Large Scale Structure: Statistics, Baryon Acoustic Oscillations, Redshift Space Distortions, ...

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These notes are online:

https://github.com/bareid/Trieste/blob/master/berkeleycosmo1.pdf

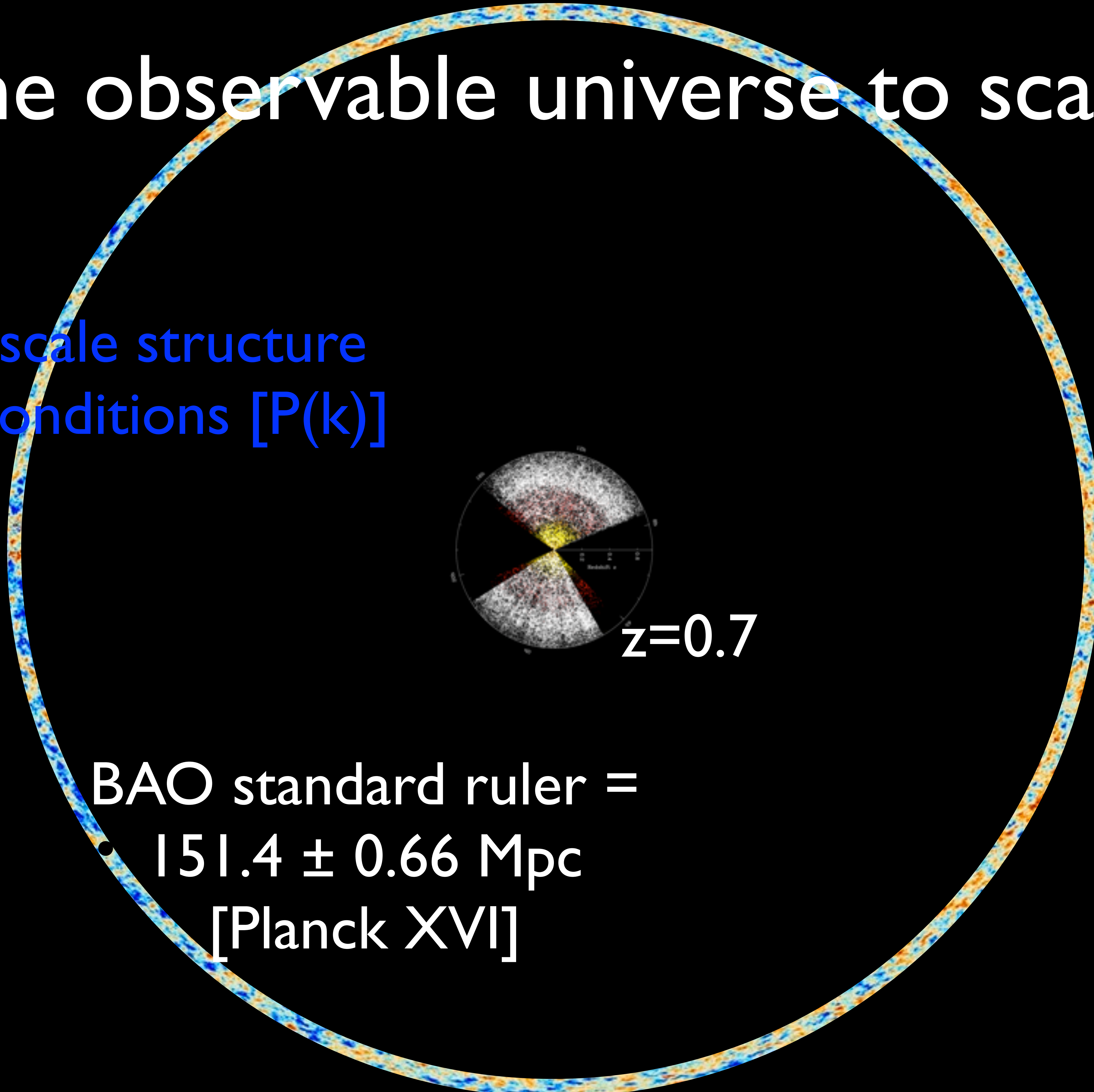
https://github.com/bareid/Trieste/blob/master/BerkeleyCosmologyLecture1.ipynb

paste address into http://nbviewer.ipython.org/ to view notebook online

Outline

- Galaxy Redshift Survey overview/history
- Statistics concepts: Gaussian random fields, Poisson process, Fisher matrices, quantifying uncertainties, choosing a data vector, model fitting
- LSS theory
- Geometric distortions in LSS
- BAO measurements

The observable universe to scale*



Large scale structure
initial conditions [P(k)]

z=0.7

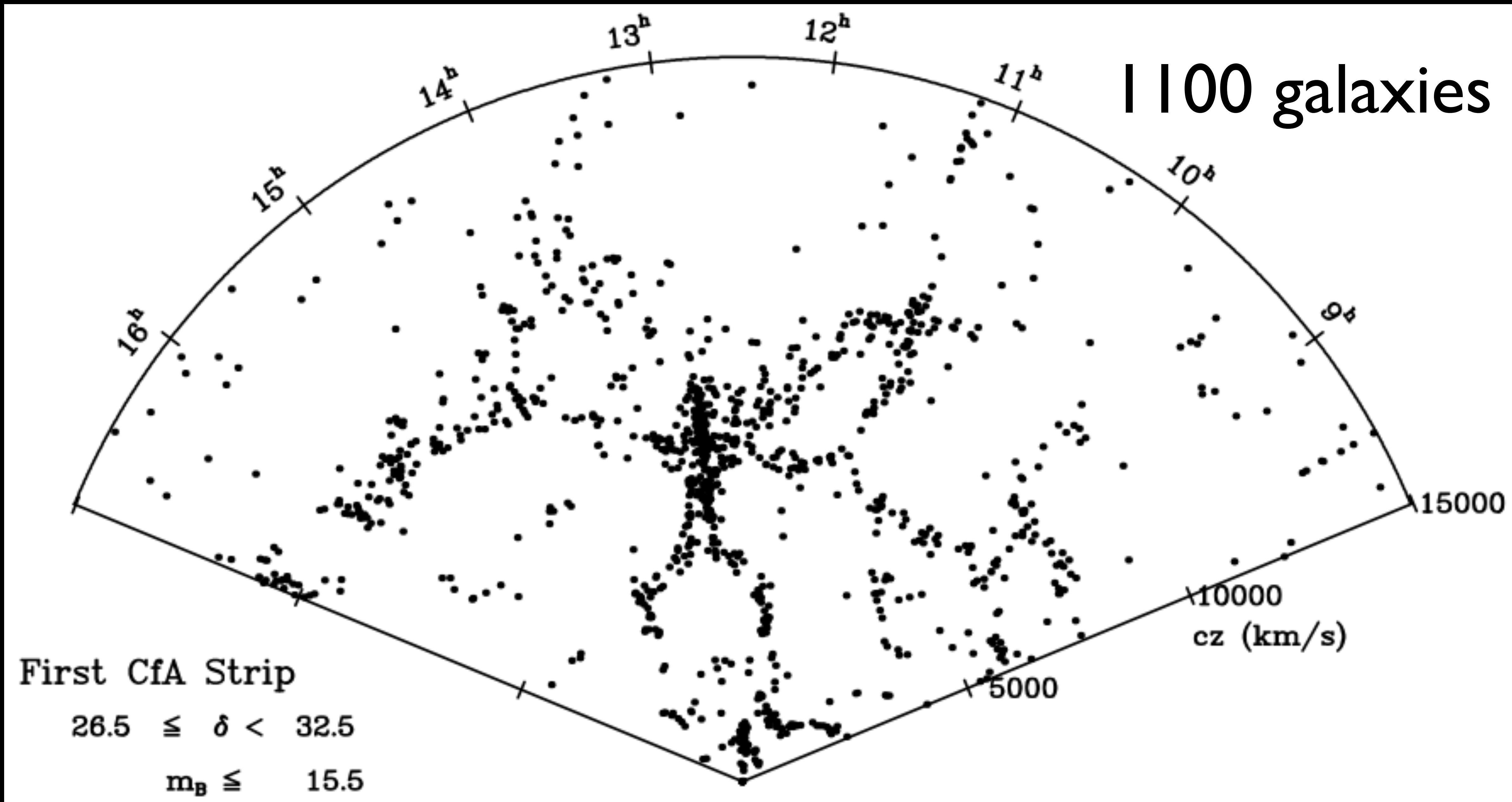
z=1091

BAO standard ruler =
151.4 ± 0.66 Mpc
[Planck XVI]

Galaxy Redshift Surveys in 4 easy steps

- Assemble a homogeneous list of targets [magnitude and/or color-cuts]
- Measure redshifts
- Make a three-dimensional galaxy density map
- Measure $\xi(r_\perp, r_\parallel)$ or $P(k_\perp, k_\parallel)$

CfA2 redshift survey



1100 galaxies

De Lapparent, Geller, Huchra, 1986, ApJL 302, L1

CfA2 redshift survey

"The best available model for generating the bubble-like structures observed in the survey is the explosive galaxy formation theory of Ostriker and Cowie, in which galaxies form on the surfaces of expanding shock waves. Most of the current models ideally assume that the structures form directly from the action of gravity on the matter perturbations, but the sharpness of the transition between the high-density regions and the voids in the survey indicates that hydrodynamic processes must be important in the formation of galaxies."

De Lapparent, Geller, Huchra, 1986, ApJL 302, L1

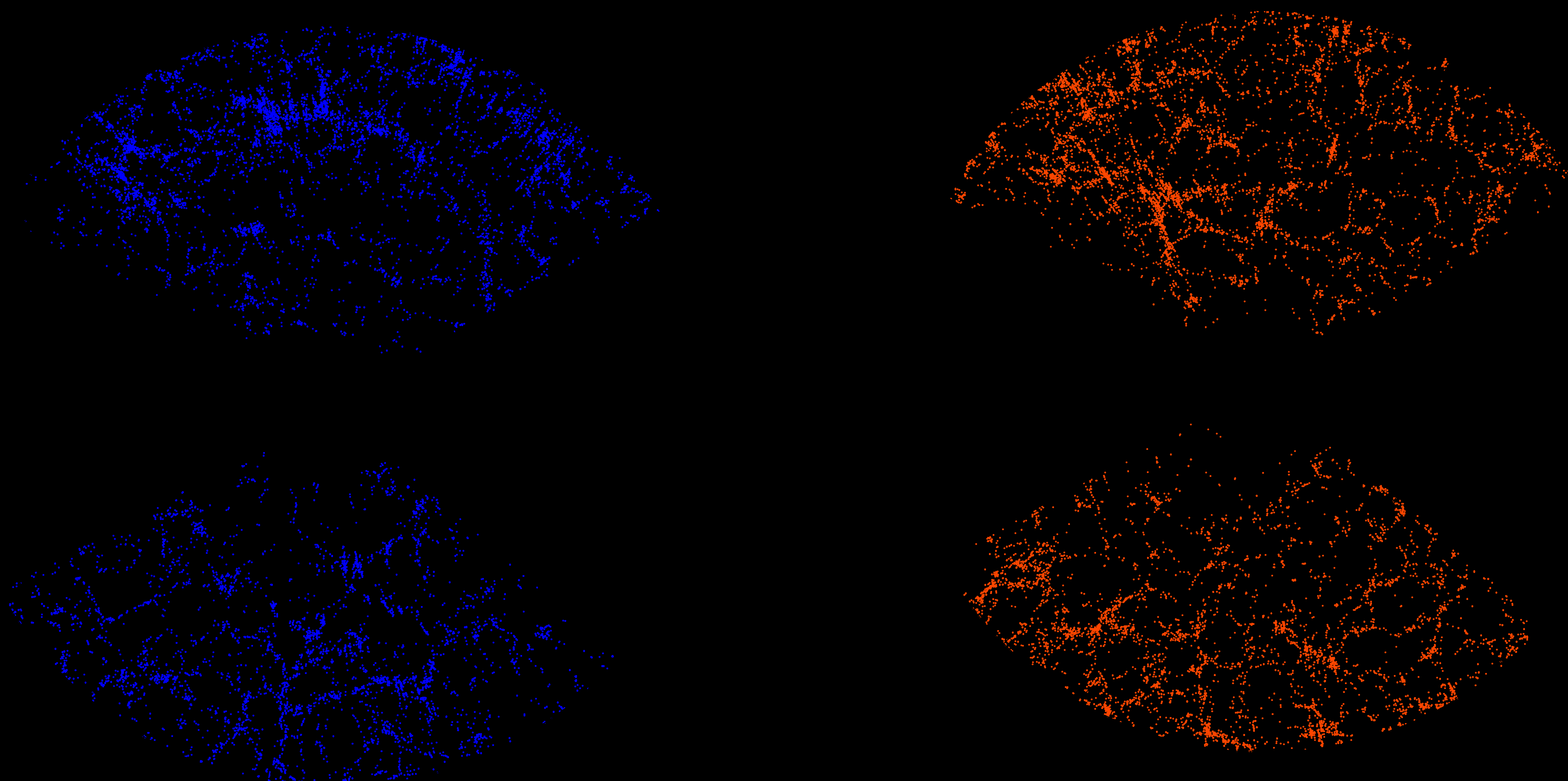
CfA2 redshift survey

"...Most of the current models ideally assume that the structures form directly from the action of gravity on the matter perturbations, but ..."

No but (yet!)

De Lapparent, Geller, Huchra, 1986, ApJL 302, L1

SDSS Main Galaxy Sample -- which is the real universe?



Credit: Andreas Berlind and Cameron McBride

SDSS Fly-through

(bonus points: what's wrong with this video??)

credit:

Miguel A Aragon (JHU), Mark Subbarao (Adler Planetarium), Alex Szalay (JHU)

2014 Shaw Prize awarded to Daniel Eisenstein for BAO

www.shawprize.org/en/shaw.php?tmp=5&twoid=79&threeid=231&fourid=411

THE SHAW PRIZE 邵逸夫獎

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Press Release

Announcement of The Shaw Laureates 2014

Tuesday, 27 May 2014. At today's press conference in Hong Kong, The Shaw Prize Foundation announced the Shaw Laureates for 2014. Information was posted on the website www.shawprize.org at Hong Kong time 15:30 (GMT 07:30).

The Shaw Prize consists of three annual prizes: Astronomy, Life Science and Medicine, and Mathematical Sciences, each bearing a monetary award of one million US dollars. This will be the Eleventh year that the Prize has been awarded and the presentation ceremony is scheduled for Wednesday, 24 September 2014.

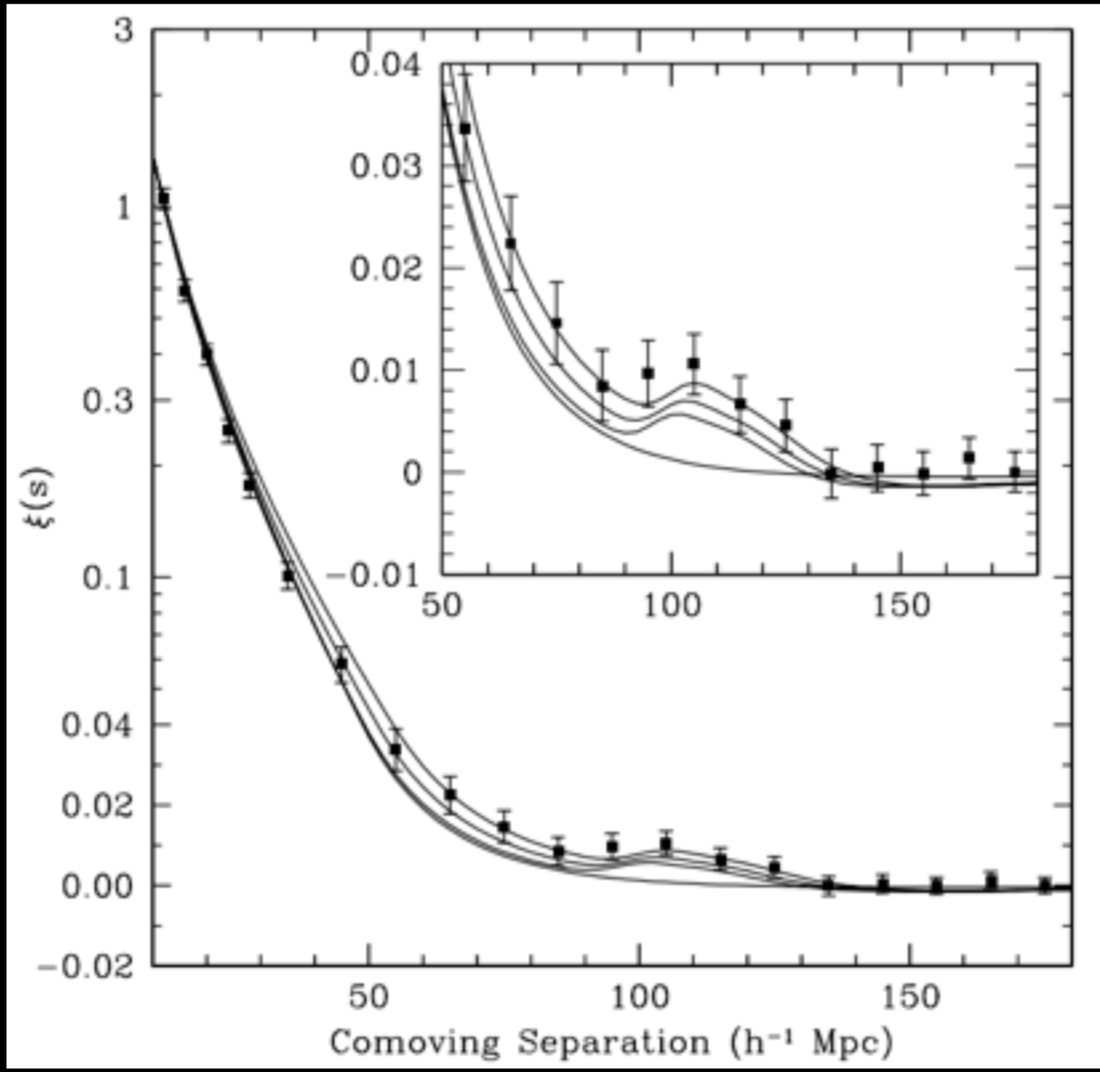
The Shaw Laureates

The Shaw Prize in Astronomy is awarded in one-half to
Daniel Eisenstein
Professor of Astronomy, Harvard University, USA
and the other half in equal shares to
Shaun Cole
Professor of Physics, Durham University, UK and
John A Peacock
Professor of Cosmology in the Institute for Astronomy, University of Edinburgh, UK

for their contributions to the measurements of features in the large-scale structure of galaxies used to constrain the cosmological model including baryon acoustic oscillations and redshift-space distortions.

2014 Shaw Prize awarded to Daniel Eisenstein for BAO

Get rich (500k!) on LSS



Eisenstein et al., 2005, ApJ, 633, 560

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- Galaxy Redshift Survey overview/history
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- LSS theory
- Geometric distortions in LSS
- BAO measurements

IPython Notebook Summary

- Galaxy redshift surveys are three-dimensional maps of the distribution of galaxies
- The simplest model for the observed galaxy density field is $\delta_g = b_g \delta_m + \varepsilon$
- δ_m is a Gaussian random field which the galaxy distribution samples as a Poisson process, so $\langle \varepsilon(k) \varepsilon(-k) \rangle = \bar{n}^{-1}$
- All cosmology information contained in $\langle \delta_m(k) \delta_m(-k) \rangle = P(k)$; now we will begin extracting it!

LSS measurement uncertainties

- For most practical purposes, there are no real *measurement* uncertainties in LSS; that is, the error in the angular position of the galaxy (ra,dec) or redshift is much smaller than the scales on which you are interested in measuring correlations

LSS measurement uncertainties

- Using the simple model from Lecture 1 (δ_m is Gaussian, Poisson sampled by discrete tracers)

$$\boxed{\delta_t(\mathbf{k}) = b_t \delta_m(\mathbf{k}) + \epsilon}$$

- the error on a bandpower measurement $P(k_i)$ has "cosmic variance" and "sampling variance" terms:

$$\sigma_{P(ki)}/P(k_i) \propto N_k \frac{b^2_t\, P(k_i) + n_t^{-1}}{b^2_t\, P(k_i)}$$

LSS measurement uncertainties

- But to estimate LSS uncertainties on $P(k_i)$ or $\xi(s_i)$ precisely, we need to go beyond this simple model and account for several important effects

LSS measurement uncertainties

- Survey Geometry -- the finite volume and complicated geometry of real surveys induce correlations between neighboring modes and change the effective number of independent modes contributing to bandpower $P(k_i)$

LSS measurement uncertainties

- Non-Gaussianity -- we know that non-linear gravitational evolution drives δ_m away from Gaussianity
- A simple example: $\delta_m >= -1$ always (matter density can't be negative), but dark matter halos reach $\delta_m >= 200$. This is proof that the one-point distribution of δ_m develops skewness under gravitational evolution.

LSS measurement uncertainties

- Solution -- brute force!
- Generate hundreds or thousands of synthetic surveys (as realistic as possible), and measure the covariance matrix of your observable from this set.

LSS measurement uncertainties

- Approximations to real (expensive to compute) gravitational dynamics + galaxy prescription include Poisson sampling of lognormal matter density fields [easiest to generate], “PTHalos”, “Addgals”, “COLA”, “QPM”, “PATCHY”, real N-body sims + halo model [currently infeasible], hydrodynamic simulations including galaxy formation [REALLY infeasible]
- Then apply survey selection function to include effects of geometry, sampling variance (shot noise), veto masks, etc.

What to measure? Your choice of data vector matters.

- Several recent papers [e.g. Percival et al., 1302.4841] pointed out that errors in the data covariance matrix estimate propagate into errors on cosmological parameters; this can be mitigated by information compression [i.e., choosing a shorter data vector]
- Percival et al. derives an optimal bin size for $P(k_i)$ or $\xi(s_i)$ for BAO and RSD measurements.

What to measure? Your choice of data vector matters.

- From a theoretical point of view, your data vector should be restricted to scales where you have good reason to believe your model is sufficiently accurate
- Parameter constraints can be quite sensitive to this choice, since the number of available modes is $N_k \propto k^2 \Delta k$!

Summary so far.

- WHAT to measure [$\xi(s_i)$ or $P(k_i)$ in carefully chosen bins]
- HOW to measure it [Landy-Szalay or FKP/Yamamoto]
- HOW to get cosmological parameter constraints [assume Gaussian likelihoods, estimate data covariances from mock surveys]

$$\chi^2_\xi = \sum_{i=1}^n (\xi(s_i) - \xi_{\mathrm{model}}(s_i, \mathbf{p_i}))C^{-1}_{\xi,ij}(\xi(s_j) - \xi_{\mathrm{model}}(s_j, \mathbf{p_j}))$$

$$\chi^2_P = \sum_{i=1}^n (P(k_i) - P_{\mathrm{model}}(k_i, \mathbf{p_i}))C^{-1}_{P,ij}(P(k_j) - P_{\mathrm{model}}(s_j, \mathbf{p_j}))$$

Summary so far.

- Now we'll switch gears and discuss how cosmological parameters enter the models for our LSS observables

$$\chi^2_\xi = \sum_{i=1}^{n} (\xi(s_i) - \xi_{\rm model}(s_i, \mathbf{p_i}))C^{-1}_{\xi,ij}(\xi(s_j) - \xi_{\rm model}(s_j, \mathbf{p_j}))$$

$$\chi^2_P = \sum_{i=1}^{n} (P(k_i) - P_{\rm model}(k_i, \mathbf{p_i}))C^{-1}_{P,ij}(P(k_j) - P_{\rm model}(s_j, \mathbf{p_j}))$$

LSS theory

$$P(k,z) = D^2(z)\, T^2(k)\, P_i(k)$$

Inflation physics

CMB-epoch physics: radiation domination and baryon acoustic oscillations

Matter/Dark energy dominated era growth function

LSS theory

$P(k,z) = D^2(z)\, T^2(k)\, P_i(k)$

Matter/Dark energy dominated era growth function obeys

$$\frac{d^2 G}{d \ln a^2} + \left(2 + \frac{d \ln H}{d \ln a}\right) \frac{dG}{d \ln a} = \frac{3}{2} \Omega_{\mathrm{m}}(a) G$$

[I use D and G interchangeably]

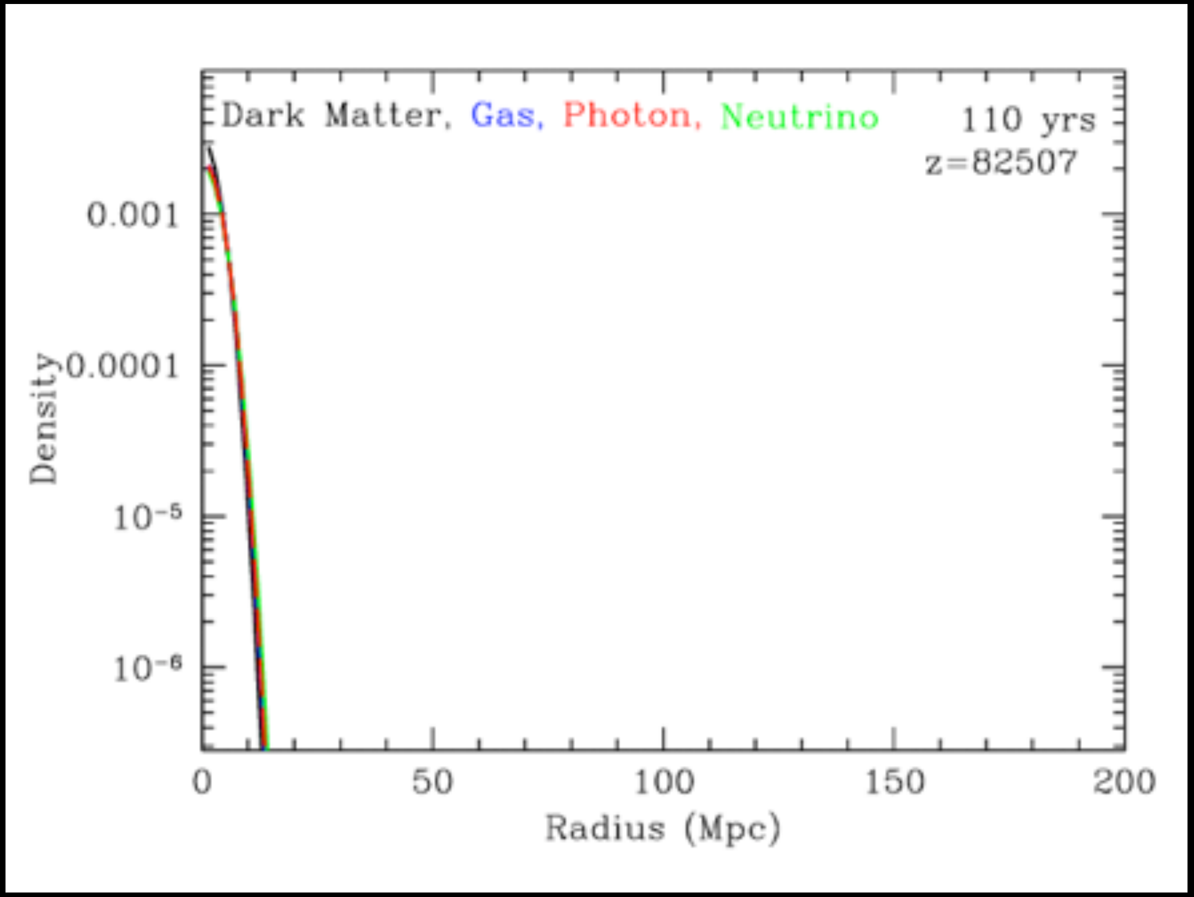
$\delta(z) = D(z)\, \delta(z_i)$

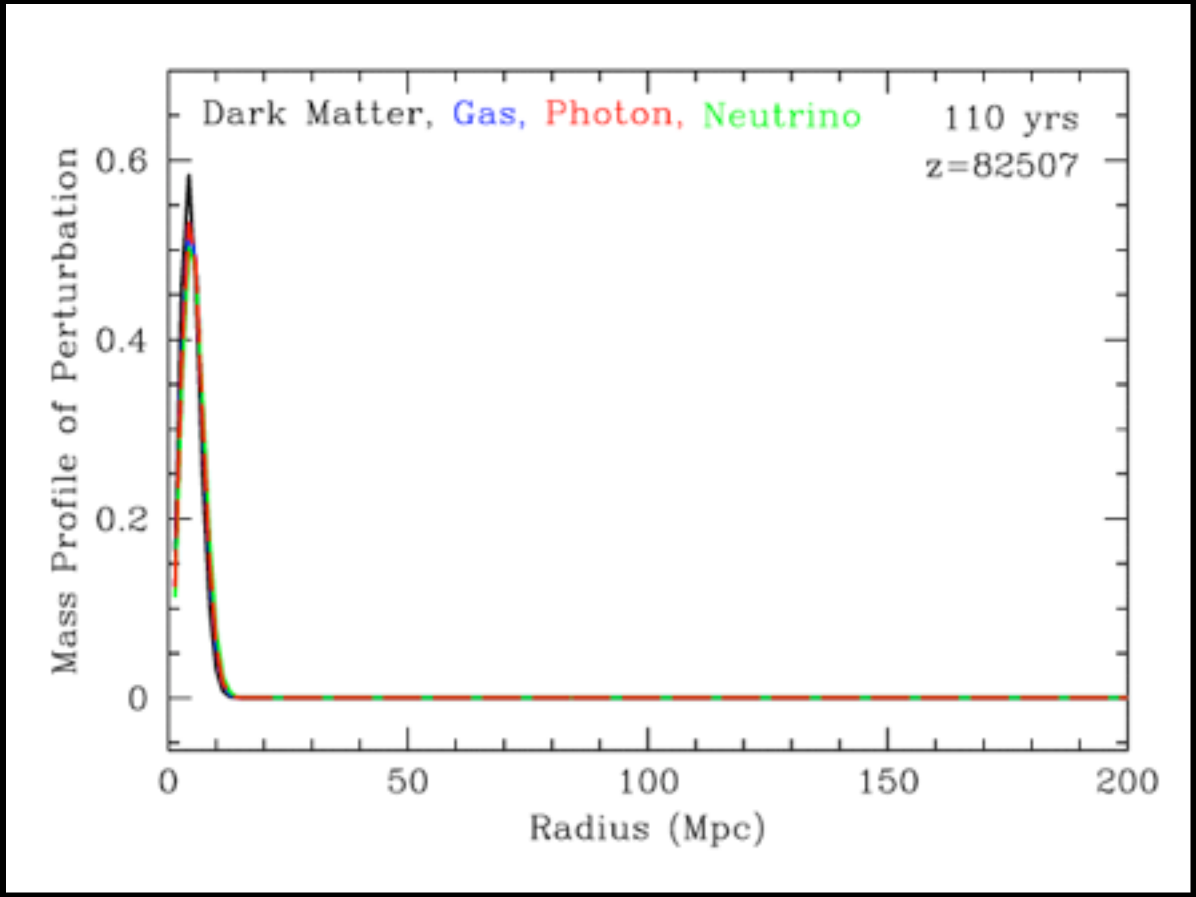
Analytic solution for w = -1 [see Sirko astro-ph/0503106 Eqn 3, Dodelson 2003 Eqn 7.77]

LSS theory

- The transfer function encapsulates impact of z >~1000 physics on the linear matter power spectrum: $P(k,z) = D^2(z)\, T^2(k)\, P_i(k)$
- Modes inside the horizon during radiation domination are damped
- Pressure breaks adiabaticity, generates baryon acoustic oscillation (BAO) feature
- After decoupling, linear perturbation structure is “frozen”; all k-modes are amplified by gravity at the same rate [growth function, D(z)]

Features in the initial conditions: Baryon Acoustic Oscillations



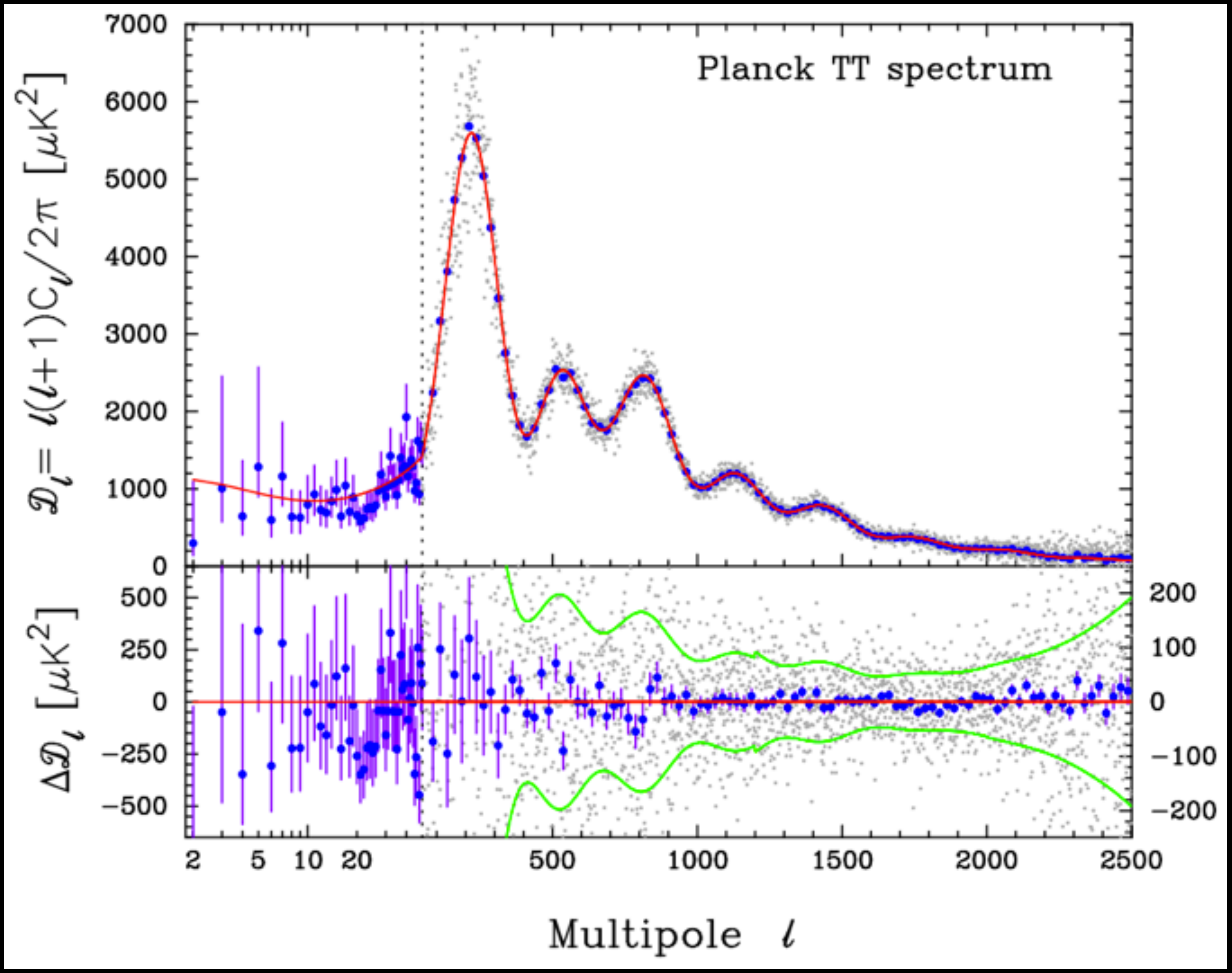


$$s_{\mathrm{BAO}} = \int_0^{t_{\mathrm{drag}}} c_s(1+z)dt = \int_{z_{\mathrm{drag}}}^{\infty} \frac{c_s dz}{H(z)}$$

s_{BAO} = 147.53 ± 0.64 Mpc (0.4%!)
(Planck XVI)

http://cmb.as.arizona.edu/~eisenste/acousticpeak/acoustic_physics.html

CMB provides LSS initial conditions



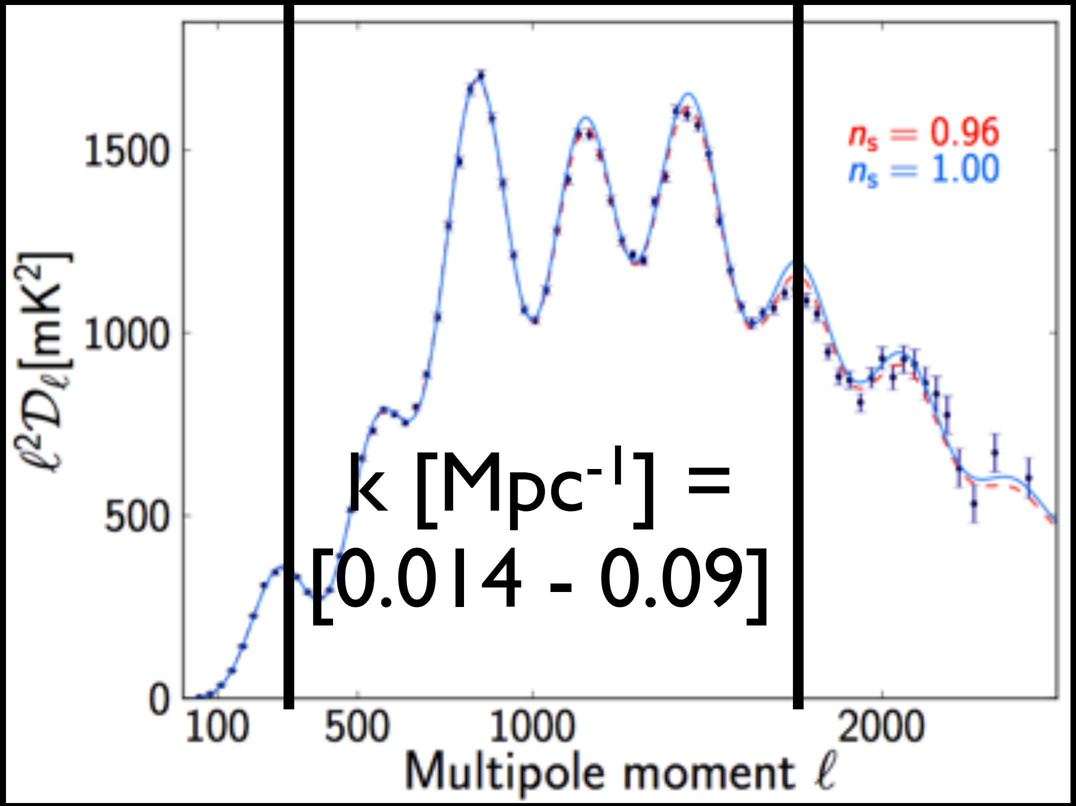
Initial Conditions from the CMB

- COBE/FIRAS measured the temperature of the CMB extremely precisely: $T\gamma$ = 2.7255 ± 0.00057 K.
- This measurement determines the energy density in both photons and (thermal relic) neutrinos. These particles were relativistic at z >~ 1000 [$\Omega_\gamma \propto a^{-4}$]
- Ratios of first to second (third) peak heights in the CMB determine $\Omega_b h^2$ ($\Omega_c h^2$)
- This simple picture works (so far); but allowing for new physics generates uncertainty in the prediction of P(k) from CMB (from e.g., Neff, r, isocurvature modes, m_ν, etc), and P(k) measurements can constrain those parameters

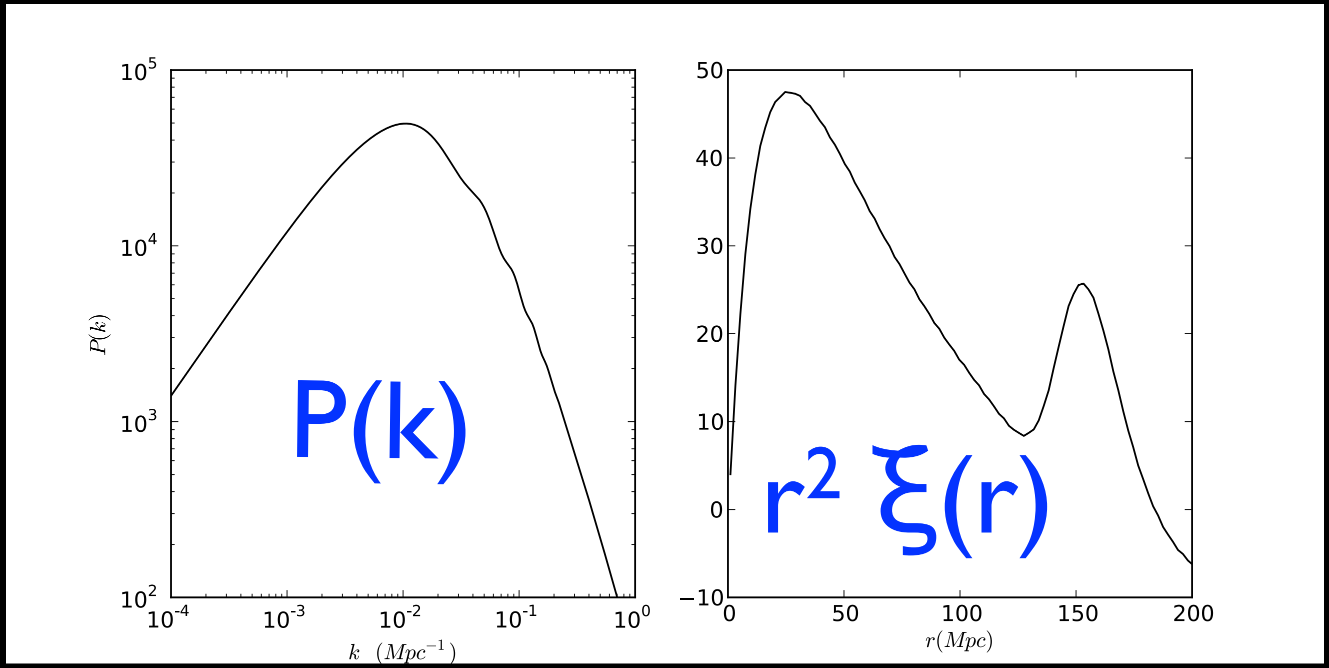
CMB constraints on initial conditions: n_s is measured on the same physical scales as LSS

photon-baryon fluid

dark matter dominated



Planck 2013 #16

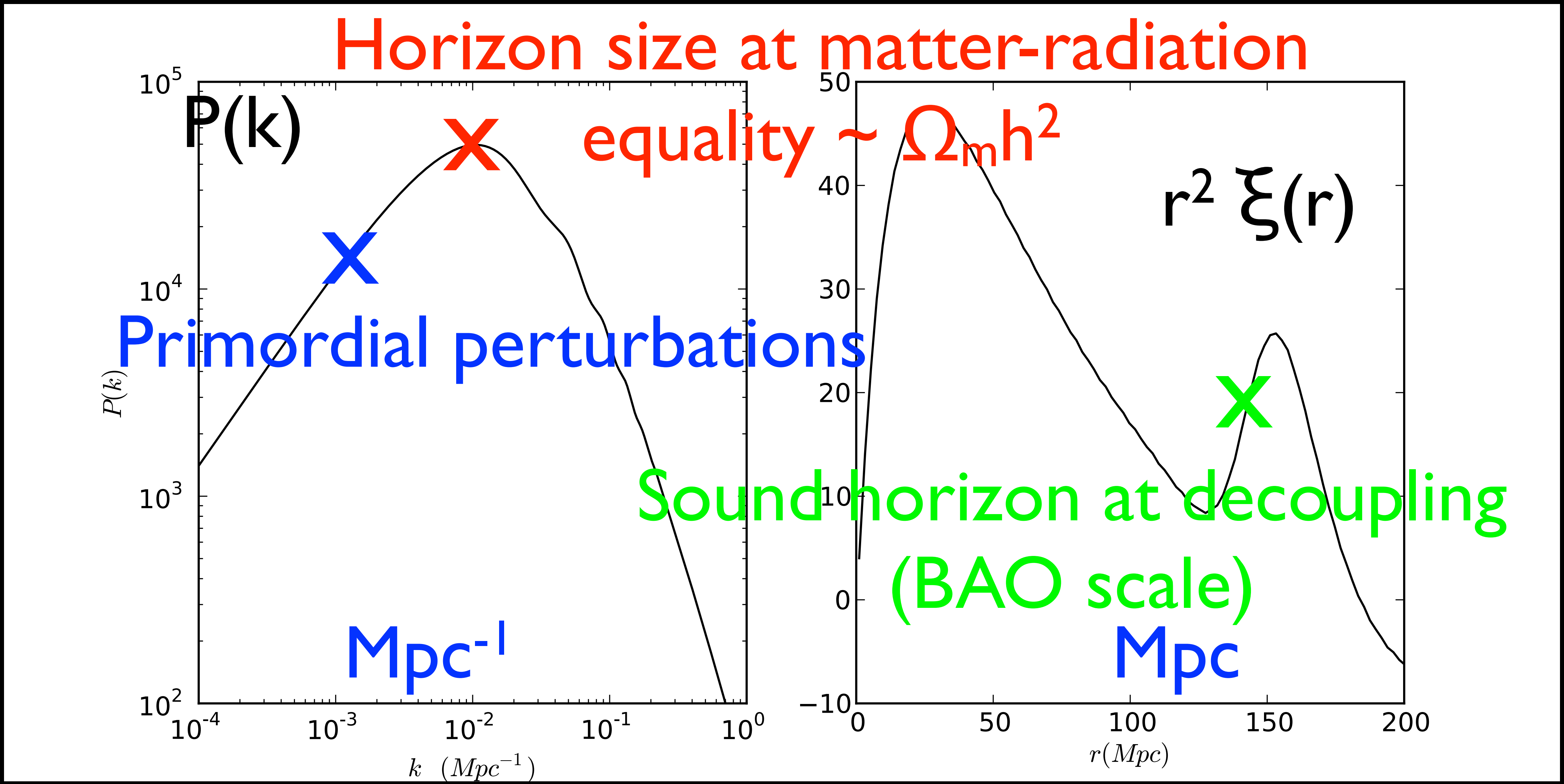


Mpc^{-1}

Mpc

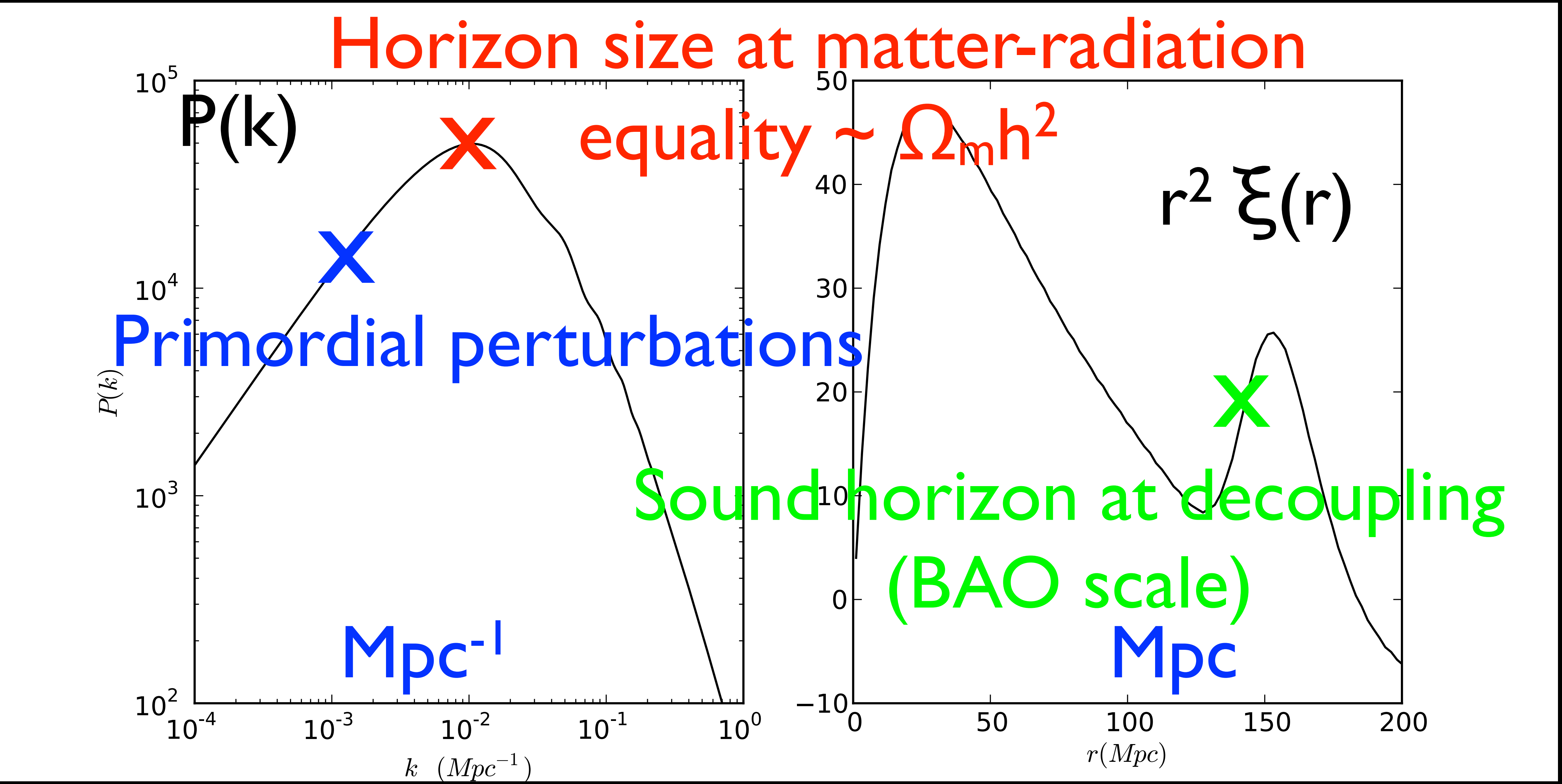
CMB constraints on initial conditions

- depends on $\Omega_{c,b,\gamma}\, h^2$ and n_s, but NOT $D_A(z_{CMB})$



CMB constraints on initial conditions

- Most important take-away: natural units are Mpc, not h^{-1} Mpc!!



CMB constraints on initial conditions

- Most important take-away: natural units are Mpc, not h^{-1} Mpc!!

Quiz:
Why does everyone always plot h^{-1} Mpc then?

CMB constraints on initial conditions

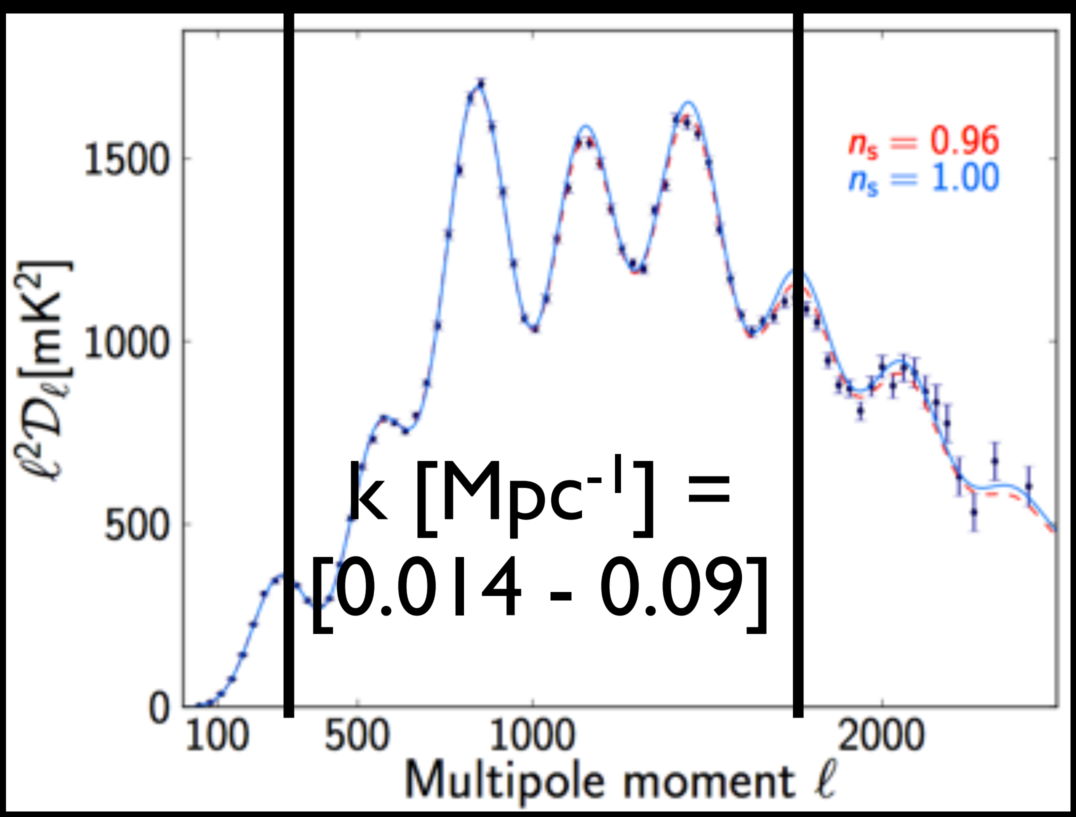
- Most important take-away: natural units are Mpc, not h^{-1} Mpc!!

Quiz:
Why does everyone always plot h^{-1} Mpc then?

Answer:
comoving distance $\chi = \int_0^z c\, dz/H(z)$
$\approx 3000z\ h^{-1}$ Mpc at $z \approx 0$
At higher redshifts, cannot neglect $H(z)$ dependence on Ω_m, Ω_{DE}, etc.

Comparison of Planck prediction with SDSS-II LRG halo power spectrum

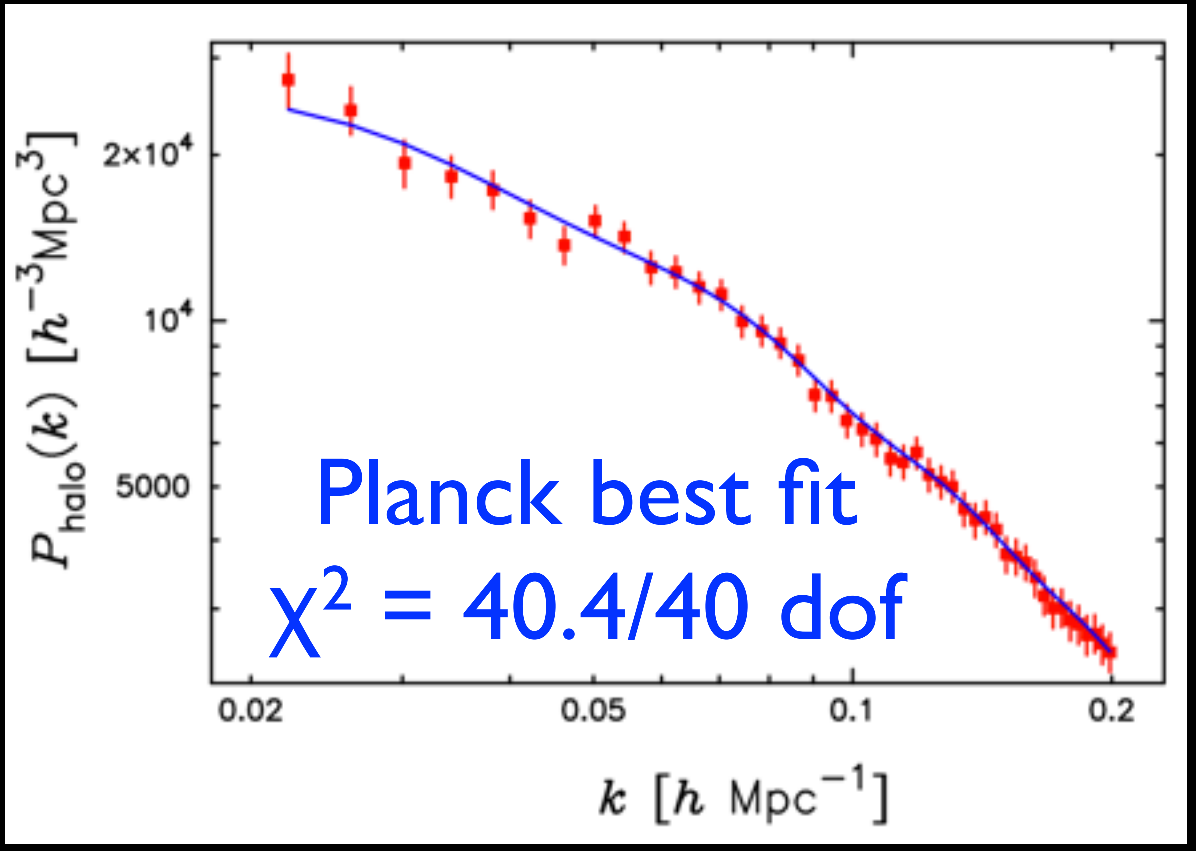
photon-baryon fluid



Planck 2013 #16

→

DM halo P(k) from SDSS-II LRGs
Reid et al 2010



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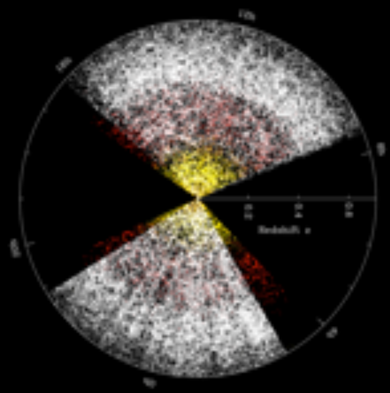
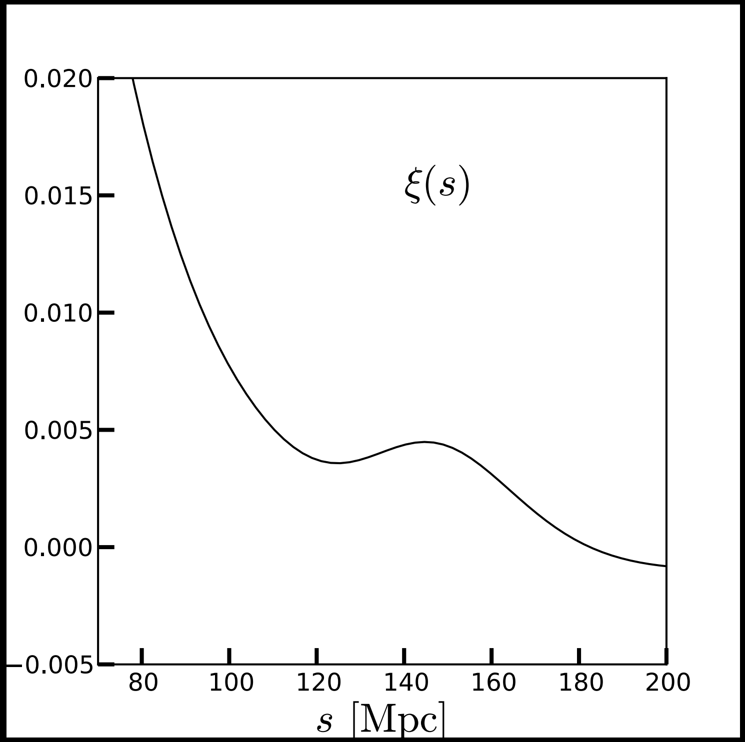
Geometric constraints from galaxy surveys

Observer space:
ra, dec, z



Theory space:
(physical) Mpc



mapping depends on the expansion history H(z) (and therefore cosmological parameters) for z in [0, z_{max}]:

$X(z) = (1+z)D_A(z) = \int_0^z c\,dz'/H(z')$ [flat universe]

Geometric constraints from galaxy surveys

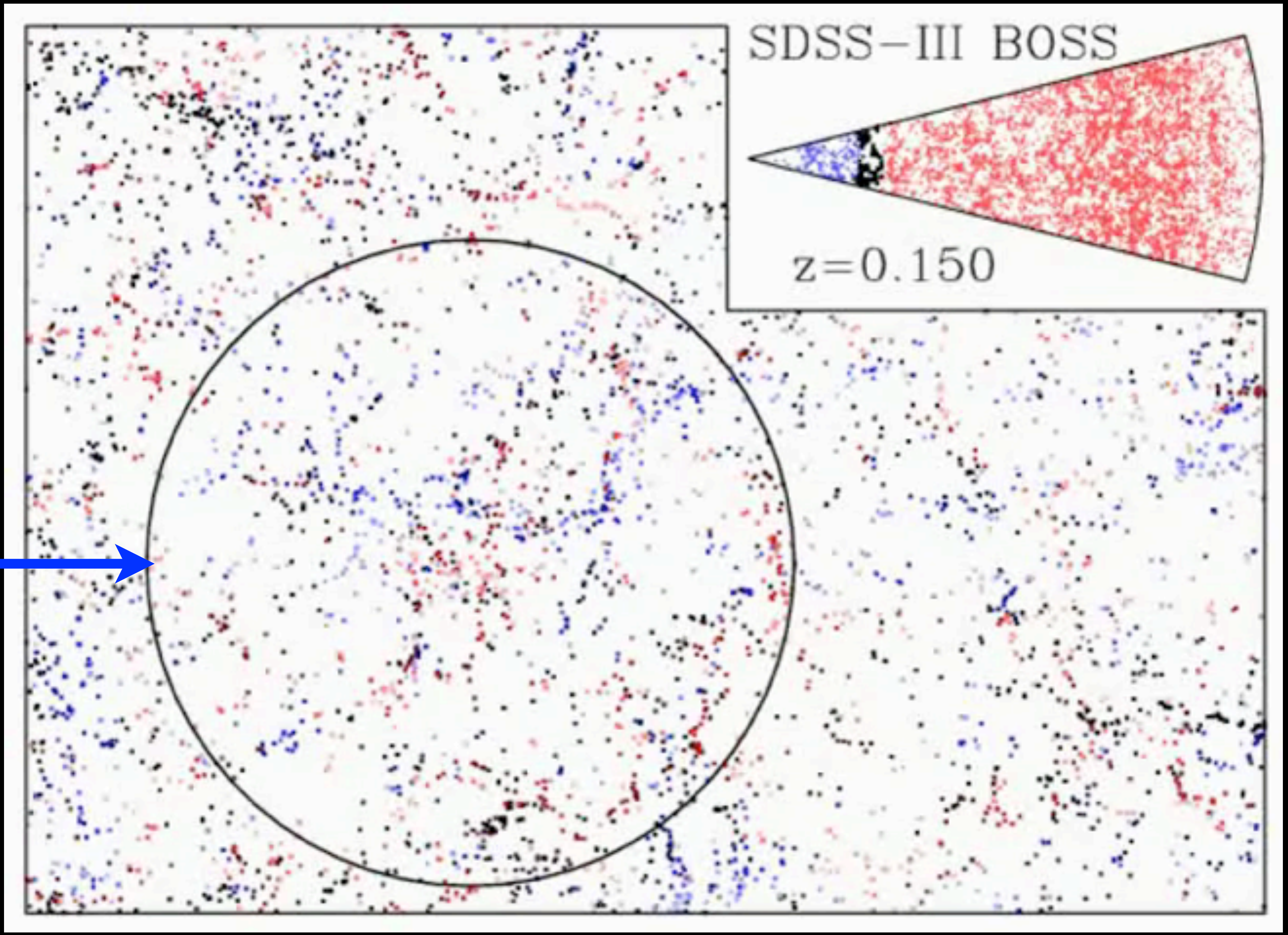
- We have two options:
  - Stick to statistics in observer coordinates -- e.g., compute the angular correlation function/power spectra in MANY redshift bins
  - Assume a fiducial cosmology to convert ra, dec, z to comoving coordinates; account for this choice in theory calculation

Geometric constraints from galaxy surveys

- We have two options:
  - Stick to statistics in observer coordinates -- e.g., compute the angular correlation function/power spectra in MANY redshift bins
  - This is a poor choice because you must have a very long data vector to retain all relevant information

SDSS-III Baryon Oscillation Spectroscopic Survey

Apparent size of the BAO ruler



53x38 degree slice; ~20% of DR11

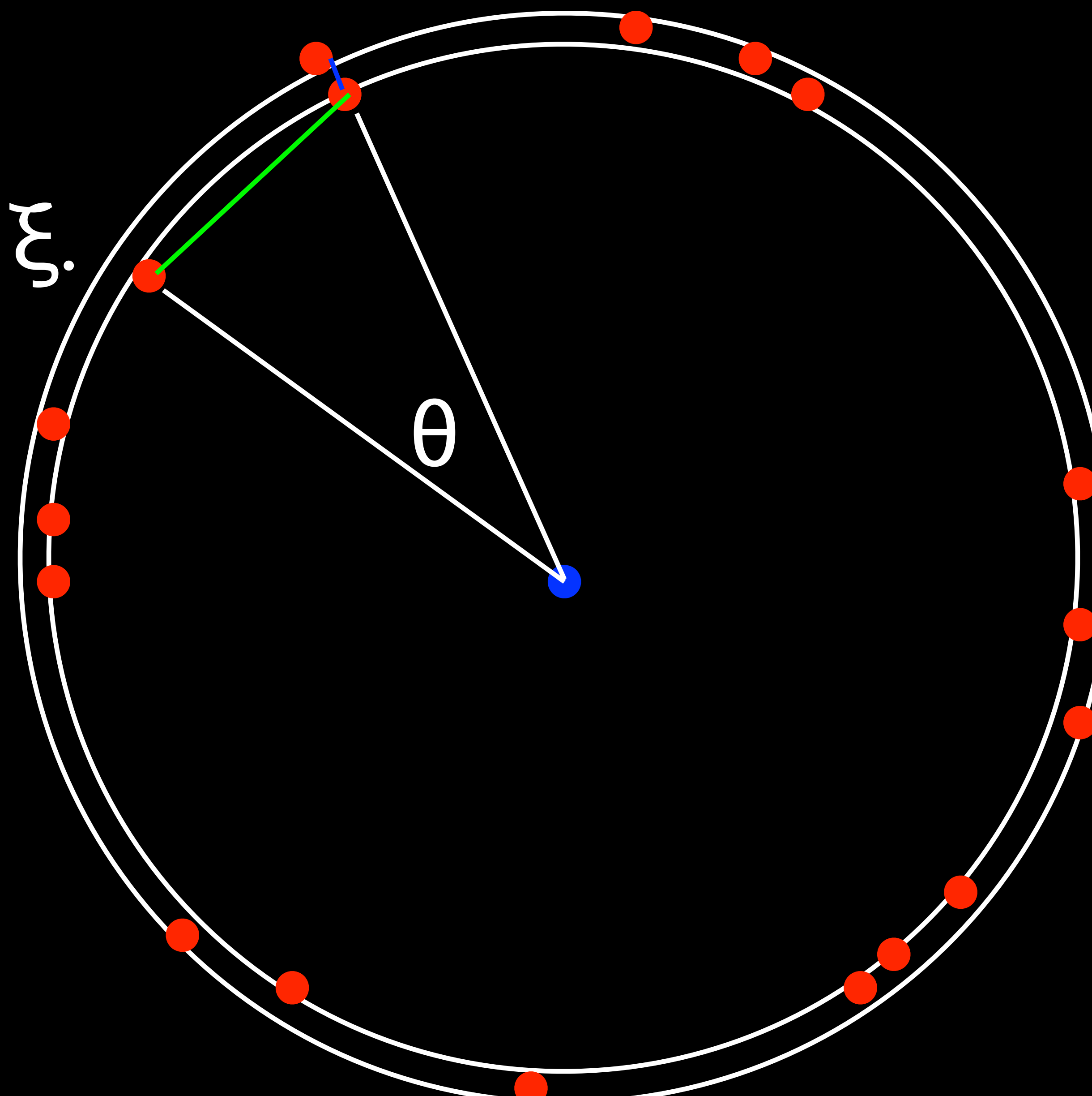
credit: Daniel Eisenstein

Geometric constraints from galaxy surveys

- We have two options:
  - Assume a fiducial cosmology to convert ra, dec, z to comoving coordinates; account for this choice in theory calculation
  - While this seems to be model-dependent, all sensible $\chi(z)$ are smooth [they are integrals!], and so the resulting geometric distortions can be modeled very accurately.

Geometric constraints from galaxy surveys

First, imagine a survey restricted to a very narrow redshift range $[z_s \pm dz/2]$. Select a "fiducial" cosmology with which to measure ξ.



The conversion between angular and transverse comoving separation $x_\perp$ is

$$x_\perp = (1+z_s)\, D_{A,fid}(z_s)\, \theta$$

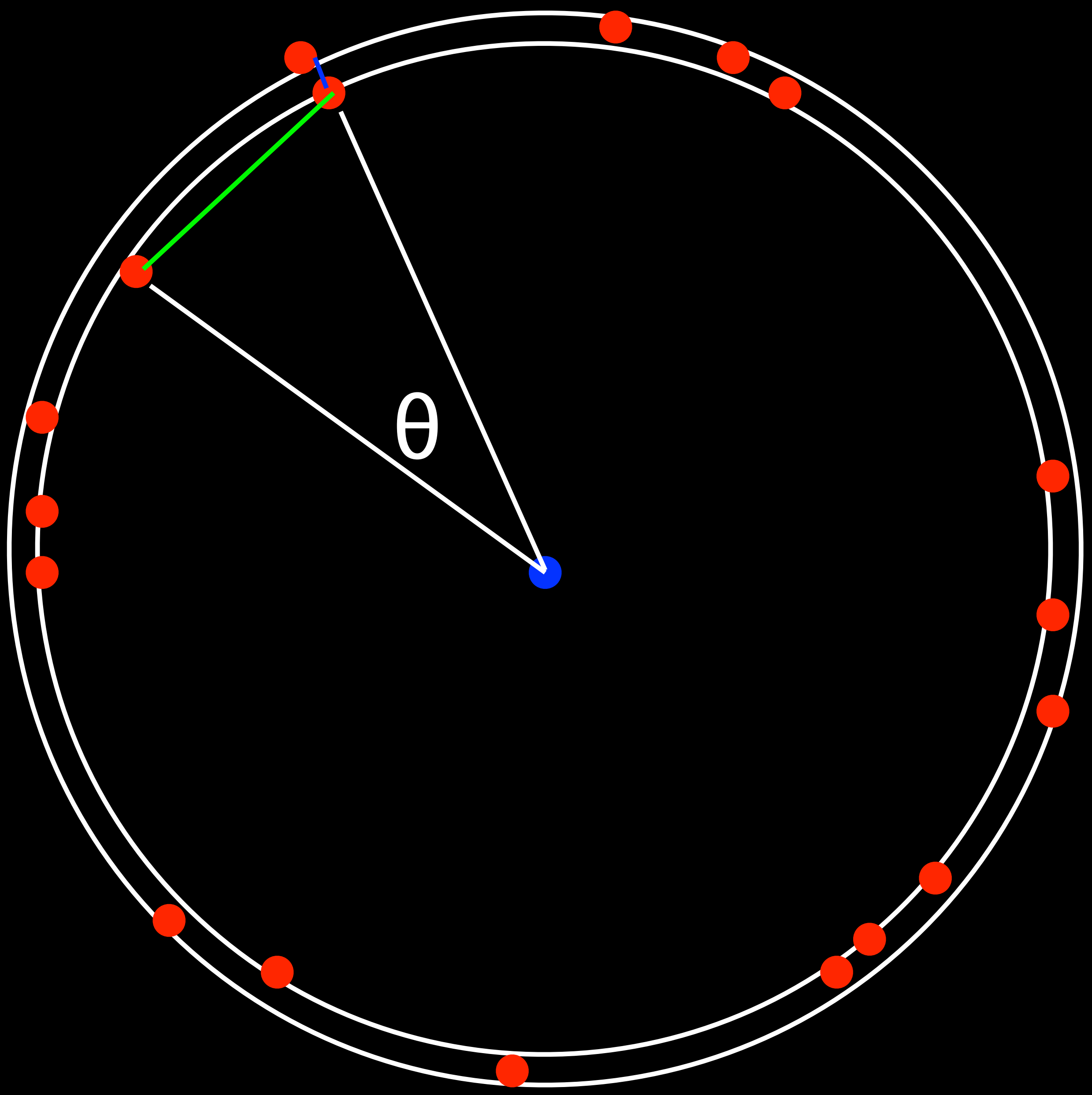
The conversion between Δz and line-of-sight (LOS) comoving separation $x_\parallel$ is

$$x_\parallel = c\Delta z \,/\, H_{fid}(z_s)$$

Geometric constraints from galaxy surveys

The theoretical prediction based on a model with a different $D_A(z_s)$ and $H(z_s)$ for the "observed" ξ^{obs} [measured with $D_A(z_s)$ and $H(z_s)$] is

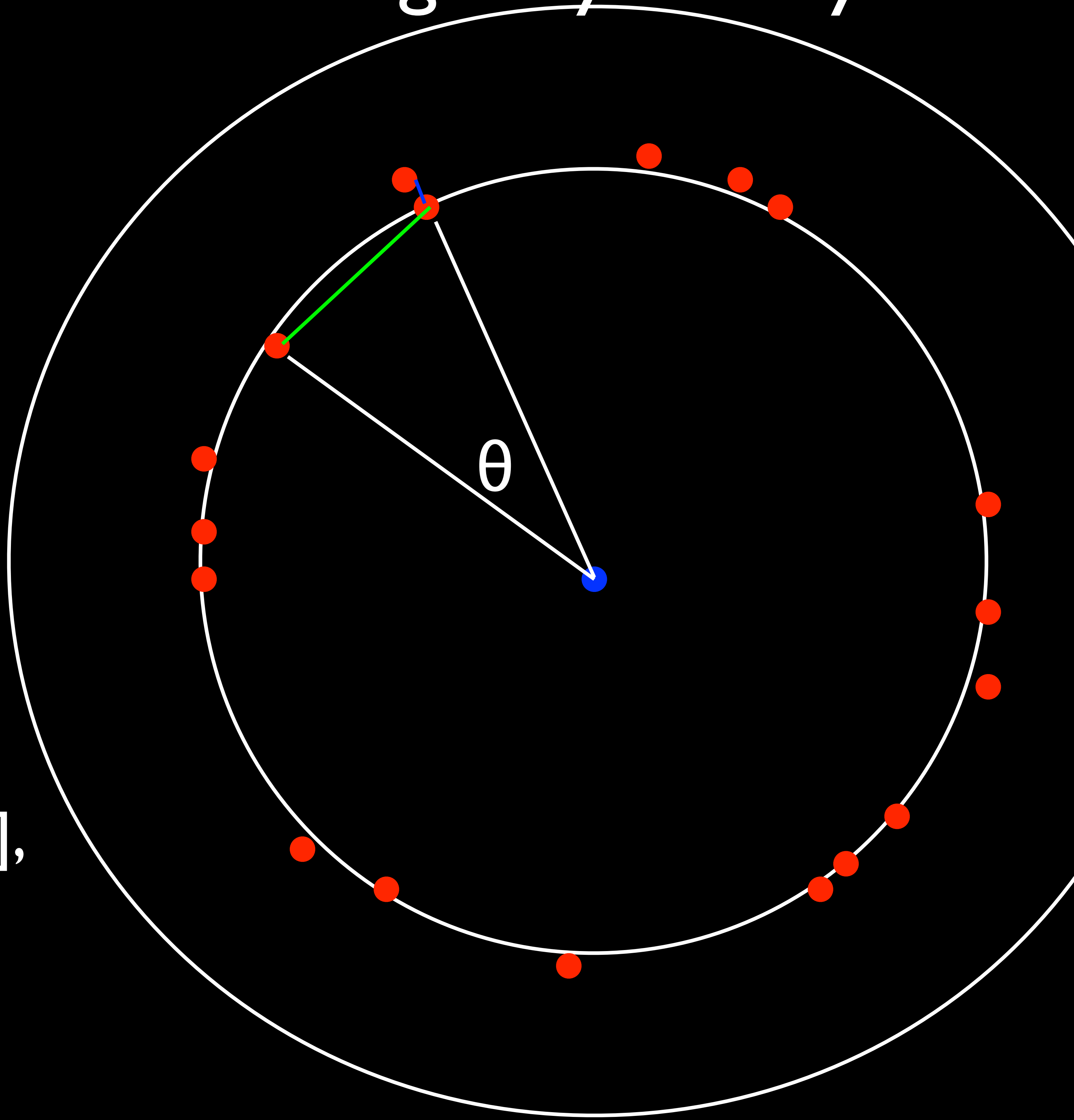
$$\xi^{obs}(s_\perp, s_\parallel) = \xi^{true}(s_\perp * [D_A(z_s)/D_{A,fid}(z_s)], s_\parallel * [H_{fid}(z_s)/H(z_s)])$$



Geometric constraints from galaxy surveys

If we generalize to a thicker redshift range, it is still a very good approximation to assume

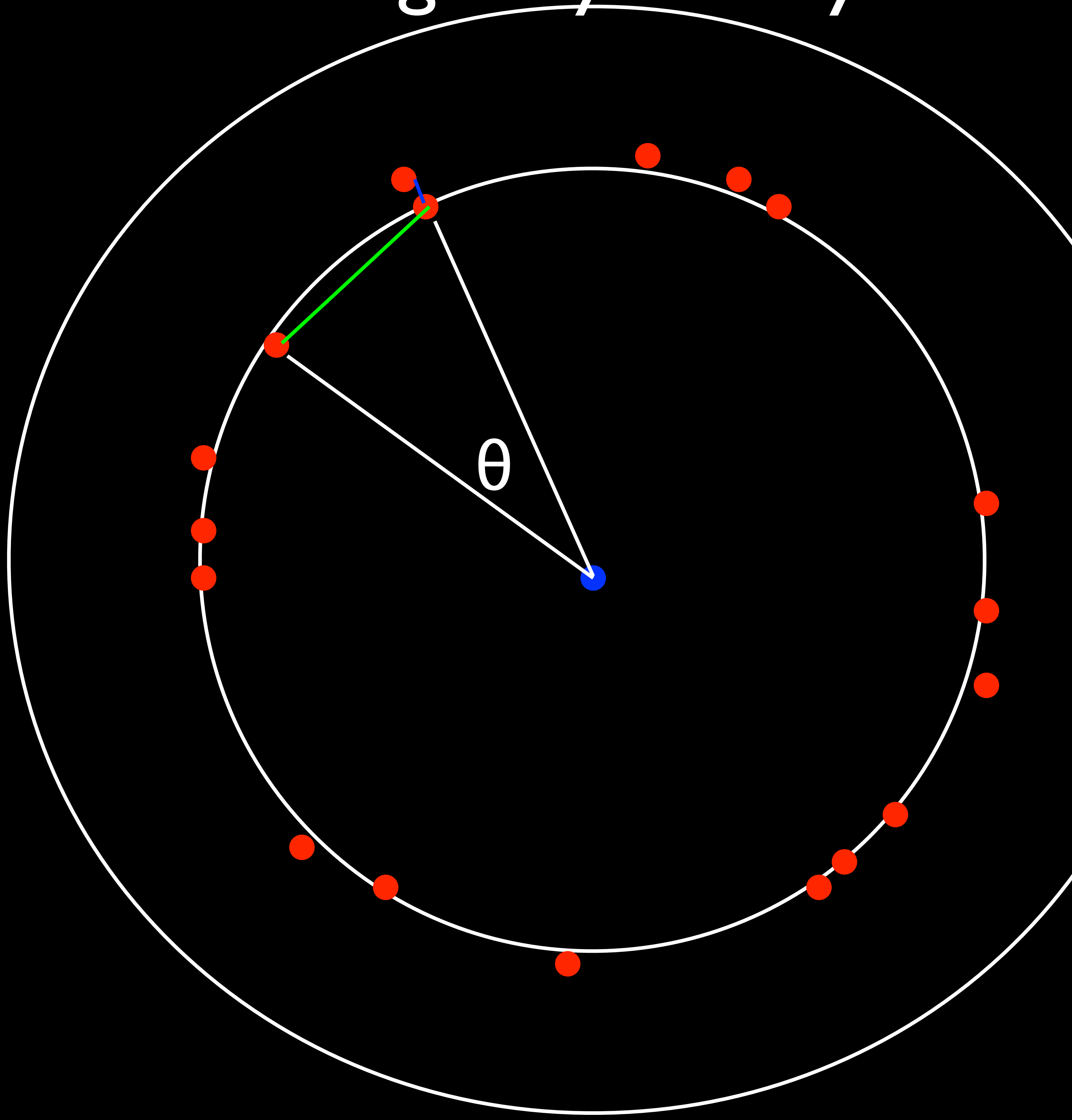
$\xi^{obs}(s_\perp, s_\parallel) =$
$\xi^{true}(s_\perp * [D_A(z_{eff})/D_{A,fid}(z_{eff})],$
$s_\parallel * [H_{fid}(z_{eff})/H(z_{eff})])$



Geometric constraints from galaxy surveys

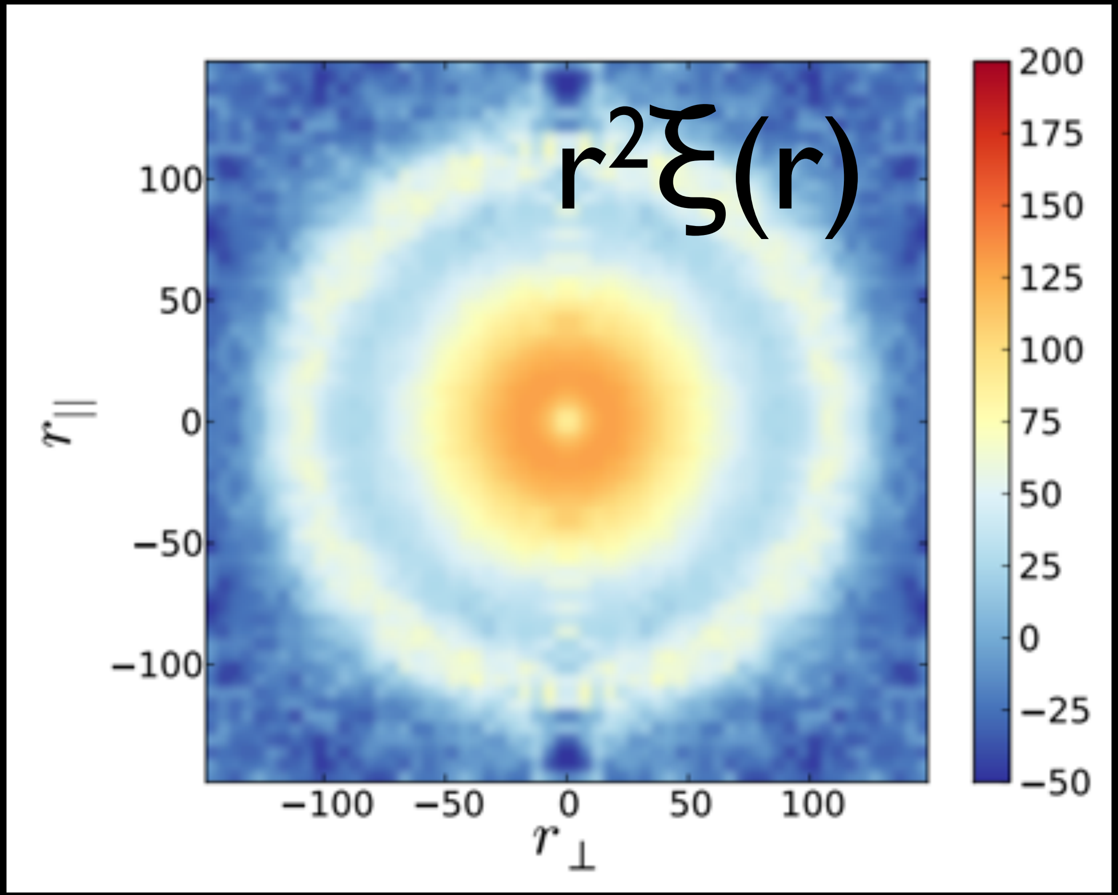
If we generalize to a thicker redshift range, it is still a very good approximation to assume

[though one could easily integrate ξ^{true} over the redshift distribution of pairs to be more exact]



The BAO standard ruler

- ξ^{model} has a feature at a characteristic scale $s_{\text{BAO}} \approx 150$ Mpc

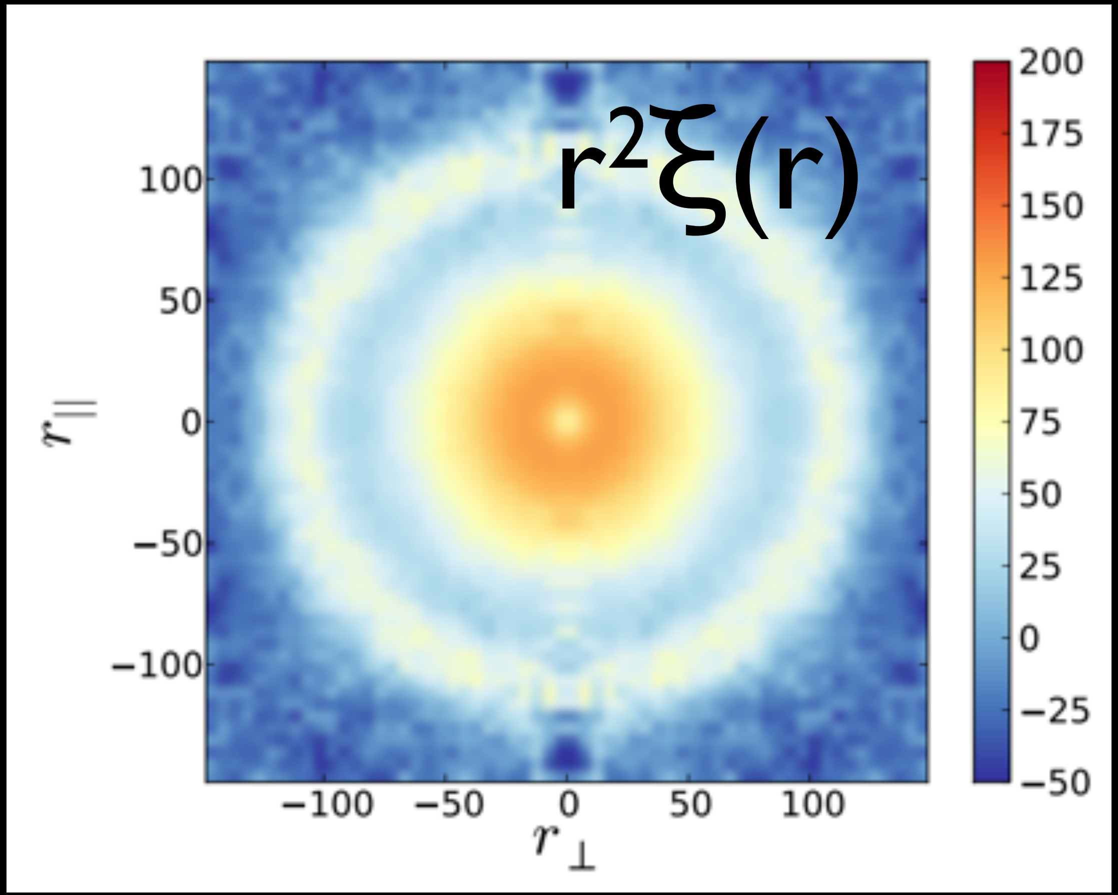


[real space; no RSD until Lecture 3]
Padmanabhan et al. 1202.0090

The BAO standard ruler

- Suppose we observe this feature at $s_\perp$' and $s_\parallel$':

$$\xi^{obs}(s_\perp', s_\parallel') =$$
$$\xi^{true}(s_{BAO} = s_\perp' * [D_A(z_{eff})/D_{A,fid}(z_{eff})],$$
$$s_{BAO} = s_\parallel' * [H_{fid}(z_{eff})/H(z_{eff})])$$



[real space; no RSD until Lecture 3]
Padmanabhan et al. 1202.0090

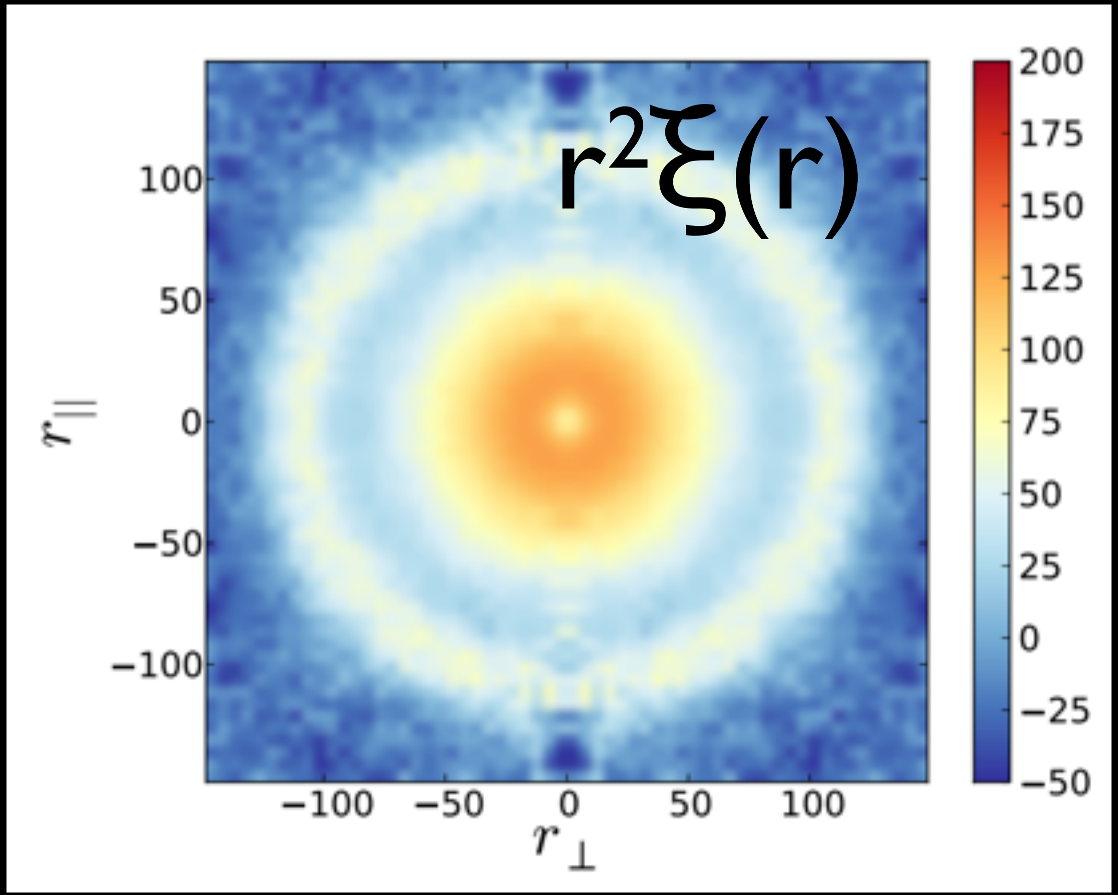
The BAO standard ruler

- Then we have measured

$$D_A(z_{eff})/[s_{BAO}{*}D_{A,fid}(z_{eff})]$$

and

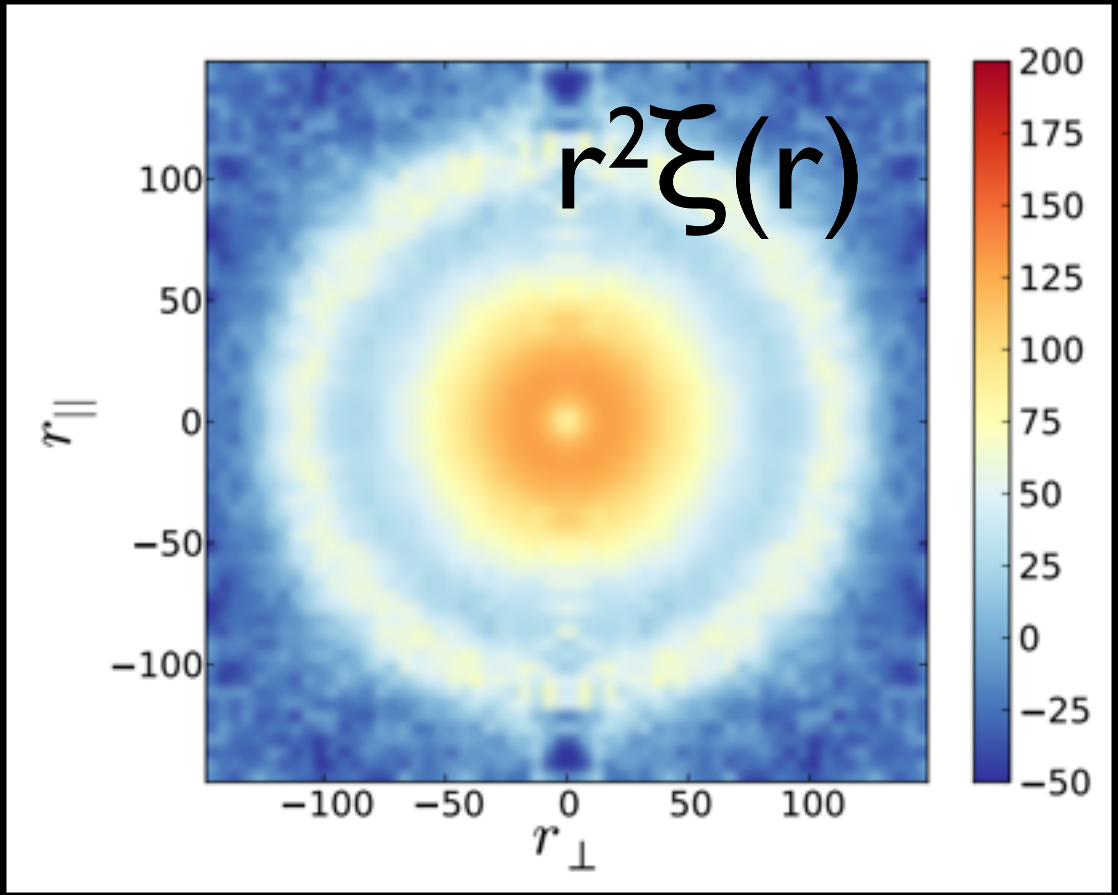
$$H_{fid}(z_{eff})/[s_{BAO}{*}\,H(z_{eff})]!$$



[real space; no RSD until Lecture 3]
Padmanabhan et al. 1202.0090

The BAO standard ruler

- BUT! The BAO signal is small, and so most BAO analyses average over all orientations and constrain $D_V(z_{eff})/s_{BAO}$.



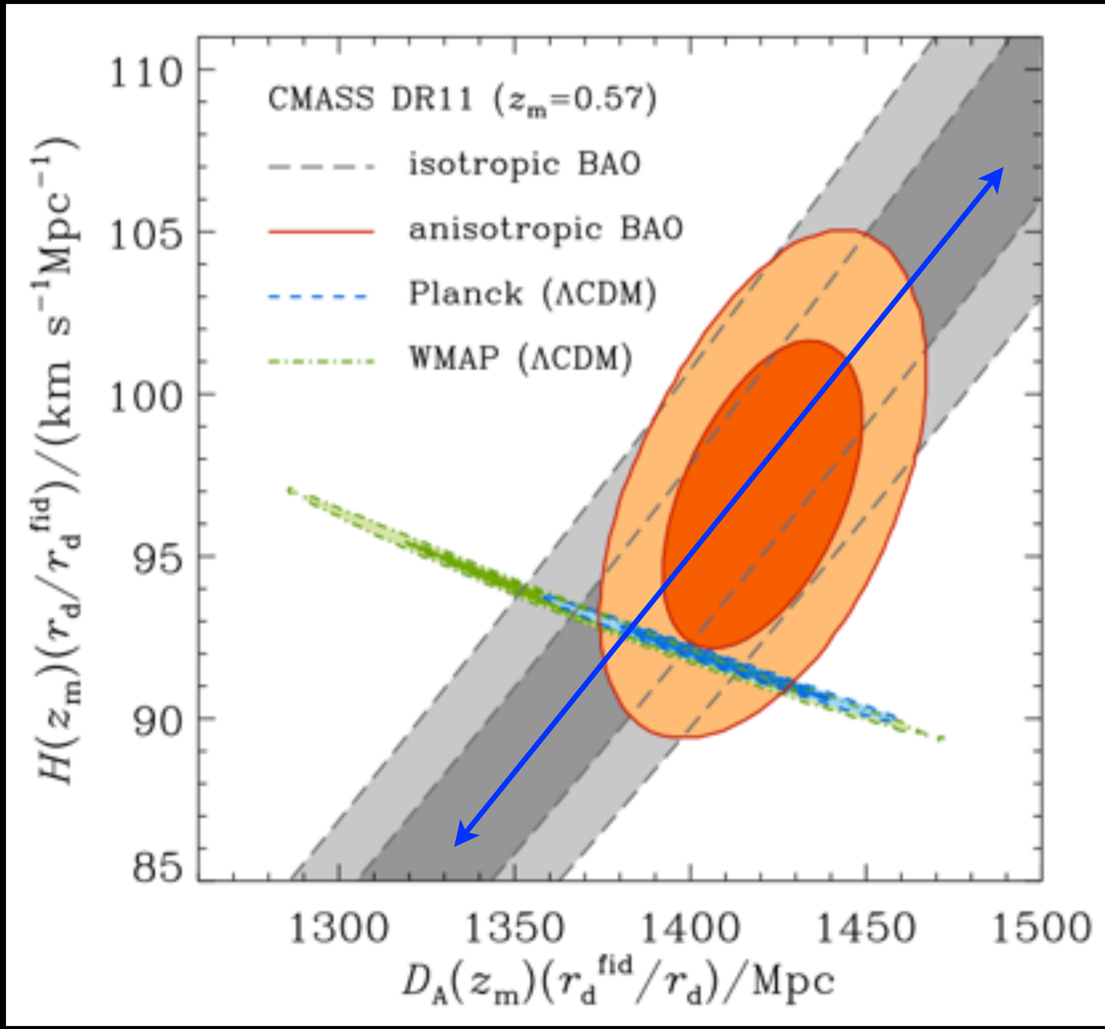
$D_V \equiv [(1+z_{eff})^2 D_A(z_{eff})^2 * cz_{eff}/H(z_{eff})]^{1/3}$
(geometric mean)

[real space; no RSD until Lecture 3]
Padmanabhan et al. 1202.0090

The BAO standard ruler

- Constraints from BOSS DR11:

BOSS, arXiv:1312.4877



D_V approximation

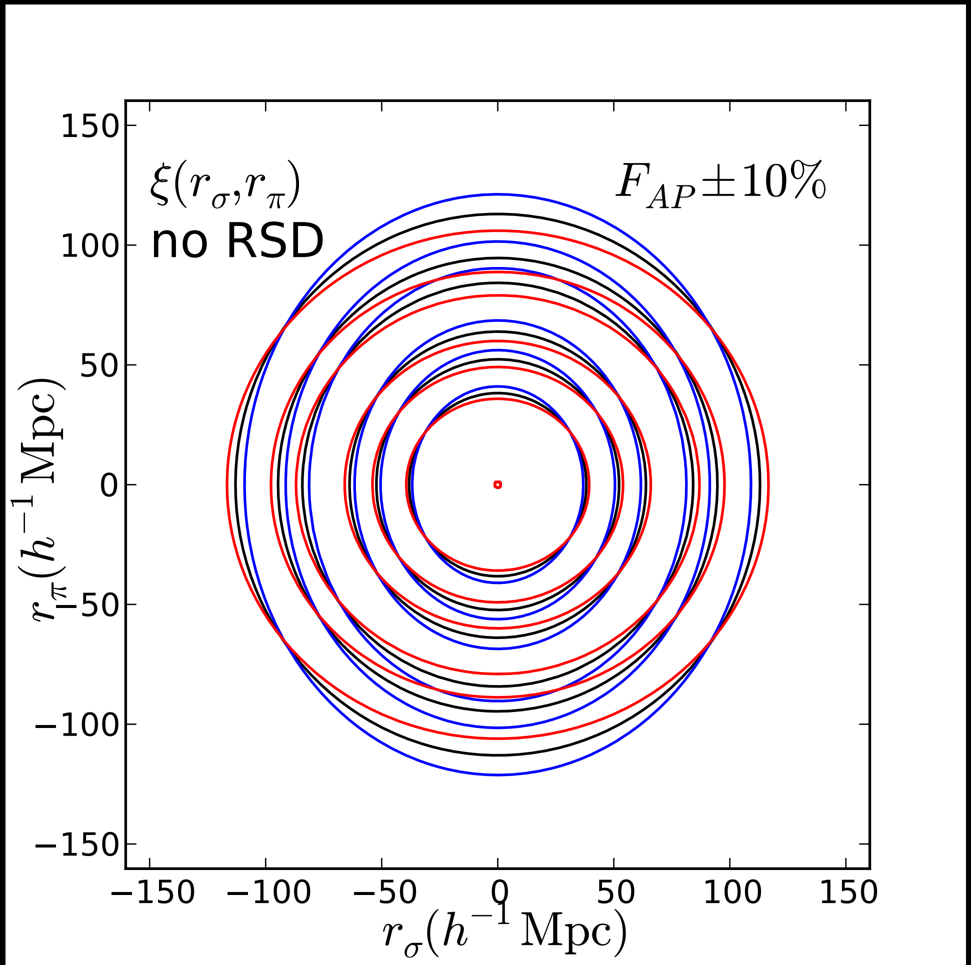
fit to D_A and H

$$D_A(z=0.57) = (1421 \pm 20\ \mathrm{Mpc})(s_{BAO}/s_{BAO,fid})$$

$$H(z=0.57) = (96.8 \pm 3.4\ \mathrm{km\ s^{-1}Mpc^{-1}})(s_{BAO,fid}/s_{BAO})$$

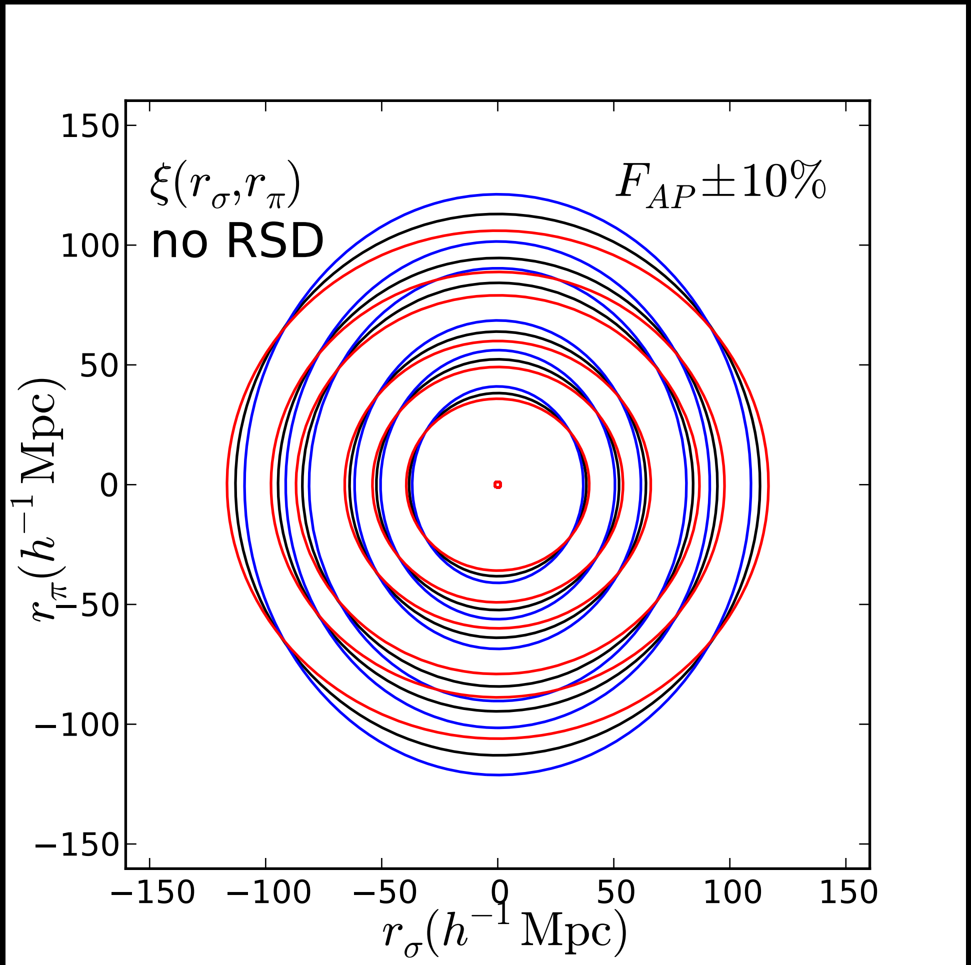
Geometric constraints from galaxy surveys: Alcock-Paczynski (1979) effect

- Assume ξ(r) is isotropic (black circular contours). The observed ξ will appear anisotropic (elliptical contours) if LOS separations are distorted relative to transverse separations; this constrains $F_{AP}(z) \equiv (1+z)\, D_A(z)\, H(z)/c$



Geometric constraints from galaxy surveys: Alcock-Paczynski (1979) effect

- The AP effect requires no standard ruler (just isotropy), so information from all scales is useful.



The BAO standard ruler

- If linear perturbation theory were completely accurate, this lecture would be over... BUT!
- Non-linear gravitational evolution degrades the BAO feature in the matter (or galaxy) correlation function
- Some of the BAO information degradation in the evolved (non-Gaussian) field can be undone by the process of reconstruction

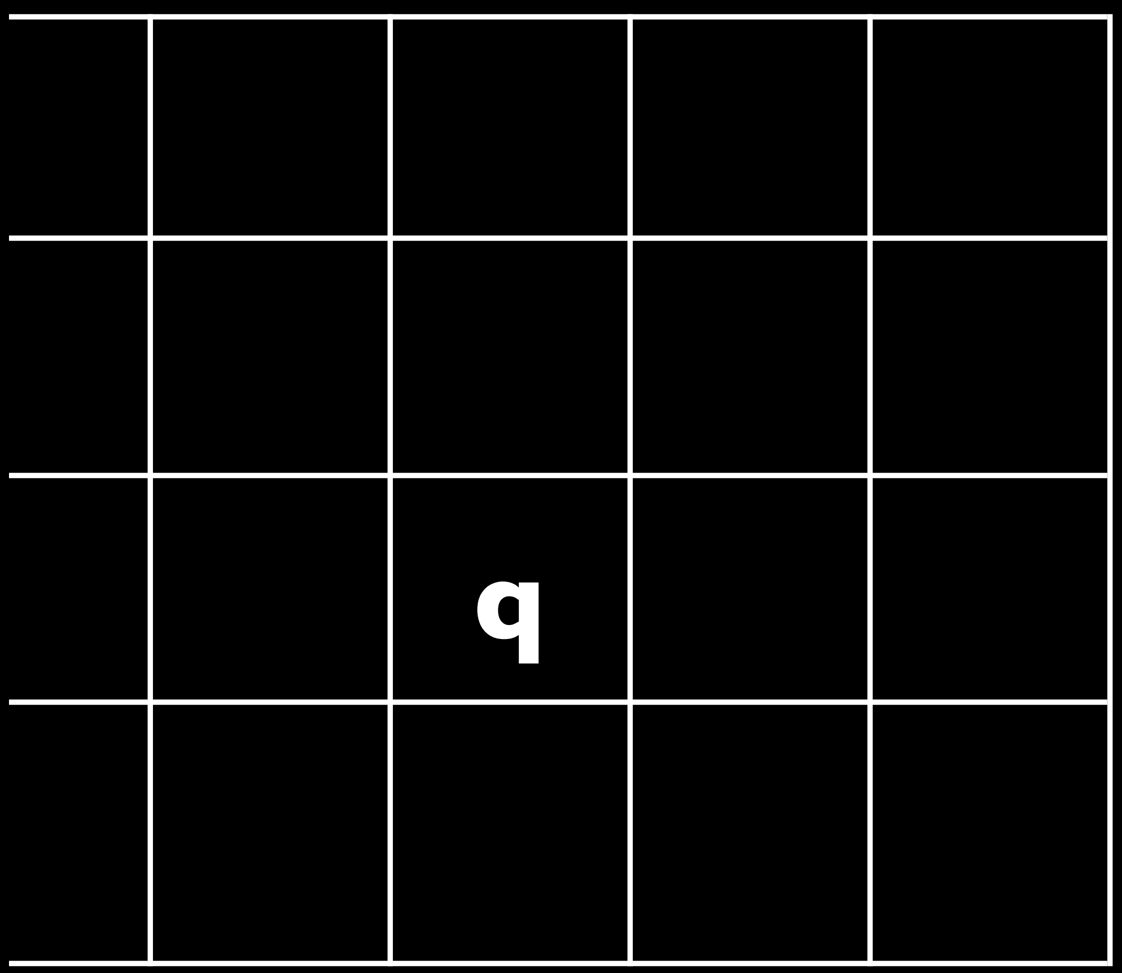
The BAO standard ruler

- The relevant physics can be understood with a very simple model -- the Zel'dovich approximation

Cosmological Perturbation Theory

- The universe is initially completely homogeneous with negligible perturbations
  - "Standard" perturbation theory tracks gravitational evolution of density contrast at co-moving coordinate $\mathbf{x}$, $\delta(\mathbf{x})$, and the divergence of the peculiar velocity field $\theta(\mathbf{x}) \equiv -\nabla \cdot \mathbf{v}_P(\mathbf{x})$.
  - In SPT (and LPT), $\nabla \times \mathbf{v}_P$ decays and is neglected.

BAO evolution in Zel'dovich approximation



- Consider a very early time when the mass distribution is homogeneous, and follow the trajectory of equal mass/volume elements labelled by initial coordinate $\mathbf{q}$ to position $\mathbf{x}$ at time t:

$$\mathbf{x} = \mathbf{q} + \boldsymbol{\Psi}(\mathbf{q},t)$$

BAO evolution in Zel'dovich approximation

$$\mathbf{x} = \mathbf{q} + \mathbf{\Psi}(\mathbf{q},t)$$

- Then $\mathbf{\Psi}(\mathbf{q},t)$ is irrotational and obeys

$$\frac{d^2\mathbf{\Psi}}{dt^2} + 2H\frac{d\mathbf{\Psi}}{dt} = -\nabla_x\phi[\boldsymbol{q} + \mathbf{\Psi}(\boldsymbol{q})]$$

$$\nabla_x^2\phi(\boldsymbol{x}) = 4\pi G\bar{\rho}a^2\delta(\boldsymbol{x})$$

Poisson Eqn

$$\delta(\boldsymbol{x}) = \int d^3q\, \delta^3\left[\boldsymbol{x} - \boldsymbol{q} - \mathbf{\Psi}(\boldsymbol{q})\right]$$

Eulerian density constrast in terms of $\mathbf{\Psi}$

[See Matsubara 0711.2521 for details]

BAO evolution in Zel'dovich approximation

$$\mathbf{x} = \mathbf{q} + \boldsymbol{\Psi}(\mathbf{q},t)$$

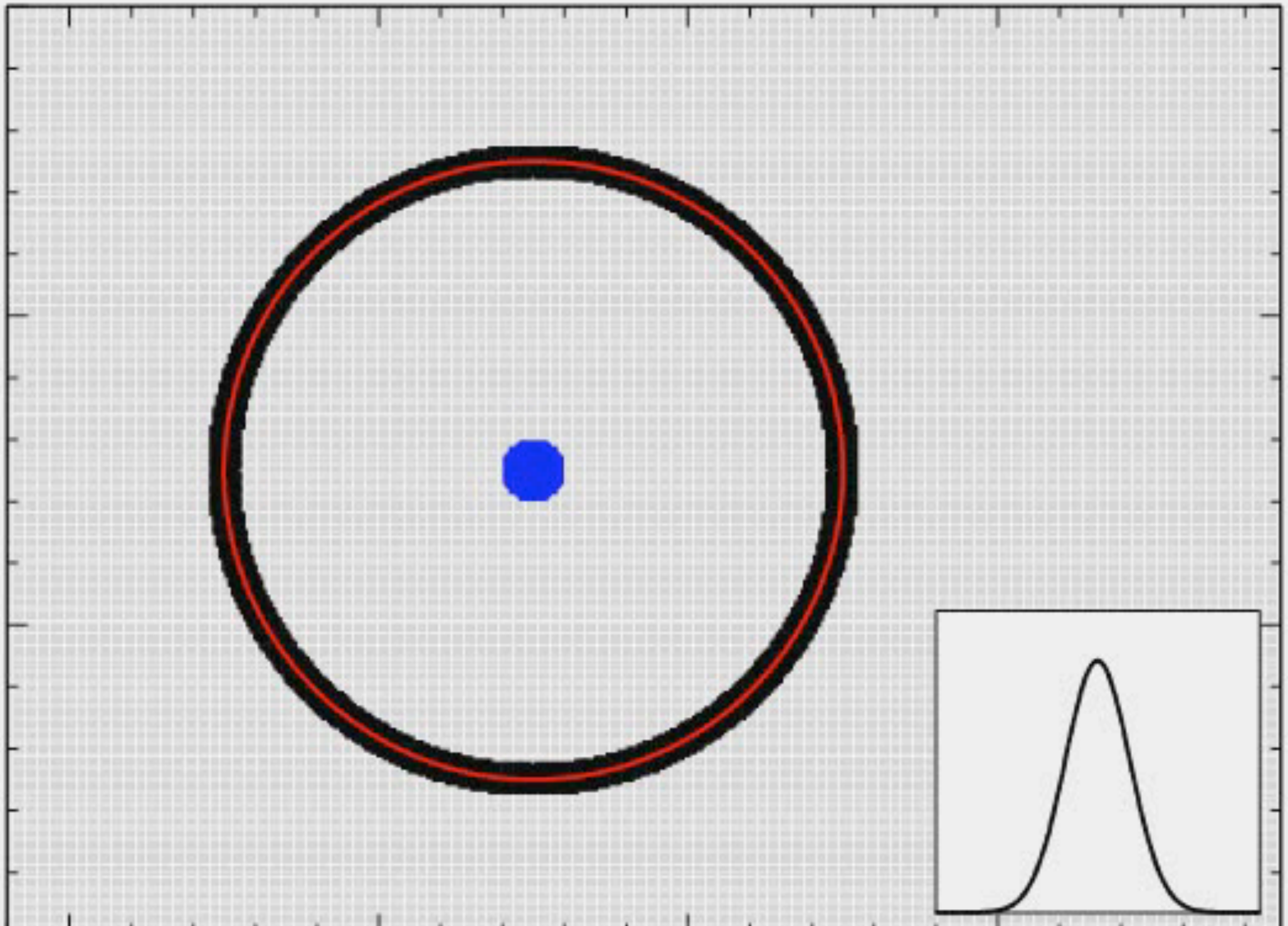
- The Zel'dovich approximation keeps only the first order term for $\boldsymbol{\Psi}$:

$$\boldsymbol{\Psi}(\mathbf{q}) = \int \frac{d^3k}{(2\pi)^3}\, e^{i\mathbf{k}\cdot\mathbf{q}}\, \frac{i\mathbf{k}}{k^2}\, \delta_L(\mathbf{k})$$

Linearly evolved density contrast at time t

- That is, motions of mass elements follow a straight line; this captures a surprising amount of the features of the LSS/cosmic web!

Nonlinear Evolution

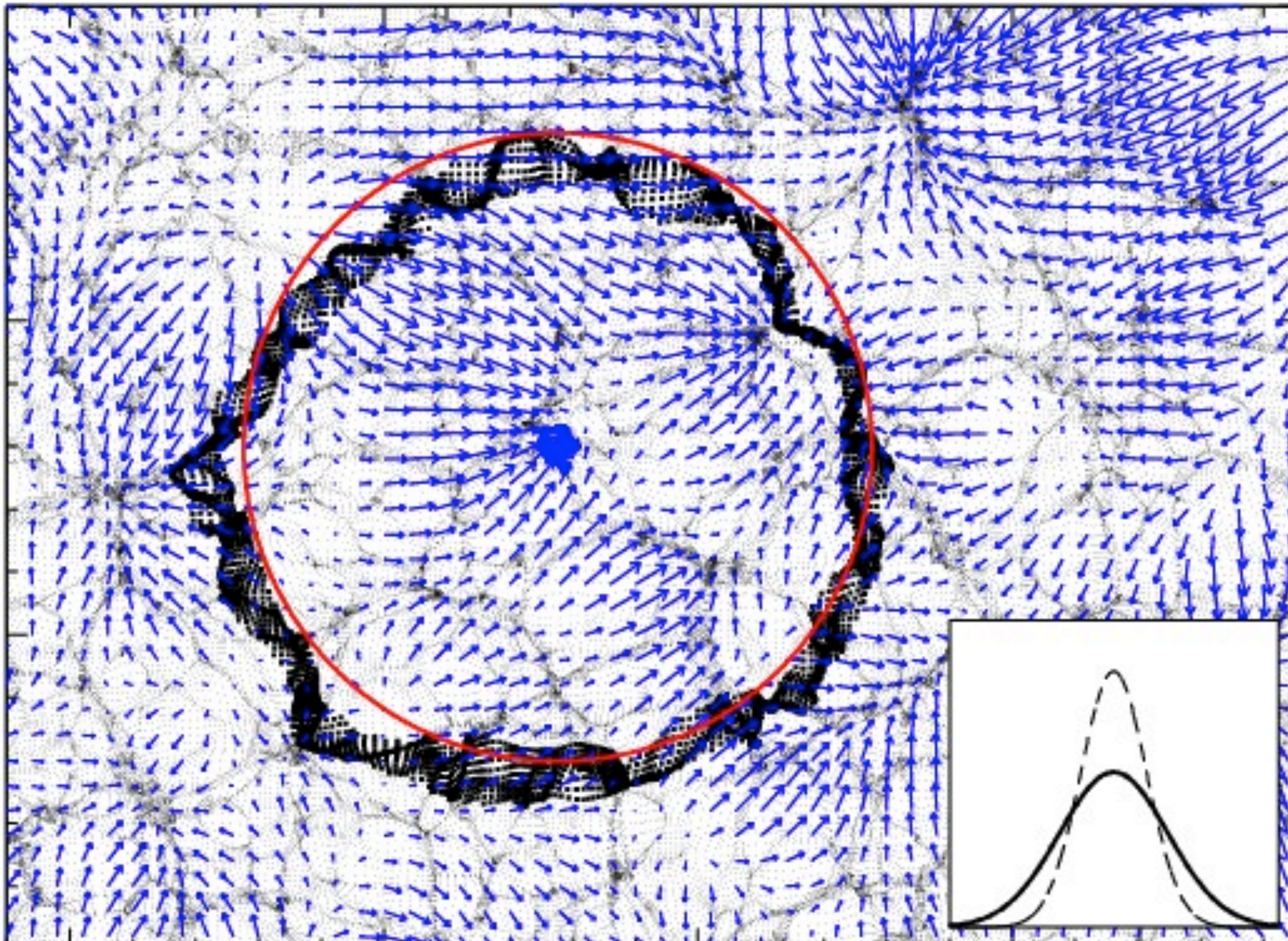


credit: Nikhil Padmanabhan

BAO evolution in Zel'dovich approximation

- Non-linear evolution smears out the BAO feature.
- This makes it harder measure the BAO location precisely, so your precision degrades.
- However! The relative displacement of particles separated by ~150 Mpc is sourced by relatively large scale (linear) density fluctuations

Reconstruction : II



credit: Nikhil Padmanabhan

BAO Reconstruction

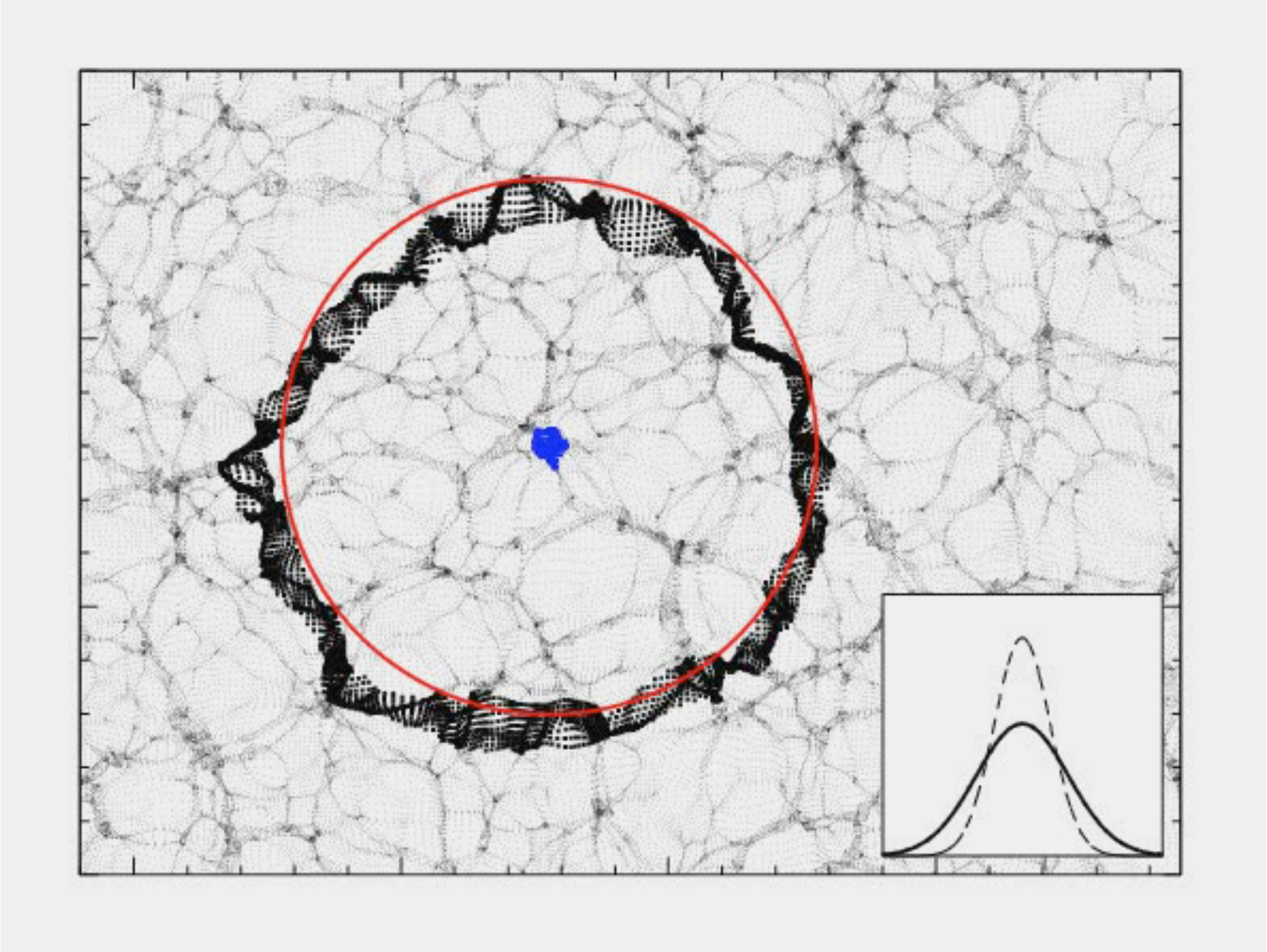
- The key insight of Eisenstein et al. 2007 (ApJ, 664, 675) was to use the evolved (non-linear) observed density field to estimate the displacement field

$$\mathbf{\Psi}(\mathbf{q}) = \int \frac{d^3k}{(2\pi)^3}\, e^{i\mathbf{k}\cdot\mathbf{q}}\, \frac{i\mathbf{k}}{k^2}\, \delta_L(\mathbf{k})$$

Replace with non-linear (observed) density field

- Using the estimated displacement field, you can move particles back to their "initial" positions

Reconstruction : III



credit: Nikhil Padmanabhan

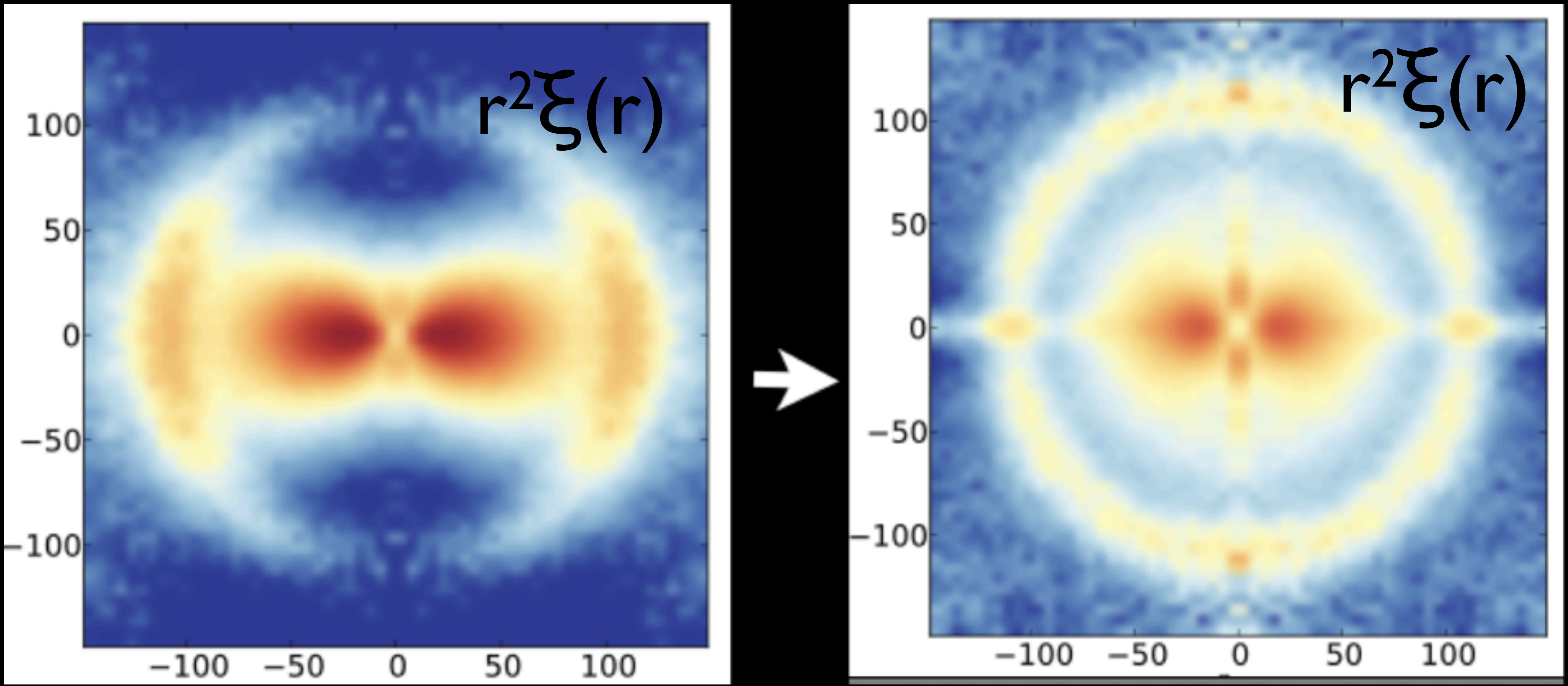
BAO Reconstruction Summary I

- A simple "reconstruction" algorithm partially restores the initial separations of pairs separated at 150 Mpc; it does not undo non-linearity on smaller scales.
- This re-sharpens the BAO feature in the reconstructed density field and increases the signal-to-noise of the BAO distance measurement towards its linear theory value
- Small non-linear shifts (~0.5%; calculable in LPT) are removed by reconstruction.

BAO Reconstruction Summary II

- See Noh, White, Padmanabhan (arXiv:0909.1802), Sherwin & Zaldarriaga (arXiv:1202.3998) for deeper explanation of the physics/magic of reconstruction
- Note that this is NOT simply a deconvolution! We are restoring information by using phase/higher order correlation information in the observed density field
- It works!

Reconstruction works: mocks

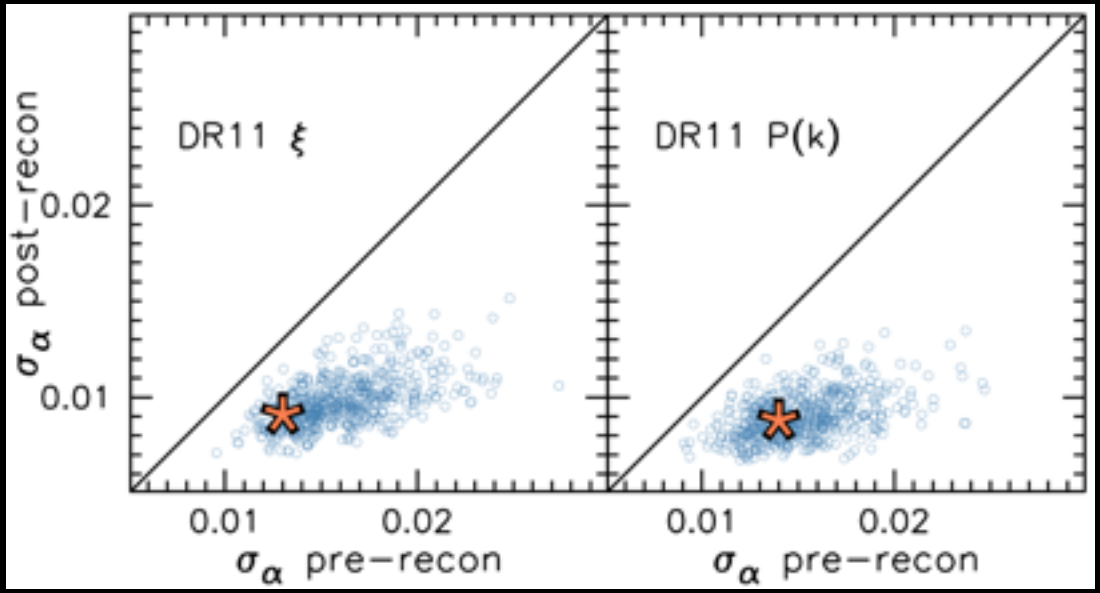


Reconstruction on 160 Las Damas mock galaxy catalogs

Padmanabhan et al., 2012, MNRAS, 427, 2132

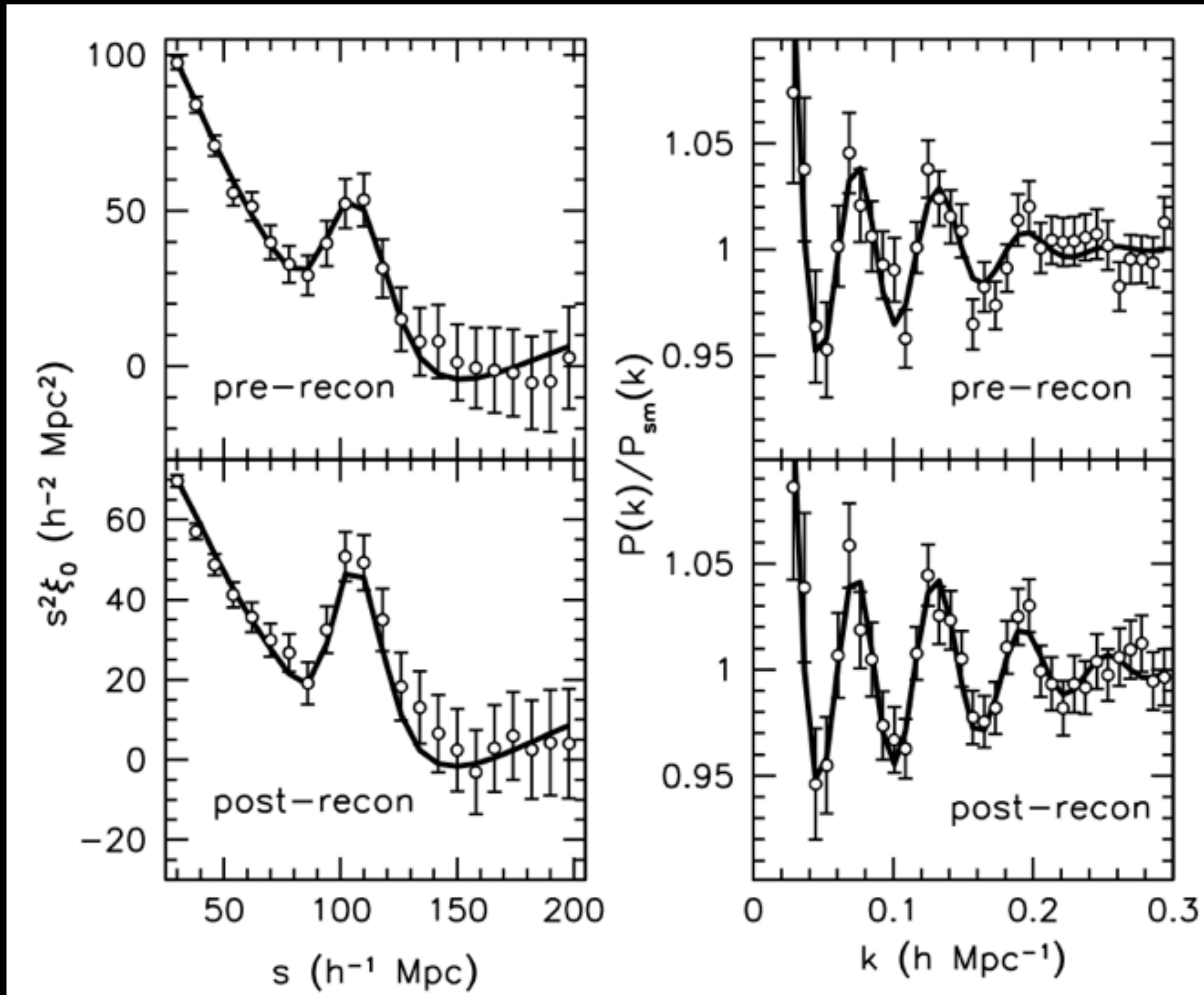
Reconstruction works: real surveys!

- SDSS-II LRGs (z=0.35): 3.5-> 1.9%
  [Padmanabhan et al., 2012, MNRAS, 427, 2132]
- SDSS-III CMASS (z=0.57) : 1.4% -> 0.9%
  [SDSS-III BOSS; arXiv:1312.4877]
- WiggleZ (z=0.4-0.7) ~1.5x improvement despite high shot noise/disjoint survey [Kazin et al., arXiv:1401.0358]



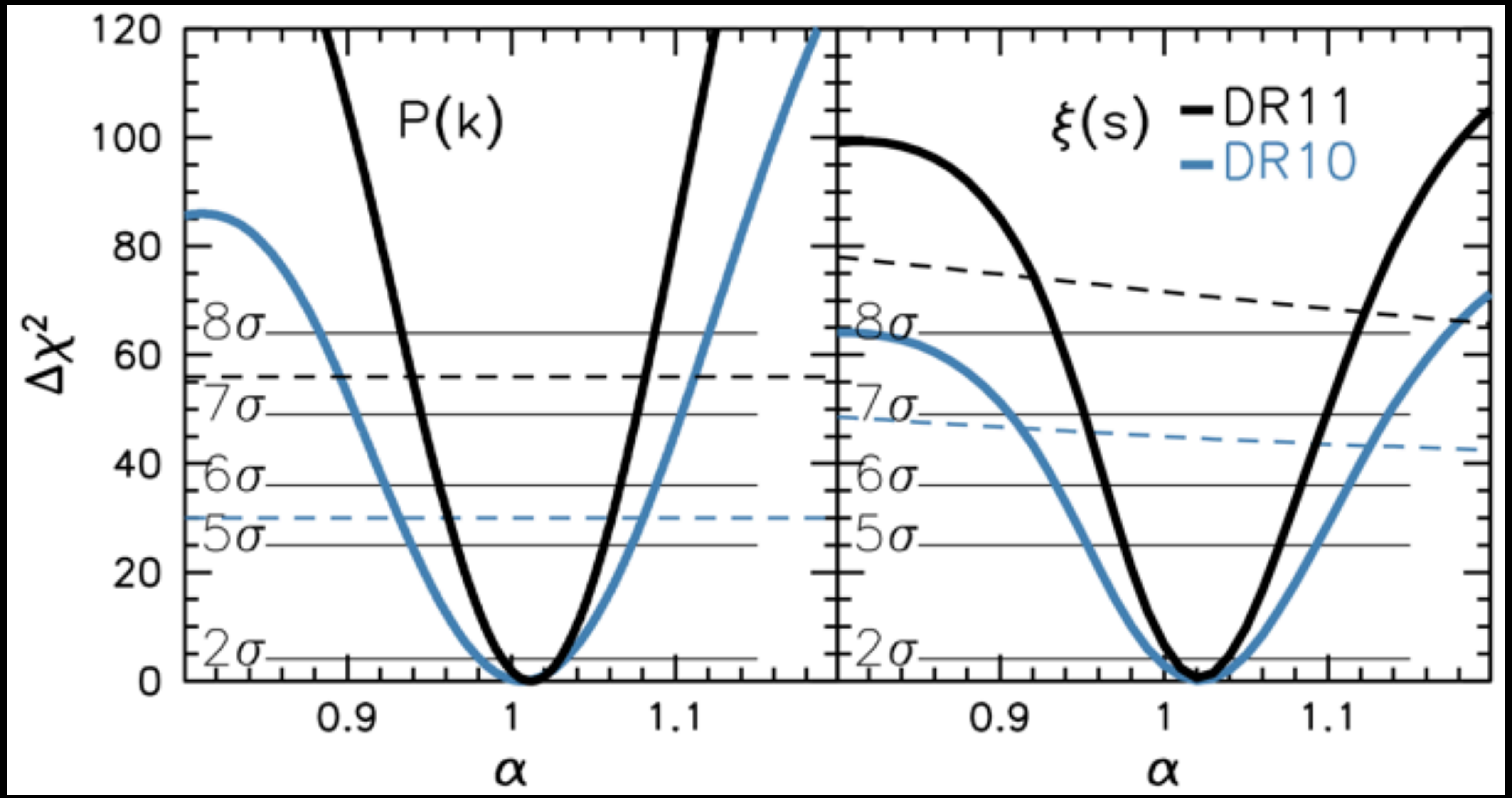
BOSS DR11 CMASS
mocks + data
arXiv:1312.4877

BAO fits: ξ and P



BOSS DR11 results
arXiv:1312.4877

BAO in SDSS-III BOSS CMASS sample: 1% distance constraint at z=0.57!

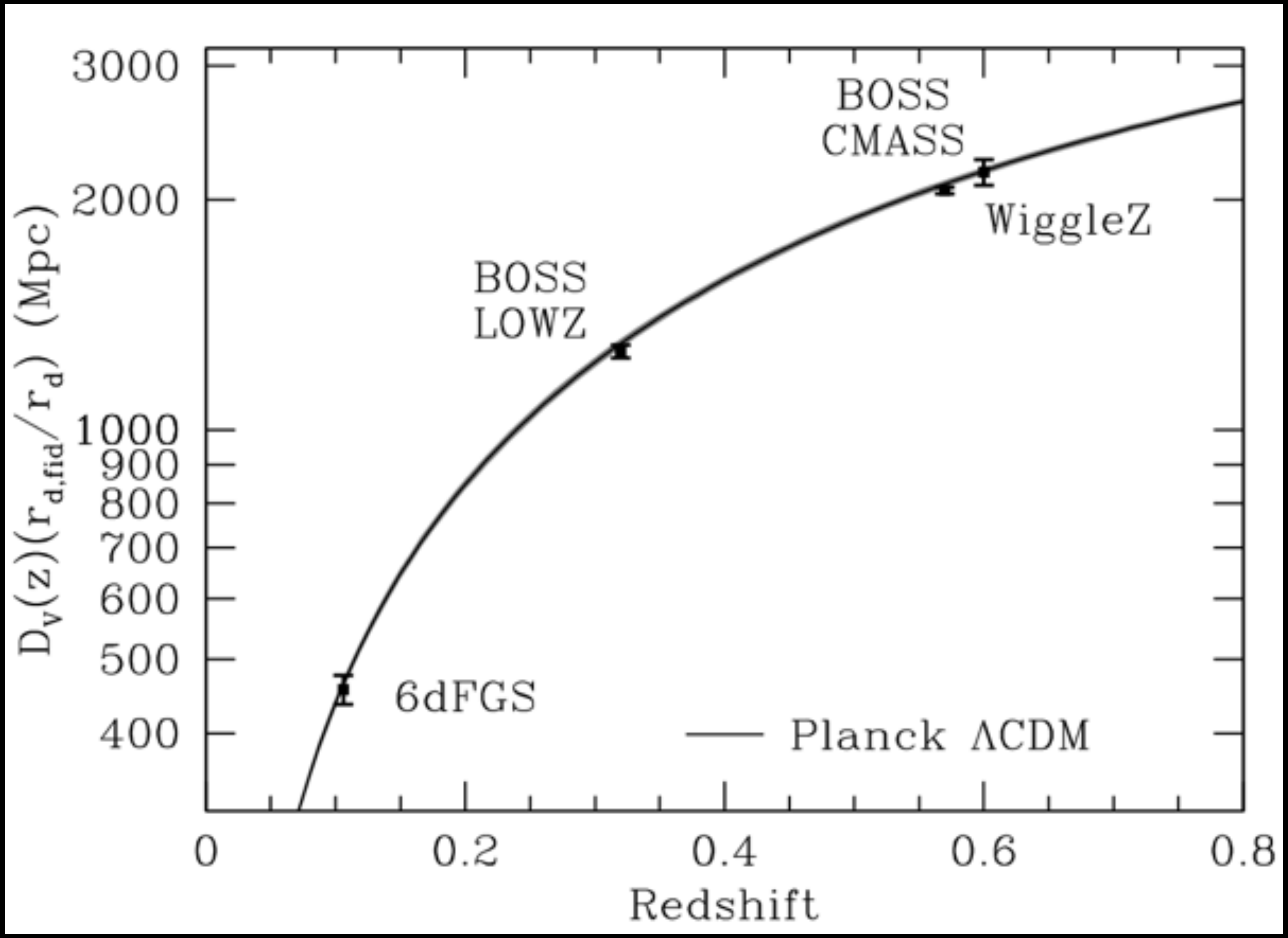


$D_V(z=0.57) = (2056 \pm 20\ \mathrm{Mpc})(s_{BAO}/s_{BAO,fid})$

BOSS, arXiv:1312.4877

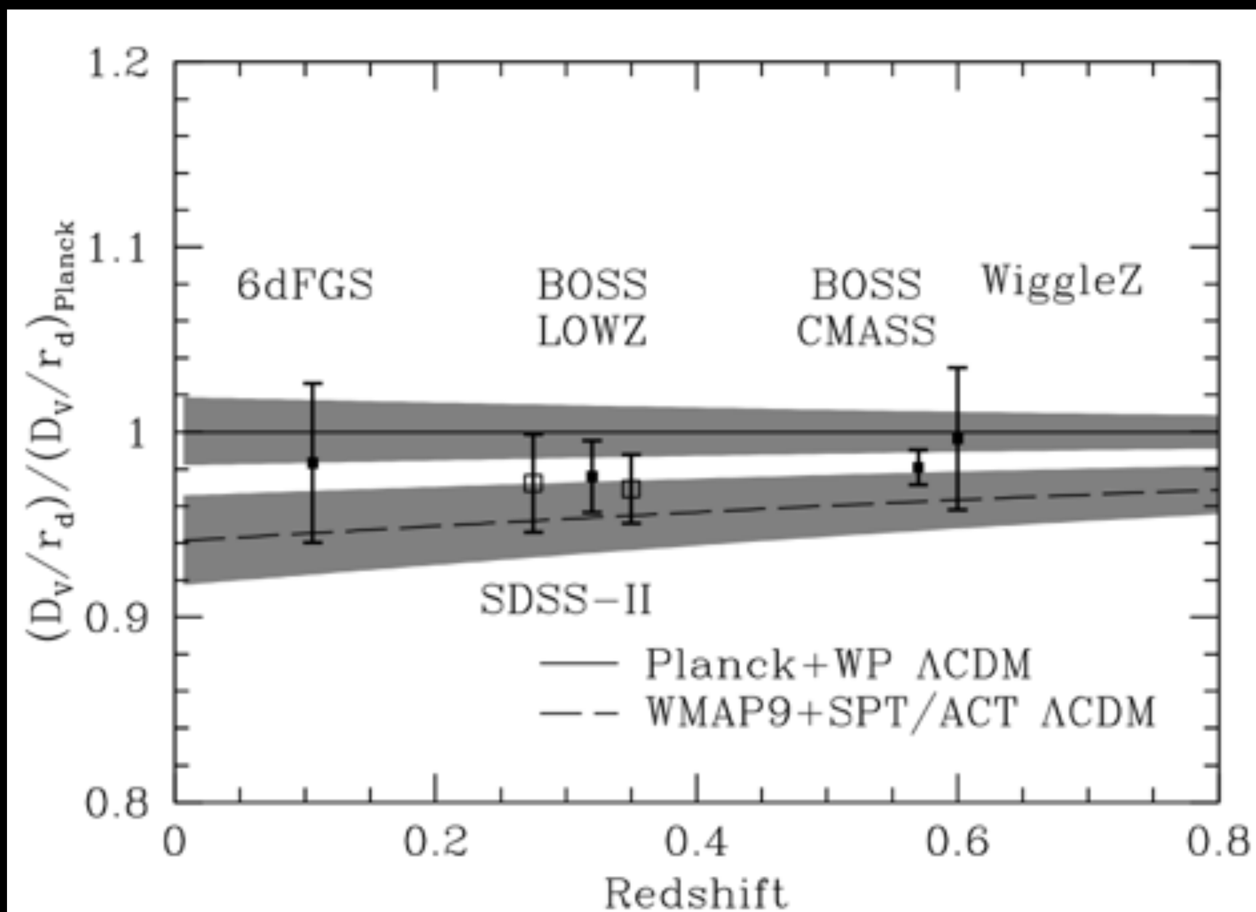
Cosmological Implications of current galaxy BAO measurements

Galaxy BAO distance ladder vs CMB ΛCDM predictions



BOSS, arXiv:1312.4877

Galaxy BAO distance ladder vs CMB ΛCDM predictions



Planck: $\Omega_m h^2 = 0.1427 \pm 0.0024$

eWMAP: $\Omega_m h^2 = 0.1353 \pm 0.0035$

ΛCDM predictions from different CMB data sets differ because of $\Omega_m h^2$ difference; unfortunately BAO data straddle those predictions!

BOSS, arXiv:1312.4877

That's it. Questions?

Large Scale Structure II: Statistics, Baryon Acoustic Oscillations, Redshift Space Distortions, ...

Beth Reid
Cosmology Data Science Fellow
UC Berkeley Center for Cosmological Physics/LBNL

The Sloan Digital Sky Survey 2.5m telescope
Apache Point, New Mexico

Lecture 2 Outline

- Redshift space distortions
- Cosmological constraints from the measurement of anisotropy in two-point statistics
- (Optional) LSS observables for this week's lectures
    - cosmological neutrinos
    - f_{NL}^{loc}
    - LSS tests of modified gravity
    - non-linear RSD details

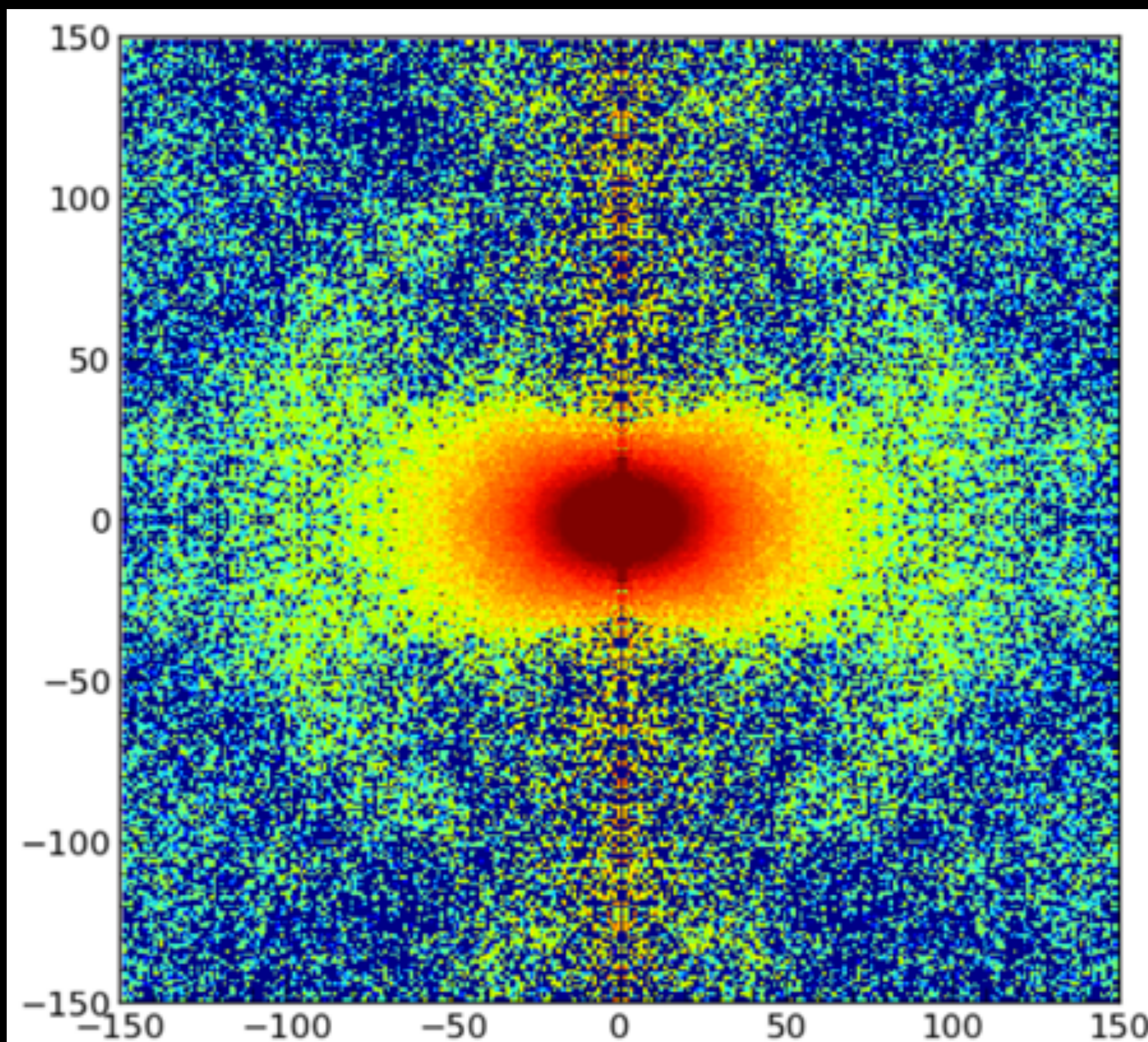
Lecture 2 Outline

- Disclaimer: This lecture contains strong personal opinions from someone working on RSD for the last four years..
- [In particular, configuration space is better than Fourier space!]
- Adult language may be used..

- So far, I have left out one very important detail:

Anisotropy in the observed ξ / P

$\xi(r_\perp, r_\parallel)$

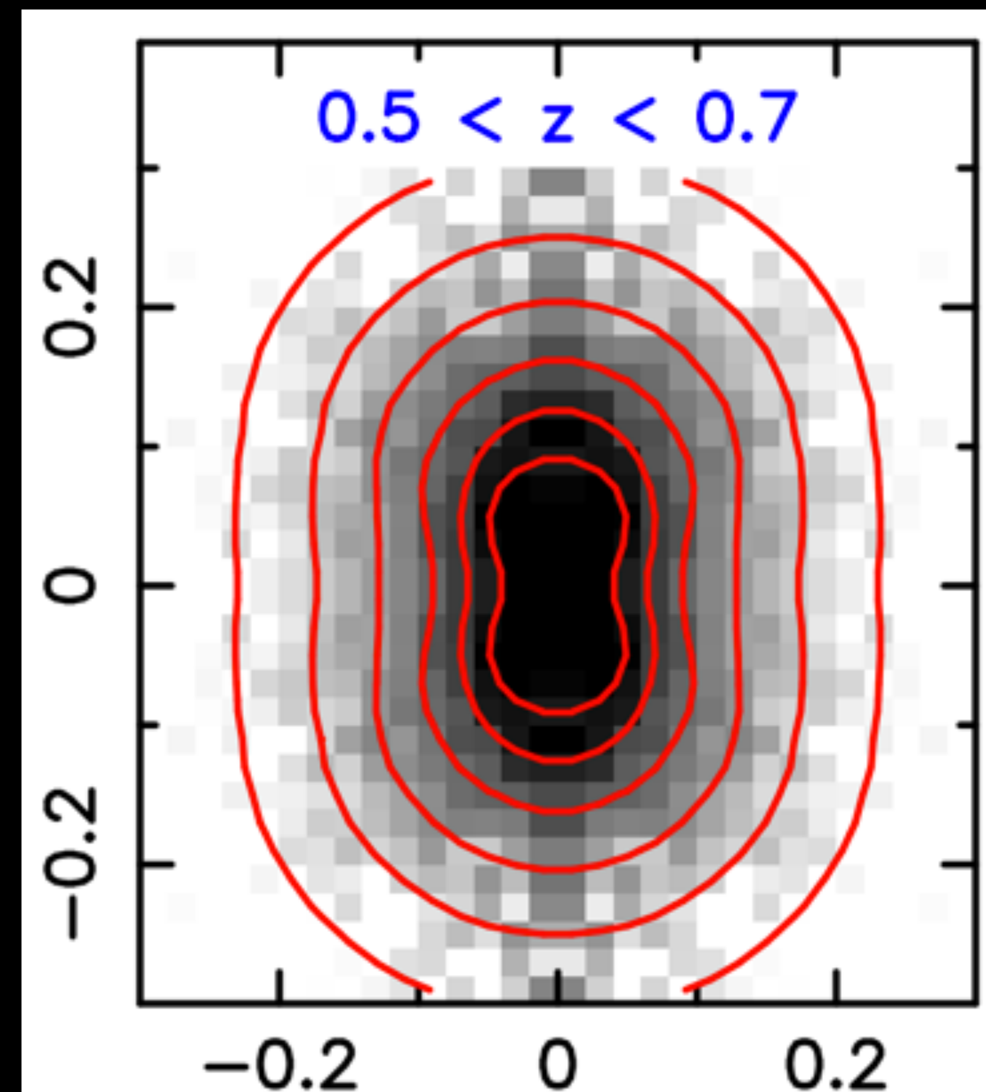


$r_\parallel$ (h^{-1} Mpc)

$r_\perp$ (h^{-1} Mpc)

BOSS DR11, Samushia et al. 2013

$P(k_\perp, k_\parallel)$



$k_\parallel$ (h Mpc $^{-1}$)

$k_\perp$ (h Mpc $^{-1}$)

WiggleZ, Blake et al. 2011

Anisotropy in the observed ξ / P

- The observed two-dimensional ξ / P function is clearly anisotropic, plotted as a function of transverse and line-of-sight (LOS) distances. The primary source of this anisotropy is "redshift space distortions" (RSD).
- The measured spectroscopic redshift can be decomposed into two terms:

$$z_{\rm spec} = z_{\rm cosmo} + \frac{v_{\rm p}^{\rm LOS}}{ac}$$

- The second term comes from the "peculiar" velocity of the object due to inhomogeneities in its local environment

Redshift Space Distortions (RSD)

$$z_{\rm spec} = z_{\rm cosmo} + \frac{v_{\rm p}^{\rm LOS}}{ac}$$

- Since we cannot separate the two terms on an object-by-object basis, we simply infer the radial coordinate of the object assuming $v_p^{LOS} = 0$ when generating 3d galaxy density maps. This leaves coherent distortions in the galaxy maps, since the galaxy density and velocity fields are correlated.

Redshift Space Distortions (RSD)

$$z_{\text{spec}} = z_{\text{cosmo}} + \frac{v_{\text{p}}^{\text{LOS}}}{ac}$$

- Propagating the v_p term into changes in apparent co-moving separation, we find

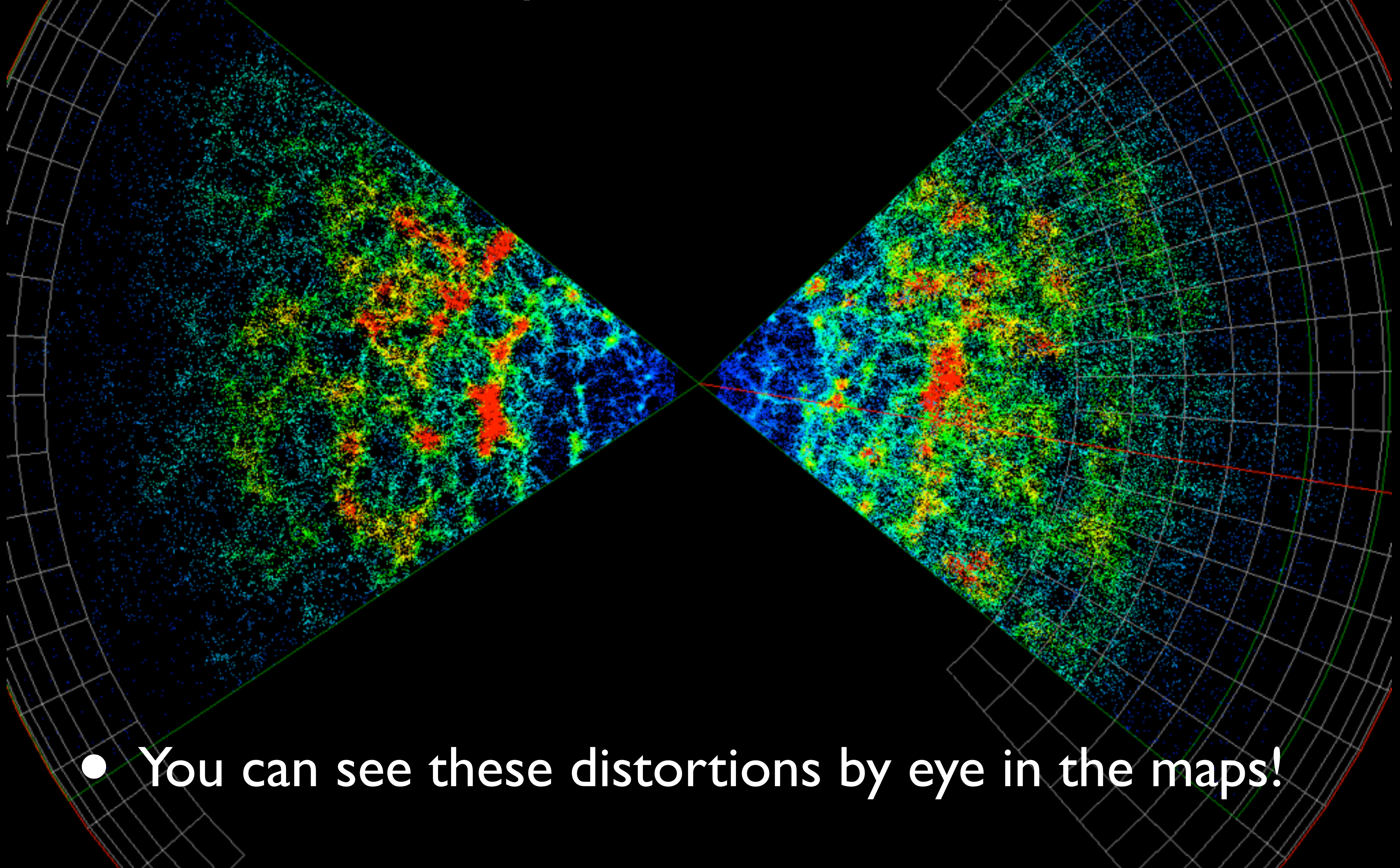
$$\chi(z_{spec}) = \chi(z_{cosmo}) + v_p/aH$$

(Here aH is evaluated at z_{cosmo})

Redshift Space Distortions (RSD)

- When distances are inferred from redshifts like this, we call the coordinate system "redshift space" (usually labelled with **s**), in contrast to "real space" (labeled with ***r***), which we can't measure (except in a simulation).

Redshift Space Distortions (RSD)



- You can see these distortions by eye in the maps!

Image Courtesy 2dFGRS

2014 Shaw Prize other half -- Cole/ Peacock for RSD

www.shawprize.org/en/shaw.php?tmp=5&twoid=79&threeid=231&fourid=411

THE SHAW PRIZE 邵逸夫獎

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Press Release

Announcement of The Shaw Laureates 2014

Tuesday, 27 May 2014. At today's press conference in Hong Kong, The Shaw Prize Foundation announced the Shaw Laureates for 2014. Information was posted on the website www.shawprize.org at Hong Kong time 15:30 (GMT 07:30).

The Shaw Prize consists of three annual prizes: Astronomy, Life Science and Medicine, and Mathematical Sciences, each bearing a monetary award of one million US dollars. This will be the Eleventh year that the Prize has been awarded and the presentation ceremony is scheduled for Wednesday, 24 September 2014.

The Shaw Laureates

The Shaw Prize in Astronomy is awarded in one-half to
Daniel Eisenstein
Professor of Astronomy, Harvard University, USA
and the other half in equal shares to
Shaun Cole
Professor of Physics, Durham University, UK and
John A Peacock
Professor of Cosmology in the Institute for Astronomy, University of Edinburgh, UK

for their contributions to the measurements of features in the large-scale structure of galaxies used to constrain the cosmological model including baryon acoustic oscillations and redshift-space distortions.

2014 Shaw Prize other half -- Cole/ Peacock for RSD

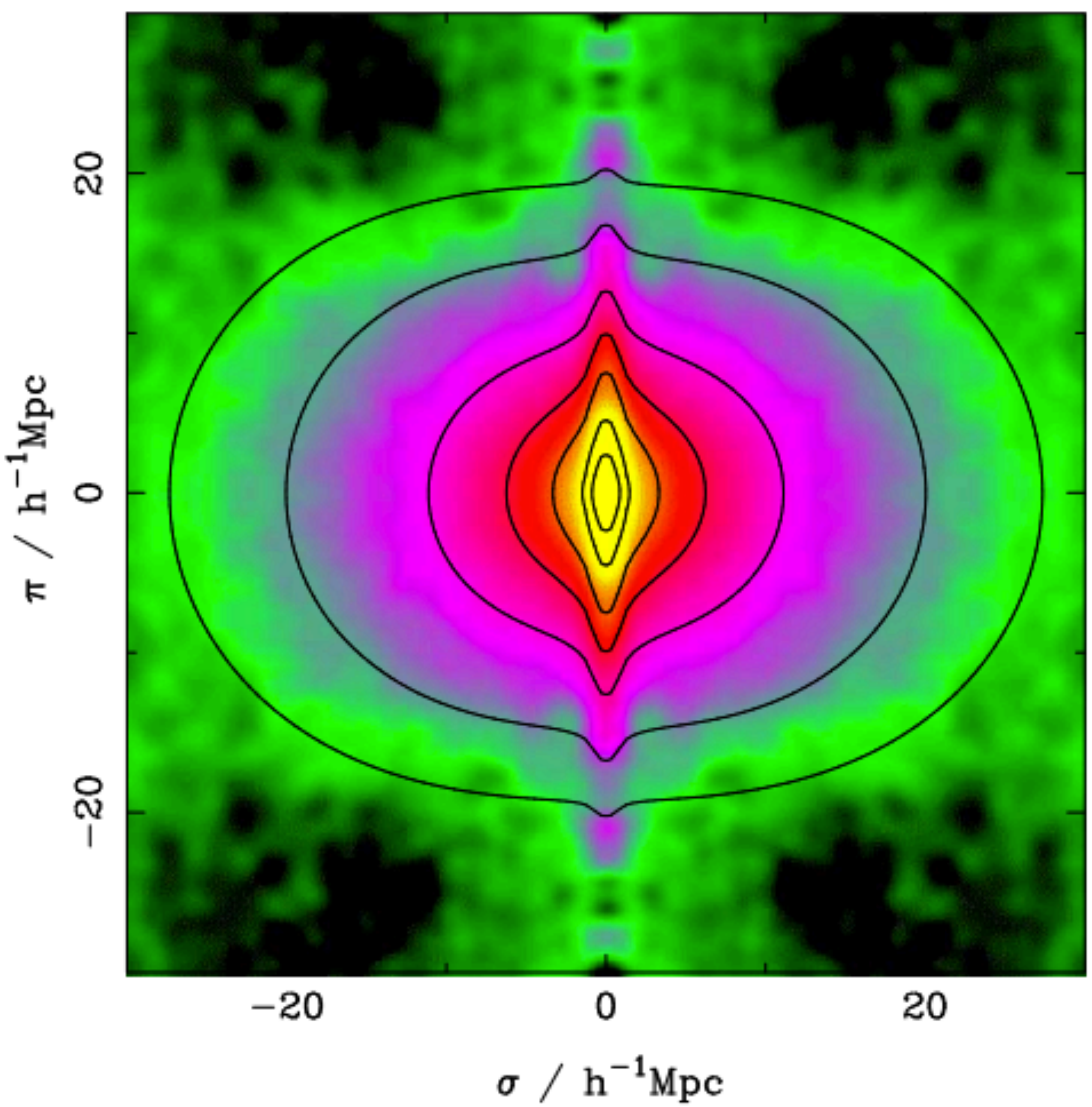


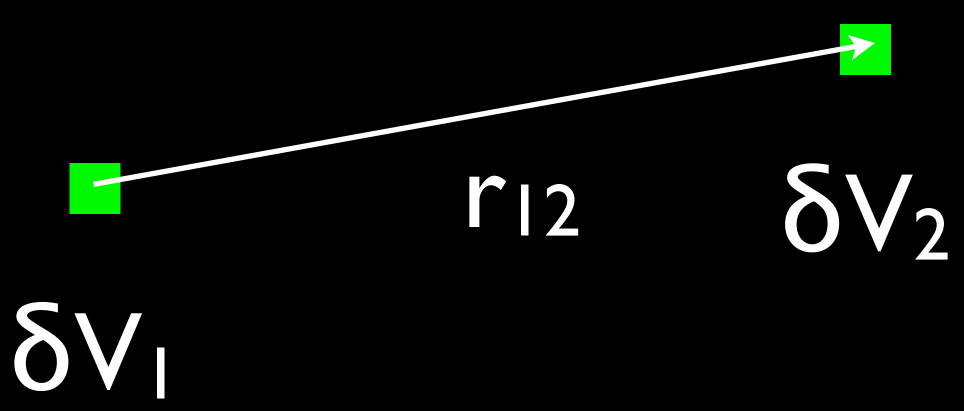
Figure 2 The redshift-space correlation function for the 2dFGRS, $\xi(\sigma, \pi)$, plotted as a function of transverse (σ) and radial (π) pair separation. The func-

Peacock, Cole, et al. Nature 410, 169 (2001)

Redshift Space Distortions (RSD)

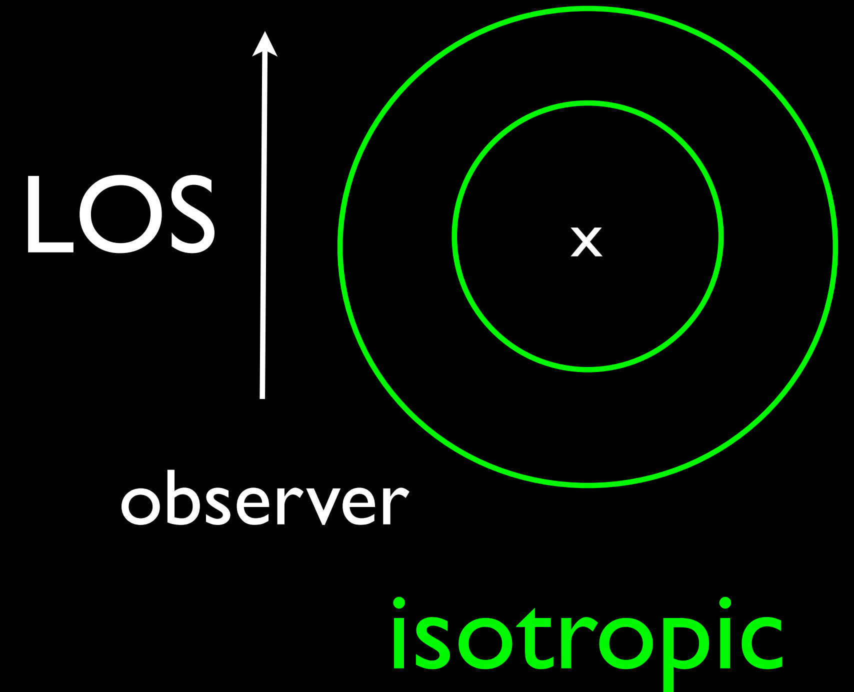
- Now let's try to get a qualitative understanding of the anisotropic distortions in ξ / P due to RSD.
- An equivalent way to think about ξ is as specifying the density field around a tracer object:

$$P(2 \mid 1) = n\,(1 + \xi(r_{12}))\,\delta V_2$$



Redshift Space Distortions (RSD)

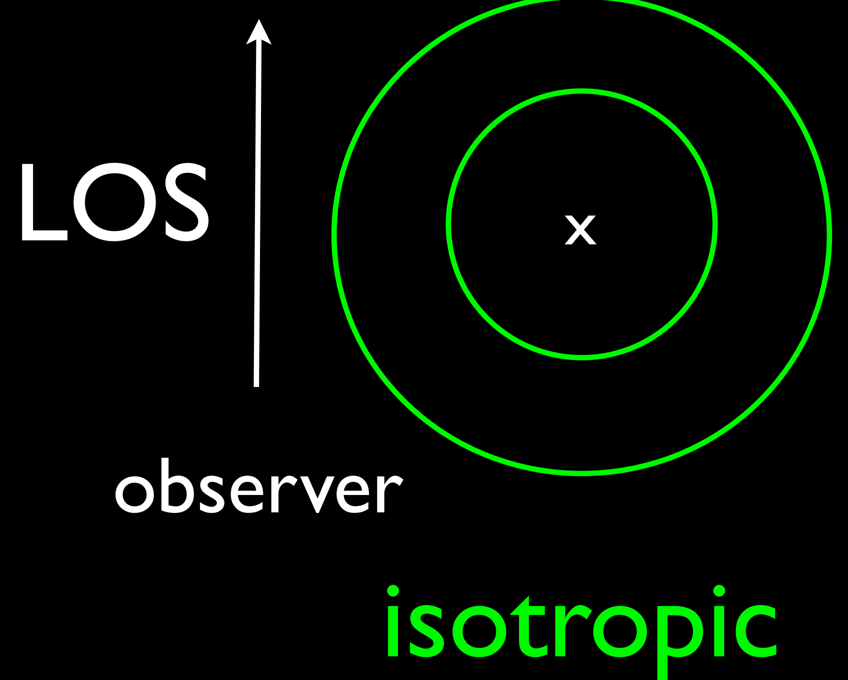
- In "real space" the iso-density contours will be circular:



- How will these contours appear in "redshift space"?

Redshift Space Distortions (RSD)

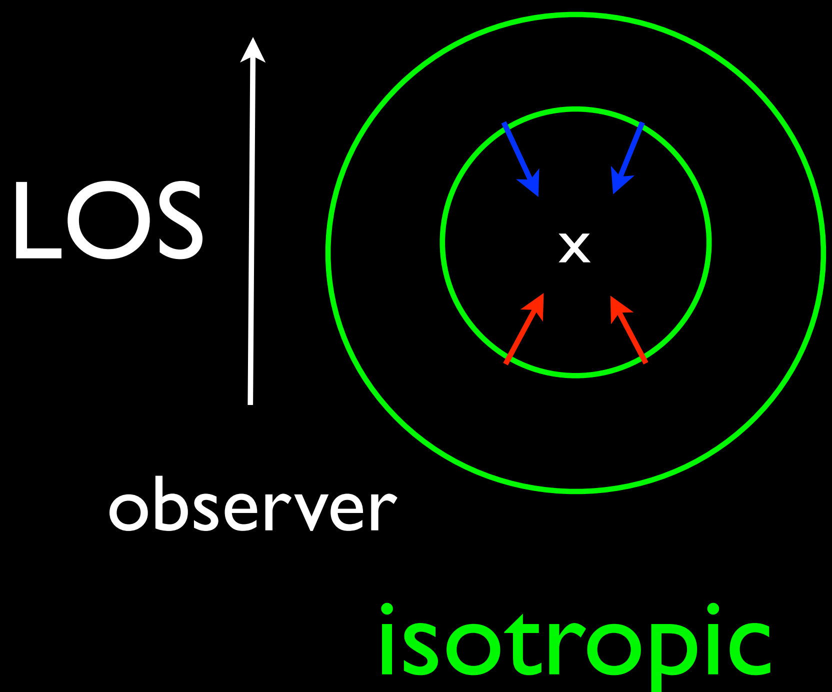
- Use the linearized continuity equation to figure out the velocity field around a point-like density perturbation:



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

Redshift Space Distortions (RSD)

- Use the linearized continuity equation to figure out the velocity field around a point-like density perturbation:



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

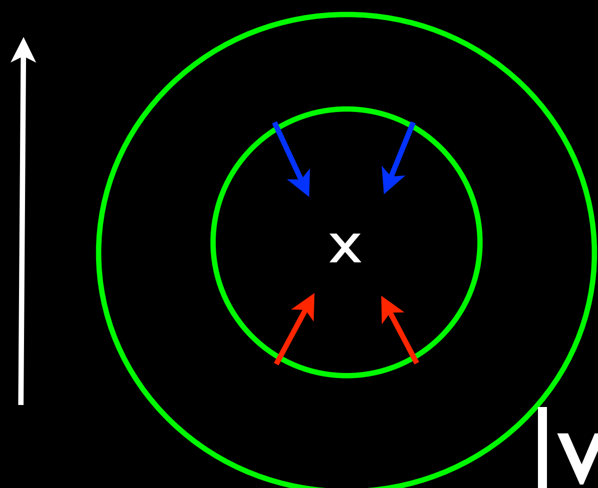
$$[\ \chi(z) = \chi_{true} + v_p/aH\ ]$$

Redshift Space Distortions (RSD)

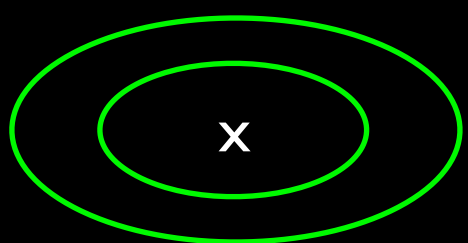
$$\nabla \cdot \mathbf{v_p} = -aHf\, \delta_m$$

[continuity eqn]

LOS



observer



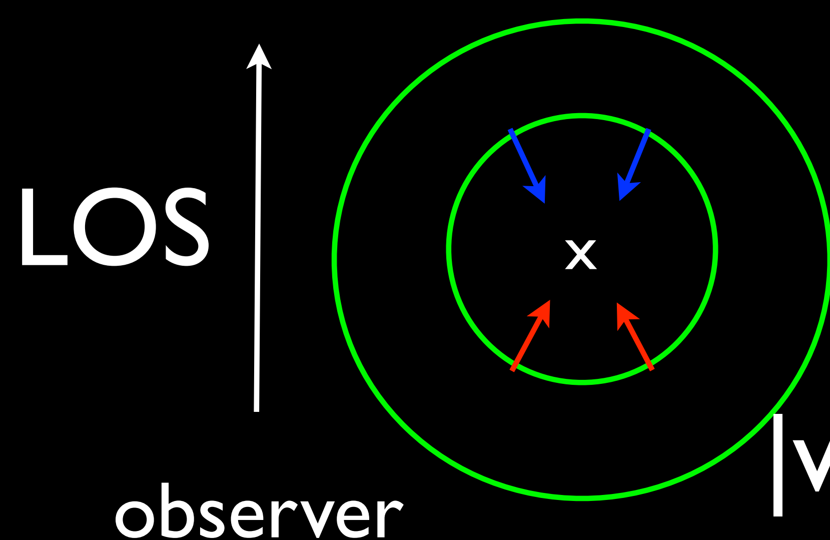
$$|v_p| \sim d\, \sigma_8/d \ln a = \boxed{\sigma_8 * f}$$

isotropic

squashed along line of sight

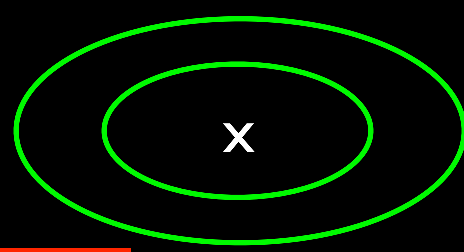
$$f = d \ln \sigma_8 / d \ln a \approx \Omega_m^{\gamma}$$

Redshift Space Distortions (RSD)



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

[continuity eqn]



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

isotropic

squashed along line of sight

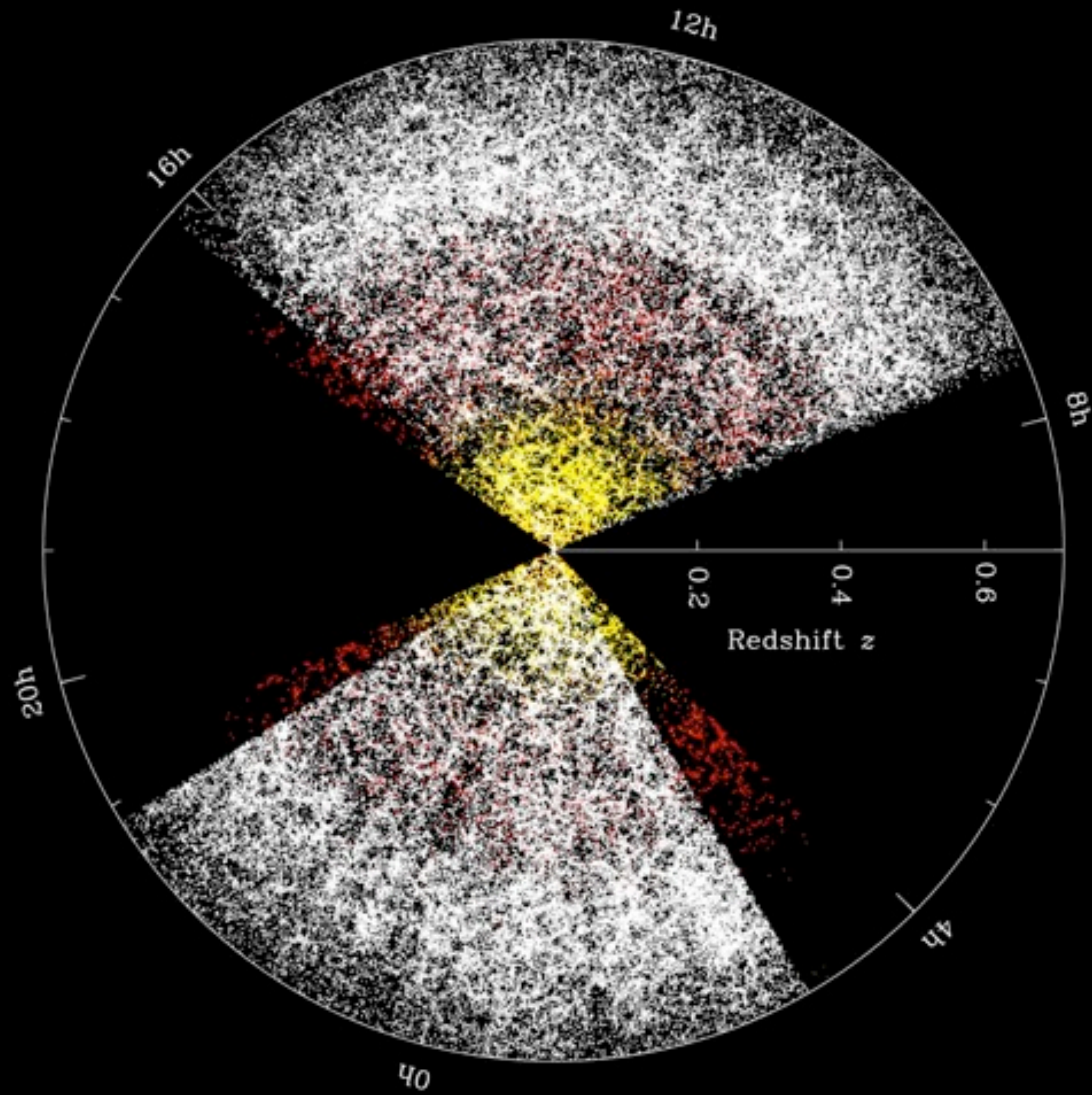
This means that by measuring the anisotropy of clustering, we should be able to measure d σ_8/d ln a, the *growth rate* of cosmic structure.

Redshift Space Distortions (RSD)

- Pop quiz -- how should the ellipticity of the contours change with pair separation r_{12}? This is conceptually important for separating RSD anisotropy from Alcock-Paczynski (geometric anisotropy).

Redshift Space Distortion (RSD) Motivation

- Dark Energy Task Force 3rd report: RSD is "among the most powerful ways of addressing whether the acceleration is caused by dark energy or modified gravity"



Why measure RSD?

- In GR, the growth of linear perturbations is scale independent (does not depend on k)
- In GR, the growth of linear perturbations is determined by the cosmic expansion history:

$$\frac{d^2G}{d\ln a^2} + \left(2 + \frac{d\ln H}{d\ln a}\right)\frac{dG}{d\ln a} = \frac{3}{2}\Omega_{\rm m}(a)G$$

- Modified gravity, dark sector interactions, massive neutrinos, etc. can potentially break GR predictions
- This is why we should measure both the expansion and growth history as precisely as possible.

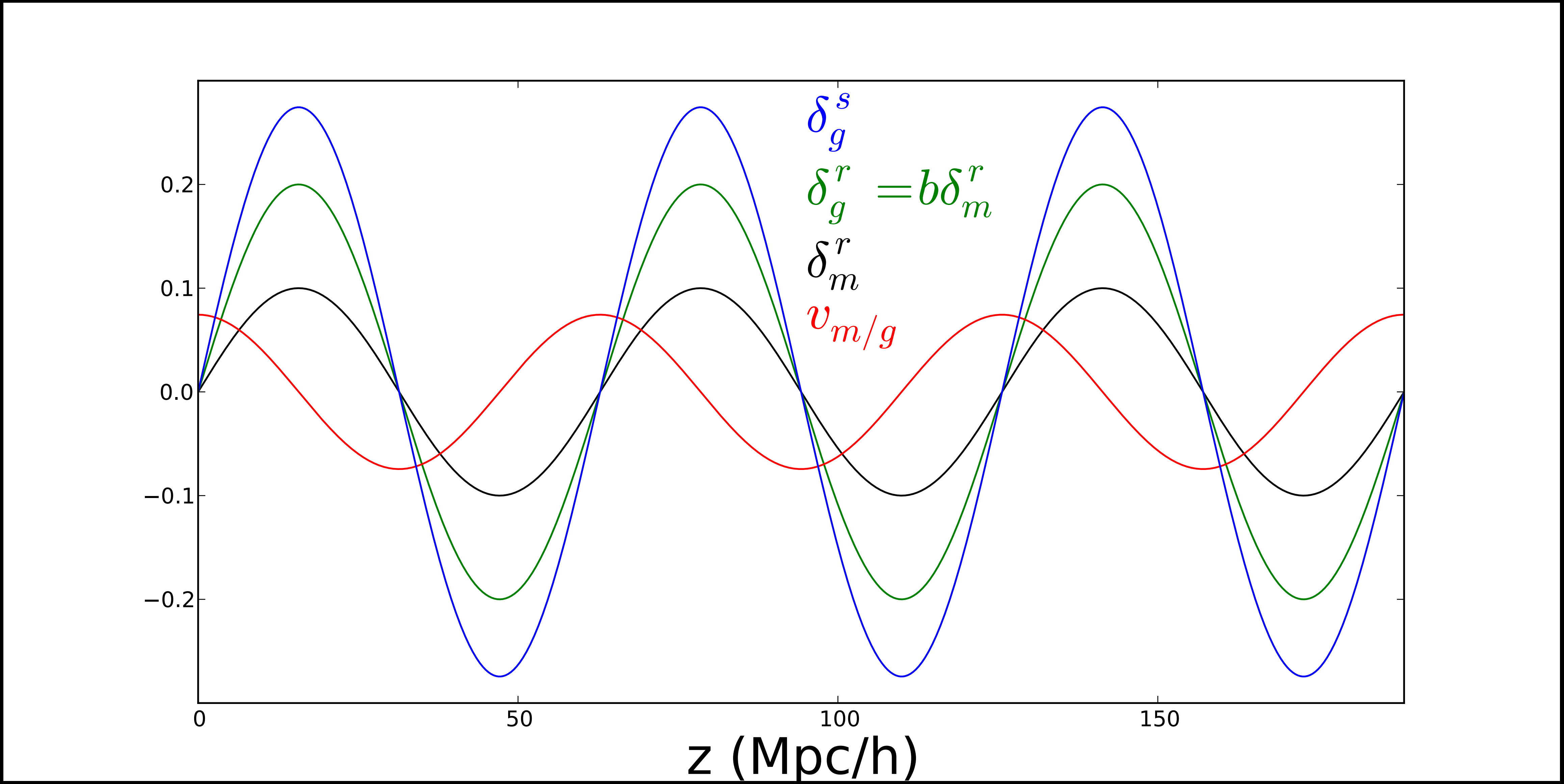
What is broadband/RSD?

- BAO-only analyses isolate information from the BAO feature, and marginalize over smooth contributions to ξ/P. Seen as much more robust to both observational and astrophysical/theoretical systematics.
- Broadband/RSD analyses use all the information in $\xi(r_\perp, r_\parallel)/P\ (k_\perp, k_\parallel)$ on large scales where perturbative models apply

What is broadband/RSD?

- Three classes of model uncertainty to address:
  - non-linear matter clustering
  - non-linear galaxy biasing
  - non-linear velocities (“fingers-of-god”)

RSD in Fourier Space (Kaiser 1987)



Redshift Space Distortions (RSD)

- We will work in the plane-parallel approximation (LOS is along a single Cartesian axis **z** rather than spherical coordinates)
- Start with the conservation of tracers (note you cannot apply this argument to the Ly-α forest, even though the Kaiser formula will hold):

$$(1 + \delta_g^s)d^3s = (1 + \delta_g)d^3r$$

- Compute the Jacobian of the $d^3r \rightarrow d^3s$ transformation

$$\frac{d^3s}{d^3r} = \left(1 + \frac{v_z}{z}\right)^2 \left(1 + \frac{dv_z}{dz}\right)$$

Neglect $v_z/z \ll 1$ [but see Papai & Szapudi 2008, Raccanelli et al 2010] on wide angle effects

Redshift Space Distortions (RSD)

$$1 + \delta_g^s = \left(1 + \delta_g\right)\left(1 + \frac{dv_z}{dz}\right)^{-1}$$

- Now switch to Fourier space, assume **v** is irrotational (so $\theta = -\nabla \cdot \mathbf{v}$): $dv_z/dz = k_z^2/k^2\, \theta(\mathbf{k}) = \mu^2\, \theta(\mathbf{k})$

$$\delta_g^s(k) = \delta_g(k) + \mu^2 \theta(k)$$

- Use linearized continuity equation to relate θ to δ:

$$\theta(k) = f\delta_{\rm mass}(k)$$

- We get a really simple result. Each k-mode remains independent with the same phases as in real space, with amplitude enhanced depending on μ^2.

Redshift Space Distortions (RSD)

- This is the famous Kaiser formula for the redshift space power spectrum:

$$P^s_g(k,\mu) = \left(b + f\mu^2\right)^2 P^r_m(k) = b^2\left(1 + \beta\mu^2\right)^2 P^r_m(k)$$

- The scale dependence of $P^r{}_m(k)$ is known precisely from the CMB (Lecture 1); its amplitude is just $\sigma_8{}^2$.
- If we marginalize over the unknown $b\sigma_8$, we can still use the μ dependence to measure $f\sigma_8$.

Redshift Space Distortions (RSD)

- As discussed last lecture, we want to minimize the number of elements in our data vector, so we don't want to use bins in $\xi(s,\mu)$ or $P(k,\mu)$. Luckily there is a handy decomposition:

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_ℓ (k)

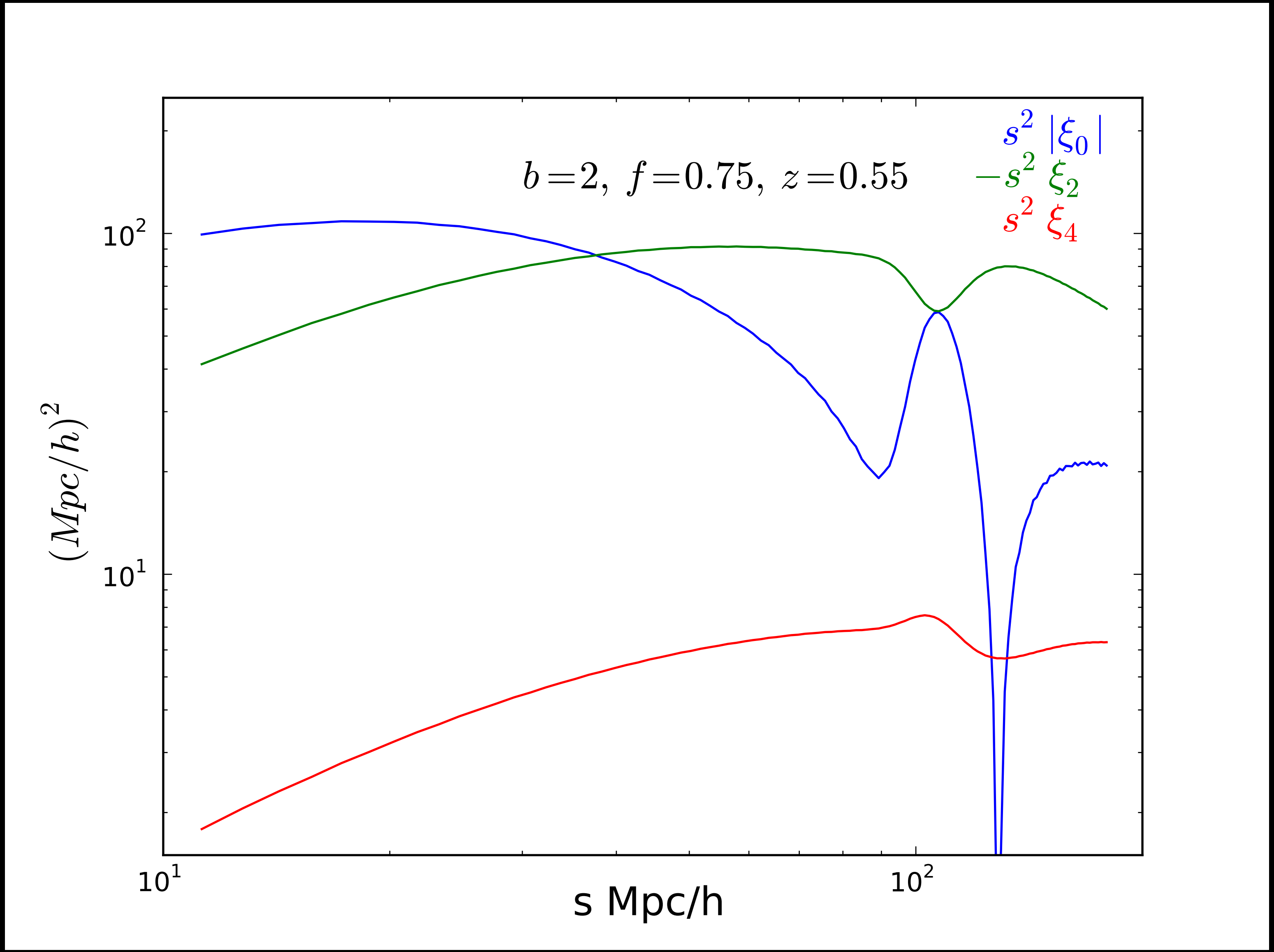
$$\xi_\ell(s) = i^\ell \int \frac{k^2\, dk}{2\pi^2} P_\ell(k) j_\ell(ks)$$

Legendre Polynomial moments: scale dependence

$L_0(\mu) = 1$

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

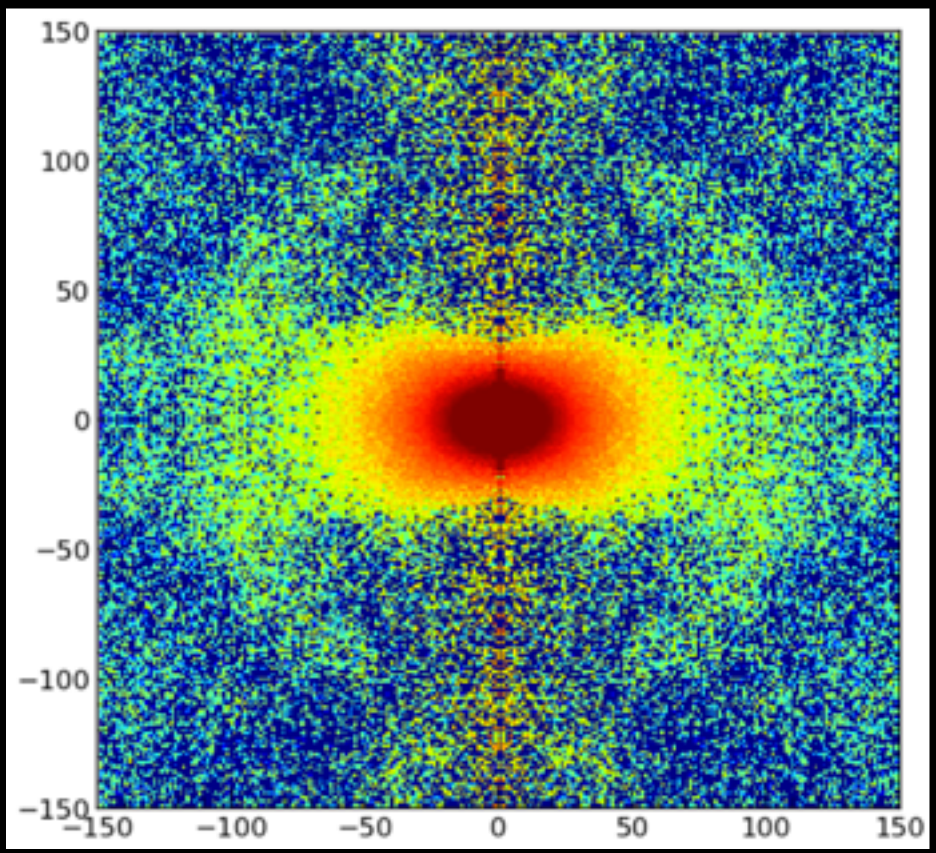
$L_4(\mu) = 4.375\mu^4 - 3.75\mu^2 + 0.375$

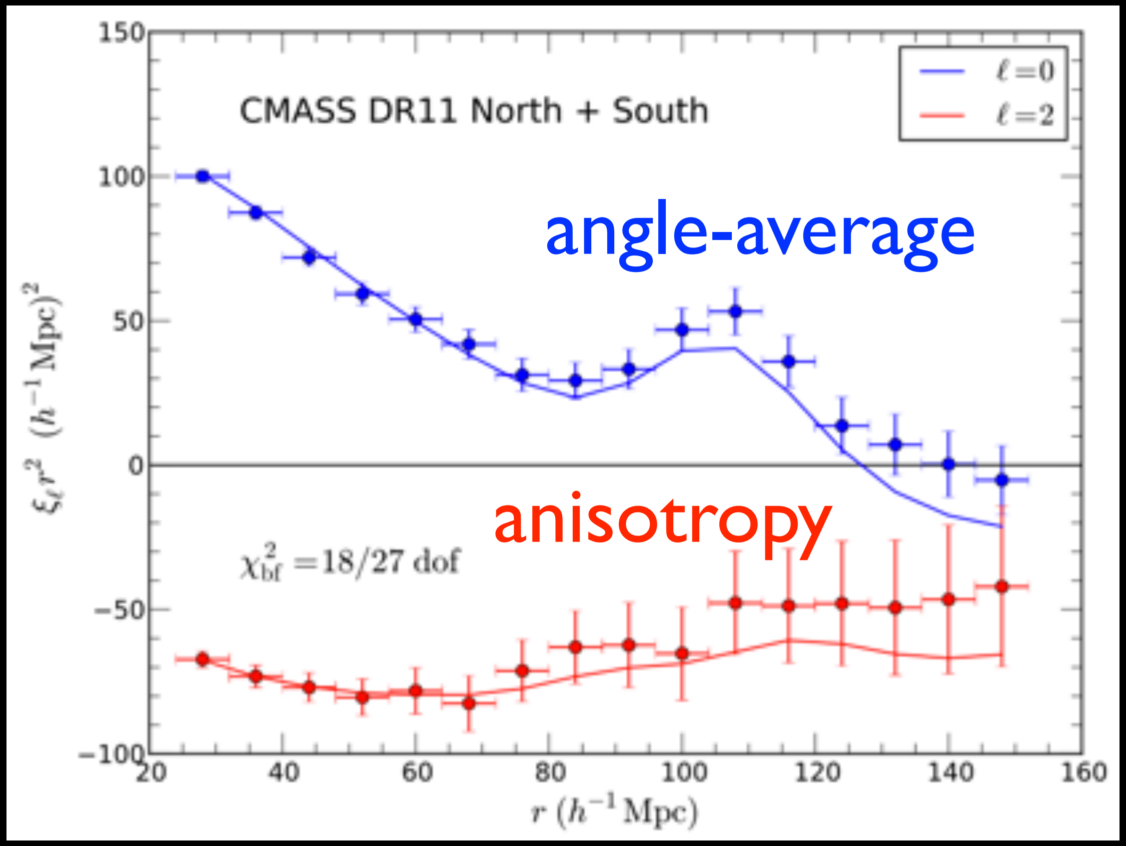


RSD data vector

$\xi(r_\perp, r_\parallel)$ $\longrightarrow$ $$\xi(s,\mu_s) = \sum_\ell \xi_\ell(s) L_\ell(\mu_s)$$

$r_\parallel$ (h^{-1} Mpc)





$r_\perp$ (h^{-1} Mpc) s (h^{-1} Mpc)

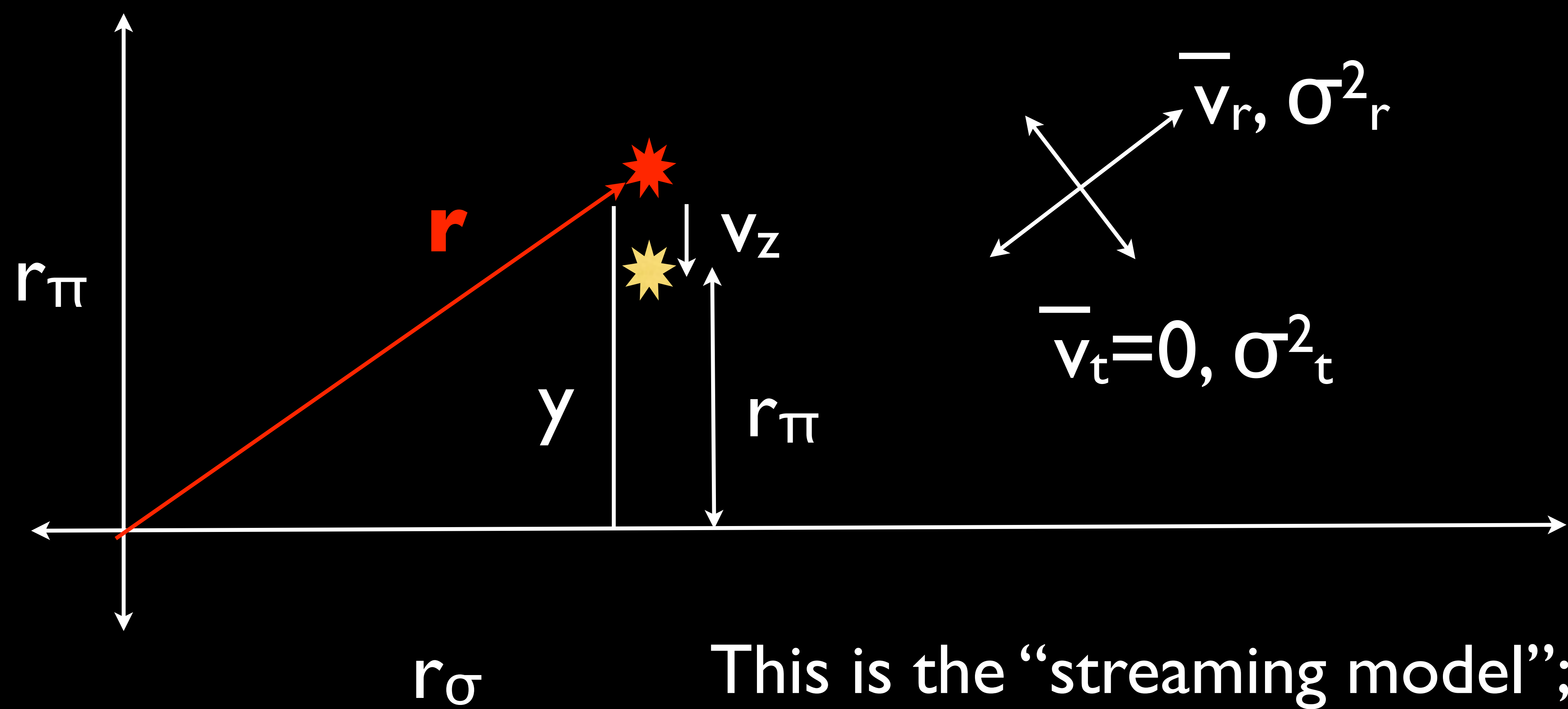
BOSS DR11, Samushia, Reid et al. 2013

Interlude: linear RSD theory in real space

- By re-deriving the Kaiser formula in real space (Fisher 1995, best paper of all time?), we see are making a further assumption (besides perturbations being linear).

Configuration space quantities of interest:

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



This is the "streaming model"; written down in simpler form by Peebles in 1980's

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

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

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

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

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

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

Fisher 1995: the Kaiser formula in configuration space

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

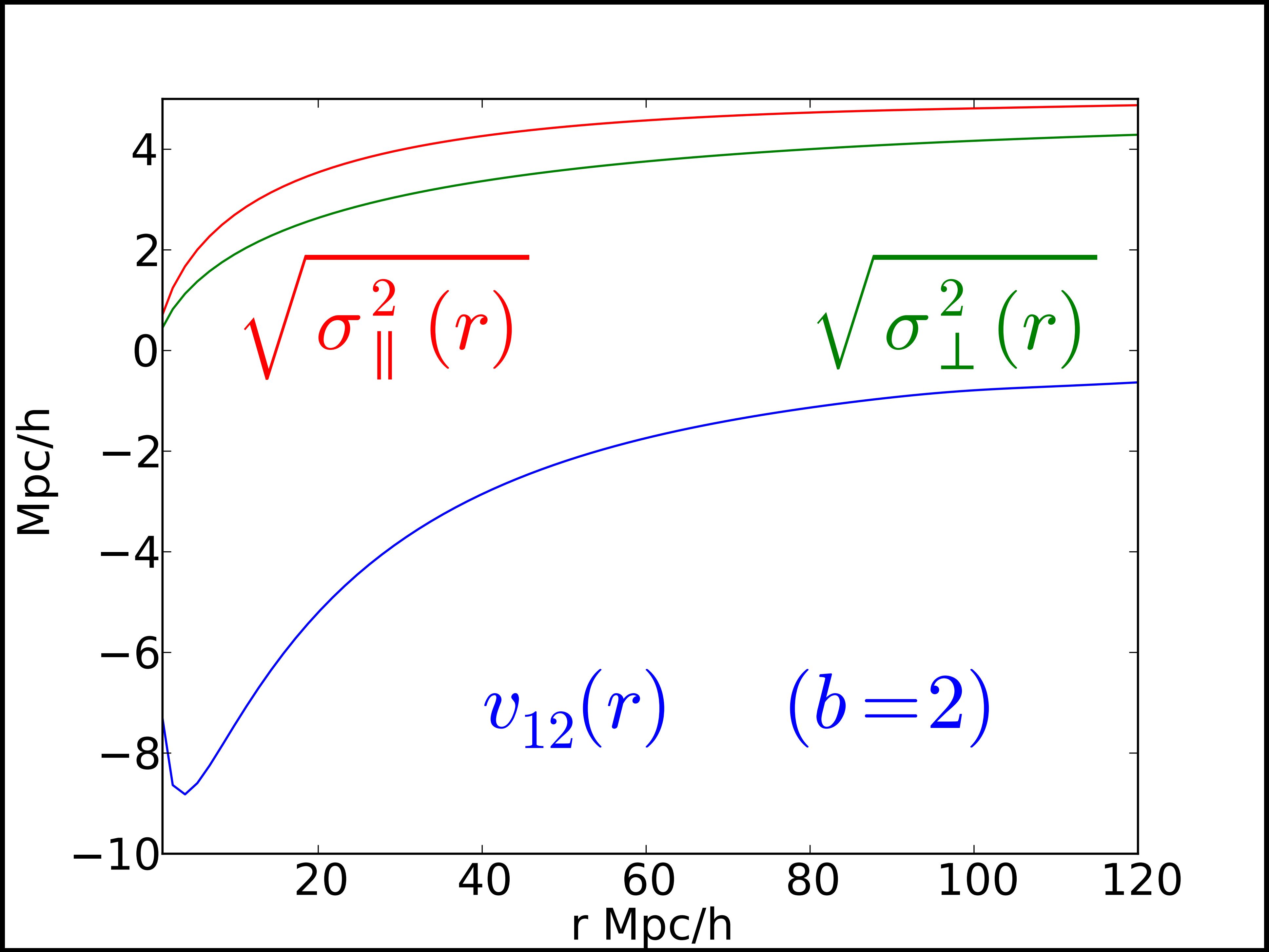
$$1+\xi_g^s(r_\sigma, r_\pi) = \int \frac{dy}{\sqrt{2\pi\sigma_{12}^2(y)}} \exp\left[-\frac{(r_\pi - y)^2}{2\sigma_{12}^2(y)}\right]\left[1+\xi_g^r(r) + \frac{y}{r}\frac{(r_\pi - y)v_{12}(r)}{\sigma_{12}^2(y)} - \frac{1}{4}\frac{y^2}{r^2}\frac{v_{12}^2(r)}{\sigma_{12}^2(y)}\left(1-\frac{(r_\pi - y)^2}{\sigma_{12}^2(y)}\right)\right]$$

- 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



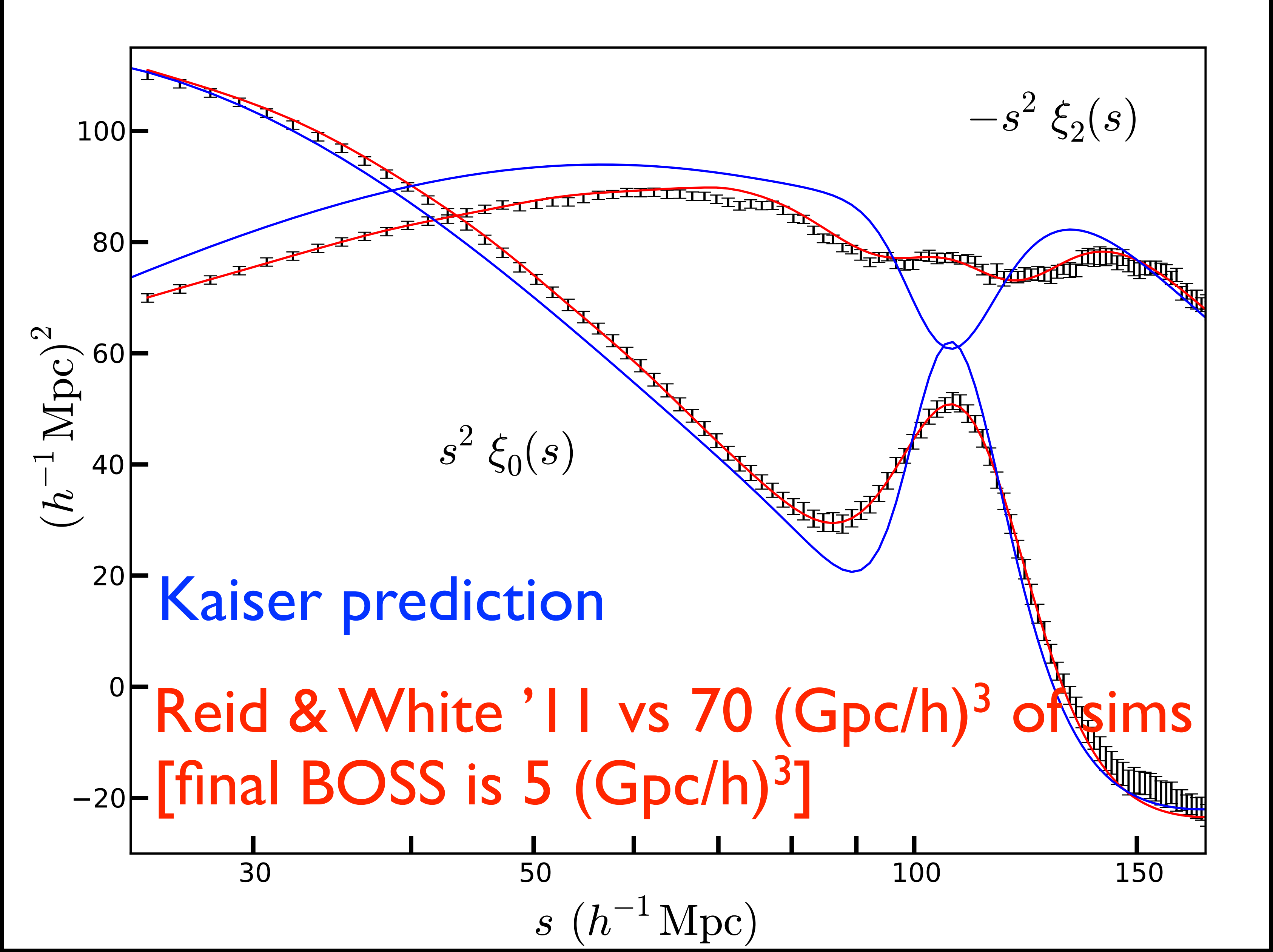
Redshift Space Distortions (RSD)

- Conceptually, we are finished --
  - Now our data vector is $\xi_0(s_i)$ and $\xi_2(s_i)$ [monopole and quadrupole correlation functions, or bandpowers $P_{0,2}(k_i)$]
  - Use the Kaiser formula predictions to fit for $f\sigma_8$ and marginalize of $b\sigma_8$, given the underlying linear matter power spectrum constrained from the cosmic microwave background.
  - But... recall from last lecture the list of modeling complications we can safely ignore for BAO analyses

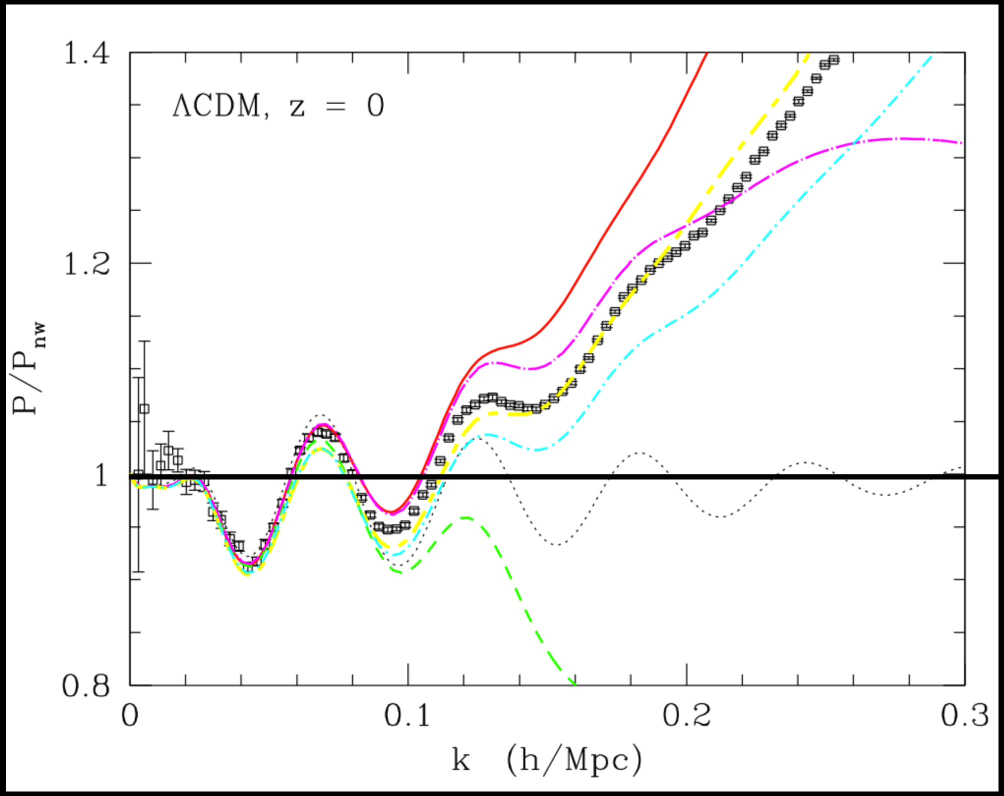
Non-linearities in galaxy clustering

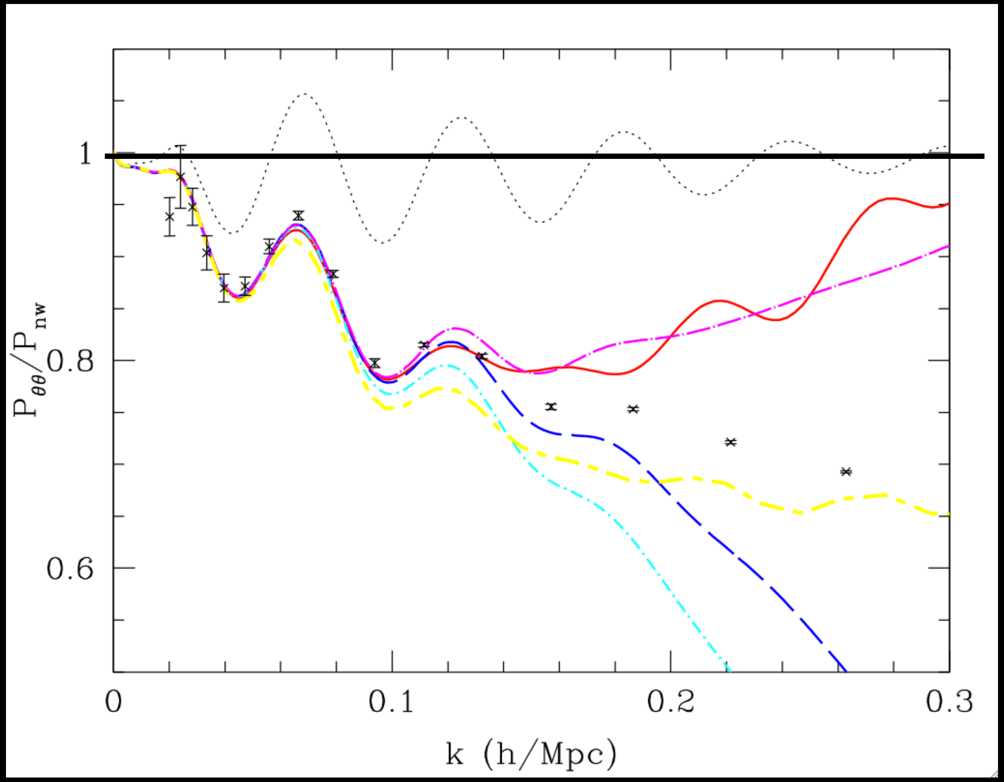
- Lots of complicated physical effects alter the galaxy ξ/P away from its linear theory behavior:
  - non-linear gravitational evolution
  - non-linear biasing between tracers and matter field [nothing new to say in this lecture, but this is a mandatory but challenging topic for any aspiring RSD theory]
  - non-linear redshift space distortions

Kaiser prediction is not accurate enough.



Velocity field is non-linear on very large scales!





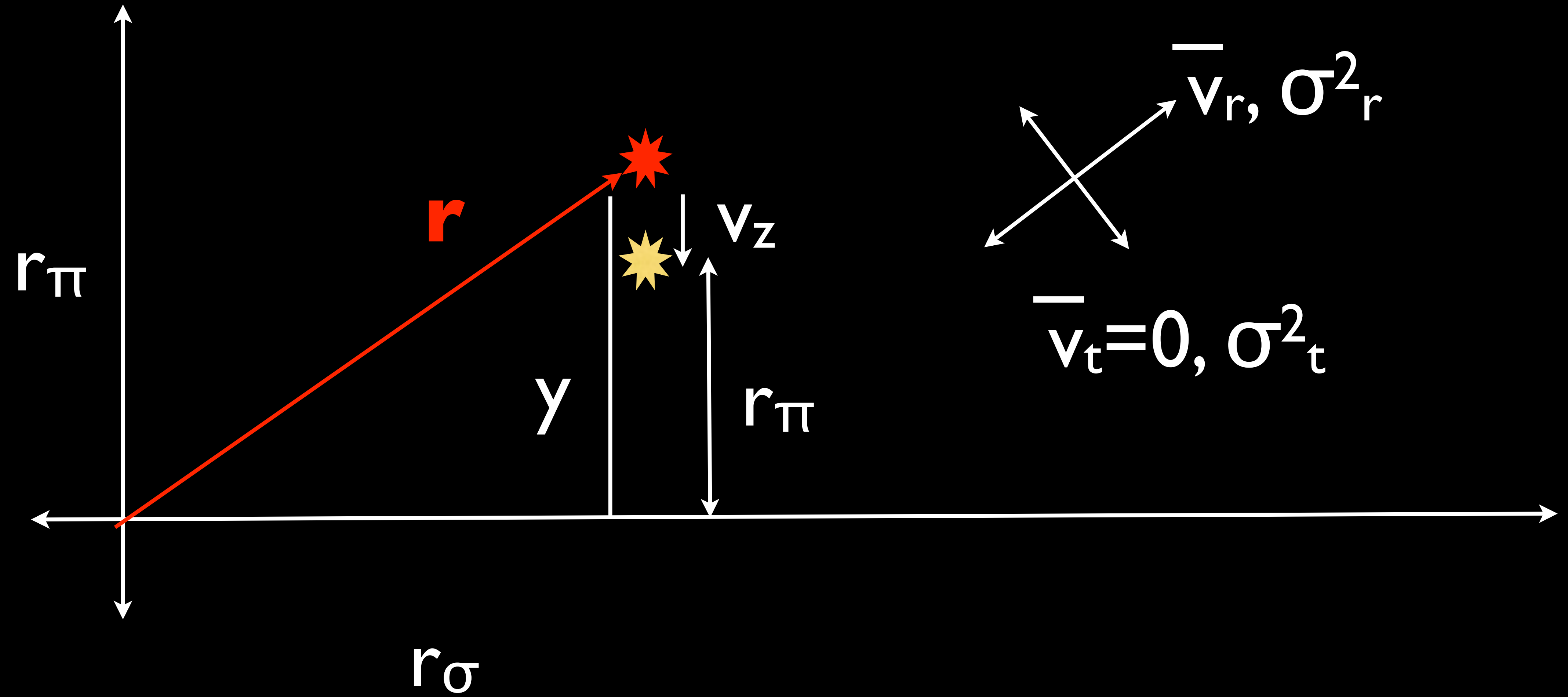
$P_{\delta\delta}/P_{nw}$ $P_{\theta\theta}/P_{nw}$

k (h/Mpc)

Carlson, White, Padmanabhan 2009 arXiv:0905.0479

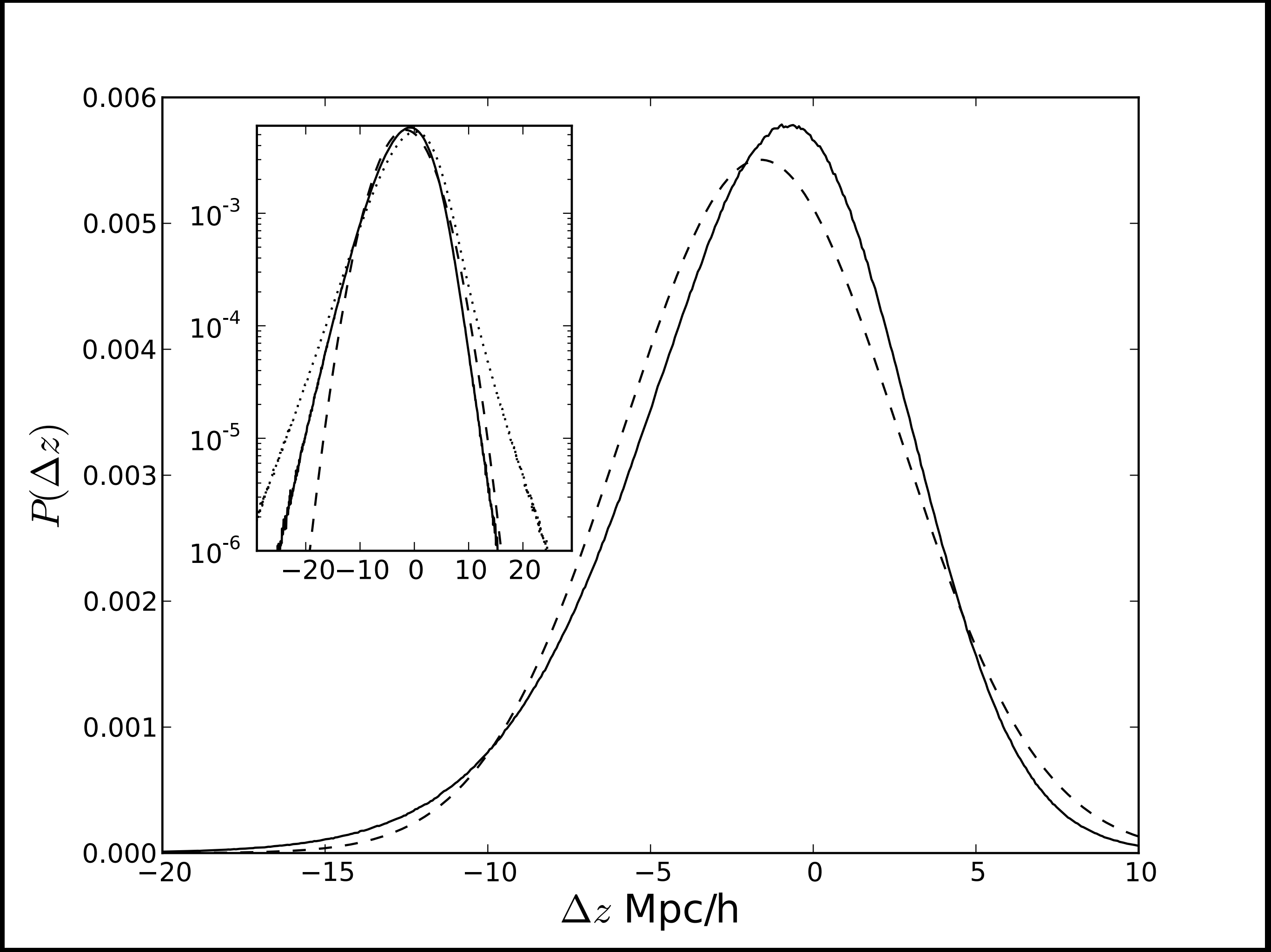
The scale-dependent Gaussian streaming model ansatz addresses the $y \approx r_\pi$ approximation

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

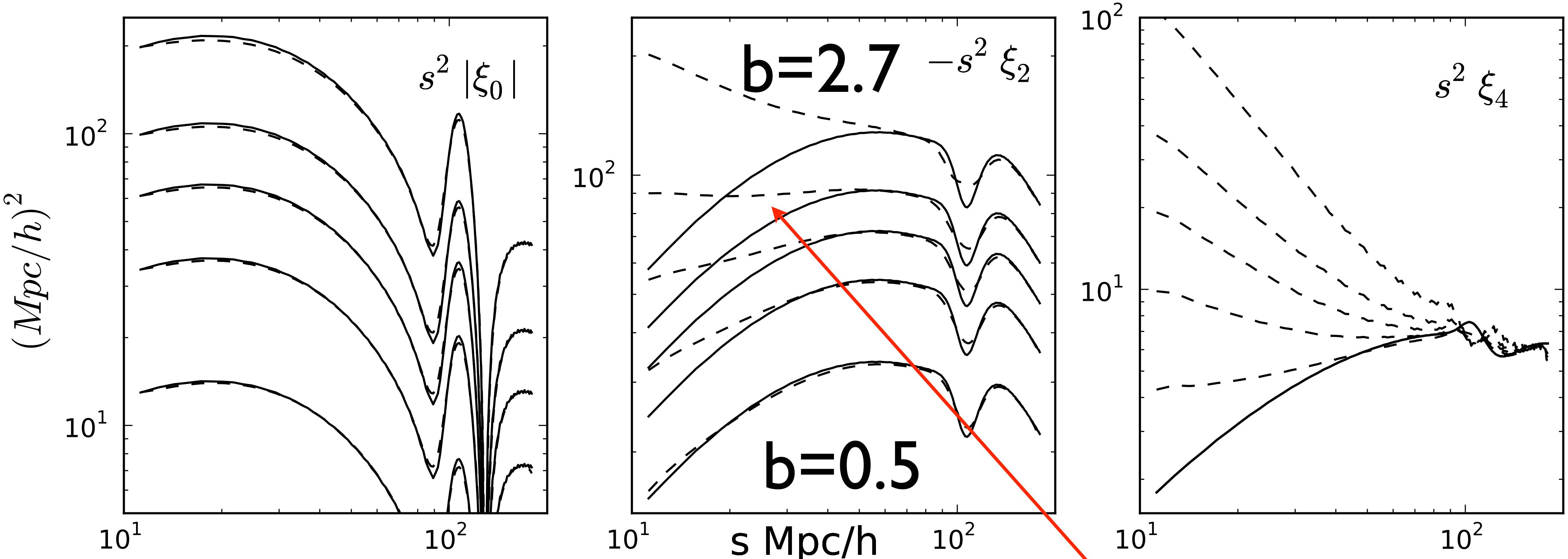


The scale-dependent Gaussian streaming model ansatz addresses the $y \approx r_\pi$ approximation

- 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
- This is the best-performing model to analyze BOSS data; Uros is trying to change that!



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



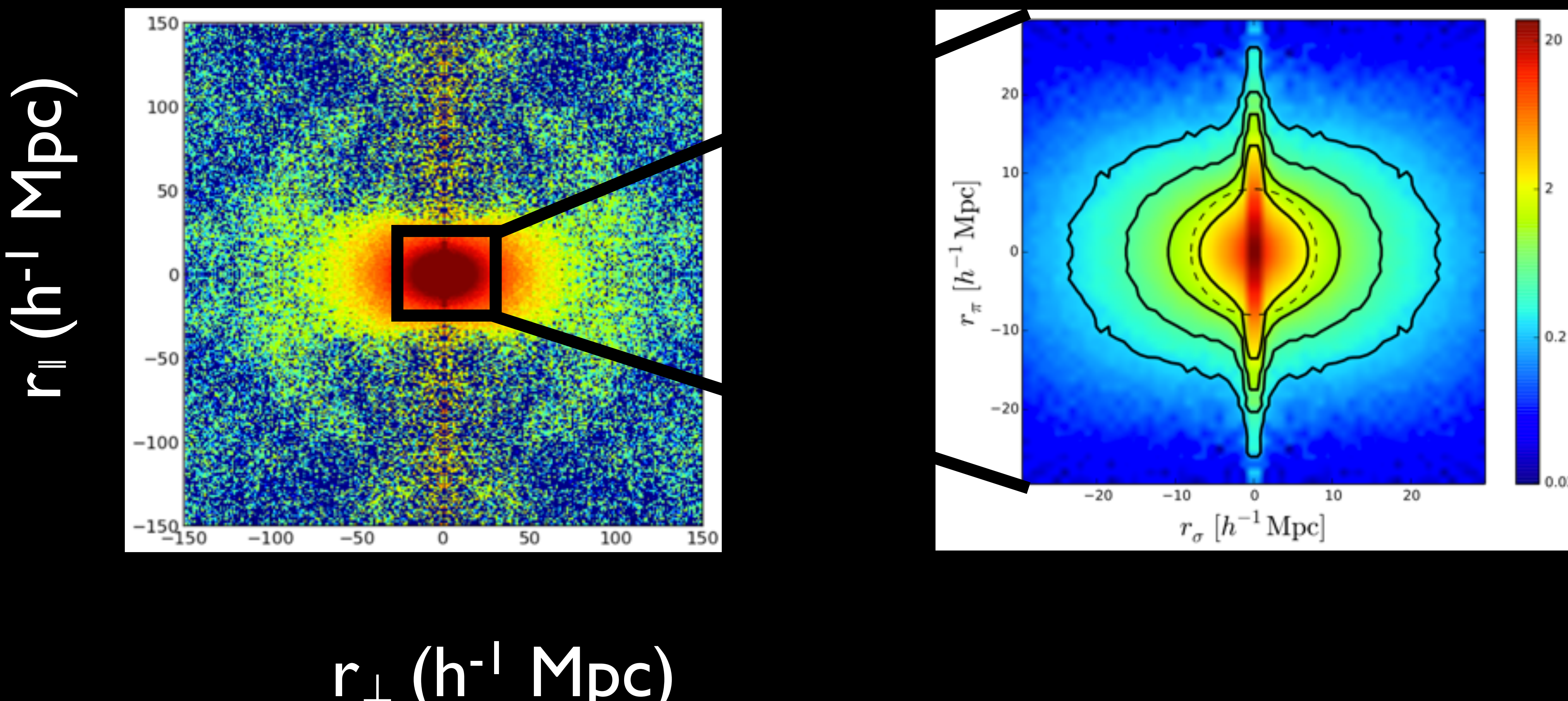
Kaiser limit

Gaussian streaming model

b³ correction !!

Fingers-of-God

- In particular, we need to account for the "Finger-of-God" (FOG) effect

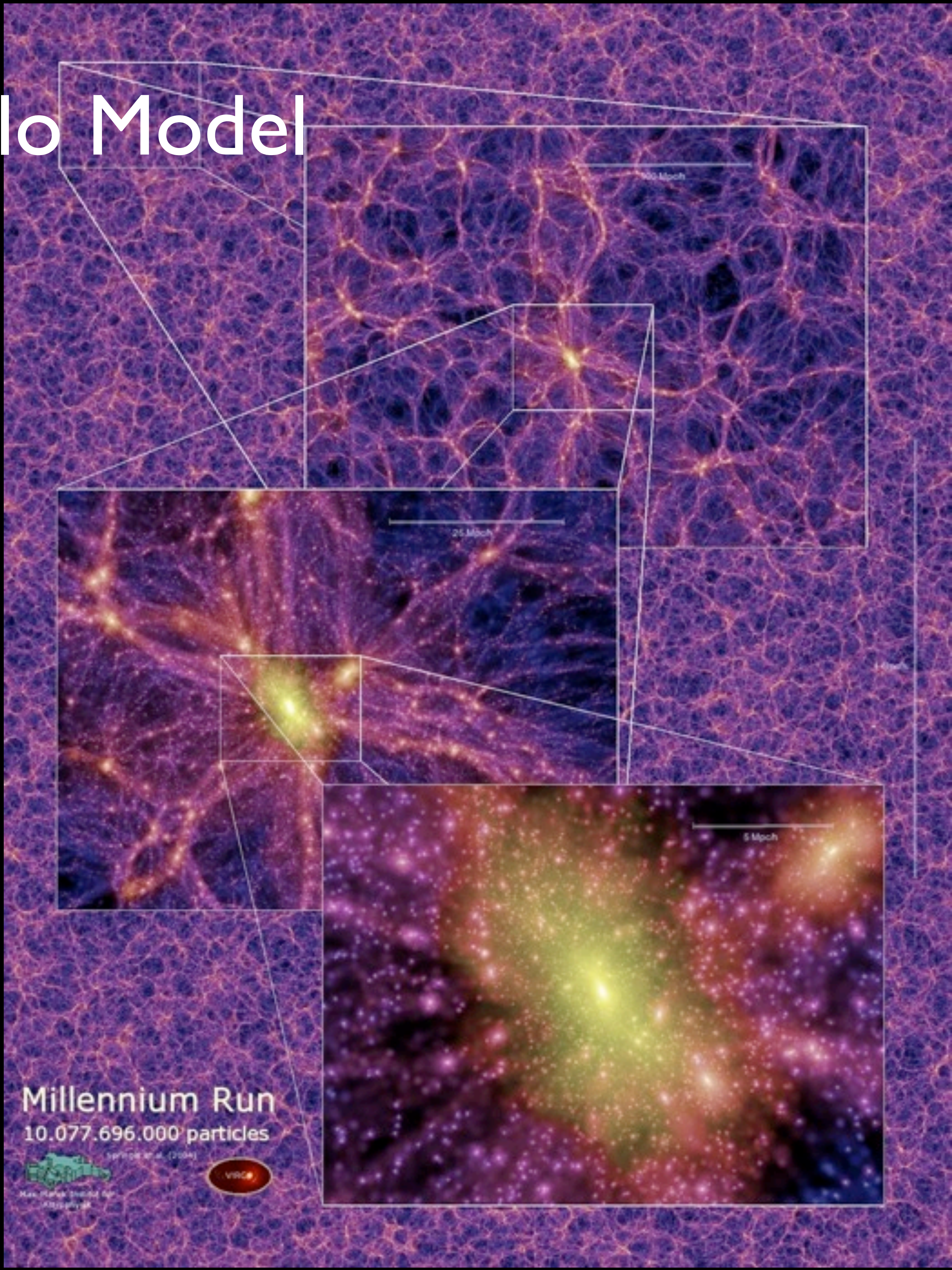


BOSS DR11, Samushia, Reid et al. 2013

Reid et al. 2014

The Halo Model

- Gas accumulates in gravitationally-bound dark matter halos, forms galaxies
- Halo mass determines $P(N_{gal})$, the probability that a given halo hosts N_{gal} galaxies
- “Central” galaxies reside at the potential minimum of the halo potential, “satellites” orbit within the halo potential
- “Fingers-of-God” are caused by the virial motions of galaxies within their host halos

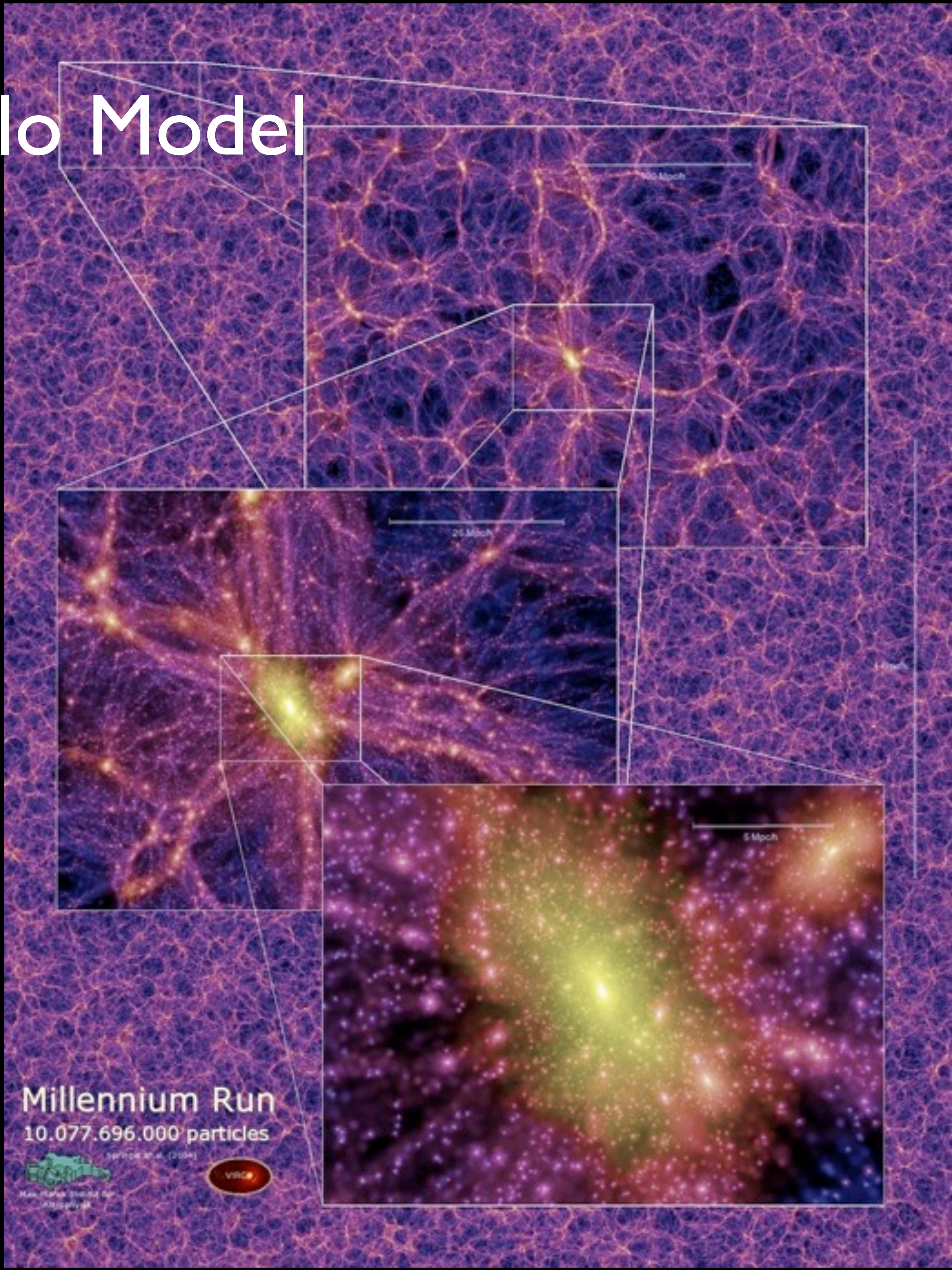


The Halo Model

- “Fingers-of-God” are caused by the virial motions of galaxies within their host halos
- If we treat the virial motions as uncorrelated with the quasi-linear velocity field of interest, then we just need to convolve our model correlation function with the probability distribution function of intrahalo velocities [often approximated as Gaussian or exponential with unknown dispersion σ^2_{FOG}; both work.]

The Halo Model

- With this ansatz (galaxies live in dark matter halos), we also compute non-linear biasing and non-linear velocity contributions by studying dark matter halo clustering in N-body simulations
- This is the gold standard by which higher-order perturbation theories are tested.



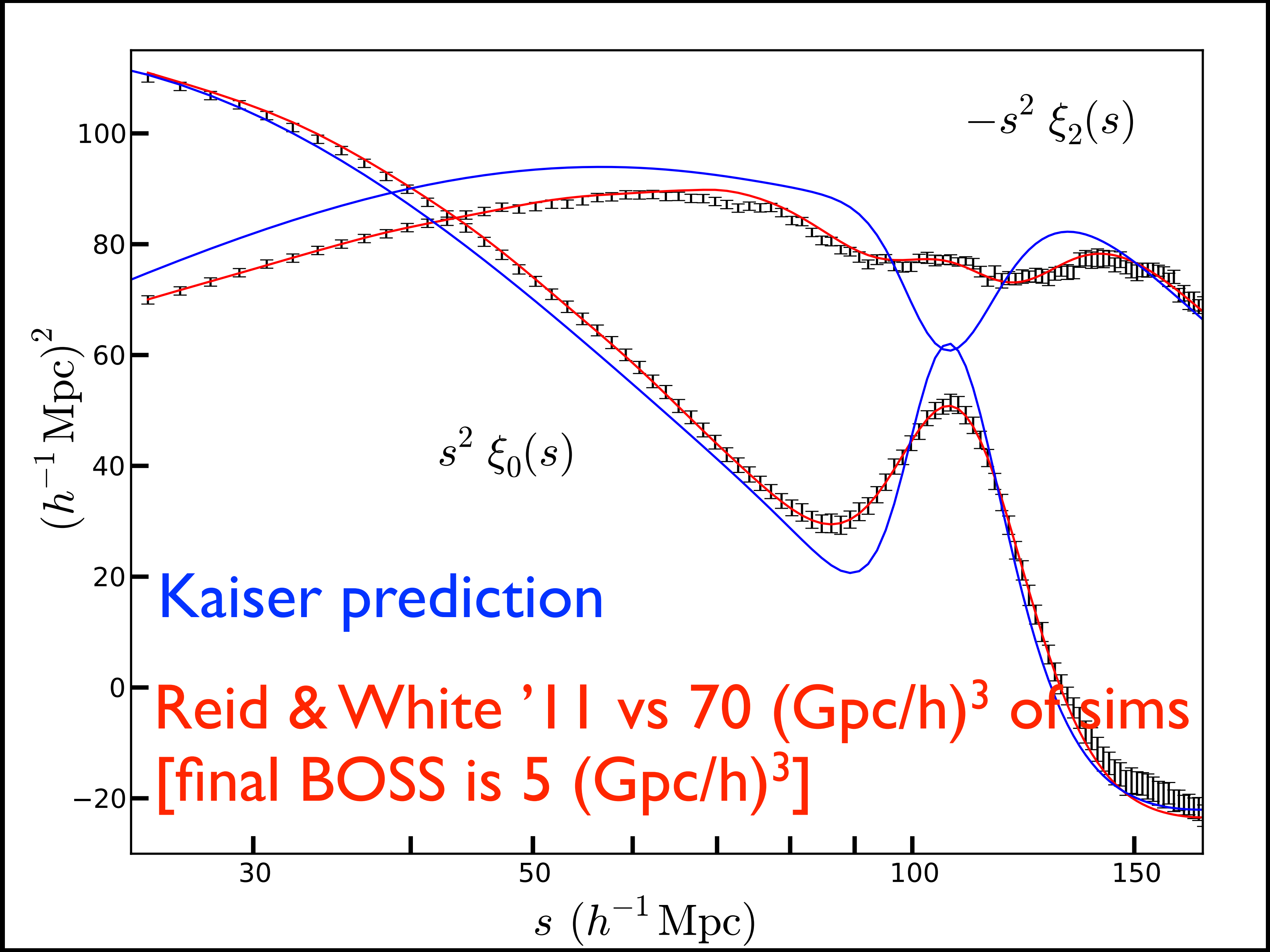
Minimal components of an RSD model

- After specifying the underlying linear P(k) and a redshift distance relation, we need 3 parameters to describe $\xi_{0,2}(s_i)$ or $P_{0,2}(k_i)$:

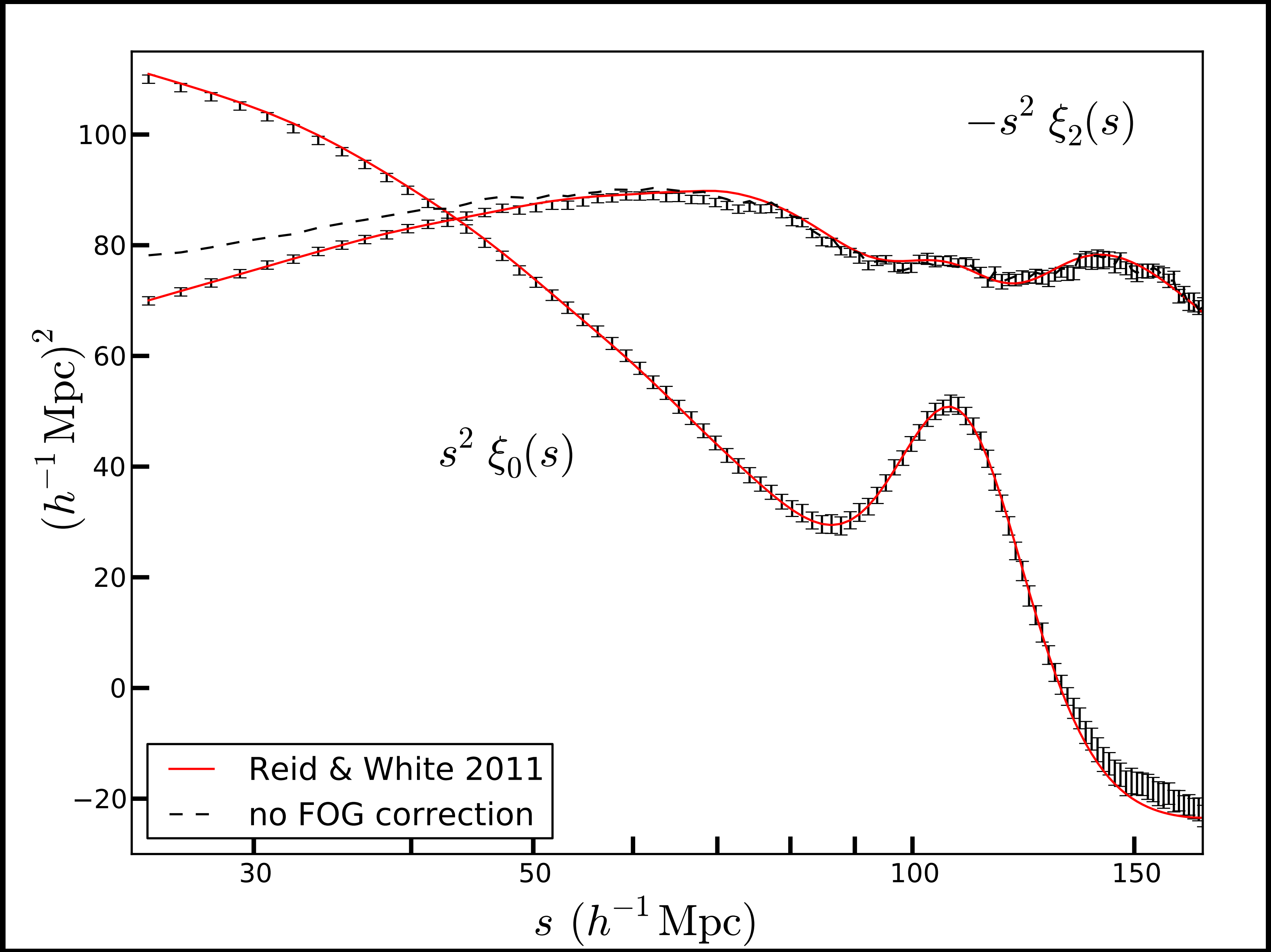
$f\sigma_8$: cosmological information!

$b\sigma_8$: galaxy bias nuisance parameter; higher order bias parameters may also be determined by b

σ^2_{FOG}: "finger-of-god" nuisance parameter

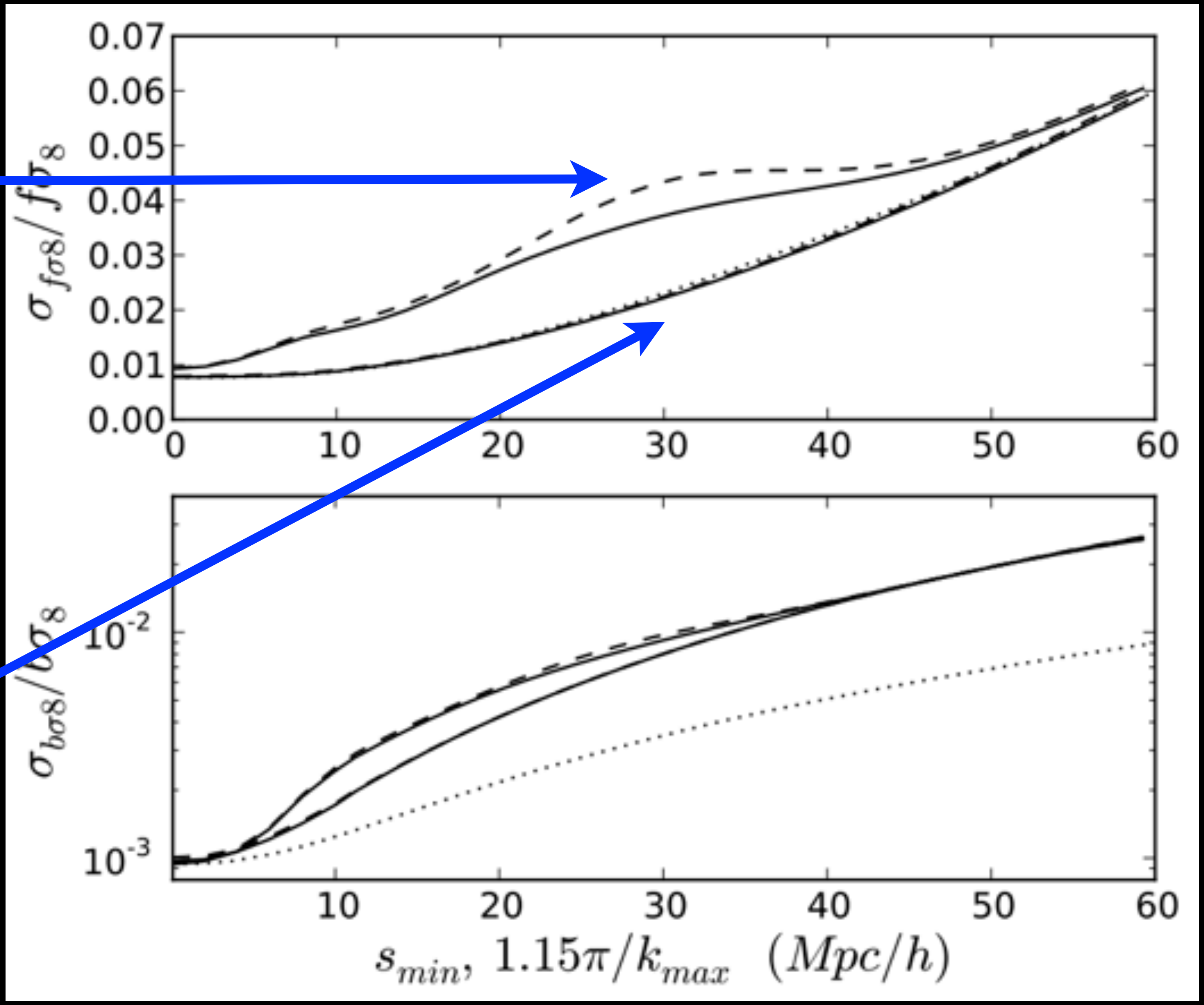


Impact of Fingers-of-God on clustering for mock BOSS-like galaxies



Degeneracy between σ^2_{FOG} and $f\sigma_8$ in Fisher Matrix projections

Constraints from $\xi_{0,2}$ flatten between 25 and 40 h^{-1} Mpc as σ^2_{FOG} becomes important but not well-constrained; therefore better perturbation theory will not translate to better constraints!



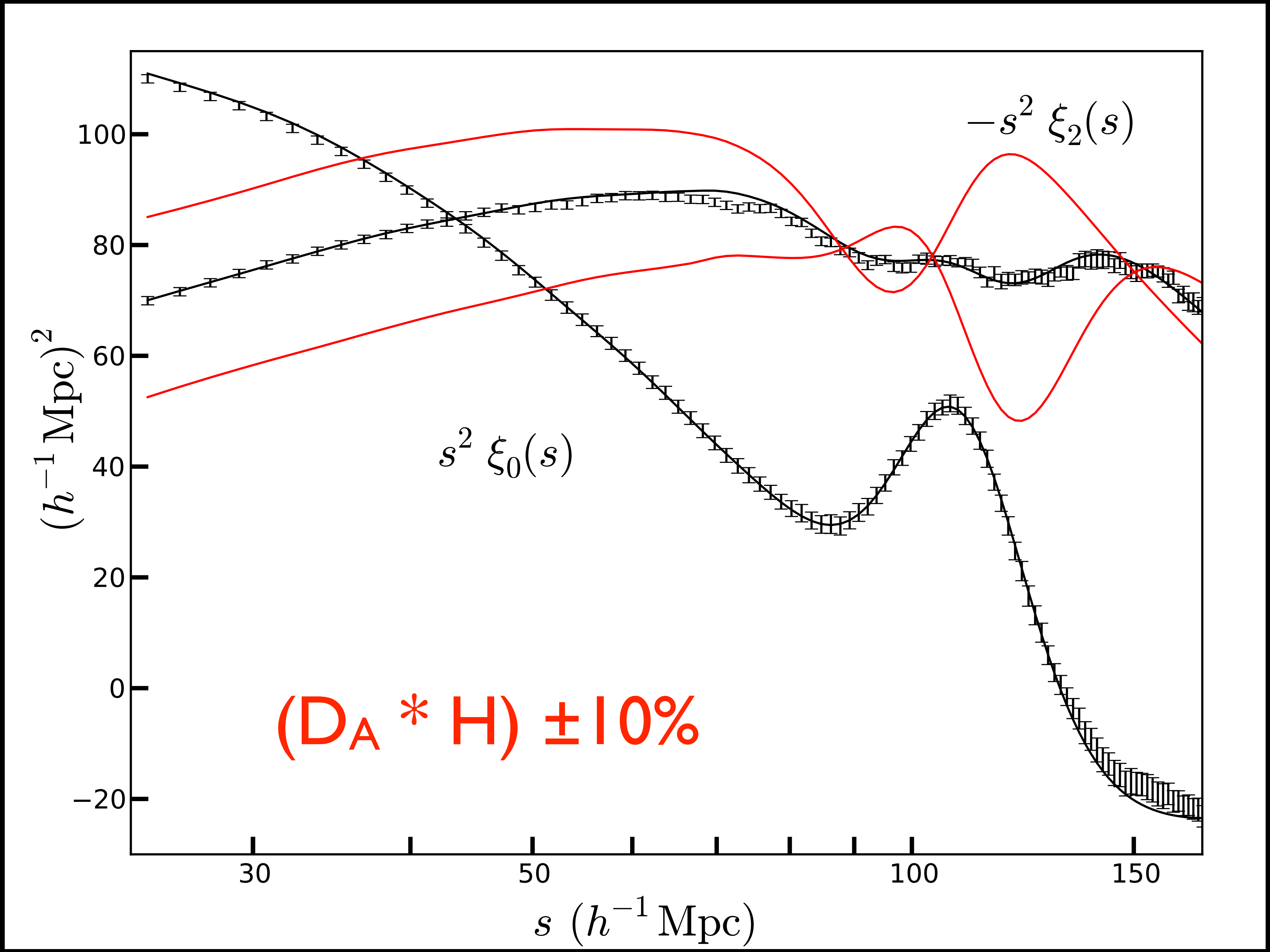
Knowing σ^2_{FOG} would put us on this curve. That information is encoded in the small-scale clustering! [last few years of my life]

Reid and White 2011

Geometric Anisotropy

- Recall from last lecture that the Alcock-Paczynski effect is a geometric distortion of the observed correlation function that induces anisotropy if the true redshift-distance relation is different from the fiducial one used to make the clustering measurement ($\propto$ [D * H]/[$D_{A,fid}$ * H_{fid}])

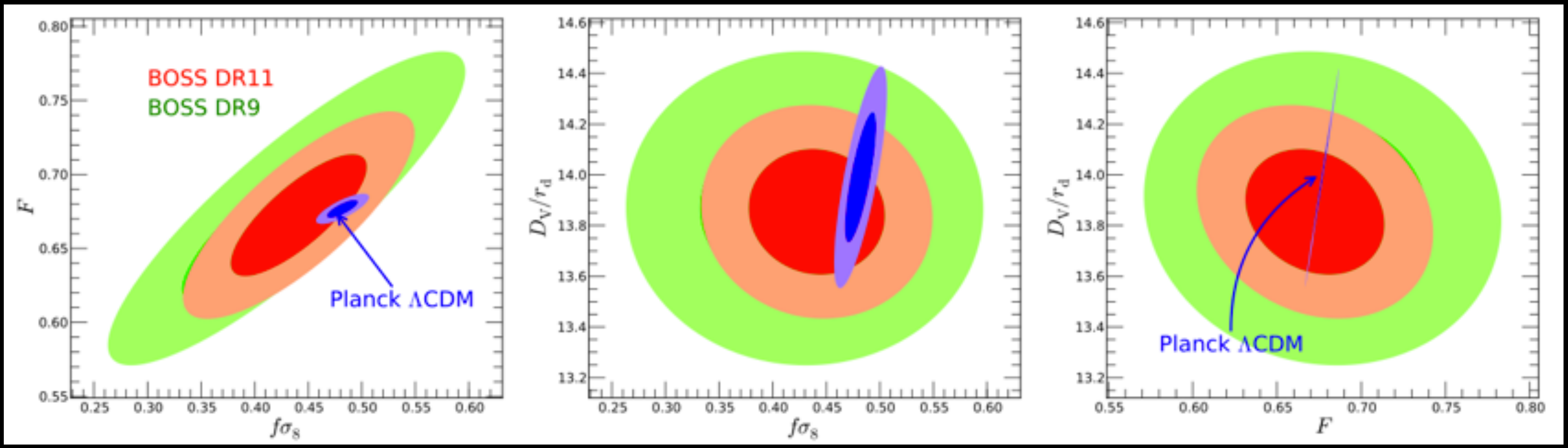
Alcock-Paczynski has different scale-dependence, distinguishable from RSD



D_V stretches s axis

Joint Fits to $D_A(z_{eff})$, $H(z_{eff})$, $f\sigma_8$

D_A*H



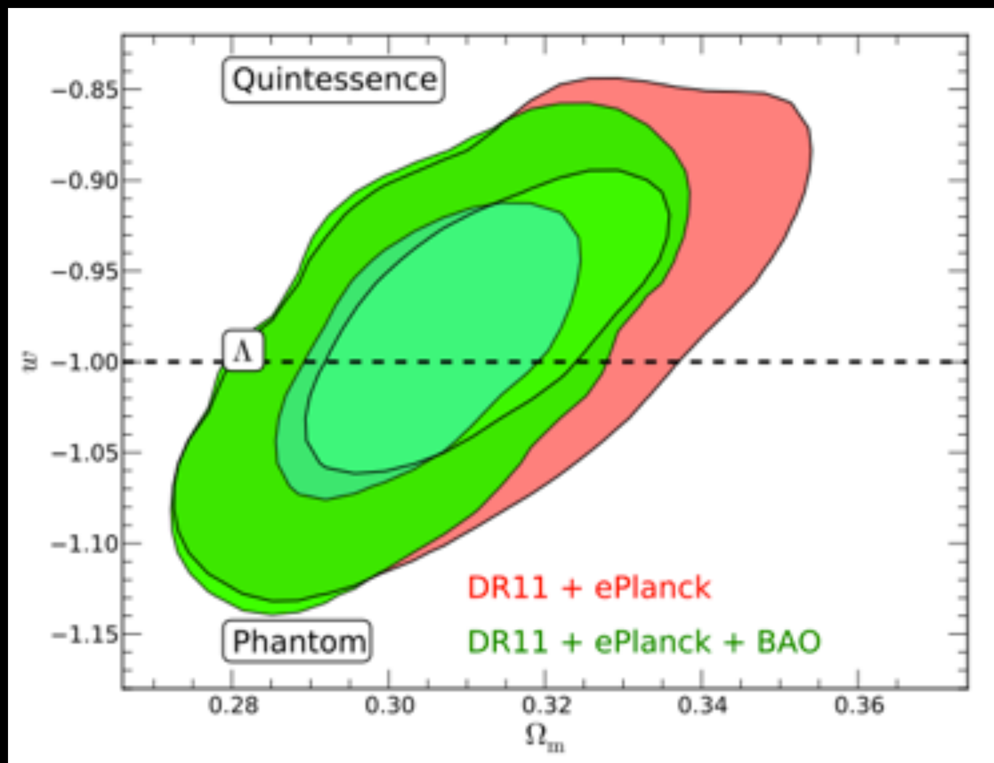
D_V

$f\sigma_8$ $f\sigma_8$ D_A*H

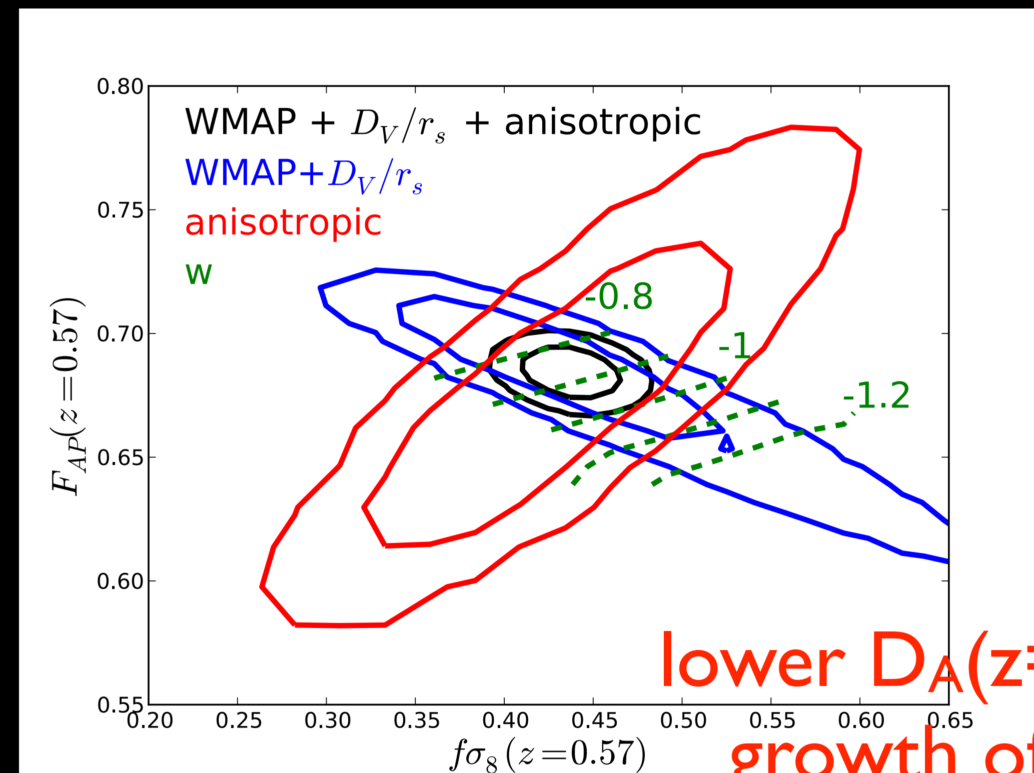
Samushia, BR, et al., 2013

Cosmological Implications: Quadrupole amplitude constrains w

w



Ω_m



D_A*H

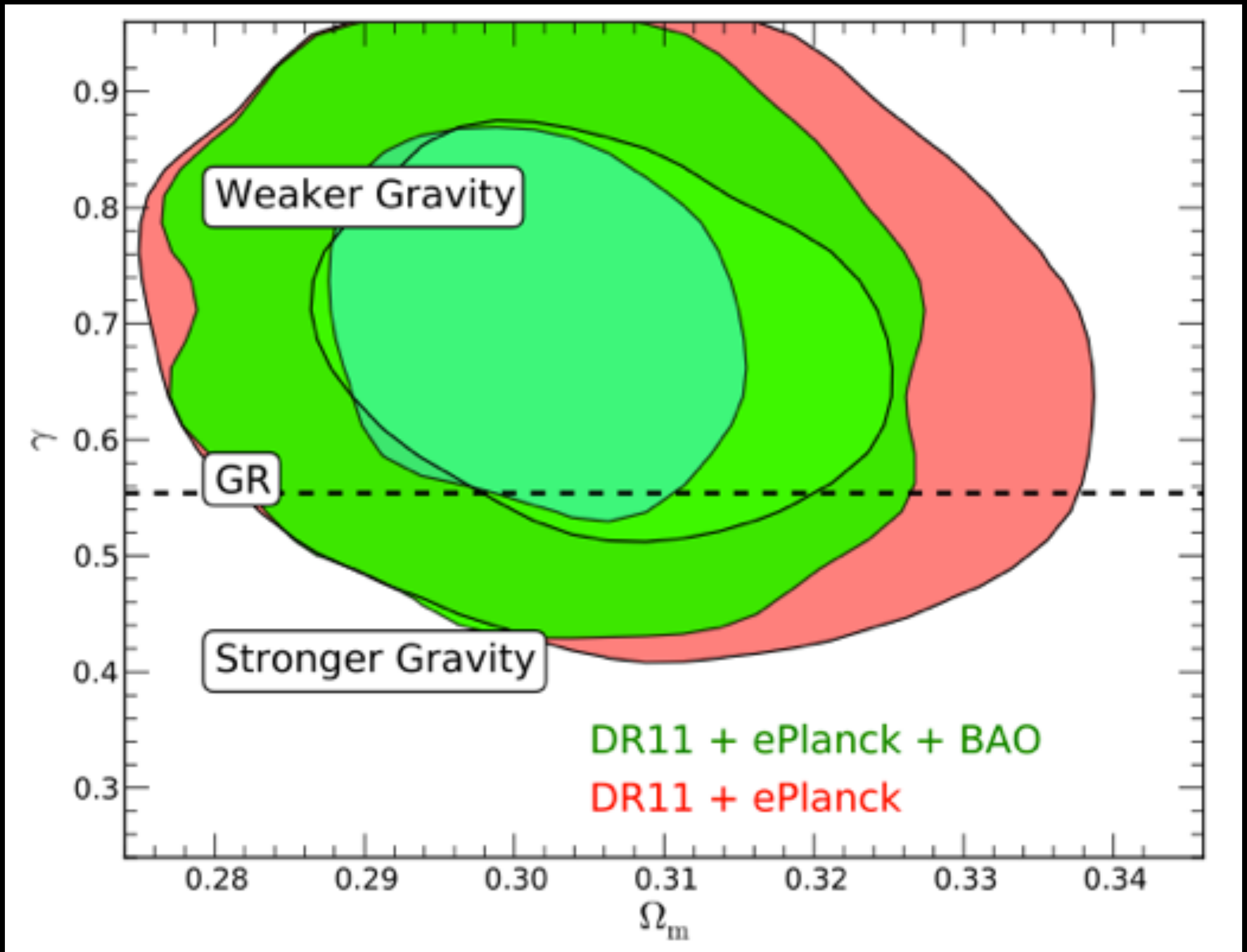
lower D_A(z=0.57), more growth of structure from z=1091 to z=0.57

$f\sigma_8$

- w = -0.983 ± 0.075
  Samushia, BR, et al. 2013
- w = -1.03 ± 0.10
  (Planck + CMASS BAO)
  [includes reconstruction gains!]

Samushia, BR, et al., 2013

Cosmological Implications

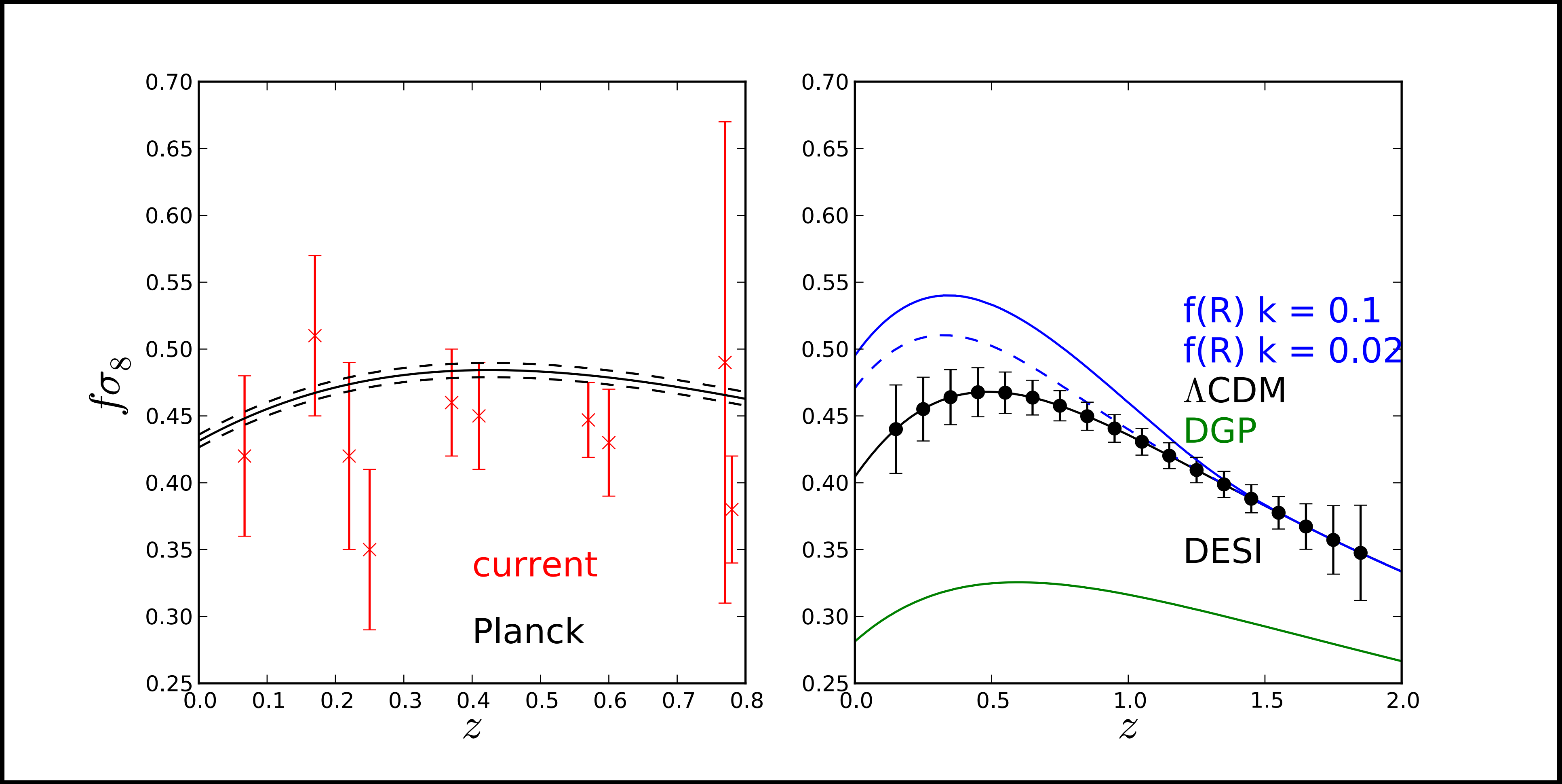


Modified Gravity test

$f = \Omega_m^{\gamma}$: $\gamma = 0.70 \pm 0.11$

($\gamma = 0.55$ in GR)

RSD measurements are ~2σ low compared to the best fit Planck ΛCDM model



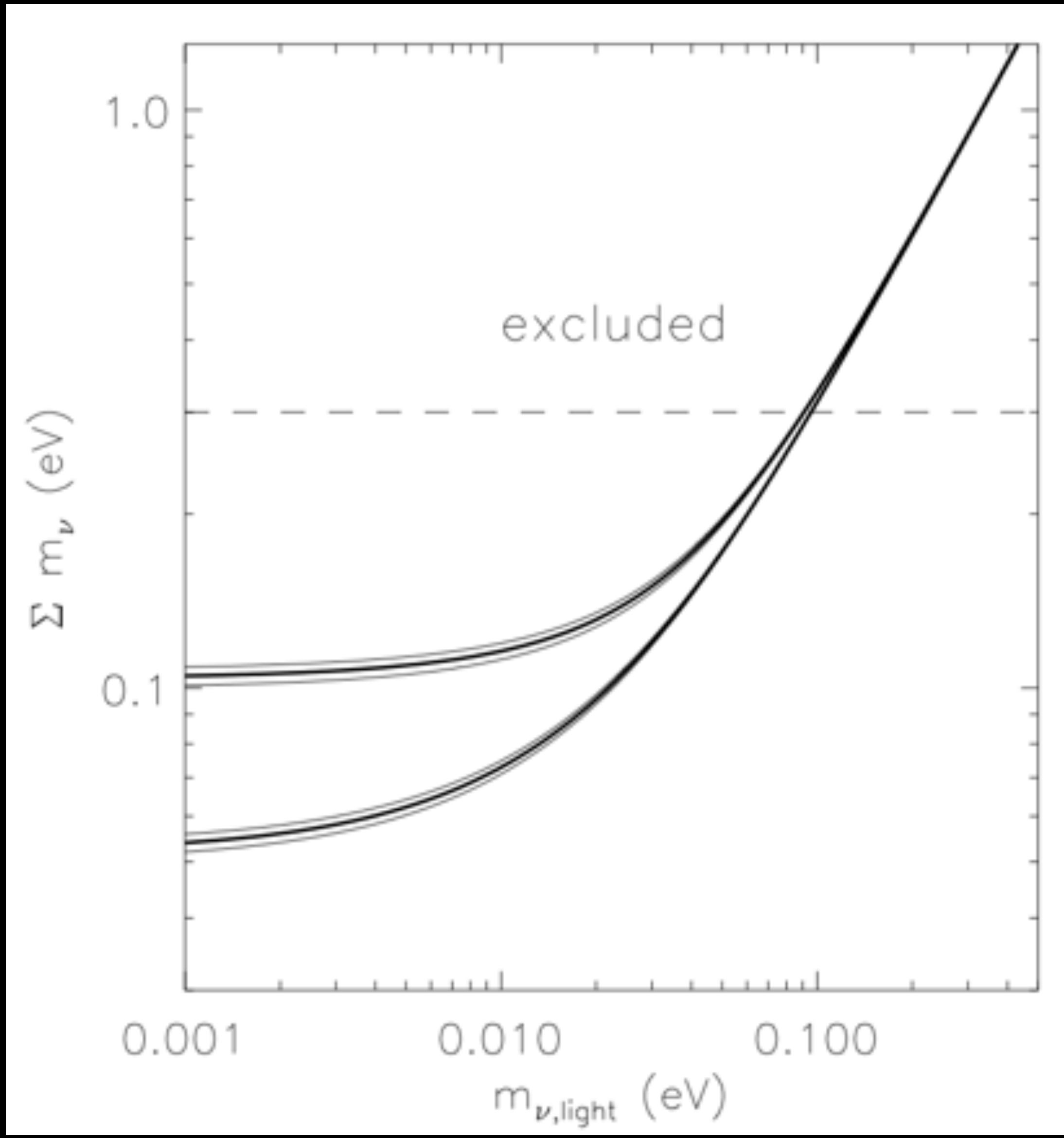
Lecture 2 Outline

- Redshift space distortions
- Cosmological constraints from the measurement of anisotropy in two-point statistics
- (Optional) LSS observables for this week's lectures
  - cosmological neutrinos
  - f_{NL}^{loc}
  - LSS tests of modified gravity
  - non-linear RSD details

Cosmological Neutrinos

- Neutrino oscillation experiments have measured two square mass differences; once you specify the lightest neutrino mass, there are two discrete possibilities for the other mass values

Normal, inverted, or degenerate?



Cosmological Probes of Neutrinos

Probe	Current $\sum m_\nu$ (eV)	Forecast $\sum m_\nu$ (eV)	Key Systematics	Current Surveys	Future Surveys
CMB Primordial	1.3	0.6	Recombination	WMAP, Planck	None
CMB Primordial + Distance	0.58	0.35	Distance measurements	WMAP, Planck	None
Lensing of CMB	∞	$0.2 - 0.05$	NG of Secondary anisotropies	Planck, ACT [39], SPT [96]	EBEX [57], ACTPol, SPTPol, POLARBEAR [5], CMBPol [6]
Galaxy Distribution	0.6	0.1	Nonlinearities, Bias	SDSS [58, 59], BOSS [82]	DES [84], BigBOSS [81], DESpec [85], LSST [92], Subaru PFS [97], HETDEX [35]
Lensing of Galaxies	0.6	0.07	Baryons, NL, Photometric redshifts	CFHT-LS [23], COSMOS [50]	DES [84], Hyper SuprimeCam, LSST [92], Euclid [88], WFIRST [100]
Lyman α	0.2	0.1	Bias, Metals, QSO continuum	SDSS, BOSS, Keck	BigBOSS [81], TMT [99], GMT [89]
21 cm	∞	$0.1 - 0.006$	Foregrounds, Astrophysical modeling	GBT [11], LOFAR [91], PAPER [53], GMRT [86]	MWA [93], SKA [95], FFTT [49]
Galaxy Clusters	0.3	0.1	Mass Function, Mass Calibration	SDSS, SPT, ACT, XMM [101] Chandra [83]	DES, eRosita [87], LSST
Core-Collapse Supernovae	∞	$\theta_{13} > 0.001^*$	Emergent ν spectra	SuperK [98], ICECube [90]	Noble Liquids, Gadzooks [7]

arXiv:1103.5083; attendees of "The future of Neutrino Mass Measurements: Terrestrial, Astrophysical, and Cosmological Measurements in the Next Decade", Seattle 2010

Cosmological neutrino basics.

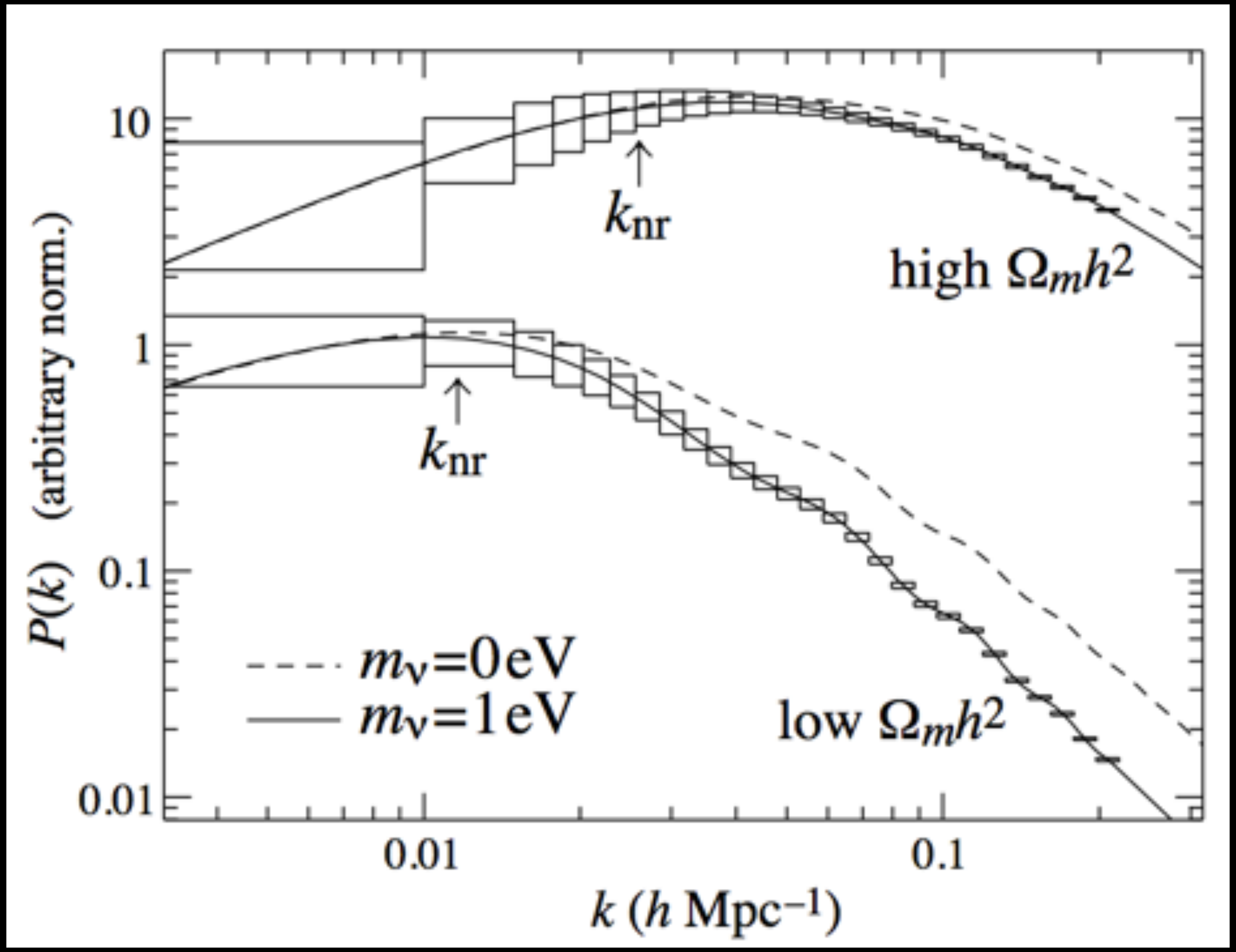
- Reviews: Lesgourgues and Pastor [0603494, 1404.1740]
- Measured mass differences imply $\Sigma m_\nu > 0.06\ (0.1)$ eV for normal (inverted) hierarchy
  - $m_\nu = kT_\nu$ by $z \sim 300$
- At high redshifts, $\Omega_\nu h^2 \sim a^{-4}$ (relativistic); then $\Omega_\nu h^2 \sim a^{-3}$ at low redshifts [use Fermi-Dirac for exact result]

Cosmological neutrino basics.

- Motivated by CMB priors, consider fixed $\Omega_{c,b}h^2$, $D_A(z^*)$. In comparison to the massless neutrino approximation, massive neutrinos alter both the expansion history and growth of perturbations
  - ---> $\Delta H_0 = -9.5$ km/s/Mpc ($\Sigma\, m_\nu$ / 1 eV)
  - ---> growth of structure suppressed

Matter power spectrum with massive neutrinos

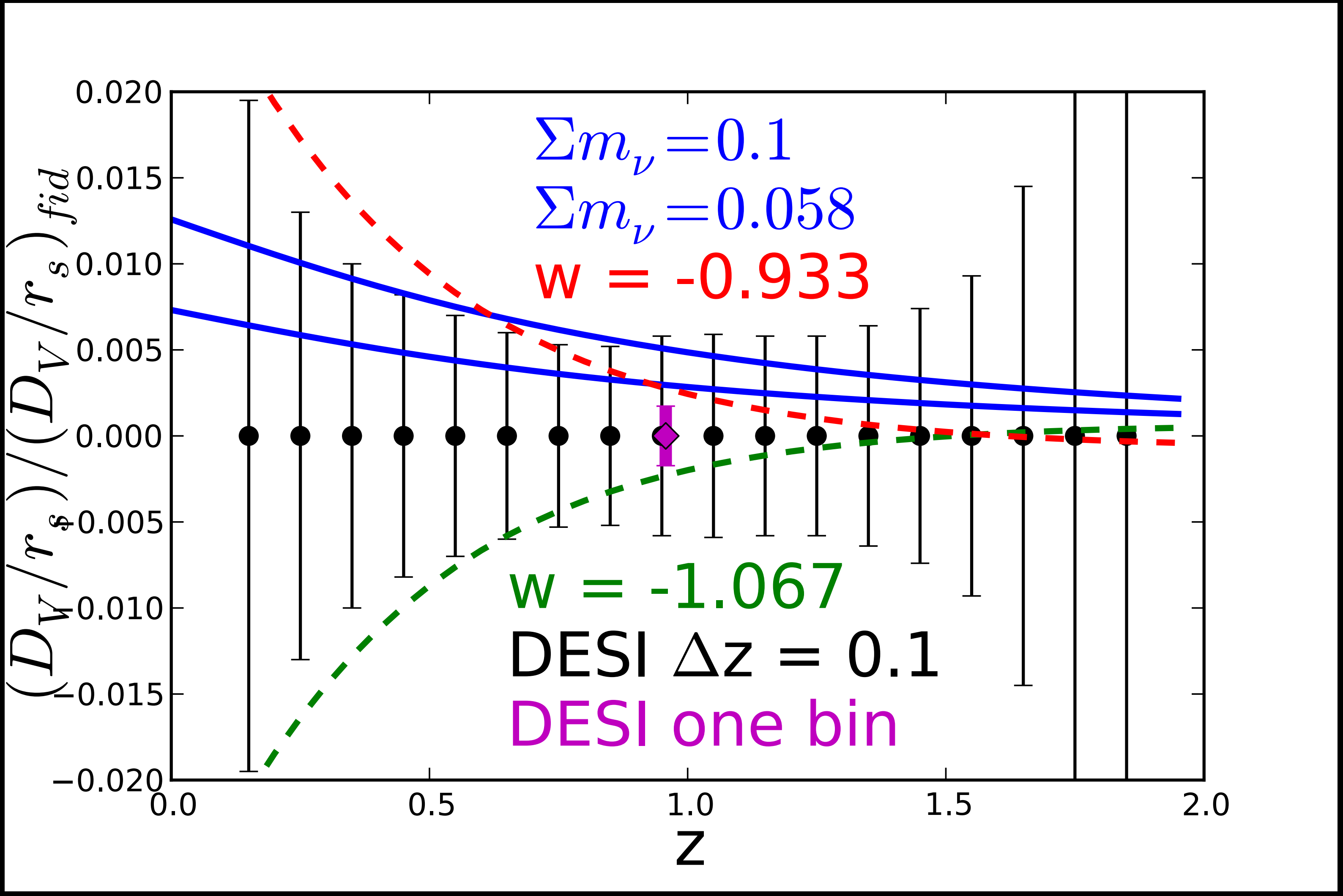
- Neutrinos free-stream out of potential wells, which suppresses the matter power spectrum on small scales



Hu, Eisenstein, Tegmark 1998, PRL 80, 5255

Neutrinos degrade dark energy constraints from BAO

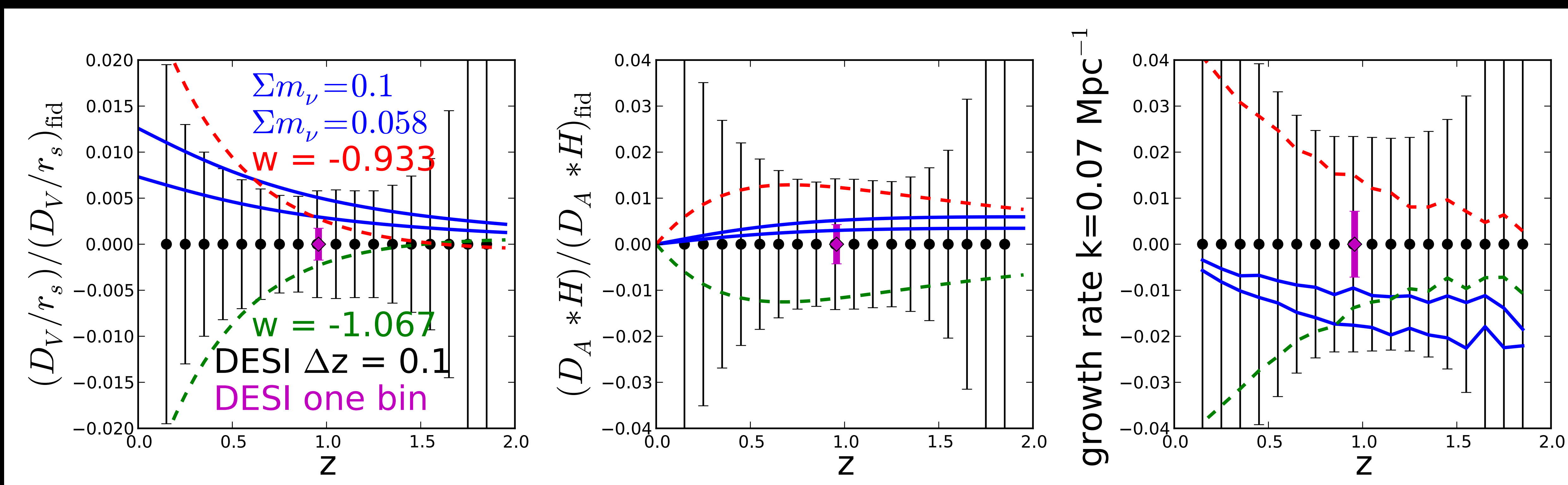
- Compare with similar change in w at $z_{DESI} \sim 1$



Neutrinos degrade dark energy constraints from BAO

BAO info only

growth rate constraint (fixed geometry)



m_ν and w have opposing effects on geometry and growth rate!

Neutrino constraints from $P(k,\mu)$

- Adding broadband to BAO info: ~4x increase in Planck + DESI dark energy constraining power (marginalizing over Σm_ν and Ω_k).
- 1σ constraint on Σm_ν 0.57 eV -> 0.058 eV (marginalizing over w_0, w_a, Ω_k)
- 1σ constraint on Σm_ν 0.09 eV -> 0.024 eV (assuming flat ΛCDM)

Neutrino constraints from LSS

- We expect similar levels of constraints from upcoming gravitational lensing surveys (like LSST) and CMB lensing, so cosmology *should* secure a detection of $\sum m_\nu$ in the next ~ decade [see Font-Ribera et al. 1308.4164]

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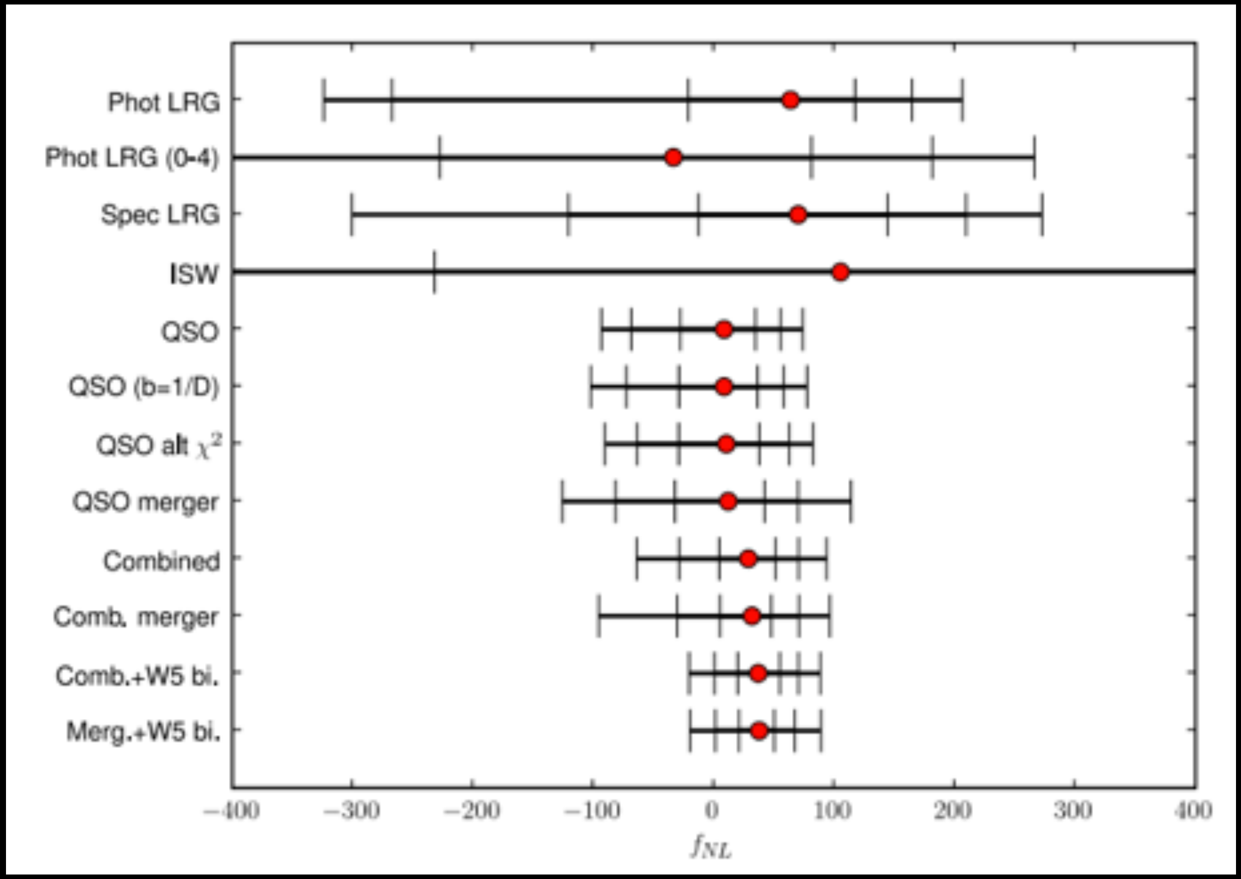
  - f_{NL}^{loc}
  - LSS tests of modified gravity.

f_{NL}^{loc}

- The CMB is currently the primary means for searching for primordial non-Gaussianity [see Planck XXIV, 1303.5084]
- But LSS will likely be more sensitive in the future [Why??]

f_{NL}^{loc}

- Dalal et al., 0710.4560 predict scale dependent bias term on large scales $\propto f_{NL}\,(b\text{-}1)\,k^{-2}$
- Slosar et al., 0805.3580 make the first LSS f_{NL} constraint



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LSS tests of modified gravity

- FRW metric:

$$ds^2 = a^2(\tau)\left[-(1+2\Phi)d\tau^2 + (1-2\Psi)\gamma_{ij}dx^i dx^j\right]$$

- GR has Φ = Ψ; modified gravity theories generically do not.

$$\frac{1}{a}\frac{d(a\boldsymbol{v})}{d\tau} = -\boldsymbol{\nabla}\Phi\ , \quad v^2 \ll 1 \quad (\mathrm{CDM})$$

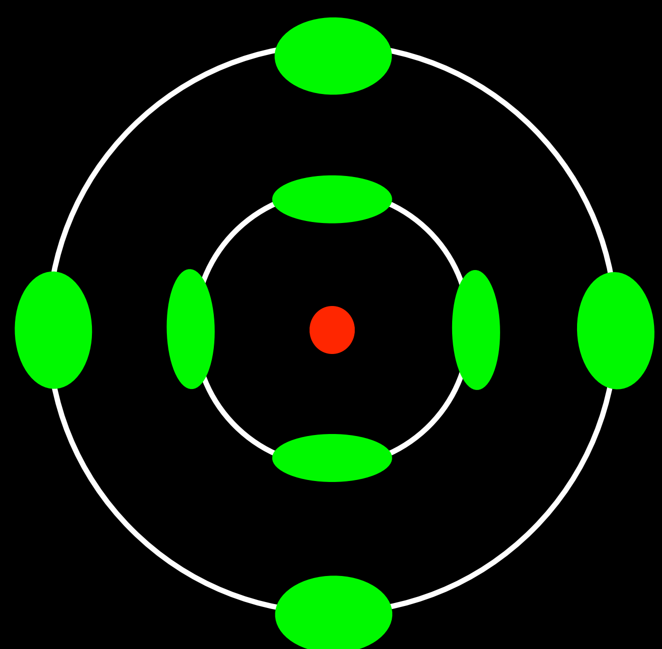
$$\frac{d\boldsymbol{v}}{d\tau} = -\boldsymbol{\nabla}_\perp(\Phi+\Psi)\ , \quad v^2 = 1 \quad (\mathrm{photons})$$

- Comparing the trajectories of photons and CDM (non-relativistic particles), we can check if Φ = Ψ.

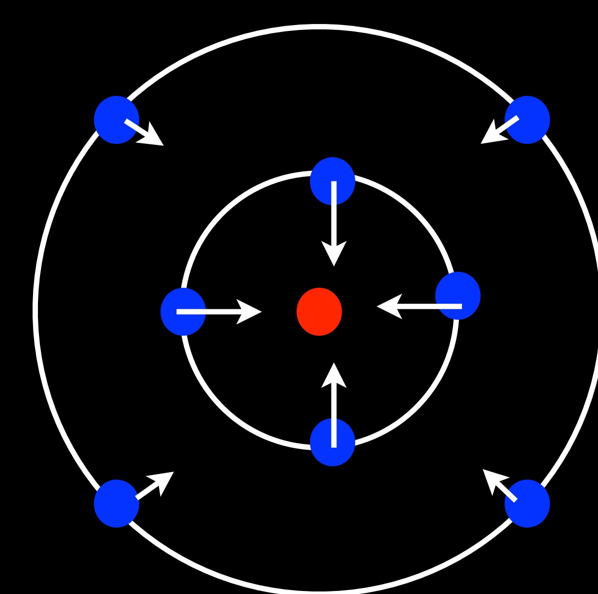
see e.g. Bertshinger 1111.4569

LSS tests of modified gravity

- Zhang et al. 2007 defined a practical test of this using both lensing and RSD profiles around galaxies measured in spectroscopic surveys



galaxy-galaxy lensing



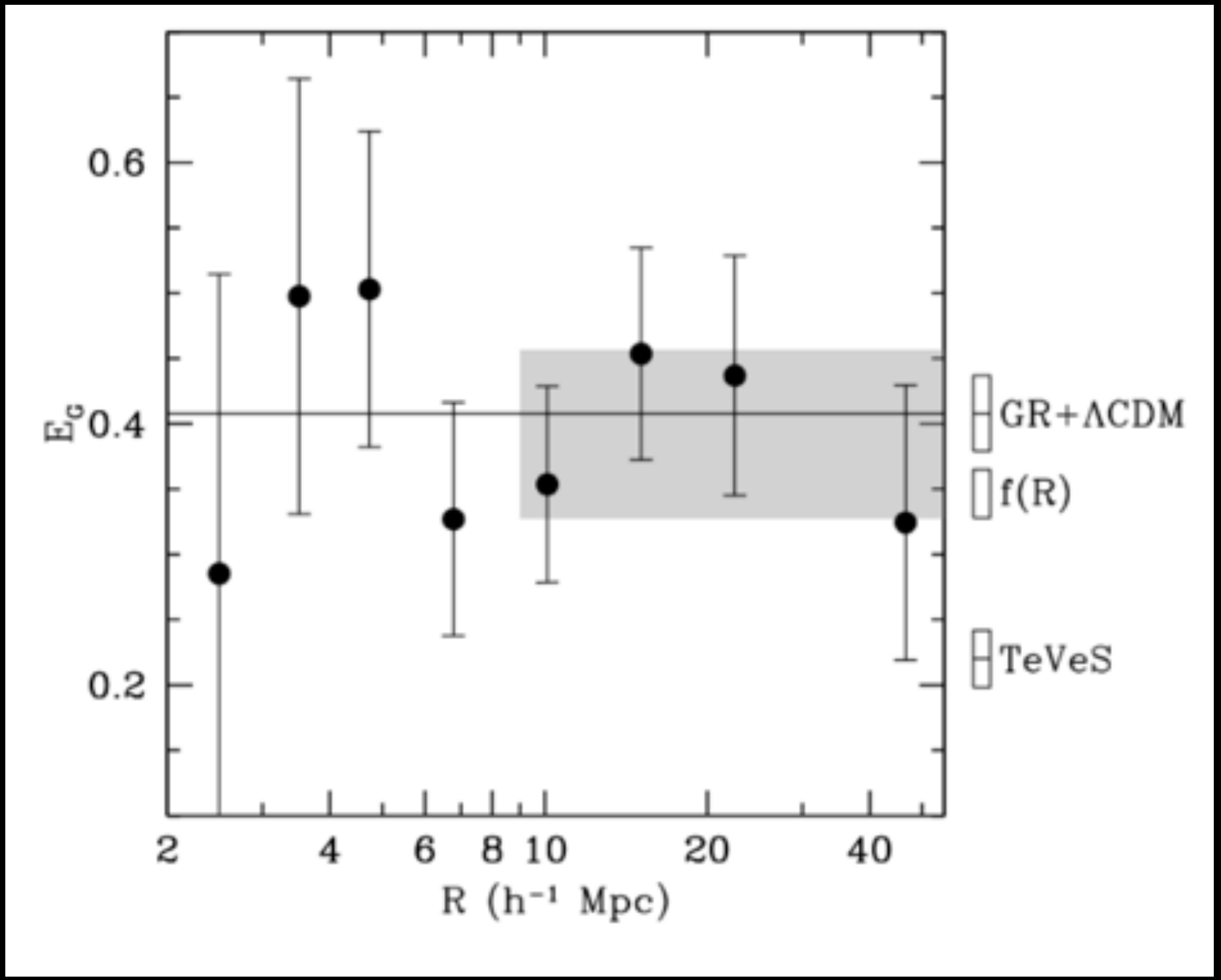
galaxy clustering and velocities (RSD)

LSS tests of modified gravity

- Reyes et al. performed this test (started at ICTP!)

$$E_G(R) = \frac{1}{\beta}\frac{\Upsilon_{\mathrm{gm}}(R)}{\Upsilon_{\mathrm{gg}}(R)}$$

gg lensing $\propto b_g \sigma_8^2 \xi_m$
gg clustering $\propto b_g^2 \sigma_8^2 \xi_m$
gg RSD $\beta = f\sigma_8 / b_g \sigma_8$



What I wanted you to learn

- Large scale structure observations seek to map out the full three-dimensional volume of the observable universe; such measurements should eventually over-power the CMB as a probe of fundamental physics (3d is better than 2d!)
- The current observational focus is on measuring the expansion history and growth of perturbations using clustering (BAO, RSD, ...) and lensing

Get creative

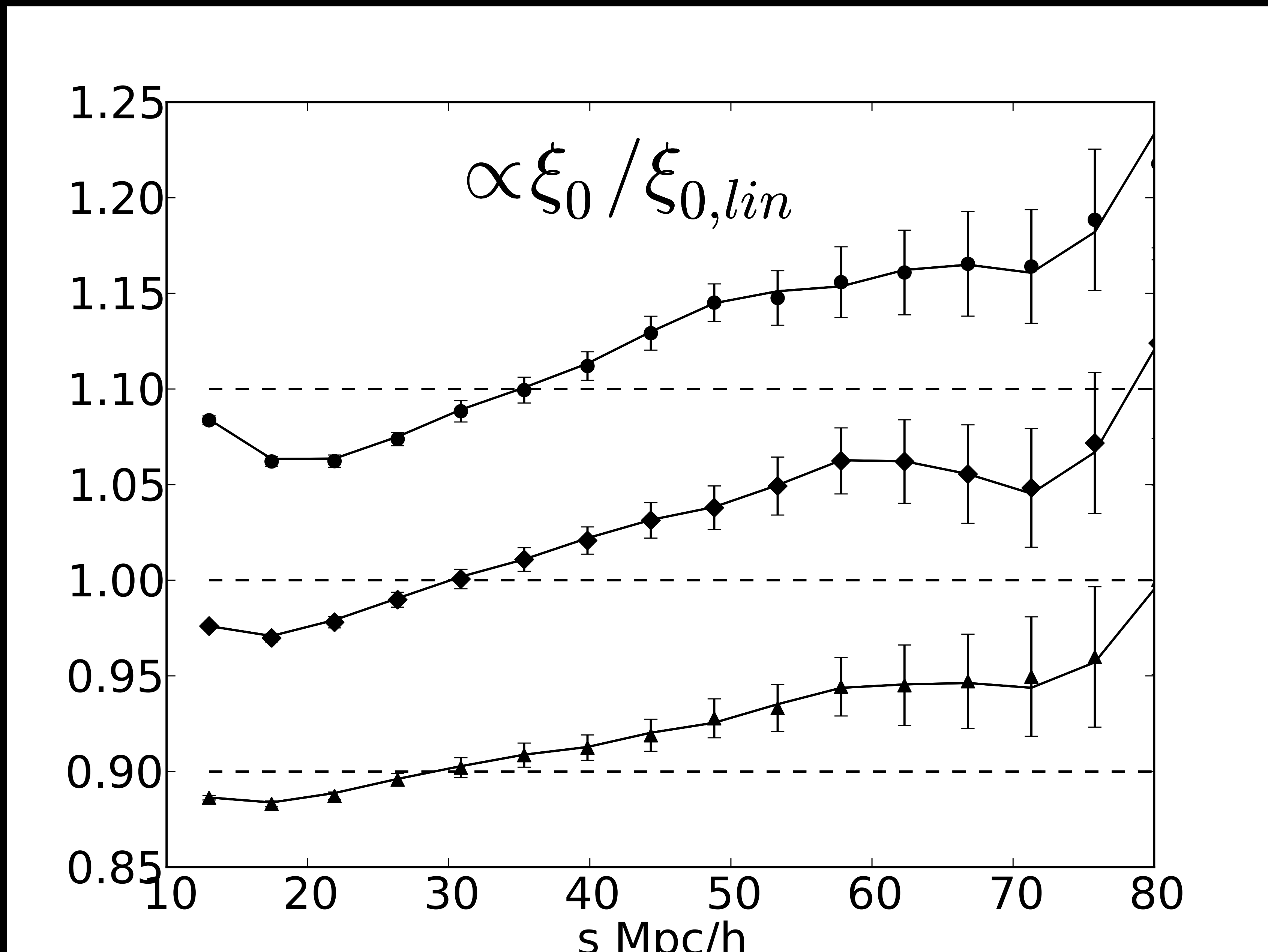
- The fact that LSS is highly non-Gaussian is a blessing and a curse; its an opportunity to think creatively about new cosmological observables (modified gravity investigations are a good example). Get to work!

Streaming model
EXTRAS

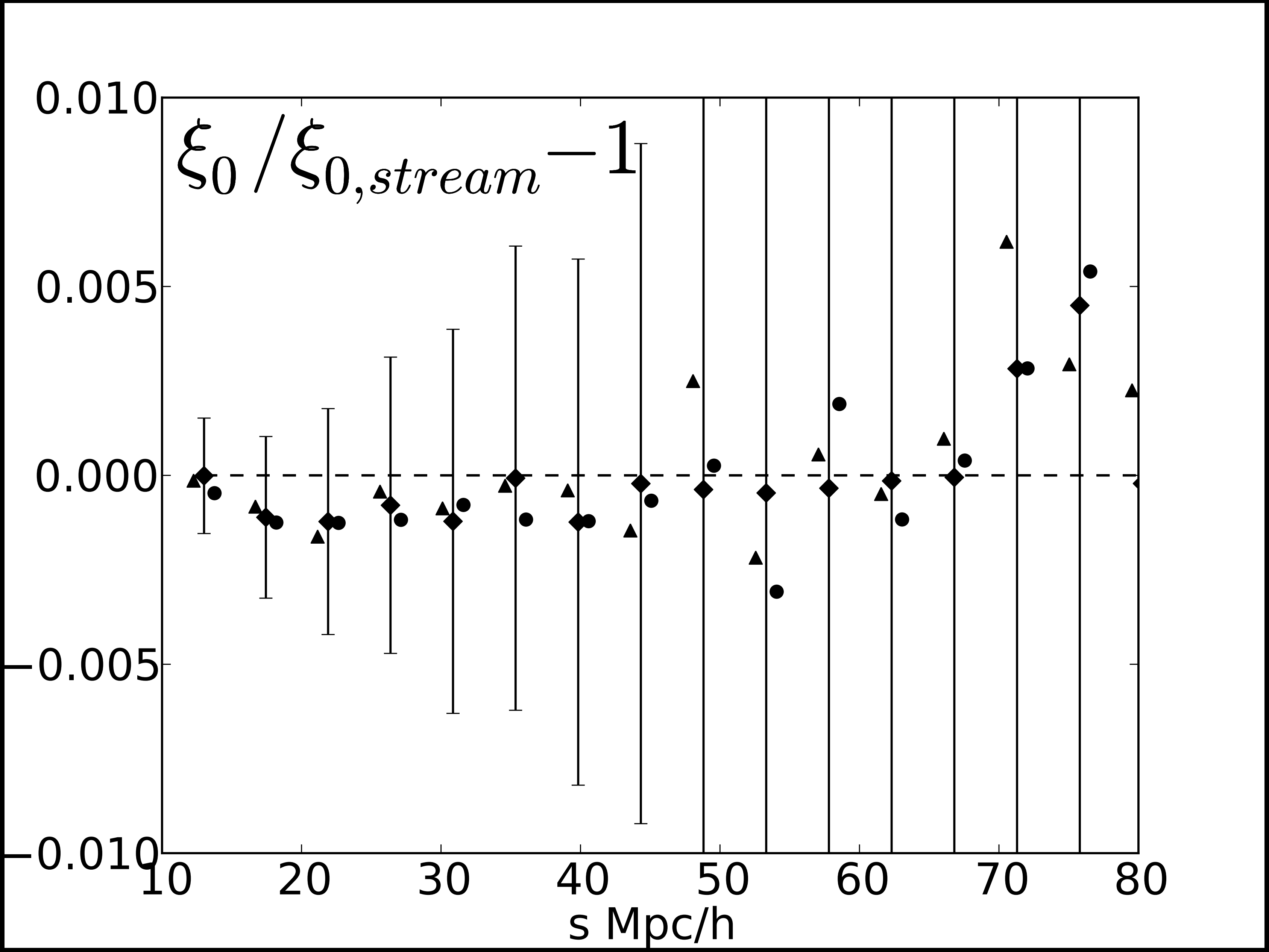
The scale-dependent Gaussian streaming model ansatz vs N-body simulations

- 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

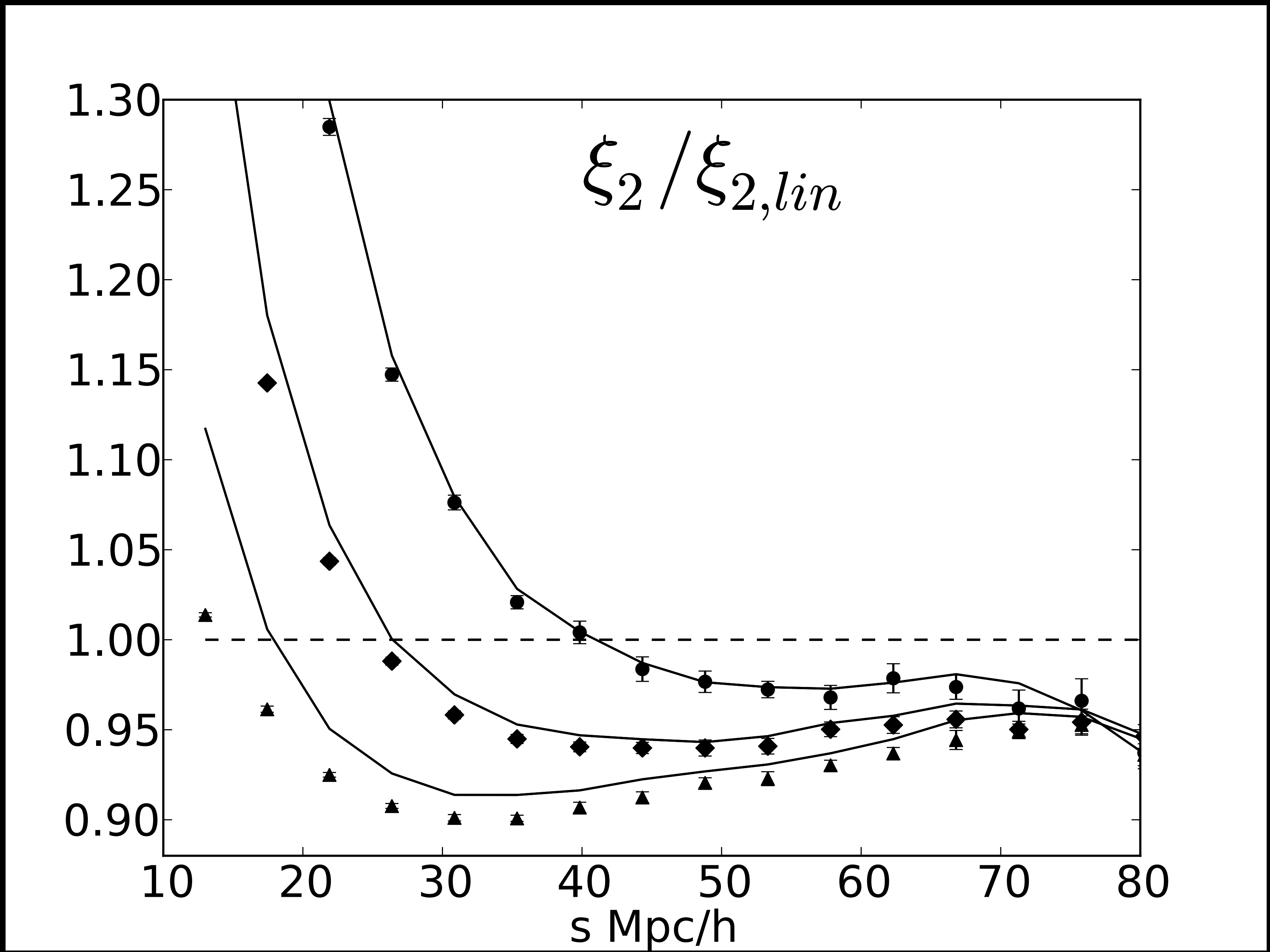
The scale-dependent Gaussian streaming model ansatz vs N-body simulations: ξ_0



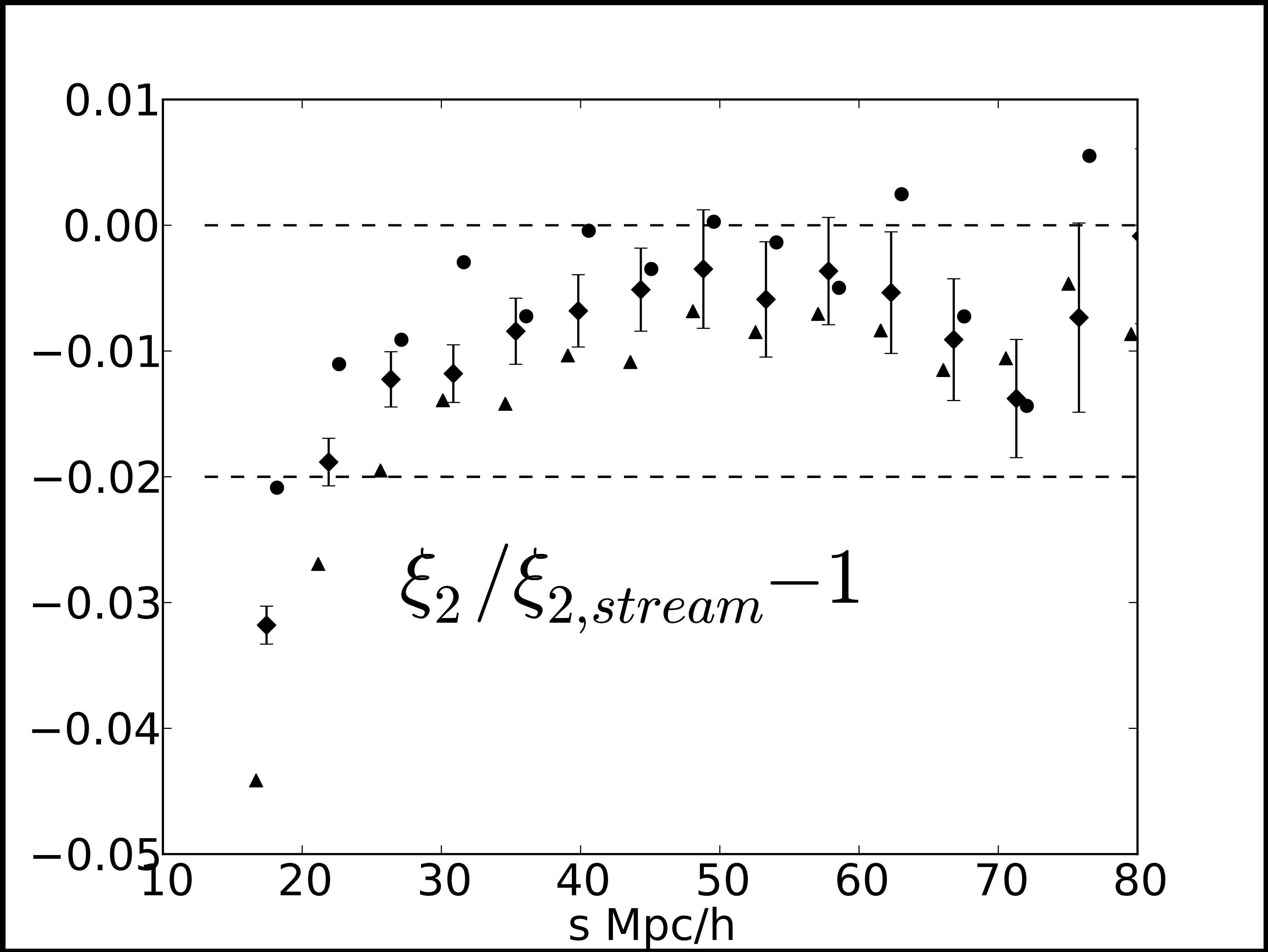
The scale-dependent Gaussian streaming model ansatz vs N-body simulations: ξ_0



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

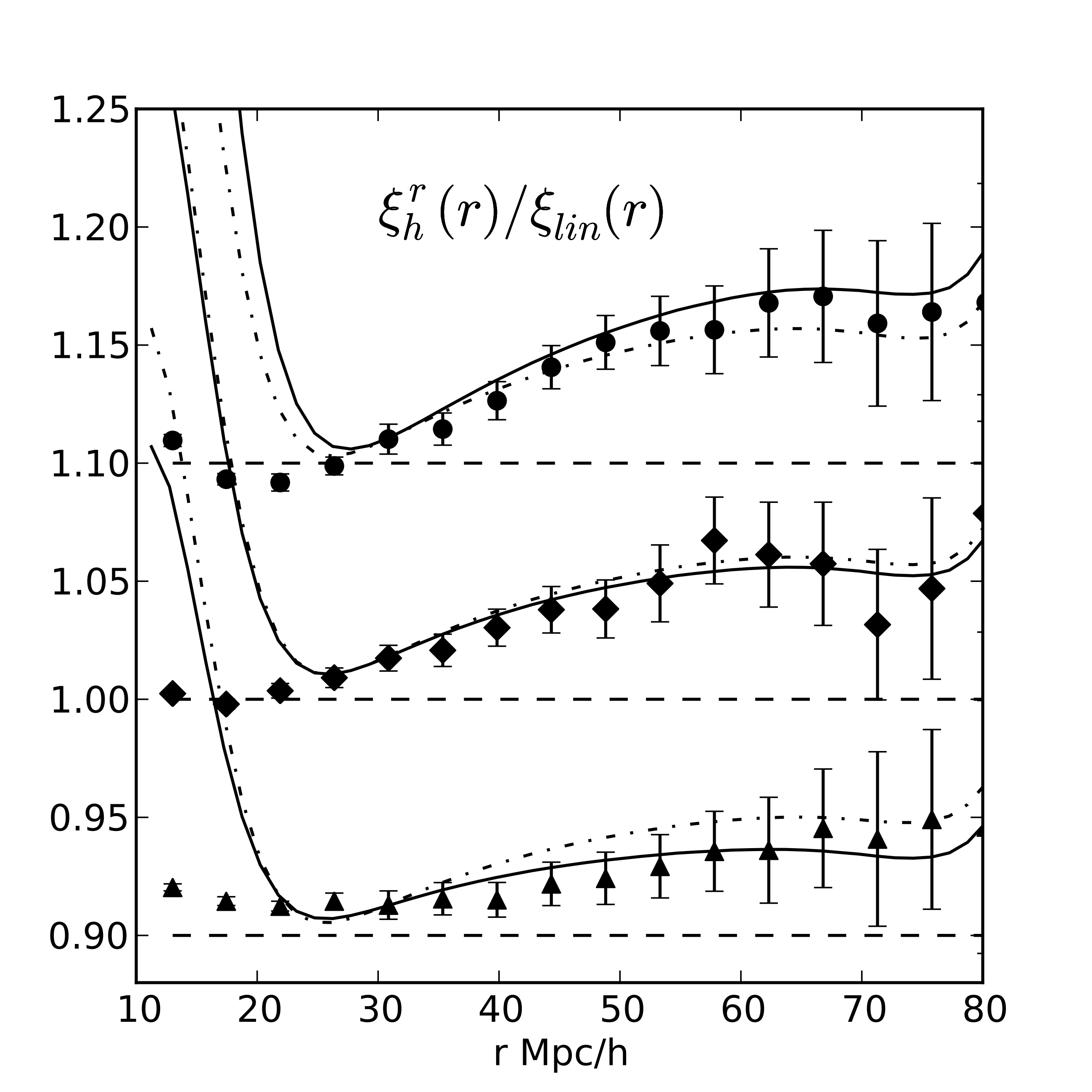


The scale-dependent Gaussian streaming model ansatz vs N-body simulations: ξ_2

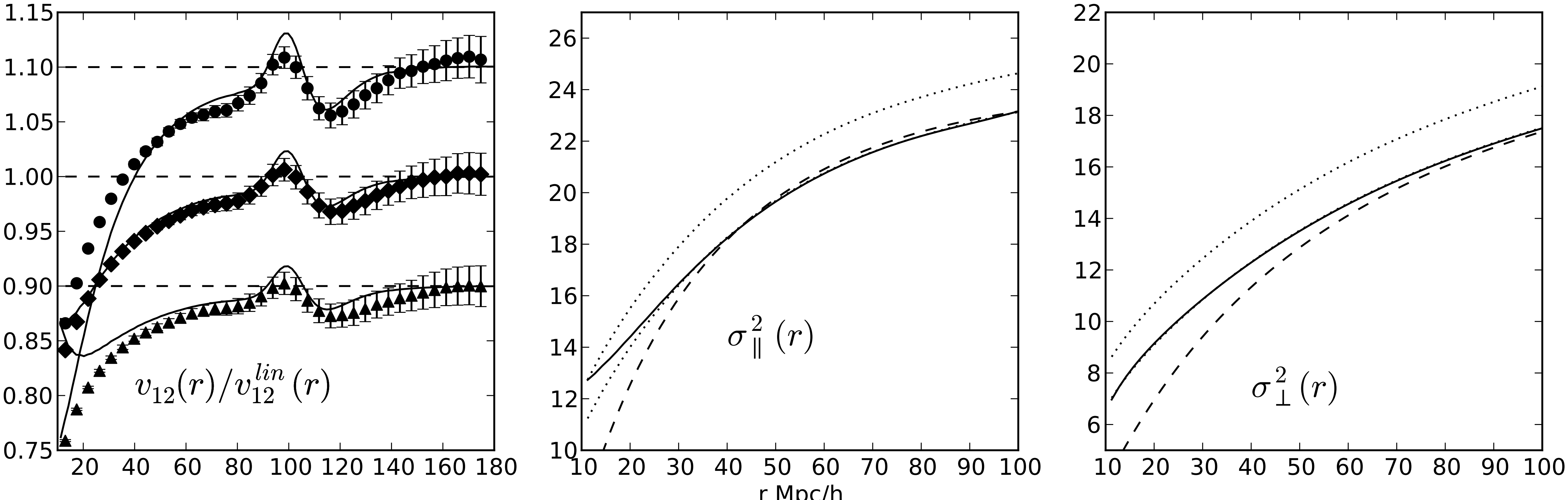


Can we predict real space halo clustering/ velocities using perturbation theory?

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



Velocity statistics in standard perturbation theory: new results



* assumes linear bias

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

Pair-weighting correction

Linear theory

$$\left[1 + b^2 \xi^r_m(r)\right] v^{PT}_{12}(r)\hat{r} = 2b \left\langle \delta_1(\mathbf{x})\mathbf{v}_1(\mathbf{x}+\mathbf{r})\right\rangle +$$

$$2b \sum_{i>0} \left\langle \delta_i(\mathbf{x})\mathbf{v}_{4-i}(\mathbf{x}+\mathbf{r})\right\rangle + 2b^2 \sum_{i,j>0} \left\langle \delta_i(\mathbf{x})\delta_j(\mathbf{x}+\mathbf{r})\mathbf{v}_{4-i-j}(\mathbf{x}+\mathbf{r})\right\rangle .$$

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

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

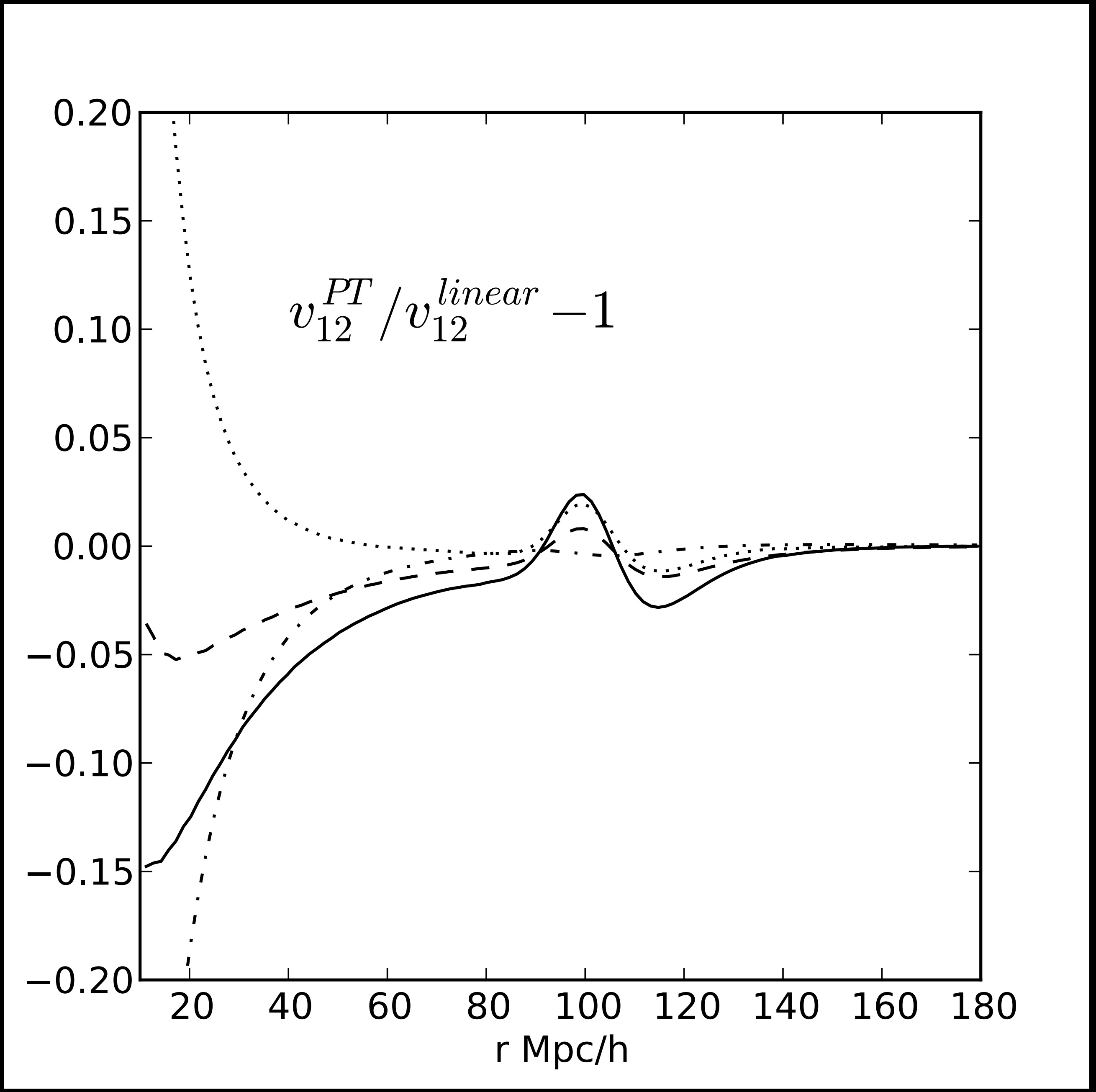
Velocity statistics in standard perturbation theory: new results

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

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

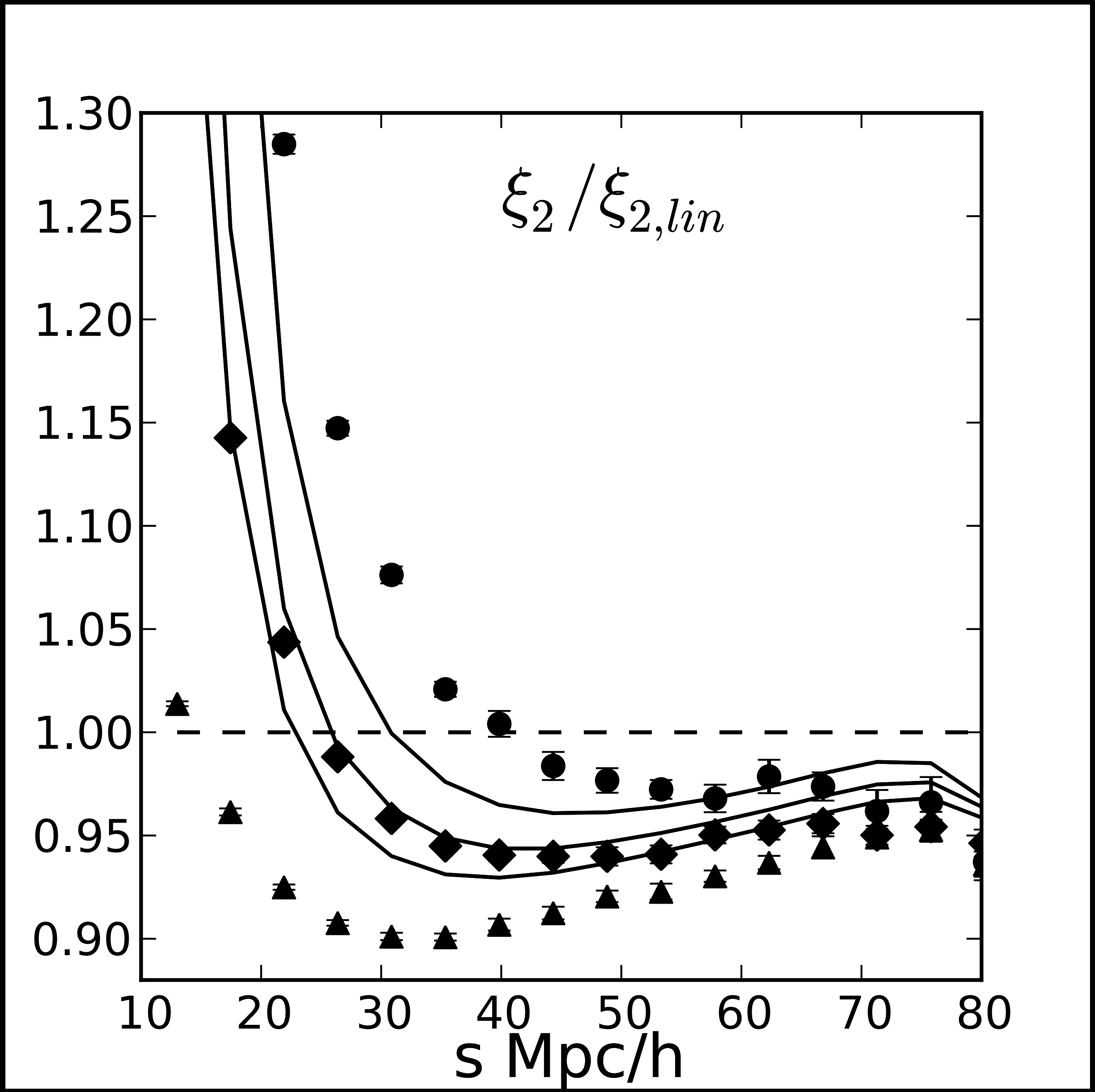
total PT correction

Pair-weighting correction



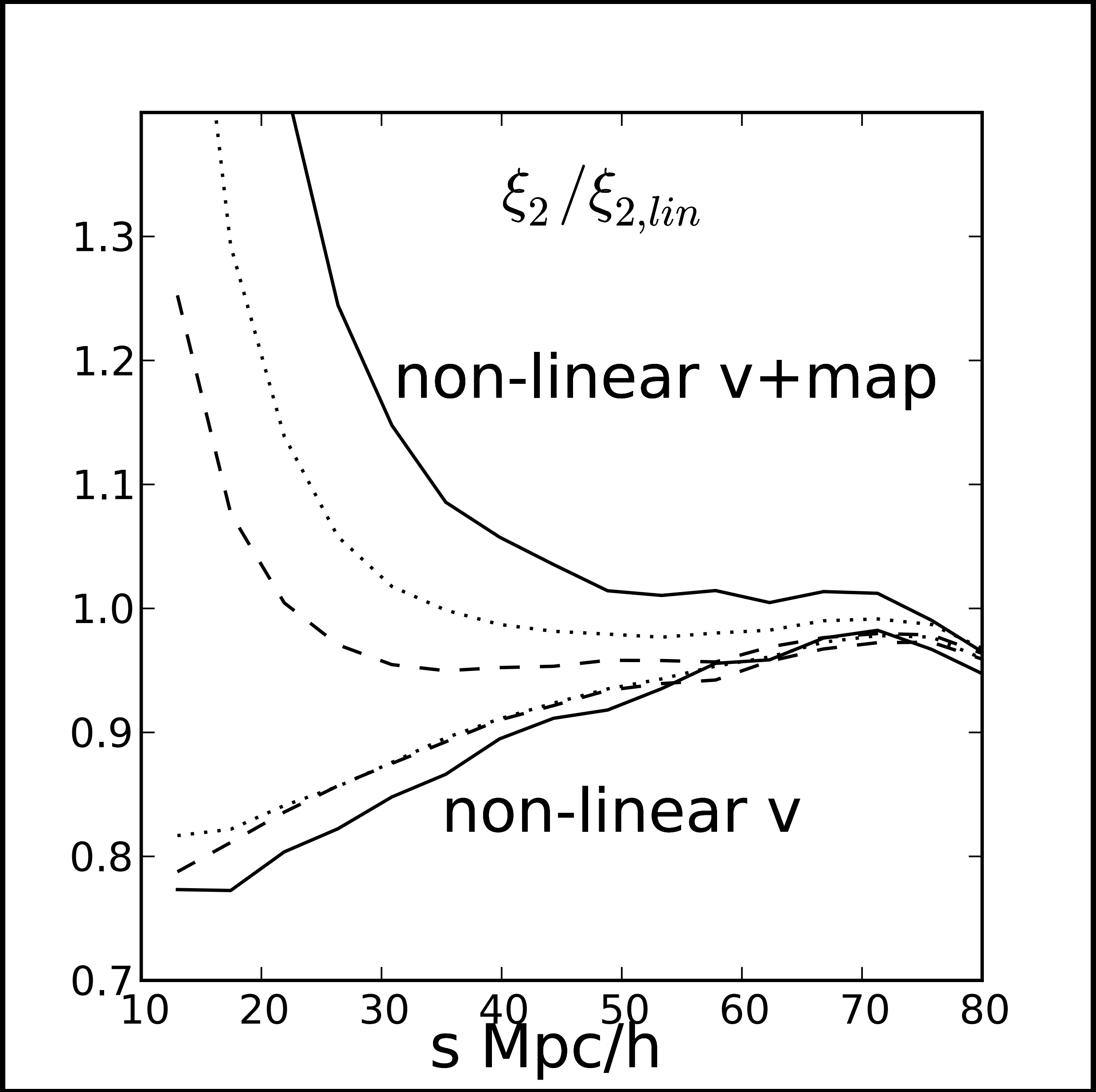
Putting it all together: fully analytic model

- 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



Take-away message

- Halo clustering in redshift space is complicated but well-understood in our model
- This is wrong!

$$P^s_m(k,\mu) = \left[P^{r,PT}_{\delta\delta}(k) + 2f\mu^2 P^{r,PT}_{\delta\theta} + f^2\mu^4 P^{r,PT}_{\theta\theta}\right] e^{-k^2\mu^2\sigma_v^2}$$

- Neglects important pair-weighting, bispectrum, and non-perturbative b^3 non-linear mapping terms