Gravitational growth: lensing and redshift space distortions

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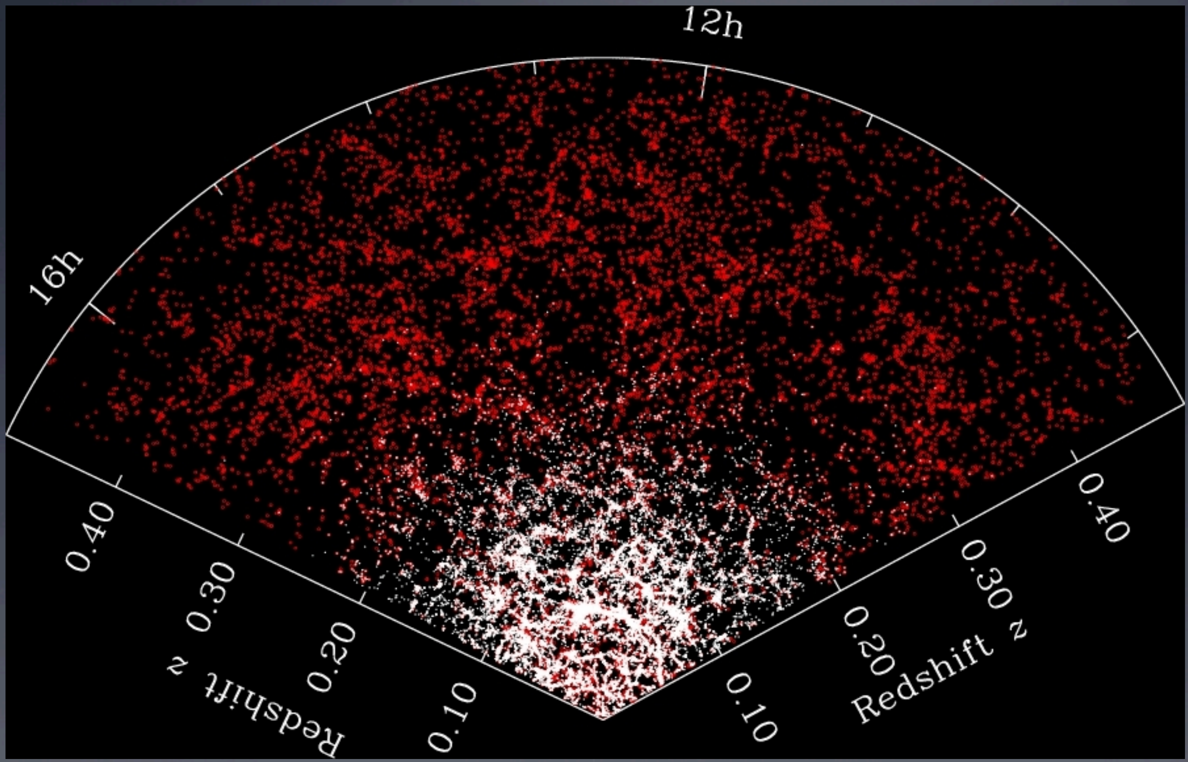
Overview

- To measure growth of structure need 3-d information: galaxies
- Galaxies are not dark matter: biasing: the large scale structure view
- Easy way: galaxy clustering combined with galaxy-shear lensing: current constraints from SDSS some of the best in weak lensing
- Hard way: galaxy clustering in redshift space: redshift space distortions. Has the potential but is subject to a lot of complications
- Combining the two can probe modifications of gravity

Collaborators: T. Baldauf, V. Desjacques, R. Mandelbaum, P. McDonald, T. Okumura, A. Slosar, Z. Vlah, J. Yoo

Galaxy clustering in redshift space



SDSS

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

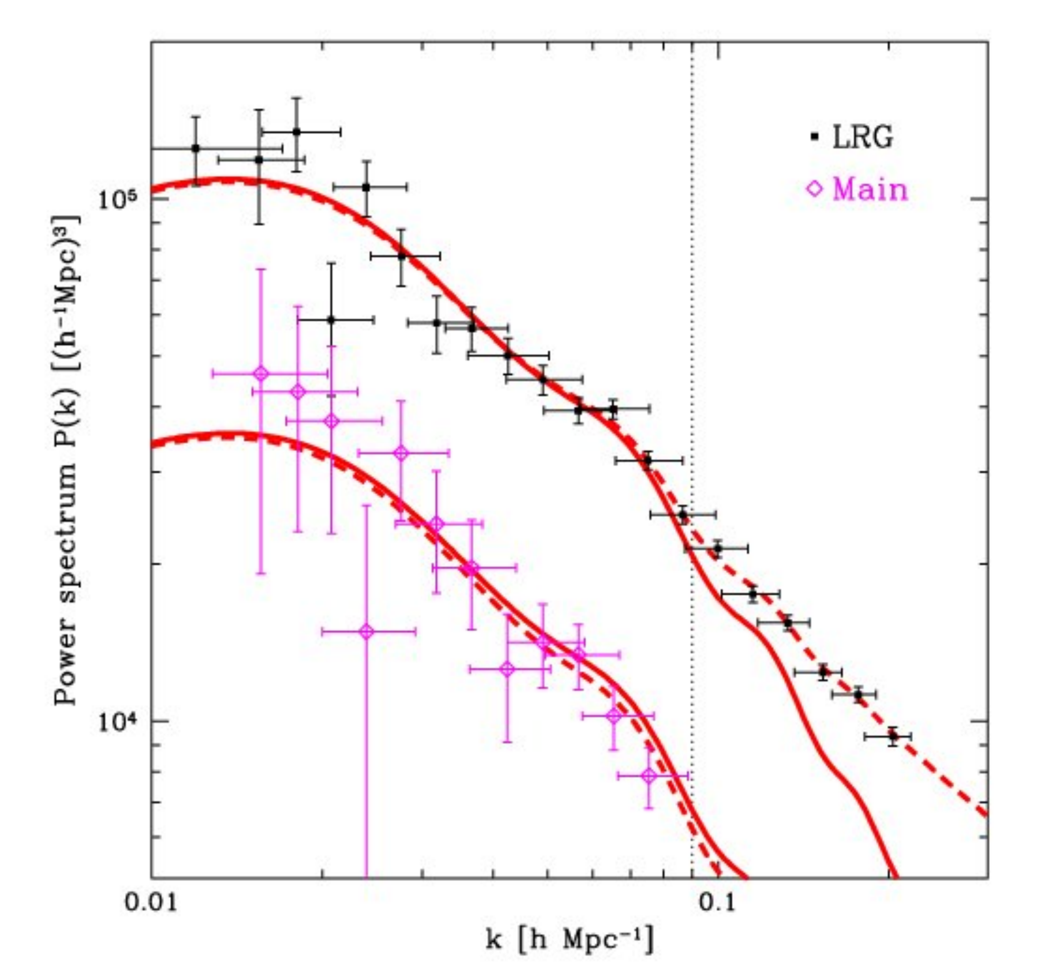
2) Easy to measure: effects of order unity, not 1%

Power Spectrum

- Galaxy clustering traces dark matter clustering: 3-d analysis contains a lot of statistical information
- Amplitude depends on galaxy type: galaxy bias b

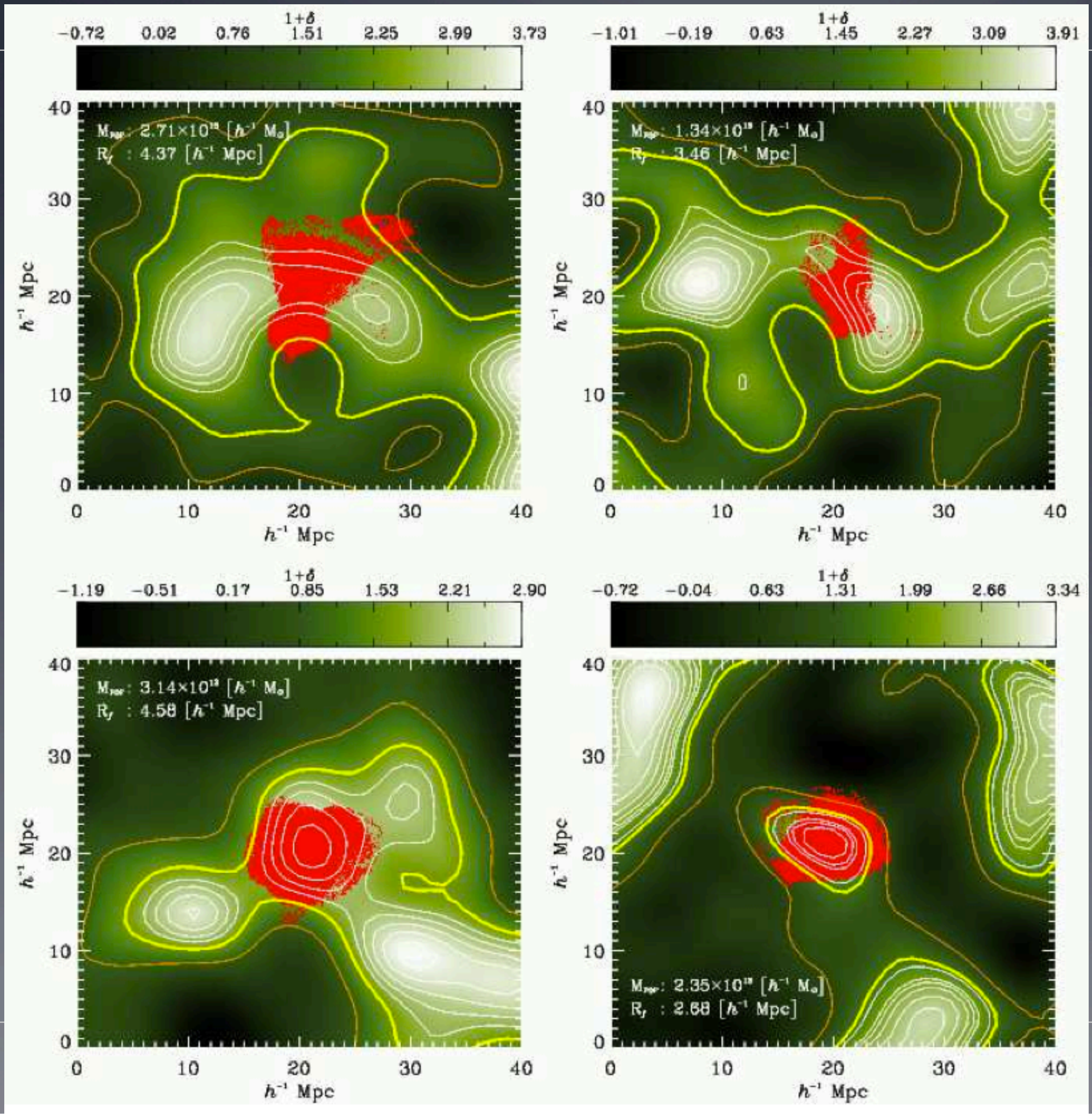
$$P_{gg}(k)=b^2(k)P_{mm}(k)$$

- 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

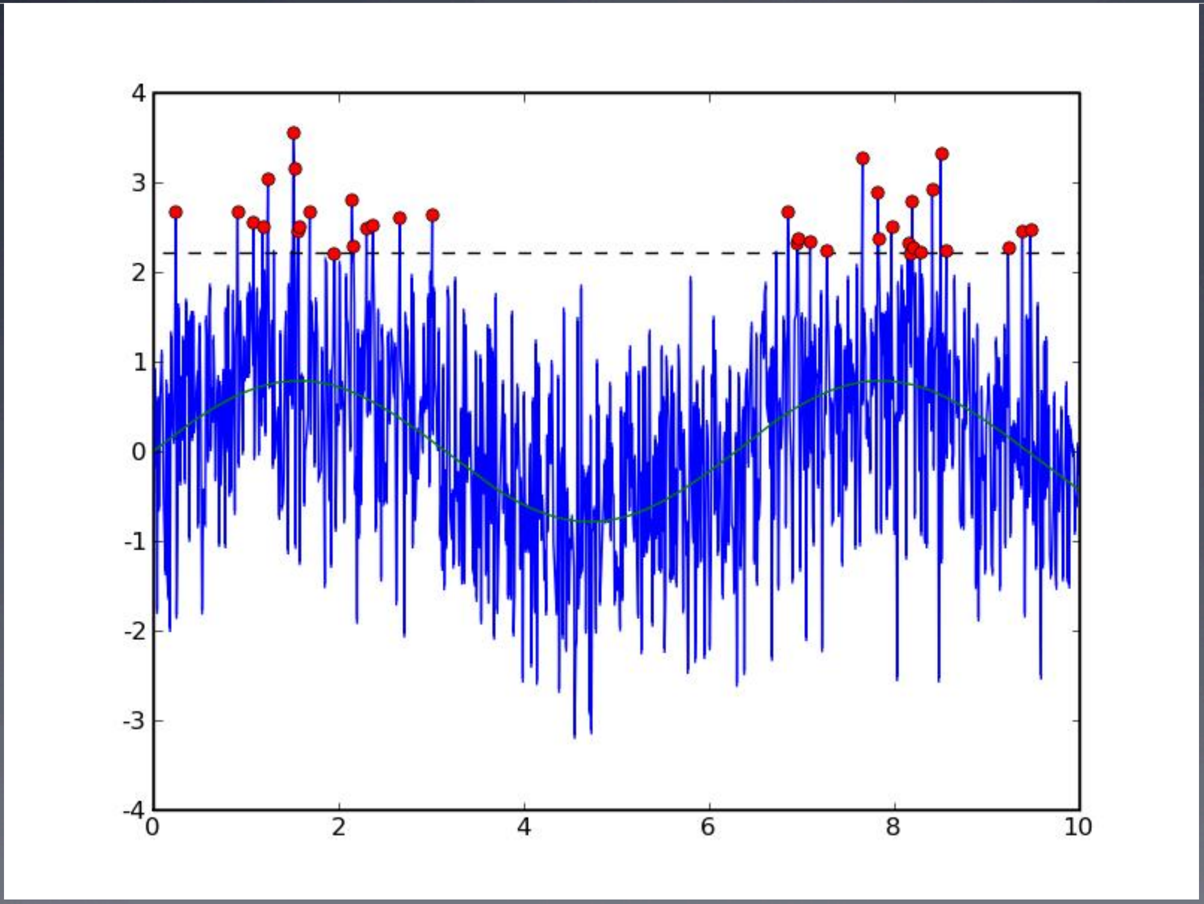


Tegmark et al. (2006)

Most halos form at initial density peaks



Complication I: 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

Bias model I: local bias

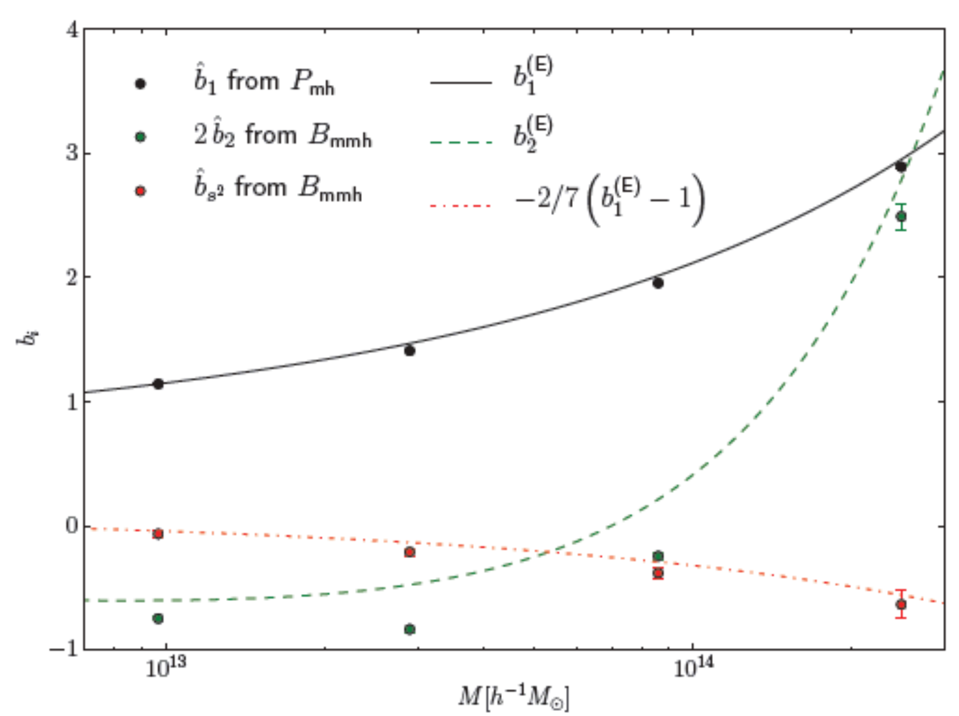
Local bias model: $\delta_h = b_1\delta_m + b_2\delta_m^2 + \ldots$

Peak-background split model:
b_1 is determined by 1^{st} derivative of halo mass function,
b_2 by 2^{nd} derivative…

$$b^{\rm L}_{10} = \frac{1}{\bar{n}}\frac{\partial n}{\partial \delta_l} = -\frac{1}{\bar{n}}\frac{2\nu}{\delta_c}\frac{\partial n}{\partial \nu}$$

$$b^{\rm L}_{01} = \frac{1}{\bar{n}}\frac{\partial n}{\partial \varphi_l} = -\frac{4 f_{\rm NL}\nu}{\bar{n}}\frac{\partial n}{\partial \nu} = 2 f_{\rm NL}\delta_c b^{\rm L}_{10}$$

$$b^{\rm L}_{20} = \frac{1}{\bar{n}}\frac{\partial^2 n}{\partial {\delta_l}^2} = \frac{4}{\bar{n}}\frac{\nu^2}{\delta_c^2}\frac{\partial^2 n}{\partial \nu^2} + \frac{2}{n}\frac{\nu}{\delta_c^2}\frac{\partial n}{\partial \nu}$$



Bias model II: non-local bias

Local bias model: $\delta_h = b_1 \delta_m + b_2 \delta_m^2 + \ldots$: Eulerian or Lagrangian?

Gravity develops nonlocal terms

$$^{(2)}\delta(\boldsymbol{x},\eta) = \frac{17}{21}\,^{(1)}\delta^2(\boldsymbol{x},\eta) - \boldsymbol{\Psi}(\boldsymbol{x},\eta)\cdot\boldsymbol{\nabla}\delta(\boldsymbol{x},\eta) + \frac{2}{7}s^2(\boldsymbol{x},\eta).$$

Tidal tensor

$$s_{ij}(\boldsymbol{x},\eta) = \partial_i\partial_j\Phi(\boldsymbol{x},\eta) - \frac{1}{3}\delta_{ij}^{(\mathrm{K})}\delta(\boldsymbol{x},\eta).$$

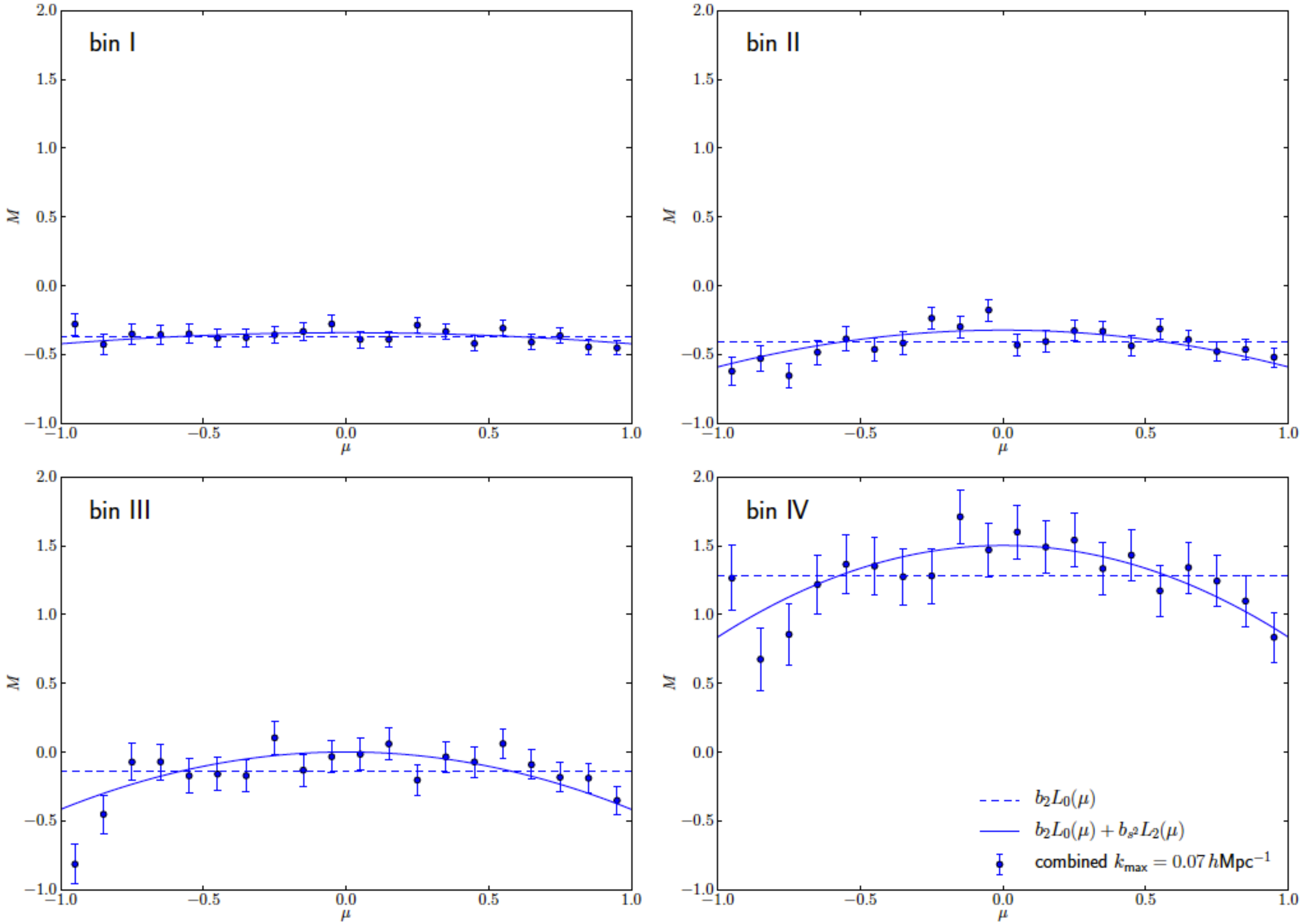
Baldauf etal, Kwan et al 2012

$$\delta_{\mathrm{h}}(\boldsymbol{x},\eta) = b_1\delta(\boldsymbol{x},\eta) + b_2\left[\delta^2(\boldsymbol{x},\eta) - \langle\delta^2(\boldsymbol{x},\eta)\rangle\right] + b_{s^2}\left[s^2(\boldsymbol{x},\eta) - \langle s^2(\boldsymbol{x},\eta)\rangle\right]$$

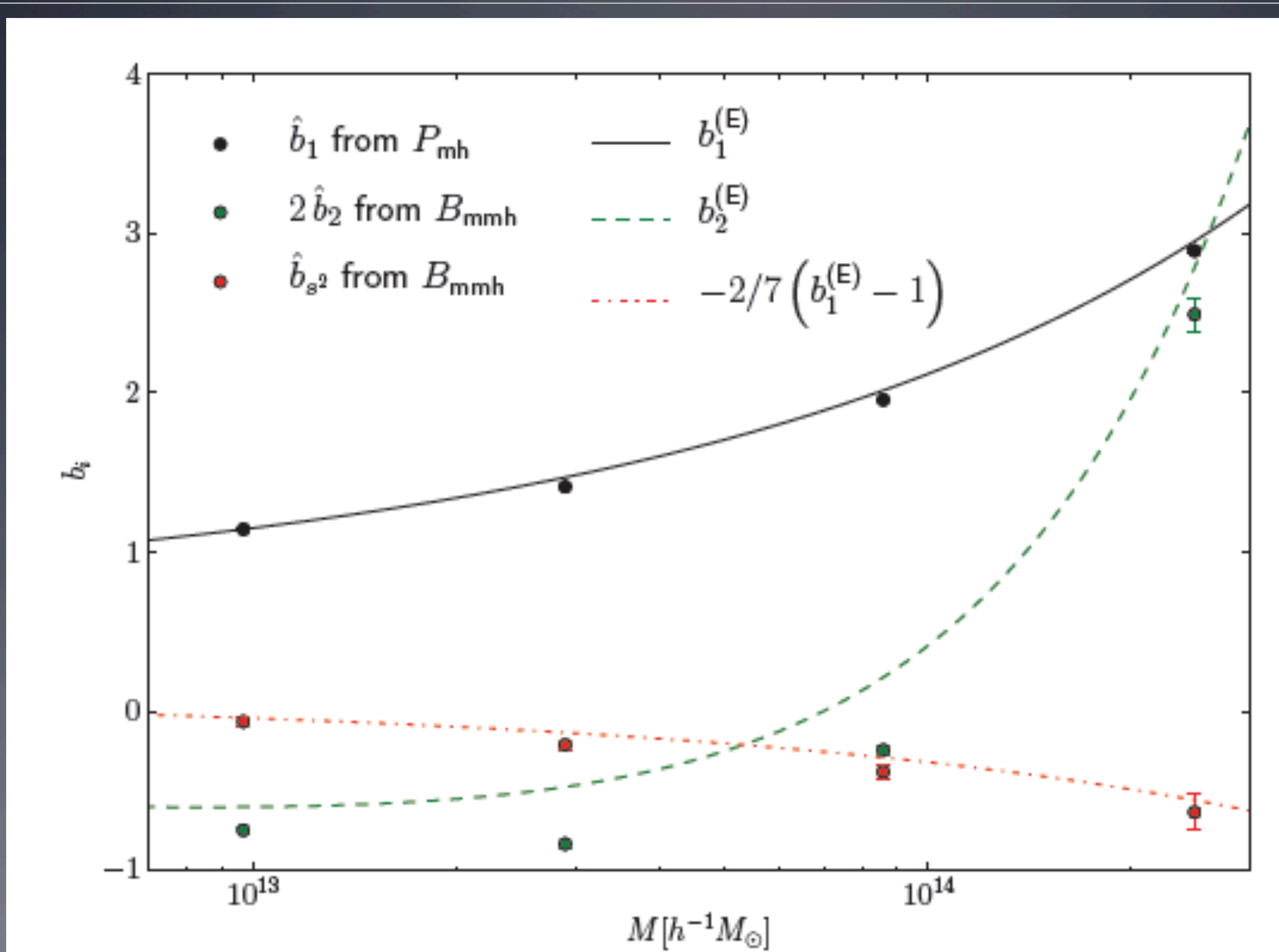
Local Lagrangian bias model predicts $b_{s2} = -2(b_1-1)/7$

We can look for it in bispectrum B_{mmh}

$$B_{\mathrm{mmh}}^{(\mathrm{unsym})}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3) - b_1 B_{\mathrm{mmm}}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3) = 2P(k_1)P(k_2)\left[b_2 + b_{s^2}\left(\mu^2 - \frac{1}{3}\right)\right].$$


bin I
bin II
bin III
bin IV
M
μ
$b_2 L_0(\mu)$
$b_2 L_0(\mu) + b_{s^2} L_2(\mu)$
combined $k_{max} = 0.07\,h\mathrm{Mpc}^{-1}$

Bispectrum fits to simulations vs peak-background split predictions



Bottom line: non-local bias exists, not possible to ignore it

Saito et al, in prep

3rd order non-local bias

Let's write all possible terms allowed by symmetry at 3rd order (McDonald and Roy 2010)

2nd-order non-local bias (tidal bias) $B^{\rm hmm} \sim \langle \delta_{\rm h}^{(2)} \delta_{\rm m}^{(1)} \delta_{\rm m}^{(1)} \rangle$

3rd-order non-local bias ~~$T^{\rm hmmm} \sim \langle \delta_{\rm h}^{(3)} \delta_{\rm m}^{(1)} \delta_{\rm m}^{(1)} \delta_{\rm m}^{(1)} \rangle$~~

$$P^{\rm hm} \sim \langle \delta_{\rm h}^{(1)} \delta_{\rm m}^{(1)} \rangle + \langle \delta_{\rm h}^{(1)} \delta_{\rm m}^{(3)} \rangle + \langle \delta_{\rm h}^{(2)} \delta_{\rm m}^{(2)} \rangle + \langle \delta_{\rm h}^{(3)} \delta_{\rm m}^{(1)} \rangle$$

linear bias x $P^{NL}m$

Combining P(k) with B(k) → 3rd-order nonlocal bias!

local bias

non-local bias

$$\delta_h(\boldsymbol{x}) = c_\delta \delta_m(\boldsymbol{x}) + \frac{1}{2} c_{\delta^2}\delta_m(\boldsymbol{x})^2 + \frac{1}{2} c_{s^2} s(\boldsymbol{x})^2 + \frac{1}{3!} c_{\delta^3}\delta_m(\boldsymbol{x})^3 + \frac{1}{2} c_{\delta s^2}\delta_m(\boldsymbol{x}) s(\boldsymbol{x})^2 + c_\psi \psi(\boldsymbol{x}) + c_{st} s(\boldsymbol{x}) t(\boldsymbol{x}) + \frac{1}{3!} c_{s^3} s(\boldsymbol{x})^3 + c_\epsilon \epsilon + \dots,$$

linear: can be measured via $P^{hm}(k)$ at large scales

2nd-order: measured via $B^{hmm}(k)$ at large scales se

3rd-order

where

$$s_{ij}(\boldsymbol{x}) \equiv \partial_i\partial_j\phi(\boldsymbol{x}) - \frac{1}{3}\delta^K_{ij}\delta_m(\boldsymbol{x}) = \left[\partial_i\partial_j\partial^{-2} - \frac{1}{3}\delta^K_{ij}\right]\delta_m(\boldsymbol{x}),$$ tidal field

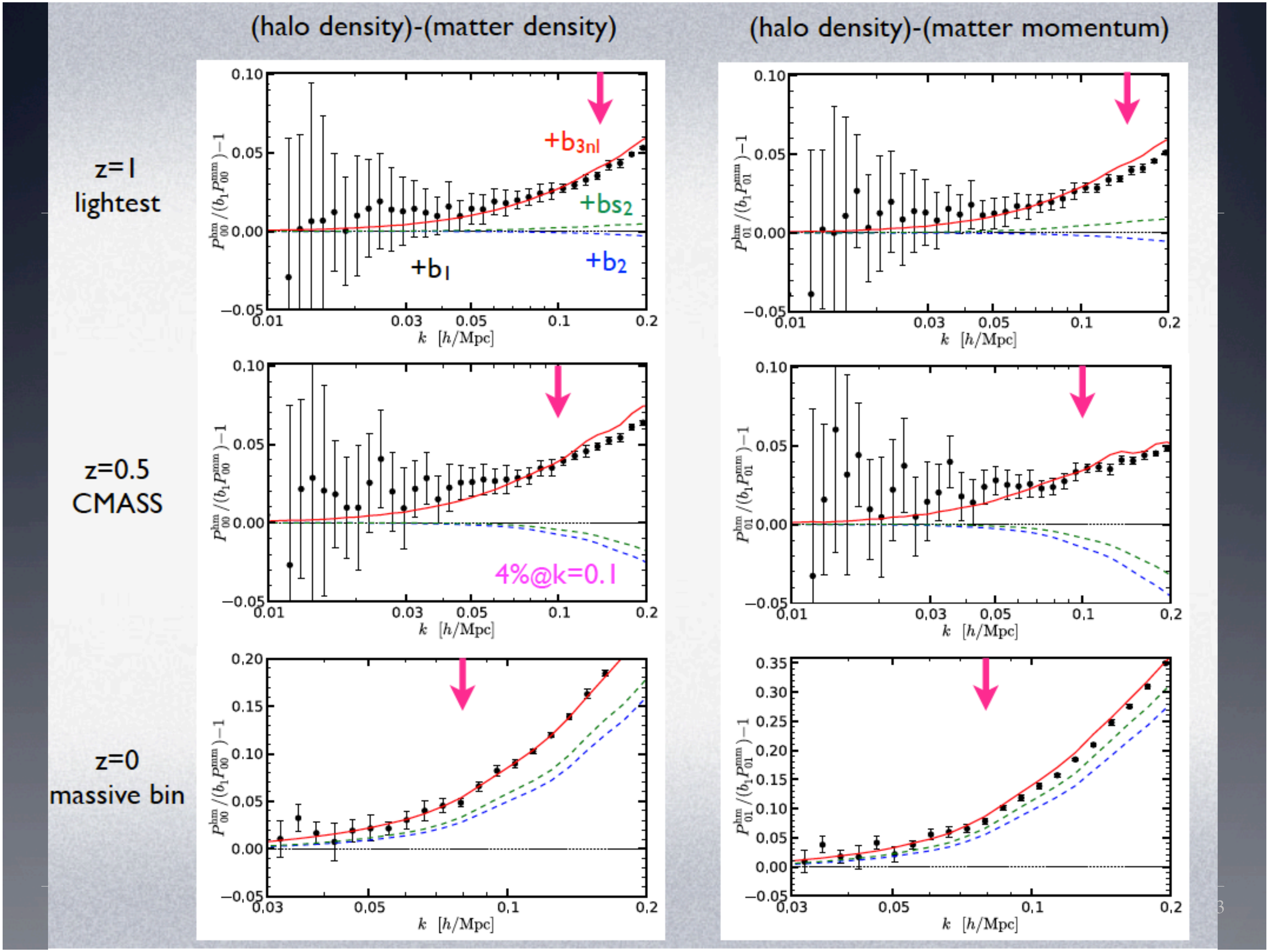
$$t_{ij}(\boldsymbol{x}) \equiv \partial_i v_j - \frac{1}{3}\delta^K_{ij}\theta_m(\boldsymbol{x}) - s_{ij}(\boldsymbol{x}) = \left[\partial_i\partial_j\partial^{-2} - \frac{1}{3}\delta^K_{ij}\right][\theta(\boldsymbol{x}) - \delta_m(\boldsymbol{x})],$$

$$\psi(\boldsymbol{x}) \equiv [\theta(\boldsymbol{x}) - \delta_m(\boldsymbol{x})] - \frac{2}{7}s(\boldsymbol{x})^2 + \frac{4}{21}\delta_m(\boldsymbol{x})^2.$$

(halo density)-(matter density) McDonald & Roy (2010)

$$\begin{aligned} P^{hm}_{00}(k) = & \left(c_\delta + \frac{34}{21}c_{\delta^2}\sigma^2 + \frac{1}{2}c_{\delta^3}\sigma^2 + \frac{1}{3}c_{\delta s^2}\sigma^2 + \frac{1}{2}c_{\delta\epsilon^2}\sigma_\epsilon^2 + \frac{68}{63}c_{s^2}\sigma^2 - \frac{16}{63}c_{st}\sigma^2\right) P^{NL}_{\delta\delta}(k) \\ & + c_{\delta^2}\int\frac{d^3q}{(2\pi)^3}P(q)P(|\boldsymbol{k}-\boldsymbol{q}|)F_S^{(2)}(\boldsymbol{q},\boldsymbol{k}-\boldsymbol{q}) \\ & + c_{s^2}\int\frac{d^3q}{(2\pi)^3}P(q)P(|\boldsymbol{k}-\boldsymbol{q}|)F_S^{(2)}(\boldsymbol{q},\boldsymbol{k}-\boldsymbol{q})S^{(2)}(\boldsymbol{q},\boldsymbol{k}-\boldsymbol{q}) \\ & + \left(-\frac{16}{21}c_{s^2} + \frac{32}{105}c_{st} + \frac{512}{2205}c_\psi\right)\sigma_3^2(k)P(k) \\ = & \; b_1 P^{NL}_{\delta\delta}(k) + b_2 P_{b2,\delta}(k) + b_{s^2}P_{bs2,\delta}(k) + b_{3nl}\,\sigma_3^2(k)P(k), \end{aligned}$$

origin: (1)x(1) or (1)x(3)→linear bias

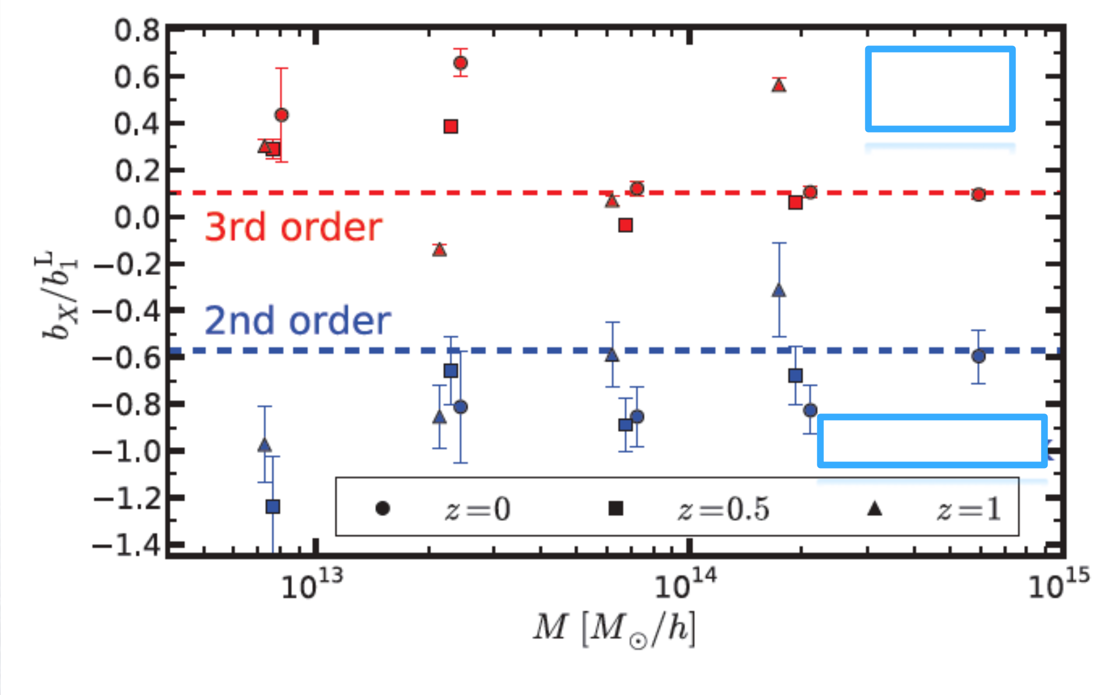

(halo density)-(matter density)
(halo density)-(matter momentum)
z=1
lightest
z=0.5
CMASS
z=0
massive bin
+b3nl
+bs2
+b1
+b2
4%@k=0.1
k [h/Mpc]

Prediction from local bias in Lagrangian space

The simple co-evolution picture predicts non-local bias as

2nd order $$b_{s^2} = -\frac{4}{7} b_1^{\rm L} = -\frac{4}{7}(b_1^{\rm E} - 1)$$

3rd order $$b_{3\rm nl} = \frac{32}{315} b_1^{\rm L} = \frac{32}{315}(b_1^{\rm E} - 1)$$

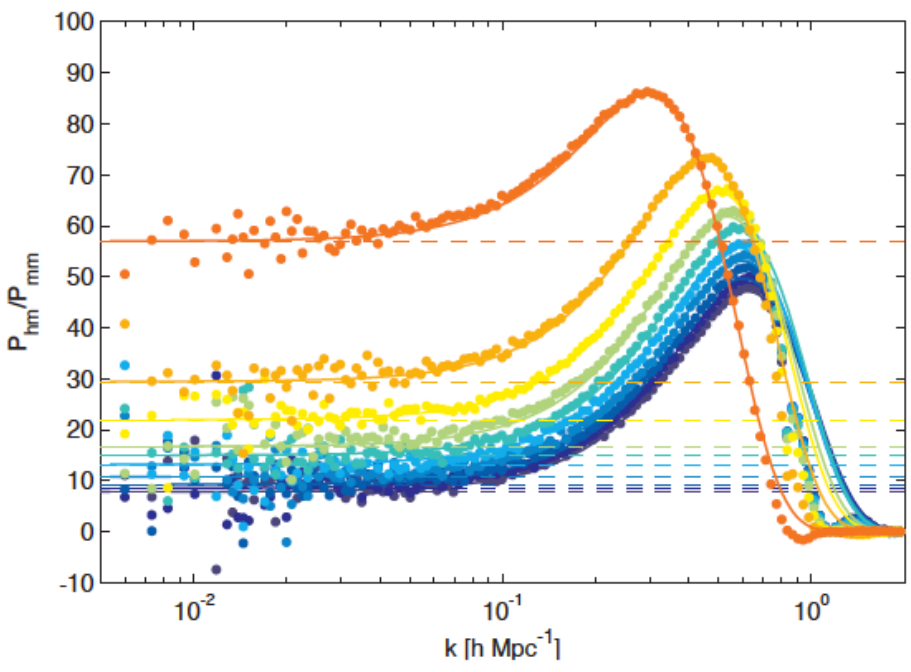


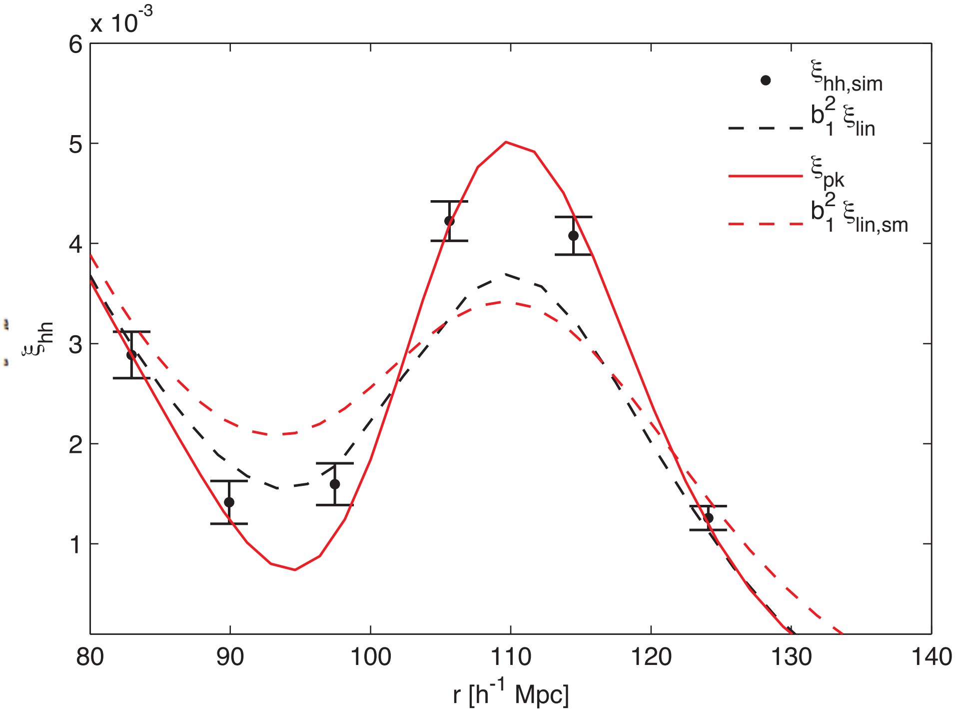
Bias model III: linear peak biasing for proto-halos

- Peak constraints depend also on 2nd derivatives of density field, in low k limit one can expand to find (Desjacques 2008)

$$P_{\rm hm}(k) = \left(b_\nu + b_\zeta k^2\right) W_{{\rm G},R_{\rm pk}}(k) P(k)$$

$$P_{\rm hh}(k) \approx \left(b_\nu + b_\zeta k^2\right)^2 W^2_{{\rm G},R_{\rm pk}}(k) P(k)$$





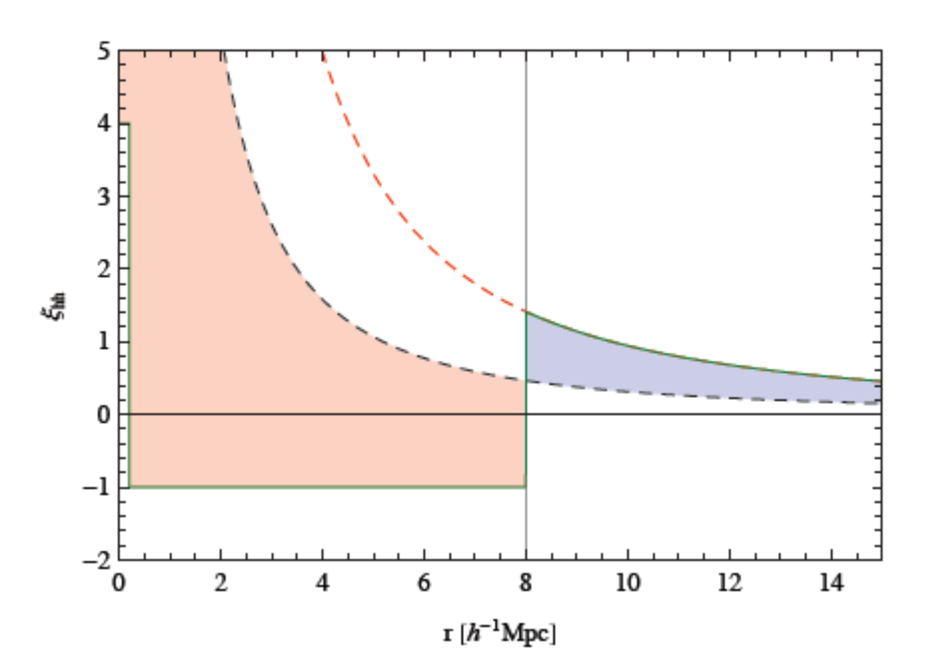
k^2 effects likely survive to z=0, but are pushed to smaller scales

Bias model IV: stochasticity from exclusion and nonlinearity

- We managed to explain P_{hm}, what about P_{hh}?
- Define stochasticity as $\sigma^2=<(\delta_h-b\delta_m)^2>=P_{hh}-2bP_{hm}+b^2P_{mm}$
- If we can model $\sigma^2(k)$ we can model P_{hh}
- Standard model:

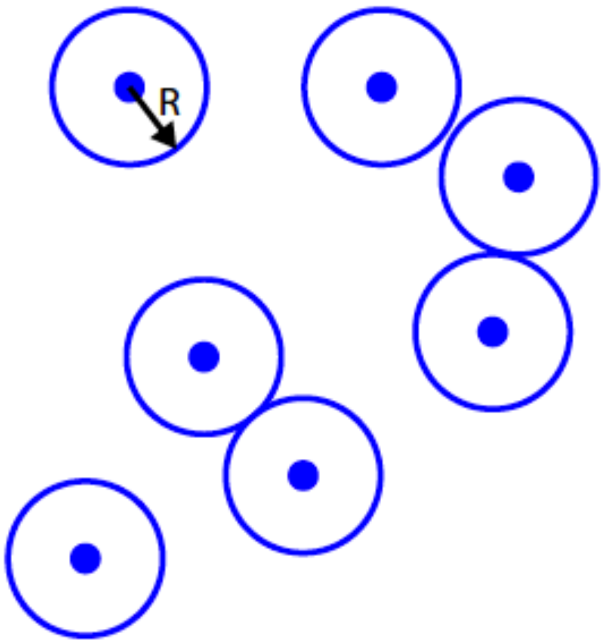
Poisson shot noise $\sigma^2=1/n$

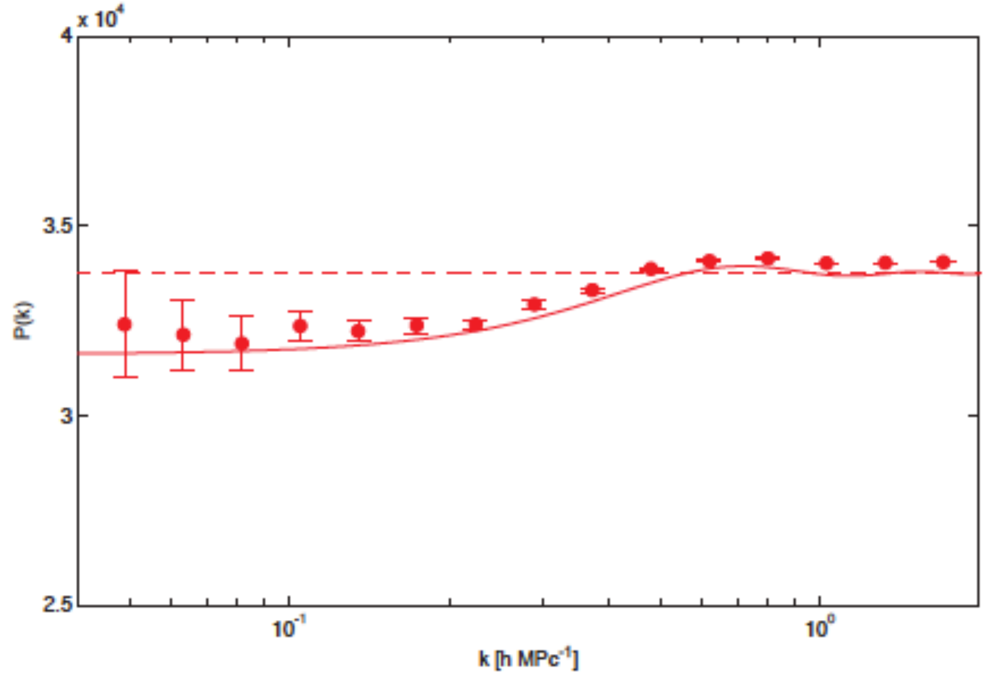
- 2 corrections: exclusion, nonlinear clustering



Baldauf et al 2013

Random Sample with Exclusion





Perturbation Theory + Exclusion

$$\sigma_{ij}(k) = \frac{1}{\bar{n}} - [P_{\rm disc} * W](k) + \frac{1}{2} b_{2,i} b_{2,j} \int \frac{\mathrm{d}^3 q}{(2\pi)^3} P(q) P(\mathbf{k} - \mathbf{q})$$

Dependence on halo mass

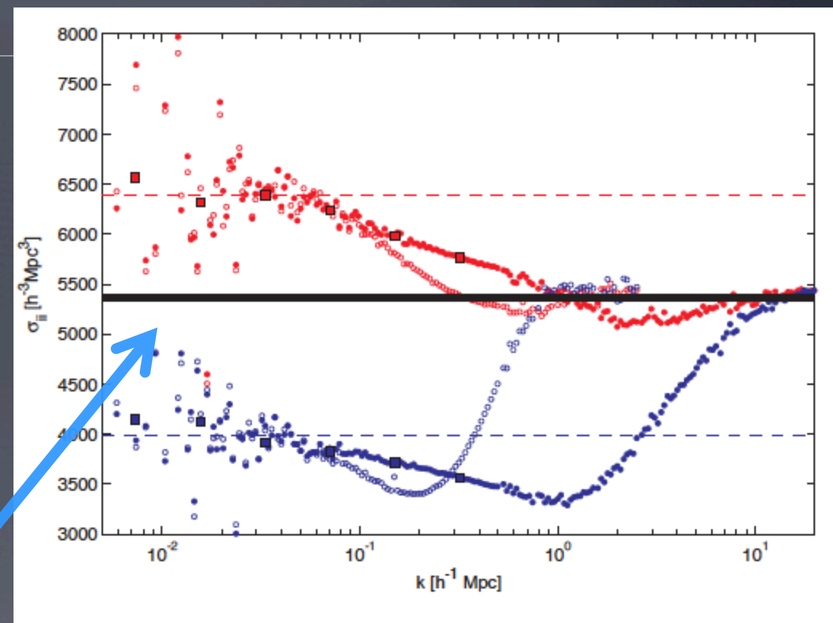
Same value of $\sigma^2(k=0)$ between $z=z_{in}$ and $z=0$: gravity cannot modify it

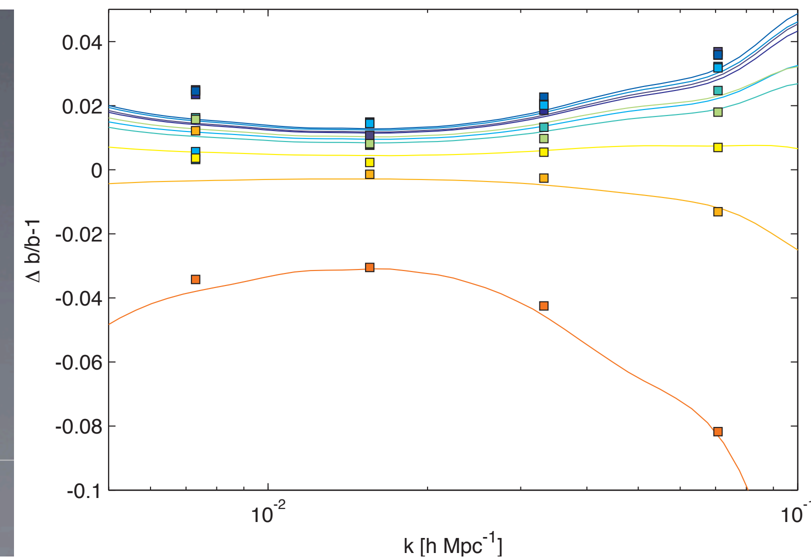
Positive (nonlinear effects dominate) for low mass, negative (exclusion dominates) for high mass

At high k 0 correction to 1/n

Transition scale shrinks at z=0 relative to $z=z_{in}$

Effects of order a few %





The large scale structure view of biasing

Q: Can we predict non-linear biasing or do we need 5+ new parameters?

A: Sort of: most of the effects are related to the halo mass. It may be possible to reduce all these effects to a single parameter, but we have not yet demonstrated that

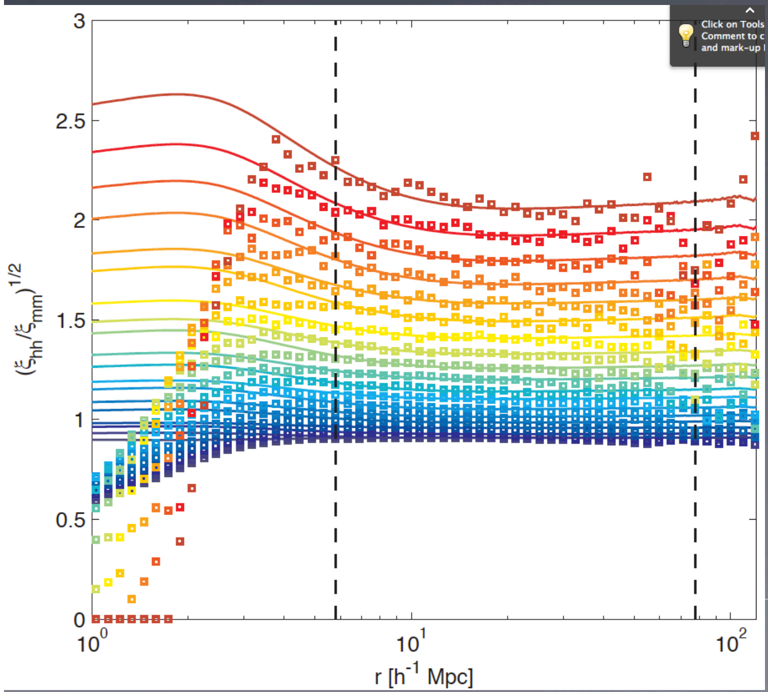
Q: What is the simplest way to reduce the nonlinear biasing?

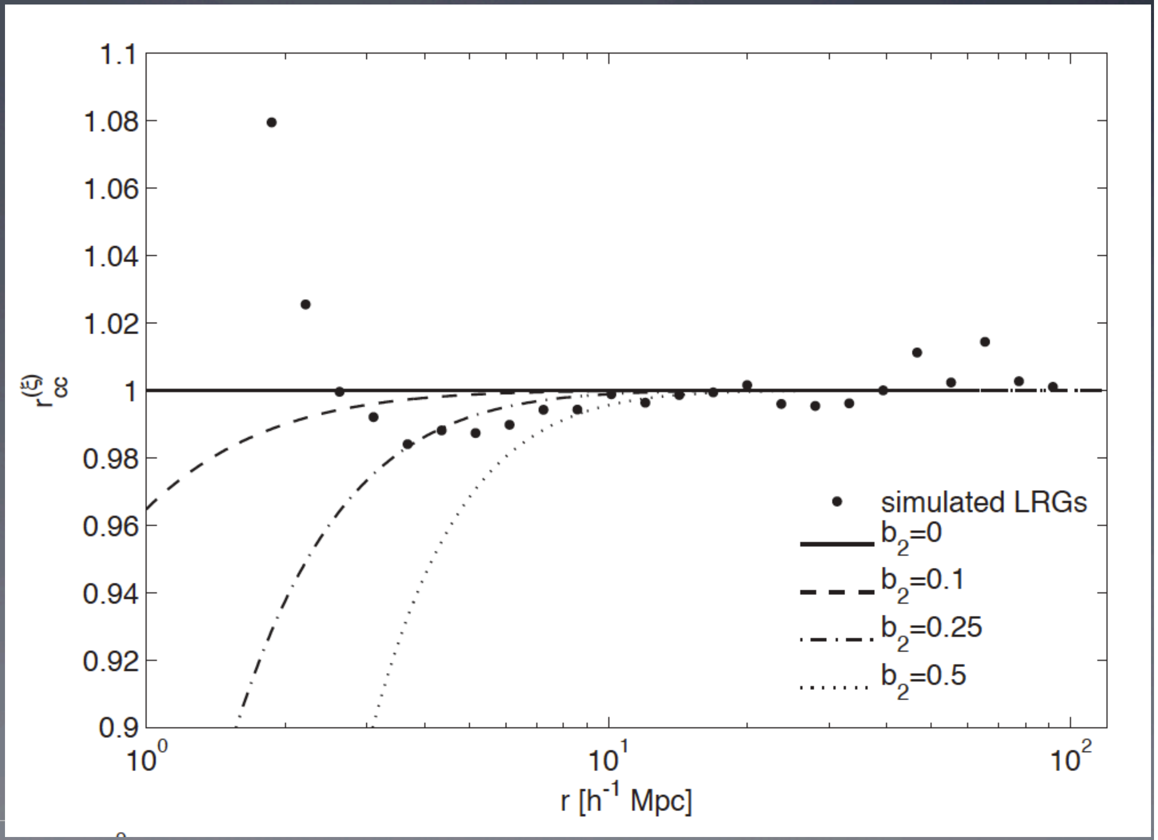
A: Most of the biasing effects show up in auto and cross-correlation statistics, they cancel in cross-correlation coefficient

Halo dark matter cross-correlation coefficient: LRG simulations

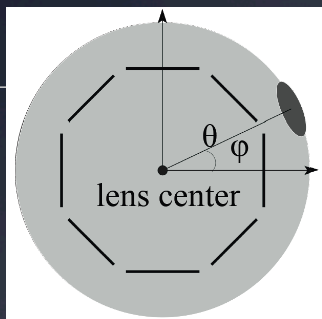
as long as galaxies are inside halos we get nearly the same correlation coefficient independent of how galaxies occupy halos

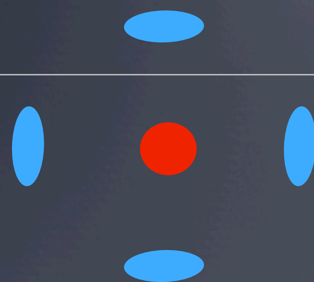
$$r = \frac{\xi_{hm}}{\sqrt{\xi_{hh}\xi_{mm}}}$$

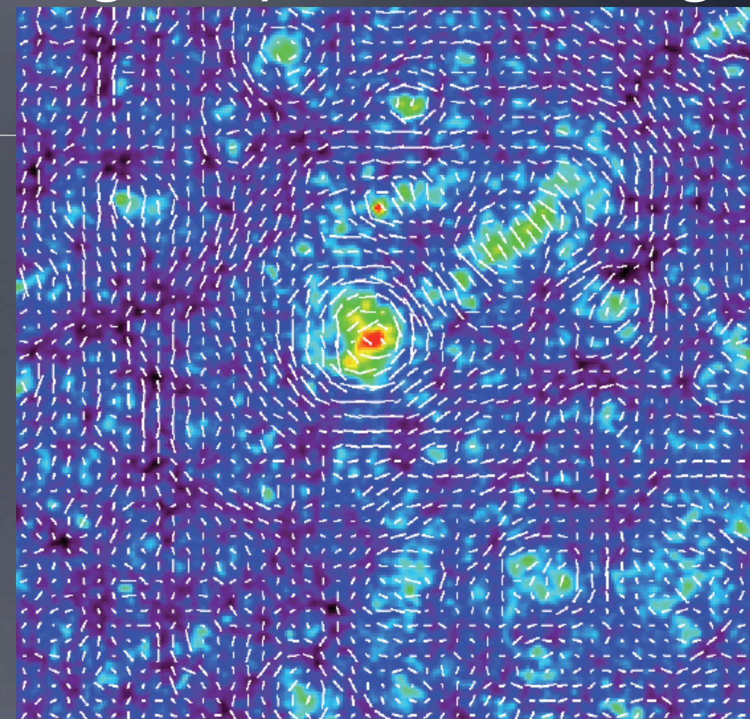




Galaxy-dark matter correlations: galaxy-shear lensing







$$R = r_L \Theta$$

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

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

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

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

Statistics 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

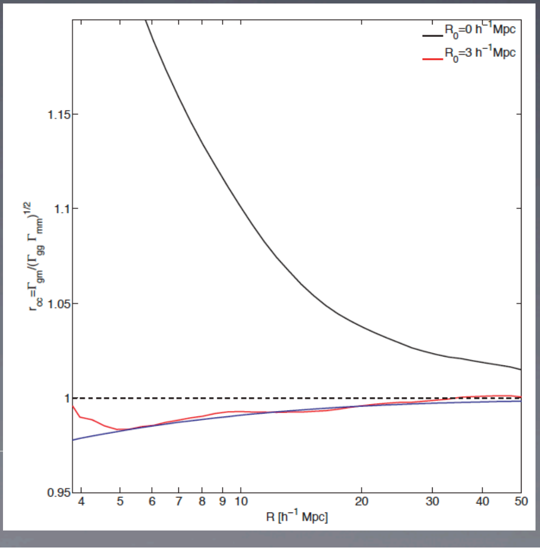
$$\Sigma(R) = \int g(\chi)\xi(\sqrt{\chi^2 + R^2})d\chi$$

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

We introduced (Baldauf etal 2009) new statistic that cancels small scale information

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

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

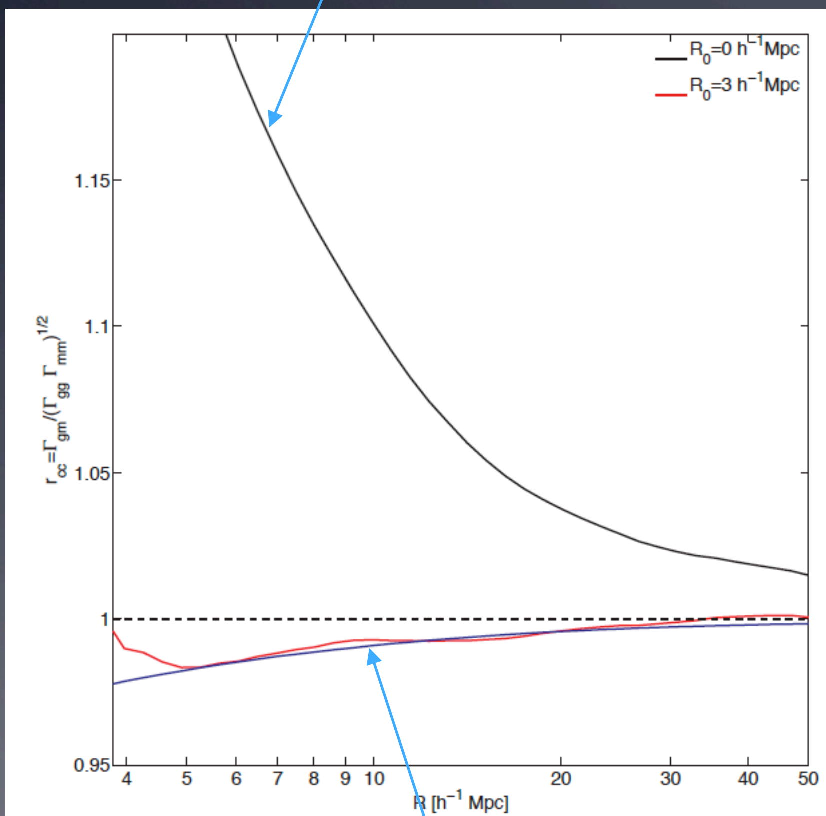


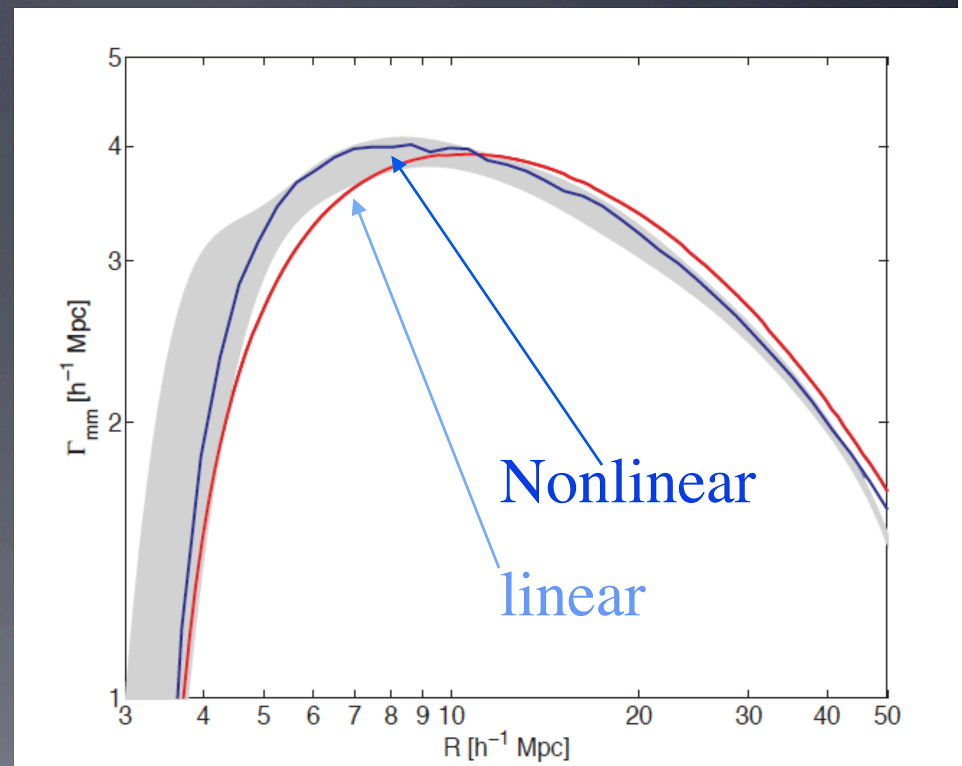
Simulations: dark matter reconstruction

Baldauf, Smith, US, Mandelbaum (2009)

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

Old statistic



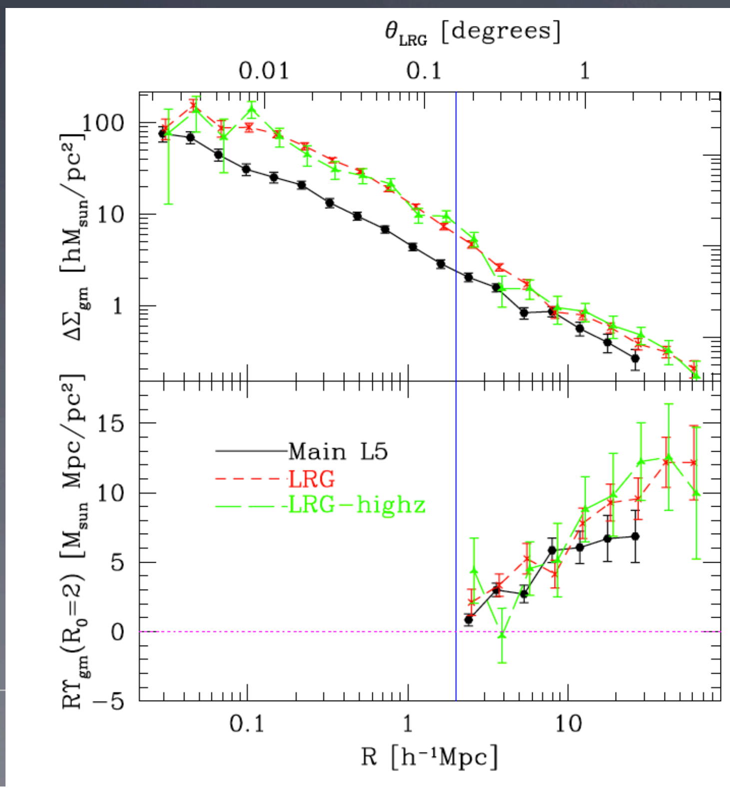


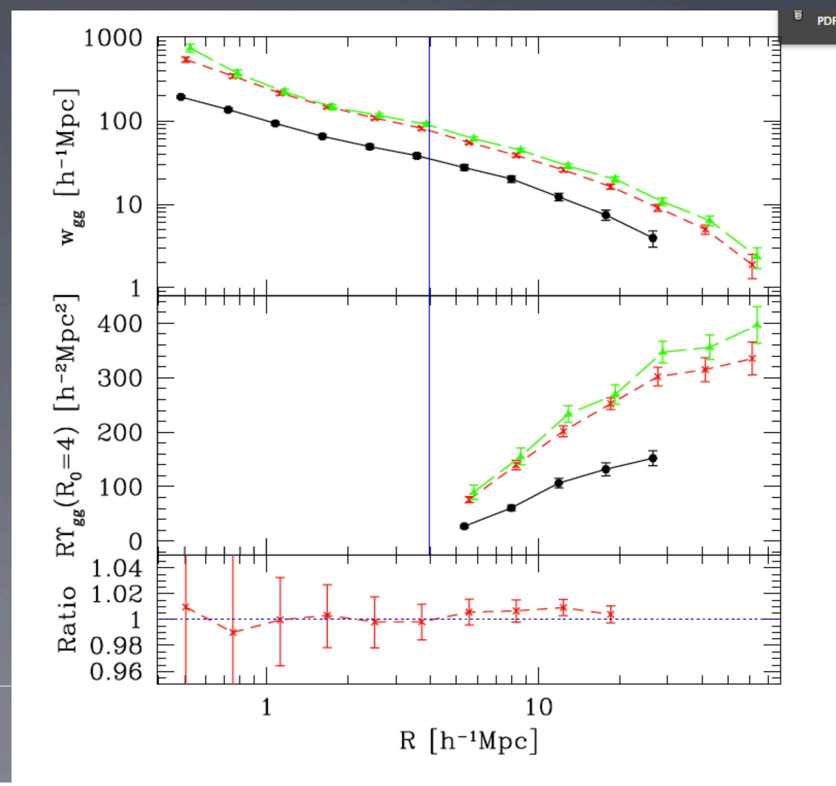
New statistic: Cross-correlation coefficient
r nearly unity

SDSS DR-7 data analysis Mandelbaum etal, 2012

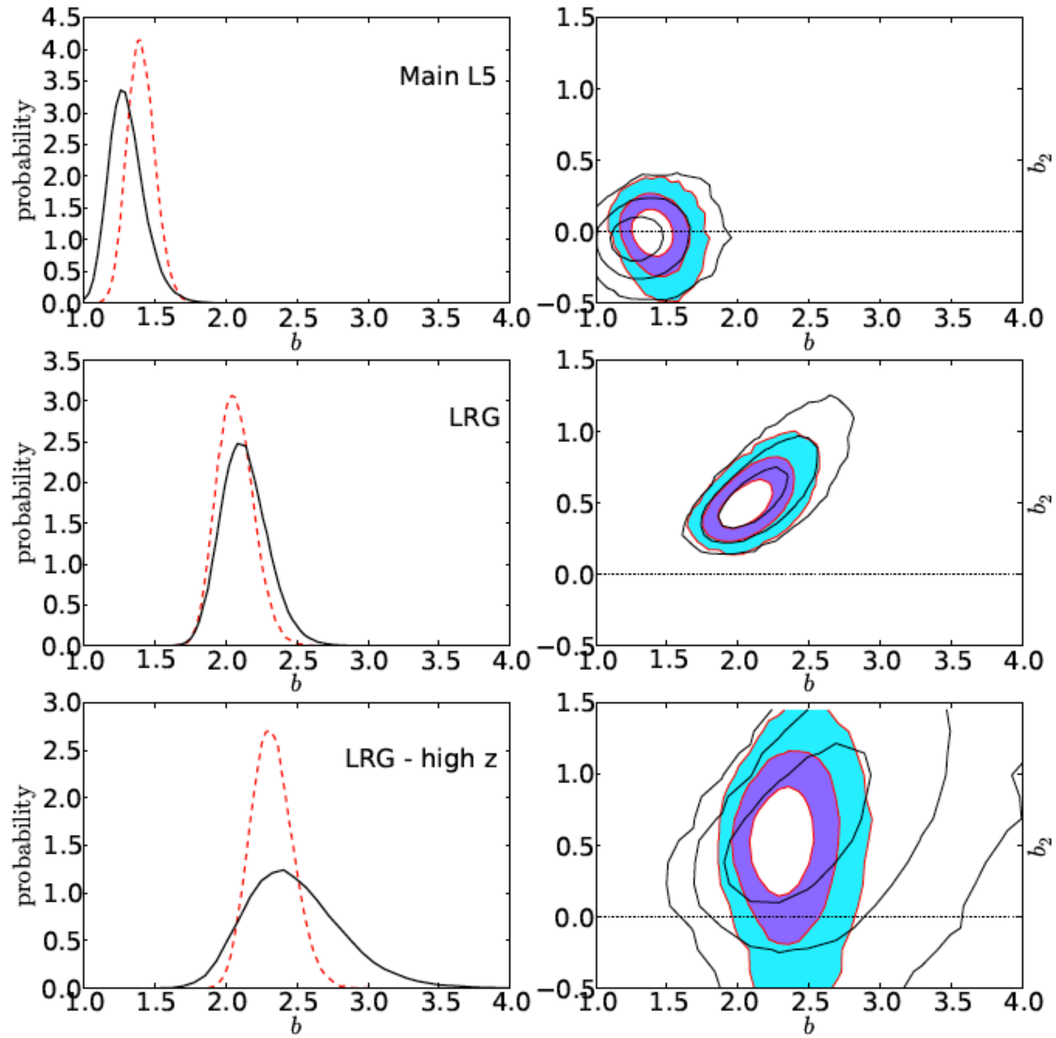
LENSES
70,000 M*-1 galaxies (z<0.15),
62,000 low z LRGs (0.16<z<0.3),
35,000 high z LRGs (0.36<z<0.47)

SOURCES
10M, well calibrated photozs
using spectroscopic surveys



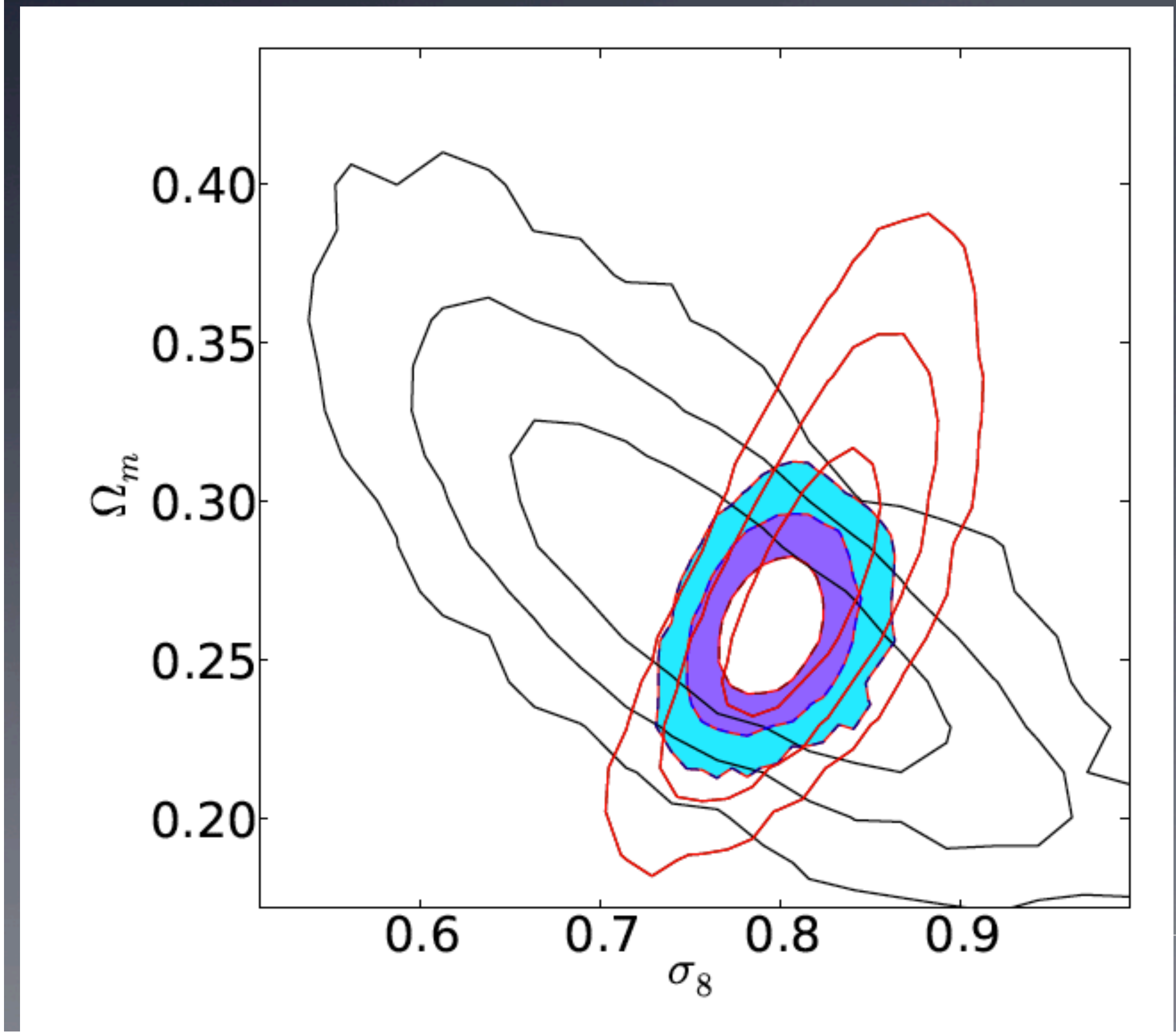


First direct detection of scale dependent bias



Cosmology constraints

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



SDSS

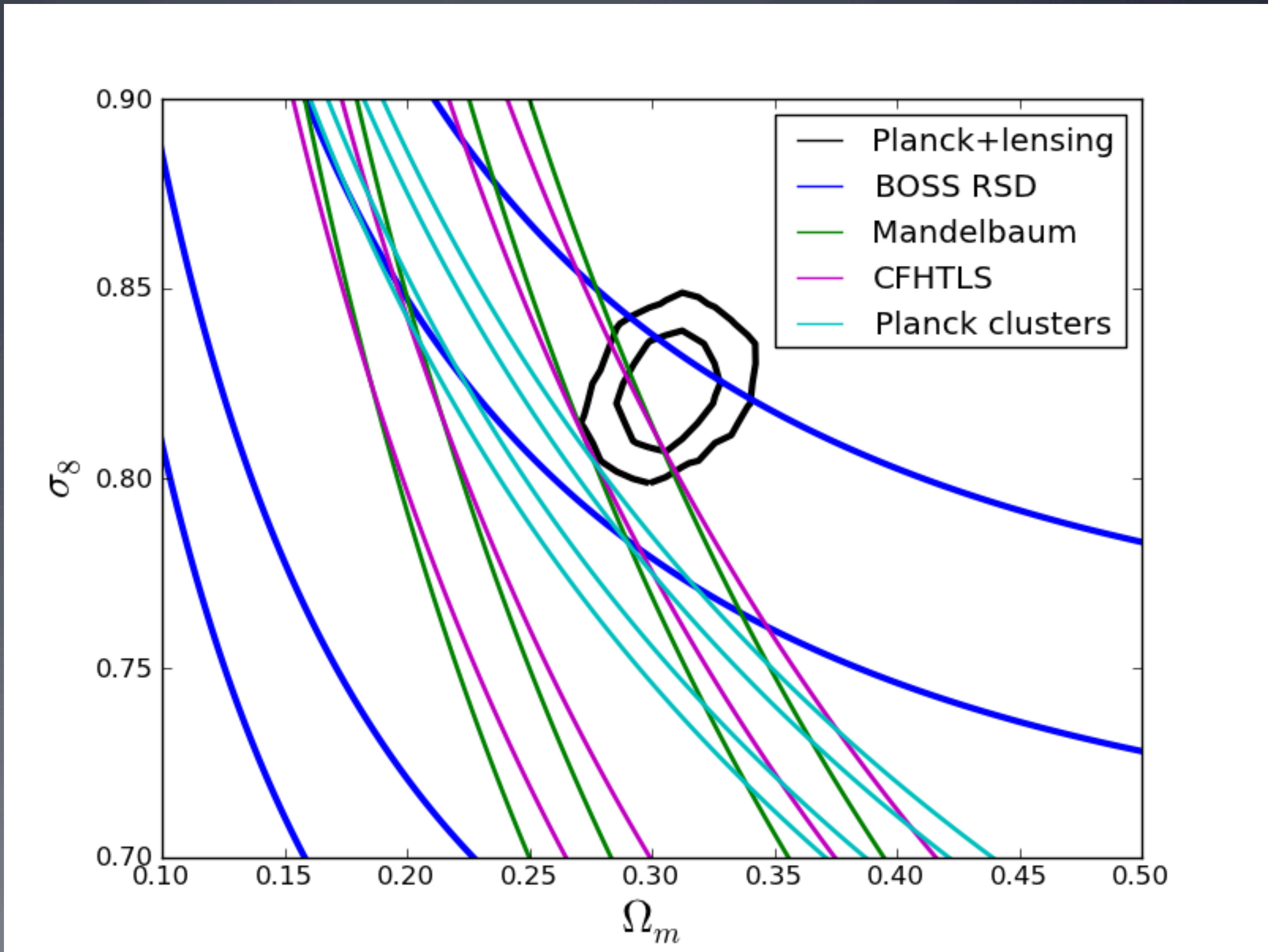
WMAP

Current LSS constraints: Planck (lensing) versus the rest of LSS

All LSS constraints (RSD, lensing, clusters) consistent

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

How to resolve this? With new data!



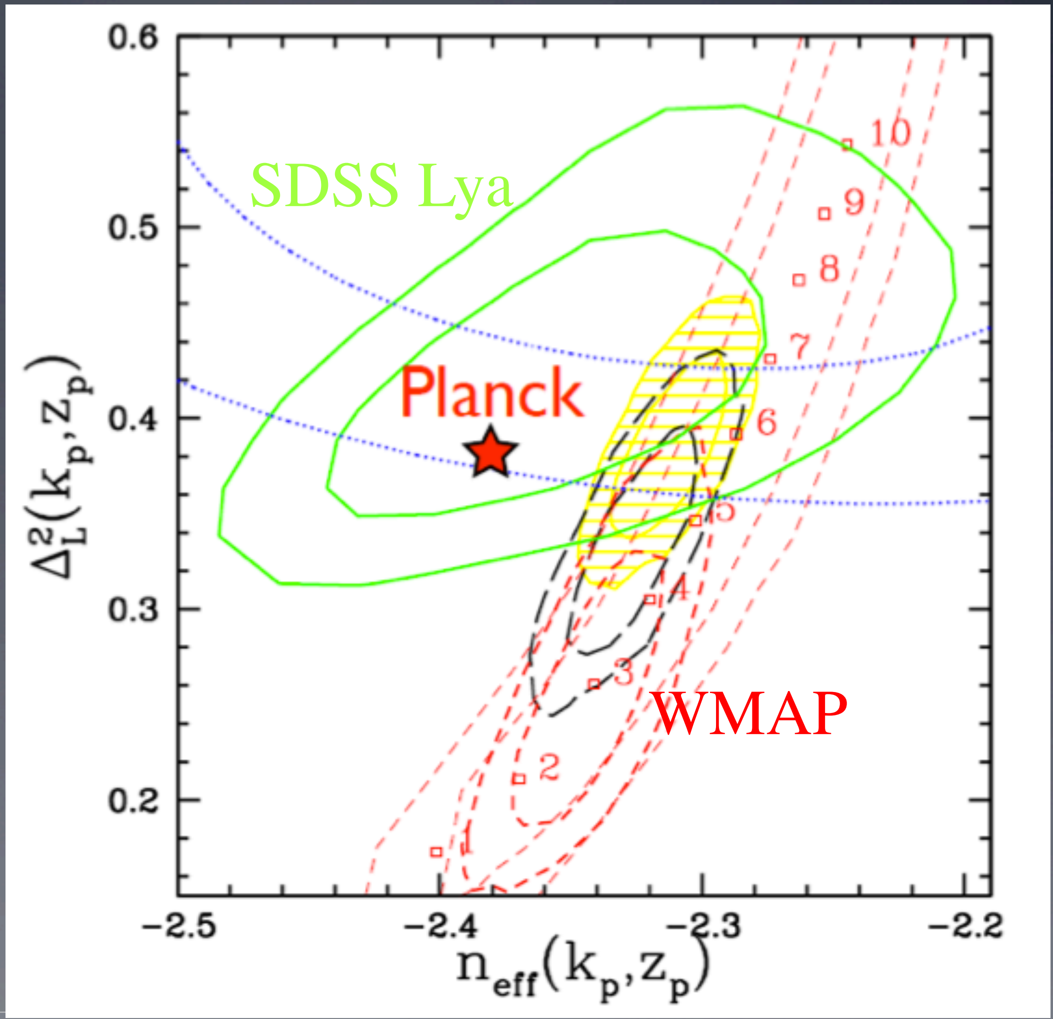
Beth Reid plot

Small scale LSS: Lya forest 2005

In 2005 SDSS Lya forest power spectrum (McDonald etal) amplitude was higher than WMAP 3 year:

$$\sum m_\nu < 0.17\text{eV at } 2\sigma$$

With Planck this bound is weakened, but Lya is now in a better agreement with CMB



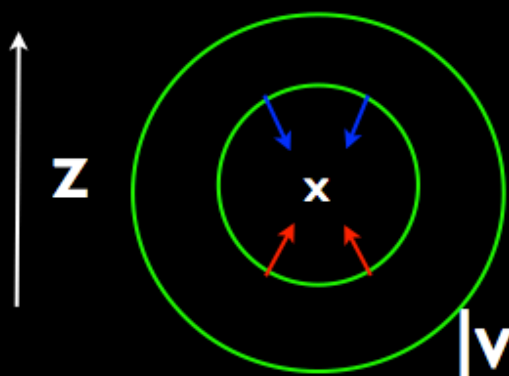
Halo-shear versus shear-shear lensing

	shear-shear	galaxy-shear
• Calibration bias:	-	-
• Intrinsic alignments	-	+
• Photoz induced error	-	-
• Instrument/sky induced correlations:	-	+
• Baryonic effects:	-	+

Lessons from last decade: shear-shear is difficult, galaxy-shear has fewer systematic uncertainties, complementary to shear-shear analysis

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

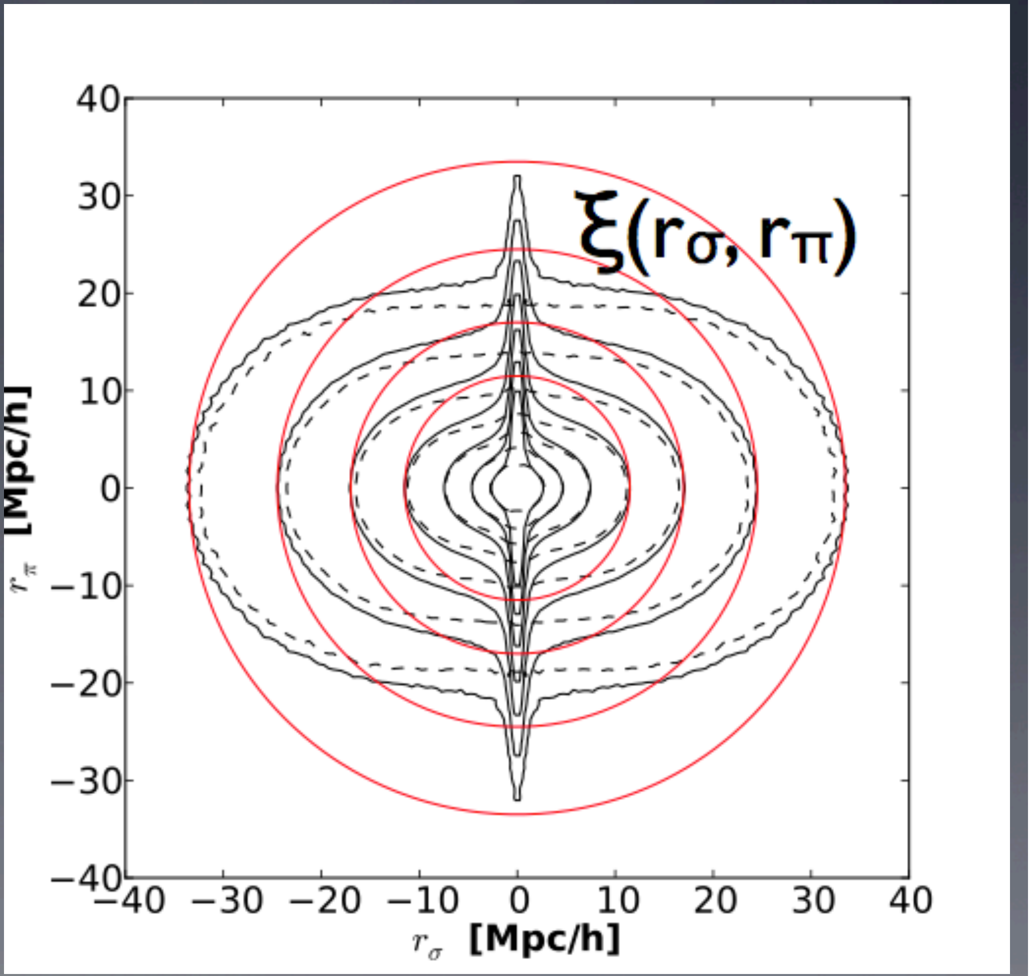
On very large scales linear RSD distortions:

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

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

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

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



White etal 2011

Velocities are probed at galaxy positions: density weighted velocity moments

US, McDonald 2011

Lowest moments: density, momentum density, stress energy density

RSD never directly probe velocity, only momentum density…

$$\rho_s(\mathbf{k}) = ma^{-3} \int d^3x \; d^3q \; f(\mathbf{x}, \mathbf{q}) \, e^{(i\mathbf{k}\cdot\mathbf{x} + ik_\parallel u_\parallel/\mathcal{H})}$$
$$= ma^{-3} \int d^3x \; e^{i\mathbf{k}\cdot\mathbf{x}} \int d^3q \; f(\mathbf{x}, \mathbf{q}) e^{ik_\parallel u_\parallel/\mathcal{H}},$$

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

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

$$T^L_\parallel(\mathbf{k}) = \int d^3\mathbf{x} \; T^L_\parallel(\mathbf{x}) e^{i\mathbf{k}\cdot\mathbf{x}}.$$

$$T^L_\parallel(\mathbf{x}) = \frac{m}{\bar{\rho}} \int d^3\mathbf{q} \; f(\mathbf{x}, \mathbf{q}) \, u^L_\parallel = \Big\langle (1 + \delta(\mathbf{x})) \, u^L_\parallel(\mathbf{x}) \Big\rangle_{\mathbf{x}}$$

RSD modeling

US & McDonald 2011

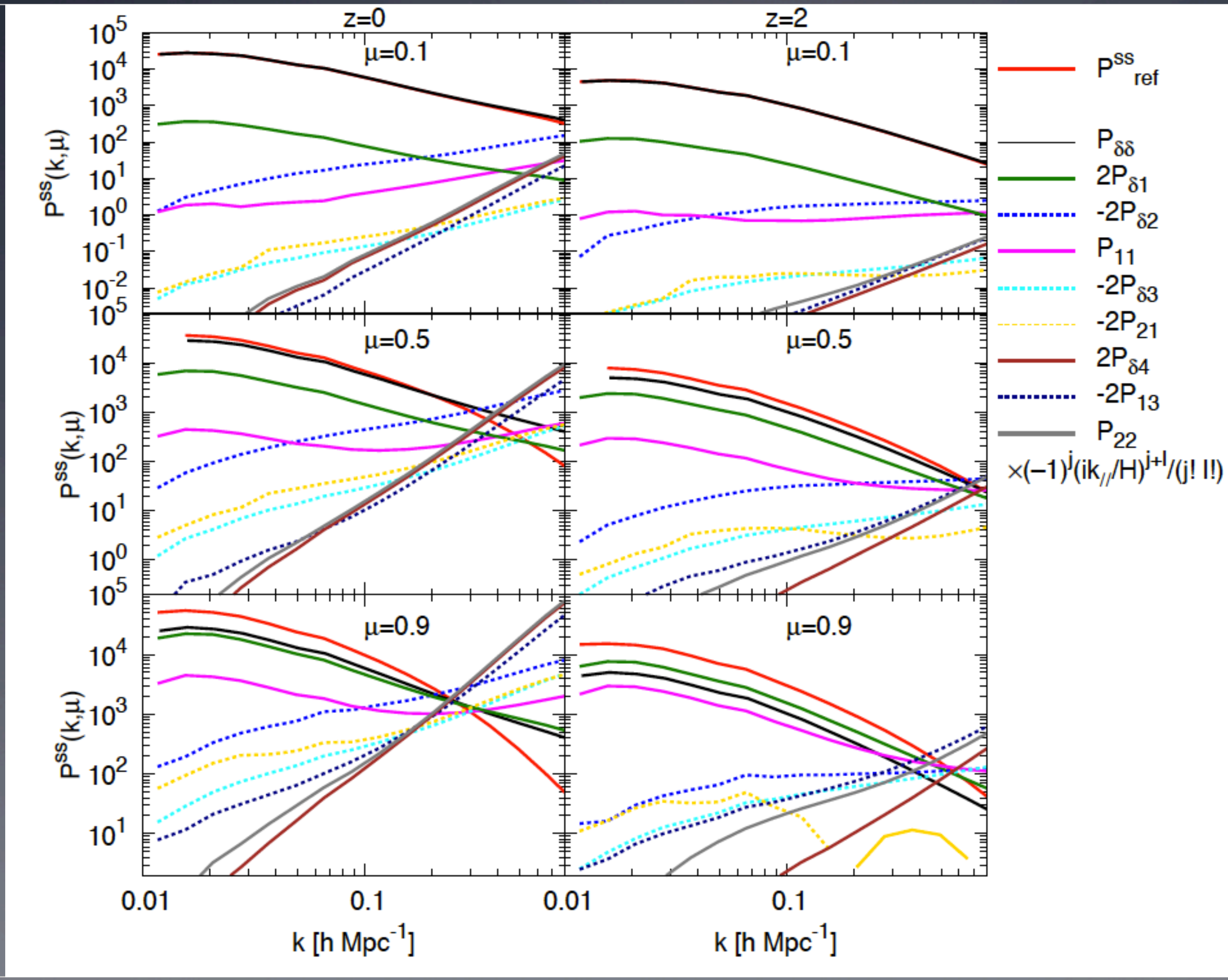
- Velocities are weighted by galaxy density: all biasing issues
- Not just momentum, but all velocity moments, weighted by galaxy density
- Need to compute all correlators allowed by symmetries

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

- Series convergent if $kv\mu<1$: breaks down at $k\mu=0.2$h/Mpc /(1+z)

Okumura etal 2011

Simulations



Series convergent for kμ<0.2h/Mpc/(1+z)

Perturbation Theory approach

Vlah et al 2013

- SPT relative to dark matter :

P_{01}^{gg}=<δ_g|(1+δ_g)v_{II}> =<($b_1\delta_m$+(|(1+$b_1\delta_m$+$b_2\delta_m{}^2$+…)v_{II}> =

b_1<δ_m|(1+δ_m)v_{II}> +<($b_1\delta_m$+ $b_2\delta_m{}^2$+…)|(b_1-1) δ_m+$b_2\delta_m{}^2$+…)v_{II}> =

$b_1P_{01}^{mm}$+<($b_1\delta_m$|(b_1-1) $\delta_m v_{II}$> +…

We see we get scale dependent bias in P_{01}^{gg} even with just scale independent bias b_1

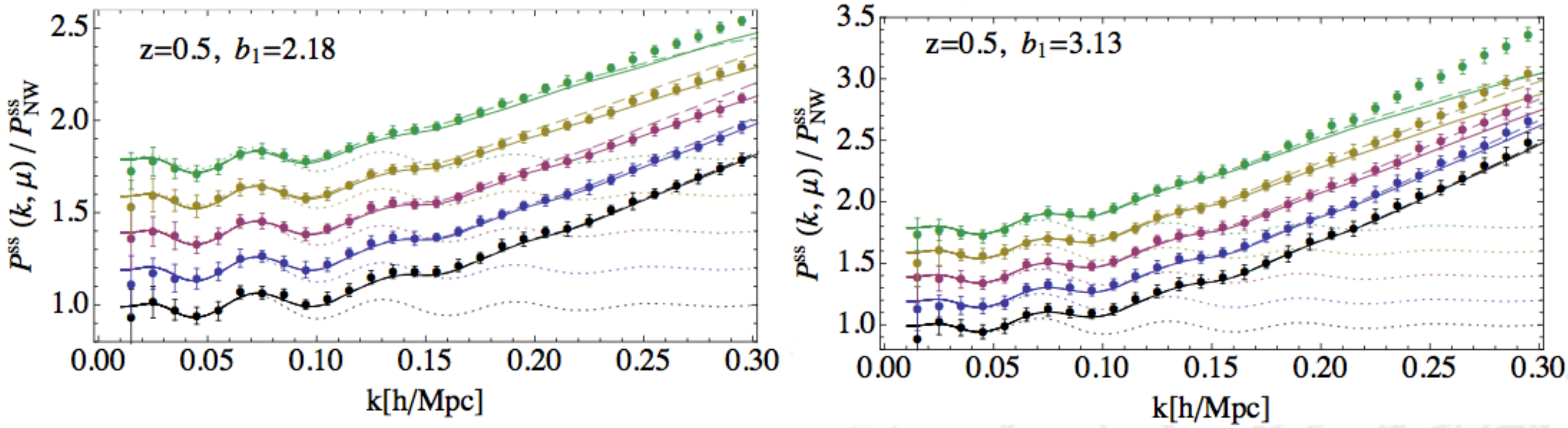
SPT captures some of these effects despite being problematic in terms of loop integrals

See other approaches by Taruya et al, Reid & White…

Current modeling status using PT

Vlah et al 2013

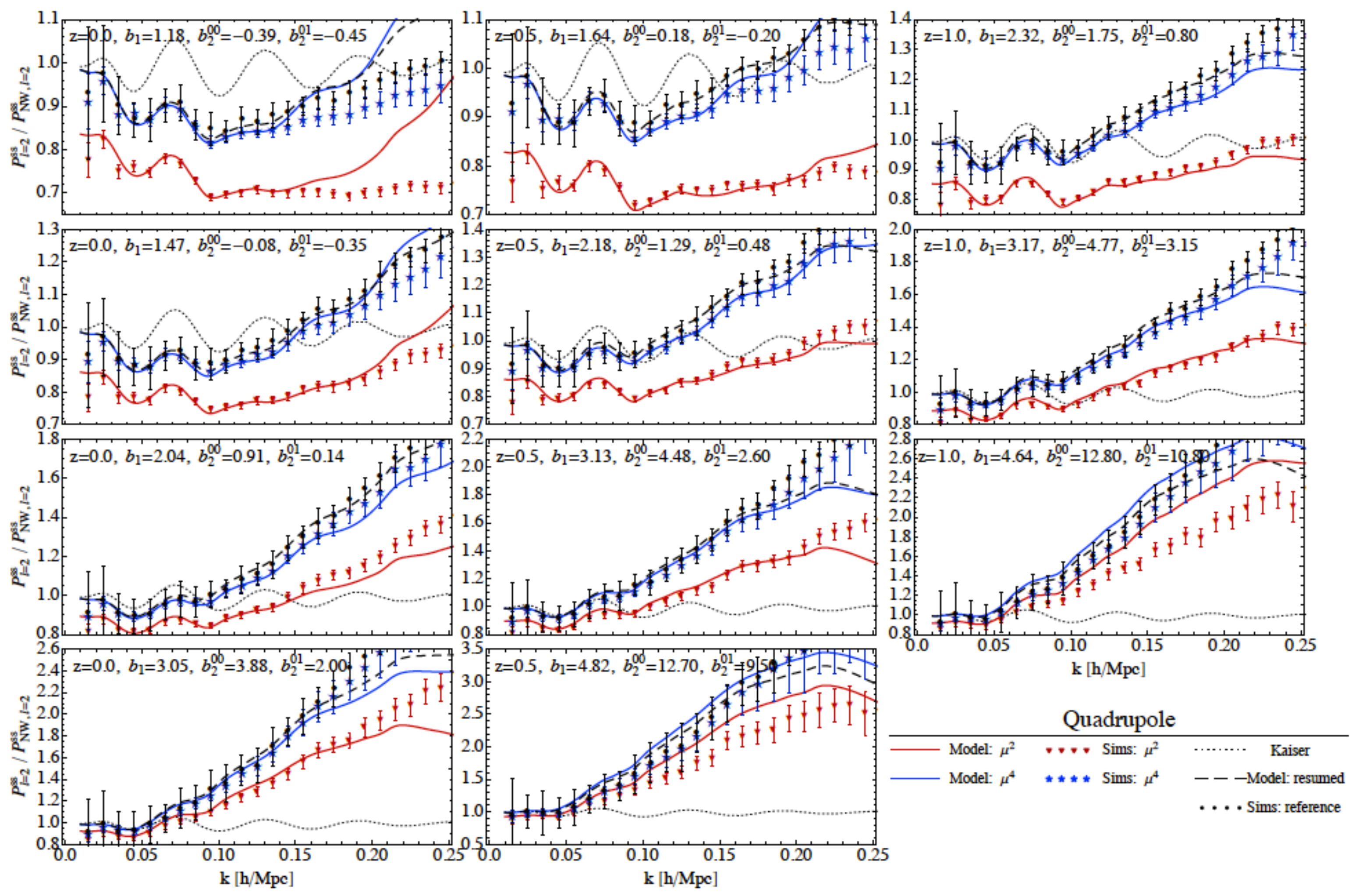
Power spectrum as a function of k and angel μ:



Models include 2 free nonlinear bias parameters b_2, b_3^{nl}

Current modeling status using PT: l=2

Note strong deviations from linear Kaiser at k<0.1h/Mpc



This is for halos, FoG yet another complication

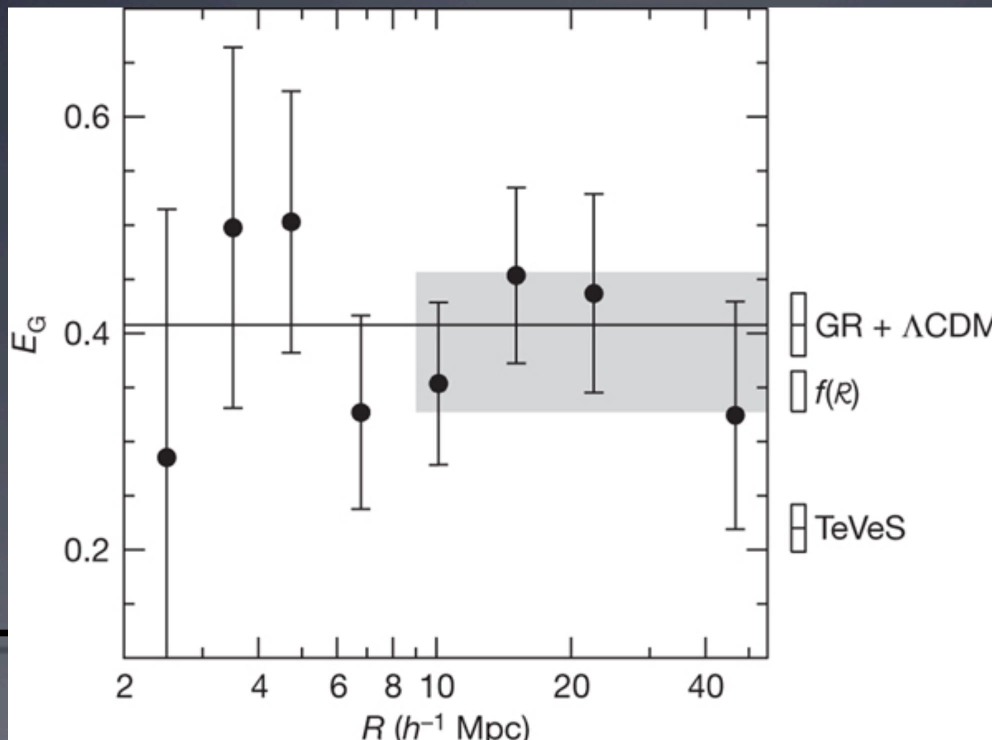
Combining galaxy-shear and RSD

- By combining redshift space distortion measurements ($bf\sigma_8$) with galaxy shear measurements ($b\Omega_m\sigma_8$) of the SAME objects we can eliminate the dependence on the amplitude of fluctuations σ_8 and bias b

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

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

This was a 6 sigma detection, with BOSS/SDSS-III we will do it at 25 sigma

nature

Conclusions

- Galaxy-shear lensing is a powerful alternative to shear-shear lensing, with fewer systematics, current SDSS-II constraints give some of the best WL constraints,
- CMB lensing is powerful: none of current LSS probes is competitive with Planck lensing, but combined they show tension with Planck lensing. New SDSS-III data will be competitive with Planck lensing. New SPT lensing data will test Planck lensing.
- Galaxy biasing is complicated, but if we can understand the different effects we may develop models that have no free parameters
- 3-d galaxy surveys have enormous statistical power, but because velocities are sampled at galaxy positions RSD are subject to biasing effects: PT models are successful in modeling nonlinear RSD effects for $k<0.15h/\mathrm{Mpc}$
- Combining lensing and RSD is a powerful way to test modified gravity