Towards a model of redshift space distortions worthy of BOSS data

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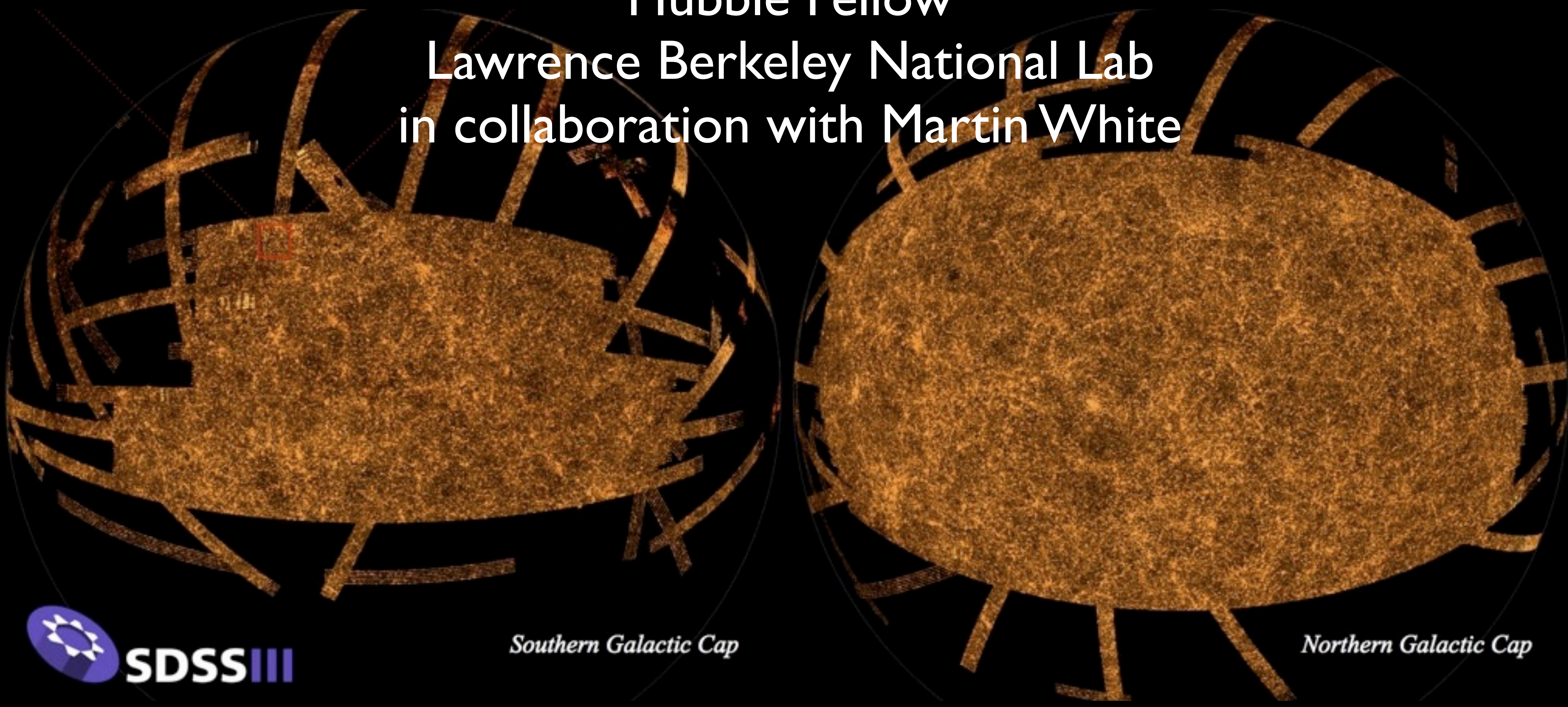
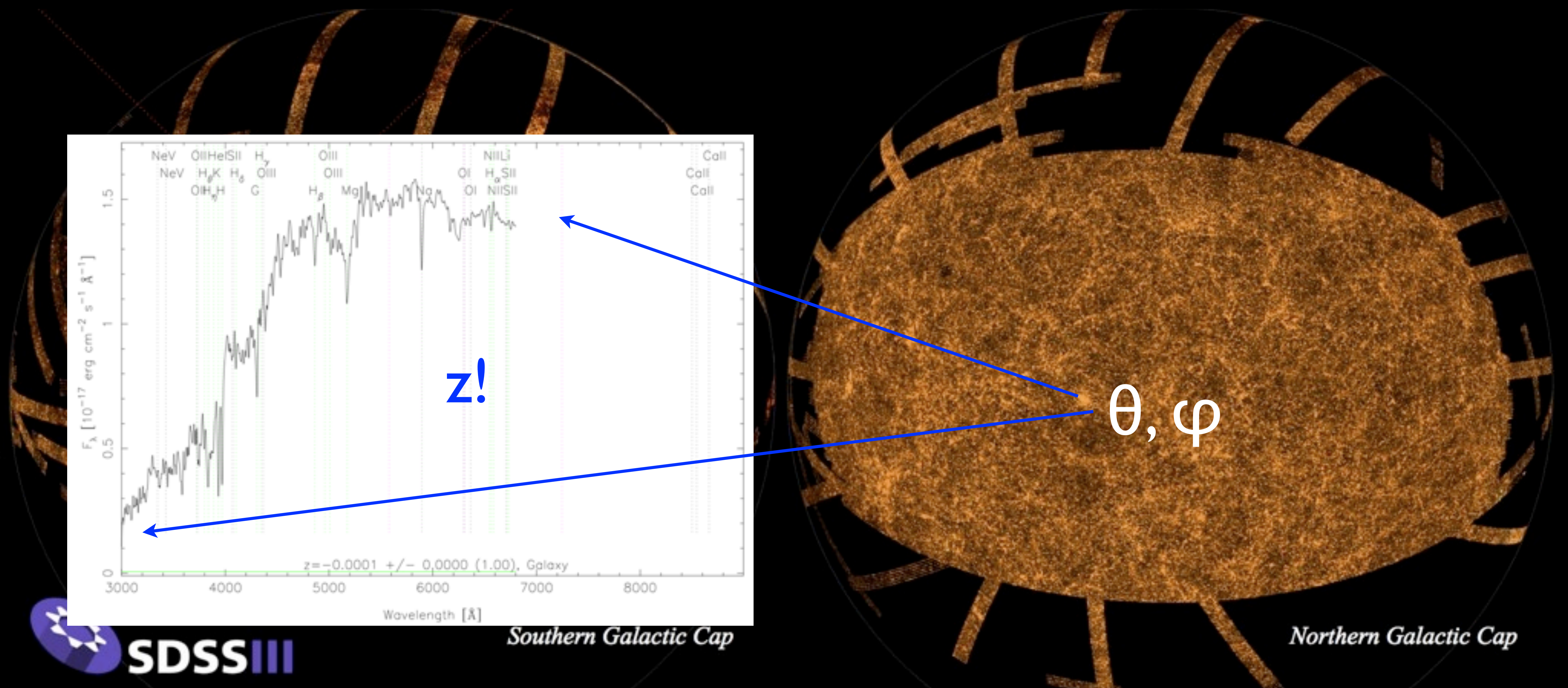


Outline

- What are redshift space distortions (RSD) and why are they the coolest cosmological probe in town?
- Projections for BOSS RSD constraints
- Step away from the Kaiser formula: building intuition in configuration space
- A model for the redshift space distortions of halos

Redshift Space Distortions: What

Redshift surveys measure: θ, φ, redshift



Redshift Space Distortions: What

θ, φ, redshift

depends on the geometry of the universe

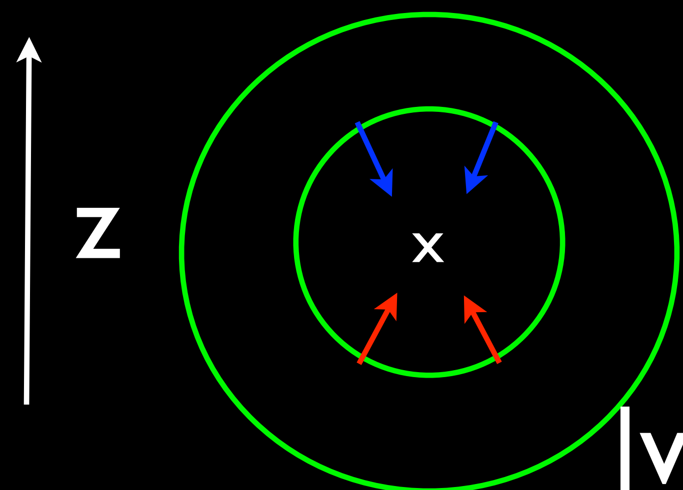
$\chi(z) = {}_0\int^z c\, dz'/H(z')$

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

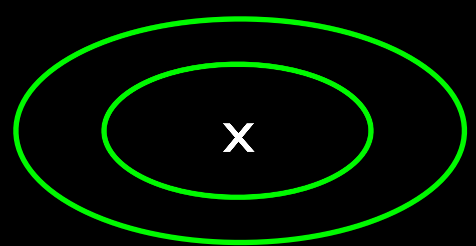
comoving coordinates: x, y, z

Redshift Space Distortions: What

real to redshift space separations



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



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

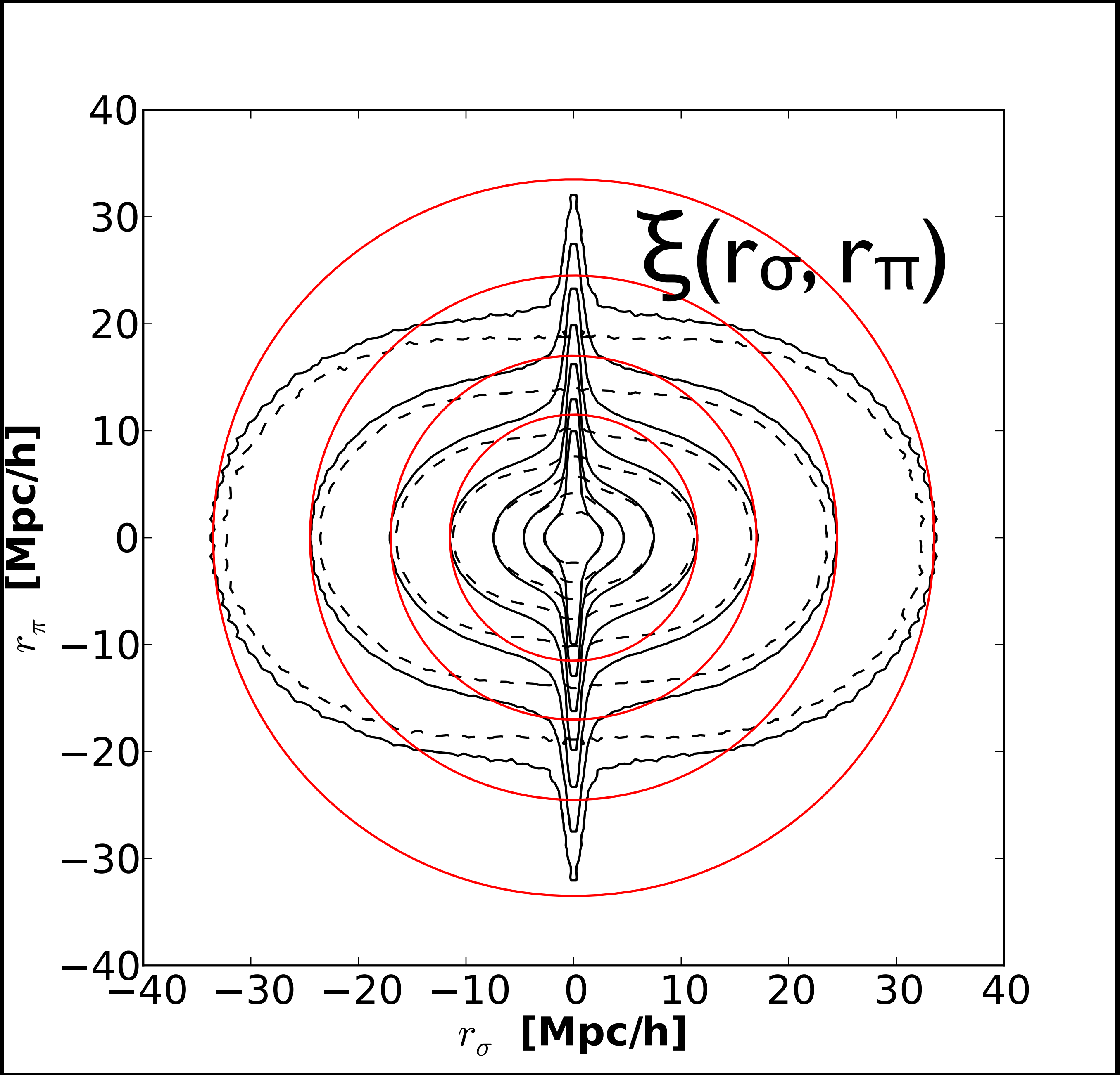
isotropic

squashed along line of sight

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

Redshift Space Distortions: How

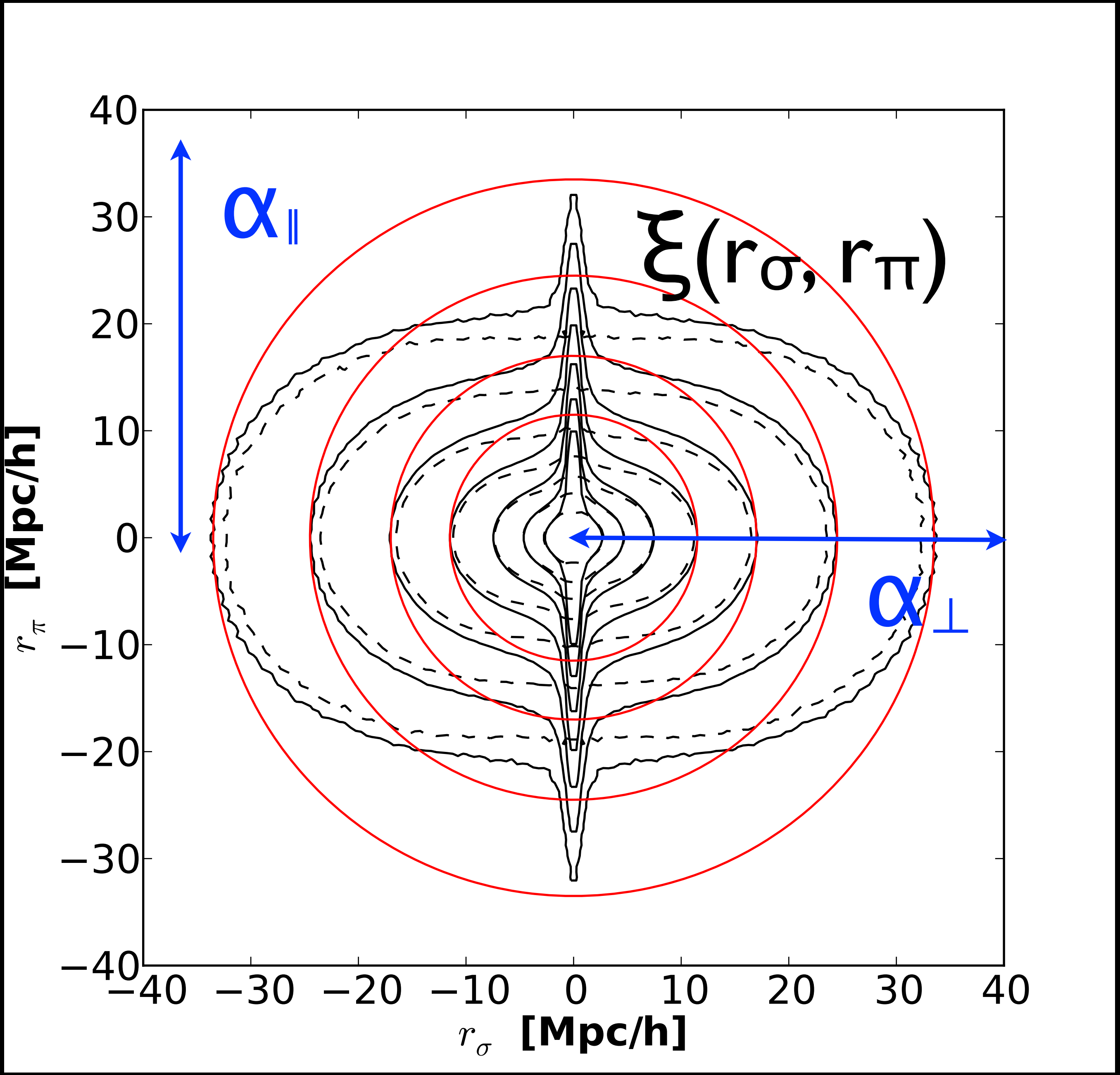
- $\xi(r_\sigma, r_\pi)$: number of pairs in excess of random as a function of pair separation OR the avg density around a galaxy



White et al. 2011 mock catalogs

Redshift Space Distortions: How

- Sidenote: Alcock-Paczynski effect is degenerate with RSD



White et al. 2011 mock catalogs

Why: Hot topic!

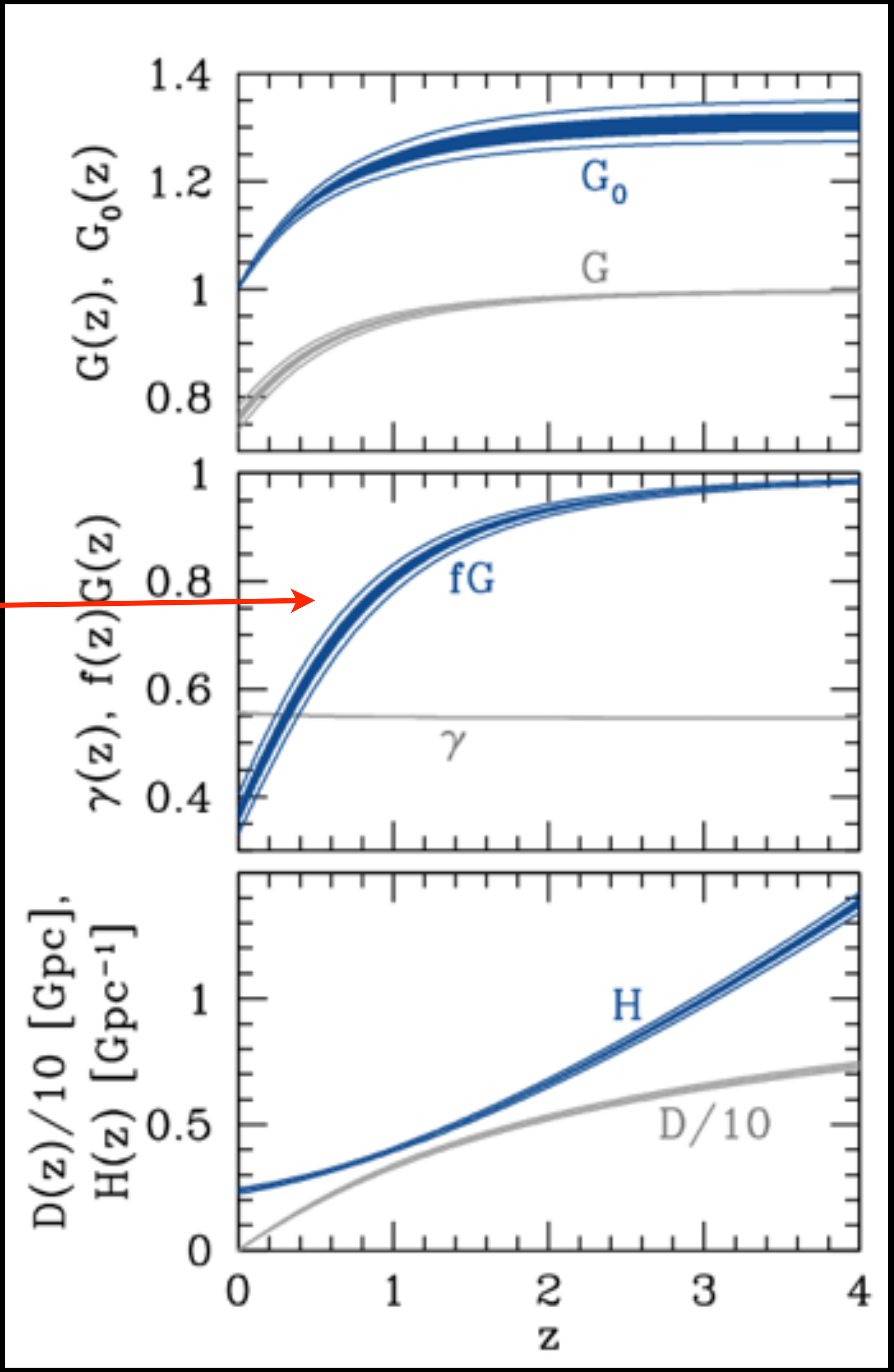
- Linder et al.: 1105.1194, 1109.1846
- Reid & White: 1105.4165
- Seljak, McDonald et al: 1109.1609, 1109.1888
- Saito et al.: 1006.0699, 1101.4723

Why: Testing General Relativity

- Growth function G(a): $\delta(\mathbf{k}, a) = aG(a)\delta_i(\mathbf{k})$
- In General Relativity G(a) is determined once H(a) is specified/measured; generically this relation is different in modified gravity models

Why: Testing General Relativity

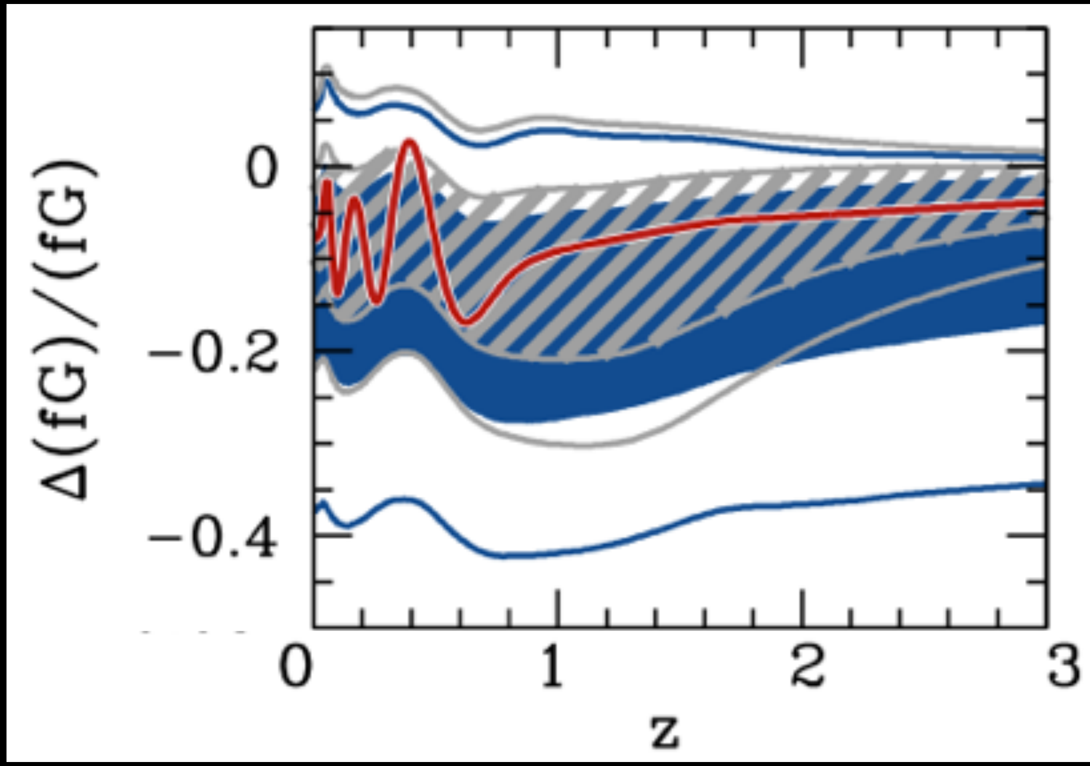
- allowed growth in ΛCDM given 2009 CMB, SN, BAO, H_0
- constrained by RSD



Mortonson, Hu, Huterer 2010, PRD, 81, 063007

Why: Testing General Relativity

- General Quintessence models, massive neutrinos suppress RSD signal



Non-flat quintessence models with early dark energy

Mortonson, Hu, Huterer 2010, PRD, 81, 063007

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Background: Linear RSD (Kaiser 1987)

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

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

Background: Legendre Polynomial moments

General Expansion

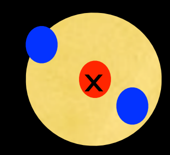
$$P(k,\mu_k) = \sum_\ell P_\ell(k) L_\ell(\mu_k)$$

Linear theory prediction

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

Background: Fingers-of-God

REAL SPACE: r ~ 1 Mpc/h

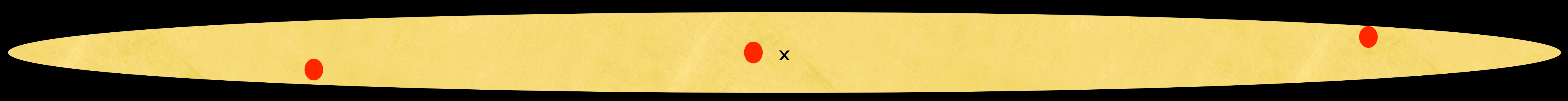


Central galaxies

Satellite galaxies

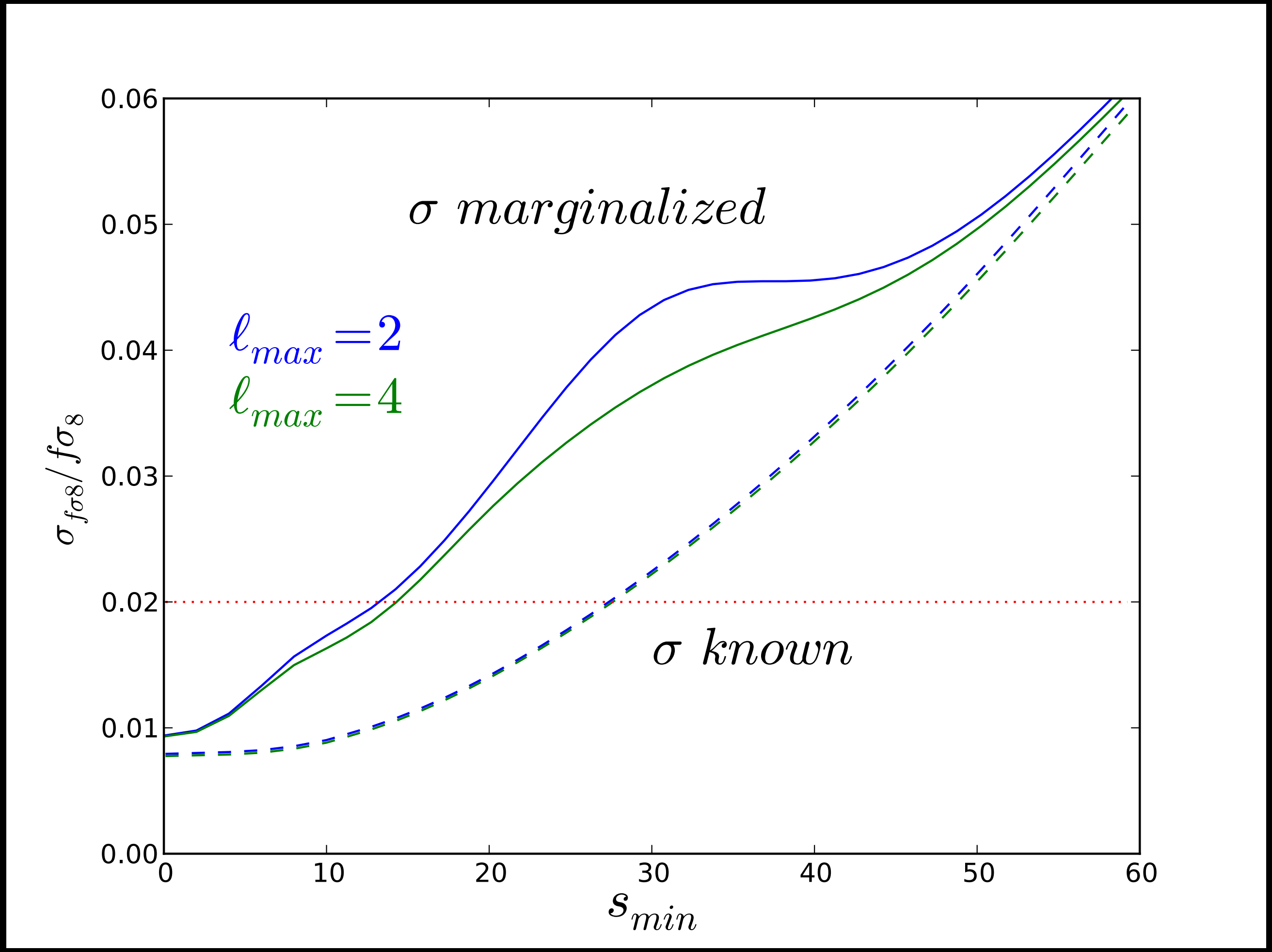
REDSHIFT SPACE: r ~ 15 Mpc/h

Finger-of-God features mix small and large scale power



Fisher Matrix forecast for BOSS

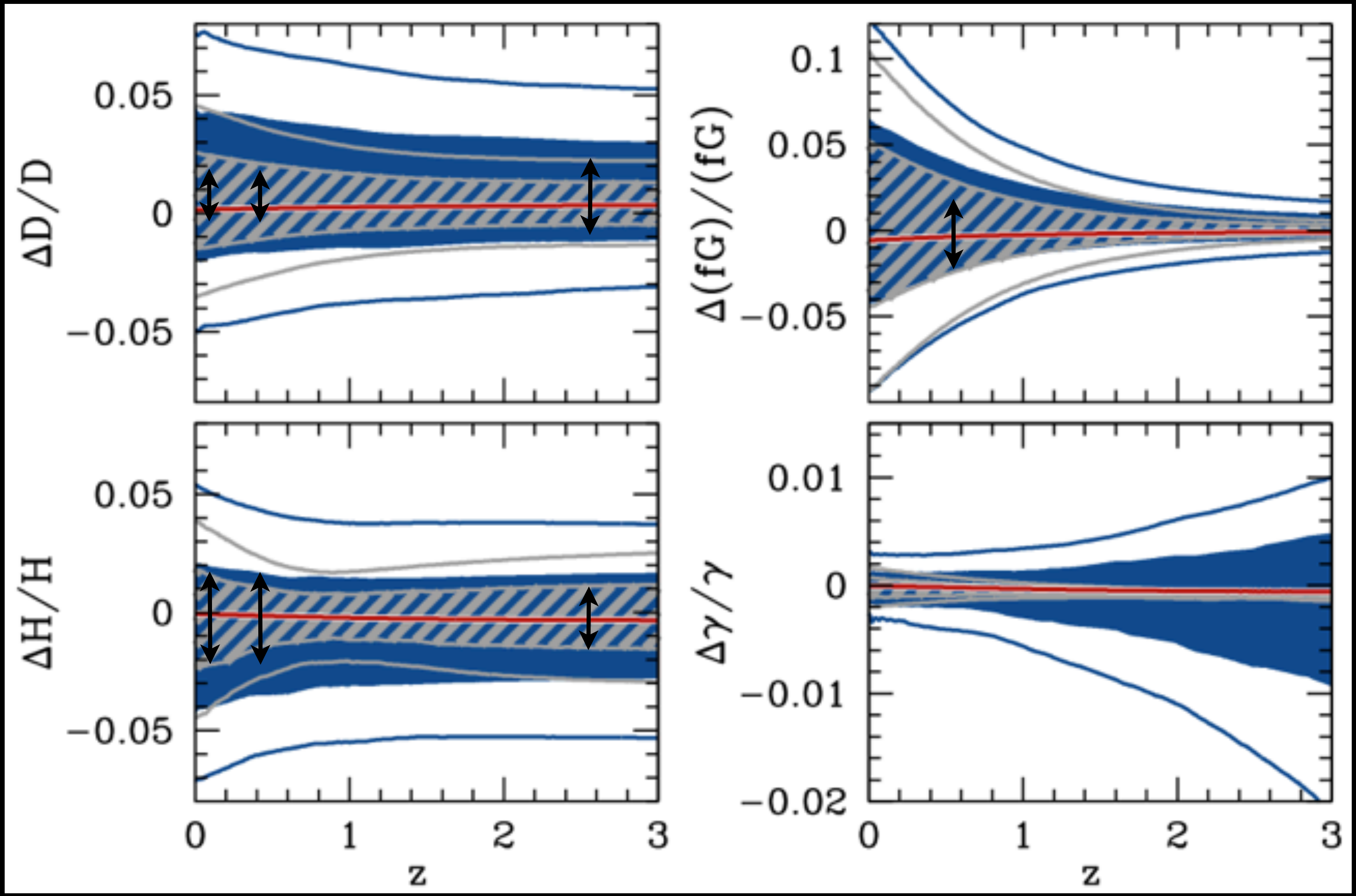
$$P_g^s(k,\mu) = \left(b + f\mu^2\right)^2 P_m^r(k)\, e^{-k^2\sigma^2\mu^2}$$



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

2% theoretical uncertainty "goal" for $\xi_{0,2}$

Fisher Matrix forecast for BOSS



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Legendre Polynomial moments

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

Legendre Polynomial moments

General Expansion

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

Relation to P$_\ell$(k)

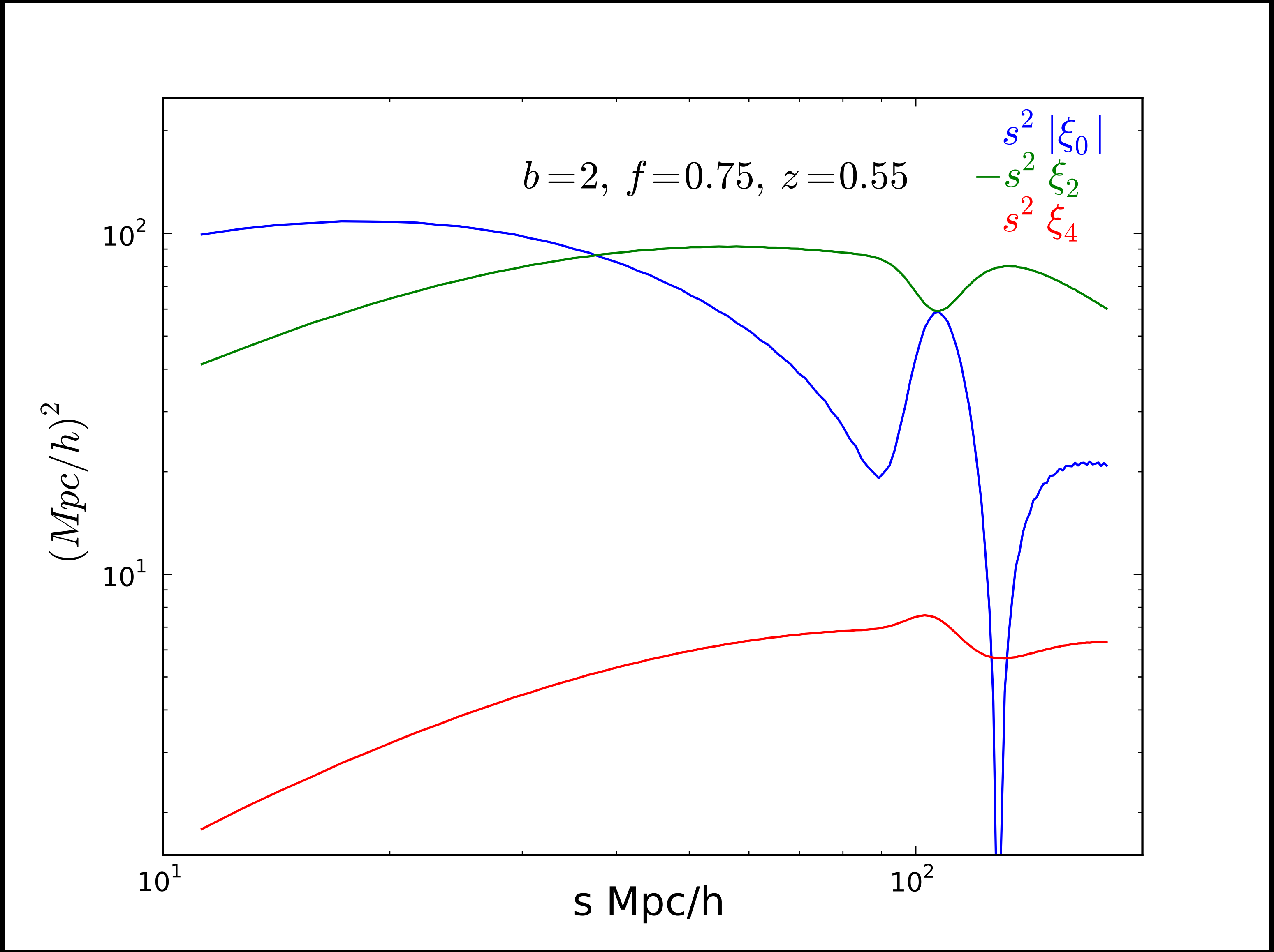
$$\xi_\ell(s) = i^\ell \int \frac{k^2\,dk}{2\pi^2} P_\ell(k) j_\ell(ks)$$

Legendre Polynomial moments: scale dependence

$L_0(\mu) = 1$

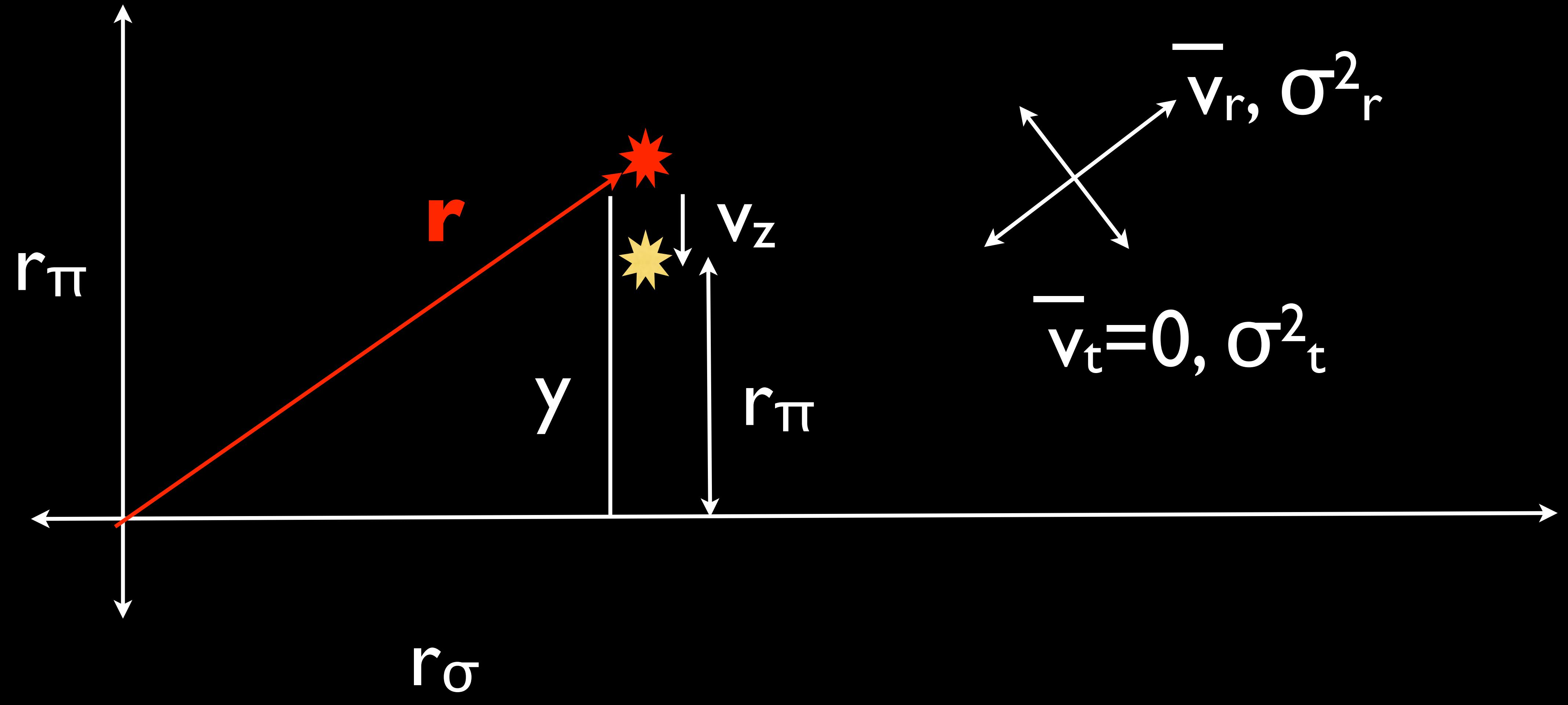
$L_2(\mu) = 1.5\mu^2 - 0.5$

$L_4(\mu) = 4.375\mu^4 - 3.75\mu^2 + 0.375$



Configuration space 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

- $\delta(\mathbf{x}), \mathbf{v}(\mathbf{x'})$ correlated Gaussian fields

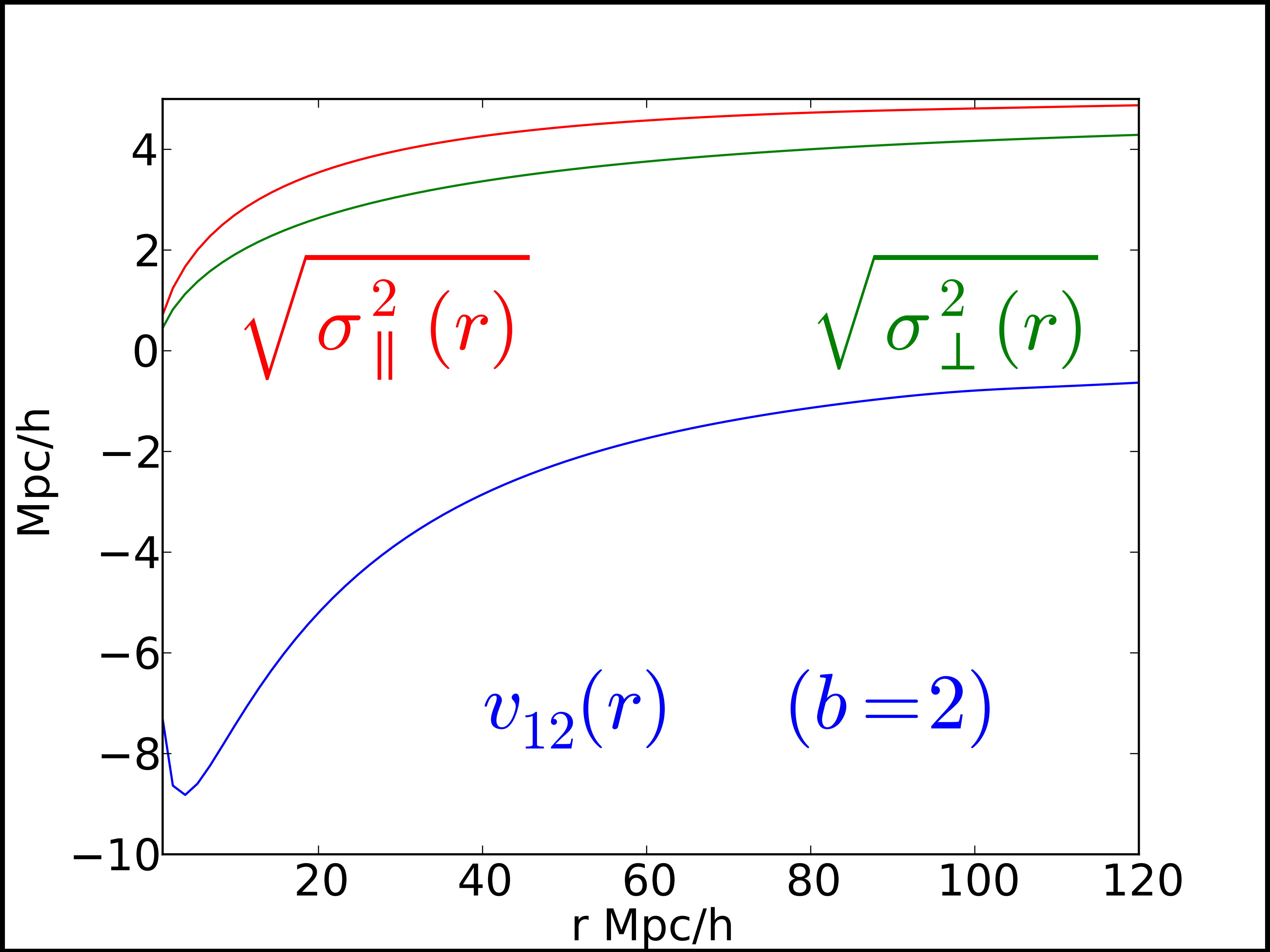
$$1 + \xi_g^s(r_\sigma, r_\pi) = \int \frac{dy}{\sqrt{2\pi\sigma_{12}^2(y)}} \exp\left[-\frac{(r_\pi - y)^2}{2\sigma_{12}^2(y)}\right] \left[1 + \xi_g^r(r) + \frac{y}{r}\frac{(r_\pi - y)v_{12}(r)}{\sigma_{12}^2(y)} - \frac{1}{4}\frac{y^2}{r^2}\frac{v_{12}^2(r)}{\sigma_{12}^2(y)}\left(1 - \frac{(r_\pi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

- Expand around $y = r_\pi$

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

- Equivalent to Kaiser formula

Pairwise velocity statistics in linear theory



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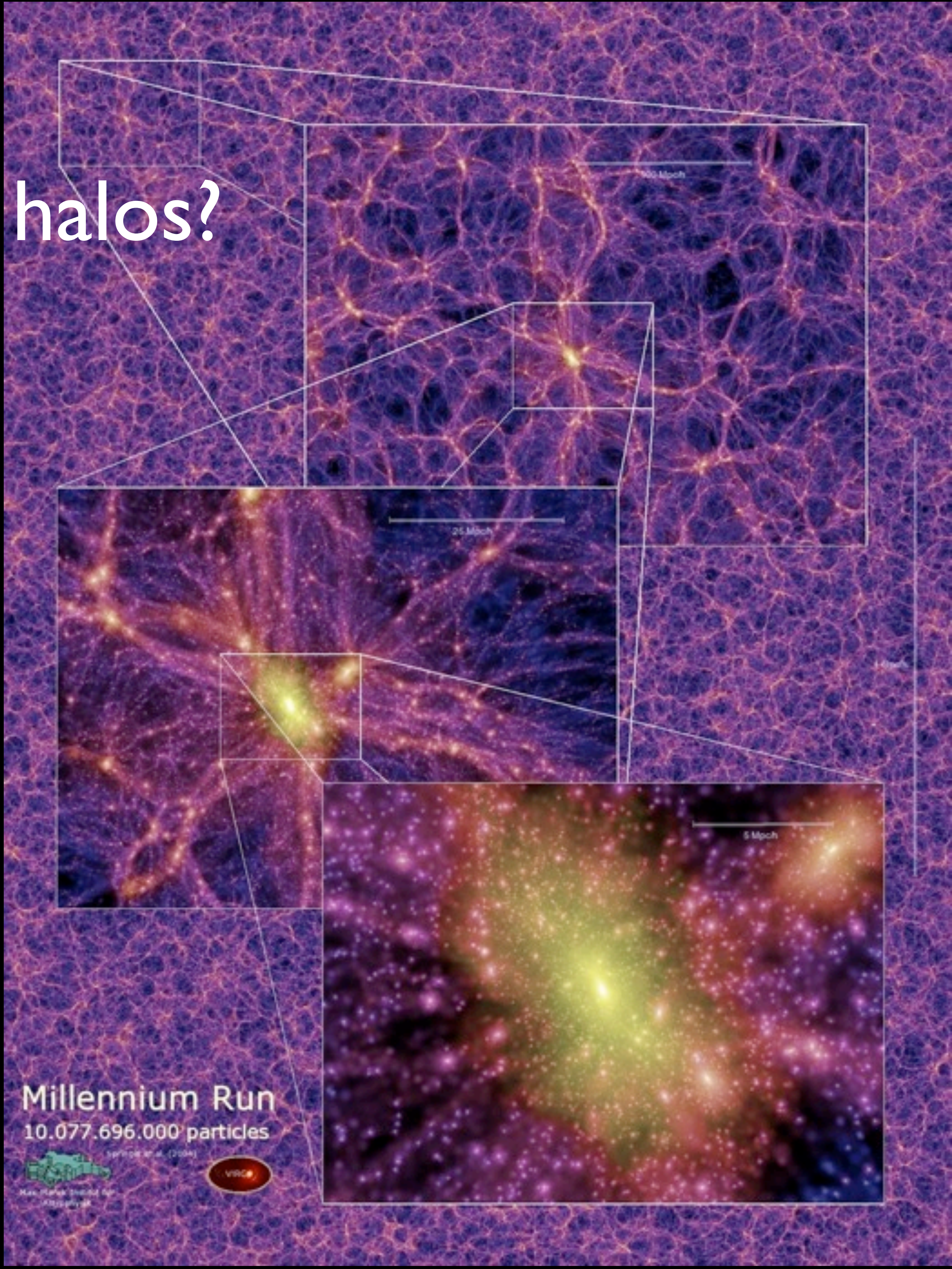
Why halos?

- 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



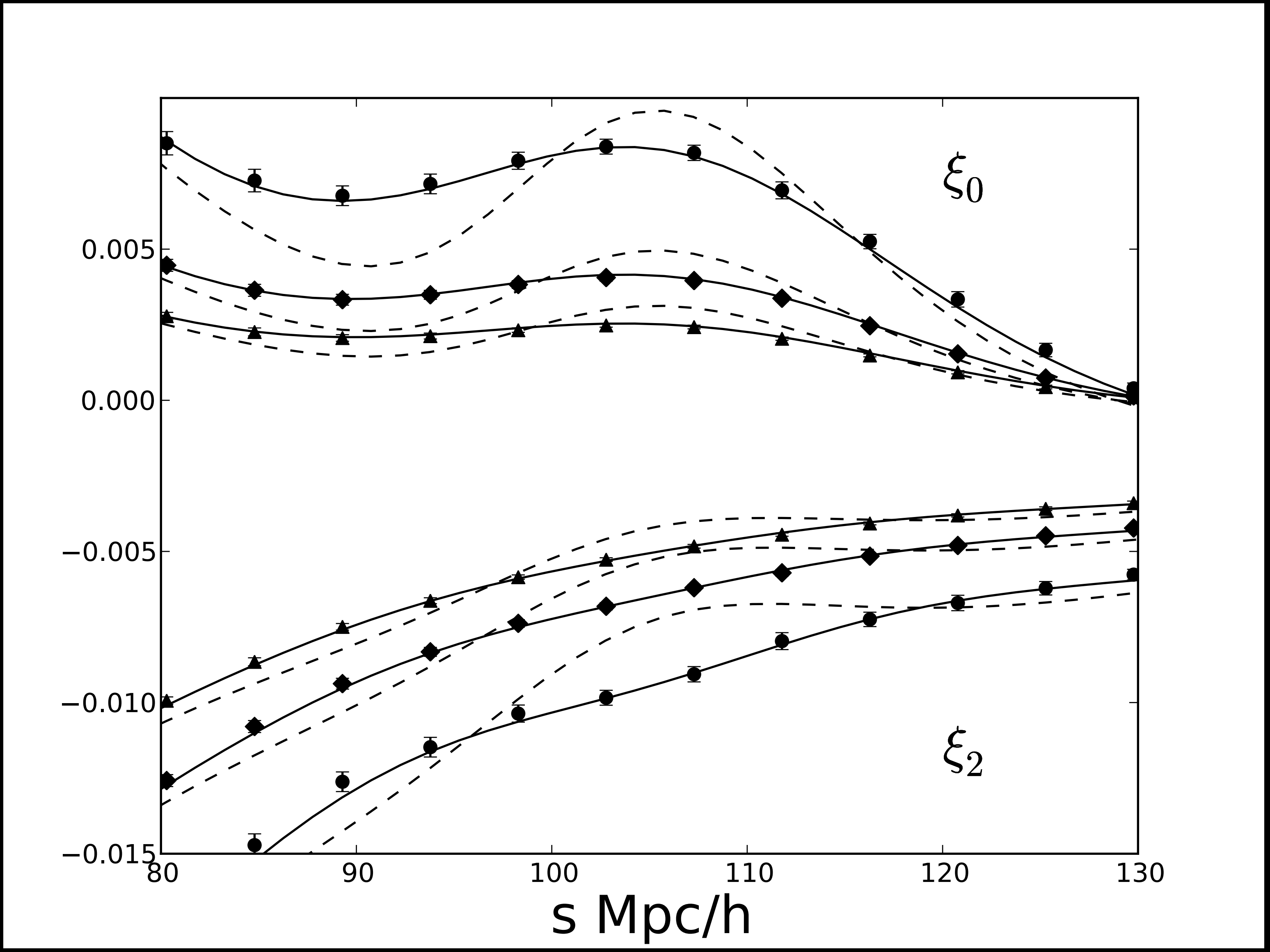
N-body Simulations

- White et al. 2011; arXiv:1010.4915
- 67.5 (Gpc/h)^3 total volume
  (for BOSS galaxies V ~ 5 (Gpc/h)^3)

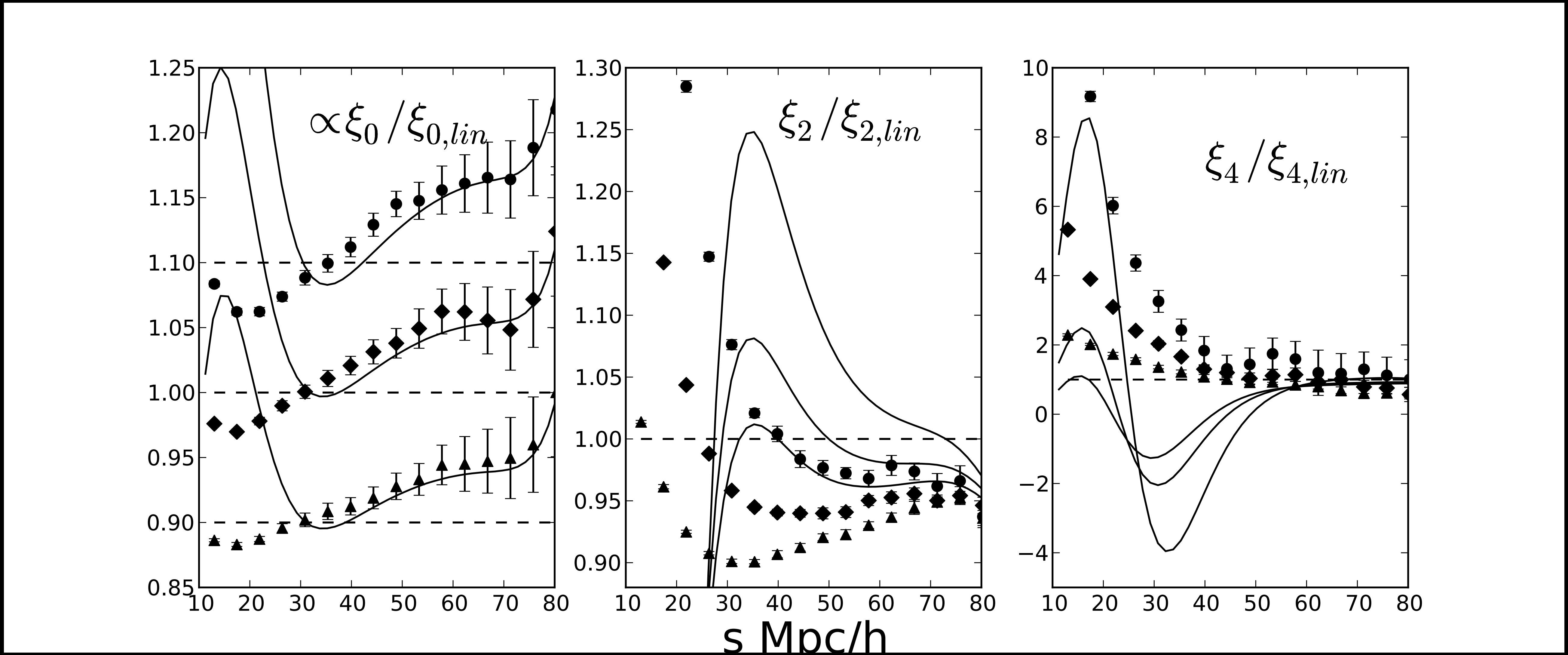
sample	$log(M)$ range	$\bar{b}_{lin}$	$\bar{b}_{LPT}$	$\bar{n}$ $(h^{-1}\mathrm{Mpc})^{-3}$
high	>13.387	2.67	2.79	7.55×10^{-5}
low	12.484 - 12.784	1.41	1.43	4.04×10^{-4}
HOD	-	1.84	1.90	3.25×10^{-4}

N-body simulations vs Linear and Lagrangian Perturbation Theories

- LPT works on BAO scales
- See Matsubara PRD 78, 083519



N-body simulations vs Linear and Lagrangian Perturbation Theories



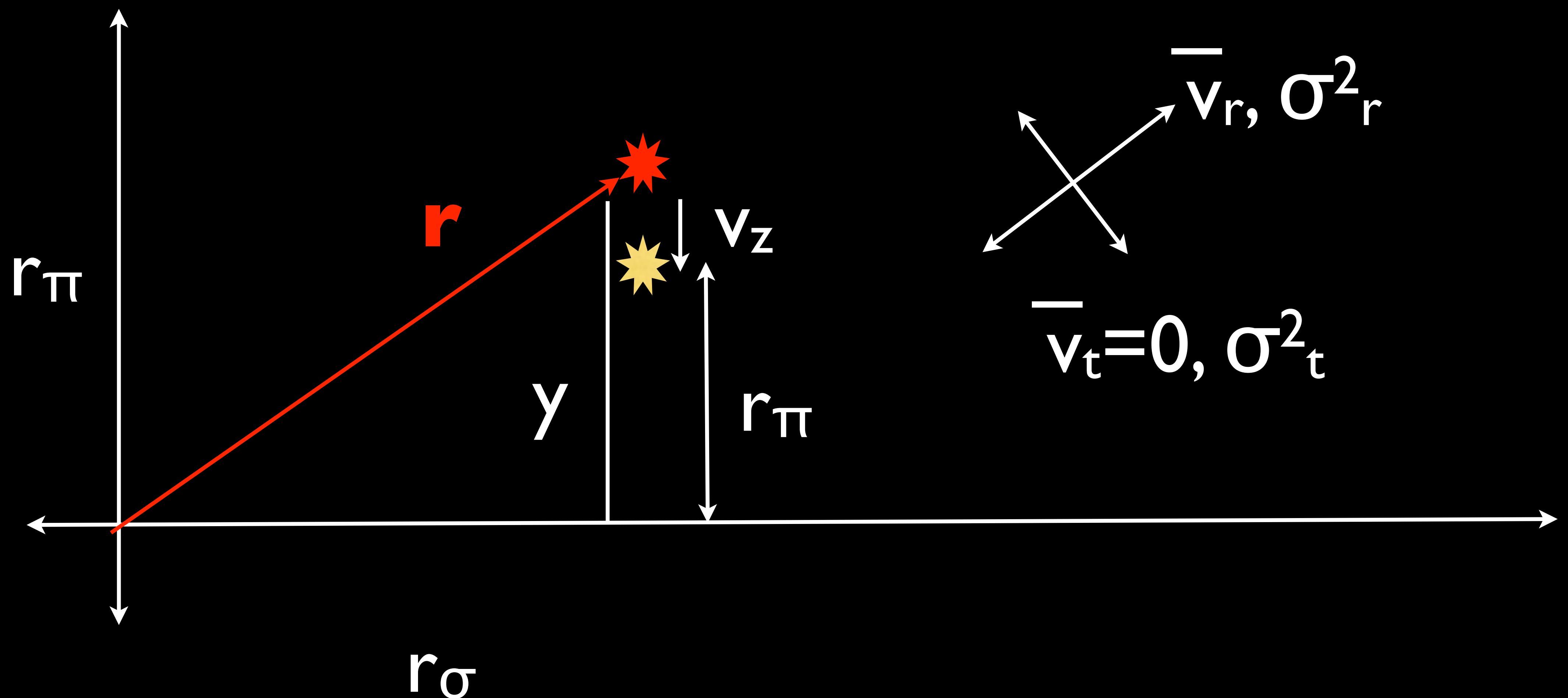
- ξ_2 suppressed by 2.5-7.5% at 50 h^{-1} Mpc, depends strongly on bias

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)

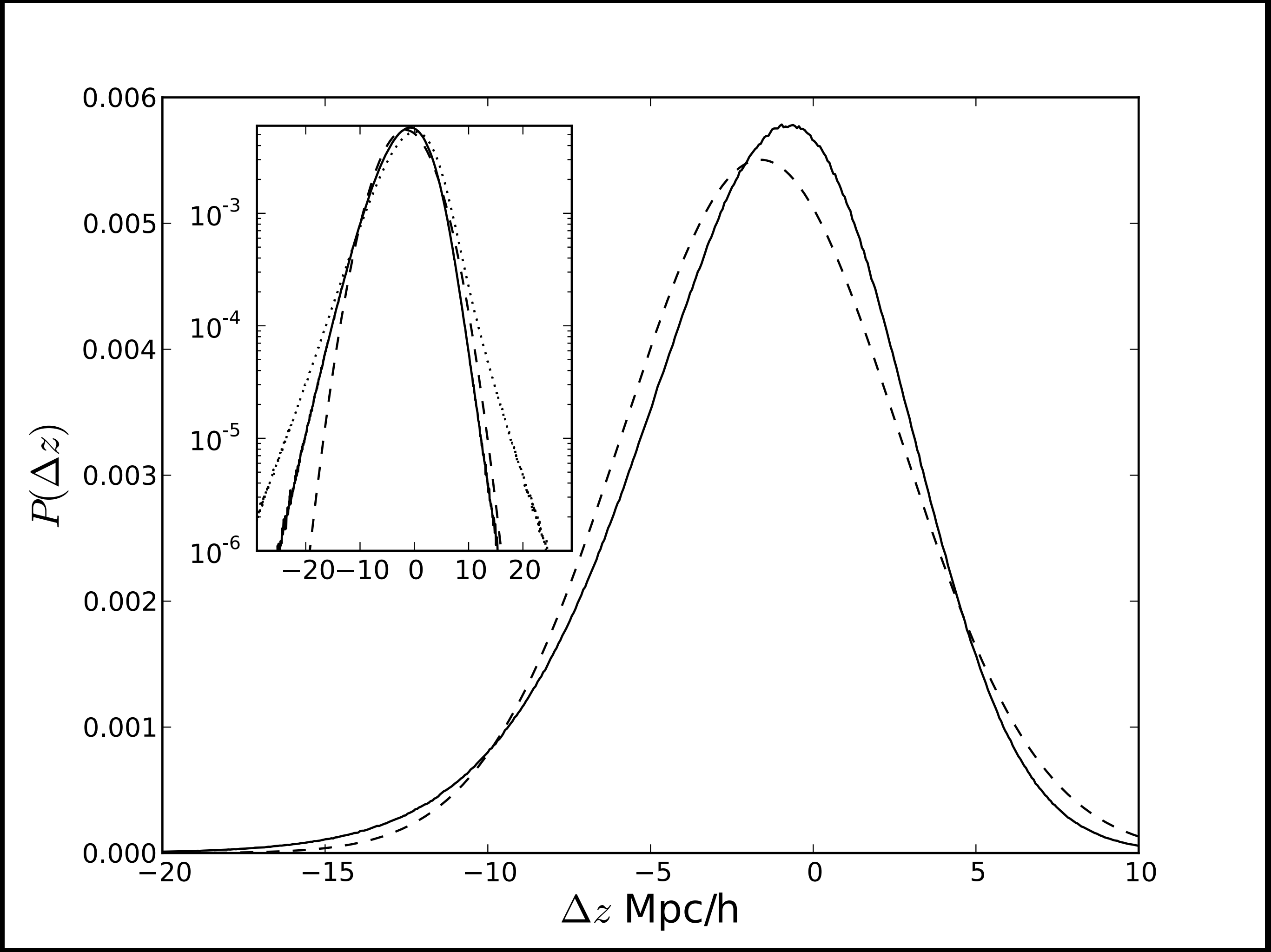
The scale-dependent Gaussian streaming model ansatz

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

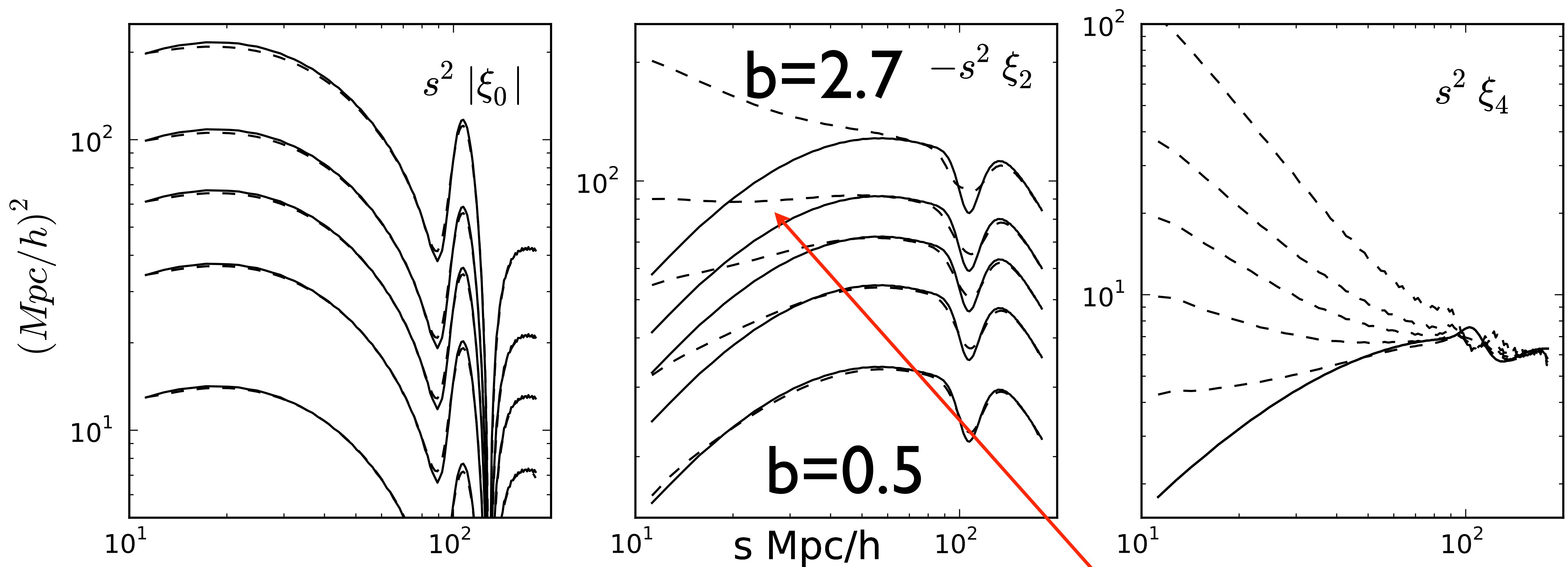


The scale-dependent Gaussian streaming model ansatz

- 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

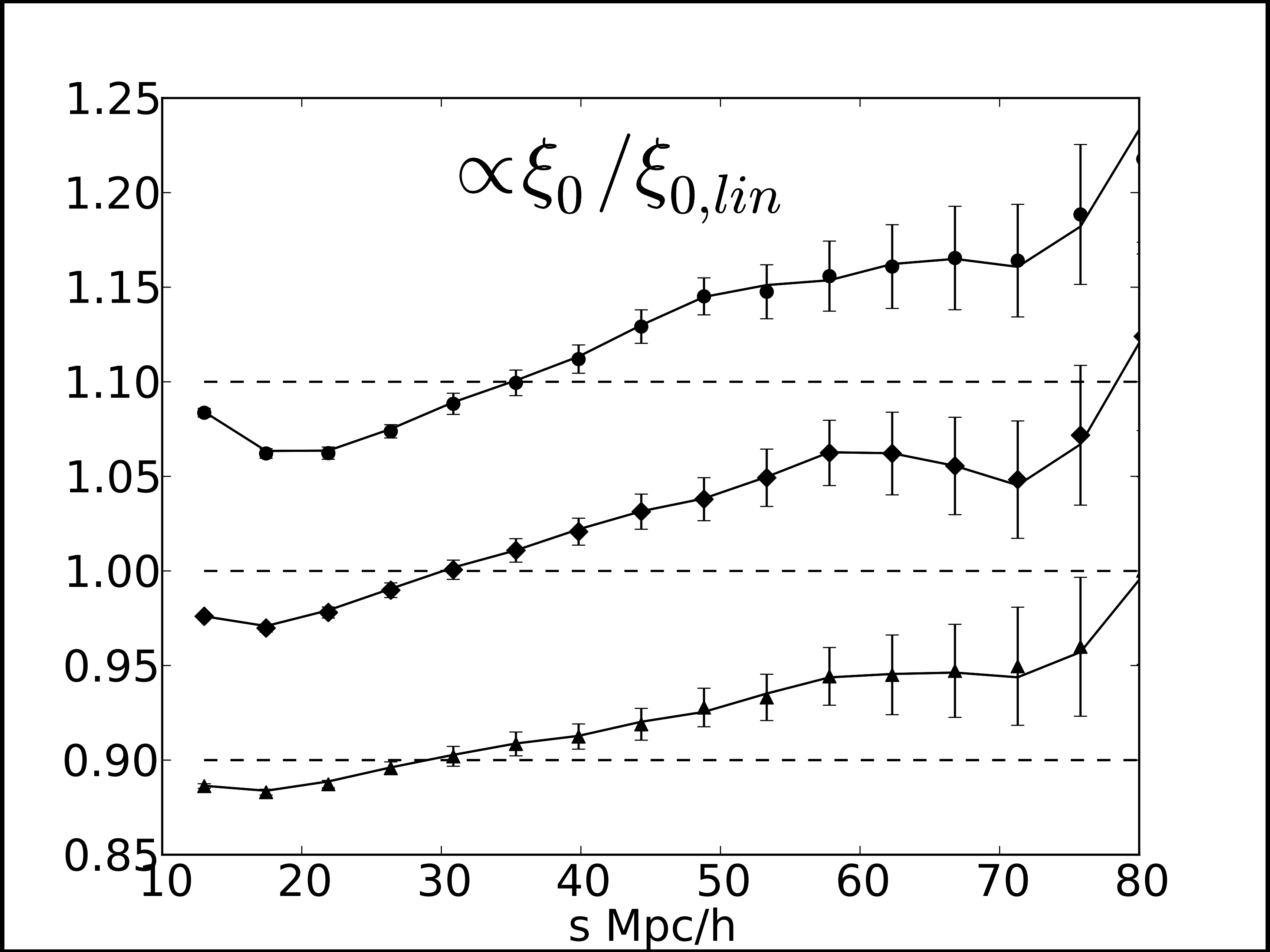
Gaussian streaming model

b^3 correction !!

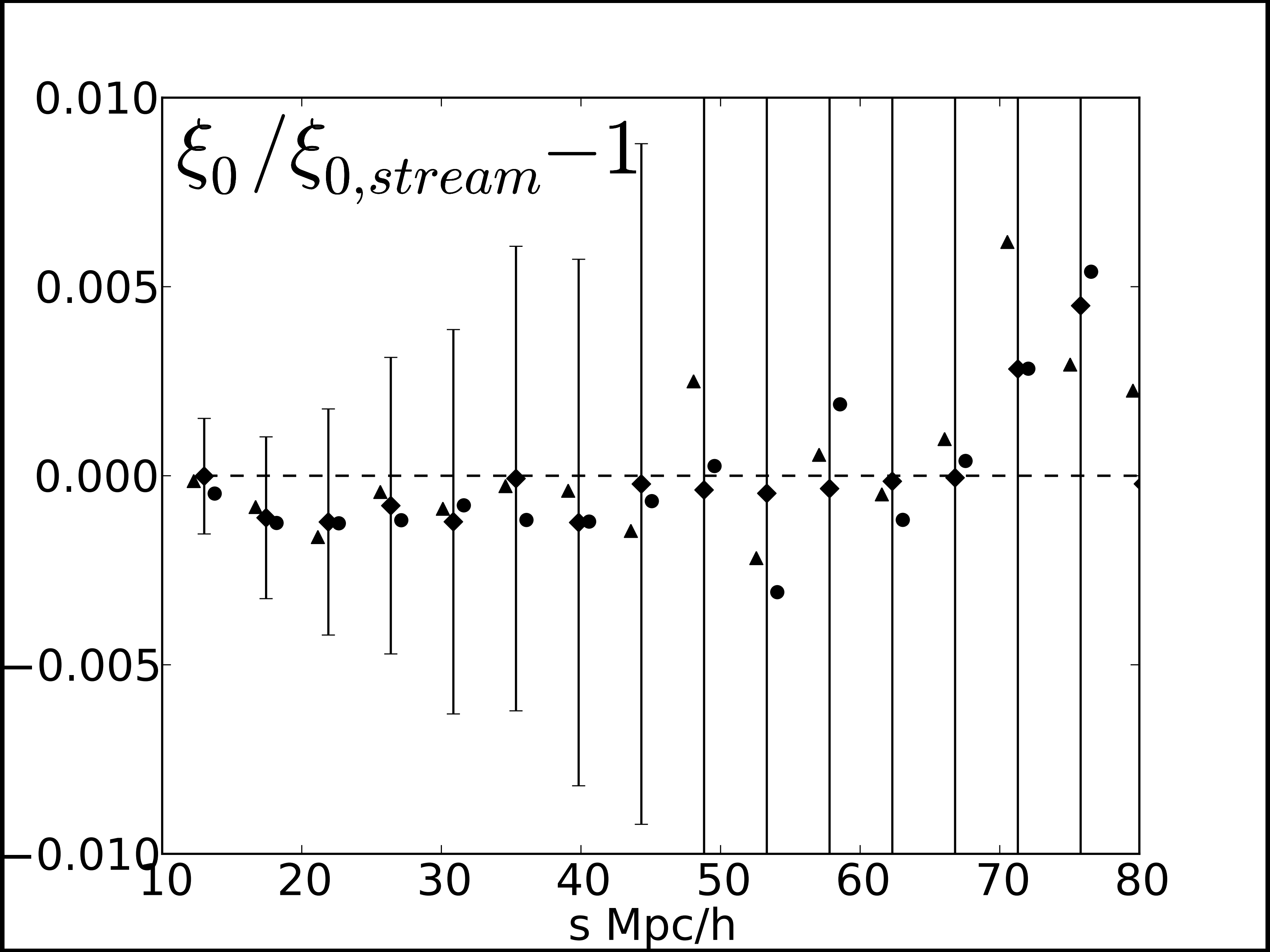
The scale-dependent Gaussian streaming model ansatz vs N-body simulations

- 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

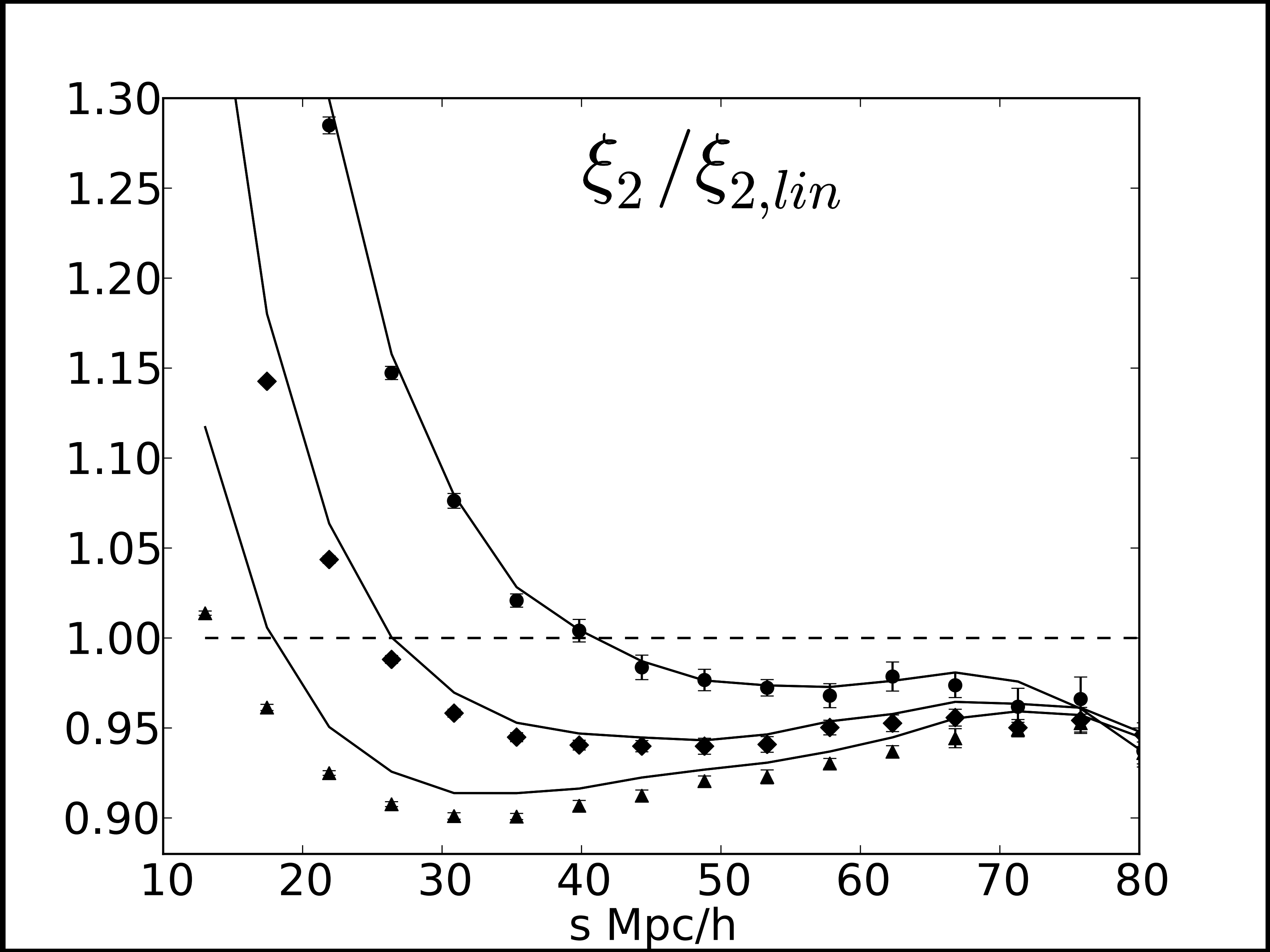
The scale-dependent Gaussian streaming model ansatz vs N-body simulations: ξ_0



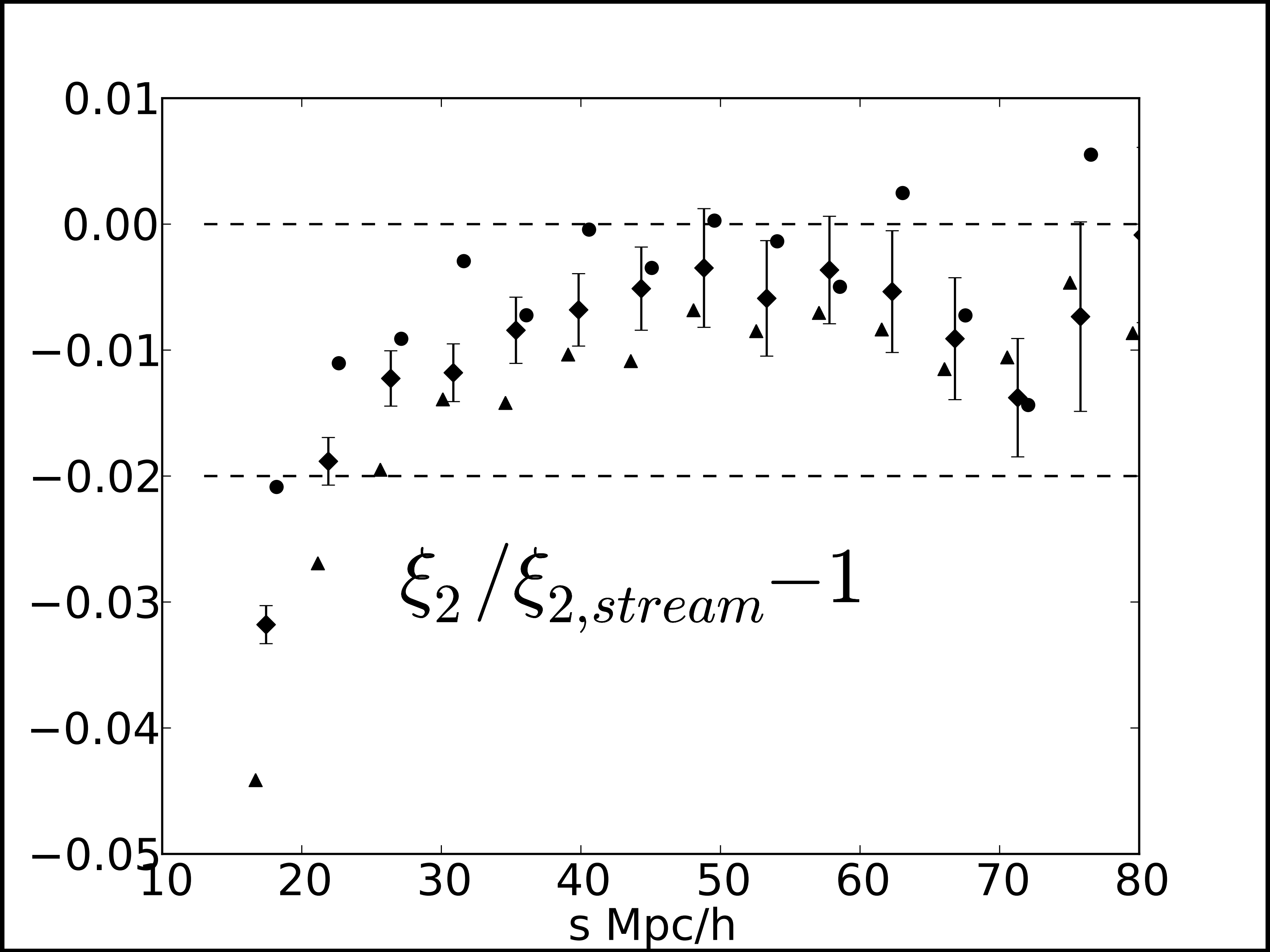
The scale-dependent Gaussian streaming model ansatz vs N-body simulations: ξ_0



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

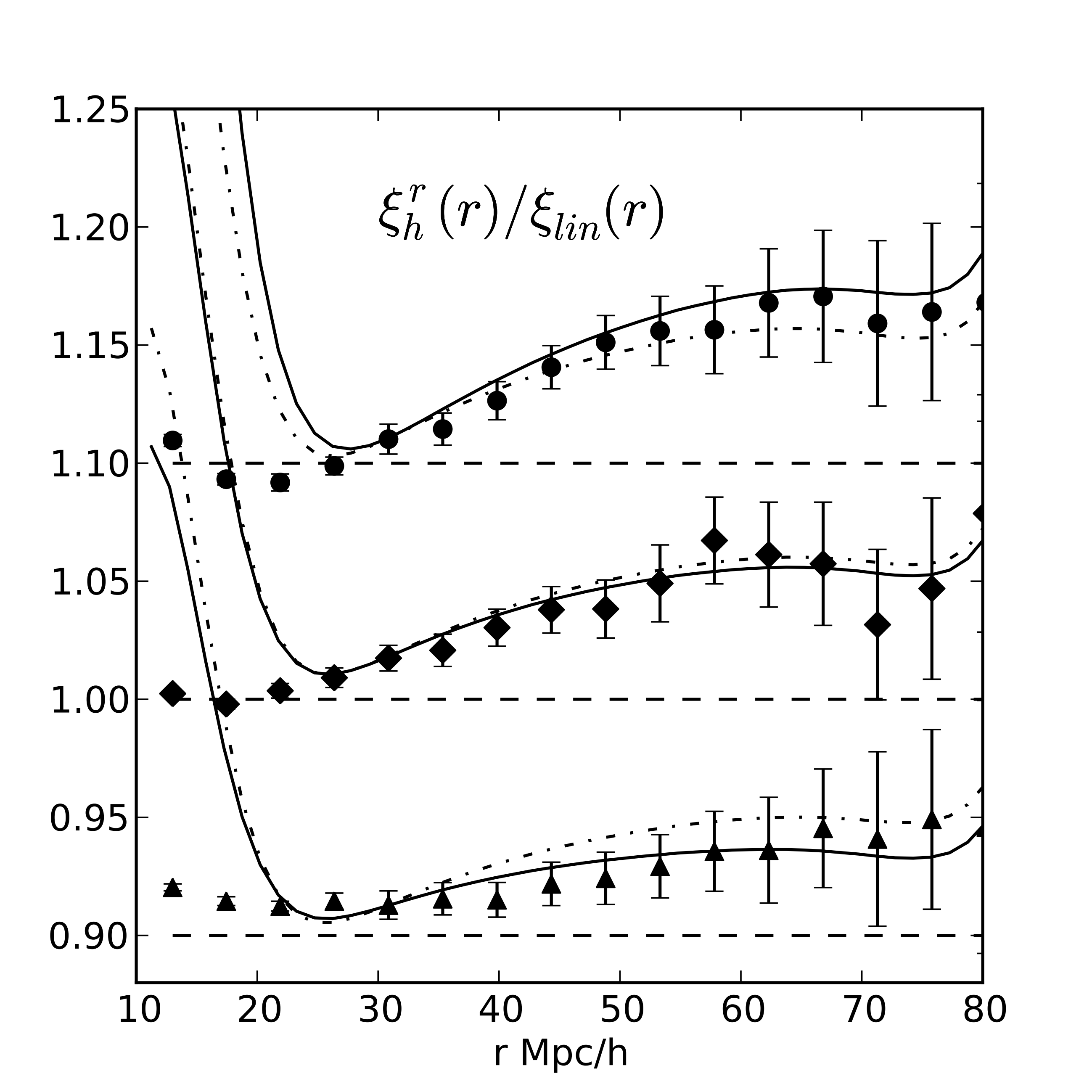


The scale-dependent Gaussian streaming model ansatz vs N-body simulations: ξ_2

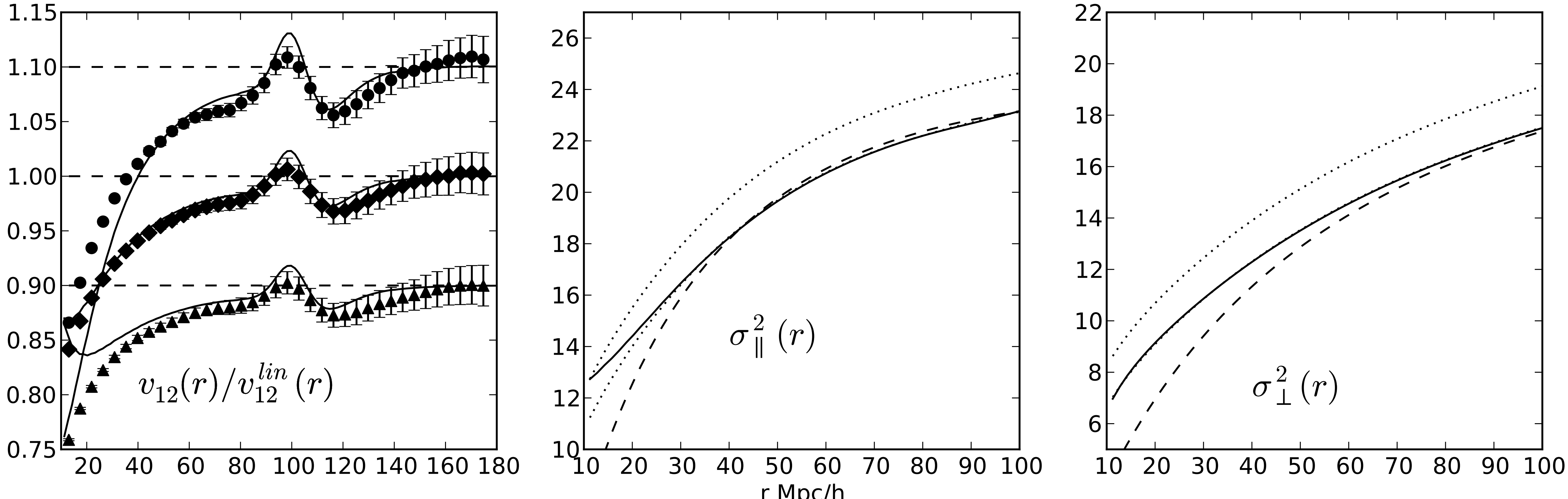


Can we predict real space halo clustering/ velocities using perturbation theory?

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



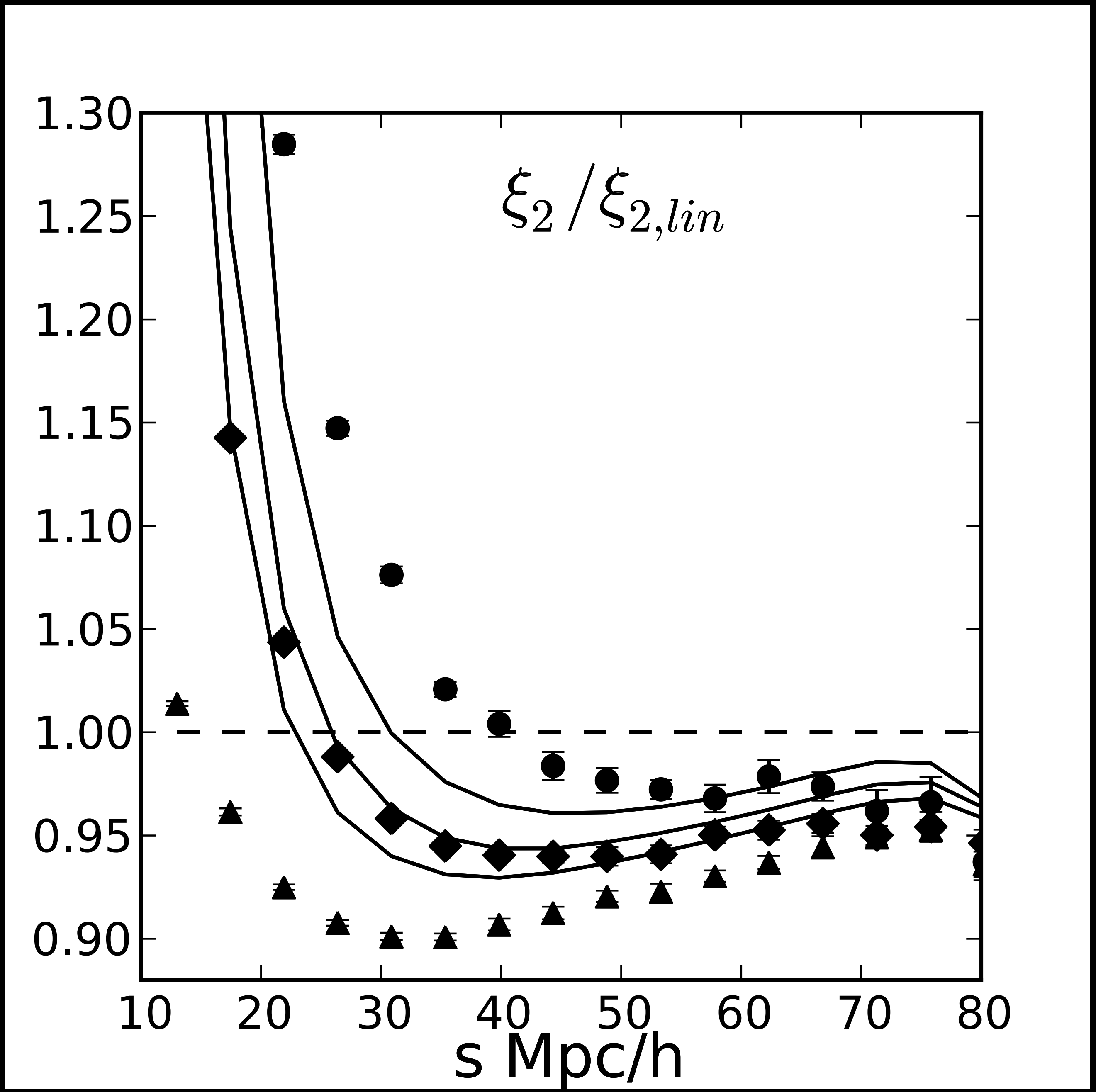
Velocity statistics in standard perturbation theory: new results



* assumes linear bias

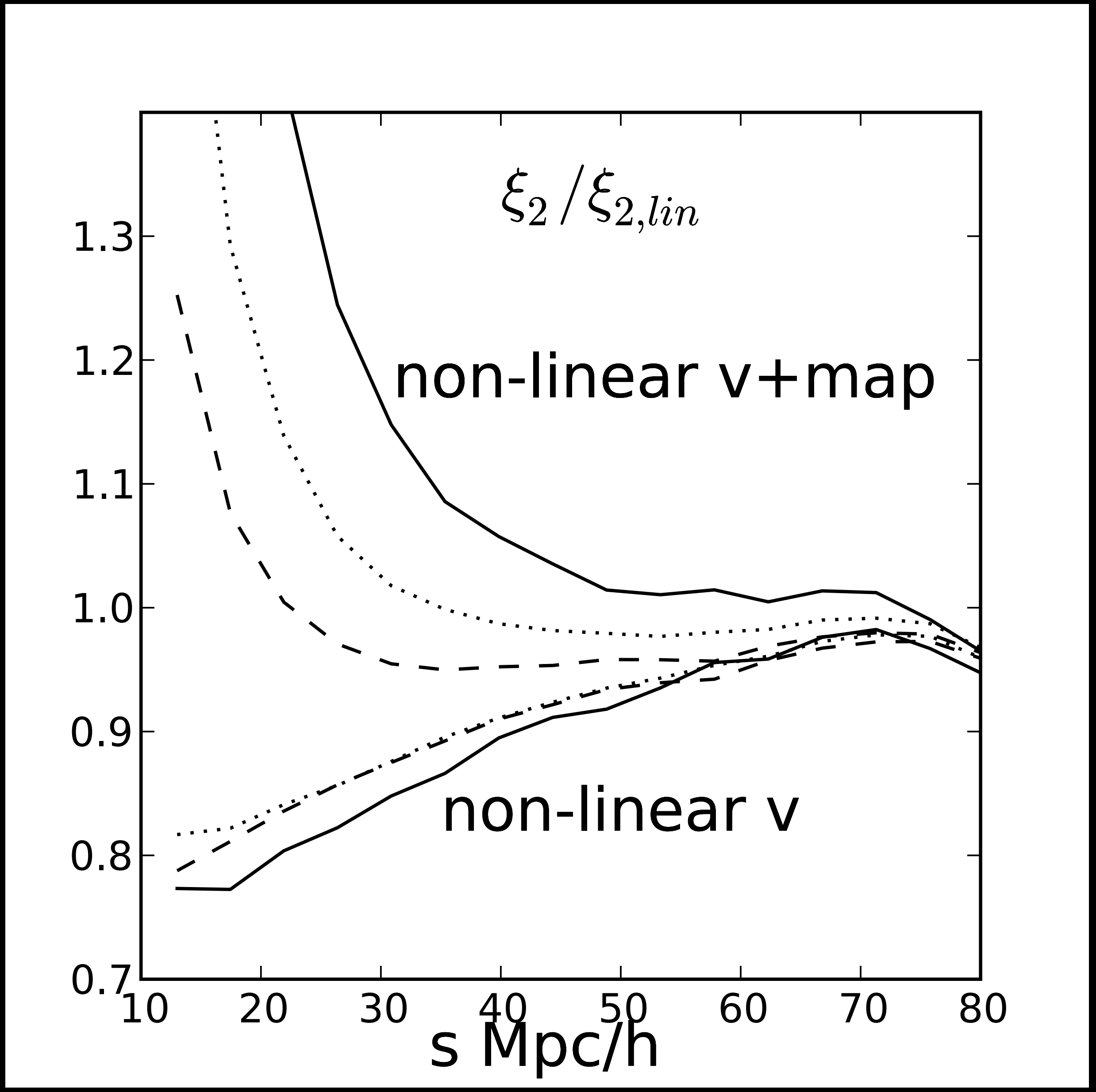
Putting it all together: fully analytic model

- Error dominated by error in $v_{12}(r)$ slope



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



What now?

- We are using this model to constrain $f\sigma_8$ using BOSS galaxies
- We have demonstrated that LPT describes the 2d clustering of halos on BAO scales ~ perfectly
- The Gaussian streaming model ansatz is more than sufficient to account for RSD effects on $\xi_0(r)$ -- use it to constrain for favorite cosmological model extensions (m_ν, N_{eff}, etc)