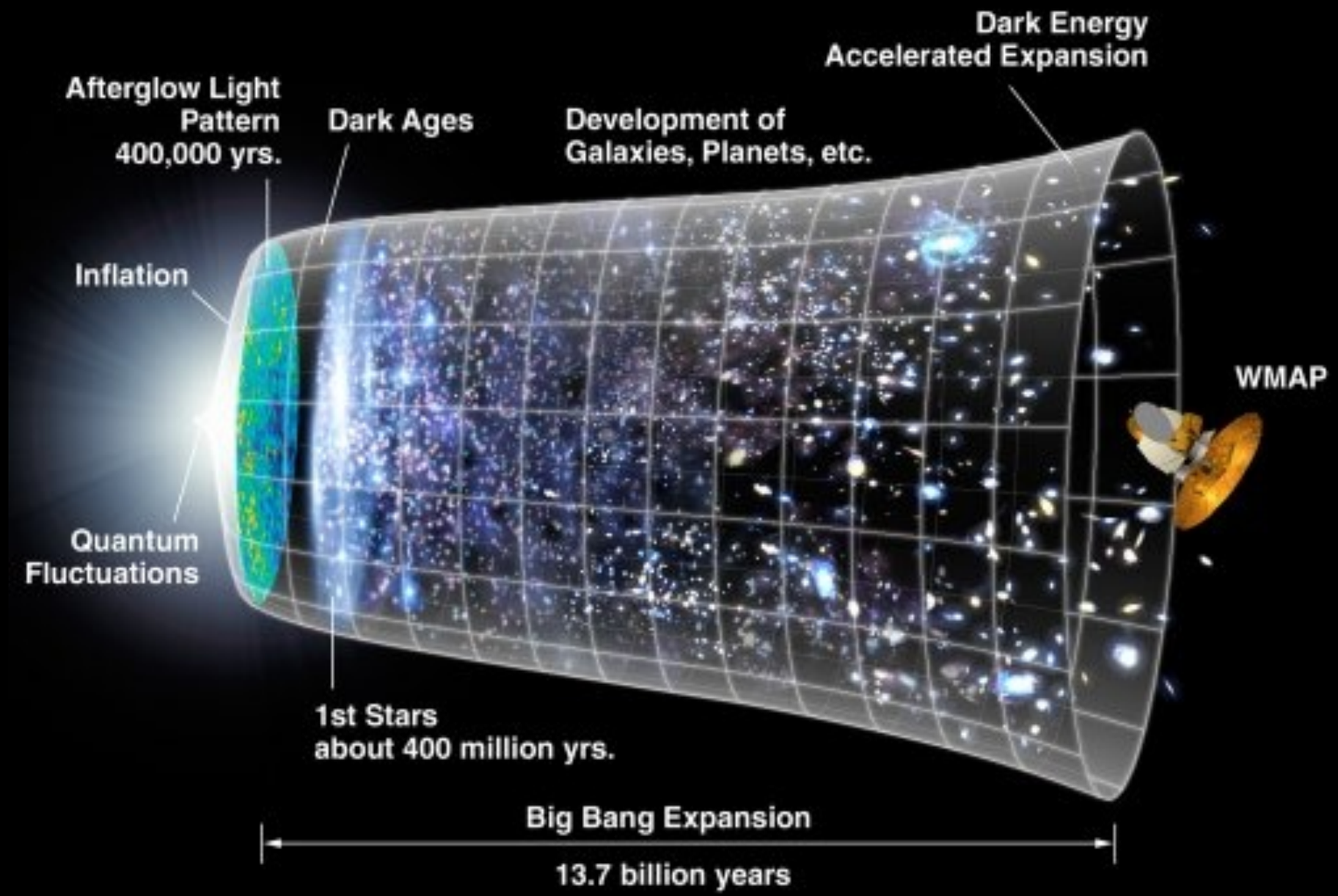
It is a HEP multilab scale project using the highest energy accelerator in the universe!

Early universe as an HEP lab



HyperPhysics (©C.R. Nave, 2010)

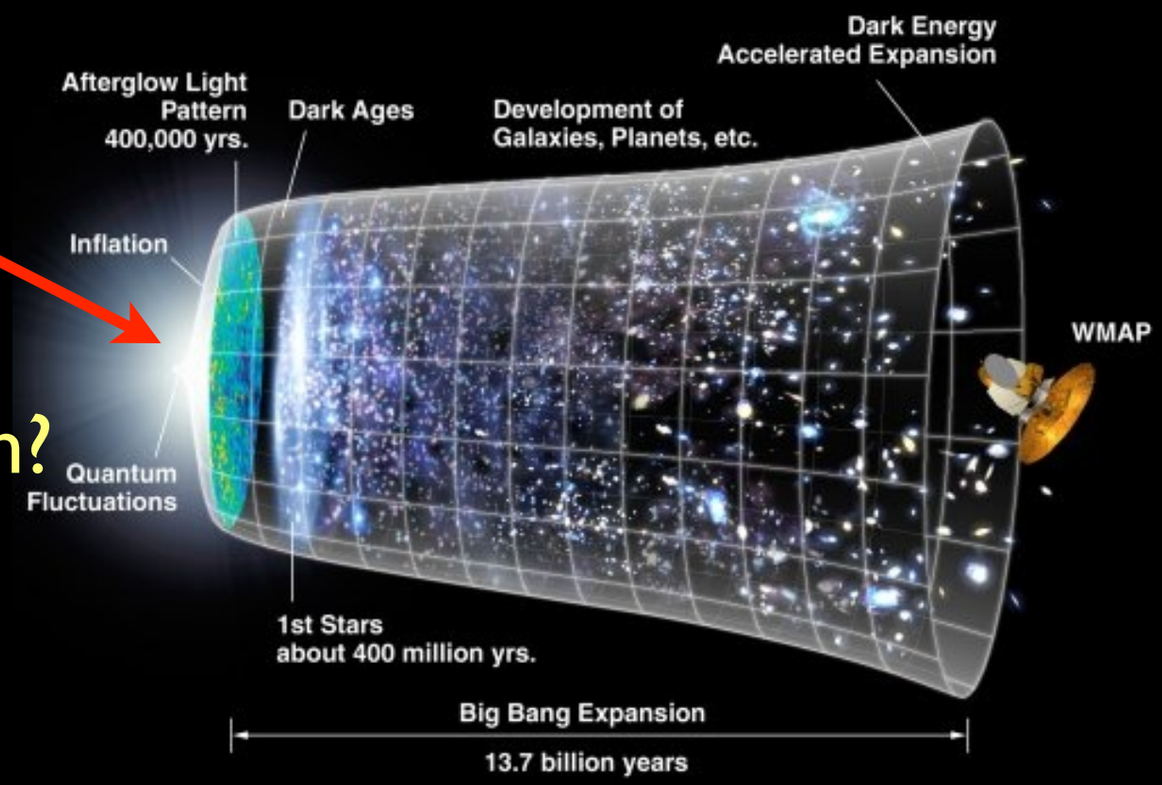
CMB measurements probe fundamental physics and cosmology



slide from NASA/WMAP

Inflation?

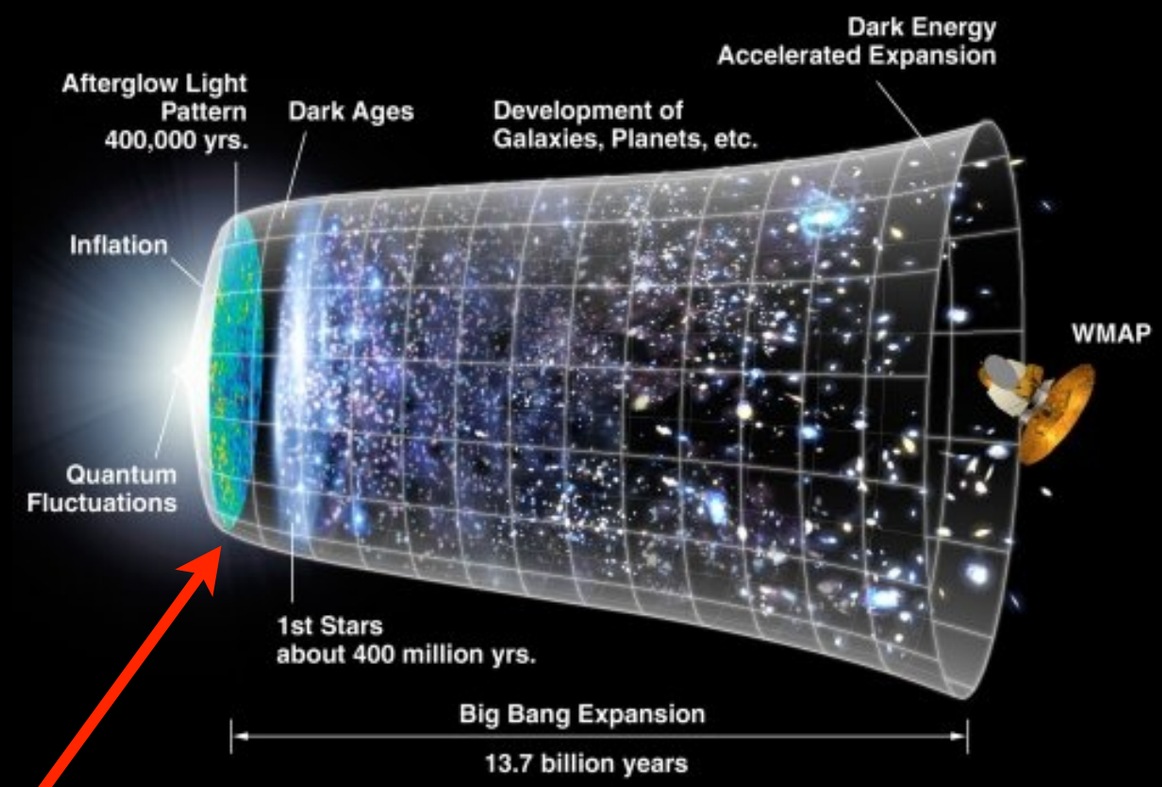
Universe expands by $>e^{60}$
solving smoothness problem,
flatness and more..



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

- spectral index of fluctuations, n_s
- constrain tensor to scalar fluctuations
- non-Gaussianity?
- inflationary gravitational waves?

➡ *need precision temperature and ultrasensitive polarization measurements of the primary CMB anisotropy angular power spectrum*

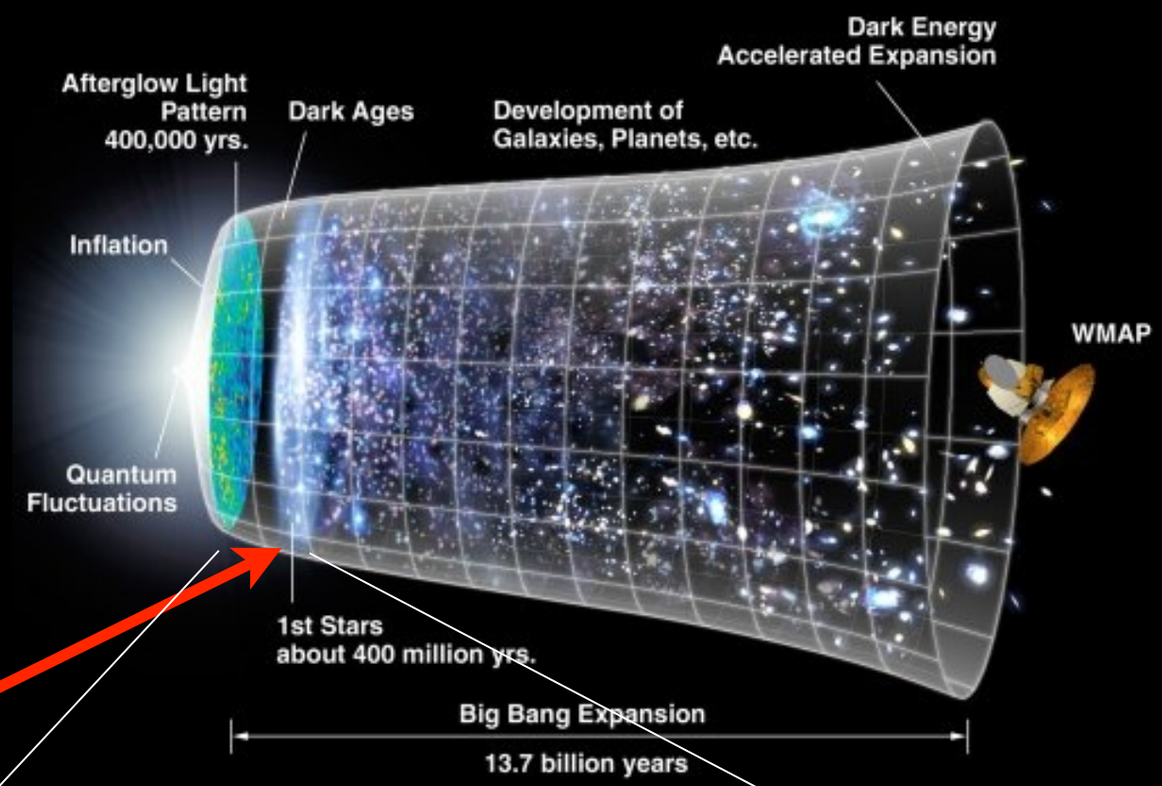


Physics at recombination

Universe cools enough to form neutral H.
Photons start free-streaming

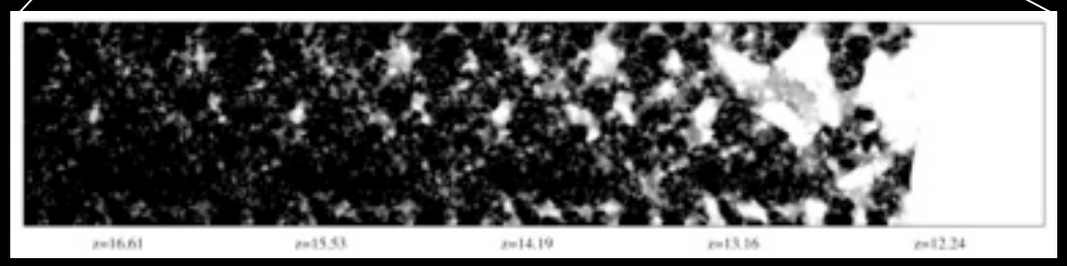
- Measure primordial fluctuations
- Inventory stuff in the universe
- Number of relativistic species, helium abundance

➡ *need precision measurement of CMB power spectrum to fine angular scales, i.e., covering the damping tail*



Reionization

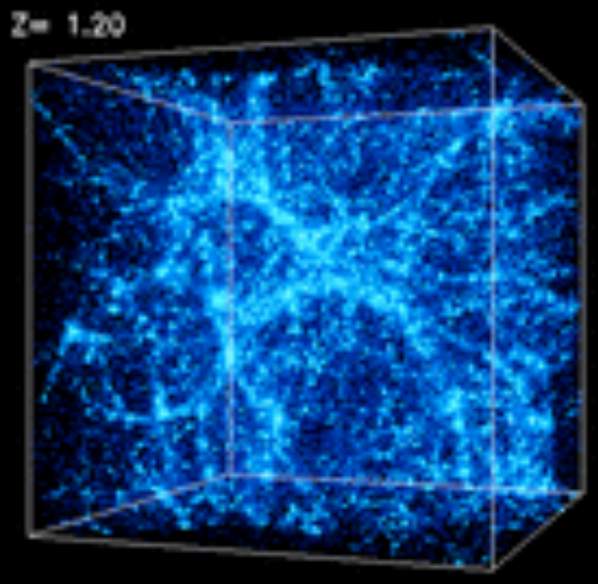
First stars(?) start producing
UV photons. Hydrogen is reionized.



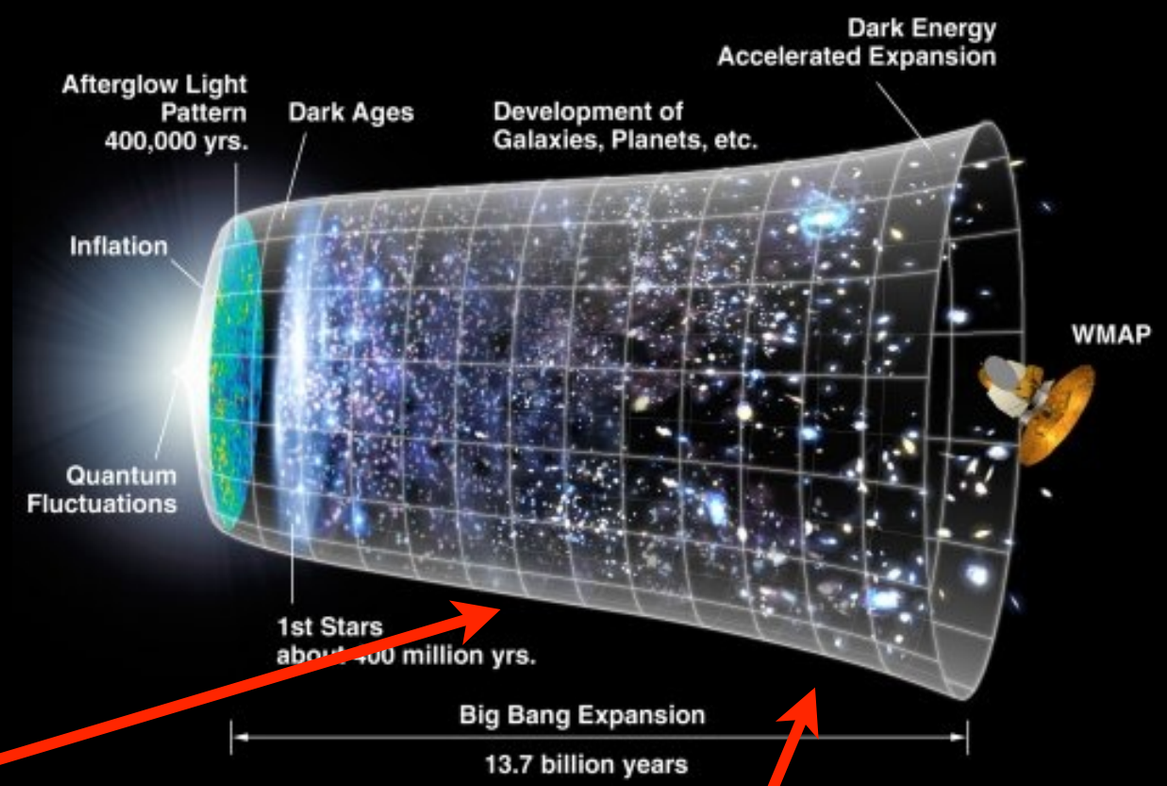
Patchy reionization, Zahn et al, 2005

How did it proceed?
Are star forming galaxies sufficient?

➡ *need high resolution measurements of diffuse kinematic SZ effect on small angular scales*



Credit: Kravtsov



Structure Formation

Gravitational collapse creates increasingly large structures

- What is dark matter?
- Masses of the neutrinos
- Constrain early dark energy models

Cosmic Acceleration

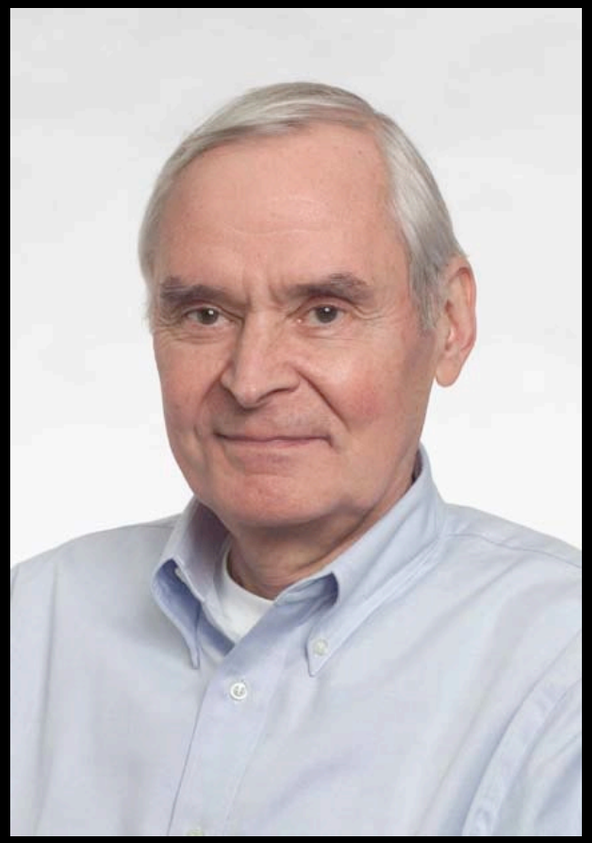
Dark energy begins accelerating the expansion of the Universe.

- Is dark energy dynamic or a cosmological constant?
- Is GR correct on large scales?

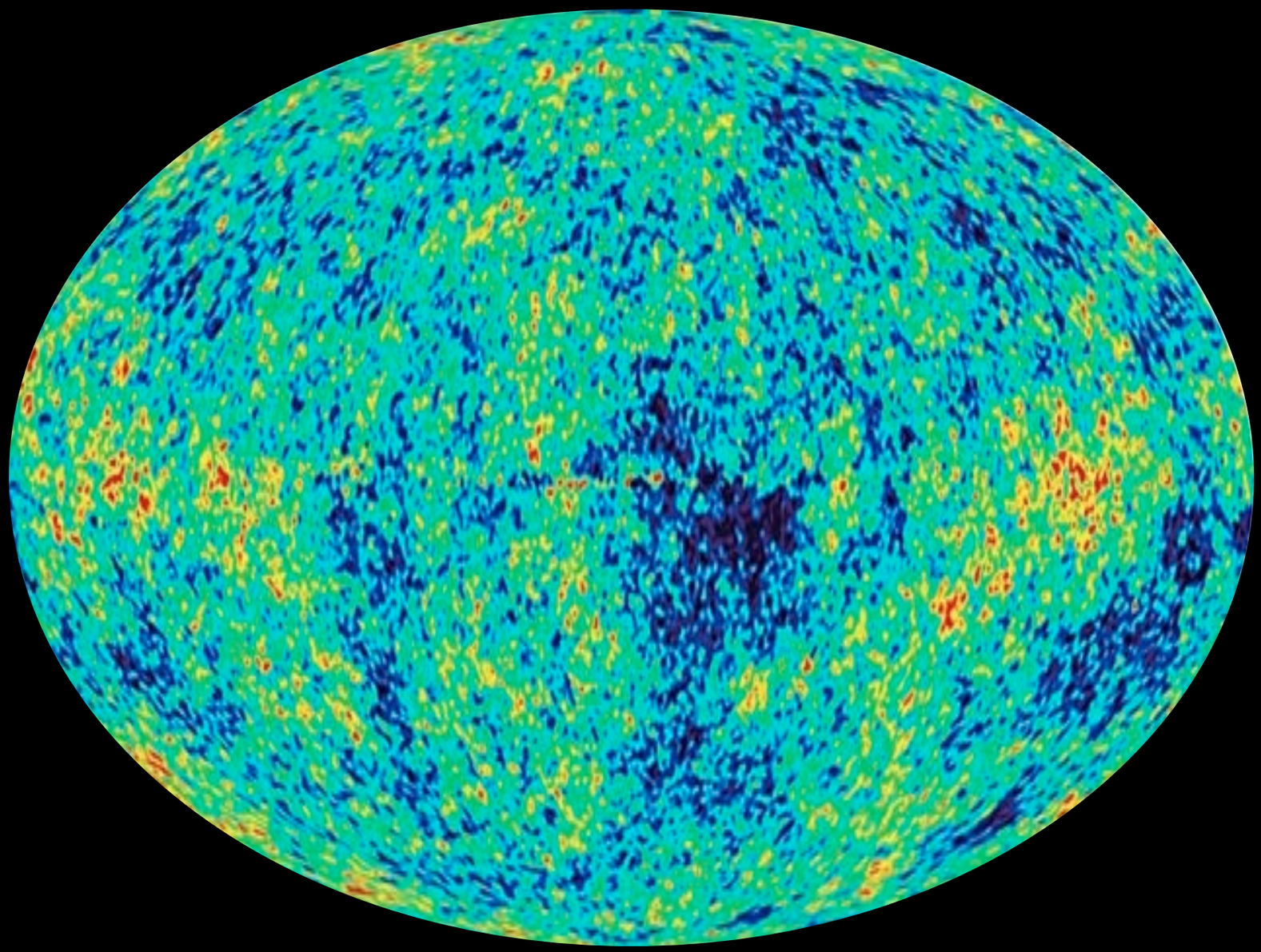
➡ *dark matter structure through lensing of the CMB*

➡ *evolution of Galaxy Clusters through thermal SZ effect*

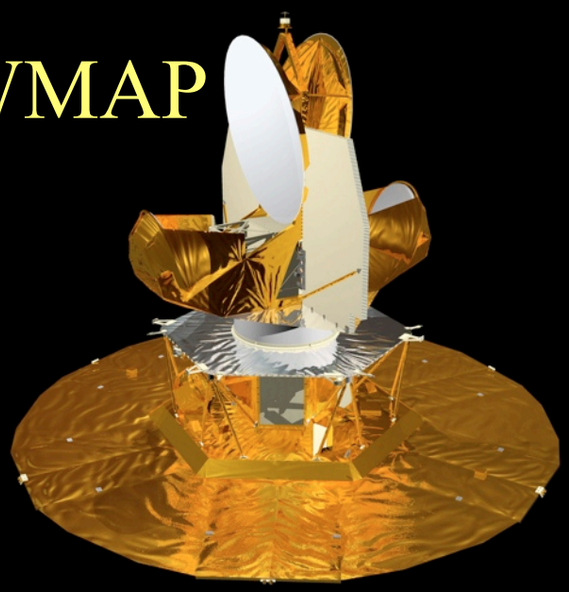
Wilkinson Microwave Anisotropy Probe (WMAP)



David Wilkinson
1935-2002

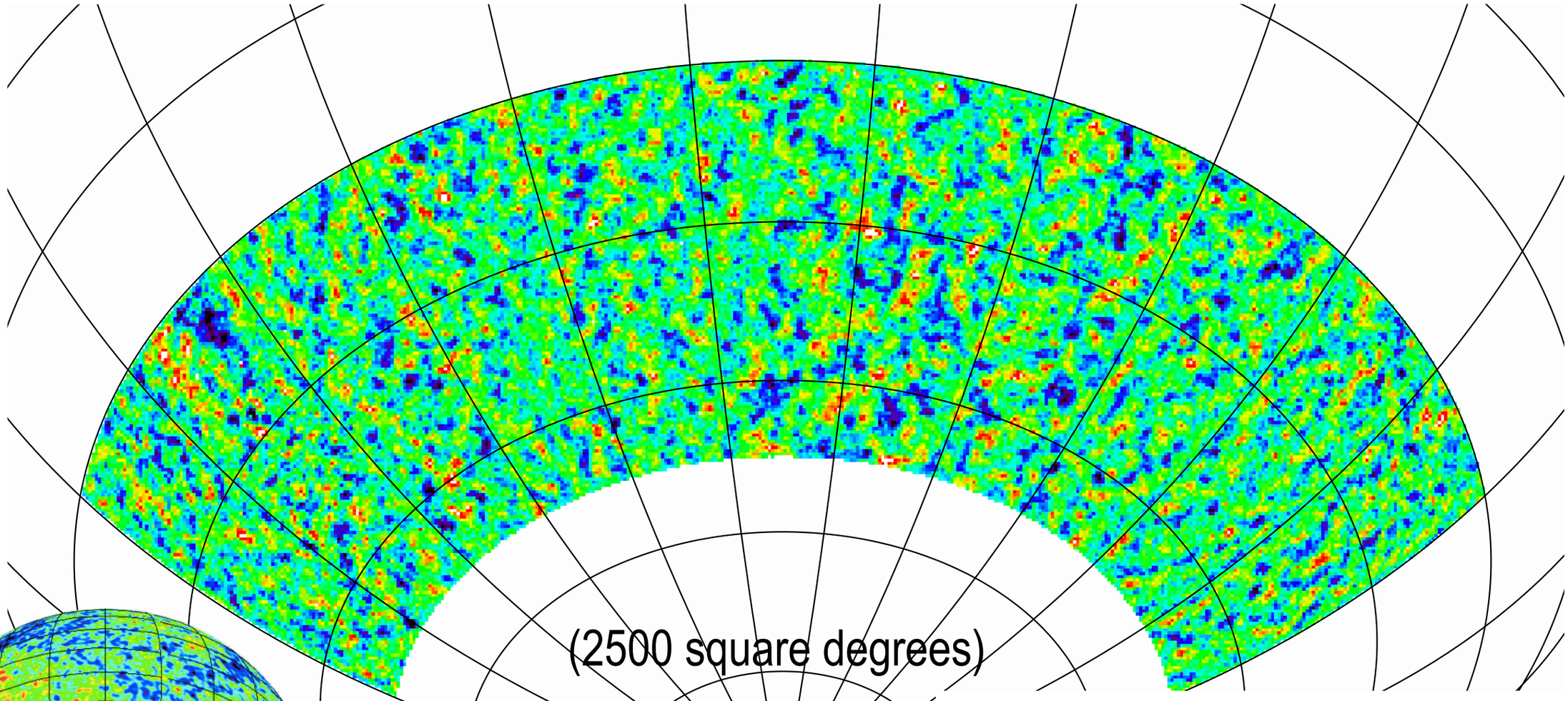


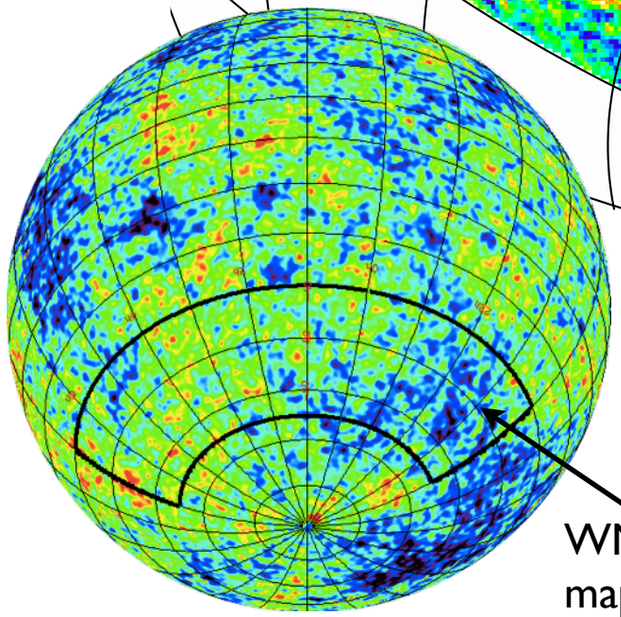
WMAP



higher resolution and sensitivity map of the CMB

covering 1/16 of the sky from SPT





WMAP lower resolution full sky map with SPT area marked

Survey depths:

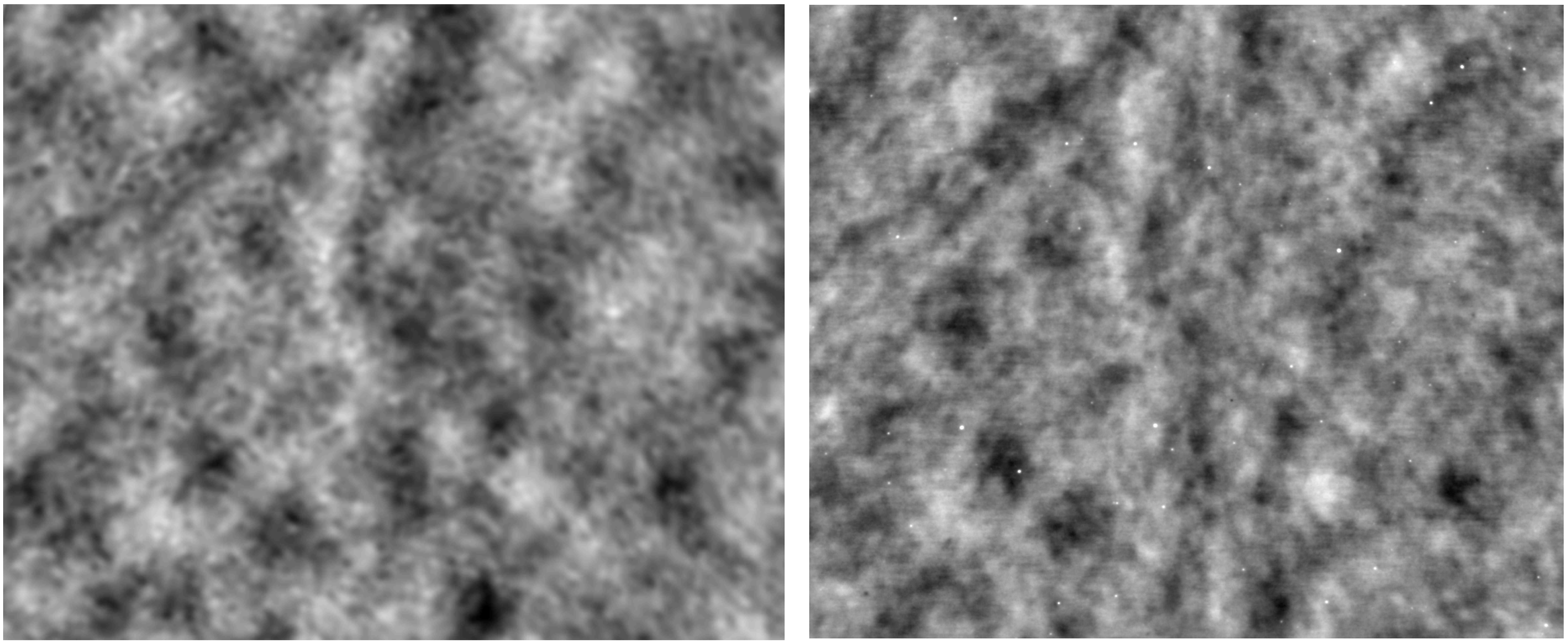
- 90 GHz: ≲42 uK$_{CMB}$-arcmin*
- 150 GHz: ≲18 uK$_{CMB}$-arcmin
- 220 GHz: ≲ 85 uK$_{CMB}$-arcmin

** In these units, the thermal Sunyaev-Zel'dovich (SZ) effect is 1.7 times brighter at 90 GHz than at 150 GHz.*

WMAP - SPT comparison over 150 deg²

WMAP

SPT



13x higher resolution and 17x deeper than WMAP
5x higher resolution and 3x deeper than Planck blue book

Shows structure from degrees to arc minutes: from large-scale CMB to SZ & unresolved sources.

Zoom in on an SPT map

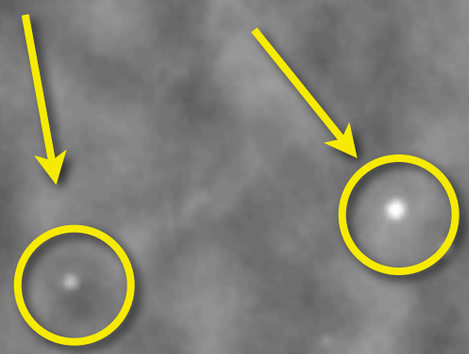
50 deg² from 2500 deg² survey

CMB Anisotropy

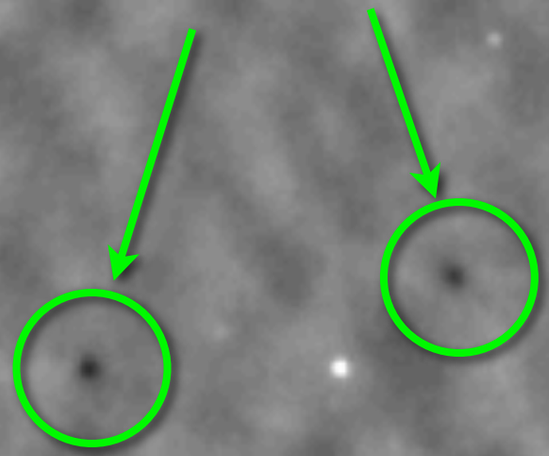
Primary and secondary CMB anisotropy & foregrounds, i.e., CIB

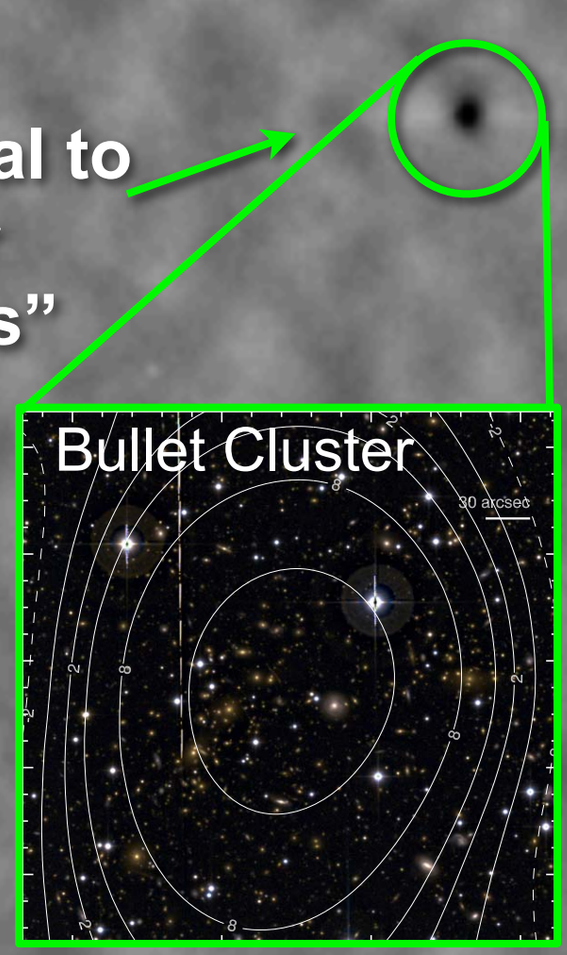
Galaxies

AGN & high-redshift lensed dusty star forming galaxies

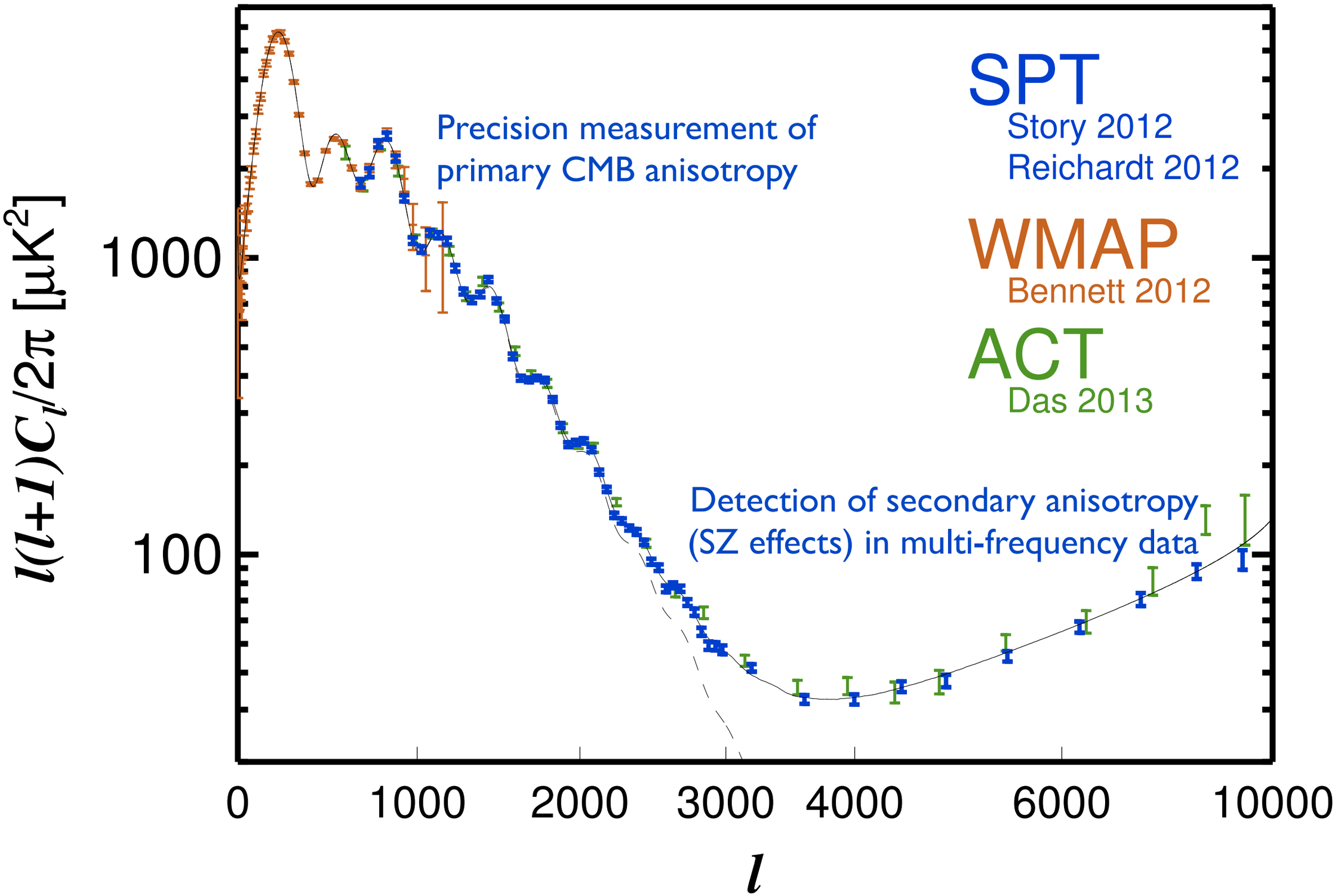


Clusters - High signal to noise SZ galaxy cluster detections as “shadows” against the CMB



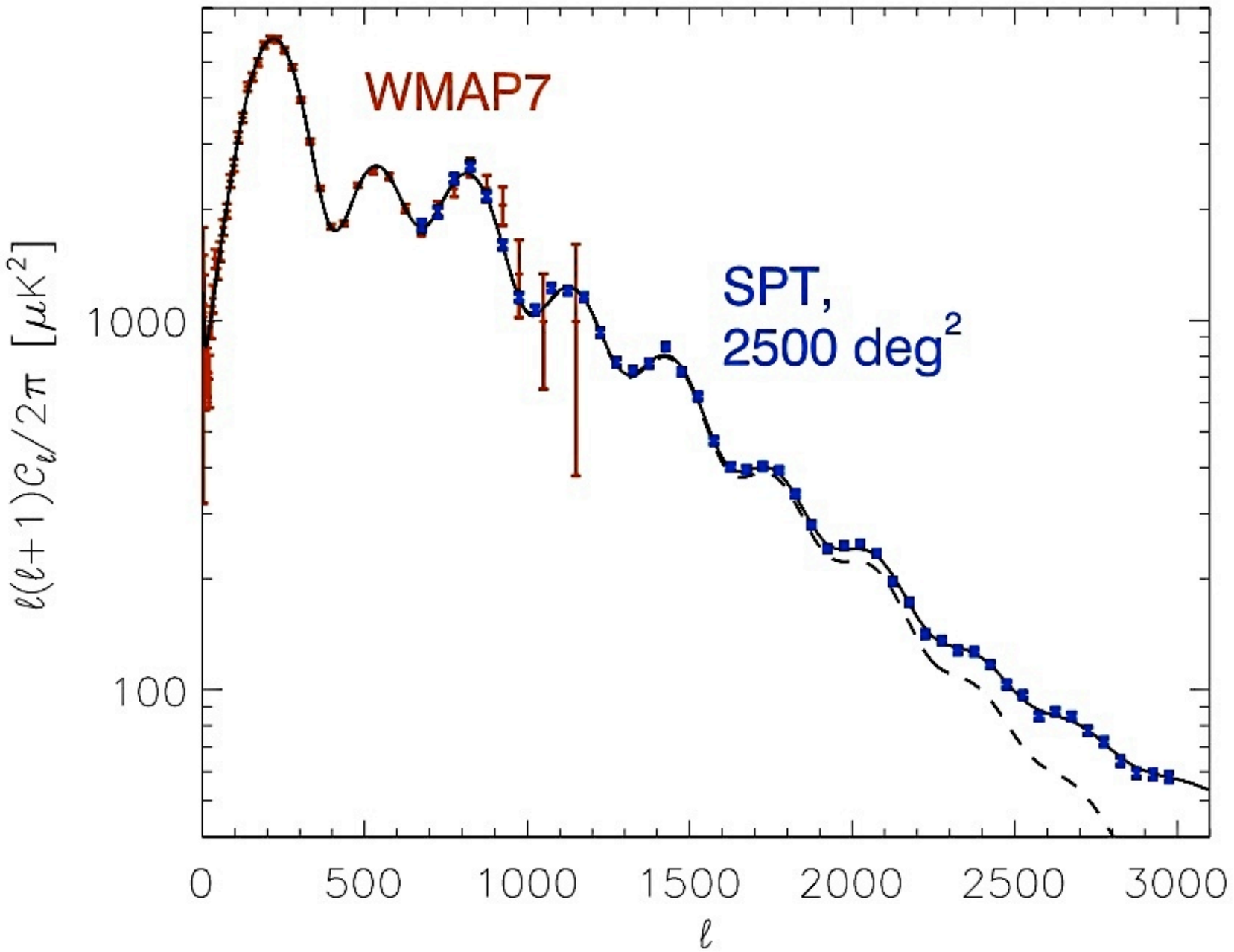


Anisotropy angular power spectrum



Primary CMB anisotropy - 9 harmonics

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



Higher resolution data provide increased precision on cosmological parameters and allow constraints on extensions to the "standard" ΛCDM model.

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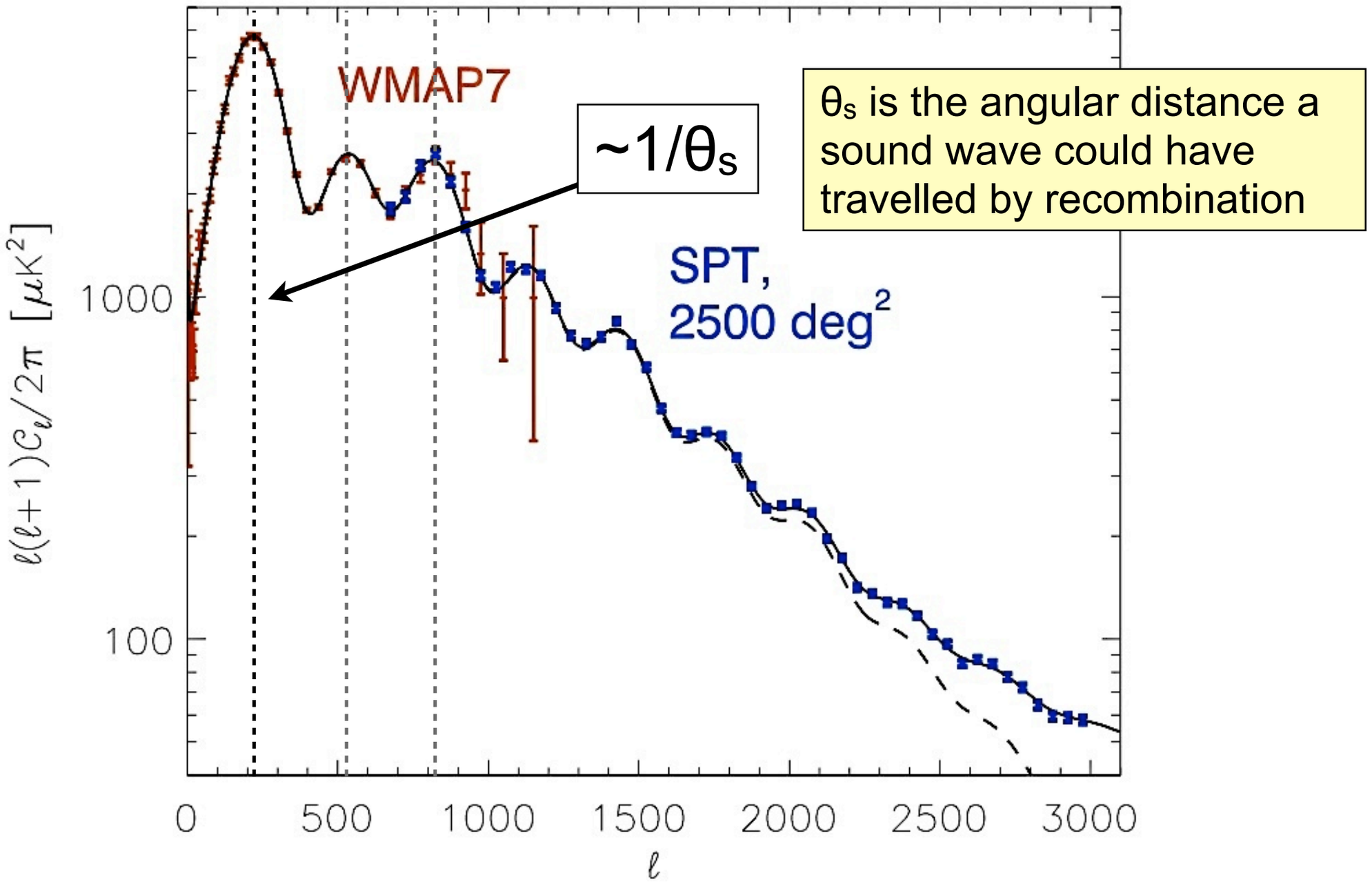
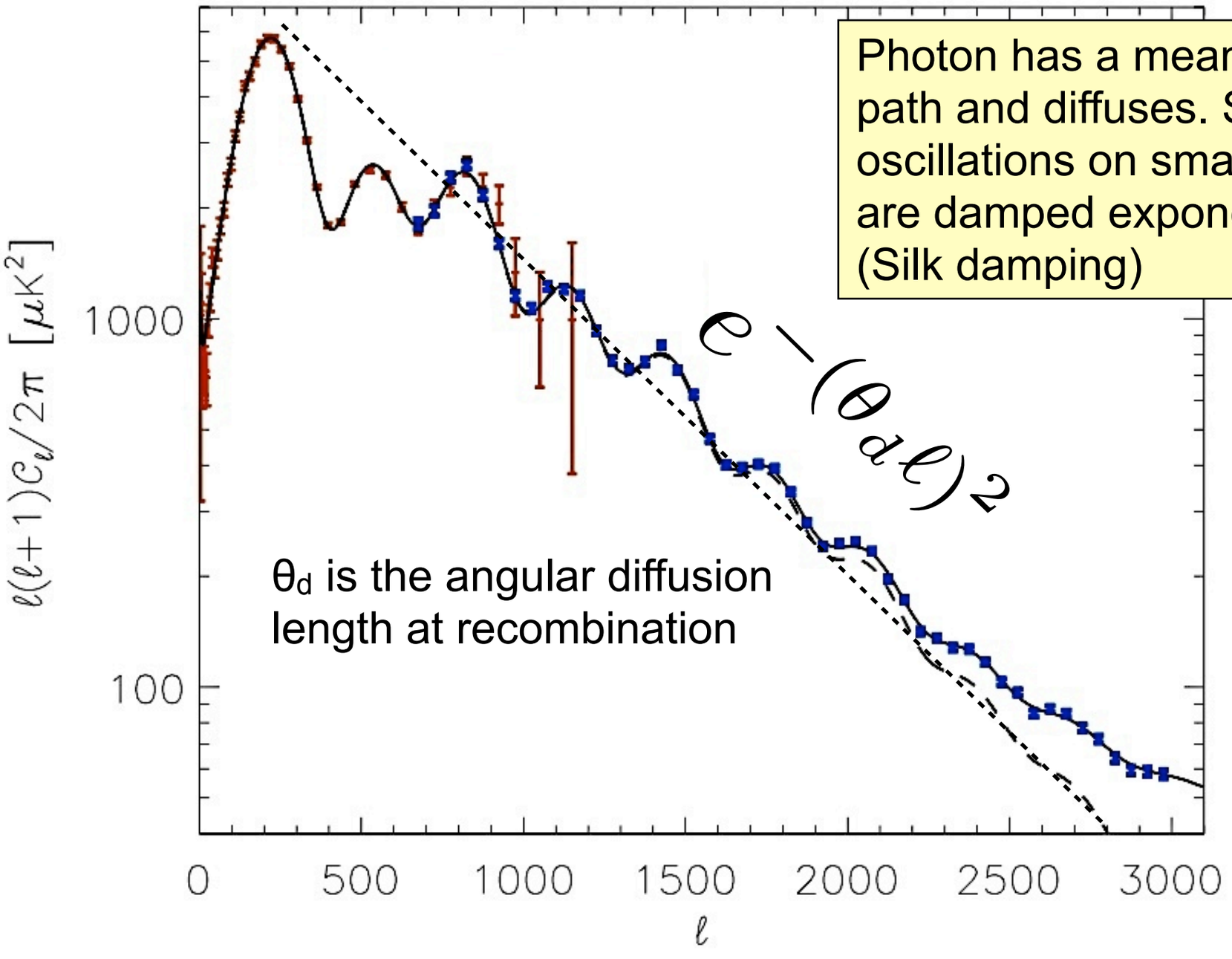
Improves precision of sound horizon, θ_s, & provides larger lever arm



Higher resolution data provide increased precision on cosmological parameters and allow constraints on extensions to the "standard" ΛCDM model.

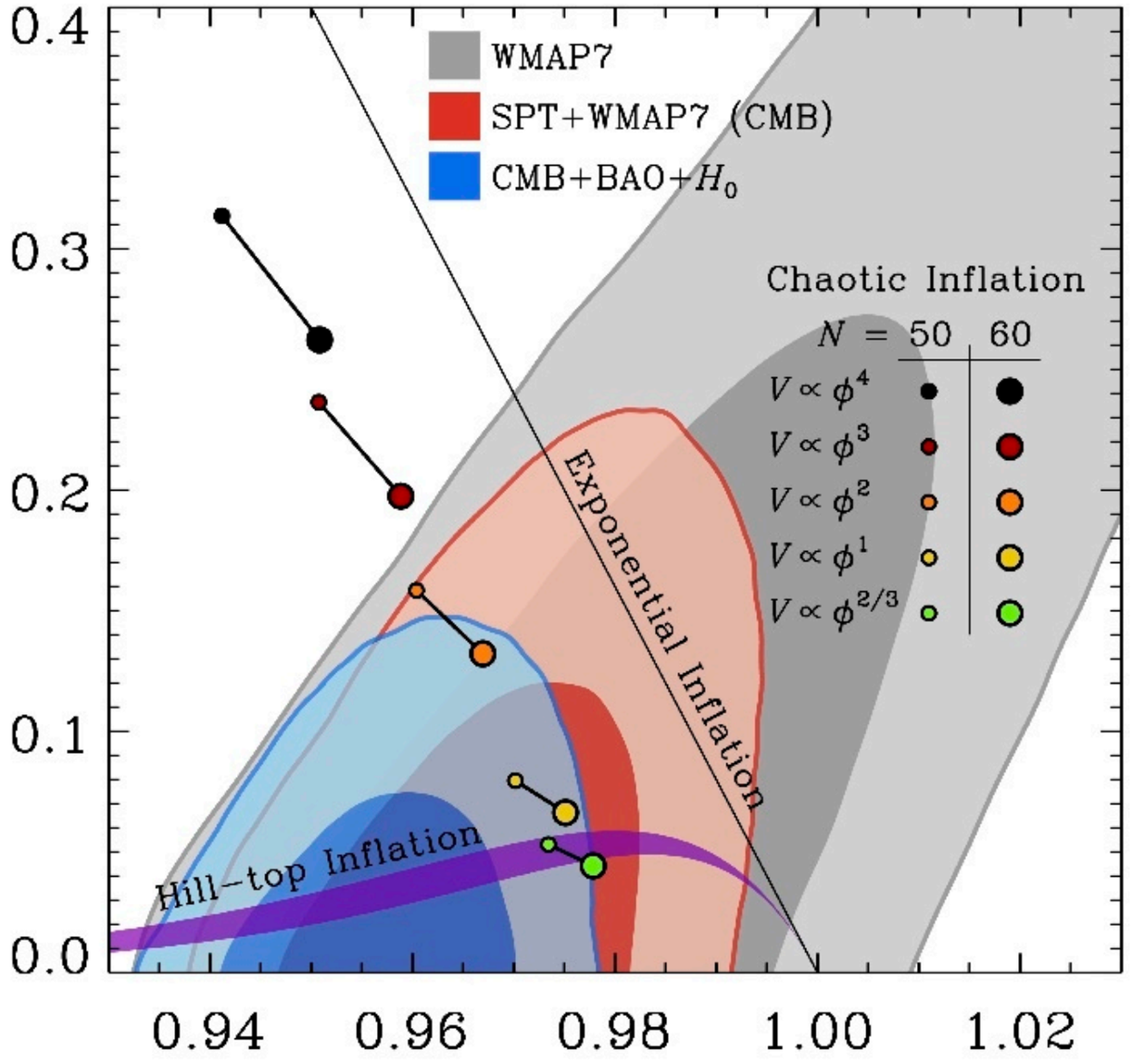
And most importantly provides determination of the damping scale, θ_d



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

Constraining inflationary models
joint r and n_s limits

Story et al., 2012 arXiv:1210.7231



ratio of tensor to scalar primordial fluctuations, r

Spectral Index of primordial fluctuations, n_s,

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

BAO: SDSS (Padmanabhan et al., 2012)
wigglez (Blake et al., 2011)
BOSS (Anderson et al., 2012)
Ho: (Reiss et al., 2011)

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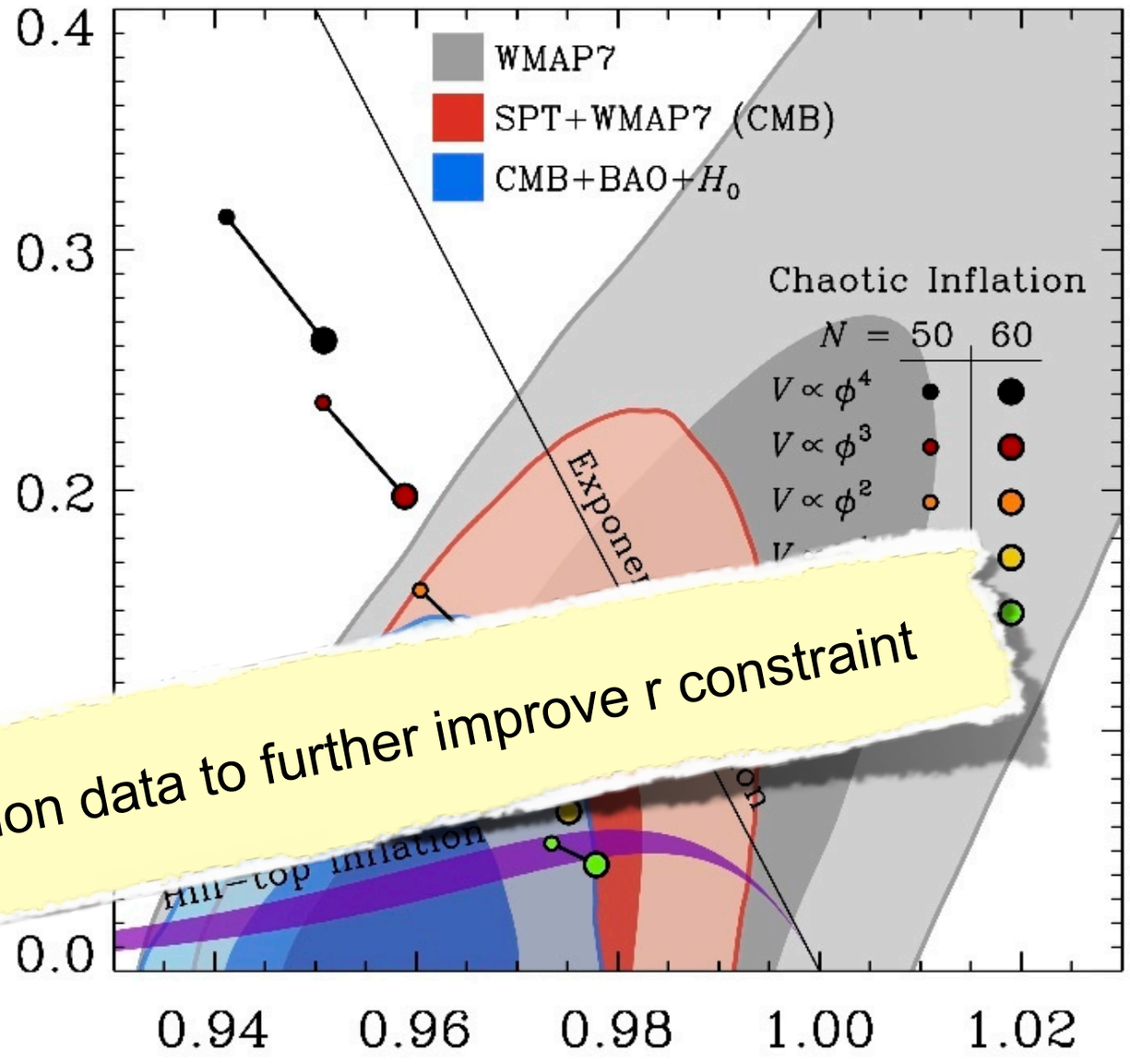

ratio of tensor to scalar primordial fluctuations, r

Now requires CMB polarization data to further improve r constraint

Spectral Index of primordial fluctuations, n_s,

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

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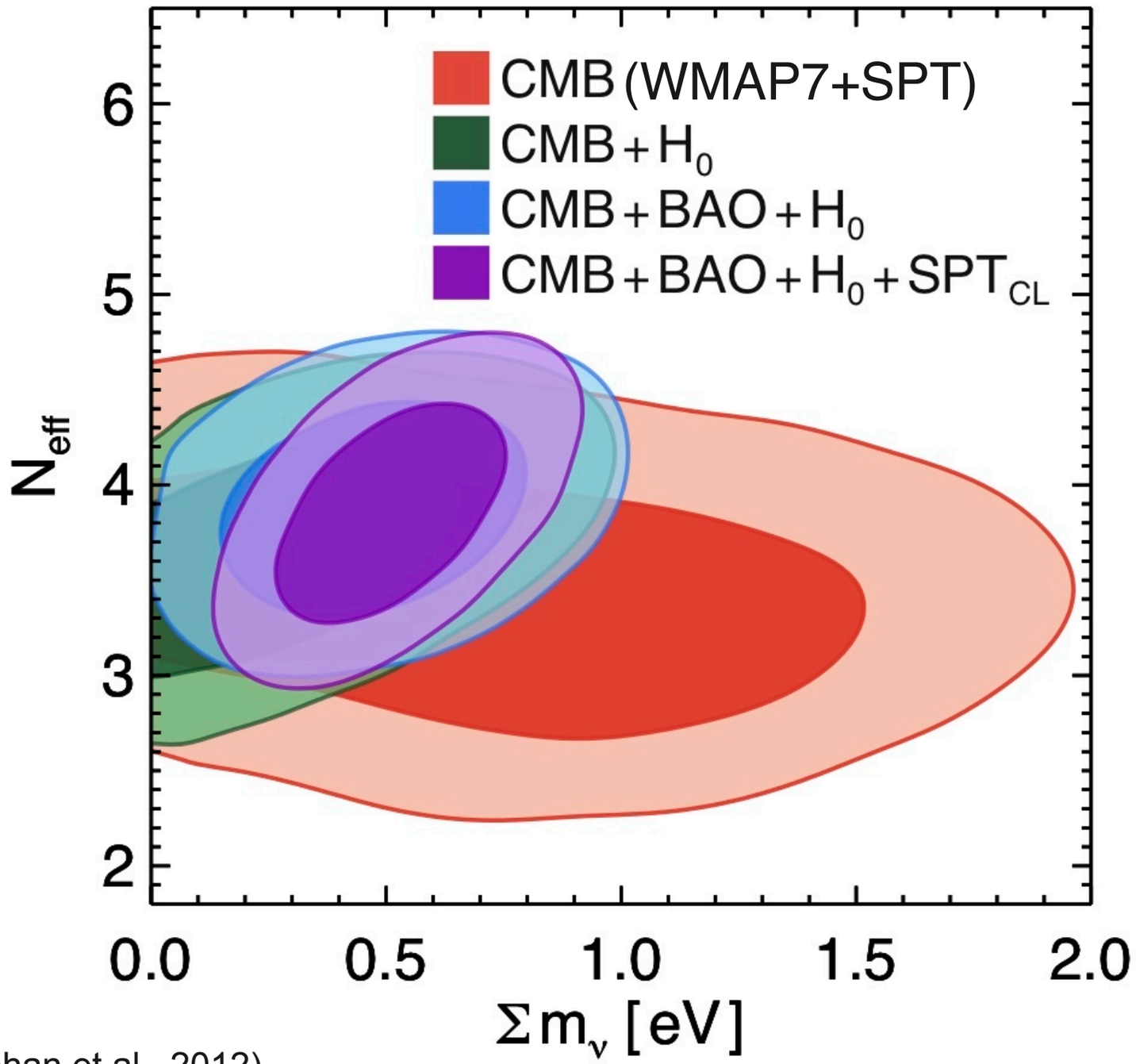
Constraining model extensions:
joint N_{eff} (# neutrinos) and Σm_ν constraints

Stage IV goal
σ(Neff) ≲ 0.04
incl degenerate parameters



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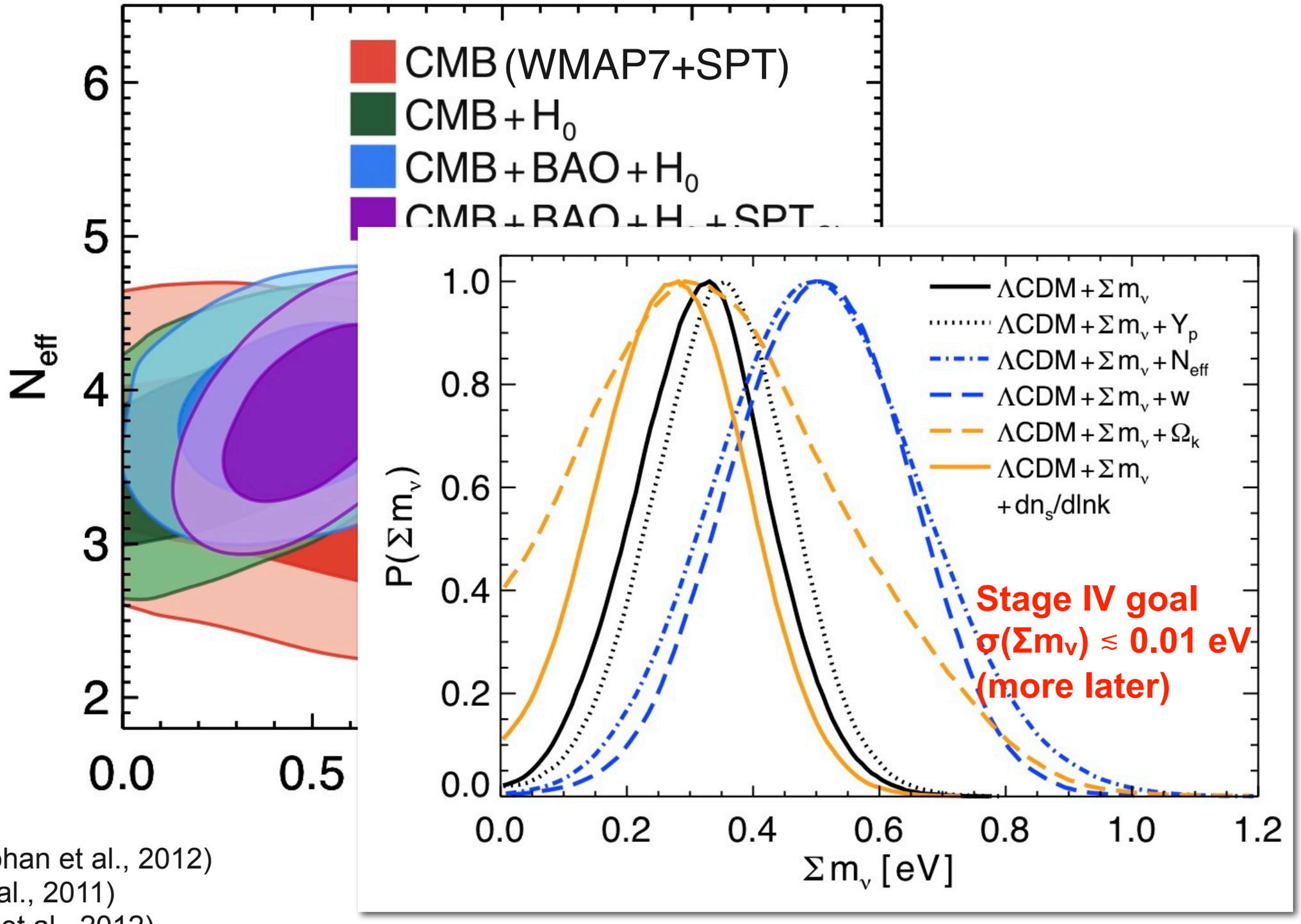

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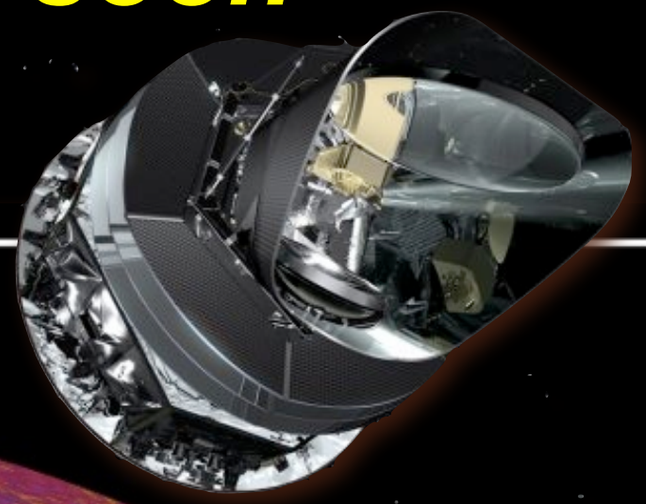
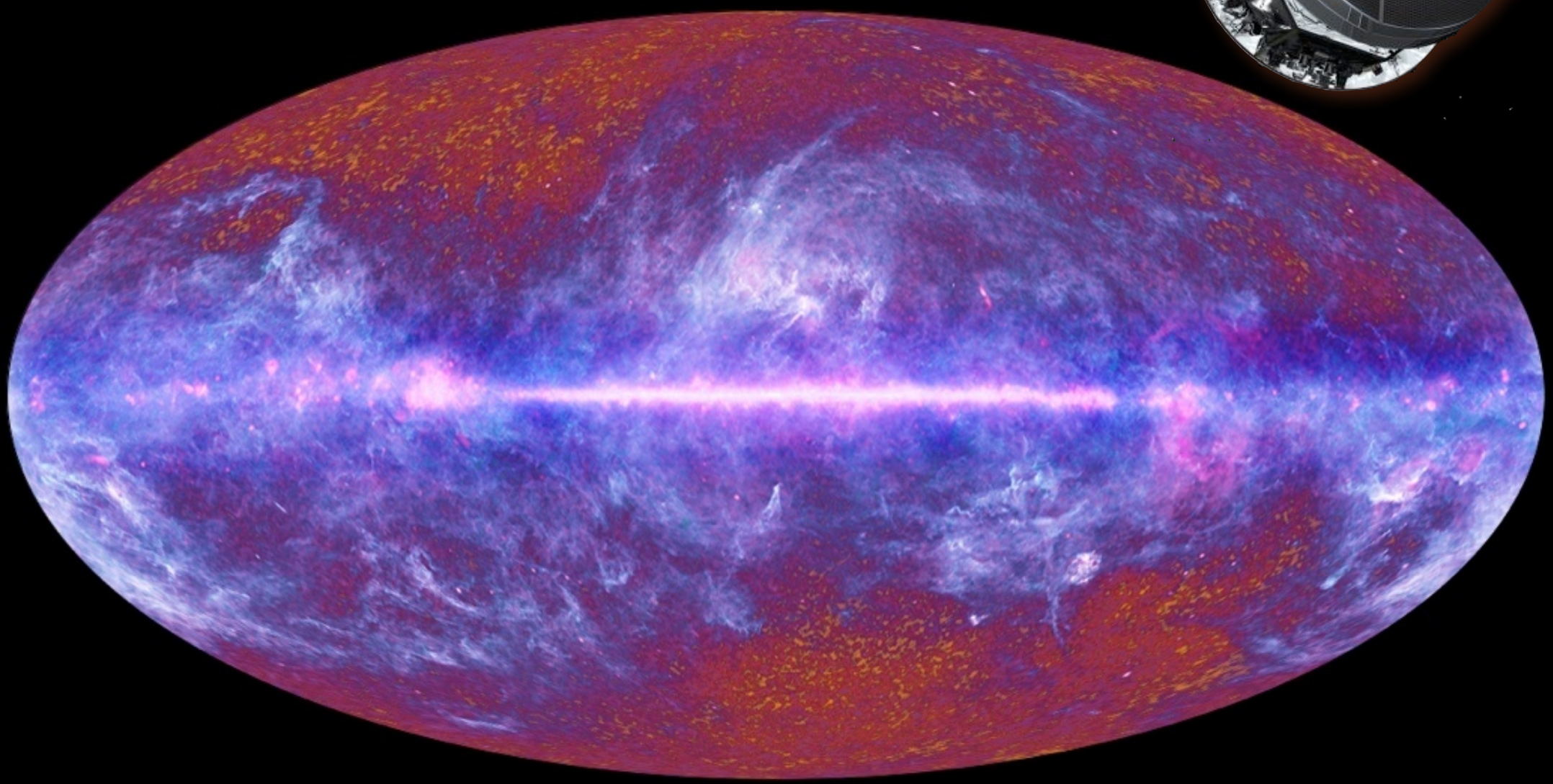
Hou et al, 2012 arXiv:1212.6267

Tighter constraints coming from ν soon from Planck



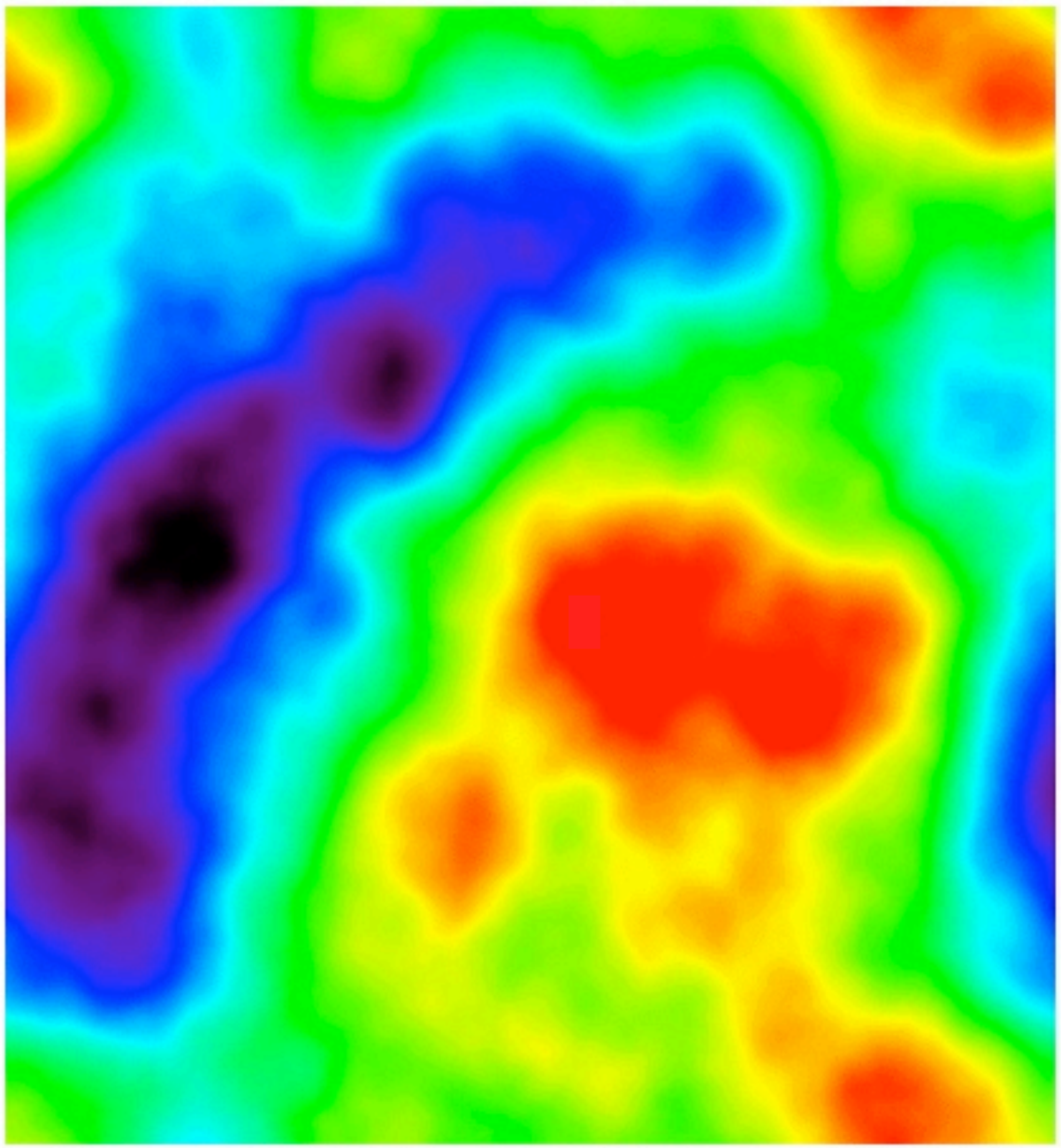


The Planck one-year all-sky survey

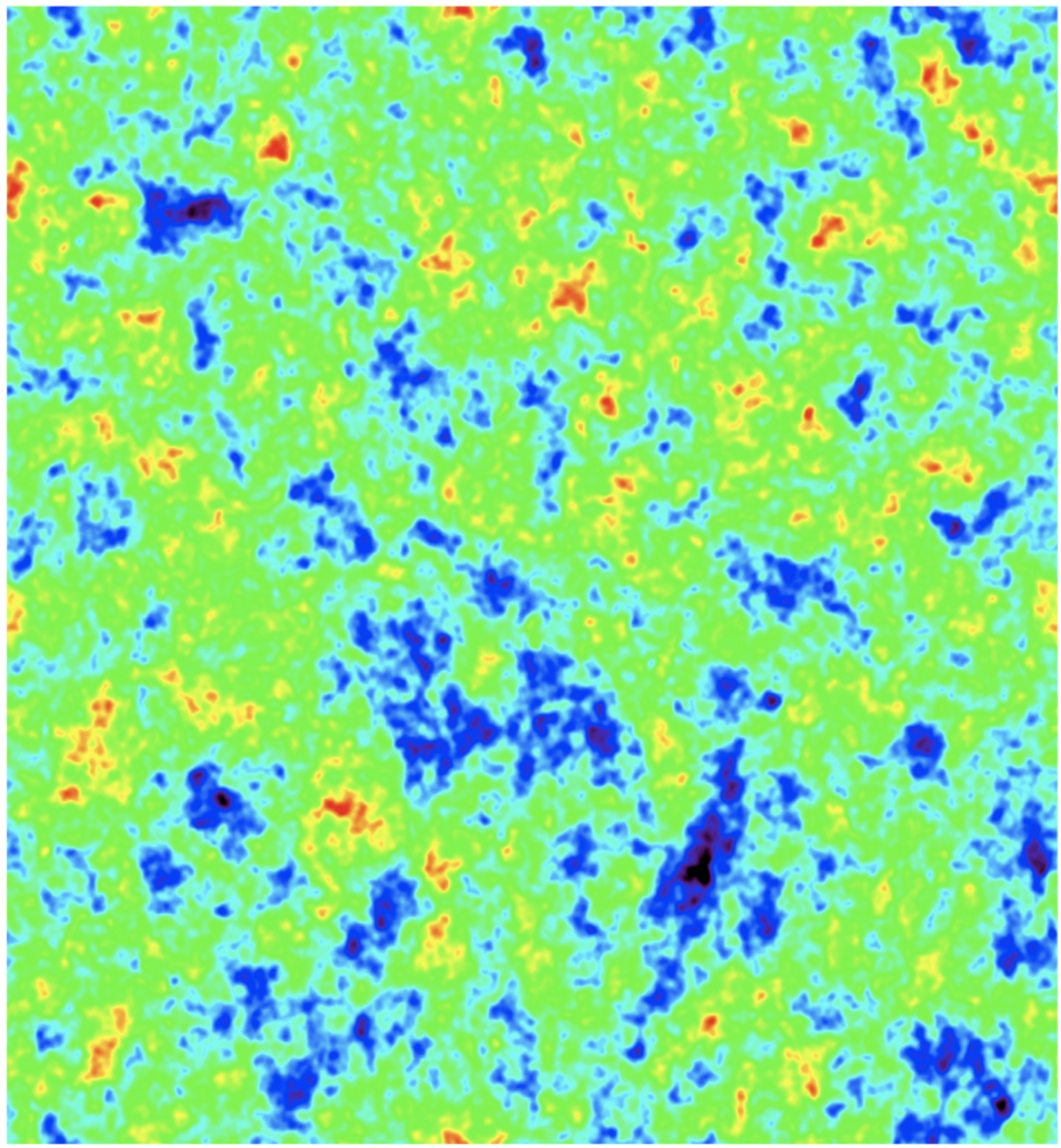
esa

Lensing of the CMB

17°x17°



lensing potential

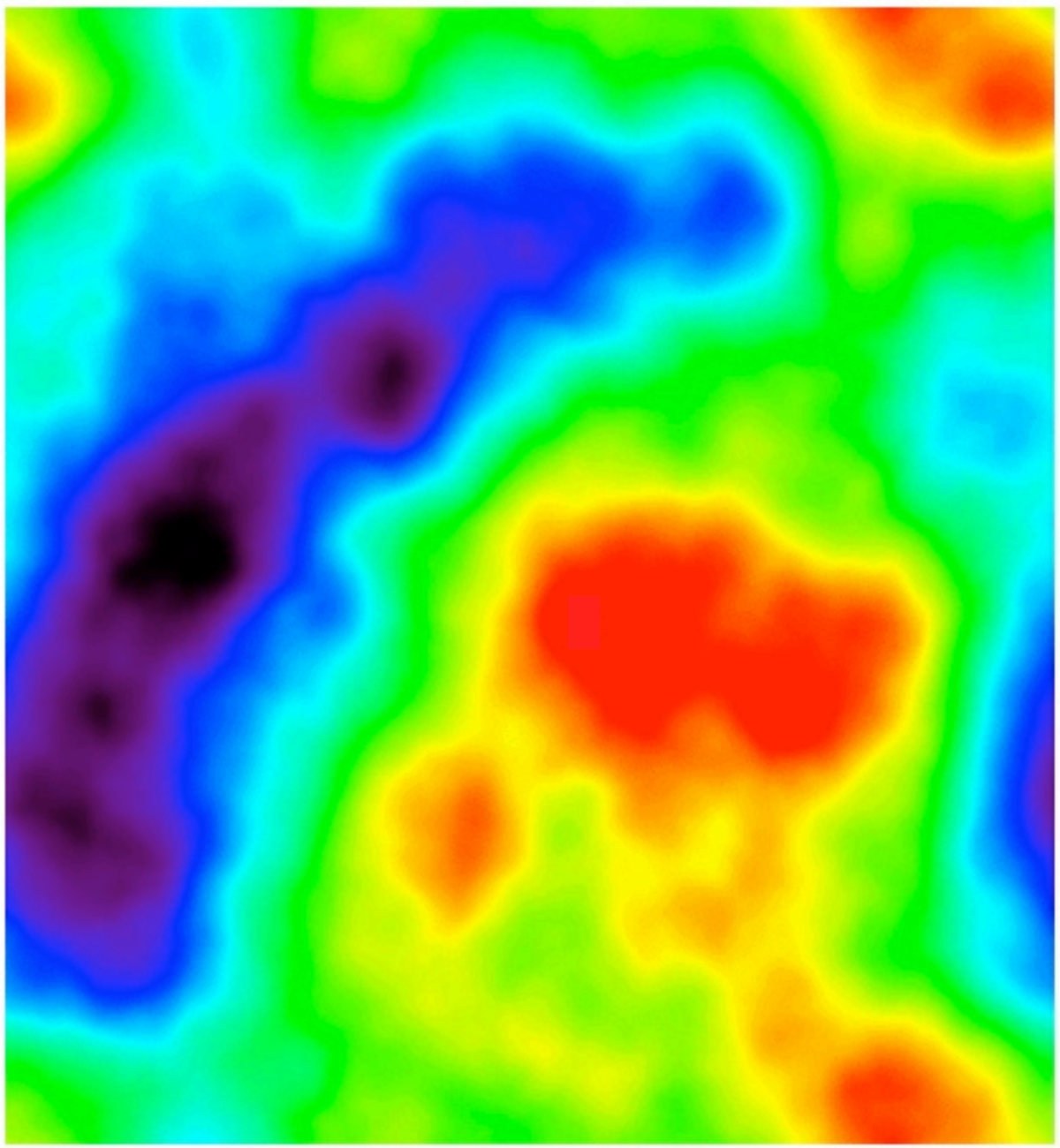


unlensed cmb

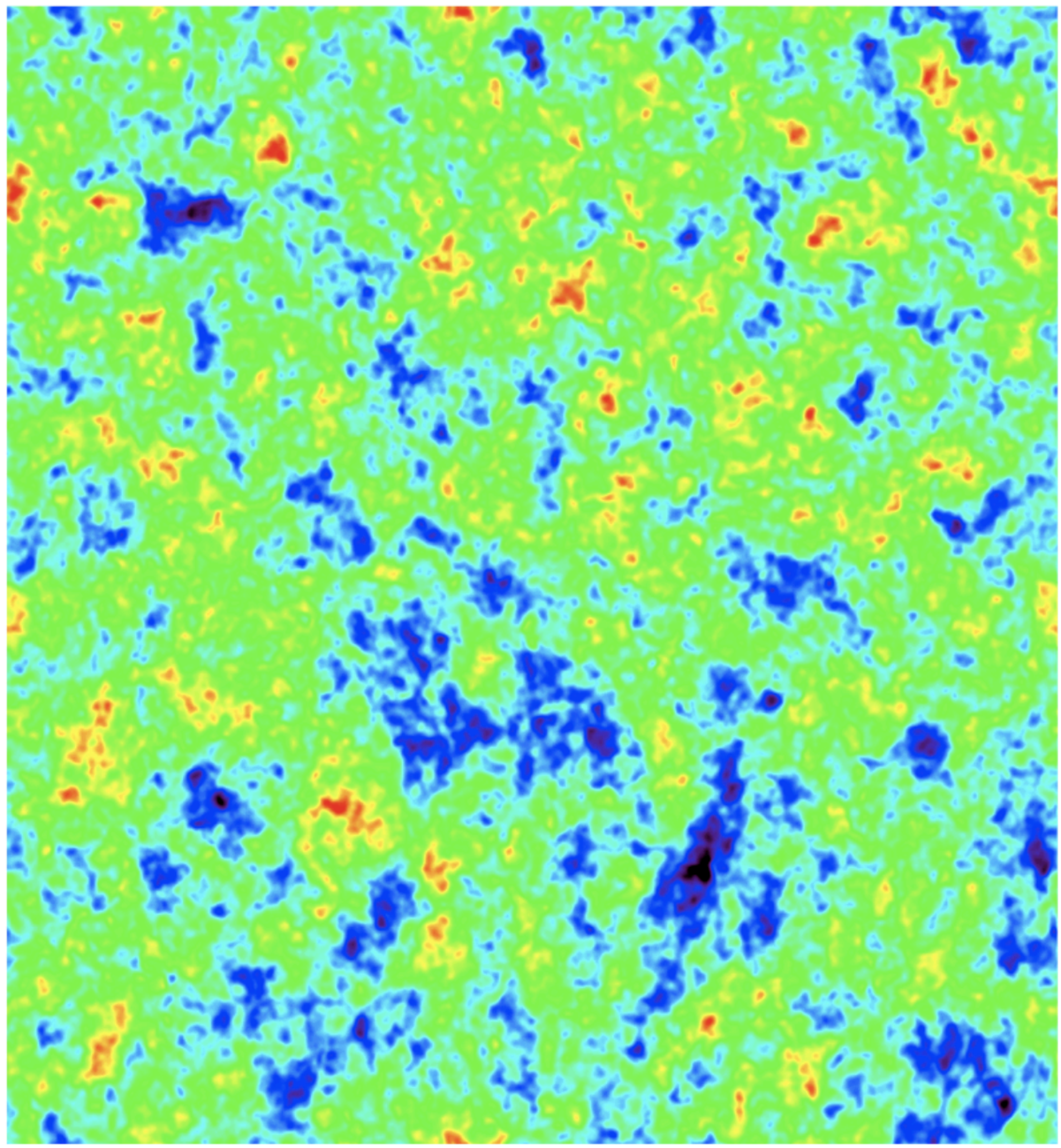
from Alex van Engelen

Lensing of the CMB

17°x17°



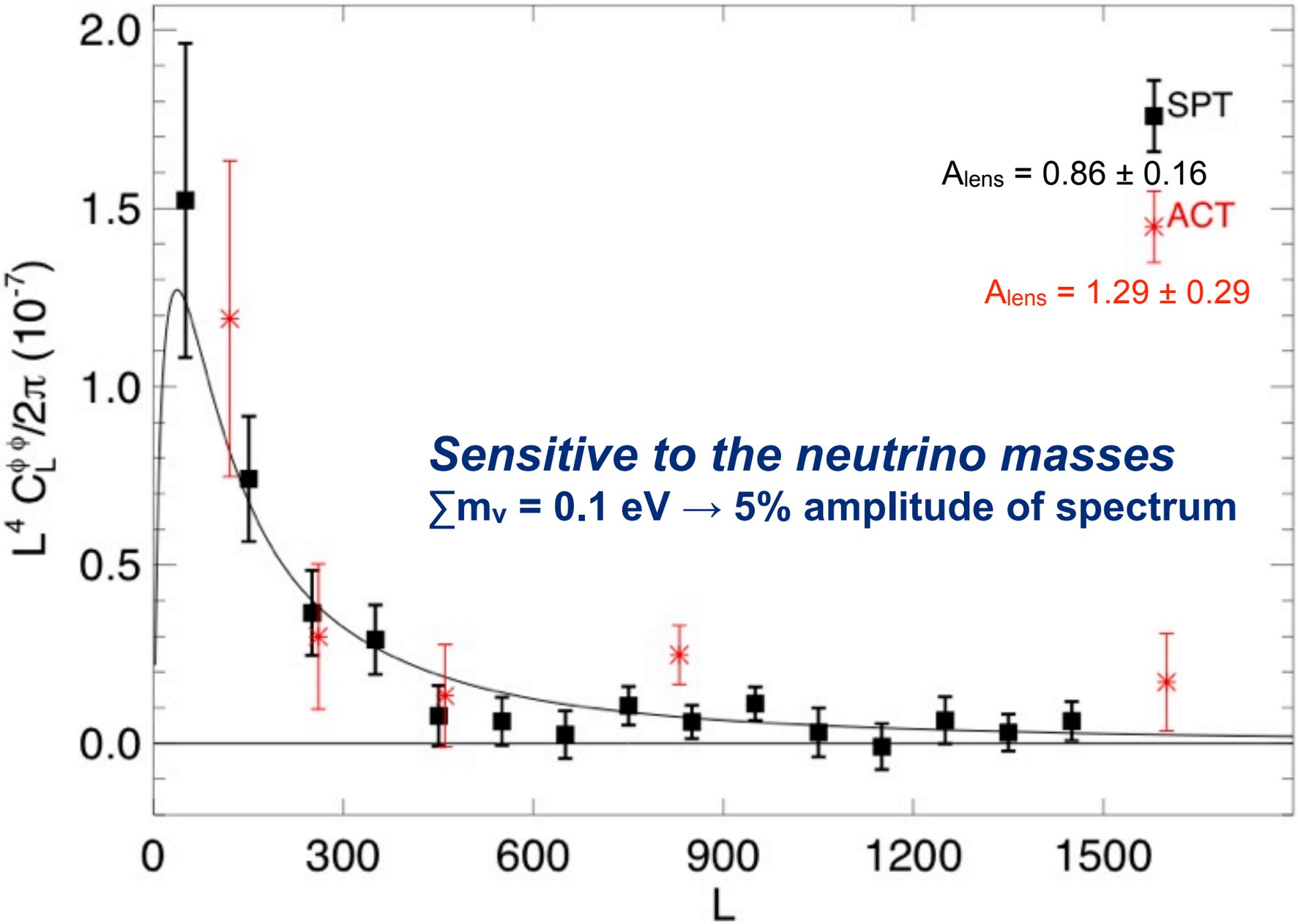
lensing potential



lensed cmb

from Alex van Engelen

Initial ACT & SPT CMB-lensing power spectra of projected gravitational potential, i.e., mass
(SPT from only 500 sq deg at 150 GHz)



Das et al., 2011
van Engelen et al., 2012

CMB lensing is the future

- 2007: 3σ (WMAP+) *Smith et al*
- 2008: 3σ (ACBAR) *Reichardt et al*
- 2011: 4σ (ACT) *Das et al (1st detection from CMB 4pt function)*
- 2011: 5σ (SPT) *Keisler et al*
- 2012: 6σ,7.7σ (SPT) *van Engelen et al., Story et al.*

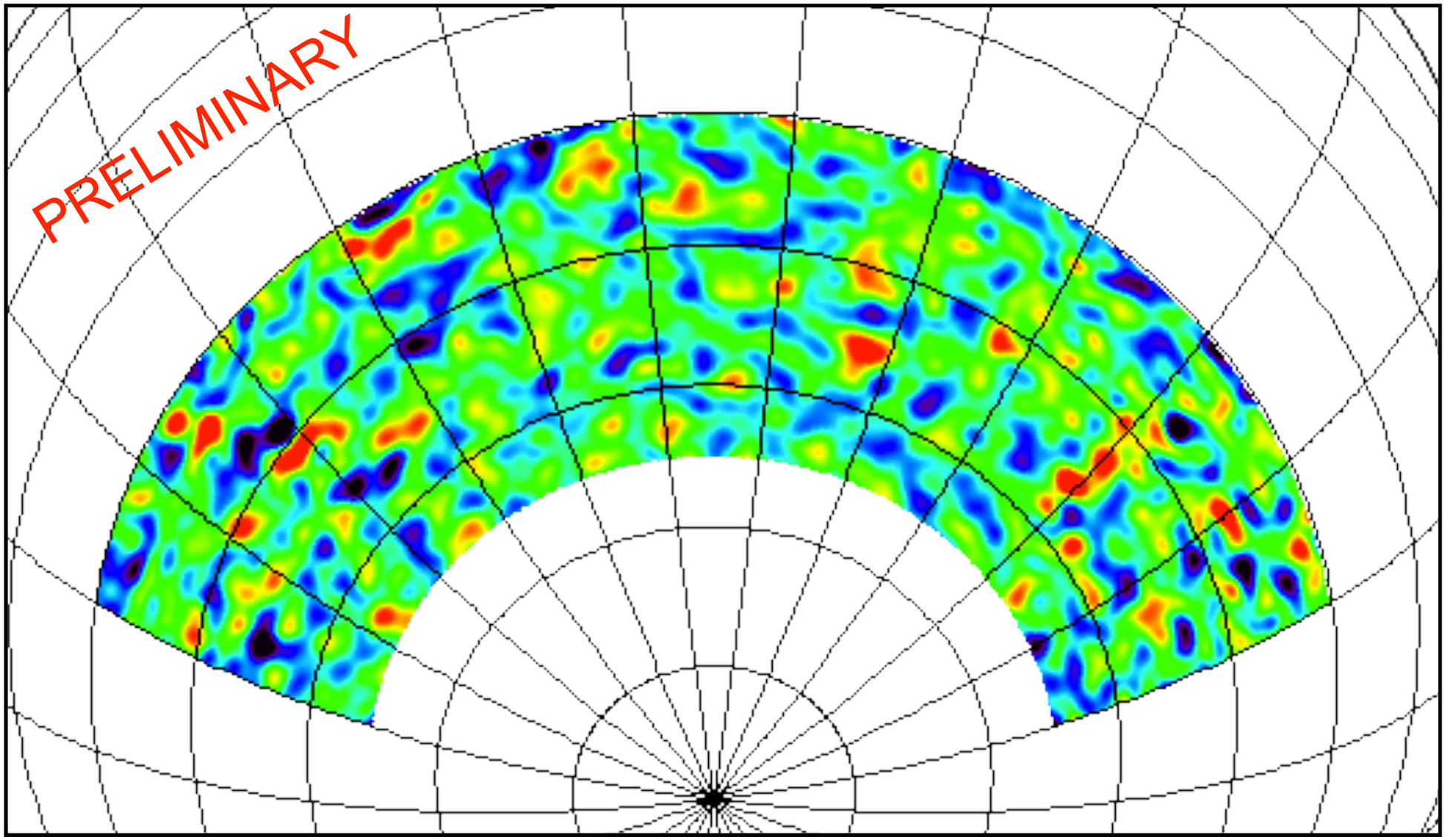
- 2013: ≳20σ (SPT) [2500 deg^2]
- 2013: ≳20σ (PLANCK) [all-sky]
- 2013+: ≳40σ from Stage II experiments
- 2016+: >100σ from Stage III $\sigma(\Sigma m_\nu) \sim 0.05$ eV

- 2020+: **Stage IV goal $\sigma(\Sigma m_\nu) \sim 0.01$ eV**

CMB Lensing Map

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

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



Zahn,Holder et al. in prep

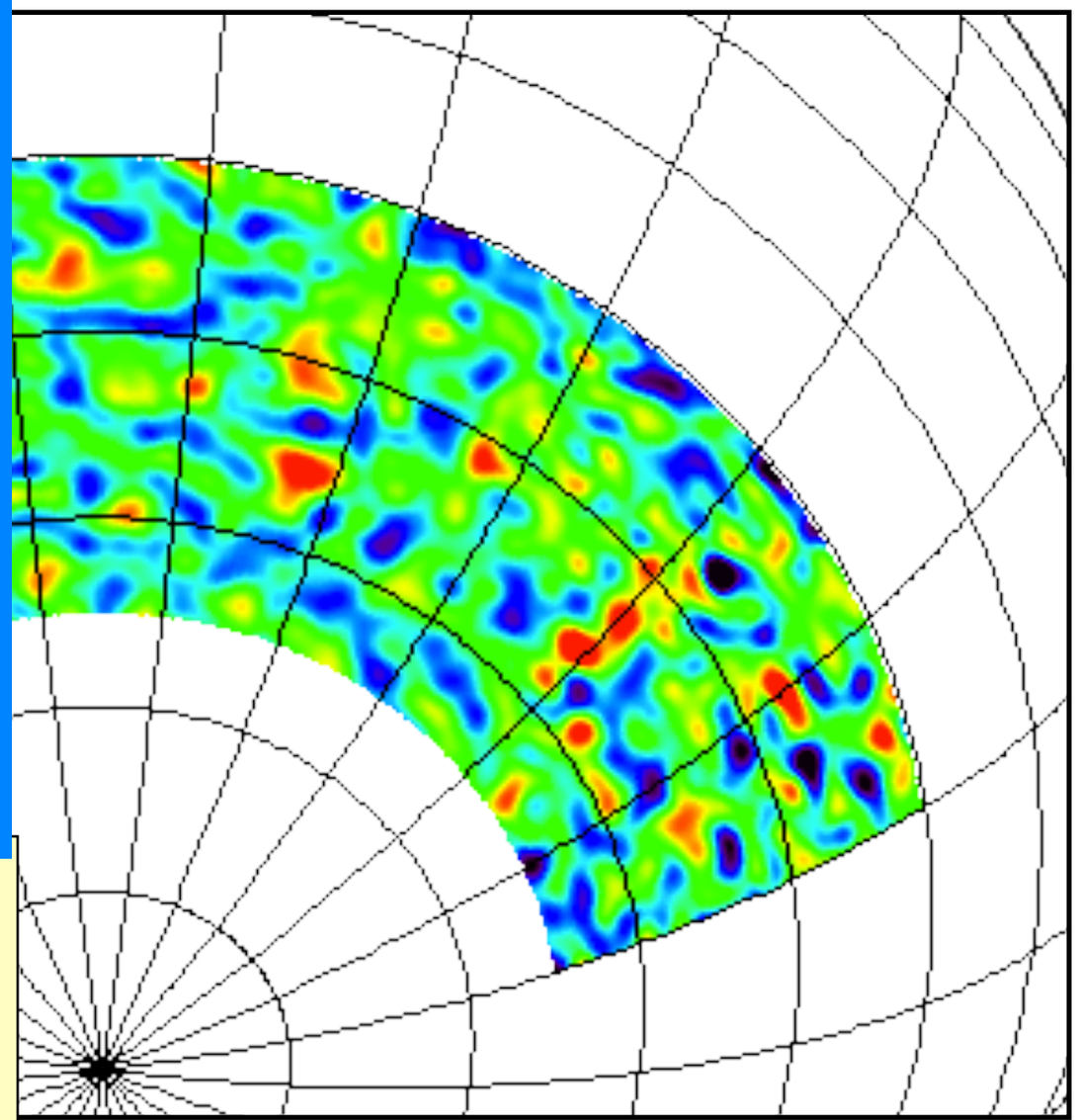
CMB Lensing Map

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

Sorry, too preliminary

smoothed to 1 deg resolution

ysis of SPT 2500 deg² survey



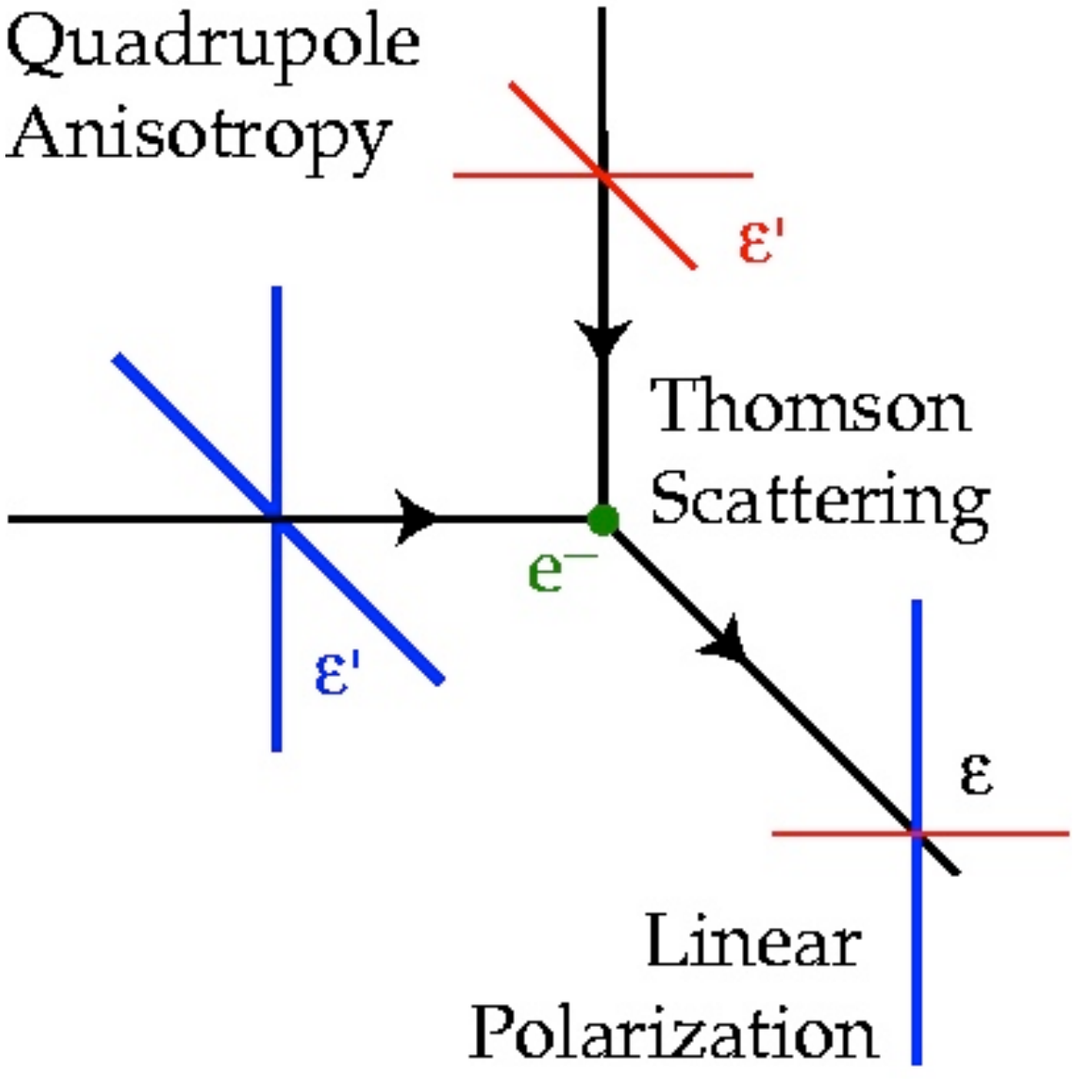
Cross Correlation Calibration

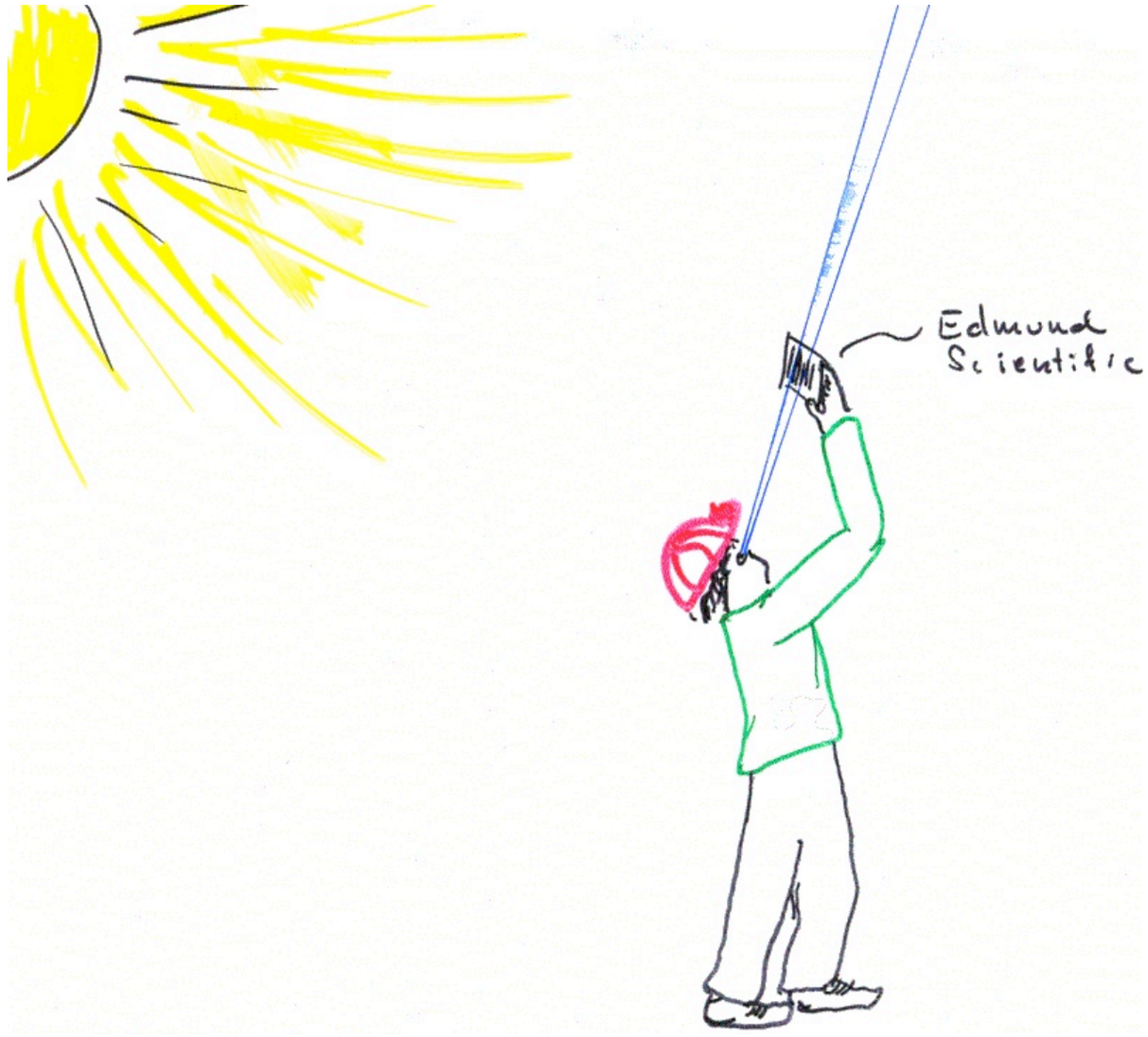
CMB mass reconstruction (contours) overlaid on Herschel 500 um galaxy density map (greyscale) smoothed to degree resolution.

Zahn,Holder et al. in prep

CMB polarization:
the next frontier for lensing & inflation

Due to Thomson scattering –
CMB must be polarized

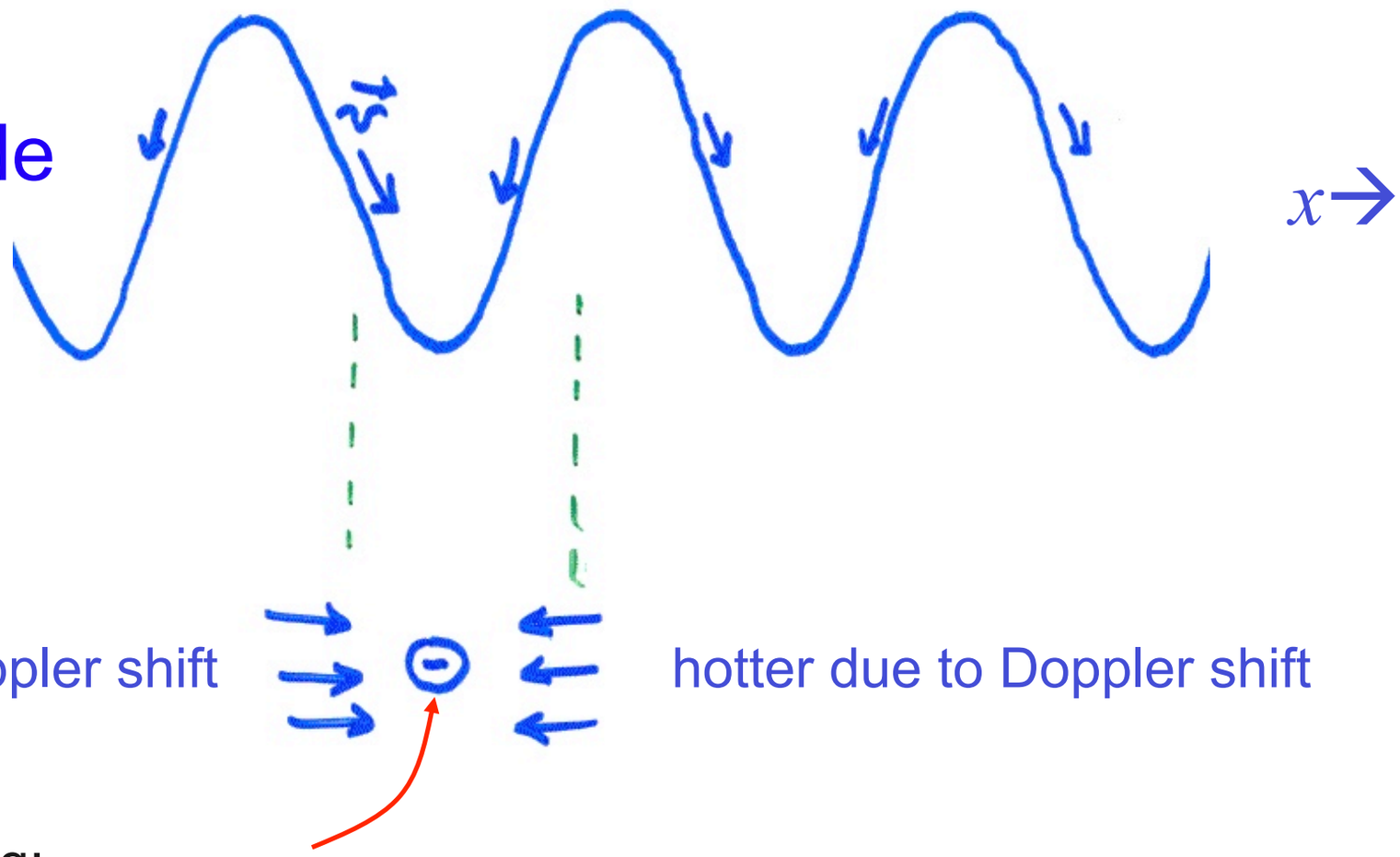




from W. Hu's web page

Generating CMB polarization

Density mode



Before decoupling:

- electron ‘sees’ only a local monopole

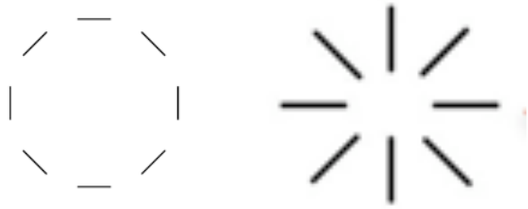
During decoupling:

- mean free path increases and electron ‘sees’ quadrupole
- scattered light is polarized

E-mode from density modes (scalar fluctuations)

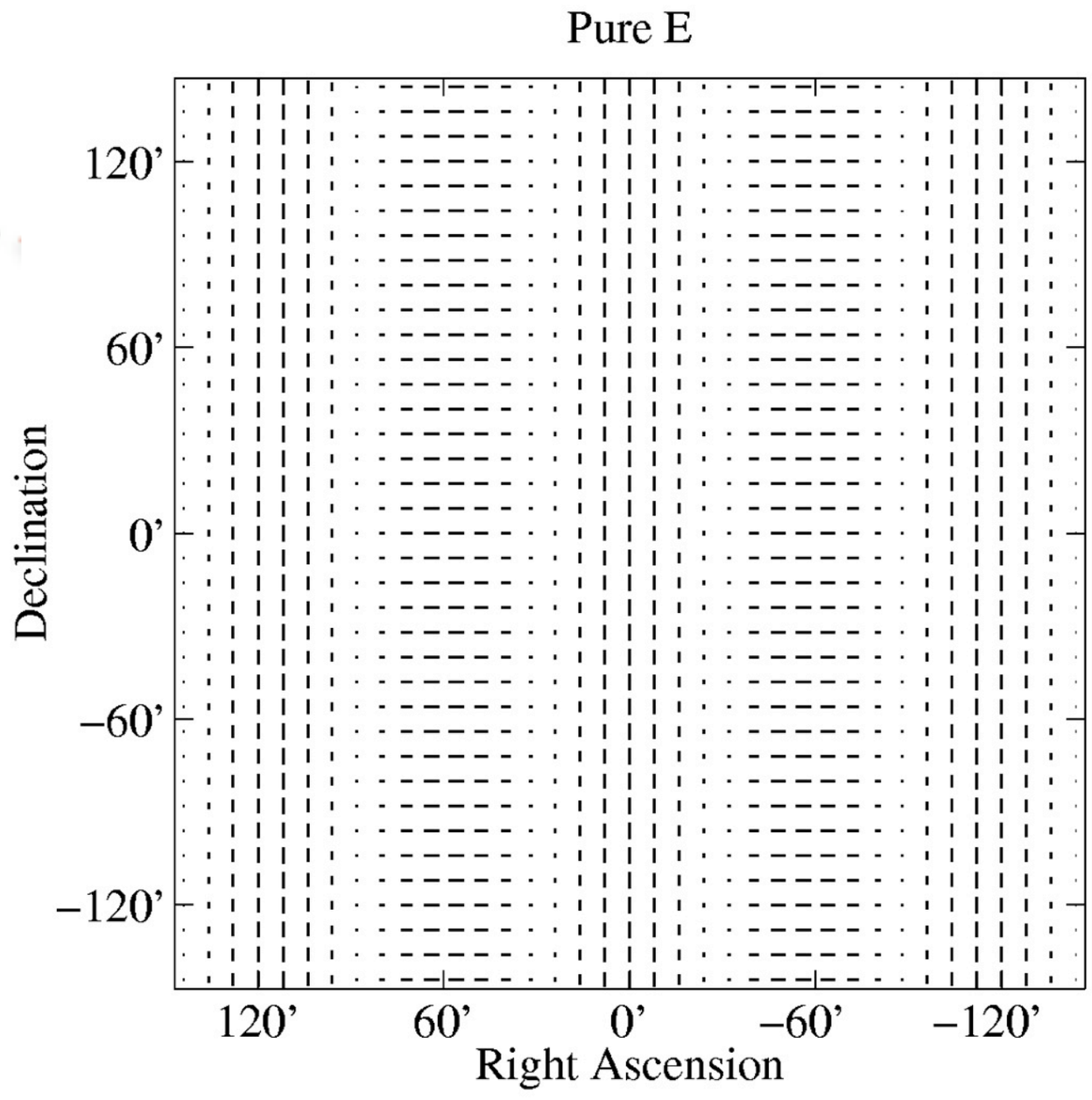
E-mode Polarization (Curl free)

Polarization parallel & perpendicular to wave vector

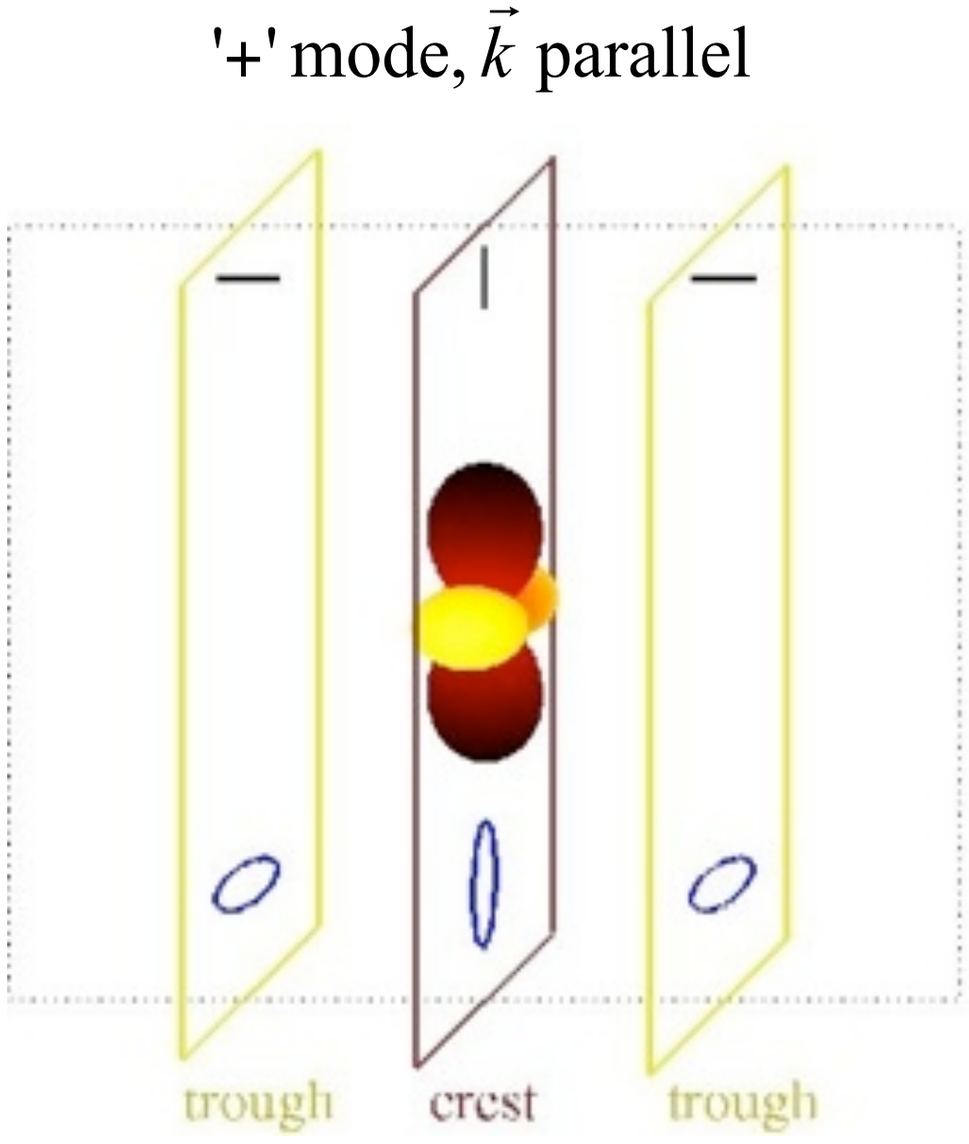


Even parity, curl-free

Density (scalar) fluctuations generate only E-Polarization



Gravitational wave induced CMB polarization

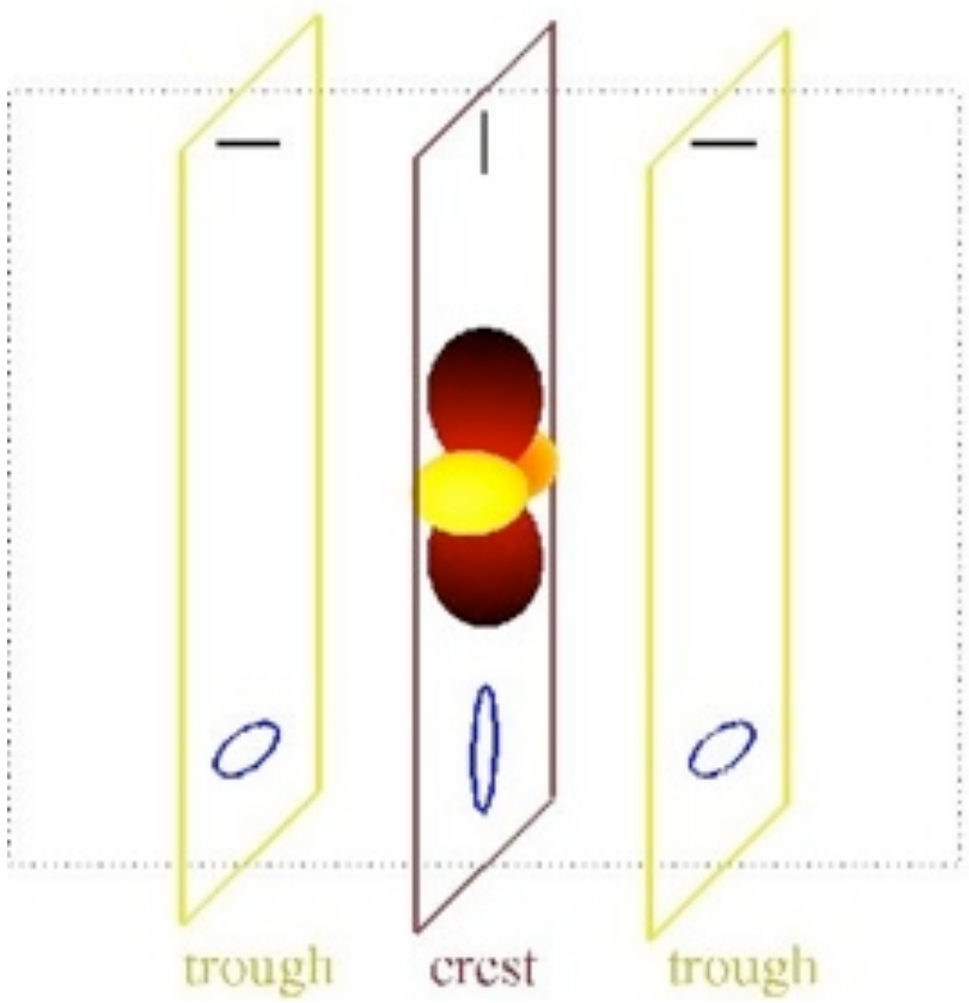


E-mode

Figure from John Kovac's thesis

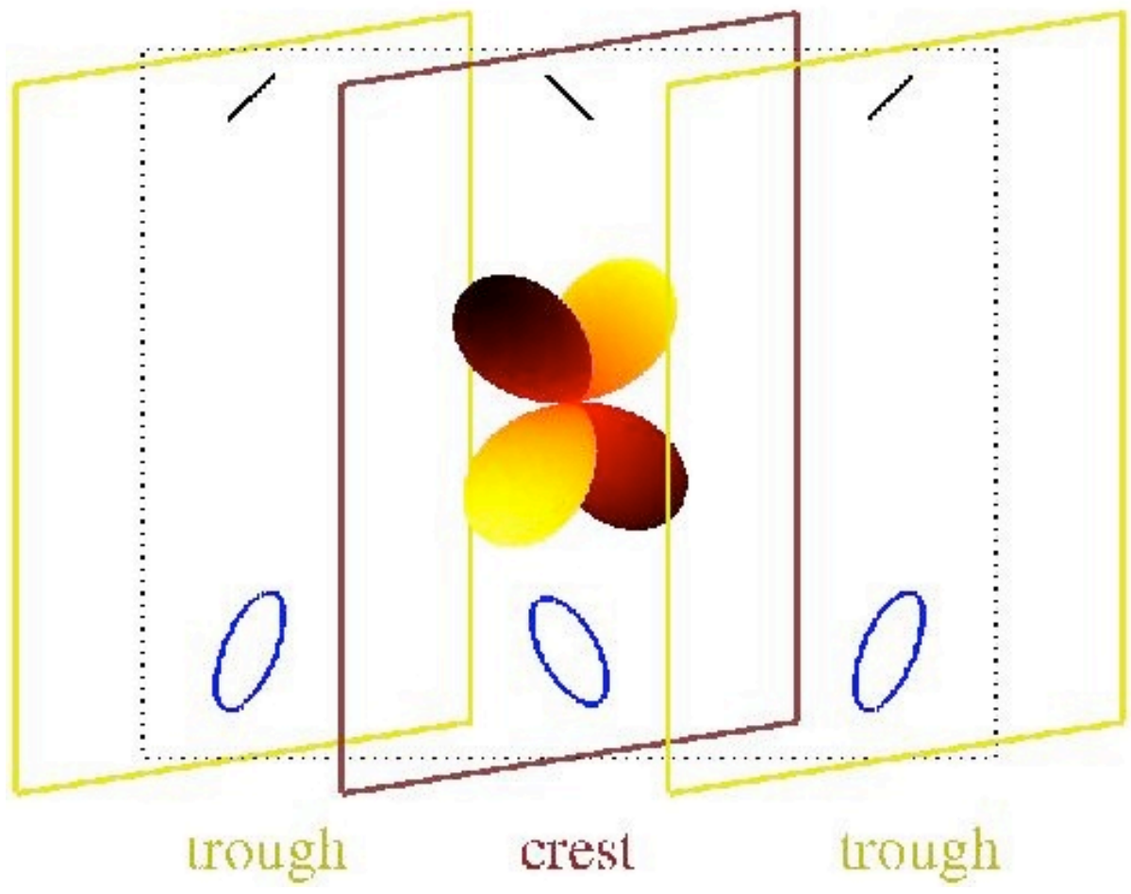
Gravitational wave induced CMB polarization

'+' 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)

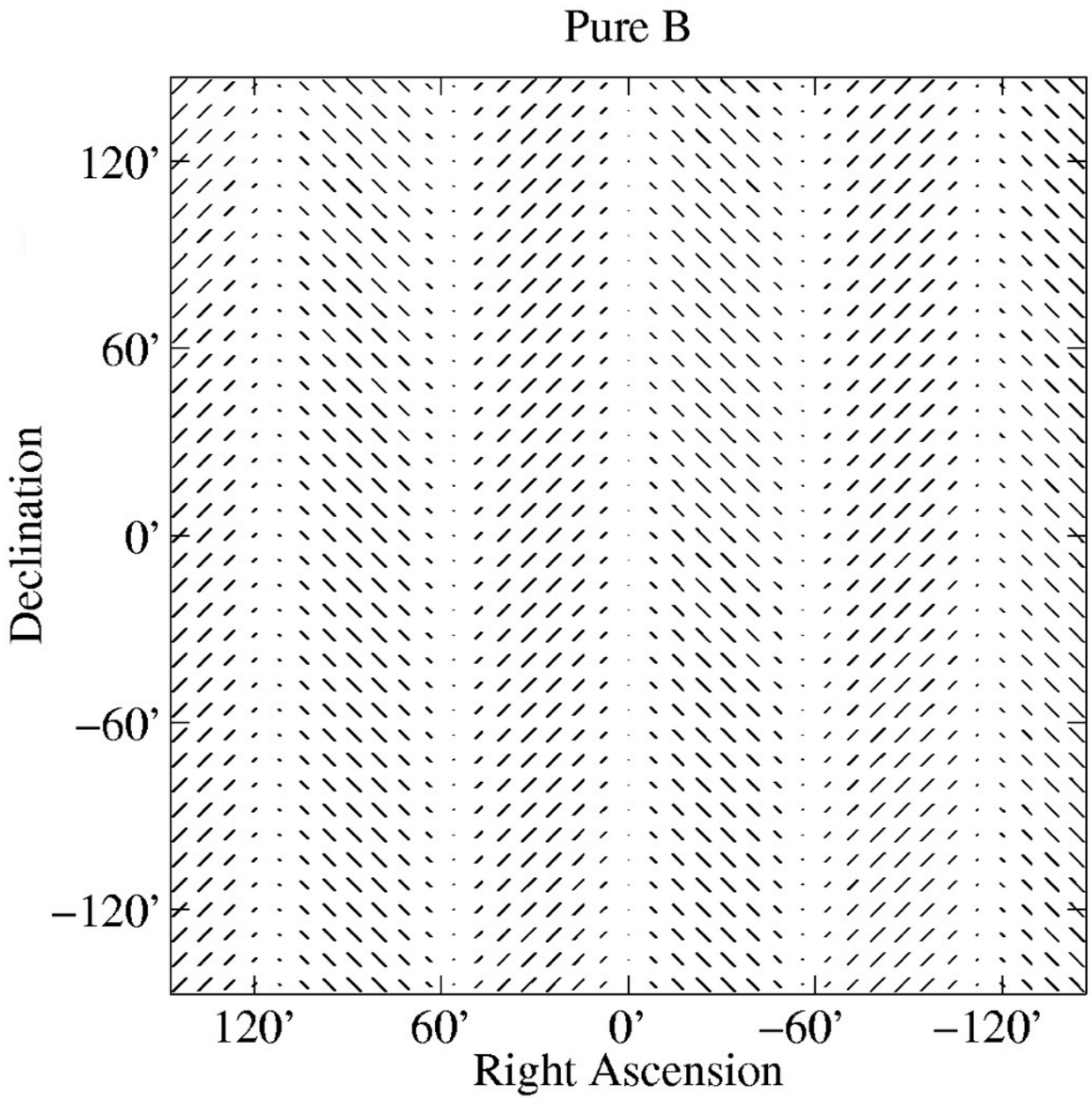
Polarization oriented ±45 degrees to wave vector

Odd parity, div free

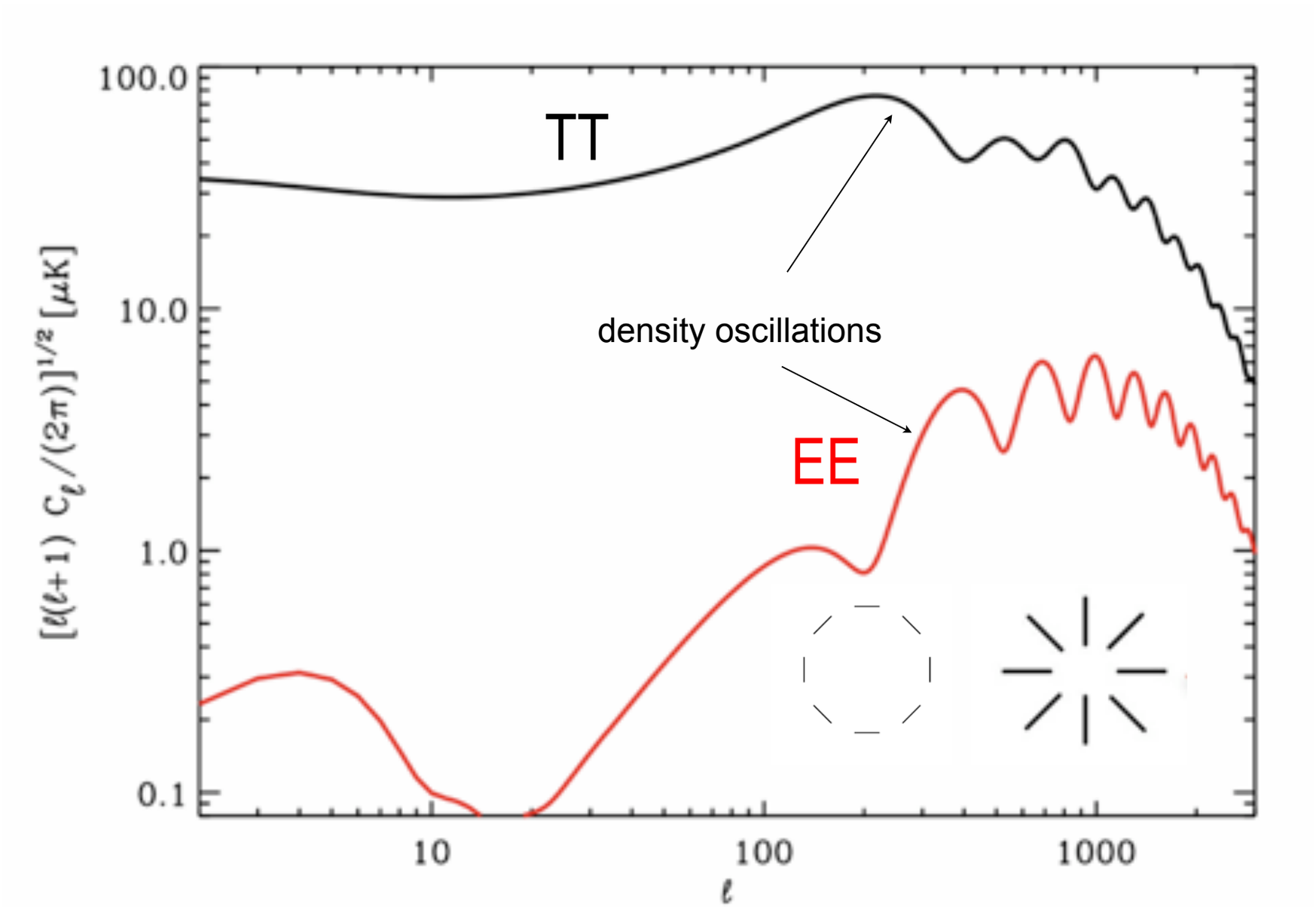
Can NOT be generated by the density fluctuations, but can be generated by gravitational waves sourced by Inflation

"Smoking gun" test of Inflation and direct measure of its energy scale

and direct evidence of quantum gravity.

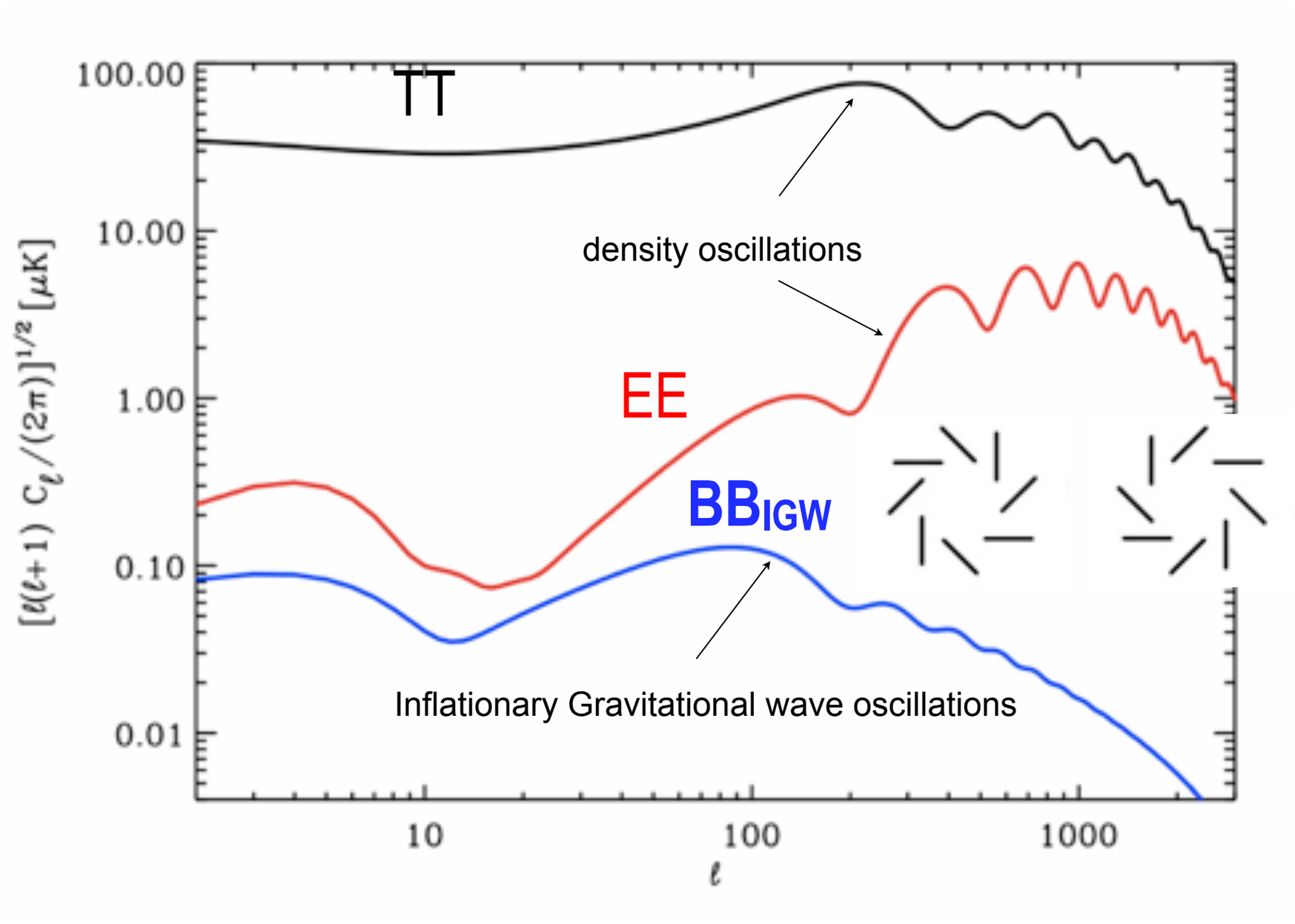


CMB polarization

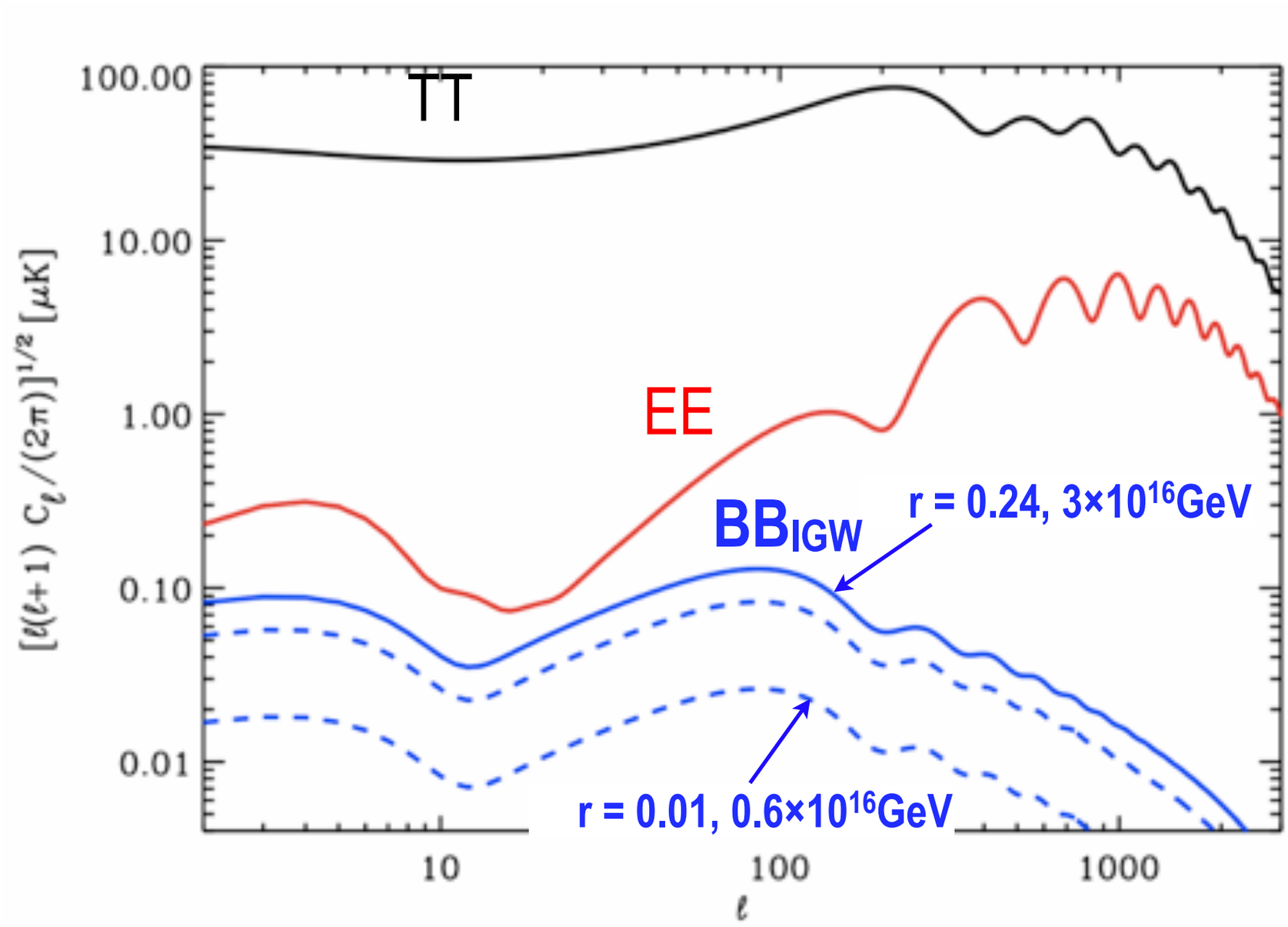


Spectra generated with WMAP7 parameters using CAMB, Lewis and Challinor

CMB polarization

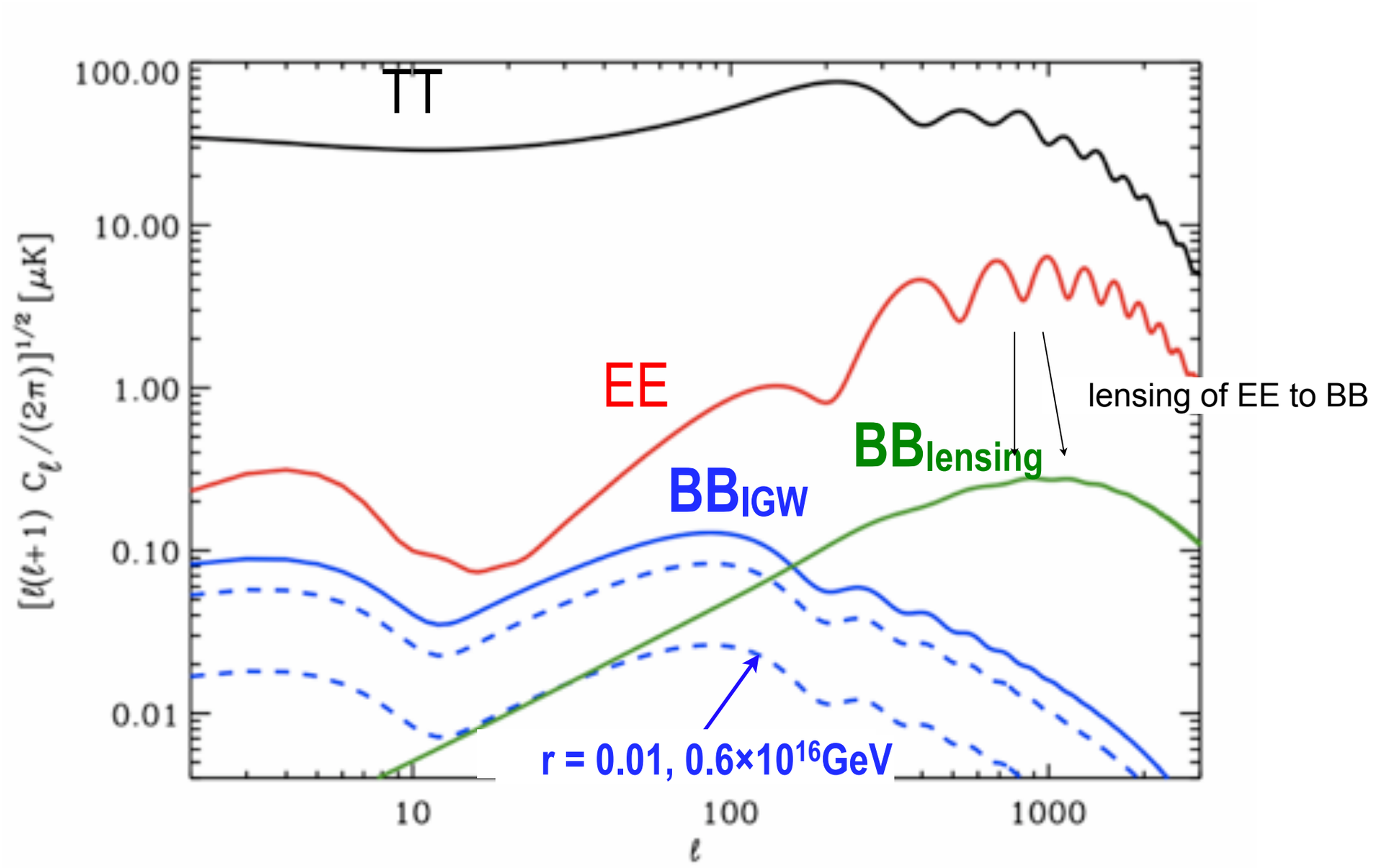


CMB polarization

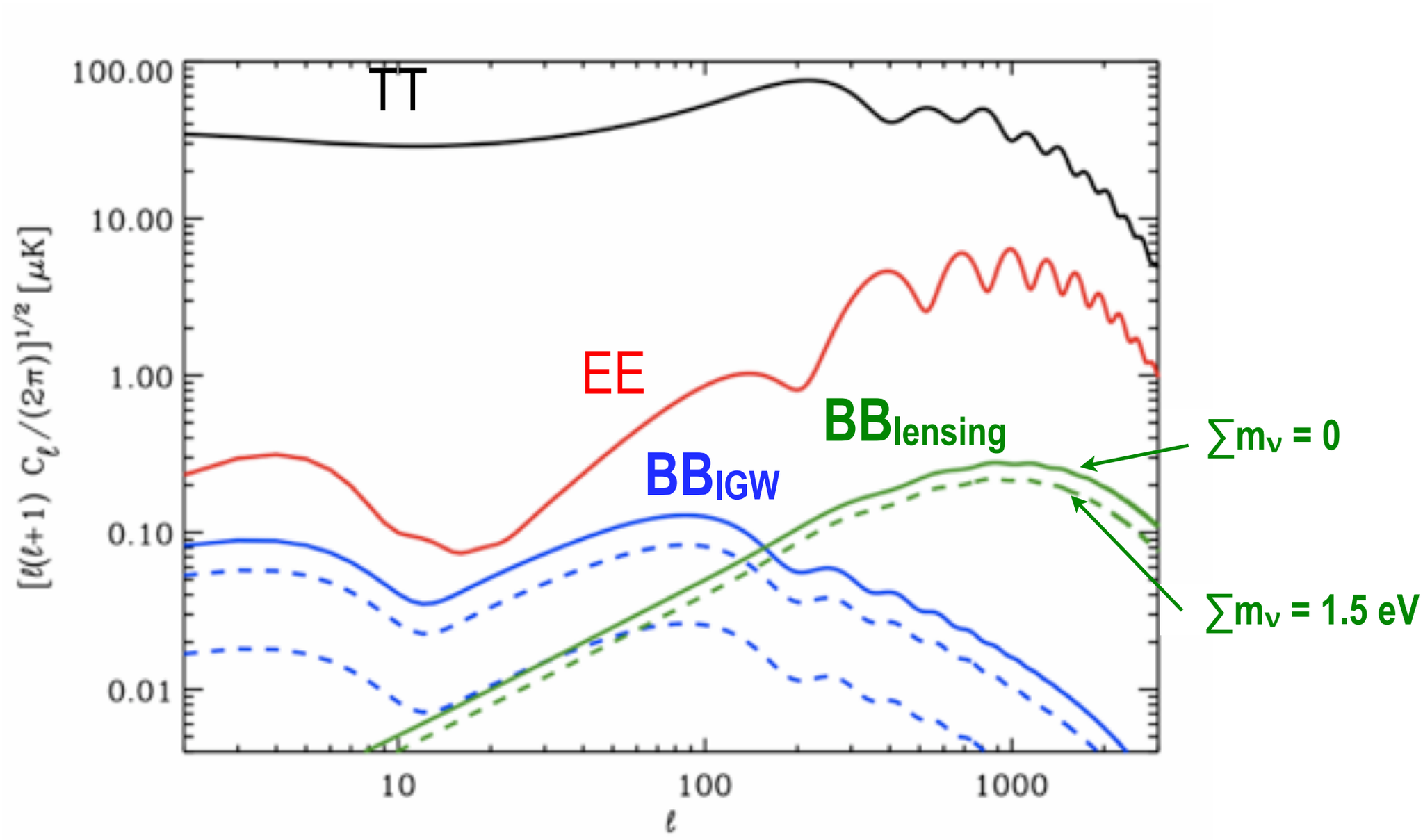


r is the tensor to scalar ratio of the primordial fluctuations

CMB polarization

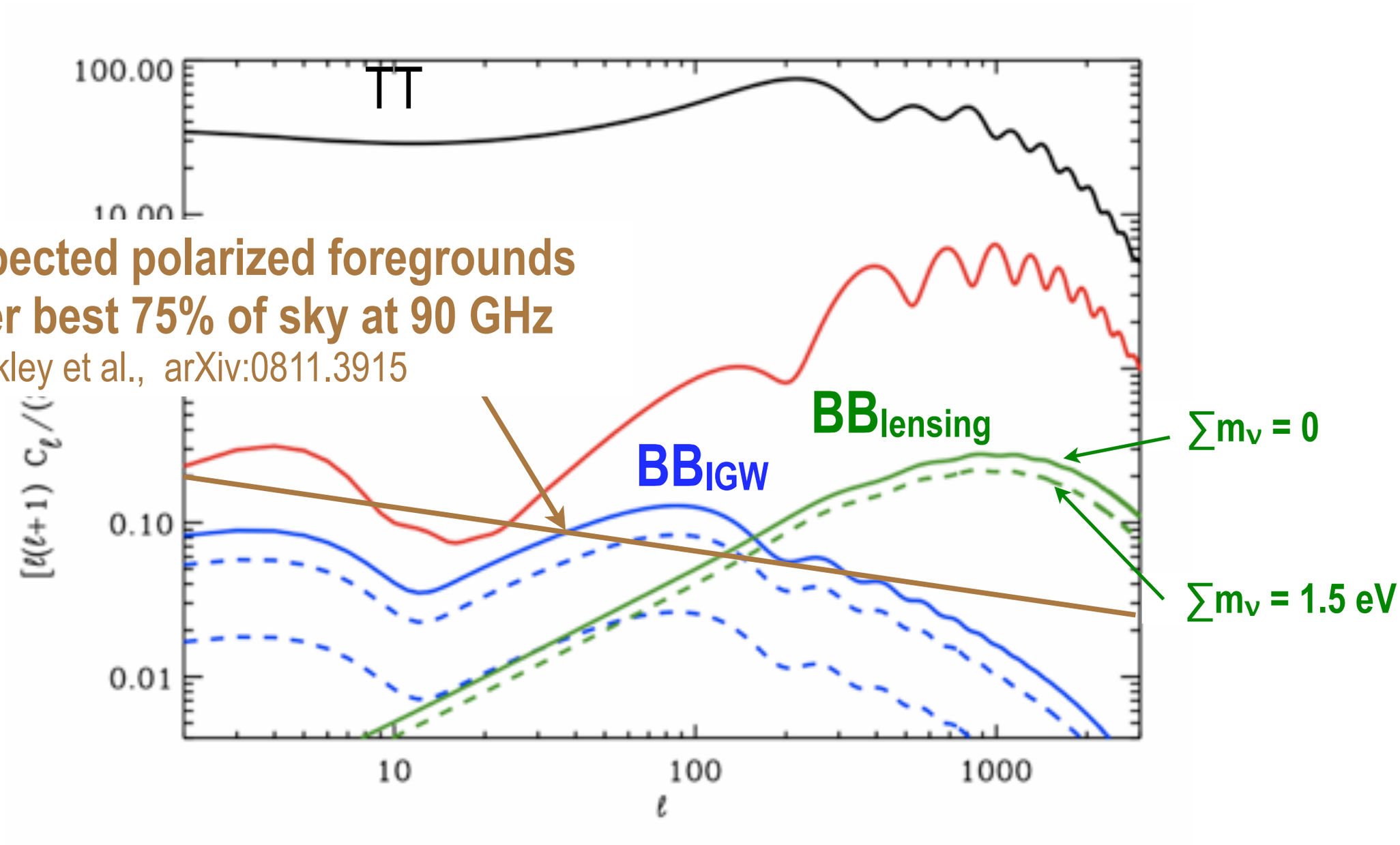


CMB polarization



Stage IV CMB goal is $\sigma(\sum m_\nu) = 0.01$eV, to resolve mass hierarchy.

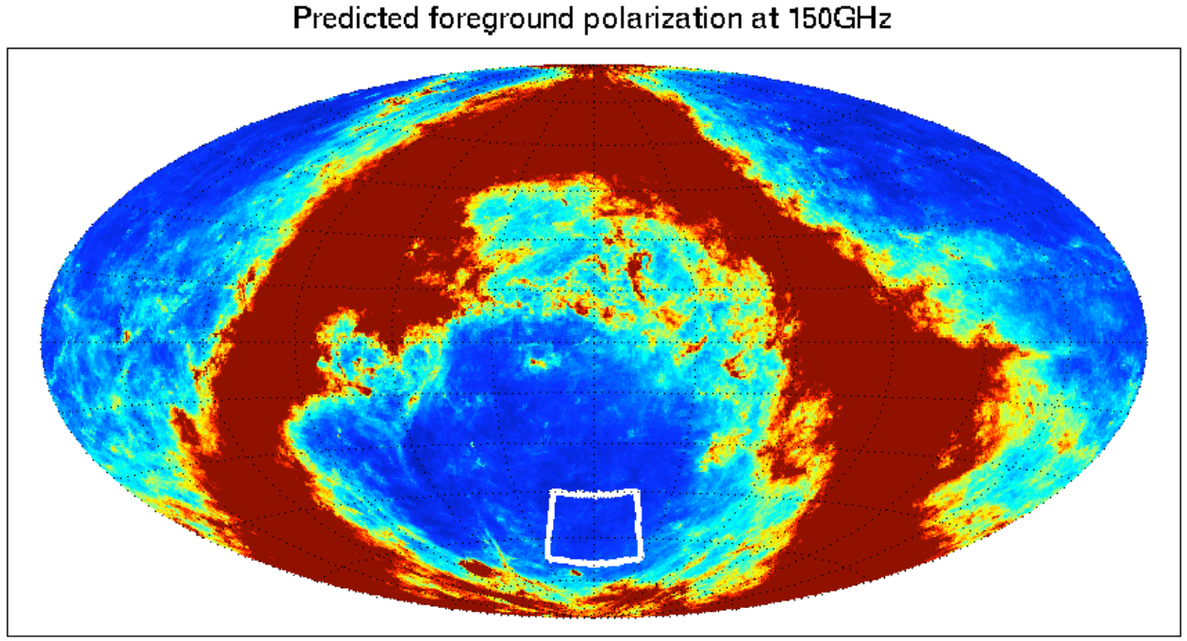
CMB polarization

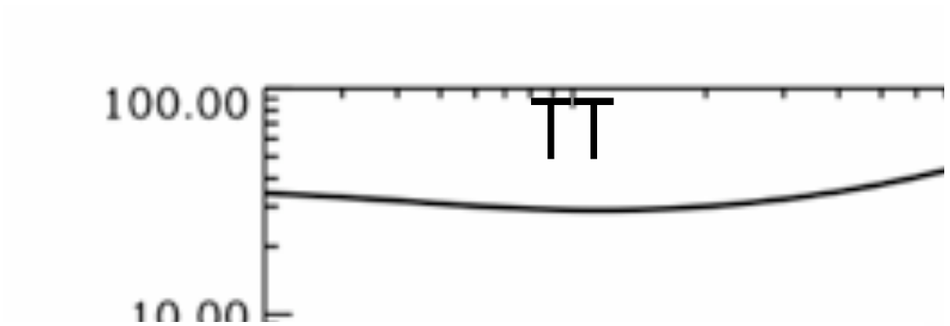


Expected polarized foregrounds over best 75% of sky at 90 GHz

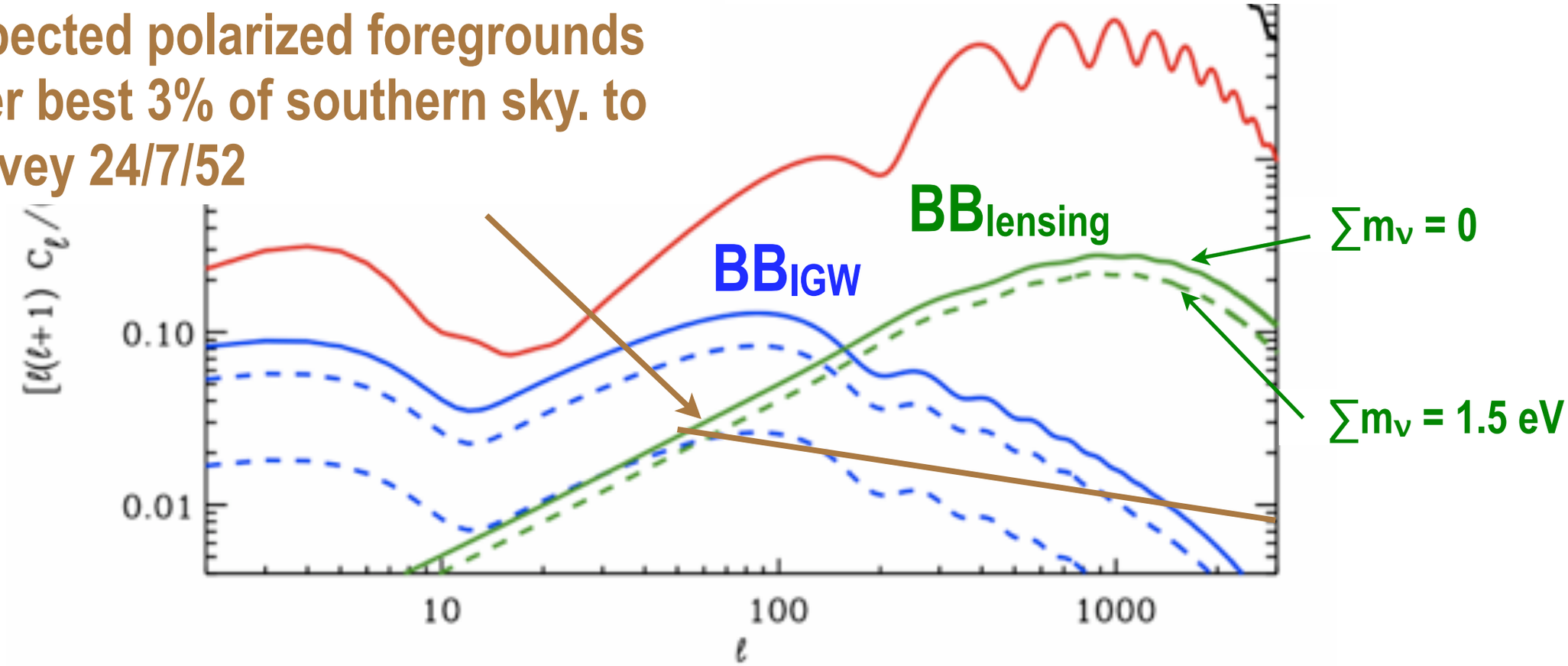
Dunkley et al., arXiv:0811.3915

CMB polarization



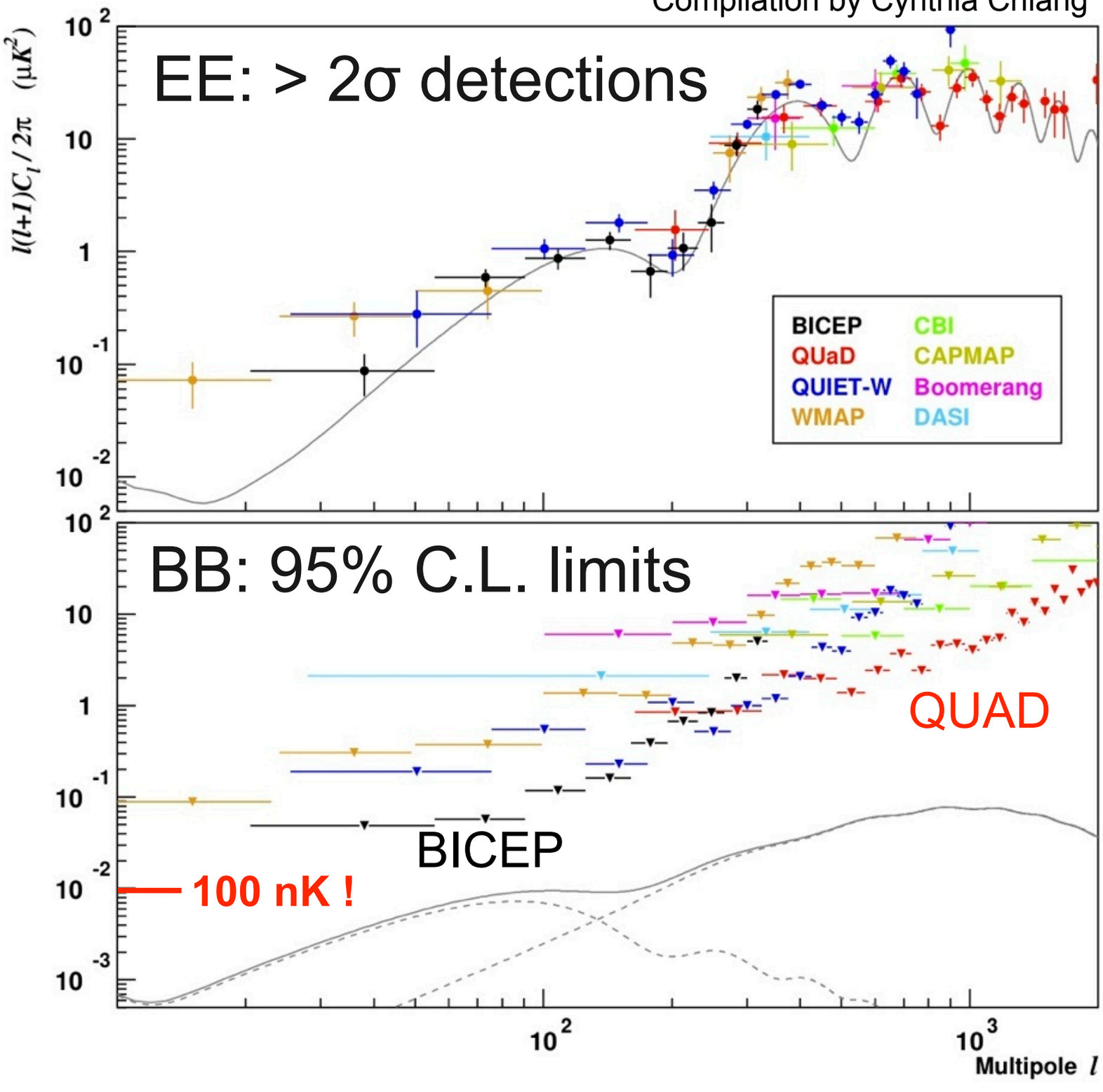


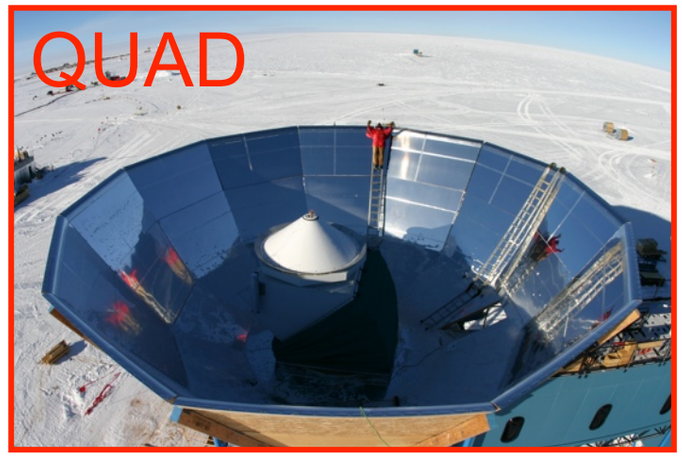
Expected polarized foregrounds over best 3% of southern sky. to survey 24/7/52

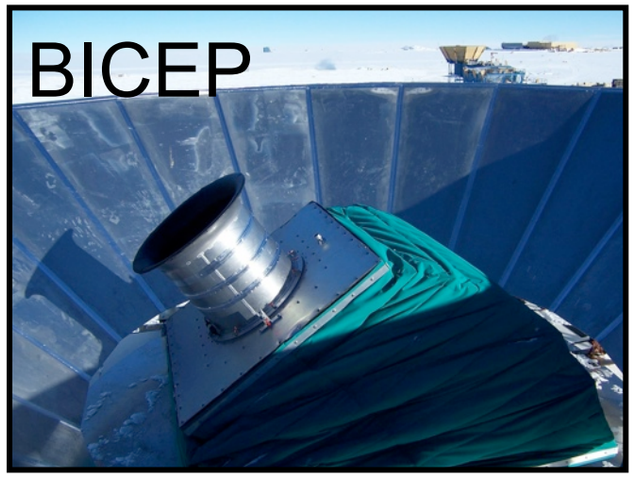


Status of B-mode experiments

Compilation by Cynthia Chiang







B-modes timeline

- 2009: r < 0.7 (BICEP) Chiang et al, 0906.1181
- 2012: no detections of inflationary or lensing B-modes

- 2013: r ≲ 0.1 from Inflationary B-modes (BICEP II) ?
- 2013: Stage II experiments detect lensing B-modes
- 2013+ Stage II experiments $\sigma(r) \lesssim 0.03$ and $\sigma(\Sigma m_\nu) \sim 0.1$ eV from lensing B-modes
- 2016+: Stage III achieve $\sigma(r) \lesssim 0.01$ & $\sigma(\Sigma m_\nu) \sim 0.05$ eV; measure lensing B-modes to L ~ 800 with s/n >1; allow "delensing" of inflation B-modes

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- 2020+: **Stage IV goal to reach r ~ 0.001 (or better?) and $\sigma(\Sigma m_\nu) \sim 0.01$ eV**

Summary

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

Stage IV CMB experiment is needed.

It will be extremely 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!