Cosmic observations

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LBNL/UC Berkeley
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Dark matter in cosmology

What can we learn about the dark matter from cosmology:

Density of dark matter

dark matter temperature: hot, warm or cold?

Neutrino contribution to dark matter

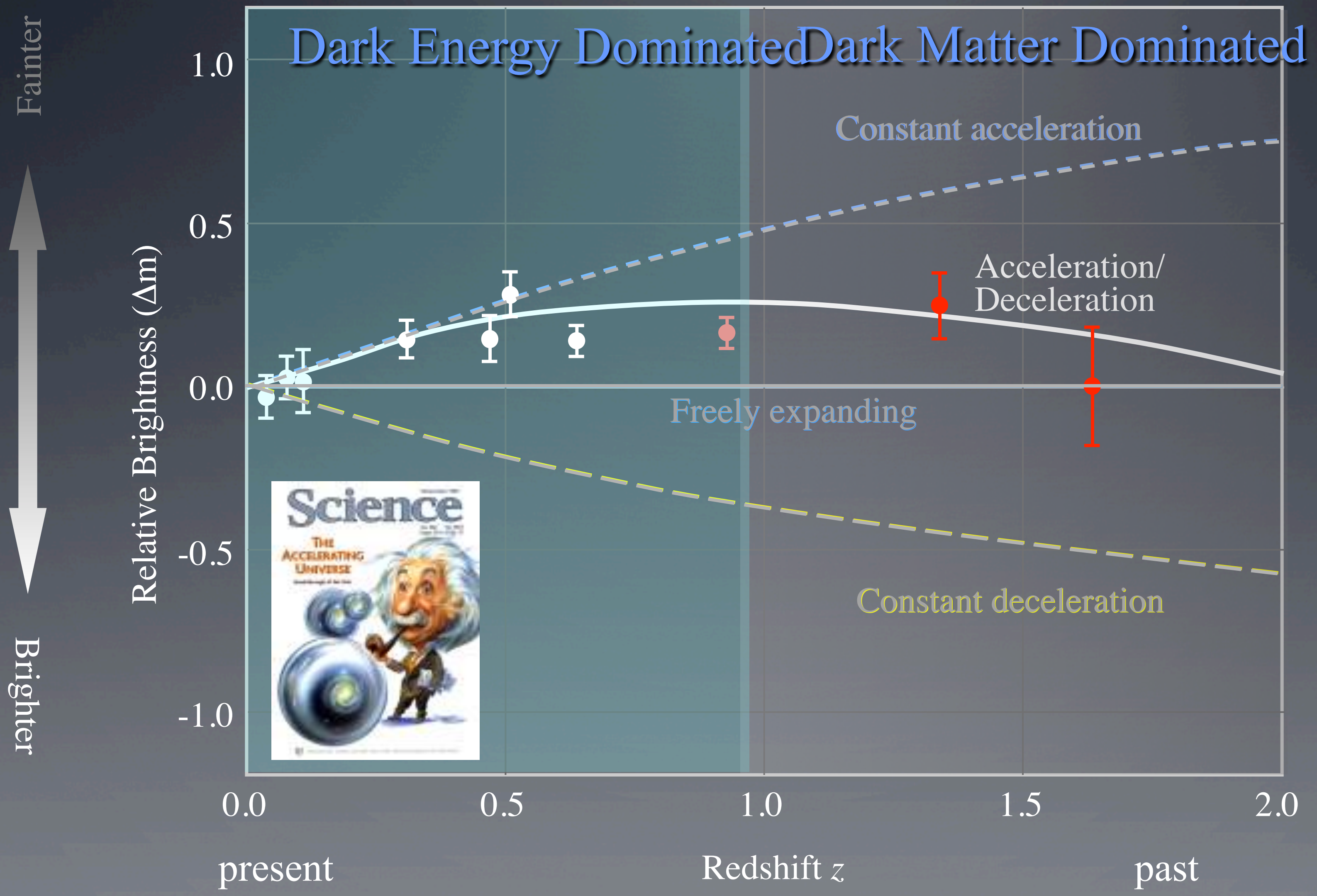
Interactions with other sectors and self-interactions

Large scale structure of the universe and cosmic microwave background can say something about all the dark matter

How to learn about dark matter using large scale structure?

1) Classical test: redshift-distance relation: Sne, baryonic acoustic oscillations (BAO): CMB + galaxy clustering+Lya
2) Growth of structure: CMB, Ly-alpha, weak lensing, clusters, galaxy clustering, Sunyaev-Zeldovich effect
3) Scale dependence of structure (same tracers as above)

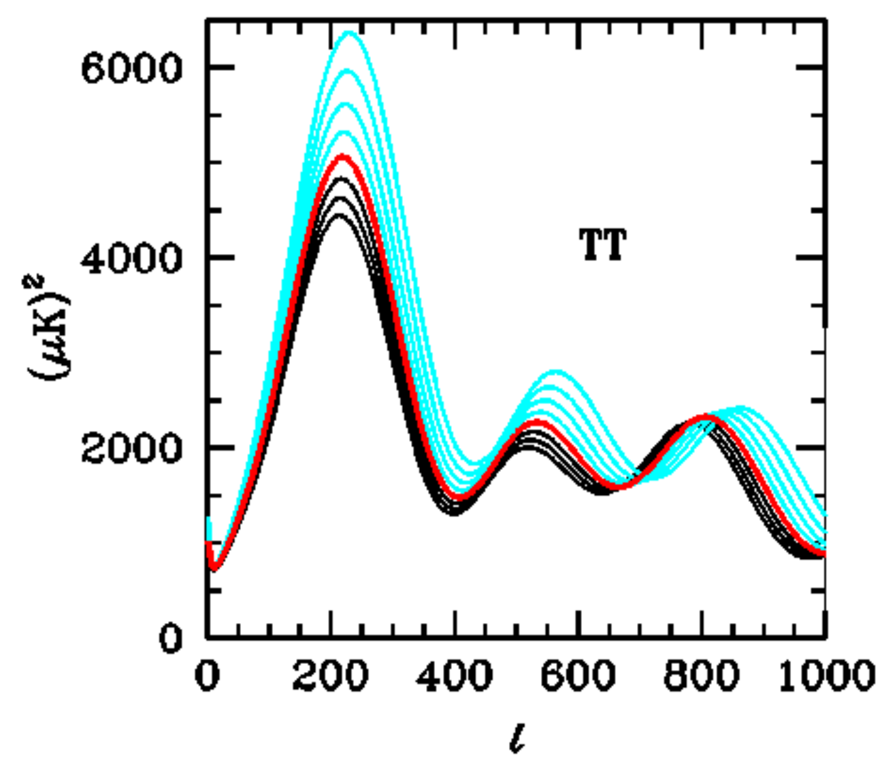
Supernovae measure dark matter density



Matter density from CMB

Sensitive to matter to radiation ratio: lowering the ratio takes us more into radiation domination at z=1100: feedback effects enhance CMB anisotropies

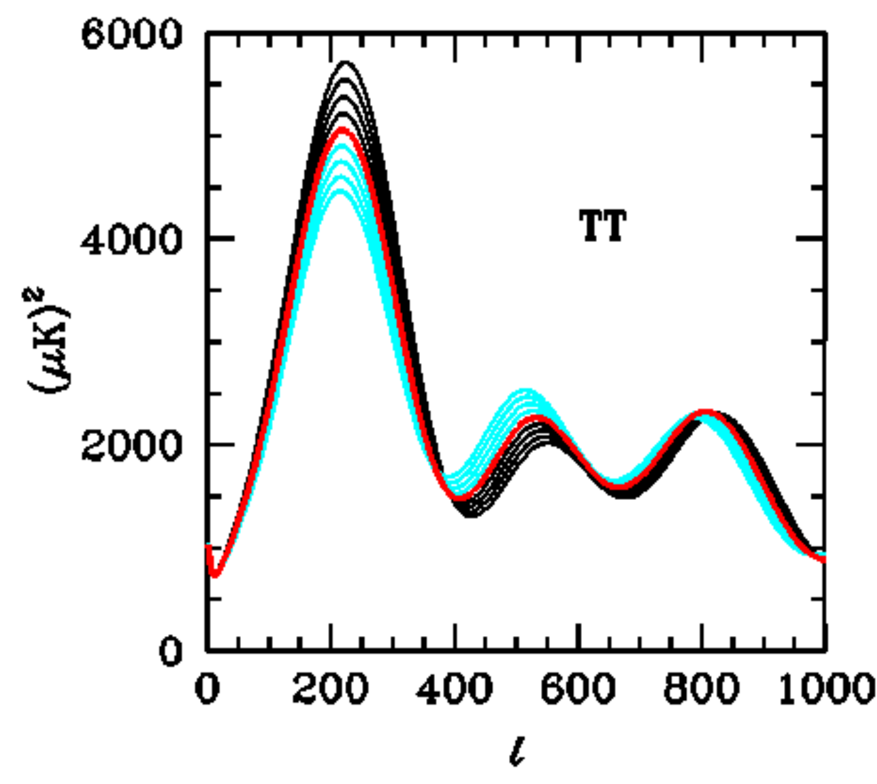
$\Omega_m h^2 = 0.16,..,0.33$



Baryon density from CMB

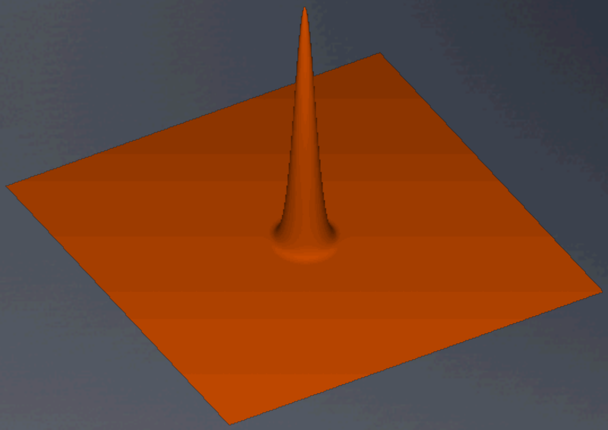
Baryon Density changes the structire of even-odd BAO peaks

$\Omega_b h^2 = 0.015, 0.017..0.031$



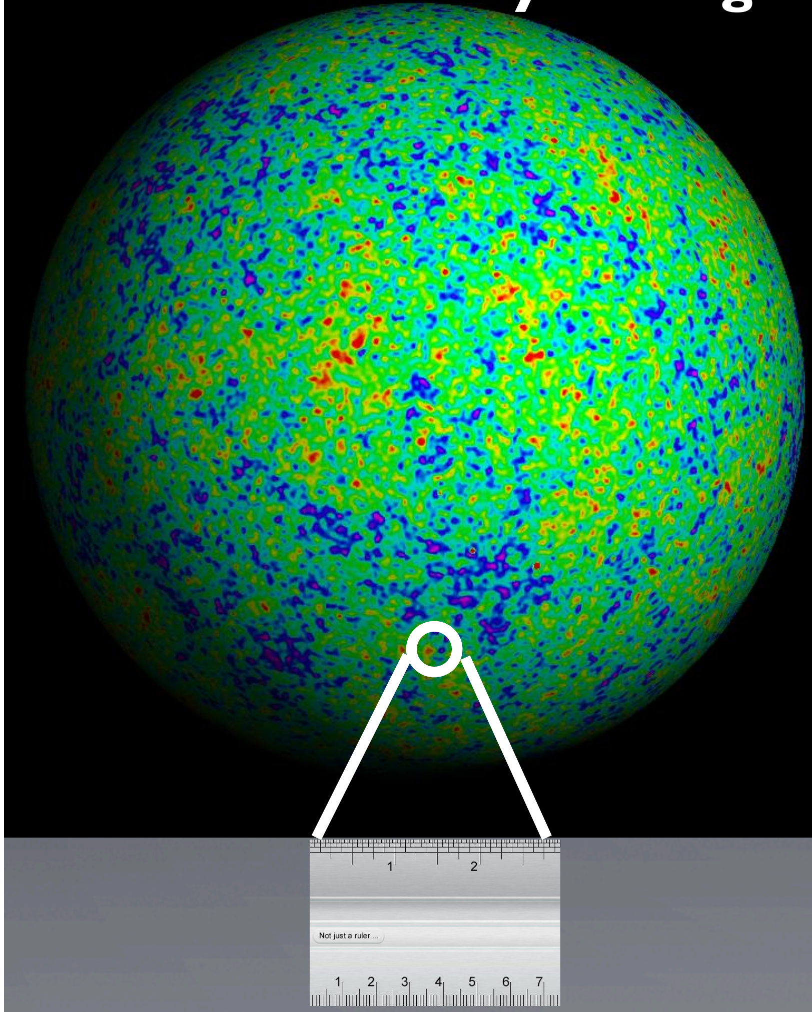
1) BAO: sound waves

- 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.

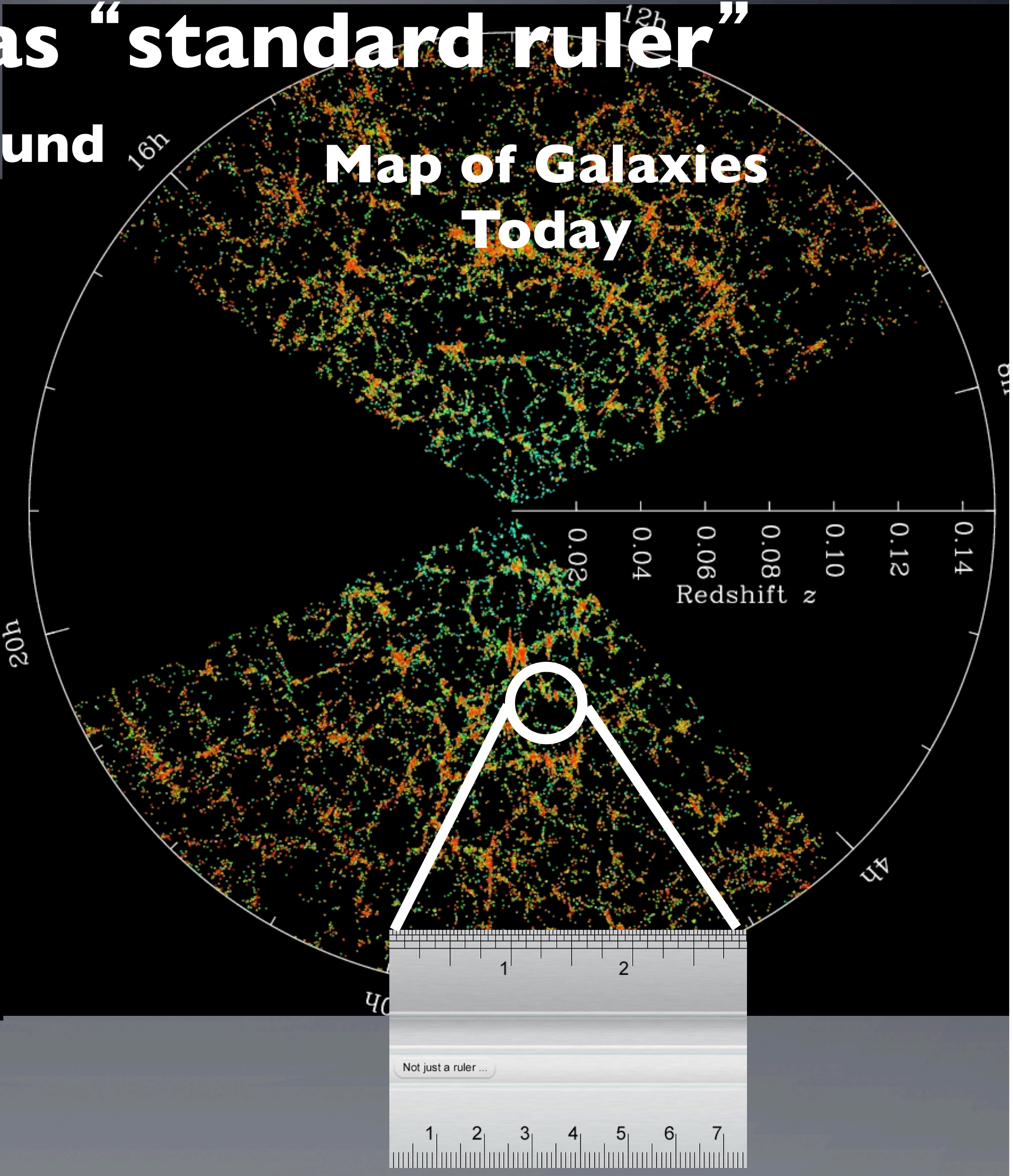


Sound waves as “standard ruler”

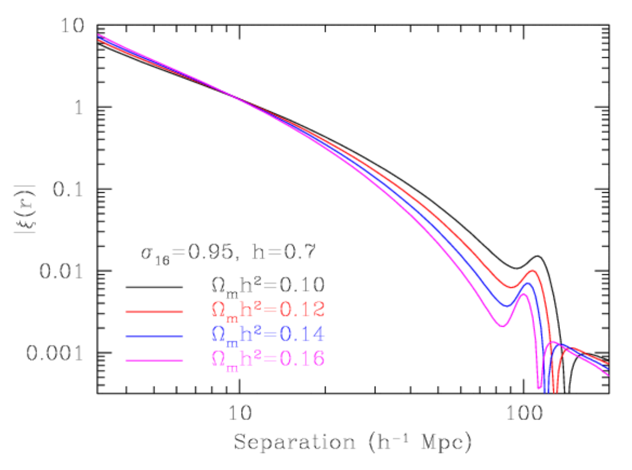
Cosmic Microwave Background
14 billion years ago



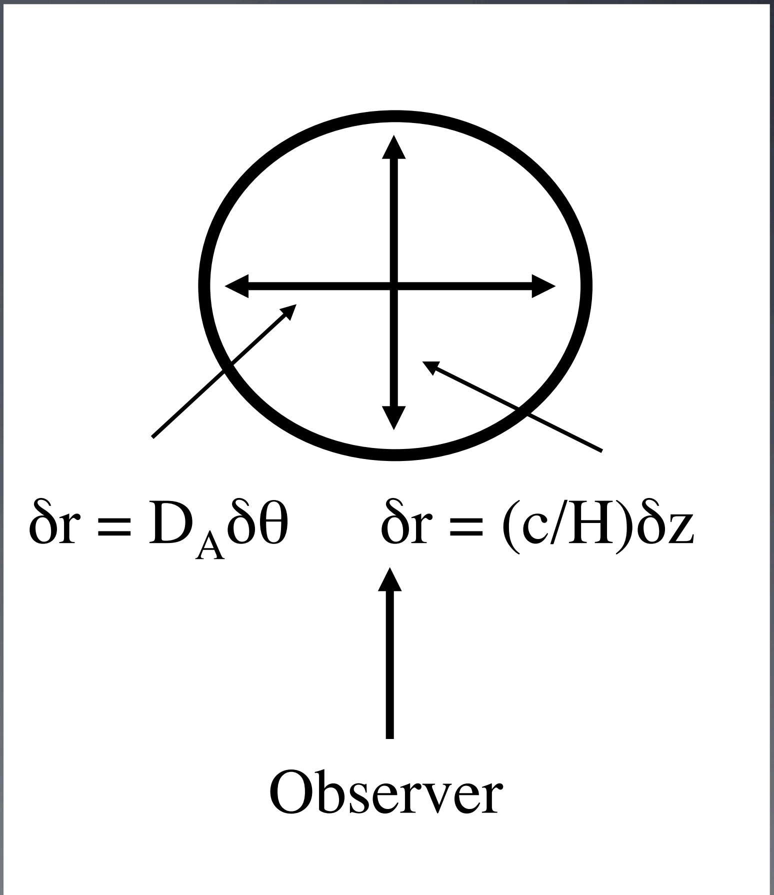
Map of Galaxies
Today



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 $D_A(z)$!

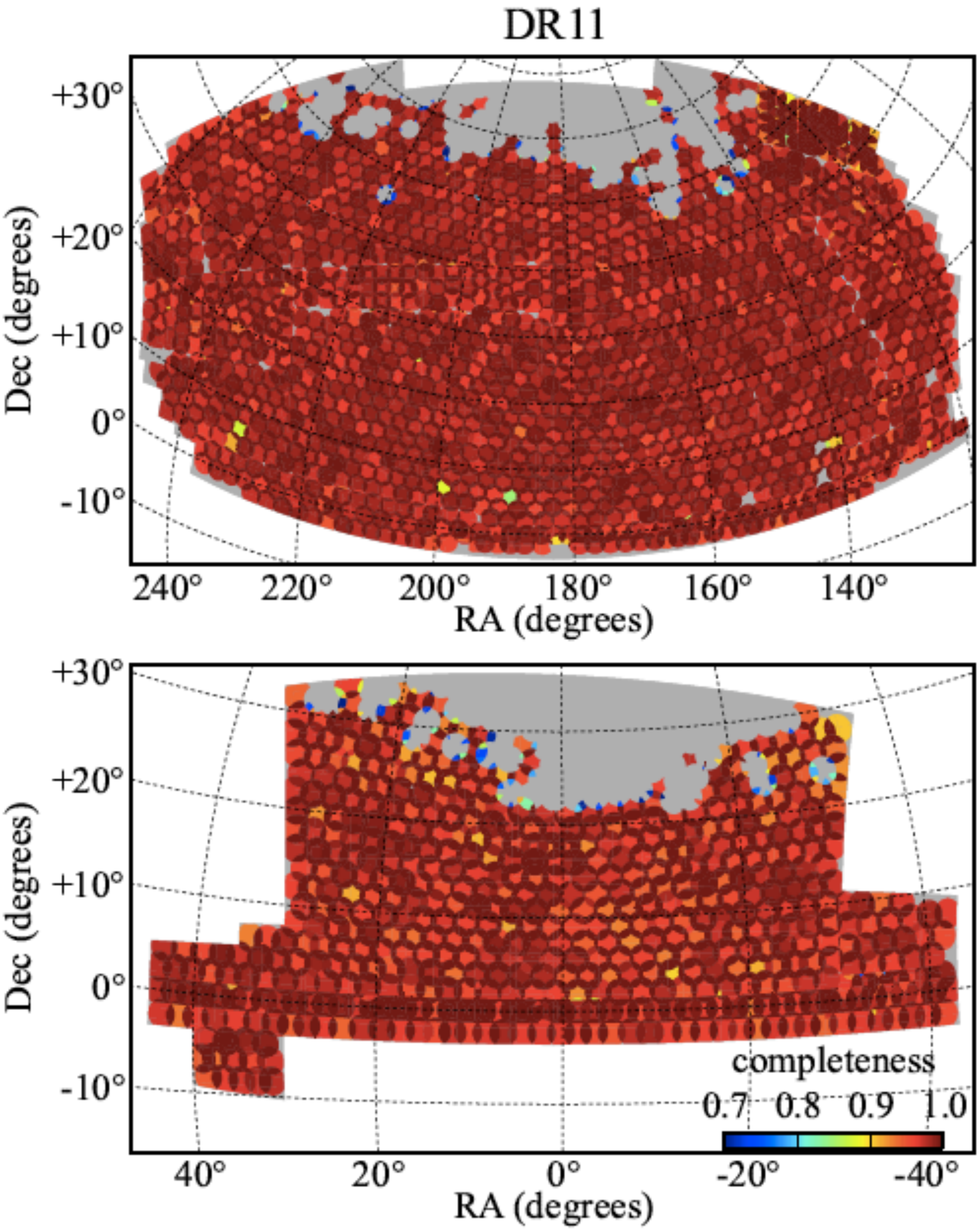


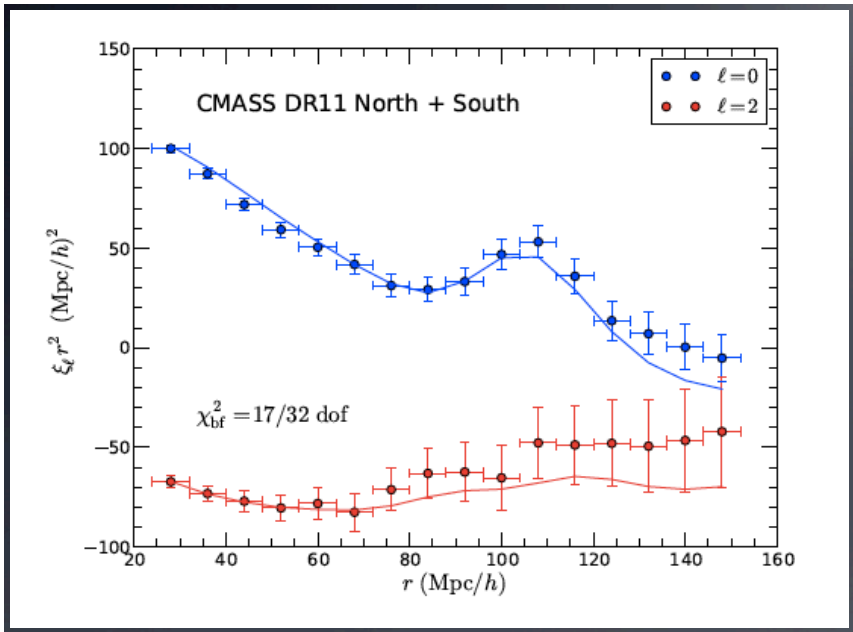
$\delta r = D_A \delta\theta$ $\delta r = (c/H)\delta z$

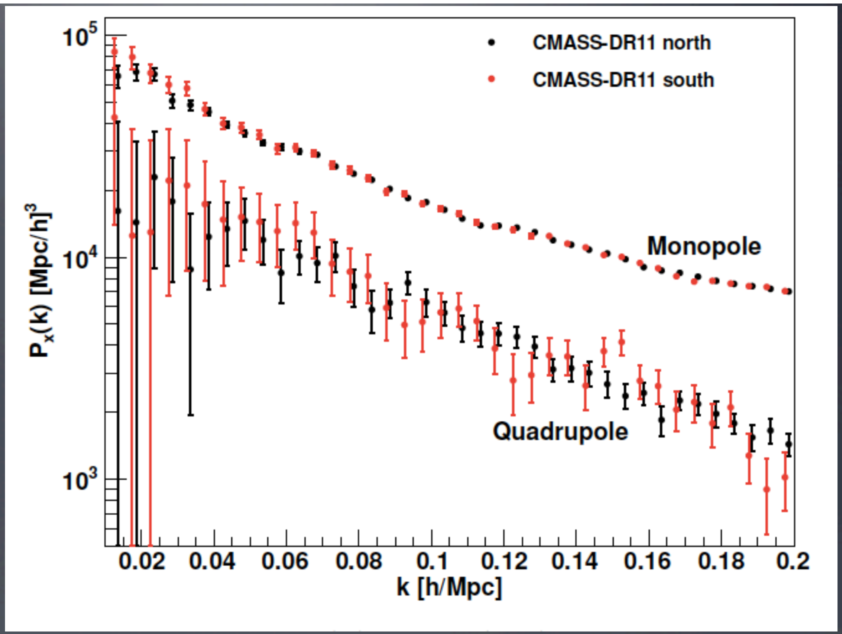
Observer

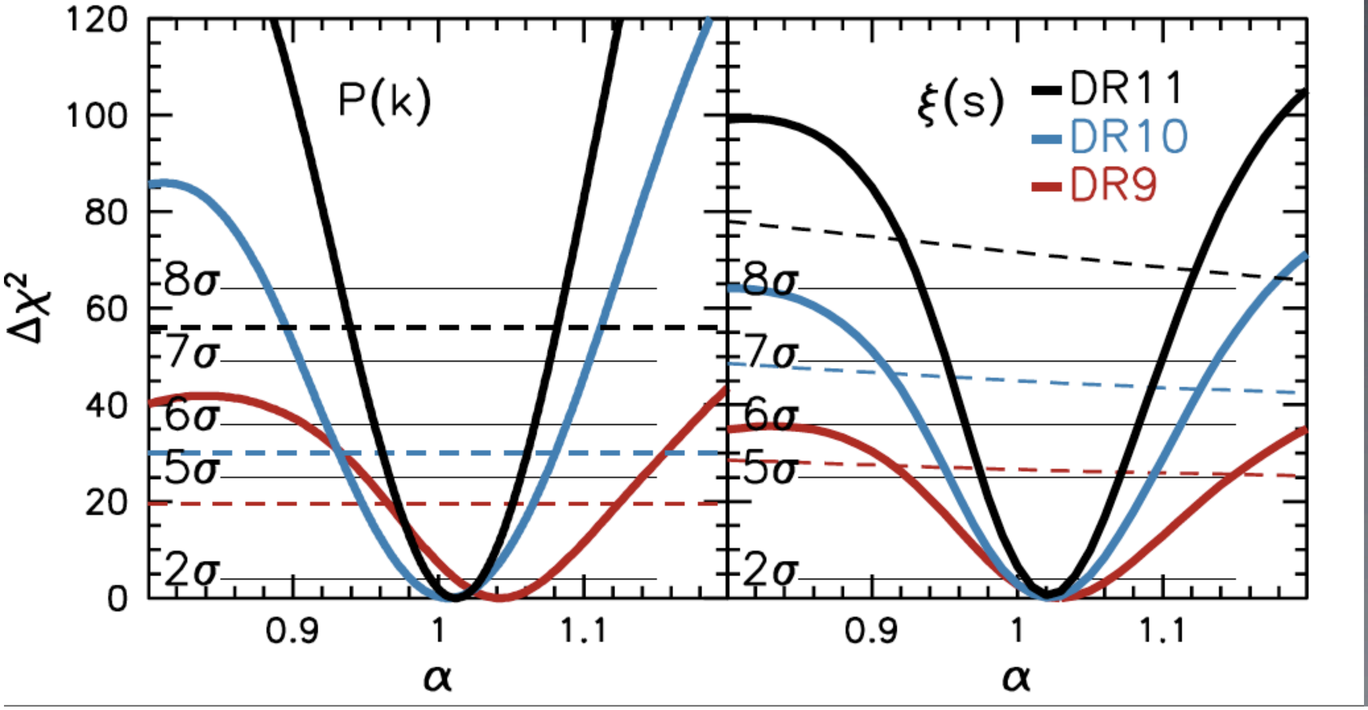
State of the art: SDSS III (aka BOSS) DR11 CMASS
1.3M redshifts over 9000 square degrees

BOSS officially completed the survey ahead of schedule: DR12 coming out later this year



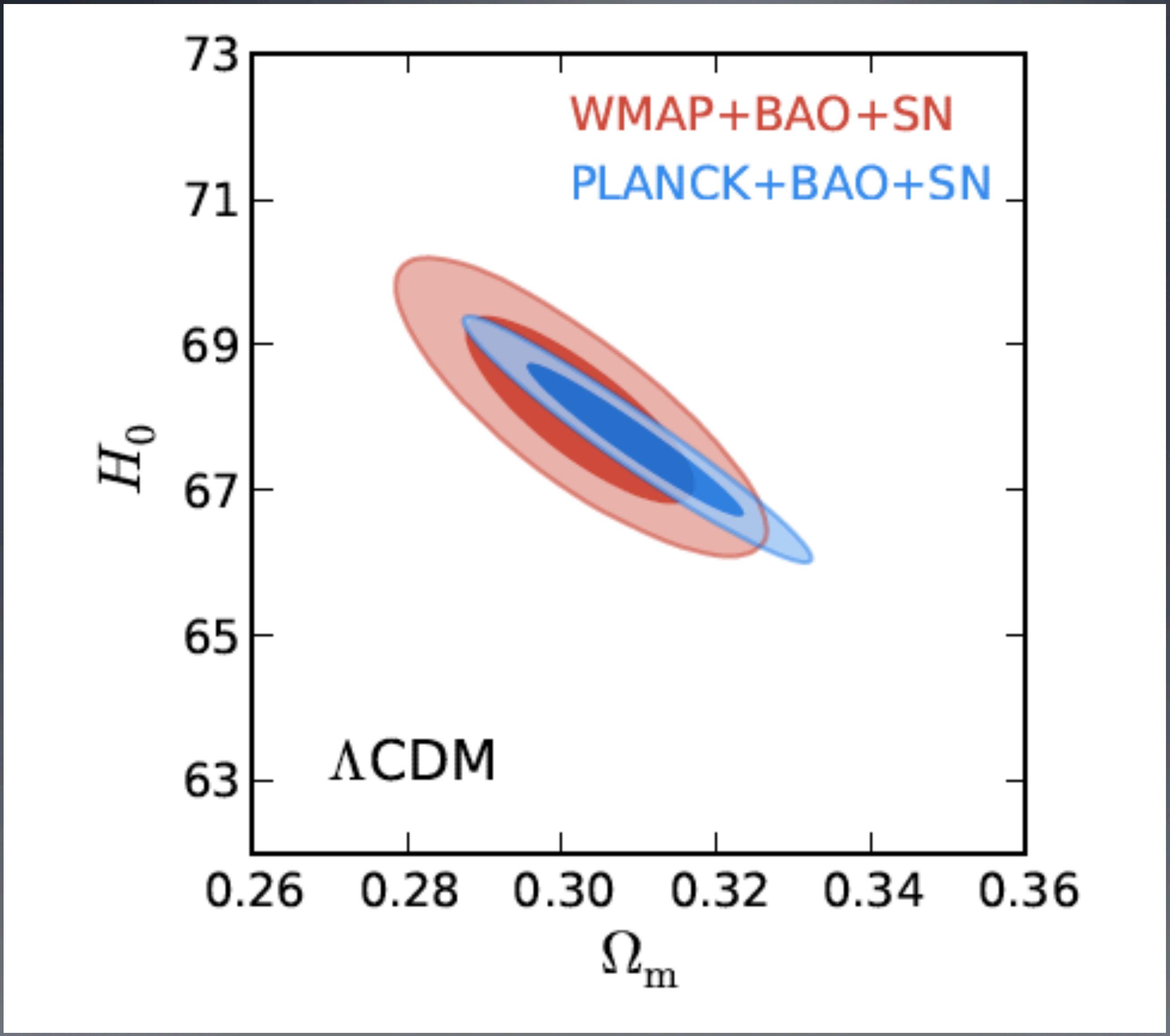






With SDSS DR11 BAO distance scale measured to 1%

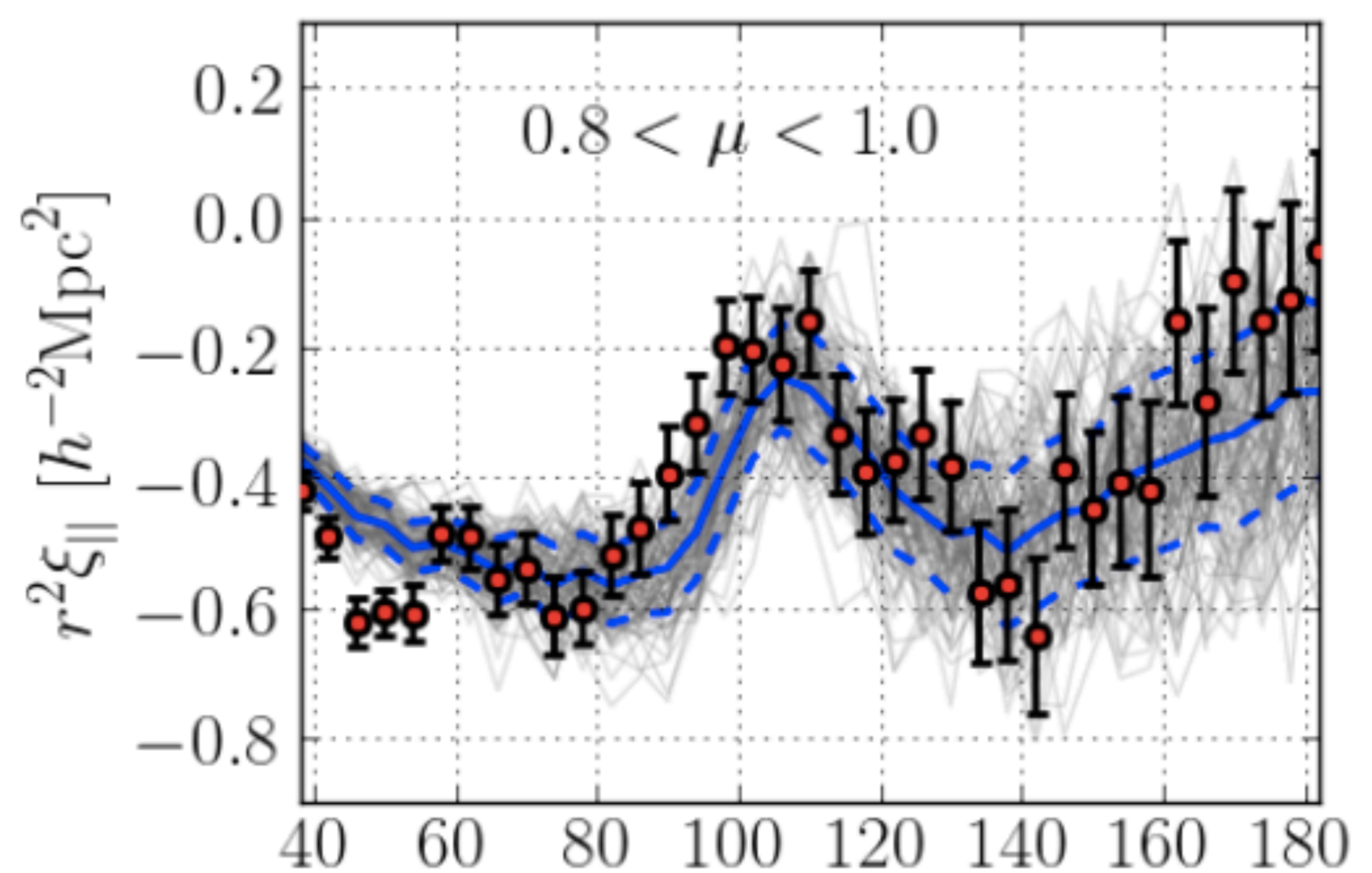
LambdaCDM fits well (w=-1+/-0.07)



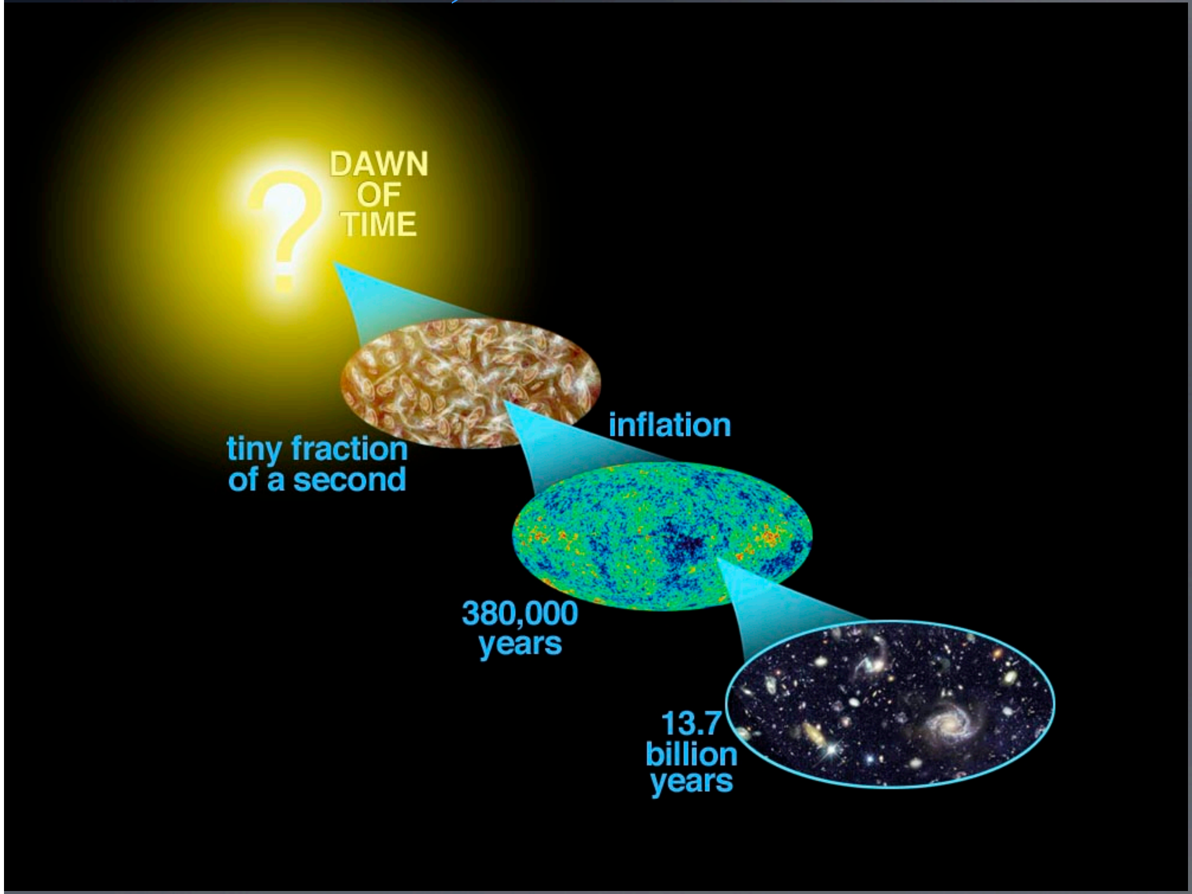
DR11: Anderson et al 2013

BAO also detected in Lyman alpha forest

Delubac etal 2014



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…

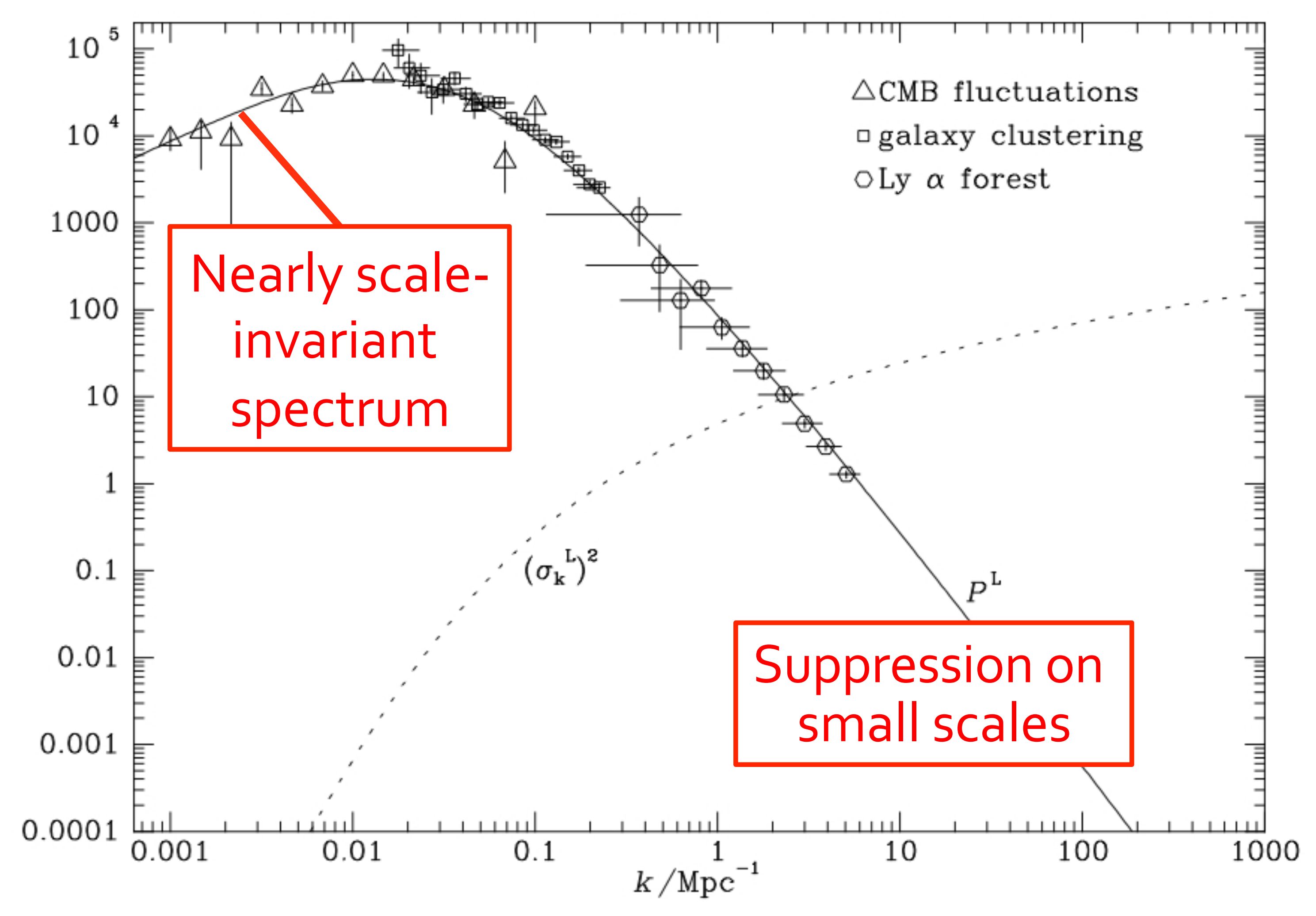
$$\ddot{\delta} + 2H\dot{\delta} = 4\pi G\bar{\rho}\delta \longrightarrow \delta(t)$$

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

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

3) Shape of matter power spectrum

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



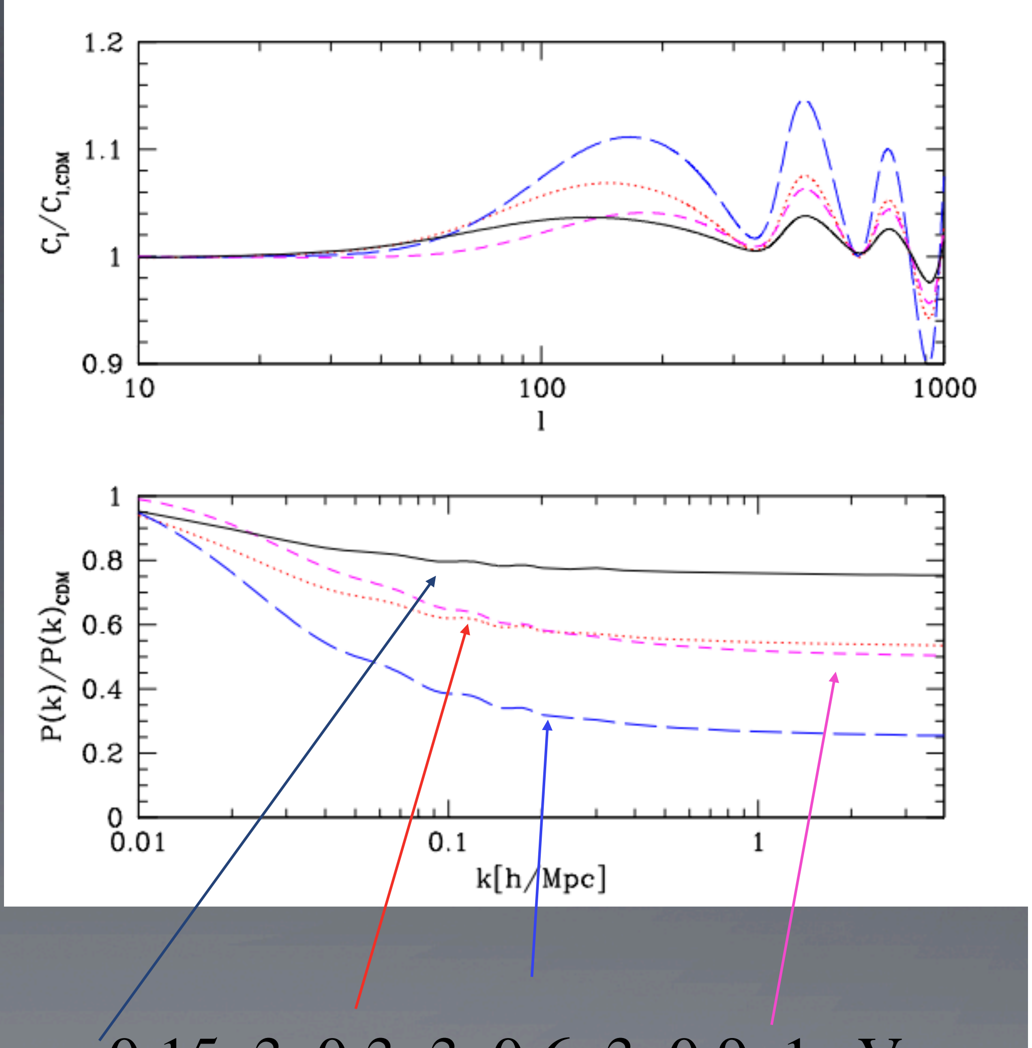
Nearly scale-invariant spectrum

Suppression on small scales

Picture from Binney & Tremaine

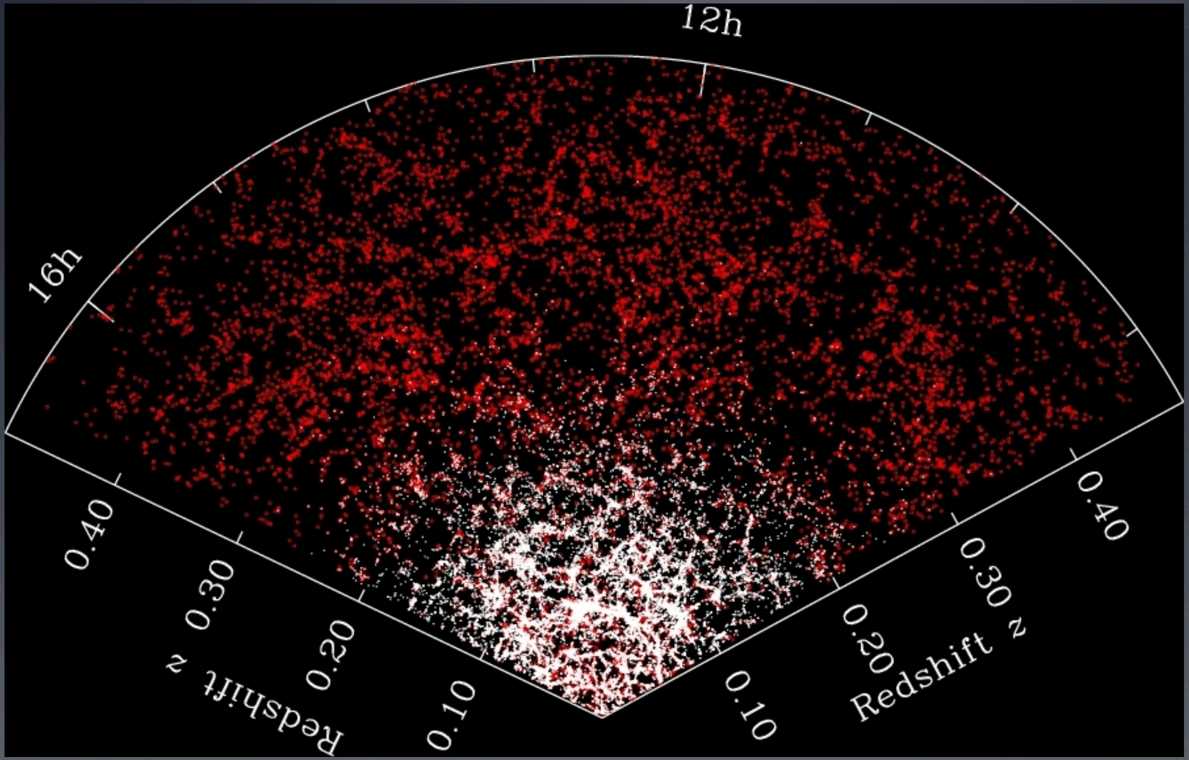
Neutrino mass can be measured by LSS

- 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



m=0.15x3, 0.3x3, 0.6x3, 0.9x1 eV

Galaxy clustering in redshift space



SDSS

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

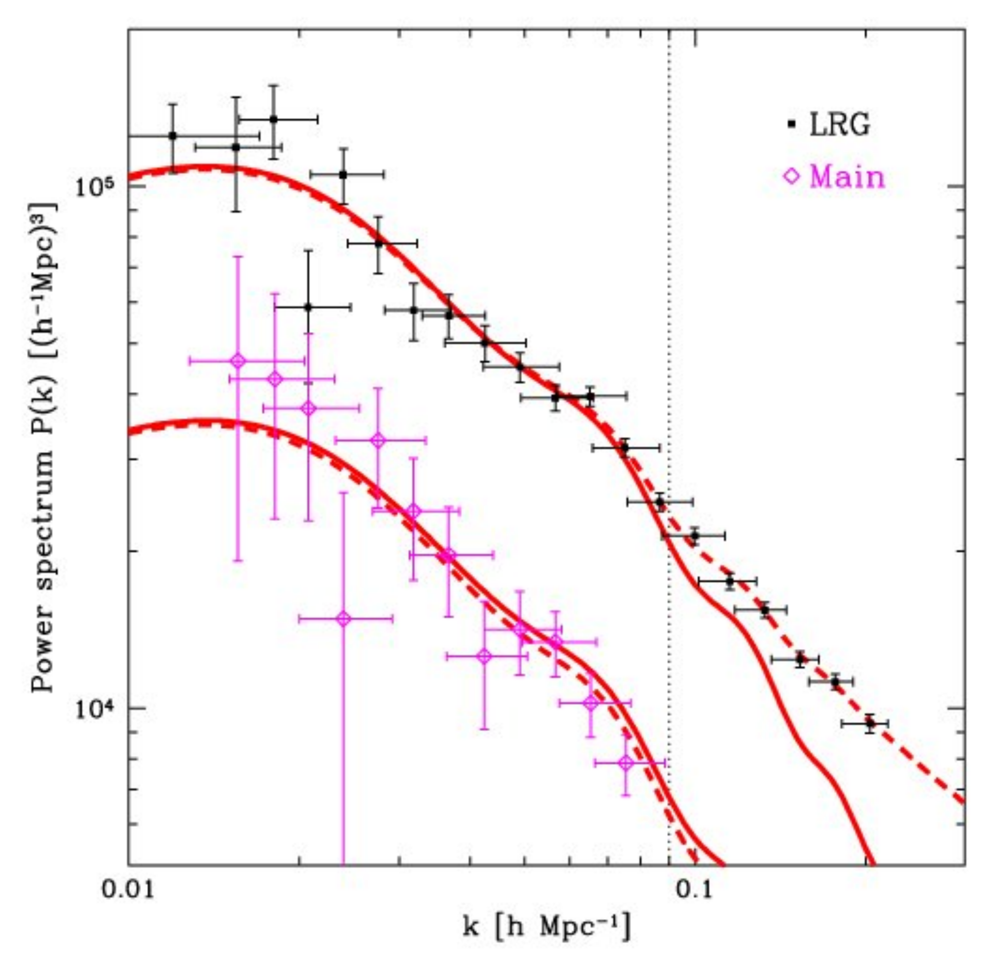
2) Easy to measure: effects of order unity, not 1%

Galaxy power spectrum: biasing

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

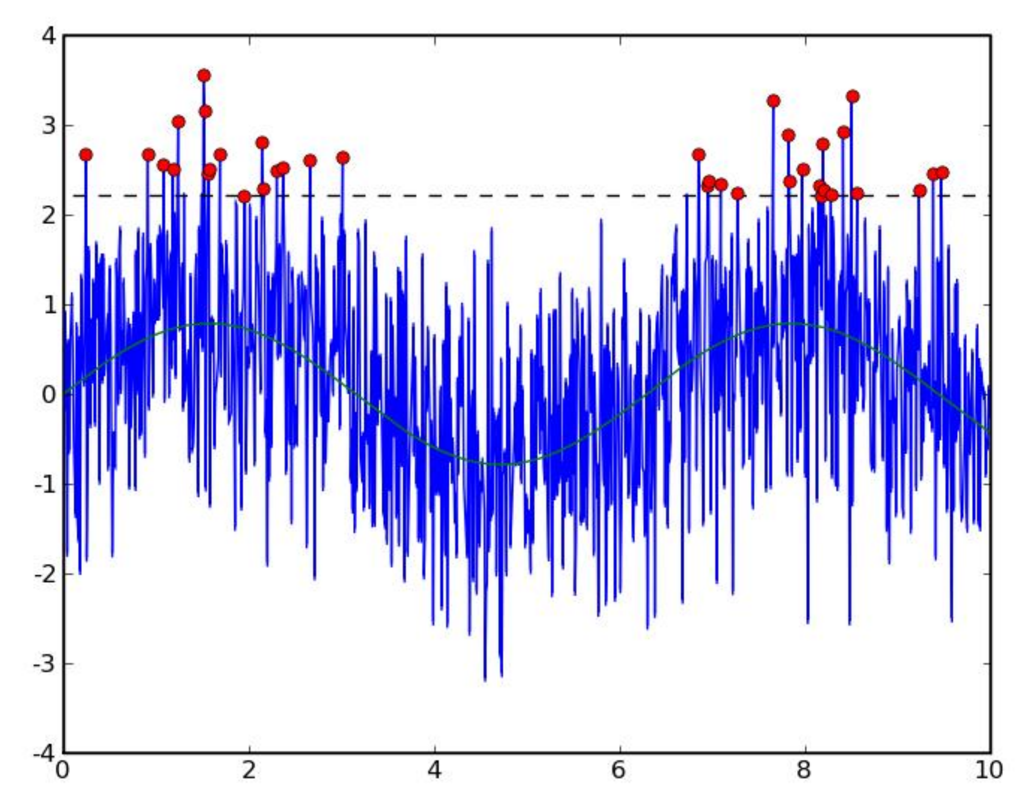
$$P_{gg}(k)=b^2(k)P_{mm}(k)$$

- 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



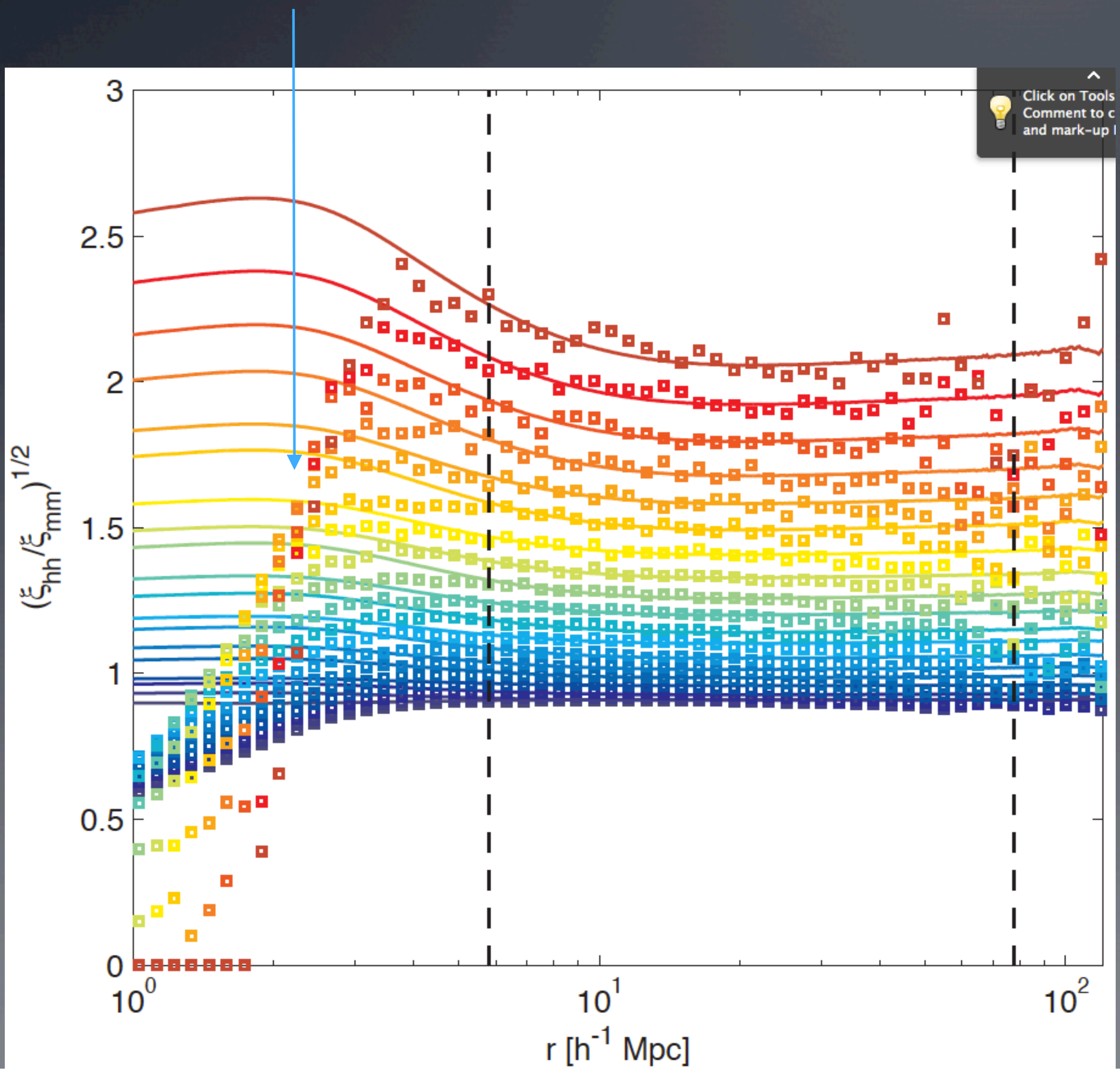
Tegmark et al. (2006)

Why are galaxies biased?
Galaxies form at high density peaks of initial density:
rare peaks are more strongly clustered



The enhancement depends on the halo mass function slope

Simulations: bias is scale dependent


Halo exclusion

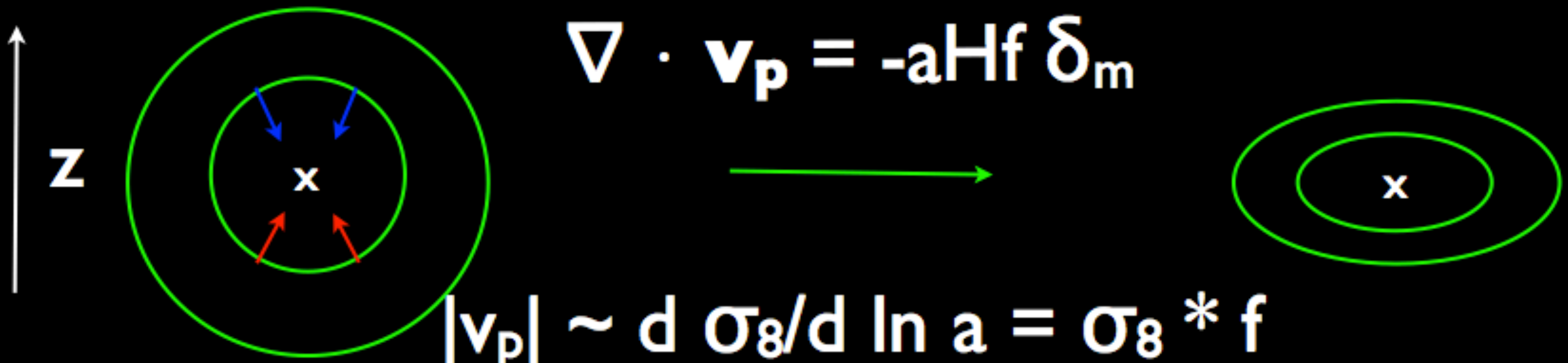
Lines are theoretical local bias model with 2 free parameters

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

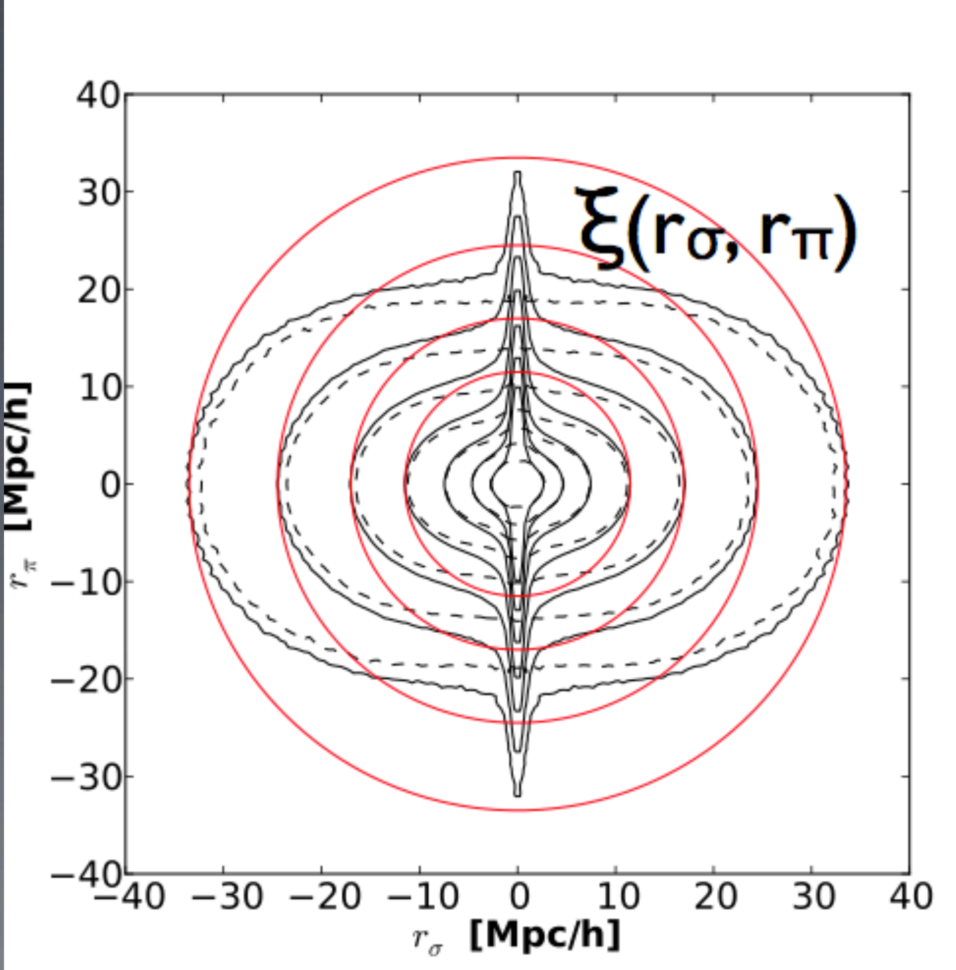
On very large scales linear RSD distortions:

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

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

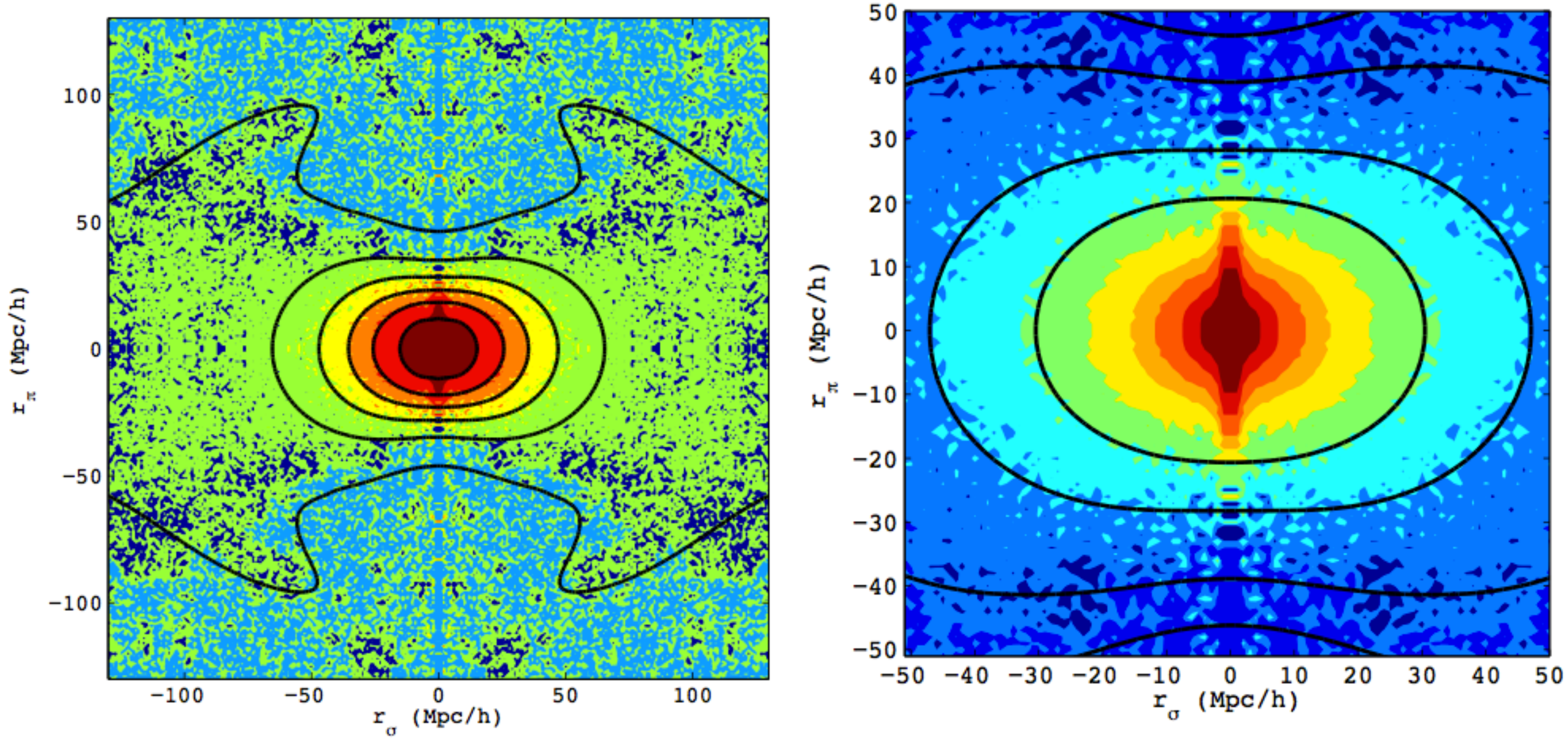
From angular dependence (l=0,2) we can determine velocity power $f\sigma_8$

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



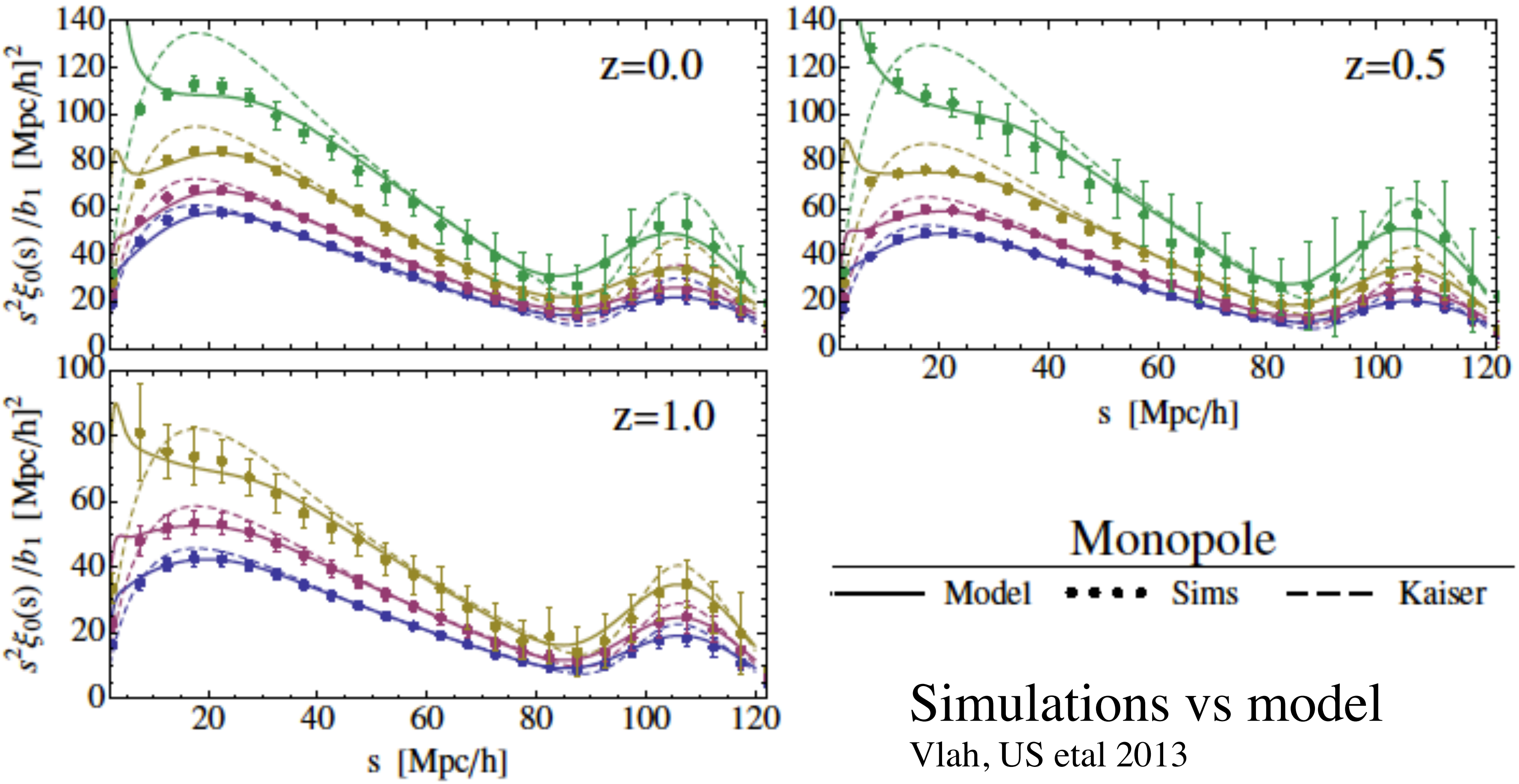
White etal 2011

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



$f\sigma_8 = 0.45 +/- 0.01$ ($z=0.57$)
(Reid et al 2014, also Samushia et al 2013, Beutler et al 2013)

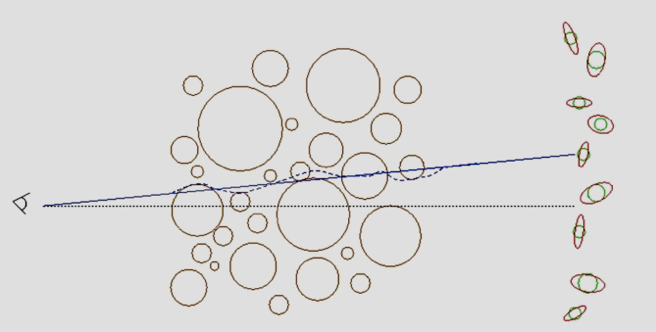
Theoretical uncertainties in redshift surveys: nonlinear effects

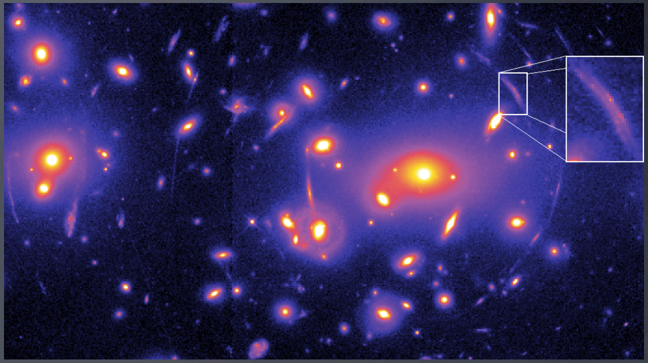


Simulations vs model

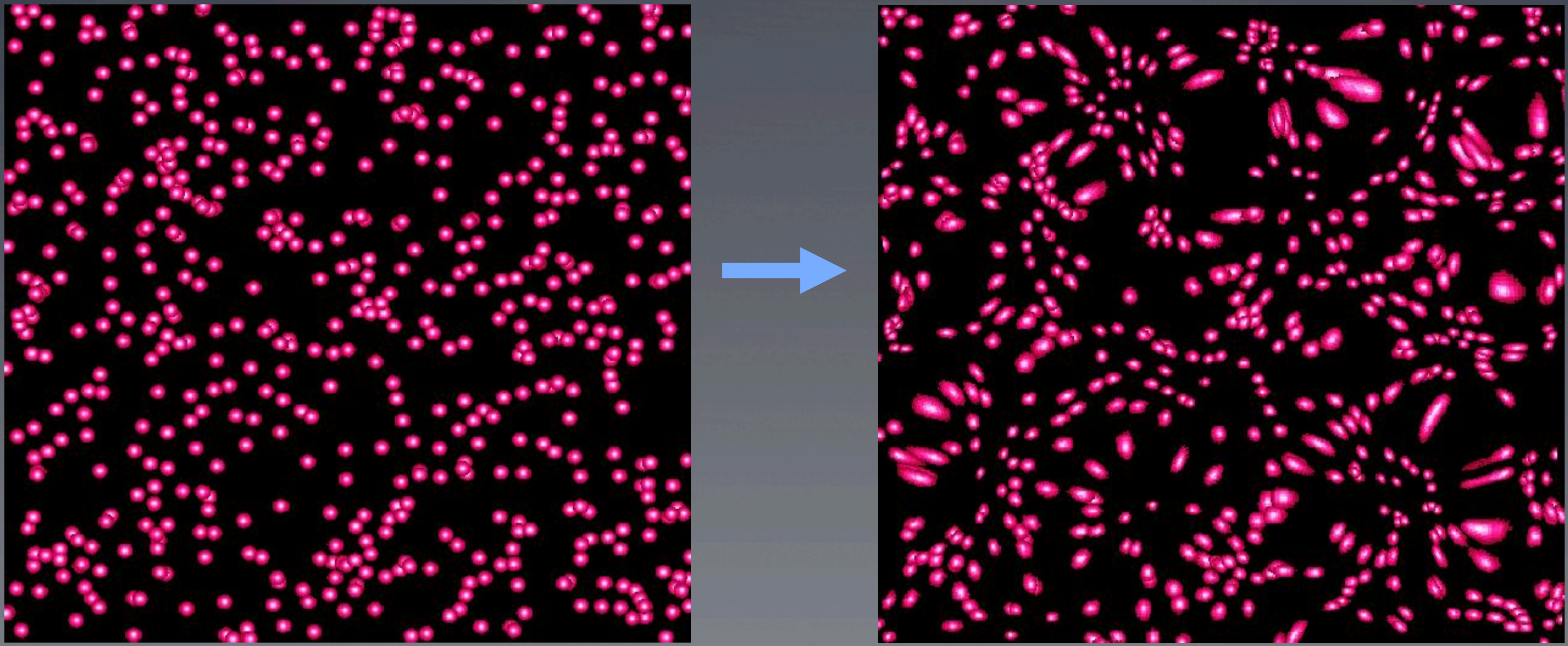
Vlah, US etal 2013

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

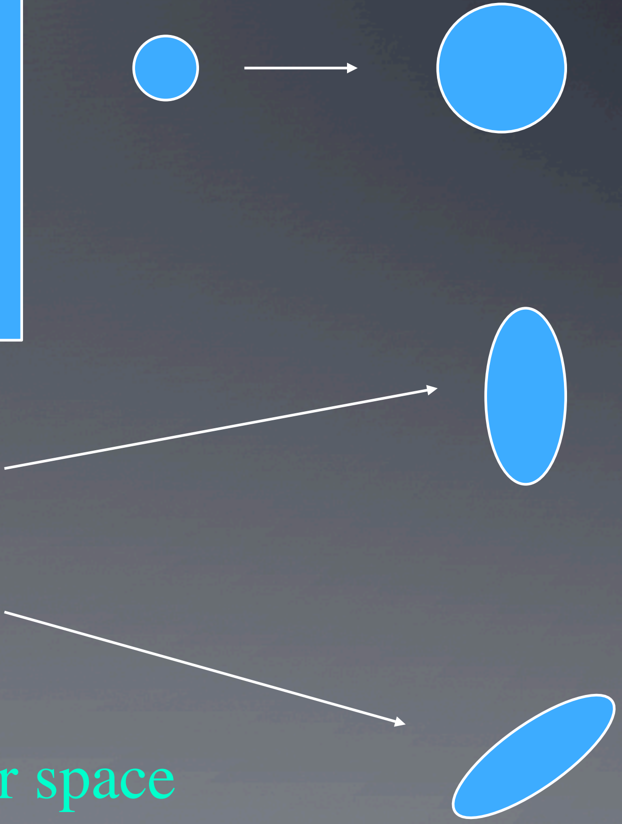
$$\kappa = \int \frac{(r_{LSS} - r)r}{r_{lSS}} \vec{\nabla}^2 \Phi dr =$$

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

shear

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

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



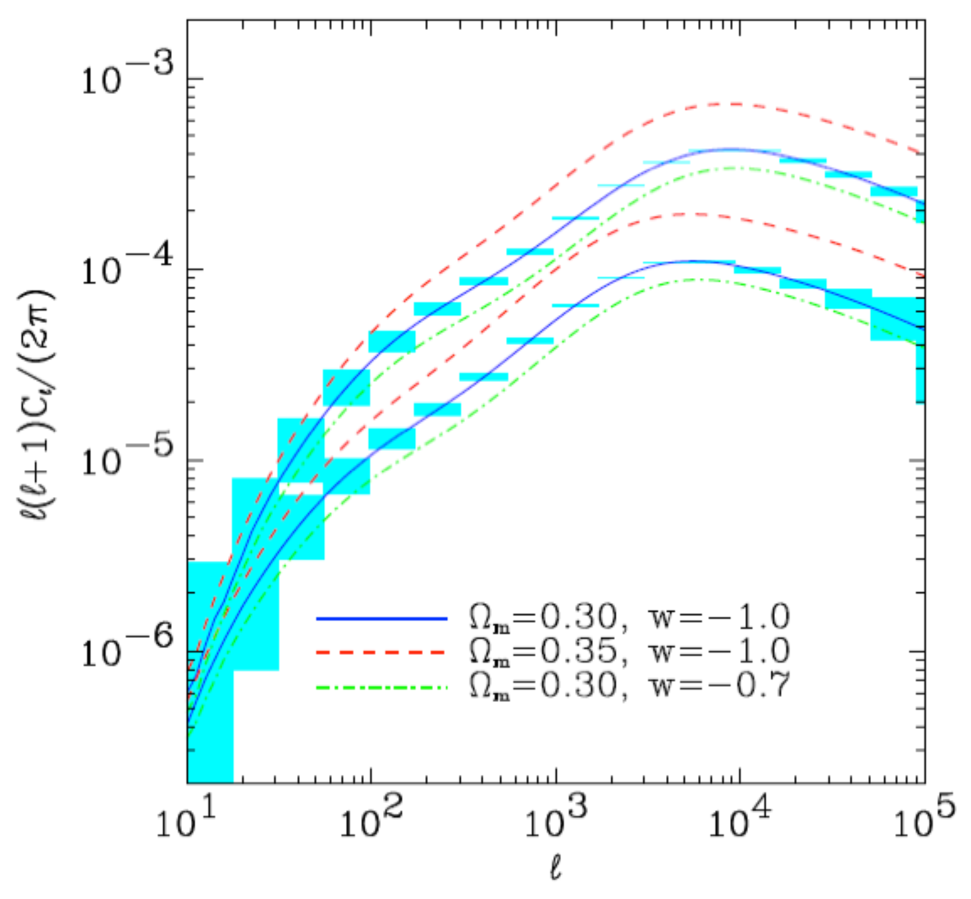
Convergence shear relation in Fourier space

Method I: shear-shear correlations

Refregier et al SNAP3

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

- 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

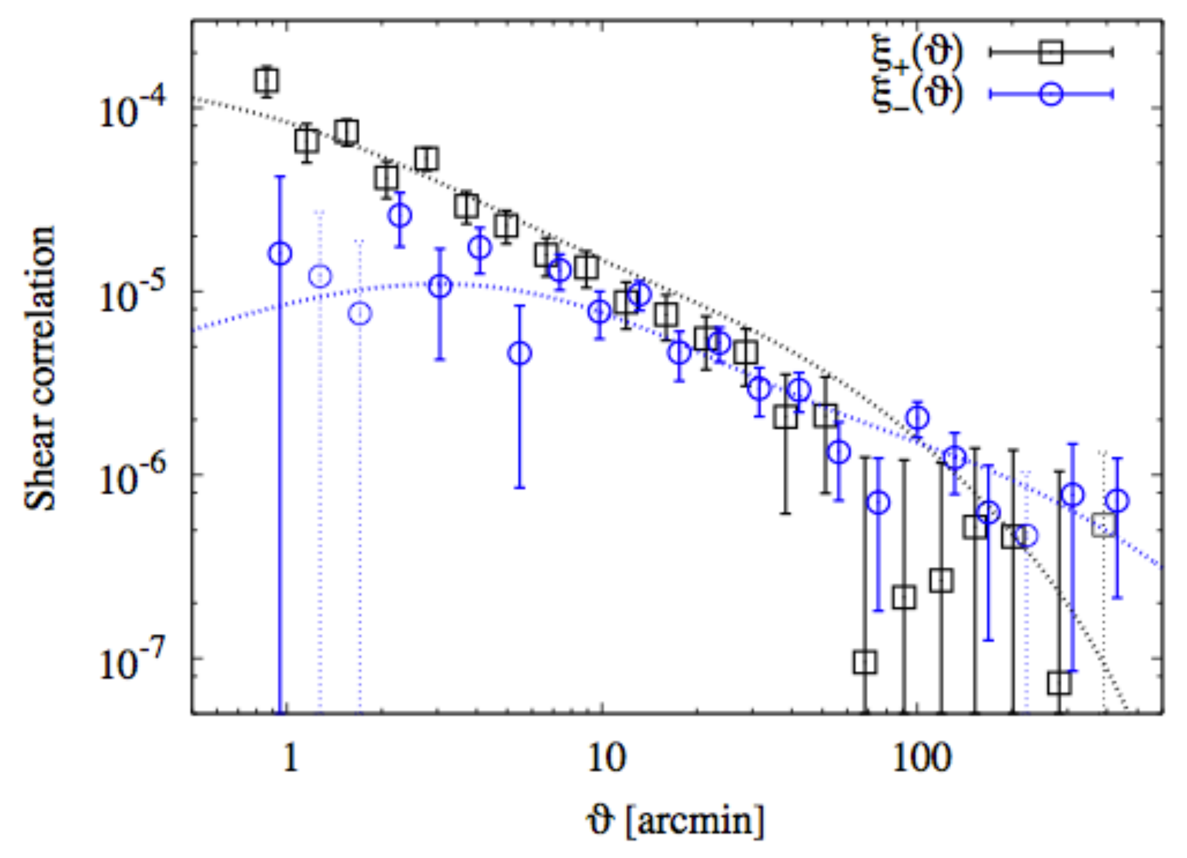
Kiblinger et al 2013

Challenges:

Small scales: could be contaminated by baryonic effects

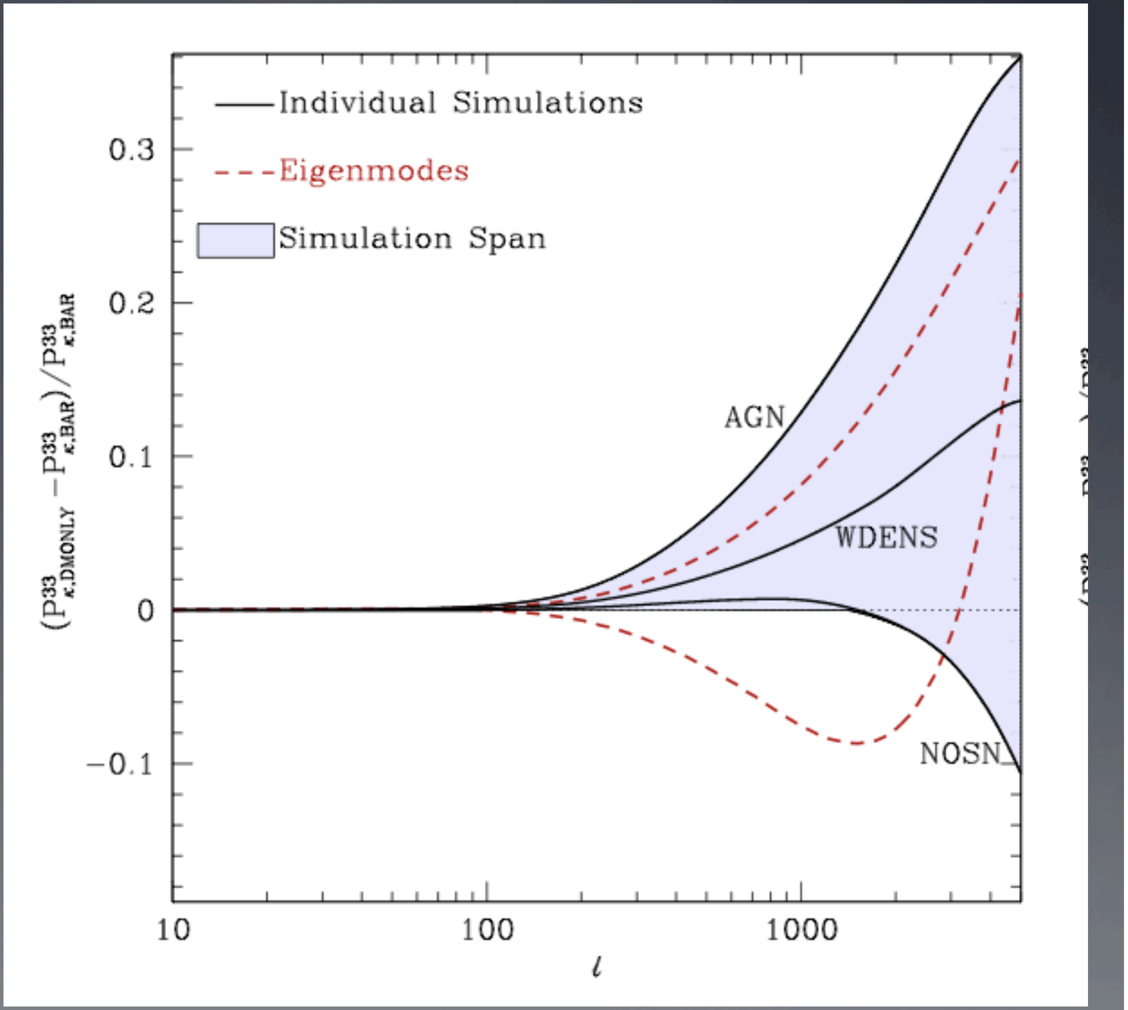
Redshift distributions not completely known

Additive systematics: a lot of data removed



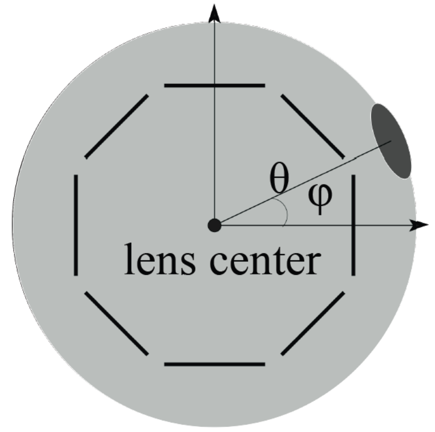
Theoretical uncertainties in weak lensing

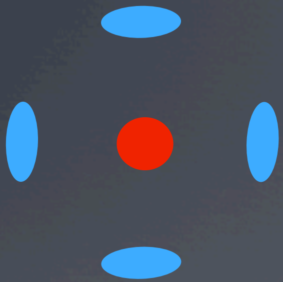
- Baryonic effects: baryons redistribute dark matter inside halos: compress (cooling) or expand (AGN feedback)?
- Challenge: small scale baryonic physics effects can be projected to low l for nearby halos

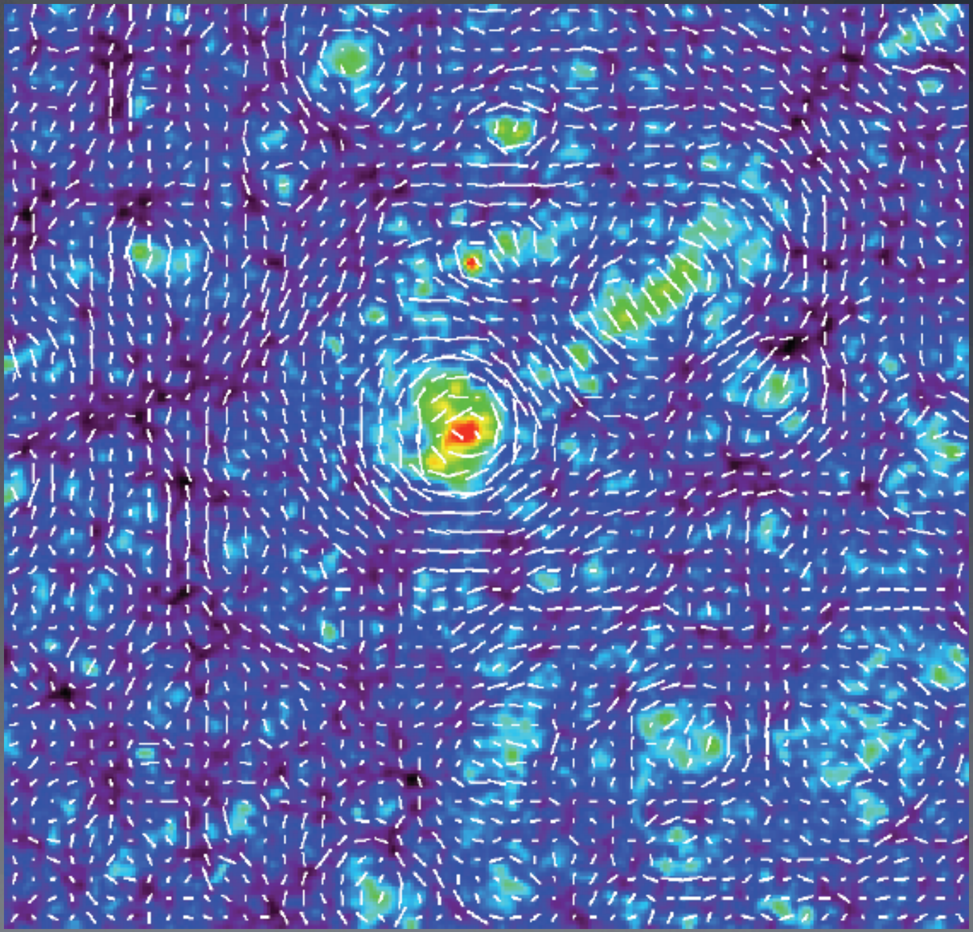


Zentner et al 2013

WL Method II: galaxy-shear correlations







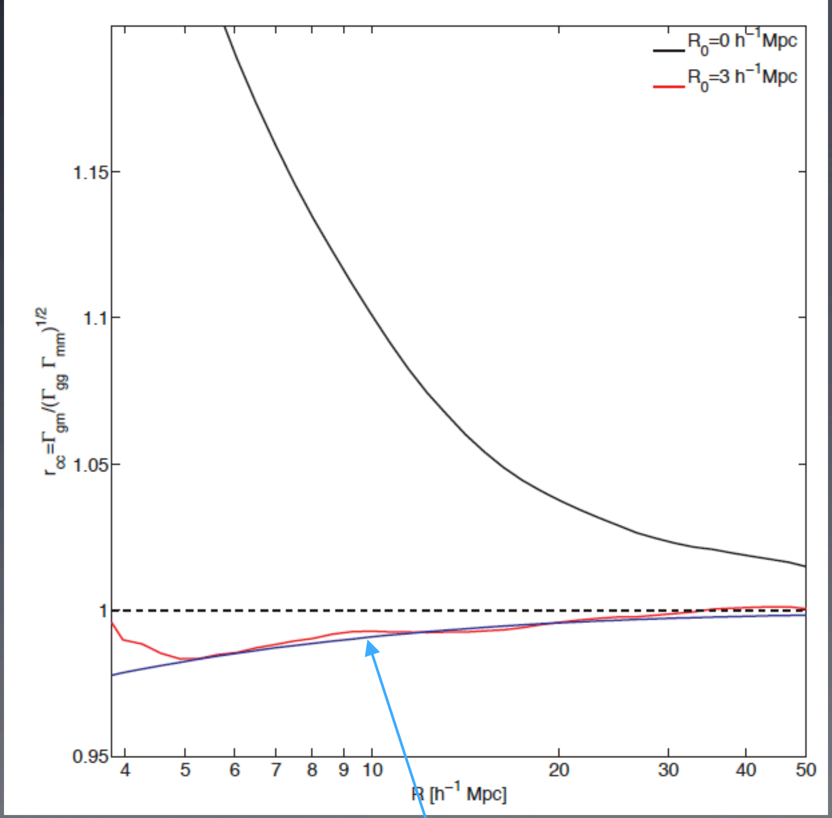
Cross-correlation proportional to bias b

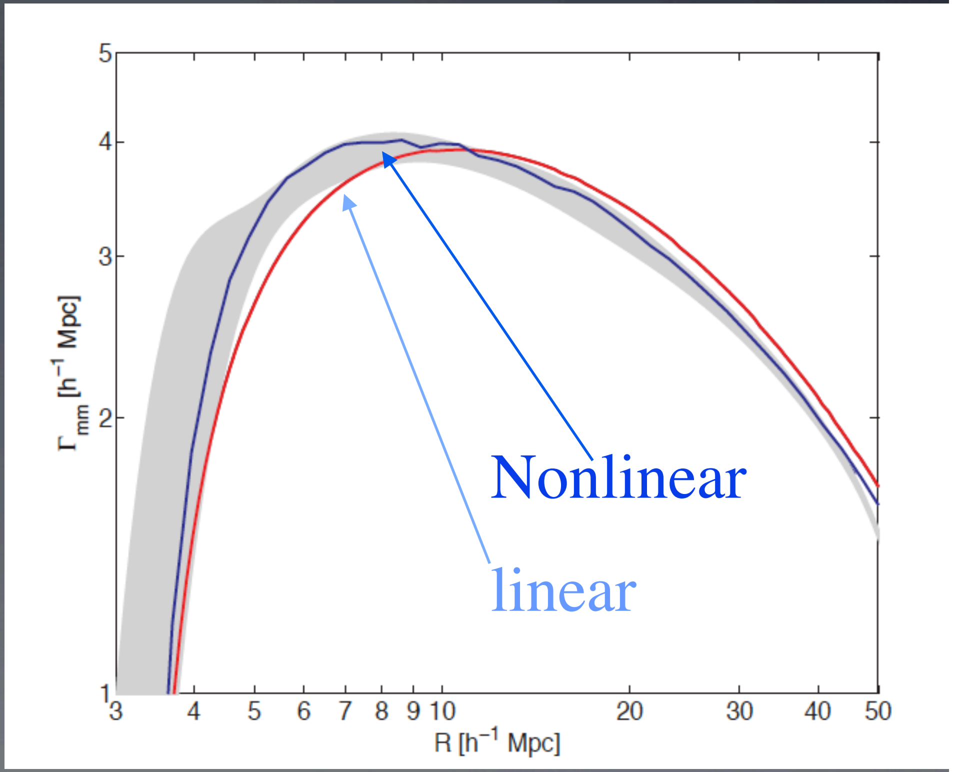
Galaxy auto-correlation proportional to b^2

Simulations: dark matter reconstruction

Baldauf, Smith, US, Mandelbaum (2009)

$$r = \frac{\xi_{hm}}{\sqrt{\xi_{hh}\xi_{mm}}} \rightarrow \xi_{mm} = \frac{\xi_{hm}^2}{r^2\xi_{hh}}$$





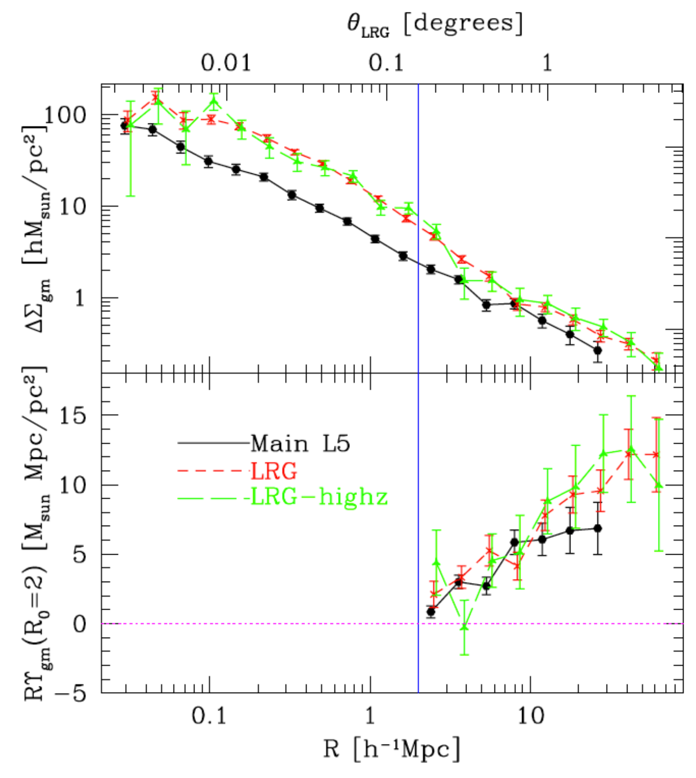
New statistic: Cross-correlation coefficient
r nearly unity

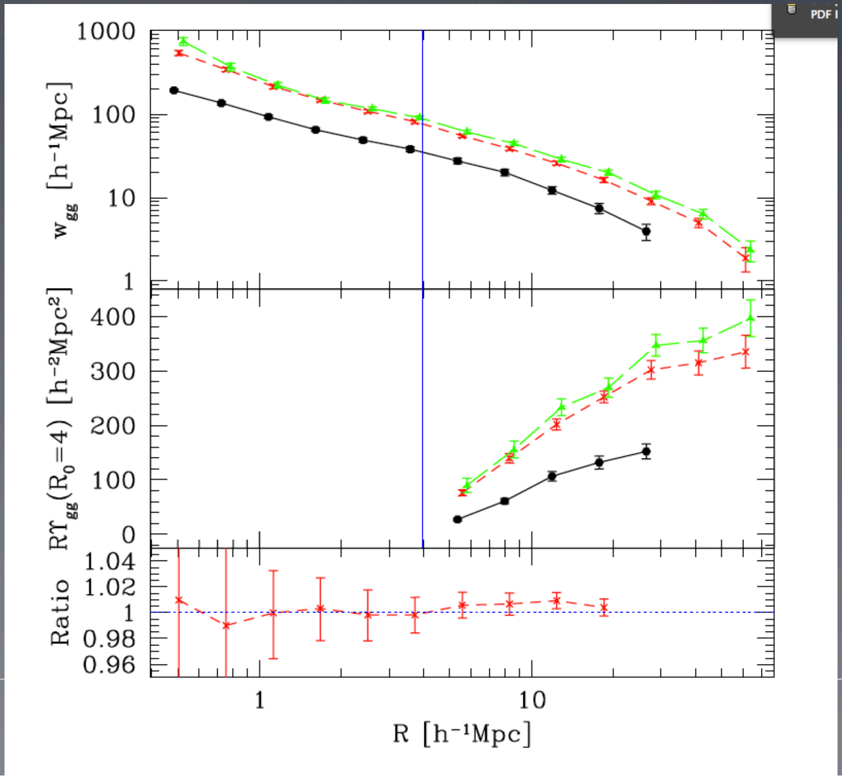
SDSS DR-7 data analysis

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)

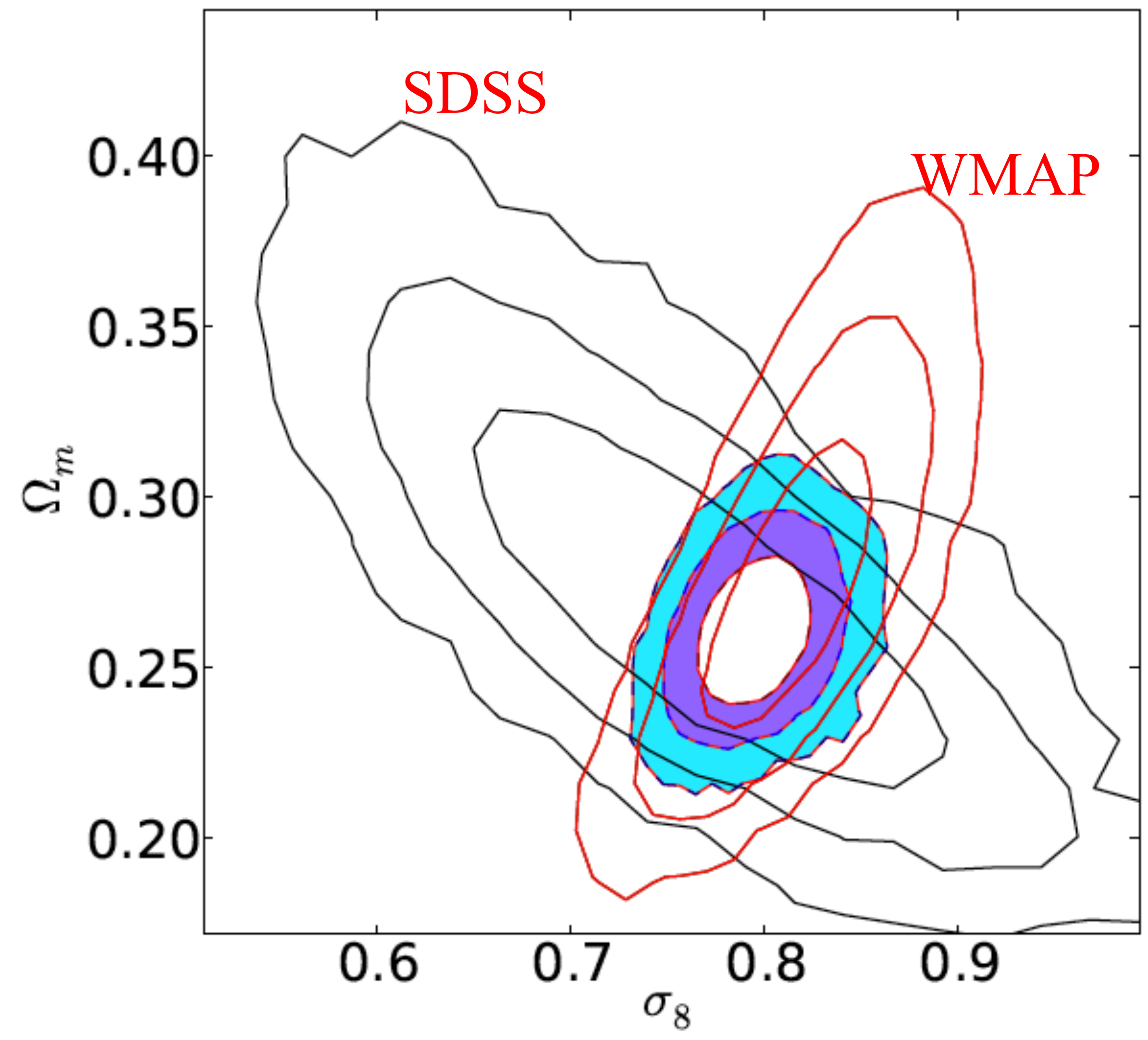
SOURCES
10M, well calibrated photozs
using spectroscopic surveys





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

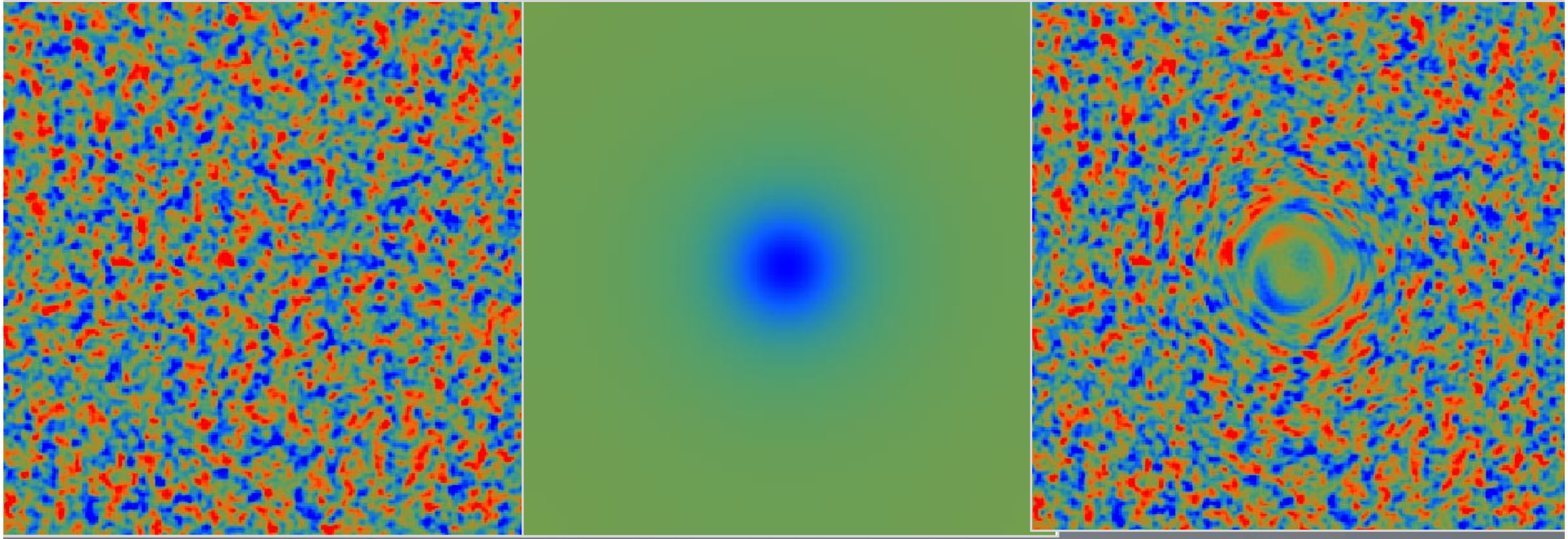
Cosmology constraints



Effect of gravitational lensing on CMB

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

- Here κ 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

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

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

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

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

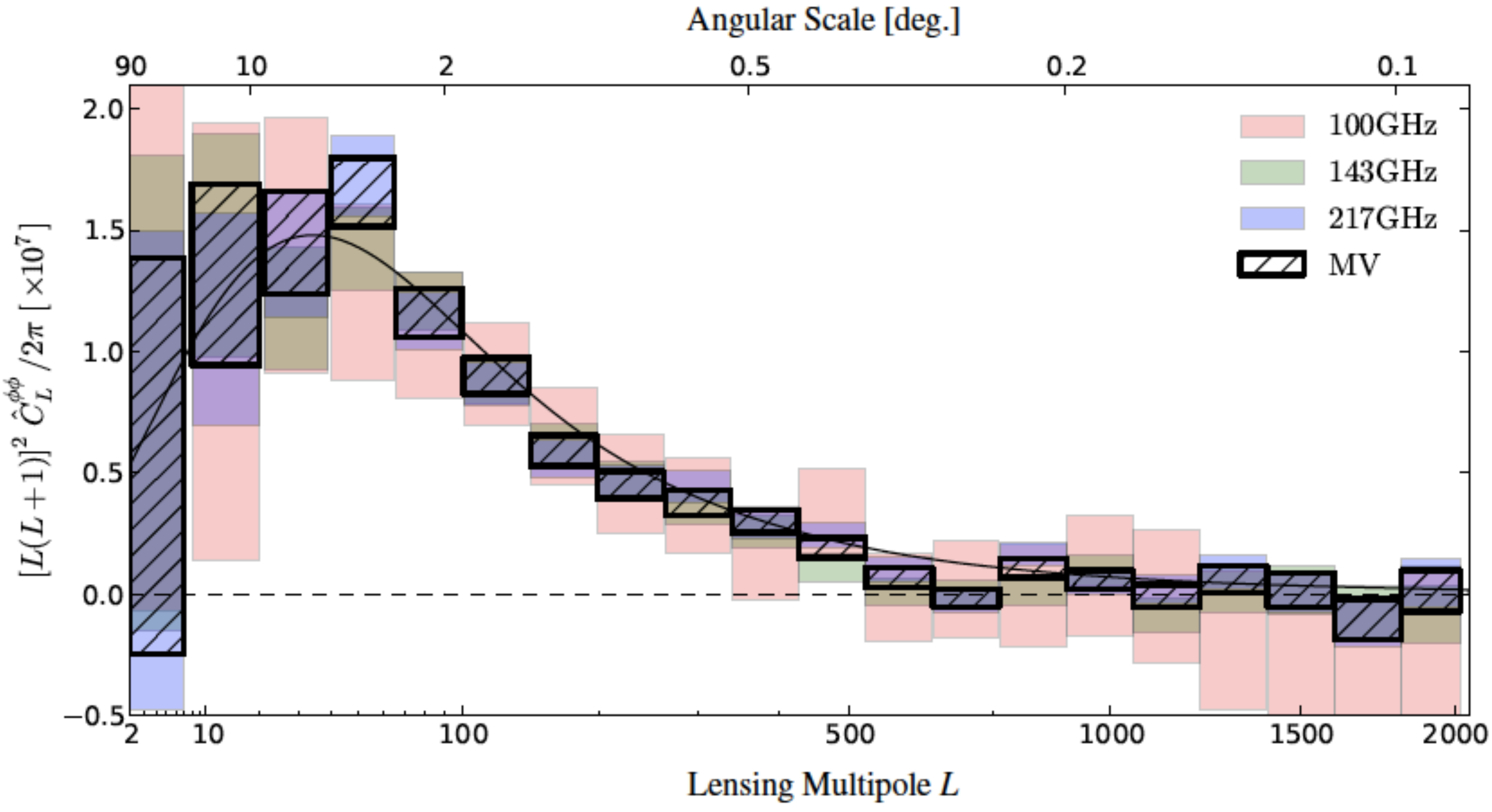
$$\varphi(\vec{l}) = \frac{1}{2} F_{ll'}^{-1} (\vec{T} C^{-1} \frac{\partial \overleftrightarrow{C}}{\partial \varphi(\vec{l}\,')} C^{-1} \vec{T})$$

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

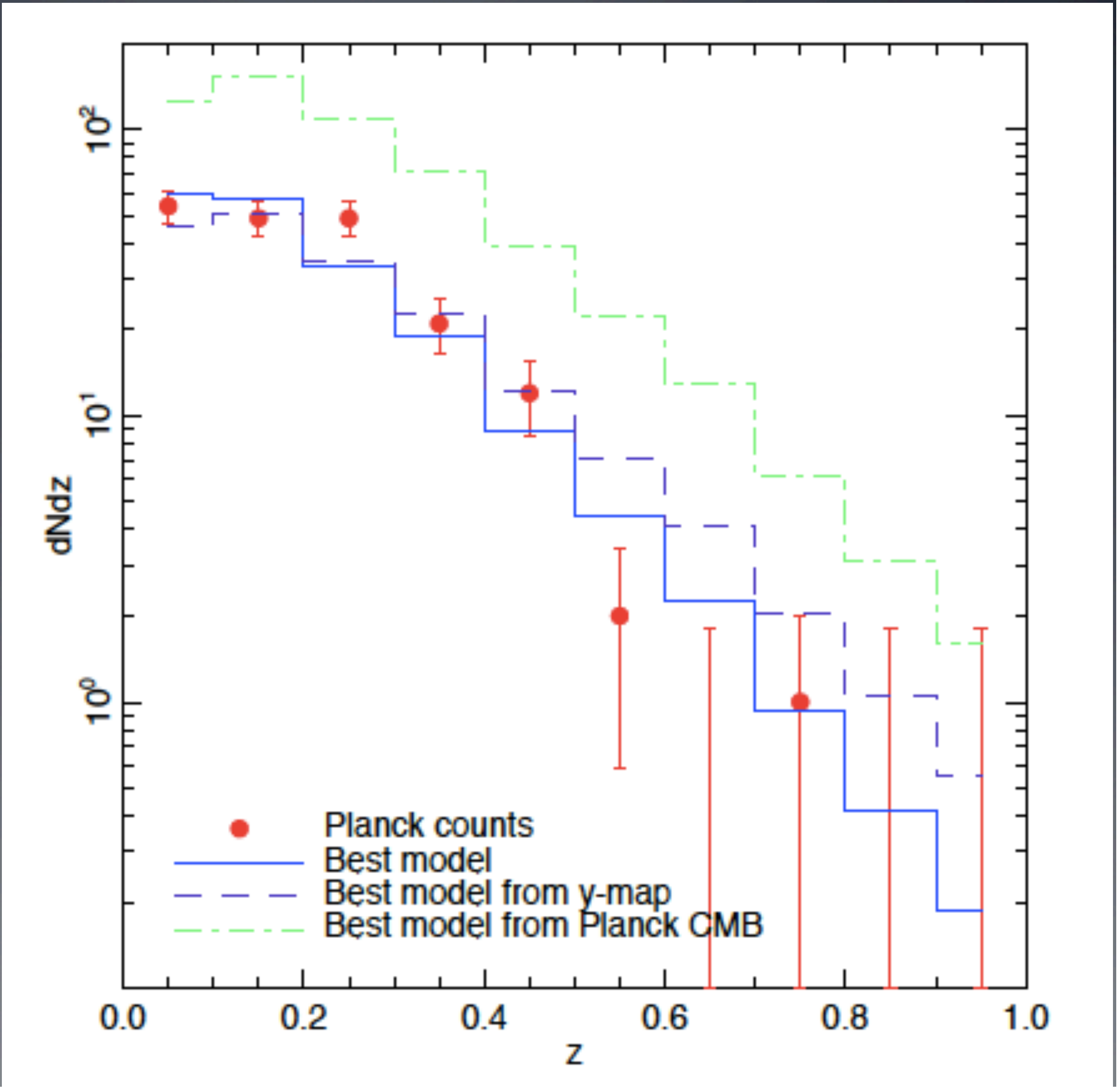
- Halo mass function steep at high mass end: highly sensitive to amplitude change
- Counting clusters is easy. Relating observable to halo mass hard
- Scatter between the two biases amplitude determination: low mass clusters scatter into the sample
- Determining mean mass is hard: WL, SZ, X-ray hydrostatic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

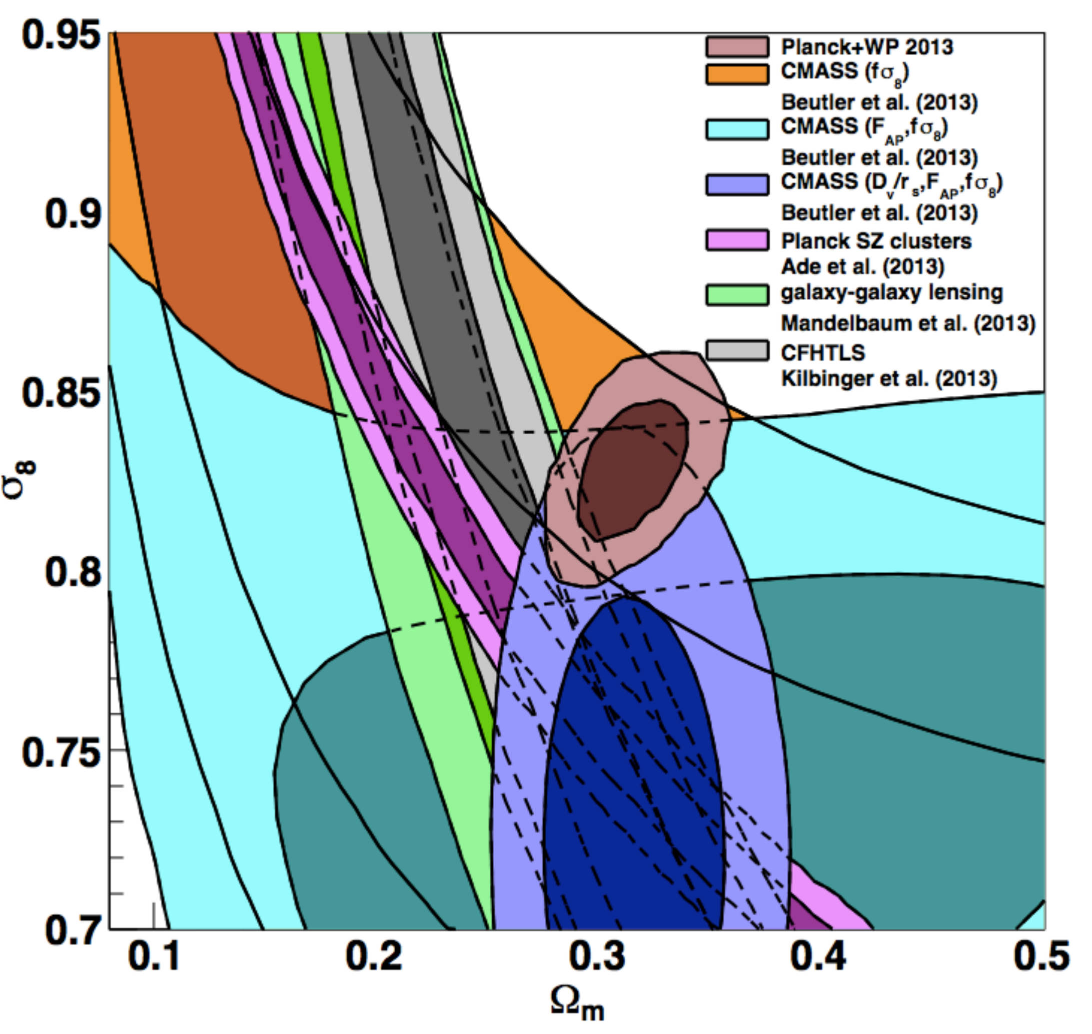


Planck versus LSS

LSS constraints (RSD, lensing, clusters) consistent

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

Planck reanalysis, more LSS data

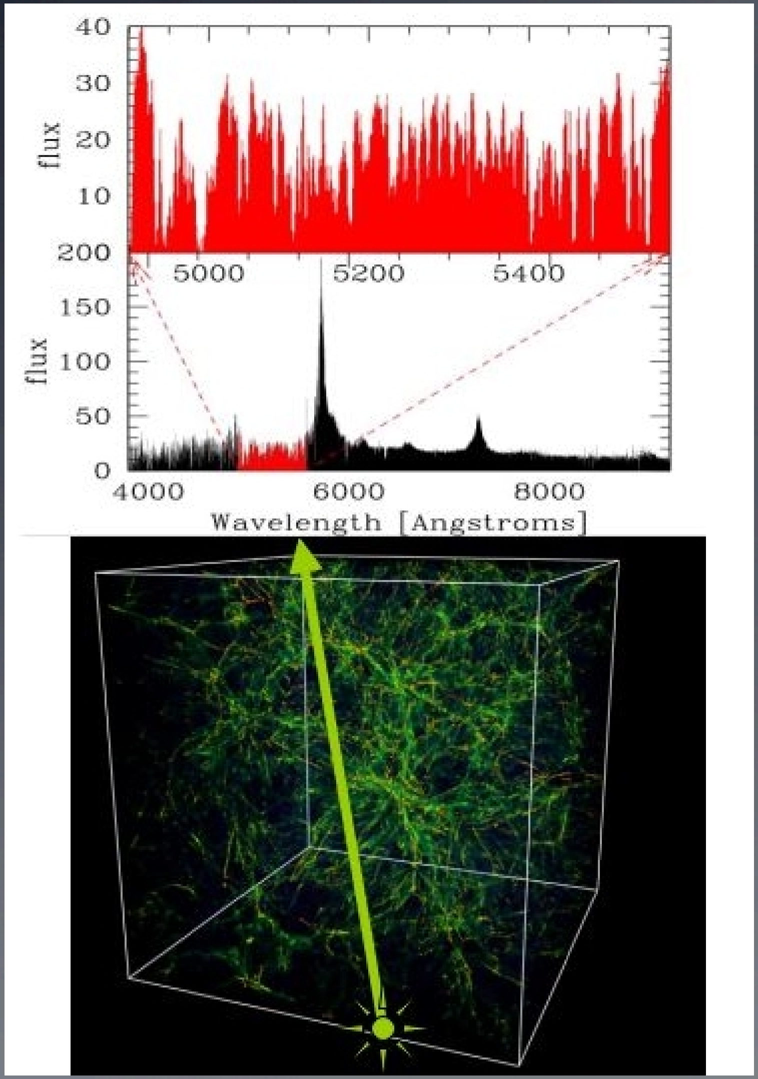


F. Beutler, see also Beutler etal 2014

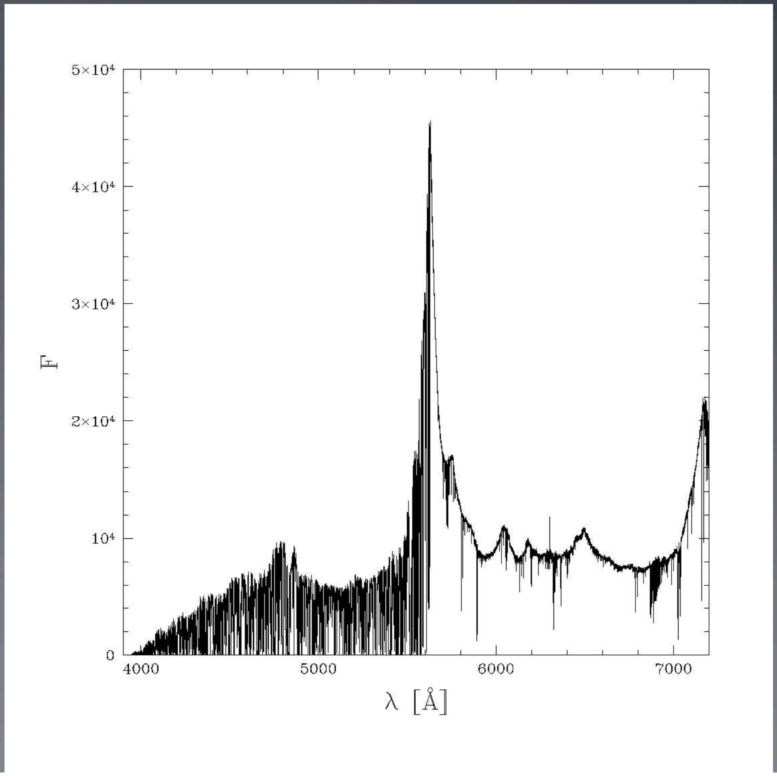
Ly-alpha forest: basics

- Neutral hydrogen leads to

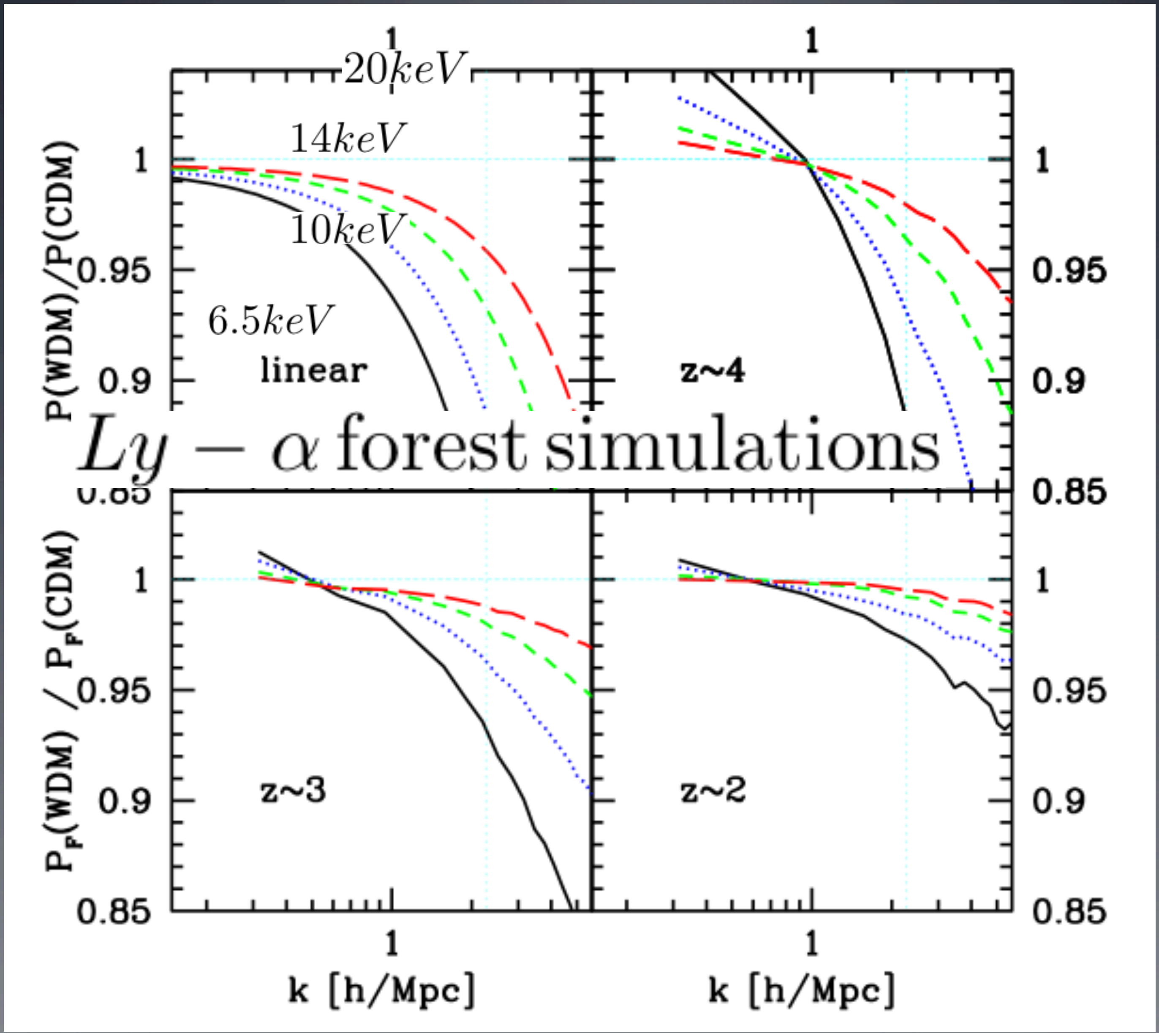
Lyman-α absorption at $\lambda < 1216\,(1+z_q)$ Å; it traces baryons, which in turn trace dark matter



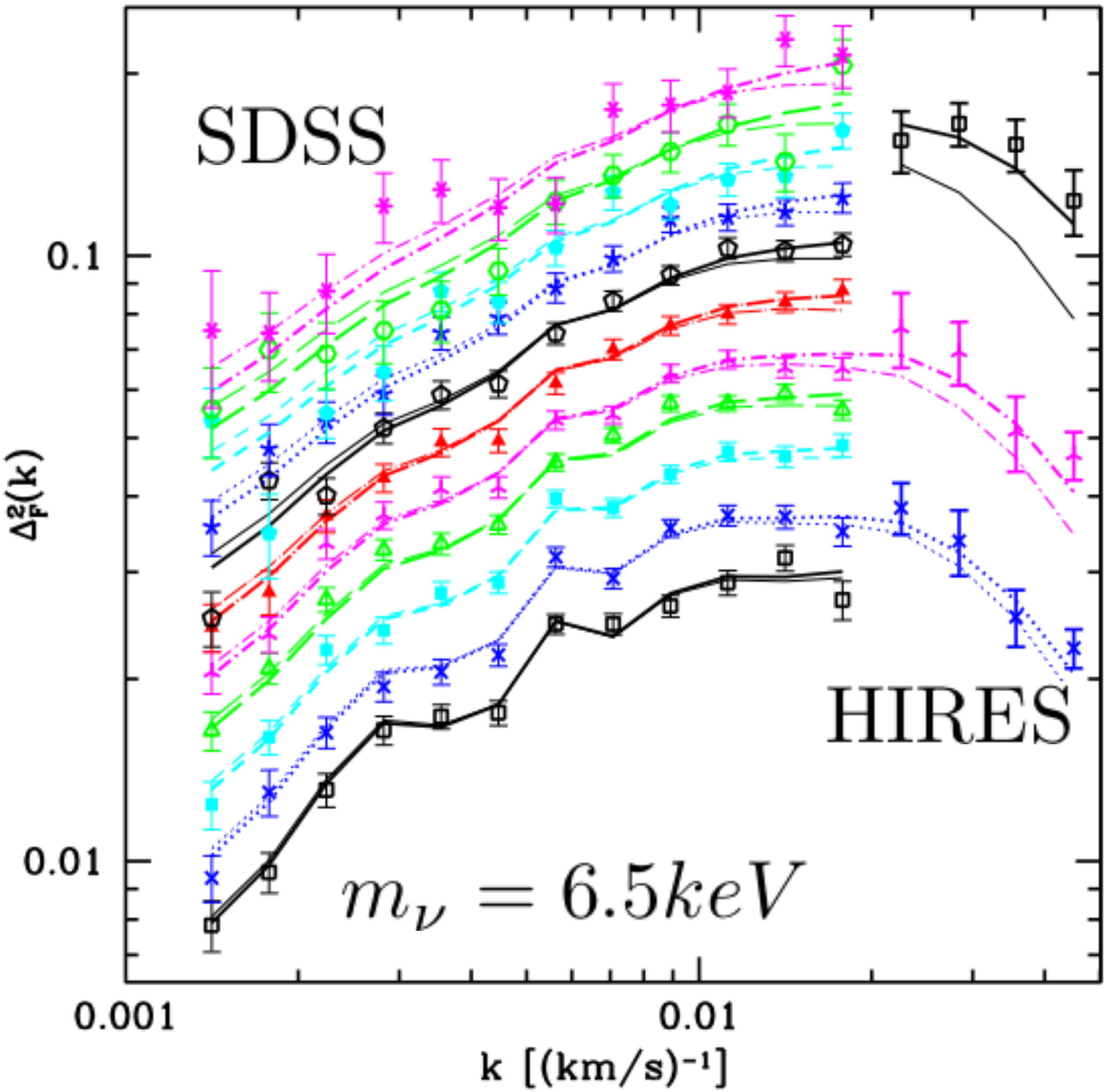
SDSS Quasar Spectrum



Probing warm dark matter (e.g. sterile neutrinos) with Lyman alpha forest



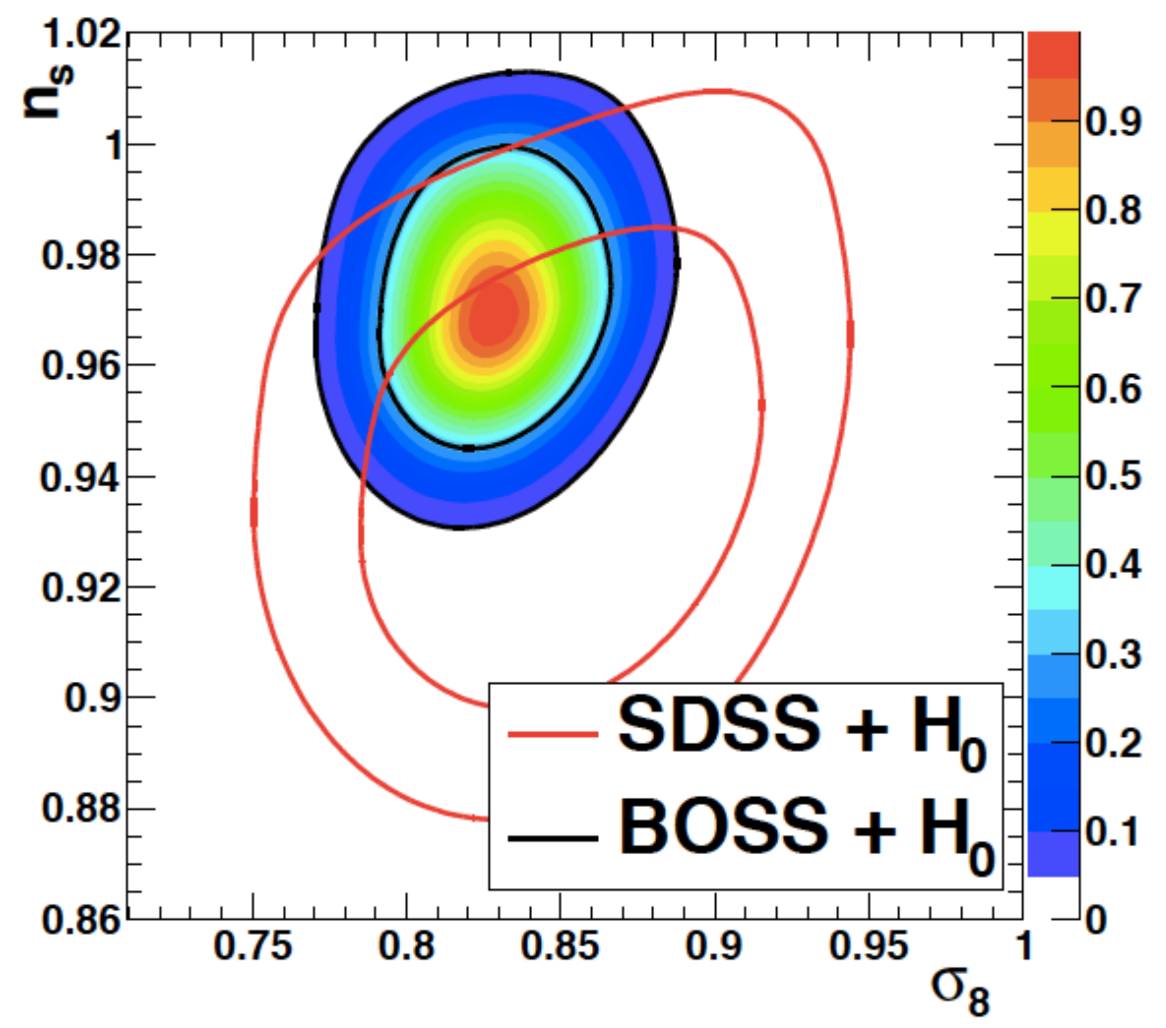
$Ly-\alpha$ forest simulations



WDM is a worse fit to the data

SDSS-III/BOSS and SDSS results

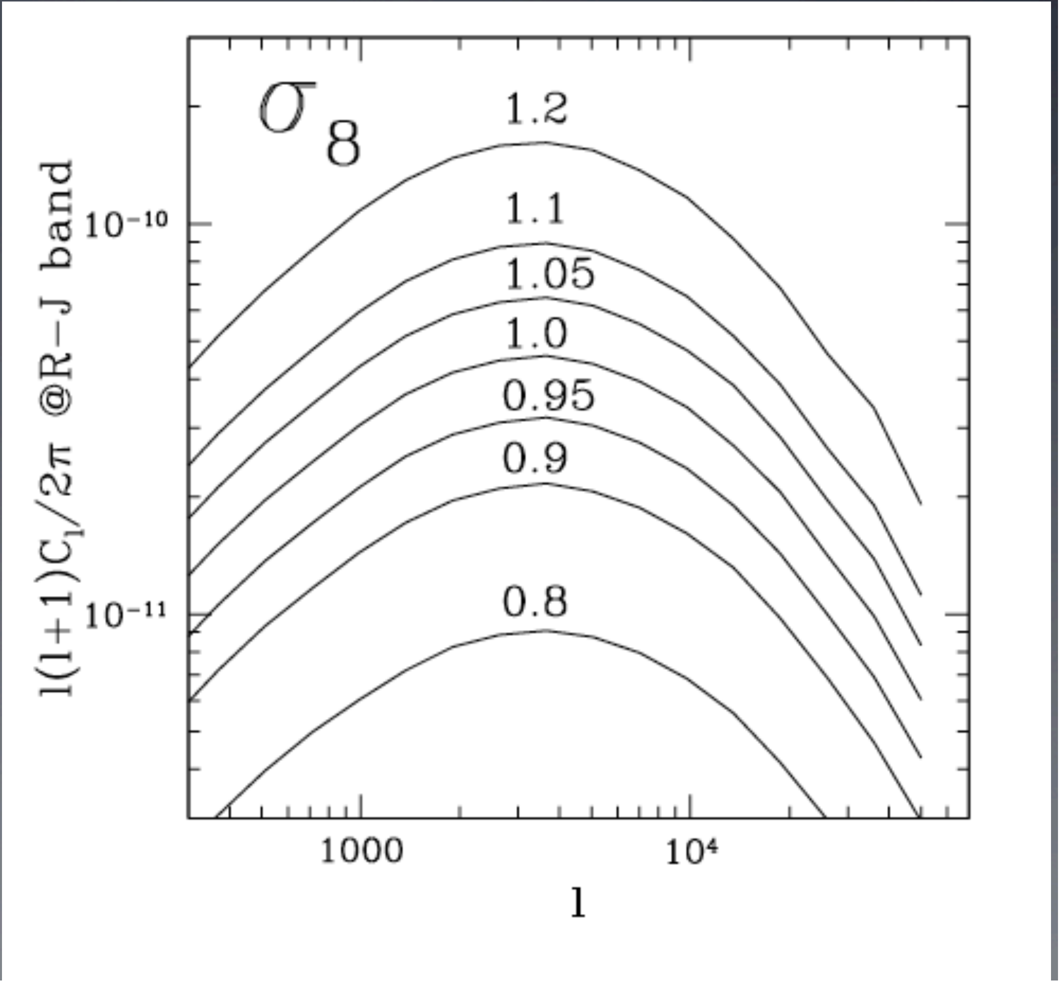
- SDSS: McDonald etal (2005)
- BOSS: Palanque-Dellabruille et al (2013)



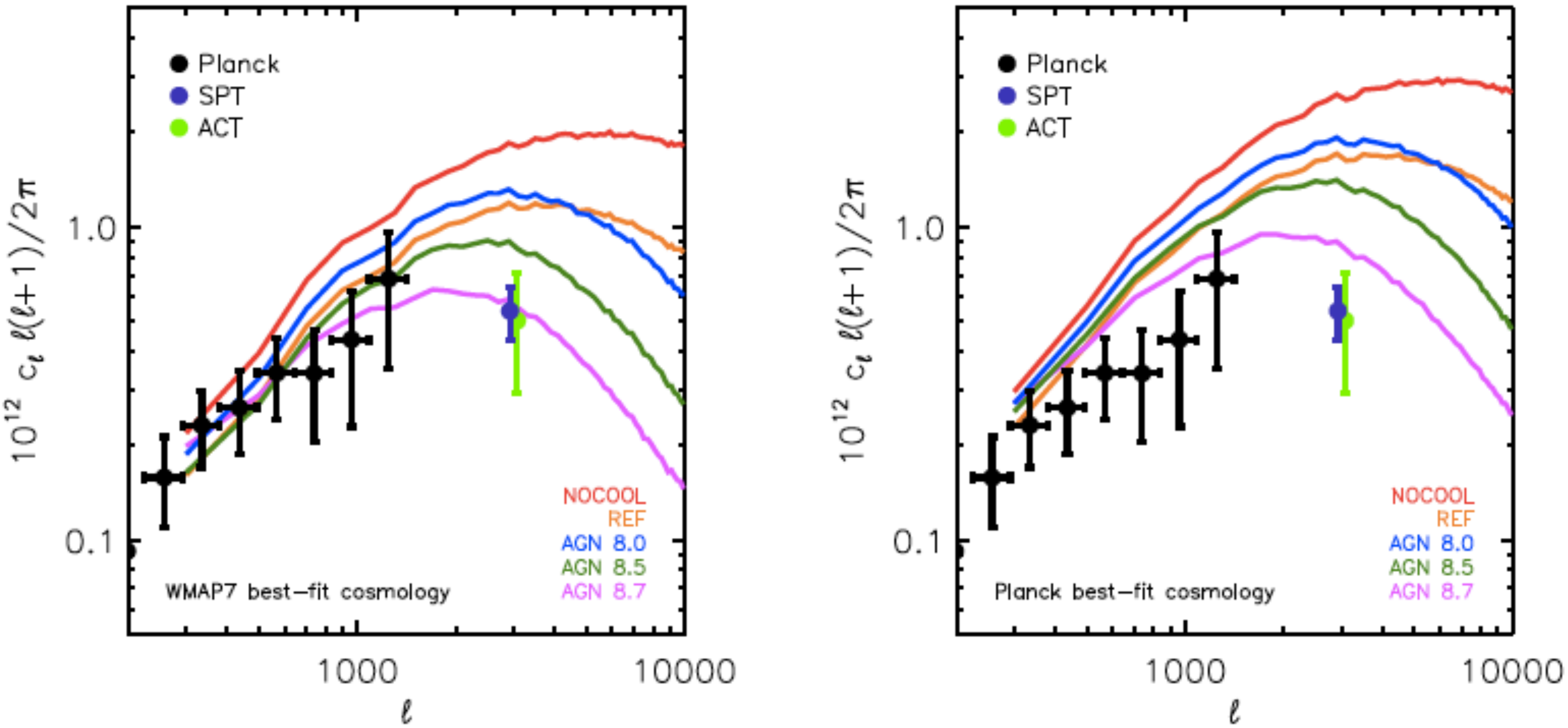
Sunyaev-Zeldovich effect

- Traces gas pressure in clusters
- Can do cluster abundance or tSZ power spectrum
- tSZ C(l) very sensitive to amplitude σ_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

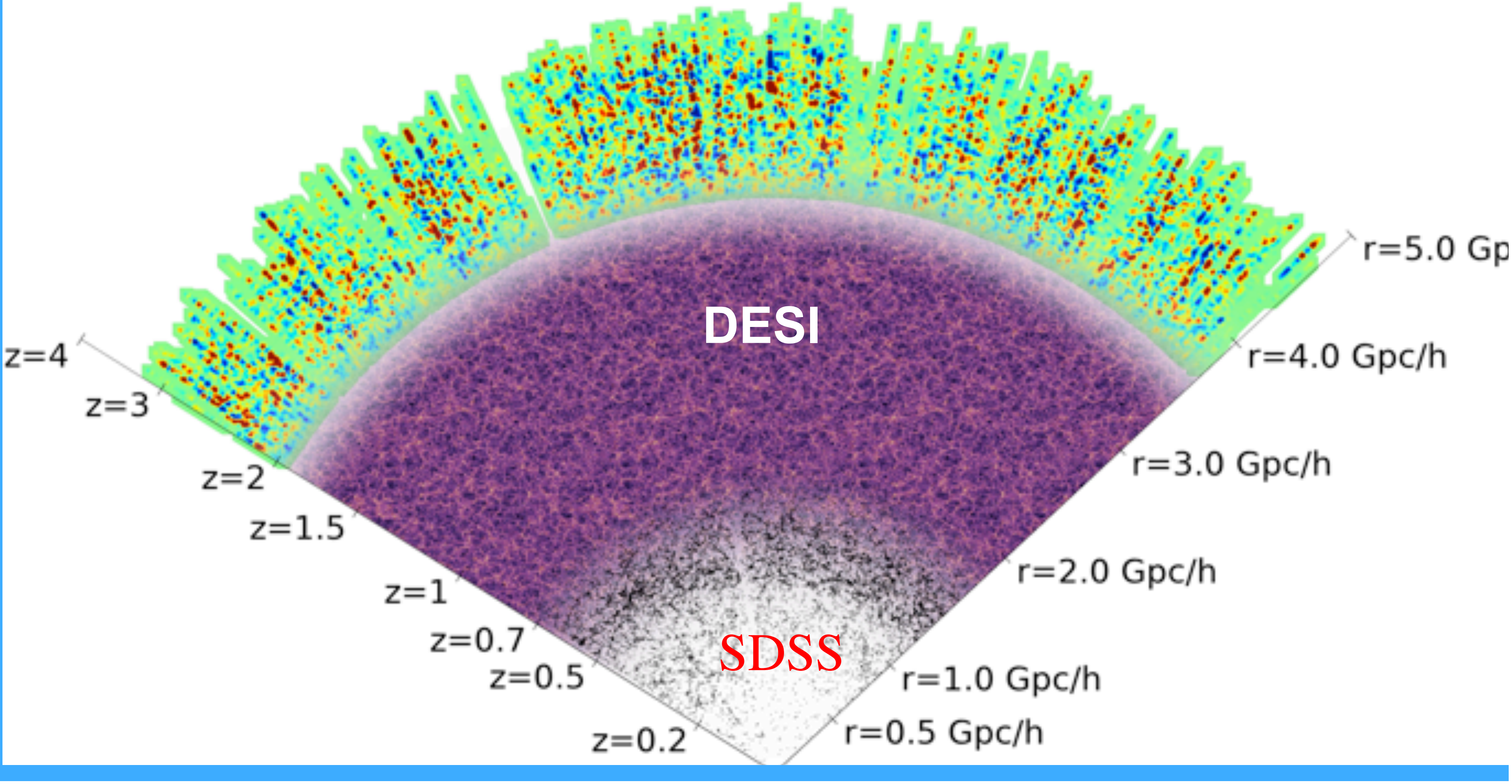
Summary of LSS

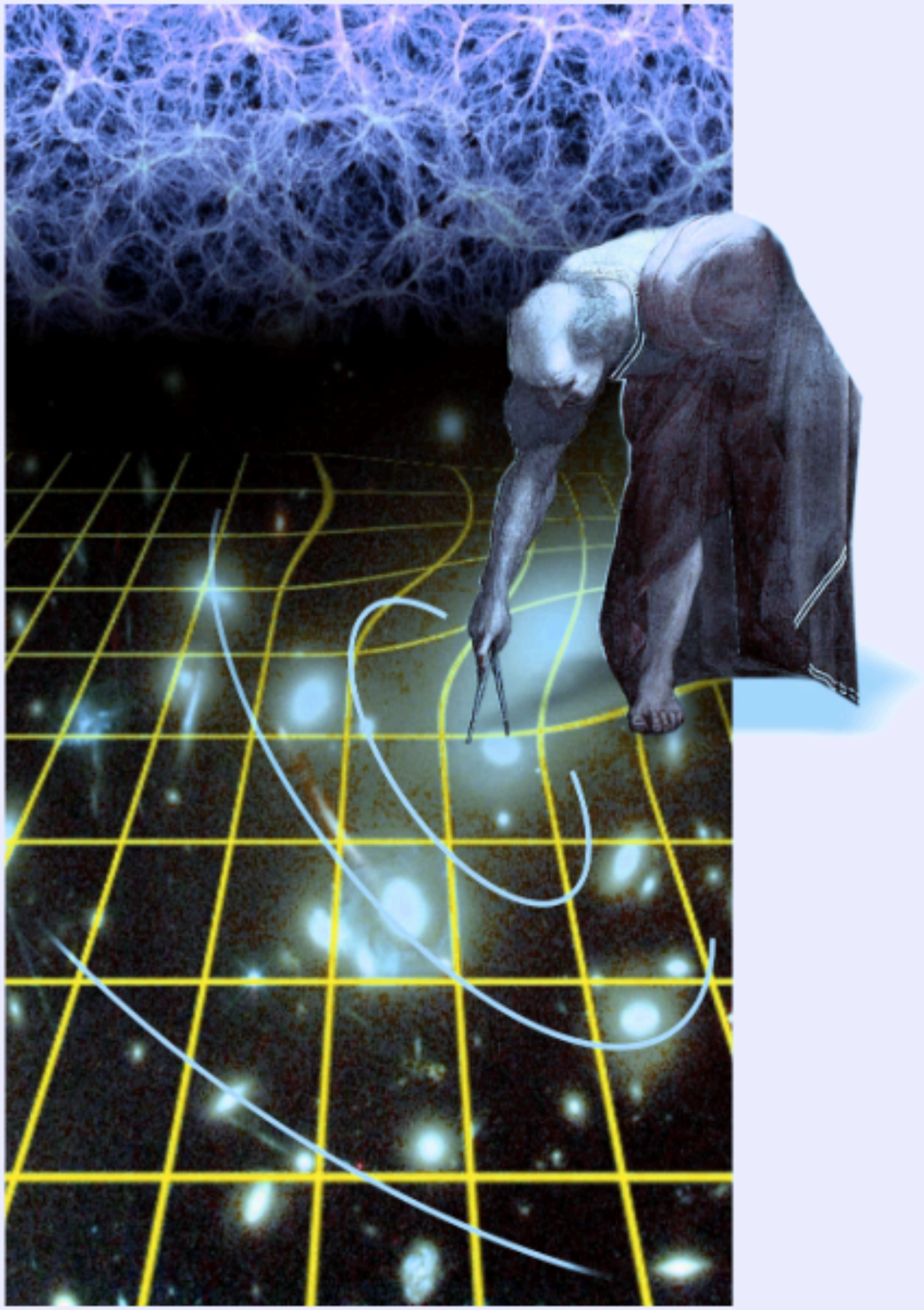
- BAO+CMB+SN determines matter density: Ω_m=0.30
- Amplitude of fluctuations at z<1 determined by several probes: some reaching 2-3% precision (BOSS RSD, CMB WL, tSZ C_l, Lya)
- Some are high, some are low, but overall a remarkable agreement at σ_8=0.80
- Is there any evidence of neutrino mass yet?
- Planck team: Σm_ν<0.20eV (95%)
- Some later analyses suggest : $\Sigma m_\nu = 0.3^+_- 0.1$eV (Beutler etal 2014)
- Still too early, but note that we are quickly approaching required statistical errors
- Planck reanalysis will be helpful (Spergel etal 2013)

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 dark matter: density, 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 2.5%
- Recent WL result from CFHT-LS, SDSS: amplitude to 3-6%
- CMB WL amplitude to 2%, tSZ C_l also 2%, Lya P(k) also 2%
- in combination there is a remarkable consistency of most probes, roughly landing where Planck is (in the absence of massive neutrinos)
- Future LSS surveys: huge efforts, 2 planned satellites, numerous ground based efforts, up to an order of magnitude improvements over current constraints