Large Scale Structure: comparison of theory with observation (III)

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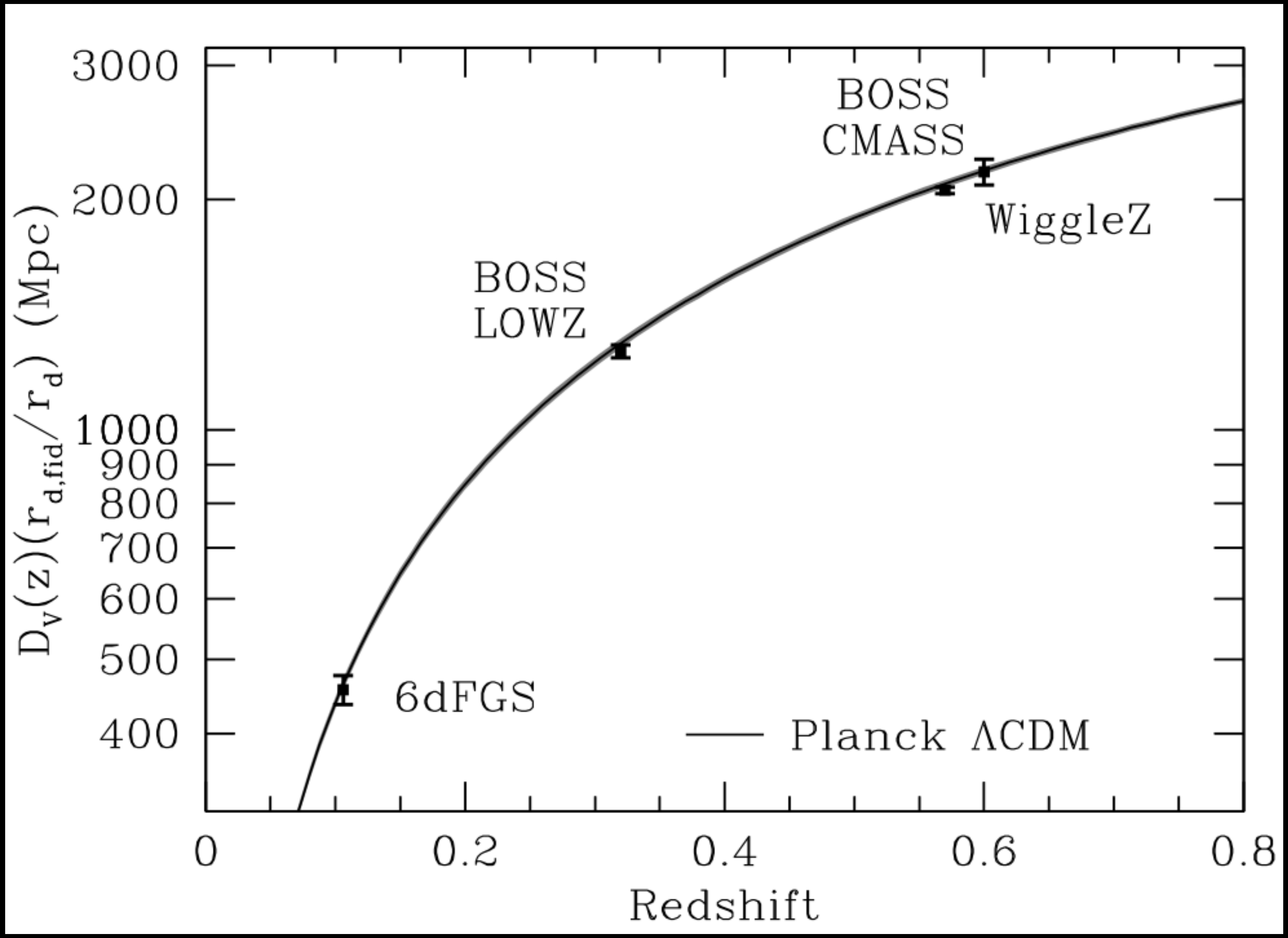
Cosmological Implications of current galaxy BAO measurements

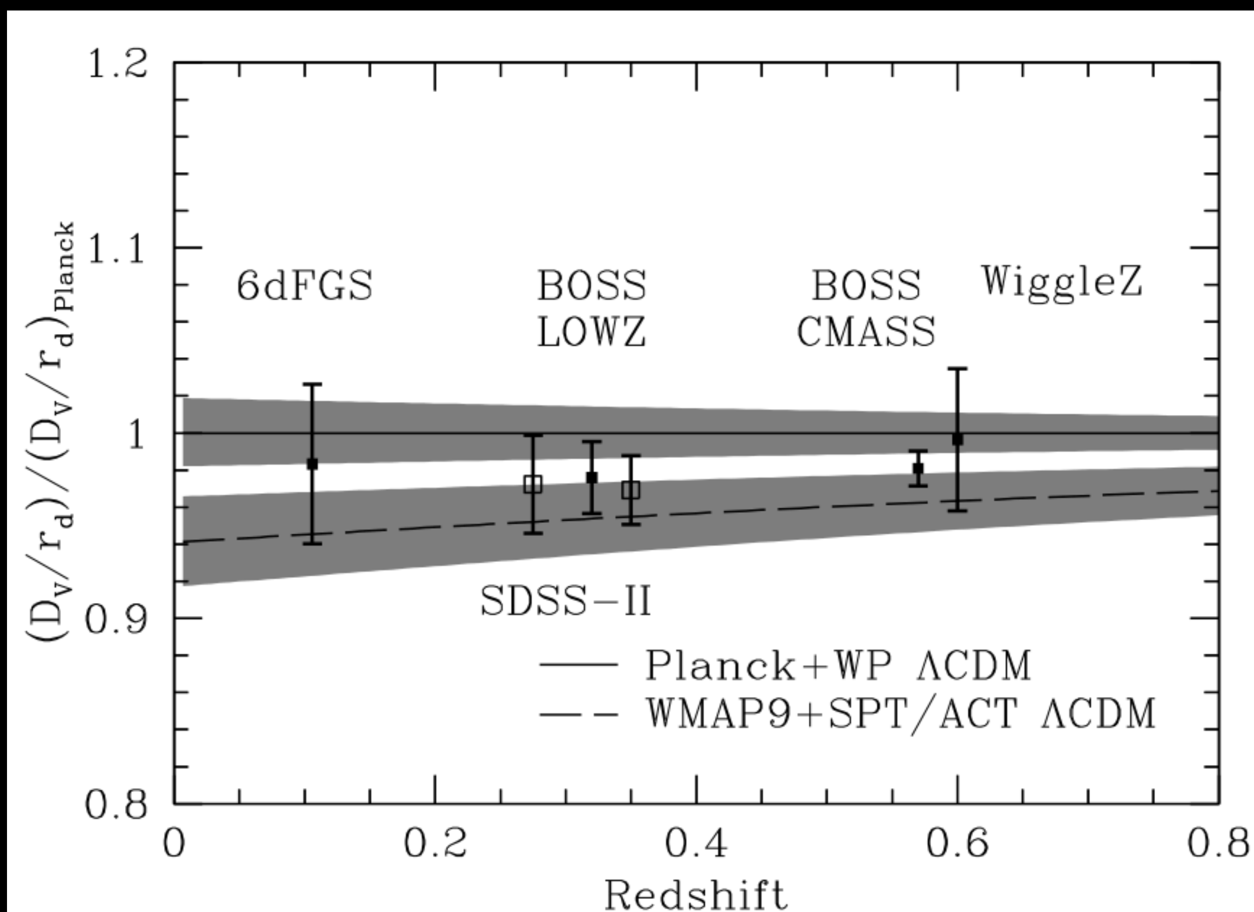
Beth Reid

Galaxy BAO distance ladder vs CMB ΛCDM predictions



BOSS, arXiv:1312.4877

Galaxy BAO distance ladder vs CMB ΛCDM predictions



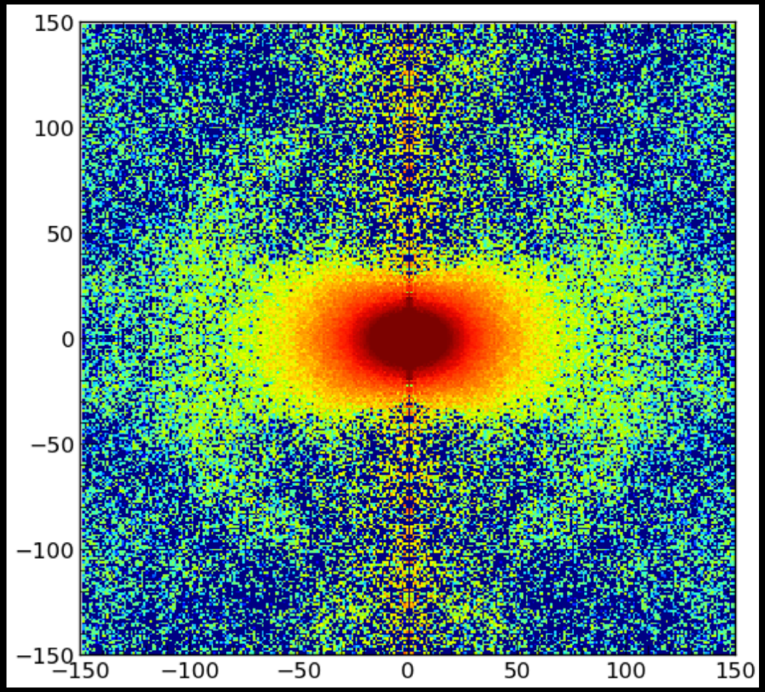
BOSS, arXiv:1312.4877

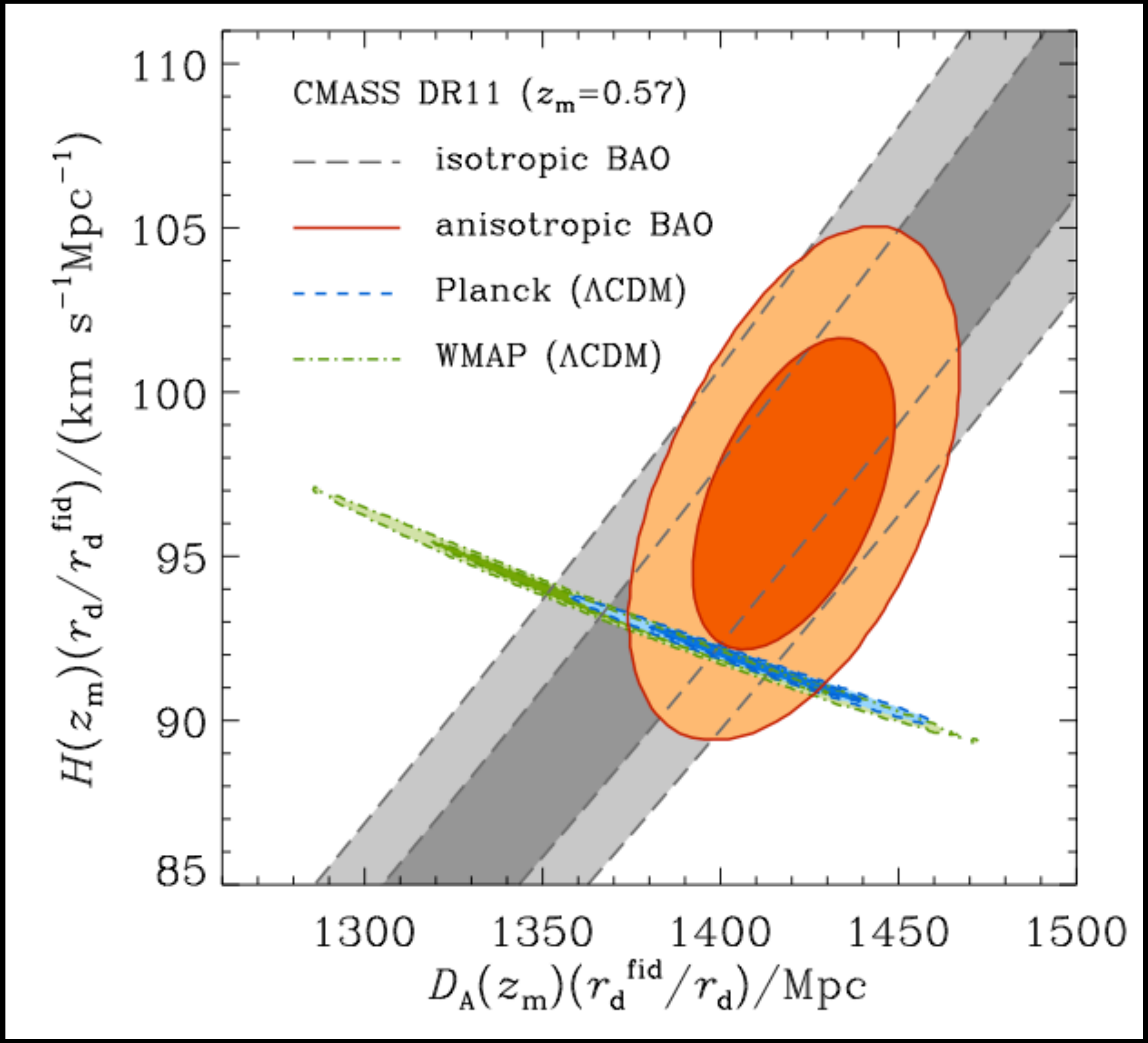
Planck: $\Omega_m h^2 = 0.1427 \pm 0.0024$

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

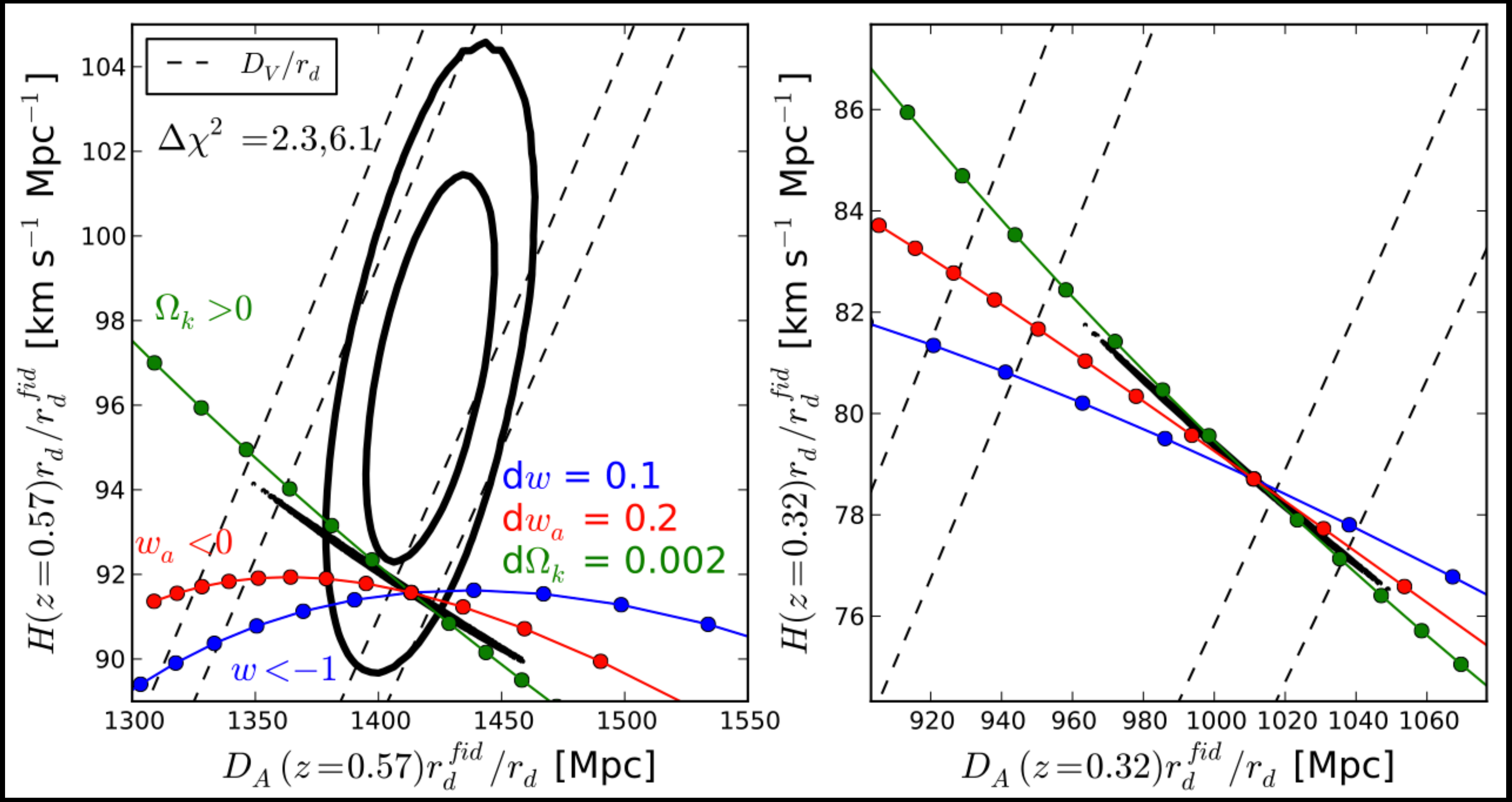
ΛCDM predictions from different CMB data sets differ because of $\Omega_m h^2$ difference; unfortunately BAO data straddle those predictions!

Anisotropic BAO fit results



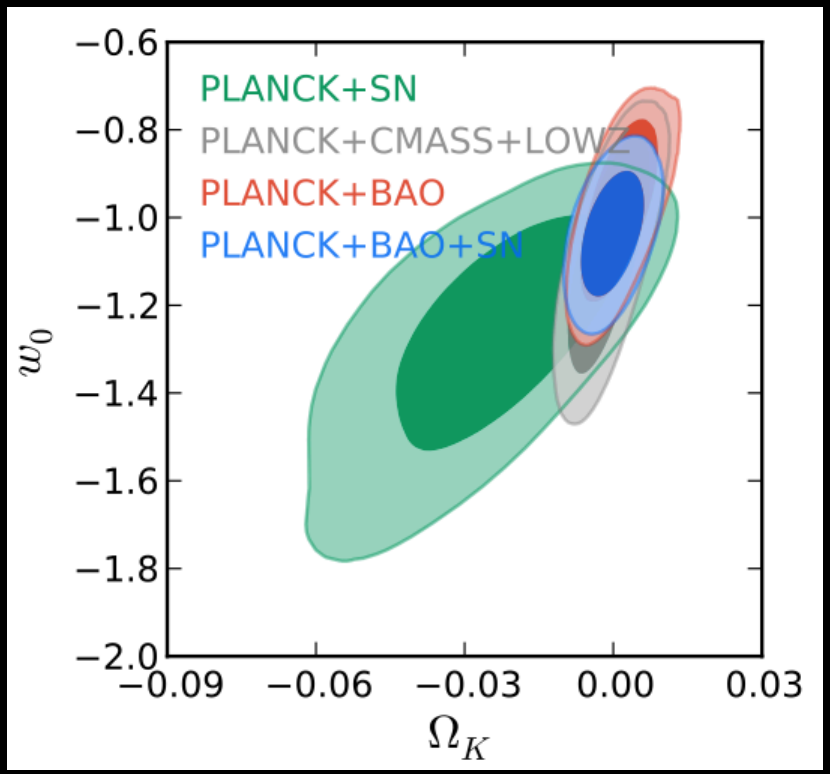


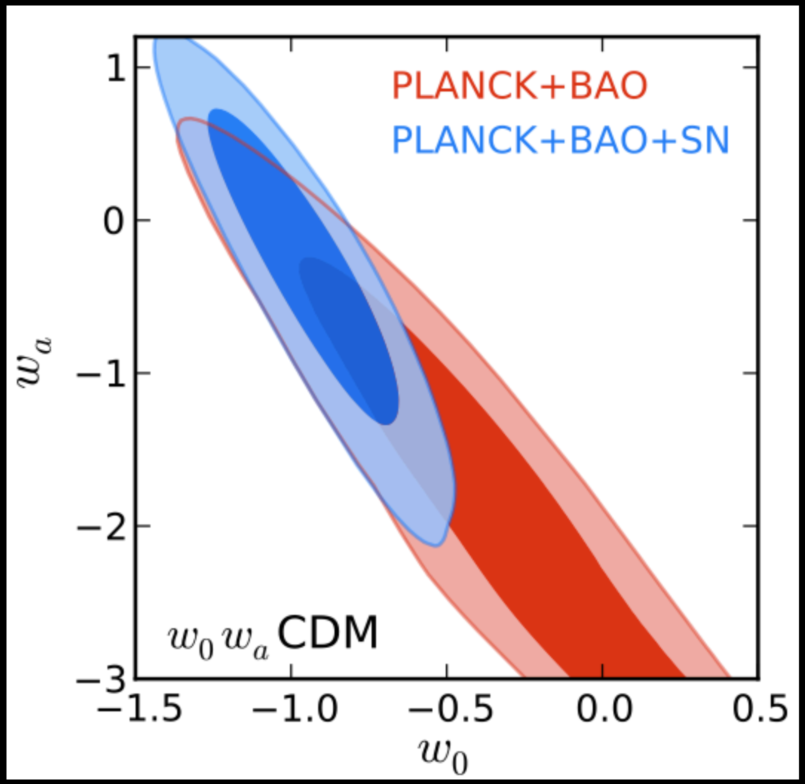
LOWZ and anisotropic CMASS BAO fits

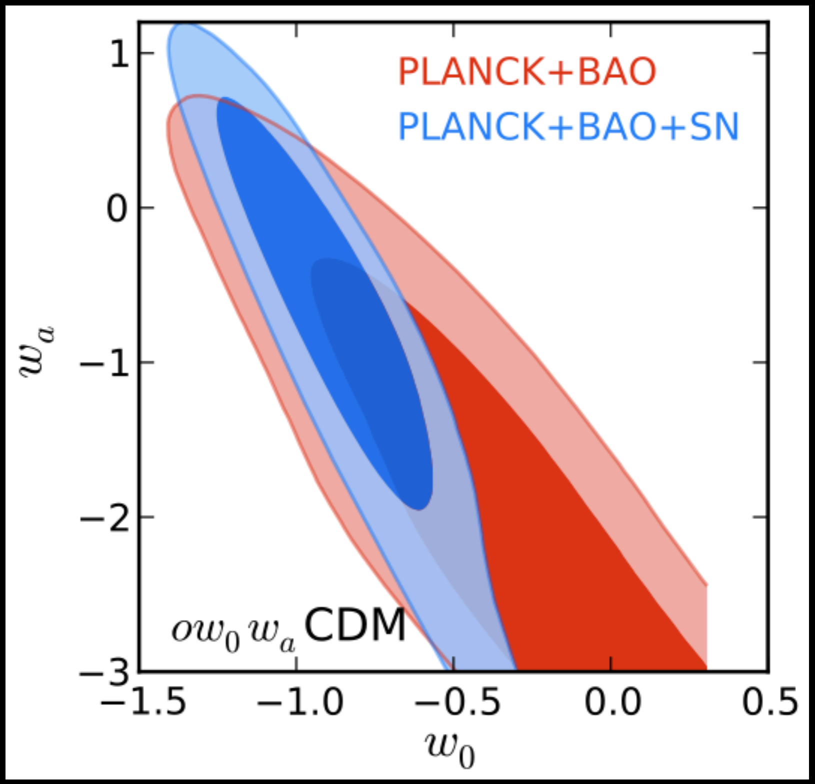


- D_A constraint improved
- D_A * H ~1.5σ high; no standard parameters predict observed value.
- $D_V(z=0.32)$ measured to 2%
- Lower redshift increases sensitivity to w_0, w_a

Galaxy BAO Cosmological Implications







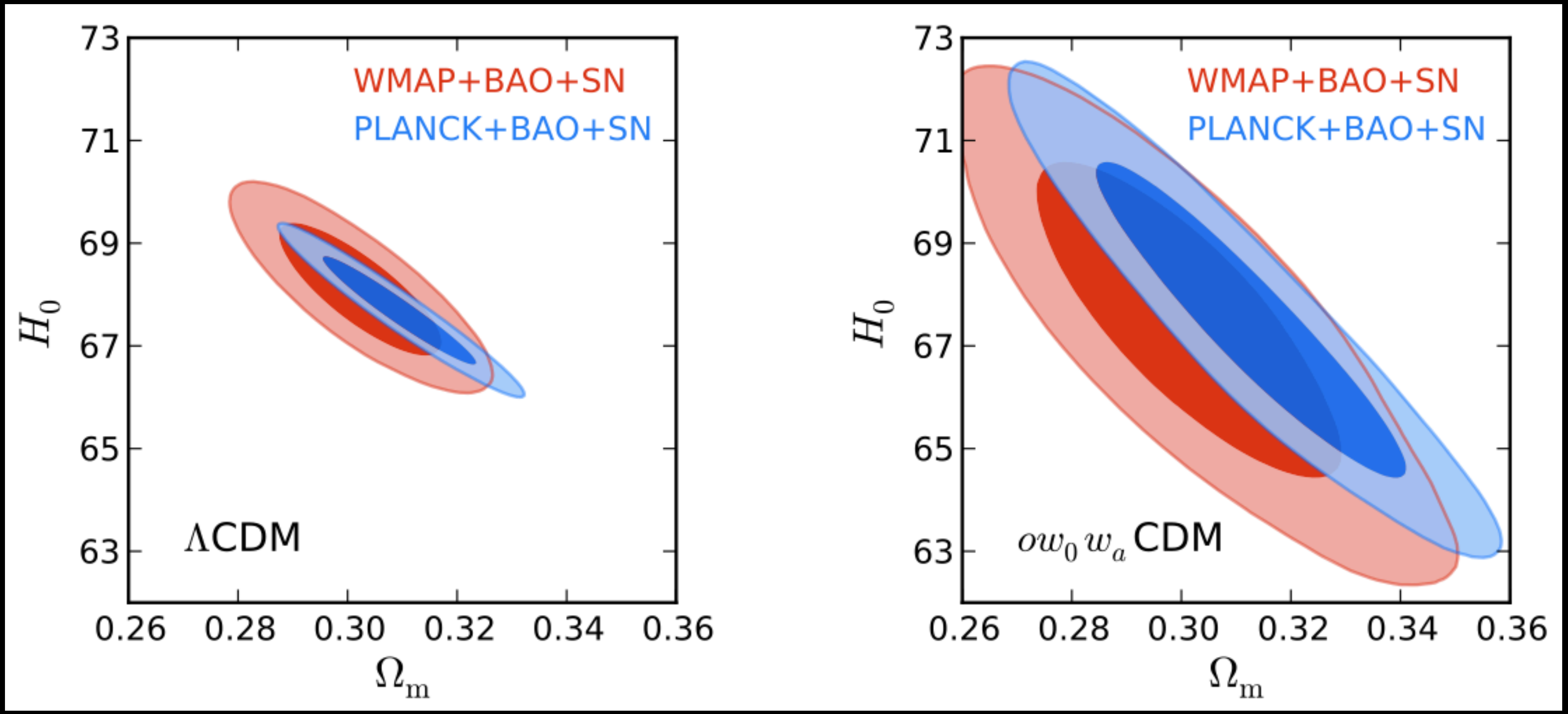
- Ω_k = 0.0002 ± 0.0033
- w = -1.04 ± 0.07

- w_0 = -0.94 ± 0.17
- w_a = -0.37 ± 0.60

- Ω_k = 0.0027 ± 0.0042
- w_0 = -0.87 ± 0.19
- w_a = -0.73 ± 0.80

[Planck + BAO + Union2 SN]

Galaxy BAO Cosmological Implications



- $\Omega_m = 0.309 \pm 0.008$
- $H_0 = 67.7 \pm 0.6$

[Planck + BAO + Union2 SN]

- $\Omega_m = 0.312 \pm 0.016$
- $H_0 = 67.5 \pm 1.7$; works in even more general DE models thanks to BAO absolute calibration and SN coverage to z=0 [BOSS + SNLS in prep]

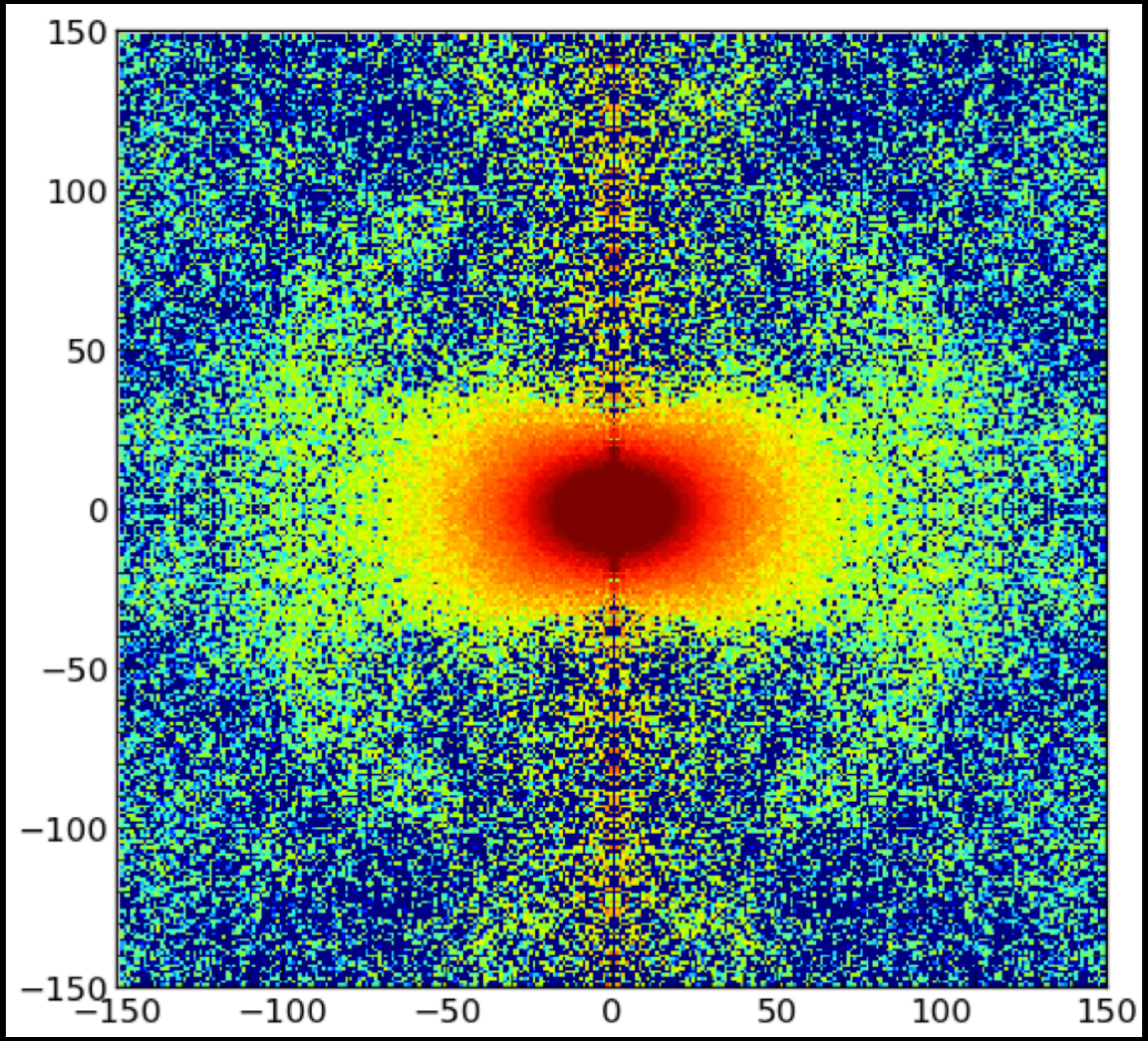
Lecture 3 Outline

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

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

Anisotropy in the observed ξ / P

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

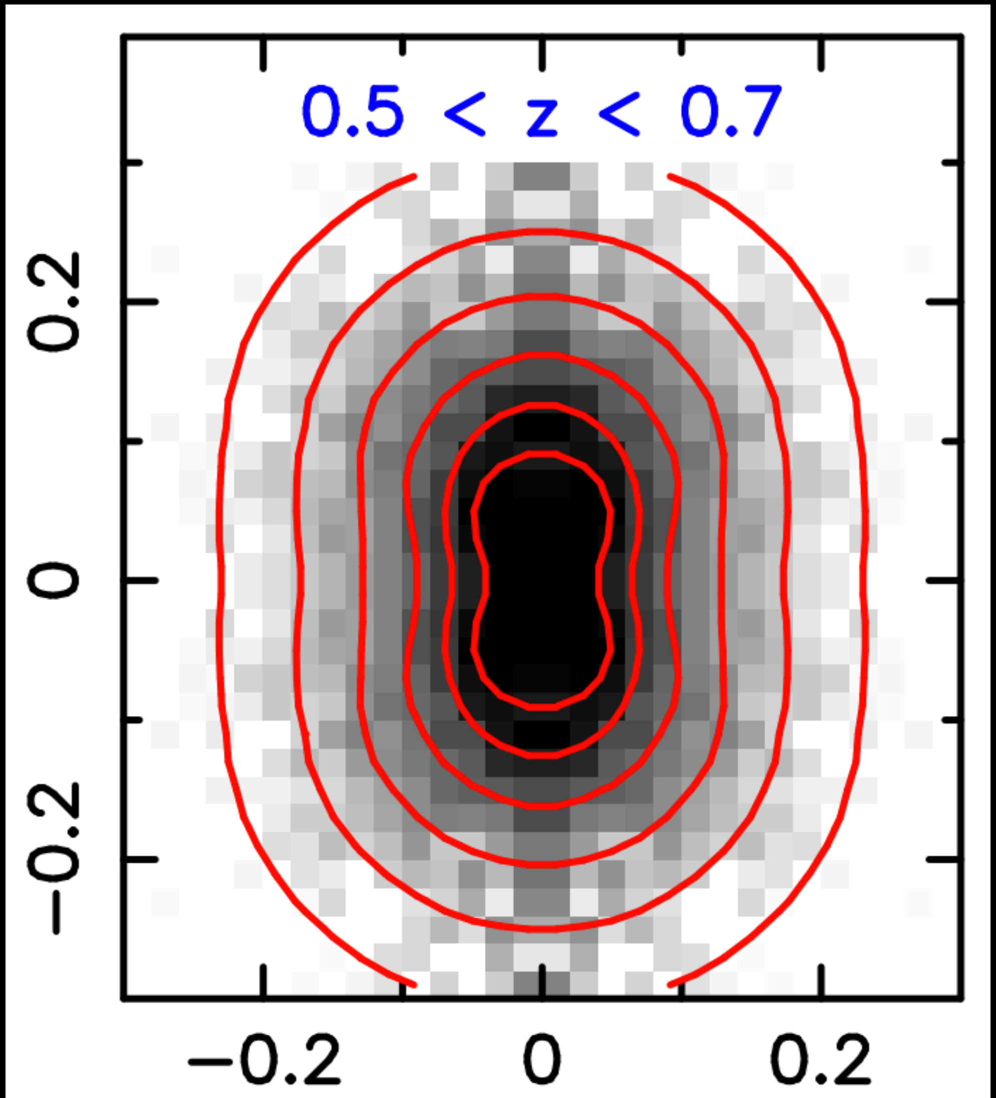


$r_\parallel$ (h^{-1} Mpc)

$r_\perp$ (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)

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

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

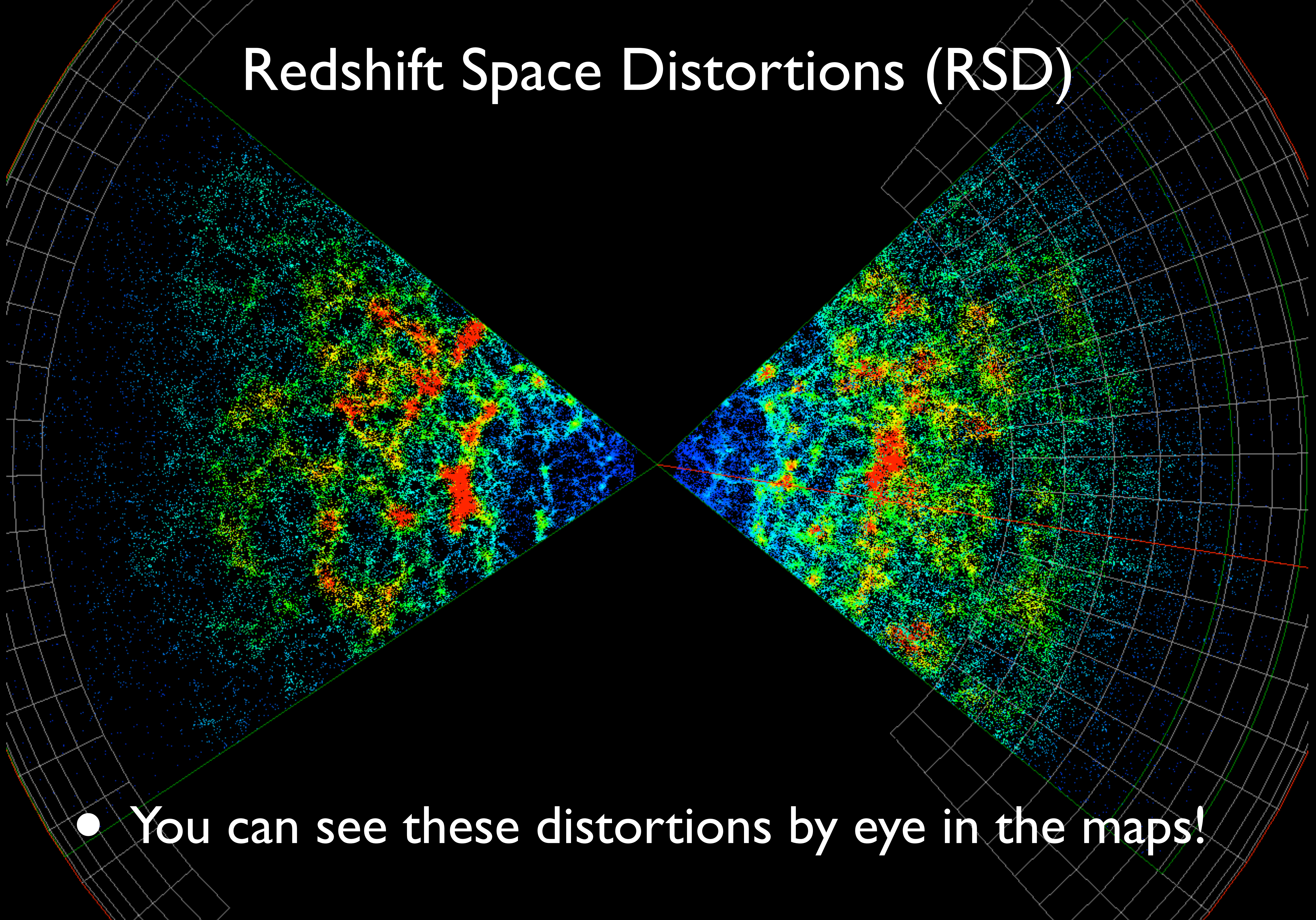
$$\chi(z_{spec}) = \chi(z_{cosmo}) + v_p/aH$$

(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

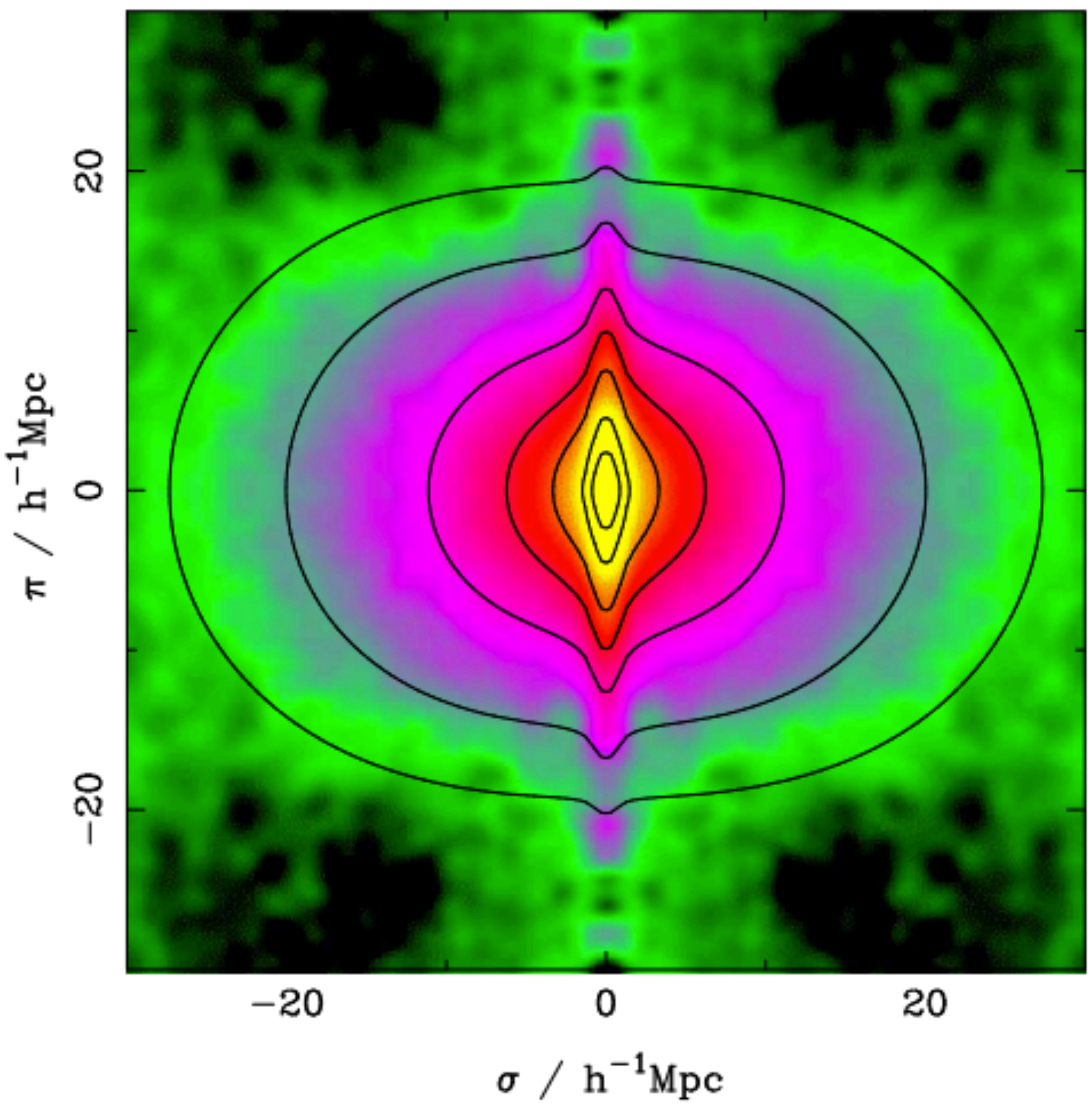


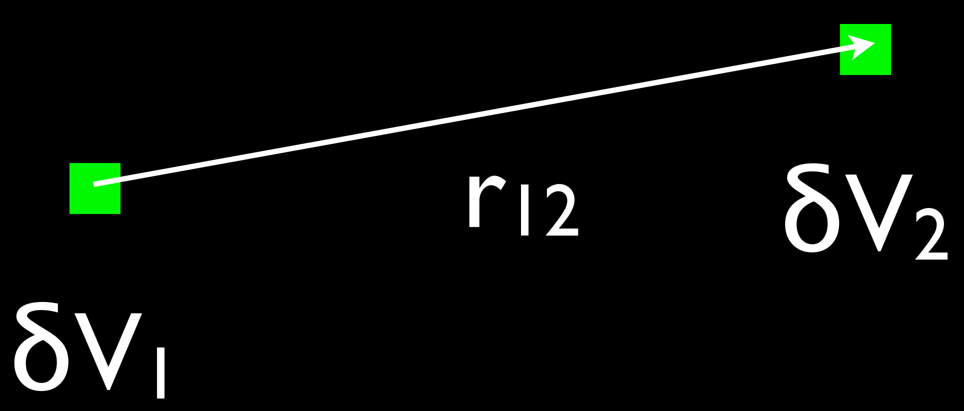
Figure 2 The redshift-space correlation function for the 2dFGRS, $\xi(\sigma, \pi)$, plotted as a function of transverse (σ) and radial (π) pair separation. The func-

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

Redshift Space Distortions (RSD)

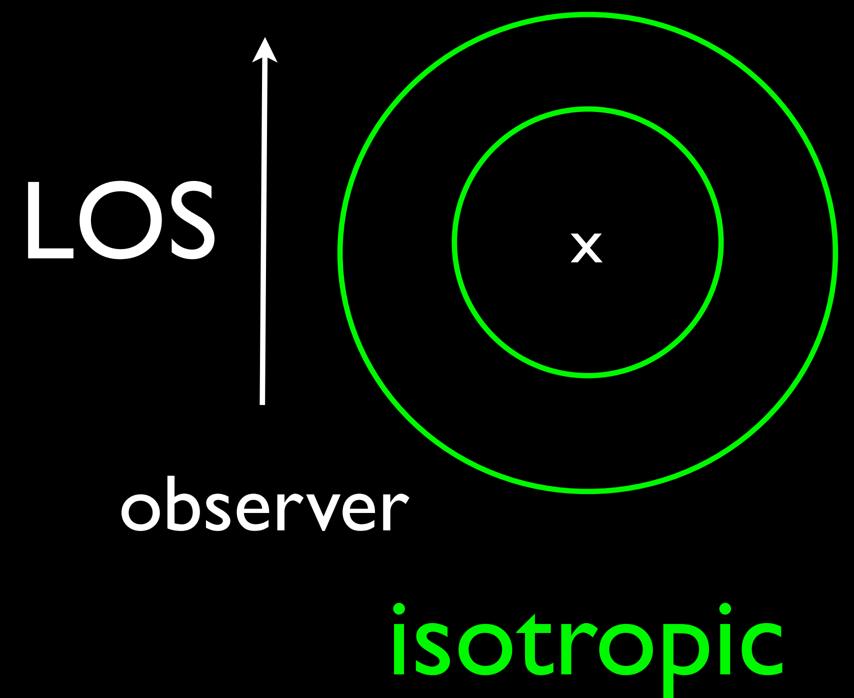
- Now let's try to get a qualitative understanding of the anisotropic distortions in ξ / P due to RSD.
- An equivalent way to think about ξ is as specifying the density field around a tracer object:

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



Redshift Space Distortions (RSD)

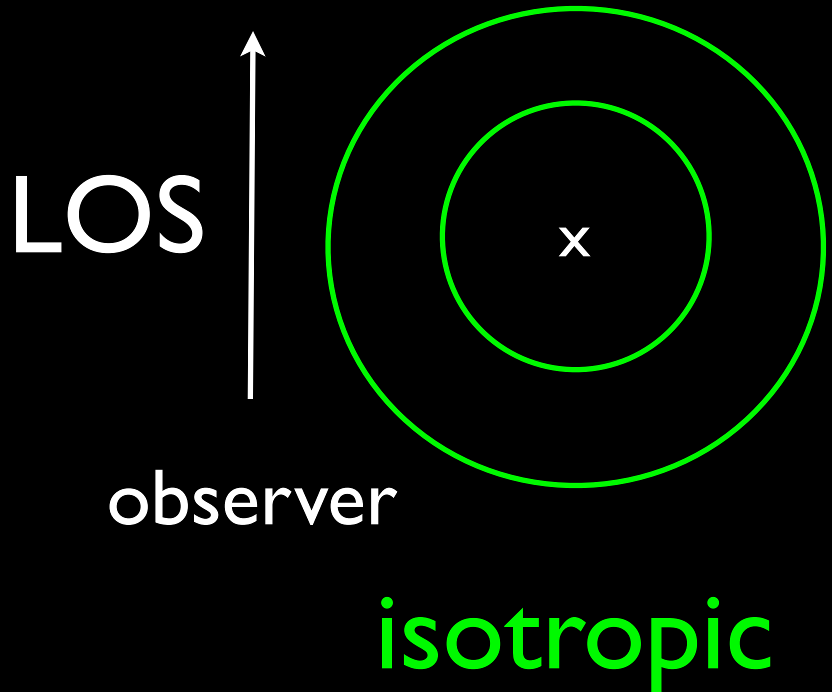
- In "real space" the iso-density contours will be circular:



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

Redshift Space Distortions (RSD)

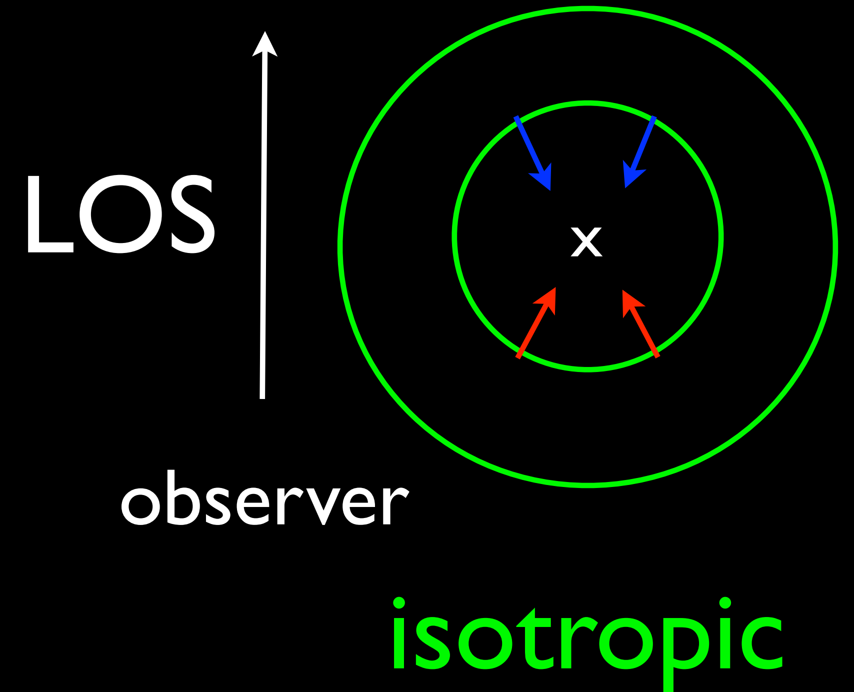
- Use the linearized continuity equation to figure out the velocity field around a point-like density perturbation:



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

Redshift Space Distortions (RSD)

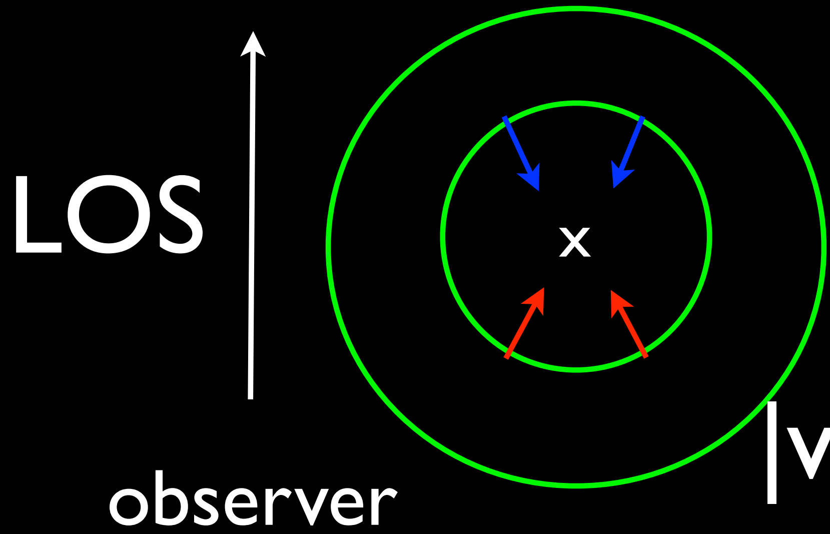
- Use the linearized continuity equation to figure out the velocity field around a point-like density perturbation:



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

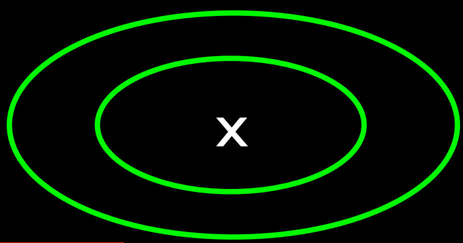
$$[\ \chi(z) = \chi_{true} + v_p/aH\ ]$$

Redshift Space Distortions (RSD)



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

[continuity eqn]



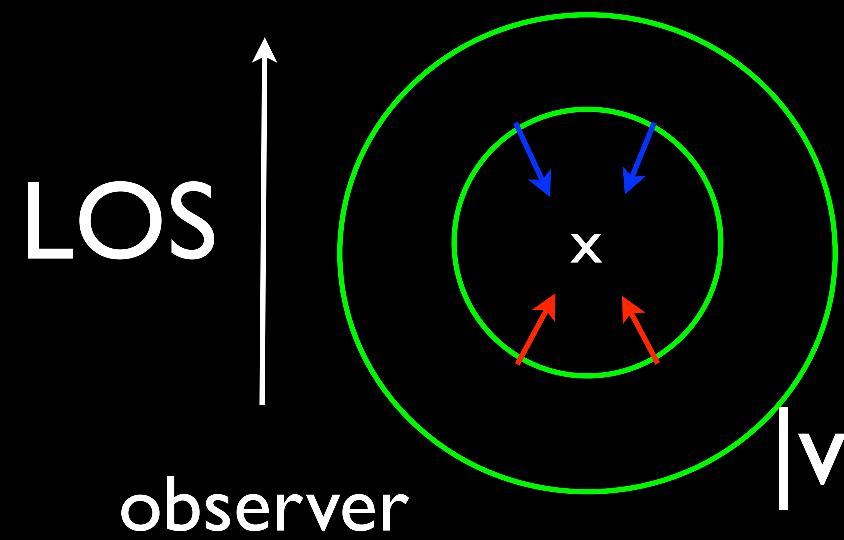
$$|v_p| \sim d\,\sigma_8/d \ln a = \boxed{\sigma_8 * f}$$

isotropic

squashed along line of sight

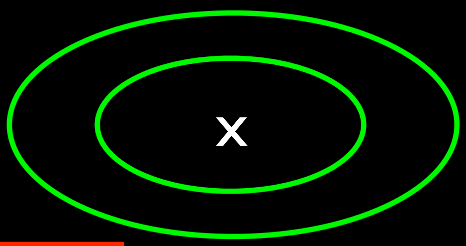
$$f = d \ln \sigma_8 /d \ln a \approx \Omega_m^{\gamma}$$

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

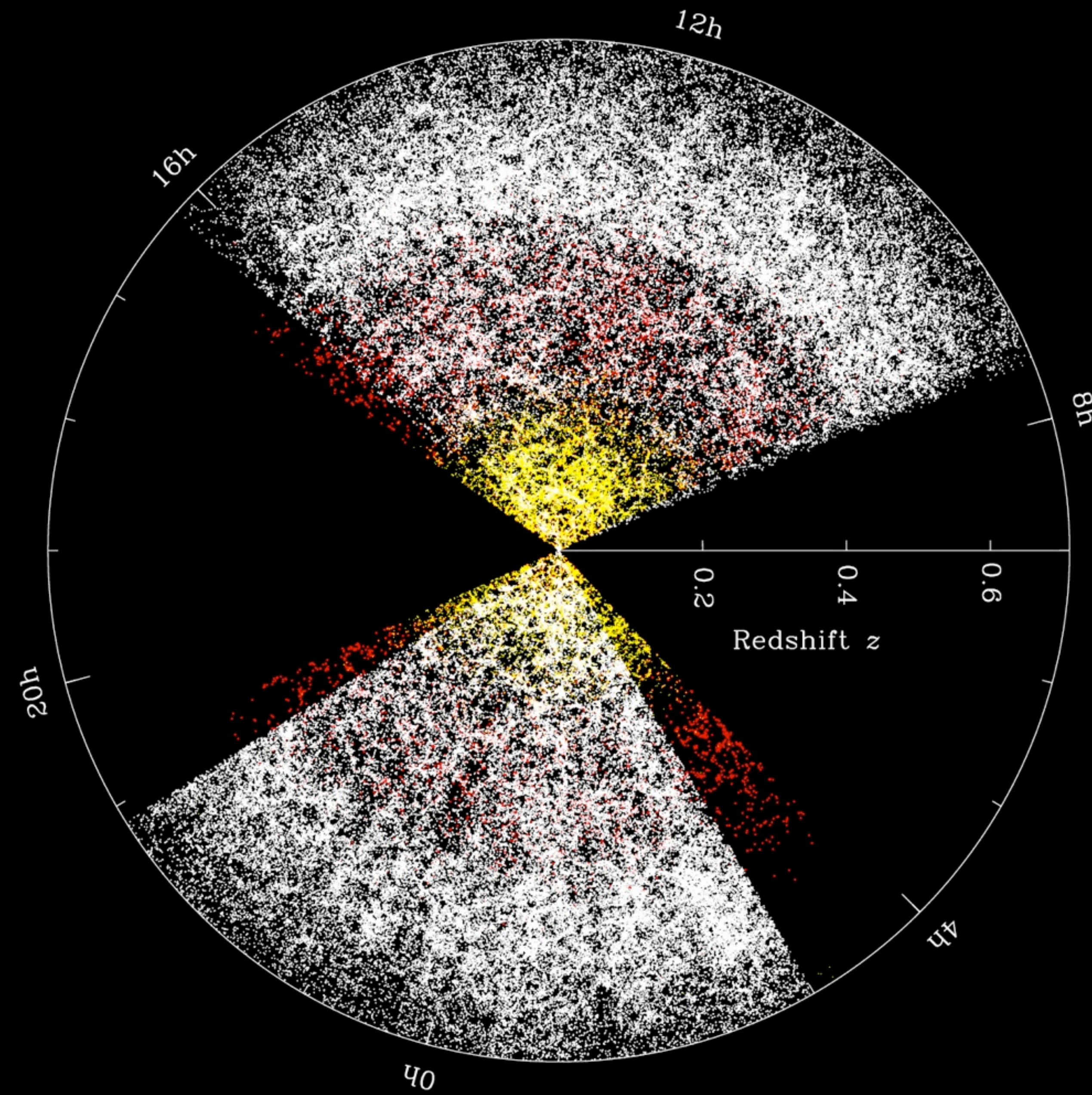
This means that by measuring the anisotropy of clustering, we should be able to measure d σ_8/d ln a, the *growth rate* of cosmic structure.

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"



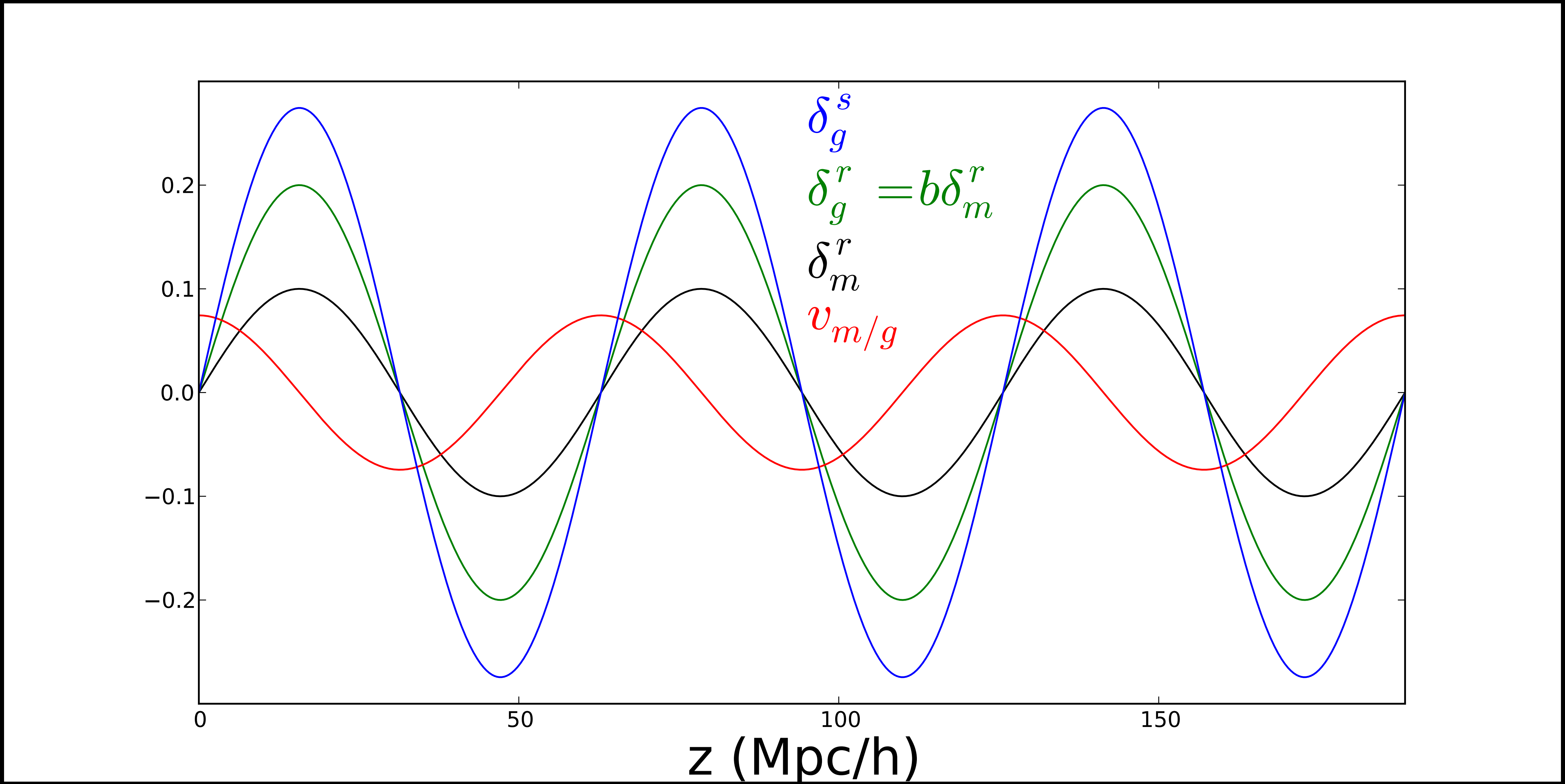
Why measure RSD?

- 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:

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

- 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.

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):

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

- Compute the Jacobian of the d^3r -> d^3s transformation

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

Neglect $v_z/z << 1$

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 σ_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

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

Legendre Polynomial moments

General Expansion

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

Relation to P_ℓ (k)

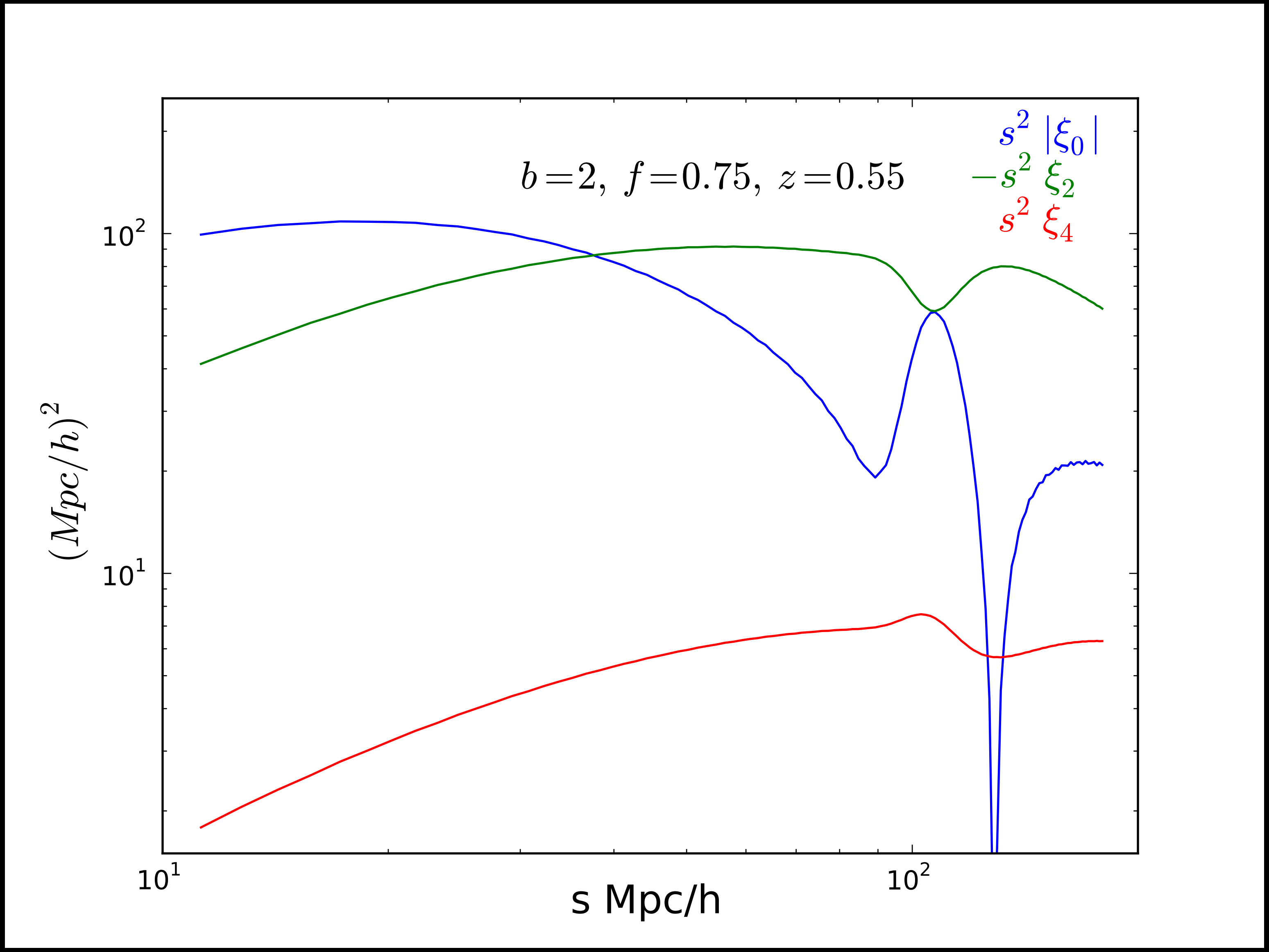
$$\xi_\ell(s) = i^\ell \int \frac{k^2\, dk}{2\pi^2} P_\ell(k) j_\ell(ks)$$

Legendre Polynomial moments: scale dependence

$L_0(\mu) = 1$

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

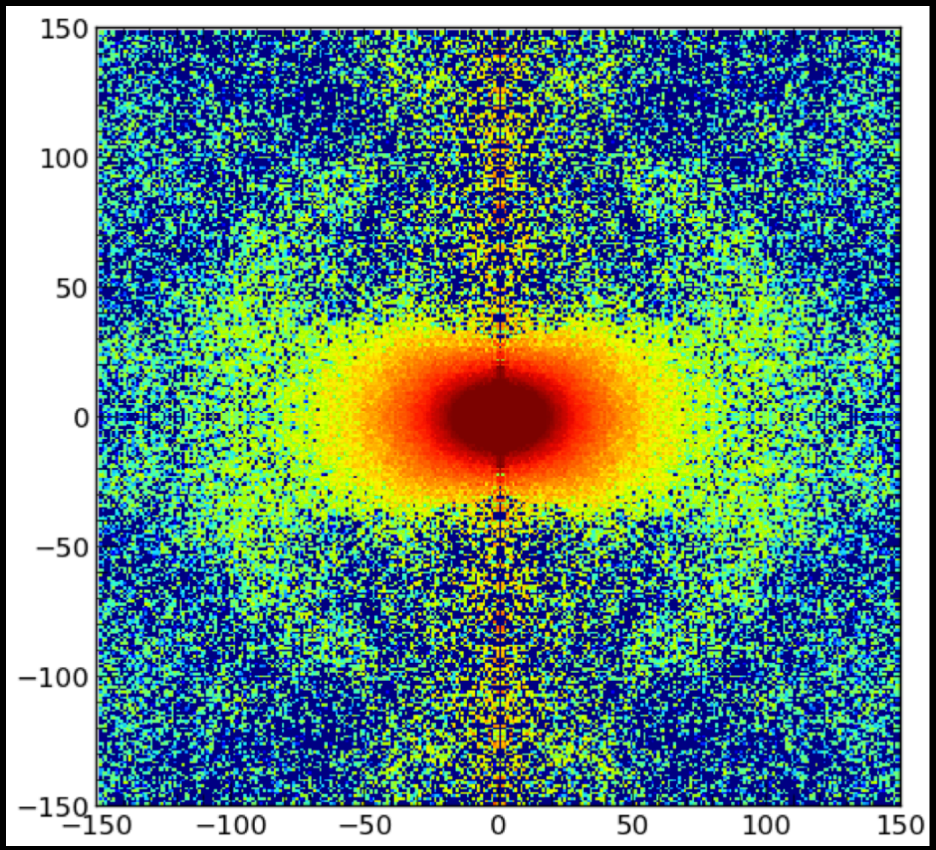
$L_4(\mu) = 4.375\mu^4 - 3.75\mu^2 + 0.375$

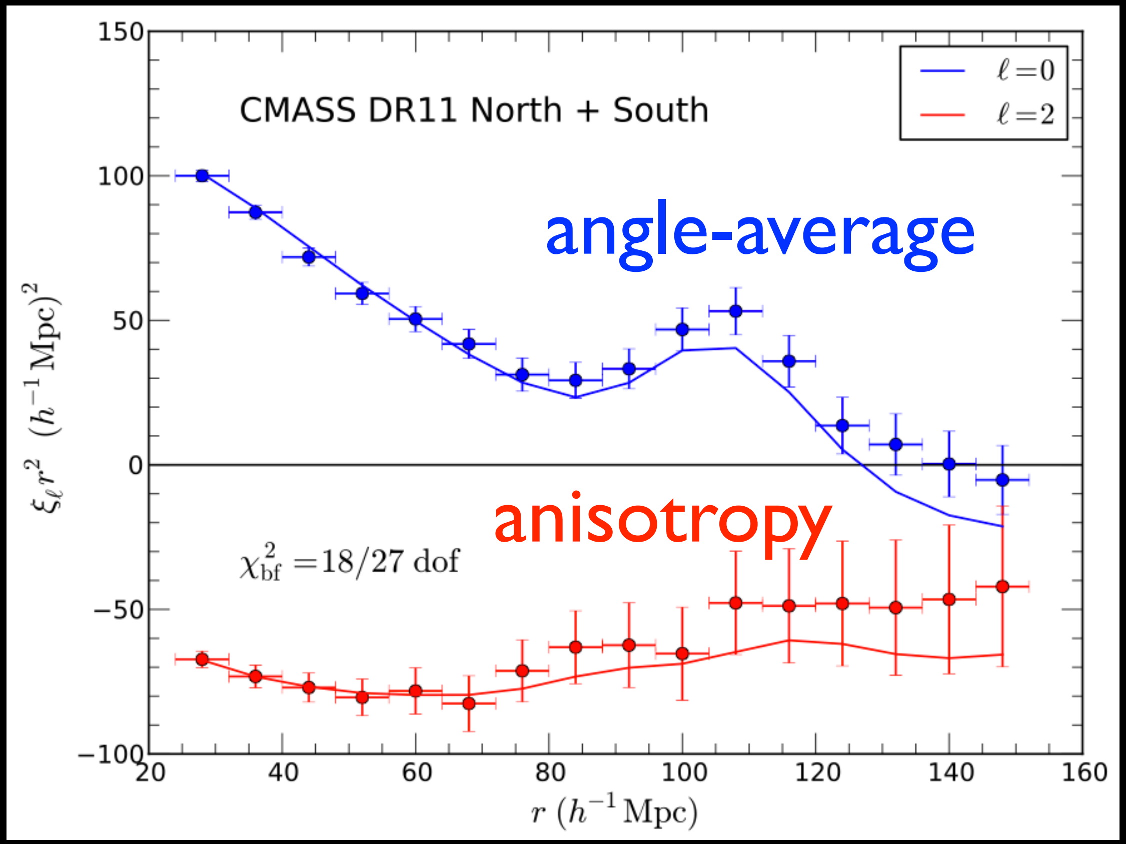


RSD data vector

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

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





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

s (h^{-1} Mpc)

BOSS DR11, Samushia, Reid et al. 2013

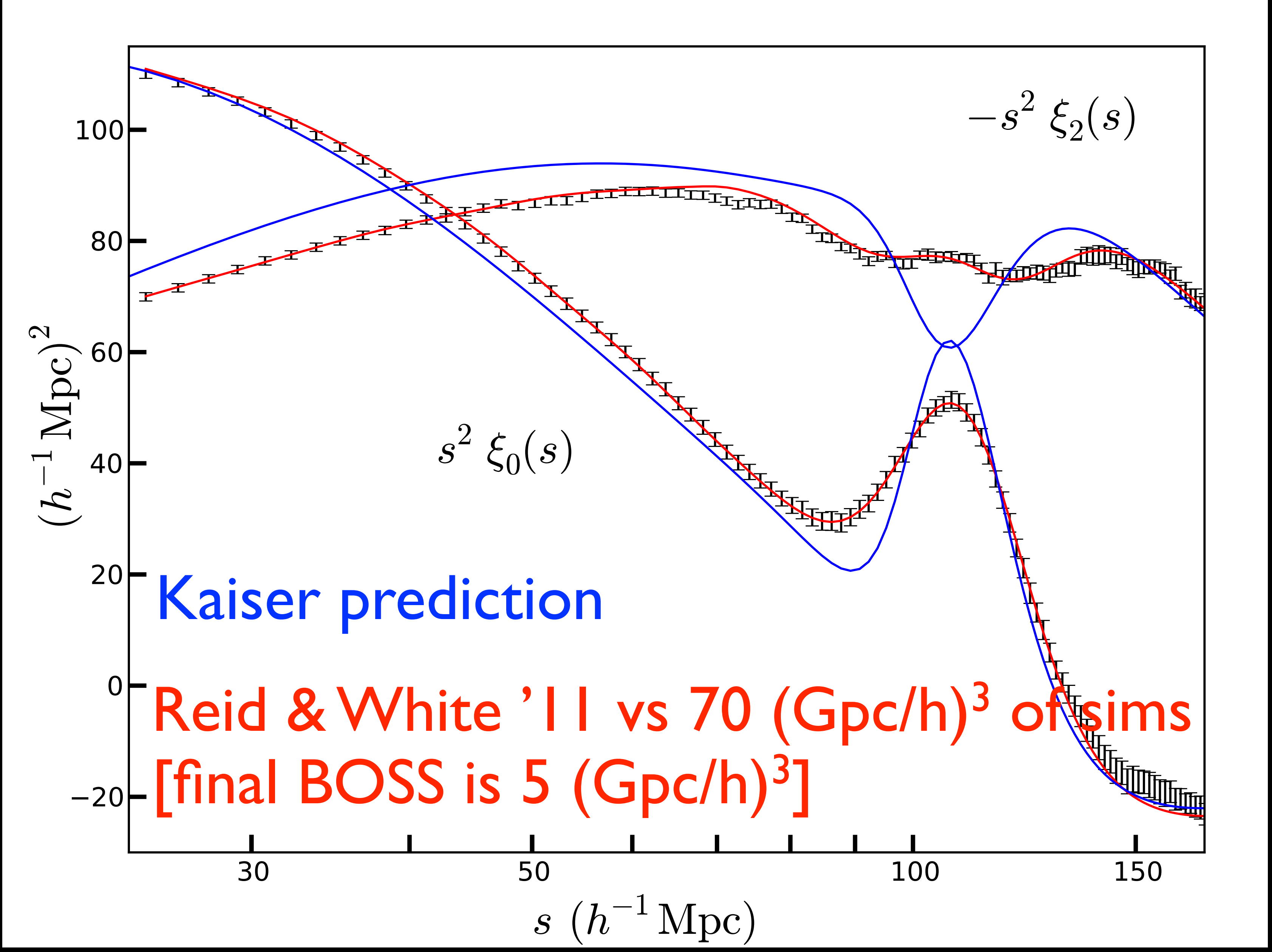
Redshift Space Distortions (RSD)

- 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

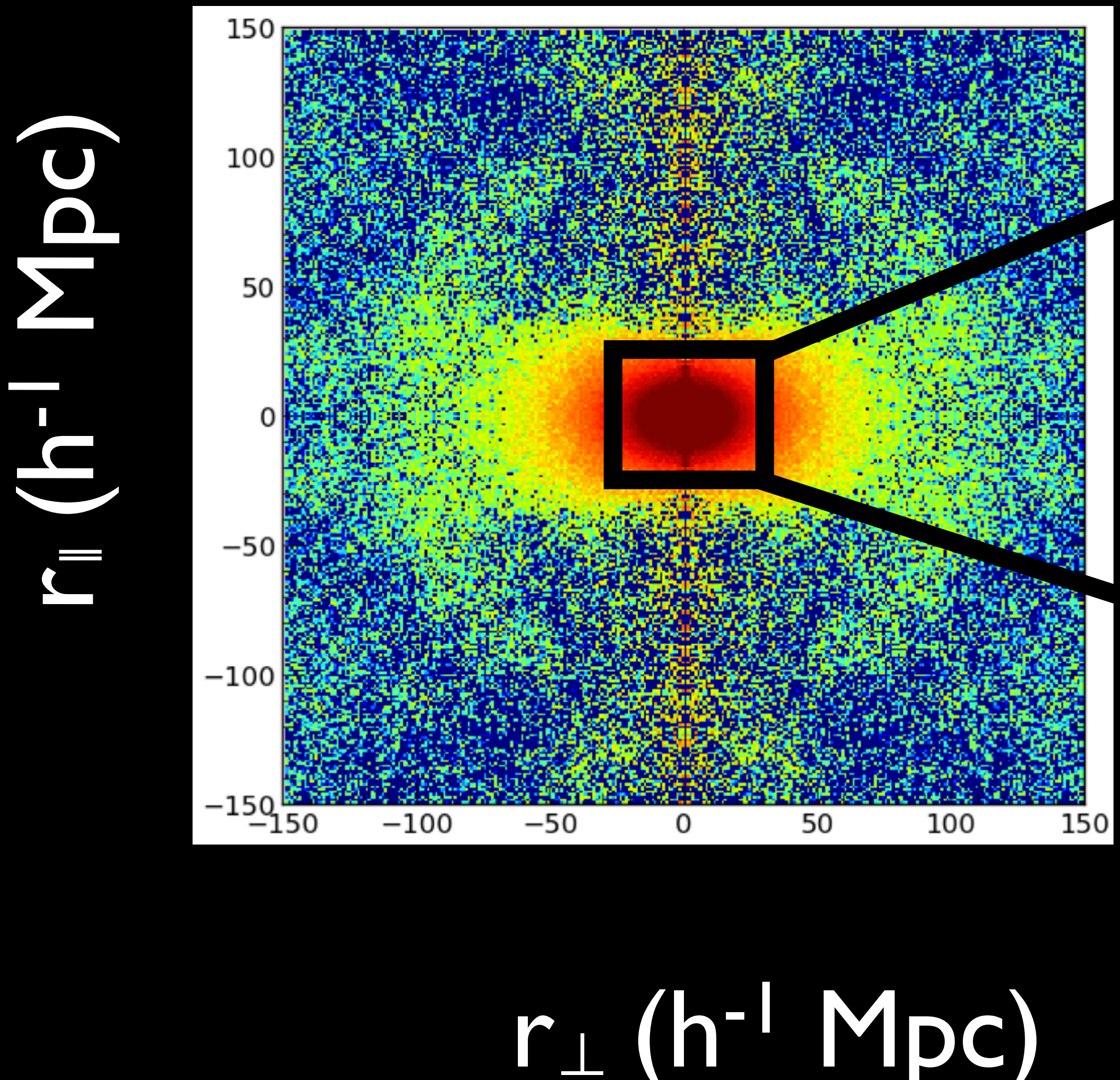
- Lots of complicated physical effects alter the galaxy ξ/P away from its linear theory behavior:
  - non-linear gravitational evolution
  - non-linear biasing between tracers and matter field
  - non-linear redshift space distortions

Kaiser prediction is not accurate enough.

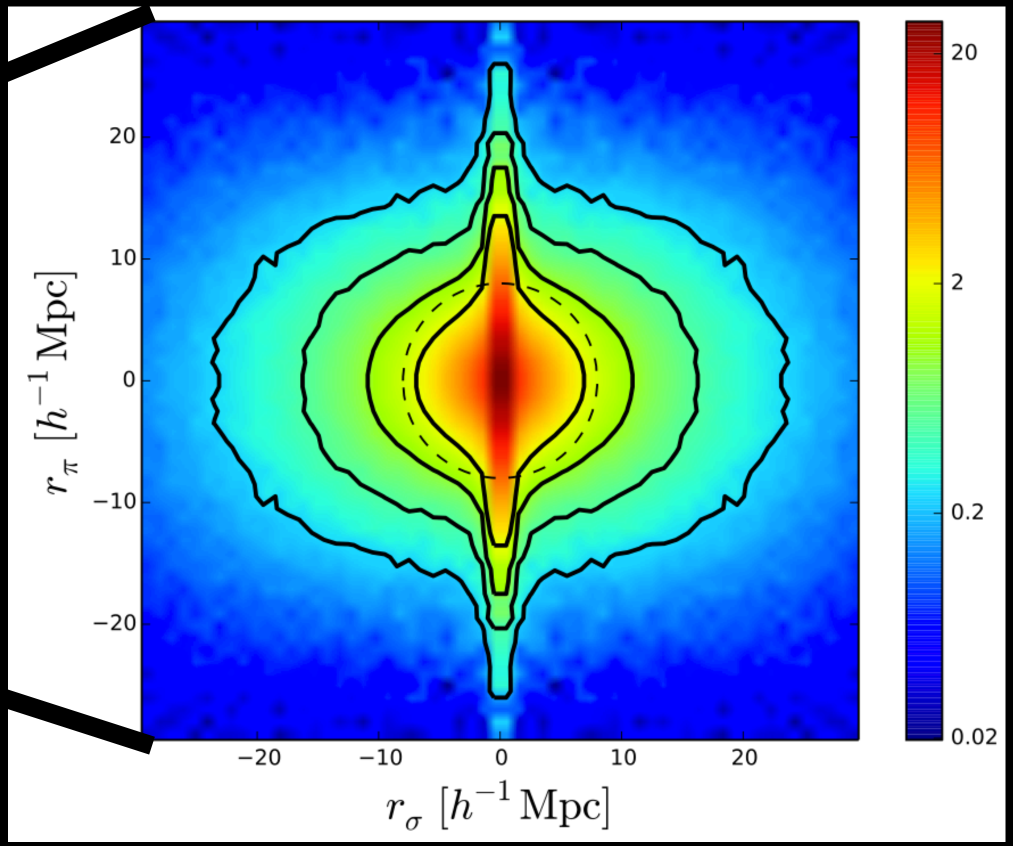


Fingers-of-God

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



BOSS DR11, Samushia, Reid et al. 2013



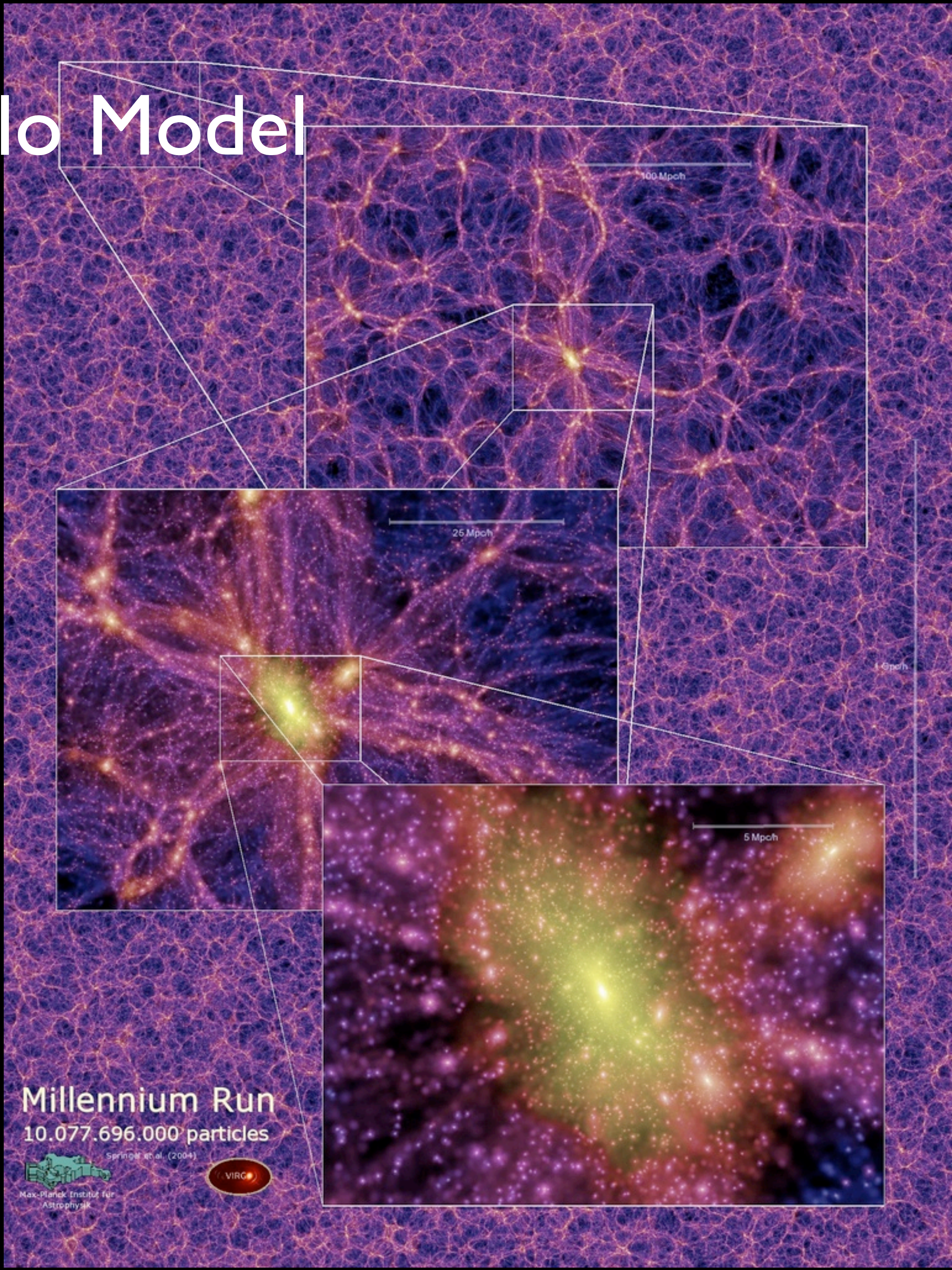
Reid et al. 2014

Non-linear theory of galaxy clustering

- I will leave the details for the LSS lectures next week, but we need the concept of the halo model to understand Fingers-of-God
- Reference -- Cooray and Sheth (astro-ph/0206508)

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

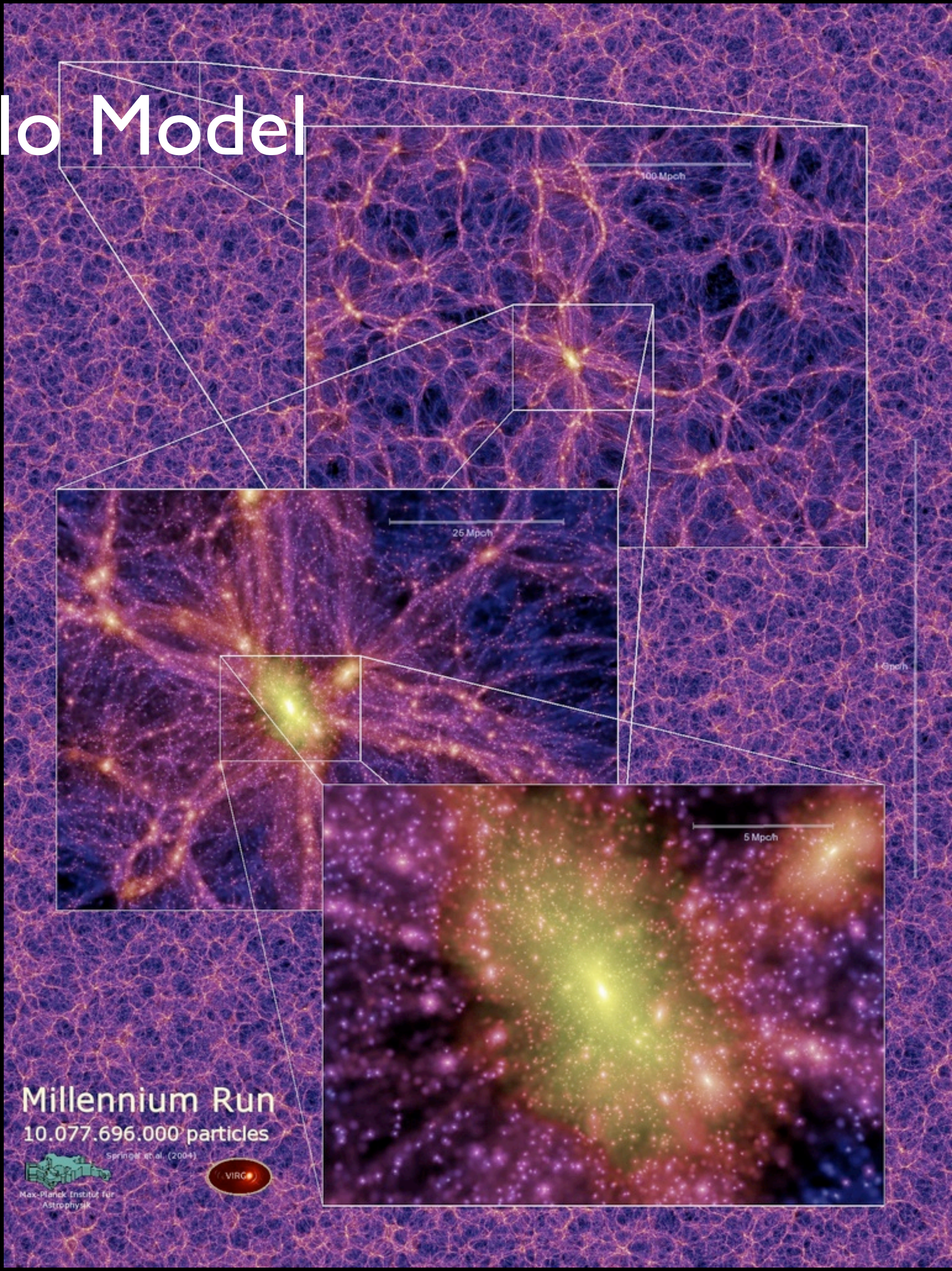


The Halo Model

- "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.



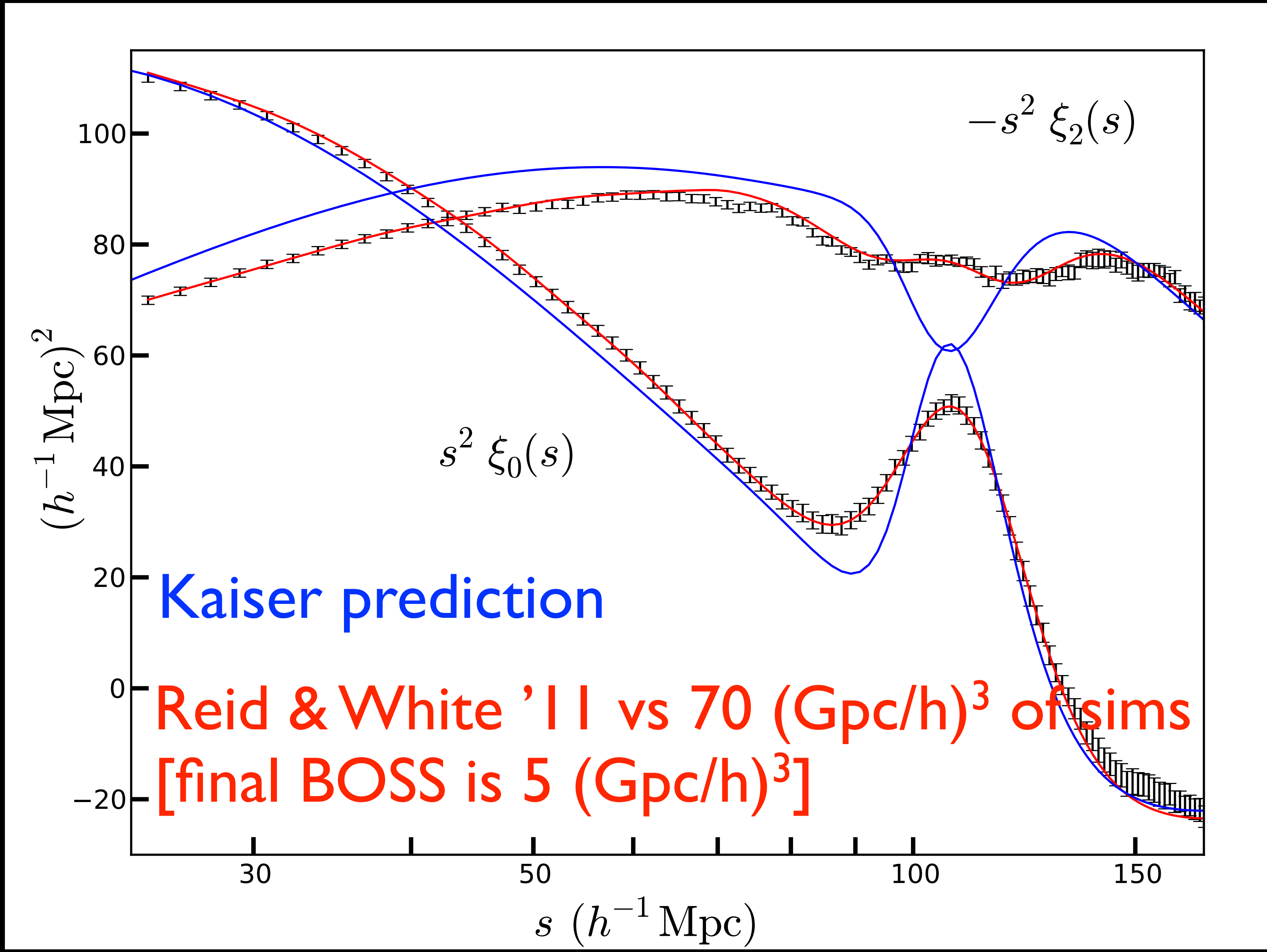
Minimal components of an RSD model

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

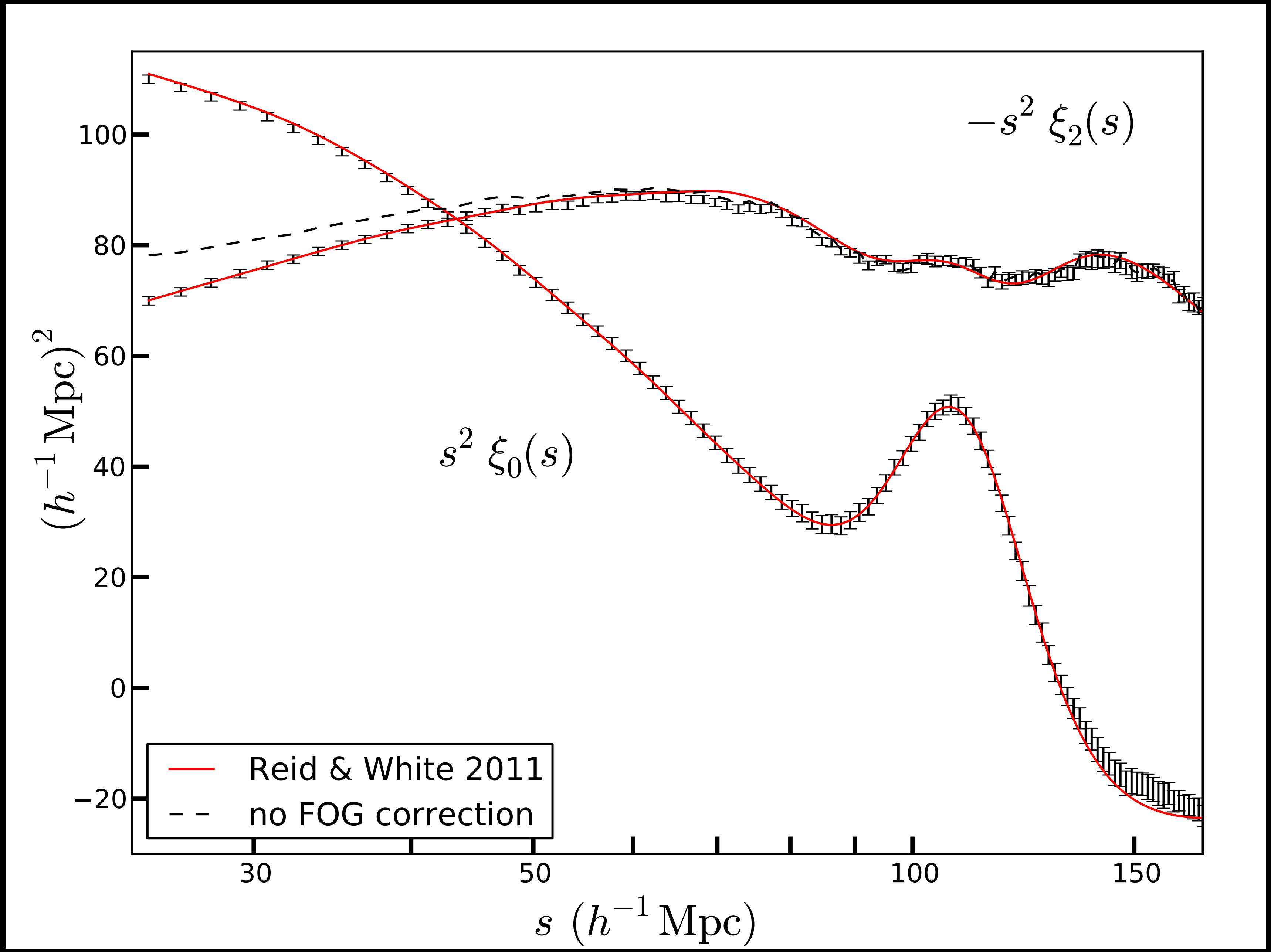
$f\sigma_8$: cosmological information!

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

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



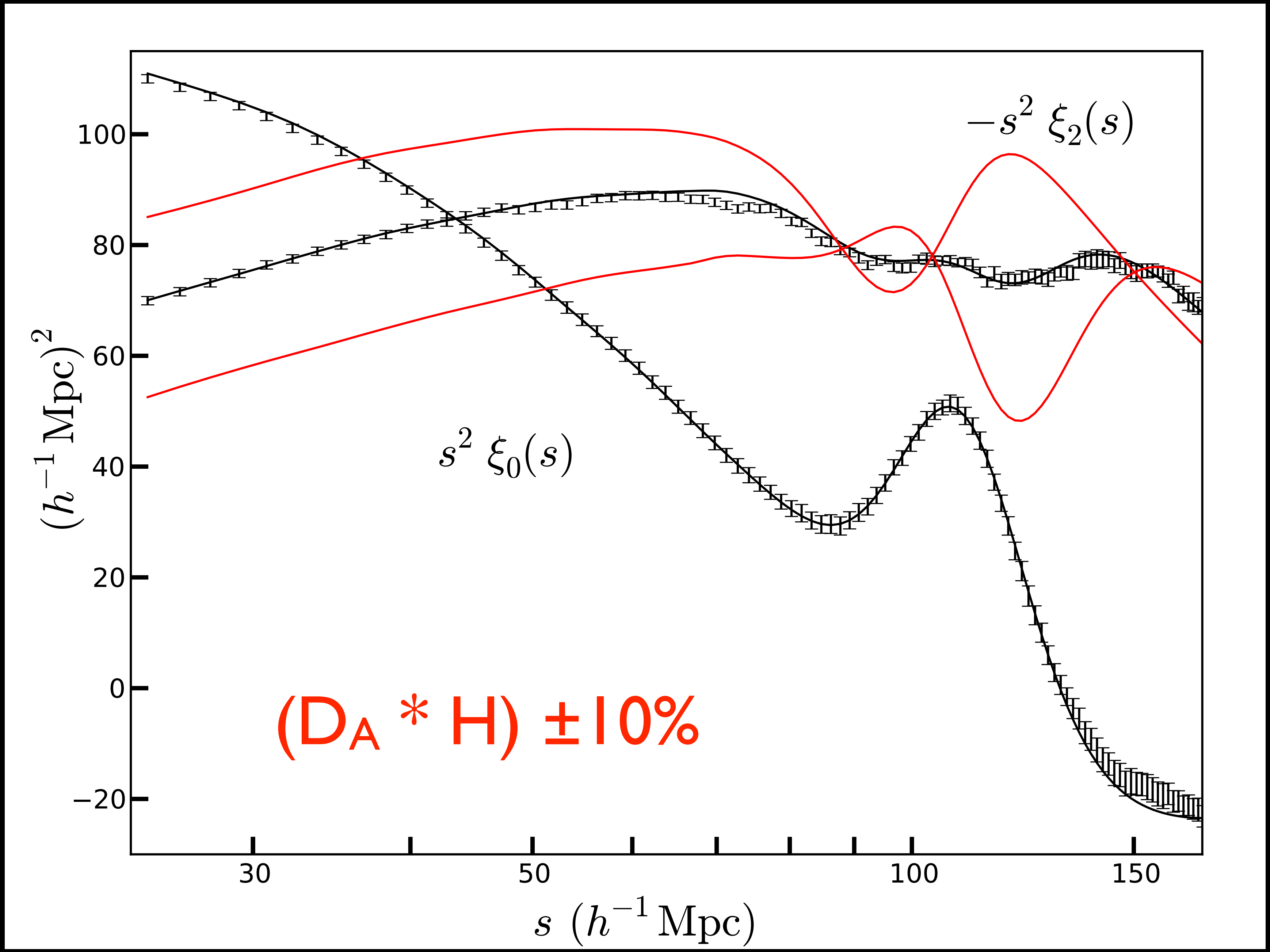
Impact of Fingers-of-God on clustering for mock BOSS-like galaxies



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

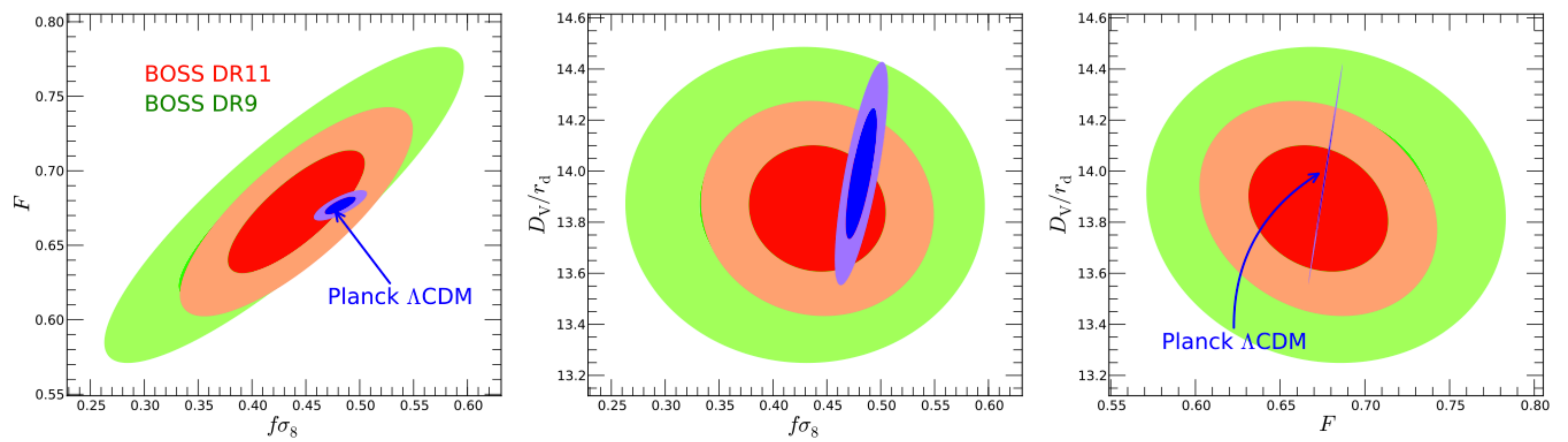


(D_A * H) ±10%

D_V stretches s axis

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

D_A*H



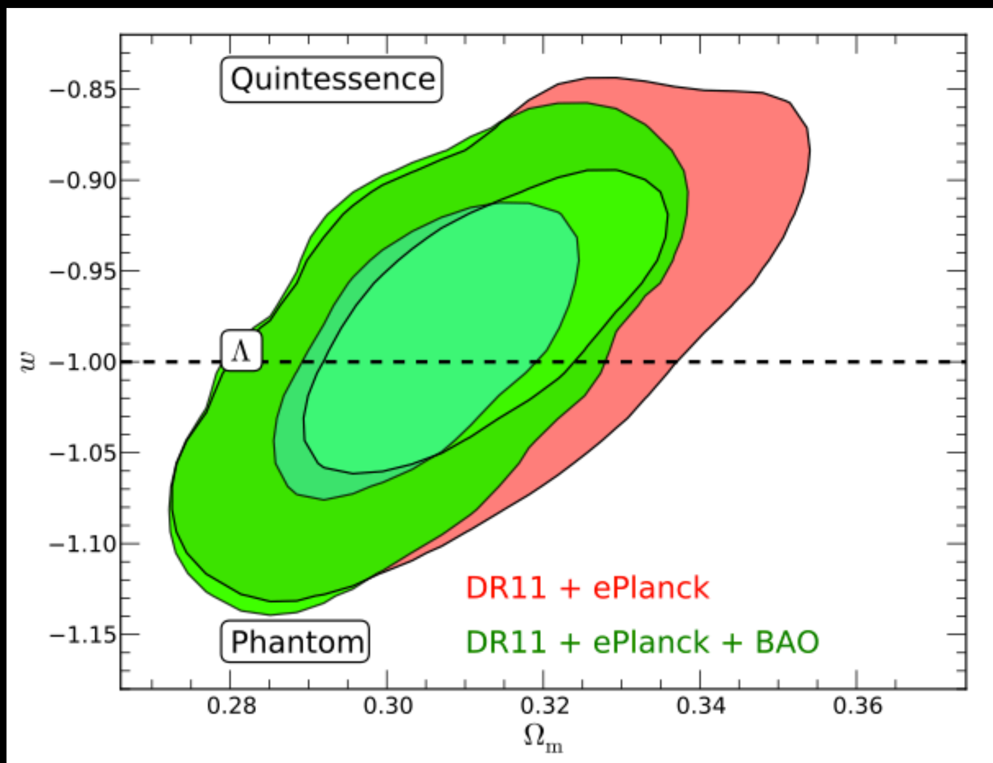
D_V

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

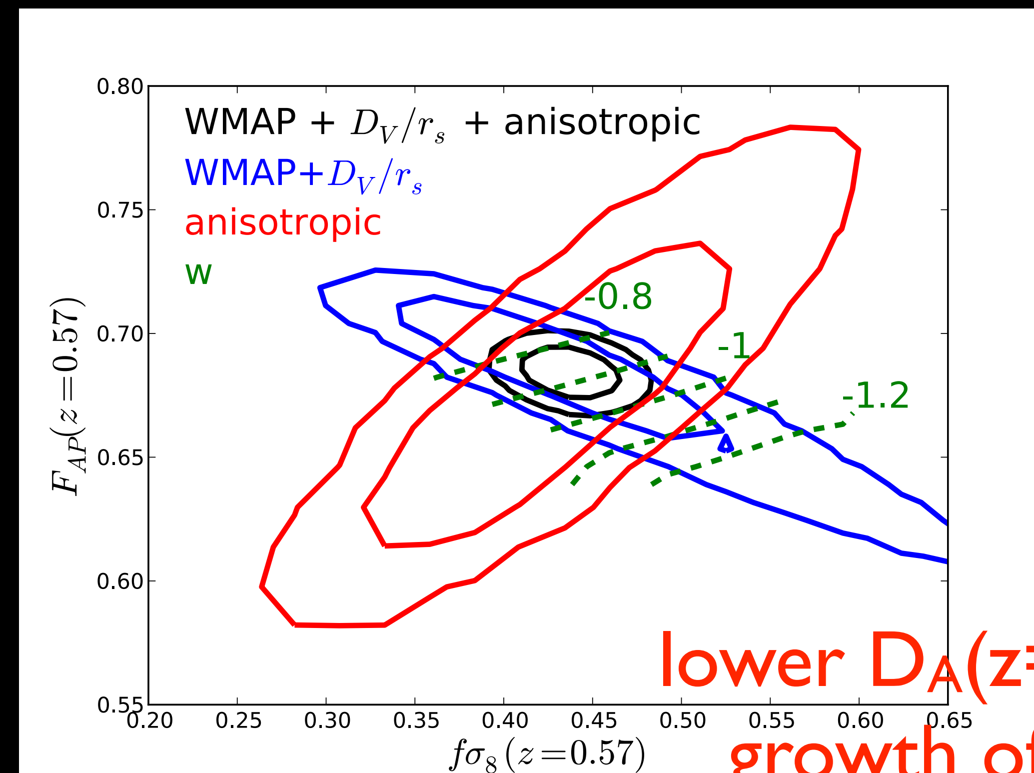
Samushia, BR, et al., 2013

Cosmological Implications: Quadrupole amplitude constrains w

w



Ω_m



D_A*H

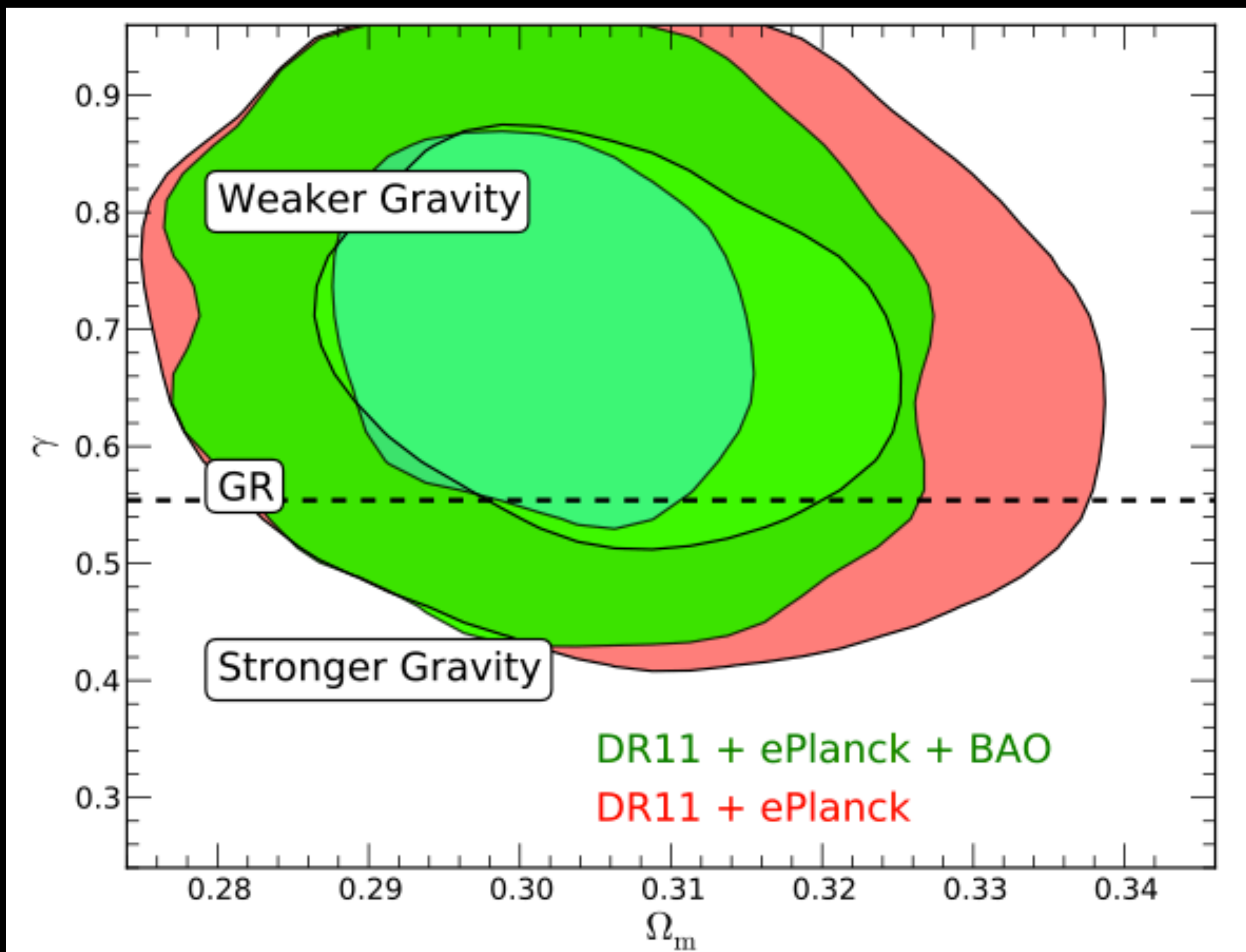
lower D_A(z=0.57), more growth of structure from z=1091 to z=0.57

$f\sigma_8$

- 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

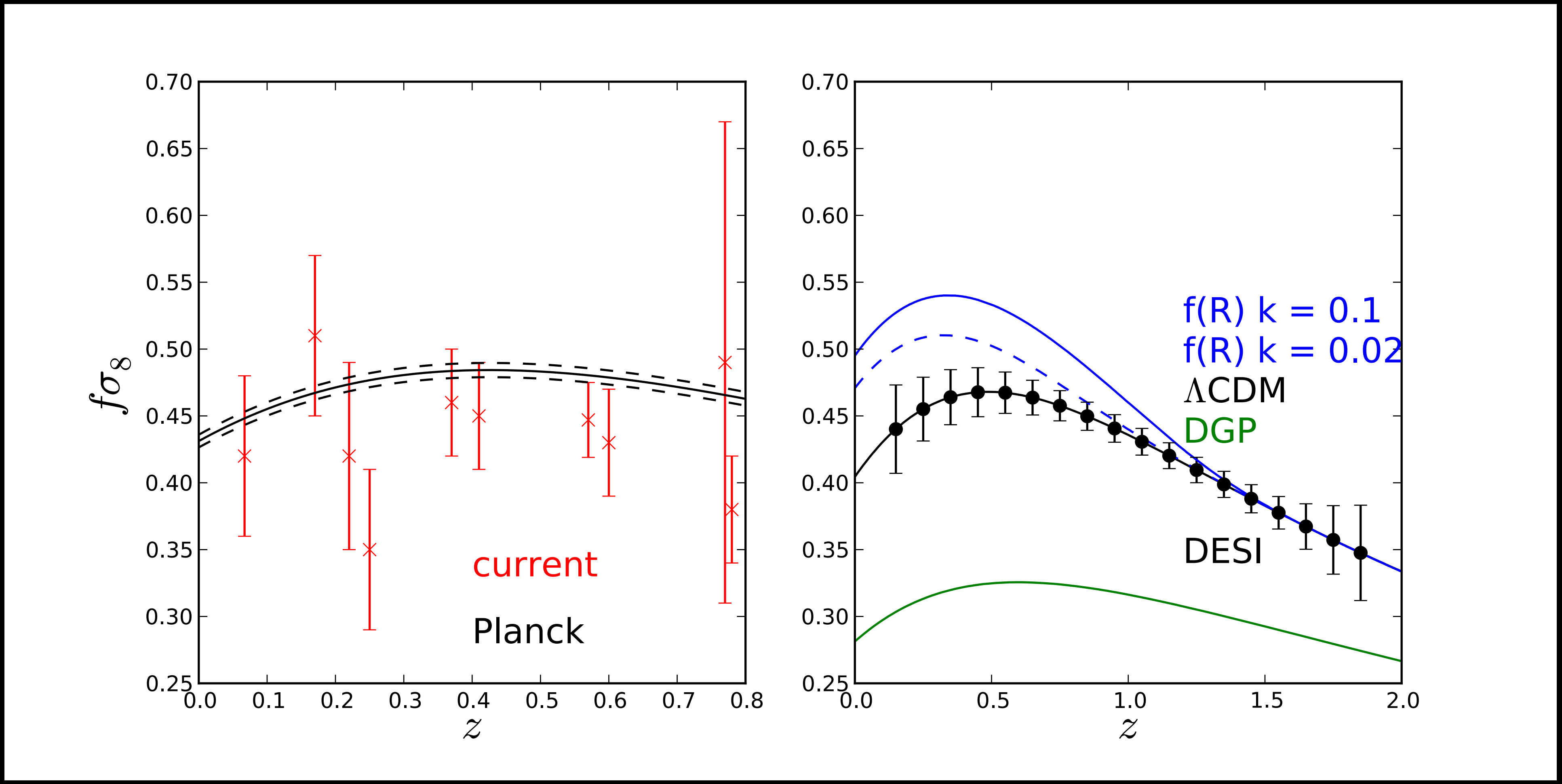


Modified Gravity test

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

($\gamma = 0.55$ in GR)

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



Lecture 3 Outline

- Redshift space distortions
- Cosmological constraints from the measurement of anisotropy in two-point statistics
- LSS observables for this week's lectures
  - cosmological neutrinos
  - f_{NL}^{loc}
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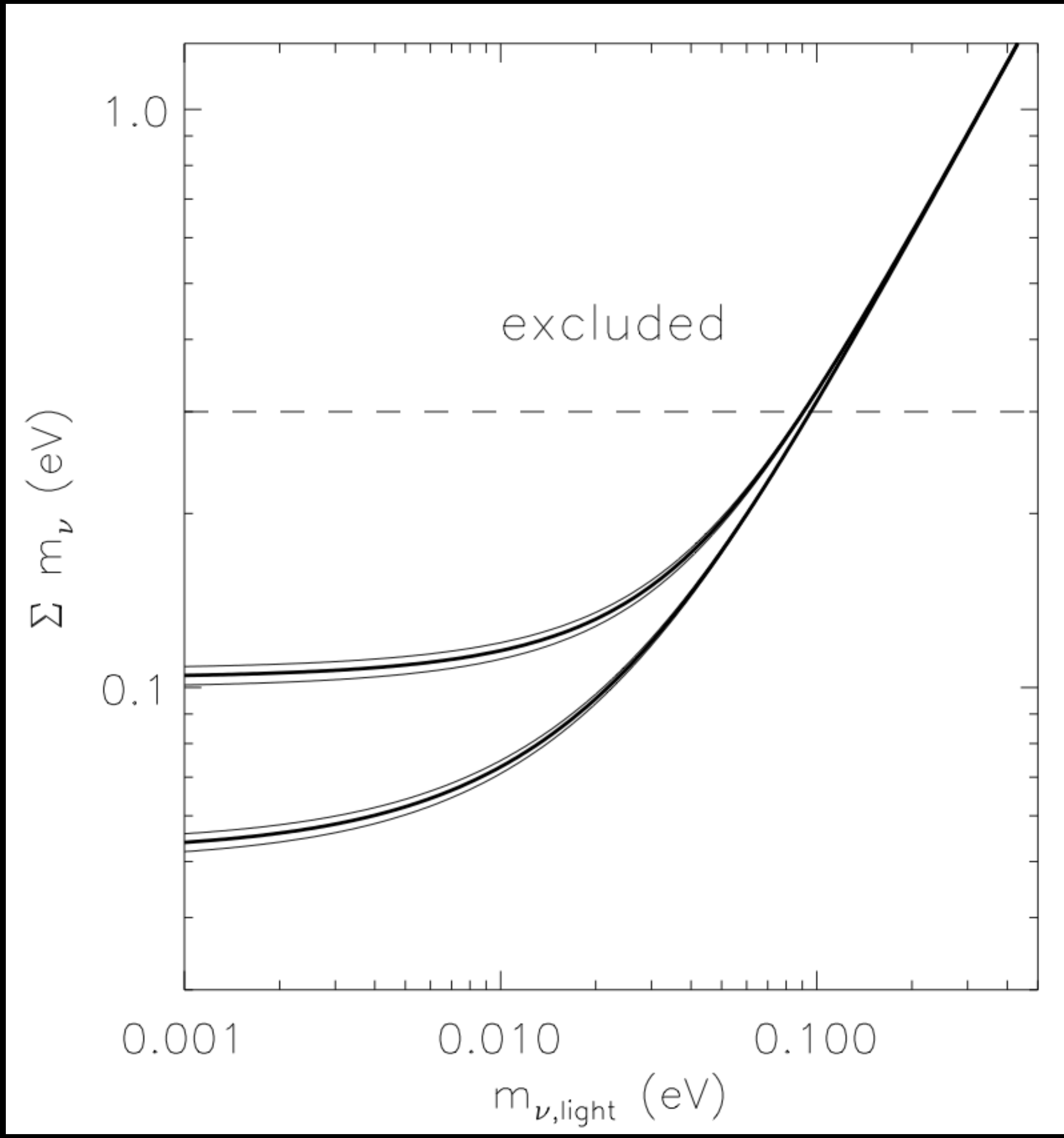
Cosmological Neutrinos

- 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]

Lesson - pay attention in Summer School!

Komatsu et al.

parame-
on angle
ated pri-
ependent

culating the peak bias presented in Section 2, B. A. Reid for discussion on the treatment of massive neutrinos in the expansion rate which has led to our exact treatment in Section 3.3, A. G. Riess for discussion on

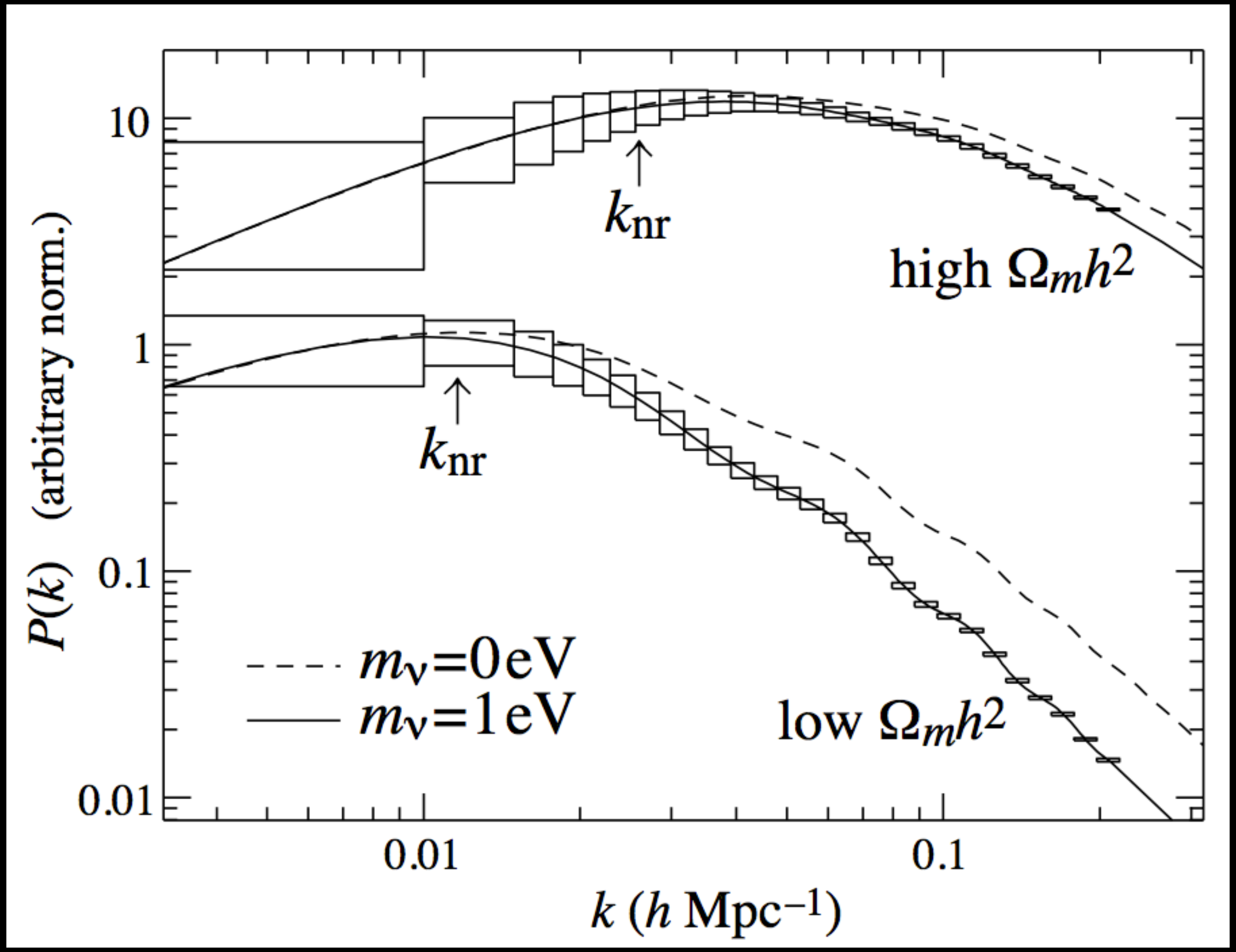
[WMAP7 cosmology paper acknowledgements]

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
  - ---> ΔH_0 = -9.5 km/s/Mpc ($\Sigma\, m_\nu$ / 1 eV)
  - ---> growth of structure suppressed

Matter power spectrum with massive neutrinos

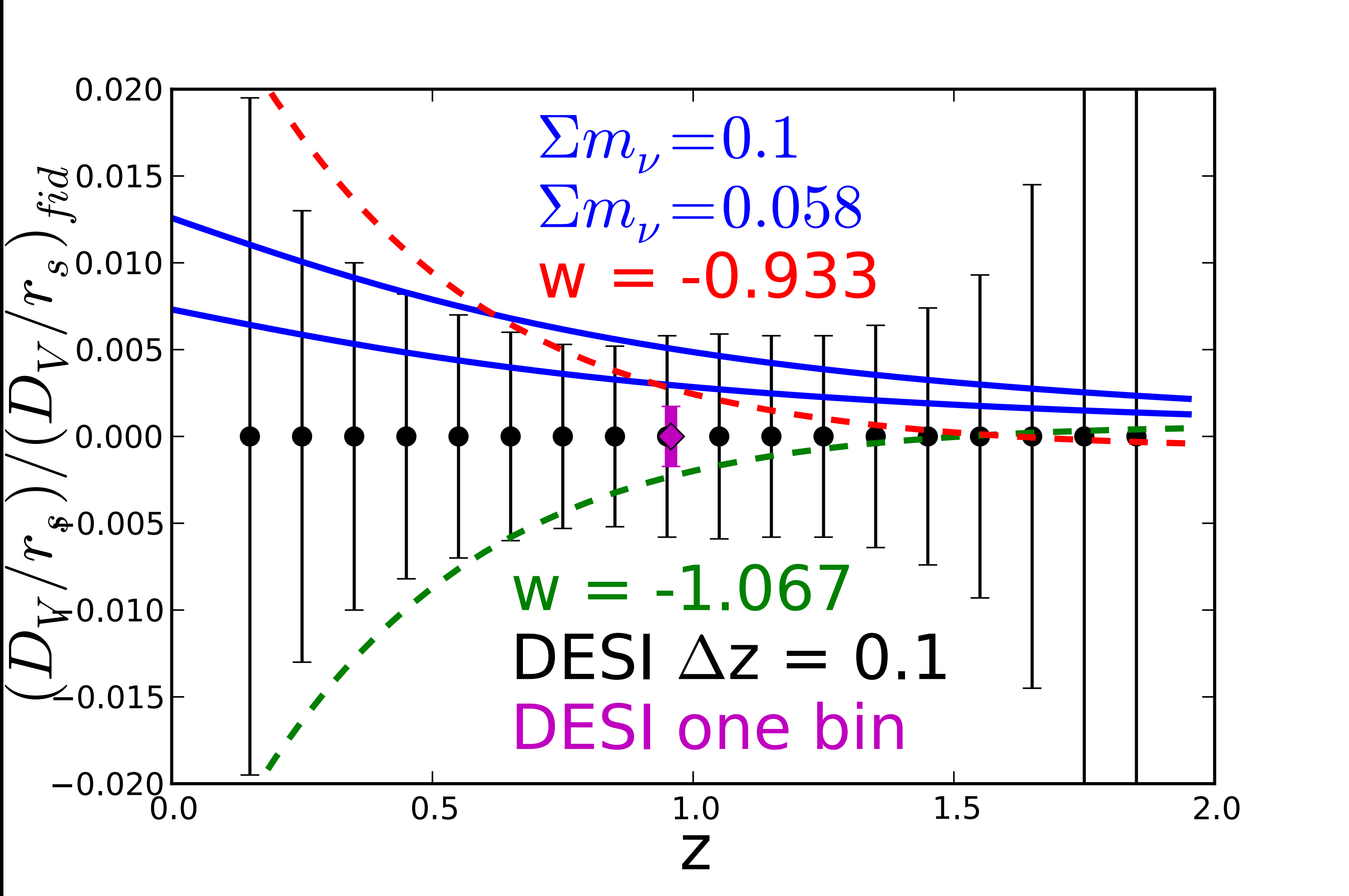
- Neutrinos free-stream out of potential wells, which suppresses the matter power spectrum on small scales



Hu, Eisenstein, Tegmark 1998, PRL 80, 5255

Neutrinos degrade dark energy constraints from BAO

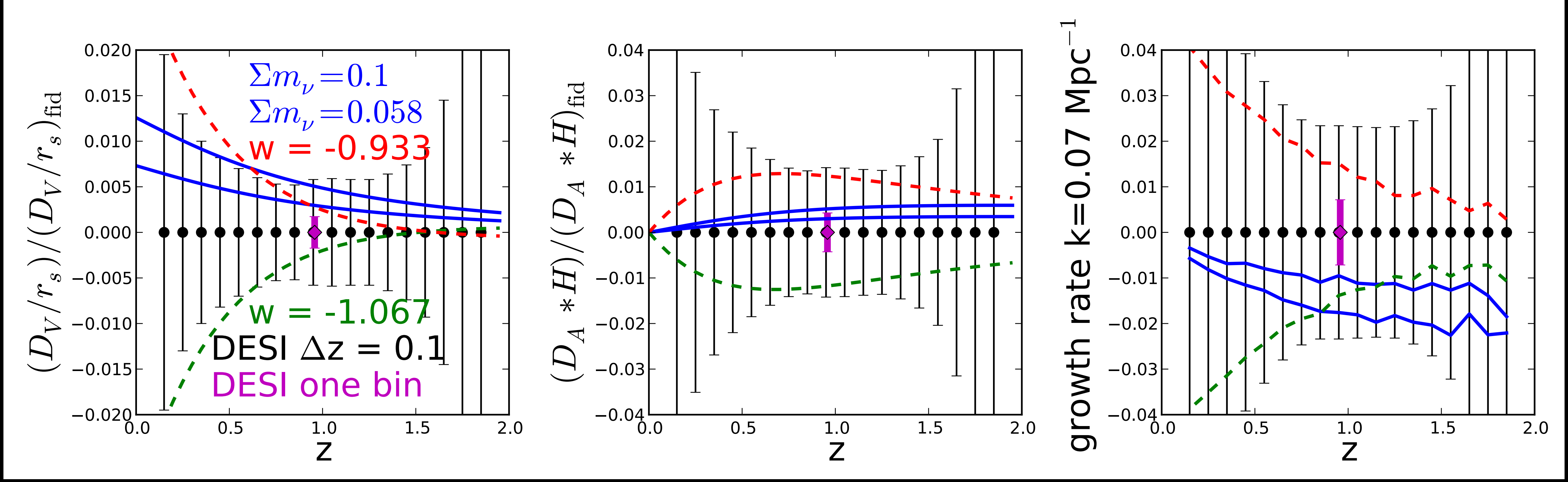
- Compare with similar change in w at $z_{DESI} \sim 1$



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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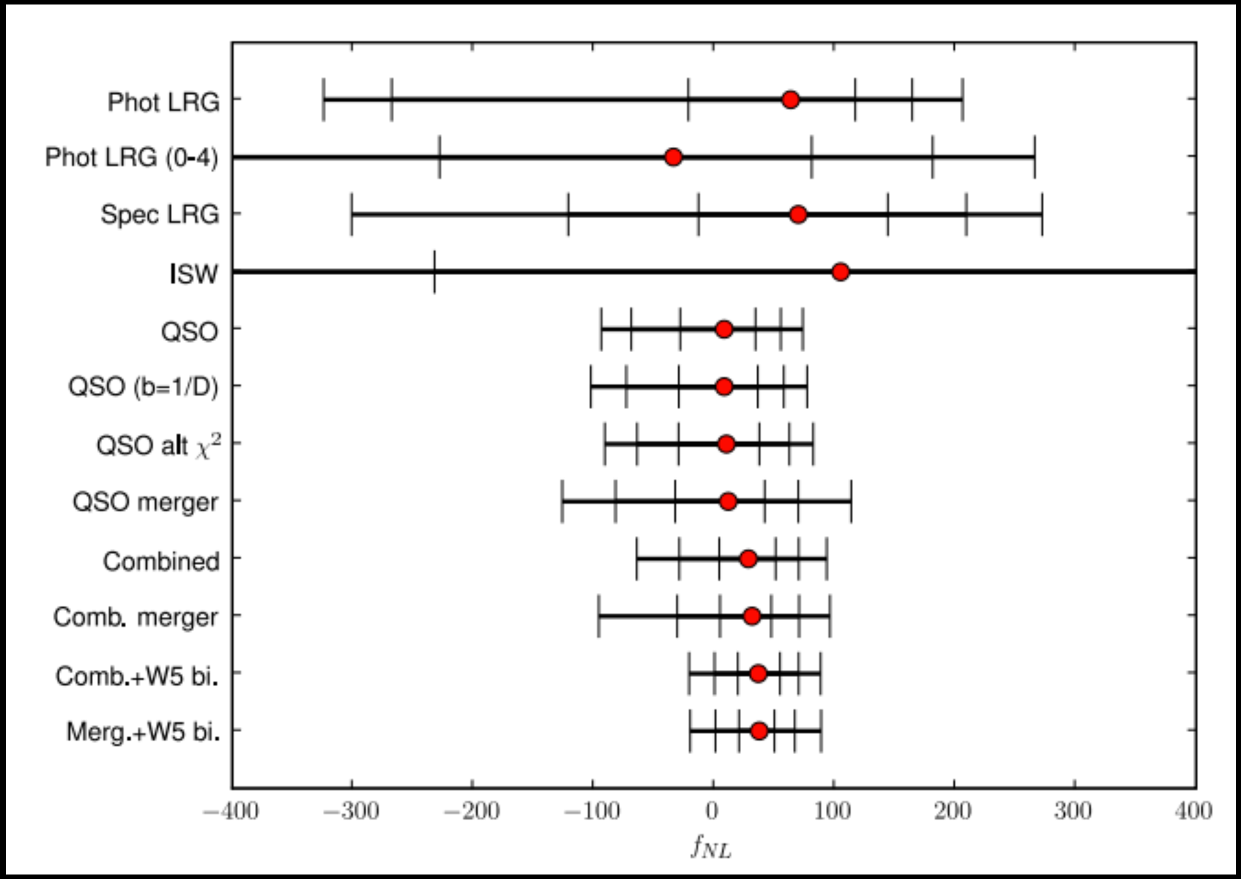
f_{NL}^{loc}

- 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 $\propto f_{NL}\,(b-1)\,k^{-2}$
- 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.

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

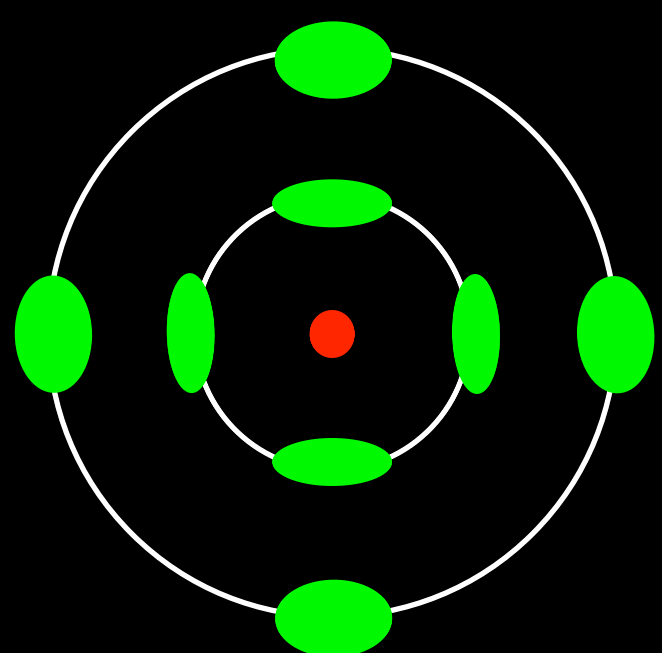
$$\frac{d\boldsymbol{v}}{d\tau} = -\boldsymbol{\nabla}_{\perp}(\Phi+\Psi)\ , \quad v^2 = 1 \quad (\mathrm{photons})$$

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

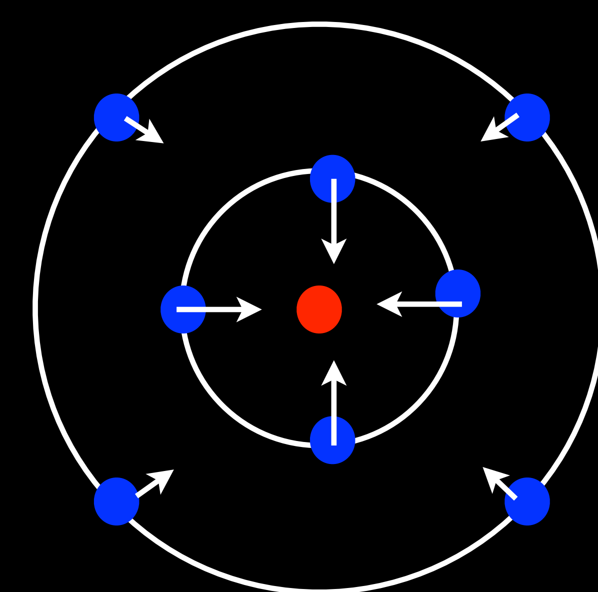
see e.g. Bertshinger 1111.4569

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



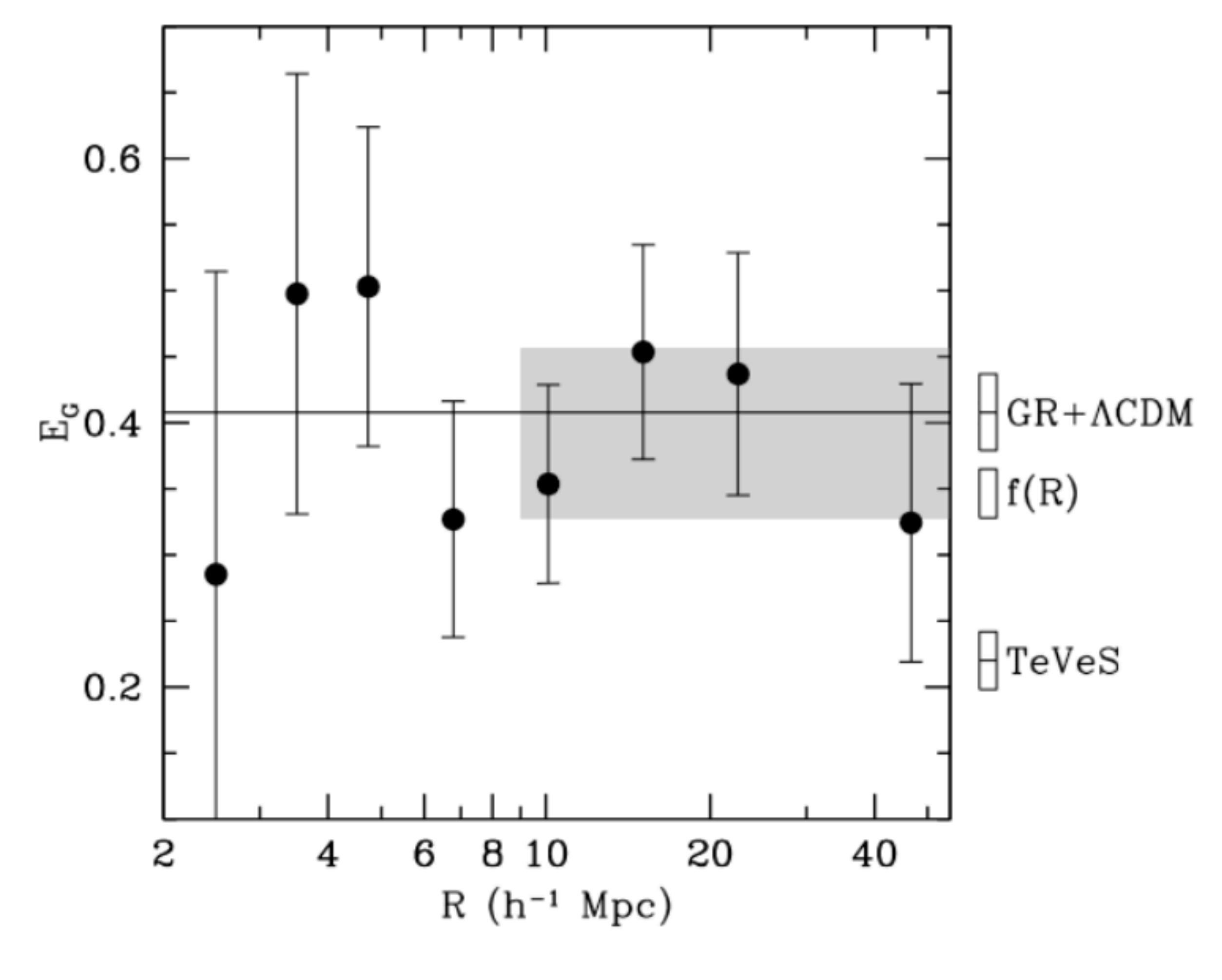
galaxy clustering and velocities (RSD)

LSS tests of modified gravity

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

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

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!