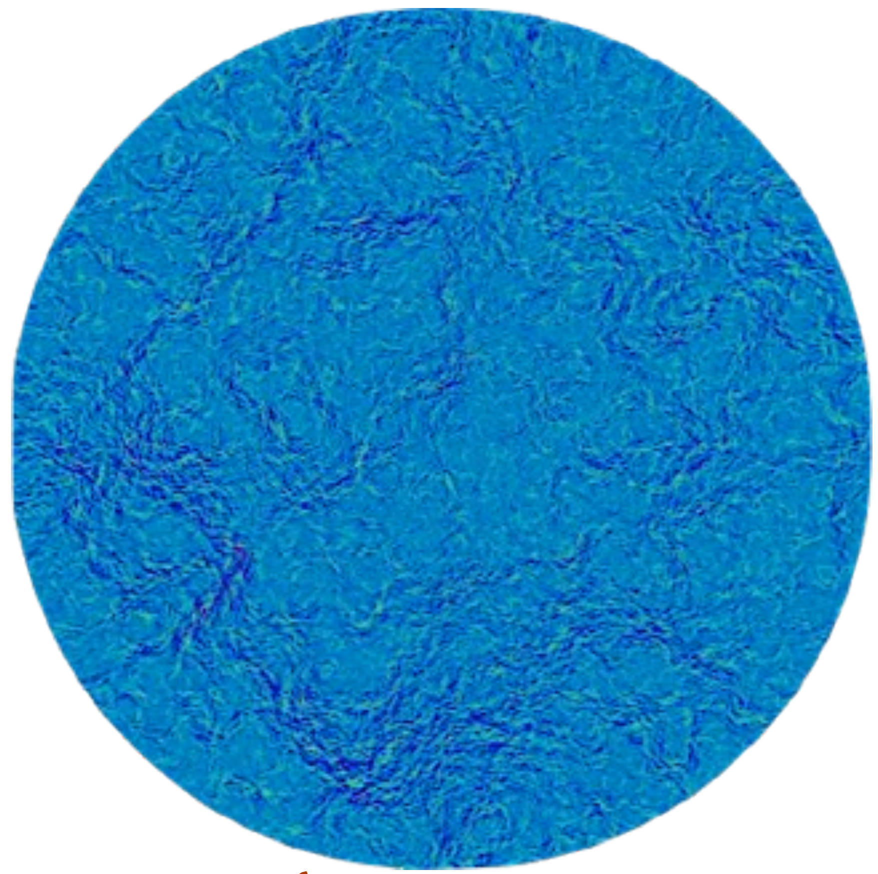
New Views of The CMB from ACT

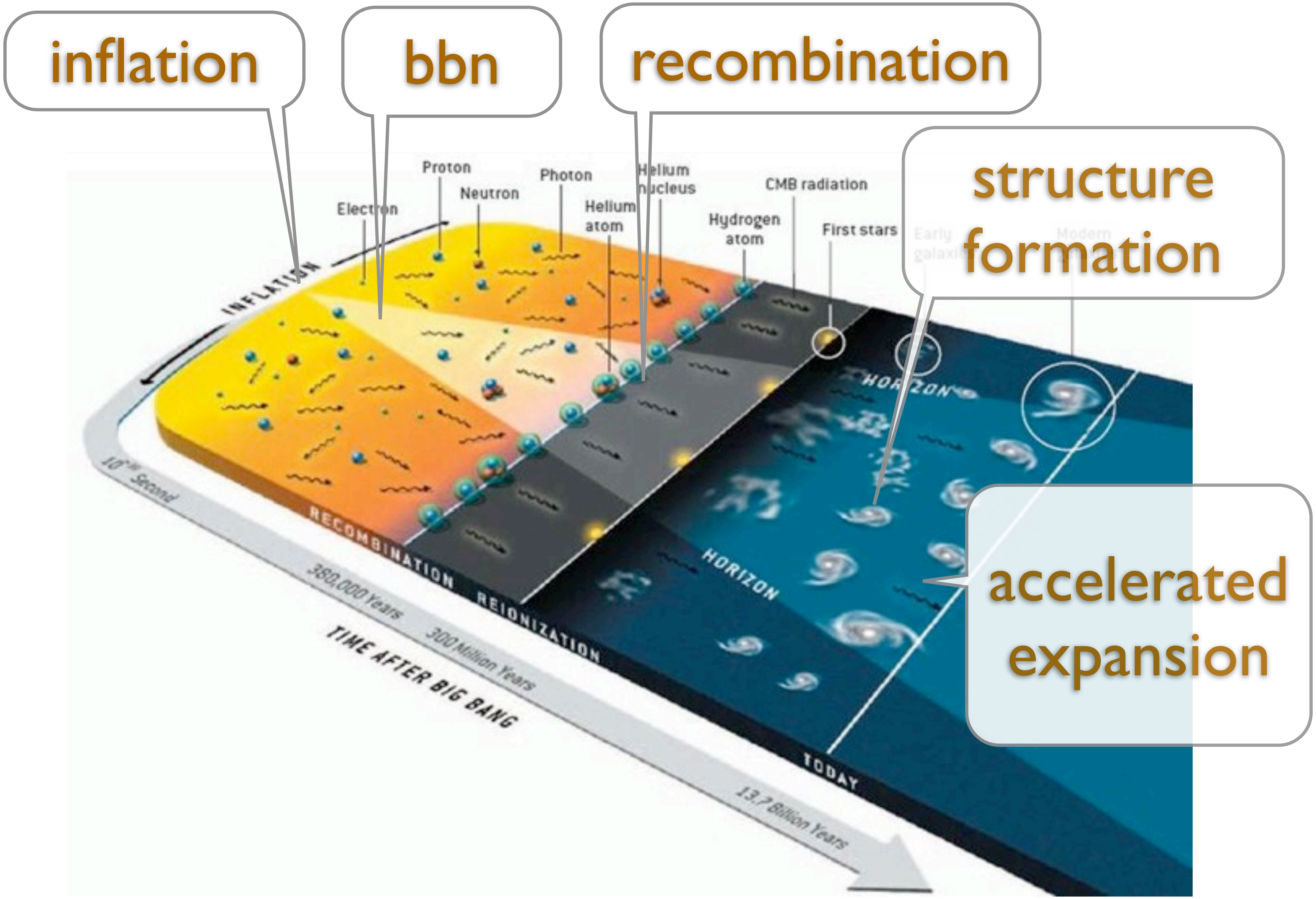


Sudeep Das

Berkeley Center for Cosmological Physics

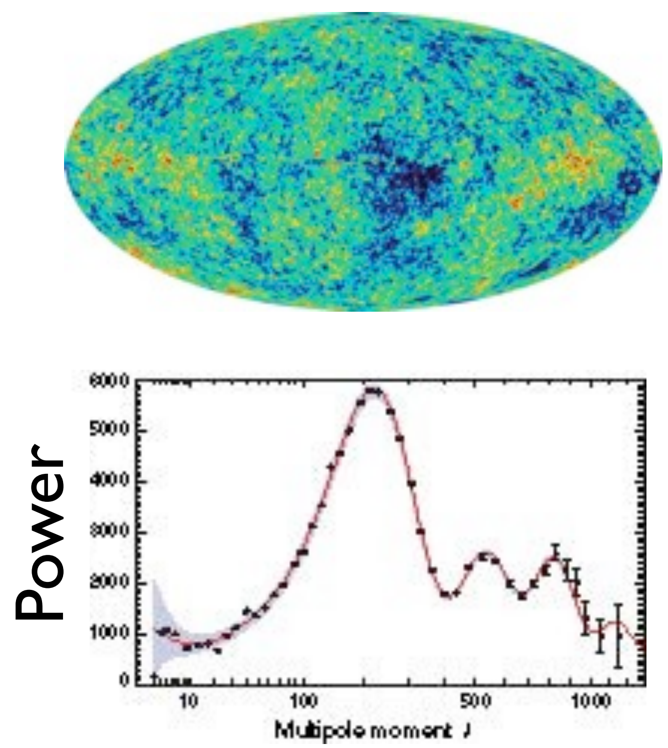
DPF, Aug 11, 2011

THE TIMELINE OF THE UNIVERSE HAS FIVE MAJOR MILESTONES

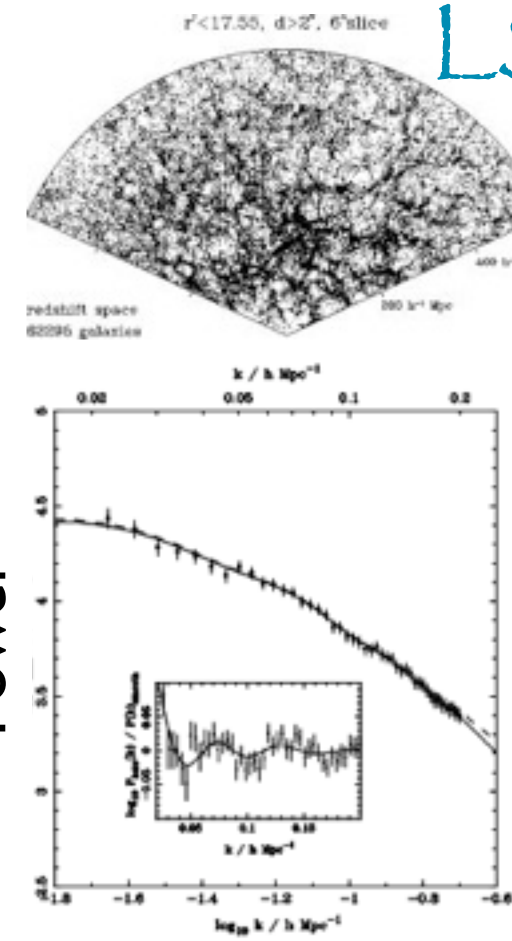


The ΛCDM model: an excellent fit to observations probing these epochs

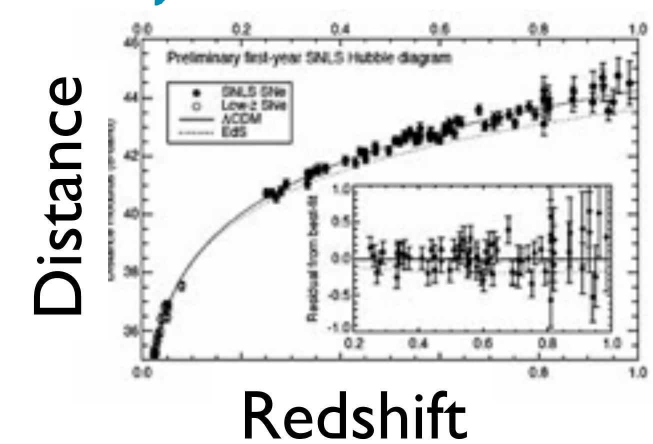
CMB



LSS

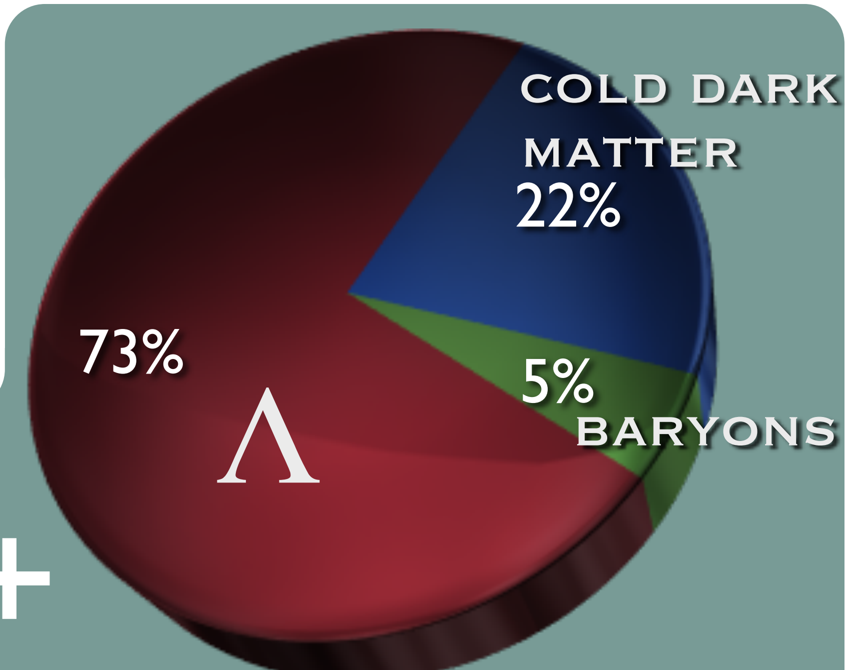


Supernovae



RECIPE

adiabatic, nearly scale invariant, power law, Gaussian fluctuations + flatness +



There are big questions within and beyond the standard model

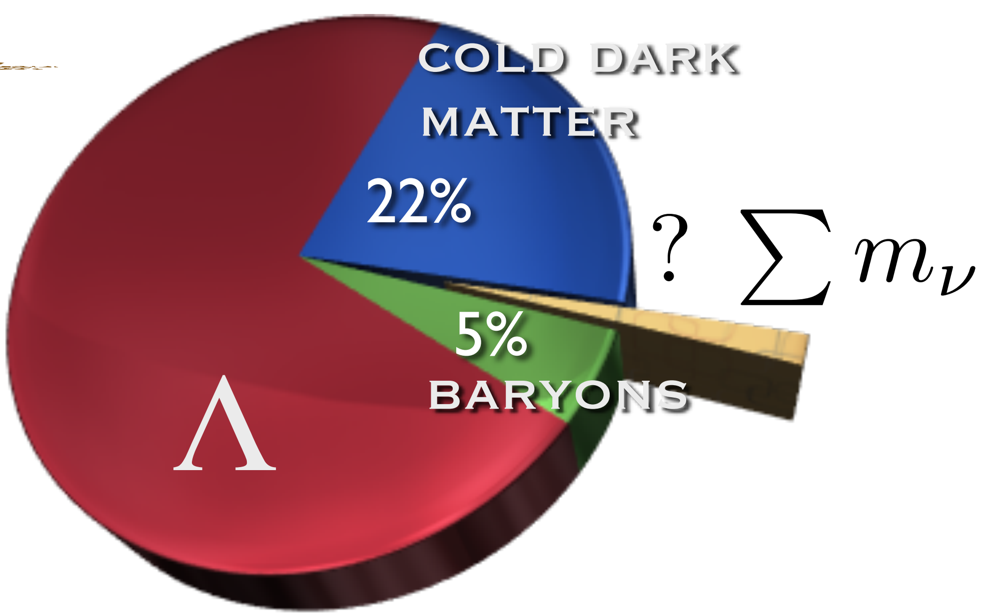
inflation

- What is the energy -scale of inflation?
- Which model?

dark sector

- Is Dark Energy a cosmological constant, or a dynamical component?
- What is the nature of Dark Matter?

particle sector



- What are the masses of the neutrinos?
- Physics beyond the Standard Model:
  - excess relativistic species during BBN?
- Sterile neutrinos?

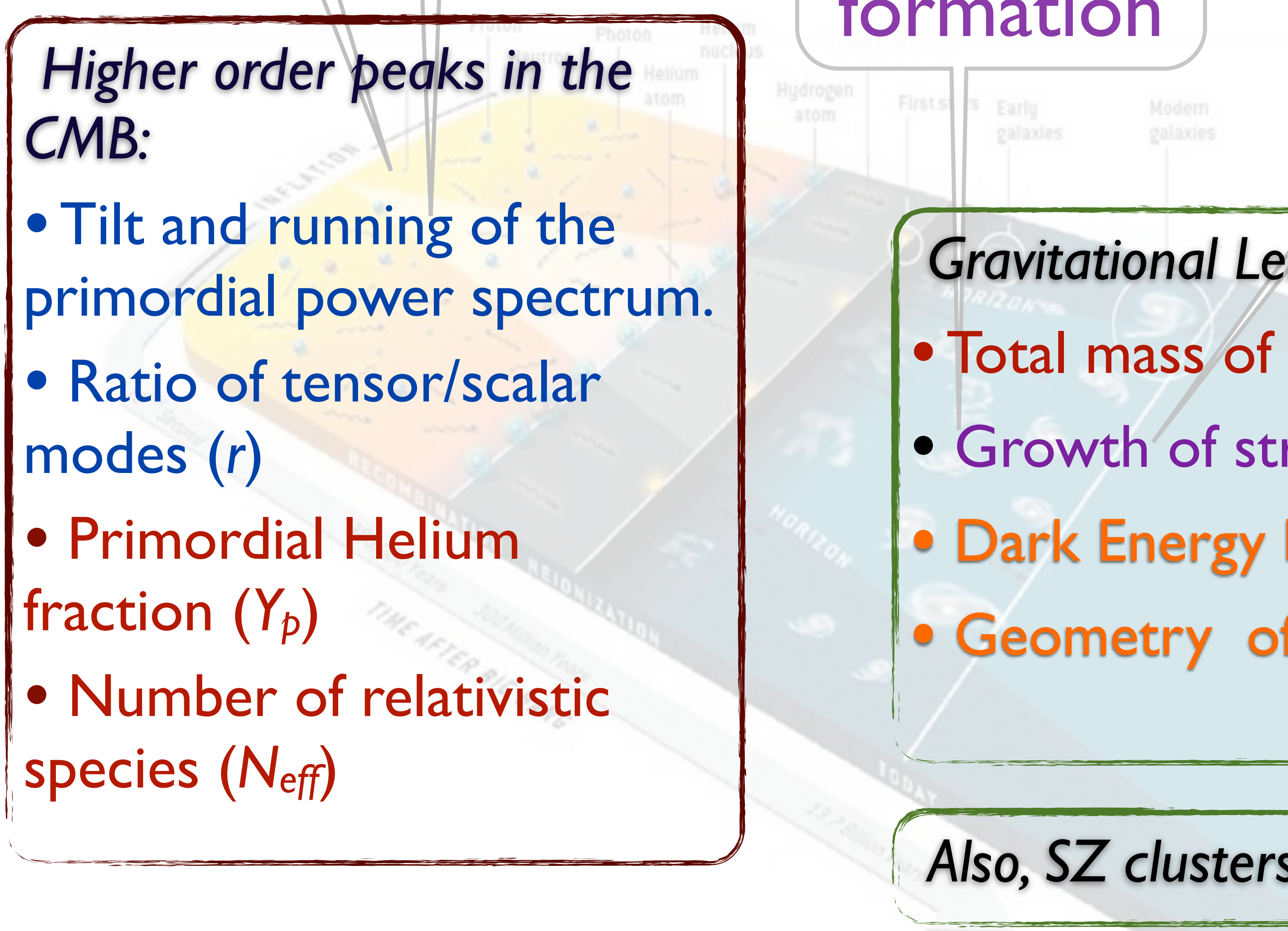
High resolution CMB observations are opening new windows on All these epochs

inflation

bbn

structure formation

accelerated expansion/ DE



Higher order peaks in the CMB:

- Tilt and running of the primordial power spectrum.
- Ratio of tensor/scalar modes (*r*)
- Primordial Helium fraction (Y_p)
- Number of relativistic species (N_{eff})

Gravitational Lensing of the CMB

- Total mass of neutrinos
- Growth of structure
- Dark Energy behavior with redshift
- Geometry of the universe

Also, SZ clusters ...

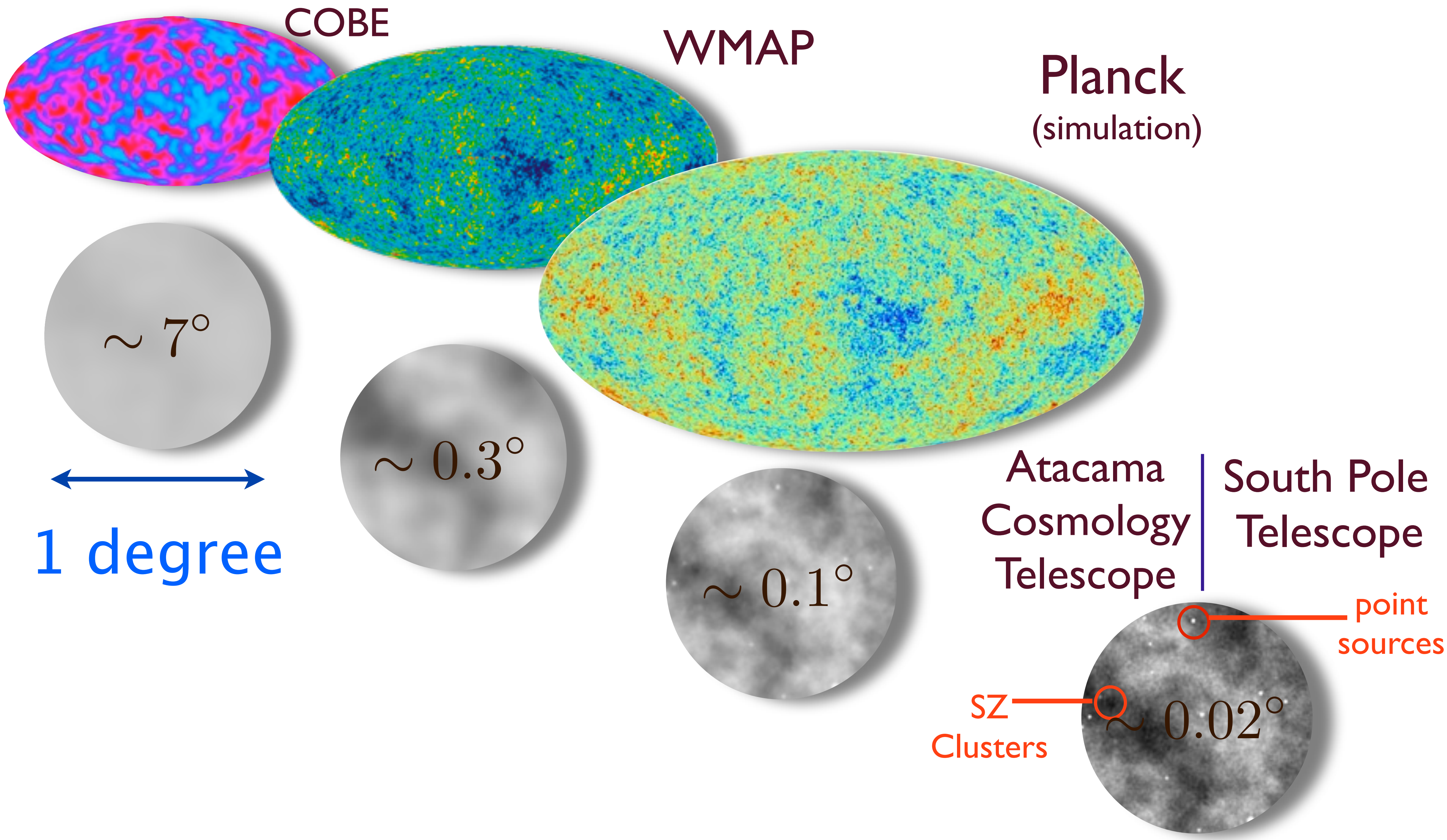
ONGOING EXPERIMENTS ARE PUSHING RESOLUTION AND SENSITIVITY TO NEW LIMITS

Planck

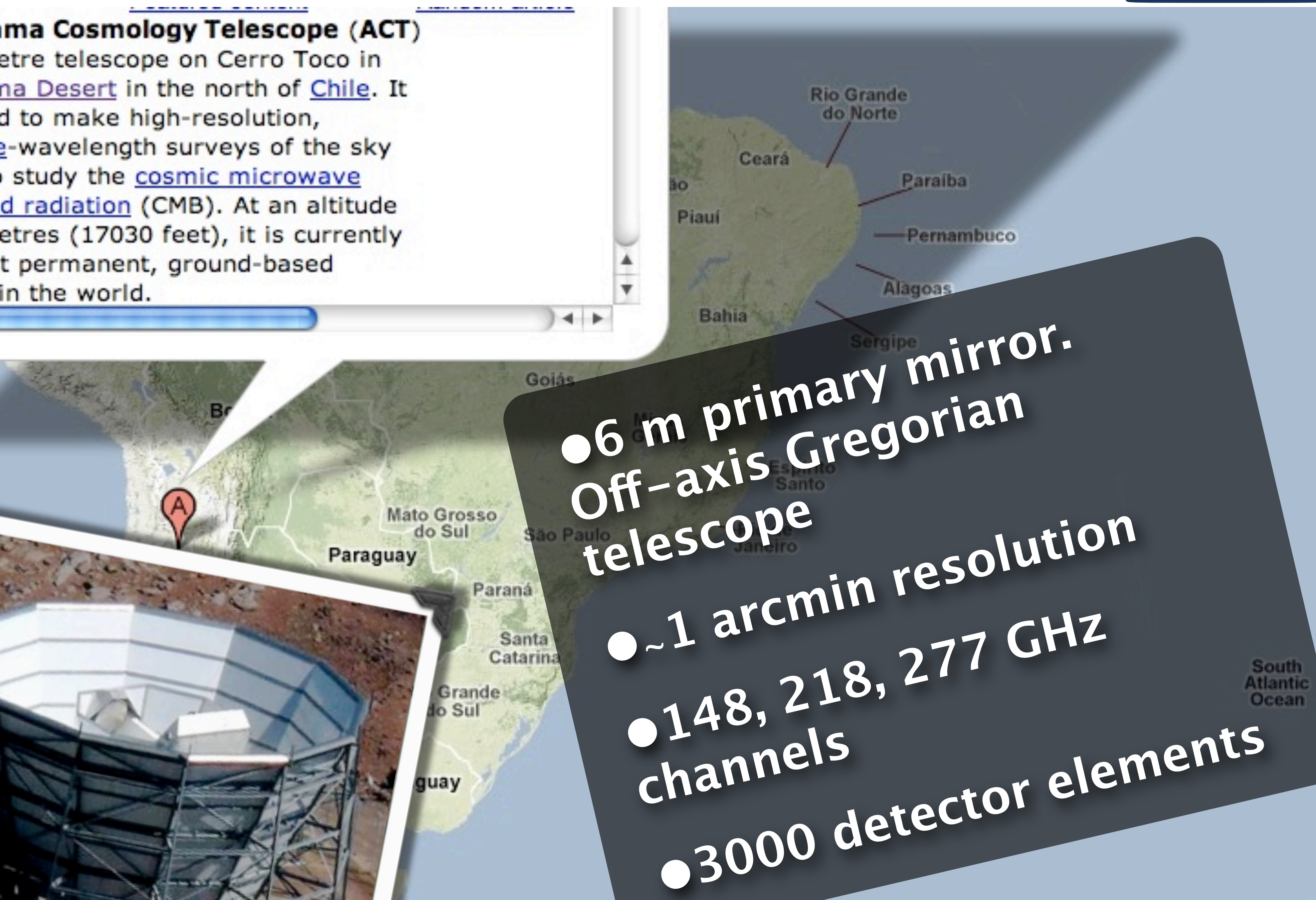
South Pole Telescope (SPT)

Atacama Cosmology Telescope (ACT)

ONGOING EXPERIMENTS ARE PUSHING RESOLUTION AND SENSITIVITY TO NEW LIMITS



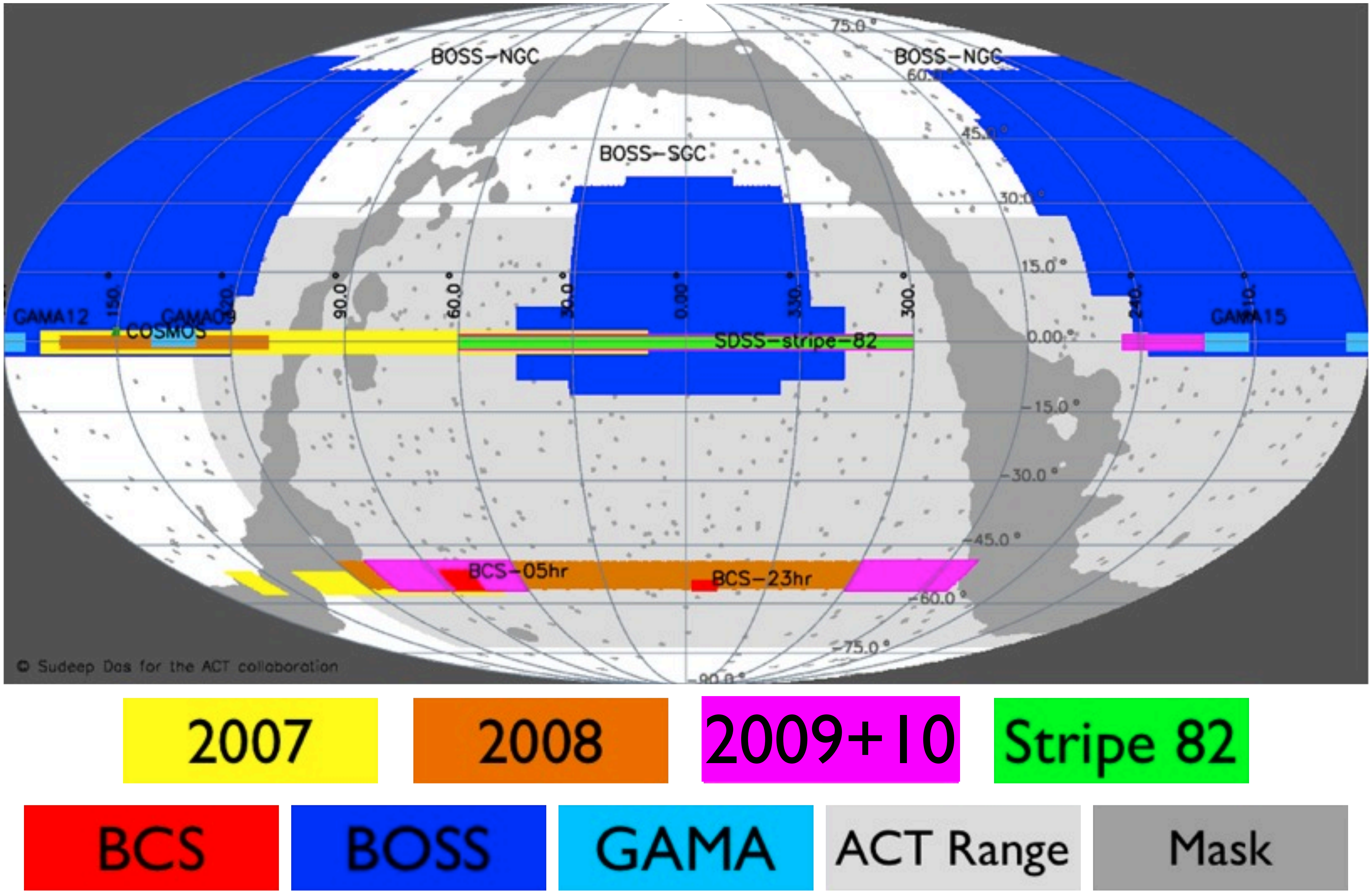
THE ATACAMA COSMOLOGY TELESCOPE



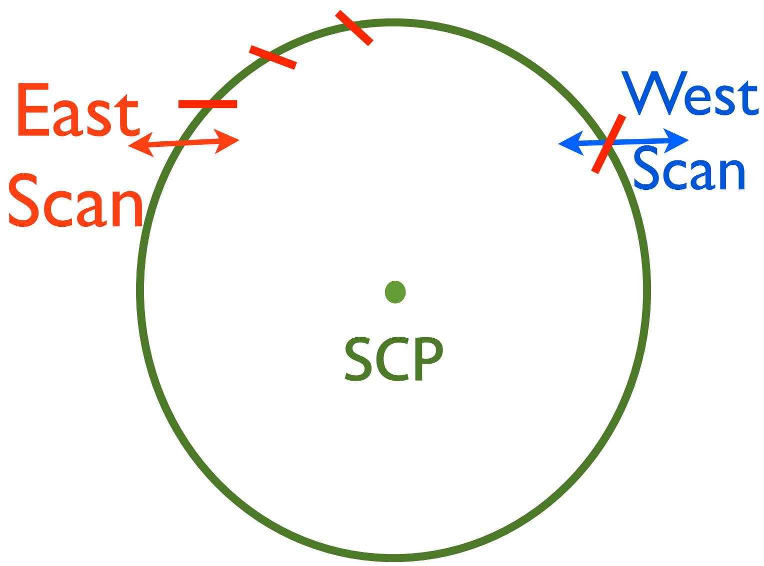
- 6 m primary mirror. Off-axis Gregorian telescope
- ~1 arcmin resolution
- 148, 218, 277 GHz channels
- 3000 detector elements

Swetz et al. (2010)

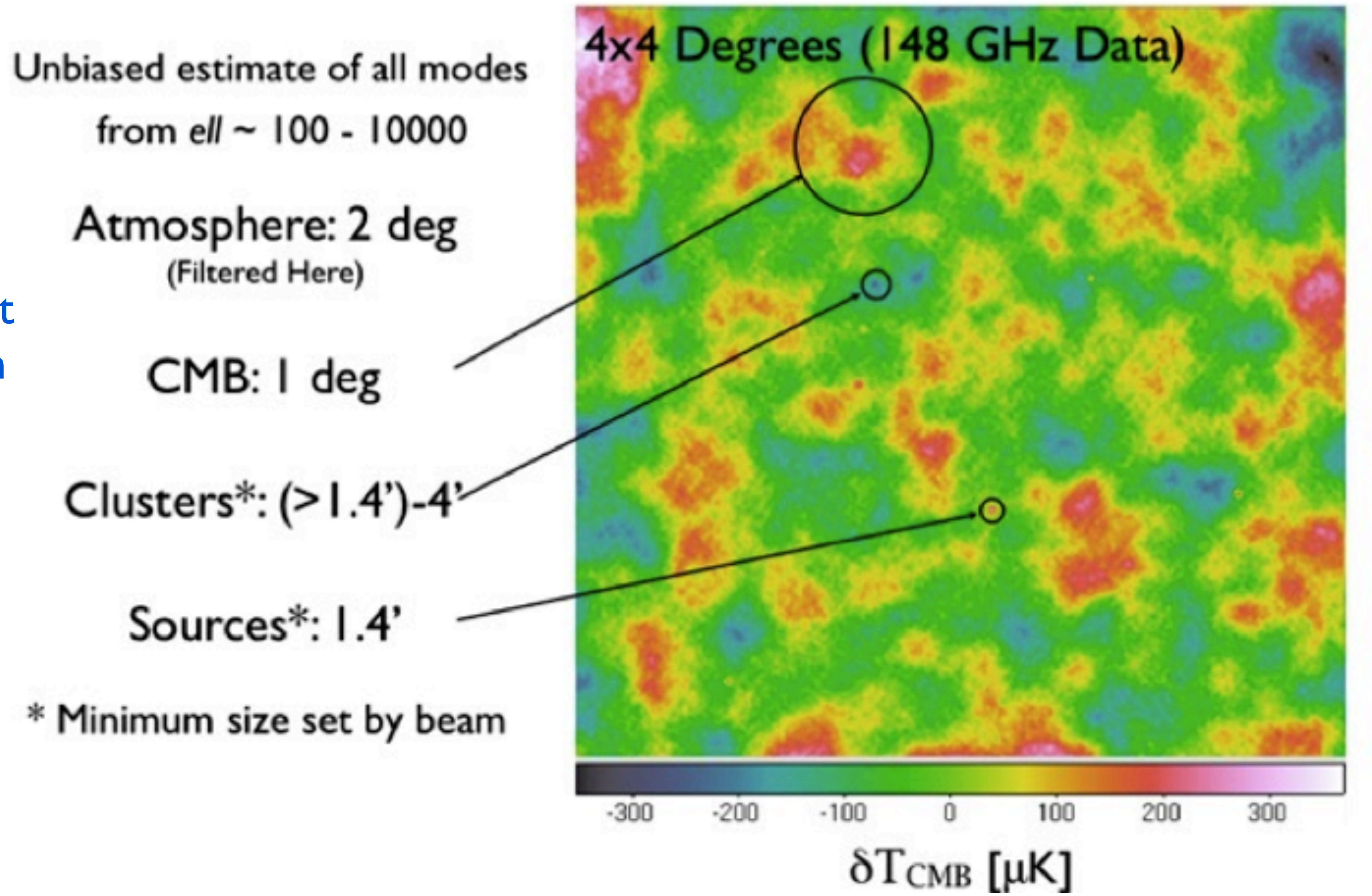
ACT HAS OBSERVED ABOUT 1800 SQ. DEGREES AT ARCMINUTE RESOLUTION!



- Relative Calibration
- Pointing and Astrometry
- Data Selection
- Map-making: Cross-linked observations help us solve for the maximum-likelihood map: true representation of the sky. Gain back modes suppressed by filtering through iteration. For one season of data, needs 100,000 CPU hours (lead: J. Sievers)



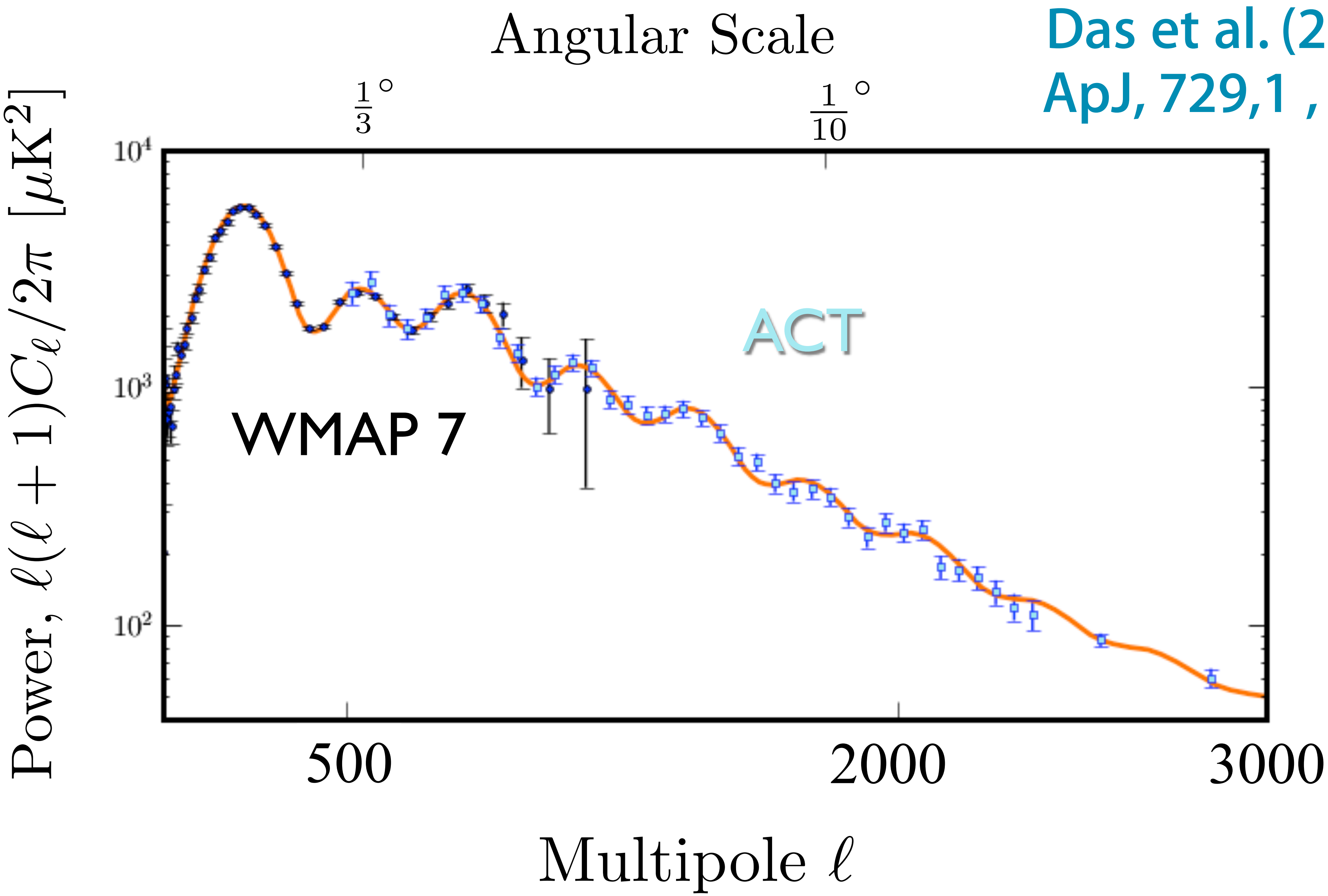
Cross-linking



Dunner et al. (in prep.)

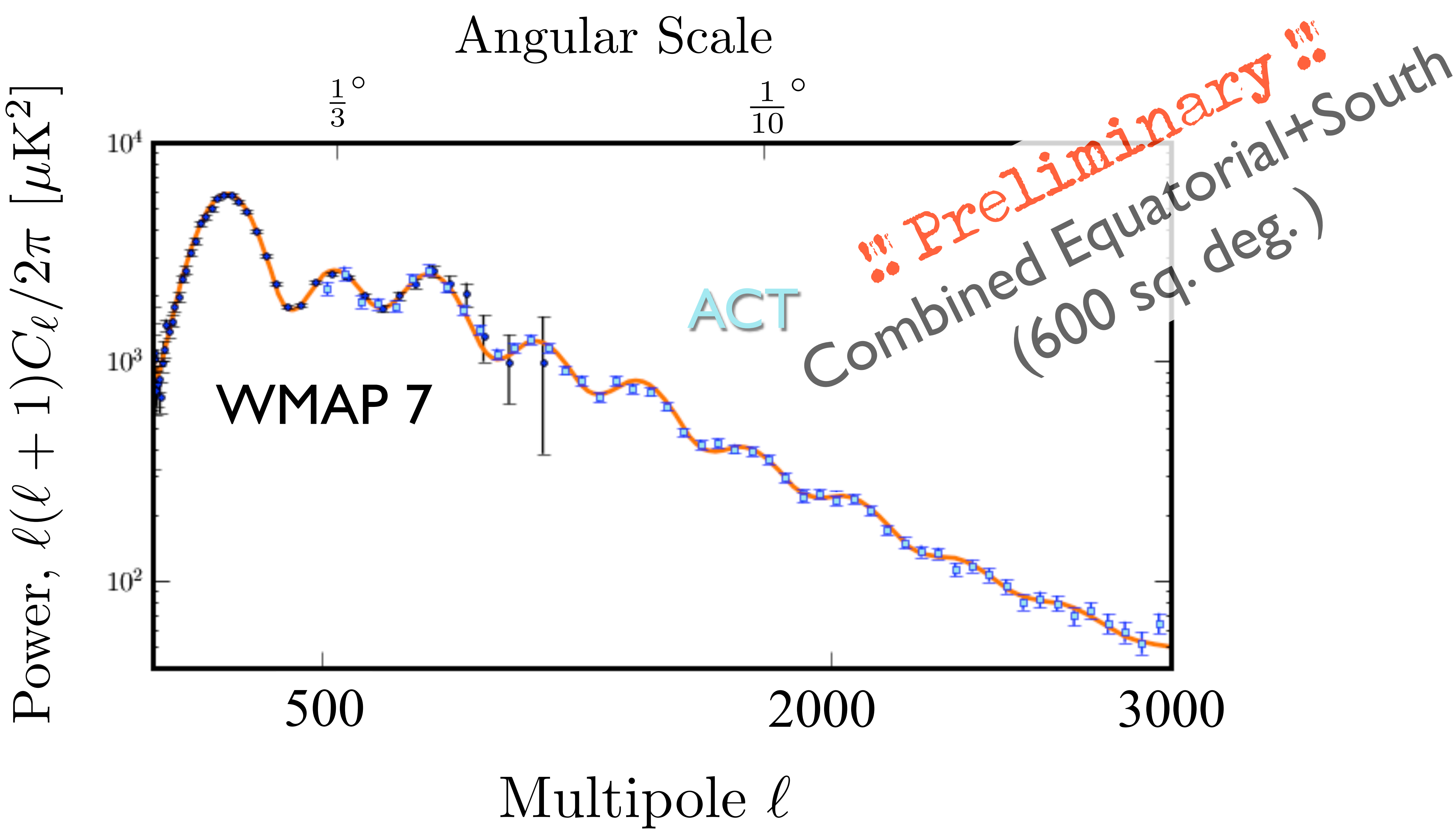
HIGH RESOLUTION POWER SPECTRUM FROM ACT

Das et al. (2011), ApJ, 729,1 , 2011



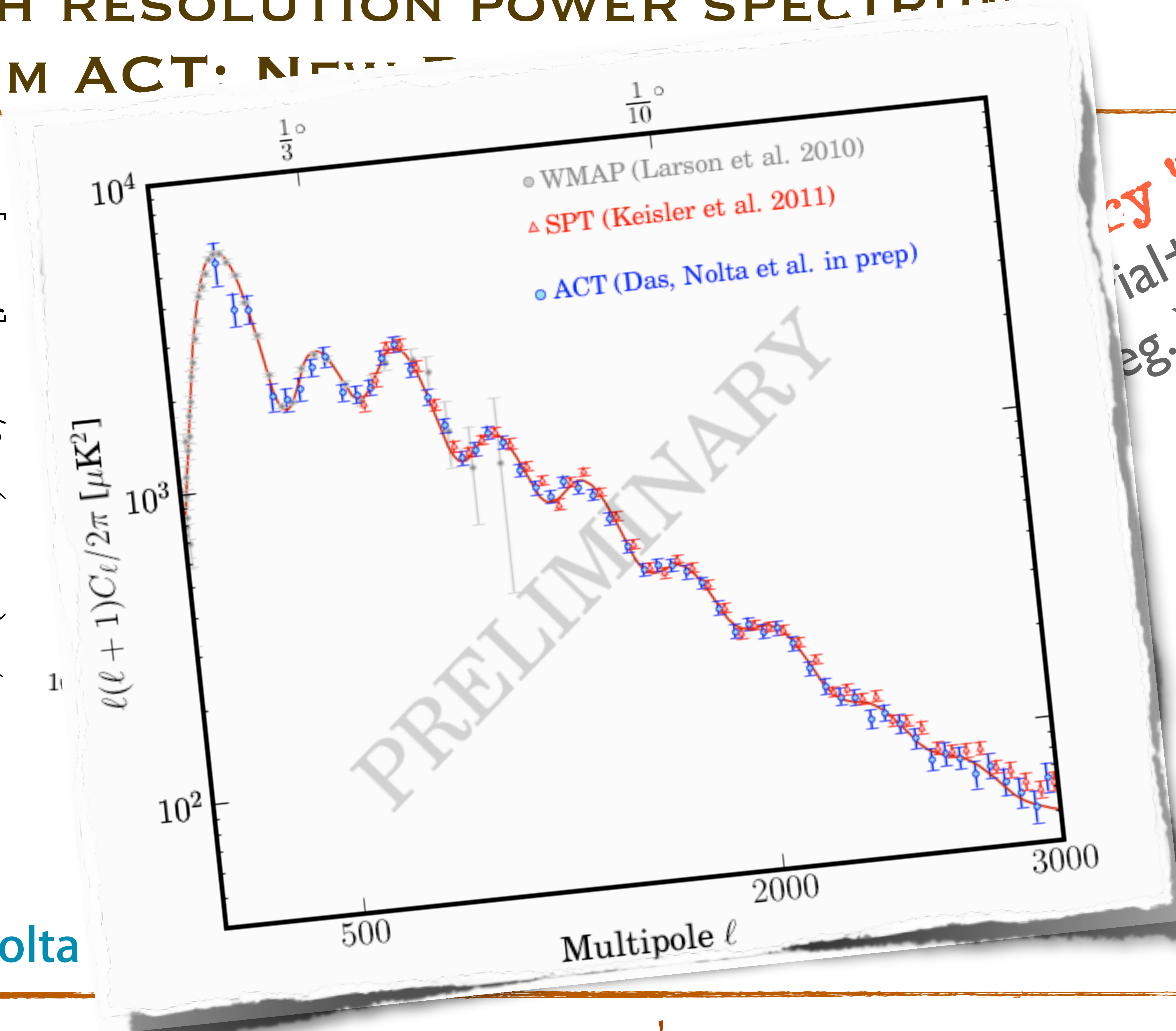
Pipeline based on Das, Hajian, Spergel (2010)

HIGH RESOLUTION POWER SPECTRUM FROM ACT: NEW RESULT!



Das, Nolta et al. (2011), in prep

HIGH RESOLUTION POWER SPECTRUM FROM ACT: NEW R...

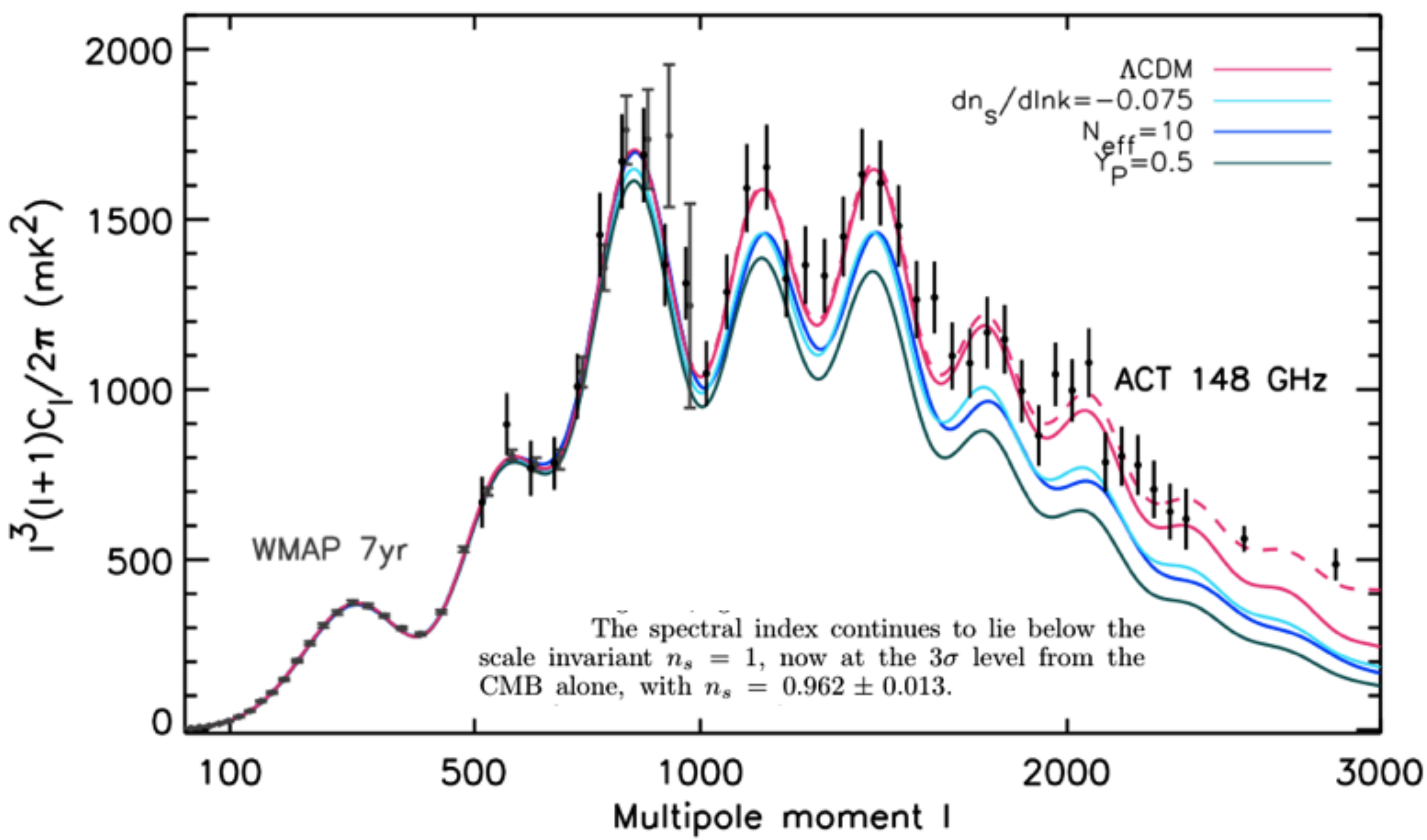


Power, $\ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$

...cy !!
...ial+South
...eg.)

Das, Nolta

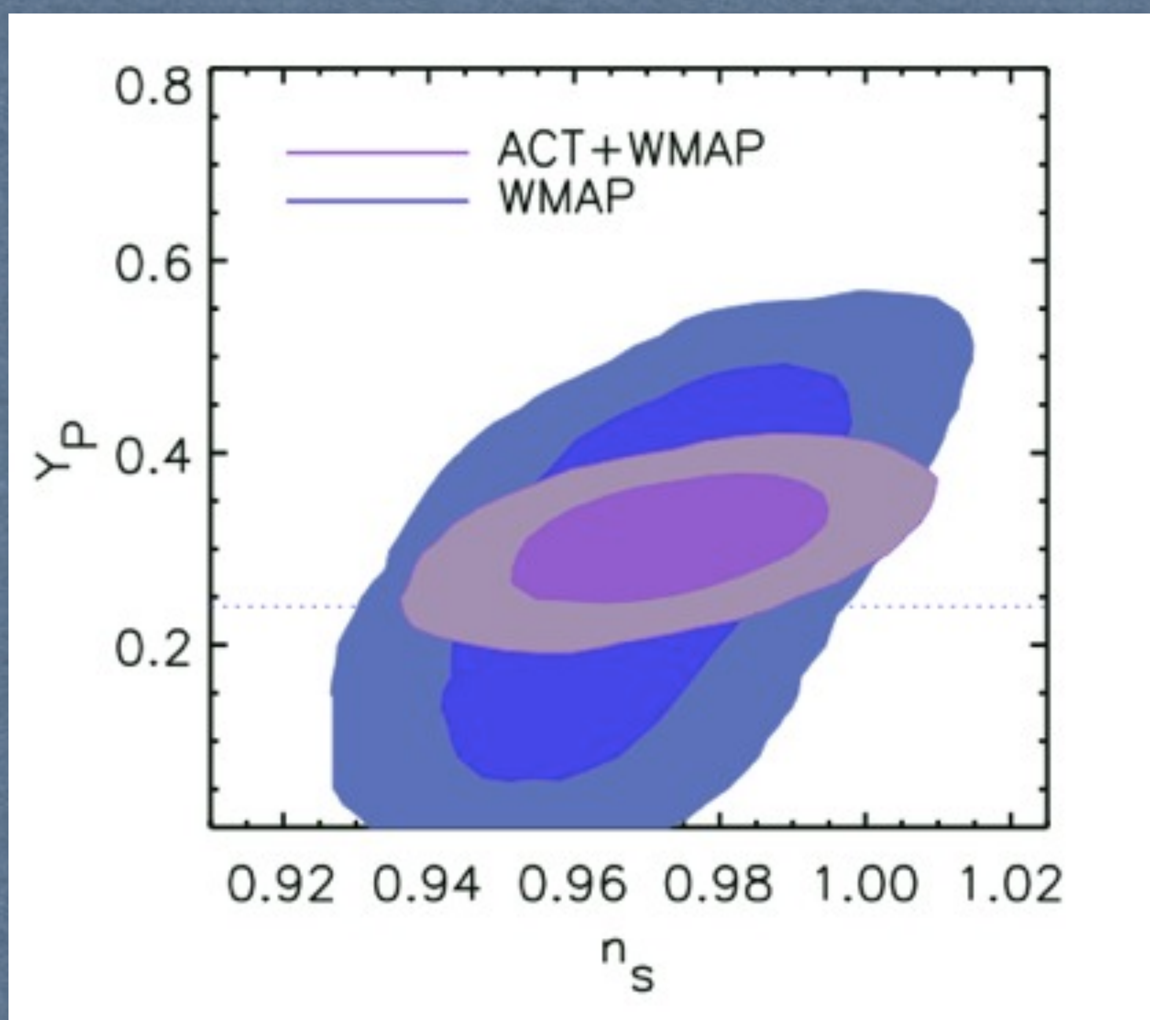
HIGHER ORDER PEAKS HELP CONSTRAIN PARAMETERS BEYOND ΛCDM



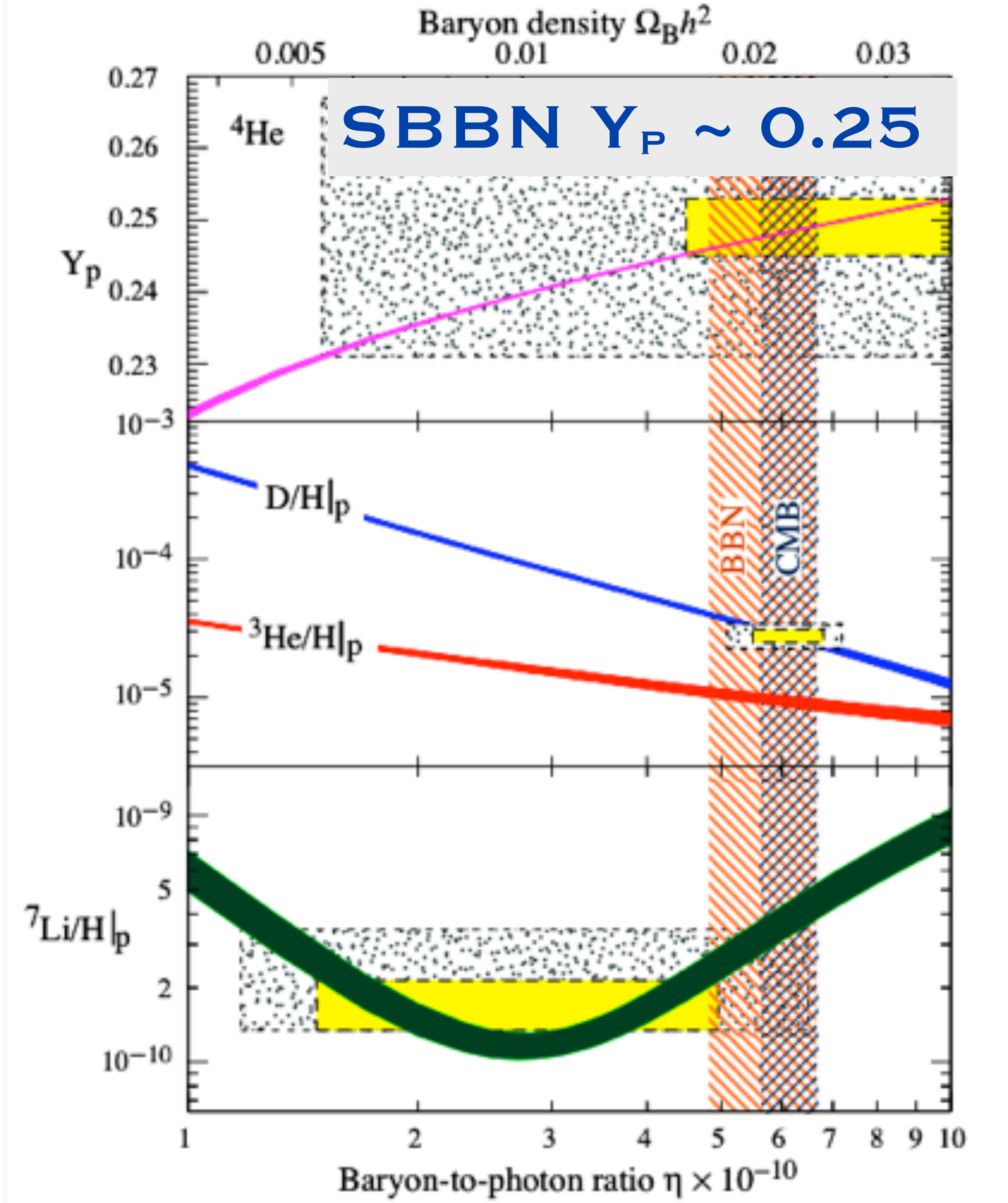
Dunkley et al. (2010)

ACT+WMAP MEASURES THE DENSITY OF HELIUM AT 380,000 YEARS AFTER BB

More helium decreases electron density, increasing Silk damping. We find
$Y_P = 0.313 \pm 0.044$ (68% CL, ACT+WMAP)
6-sigma detection from CMB alone.

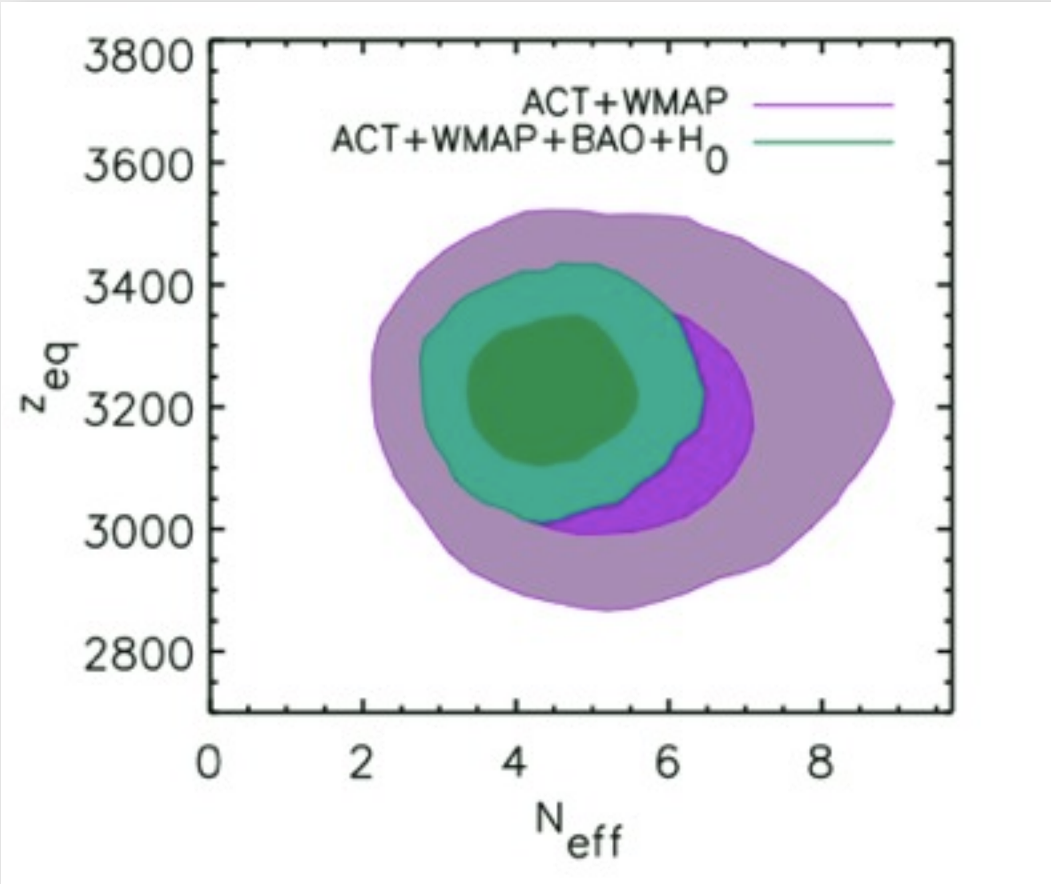


BBN ~ 3 MINS



Dunkley et al. (2010)

ACT+WMAP constrains number of relativistic species



Changing N_{eff} changes equality redshift.
Also suppress early acoustic oscillations in primary CMB.
For ACT+WMAP we find $N_{eff} = 5.3 \pm 1.3$
(CMB now constrains it from above !)

$$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right] \frac{\pi^2}{15} T_\gamma^4 \, .$$

In standard BBN
$N_{\rm eff} = 3.04$

ACT's data is comfortably consistent with SBBN. No cause for alarm yet.

Could these be early hints?

Dunkley et al. (2010)

UPCOMING DATA FROM ACT/POL, SPT/POL AND PLANCK WILL CONSTRAIN BEYOND SM PHYSICS

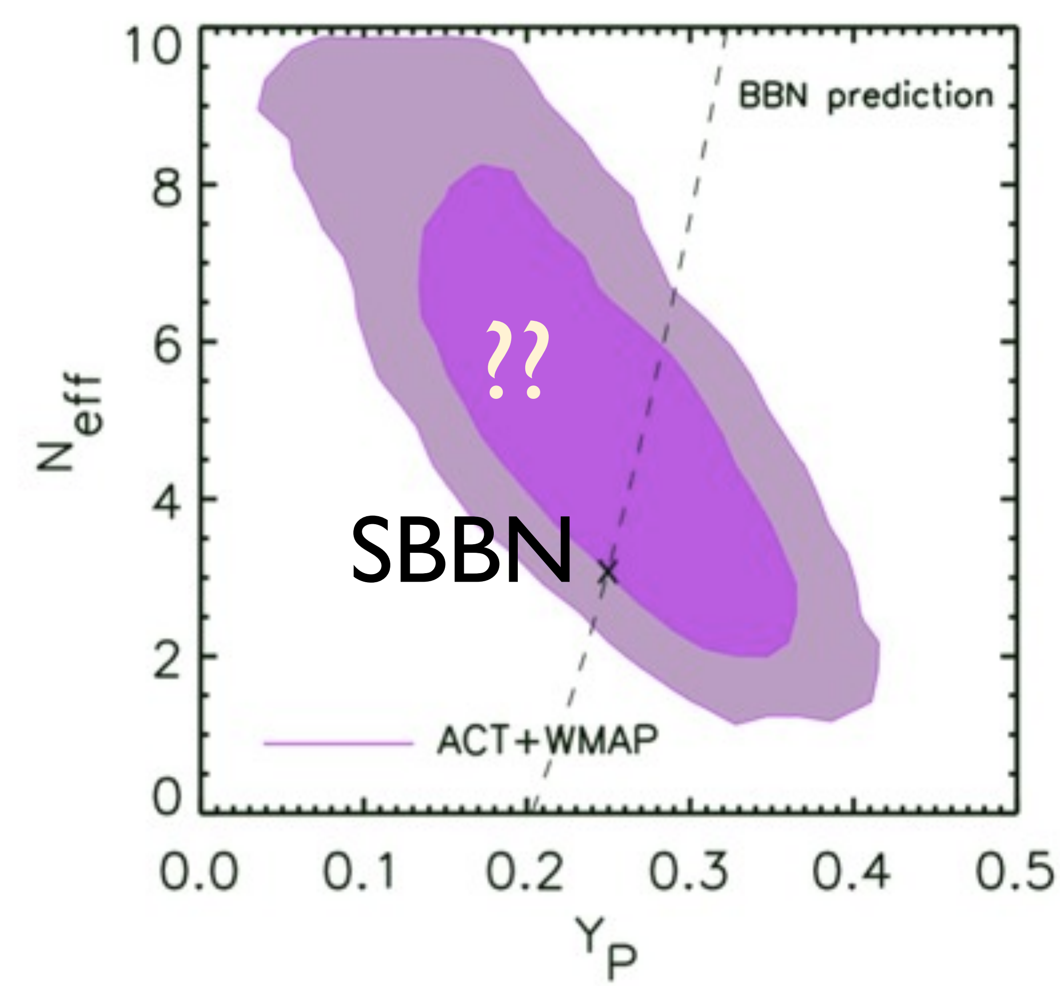
Helium fraction is essentially set by weak interaction freeze-out.

Izotov & Thuan (2010):

$$Y_p = 0.2565 \pm 0.0010(\text{stat.}) \pm 0.0050(\text{syst.})$$

Higher Helium fraction may mean more radiation during BBN, i.e. higher N_{eff}

$N_{eff} > 3.04$ could mean extra relativistic species (gravitons, axions, sterile neutrinos?) or non-thermal/beyond standard model interactions.



With polarization, where foregrounds and secondaries are lower, we should be able to see deeper into the CMB damping tail .

Dunkley et al. (2010)

UPCOMING DATA FROM ACT/POL, SPT/POL AND PLANCK WILL CONSTRAIN BEYOND SM PHYSICS

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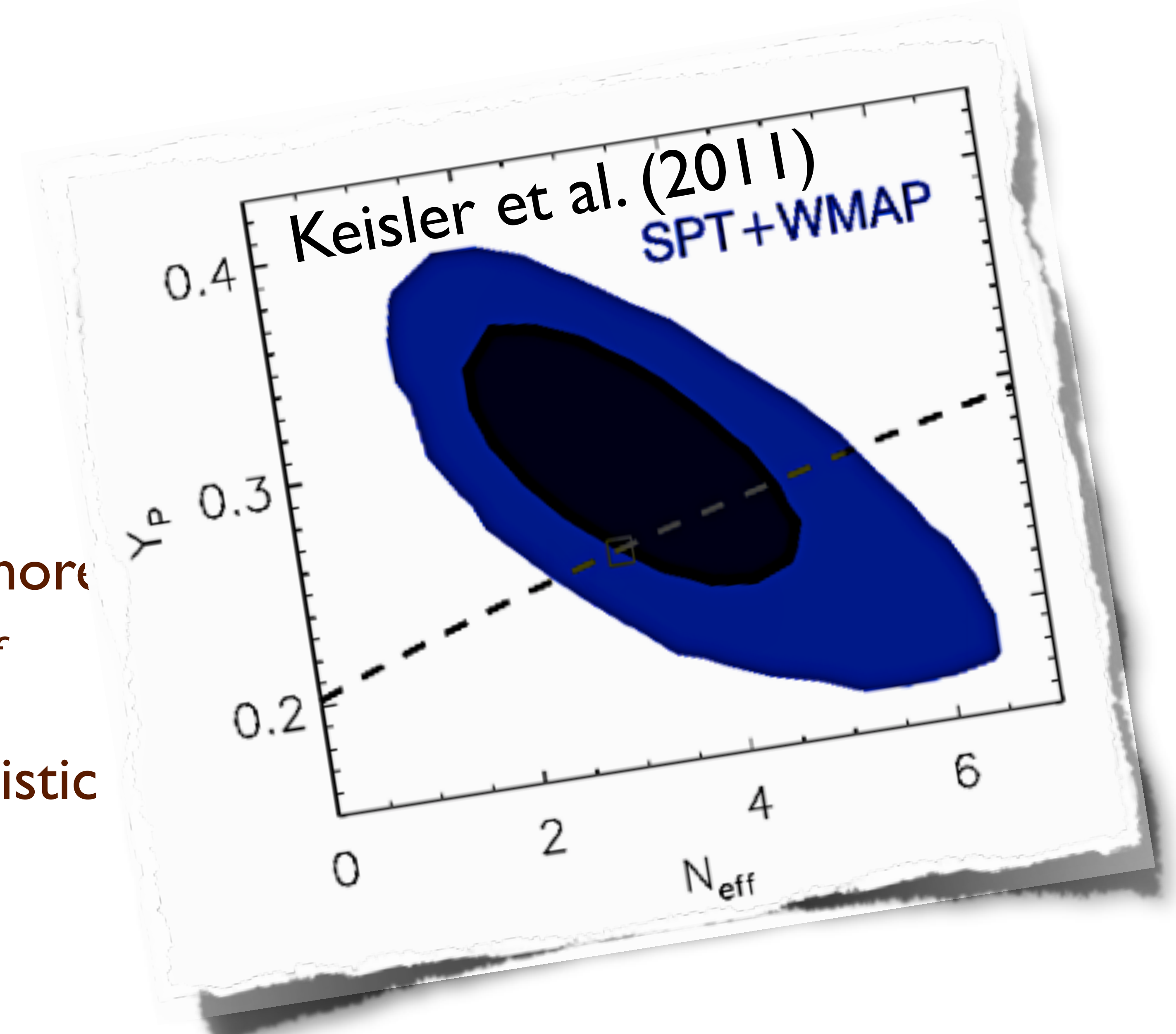

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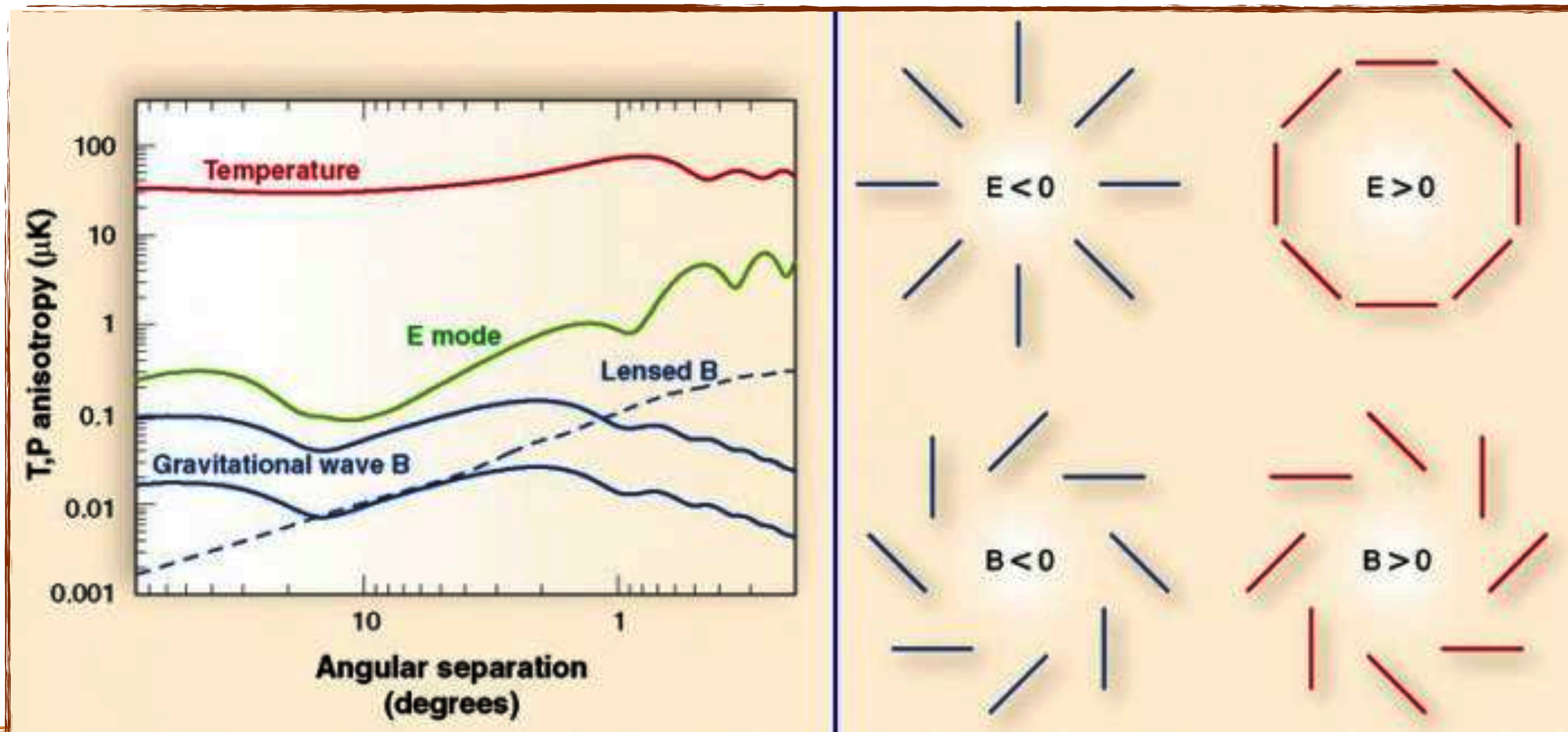
Dunkley et al. (2010)

CMB POLARIZATION CONTAINS COMPLEMENTARY INFORMATION

CMB Polarization is usually decomposed into E (curl-free) and B (gradient-free) modes.

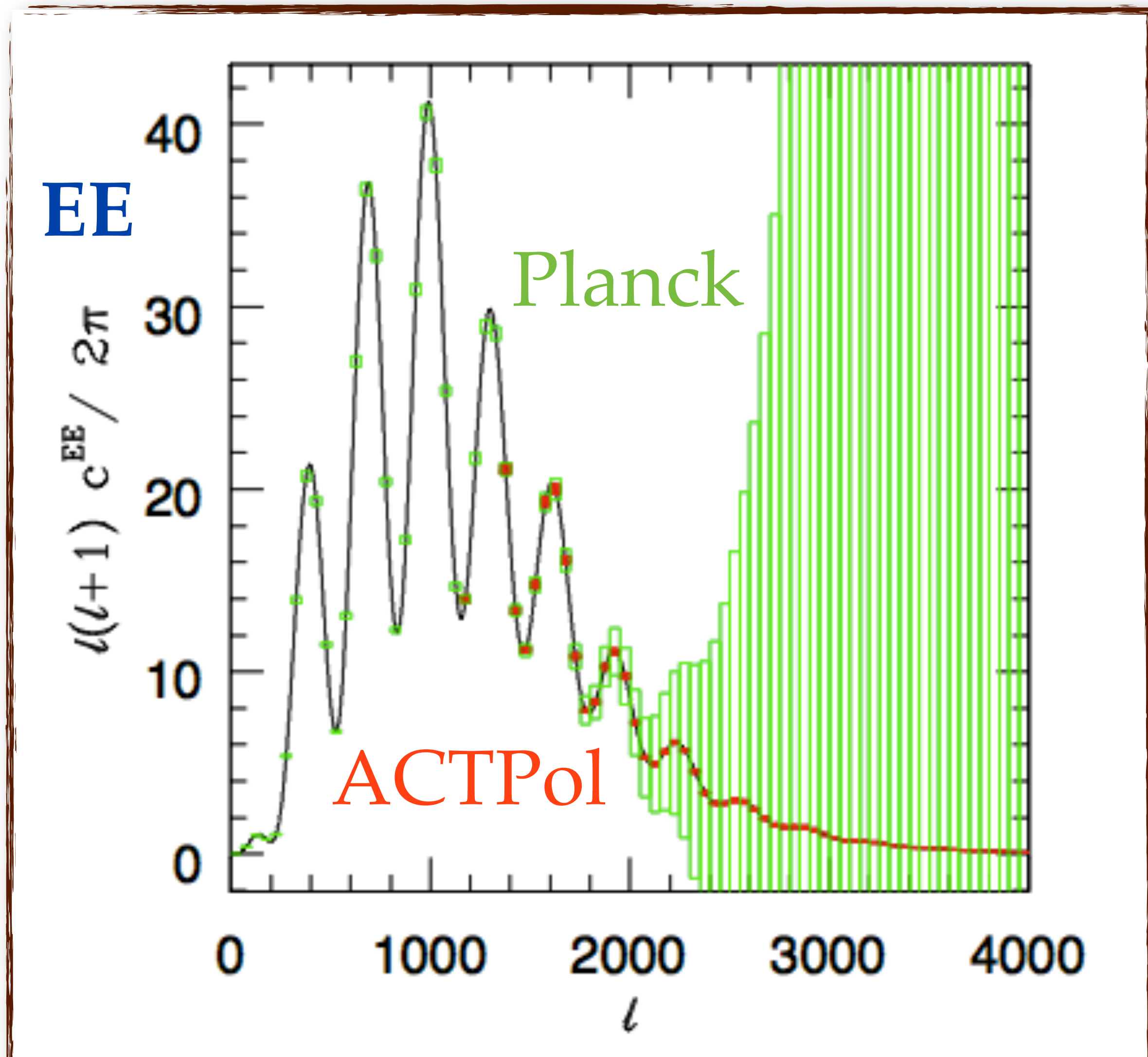
The polarized signals: EE, BB are much weaker than the TT, but foregrounds and secondaries are expected to be much lower.

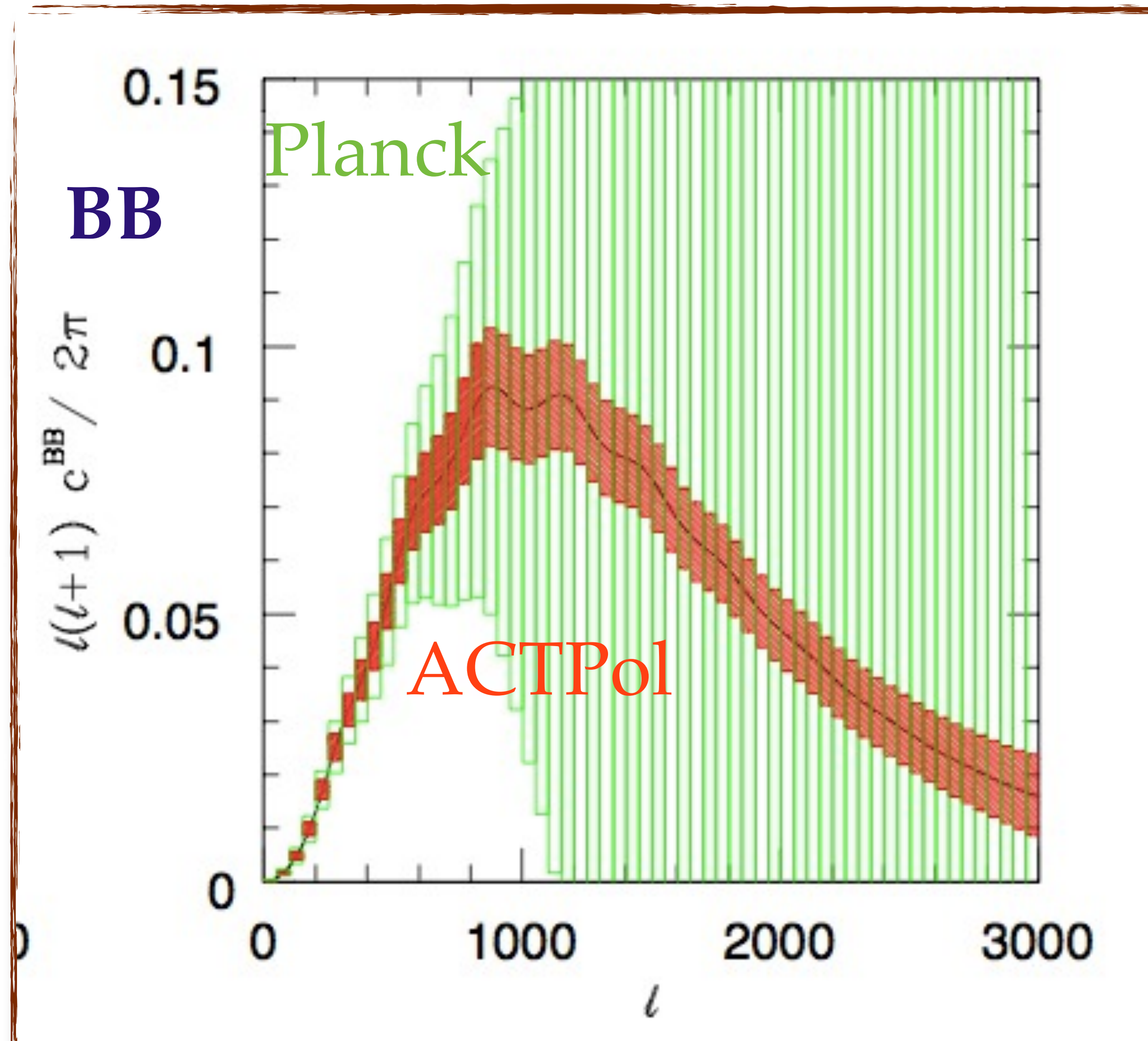


ACTPol: adding polarization to ACT

Also upcoming are polarbear and sptpol

ACTPol will make precise measurements of small scale CMB polarization spectrum. ACTPol is funded, and will start in 2012.



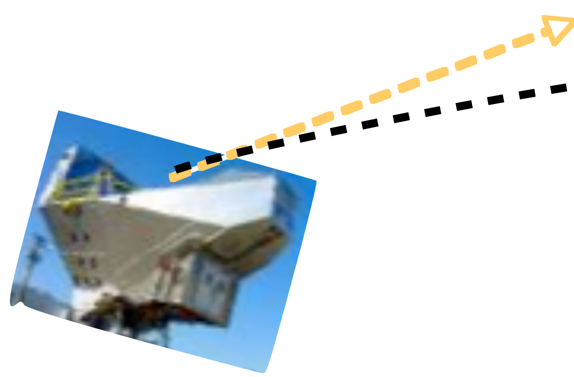


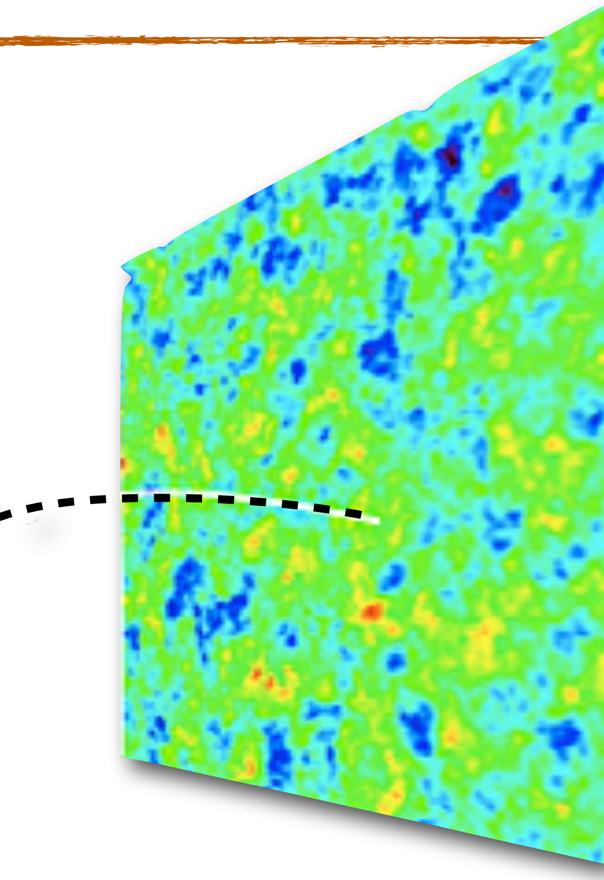
For BB, the high-l spectrum comes primarily from *gravitational lensing of the CMB E-modes*.

See Niemack et al (2010)

Gravitational lensing of the CMB

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



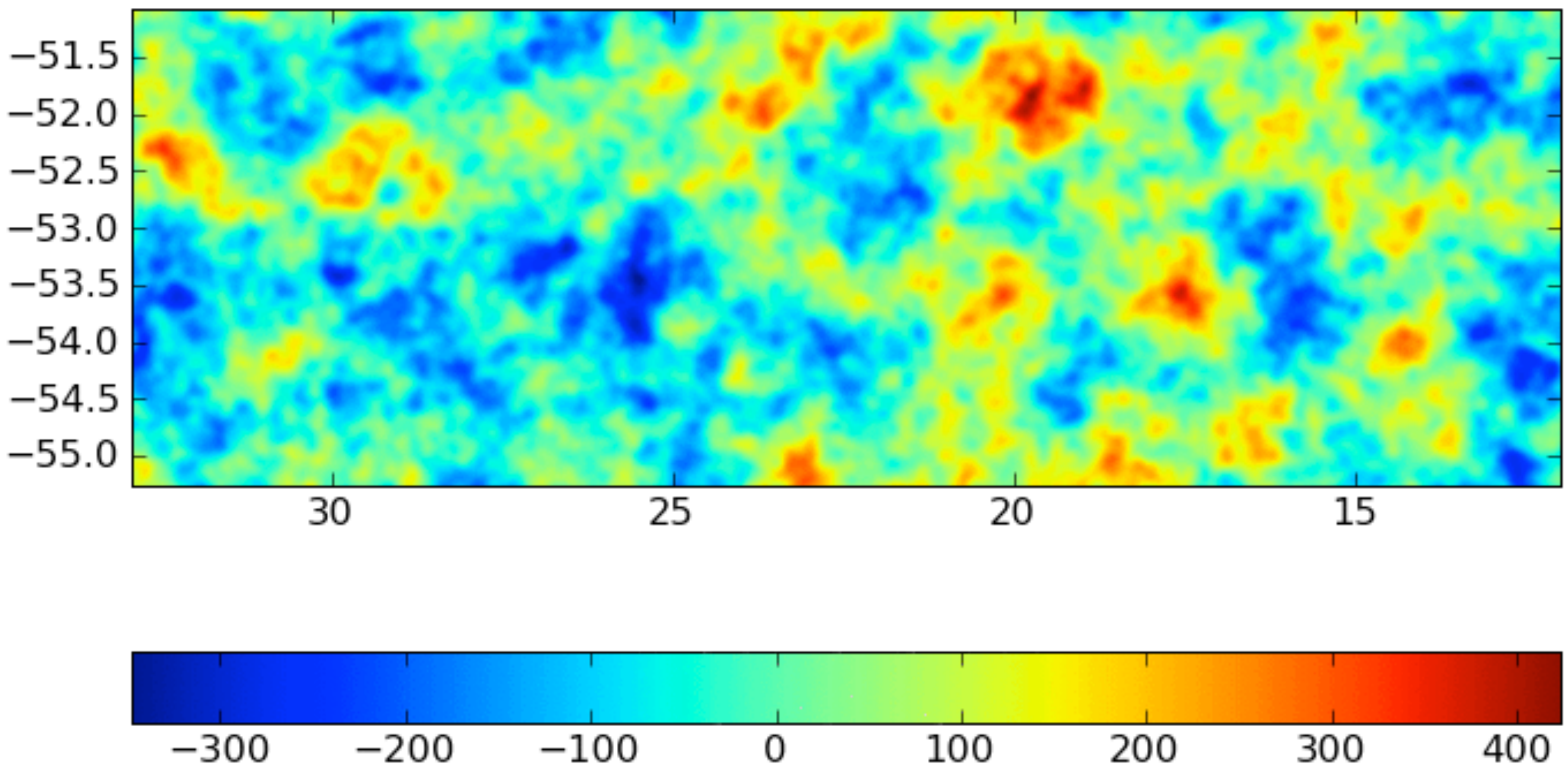


The RMS deflection is about 2.7 arcmins, but the deflections are coherent on degree scales.

Lensing remaps & magnifies/de-magnifies CMB patches, smoothing out peaks

$$\tilde{\Theta}(\hat{n}) = \Theta(\hat{n} + \nabla\phi)$$

lensed unlensed deflection



Simulation from Das & Bode (2008)

Lens-speak:

Lensing potential: ϕ

Deflection field: $\mathbf{d} = \nabla\phi$

Convergence: $\kappa = \frac{1}{2}\nabla \cdot \mathbf{d}$

Lensing remaps & magnifies/de-magnifies CMB patches, smoothing out peaks

$$\tilde{\Theta}(\hat{n}) = \Theta(\hat{n} + \nabla\phi)$$

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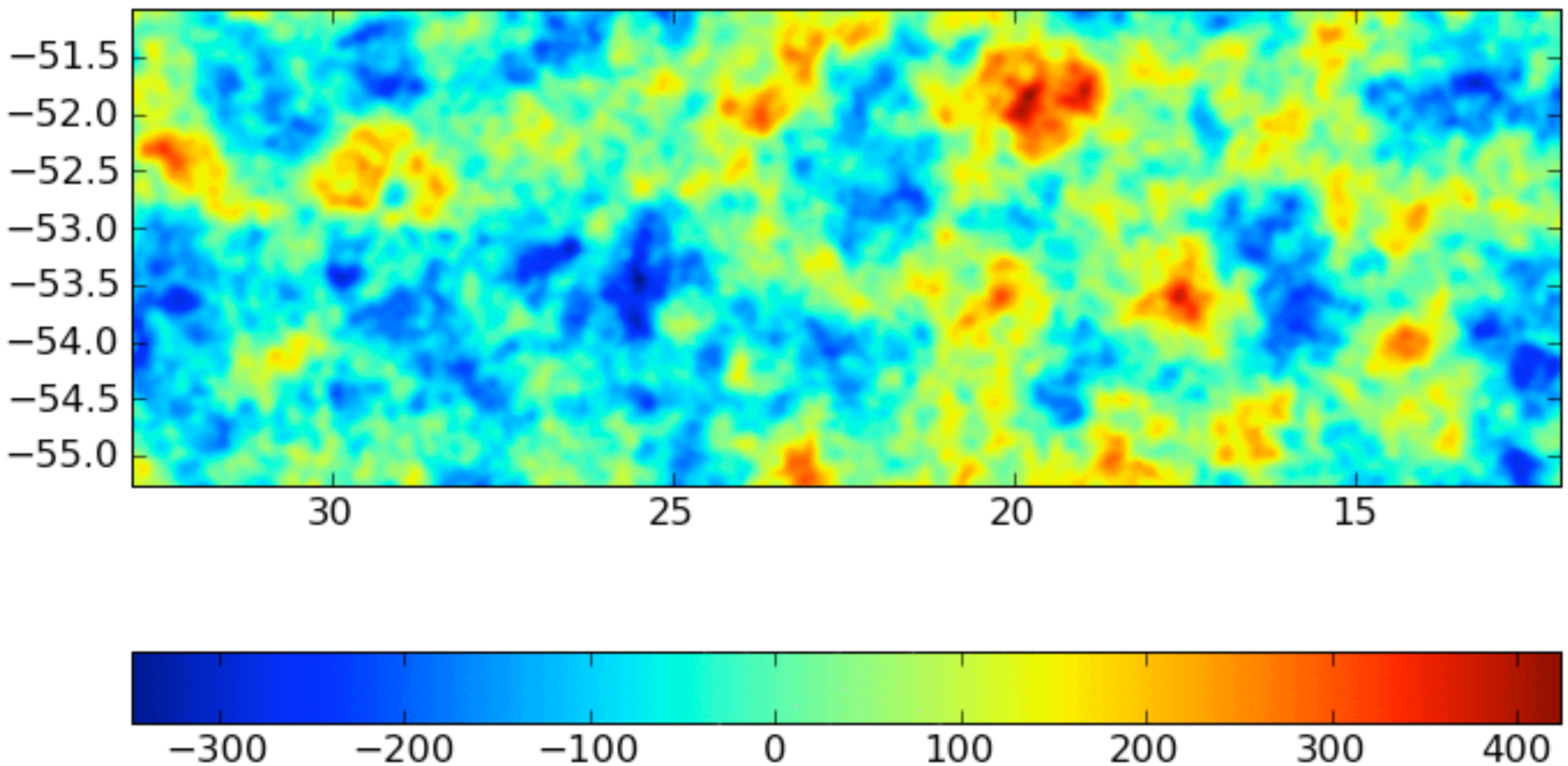

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Lens-speak:

Lensing potential: ϕ

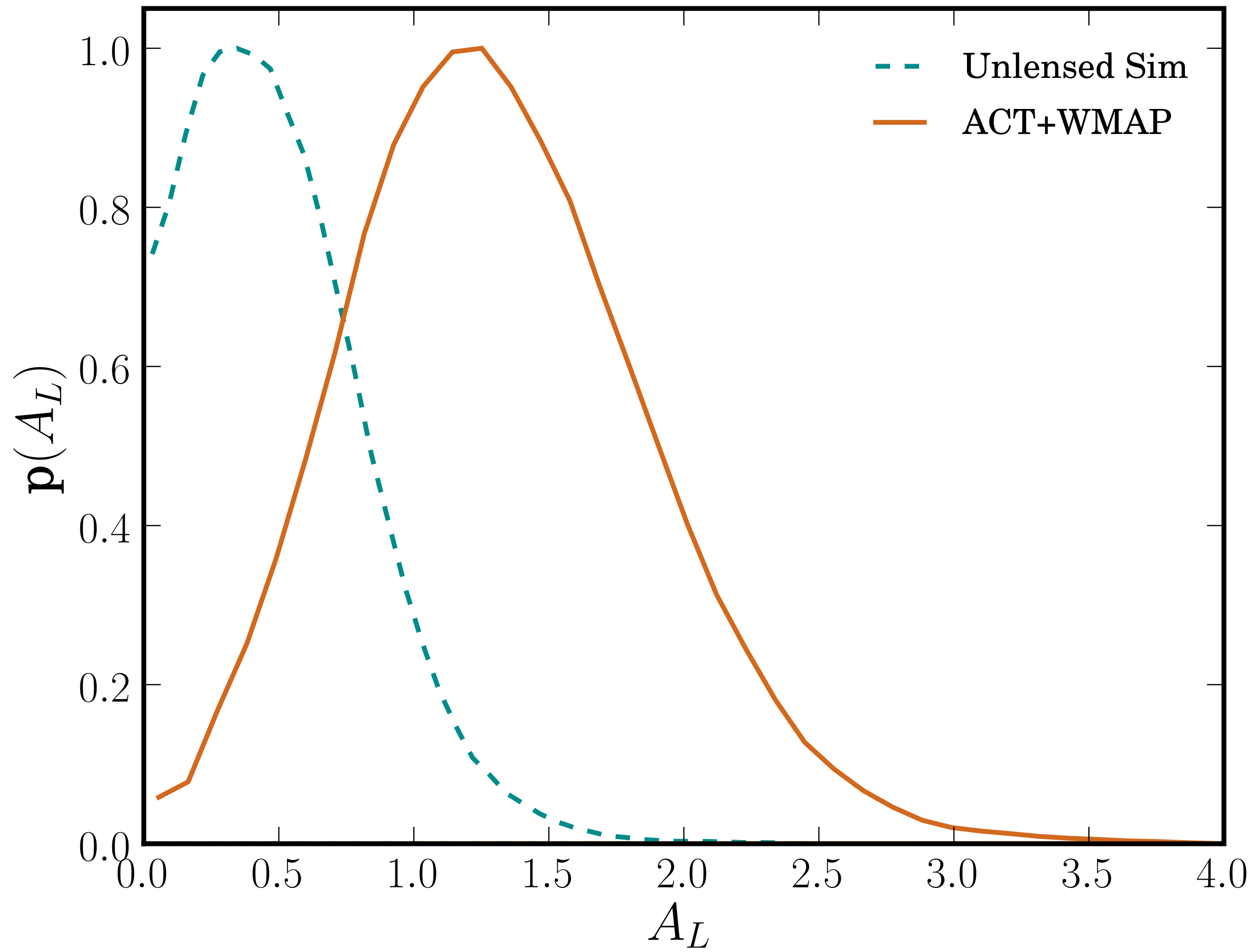
Deflection field: $\mathbf{d} = \nabla\phi$

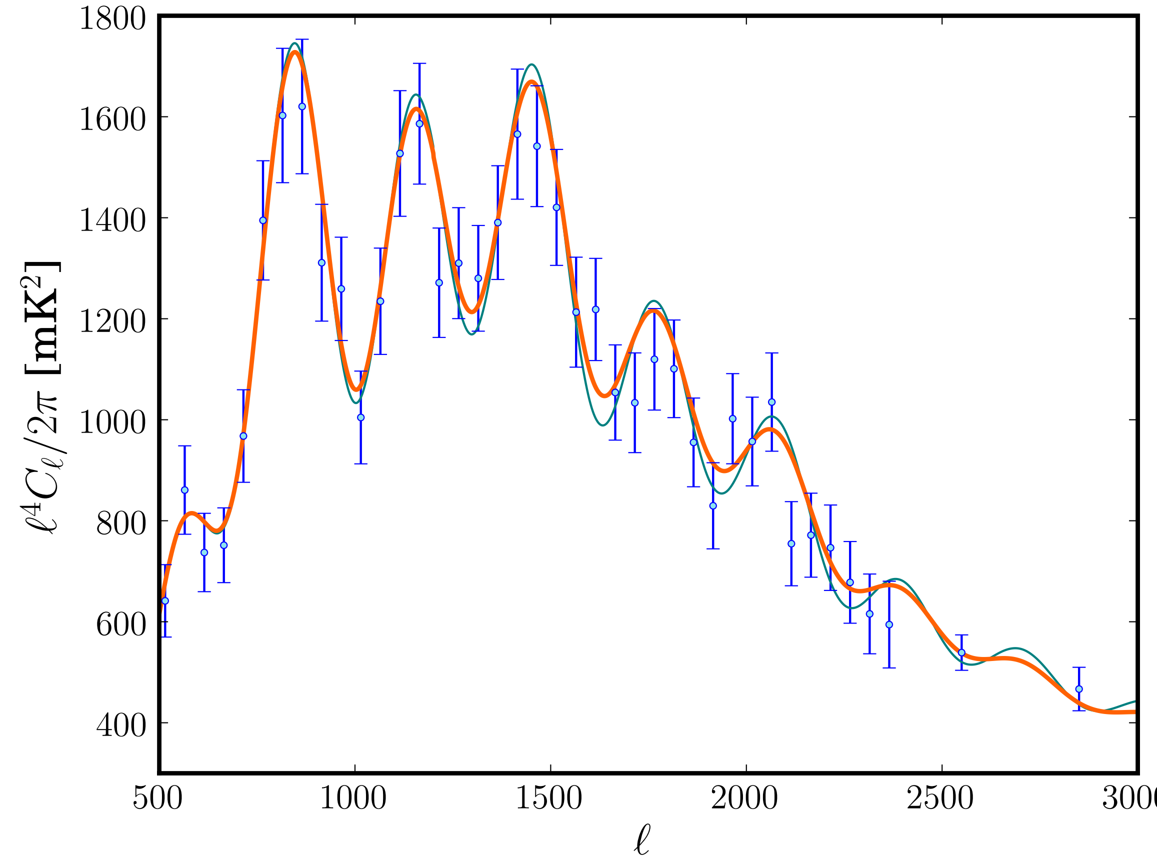
Convergence: $\kappa = \frac{1}{2}\nabla \cdot \mathbf{d}$

Smearing of acoustic peaks in ACT's spectrum lets us see lensing at ~ 3σ

Das et al.
ApJ, 729, 1 (2011)

$$C_\ell^{\phi\phi} \rightarrow A_L C_\ell^{\phi\phi}$$

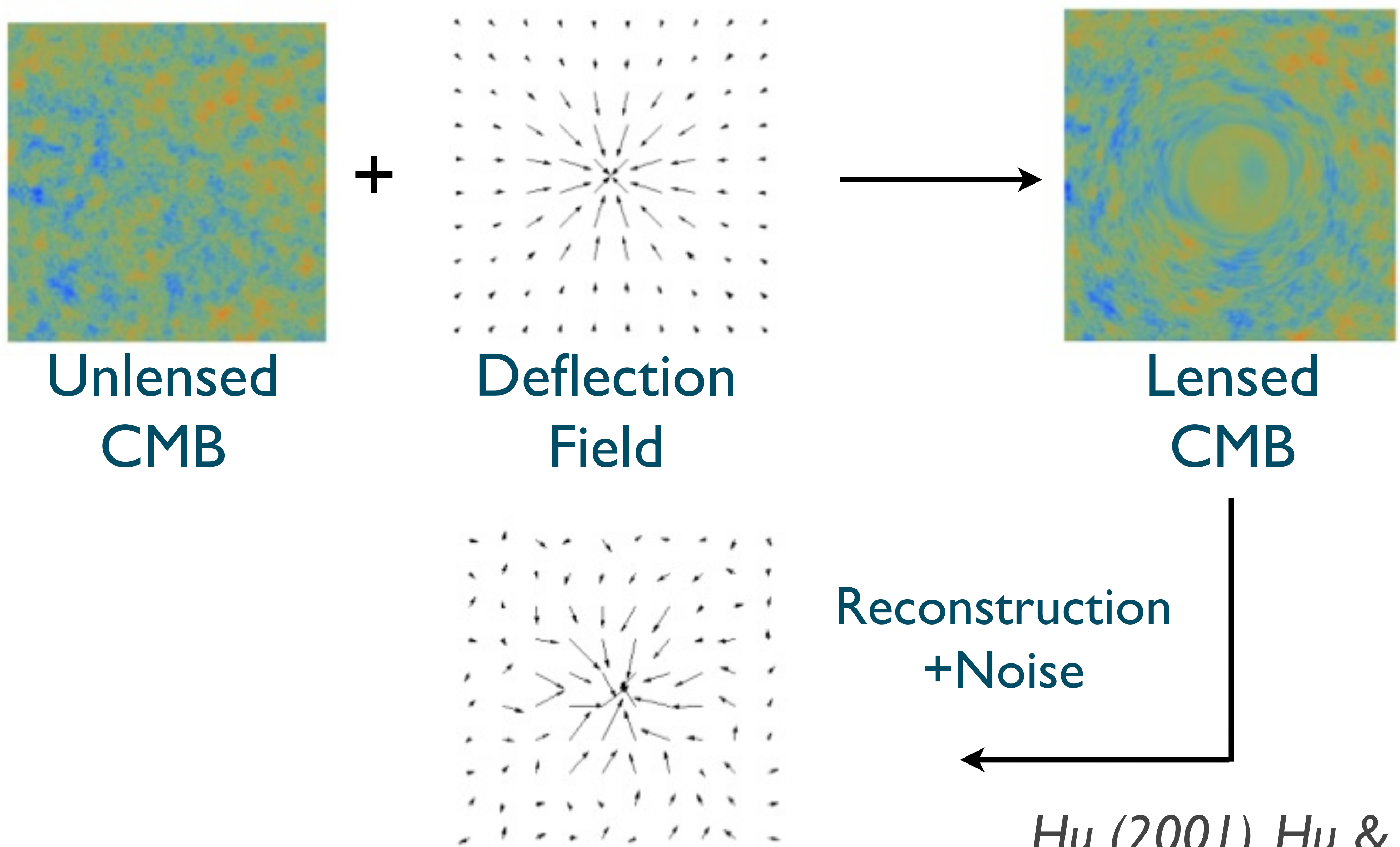




- Test for lensing in spectrum by marginalizing over (unphysical) parameter A_L, scaling lensing potential. [Calabrese et al 2008]
- Expect $A_L = 1$, and unlensed has $A_L = 0$. See lensing at almost 3σ level.

LENSING RECONSTRUCTION

Given only the lensed CMB sky, can we estimate the deflection field?



Hu (2001), Hu & Okamoto (2002)

See Sherwin & Das (2010) for a new bias free method.

LENSING MAKES THE CMB UNIQUELY SENSITIVE TO GEOMETRY AND STRUCTURE

CMB lensing can be fully described via the deflection field:

$$\Theta(\hat{n}) = \tilde{\Theta}(\hat{n} + \nabla\phi)$$

Lensed — Unlensed — Deflection Field

$$\phi = -2 \int \frac{d_A(\eta_0 - \eta)}{d_A(\eta) d_A(\eta_0)} \Phi(\eta\hat{n}, \eta)\, d\eta$$

Effective Lensing Potential — Geometry — Matter potential

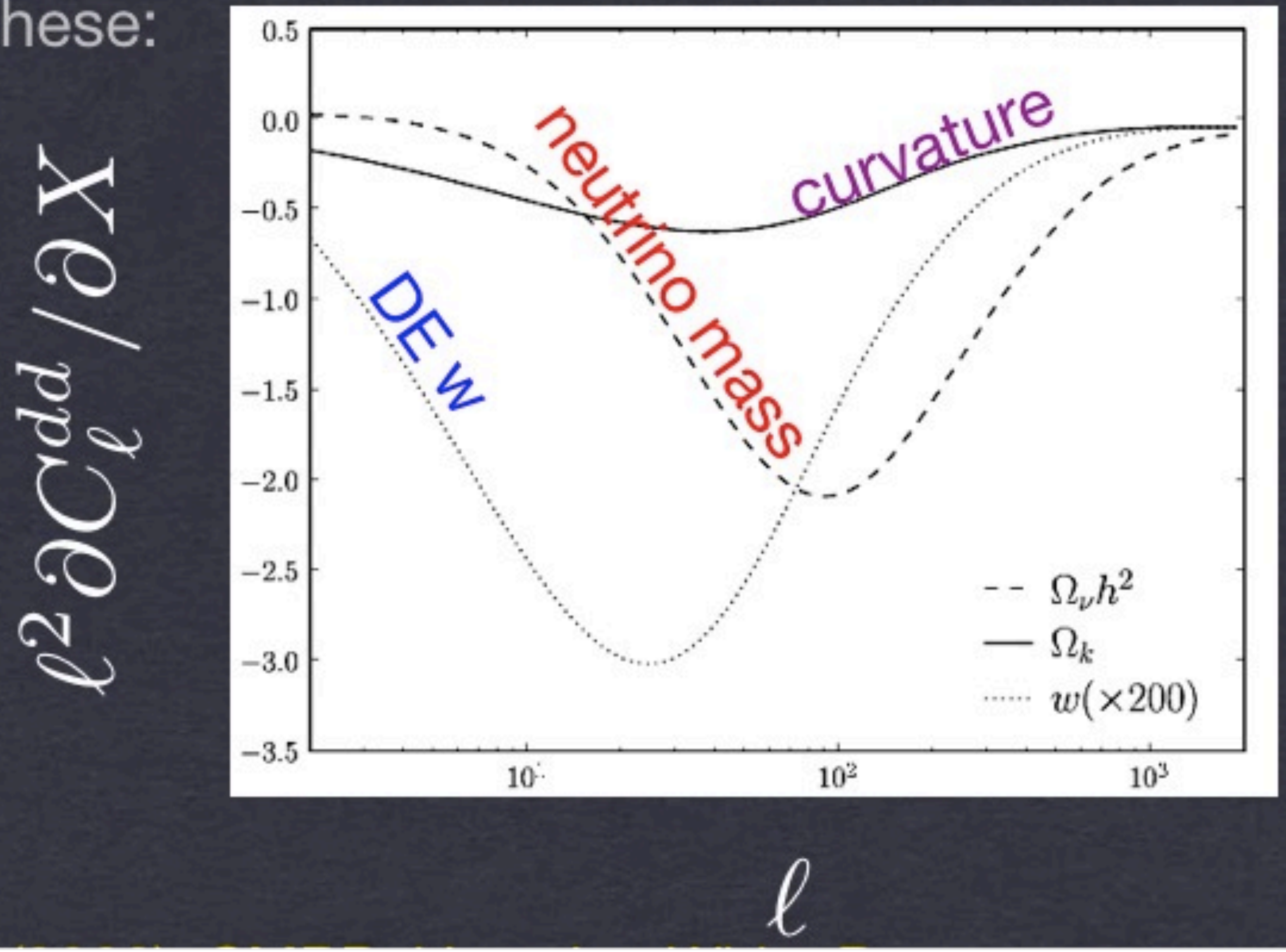
Affected by parameters that affect distance scales and growth of structure in the late universe.

For high z lenses (clusters, galaxies) CMB is the only source !

LENSING MAKES THE CMB UNIQUELY SENSITIVE TO GEOMETRY AND STRUCTURE

The primary CMB can be kept nearly unchanged under variations of neutrino mass, dark energy equation of state or curvature. But the deflection field cares about these:

Lensing breaks the angular diameter distance degeneracy!



Smith, Cooray, Das, Dore et al., CMBPOL Lensing White Paper (2009)

Sudeep Das, DPF, Aug 11, 2011

We also detect lensing at 4-sigma internally from the CMB 4-point function

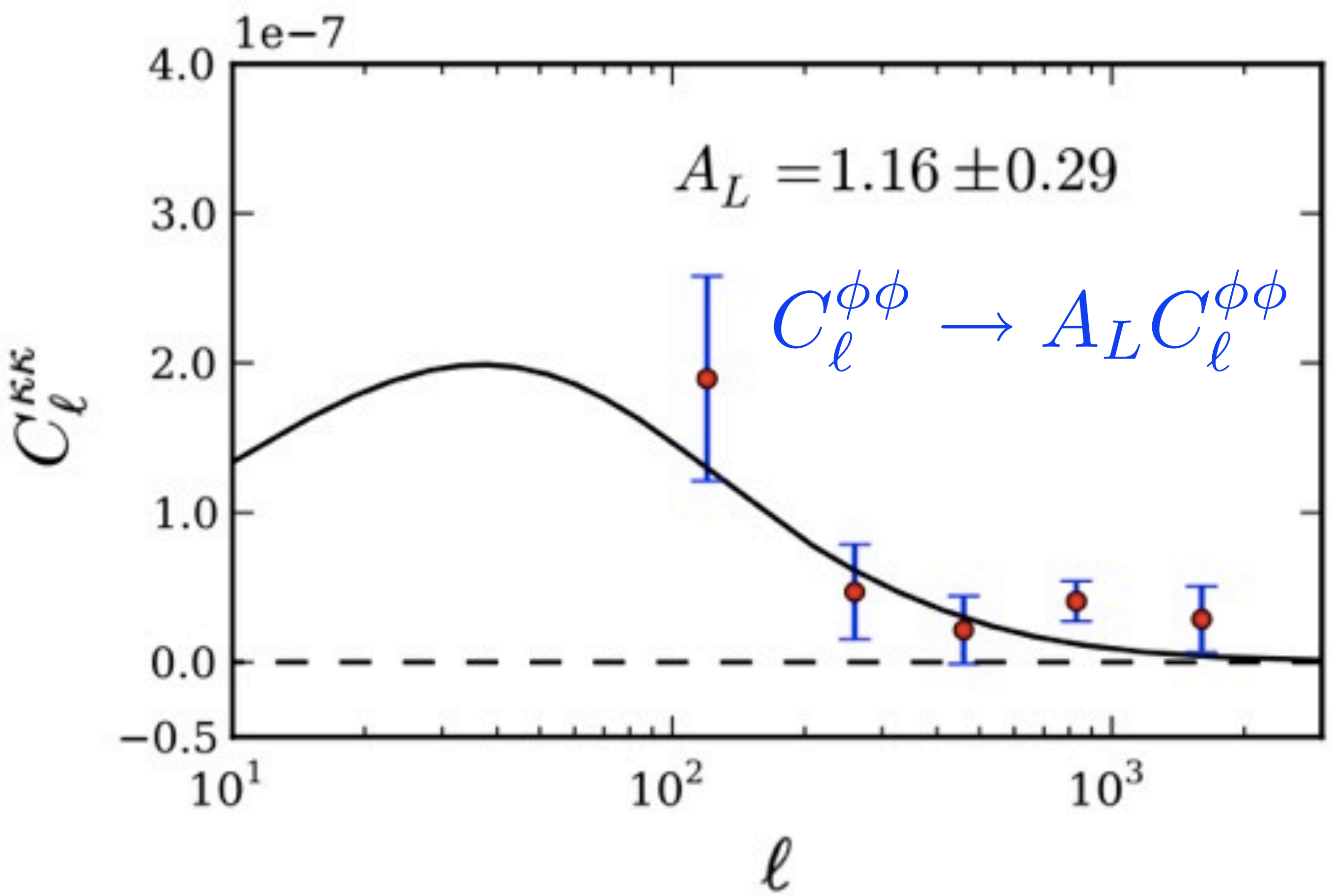


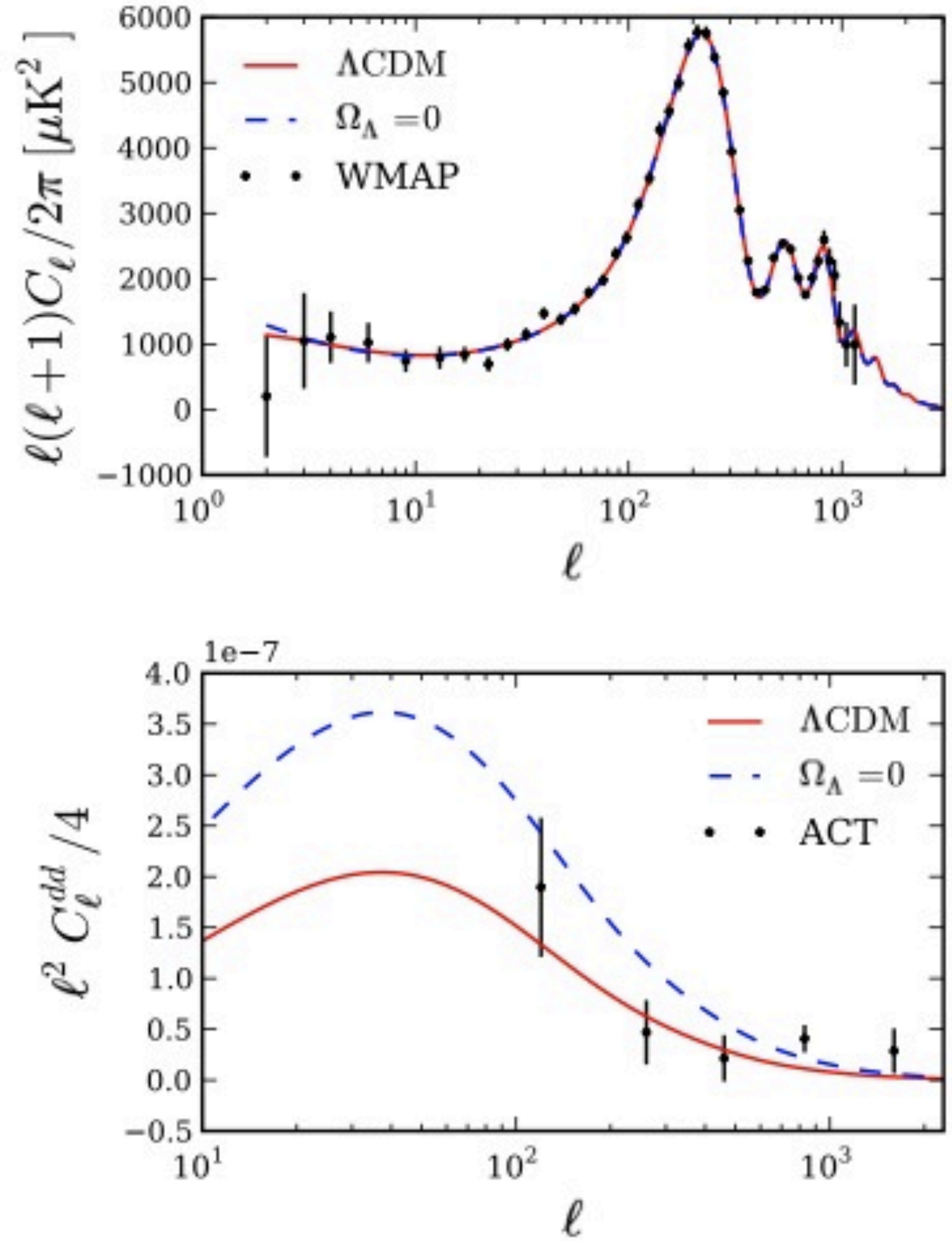
FIG. 2. Convergence power spectrum (red points) measured from ACT equatorial sky patches. The solid line is the power spectrum from the best-fit WMAP+ACT cosmological model with amplitude $A_L = 1$, which is consistent with the measured points. The error bars are from the Monte Carlo simulation results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

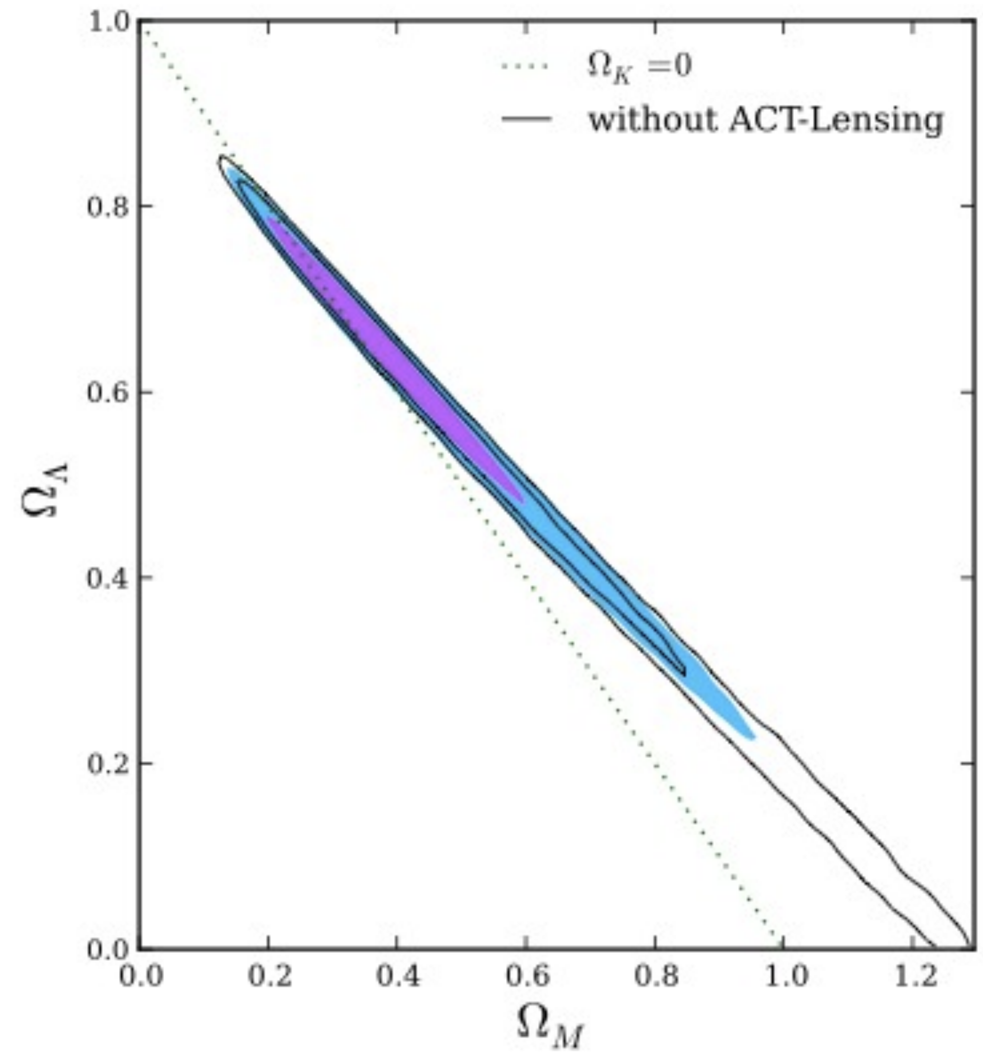
First internal detection of CMB lensing.

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

Das, Sherwin et al., PRL 107:021301 (2011)

DARK ENERGY FROM CMB ALONE





Sherwin, Dunkley, Das et al., PRL 107:021302 (2011)

POLARIZATION GIVES EXTRA LEVERAGE FOR LENSING RECONSTRUCTION

Gravitational lensing remaps the primordial CMB temperature and polarization fields through the deflection field **d(n)**:

$$\begin{aligned} \tilde{T}(\hat{\mathbf{n}}) &= T(\hat{\mathbf{n}} + \mathbf{d}(\hat{\mathbf{n}})) \\ [\tilde{Q} \pm i\tilde{U}](\hat{\mathbf{n}}) &= [Q \pm iU](\hat{\mathbf{n}} + \mathbf{d}(\hat{\mathbf{n}})) \end{aligned}$$

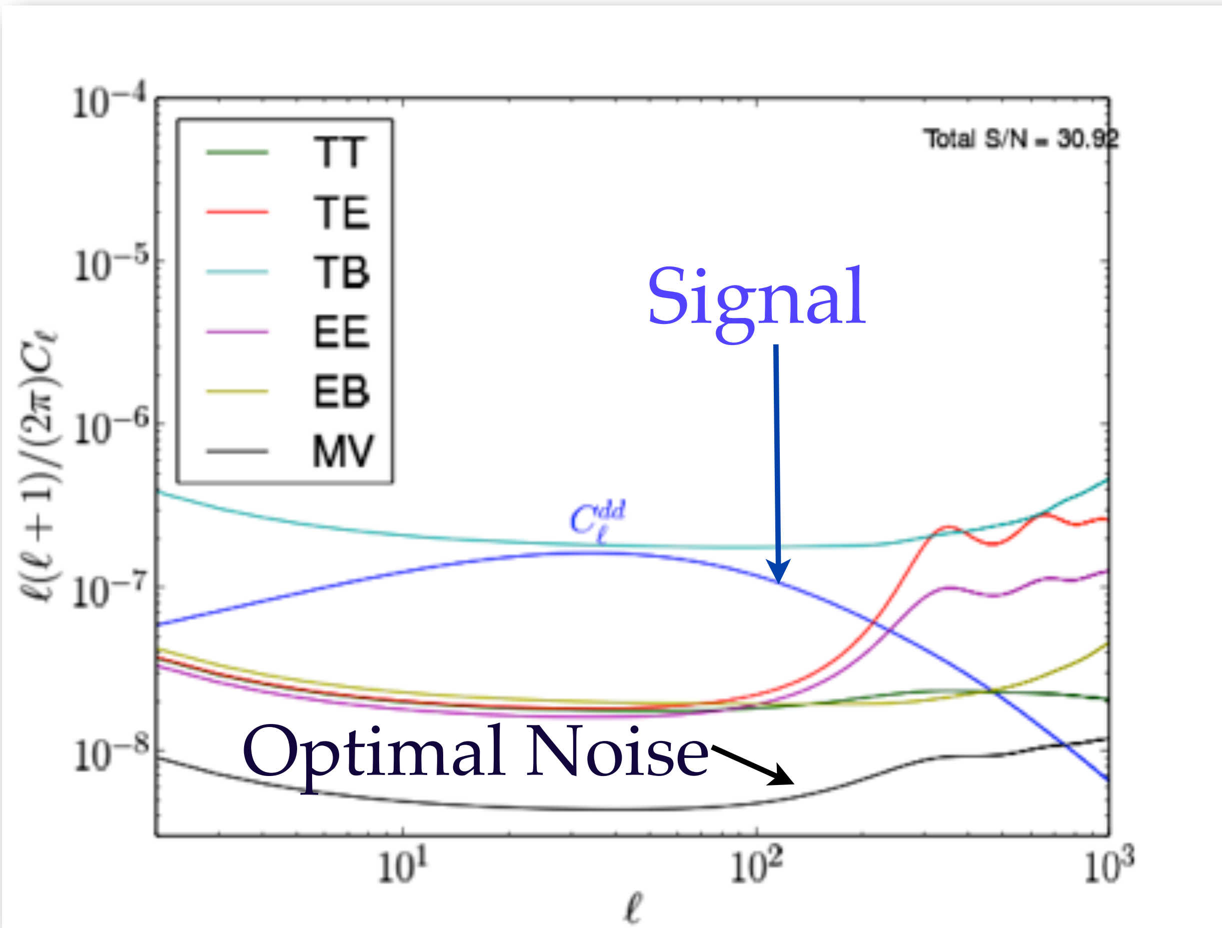
In the Fourier space, lensing introduces correlations between different Fourier modes $\boldsymbol{\ell}, \ \boldsymbol{\ell}'$, which are uncorrelated for the primordial signals. This correlation is used to write down an estimator of the deflection field from the observed fields. Schematically:

$$\hat{\mathbf{d}}_{XY}(\mathbf{L}) \propto \tilde{X}(\boldsymbol{\ell})\tilde{Y}(\mathbf{L}-\boldsymbol{\ell})$$

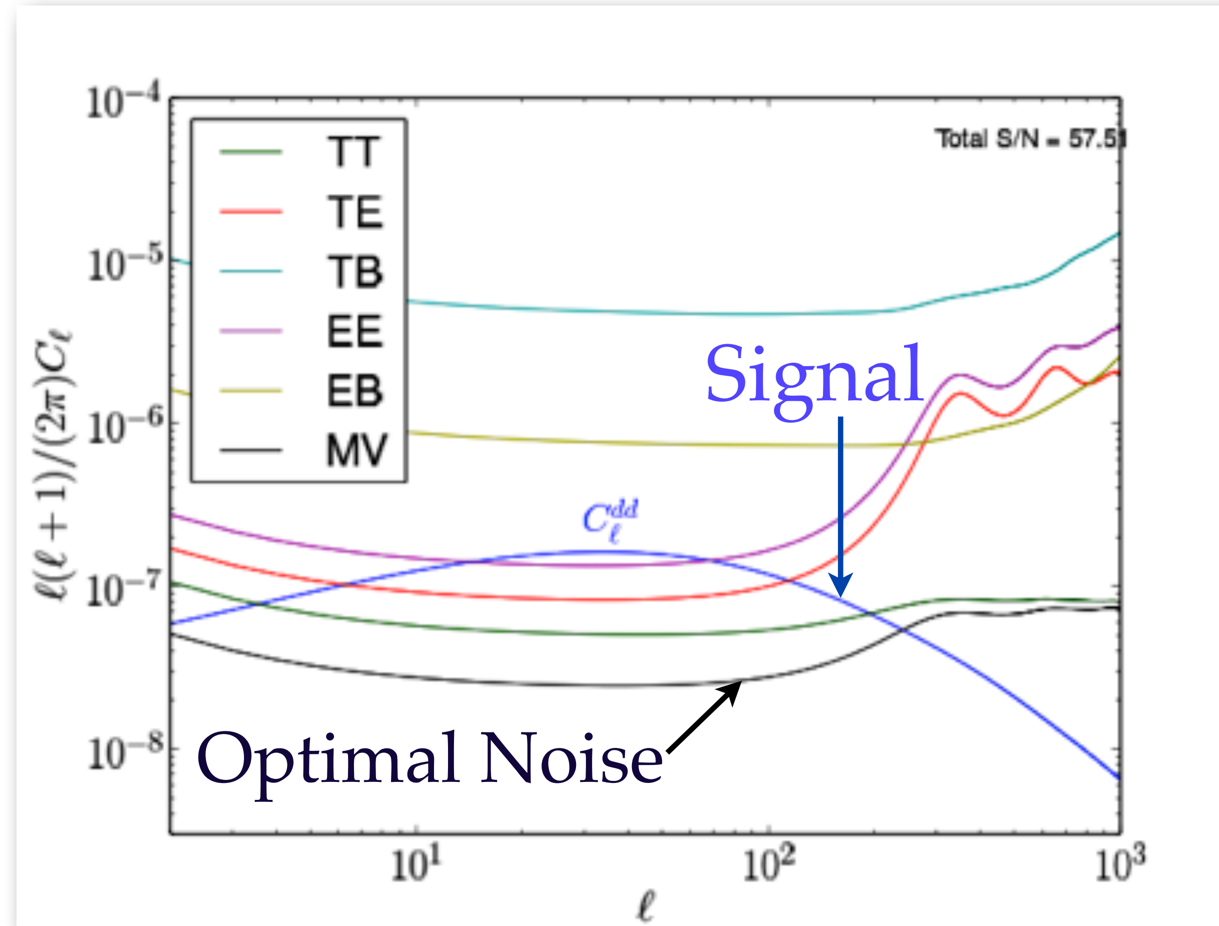
where $X, Y \in (\tilde{T}, \tilde{E}, \tilde{B})$

ACTPOL: DESIGNED TO BE A POWERFUL CMB LENSING MACHINE

Assuming no systematics other than instrumental noise, these plots show the signal and noise power spectra for the Deep and Wide configurations.



ACTPOL-DEEP:
150 sq-deg @ 3 μK-arcmin (temp) and 5 μK-arcmin (pol)



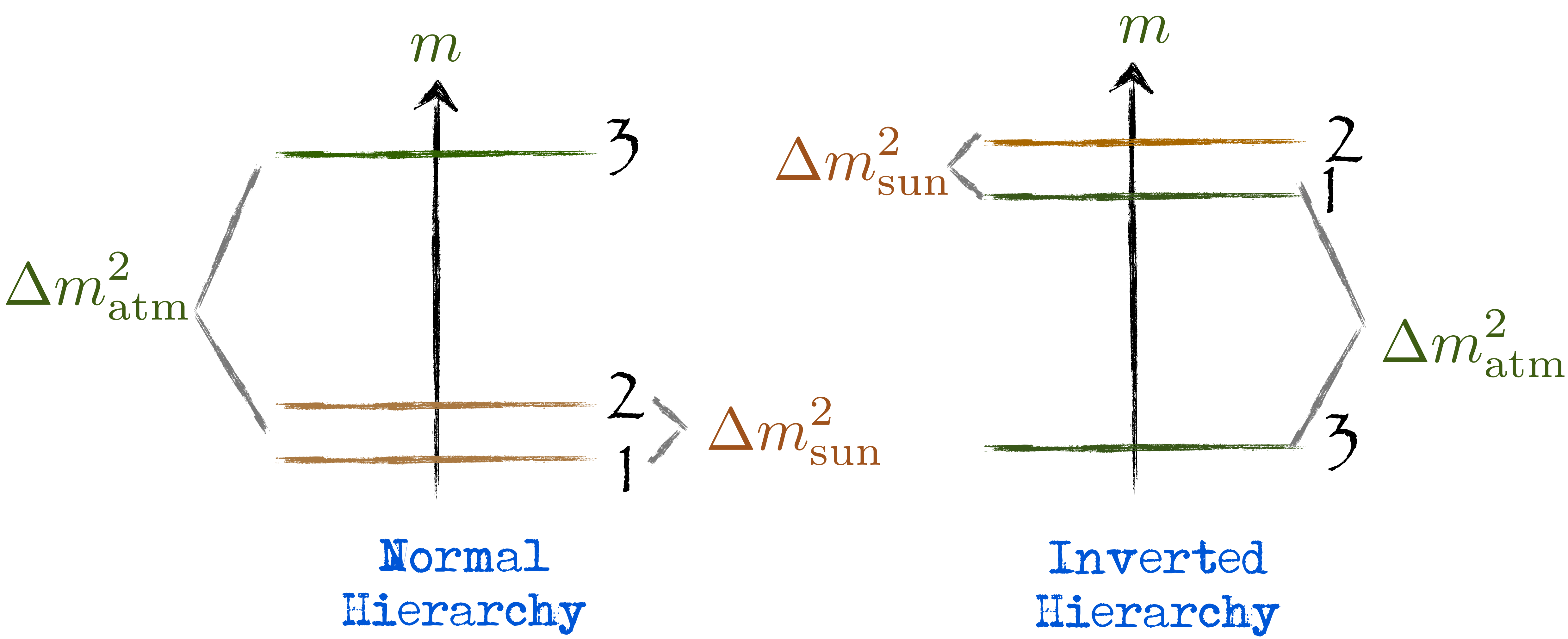
ACTPOL-WIDE:
4000 sq-deg @ 20 μK-arcmin (temp) and 28 μK-arcmin (pol)

CMB LENSING APPLICATION: TOTAL MASS OF NEUTRINOS

Some Facts about Neutrinos

neutrino oscillations imply a **minimum sum of neutrino masses of** 0.05 eV

$|\Delta m^2_{\rm atm}| \sim 2.4 \times 10^{-3}\ {\rm eV}^2 \quad \Delta m^2_{\rm sun} \sim 8 \times 10^{-5}\ {\rm eV}$



SUB-EV NEUTRINOS ACT AS RADIATION AT Z<1000 AND AS MATTER AT LATE TIMES

Non-relativistic neutrinos have large thermal speeds:

$$c_\nu \simeq 81\ (1+z)\left(\frac{\mathrm{eV}}{m_\nu}\right)\ \mathrm{km\ s}^{-1}$$

Compare: Velocity dispersion in a galaxy ~ 100 km/s.

free streaming length scale

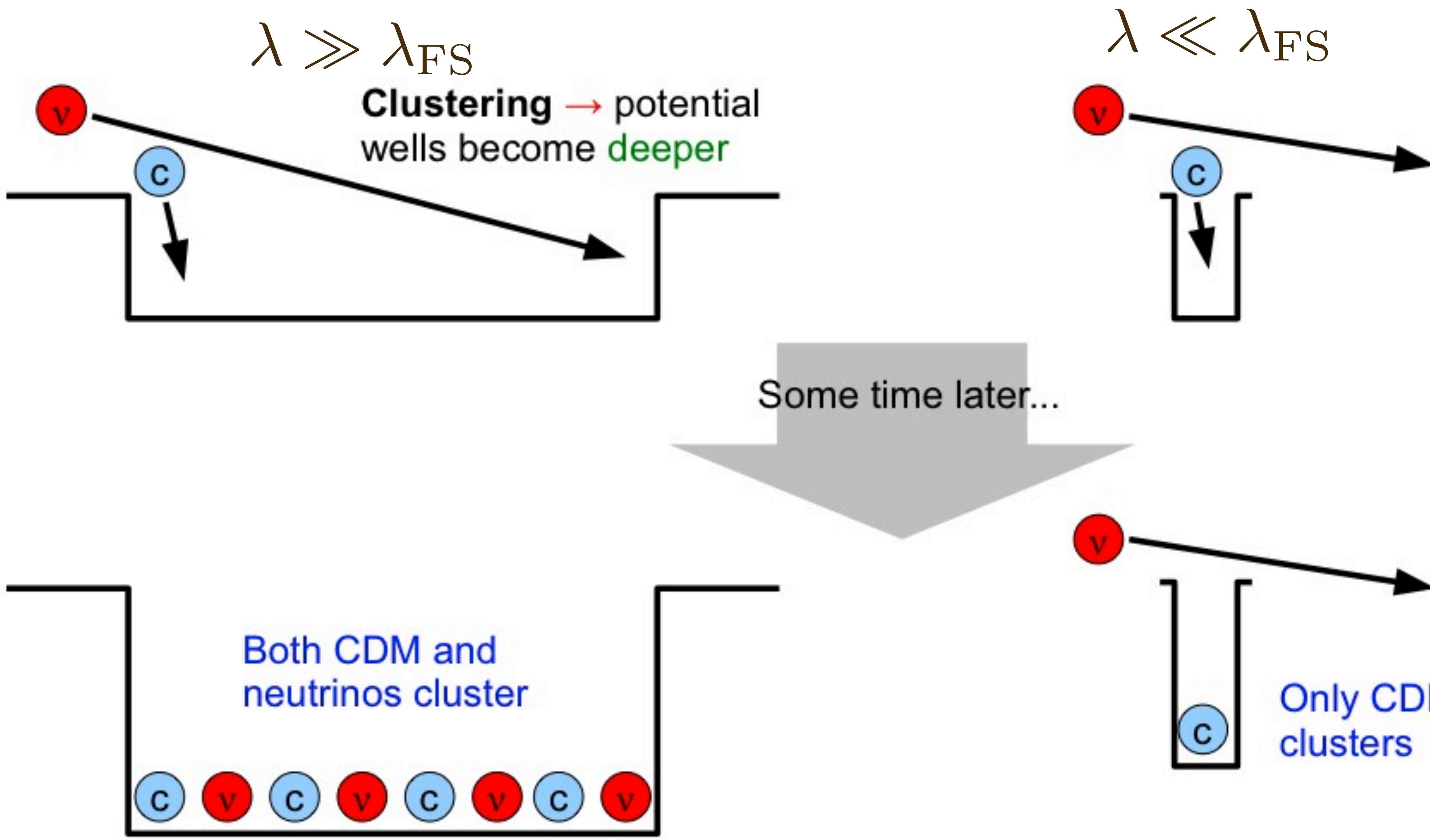
$$\lambda_{\mathrm{FS}} \equiv \sqrt{\frac{8\pi^2 c_\nu^2}{3\Omega_m H^2}} \simeq 4.2\sqrt{\frac{1+z}{\Omega_{m,0}}}\left(\frac{\mathrm{eV}}{m_\nu}\right)\ h^{-1}\ \mathrm{Mpc}$$

frequency

$$k_{\mathrm{FS}} \equiv \frac{2\pi}{\lambda_{\mathrm{FS}}}$$

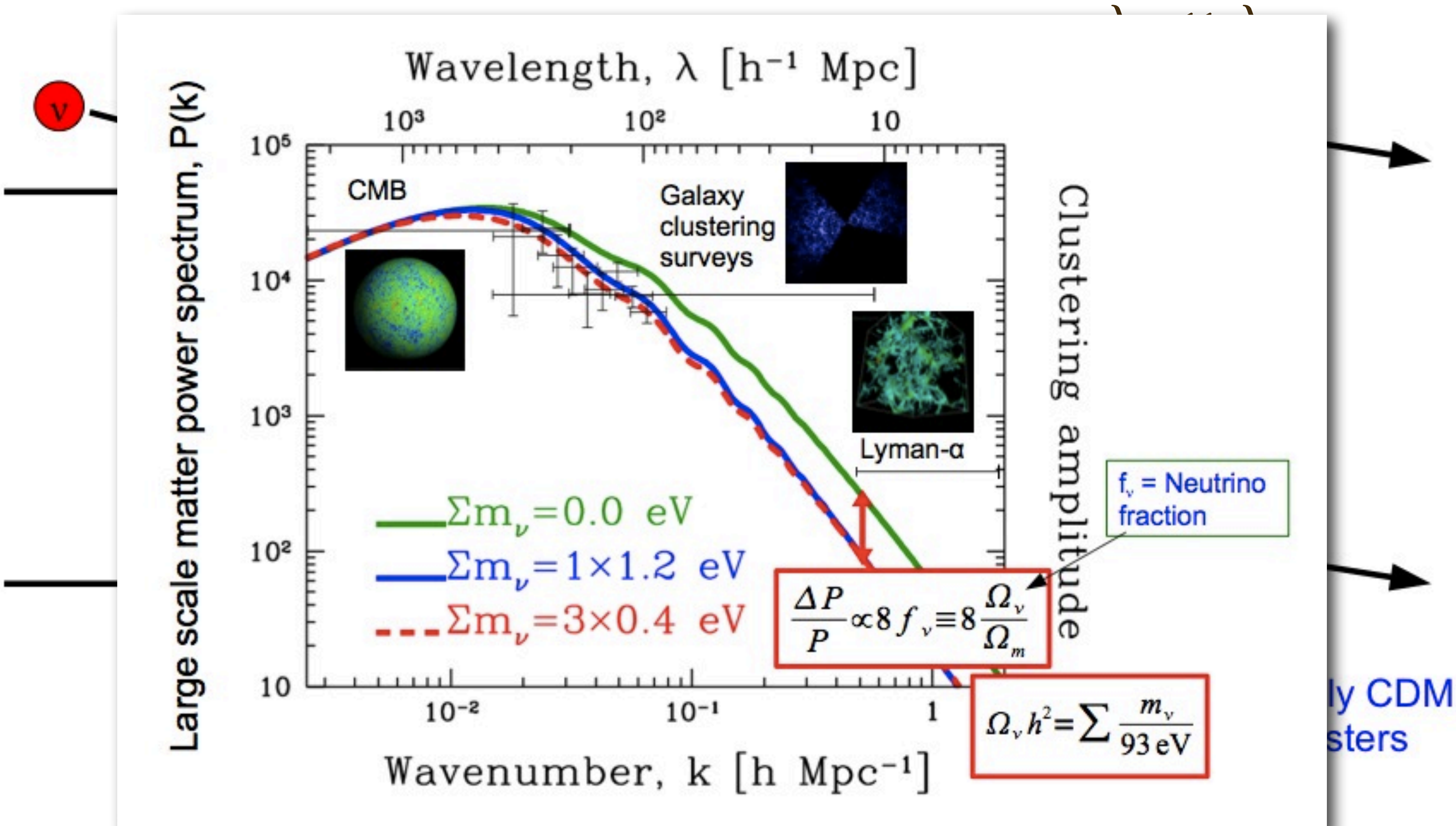
Non-relativistic neutrinos do not cluster for $\lambda \ll \lambda_{\mathrm{FS}}$ (small scales or large k's)

MASSIVE NEUTRINOS DO NOT CLUSTER ON SMALL SCALES



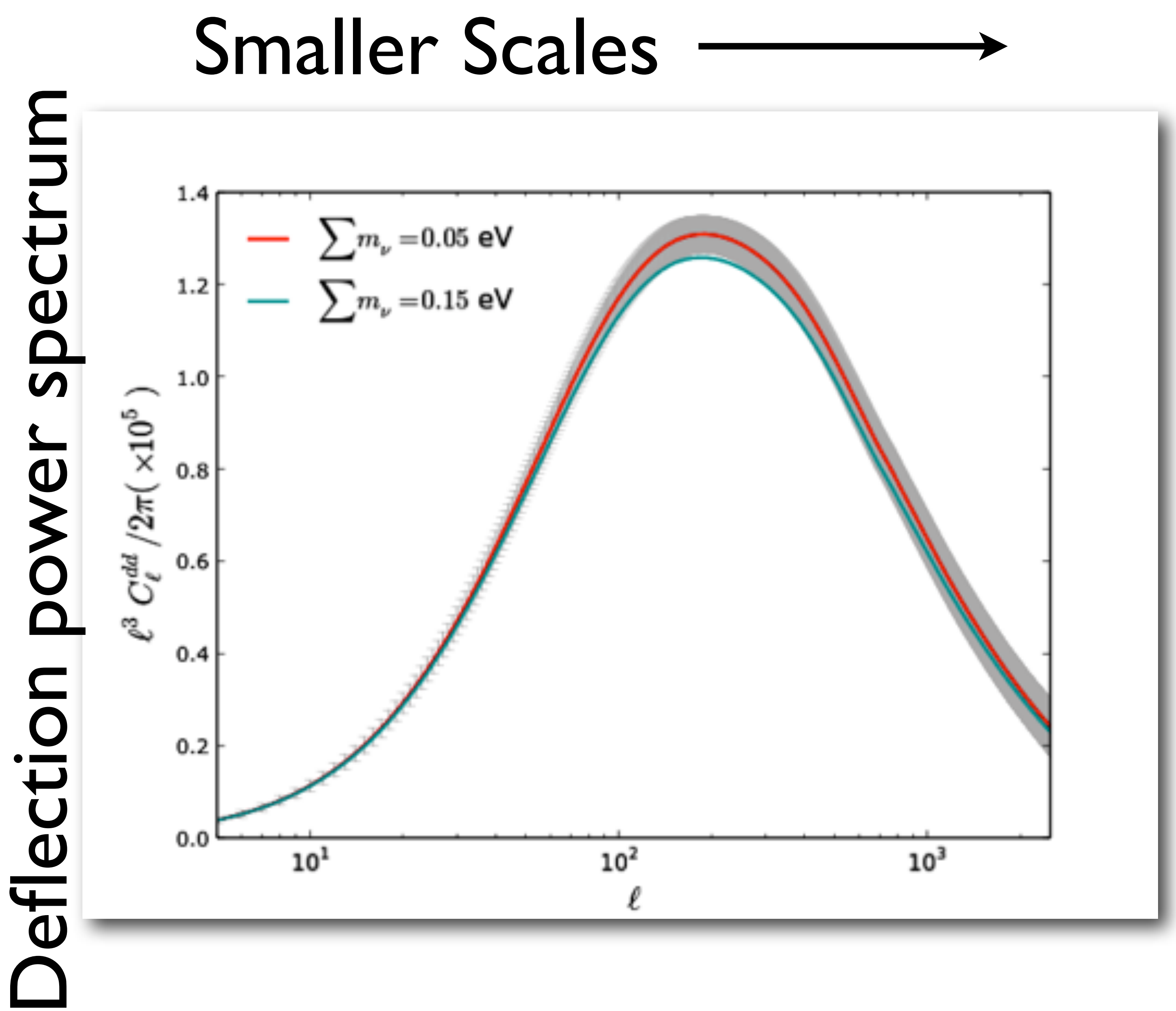
Graphics from Y. Wong

MASSIVE NEUTRINOS SUPPRESS STRUCTURE FORMATION ON SMALL SCALES



Graphics from Y. Wong

CMB LENSING IS A CLEAN AND SENSITIVE PROBE OF NEUTRINO MASS



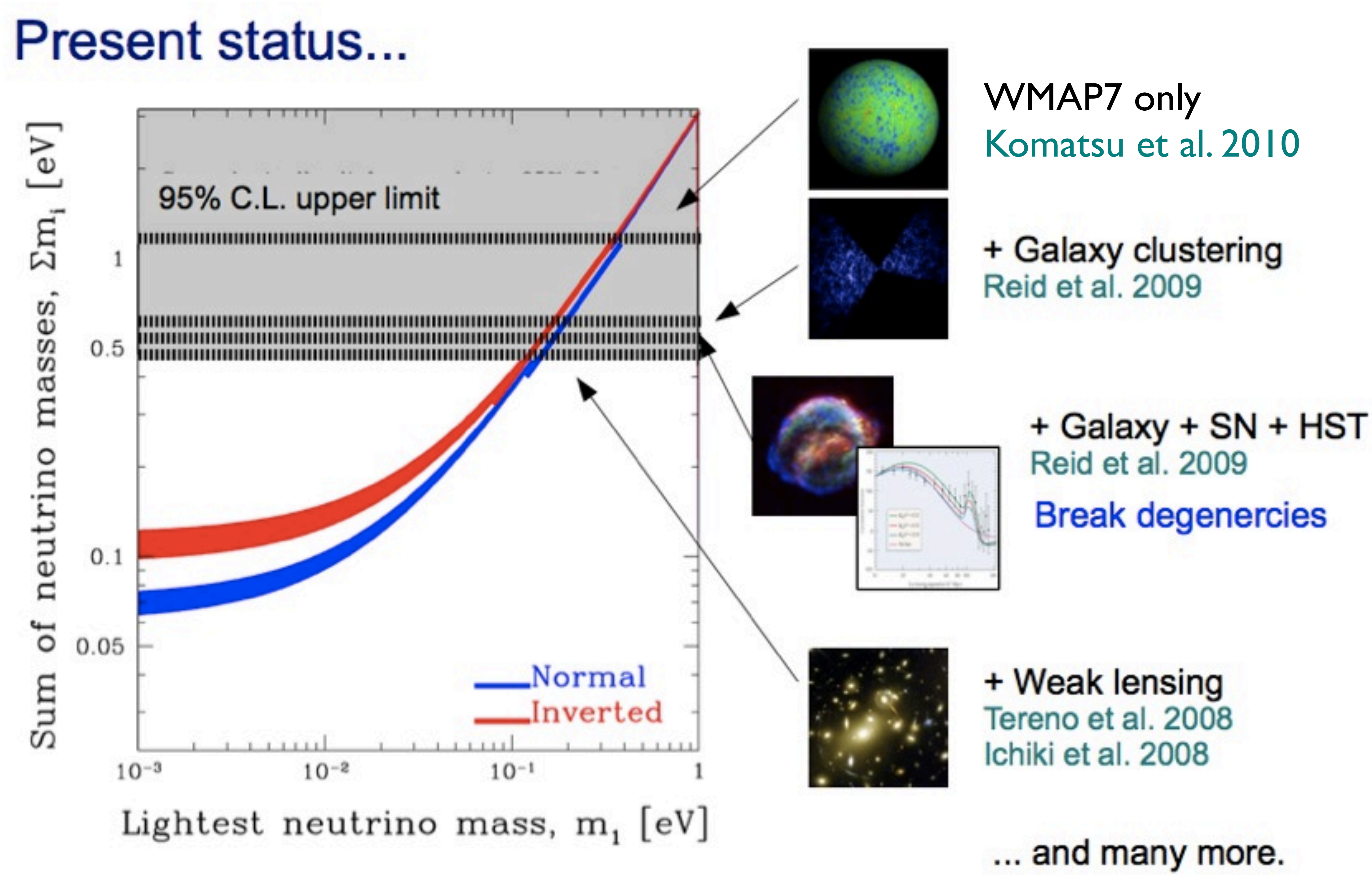
CMB lensing is sensitive:

The deflection field contains cumulative information from a large range of redshift, peaking around z~ 2-3.

CMB lensing is clean:

- CMB redshift known
- Most contributions from linear scales.
- No confusion from galaxy bias.

ACTPOL CAN HELP CONSTRAIN NEUTRINO HIERARCHIES!



Graphic from Y. Wong

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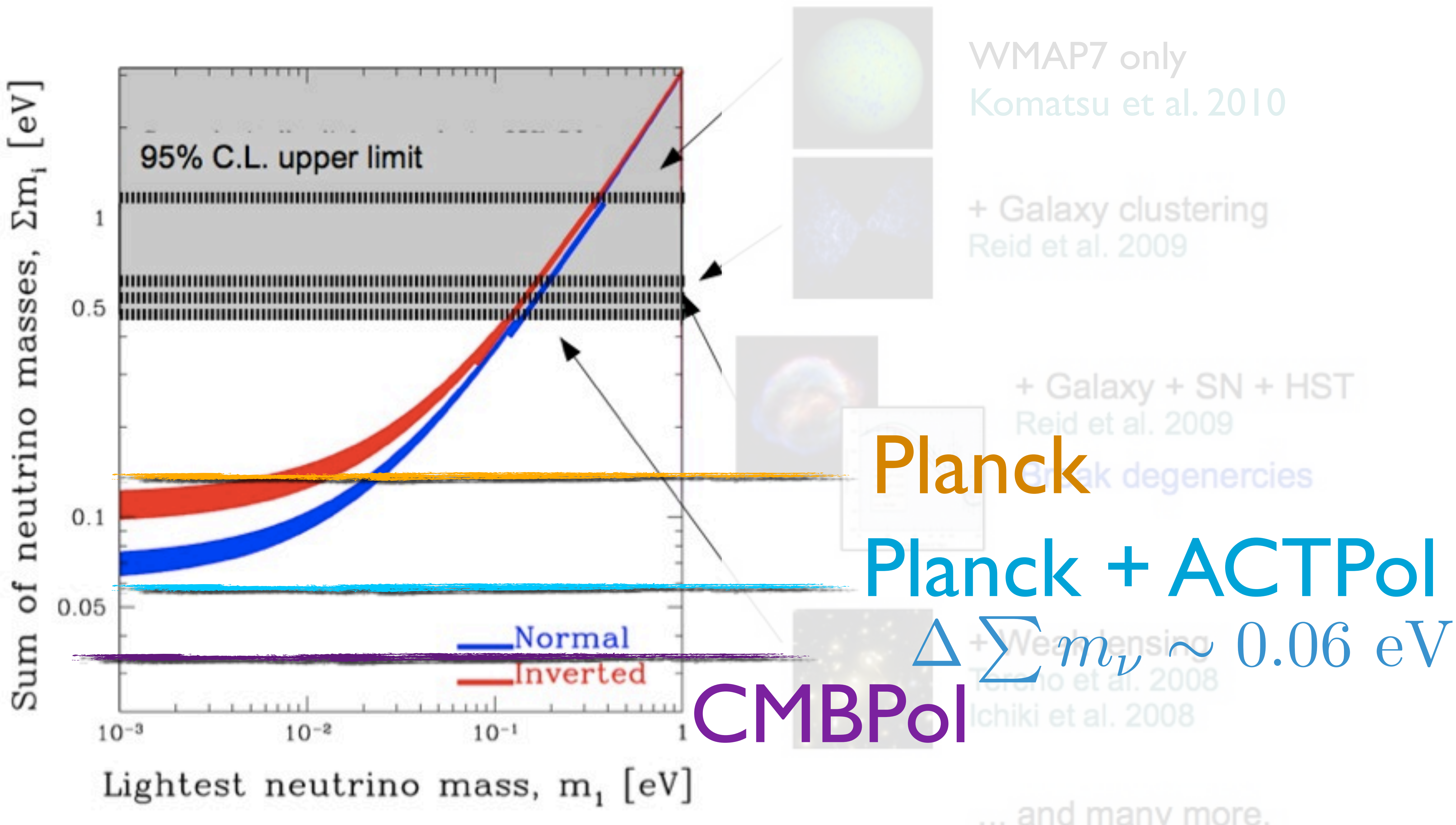

Graphic from Y. Wong

LOOKING AHEAD ... EXCITING TIMES IN CMB PHYSICS!

- Two keywords in the future of CMB: high resolution, polarization
- ACT is a working example, and is already probing fundamental physics.
- CMB lensing is a new and powerful tool.
- Small-scale polarization experiments like PolarBeaR, ACTPol and SPTPol will be primarily CMB lensing machines.
- CMB lensing will provide new constraints on neutrino mass, dark energy, and deviations from GR.
- A large array of cross-correlation projects are possible with the wealth of data in multiple frequencies.
- Be prepared to witness a very productive interplay of CMB, fundamental physics, and astrophysics in the coming years!

Thank YOU!