Estimating the BAO scale

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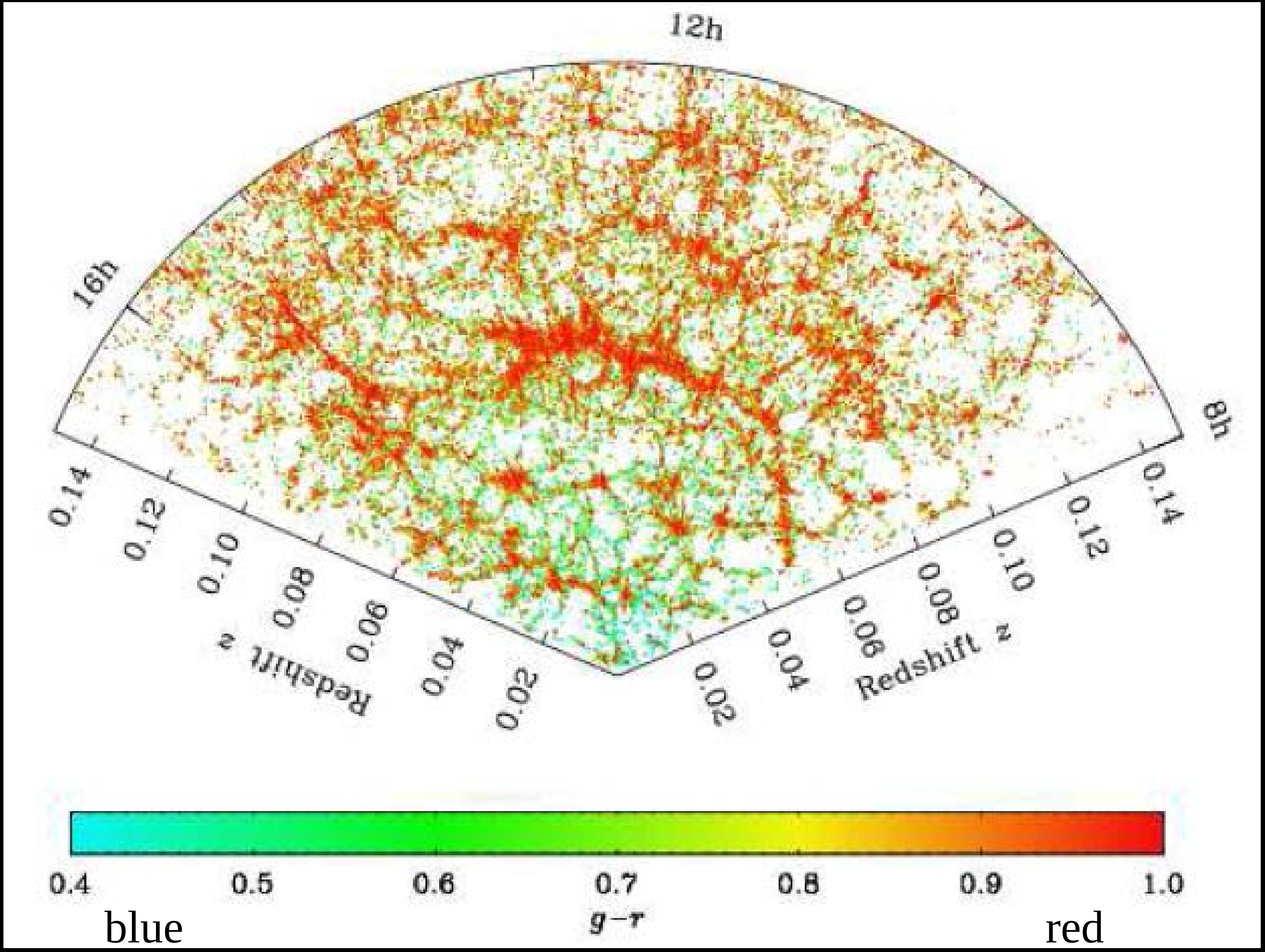
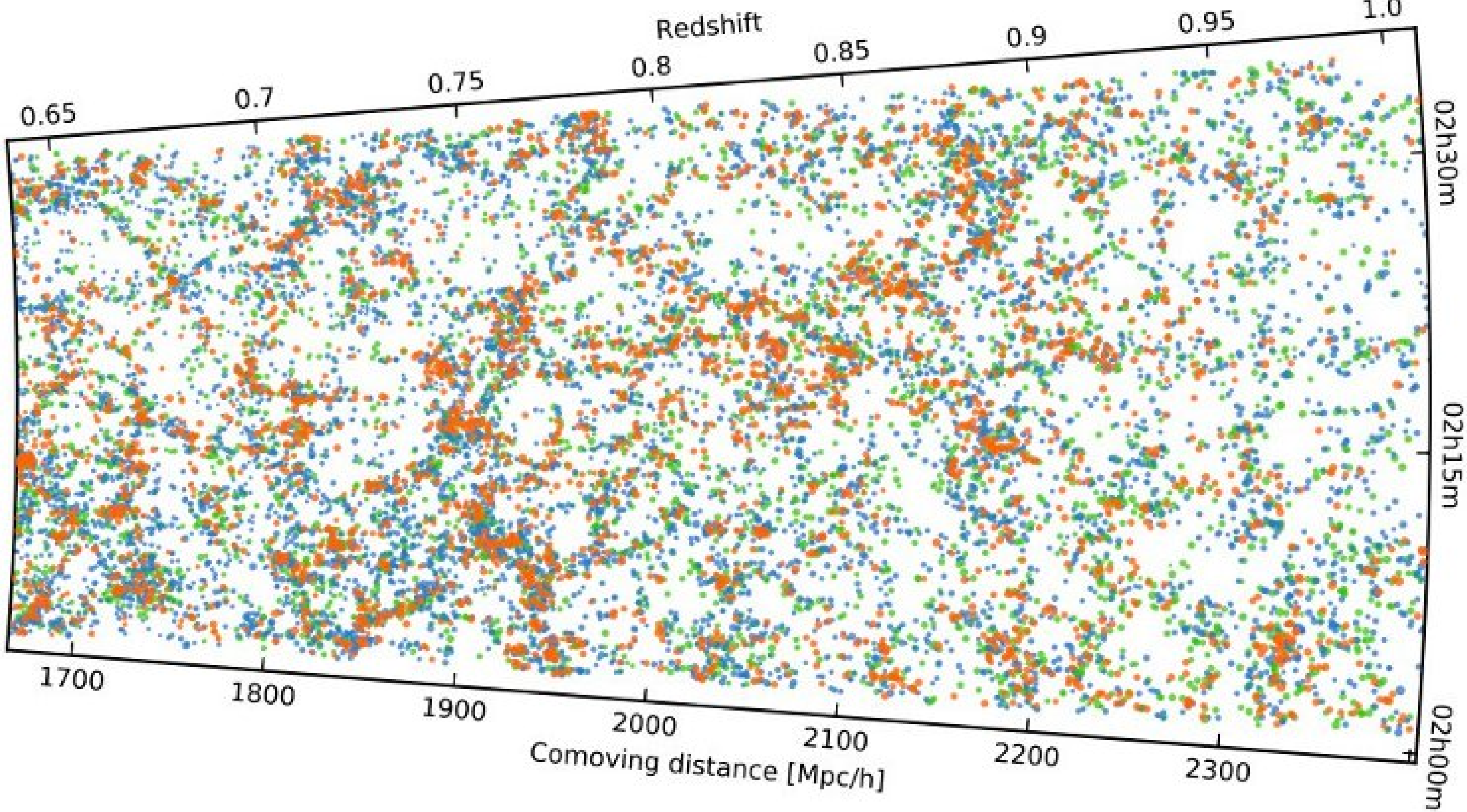
with S. Anselmi, G. Starkman

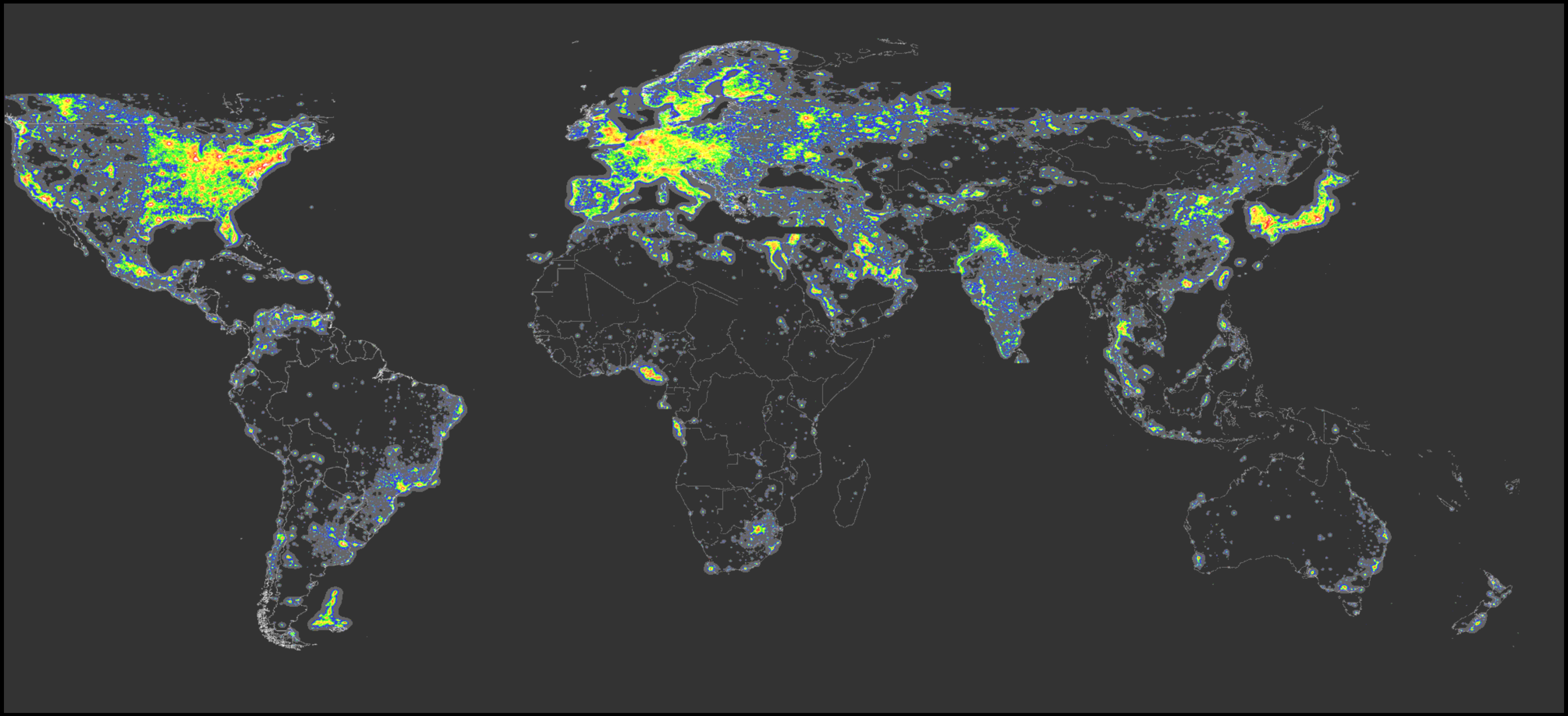


Zehavi et al. 2010 (SDSS)

VIPERS (Guzzo et al. 2013)



Complication: Light is a biased tracer



Not all galaxies are fair tracers of dark matter;

To use galaxies as probes of underlying dark matter distribution, must understand 'bias'

Cosmology constraints from geometry (distance-redshift) and dynamics (clustering-redshift), both of which are sensitive to expansion history

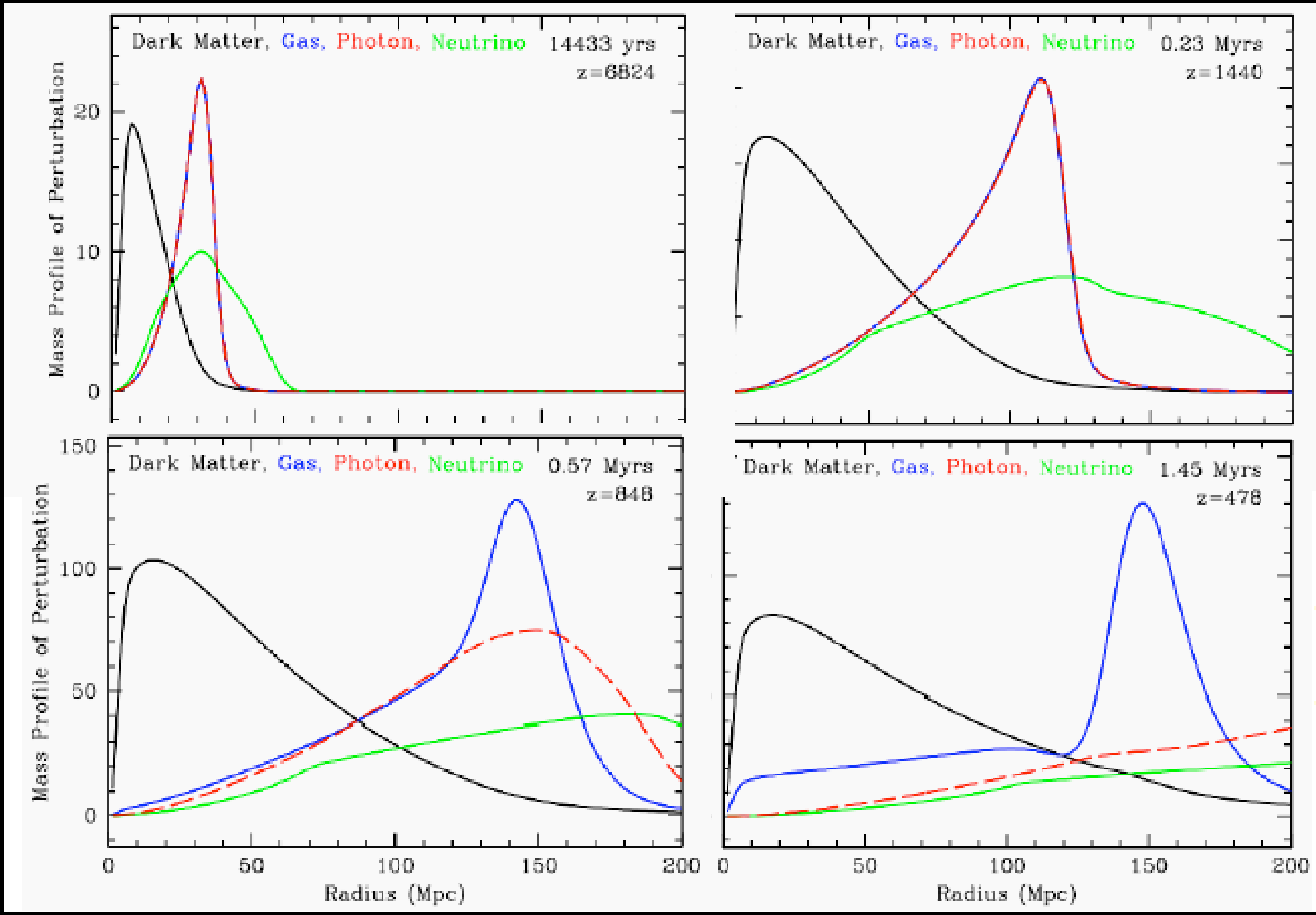
Galaxy formation much less 'understood'

Cosmology from the same physics imprinted in the galaxy distribution at different redshifts:

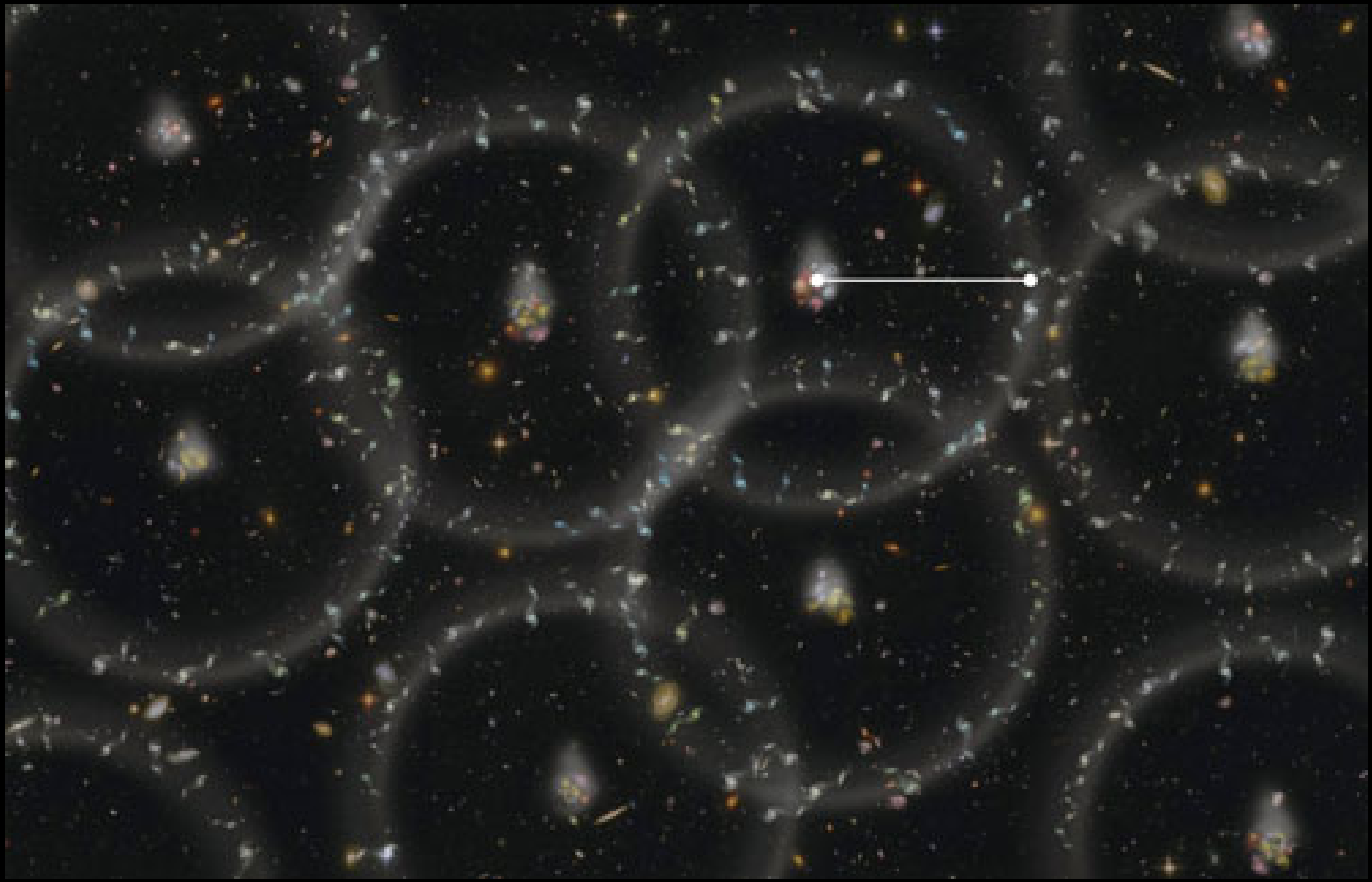
Baryon Acoustic Oscillations

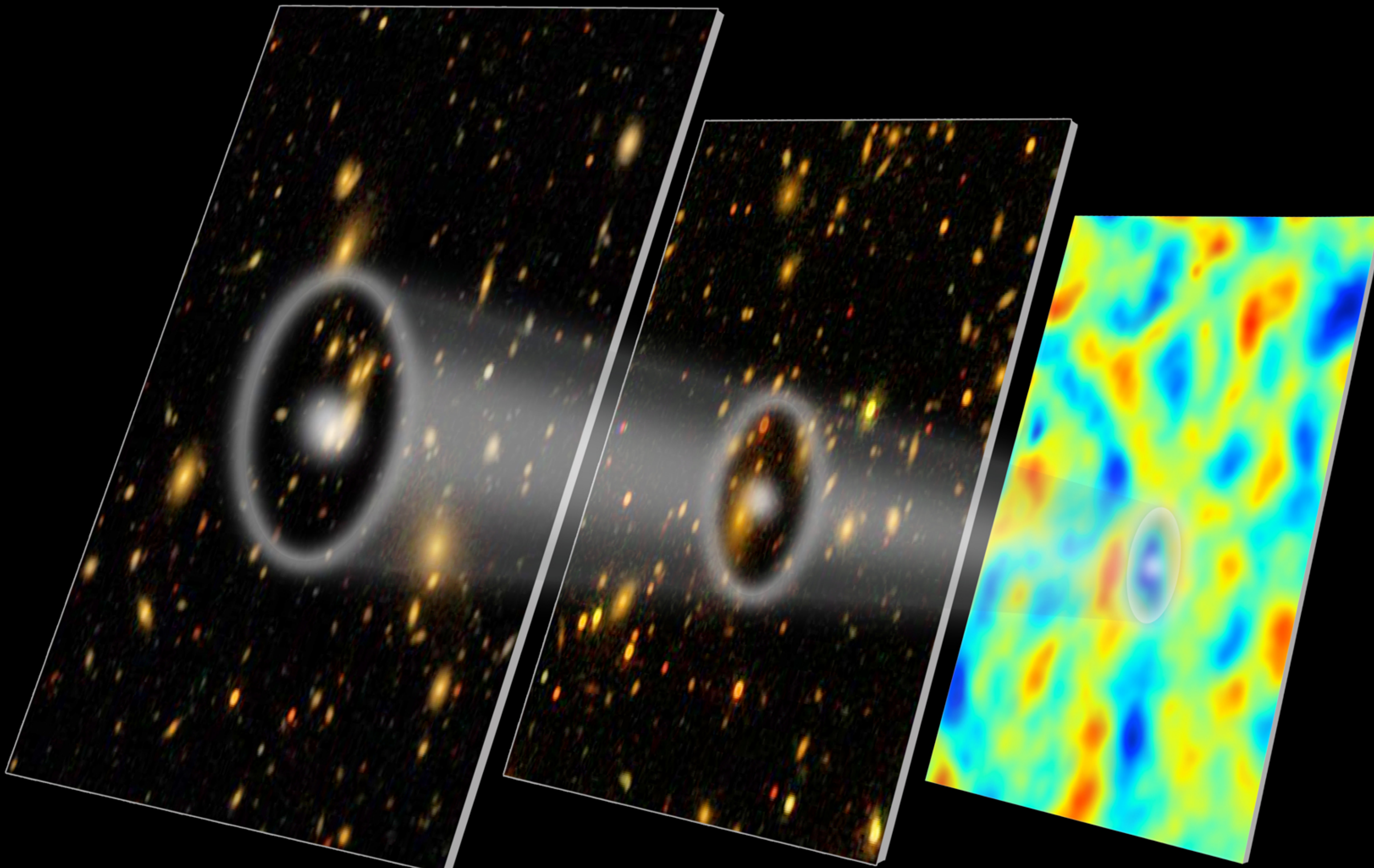
CMB from interaction between photons and baryons when Universe was 3,000 degrees (about 300,000 years old)

- Do galaxies which formed much later carry a memory of this epoch of last scattering?



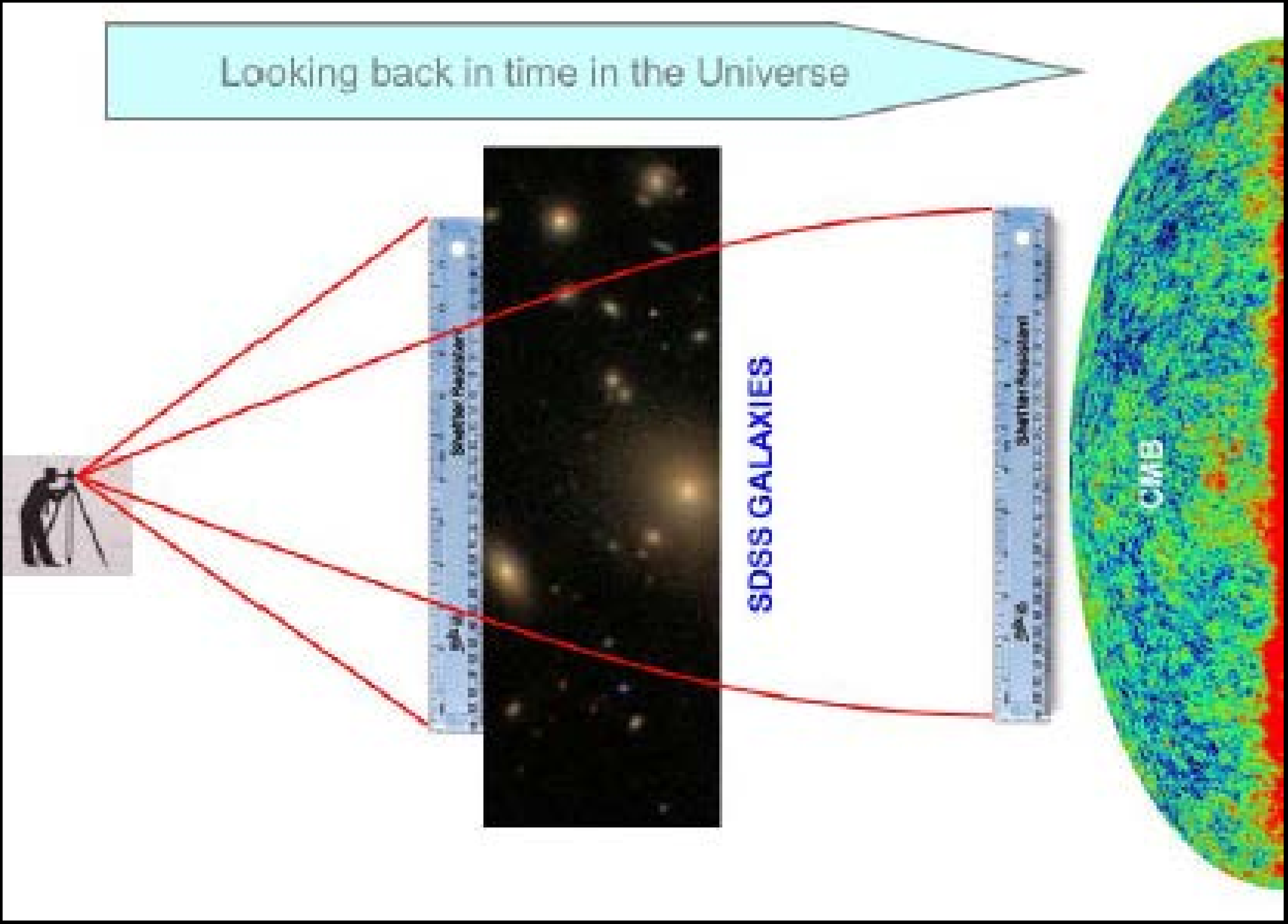
Eisenstein, Seo, White 2007



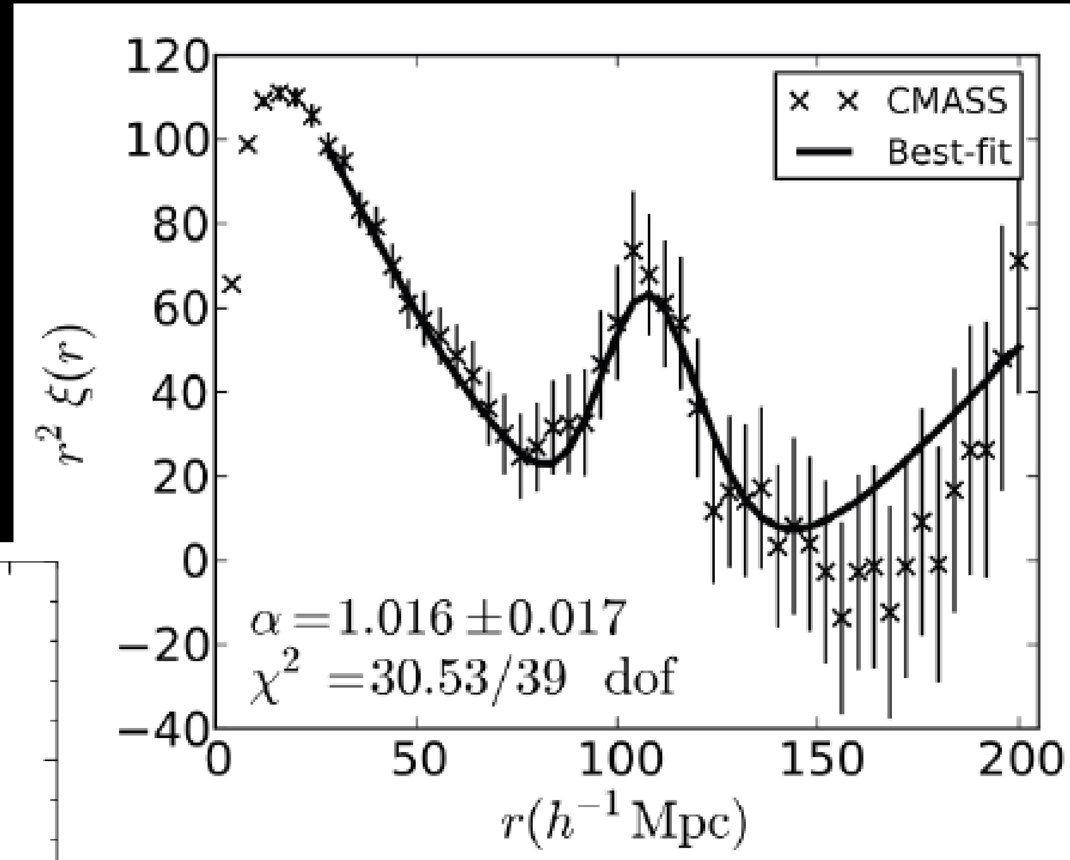


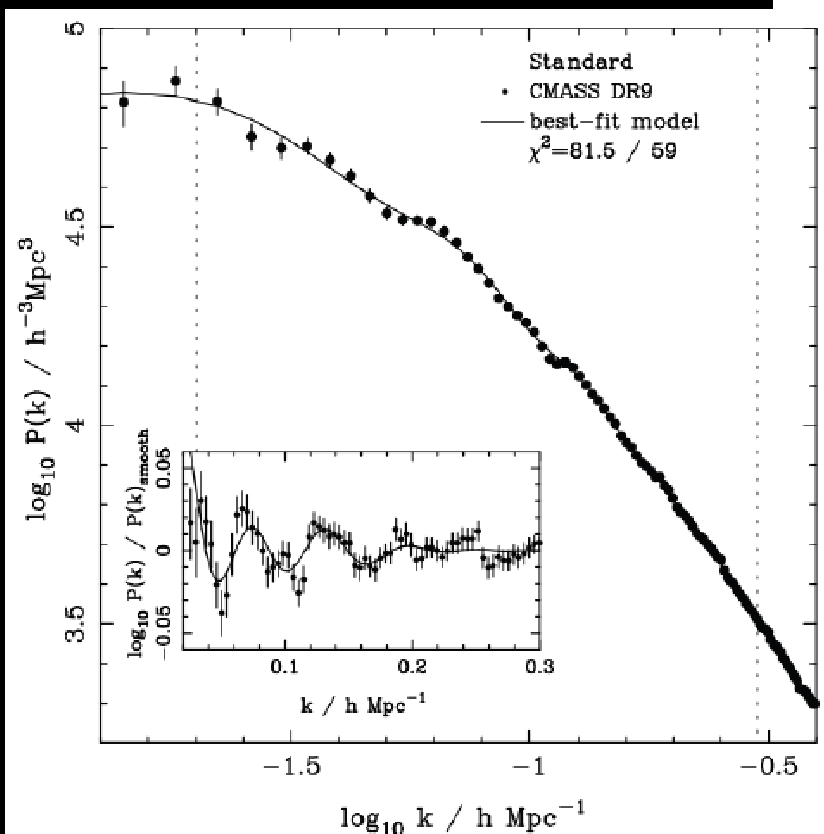
Galaxy map 3.8 billion years ago   Galaxy map 5.5 billion years ago   CMB 13.7 billion years ago

Baryon Oscillations in the Galaxy Distribution



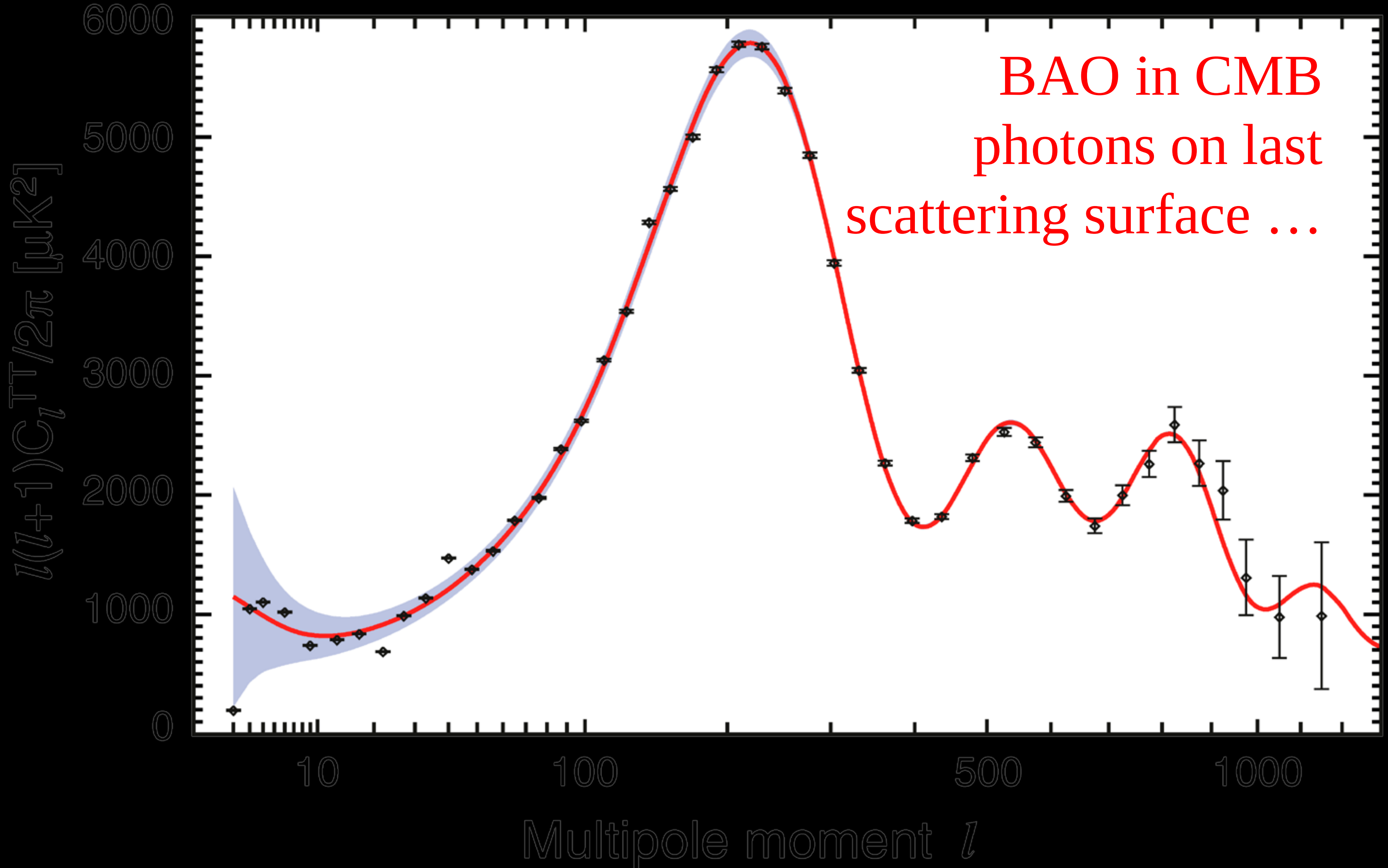
Spike in real space $\xi(r)$ means $\sin(kr_{BAO})/kr_{BAO}$ oscillations in Fourier space $P(k)$

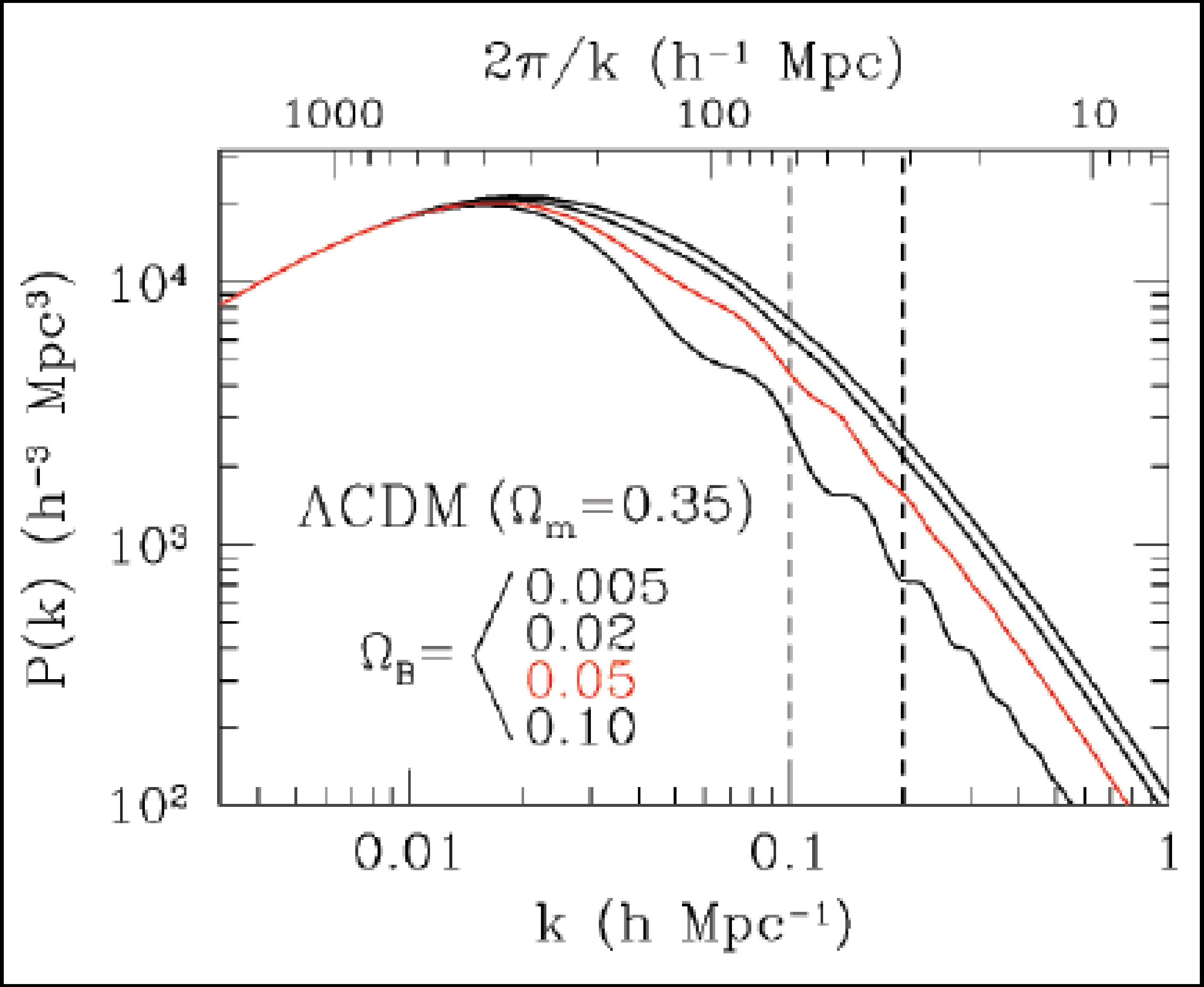




In fact, spike is not delta function because surface of last scattering not instantaneous:

$e^{-(k/k_{Silk})^{1.4}} \sin(kr_{BAO})/kr_{BAO}$


BAO in CMB
photons on last
scattering surface …
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
Multipole moment l
l(l+1)C_l^TT/2π [μK²]

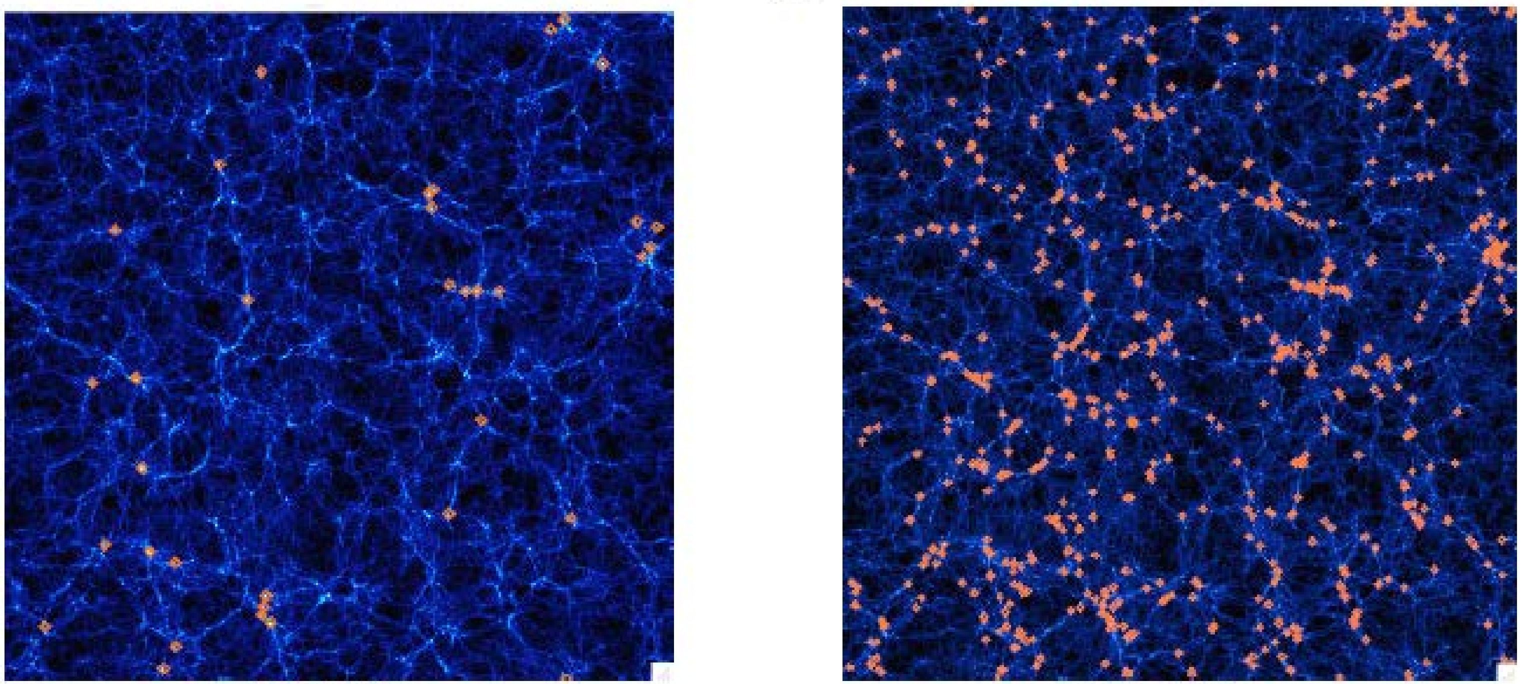


… should/are seen in matter distribution at later times

…we need a tracer of the baryons

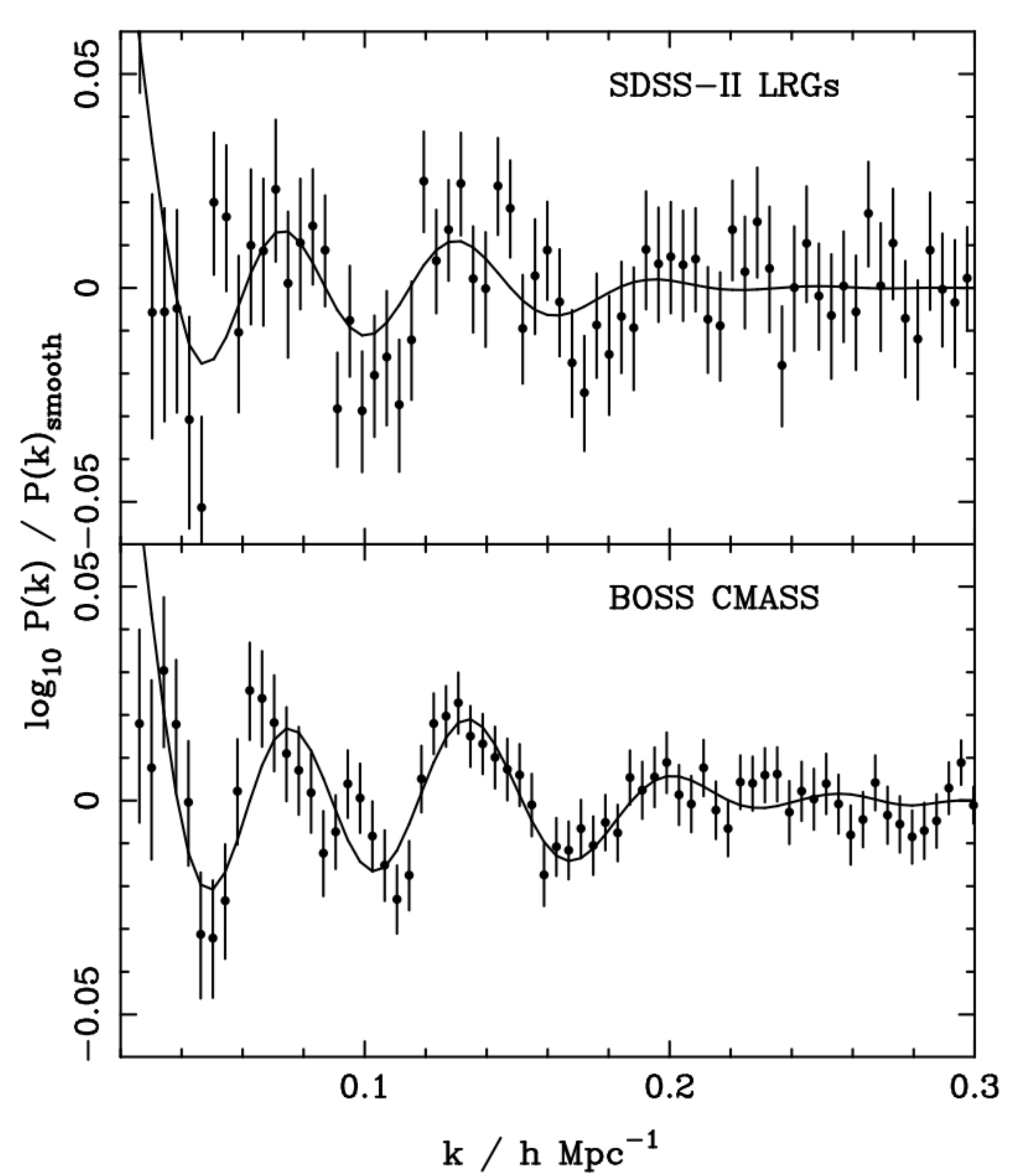
- Luminous Red Galaxies
  - Luminous, so visible out to large distances
  - Red, presumably because they are old, so probably single burst population, so evolution relatively simple
  - Large luminosity suggests large mass, so probably strongly clustered, so signal easier to measure
  - Linear bias on large scales, so *length of rod* not affected by galaxy tracer!

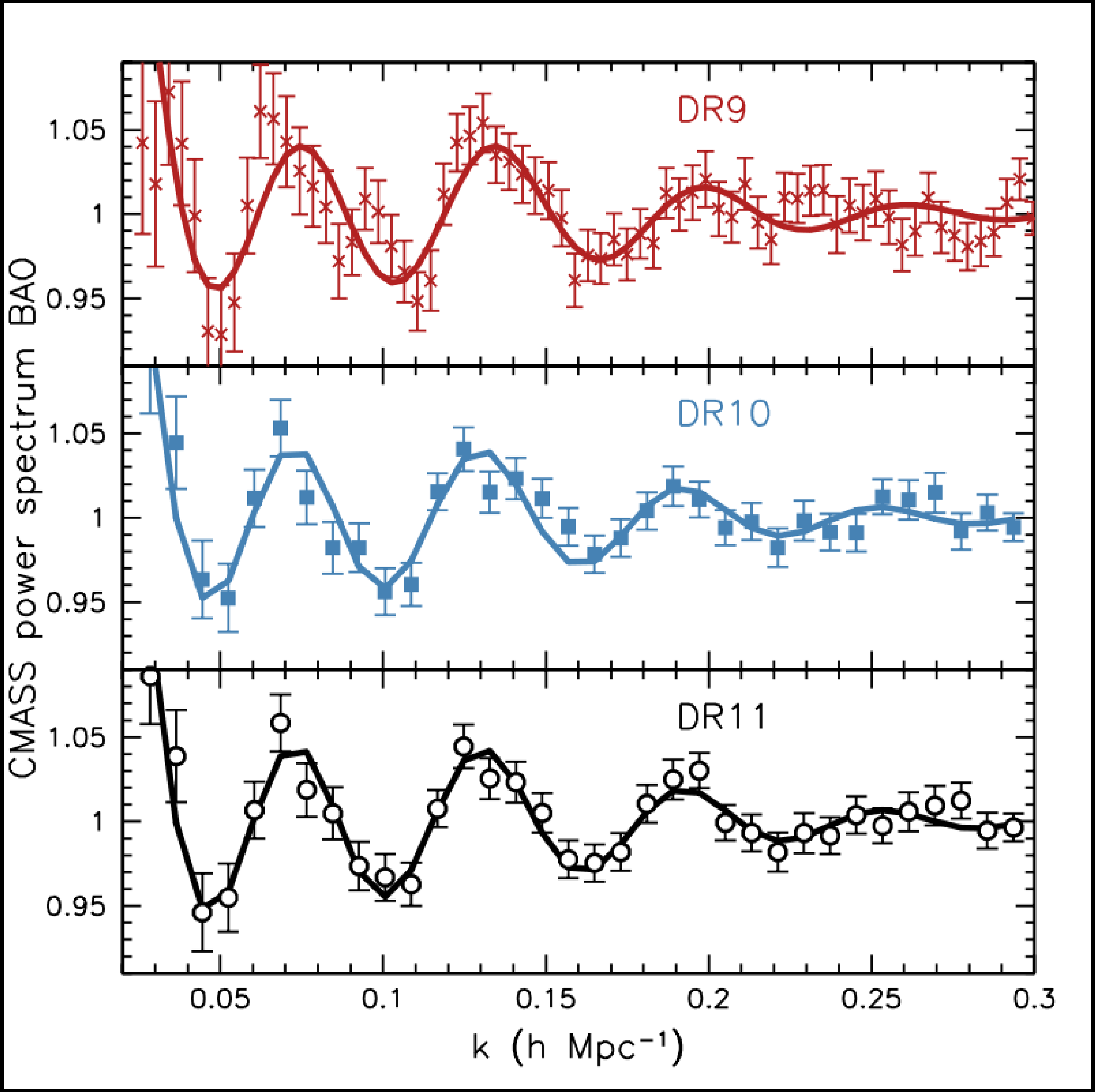
The cosmic web at $z \sim 0.5$, as traced by luminous red galaxies



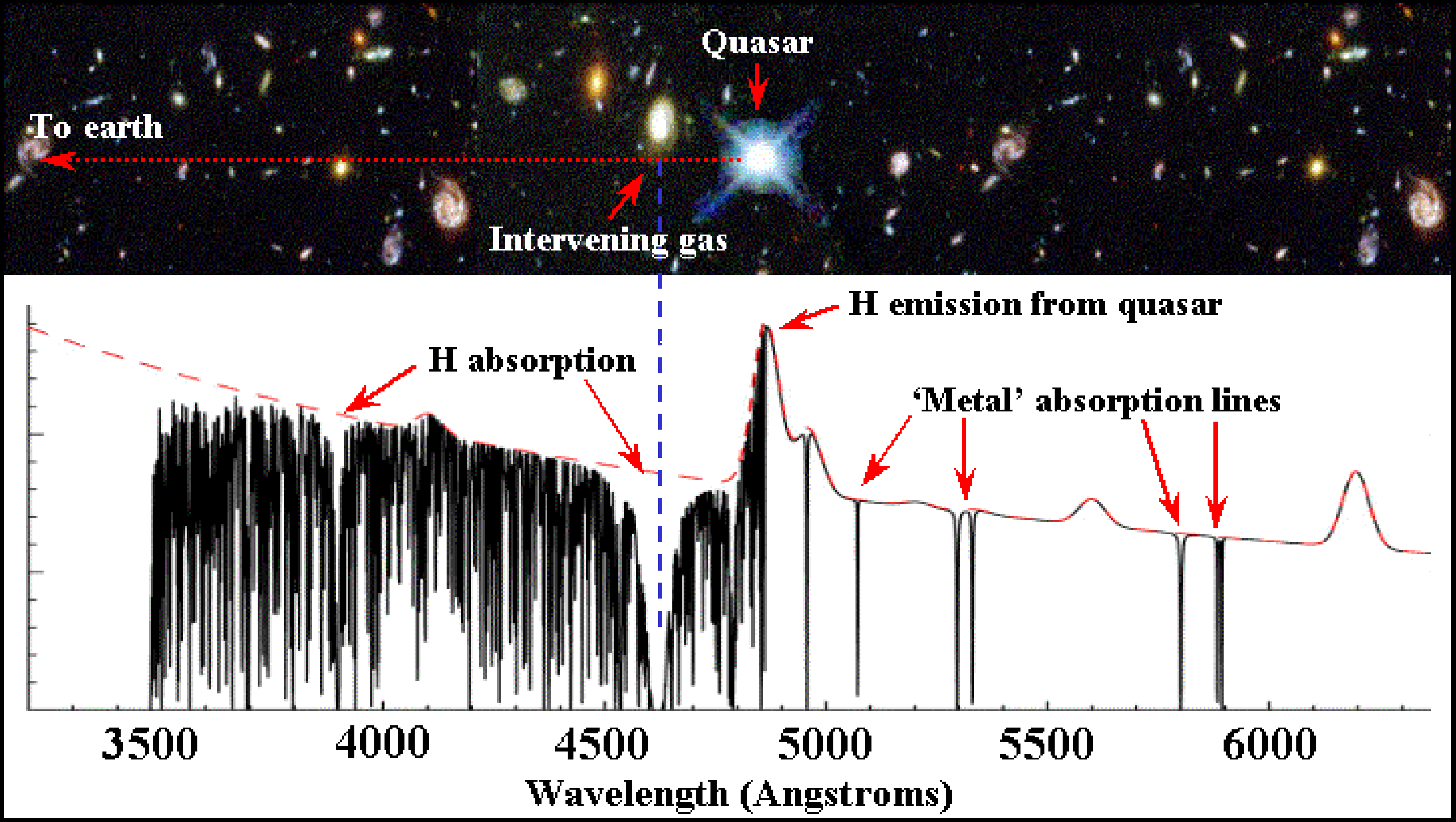
SDSS (M. White 2010) BOSS

A slice $500 h^{-1}$ Mpc across and $10\ h^{-1}$ Mpc thick


SDSS−II LRGs
BOSS CMASS
$\log_{10} P(k) / P(k)_{smooth}$
0.05
0
−0.05
0.1
0.2
0.3
k / h Mpc^{-1}

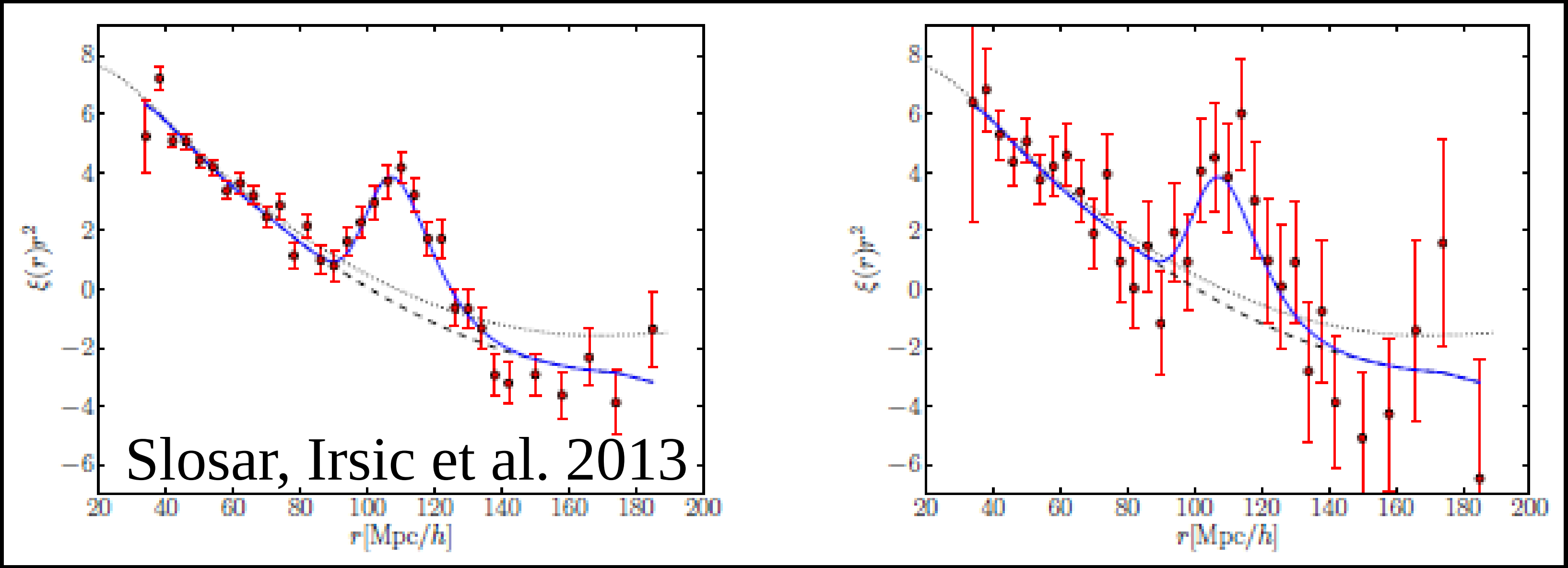

DR9
DR10
DR11
CMASS power spectrum BAO
1.05
1
0.95
0.05
0.1
0.15
0.2
0.25
0.3
k (h Mpc⁻¹)

Can see baryons that are not in stars …



High redshift structures constrain neutrino mass

BAO in Ly-α forest at z~2.4

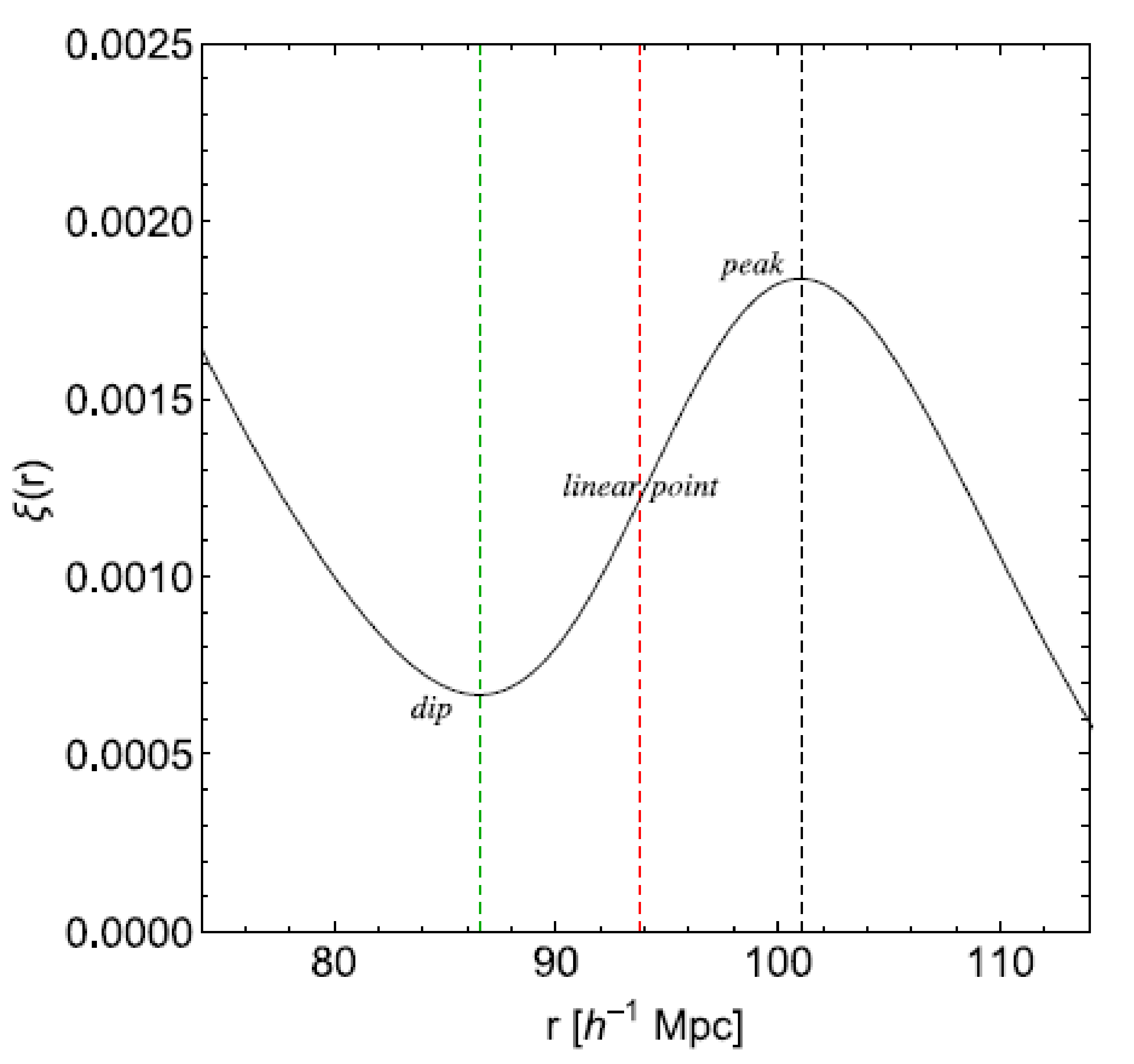


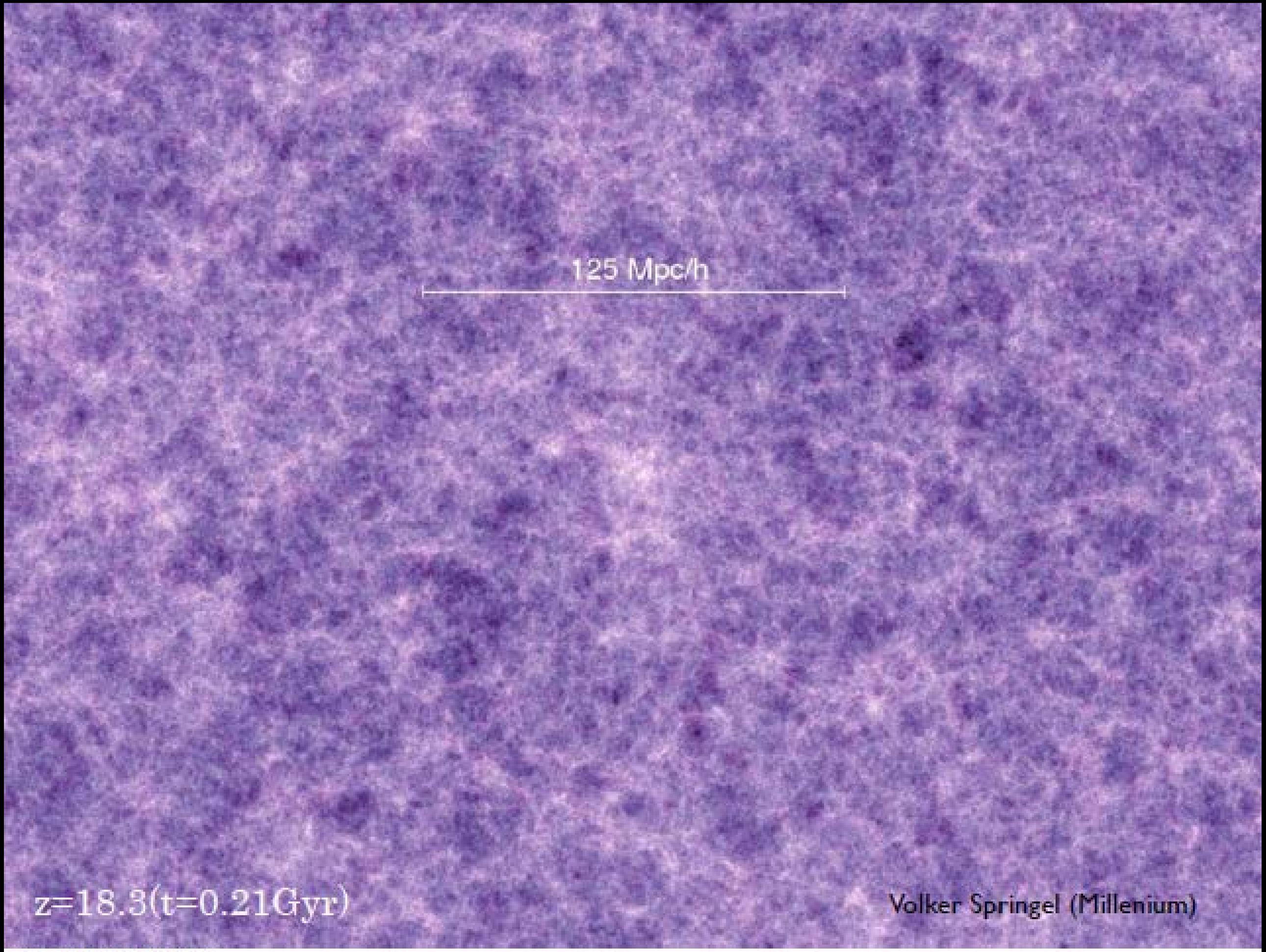
- Signal from cross-correlating different lines of sight

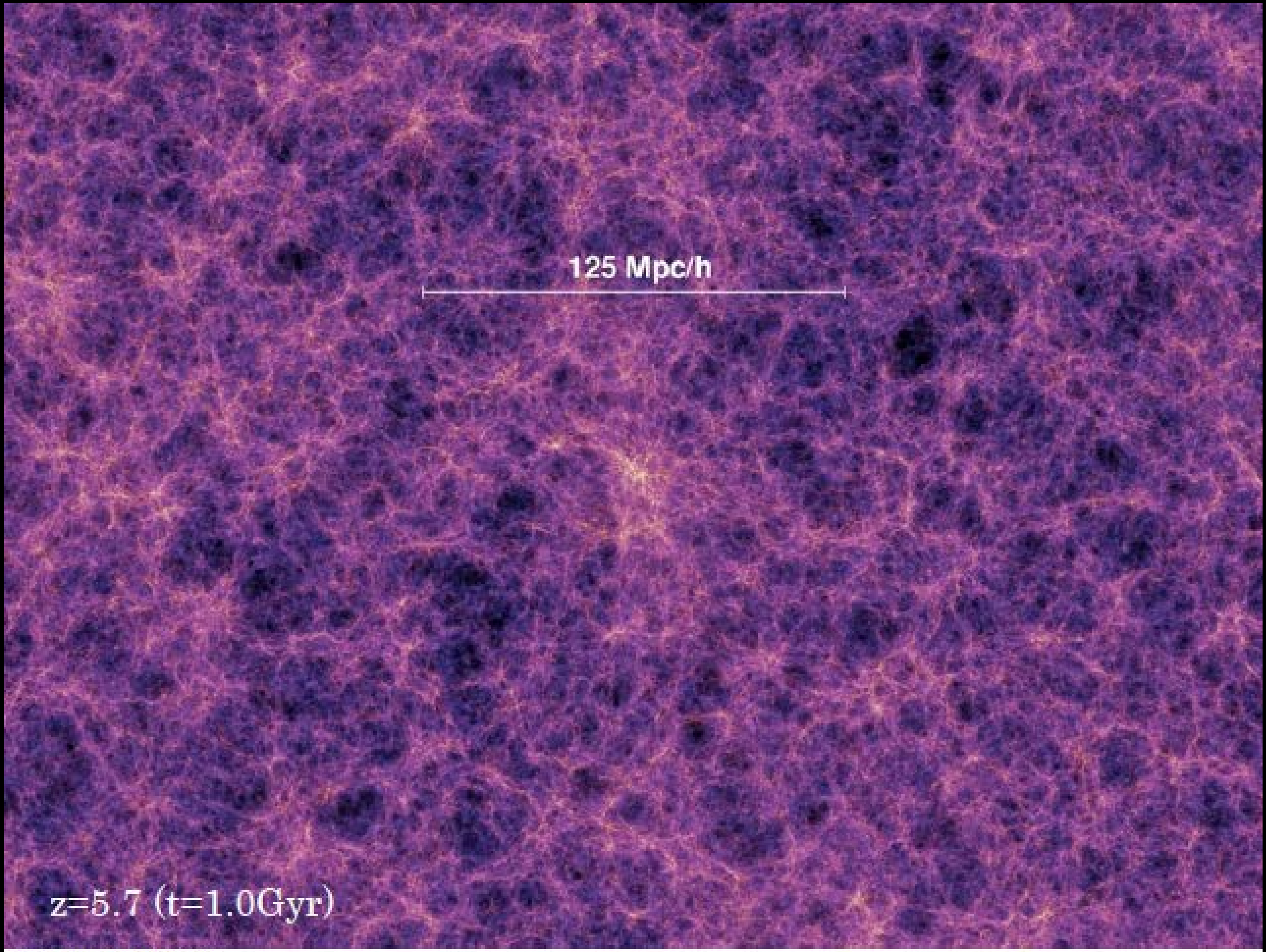
- The baryon distribution today ‘remembers’ the time of decoupling/last scattering; can use this to build a ‘standard rod’

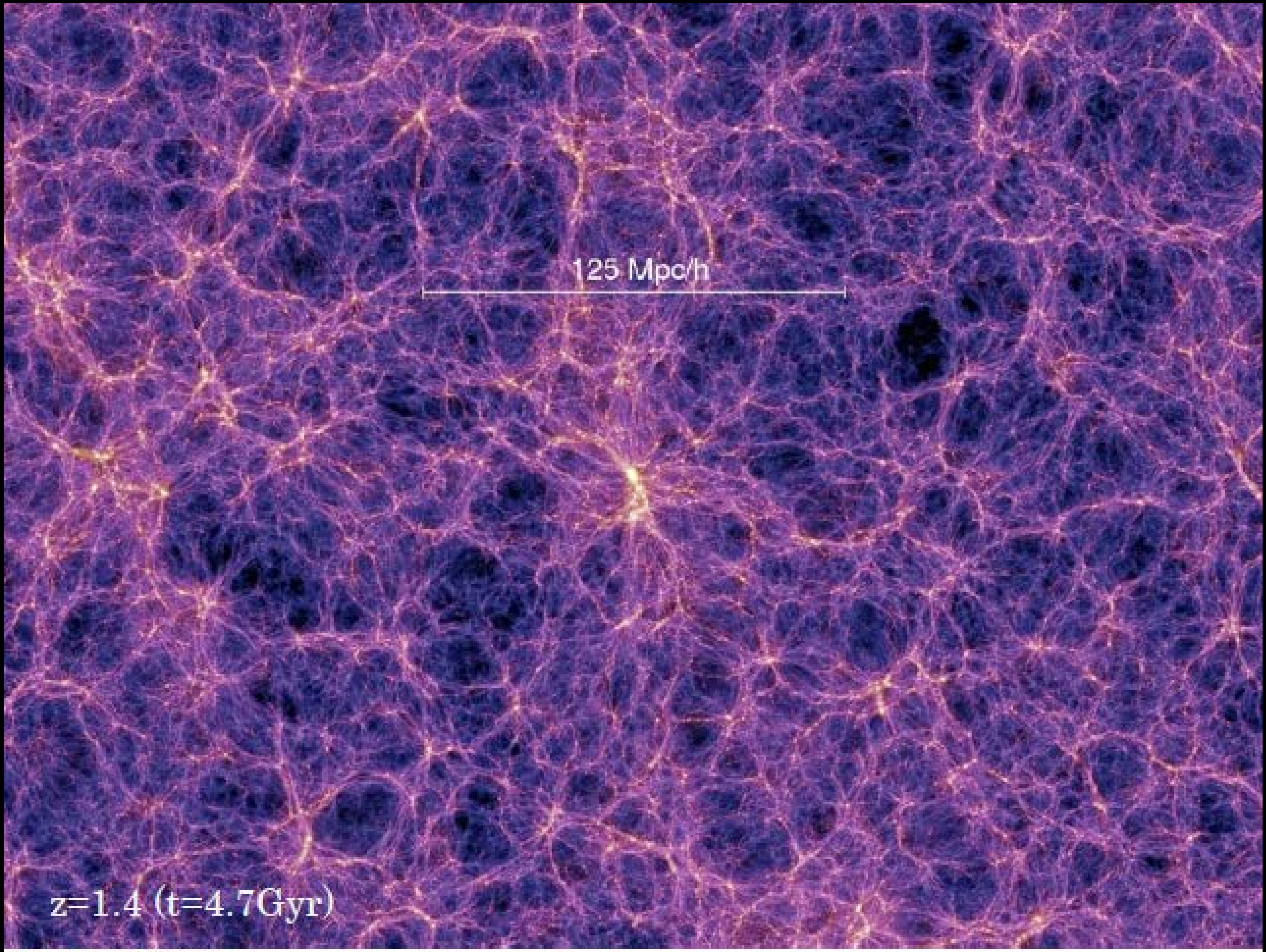
- Next decade will bring observations of this standard rod out to redshifts $z \sim 2$ Constraints on model parameters from 10% to 1%

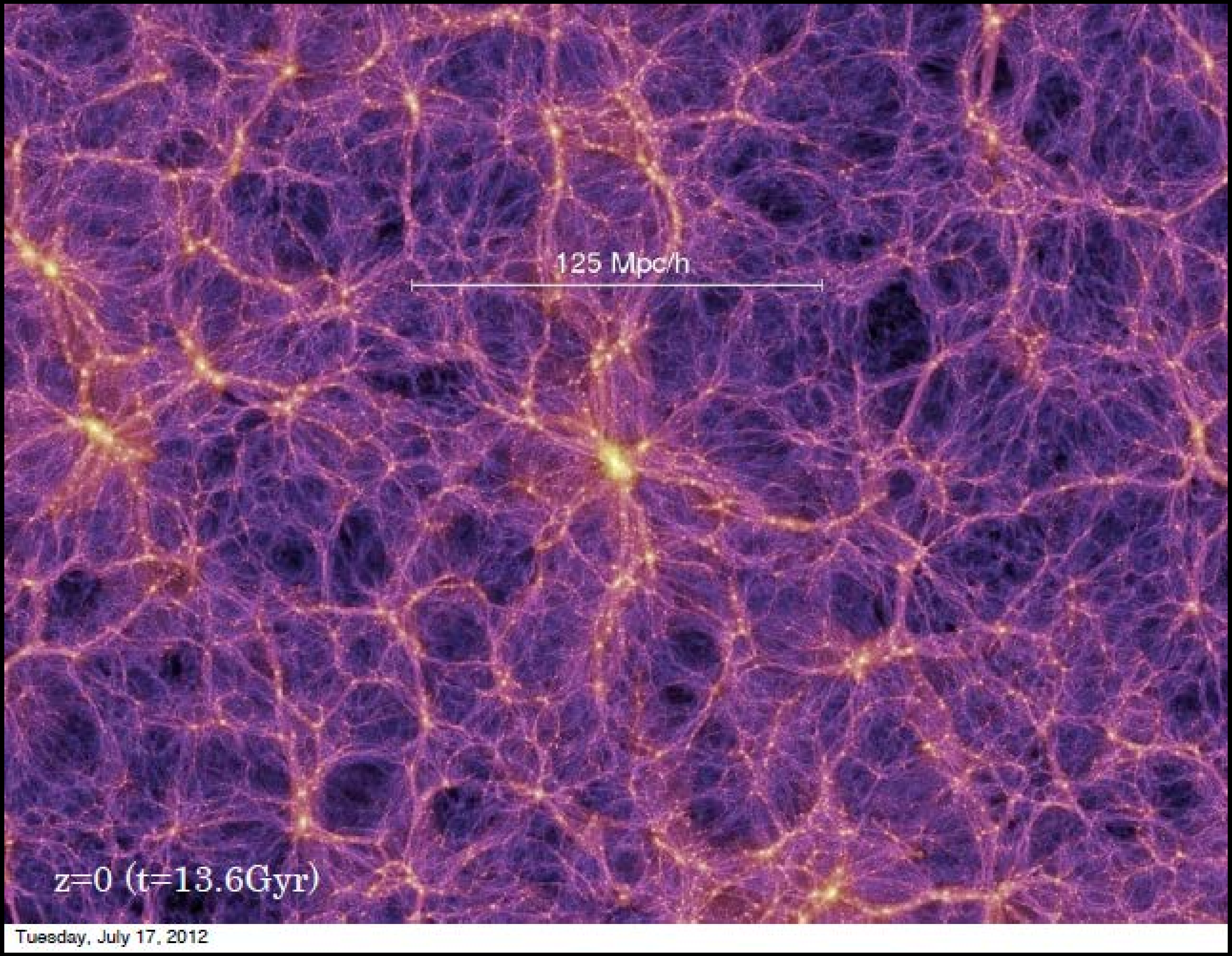
How standard is the rod?




125 Mpc/h
z=18.3(t=0.21Gyr)
Volker Springel (Millenium)

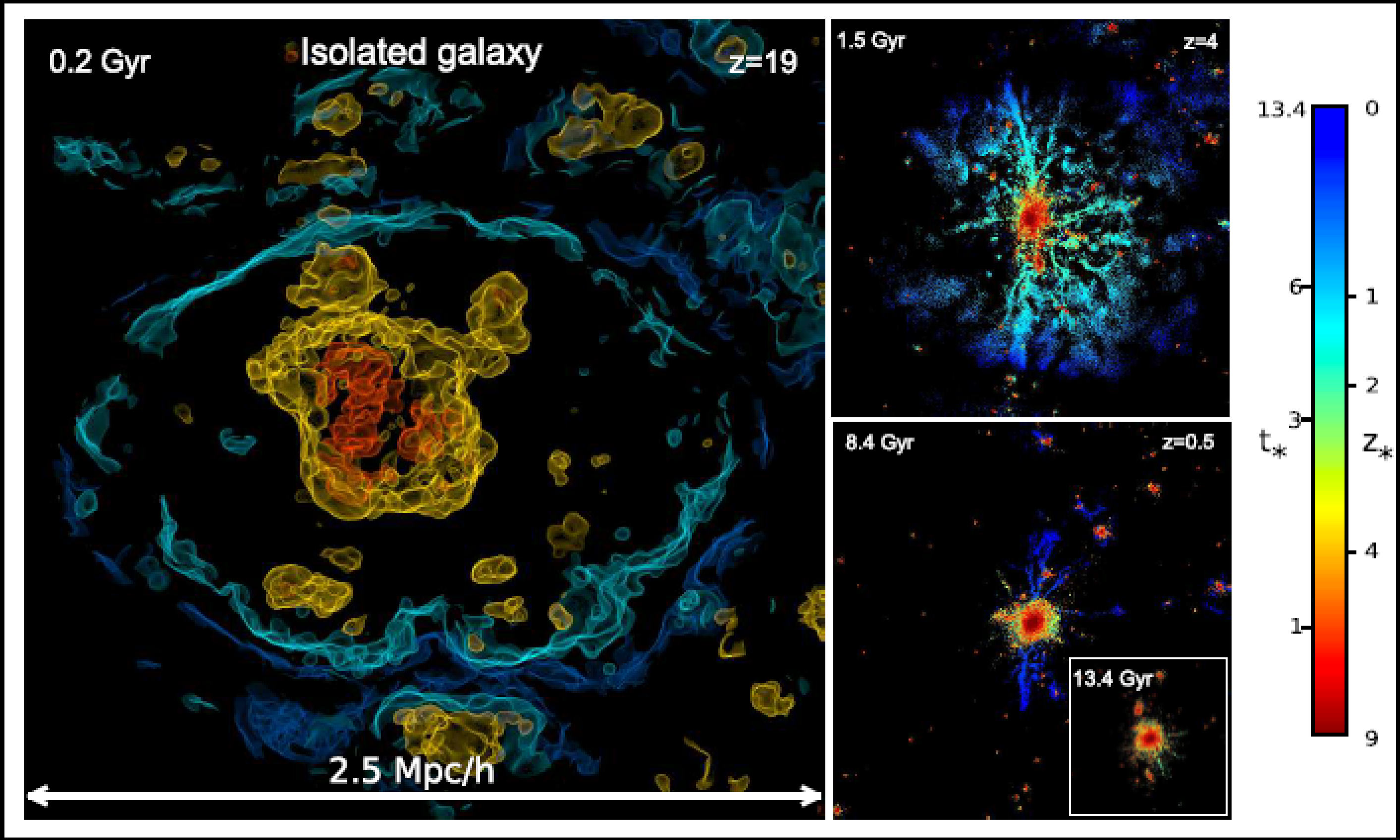

125 Mpc/h
z=5.7 (t=1.0Gyr)

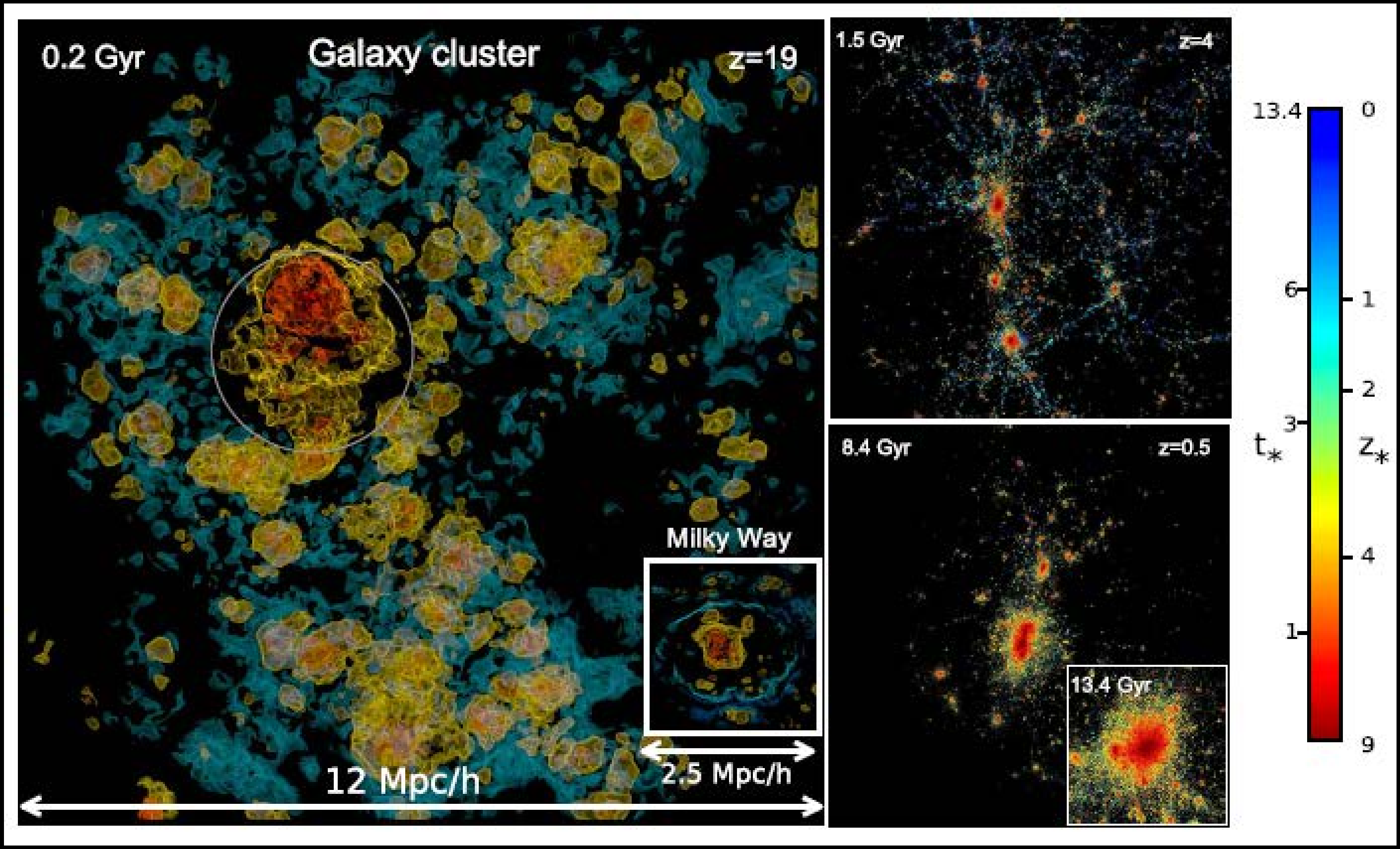

125 Mpc/h
z=1.4 (t=4.7Gyr)



Structure formation 'local' as nothing moved far

Gastrophysics also local





0.2 Gyr
Galaxy cluster
z=19
Milky Way
2.5 Mpc/h
12 Mpc/h
1.5 Gyr
z=4
8.4 Gyr
z=0.5
13.4 Gyr
13.4
6
3
1
0
1
2
4
9
t_*
z_*

Typical displacement

We move 600 km/s. What does this mean?

1000 km/s for 10 billion years

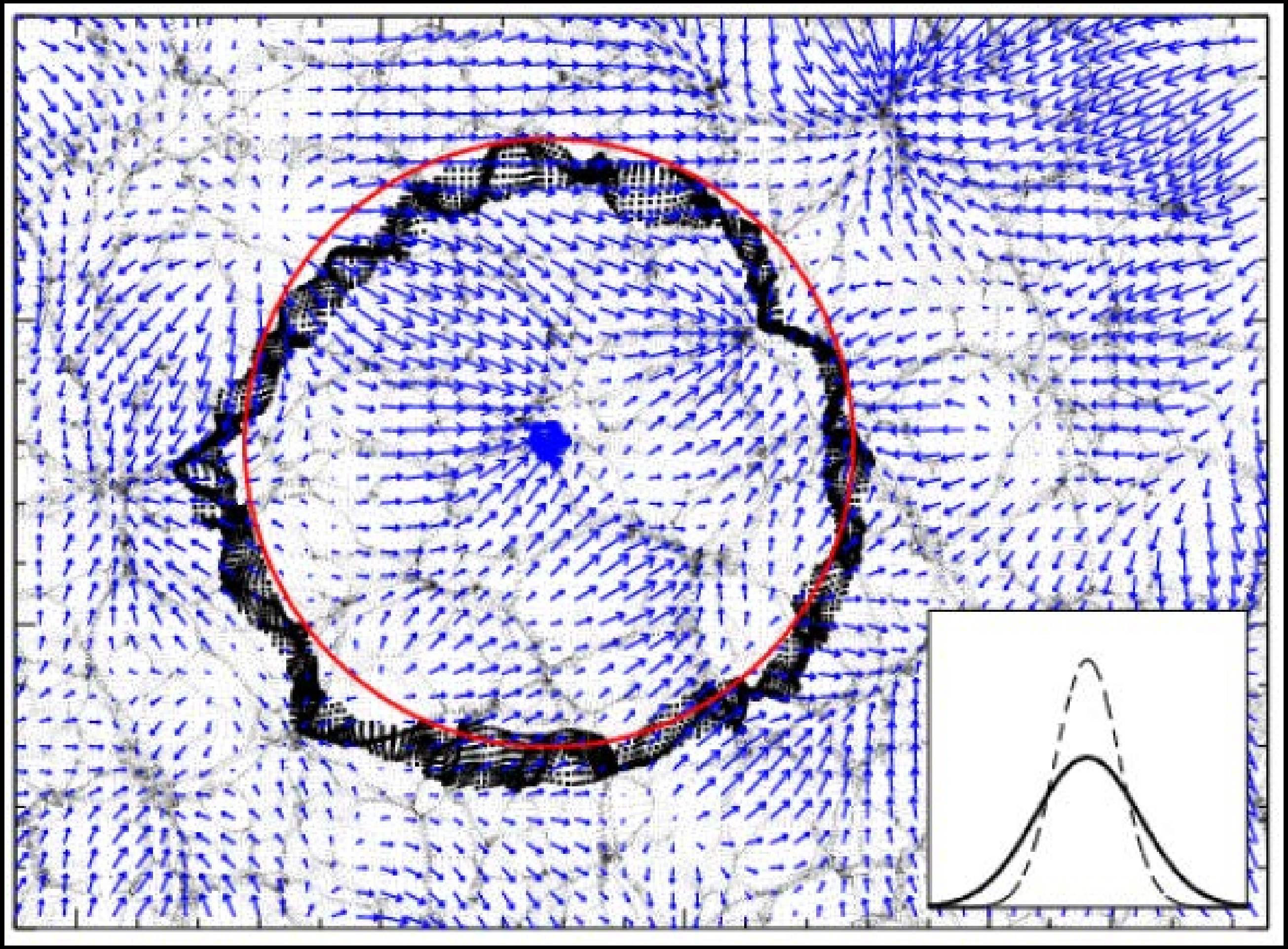
= (1000 km/s)/c × 10^{10} light years

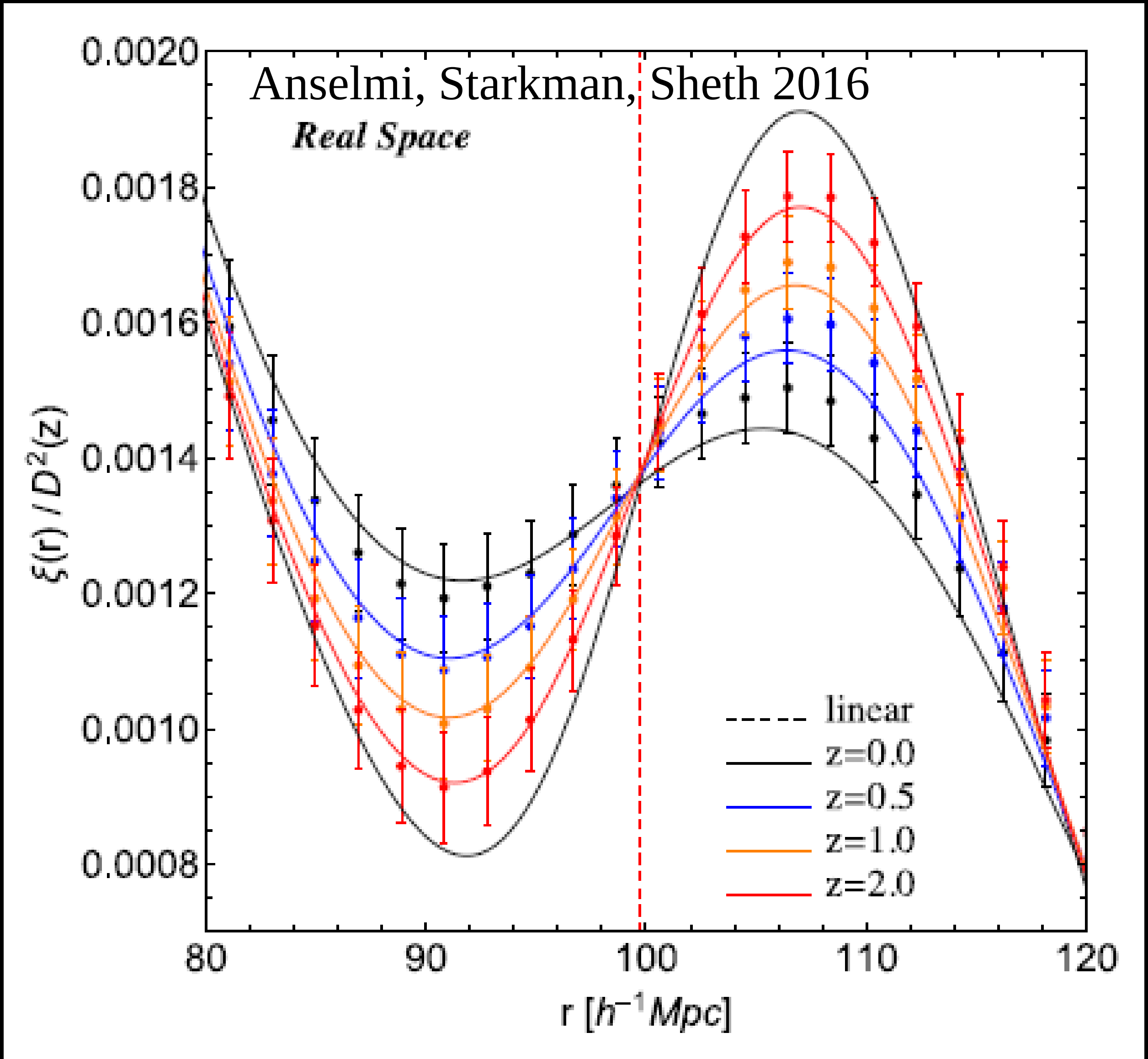
1 Megaparsec = 3.2 × 10^6 light years

~ 10 Mpc

In CDM nothing has moved much more than 10 Mpc (comoving) since the Big Bang

Zeldovich displacements (further) smear out the BAO spike





Anselmi, Starkman, Sheth 2016
Real Space
0.0020
0.0018
0.0016
0.0014
0.0012
0.0010
0.0008
ξ(r) / D²(z)
80
90
100
110
120
r [h⁻¹Mpc]
linear
z=0.0
z=0.5
z=1.0
z=2.0

Stability of inflection point

- Nonlinear smearing: $\exp(-k^2 R_{NL}^2) \sim 1 - k^2 R_{NL}^2$ so correction is like k^2
- k^2 is like a Laplacian
- In real space: $R_{NL}^2 [2/r\, d\xi/dr + d^2\xi/dr^2]$
- At local maximum $d\xi/dr = 0$ but second derivative large

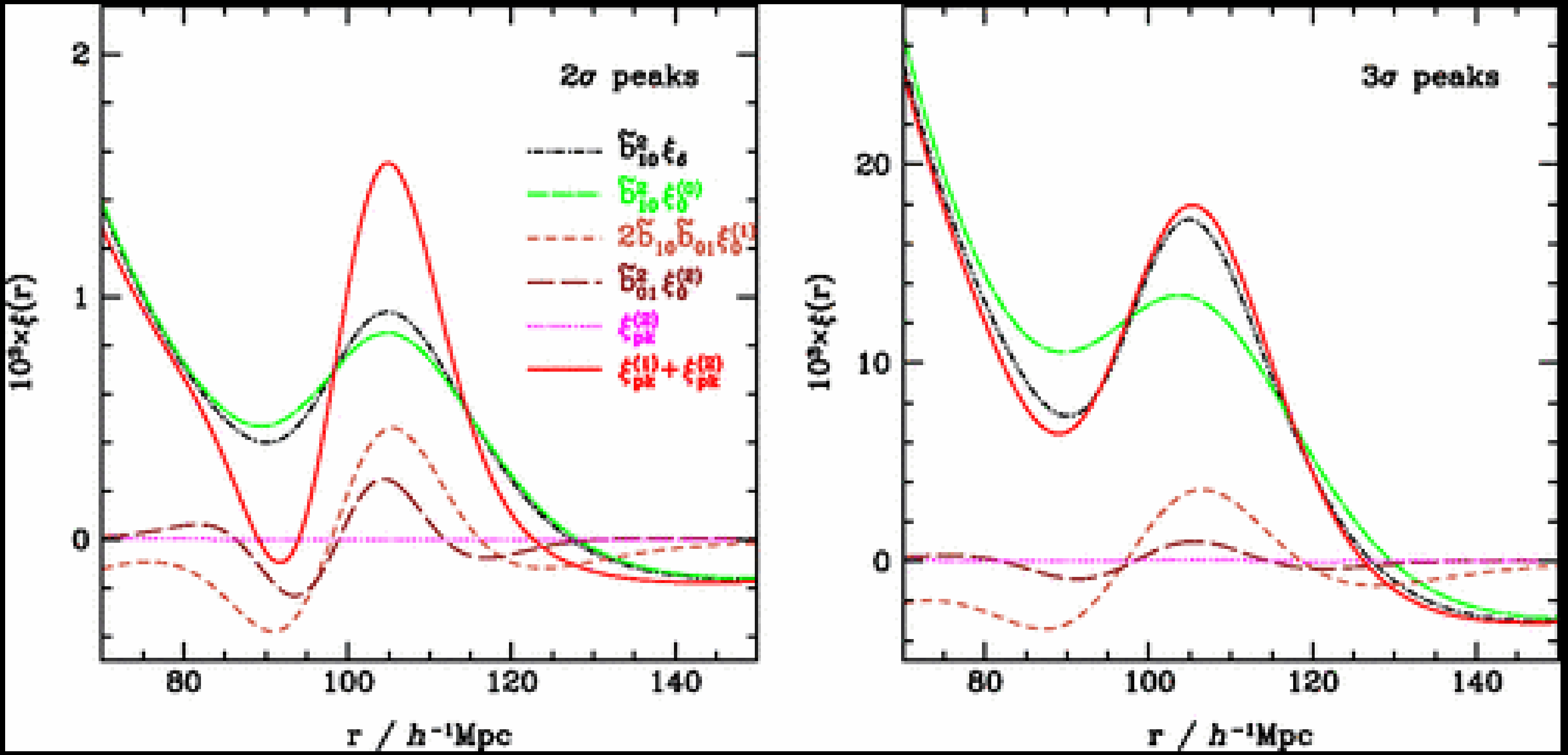
At inflection point $d^2\xi/dr^2 = 0$, and $d\xi/dr$ term suppressed by $(R_{NL}/r_{BAO})^2 \sim (10/100)^2$

Standard lore

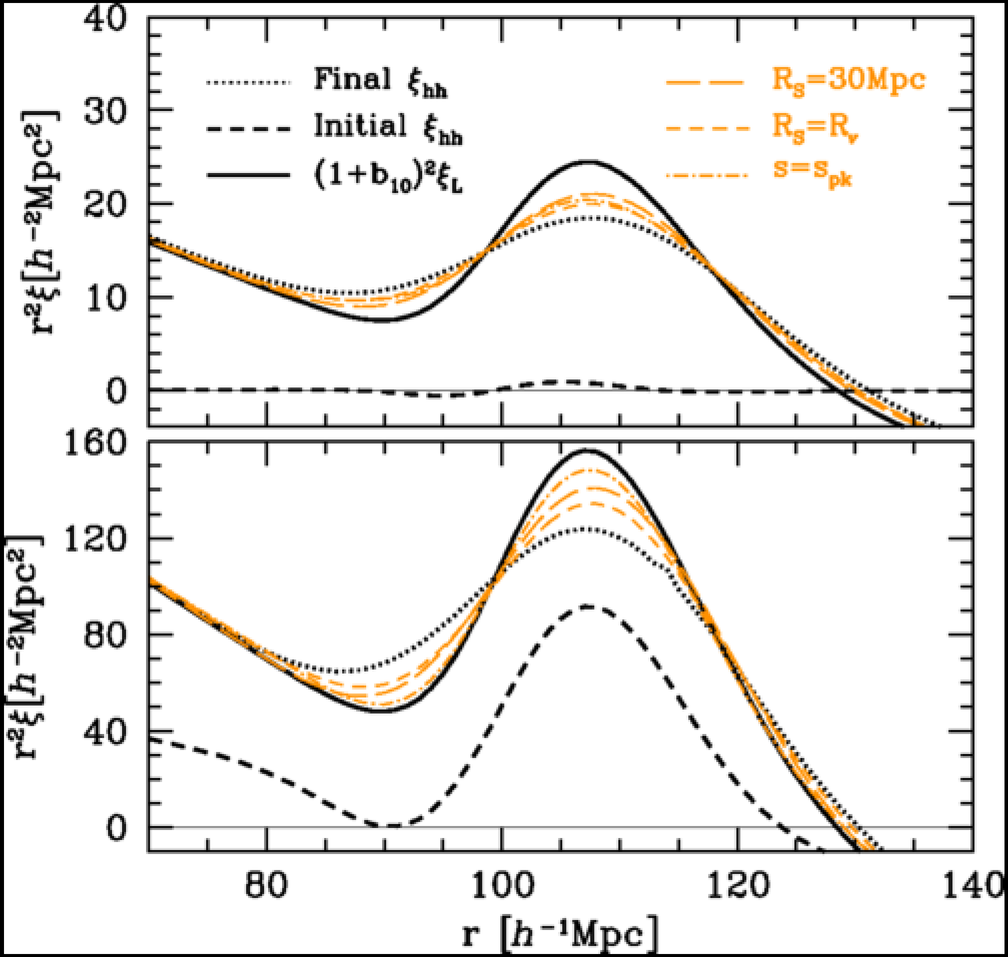
- Gravitational clustering creates nonlinear objects called haloes
- Halo properties (assembly, clustering) correlate most strongly with their mass
- Galaxies form in haloes
- Understand halos to understand galaxies

k^2-bias and the inflection point

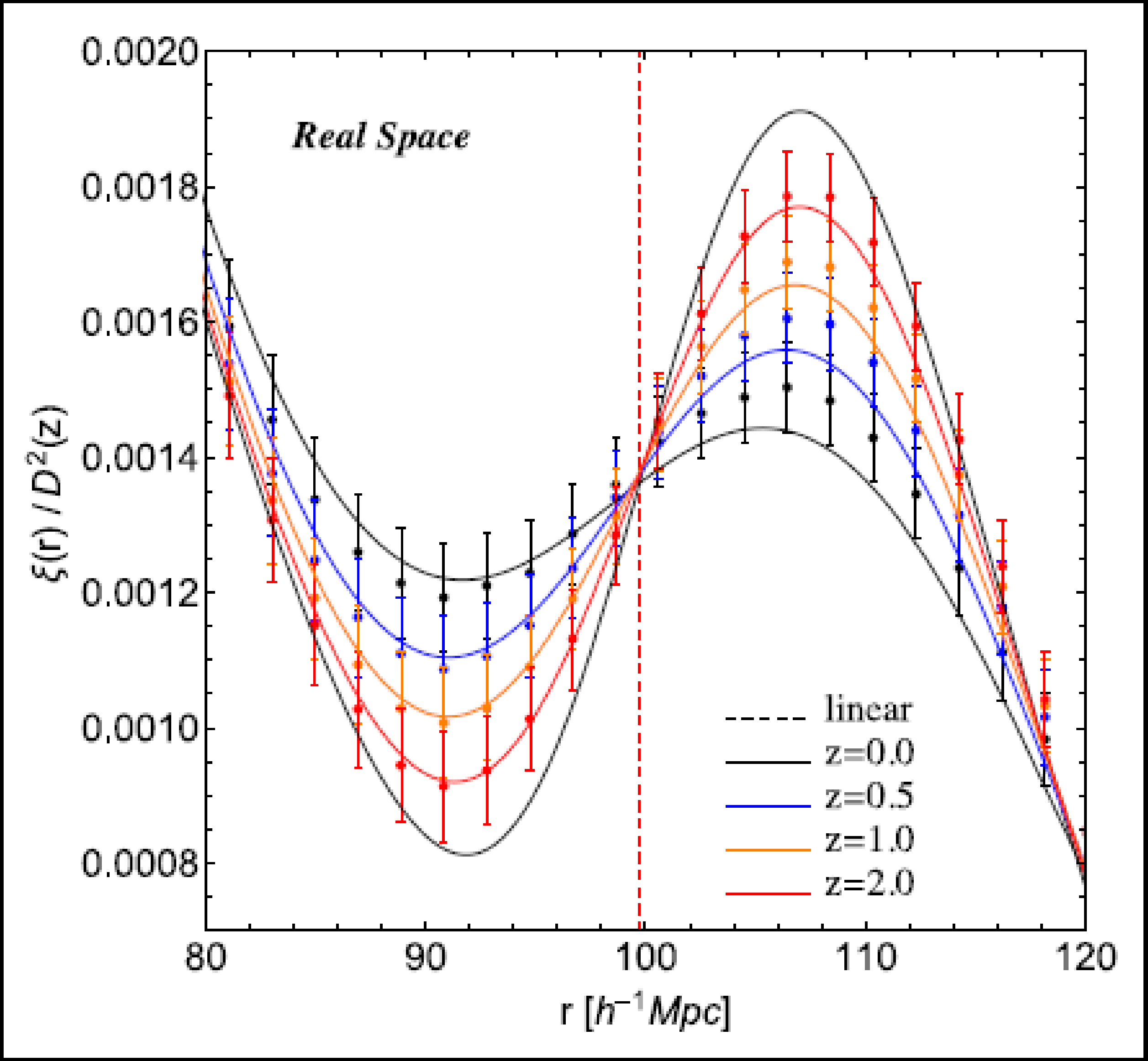
- k^2 from a Laplacian
- In real space: $b_{01} R_h^2 [2/r\, d\xi/dr + d^2\xi/dr^2]$
- At local maximum $d\xi/dr = 0$ but second derivative large
- At inflection point $d^2\xi/dr^2 = 0$, and $d\xi/dr$ term suppressed by two powers of (R_h/r_{BAO}) ~ (5/100)

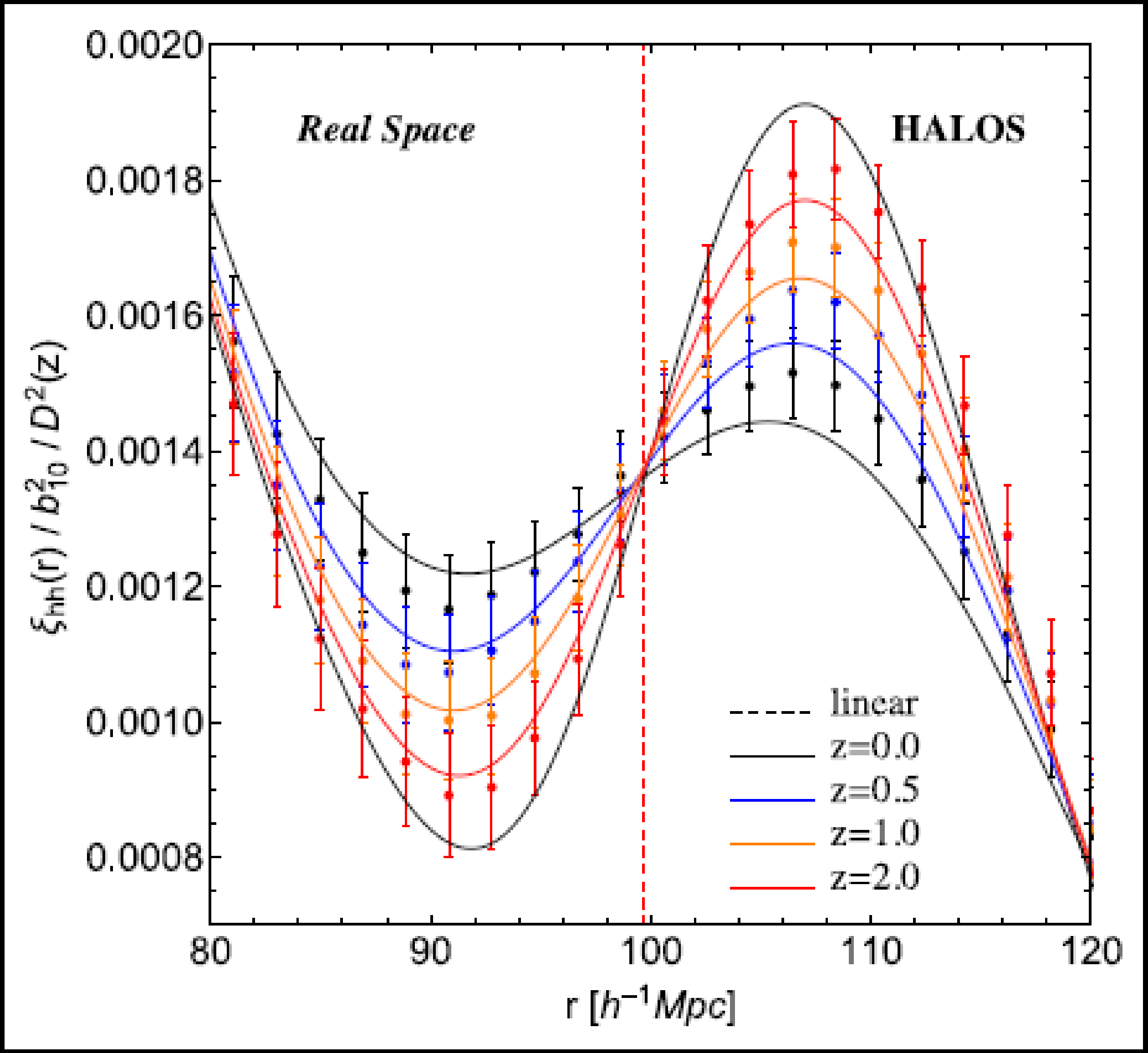


2σ peaks
$\tilde{b}_{10}^2\xi_\delta$
$\tilde{b}_{10}^2\xi_0^{(0)}$
$2\tilde{b}_{10}\tilde{b}_{01}\xi_0^{(1)}$
$\tilde{b}_{01}^2\xi_0^{(2)}$
$\xi_{pk}^{(2)}$
$\xi_{pk}^{(1)}+\xi_{pk}^{(2)}$
$10^2\times\xi(r)$
r / h^{-1}Mpc
3σ peaks
$10^3\times\xi(r)$
r / h^{-1}Mpc



Final ξ_{hh}
Initial ξ_{hh}
$(1+b_{10})^2\xi_L$
R_S=30Mpc
$R_S=R_v$
$s=s_{pk}$
$r^2\xi[h^{-2}Mpc^2]$
$r^2\xi[h^{-2}Mpc^2]$
r [h^{-1}Mpc]


Real Space
linear
z=0.0
z=0.5
z=1.0
z=2.0
0.0020
0.0018
0.0016
0.0014
0.0012
0.0010
0.0008
80
90
100
110
120
ξ(r) / D²(z)
r [h⁻¹Mpc]


Real Space
HALOS
0.0020
0.0018
0.0016
0.0014
0.0012
0.0010
0.0008
80
90
100
110
120
$\xi_{hh}(r) / b_{10}^2 / D^2(z)$
r [$h^{-1}Mpc$]
linear
z=0.0
z=0.5
z=1.0
z=2.0

In practice, BAO feature involves two components of distance across line of sight, and one component along line of sight. So 'average distance' is:

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

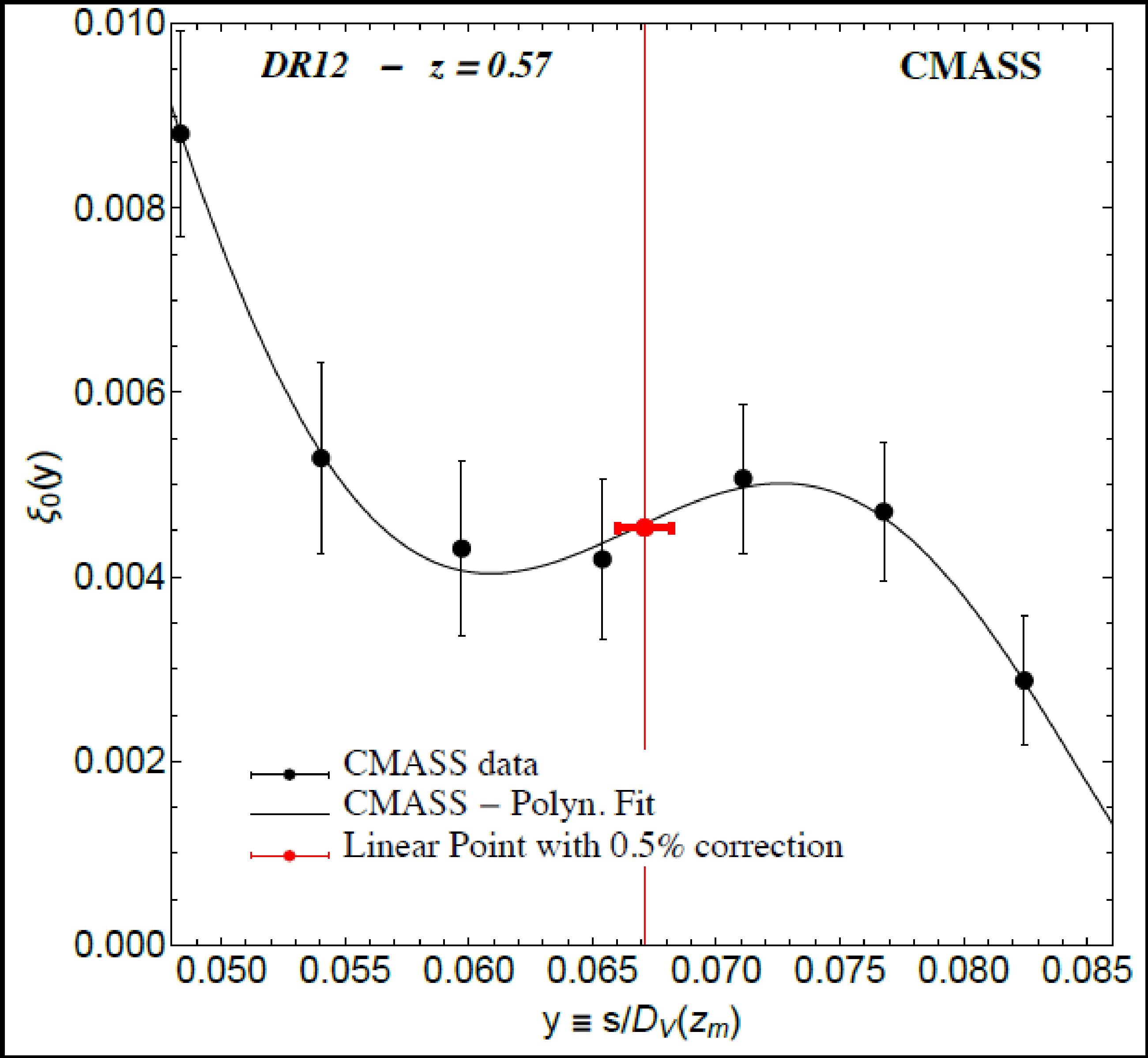
In addition, we must convert measured angles/redshifts into comoving distances. We must assume a fiducial cosmology to do so. However,

$$\xi_0(s^{\rm fid}(z)/D_V^{\rm fid}(z)) \simeq \xi_0(s^{\rm true}(z)/D_V^{\rm true}(z))$$

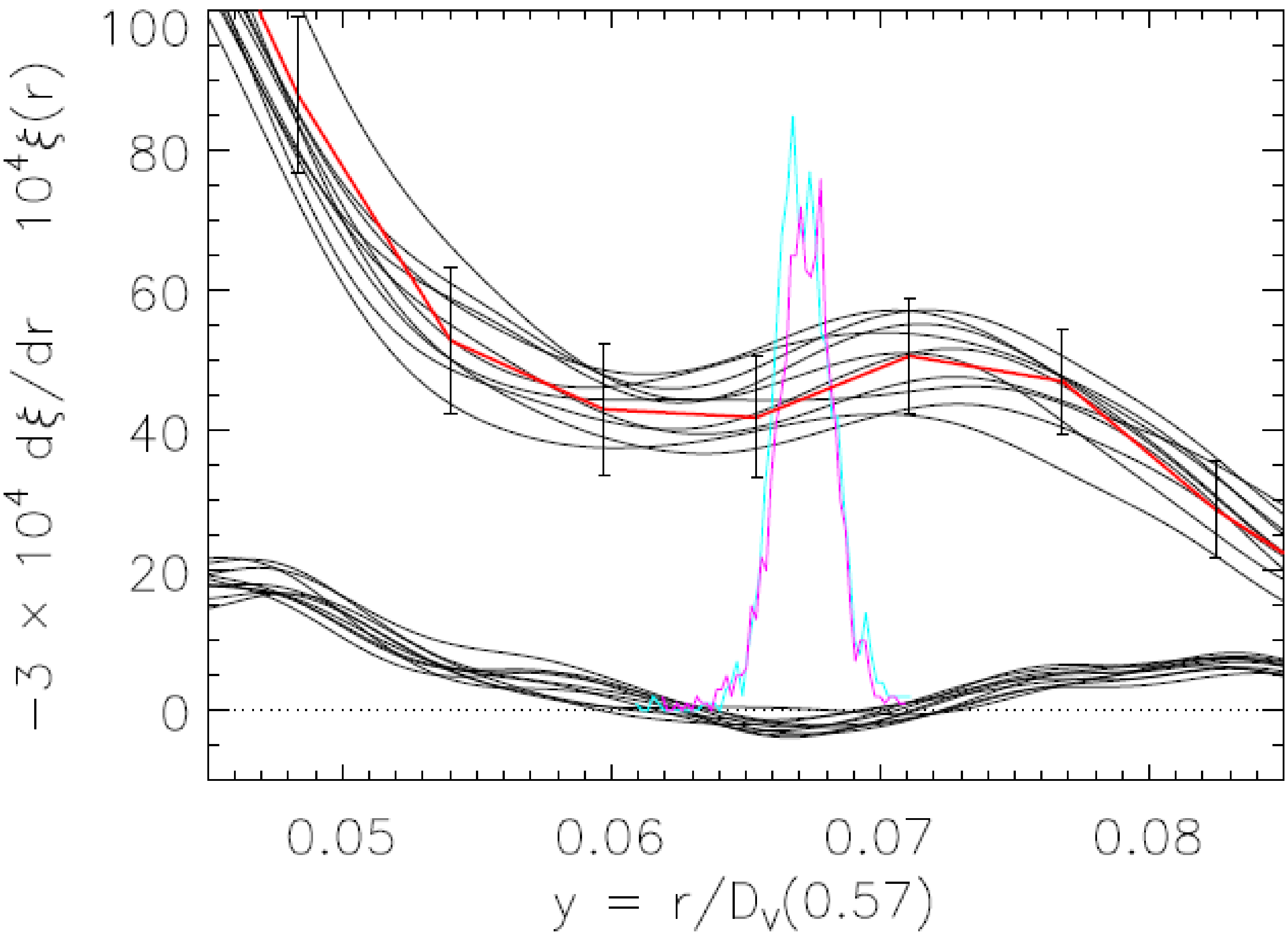
Usual analysis uses shape of Pk in fiducial cosmology to estimate BAO scale.

LP can estimate BAO scale with

- no prejudice about shape of Pk.
- no reconstruction.



DR12 – z = 0.57
CMASS
0.010
0.008
0.006
0.004
0.002
0.000
$\xi_0(y)$
0.050
0.055
0.060
0.065
0.070
0.075
0.080
0.085
$y \equiv s/D_V(z_m)$
CMASS data
CMASS – Polyn. Fit
Linear Point with 0.5% correction



100
80
60
40
20
0
$10^4\xi(r)$
$-3 \times 10^4\ d\xi/dr$
0.05
0.06
0.07
0.08
$y = r/D_V(0.57)$

Usual analysis uses shape of Pk in fiducial cosmology to estimate BAO scale.

LP can estimate BAO scale with

- no prejudice about shape of Pk.
- no reconstruction
- good agreement with published scale