Large scale structure: weak lensing and galaxy clustering

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Overview

- Setting the stage: why do we care?
- Galaxy-dark matter connection
- Shot noise and sampling variance errors
- Searching for non-gaussianity in galaxy surveys

Collaborators: R. Mandelbaum, R. Reyes, A. Slosar, C. Hirata, R. Nakajima, T. Baldauf, N. Hamaus, L. Lombriser, V. Desjacques, P. McDonald, T. Okumura, Z. Vlah, R. Smith, M. Sato, J. Gunn…

Big questions in cosmology today

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) or alternatives (cyclic/ekpyrotic…)

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

Any one of these is a potential probe of string theory!

How to answer them?

1) Classical tests: redshift-distance relation (SN1A, BAO, AP etc)…

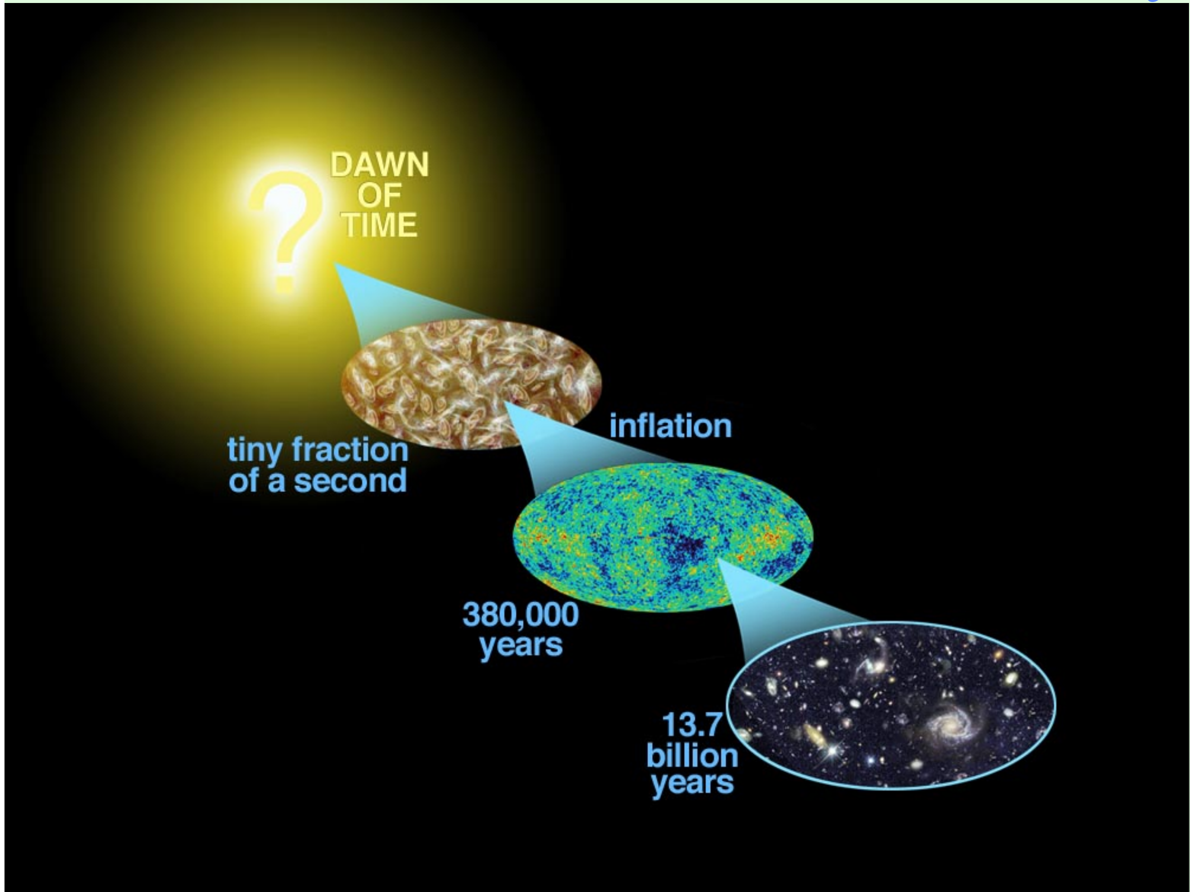
2) Growth of structure: CMB, Ly-alpha, weak lensing, clusters, galaxy clustering

   Scale dependence of structure (same tracers as above)

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

3) Tests of primordial non-gaussianity

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, clusters z=0-2

Sensitive to dark energy, neutrinos…

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

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

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

Scale dependence of cosmological probes

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

WMAP

$z \approx 1088$

CBI ACBAR

Lyman alpha forest

SDSS

$z \approx 0$

$z \approx 3$

Galaxy clustering

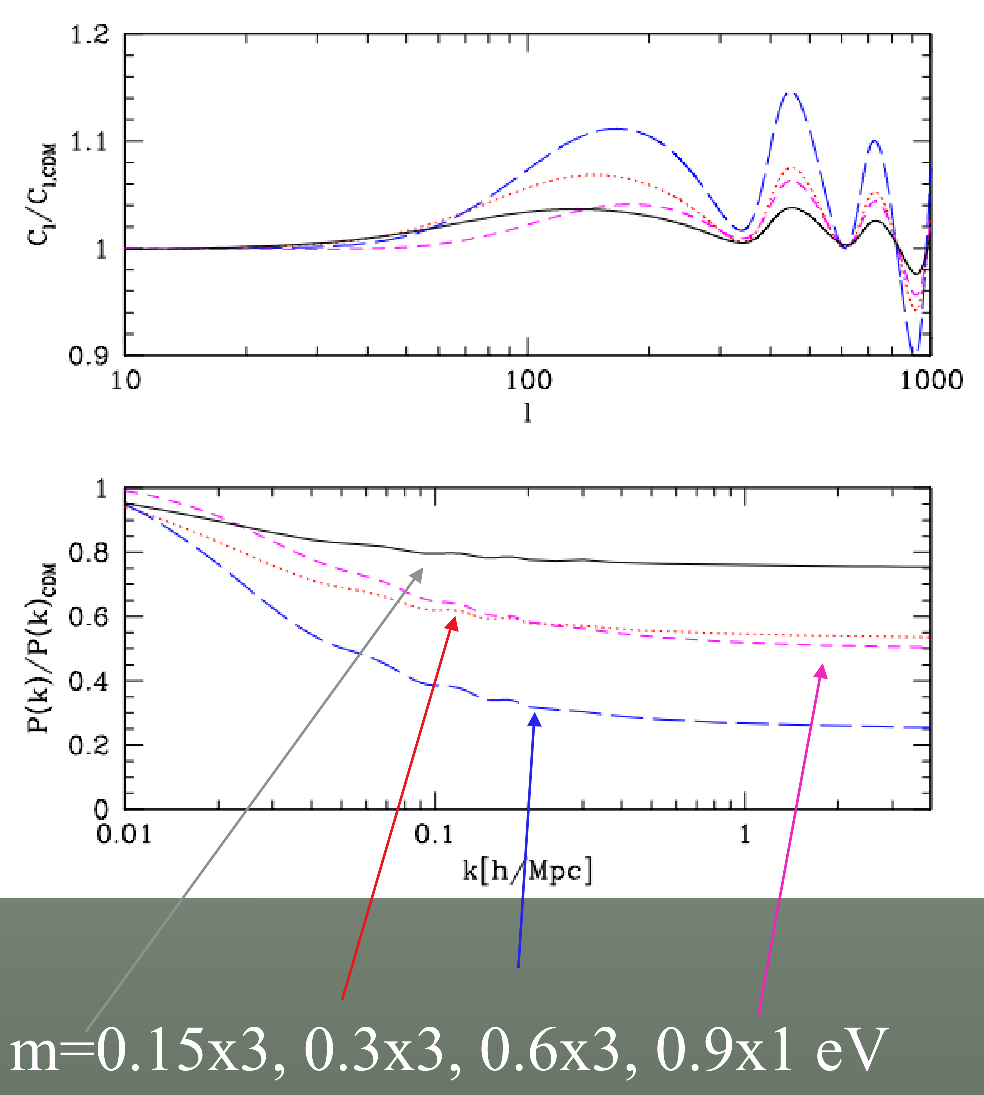
Weak lensing

Cluster abundance

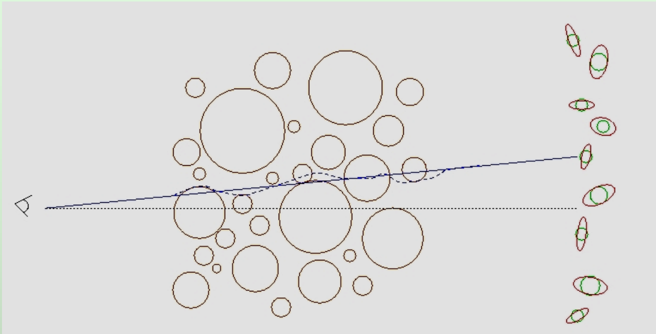
Complementary in scale and redshift

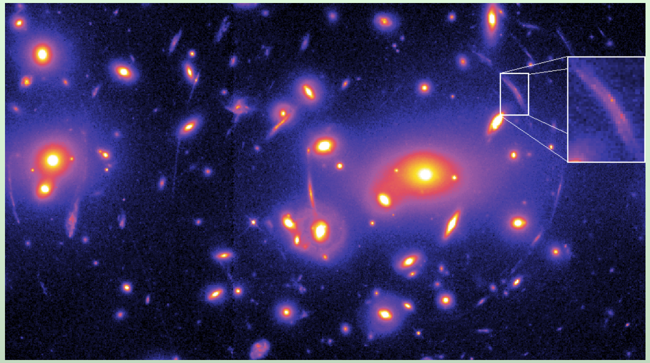
Weighing neutrinos

- Neutrino mass is of great importance in particle physics (are masses degenerate? Is mass hierarchy inverted?): large next generation experiments proposed
- 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
- For m=0.1-1eV free-streaming scale is >>10Mpc
- Neutrinos are quasi-relativistic at z=1000: effects on CMB also important (anisotropic stress etc)
- opposite sign, unique signature!

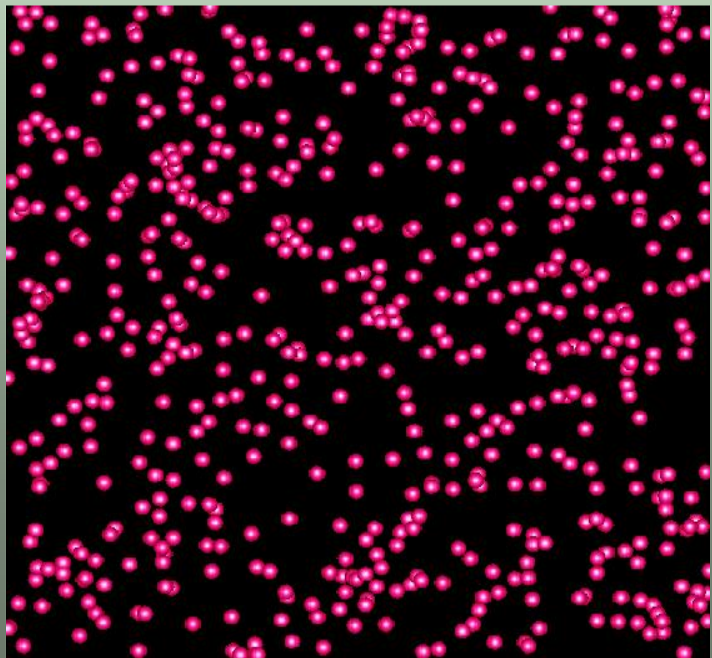


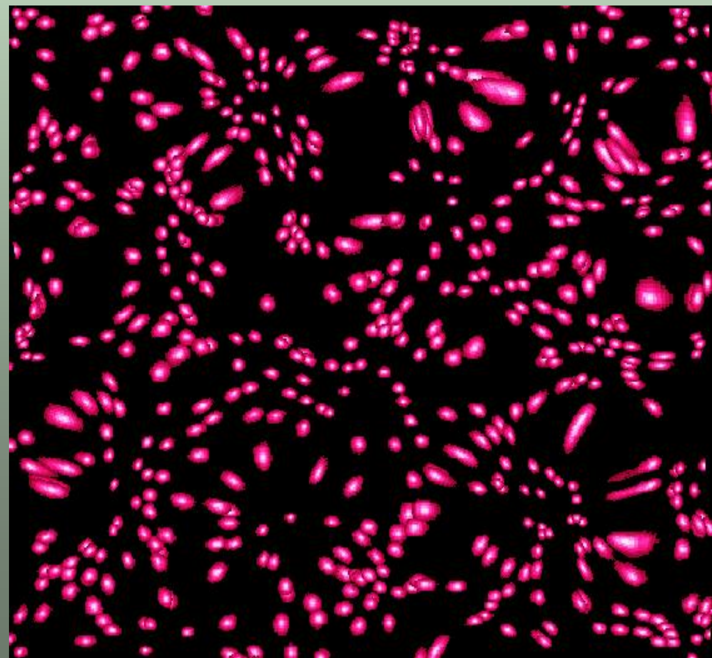
Weak Gravitational Lensing





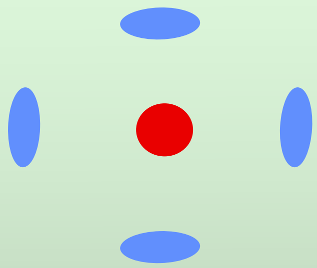
Distortion of background images by foreground matter

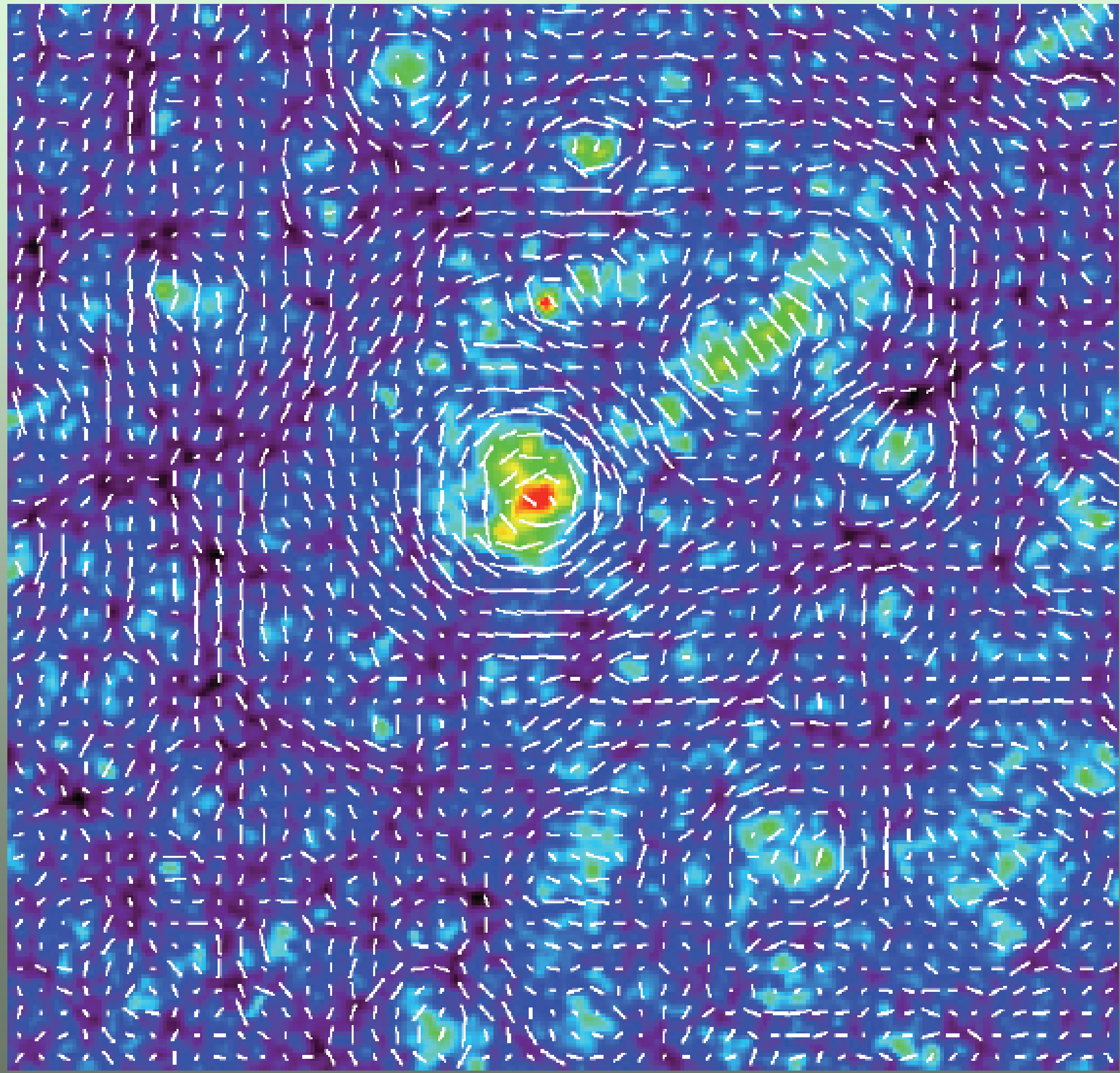




Unlensed   Lensed

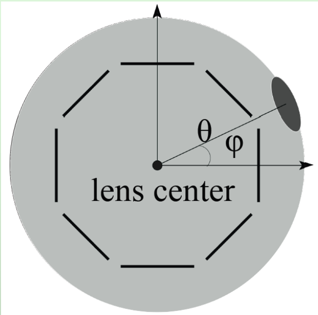
Halo-shear lensing : galaxy or cluster-dark matter correlations

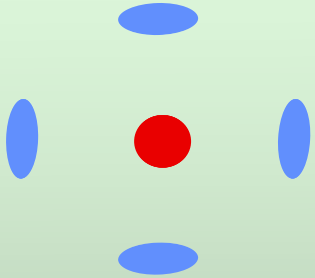




- dark matter around galaxies/clusters induces tangential distortion of background galaxies
- Specially useful if one has redshifts of foreground galaxies

Galaxy-dark matter correlations: galaxy-galaxy lensing





$$R = r_L \Theta$$

$$\gamma_T = \frac{\Delta\Sigma(R)}{\Sigma_{\rm crit}}$$

$$\Delta\Sigma(R) = \bar{\Sigma}(R) - \Sigma(R)$$

$$\Sigma(R) = \int \rho(\sqrt{R^2 + \chi^2})d\chi$$

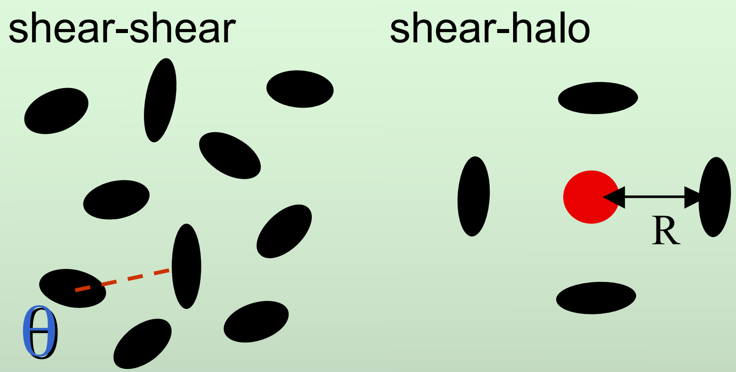
$$\Sigma_{crit} = \frac{c^2}{4\pi G} \frac{D_S}{D_L D_{LS}(1+z_L)^2}$$

♦+: Express signal in terms of projected surface density and transverse separation R: one projection less than shear-shear correlations

♦+: with photozs not sensitive to intrinsic alignments

♦-: for LSS one needs to model cross-correlation coefficient between dark matter and galaxies: simulations

Halo-shear versus shear-shear lensing

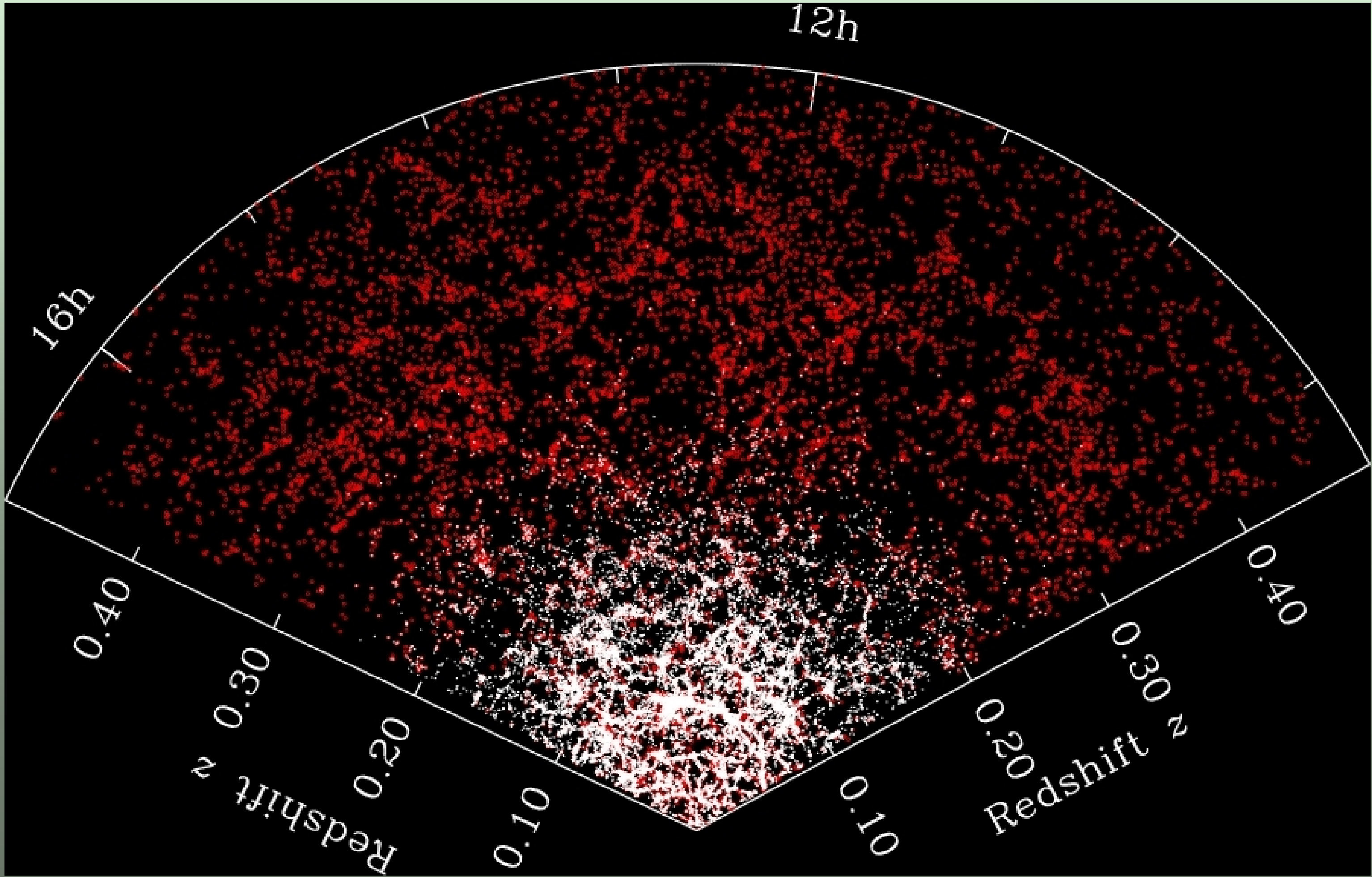


	shear-shear	shear-halo
• Calibration bias:	-	-
• Intrinsic alignments:	-	+?
• Photoz induced errors:	-	-
• Instrument/sky induced correlations:	-	+?
• Baryonic effects:	-	+
• Statistical power:	-	+

Lessons from last decade: shear-shear is difficult

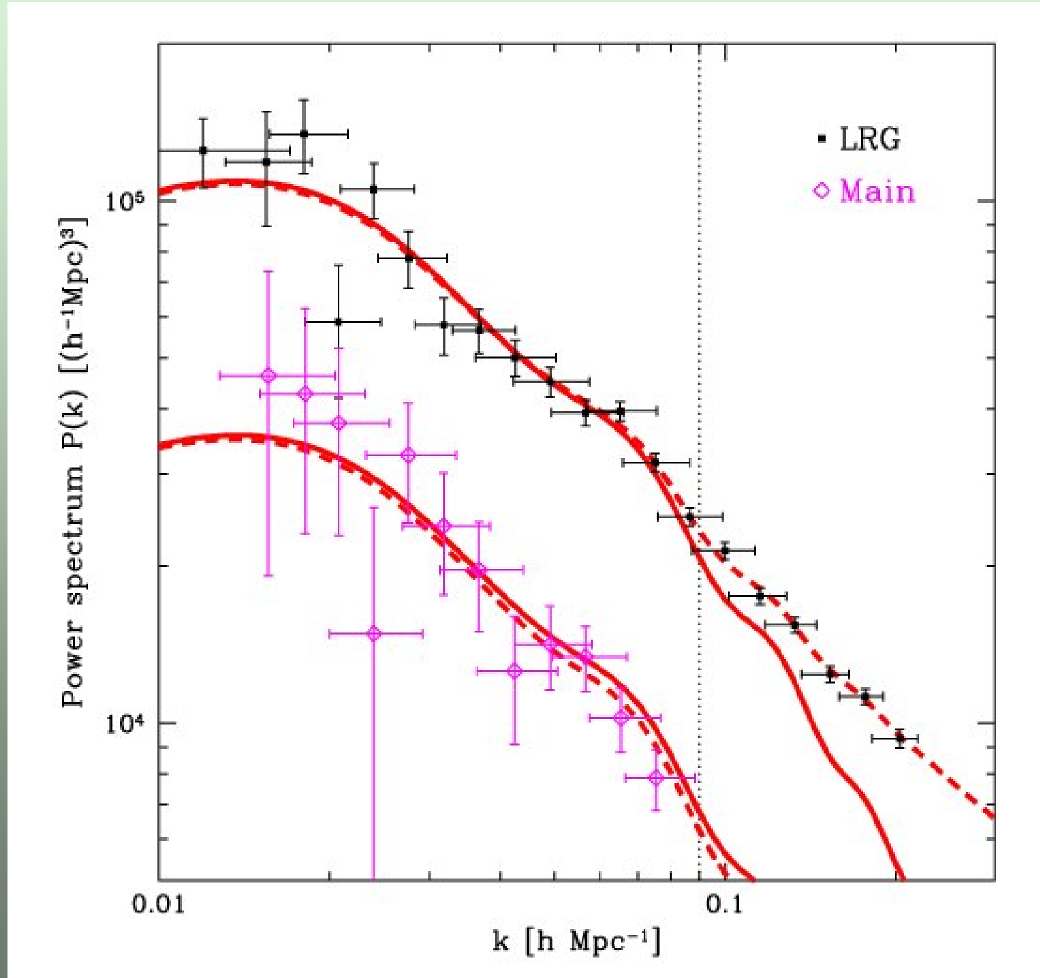
Shear-halo has fewer systematic uncertainties, how about theoretical?

Large-Scale Structure: galaxy clustering in SDSS



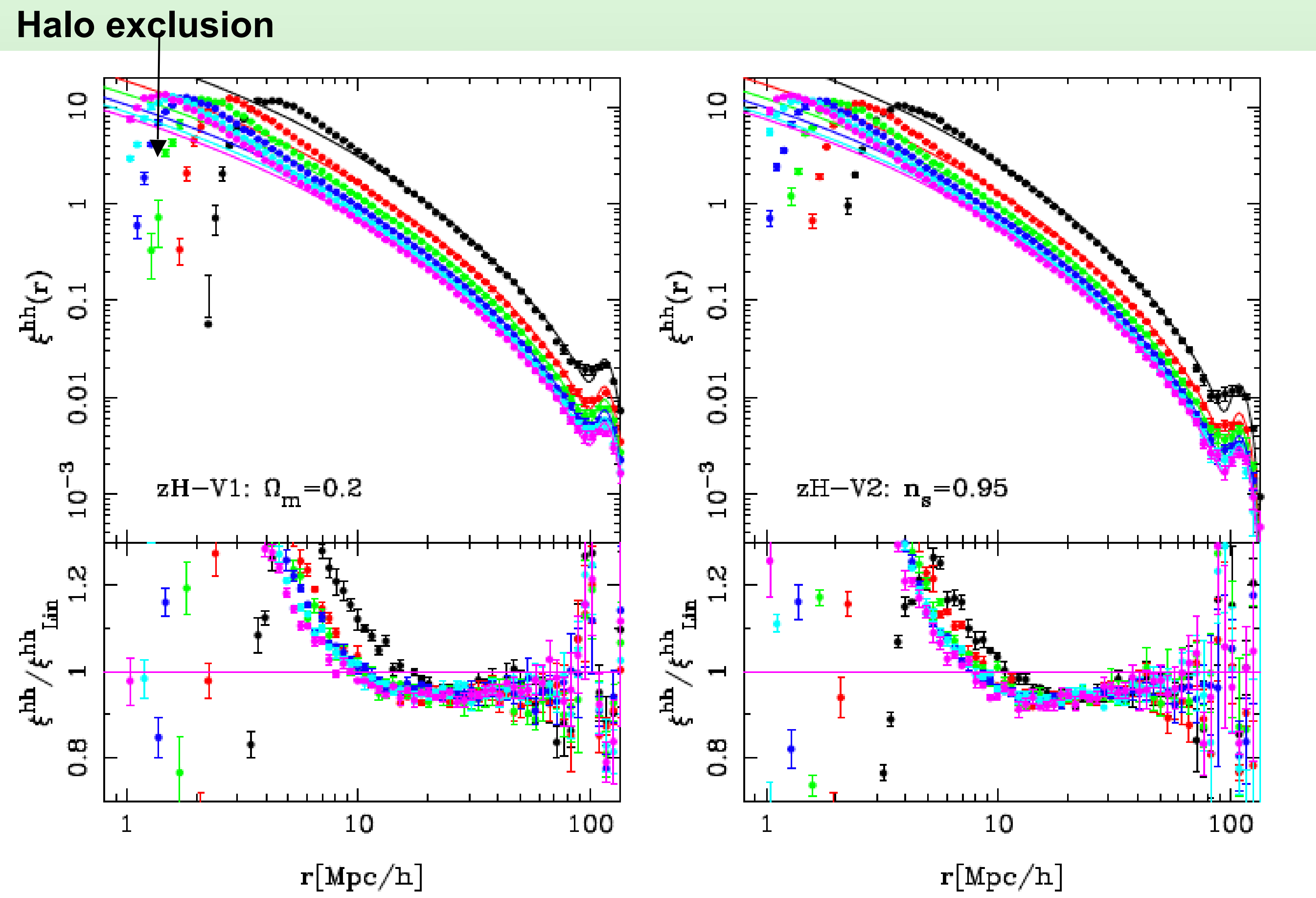
Power Spectrum

- Galaxy clustering traces dark matter clustering: 3-d analysis contains a lot of statistical information
- Amplitude depends on galaxy type: galaxy bias
- To determine bias we need additional (external) information
- Galaxy bias is scale dependent



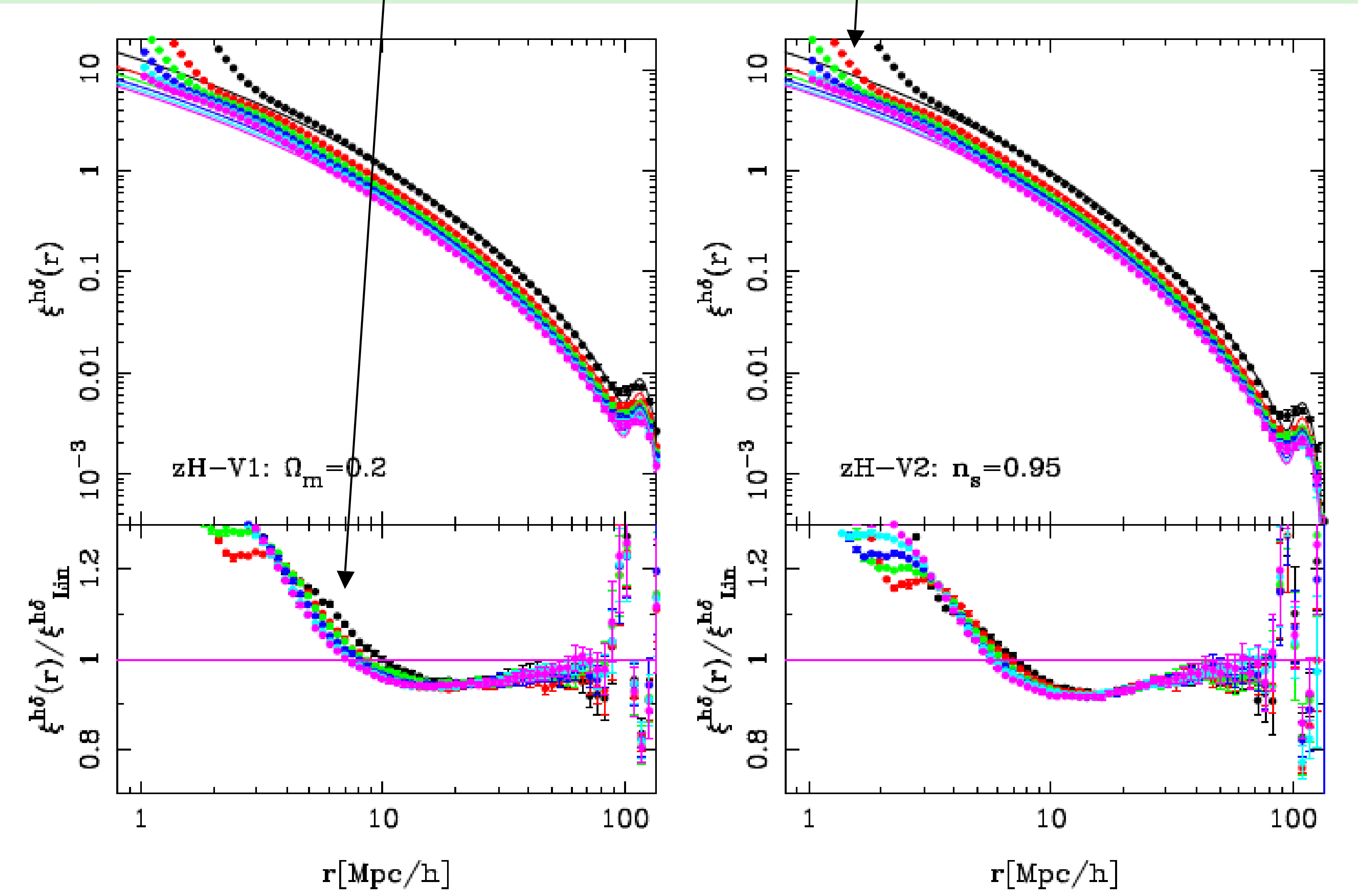
Tegmark et al. (2006)

A look at simulations: halos trace dark matter, but bias is scale dependent

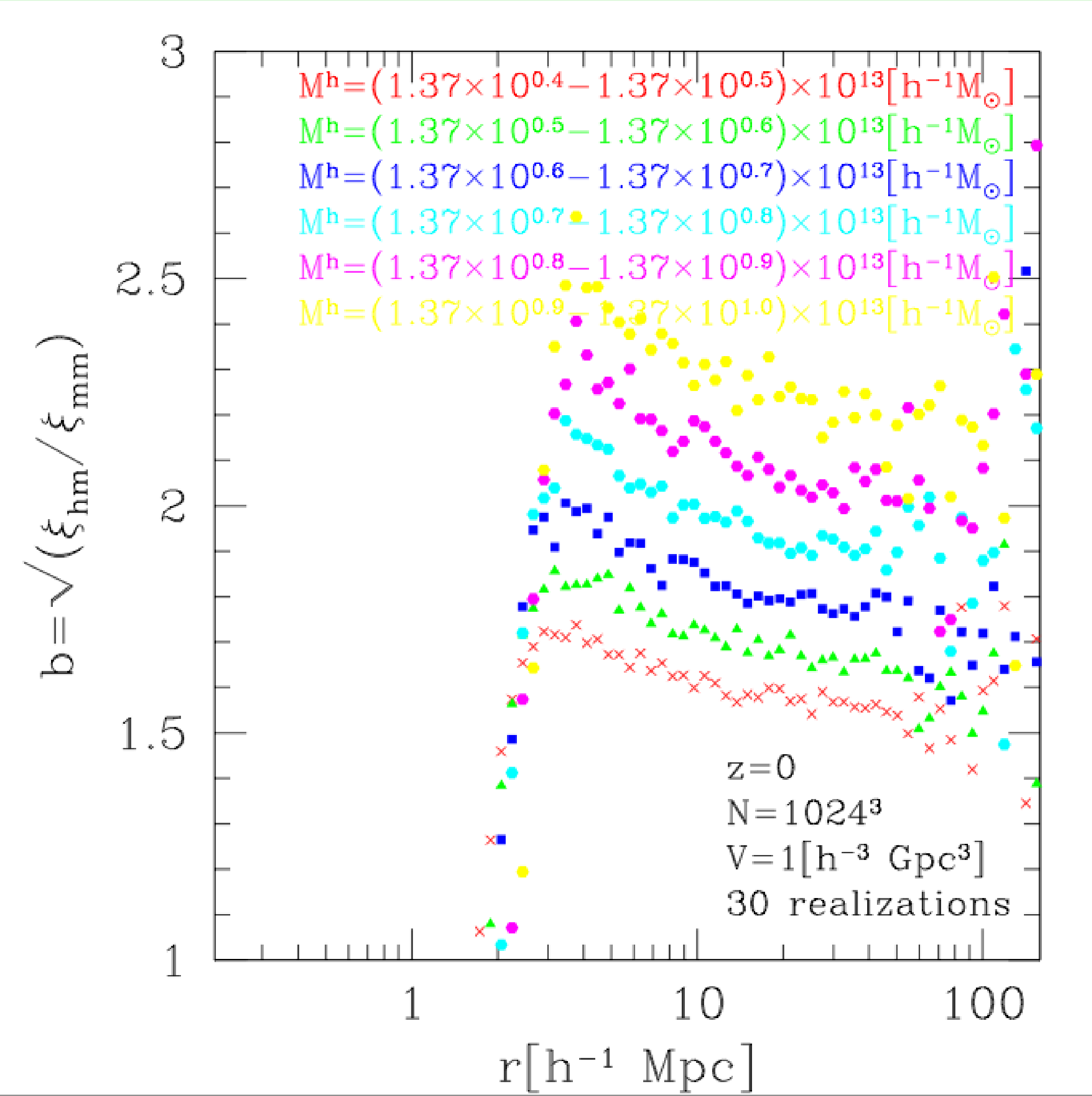


Galaxy-dark matter correlation function

- **Also scale dependent bias, small scales dark matter profile**

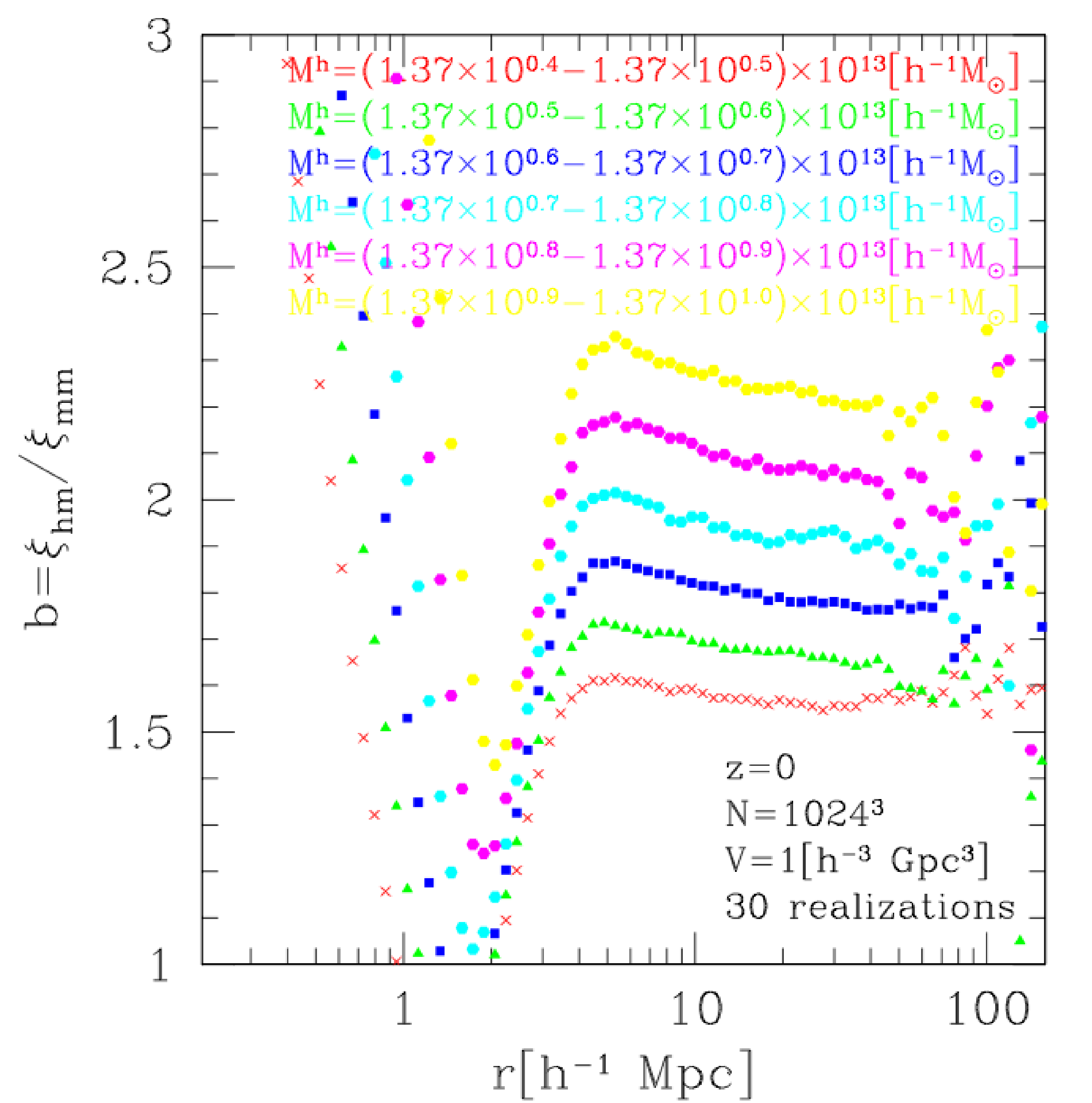


Halo bias: autocorrelation



M. Sato simulations

Halo bias: cross-correlation

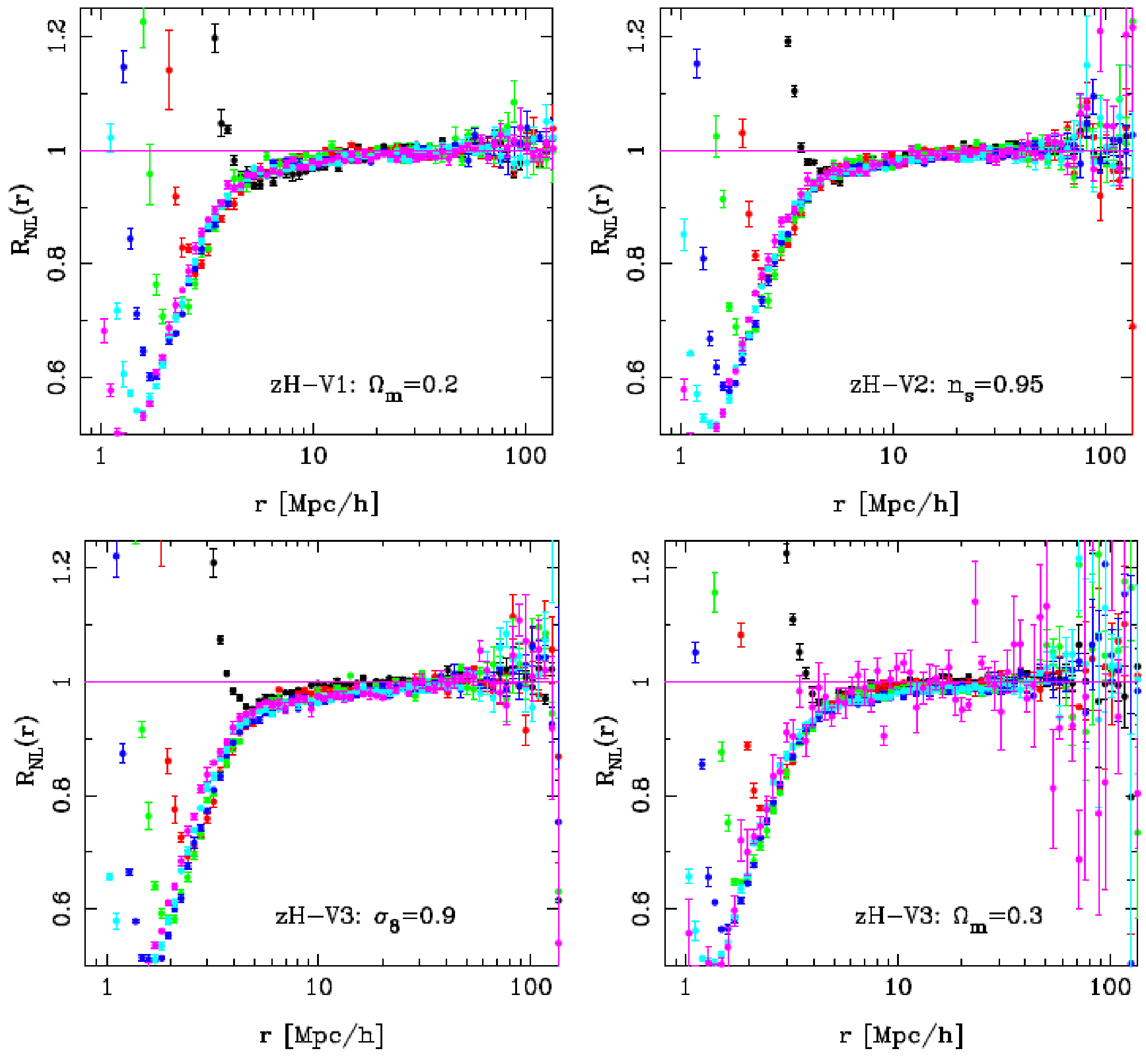


Halo dark matter cross-correlation coefficient: simulations

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

- **Dark matter-halo relation is universal outside 2 x virial radius: almost independent of halo mass and cosmology**

  This means that as long as galaxies are inside halos we get the same correlation coefficient independent of HOD



Perturbation theory prediction

$$\rho_{\rm g} = \rho_0 + \rho_0'\delta + \frac{1}{2}\rho_0''\delta^2 + \frac{1}{6}\rho_0'''\delta^3 + \epsilon + \mathcal{O}(\delta^4)$$

$$P_{\rm gm}(k) = b_1 P_{\rm NL}(k) + b_2 A(k),$$

$$P_{\rm gg}(k) = b_1^2 P_{\rm NL}(k) + 2b_1 b_2 A(k) + \frac{b_2^2}{2} B(k) + N$$

$$A(k) = \int \frac{{\rm d}^3 q}{(2\pi)^3} P_{\rm lin}(q) P_{\rm lin}(|\mathbf{k}-\mathbf{q}|) F_2(\mathbf{q}, \mathbf{k}-\mathbf{q})$$

$$B(k) = \int \frac{{\rm d}^3 q}{(2\pi)^3} P_{\rm lin}(|\mathbf{q}|) \left[P_{\rm lin}(|\mathbf{k}-\mathbf{q}|) - P_{\rm lin}(q)\right]$$

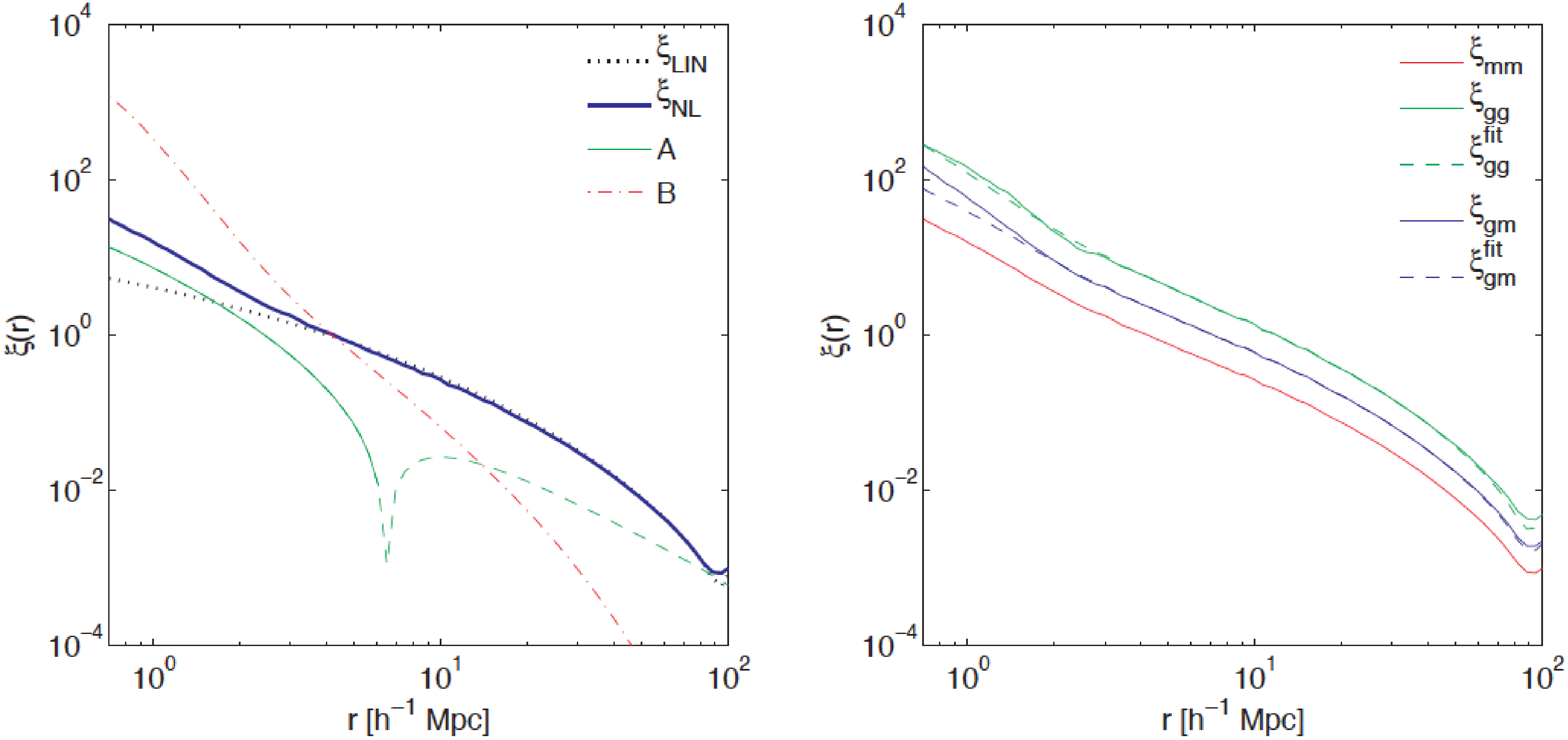
$$r_{\rm cc}^{(\xi)} = \frac{\xi + \alpha A}{\sqrt{\xi(\xi + 2\alpha A + \alpha^2 B/2)}} \; ; \qquad \alpha = \frac{b_2}{b_1}$$

$$\approx 1 - \frac{1}{4}\alpha^2 \frac{B}{\xi} - \alpha^2 \frac{A^2}{\xi^2} - \frac{1}{4}\alpha^3 \frac{AB}{\xi^2}$$

$$\approx 1 - \frac{1}{4}\alpha^2 \frac{B(r)}{\xi(r)} \; ;$$

$$\approx 1 - \frac{1}{4}\alpha^2 \xi(r) \; .$$

PT vs simulations



Old and new statistic for halo-shear lensing

- **Problem: cross-correlation coefficient does not follow RPT on small scales (halo exclusion, nonlinear effects, satellites)**
- **Shear is sensitive to small scale information**

$$\Sigma(R) = \int g(\chi)\xi(\sqrt{\chi^2 + R^2})d\chi$$

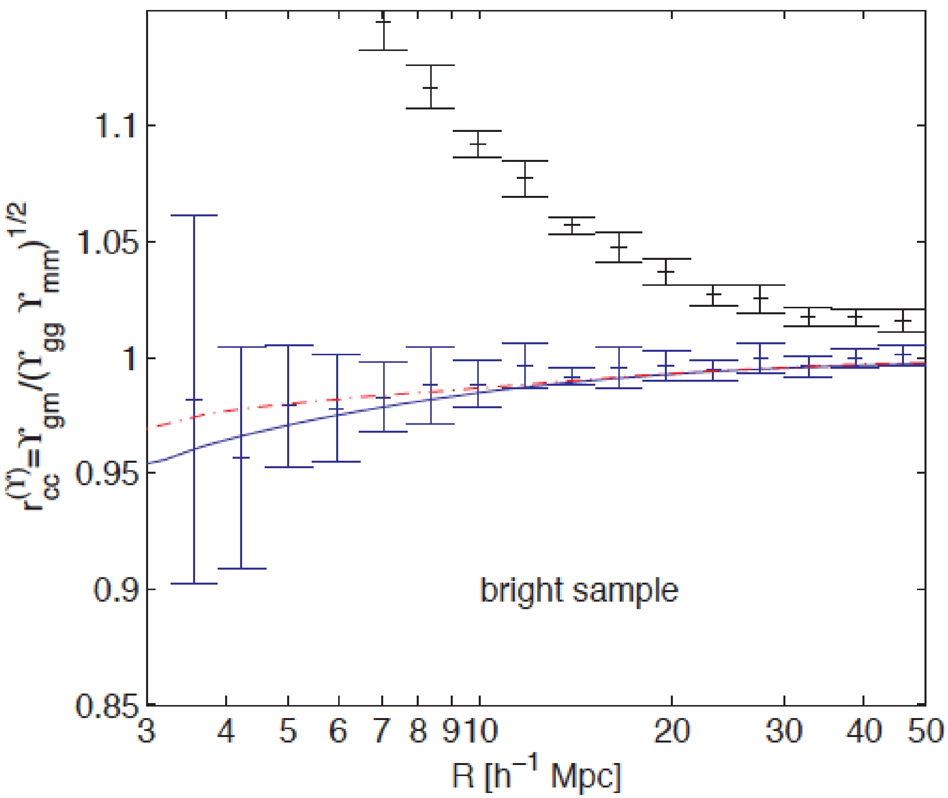
$$\Delta\Sigma = \bar{\Sigma}(R) - \Sigma(R) = \int_0^R R' dR' \Sigma(R') - \Sigma(R)$$

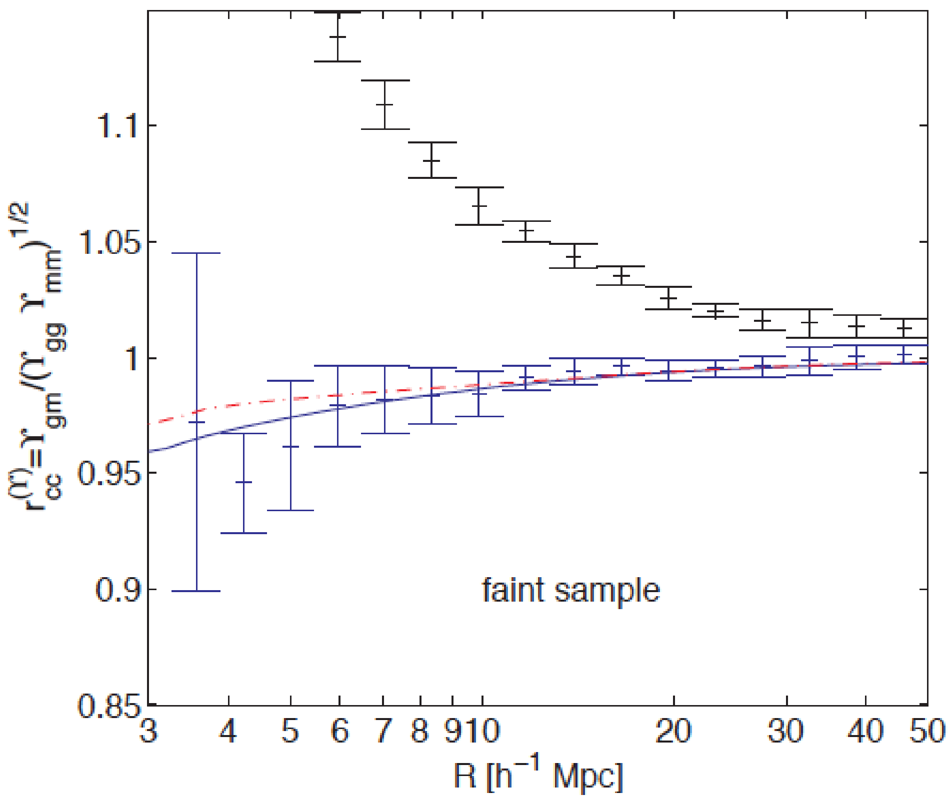
- **We introduce new statistic that cancels small scale information which is most problematic**

$$\Upsilon(R) = \Delta\bar{\Sigma}(R) - \Delta\Sigma(R_0)\frac{R_0^2}{R^2} =$$

$$= \frac{2}{R^2}\int_{R_0}^R R' dR' \Sigma(R') - \Sigma(R) + \Sigma(R_0)\frac{R_0^2}{R^2}$$

Cross-correlation coefficient

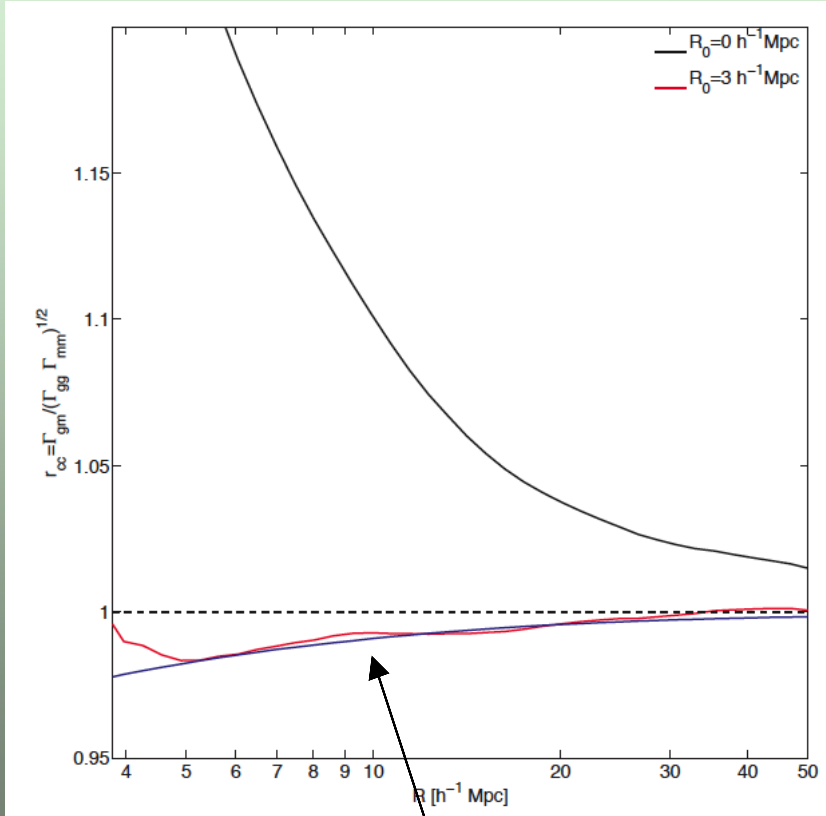


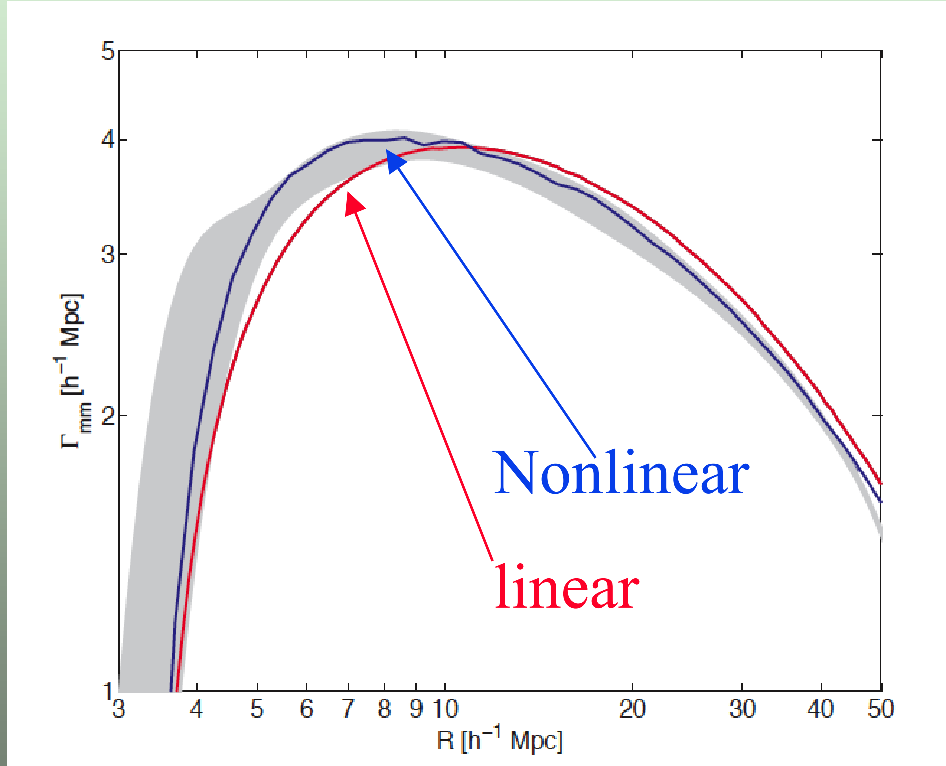


Simulations: dark matter reconstruction

Baldauf, Smith, US, Mandelbaum (2009)

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



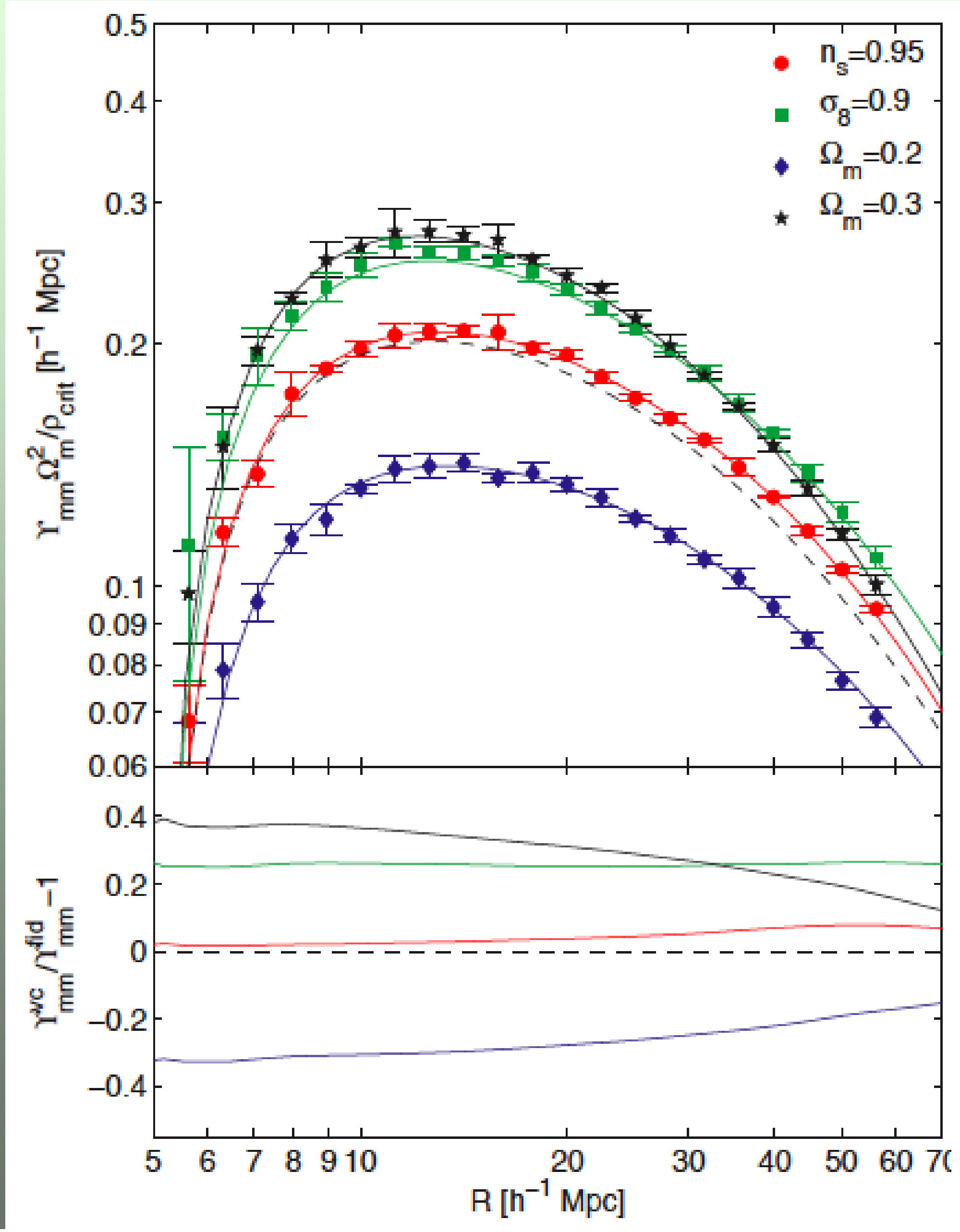


Use simulations with realistic HOD galaxy model to model galaxies

Cross-correlation coefficient r nearly unity

Dark matter power spectrum reconstruction from galaxy power spectrum and galaxy-shear power spectrum unbiased

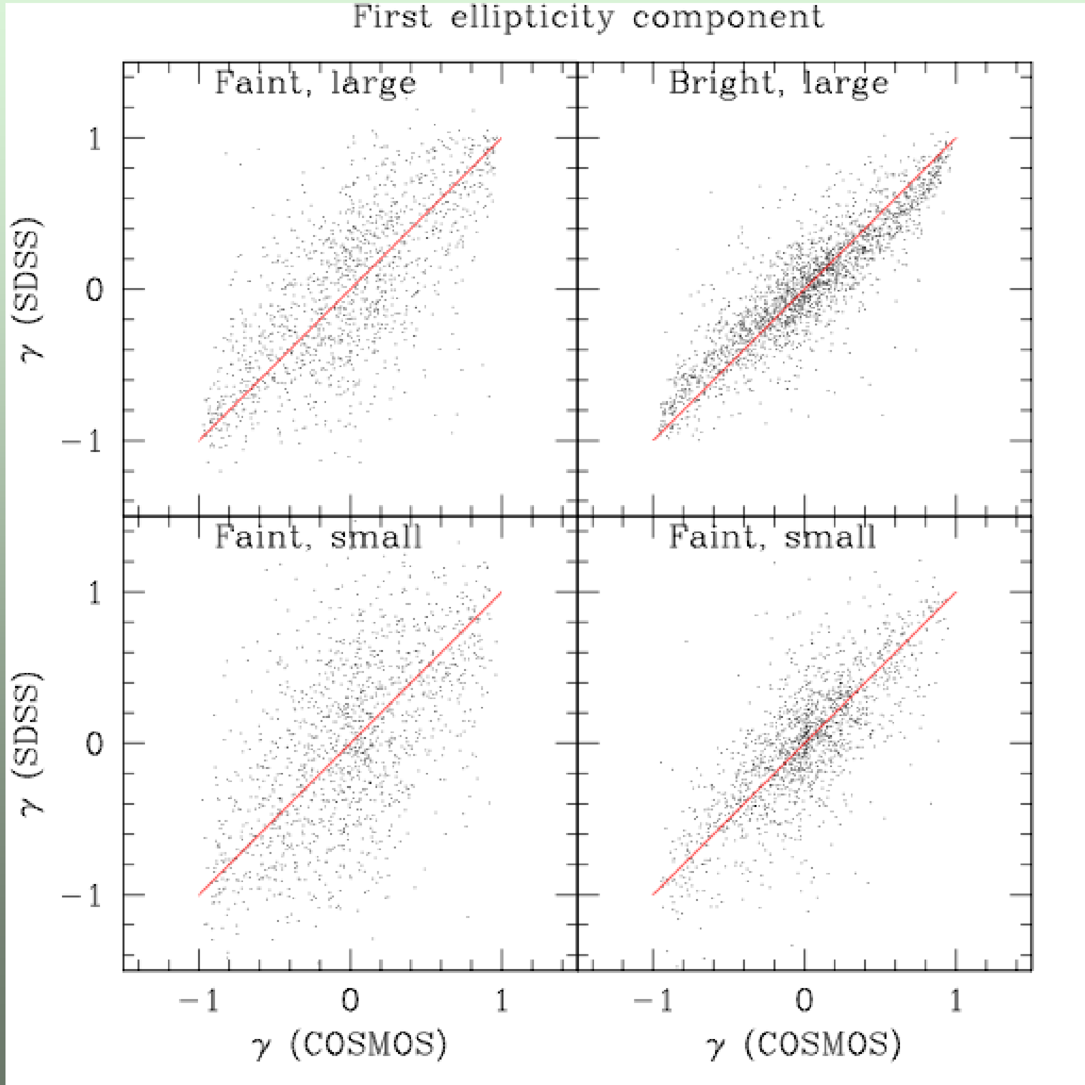
Dark matter clustering reconstruction



Application to SDSS

- RegLENS lensing code (Hirata and US 2005, Mandelbaum etal 2006) tested on STEPII and COSMOS
- Lenses: main sample spectroscopic galaxies (1M), spectroscopic LRGs (100k), MaxBCG clusters (10k), in the future photometric galaxies (10M)
- Sources: photometric galaxies (20M)

SDSS data: use space to calibrate ground based observations



Our code: REGLENS, STEP2: bias within 2%

Compare reduced shear between space and ground observations

SDSS: ground based observations, COSMOS: space based observations (Hubble ACS)

No bias in relation, SDSS data noisier

(R. Mandelbaum and A. Leauthaud)

Calibrating photometric redshifts with spectroscopic surveys: SDSS

Weak lensing more powerful with known redshifts of source galaxies

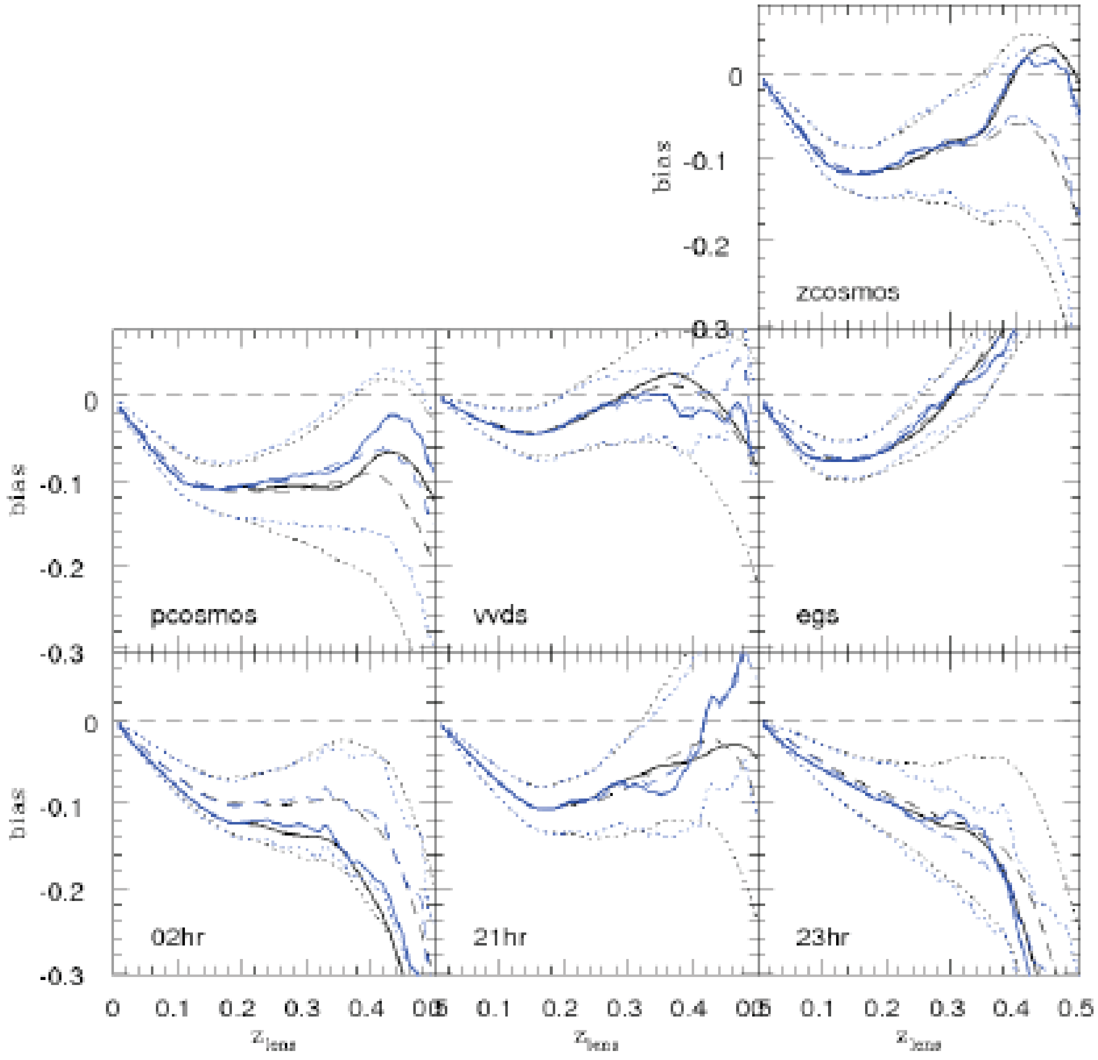
No need to have high accuracy, but need to be well calibrated

Use existing redshift surveys to calibrate photozs (Zebra)

Photoz bias at the level of 0.1, can mostly be removed

Next step: use photometric galaxies as lenses (a factor of 10 increase in lenses!)

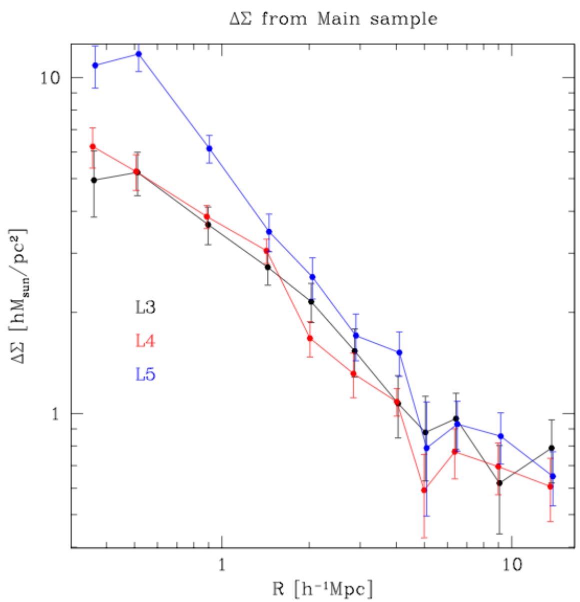
(preliminary, w. R. Nakajima and R. Mandelbaum)

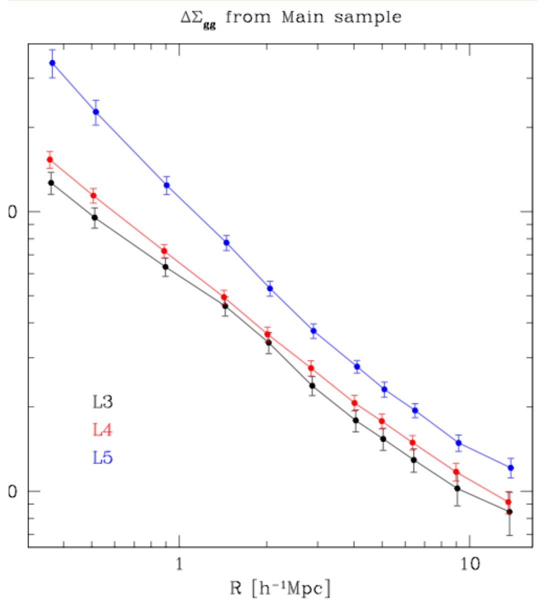


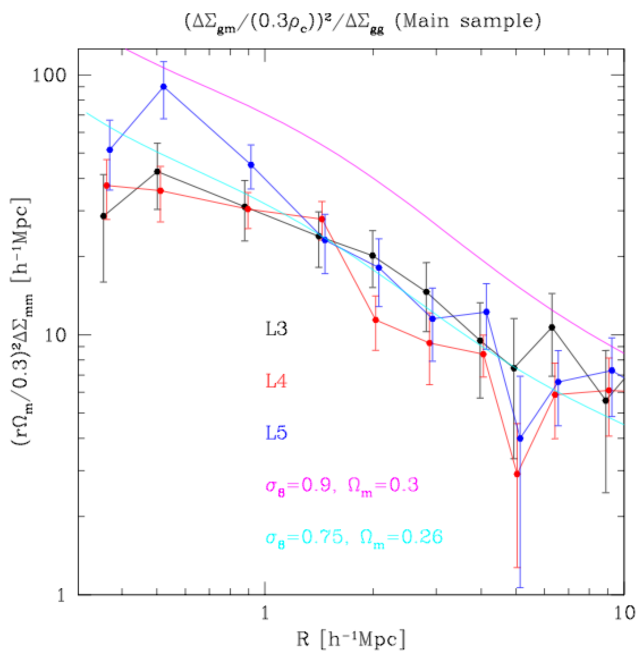
Application to SDSS data: main sample

first application: preliminary

Mandelbaum, US et al., in prep.







Main sample of SDSS galaxies: L4=L*, one magnitude above (L5) and below (L3)

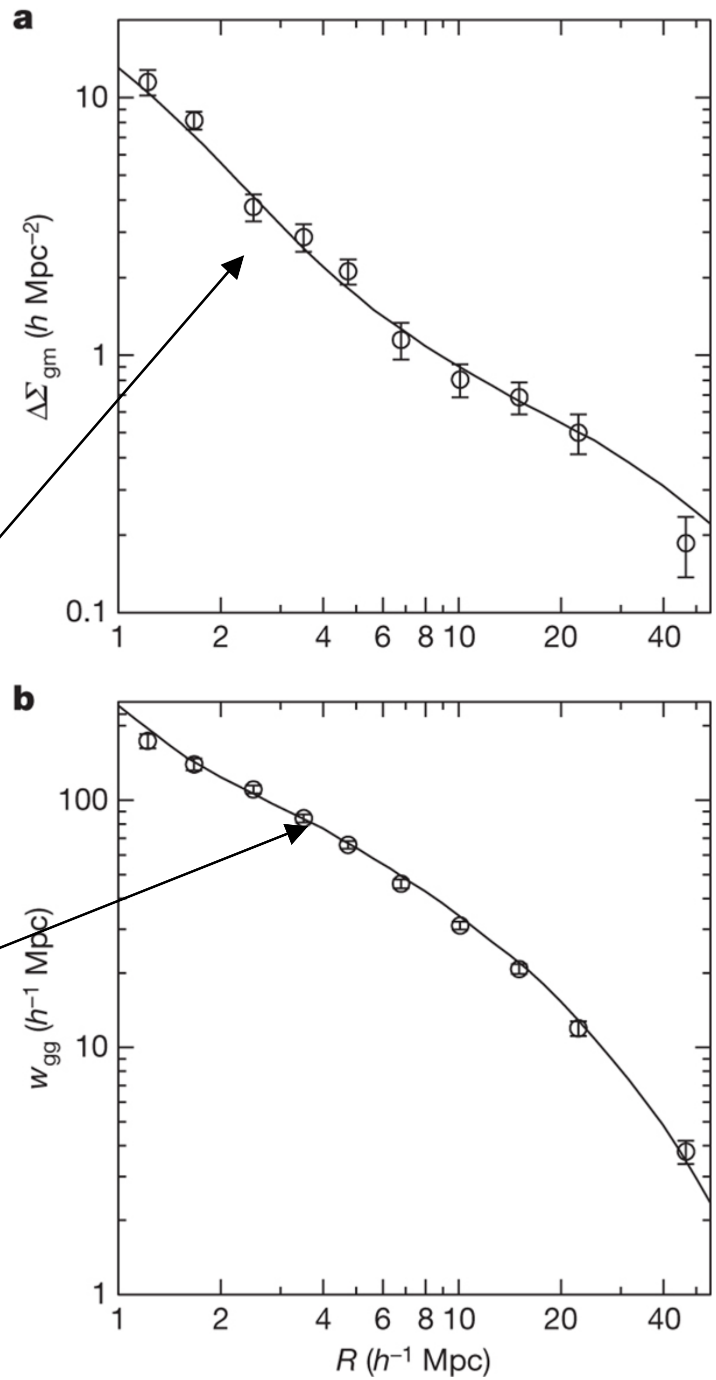
Application to SDSS: LRGs

Probes of large-scale structure measured from ~70,000 LRGs.

Galaxy-galaxy lensing

Galaxy clustering

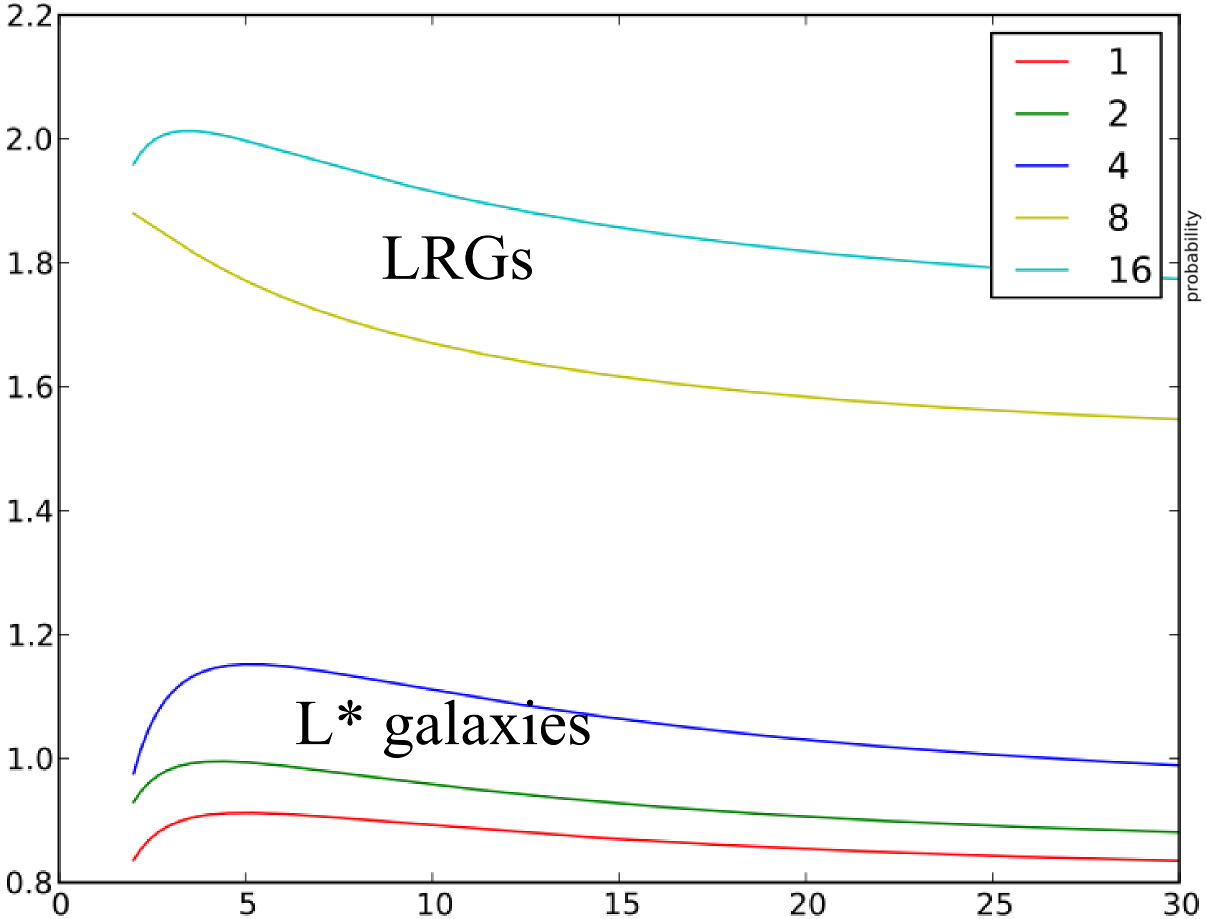
Lines: HOD simulations

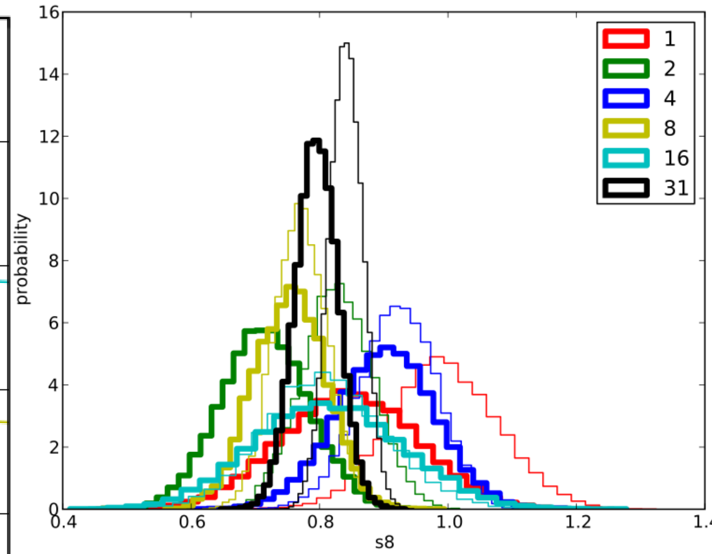


R Reyes *et al.* *Nature* **464**, 256-258 (2010) doi:10.1038/nature08857

A first determination of scale dependence of bias: SDSS observations

Mandelbaum, US, Slosar etal, in prep



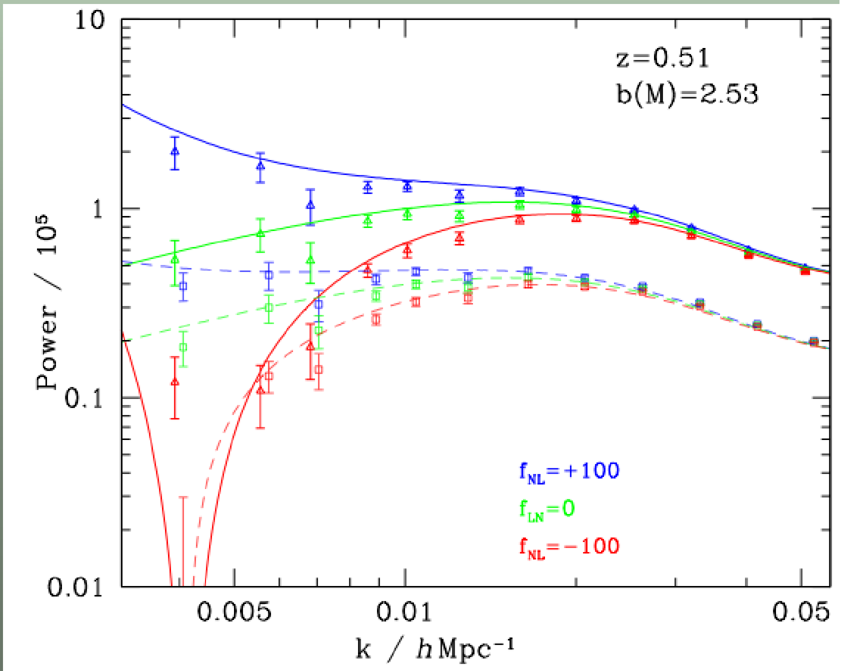


$$\sigma_8 = 0.80 \pm 0.04$$

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 give $f_{nl} >> 1$**
- **Ekpyrotic/cyclic models generically give $f_{nl} >> 1$**
- **WMAP5 constraint $-9 < f_{nl} < 111$ (95% cl, Komatsu etal 2008)**
- **Other models give different angular dependence of bispectrum (e.g. equilateral in DBI model, Silverstein…)**
- **Scale dependent bias (Dalal etal 2008)**

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



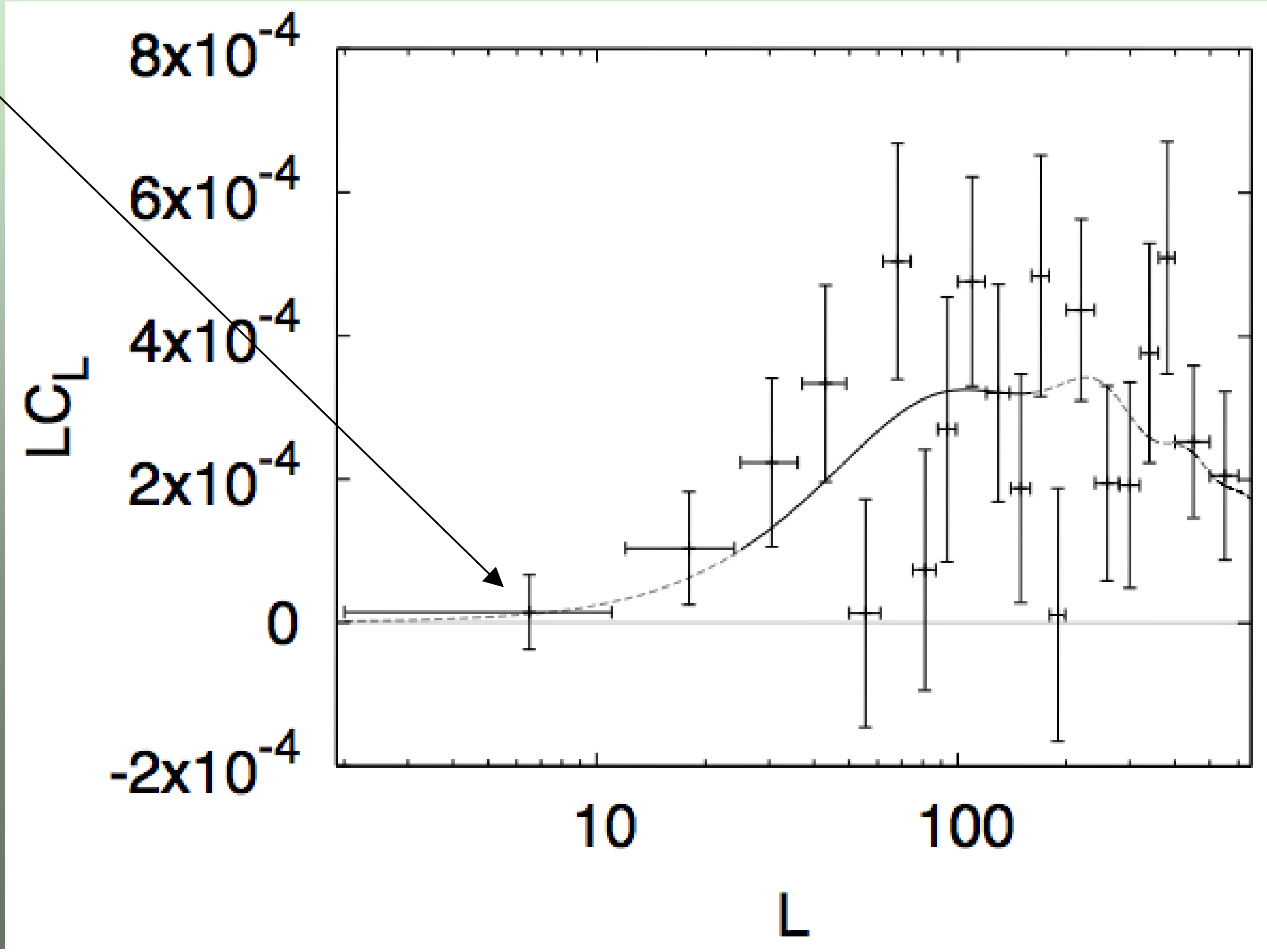
Tracers: SDSS photometric QSOs

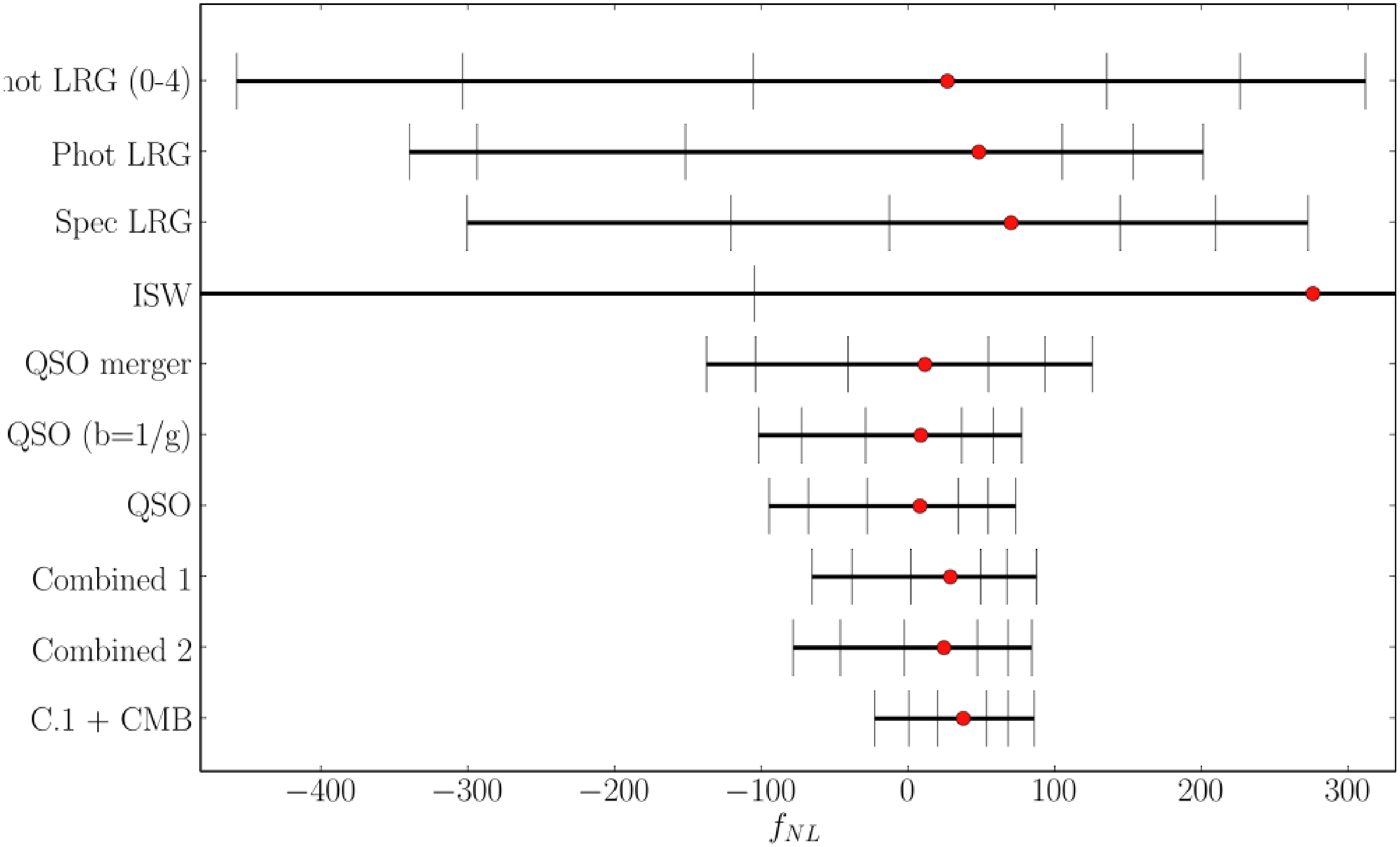
Peak at
k=0.002h/Mpc

Mean bias 2.75
Mean redshift 1.8

No evidence of excess power: no evidence of f_nl

Some uncertainty in fnl effect: ePS predicts effect scales as b-1.6 if QSOs are due to recent mergers





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

Slosar, Hirata, US etal, 2008

How to improve?
I) Bispectrum analysis

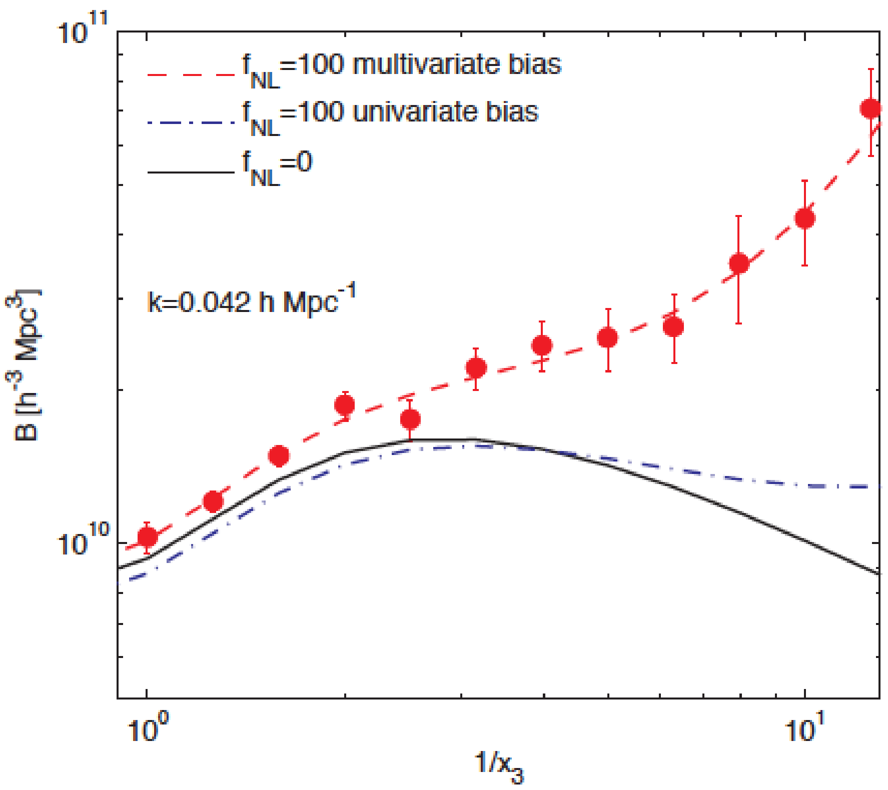
Baldauf, US, Senatore 2010

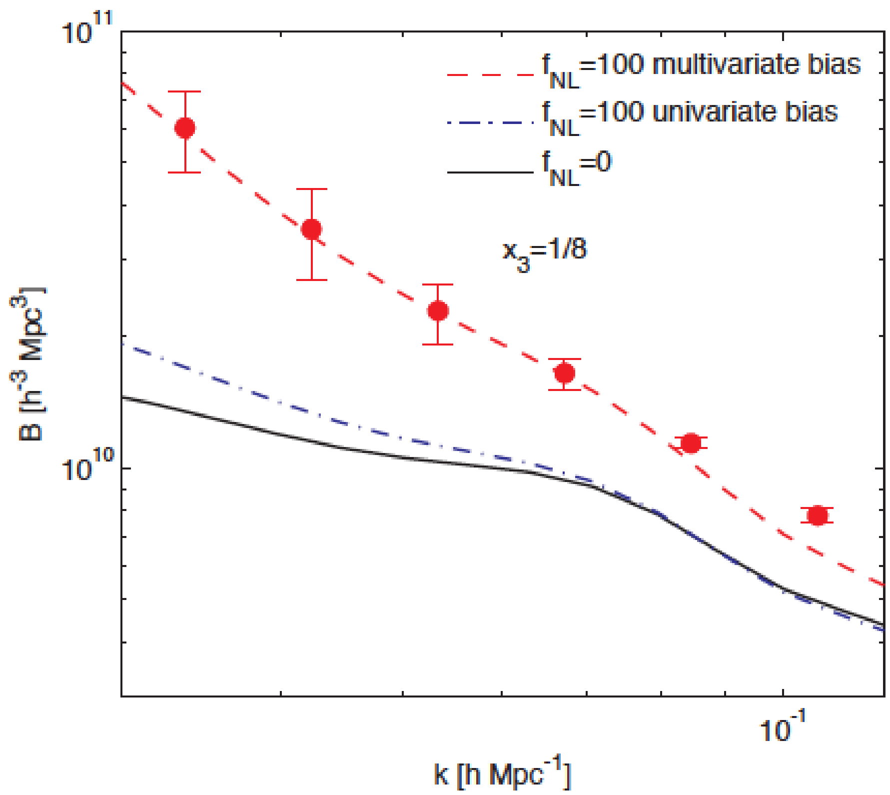
Peak-background split

$$\delta_{\mathrm{h}}^{\mathrm{L}}(\boldsymbol{x}) = b_{10}^{\mathrm{L}}\delta_0(\boldsymbol{x}) + b_{01}^{\mathrm{L}}\varphi(\boldsymbol{x}) + \frac{b_{20}^{\mathrm{L}}}{2!}\delta_0^2(\boldsymbol{x}) + b_{11}^{\mathrm{L}}\delta_0(\boldsymbol{x})\varphi(\boldsymbol{x}) + \frac{b_{02}^{\mathrm{L}}}{2!}\varphi^2(\boldsymbol{x})$$

$$\begin{aligned}
b_{10}^{\mathrm{L}} &= \frac{1}{\bar{n}}\frac{\partial n}{\partial \delta_{\mathrm{l}}} = -\frac{1}{\bar{n}}\frac{2\nu}{\delta_c}\frac{\partial n}{\partial \nu} \\
b_{01}^{\mathrm{L}} &= \frac{1}{\bar{n}}\frac{\partial n}{\partial \varphi_{\mathrm{l}}} = -\frac{4 f_{\mathrm{NL}}\nu}{\bar{n}}\frac{\partial n}{\partial \nu} = 2 f_{\mathrm{NL}}\delta_c b_{10}^{\mathrm{L}} \\
b_{20}^{\mathrm{L}} &= \frac{1}{\bar{n}}\frac{\partial^2 n}{\partial {\delta_l}^2} = \frac{4}{\bar{n}}\frac{\nu^2}{\delta_c^2}\frac{\partial^2 n}{\partial \nu^2} + \frac{2}{n}\frac{\nu}{\delta_c^2}\frac{\partial n}{\partial \nu} \\
b_{11}^{\mathrm{L}} &= \frac{1}{\bar{n}}\frac{\partial^2 n}{\partial \varphi_{\mathrm{l}}\partial \delta_{\mathrm{l}}} = \frac{8 f_{\mathrm{NL}}}{\bar{n}}\left(\frac{\nu^2}{\delta_c}\frac{\partial^2 n}{\partial \nu^2} + \frac{\nu}{\delta_c}\frac{\partial n}{\partial \nu}\right) \\
&= 2 f_{\mathrm{NL}}\left(\delta_c b_{20}^{\mathrm{L}} - b_{10}^{\mathrm{L}}\right) \\
b_{02}^{\mathrm{L}} &= \frac{1}{\bar{n}}\frac{\partial^2 n}{\partial {\varphi_{\mathrm{l}}}^2} = \frac{8 f_{\mathrm{NL}}^2}{\bar{n}}\left(2\nu^2\frac{\partial^2 n}{\partial \nu^2} + 3\nu\frac{\partial n}{\partial \nu}\right) - \frac{12\nu g_{\mathrm{NL}}}{\bar{n}}\frac{\partial n}{\partial \nu} \\
&= 4 f_{\mathrm{NL}}^2\delta_c\left(b_{20}^{\mathrm{L}}\delta_c - 2 b_{10}^{\mathrm{L}}\right) + 6\delta_c g_{\mathrm{NL}} b_{10}^{\mathrm{L}}
\end{aligned}$$

Comparison to simulations



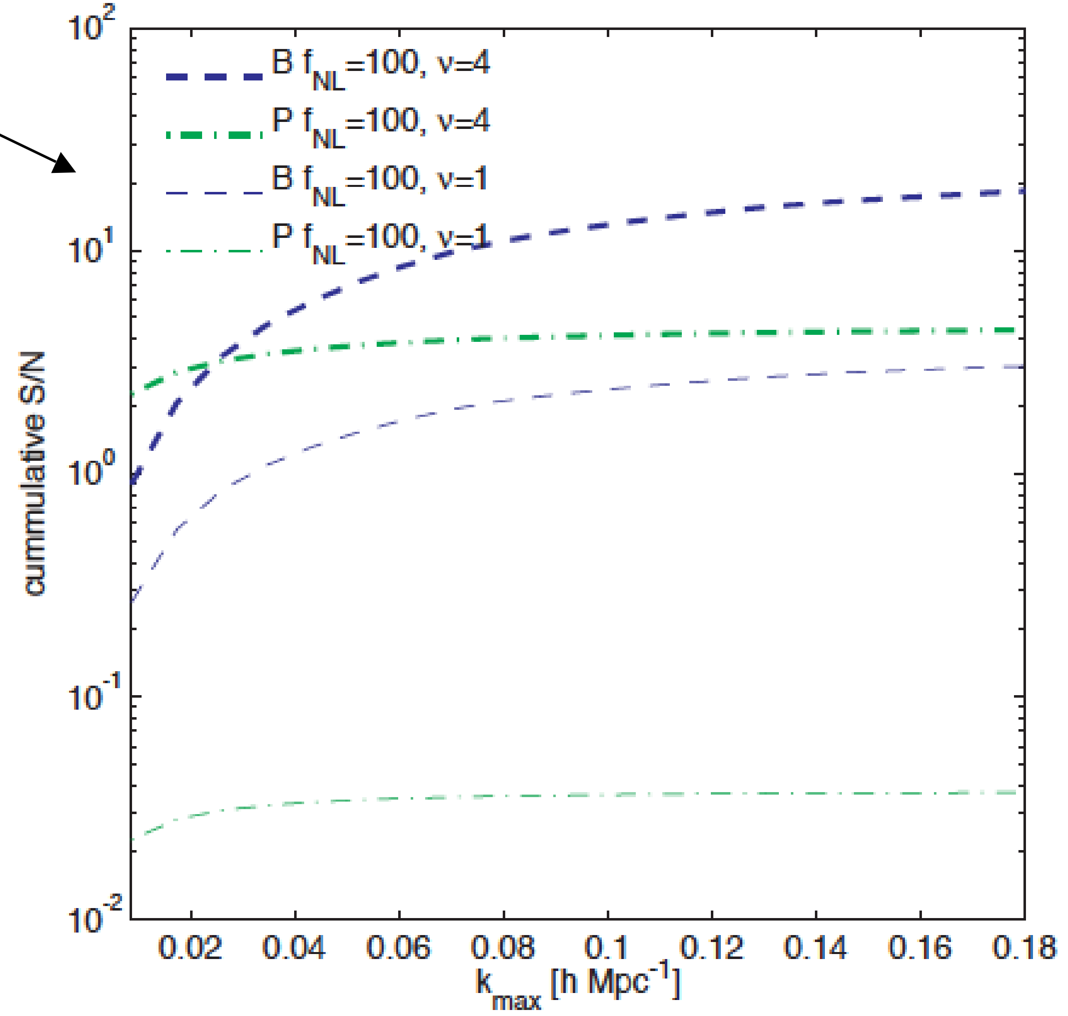


Signal to noise: bispectrum vs power spectrum

S/N for fnl=100

Bispectrum is better than single tracer P(k)

Still to do: multi-tracer power spectrum-bispectrum analysis



How to improve these limits?
II) reduction of sampling variance

US 2008

- **Effect scales as (b-1), ie no effect for b=1**
- **On large scales limited by cosmic variance: finite number of large scale patches (modes), which are gaussian random realizations, but we need to measure average power**
- **Two tracers:**

$$\delta_1 = (b_1 + (b_1 - 1)\alpha(k))\delta$$

$$\delta_2 = (b_2 + (b_2 - 1)\alpha(k))\delta$$

- **Take the ratio**

$$\frac{\delta_1}{\delta_2} = \frac{b_1 + (b_1 - 1)\alpha(k)}{b_2 + (b_2 - 1)\alpha(k)}$$

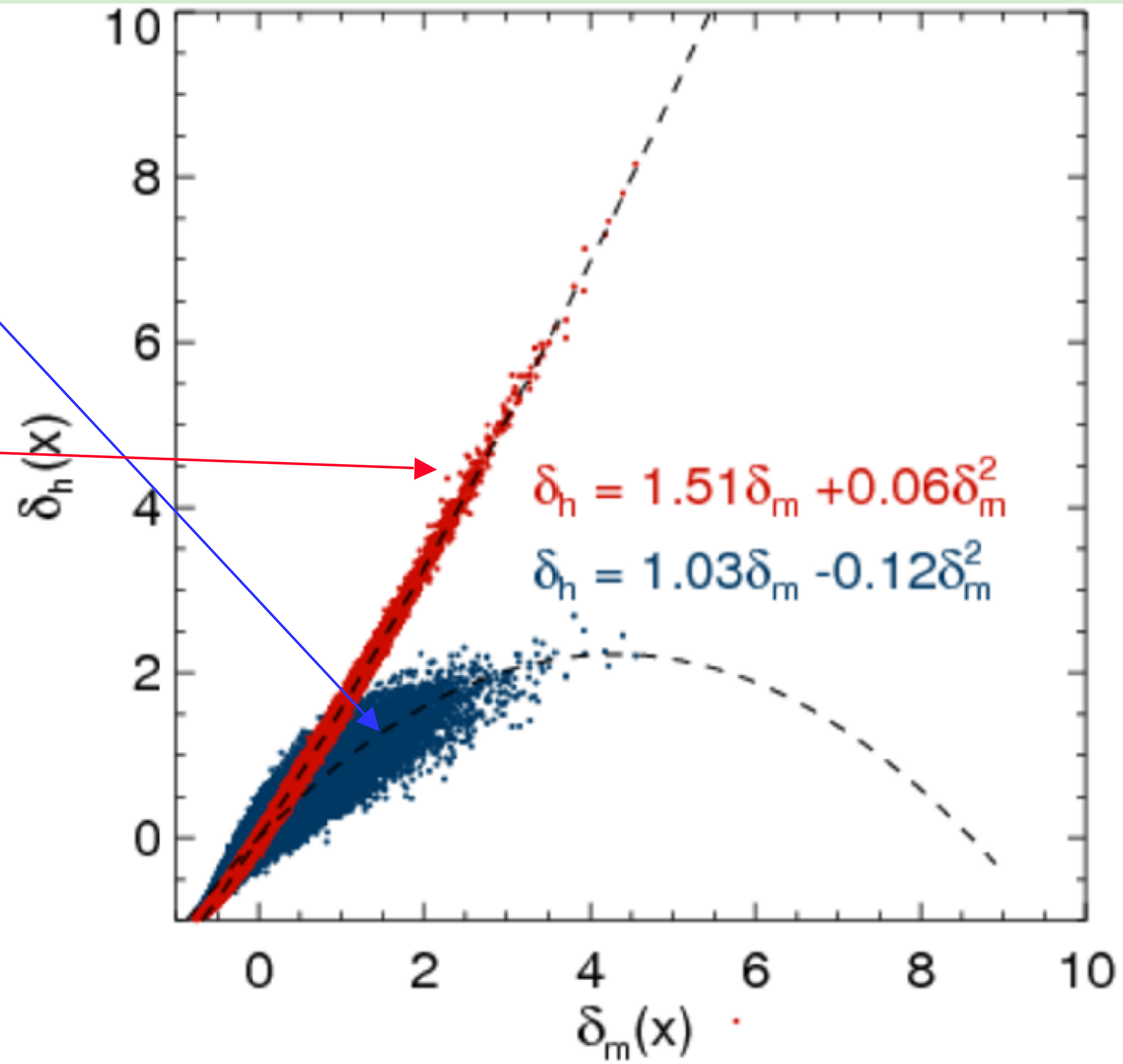
- **Density perturbation drops out, so no cosmic variance!**

How to improve these limits: III) noise reduction

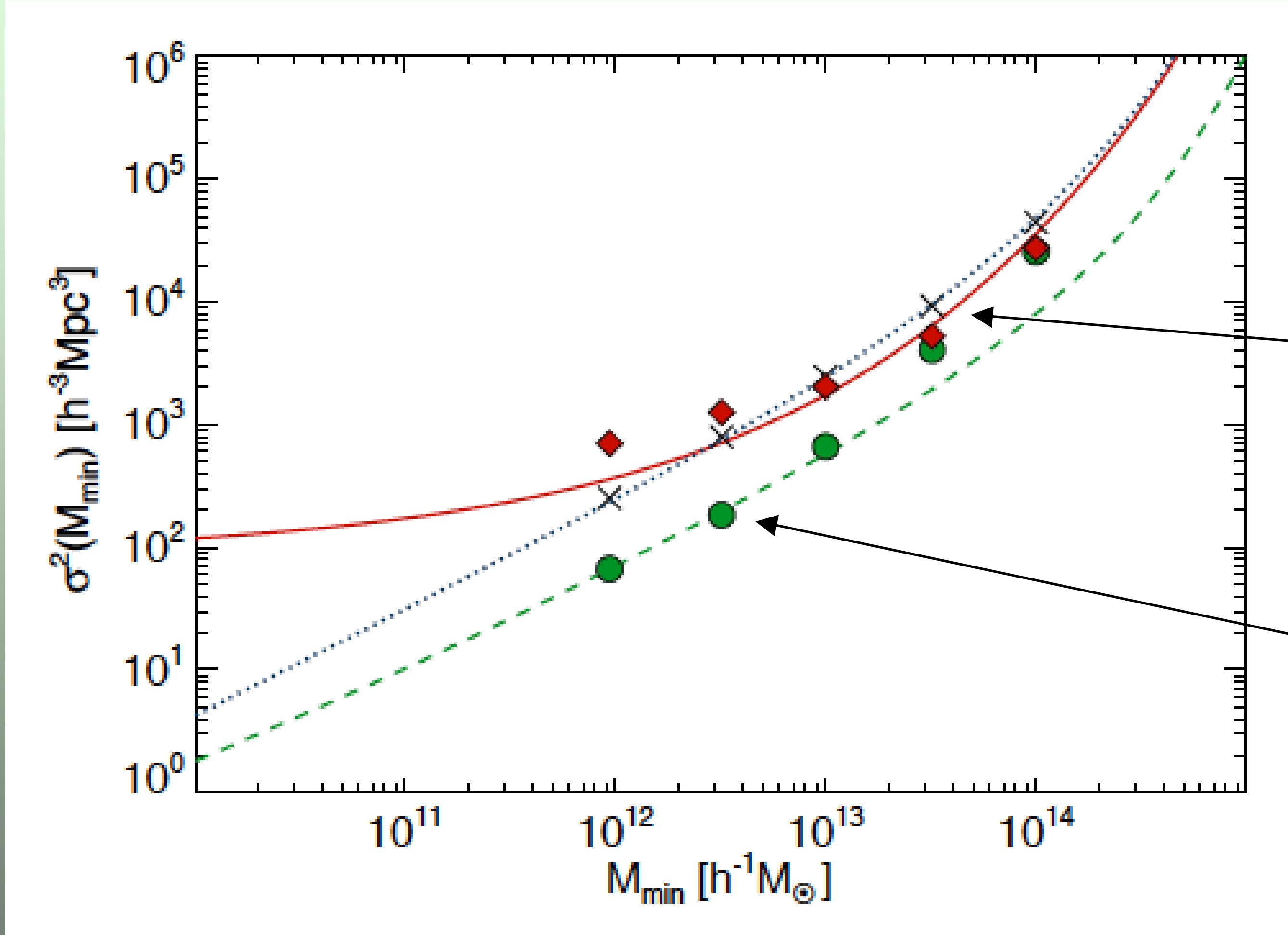
- **Uniform weighting has large stochasticity**

- **Weighting galaxies by halo mass reduces scatter**

  (Hamaus, US, Desjacques 2010)



How small can noise get?



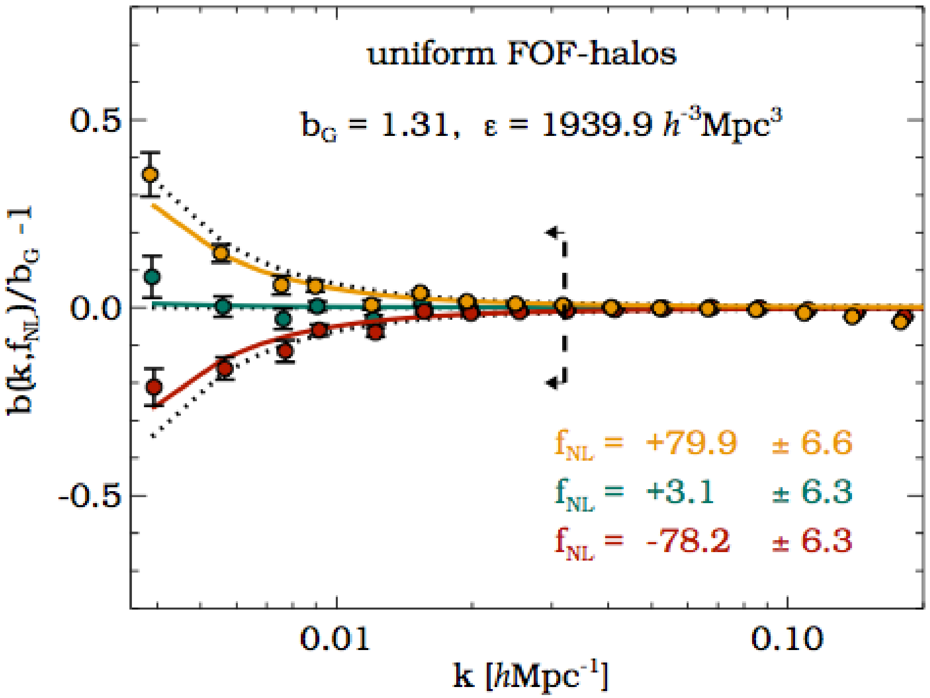
Uniform weighting

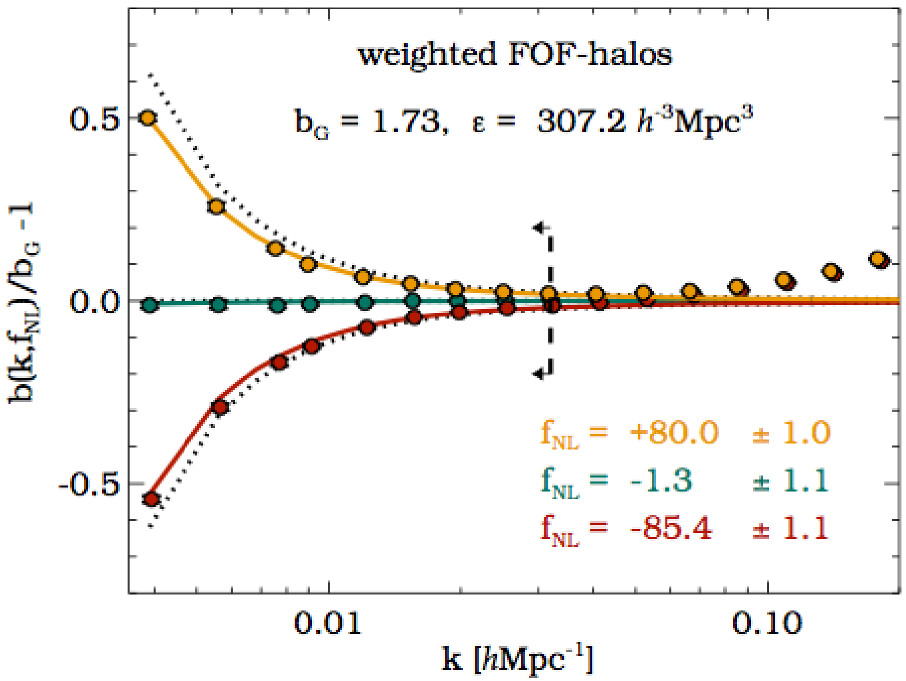
Optimal mass weighting

Compare to $P(k) \sim 10^5 (Mpc/h)^3$ at the peak

Uniform vs optimal mass weighted

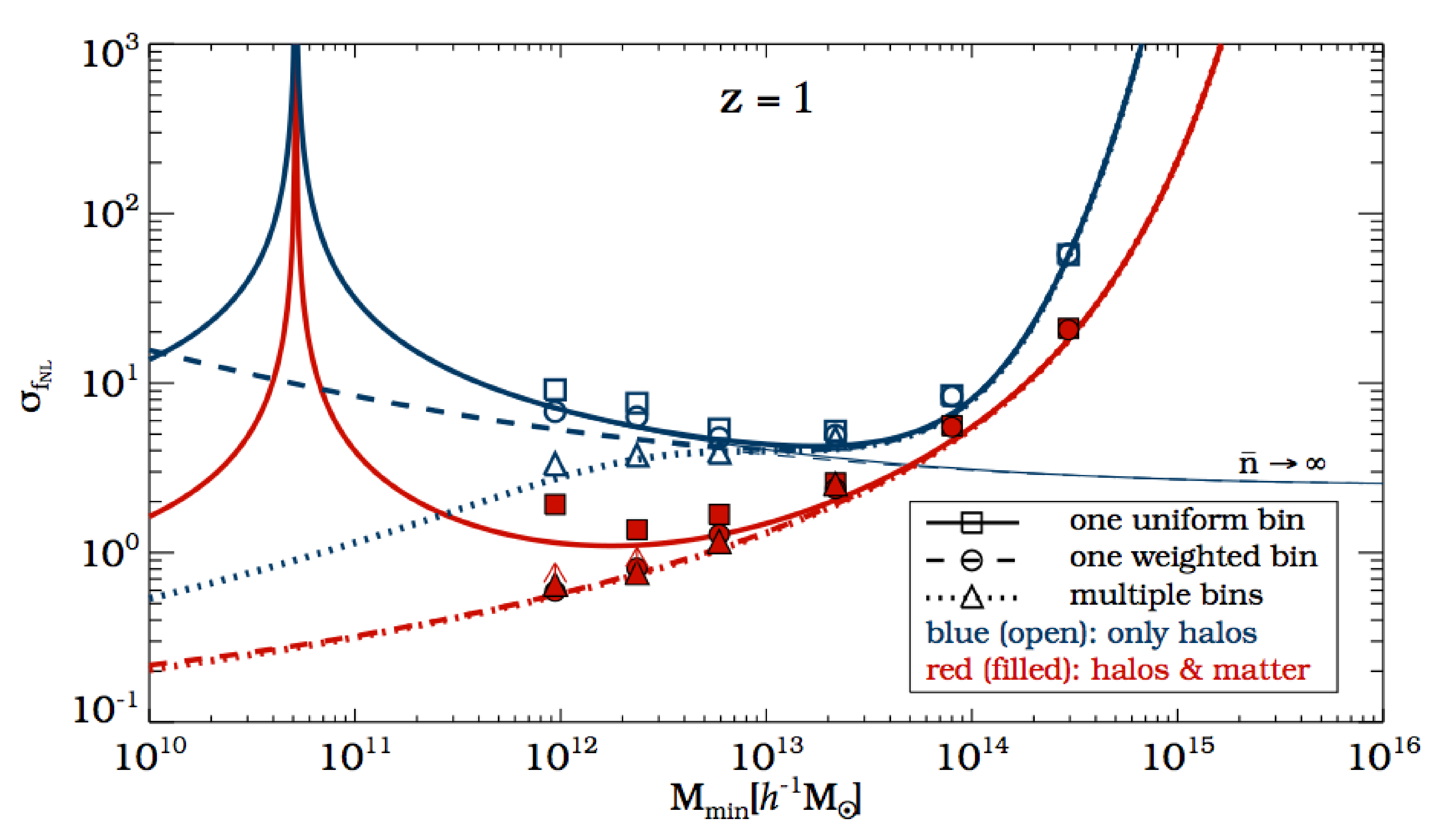
Hamaus, US, Desjacques 2011





Optimal analysis of 2-point function

Hamaus, US, Desjacques 2011



Redshift space distortions

- **In Fourier space: anisotropy in angle**

$$\delta_g = (b + f\mu^2)\delta = b(1+\beta\mu^2)\delta \qquad \mu = \vec{k}\cdot\vec{n}/k$$

$$f = d\ln D/d\ln a \approx \Omega_m^{0.55} \qquad \beta = f/b$$

Velocity related to density via continuity equation: time dependence of growth rate D is given by f

Galaxy density related to density via bias b

- **Usual approach: measure power along the radial direction ($\mu = 1$) and compare to power along transverse direction ($\mu = 0$) to determine β**

$$< \delta_\sigma^2 > \ vs < \delta_\pi^2 >$$

- **Only works in linear regime, ie large scales, but there it is limited by sampling variance**

How to eliminate cosmic variance in RSD?

McDonald & US 2008

- Two tracers, both tracing the same structure:

$$\delta_{g1} = b_1(1+\beta_1\mu^2)\delta$$

$$\delta_{g2} = b_2(1+\beta_2\mu^2)\delta$$

- Take the ratio

$$\frac{\delta_{g1}}{\delta_{g2}} = \alpha\frac{1+\alpha\beta_2\mu^2}{1+\beta_2\mu^2}, \quad \alpha = \frac{b_1}{b_2}$$

- Density perturbation drops out, so no cosmic variance
- Radial and transverse allow to determine bias ratio alpha and beta separately

  β can be combined with galaxy power spectrum to eliminate bias, one can measure f*amplitude as a function of redshift
- At other angles:

$$\mu^2 = \frac{k_\perp^2}{k_\perp^2 + k_{||}^2} = f(HD); \quad k_\perp \propto D_A^{-1}; \quad k_{||} \propto H$$

- We measure $H(z)D_A(z)$: AP test without cosmic variance!
- What limits the measurement is shot noise instead of cosmic variance. Can we suppress the shot noise significantly? Stay tuned…

Understanding RSD: distribution function approach

US, McDonald in prep

$$\delta_s(\mathbf{k}) = \sum_{L=0} \frac{1}{L!} \left(\frac{ik_\parallel}{H}\right)^L T_\parallel^L(\mathbf{k}) \ ,$$

where $T_\parallel^L(\mathbf{k})$ is the Fourier transform of $T_\parallel^L(\mathbf{x})$.

$$T_\parallel^L(\mathbf{k}) = \int d^3\mathbf{x}\ T_\parallel^L(\mathbf{x}) e^{i\mathbf{k}\cdot\mathbf{x}}.$$

$$T_\parallel^L(\mathbf{x}) = \frac{m}{\bar{\rho}} \int d^3\mathbf{q}\ f(\mathbf{x},\mathbf{q})\, u_\parallel^L = \left\langle (1+\delta(\mathbf{x}))\, u_\parallel^L(\mathbf{x}) \right\rangle_{\mathbf{x}}$$

f: distribution function (phase space density)

These velocity moments are radial components of rank L tensors

Lowest moments: density, momentum density, stress energy density

Angular decomposition into helicity eigenstates

$$f(\mathbf{k}, q, \theta, \phi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{m=l} f_l^m(\mathbf{k}, q) Y_{lm}(\theta, \phi),$$

$$f_l^m(\mathbf{k}, q)' = e^{im\psi} f_l^m(\mathbf{k}, q).$$

$$T_l^{L,m}(\mathbf{k}) = \frac{4\pi m}{\bar{\rho}} \int q^2 dq u^L f_l^m(\mathbf{k}, q).$$

$$T_{||}^L(\mathbf{k}) = \sum_{(l=L,L-2,..)} \sum_{m=-l}^{m=l} T_l^{L,m}(k) Y_{lm}(\theta, \phi).$$

Generalization of scalar, vector, tensor (SVT) decomposition

Power spectra: only equal helicity states correlate

$$P^{ss}(\mathbf{k}) = \sum_{L=0}^{\infty} \frac{1}{L!^2} \left(\frac{k\mu}{H}\right)^{2L} P_{LL}(\mathbf{k}) + 2Re \sum_{L=0}^{\infty} \sum_{L'>L} \frac{(-1)^{L'}}{L!\, L'!} \left(\frac{ik\mu}{H}\right)^{L+L'} P_{LL'}(\mathbf{k})$$

$$P_{LL'}(\mathbf{k}) = \sum_{(l=L,L-2,..)} \sum_{(l'=L',L'-2,..)} \sum_{m=0}^{l} P_{l,l'}^{L,L',m}(k) P_l^m(\mu) P_{l'}^m(\mu)$$

P_00: density-density correlator

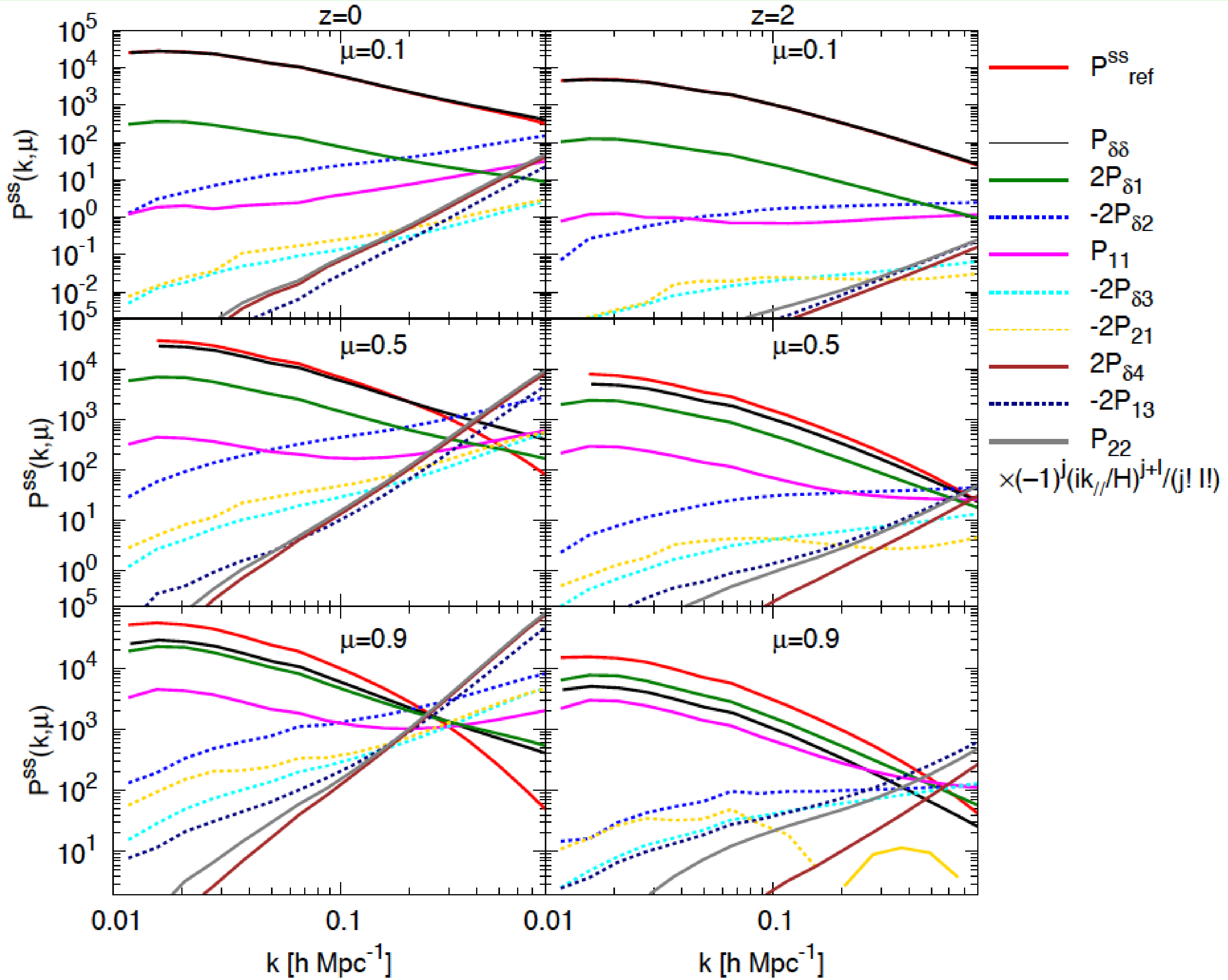
P_01: density-momentum density correlator: only scalar contribution

P_11: momentum density-momentum density correlator: scalar and vector (vorticity) components

P_02: density-energy density and density-anisotropic stress (scalar part) correlator: FoG term

Simulations

Okumura etal, in prep



Implications

- Only mass density or number density weighted quantities enter RSD: momentum density, not velocity, energy density, not velocity dispersion. This solves the long standing problem of how to define RSD quantities in sparse systems like galaxies
- Series convergent on large scales, divergent on small scales
- Only the lowest orders contribute to low order angular terms
- Correlators of galaxy momentum density differ from dark matter even for linear bias, only if $\delta \ll 1$ the two agree
- One expects strong scale dependent bias of RSD, stronger than in real space. This is on top of FoG effects
- Much more coming, stay tuned (simulations: Okumura etal, PT analysis: Vlah etal)

Combining lensing and redshift space distortions

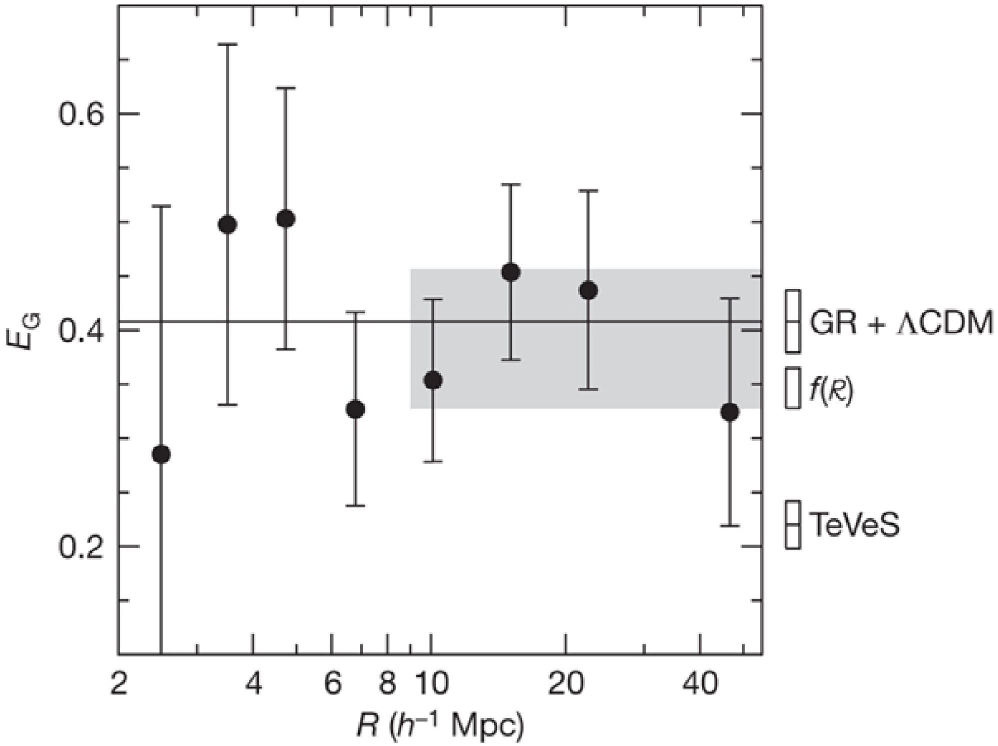
- **So far cosmological tests have been either based on background cosmology (eg SN1A, BAO) or on measuring amplitude of perturbations as a function of redshift and scale (eg CMB, LSS, WL, Ly-alpha…)**

- **By combining redshift space distortion measurements (β) 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

Comparison of observational constraints with predictions from general relativity and viable modified theories of gravity.



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

nature

Summary

- Galaxy clustering is useful as a tracer of dark matter, but suffers from scale dependent bias
- Weak lensing traces dark matter, but has significant observational issues/systematics
- Combining clustering and galaxy-galaxy lensing gives dark matter clustering and scale dependent bias: first results from SDSS
- sampling variance reduction techniques and shot noise suppression techniques
- Nongaussianity: bispectrum and power spectrum analysis: we can potentially reach fnl error below 1 (0.1?)
- Redshift space distortions: new formalism based on phase space approach may provide better insights
- Plenty of galaxy clustering data available, but we need better theoretical understanding of how they connect to dark matter: lots of work left for theorists!