

Recent Progress in Theory of BAO with Galaxy Surveys

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“Cosmology Near and Far: Science with WFMOS

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Part I

Motivation for dark energy

Motivation for dark energy

- Einstein's cosmological constant

$$R^\mu{}_\nu - \frac{1}{2} \delta^\mu{}_\nu R + \Lambda \delta^\mu{}_\nu = \frac{8\pi G}{c^4} T^\mu{}_\nu$$

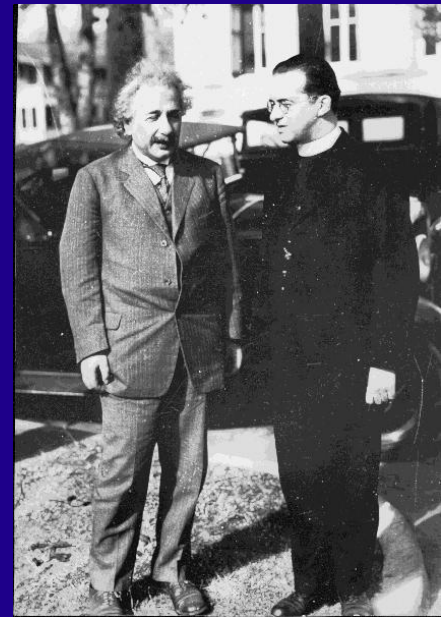
- Ugly constant in cosmology
- Biggest blunder for Einstein

- Pauli's vacuum energy density

$$\rho_{\text{vac}} = \int \frac{d^3k}{(2\pi)^3} \frac{1}{2} \hbar c k = \frac{\hbar c k_{\text{max}}^4}{16\pi^2}$$

- Divergent..., if Planck cut off $\Rightarrow 10^{123} \Omega_0$
- Still observable: Casimir effect (actually obsvd)

$$1^3 + 2^3 + 3^3 + 4^3 + \dots = \frac{1}{120}$$



Motivation for dark energy

- Nearly constant density of energy accelerates the expansion of the universe
 - The first law of thermodynamics:

$$\rho \approx \text{const.} : dU \approx \rho dV$$

$$\text{Adiabatic} : dU = -pdV \quad \therefore p \approx -\rho$$

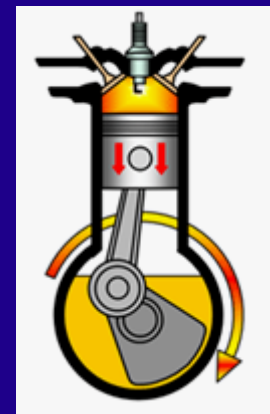
- Einstein equation:

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2} (\rho + 3p) \approx \frac{8\pi G}{3c^2} \rho > 0$$

- Dark energy equation-of-state parameter “ w ”

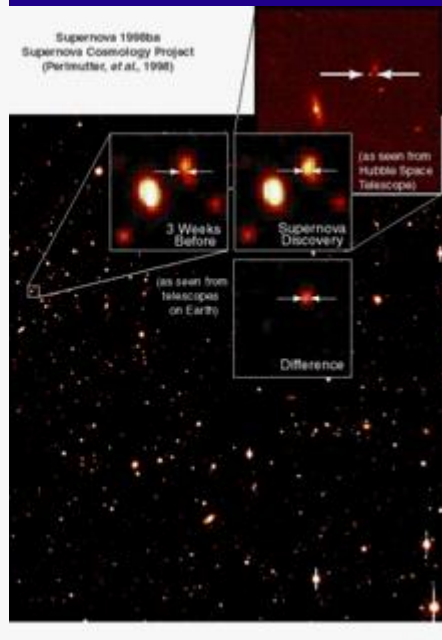
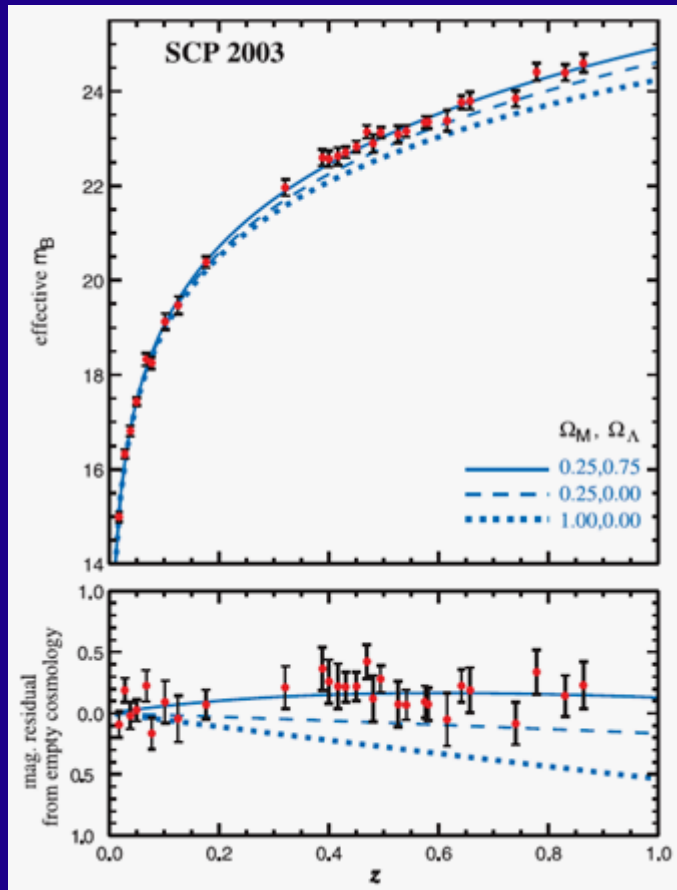
$$p = w_{\text{DE}} \rho$$

- Universe accelerates if $w_{\text{DE}} < -1/3$

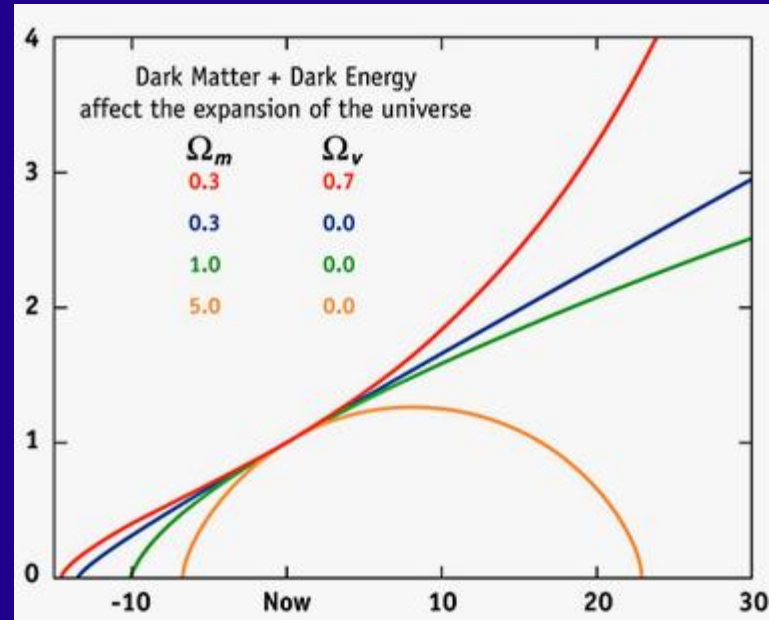


Motivation for dark energy

- The Universe is actually accelerating!
 - Consistent with nearly constant density of energy



Knop et al. (2003)



Simple examples of dark energy

- Einstein's cosmological constant

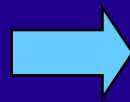
$$R^\mu{}_\nu - \frac{1}{2} \delta^\mu{}_\nu R + \Lambda \delta^\mu{}_\nu = \frac{8\pi G}{c^4} T^\mu{}_\nu$$

$$p_\Lambda = -\rho_\Lambda = -\frac{c^4 \Lambda}{8\pi G} \quad \therefore w_{\text{DE}} = -1$$



- A scalar field

$$L = -\frac{1}{2} \partial_\mu \phi \partial^\mu \phi - V(\phi)$$



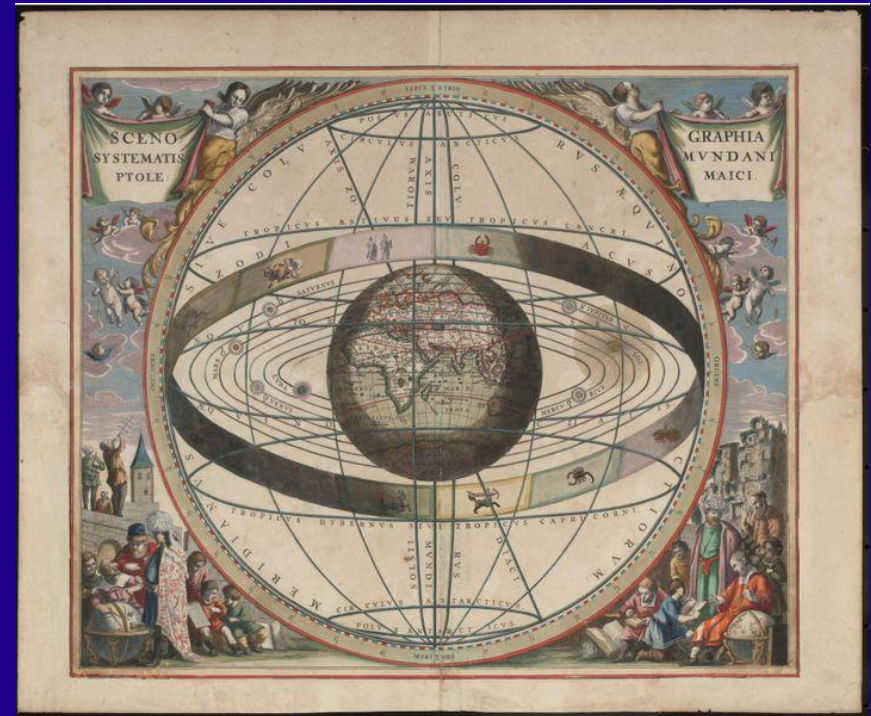
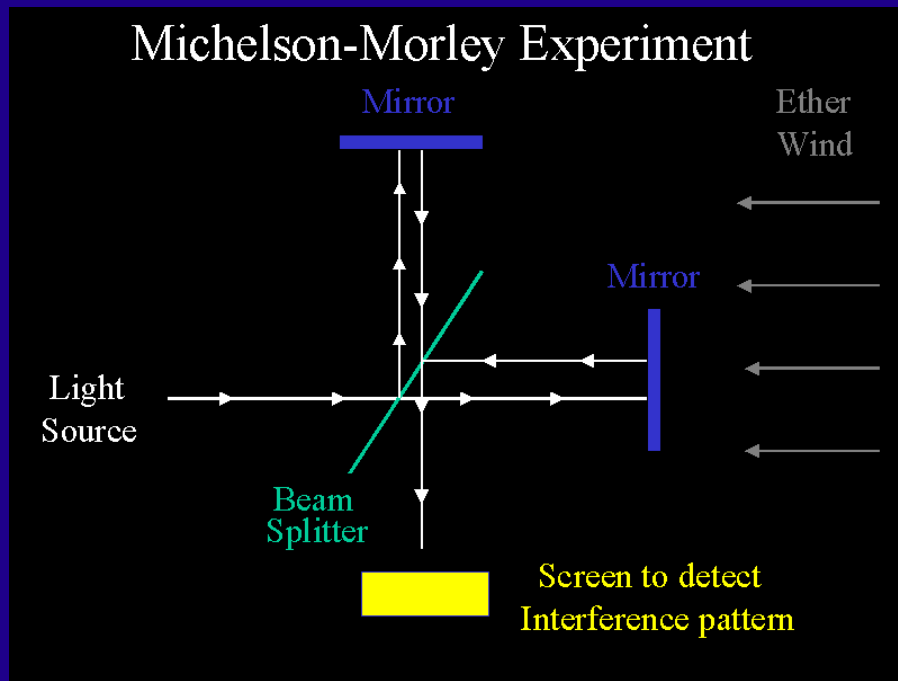
$$\rho = \frac{\phi'^2}{2a^2} + V, \quad p = \frac{\phi'^2}{2a^2} - V$$

- Slow roll (flat potential): $\phi' \approx 0$

$$w_{\text{DE}} = \left(\frac{\phi'^2}{2a^2} - V \right) / \left(\frac{\phi'^2}{2a^2} + V \right) \approx -1$$

Need for paradigm shift?

- Dark energy
 - Essential component of modern cosmology: **Unidentified!**
 - “Ether” or “epicycles” of our times?



Precise measurements of the universe: **URGENT!**

Part II

BAO as a geometric test for the dark energy

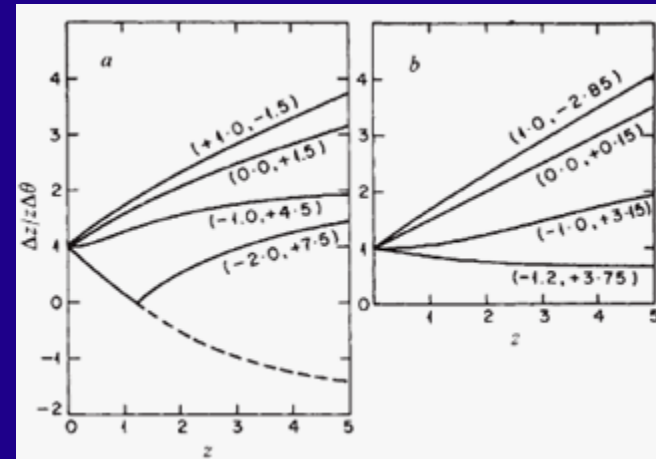
Geometric test for the dark energy

- Alcock & Paczynski (1979)

An evolution free test for non-zero cosmological constant

Charles Alcock
The Institute for Advanced Study, Princeton, New Jersey 08450

Bohdan Paczyński*
Department of Astronomy, University of California at Berkeley, Berkeley, California 94720 and Princeton University Observatory, Princeton, New Jersey 08540



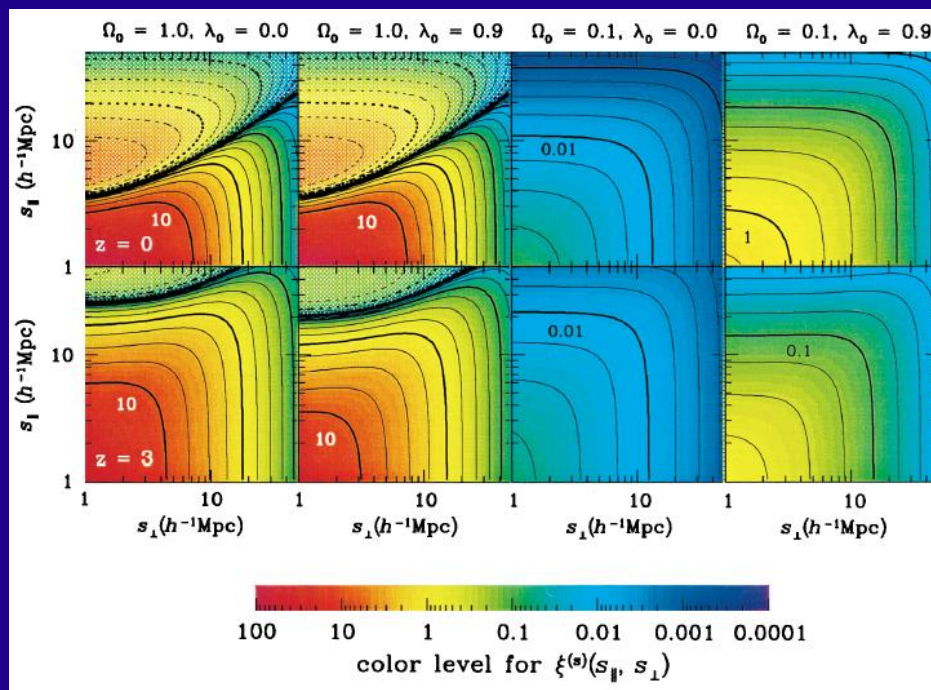
comoving space z-space

$$\frac{H(z)}{H_0} = \sqrt{(1+z)^3 \Omega_M + (1+z)^2 (1 - \Omega_M - \Omega_{DE}) + (1+z)^3 \exp\left(3 \int_0^z \frac{w_{DE} dz}{1+z}\right) \Omega_{DE}}$$

$$D_A(z) = \frac{1}{H_0 \sqrt{1 - \Omega_M - \Omega_{DE}}} \sinh \left(H_0 \sqrt{1 - \Omega_M - \Omega_{DE}} \int_0^z \frac{dz'}{H(z')} \right)$$

Geometric test for the dark energy

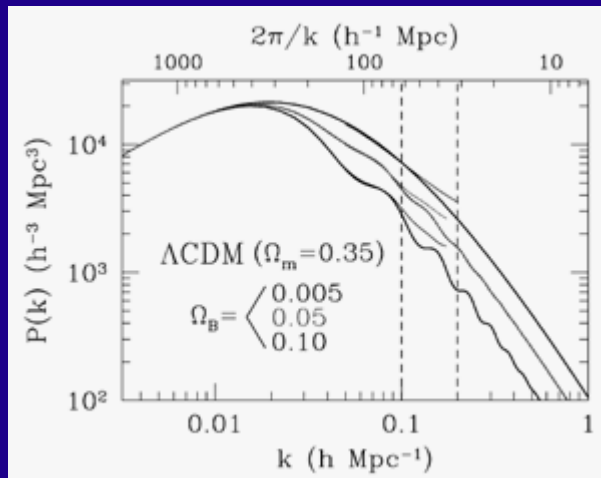
- Galaxy clustering in deep redshift space as a probe of dark energy
 - Ballinger et al. (1996); T.M. & Suto (1996)
 - Modeling redshift-space distortions in high- z universe to constrain dark energy



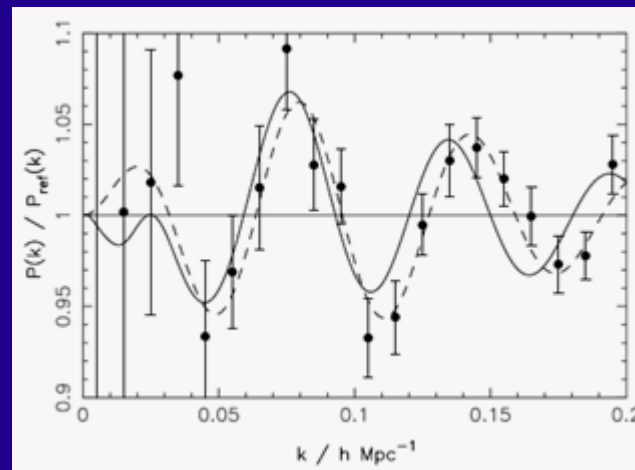
2D correlation function
of the CDM model
(T.M. & Suto 1996)

Geometric test using BAO

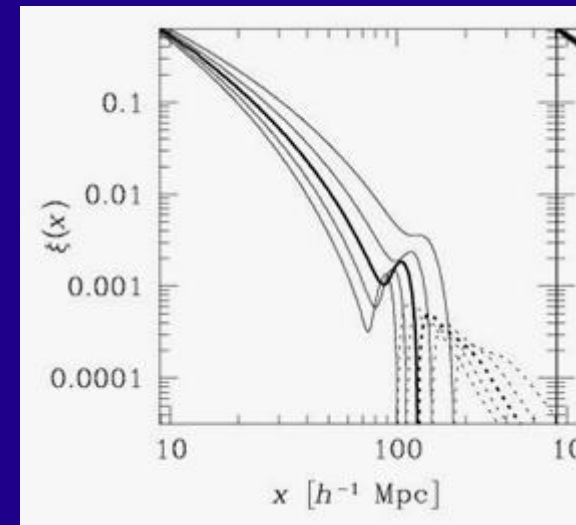
- Geometric test using Baryon Acoustic Oscillations
 - “Baryonic features yield a standard ruler, whose length can be accurately inferred by the CMB and can be measured in redshift space using large-redshift surveys”
(Eisenstein, Hu & Tegmark, 1998)



Baryon wiggles in the power spectrum
(Eisenstein et al. 1998)



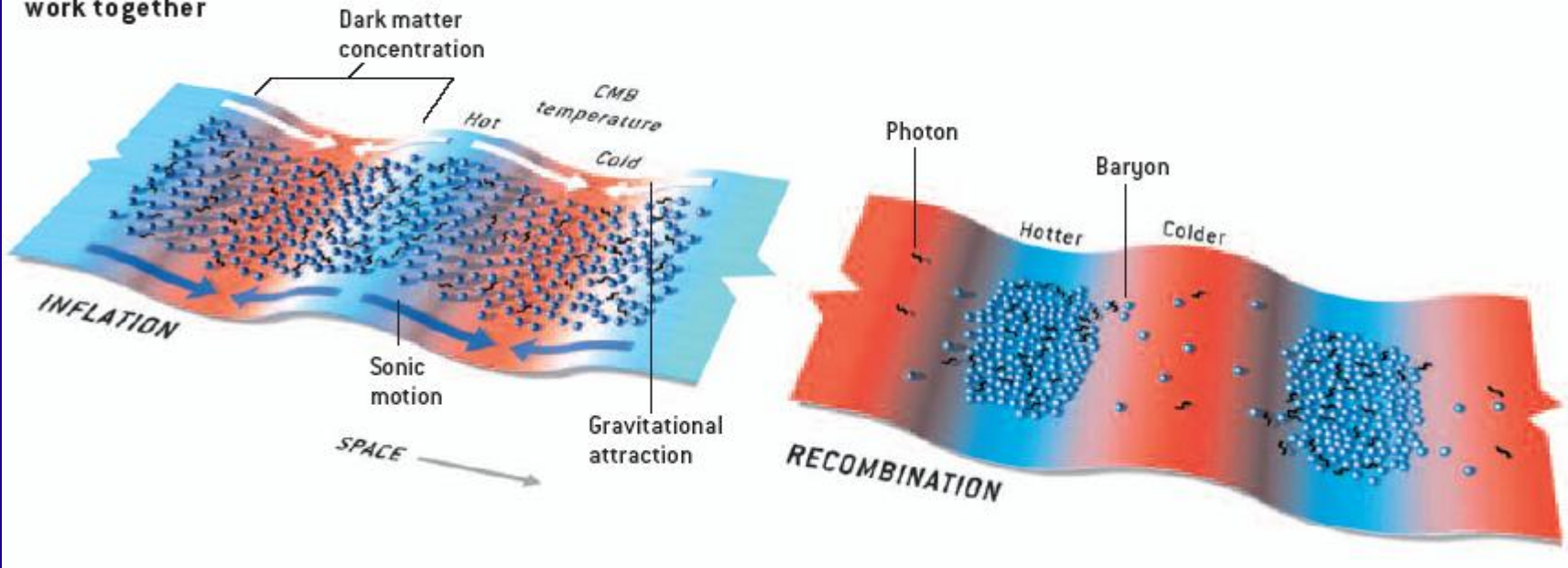
Simulated detection of the wiggles
(Blake & Glazebrook 2003)



Baryon peak in the correlation function
(T.M. 2004)

FIRST PEAK

Gravity and sonic motion
work together

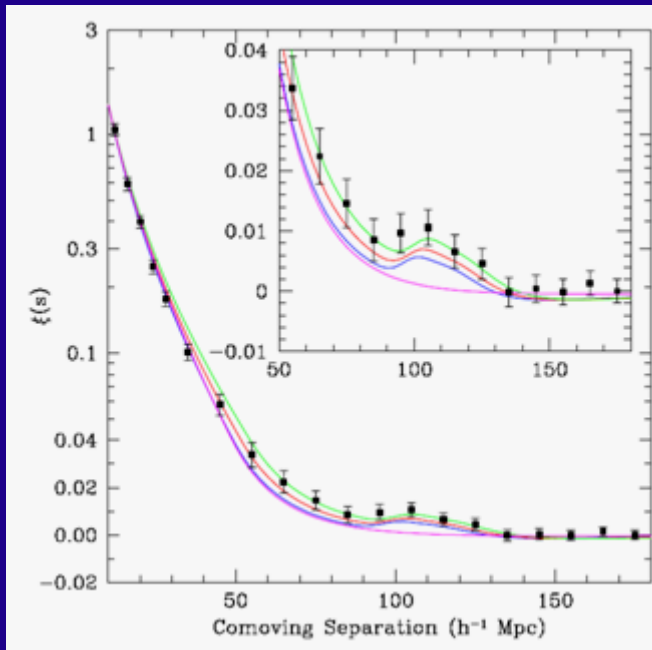


Hu & White (2004)

Observational detection of the BAO

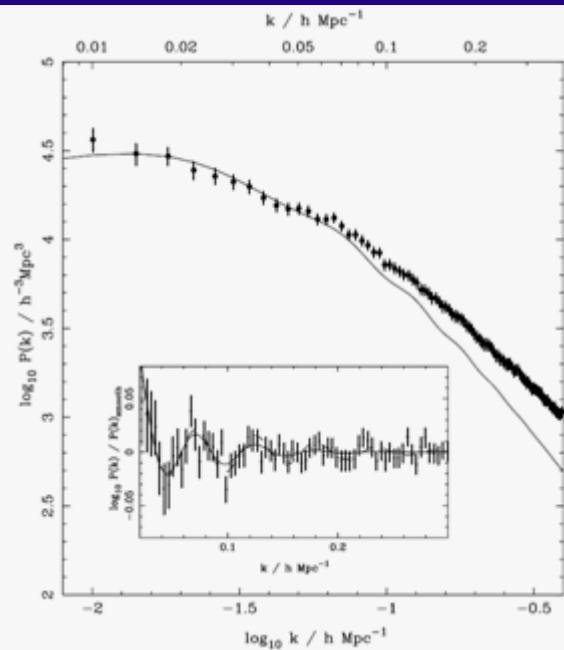
- BAO has been clearly detected by observations

In correlation function

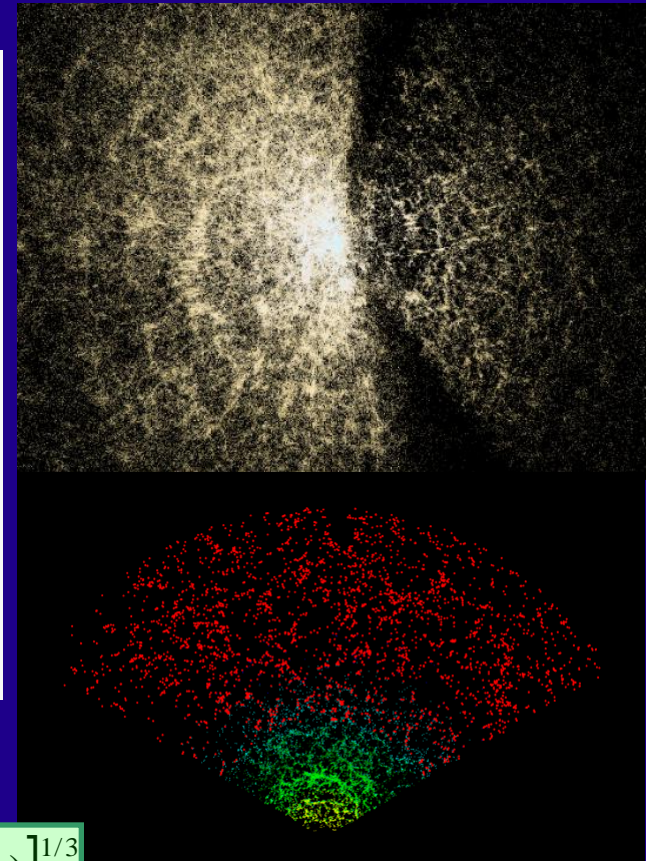


Eisenstein et al. (SDSS, 2005)

In power spectrum



Percival et al. (SDSS, 2007)

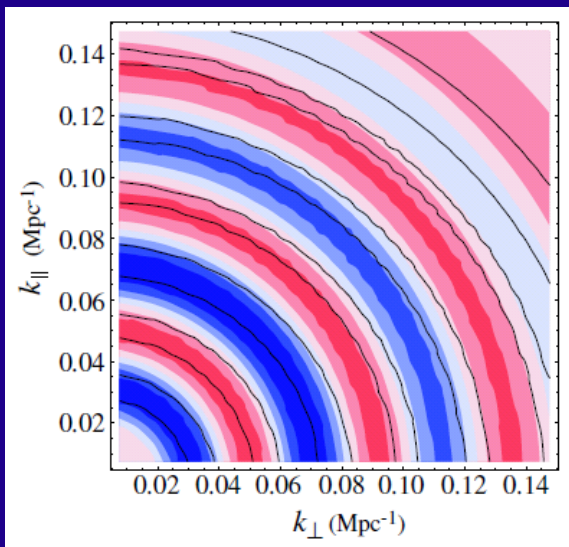


(SDSS survey)

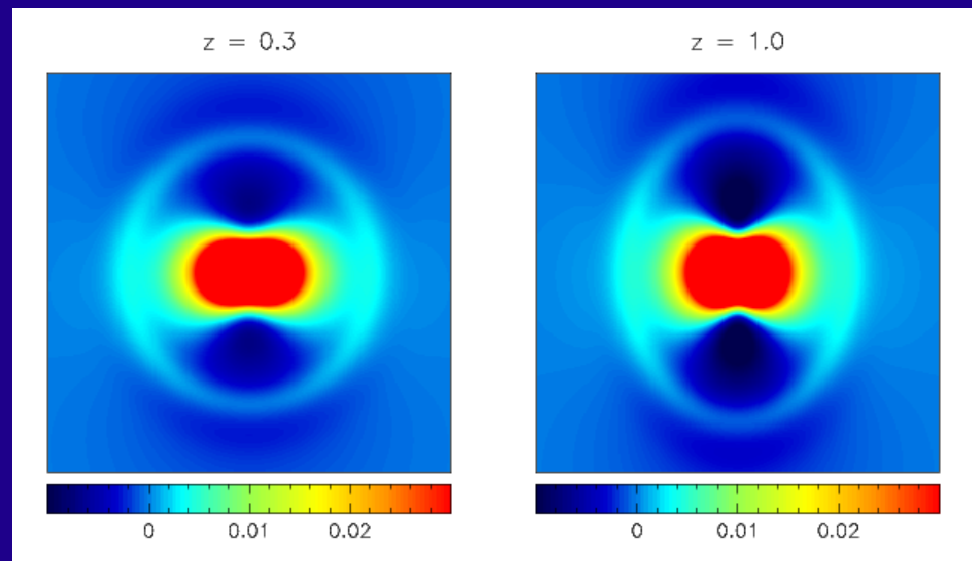
- DE is constrained by 1D scale: $D_V(z) = \left[(1+z)^2 D_A^2(z) cz / H(z) \right]^{1/3}$

2D analysis of BAO

- 2D clustering and BAO
 - parallel & perpendicular to the lines of sight: independent geometric information



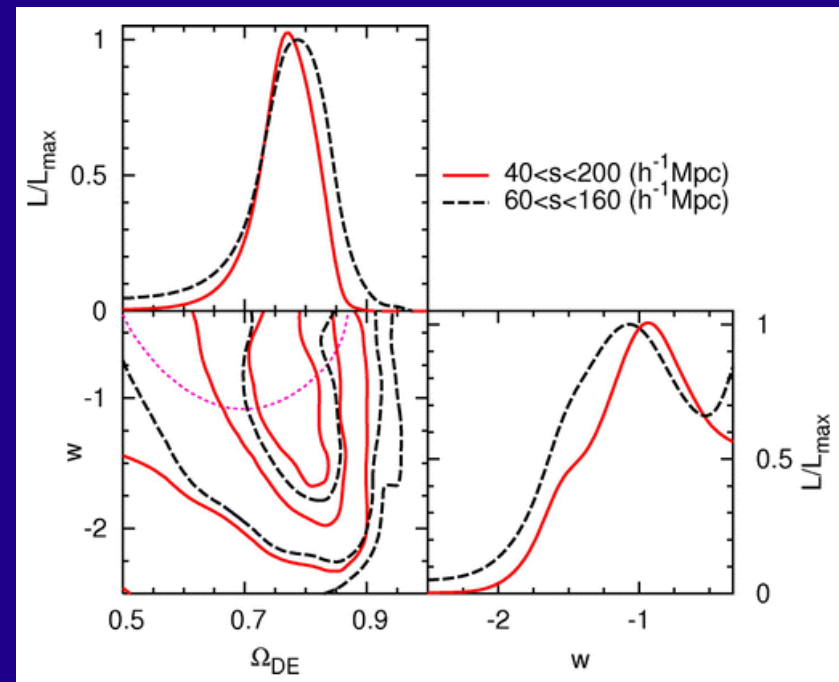
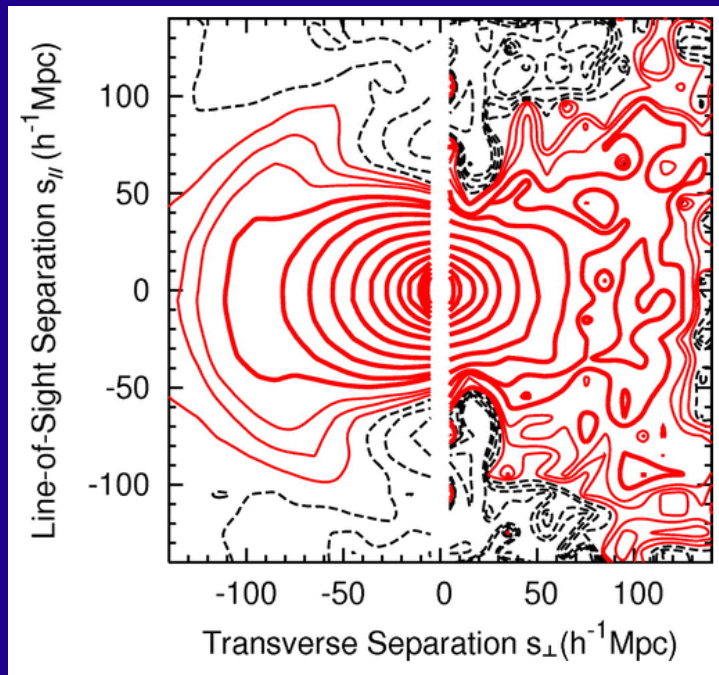
2D power spectrum with BAO
(Hu & Haiman 2003)



2D correlation function with BAO
(T.M. 2004)

2D analysis of BAO

- 2D Analysis of SDSS LRG correlation function
 - 2D correlation function & constraints on dark energy



Okumura et al. (2008)

- promising method for WFMOS

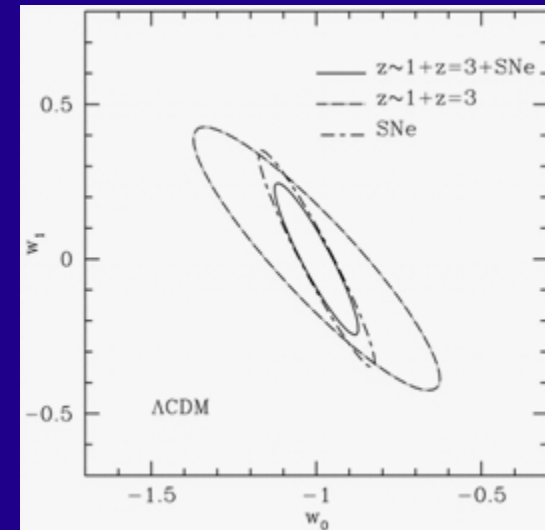
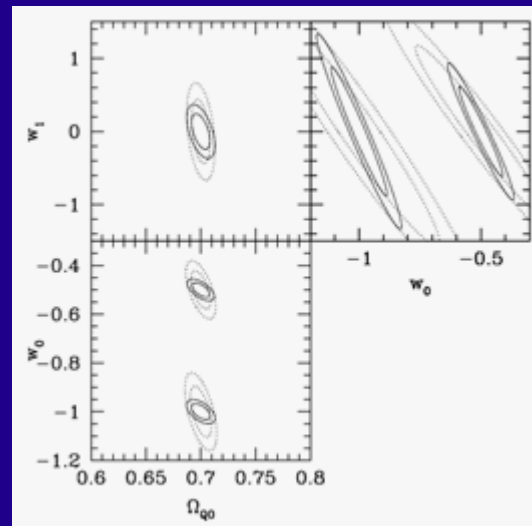
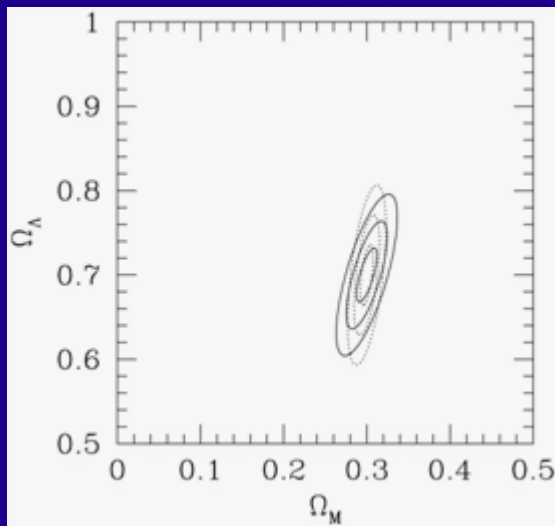
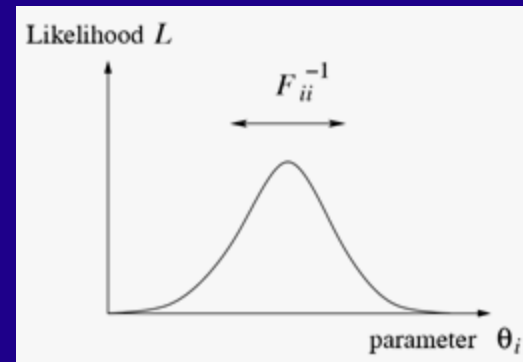
Part III

Theoretical Developments

Fisher information matrix (FIM)

- FIM gives “Error forecasts” for galaxy surveys
 - Vogeley & Szalay 1996; Tegmark et al. 1997

$$F_{ij} = - \left\langle \frac{\partial^2 \ln L}{\partial \theta_i \partial \theta_j} \right\rangle$$



First FIM forecast for DE from a galaxy survey
(T.M. & Szalay 2001;2003)

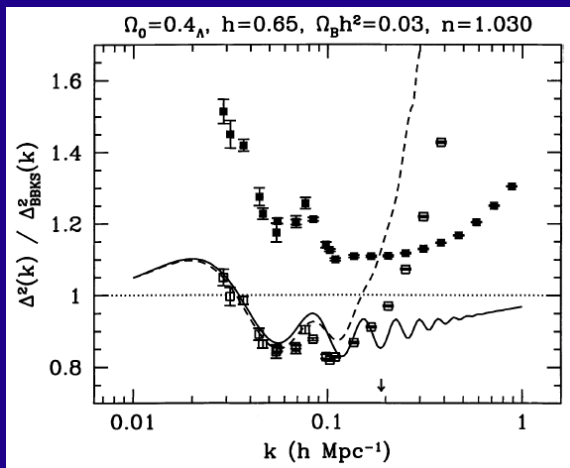
Fourier-based FIM method
(Seo & Eisenstein 2003)

Theoretical modeling of BAO

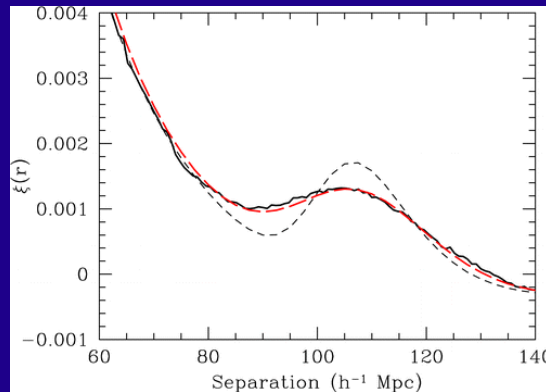
- The BAO dynamics is qualitatively captured by linear theory, but...
- Nonlinearity in various aspects should be theoretically elucidated, otherwise the estimation of dark energy would be biased.
 - Nonlinearity in dynamics
 - Nonlinearity in redshift-space distortions
 - Nonlinearity in halo/galaxy bias

Nonlinearity in dynamics

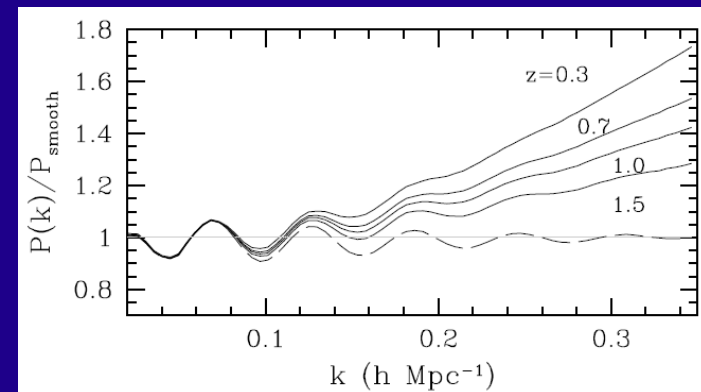
- Nonlinear dynamics distorts the BAO signature
 - N-body experiments \Rightarrow Yoshida-kun's talk for detail



Power spectrum,
N-body & 1-loop PT
Meiksin et al. (1999)



Correlation function,
large N-body simulation
Eisenstein et al. (2007)

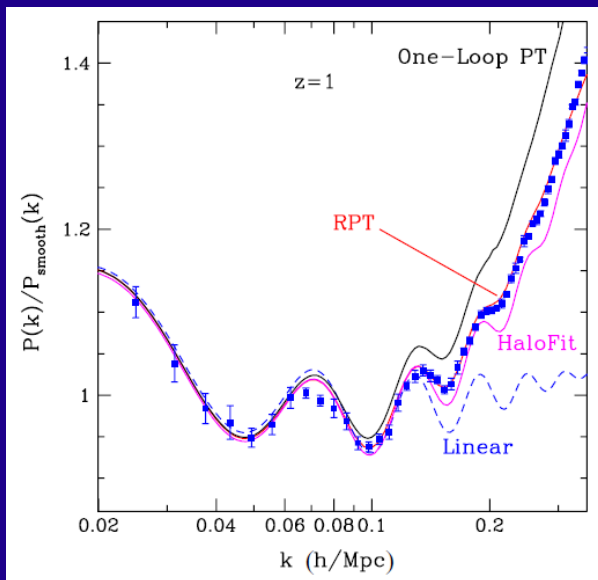


Power spectrum,
large N-body simulation
Seo et al. (2008)

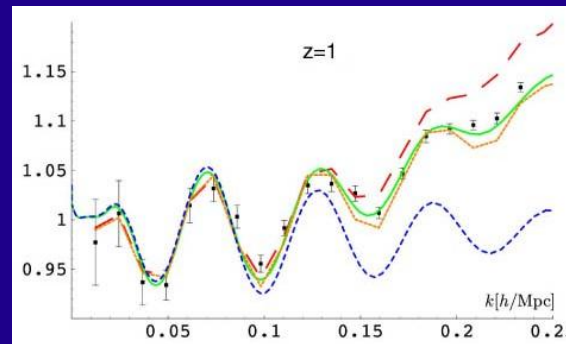
- Simple nonlinear perturbation theory does not work well at relevant redshift $z < 3$

Theory for nonlinear dynamics

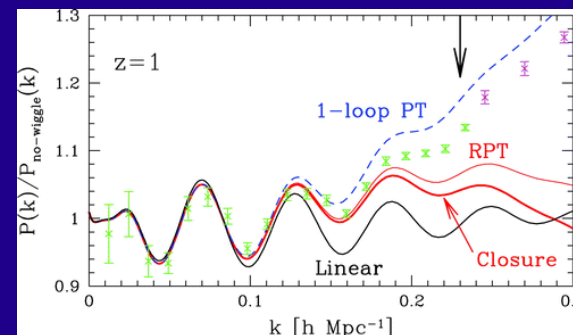
- Renormalized perturbation theory and its variants
 - Mostly based on Scoccimarro (2001)'s reformulation of fluid equations to utilize tools of field theory
 - Infinitely higher-order perturbations are reorganized and partially resummed
⇒ Taruya-kun's talk for detail



“Renormalized perturbation theory”
Croce & Scoccimarro (2008)



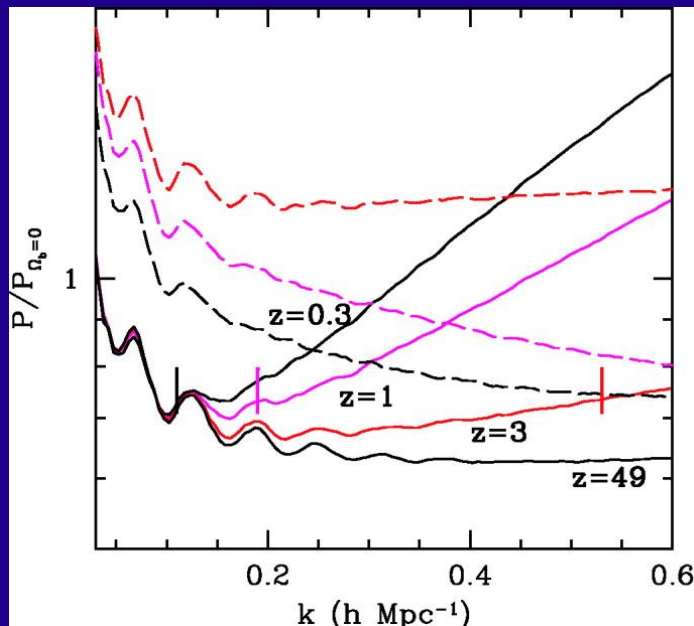
“Renormalization group method”
Matarrese & Pietroni (2008)



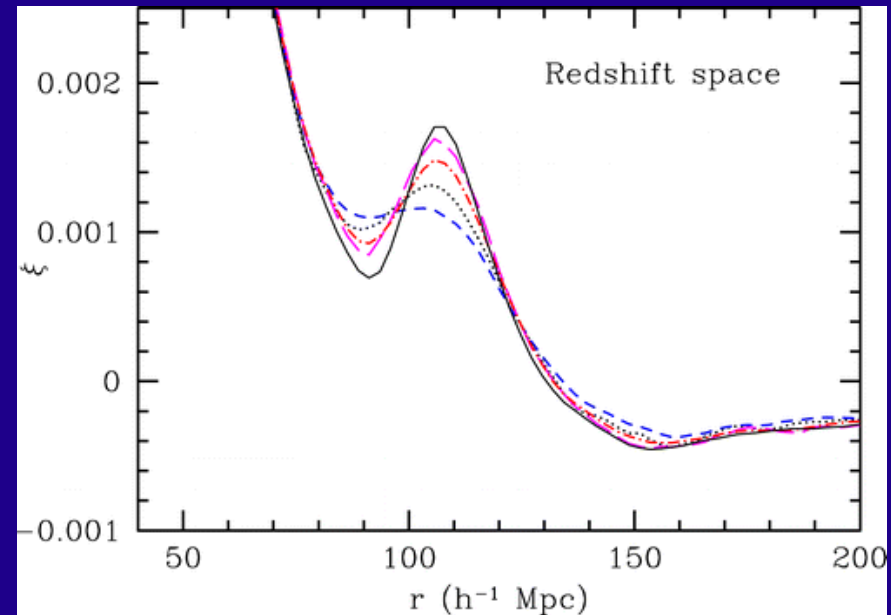
“Closure theory”
Taruya & Hiramatsu (2008)

Nonlinearity in redshift-space distortions

- Redshift-space distortions change the nonlinear effects on BAO
 - $P(k)$: Small-scale enhancement relative to the large-scale power is much less (but overall Kaiser enhancement)
 - $\xi(r)$: Nonlinear degradation is larger



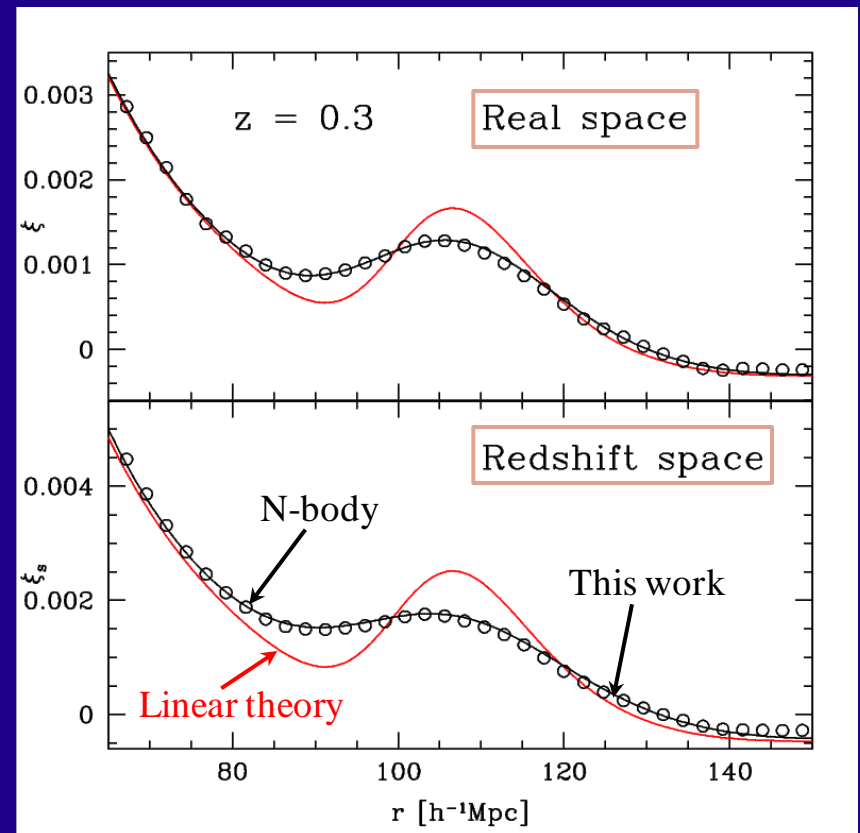
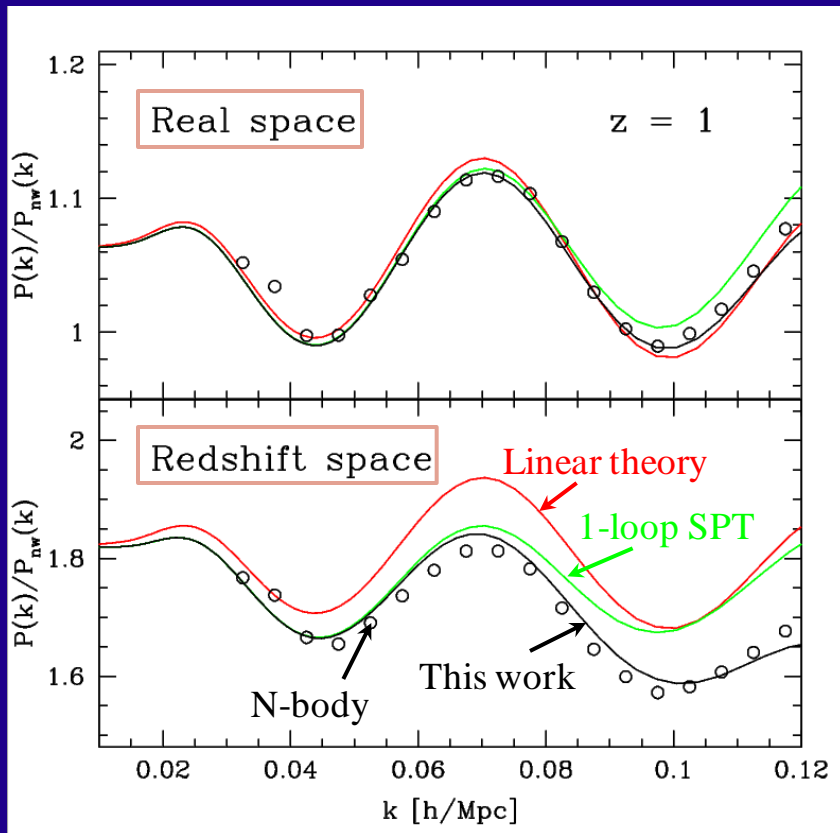
N-body, Seo et al. (2005)



N-body, Eisenstein et al. (2007)

Theory for nonlinear redshift-space distortions

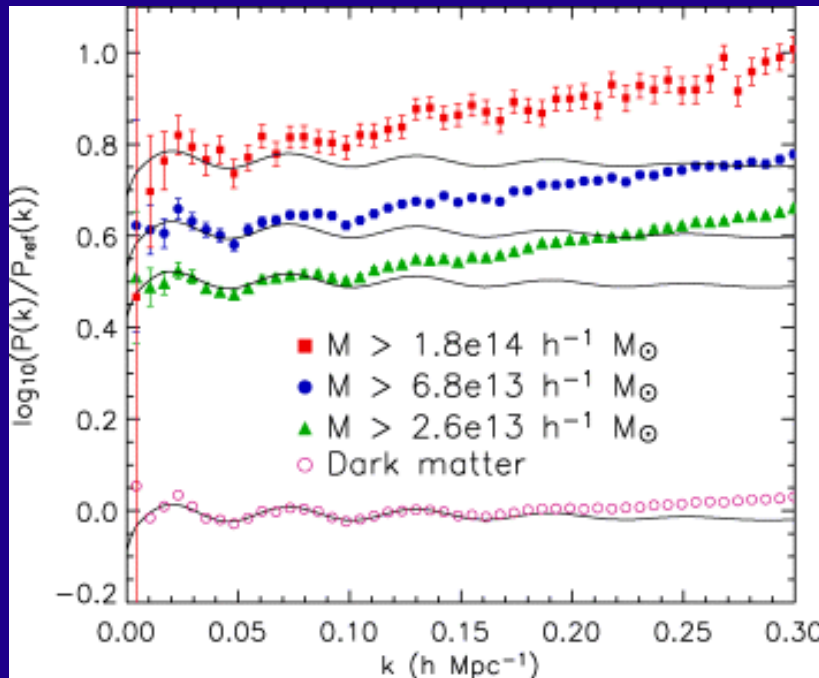
- Nonlinear perturbation theory in redshift space
 - Resummation via the Lagrangian picture (T.M. 2008)



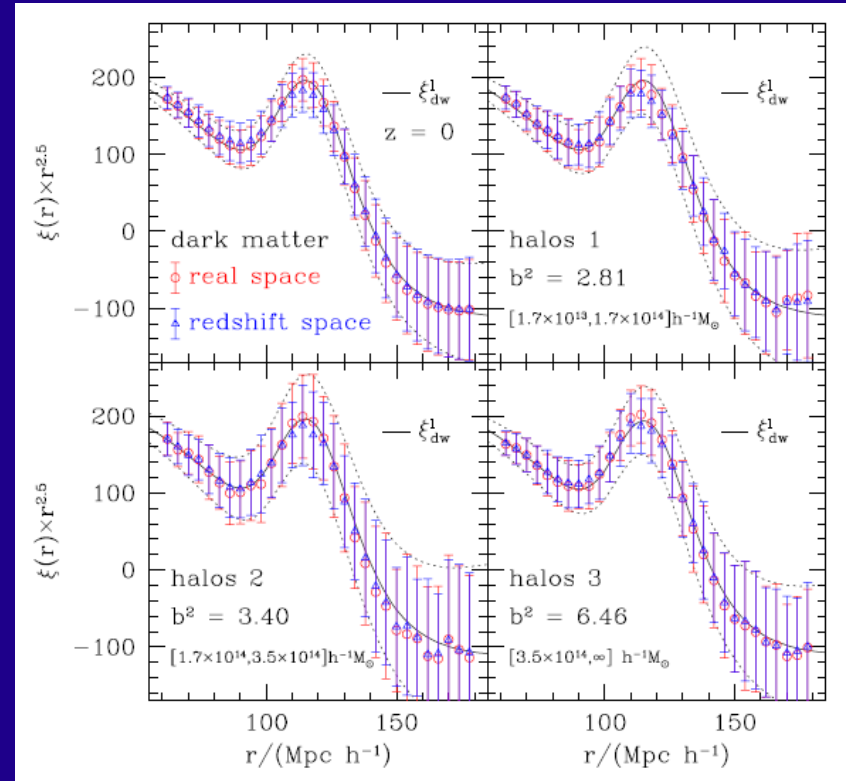
(Points from N-body simulation of Eisenstein & Seo 2005)

Nonlinearity in halo bias

- Effects of nonlinear halo bias
 - $P(k)$: Scale-dependent bias is induced by nonlinearity
 - $\xi(r)$: Linear bias seems good for $r > 60 h^{-1}\text{Mpc}$



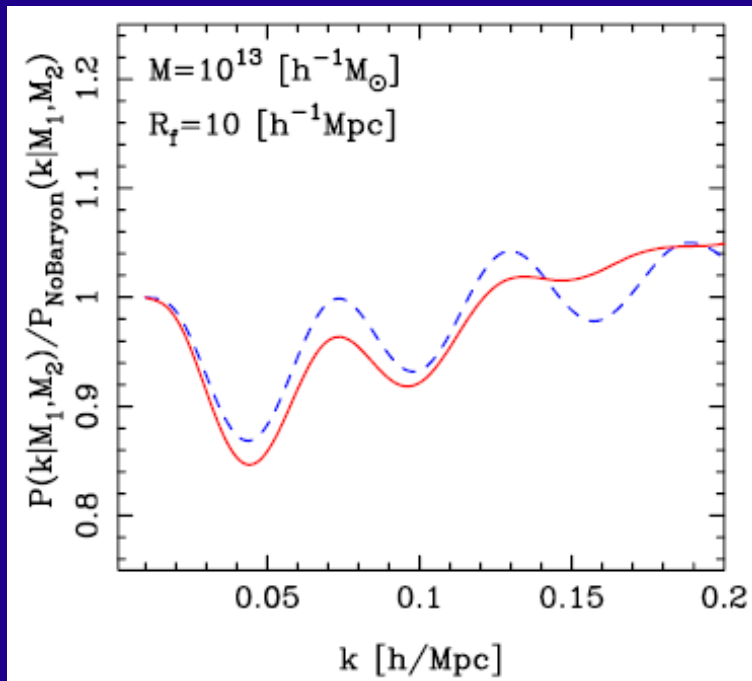
N-body, Angulo et al. (2005)



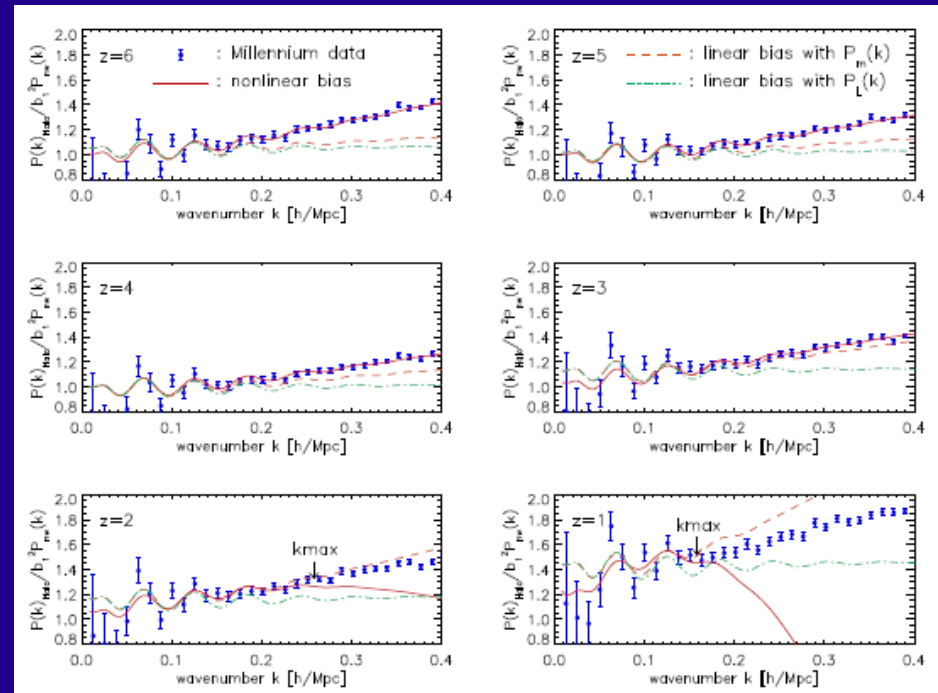
N-body, Sanchez et al. (2008)

Theory for nonlinear halo bias

- Nonlinear perturbation theory with simple local bias is not straightforward
 - Smith et al. (2007): 1-loop PT + halo-like bias
 - McDonald (2006): bias renormalization



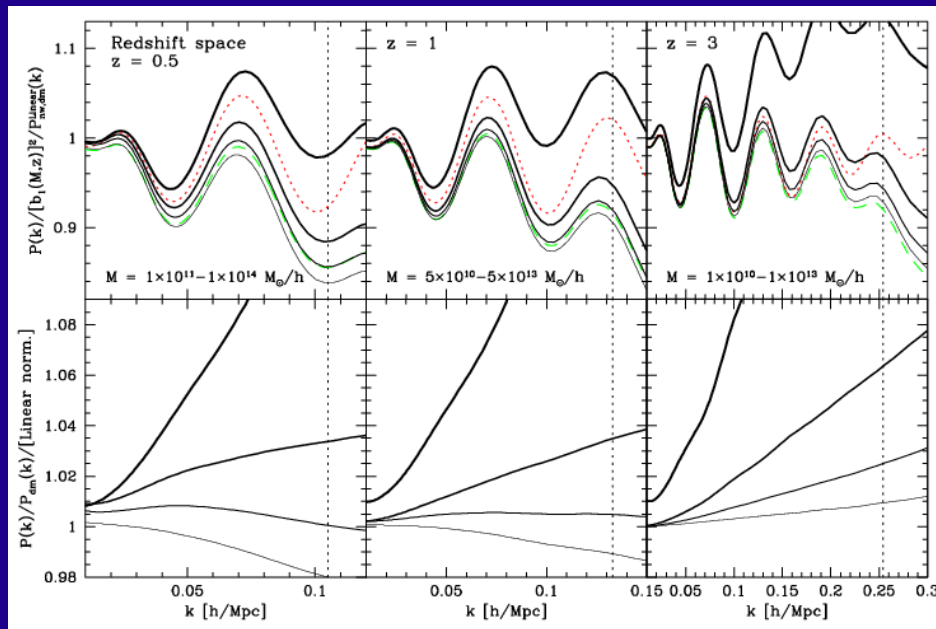
Smith et al. (2007)



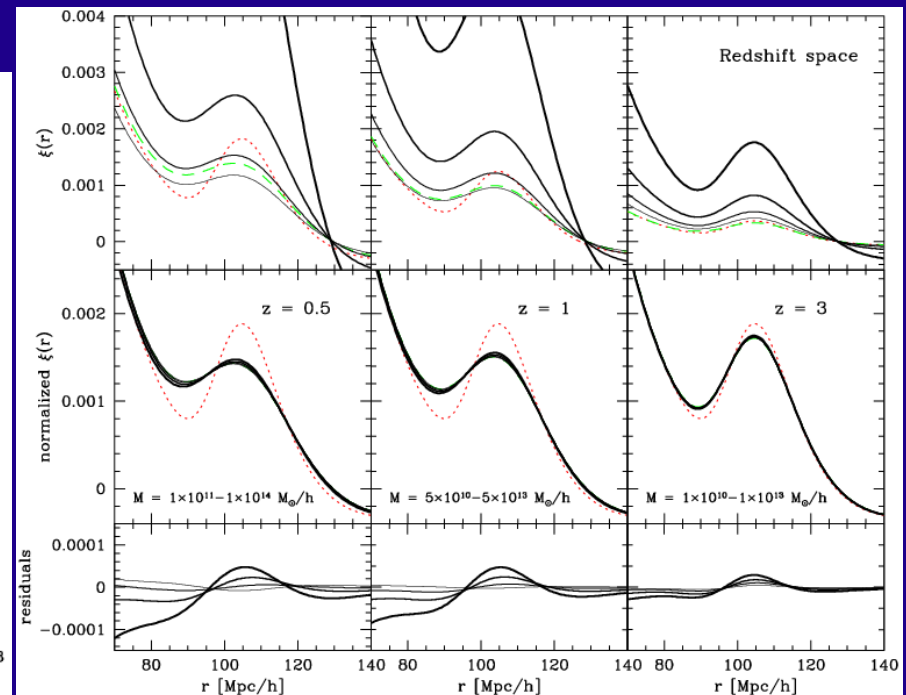
Jeong & Komatsu (2008)

Theory for nonlinear halo bias

- Nonlinear perturbation theory with halo bias
 - T.M. (in prep.):
 - 1-loop PT via LPT + halo bias + redshift-space distortions (Lagrangian formulation)



$P(k)$



$\xi(r)$

T.M. (in prep.)

Summary

- Dark energy as a fundamental problem in the Universe
- BAO: geometric test of dark energy
- Theoretical modeling of BAO in progress