# The large scale structure of the universe: current constraints and future challenges

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UC Berkeley/LBNL
CSL, Jan 15, 2014

# Welcome by BCCP

- Berkeley center for cosmological physics established in 2006 by G. Smoot
- Supports postdocs: BCCP fellowships
- Change of guard in 2012 (Perlmutter and Seljak)
- Major expansion in 2013/2014: computational data science fellowships
- Supports extensive visitors program: visit http://bccp.berkeley.edu

# Big questions in cosmology

1) Nature of acceleration of the universe:

dark energy

modification of gravity

something else?

2) Initial conditions for structure in the Universe:

Inflation (of many flavors)

Something else?

3) Nature of matter (dark matter, neutrino mass…)

Large scale structure of the universe can say something about all these

# How to answer them using large scale structure?

1) Classical test: redshift-distance relation: baryonic acoustic oscillations (BAO): CMB + galaxy clustering

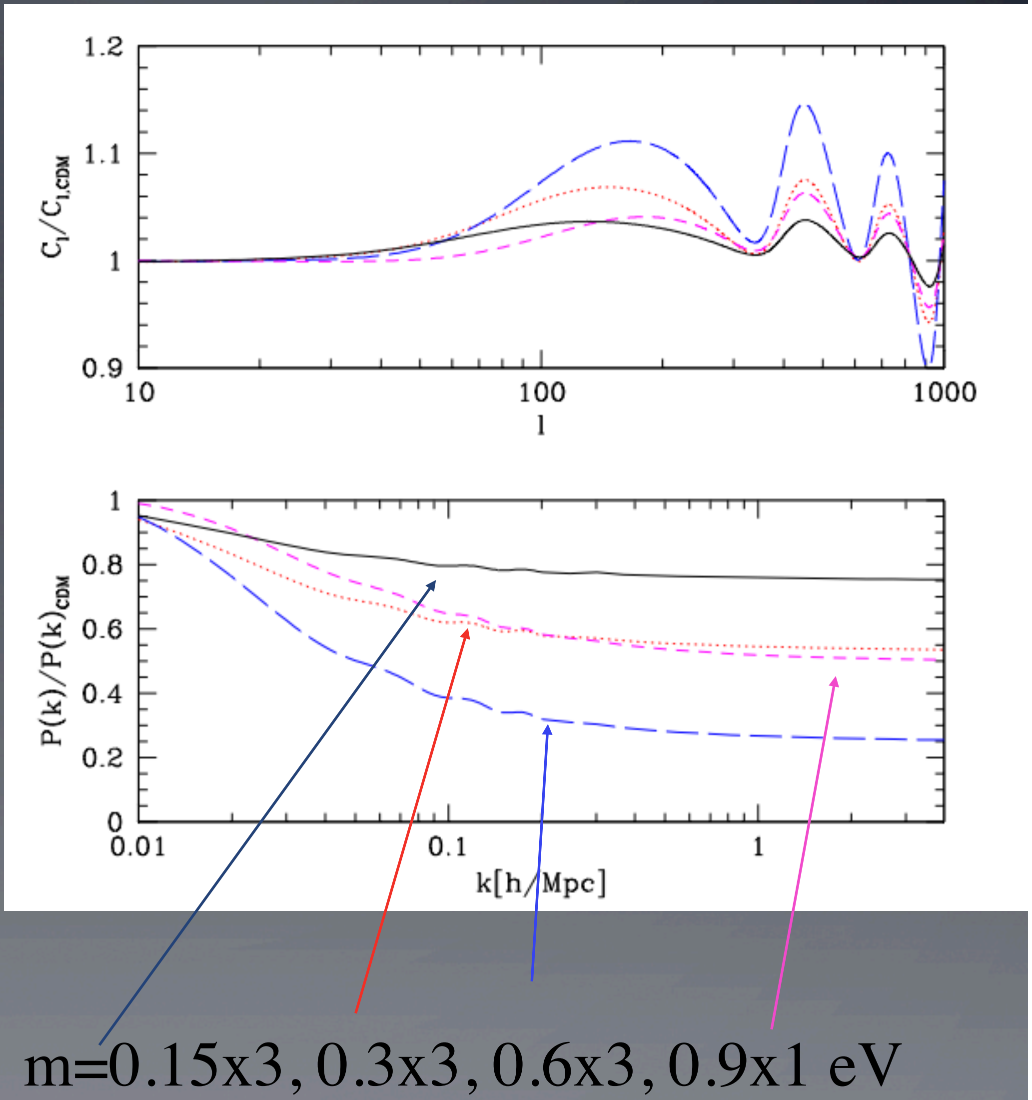
2) Growth of structure: CMB, Ly-alpha, weak lensing, clusters, galaxy clustering, Sunyaev-Zeldovich effect

3) Scale dependence of structure (same tracers as above)

4) Comparing the above tracers (e.g., differentiates between dark energy and modified gravity theories)

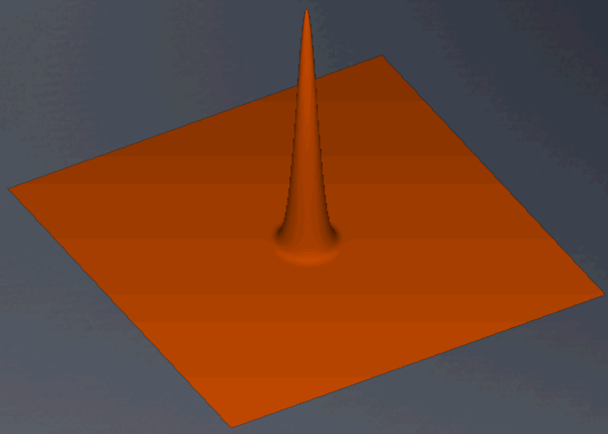
# Neutrino mass can be measured by LSS

- Neutrino free streaming inhibits growth of structure on scales smaller than free streaming distance
- If neutrinos have mass they contribute to the total matter density, but since they are not clumped on small scales dark matter growth is suppressed
- Minimum signal at 0.06eV level makes 4% suppression in power, mostly at k<0.1h/Mpc
- SDSS coud reach this at 1sigma, DESI at 2-3 sigma
- LSS: weak lensing of galaxies and CMB, galaxy clustering

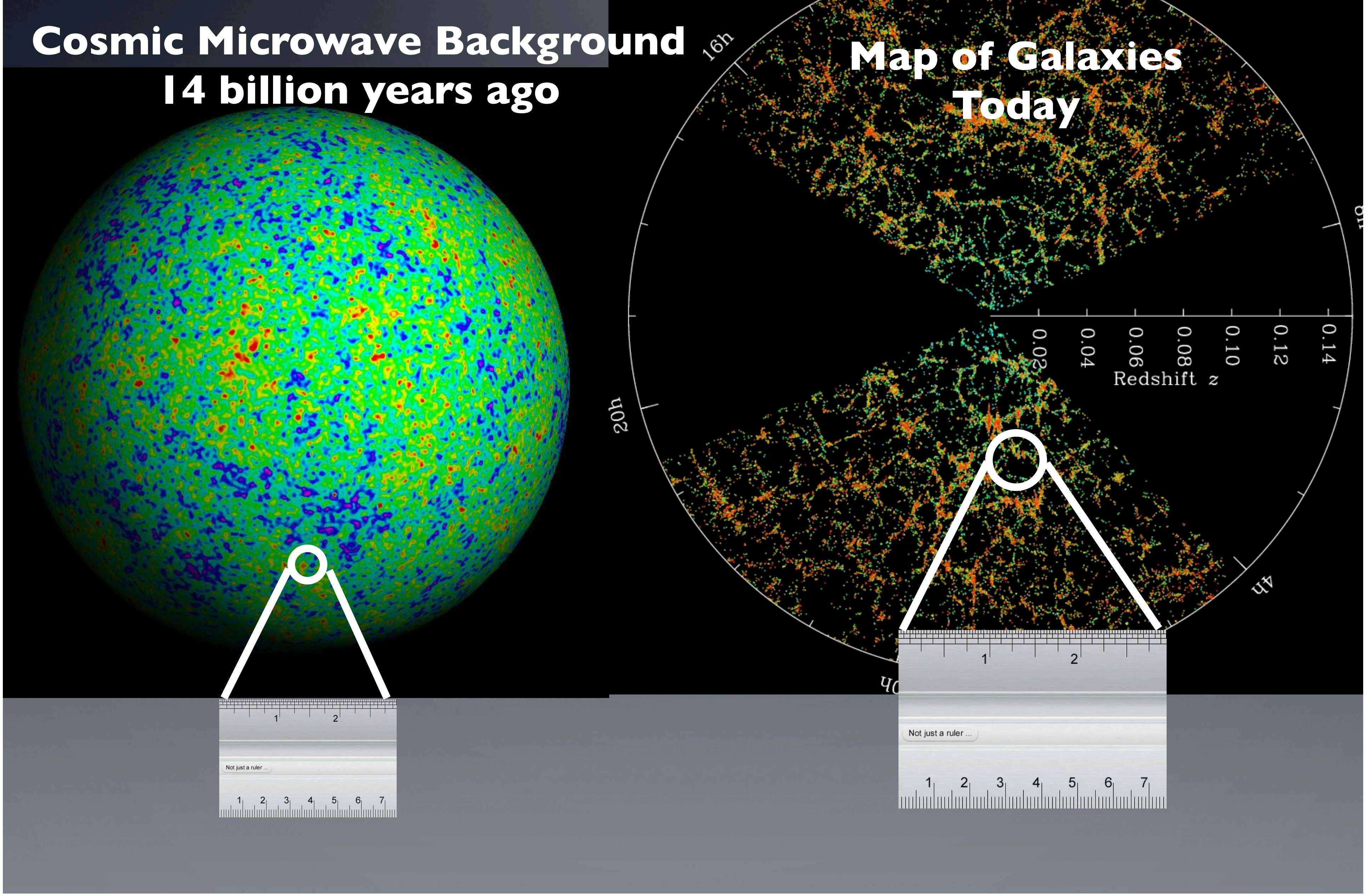


# 1) BAO: sound waves

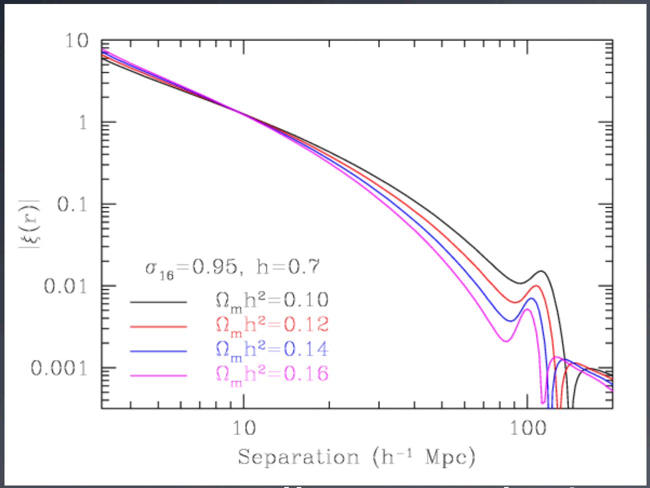
- Each initial overdensity (in DM & gas) is an overpressure that launches a spherical sound wave.
- This wave travels outwards at 57% of the speed of light.
- Pressure-providing photons decouple at recombination. CMB travels to us from these spheres.
- Sound speed plummets. Wave stalls at a radius of 150 Mpc.
- Seen in CMB as acoustic peaks
- Overdensity in shell (gas) and in the original center (DM) both seed the formation of galaxies. Preferred separation of 150 Mpc.

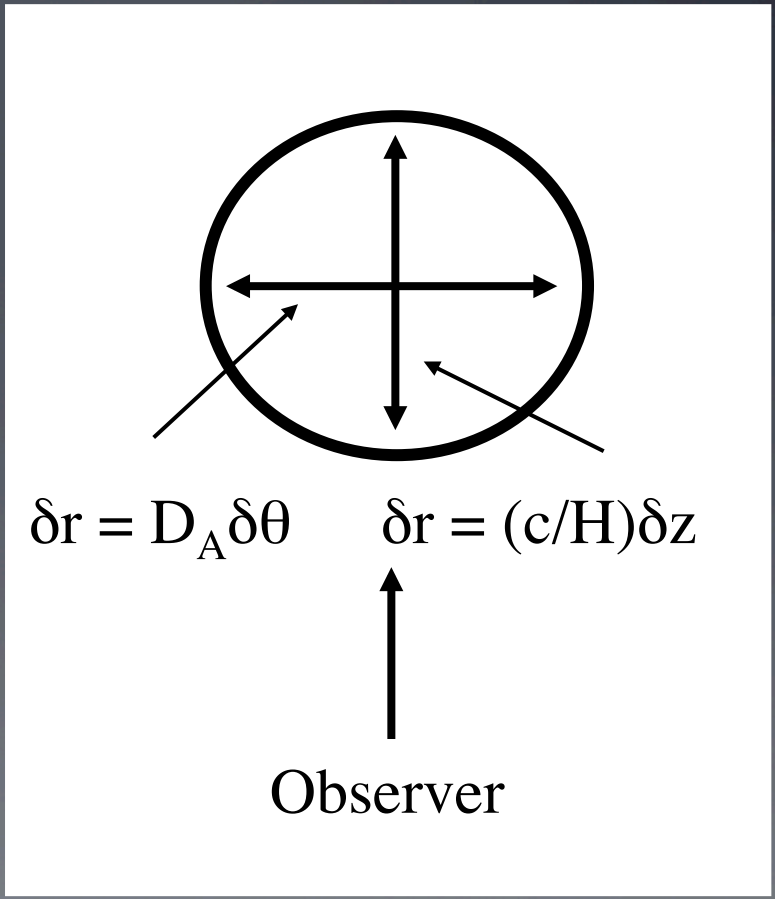


# Sound waves as “standard ruler”



# BAO in galaxy redshift surveys

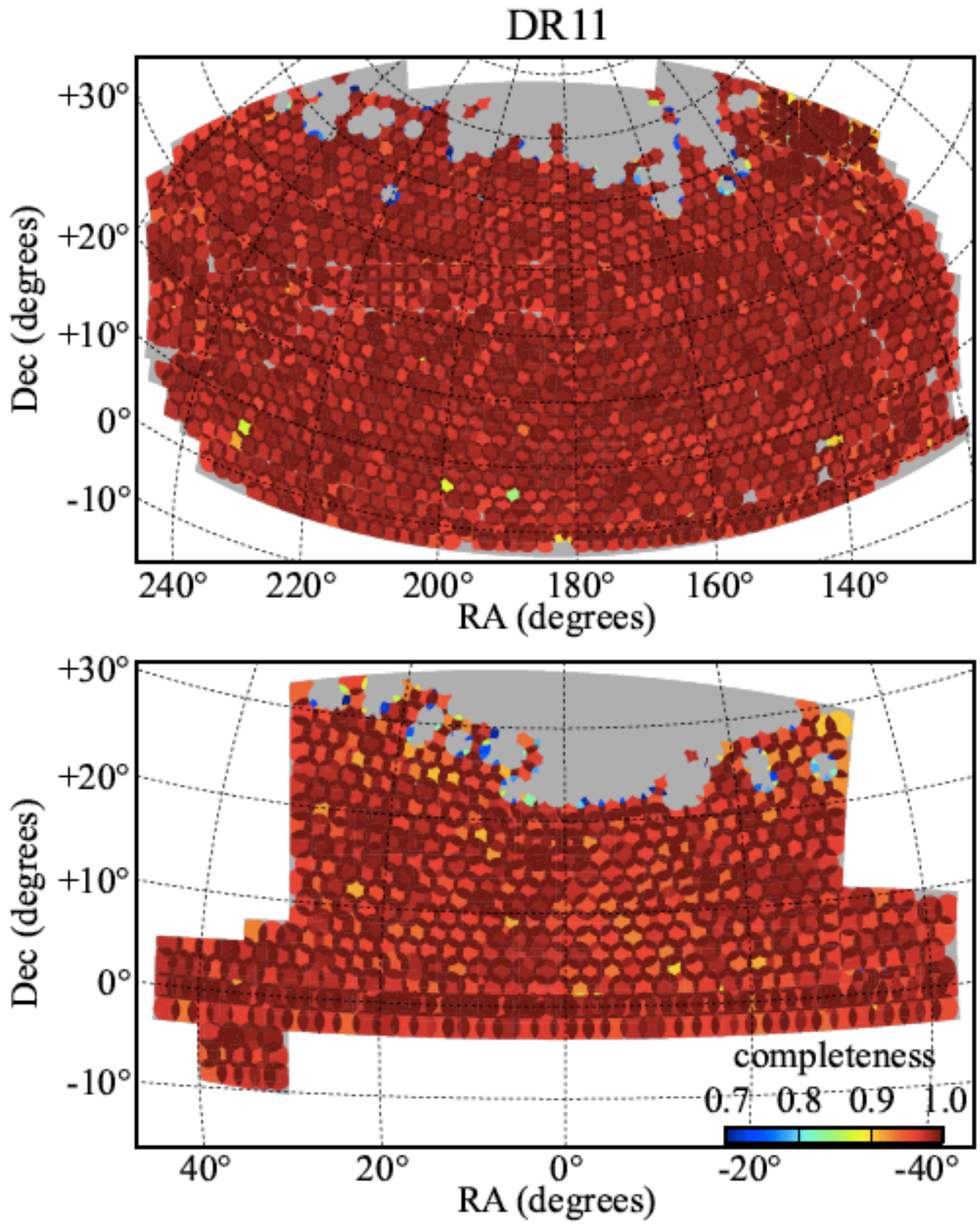


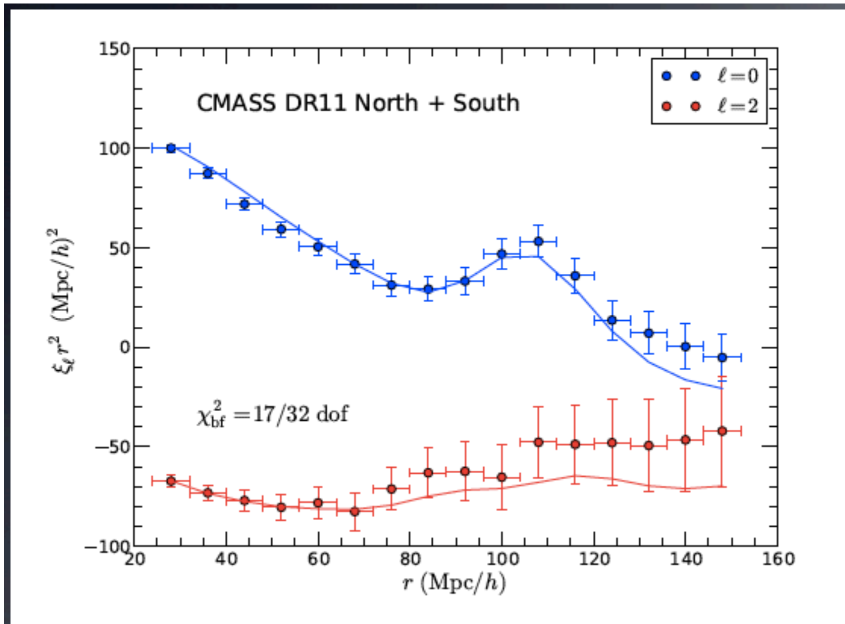



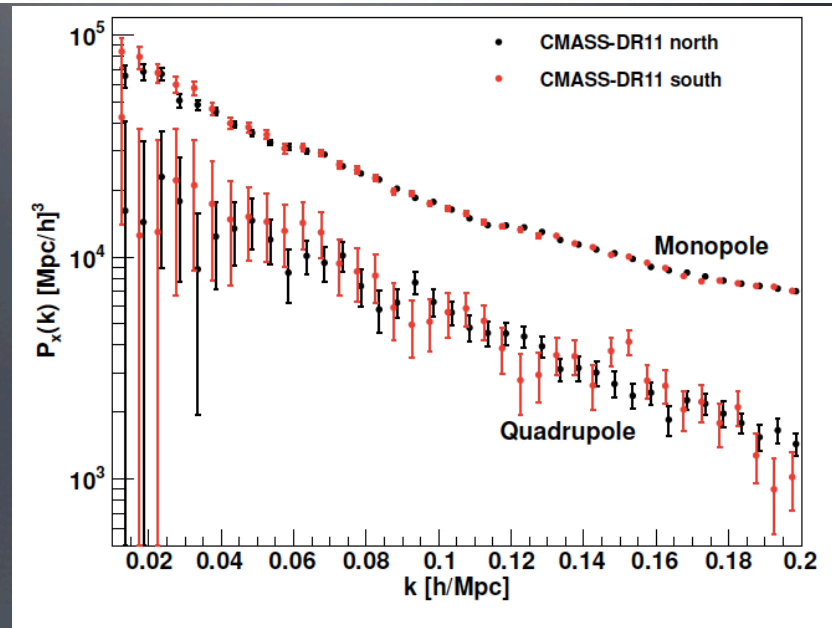

- The acoustic oscillation scale depends on the matter-to-radiation ratio ($\Omega_m h^2$) and the baryon-to-photon ratio ($\Omega_b h^2$).
- The CMB anisotropies measure these and fix the oscillation scale.
- In a redshift survey, we can measure this along and across the line of sight.
- Yields $H(z)$ and $D_A(z)$!

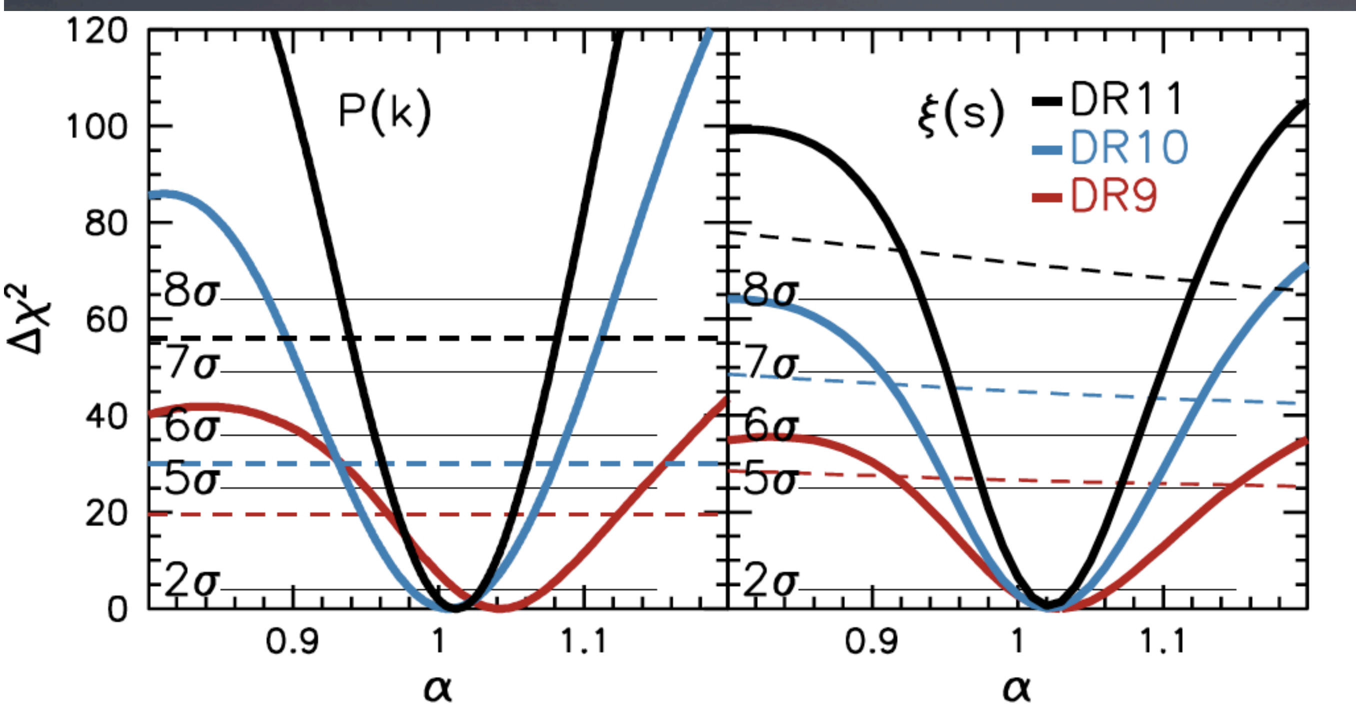
State of the art: SDSS DR11 CMASS

1.3M redshifts over 9000 square degrees



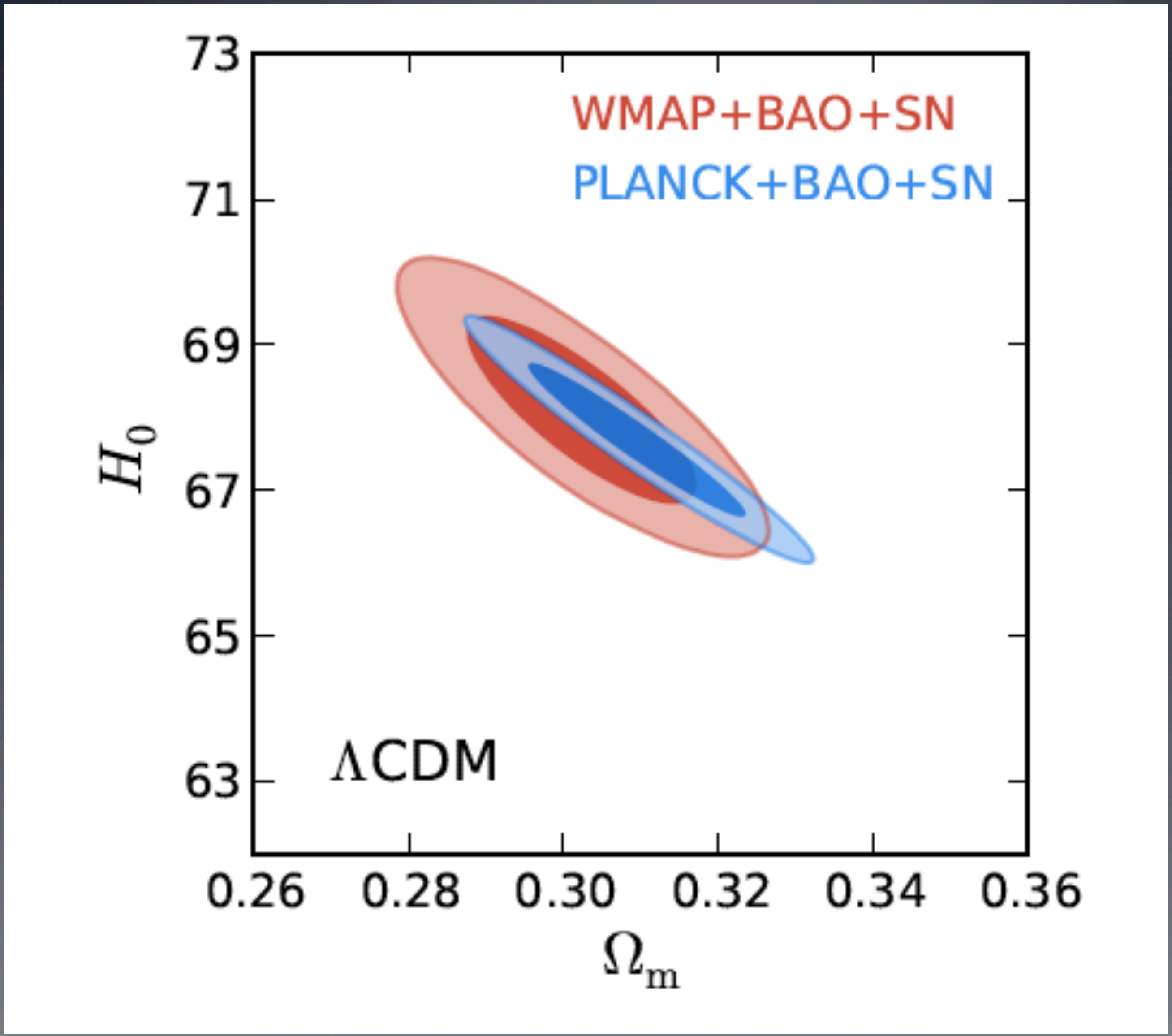


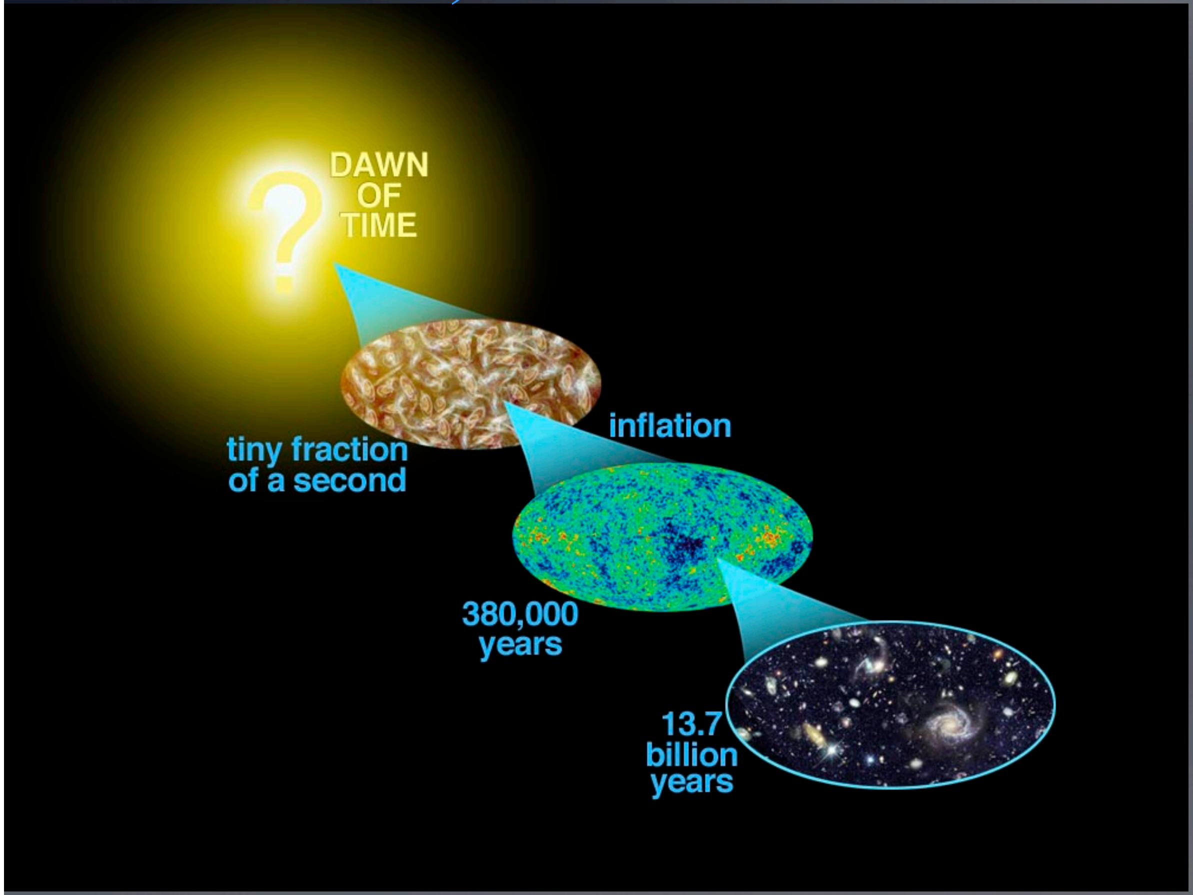

With SDSS DR11 BAO distance scale measured to 1%

LambdaCDM fits well (w=-1+/-0.07) Several papers coming (Anderson etal, Beutler etal, Samushia etal…)




DR11: Anderson et al 2013

# 2) Growth of structure by gravity




♦Perturbations can be measured at different epochs:

1. CMB z=1000
2. 21cm z=10-20 (?)
3. Ly-alpha forest z=2-4
4. Weak lensing z=0.3-2
5. Galaxy clustering z=0-2

Sensitive to dark energy, neutrinos…

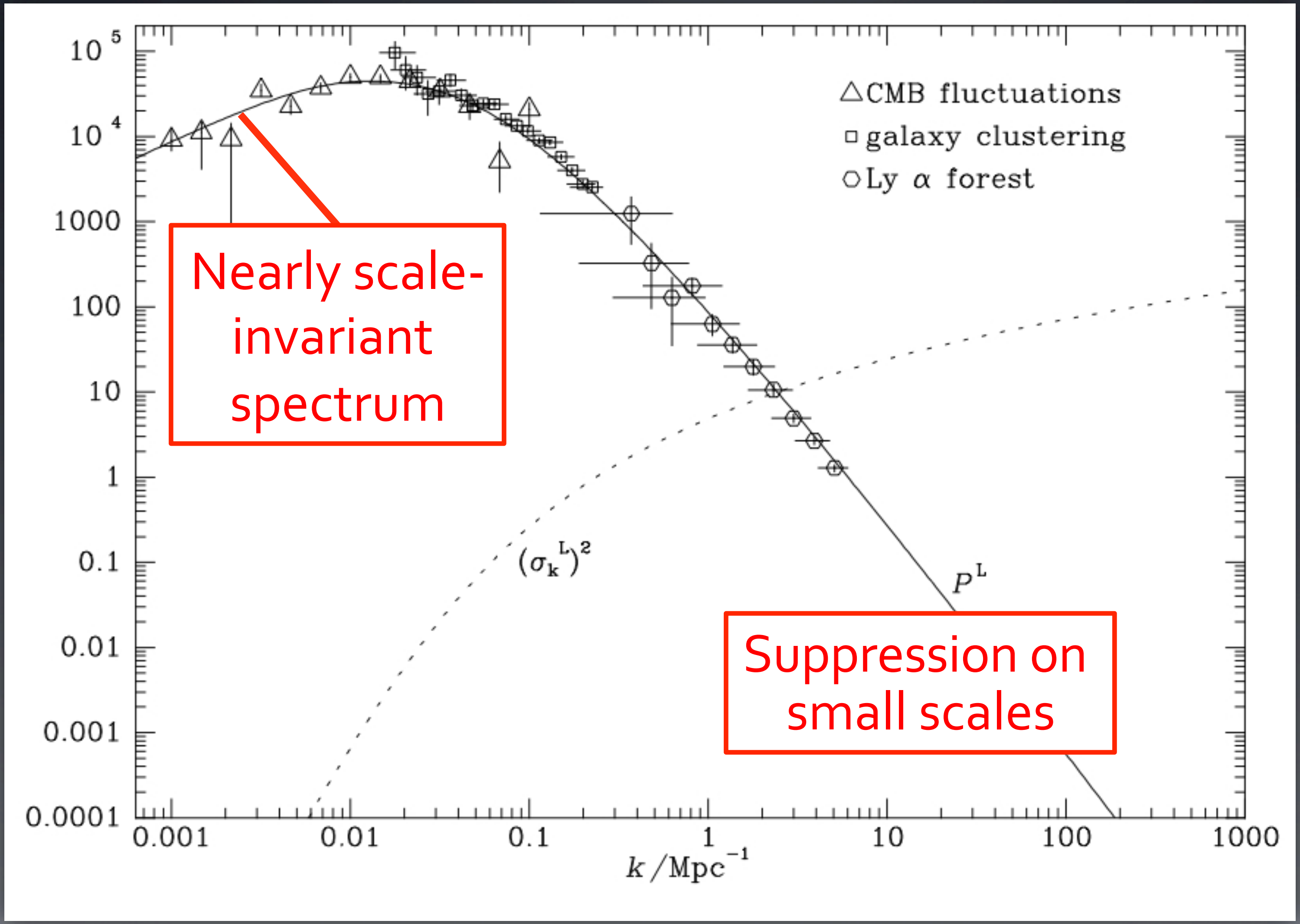
$$\ddot{\delta} + 2H\dot{\delta} = 4\pi G\bar{\rho}\delta \rightarrow \delta(t)$$

$$\left(\frac{\dot{a}}{a}\right)^2 = H^2 = \frac{8}{3}\pi G\bar{\rho} - Ka^{-2}$$

$$\bar{\rho} = \rho_m a^{-3} + \rho_{\rm de} a^{-3(1+w)} + \rho_\gamma a^{-4} + \rho_\nu F(a)$$

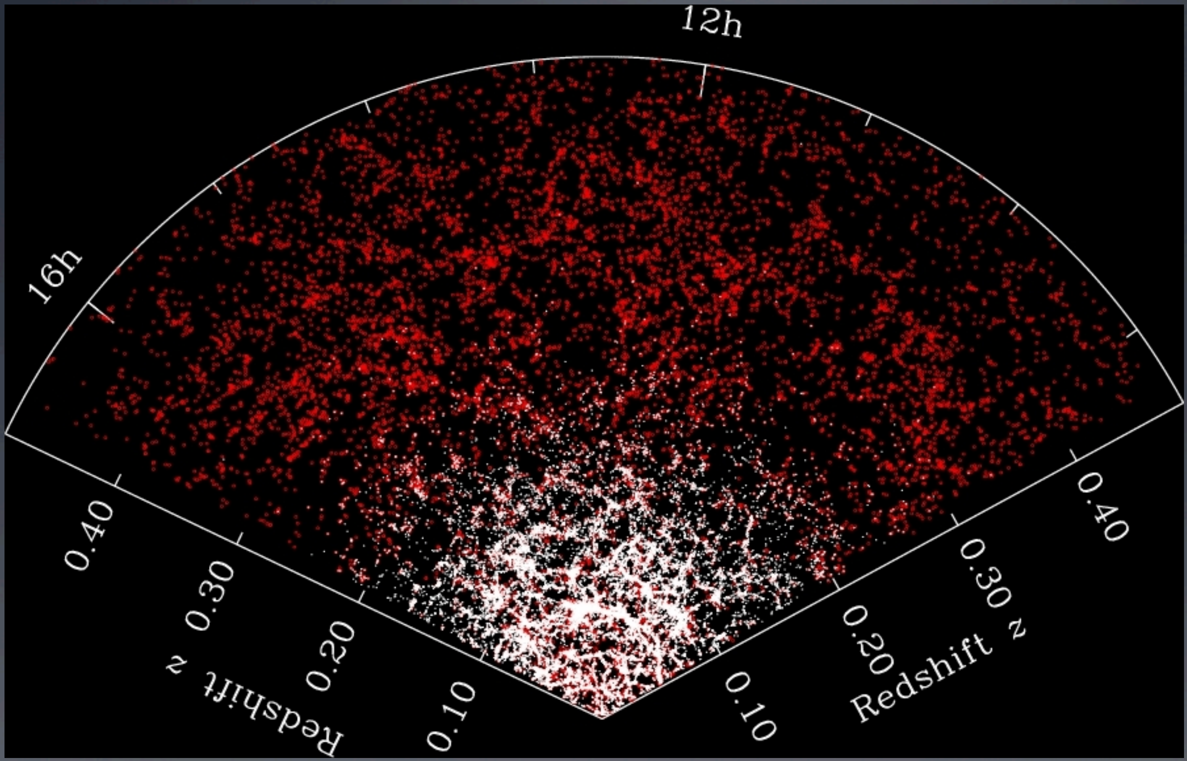
# 3) Shape of matter power spectrum

$$\langle \delta(k)\delta^*(k') \rangle = P(k)\delta_D(k - k')$$




Picture from Binney & Tremaine

# Galaxy clustering in redshift space




SDSS

1) Measures 3-d distribution, has many more modes than projected quantities like shear from weak lensing

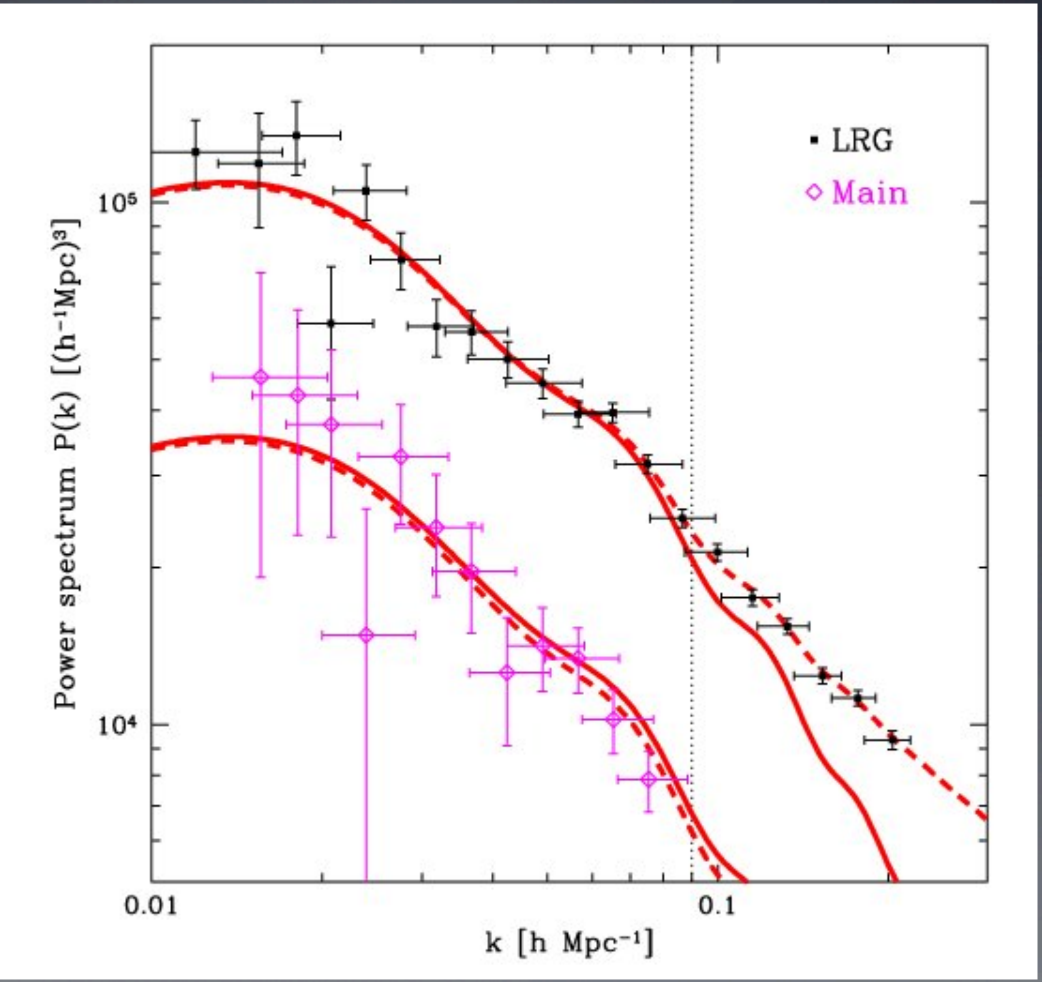
2) Easy to measure: effects of order unity, not 1%

# Galaxy power spectrum: biasing

- Galaxy clustering traces dark matter clustering
- Amplitude depends on galaxy type: galaxy bias b

$$P_{gg}(k)=b^2(k)P_{mm}(k)$$

- To determine bias we need additional (external) information
- Galaxy bias can be scale dependent: b(k)
- Once we know bias we know how dark matter clustering grows in time




Tegmark et al. (2006)

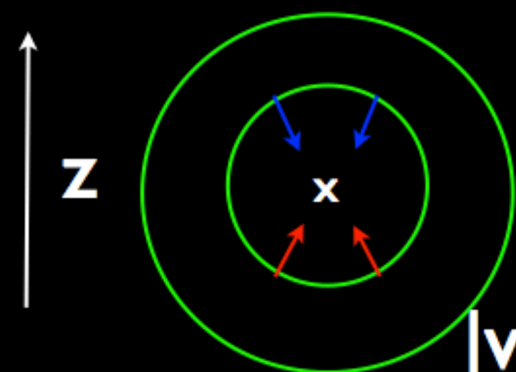
# How to determine bias?

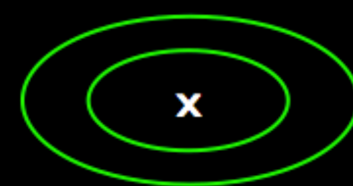
## Redshift space distortions

## redshift $cz = aHr + v_p$

**real to redshift space separations**

$$\nabla \cdot \mathbf{v_p} = -aHf\,\delta_m$$




$$|v_p| \sim d\,\sigma_8/d\ln a = \sigma_8 * f$$

**isotropic** **squashed along line of sight**

$$f = d\ln\sigma_8\,/d\ln a$$

Reid

# Linear and nonlinear effects

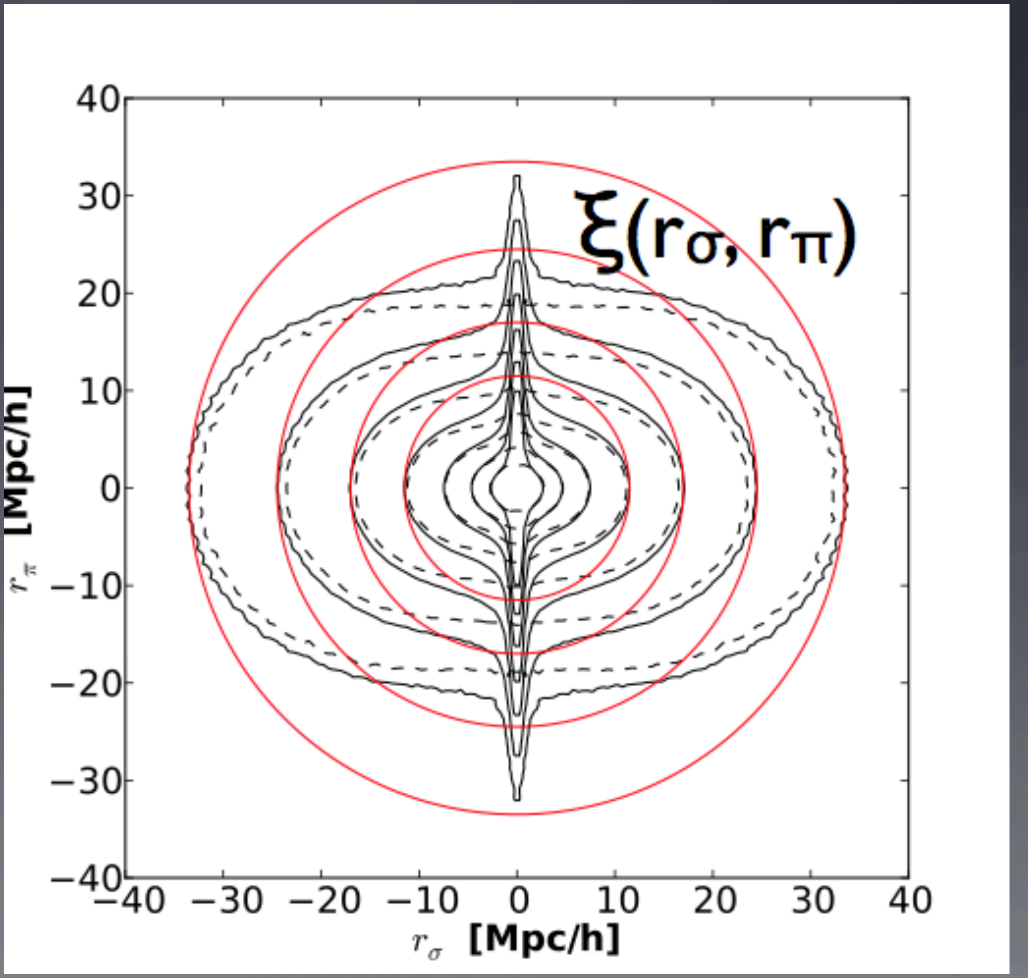
On very large scales linear RSD distortions:

$$\delta_g = (b + f\mu^2)\delta = b(1+\beta\mu^2)\delta$$

$$\mu = \vec{k}\cdot\vec{n}/k \qquad \beta = f/b$$

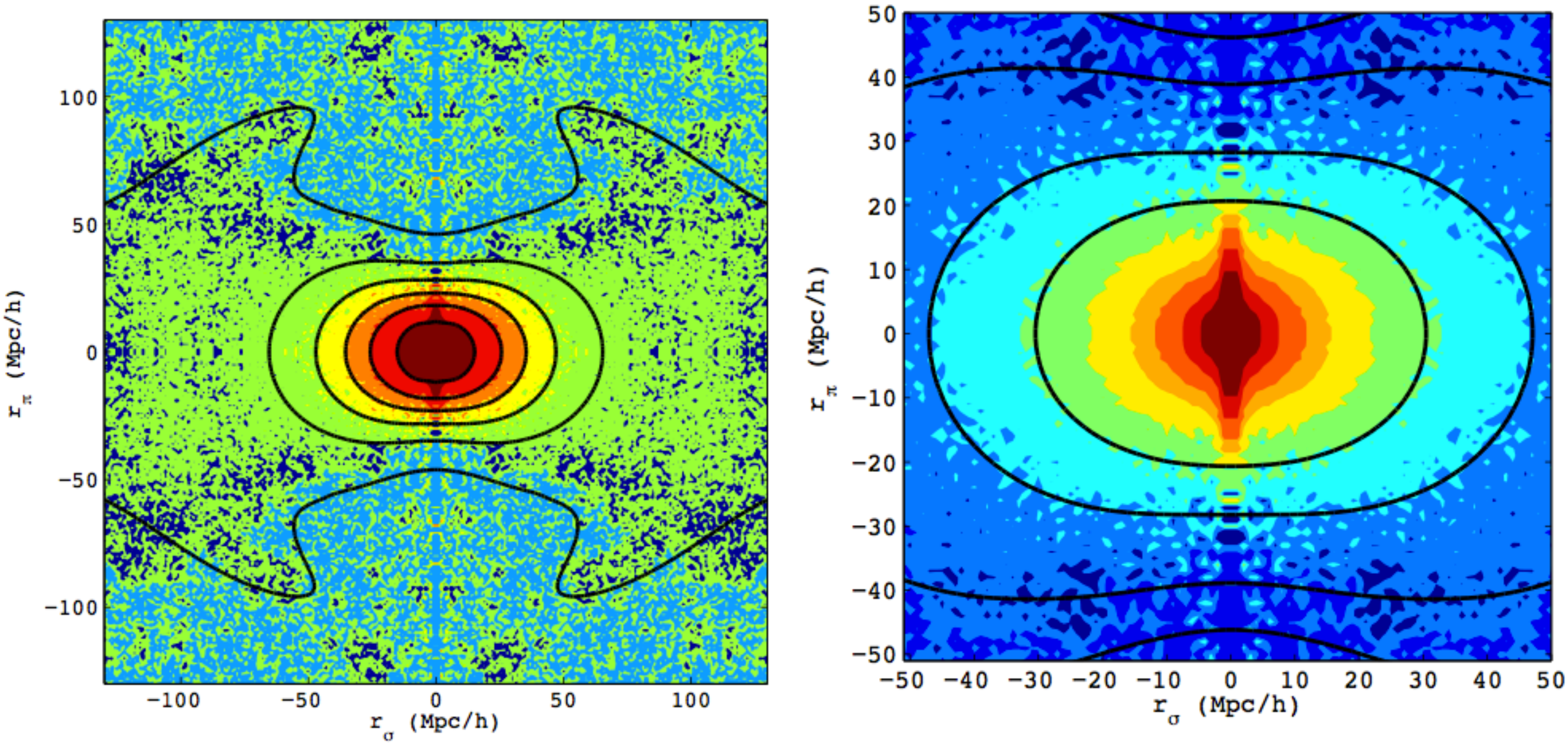
From angular dependence (l=0,2) we can determine velocity power $f\sigma_8$

On small scales: virialized velocities within halos lead to FoG, extending radially 10 times farther than transverse




White etal 2011

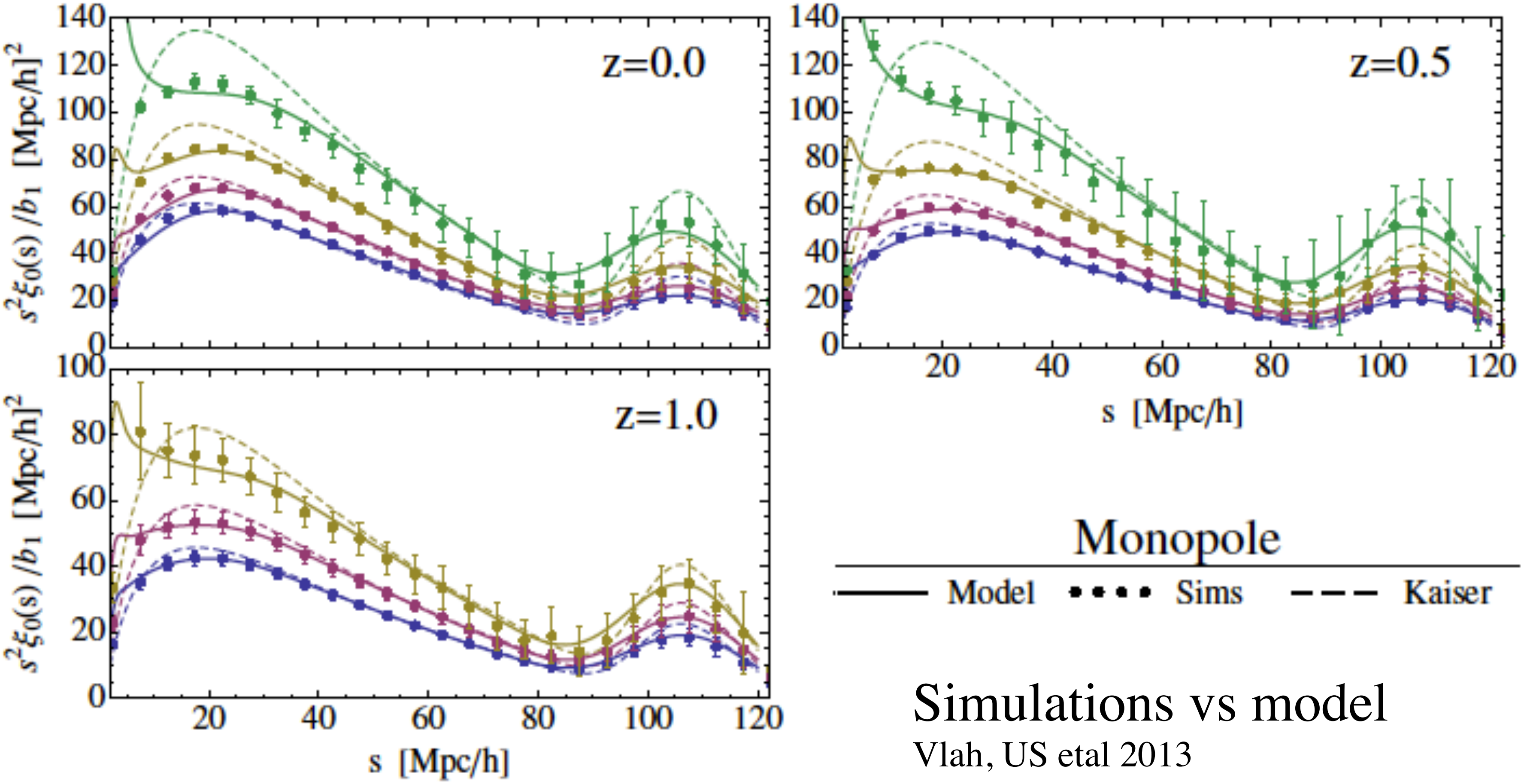
# RSD observations state of the art: SDSS-III/BOSS




$f\sigma_8 = 0.415 +/- 0.033$ (z=0.57)

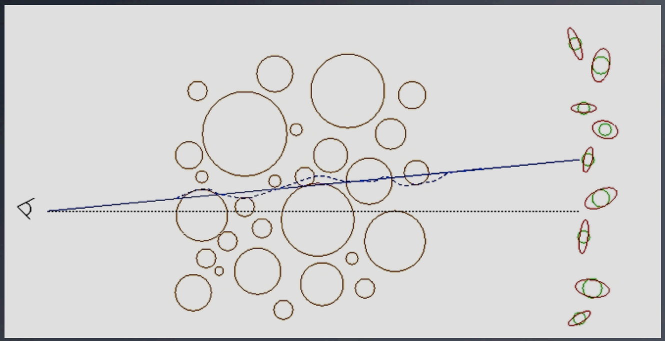
(Reid et al 2012, Samushia et al 2013, Beutler et al 2013)

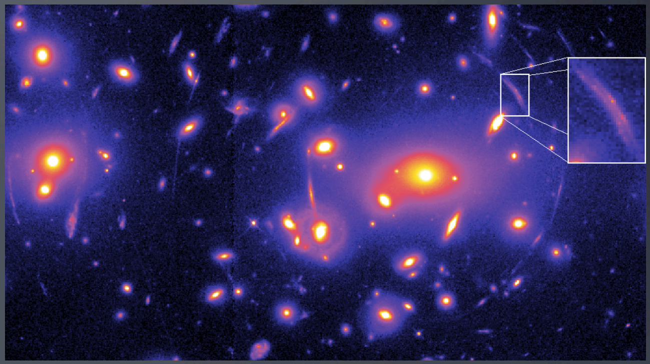
# Theoretical uncertainties in redshift surveys: nonlinear effects



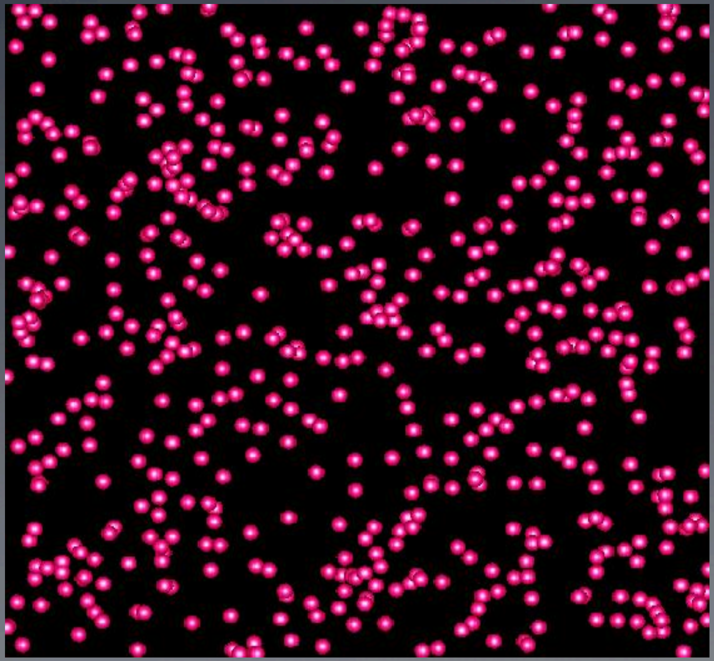

Simulations vs model
Vlah, US etal 2013

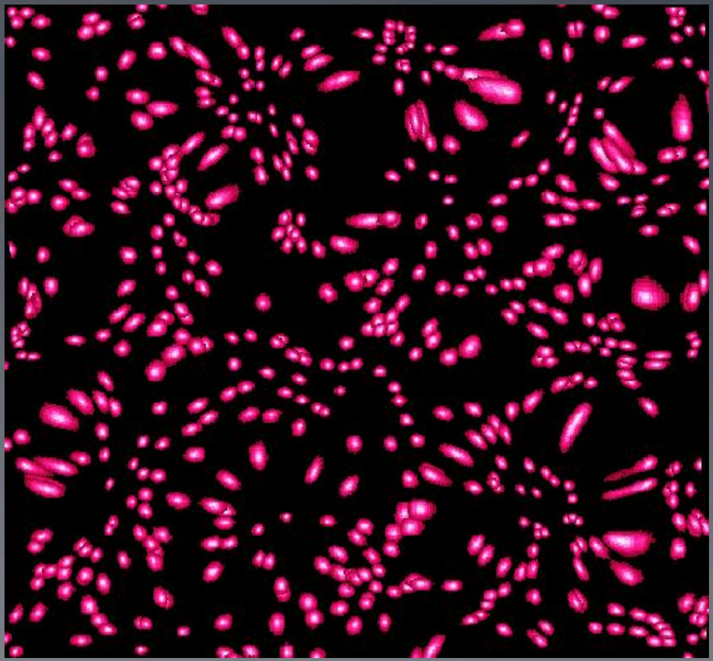
Second LSS Method: Weak Gravitational Lensing: sensitive to total mass distribution (DM dominated)





**Distortion of background images by foreground matter**





**Unlensed** → **Lensed**

# Convergence and shear

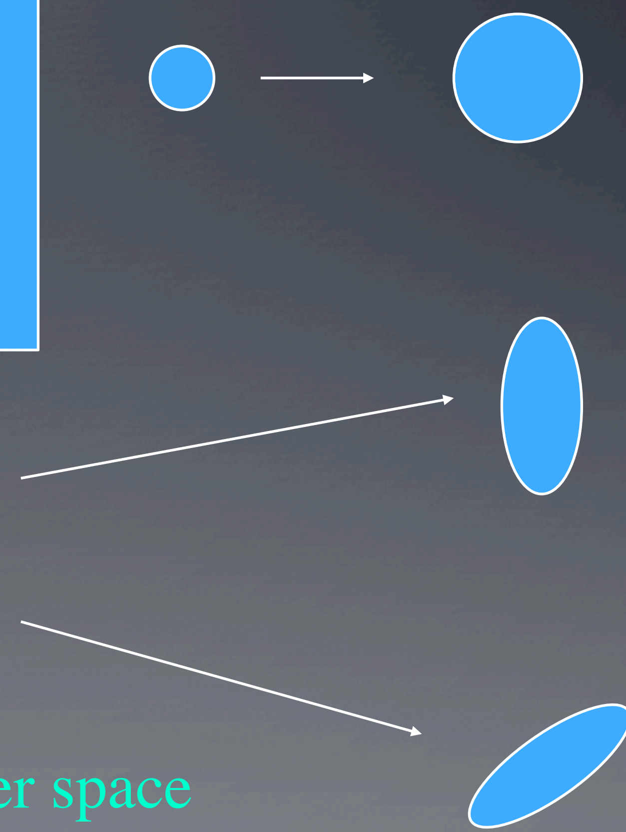
convergence

$$\kappa = \int \frac{(r_{LSS} - r)r}{r_{lSS}} \vec{\nabla}^2 \Phi dr = \frac{3}{2}\Omega_m H_0^2 \int \frac{(r_{LSS} - r)r}{r_{lSS}} dr \frac{\delta}{a}$$

shear

$$\gamma_1(\vec{l}\,) = \kappa(\vec{l}\,)\cos 2\varphi_l$$

$$\gamma_2(\vec{l}\,) = \kappa(\vec{l}\,)\sin 2\varphi_l$$



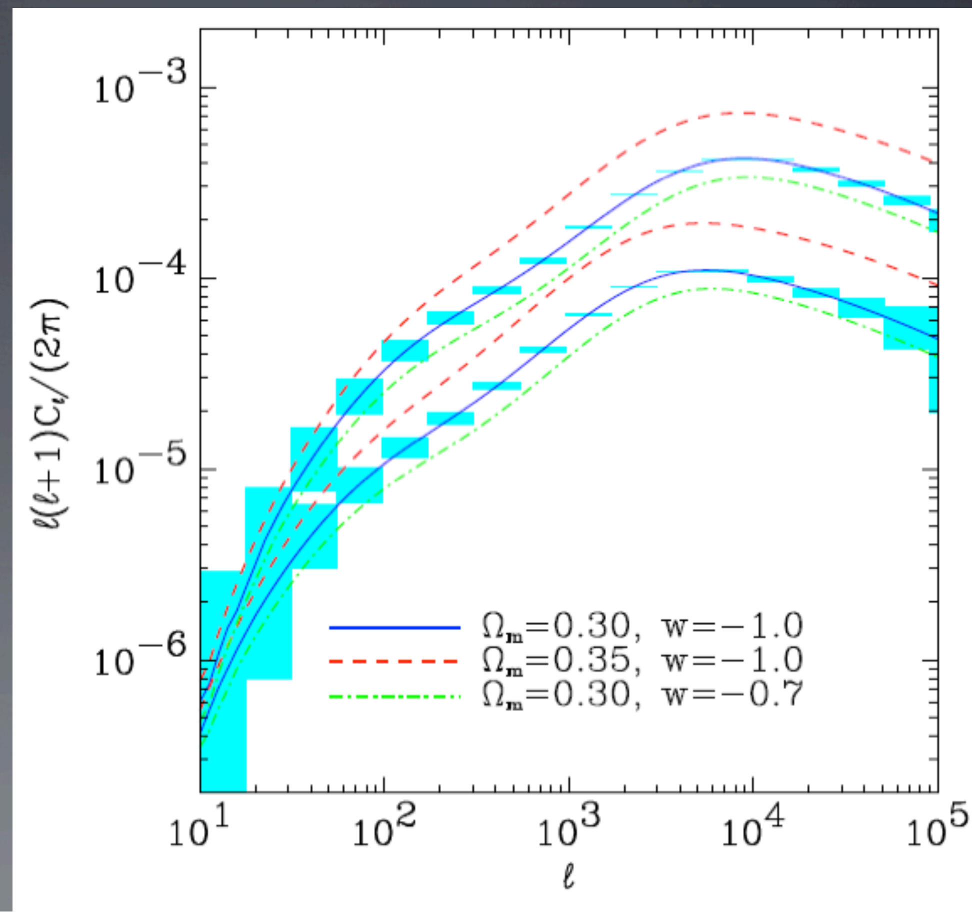
Convergence shear relation in Fourier space

# Method I: shear-shear correlations

Refregier et al SNAP3

$$C_l^{\kappa} = \frac{9}{4}\Omega_0^2 \int_0^{w_s} \mathrm{d}w \frac{g^2(w)}{a^2(w)} P_{3D}\left(\frac{l}{f_K(w)}; w\right) \times \frac{f_K(w_s - w) f_K(w)}{f_K(w_s)}.$$

- Just a projection of total matter P(k)
- Need P(k) for dark matter: use N-body simulations (solved problem)
- Sensitive to many cosmological parameters



# State of the art in shear-shear: CFHT-LS

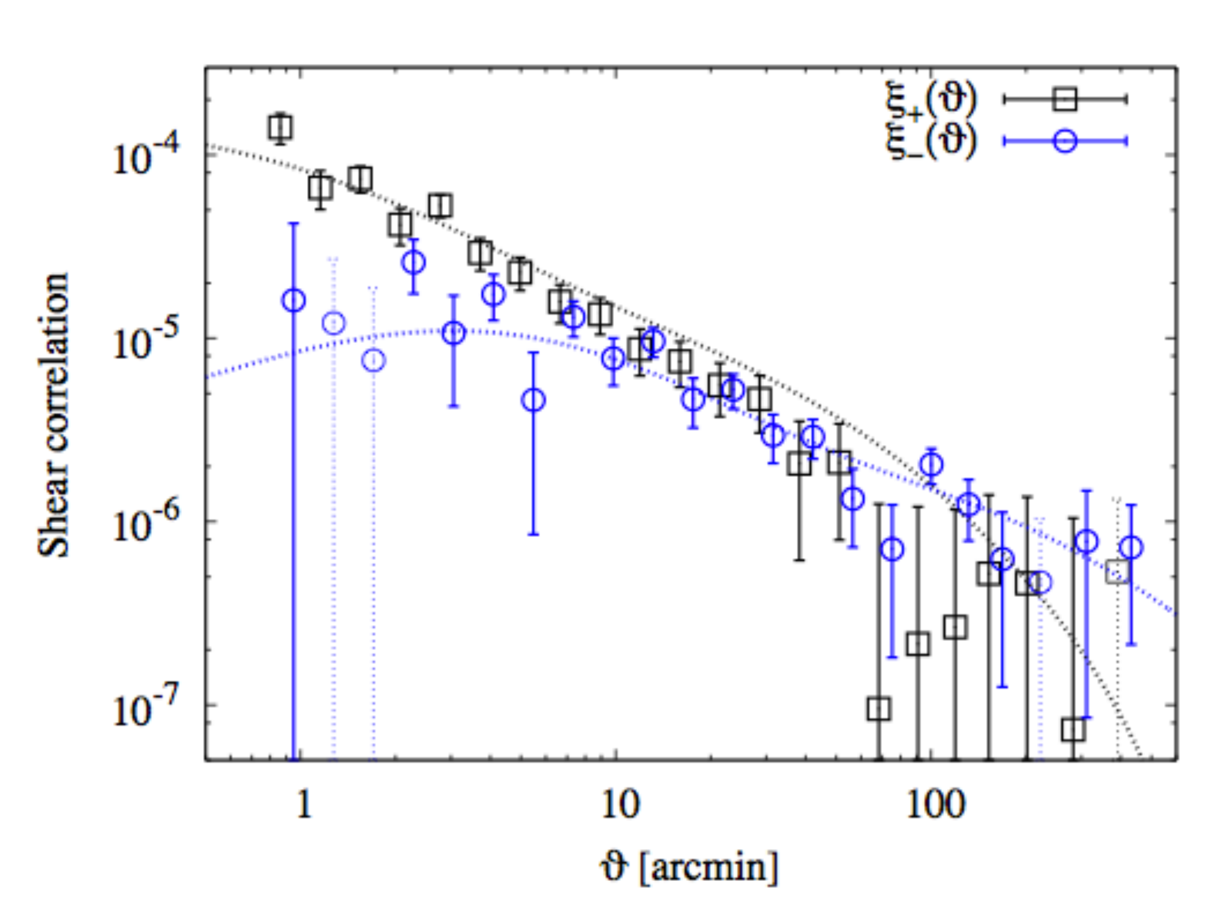
Kiblinger et al 2013

Challenges:

Small scales: could be contaminated by baryonic effects

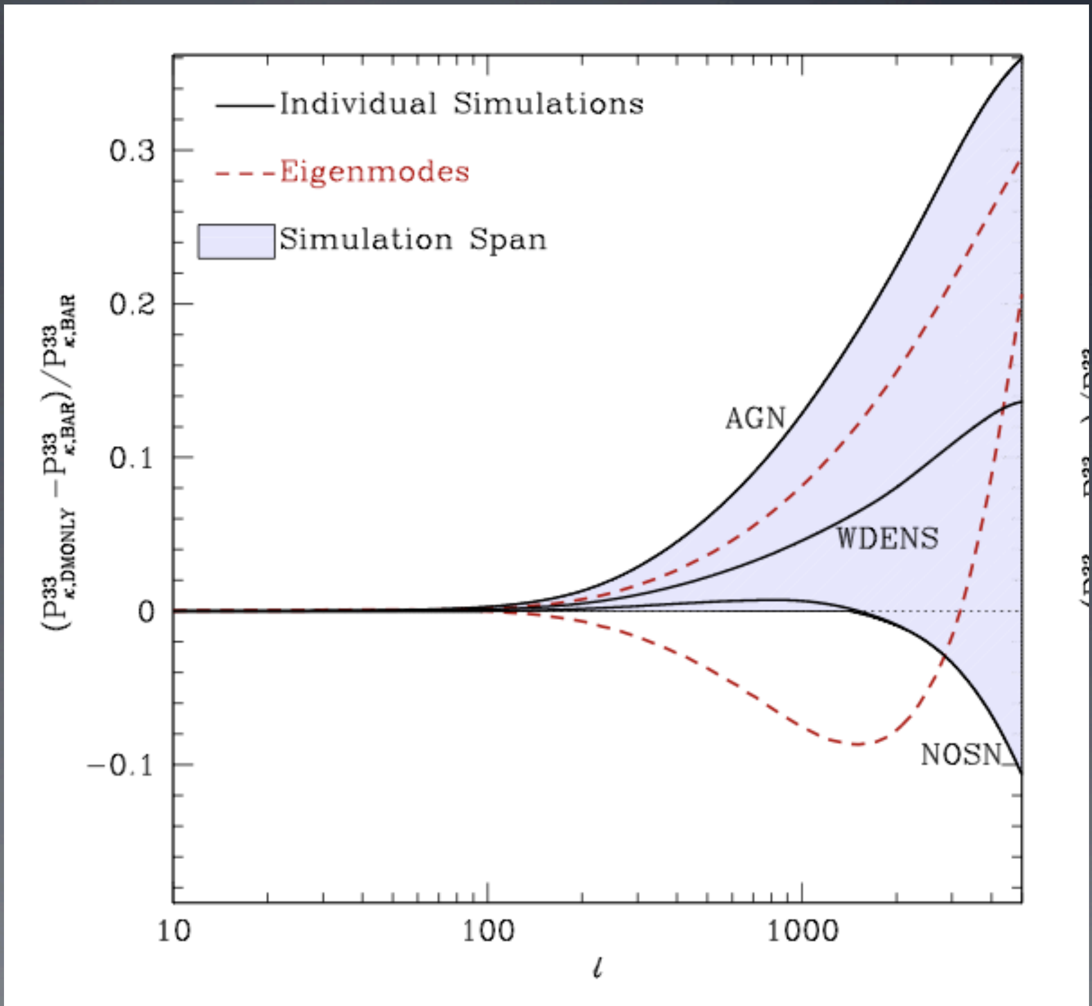
Redshift distributions not completely known

Additive systematics: a lot of data removed



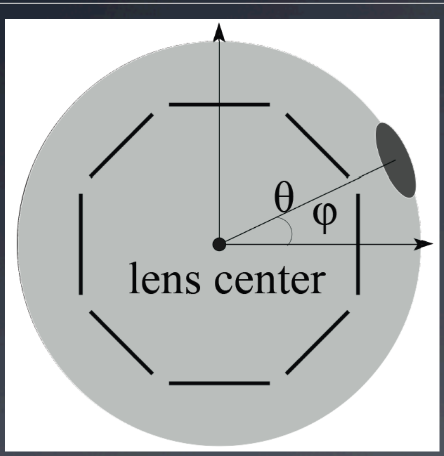
# Theoretical uncertainties in weak lensing

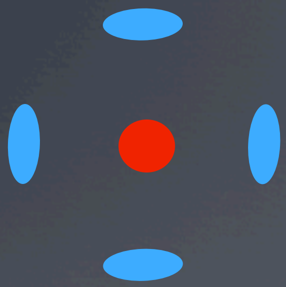
- Baryonic effects: baryons redistribute dark matter inside halos: compress (cooling) or expand (AGN feedback)?
- Challenge: small scale baryonic physics effects can be projected to low l for nearby halos

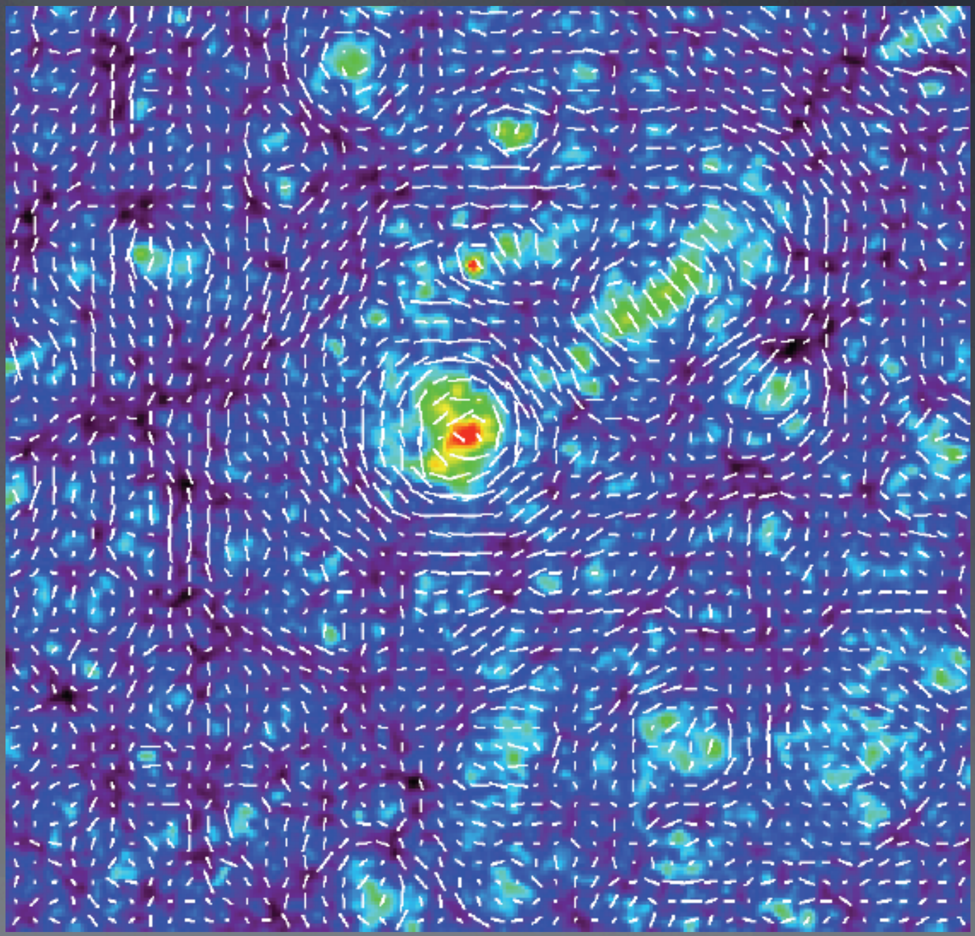



Zentner et al 2013

# WL Method II: galaxy-shear correlations





Cross-correlation proportional to bias b

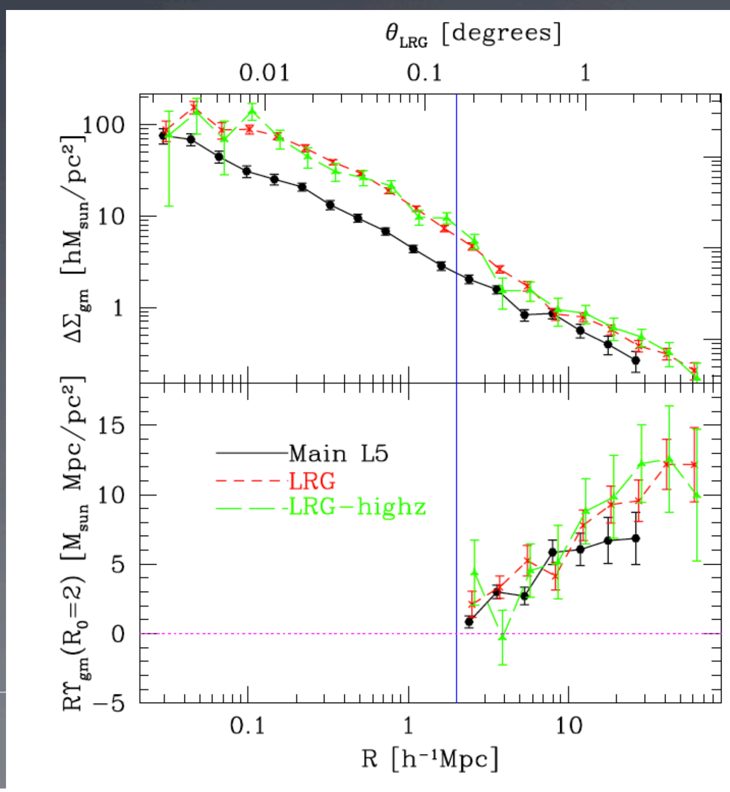
Galaxy auto-correlation proportional to $b^2$

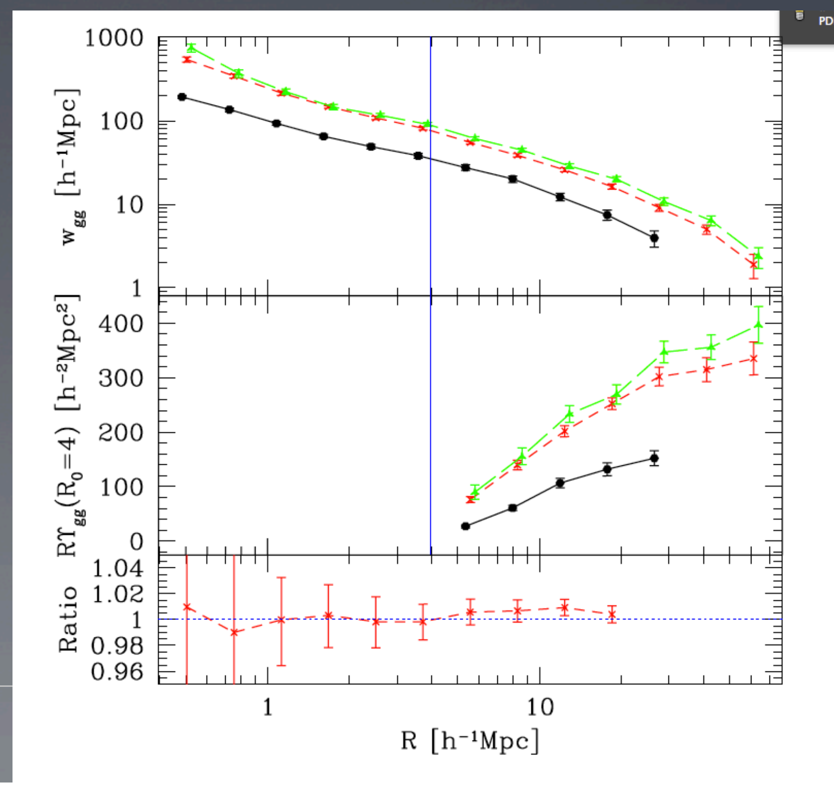
# SDSS DR-7 data analysis

Mandelbaum etal, 2013

LENSES
70,000 M*-1 galaxies (z<0.15),
62,000 low z LRGs (0.16<z<0.3),
35,000 high z LRGs (0.36<z<0.47)

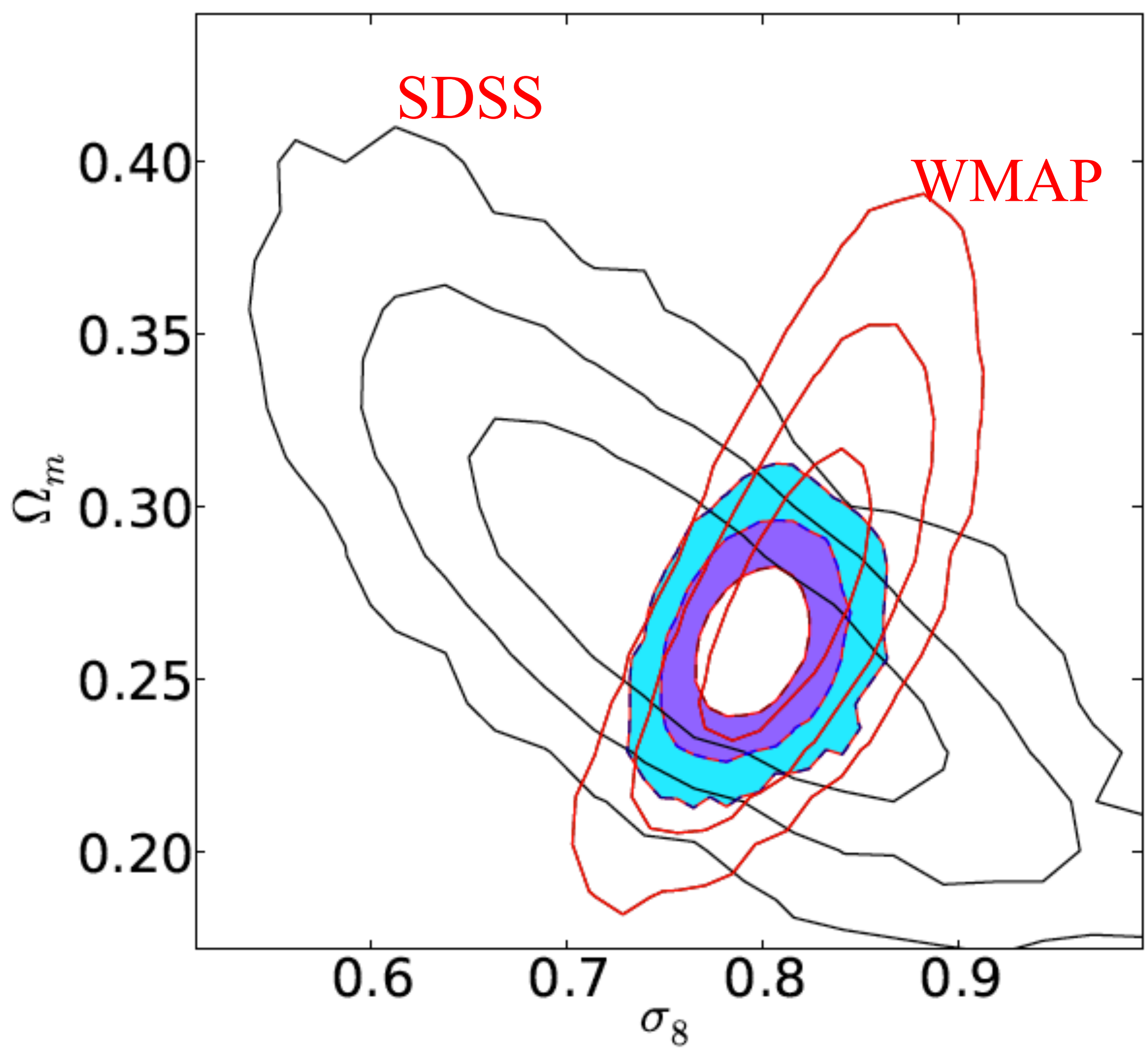
SOURCES
10M, well calibrated photozs using spectroscopic surveys



$$\sigma_8(\Omega_m/0.25)^{0.57} = 0.795 \pm 0.048$$

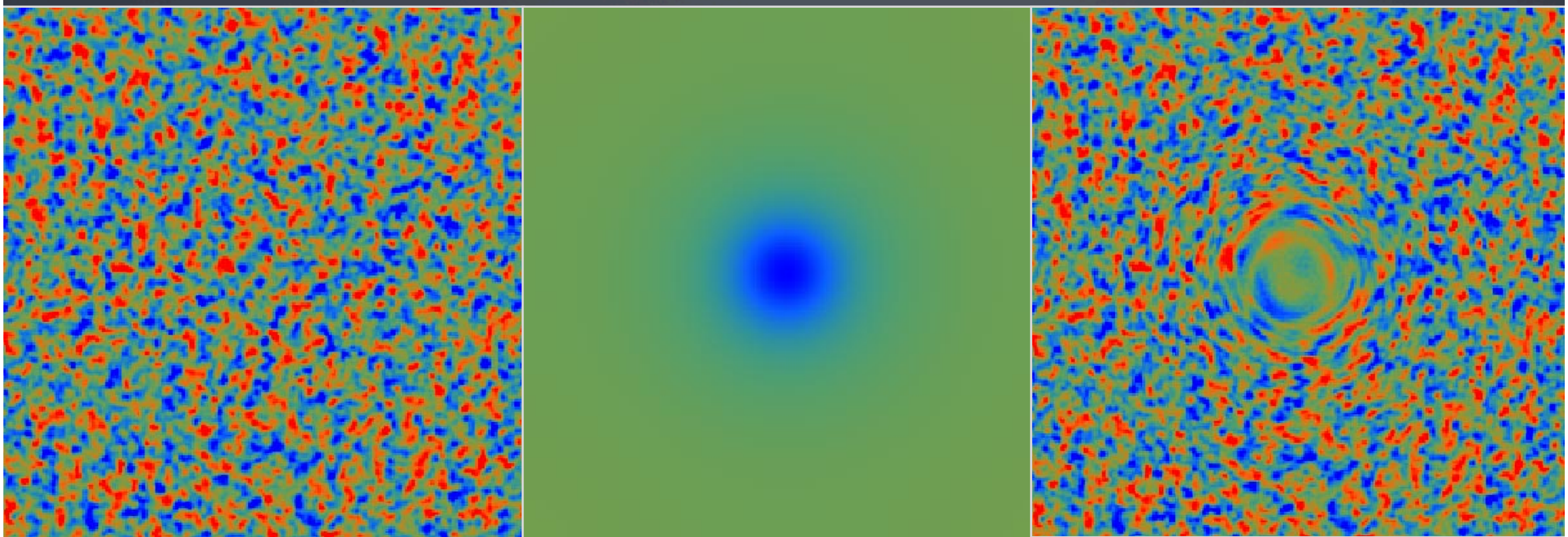
# Cosmology constraints



# Effect of gravitational lensing on CMB

$$T_{lensed}(\vec{\mathbf{n}}) = T_{unlensed}(\vec{\mathbf{n}} + \vec{\mathbf{d}}) \qquad \vec{\mathbf{d}} = -2\vec{\nabla}\nabla^{-2}\kappa$$

- Here $\kappa$ is the convergence and is a projection of the matter density perturbation.



Okamoto and Hu 2002

# Gravitational lensing in CMB: reconstruction of lensing

$$\kappa \propto (\nabla_x T)^2 + (\nabla_y T)^2$$

$$\gamma_1 \propto (\nabla_x T)^2 - (\nabla_y T)^2$$

$$\gamma_2 \propto 2(\nabla_x T)(\nabla_y T)$$

Local estimate of typical patch size or shape

Compare to global average

Zaldarriaga & US 1998

$$T_{lensed}(\vec{\vartheta}) = T_{unlensed}(\vec{\vartheta} + \vec{\delta}) \approx T_{unlensed}(\vec{\vartheta}) + \vec{\delta} \bullet \vec{\nabla} T_{unlensed} + \ldots$$

$$T_{lensed}(\vec{L}) = T_{unlensed}(\vec{L}) + \sum_{l} T_{unlensed}(\vec{l})(\vec{L} - \vec{l}) \bullet \vec{l}\, \varphi(\vec{L} - \vec{l}) + \ldots$$

$$\vec{\delta}(\vec{l}) = \vec{l}\, \varphi(\vec{l})$$

$$\vec{C} = \left\langle T(\vec{l}) T(\vec{l}\,') \right\rangle = C_l \delta_{ll'} + (\vec{l} - \vec{l}\,')(C_l \vec{l} - C_{l'} \vec{l}\,') \varphi(\vec{l} - \vec{l}\,')$$

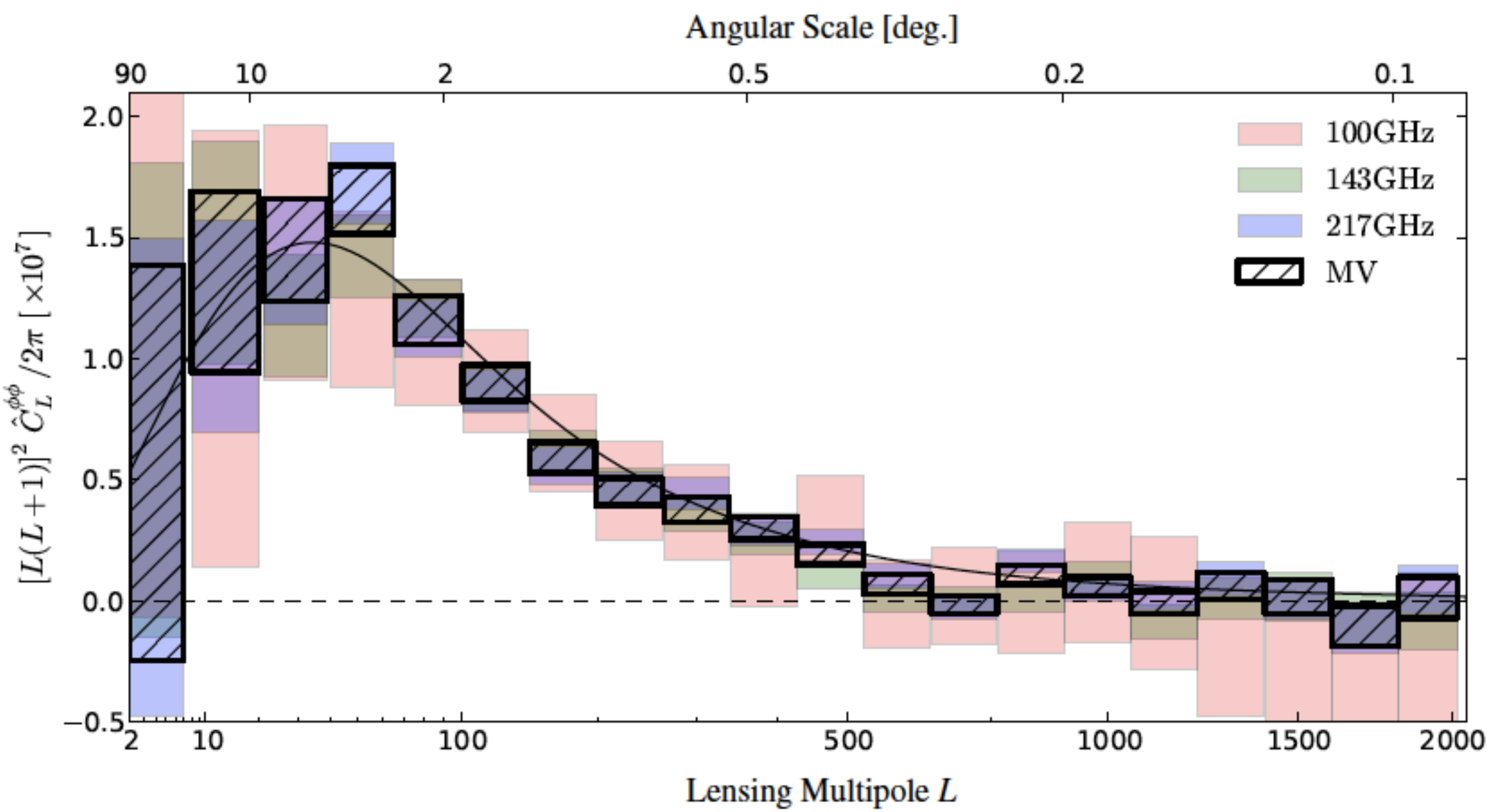
$$\varphi(\vec{l}) = \frac{1}{2} F_{ll'}^{-1} (\vec{T} C^{-1} \frac{\partial \vec{C}}{\partial \varphi(\vec{l}\,')} C^{-1} \vec{T})$$

Optimal quadratic estimator

Okamoto and Hu 2002

# Current status: Planck and more

- Planck measures WL at 25 sigma
- See also ACT, Polarbear, and specially SPT results



# Future promise: CMB polarization, the ultimate weak lensing experiment?

- For low detector noise main statistical information is provided by B mode polarization (Hirata & Seljak 2003): B mode polarization is not present in primary anisotropy (except for non-scalar modes), therefore with B mode polarization we measure lensing, we are not limited by statistical fluctuations in the primary CMB, rather by noise, systematics, foregrounds, …
- Cleanest probe of dark matter clustering: largest scales, linear growth, highest redshift, known to be 1100, very few systematics (contrast to galaxy lensing)
- Helps clean out B contamination
- Can calibrate LSS weak lensing surveys

# Cluster counting

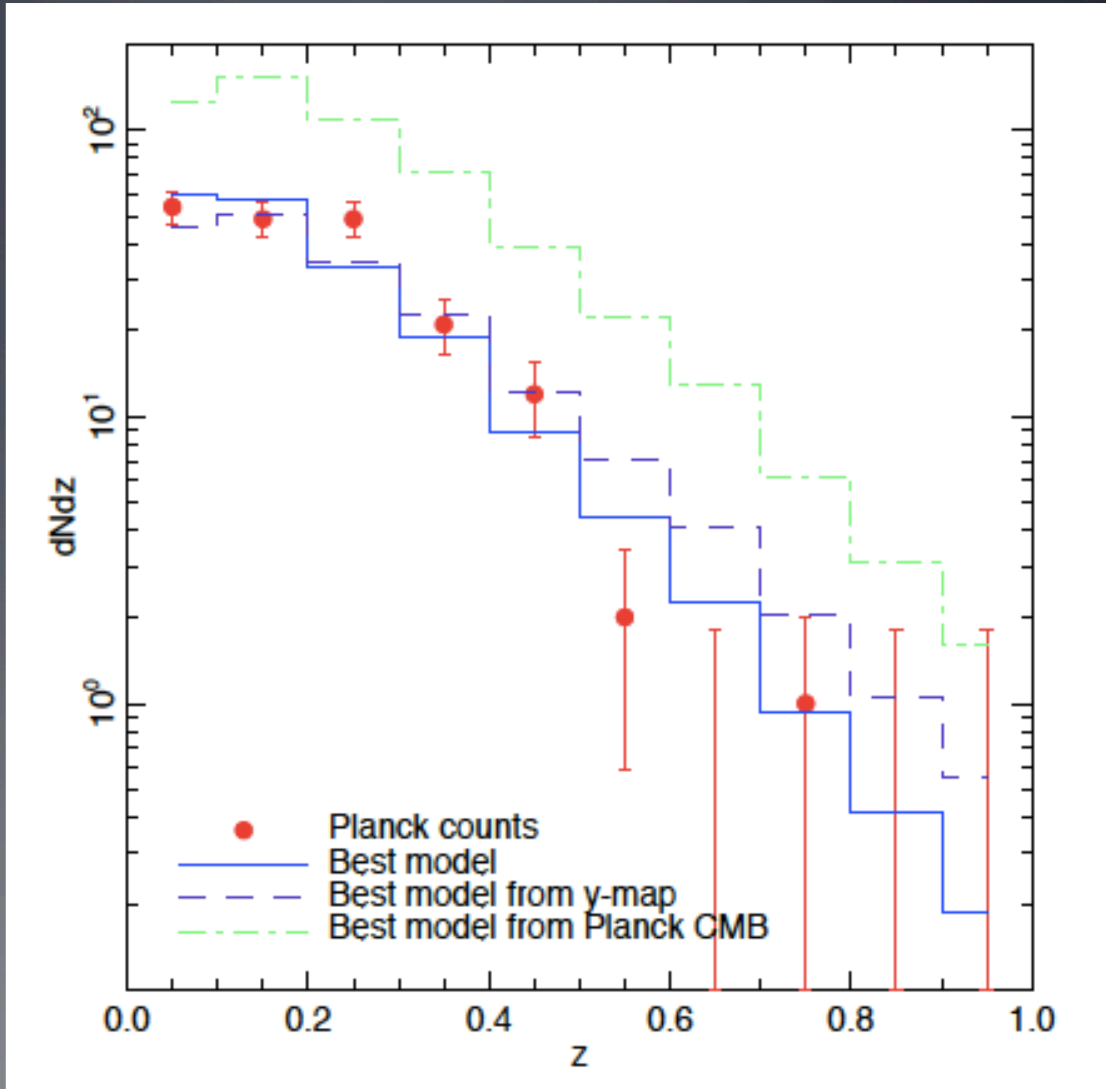
- Halo mass function steep at high mass end: highly sensitive to amplitude change
- Counting clusters is easy. Relating observable to halo mass hard
- Scatter between the two biases amplitude determination: low mass clusters scatter into the sample
- Determinimg mean mass is hard: WL, SZ, X-ray hydrostatic equilibrium

# Planck cluster counting with SZ

Appears to favor lower amplitude than Planck CMB

But this could be caused by a bias in SZ flux-mass relation

Note that SZ $C_l$ does not require explicit calibration

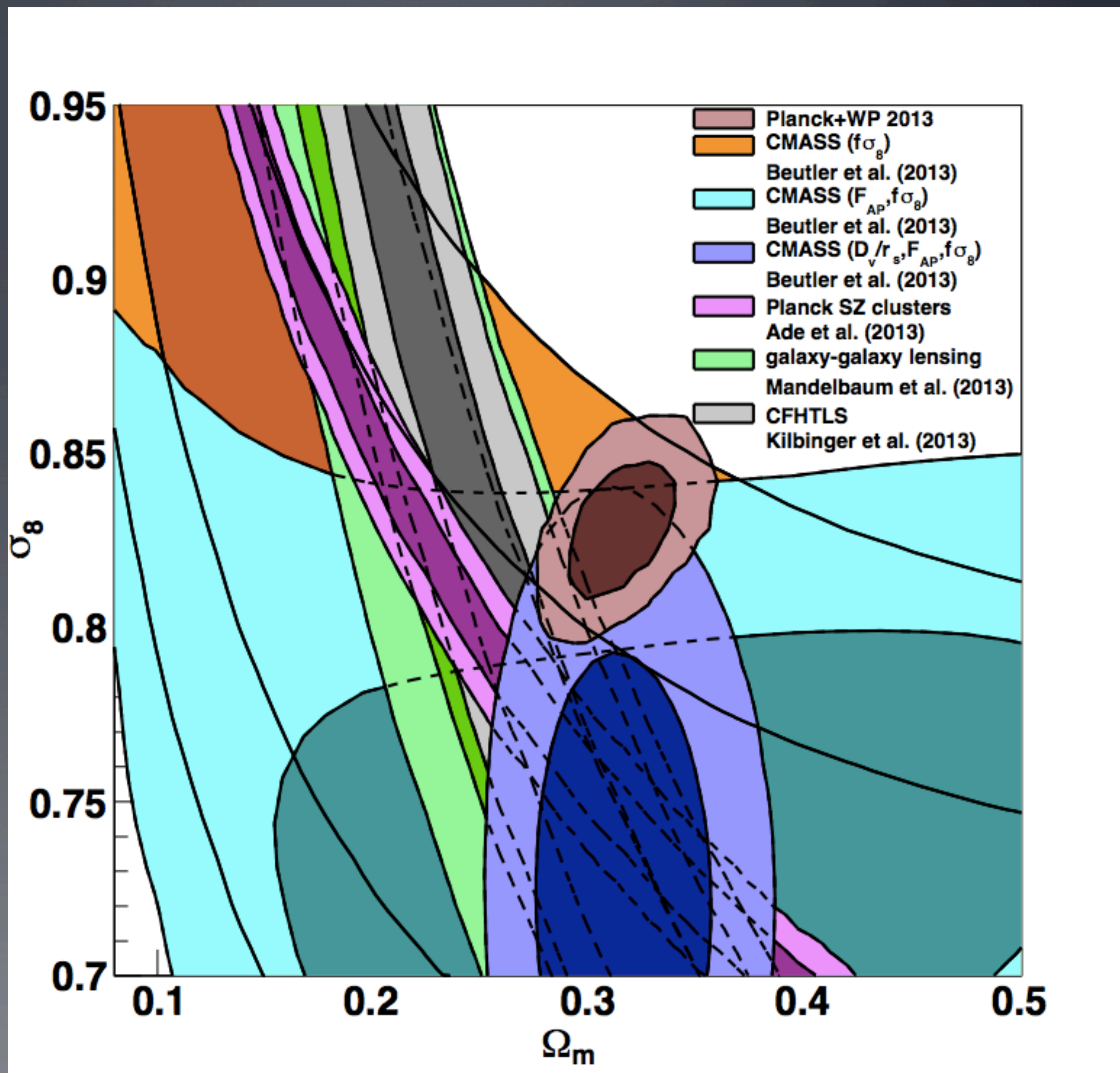


# Planck versus LSS

LSS constraints (RSD, lensing, clusters) consistent

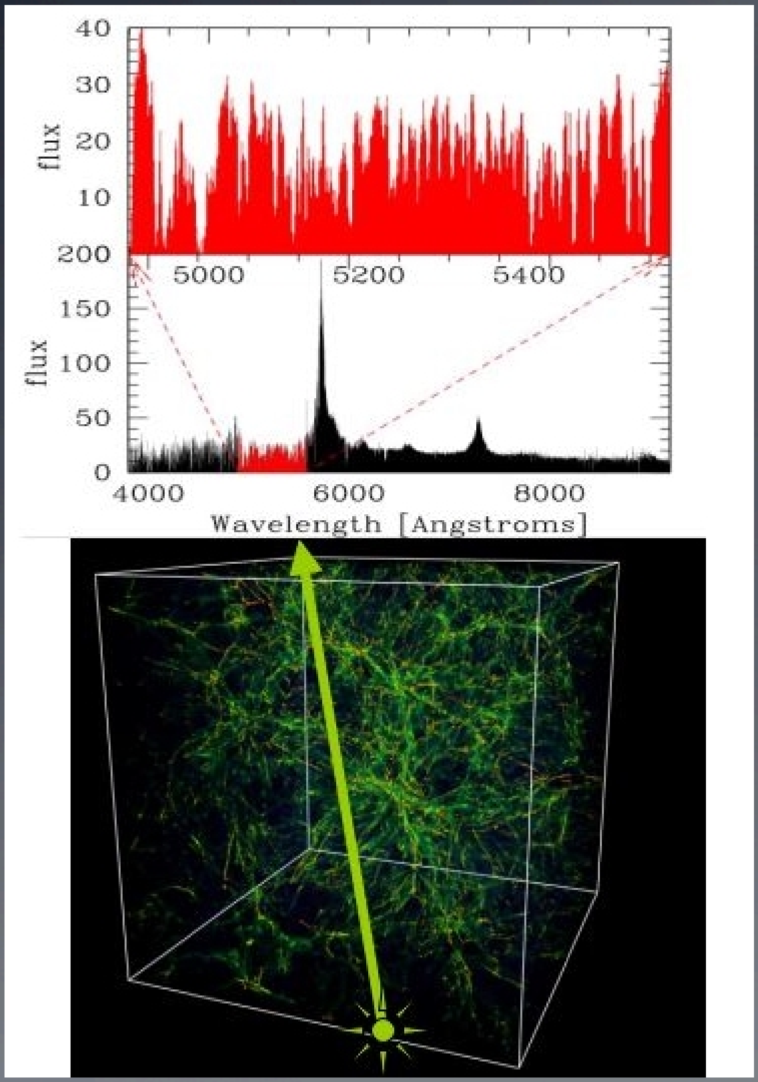
All to the left of Planck (prefer lower $\sigma_8 \Omega_m^x$)

Planck reanalysis, more LSS data




F. Beutler

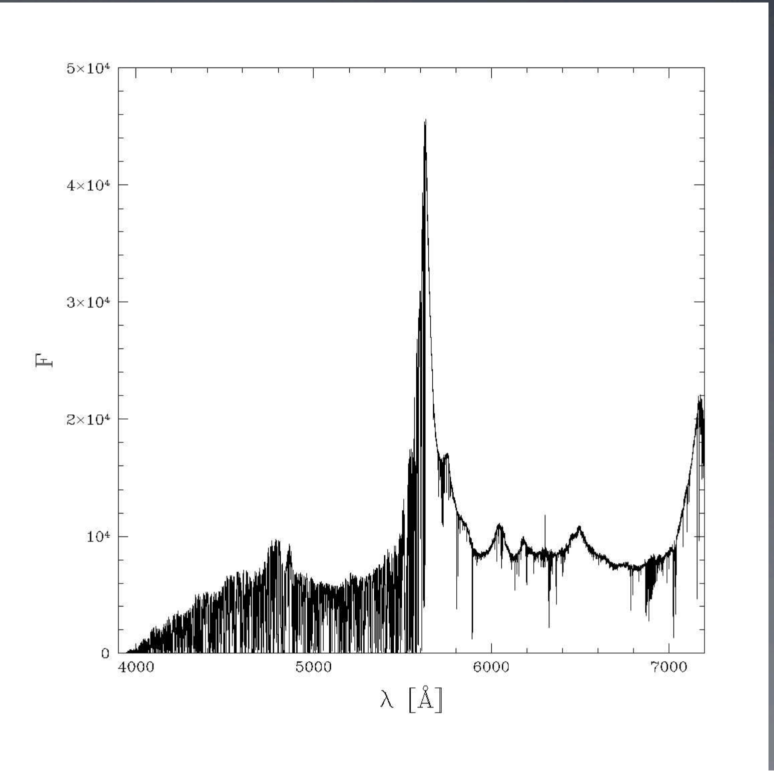
# Ly-alpha forest: basics

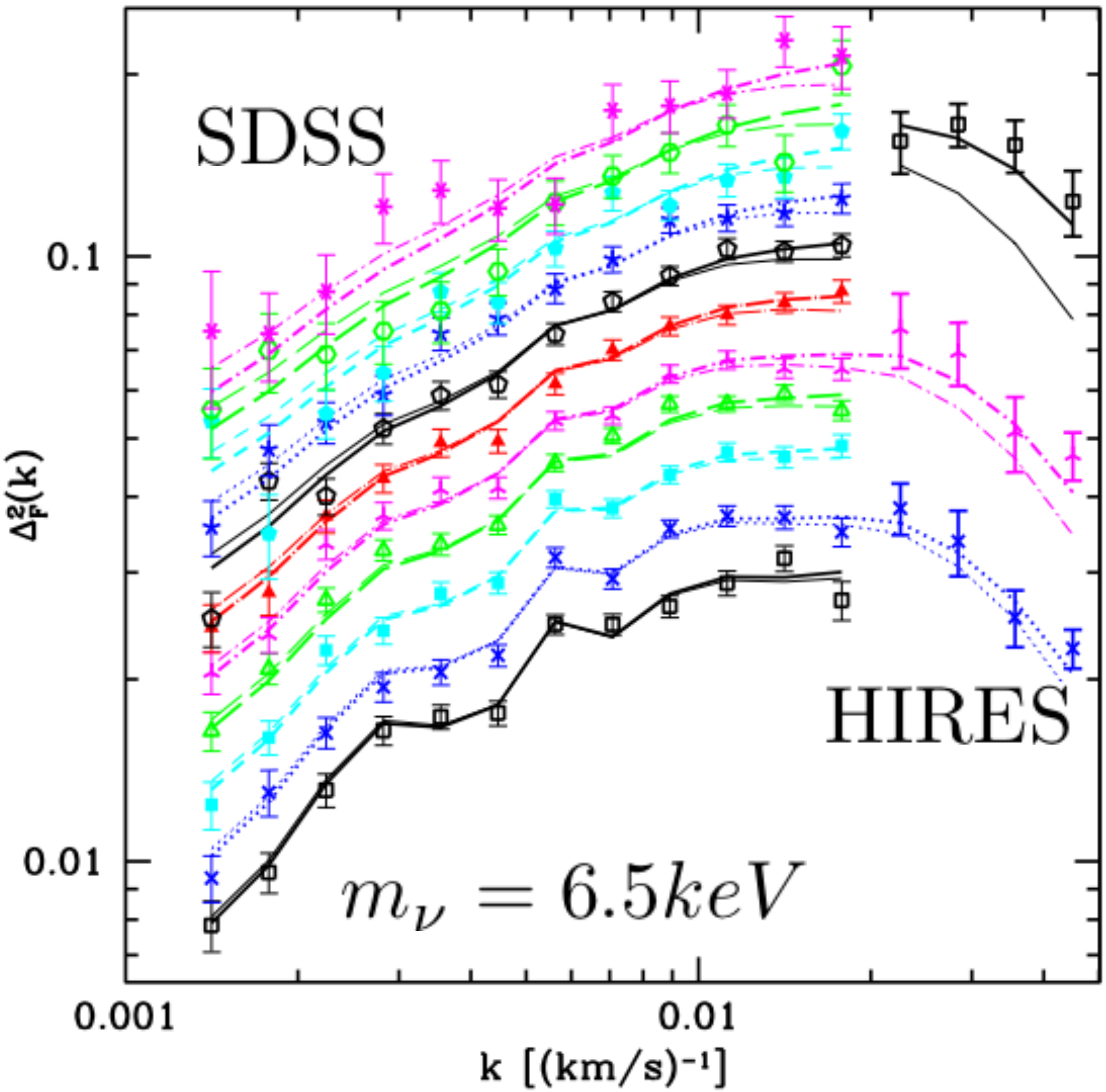



SDSS Quasar Spectrum

- Neutral hydrogen leads to

Lyman-$\alpha$ absorption at $\lambda < 1216\,(1+z_q)$ Å; it traces baryons, which in turn trace dark matter

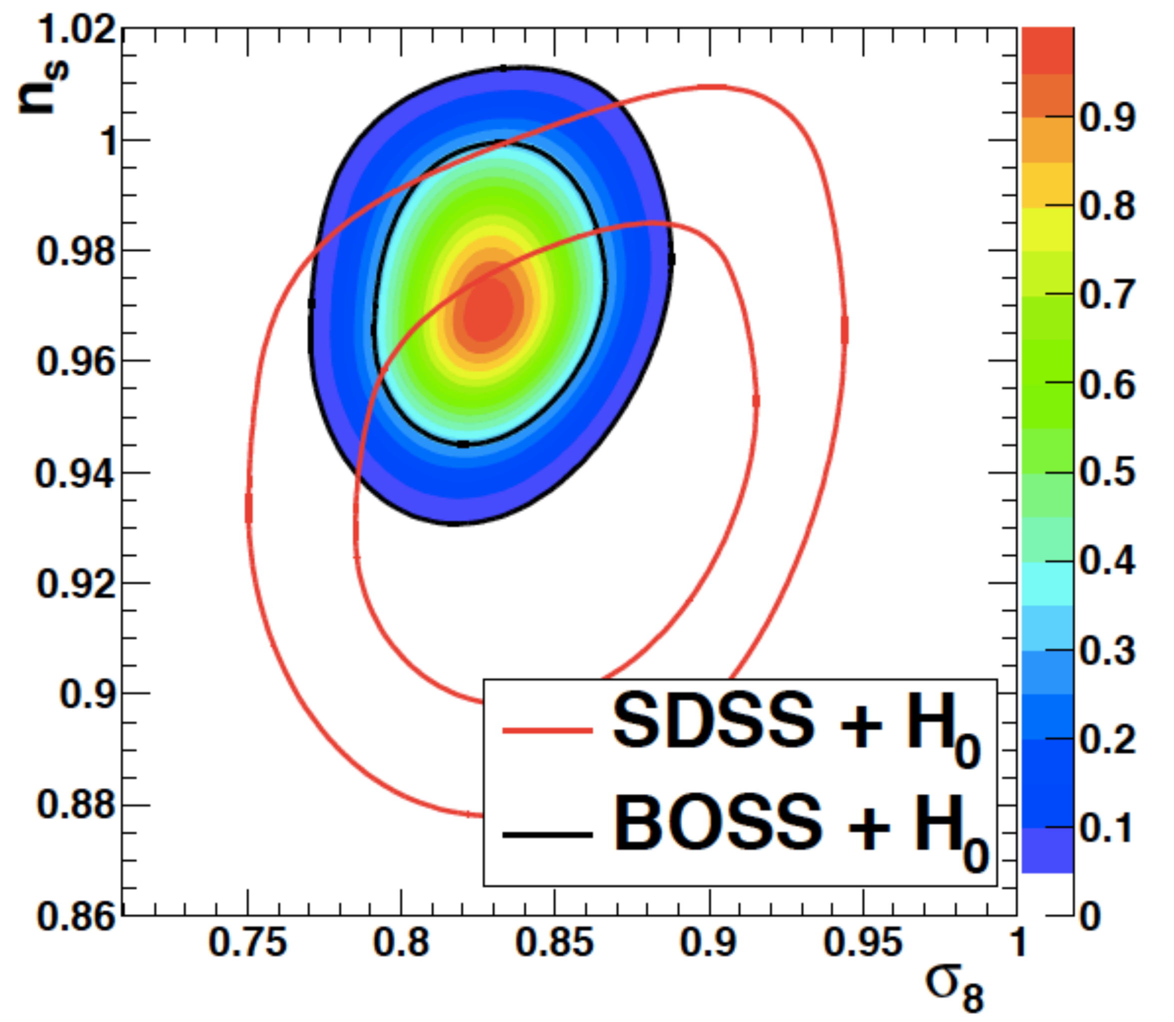





WDM is a worse fit to the data

# SDSS-III/BOSS and SDSS results

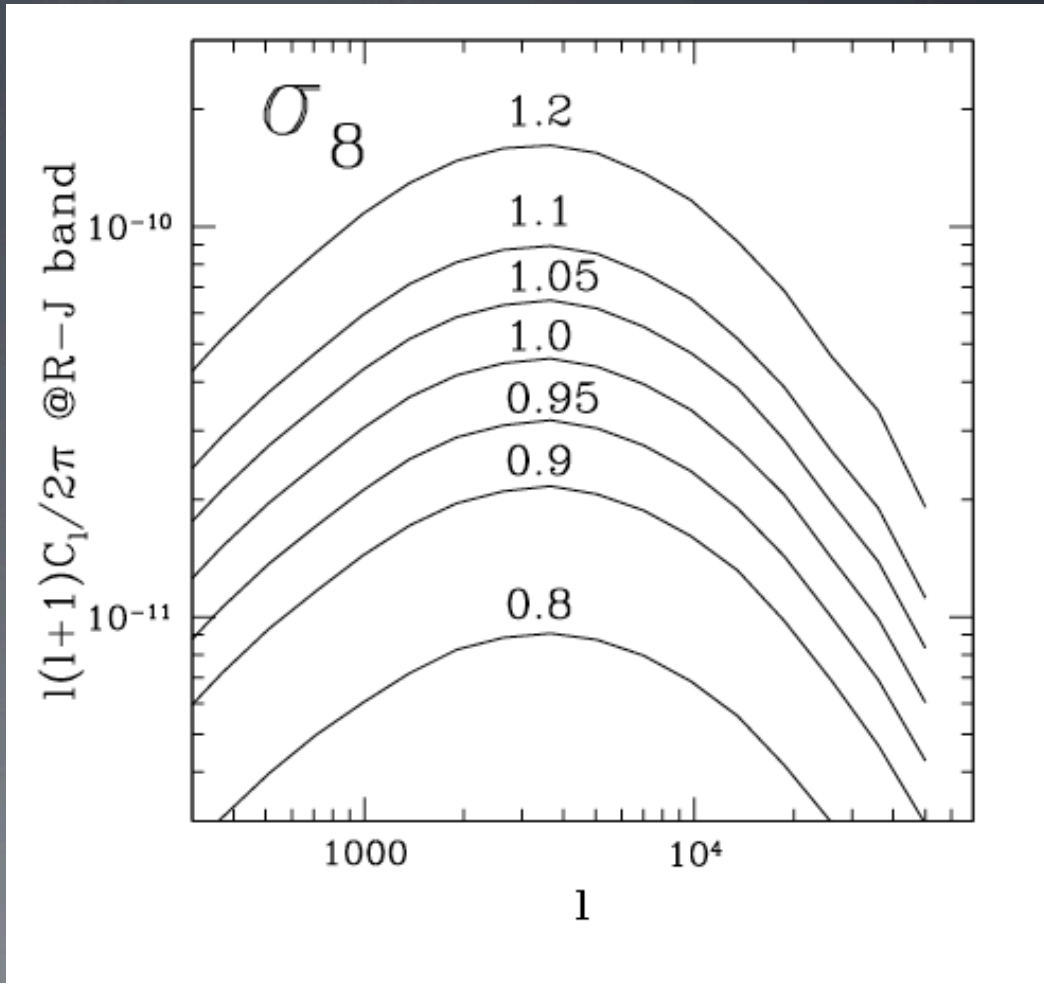
- SDSS: McDonald etal (2005)
- BOSS: Palanque-Dellabruille et al (2013)



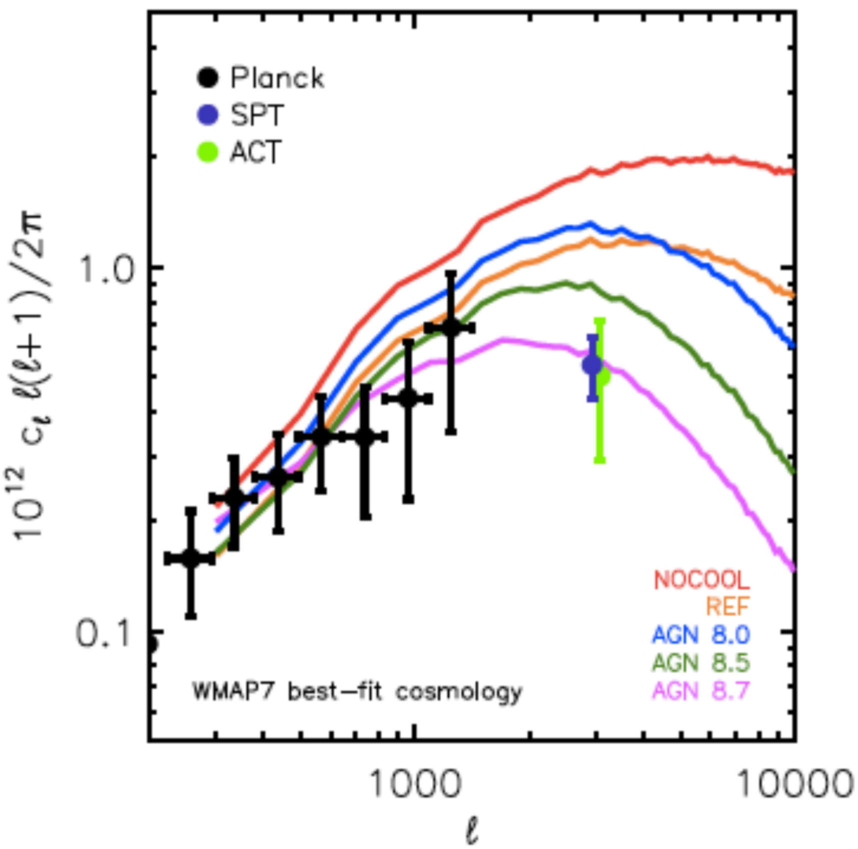
# Sunyaev-Zeldovich effect

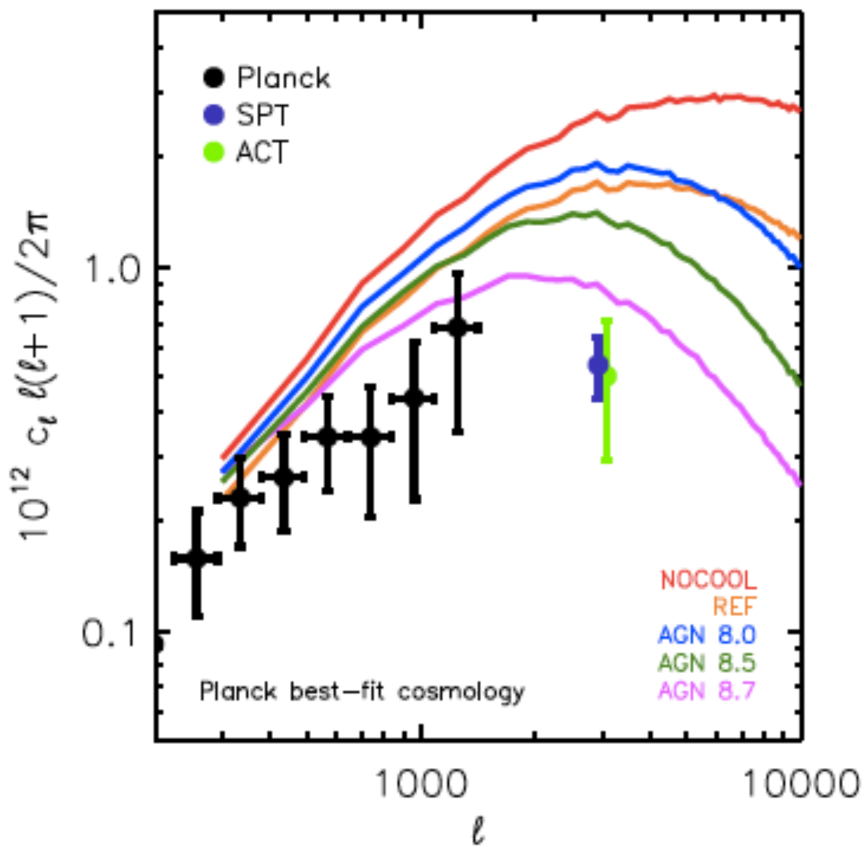
- Traces gas pressure in clusters
- Can do cluster abundance or tSZ power spectrum
- tSZ C(l) very sensitive to amplitude $\sigma_8^8$
- Some astrophysical uncertainty, but small at low l

Komatsu & Seljak 2003

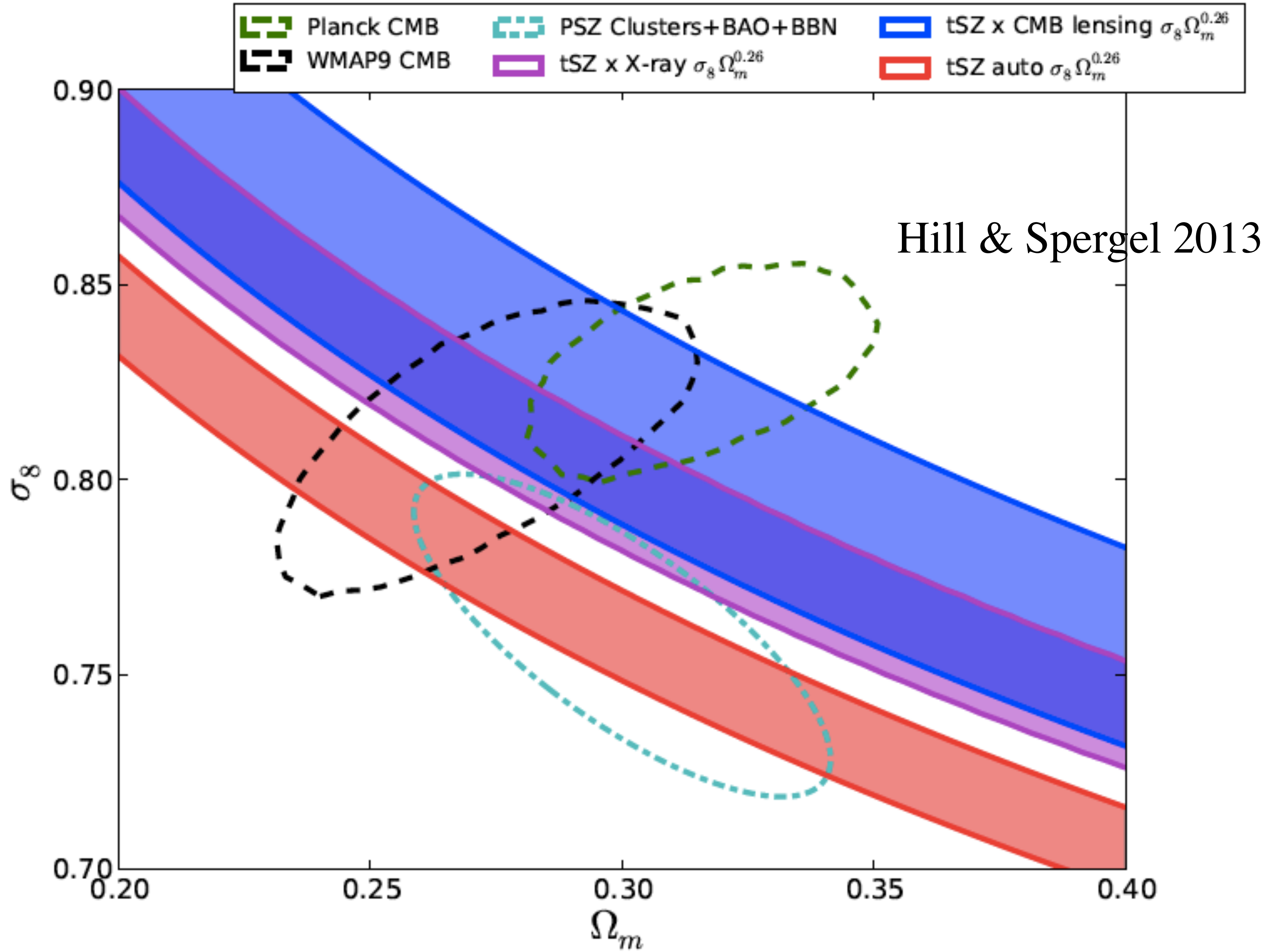


# Planck results vs simulations




Data: Planck paper 21, ACT+SPT, simulations: McCarthy etal 2013
tSZ $C_l$ could be underestimated by 20% due to CIB uncertainty



Planck CMB
WMAP9 CMB
PSZ Clusters+BAO+BBN
tSZ x X-ray $\sigma_8 \Omega_m^{0.26}$
tSZ x CMB lensing $\sigma_8 \Omega_m^{0.26}$
tSZ auto $\sigma_8 \Omega_m^{0.26}$
Hill & Spergel 2013
0.90
0.85
0.80
0.75
0.70
$\sigma_8$
0.20
0.25
0.30
0.35
0.40
$\Omega_m$

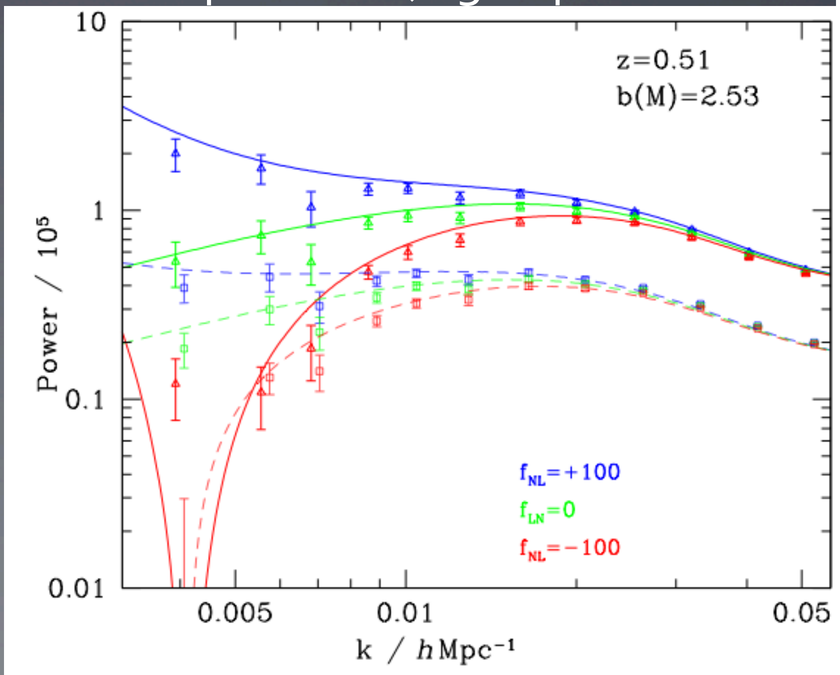
# Summary of LSS

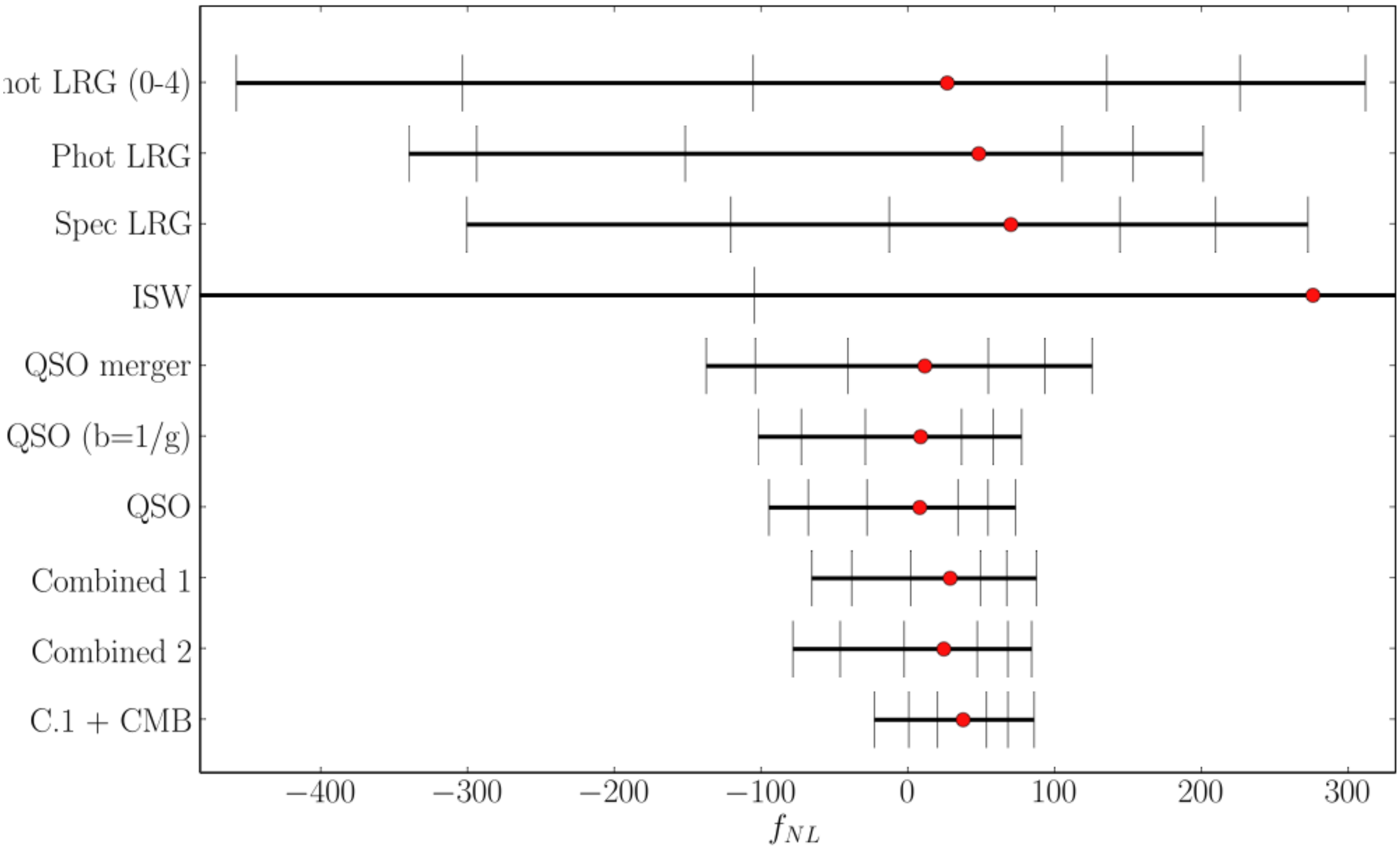
- BAO+CMB determines matter density: $\Omega_m$=0.30
- Amplitude of fluctuations at z<1 determined by several probes: some reaching 2% precision (CMB WL, tSZ $C_l$, Lya)
- Some are high, some are low, but a remarkable agreement at $\sigma_8$=0.80 (ignoring a few outliers for good reasons)
- No evidence of neutrino mass yet: $\Sigma m_\nu$<0.20eV (95%)
- So what is next?

# Primordial non-gaussianity

- Local model $$\Phi(x) = \Phi_G(x) + f_{NL}\Phi_G^2(x)$$
- Simple single field slow roll inflation predicts $f_{nl} << 1$
- Inflationary models beyond single field slow roll can give $f_{nl} >> 1$
- Alternatives to inflation generically give $f_{nl} >> 1$?
- Other models give different angular dependence of bispectrum (e.g. equilateral in DBI model, Silverstein…)
- Scale dependent bias (Dalal etal 2008)

$$b_{f_{nl}} \propto f_{nl}(b-1)k^{-2}T(k)$$





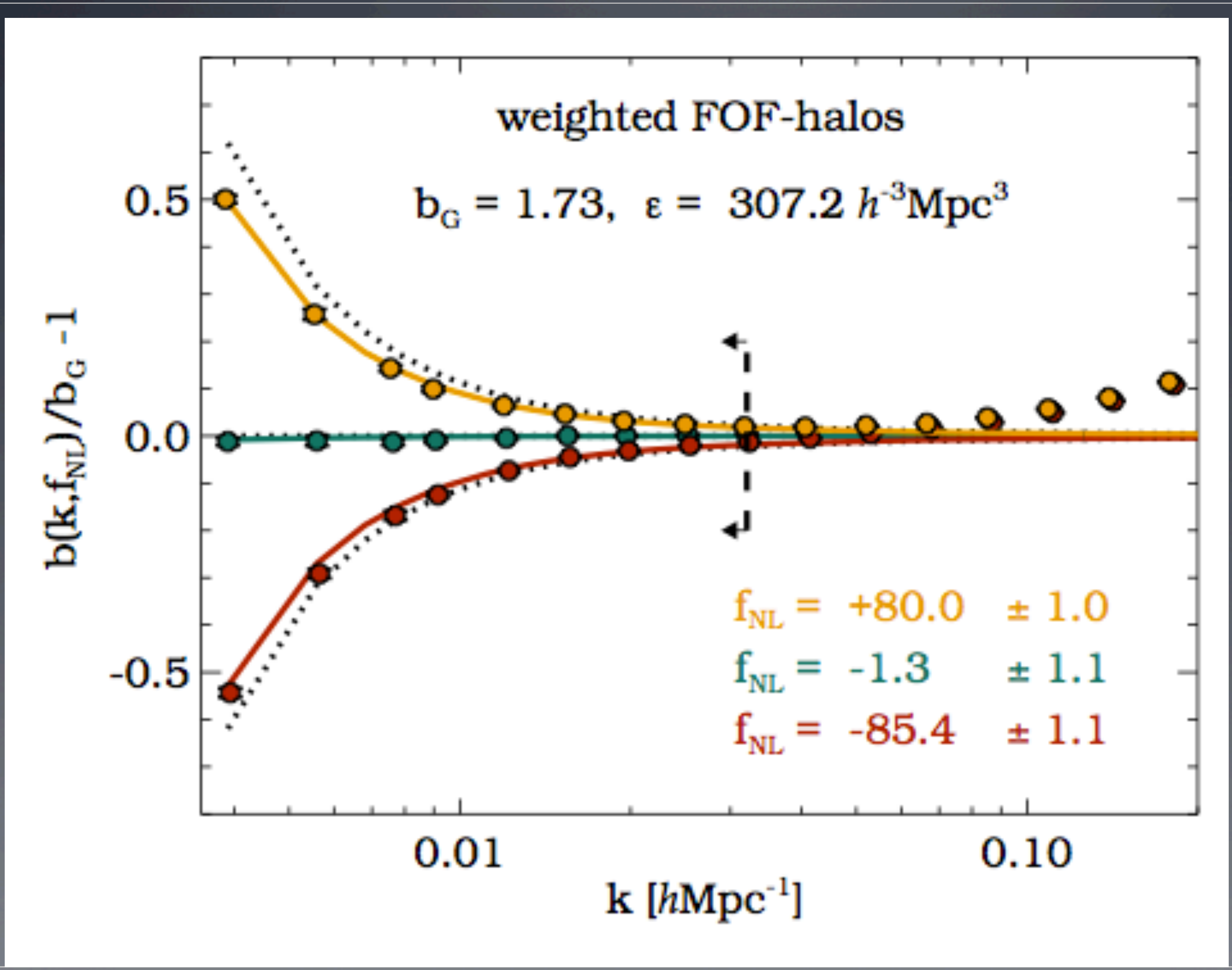

$$-29 < f_{nl} < 70 (95\% cl)$$

Planck limits better: 3+/-6

Slosar, Hirata, US etal, 2008

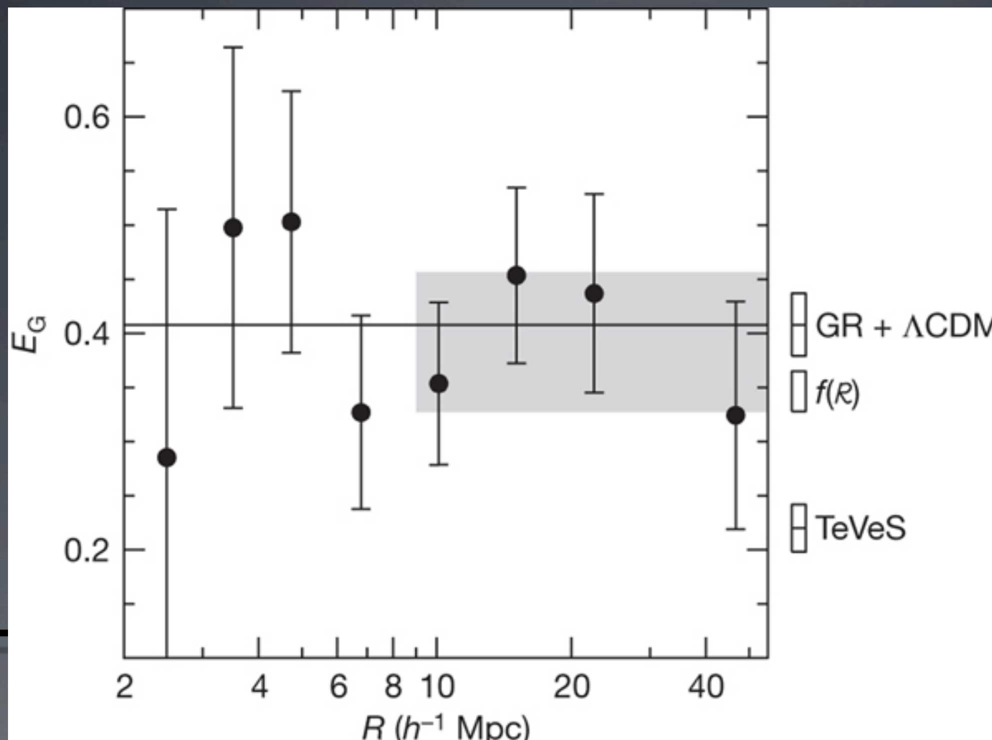
# $f_{nl}$ with several tracers

Hamaus, US, Desjacques 2011




Future surveys (DESI, Euclid) could reach $f_{nl}$ around 1

# Combining RSD with weak lensing: modified gravity tests



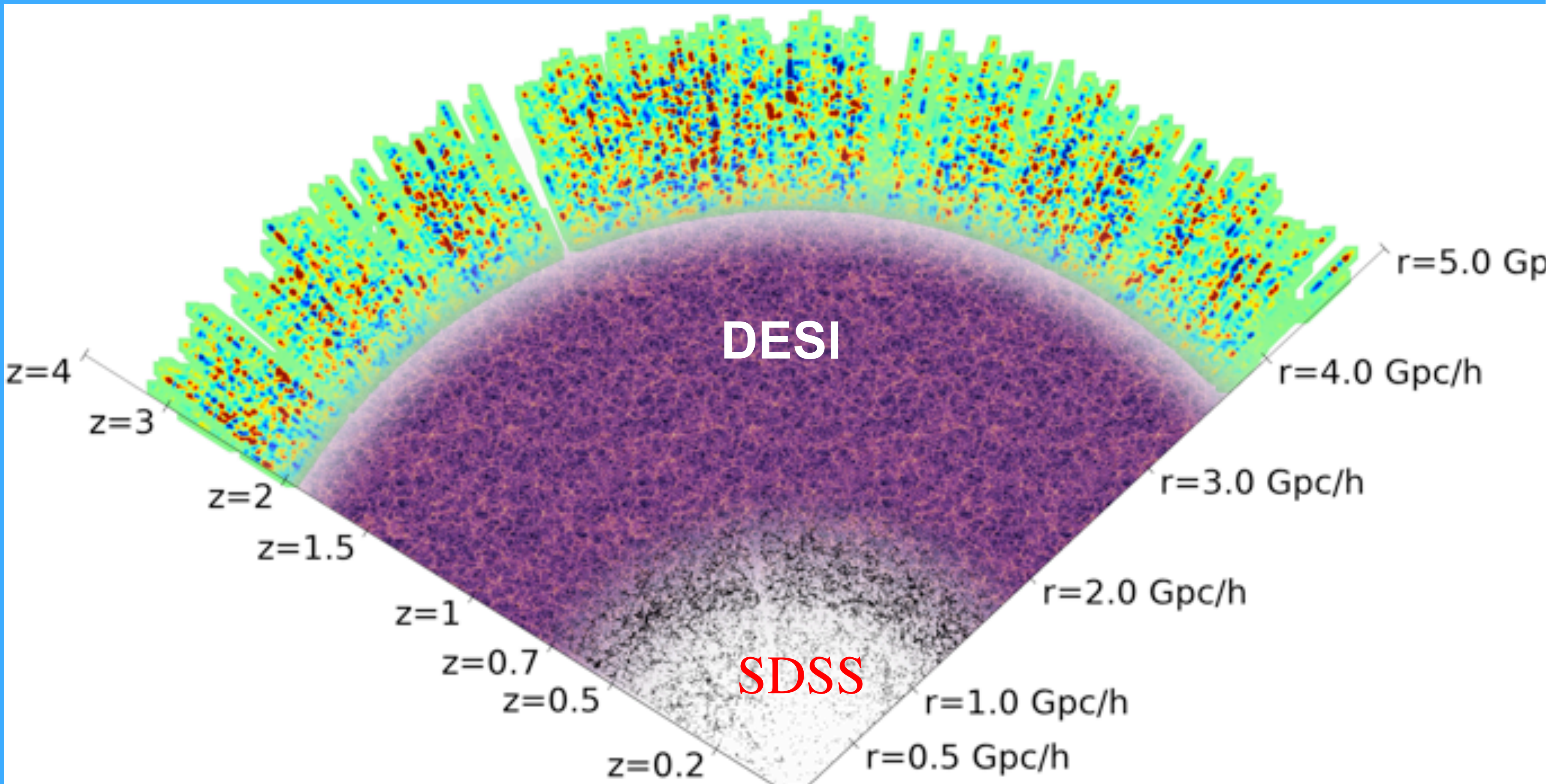

R Reyes *et al.* *Nature* **464**, 256-258 (2010) doi:10.1038/nature08857

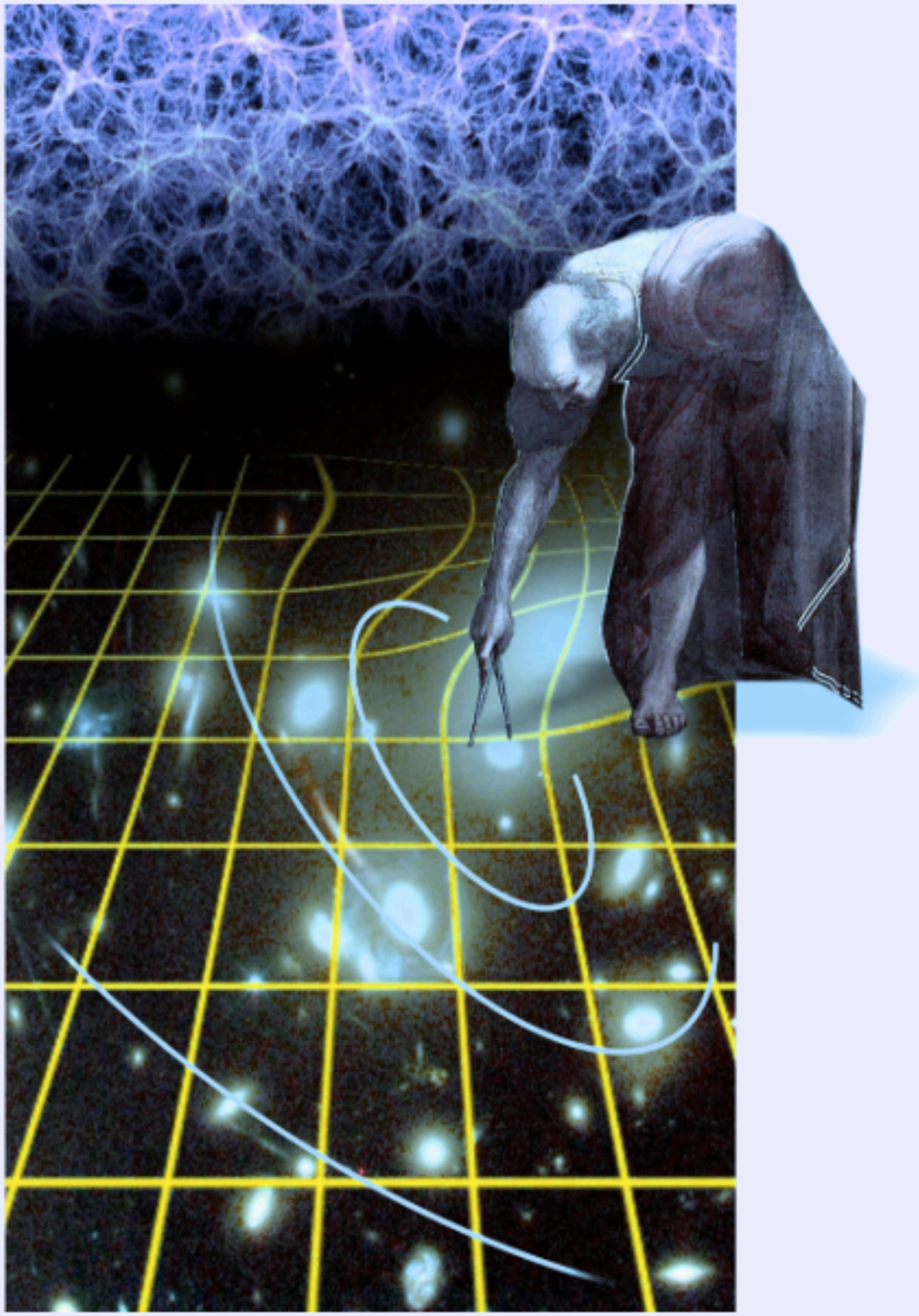
First detection 6 sigma, with BOSS/SDSS-III 25 sigma

nature

# Future redshift surveys: DESI, Euclid, WFIRST…

Plan: measure $10^7$ redshifts
Promise: detection of neutrino mass, unprecedented dark energy equation of state





# Future WL surveys: DES, HSC, Euclid, LSST…

Plan: $10^8$-$10^9$ galaxies (without redshifts)

LSS surveys will continue to produce new results

# Conclusions

- LSS surveys powerful probe of cosmology: dark energy, inflation, neutrino mass…
- Weak lensing and galaxy clustering (RSD) complementary
- Enormous observational progress in recent years: CMB WL, tSZ…
- Recent galaxy clustering results from SDSS III: BAO to 1%, amplitude to 6%
- Recent WL result from CFHT-LS, SDSS: amplitude to 3-6%
- CMB WL: amplitude at 2%, tSZ $C_l$ also 2%, Lya P(k) also 2%
- in combination there is a remarkable consistency of most probes
- Future LSS surveys: huge efforts, 2 planned satellites, numerous ground based efforts, up to an order of magnitude improvements over current constraints