The large scale structure of the universe: the promise, current status and future prospects

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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

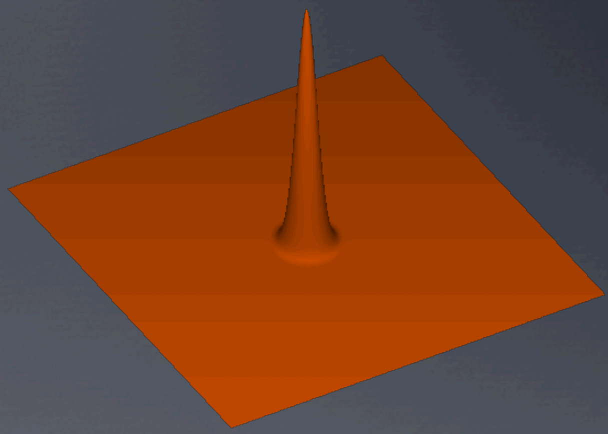
2) Growth of structure: CMB, Ly-alpha, weak lensing, clusters, galaxy clustering

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

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

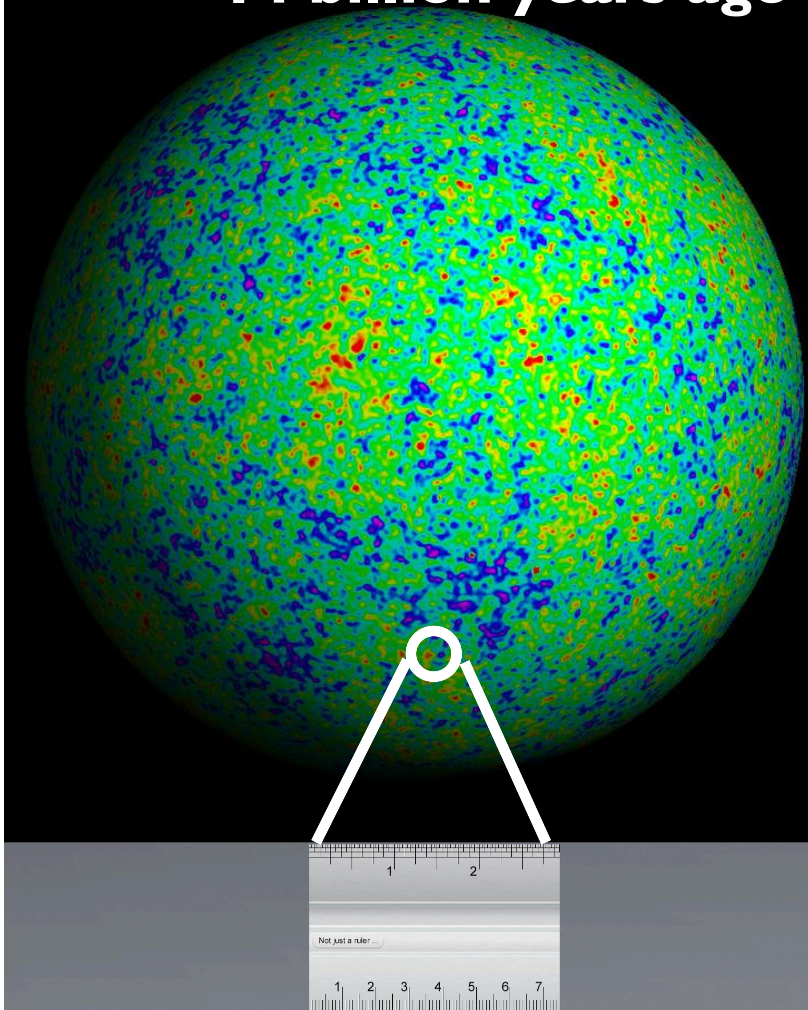
1) BAO: sound waves

- 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.

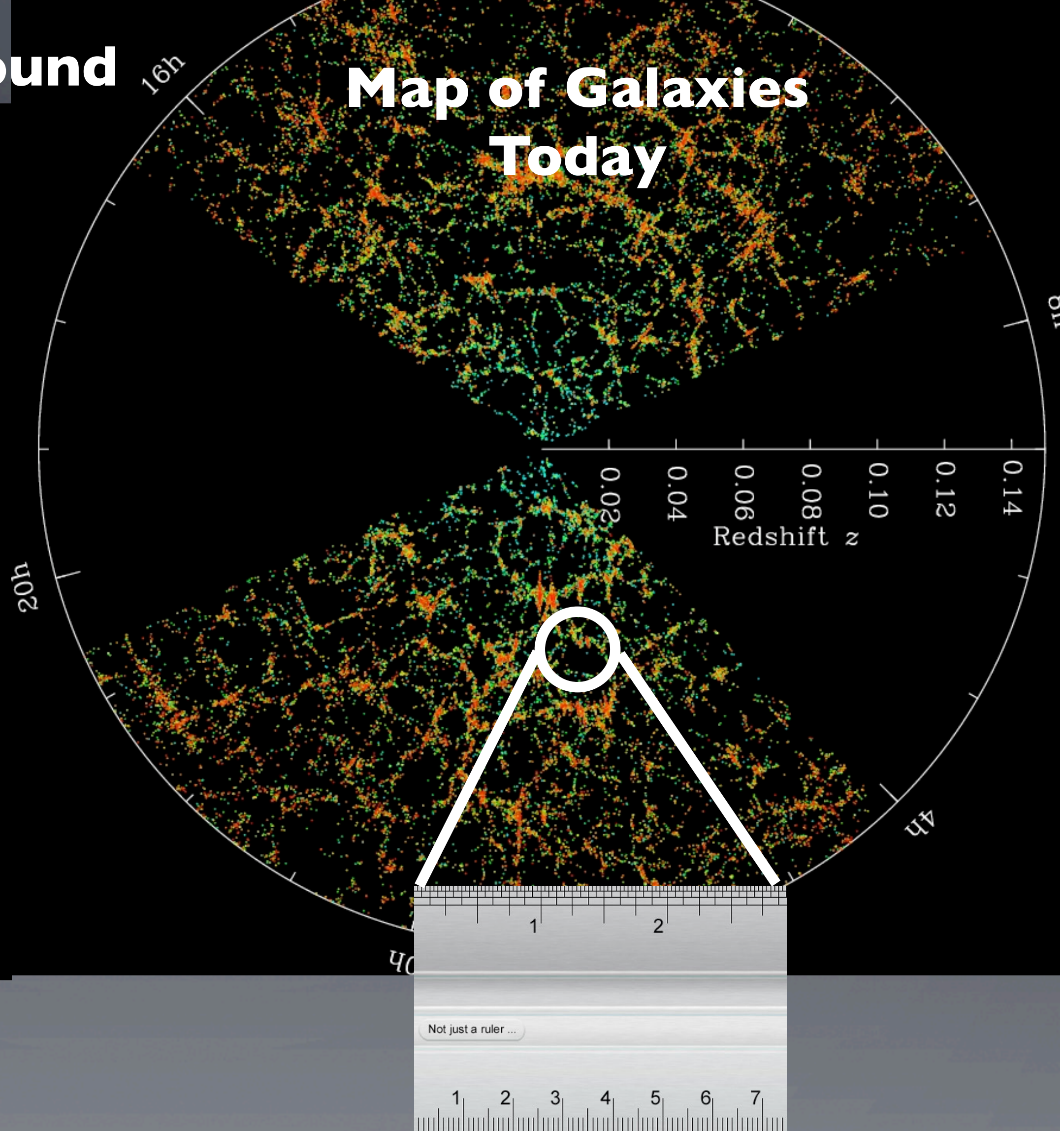


Sound waves as “standard ruler”

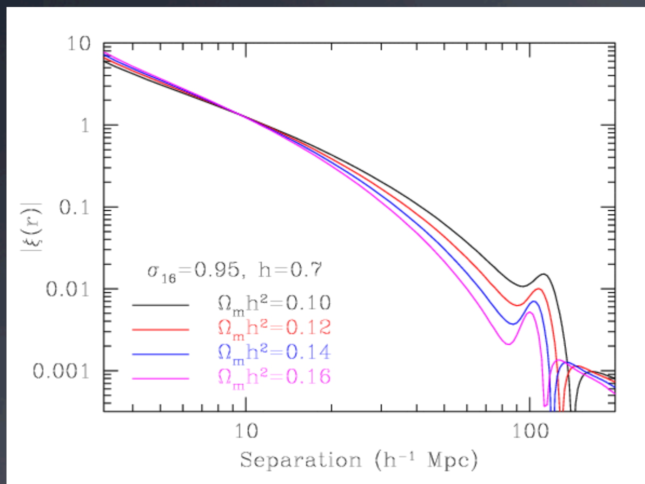
Cosmic Microwave Background
14 billion years ago



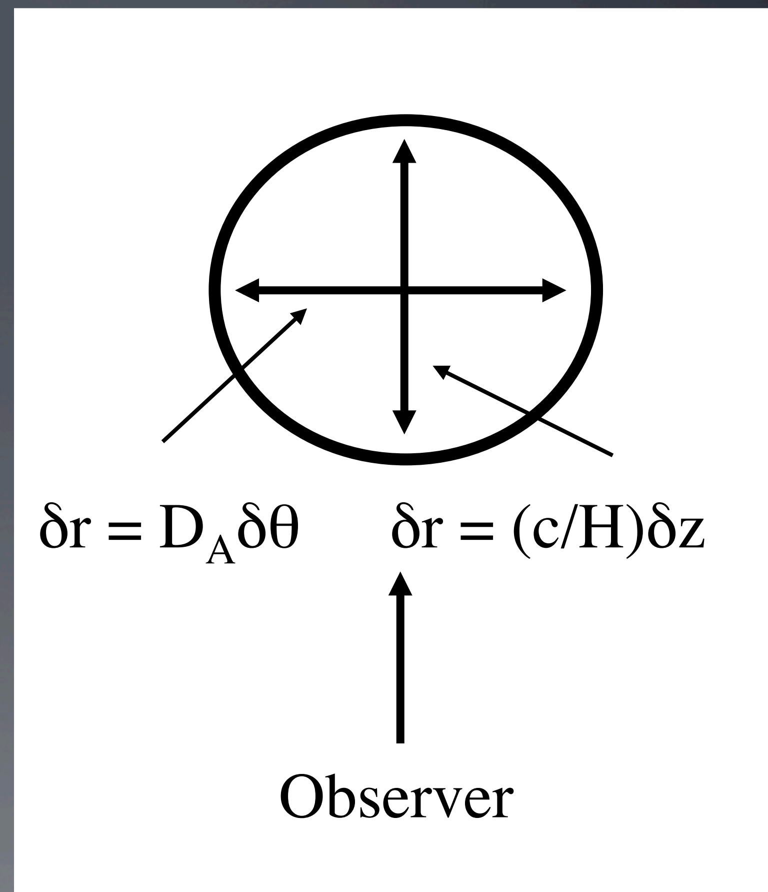
Map of Galaxies Today



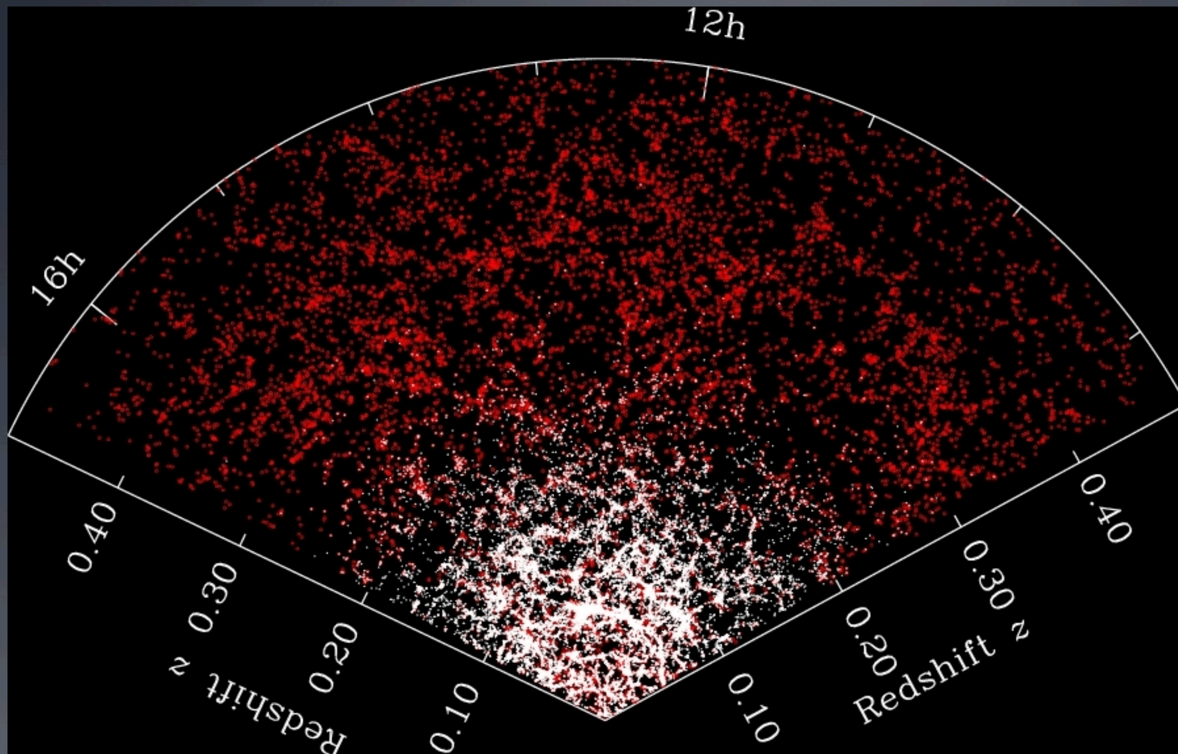
BAO in galaxy redshift surveys



- 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 $D_A(z)$!



State of the art: Sloan Digital Sky Survey

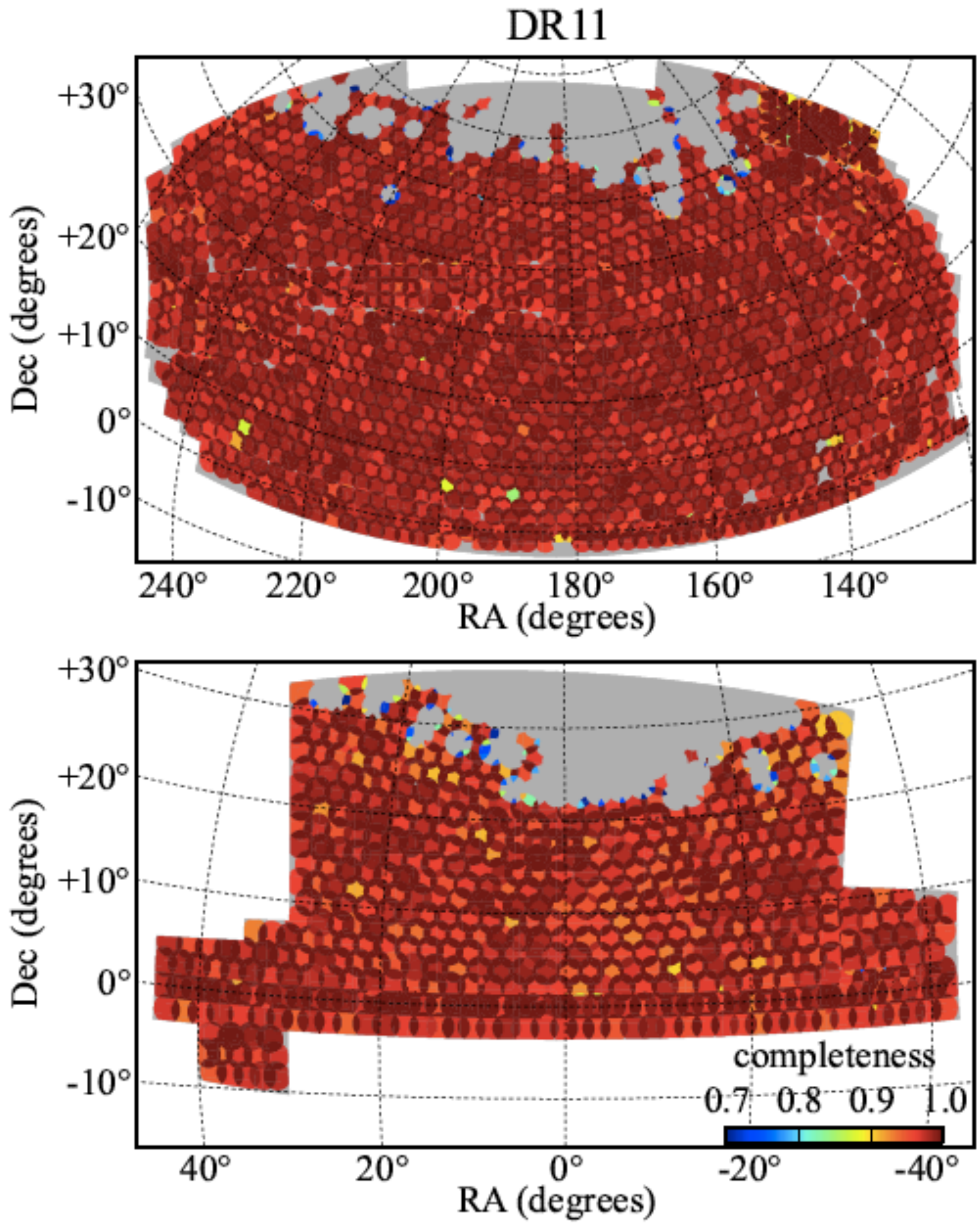


SDSS
LRGS
Main sample

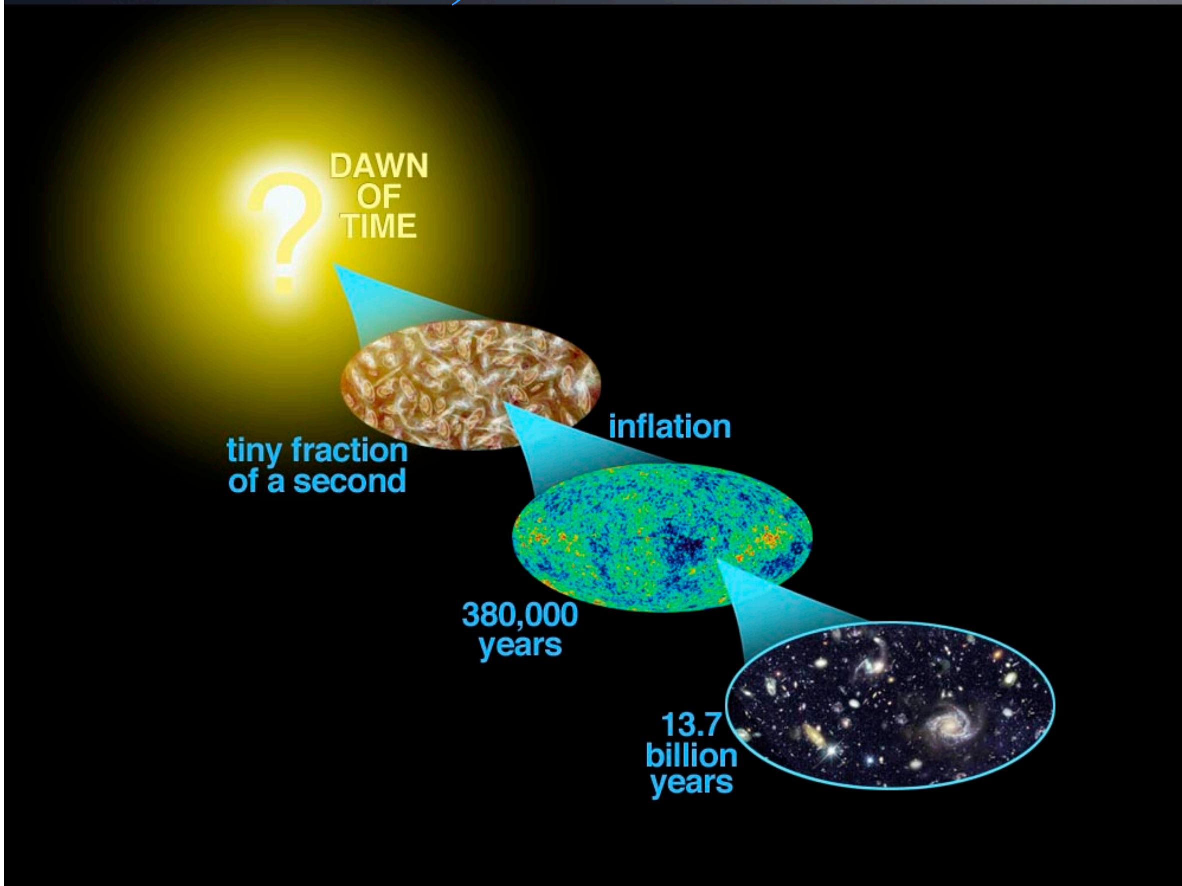
1) Measured redshifts give 3-d galaxy distribution, which has many more modes than projected quantities like CMB or weak lensing

2) Easy to measure: effects of order unity

State of the art:
SDSS DR11
CMASS
1.3M redshifts
over 9000 square
degrees



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…

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

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

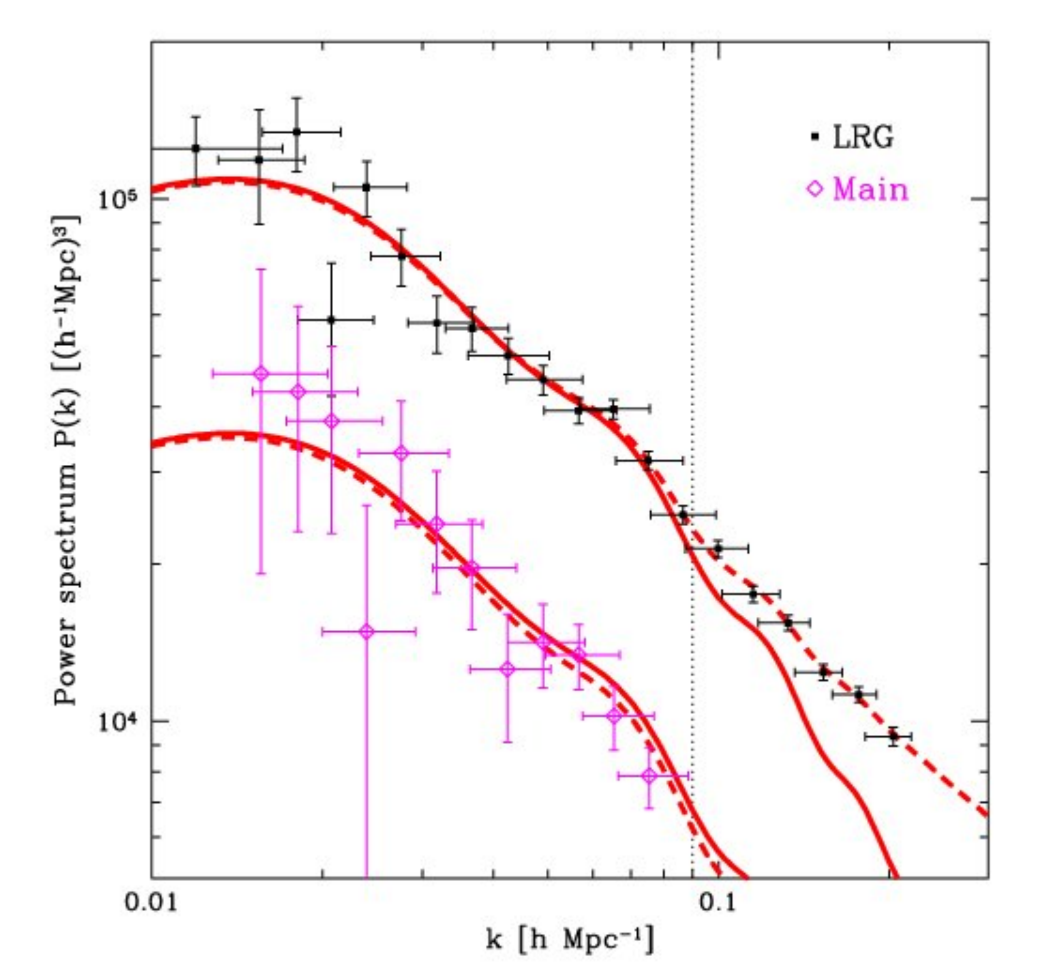
$$\bar{\rho} = \rho_m a^{-3} + \rho_{\rm de} a^{-3(1+w)} + \rho_\gamma a^{-4} + \rho_\nu F(a)$$

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



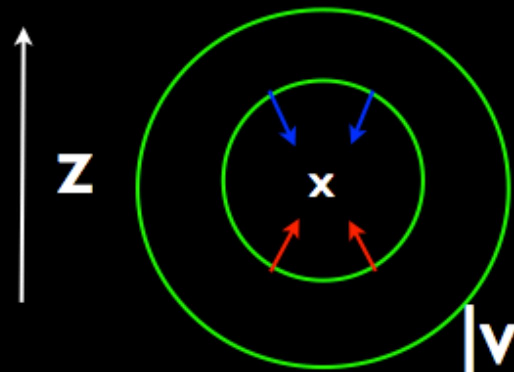
Tegmark et al. (2006)

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

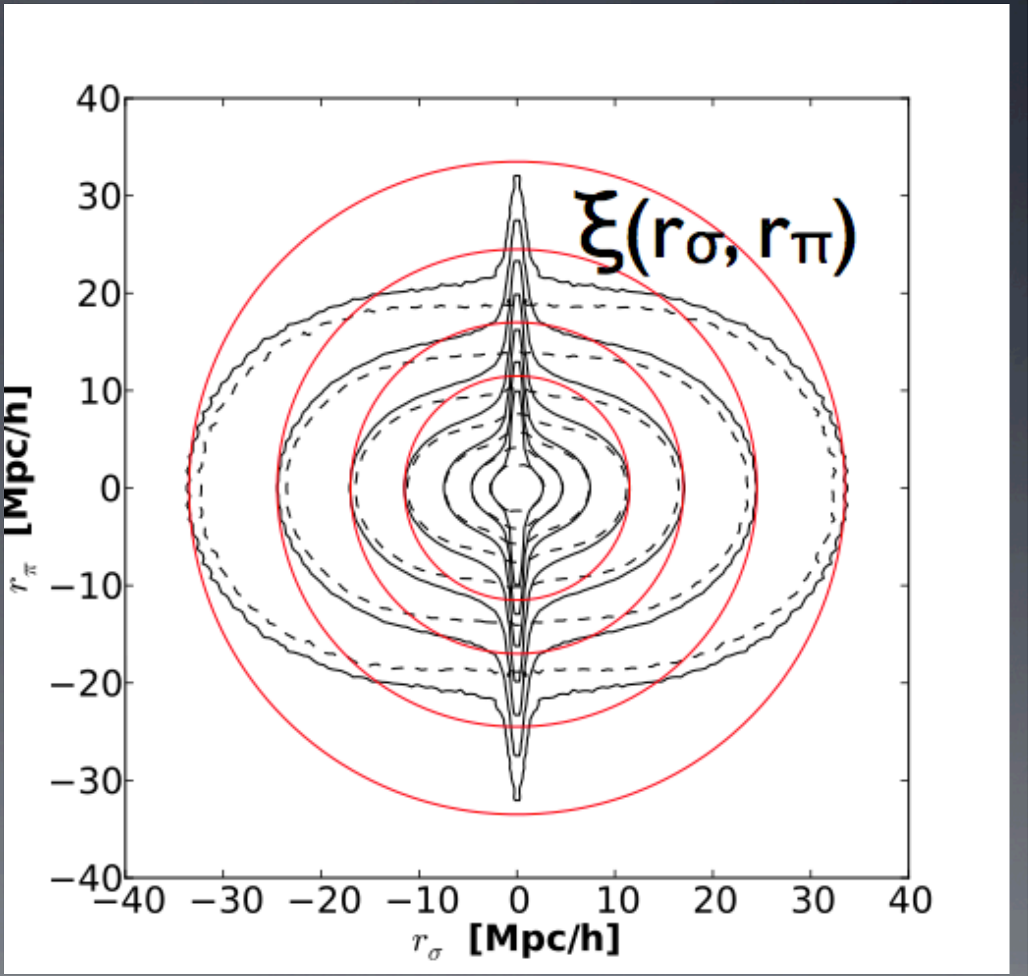
On very large scales linear RSD distortions:

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

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

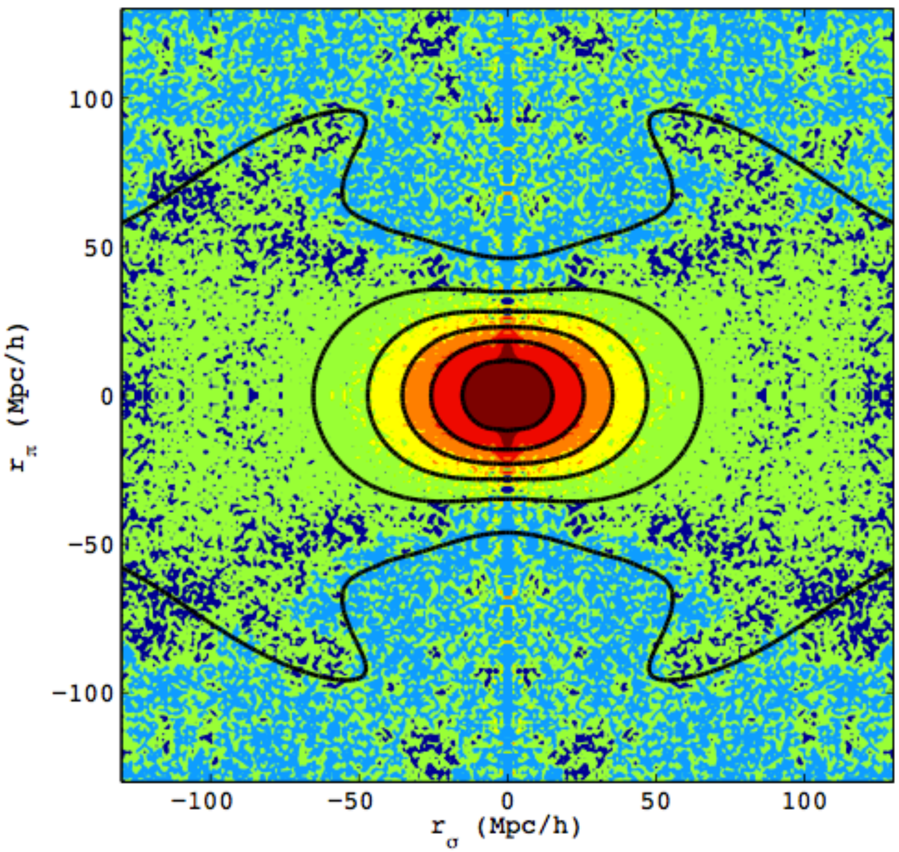
From angular dependence (l=0,2) we can determine velocity power $f\sigma_8$

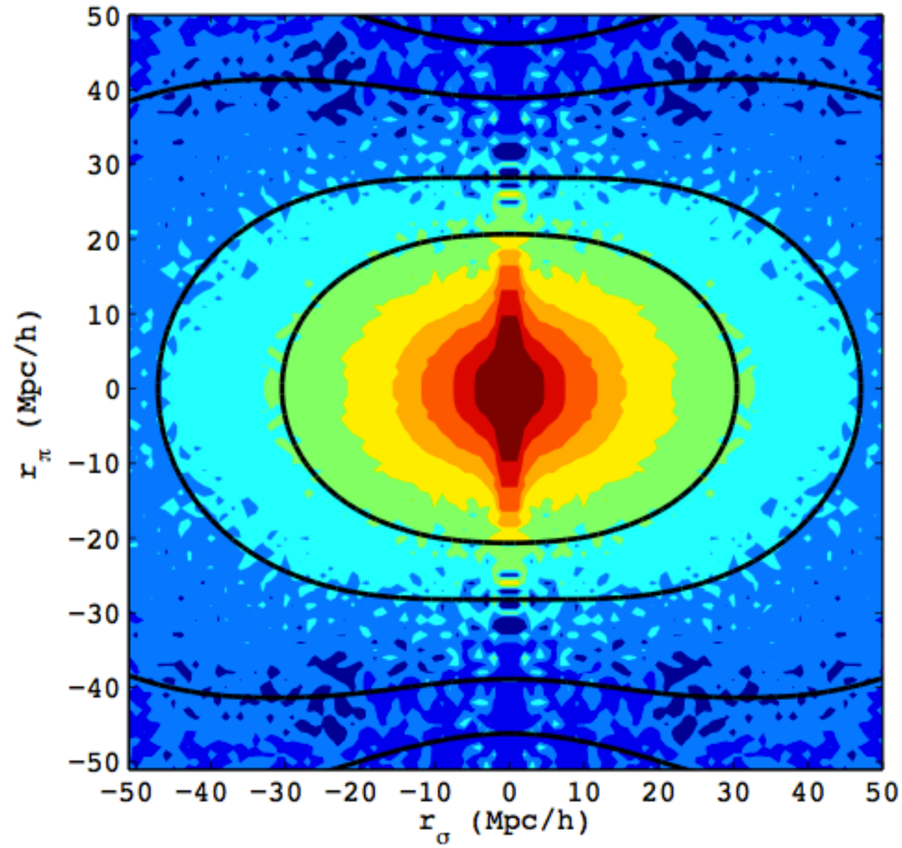
On small scales: virialized velocities within halos lead to FoG, extending radially 10 times farther than transverse



White etal 2011

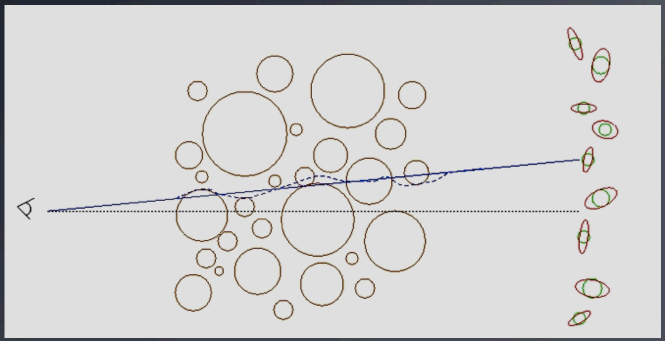
RSD observations state of the art: SDSS-III/BOSS

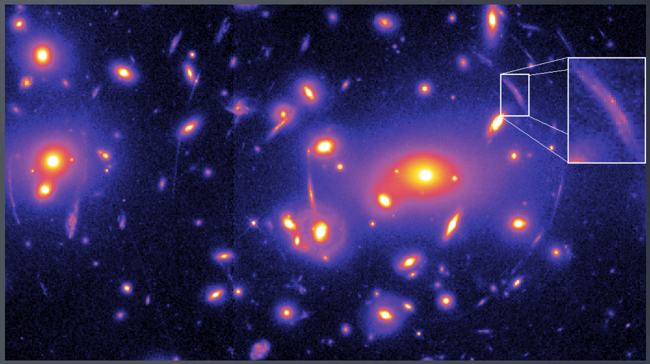




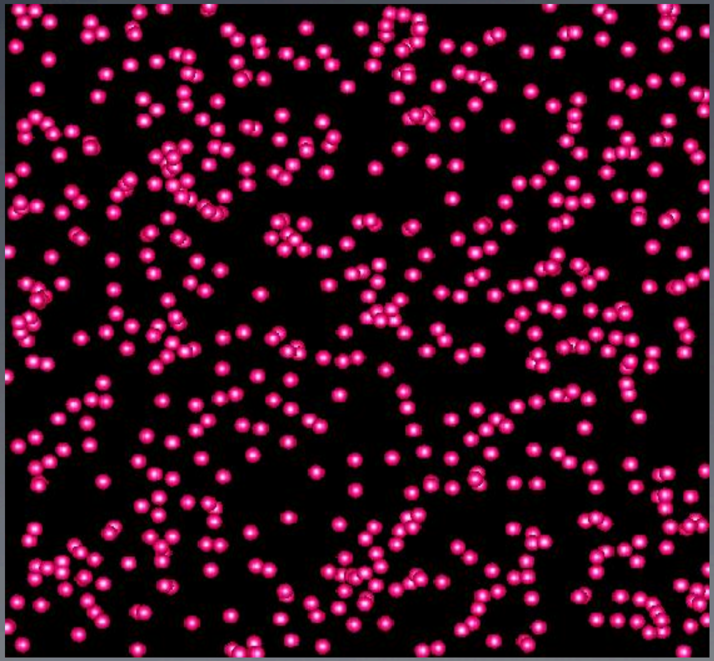
$f\sigma_8$ = 0.415 +/− 0.033 (z=0.57)
(Reid et al 2012)

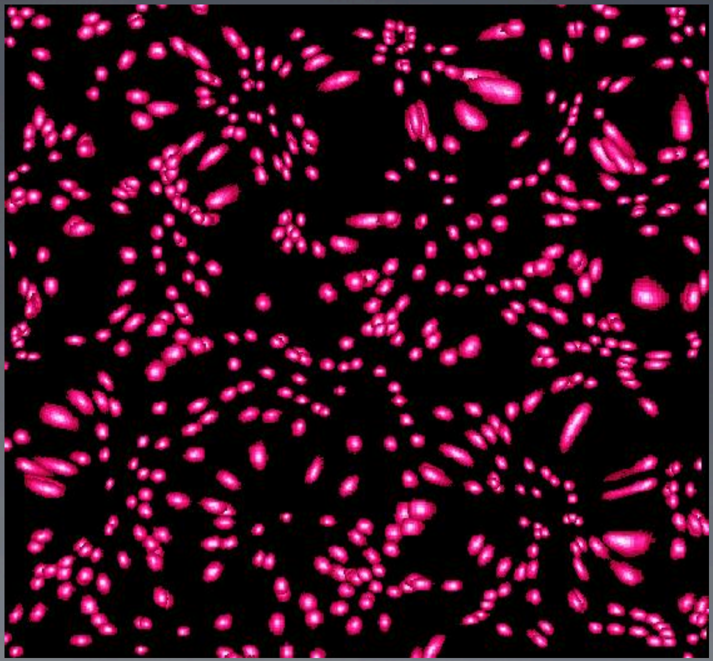
Second LSS Method: Weak Gravitational Lensing: sensitive to total mass distribution (DM dominated)





Distortion of background images by foreground matter





Unlensed **Lensed**

Convergence and shear

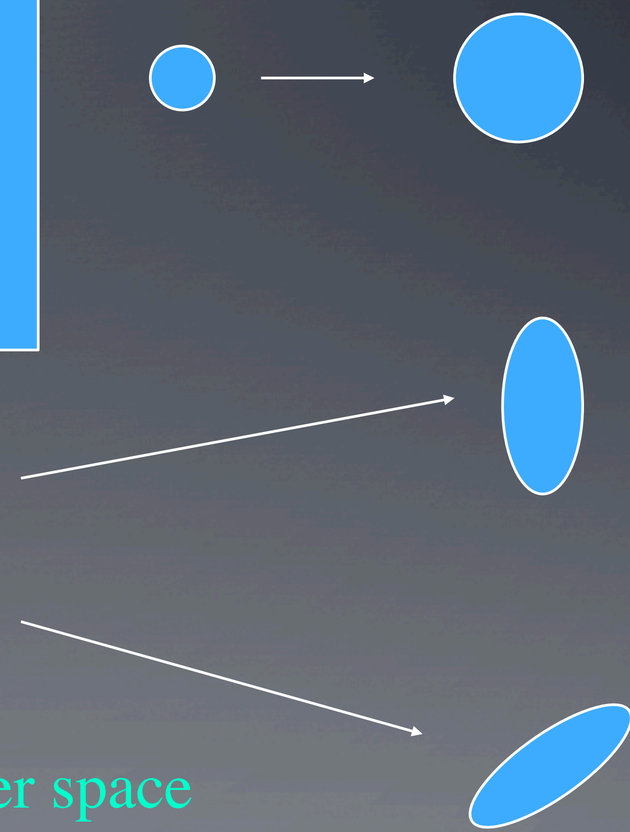
convergence

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

shear

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

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



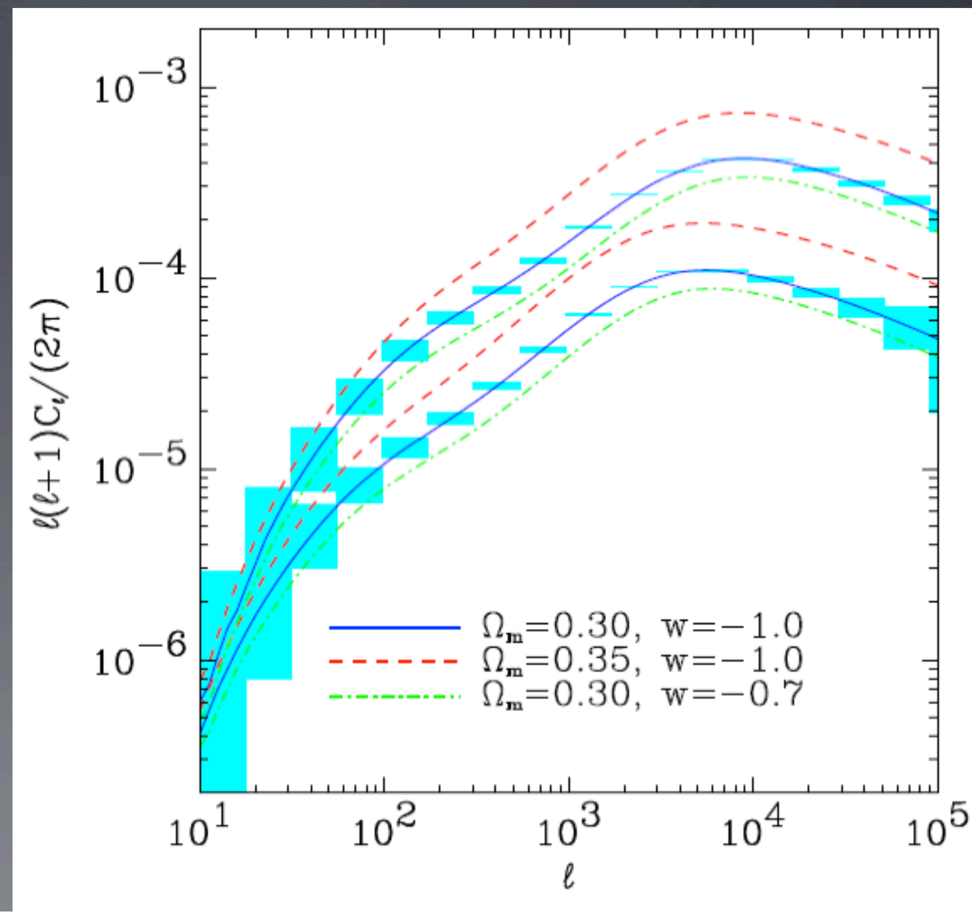
Convergence shear relation in Fourier space

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

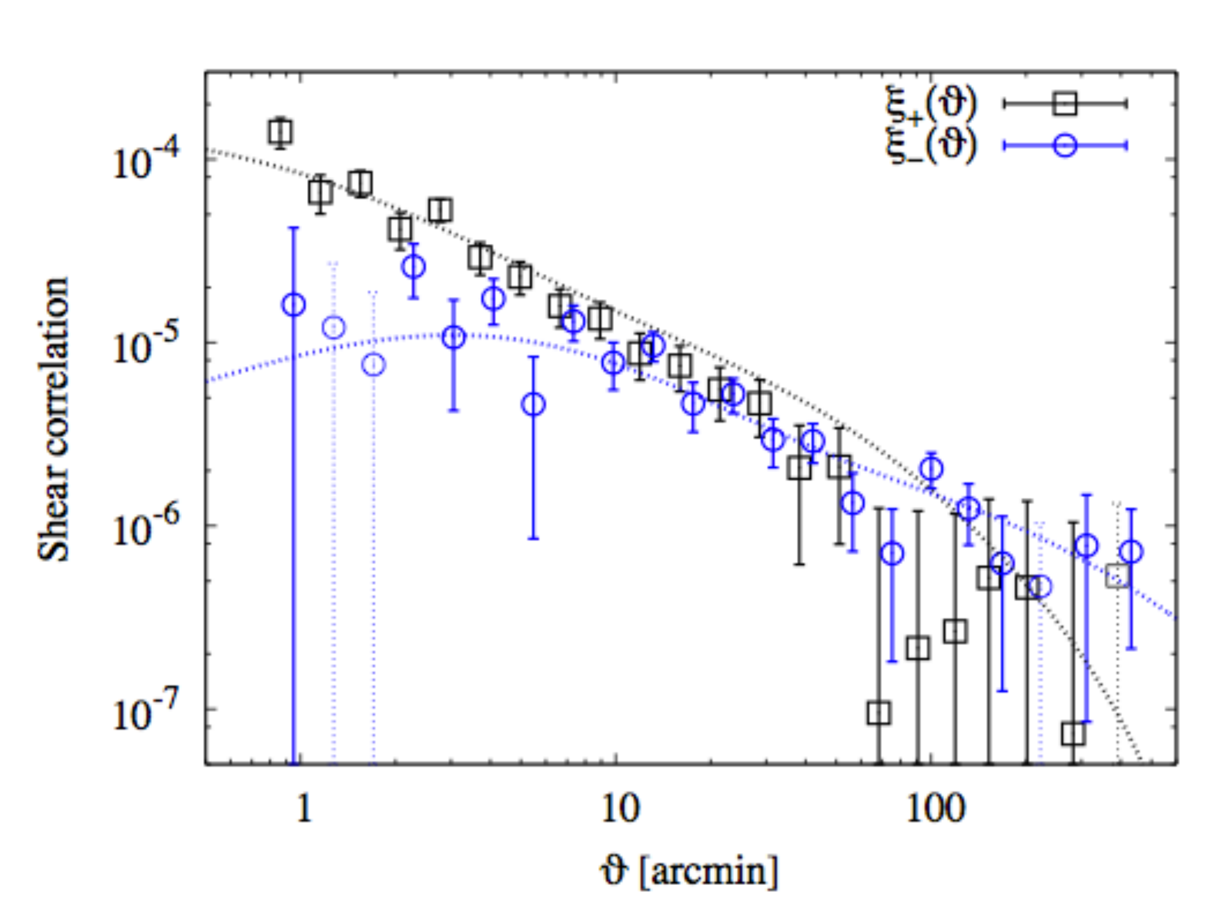
Kiblinger et al 2013

Challenges:

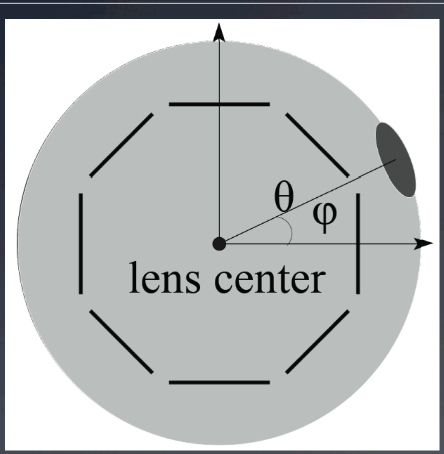
Small scales: could be contaminated by baryonic effects

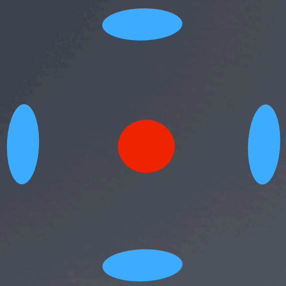
Redshift distributions not completely known

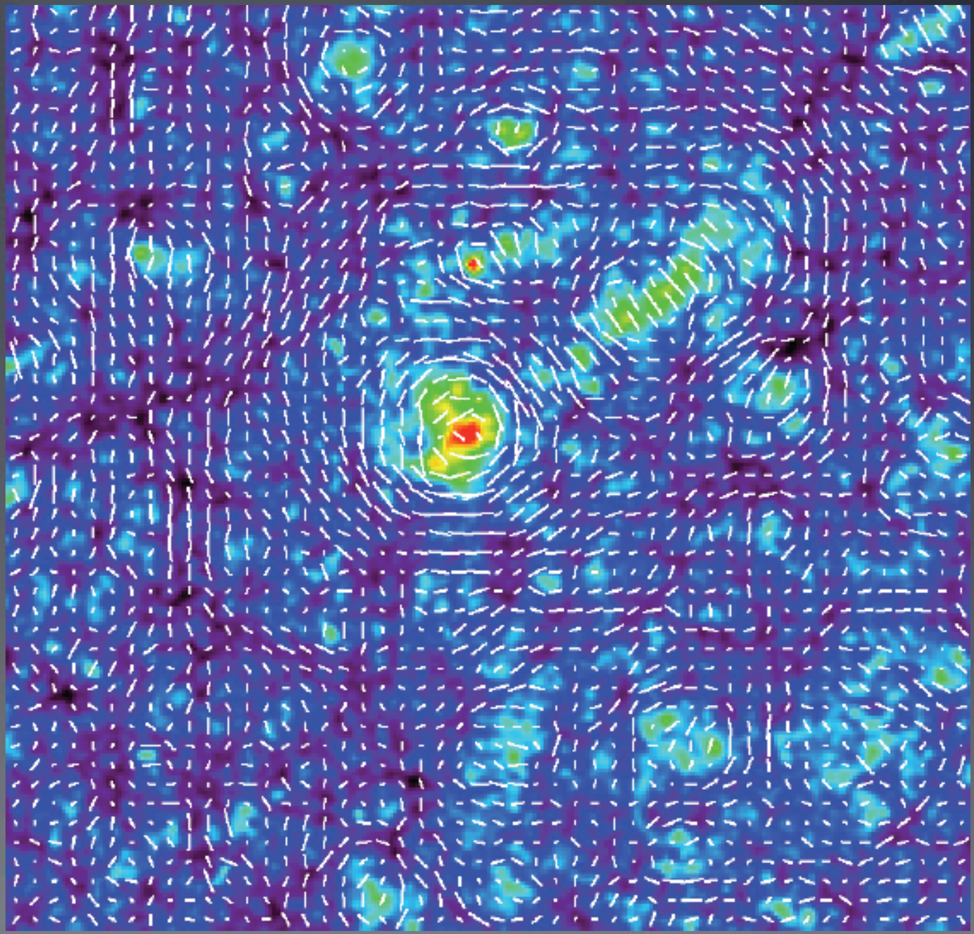
Additive systematics: a lot of data removed



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

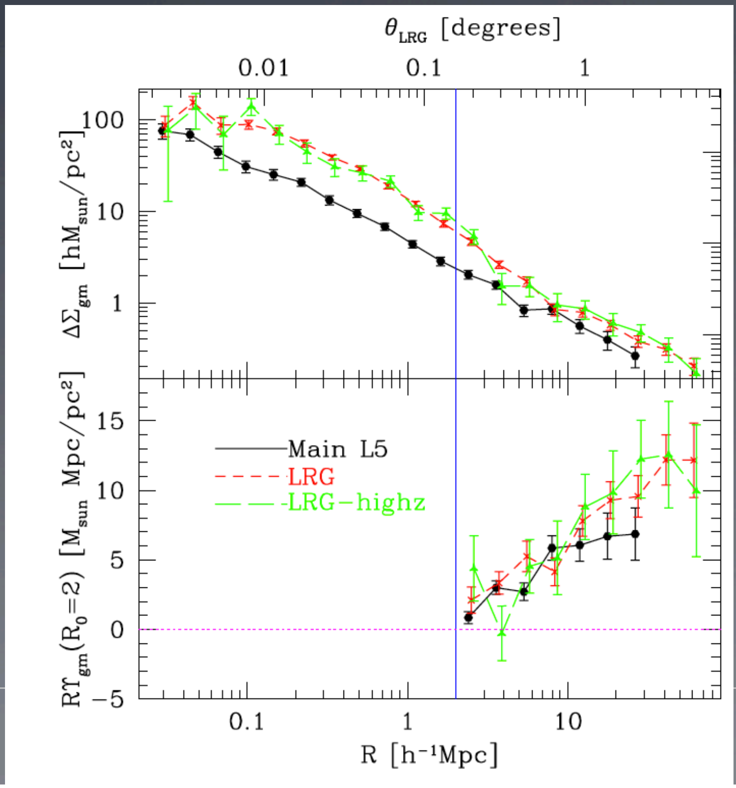
70,000 M*-1 galaxies (z<0.15),

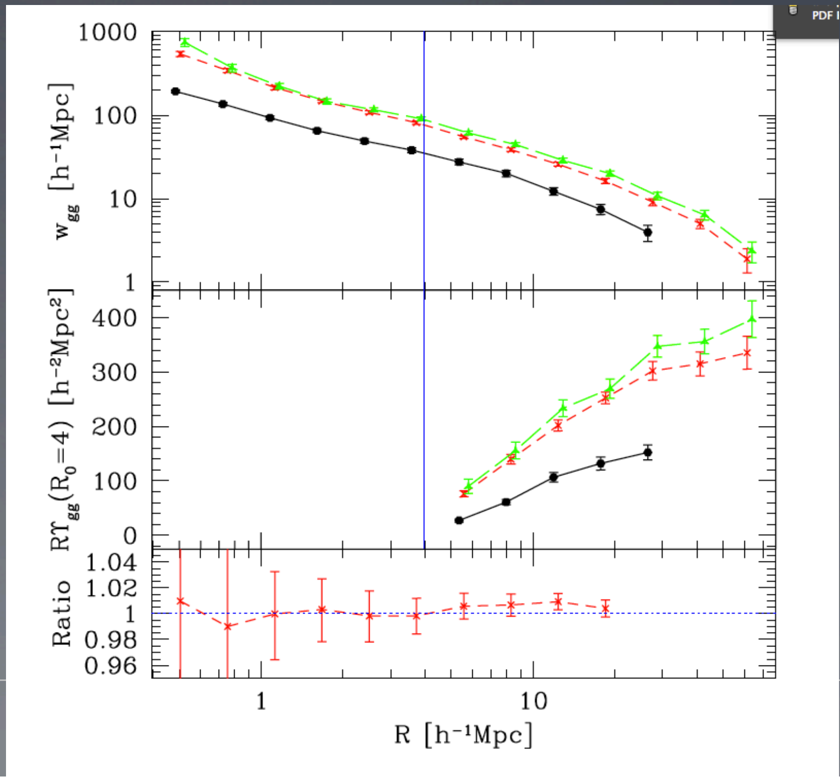
62,000 low z LRGs (0.16<z<0.3),

35,000 high z LRGs (0.36<z<0.47)

SOURCES

10M, well calibrated photozs using spectroscopic surveys



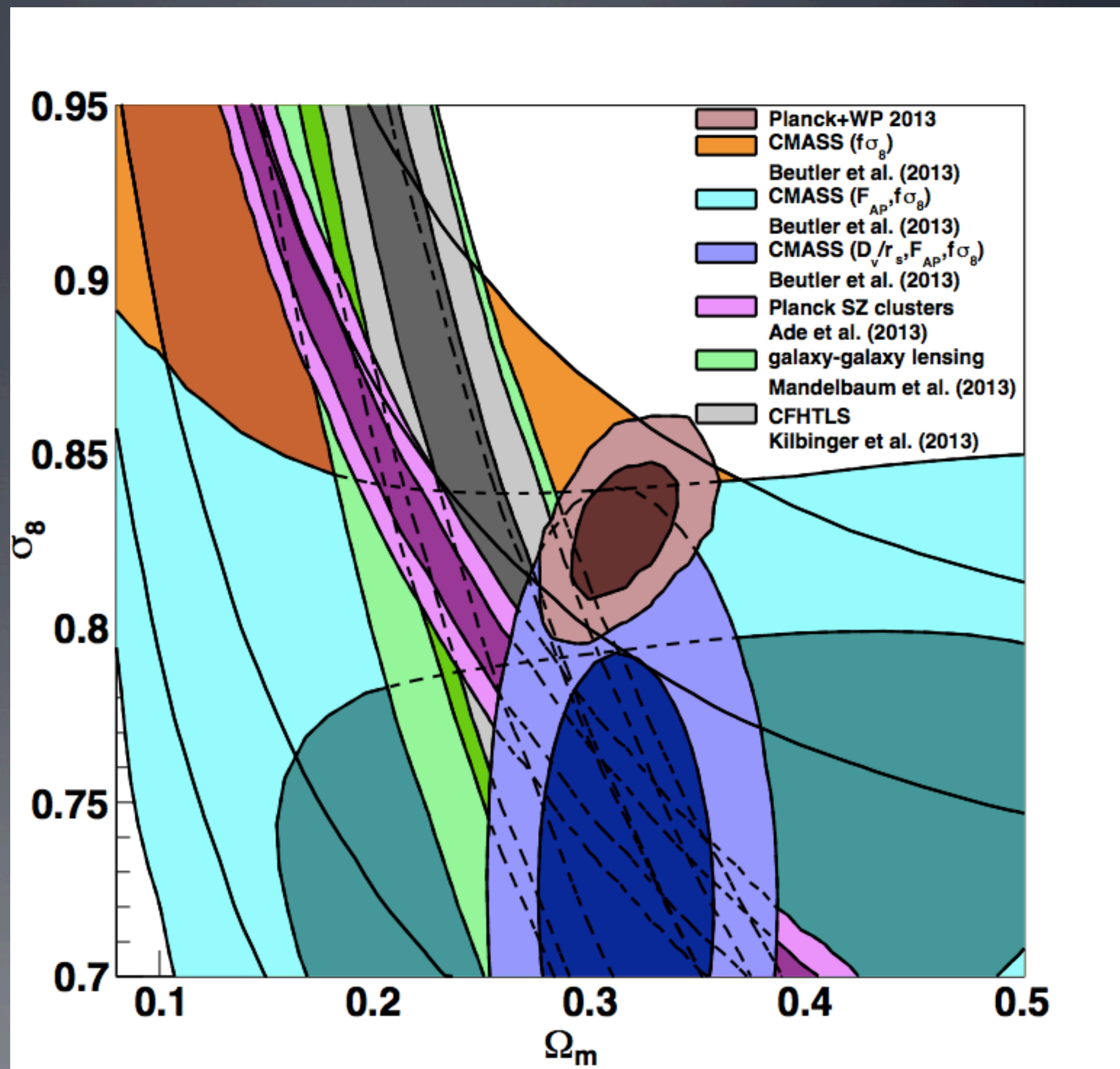


Planck versus LSS tension

All LSS constraints (RSD, lensing, clusters) consistent

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

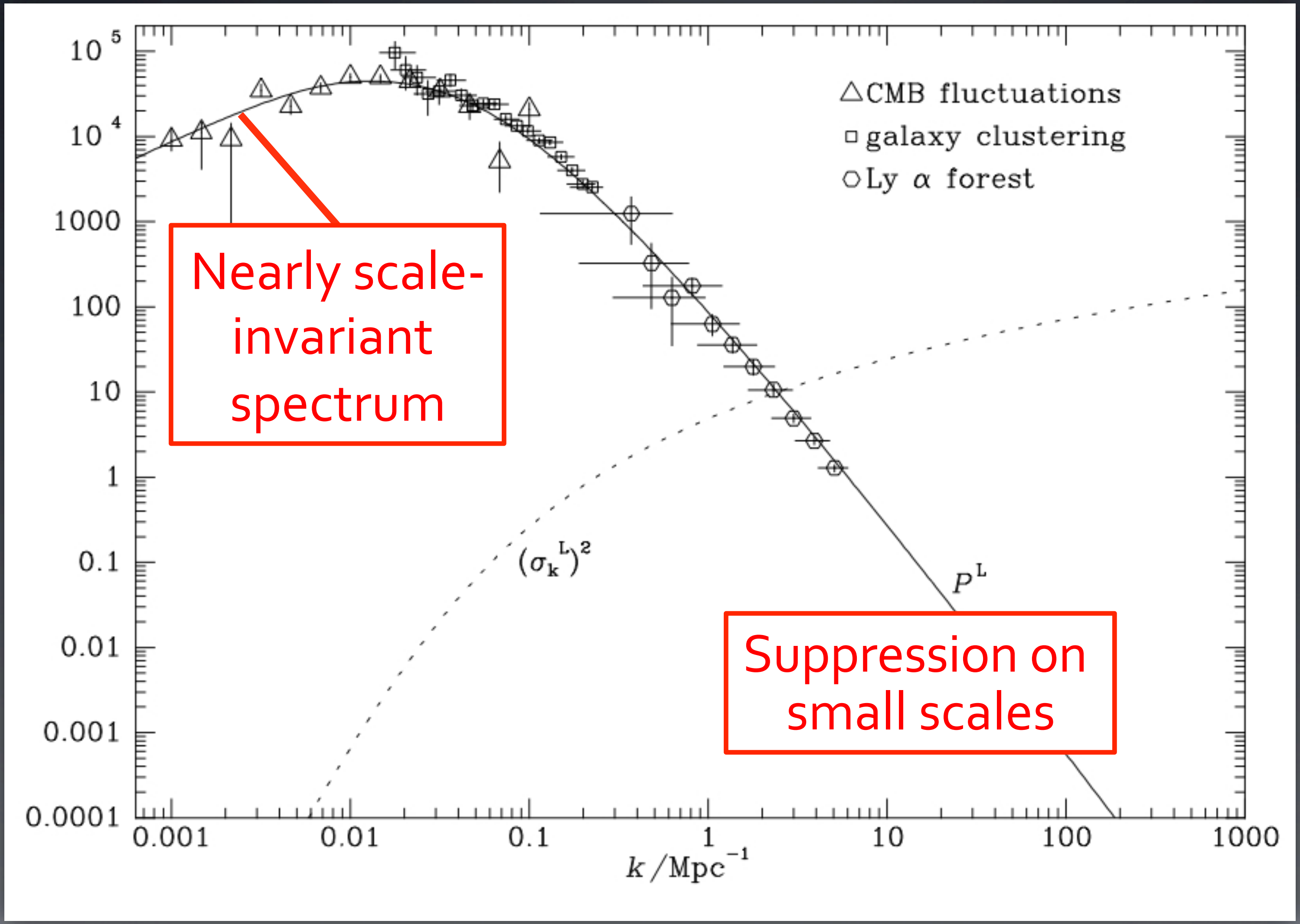
How to resolve this? Planck reanalysis, more LSS data



F. Beutler

3) Shape of matter power spectrum

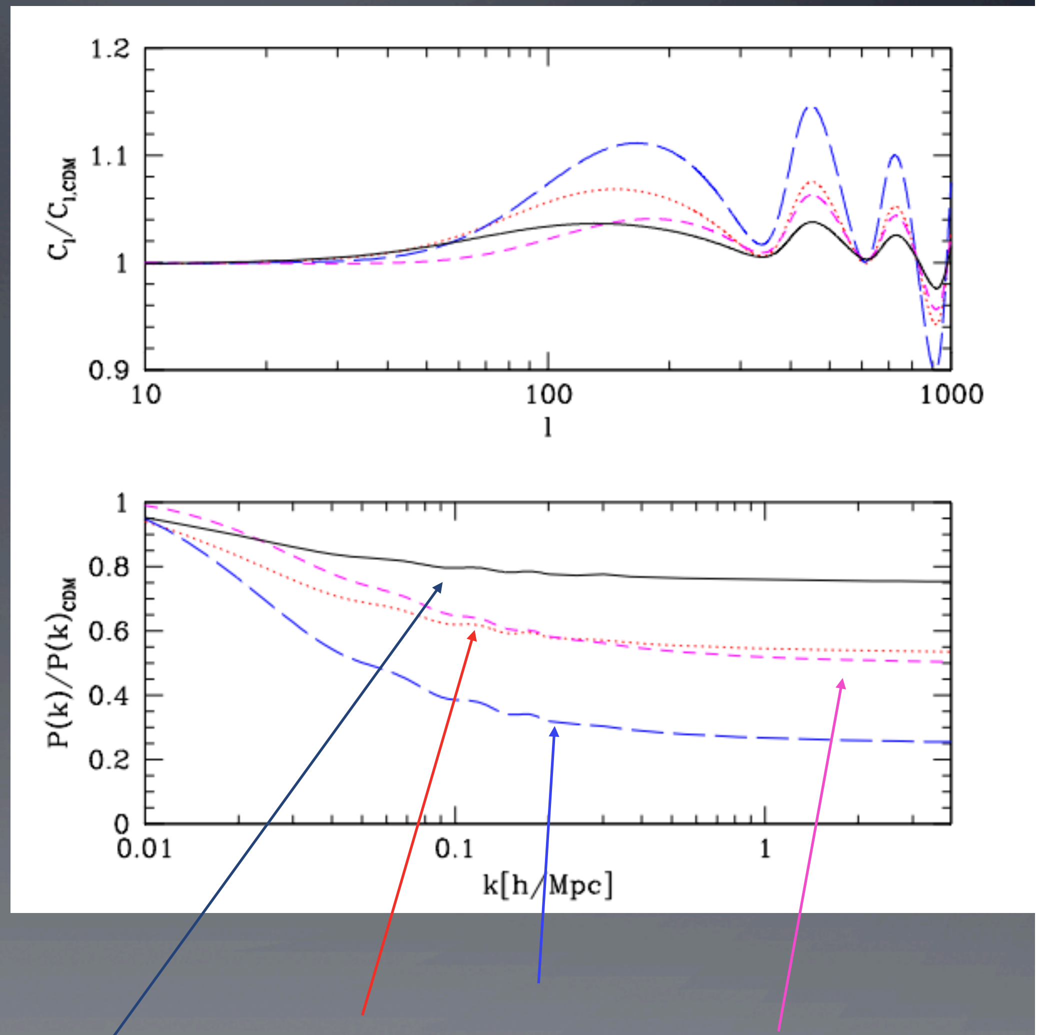
$$\langle \delta(k)\delta^*(k') \rangle = P(k)\delta_D(k - k')$$



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



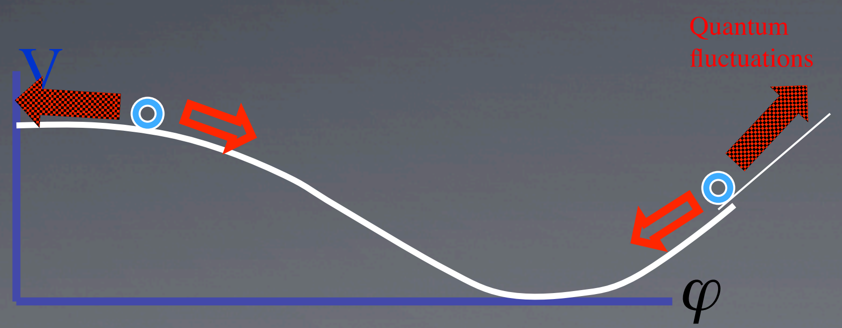
m=0.15x3, 0.3x3, 0.6x3, 0.9x1 eV

Initial conditions: Inflation

Consider a scalar field with non-zero potential

⇨ If V(phi)>> all space and time derivative (squared) terms

$$H^2 = V$$



Scalars $P(k) \propto \frac{H^2}{\dot{\phi}}$

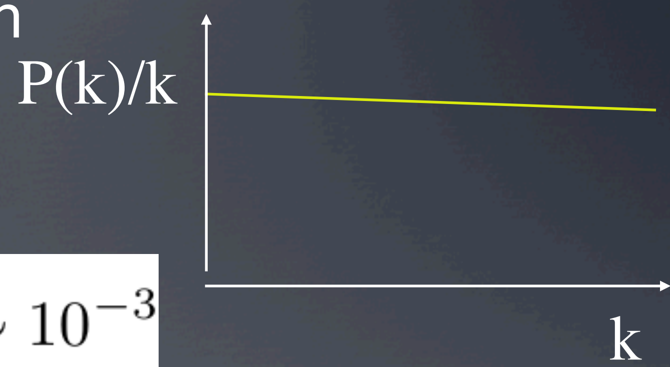
Tensors $P_g = \frac{2}{M_{pl}^2}(\frac{H}{2\pi})^2$

Quantum fluctuations converted into classical space-time perturbations of scalars and tensors (gravity waves)

Inflation predictions

- Inflation must end, number of e-folds 50-60
- Predicts almost scale invariant spectrum

$$P(k) \propto k^{n_s}$$



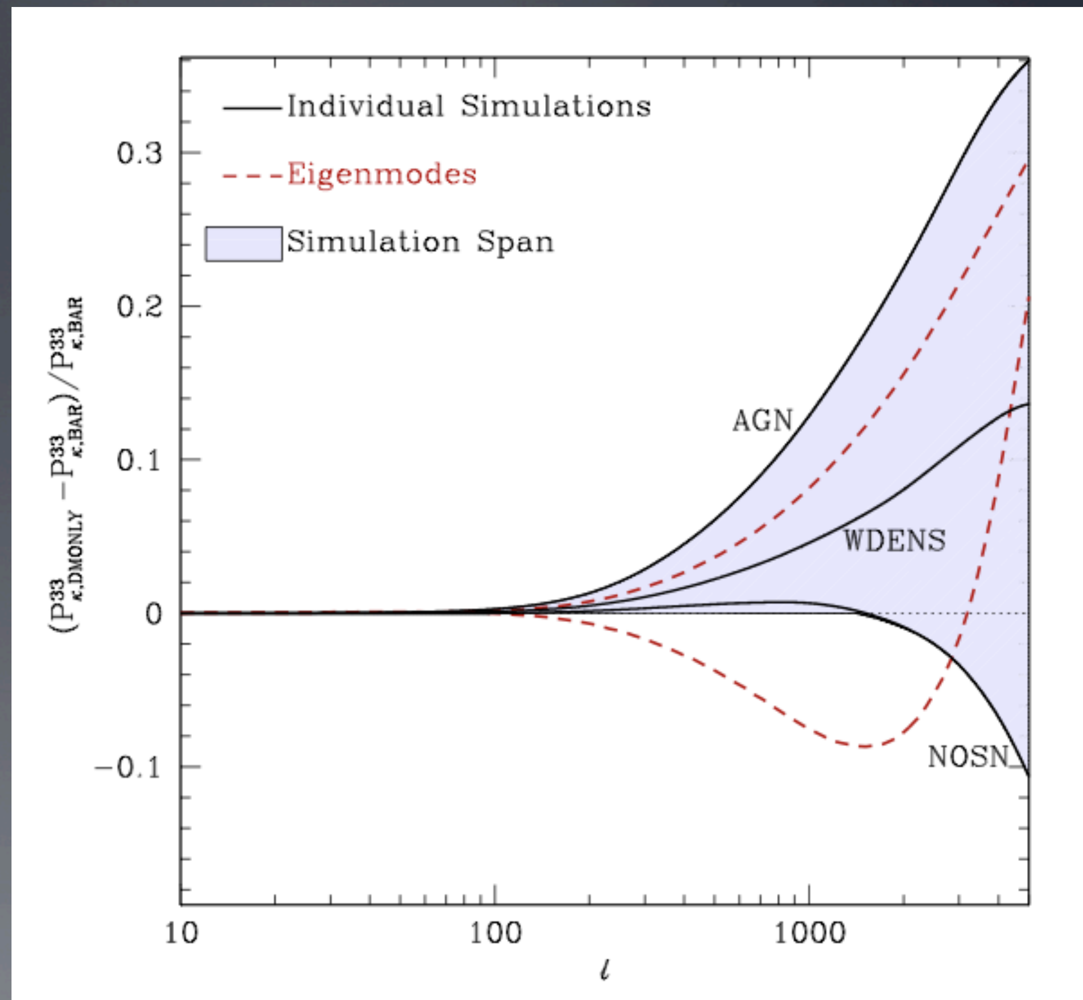
$$|n_s - 1| \sim 10^{-2}, \alpha_s = \frac{dn_s}{d\ln k} \sim (n_s - 1)^2 \sim 10^{-3}$$

LSS+CMB can probe shape of primordial P(k)

Theoretical uncertainties in weak lensing

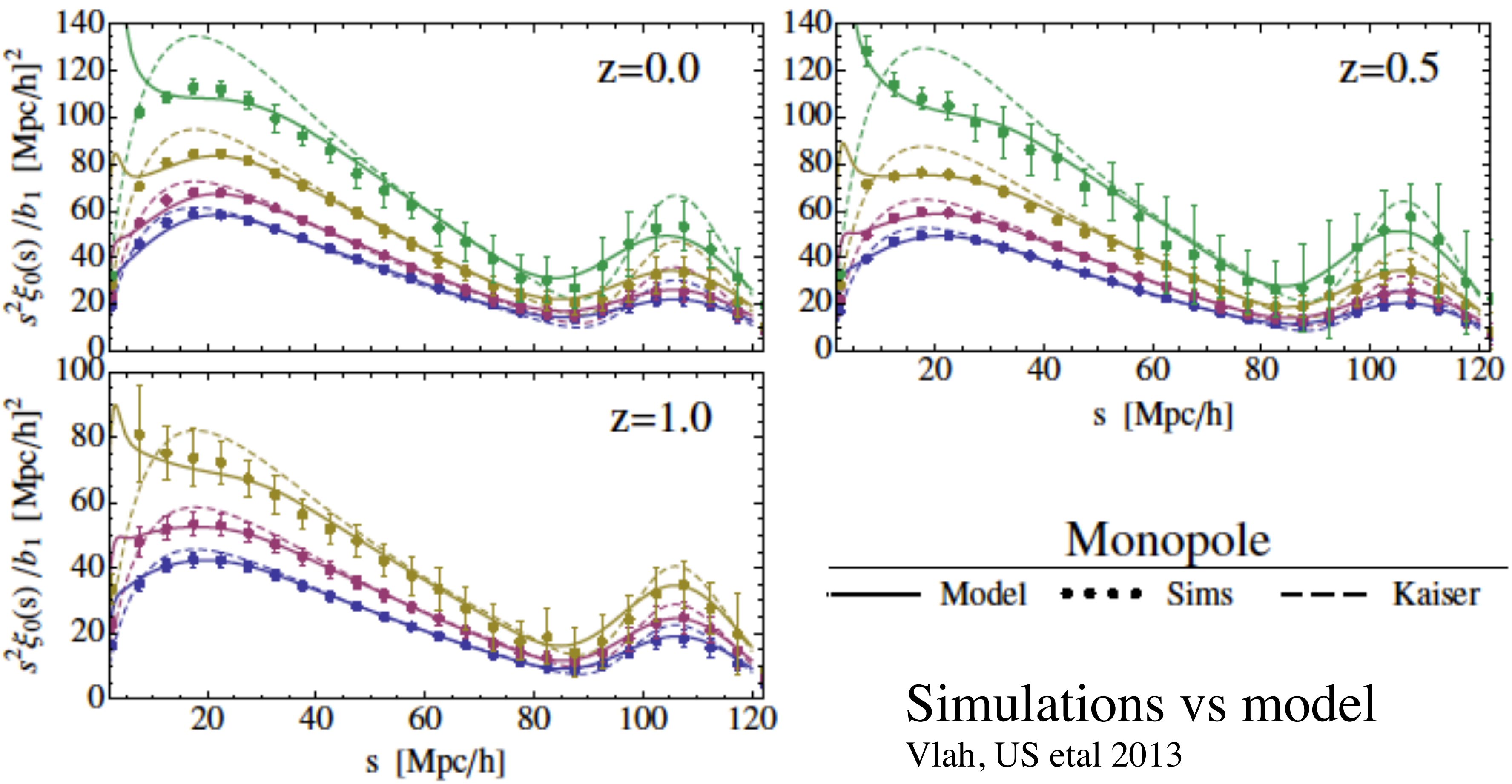
- Baryonic effects: baryons redistribute dark matter inside halos: compress (cooling) or expand (AGN feedback)?

- Challenge: small scale baryonic physics effects can be projected to low l for nearby halos



Zentner et al 2013

Theoretical uncertainties in redshift surveys: nonlinear effects



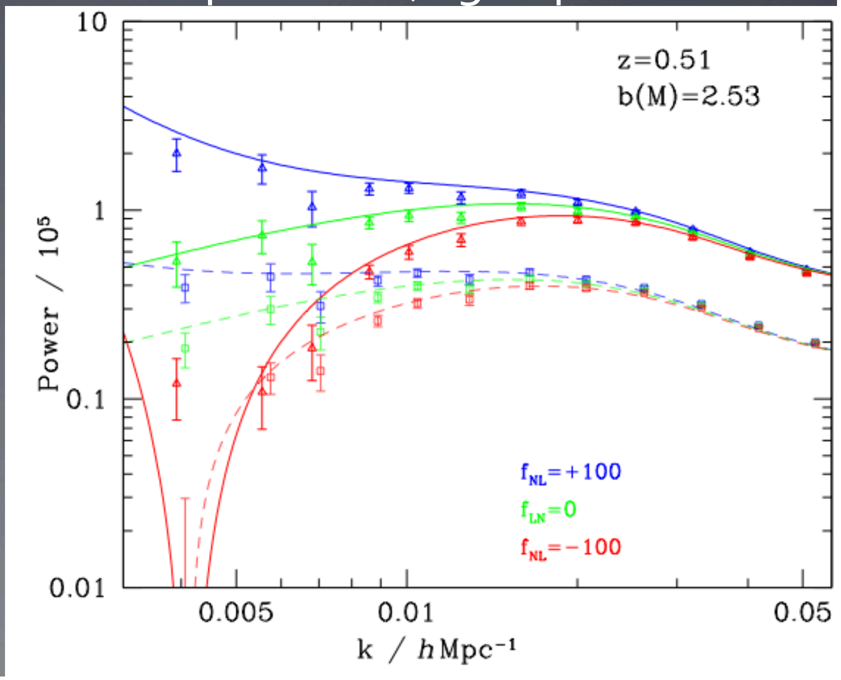
Simulations vs model

Vlah, US etal 2013

Primordial non-gaussianity

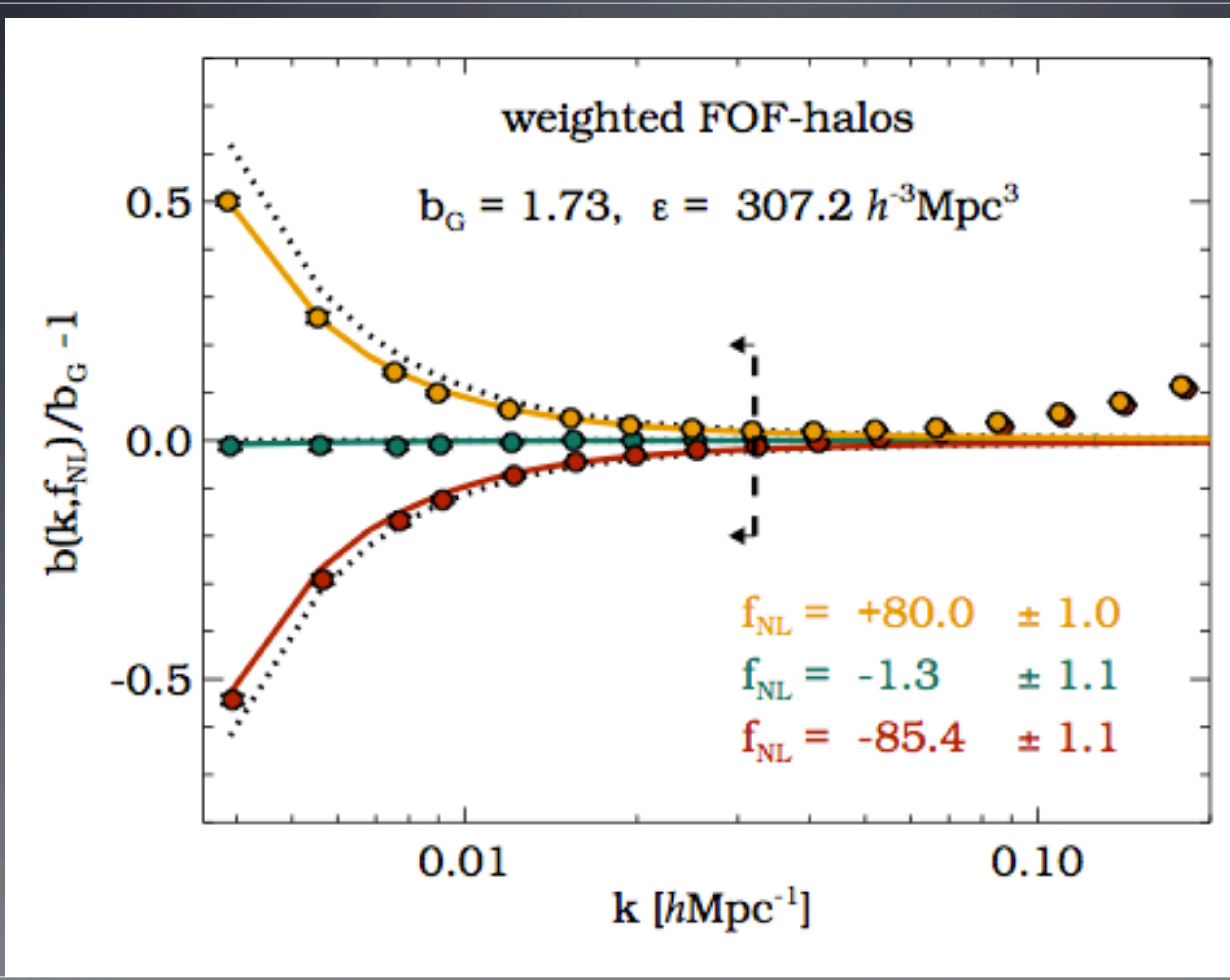
- Local model $\Phi(x) = \Phi_G(x) + f_{NL}\Phi_G^2(x)$
- Simple single field slow roll inflation predicts $f_{nl} \ll 1$
- Inflationary models beyond single field slow roll can give $f_{nl} \gg 1$
- Alternatives to inflation generically give $f_{nl} \gg 1$?
- Other models give different angular dependence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

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



f_{nl} with several tracers

Hamaus, US, Desjacques 2011



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

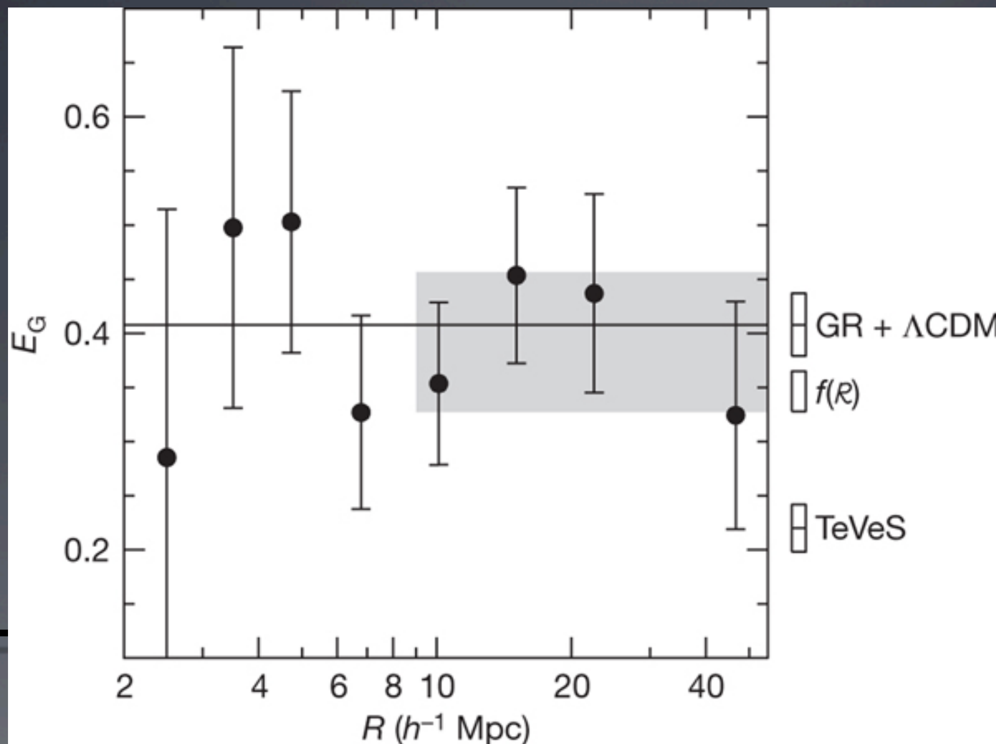
Combining WL and RSD

- By combining redshift space distortion measurements of LRGs with weak lensing measurements and galaxy clustering of the SAME objects we can eliminate the dependence on the amplitude of fluctuations AND bias

$$E_G(R) = \frac{\Delta\Sigma_{gm}}{\beta\Delta\Sigma_{gg}} = \frac{\Omega_{m0}}{f}$$

Zhang etal 2007

Combining RSD with weak lensing: modified gravity tests



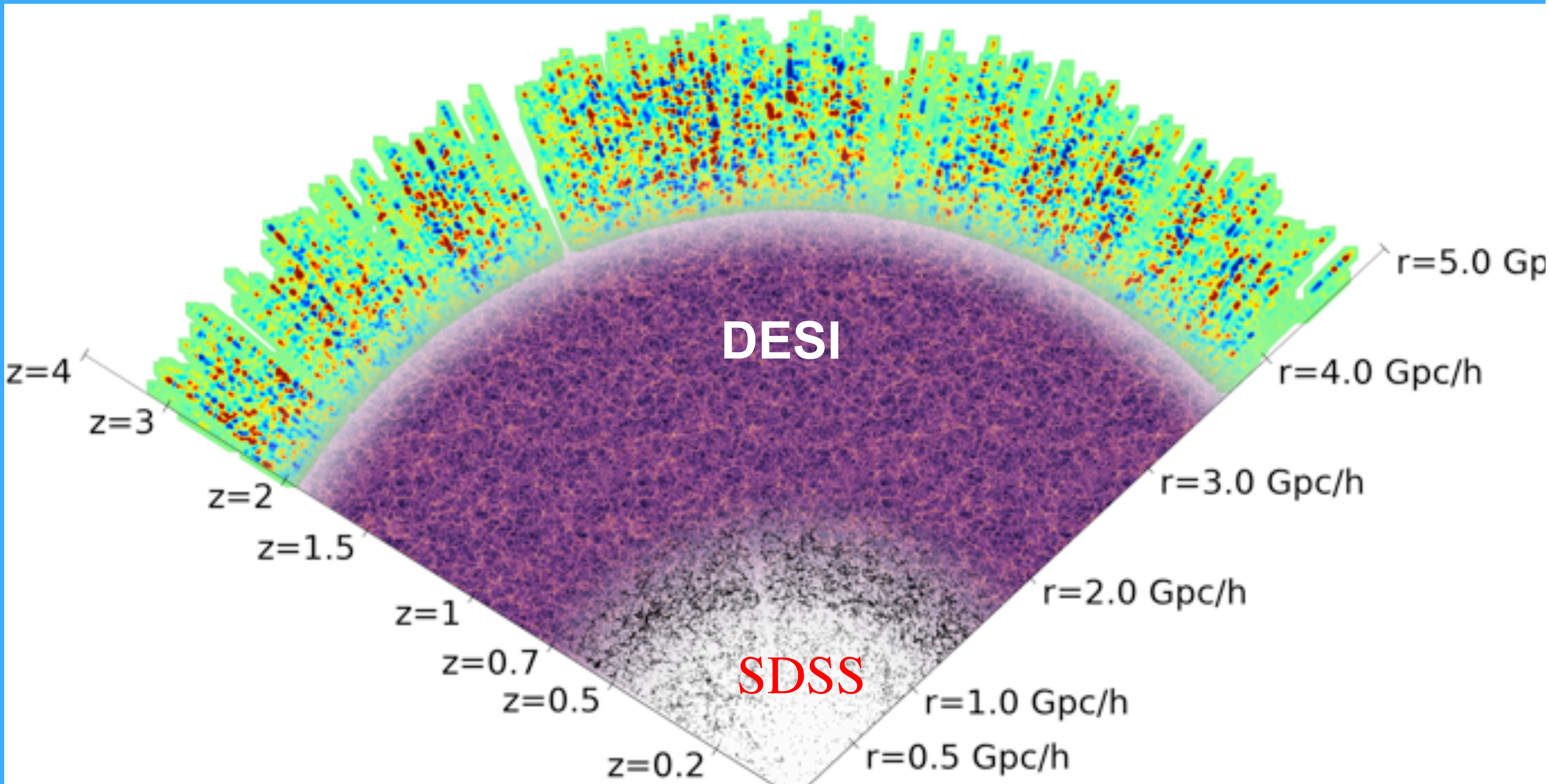
R Reyes *et al.* *Nature* **464**, 256-258 (2010) doi:10.1038/nature08857

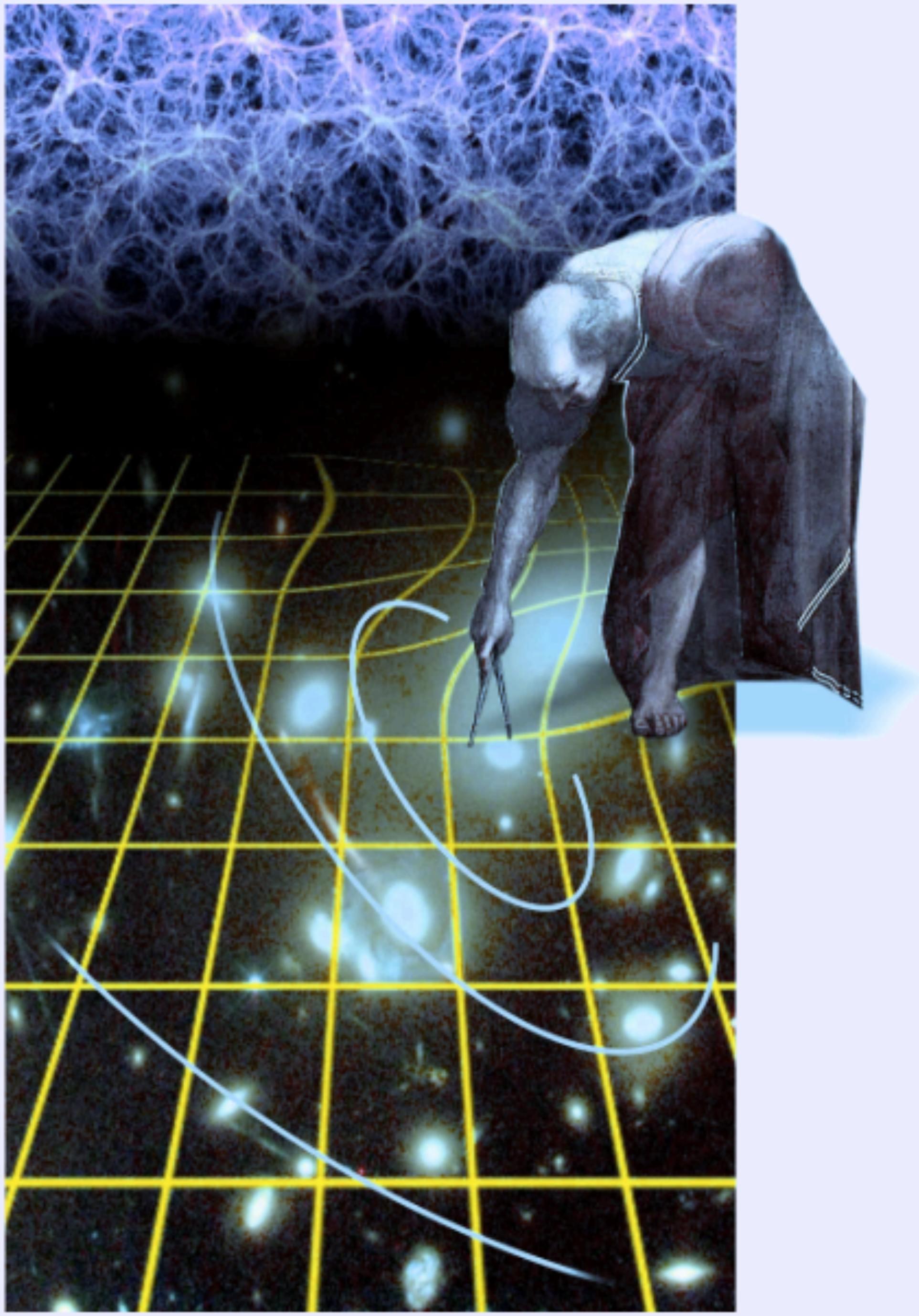
First detection, with BOSS/SDSS-III 25 sigma

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
- Recent galaxy clustering results from SDSS III: BAO to 1%, amplitude to 6%
- Recent WL result from CFHT-LS, SDSS: amplitude to 3-6%
- Some tension with Planck in current data
- Challenges: nonlinear effects
- Future LSS surveys: huge efforts, 2 planned satellites, numerous ground based efforts, up to an order of magnitude improvements over current constraints