Modeling and Measuring Redshift Space Distortions and the Alcock-Paczynski Effect in the Baryon Oscillation Spectroscopic Survey

Beth Reid
Hubble Fellow
Lawrence Berkeley National Lab
in collaboration with Martin White, Lado Samushia, Will Percival, BOSS galaxy clustering working group

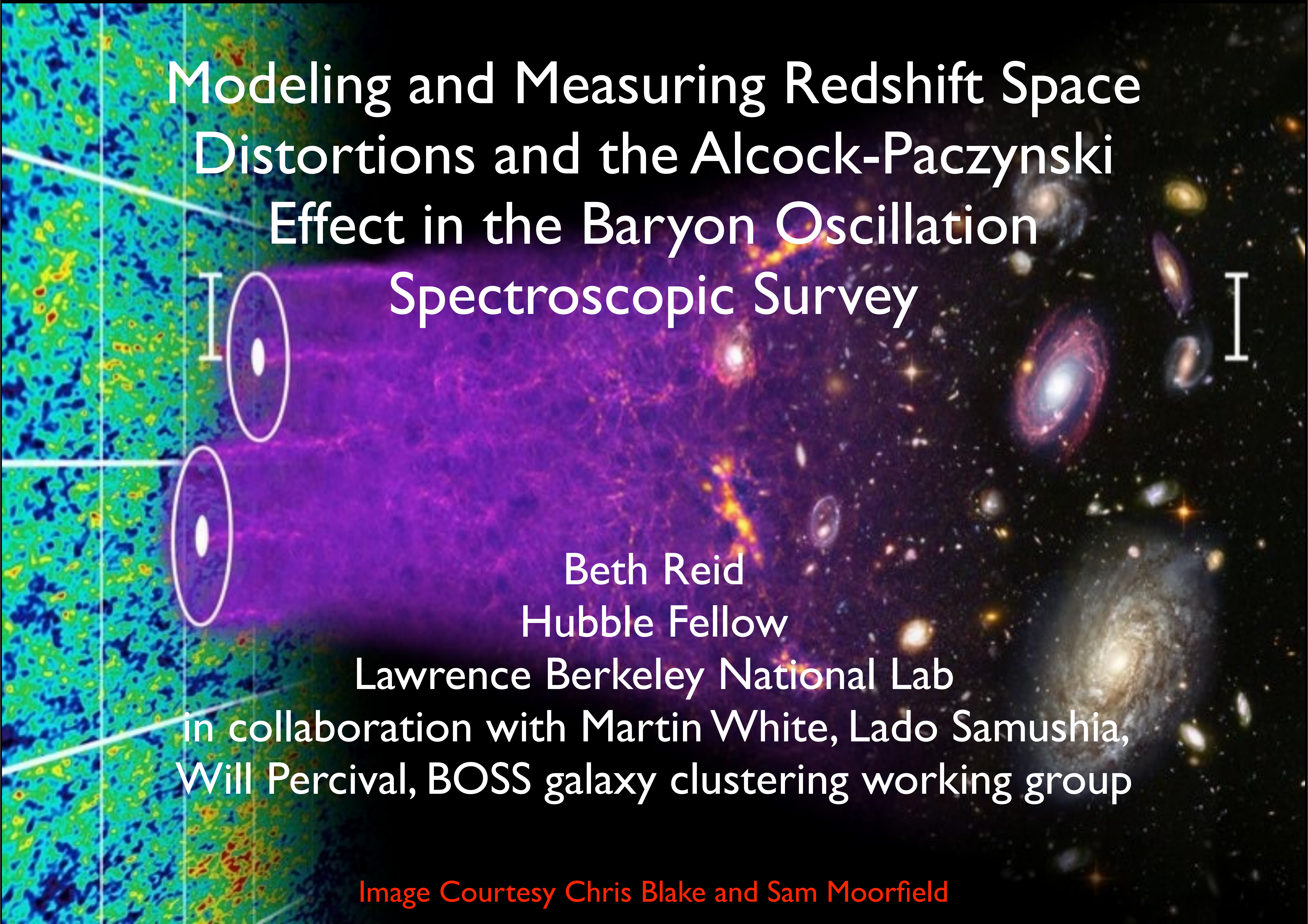


Image Courtesy Chris Blake and Sam Moorfield

Outline

- Motivation
- Basic redshift space distortions (RSD) in configuration space
- Reid and White 2011 configuration space RSD model (+ connections to other recent RSD work)
- From halos to galaxies...
- BOSS DR9 first results: BAO, RSD and AP constraints
- Future prospects

RSD motivation: Testing General Relativity

- Once we know the expansion history H(a), we know how perturbations grow in GR: $\delta(\mathbf{k}, a) = aG(H(a))\delta_i(\mathbf{k})$
- We want to test both scale (**k**) and time (a) dependence

RSD in 3d Galaxy Maps

θ, φ, redshift

$\downarrow$

depends on the geometry of the universe

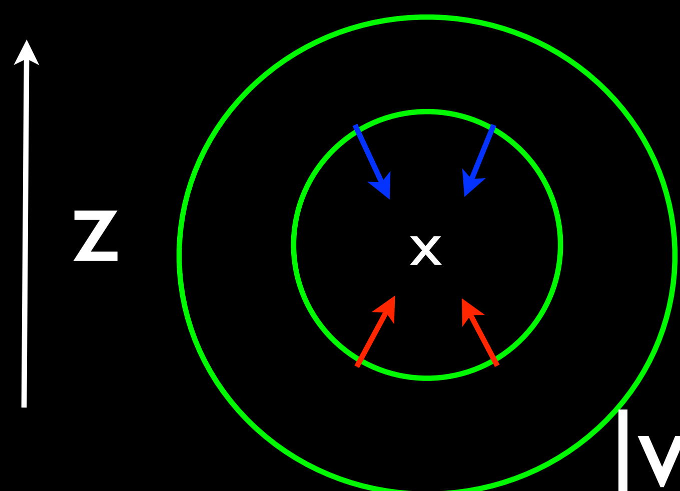
$\chi(z) = {}_0\int^z c\, dz'/H(z')$

$\chi(z) = \chi_{true} + v_p/aH(a)$

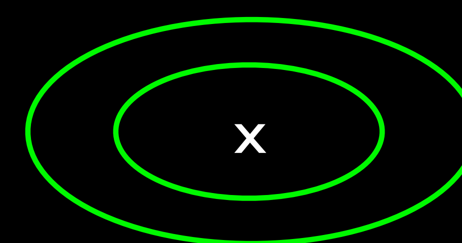
comoving coordinates: x, y, z

RSD in configuration space

real to redshift space separations



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



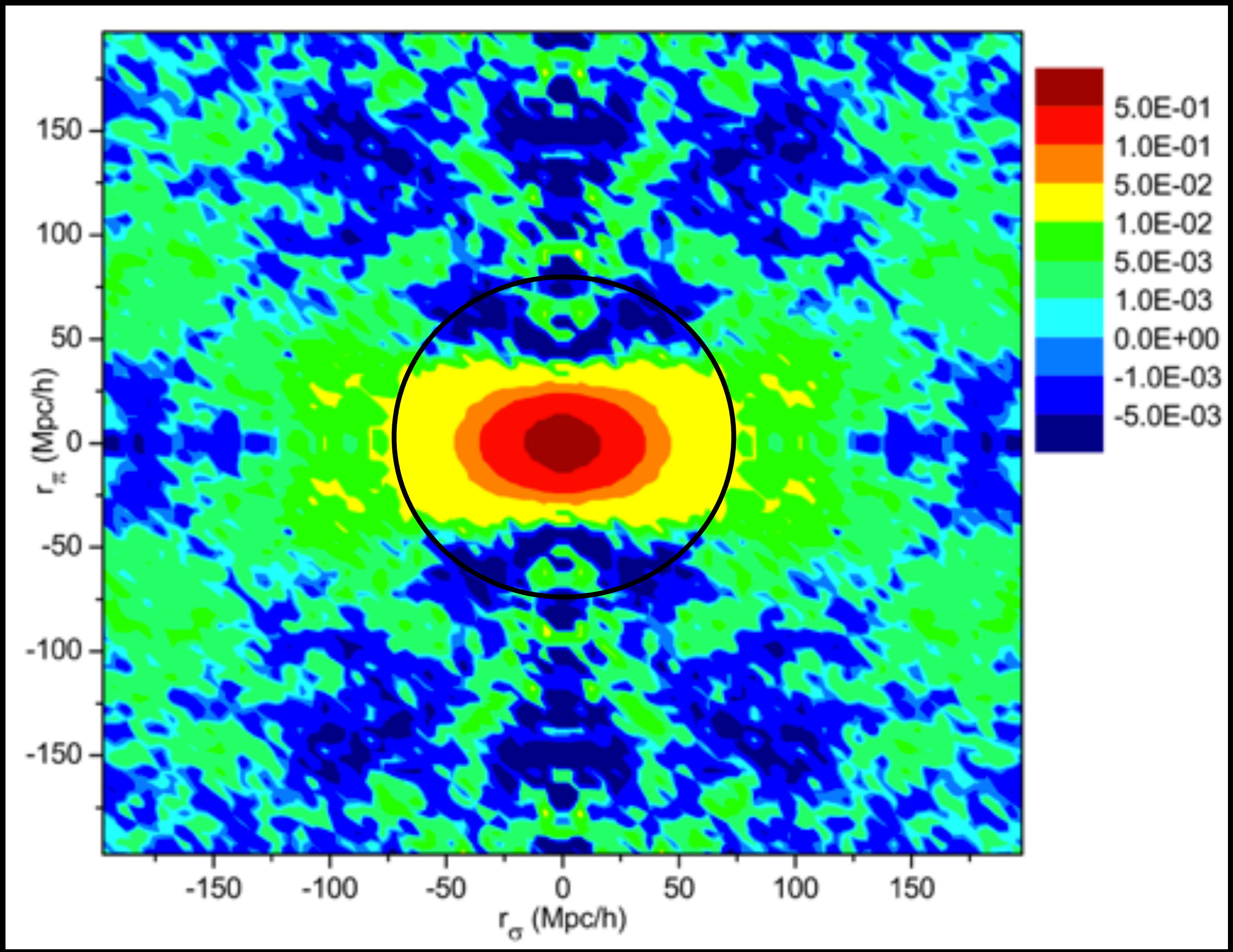
$$|v_p| \sim d\,\sigma_8/d\ln a = \sigma_8 * f$$

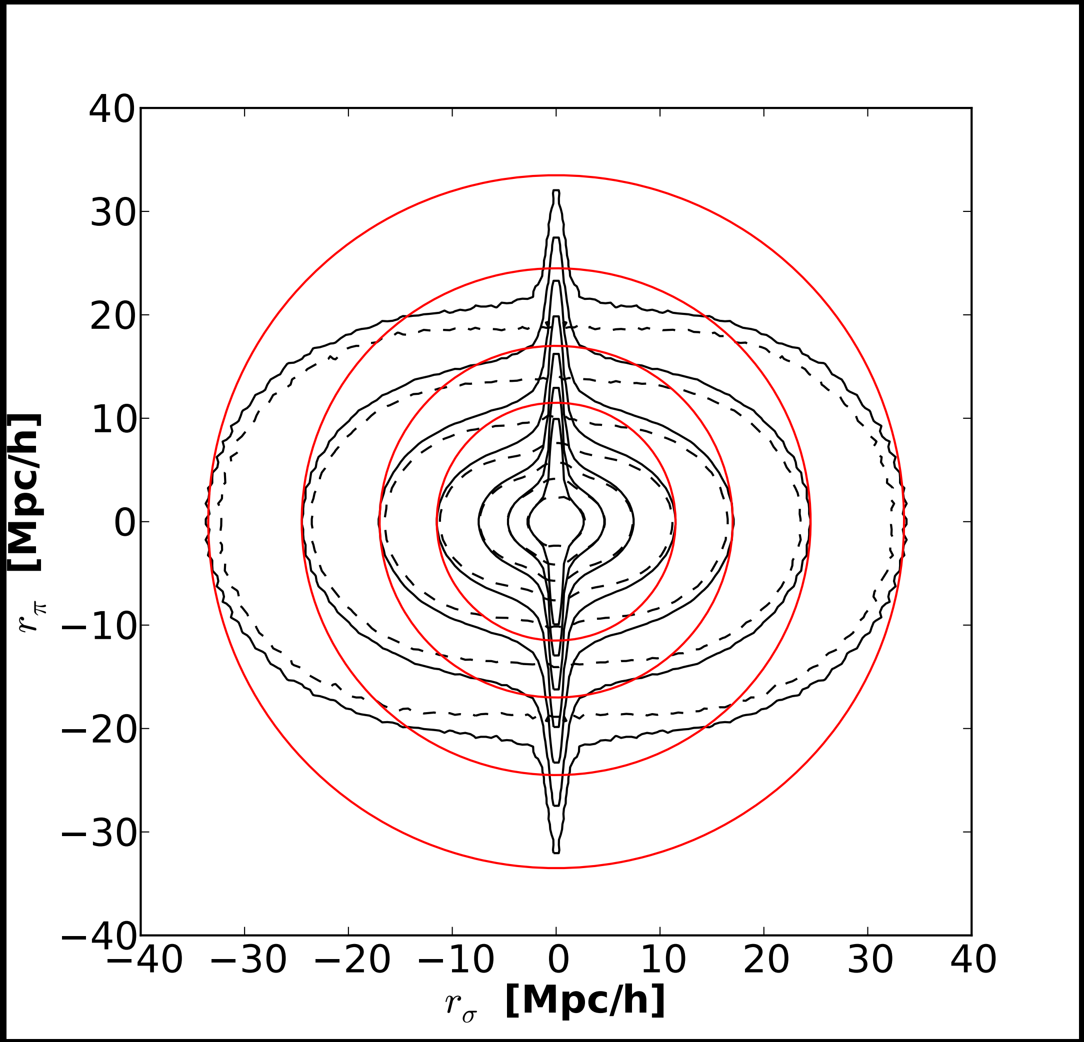
isotropic

squashed along line of sight

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

RSD: Anisotropy in $\xi(r_\sigma, r_\pi)$





BOSS DR9: Reid et al., Samushia et al. (in prep)

White et al. 2011 mock catalogs

Linear RSD (Kaiser 1987)

$$\delta_g^s(k) = (b + f\mu_k^2)\delta_m^r(k)$$

$$\mu_k^2 = k_z^2/k^2$$

Linear RSD: Legendre Polynomial moments

General Expansion

$$P(k,\mu_k) = \sum_\ell P_\ell(k) L_\ell(\mu_k)$$

Linear theory prediction

$$\begin{pmatrix} P_0(k) \\ P_2(k) \\ P_4(k) \end{pmatrix} = P^r_m(k) \begin{pmatrix} b^2 + \frac{2}{3}bf + \frac{1}{5}f^2 \\ \frac{4}{3}bf + \frac{4}{7}f^2 \\ \frac{8}{35}f^2 \end{pmatrix}$$

Legendre Polynomial moments

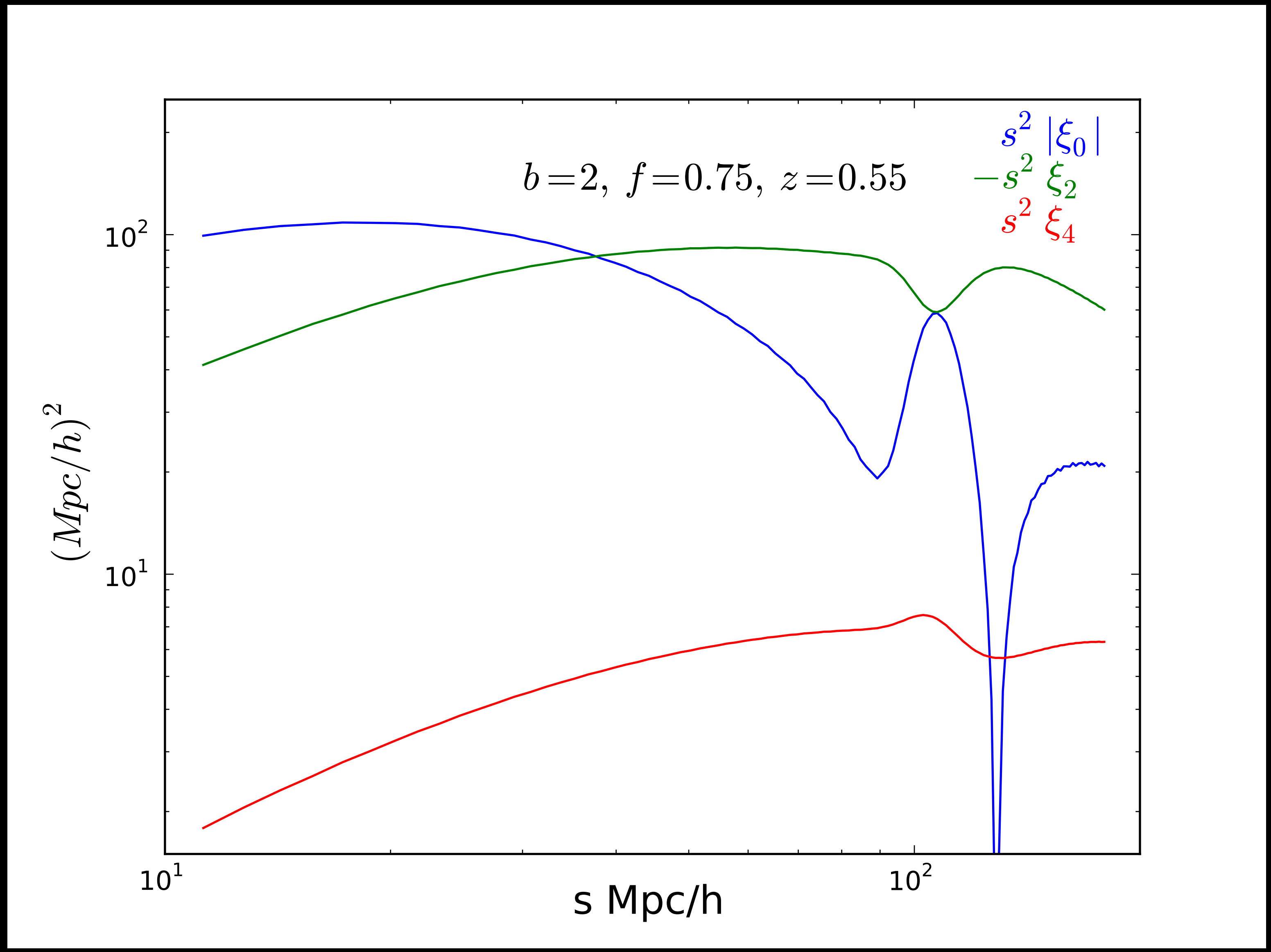
General Expansion

$$\xi(s,\mu_s) = \sum_\ell \xi_\ell(s) L_\ell(\mu_s)$$

Relation to P$_\ell$(k)

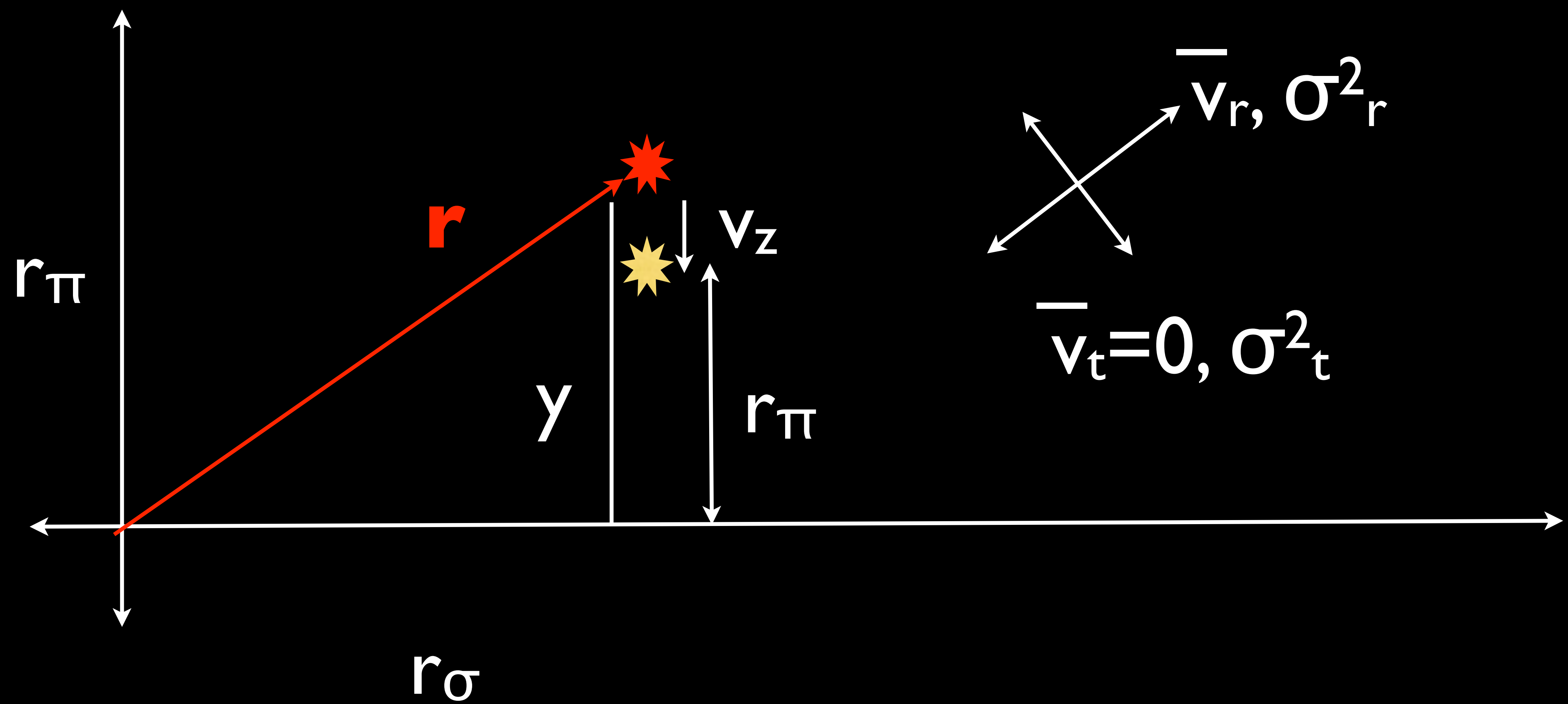
$$\xi_\ell(s) = i^\ell \int \frac{k^2\,dk}{2\pi^2} P_\ell(k) j_\ell(ks)$$

Linear theory Legendre polynomial moments: scale dependence



RSD in configuration space: new quantities of interest

$$1 + \xi_s(r_\sigma, r_\pi) = \int_{-\infty}^{\infty} dy\,[1 + \xi(r)]\,\mathcal{P}(v_z \equiv r_\pi - y, \mathbf{r})$$



Linear theory pairwise velocities ($\delta_g = b\delta_m$)

$$\mathbf{v}_{12}(r) = v_{12}(r)\hat{r} = -\hat{r}\frac{fb}{\pi^2}\int dk\, k\, P^r_m(k)\, j_1(kr)$$

$$\left\langle \mathbf{v}_i(\mathbf{r}' + \mathbf{r})\mathbf{v}_\mathbf{j}(\mathbf{r}')\right\rangle = \Psi_\perp(\mathbf{r})\delta^K_{ij} + [\Psi_\parallel(r) - \Psi_\perp(r)]\hat{r}_i\hat{r}_j$$

$$\Psi_\perp(r) = \frac{f^2}{2\pi^2}\int dk\, P^r_m(k)\frac{j_1(kr)}{kr}$$

$$\Psi_\parallel(r) = \frac{f^2}{2\pi^2}\int dk\, P^r_m(k)\left[j_0(kr) - \frac{2j_1(kr)}{kr}\right]$$

$$\sigma^2_{12}(r,\mu^2) = 2\left[\sigma^2_v - \mu^2\Psi_\parallel(r) - (1-\mu^2)\Psi_\perp(r)\right]$$

Fisher 1995: the Kaiser formula in configuration space

- δ(**x**), **v**(**x'**) correlated Gaussian fields

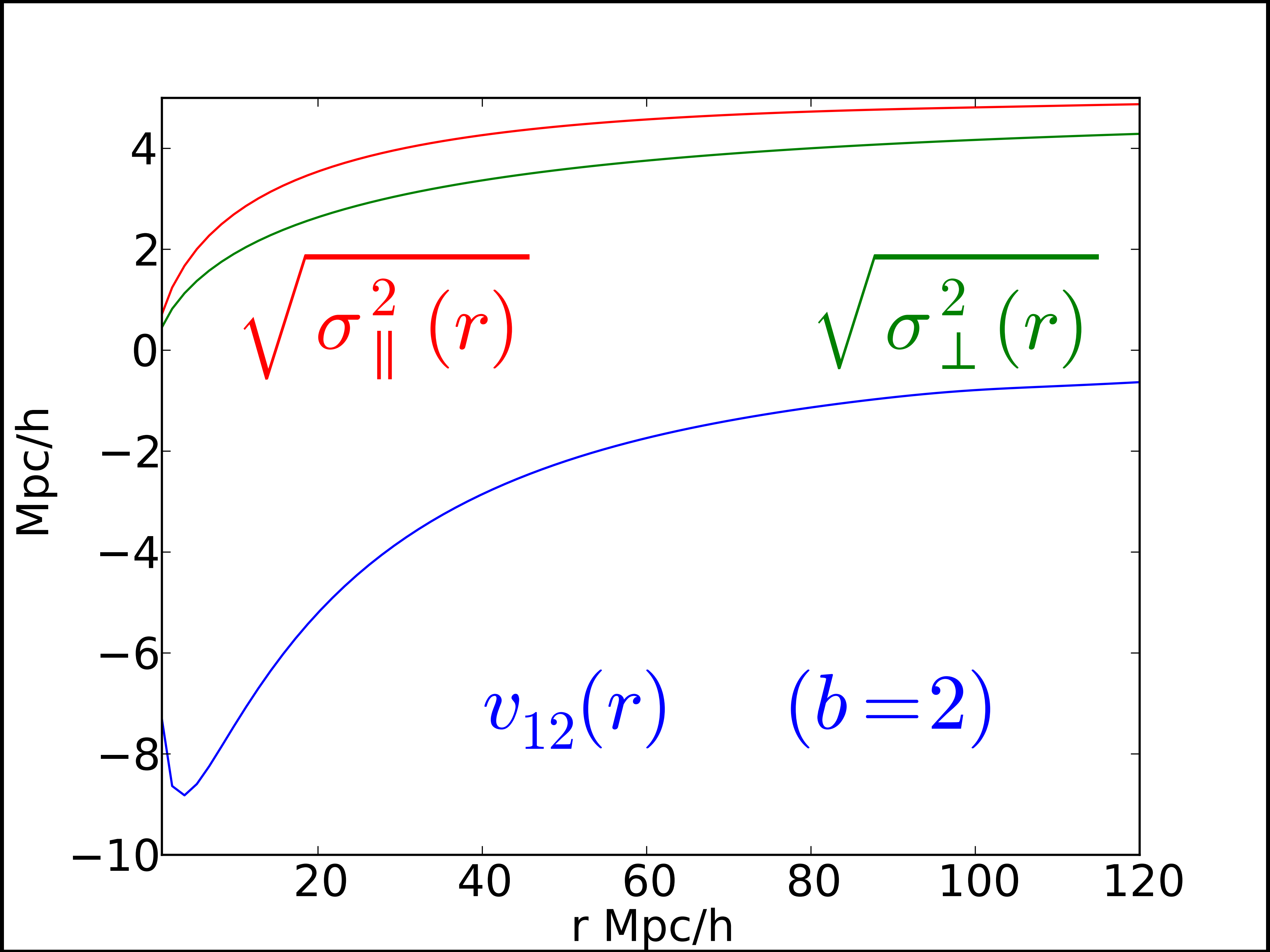
$$1+\xi_g^s(r_\sigma,r_\pi)=\int\frac{dy}{\sqrt{2\pi\sigma_{12}^2(y)}}\exp\left[-\frac{(r_\pi-y)^2}{2\sigma_{12}^2(y)}\right]\left[1+\xi_g^r(r)+\frac{y}{r}\frac{(r_\pi-y)v_{12}(r)}{\sigma_{12}^2(y)}-\frac{1}{4}\frac{y^2}{r^2}\frac{v_{12}^2(r)}{\sigma_{12}^2(y)}\left(1-\frac{(r_\pi-y)^2}{\sigma_{12}^2(y)}\right)\right]$$

- Expand around y = r_π

$$\xi_g^s(r_\sigma,r_\pi)=\xi_g^r(s)-\frac{d}{dy}\left[v_{12}(r)\frac{y}{r}\right]\bigg|_{y=r_\pi}+\frac{1}{2}\frac{d^2}{dy^2}\left[\sigma_{12}^2(y)\right]\bigg|_{y=r_\pi}$$

- Equivalent to Kaiser formula

Pairwise velocity statistics in linear theory



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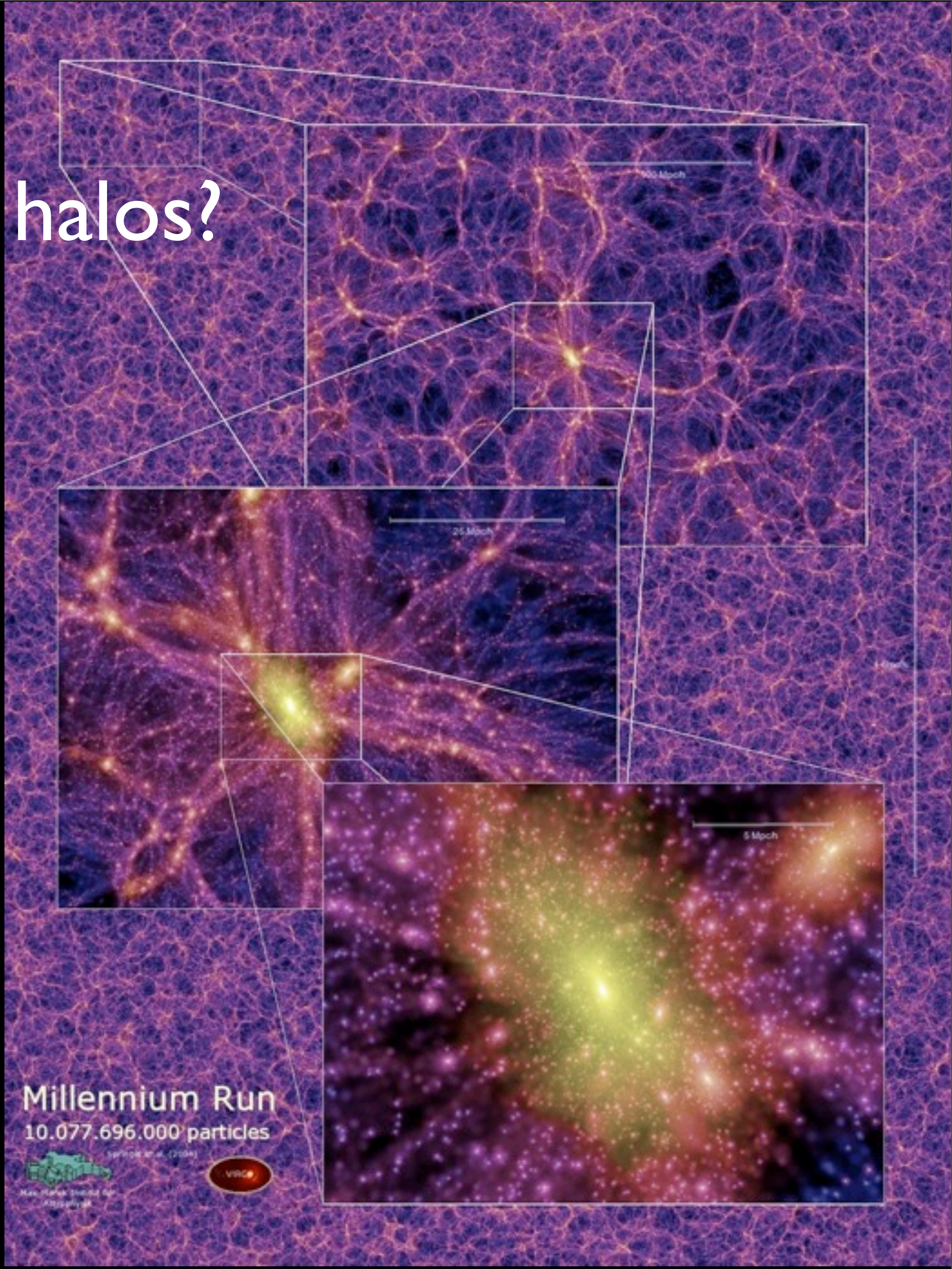
Recent work: Matter Density Field

	Model	Damping	Fitted parameters	Reference
1.	Empirical Lorentzian with linear $P_{\delta\delta}(k)$	Variable	f, b, σ_v	e.g. Hatton & Cole (1998)
2.	Empirical Lorentzian with non-linear $P_{\delta\delta}(k)$	Variable	f, b, σ_v	
3.	$P_{\delta\delta}$, $P_{\delta\theta}$, $P_{\theta\theta}$ from 1-loop SPT	None	f, b	e.g. Vishniac (1983), Juszkiewicz et al. (1984)
4.	$P_{\delta\delta}$, $P_{\delta\theta}$, $P_{\theta\theta}$ from 1-loop SPT	Variable	f, b, σ_v	
5.	$P_{\delta\delta}$, $P_{\delta\theta}$, $P_{\theta\theta}$ from 1-loop SPT	Linear	f, b	
6.	$P_{\delta\delta}$, $P_{\delta\theta}$, $P_{\theta\theta}$ from 1-loop RPT	None	f, b	Crocce & Scoccimarro (2006)
7.	$P_{\delta\delta}$, $P_{\delta\theta}$, $P_{\theta\theta}$ from 1-loop RPT	Linear	f, b	
8.	$P_{\delta\delta}$, $P_{\delta\theta}$, $P_{\theta\theta}$ from 2-loop RPT	None	f, b	
9.	$P_{\delta\delta}$, $P_{\delta\theta}$, $P_{\theta\theta}$ from 2-loop RPT	Variable	f, b	
10.	$P_{\delta\delta}$, $P_{\delta\theta}$, $P_{\theta\theta}$ from 2-loop RPT	Linear	f, b	
11.	$P(k,\mu)$ from 1-loop SPT	None	f, b	Matsubara (2008)
12.	$P(k,\mu)$ from 1-loop SPT	Linear	f, b	
13.	$P(k,\mu)$ with additional corrections	None	f, b	Taruya et al. (2010)
14.	$P(k,\mu)$ with additional corrections	Variable	f, b, σ_v	
15.	$P(k,\mu)$ with additional corrections	Linear	f, b	
16.	Fitting formulae from N-body simulations	None	f, b	Smith et al. (2003), Jennings et al. (2010)
17.	Fitting formulae from N-body simulations	Variable	f, b, σ_v	
18.	Fitting formulae from N-body simulations	Linear	f, b	

Blake et al., arXiv:1105.2862; see also Scoccimarro 2004

Why halos?

- Galaxies live there!
- Halos occupy "special" places in the density field; θ is a volume-averaged statistic
- Dependence on halo bias is complex; studies of matter correlations not easily generalized



Recent Work: Halos

- Tinker, Weinberg, Zheng 2006; Tinker 2007 (+ galaxies in halo model)
- Matsubara 2008ab [LPT with biasing]
- Tang, Kayo, Takada arXiv:1103.3614
- Nishimichi, Taruya arXiv:1106.4562
- ....

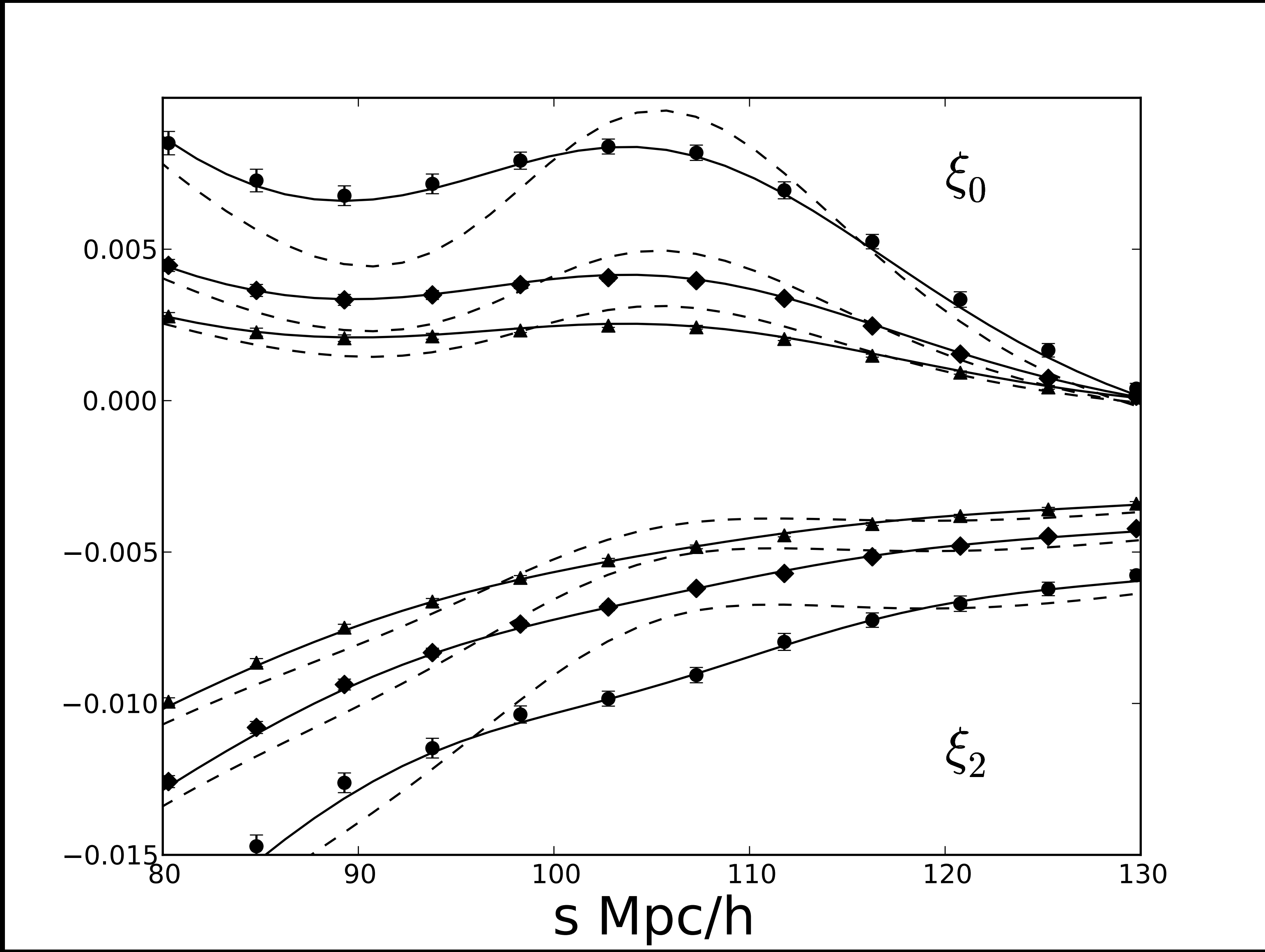
N-body Simulations

- White et al. 2011; arXiv:1010.4915
- 67.5 $(\mathrm{Gpc}/h)^3$ total volume
  (for BOSS galaxies $V \sim 5\ (\mathrm{Gpc}/h)^3$)

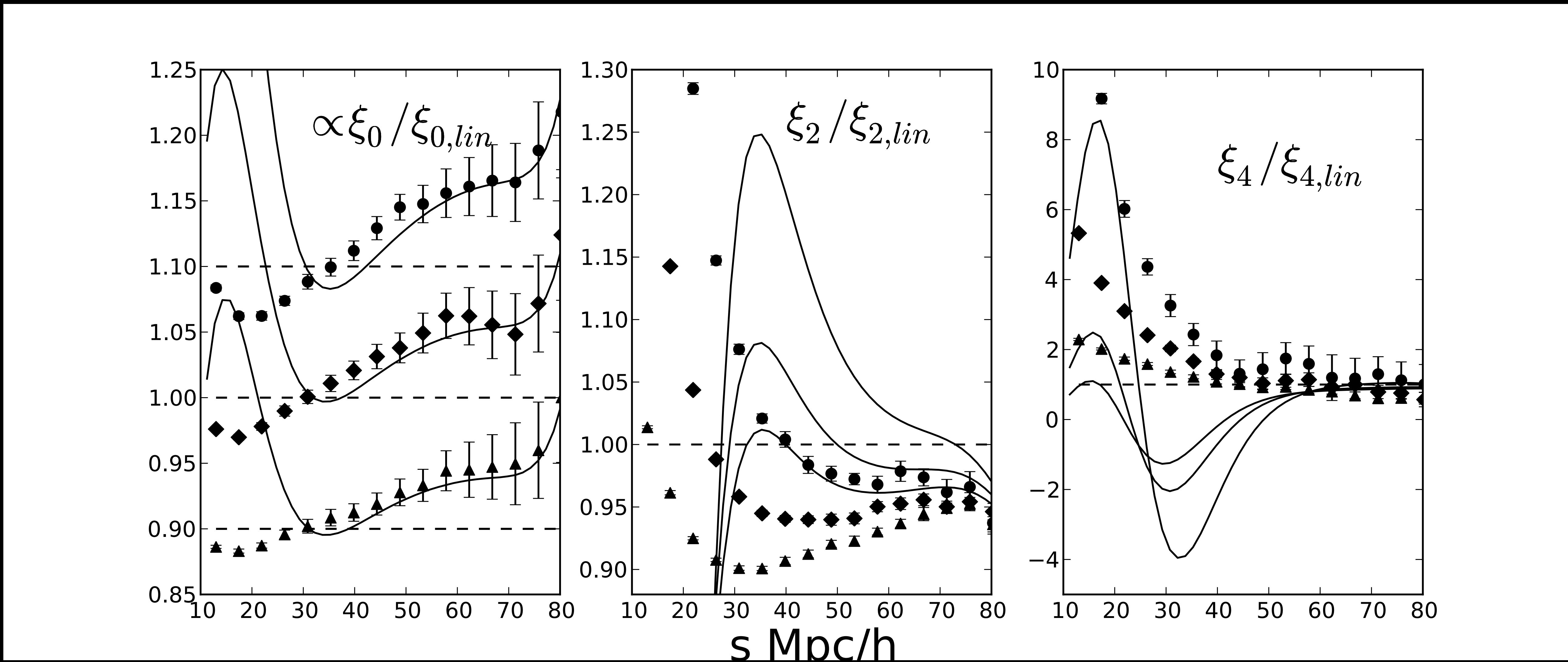
sample	$log(M)$ range	$\bar{b}_{lin}$	$\bar{b}_{LPT}$	$\bar{n}\ (h^{-1}\mathrm{Mpc})^{-3}$
high	>13.387	2.67	2.79	7.55×10^{-5}
low	12.484 - 12.784	1.41	1.43	4.04×10^{-4}
HOD	-	1.84	1.90	3.25×10^{-4}

N-body simulations vs Linear and Lagrangian Perturbation Theories

- LPT works on BAO scales
- See Matsubara PRD 78, 083519; arXiv:1105.5007



N-body simulations vs Linear and Lagrangian Perturbation Theories



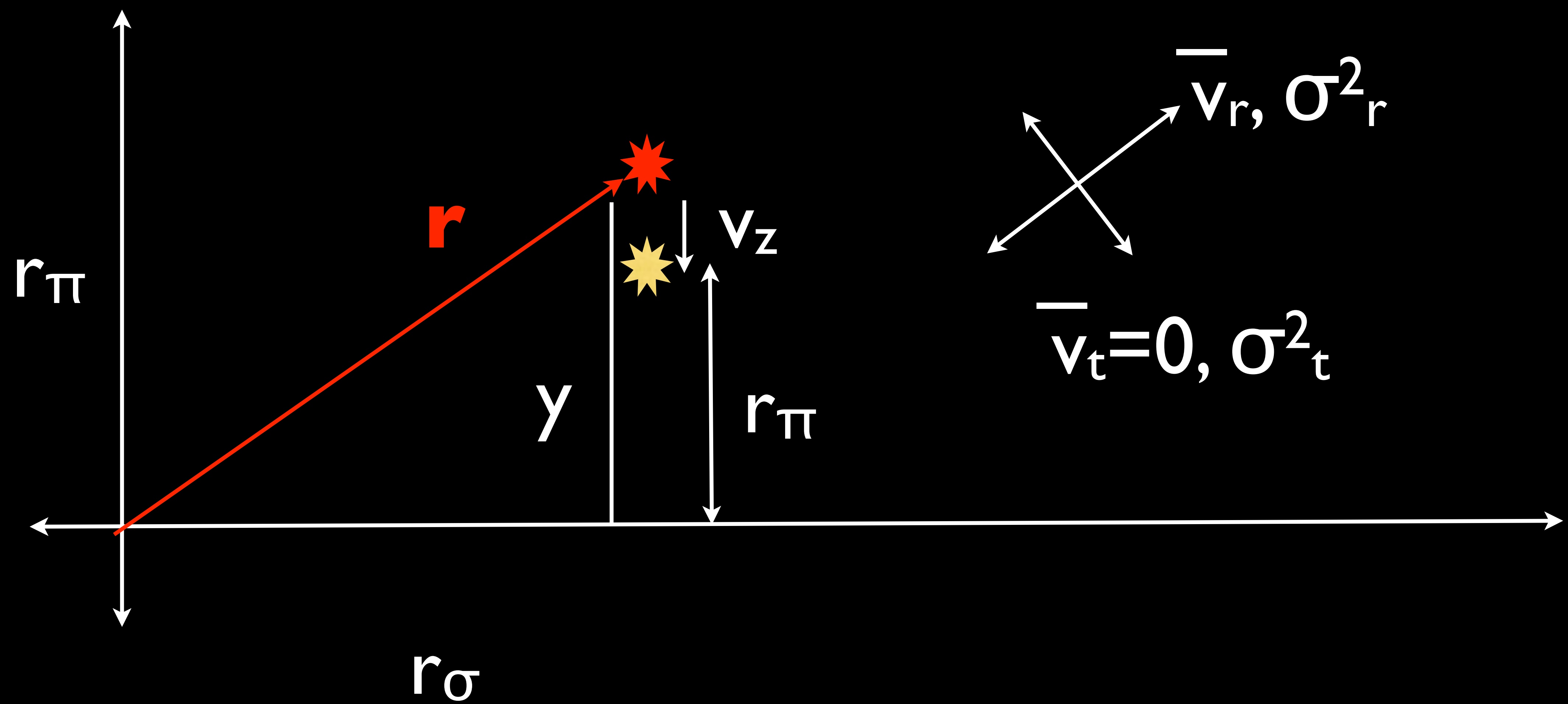
- ξ_2 suppressed by 2.5-7.5% at 50 h^{-1} Mpc, depends strongly on bias

Our approach

- Two distinct sources of nonlinearity:
  - Nonlinear growth of structure/biasing -- affects both halo clustering and velocities (study in N-body sims/perturbation theory)
  - Nonlinear mapping from real to redshift space coordinates (non-perturbative)
  - Recall: to get Kaiser: dv_z/dz small (P) or expand around $y = r_\pi$ (ξ)

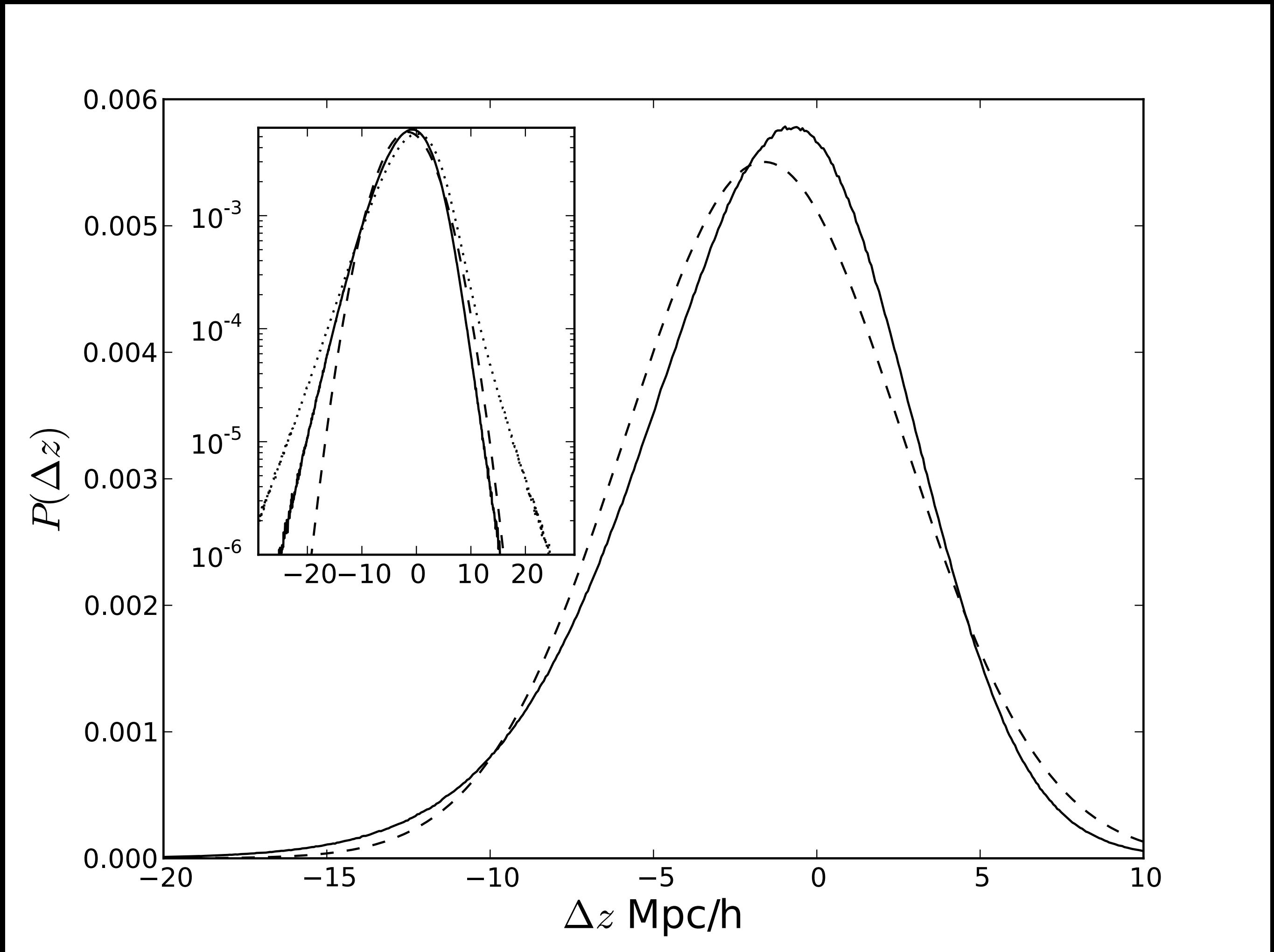
The scale-dependent Gaussian streaming model ansatz

$$1 + \xi_s(r_\sigma, r_\pi) = \int_{-\infty}^{\infty} dy\,[1 + \xi(r)]\,\mathcal{P}(v_z \equiv r_\pi - y, \mathbf{r})$$

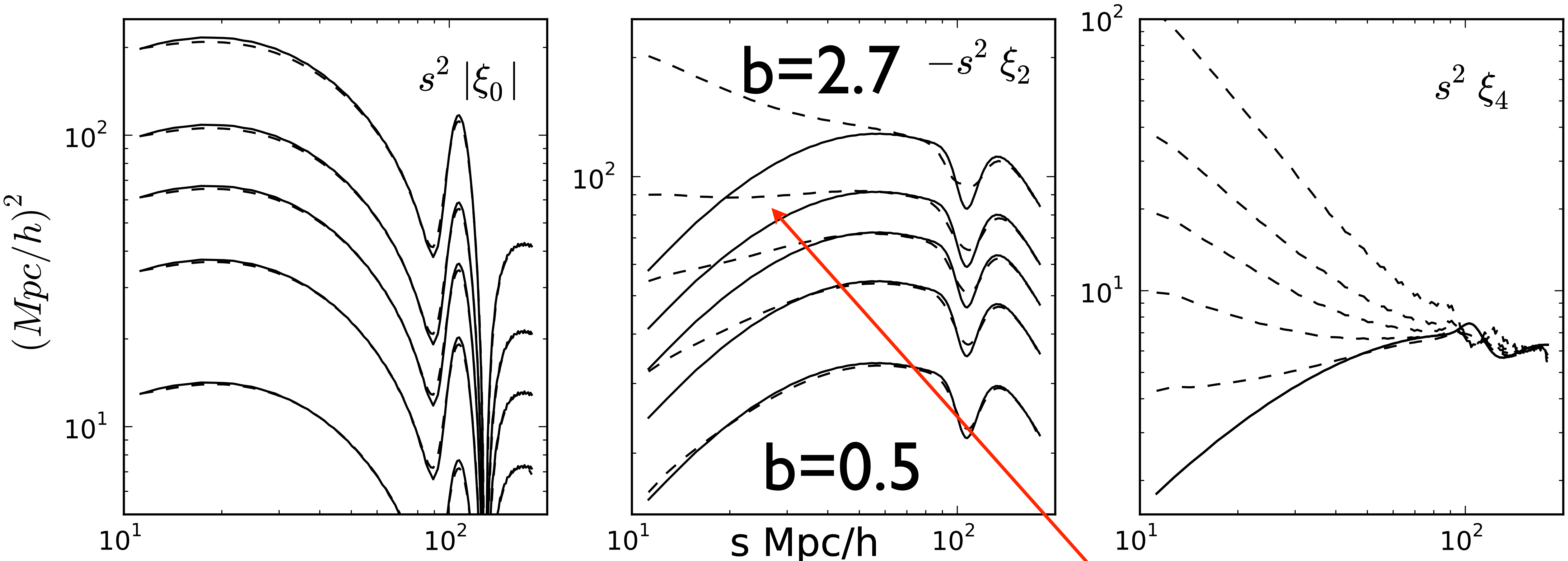


The scale-dependent Gaussian streaming model ansatz

- Non-perturbative!
- Approximate pairwise velocity PDF $P(v_z, r)$ with a Gaussian; match 1st and 2nd moments
- Agrees at linear order with Kaiser/exact



The scale-dependent Gaussian streaming model ansatz: "linear" theory predictions



Kaiser limit

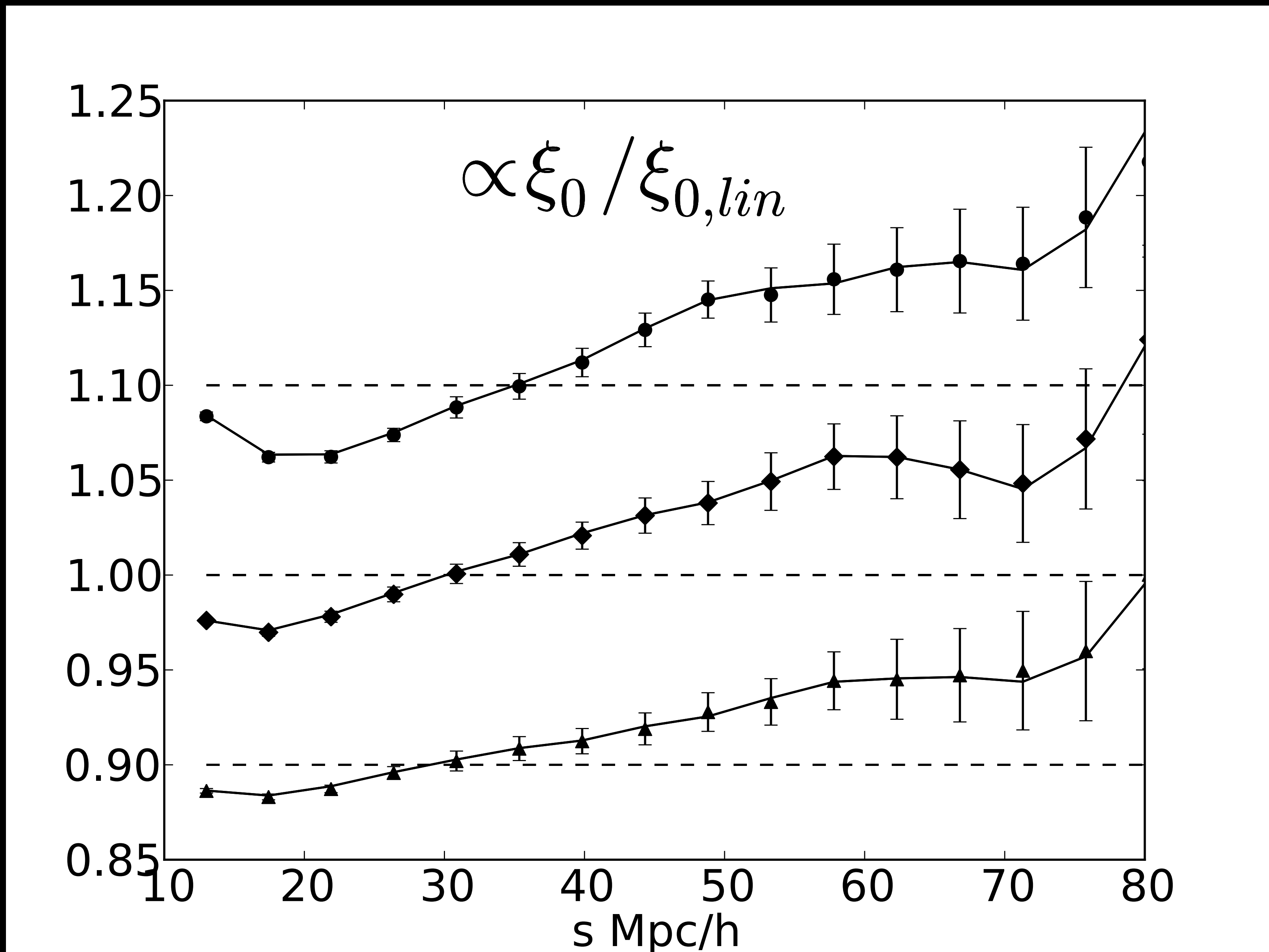
Gaussian streaming model

b³ correction !!

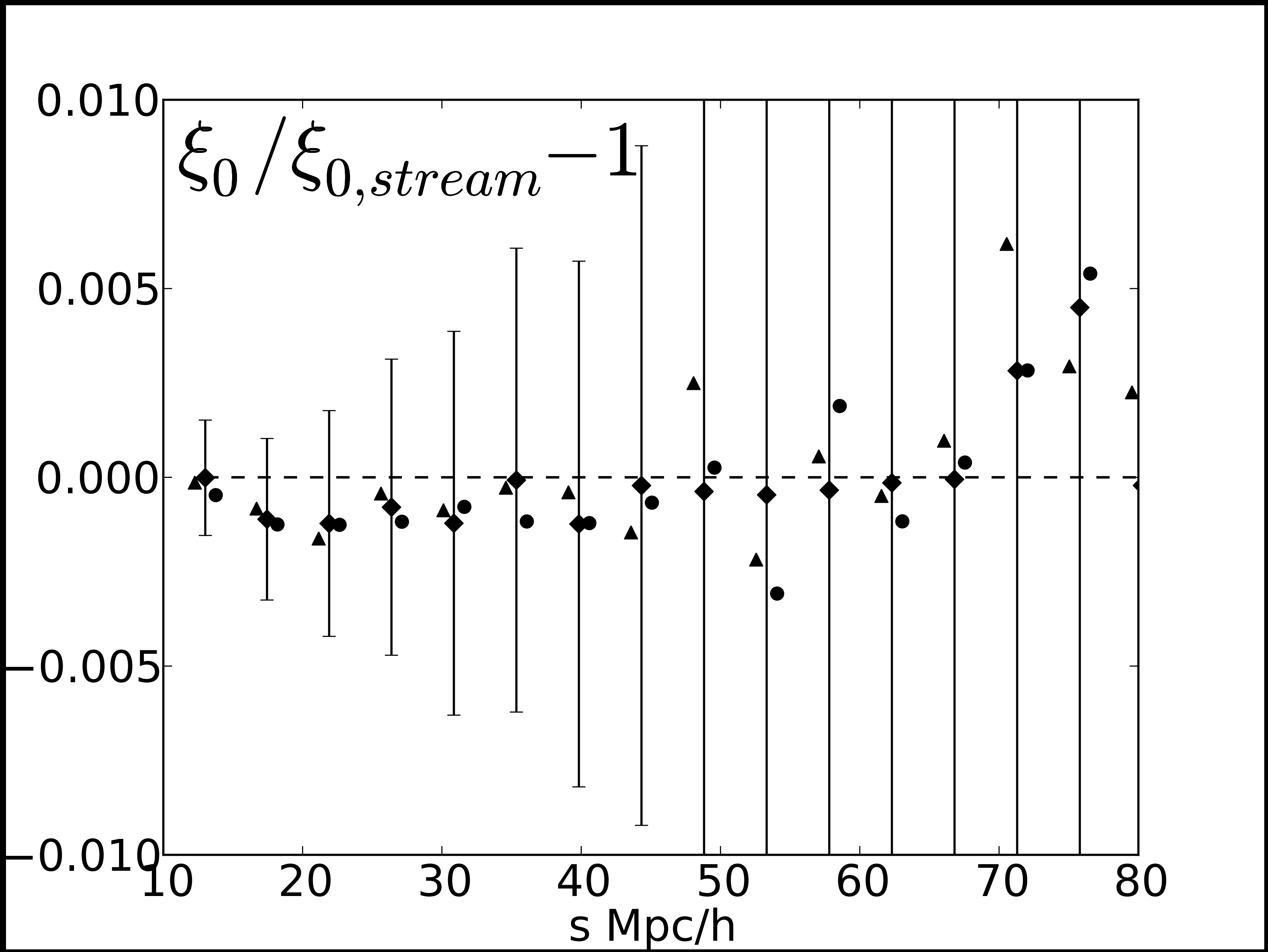
The scale-dependent Gaussian streaming model ansatz vs N-body simulations

- Start with $\xi(r)$, $v(r)$, $\sigma^2_{\perp,\parallel}(r)$ measured from N-body halos in real space
- Compare with N-body halo clustering in *redshift* space

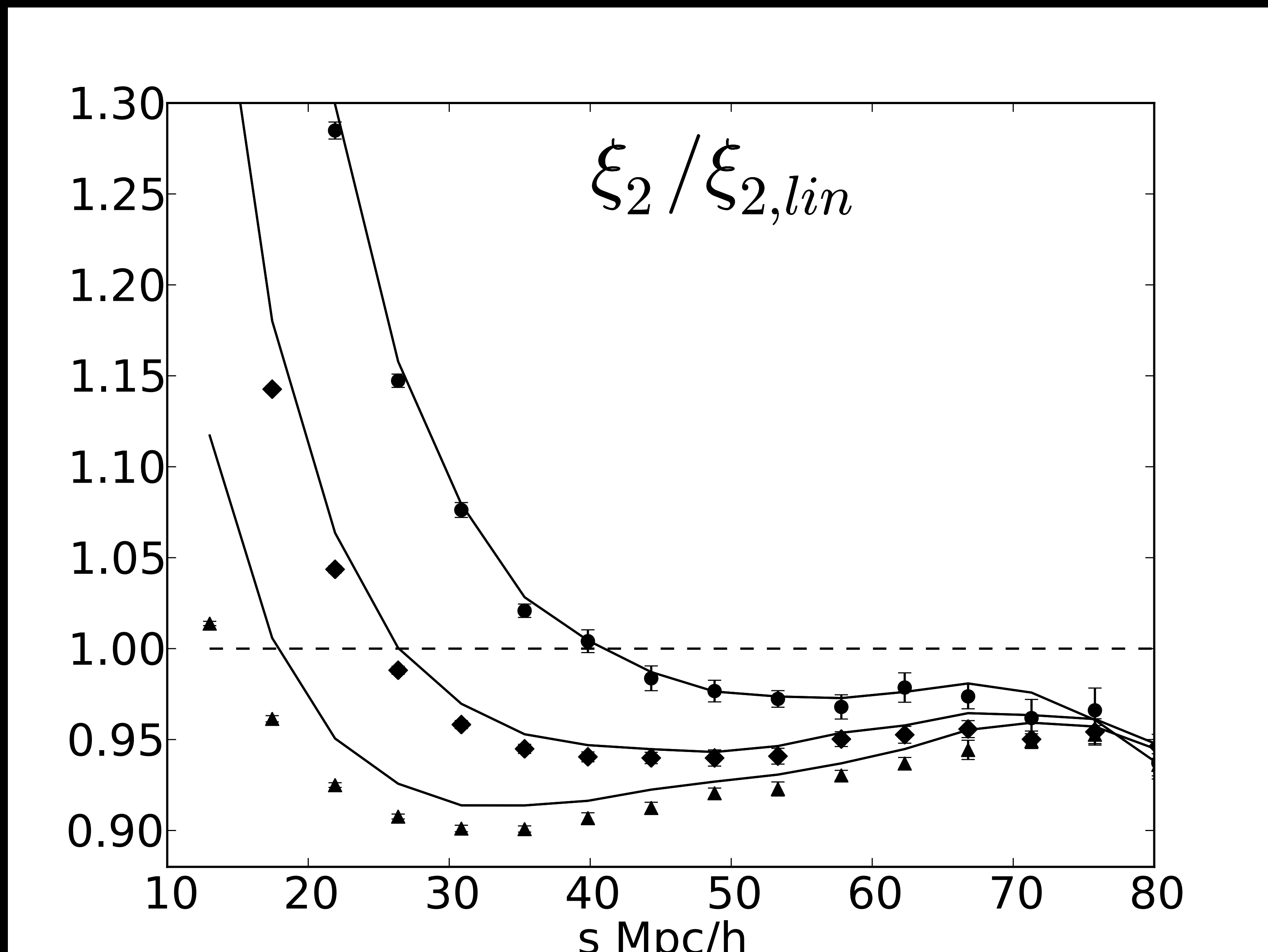
The scale-dependent Gaussian streaming model ansatz vs N-body simulations: ξ_0



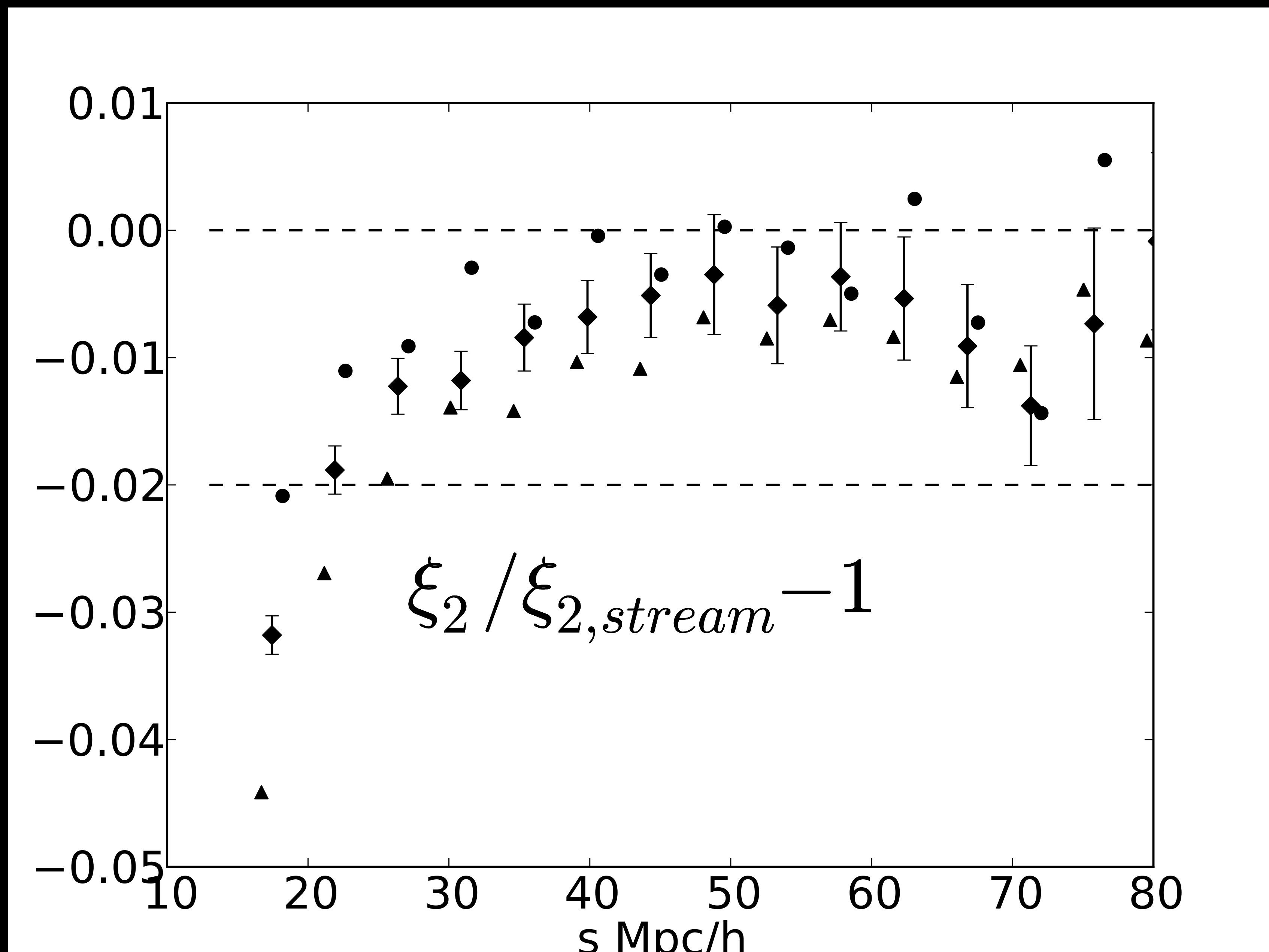
The scale-dependent Gaussian streaming model ansatz vs N-body simulations: ξ_0



The scale-dependent Gaussian streaming model ansatz vs N-body simulations: ξ_2

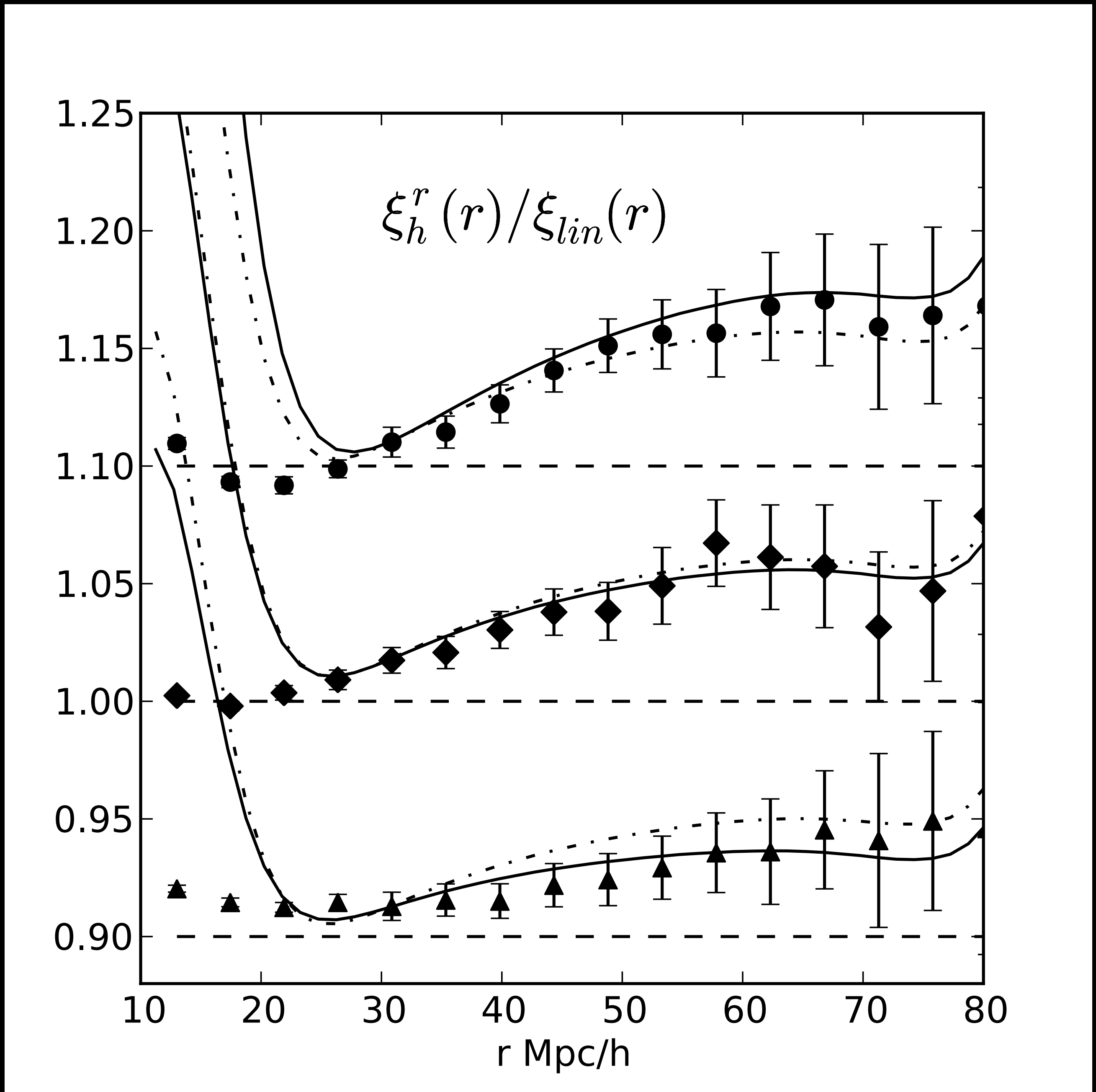


The scale-dependent Gaussian streaming model ansatz vs N-body simulations: ξ_2



Can we predict real space halo clustering/ velocity PDFs using perturbation theory?

- LPT (including nonlinear bias) predicts halo ξ(r) down to 25 Mpc/h



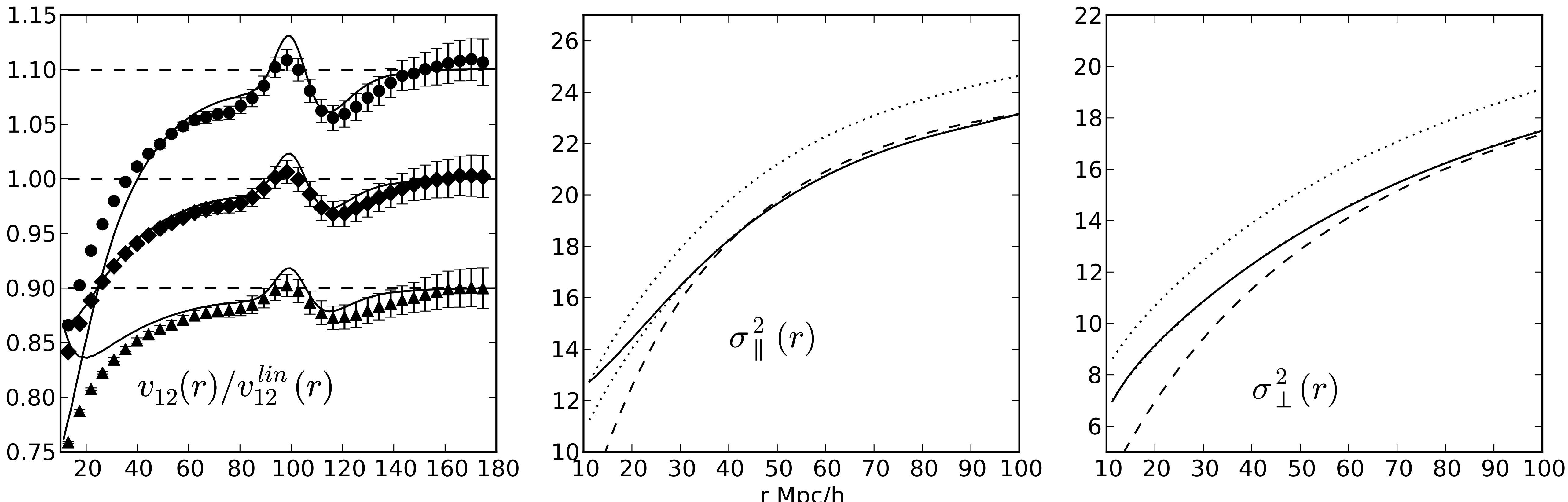
Velocity statistics in standard perturbation theory: new results

- Pair-weighted, not volume weighted!

$$v_{12}(r)\hat{r} = \frac{\langle[1 + b\delta(\mathbf{x})][1 + b\delta(\mathbf{x}+\mathbf{r})][\mathbf{v}(\mathbf{x}+\mathbf{r}) - \mathbf{v}(\mathbf{x})]\rangle}{\langle[1 + b\delta(\mathbf{x})][1 + b\delta(\mathbf{x}+\mathbf{r})]\rangle}$$

$$\sigma^2_{12}(r,\mu^2) = \frac{\left\langle(1 + b\delta(\mathbf{x}))(1 + b\delta(\mathbf{x}+\mathbf{r}))(v^\ell(\mathbf{x}+\mathbf{r}) - v^\ell(\mathbf{x}))^2\right\rangle}{\langle(1 + b\delta(\mathbf{x}))(1 + b\delta(\mathbf{x}+\mathbf{r}))\rangle}$$

Velocity statistics in standard perturbation theory: new results



* assumes linear bias

Velocity statistics in standard perturbation theory: new results

Pair-weighting correction

Linear theory

$$\left[1 + b^2 \xi^r_m(r)\right] v_{12}^{PT}(r)\hat{r} = 2b\left\langle \delta_1(\mathbf{x})\mathbf{v}_1(\mathbf{x}+\mathbf{r})\right\rangle + 2b \sum_{i>0} \left\langle \delta_i(\mathbf{x})\mathbf{v}_{4-i}(\mathbf{x}+\mathbf{r})\right\rangle + 2b^2 \sum_{i,j>0} \left\langle \delta_i(\mathbf{x})\delta_j(\mathbf{x}+\mathbf{r})\mathbf{v}_{4-i-j}(\mathbf{x}+\mathbf{r})\right\rangle .$$

PT correction to $P_{\delta\theta}$

Bispectrum terms: $B_{\delta\delta\theta}$

Velocity statistics in standard perturbation theory: new results

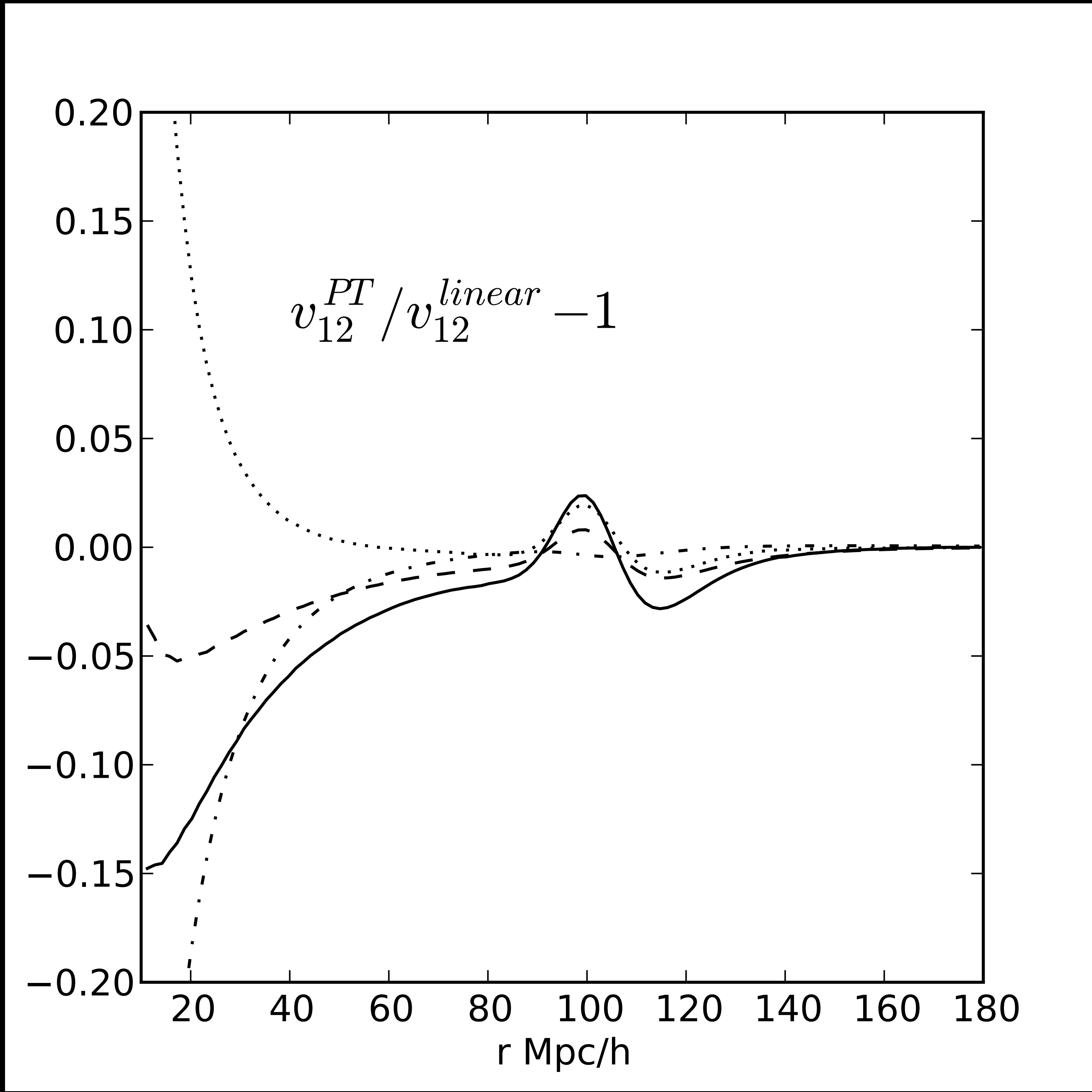
Bispectrum terms: $B_{\delta\delta\theta}$

$B_{\delta\delta\theta}$, $P_{\delta\theta}$ terms appear in Tang et al., Nishimishi et al.

PT correction to $P_{\delta\theta}$

total PT correction

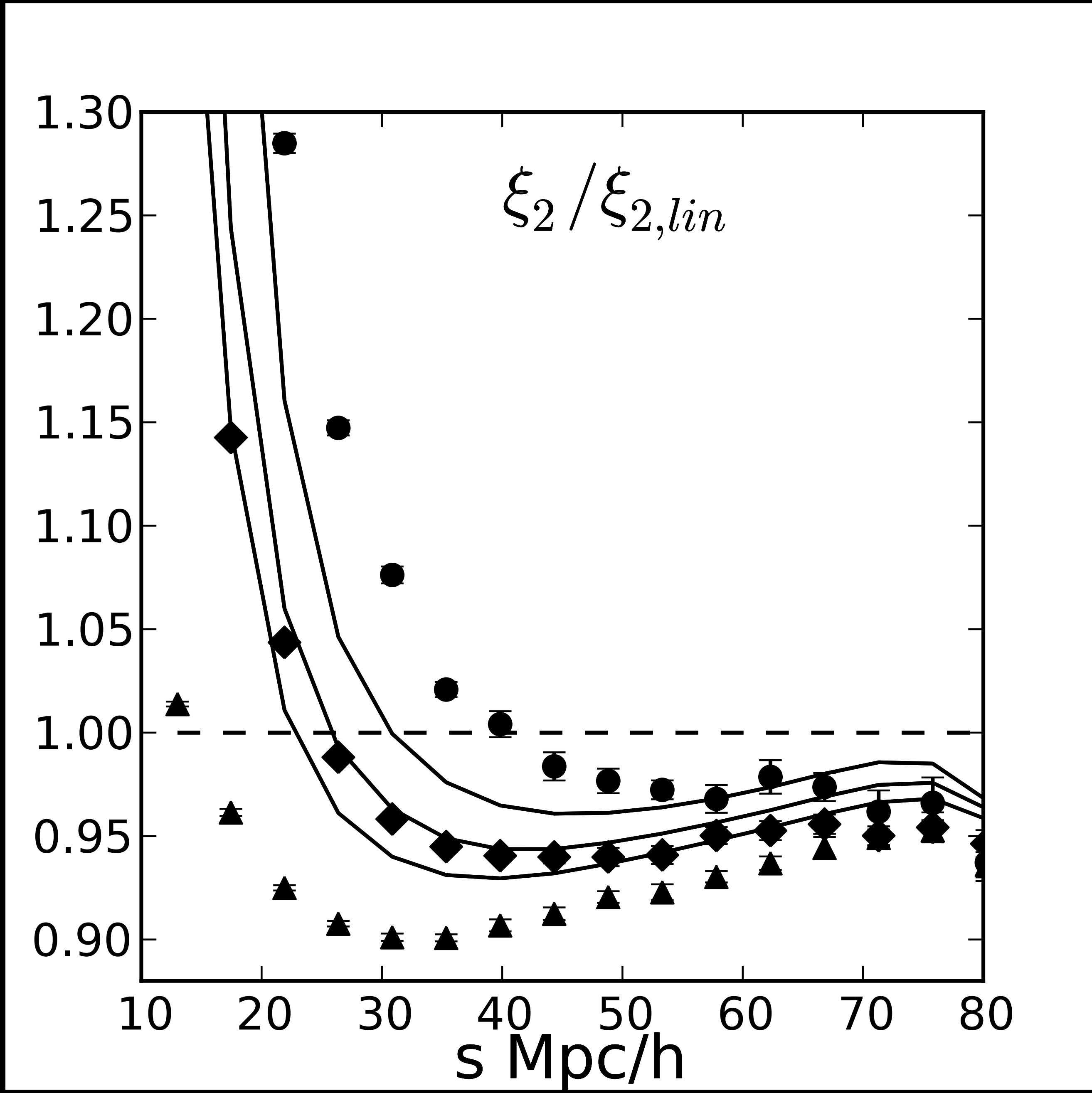
Pair-weighting correction



Beth Reid

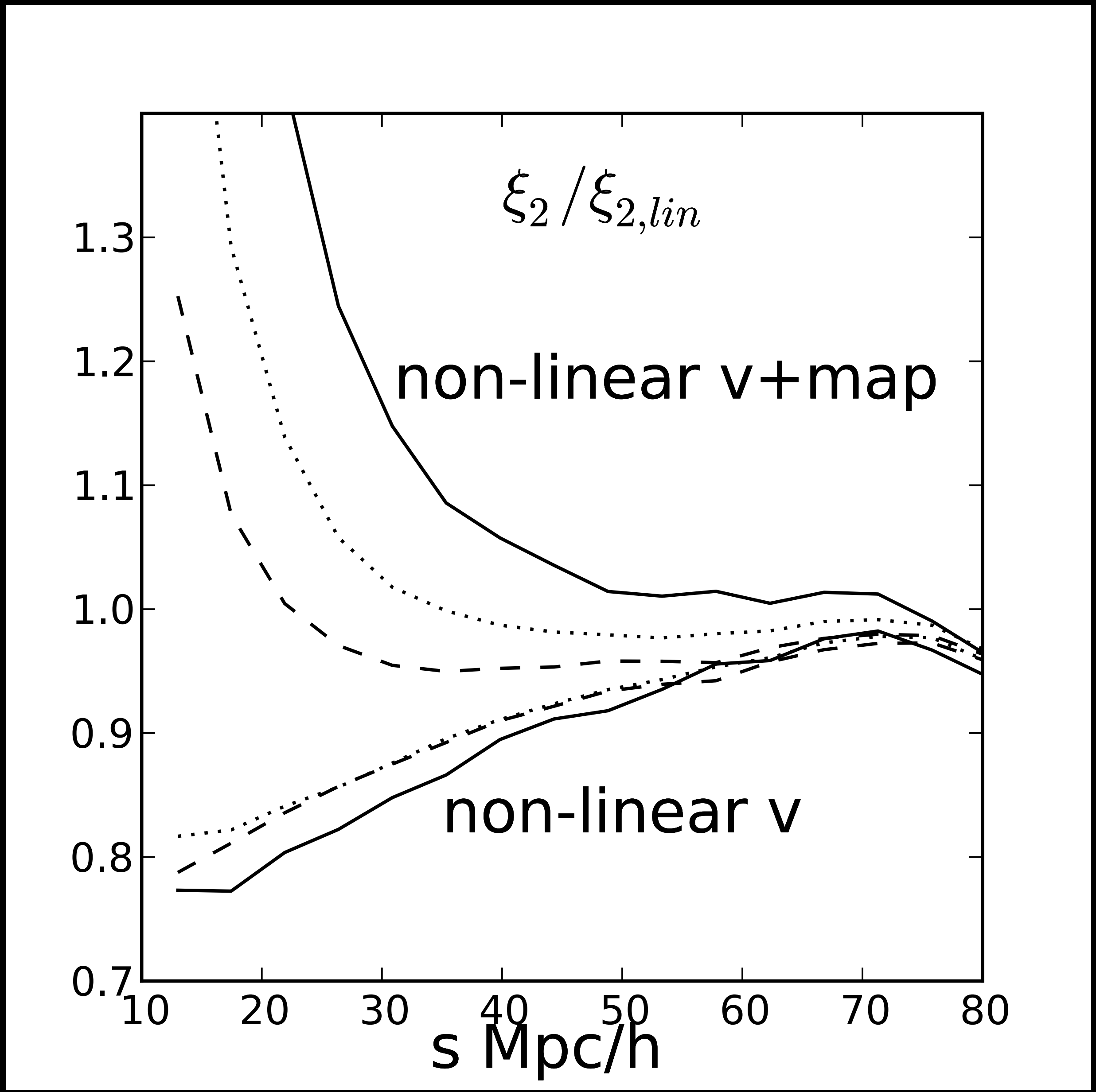
Putting it all together: fully analytic model

- Error dominated by error in $v_{12}(r)$ slope
- Works where $b_2^L = 0$ (i.e., for BOSS galaxies)
- New LPT calculation in prep: Carlson et al., 2012



Summary: Two distinct effects

- Non-linear gravitational evolution: MUST be accounted for given current statistical errors: ξ_2 suppressed by 2.5-7.5% at 50 h^{-1} Mpc!
- Non-linear real-to-redshift space mapping: b^3 term



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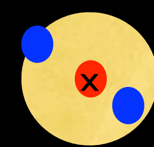
- Interlude: SDSS DR9 first results
- Future prospects

Dominant impact of galaxies: Fingers-of-God

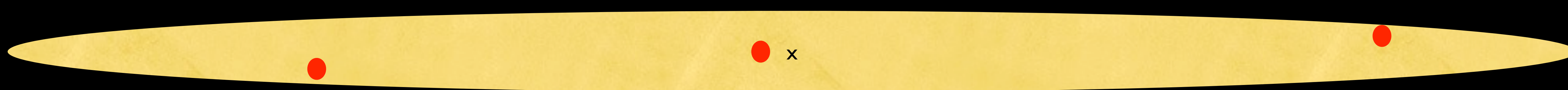
REAL SPACE: r ~ 1 Mpc/h



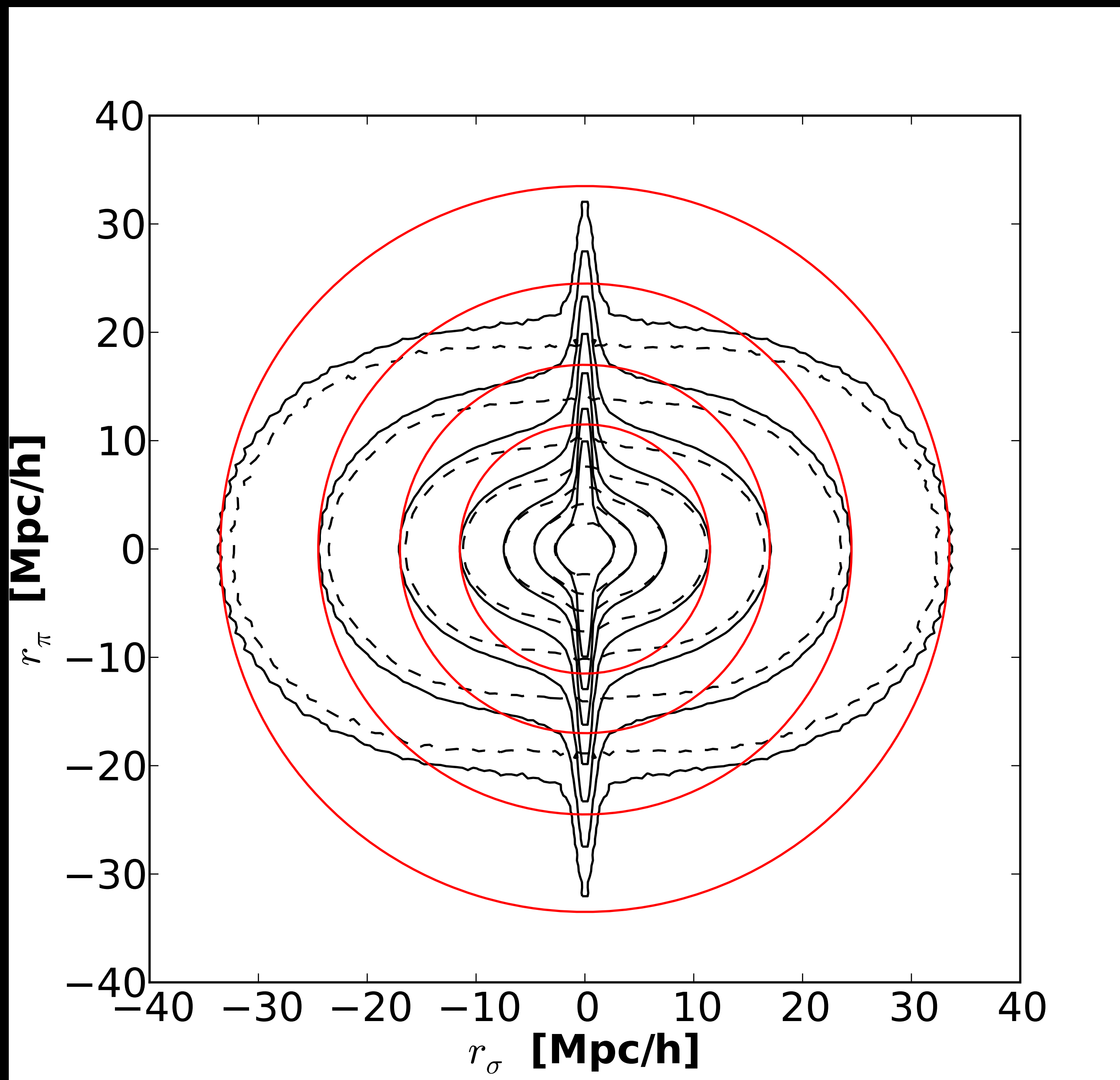
Central galaxies

Satellite galaxies

REDSHIFT SPACE: r ~ 15 Mpc/h
Finger-of-God features mix small and large scale power



Fingers-of-God in ξ(r_σ, r_π)

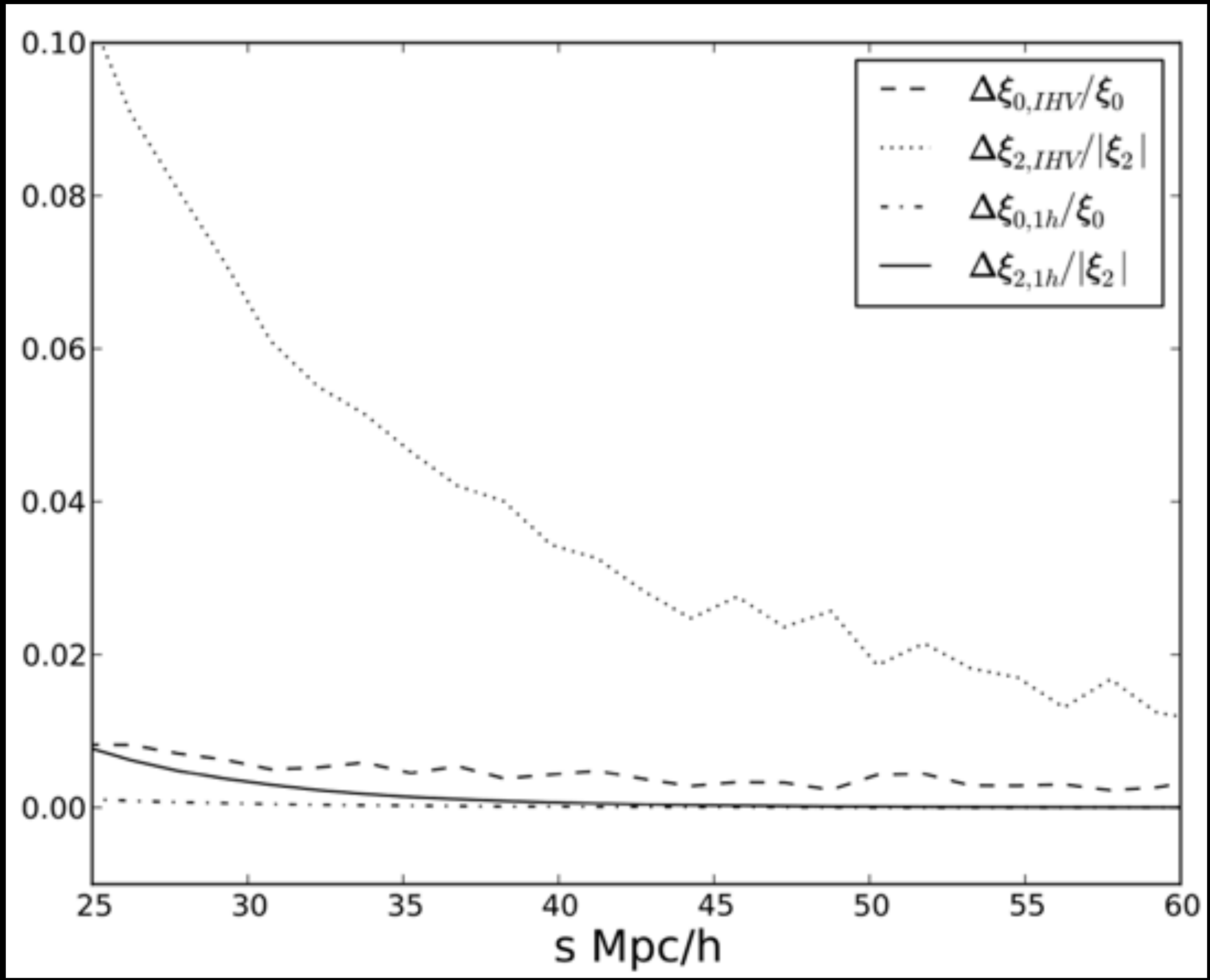


From halos to galaxies

- In principle, straightforward to model in $\xi(r_\sigma, r_\pi)$ -- just another convolution with intrahalo velocity PDF
- In practice 3 (broad) distinct PDFs: cs, ss (1h), ss (2h)
- Inaccarucy of halo $\xi(r_\sigma, r_\pi)$ on small scales inhibits this approach

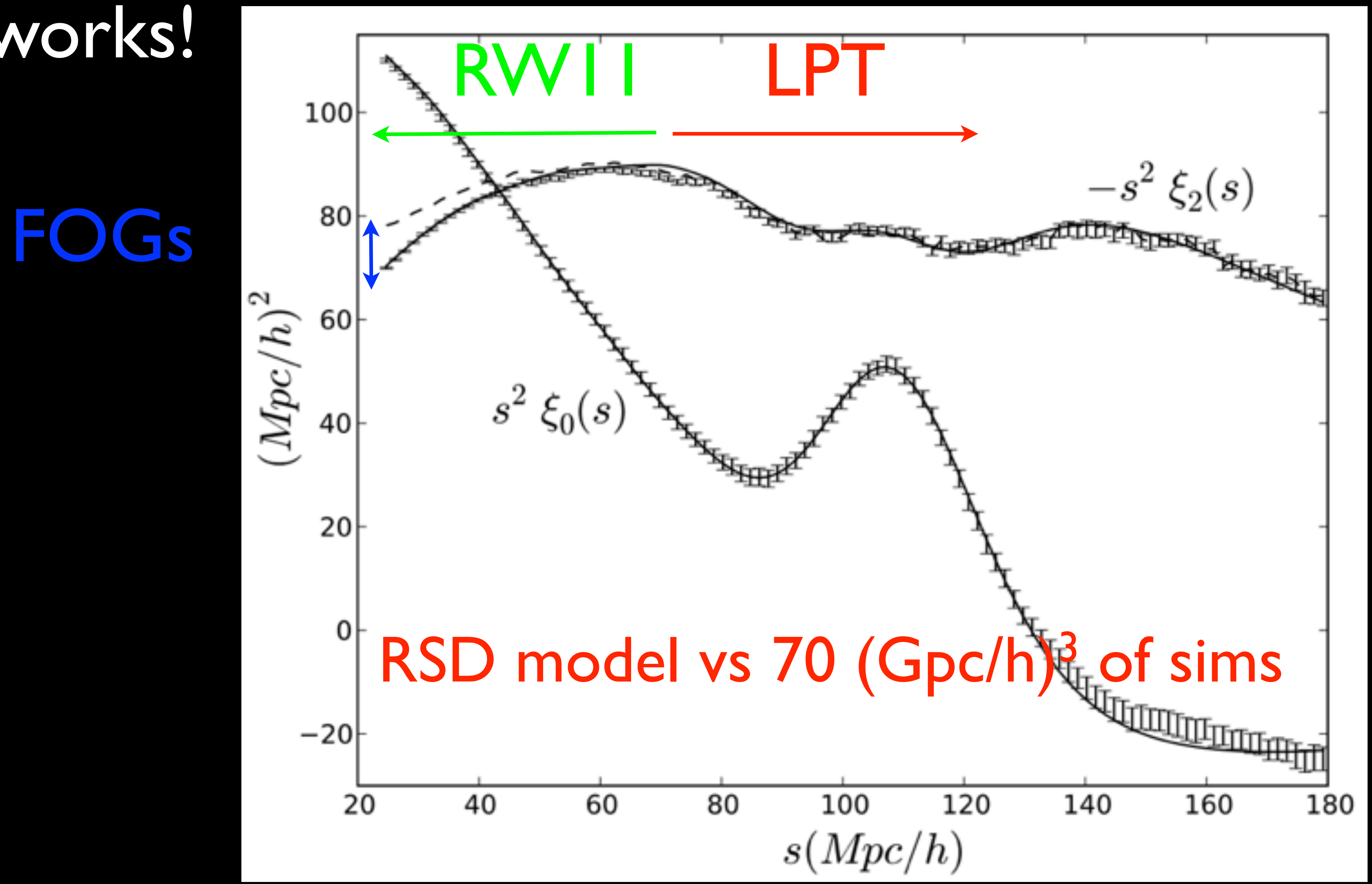
Safe on quasilinear scales...

- One-halo (classical FOG) unimportant
- ~ 10% effect at 25 Mpc/h for BOSS galaxies



From halos to galaxies

- Marginalizing over additional Gaussian dispersion works!



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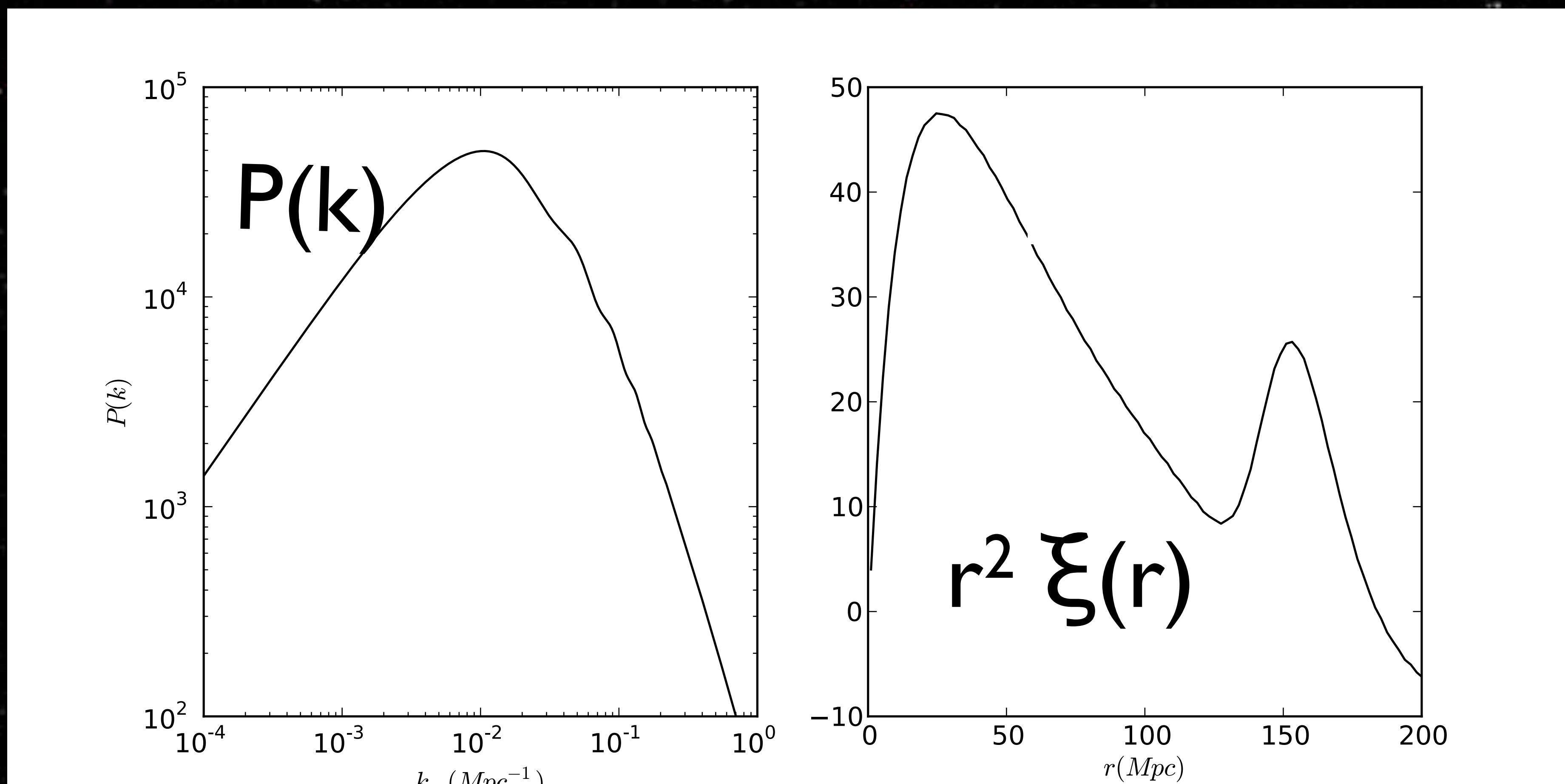
Galaxy clustering lightning theory review

- Theory I: underlying matter power spectrum (determined at $z >\sim z_{CMB}$, neglecting ν)
- Theory II: Expansion history $H(0 < z < z_{GAL})$

Matter Power Spectrum

- Entire P(k) (not just BAO) acts as standard ruler determined by CMB
- We marginalize over the (negligible) uncertainty

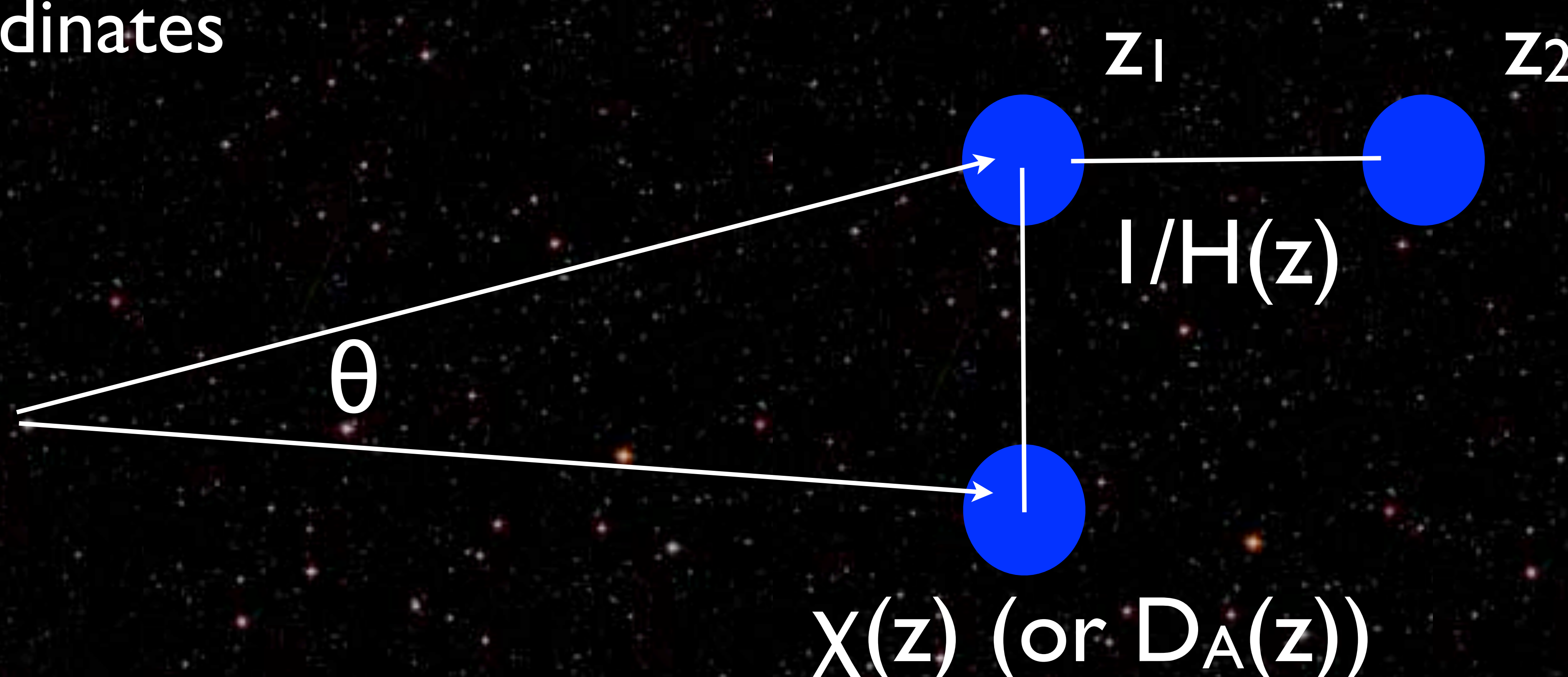


Mpc^{-1}

Mpc

Theory II: geometry

- We measure θ, φ, and z for each galaxy, and use a cosmological model to convert to comoving coordinates



Theory II: Alcock-Paczynski

- $\xi(r_p, \pi)$ appears anisotropic if you assume the wrong cosmological model (constrain $\eta_{AP} = D_A * H$)

$$\chi(z) = \int_0^z c\, dz'/H(z')$$

BAO in $\xi_0(s)$ determines "geometric mean" $D_V \propto (D_A^2\, H^{-1})^{1/3}$

$c\, \Delta z / H(z)$

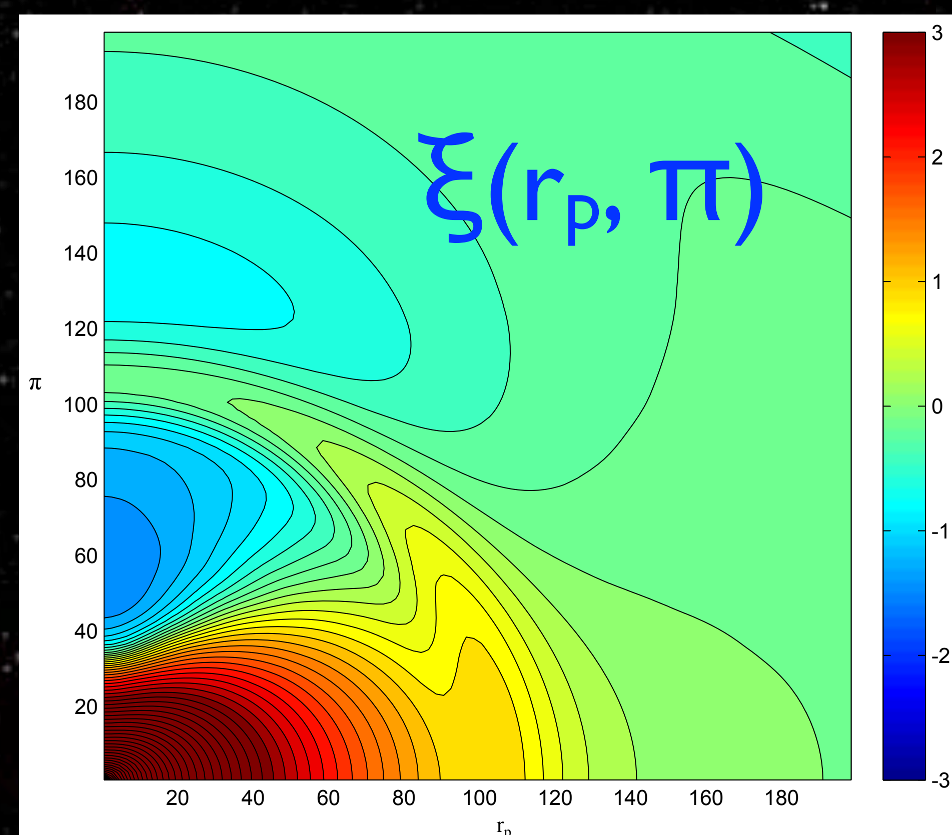


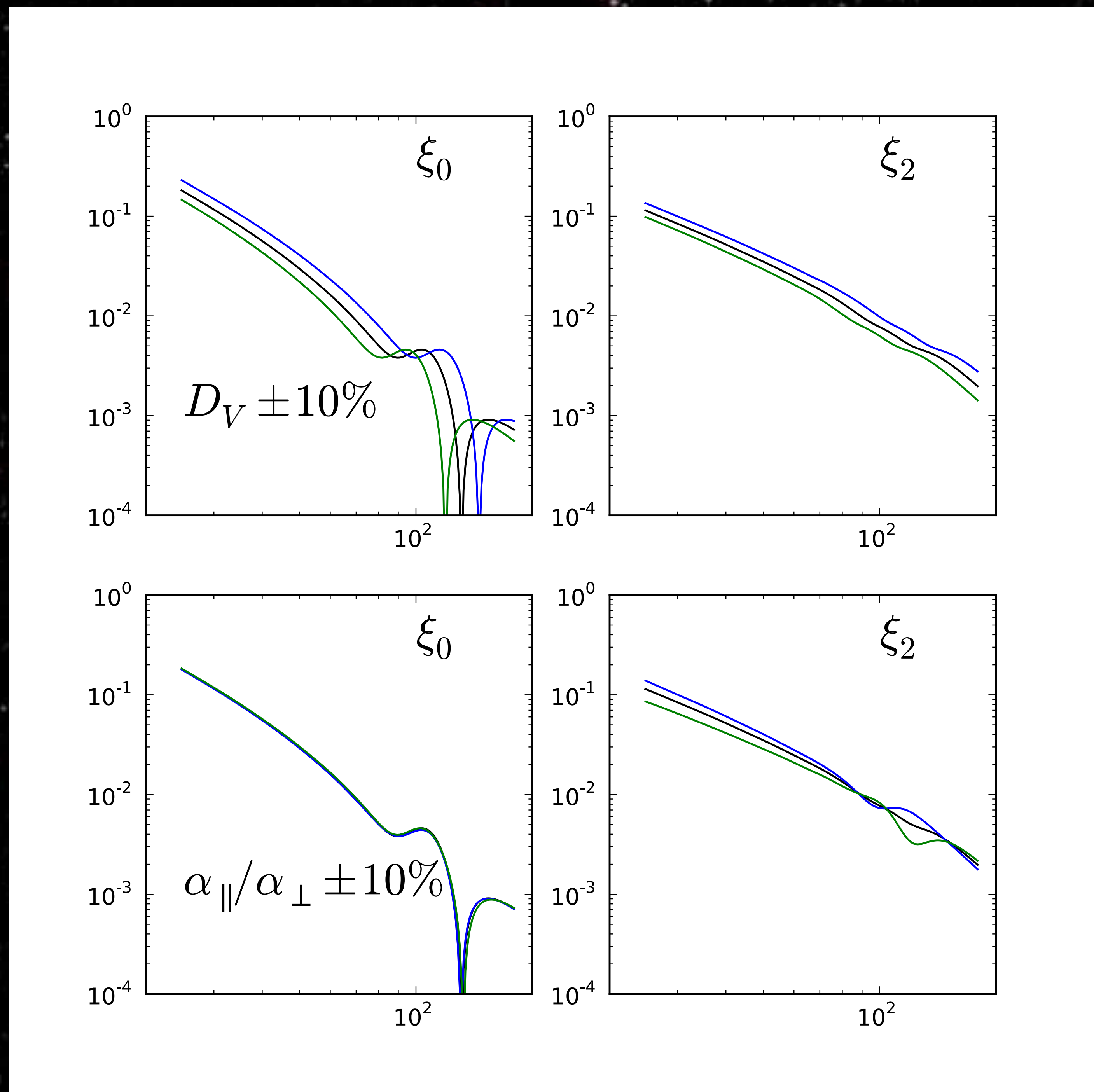
Image from Tian et al. arXiv:1011.2481

$\chi(z)*\Delta\theta$

Fitting to 2d clustering

- Use full model of $\xi_{0,2}(s \geq 25\ h^{-1}\ \mathrm{Mpc})$ to constrain:
  - growth of structure ($f\sigma_8$)
  - $D_V \propto (D_A^2/H)^{1/3}$
  - Alcock-Paczynski ($\eta_{AP} \propto D_A(z_{eff}) * H(z_{eff})$)
  - marginalizing over shape of underlying linear P(k), $b\sigma_8$, σ^2_{FOG}

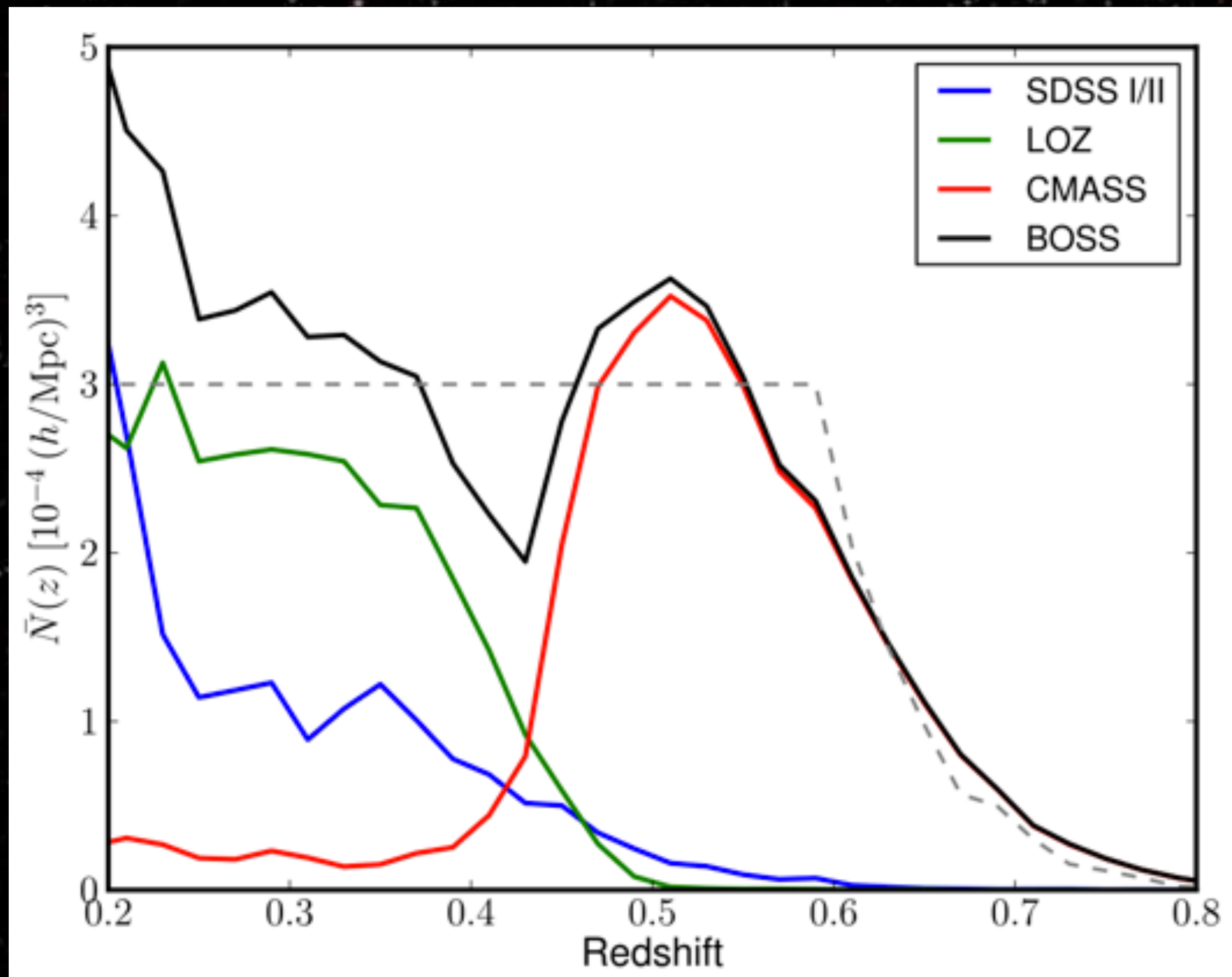
Alcock-Paczynski in multipoles



DR9 spectroscopic results: preliminary!

- DR9 data final (public July 2012), clustering/ covariances ~final, cosmological constraints preliminary
- Current uncertainties reported, not central values

BOSS "CMASS" (z_{eff} = 0.57) galaxy sample in perspective



Eisenstein et al. arXiv:1101.1529

BAO fits in P(k)/ξ(r) consistent

X. Xu et al. (in prep; DR7)
BOSS Galaxy Clustering (in prep.)

plot of BAO feature here

- 2-3% uncertainty on BAO position in angle-averaged P(k)/ξ(r)
- Constrains $D_V \propto (D_A^2/H)^{1/3}$

The CMASS measurements

- 26 log bins in s for ξ_0 and ξ_2 = 52 DOF

plot of ξ_0 and ξ_2 here

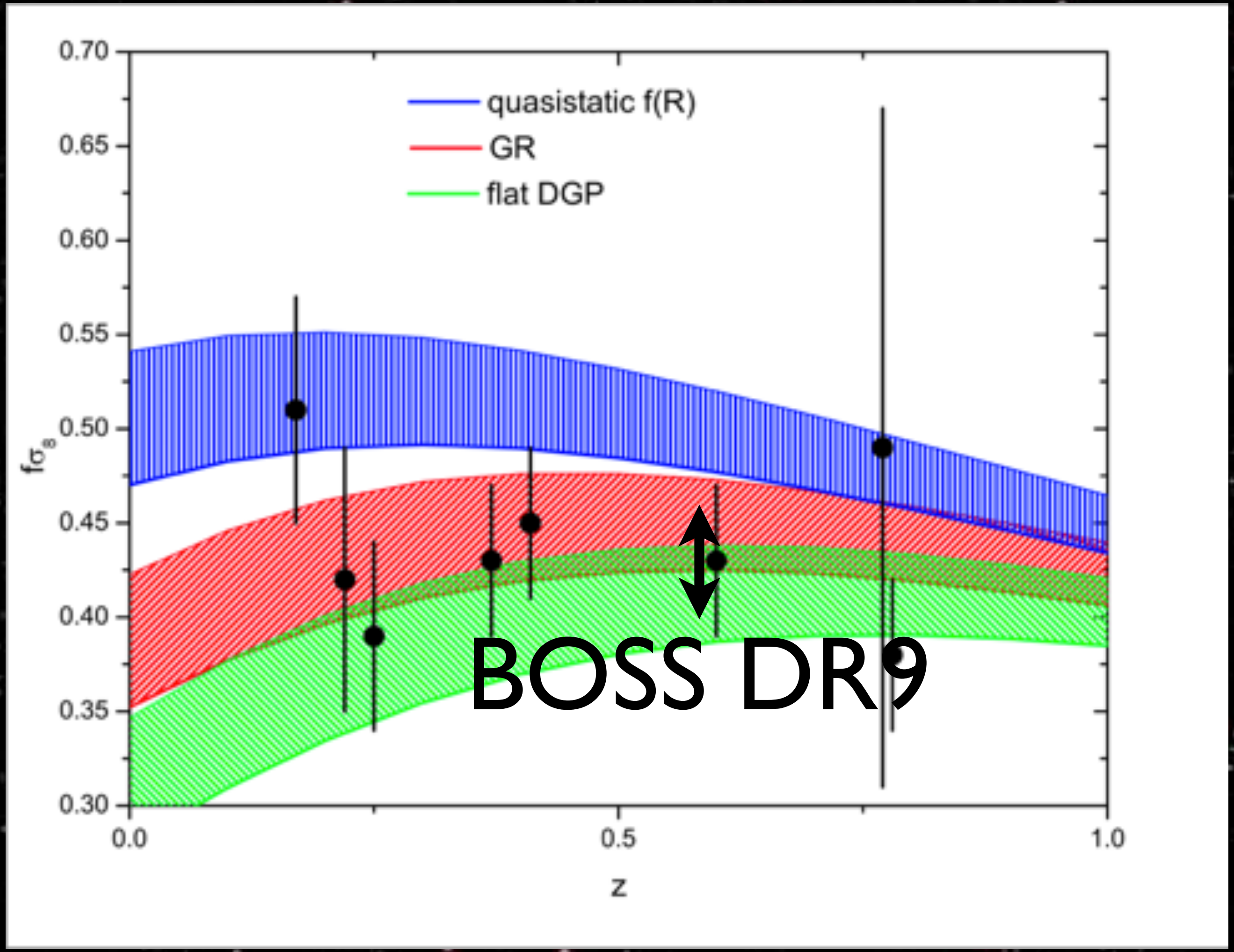
Model Fits

- We test the LCDM hypothesis in 4 models, always marginalizing over P(k) shape and σ^2_{FOG}:
  - LCDM ($b\sigma_8$)
  - LCDM + $f\sigma_8$: ($b\sigma_8$, $f\sigma_8$)
  - LCDM + geometry: ($b\sigma_8$, D_V, D_A*H)
  - LCDM++: ($b\sigma_8$, $f\sigma_8$, D_V, D_A*H)

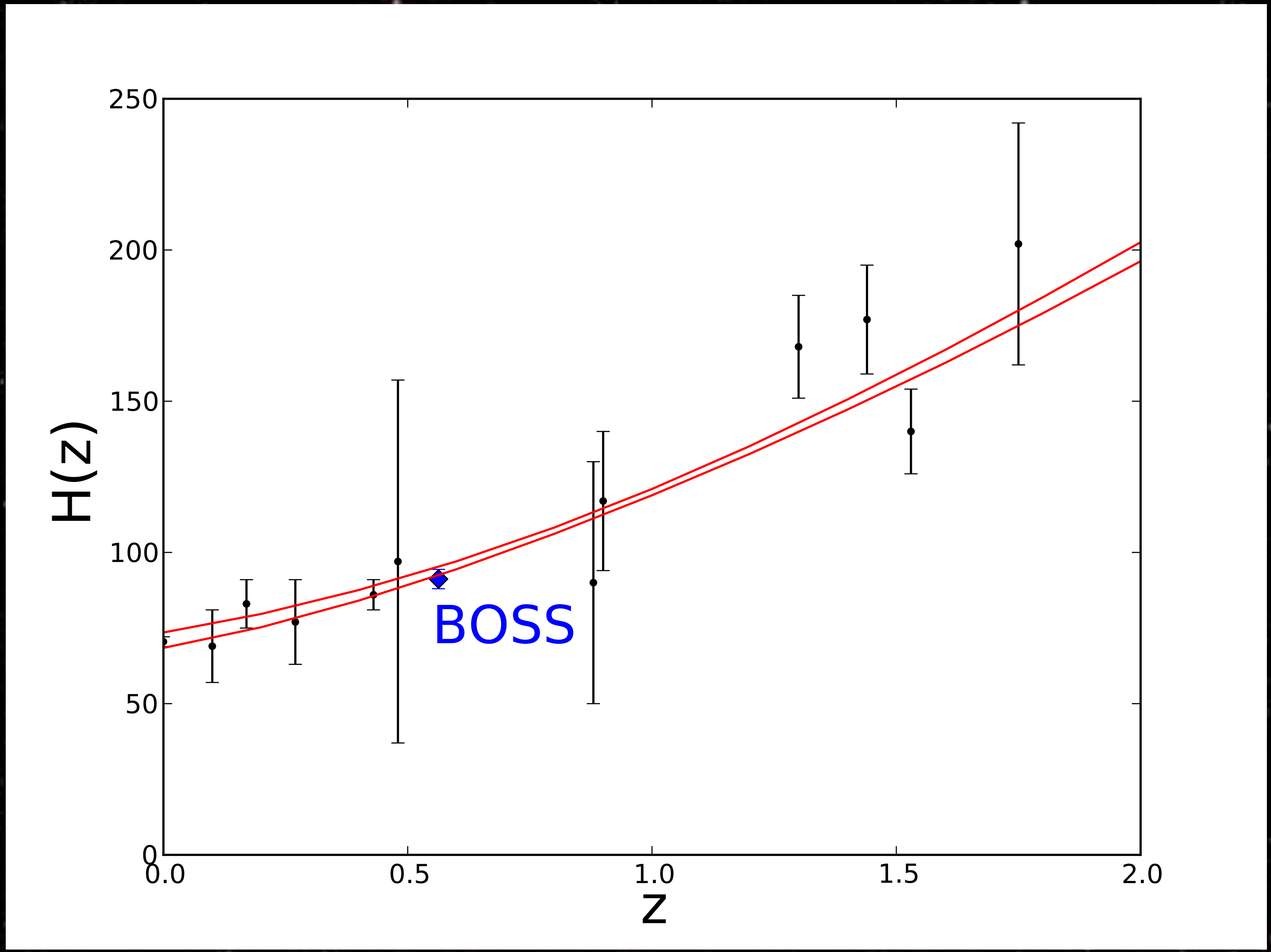
Current status

- $D_V/D_{V,\text{fid}} = x \pm 0.019$ (i.e., minimal information gain on D_V compared to BAO only!)
- Geometry LCDM: $f\sigma_8 = xx \pm 0.03$ (7%) [WMAP7 LCDM: 0.45 ± 0.025]
- $f\sigma_8$ LCDM: $\eta = xx \pm 0.04$ (4%) [WMAP7 LCDM: 1.00 ± 0.012]
- Fit both: $f\sigma_8 = xx \pm 0.07$, $\eta = xx \pm 0.07$

Testing alternative models with amplitude of peculiar velocities



Expansion rate at z=0.57



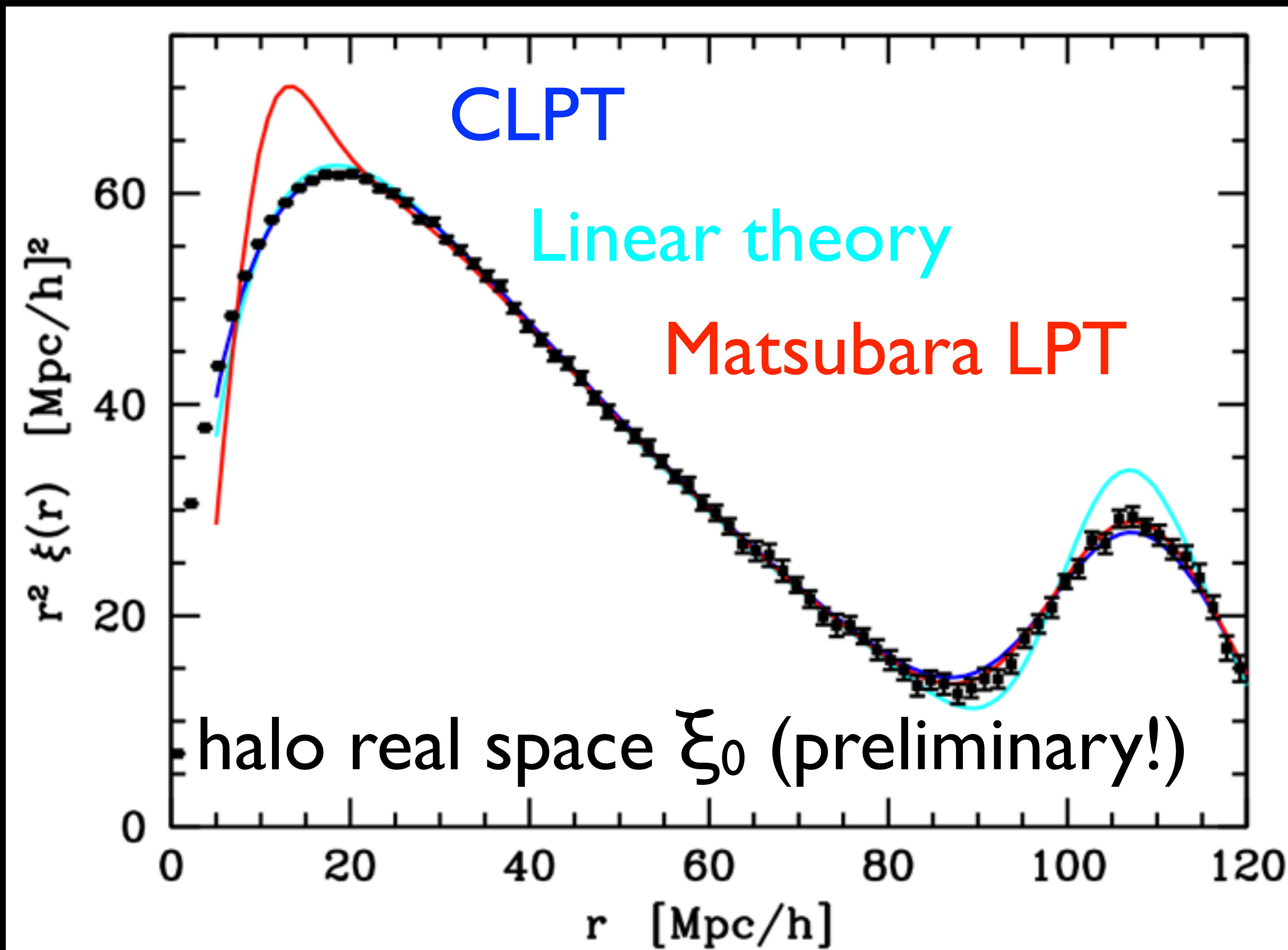
Outline

- Motivation
- Basic redshift space distortions (RSD) in configuration space
- Reid and White 2011 configuration space RSD model (+ connections to other recent RSD work)
- From halos to galaxies...
- Interlude: SDSS DR9 first results
- Future prospects

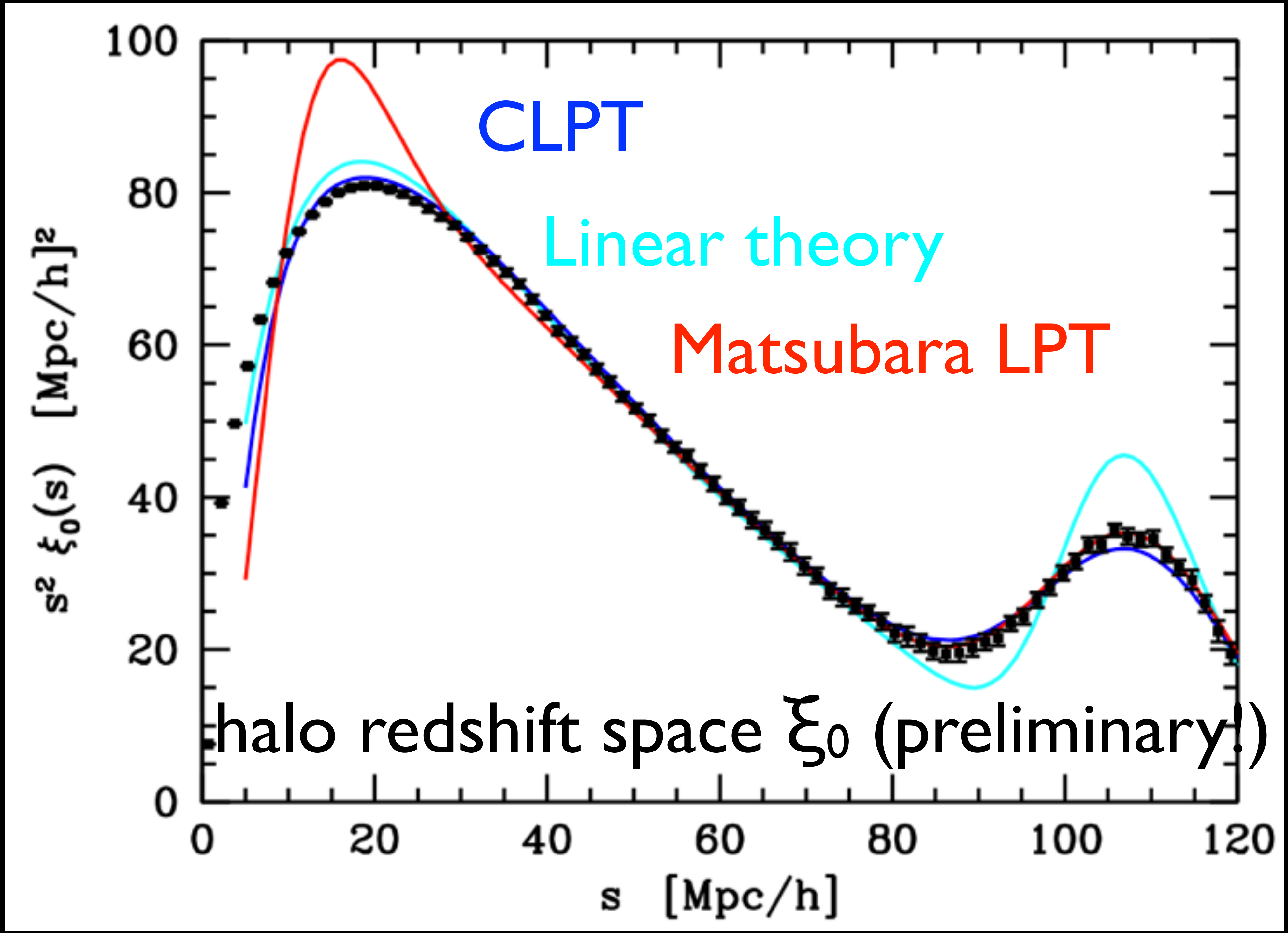
Future Prospects: "convolutional" LPT (Jordan Carlson, et al., in prep)

- Fourier transform formal LPT $P(k, \mu)$ expression; use cumulant expansion thm + Gaussian integrals
- Recovers Zel'dovich approximation exactly -> b^3 nonlinear mapping term (?)

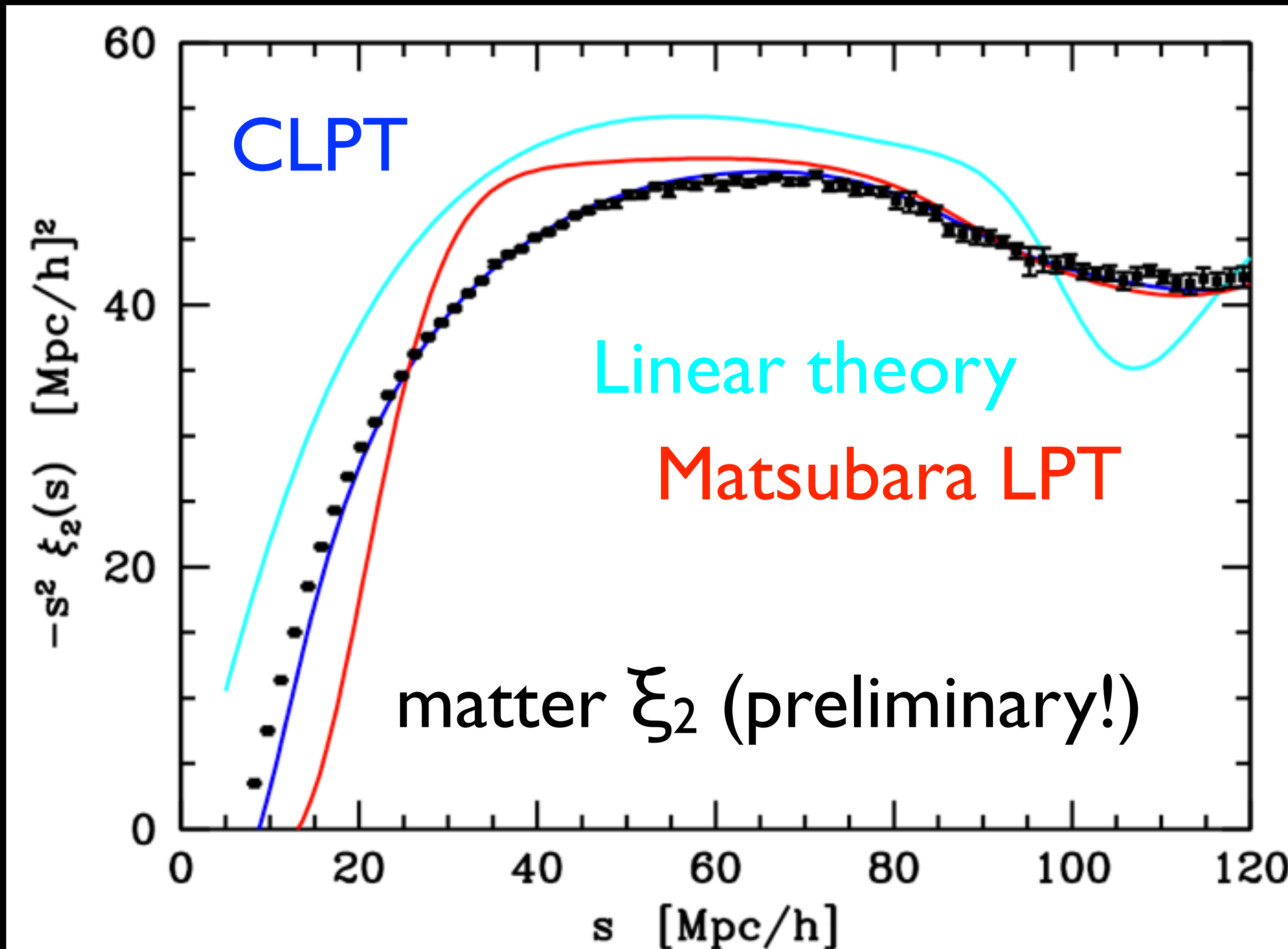
Future Prospects: "convolutional" LPT (Jordan Carlson, et al., in prep)



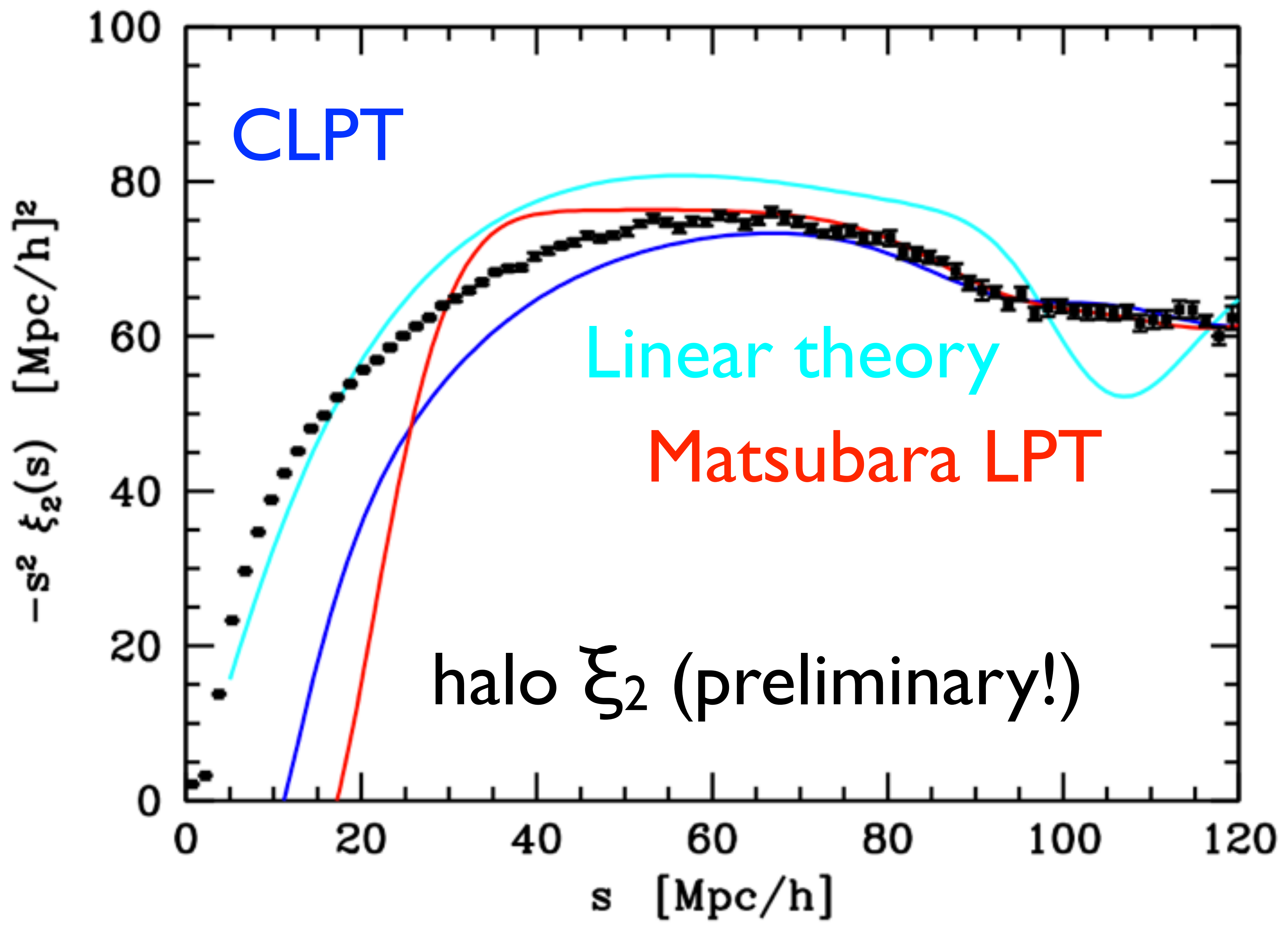
Future Prospects: "convolutional" LPT (Jordan Carlson, et al., in prep)



Future Prospects: "convolutional" LPT (Jordan Carlson, et al., in prep)



Future Prospects: "convolutional" LPT (Jordan Carlson, et al., in prep)



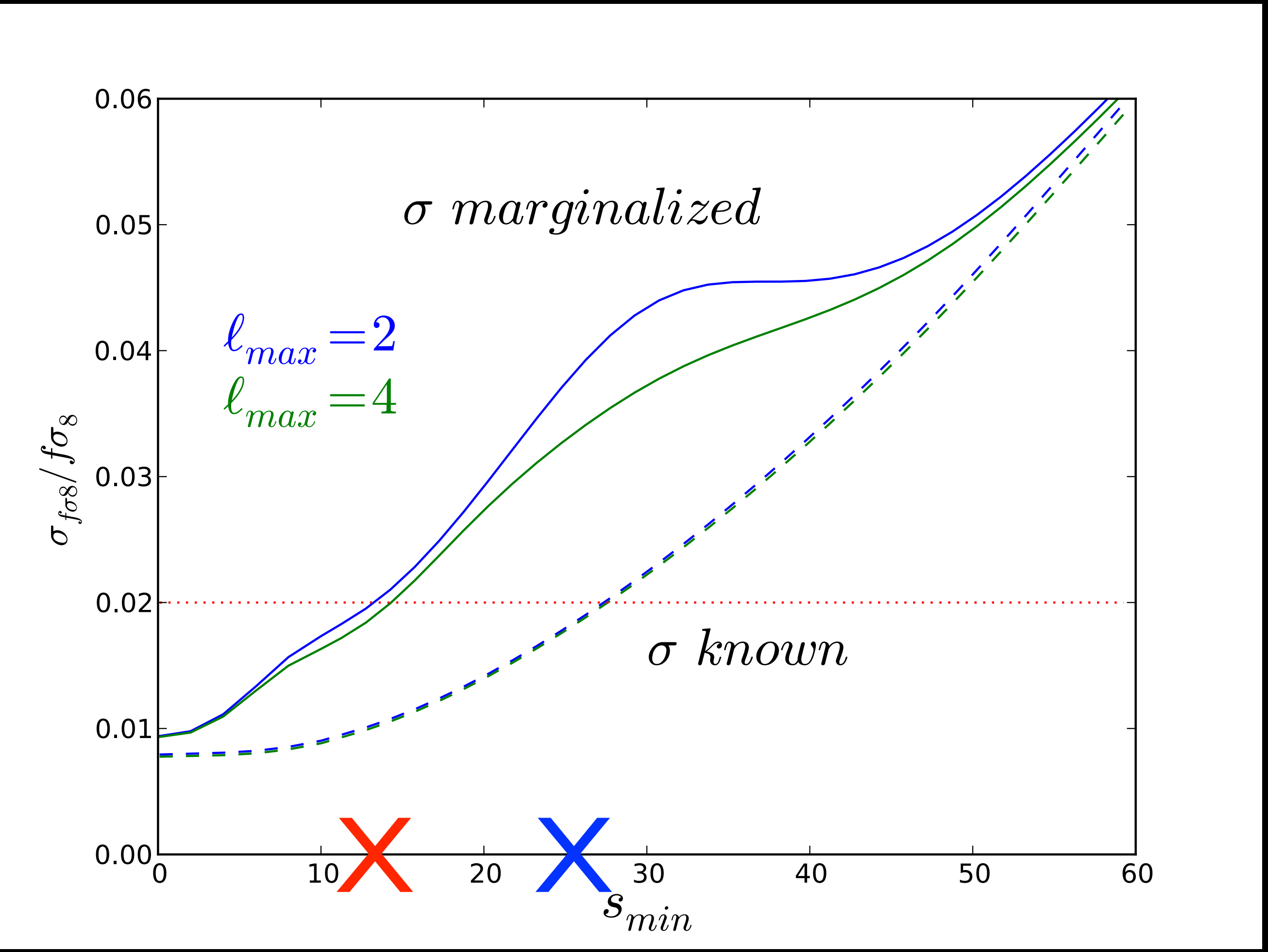
Tuesday, January 31, 2012

Future Prospects: "convolutional" LPT (Jordan Carlson, et al., in prep)

- New real space $\xi(r)$ fits to ~ 10 Mpc/h !!
- Repeat $v_{12}(r)$, $\sigma^2_{\perp,\parallel}(r)$ calculations in LPT (including b_2^L) may extend analytic Gaussian streaming model to smaller scales

Future Prospects: using small-scale clustering to infer σ^2_{FOG}

$$P_g^s(k,\mu) = \left(b + f\mu^2\right)^2 P_m^r(k)\, e^{-k^2\sigma^2\mu^2}$$



IF we can determine σ from small-scale clustering (e.g., HOD), gain factor of 2 on RSD

s_{min}, WiggleZ

s_{min}, BOSS

Conclusions

- Configuration space simplifies many conceptual issues in modeling RSD
- Worked example of developing/modelling target (BOSS) galaxies: 2% accurate to 25 h^{-1} Mpc
- 7% measurement of $f\sigma_8$ in DR9 CMASS galaxies, ~4% final (barring further modeling improvements)
- Further development underway (CLPT, small scale/ HOD modeling, ...)