



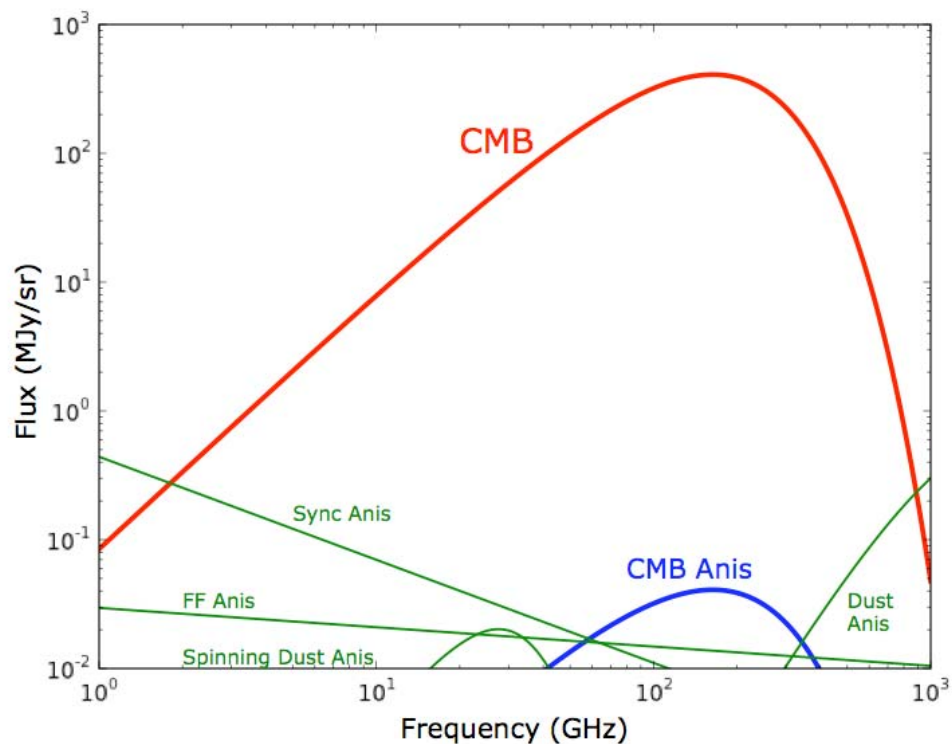
ACT and WMAP

The 16th Paris Cosmology Colloquium Chalonge
July 25, 2012

We can all measure the CMB

$$T_{\text{CMB}} = 2.7255 \pm 0.00 \text{ K}$$

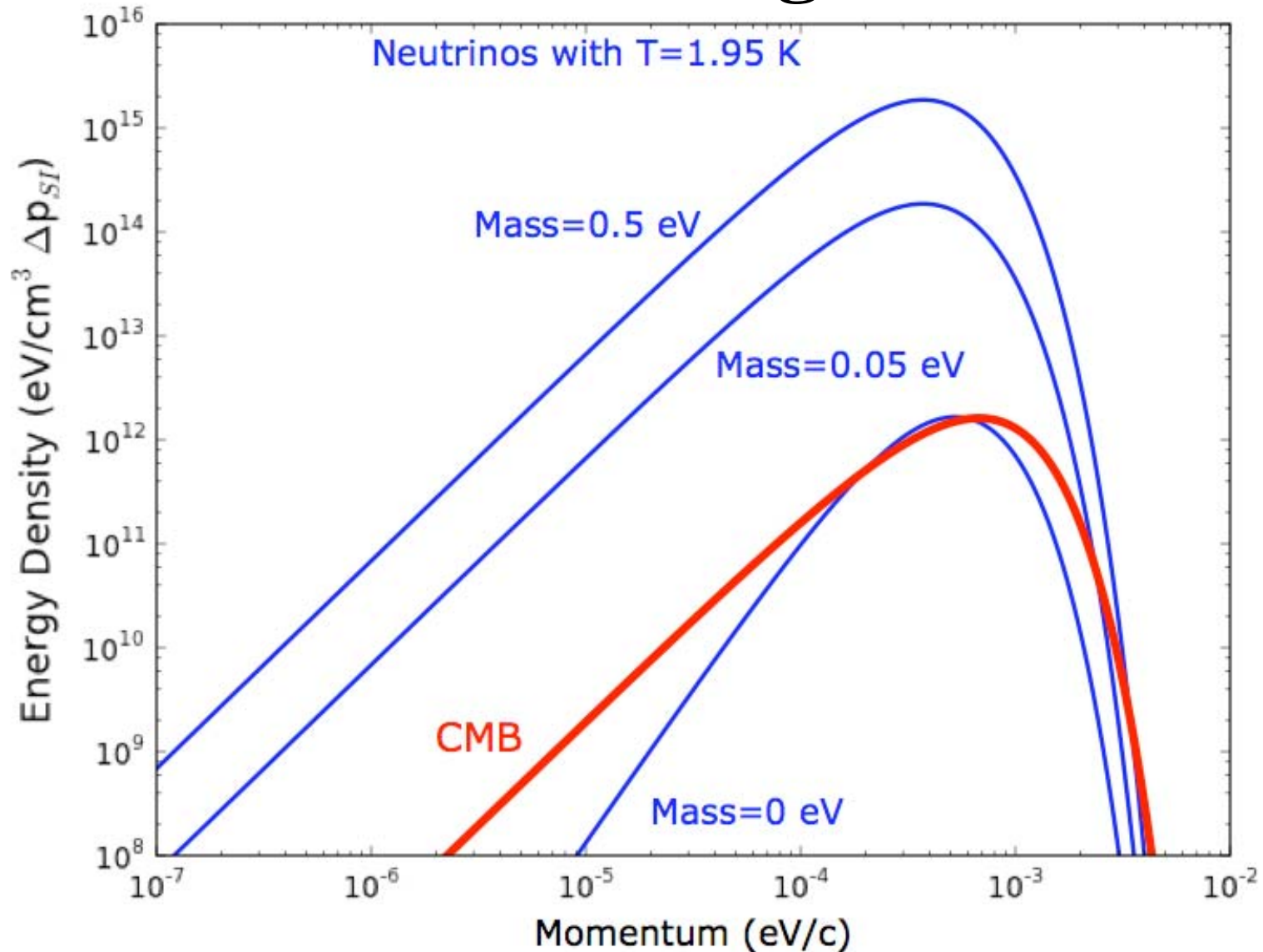
400 photons/cc at 0.28 eV/cc



CMB approx 1% of TV noise!



But no one has measured the neutrino background.





Neutrinos

$$T_\nu = 1.945 \text{ K}$$

- 3 known families, ~equal numbers of neutrinos and antineutrinos.
- 113 neutrinos/cc/family

From particle physics:

$$0.05 \text{ eV} < \sum m_\nu < 2.3 \text{ eV} \quad (95\% \text{ cl})$$

From atmospheric neutrinos at SuperK ,

$$\nu_\mu \leftrightarrow \nu_\tau$$

Tritium end point plus mass splittings.

(Kraus et al., 2005)

When I say “neutrinos”....



Neutrinos

$$T_\nu = 1.945 \text{ K}$$

- 3 known families, ~equal numbers of neutrinos and antineutrinos.
- 113 neutrinos/cc/family

$$0.05 \text{ eV} < \Sigma m_\nu < 1.2 \text{ eV} \quad (95\% \text{ cl})$$

From atmospheric neutrinos at SuperK ,

$$\nu_\mu \leftrightarrow \nu_\tau$$

WMAP alone



Neutrinos

$$T_\nu = 1.945 \text{ K}$$

- 3 known families, ~equal numbers of neutrinos and antineutrinos.
- 113 neutrinos/cc/family

$$0.05 \text{ eV} < \sum m_\nu < 0.58 \text{ eV} \quad (95\% \text{ cl})$$

From atmospheric neutrinos at SuperK ,

WMAP+BAO+H₀

$$\nu_\mu \leftrightarrow \nu_\tau$$



Neutrinos

$$T_\nu = 1.945 \text{ K}$$

- 3 known families, ~equal numbers of neutrinos and antineutrinos.
- 113 neutrinos/cc/family

$$0.05 \text{ eV} < \sum m_\nu < 0.2 \text{ eV} \quad (95\% \text{ cl})$$

From atmospheric neutrinos at SuperK ,

$$\nu_\mu \leftrightarrow \nu_\tau$$

Expected from
KATRIN (Franenkel,
2011)



Neutrinos

$$T_\nu = 1.945 \text{ K}$$

- 3 known families, ~equal numbers of neutrinos and antineutrinos.
- 113 neutrinos/cc/family

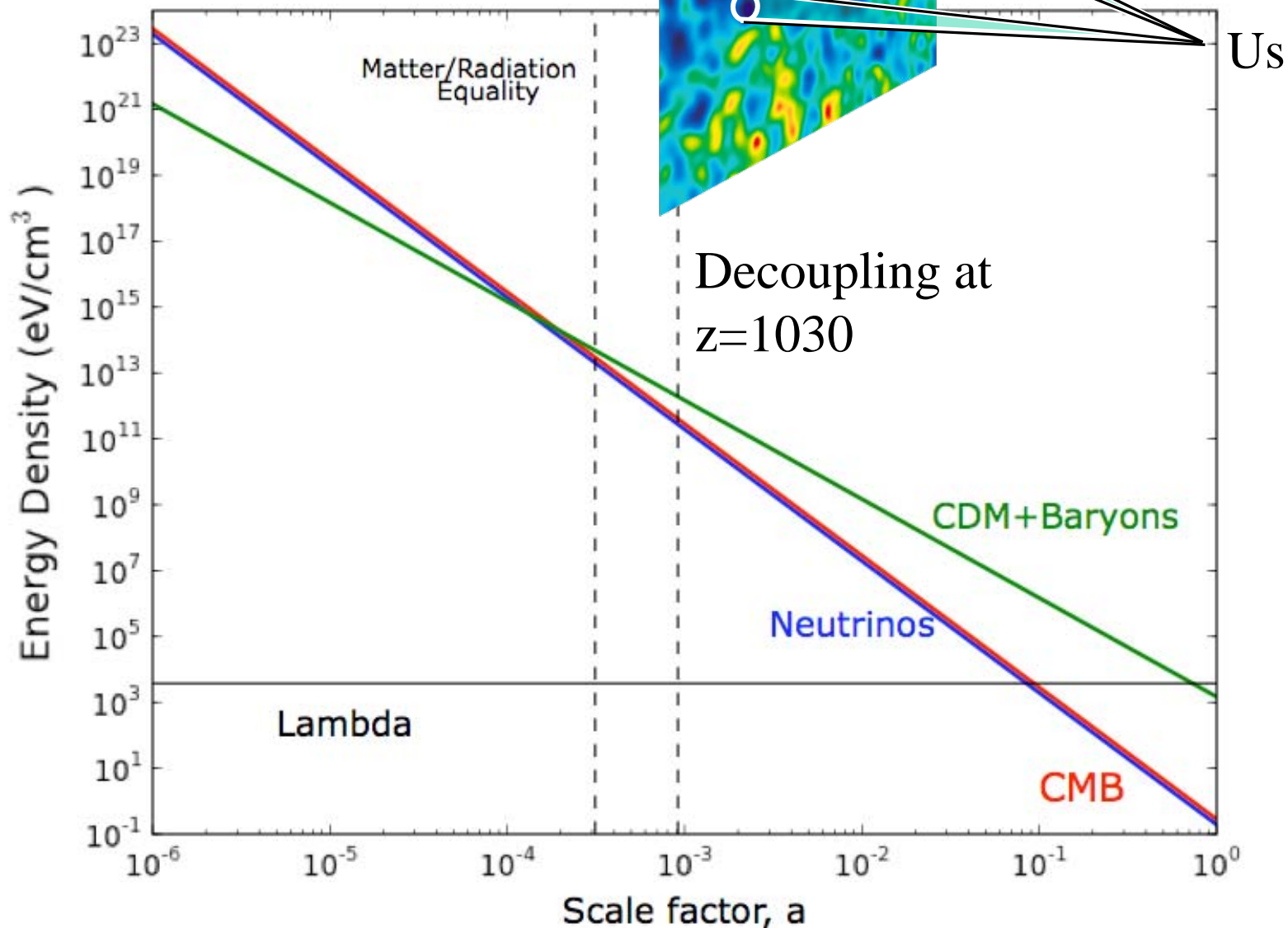
$$0.05 \text{ eV} < \sum m_\nu < 0.06\text{-}0.1 \text{ eV}$$

From $\nu_\mu \leftrightarrow \nu_\tau$ oscillation
 (at 50% spl)
 neutrinos at SuperK ,

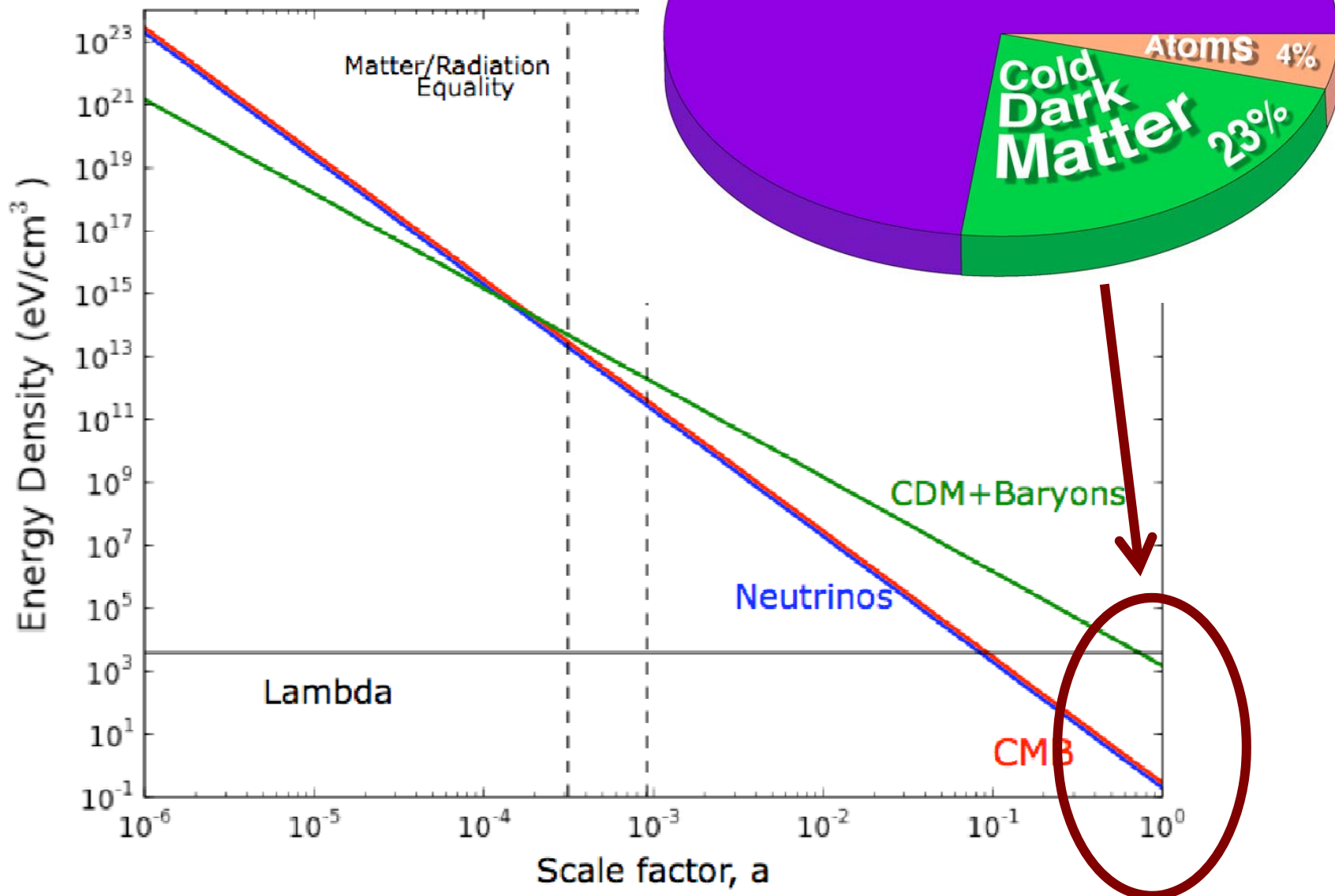
$$\nu_\mu \leftrightarrow \nu_\tau$$

From Planck plus fine
 scale CMB polarization
 measurements (ACT,
 SPT....)

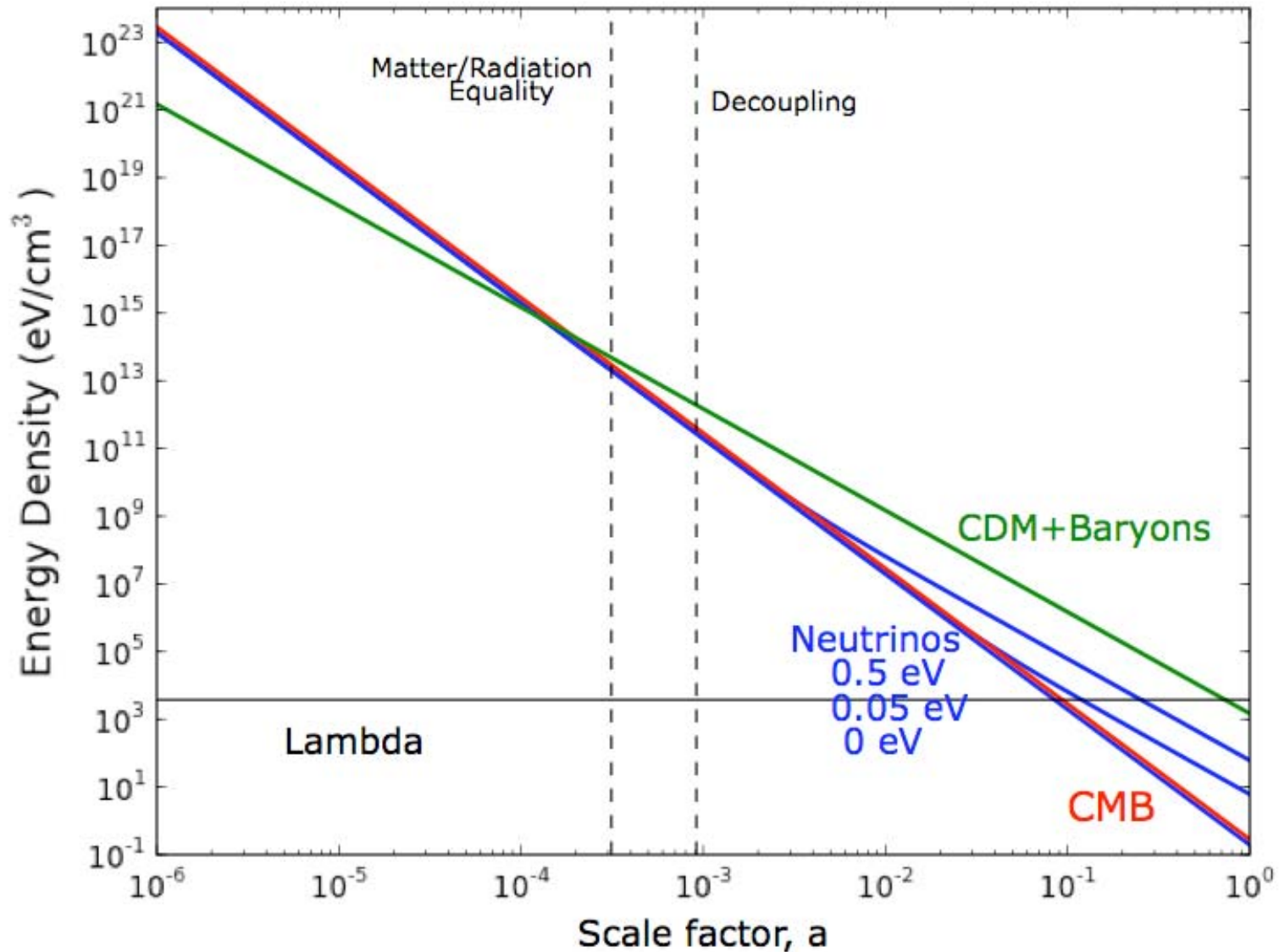
Cosmic Evolution



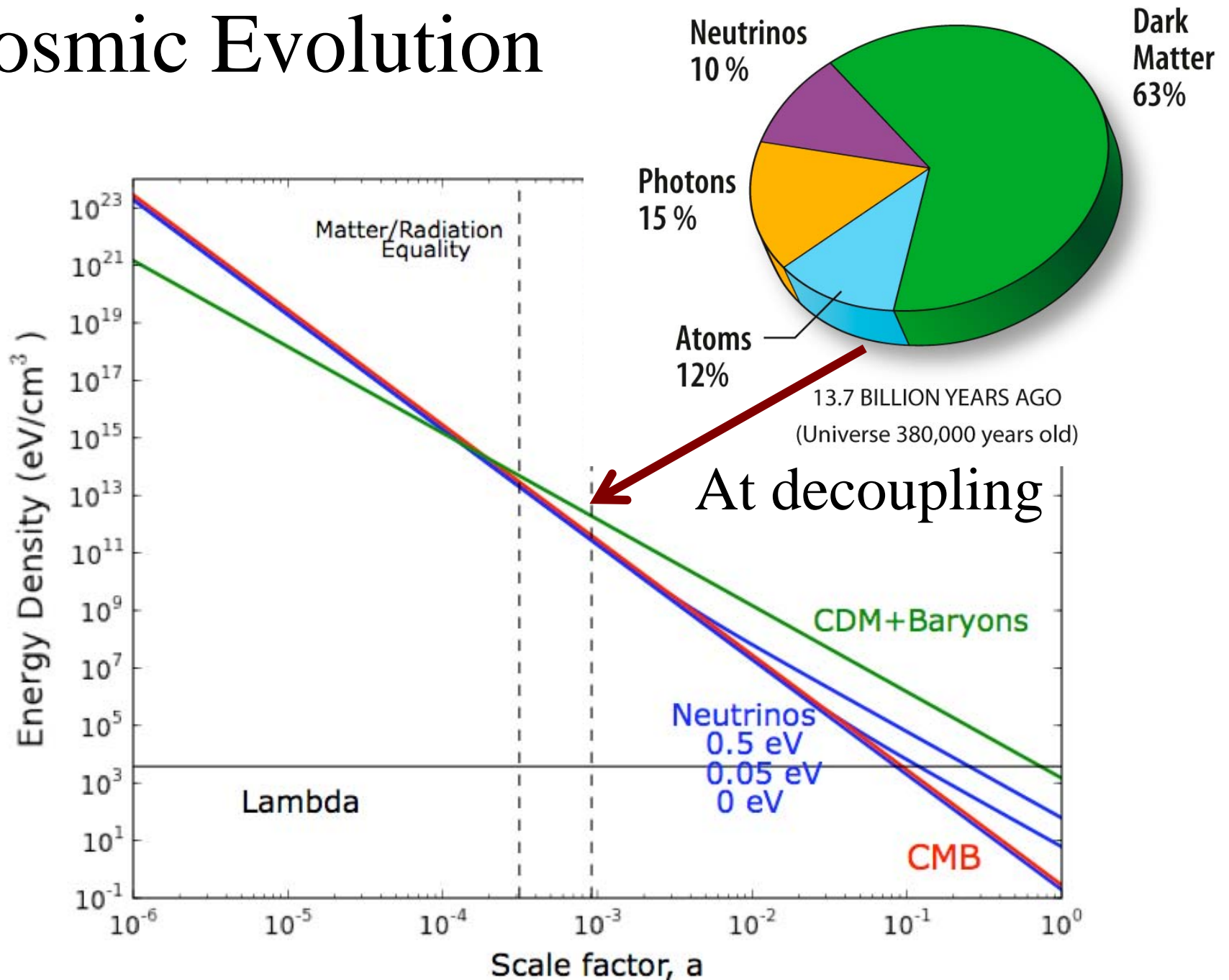
Cosmic Evolution



Cosmic Evolution



Cosmic Evolution



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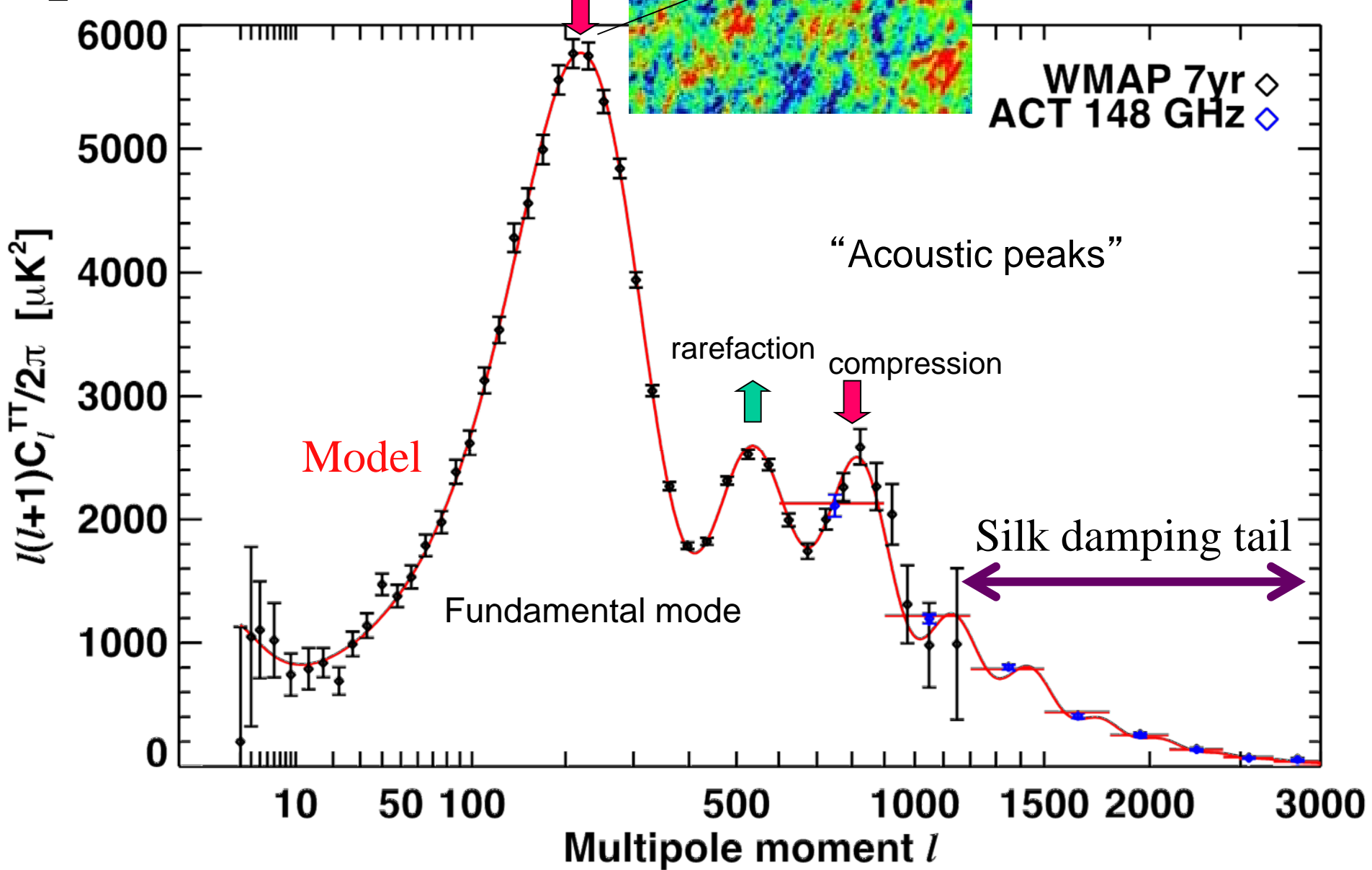
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Dear Alex,

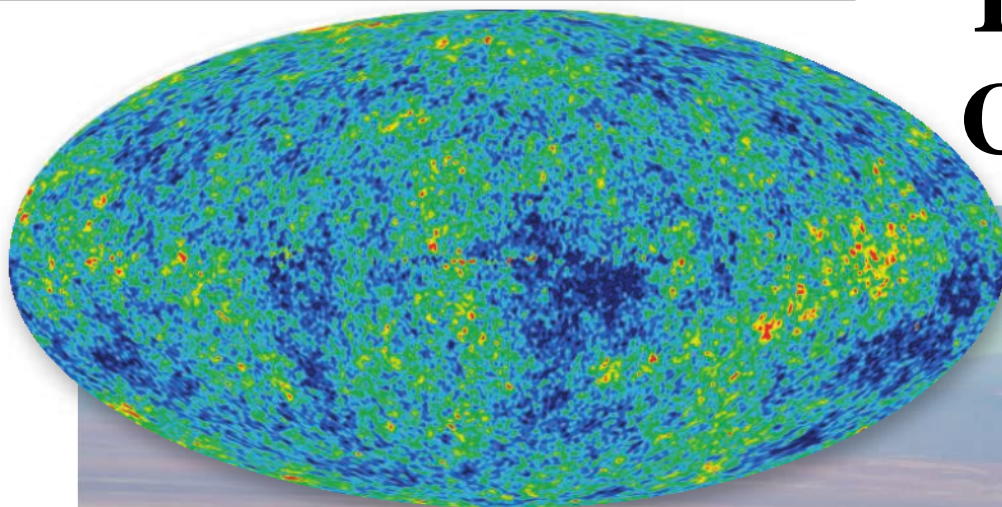
Thank you for
your hospitality and
help in Balatonfüred
and Debrecen. I won't
forget my visit. I was
surprised to learn
that neutrino mass
could be limited by
thoughts of cosmology!

Richard Feynman

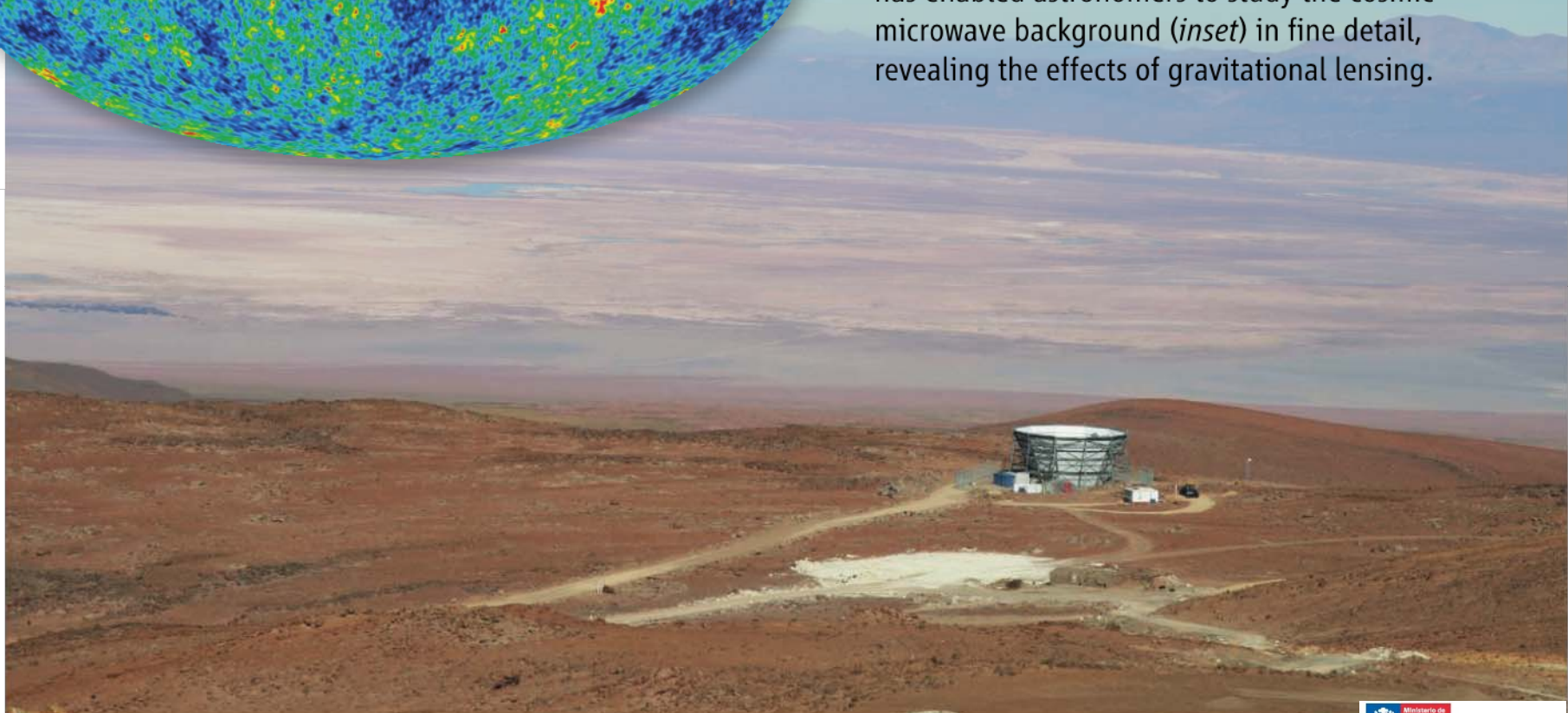
Angular Power Spectrum



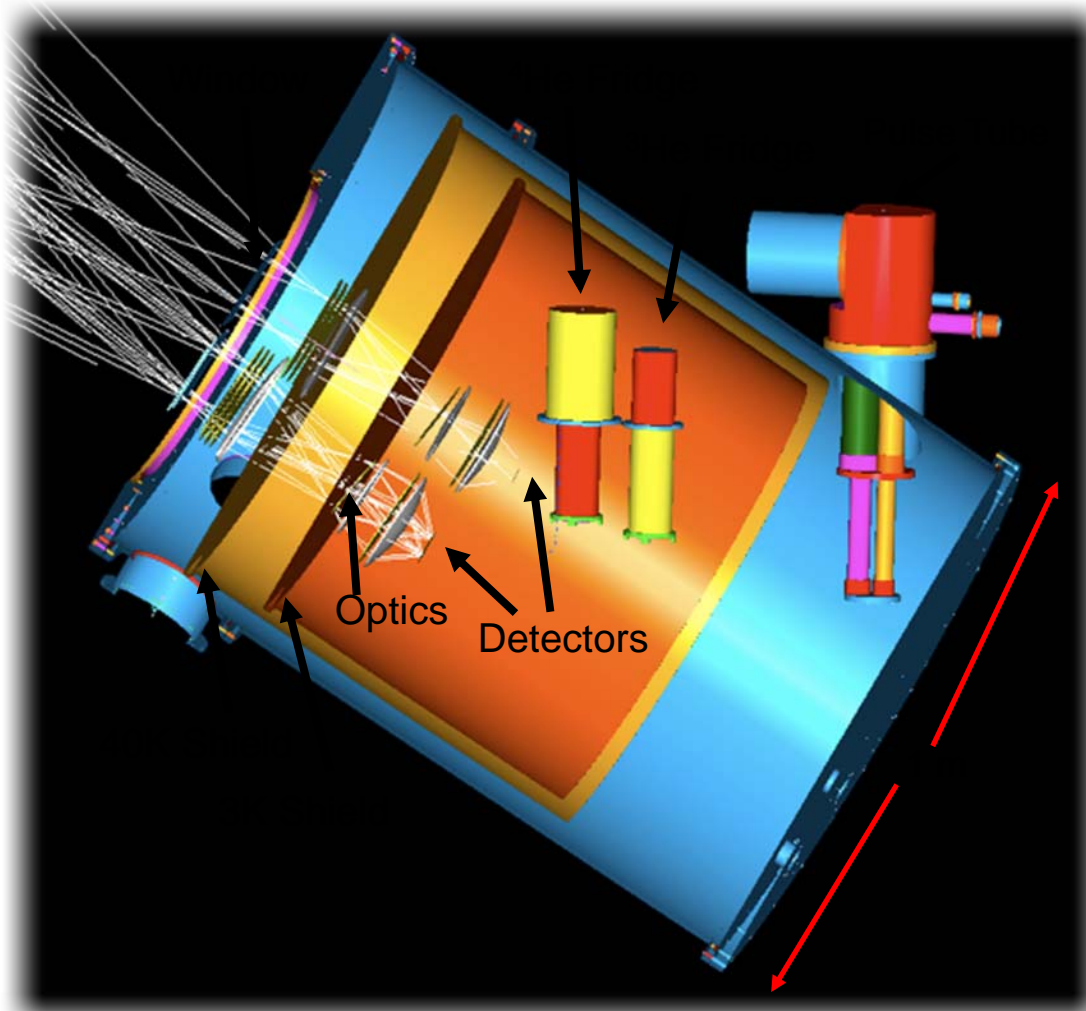
The Atacama Cosmology Telescope



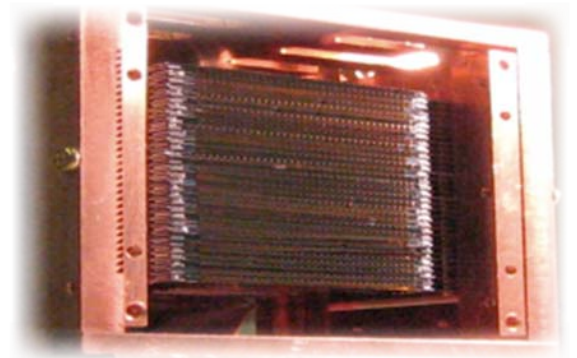
High definition. The Atacama Cosmology Telescope has enabled astronomers to study the cosmic microwave background (*inset*) in fine detail, revealing the effects of gravitational lensing.



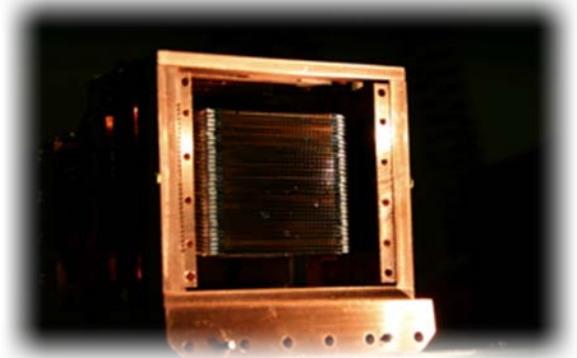
The Millimeter Bolometric Array Camera



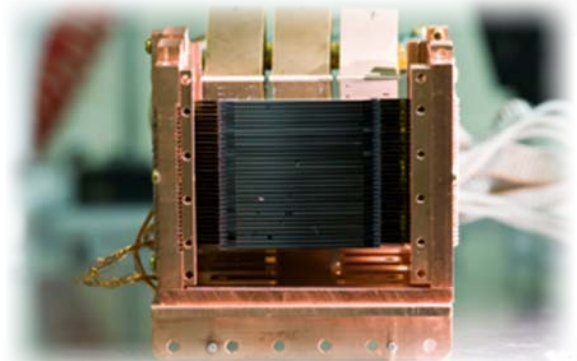
148 GHz

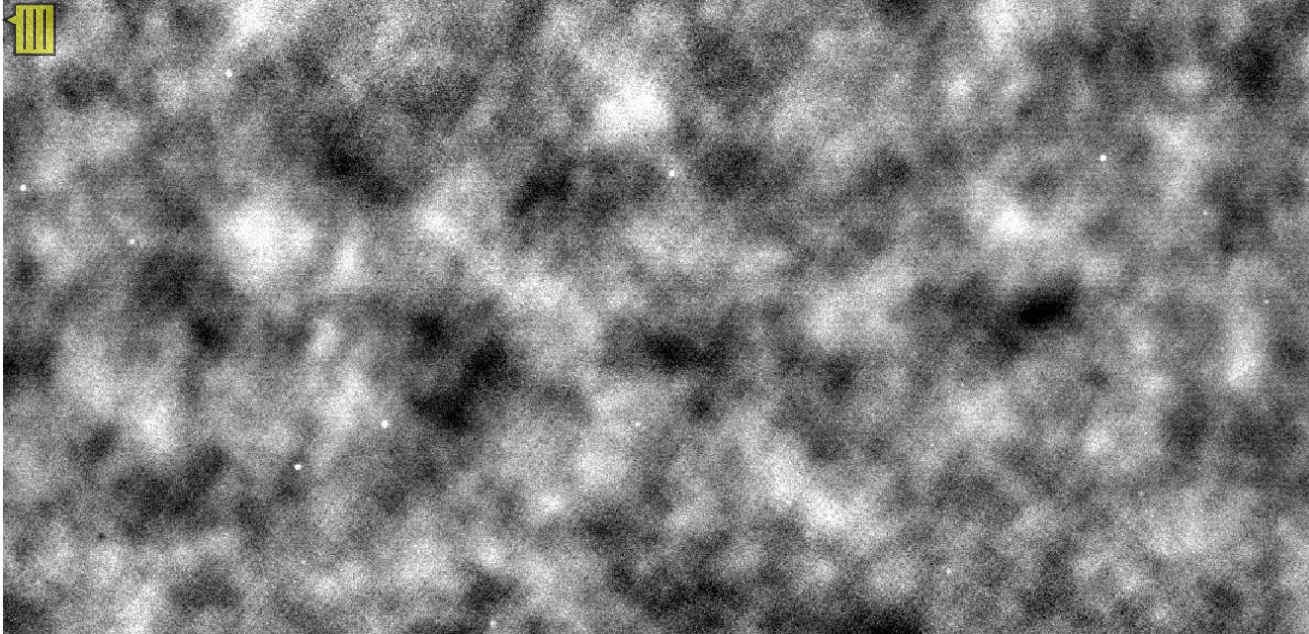


218 GHz

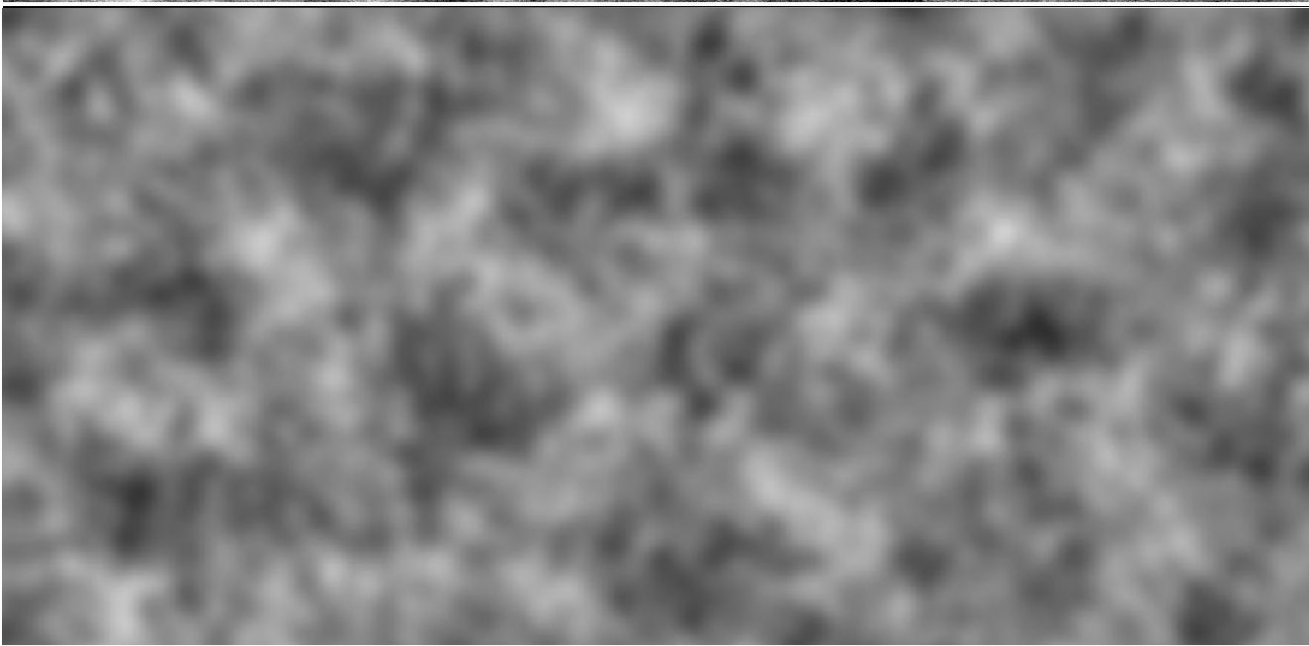


277 GHz



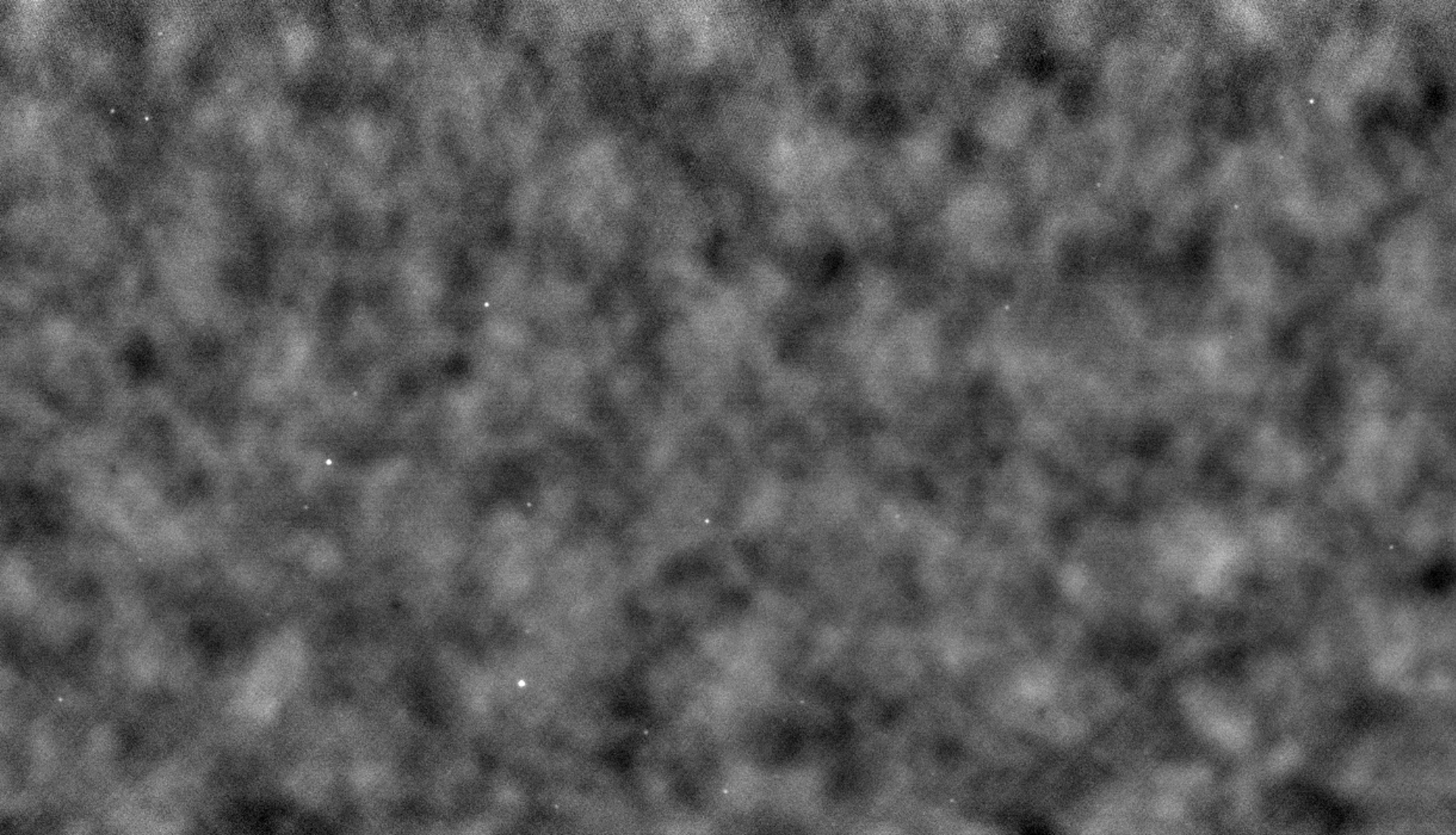


ACT



WMAP

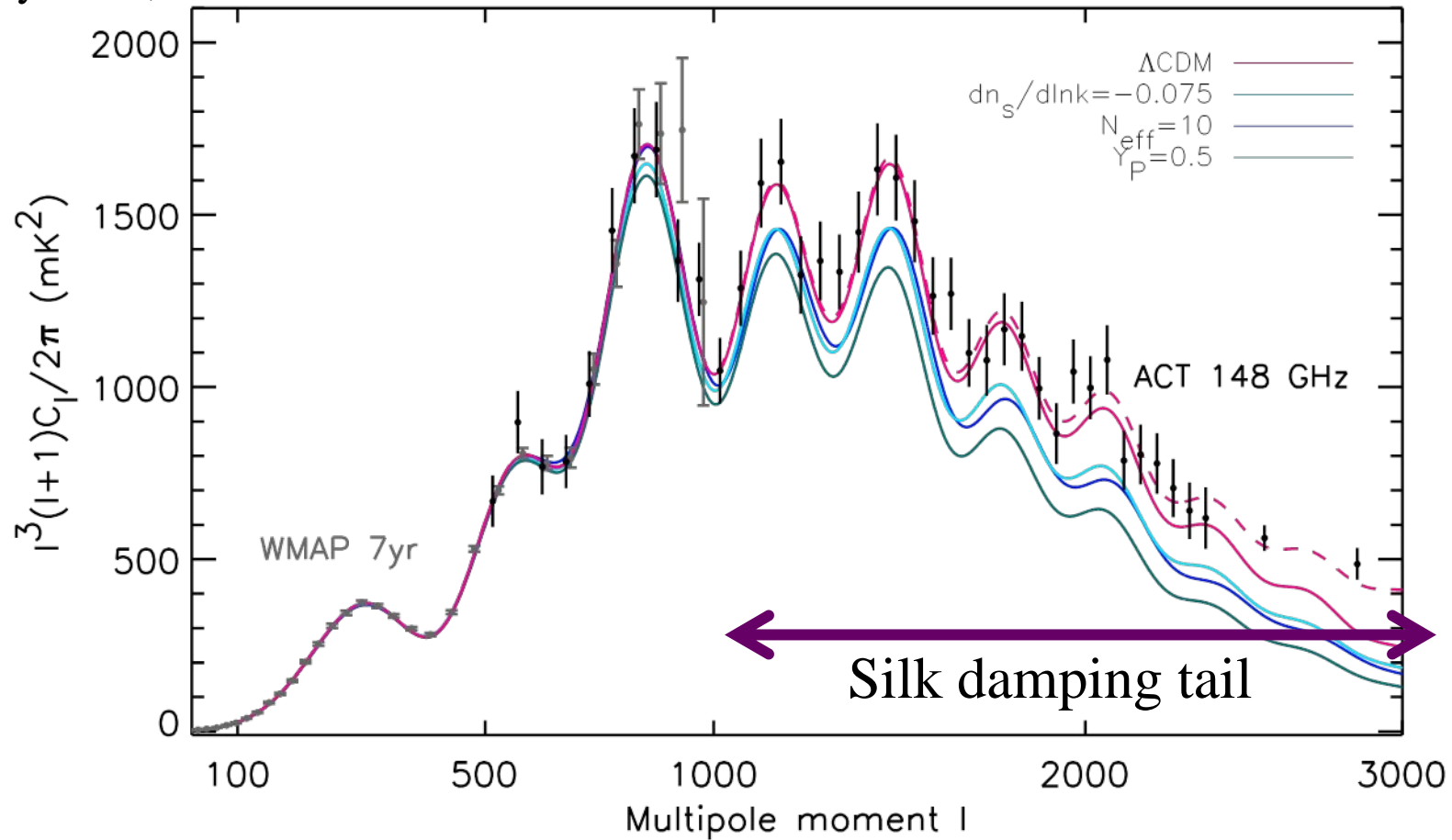
40 deg²



ACT ell > 300

Number of relativistic species, N_{eff}

Dunkley et al., 2011



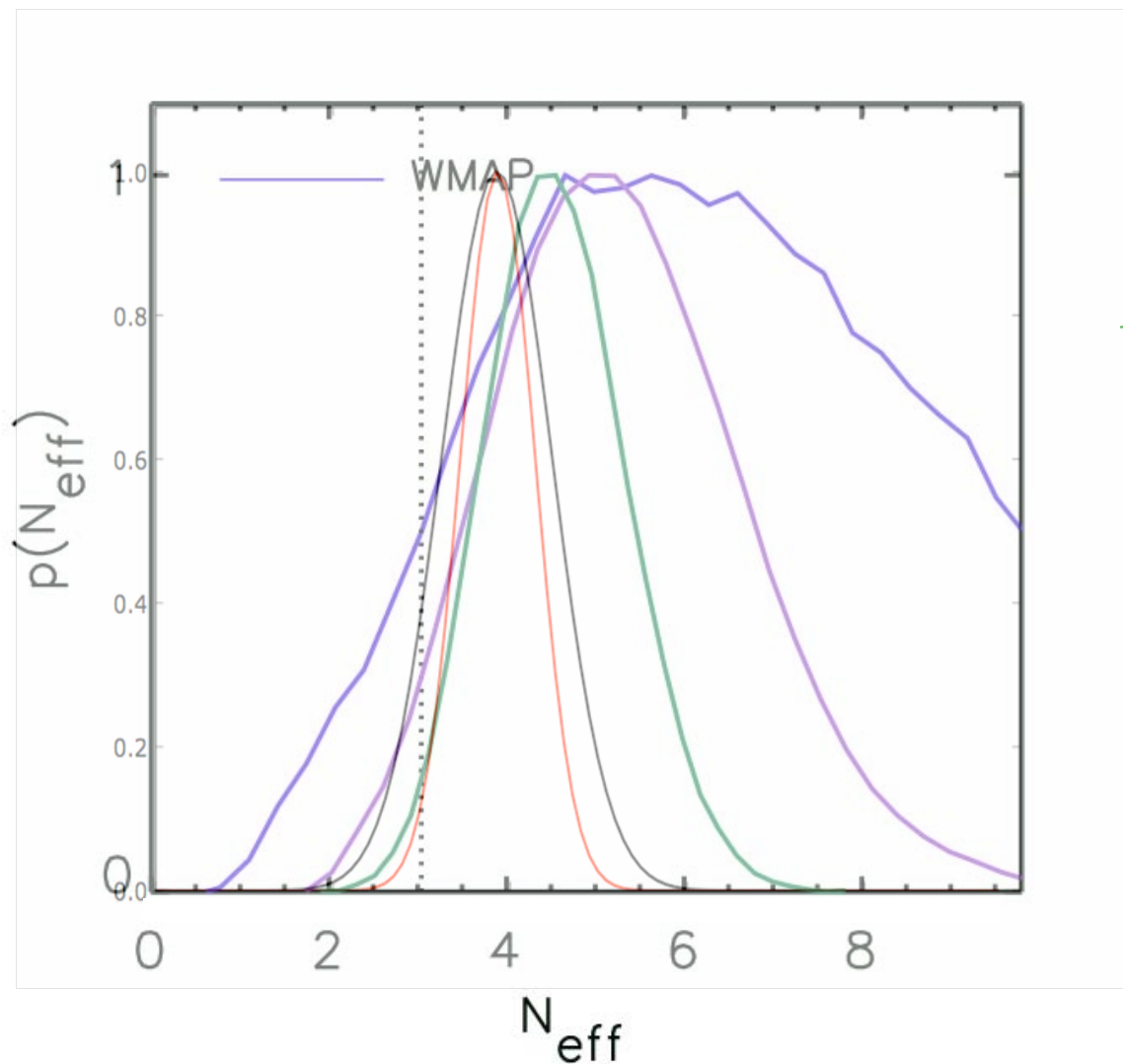
The key to limiting N_{eff} is to identify the increased damping at small angular scales in the CMB.

Jungman, Kamionkowski, Kosowsky, Spergel 1996

Hou et al., 2011

Bashinsky & Seljak, 2004

N_{eff}



WMAP

ACT+WMAP

5.3 +/- 1.3

ACT+WMAP+BAO+H₀

4.56 +/- 0.75

SPT+WMAP

3.85 +/- 0.62

SPT+WMAP+BAO+H₀

3.86 +/- 0.42

Komatsu et al., 2011

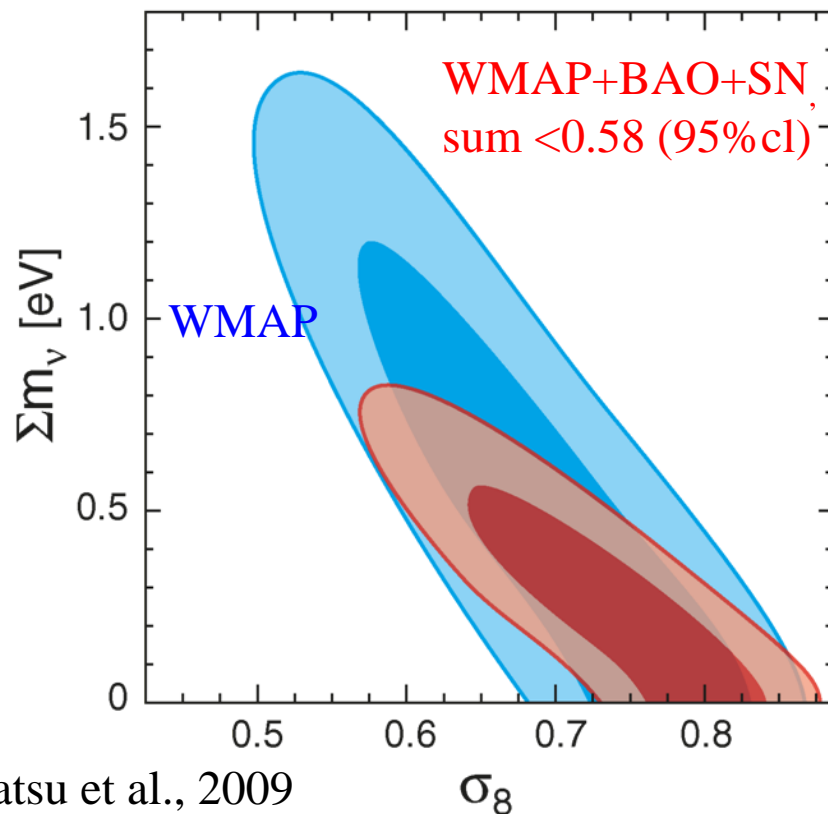
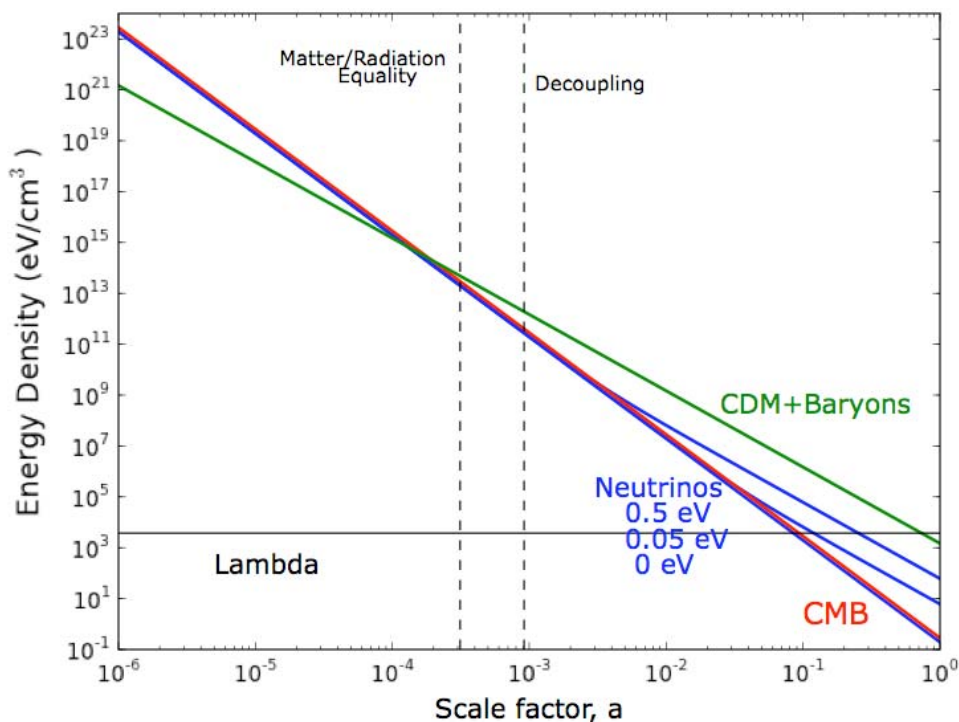
Dunkley et al., 2011

Keisler et al., 2011

Neutrino Mass #1

Compare Ω_m today to that at decoupling. Greater relativistic Σm_ν means smaller ρ_m/ρ_r , enhanced potential evolution, and producing less cosmic structure.

e.g., Ichikawa et al., 2005



Komatsu et al., 2009



Neutrino Mass #2

Use the cosmic structure between us and the surface of last scattering to **lens** the CMB, especially the small angles where a massive neutrino inhibits the formation of structure.

Lensing is characteristically sensitive to m_ν

Lensing smooths out the peaks and alters the statistics of the CMB

$$\bar{\Theta}(\hat{n}) = \Theta(\hat{n} + \square \varphi)$$

lensed unlensed deflection

Lens-speak:

Lensing potential:

φ

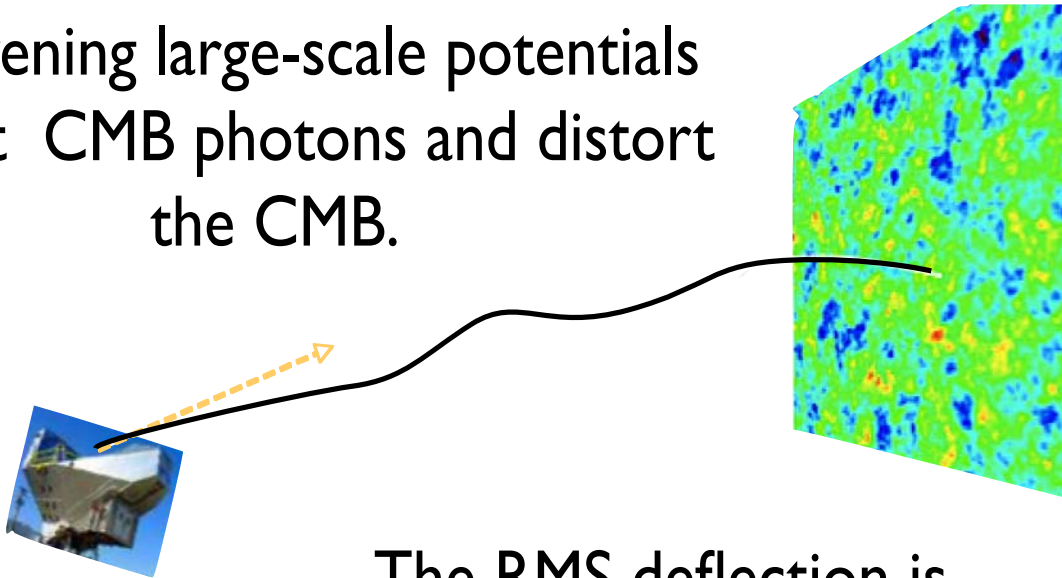
Deflection field:

$$d = \square \varphi$$

Convergence:

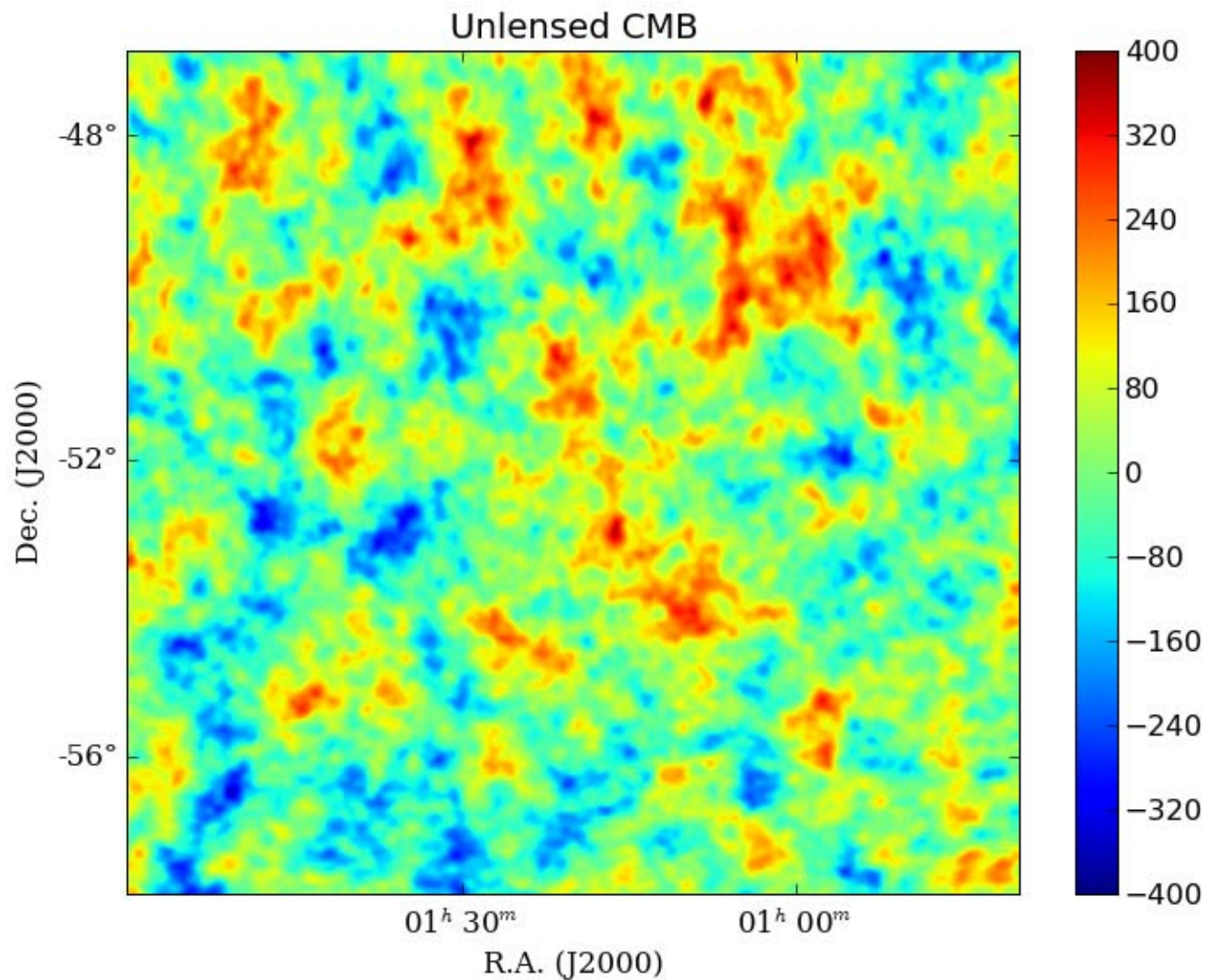
$$\kappa = \frac{1}{2} \square \cdot d$$

Intervening large-scale potentials deflect CMB photons and distort the CMB.



The RMS deflection is about 2.7 arcmins, but the deflections are coherent on degree scales.

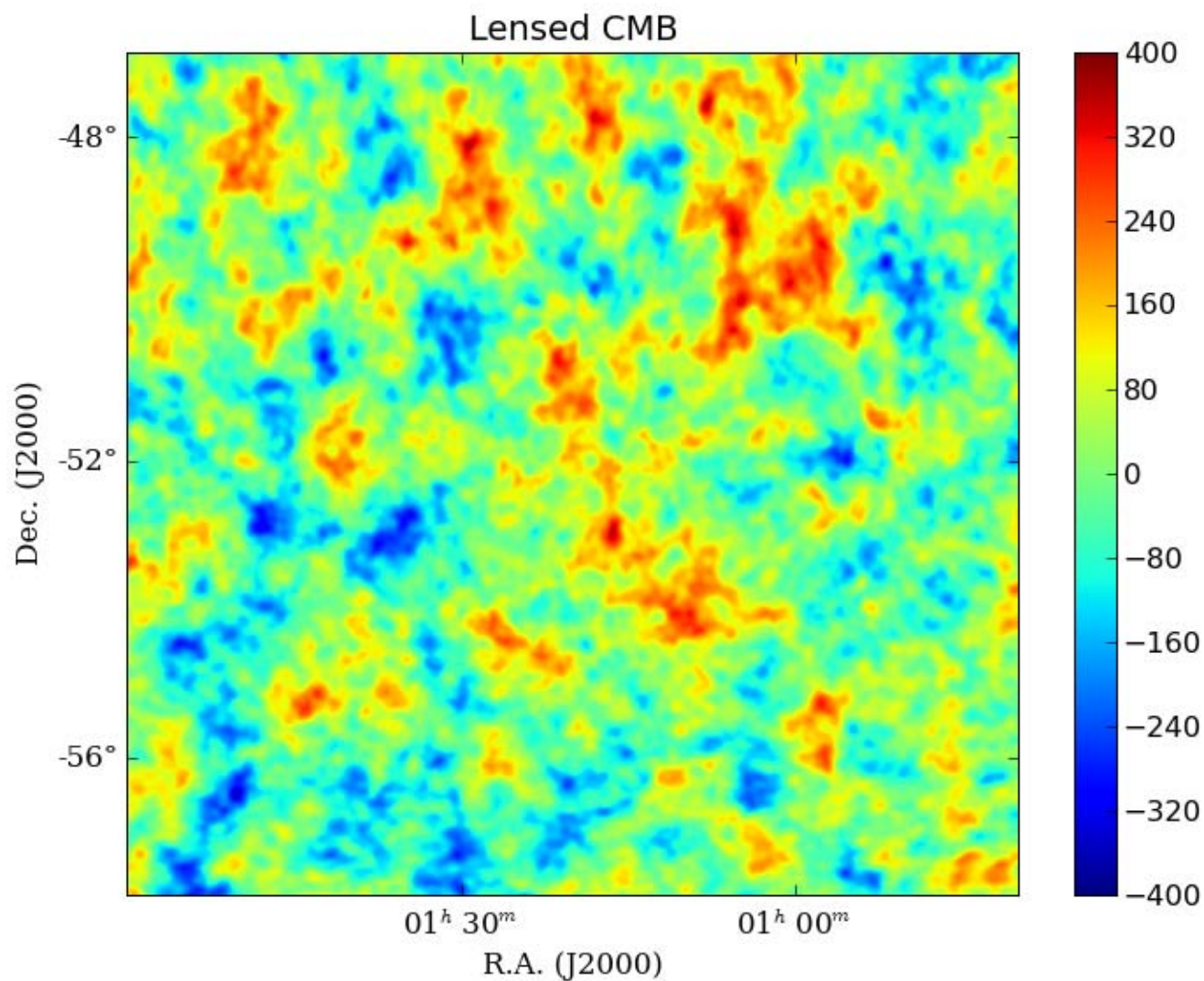
Simulations



uK

100 deg²

Simulations



uK

100 deg²

Lensing of CMB detected at 4σ

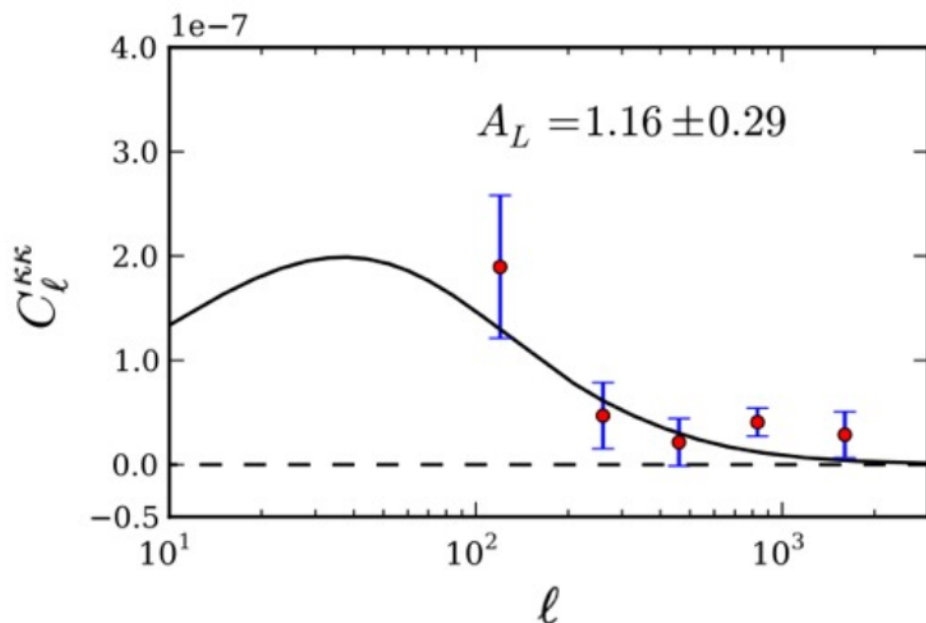


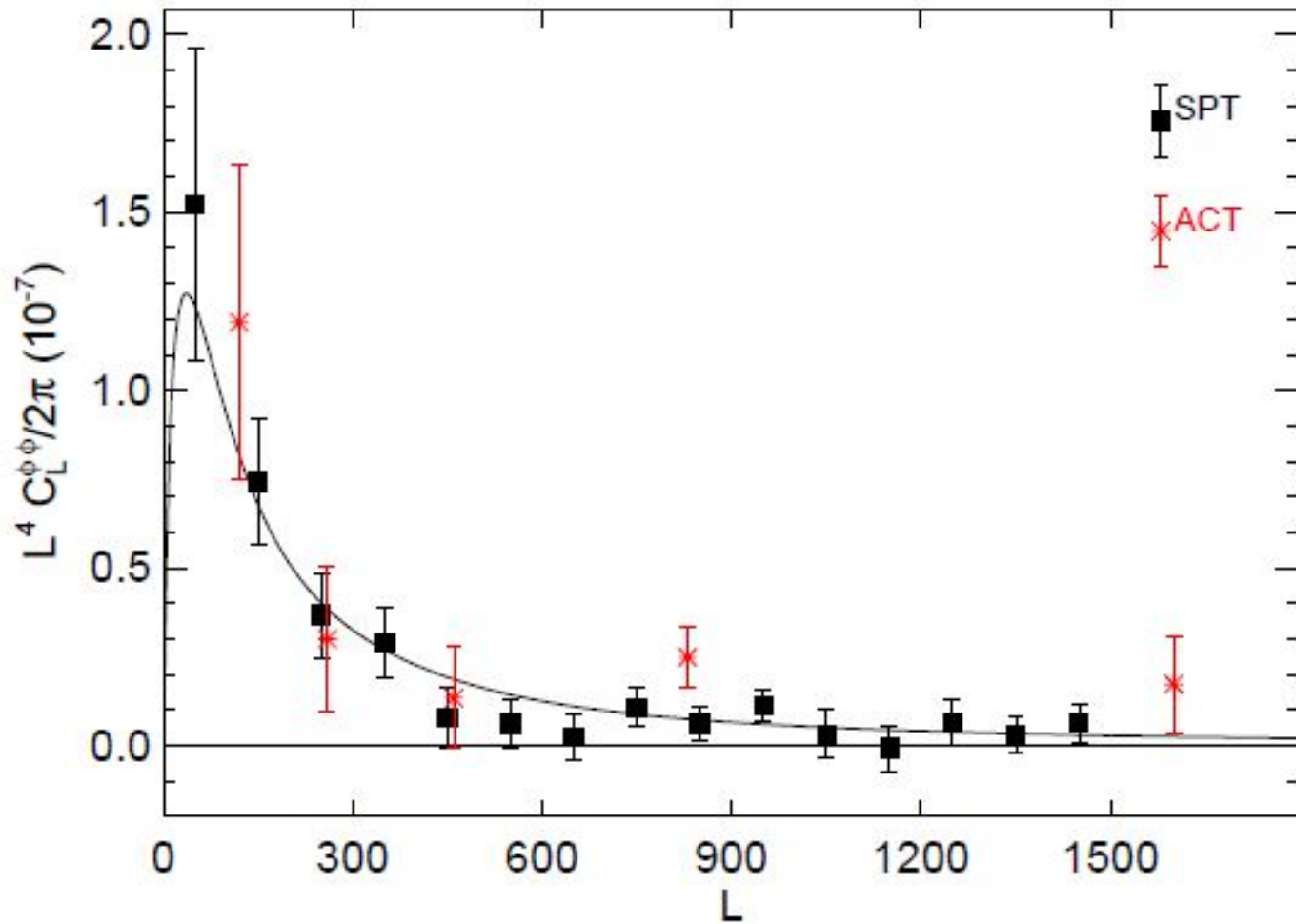
FIG. 2. Convergence power spectrum (red points) measured from ACT equatorial sky patches. The solid line is the power spectrum from the best-fit WMAP+ACT cosmological model with amplitude $A_L = 1$, which is consistent with the measured points. The error bars are from the Monte Carlo simulation results displayed in Fig. 1. The best-fit lensing power spectrum amplitude to our data is $A_L = 1.16 \pm 0.29$

Based on Hu & Okamoto estimator plus phase randomization.

Detection is from 320 sq. degree of ACT equatorial data only.

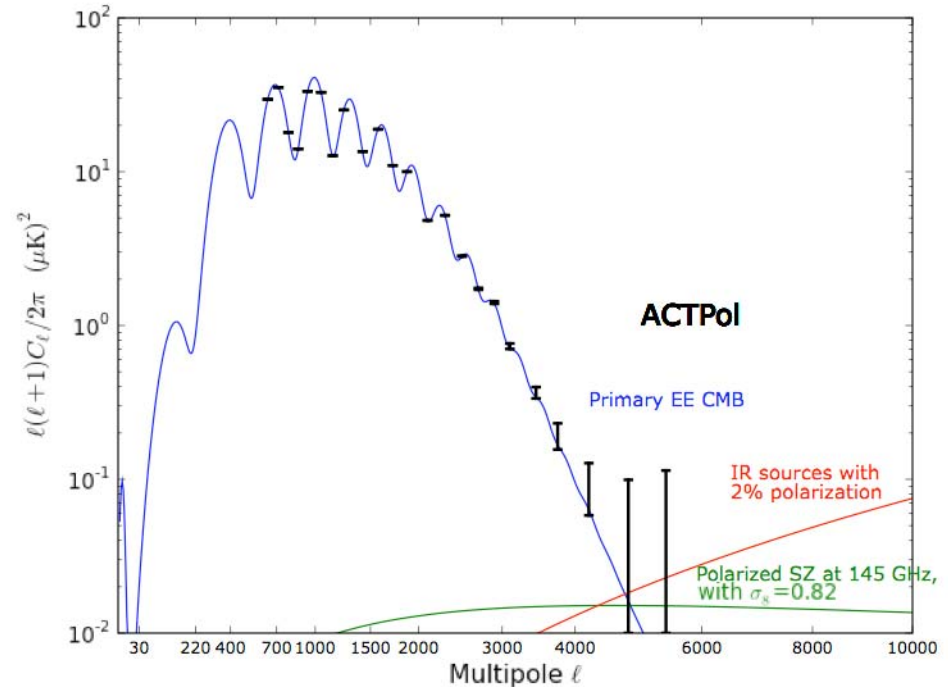
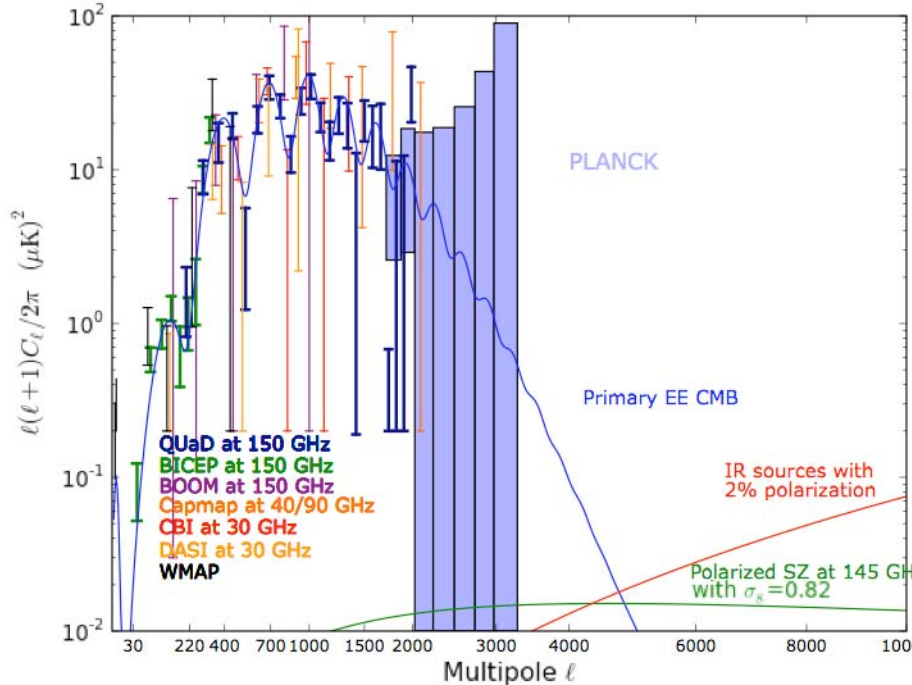
Shape sensitive to neutrino mass.

And from SPT



Neutrino Mass #3

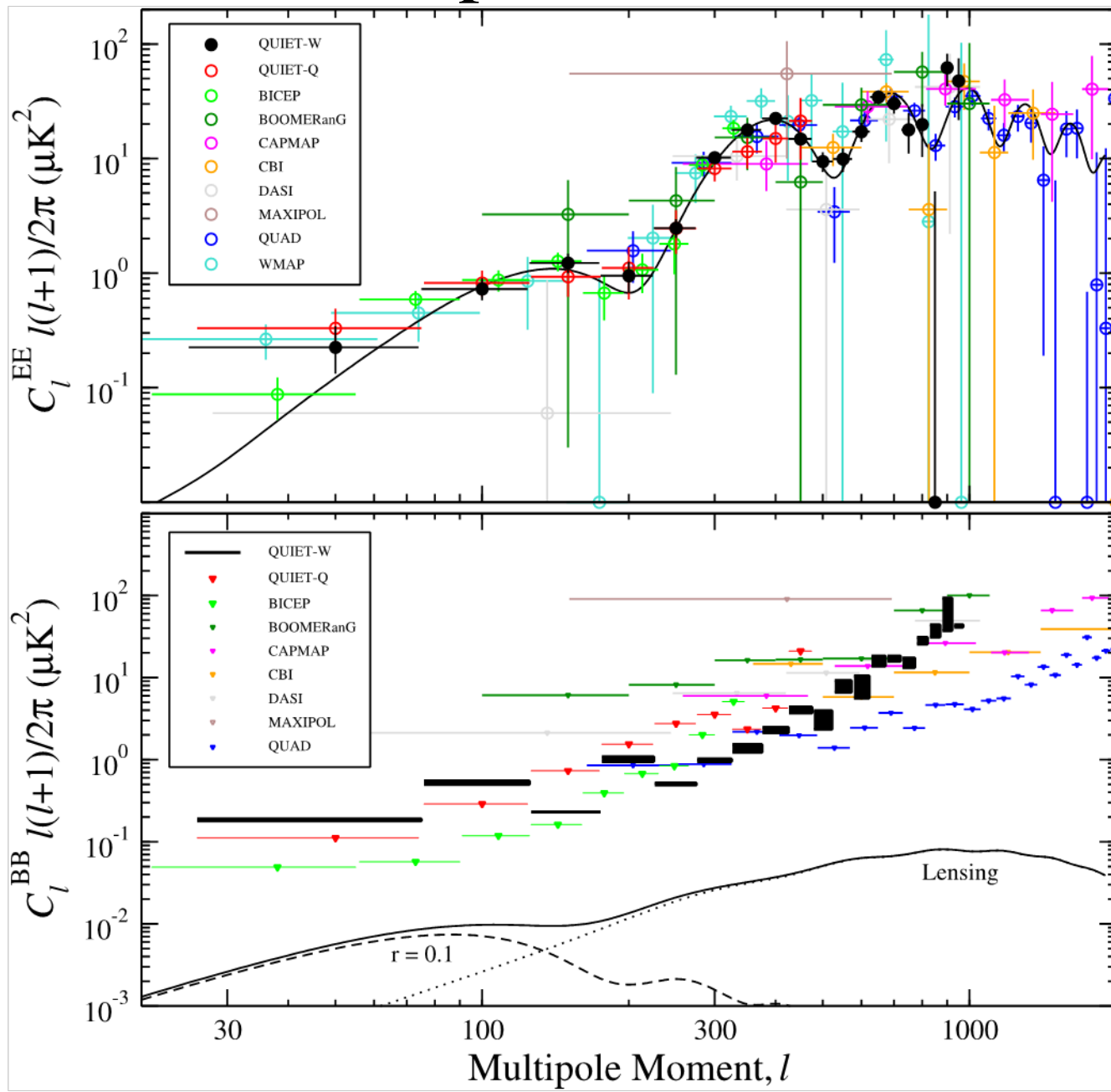
Planck: sensitive to $l=2000$ in polarization



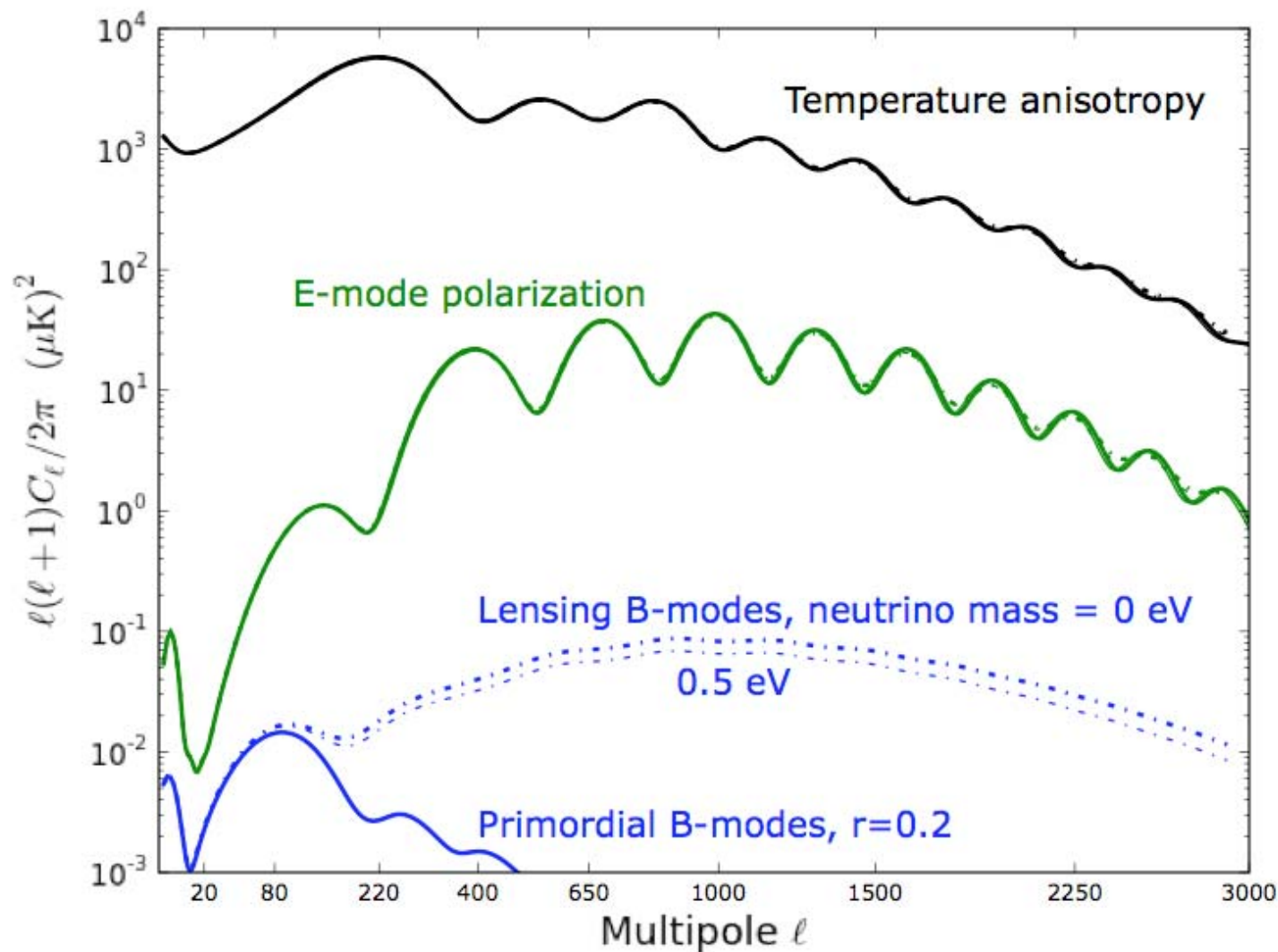
Can look through foregrounds in EE at $l > 2000$.

Instruments & measurements underway
by ACTPol, Polar, Polarbear, SPTPol.

Hot off the press: QUIET results



Gravitational lensing turns E-modes into B-modes.
Look for the effects of neutrinos in polarization.





Scalar spectral index, n_s

The standard model of cosmology has adiabatic and Gaussian scalar fluctuations in a flat lambda-dominated universe. These assumptions are tested. Six parameters characterize the model.

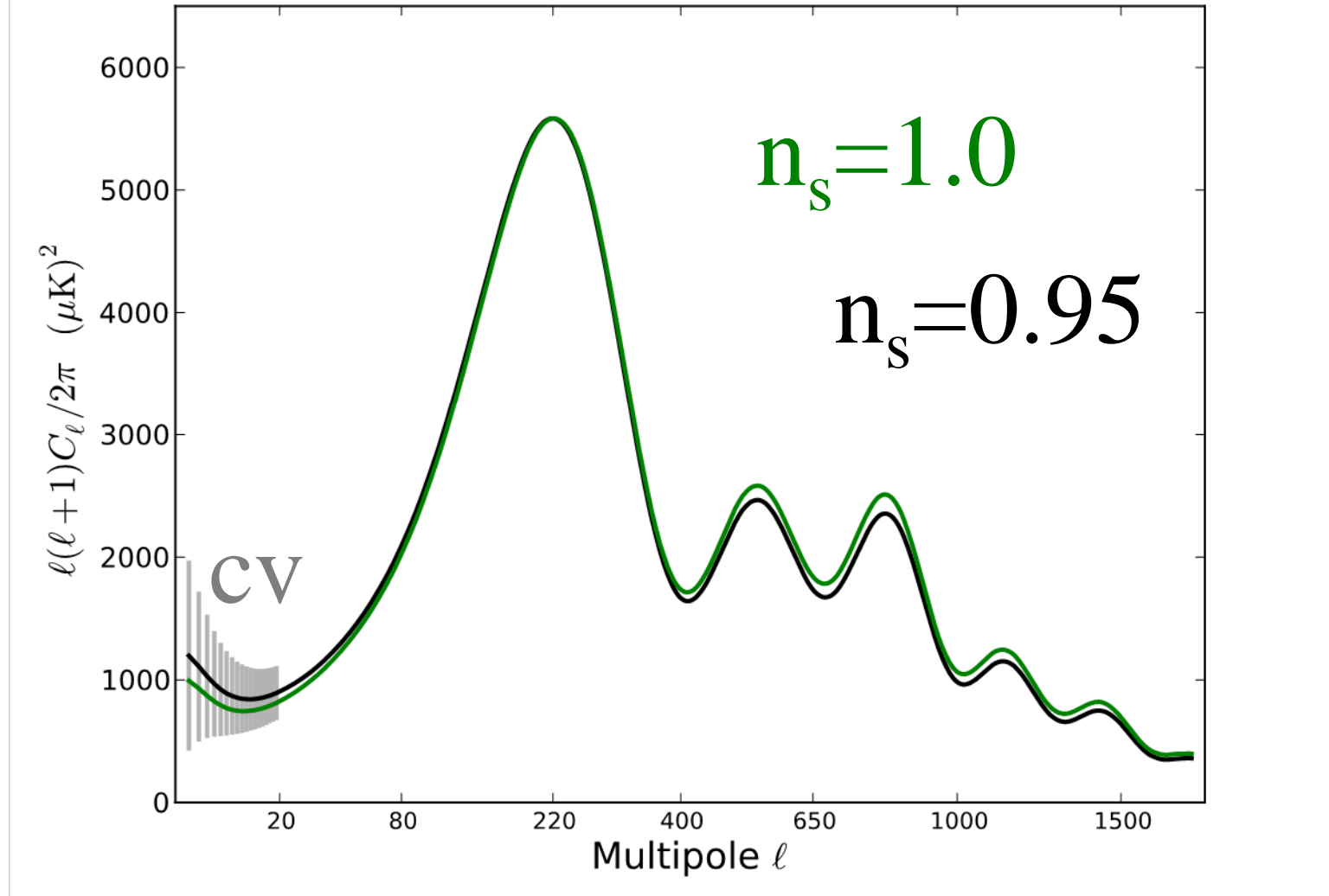
The primordial fluctuations are characterized by two of the parameters, a fluctuation amplitude and a slope.

$$\Delta_R^2 = 2.43 \pm 0.11 \times 10^{-9}$$

$$n_s = 0.967 \pm 0.014$$



n_s



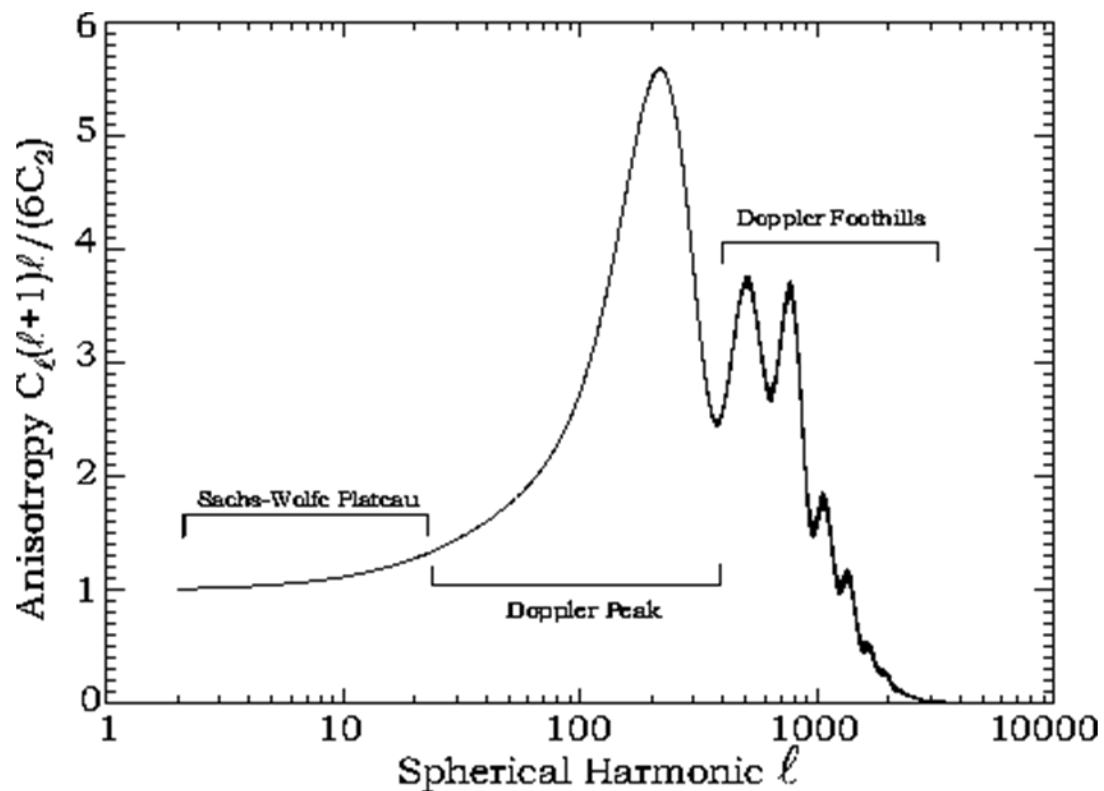
Early History

With COBE/DMR: Smoot et al ApJ 396:L1, 1992

$$n_s = 1.15 +0.45/-0.65$$

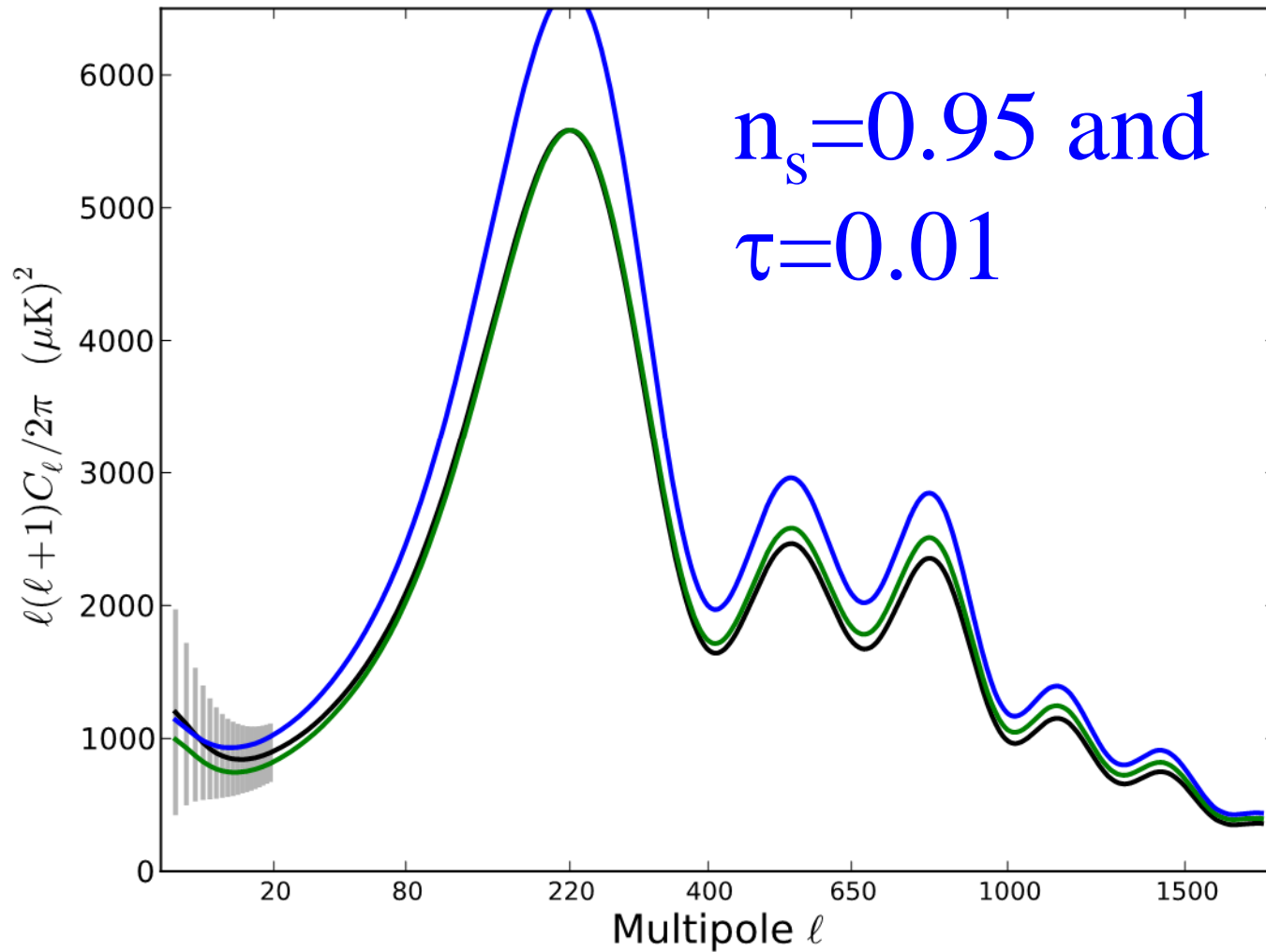
With FIRS: Ganga,
Page, Cheng, Meyer,
ApJ 432:L15, 1994

$$n_s = 1 +/- 1$$

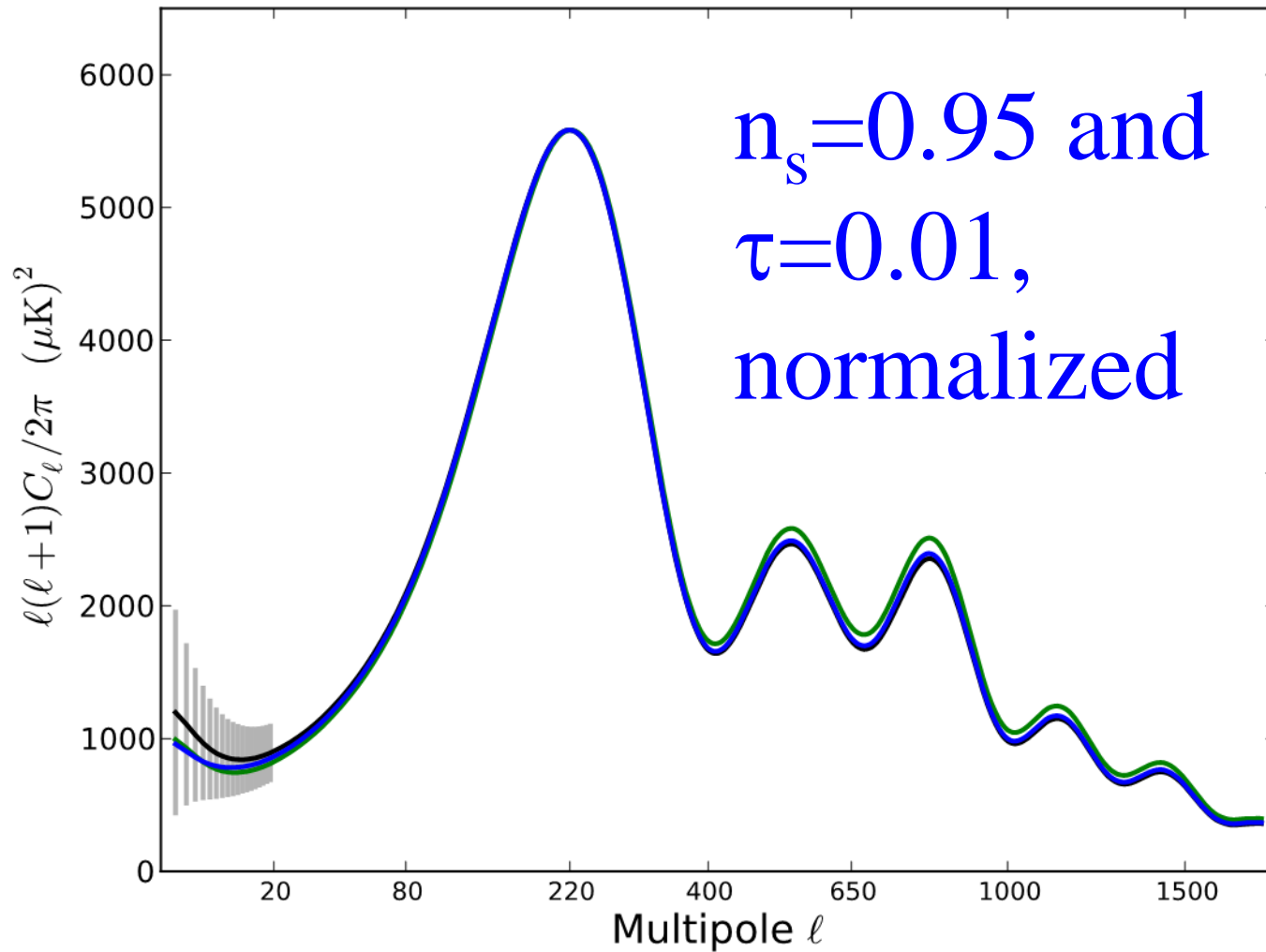


From Jodrell Bank group

n_s and reionization



n_s and reionization





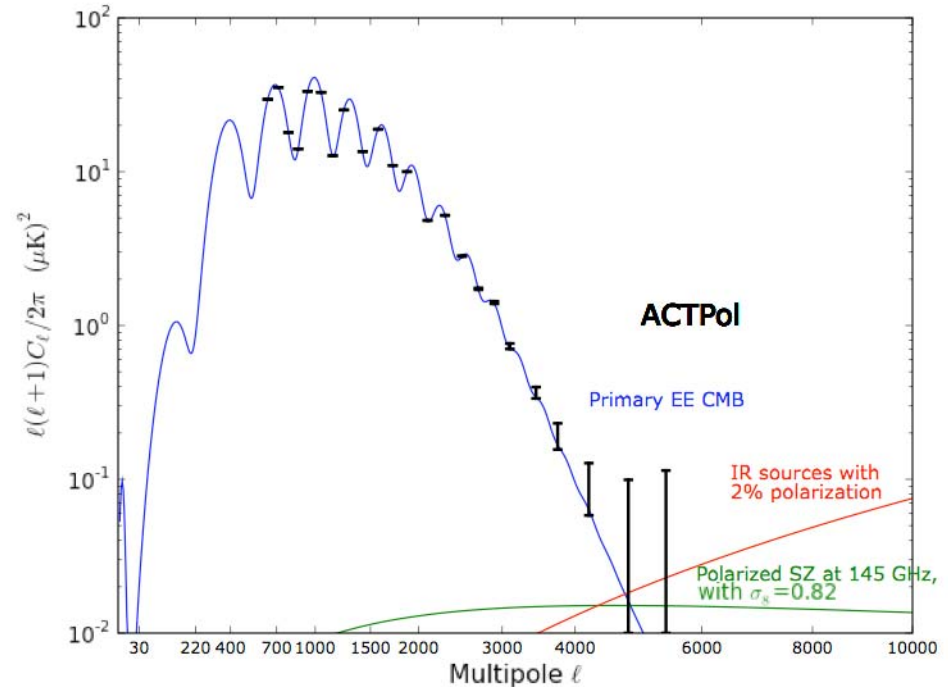
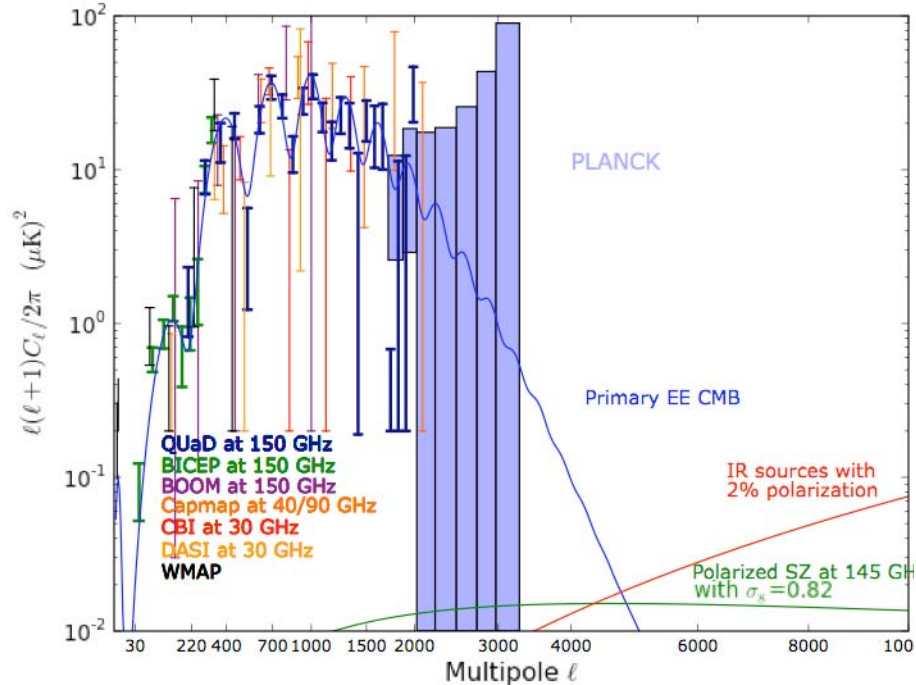
Status for n_s

With no tensor modes in the 6 parameter model.

$1-n_s = 0.037 \pm 0.014$	WMAP7	Komatsu et al.
$1-n_s = 0.037 \pm 0.012$	WMAP7+BAO+ H_0	Komatsu et al.
$1-n_s = 0.038 \pm 0.013$	WMAP5+QUAD+ACBAR	Brown et al.
$1-n_s = 0.038 \pm 0.013$	WMAP7+ACT	Dunkley et al.
$1-n_s = 0.034 \pm 0.011$	WMAP7+SPT	Keisler et al.
$1-n_s = ? \pm 0.005$	Planck	

The small angular scale forefront

Planck: sensitive to $l=2000$ in polarization



Can look through foregrounds in EE at $l > 2000$.

Instruments & measurements underway
by ACTPol, Polar, Polarbear, SPTPol.

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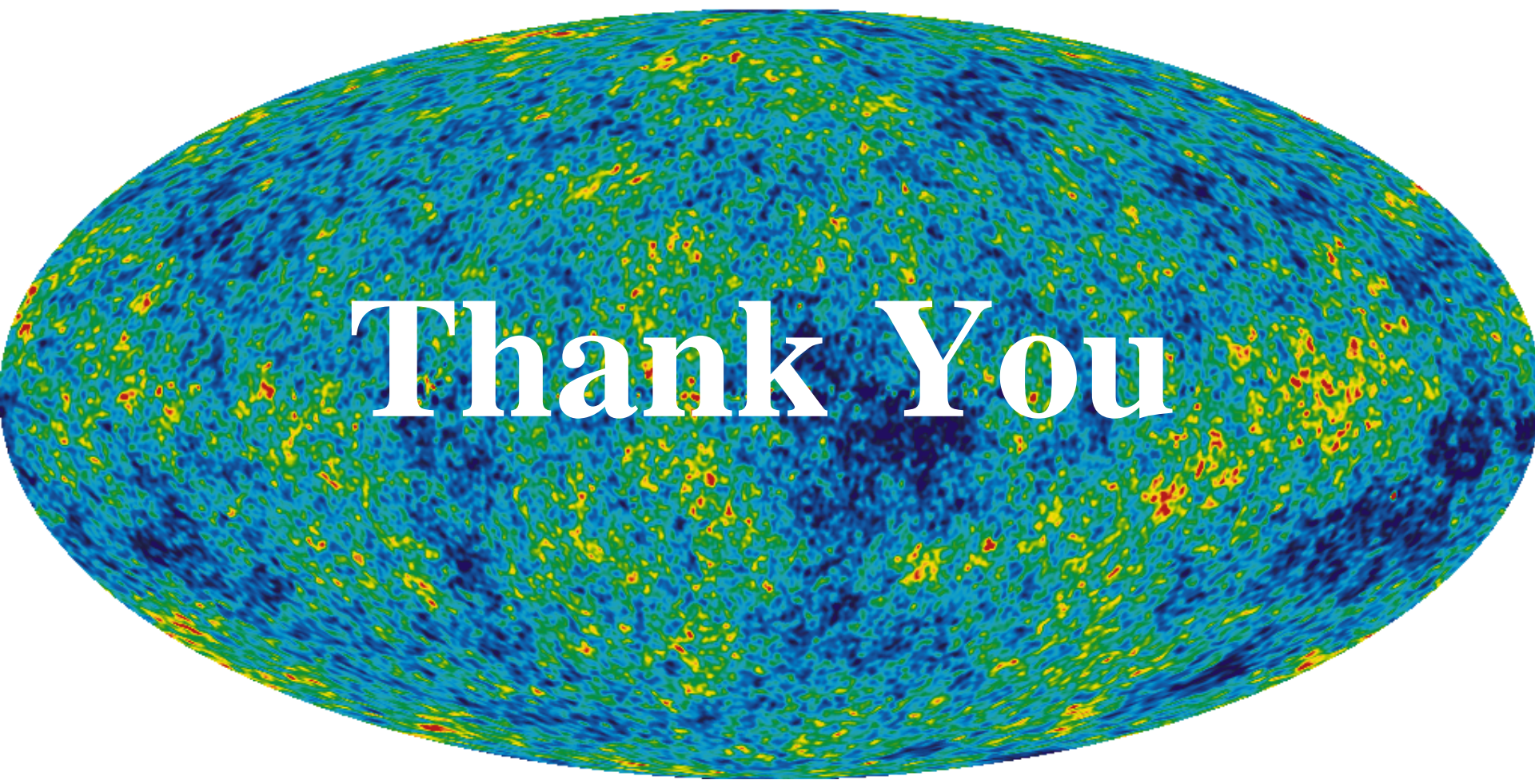
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Thank You