

# **Baryon Acoustic Oscillations and Beyond: Galaxy Clustering as Dark Energy Probe**

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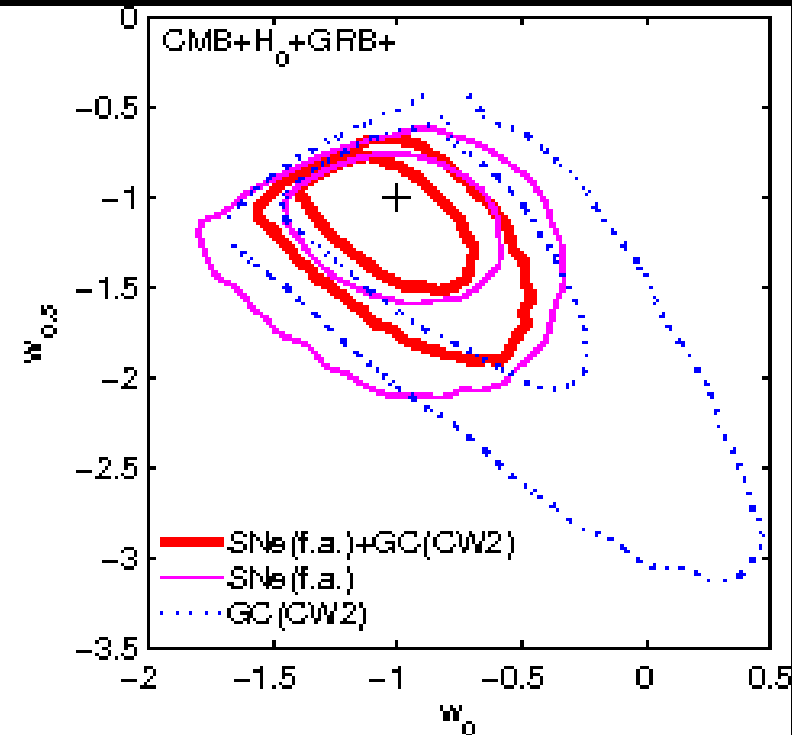
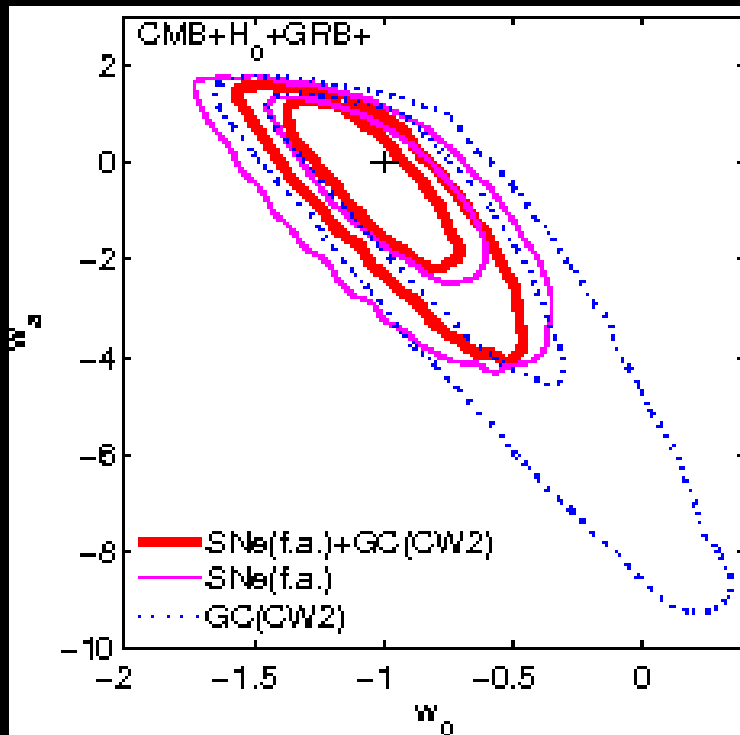
# Plan of the Lectures

- Lecture I: Overview
- Lecture II: The galaxy power spectrum method
- Lecture III: The galaxy correlation function method
- Lecture IV:
  - Modeling/mitigating systematic uncertainties
  - Make forecasts for future surveys

# Outline of Lecture I

- I. Introduction
- II. Current BAO/GC Data
- III. Systematic uncertainties
- IV. Modeling of BAO/GC data
- V. Forecasts of future galaxy redshift surveys
- VI. Summary

# I. Introduction



$$w(z) = w_0 + w_a(1-a);$$

$$w(z) = w_0(3a-2) + 3w_{0.5}(1-a)$$

$1+z = 1/a$ ;  $z$ : cosmological redshift;  $a$ : cosmic scale factor

**CMB: WMAP7 (Komatsu et al. 2011)**

**$H_0 = 73.8 \pm 2.4$  km/s/Mpc (Riess et al. 2011)**

**GRBs (compiled by Wang 2008)**

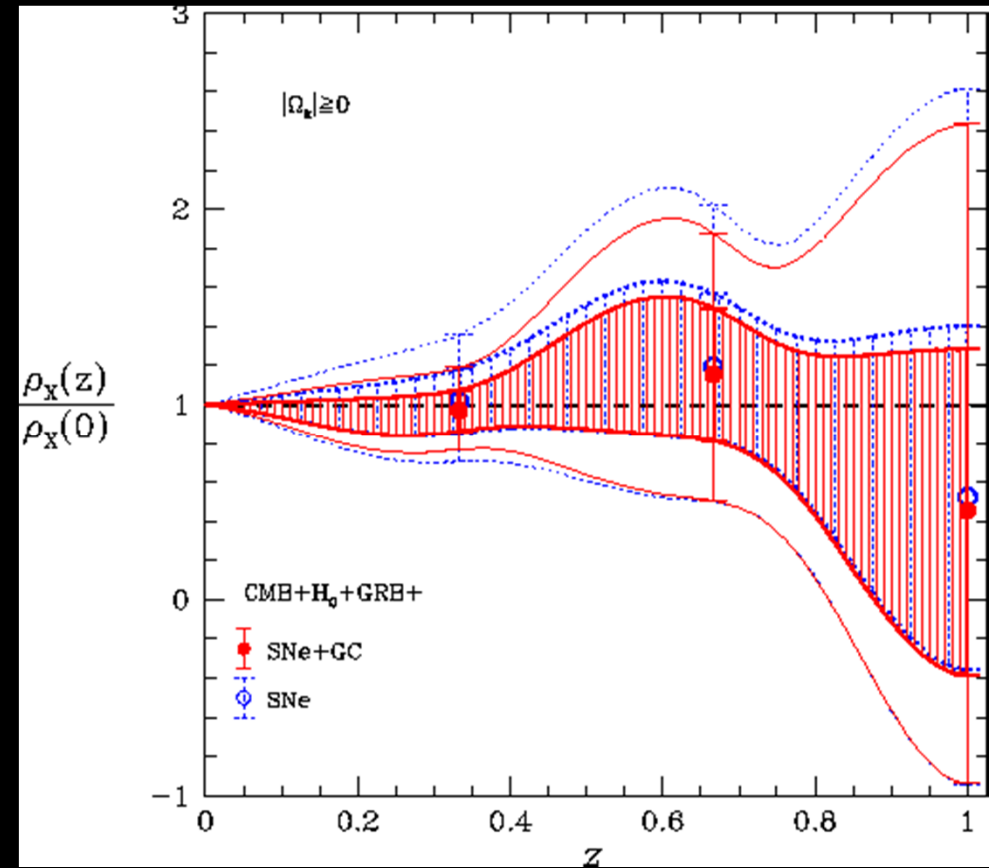
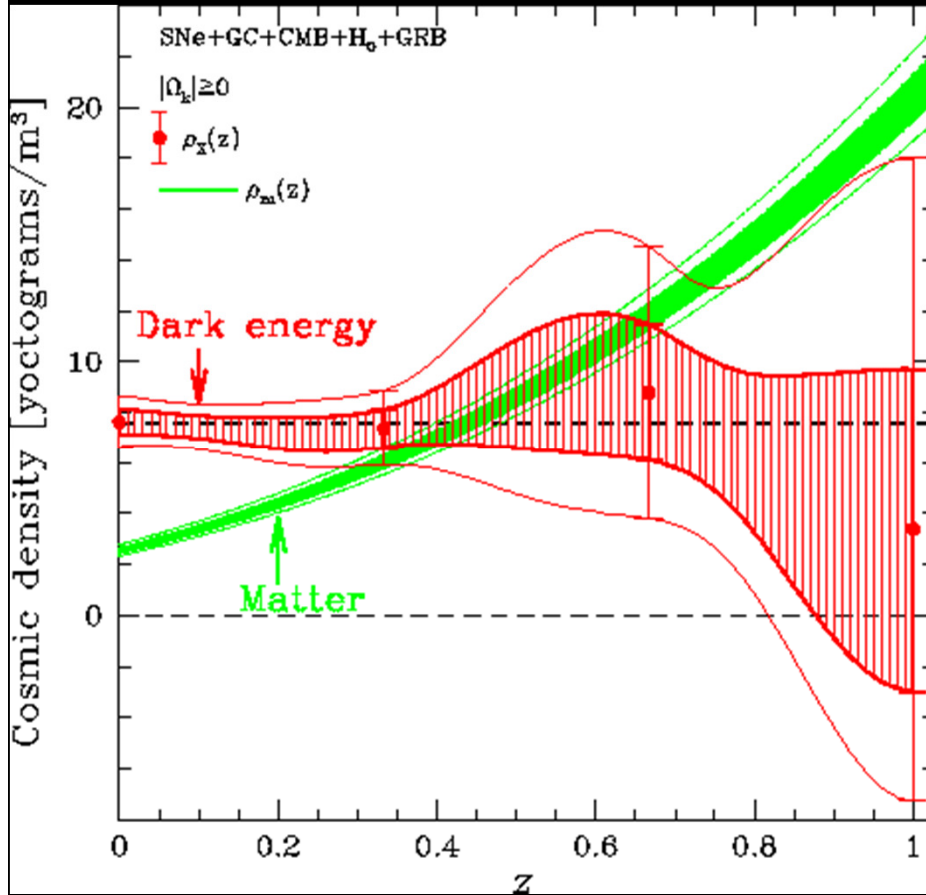
**SNe: 472 SNe Ia (compiled by Conley et al. 2011)**

**GC: [ $H(0.35)$ ,  $D_A(0.35)$ ] from SDSS LRGs (Chuang & Wang, arXiv:1102.2251)**

(Wang, Chuang, & Mukherjee 2012)

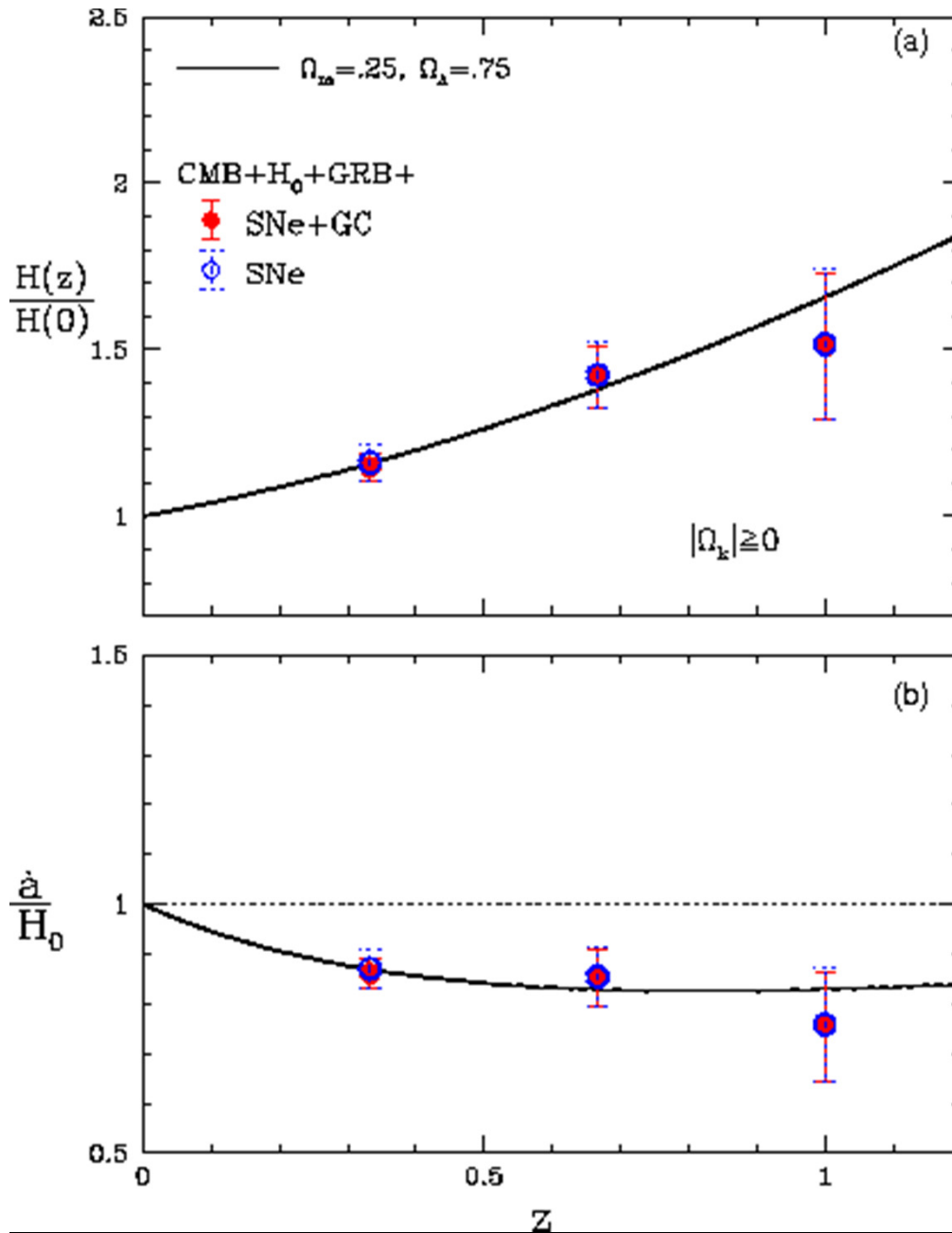
# Model-independent constraints on dark energy

(as proposed by Wang & Garnavich 2001)



1 yoctogram =  $10^{-24}$ g

Wang, Chuang, & Mukherjee (2012)

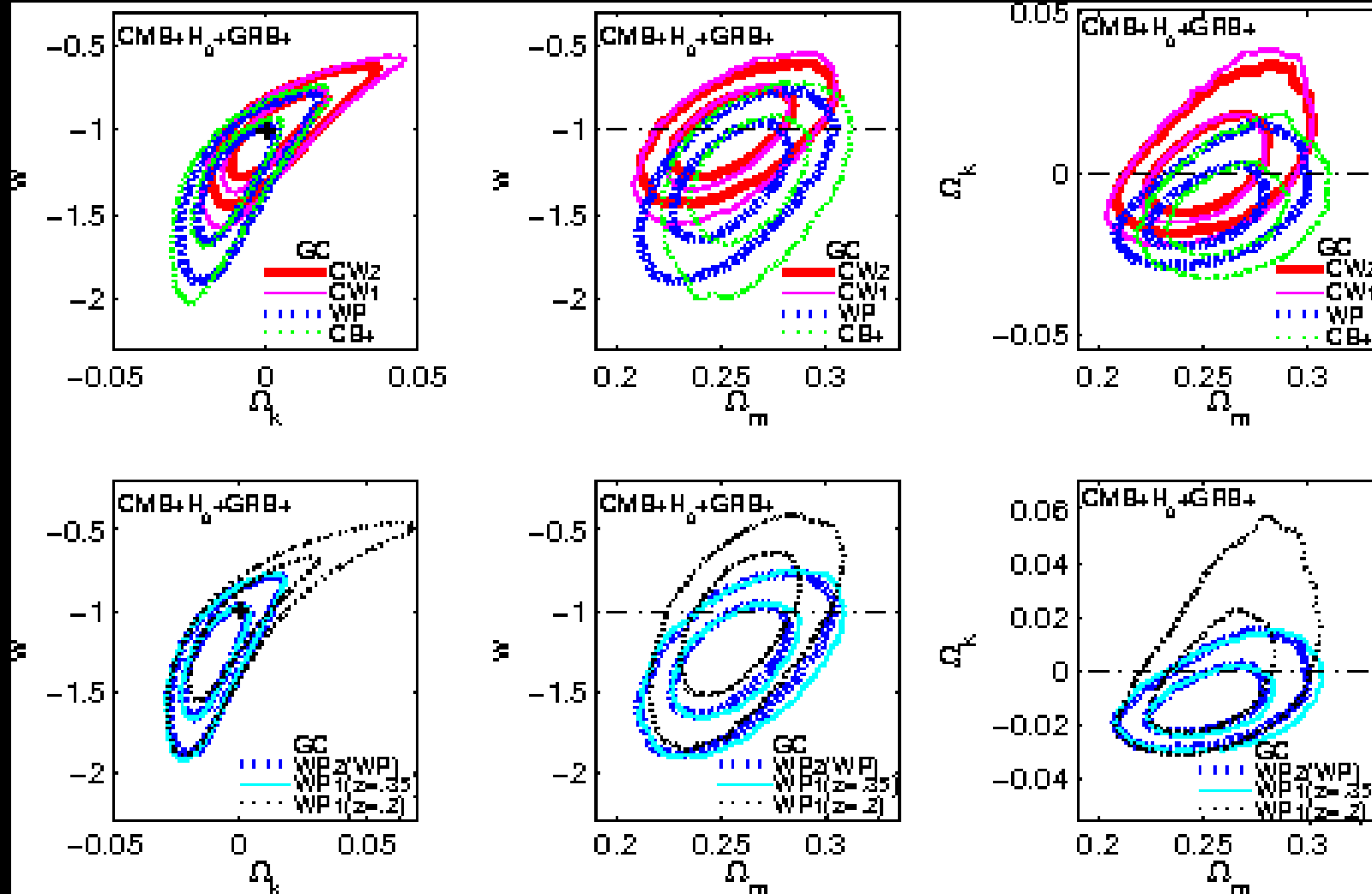


Wang, Chuang, & Mukherjee  
(2012)

[See Wang & Tegmark  
(2005) for the method to  
derive uncorrelated estimate  
of  $H(z)$  using SNe.]

$$H(z) = [da/dt]/a$$

# Different analyses of GC/BAO



GC results from Chuang & Wang (2011) favors  $w = -1$ , while the results from some other groups favor  $w < -1$ . *Wang, Chuang, & Mukherjee (2012)*

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# How We Probe Dark Energy

- *Cosmic expansion history  $H(z)$  or DE density  $\rho_X(z)$*   
tells us whether DE is a cosmological constant

$$H^2(z) = 8\pi G[\rho_m(z) + \rho_r(z) + \rho_X(z)]/3 - k/a^2$$

- *Growth history of cosmic large scale structure [growth rate  $f_g(z)$  or growth factor  $G(z)$ ]*

tells us whether general relativity is modified, given  $H(z)$

# Observational Methods for Probing Dark Energy

- **SNe Ia (Standard Candles):** method through which DE was discovered; independent of clustering of matter, probes  $H(z)$ .
- **Baryon Acoustic Oscillations (Standard Ruler):** calibrated by CMB, probes  $H(z)$ . Redshift-space distortions from the same data probe  $f_g(z)$ .
- **Weak Lensing Tomography and Cross-Correlation Cosmography:** probe a combination of  $G(z)$  and  $H(z)$ .
- **Galaxy Cluster Statistics:** probes  $H(z)$
- **Other Methods**

# The Origin of Baryon Acoustic Oscillations

- At the last scattering of CMB photons, the acoustic oscillations in the photon-baryon fluid became frozen and imprinted on
  - CMB (acoustic peaks in the CMB)
  - Matter distribution (BAO in the galaxy power spectrum)
- The BAO scale is the sound horizon scale at the drag epoch
  - The drag epoch occurred shortly after decoupling of photons
  - WMAP data give  $s = 153.3 \pm 1.7$  Mpc,  $z_d = 1019.6 \pm 1.4$   
*(Komatsu et al. 2011)*

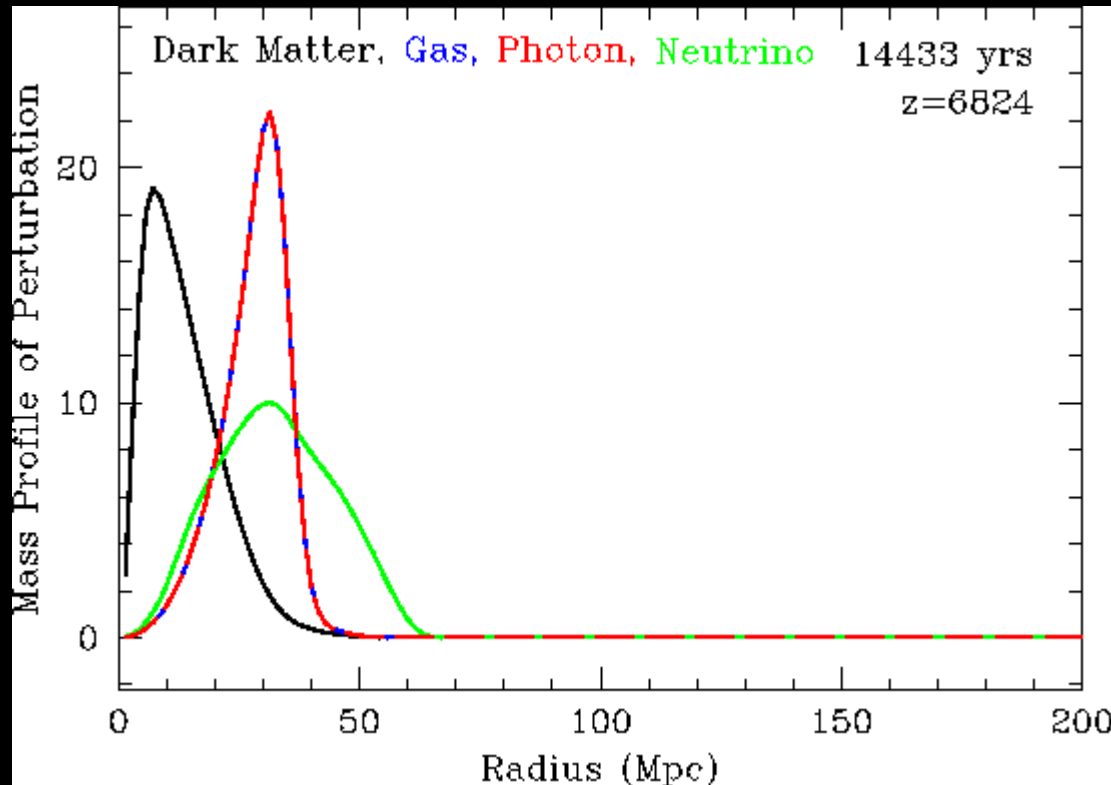
# The Drag Epoch

- The BAO scale is the sound horizon scale at the drag epoch, when photon pressure can no longer prevent gravitational instability in baryons.
  - Epoch of photon-decoupling:  $\tau(z_*)=1$
  - Drag epoch:  $\tau_b(z_d)=1$ ,  $z_d < z_*$
  - The higher the baryon density, the earlier baryons can overcome photon pressure.
    - $R_b = (3\rho_b)/(4\rho_\gamma) = 31500\Omega_b h^2 / [(1+z)(T_{\text{CMB}}/2.7\text{K})^4]$
    - $z_d = z_*$  only if  $R_b = 1$
    - Our universe has low baryon density:  $R_b(z_*) < 1$ , thus  $z_d < z_*$   
(Hu & Sugiyama 1996)

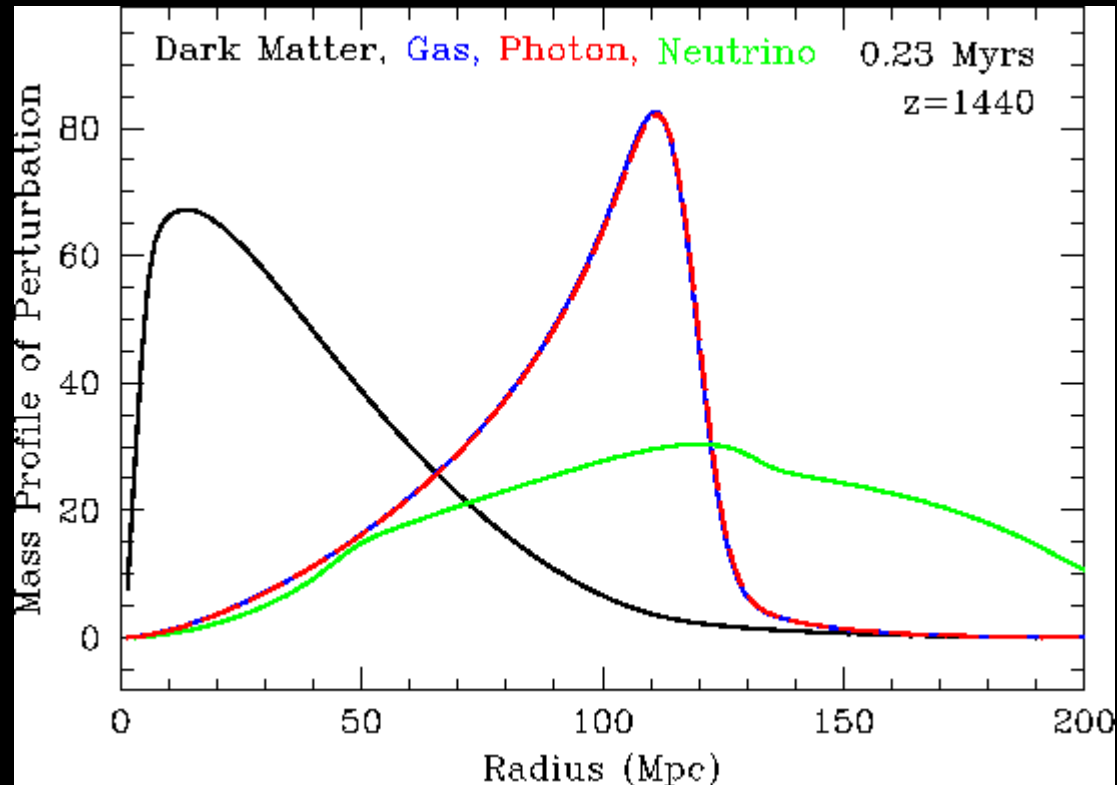
# The Generation of the BAO Peak

- Illustrated via the linear-theory response to an initially point-like overdensity at the origin.
- Each panel shows the radial perturbed mass profile in each of the four species: dark matter (black), baryons (blue), photons (red), and neutrinos (green).
- All perturbations are fractional for that species. We have multiplied the radial density profile of the perturbation by the square of the radius in order to yield the mass profile.
- We begin with a compact but smooth profile at the origin, hence the mass profiles go to zero there.

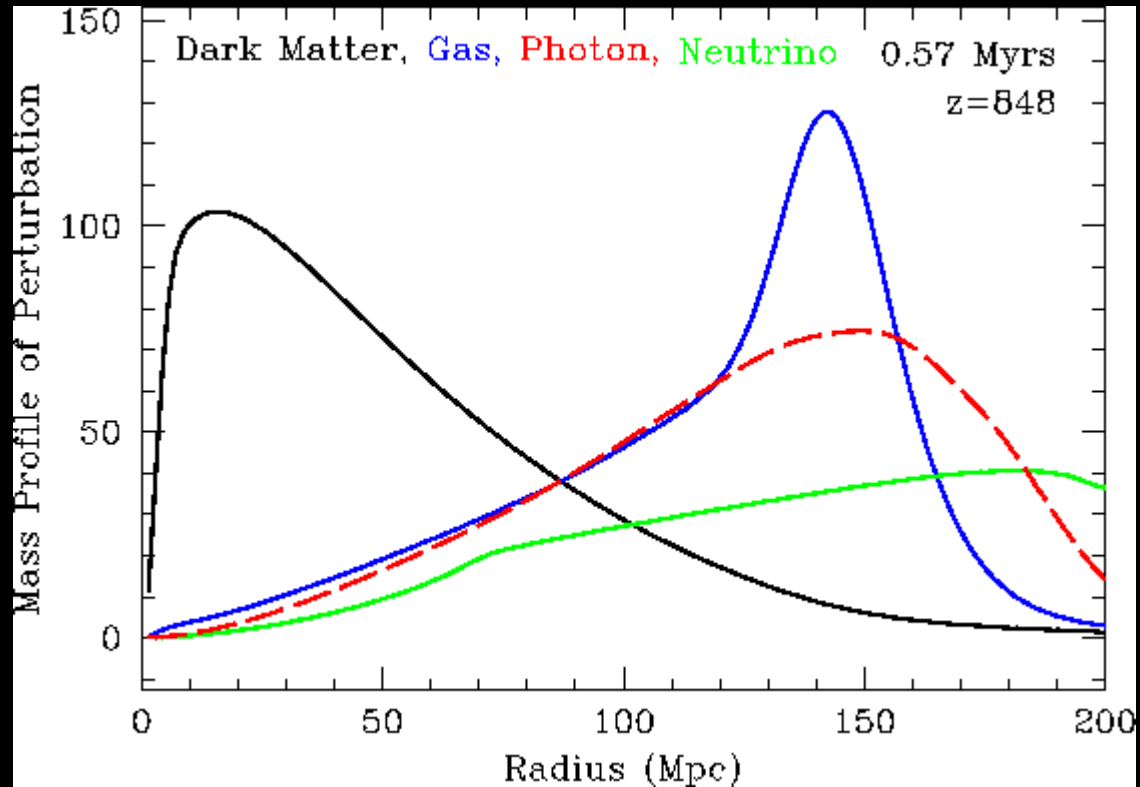
Eisenstein et al. (2007)



a) Near the initial time, the photons and baryons are tightly coupled in a spherical traveling wave.

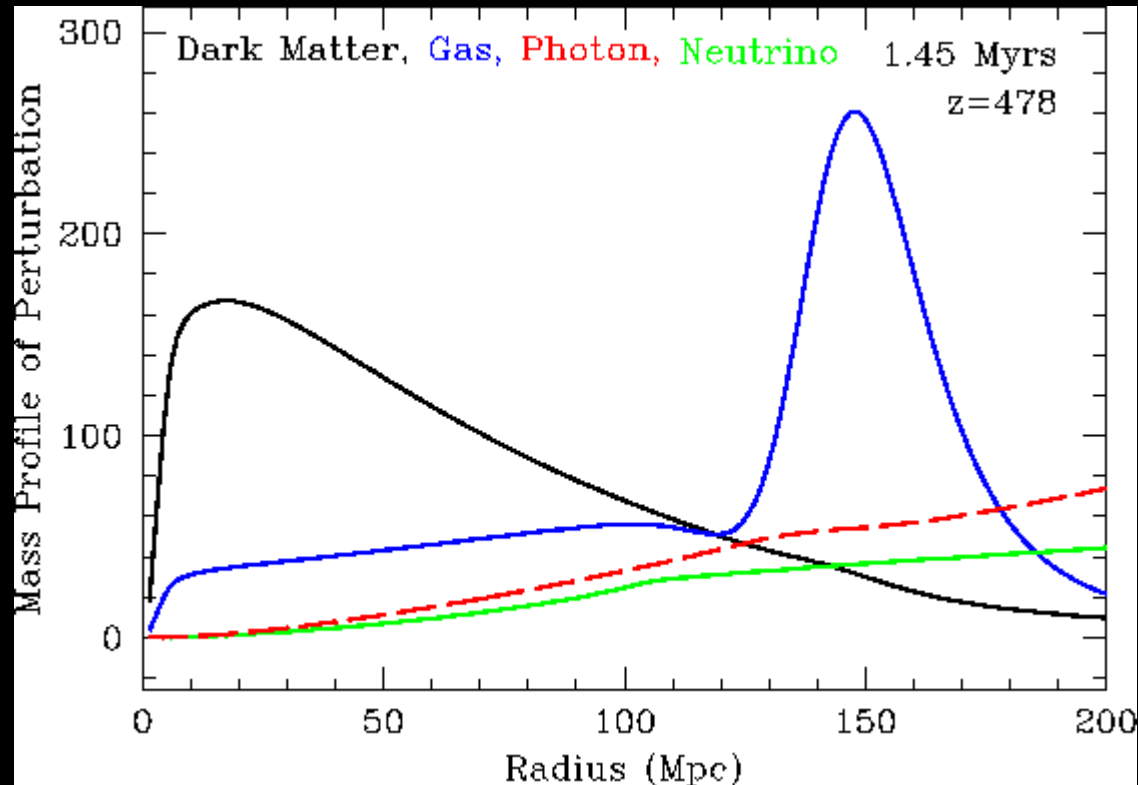


b) The outward-going wave of baryons and relativistic species increases the perturbation of the cold dark matter, similar to raising a wake.

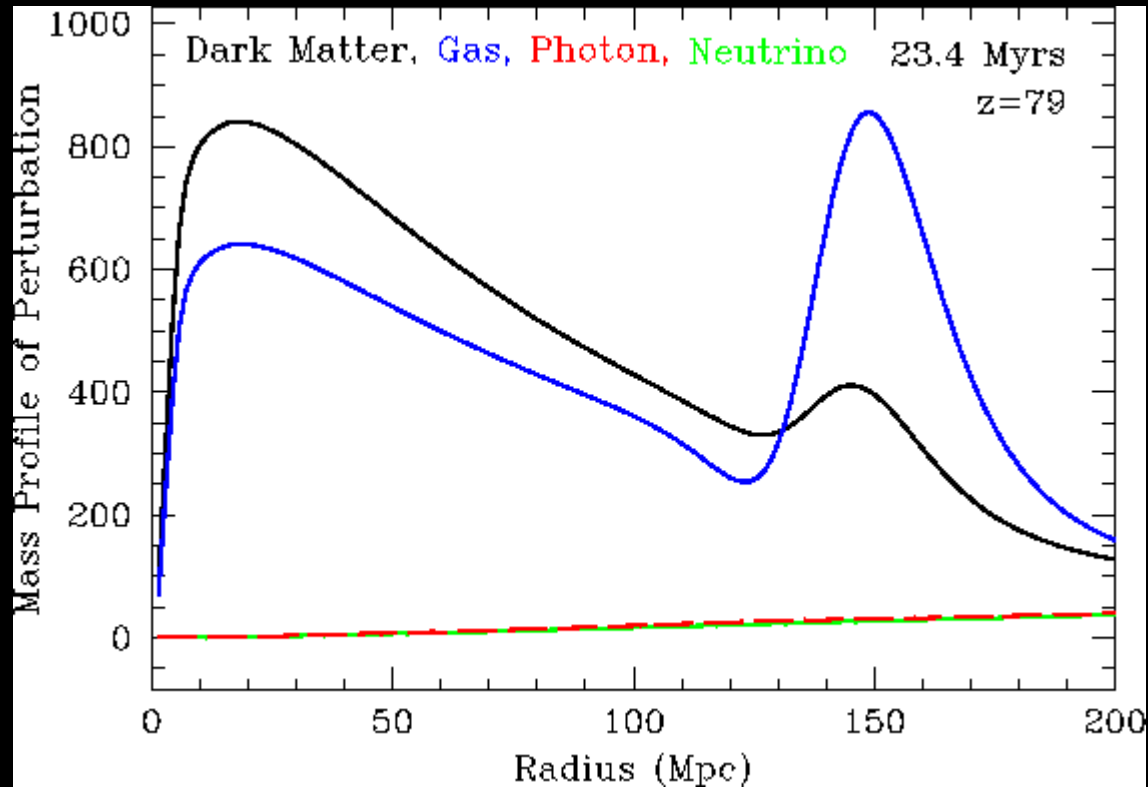


c) At recombination, the photons decouple from the baryons.

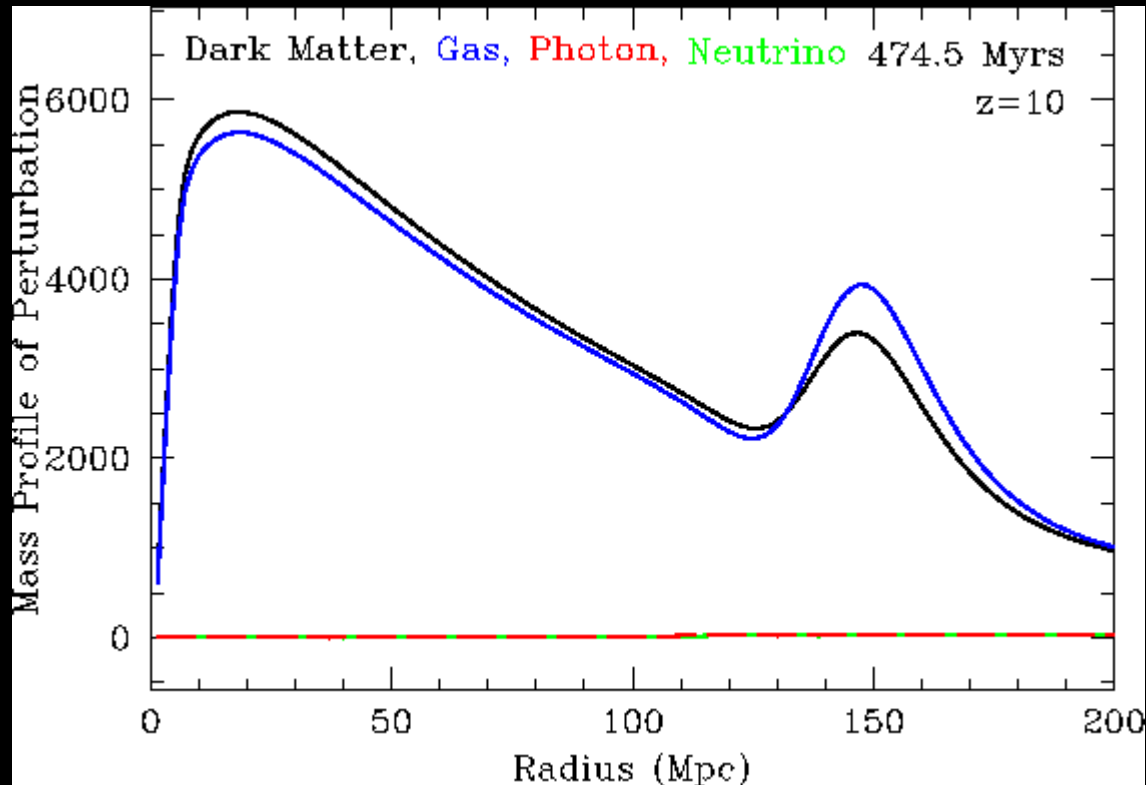




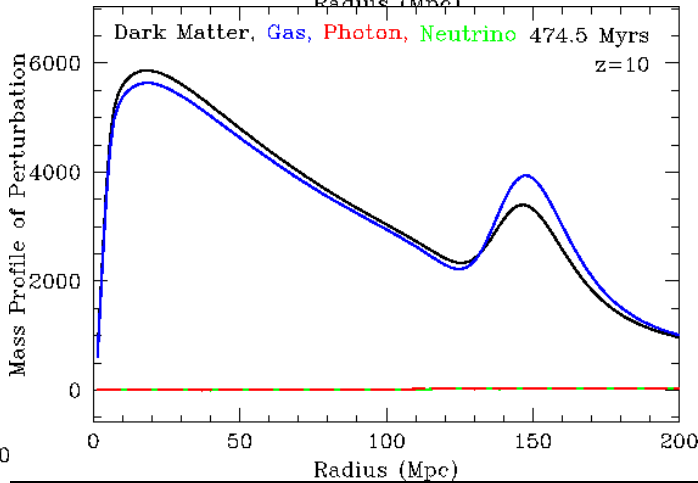
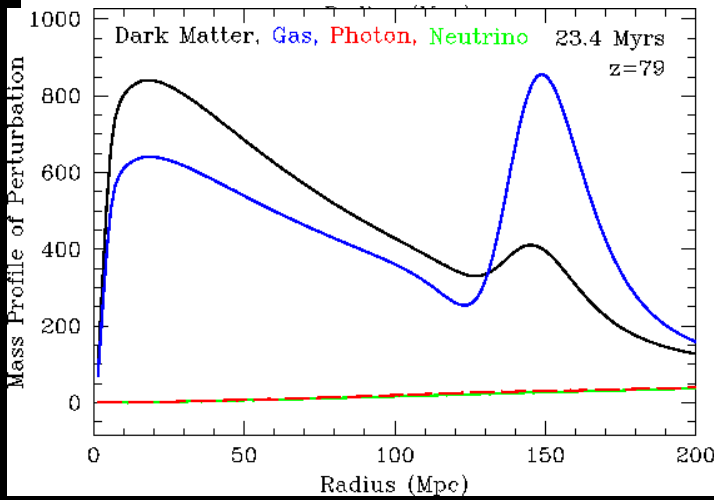
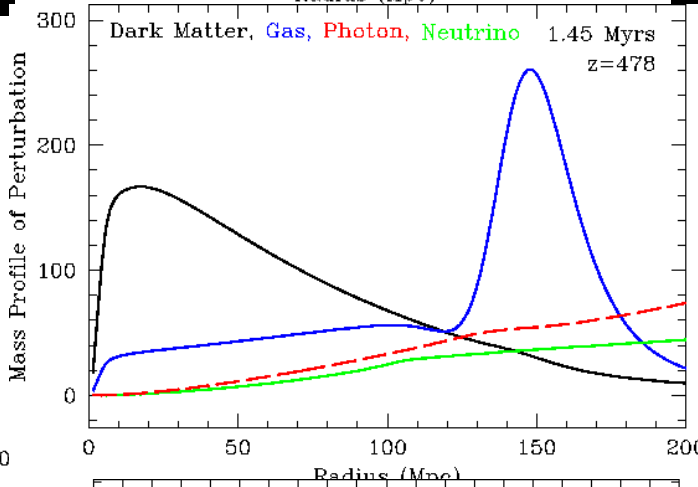
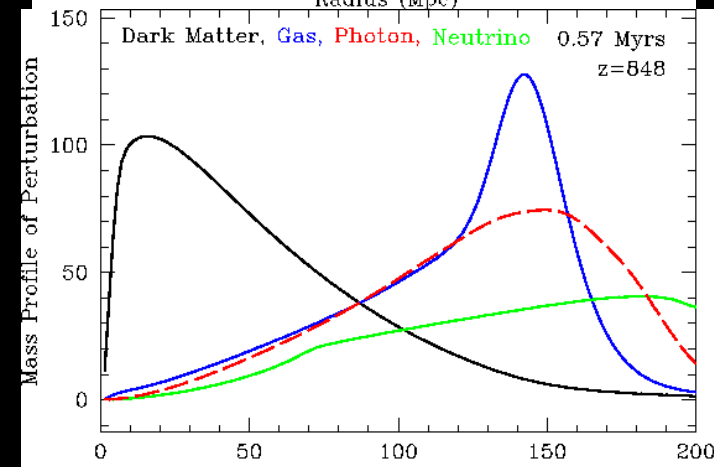
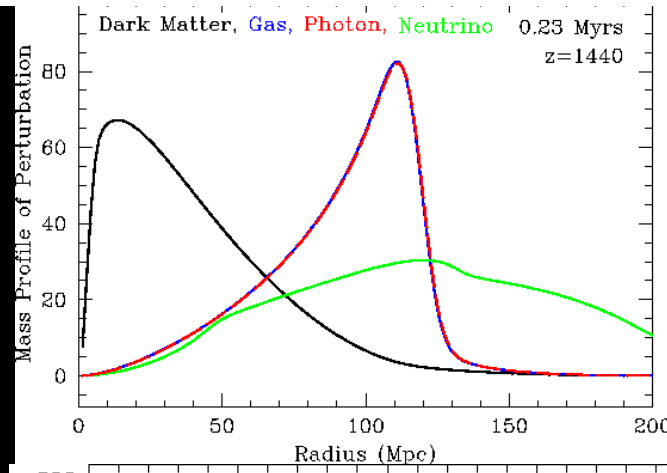
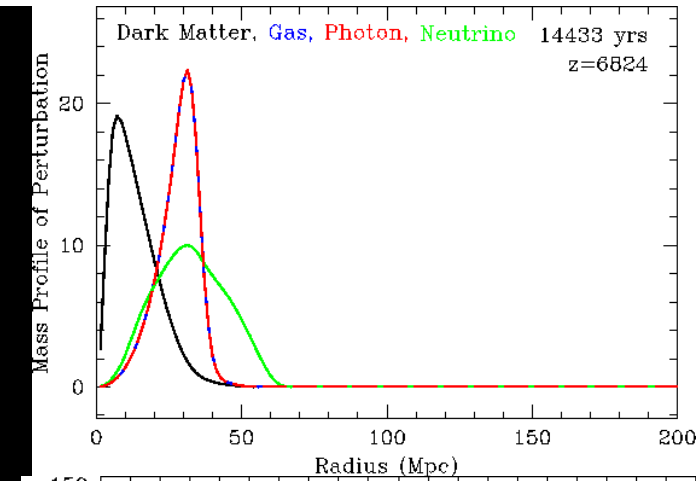
d) With recombination complete, the CDM perturbation is near the origin, while the baryonic perturbation is in a shell of 150 Mpc.



e) With pressure forces now small, baryons and dark matter are attracted to these overdensities by gravitational instability.



f) Because most of the growth is drawn from the homogeneous bulk, the baryon fraction converges toward the cosmic mean at late times. Galaxy formation is favored near the origin and at a radius of 150 Mpc.



Eisenstein et al.  
(2007)

# BAO as a Standard Ruler

Blake & Glazebrook 2003

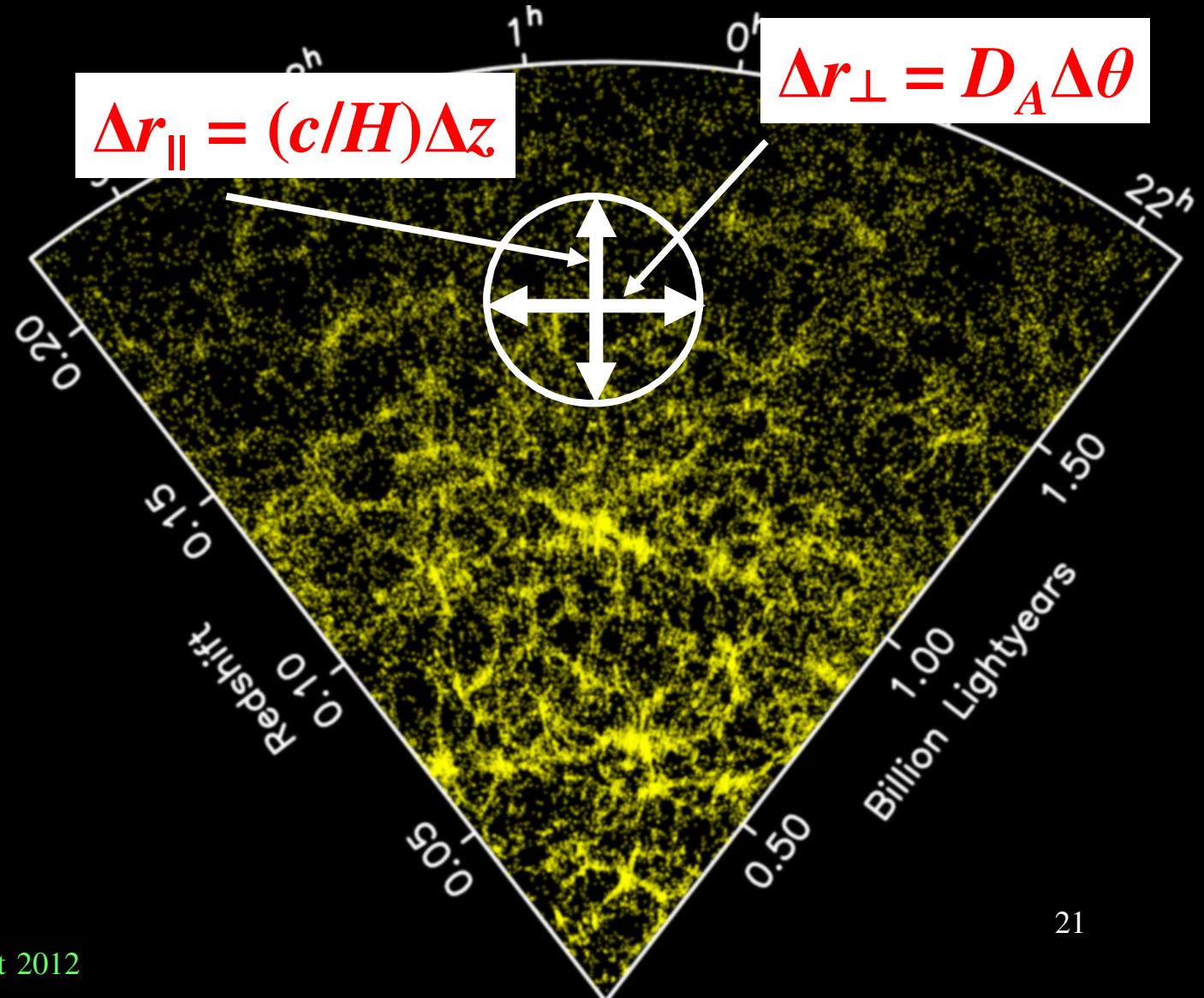
Seo & Eisenstein 2003

BAO “wavelength”  
in radial direction  
in slices of  $z : H(z)$

BAO “wavelength”  
in transverse  
direction in slices  
of  $z : D_A(z)$

BAO systematics:

- Bias
- Redshift-space distortions
- Nonlinear effects



# **BAO Advantages and Challenges**

- **Advantages:**
  - **Observational requirements are least demanding among all methods (redshifts and positions of galaxies are easy to measure).**
  - **Systematic uncertainties (bias, nonlinear clustering, redshift-space distortions) can be made small through theoretical progress in numerical modeling of data.**
- **Challenges:**
  - **Full modeling of systematic uncertainties**
  - **Translate forecasted performance into reality**

# Use galaxy clustering to differentiate dark energy and modified gravity

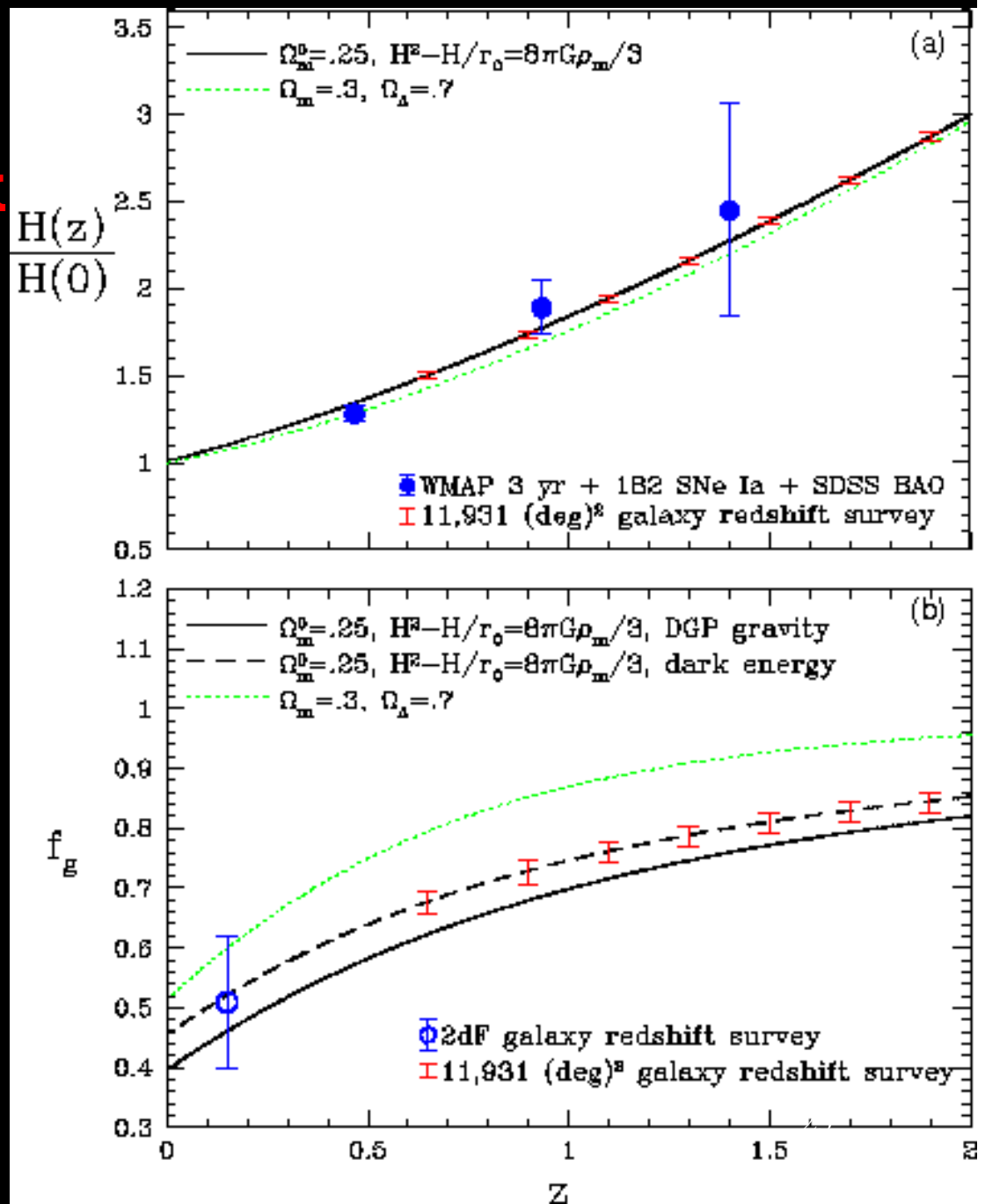
Measuring redshift-space distortions  $\beta(z)$  and bias  $b(z)$  allows us to measure  $f_g(z) = \beta(z)b(z)$

$$[f_g = d \ln \delta / d \ln a]$$

$H(z)$  and  $f_g(z)$  allow us to differentiate dark energy and modified gravity.

Wang (2008)

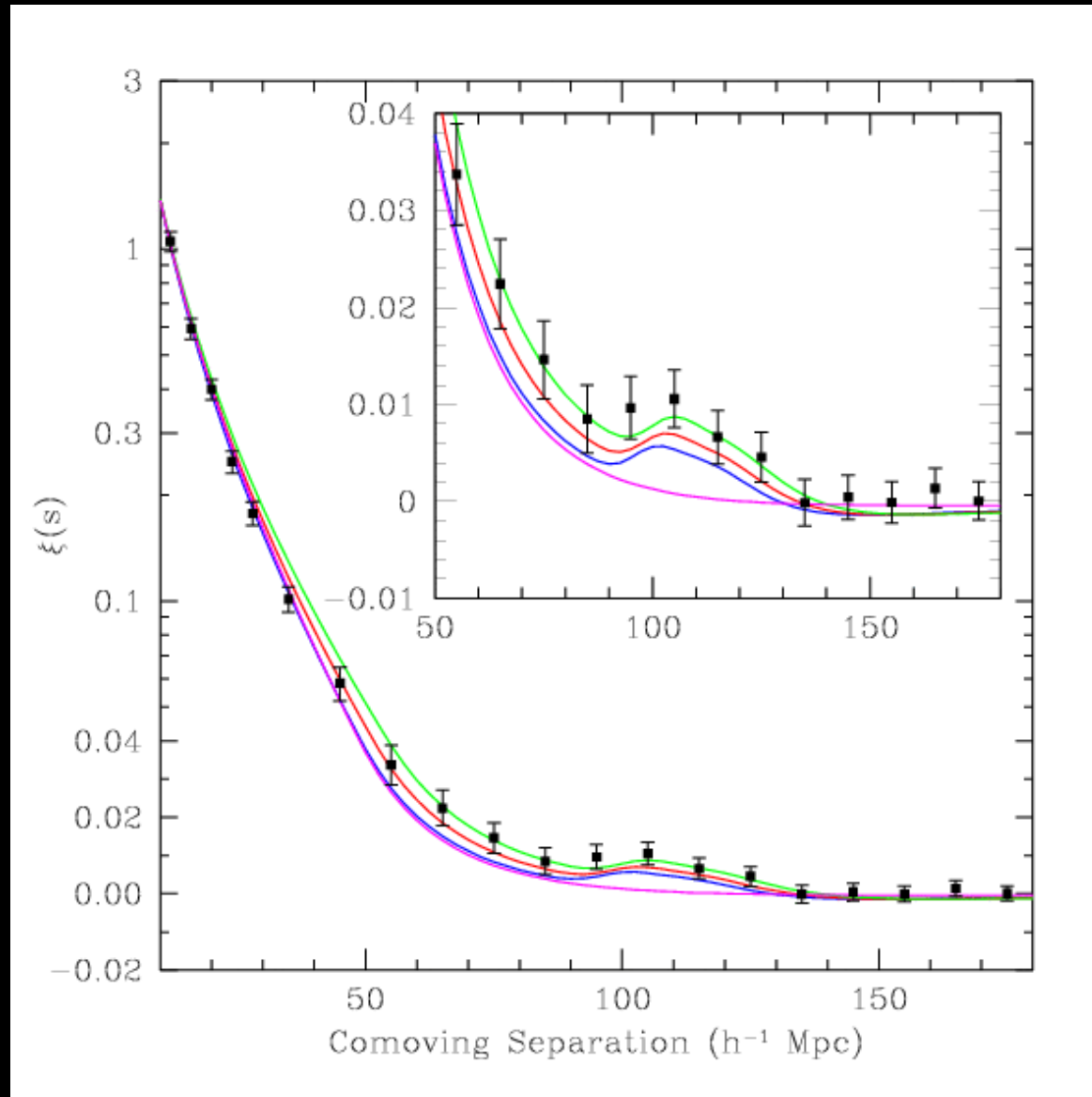
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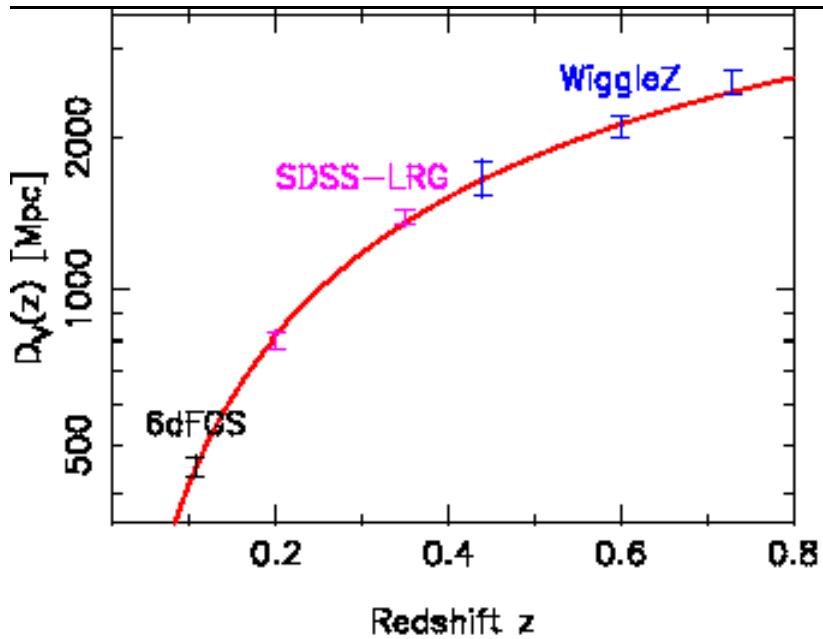


## **II. Current BAO/GC Data**



# Detection of BAO in the SDSS data [Eisenstein et al. 2005]



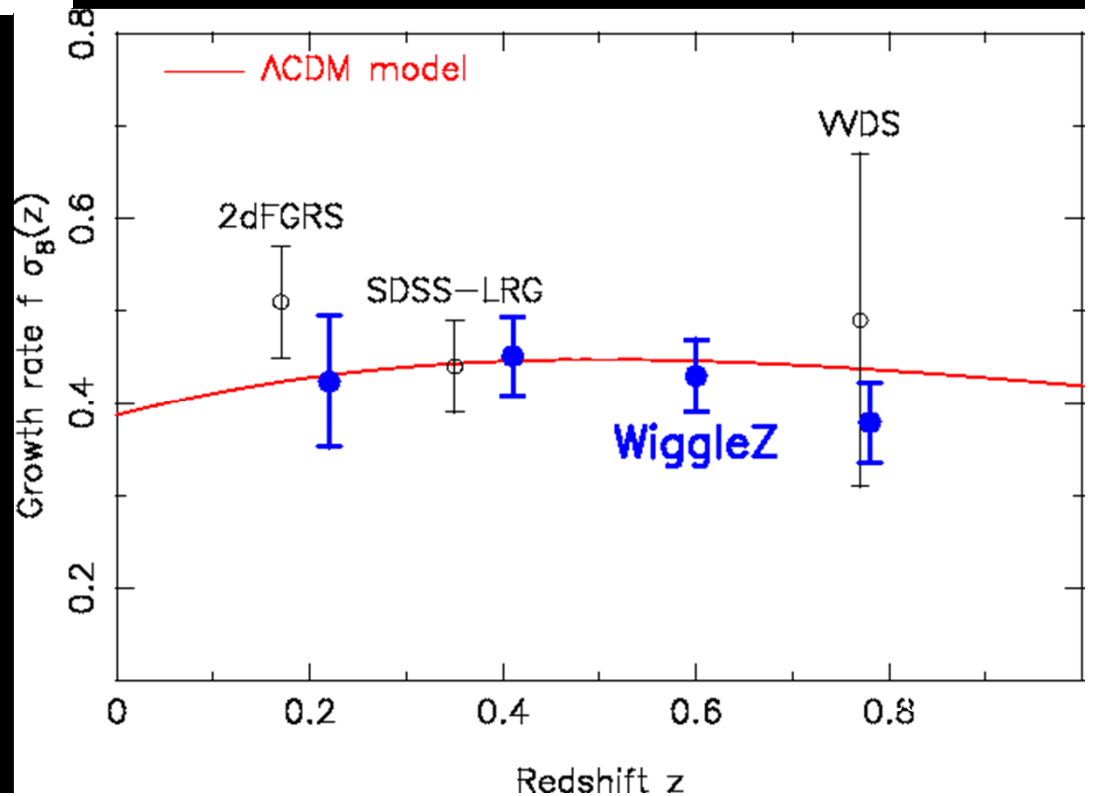


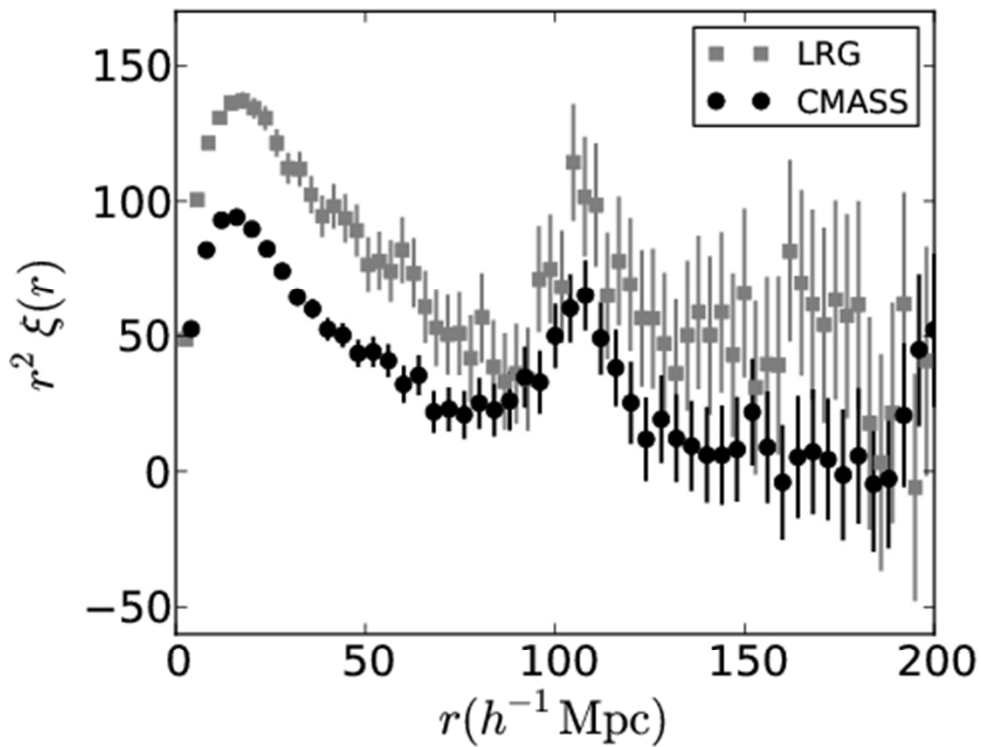
# Results from WiggleZ

Right: background cosmology fixed.

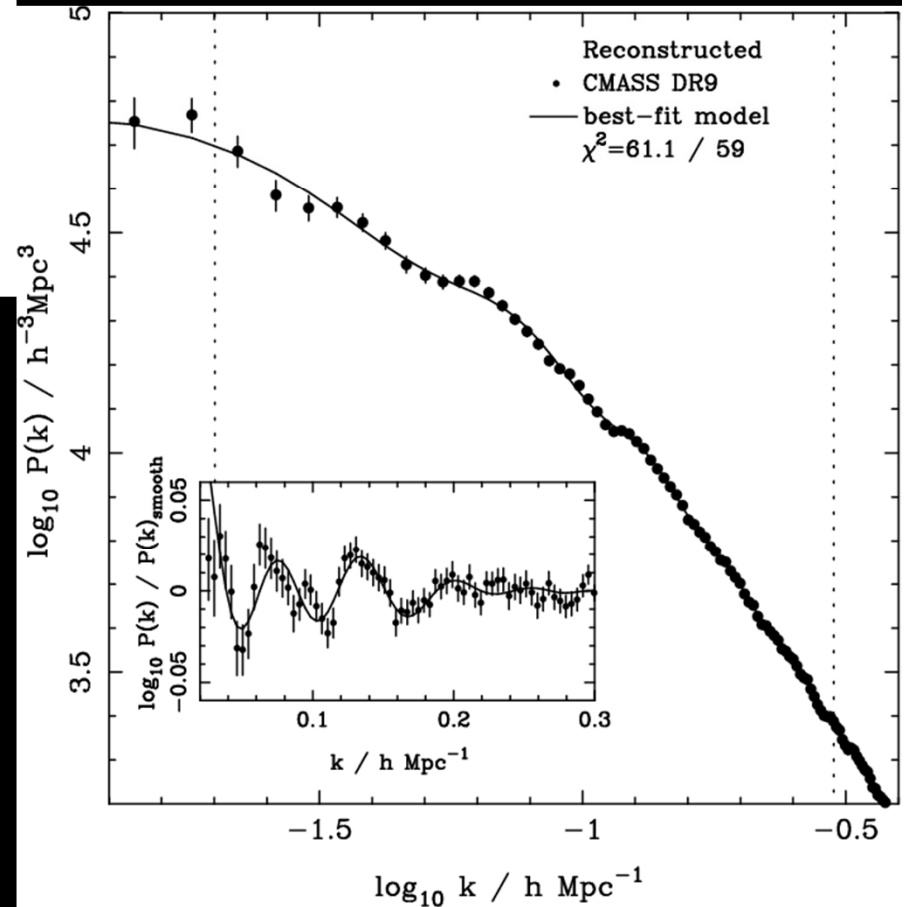
Blake et al. (2011ab)

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# Results from SDSS III (BOSS)



Spherically-averaged galaxy correlation function (top) and galaxy power spectrum (right).

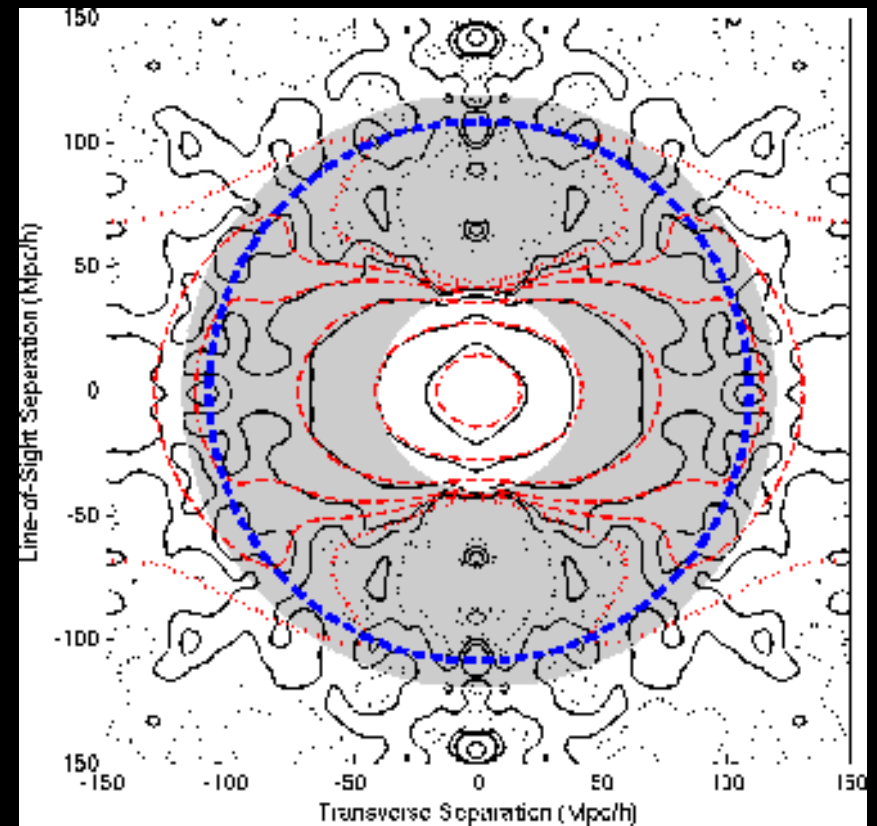
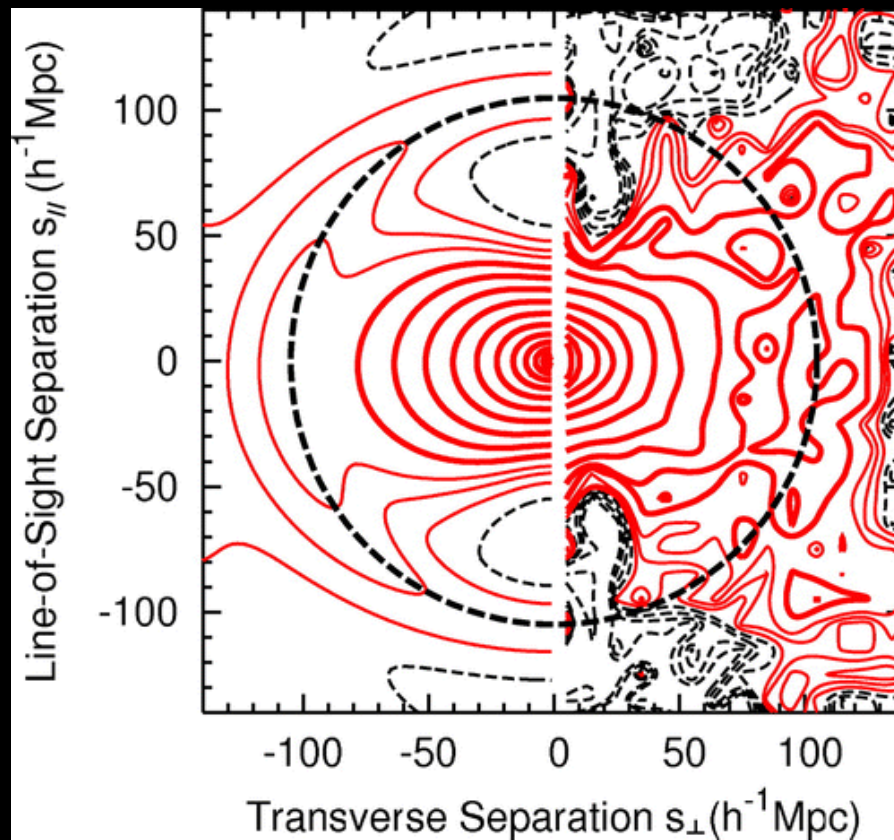
Anderson et al. (2012)

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# Challenge in 2D: Proper Modeling of SDSS Data

*Okumura et al. (2008)*

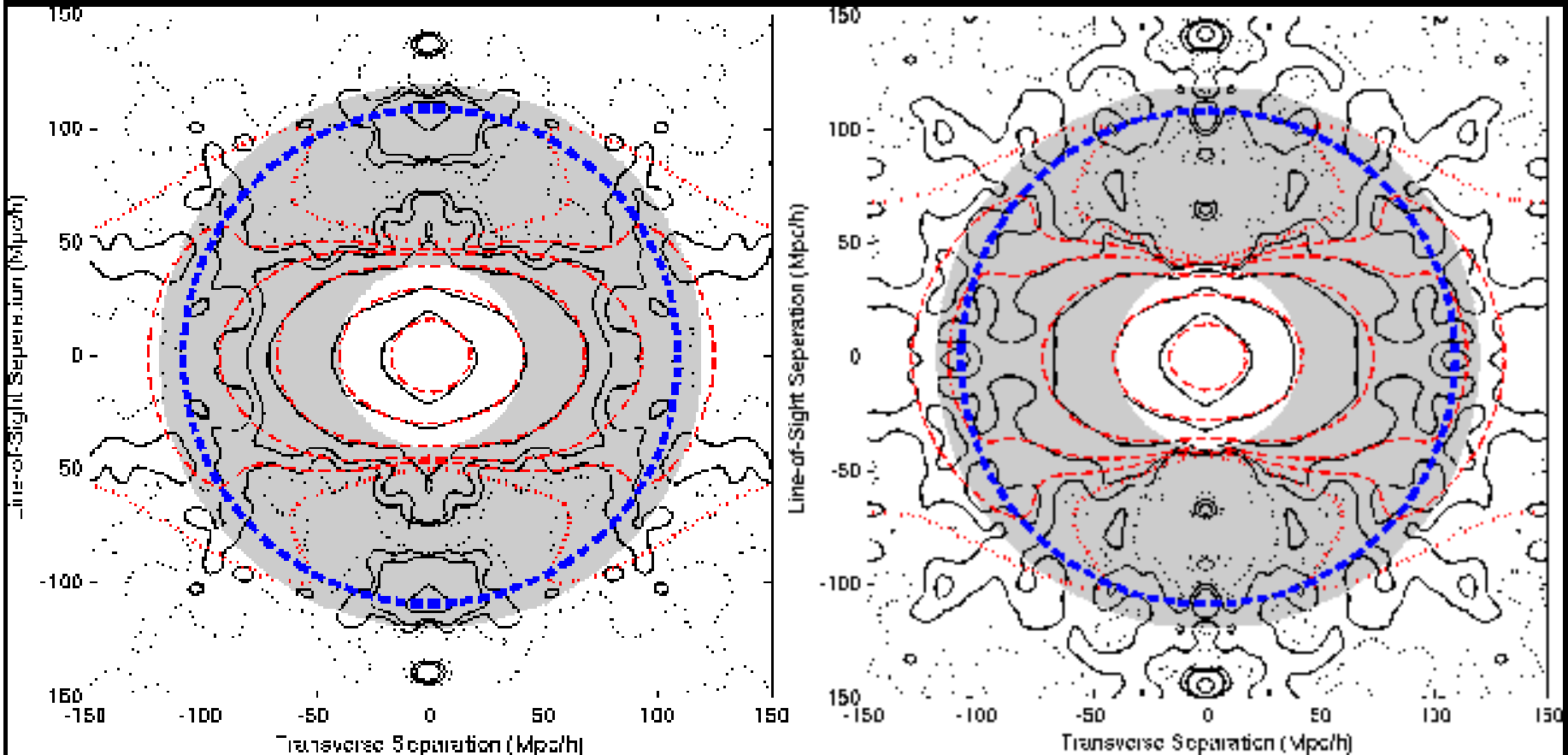
*Chuang & Wang, arXiv:1102.2251*



# First Measurements of $H(z)$ & $D_A(z)$ from Data

*LasDamas mock catalog*

*SDSS LRG catalog*

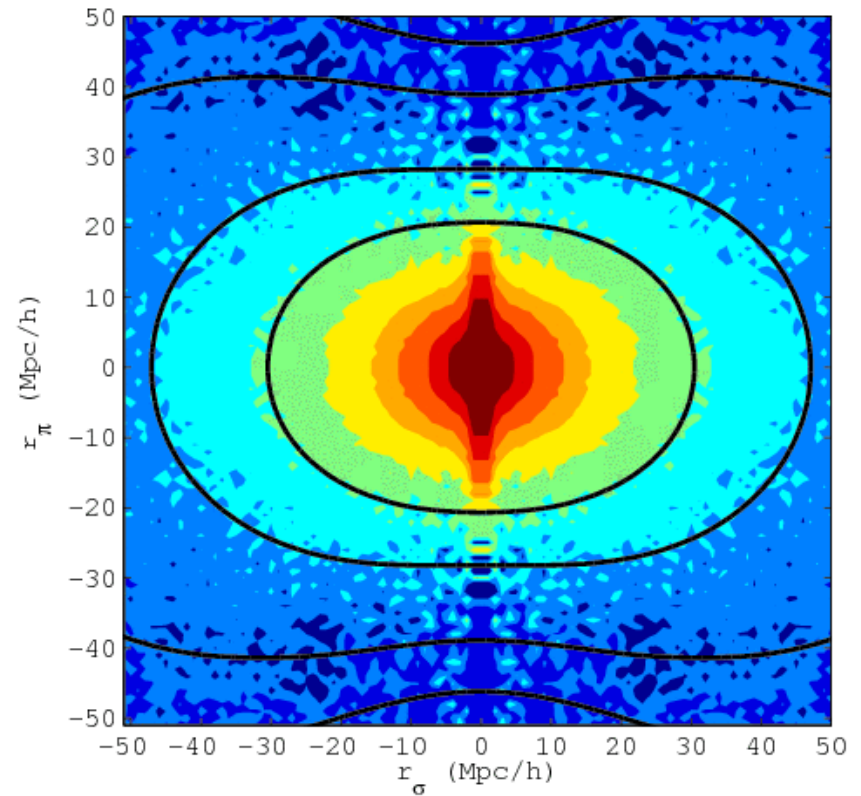
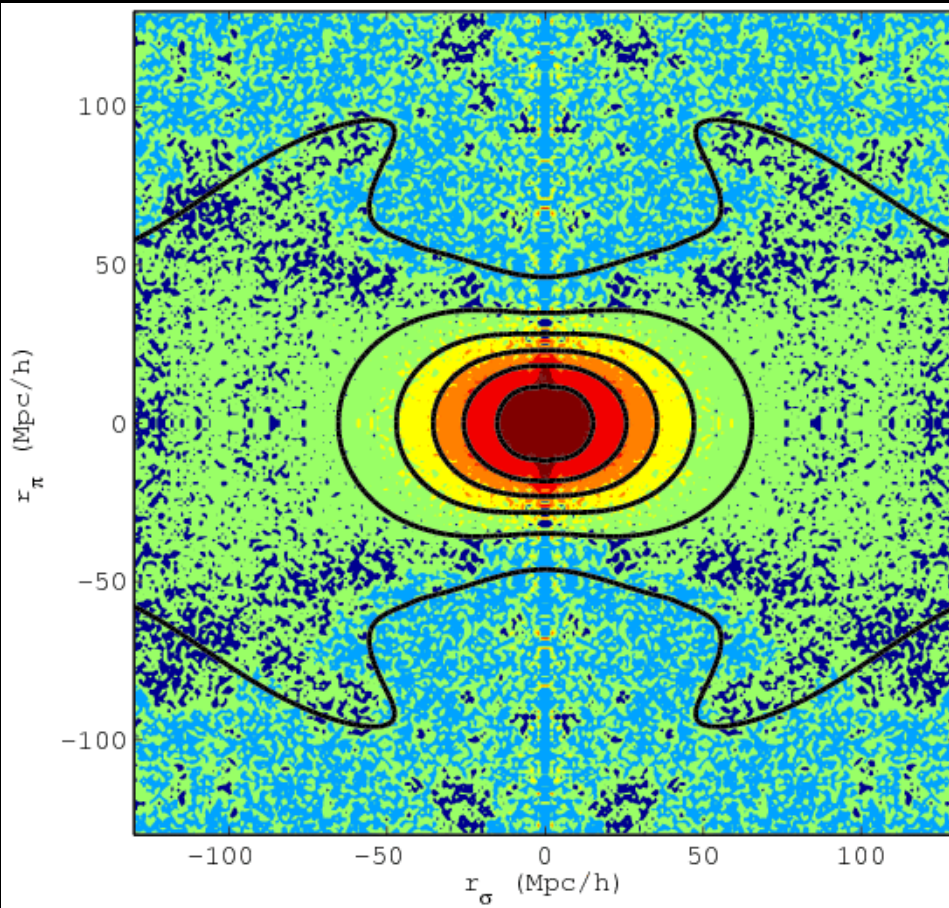


$$x_h(z) = H(z)s = 0.04339 \pm 0.00178 \text{ (4.1\%)}; x_d(z) = D_A(z)/s = 6.599 \pm 0.263 \text{ (4.0\%)} \\ r(x_h, x_d) = 0.0604 \quad (z=0.35, s: \text{BAO scale, i.e., sound horizon at the drag epoch})$$

*Chuang & Wang, arXiv:1102.2251*

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# BOSS Results at $z=0.57$

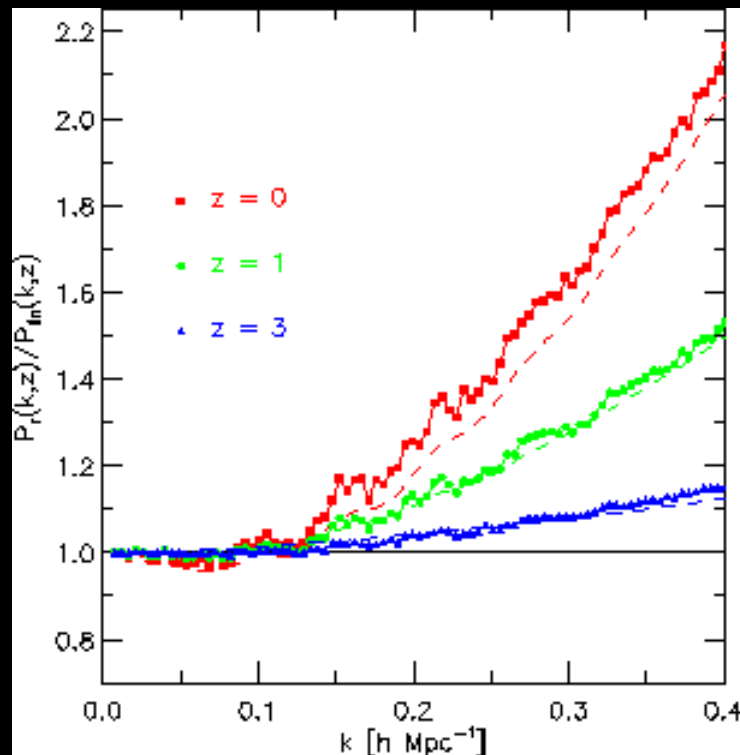


*Reid et al. (2012) measured  $H(z)$ ,  $D_A(z)$ ,  $f_g(z)\sigma_8(z)$  assuming WMAP7 priors*

# III. Systematic Uncertainties

# BAO Systematic Effect: Nonlinear Gravitational Clustering

- Mode-coupling
  - Small scale information in  $P(k)$  destroyed by cosmic evolution due to mode-coupling (nonlinear modes); intermediate scale  $P(k)$  also altered in shape
  - Its effect can be reduced by: (1) Density field reconstruction (Eisenstein et al. 2007)



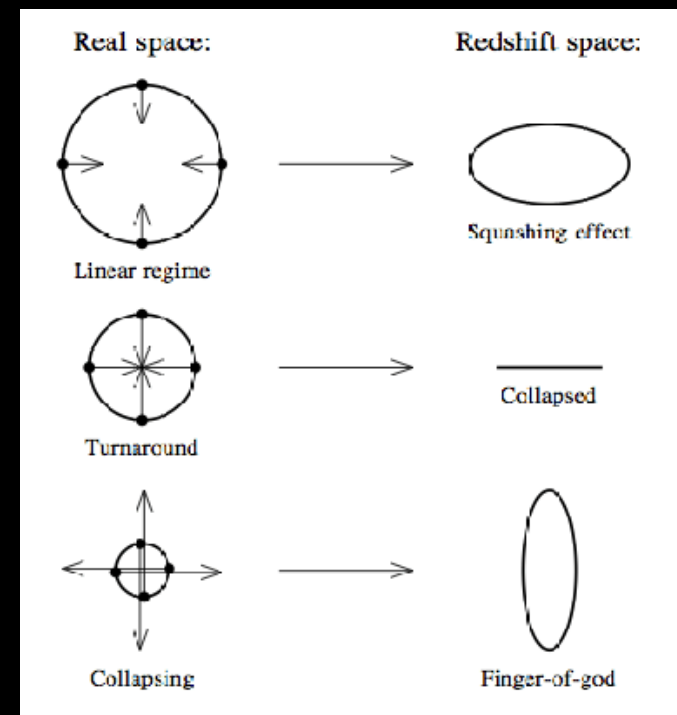
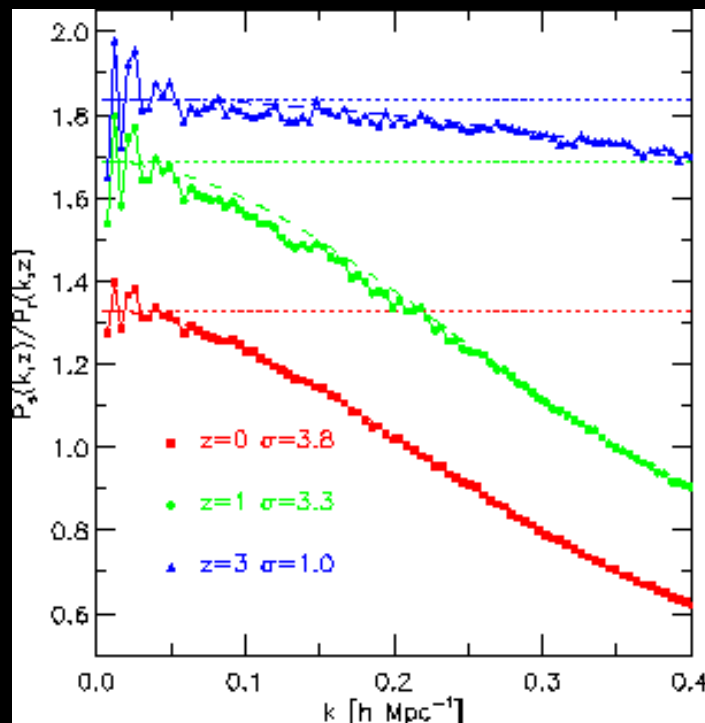
- (2) Extracting “wiggles only” constraints (discard  $P(k)$  shape info)
- (3) Full modeling of correlation function (Sanchez et al. 2008)

Ratio of nonlinear and linear  $P(k)$   
Horizontal line: no nonlinearity  
Dashed lines: model  
Dark matter only  
(Augulo et al. 2008)



# BAO Systematic Effect: Redshift Space Distortions

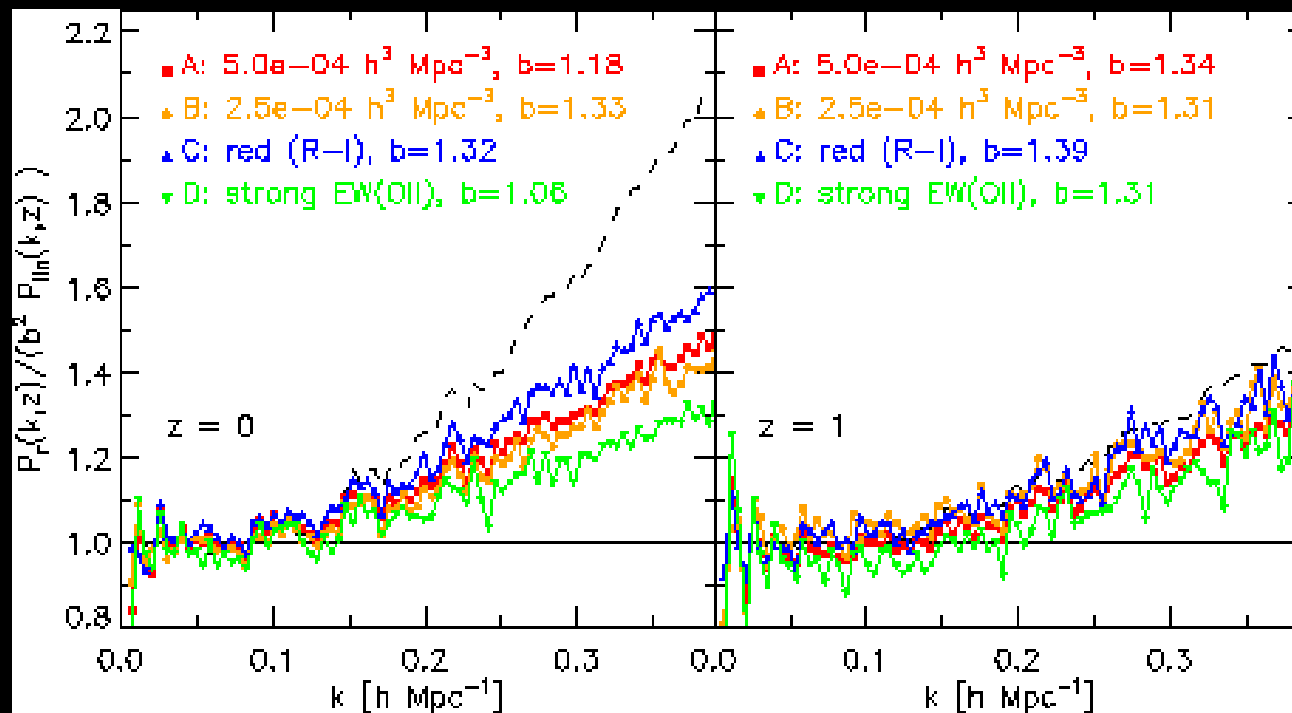
- Artifacts not present in real space
  - Large scales: coherent bulk flows (out of voids and into overdense regions). These boost BAO; can be used to probe growth rate  $f_g(z)$
  - Small scales: smearing due to galaxy random motion (“Finger of God” effect)



➔ Left: Ratio of redshift-space and real-space power spectra. Horizontal lines: coherent bulk flows only. Dashed lines: model (Angulo et al. 2008)

# BAO Systematic Effect: Galaxy Clustering Bias

- How galaxies trace mass distribution
  - Could be scale-dependent
  - Only modeled numerically for a given galaxy sample selection (Angulo et al. 2008)

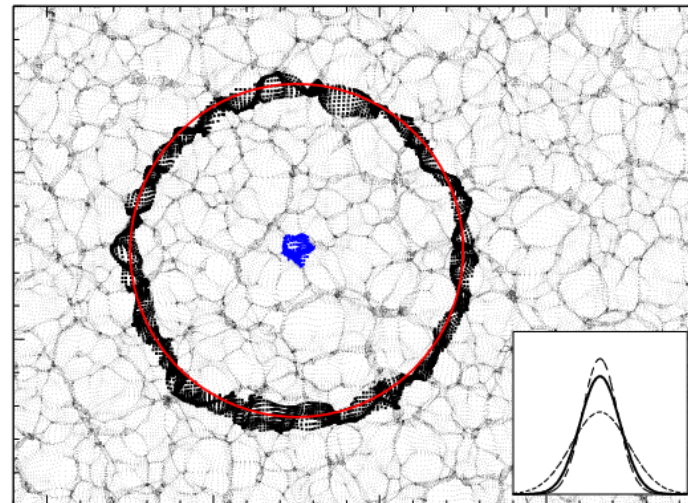
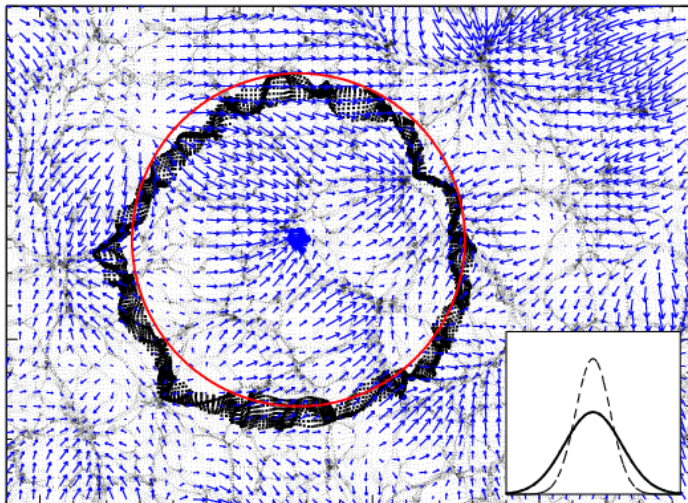
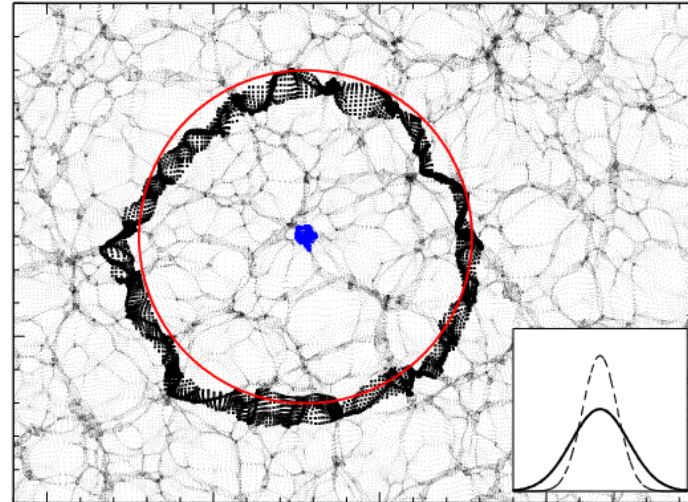
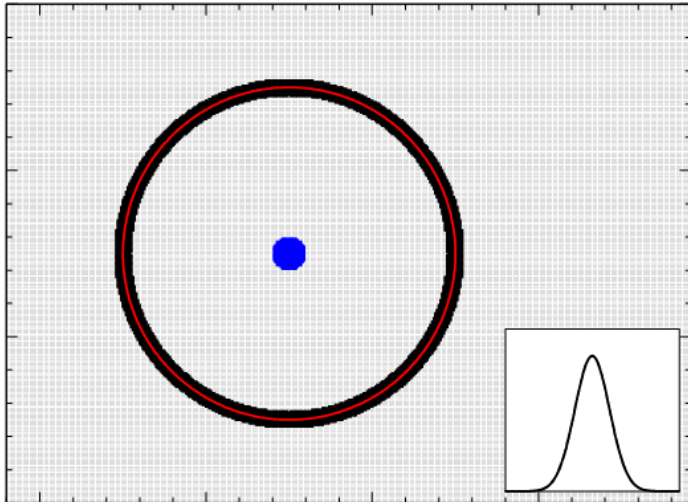


Ratio of galaxy power spectrum over linear matter power spectrum  
Horizontal lines: no scale dependence in bias. Dashed lines: model

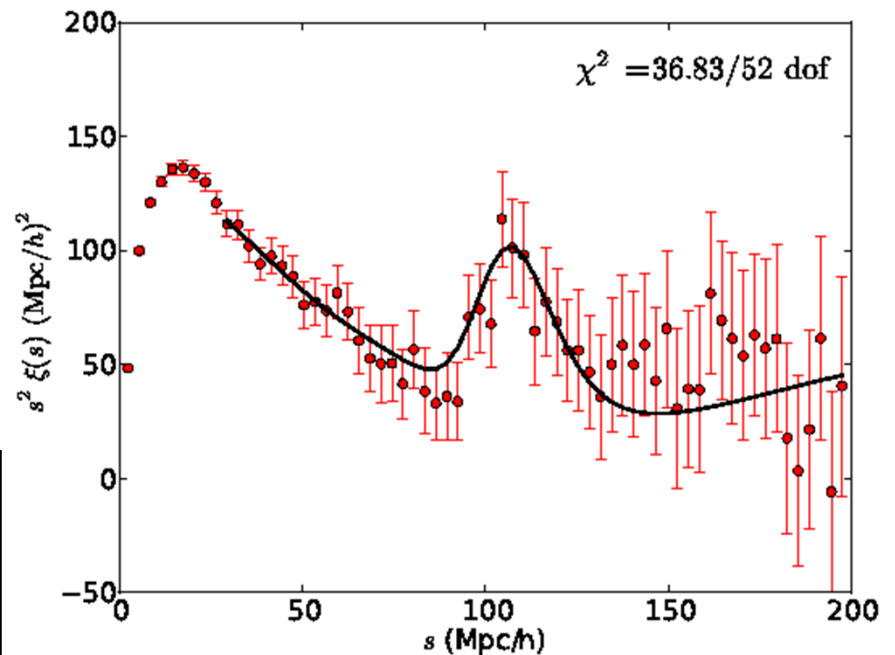
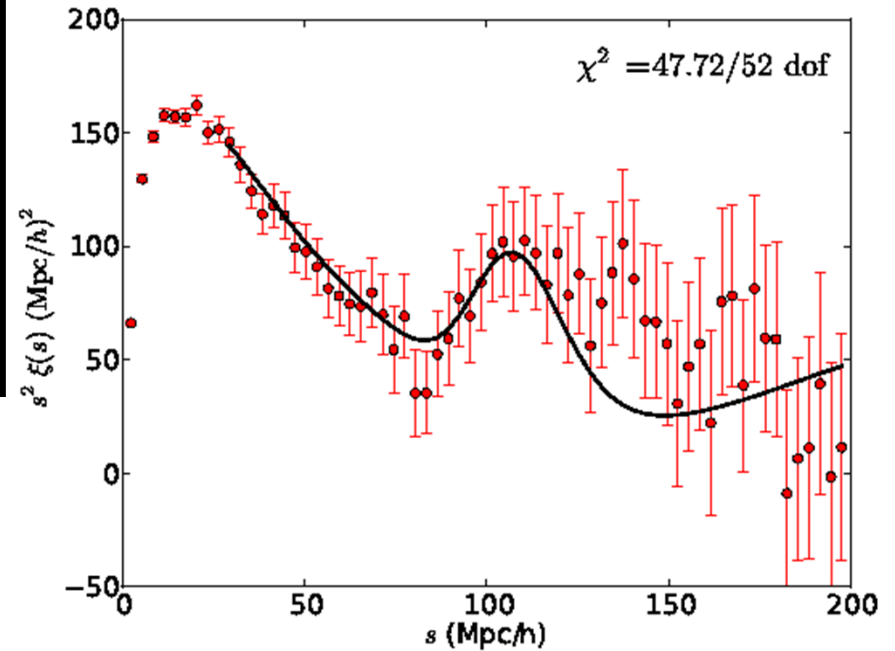
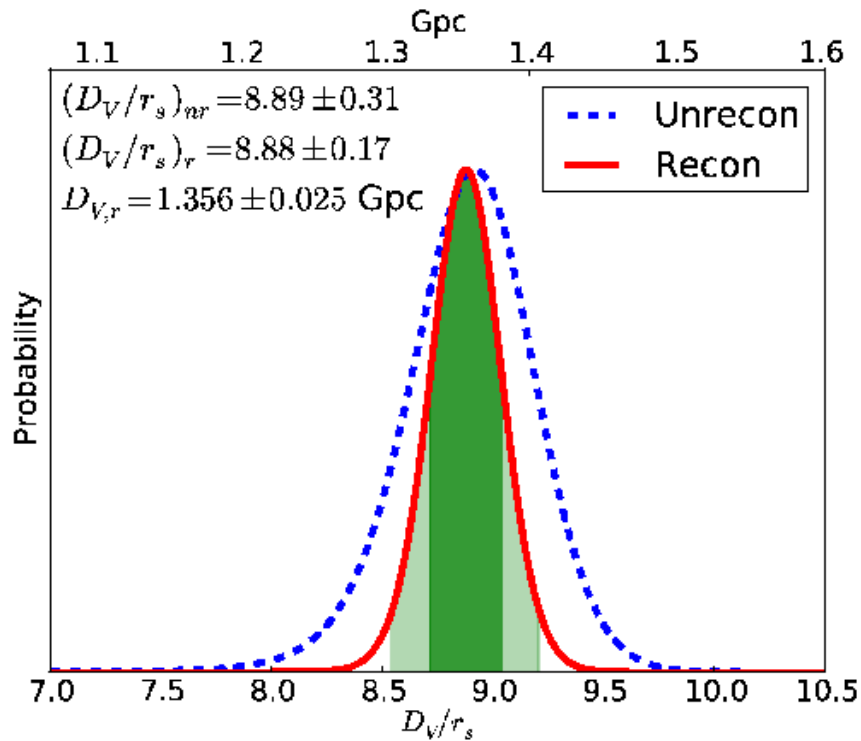
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# **IV. Modeling of BAO/GC Data**

# Reducing NL: BAO Reconstruction



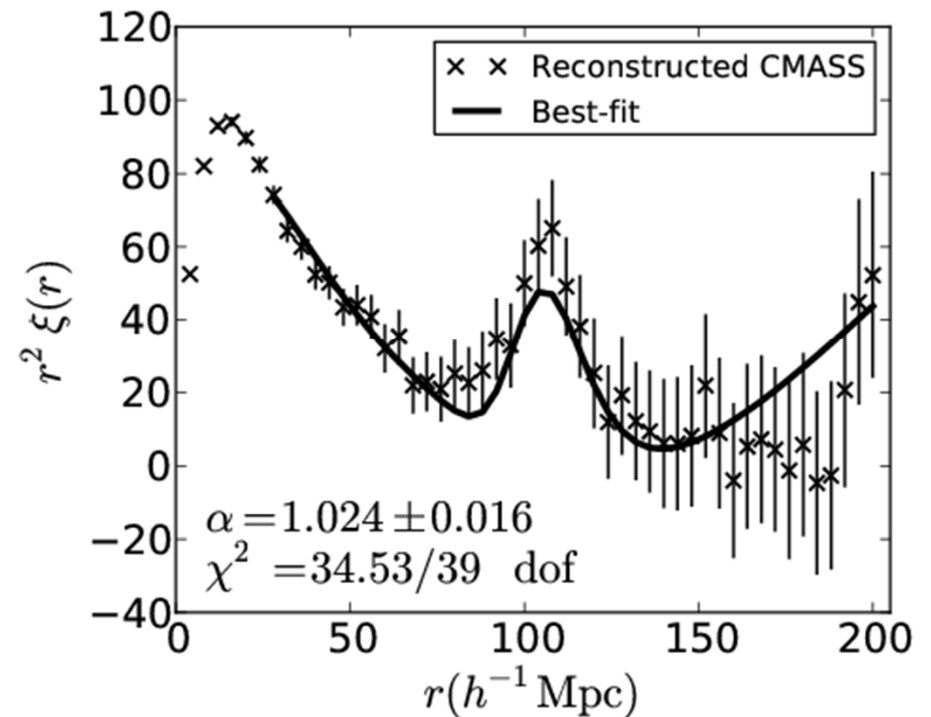
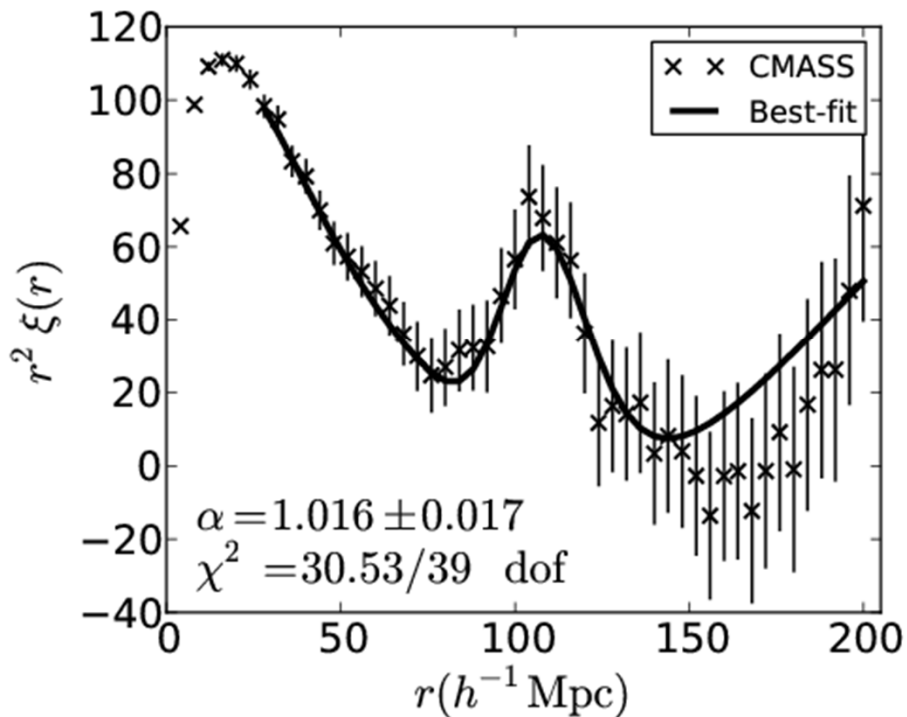
# BAO Reconstruction With SDSS DR7 LRGs



Padmanabhan et al. (2012)

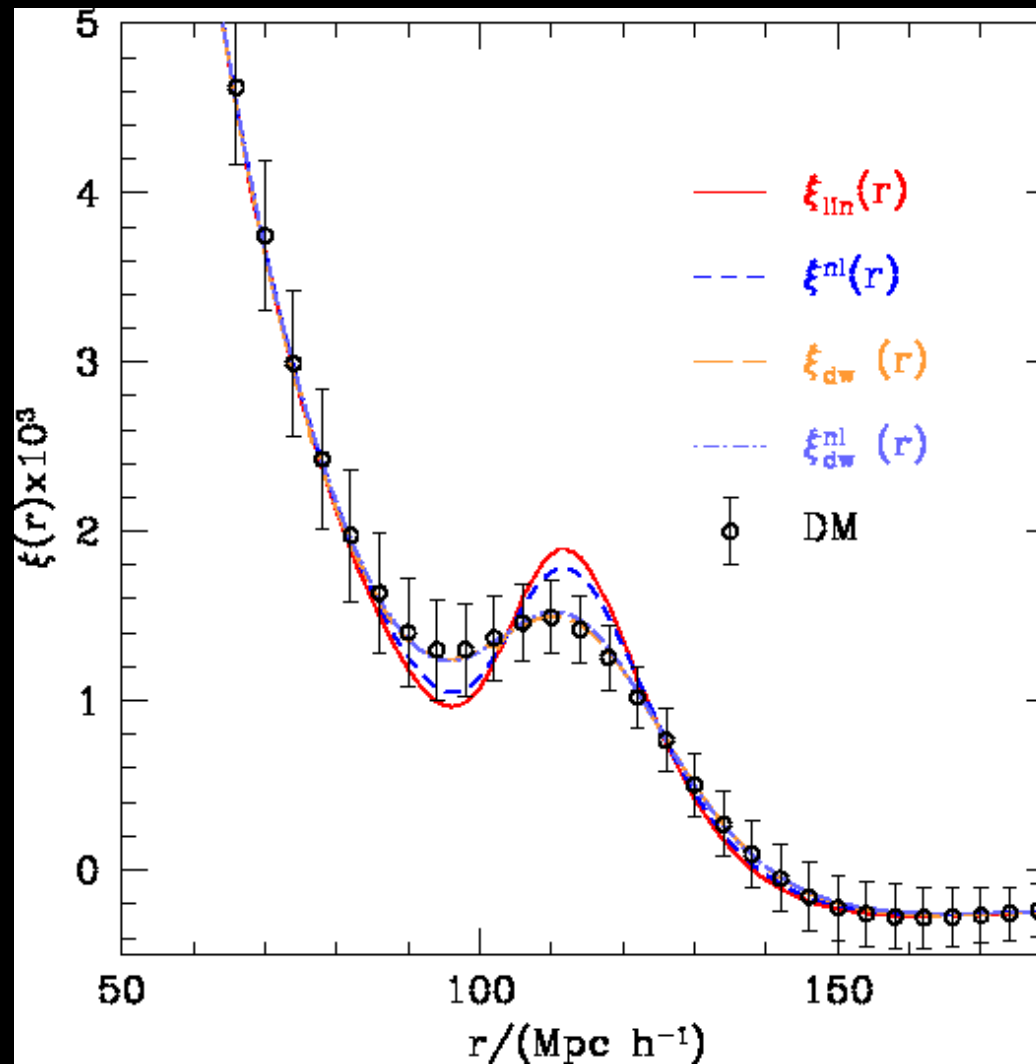
Yun Wang, August 2012

# BAO Reconstruction with BOSS Data



Anderson et al. (2012)

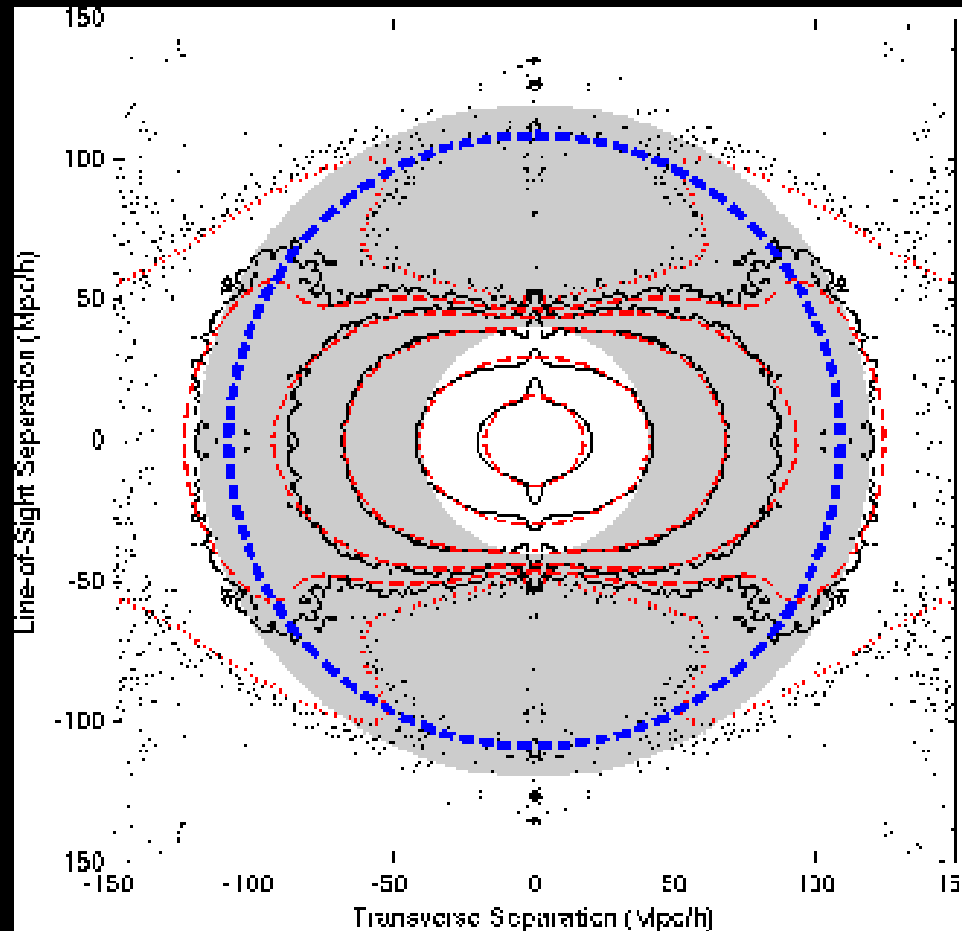
# Full Modeling of Galaxy Correlation Function



Sanchez, Baugh, Angulo (2008)

# Status of the Modeling

*Average of 160 LasDamas SDSS LRG mock catalogs*



*Chuang & Wang, arXiv:1102.2251*



# **V. Forecast of Future Galaxy Redshift Surveys**

# DE Forecasting from GC

- Propagate the measurement errors in  $\ln P_g(k)$  into measurement errors for the parameters  $p_i$ :

$$F_{ij} = \int_{k_{\min}}^{k_{\max}} \frac{\partial \ln P_g(\mathbf{k})}{\partial p_i} \frac{\partial \ln P_g(\mathbf{k})}{\partial p_j} V_{\text{eff}}(\mathbf{k}) \frac{d\mathbf{k}^3}{2(2\pi)^3}$$

- $\Delta \ln P_g(k) \propto [V_{\text{eff}}(k)]^{-1/2}$

$$V_{\text{eff}}(\mathbf{k}) = \int d\mathbf{r}^3 \left[ \frac{n(\mathbf{r}) P_g(k, \mu)}{n(\mathbf{r}) P_g(k, \mu) + 1} \right]^2$$

$$= \left[ \frac{n P_g(k, \mu)}{n P_g(k, \mu) + 1} \right]^2 V_{\text{survey}}$$

$$\mu = \mathbf{k} \cdot \mathbf{r} / kr$$

# Two Approaches:

- “Full  $P(k)$ ” method:

parametrize  $P(k)$  using  $[H(z_i), D_A(z_i), \beta(z_i), \underline{G}(z_i), P_{\text{shot}}^i, n_s, \Omega_m h^2, \Omega_b h^2]$

- BAO “wiggles only”:

$$P(k) \propto P(k_{0.2}, \mu|z) [\sin(x)/x] \cdot \exp[-(k\Sigma_s)^{1.4} - k^2 \Sigma_{nl}^2/2]$$

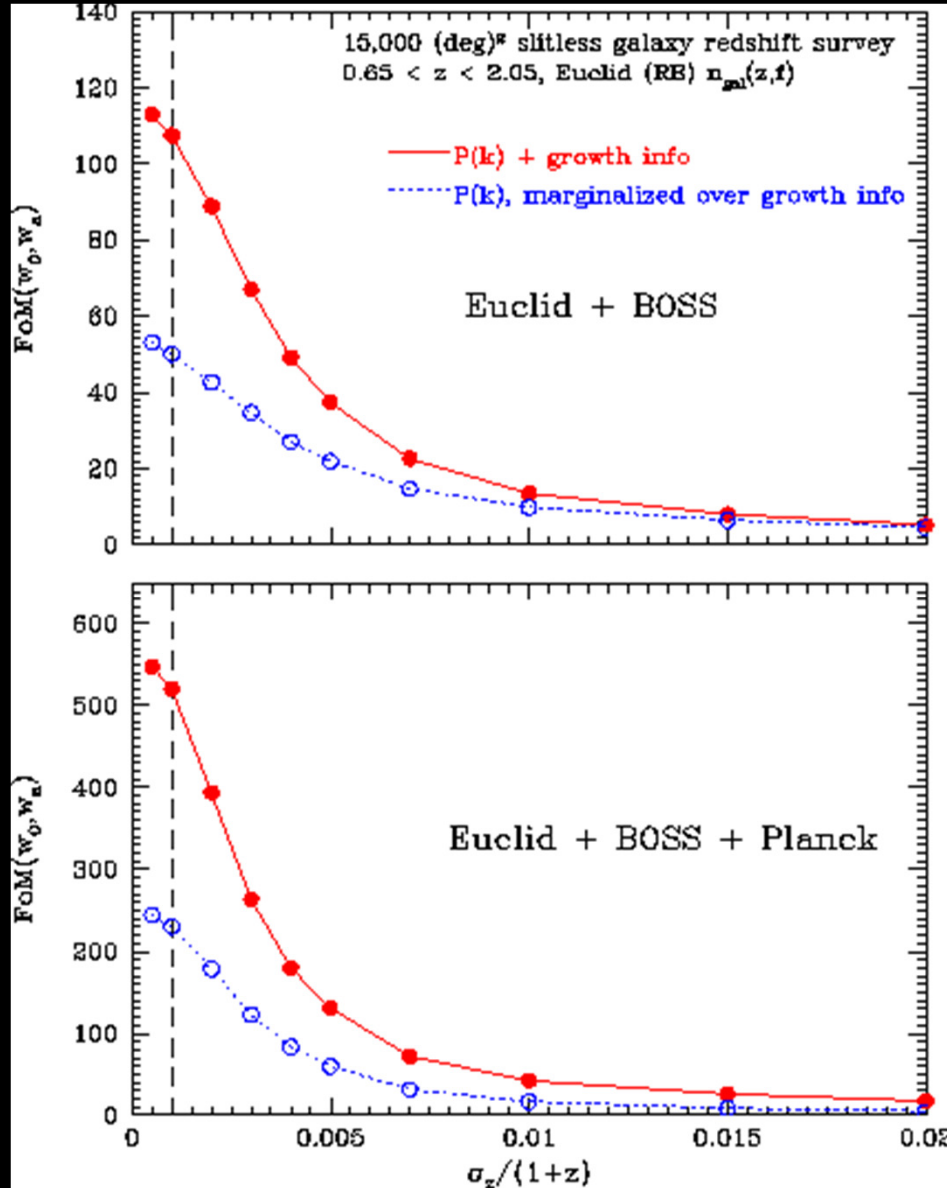
$$x = (k_{\perp}^2 s_{\perp}^2 + k_{\parallel}^2 s_{\parallel}^2)^{1/2}$$

$$p_1 = \ln s_{\perp}^{-1} = \ln(D_A/s); \quad p_2 = \ln s_{\parallel} = \ln(sH);$$

# Figure of Merit vs Redshift Accuracy

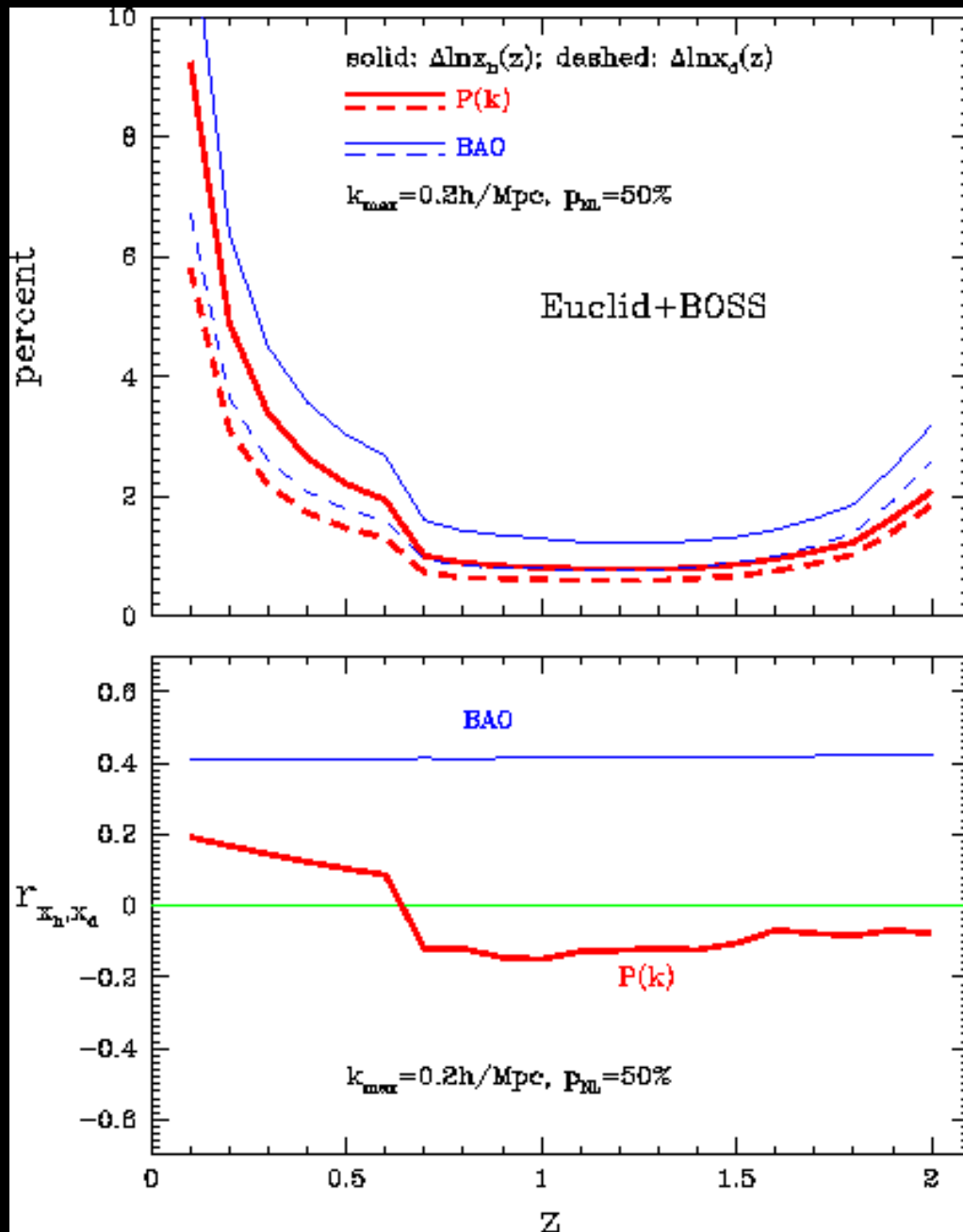
Assuming Euclid Red Book Baseline:

- $15,000 \text{ (deg)}^2$
- $0.65 < z < 2.05$
- $e(f, z)$



\*Updated from Wang et al. (2010)

# Expansion History H(z): BAO vs P(k)

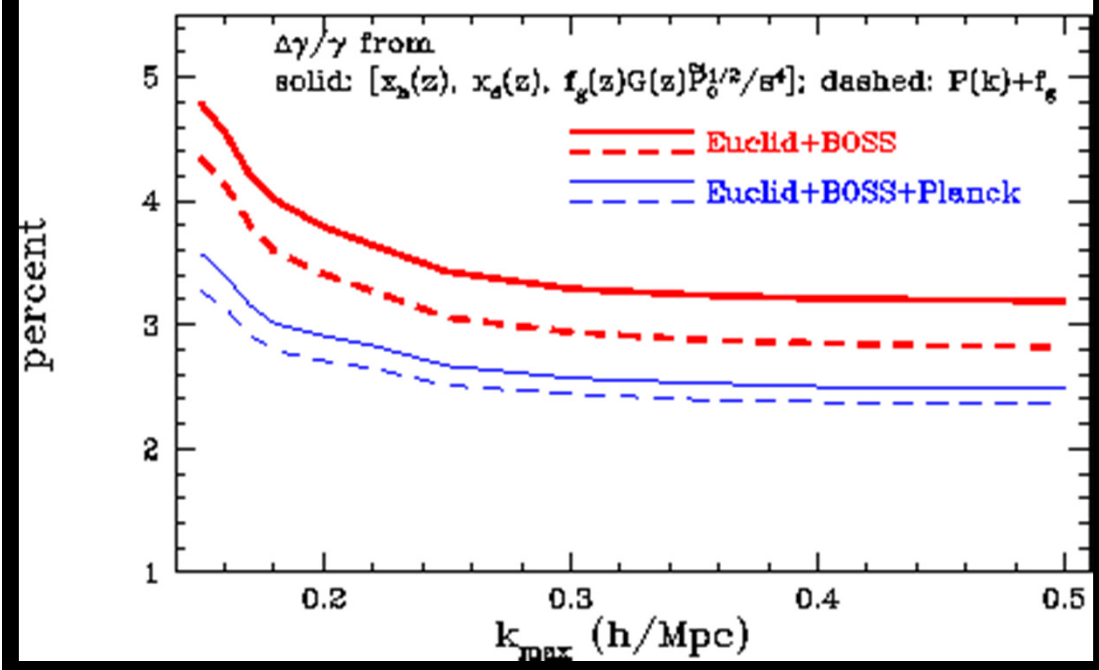
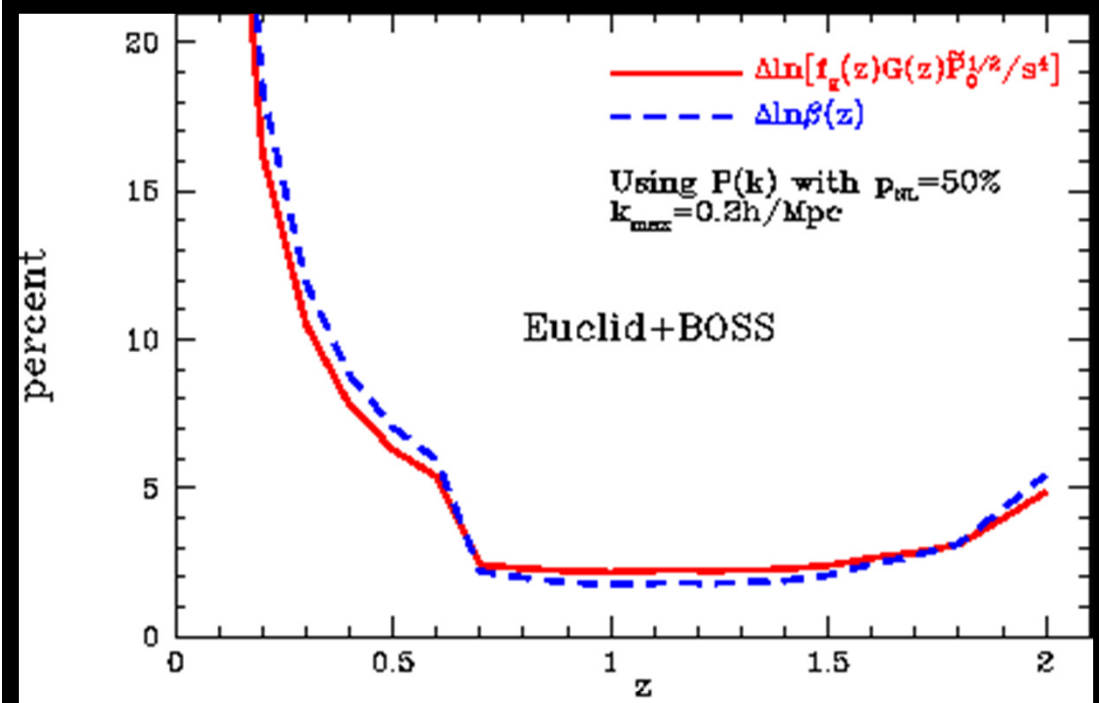


$$x_h(z) = H(z)s$$

$$x_d(z) = D_A(z)/s$$

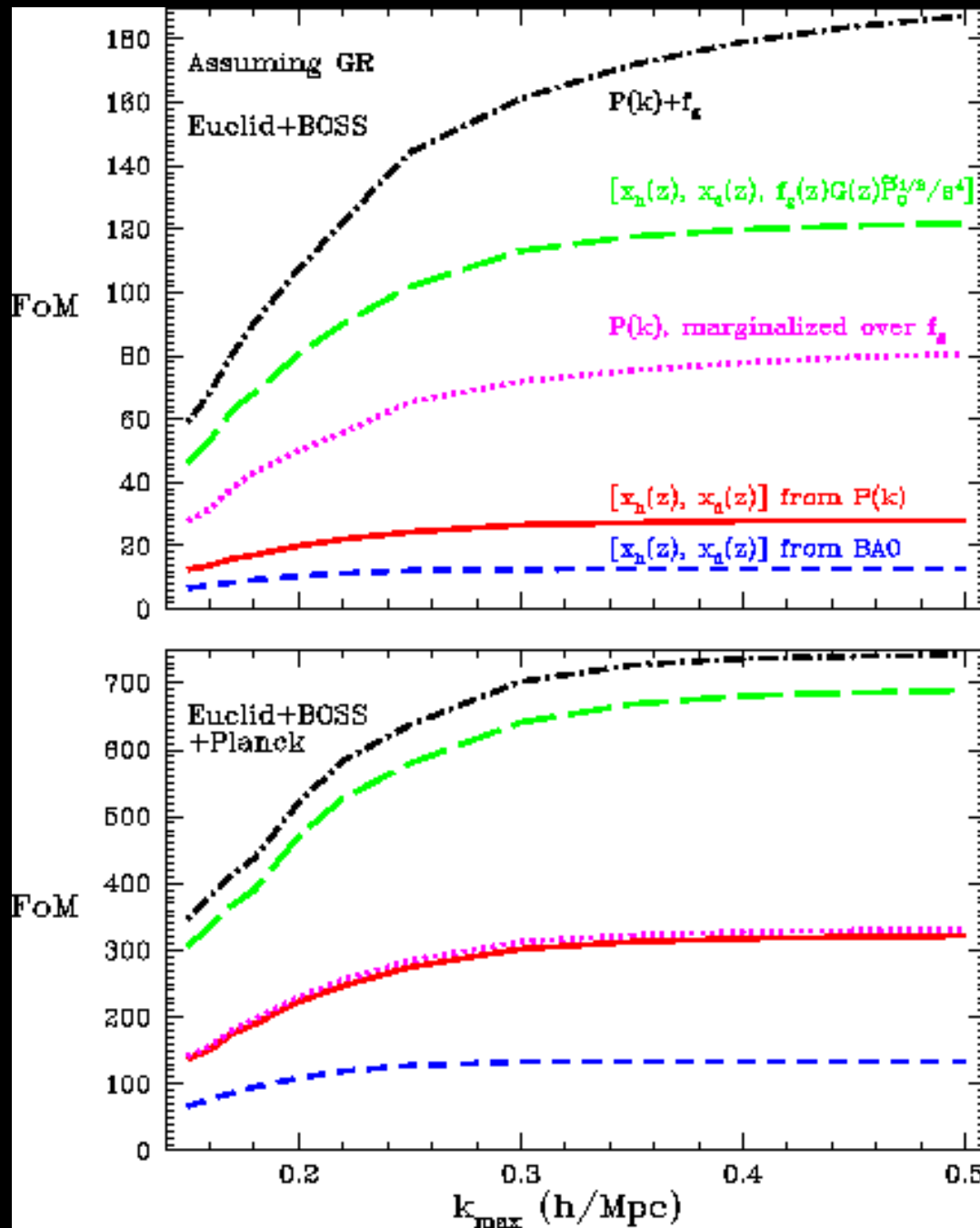
\*Updated from Wang et al. (2010)  
for Euclid RB baseline  
\*Based on Wang (2012)

# Constraints on Growth Rate



\*Based on Wang (2012)

# DE FoM vs Information Used



$$x_h(z) = H(z)s$$

$$x_d(z) = D_A(z)/s$$

$$p_{NL} = 50\%$$

\*Updated from Wang et al. (2010)  
for Euclid RB baseline

\*Based on Wang (2012)

# Space/Ground Complementarity

- Ongoing ground-based surveys (WiggleZ, BOSS) enable better understanding of galaxy clustering, and improved modeling of systematic effects, which benefit Euclid.
- Overlaps in redshift range (BOSS, BigBOSS, and Euclid) enable clustering statistics using multiple tracers (LRG, OII3727, and H $\alpha$  emitters), which improves DE constraints and the modeling of systematic effects.



# VI. Summary

- BAO/GC: a powerful probe of DE and gravity
  - Current data already give very useful results
  - Future data will be key to solving the puzzle of cosmic acceleration
- Next three lectures (technical details):
  - L2: The galaxy power spectrum method
  - L3: The galaxy correlation function method
  - L3: (1) Modeling/mitigating systematic uncertainties
    - (2) Making forecasts for future surveys