

# LSS and BAO: current status and prospects

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for the SDSS-III Baryon Oscillation  
Spectroscopic Survey (BOSS)

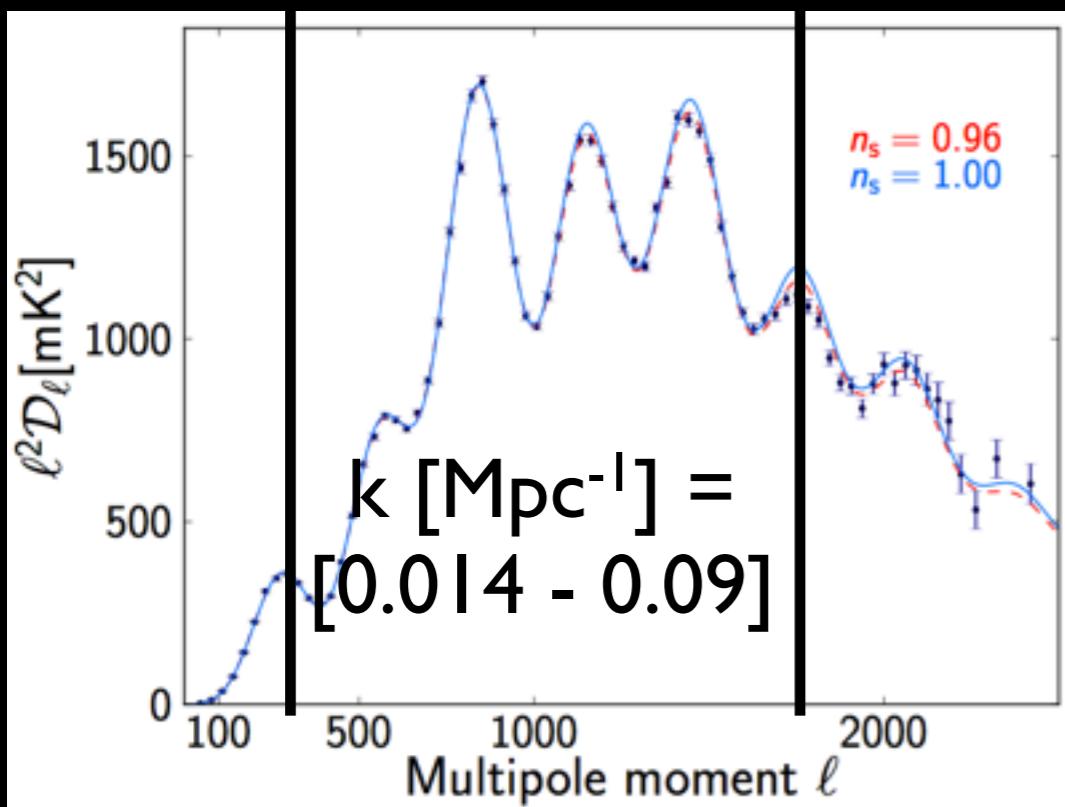
Image Courtesy Chris Blake and Sam Moorfield

# Outline

- Recent developments in Baryon Acoustic Oscillations (BAO)
- Anisotropic clustering: Alcock-Paczynski (AP) and redshift space distortions (RSD)
- Prospects for the next decade of redshift surveys

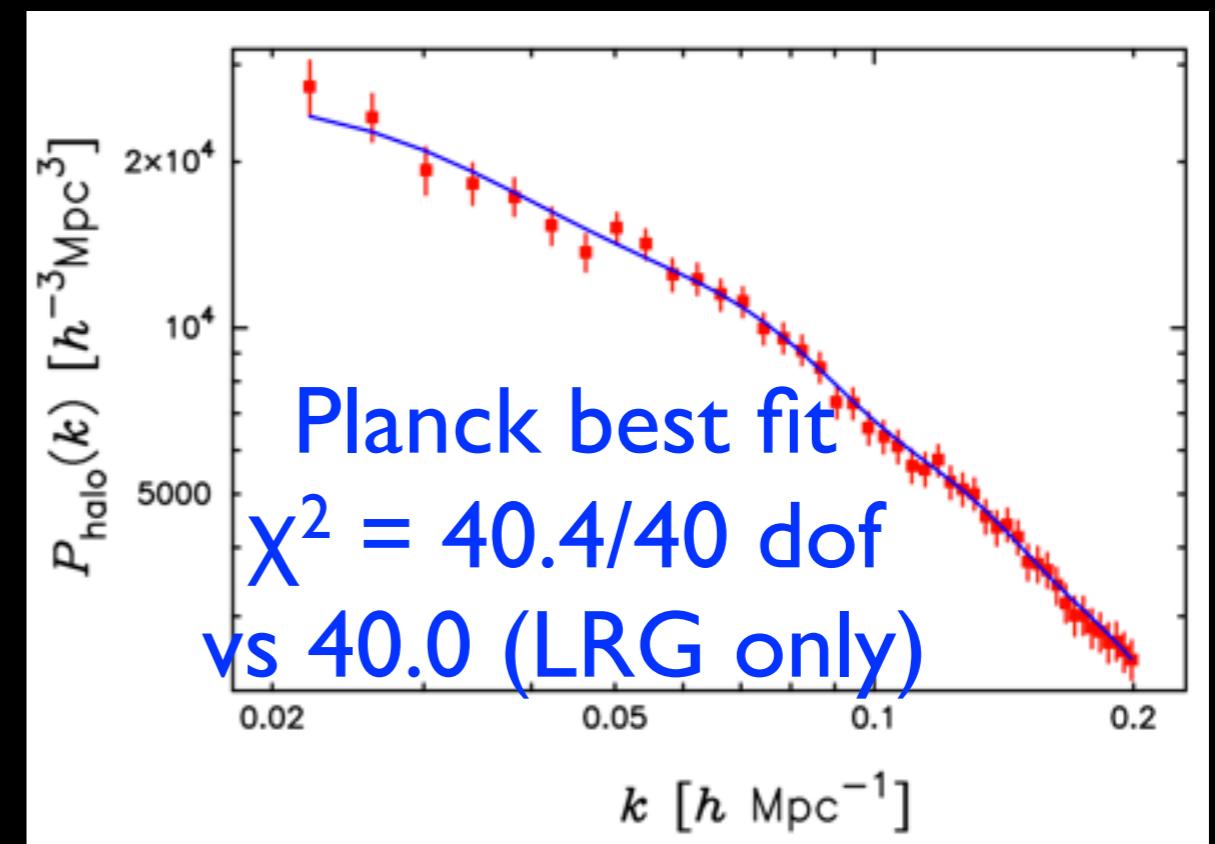
# Aside: CMB and LSS $P(k)$ agree!

Planck



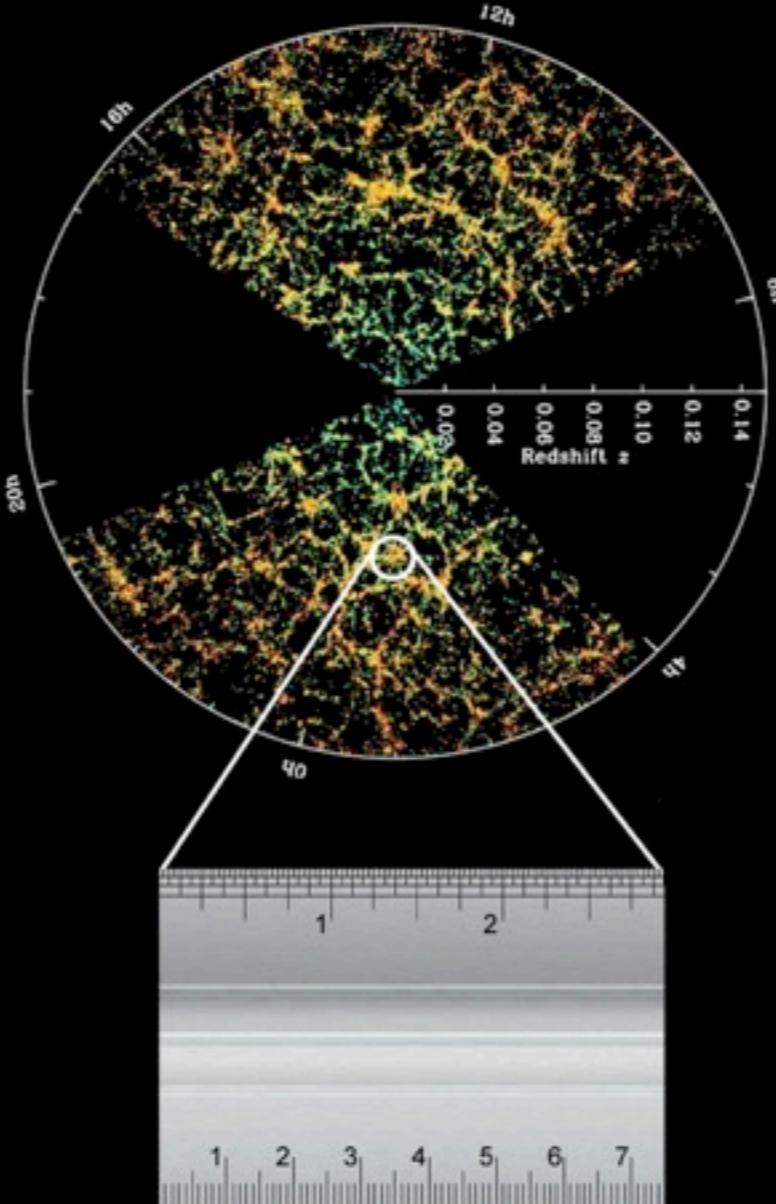
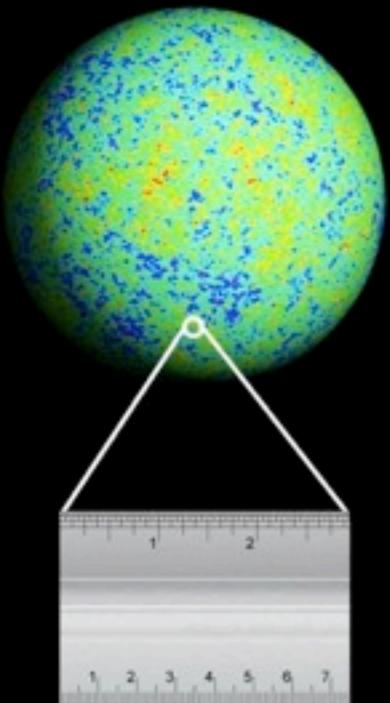
Planck 2013 #16

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



$P(k)$  broadband “useful” only in extended models ( $N_{\text{eff}}$ ,  $m_V$ , MG...?)

# The BAO standard ruler



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

$$= 147.5 \pm 0.6 \text{ Mpc (0.4%!)}$$

[Planck XVI]

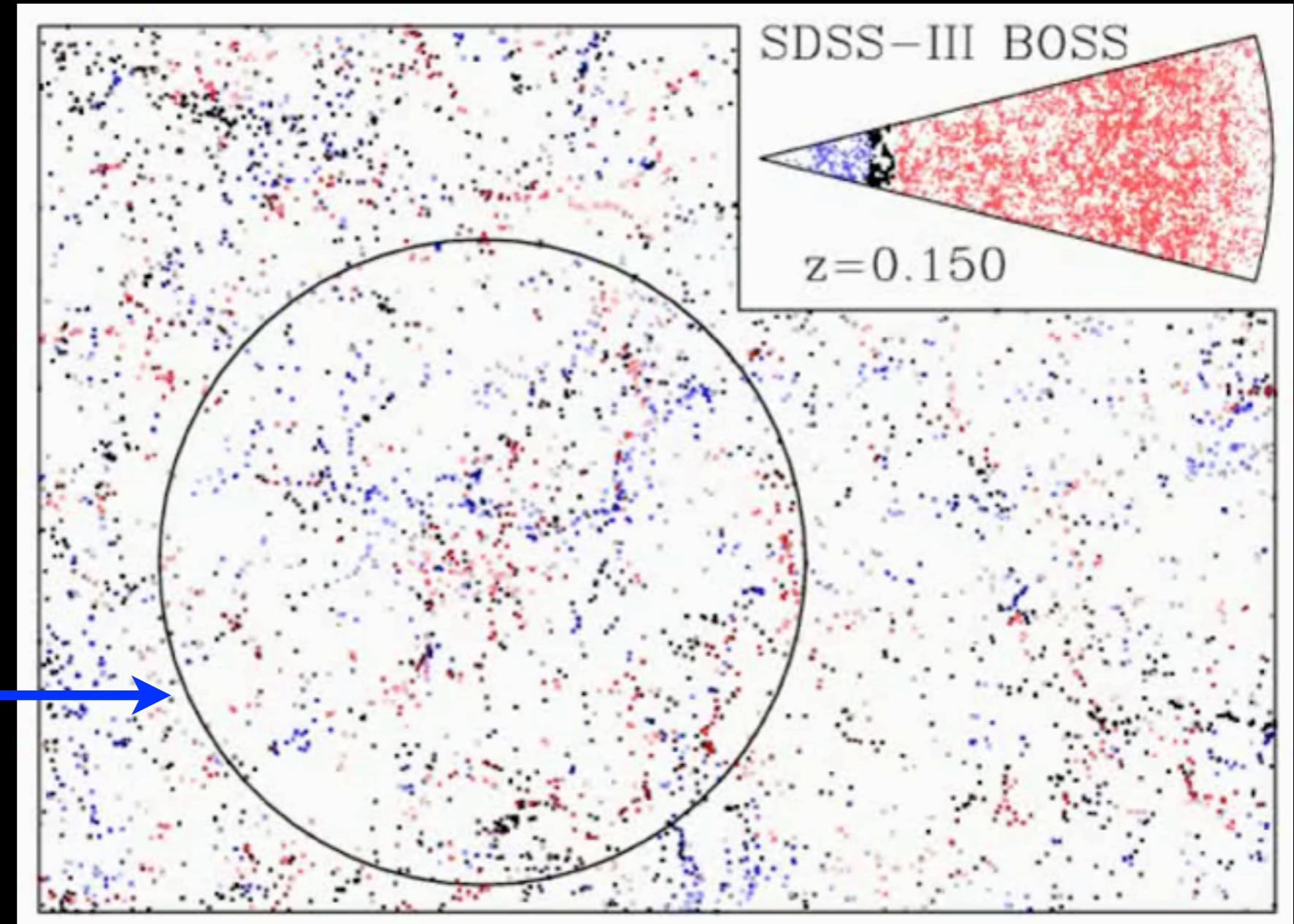
-- Relative calibration requires  $n_b/n_\gamma$  and  $z_{\text{eq}}$ ; absolute also requires  $\Omega_m h^2$   
[Eisenstein and White, PRD, 70, 103523 (2004)]

-- Isocurvature IC shift BAO scale as well; marginalize!  
[Mangilli, Verde, Beltran, JCAP, 20, 9 (2010)]

# “Raw” data: 3d galaxy map from the SDSS-III Baryon Oscillation Spectroscopic Survey

Non-gaussianity  
of galaxy  
density field is a  
challenge and  
opportunity

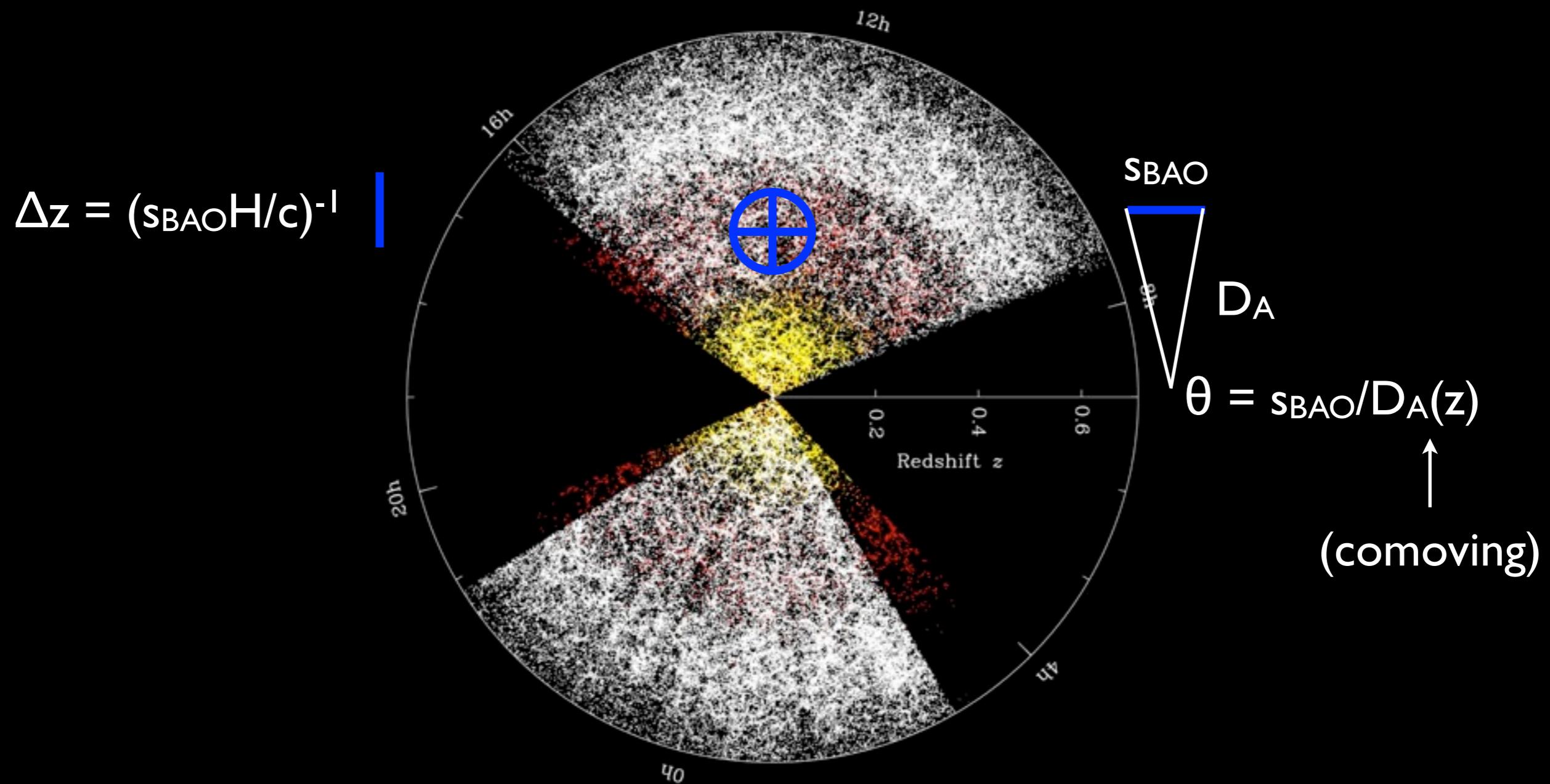
Apparent size  
of the BAO  
ruler



53x38 degree slice; ~20% of DR11

credit: Daniel Eisenstein

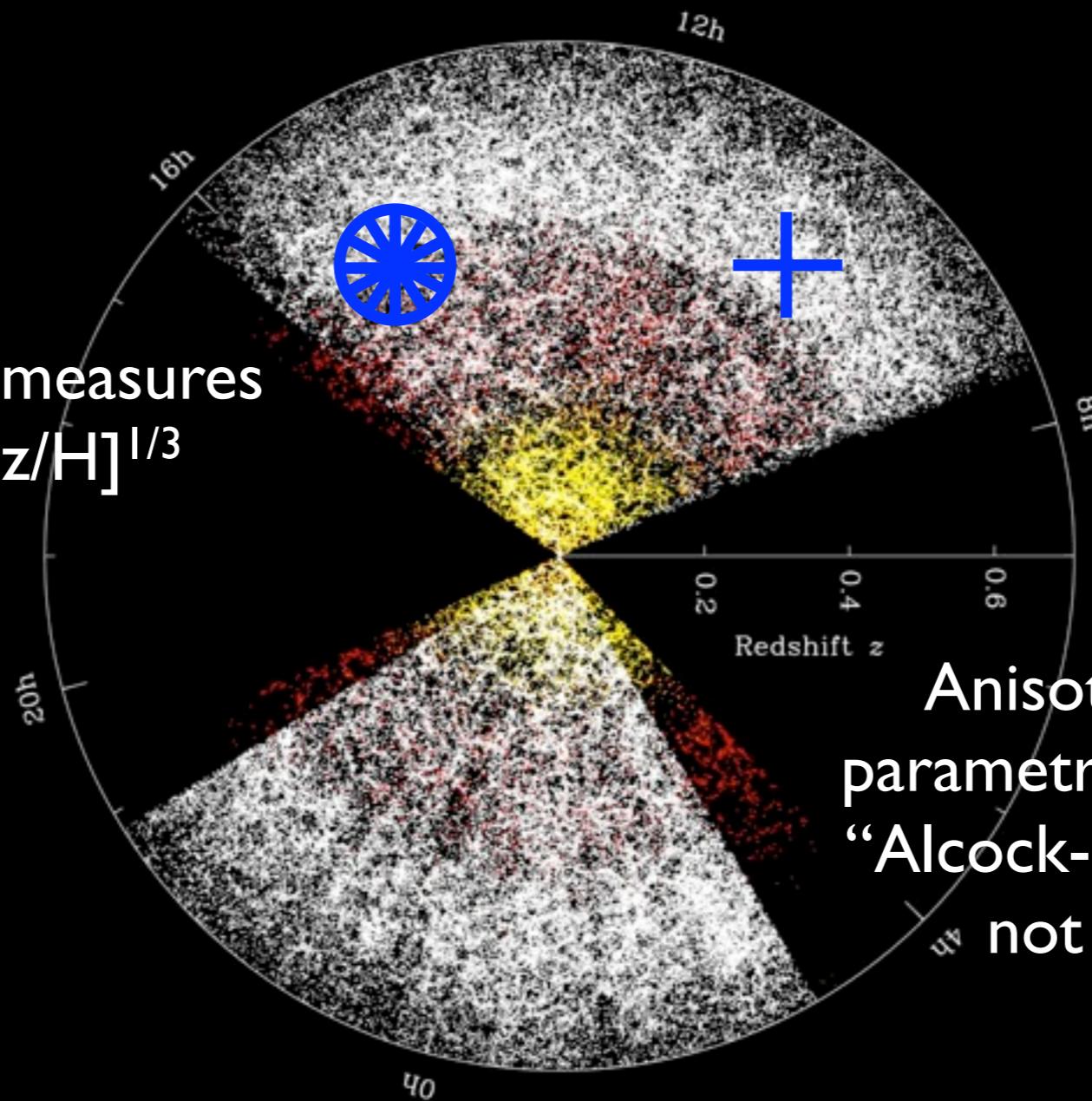
# Spectroscopic surveys can measure both $D_A$ and $H$ with the BAO standard ruler



# Spectroscopic surveys can measure both $D_A$ and $H$ with the BAO standard ruler

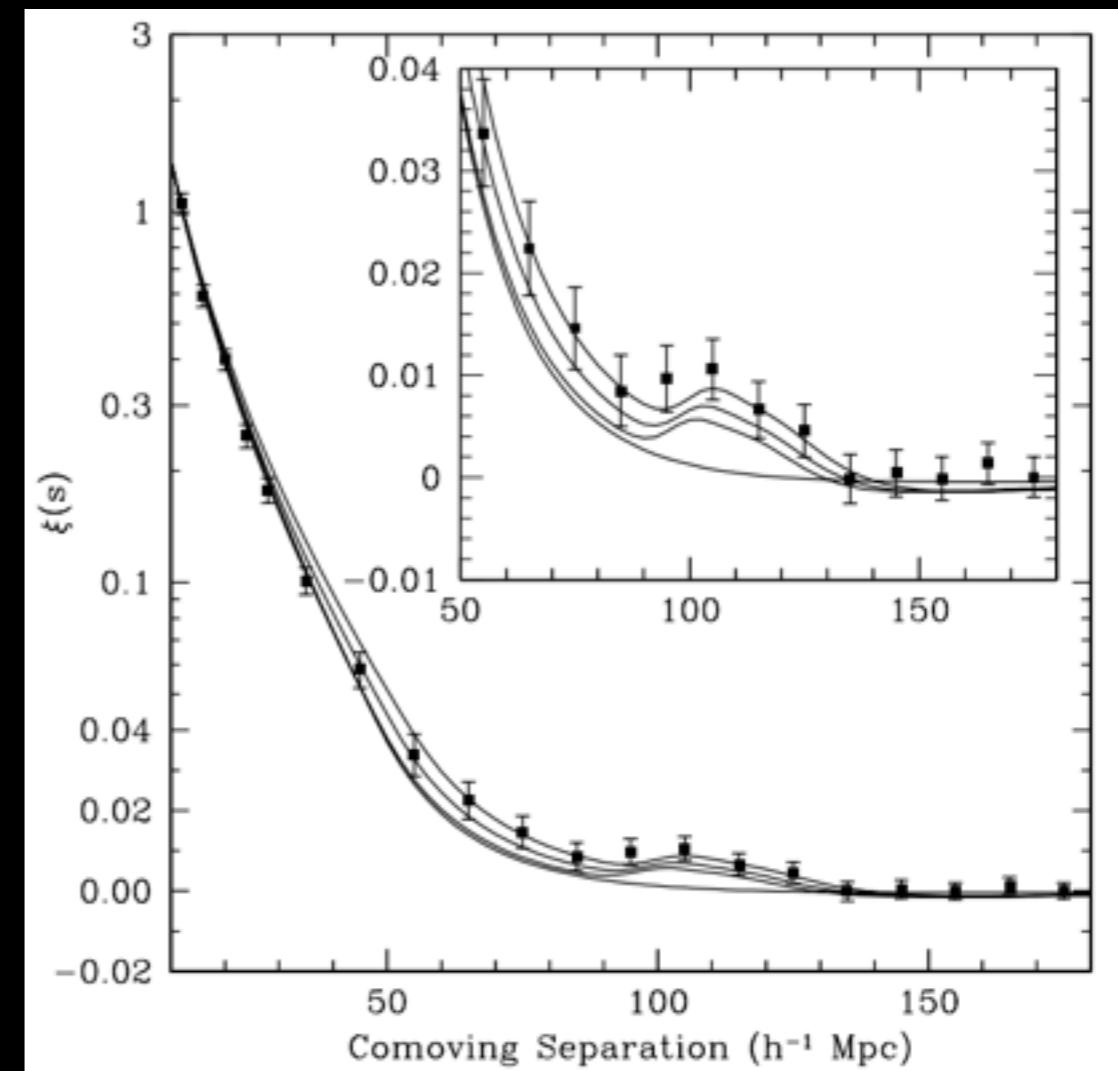
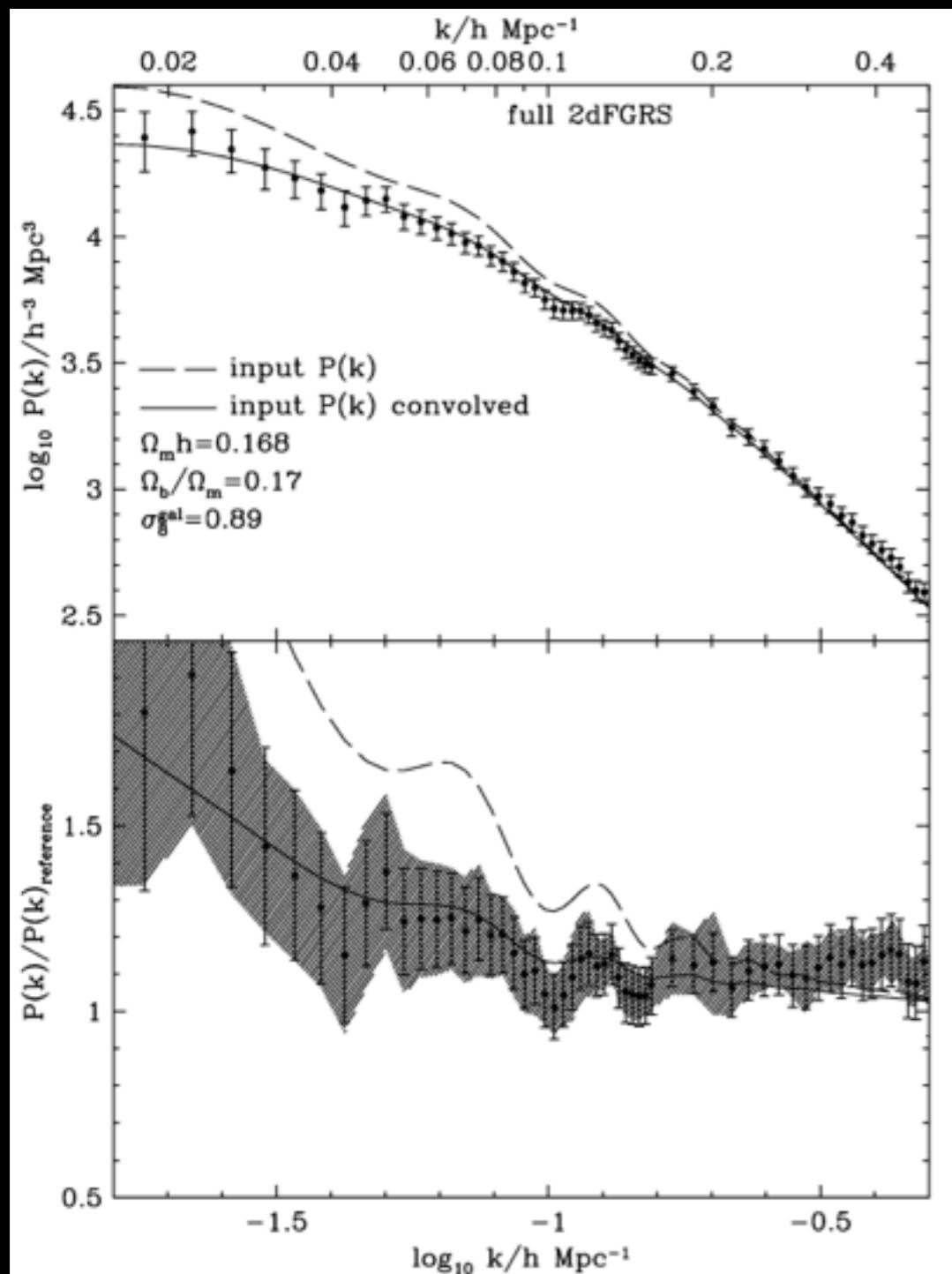
Angle-averaged BAO measures

$$D_V/s_{\text{BAO}} = [D_A^2 * cz/H]^{1/3}$$



Anisotropic component  
parametrized by  $F_{\text{AP}} = D_A * H$   
“Alcock-Paczynski” test; does  
not require a ruler!

# Initial BAO detections (2005)



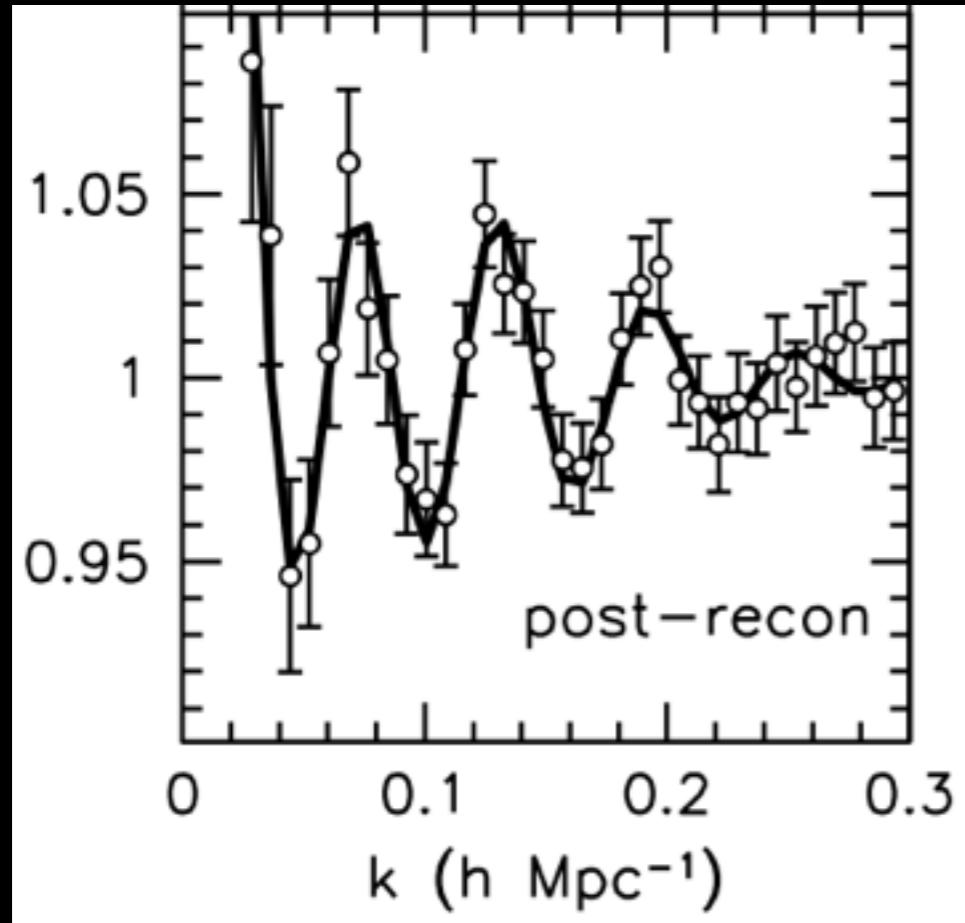
Cole et al., 2005, MNRAS, 362, 505

Beth Reid

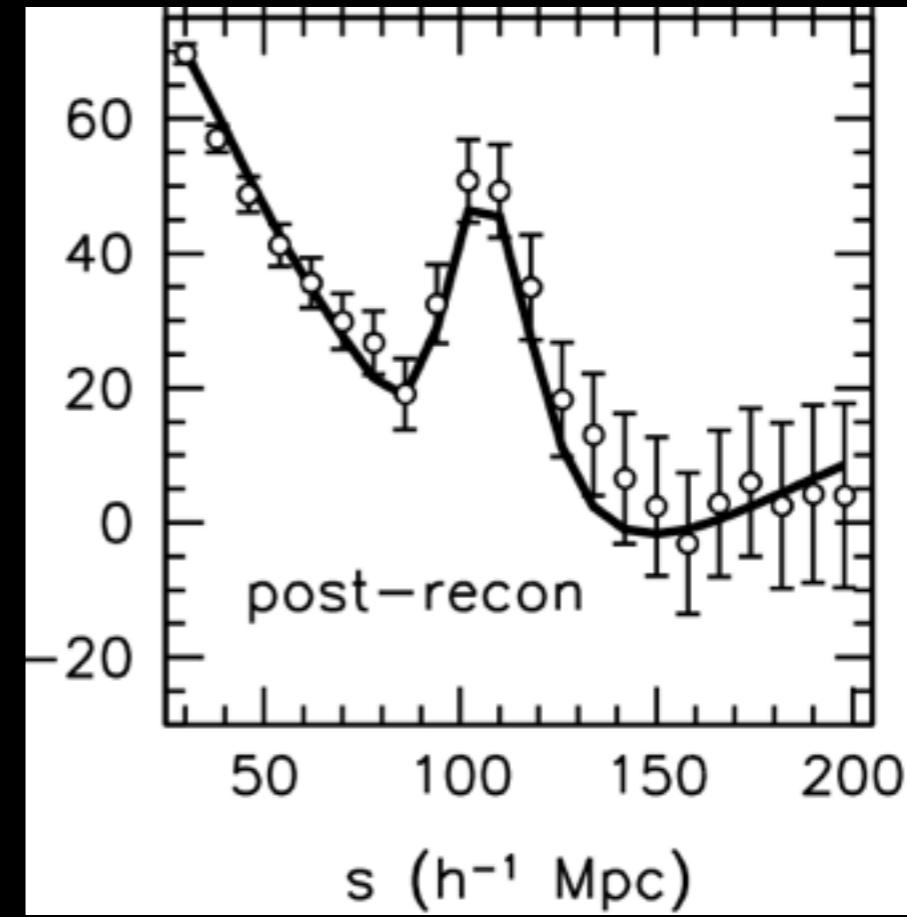
Eisenstein et al., 2005, ApJ, 633, 560

PONT Avignon 2014

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



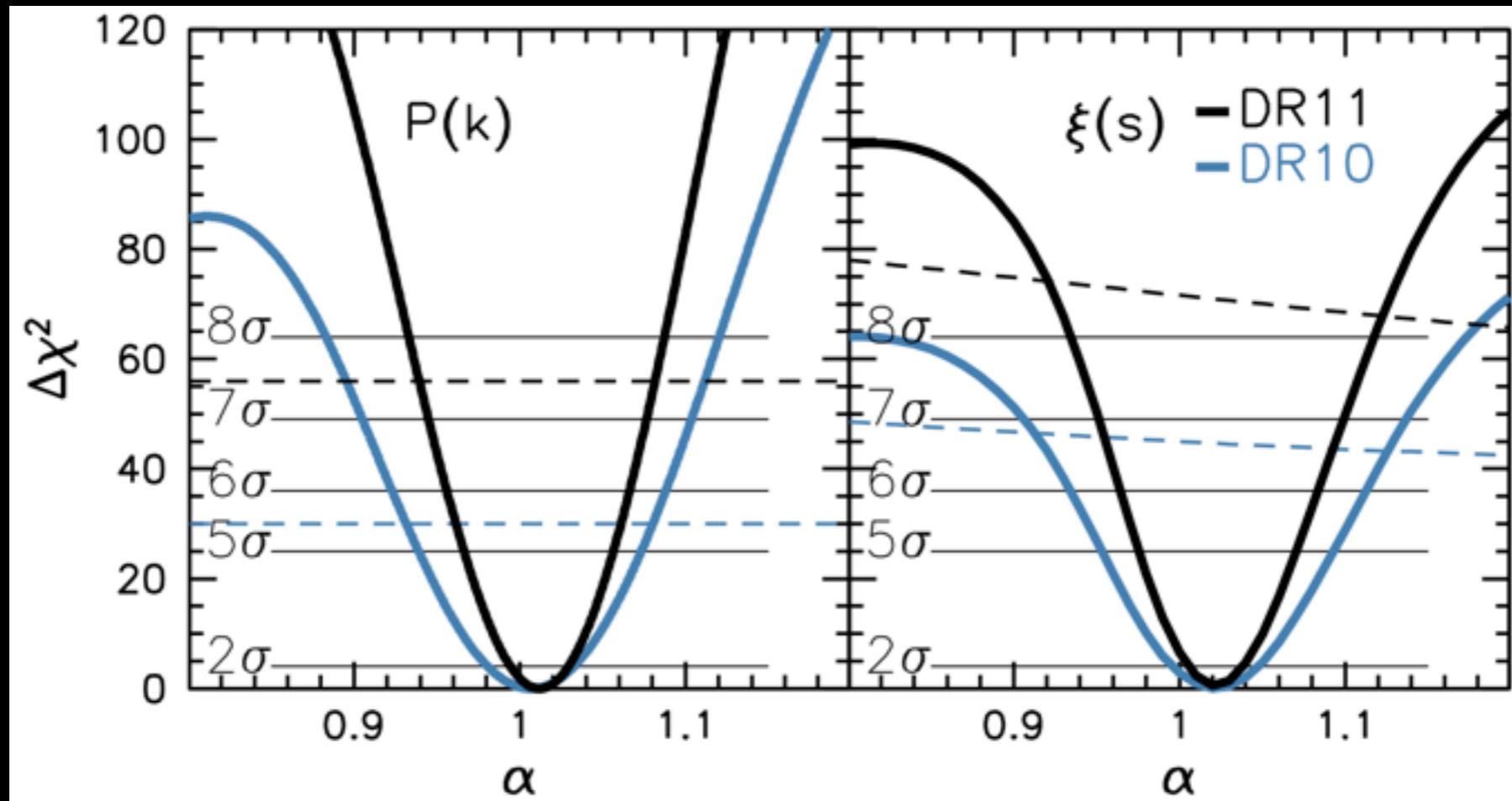
$P(k)/P_{\text{smooth}}(k)$



$s^2 \xi(s)$

BOSS, arXiv:1312.4877

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



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

BOSS, arXiv:1312.4877

# Recent developments in BAO: reconstruction

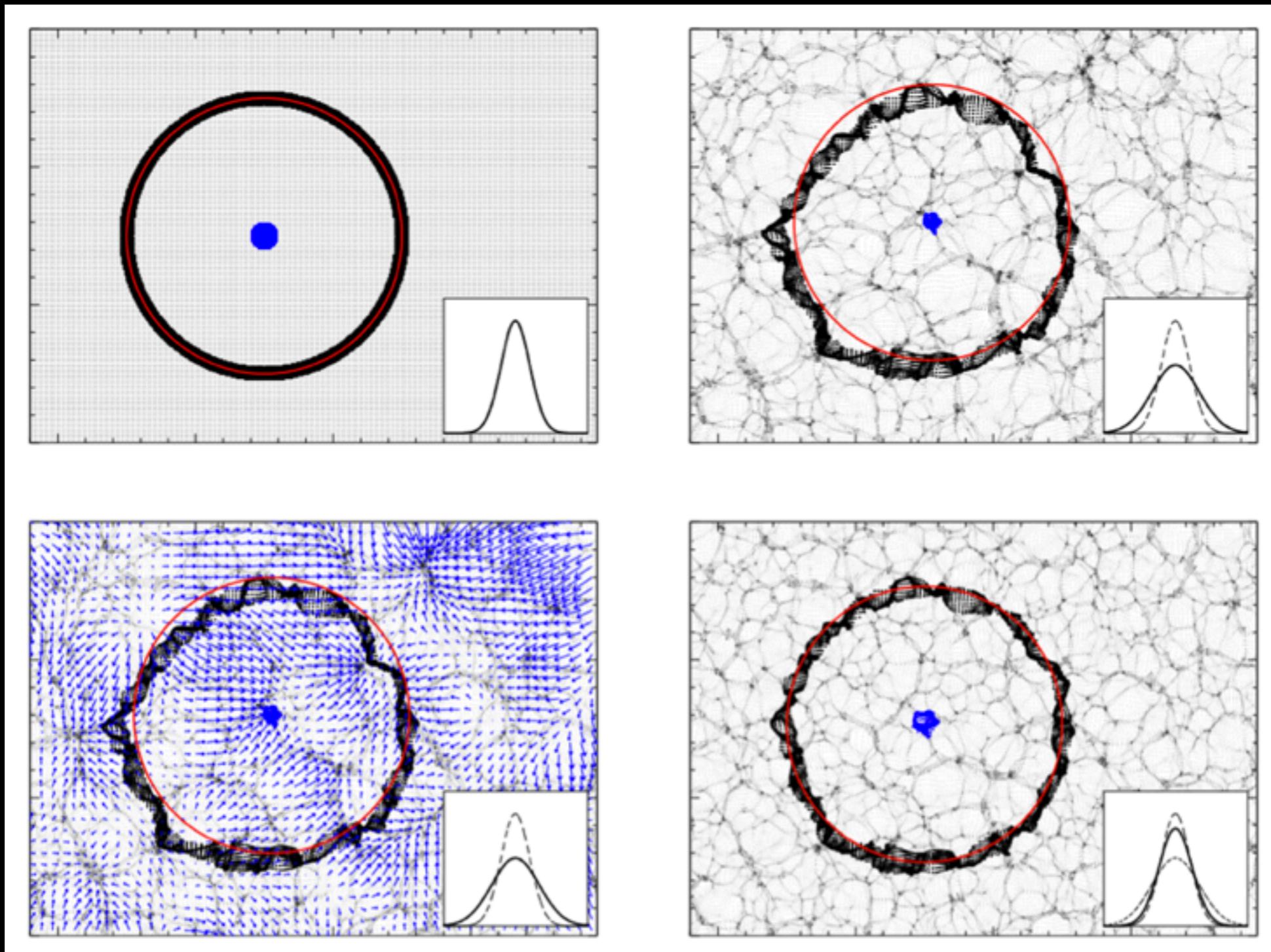
- Large-scale flows smear the BAO feature at low redshift
- Reconstruction undoes these flows, reducing both bias and smearing of the BAO scale
- The “displacement field” between initial and final positions can be estimated from the observed density field under the Zel'dovich approximation:

$$\nabla \cdot \mathbf{F} = \nabla \cdot \Psi + f \nabla \cdot (\Psi_s \hat{\mathbf{s}}) = -\frac{\delta_{\text{gal}}}{b}$$

Concept: Eisenstein, Seo, Sirk, Spergel, 2007, ApJ, 664, 675

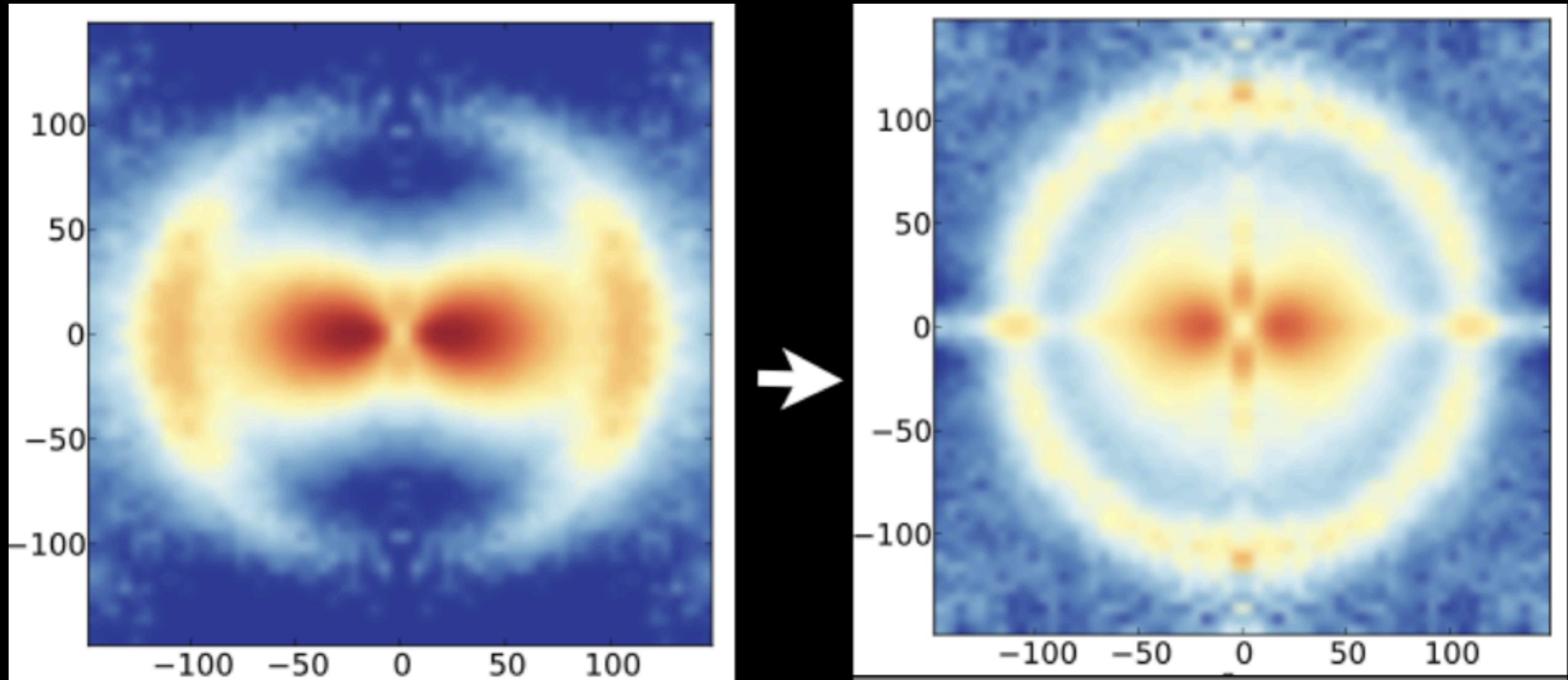
Applicaton to data: Padmanabhan et al., 2012, MNRAS, 427, 2132

# Recent developments in BAO: reconstruction



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

# Recent developments in BAO: reconstruction

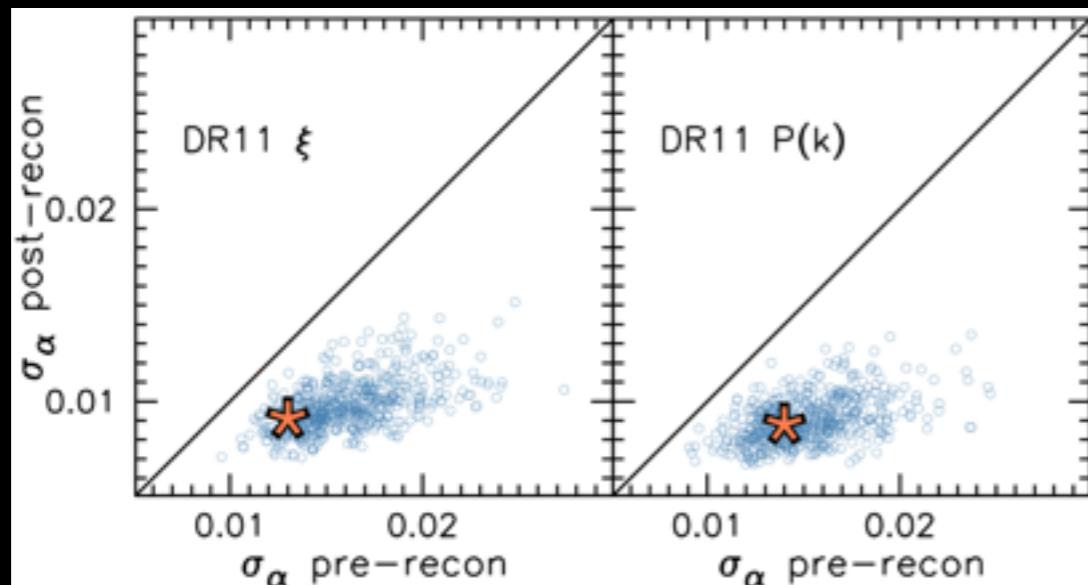


Reconstruction on 160 Las Damas mock galaxy catalogs

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

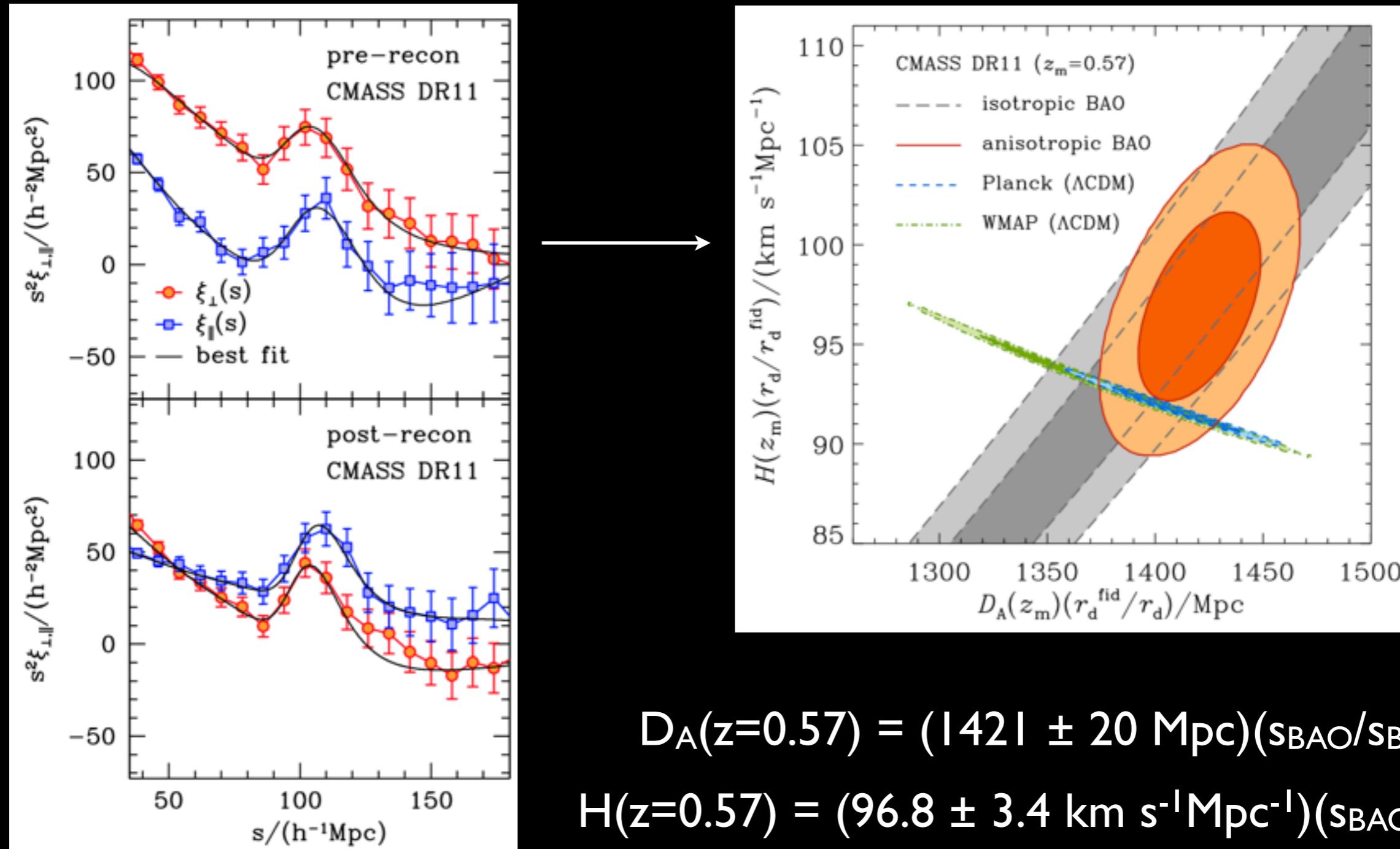
# Recent developments in BAO: reconstruction

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



BOSS DR11 CMASS  
mocks + data  
arXiv:1312.4877

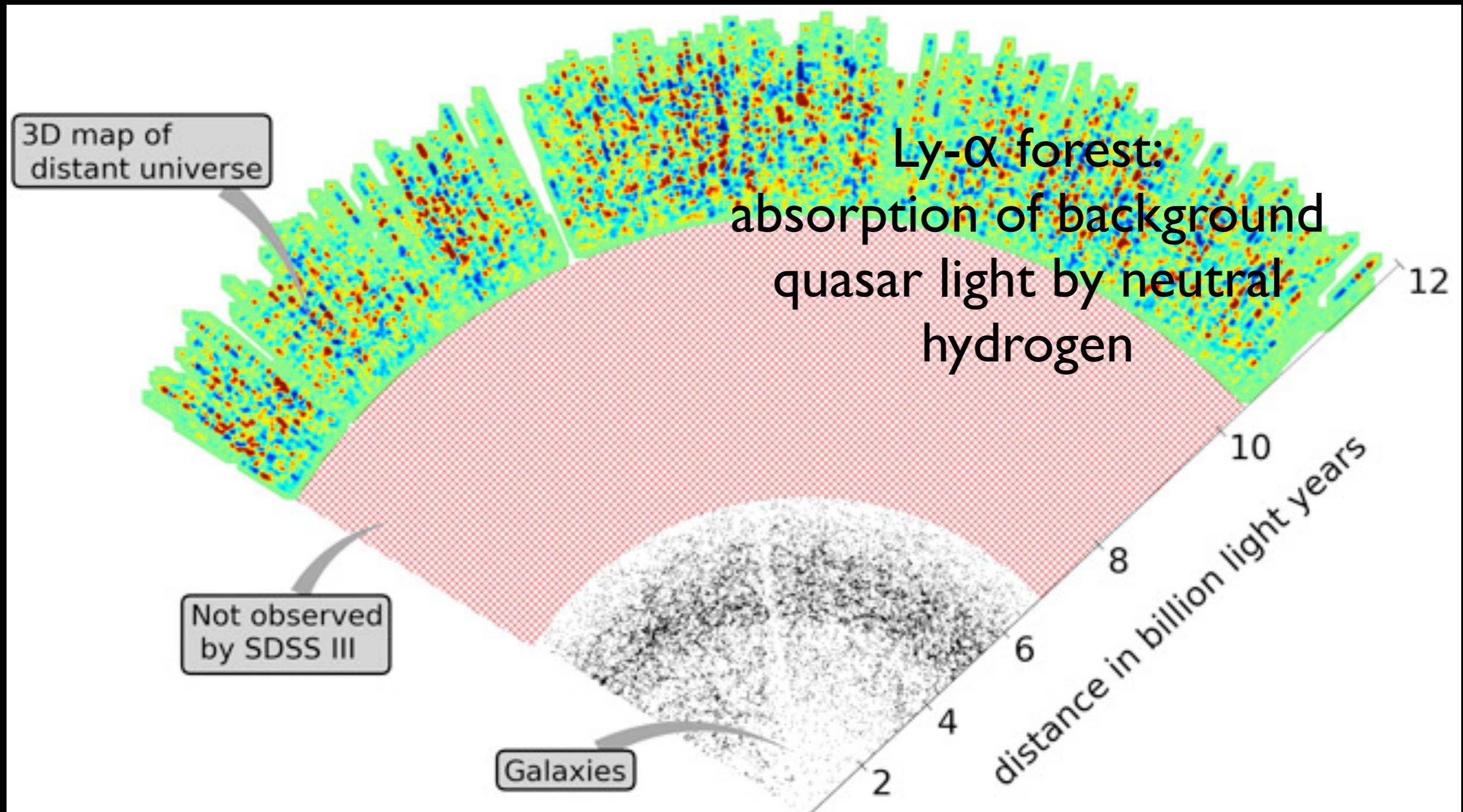
# Recent developments in BAO: simultaneous constraints on $D_A$ and $H$



$$D_A(z=0.57) = (142 \pm 20 \text{ Mpc})(s_{\text{BAO}}/s_{\text{BAO,fid}})$$

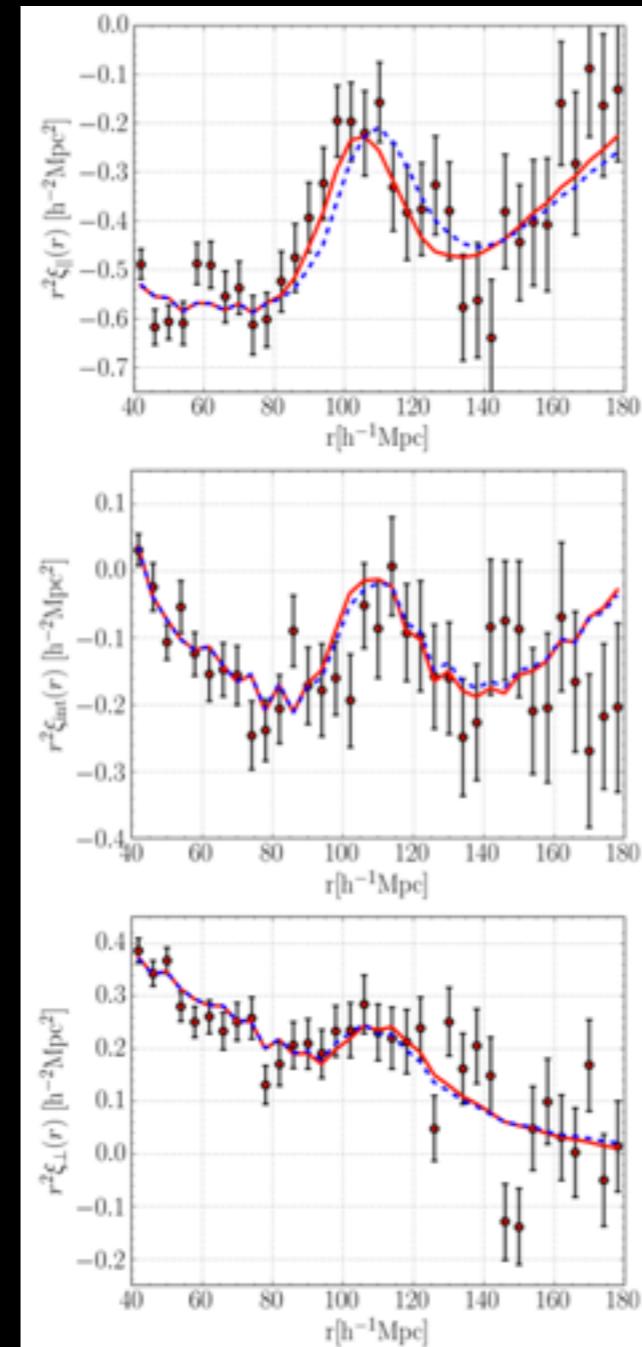
$$H(z=0.57) = (96.8 \pm 3.4 \text{ km s}^{-1} \text{Mpc}^{-1})(s_{\text{BAO,fid}}/s_{\text{BAO}})$$

# Recent developments in BAO: Ly- $\alpha$ forest



# Recent developments in BAO: Ly- $\alpha$ forest

- First detected in BOSS DR9 [Busca et al., Slosar et al.]
- Detected in DR11 in Ly- $\alpha$  auto-correlation [Delubac et al., arXiv:1401.1801] and quasar/Ly- $\alpha$  cross-correlation [Font-Ribera et al., 1311.1767]



$0.8 < \mu < 1$

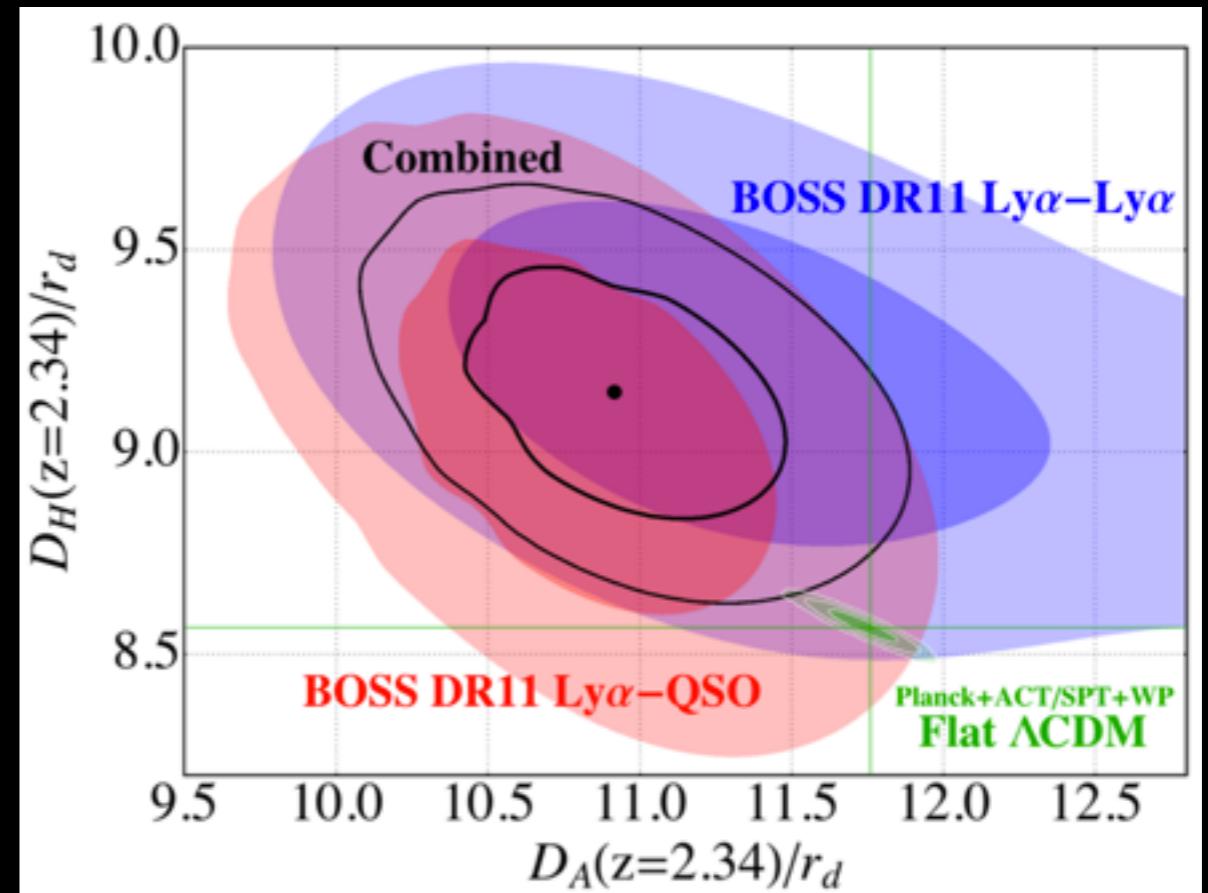
$0.5 < \mu < 0.8$

$0.0 < \mu < 0.5$

Delubac et al., arXiv:1401.1801

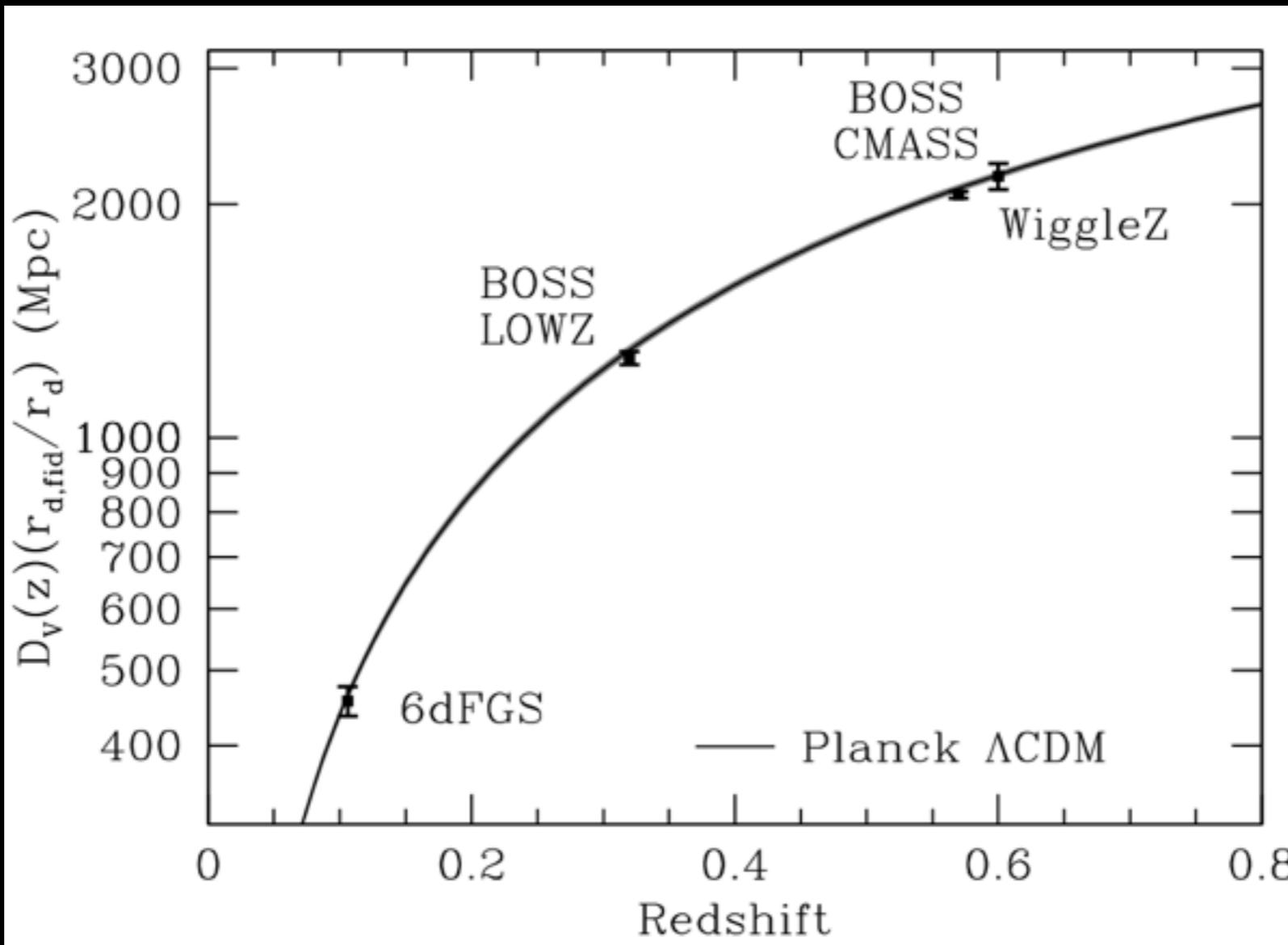
# Recent developments in BAO: Ly- $\alpha$ forest

- Another  $\sim 2.5\sigma$  “tension”
- Not simply solved by a normal LCDM extension



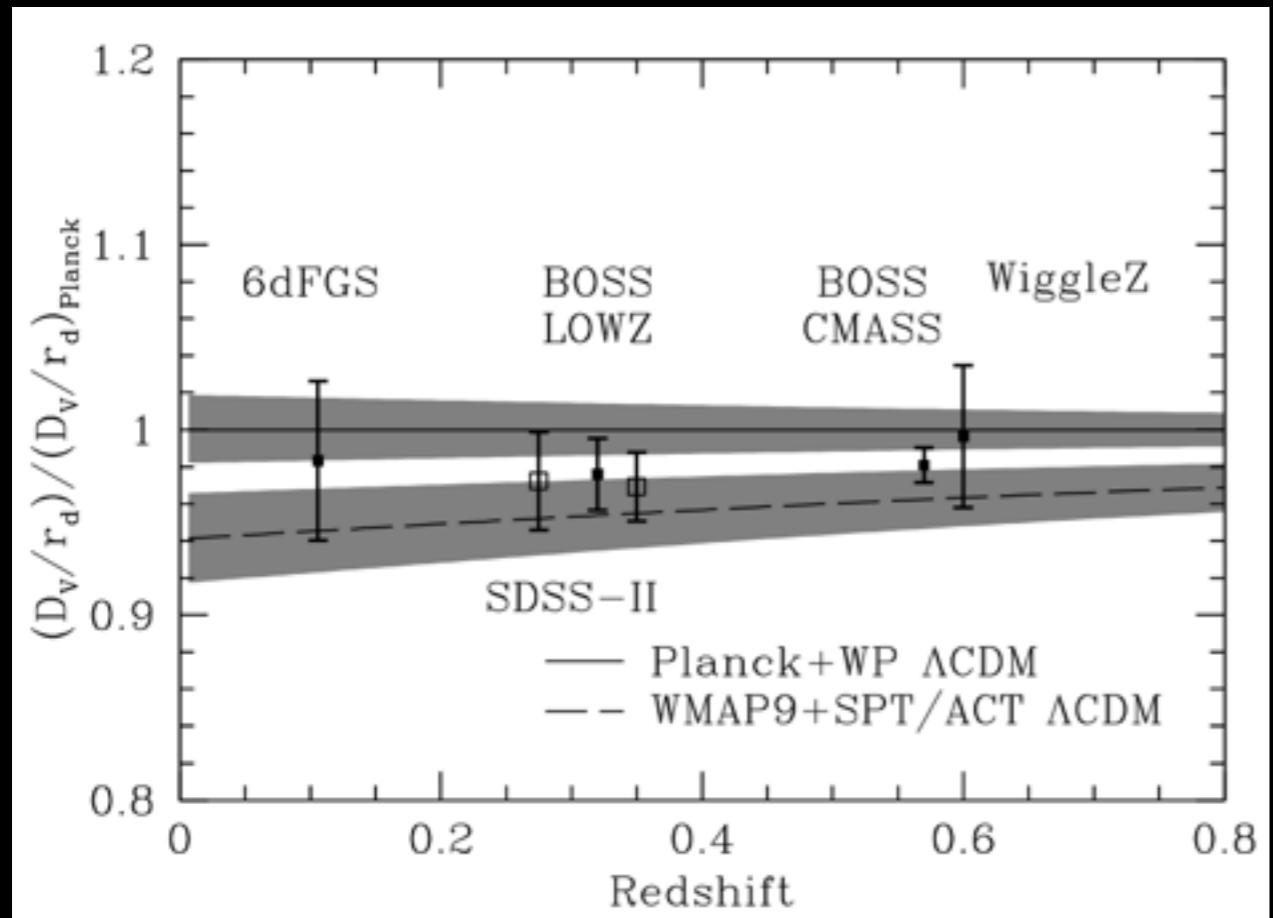
Delubac et al., arXiv:1401.1801

# Galaxy BAO distance ladder vs CMB $\Lambda$ CDM predictions



BOSS, arXiv:1312.4877

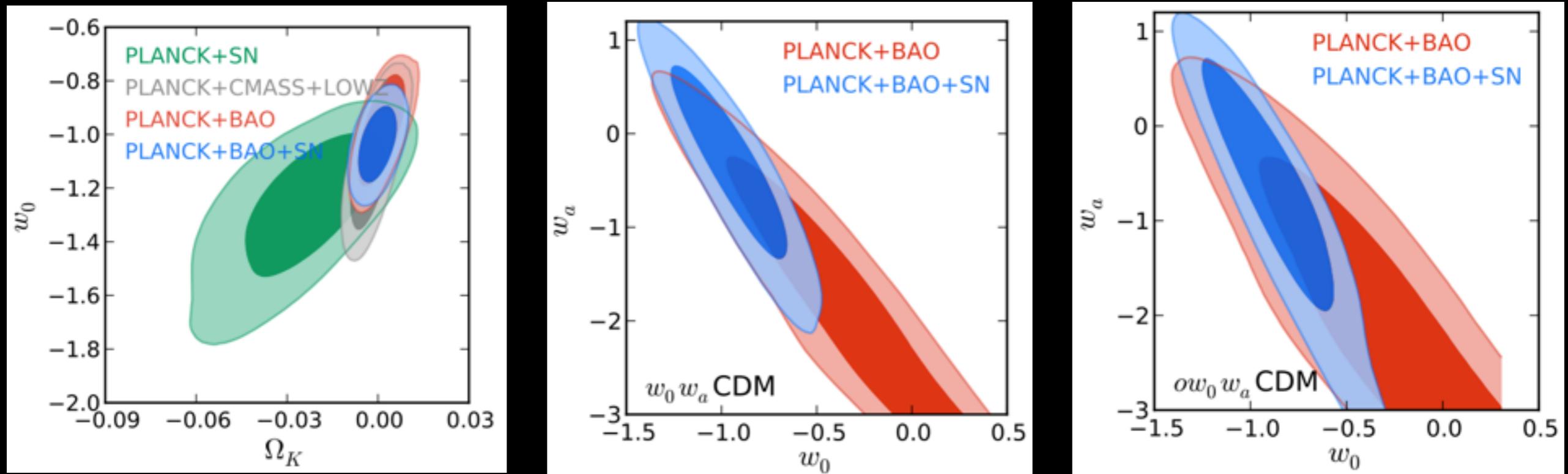
# Galaxy BAO distance ladder vs CMB $\Lambda$ CDM predictions



Planck:  $\Omega_m h^2 = 0.1427 \pm 0.0024$   
eWMAP:  $\Omega_m h^2 = 0.1353 \pm 0.0035$

BOSS, arXiv:1312.4877

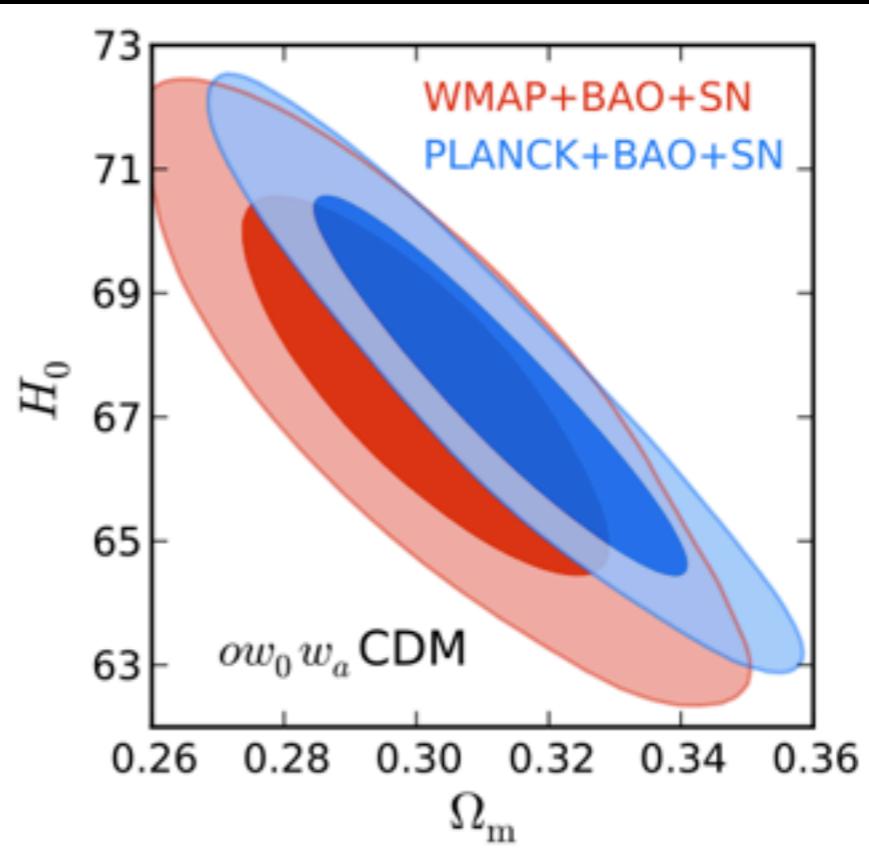
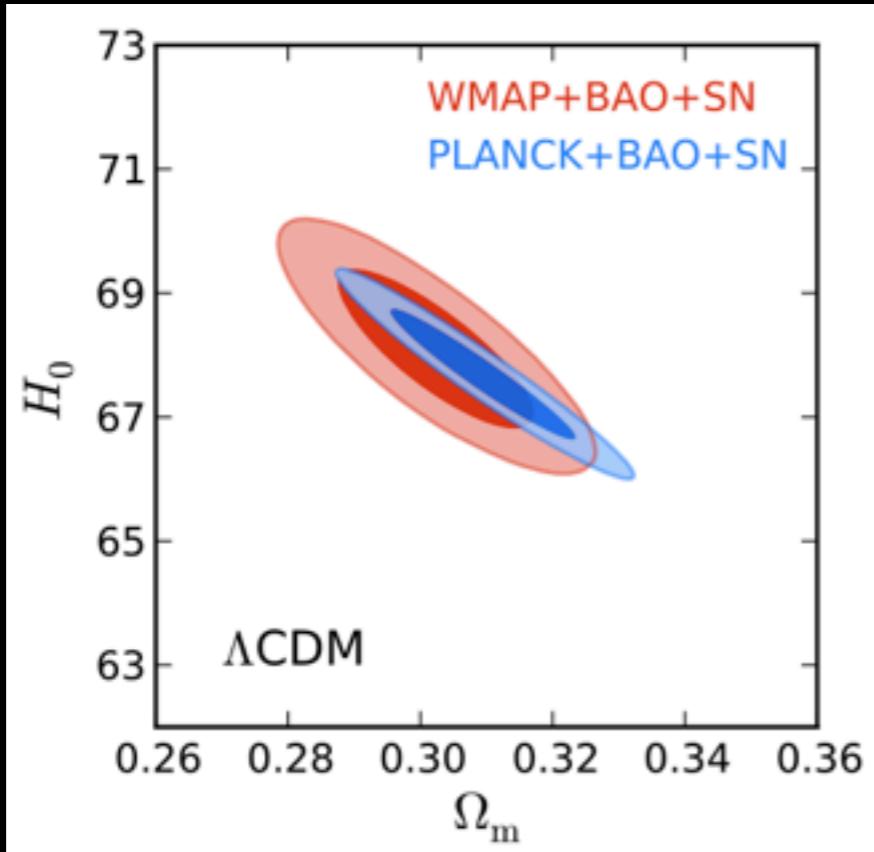
# Galaxy BAO Cosmological Implications



- $\Omega_k = 0.0002 \pm 0.0033$
- $w = -1.04 \pm 0.07$
- $w_0 = -0.94 \pm 0.17$
- $w_a = -0.37 \pm 0.60$
- $\Omega_k = 0.0027 \pm 0.0042$
- $w_0 = -0.87 \pm 0.19$
- $w_a = -0.73 \pm 0.80$

[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]

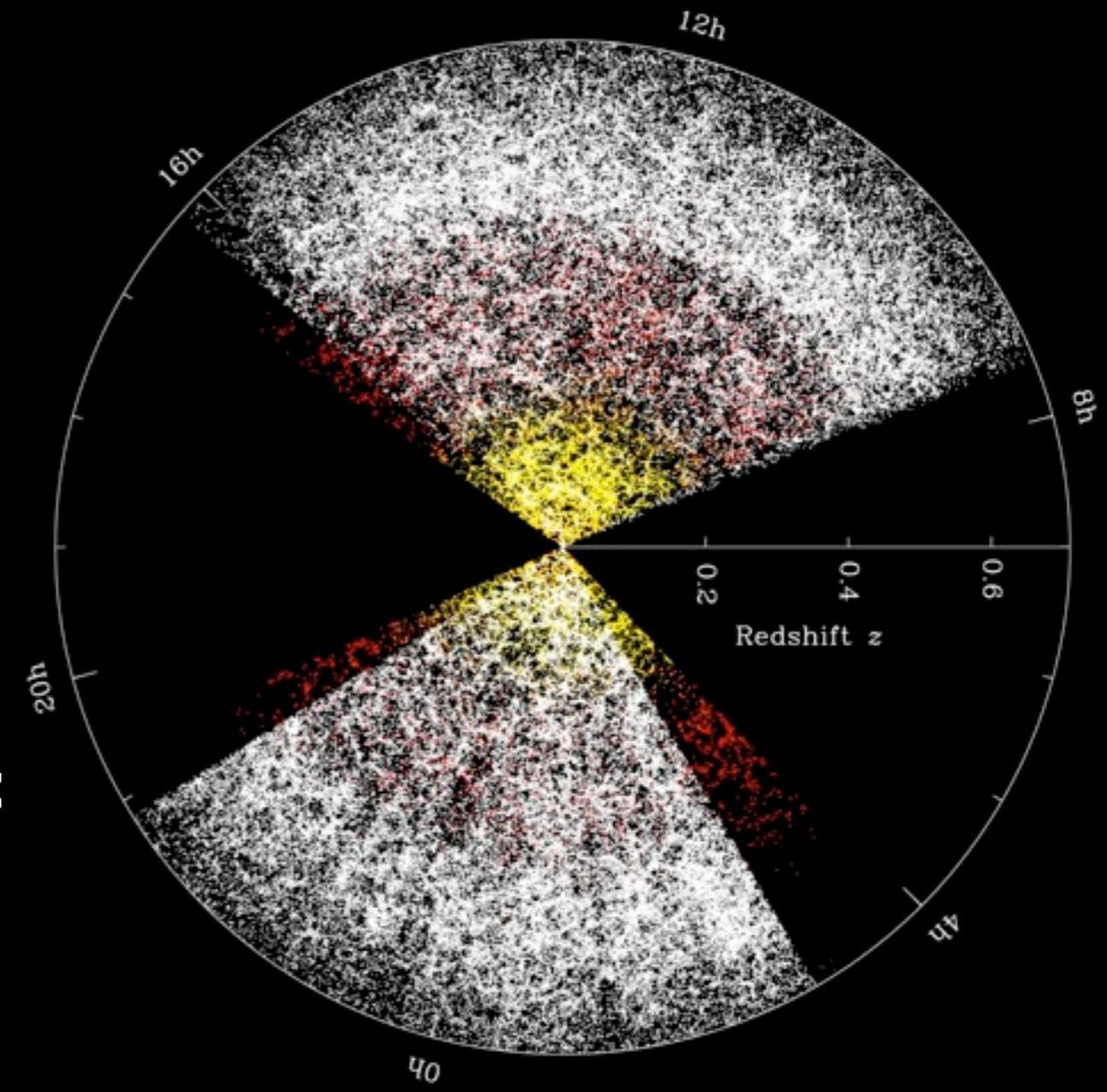
- $\Omega_m = 0.312 \pm 0.016$
- $H_0 = 67.5 \pm 1.7$ ; works in even more general DE models thanks to BAO absolute calibration and SN coverage to  $z=0$  [BOSS + SNLS in prep]

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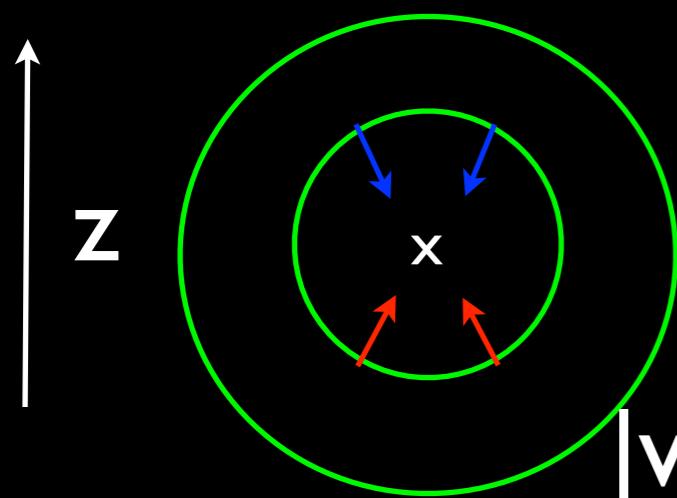
# Redshift Space Distortion (RSD) Motivation

- 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”



# Redshift Space Distortions (RSD)

real to redshift space separations:  $X(z) = X_{\text{true}} + v_p/aH$

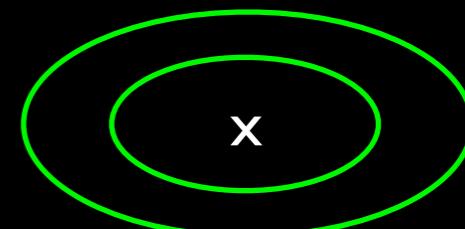


isotropic

$$\nabla \cdot \mathbf{v}_p = -aHf \delta_m$$



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

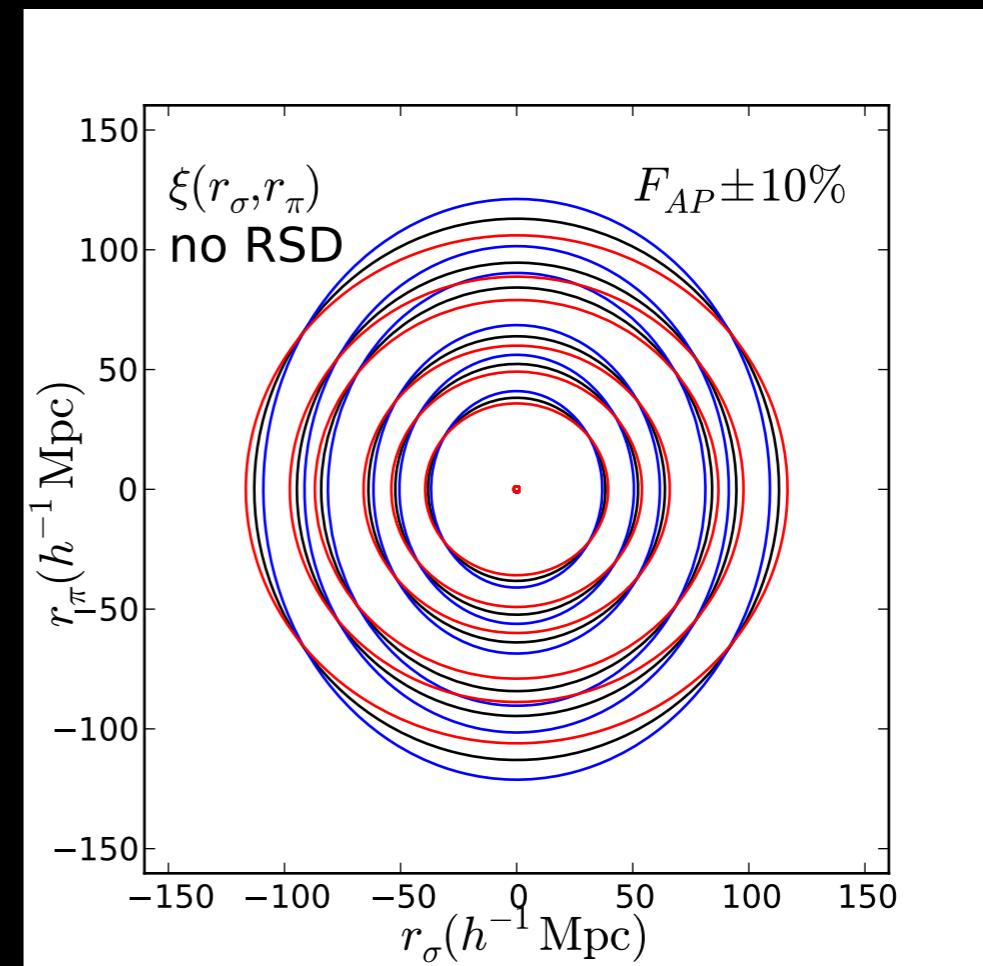
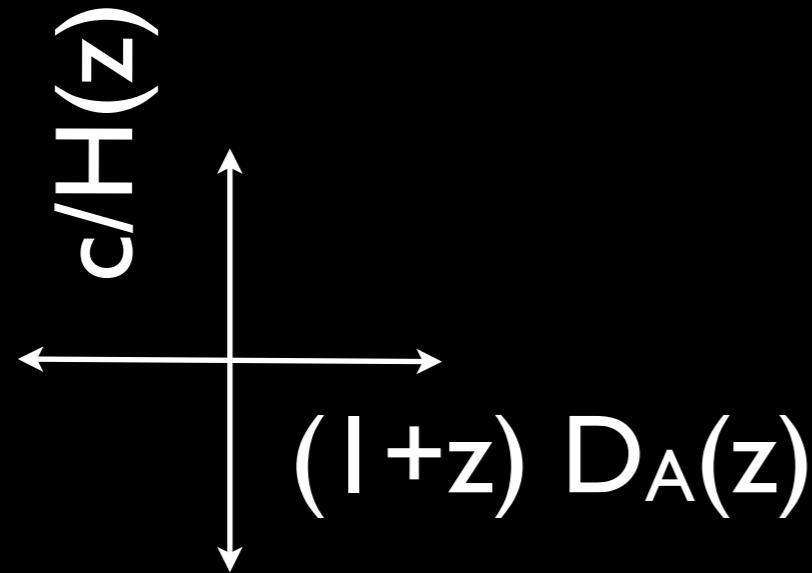


squashed along line of sight

$$f = d \ln \sigma_8 / d \ln a \approx \Omega_m^Y$$

# Alcock-Paczynski Effect

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



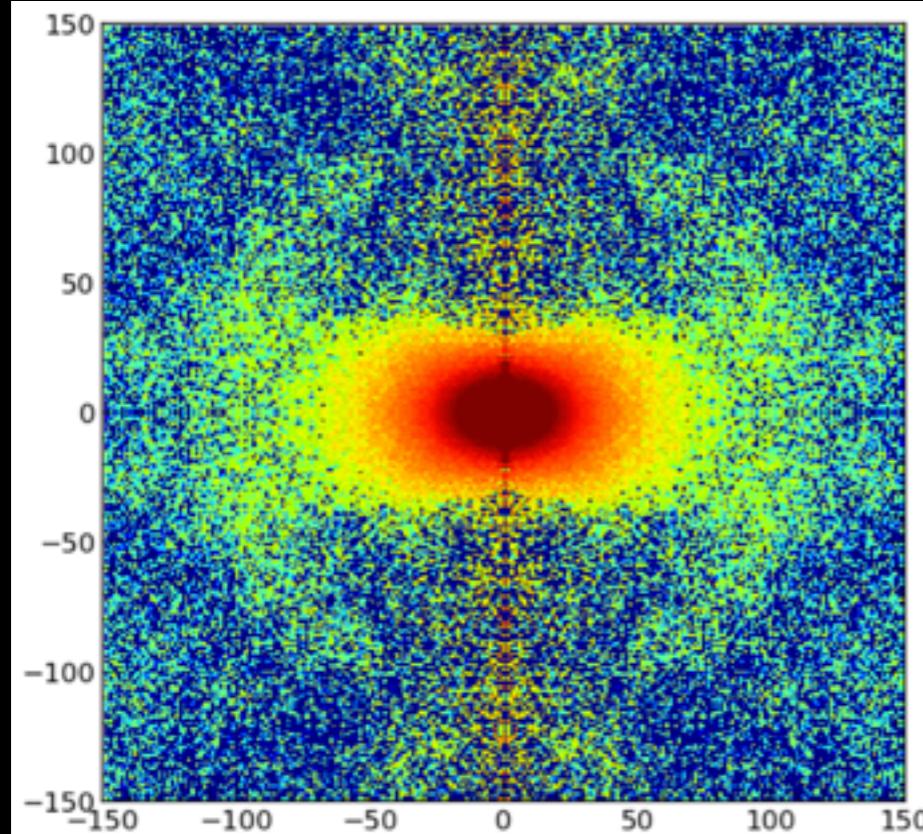
# “Full shape” fits to quasi-linear $\xi$ : Information compression with Legendre polynomials

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

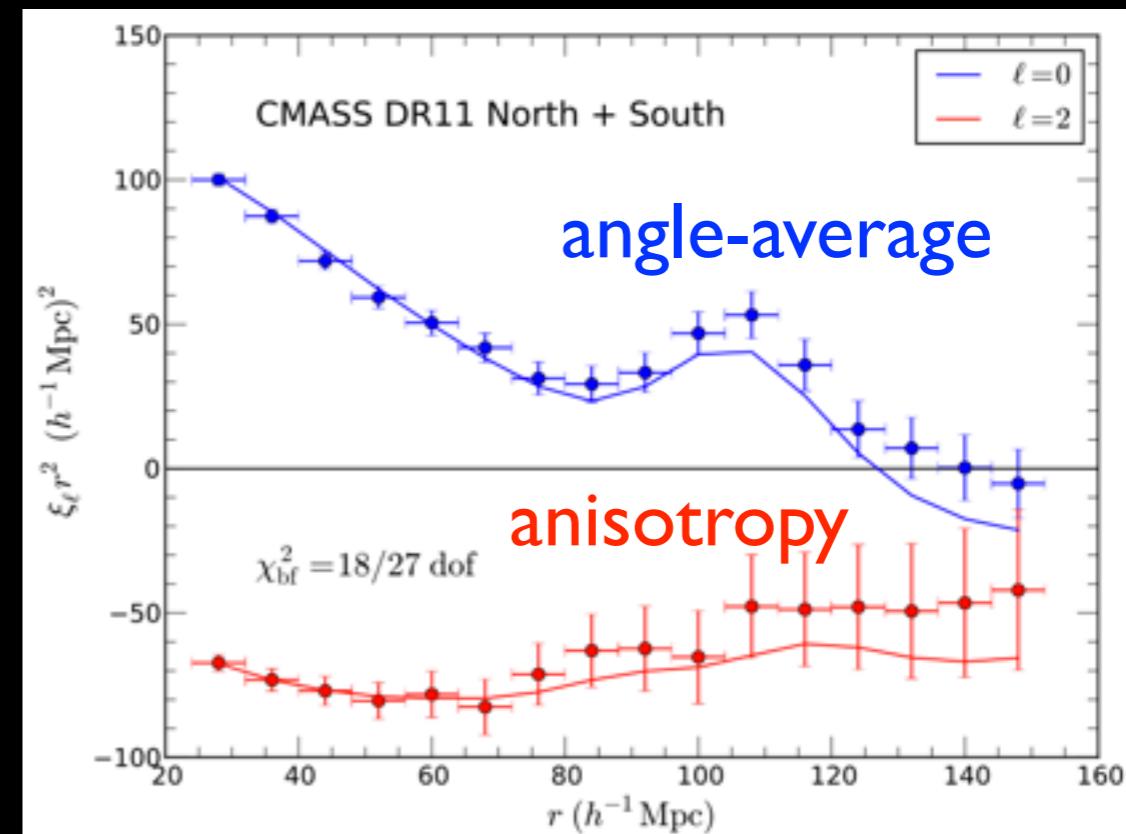


$$\xi(s, \mu_s) = \sum_{\ell} \xi_{\ell}(s) L_{\ell}(\mu_s)$$

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



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

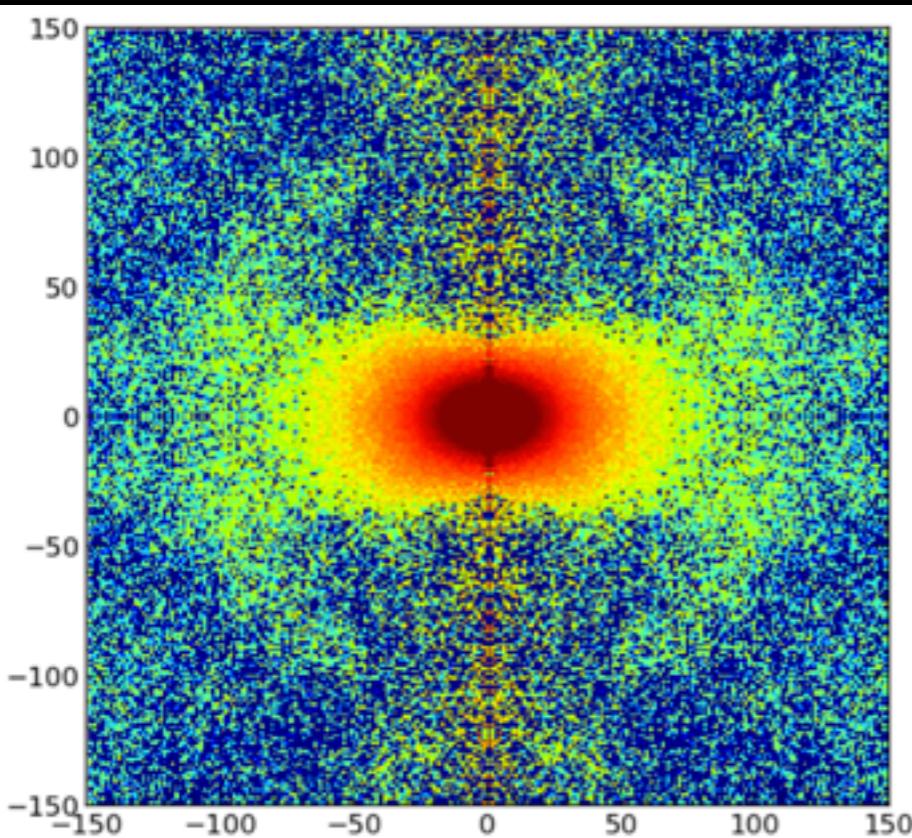


$s (h^{-1} \text{ Mpc})$

BOSS DR11, Samushia, BR, et al. 2013

# “Full shape” fits to quasi-linear $\xi$

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



Must model:

- Non-linear biasing
- Non-linear velocities
- Uncertain galaxy  $\leftrightarrow$  dark matter mapping

Potentially more susceptible to observational systematics than BAO, though no evidence in current surveys

BOSS DR11, Samushia, BR, et al. 2013

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

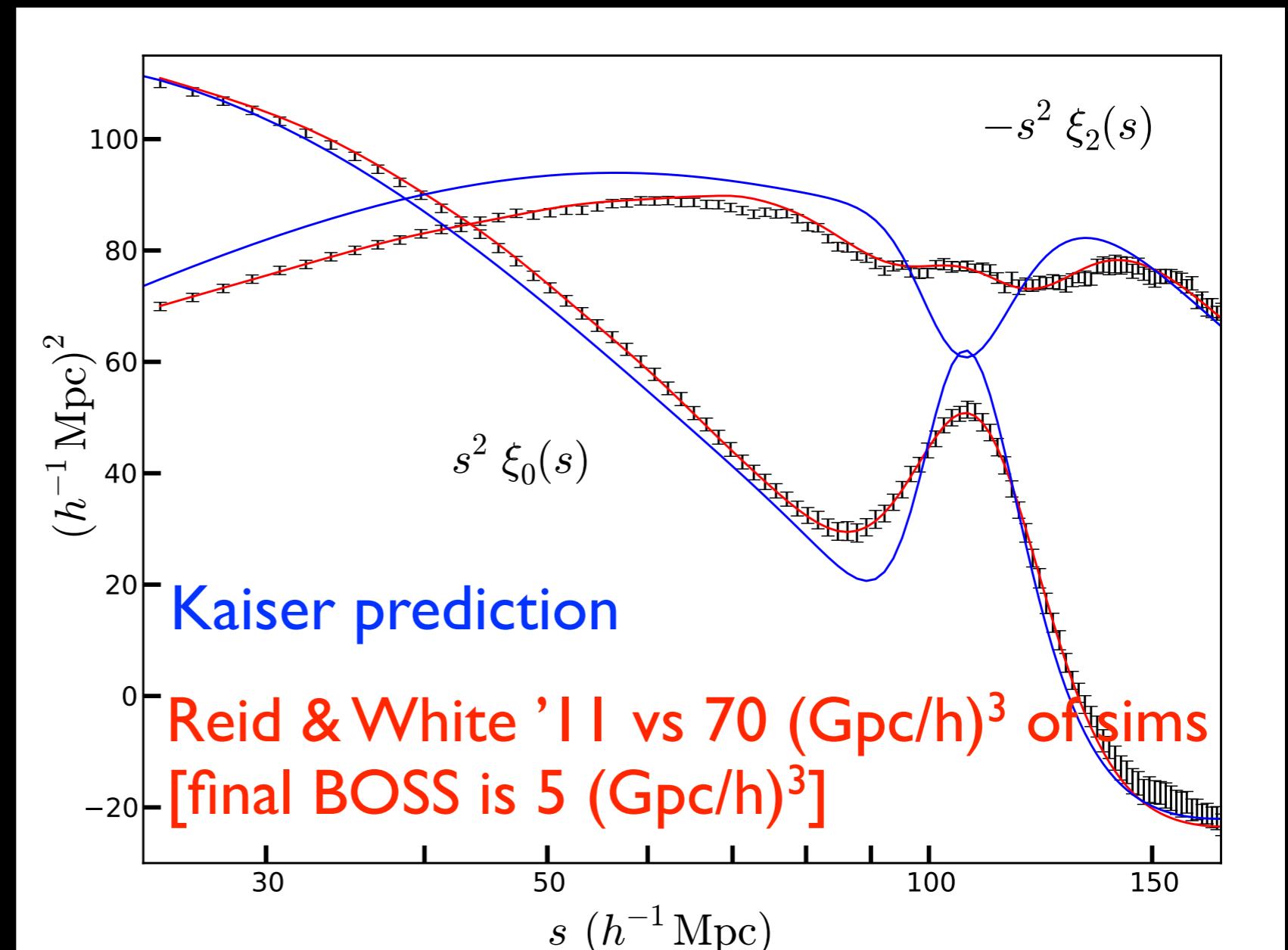
- $b\sigma_8, f\sigma_8$  determine amplitude of  $\xi_{0,2}$

$\sigma_8$ : amplitude of matter fluctuations

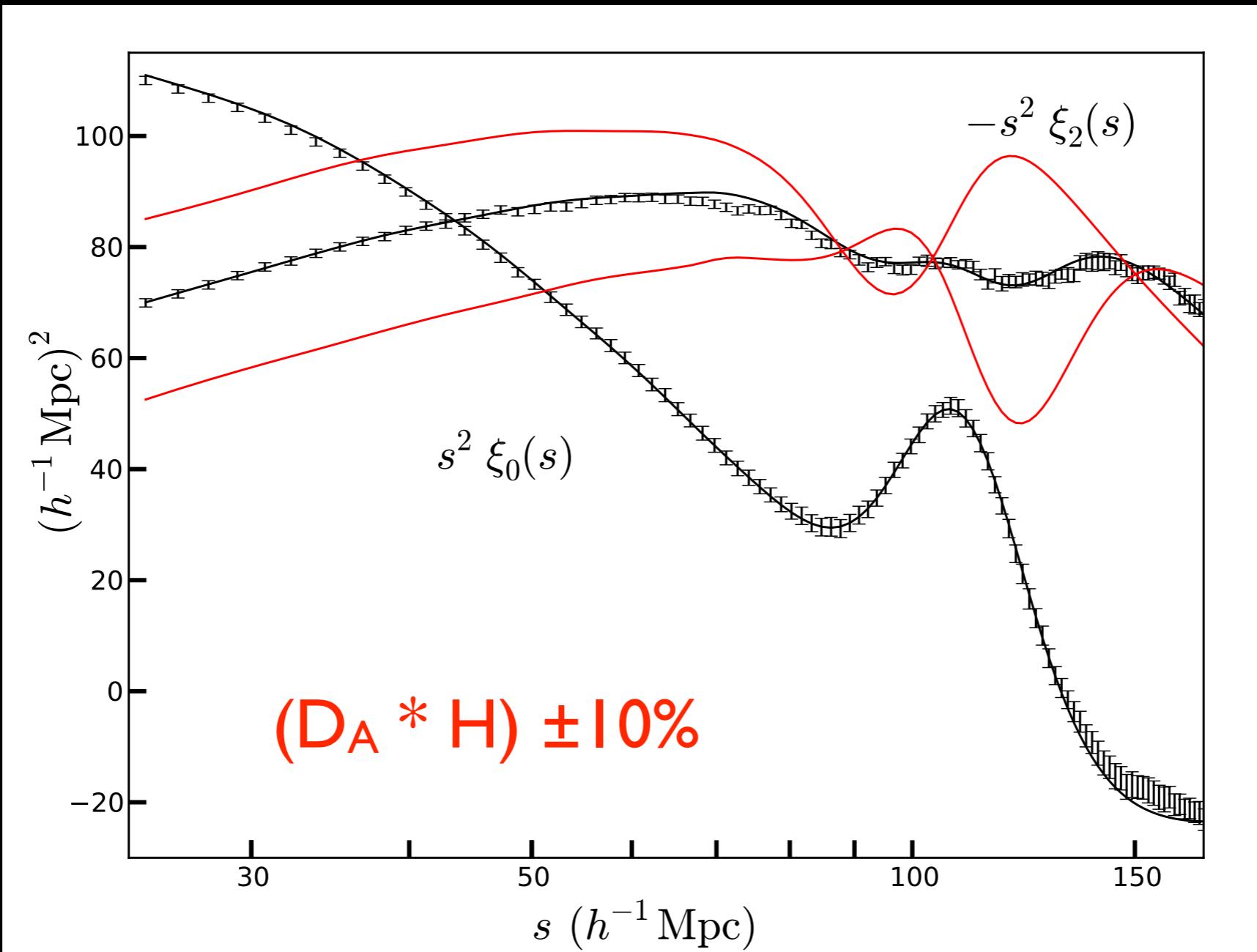
$b$ : unknown conversion factor between galaxy and matter fluctuations

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

$\sigma^2_{\text{FOG}}$ : “finger-of-god” nuisance parameter

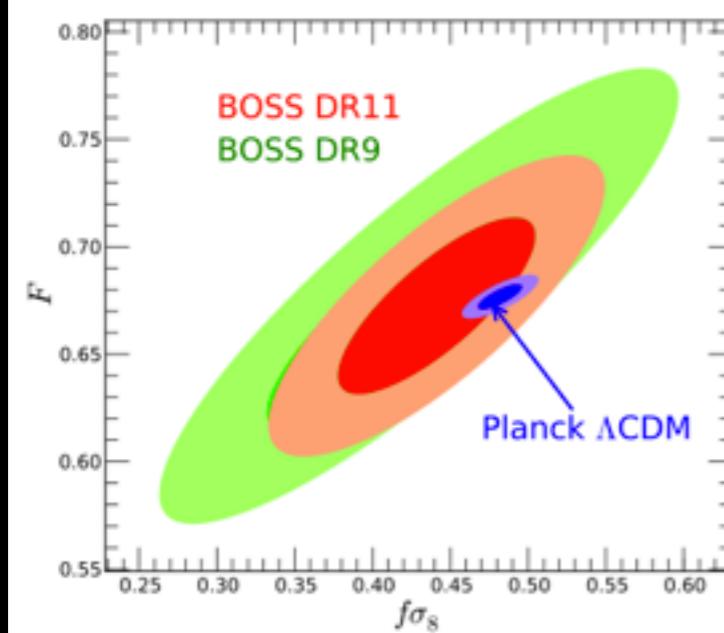


# Alcock-Paczynski has different scale-dependence, distinguishable from RSD

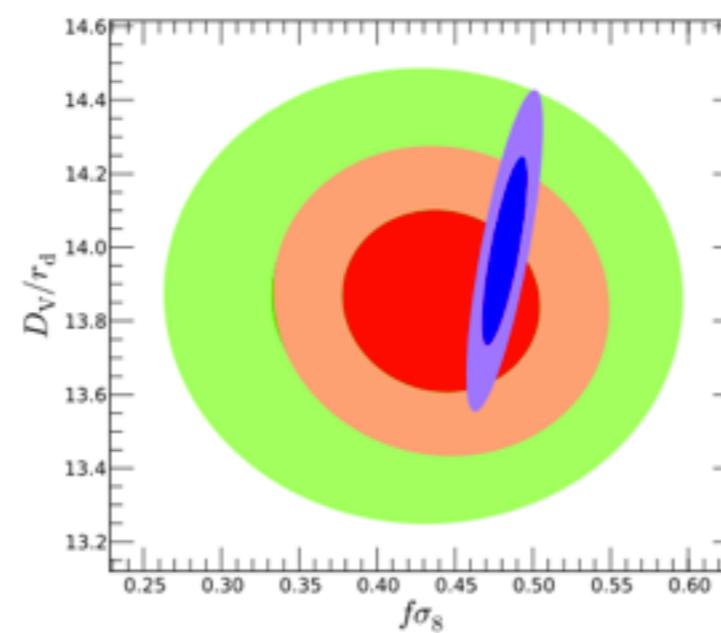


# Joint Fits to $D_A(z_{\text{eff}})$ , $H(z_{\text{eff}})$ , $f\sigma_8$ [no reconstruction]

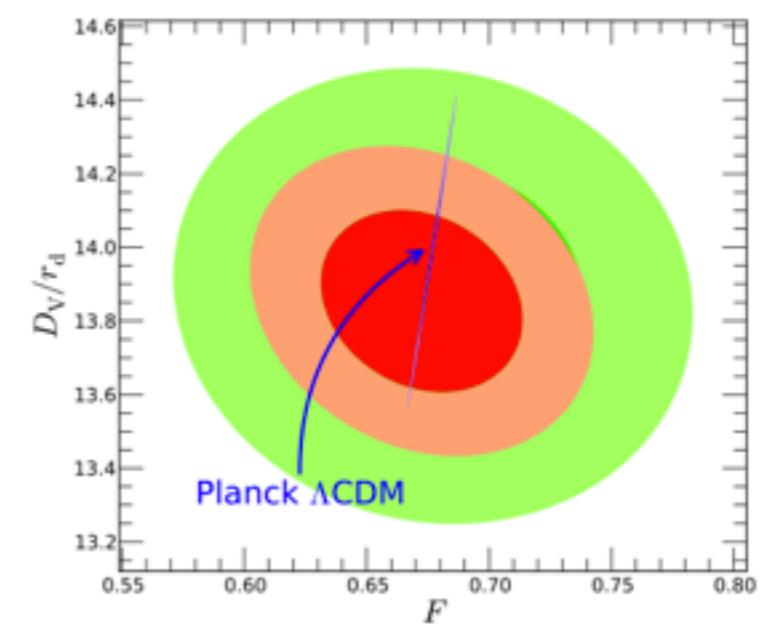
$D_A^*H$



$f\sigma_8$



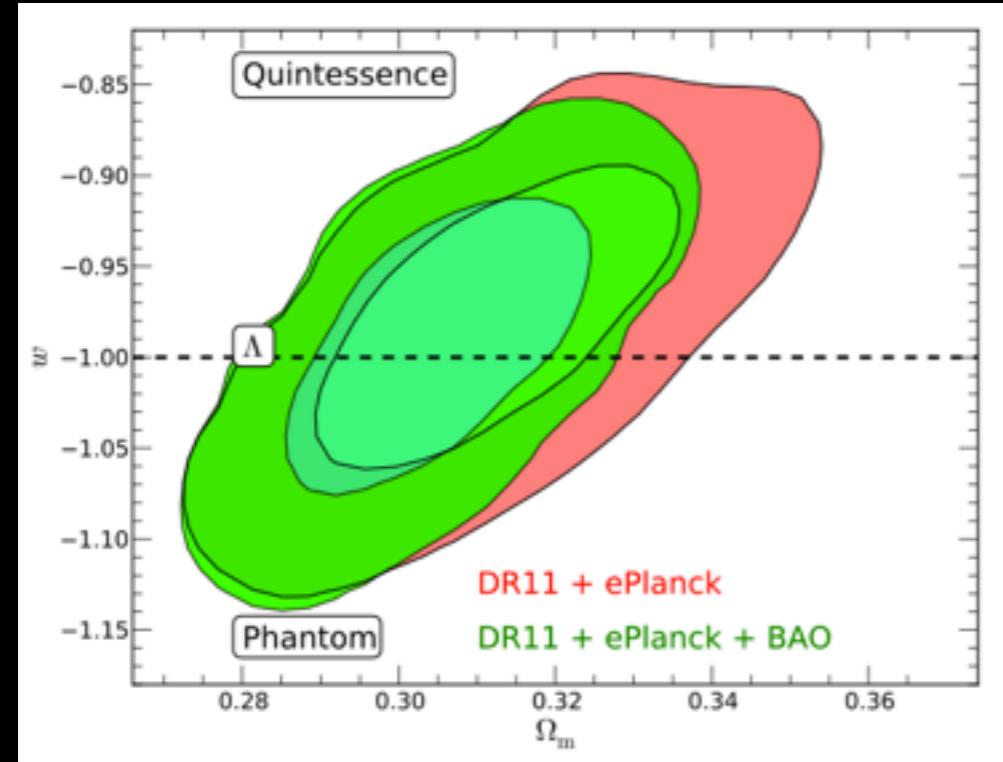
$f\sigma_8$



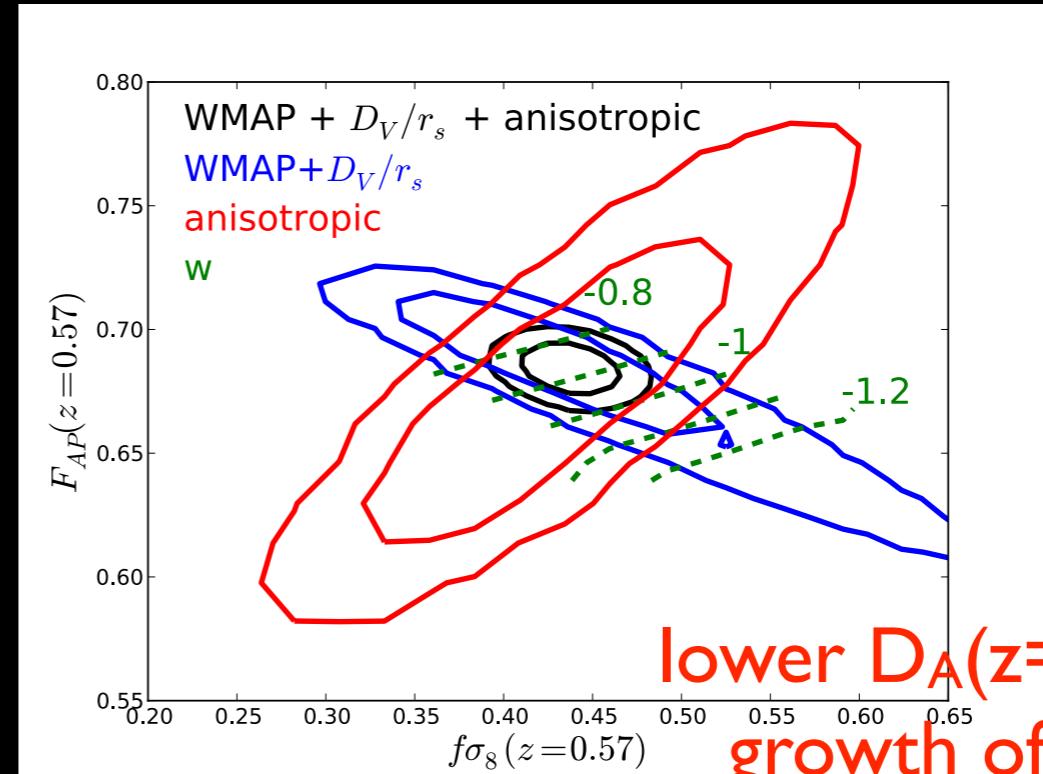
$D_A^*H$

Samushia, BR, et al., 2013

# Full Shape Cosmological Implications: Quadrupole amplitude constrains $w$


 $\Omega_m$ 

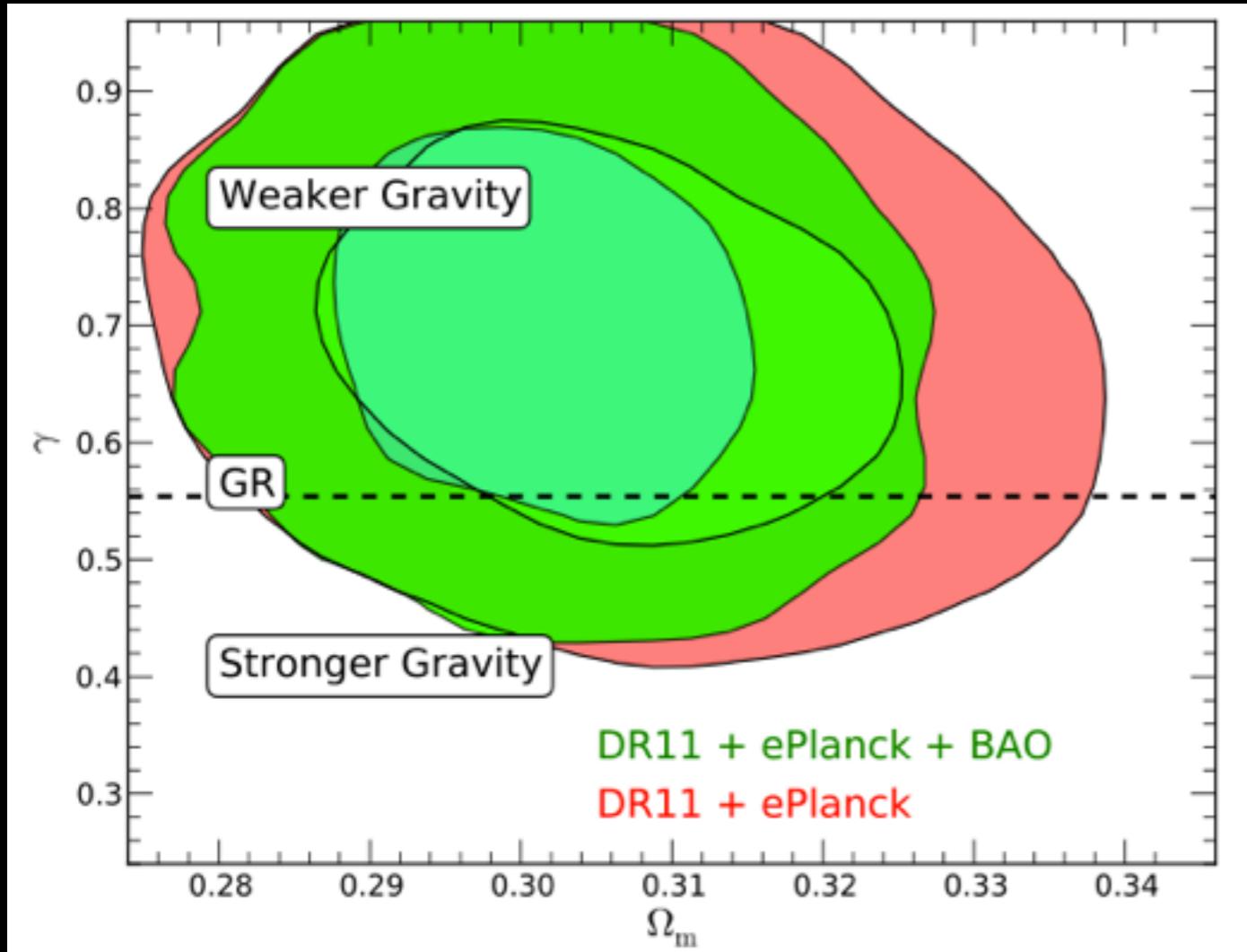
- $w = 0.983 \pm 0.075$   
Samushia, BR, et al. 2013
- $w = -1.03 \pm 0.10$   
(Planck + CMASS BAO)


 $f\sigma_8$ 

Samushia, BR, et al., 2013/2012

 $D_A^* H$

# Full Shape Cosmological Implications



Modified Gravity test

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

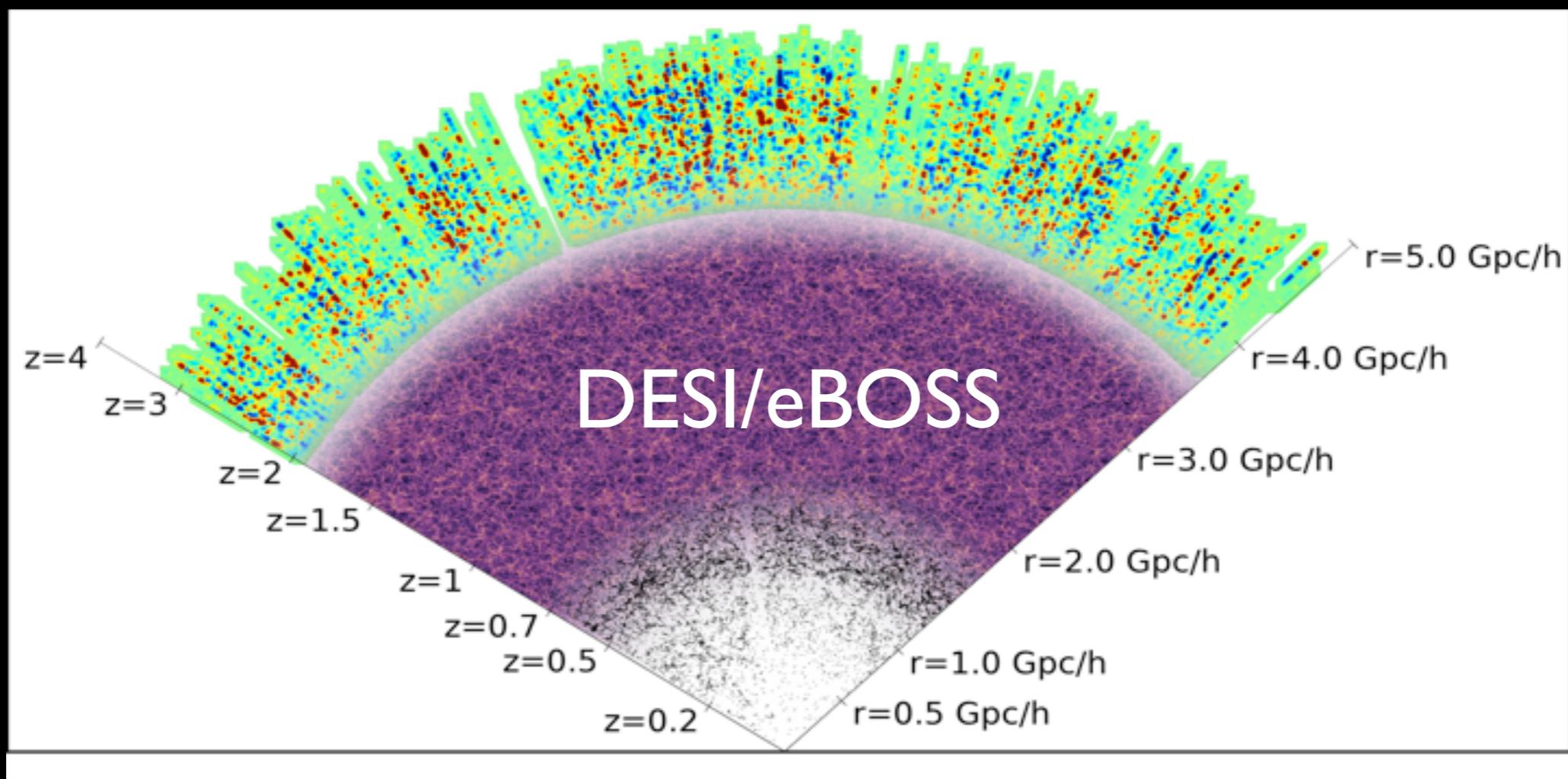
$$(\gamma = 0.55 \text{ in GR})$$

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[\*biased selection\*]

# Future Prospects

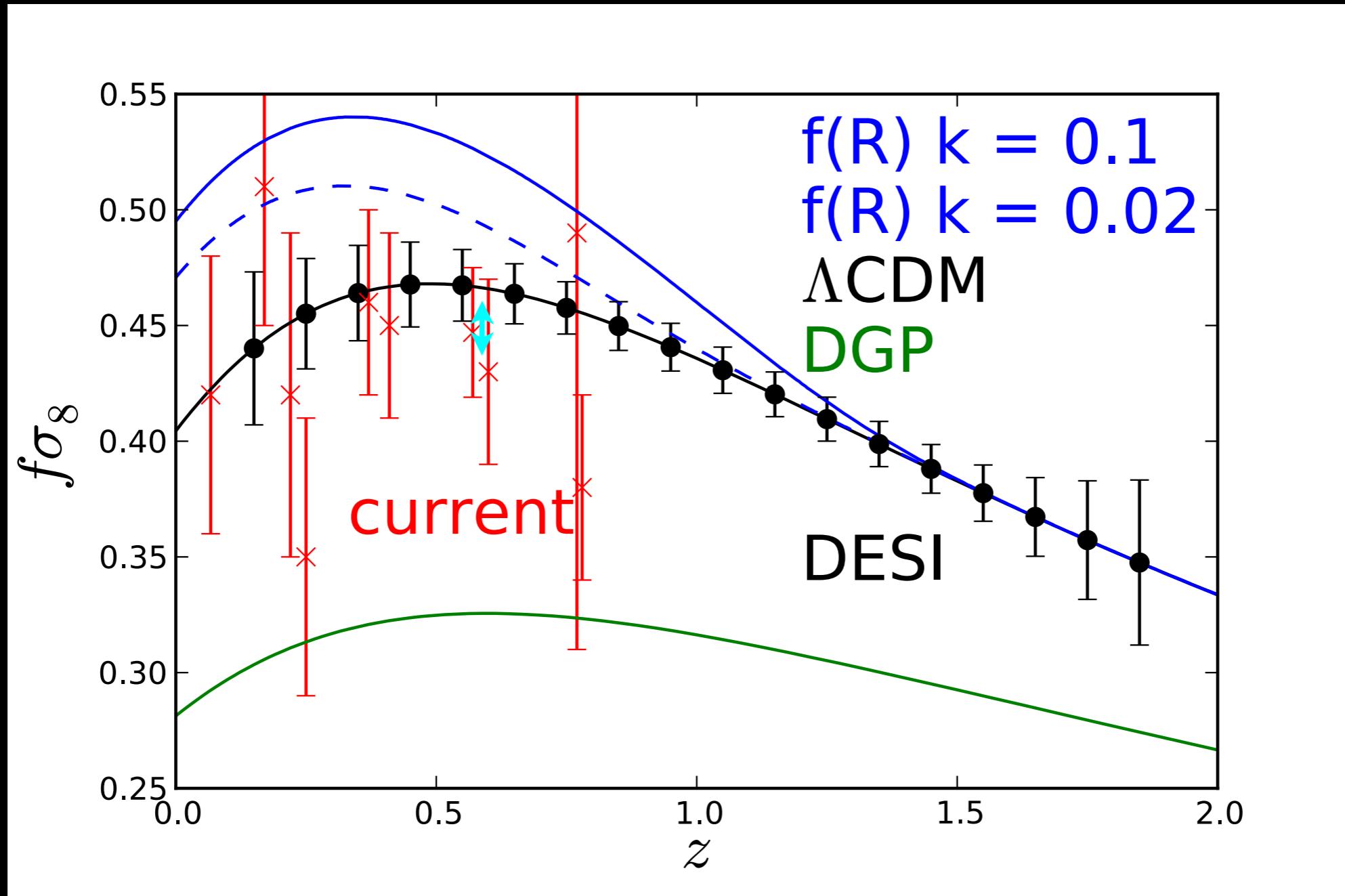
- BOSS projected two 1% distances; DESI will make 35 1% BAO distance measurements



<http://www.sdss3.org/future/eboss.php>

<http://desi.lbl.gov/>

# RSD measurements: current and future (DESI)



\* new this week! Reid et al., arXiv:1404.3742

# DESI example: DE/neutrino mass degeneracy

- Adding broadband to BAO info: ~4x increase in Planck + DESI dark energy constraining power (marginalizing over  $\Sigma m_\nu$  and  $\Omega_k$ ).
- $1\sigma$  constraint on  $\Sigma m_\nu$  0.57 eV  $\rightarrow$  0.058 eV (marginalizing over  $w_0, w_a, \Omega_k$ )
- $1\sigma$  constraint on  $\Sigma m_\nu$  0.09 eV  $\rightarrow$  0.024 eV (assuming flat  $\Lambda$ CDM)

Font-Ribera et al., arXiv:1308.4164

# Conclusions

- Lots of data/methodological progress on BAO in 9 years!
- BAO surveys also give you  $P_{\text{matter}}(k)$ , RSD -- use them! But this will be more challenging for next generation of surveys
- Cosmology surveys in the next decade will detect  $\sum m_v$ ; must be marginalized over for DE constraints.

Thanks to the organizers for a wonderful conference!!