2D galaxy clustering in SDSS-III BOSS: growth of structure, geometry, and small scale galaxy motions at z=0.57

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BOSS DR9 CMASS papers

- Ross++: Systematics arXiv:1203.6499
- Manera++: Mock catalogs arXiv:1203.6609
- Anderson++: BAO arXiv:1203.6594
- Sanchez++: fits to monopole $\xi(s)$ arXiv:1203.6616
- Reid++: fits to anisotropic clustering arXiv:1203.6641
- Tojeiro: RSD with passive galaxies arXiv:1203.6565
- Samushia, Reid++: ΛCDM, GR tests arXiv:1206.5309

Outline

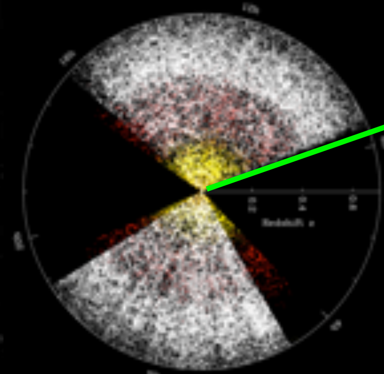
- Hitchhiker's guide to galaxy redshift surveys
- Galaxy clustering in 2d: $\xi(r_\sigma, r_\pi)$
  - Information in the spherical avg: $\xi_0(s)$
  - Information from anisotropy: $\xi_2(s)$
- Cosmological Implications
- Brief note on DR10 work in progress...

The universe in perspective

Large scale structure
initial conditions

comoving angular diameter
distance:
$(1+z)D_A(z) = {}_0\int^z c\, dz'/H(z')$

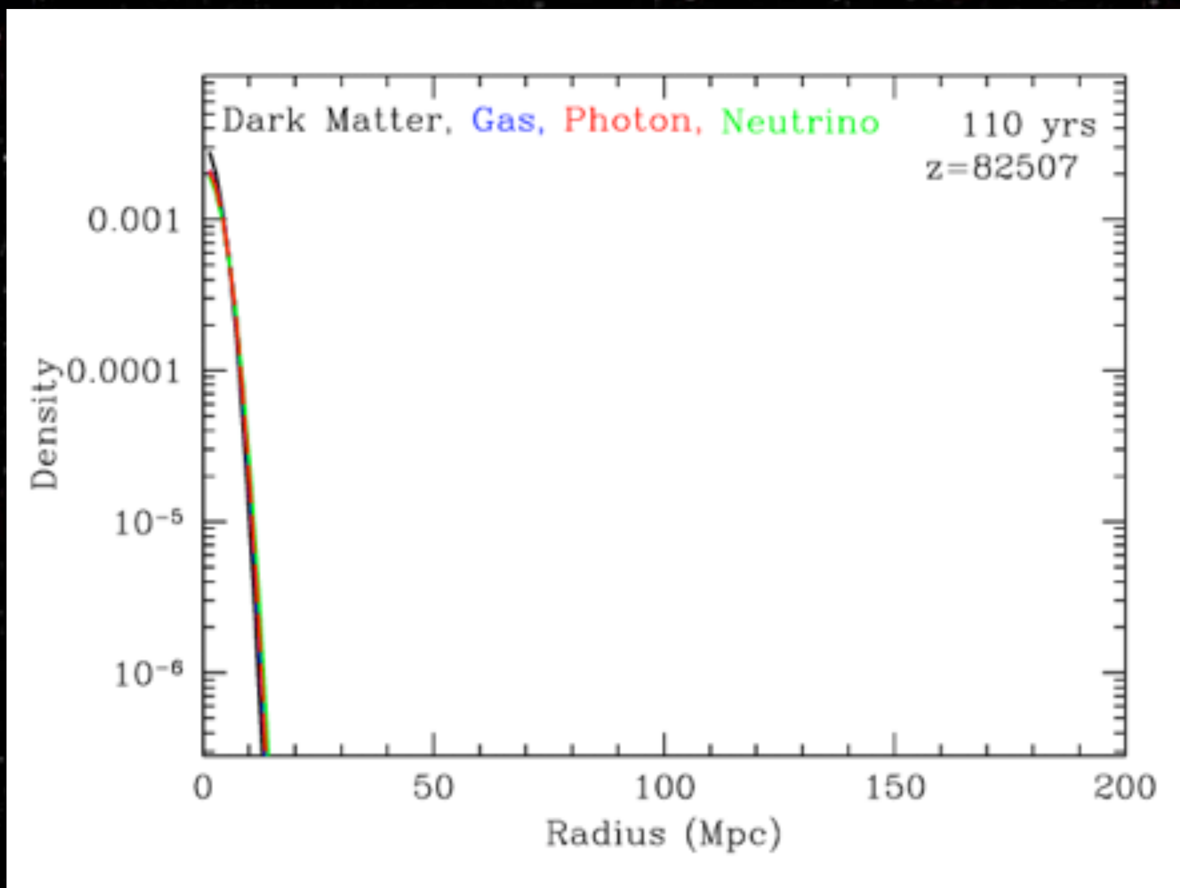
CMB
z=1091

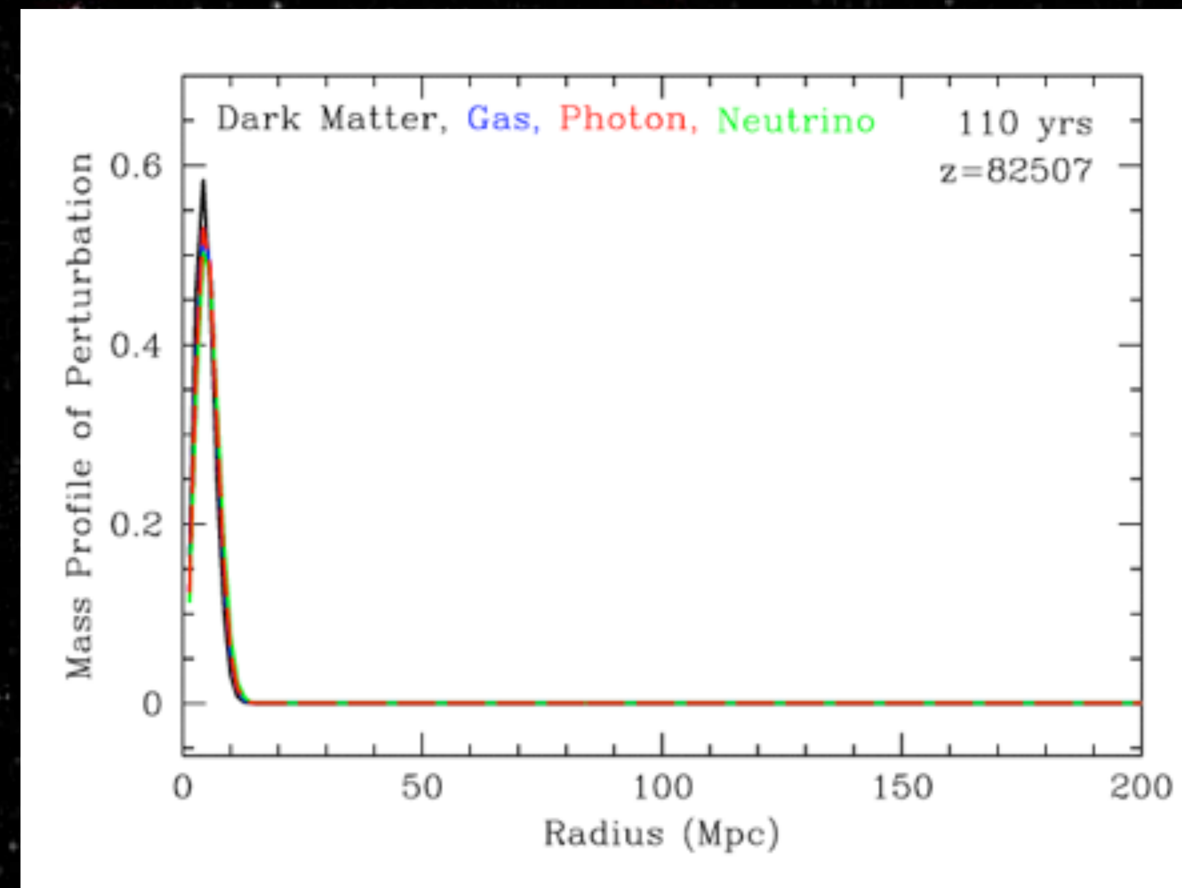


z=0.7

- Sound horizon scale =
  BAO standard ruler

Physics of the Baryon Acoustic Oscillations: Evolution of a point-like adiabatic perturbation





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

r_s = 153.2 ± 1.7 Mpc (WMAP7)

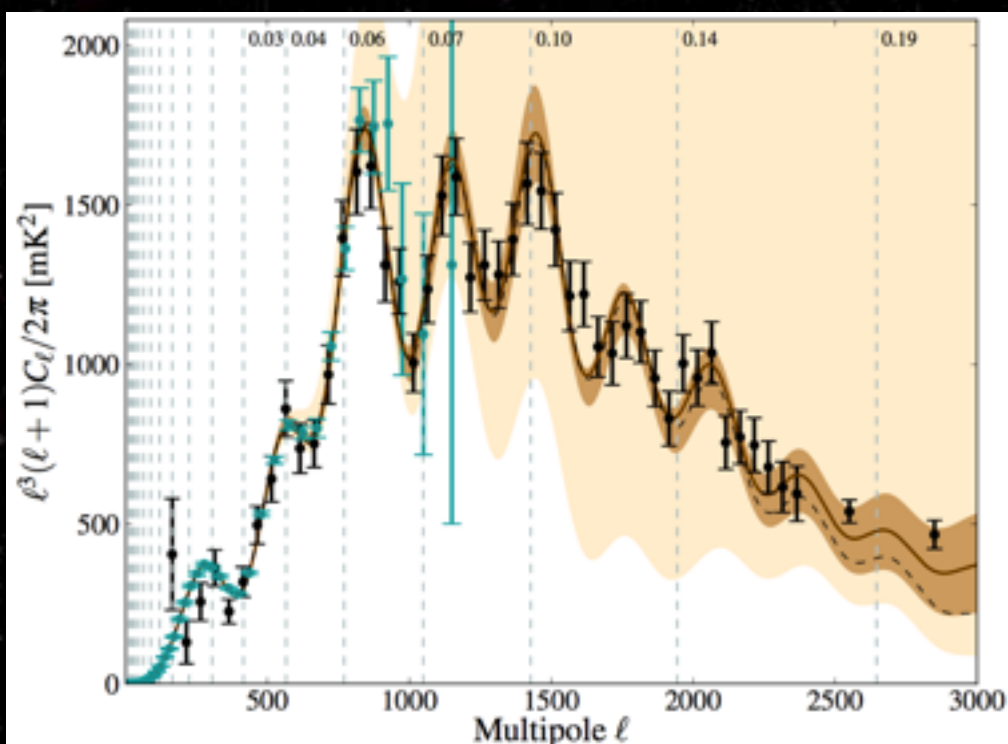
± 0.36 Mpc (Planck)

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

CMB precisely predicts full P(k), not just BAO feature

photon-baryon fluid

dark matter dominated



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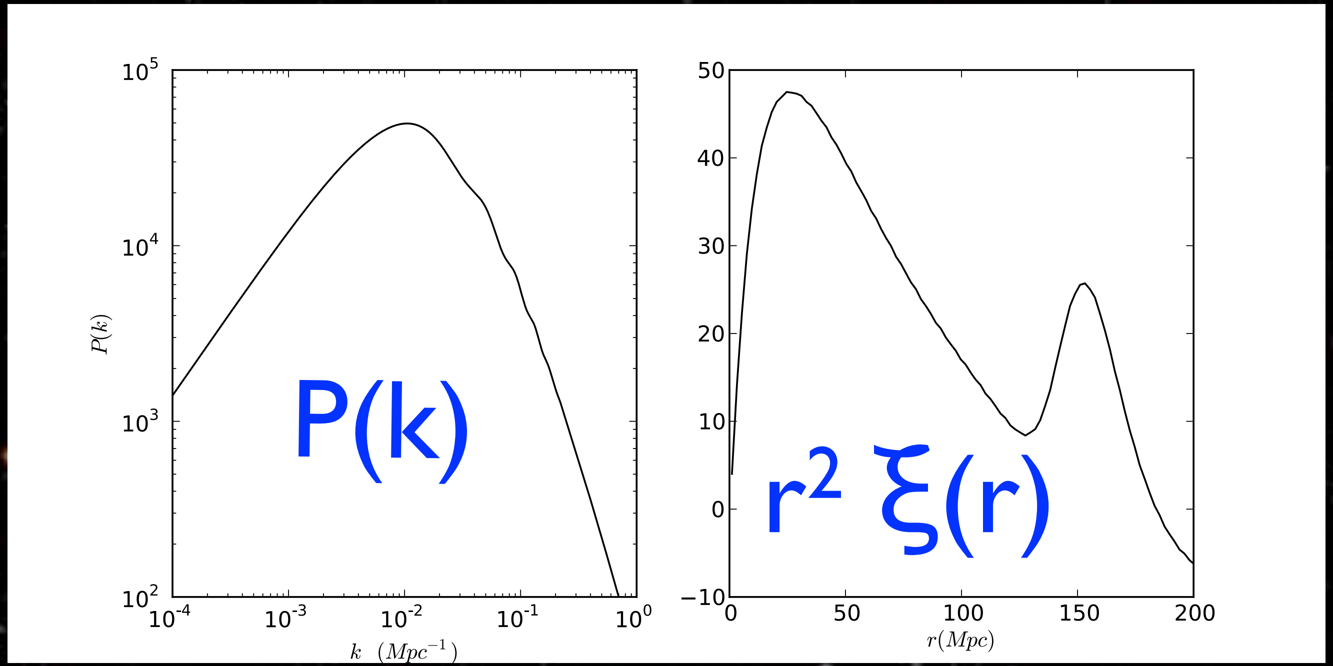


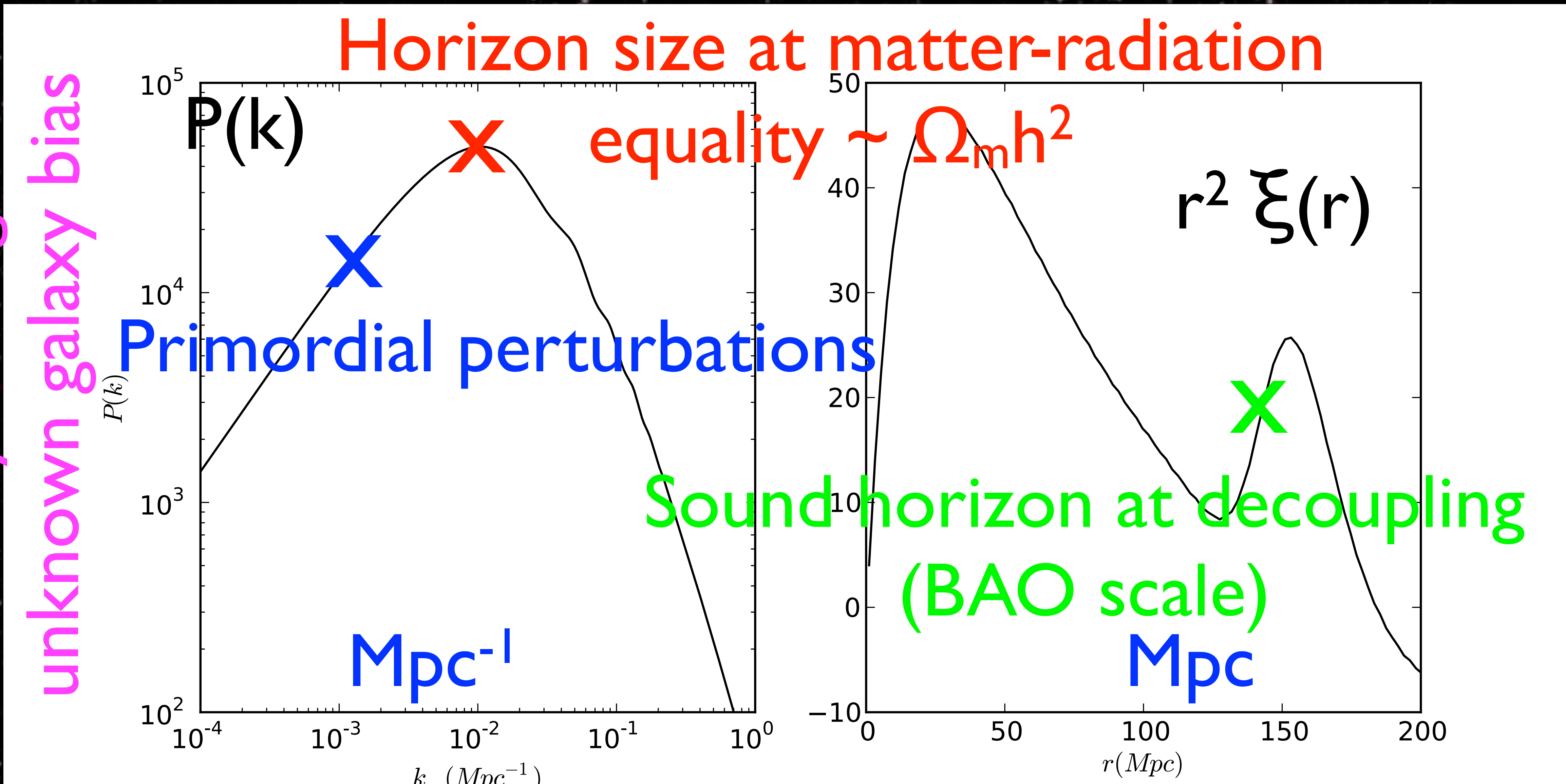
Hlozek et al., 2012 ApJ, 749, 90

Mpc^{-1} Mpc

CMB provides template P(k) / ξ(r)

- depends on $\Omega_m h^2$, $\Omega_b h^2$, n_s, NOT $D_A(z_{CMB})$

Arbitrary scaling from unknown galaxy bias



CMB provides template P(k) / ξ(r)

- depends on $\Omega_m h^2$, $\Omega_b h^2$, n_s [marginalized over]
- Advantage: final anisotropic fits are simple 3x3 Gaussian likelihood
- Disadvantage: we require further cosmological model assumptions -- no running, $N_{eff} = 3.04$, $\sum m_\nu$ negligible...

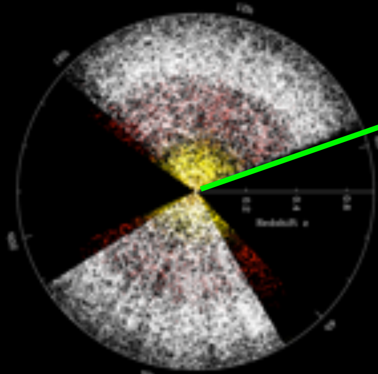
The universe in perspective

Large scale structure initial conditions

comoving angular diameter distance:

$$(1+z)D_A(z) = {}_0\int^z c\, dz'/H(z')$$

CMB
z=1091

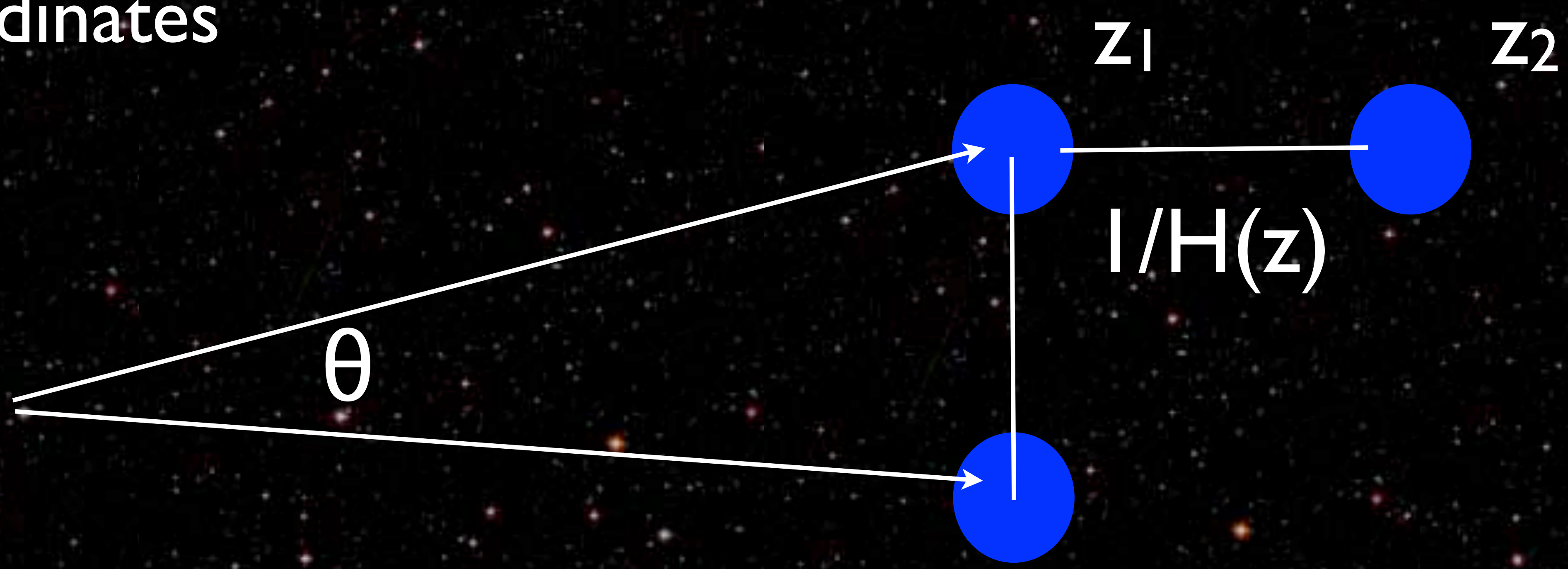


z=0.7

- Sound horizon scale = BAO standard ruler

Geometric constraints from galaxy surveys

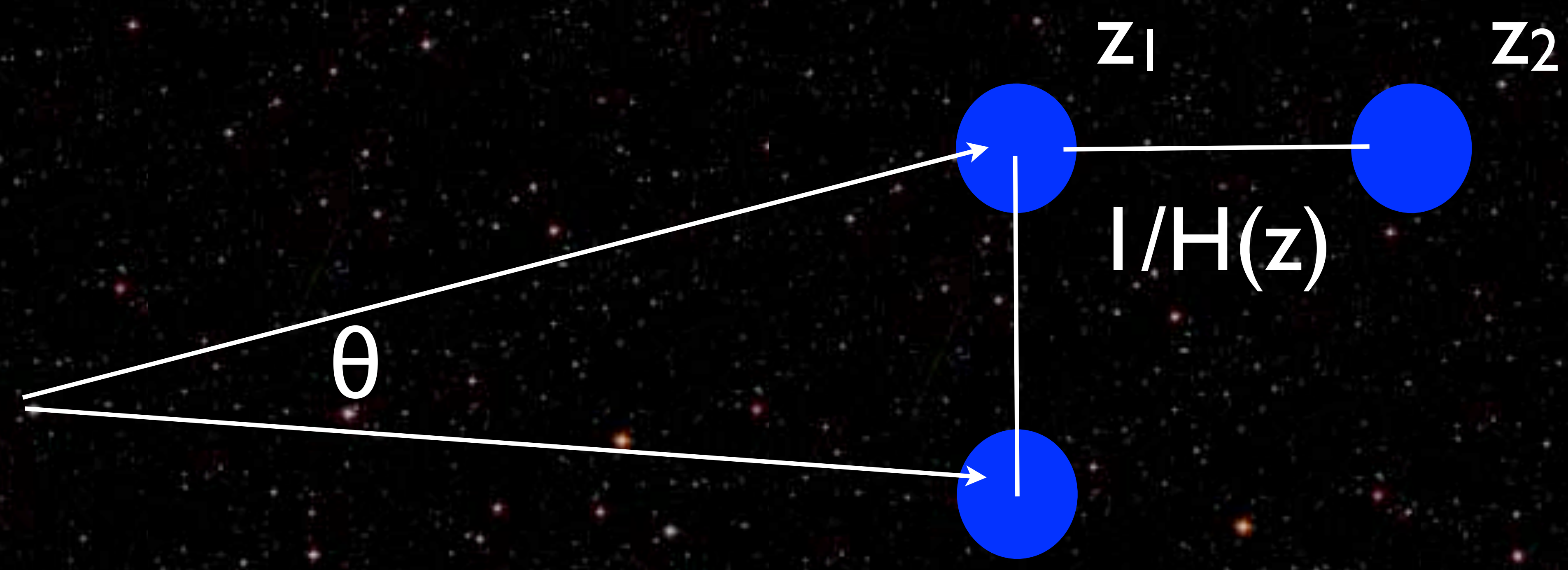
- We measure θ, φ, and z for each galaxy, and use a cosmological model to convert to comoving coordinates



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

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 ≡ $(1+z)\ D_A(z)$

What contributes to H(z)?

$$H^2(a) = H_0^2 \;\; X$$

$$[\Omega_r a^{-4} + \Omega_m a^{-3} + \Omega_k a^{-2} + \Omega_{DE} \exp\{3 \int_a^1 da' \,[1+w(a')]/a'\} + ..]$$

photons
relativistic species

Dark Energy

baryons
dark matter
neutrinos today (T = 2 K!)

One more wonderful complication -- line of sight is special!

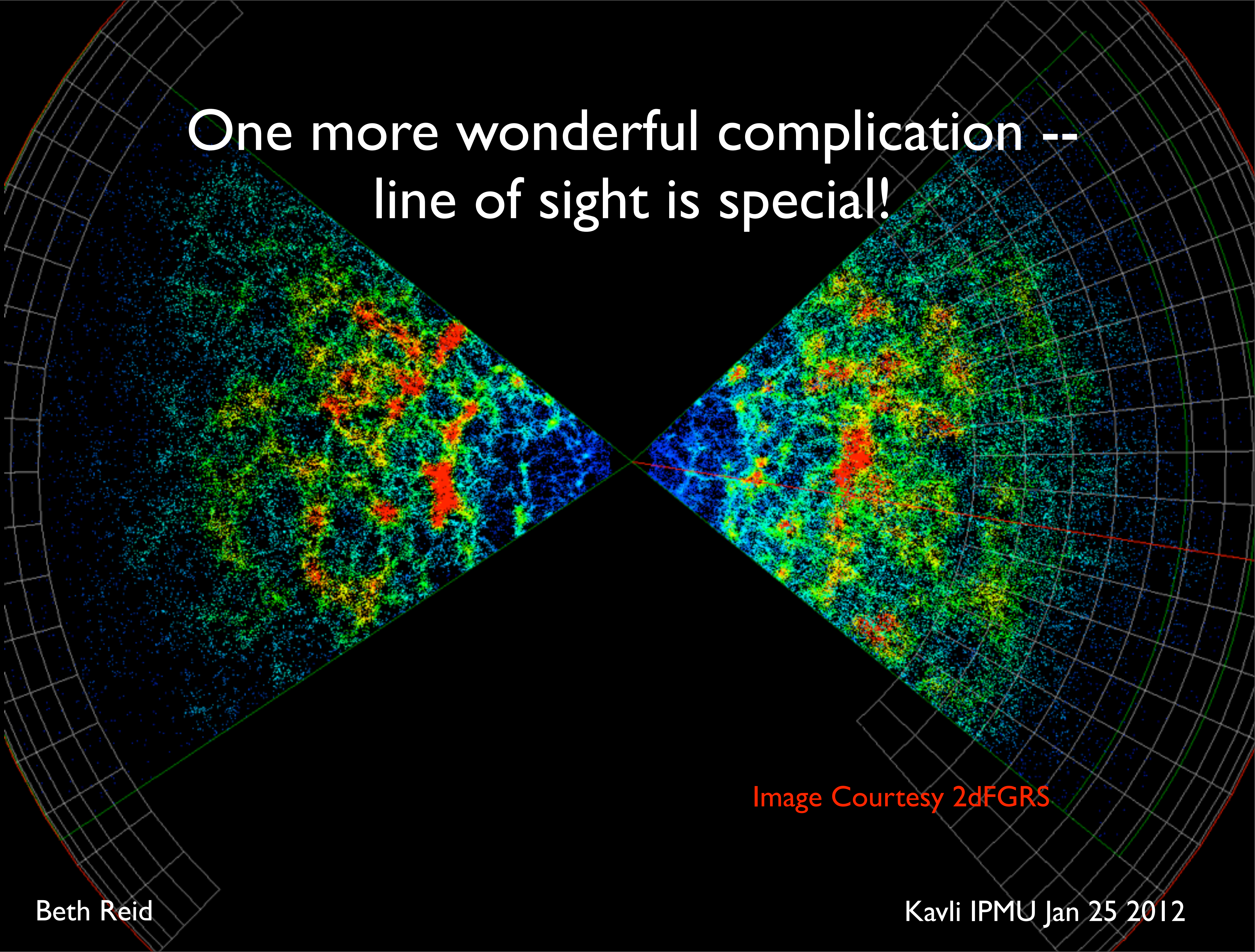
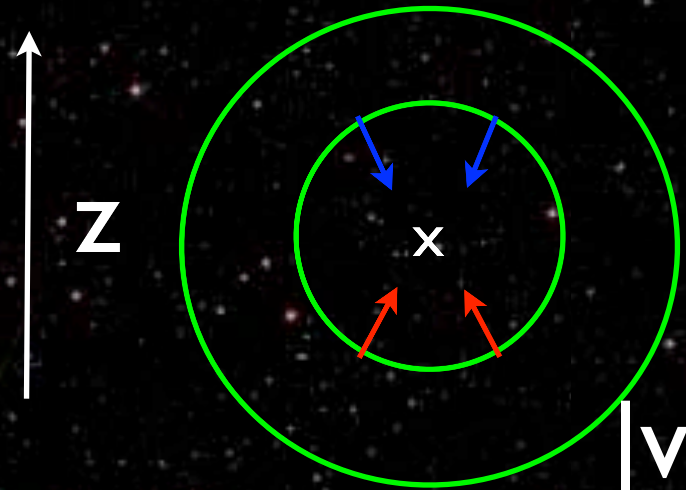


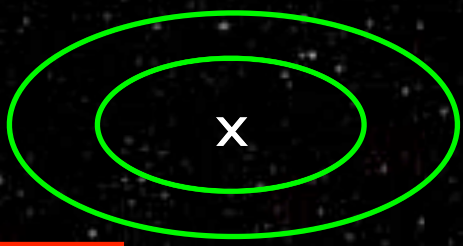
Image Courtesy 2dFGRS

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

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

Dark Energy or modified gravity?

- Our strongest evidence for DE is from geometric measures: SNIa, BAO, H_0 + distance to CMB, AP, ... [probes *homogeneous* universe]
- We can distinguish modified gravity from exotic fluid in GR as the reason for cosmic acceleration by the growth of *inhomogeneities*

growth in GR: $$\frac{d^2G}{d\ln a^2} + \left(2 + \frac{d\ln H}{d\ln a}\right)\frac{dG}{d\ln a} = \frac{3}{2}\Omega_m(a)G$$

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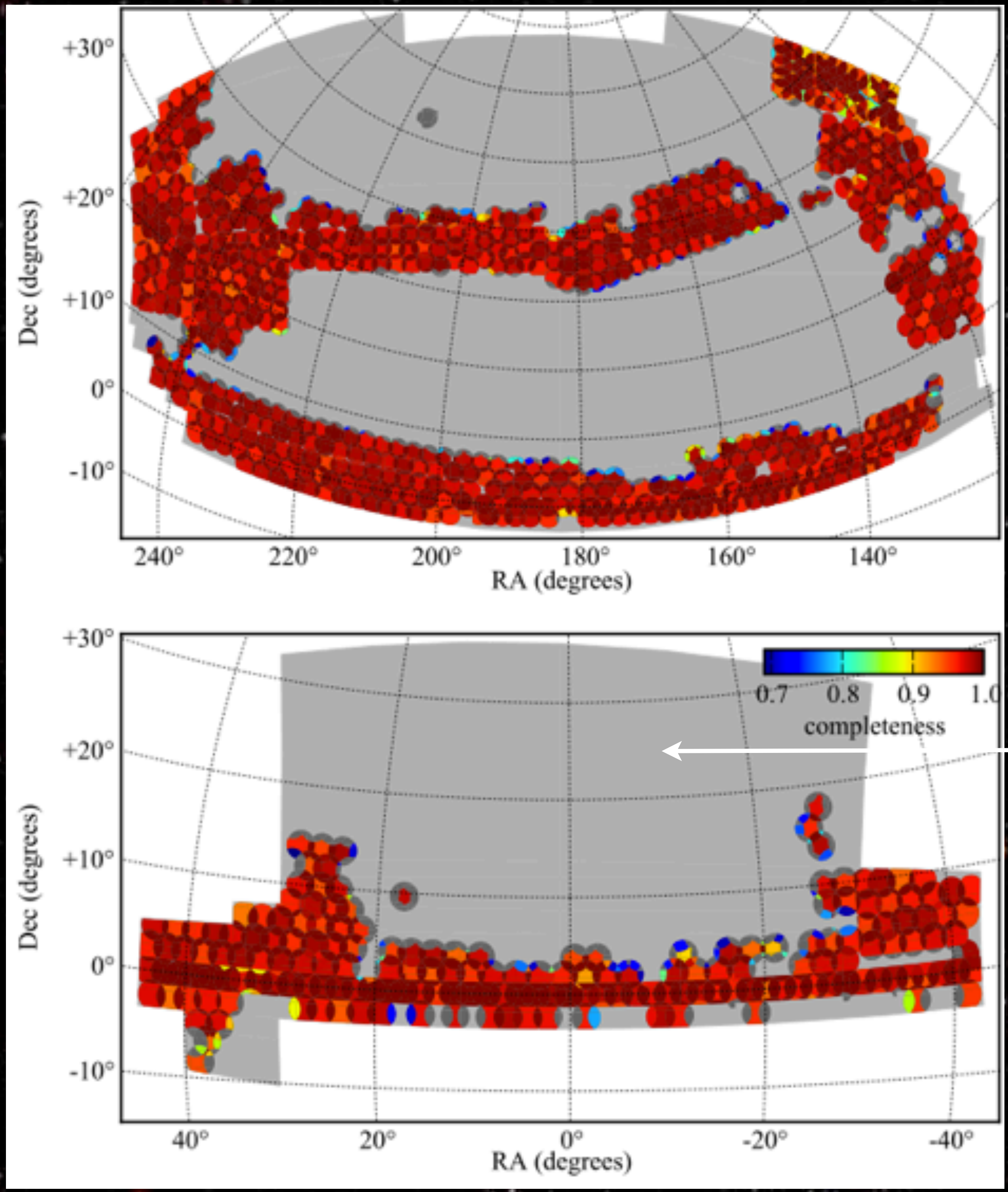
Sky Coverage of DR9: 3275 deg^2

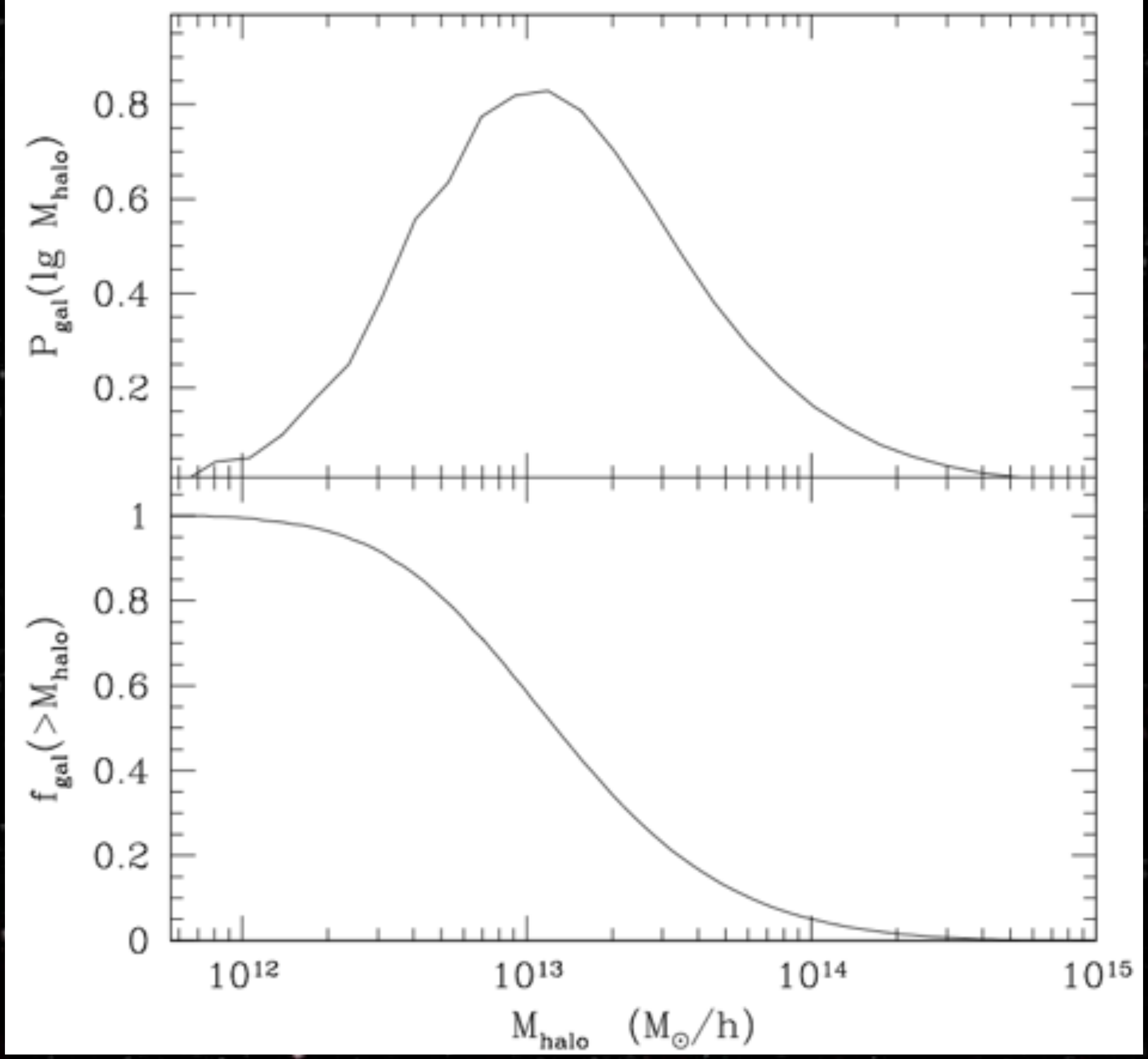


(DR10: twice the area of DR9)

New BOSS Imaging

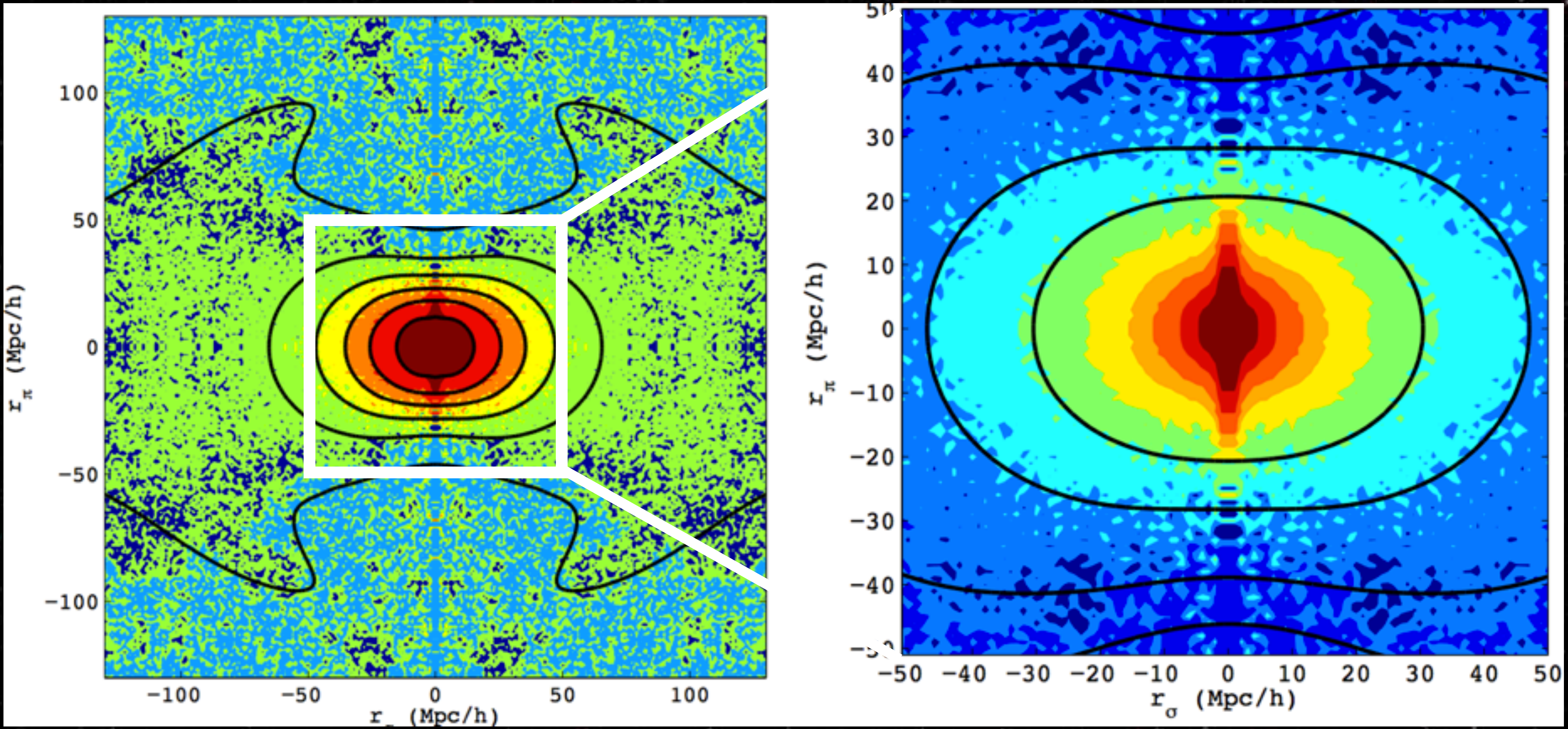
The BOSS CMASS sample

- target selection color cuts designed for "constant stellar mass" sample
- b ≈ 2, ≈10% satellite fraction
- DR9 V_{eff} = 2.2 Gpc^3
- $0.43 < z < 0.7$; $z_{eff} = 0.57$

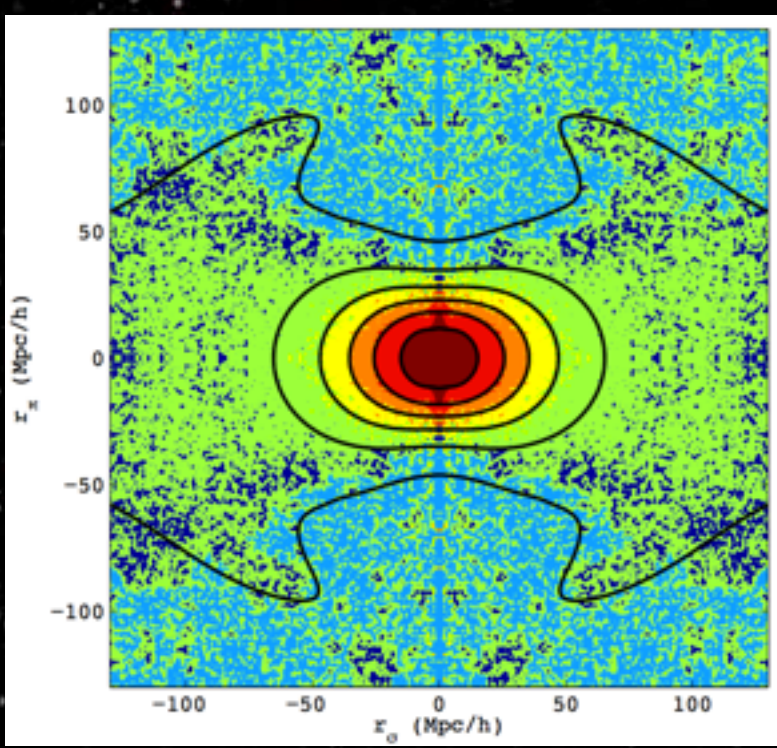


White et al., 2011, arXiv:1010.4915

Our Mission: Extract as much information as possible from $\xi(r_\sigma, r_\pi)$



Legendre Polynomial moments: $\xi_\ell(s)$

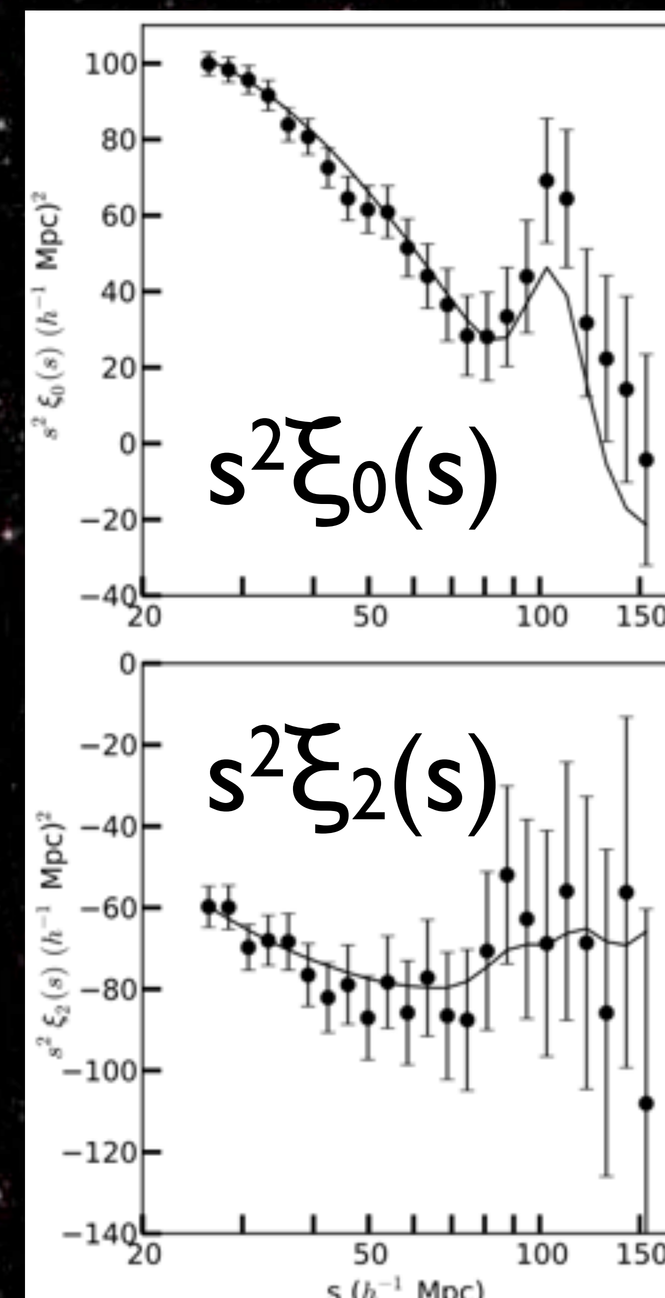


$$\xi(s,\mu_s) = \sum_\ell \xi_\ell(s) L_\ell(\mu_s)$$

$L_0 = 1$

$L_2 = (3\mu^2 - 1)/2$

$\mu = r_\pi/(r_\pi^2 + r_\sigma^2)^{1/2}$

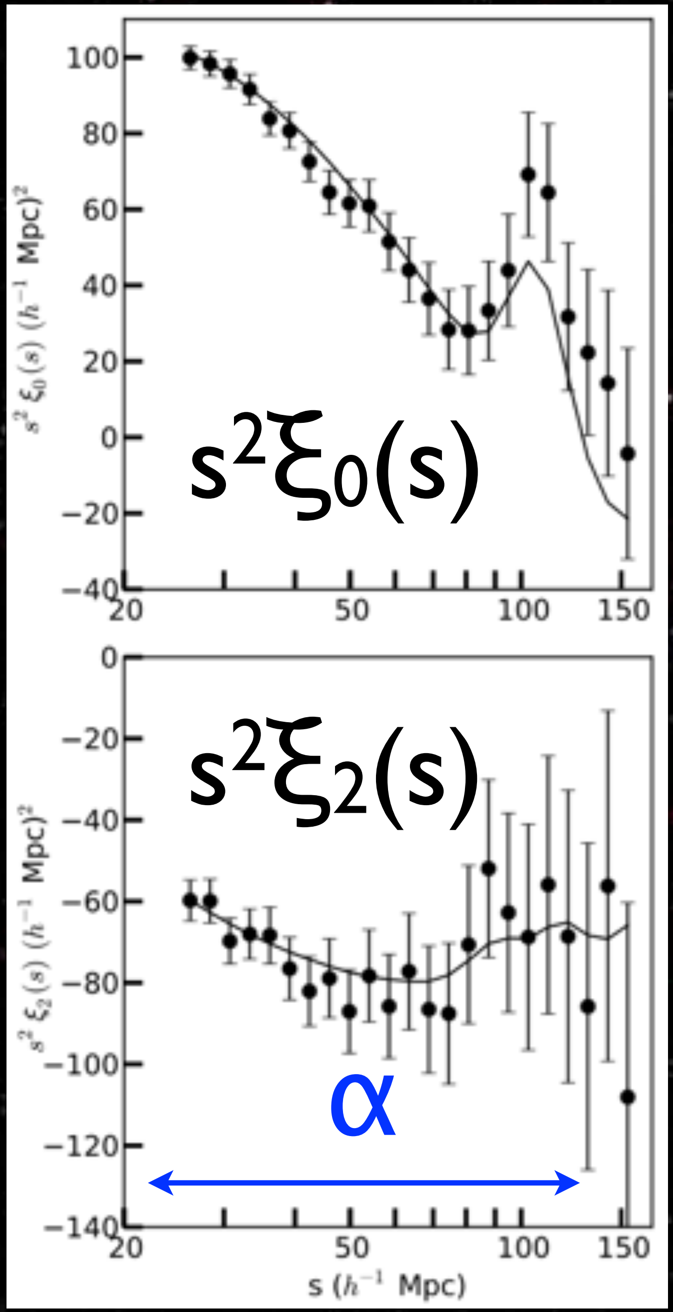


Fitting $\xi_\ell(s)$

- With strong CMB shape prior, we're just fitting two amplitudes [$\xi_{0,2}(s)$] and a rescaling of the s axis:

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

$$D_V/r_s = \alpha\,(D_V/r_s)_{\rm fid}$$



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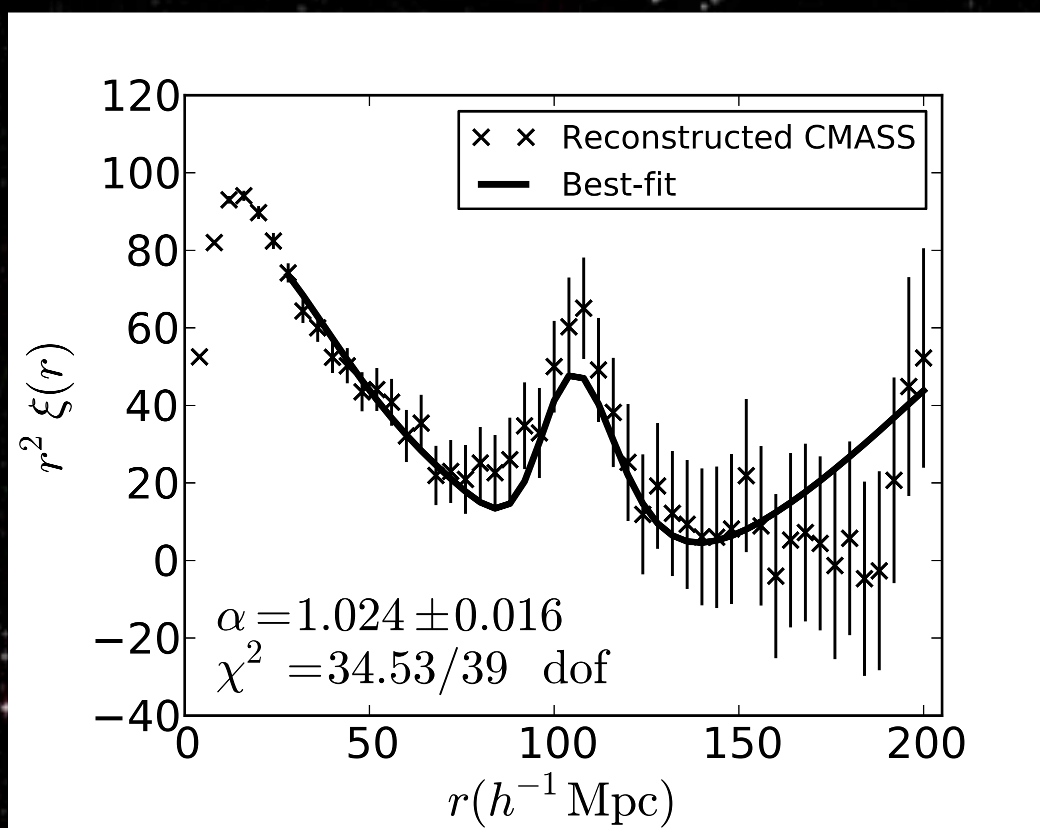
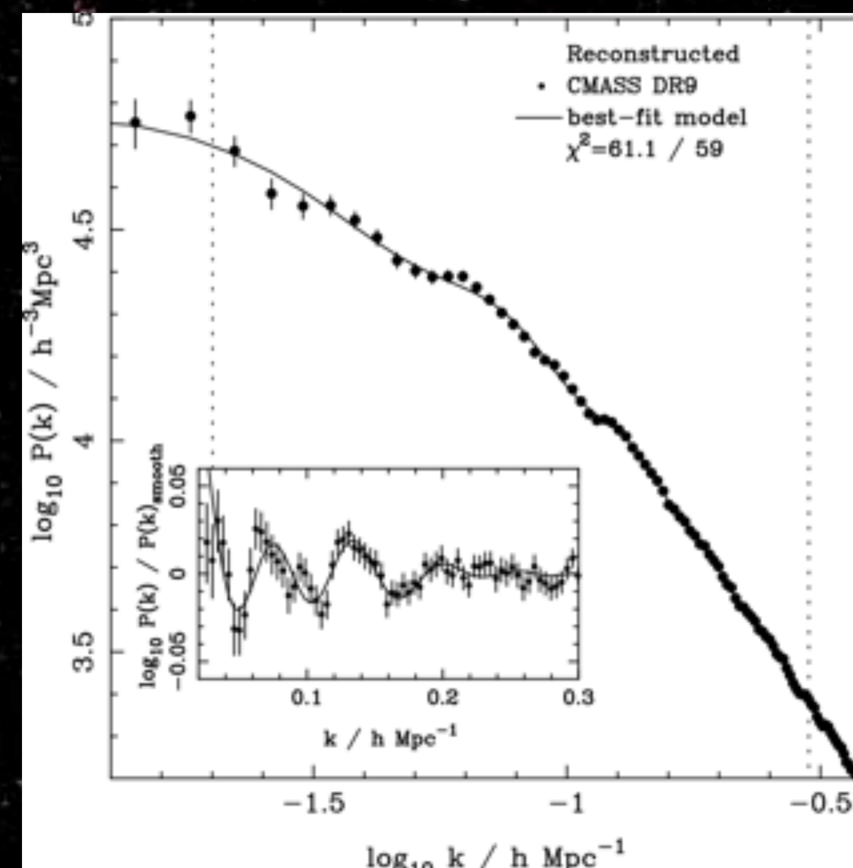
Anderson et al. recap: fits to α for "reconstructed" ξ(s) and P(k)





Reid et al.: $\alpha = 1.023 \pm 0.019$

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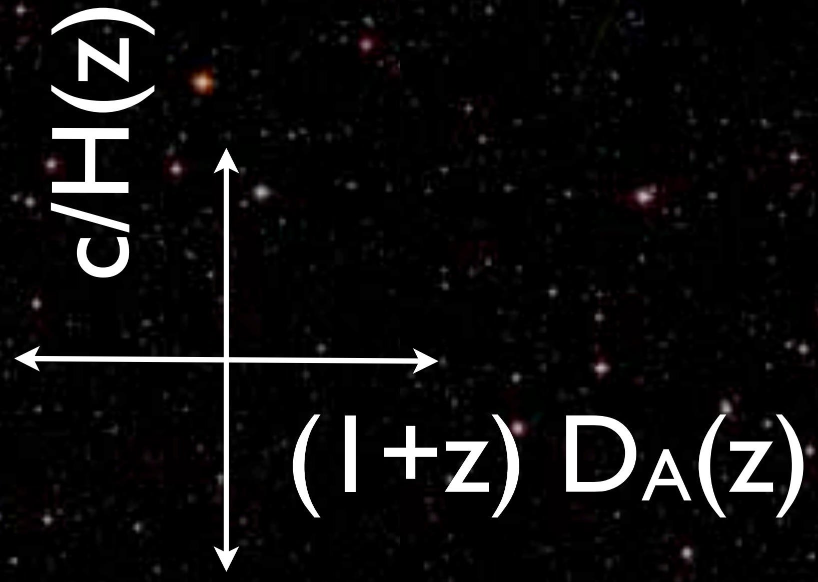
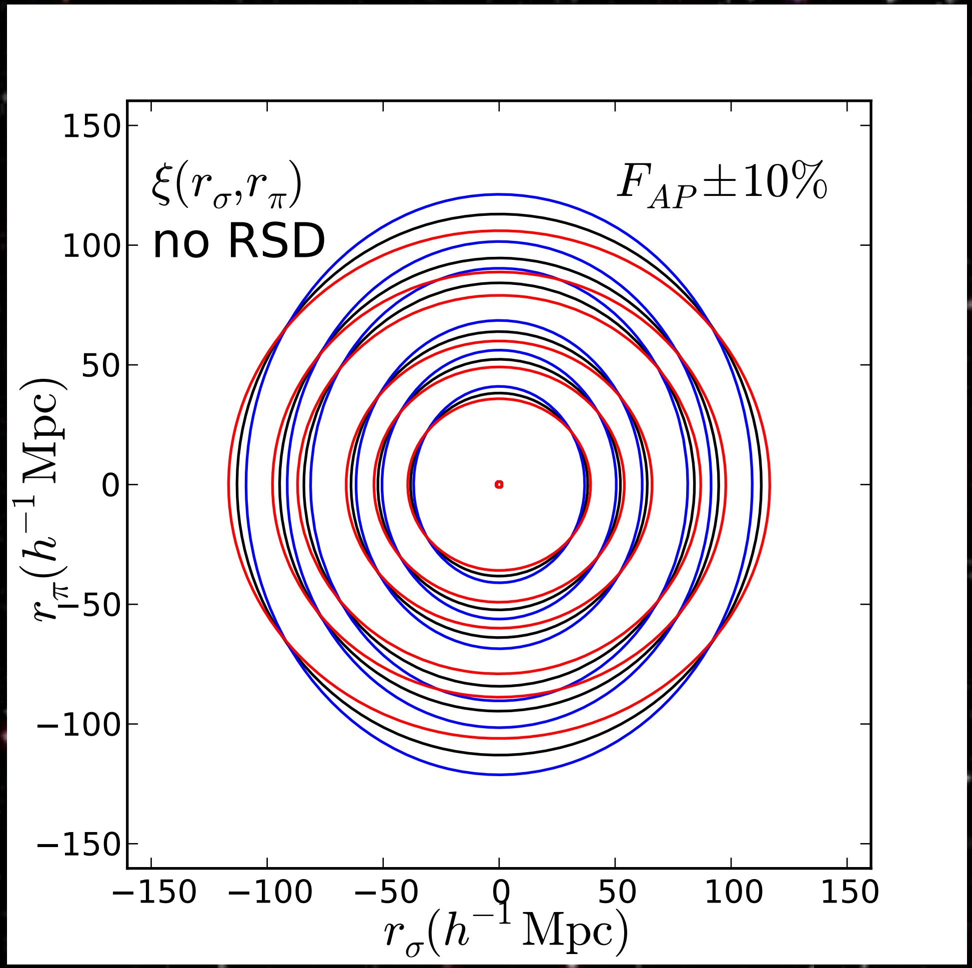
Alcock-Paczynski Effect

$\xi(r_p, \pi)$ appears anisotropic if you assume the wrong cosmology; constrains

$F(z) \equiv (1+z)\, D_A(z)\, H(z)/c$





Geometric distortions can be modeled exactly*

$$\xi^{\rm fid}(r_\sigma, r_\pi) = \xi^{\rm true}(\alpha_\perp r_\sigma, \alpha_\parallel r_\pi),$$

$$\alpha_\perp = \frac{D_A^{\rm fid}(z_{\rm eff})}{D_A^{\rm true}(z_{\rm eff})}, \qquad \alpha_\parallel = \frac{H^{\rm true}(z_{\rm eff})}{H^{\rm fid}(z_{\rm eff})},$$

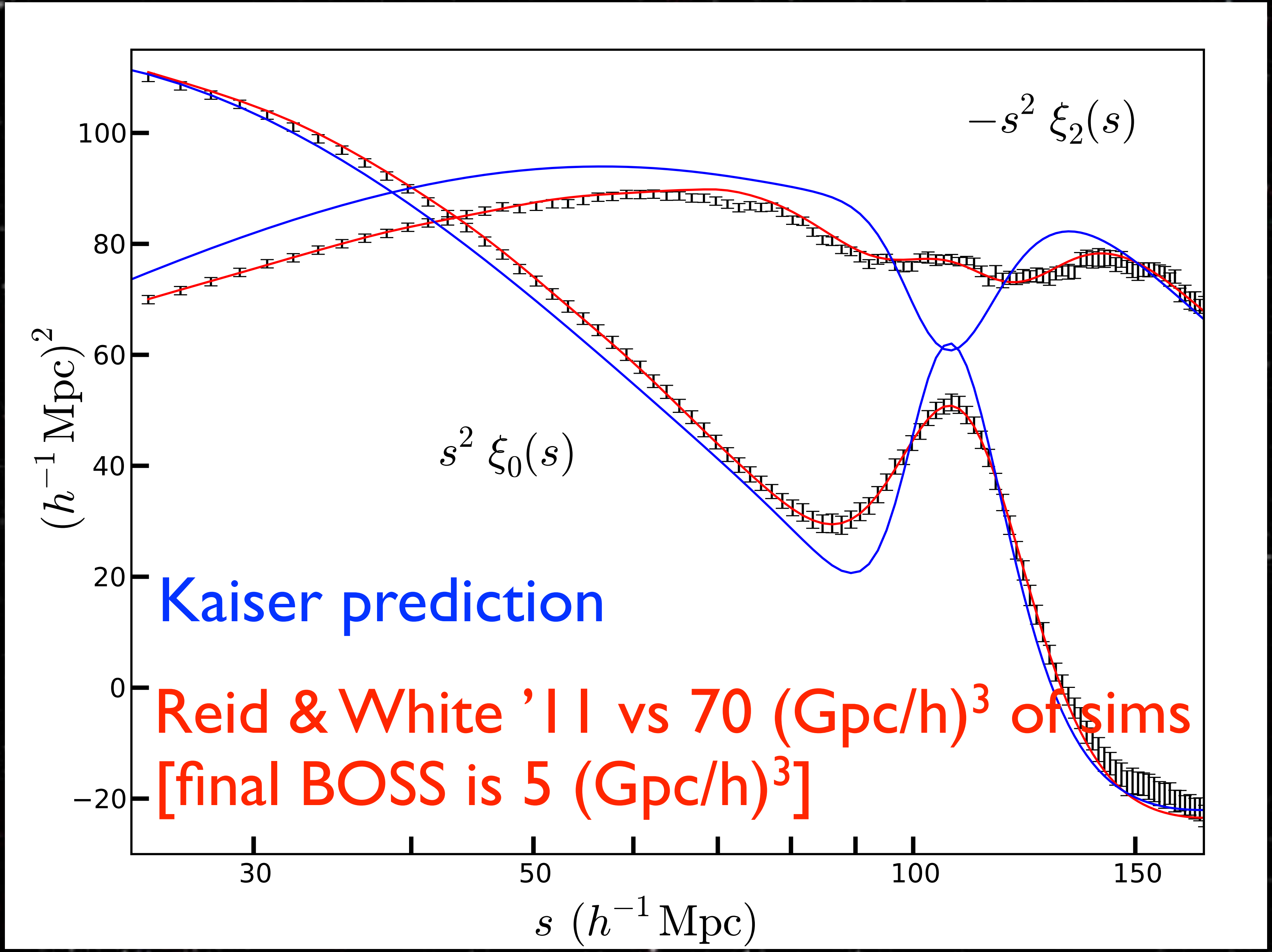
Modeling the full shape of $\xi_{0,2}$ (Reid & White 2011)

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

σ_8: amplitude of matter fluctuations

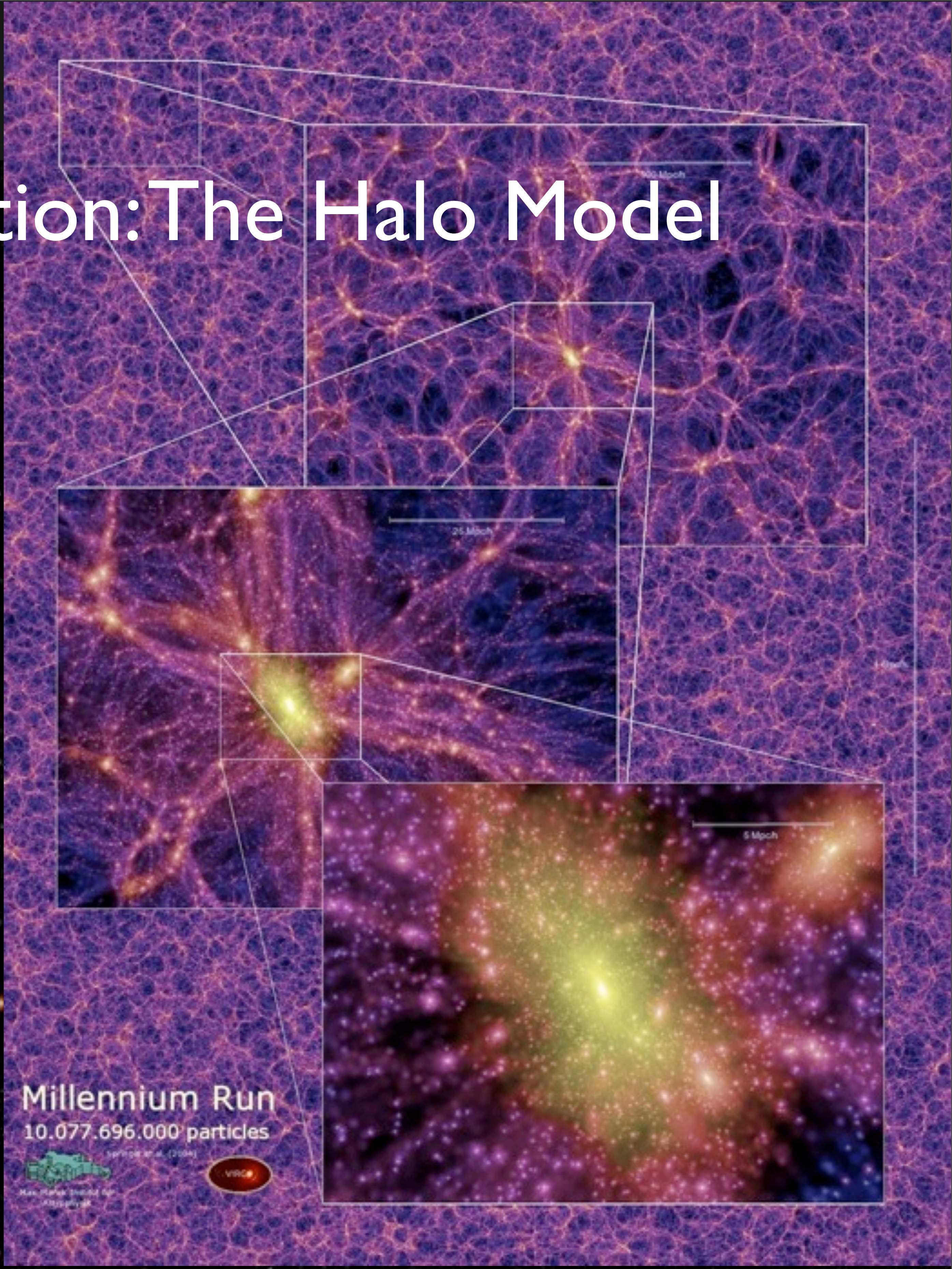
b: unknown conversion factor between galaxy and matter fluctuations

f = d ln σ_8/d ln a; conversion factor between matter and velocity fluctuations



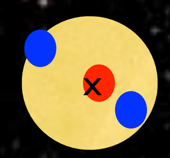
Theoretical foundation: The Halo Model

- Gas accumulates in gravitationally-bound dark matter halos, forms galaxies
- Dark-matter only N-body simulations of gravitational evolution used to calibrate/test galaxy clustering models
- "Fingers-of-God" are virial motions within halos



Dominant systematic: Fingers-of-God

REAL SPACE: r ~ 1 Mpc/h

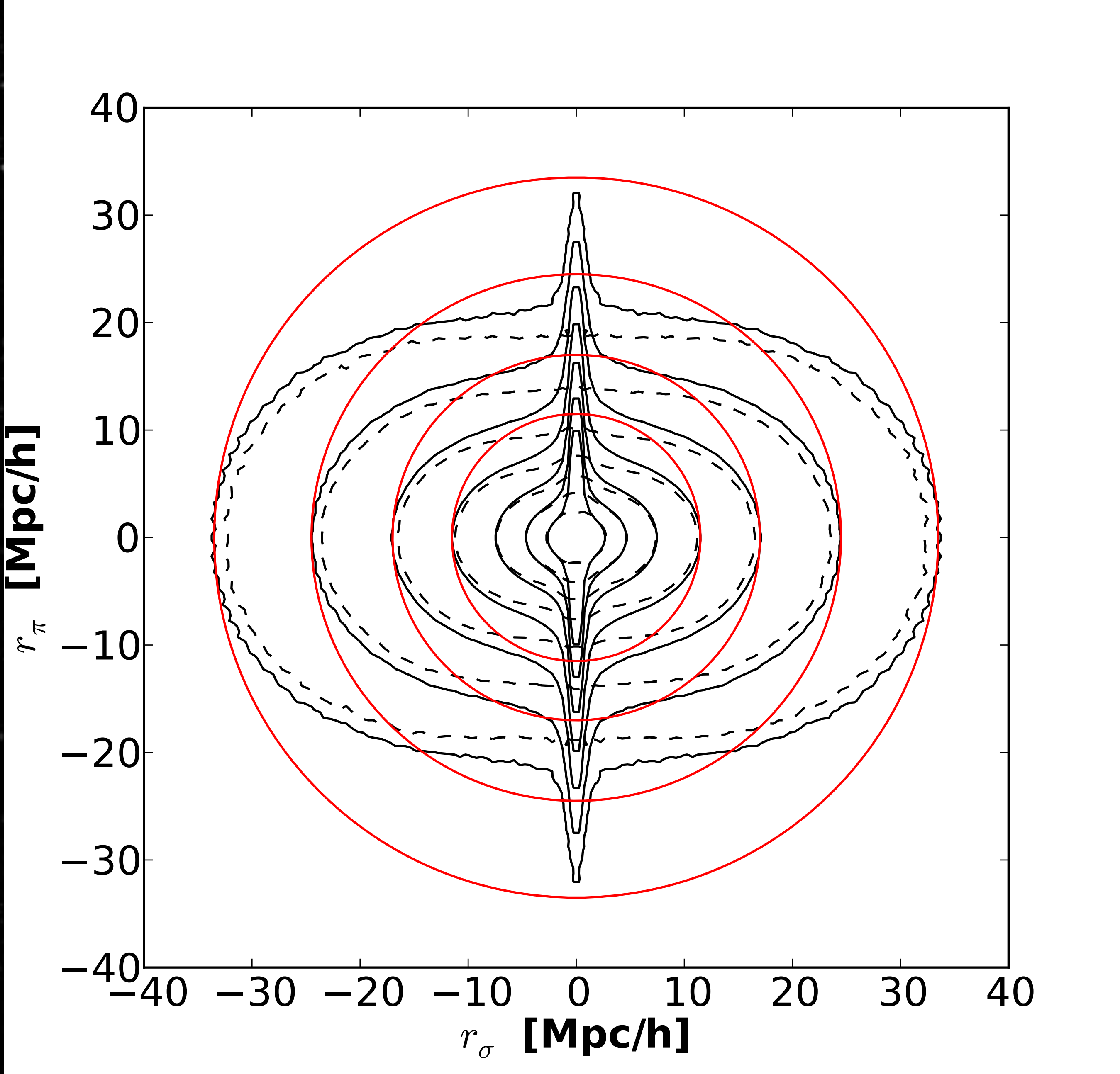


Central galaxies

Satellite galaxies

REDSHIFT SPACE: r ~ 15 Mpc/h
Finger-of-God features mix small and large scale power

Fingers-of-God in $\xi(r_\sigma, r_\pi)$



Brief model description

- 2LPT (Matsubara et al. 2008) $s > 100$ Mpc
- $s < 100$ Mpc: Gaussian streaming approximation

$$1 + \xi^s_g(r_\sigma, r_\pi) = \int \left[1 + \xi^r_g(r)\right] e^{-[r_\pi - y - \mu v_{12}(r)]^2 / 2\sigma^2_{12}(r,\mu)} \frac{dy}{\sqrt{2\pi\sigma^2_{12}(r,\mu)}}$$

2LPT
2nd order bias included

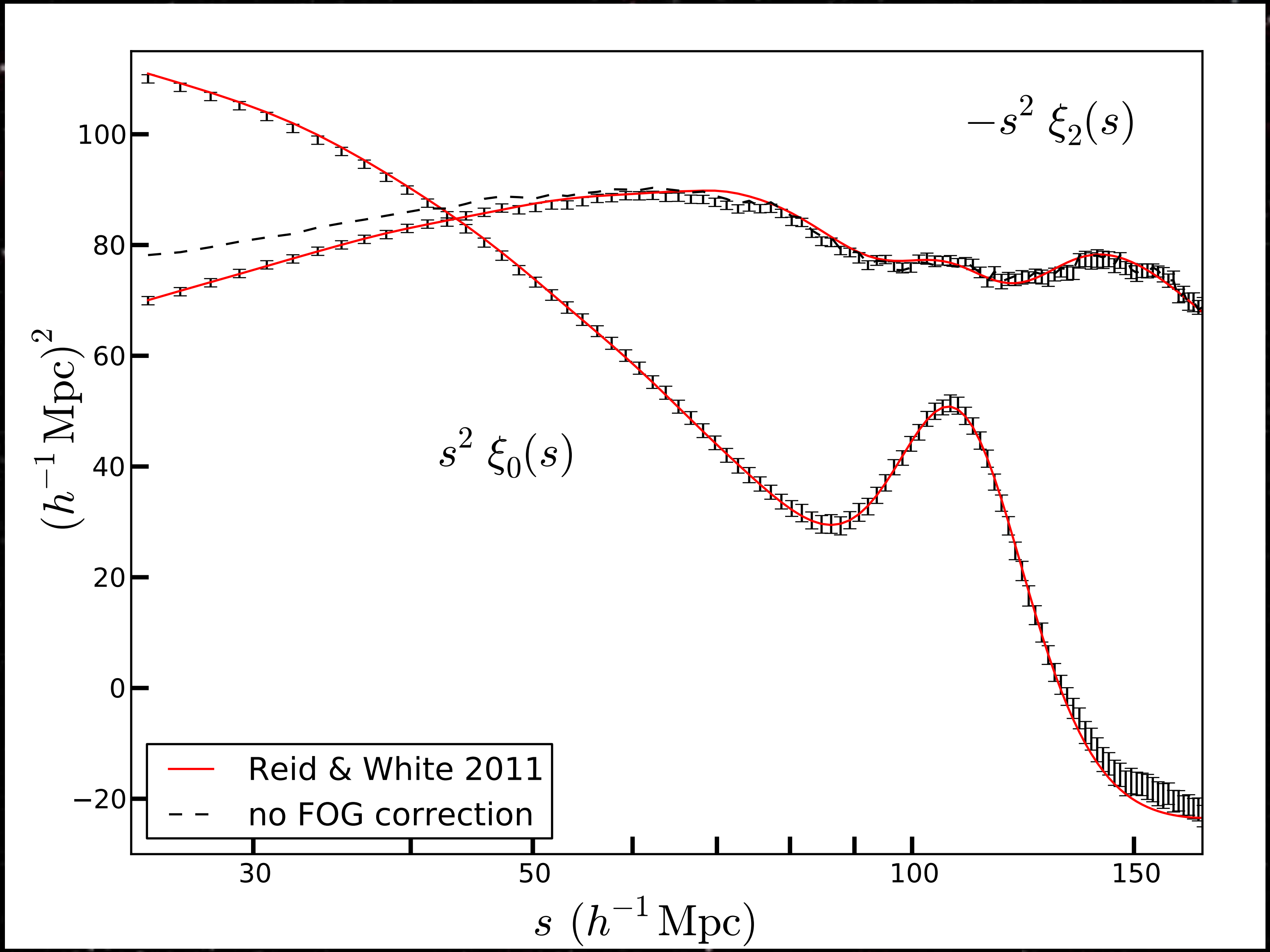
2SPT
1st order bias only

* LPT in progress! *

- FOGs included with additive isotropic σ^2_{FOG}

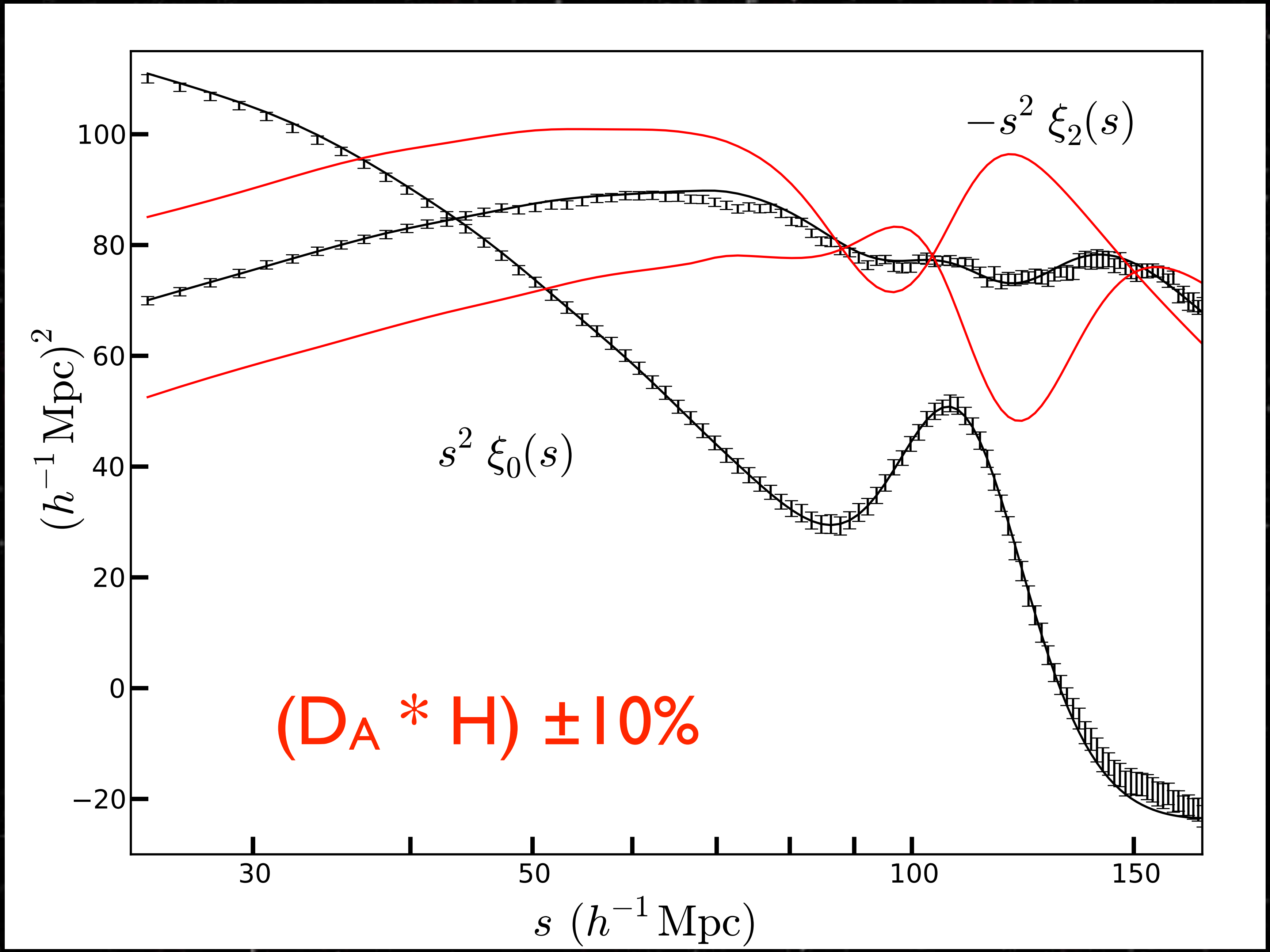
Effect of intrahalo satellite velocities (aka "Fingers of God")

DR9 Battle plan: marginalize over nuisance parameter σ^2_{FOG} with hard prior informed by small-scale galaxy clustering



DR10: derive FOG velocity distribution directly from observed small-scale clustering

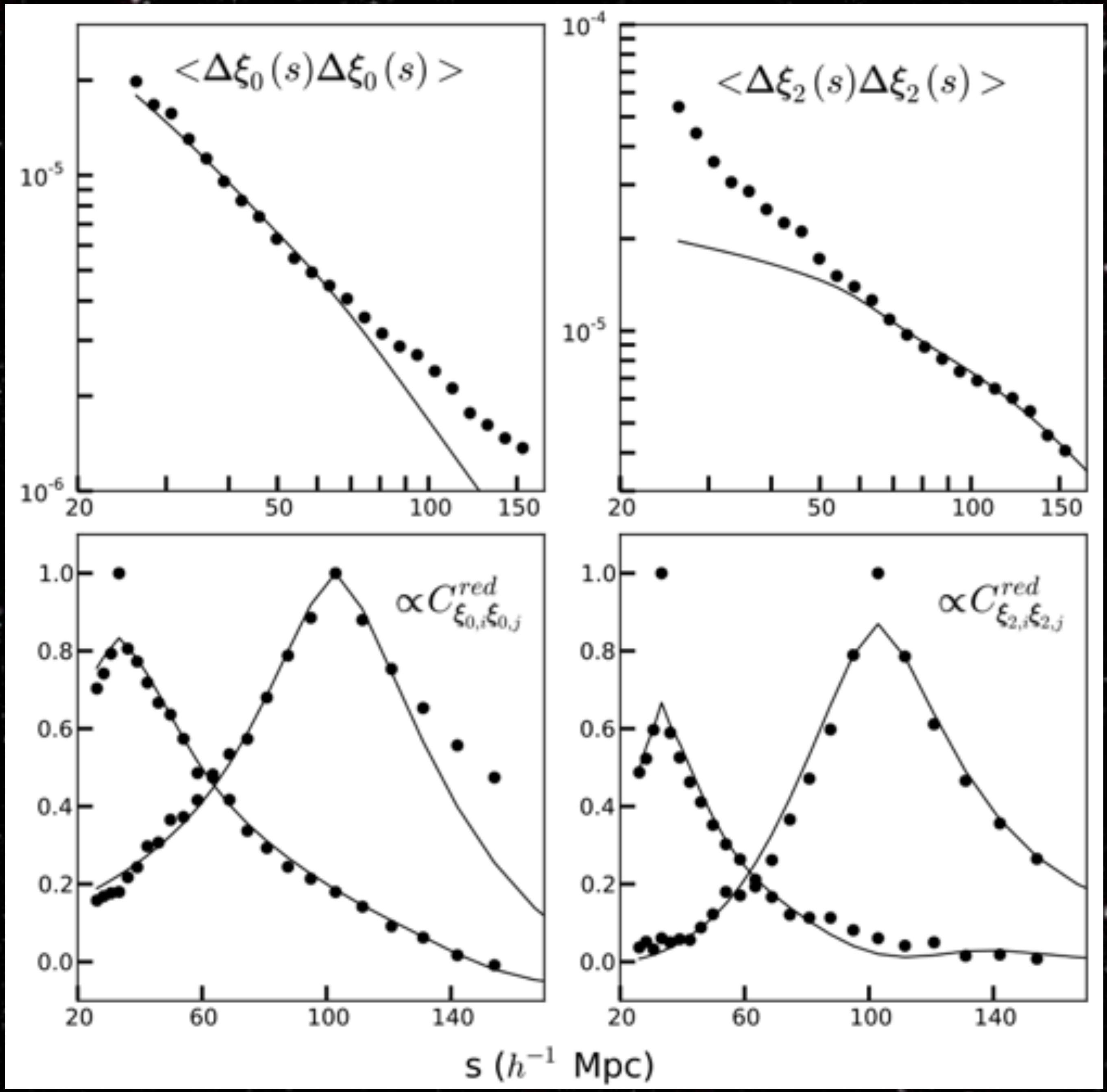
Alcock-Paczynski has different scale-dependence, distinguishable from RSD



D_V stretches s axis ⟷

Final ingredient: Covariance matrix

- 600 (L)PT halos mocks described in Manera et al.
- Neighboring points in ξ highly correlated -- no χ^2 by eye!

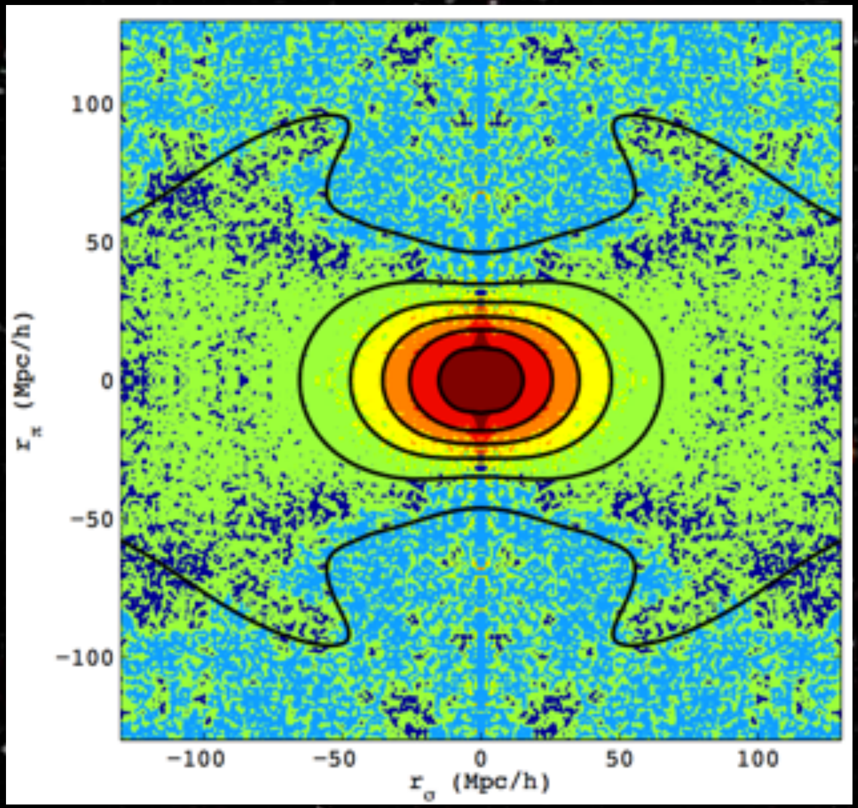


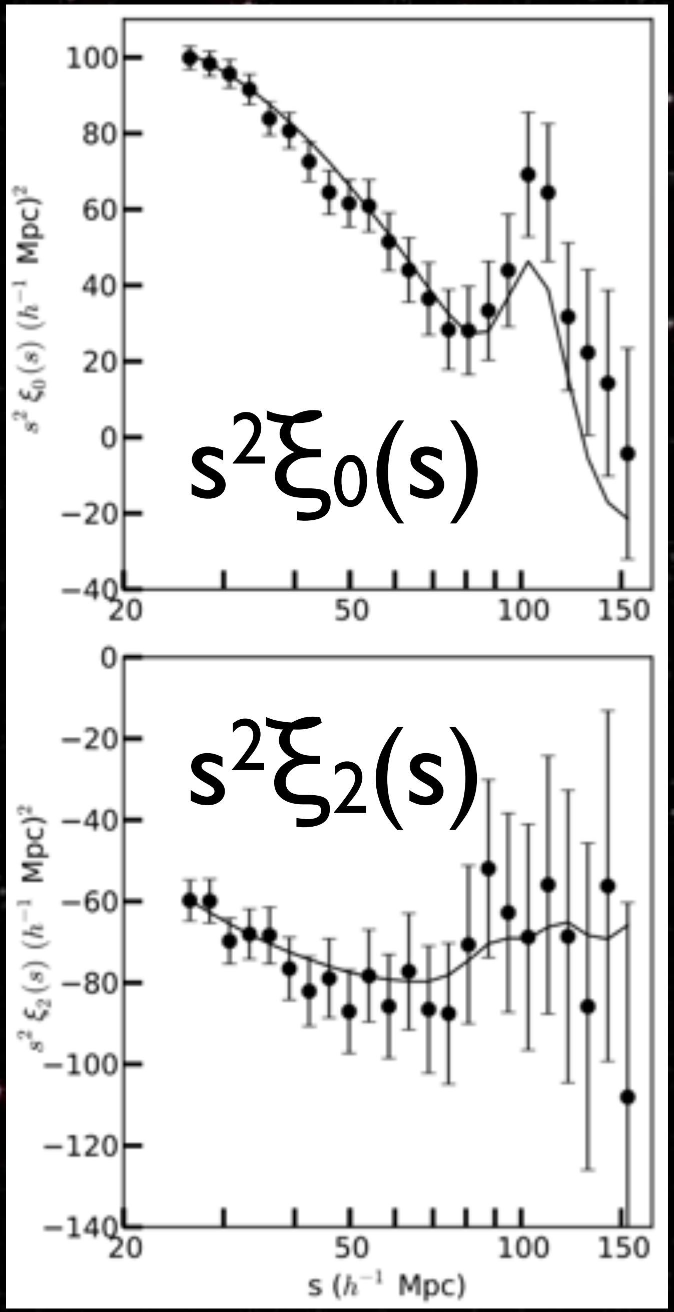
Results: Fitting to 2d clustering

- Use full model of $\xi_{0,2}(s \geq 25\ h^{-1}\ \mathrm{Mpc})$ to constrain:
  - $D_V = [(1+z)^2 D_A^2\, cz/H]^{1/3}$
  - growth of structure ($f\sigma_8$)
  - Alcock-Paczynski $F(z) \equiv (1+z)\, D_A(z)\, H(z)/c$
  - marginalizing over shape of underlying linear $P(k)$, $b\sigma_8$, σ^2_{FOG}

Best fit model: χ^2 = 39 (41 DOF)

- growth: $f\sigma_8$ = 0.437
- geometry: D_A = 2184 Mpc, H = 91.5 km s^{-1} Mpc^{-1}
- nuisance: $b\sigma_8$ = 1.235, σ^2_{FOG} = 40 Mpc^2
- shape: $\Omega_m h^2$ = 0.1364, $\Omega_b h^2$ = 0.02271, n_s = 0.967





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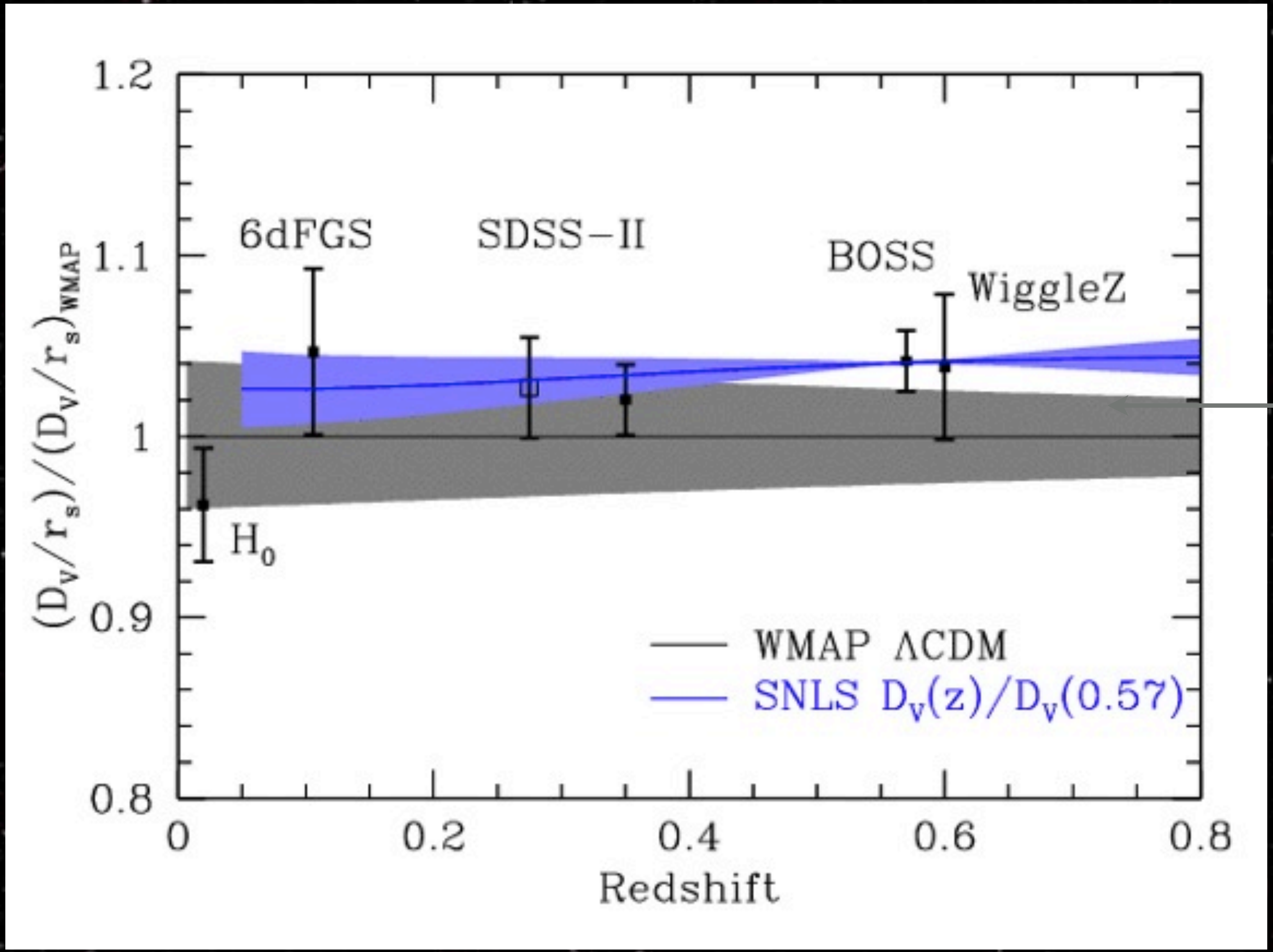
BAO Hubble Diagram: Comparison with, CMB, H_0, and SN



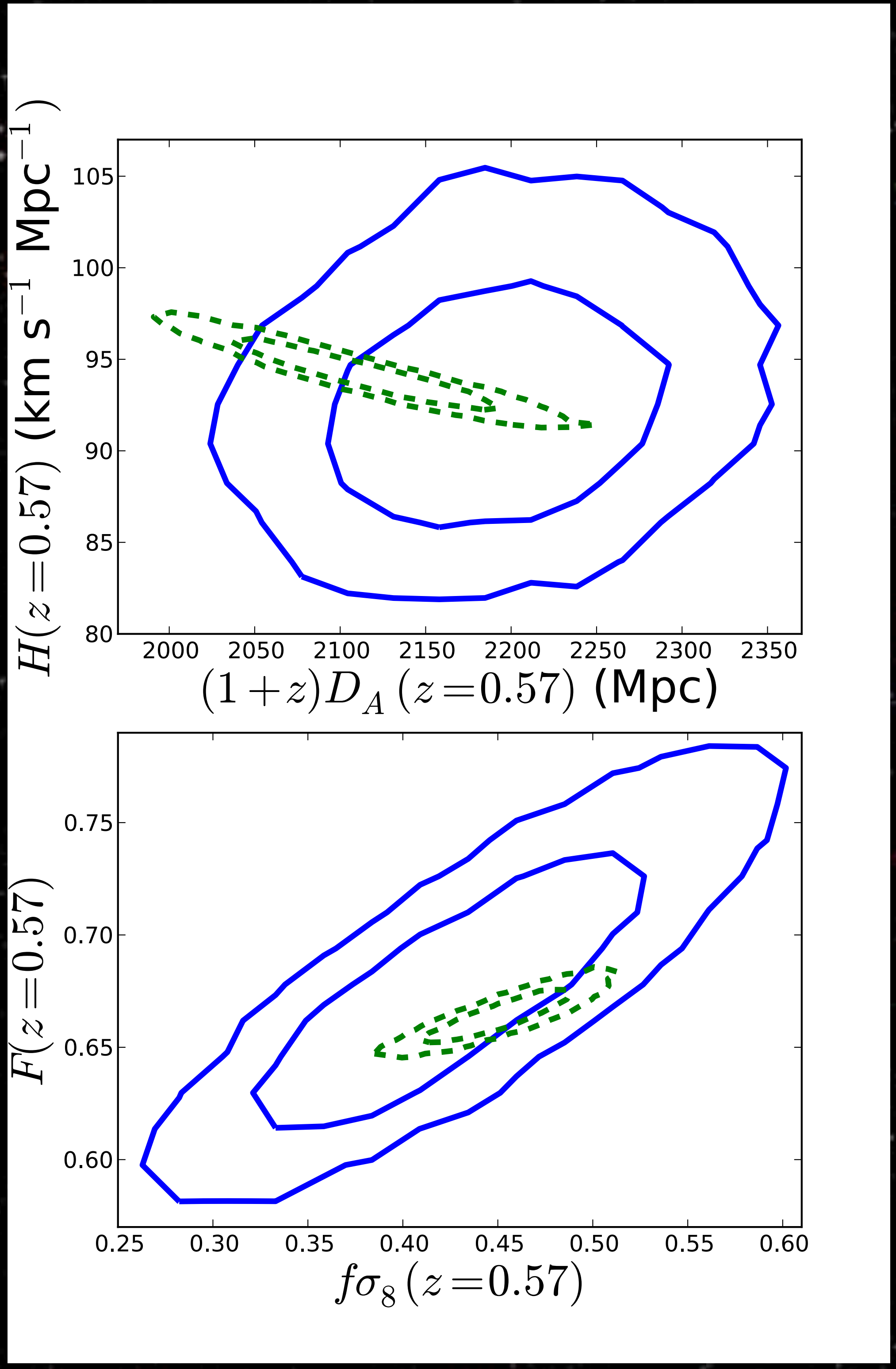
+1σ in $\Omega_m h^2$ (WMAP7), ~2σ (WMAP7+SPT)

ξ_0 BAO + ξ_2: D_A, H, $f\sigma_8$ at z=0.57

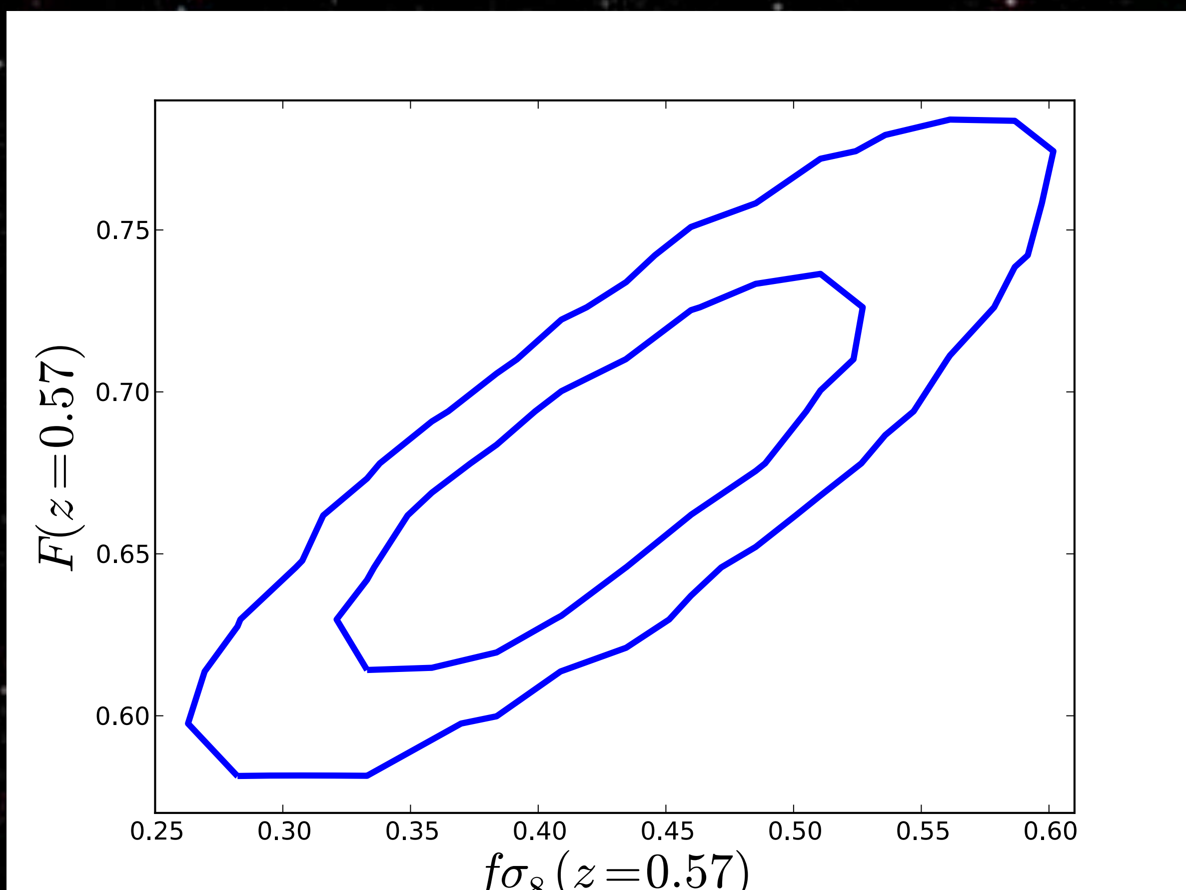
- $f\sigma_8(0.57) = 0.43 \pm 0.069$
- $H(0.57) = 92.4 \pm 4.5$ km s^{-1} Mpc^{-1}
- $D_A(0.57) = 2190 \pm 61$ Mpc

WMAP ΛCDM prediction

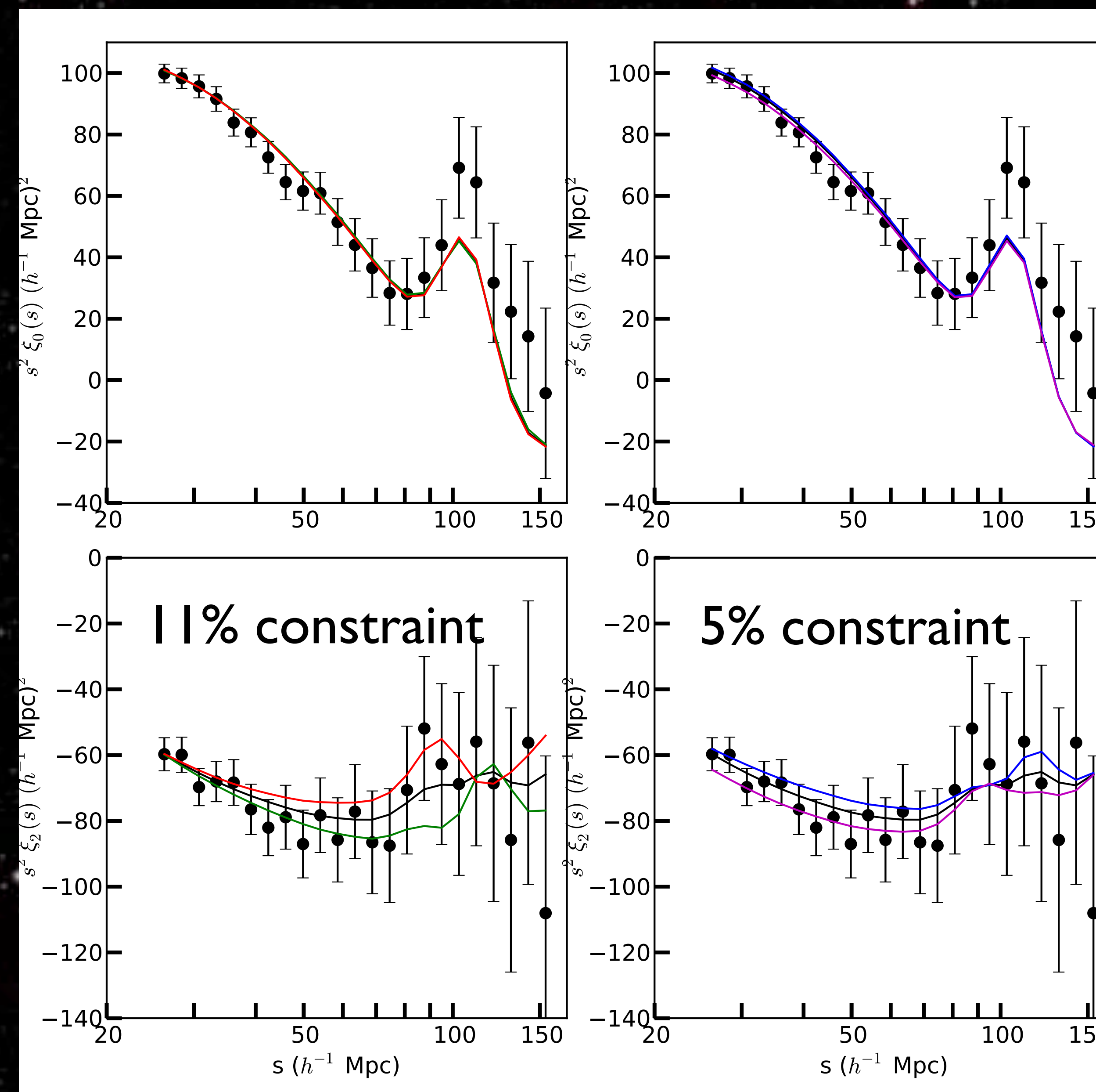
- $f\sigma_8(0.57) = 0.451 \pm 0.025$
- $H(0.57) = 94.2 \pm 1.4$ km s^{-1} Mpc^{-1}
- $D_A(0.57) = 2113 \pm 53$ Mpc



Breaking the degeneracy between $f\sigma_8$ and F

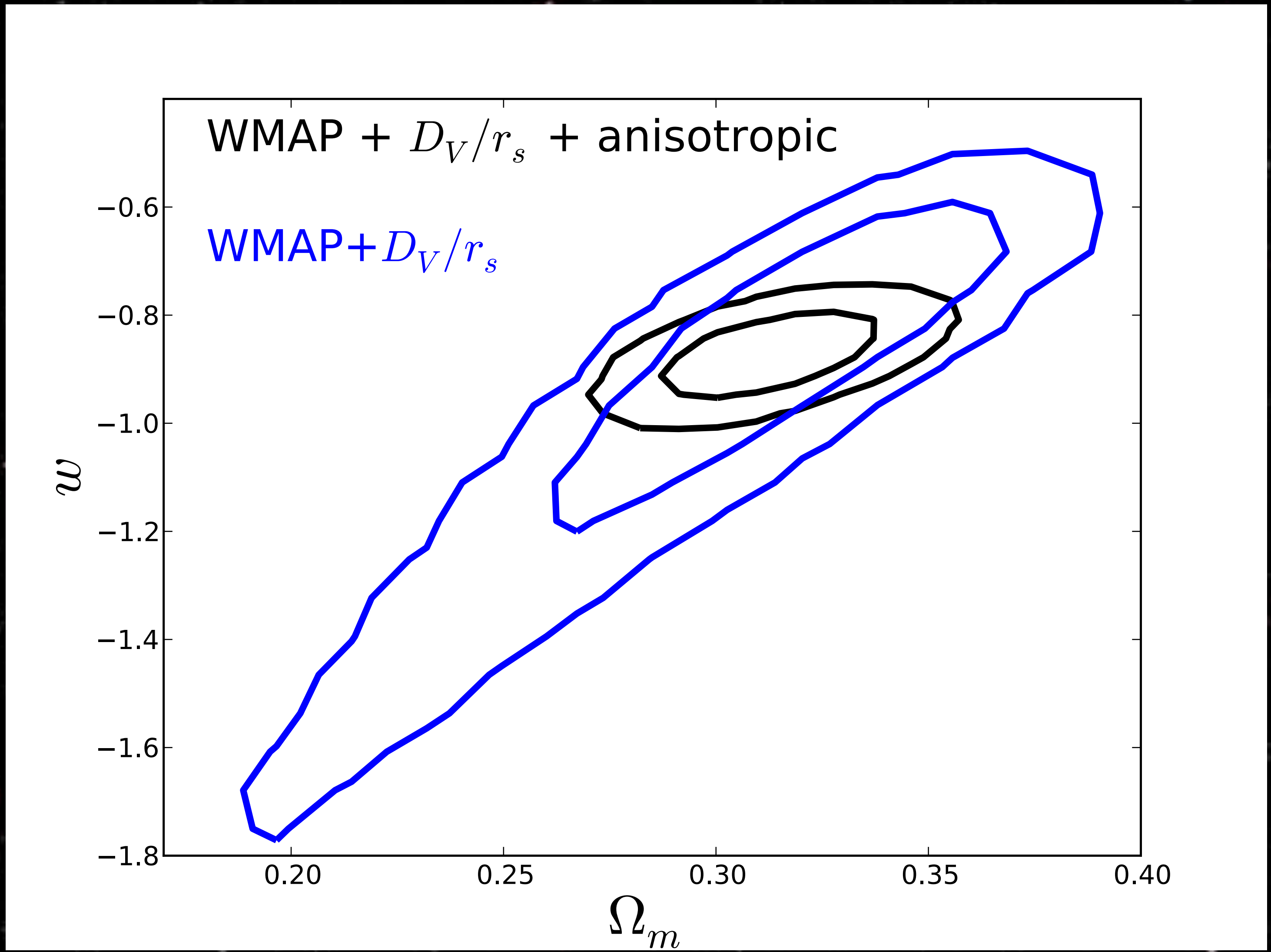


Compute eigenvectors in F-$f\sigma_8$ plane, project back onto $\xi_{0,2}$; minimize χ^2 wrt D_V, $b\sigma_8$, σ^2_{FOG}



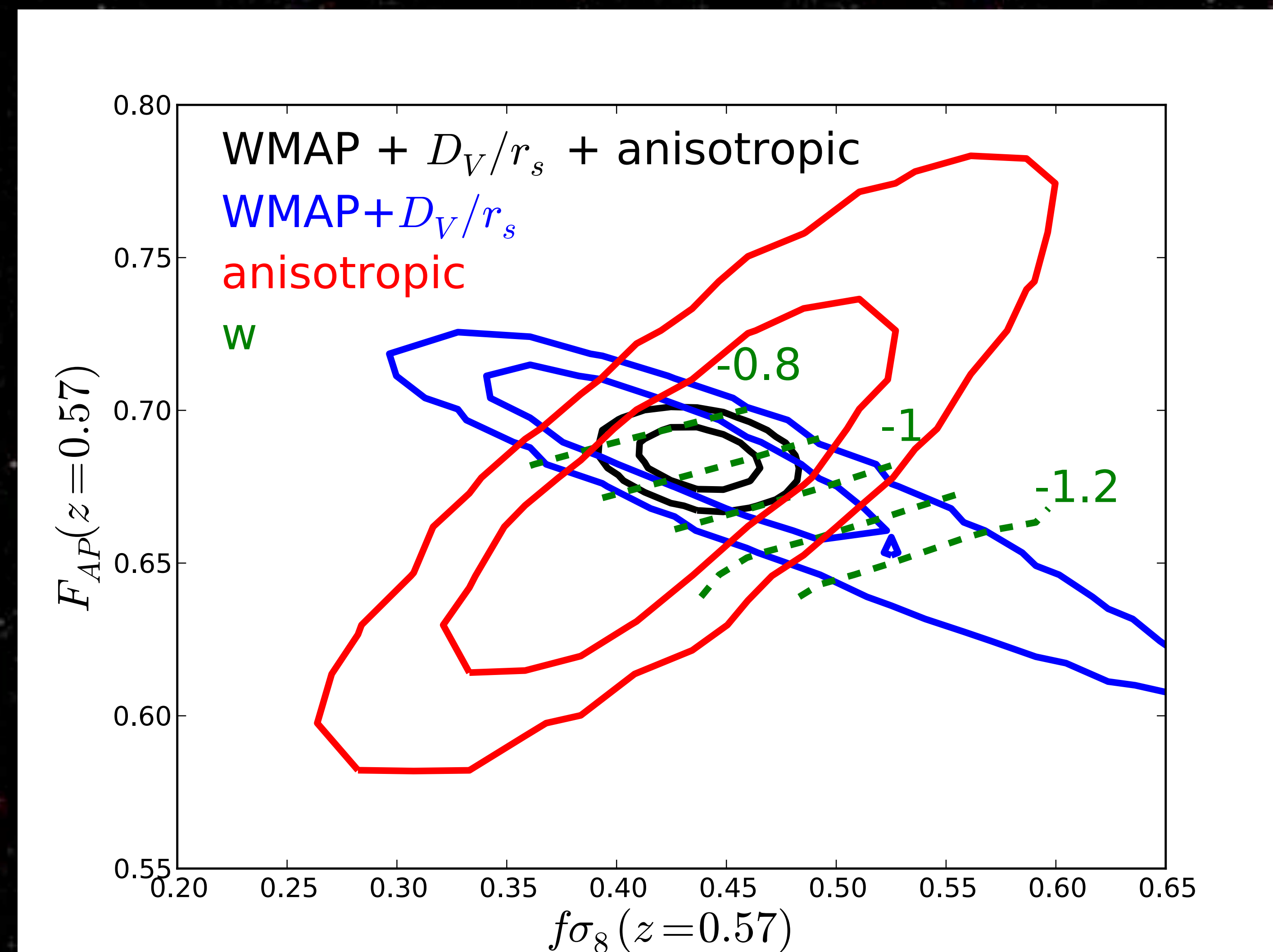
Cosmological implications: flat wdcm (Samushia, BR et al.)

- Anisotropic clustering allows huge improvement on dark energy parameters!
- w = -0.95 ± 0.25 (WMAP + $D_V(0.57)/r_s$)
- w = -0.88 ± 0.055 (WMAP + anisotropic) Same precision as WMAP +SN!



Cosmological implications: flat wdcm (Samushia, BR et al.)

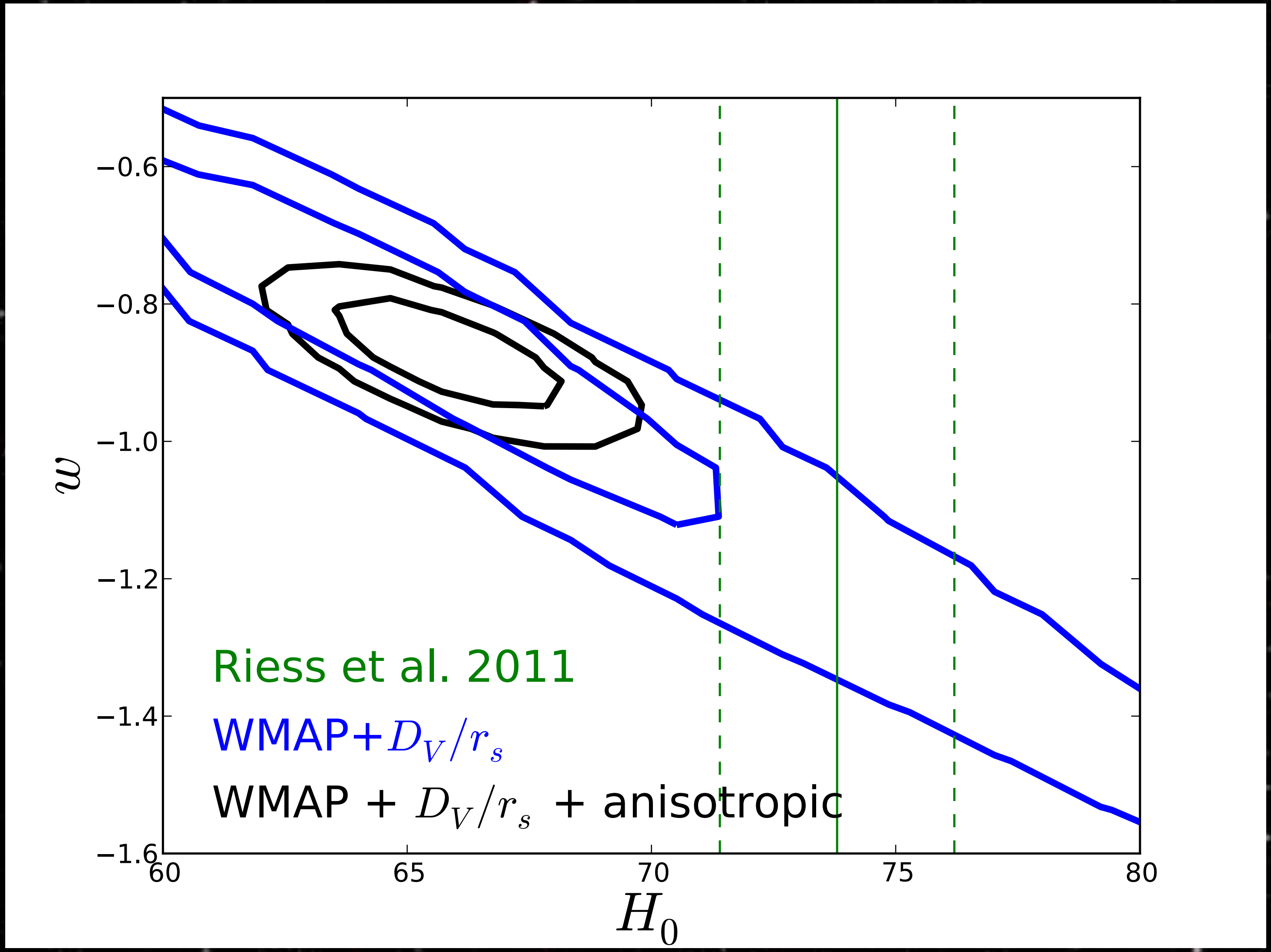
- Anisotropic clustering allows huge improvement on w!
- Thanks to fortuitous degeneracy direction between F_{AP} and $f\sigma_8$



Samushia, BR, et al., 2012

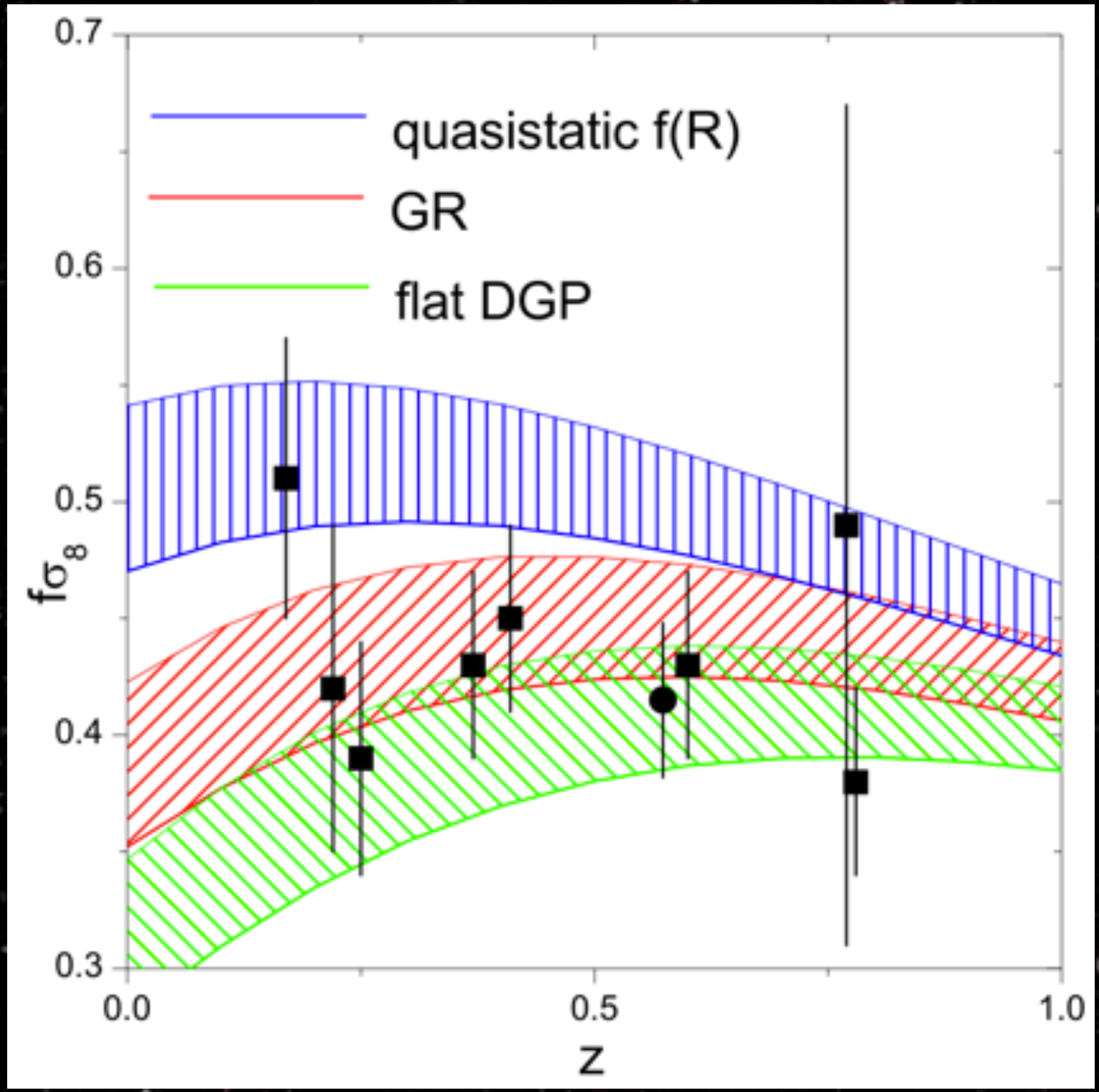
Cosmological implications: flat wdcm (Samushia, BR et al.)

- Both SN, H_0 push back towards w = -1



Dark Energy or modified gravity?

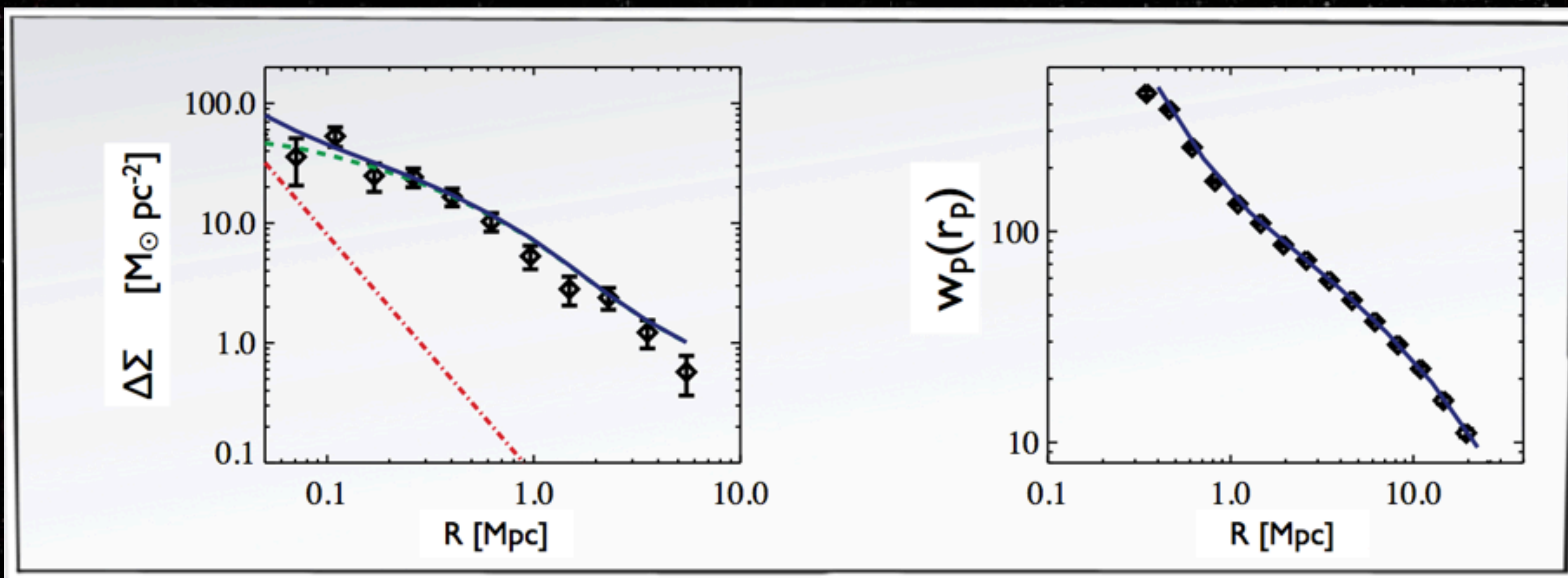
- CMASS geometric constraints tighten ΛCDM $f\sigma_8$ prediction, shift it up
- CMASS $f\sigma_8$ is low by ~ 1.5σ
- Same story -- other measurements pull towards GR



Samushia, BR, et al., 2012

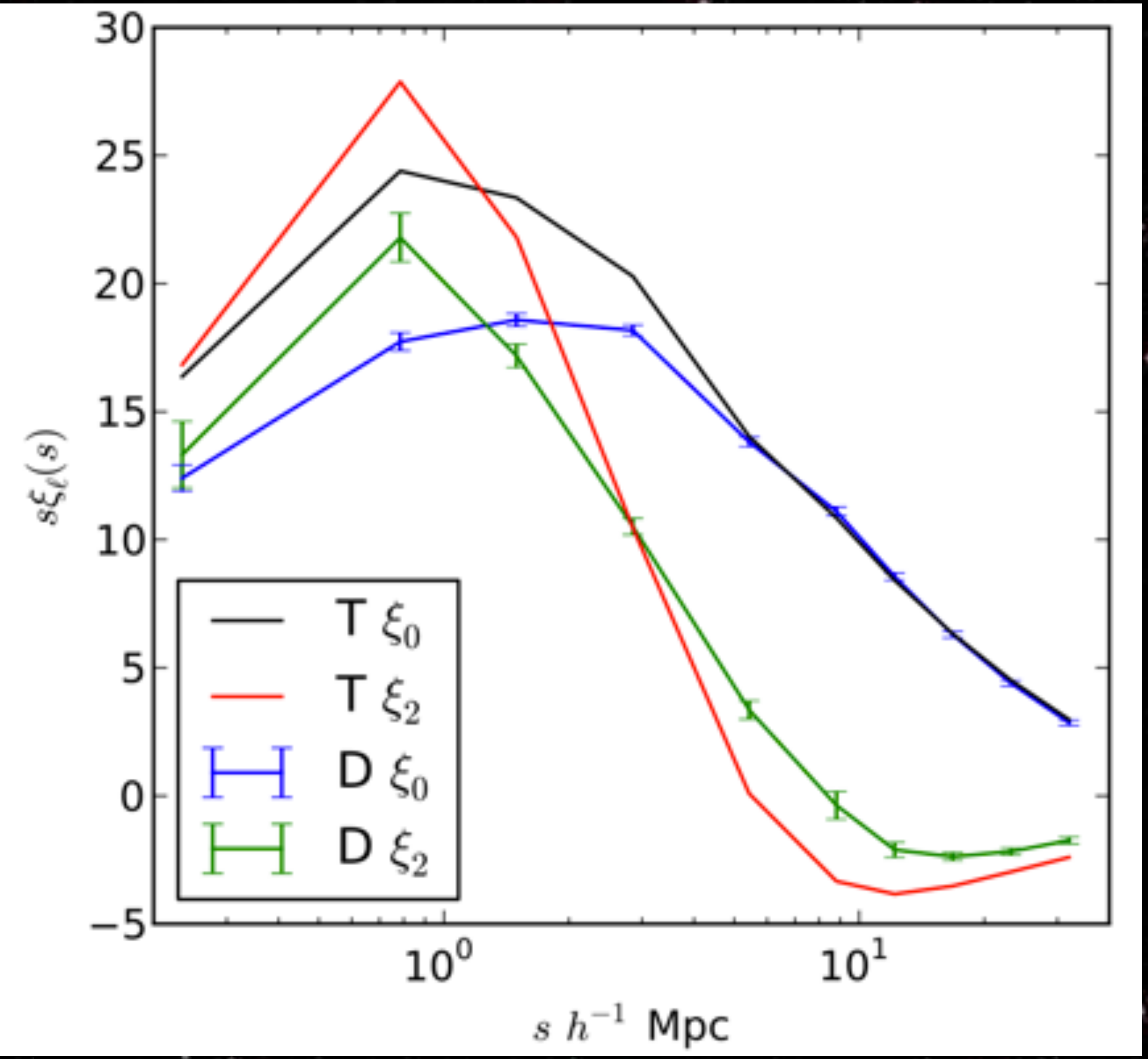
DR10 Work in Progress

- We can find a std HOD that fits the *projected* mass and galaxy distributions around CMASS galaxies:



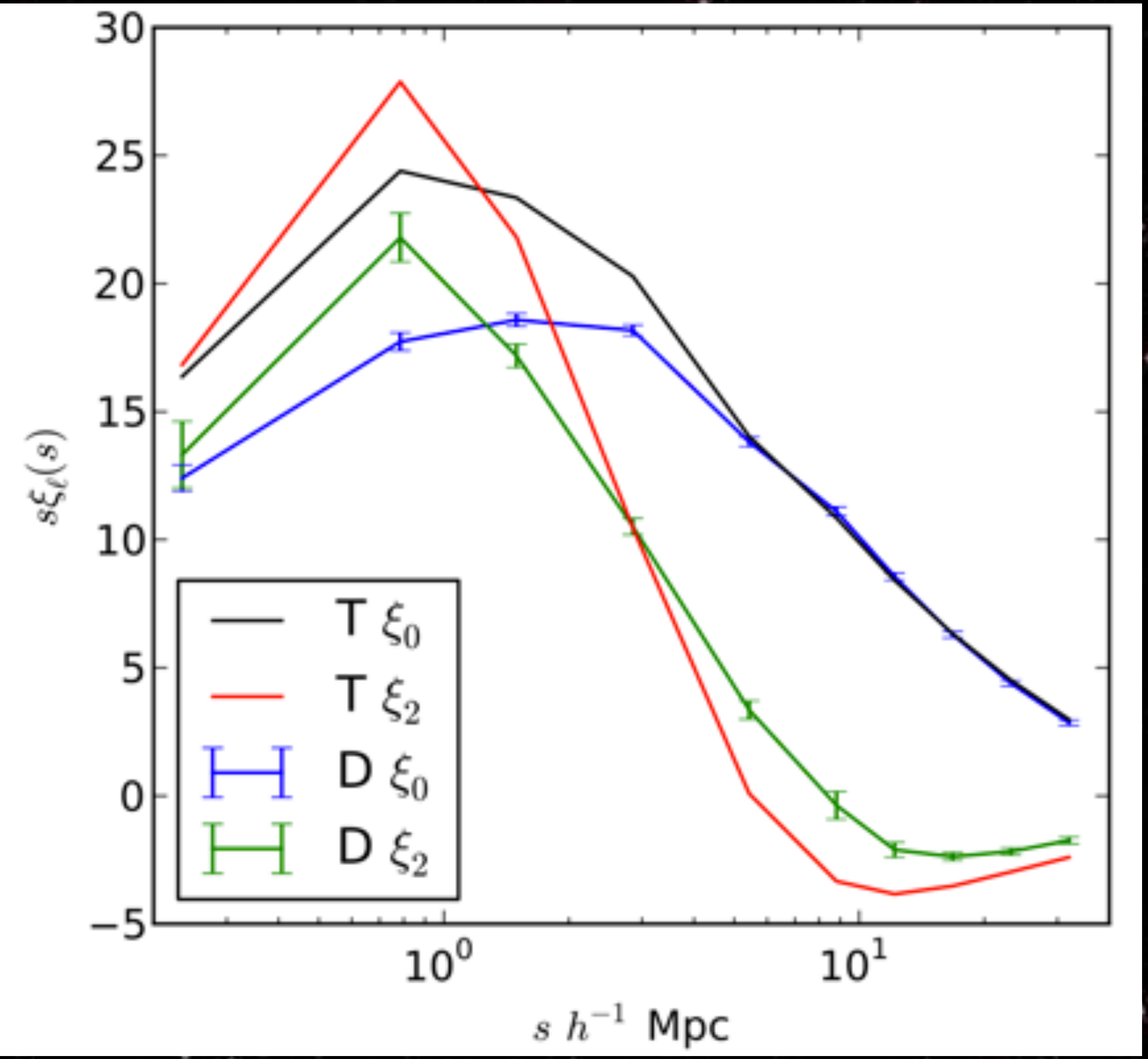
DR10 Work in Progress

- But's it's a terrible fit to small-scale $\xi_{0,2}$ (at fixed WMAP7 cosmology)
- Need to explore more complicated velocity structure in HOD, allow relevant cosmological parameters to float, ...



DR10 Work in Progress

- ... in order to infer the distribution of small-scale galaxy velocities.



Summary

- 1.7% BAO distance constraint at z=0.57
- (First?) Best measurement of H(z) using BAO + Alcock-Paczynski effect
- 7% growth rate measurement, 1.5σ low compared to ΛCDM+GR
- WMAP+BOSS constraining power on dark energy substantially improved (~factor of 4 in flat wcdm!) when including anisotropic clustering