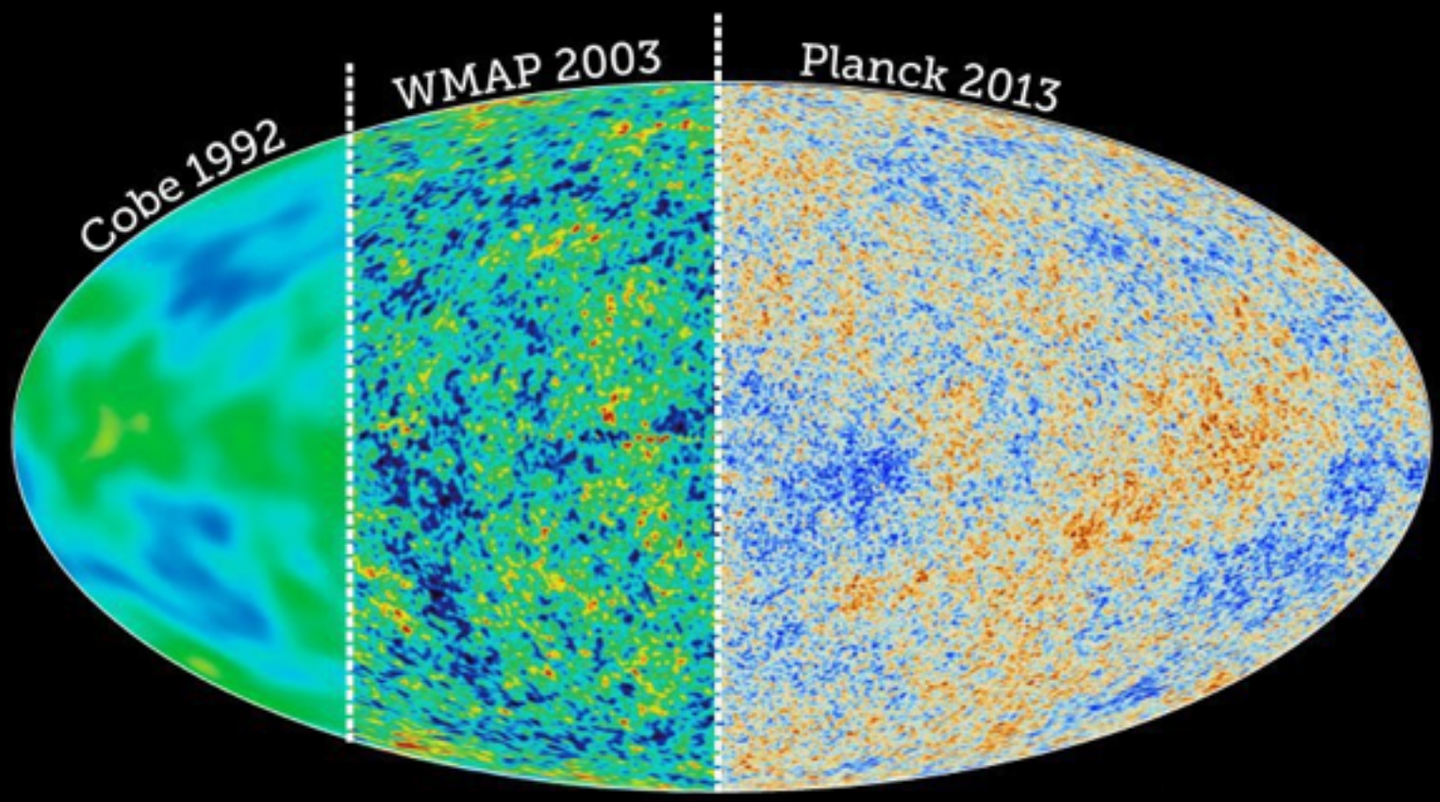
What did we learn about neutrinos from *Planck*?

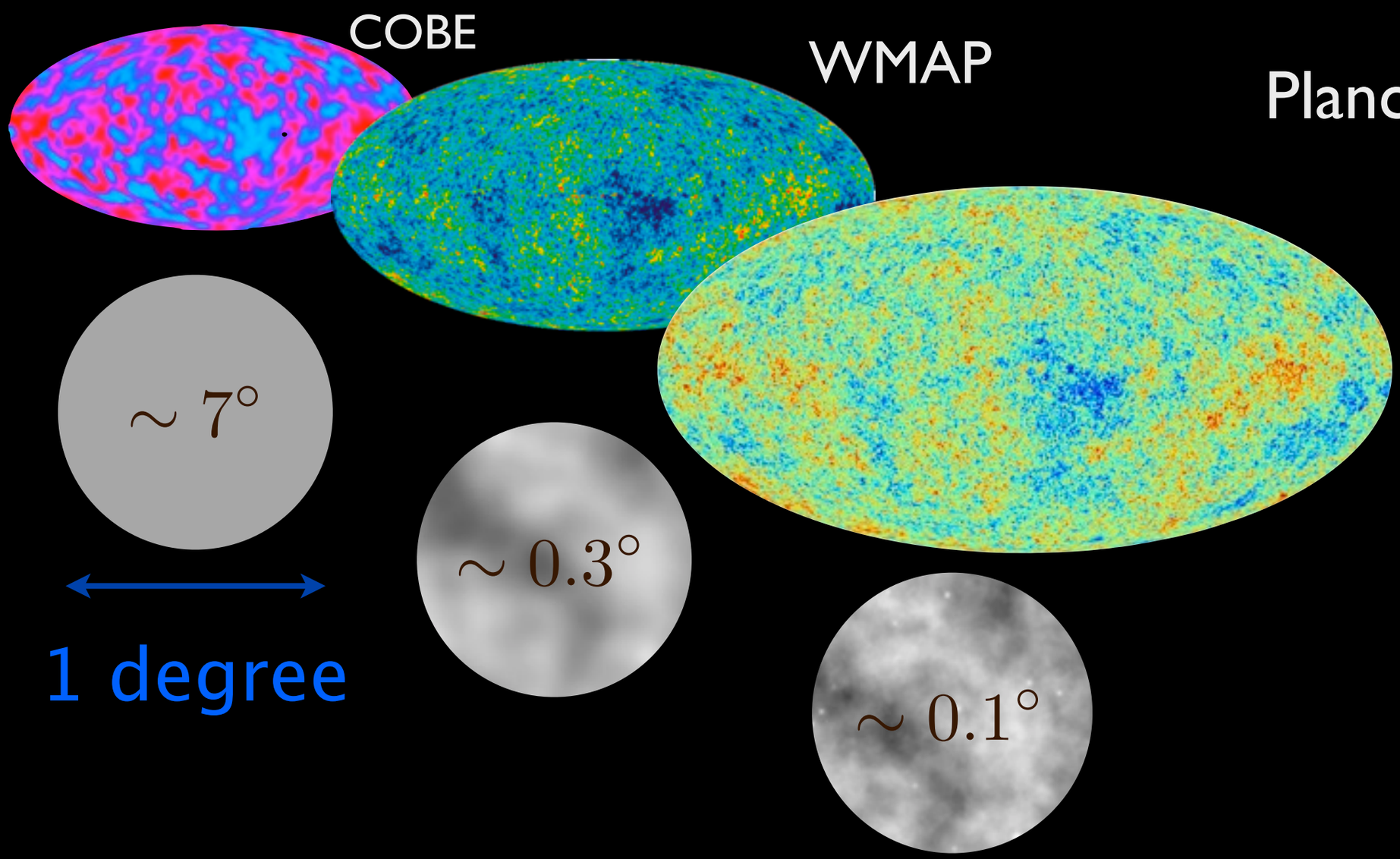


Sudeep Das

DAVID SCHRAMM FELLOW
ARGONNE NATIONAL LABORATORY

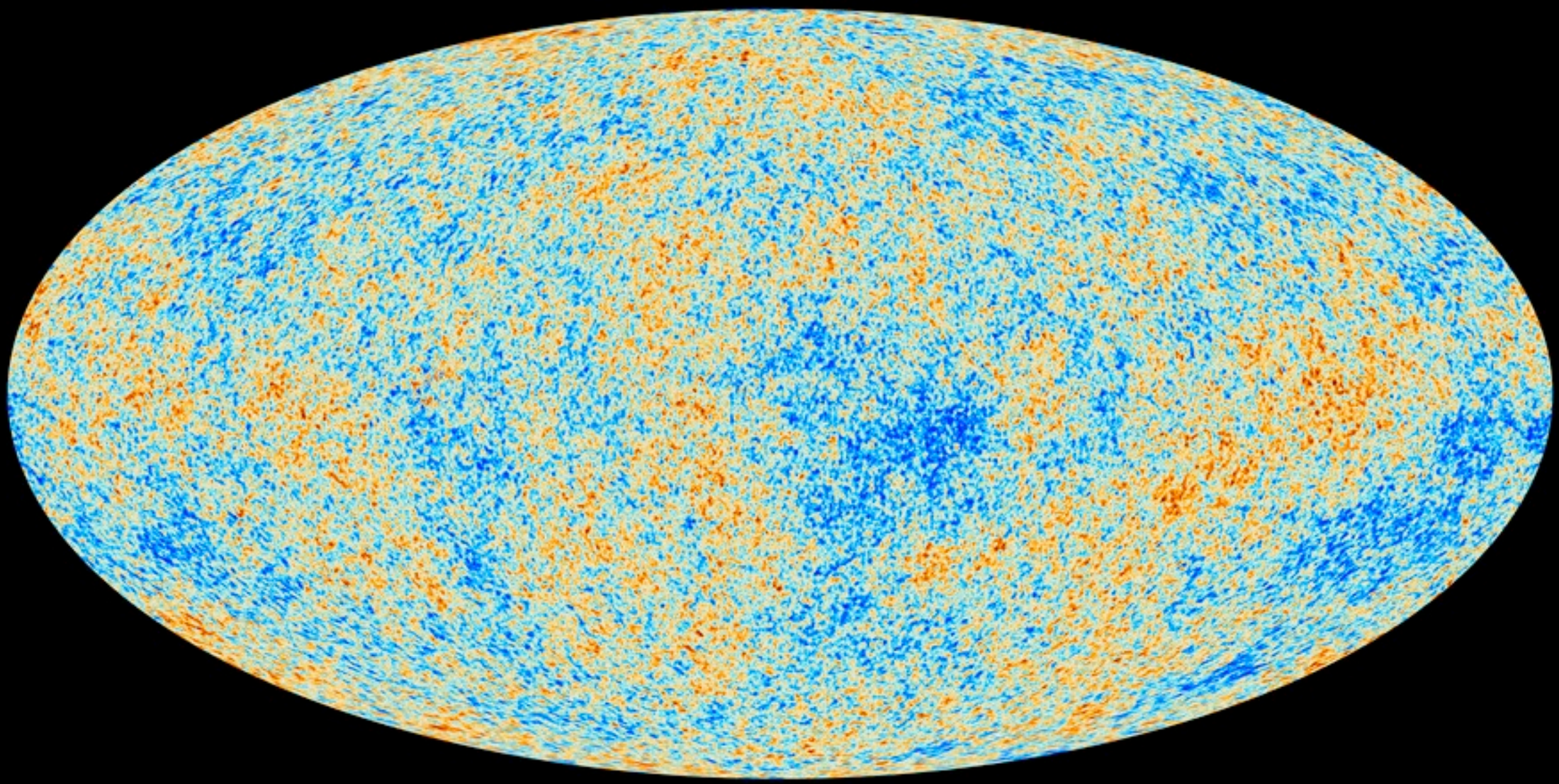
Argonne NATIONAL LABORATORY

Planck: the CMB satellite mission was launched in 2009

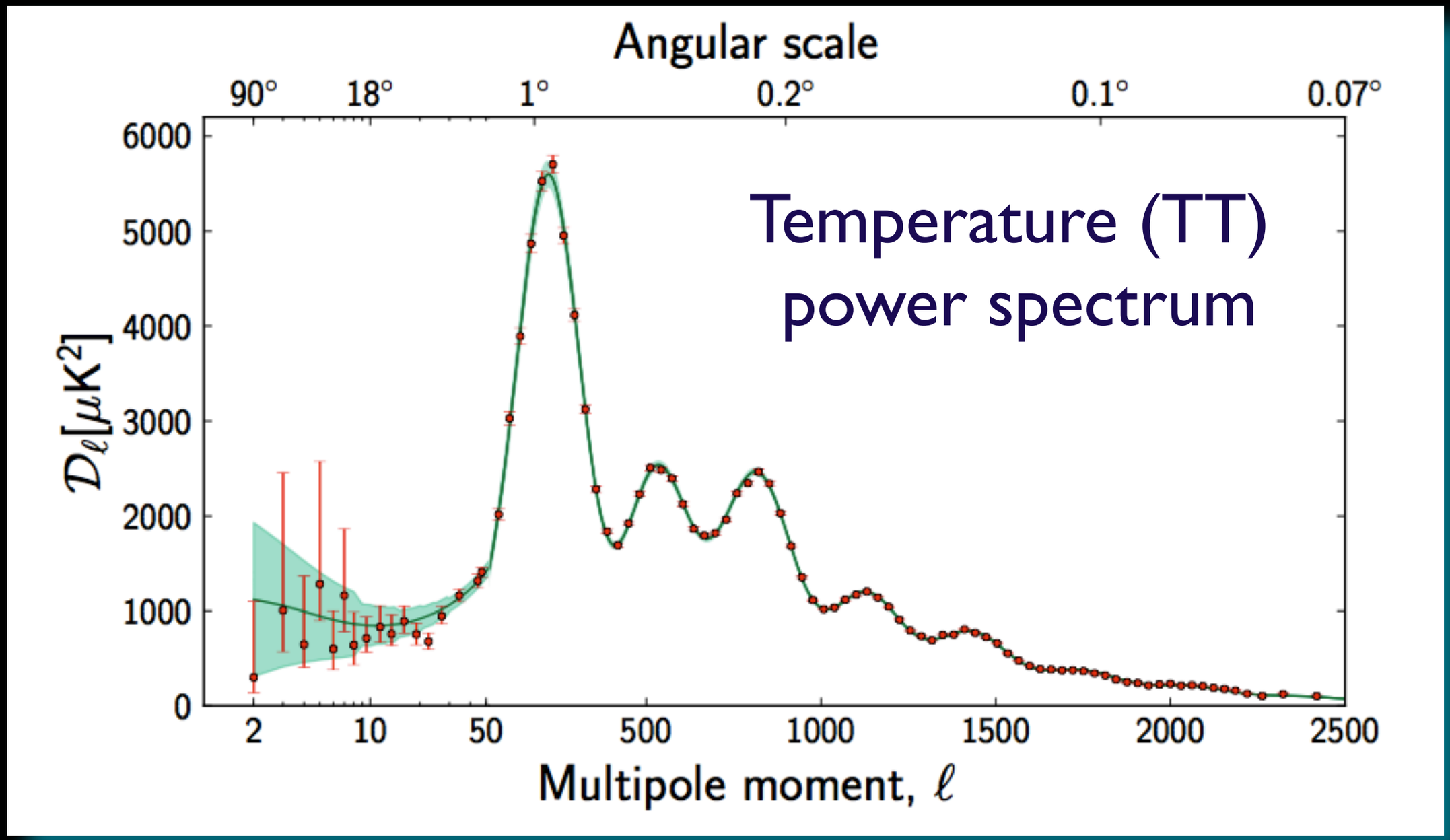


.. the first cosmological results came out in March 2013

Planck observes the full CMB sky at ~ 0.1 degree angular resolution



The CMB power spectrum from Planck shows seven acoustic peaks.



To obtain CMB-only cosmological constraints Planck needs to use:

Polarization to constrain optical depth of reionization:

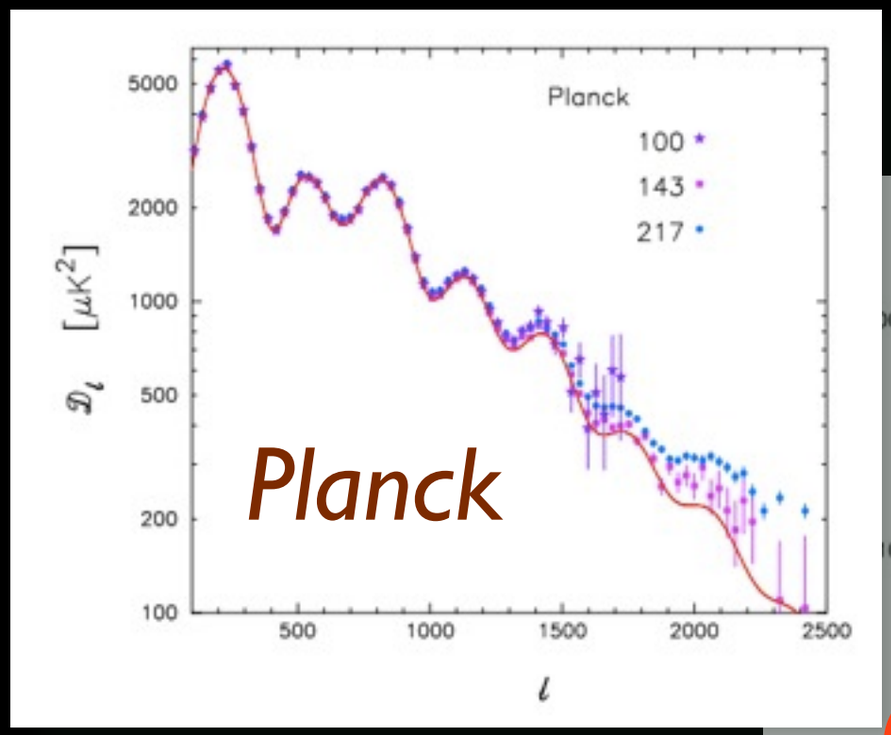
Low multipole polarization spectra from WMAP 9 year observations (WP) .

Higher resolution power spectrum to constrain foregrounds:

High multipole spectra from the Atacama Cosmology Telescope (ACT) and the South Pole Telescope (SPT) (highL)

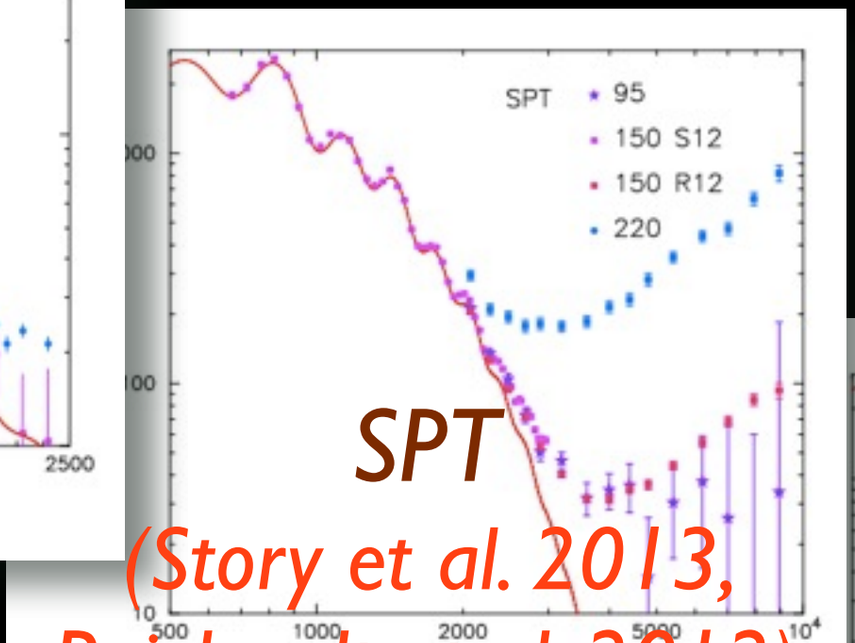
Most constraints come from:
Planck + WP + highL

High resolution spectra help constrain foreground contamination



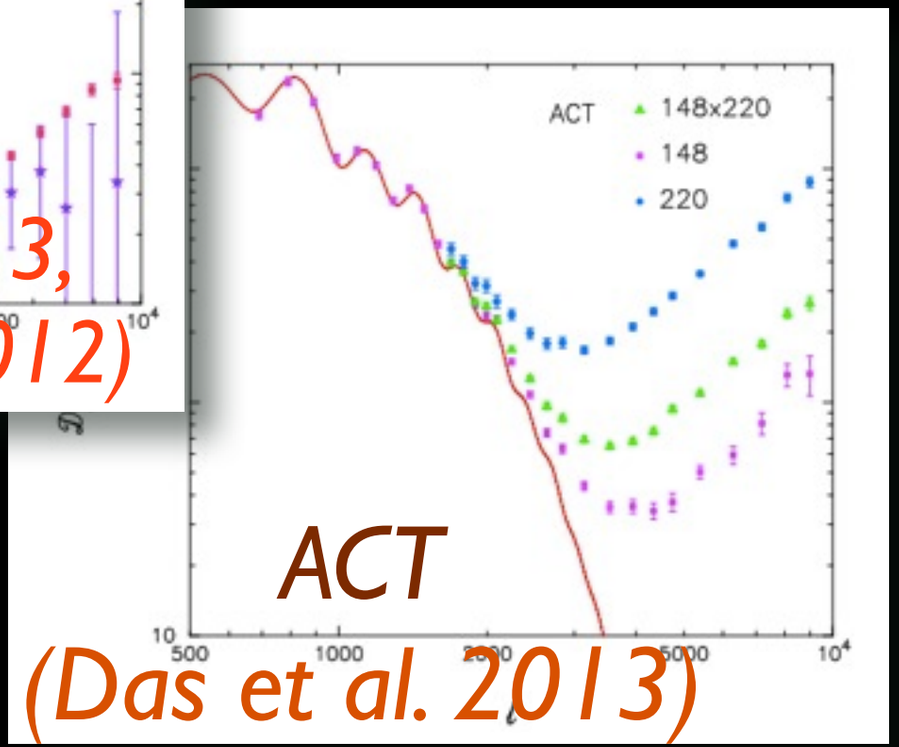
Planck

2 - 2500



SPT

(Story et al. 2013, Reichardt et al. 2012)



ACT

(Das et al. 2013)

500 - 10,000

Most constraints come from:
Planck + WP + highL

How does the CMB probe neutrino physics?

CMB is mainly sensitive to:

$\sum m_\nu$ Total mass in neutrinos

$N_{\rm eff}$ Effective number of relativistic species in the early universe *(3.046 if only 3 neutrinos)*

Total mass in neutrinos affect the CMB power spectrum in mainly two ways:

$$\sum m_\nu > 0.06 \text{ eV (NH) or } 0.1 \text{ eV (IH)}$$

1. Early/Late Integrated Sachs-Wolfe (ISW) Effect

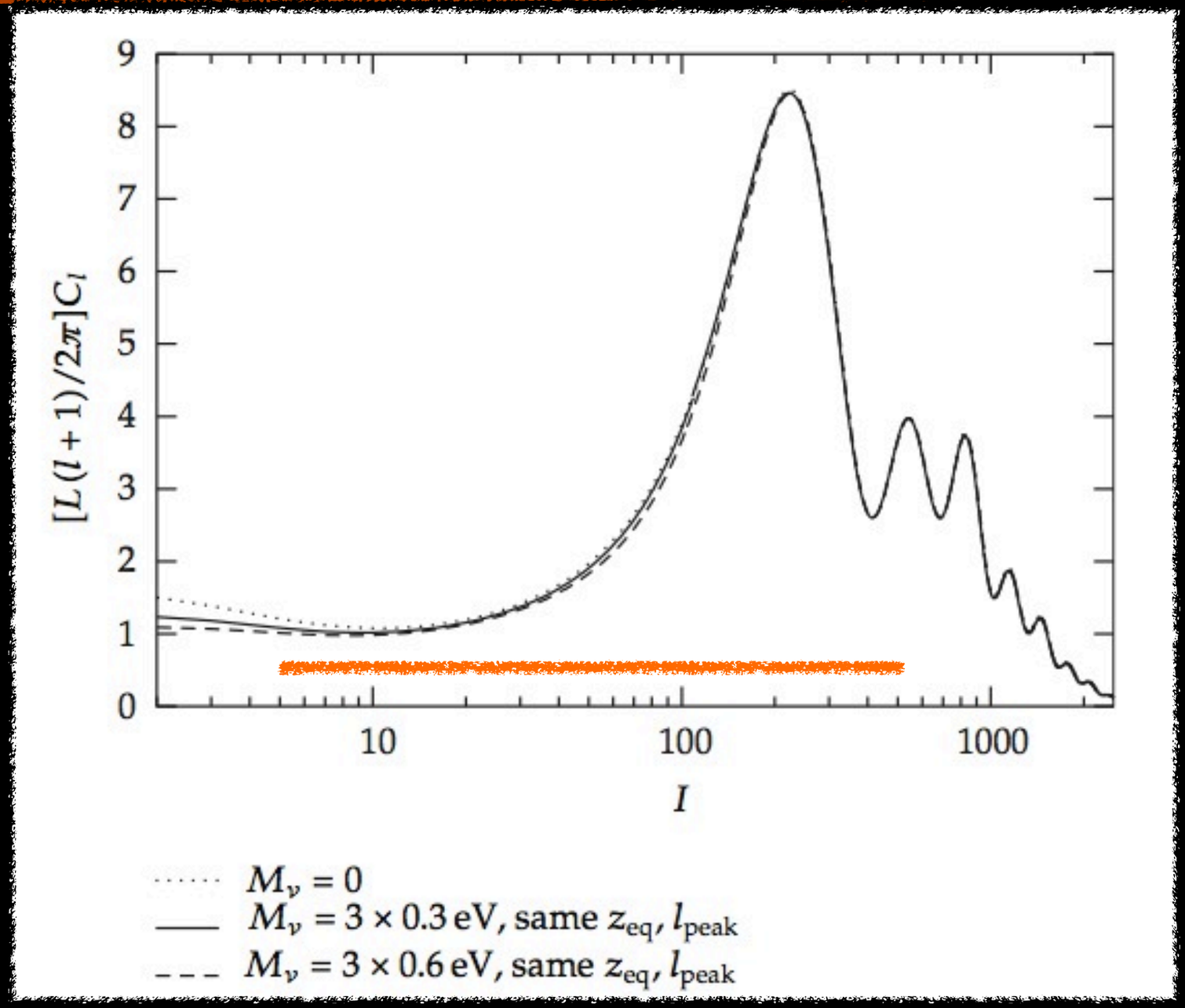
When neutrinos become non-relativistic, they reduce the time variation of the gravitational potential inside the Hubble radius. This affects the photon temperature through the early ISW effect and leads to a depletion in the temperature spectrum on multipoles $20 < l < 500$.

The late ISW effect happens due to decay of potentials due to accelerated expansion in recent past ($5 < l < 50$). Massive neutrinos contribute to the total matter density and shifts the balance between dark energy density and matter density.

Total mass in neutrinos affect the CMB power spectrum in mainly two ways:

$$\sum m_\nu > 0.06 \text{ eV (NH) or } 0.1 \text{ eV (IH)}$$

1. Early/Late Integrated Sachs-Wolfe (ISW) Effect

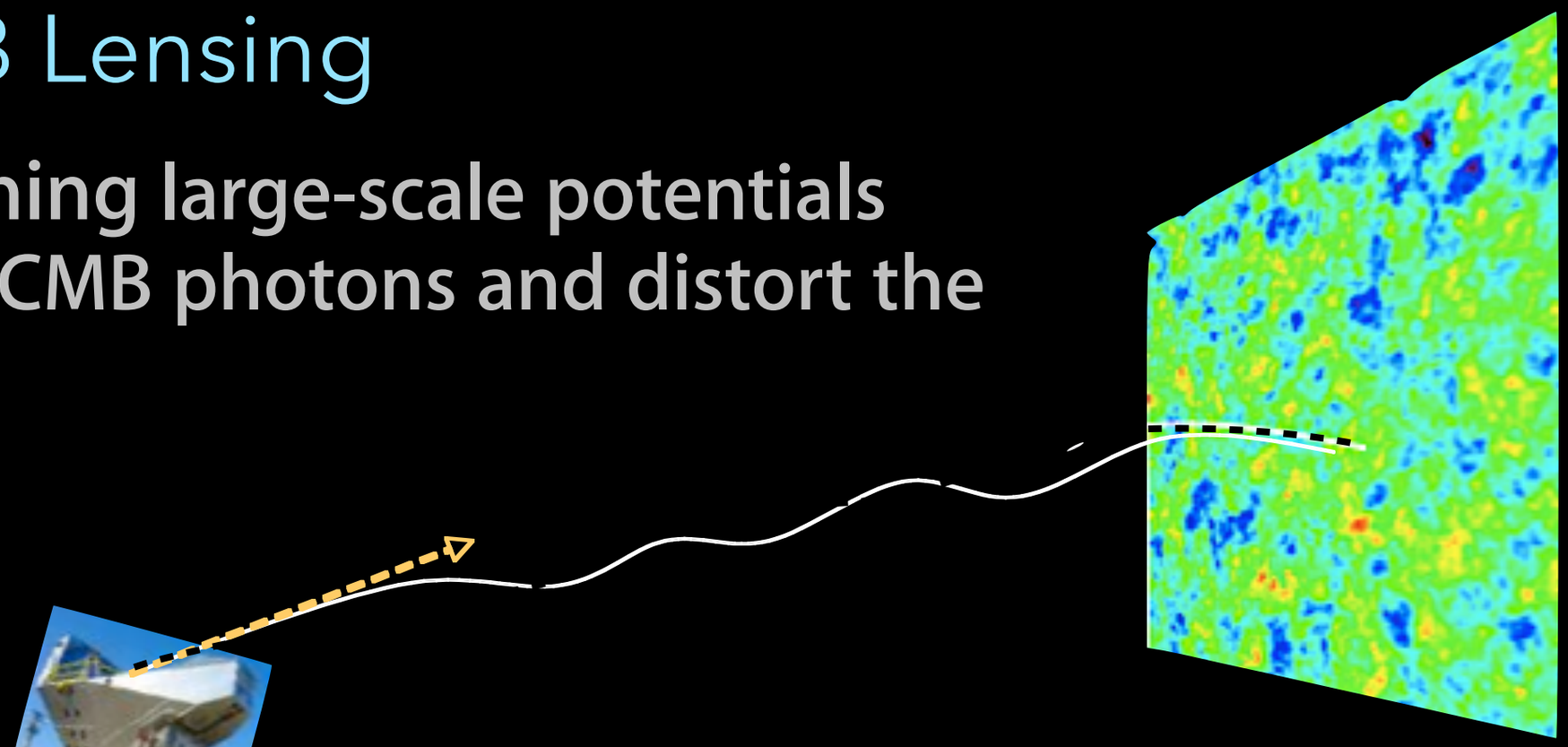


Total mass in neutrinos affect the CMB power spectrum in mainly two ways:

$$\sum m_\nu > 0.06 \text{ eV (NH) or } 0.1 \text{ eV (IH)}$$

2. CMB Lensing

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

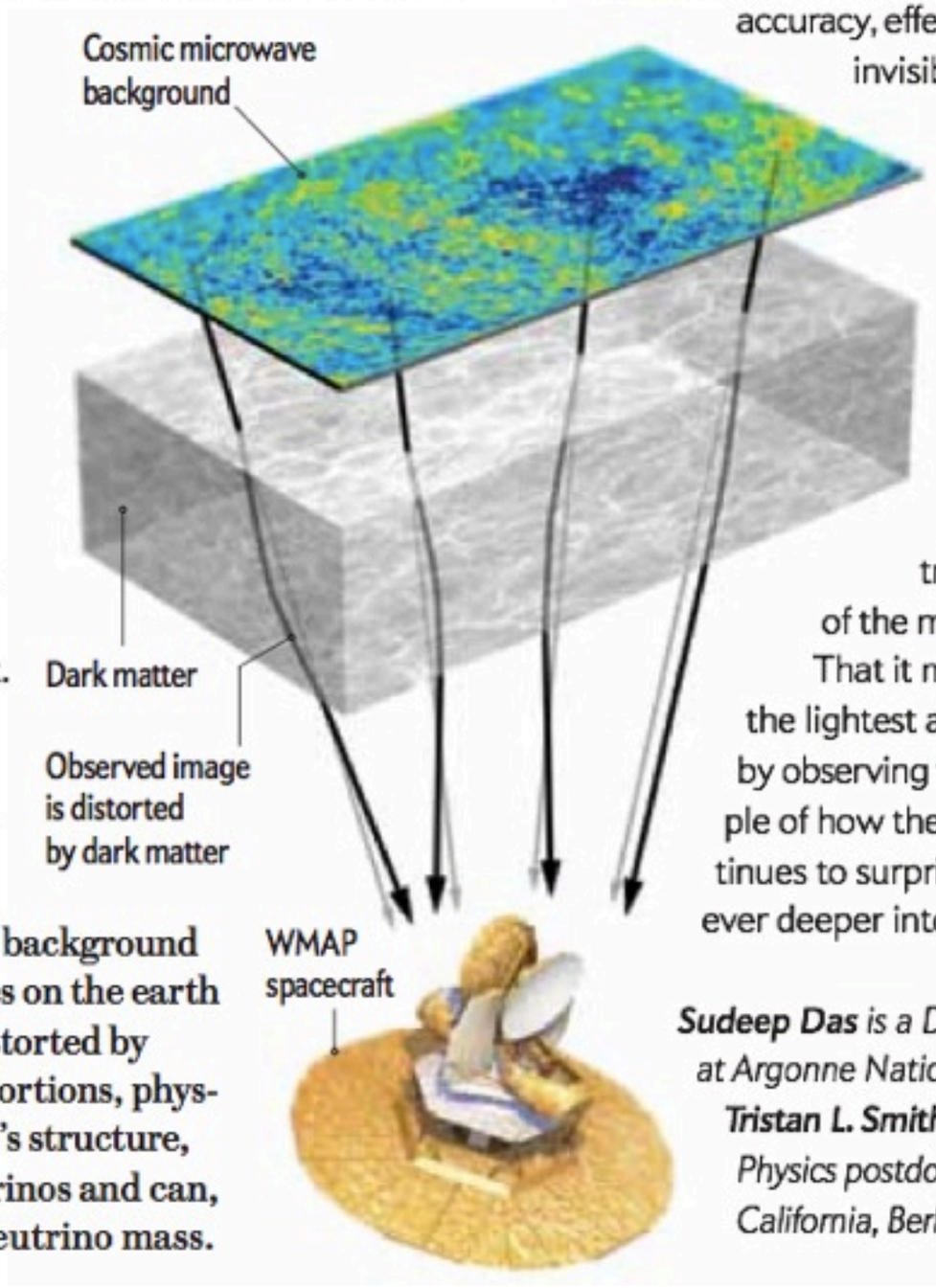


The RMS deflection is about 2.7 arcmins, but the deflections are coherent on degree scales.

Gravitational lensing of the CMB

particle soup were amplified; in regions of above-average density, gravity tried to pull more material in.

Dark matter, the essentially invisible stuff that accounts for a goodly portion of the universe's mass, collapsed into clumps first because it only interacts through gravity. These initial clumps of dark matter formed the seeds of the galaxies and the clusters of galaxies that we see today. Neutrinos, being extremely light, began to clump somewhat later on in the universe's development. In fact, by zipping so freely through the cosmos, neutrinos have actually slowed the clump-



WARPED: Cosmic microwave background radiation collected by telescopes on the earth and in space has been subtly distorted by dark matter. By tracing the distortions, physicists can chart the dark matter's structure, which has been shaped by neutrinos and can, in turn, place strict limits on neutrino mass.

will enable us to measure the lensing distortions to very high accuracy, effectively mapping out the otherwise invisible dark matter. If the distribution of dark matter is confined to sharp-edged structures separated by voids, we can infer that the neutrino masses are small; if instead the edges are blurred, we will know that the neutrino masses are larger. The new generation of CMB experiments should allow us to pin down the combined masses of the three neutrino types to within one five-millionth of the mass of the electron.

That it may be possible to measure the mass of the lightest and most elusive of subatomic particles by observing the entire universe is just another example of how the study of physics, across all scales, continues to surprise and inspire astrophysicists to delve ever deeper into the workings of the natural world.

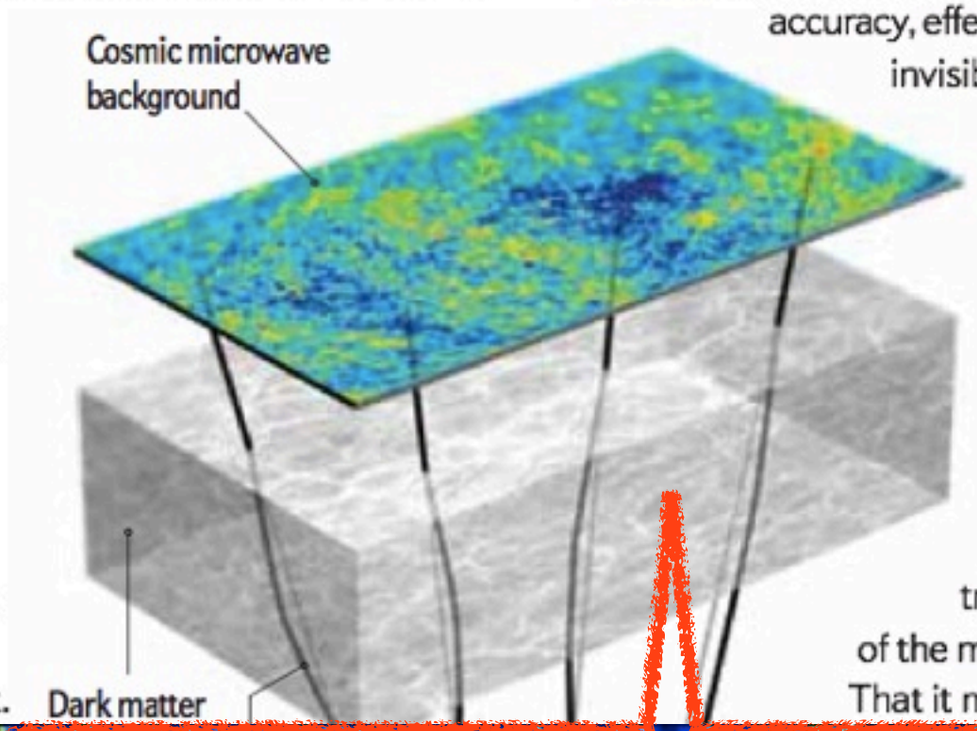
Sudeep Das *is a David Schramm postdoctoral fellow at Argonne National Laboratory.*

Tristan L. Smith *is a Berkeley Center for Cosmological Physics postdoctoral fellow at the University of California, Berkeley.*

Gravitational lensing of the CMB

particle soup were amplified; in regions of above-average density, gravity tried to pull more material in.

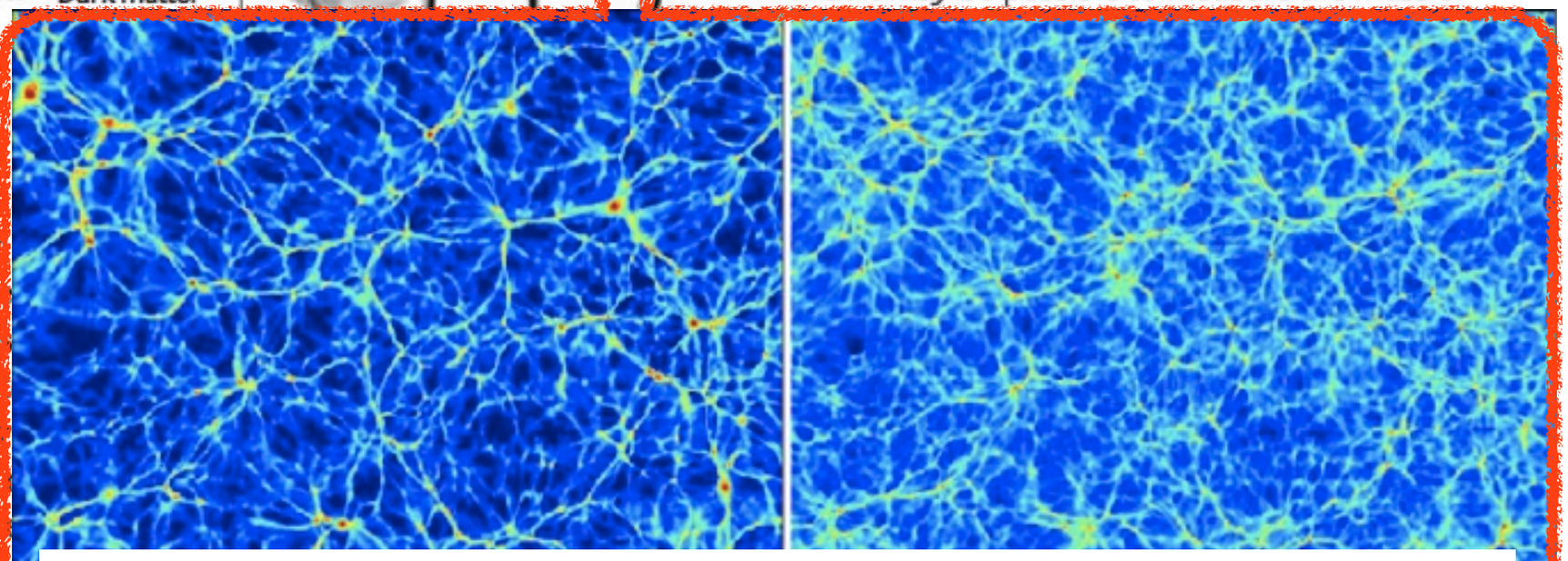
Dark matter, the essentially invisible stuff that accounts for a goodly portion of the universe's mass, collapsed into clumps first because it only interacts through gravity. These initial clumps of dark matter formed the seeds of the galaxies and the clusters of galaxies that we see today. Neutrinos, being extremely light, began to clump somewhat later on in the universe's development. In fact, by zipping so freely through the cosmos, neutrinos have actually slowed the clump



WARPED: Cosmic microwave radiation collected by telescop and in space has been subtly di dark matter. By tracing the dis icists can chart the dark matte which has been shaped by neut in turn, place strict limits on n

will enable us to measure the lensing distortions to very high accuracy, effectively mapping out the otherwise invisible dark matter. If the distribution of dark matter is confined to sharp-edged structures separated by voids, we can infer that the neutrino masses are small; if instead the edges are blurred, we will know that the neutrino masses are larger. The new generation of CMB experiments should allow us to pin down the combined masses of the three neutrino types to within one five-millionth of the mass of the electron.

That it may be possible to measure the mass of

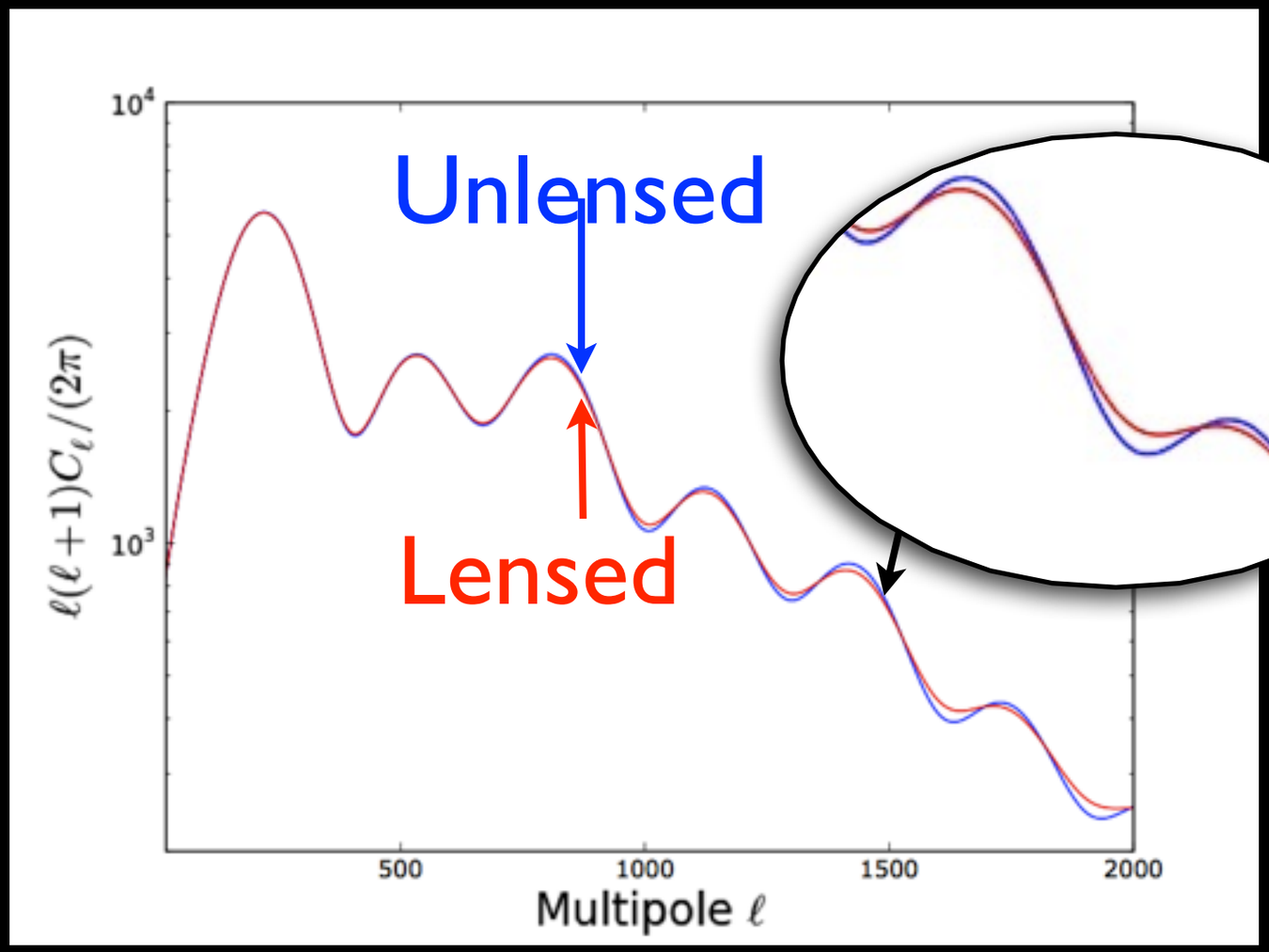


Left: dark matter clustering with zero neutrino mass, right: same with sum of three neutrino masses equal to 250000th that of the electron. Massive neutrinos make structure in the universe more blurry. From Agarwal and Feldmann (2012)

Total mass in neutrinos affect the CMB power spectrum in mainly two ways:

$$\sum m_\nu > 0.06 \text{ eV (NH) or } 0.1 \text{ eV (IH)}$$

2. CMB Lensing



Lensing smears acoustic peaks. Higher neutrino mass -> less amplitude of matter fluctuations -> less lensing -> less smearing

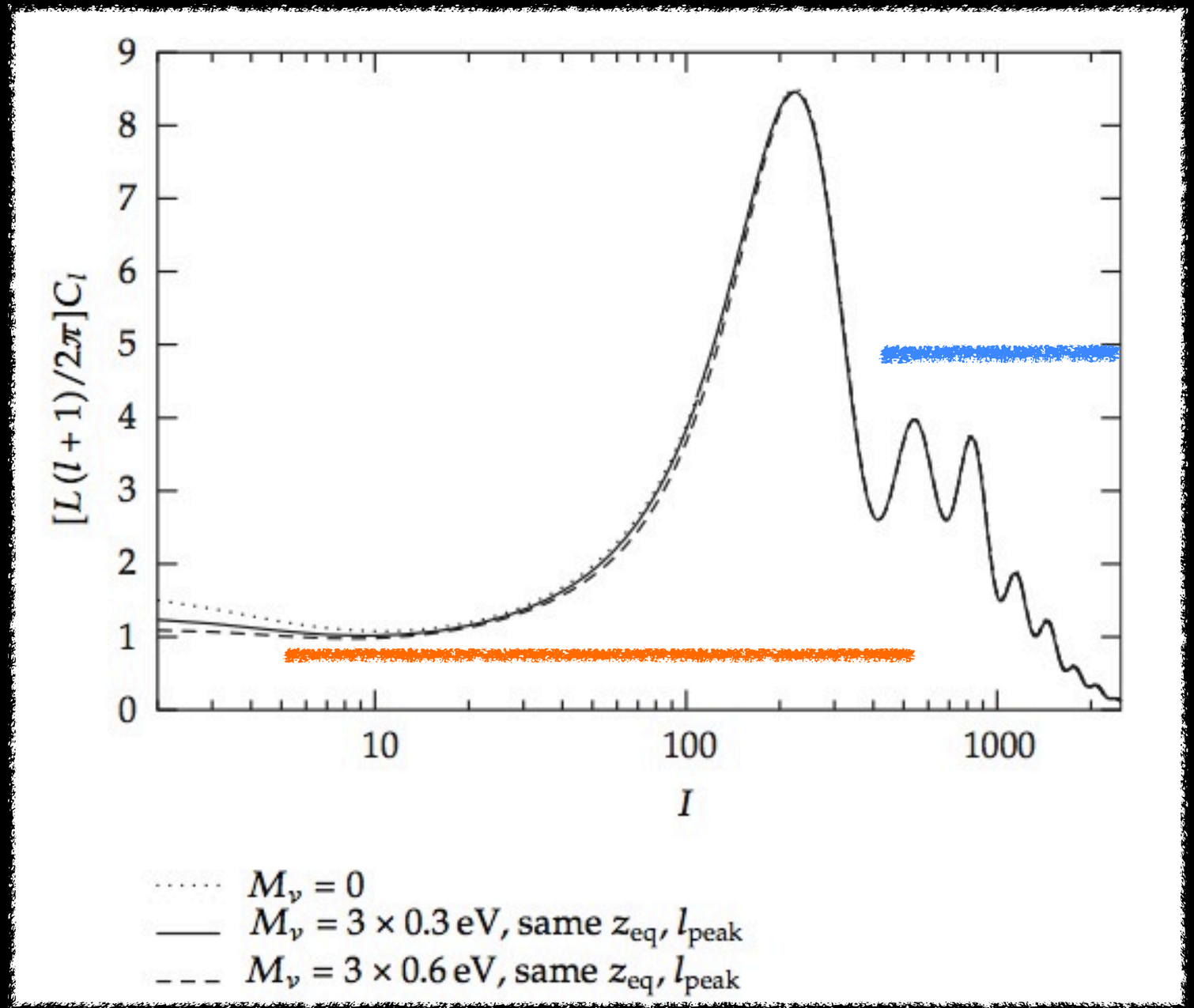
Total mass in neutrinos affect the CMB power spectrum in mainly two ways:

$$\sum m_\nu > 0.06 \text{ eV (NH) or } 0.1 \text{ eV (IH)}$$

1. ISW

2. LENSING

Most of Planck's power in constraining neutrino mass comes from lensing.



Constraint from the CMB power spectrum alone, and CMB + BAO

CMB ALONE

$$\sum m_\nu < 0.66\,\mathrm{eV} \quad (95\%;\ \textit{Planck}+\mathrm{WP}+\mathrm{highL}).$$

Apart from its impact on the early-ISW effect and lensing potential, the total neutrino mass affects the angular-diameter distance to last scattering, and can be constrained through the angular scale of the first acoustic peak. However, this is degenerate with dark energy density. Low redshift measurements of angular diameter distance through Baryon Acoustic Oscillations (BAO) alleviates this degeneracy and gives a tighter constraint:

CMB + BAO

$$\sum m_\nu < 0.23\,\mathrm{eV} \quad (95\%;\ \textit{Planck}+\mathrm{WP}+\mathrm{highL}+\mathrm{BAO}).$$

Constraining N_{eff} — the effective number of relativistic particles.

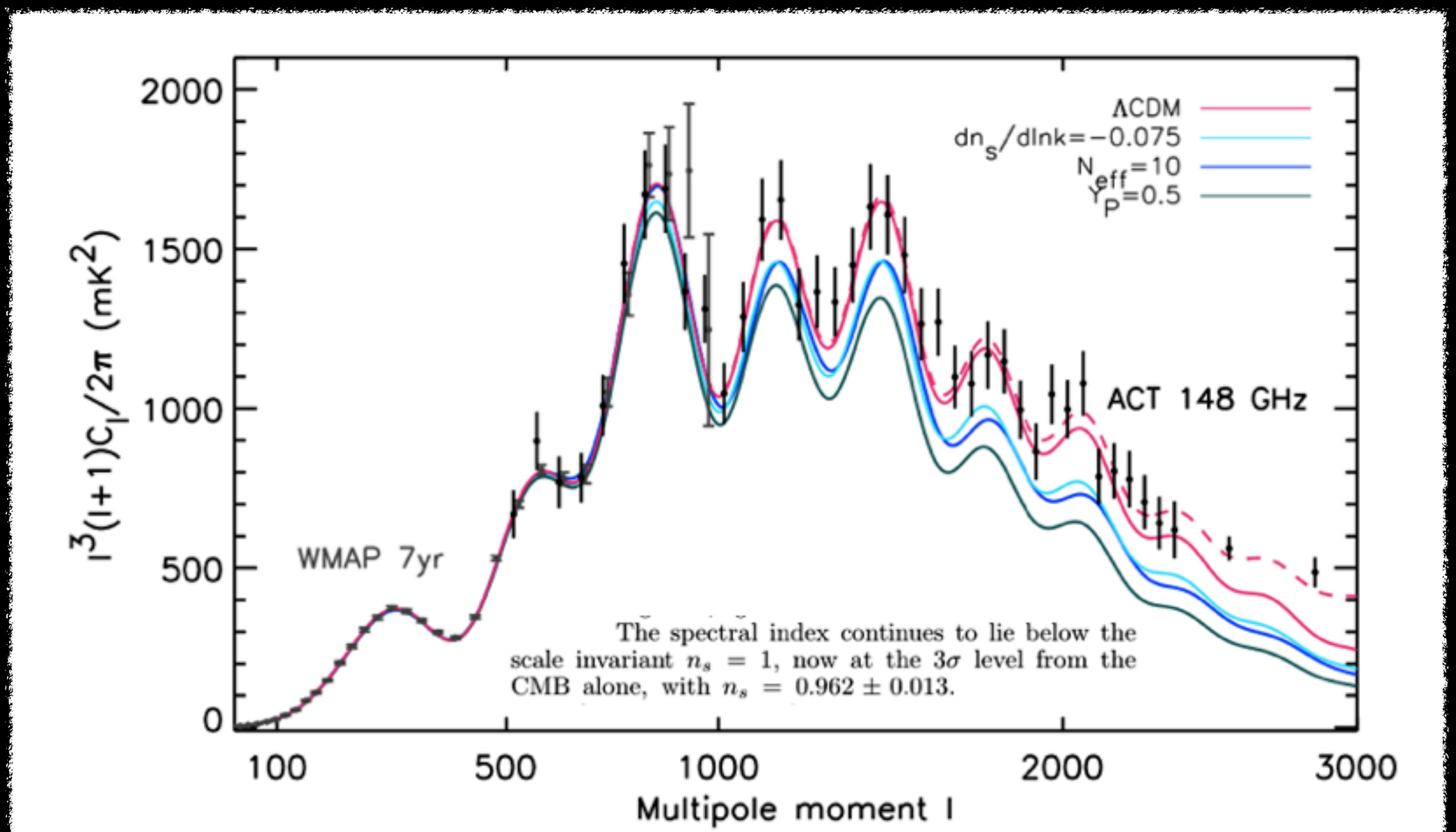
The energy density in neutrino-like relativistic particles in the early universe can be parameterized as:

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

where N_{eff} is 3.046 in the standard picture where the only relativistic particles are 3 species of neutrinos.

Recently, there has been some mild preference for Neff > 3.046 from recent CMB anisotropy measurements (*Komatsu et al. 2011; Dunkley et al. 2011; Keisler et al. 2011; Archidiacono et al. 2011; Smith et al. 2011, Hinshaw et al. 2012; Hou et al. 2012*).

Increasing N_{eff} while keeping the position and height of the first CMB peak fixed leads to increased damping on small scales



Dunkley et al. (2010)

Planck's measurements of the high order peaks lets us constrain N_{eff}.

CMB ALONE

$N_{\rm eff} = 3.36^{+0.68}_{-0.64}$ (95%; *Planck*+WP+highL).

CMB + BAO

Increasing Neff at fixed θ_* and z_eq necessarily raises the expansion rate at low redshifts. Combining CMB with distance measurements can therefore improve constraints

$N_{\rm eff} = 3.30^{+0.54}_{-0.51}$ (95%; *Planck*+WP+highL+BAO).

$H_0 = (73.8 \pm 2.4)\,{\rm km\,s^{-1}\,Mpc^{-1}}$ (Cepheids+SNe Ia),

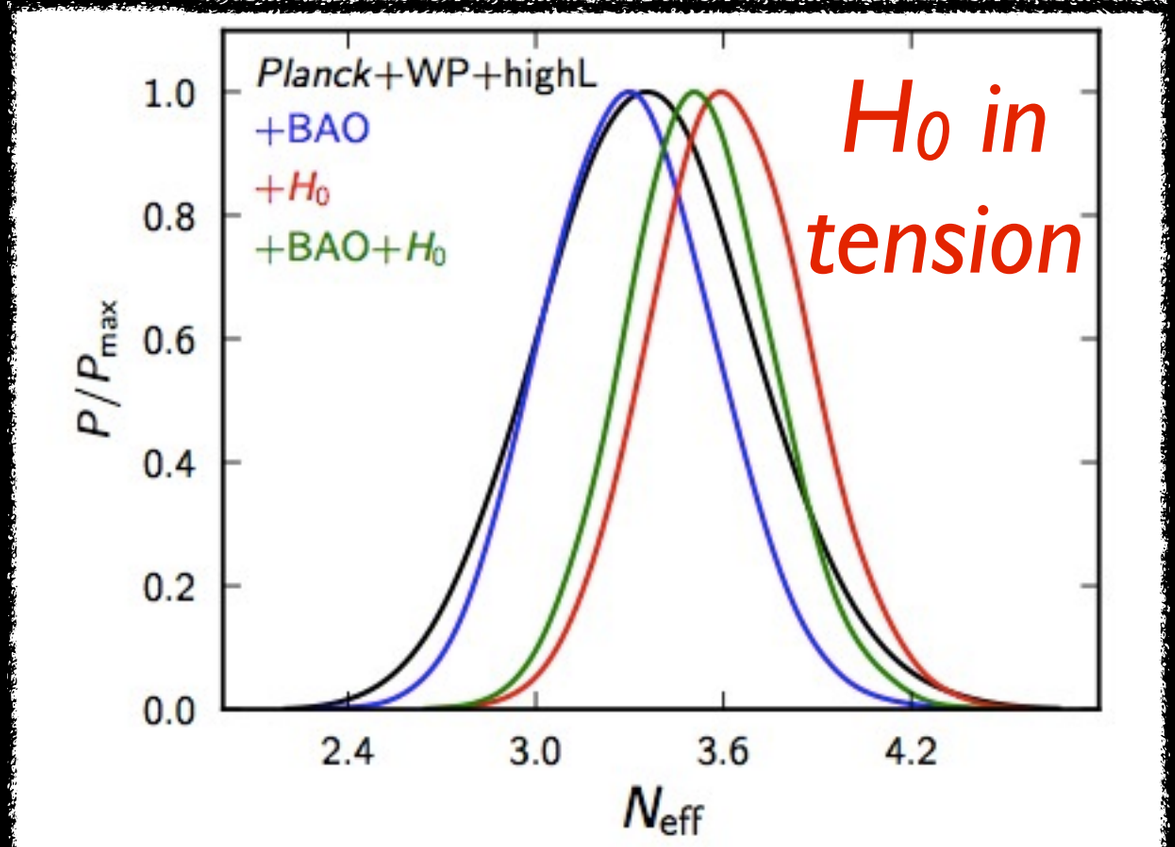
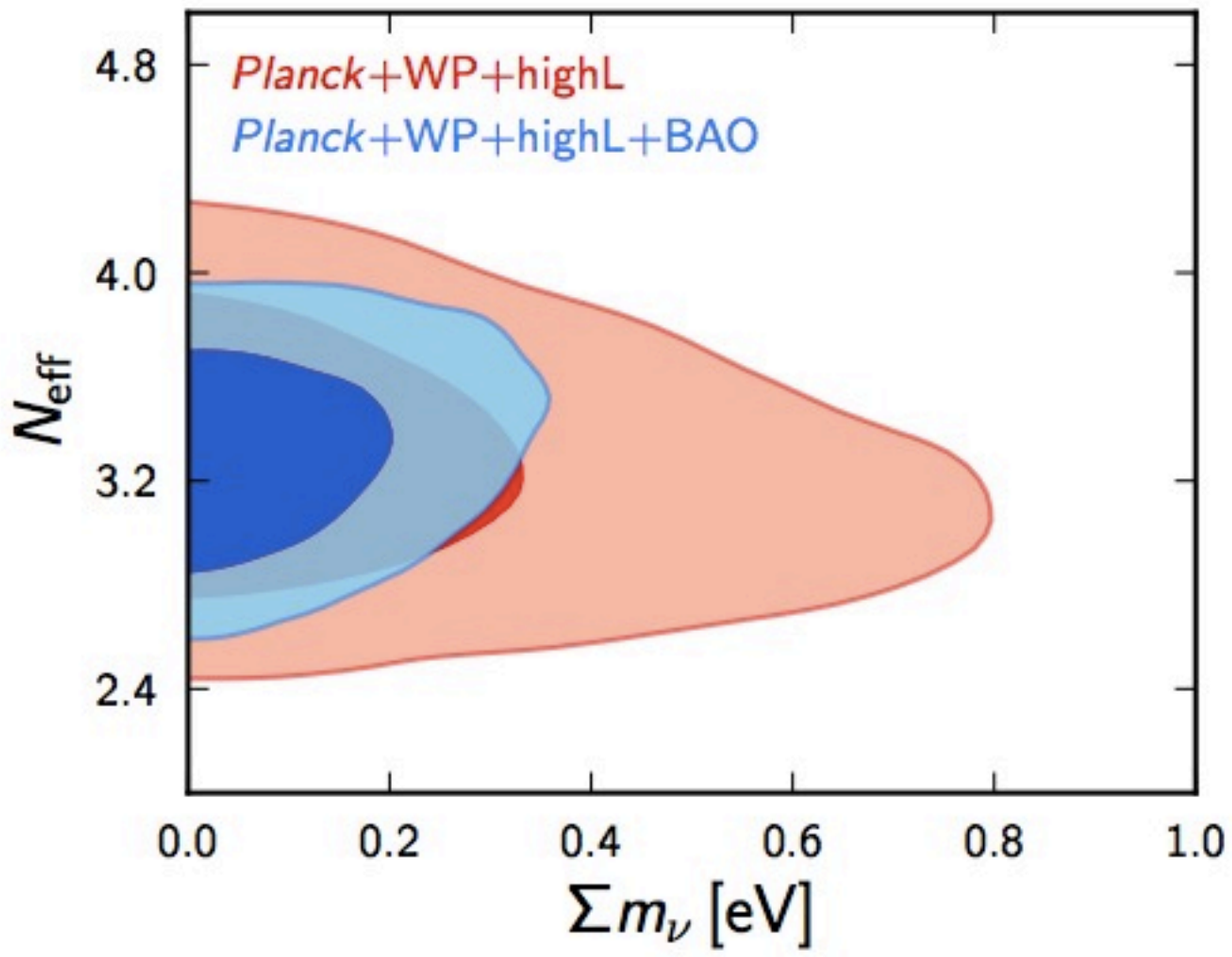


Fig. 27. Marginalized posterior distribution of $N_{\rm eff}$ for *Planck*+WP+highL (black) and additionally BAO (blue), the H_0 measurement (red), and both BAO and H_0 (green).

The effects of Neff and mass are distinct enough on the CMB that they can be jointly constrained.



CMB ALONE

$$\left.\begin{aligned} N_{\rm eff} &= 3.29^{+0.67}_{-0.64} \\ \textstyle\sum m_\nu &< 0.60\,{\rm eV} \end{aligned}\right\} \quad (95\%;\ \textit{Planck}{+}{\rm WP}{+}{\rm highL}).$$

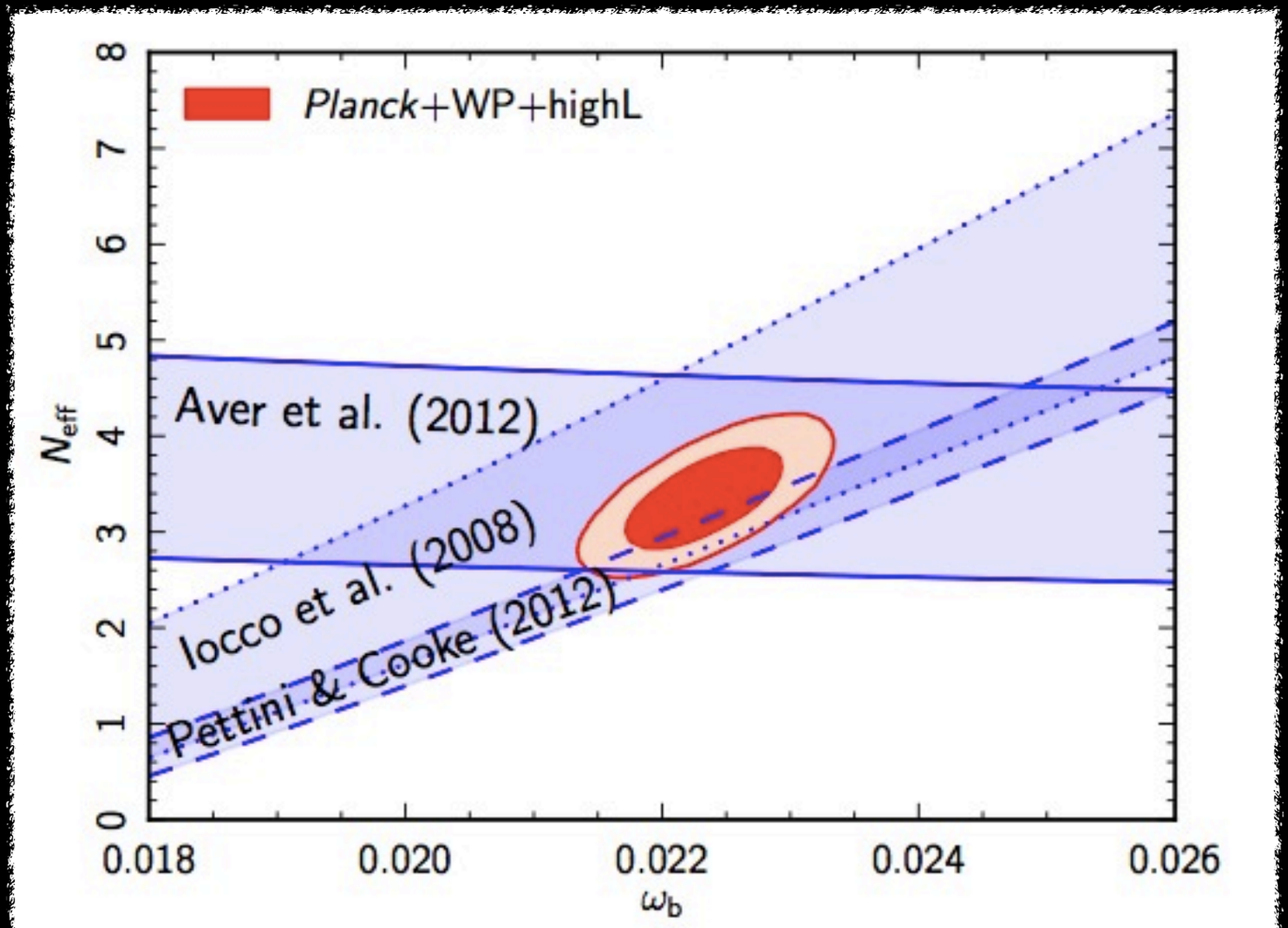
CMB + BAO

$$\left.\begin{aligned} N_{\rm eff} &= 3.32^{+0.54}_{-0.52} \\ \textstyle\sum m_\nu &< 0.28\,{\rm eV} \end{aligned}\right\} \quad (95\%;\ \textit{Planck}{+}{\rm WP}{+}{\rm highL}{+}{\rm BAO}).$$

(assumes degenerate eigenstates, and extra species as massless)

CMB, Neutrinos and Big Bang Nucleosynthesis

Add observed Helium and Deuterium abundances to CMB constraint:



$$N_{\rm eff} = \begin{cases} 3.41 \pm 0.30, & Y_{\rm P}\ \text{(Aver et al.)}, \\ 3.43 \pm 0.34, & y_{\rm DP}\ \text{(Iocco et al.)}, \\ 3.02 \pm 0.27, & y_{\rm DP}\ \text{(Pettini and Cooke)}. \end{cases}$$

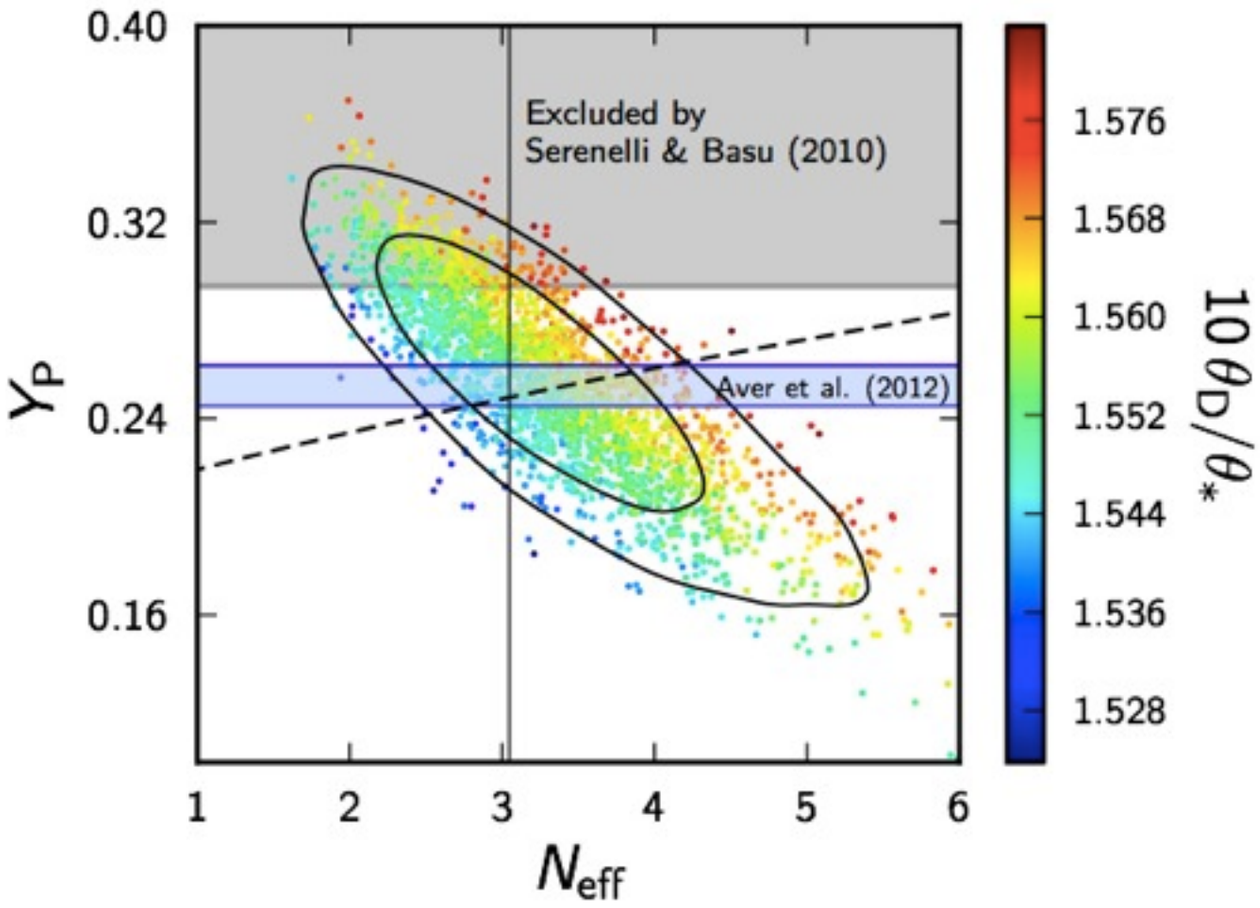
Combined

$N_{\rm eff} = 3.36 \pm 0.34$ (68%; *Planck*+WP+highL).

(assumes Y_p determined from Neff and w_b using BBN consistency relation).

CMB, Neutrinos and Big Bang Nucleosynthesis

Let both Helium fraction and Neff be constrained using CMB



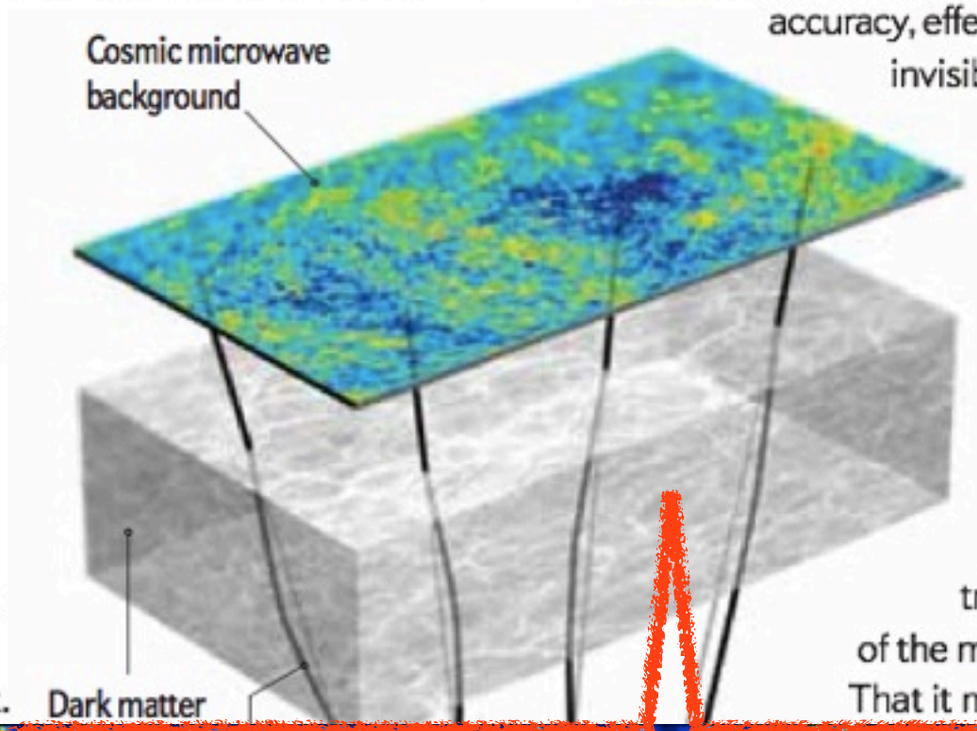
$$N_{\rm eff} = 3.33^{+0.59}_{-0.83} \quad (68\%;\ \textit{Planck}{+}\text{WP}{+}\text{highL}),$$
$$Y_{\rm P} = 0.254^{+0.041}_{-0.033} \quad (68\%;\ \textit{Planck}{+}\text{WP}{+}\text{highL}).$$

Fig. 32. 2D joint posterior distribution for $N_{\rm eff}$ and $Y_{\rm P}$ with both parameters varying freely, determined from *Planck*+WP+highL data. Samples are colour-coded by the value of the angular ratio $\theta_{\rm D}/\theta_*$, which is constant along the degeneracy direction. The $N_{\rm eff}$–$Y_{\rm P}$ relation from BBN theory is shown by the dashed curve. The vertical line shows the standard value $N_{\rm eff} = 3.046$. The region with $Y_{\rm P} > 0.294$ is highlighted in grey, delineating the region that exceeds the $2\,\sigma$ upper limit of the recent measurement of initial Solar helium abundance (Serenelli & Basu 2010), and the blue horizontal region is the 68% confidence region from the Aver et al. (2012) compilation of ^{4}He measurements.

Gravitational lensing of the CMB

particle soup were amplified; in regions of above-average density, gravity tried to pull more material in.

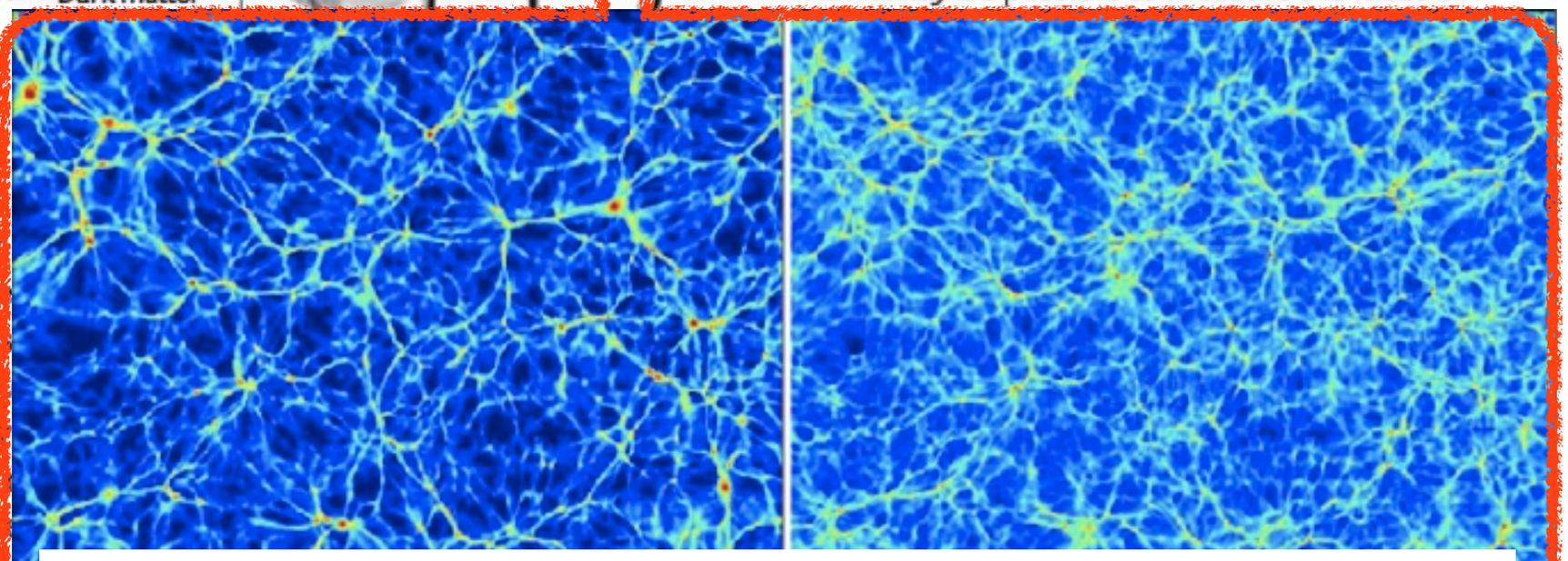
Dark matter, the essentially invisible stuff that accounts for a goodly portion of the universe's mass, collapsed into clumps first because it only interacts through gravity. These initial clumps of dark matter formed the seeds of the galaxies and the clusters of galaxies that we see today. Neutrinos, being extremely light, began to clump somewhat later on in the universe's development. In fact, by zipping so freely through the cosmos, neutrinos have actually slowed the clump



WARPED: Cosmic microwave radiation collected by telescop and in space has been subtly di dark matter. By tracing the dis icists can chart the dark matte which has been shaped by neut in turn, place strict limits on n

will enable us to measure the lensing distortions to very high accuracy, effectively mapping out the otherwise invisible dark matter. If the distribution of dark matter is confined to sharp-edged structures separated by voids, we can infer that the neutrino masses are small; if instead the edges are blurred, we will know that the neutrino masses are larger. The new generation of CMB experiments should allow us to pin down the combined masses of the three neutrino types to within one five-millionth of the mass of the electron.

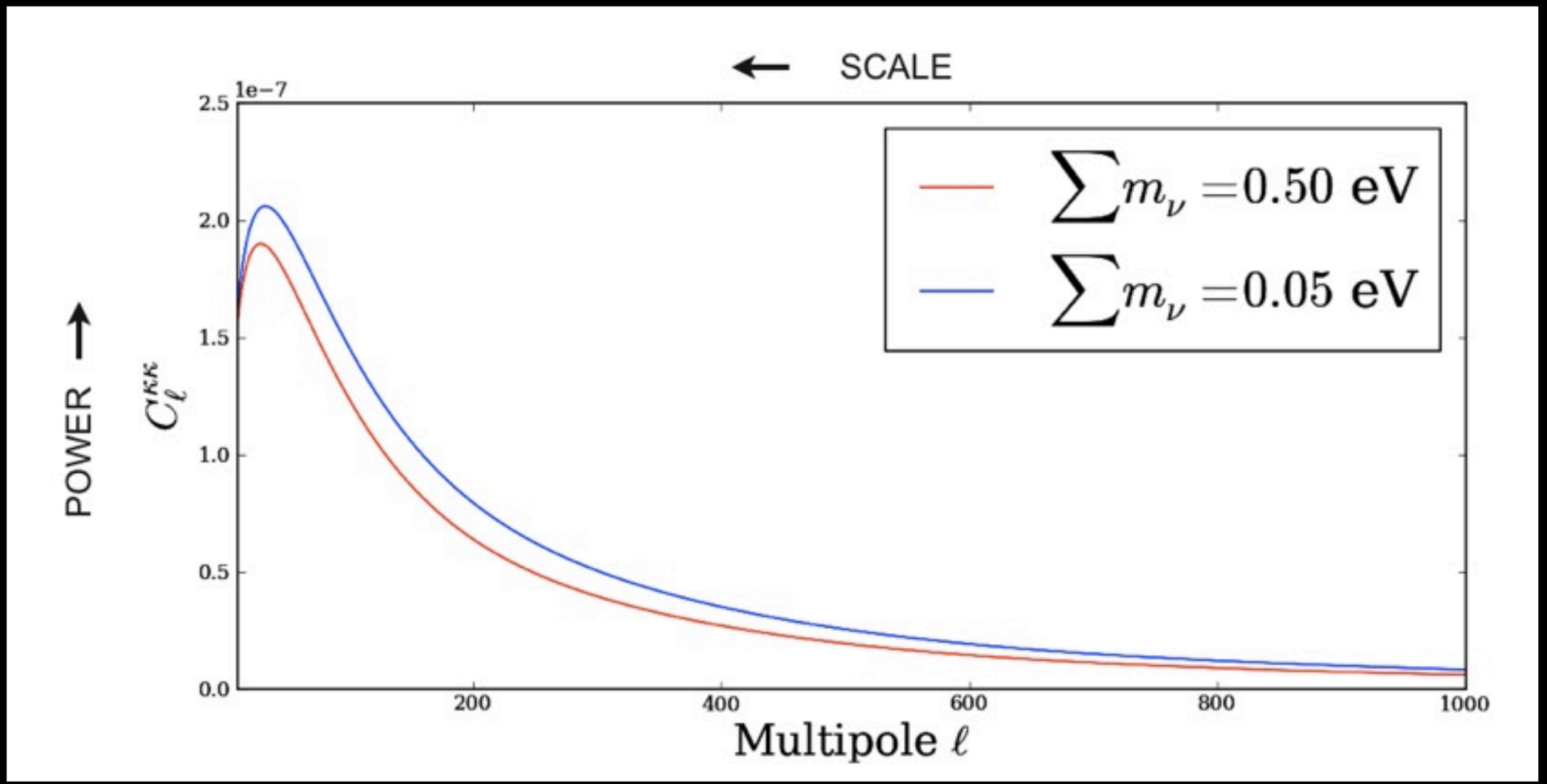
That it may be possible to measure the mass of



Left: dark matter clustering with zero neutrino mass, right: same with sum of three neutrino masses equal to 250000th that of the electron. Massive neutrinos make structure in the universe more blurry. From Agarwal and Feldmann (2012)

Future: CMB lensing from Planck polarization + high resolution CMB experiments.

Power spectrum of projected matter in the universe

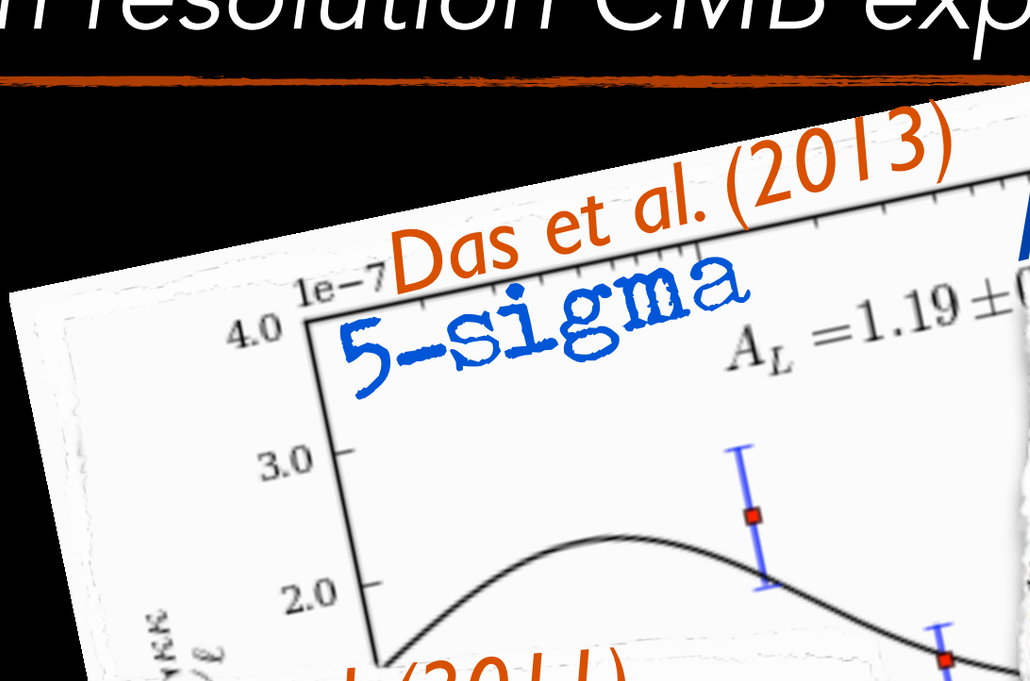


Future: CMB lensing from Planck polarization + high resolution CMB experiments.

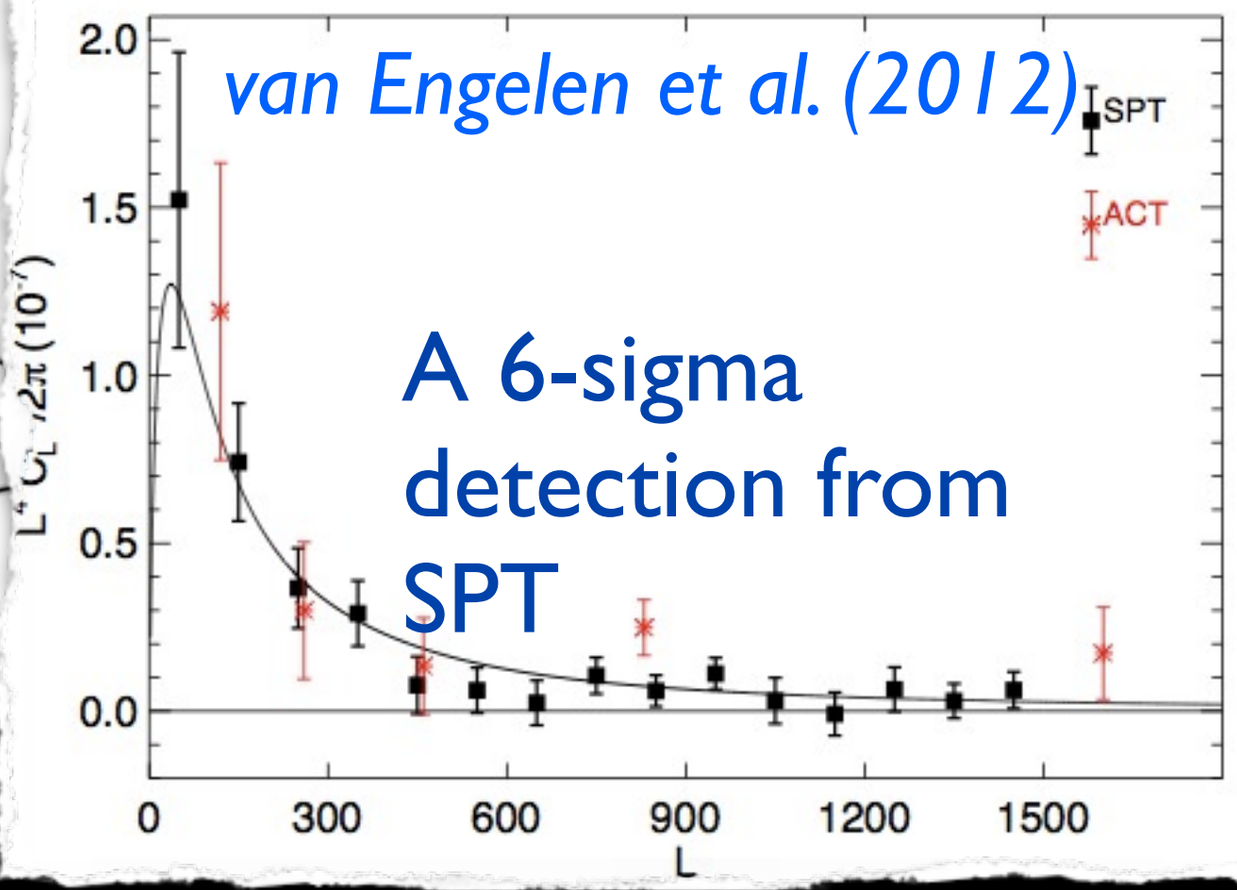
Das et al. (2013)

5-sigma

ACT+

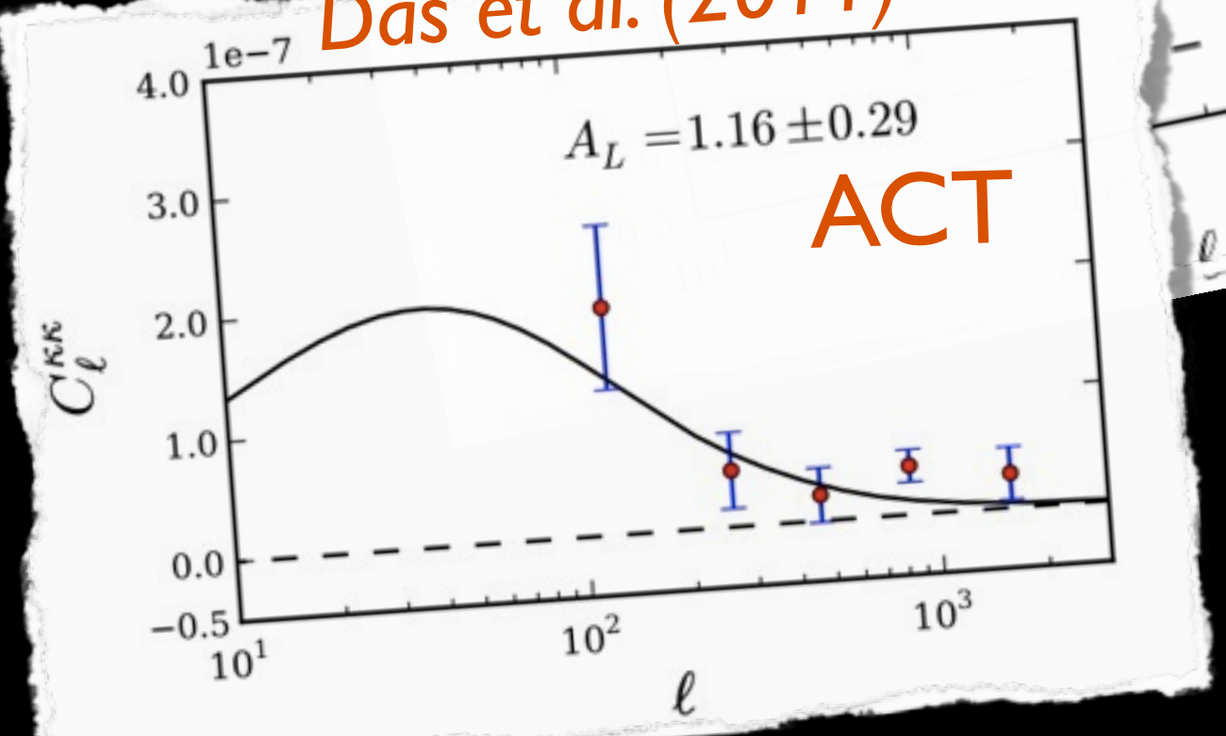


van Engelen et al. (2012)

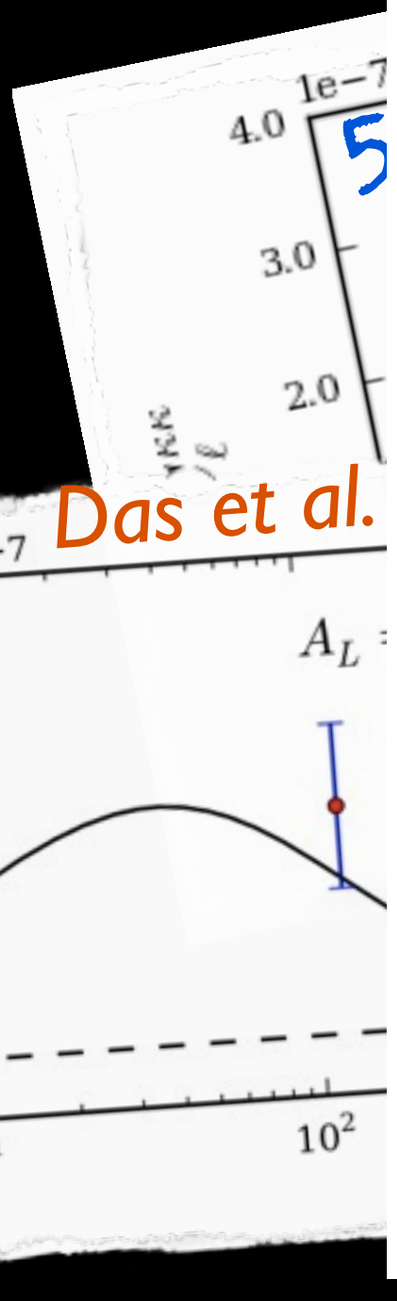


A 6-sigma detection from SPT

Das et al. (2011)



Future: CM… …olarization + high resolu…



Das et al.

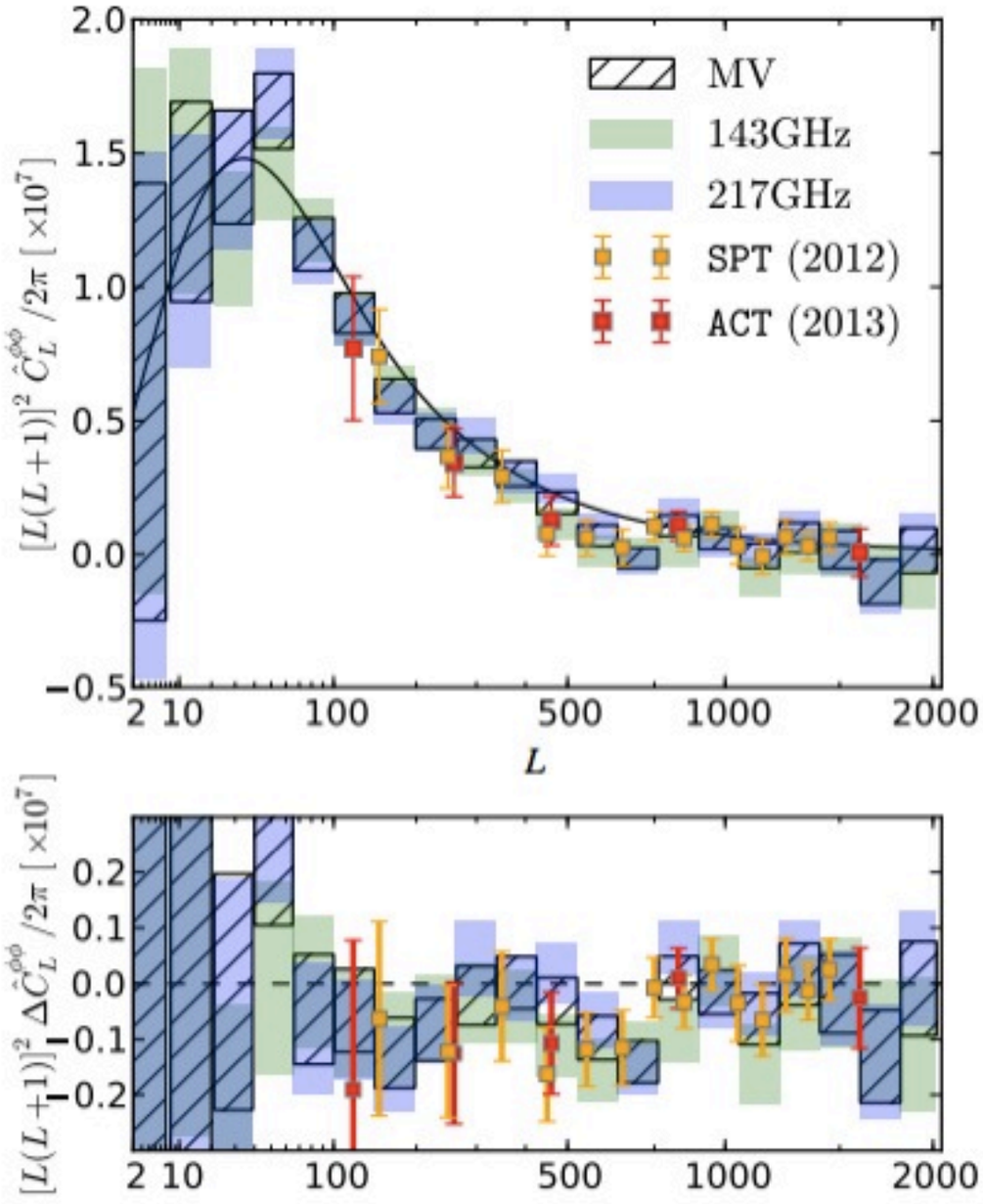
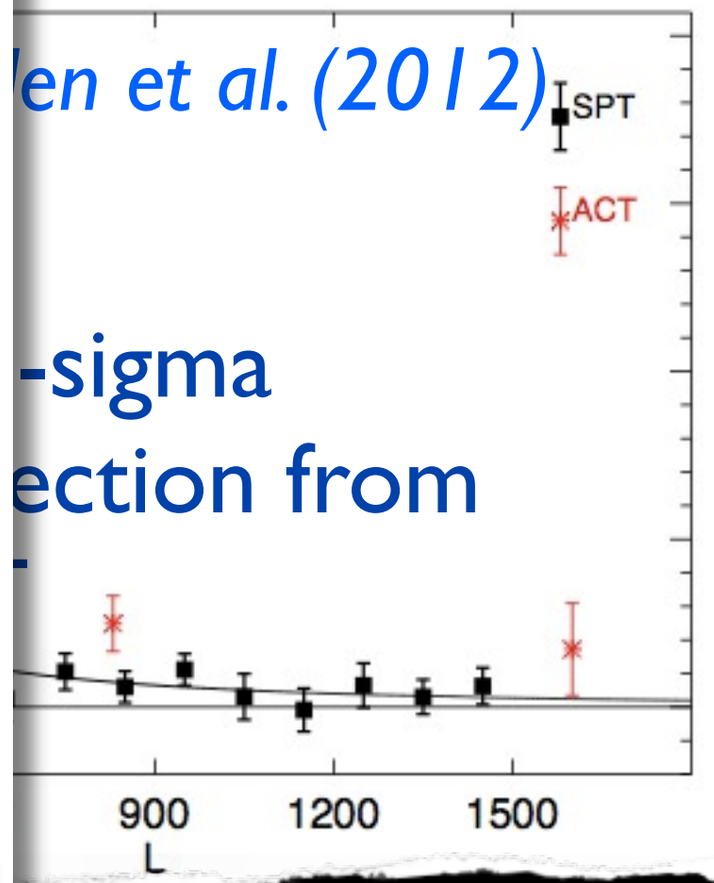


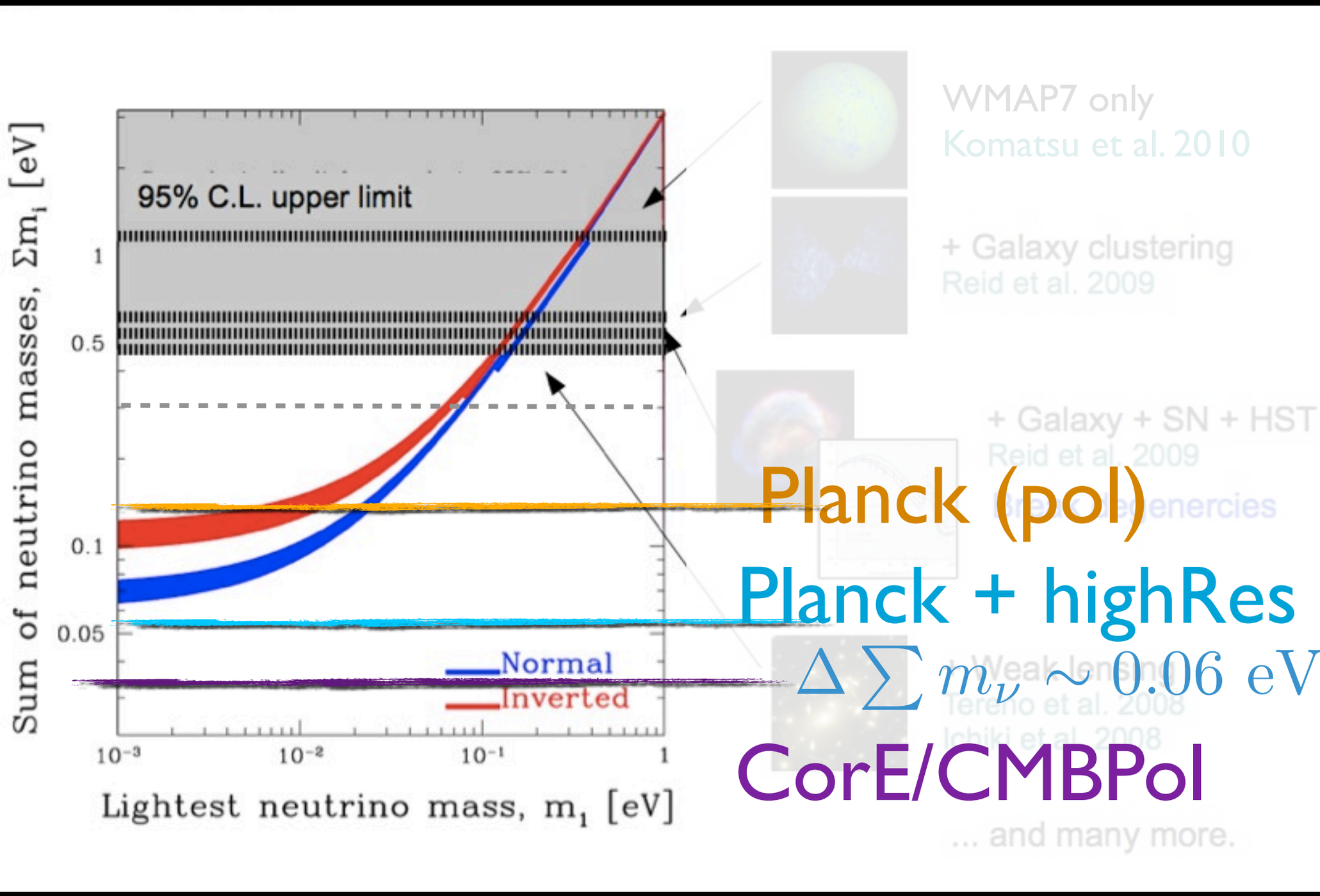
Fig. 11. Replotting of Fig. 10, removing 100 GHz for easier comparison of 143 and 217 GHz. Also plotted are the SPT bandpowers from van Engelen et al. (2012), and the ACT bandpowers from Das et al. (2013). All three experiments are very consistent. The lower panel shows the difference between the measured bandpowers and the fiducial best-fit ΛCDM model.



…len et al. (2012)

…-sigma
…ection from
…

Planck + high res experiments like PolarBear, ACTPol, SPTPol can tightly constrain neutrino mass



Conclusions

Planck + high resolution CMB experiments + BAO constrains neutrino mass sum to have an upper limit of 0.23 eV

Planck + high resolution CMB experiments + BAO do not find any strong evidence for extra relativistic species beyond 3 neutrinos.

Neutrino mass sum will be strongly constrained with CMB lensing (and large scale structure) in near future.