Title: SDSS-III BOSS and Beyond: fundamental physics with galaxy redshift surveys

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Abstract: The SDSS-III Baryon Oscillation Spectroscopic Survey, now nearly complete, is measuring the three-dimensional cosmic structure with 1.35 million new redshifts. Galaxy clustering measurements provide constraints on the cosmic expansion history through the baryon acoustic oscillation feature and the Alcock-Paczynski effect. In addition, the imprint of galaxy peculiar velocities on the observed galaxy clustering, "redshift-space distortions", provides a measurement of the growth rate of matter perturbations. Taken together, these measurements provide excellent constraints on dark energy and test the relation between expansion history and growth of perturbations expected in General Relativity. I will summarize results from BOSS's recent DR11 results and highlight what we may learn about fundamental physics (especially neutrinos) from the upcoming Dark Energy Spectroscopic Instrument (DESI).

SDSS-III BOSS and Beyond: fundamental physics with galaxy redshift surveys

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

in collaboration with Martin White, Will Percival, Lado Samushia, Alexie Leautheaud, Jeremy Tinker, Andreu Font-Ribera, Patrick McDonald, Nick Mostek, Hee-Jong Seo, Anze Slosar, Baryon Oscillation Spectroscopic Survey [BOSS] collaboration

Outline

- Galaxy redshift surveys: conceptual review
- SDSS-III BOSS DR11 results
- In pursuit of modified gravity: small-scale RSD
- Prospects for the next decade of redshift surveys

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

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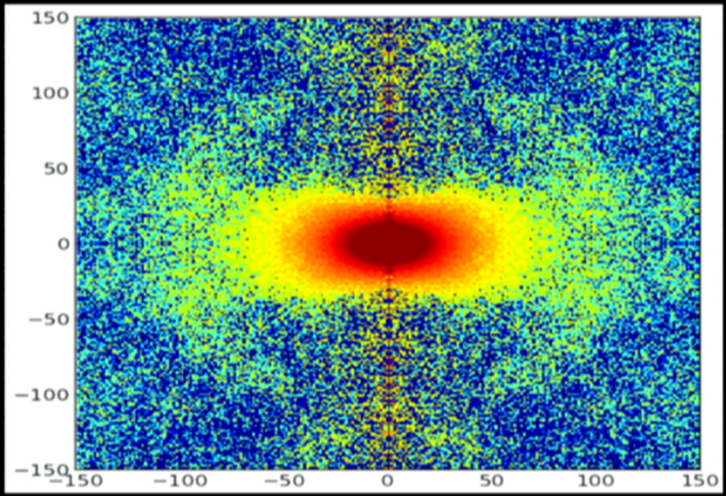
Galaxy Redshift Surveys in 4 easy steps

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

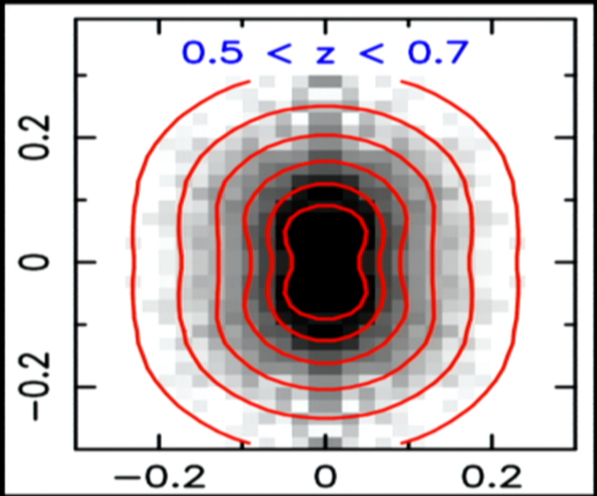


$r_\parallel$ (h^{-1} Mpc)

$r_\perp$ (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

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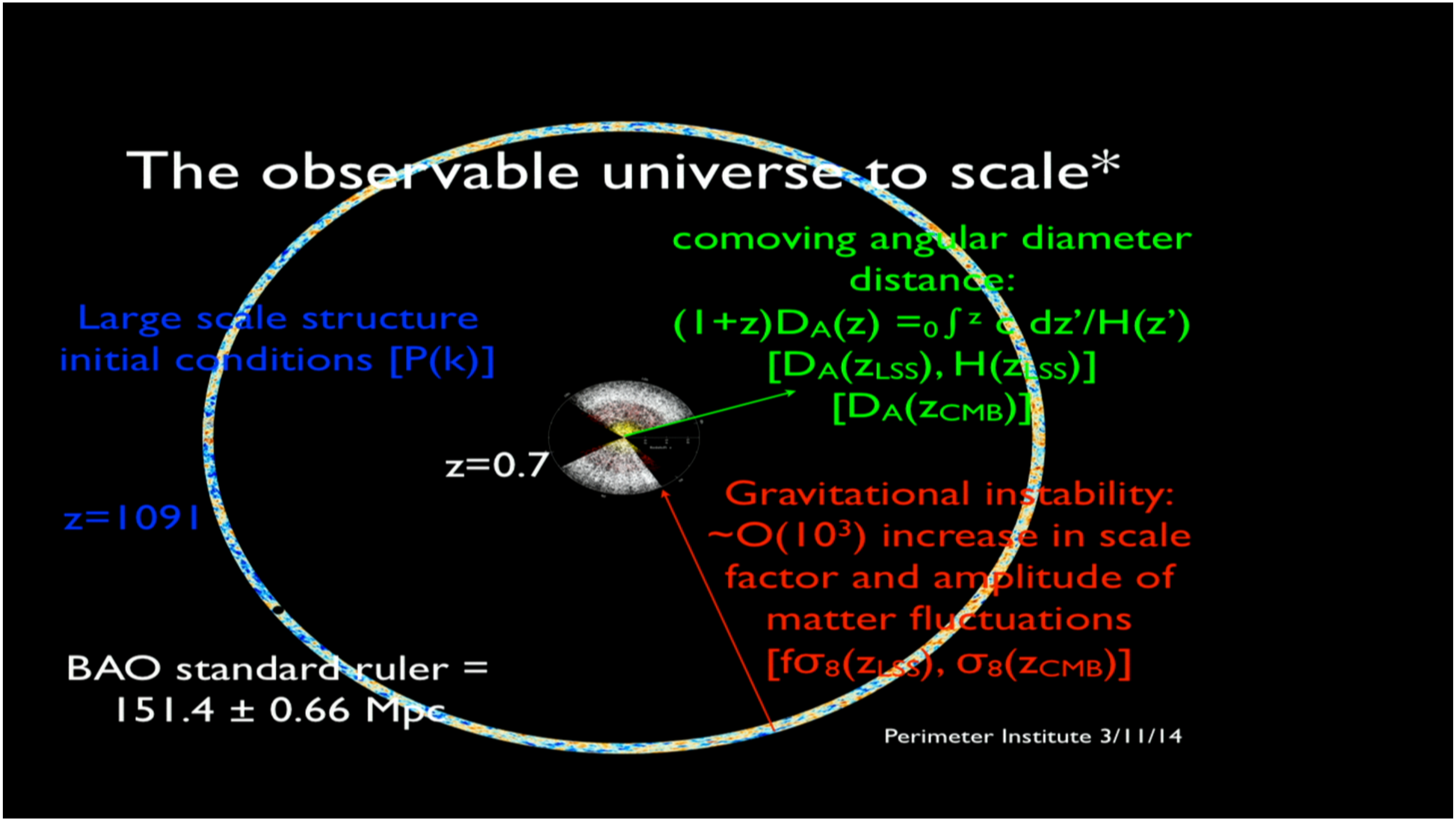

The observable universe to scale*
comoving angular diameter distance:
(1+z)DA(z) =0∫z c dz'/H(z')
[DA(zLSS), H(zLSS)]
[DA(zCMB)]
Large scale structure initial conditions [P(k)]
z=0.7
z=1091
Gravitational instability: ~O(10³) increase in scale factor and amplitude of matter fluctuations
[fσ8(zLSS), σ8(zCMB)]
BAO standard ruler = 151.4 ± 0.66 Mpc
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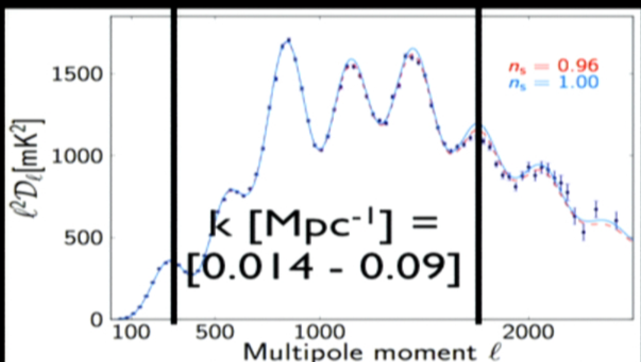
CMB as LSS initial conditions

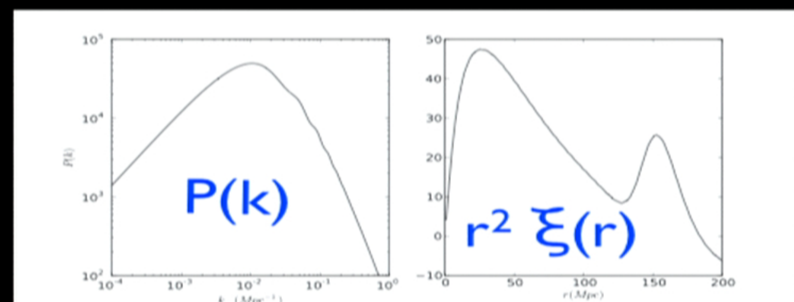
LSS initial conditions:
$\Omega_c h^2$, $\Omega_b h^2$, n_s
NOT $D_A(z_{CMB})$

photon-baryon fluid

dark matter dominated



Planck 2013 #16



Mpc⁻¹ Mpc

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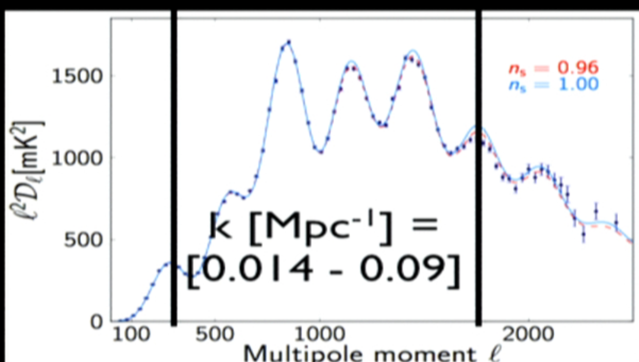
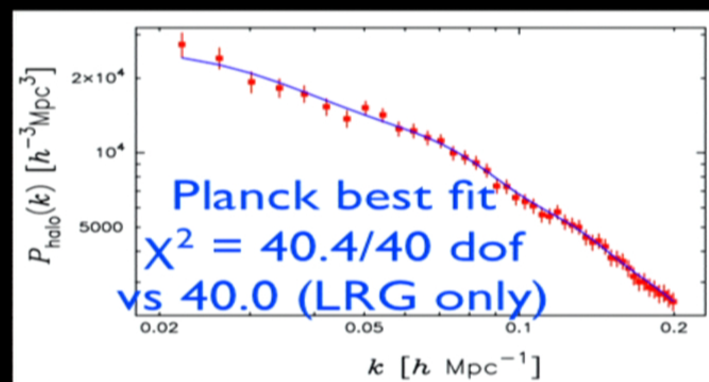


Planck 2013 #16

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



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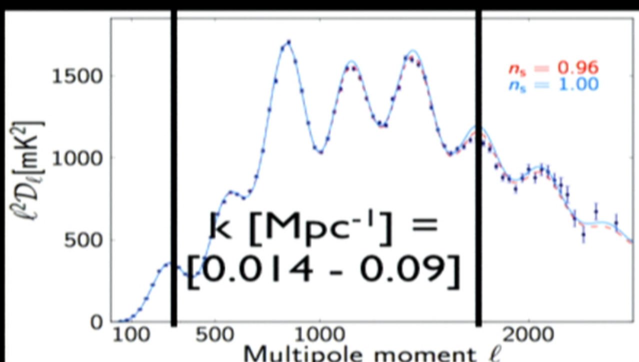

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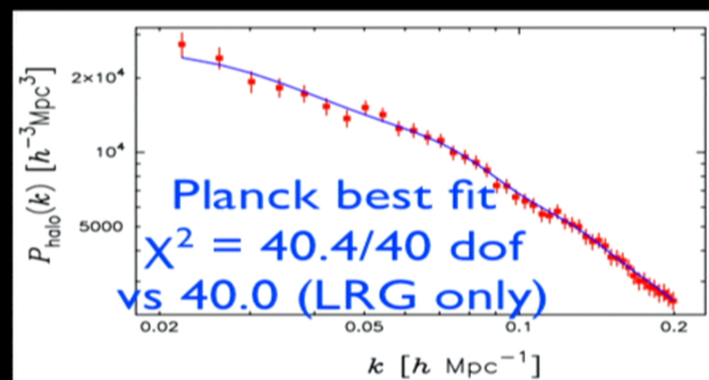

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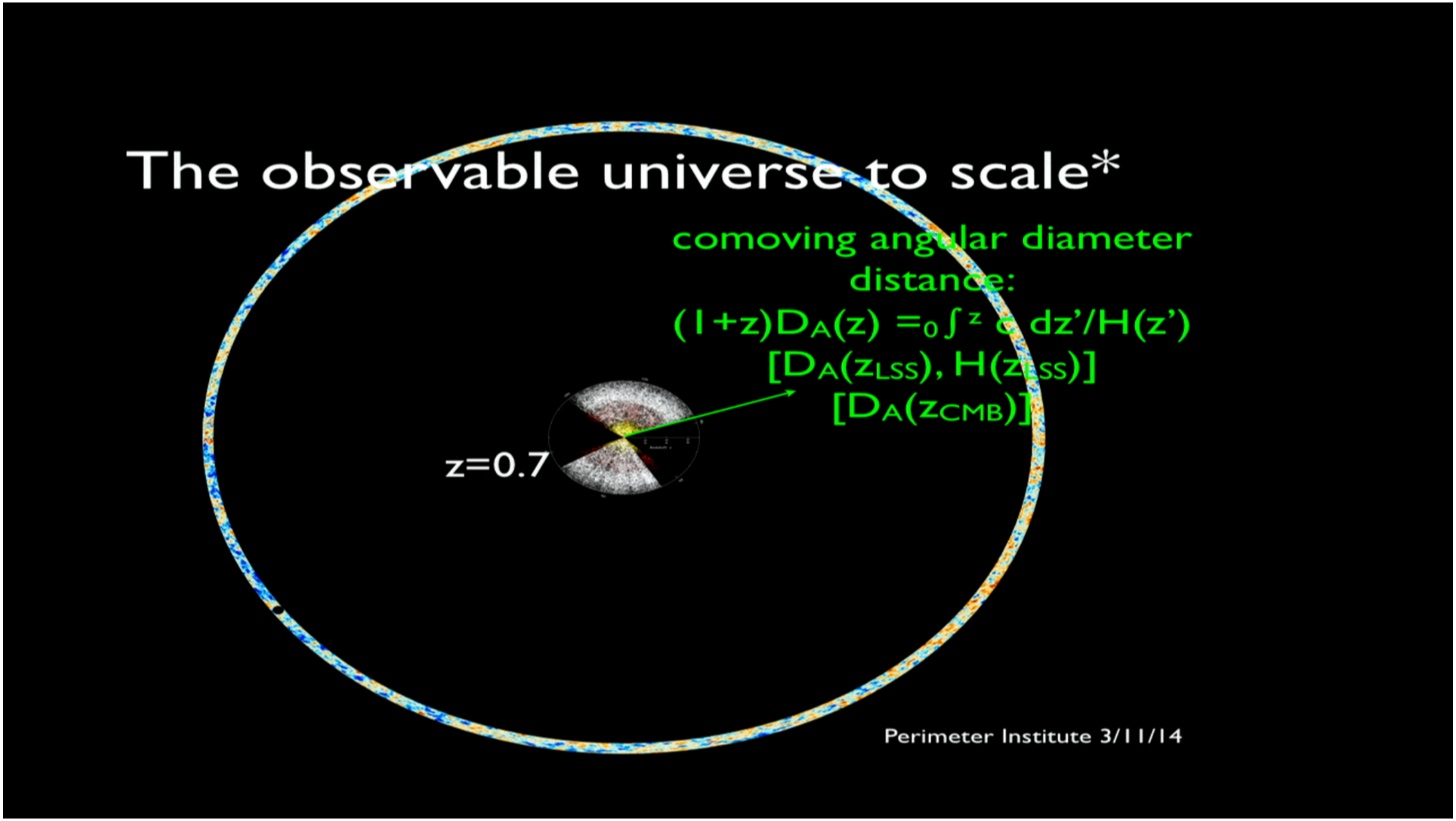
The observable universe to scale*
comoving angular diameter distance:
$(1+z)D_A(z) = {}_0\int^z c\,dz'/H(z')$
$[D_A(z_{LSS}), H(z_{LSS})]$
$[D_A(z_{CMB})]$
z=0.7
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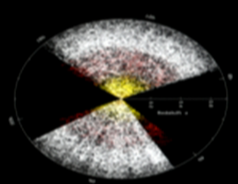
Geometric constraints from galaxy surveys

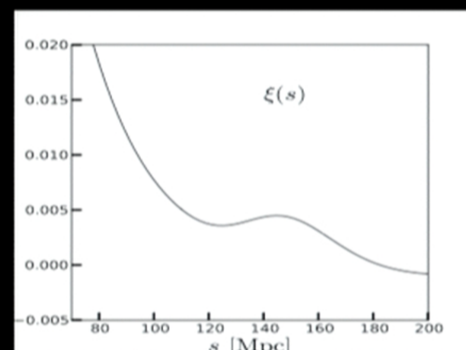
Observer space:
ra, dec, z



depends on H(z)
for z in [0, z_{max}]

↔

Theory space:
(physical) Mpc



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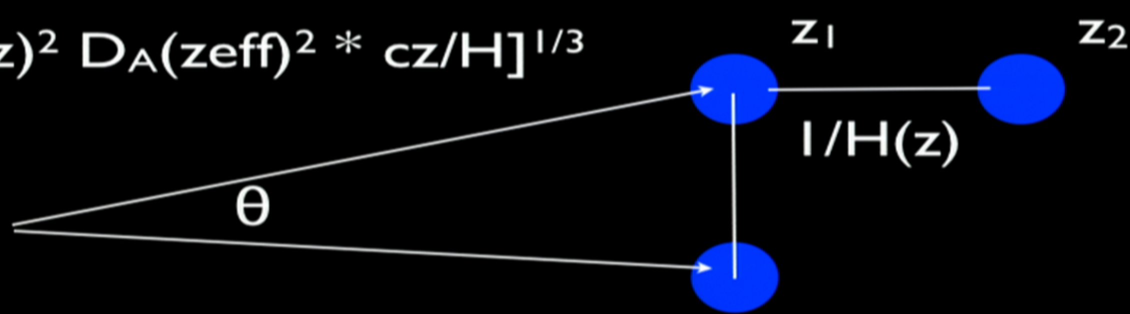
BAO standard ruler

- The BAO feature in the angle-averaged correlation function constrains $\alpha = [D_V(z_{eff})/r_s]/[D_V(z_{eff})/r_s]_{fiducial}$

$D_V \equiv [(1+z)^2 D_A(zeff)^2 * cz/H]^{1/3}$



comoving angular diameter distance $\equiv (1+z)\, D_A(z)$

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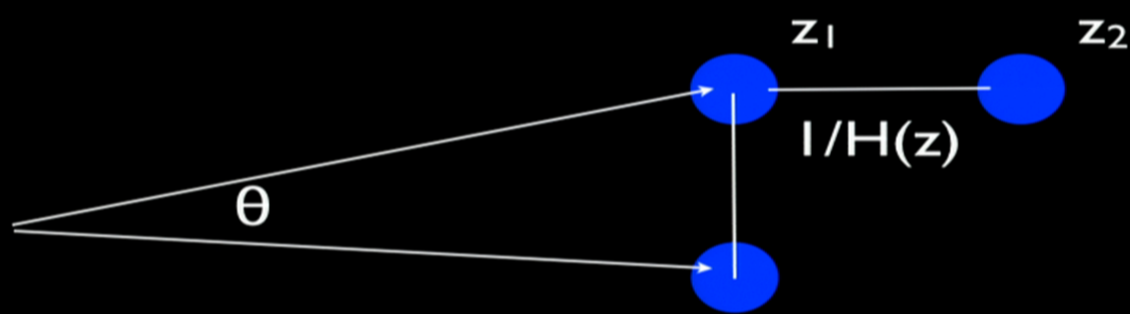
Alcock-Paczynski effect

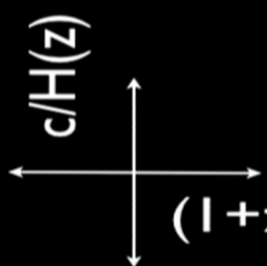
- Even without a standard ruler, comparing clustering along and perpendicular to the LOS allows us to measure $D_A * H$

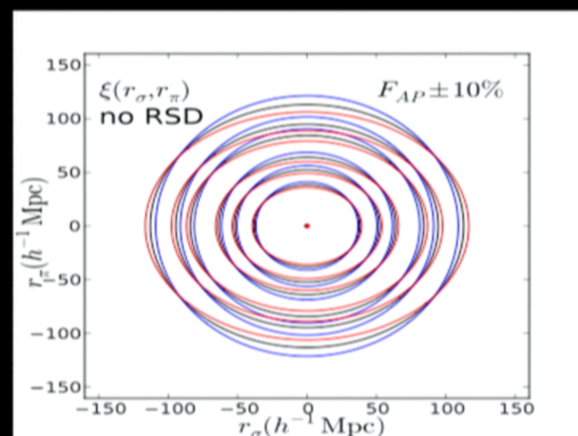


comoving angular diameter distance ≡ $(1+z)\ D_A(z)$

Alcock-Paczynski Effect

$\xi(r_p, \pi)$ appears anisotropic if you assume the wrong cosmology; constrains $F(z) \equiv (1+z)\, D_A(z)\, H(z)/c$





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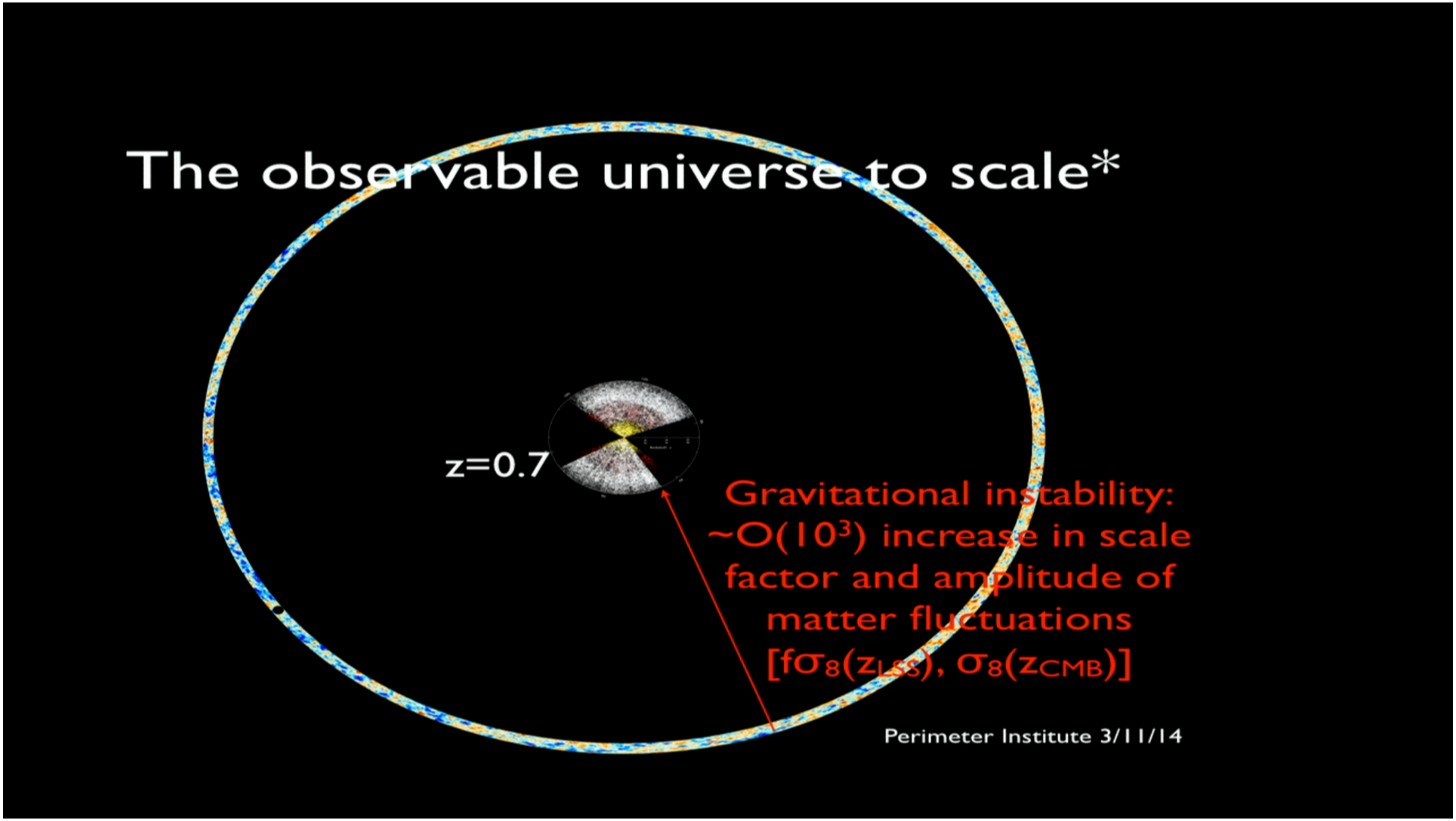
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Gravitational instability:
~O(10³) increase in scale
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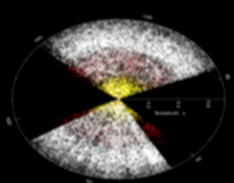
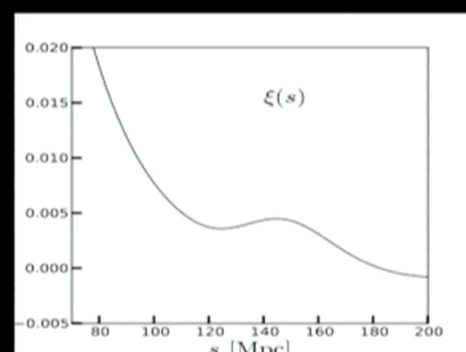
Dynamical constraints from galaxy surveys

Observer space:
ra, dec, z



$z = z_{cosmo} + (1+z_{cosmo})v_p/c$

Theory space:
(physical) Mpc



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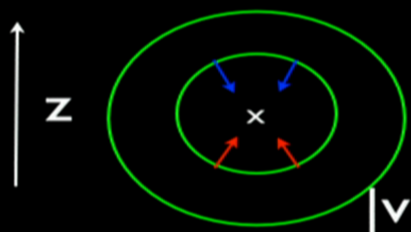
Redshift Space Distortions (RSD)

real to redshift space separations: $\chi(z) = \chi_{true} + v_p/aH$



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

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

isotropic

squashed along line of sight

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

Gravitational Instability

- To linear order in GR, $P(k, z) = G^2(z, z_i)\ P(k, z_i)$ [scale-dependence unaltered]
- GR consistency relation between growth of linear perturbations and cosmic expansion history:

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

- A joint fit to CMB and LSS data is an extremely powerful test of GR and/or the properties of DM/DE
- Modified gravity, dark sector interactions, massive neutrinos, etc. can potentially break both!

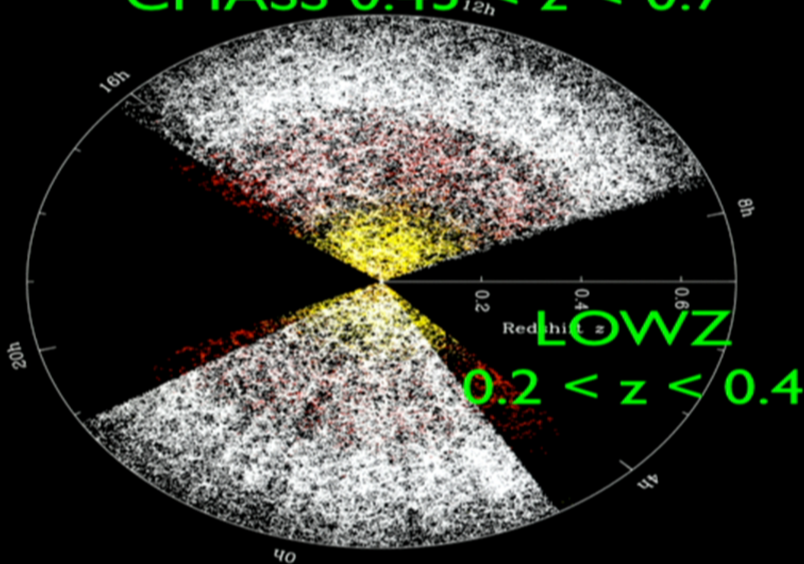
SDSS-III Baryon Oscillation Spectroscopic Survey

- 10,000 deg^2, 1.35M new redshifts

BOSS galaxies

SDSS Main

SDSS LRGs



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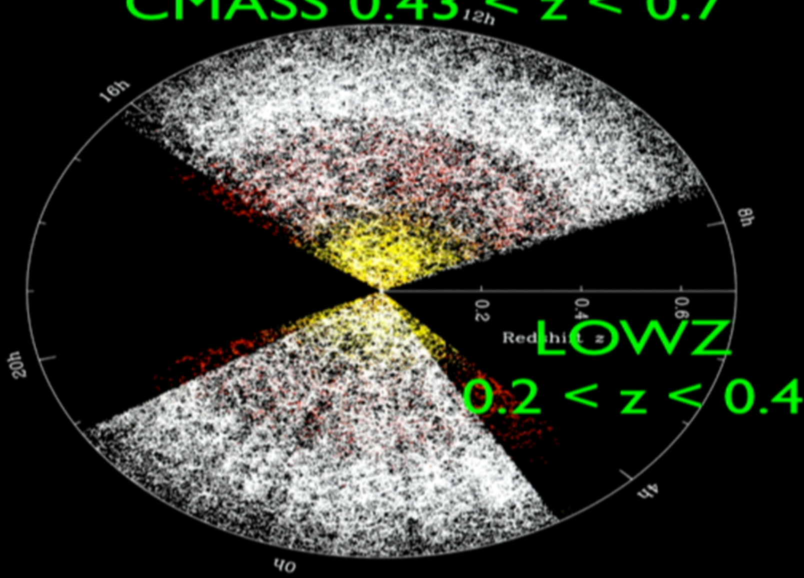

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BOSS survey status

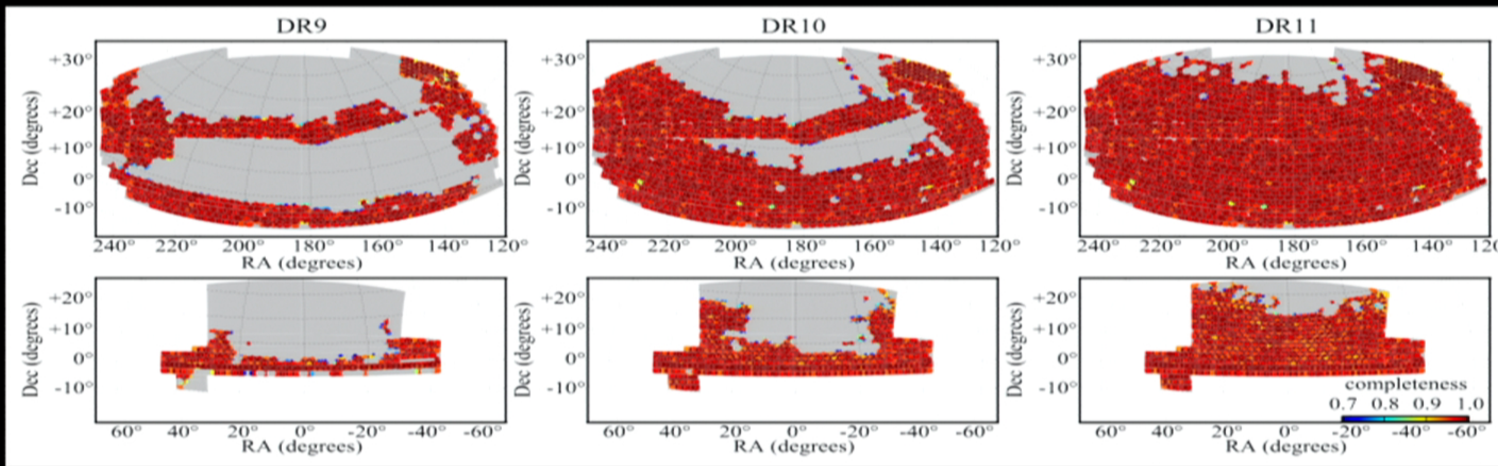

figure credit Molly Swanson

Old news	Public! data.sdss3.org	Released with final data set
A_{eff}: 3275 deg^2	6161 deg^2	8387 deg^2

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DR11 papers

- BAO (CMASS + LOWZ): Anderson et al. 2013
- Anisotropic BAO fitting systematics: Magaña et al. 2013
- Full anisotropic fits: Samushia, BR, et al., Beutler et al., Sanchez et al., Chuang et al. 2013
- Mock covariance matrix errors: Percival et al. 2013
- LOWZ sample: Tojeiro et al. 2013
- LOWZ mocks: Manera et al. 2014
- Color dependence (DR10): Ross et al. 2013

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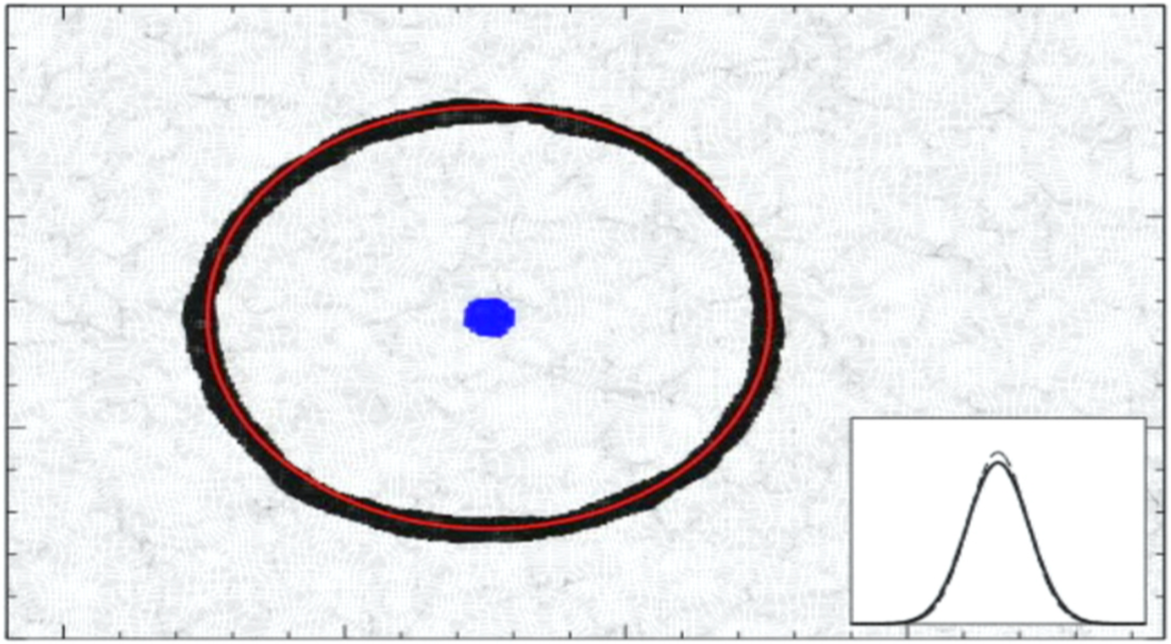
Three LSS "philosophies"

- BAO-only: extract information only from BAO feature; use reconstruction to boost signal/noise. No RSD information retained.
- Full shape analysis: Use both the scale and angular dependence to extract cosmological information, including $DA(z_{eff})$, $H(z_{eff})$, $f\sigma_8(z_{eff})$; nuisance parameters describe galaxy-dark matter connection
- Joint fit to cosmology and galaxy-dark matter connection using all scales

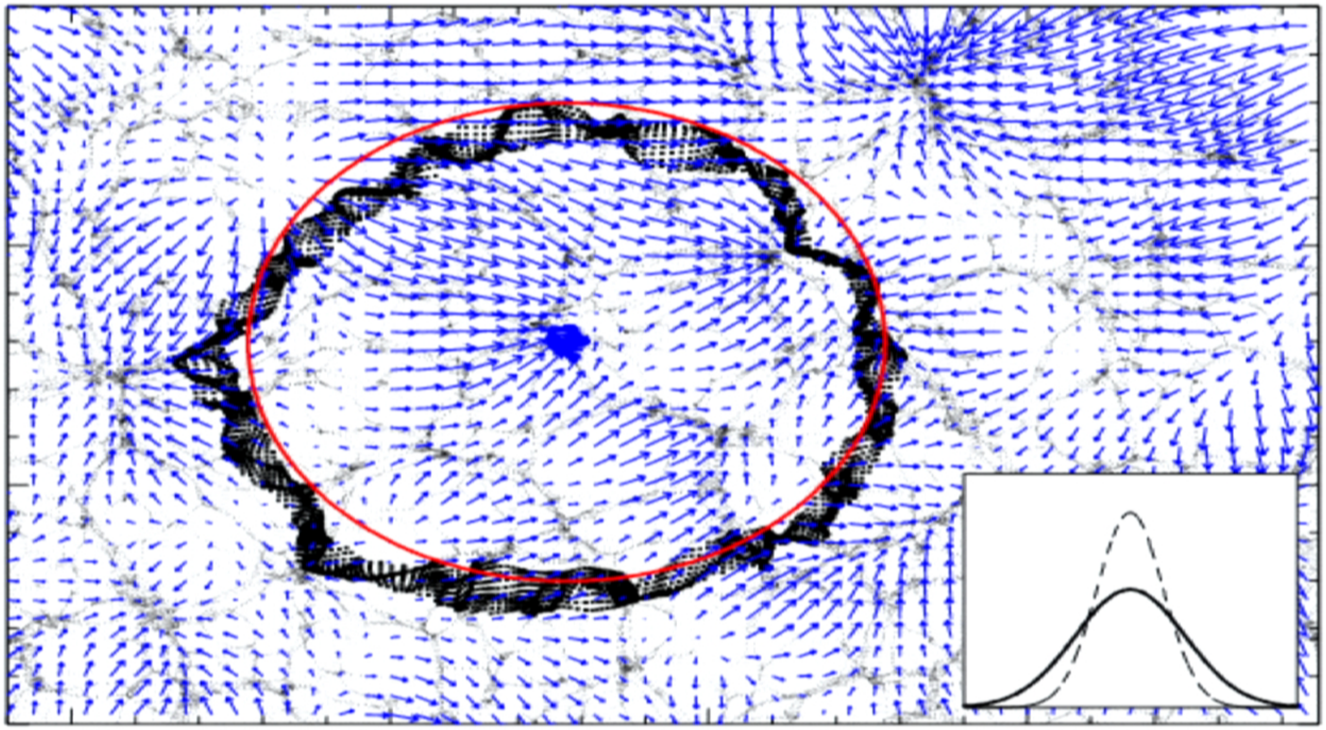
Nonlinear Evolution



credit: Nikhil Padmanabhan

24

Reconstruction : II



credit: Nikhil Padmanabhan

25

BAO model

- Start with linear P(k)/ξ(r); damp the BAO feature

$$P^{\rm fit}(k) = P^{\rm sm}(k)\left[1 + (O^{\rm lin}(k/\alpha) - 1)e^{-\frac{1}{2}k^2\Sigma_{nl}^2}\right]$$

- add broadband nuisance terms

$$A^{\xi}(s) = \frac{a_1}{s^2} + \frac{a_2}{s} + a_3$$

- Marginalize to get p(α)

$$\xi^{\rm fit}(s) = B_{\xi}^2\xi^{\rm mod}(\alpha s) + A^{\xi}(s)$$

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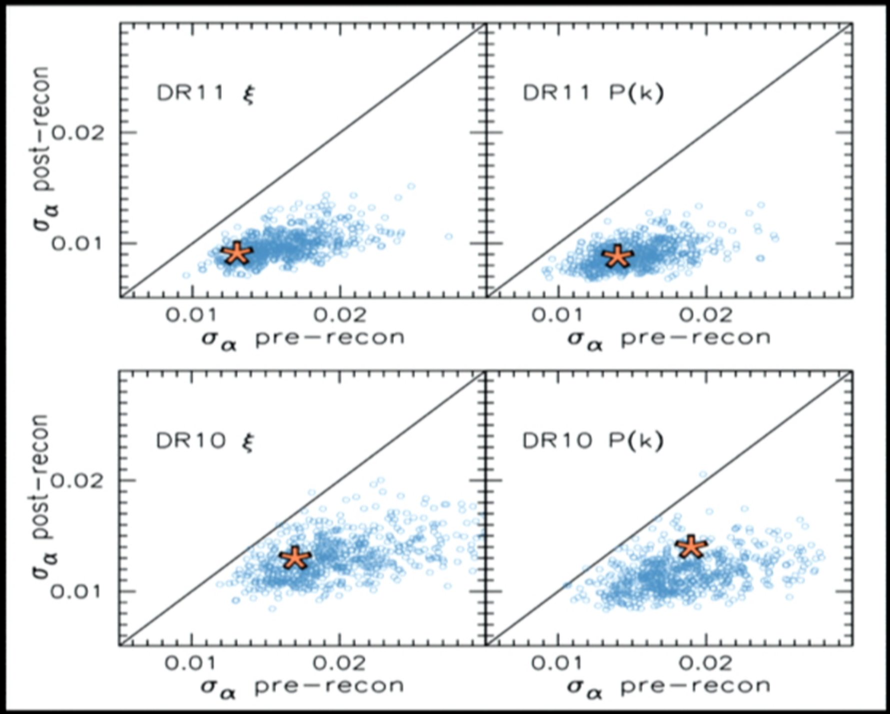
Test with mocks: Fits unbiased

Estimator	$\langle\alpha\rangle$	S_α	$\langle\sigma\rangle$	$\langle\chi^2\rangle$/dof
DR11				
Consensus $P(k)+\xi(s)$	**1.0000**	**0.0090**	**0.0088**	
combined $P(k)$	1.0001	0.0092	0.0089	
combined $\xi(s)$	0.9999	0.0091	0.0090	
post-recon $P(k)$	1.0001	0.0093	0.0090	28.6/27
post-recon $\xi_0(s)$	0.9997	0.0095	0.0097	17.6/17
pre-recon $P(k)$	1.0037	0.0163	0.0151	27.7/27
pre-recon $\xi_0(s)$	1.0041	0.0157	0.0159	15.7/17
DR10				
post-recon $P(k)$	1.0006	0.0117	0.0116	28.4/27
post-recon $\xi_0(s)$	1.0014	0.0122	0.0126	17.2/17
pre-recon $P(k)$	1.0026	0.0187	0.0184	27.7/27
pre-recon $\xi_0(s)$	1.0038	0.0188	0.0194	15.8/17

Test with mocks: DR10/11 "typical"



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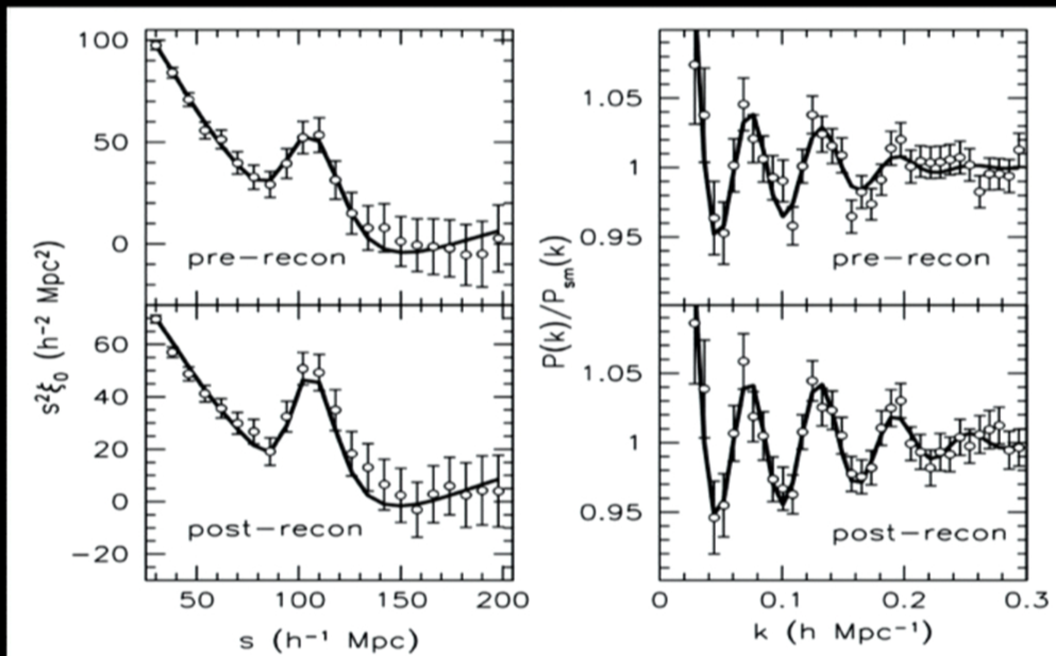
BAO fits: ξ and P



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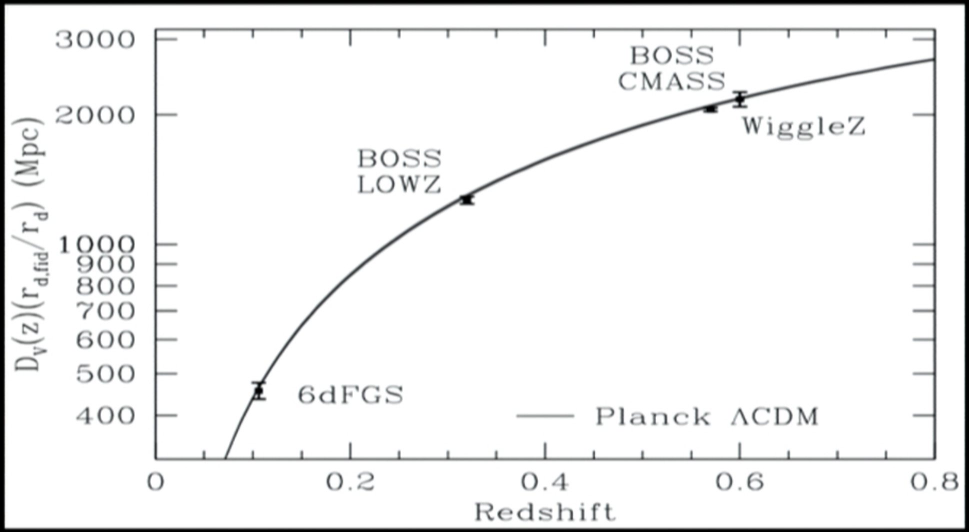
BAO distance ladder vs CMB ΛCDM predictions



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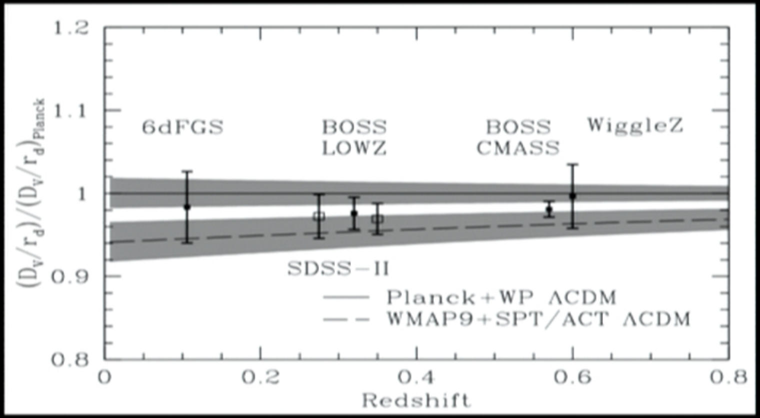

Planck: $\Omega_m h^2 = 0.1427 \pm 0.0024$

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

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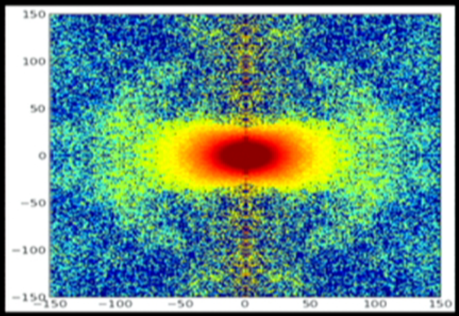
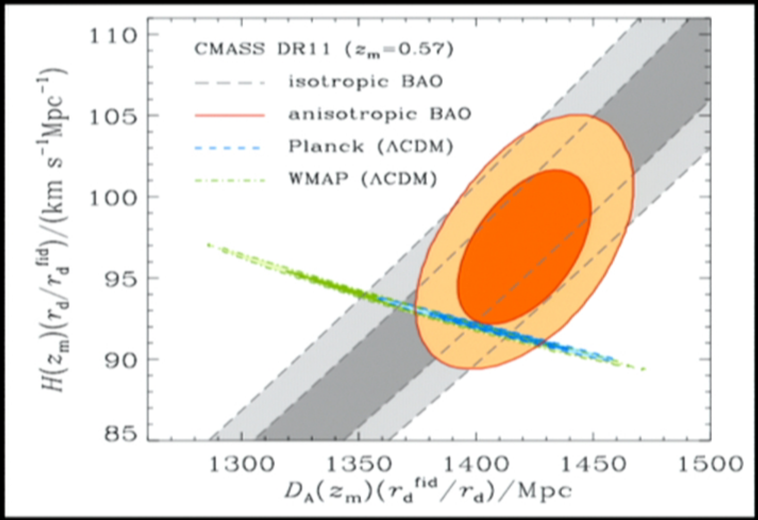
Anisotropic BAO fit results





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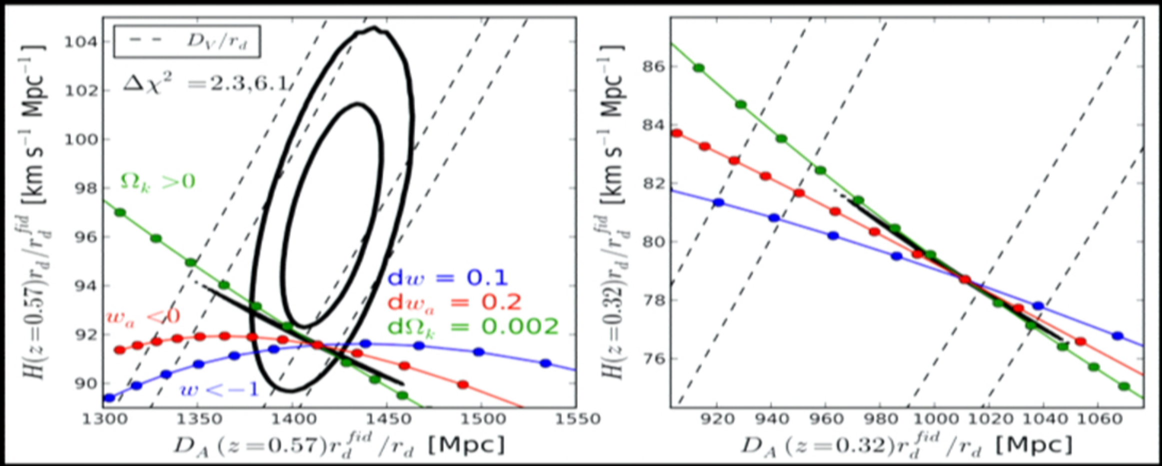
LOWZ and anisotropic CMASS BAO fits



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

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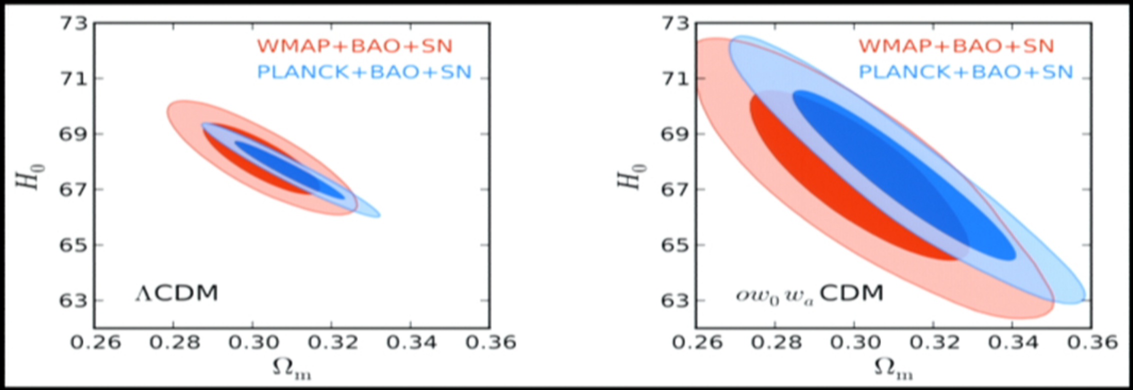
Cosmological Implications



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

- $\Omega_m = 0.312 \pm 0.016$
- $H_0 = 67.5 \pm 1.7$

[Planck + BAO + SN]

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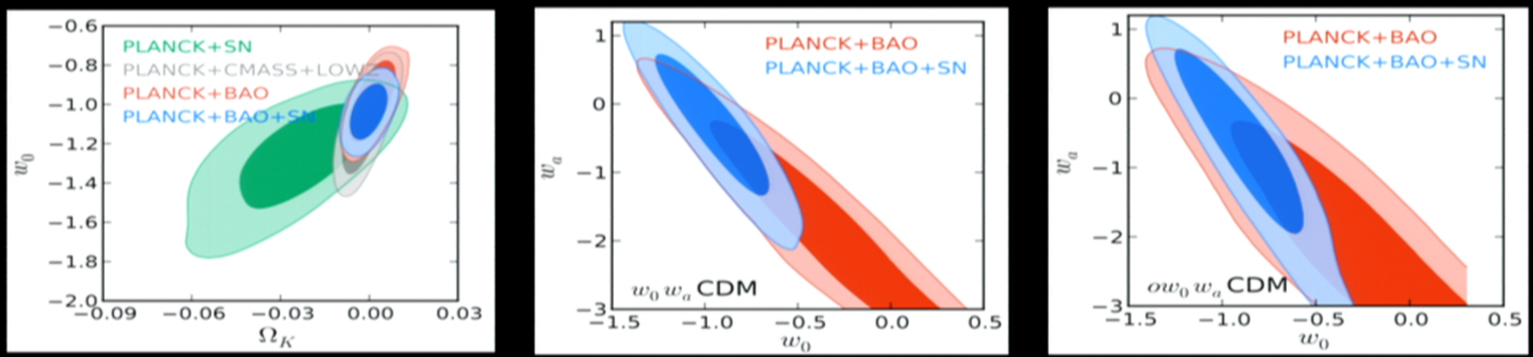
Cosmological Implications



- $\Omega_k = 0.0002 \pm 0.0033$
- $w = -1.04 \pm 0.07$
- $w_0 = -0.94 \pm 0.17$
- $w_a = -0.37 \pm 0.60$
- $w_0 = -0.87 \pm 0.19$
- $w_a = -0.73 \pm 0.80$

[Planck + BAO + SN]

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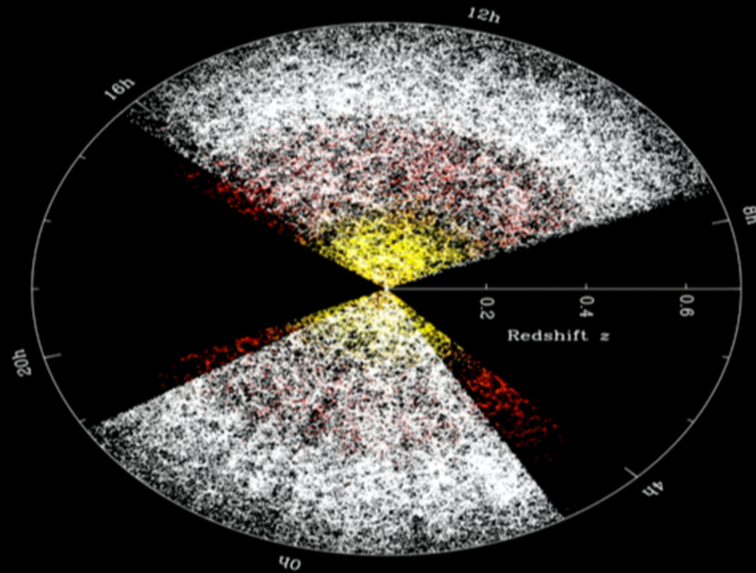
Redshift Space Distortion (RSD) Motivation

- There is *much* more information in this 3d map than the BAO feature
- DETF III: RSD is "among the most powerful ways of addressing whether the acceleration is caused by dark energy or modified gravity"



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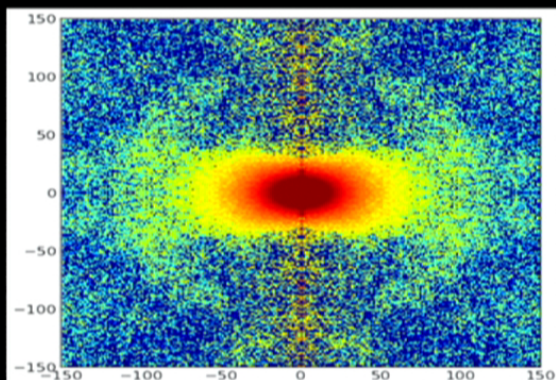
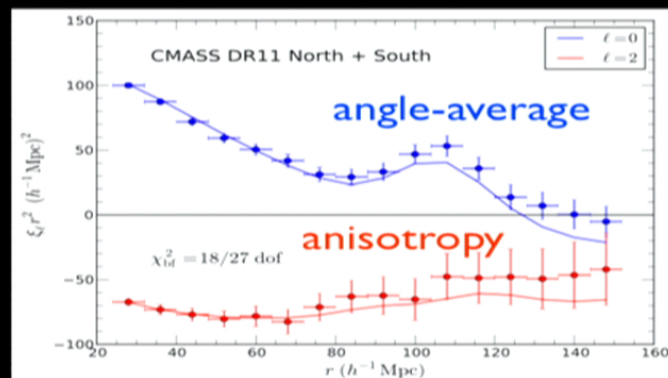
Full Shape Fits: Information compression with Legendre polynomials

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

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





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

s (h^{-1} Mpc)

BOSS DR11, Samushia et al. 2013

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Modeling the full shape of $\xi_{0,2}$ (Reid & White 2011)

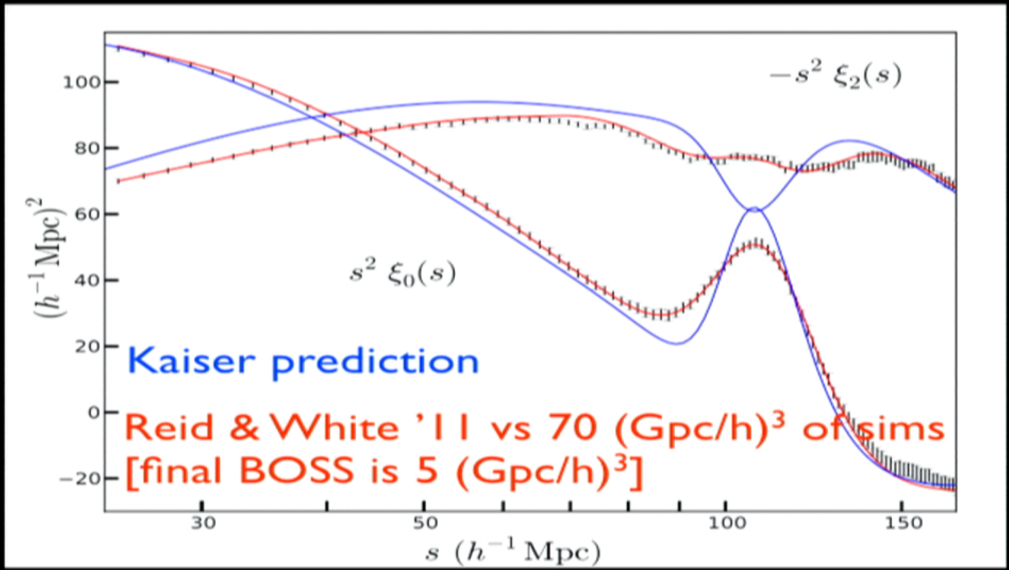
- $b\sigma_8$, $f\sigma_8$ determine amplitude of $\xi_{0,2}$

σ_8: amplitude of matter fluctuations

b: unknown conversion factor between galaxy and matter fluctuations

$f = d \ln \sigma_8 / d \ln a$; conversion factor between matter and velocity fluctuations

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



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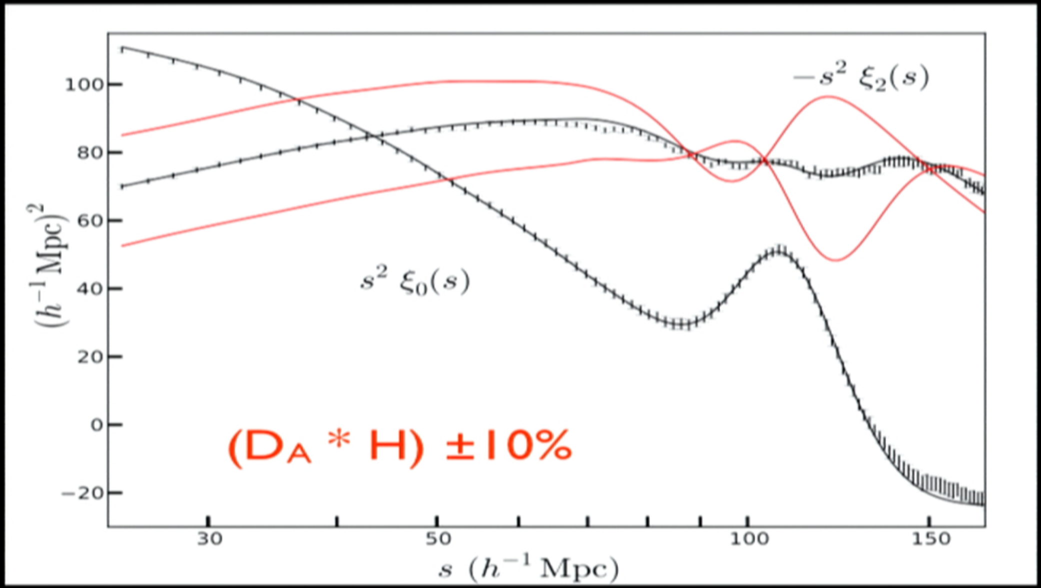
Alcock-Paczynski has different scale-dependence, distinguishable from RSD



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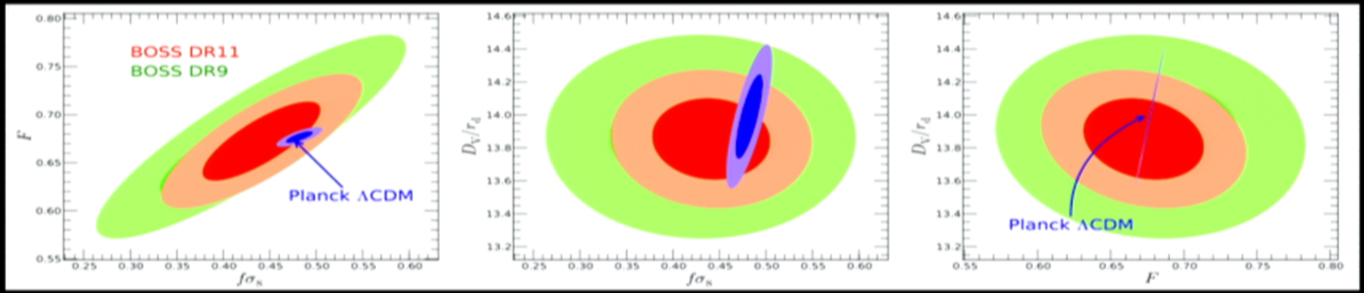
Joint Fits to $D_A(z_{eff})$, $H(z_{eff})$, $f\sigma_8$



D_A*H | $f\sigma_8$ | $f\sigma_8$ | D_A*H | D_V

Samushia, BR, et al., 2013

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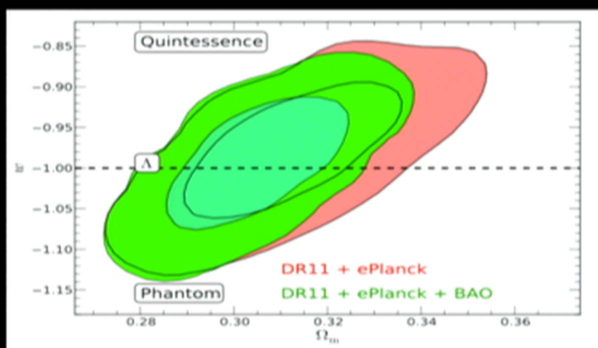
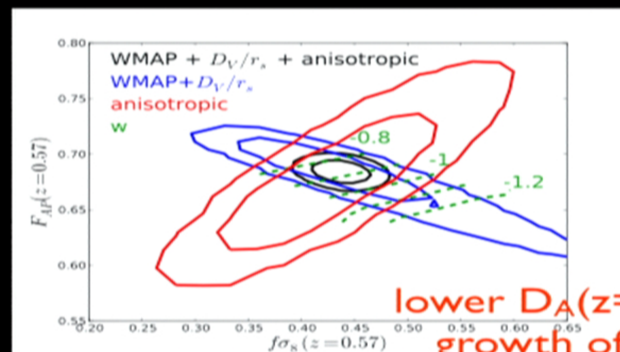
Full Shape Cosmological Implications: Quadrupole amplitude constrains w

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)

Samushia, BR, et al., 2013/2012

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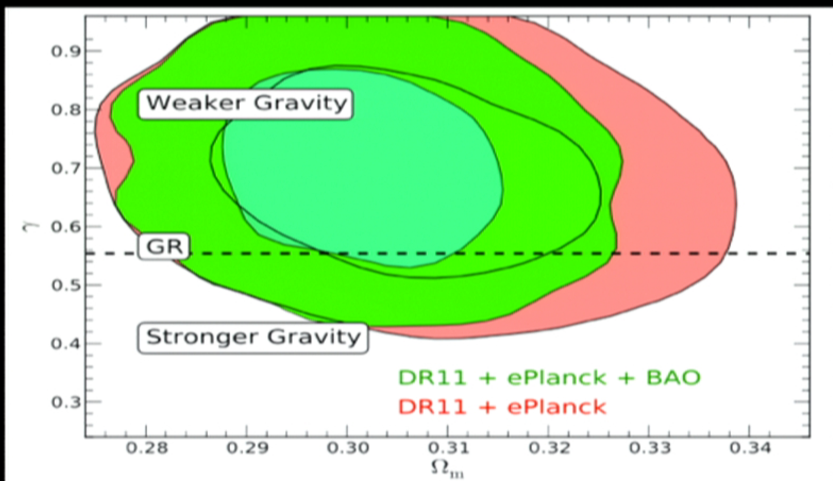
Full Shape Cosmological Implications



Modified Gravity test

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

($\gamma = 0.55$ in GR)

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Outline

- Galaxy redshift surveys: conceptual review
- SDSS-III BOSS DR11 results
- In pursuit of modified gravity
- Prospects for the next decade of redshift surveys

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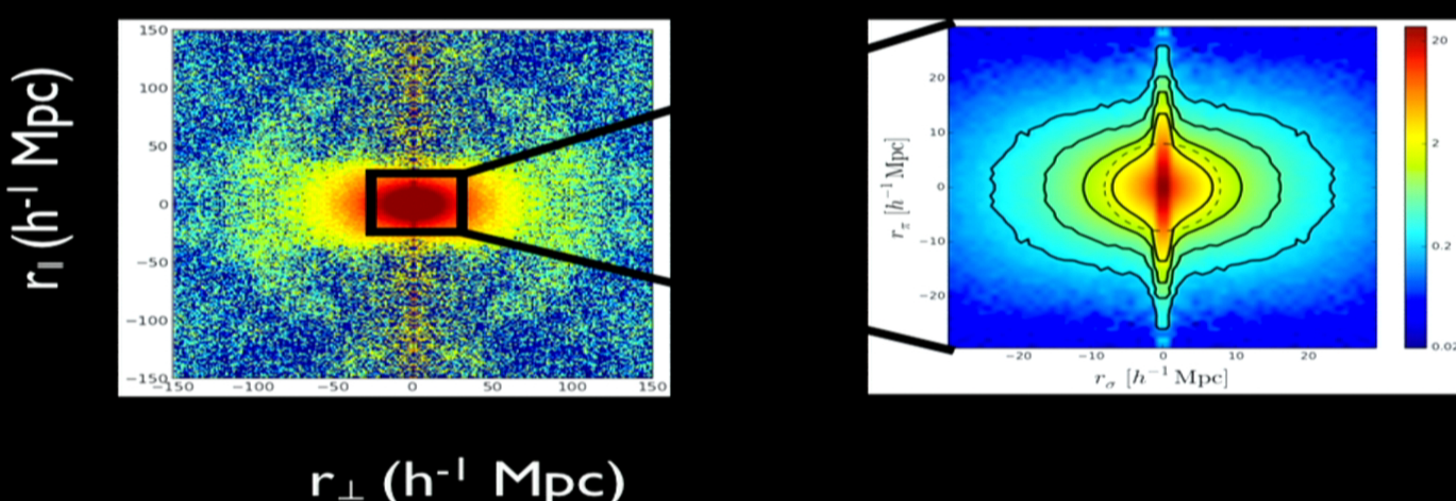
Using small-scale clustering to constrain gravity

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



BOSS DR11, Samushia et al. 2013

Reid et al. prep

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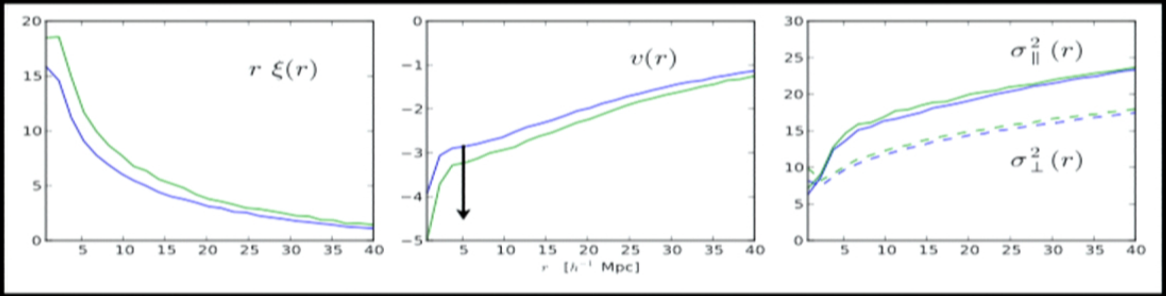
Small-scale clustering in real space: GR and modified gravity predictions



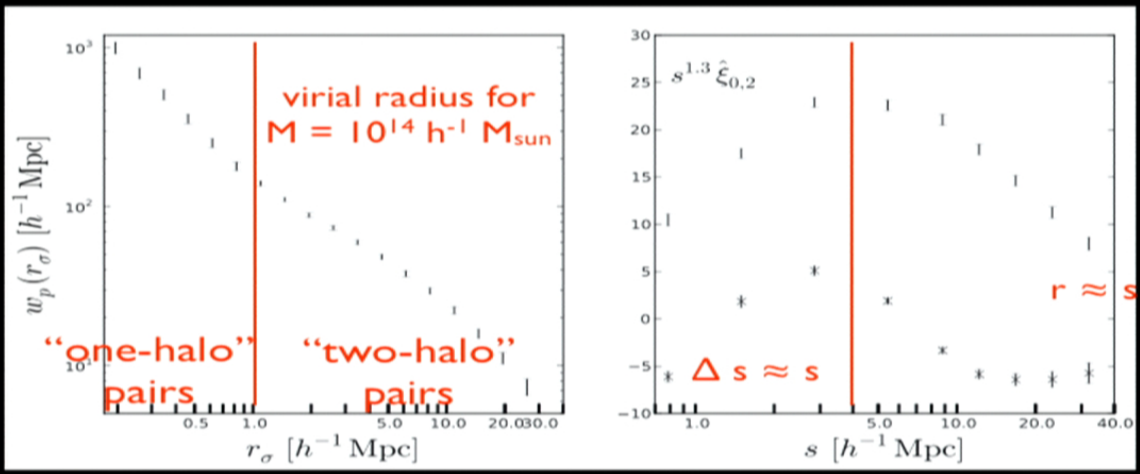
~1-2 h^{-1} Mpc enhancement in v(r) at r =5 h^{-1} Mpc for both f(R) and Galileon simulations [Zu et al. 2013]

Map to redshift space:

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

Best fit HOD model to small-scale clustering

Projected Clustering



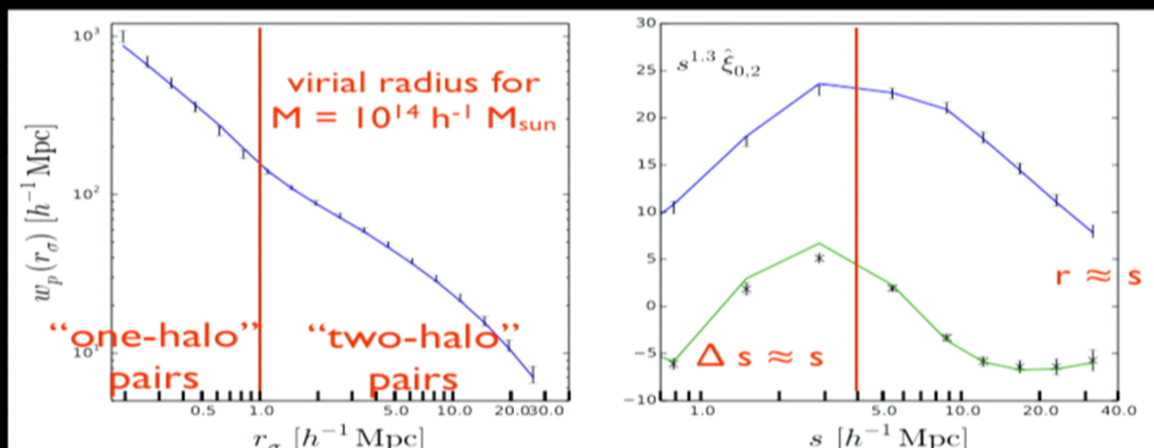
$s^{1.3}\xi_{0,2}$

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

Reasonably good fit: $\chi^2 = 32$ for 21 dof

Best fit HOD model to small-scale clustering

Projected Clustering

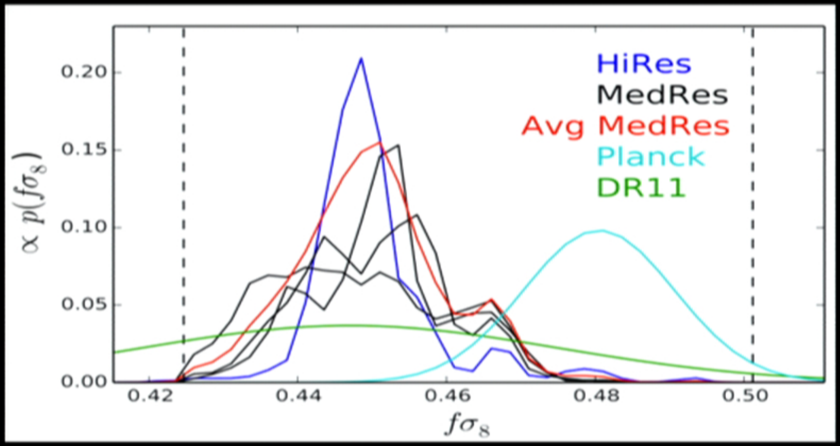


$s^{1.3}\xi_{0,2}$

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

Reasonably good fit: $\chi^2 = 32$ for 21 dof

Constraints on the growth rate $f\sigma_8$



- DR11 large scales: $f\sigma_8 = 0.447 \pm 0.028$
- DR10 small scales: $f\sigma_8 = 0.450 \pm 0.011$
- Planck ΛCDM prediction: $f\sigma_8 = 0.480 \pm 0.010$

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