Baryon Acoustic Oscillations

BAO

Francisco Javier Castander

Institut de Ciències de l'Espai, IEEC/CSIC, Barcelona

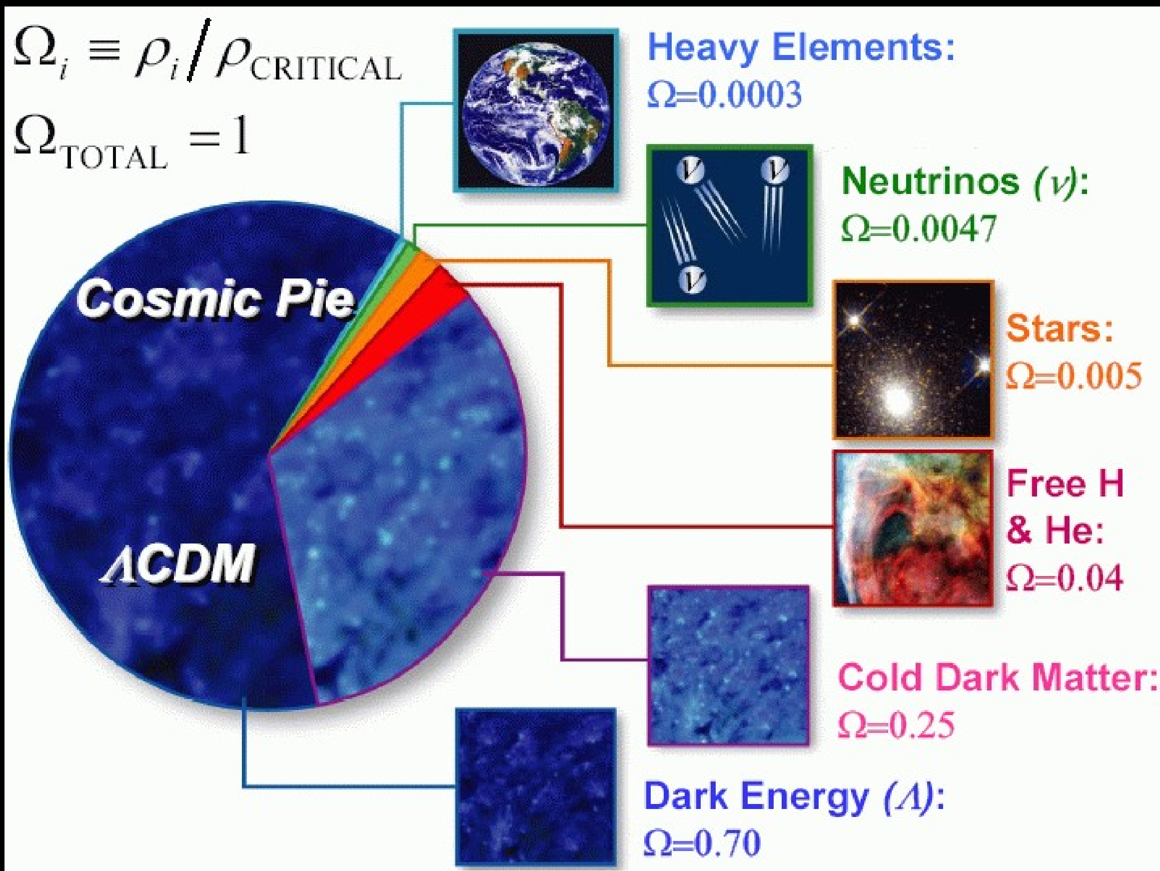
Outline

- Dark energy context
- The BAO probe
- How standard is the BAO ruler?

Material borrowed mainly from these sources

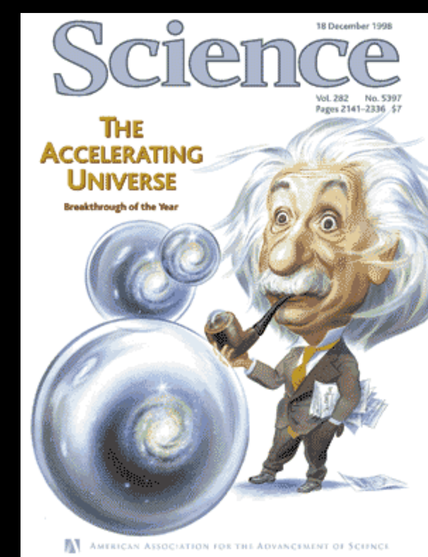
- http://cdm.berkeley.edu/doku.php?id=baopages
- http://cmb.as.arizona.edu/~eisenstein/acousticpeak/
- http://mwhite.berkeley.edu/BAO

The Big Problems: Dark Energy and Dark Matter



The confirmation of Dark Energy points to major holes in our understanding of fundamental physics

95% of the Universe is in forms unknown to us



1998 Science breakthrough of the year

Probing Dark Energy

- Dark energy is probed through how it influences the expansion rate of the universe H(z) and the rate growth of structure g(z)

$$H^2(z) = H^2_0 \; [\; \Omega_M (1+z)^3 + \Omega_R (1+z)^4 + \Omega_K (1+z)^2 + \Omega_{DE} (1+z)^{3(1+w)} \;]$$

matter radiation curvature dark energy

g(z) in general a complicated function of cosmological parameters

Probing Dark Energy

Best observational probes (DETF)

- Weak lensing (geometrical & growth)
- Baryon acoustic oscillations (geometrical)
- Supernovae (geometrical)
- Clusters of galaxies (growth & geometrical)

Probing Dark Energy

- Geometric test: integrals over $H(z)$:

Comoving distance		$r(z) = F[\int dz/H(z)]$
Standard Candles	Supernovae	$D_L(z) = (1+z)\, r(z)$
Standard Rulers	Baryon Oscillations	$D_A(z) = (1+z)^{-1}\, r(z)$
Standard Population	Clusters	$dV/dzd\Omega = r^2(z)/H(z)$

- Growth of Structure test: $g(z)$

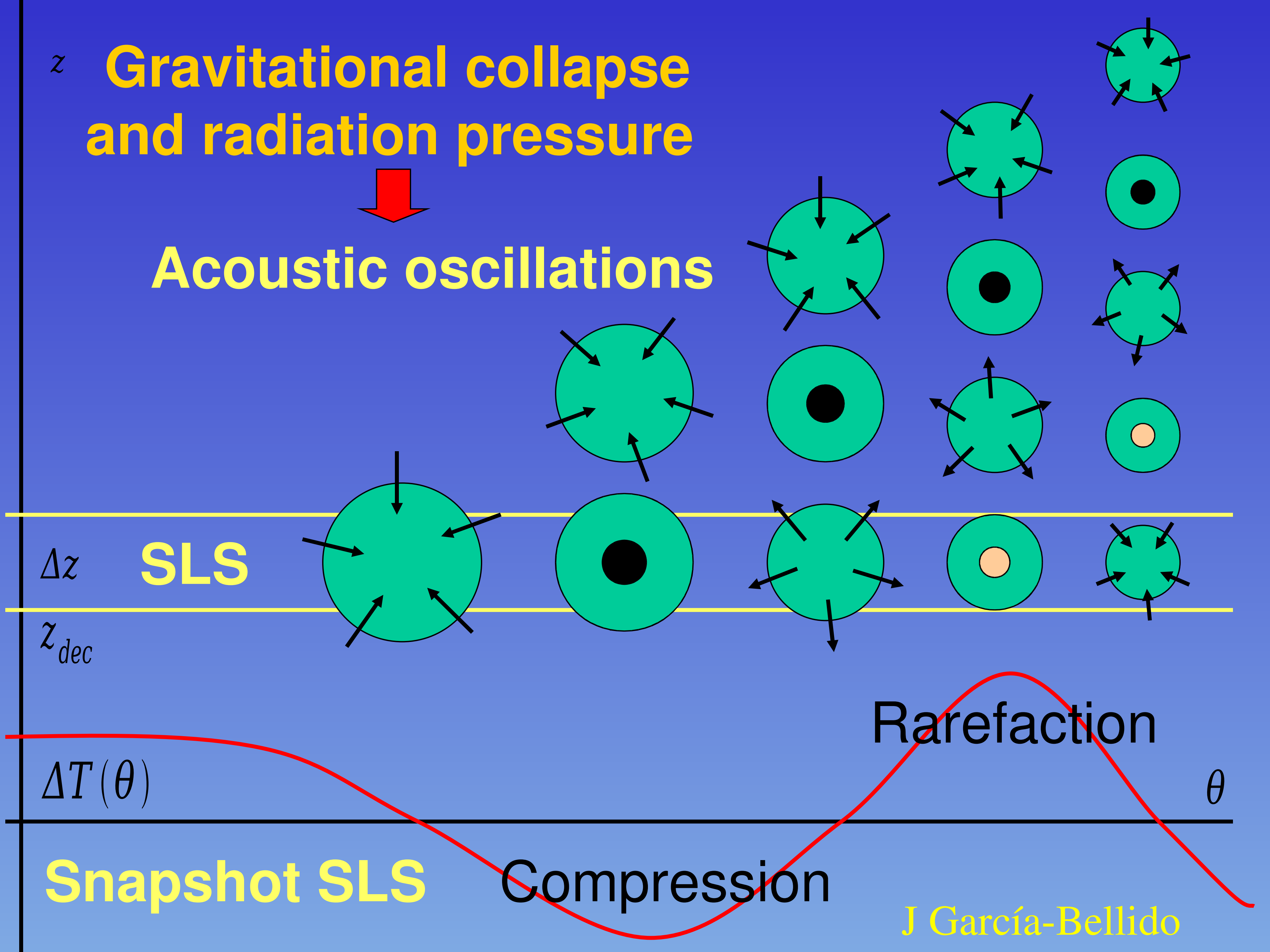
Clusters, Weak lensing, clustering

- DE equation of state: $w = P/\rho$

- DE parameterization: $w(z) = w_0 + w_a z/(1+z)$

The BAO probe

- The early universe composed of photons, baryons and dark matter
- Photons and baryons tightly coupled
- The early universe very homogeneous except tiny fluctuations
- Evolution:
    - as it expands it becomes cooler and less dense
    - fluctuations grow due to gravity
- Acoustic waves are generated as the photon-baryon fluid is attracted and falls onto the overdensities: compressions and rarefactions



z
Gravitational collapse and radiation pressure
Acoustic oscillations
Δz
SLS
z_dec
Rarefaction
ΔT(θ)
θ
Snapshot SLS
Compression
J García-Bellido

The BAO probe

- These acoustic waves propagate until the universe becomes cool enough for the electrons and protons to recombine and then the baryons and photons decouple

- The time when the baryons are "released" from the drag of the photons is known as the drag epoch, z_d

- From then on photons expand freely while the acoustic waves "freeze in" the baryons in a scale given by the size of the horizon at the drag epoch

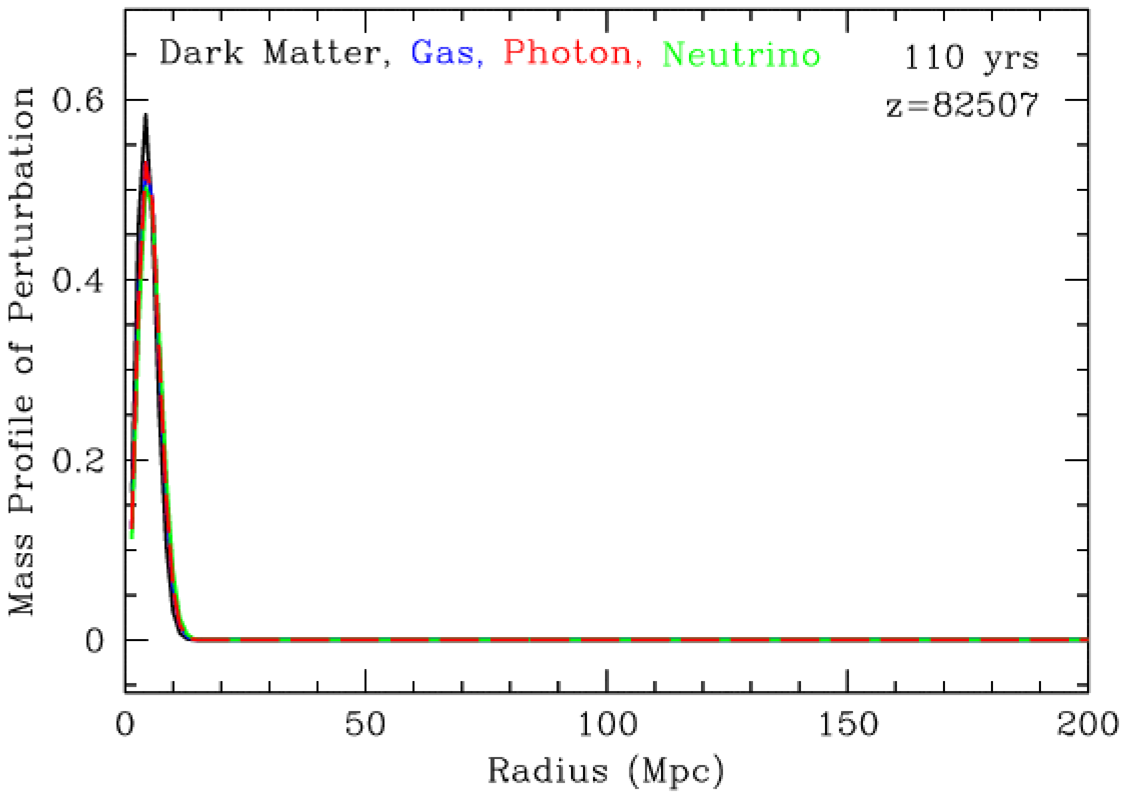
- Progressively, baryons fall into dark matter potential wells but also dark matter is attracted to baryon overdendities

The BAO generation description

Description of one perturbation (Eisenstein)

- Four species: Dark matter, Baryons, Photons & Neutrinos
- Initial perturbations adiabatic: all species perturbed approximately same fractional amount

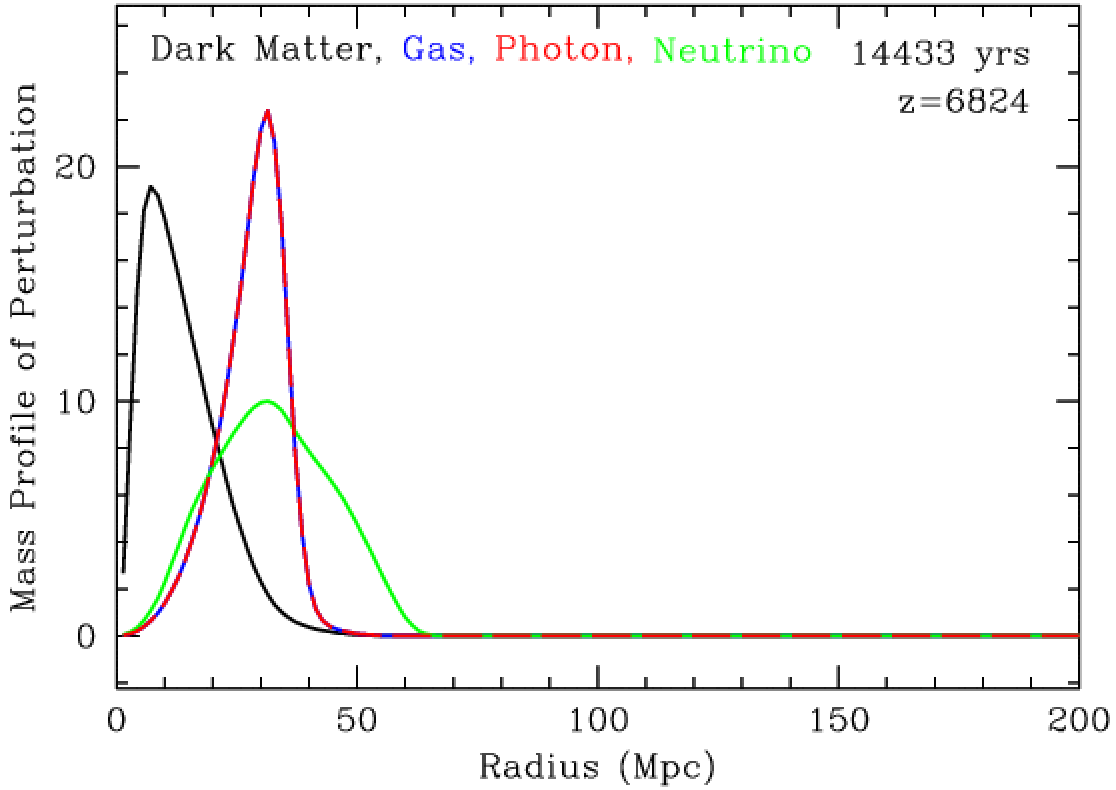
The BAO generation description



The BAO generation description

- Neutrinos do not interact and move too fast to be stopped by gravity, so they stream away
- Dark matter responds to gravity and falls onto the perturbation overdensity
- Perturbation dominated by photons and baryons as they are coupled. Perturbation is overdensity and overpressure. Overpressure tries to equalize with surrounding resulting in an expanding sound wave moving at the speed of sound which is approximately 2/3 the speed of light
- The perturbation in photons & baryons is carried outward

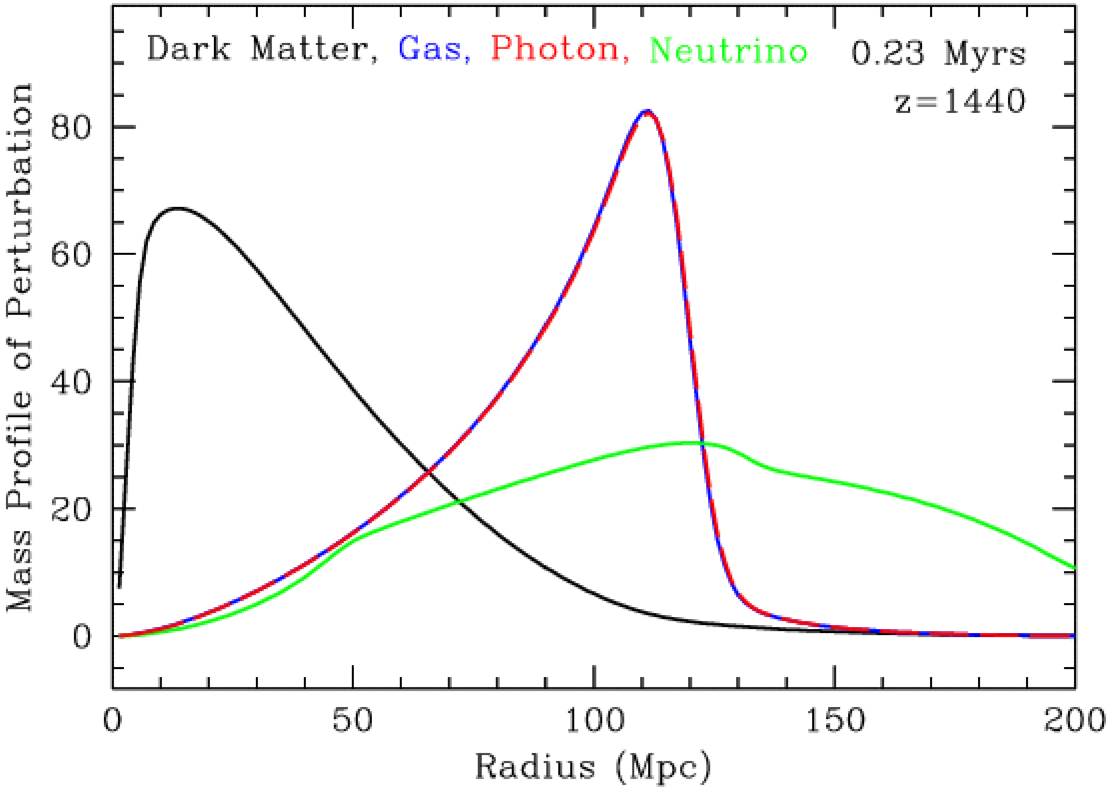
The BAO generation description



The BAO generation description

- The photons & baryons continue to expand
- Neutrinos spread out
- Dark matter continues to fall into perturbations, which grows

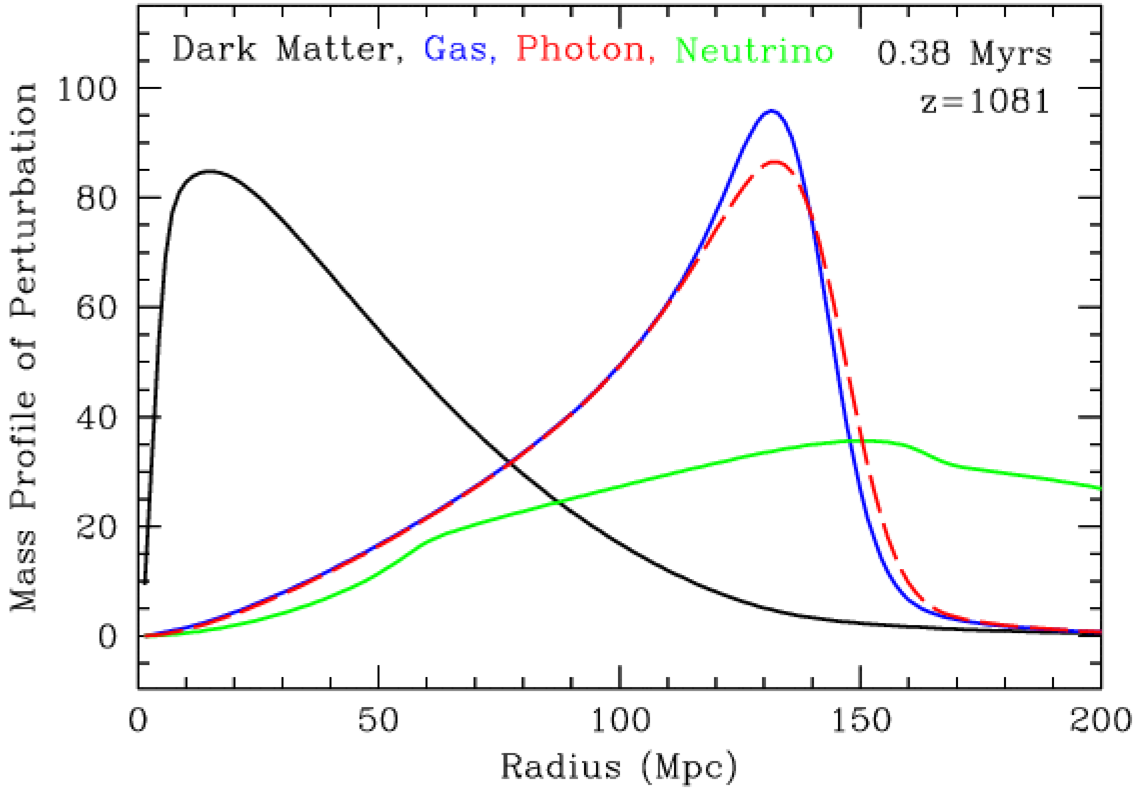
The BAO generation description



The BAO generation description

- As the expanding universe cools down, it reaches a point when the electrons and protons begin to combine
- Photons do not scatter as efficiently and start to decouple
- The sound speed drops and the pressure wave slows down

The BAO generation description

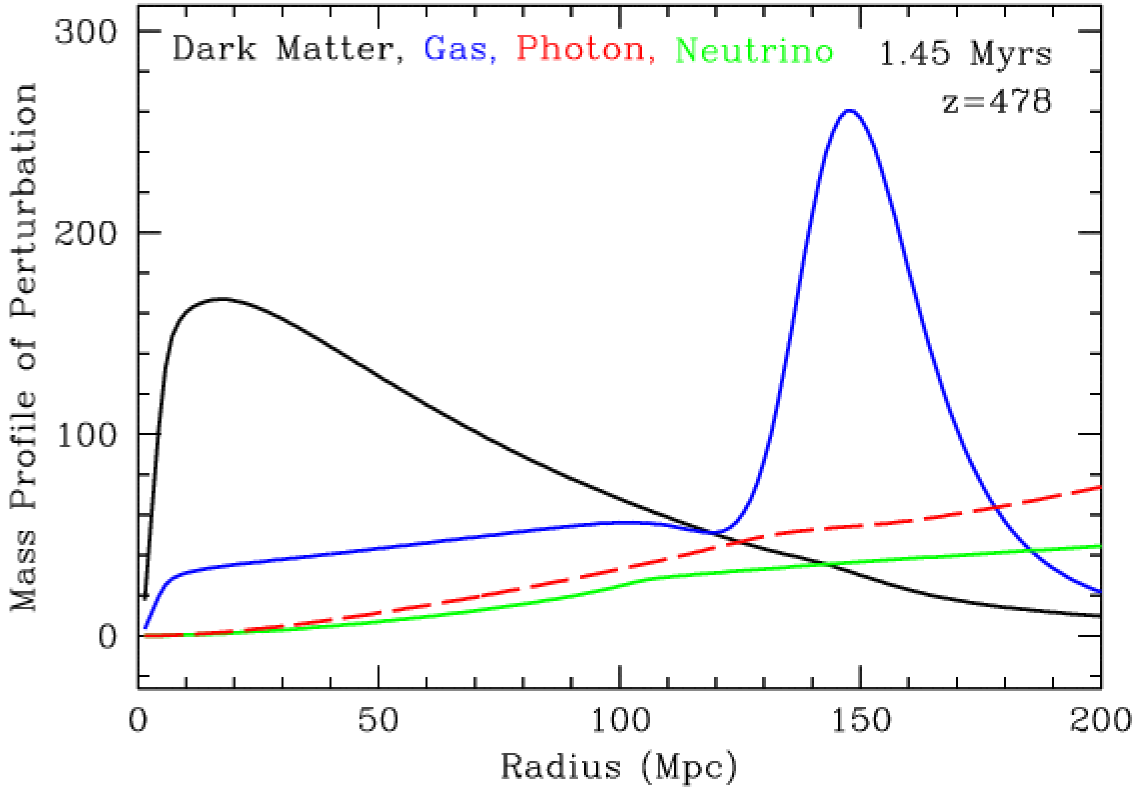


The BAO generation description

- The process continues until the photons completely decouple and then its perturbation smoothes out

- The sound speed of the baryon perturbation drops so much that the pressure wave stalls

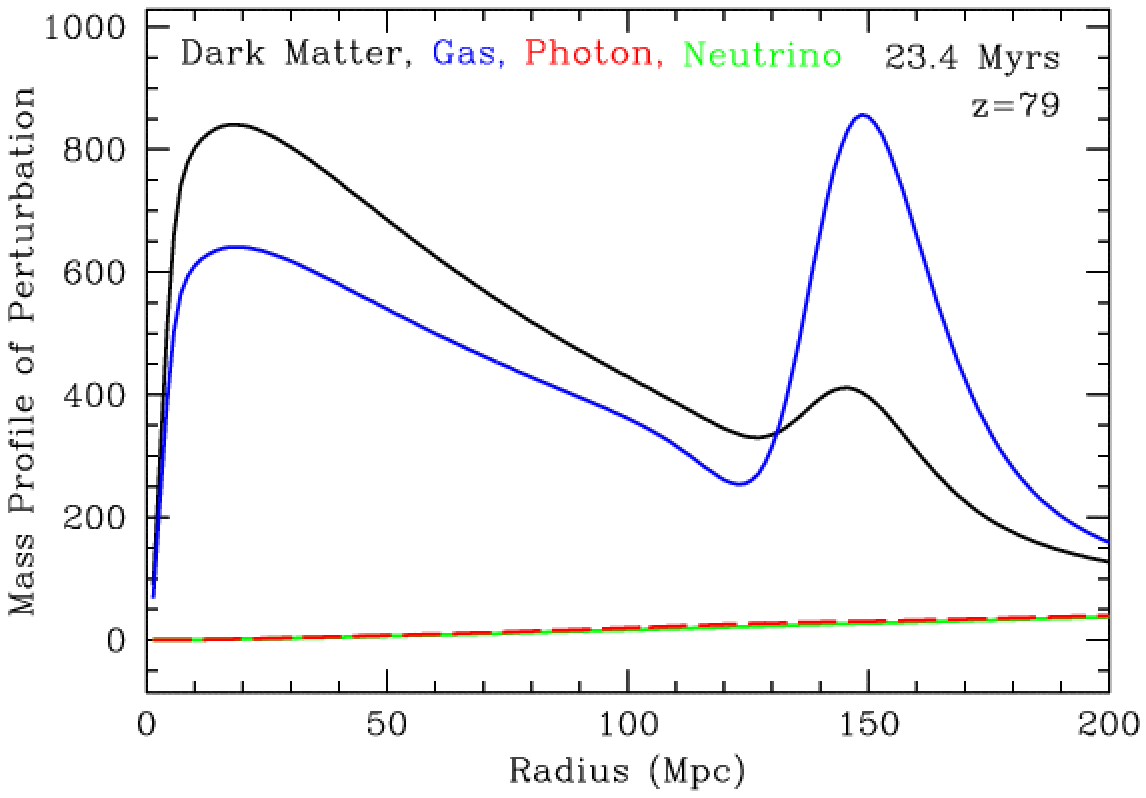
The BAO generation description



The BAO generation description

- We are left with the original dark matter perturbation surrounded by a baryon perturbation in a shell
- The two components attract each other and the perturbation start to mix

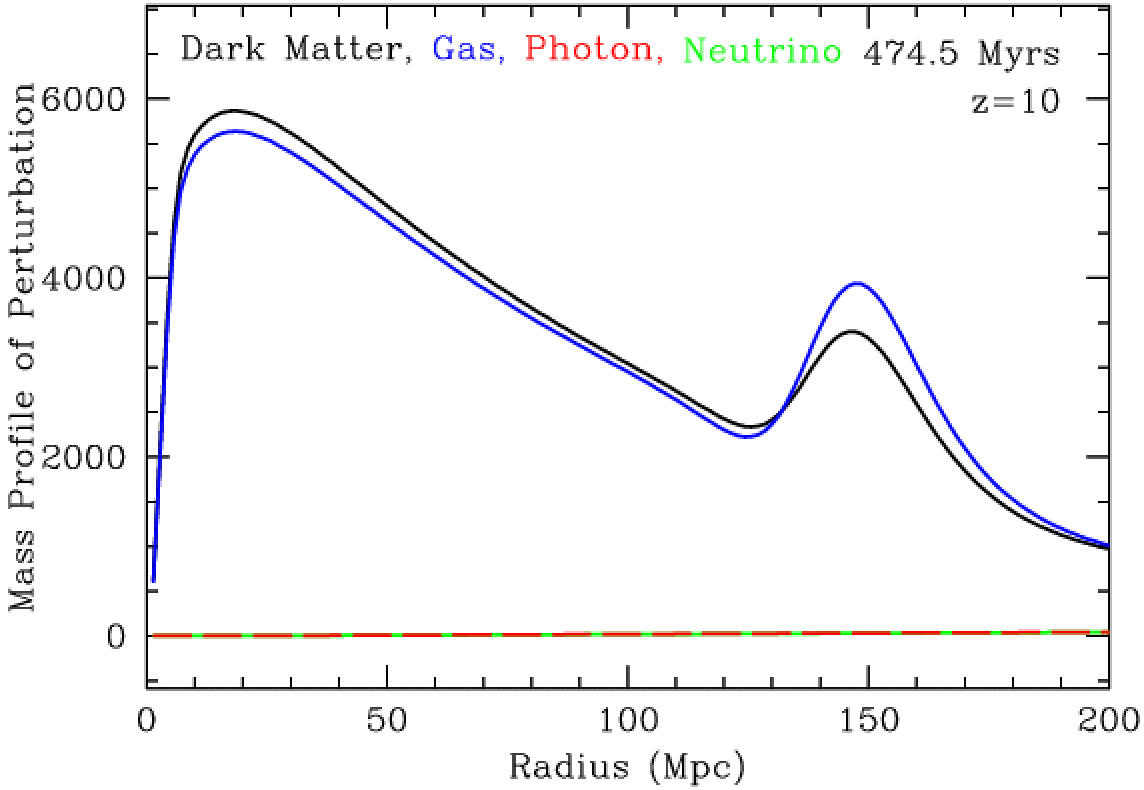
The BAO generation description



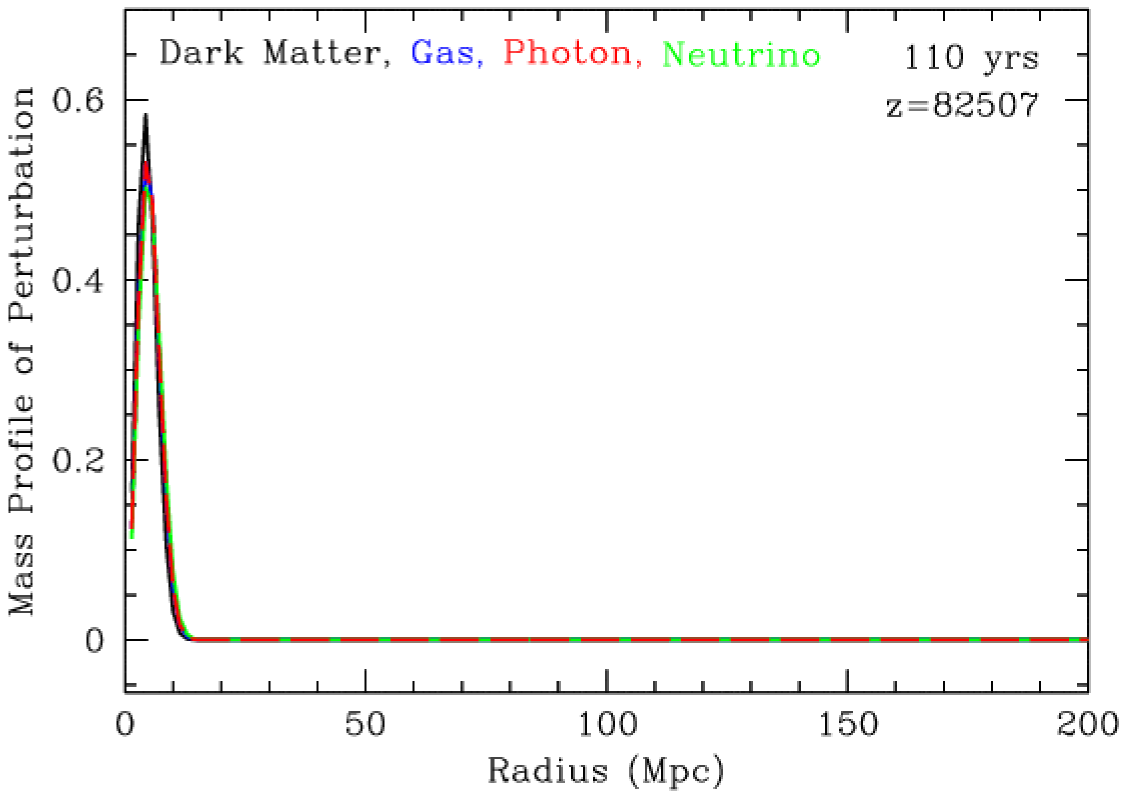
The BAO generation description

- Eventually the dark matter and baryon perturbations come together
- The acoustic peak perturbation is lower as the dark matter dominated in mass the baryons

The BAO generation description

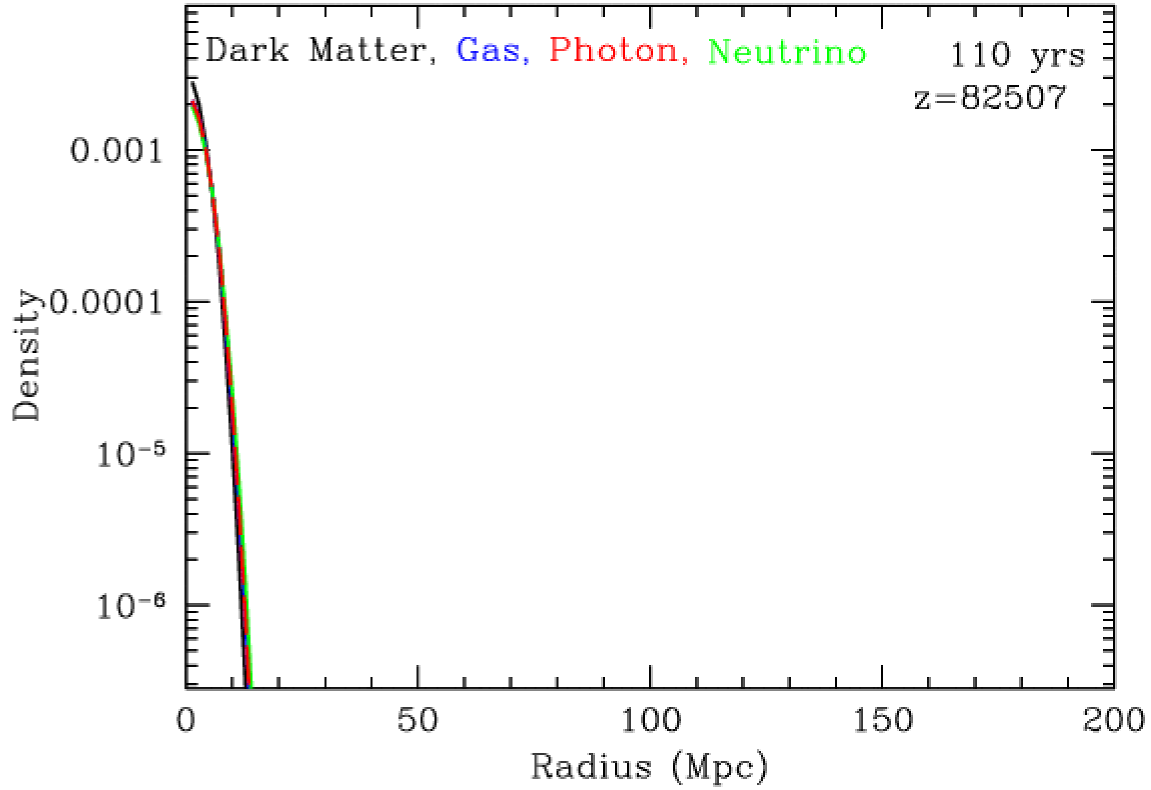


The BAO generation description



Daniel Eisenstein

The BAO generation description



Daniel Eisenstein

The BAO generation description

- As galaxies form in matter (dark matter and baryons) overdensities, most of galaxies are at the original perturbation position, but there is a 1% enhancement of galaxies at the scale of the acoustic scale than can be seen in the galaxy correlation function

The BAO probe

- Photons and baryons decouple at the drag epoch

$$z_d = 1291 \frac{(\Omega_0 h^2)^{0.251}}{1 + 0.659(\Omega_0 h^2)^{0.828}} [1 + b_1(\Omega_b h^2)^{b_2}] ,$$
$$b_1 = 0.313(\Omega_0 h^2)^{-0.419}[1 + 0.607(\Omega_0 h^2)^{0.674}] ,$$
$$b_2 = 0.238(\Omega_0 h^2)^{0.223} , \qquad (4)$$

- Photon-baryon fluid acoustic waves propagate at the sound speed: $c_s = 1/[3(1+R)]^{1/2}$

$$R \equiv 3\rho_b/4\rho_\gamma = 31.5\Omega_b h^2 \Theta_{2.7}^{-4}(z/10^3)^{-1} . \qquad (5)$$

The BAO probe

- Sound horizon at the drag epoch is the comoving distance a wave can travel prior to z_d

$$s = \int_0^{t(z_d)} c_s(1+z)dt$$
$$= \frac{2}{3k_{\rm eq}}\sqrt{\frac{6}{R_{\rm eq}}}\ln\frac{\sqrt{1+R_d}+\sqrt{R_d+R_{\rm eq}}}{1+\sqrt{R_{\rm eq}}}, \qquad (6)$$

- The transition from a radiation to matter dominated universe happens at

$$z_{\rm eq} = 2.50\times 10^4 \Omega_0 h^2 \Theta_{2.7}^{-4}, \qquad (2)$$

- At small scales, Silk damping: photons and baryons diffuse during decoupling

$$k_{\rm Silk} = 1.6(\Omega_b h^2)^{0.52}(\Omega_0 h^2)^{0.73}[1+(10.4\Omega_0 h^2)^{-0.95}] \ {\rm Mpc}^{-1}, \qquad (7)$$

The BAO probe

- Sound horizon depends on

$$s = \int_0^{t_{\rm rec}} c_s\,(1+z)dt = \int_{z_{\rm rec}}^{\infty} \frac{c_s\,dz}{H(z)}$$

  - epoch of recombination
  - expansion of the universe
  - baryon-to-photon ratio

The BAO probe

- Sound horizon well determined by the CMB measurements of the acoustic peaks

	Quantity	Eq.	5-year WMAP
CMB	z_*	(66)	1090.51 ± 0.95
CMB	$r_s(z_*)$	(6)	146.8 ± 1.8 Mpc
Matter	z_d	(3)	1020.5 ± 1.6
Matter	$r_s(z_d)$	(6)	153.3 ± 2.0 Mpc

Komatsu et al

The BAO probe

- Power spectrum

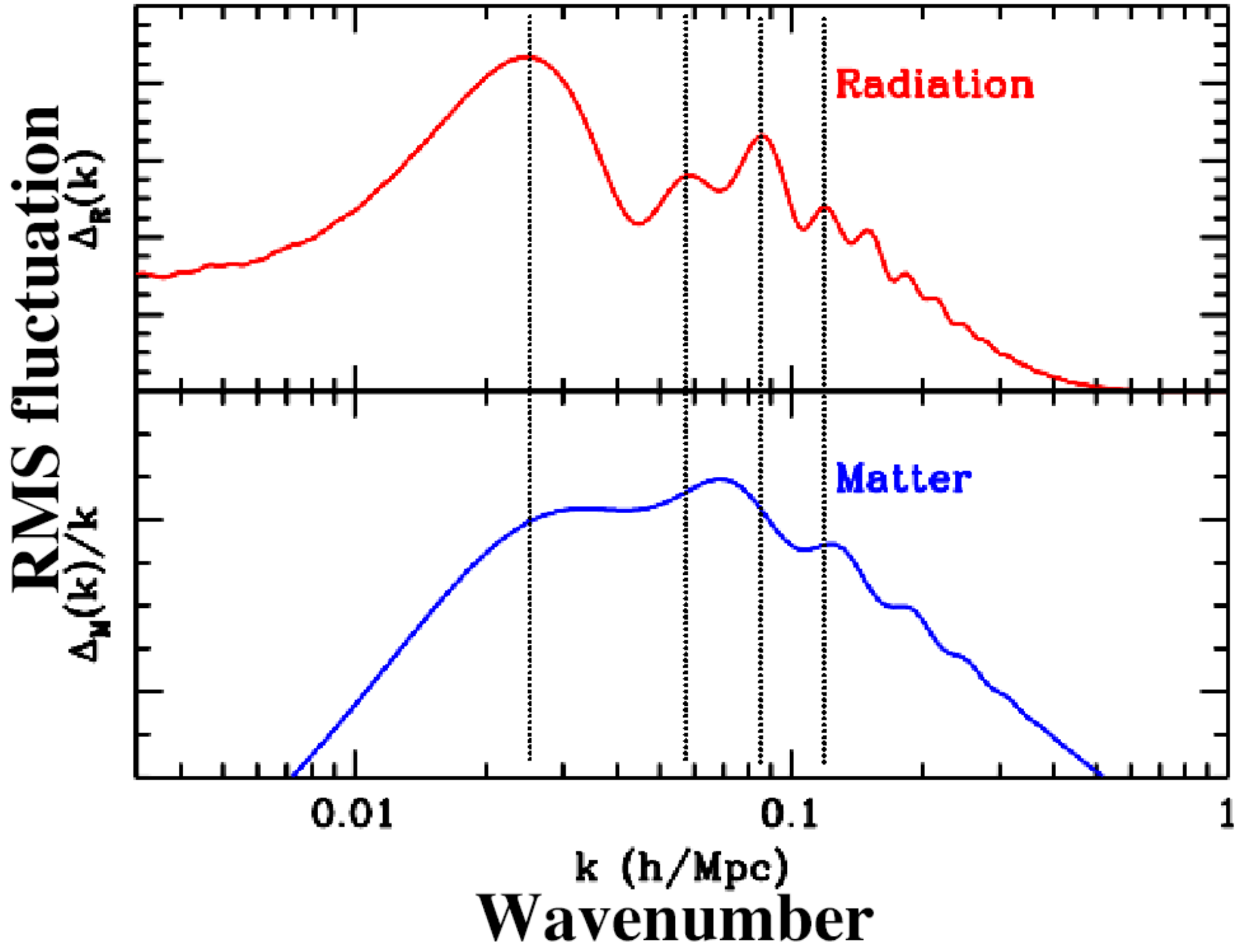
$$T(k) = \frac{\Omega_b}{\Omega_0} T_b(k) + \frac{\Omega_c}{\Omega_0} T_c(k) \ . \qquad (8)$$

- The baryon part can be approximated as

$$T_b \to \alpha_b \frac{\sin(ks)}{ks} \mathscr{D}(k) \ . \qquad (13)$$

The BAO probe

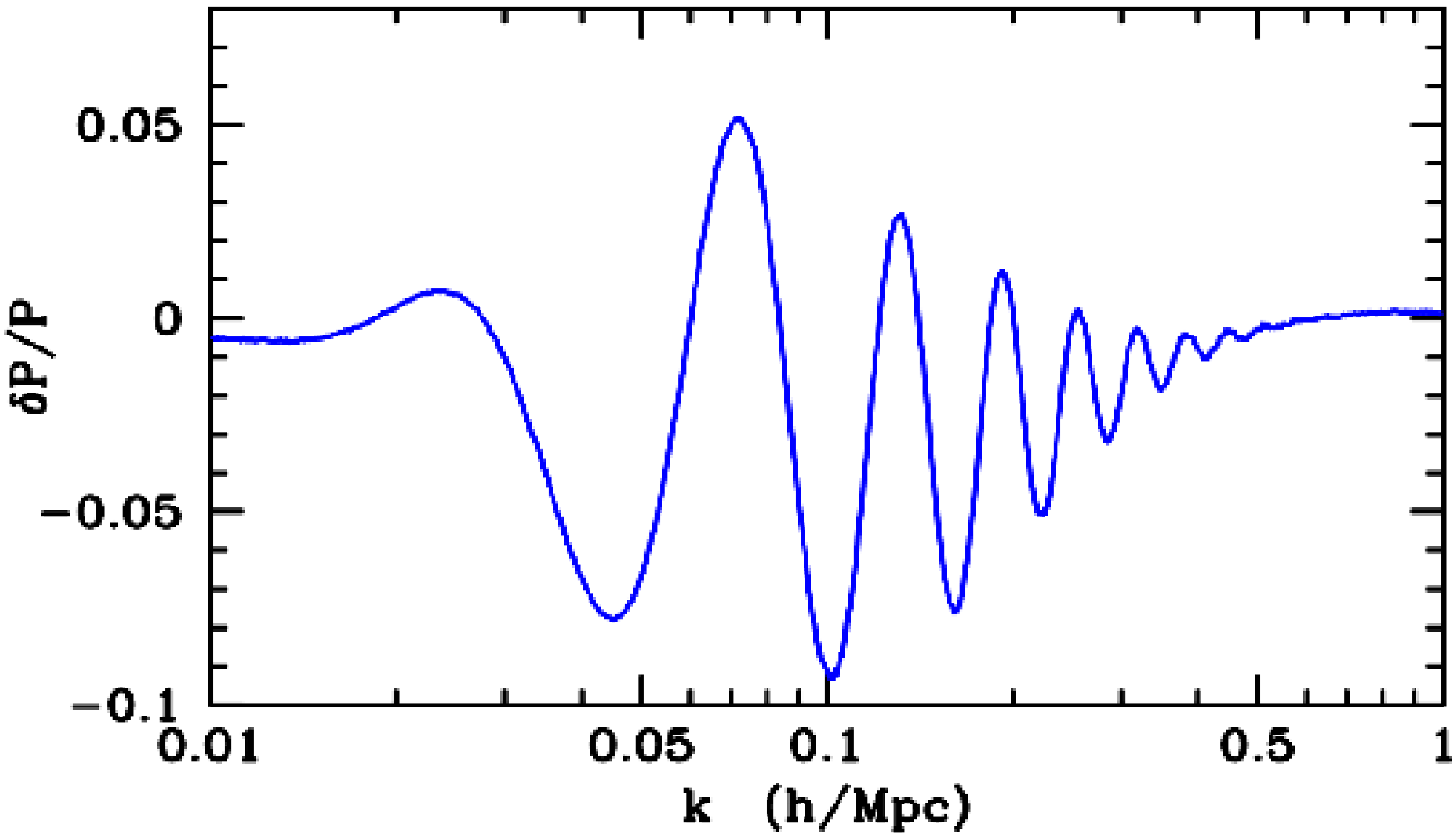
- Power spectrum



Martin White

The BAO probe

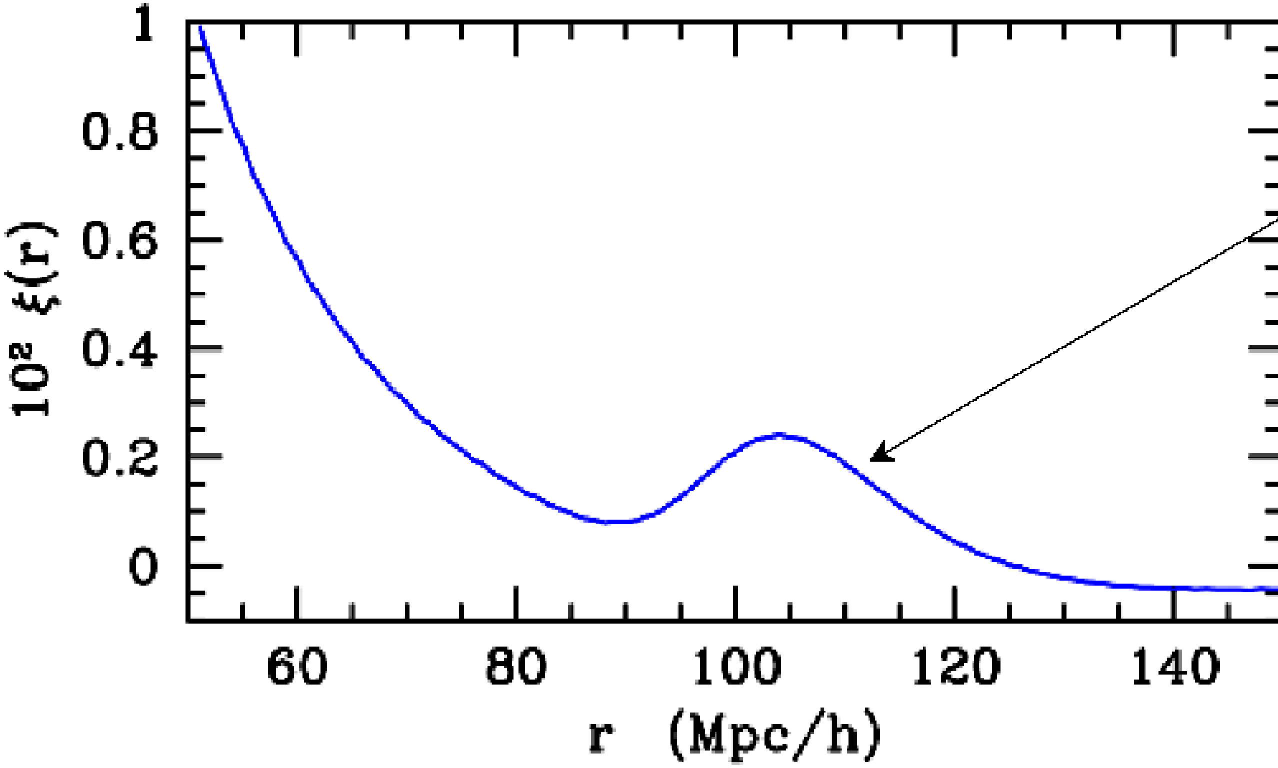
- Power spectrum



Martin White

The BAO probe

- Correlation function



Acoustic feature at ~100 Mpc/h with width ~10 Mpc/h (Silk scale)

Martin White

The BAO probe

- The baryon acoustic oscillations provide a characteristic scale that is "frozen" in the galaxy distribution providing a standard ruler that can be measured as a function of redshift in either the galaxy correlation function or the galaxy power spectrum
- The BAO determination of the universe geometry is quite robust against systematics

The BAO standard ruler

- The BAO standard ruler provides a measurement of the angular diameter distance as a function of redshift

$$\Delta\theta = \ell/(d_A\,(1+z))$$

$$d_A(z) = r(z)/(1+z)$$

$$r(z) = \int_0^z \frac{dz'}{H(z')}$$

$\Delta\theta$: angle subtended

ℓ : intrinsic length

d_A : angular distance

$r(z)$: co-moving distance

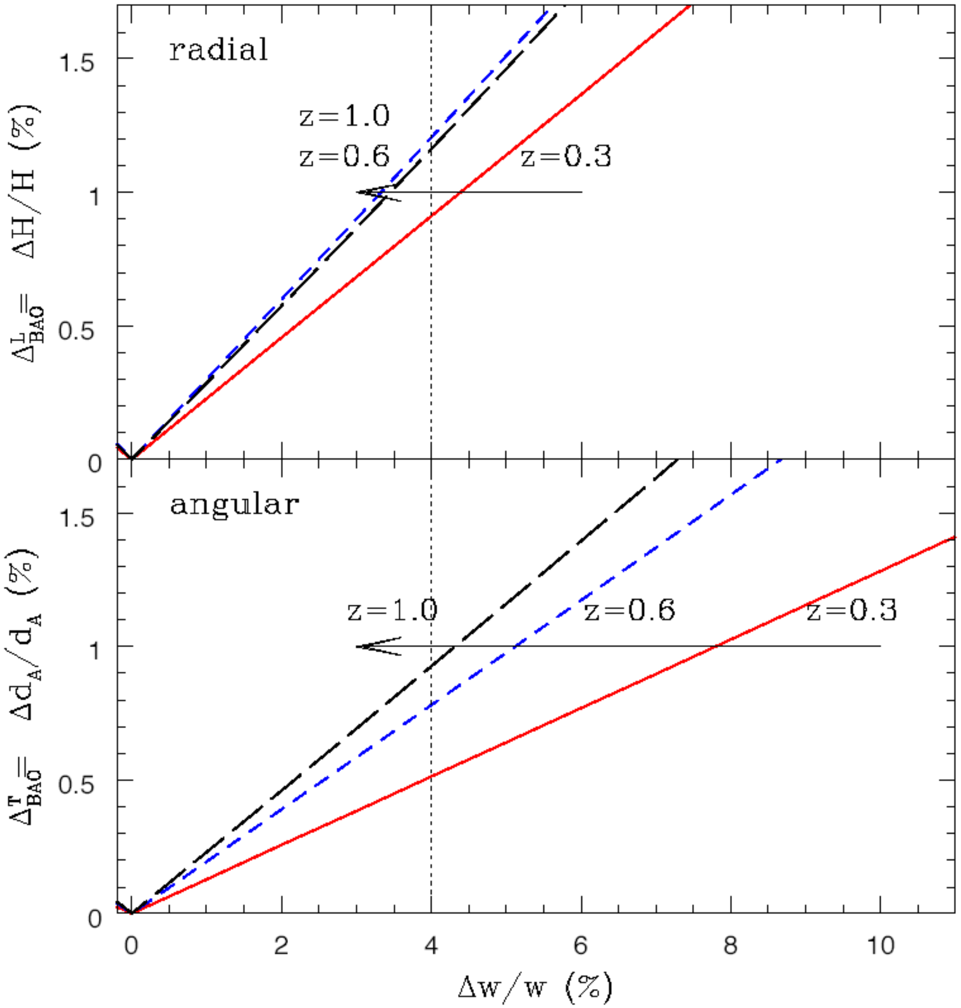
- The standard ruler can also be used in the line of sight and measure H(z) directly

$$\ell = \Delta z / H(z)$$

Δz : redshift subtended

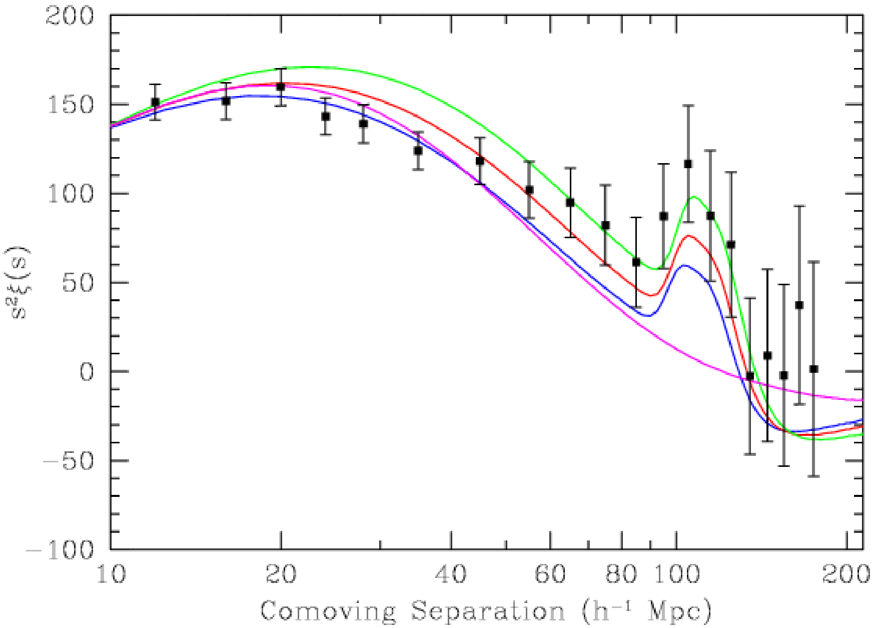
The BAO standard ruler

- The BAO sensitivity to dark energy

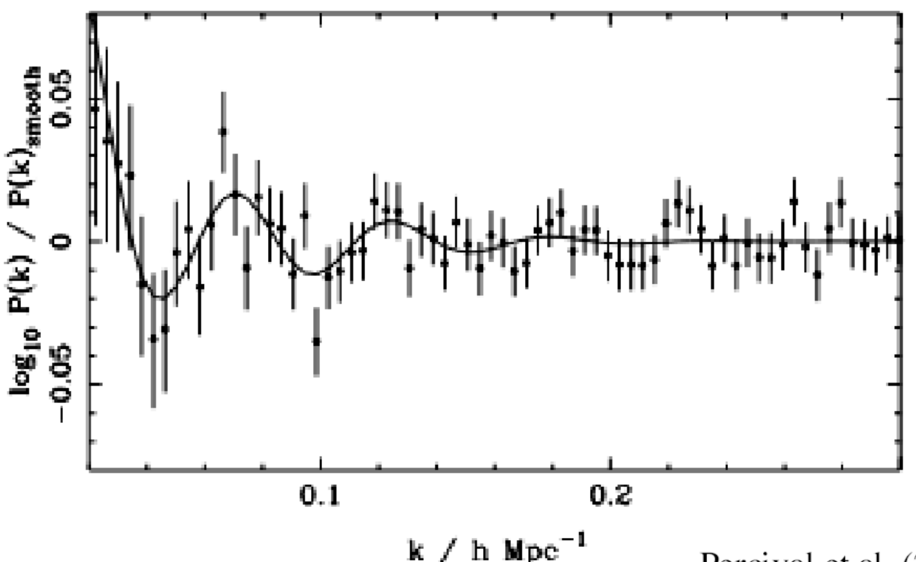


BAO measurements

- The BAO scale has been measured in the SDSS and 2dFGRS



Eisenstein et al 2005



Percival et al. (2007)

The BAO probe

Is it a standard ruler?

- So far, we have dealt with linear theory in real space
- However, we measure the non-linear power spectrum of galaxy tracers in redshift space
- Simulations help us to understand & treat these effects

The BAO probe

Non-linearities

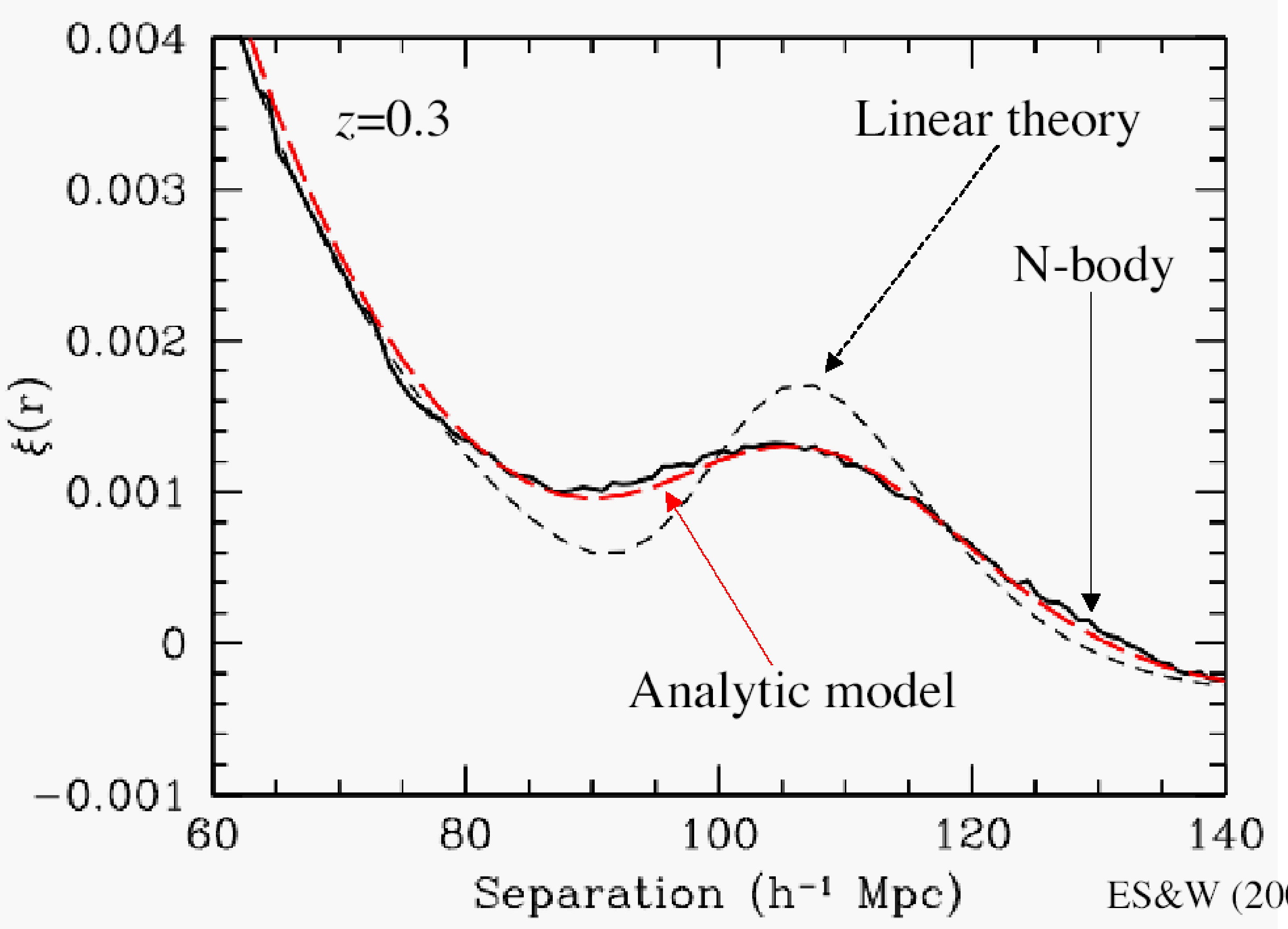
- As structure forms, neighbouring galaxies smear the baryon shell. This produces a broadening of the peak and non-linear power on small scales

- According to simulations it can be modelled

$$P_{nl} = P_l \exp\left(-k^2\Sigma_{nl}\right)$$

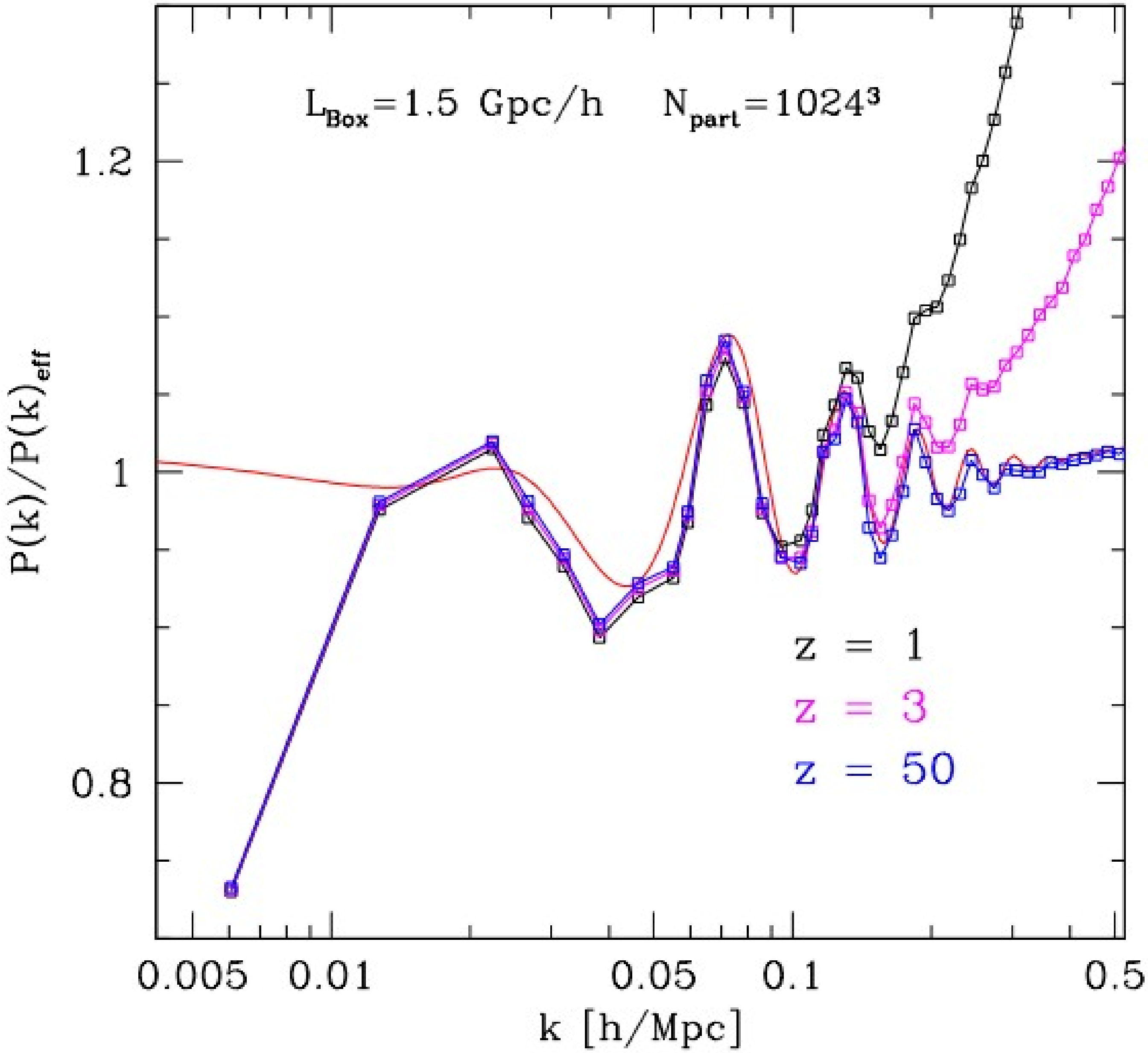
The BAO probe

Non-linearities



ES&W (2007)

Baryon Acoustic Oscillations



The BAO probe

Non-linearities

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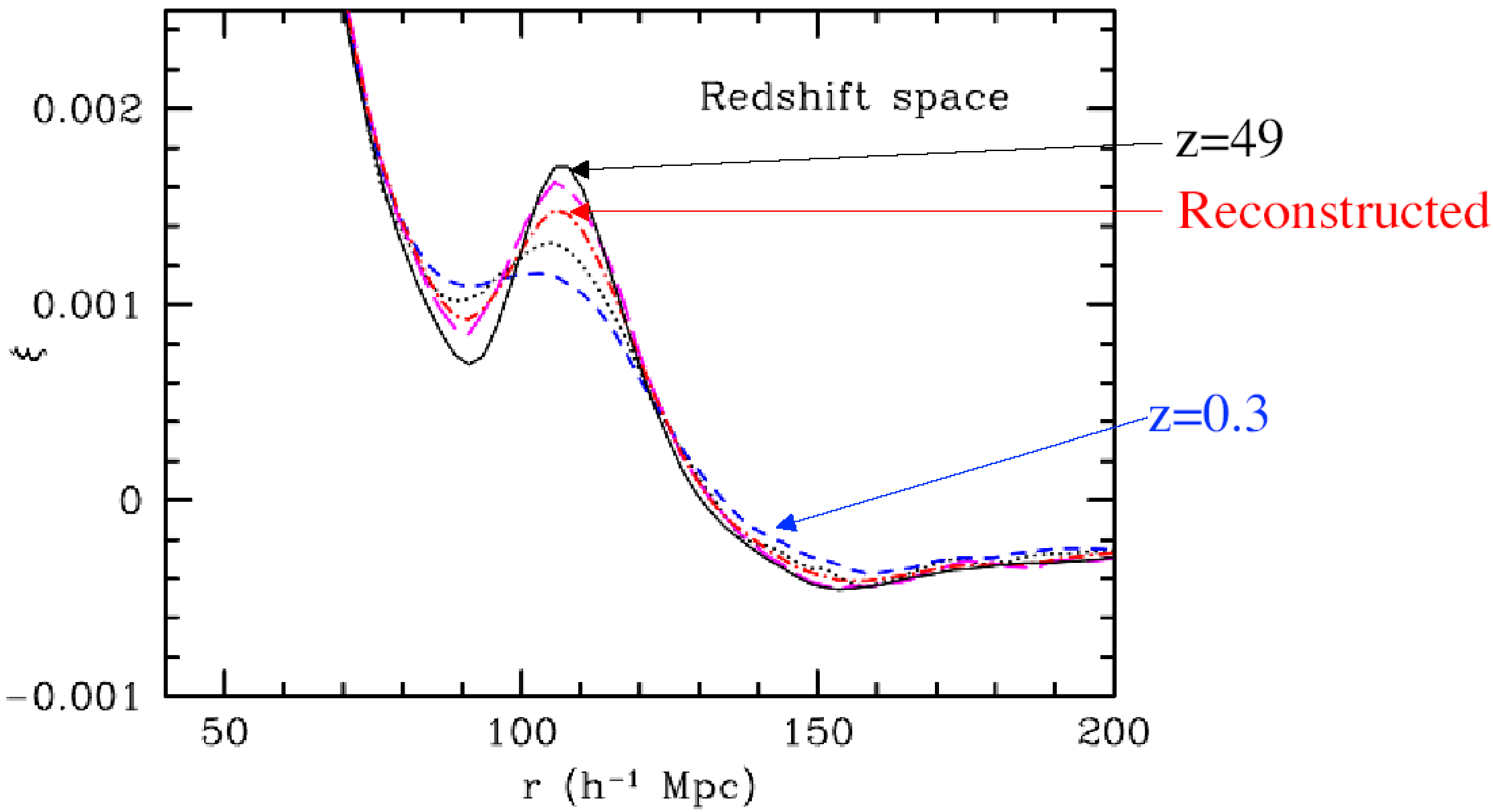
$$P_{nl} = P_l \exp(-k^2\Sigma_{nl})$$

- Can it be corrected? Reconstruction (Eisenstein et al 07)

The BAO probe

Non-linearities

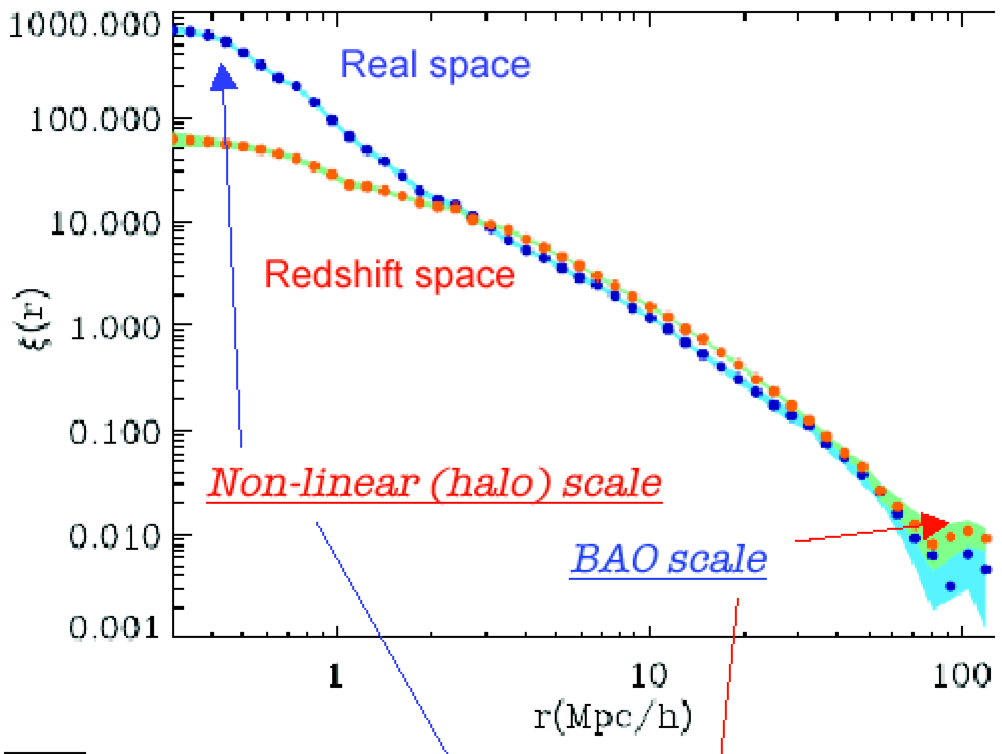


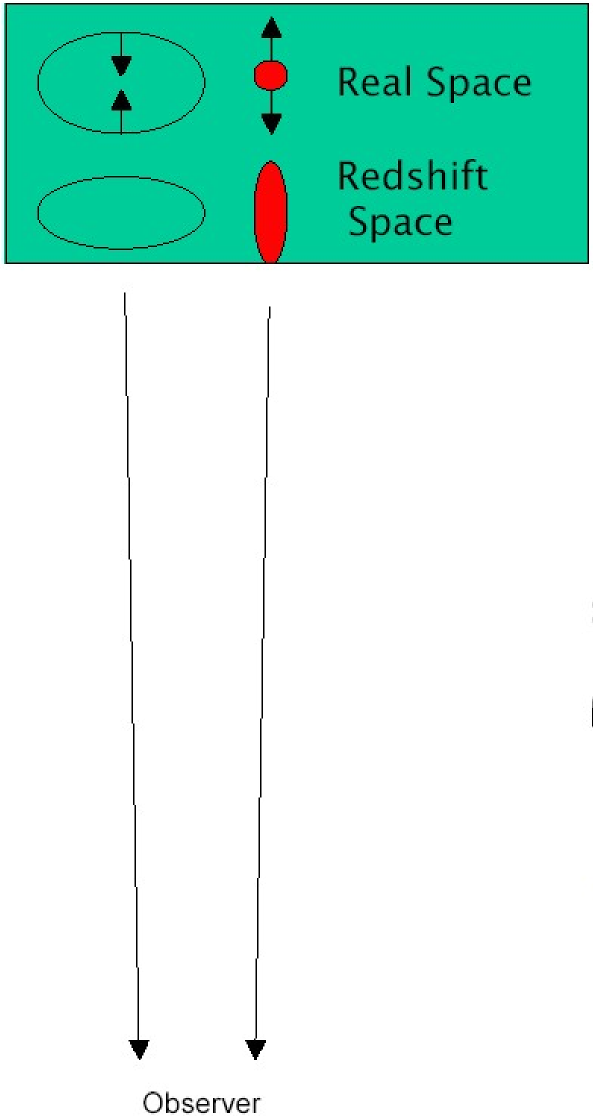
From Eisenstein et al. (2007)

The BAO probe

Readshift space distortion

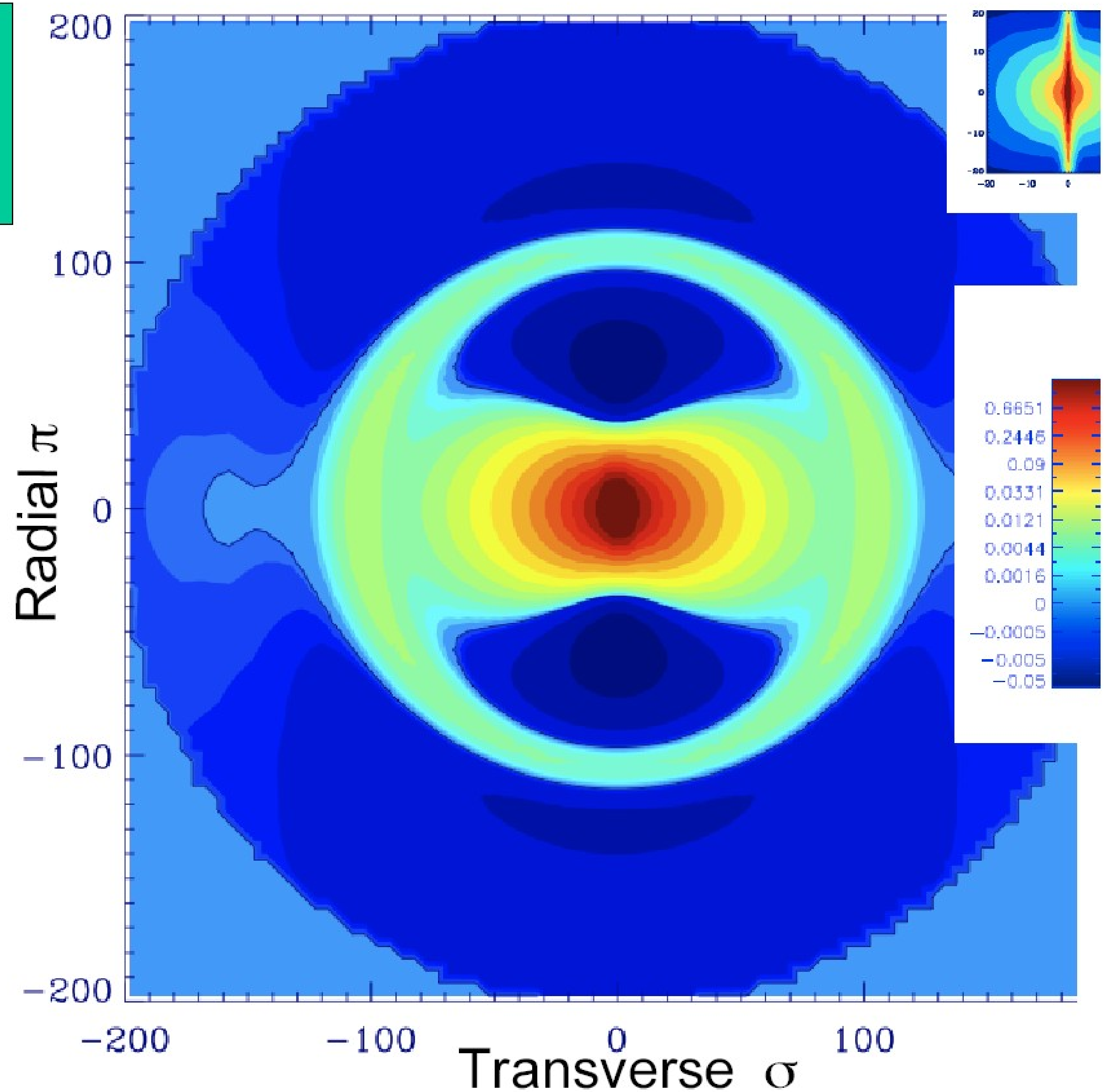
- The distortion depends on the density and velocity fields
- They can be modelled

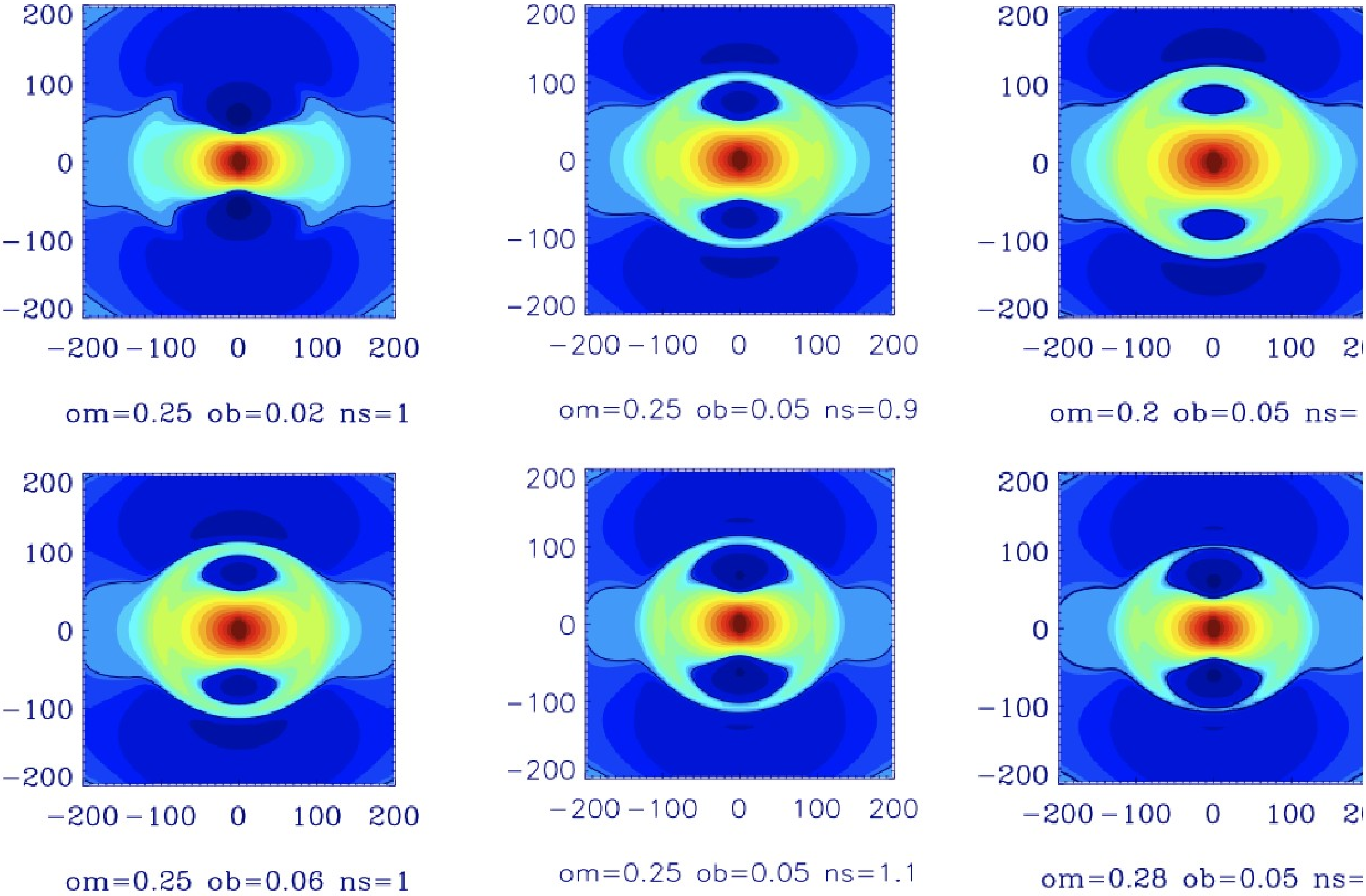




$\theta = -\beta\,\delta$

$v_p = \pi - \sigma$





om=0.25 ob=0.02 ns=1
om=0.25 ob=0.05 ns=0.9
om=0.2 ob=0.05 ns=
om=0.25 ob=0.06 ns=1
om=0.25 ob=0.05 ns=1.1
om=0.28 ob=0.05 ns=

MICE

Marenostrum Institut
de Ciències de l'Espai
Simulations

project web: www.ice.cat/mice

What is MICE ?

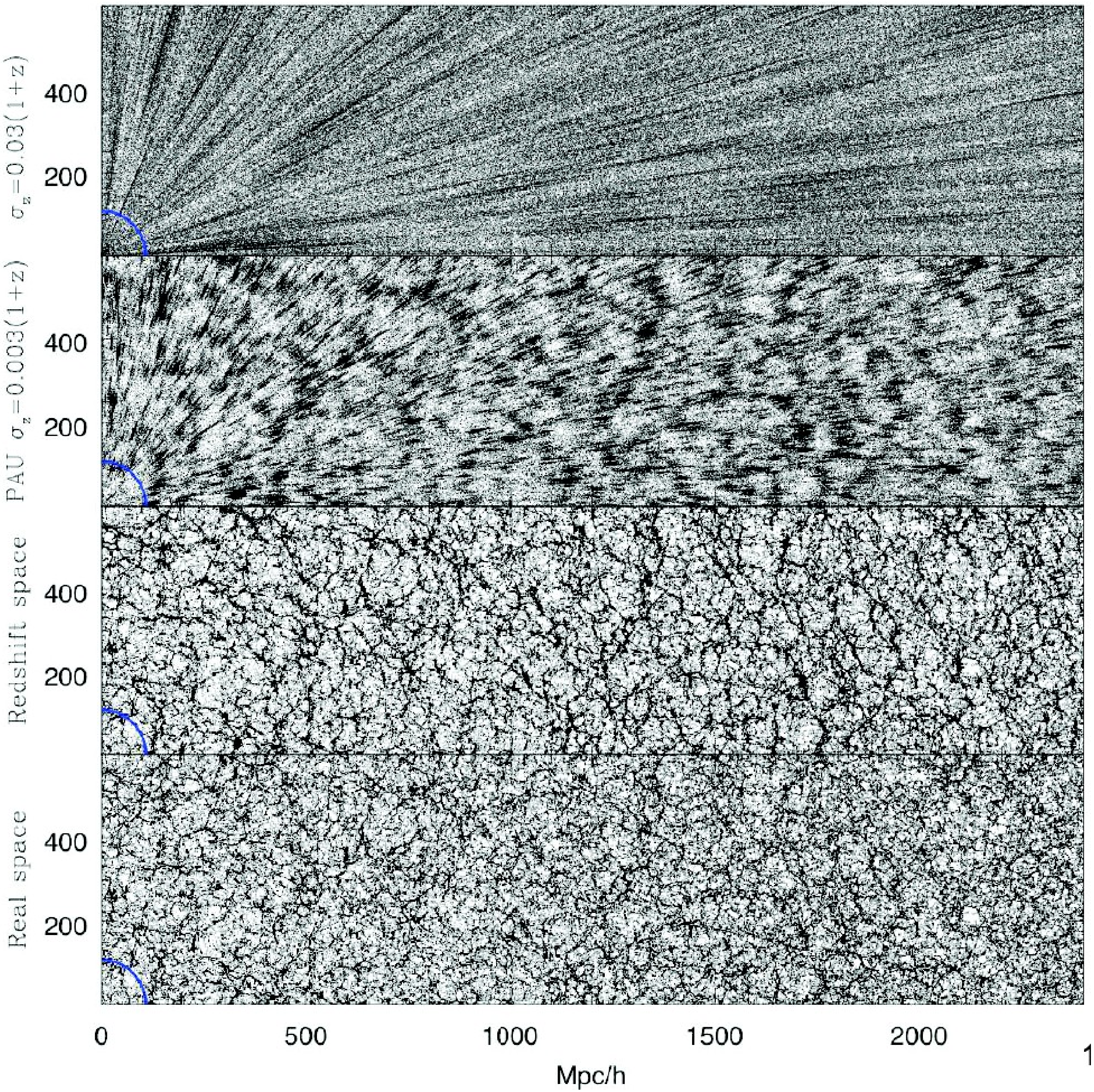
➢ Project to develop very large numerical simulations in cosmology using the **Marenostrum** supercomputer (Barcelona)

- 10.000 processors, 20 TB RAM , 100 Teraflops

- GADGET N-body simulations with 10^9-10^{10} dark-matter particles in volumes 1-500 Gpc^3
  ⇨ ***dynamical range of 5 orders of magnitude***

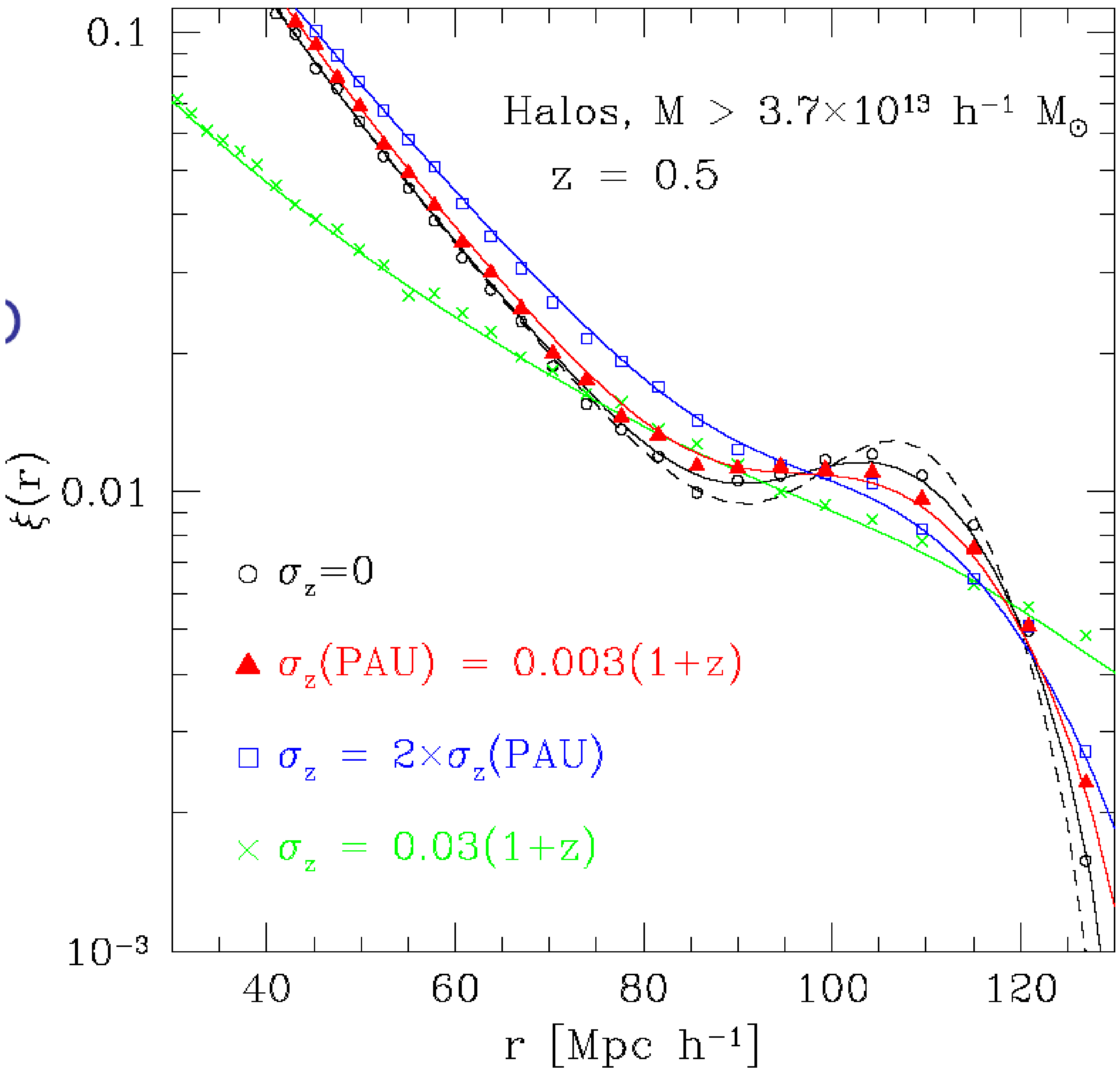
- Terabytes of simulated data stored at Port d'Informació Cientifica
  (LHC data storage center @ Barcelona)

➢Team:
Core (ICE): P.Fosalba, F.Castander, E.Gaztañaga
Collaborators: V.Springel (MPA), C.Baugh (Durham), M.Manera (NYU), M.Crocce, A.Gonzalez, A.Cabré, J.Miralda-Escudé



σ_z=0.03(1+z)
PAU σ_z=0.003(1+z)
Redshift space
Real space
400
200
0
500
1000
1500
2000
Mpc/h

1



Halos, M > 3.7×10¹³ h⁻¹ M☉
z = 0.5
σz=0
σz(PAU) = 0.003(1+z)
σz = 2×σz(PAU)
σz = 0.03(1+z)
ξ(r)
0.1
0.01
10⁻³
40
60
80
100
120
r [Mpc h⁻¹]

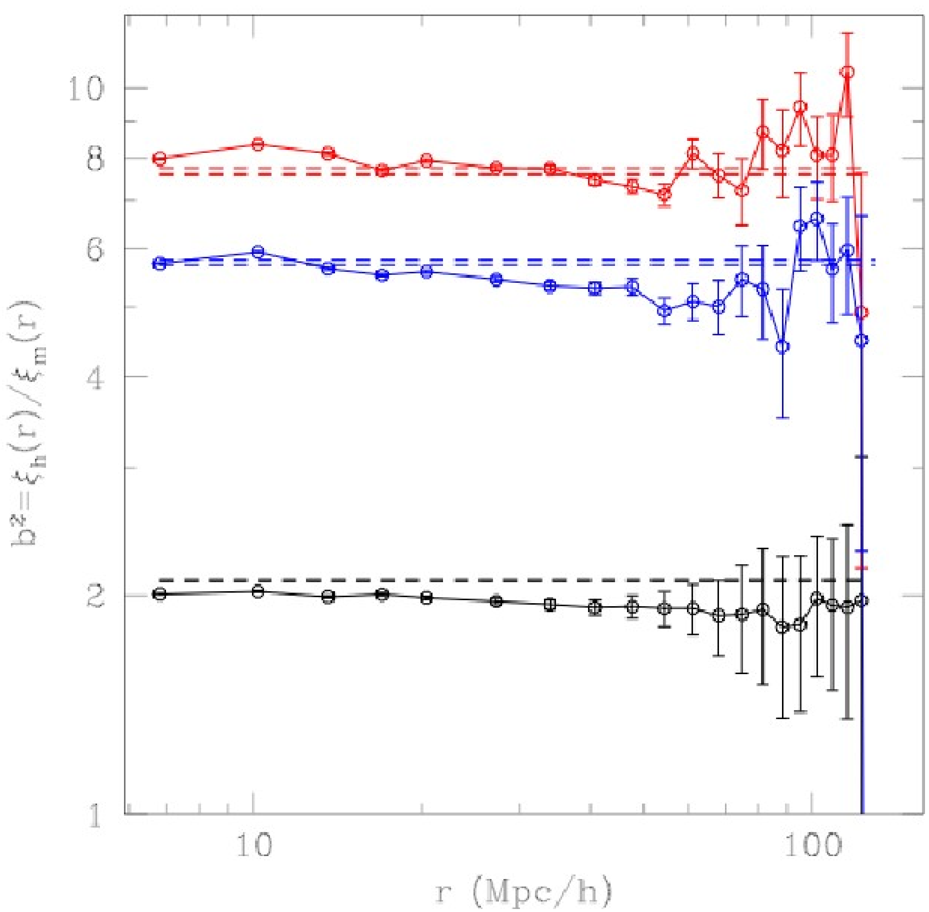
The BAO probe

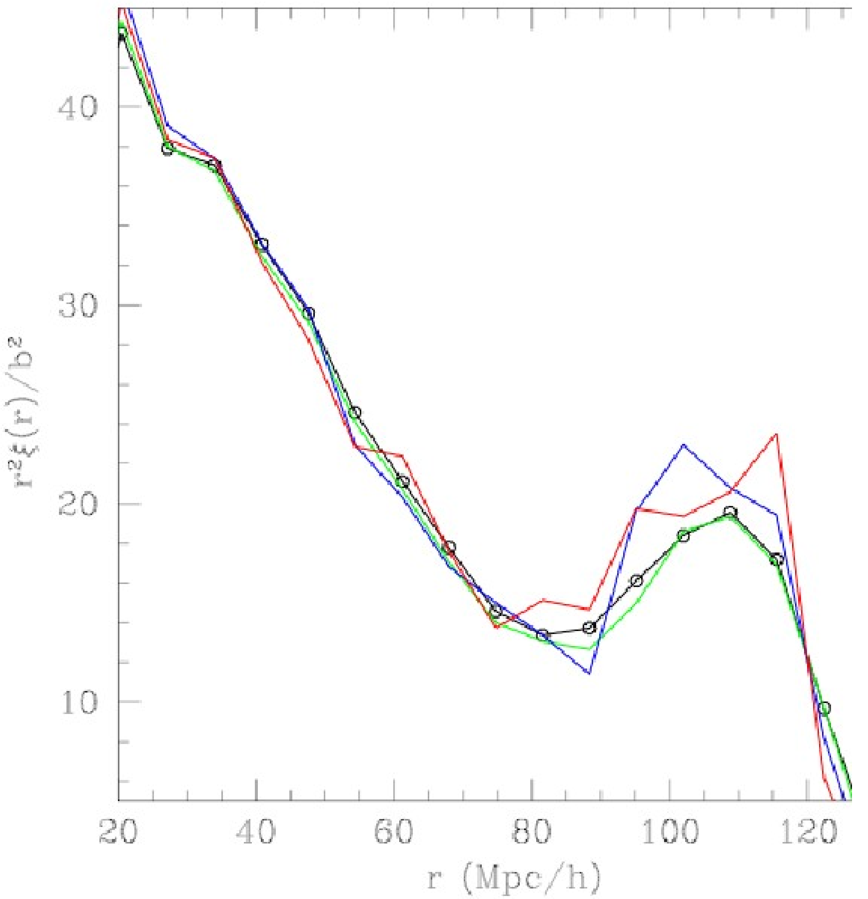
Galaxy bias

- Galaxies are a bias tracer of the underlying dark matter distribution
- Uncertainties in peak determination if bias is scale dependent
- The expectation is that at the BAO scale the effect of bias should depend on scale in a smooth manner

BAO test In simulations

With M.Manera & MICE





The BAO probe

How robust is the BAO method?

- Recent claims that the BAO scale is not fixed but depends on non-linearities, bias,…

- e.g., Smith et al 2008, Sanchez et al 2007

The BAO probe

Final Considerations

- What method is better suited: configuration space or Fourier space?
- Comparison observations-theory (simulations)
- Future surveys: sample variance limited $$\frac{\sigma}{P} = \sqrt{\frac{2}{n_{\rm modes}}}\left(1 + \frac{1}{P\bar{n}}\right)$$
- Error determination -> simulations

The BAO probe

Conclusions

- the BAO signature provides a standard ruler that can be used to measure the geometry of the universe
- it can measure both the angular diameter distance $D_A(z)$ and the expansion rate $H(z)$
- it has already been measured
- it is fairly robust against systematics