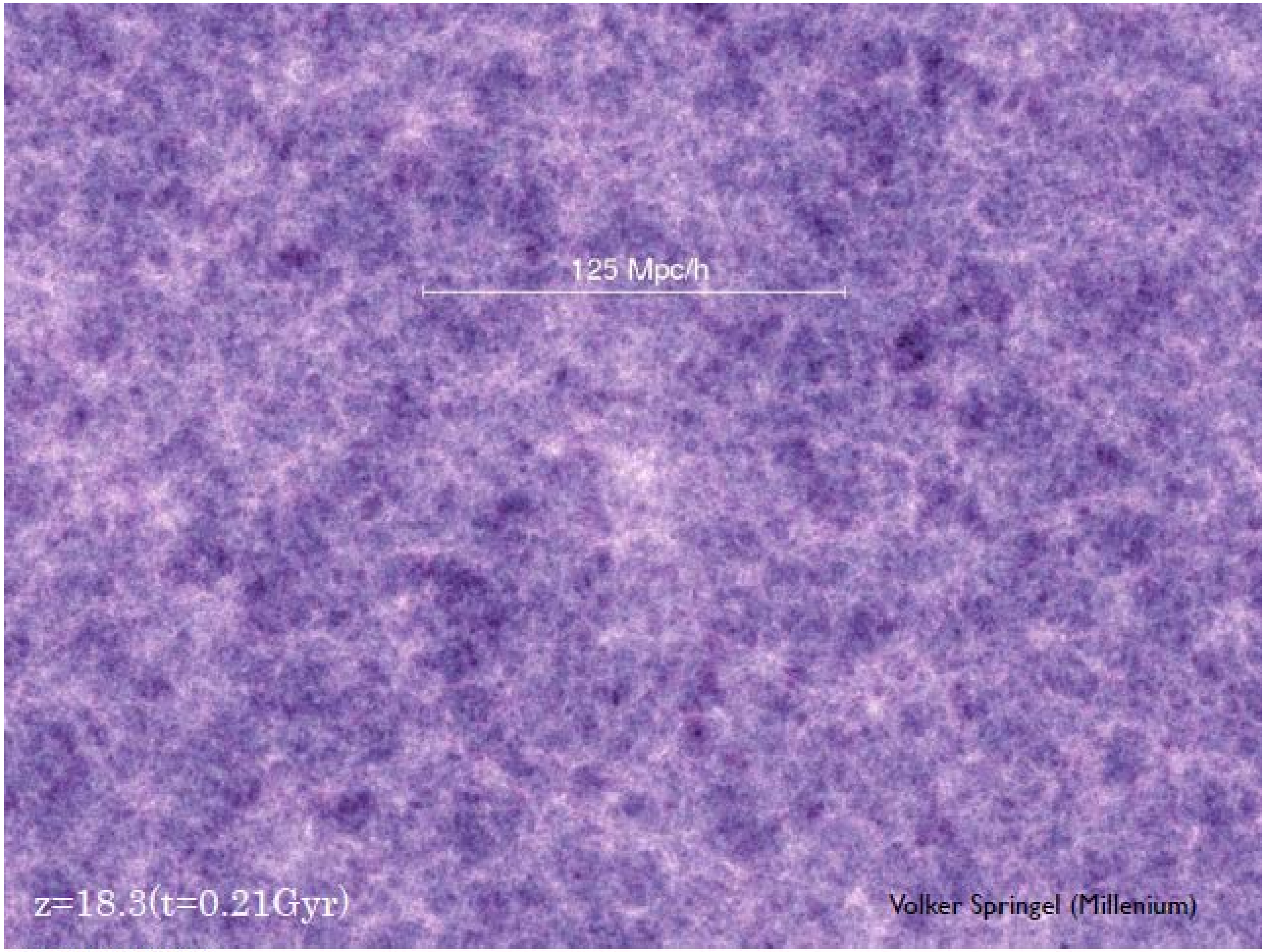
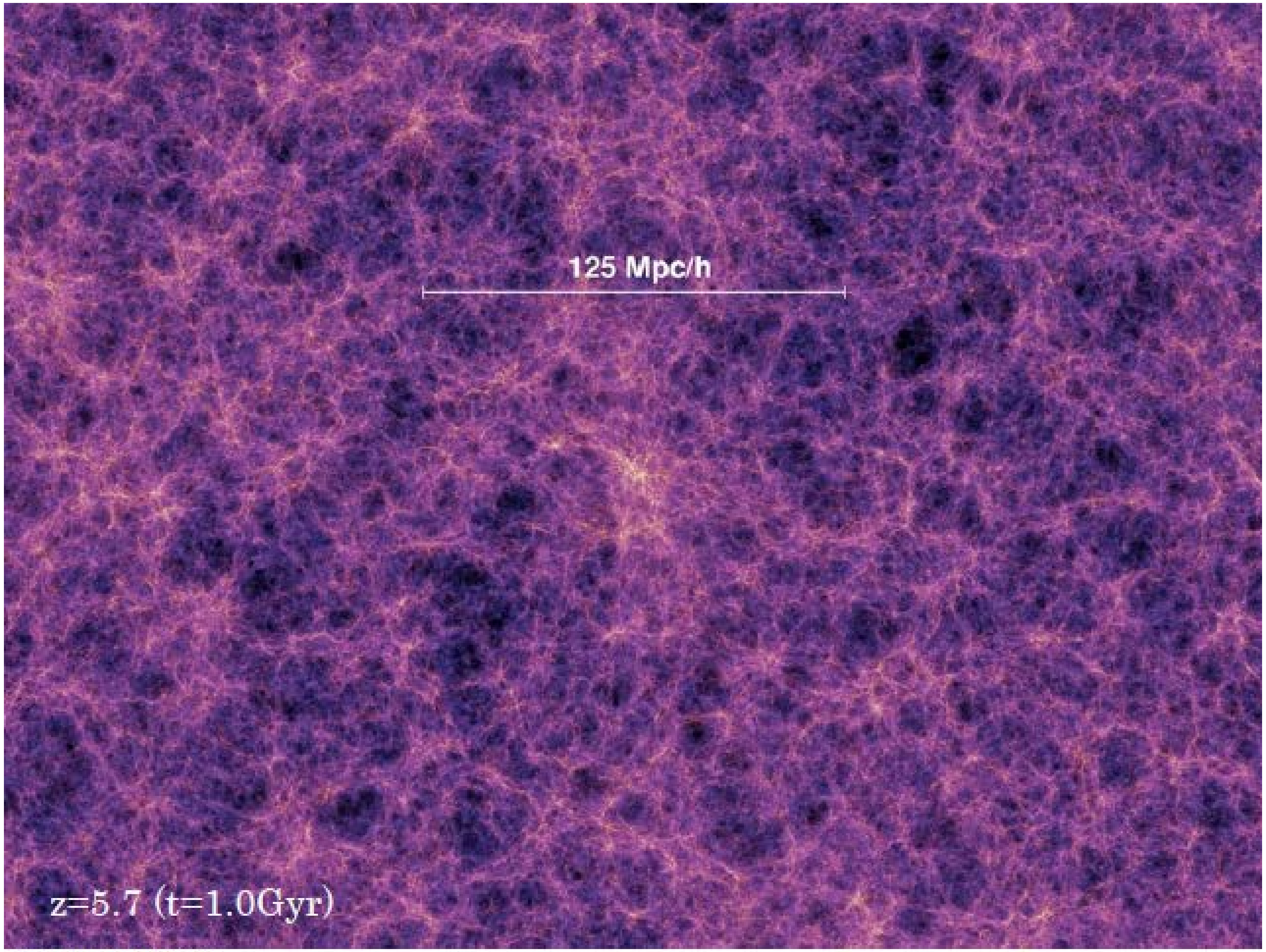
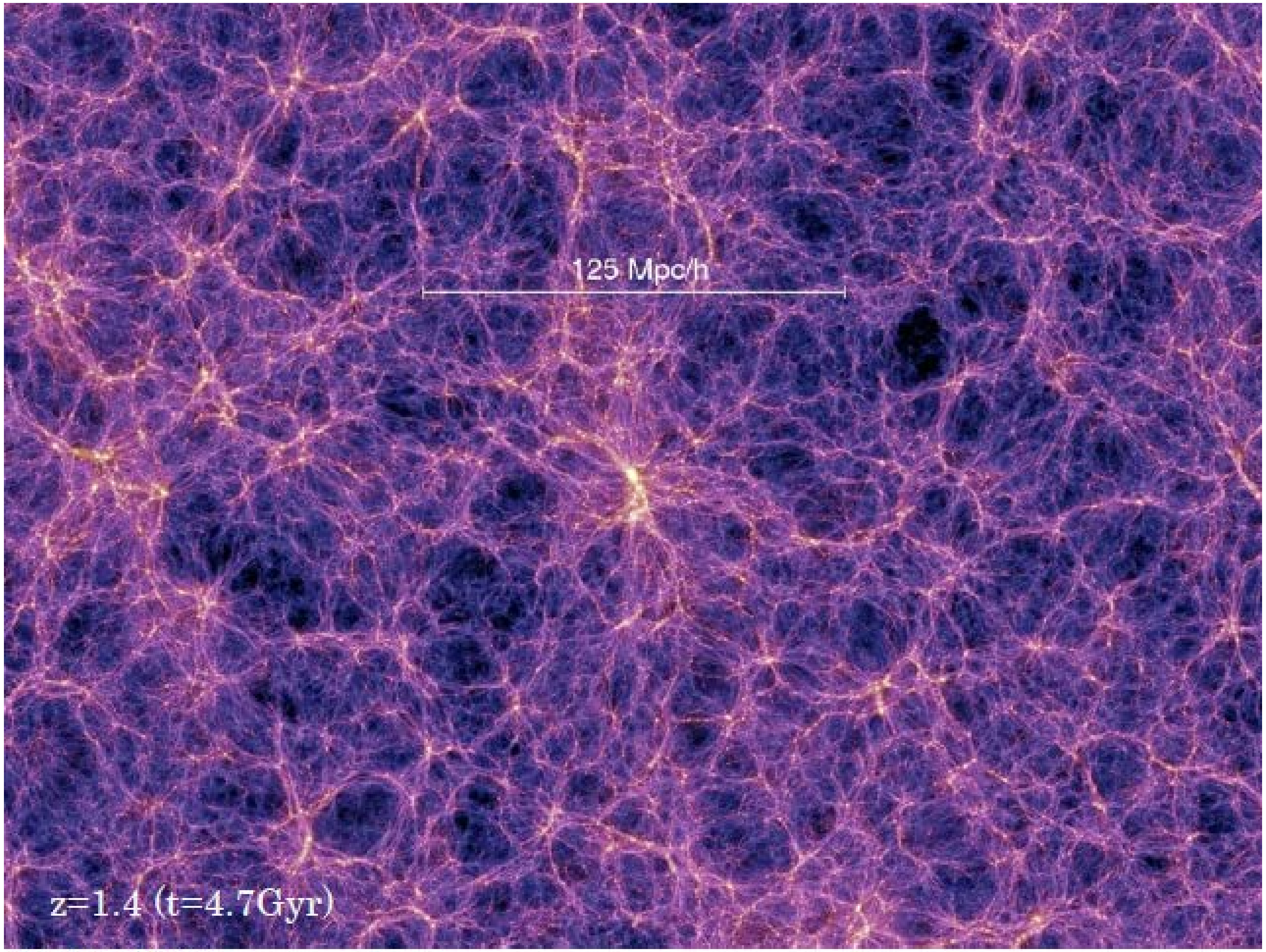
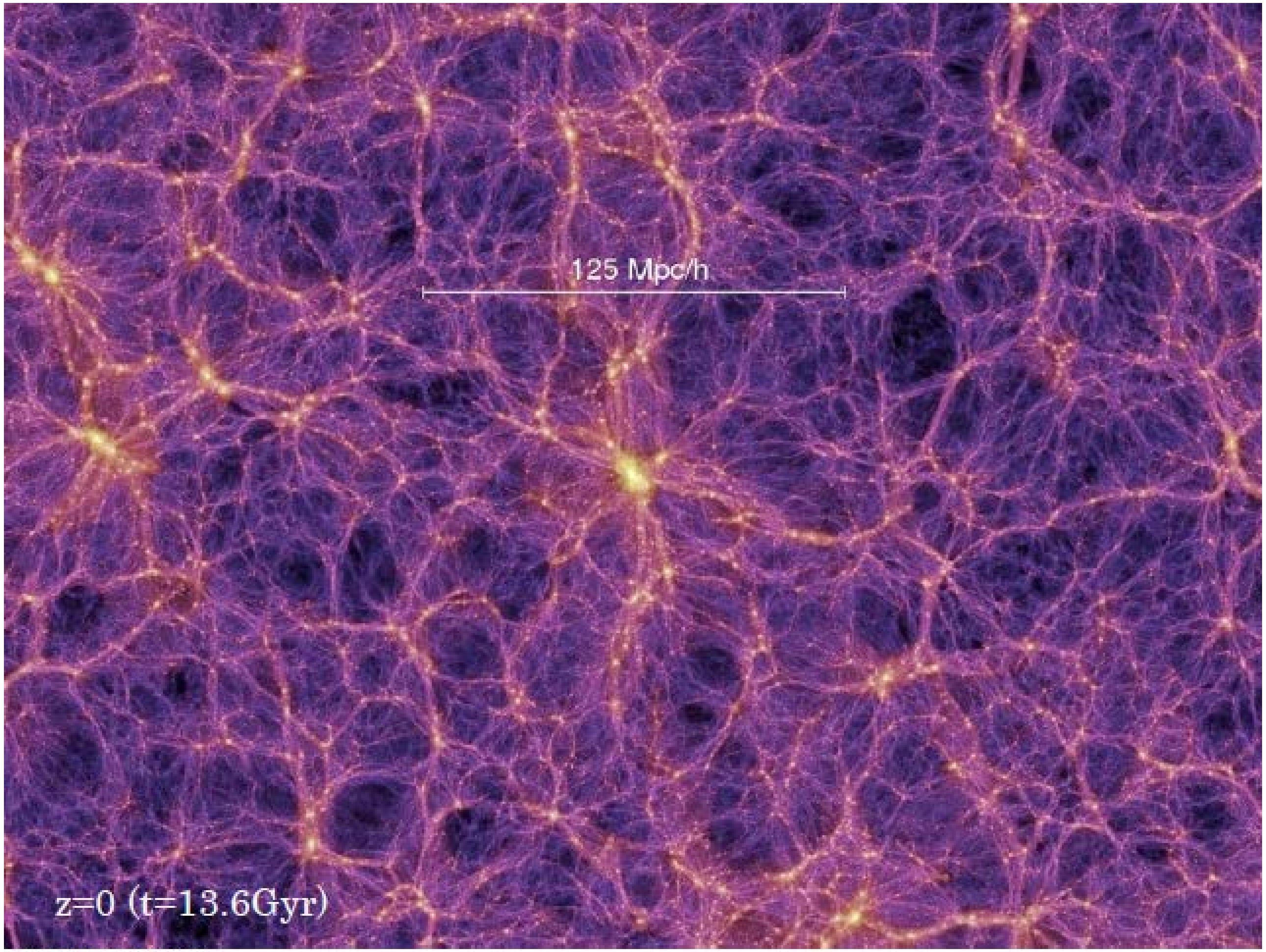
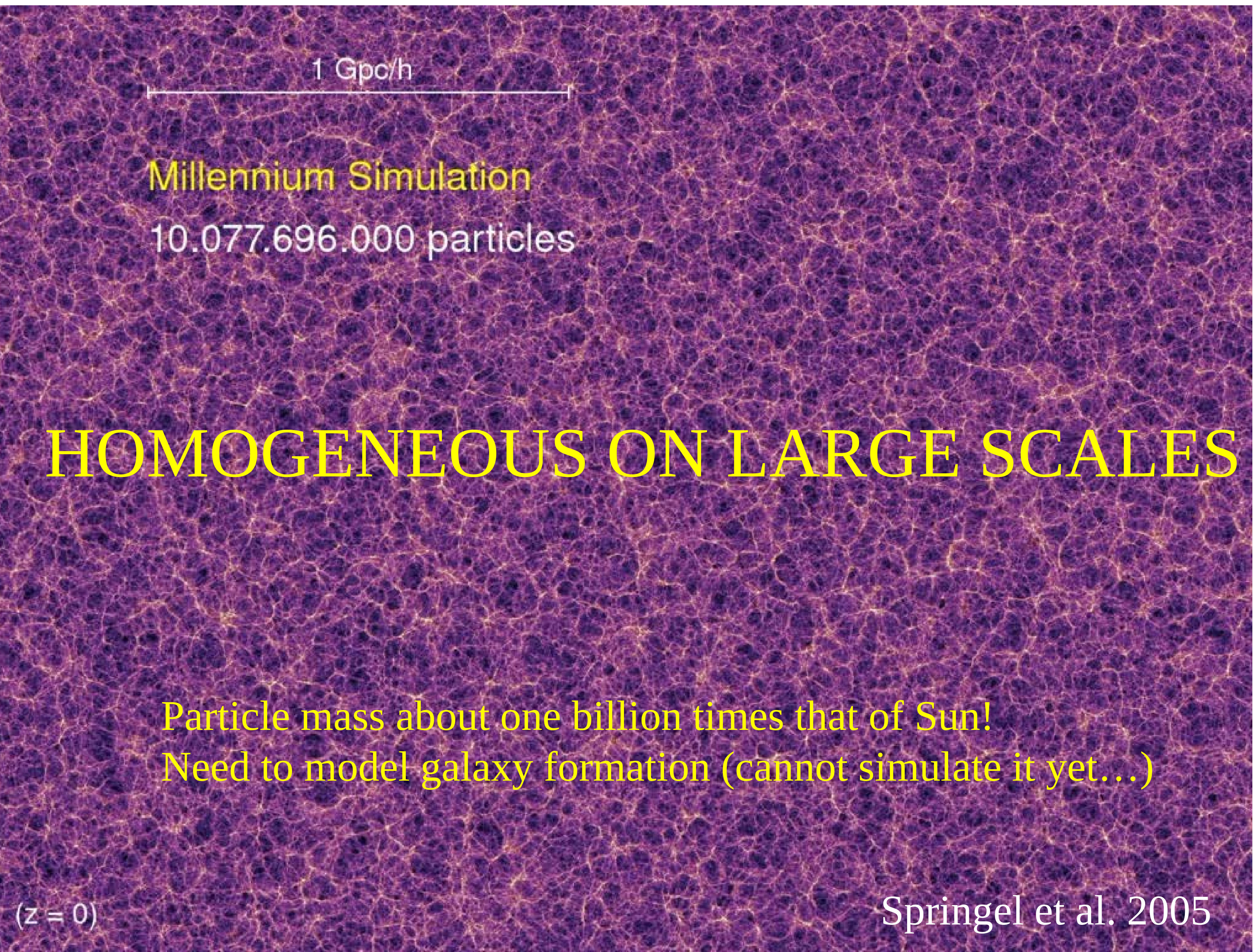
Mapping expansion history: Baryon Acoustic Oscillation signal in galaxy distribution


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)


125 Mpc/h
z=0 (t=13.6Gyr)



HOMOGENEOUS ON LARGE SCALES

Particle mass about one billion times that of Sun!
Need to model galaxy formation (cannot simulate it yet…)

Springel et al. 2005

Cold Dark Matter

Cold: speeds are non-relativistic

To illustrate, 1000 km/s $\times$10Gyr $\approx$ 10Mpc

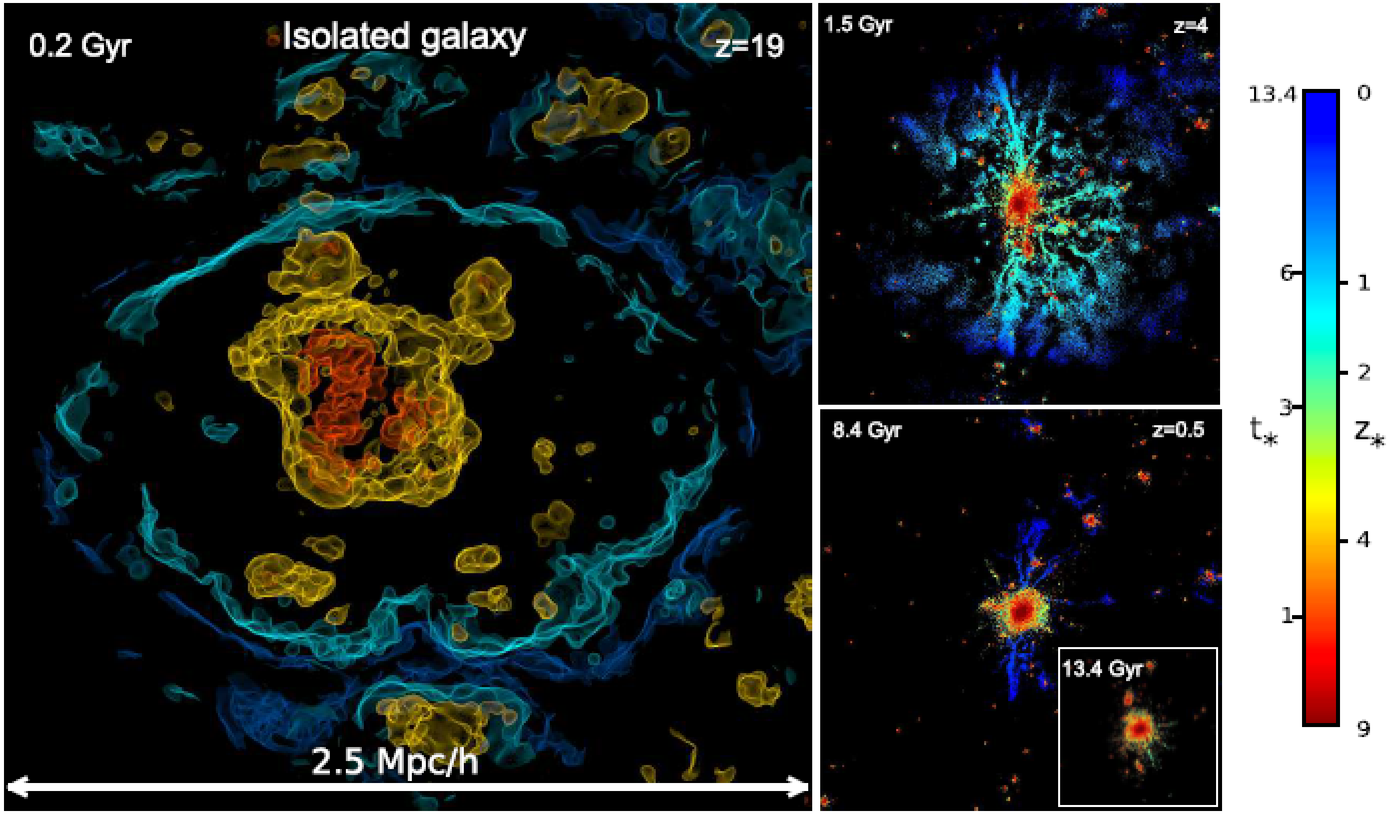
From z~1000 to present, nothing (except photons!) travels more than ~ 10Mpc

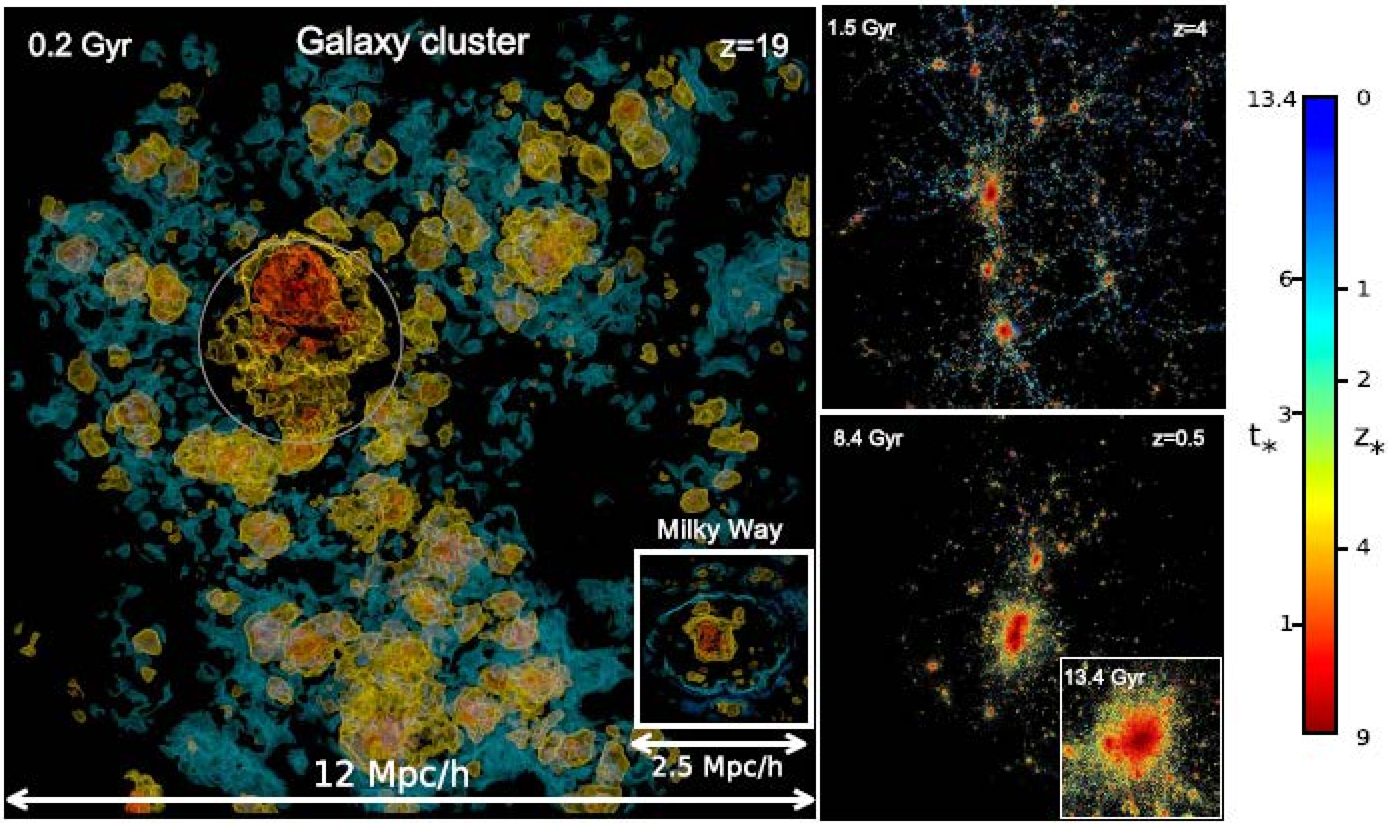
Dark: no idea (yet) when/where the stars light-up

Matter: gravity the dominant interaction

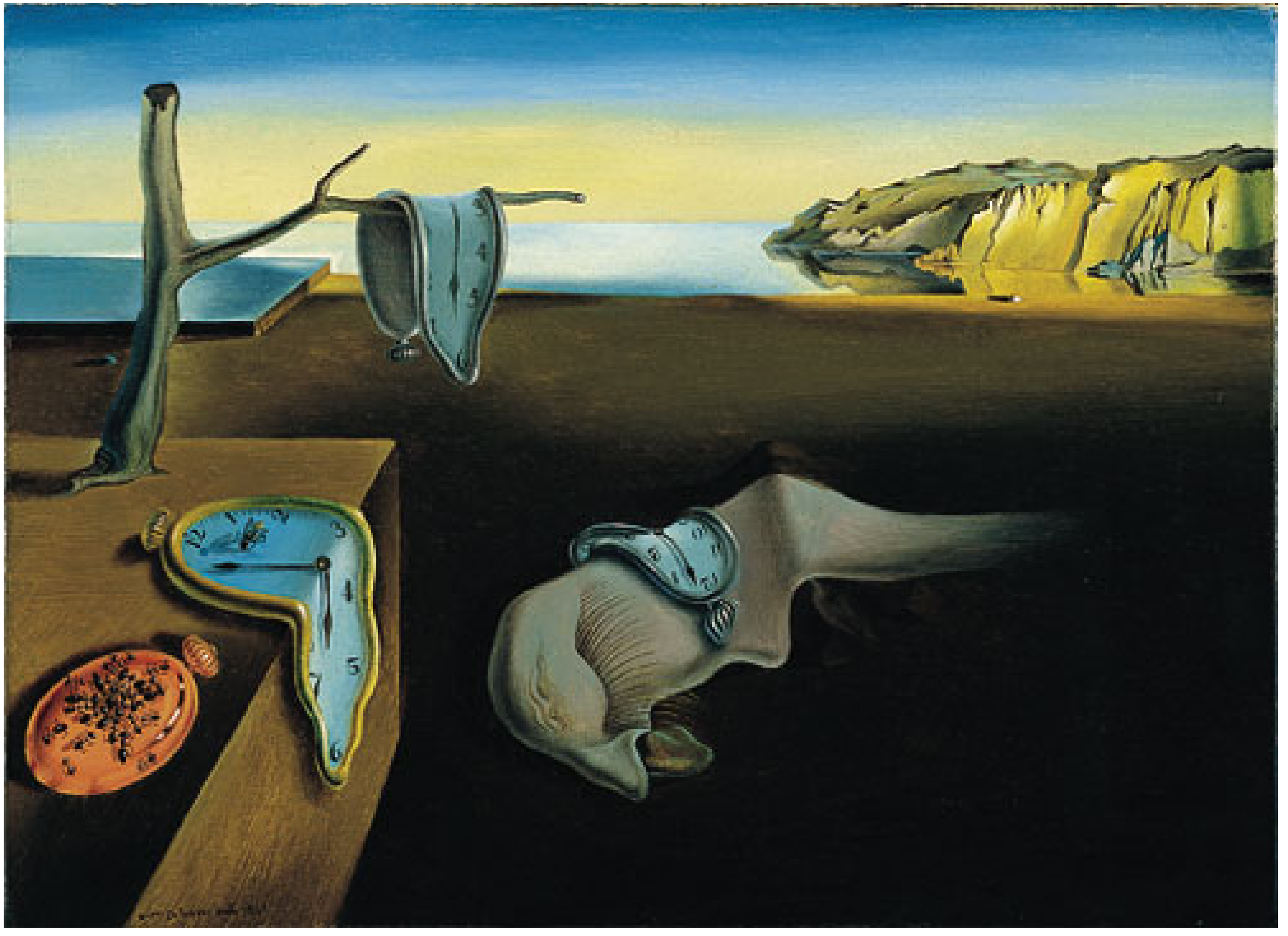
Late-time field retains memory of initial conditions

Gastrophysics also local

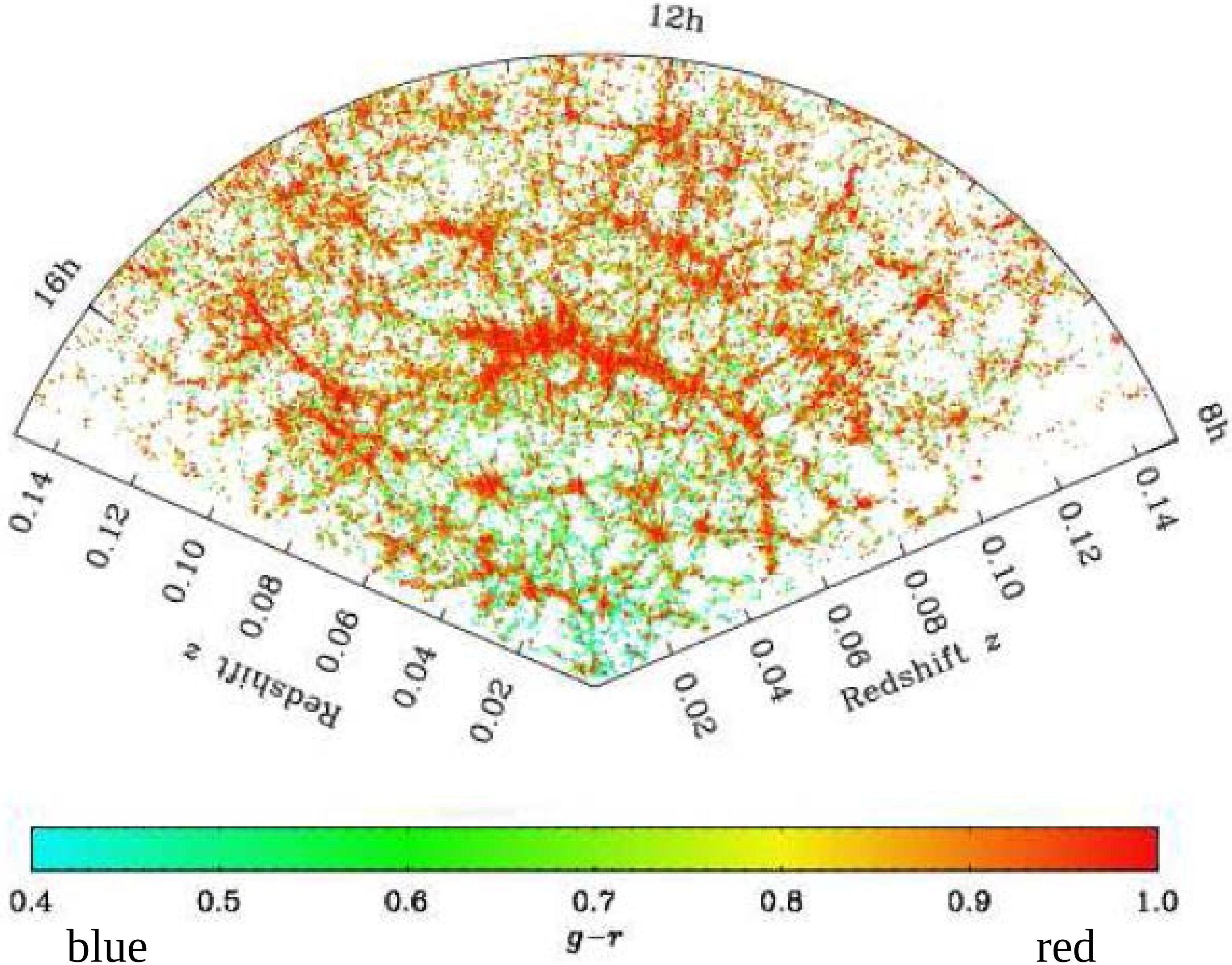



0.2 Gyr
Galaxy cluster
z=19
Milky Way
2.5 Mpc/h
12 Mpc/h
1.5 Gyr
z=4
8.4 Gyr
z=0.5
13.4 Gyr
13.4
6
3
1
t_*
0
1
2
4
9
Z_*

Hierarchical clustering in GR

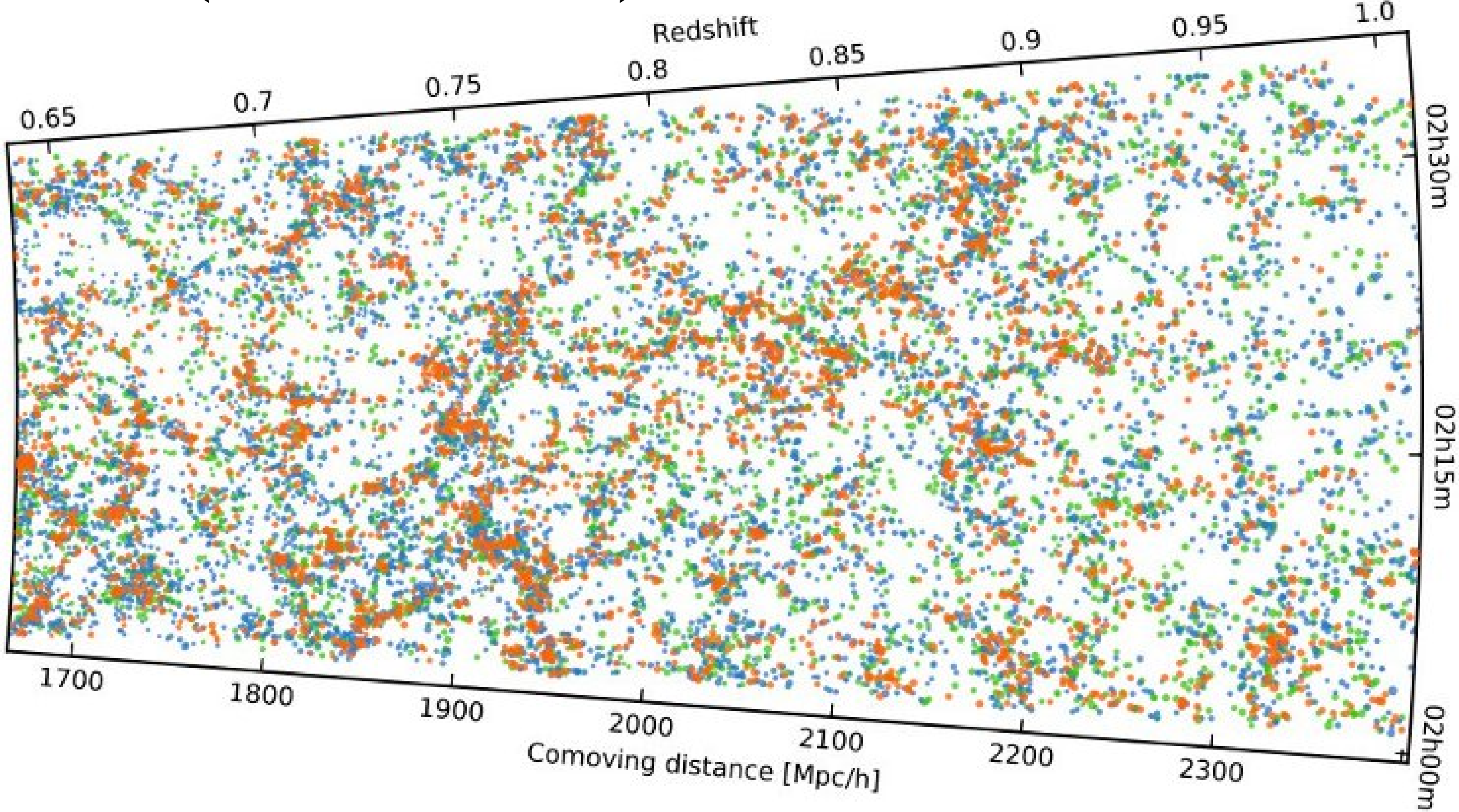


= the persistence of memory

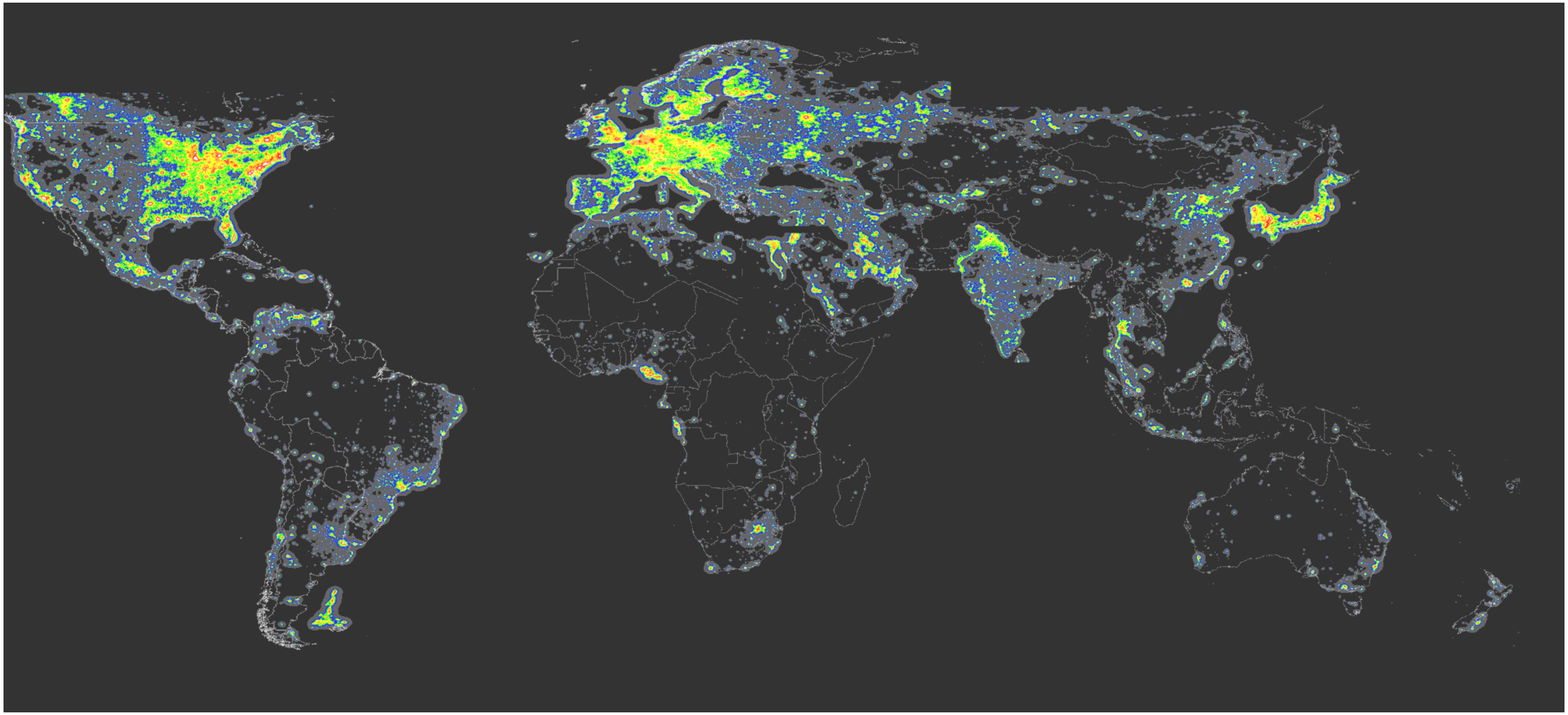


SDSS: Zehavi et al. 2011

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’

Biased standard lore

Biased tracers, such as galaxies, form in small-scale overdensities. Quantify bias by estimating $<\Delta|\delta_b>$.

In Gaussian field, $<\Delta|\delta_b> = \delta_b <\Delta\delta>/<\delta\delta>$
- multiplicative factor $b = \delta_b /<\delta\delta>$ times $<\Delta\delta>$
- bias larger for massive objects

Bias affects amplitude but not shape/scale dependence of correlation signal

(For Gaussian initial conditions) bias is ‘linear’ ‘scale-independent’

Standard lore

-Galaxy formation surely more complicated

-This will complicate bias: $<\Delta|\delta_b\ ,\ \delta_b'\ ,\ \mathrm{shear}_b\ \ldots >$

-Expect these involve derivatives (e.g., if galaxies form in small scale peaks in the density field)

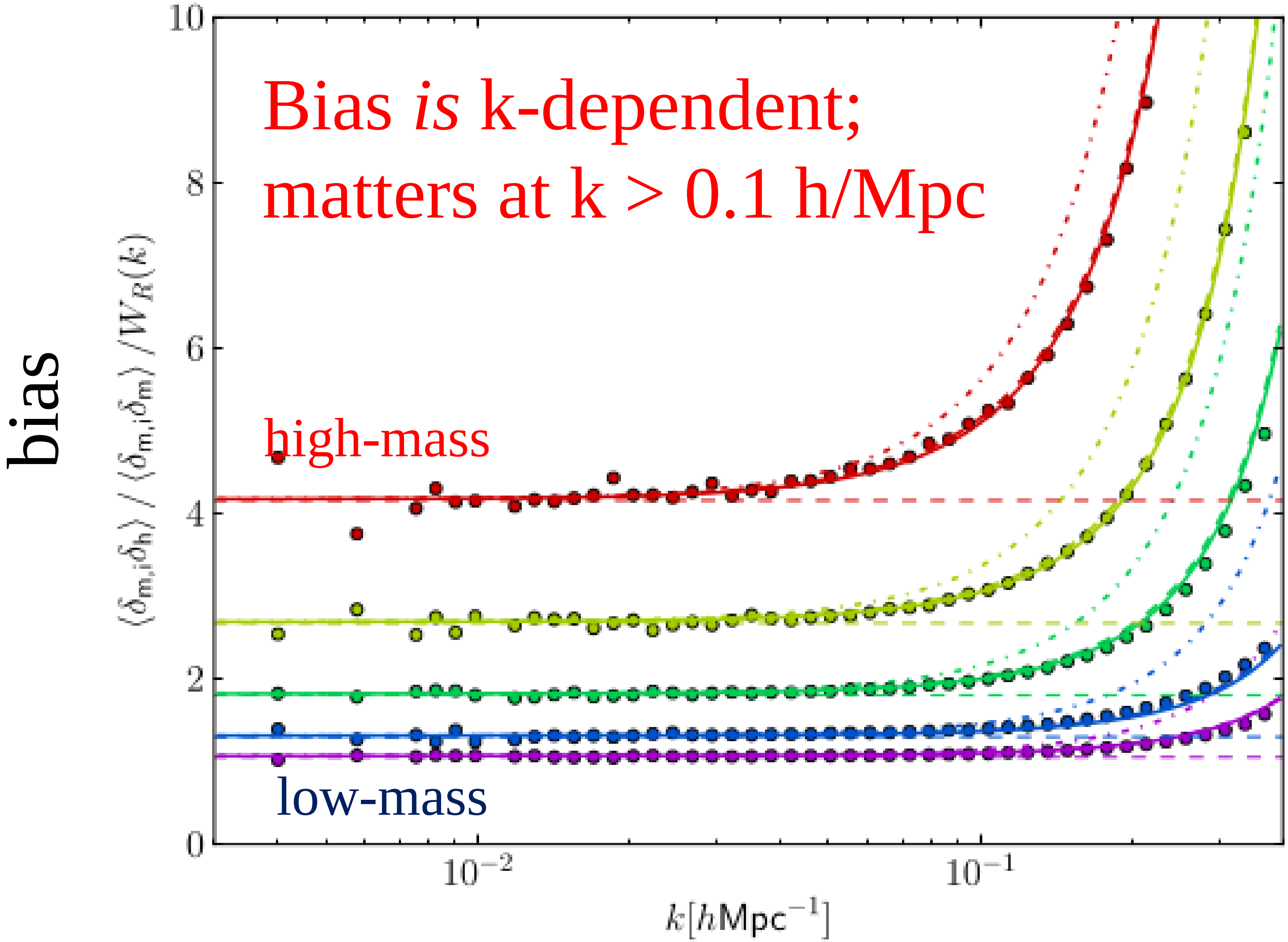
-So bias will be k-dependent

-Isotropy: leading order is $\mathrm{bias}(k) = b_{10} + b_{01}\,k^2$

-This is generic

-Modifications to GR also lead to k^2 corrections

(For Gaussian initial conditions) bias is ‘linear’ ‘scale-independent’ at small k (on large-scales)



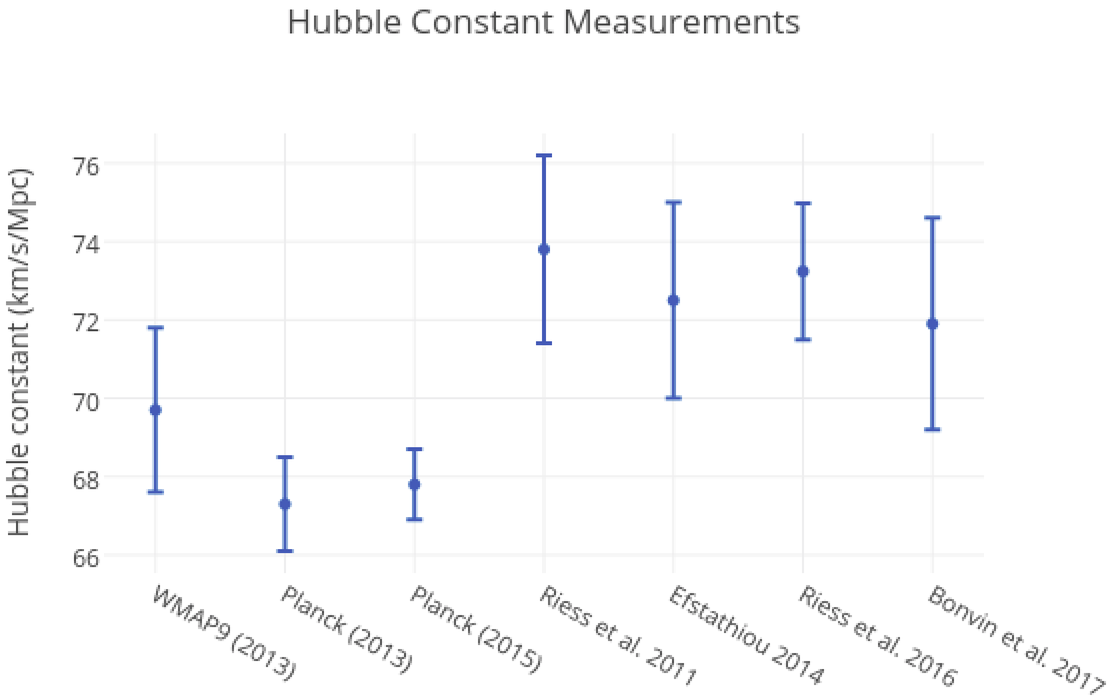
Baldauf, Desjacques, Seljak (2015)

Galaxy surveys to test GR

Number of modes increases dramatically with k

Understanding k-dependence of bias lets one use many more modes to increase ‘reach’

Current tension in H_0



Would be nice to probe intermediate z

If this is new physics, would like probe to not be too tied to standard model

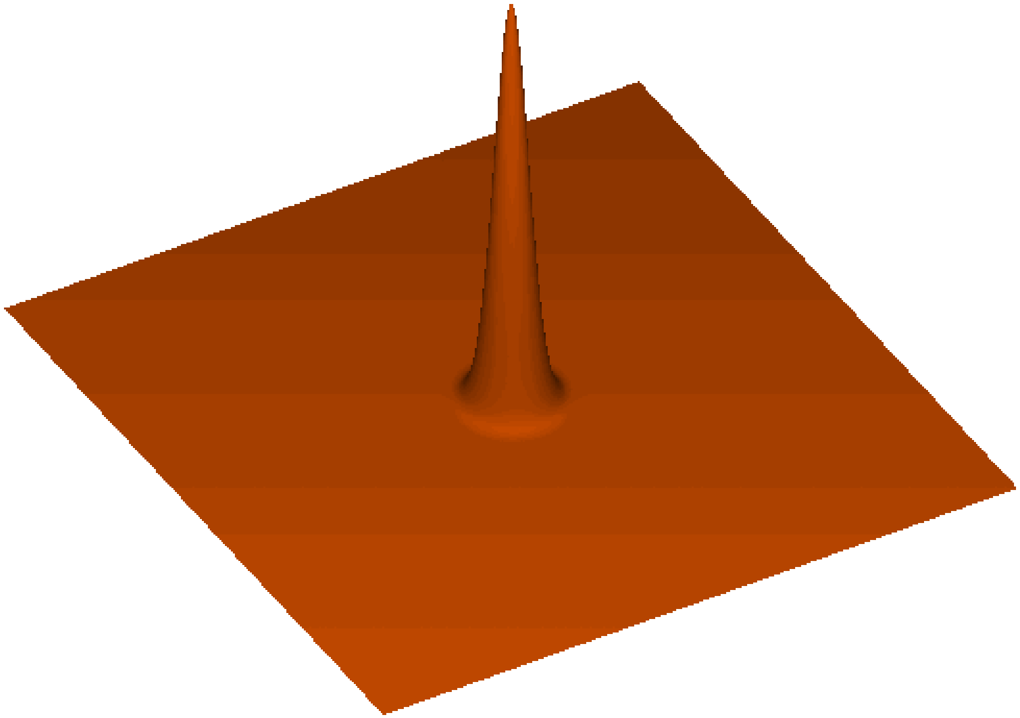
Cosmology from the same physics imprinted in the galaxy distribution at different redshifts:

Baryon Acoustic Oscillations

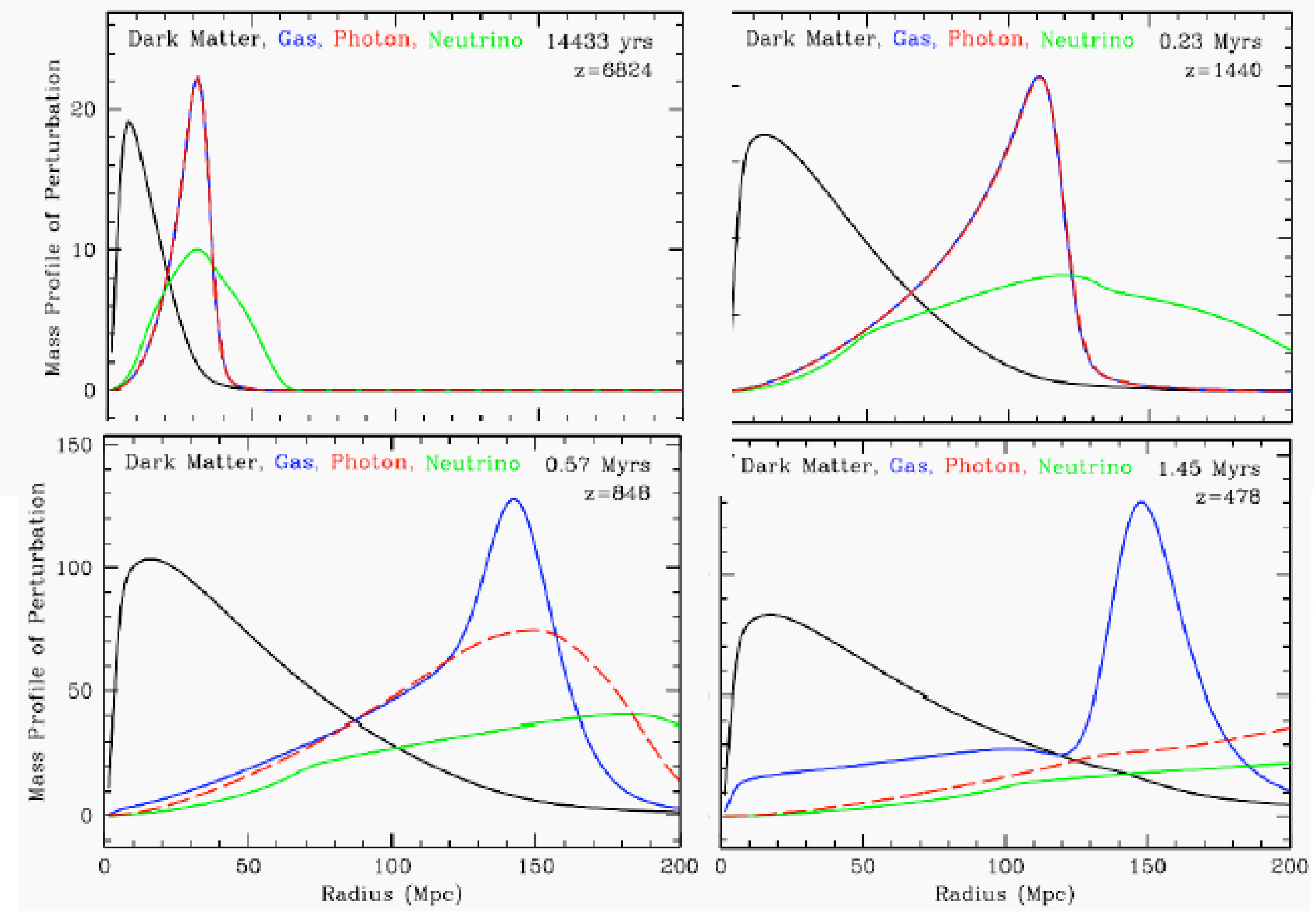
CMB from interaction between photons and baryons when Universe was 3,000 degrees (about 300,000 years old)

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

Photons 'drag' baryons for ~400,000 years (time set by $\Omega_m h^2$) at speed ~ $c/[3(1 + 3\rho_b/4\rho_\gamma)]^{½}$ (set by $\Omega_b h^2$) …
300,000 light years ~ 100,000 pc ~ 100 kpc

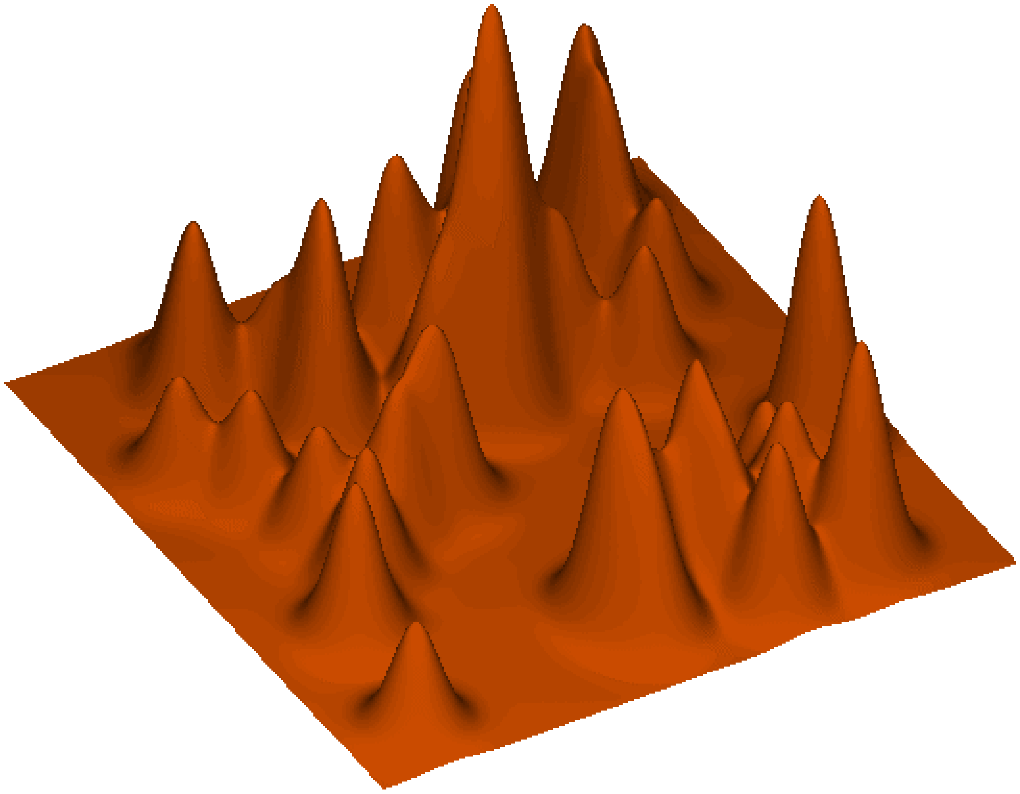


Expansion of Universe since then stretches this to (3000/2.725) ×100 kpc ~ 100 Mpc



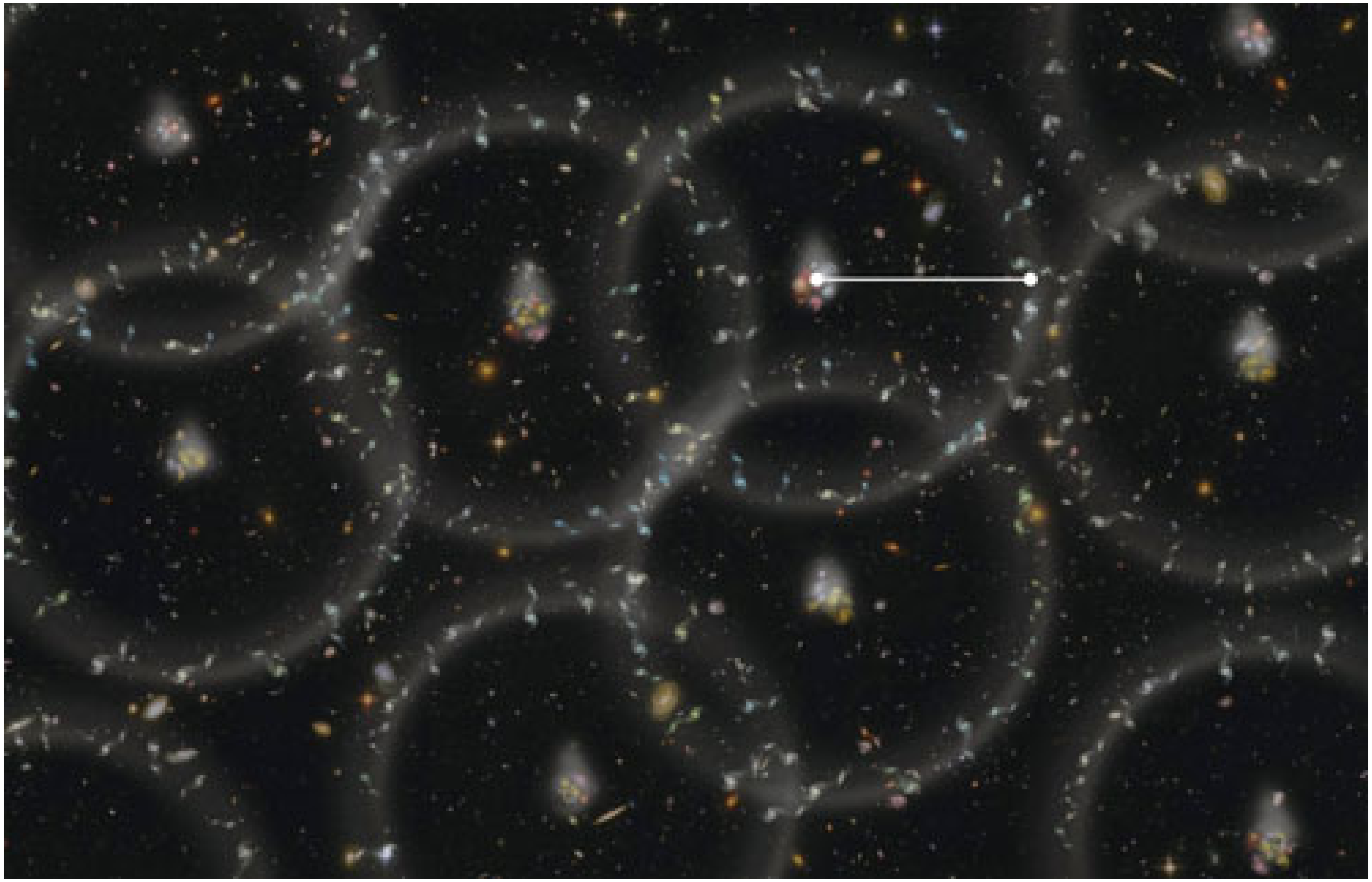
Eisenstein, Seo, White 2007

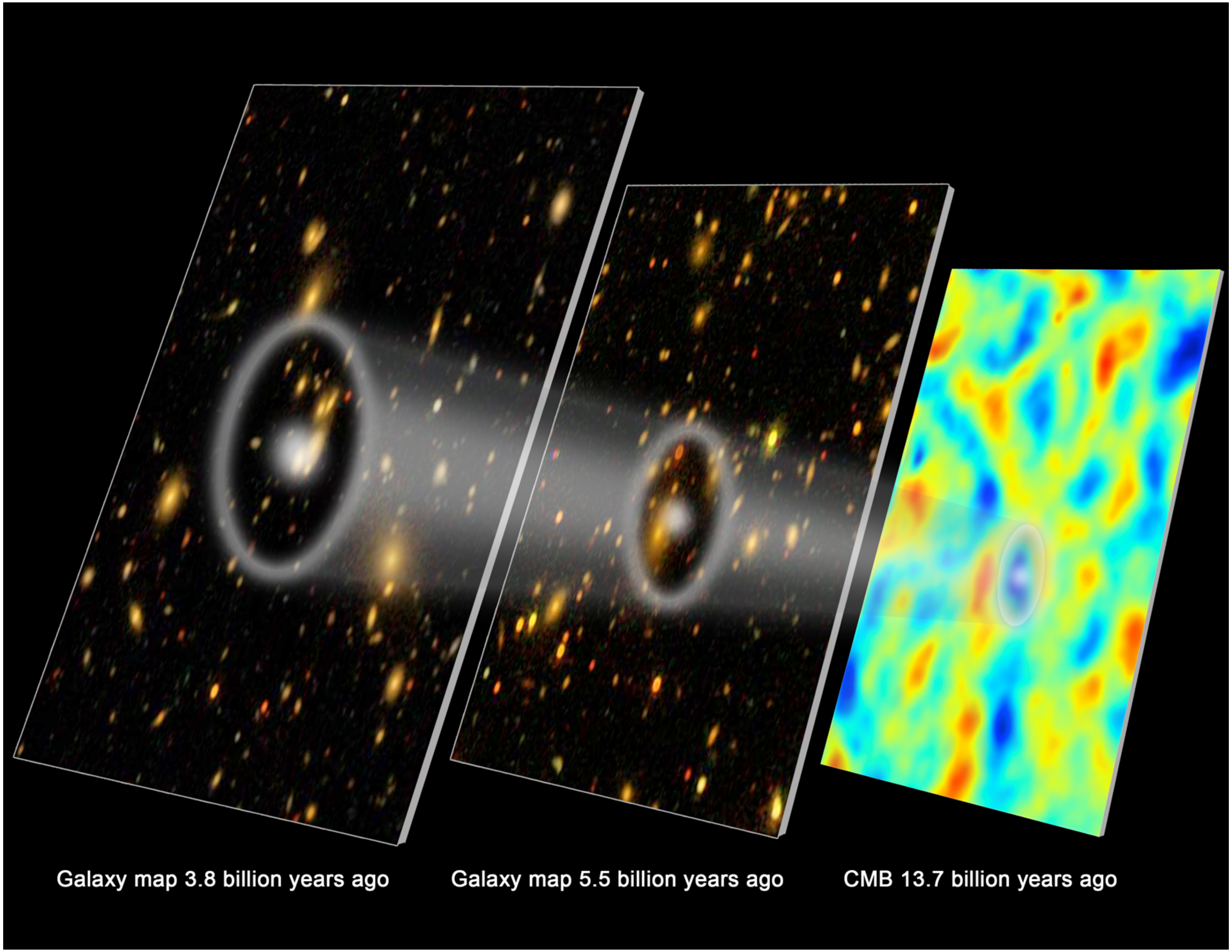
Expect to see a feature in the Baryon distribution on scales of 100 Mpc today



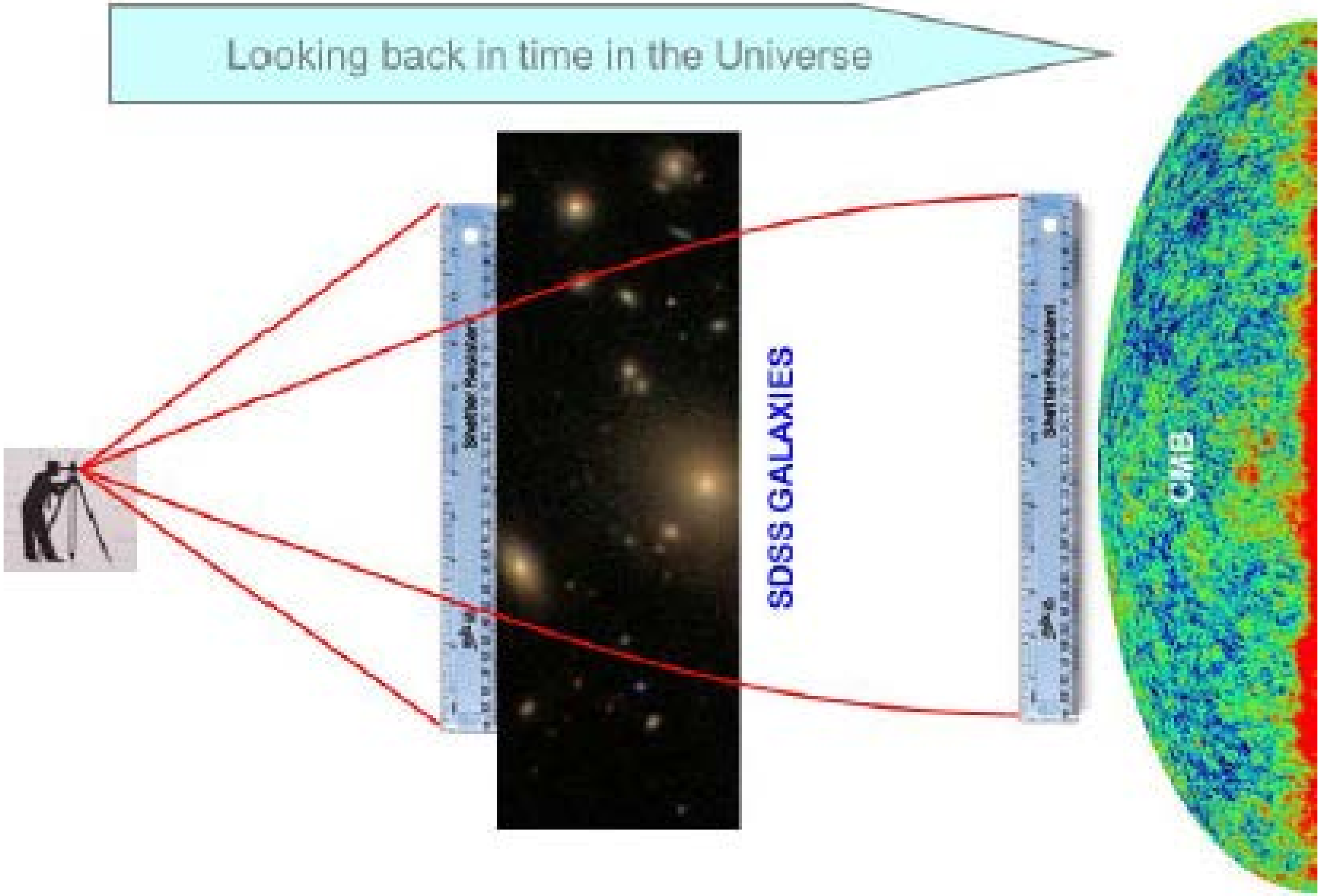
But this feature is like a standard rod:
We see it in the CMB itself at z~1000;
should see it in galaxy distribution at other z

Cartoon of expected effect

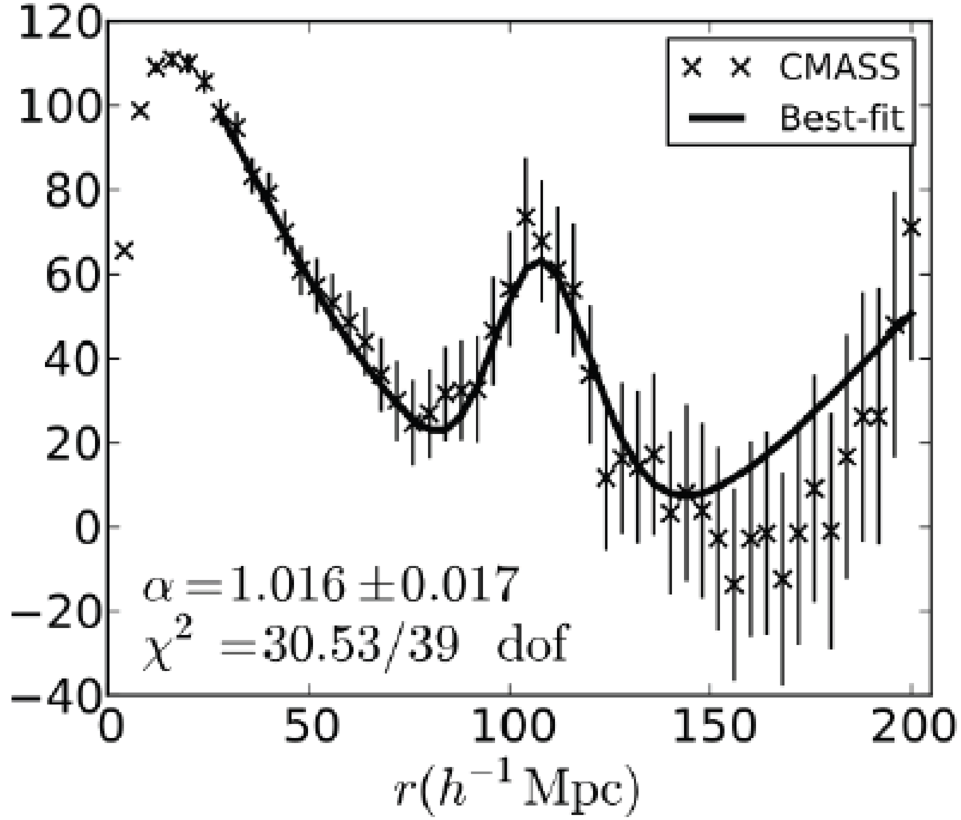


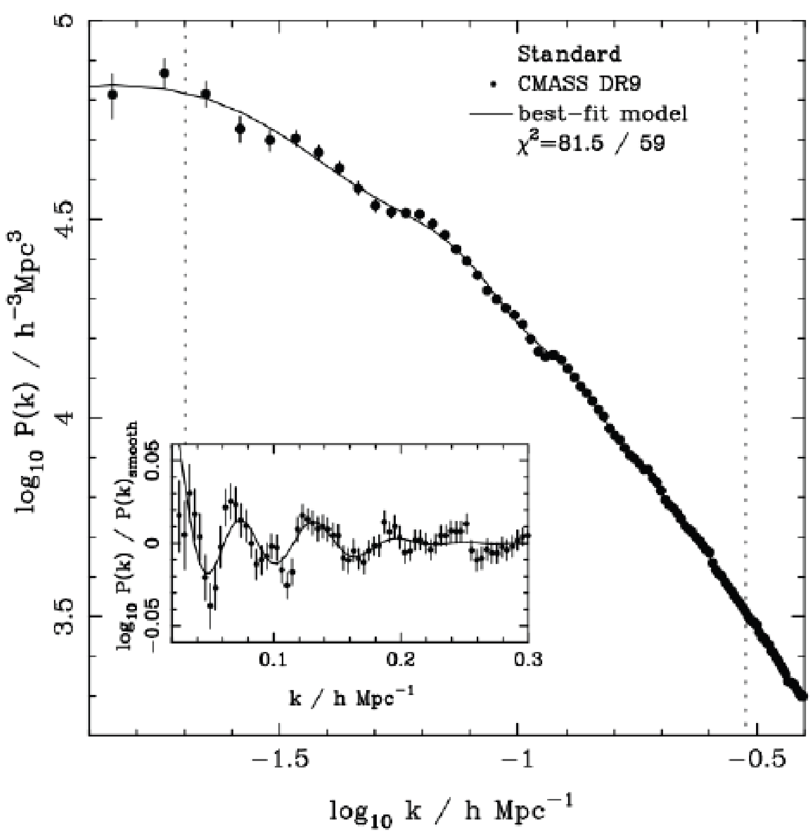

Galaxy map 3.8 billion years ago
Galaxy map 5.5 billion years ago
CMB 13.7 billion years ago

Baryon Oscillations in the Galaxy Distribution



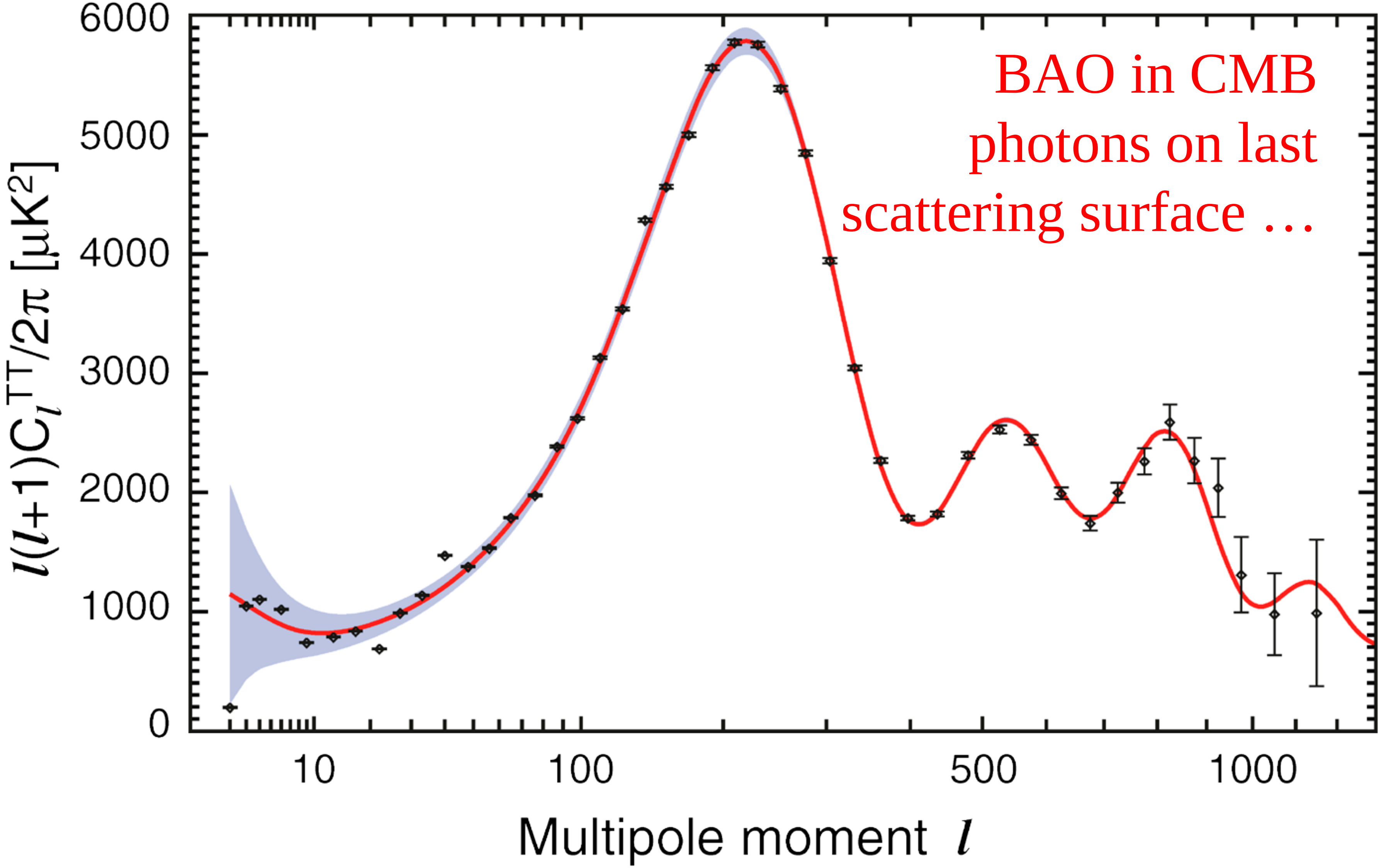
Spike in real space $\xi(r)$ means $\sin(kr_{BAO})/kr_{BAO}$ oscillations in Fourier space P(k)



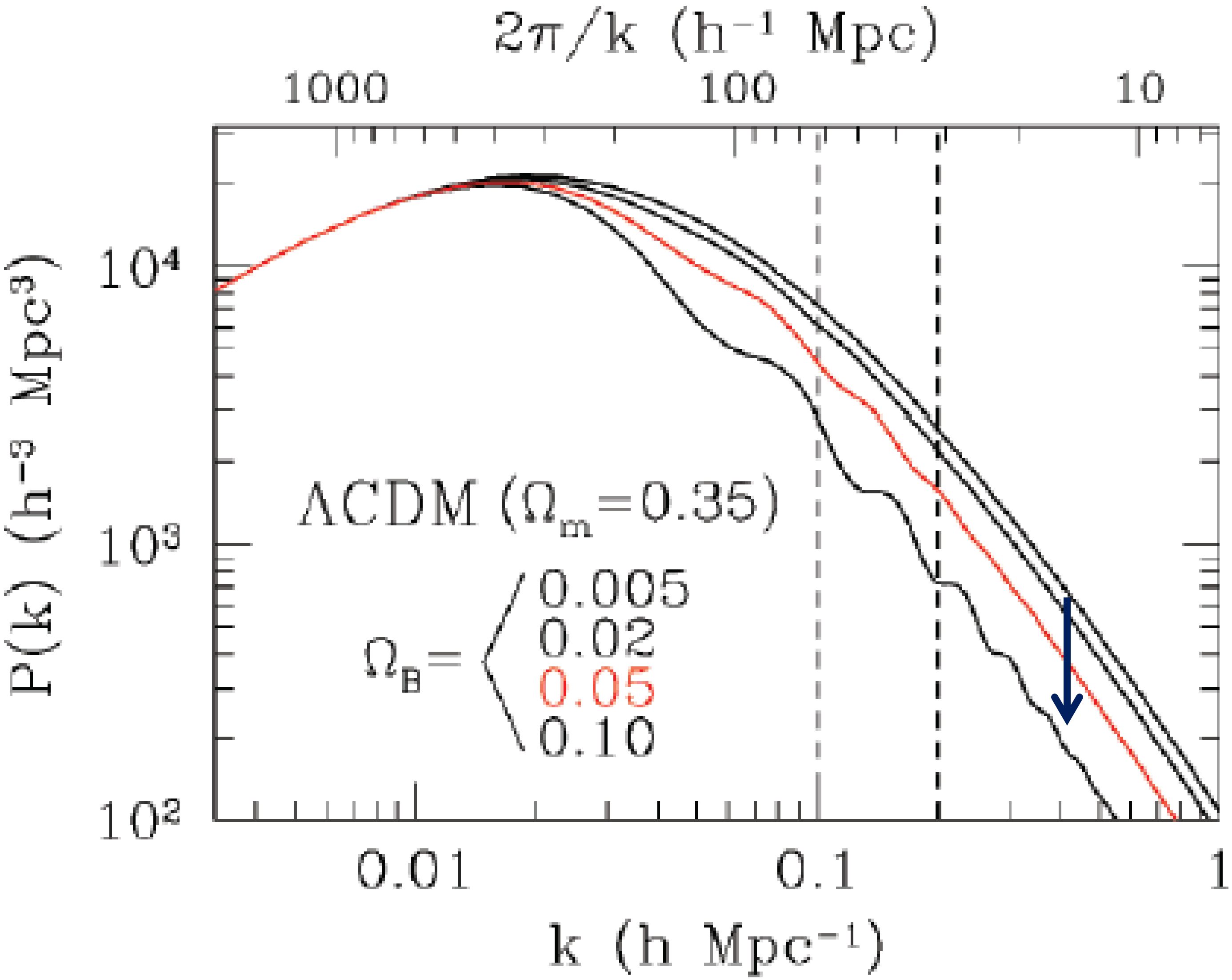


In fact, spike is not delta function because photons-baryons not perfectly coupled and last scattering not instantaneous:

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



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

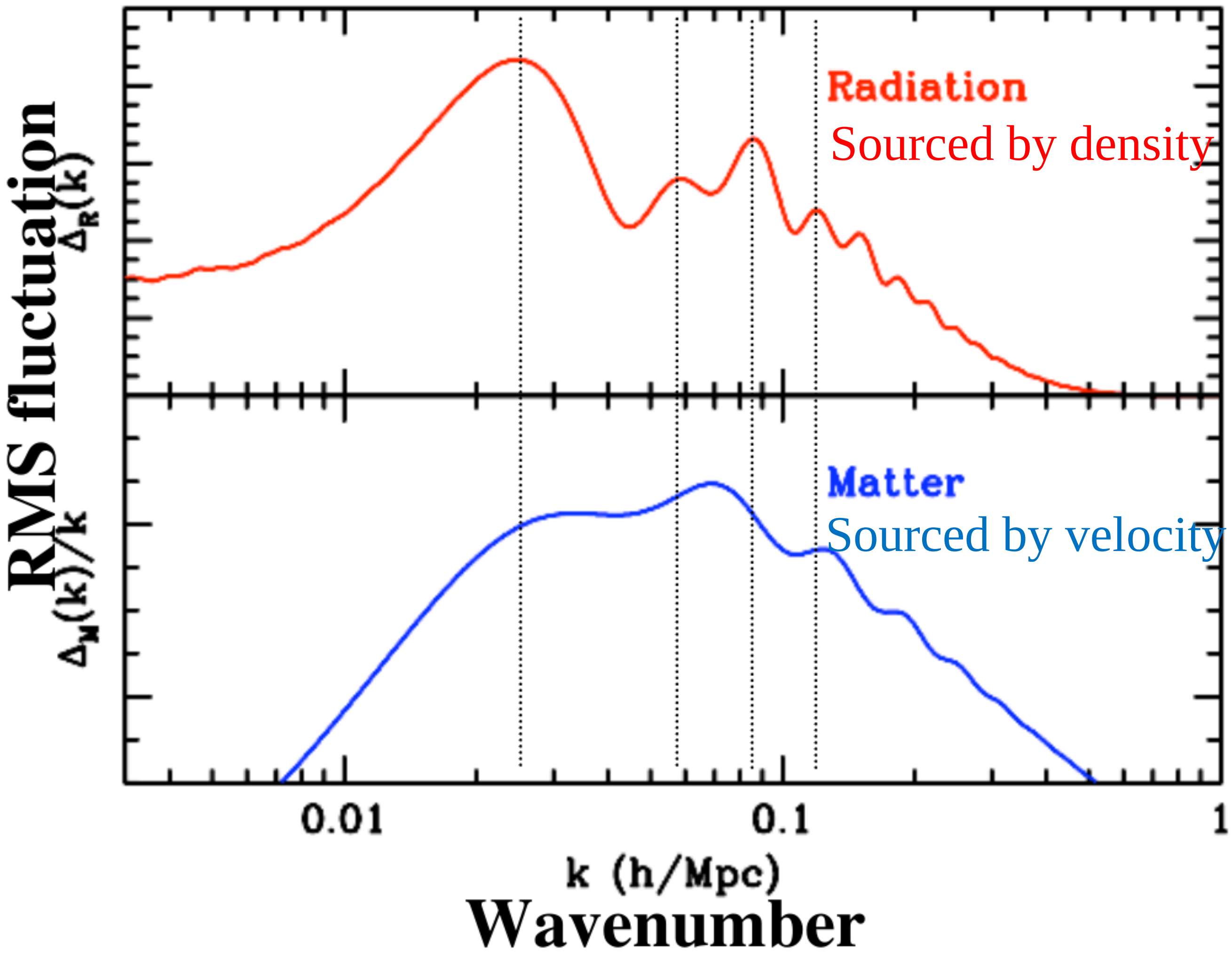


If all matter baryonic, power below 200 Mpc/h is suppressed

Need nonbaryonic gravitating dark matter to explain structure formation

… should/are seen in matter distribution at later times

Baryon oscillations in matter smaller than in photons by factor of Ω_b / Ω_m.

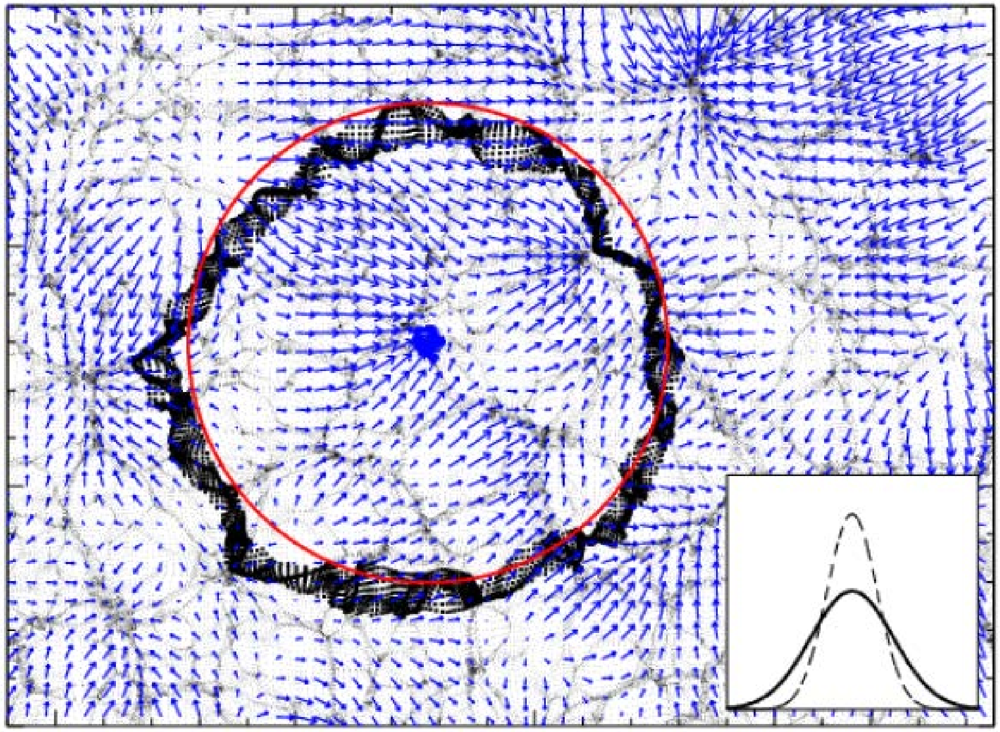


We need a tracer of the baryons

- 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!

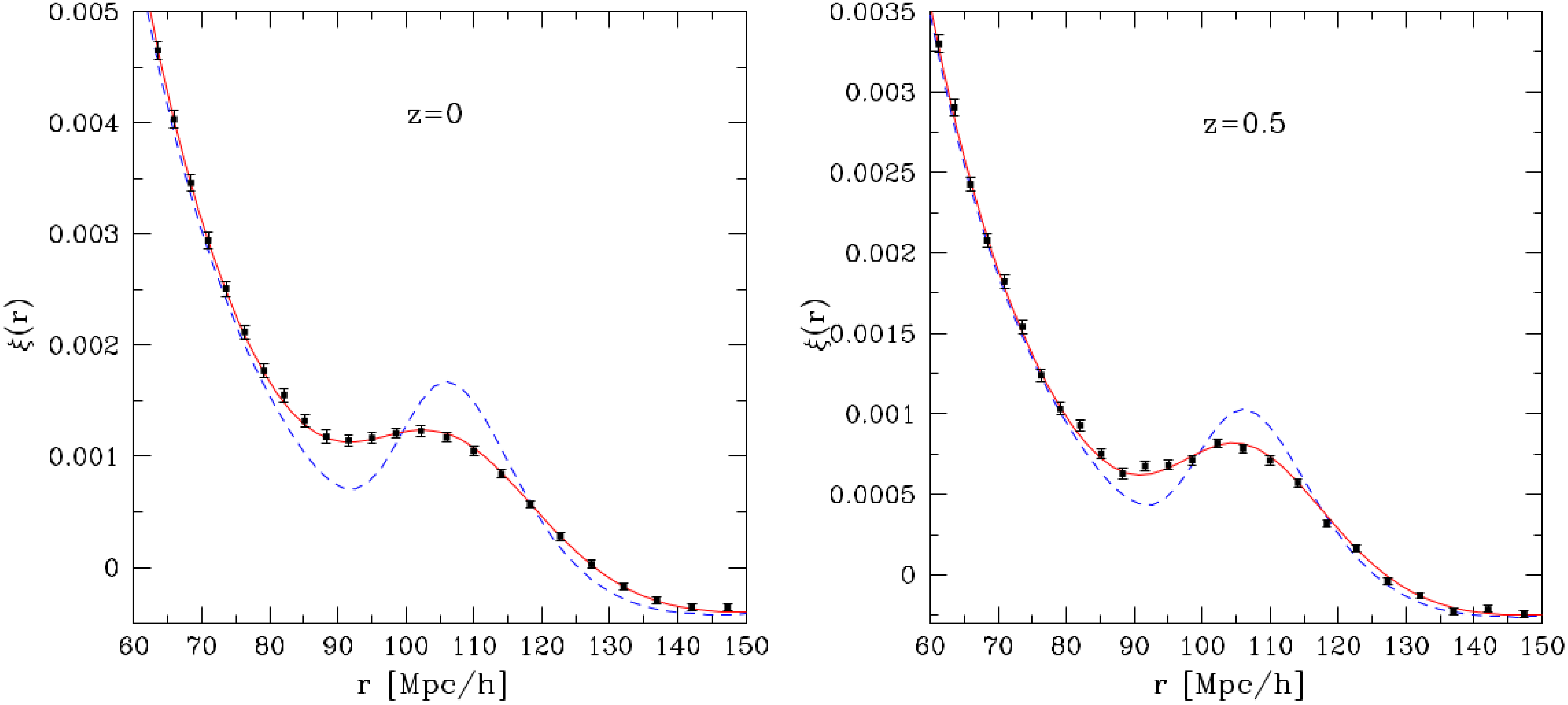
Although length 'not' affected, BAO 'peak' is smeared out (Bharadwaj 1996)

$x = q + S(t|q)$
S is shift from initial to final position. It is speed x time ~ Gaussian random number with rms ~7 Mpc



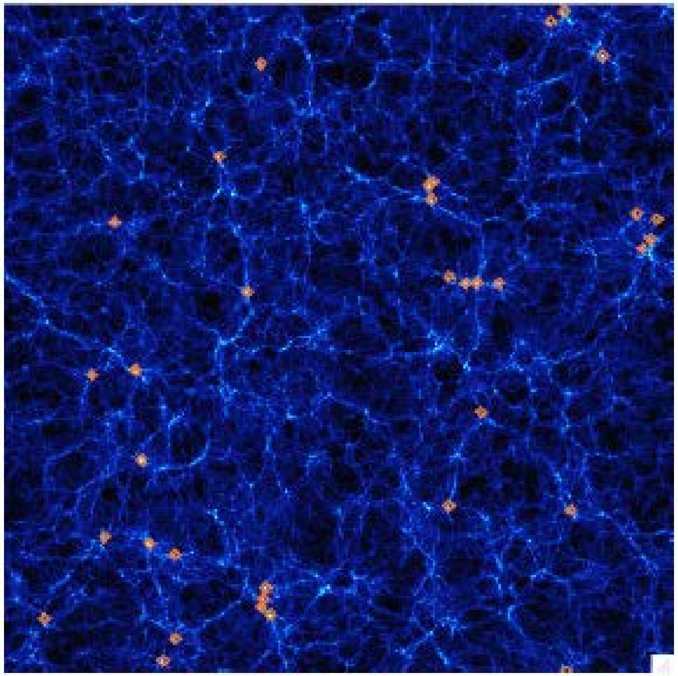
Padmanabhan et al. 2012

Smearing of BAO peak is dramatic

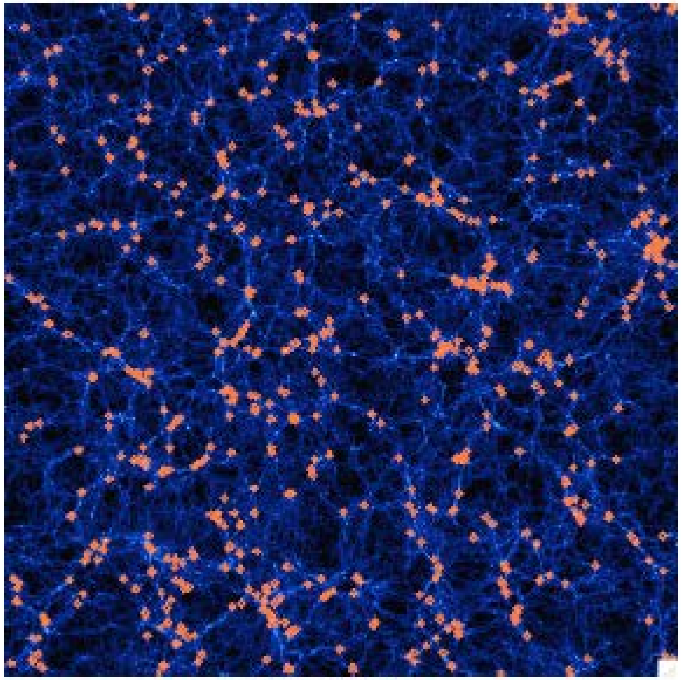


Crocce & Scoccimarro 2008

The cosmic web at z~0.5, as traced by luminous red galaxies



SDSS

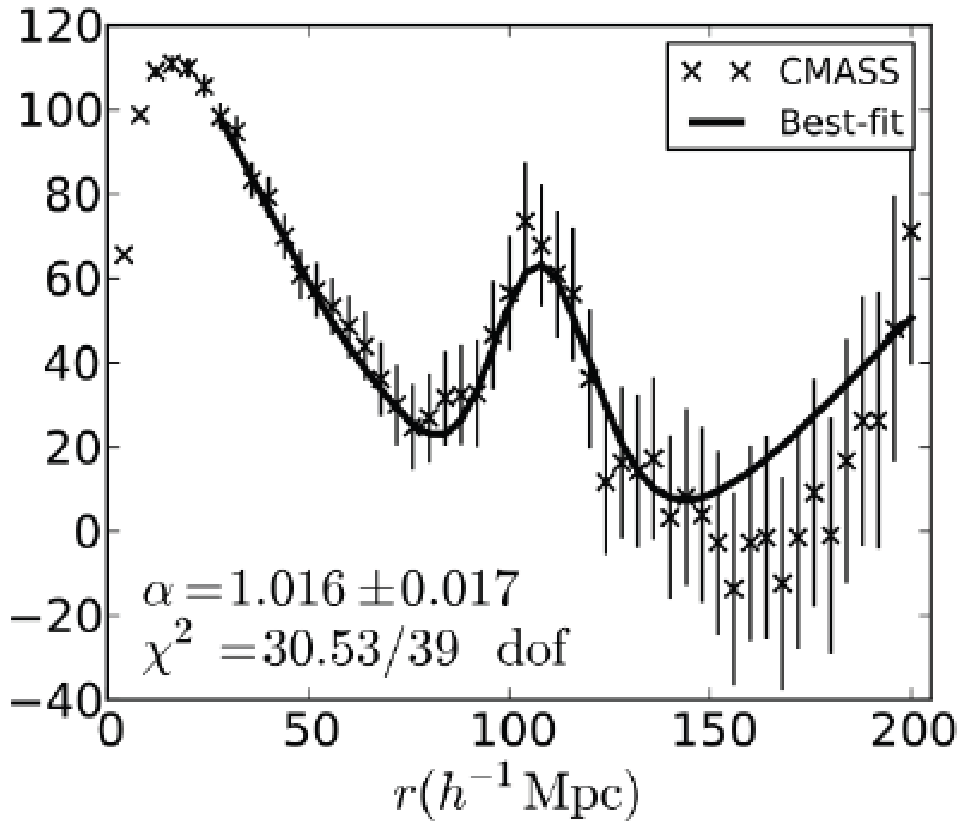


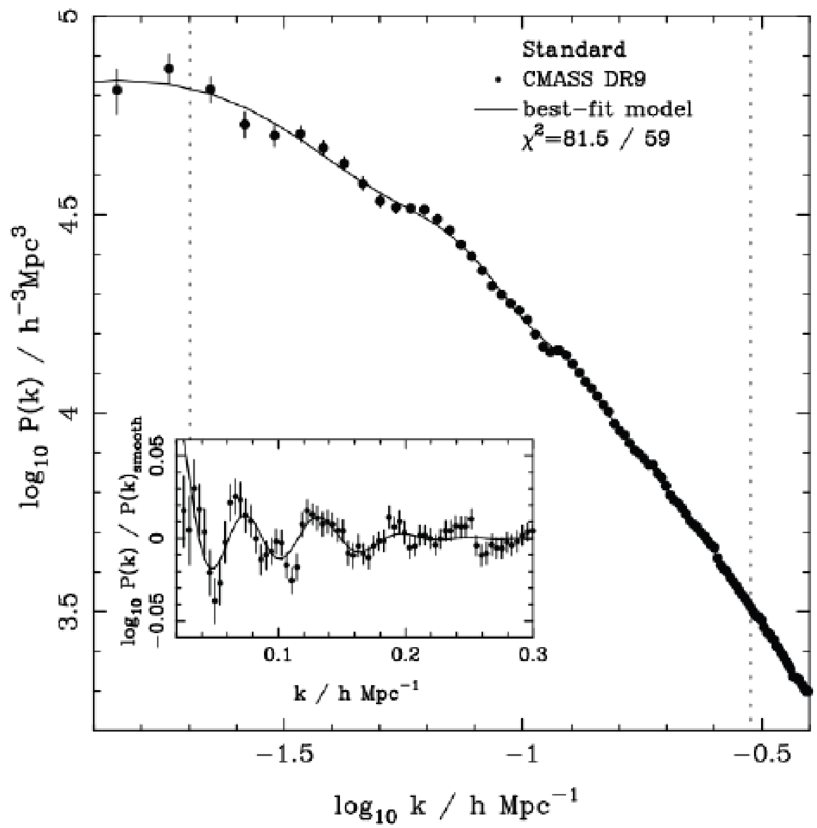
BOSS

(M. White 2010)

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

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

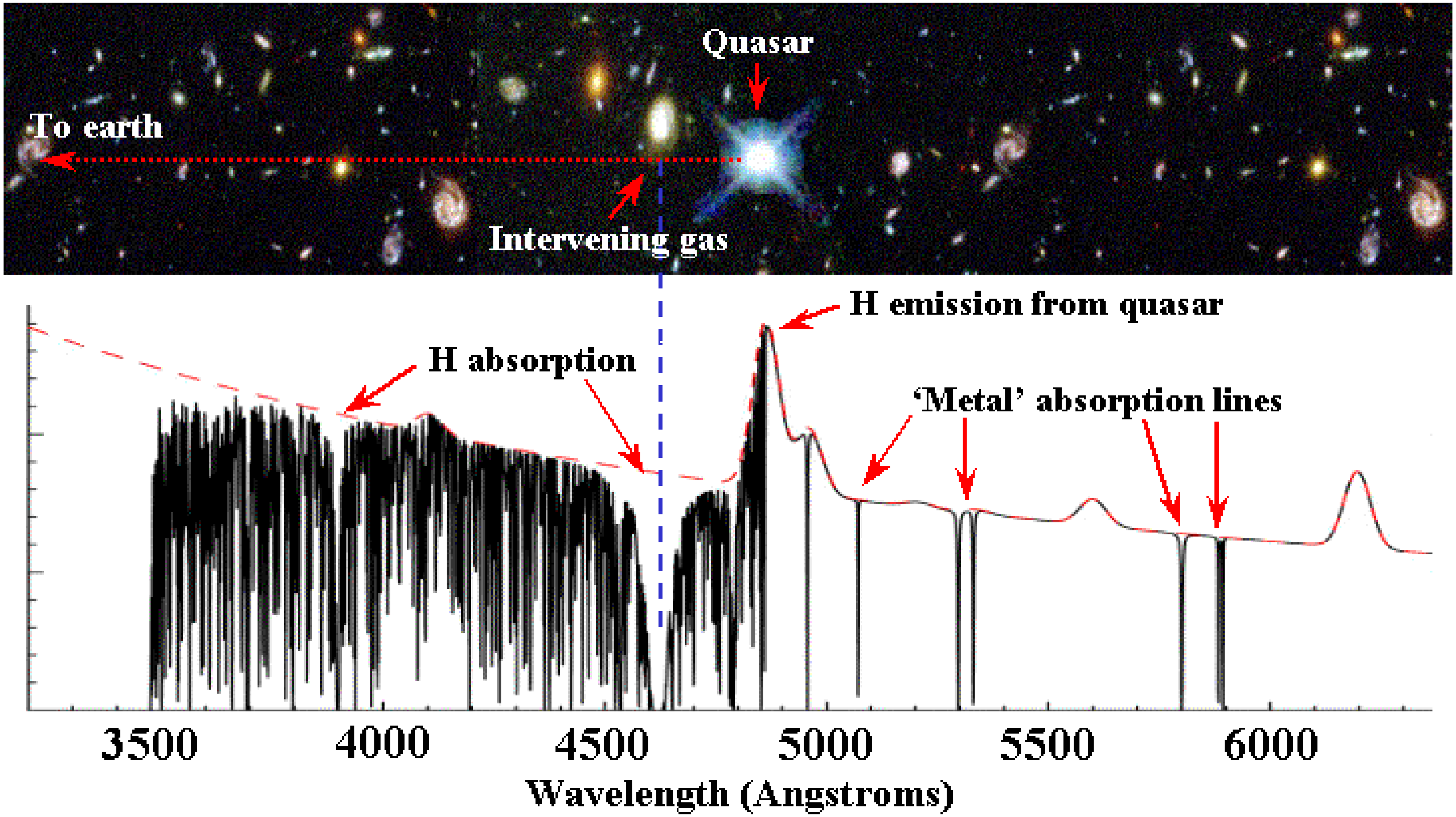




In fact, spike is not delta function because photons-baryons not perfectly coupled and last scattering not instantaneous:

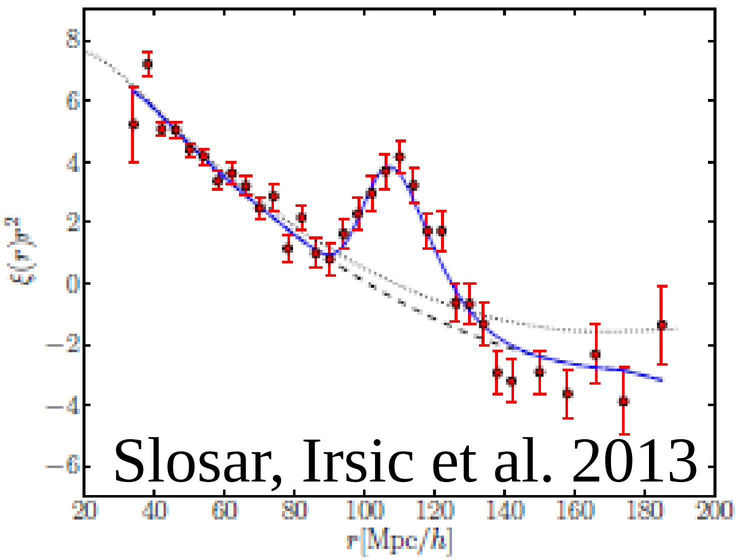
$e^{-(k/k_{Silk})^{1.4}} \sin(kr_{BAO})/kr_{BAO}$

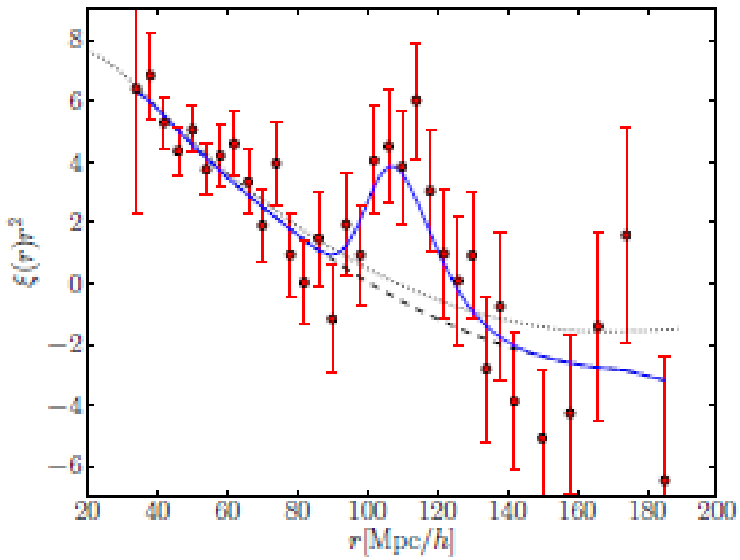
Can see baryons that are not in stars …



High redshift structures constrain neutrino mass

BAO in Ly-α forest at z~2.4





- Signal from cross-correlating different lines of sight

How to estimate the ‘scale’?

Position of peak not affected; height/width are

Noisy data = don’t differentiate measured $\xi(r)$!

Standard approach is to fit a model to $\xi(r)$ or $P(k)$ or to undo smearing ‘reconstruct’ and then fit a model

In either case, require cosmological template

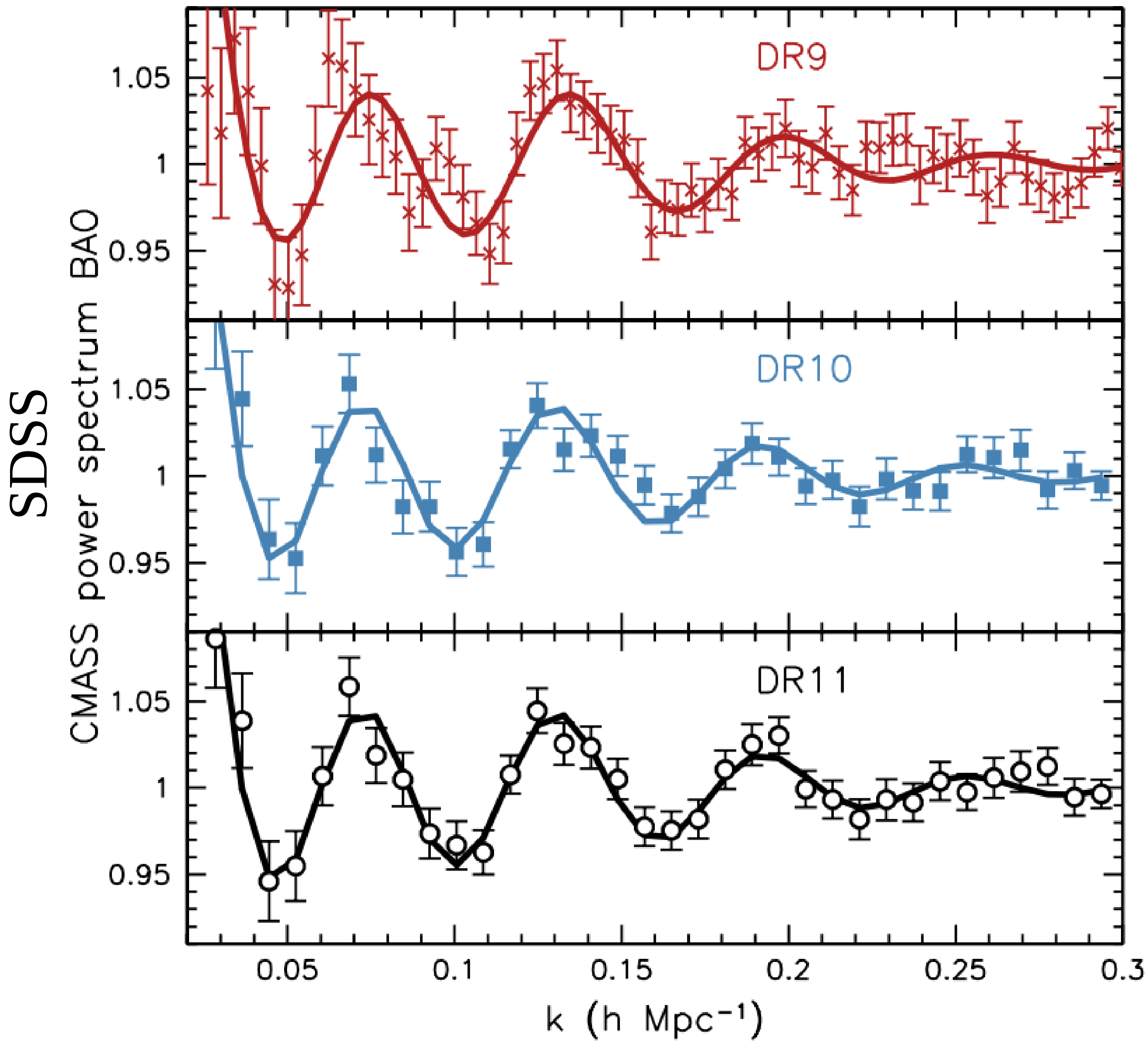
In addition, BAO feature involves two components of distance across line of sight, and one component along line of sight. So ‘average distance’ is:

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

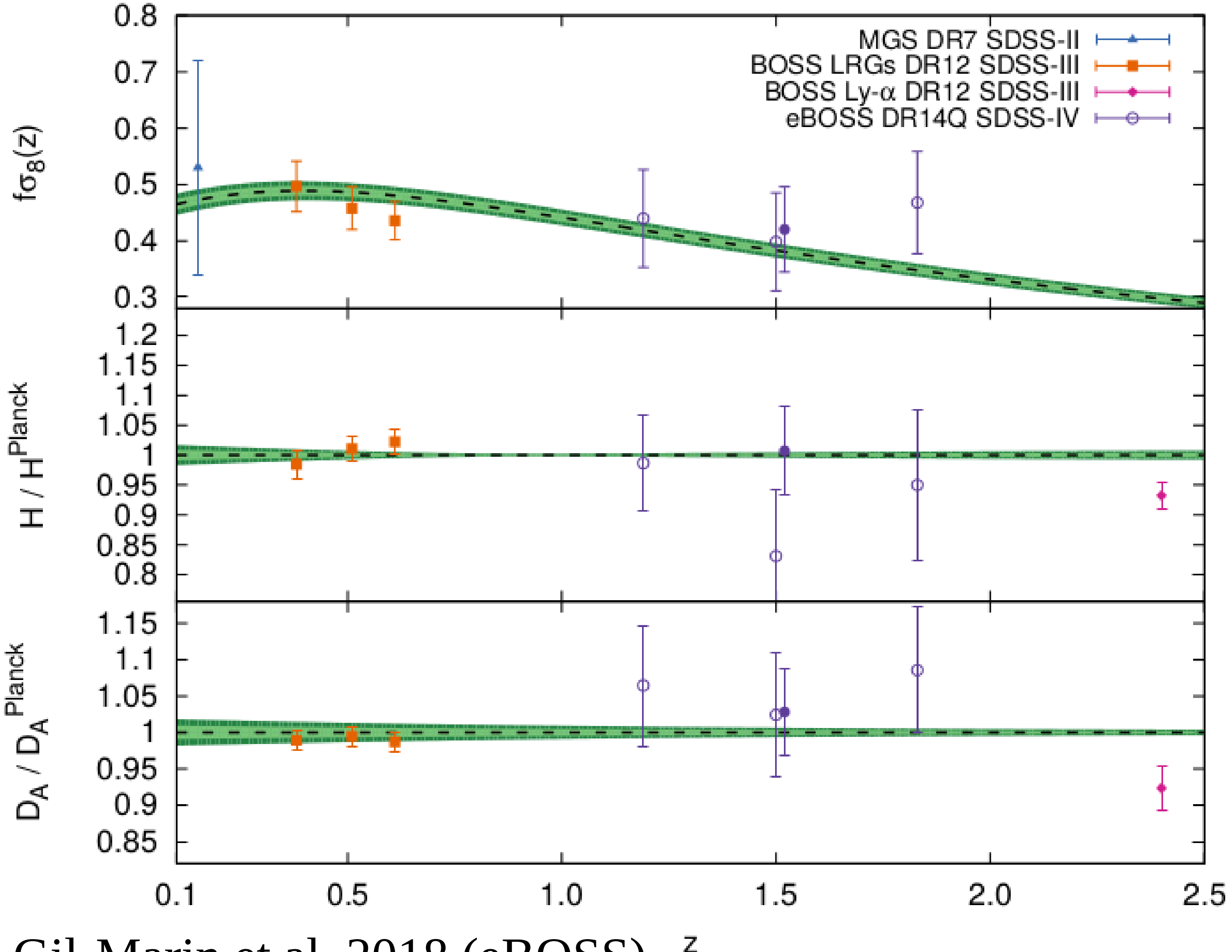
To convert measured angles/redshifts into comoving distances, one must assume a fiducial cosmology, and then ask if the BAO scale comes out to the expected one.

To convert measured angles/redshifts into comoving distances, one must assume a fiducial cosmology, and then ask if the BAO scale comes out to the expected one.

Usual analysis also assumes a fiducial cosmology to predict the shape of Pk. This shape is used to guide the estimate of the BAO scale. E.g., to better see the BAO, one might use it to remove a smooth component, leaving only the $j0(kr_{BAO})$ 'wiggles' to be fit.

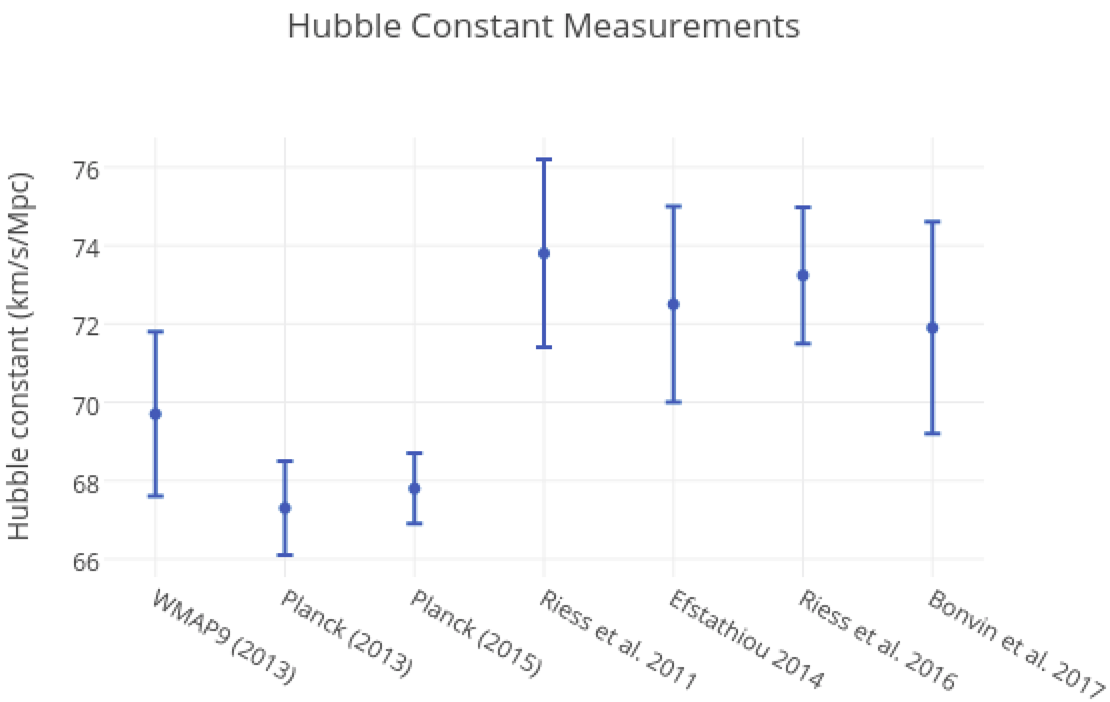


SDSS
CMASS power spectrum BAO
DR9
DR10
DR11
1.05
1
0.95
0.05
0.1
0.15
0.2
0.25
0.3
k (h Mpc⁻¹)



Gil-Marin et al. 2018 (eBOSS)

Current tension in H_0

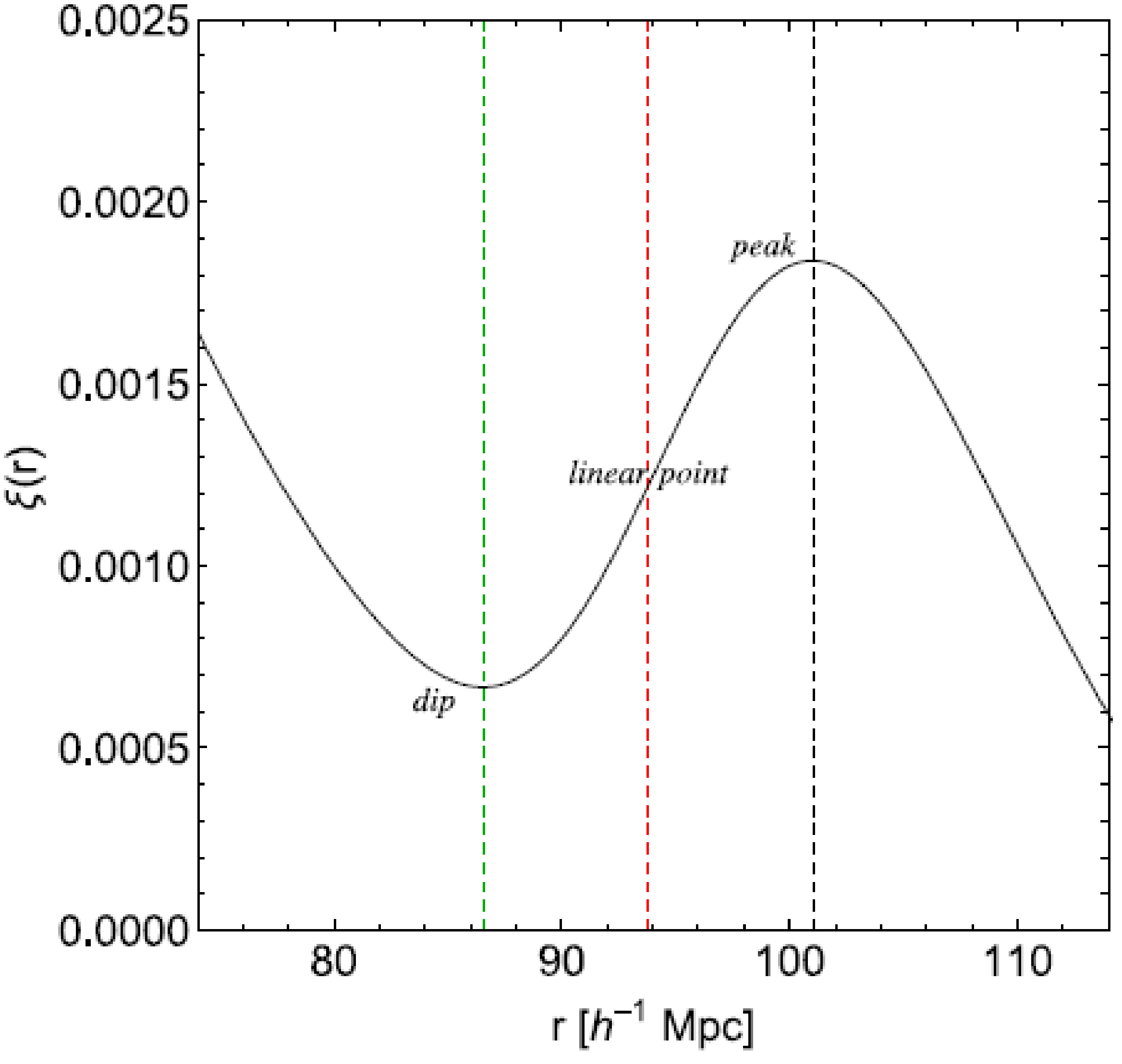


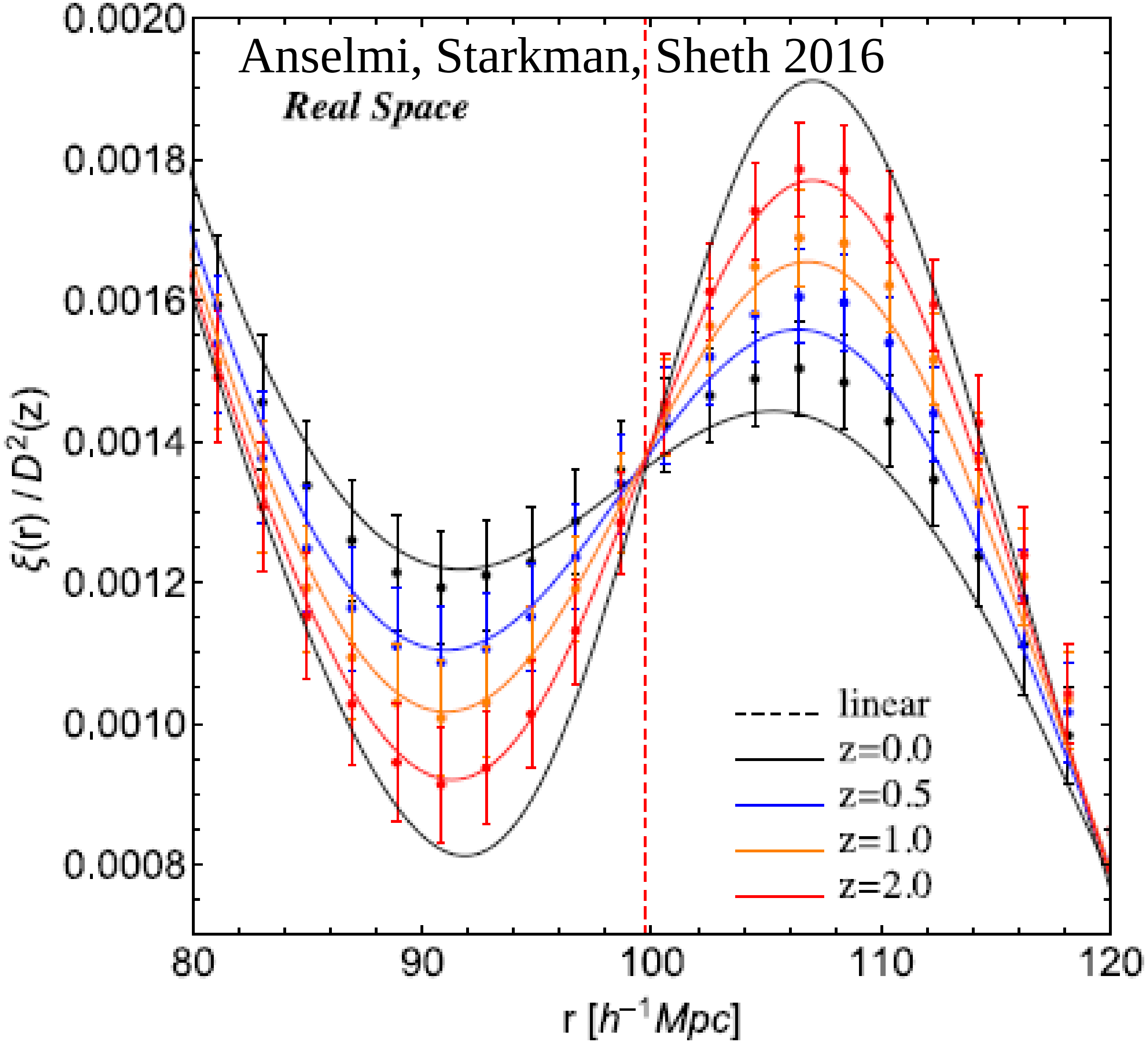
Would be nice to probe intermediate z

If this is new physics, would like probe to not be too tied to standard model

Can we be less model dependent?

Rethink: What is the 'rod'?





Although peak height changes, midpoint – linear point – doesn’t

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 ~ 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 remaining $d\xi/dr$ term scales as $2\,(R_{NL}/r_{inf})^2\, d\xi/d\ln r$; this is small because $(R_{NL}/r_{inf})^2 \sim (10/100)^2$

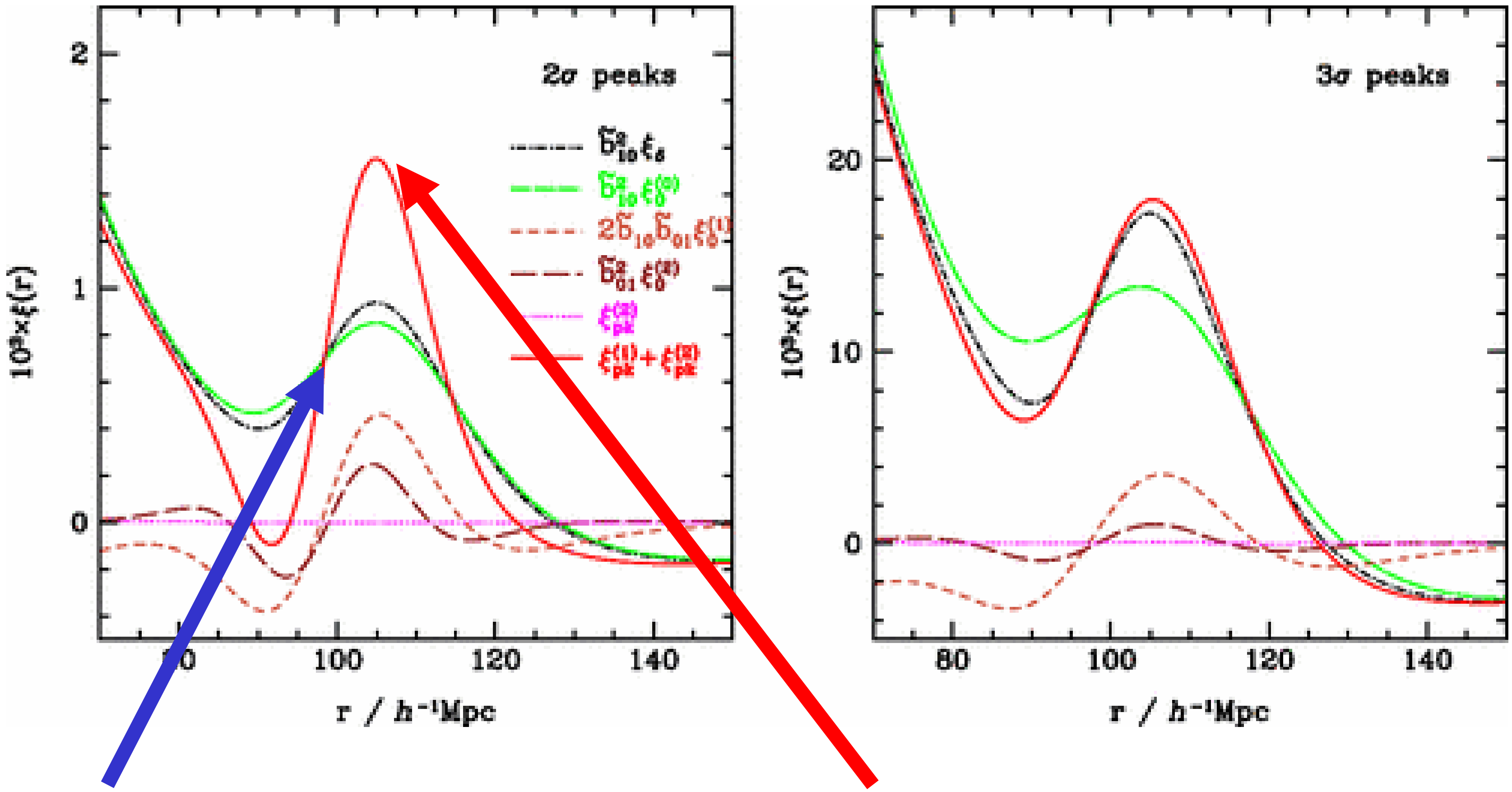
Standard lore

- 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

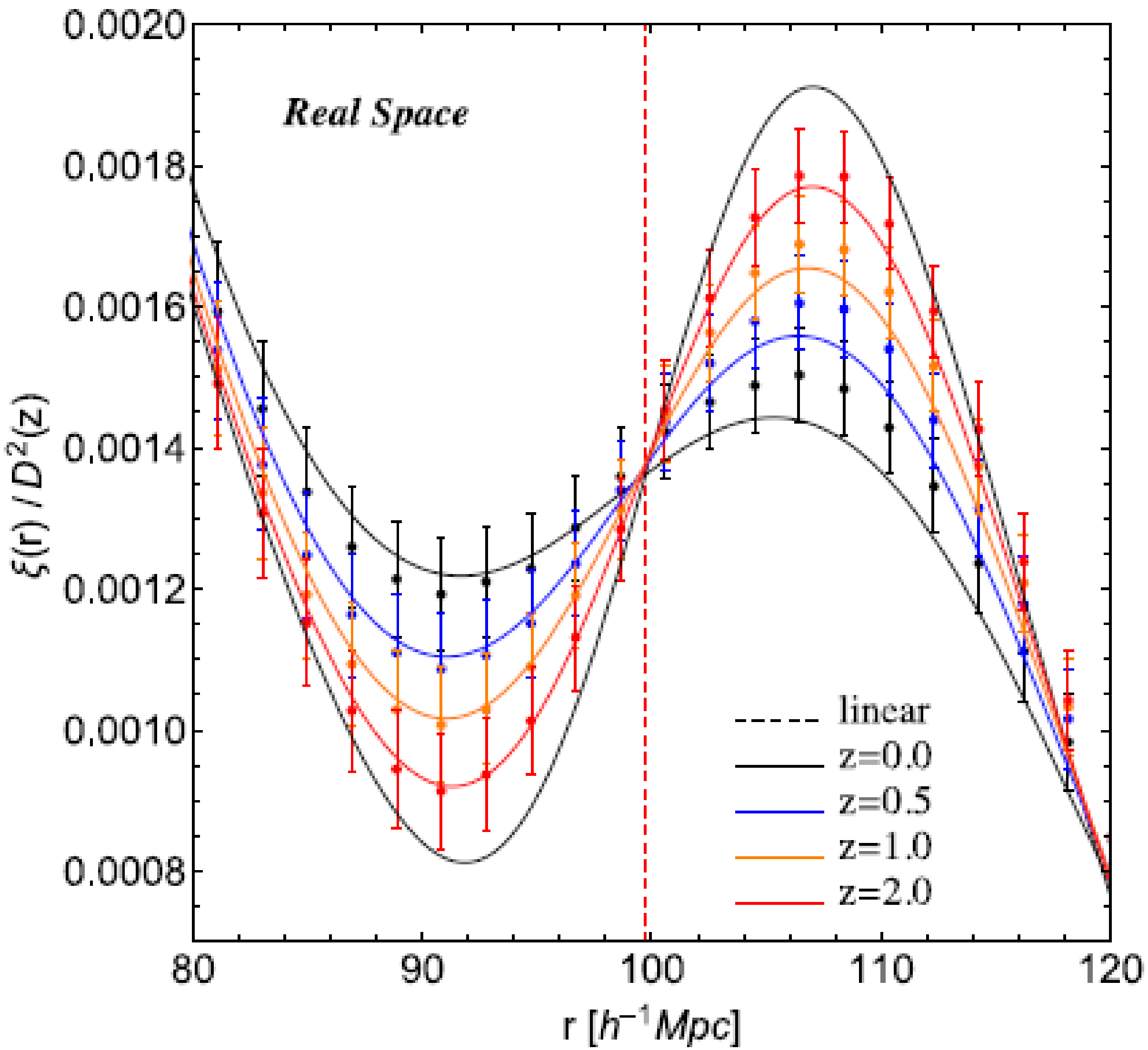
- k^2 from a Laplacian
- In real space: $b_{01} R_h^2 [2/r\, d\xi/dr + d^2\xi/dr^2]$
- At local maximum $d\xi/dr = 0$ but second derivative large
- At inflection point $d^2\xi/dr^2 = 0$, and $d\xi/dr$ term suppressed by $(R_h/r_{BAO})^2 \sim (5/100)^2$

Maximum vs inflection in the Peaks bias model

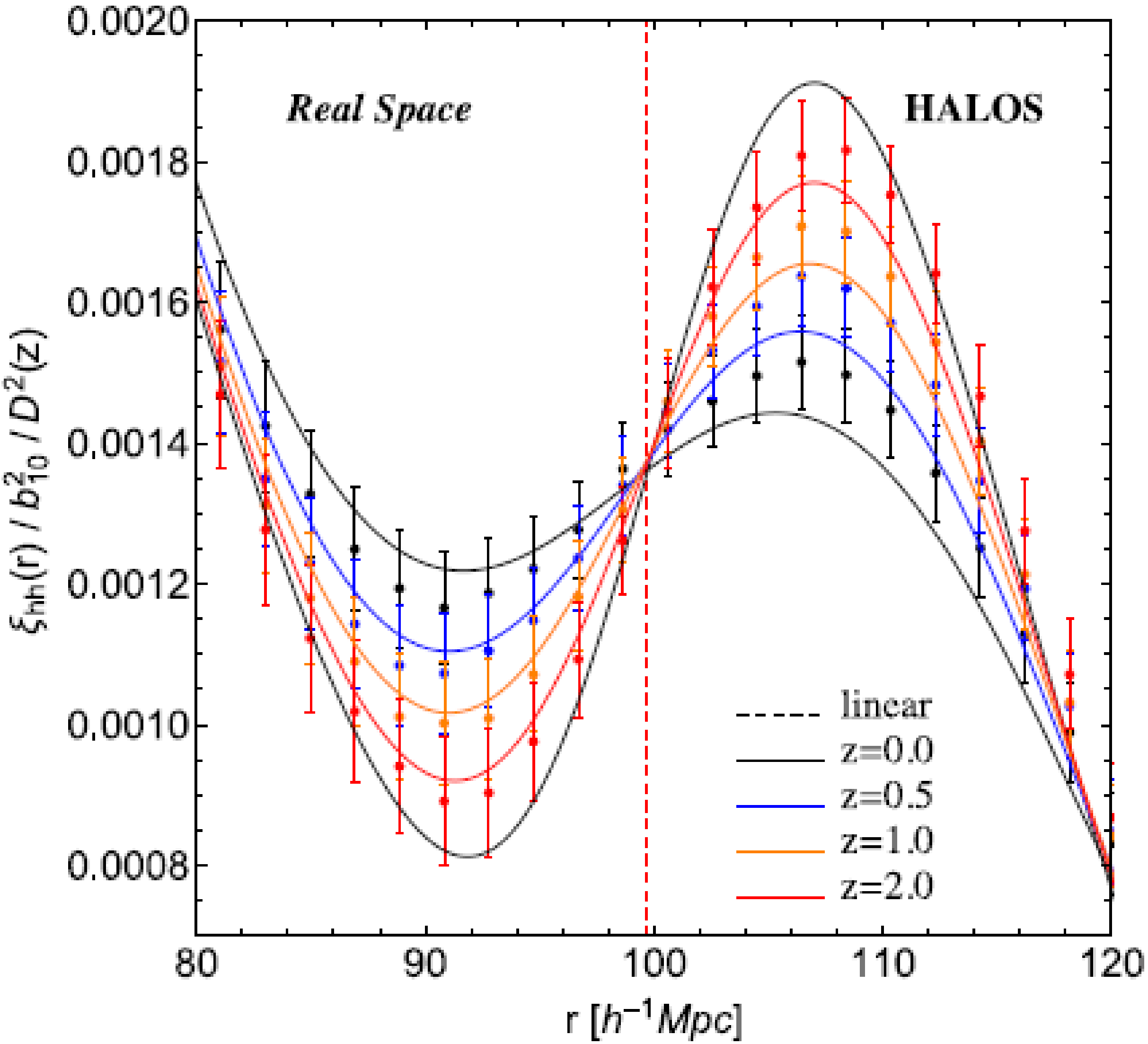


Anselmi et al. 2016

Desjacques et al 2010



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
$\xi(r) / D^2(z)$
$r\ [h^{-1} Mpc]$



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

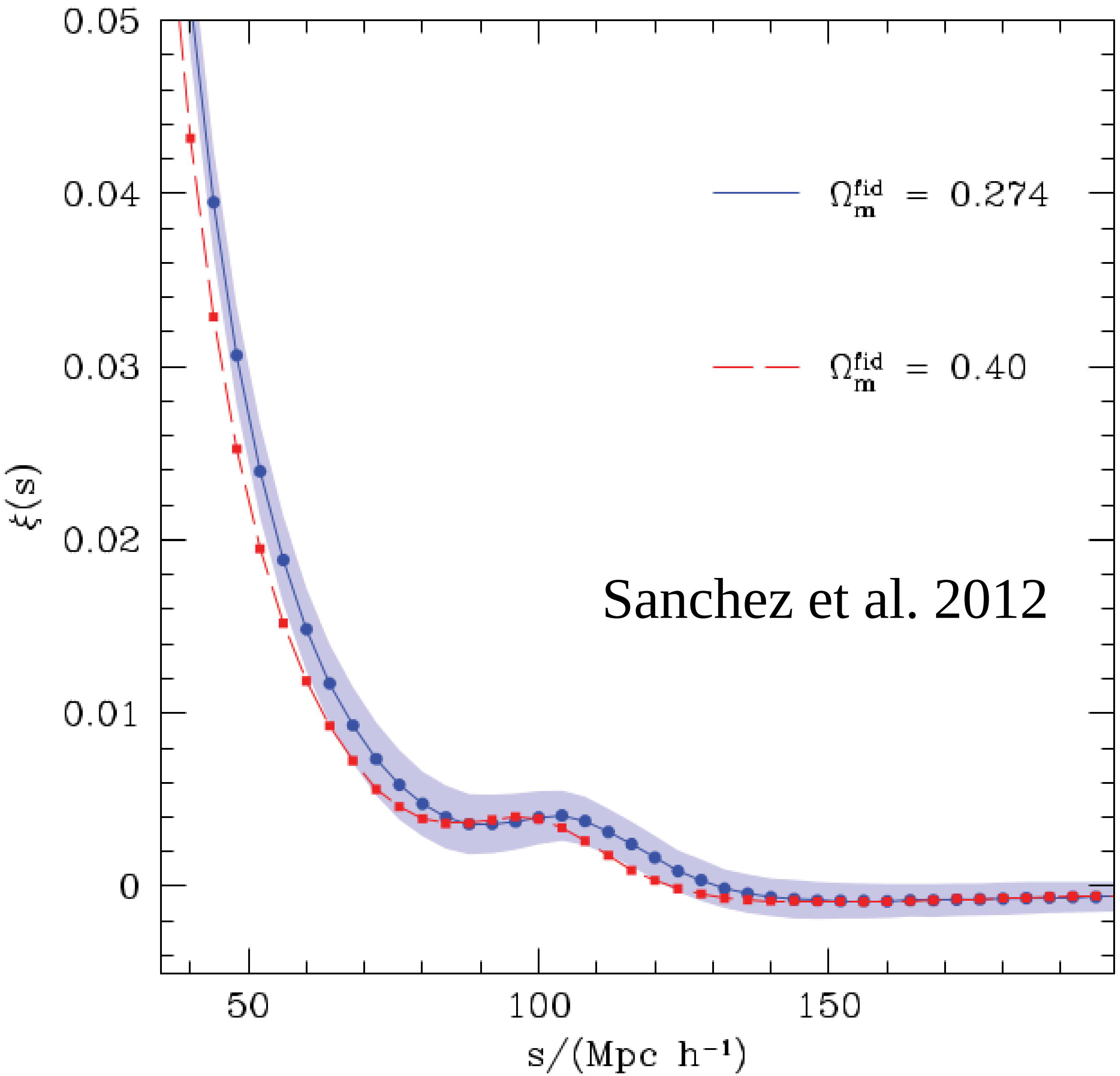
In practice, BAO feature involves two components of distance across line of sight, and one component along line of sight. So ‘average distance’ is:

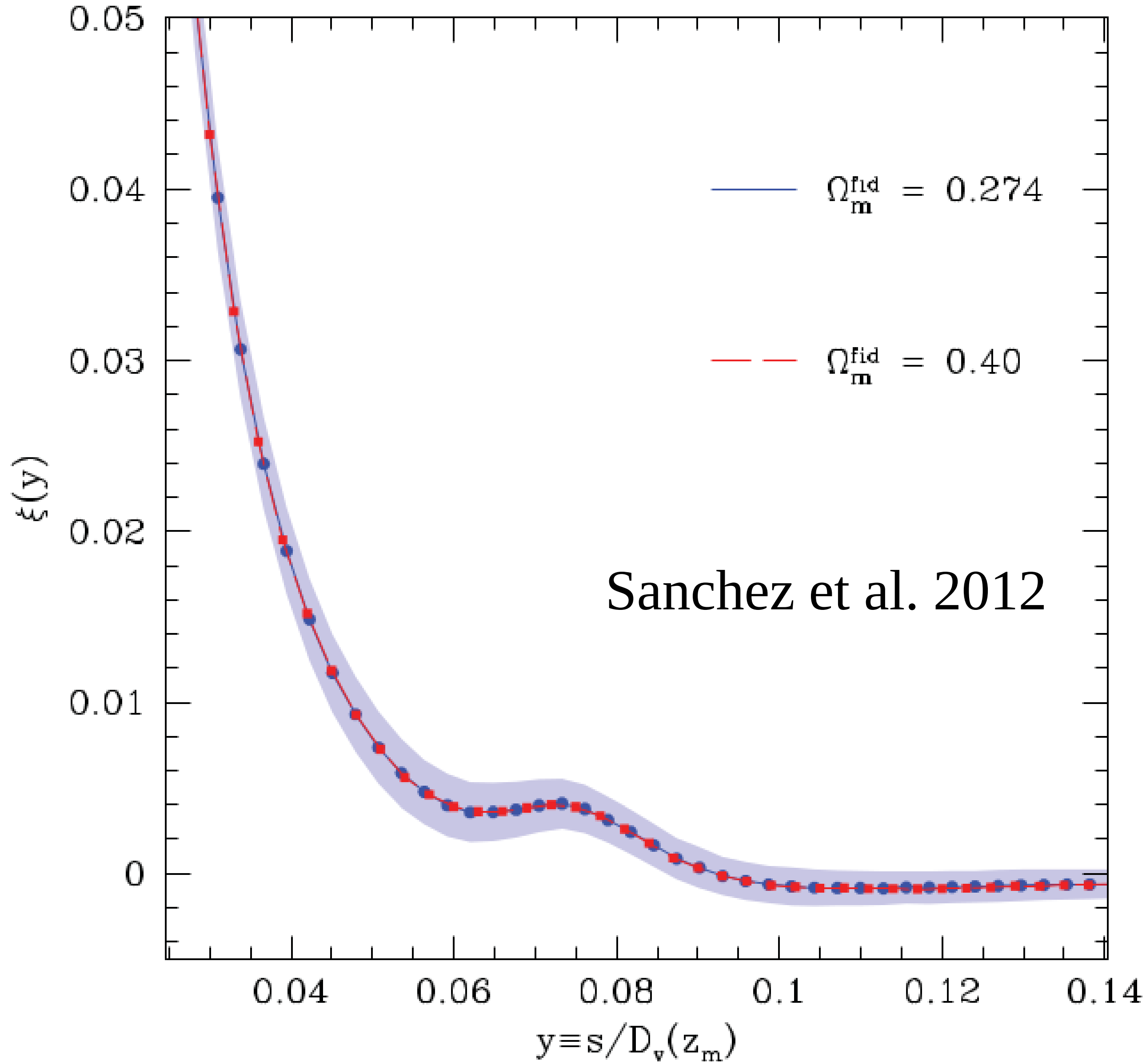
$$D_V(z) \equiv \left[(1+z)^2 D_A(z)^2 \frac{cz}{H(z)}\right]^{1/3}$$

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

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

(Sanchez et al. 2012).


0.05
0.04
0.03
0.02
0.01
0
$\xi(s)$
50
100
150
$s/(\mathrm{Mpc}\ h^{-1})$
$\Omega_m^{fid} = 0.274$
$\Omega_m^{fid} = 0.40$
Sanchez et al. 2012

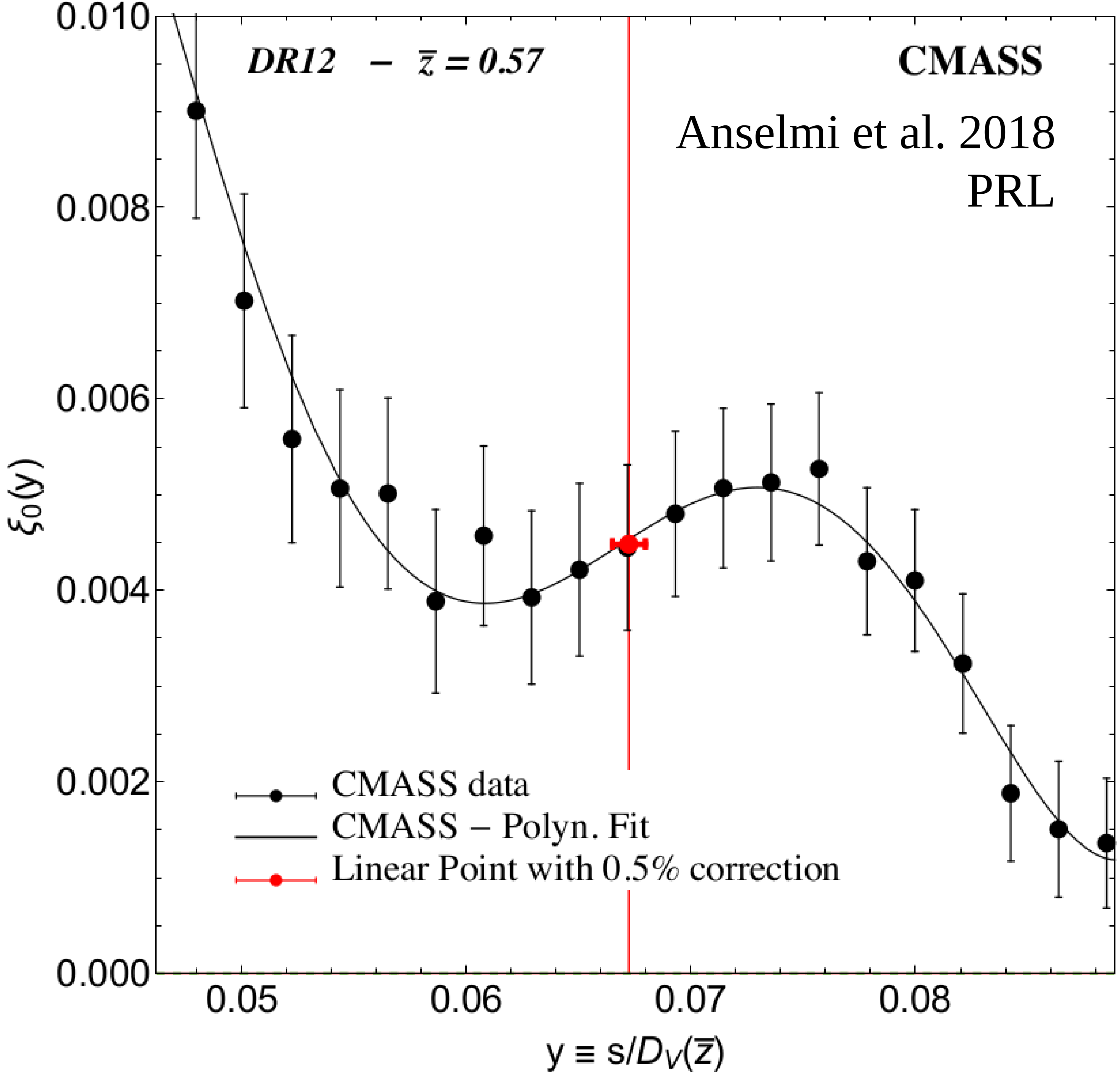


0.05
0.04
0.03
0.02
0.01
0
$\xi(y)$
0.04
0.06
0.08
0.1
0.12
0.14
$y \equiv s/D_v(z_m)$
$\Omega_m^{fid} = 0.274$
$\Omega_m^{fid} = 0.40$
Sanchez et al. 2012

Usual analysis uses shape of Pk in fiducial cosmology to estimate BAO scale. Must account for smearing, or massage data to remove it (known as ‘reconstruction’)

LP can estimate BAO scale by fitting (5^{th} order) polynomial

- no prejudice about shape of Pk
- no reconstruction



0.010
0.008
0.006
0.004
0.002
0.000
0.05
0.06
0.07
0.08
$\xi_0(y)$
$y \equiv s/D_V(\bar{z})$
DR12 – $\bar{z}$ = 0.57
CMASS
Anselmi et al. 2018
PRL
CMASS data
CMASS – Polyn. Fit
Linear Point with 0.5% correction

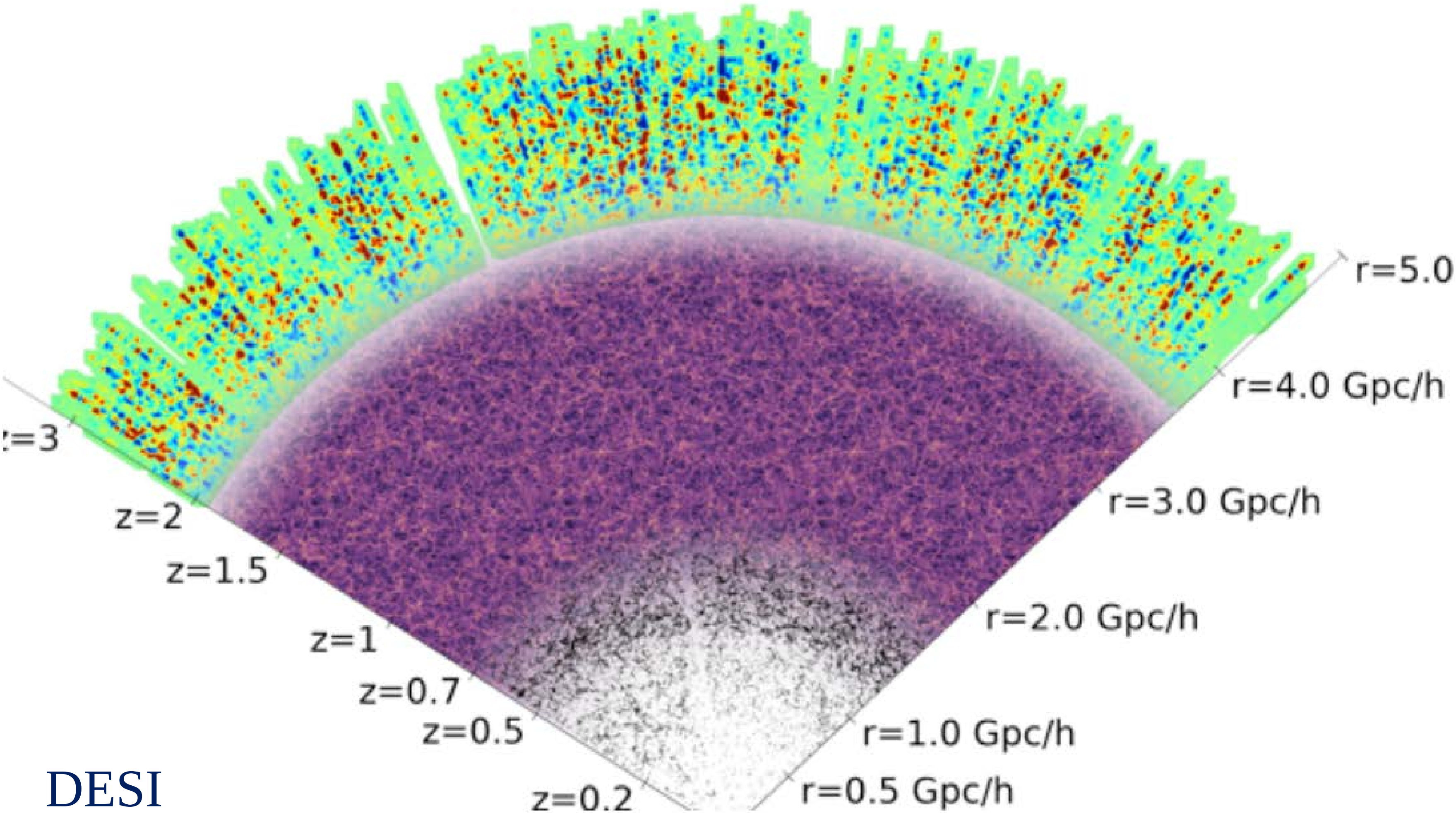
$$
\begin{aligned}
D_V^{\mathrm{LP}}(\bar{z}_{\mathrm{LOWZ}} = 0.32) &= (1264 \pm 28)\,\mathrm{Mpc} \\
D_V^{\mathrm{LP}}(\bar{z}_{\mathrm{CMASS}} = 0.57) &= (2056 \pm 22)\,\mathrm{Mpc}
\end{aligned}
$$

$$
\begin{aligned}
D_V^{\mathrm{BOSS;PRE-RECON}}(\bar{z}_{\mathrm{LOWZ}} = 0.32) &= (1247 \pm 37)\mathrm{Mpc} \\
D_V^{\mathrm{BOSS;PRE-RECON}}(\bar{z}_{\mathrm{CMASS}} = 0.57) &= (2043 \pm 27)\mathrm{Mpc}
\end{aligned}
$$

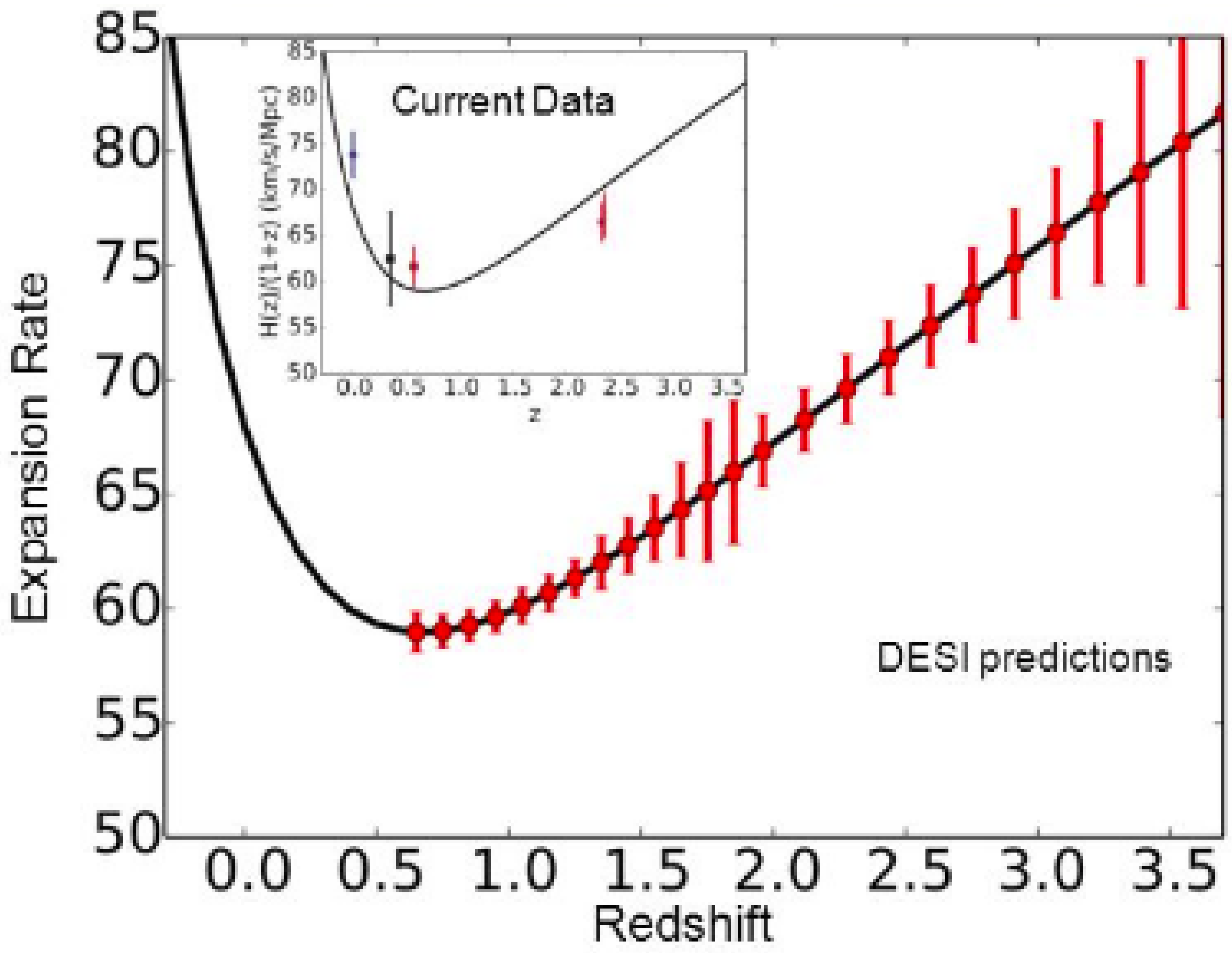
$$
\begin{aligned}
D_V^{\mathrm{BOSS;POST-RECON}}(\bar{z}_{\mathrm{LOWZ}} = 0.32) &= (1265 \pm 21)\mathrm{Mpc} \\
D_V^{\mathrm{BOSS;POST-RECON}}(\bar{z}_{\mathrm{CMASS}} = 0.57) &= (2031 \pm 20)\mathrm{Mpc}
\end{aligned}
$$

- 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 $z \sim 2$
- Sub-percent level constraints on model parameters


r=5.0
r=4.0 Gpc/h
r=3.0 Gpc/h
r=2.0 Gpc/h
r=1.0 Gpc/h
r=0.5 Gpc/h
z=3
z=2
z=1.5
z=1
z=0.7
z=0.5
z=0.2

DESI



Current Data
H(z)/(1+z) (km/s/Mpc)
z
DESI predictions
Expansion Rate
Redshift

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

LP can estimate BAO scale with

- no prejudice about shape of P(k)
- good agreement with traditional estimate
- no reconstruction required
- we understand why (robust to k^2)

Linear Point allows estimate of distance scale with fewer assumptions about cosmological dependence of signal

In progress:
- quadrupole
- growth factor?