Theoretical developments for BAO Surveys

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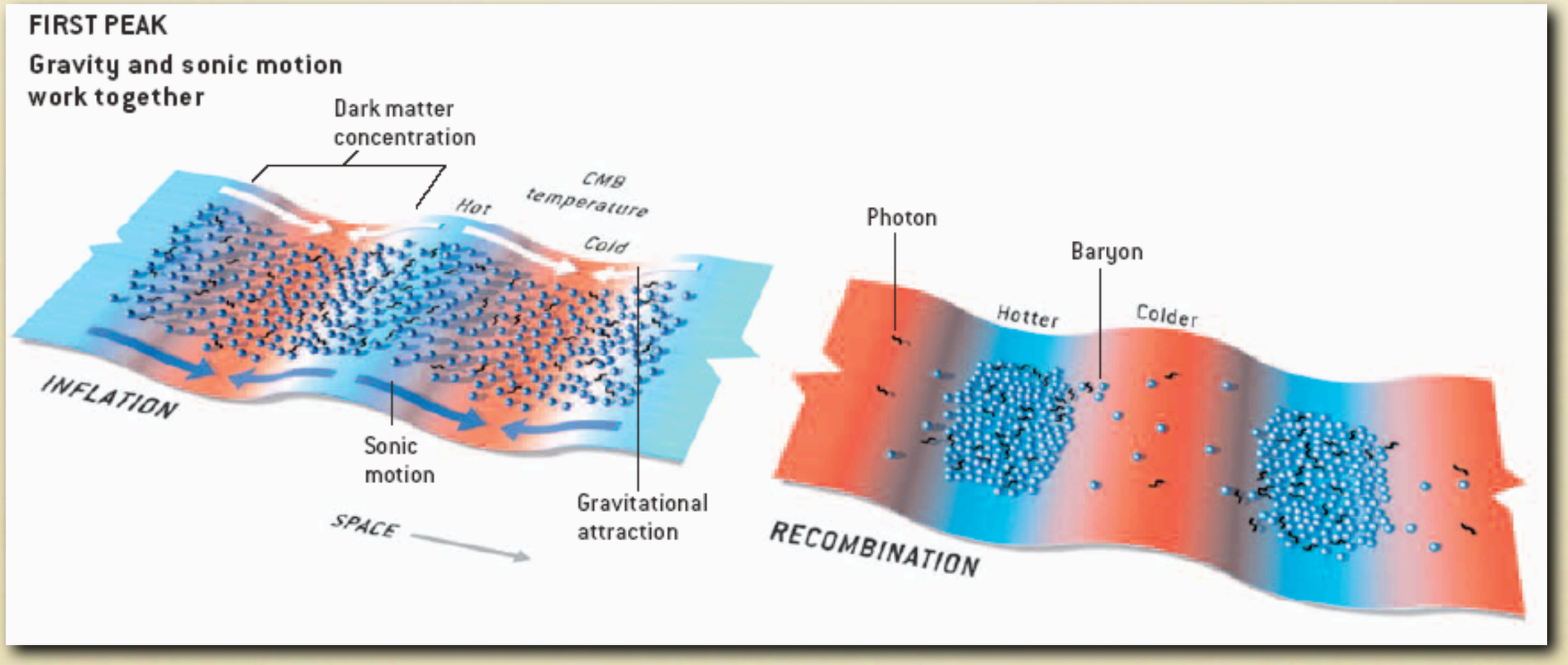
Baryon Acoustic Oscillations

- Photons and baryons are strongly coupled by Thomson & Coulomb scattering before photon decoupling (z > 1090)
- Acoustic Oscillations due to Pressure & Gravity



Hu & White (2004) Scientific American

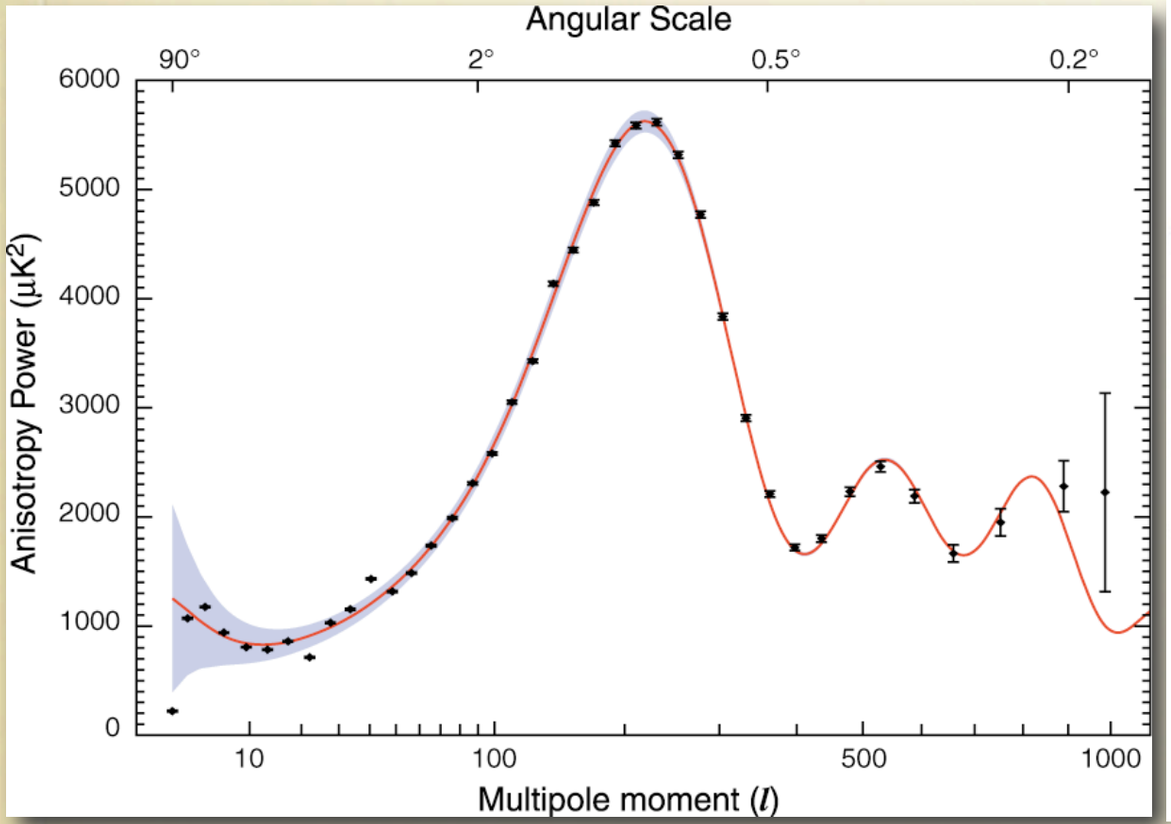
Characteristic Scale of BAO

- BAO stops at the photon decoupling time (z=1090)
- Characteristic scale: “Sound Horizon”
  - How far sound waves can travel by the decoupling time

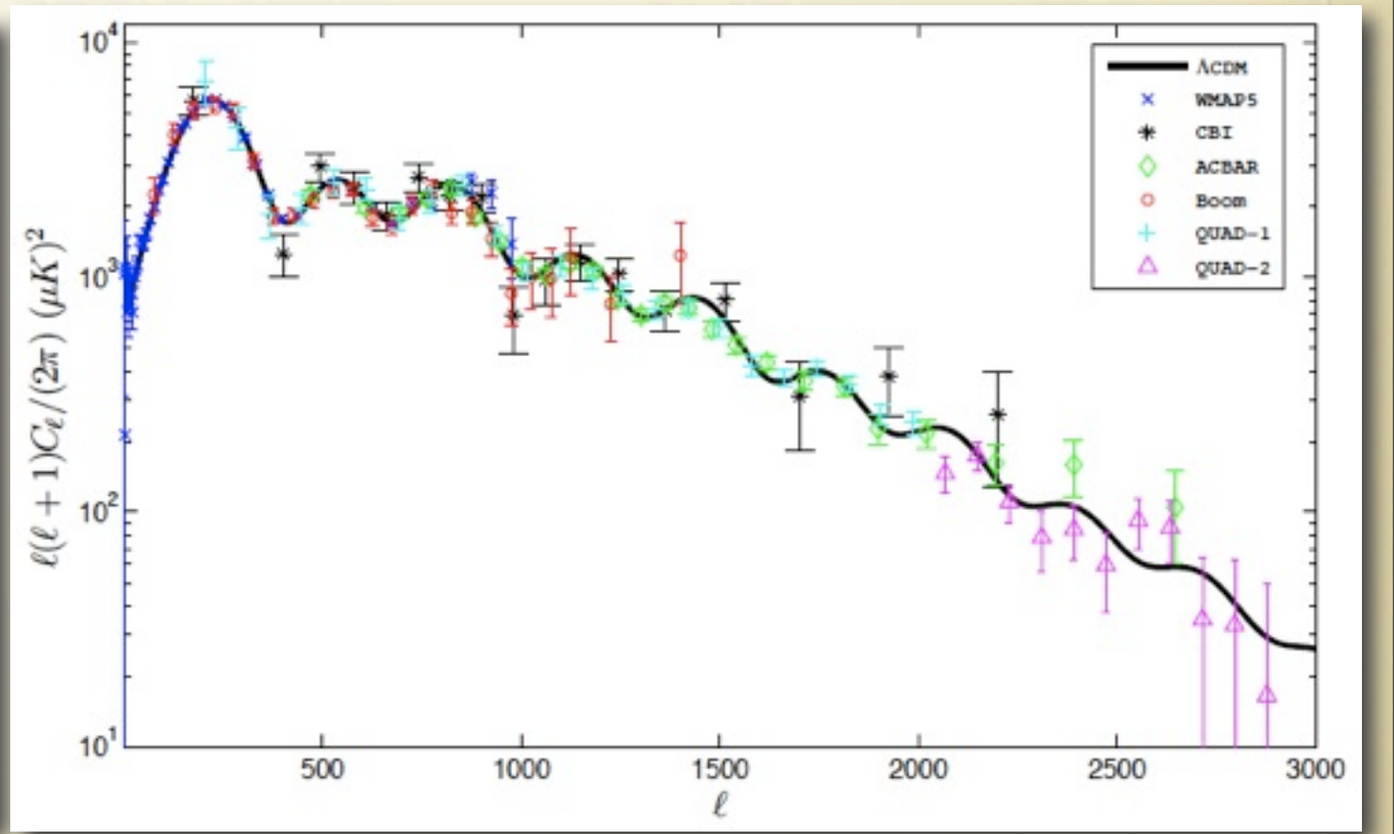
$$\text{sound horizon} \quad s = \int_0^t c_s \frac{dt}{a}$$

Acoustic Scale & CMB

- **Acoustic Scale is precisely constrained by CMB power spectrum**



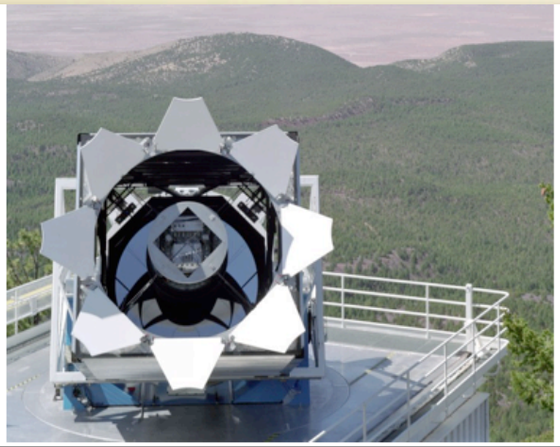
Hinshow et al. (2006)

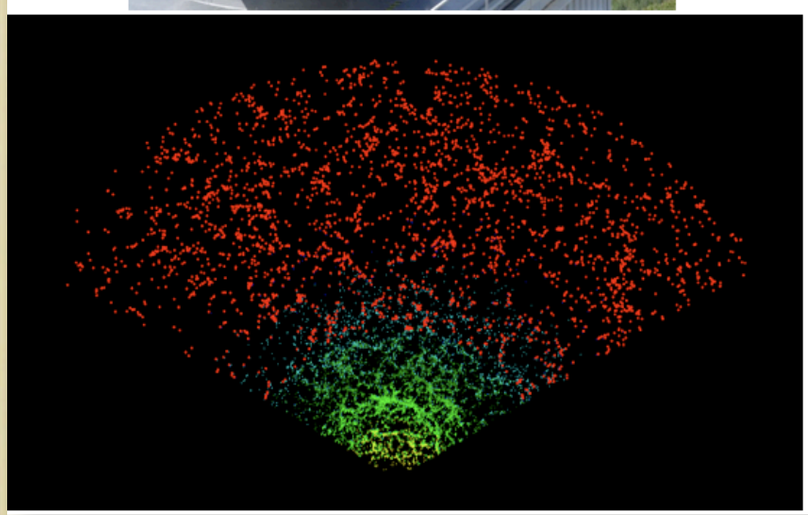


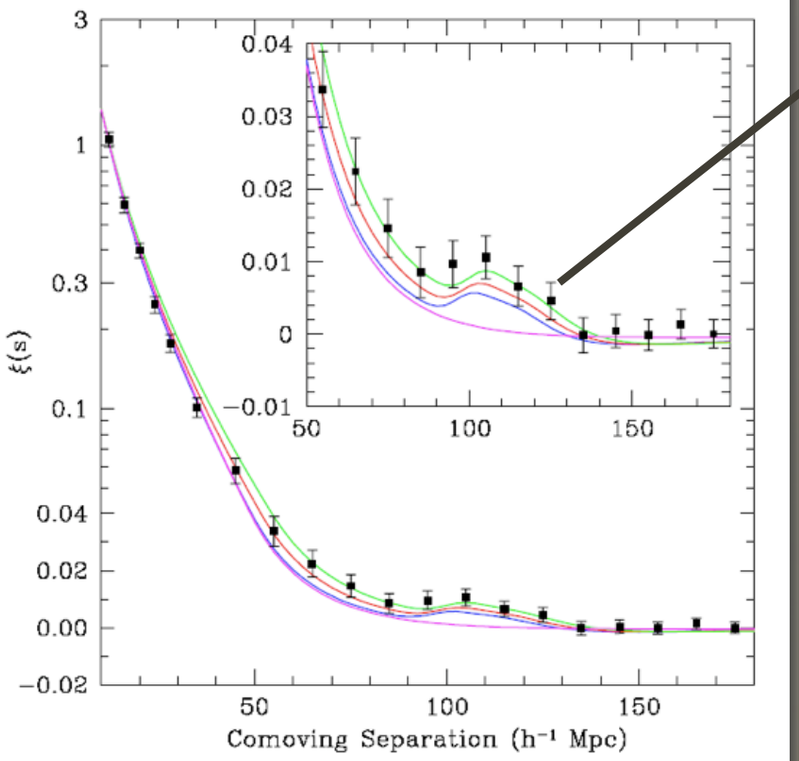
Barreiro (2009)

BAO in the Large-scale Structure

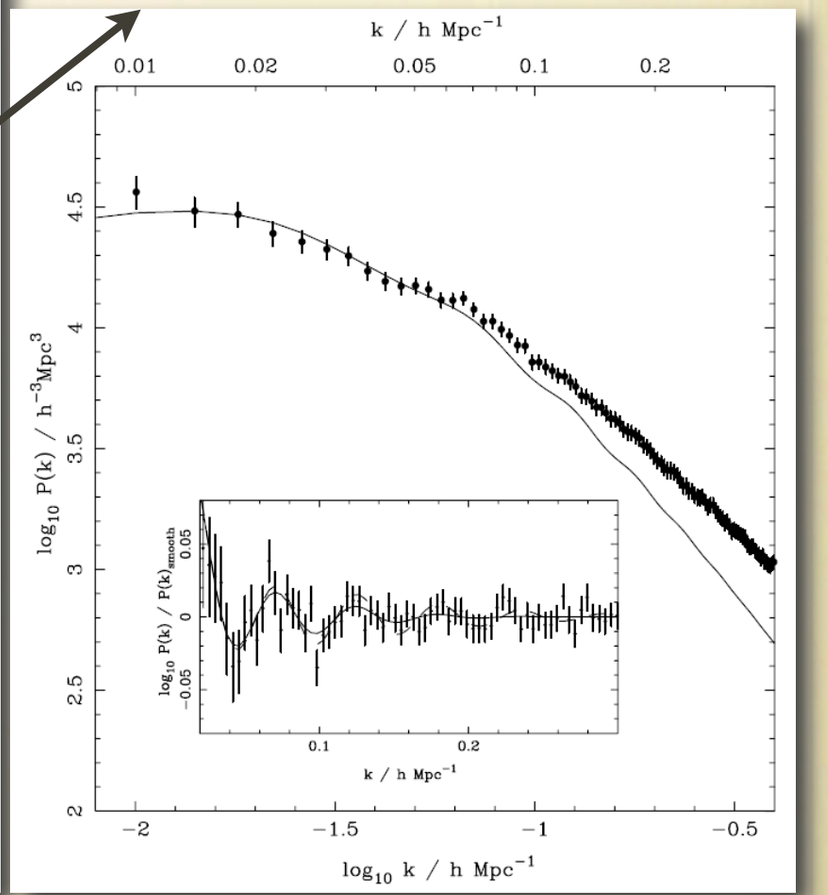
- BAO is encoded in the spatial clustering of galaxies
- Offering a standard ruler for cosmology







$s_{dec} = 105\ h^{-1}\mathrm{Mpc}$



Eisenstein et al. (2005)

Percival et al. (2007)

Importance of the standard ruler

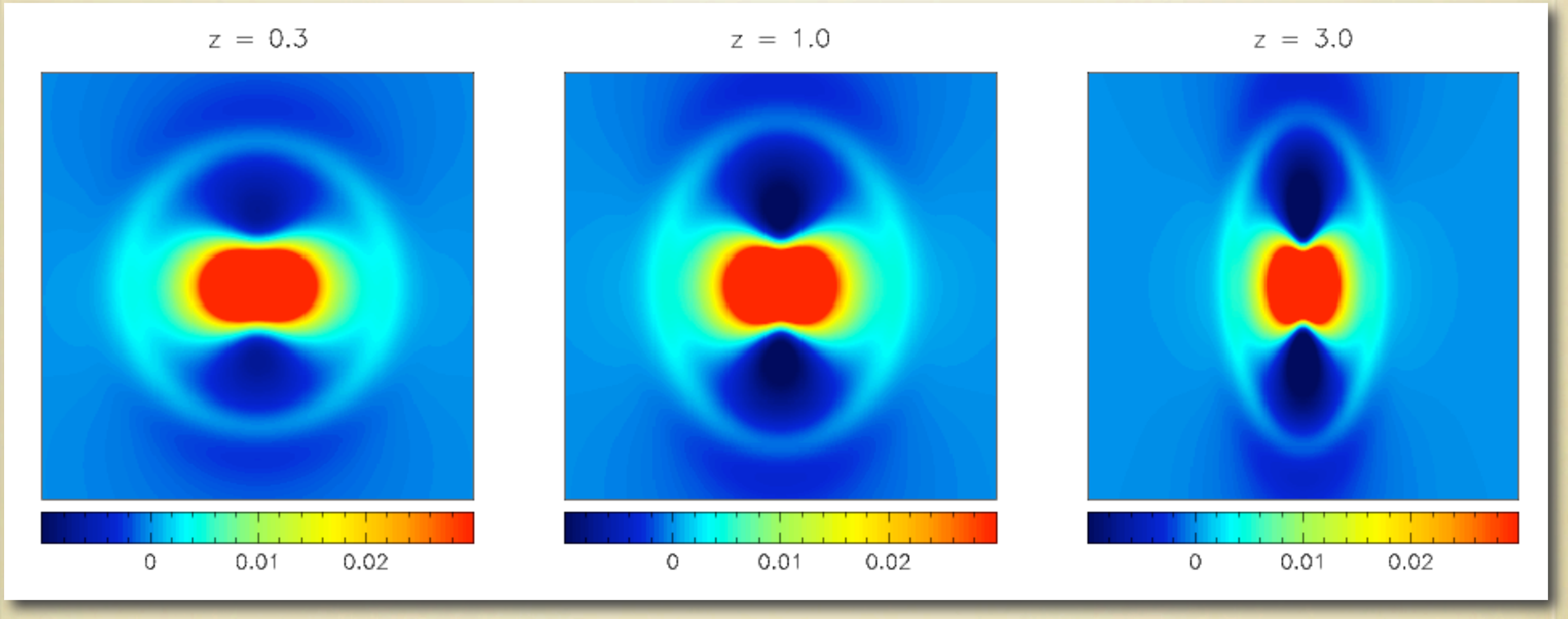
- Having a standard ruler (candle) is extremely important in cosmology
  - Hubble's discovery of expanding universe
    - Cepheid variables
  - Determination of the Hubble's constant
    - Many standard candles (TF, FP, SB, SN)
  - Discovery of accelerating universe
    - Supernovae Ia

BAO as a standard ruler

- Having a standard ruler is extremely important in cosmology
  - Geometry of the universe
    - Finite or infinite? Open, flat, or closed?
  - Expansion history <=> Energy components
    - Nature of dark matter & dark energy
- Existence of dark energy is one of the most fundamental problem in Physics
  - Origin of space and time
  - No natural explanation known so far

BAO scale is distorted in redshift survey

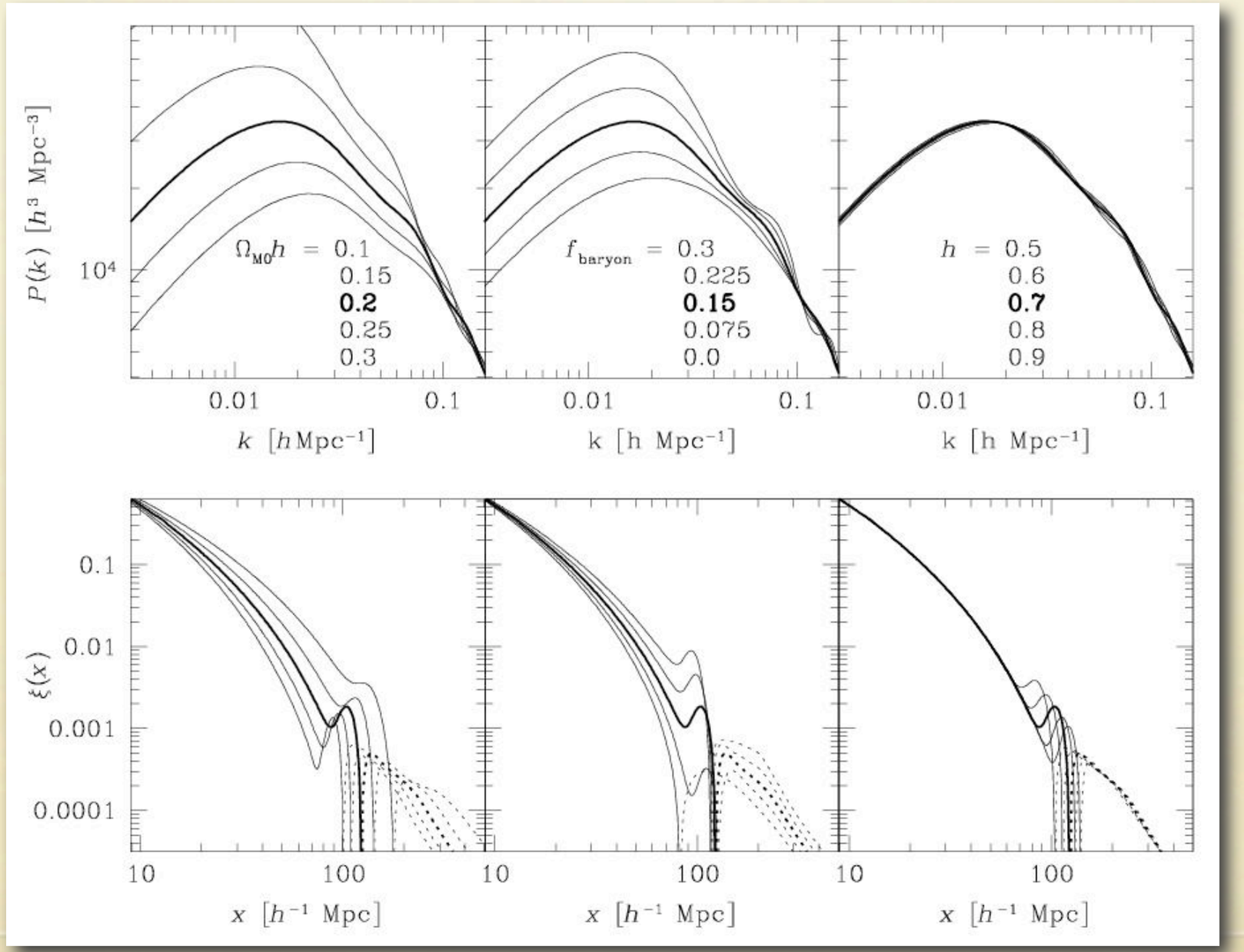
- **Example: 2D correlation function in redshift space (Linear theory)**



TM (2004)

Statistical tools for BAO survey

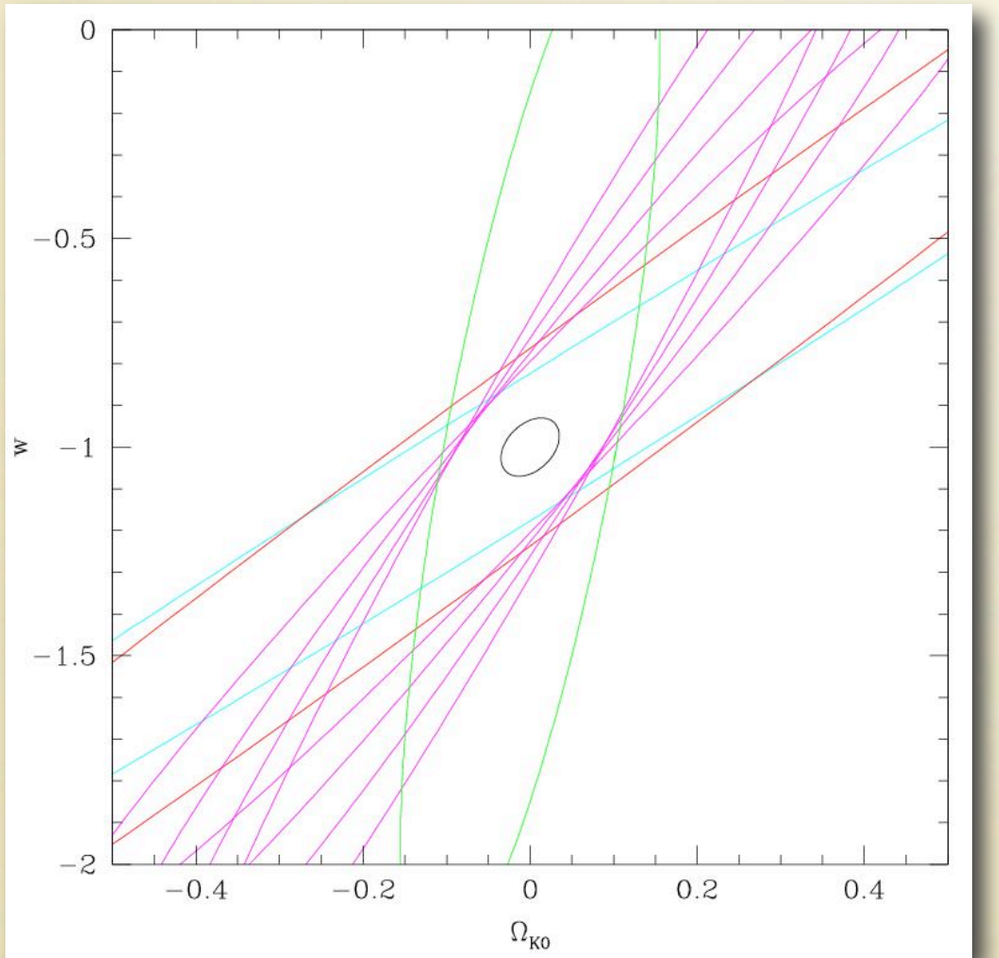
- Power spectrum: Fourier space
- Correlation function: Real space

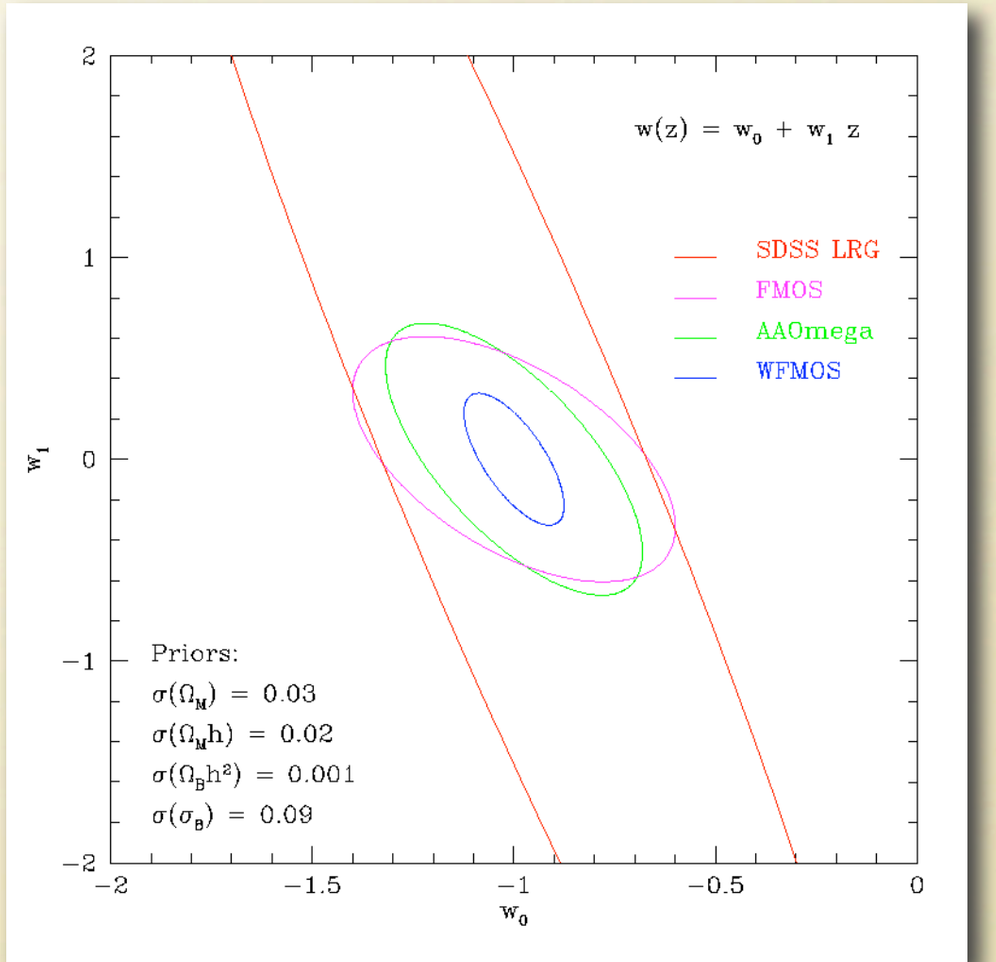


TM (2004)

Sample calculation of Fisher Matrix

- **Fisher matrix**
  - **A powerful tool for predicting how well a given survey can constrain parameters**





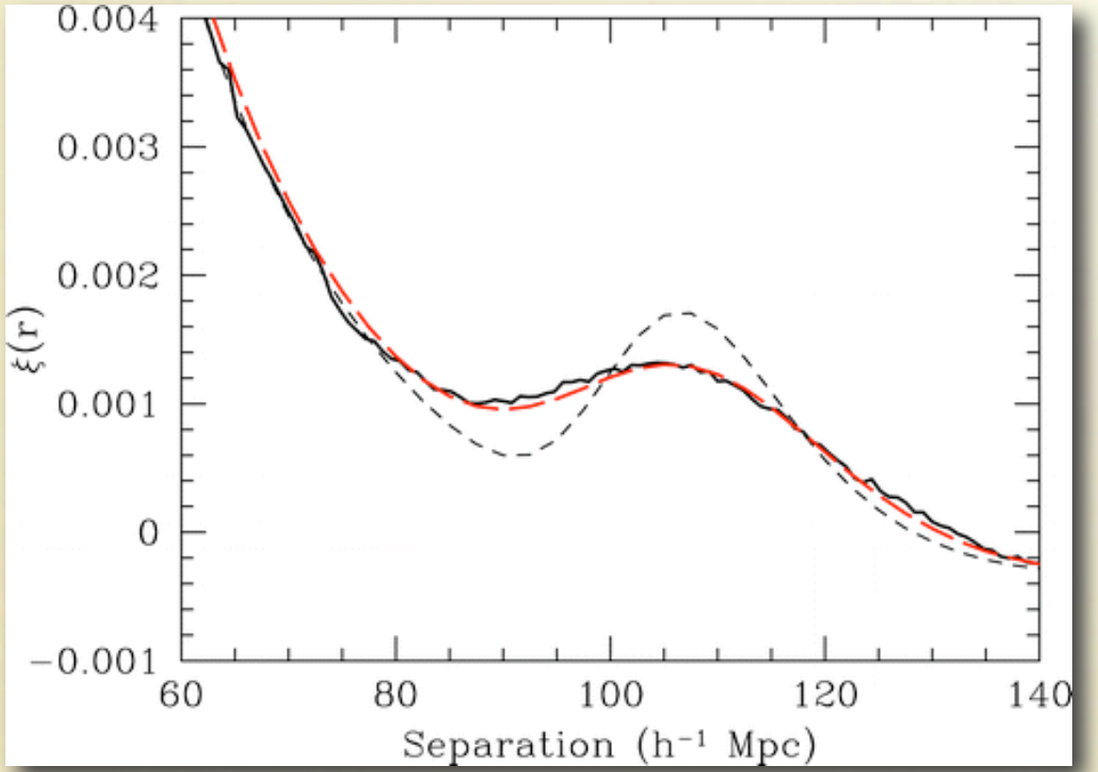
TM (2004, 2006)

Theoretical issues

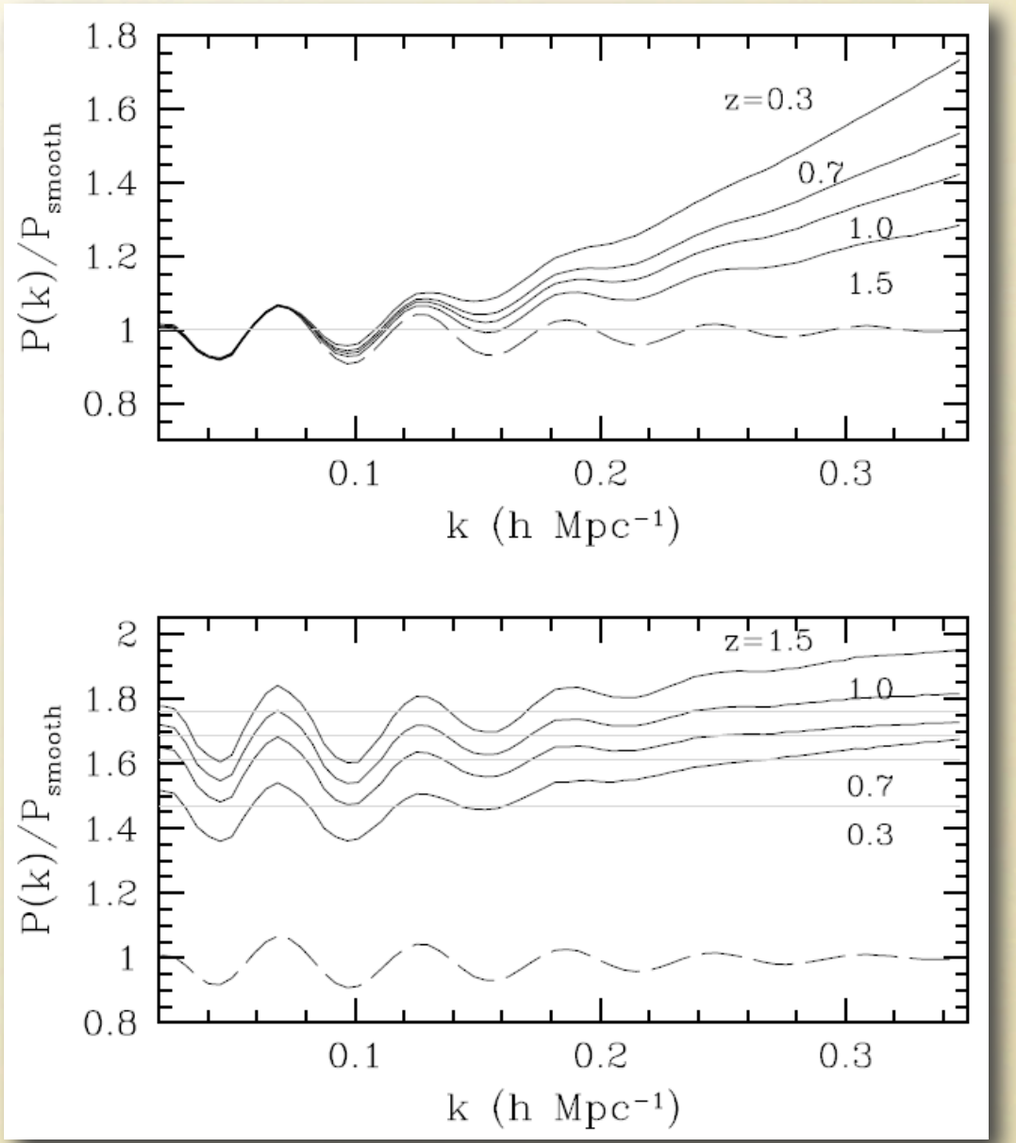
- Linear analysis of BAO in galaxy clustering is not quantitatively satisfactory
- Nonlinearity in various aspects should be theoretically elucidated, otherwise the estimation of dark energy etc. would be biased
  - Nonlinearity in dynamics
  - Nonlinearity in redshift-space distortions
  - Nonlinearity in halo/galaxy bias
- For FMOS, those issues may not be serious because of S/N, but theoretically better modeling is desirable

Nonlinearity in dynamics

- Nonlinear dynamics distorts the BAO signature
  - N-body simulations



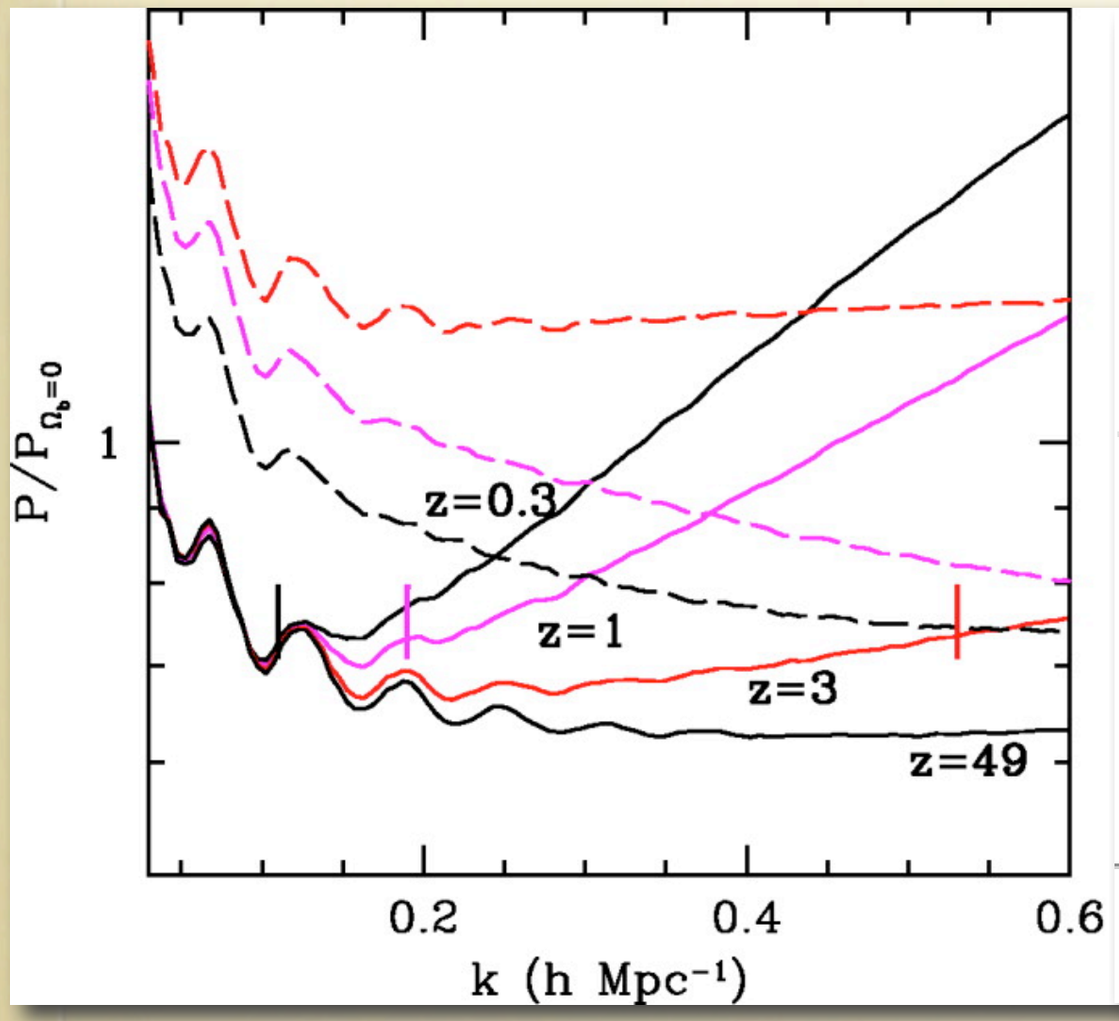
Eisenstein et al. (2007)



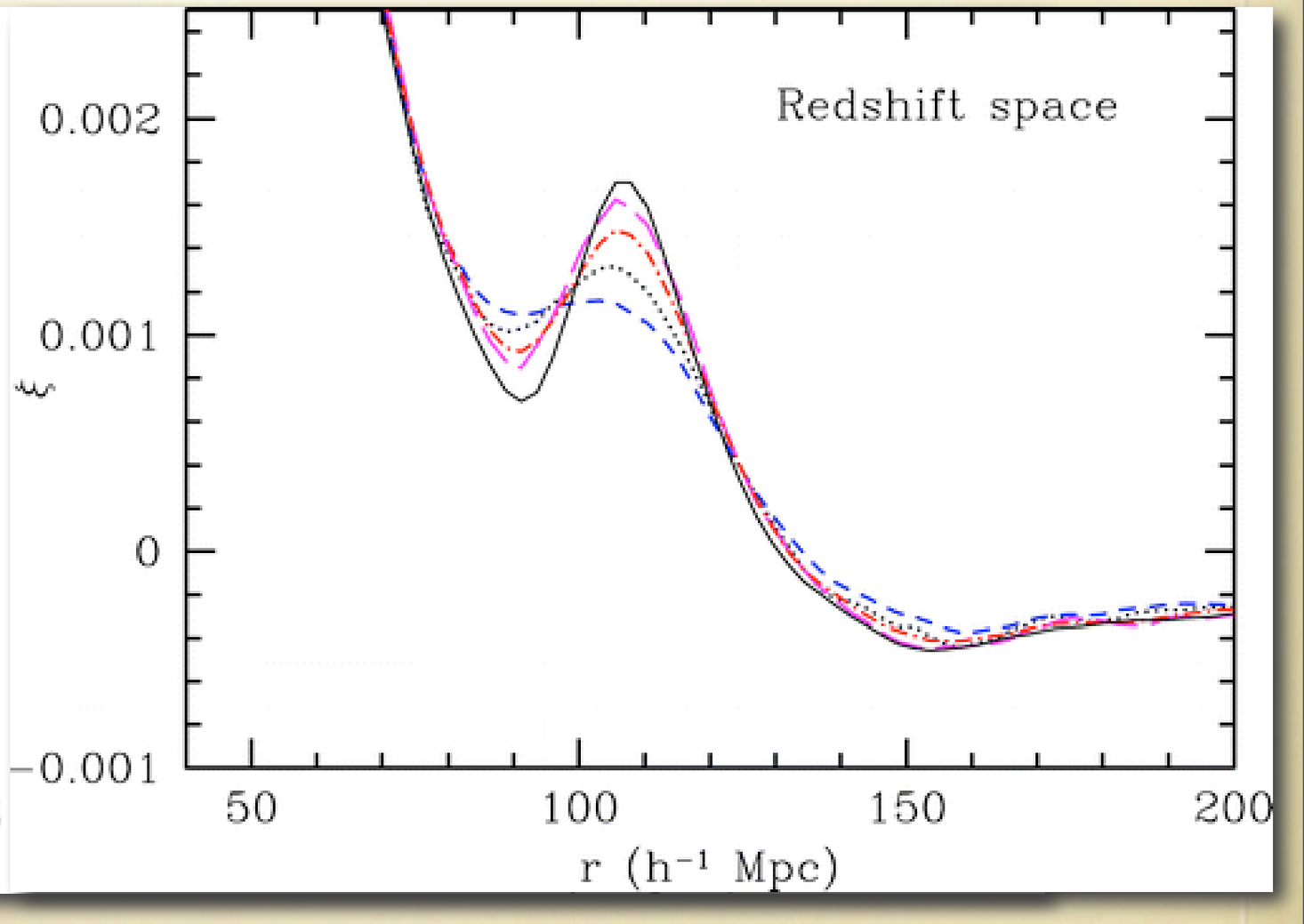
Seo et al. (2008)

Nonlinearity in redshift-space distortions

- Redshift-space distortions change the nonlinear effects on BAO
  - P(k):small-scale suppressed, xi(r): degradation larger



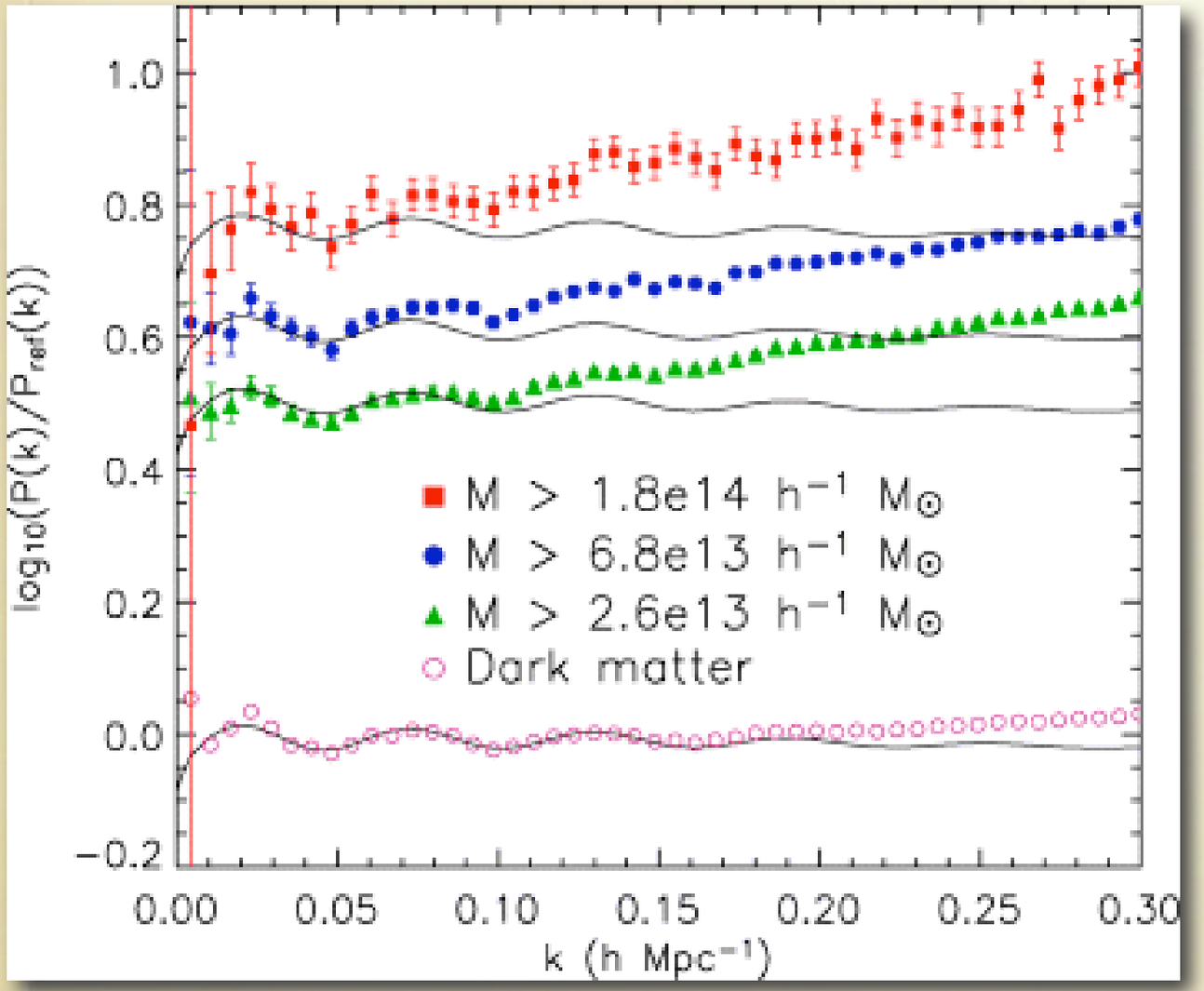
Seo et al. (2005)



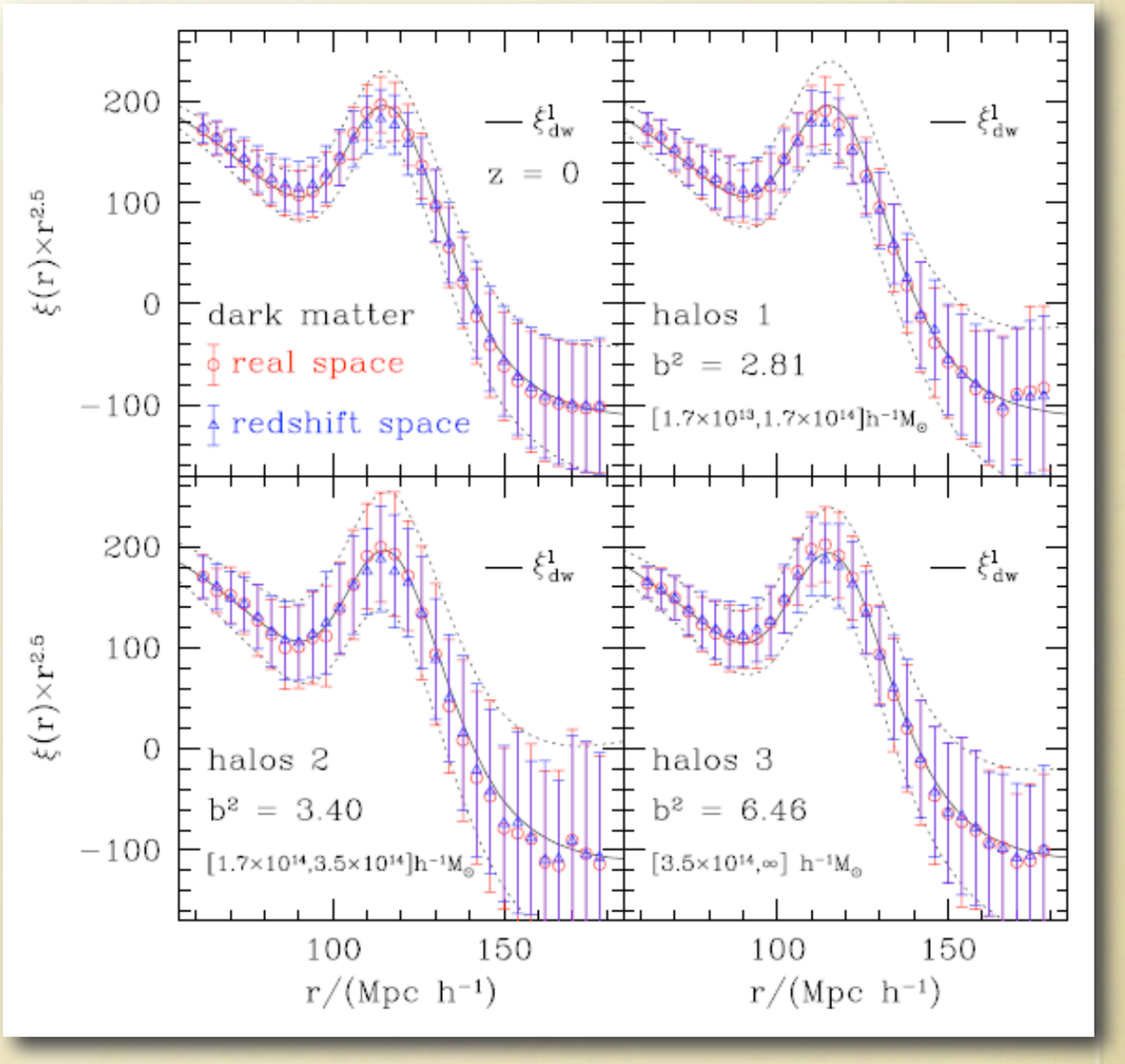
Eisenstein et al. (2007)

Nonlinearity in bias

- **Effects of nonlinear (halo) bias**



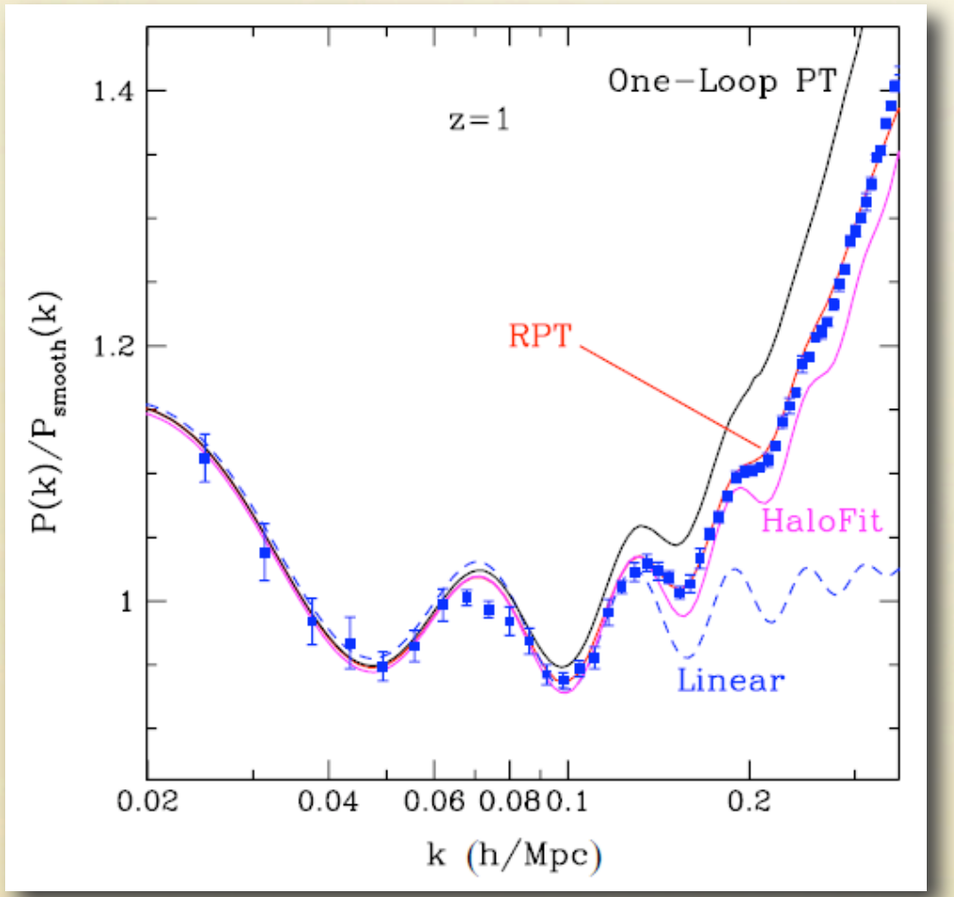
Angulo et al. (2005)



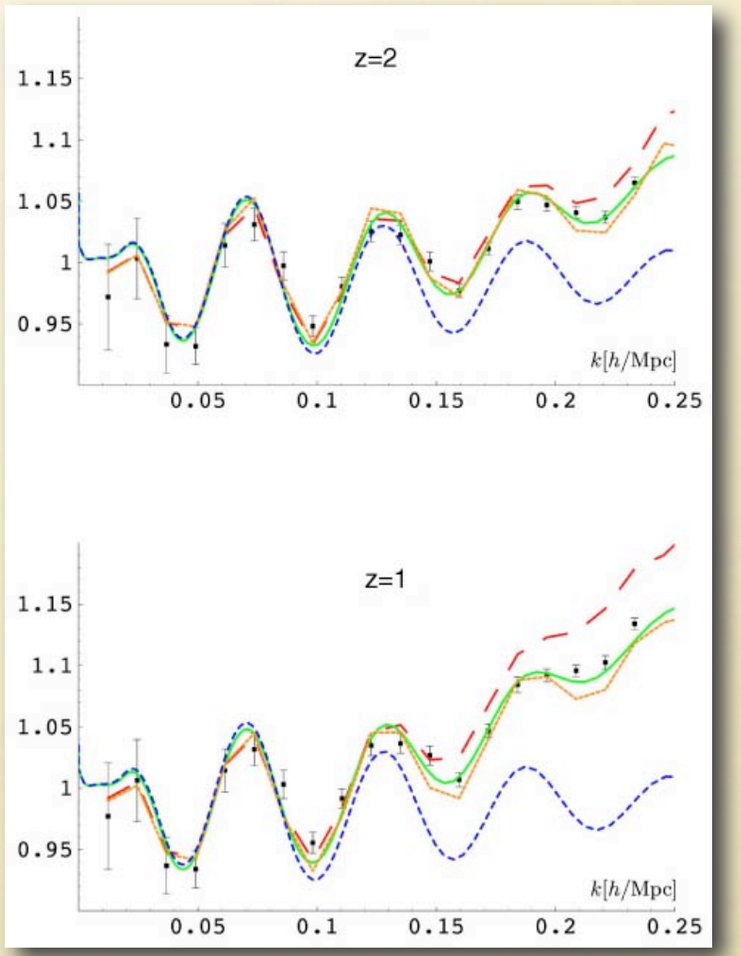
Sanchez et al. (2008)

Recent progress on theoretical modeling

- **Nonlinear dynamics**
  - **Standard perturbation theory does not give satisfactory results**
  - **Developments of renormalized perturbation theories etc.**
  - **However, such methods so far only works for mass density fields in real space**



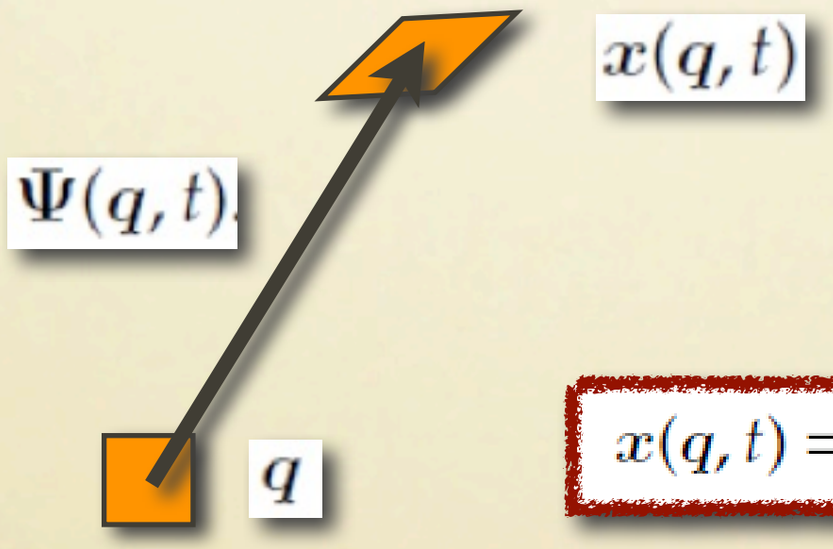
Crocce & Scoccimarro (2008)



Matarrese & Pietroni (2008)

Recent progress on theoretical modeling

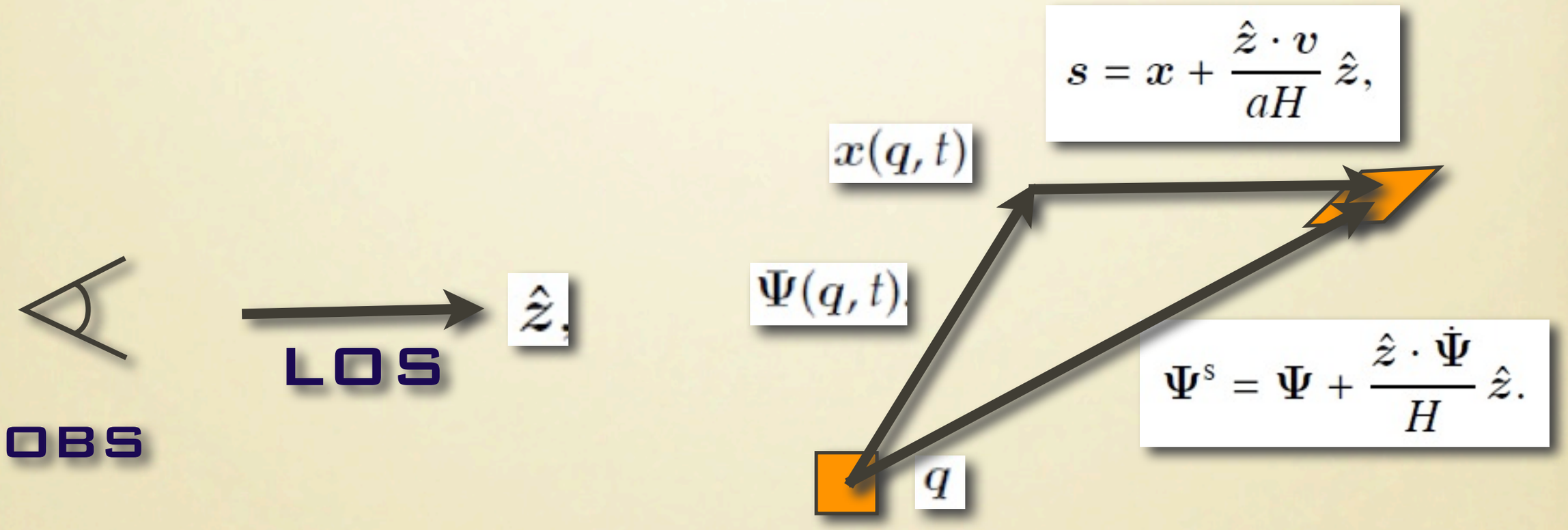
- **Application of the Lagrangian perturbation theory (LPT)**
  - **LPT can naturally handle nonlinear dynamics, nonlinear redshift-space distortions, and nonlinear halo bias at the same time [TM (2008a,2008b)]**



$$x(q,t) = q + \Psi(q,t).$$

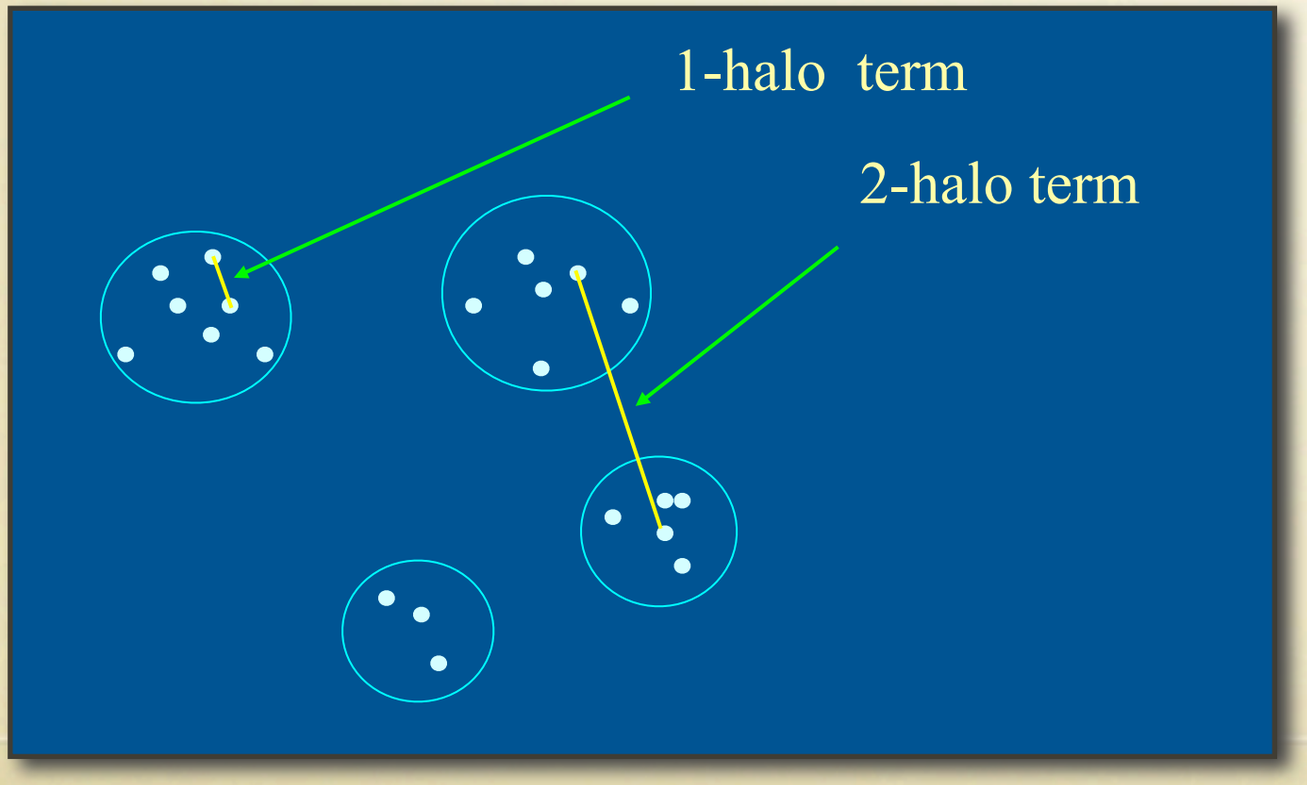
Redshift-space distortions in LPT

- Redshift-space distortions are linear in LPT displacement field
  - Conceptually simpler than in Standard PT



Halo bias and LPT

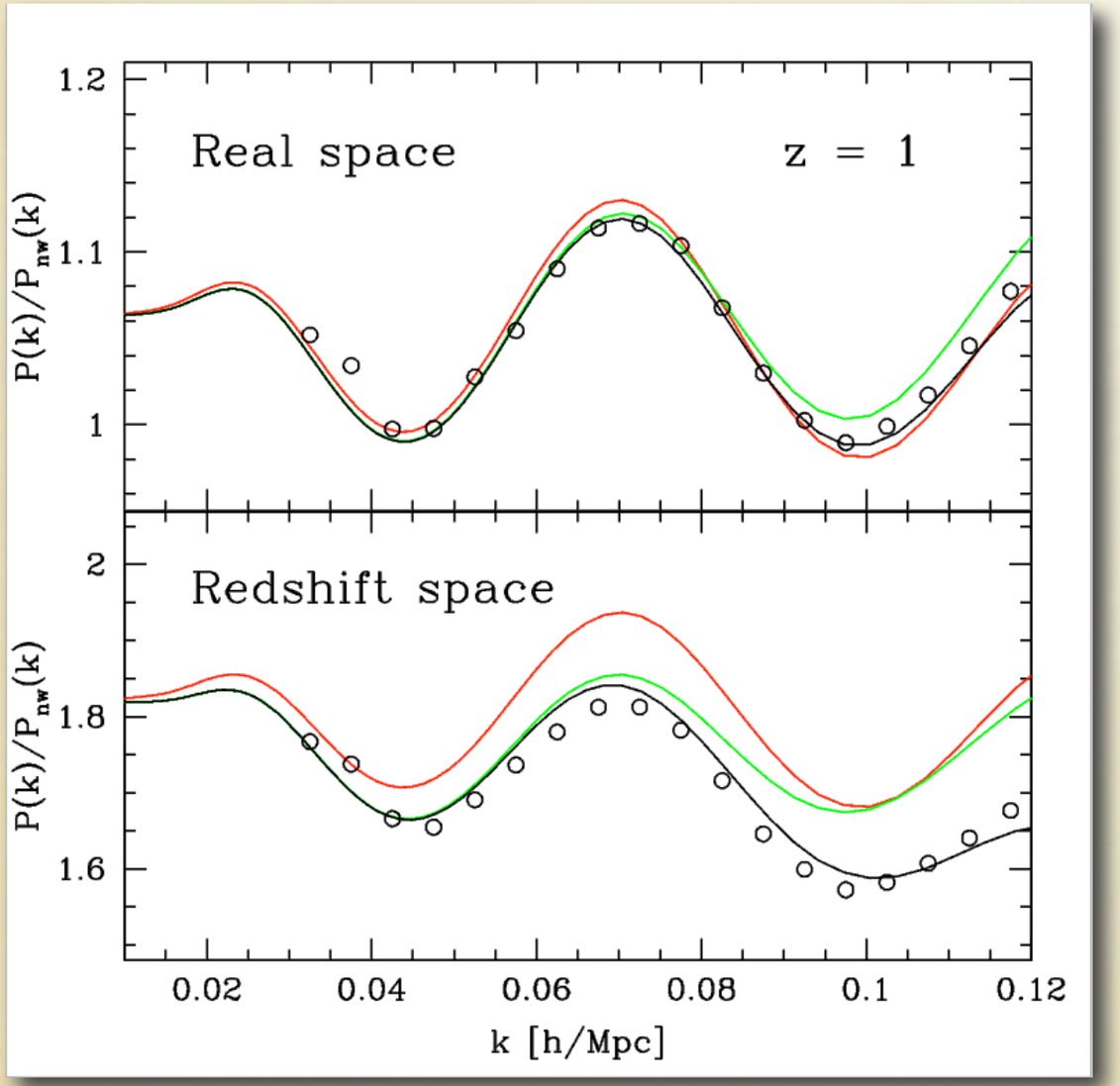
- Galaxy bias is not easy to handle
  - Clustering on small scales is largely affected by galaxy biasing
- However, bias on large scales has been successfully modeled by analytic halo model
- Halo is biased in Lagrangian space
  - Halo bias is naturally incorporated to LPT

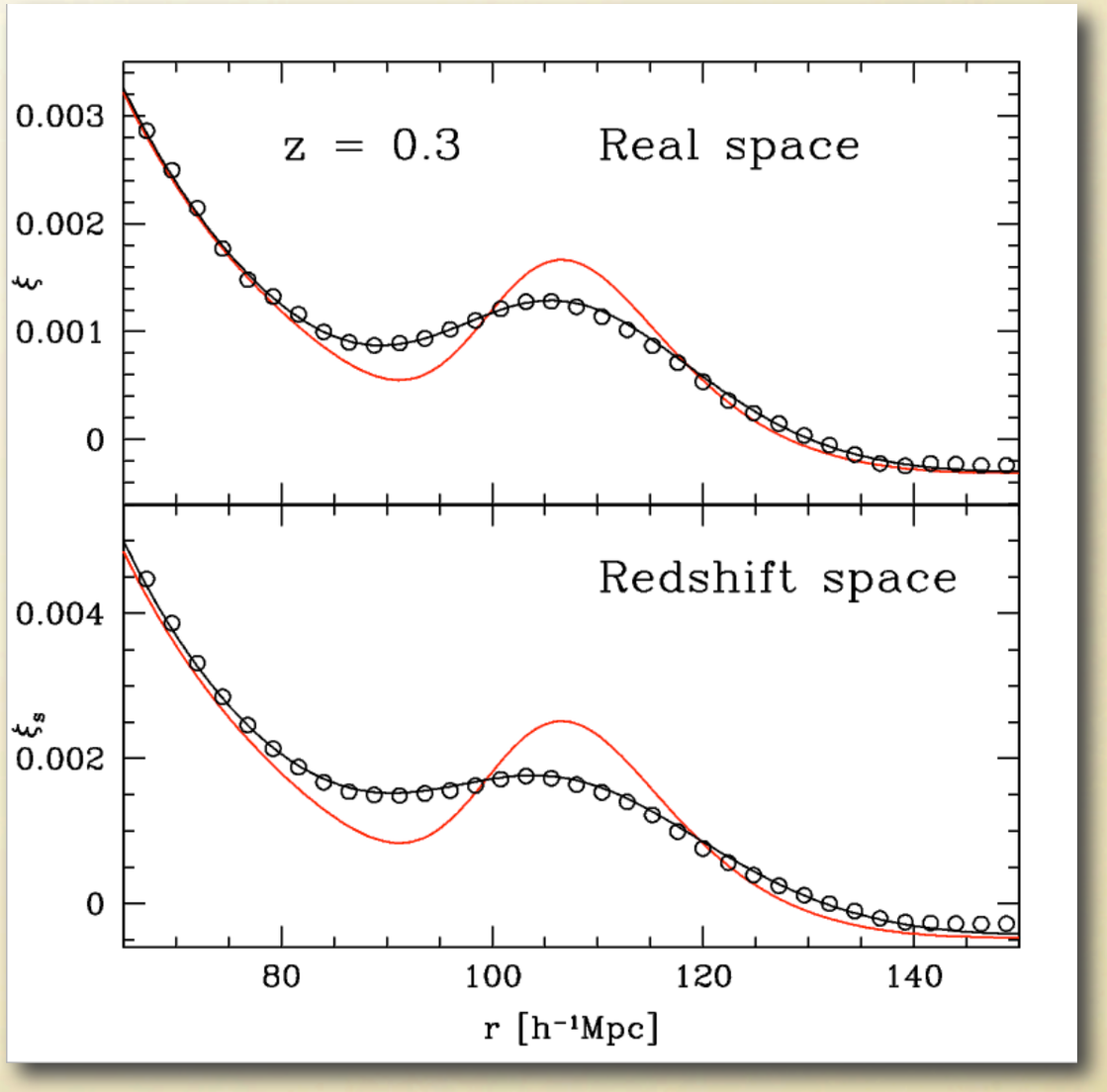


$$\mathcal{N}(1|0)\,\mathrm{d}M_1 \equiv \frac{M_0}{M_1} f(1|0)\,\frac{\mathrm{d}\Delta_1^2}{\mathrm{d}M_1}\,\mathrm{d}M_1,$$

New modeling with LPT

- Although LPT does not fit P(k) on small scales, it correctly reproduces nonlinear smearing effects
- No other such theory in redshift space

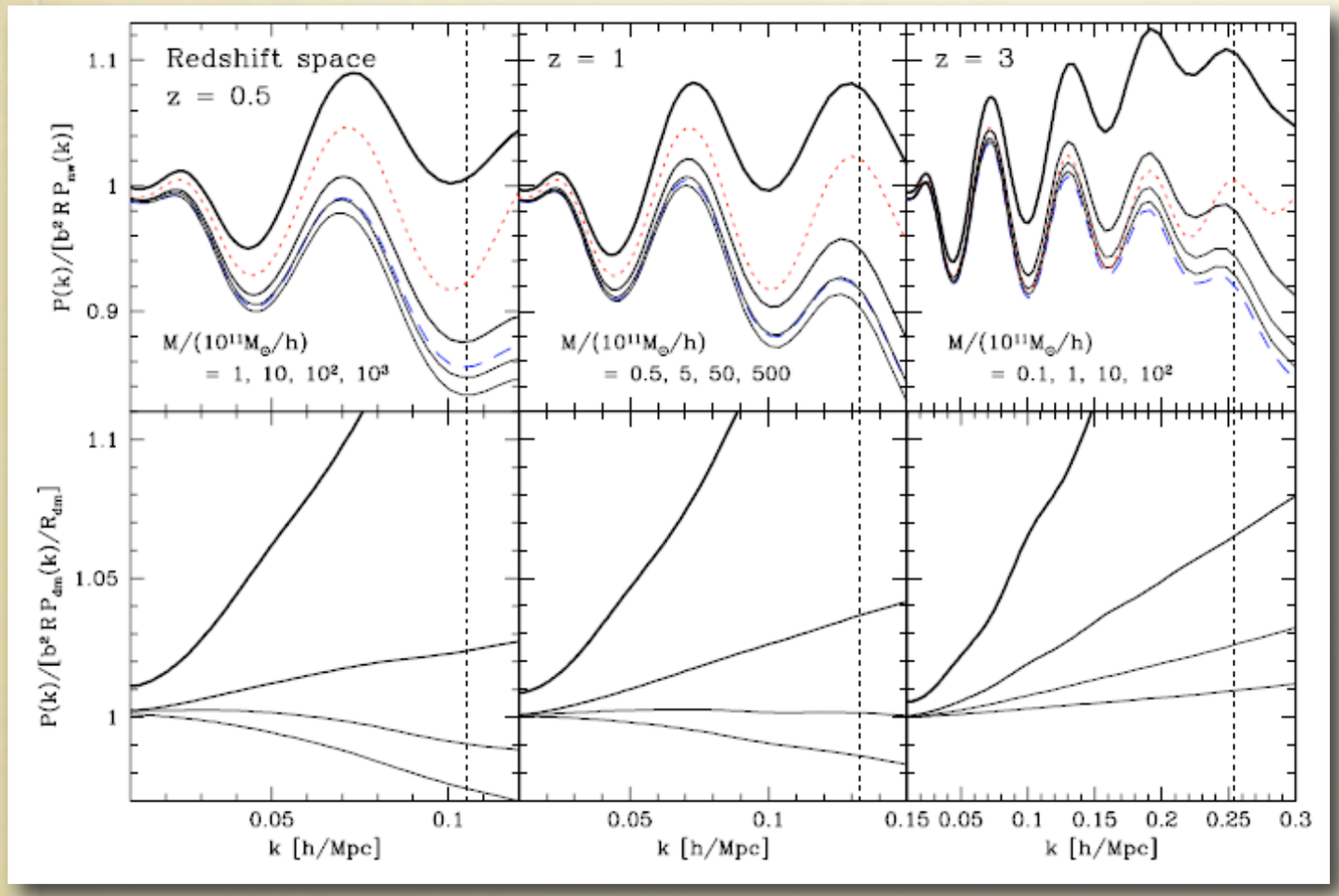


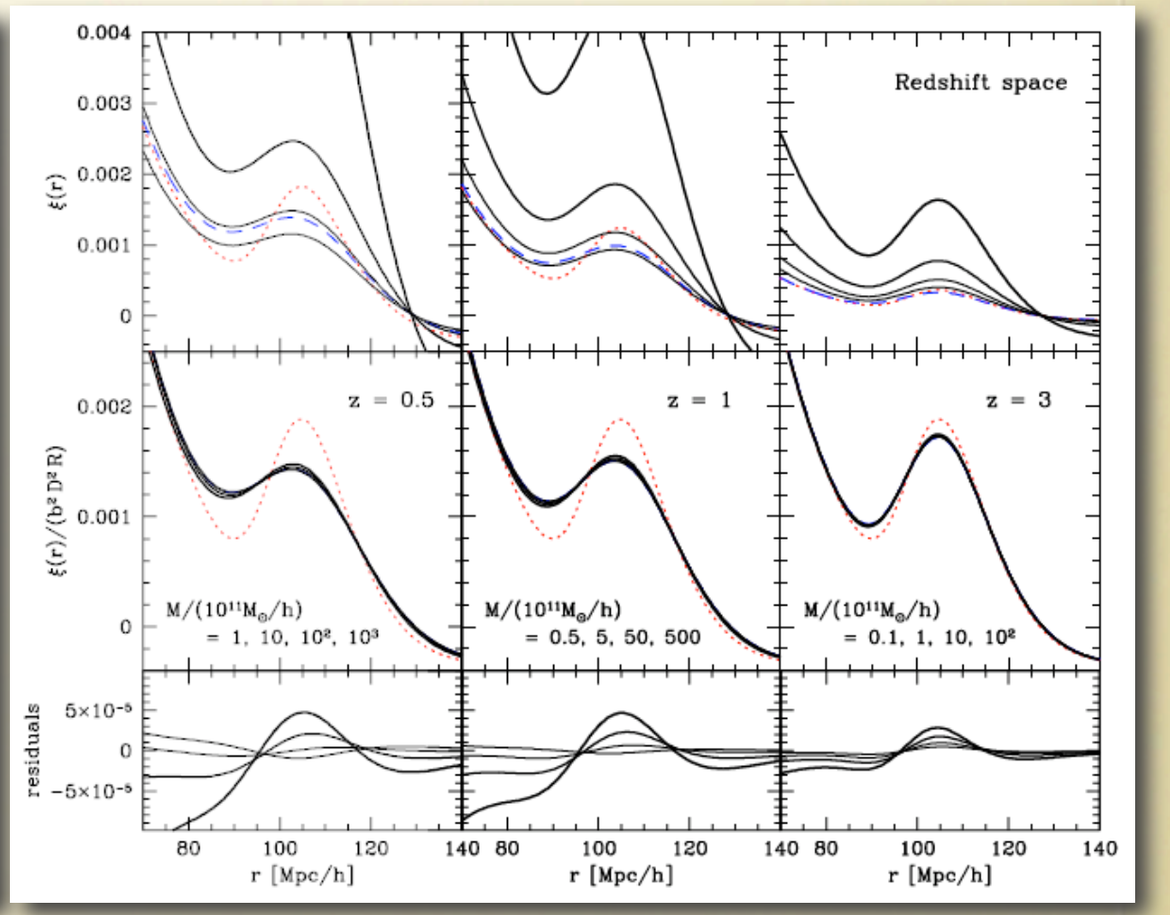


TM (2008a)

New modeling with LPT

- Halo bias is naturally incorporated in this formulation
- Halo bias does not significantly change the BAO scale





TM (2008b)

Summary

- BAO is a nearly ideal standard ruler
- Nonlinearity, redshift-space distortions, effects of bias should be understood
- Developments of a theory with Lagrangian picture
- Analytic method is desirable