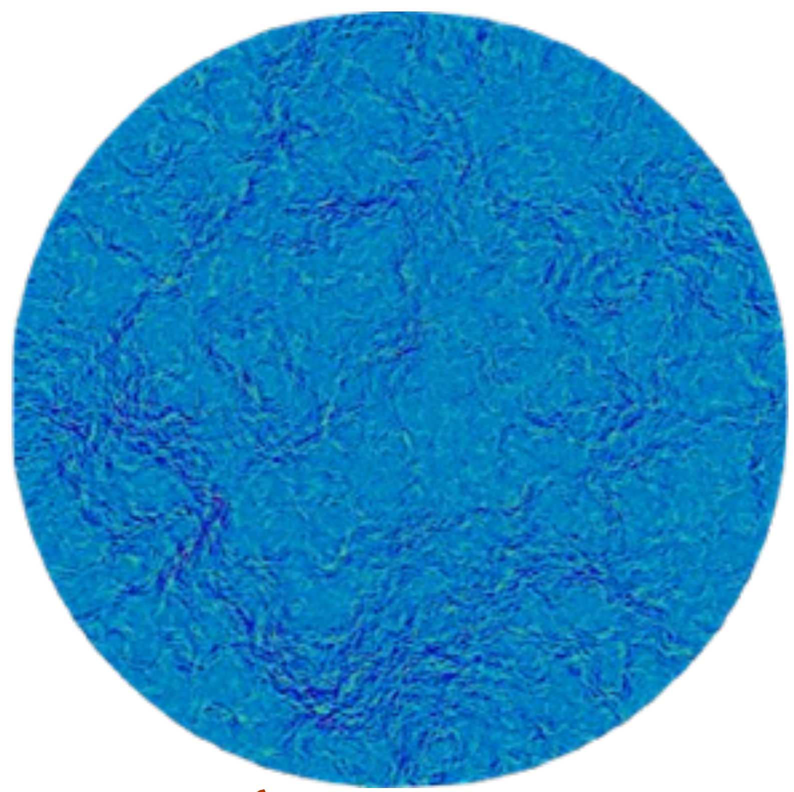
Gravitational Lensing of the Cosmic Microwave Background: A New Frontier

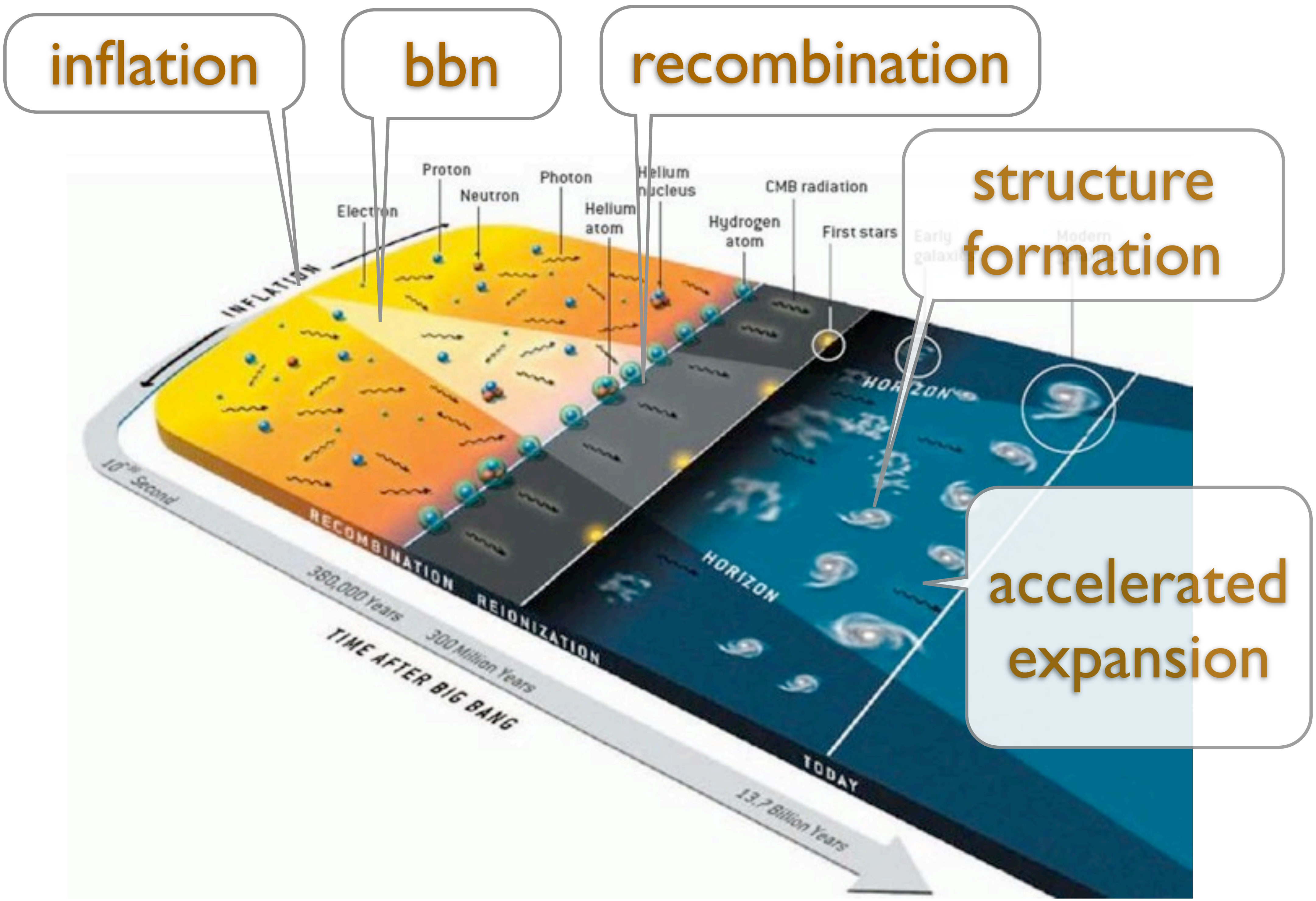


Sudeep Das

Berkeley Center for Cosmological Physics

Paris, July 27, 2012

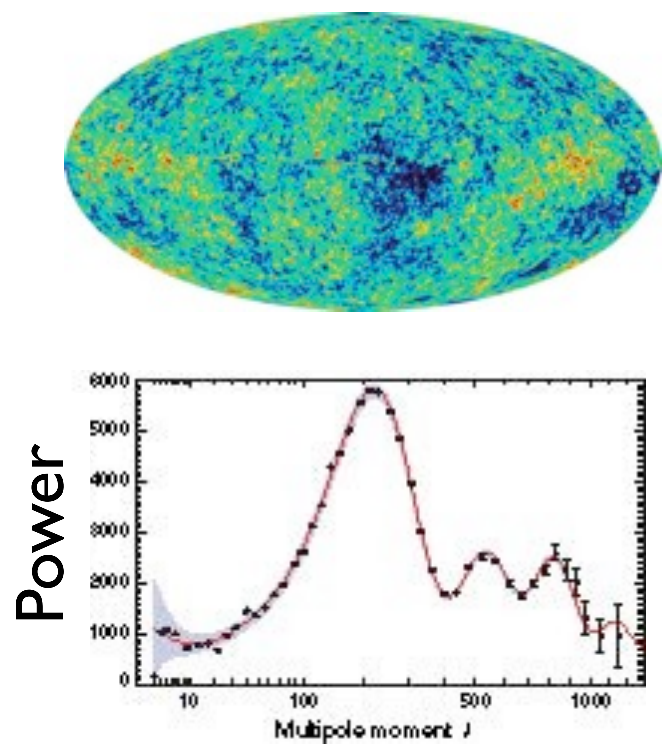
THE TIMELINE OF THE UNIVERSE HAS FIVE MAJOR MILESTONES



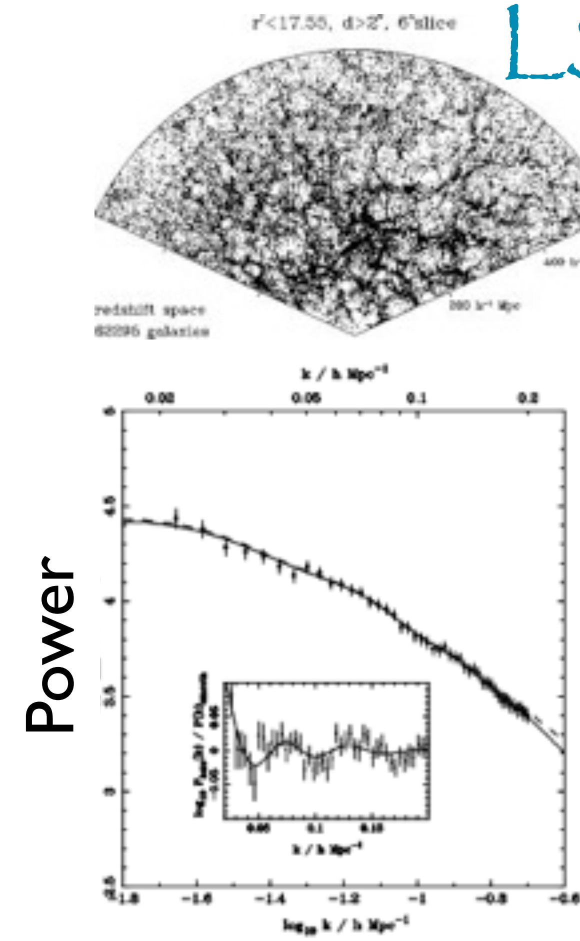
Sudeep Das, Paris, July 27, 2012

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

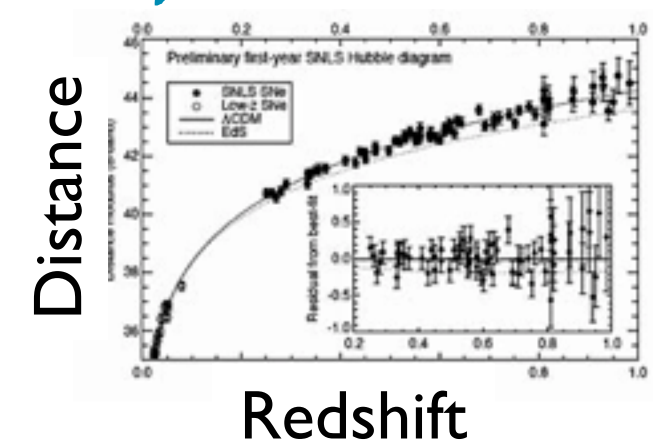
CMB

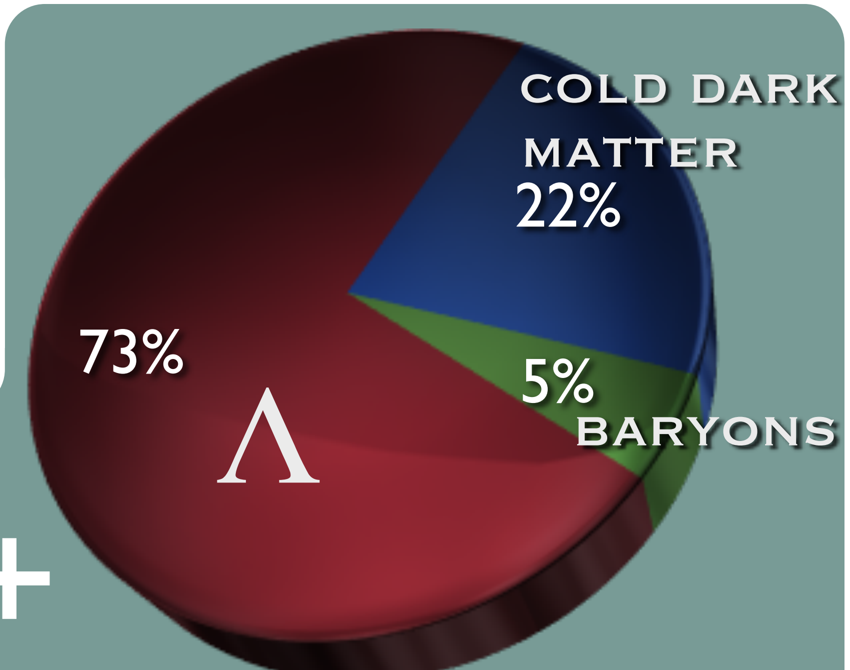


LSS



Supernovae





RECIPE

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

There are big questions within and beyond the standard model

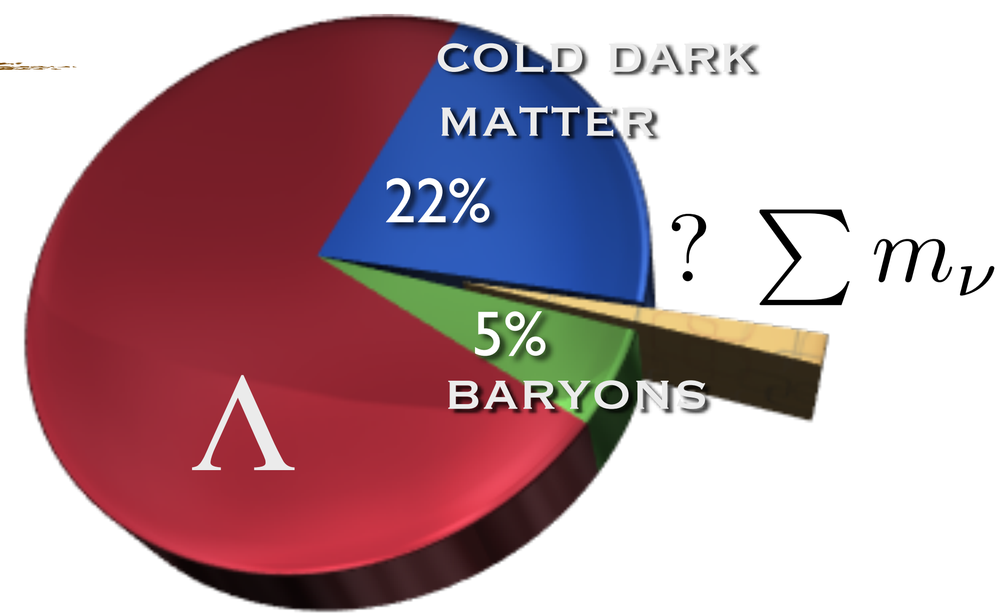
inflation

- 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?

There are big questions within and beyond the standard model

inflation

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

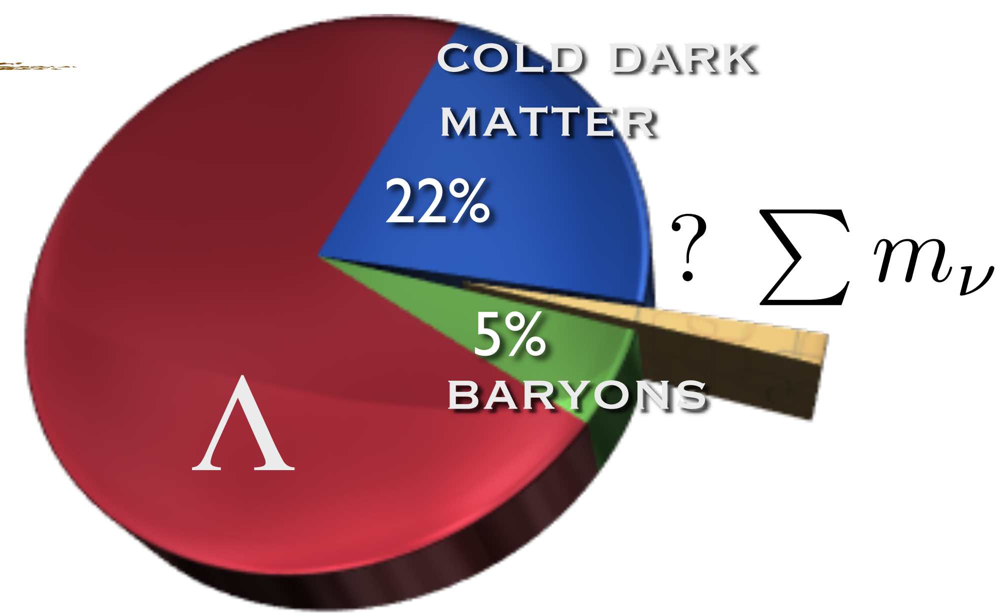
dark sector

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

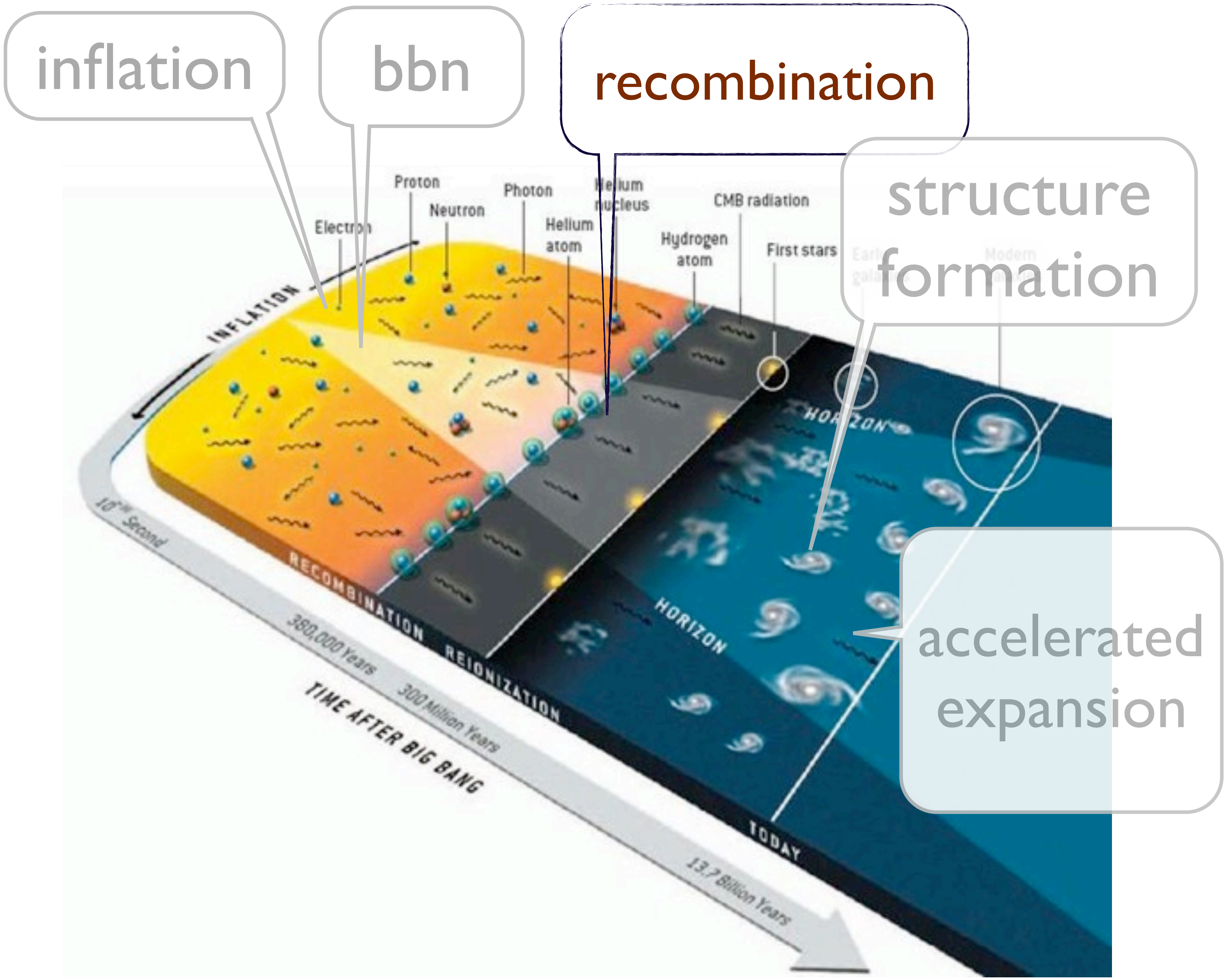
Gravitational Lensing of the CMB is a new tool to probe these issues.

particle sector

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

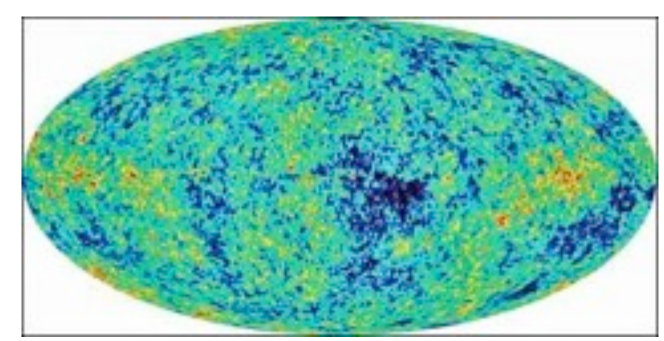


At recombination, the CMB is formed

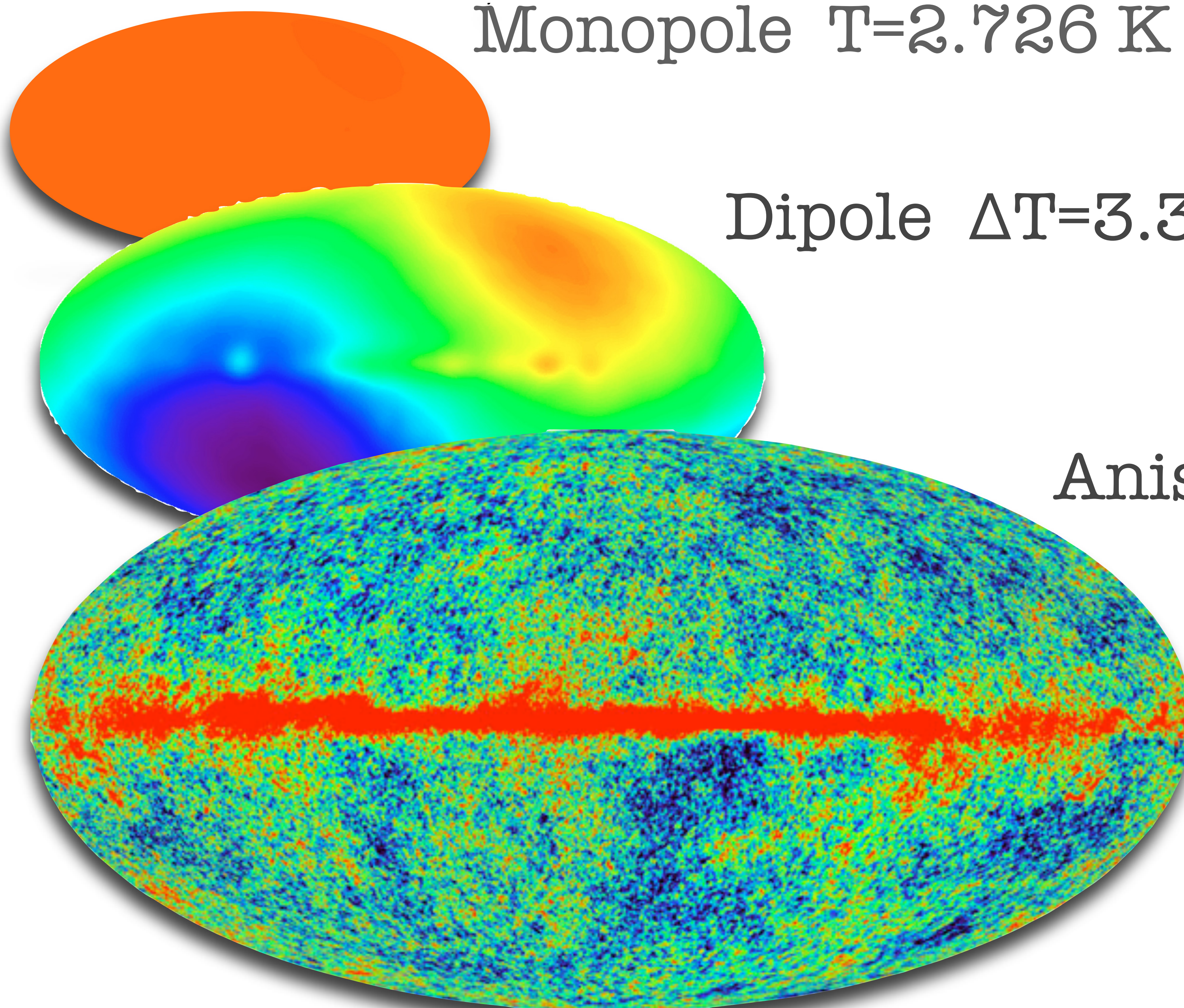


~ 380,000 years since BB

Universe has cooled enough to allow neutral H to form. Free electrons get depleted, and photons start streaming freely.



THE CMB IS EXTREMELY UNIFORM BUT HAS TINY TINY ANISOTROPIES!



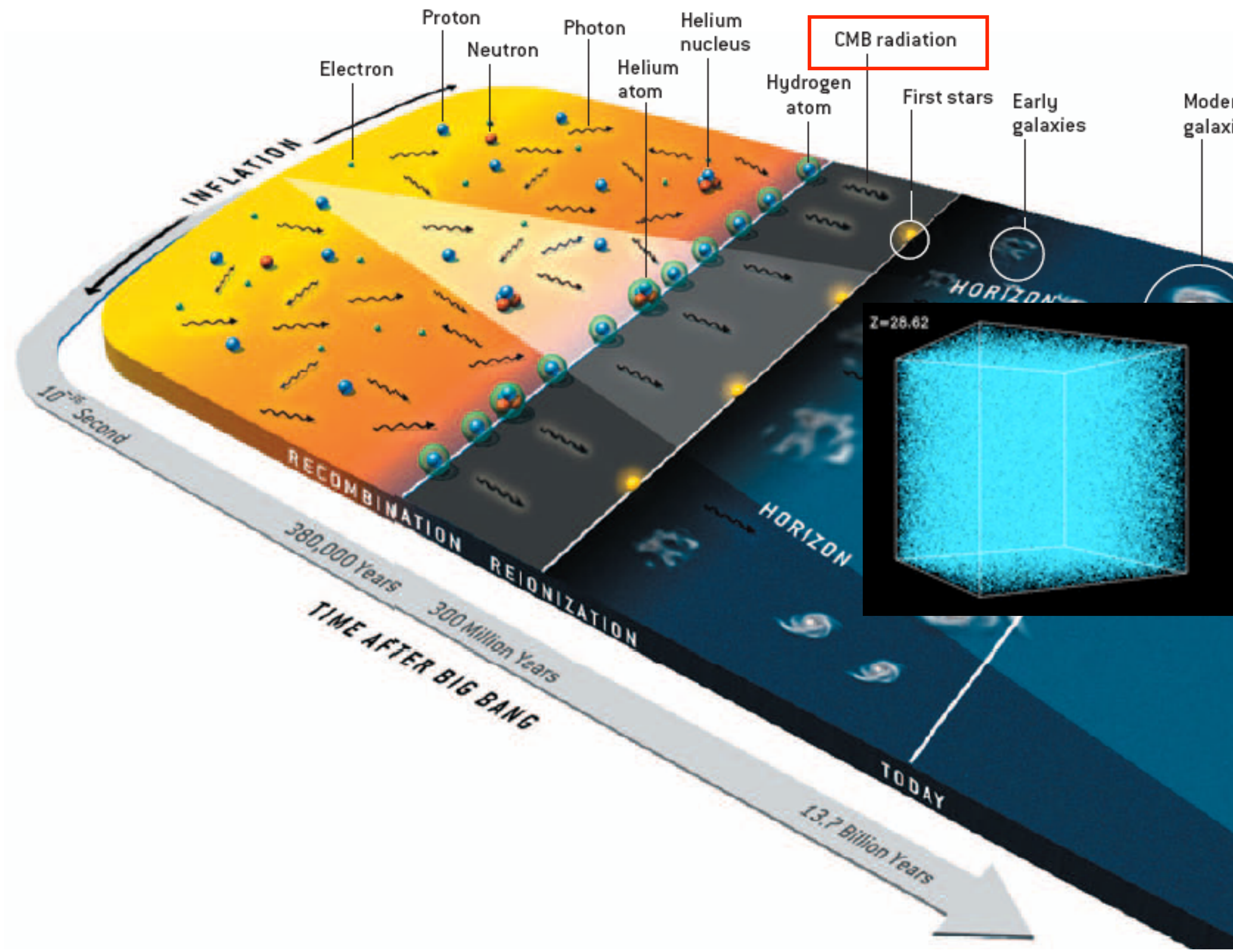
Monopole T=2.726 K

Dipole ΔT=3.353 mK

Anisotropies

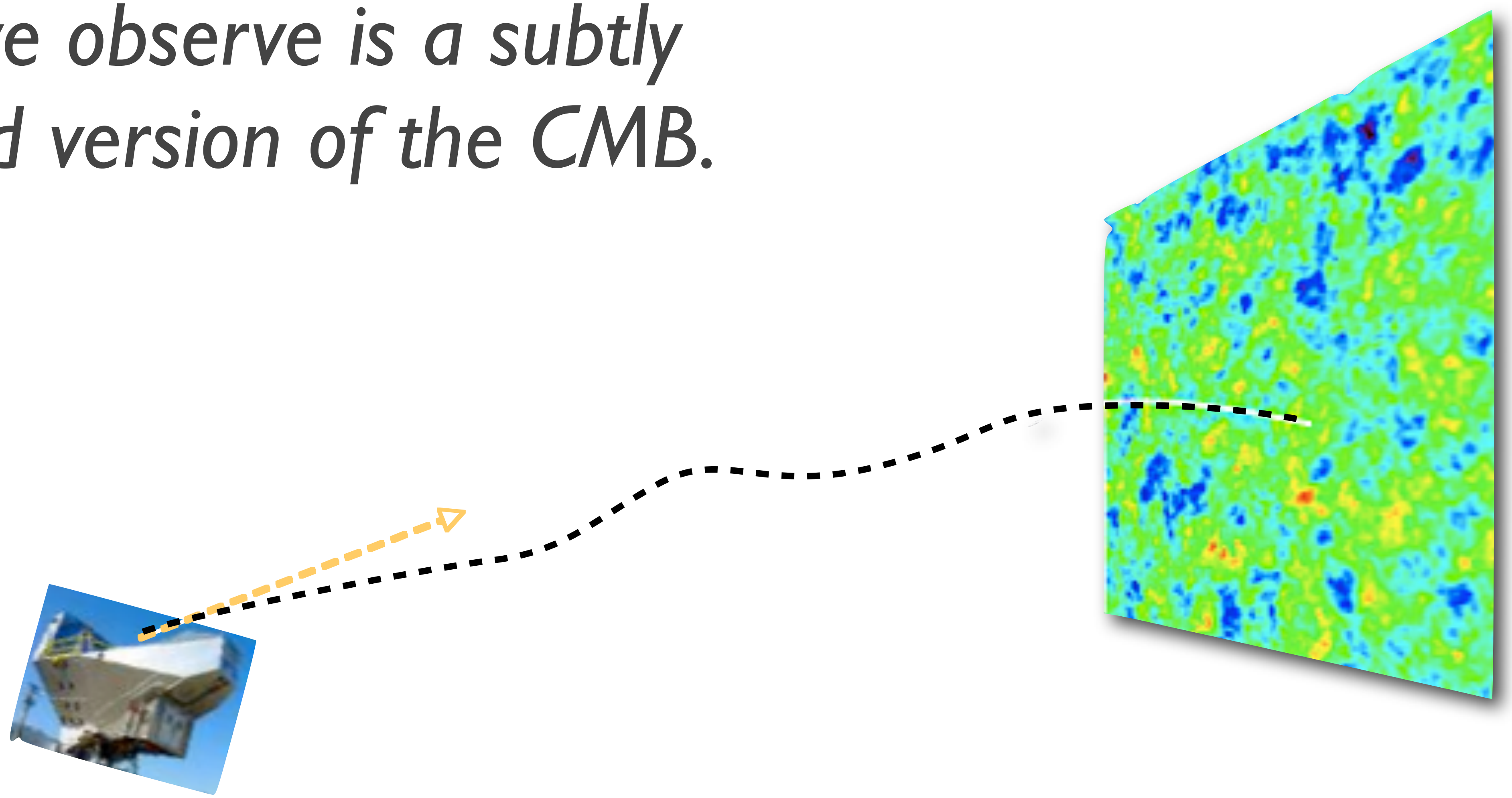
~100 μK rms

CMB photons propagate through evolving large scale structure



Intervening large-scale structure potentials deflect CMB photons

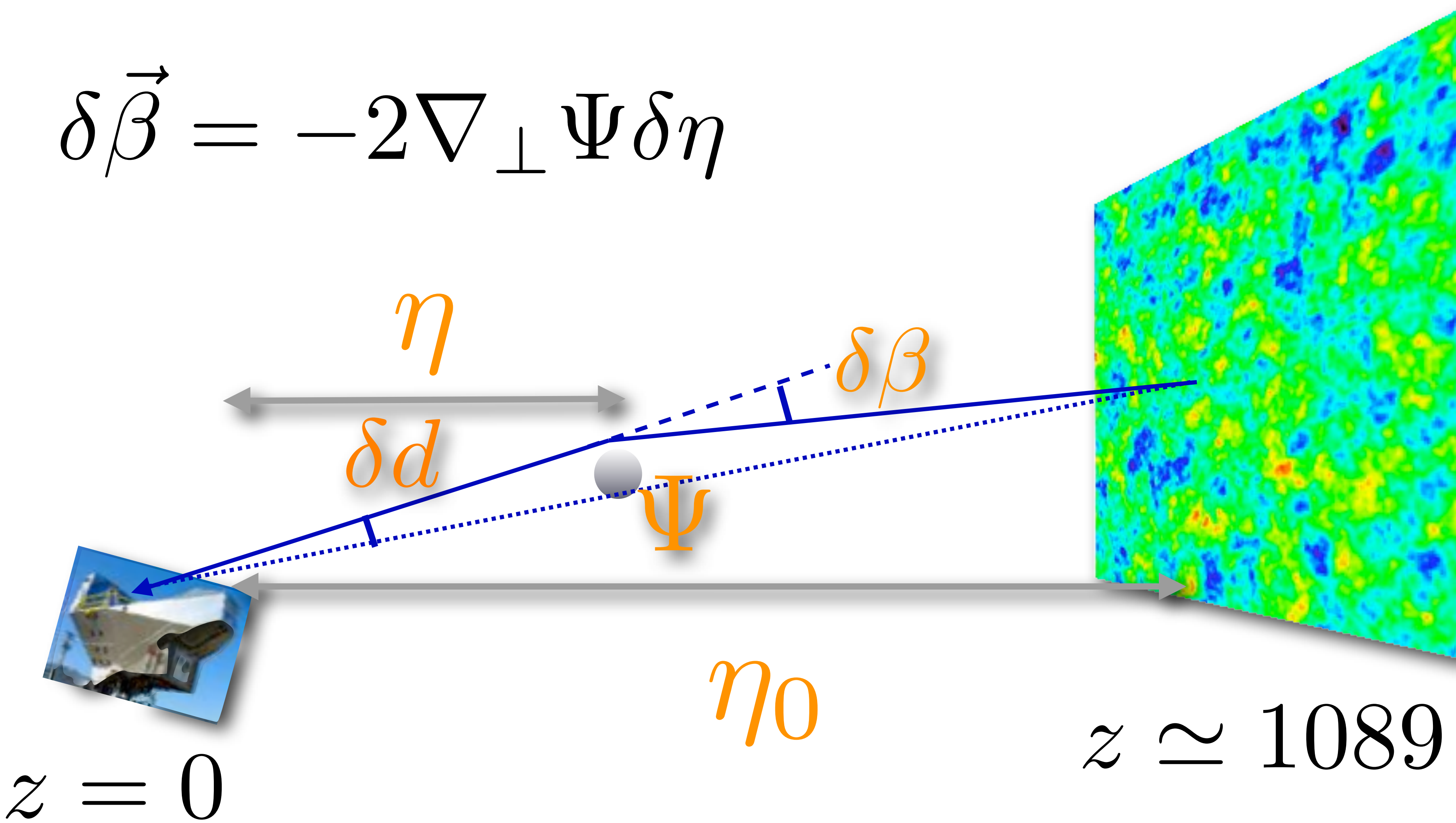
What we observe is a subtly distorted version of the CMB.



This is CMB Lensing!

Deflection of a CMB photon by a single potential well:

$$\delta\vec{\beta} = -2\nabla_\perp \Psi \delta\eta$$



ADDING UP THE DEFLECTIONS ALONG THE LINE OF SIGHT...

Born Approx.

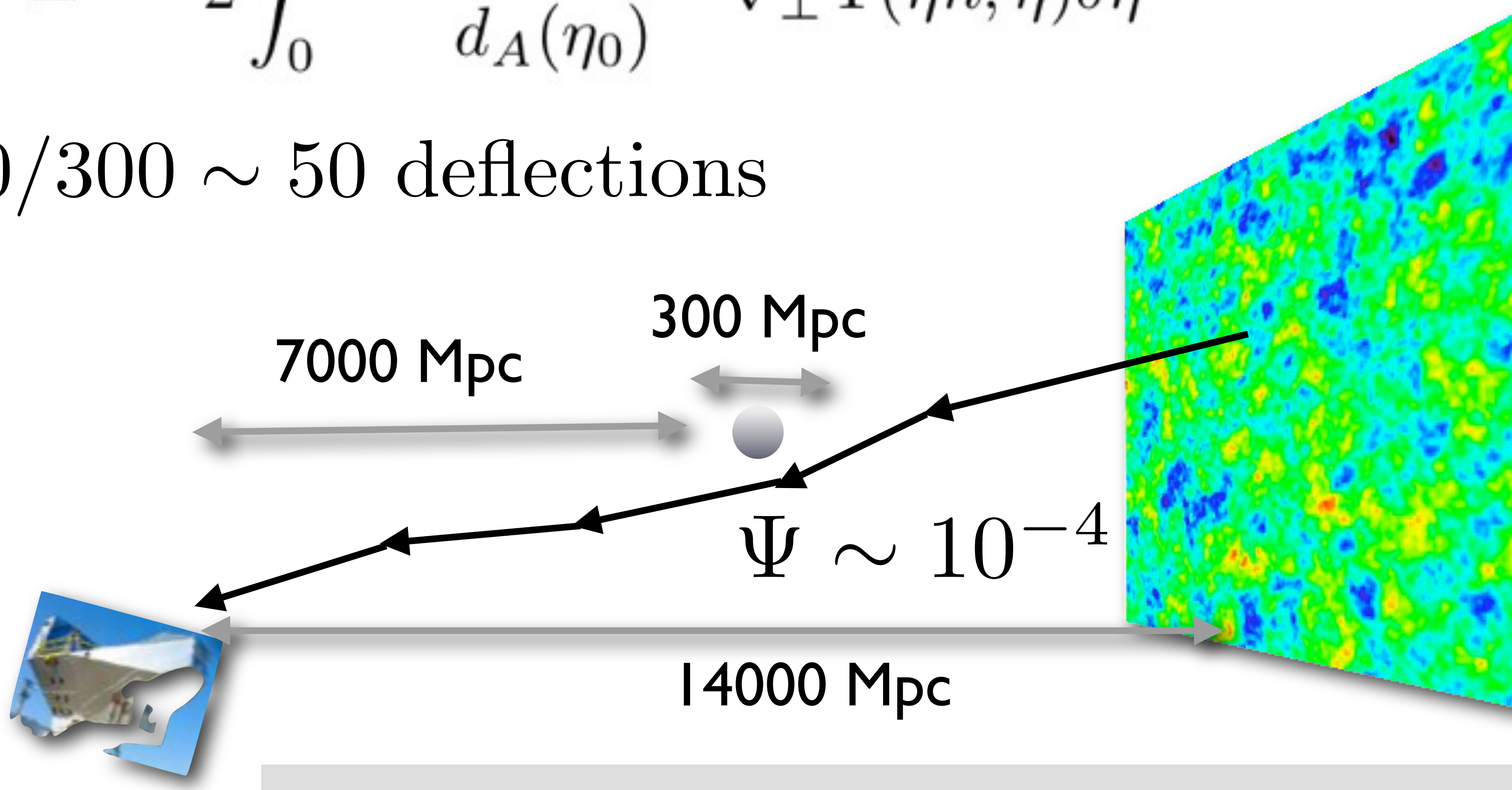
$$\vec{d}(\hat{n}) \quad = \quad \nabla_{\hat{n}} \underbrace{\left[-2\int_0^{\eta_0} \frac{d_A(\eta_0-\eta)}{d_A(\eta_0)d_A(\eta)}\Psi(\eta\hat{n},\eta)\right]\delta\eta}_{\phi}$$

ϕ is the lensing potential and $\vec{d}(\hat{n})$ is the deflection field, which is a pure gradient field.

A back of the envelope calculation

$$\vec{d}(\hat{n}) = -2\int_0^{\eta_0} \frac{d_A(\eta_0-\eta)}{d_A(\eta_0)} \nabla_\perp \Psi(\eta\hat{n},\eta)\delta\eta$$

$14000/300 \sim 50$ deflections

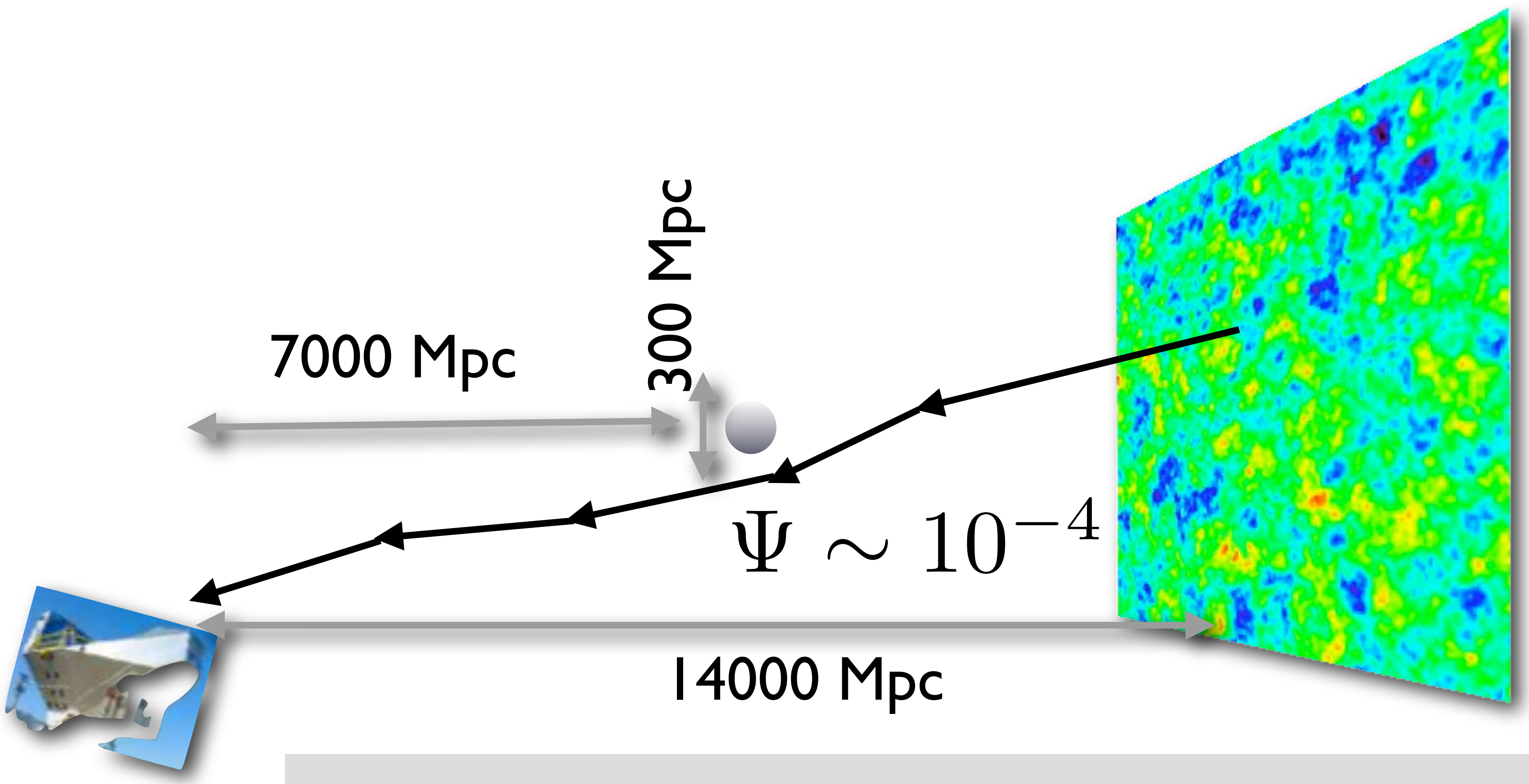


Assume Random Walk:

$$d(\hat{n}) \simeq 2 \times \sqrt{50} \times \tfrac{1}{2} \times 10^{-4}$$

$$\simeq 7 \times 10^{-4} = 2.4 \text{ arcmin}$$

A back of the envelope calculation

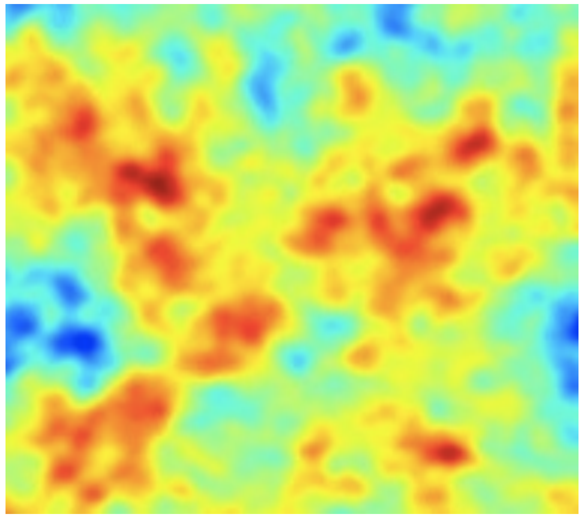


Deflections are coherent over $300/7000 \simeq 2$ degrees.

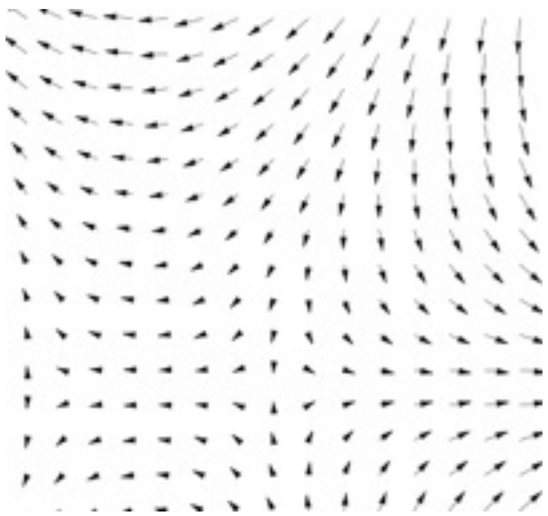
DEFLECTION FIELD IS THE KEY QUANTITY

CMB lensing is essentially a remapping of the CMB fields by the deflection field.

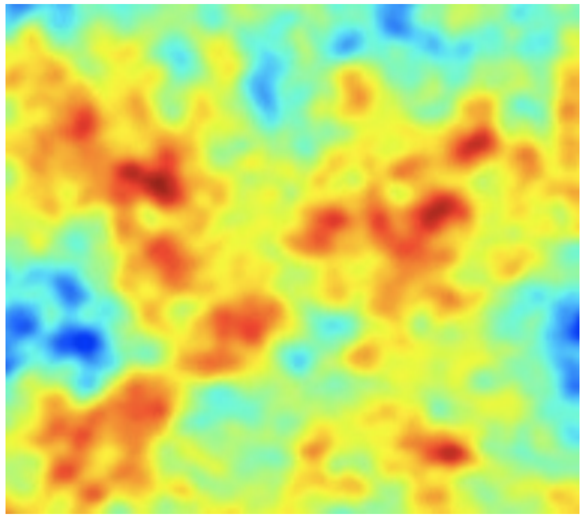
Unlensed



Deflection



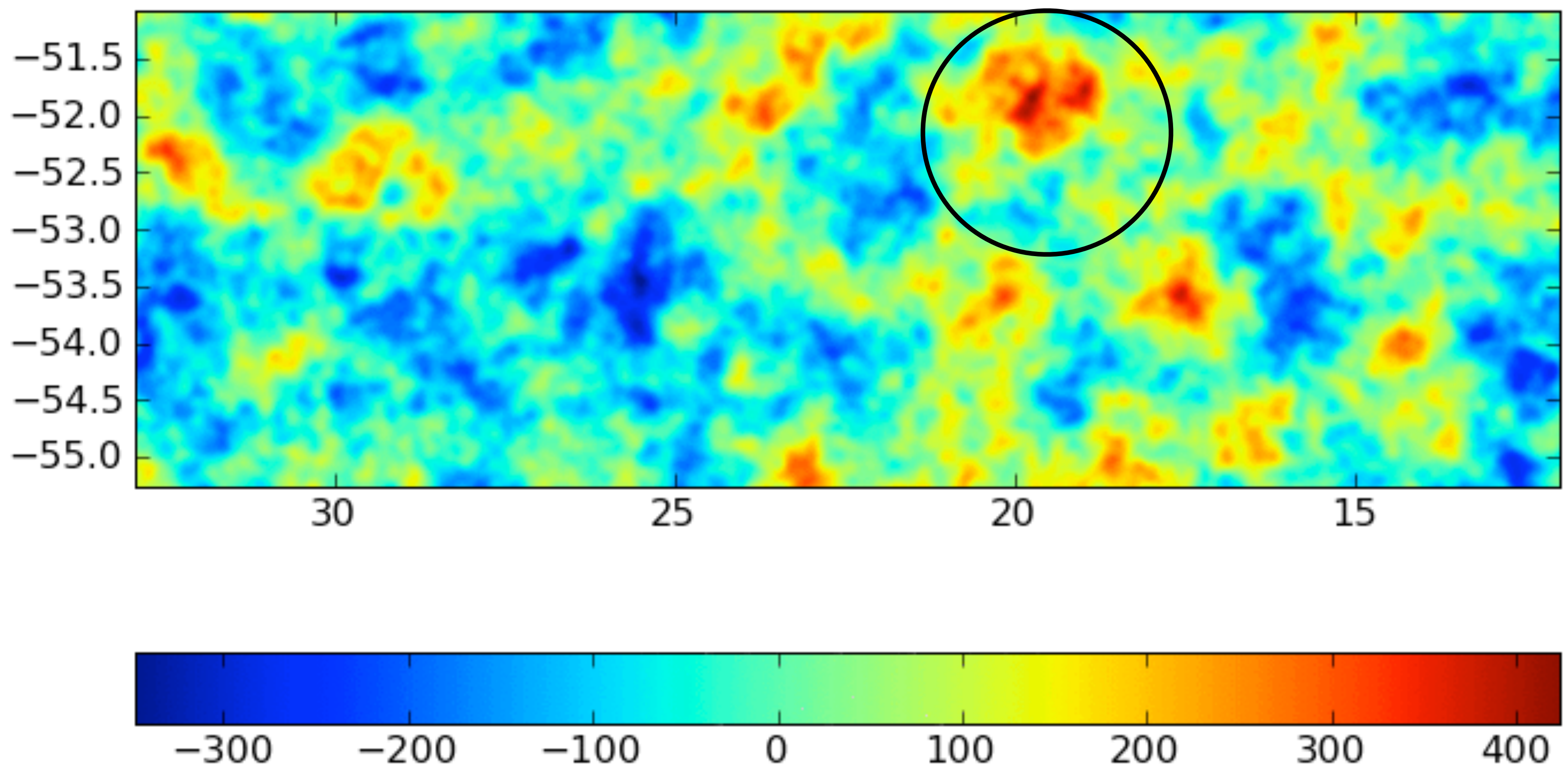
Lensed



$$\tilde{T}(\hat{n}) = T(\hat{n} + \vec{d})$$

CMB lensing can be discussed completely in terms of the deflection field (no shear/convergence necessary).

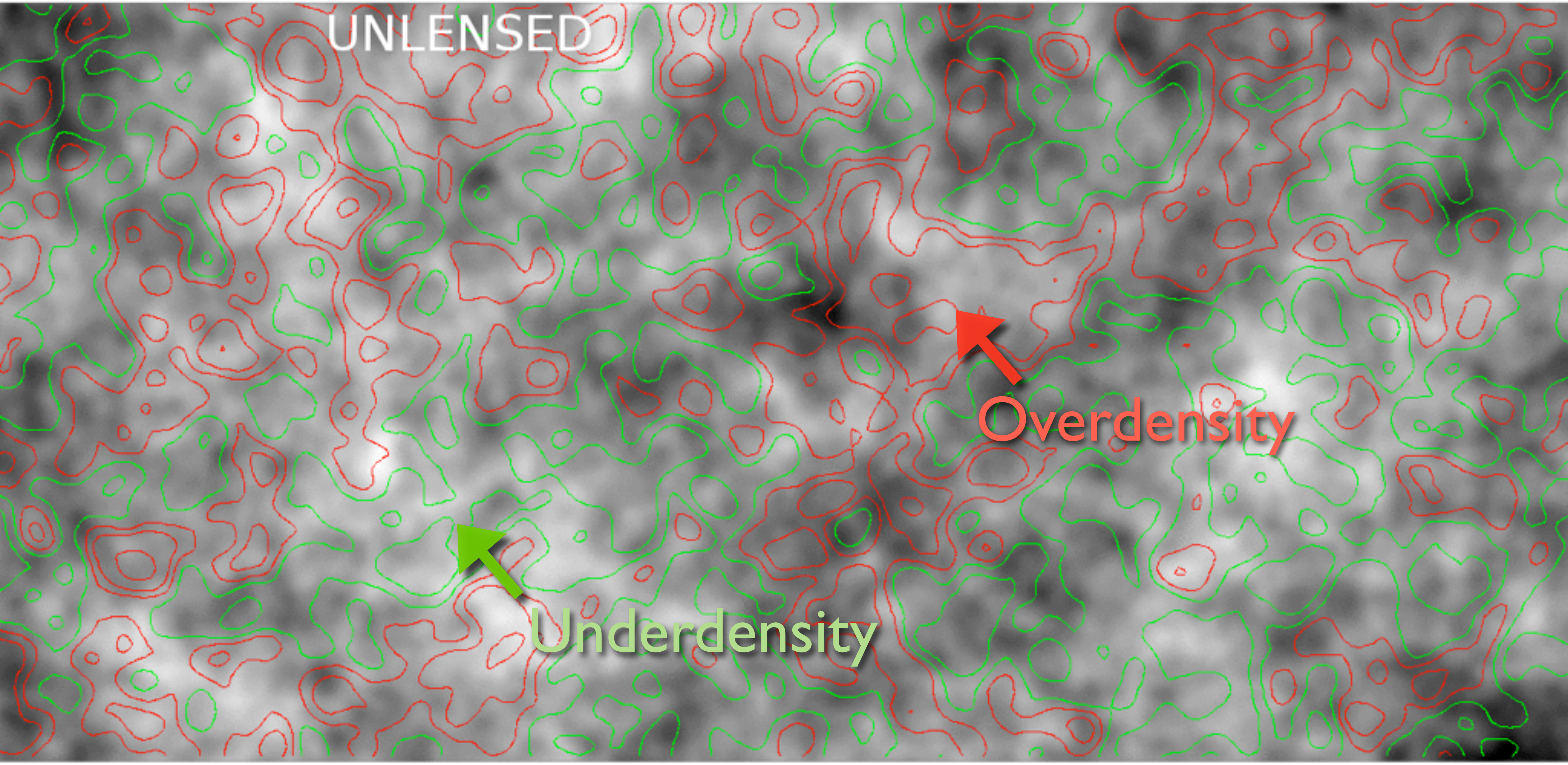
CMB Lensing in action ...



Simulation from Das & Bode (2008)

" 2-3 arcmin deflections, coherent over 2-3 degrees, mainly coming from redshifts of 2-3 !"

Lensing remaps & magnifies/de-magnifies CMB patches.



Simulation from Das & Bode (2008)

THERE ARE THREE MAIN AVENUES FOR COSMOLOGY WITH CMB LENSING

Smearing of CMB power spectrum peaks and small scale B-mode power.

Reconstruction of the deflection/ convergence field and its power spectrum.

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

Effective Lensing Potential

Geometry

Matter potential

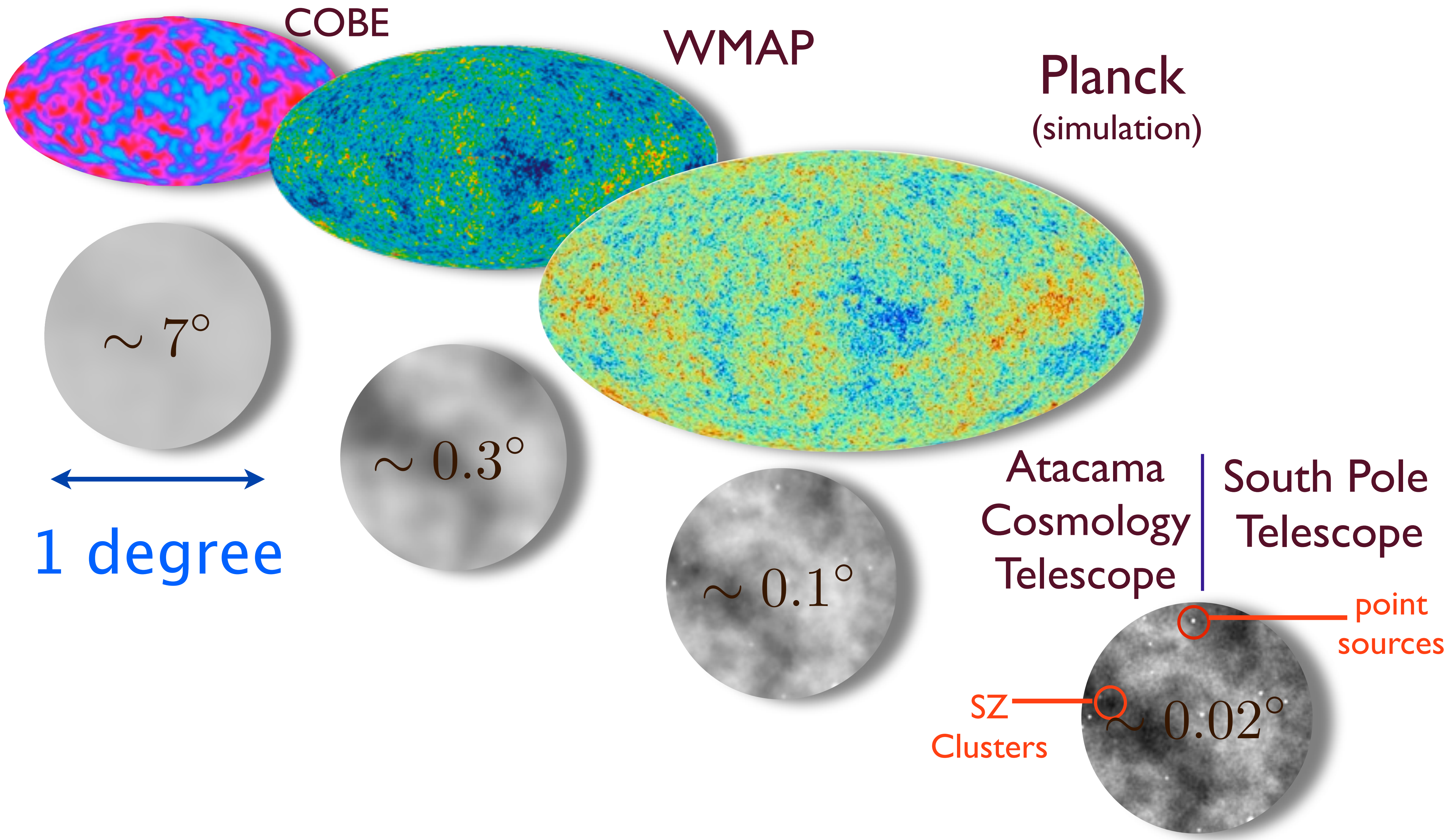
Cross correlation of the deflection field with other cosmological probes.

e.g. *weak lensing, galaxy counts, CIB* ...

- *break degeneracies.*
- *constrain systematics.*
- *constrain galaxy bias*

Highest science impact expected on: *neutrino mass sum, (early) dark energy, test of GR, and understanding galaxy evolution.*

To study the lensing effect we need to look at the CMB at high resolution



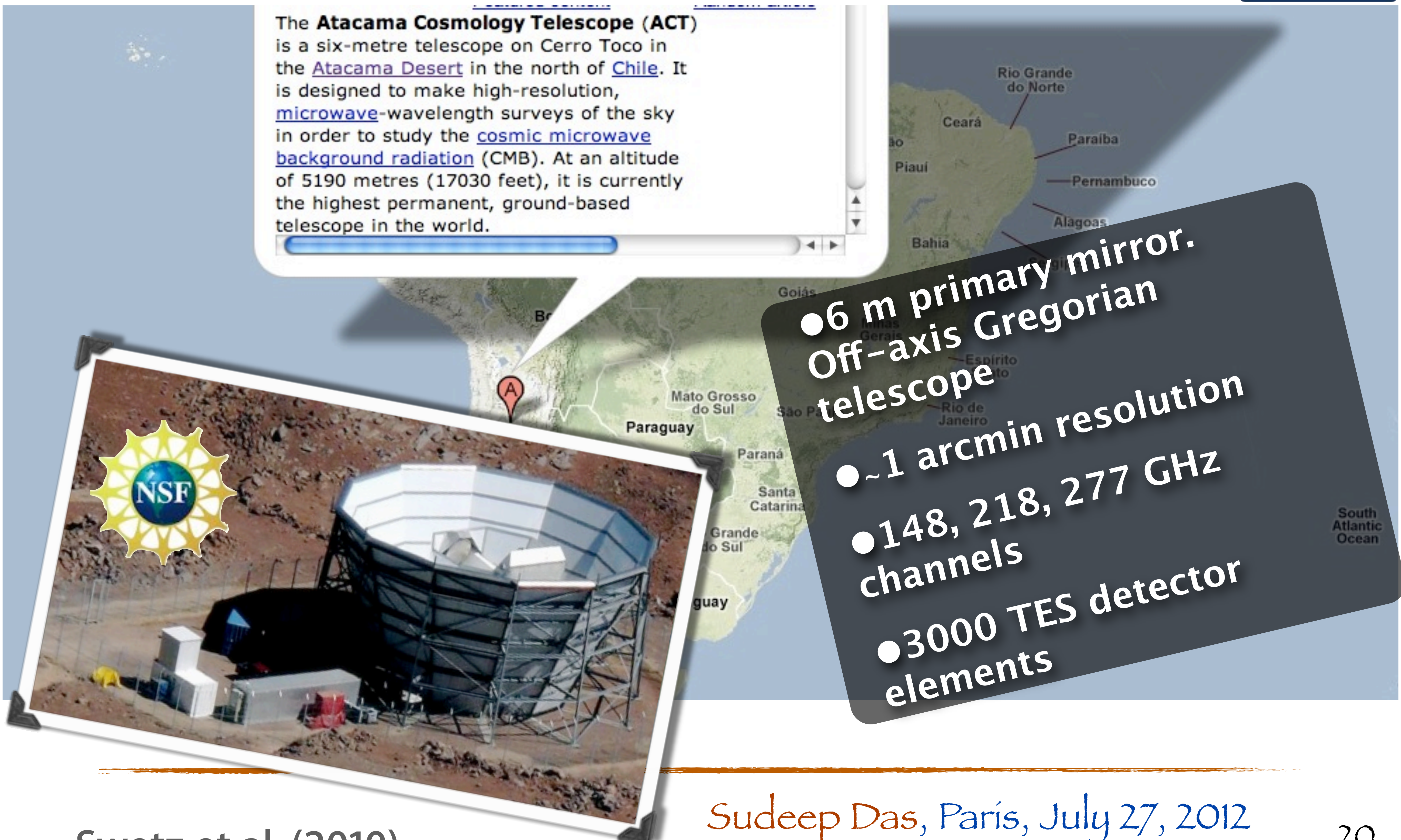
ONGOING EXPERIMENTS ARE PUSHING RESOLUTION AND SENSITIVITY TO NEW LIMITS

Planck

South Pole Telescope (SPT)

Atacama Cosmology Telescope (ACT)

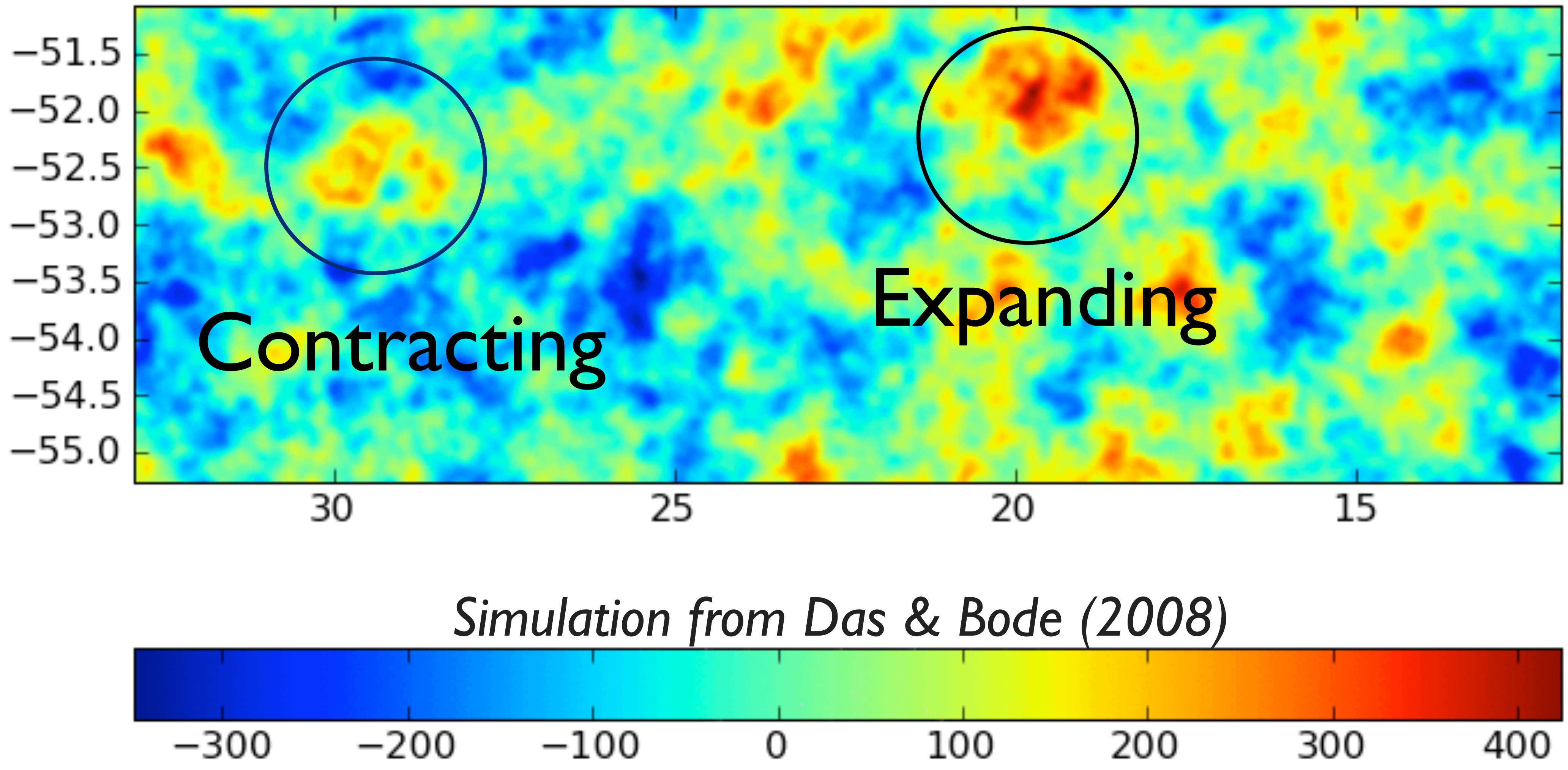
THE ATACAMA COSMOLOGY TELESCOPE



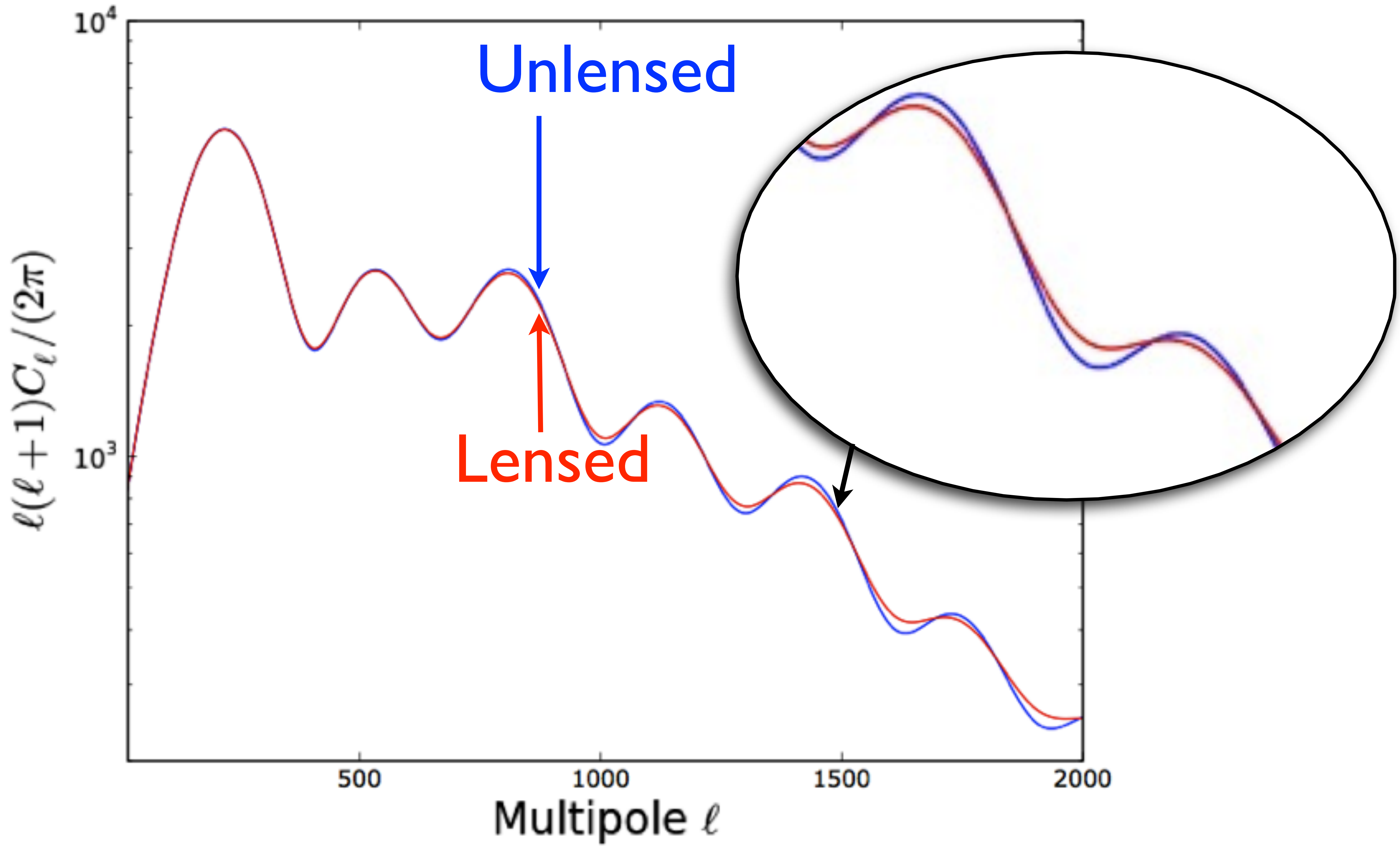
- 6 m primary mirror. Off-axis Gregorian telescope
- ~1 arcmin resolution
- 148, 218, 277 GHz channels
- 3000 TES detector elements

Swetz et al. (2010)

Lensing broadens the size distribution of acoustic features

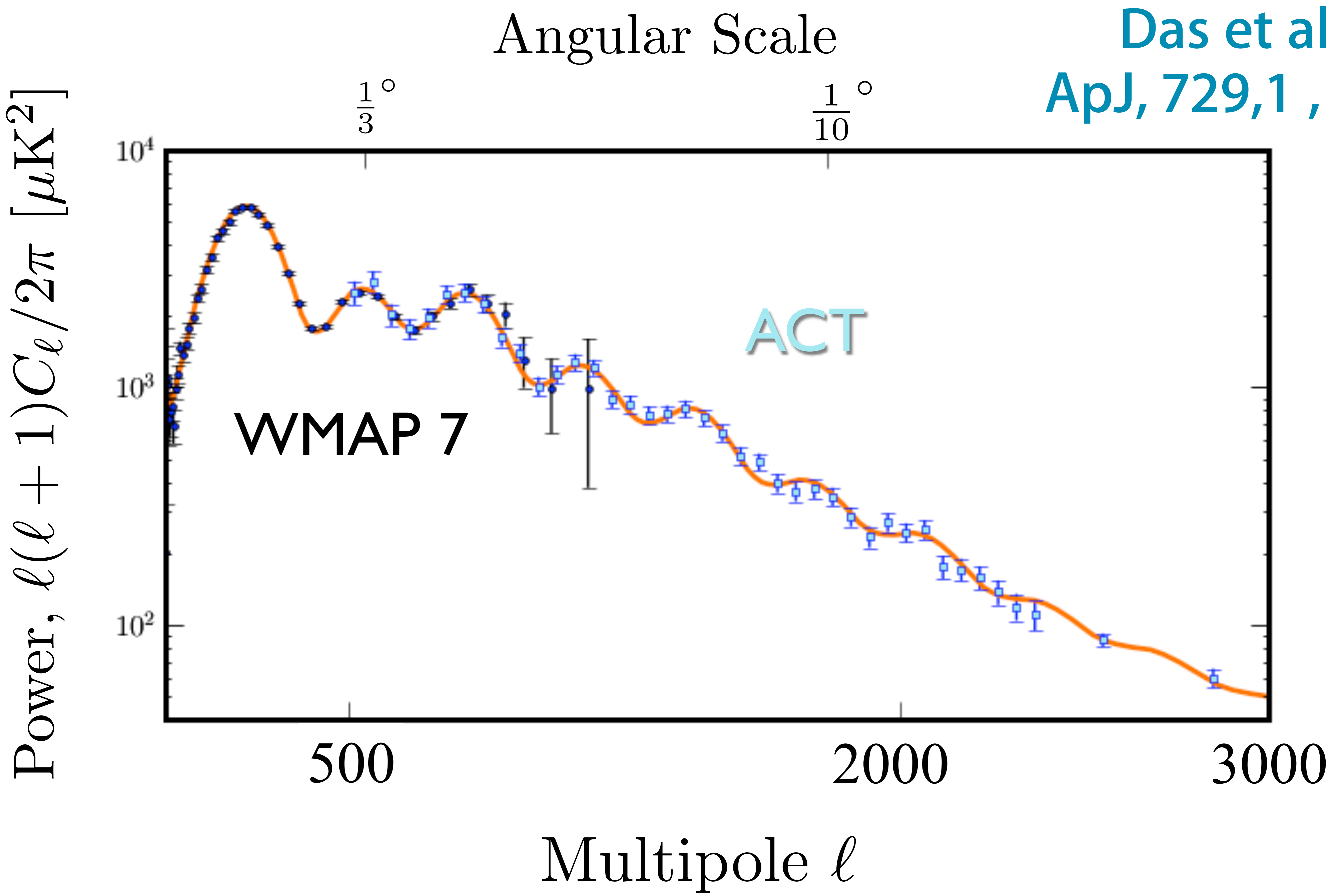


Lensing smears out acoustic peaks



HIGH RESOLUTION POWER SPECTRUM FROM ACT

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

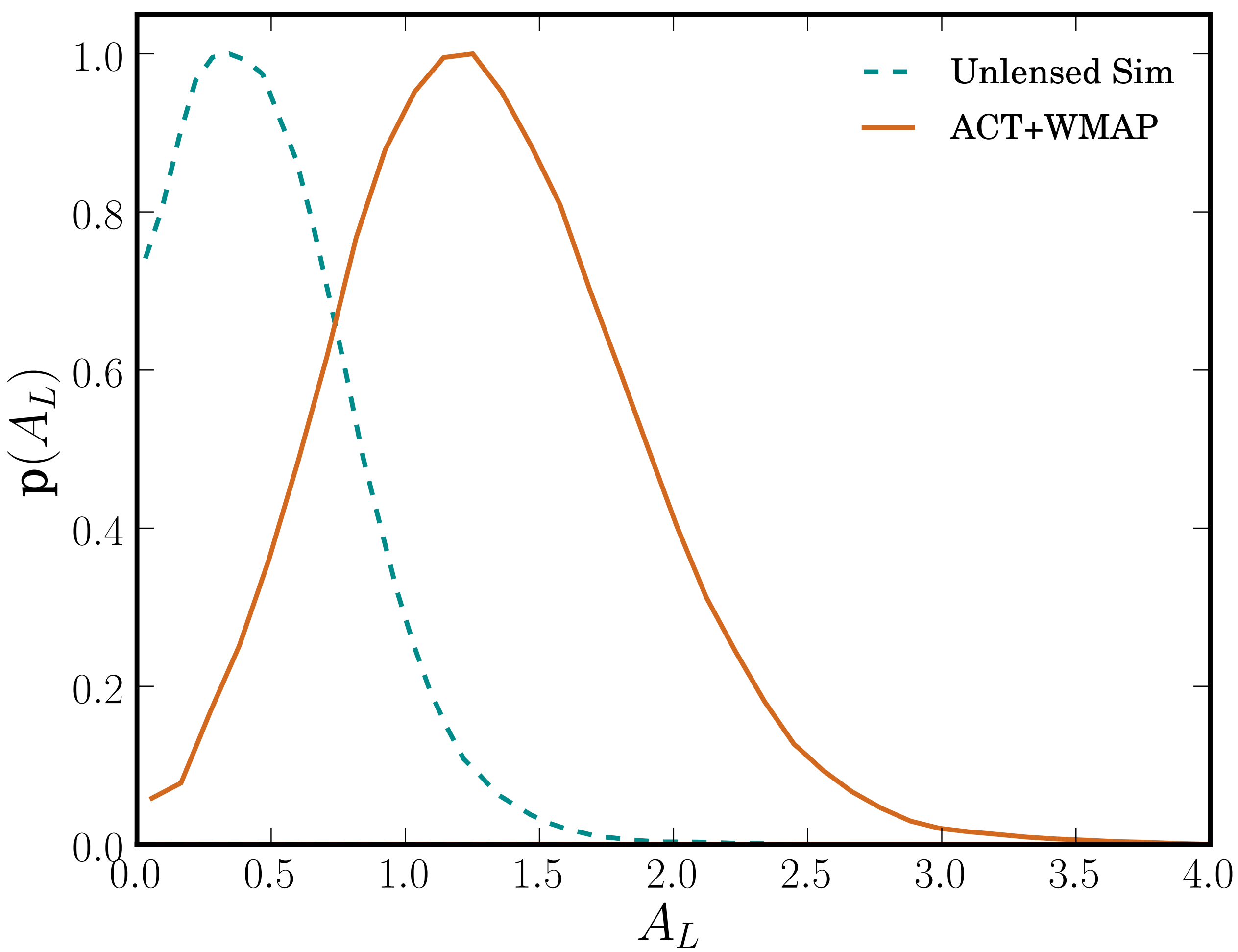


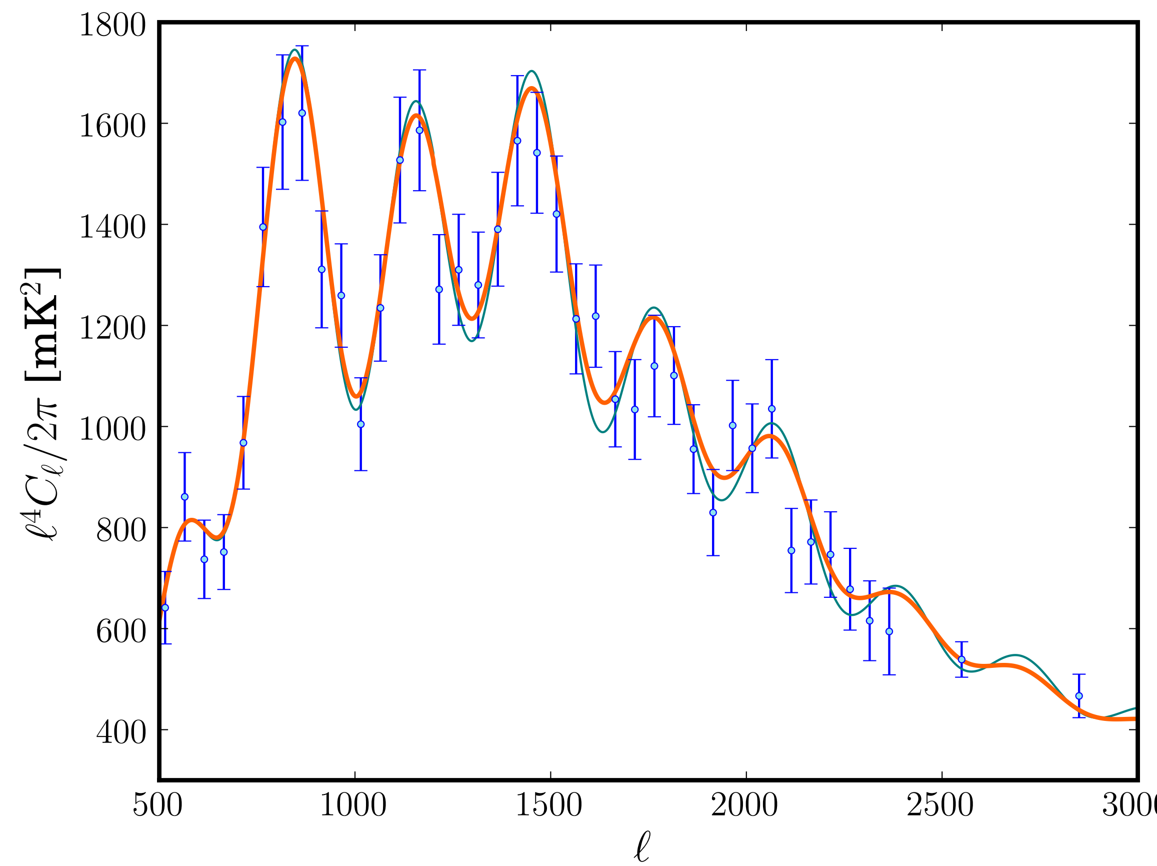
Pipeline based on Das, Hajian, Spergel (2010)

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

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

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

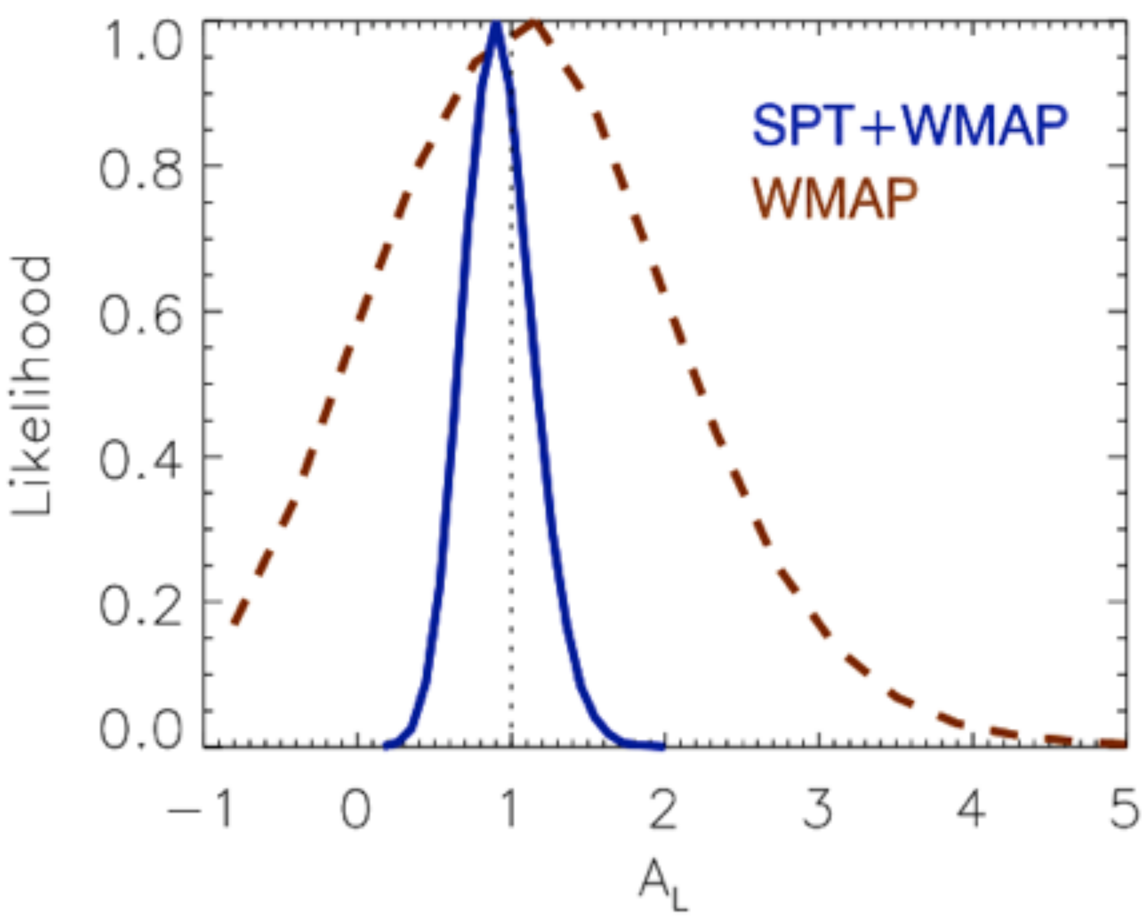


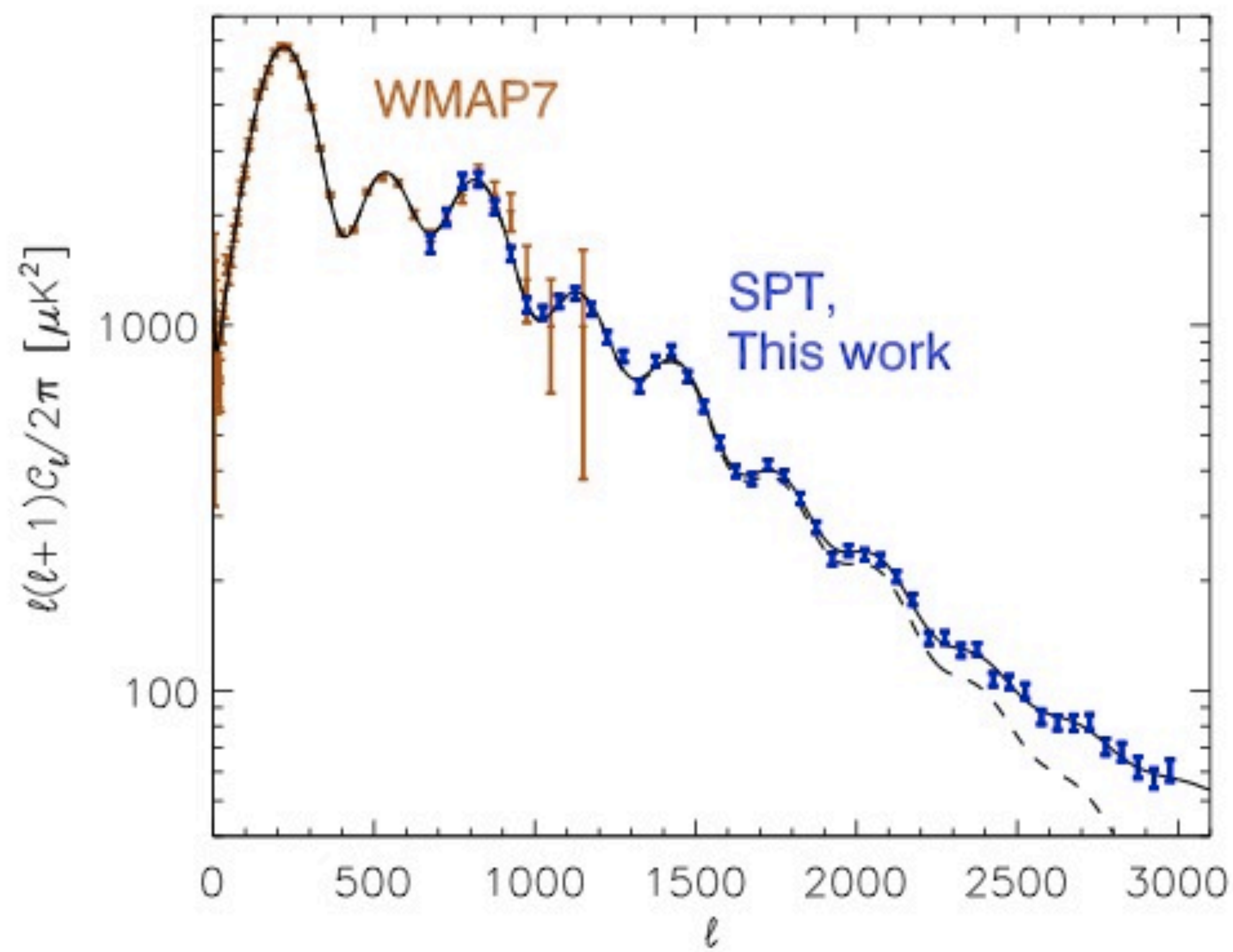


- Test for lensing in spectrum by marginalizing over (unphysical) parameter A_L, scaling lensing potential. [Calabrese et al 2008]
- Expect A_L=1, and unlensed has A_L=0. See lensing at almost 3σ level.

Smearing of acoustic peaks in the recent SPT spectrum lets us see lensing at ~ 5σ

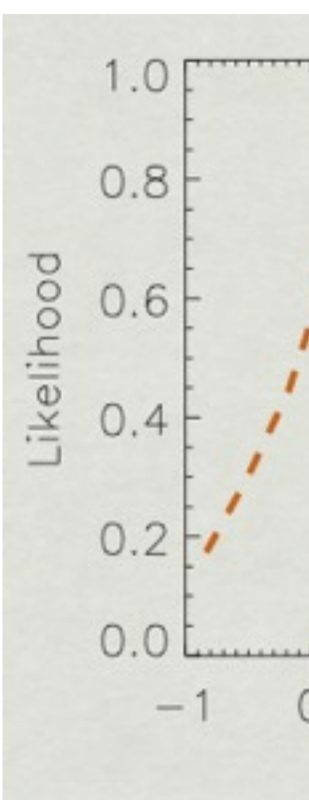
Keisler et al. (2011)

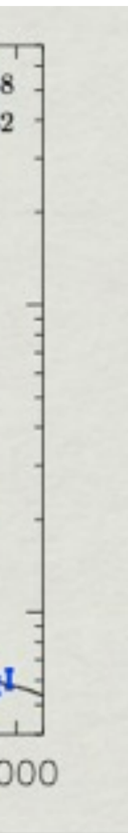


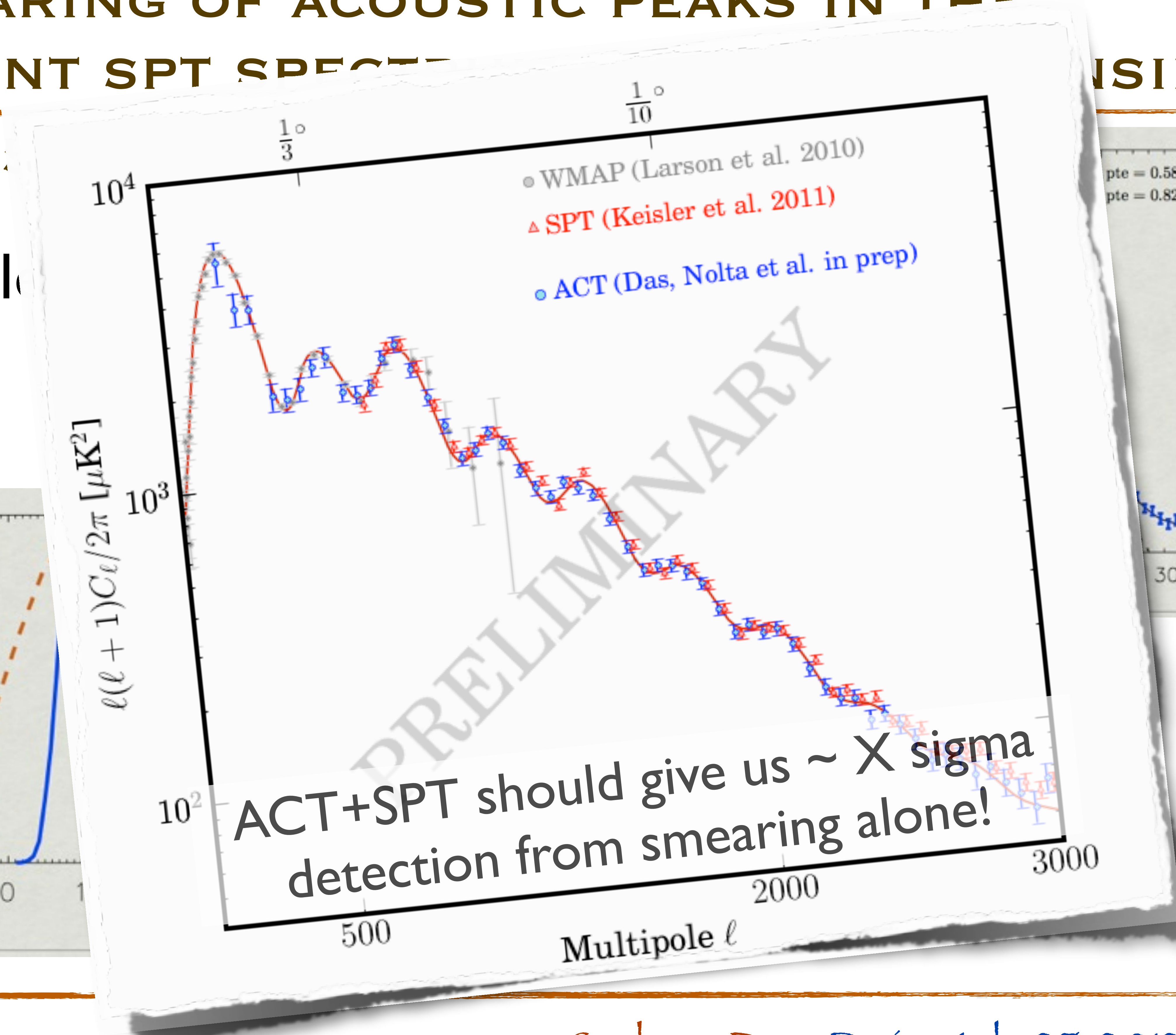


Smearing of acoustic peaks in the recent SPT spectr… …nsing at ~ …

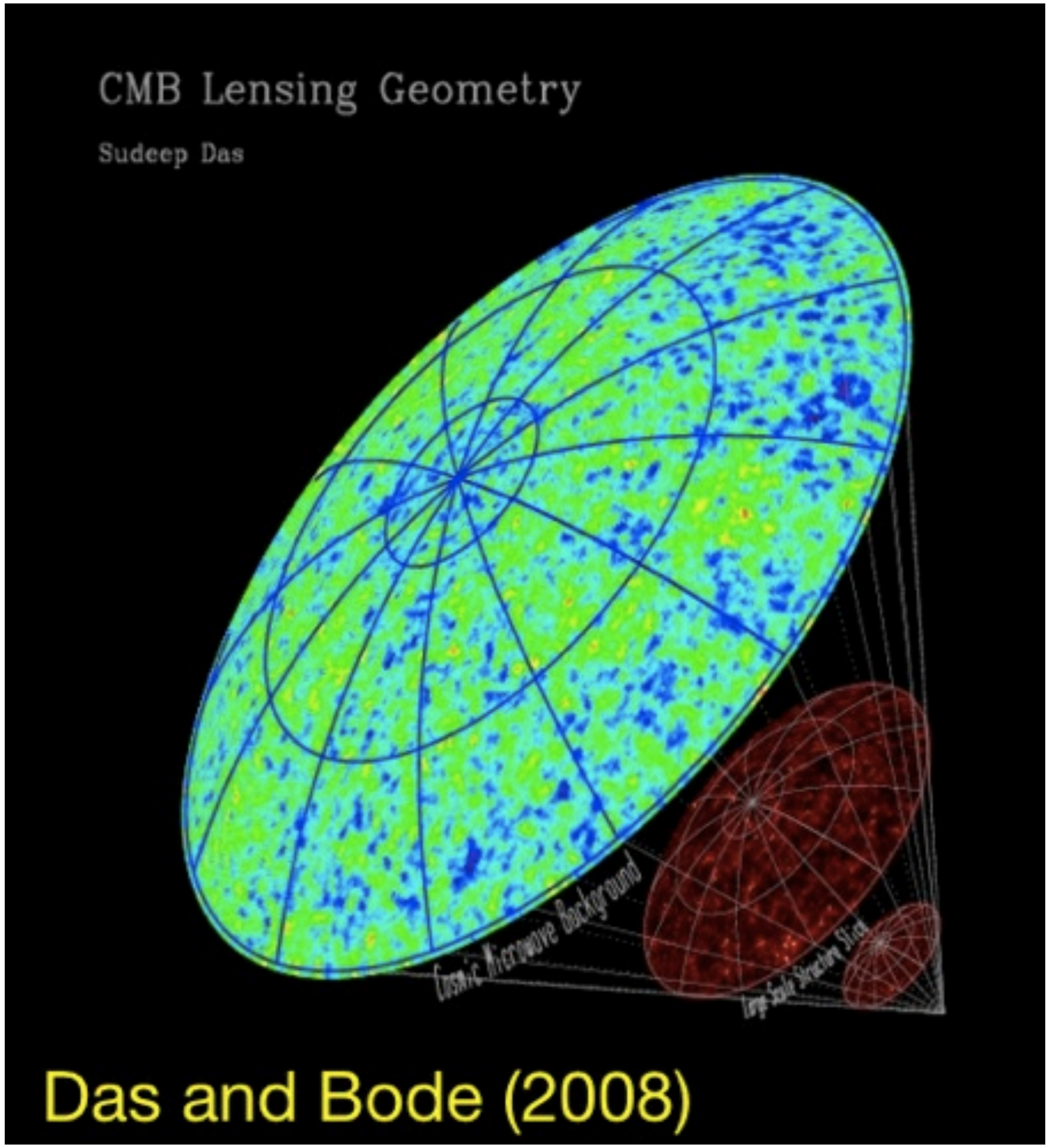
Keisl…



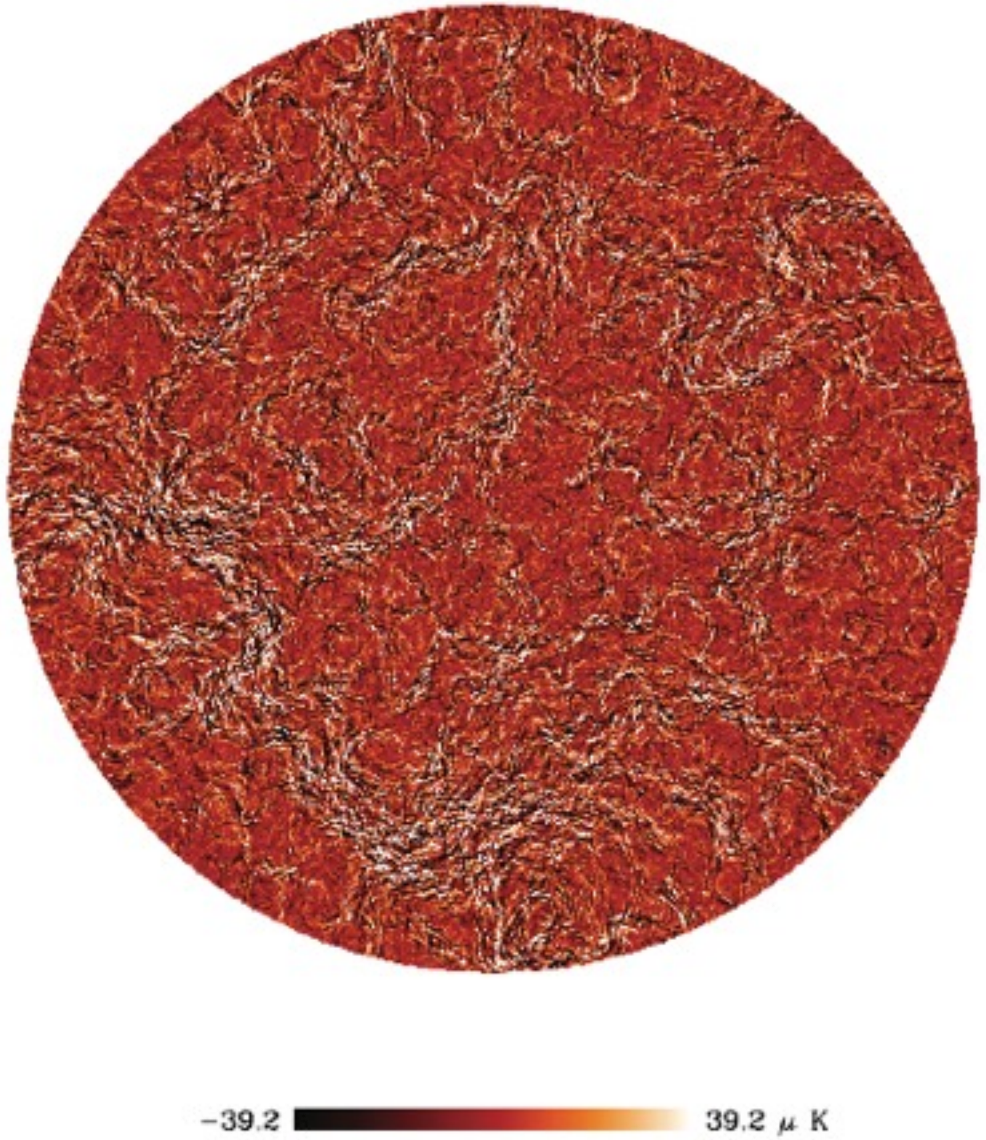




LENSING INDUCES NON-GAUSSIANITY



Difference between lensed and unlensed CMB



LENSING INDUCES NON-GAUSSIANITY

Taylor-expand lensed CMB in powers of deflection field:

$$\begin{aligned} T(\mathbf{n})_{\rm lensed} &= T(\mathbf{n}+\mathbf{d}(\mathbf{n}))_{\rm unl} \\ &= T(\mathbf{n})_{\rm unl} + d_i(\mathbf{n})\nabla_i T(\mathbf{n})_{\rm unl} \\ &\quad + \frac{1}{2} d_i(\mathbf{n}) d_j(\mathbf{n}) \nabla_i \nabla_j T(\mathbf{n})_{\rm unl} + \cdots \end{aligned}$$

All terms beyond the first are non-Gaussian

=> statistics not fully determined by power spectrum

THE QUADRATIC ESTIMATOR FOR LENS RECONSTRUCTION

For the primordial CMB, which is a Gaussian random field, different Fourier modes (l,l') are independent.

$$\langle T(\boldsymbol{\ell})T(\boldsymbol{\ell}')\rangle_{\rm CMB} = 0 \text{ for } \boldsymbol{\ell} \neq \boldsymbol{\ell}'$$

But after lensing:

$$\tilde{T}(\hat{\mathbf{n}}) \simeq T(\hat{\mathbf{n}}) + \mathbf{d}(\hat{\mathbf{n}}) \cdot \nabla T(\hat{\mathbf{n}})$$

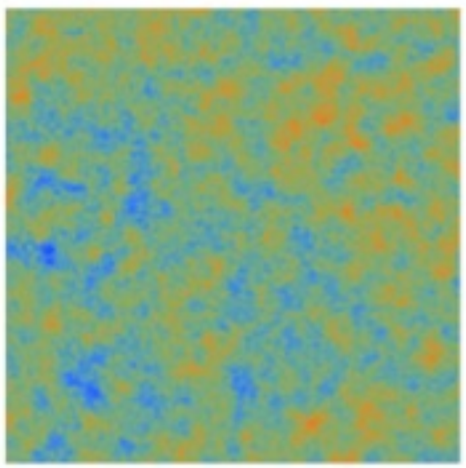
off-diagonal modes become weakly correlated:

$$\left\langle \tilde{T}(\boldsymbol{\ell})\tilde{T}(\boldsymbol{\ell}') \right\rangle_{\rm CMB} = f(\boldsymbol{\ell},\boldsymbol{\ell}')\mathbf{d}(\boldsymbol{\ell}+\boldsymbol{\ell}')$$

Therefore, we can construct an estimator for the deflection field that is quadratic in temperature.

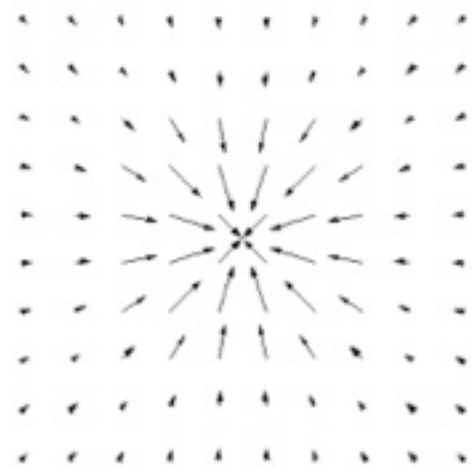
LENSING RECONSTRUCTION

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



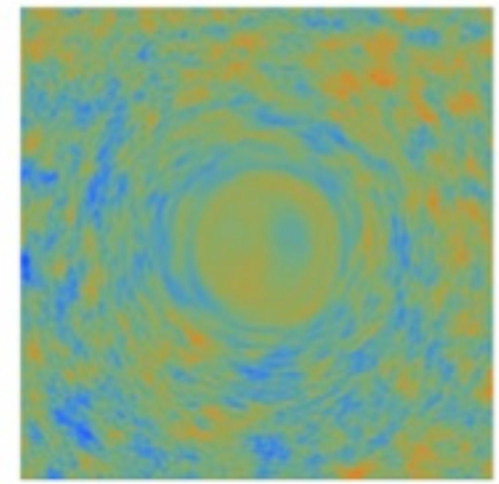
Unlensed CMB

+



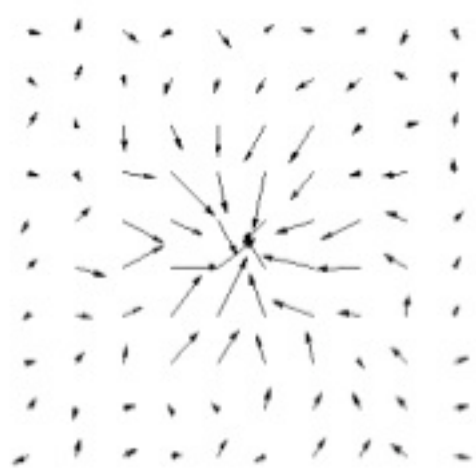
Deflection Field

→



Lensed CMB

Statistics Altered

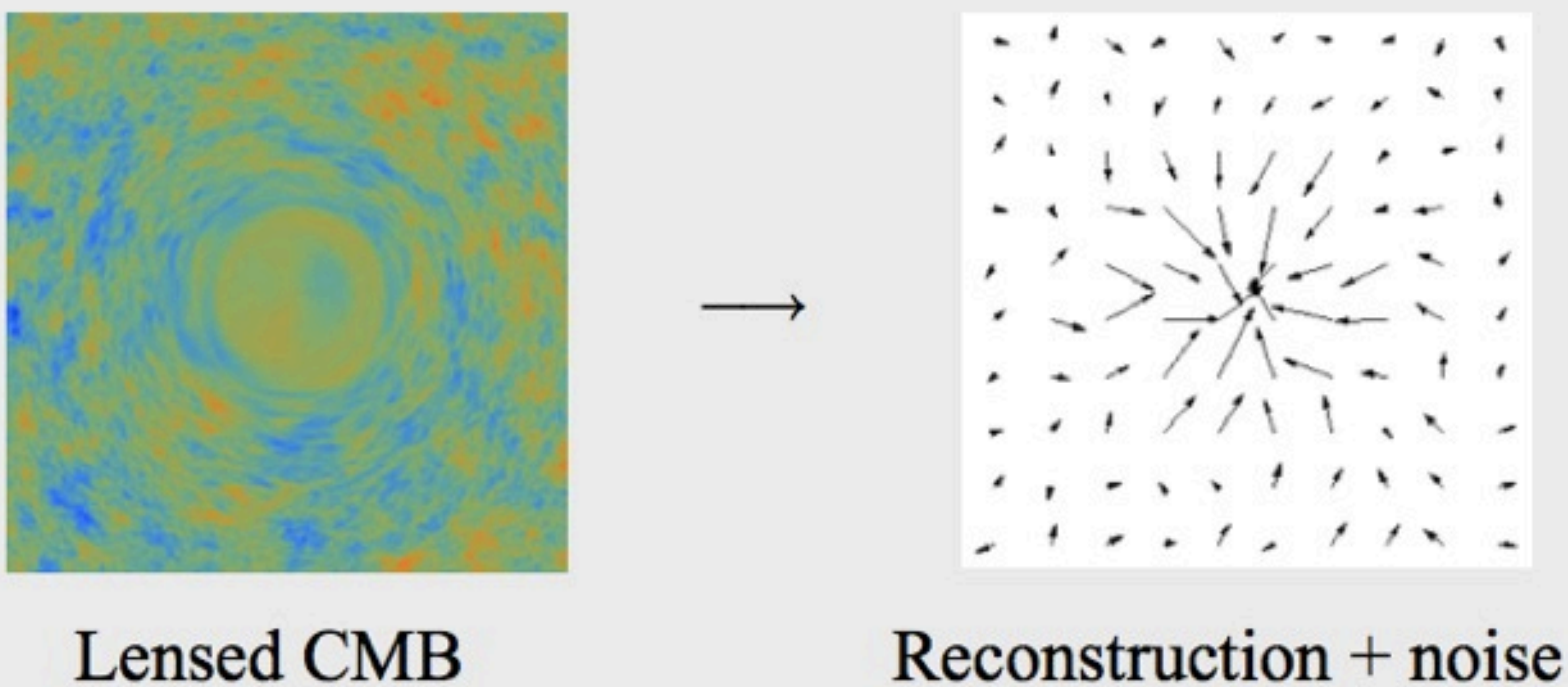


Reconstruction +Noise

Hu (2001), Hu & Okamoto (2002)

THE QUADRATIC ESTIMATOR FOR LENS RECONSTRUCTION (HU AND OKAMOTO 2002)

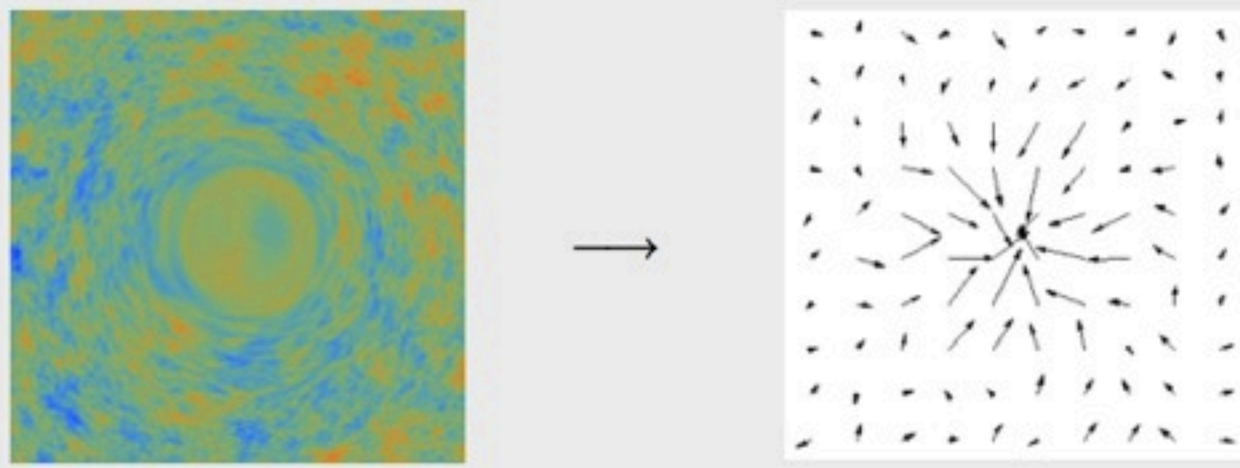
$$\hat{\mathbf{d}}(\mathbf{l}) \propto \int \frac{d^2\mathbf{l}_1}{(2\pi)^2}[\mathbf{l}_1 C_{\ell_1} + \mathbf{l}_2 C_{\ell_2}] \frac{T(\mathbf{l}_1)T(\mathbf{l}_2)}{(C_{\ell_1}+N_{\ell_1})(C_{\ell_2}+N_{\ell_2})}$$



Courtesy: Kendrick Smith

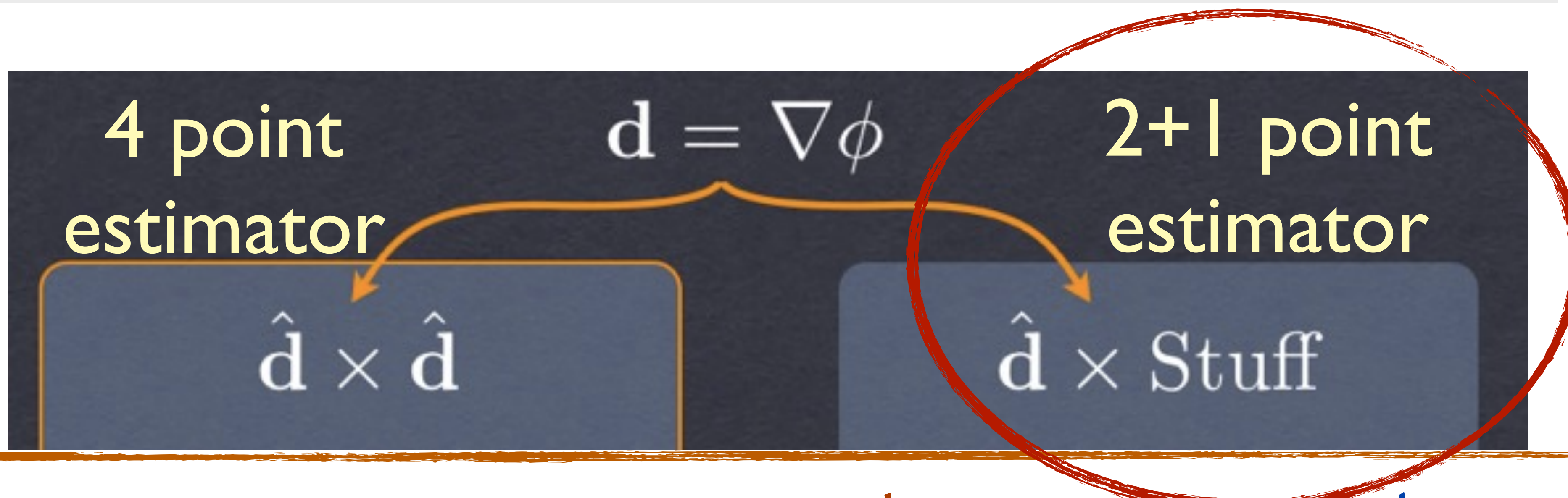
Detections using higher point statistics

$$\hat{\mathbf{d}}(\mathbf{l}) \propto \int \frac{d^2\mathbf{l}_1}{(2\pi)^2}[\mathbf{l}_1 C_{\ell_1} + \mathbf{l}_2 C_{\ell_2}] \frac{T(\mathbf{l}_1)T(\mathbf{l}_2)}{(C_{\ell_1}+N_{\ell_1})(C_{\ell_2}+N_{\ell_2})}$$



Lensed CMB → Reconstruction + noise

Courtesy: Kendrick Smith



logic: Galaxies trace the same large scale structure that lens the CMB:

Therefore, a non-zero cross correlation is expected between galaxies and reconstructed deflection field

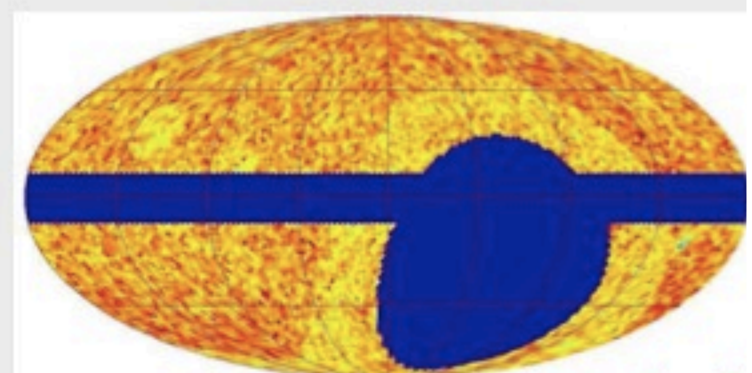
Smith, Zahn, Dore & Nolta 2007 (see also Hirata et al 2008)

NVSS: NRAO VLA Sky Survey

Courtesy: Kendrick Smith

1.4 GHz source catalog,
50% complete at 2.5 mJy

Mostly extragalactic sources:
- AGN-powered radio galaxies
- Quasars
- Star-forming galaxies



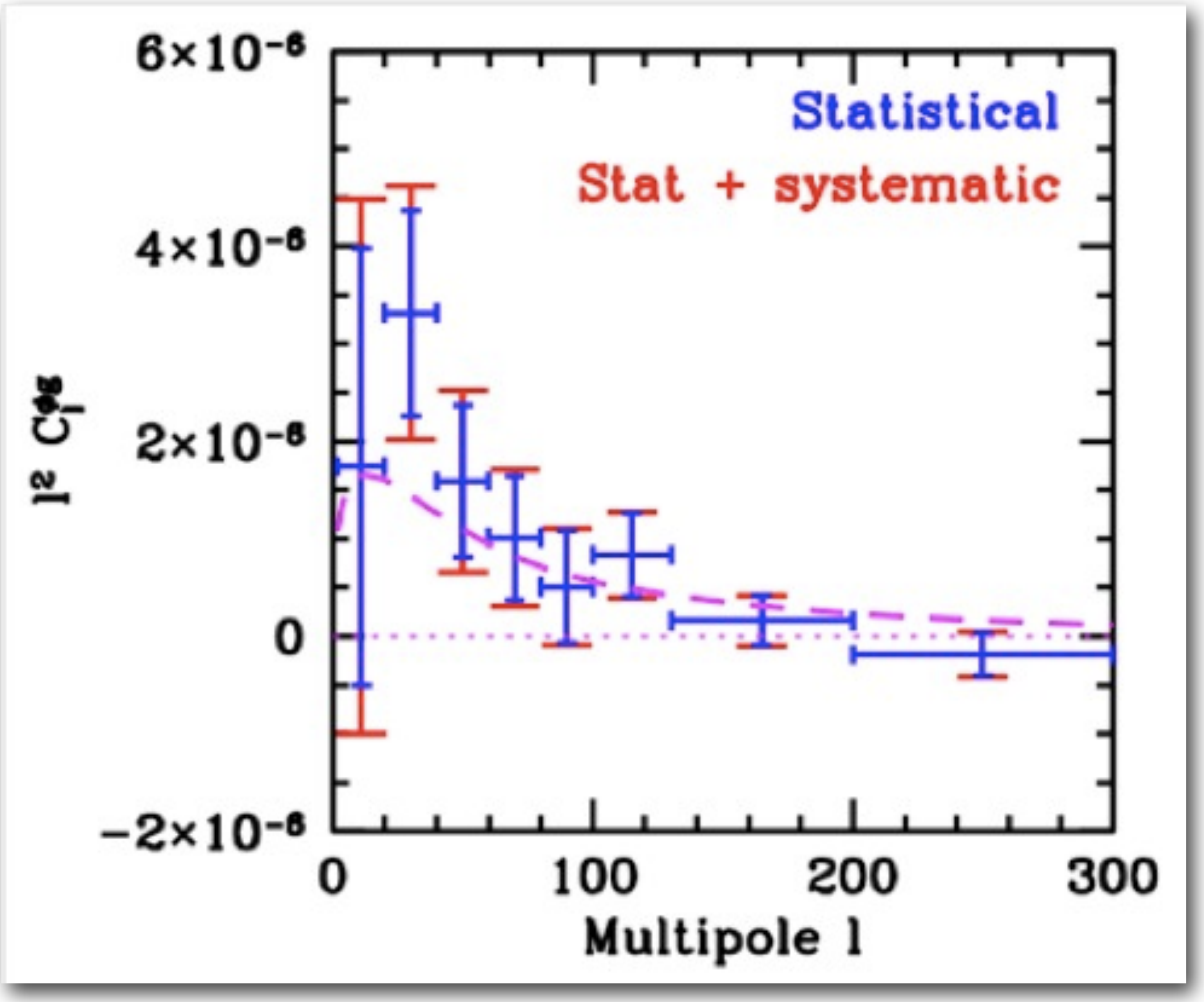
galaxy counts (masked)

Well-suited for cross-correlating to WMAP lens reconstruction:

Nearly full sky coverage ($f_{\rm sky} = 0.8$)
Low shot noise ($b_g = 2,\ N_{\rm gal} = 1.8 \times 10^6$)
High redshift ($z_{\rm median} = 2$)

WMAP-NVSS ANALYSIS

First detection (3.4σ) of CMB lensing, via 3-point signal

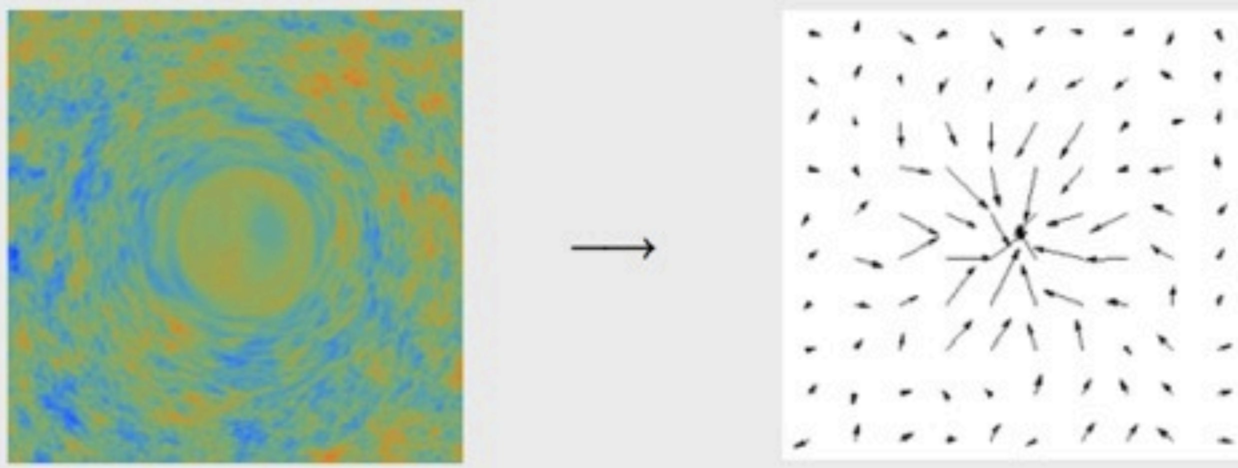


Smith, Zahn, Dore & Nolta (2007)

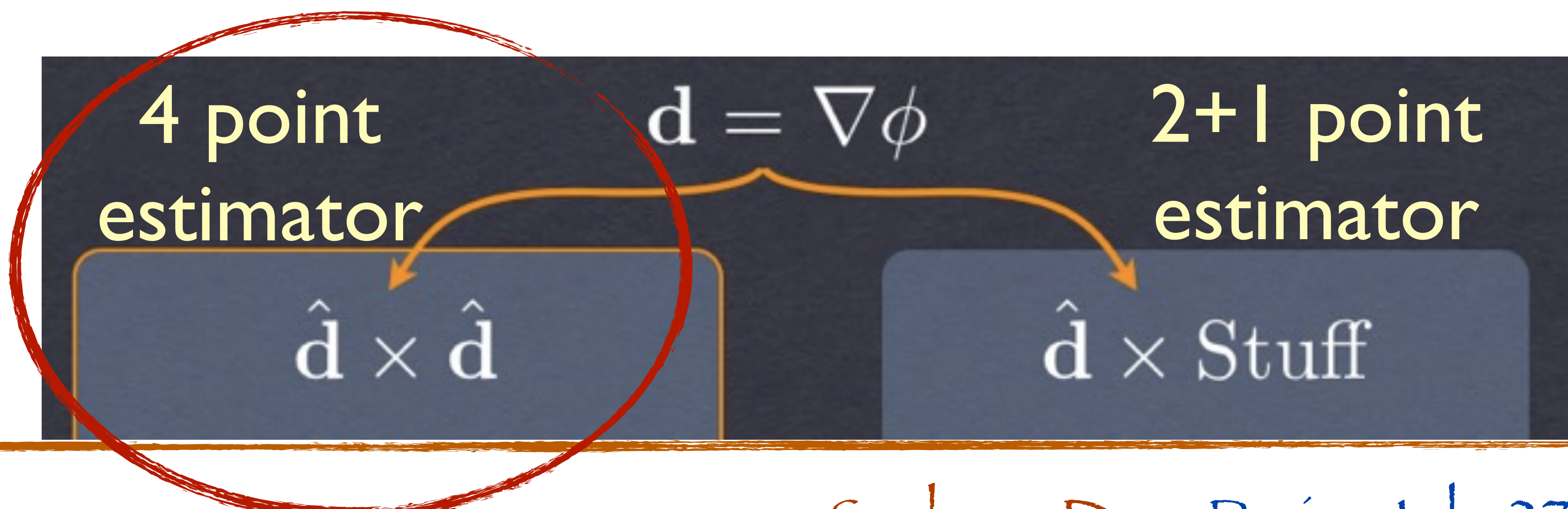
(see also Hirata et al 2008)

Detections using higher point statistics

$$\hat{\mathbf{d}}(\mathbf{l}) \propto \int \frac{d^2\mathbf{l}_1}{(2\pi)^2}[\mathbf{l}_1 C_{\ell_1} + \mathbf{l}_2 C_{\ell_2}] \frac{T(\mathbf{l}_1)T(\mathbf{l}_2)}{(C_{\ell_1}+N_{\ell_1})(C_{\ell_2}+N_{\ell_2})}$$



Courtesy: Kendrick Smith



First internal detection of lensing (4-sigma) from the CMB 4-point function

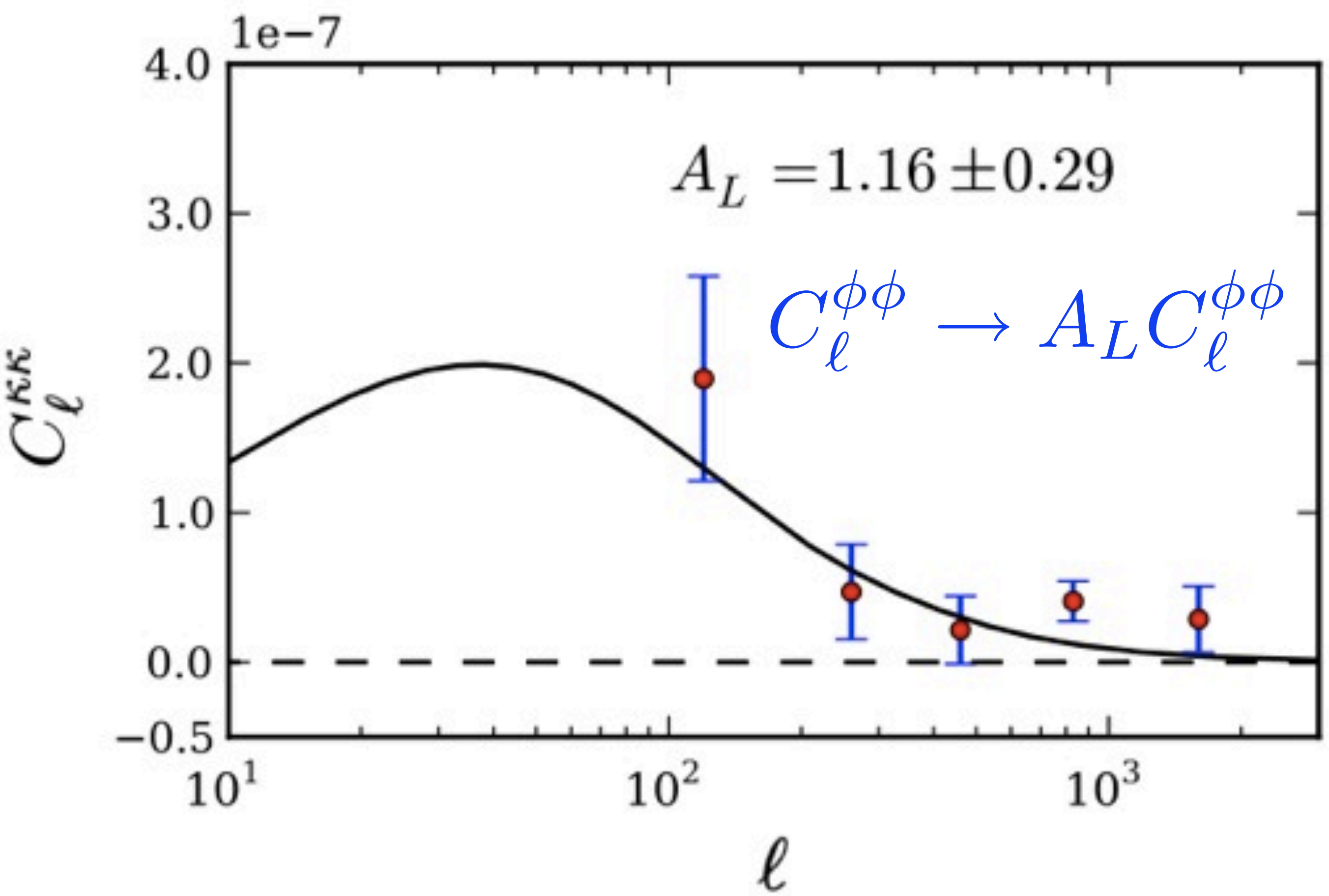


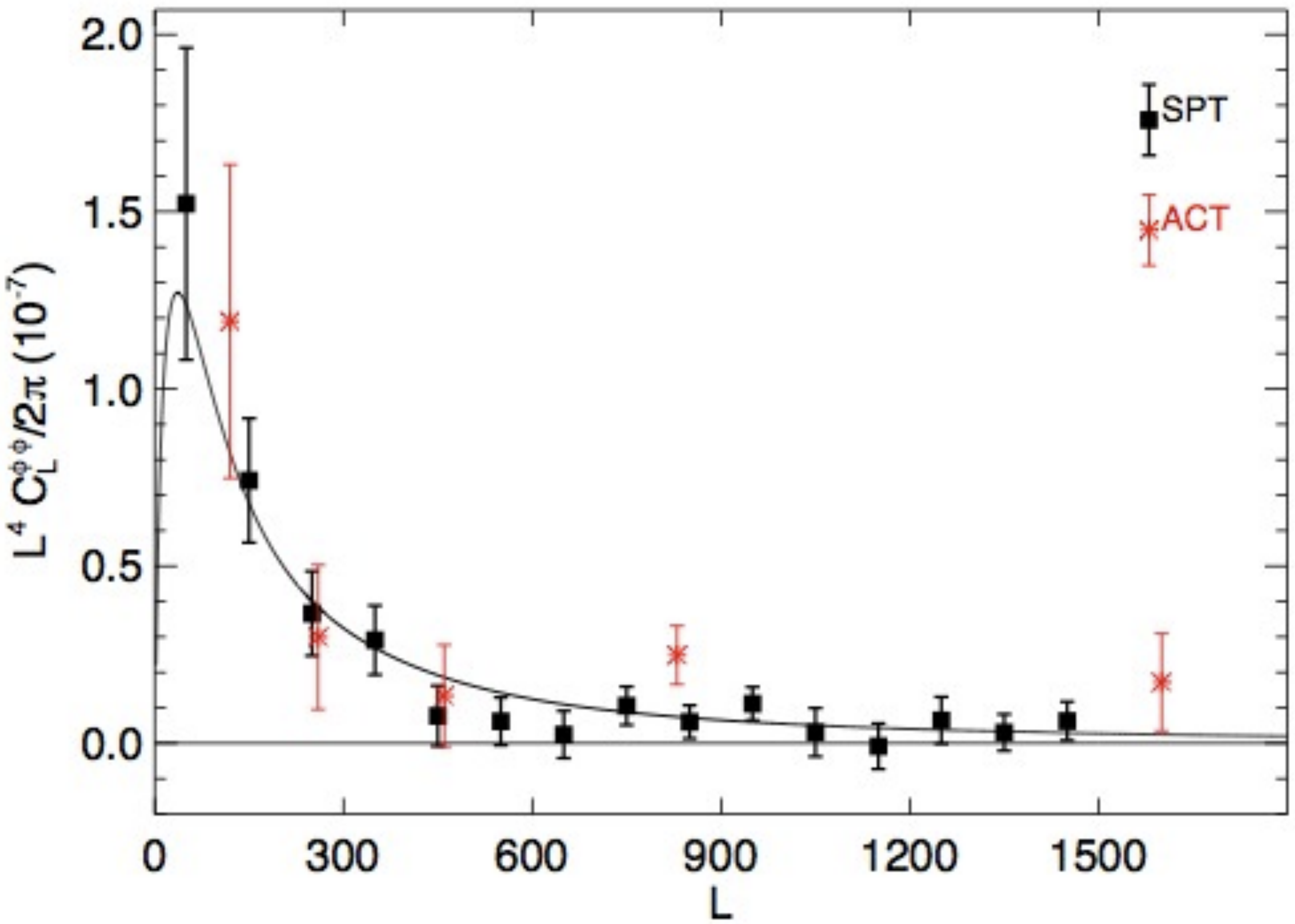
FIG. 2. Convergence power spectrum (red points) measured from ACT equatorial sky patches. The solid line is the power spectrum from the best-fit WMAP+ACT cosmological model with amplitude $A_L = 1$, which is consistent with the measured points. The error bars are from the Monte Carlo simulation results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

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

First CMB-only detection of CMB lensing.

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

First internal detection of lensing (4-sigma) from the CMB 4-point function



van Engelen et al. (2012)

A 6.3 sigma detection from SPT

First internal detection of lensing (4-sigma) from the CMB 4-point function

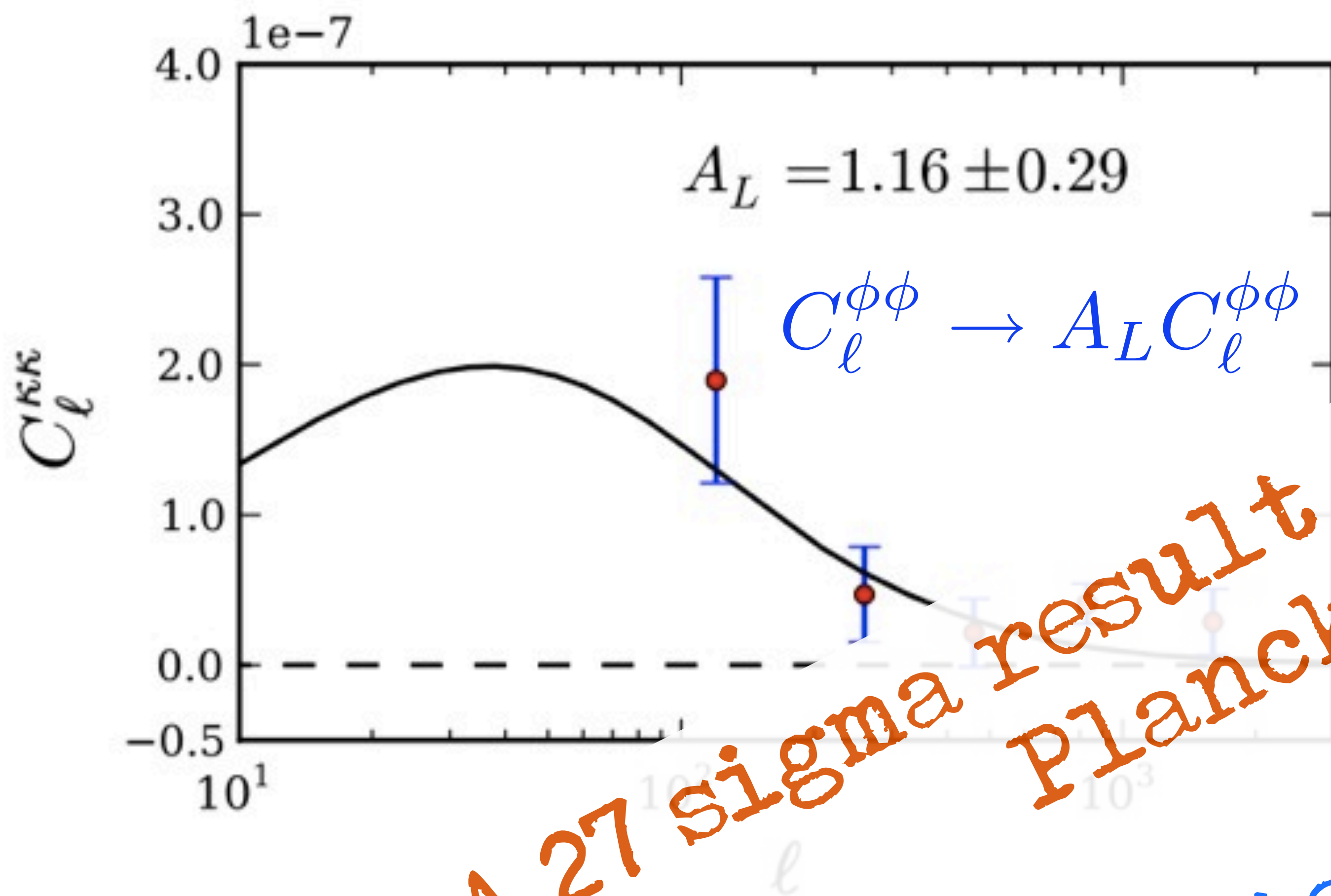


FIG. 2. Convergence power spectrum (red points) measured from ACT equatorial sky patches. The solid line is the power spectrum from the best-fit WMAP+ACT cosmological model with amplitude $A_L = 1$, which is consistent with the measured points. The error bars are from the Monte Carlo simulation results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

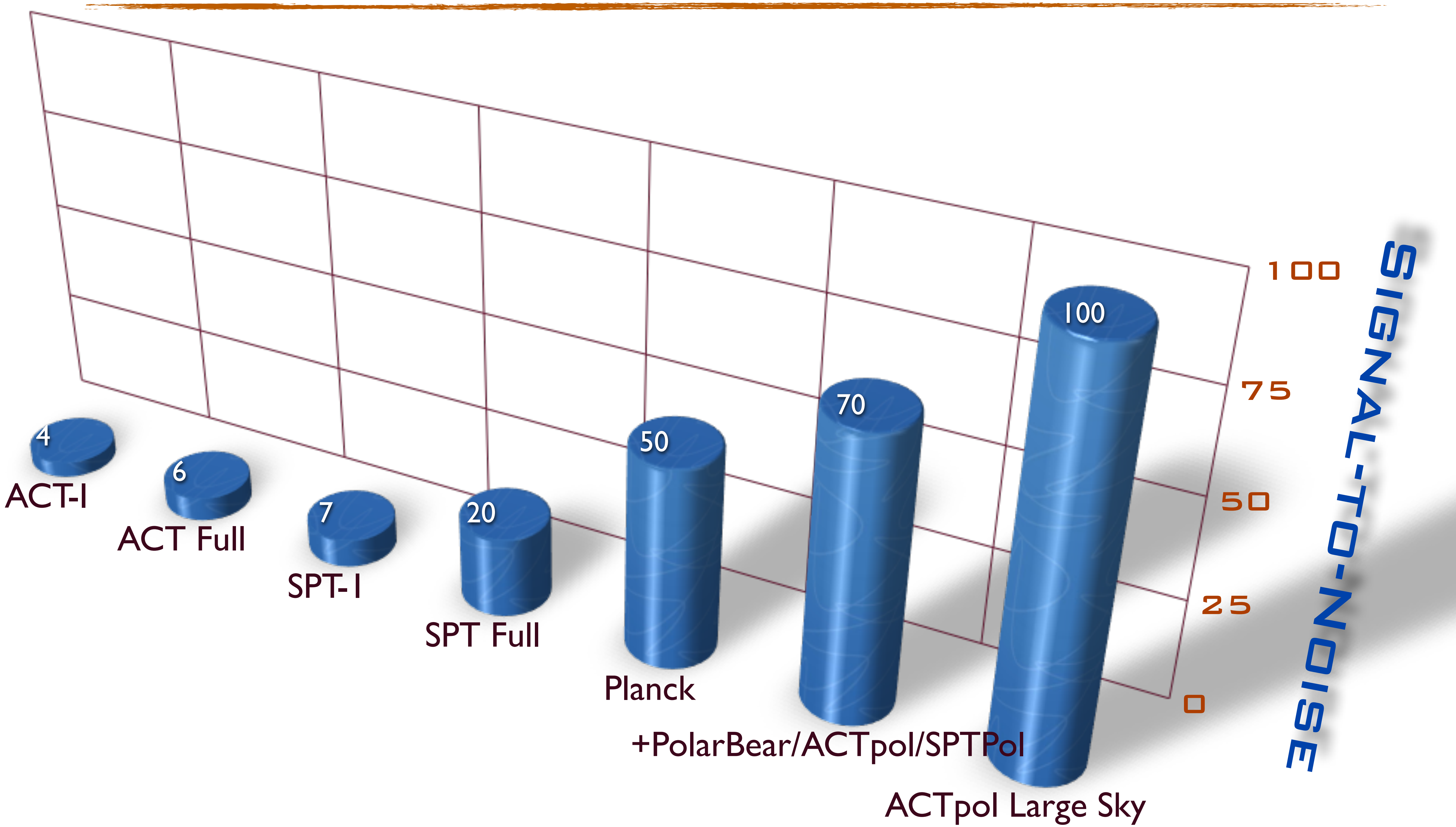
Detection is from 320 sq. degrees of ACT equatorial data only

Das, Sherwin et al. (2011)

A 27 sigma result is predicted for Planck (2013).

We are entering the era of precision CMB lensing!

CMB Lensing is going to explode as a field in the next few years



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

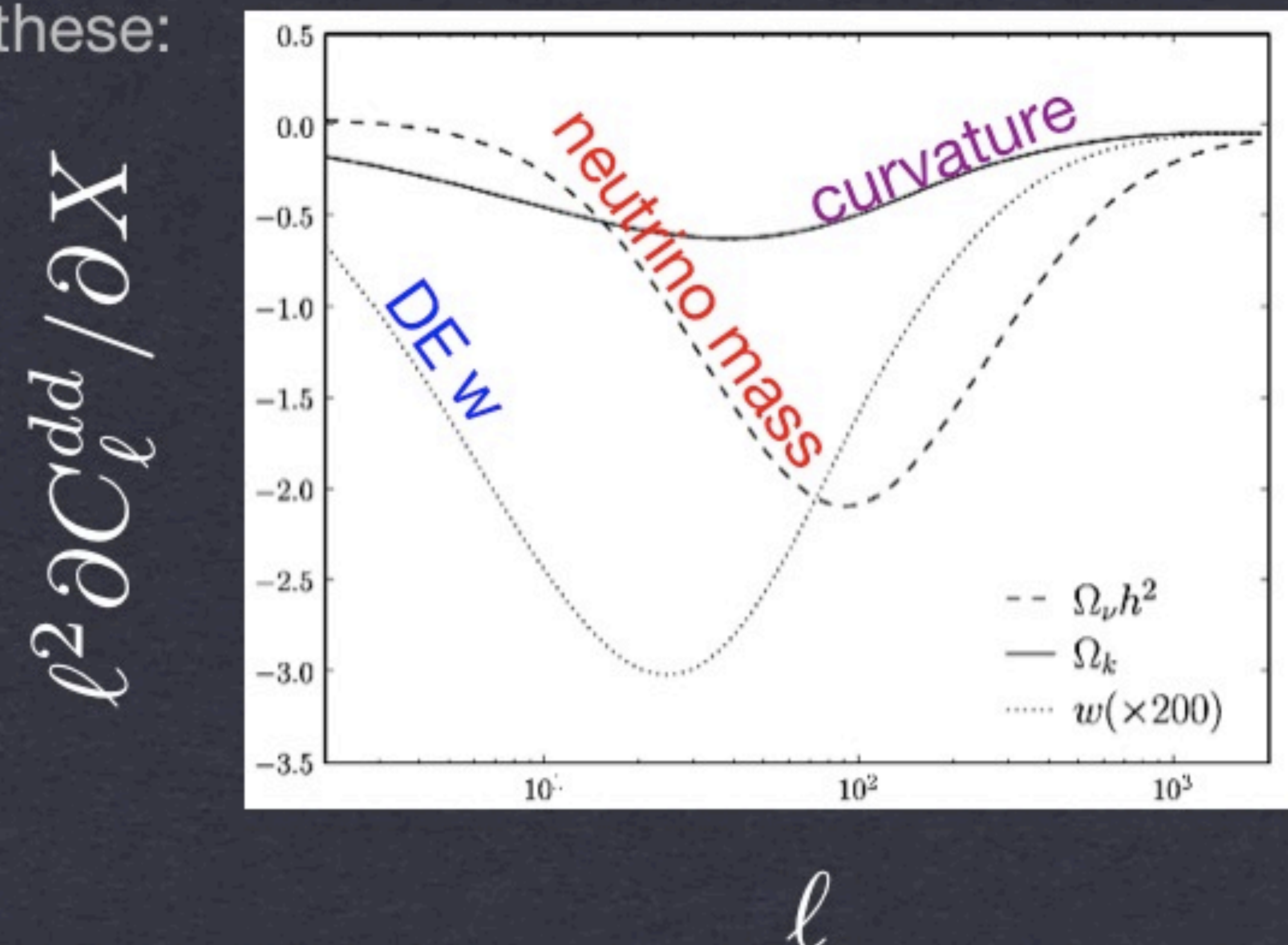
Affected by parameters that affect distance scales and growth of structure in the late universe.

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

The deflection power spectrum is a clean and unique probe

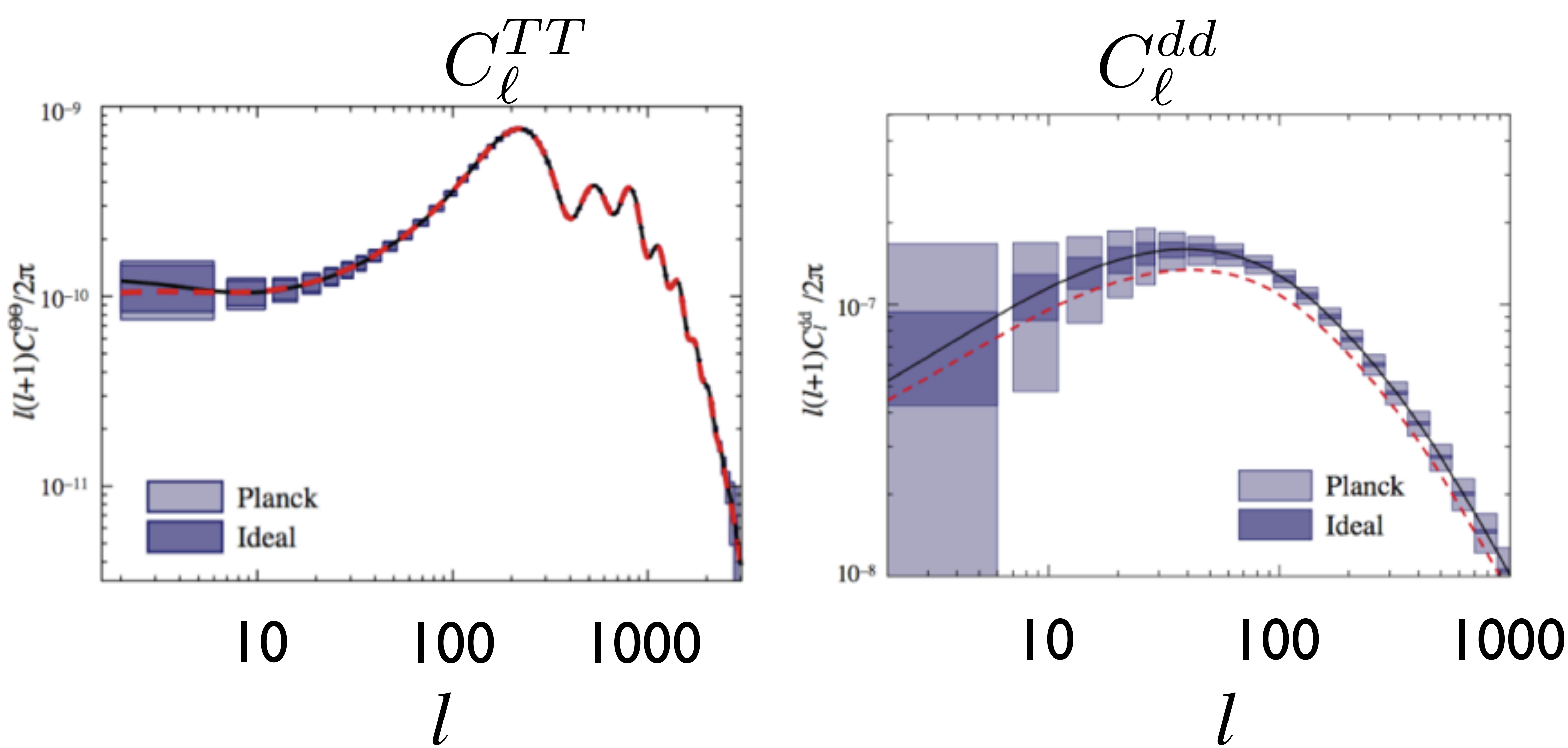
The primary CMB can be kept nearly unchanged under variations of neutrino mass, dark energy equation of state or curvature. But the deflection field cares about these:

Lensing breaks the angular diameter distance degeneracy!



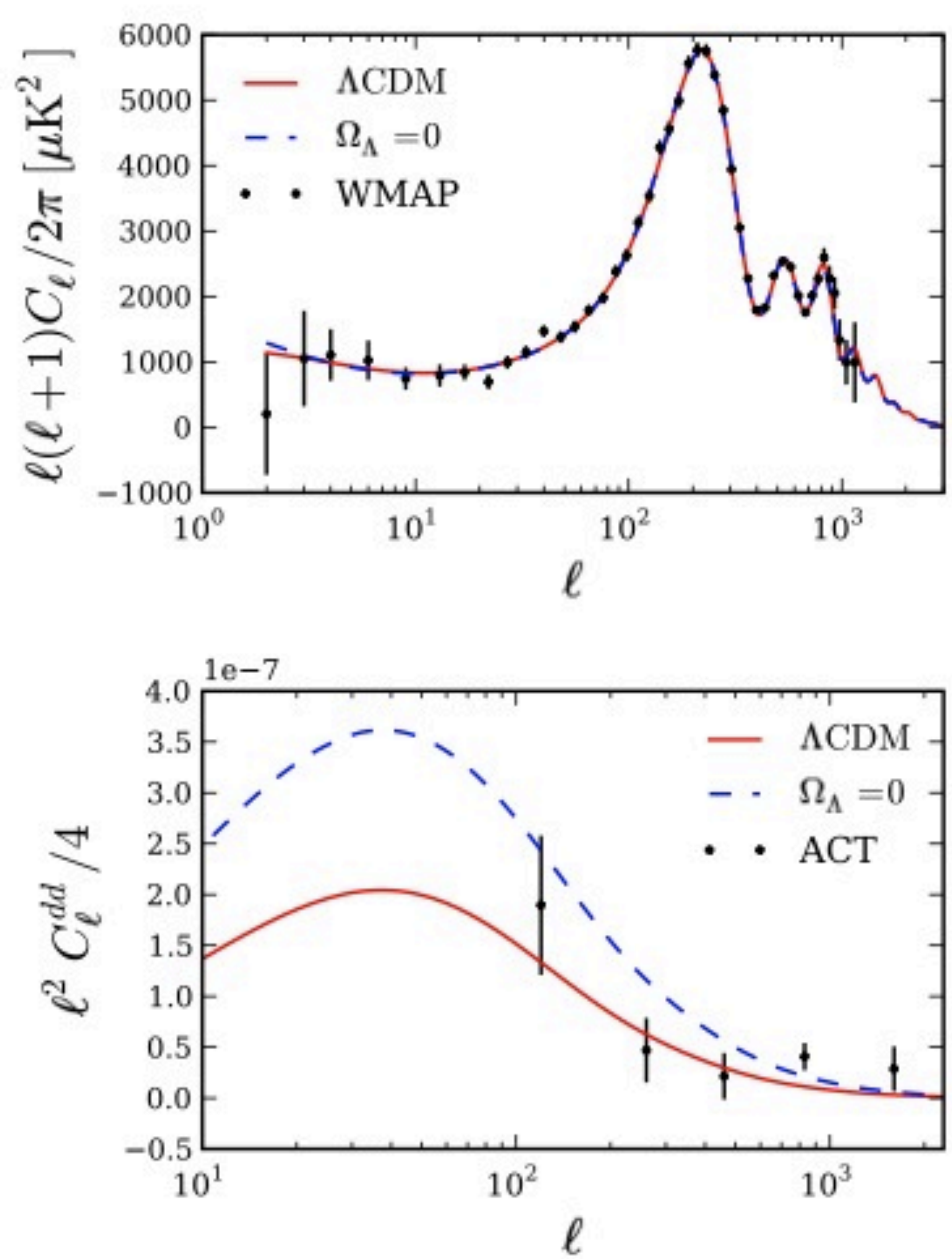
An example

Example from Hu 2001: w=-1 and w=-2/3 models with same D_*



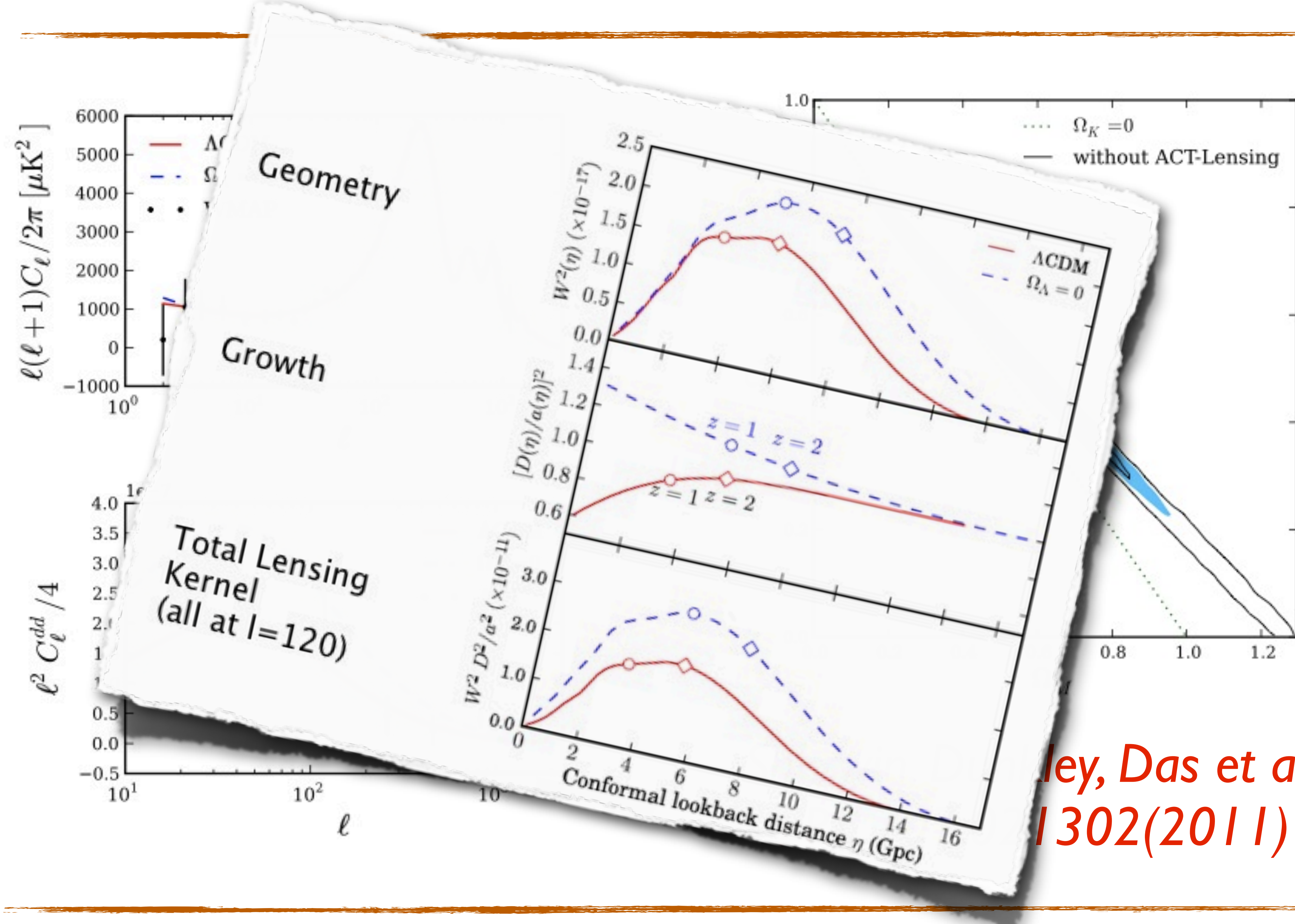
CMB lensing is especially constraining for the so-called early DE models (see, dePutter, Zahn, Linder, 2009)

A COOL FIRST APPLICATION: DARK ENERGY FROM CMB ALONE (3.2 SIGMA)



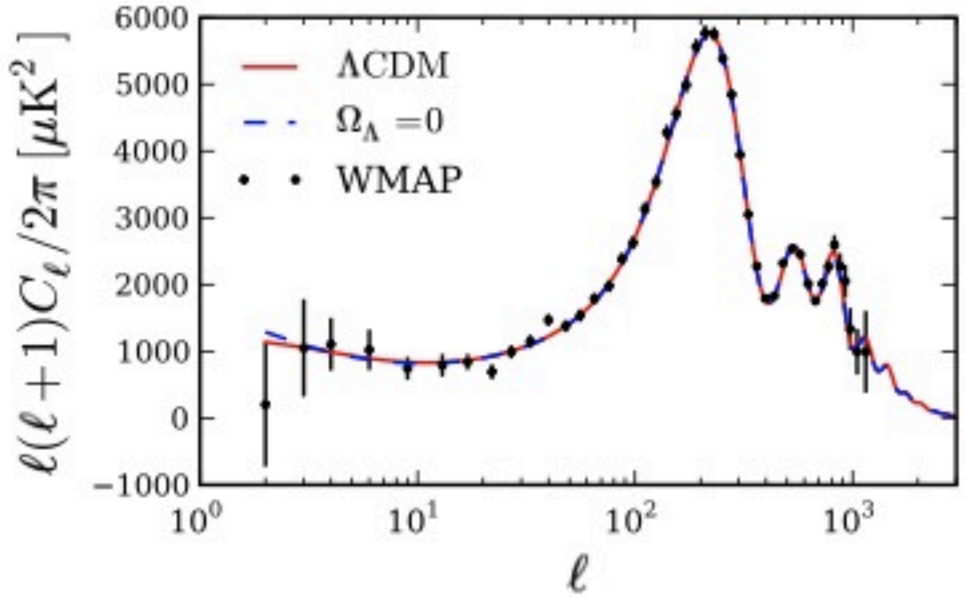
Sherwin, Dunkley, Das et al., PRL 107:021302(2011)

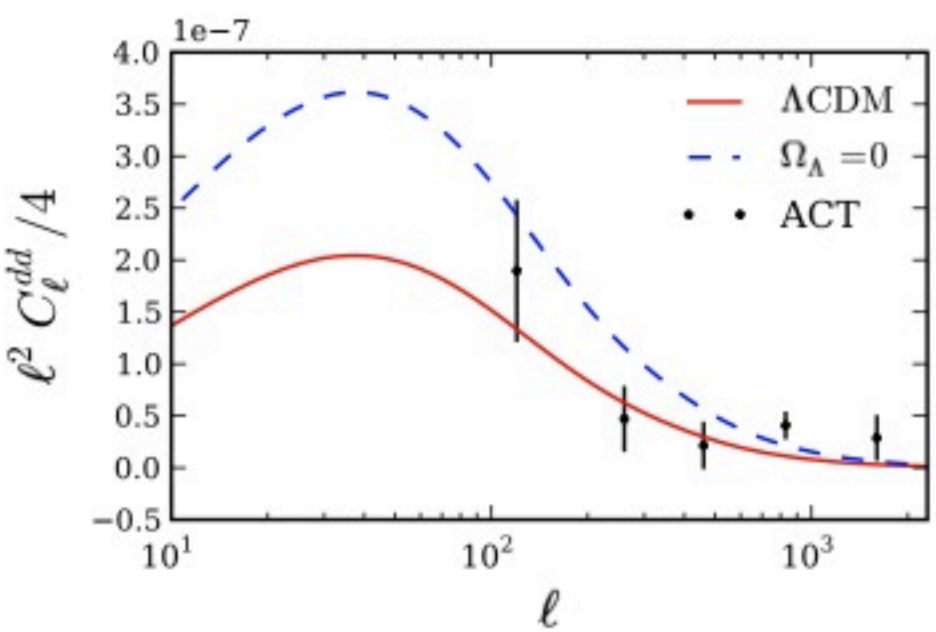
A COOL FIRST APPLICATION: DARK ENERGY FROM CMB ALONE (3.2 SIGMA)

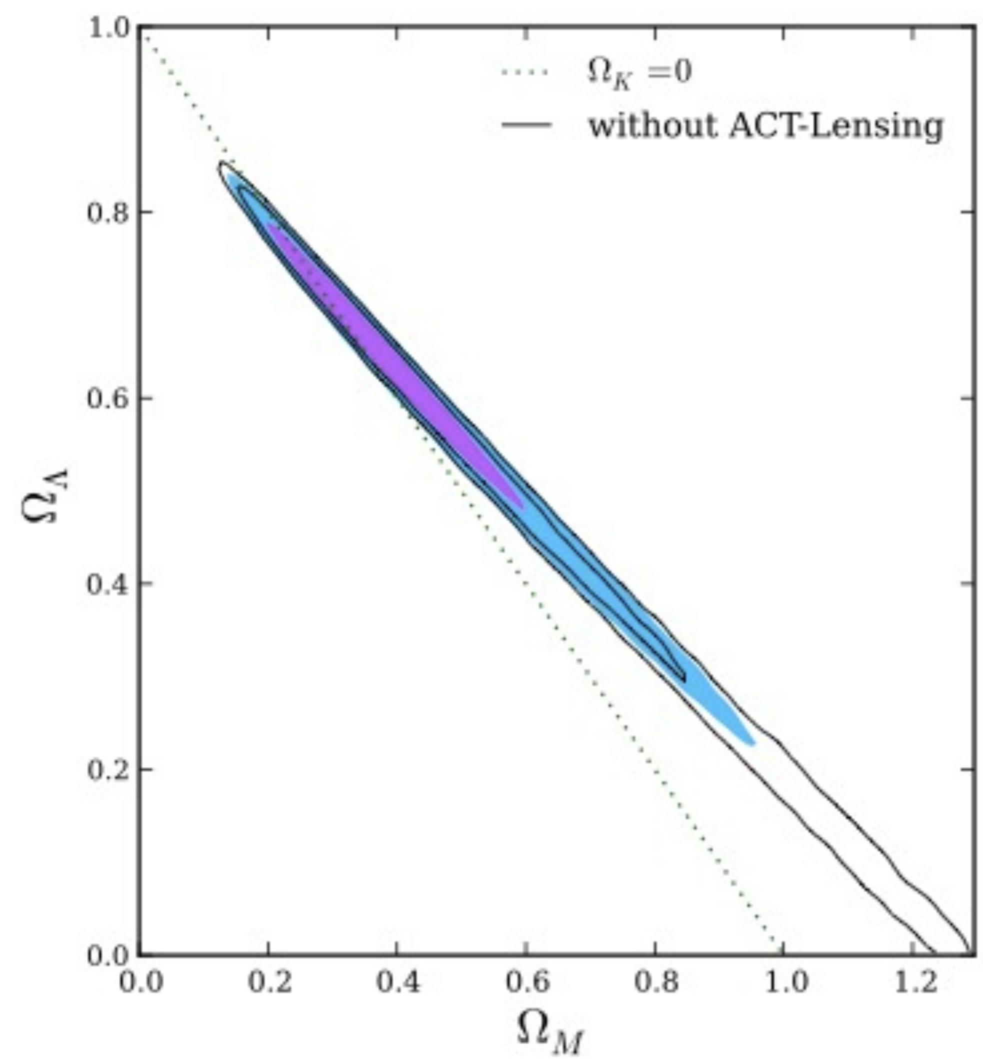


ley, Das et al.,
1302(2011)

A COOL FIRST APPLICATION: DARK ENERGY FROM CMB ALONE (3.2 SIGMA)

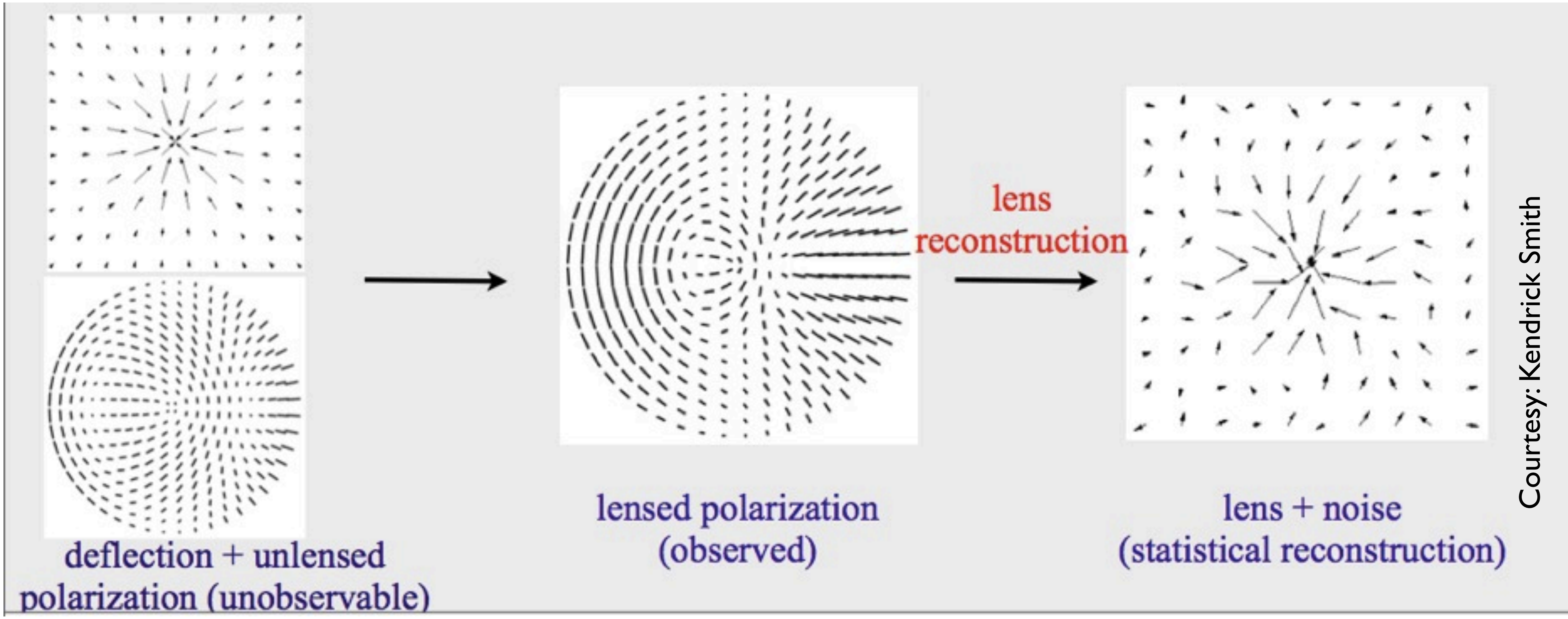






Sherwin, Dunkley, Das et al., PRL 107:021302(2011)

USING CMB POLARIZATION IS THE NEXT BIG THING IN LENSING



From pure E-modes lensing will create a mixture of E and B-modes.

PolarBeaR, ACTPol, SPTPol are gearing up to be premier CMB lensing experiments using polarization.

POLARIZATION GIVES EXTRA LEVERAGE FOR LENSING RECONSTRUCTION

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

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

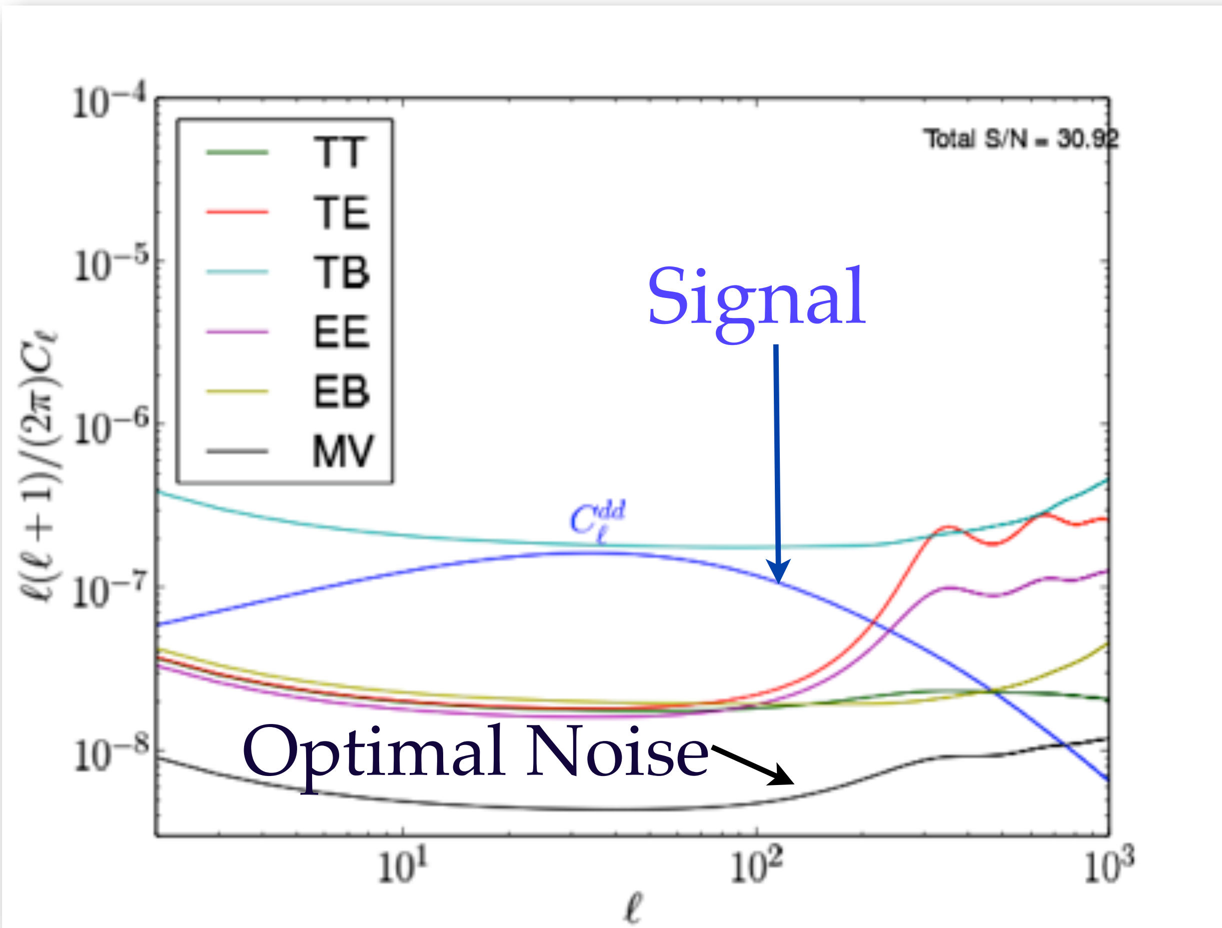
In the Fourier space, lensing introduces correlations between different Fourier modes $\boldsymbol{\ell}, \ \boldsymbol{\ell}'$, which are uncorrelated for the primordial signals. This correlation is used to write down an estimator of the deflection field from the observed fields. Schematically:

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

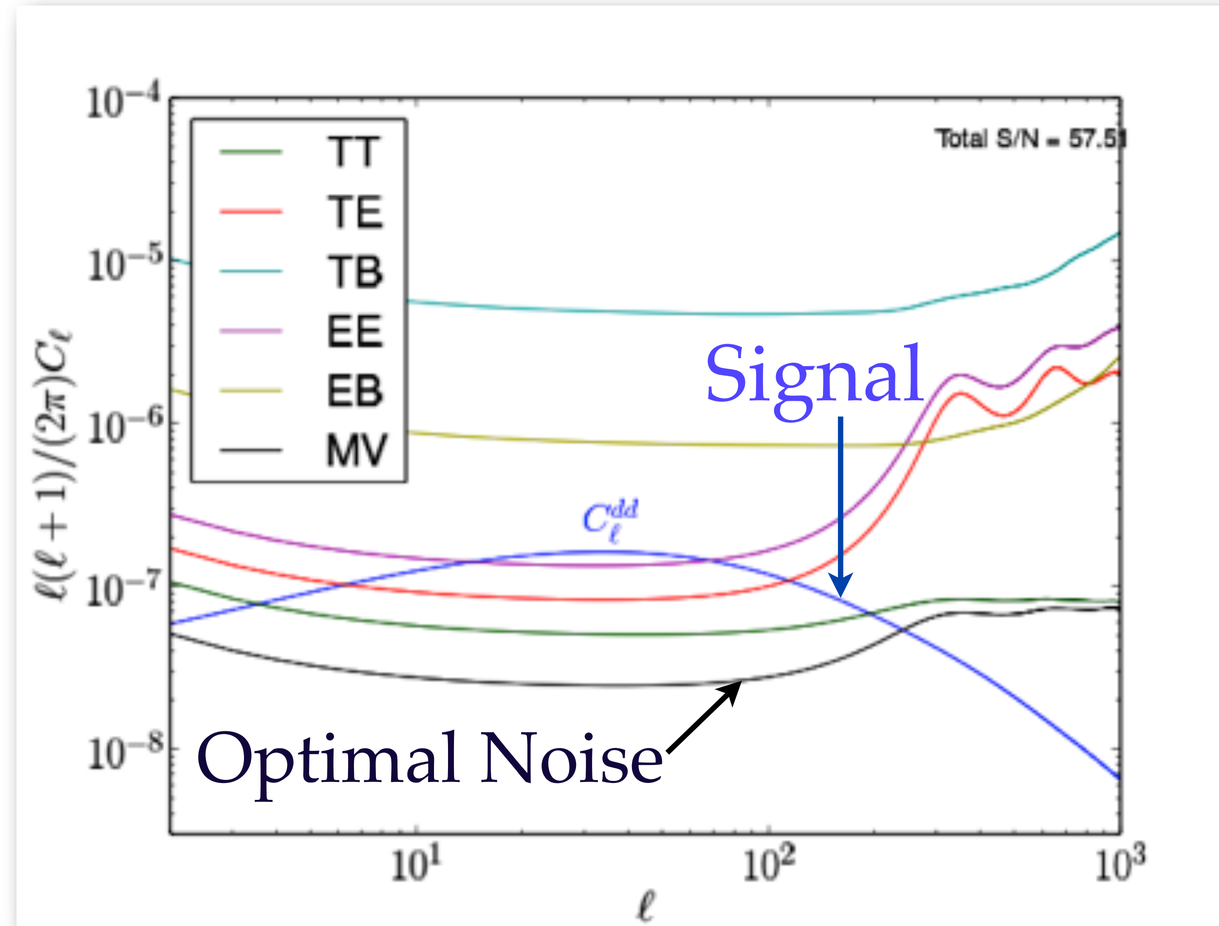
where $X, Y \in (\tilde{T}, \tilde{E}, \tilde{B})$

HIGH RES. POLARIZATION EXPERIMENTS ARE POWERFUL CMB LENSING MACHINES

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



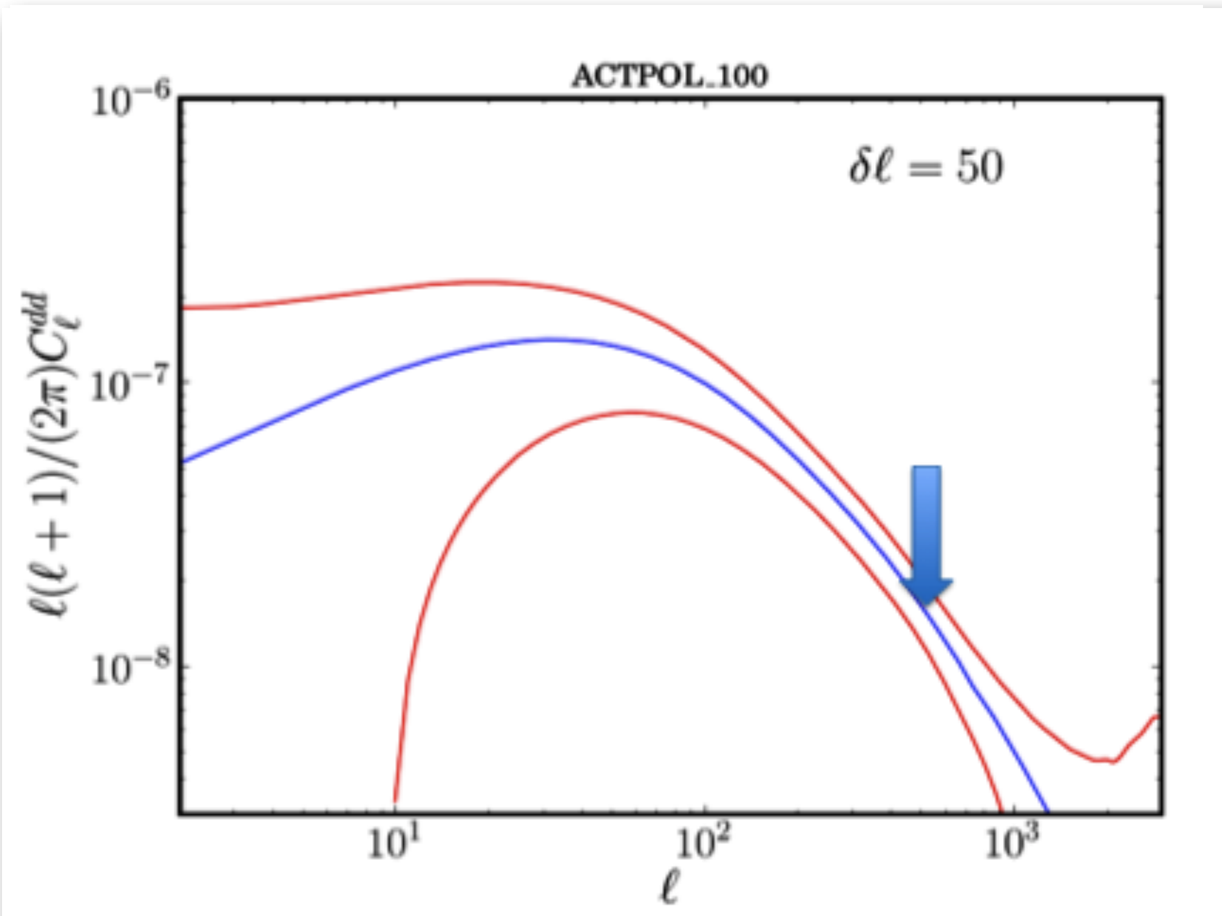
ACTPOL-DEEP:
150 sq-deg @ 3 μK-arcmin (temp)
and 5 μK-arcmin (pol)



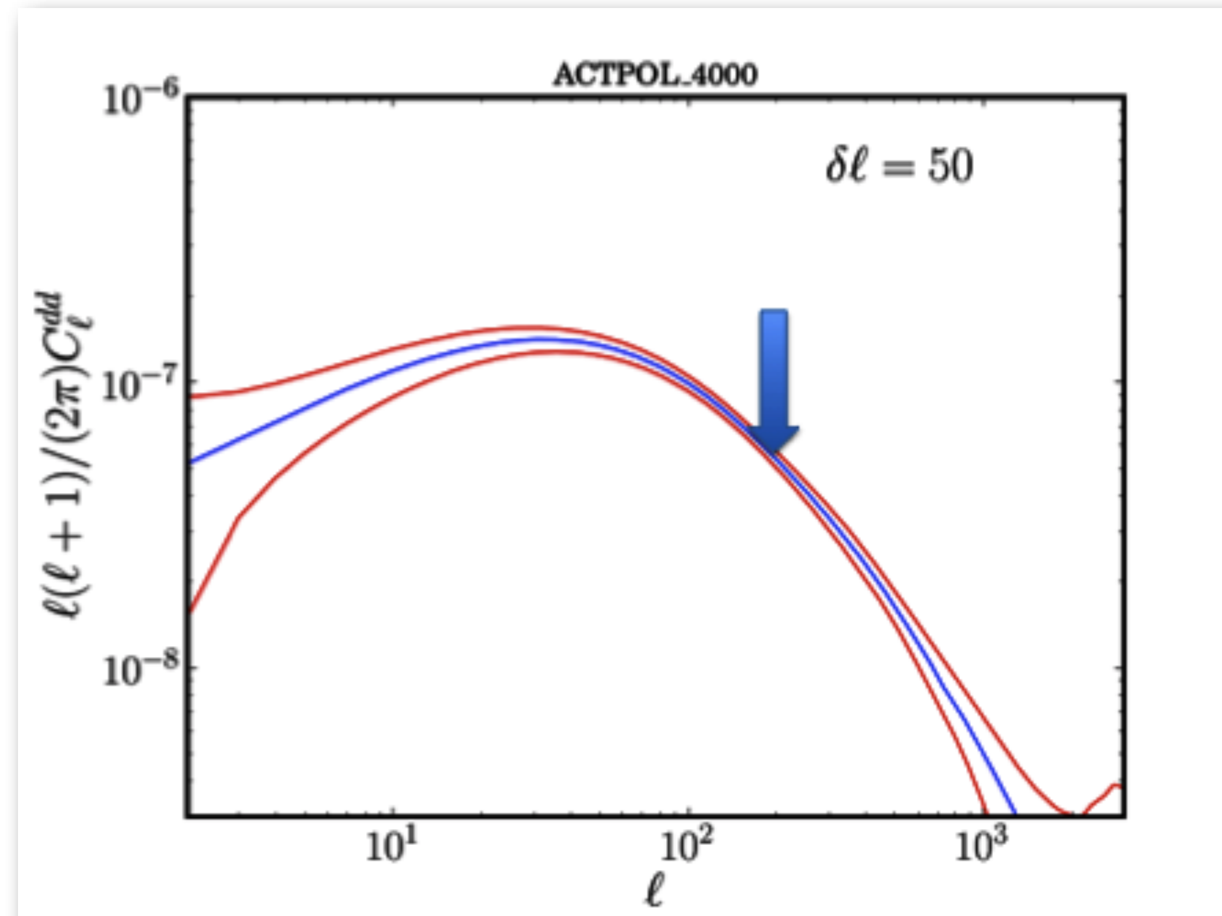
ACTPOL-WIDE:
4000 sq-deg @ 20 μK-arcmin (temp)
and 28 μK-arcmin (pol)

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)

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.

$10^\circ \times 10^\circ$

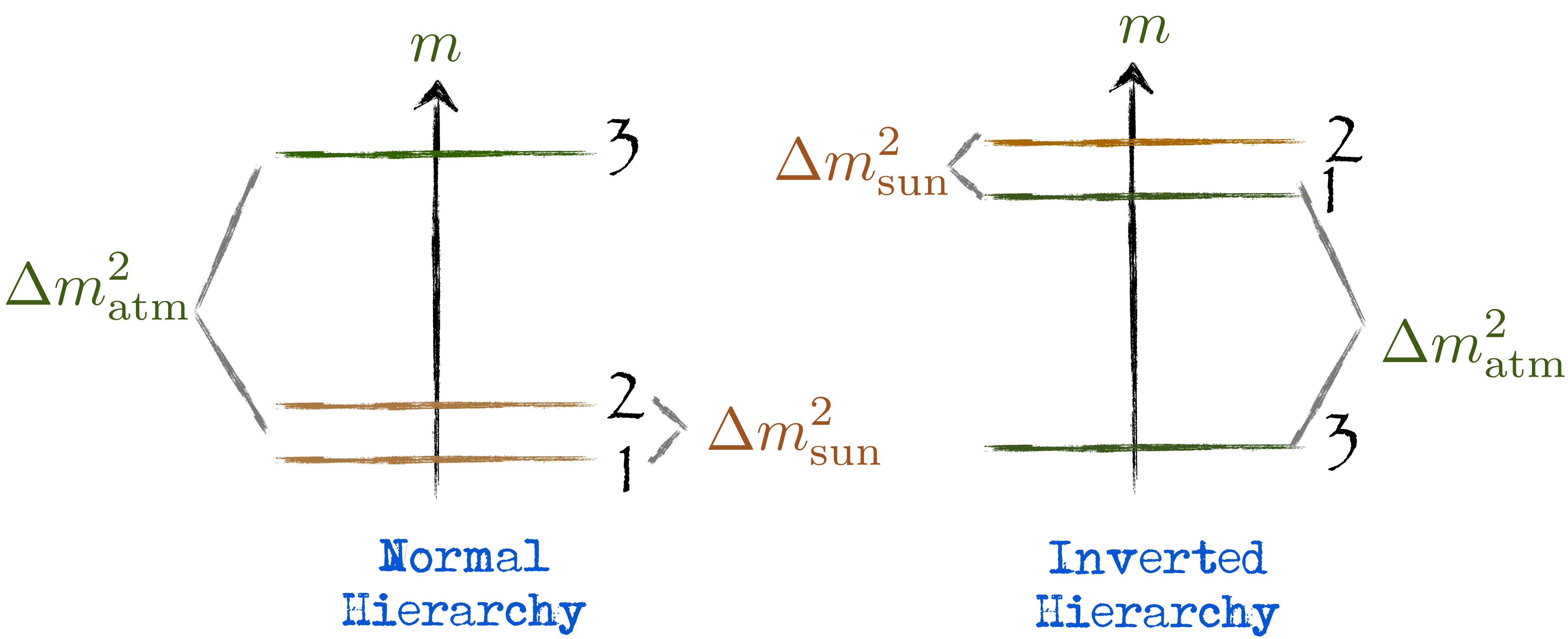
ACTPOL-DEEP:
150 sq-deg @ 3 μK-arcmin (temp) and 5 μK-arcmin (pol)

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

Some Facts about Neutrinos

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

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



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

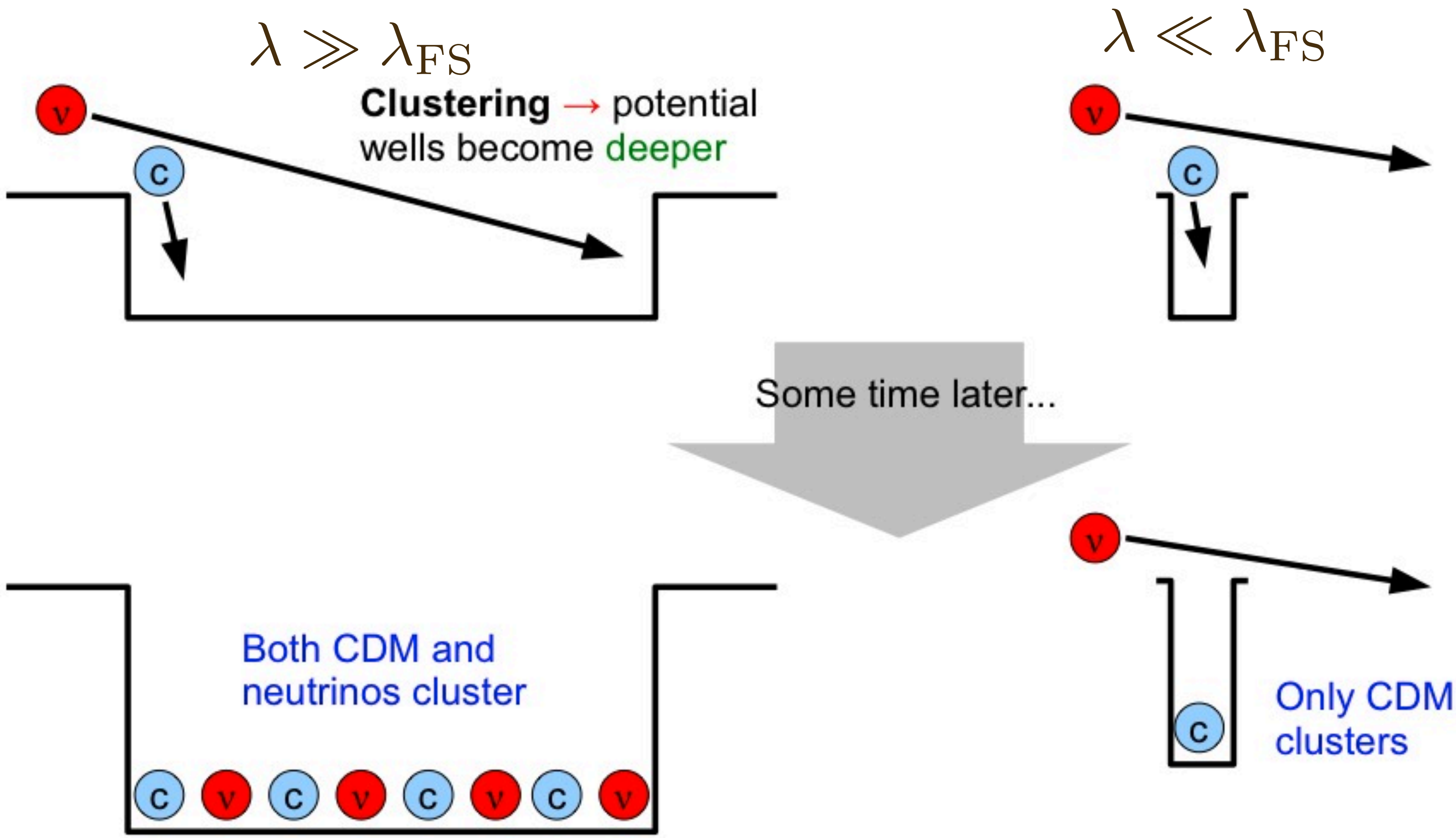
$$\lambda_{FS} \equiv \sqrt{\frac{8\pi^2 c_\nu^2}{3\Omega_m H^2}} \simeq 4.2\sqrt{\frac{1+z}{\Omega_{m,0}}}\left(\frac{\mathrm{eV}}{m_\nu}\right)\ h^{-1}\ \mathrm{Mpc}$$

frequency

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

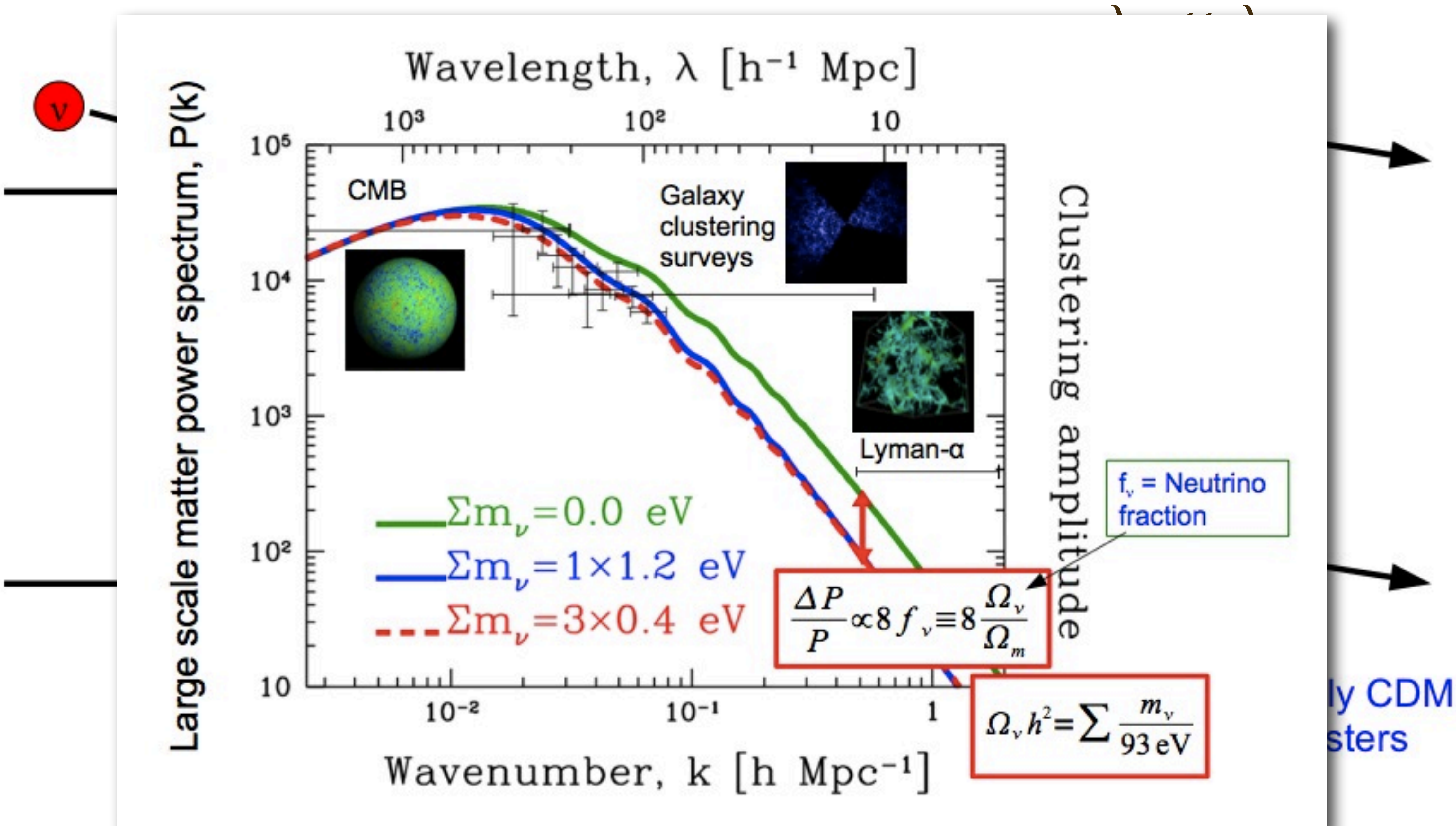
Non-relativistic neutrinos do not cluster for $\lambda \ll \lambda_{\mathrm{FS}}$ (small scales or large k's)

MASSIVE NEUTRINOS DO NOT CLUSTER ON SMALL SCALES



Graphics from Y. Wong

MASSIVE NEUTRINOS SUPPRESS STRUCTURE FORMATION ON SMALL SCALES

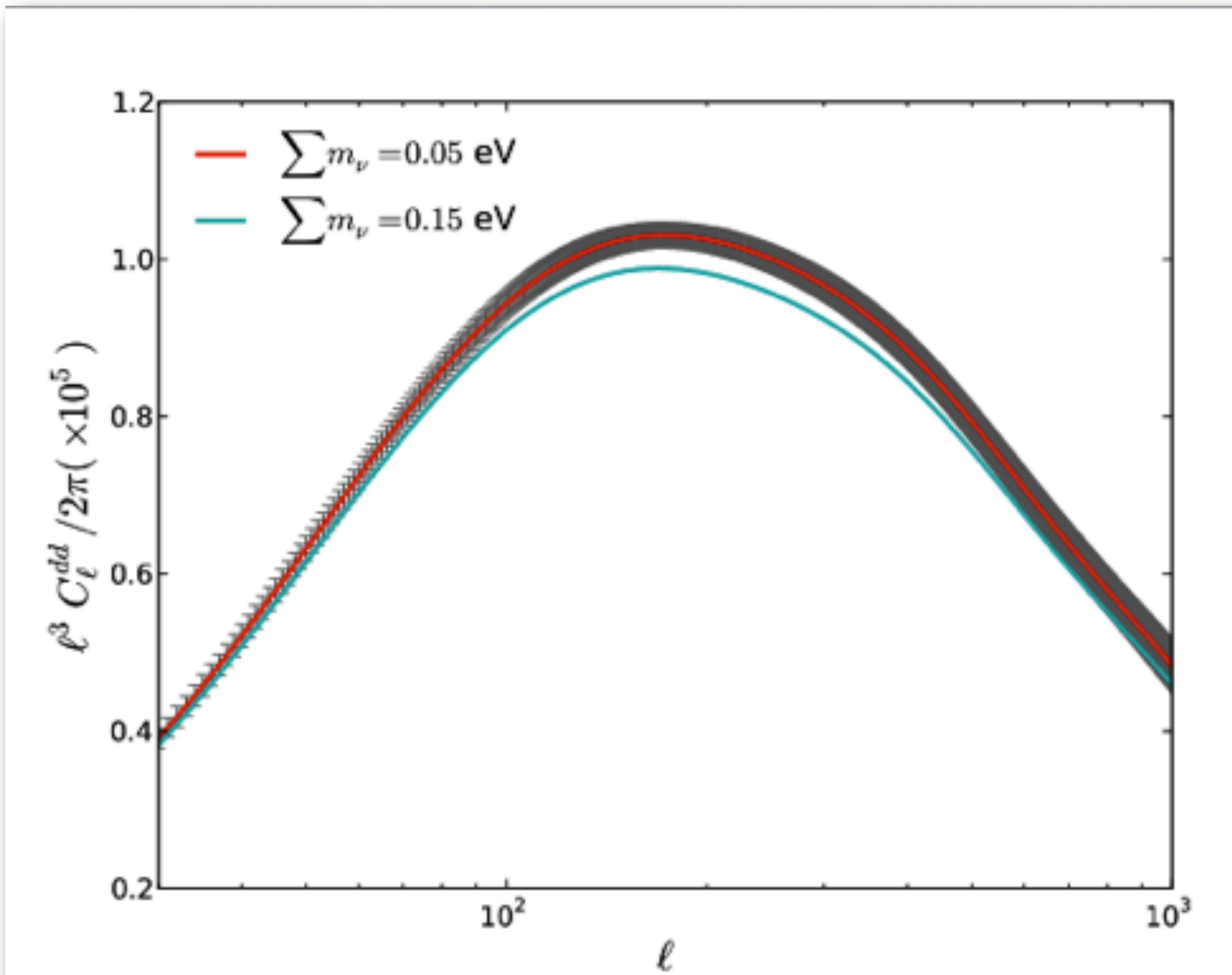


Graphics from Y. Wong

CMB LENSING IS A CLEAN AND SENSITIVE PROBE OF NEUTRINO MASS

Smaller Scales →

Deflection power spectrum



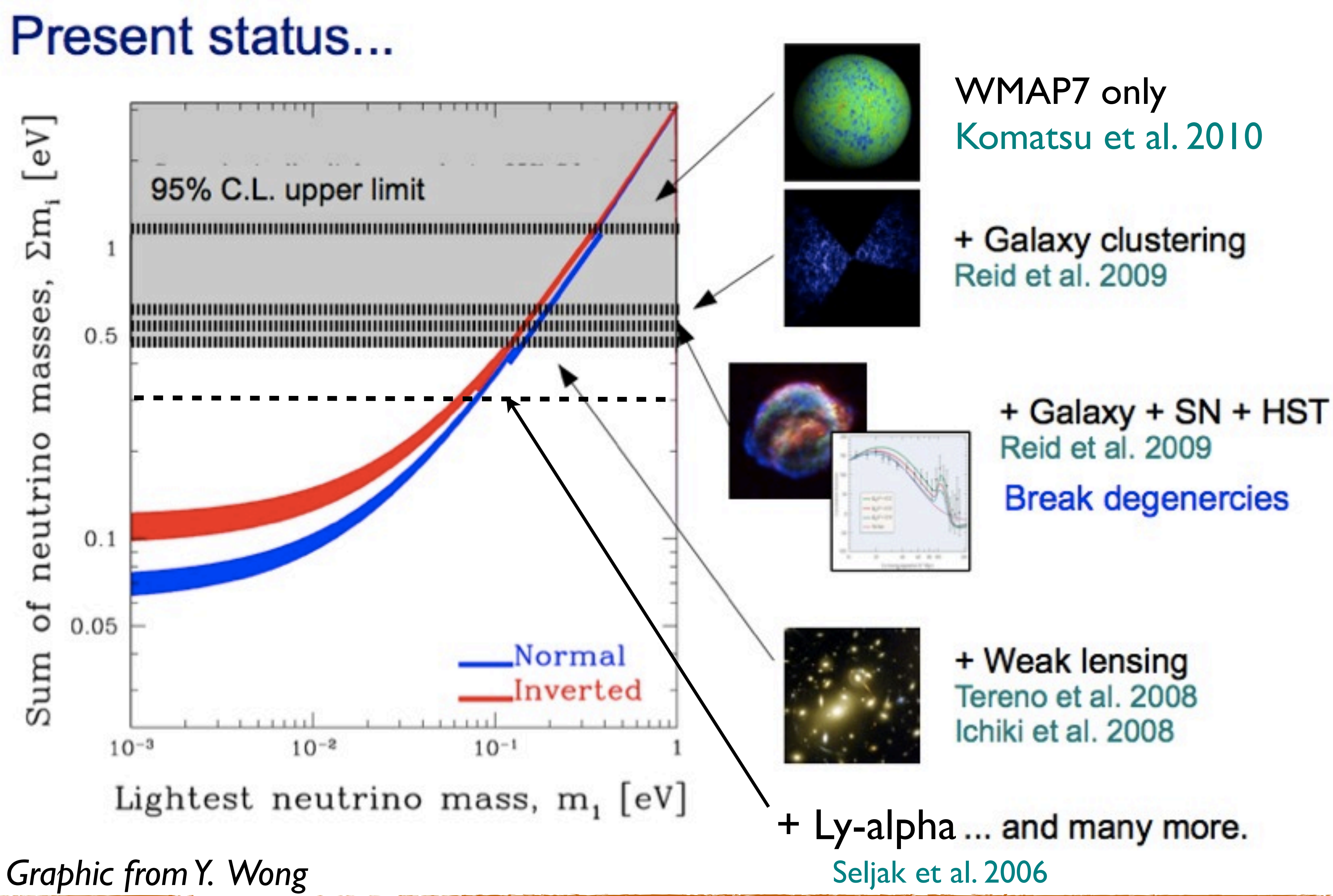
CMB lensing is sensitive:

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

CMB lensing is clean:

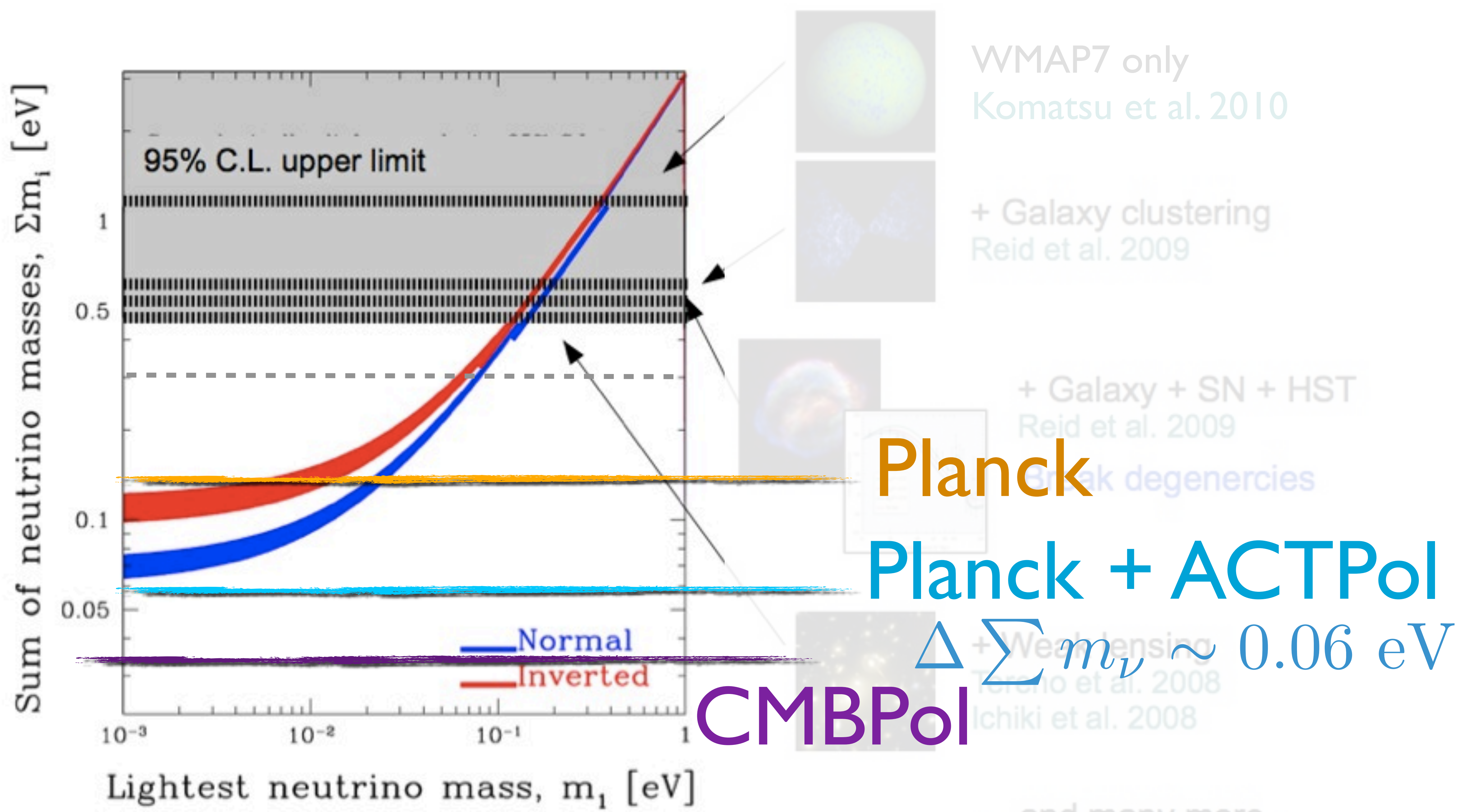
- CMB redshift known
- Most contributions from linear scales.
- No confusion from galaxy bias.

ACTPOL CAN HELP CONSTRAIN NEUTRINO HIERARCHIES!



Graphic from Y. Wong

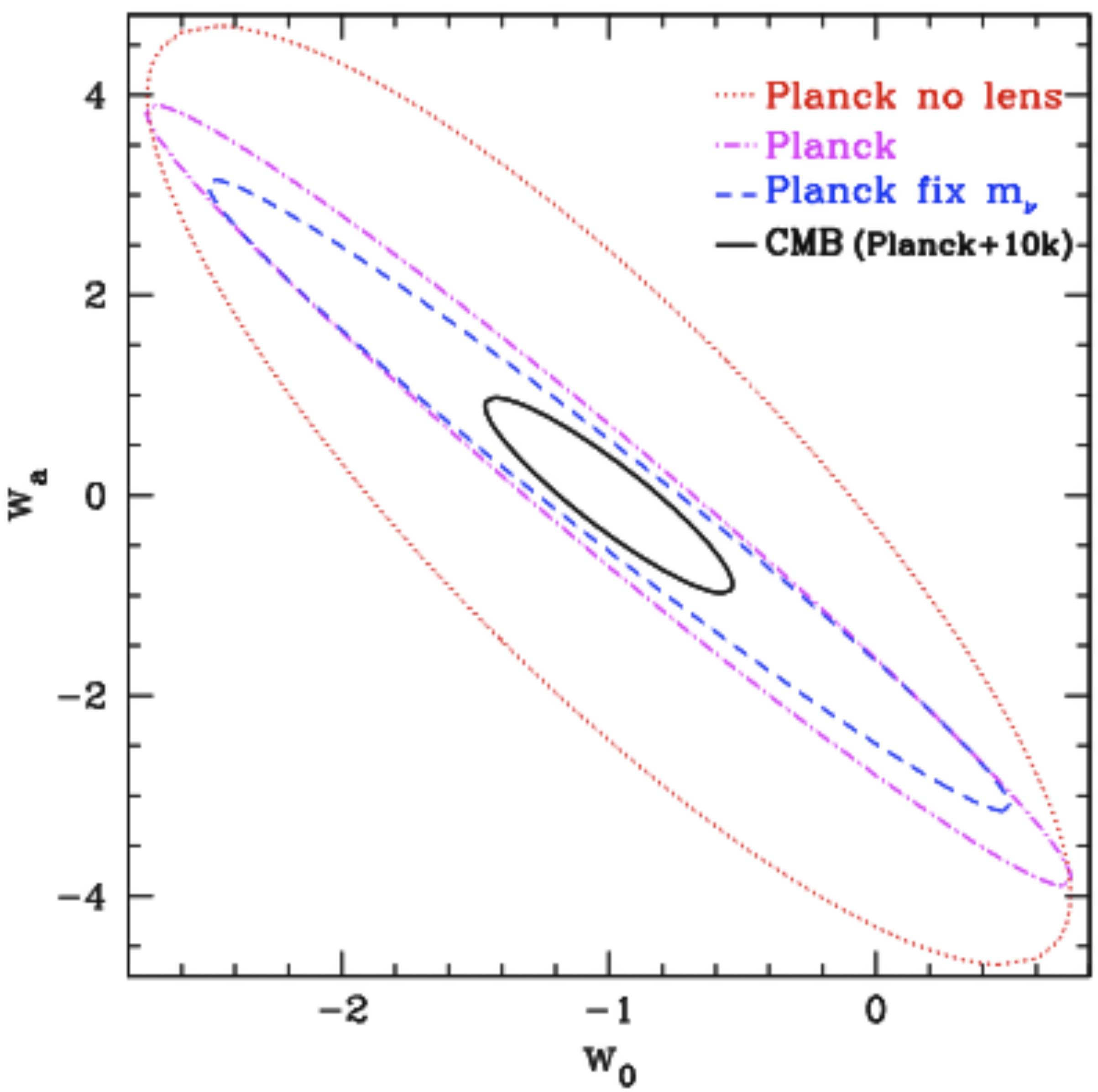
ACTPOL CAN HELP CONSTRAIN NEUTRINO HIERARCHIES!

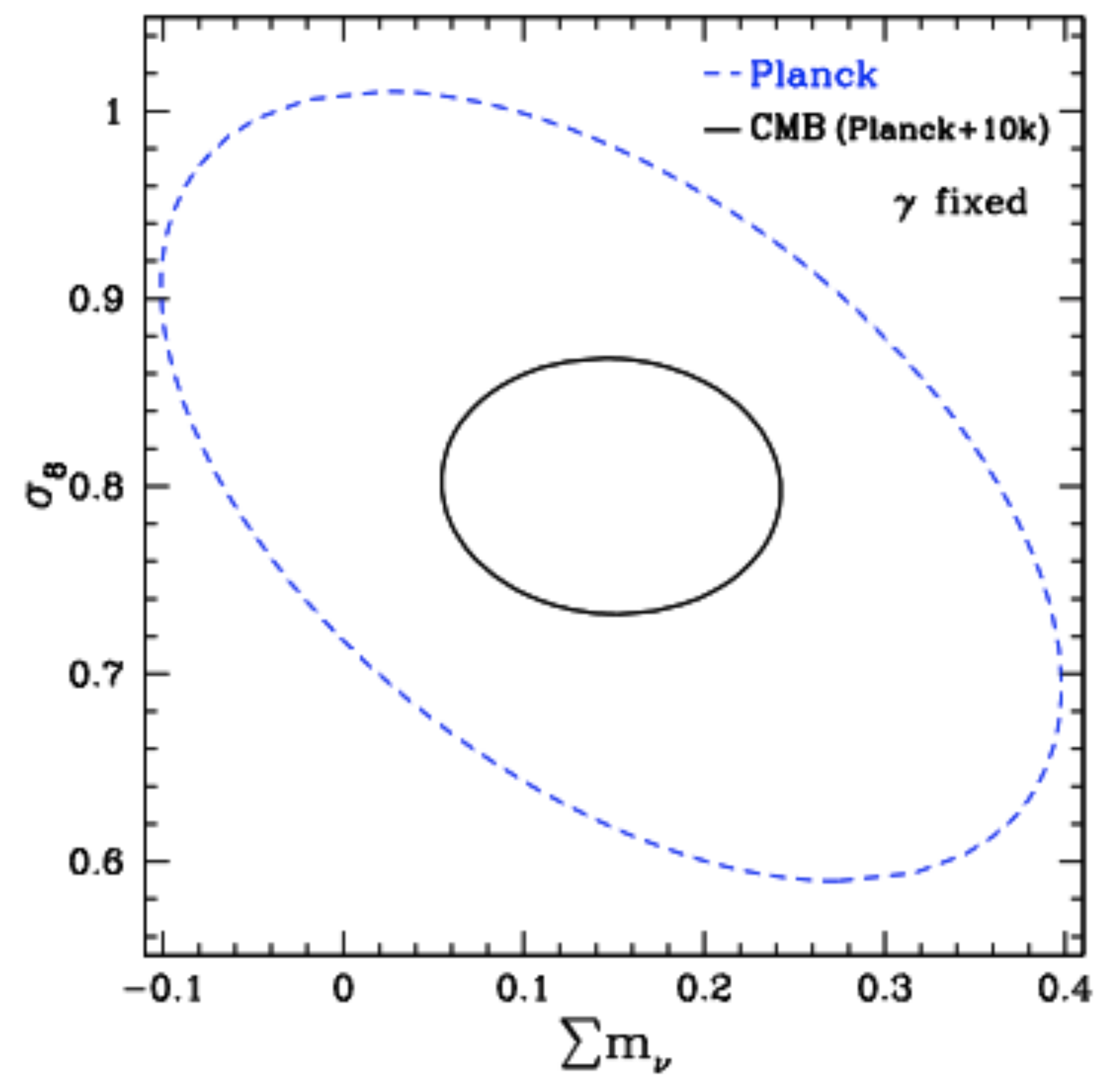


Graphic from Y. Wong

COMBINED WITH PLANCK, HIGH RES EXPERIMENTS WILL BE VERY POWERFUL

Assume Planck + 10,000 sq deg high res. data at 5 muk-arcmin.





Das and Linder (2012)

THERE ARE THREE MAIN AVENUES FOR COSMOLOGY WITH CMB LENSING

☑ Smearing of CMB power spectrum peaks and small scale B-mode power.

☑ Reconstruction of the deflection/convergence field and its power spectrum.

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

Effective Lensing Potential — Geometry — Matter potential

☐ Cross correlation of the deflection field with other cosmological probes.

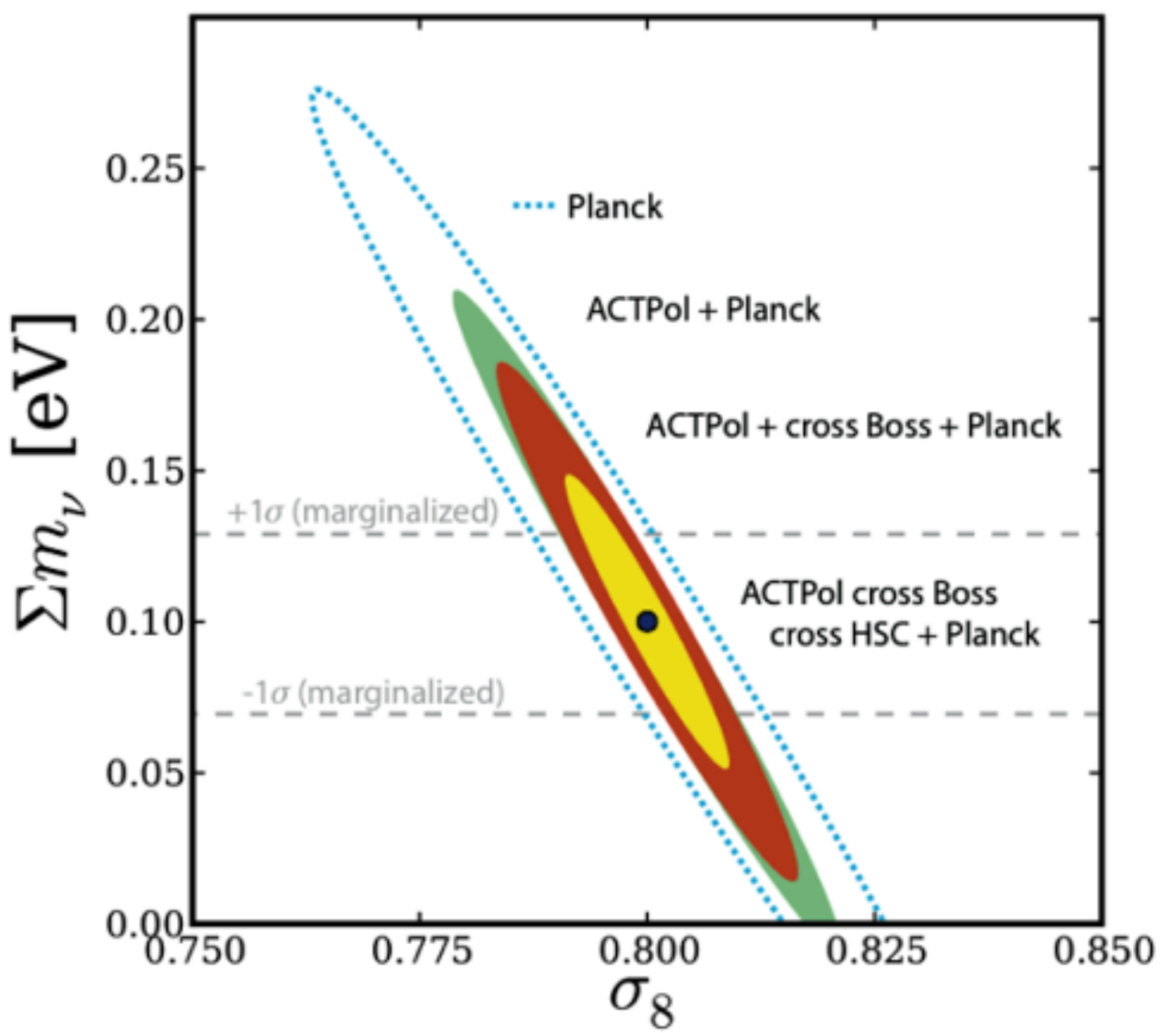
e.g. weak lensing, galaxy counts, CIB ...

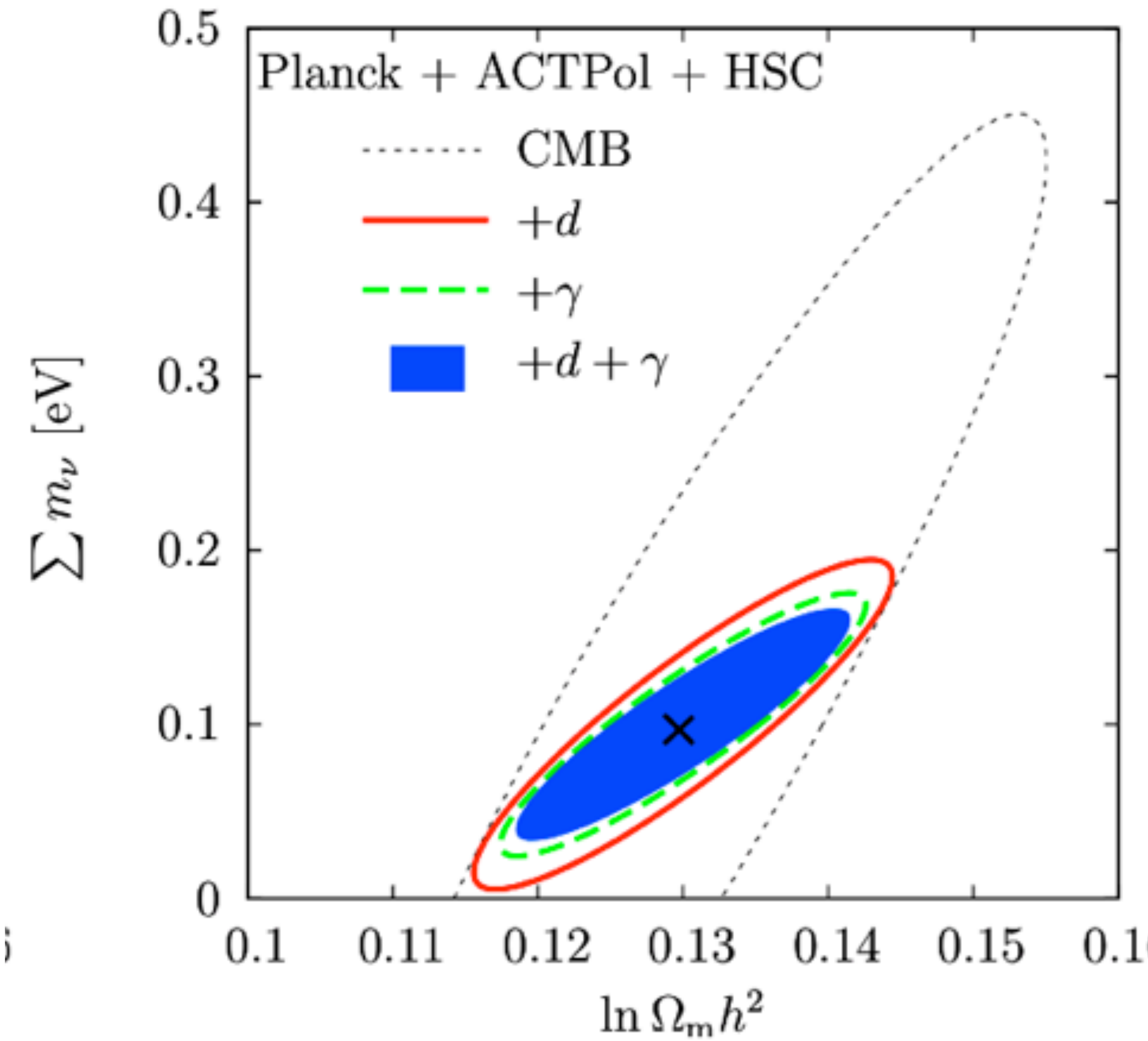
- *break degeneracies.*
- *constrain systematics.*
- *constrain galaxy bias*

Highest science impact expected on: *neutrino mass sum, dark energy, test of GR, and understanding galaxy evolution.*

Cross correlations: SYNERGY WITH GALAXY AND WEAK LENSING SURVEYS (BigBOSS,DES, LSST)

CMB lensing X Galaxy density X Galaxy Lensing





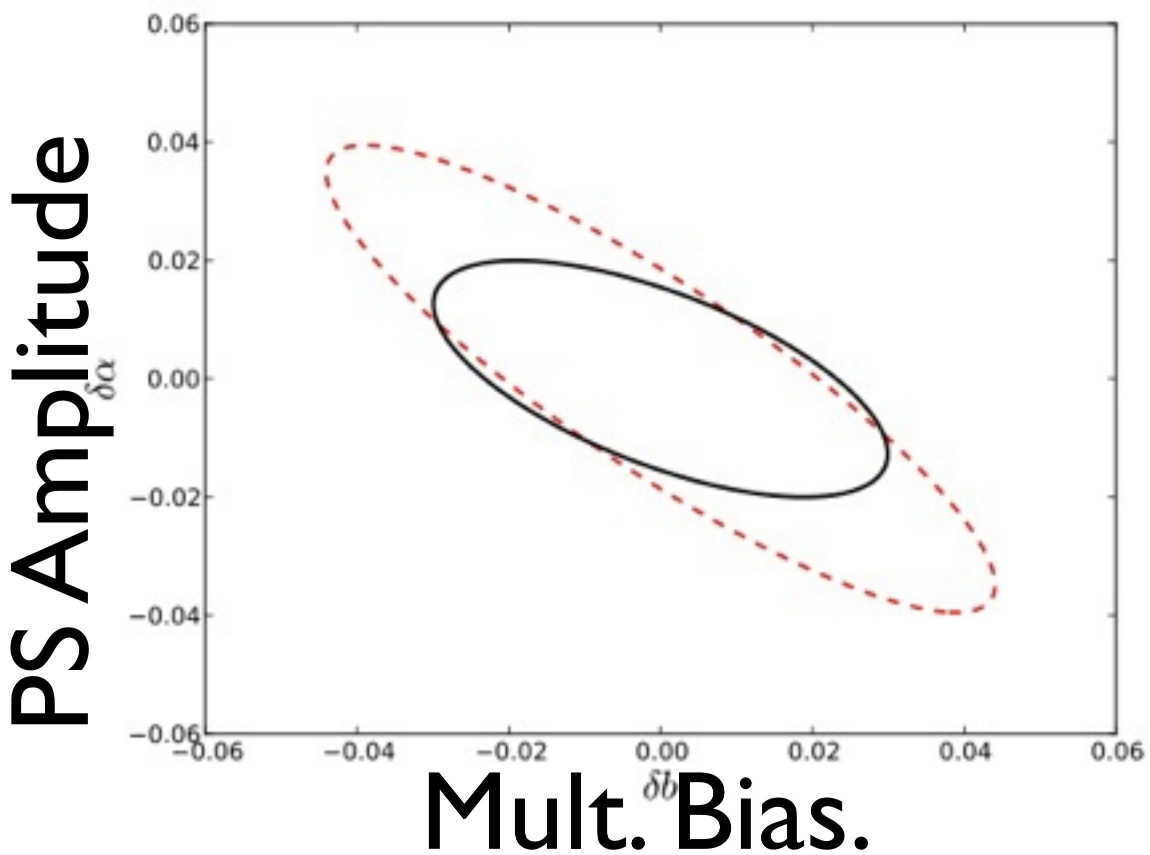
Namikawa et al (2010)

Cross correlations can be used to control systematics in other probes

Example: *Cosmic shear multiplicative bias*

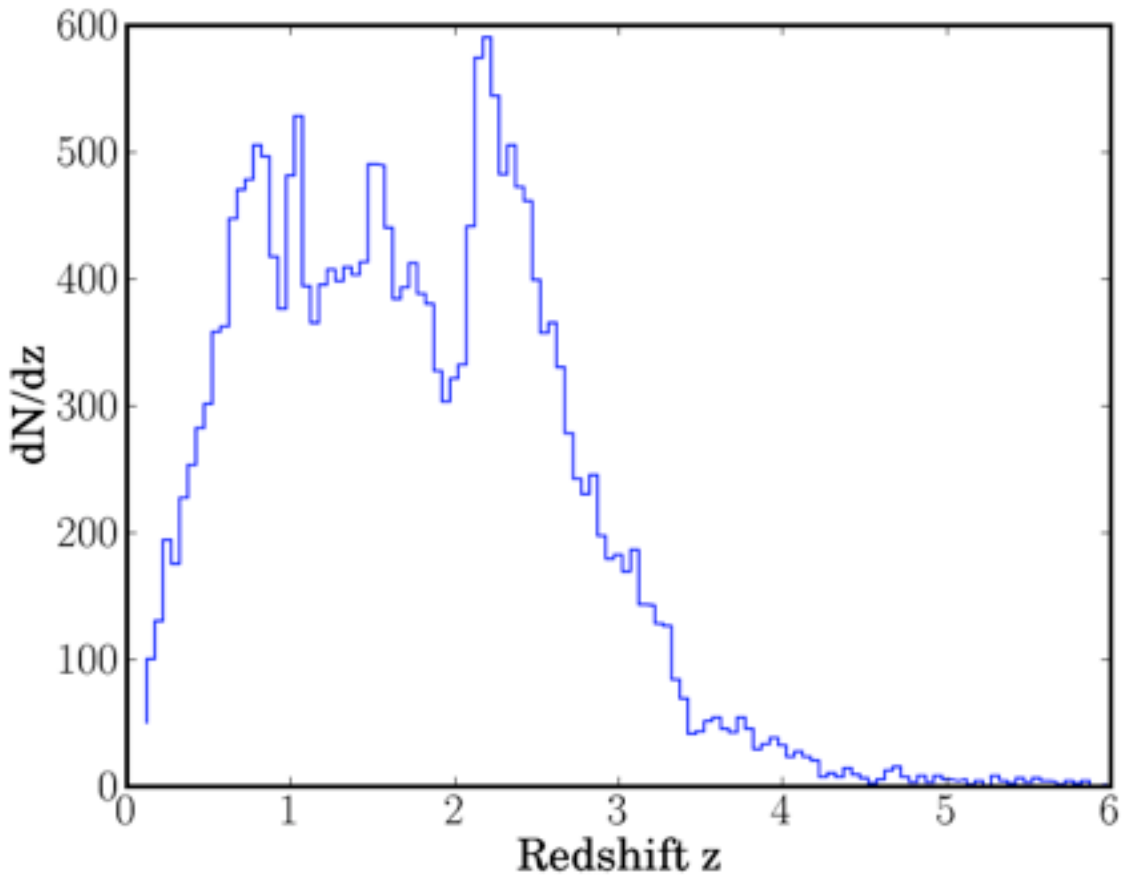
$$\kappa_{opt} = m \times \kappa_{true}$$

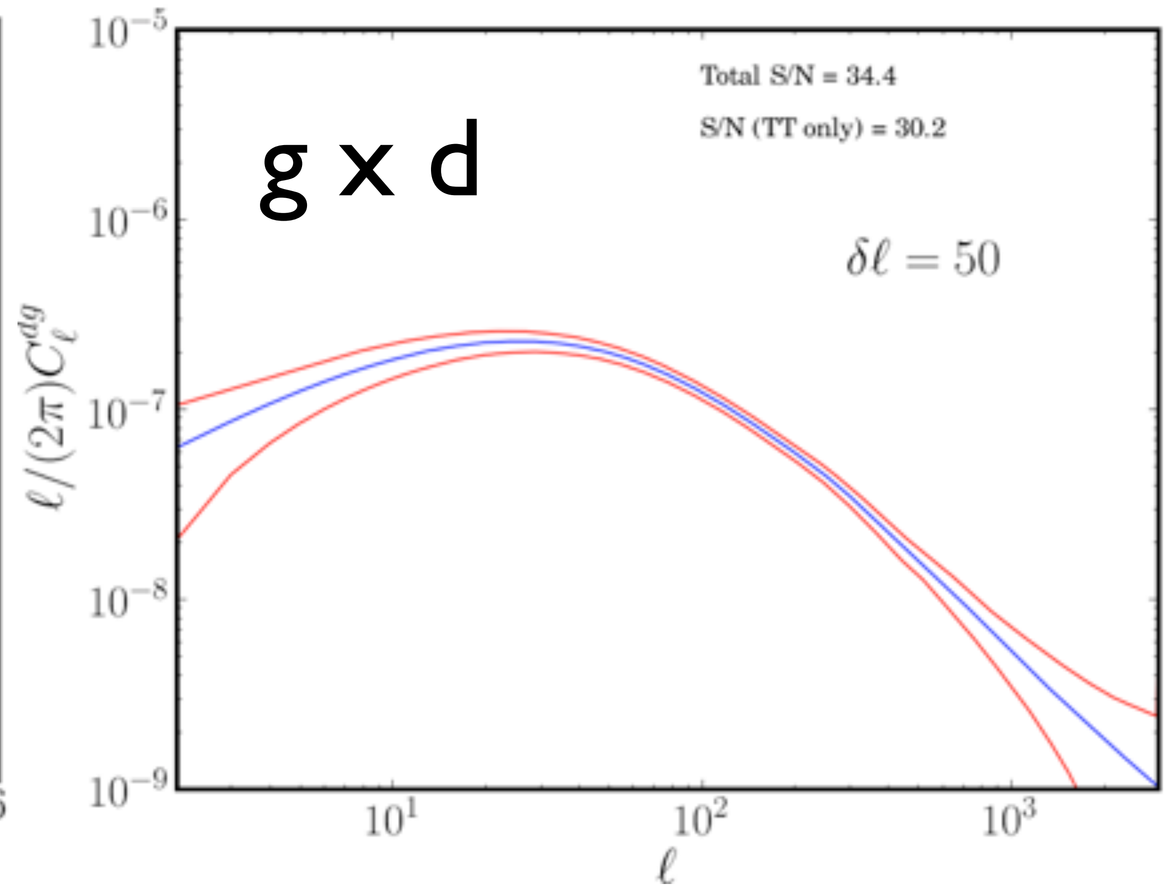
$$\frac{\text{CMBL x WL}}{\text{CMBL x CMBL}} \qquad \frac{C_l^{\kappa_{CMB}\kappa_{opt}}}{C_l^{\kappa_{CMB}\kappa_{CMB}}} = m \frac{\int d\eta \left(\frac{g_{opt}(\eta)}{a(\eta)}\right)\left(\frac{g_{CMB}(\eta)}{a(\eta)}\right) P\left(\frac{l}{d_A}, \eta\right)}{\int d\eta \left(\frac{g_{CMB}(\eta)}{a(\eta)}\right)^2 P\left(\frac{l}{d_A}, \eta\right)}$$



(Vallinotto 2011)
(Das, Spergel et al. *in prep*)

Cross correlations can be used to measure bias of tracers

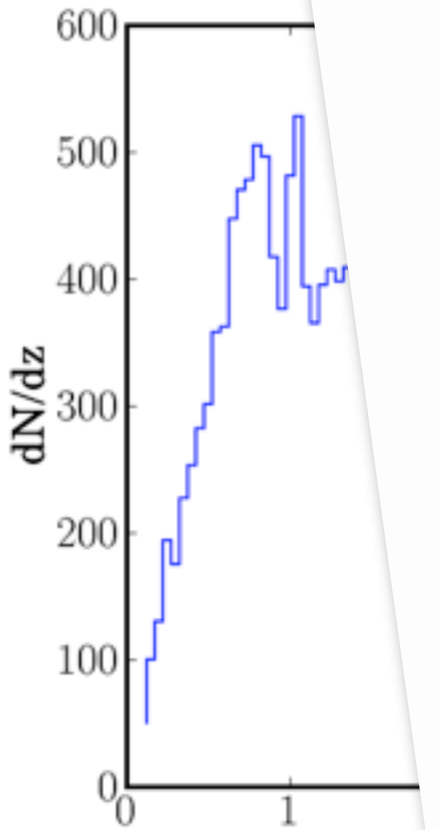


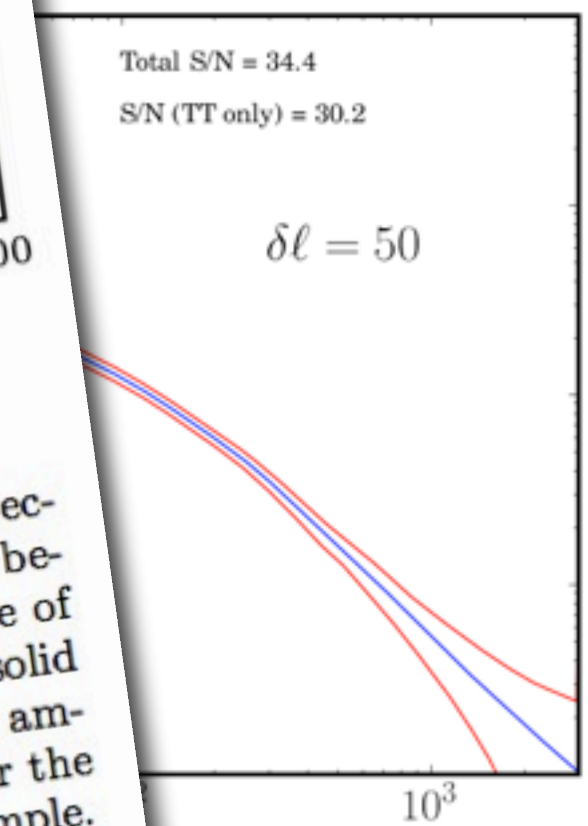


Assume 80 QSOs/sq. degree.
Linear Bias = 3
Total S/N = 34 (1000 sq. deg.)
For LCDM, translates to measurement of bias to 3%.

(Also interesting is the IR/submm xcorr)

Cross cor[...] to measur[...]





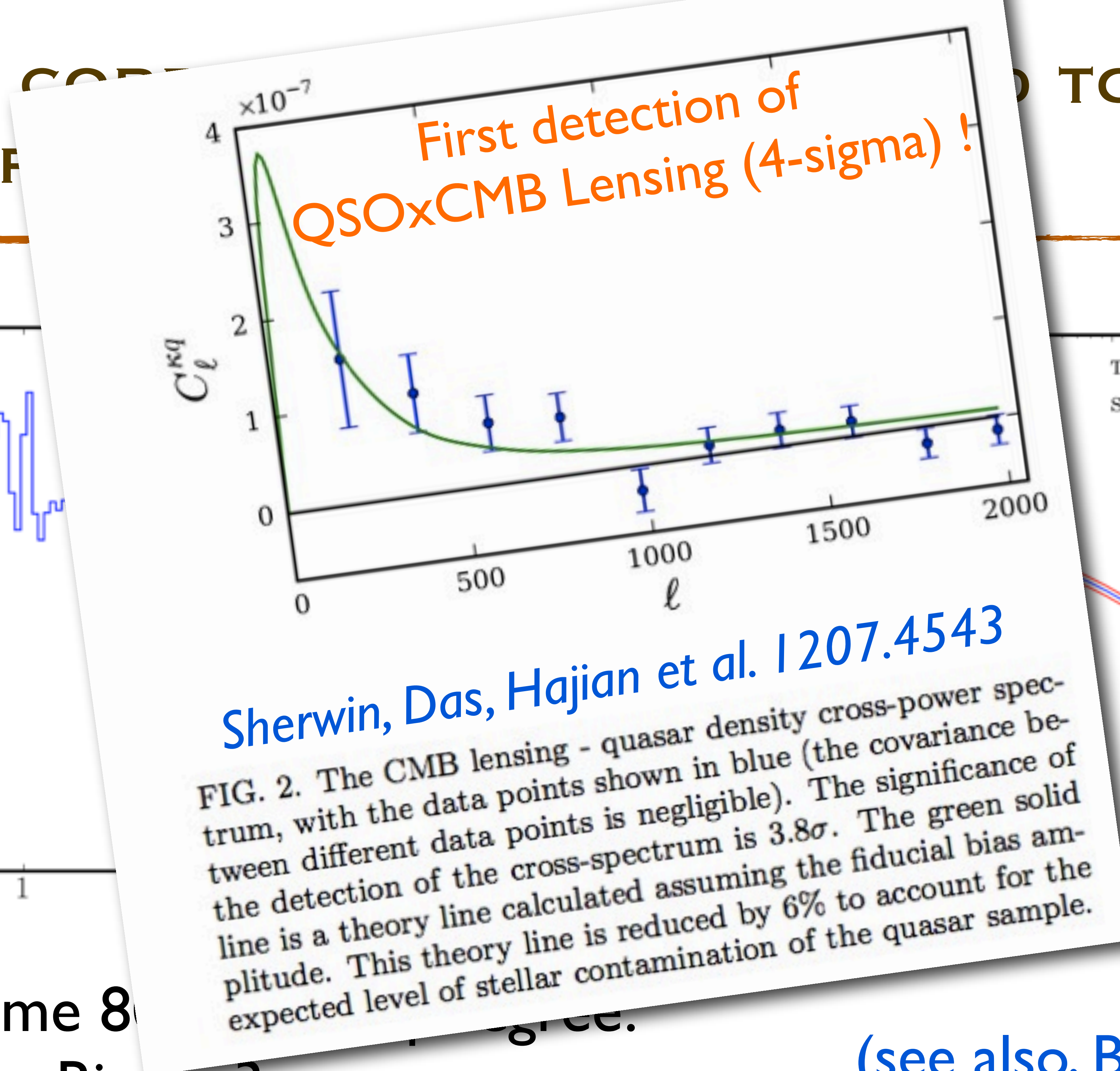


FIG. 2. The CMB lensing - quasar density cross-power spectrum, with the data points shown in blue (the covariance between different data points is negligible). The significance of the detection of the cross-spectrum is 3.8σ. The green solid line is a theory line calculated assuming the fiducial bias amplitude. This theory line is reduced by 6% to account for the expected level of stellar contamination of the quasar sample.

Assume 8[...] [...]egree.

Linear Bias = 3

Total S/N = 34 (1000 sq. deg.)

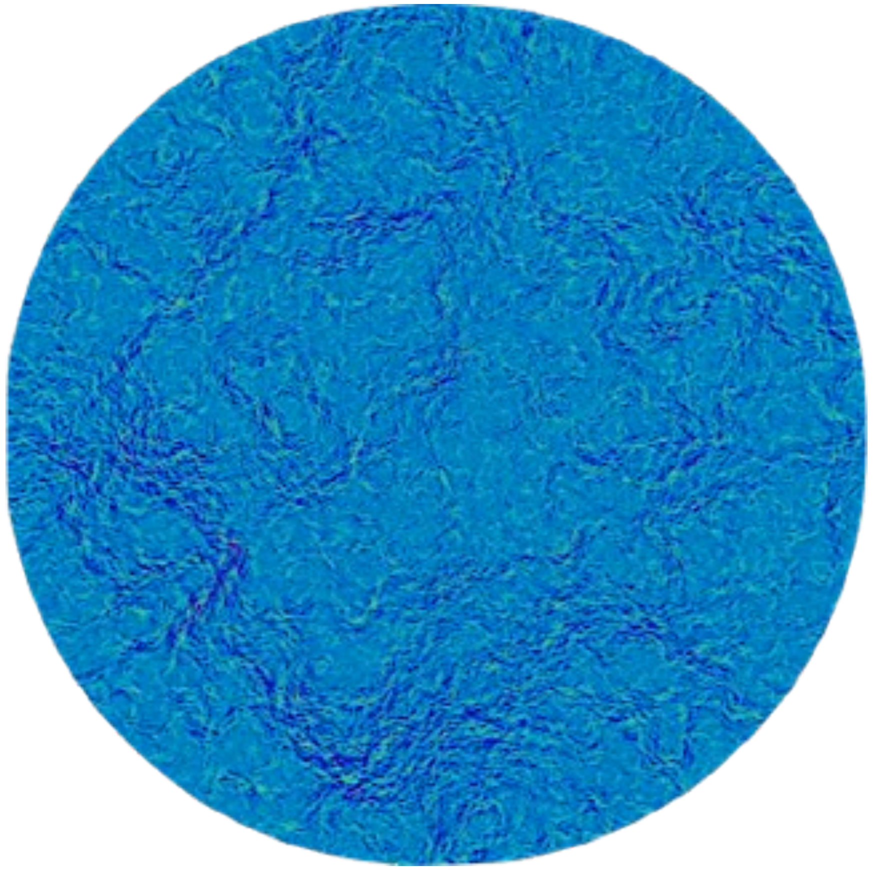
For LCDM, translates to measurement of bias to 3%.

(see also, Bleem et al. 2012)

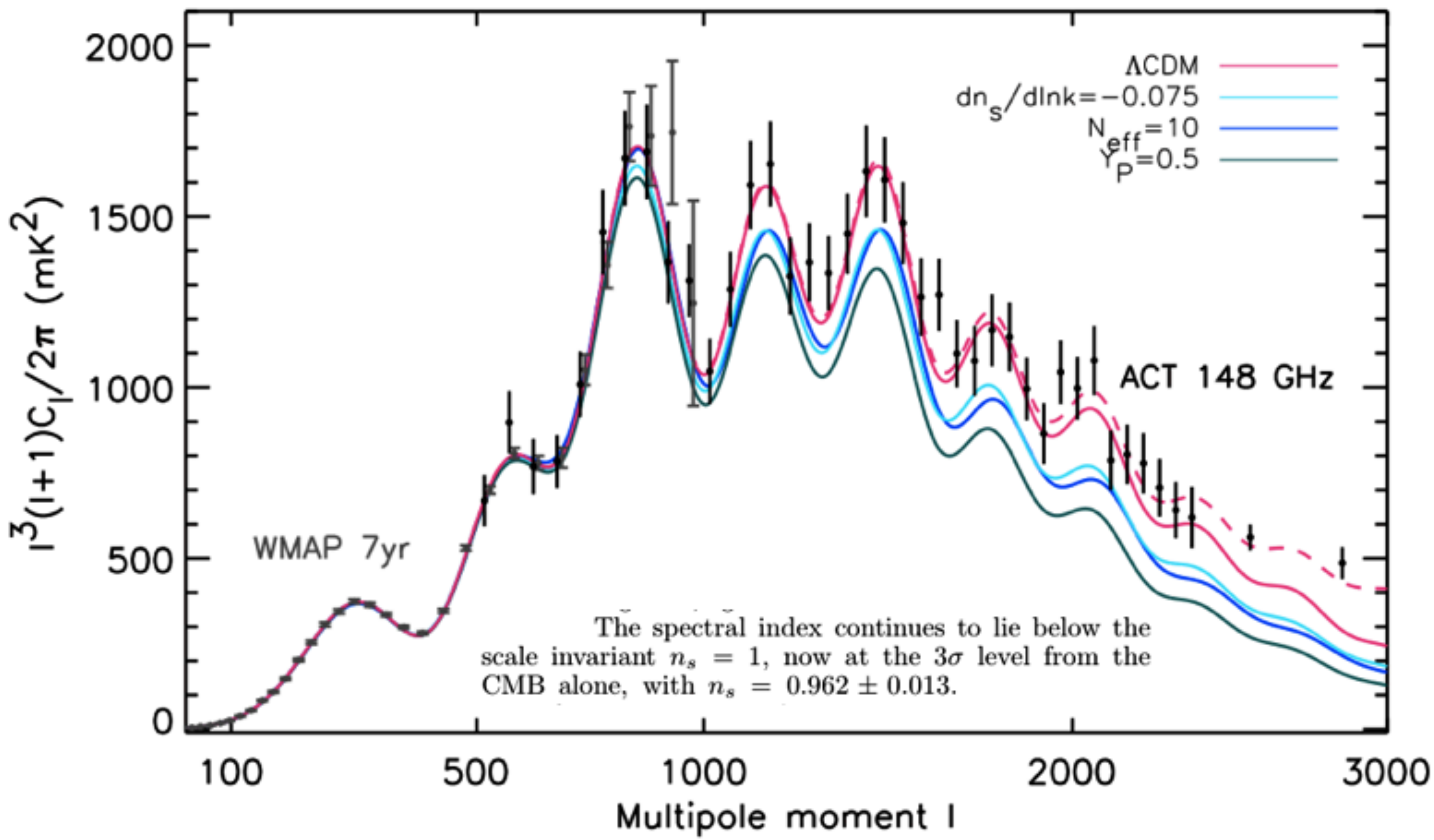
SUMMARY

- Two keywords in the future of CMB: high resolution, polarization
- CMB lensing is a new and powerful tool. First measurements and applications and coming in.
- High resolution polarization experiments like PolarBeaR, ACTPol and SPTPol will be primarily CMB lensing machines.
- CMB lensing will provide new constraints on neutrino mass, dark energy, curvature, ...
- A large array of cross-correlation projects are possible with the wealth of data in multiple frequencies. These will help constrain galaxy formation models, GR. geometry, and other cosmological parameters.
- *Be prepared to witness a very productive interplay of CMB, fundamental physics, and astrophysics in the coming years!*

Thank YOU!

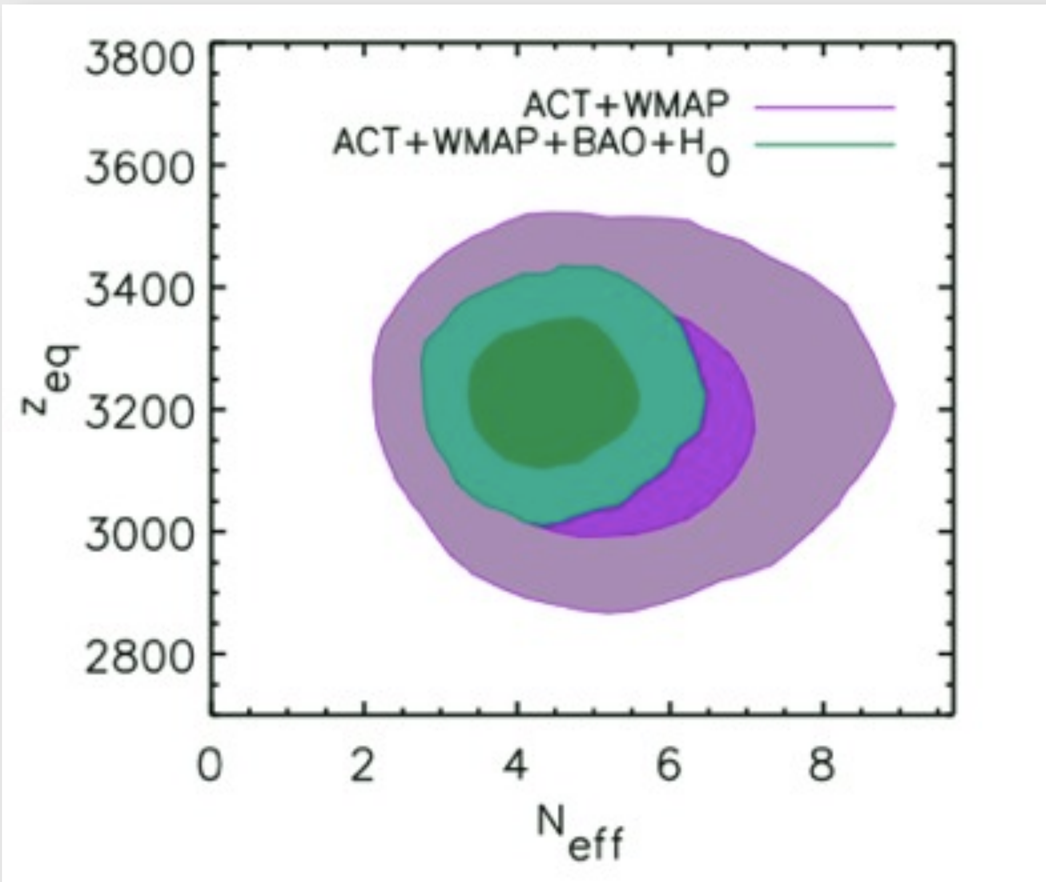


HIGHER ORDER PEAKS HELP CONSTRAIN PARAMETERS BEYOND ΛCDM



Dunkley et al. (2011)

ACT+WMAP constrains number of relativistic species in the early universe



Changing N_{eff} increases radiation density and leads to enhanced Silk Damping (Hou et al. 2011)

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

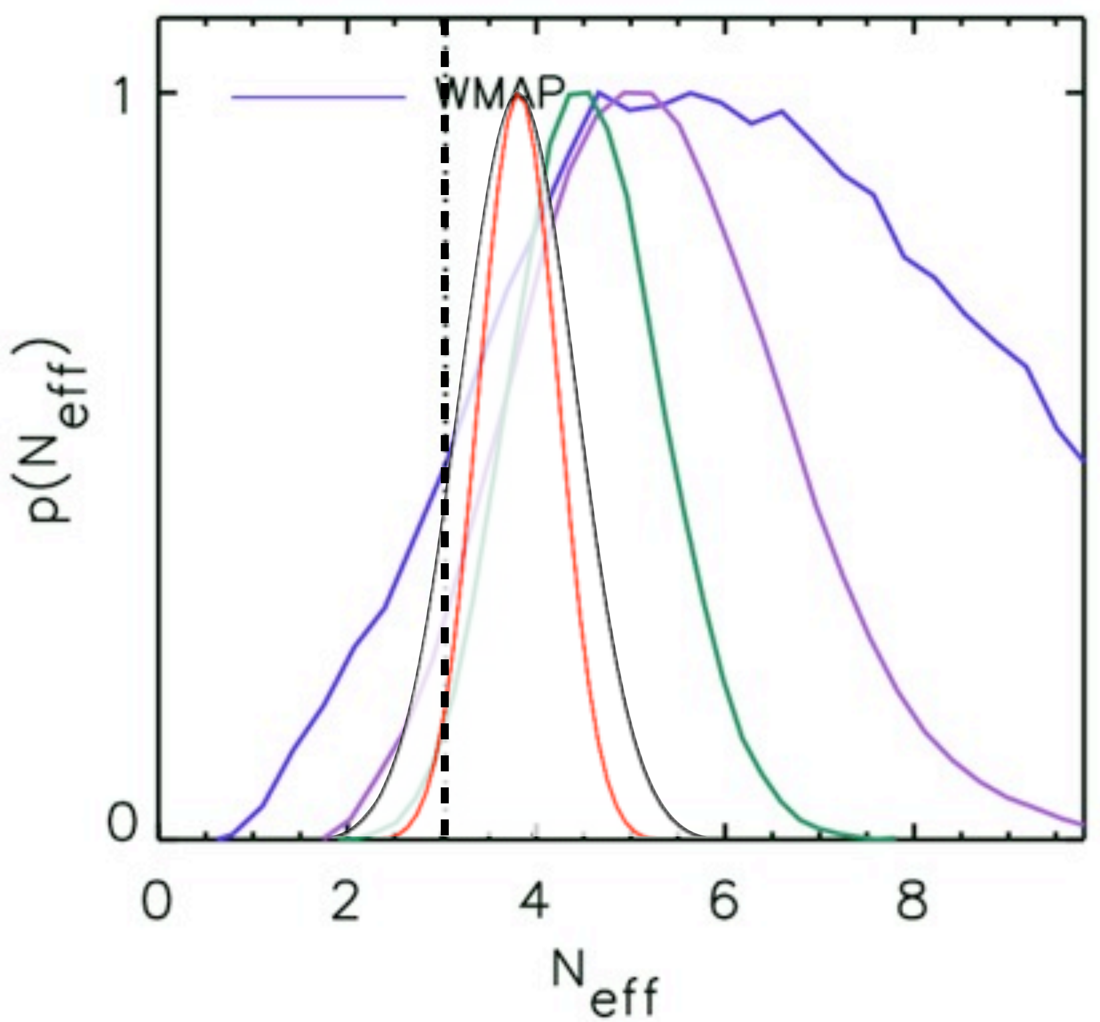
In standard BBN $N_{\rm eff} = 3.04$

For ACT+WMAP we find N_{eff} = 5.3 ± 1.3

(The first time CMB constrained it from above !)

Dunkley et al. (2011)

ARE HIGH RESOLUTION CMB OBSERVATIONS POINTING US TO AN $N_{EFF} > 3$?



Summary of recent Neff constraints from cosmology.

In standard BBN

$N_{\rm eff} = 3.04$

WMAP 7: **> 2.7 (95%)**
Komatsu et al. (2011)

ACT+WMAP: **5.3 +/- 1.3 (68%)**
ACT+WMAP+BAO+H_0: **4.56 +/- 0.75**
Dunkley et al. (2011)

SPT+WMAP: **3.85 +/- 0.62**
SPT+WMAP+BAO+H_0 **3.86 +/- 0.42**
Keisler et al. (2011)

Not shown:

ACT+ SPT+WMAP+BAO+H_0 4.0 +/- 0.18

Smith, Das, Zahn, (2011)
Archidiacono et al. (2011)

Cross correlation studies with CMB lensing

Galaxy Bias

$\hat{\mathrm{d}} \times$ galaxies

Great Signal-to-noise!

Galaxy Survey	$\hat{n}$	$A/10^3$	z_c	b	CMB Expt.	(S/N)	$\Delta b/b(\%)$
SDSSLRG	12.4	3.8	0.31	2	PLANCK	5.8	17.3
					PACT	11.4	8.8
					IDEAL	20.4	4.9
BOSS1	40.	10	0.3	2	PLANCK	10.8	9.3
					PACT	25.5	3.9
					IDEAL	52.5	1.9
BOSS2	110.	10	0.6	2	PLANCK	17.0	5.9
					PACT	39.4	2.5
					IDEAL	78.2	1.3
ADEPT	3500	27	1.35	1	PLANCK	52.8	1.9
					PACT	107.5	0.9
					IDEAL	228.3	0.4

Acquavivia, Hajian, Spergel and Das,
PRD 78, 043514 (2008)

Galaxy Bias

$\hat{\mathbf{d}} \times$ galaxies

Large Scale Structure (LSS) surveys measure autocorrelations of galaxies.

From this, we try to infer the correlations among dark matter halos.

Such inferences are limited by our lack of understanding of bias - or how luminous matter traces dark matter.

If we cross-correlate the reconstructed deflection field with the galaxy number counts, we go one step closer to the truth by directly measuring the galaxy-dark matter correlation.

CMB lensing is particularly relevant for high z objects, behind which there are no galaxies to be lensed!

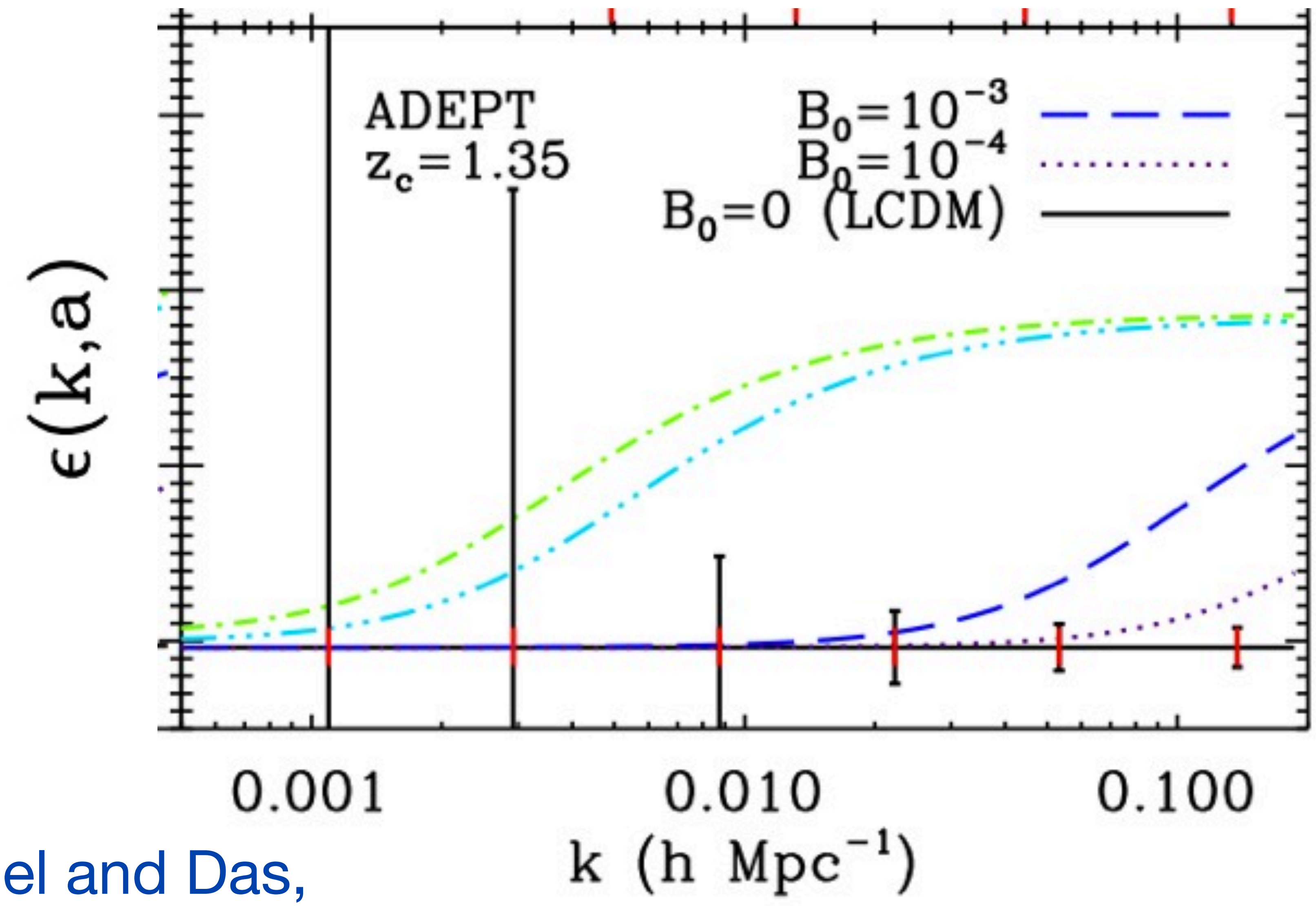
TESTING GENERAL RELATIVITY

$$\epsilon(k,a) = \Omega_m^{-\gamma(a)} \frac{d\ln D}{d\ln a} - 1$$

$\gamma(z) \simeq 0.557 - 0.02z$ is accurate at the 0.3% level

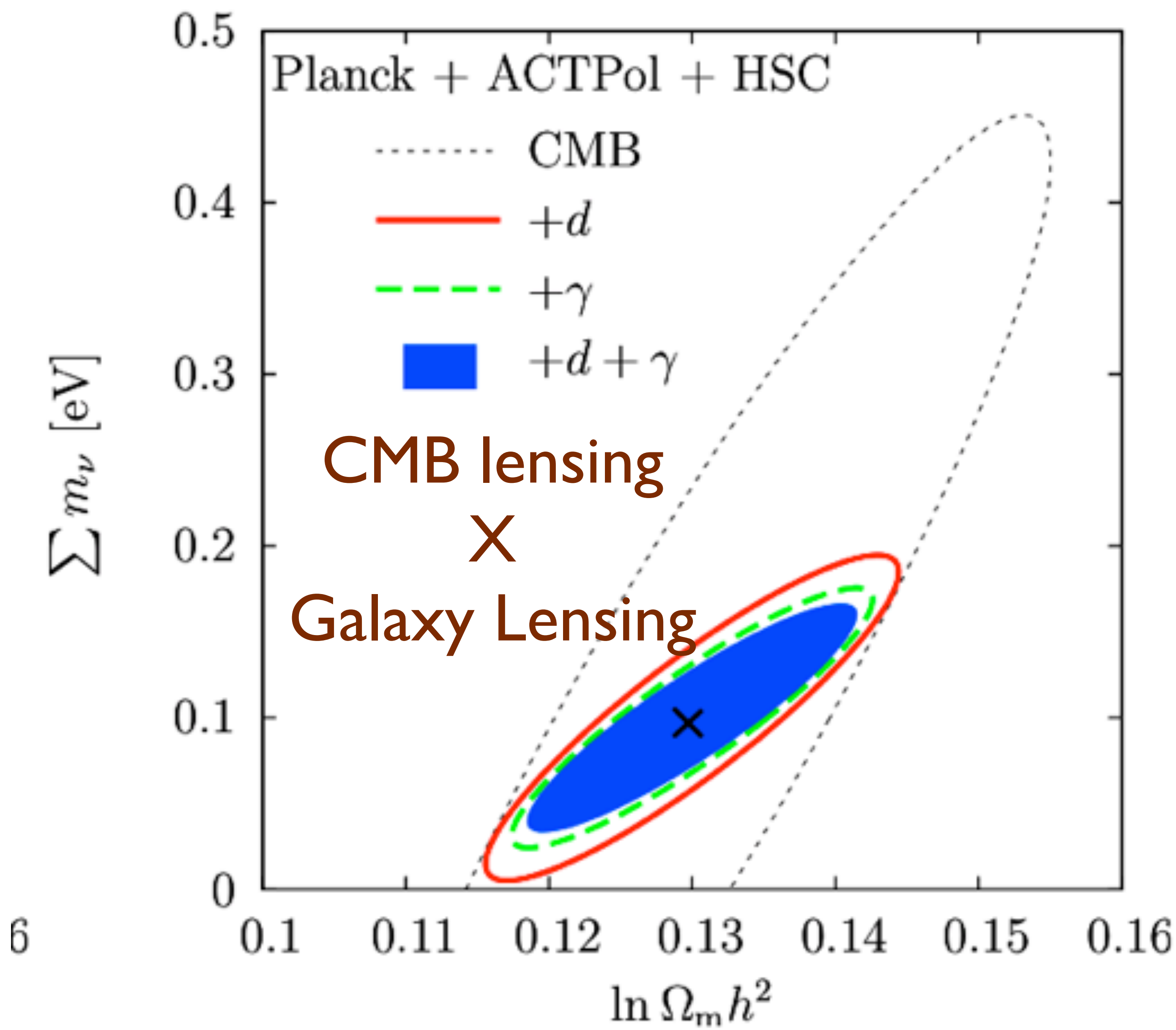
$$P^s(\mathbf{k}) = (1+\beta\mu_{\mathbf{k}}^2)^2 P(k),$$

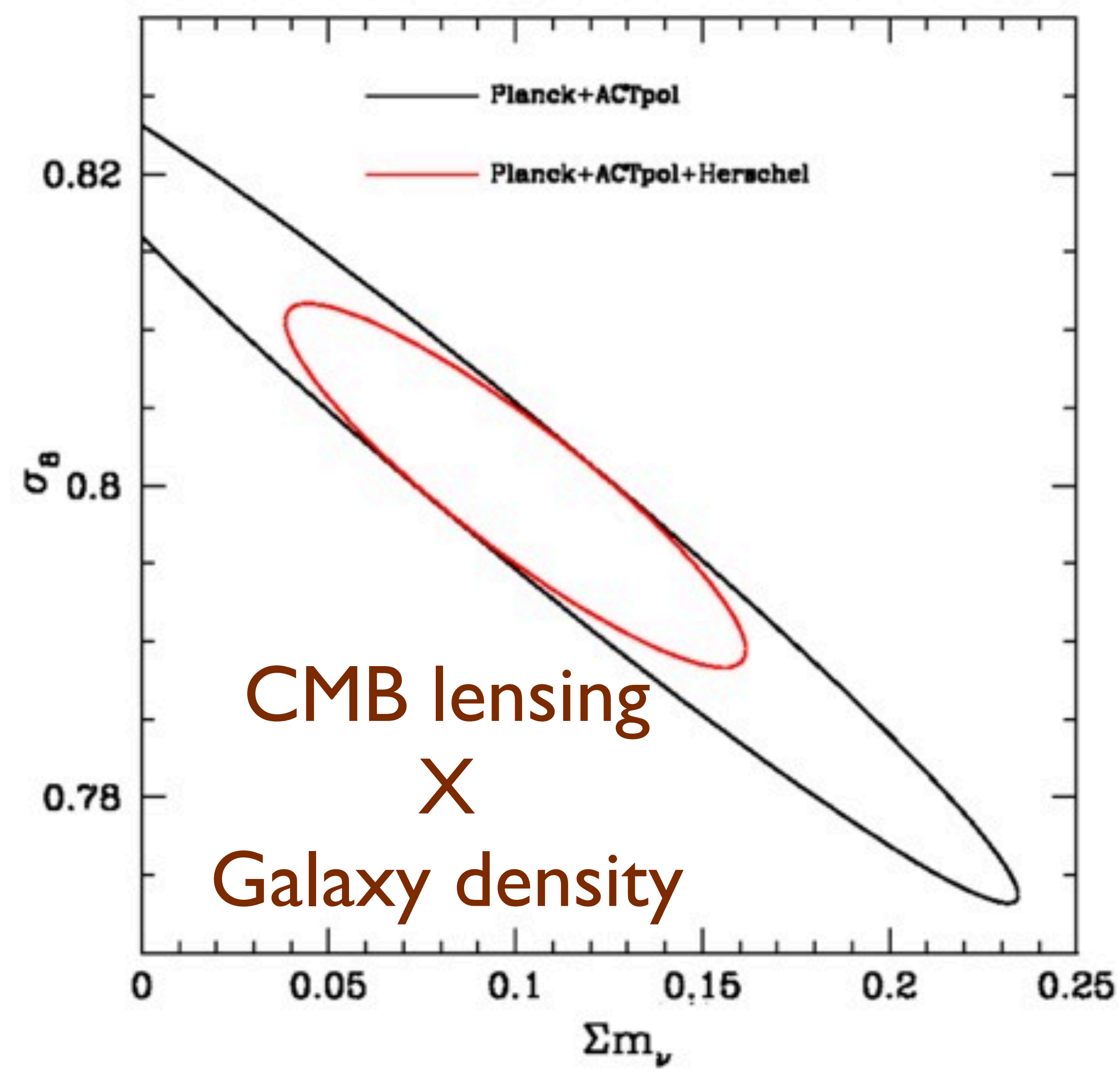
$$\beta(a) = \frac{1}{b}\frac{d\ln D}{d\ln a};$$



Acquavivia, Hajian, Spergel and Das, PRD 78, 043514 (2008)

CMB LENSING: SYNERGY WITH GALAXY AND WEAK LENSING SURVEYS (BIGBOSS,DES, LSST)

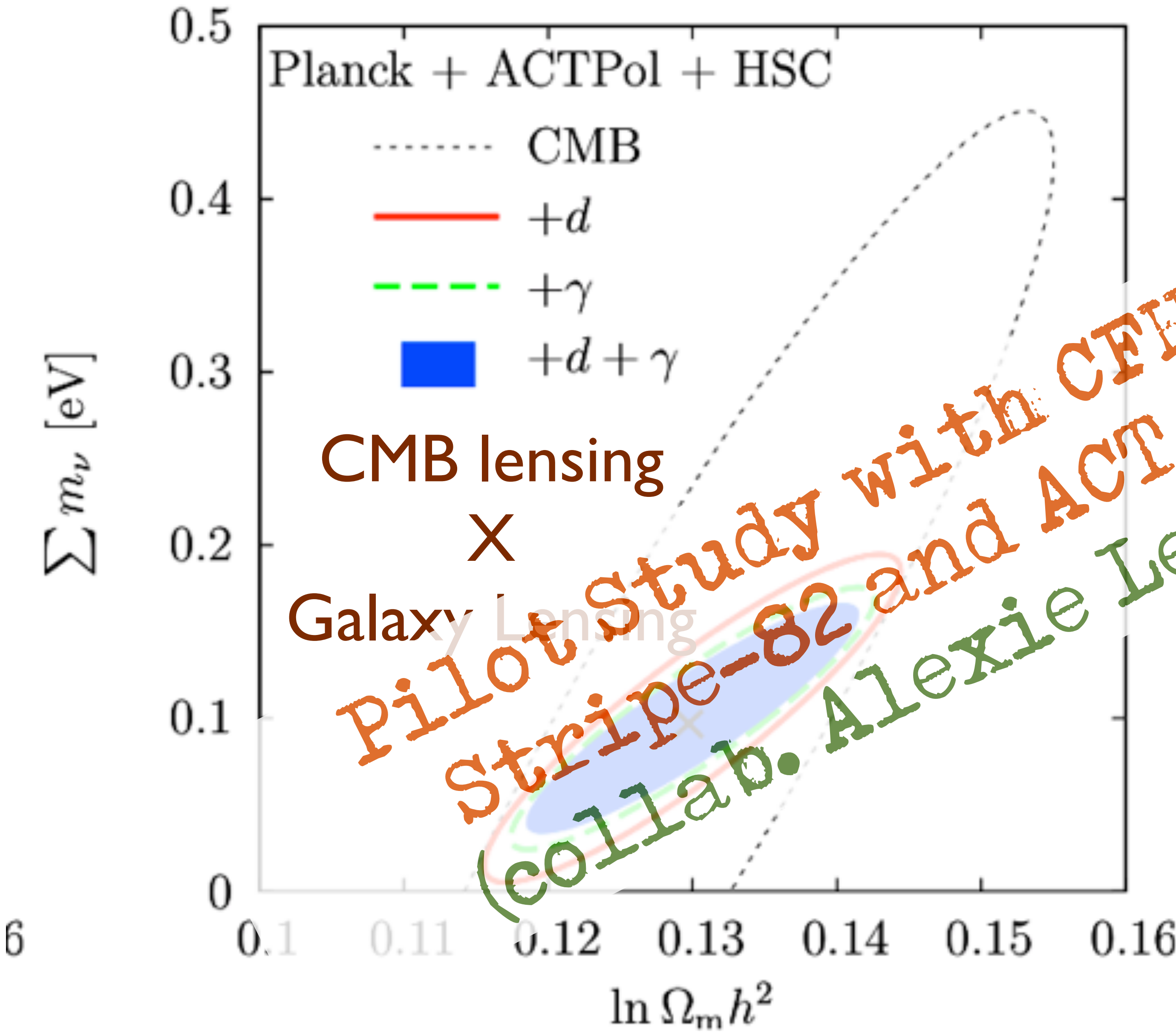




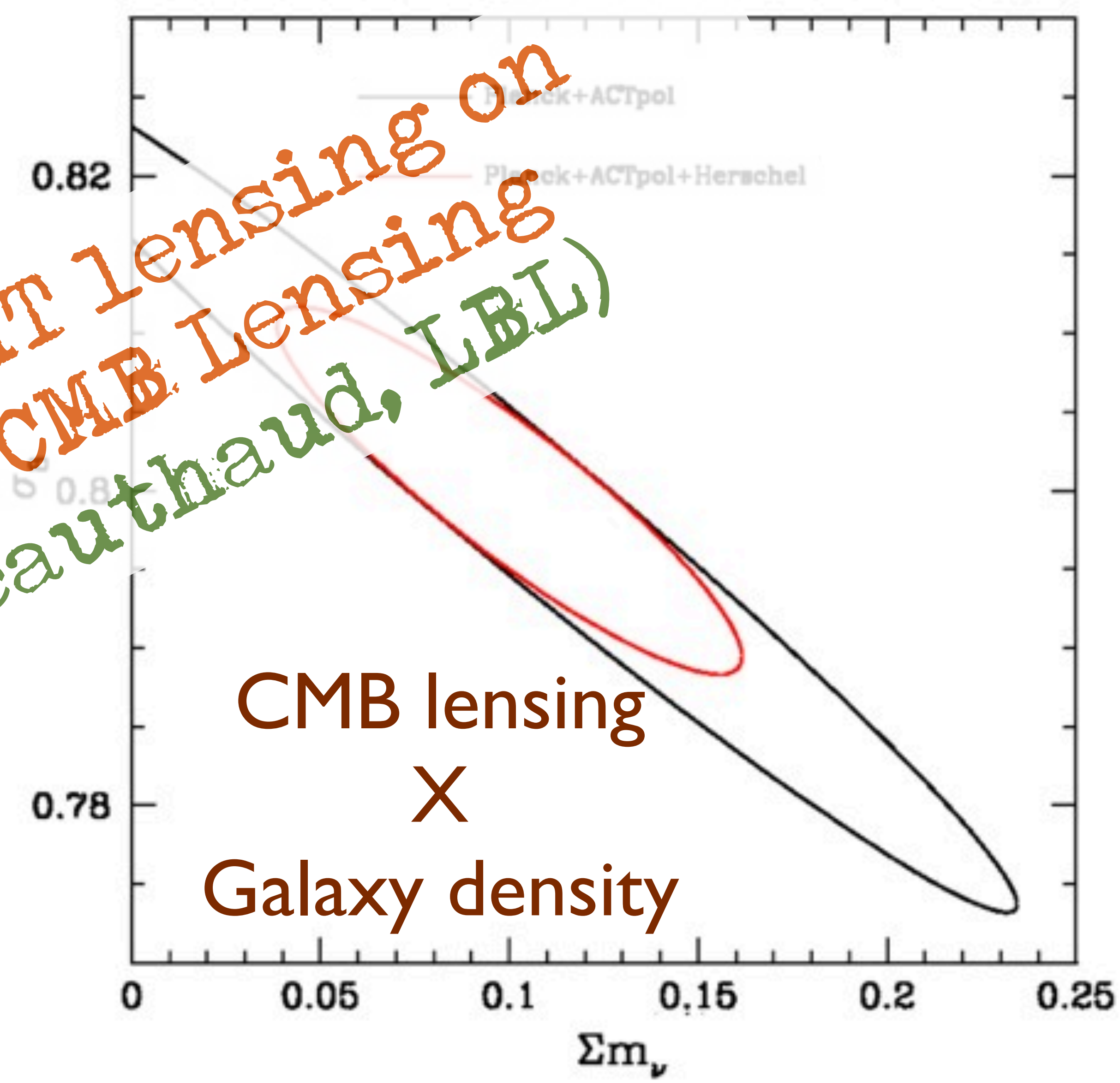
Namikawa et al (2010)

Das & De Putter, in prep.

CMB LENSING: SYNERGY WITH GALAXY AND WEAK LENSING SURVEYS (BOSS,DES, LSST)



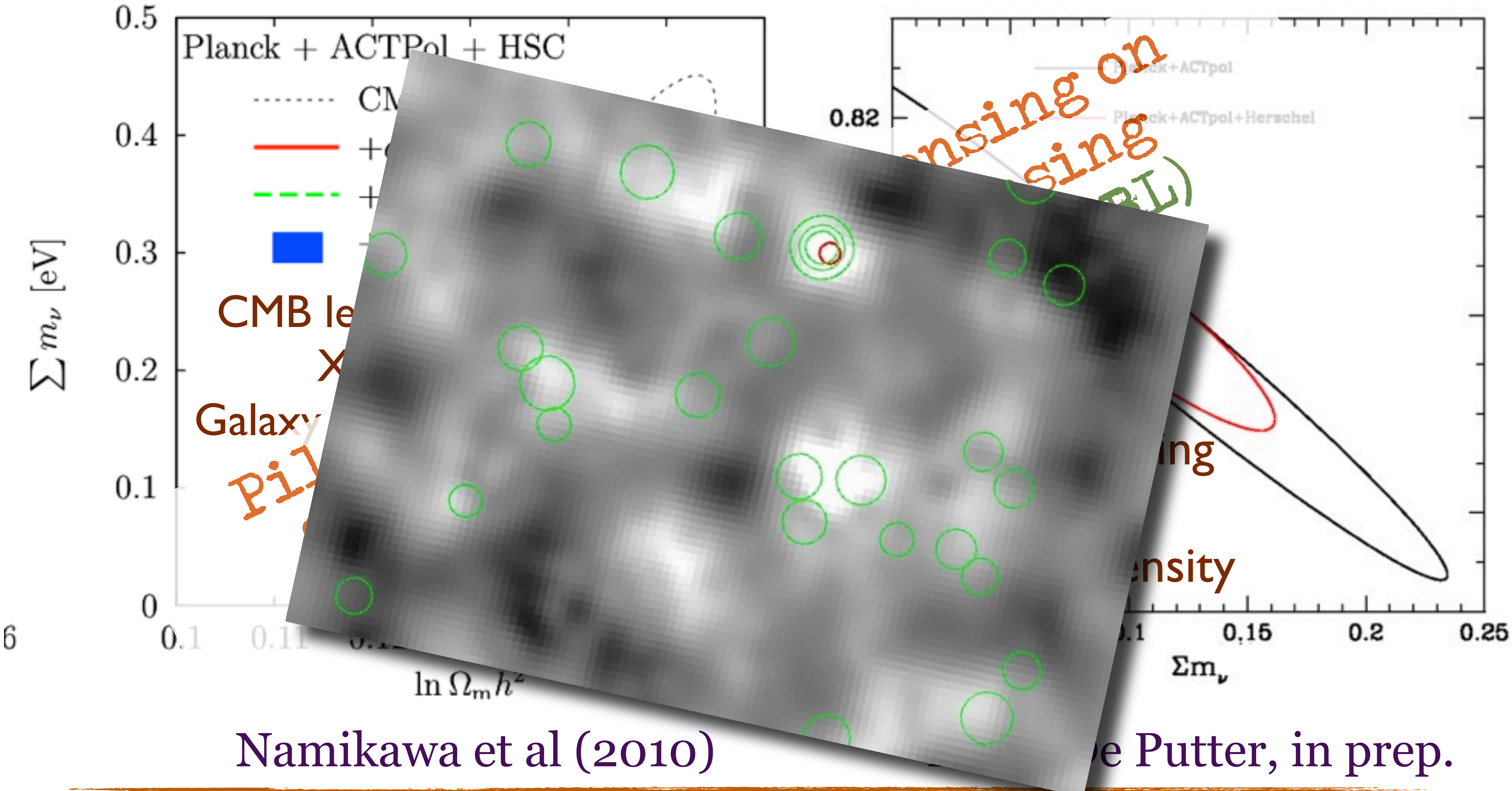
Namikawa et al (2010)



Das & De Putter, in prep.

Pilot Study with CFHT lensing on Stripe-82 and ACT CMB Lensing (collab. Alexie Leauthaud, LBL)

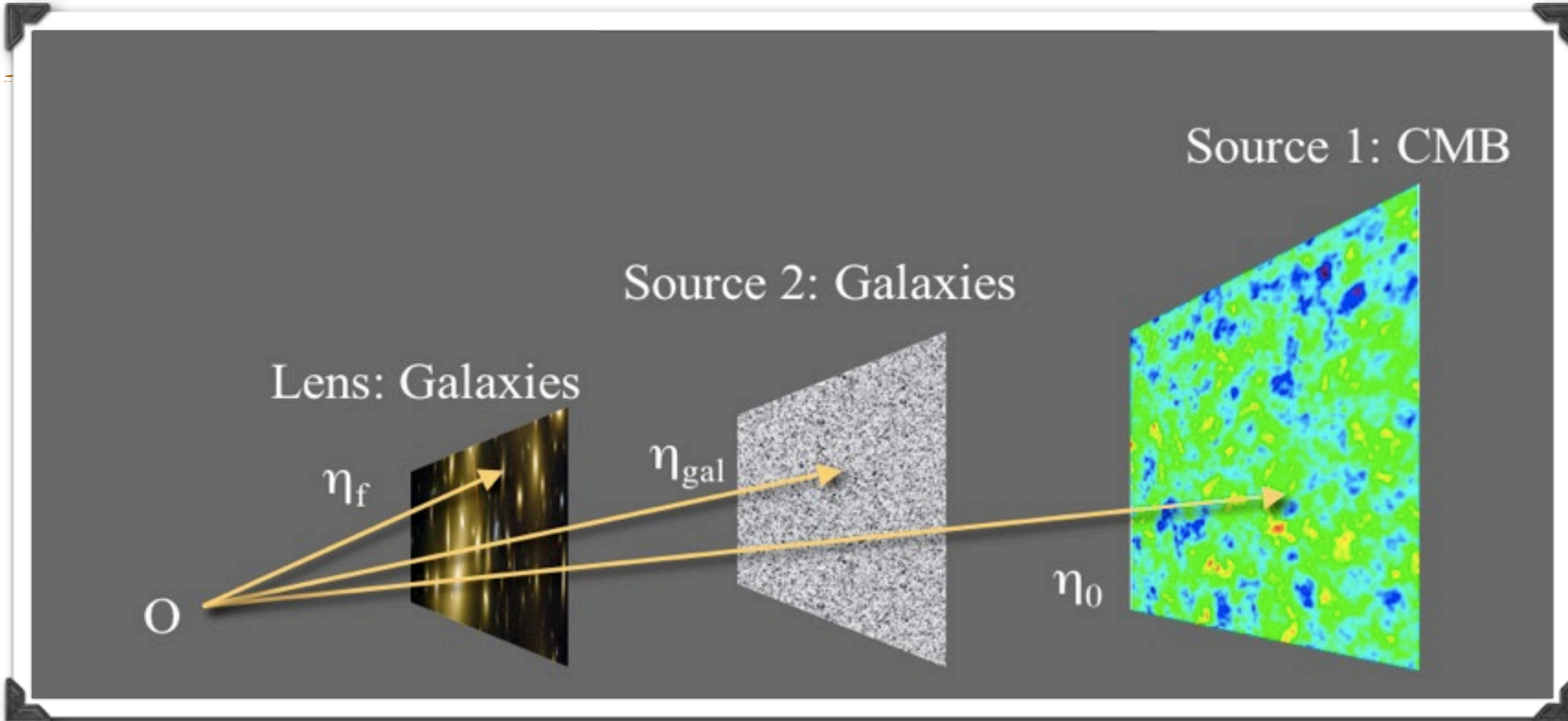
CMB LENSING: SYNERGY WITH GALAXY AND WEAK LENSING SURVEYS (BOSS,DES, LSST)



Namikawa et al (2010)

...e Putter, in prep.

Measuring geometry with cross-correlations



$$r \equiv \frac{C_\ell^{\kappa_{\rm CMB}\Sigma}}{C_\ell^{\kappa_{\rm gal}\Sigma}} \sim \frac{d_A(\eta_0 - \eta_f) d_A(\eta_{\rm gal})}{d_A(\eta_{\rm gal} - \eta_f) d_A(\eta_0)}.$$

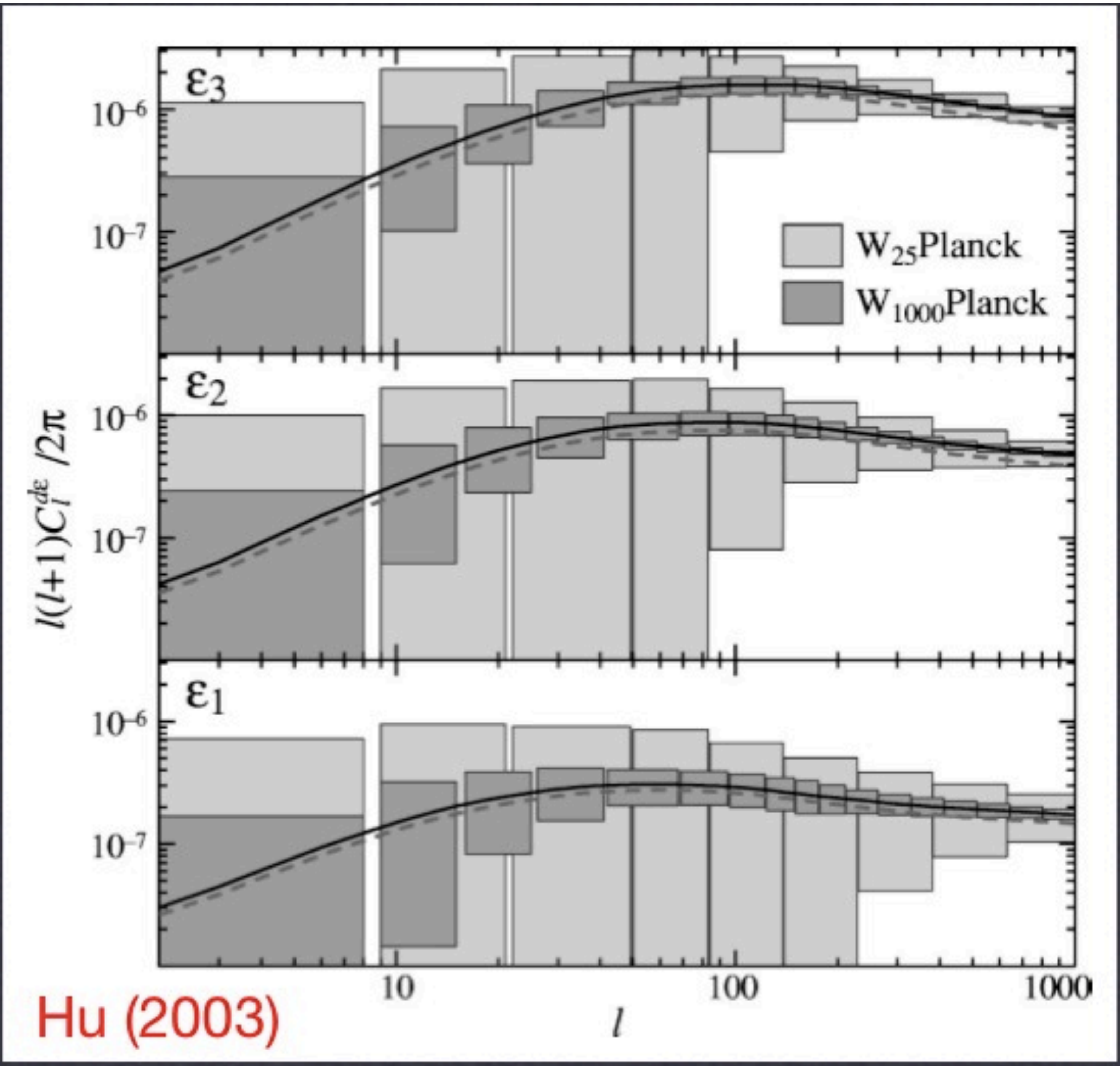
Das and Spergel (2008)

Measuring DM Growth, and early DE

Cross-correlating CMB lensing with cosmic shear in redshift slices will probe growth of structure directly!

Deviations from GR?

Das, de Putter, et al in prep



Things I left out

Primordial B-modes: confusion due to lensing, and the idea of de-lensing using polarization.

Systematics in temperature and polarization lensing.

Cross-correlation with Lyman-alpha (see Alberto's talk)

And maybe some more applications ....