On standard rods when making maps

Baryon Acoustic Oscillations

We must admit with humility that, while number is purely a product of our minds, space has a reality outside our minds, so that we cannot completely prescribe its properties a priori.

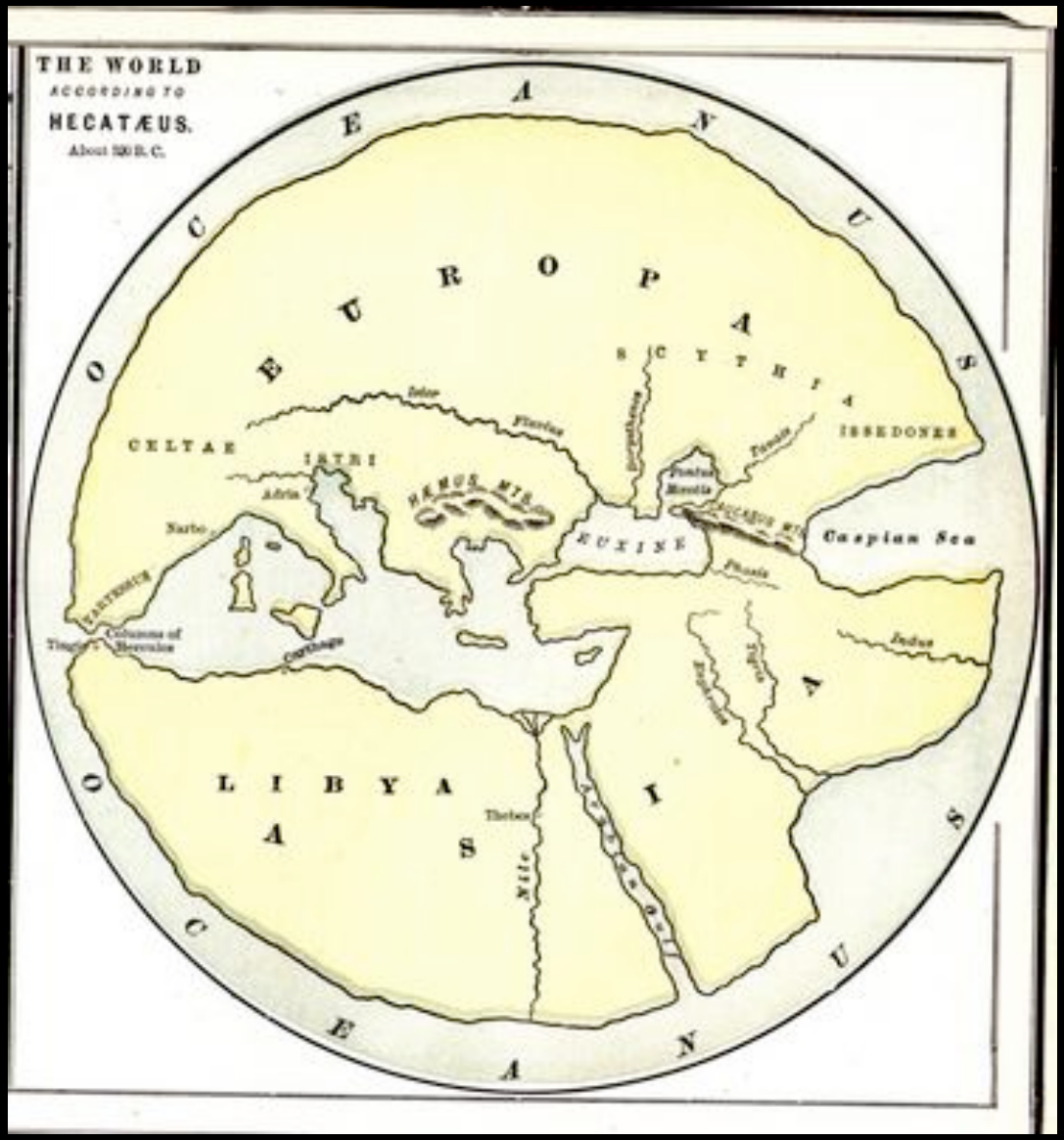
Gauss to Bessel, 1830.

Outline

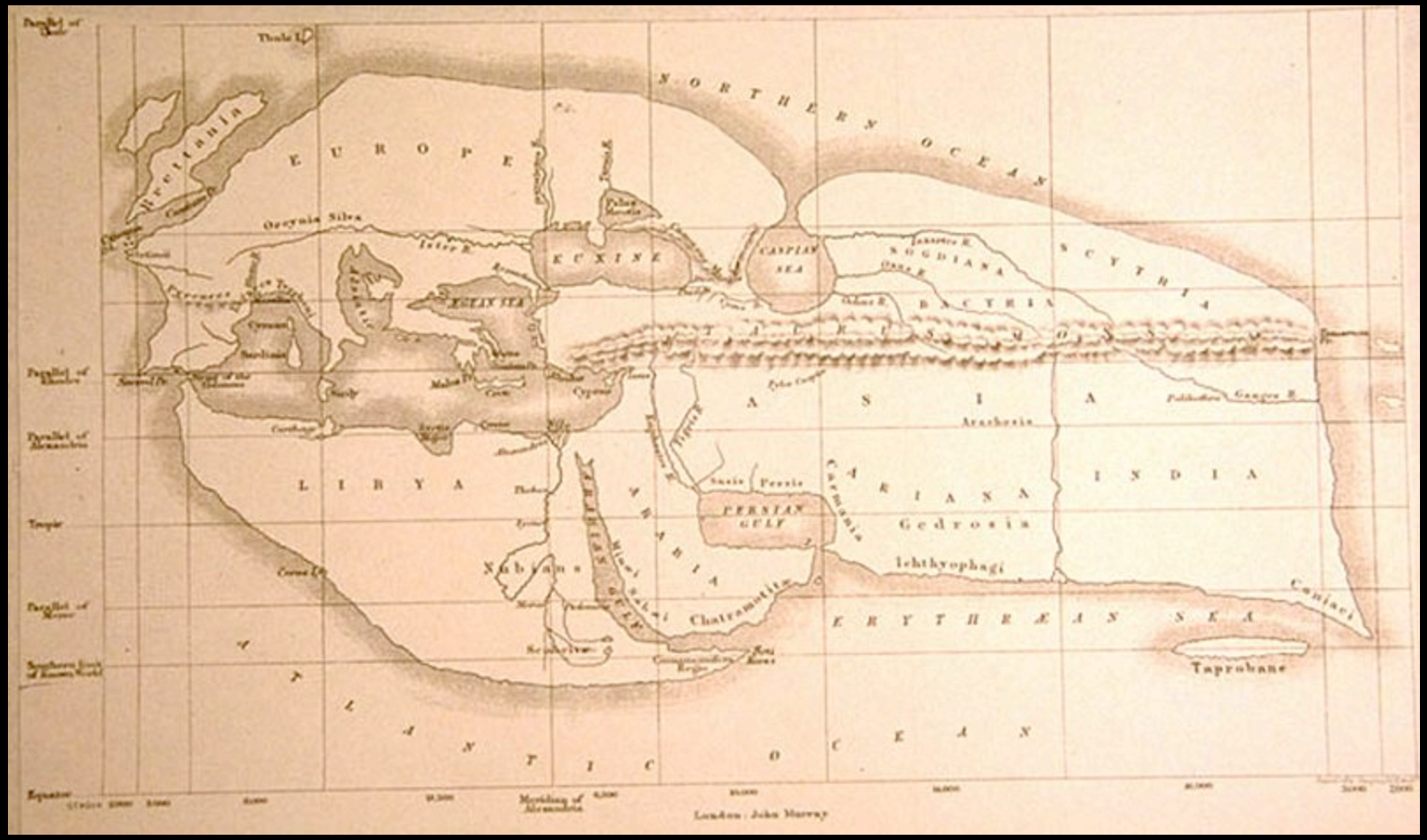
- Maps, metrics and models
- Observational probes
- Theory models for sub-percent precision
  - 1% in distance ~ 4% in w
  - Standard vs standardizable rods

Ravi K. Sheth (UPenn)

- Map what is known
- Assume simple model for unknown
- 600 BC: Earth is flat circle atop cylinder



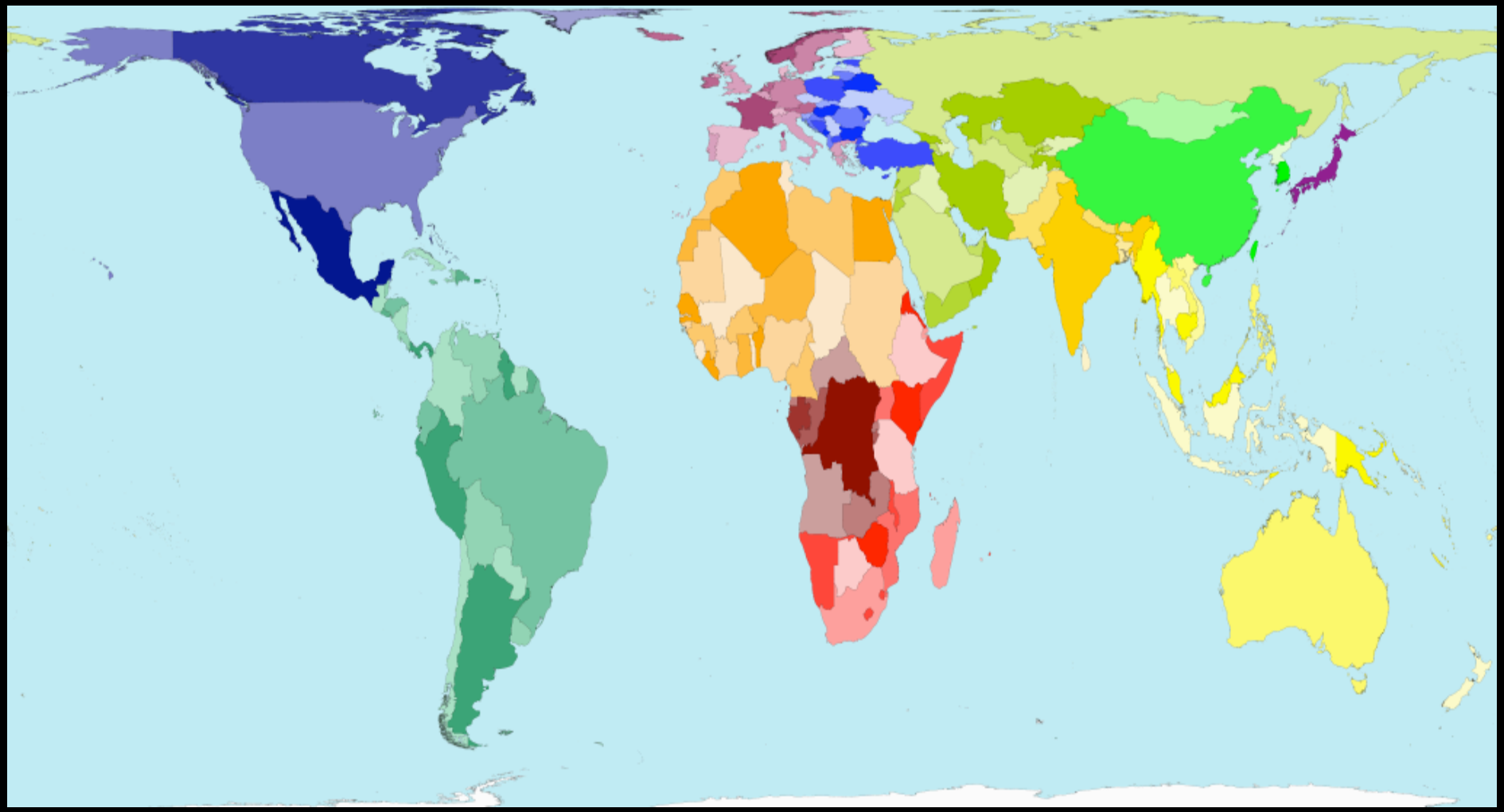
500 BC: Earth is flat, but not on cylinder or, surrounded by water! (Note similarity to human skull…)



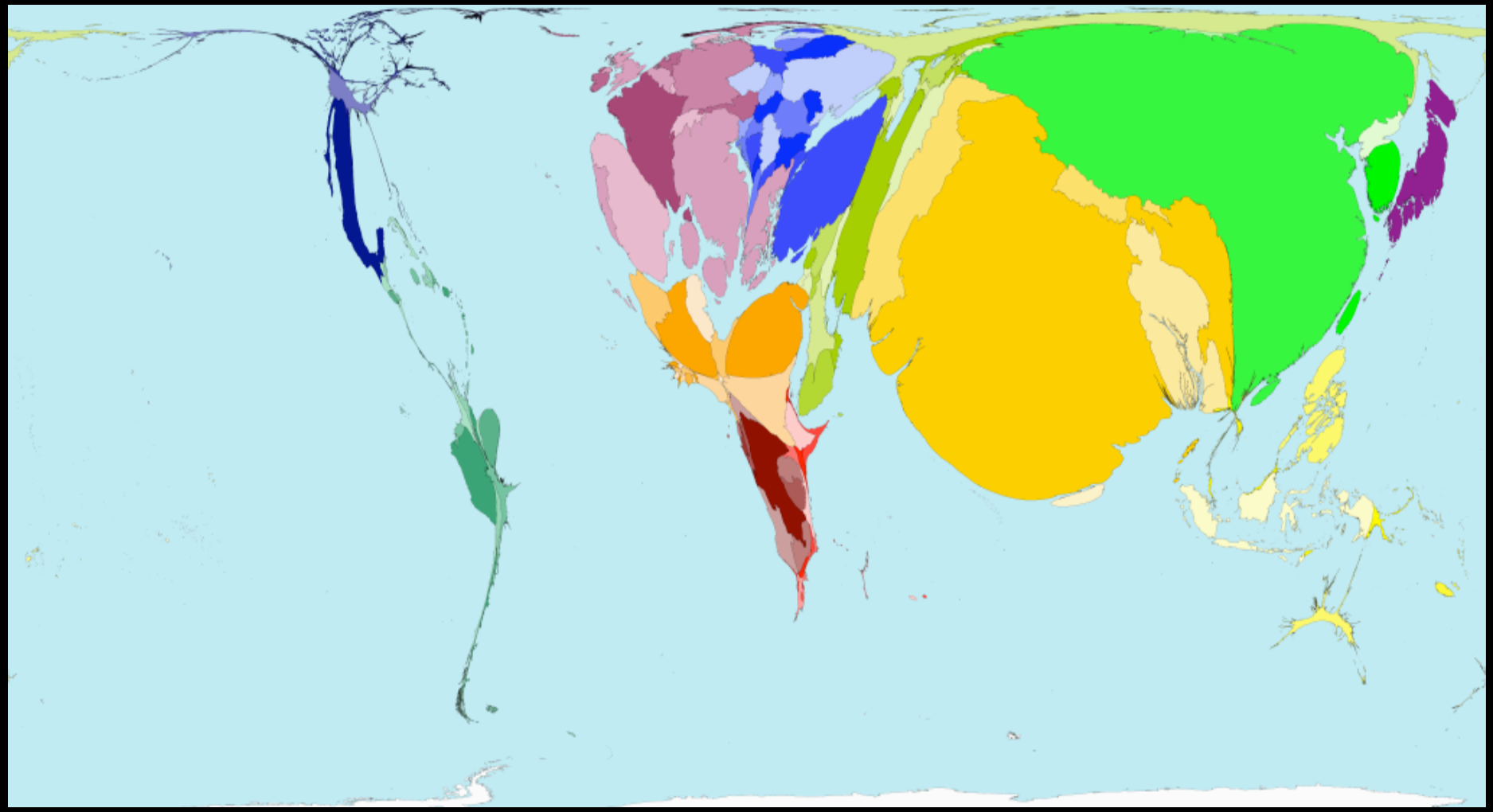
Alexander the Great's travels mean Asia larger than previously thought …

Known inhabited world much smaller than expected if radius computed by Eratosthenes correct

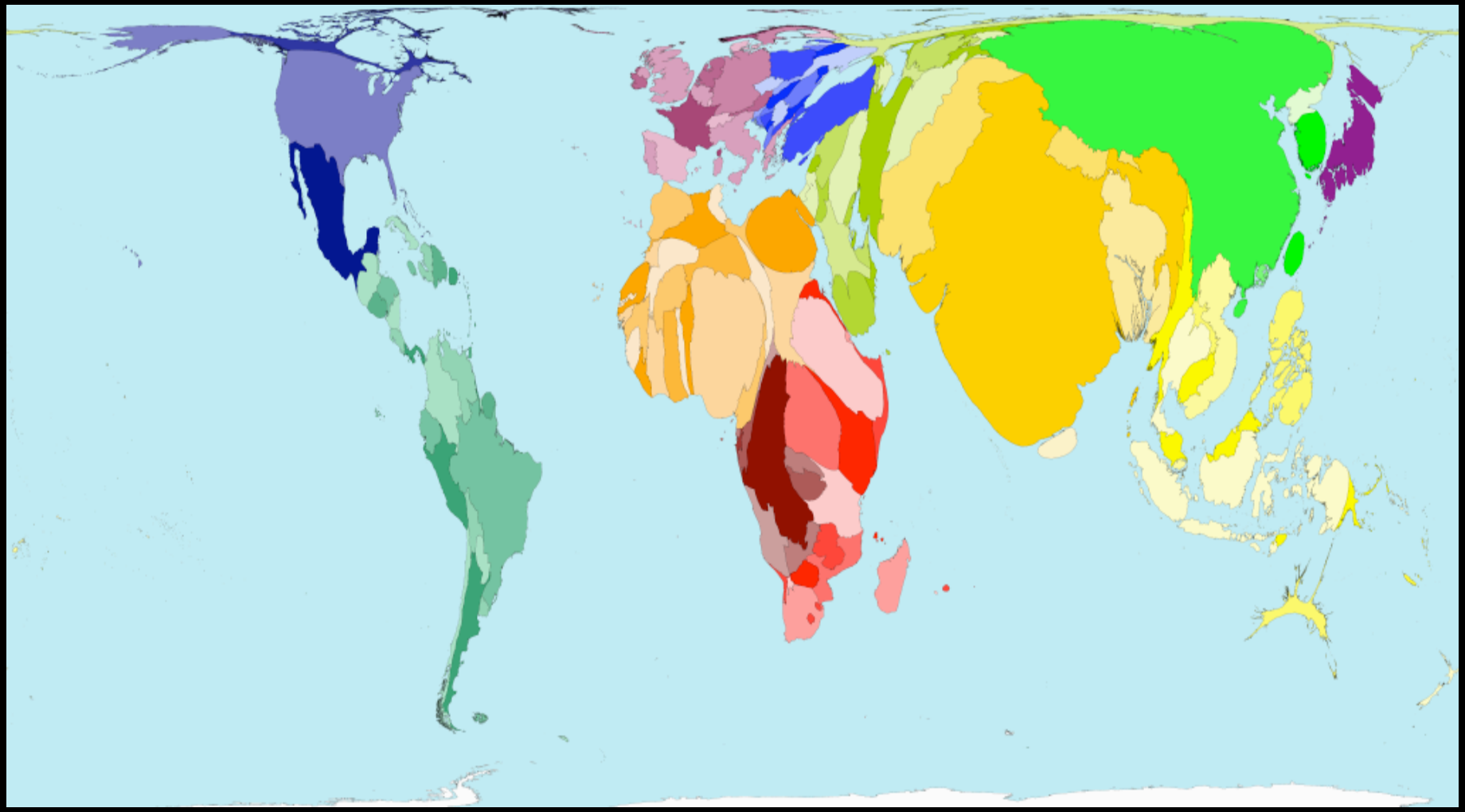
150 BC: Crates postulates three other identical landmasses, symmetrically located, separated by water



2007 AD: www.worldmapper.org

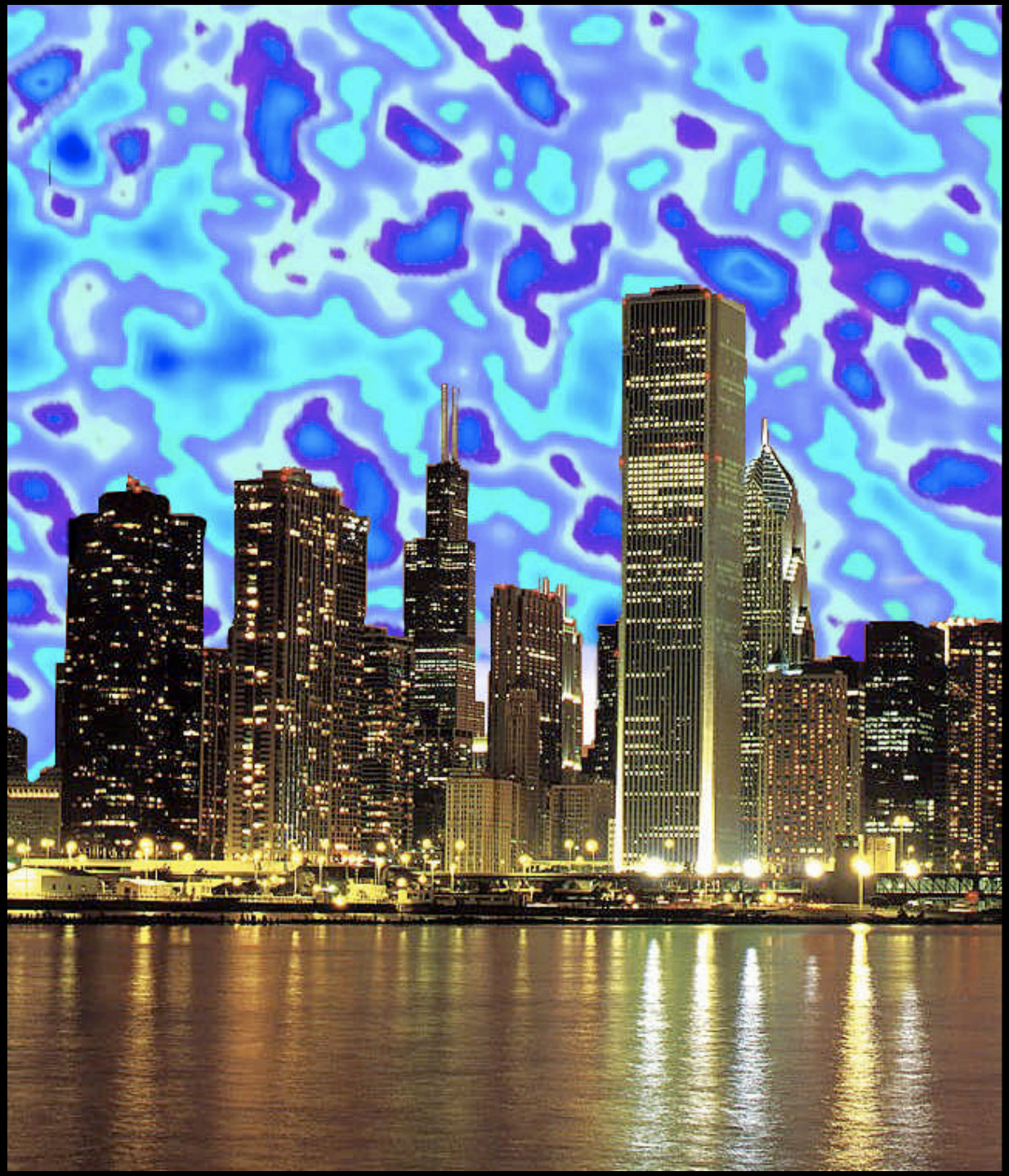


Population 1 AD

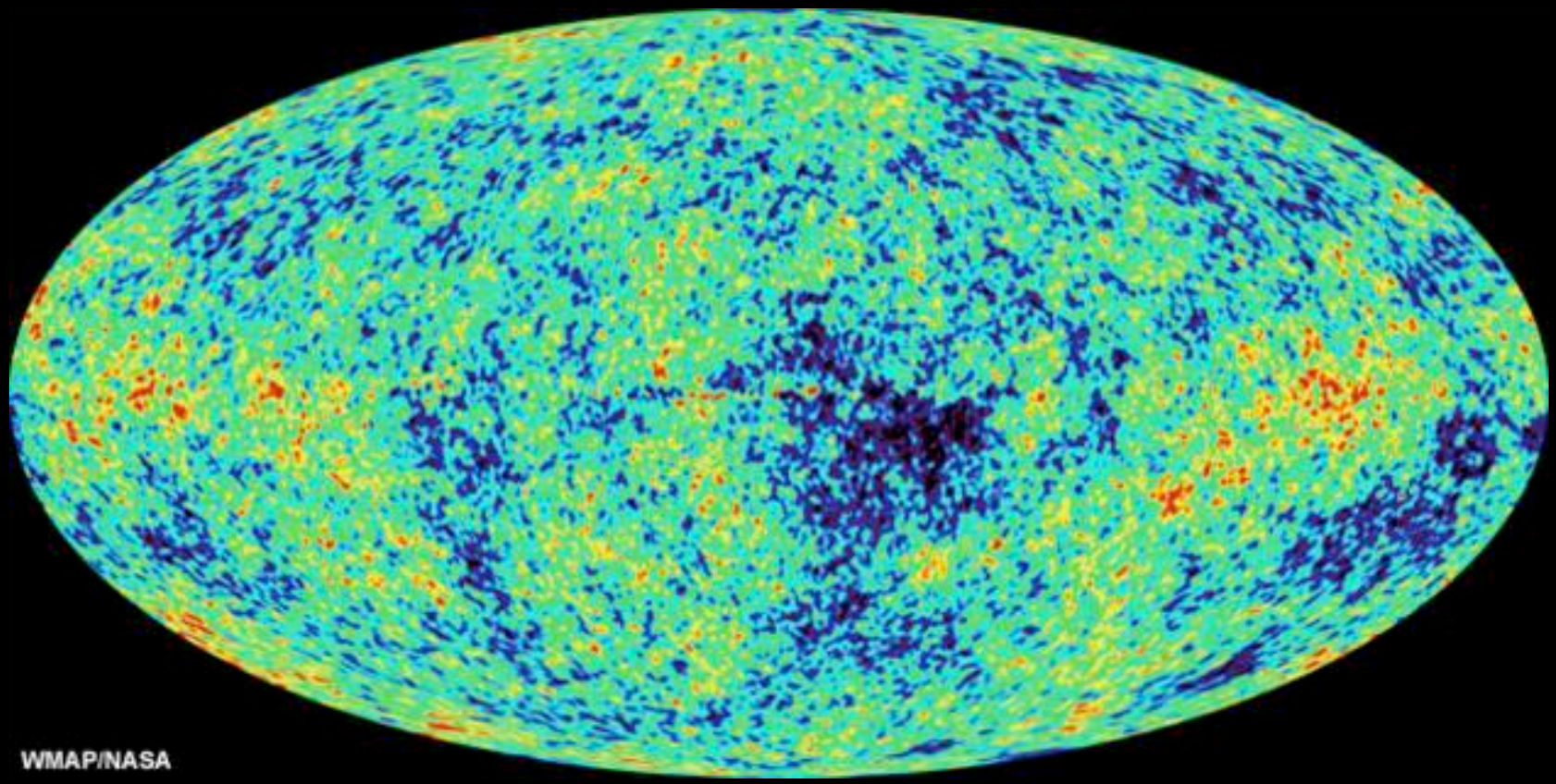


Population 2007 AD

Fluctuations in microwave sky above Chicago



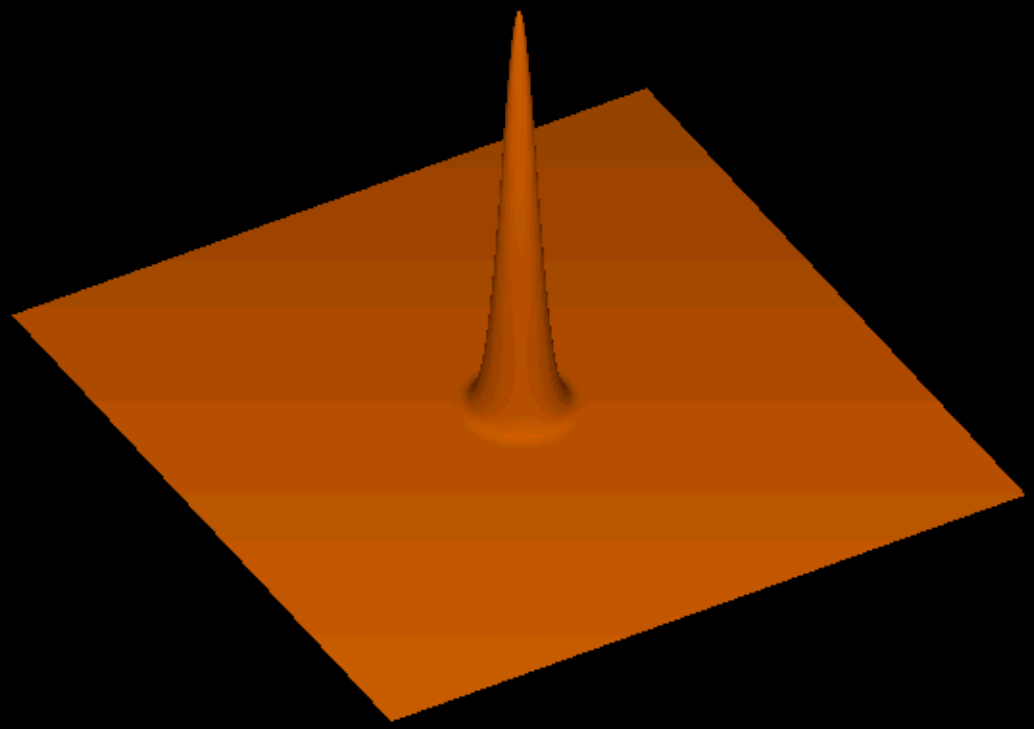
WMAP of Distant Universe



The acoustic oscillation feature

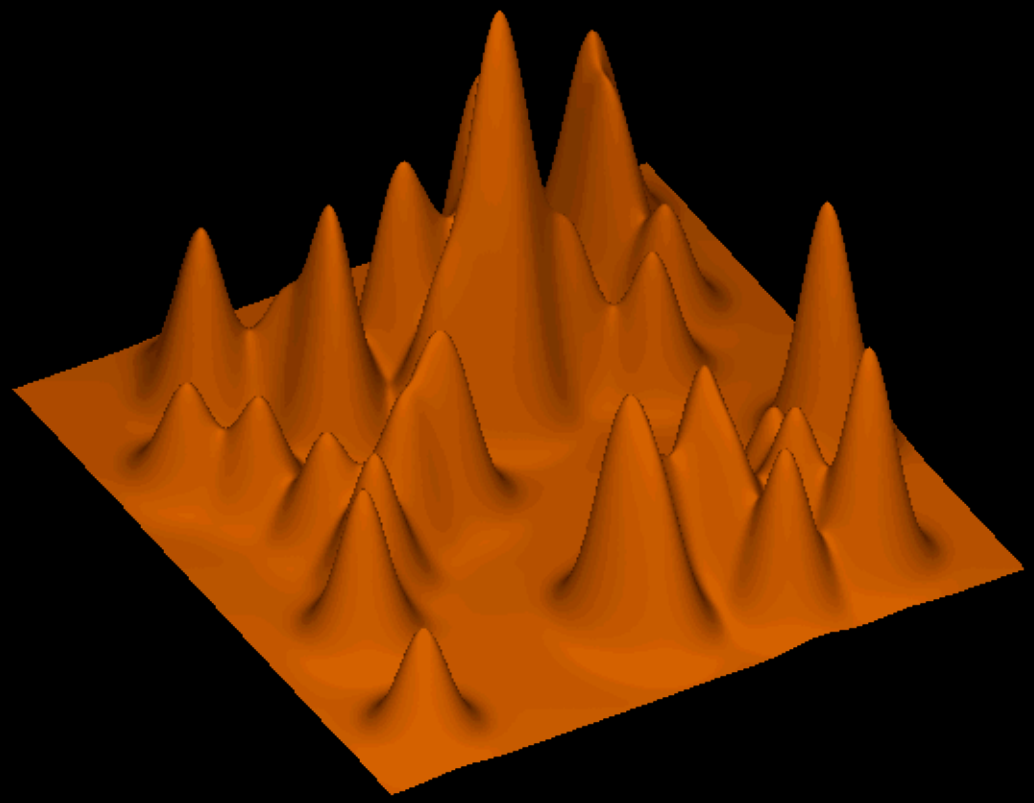
- Radius of shell set by sound speed and travel time
- Sound speed set by balance of radiation pressure and inertia of baryons: i.e., the baryon-photon ratio
- Travel time is set by redshift of matter-radiation equality, which depends on matter-radiation ratio
- So $\Omega_b h^2$ and $\Omega_m h^2$ $\therefore$ Angular diameter distance + Hubble parameter as functions of redshift

Photons ‘drag’ baryons for ~10^6 years…

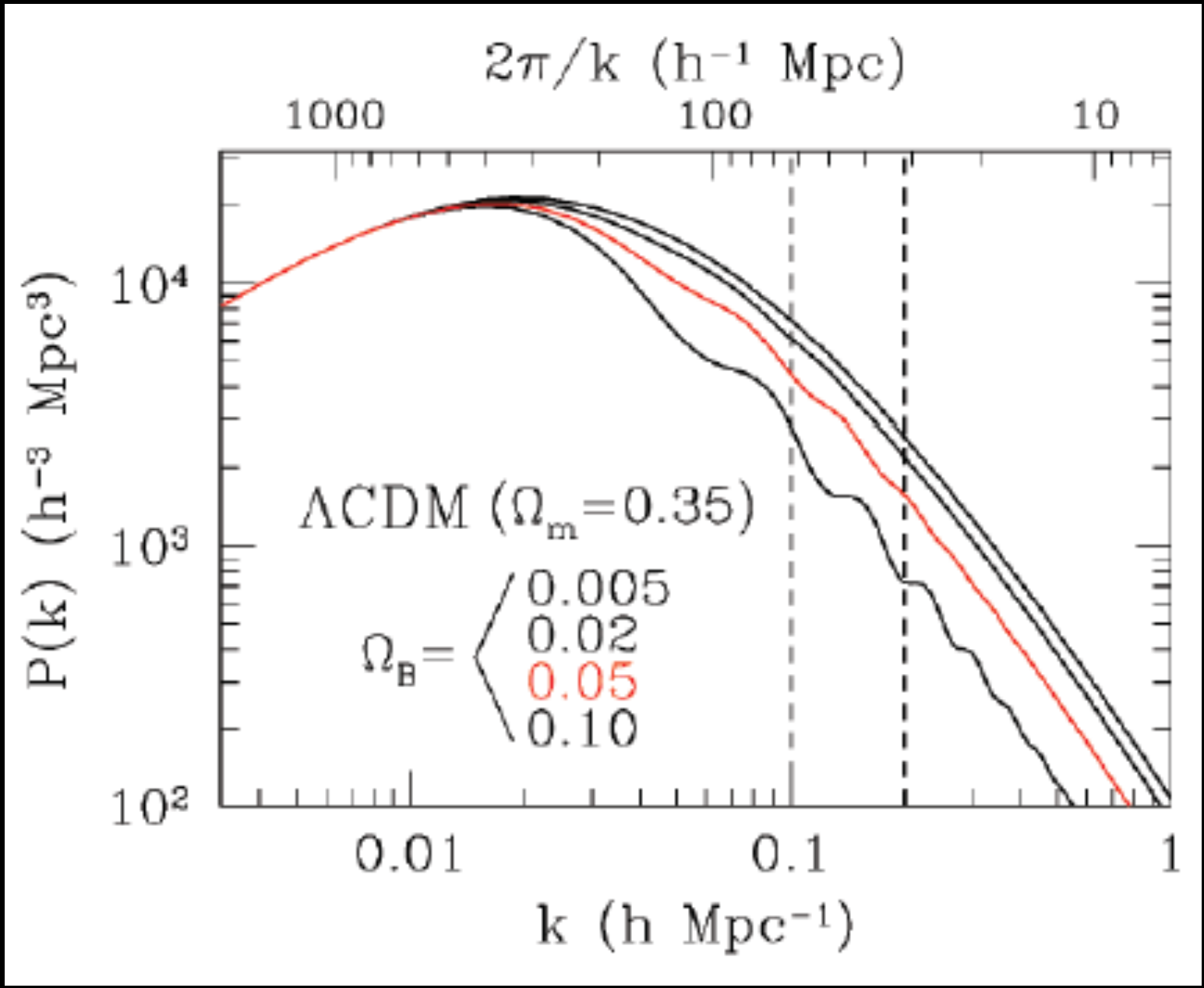


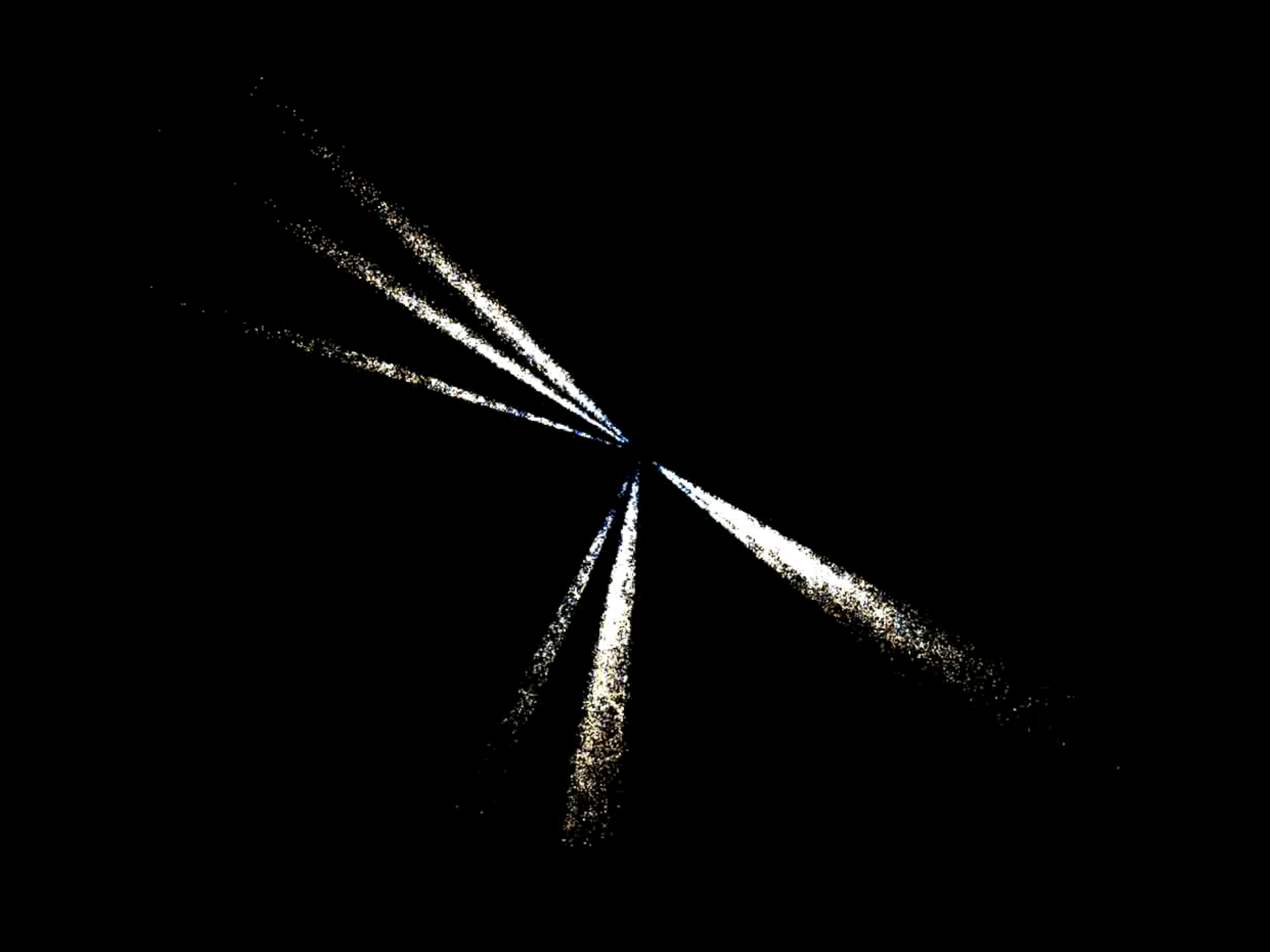
Expansion of Universe since then stretches this to (3000/2.725) ×100 kpc ~ 100 Mpc

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~1100
Should see it in the galaxy distribution at other z

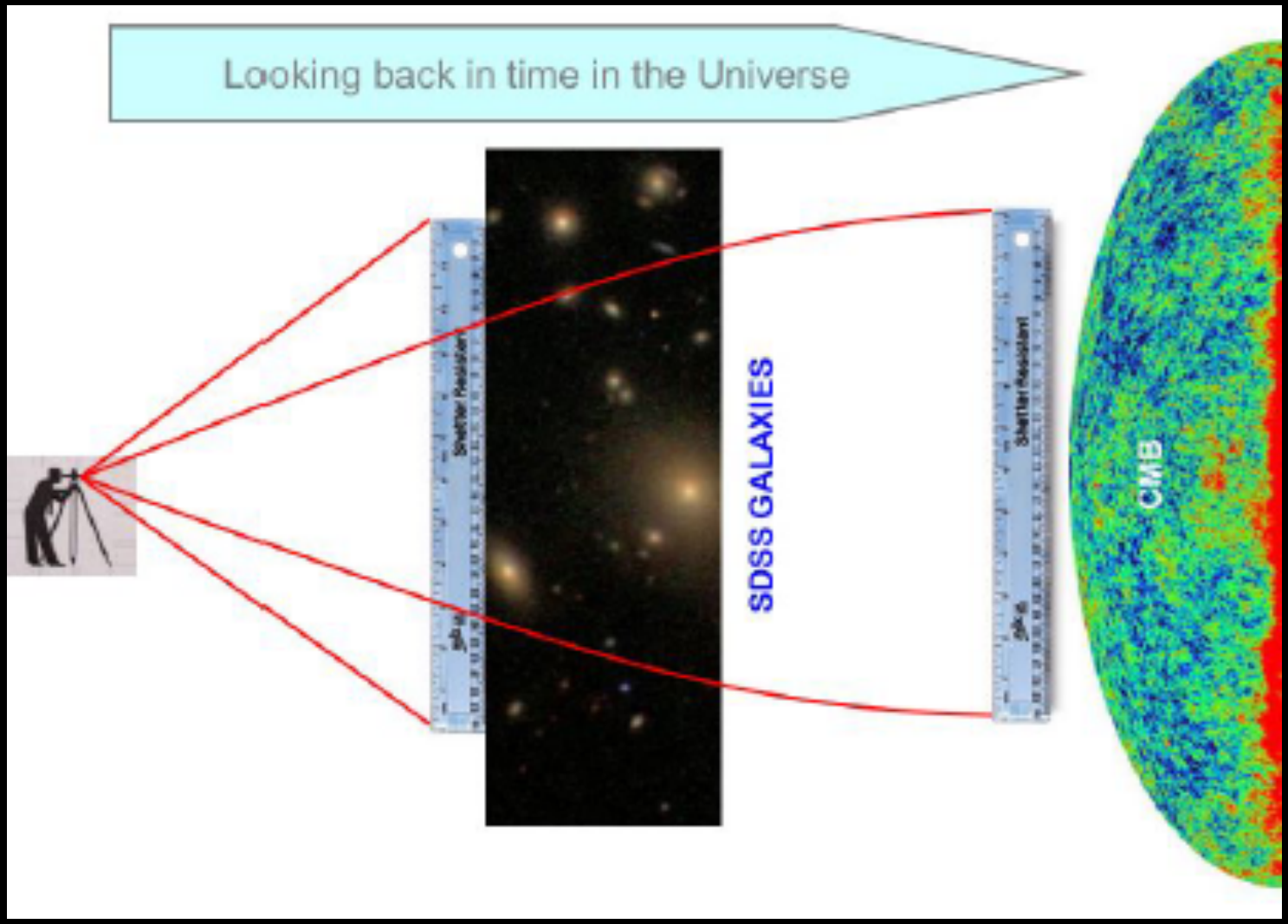

2π/k (h⁻¹ Mpc)
1000
100
10
P(k) (h⁻³ Mpc³)
10⁴
10³
10²
ΛCDM (Ω_m=0.35)
Ω_B = 0.005
0.02
0.05
0.10
0.01
0.1
1
k (h Mpc⁻¹)



CMB from interaction between photons and baryons when Universe was 3,000 degrees (about 379,000 years old)

- Expect galaxies which formed much later carry a memory of this epoch of last scattering (Peebles & Yu 1970; Sunyaev & Zeldovich 1970; Eisenstein & Hu 1998)

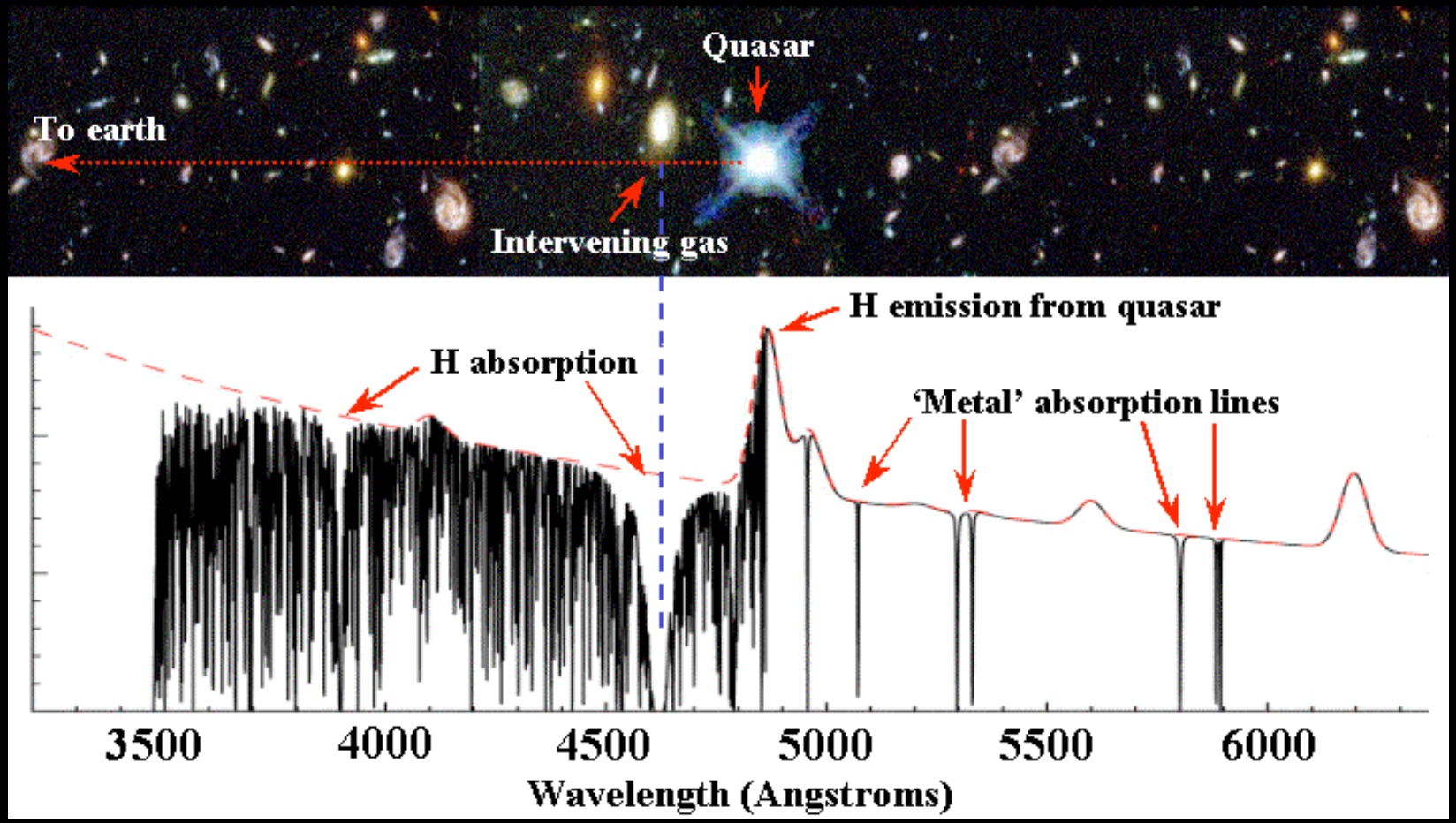
Baryon Oscillations in the Galaxy Distribution



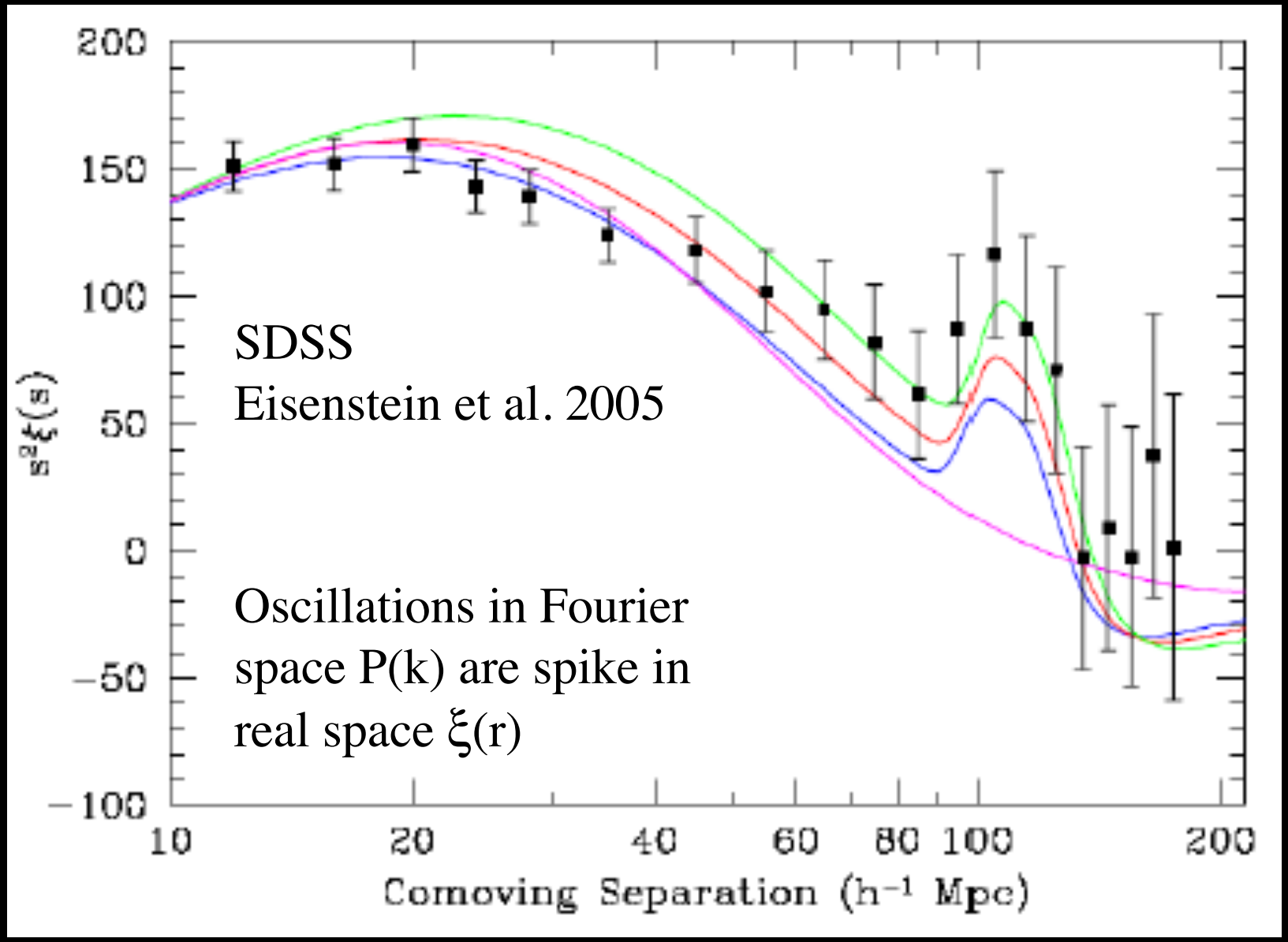
…we need a tracer of the baryons

- 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
  - If linear bias on large scales, then *length* of rod not affected by galaxy tracer!

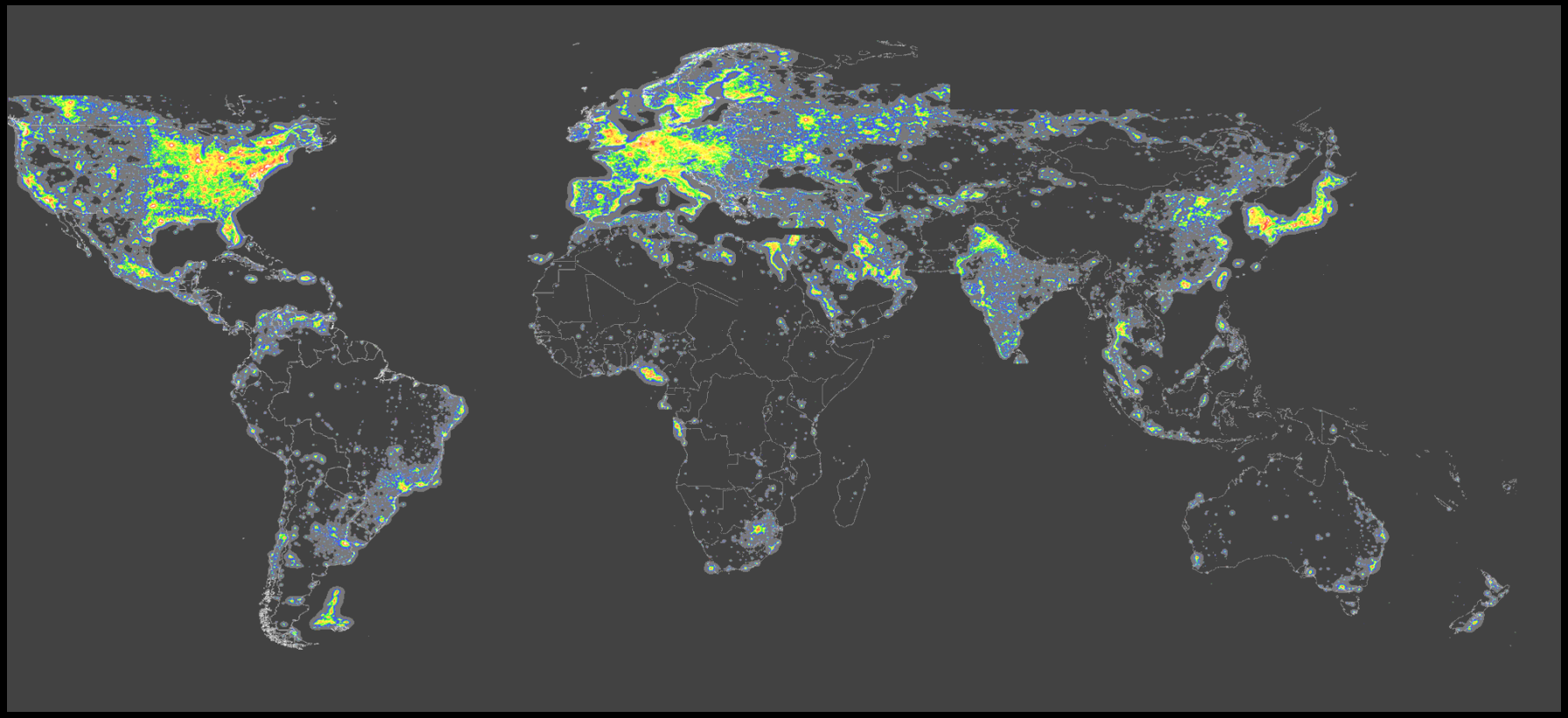
Should also see signature in the baryons of the Lyman-alpha forest



… but on scales where QSO continuum subtraction important


SDSS
Eisenstein et al. 2005
Oscillations in Fourier space P(k) are spike in real space ξ(r)
200
150
100
50
0
−50
−100
10
20
40
60
80
100
200
Comoving Separation (h⁻¹ Mpc)
s²ξ(s)

Map of Light is a biased tracer



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

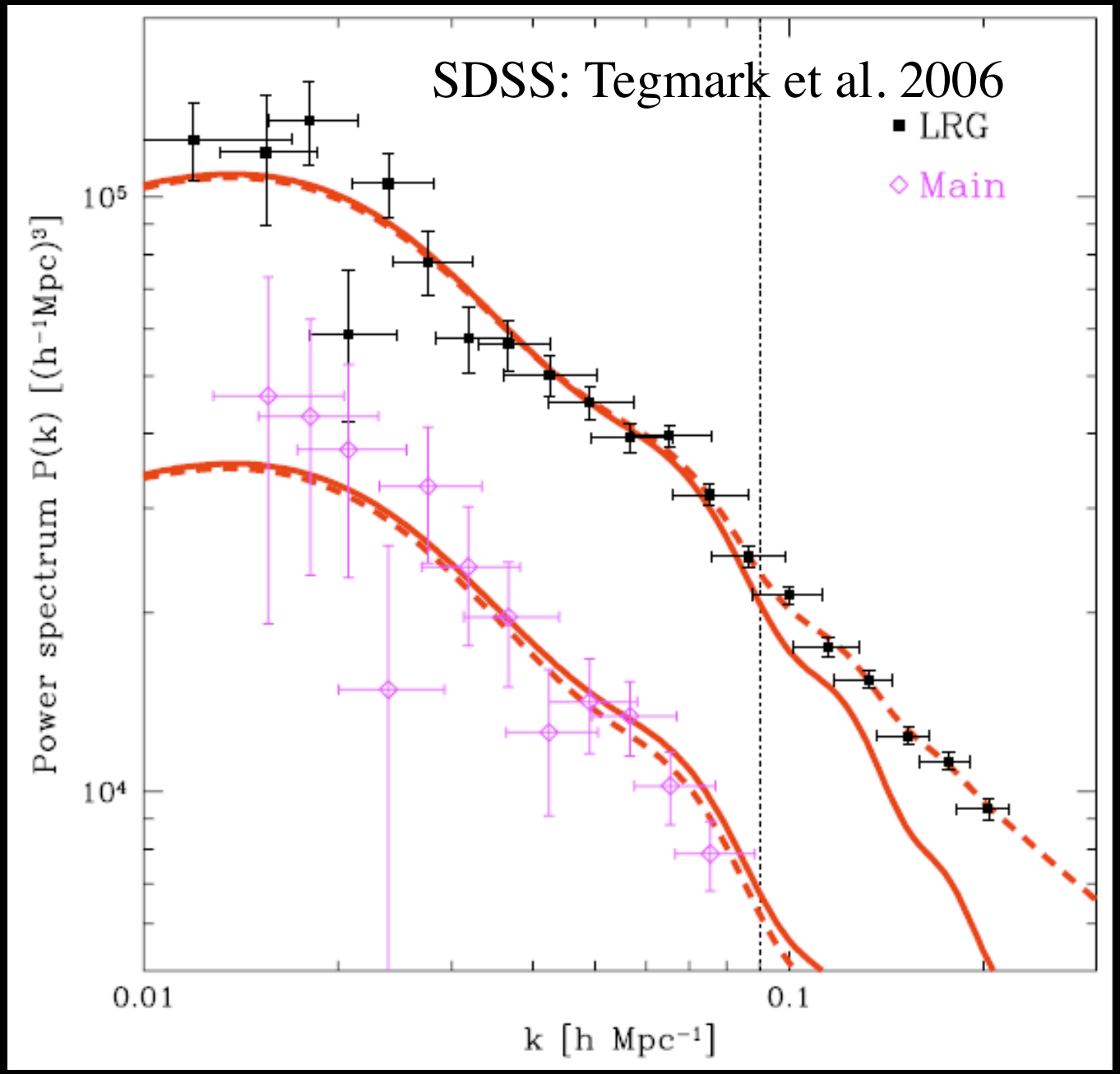
- The baryon distribution today ‘remembers’ the time of decoupling/last scattering; can use this to build a ‘standard rod’

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

- Important to test if standard rod is standard, or standardizable, at this level of precision

Real space spike at r_p becomes $\sin(kr_p)/kr_p$ in Fourier space

Linear bias OK at ~10% precision



THE ASTROPHYSICAL JOURNAL, 472:1–13, 1996 November 20

THE EVOLUTION OF CORRELATION FUNCTIONS IN THE ZELDOVICH APPROXIMATION AND ITS IMPLICATIONS FOR THE VALIDITY OF PERTURBATION THEORY

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Received 1995 April 26; accepted 1996 June 13

ABSTRACT

We investigate whether it is possible to study perturbatively the transition in cosmological clustering from a single-streamed flow to a multistreamed flow. We do this by considering a system whose dynamics is governed by the Zeldovich approximation (ZA) and calculating the evolution of the two-point correlation function using two methods, (1) distribution functions and (2) hydrodynamic equations without pressure and vorticity. The latter method breaks down once multistreaming occurs whereas the former does not. We find that the two methods yield the same results to all orders in a perturbative expansion of the two-point correlation function. We thus conclude that we cannot study the transition from a single-streamed flow to a multistreamed flow in a perturbative expansion. We expect this conclusion to hold even if full gravitational dynamics (GD) is used instead of ZA.

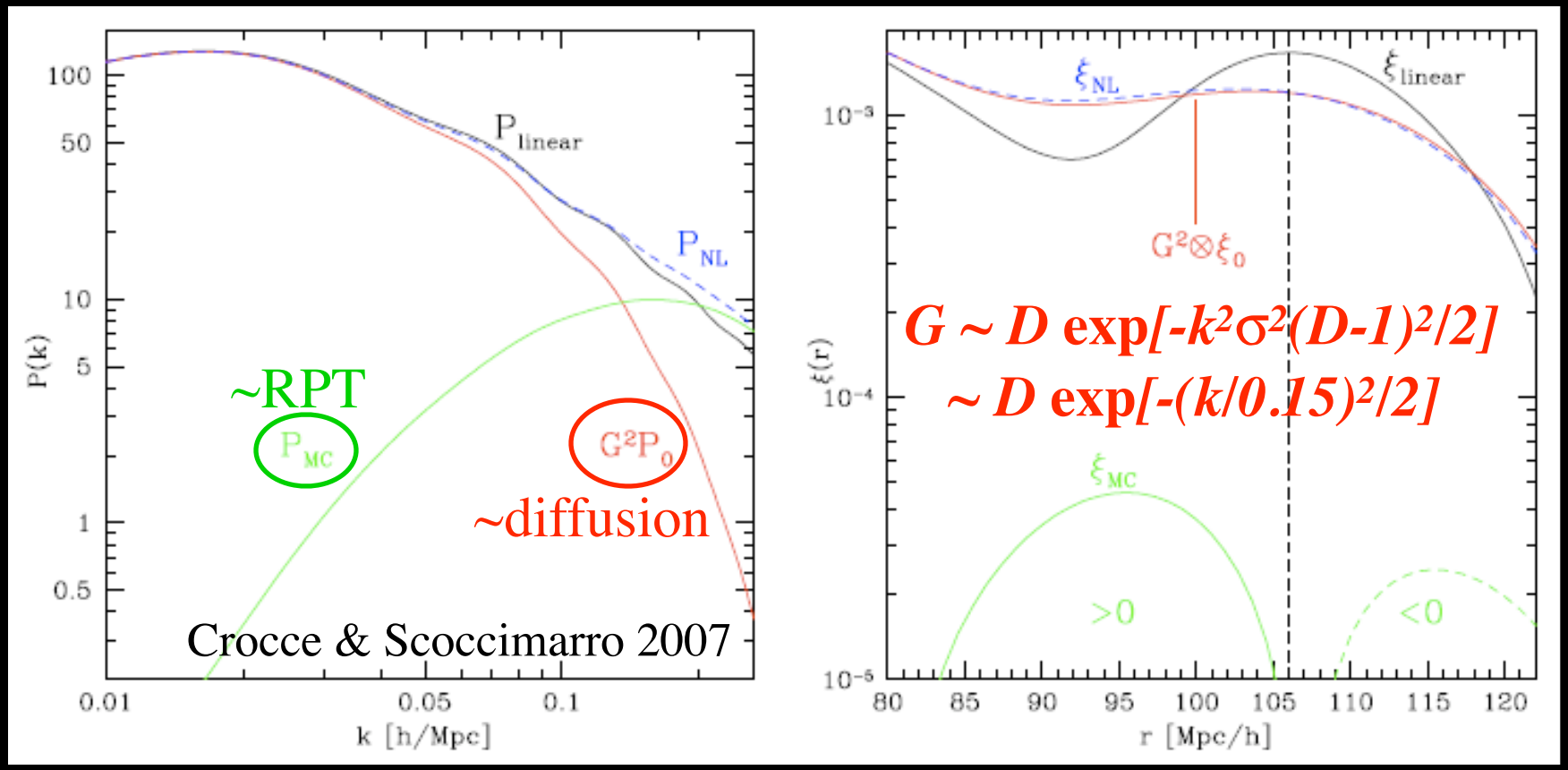
We use ZA to look at the evolution of the two-point correlation function at large spatial separations, and we find that, until the onset of multistreaming, the evolution can be described by a diffusion process in which the linear evolution at large scales is modified by the rearrangement of matter on small scales. We compare these results with the lowest order nonlinear results from GD. We find that the difference is only in the numerical value of the diffusion coefficient, and we interpret this physically.

We also use ZA to study the induced three-point correlation function. At the lowest order of nonlinearity, we find that, as in the case of GD, the three-point correlation does not necessarily have the hierarchical form. We also find that at large separations the effect of the higher order terms for the three-point correlation function is very similar to that for the two-point correlation, and in this case too the evolution can be described in terms of a diffusion process.

Subject headings: cosmology: theory — galaxies: clusters: general — large-scale structure of universe — methods: analytical

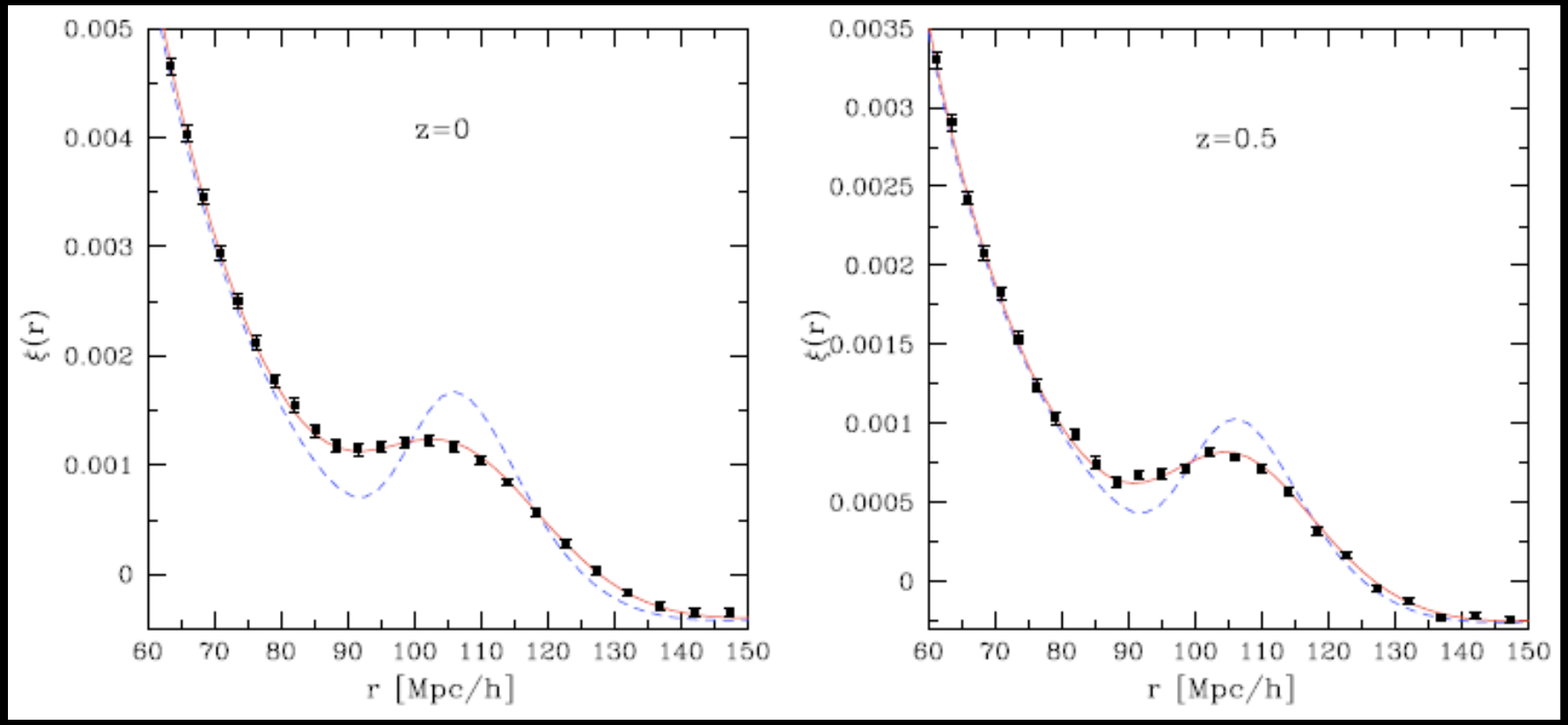
Rediscovered by Eisenstein et al. 2007

Renormalized Perturbation Theory



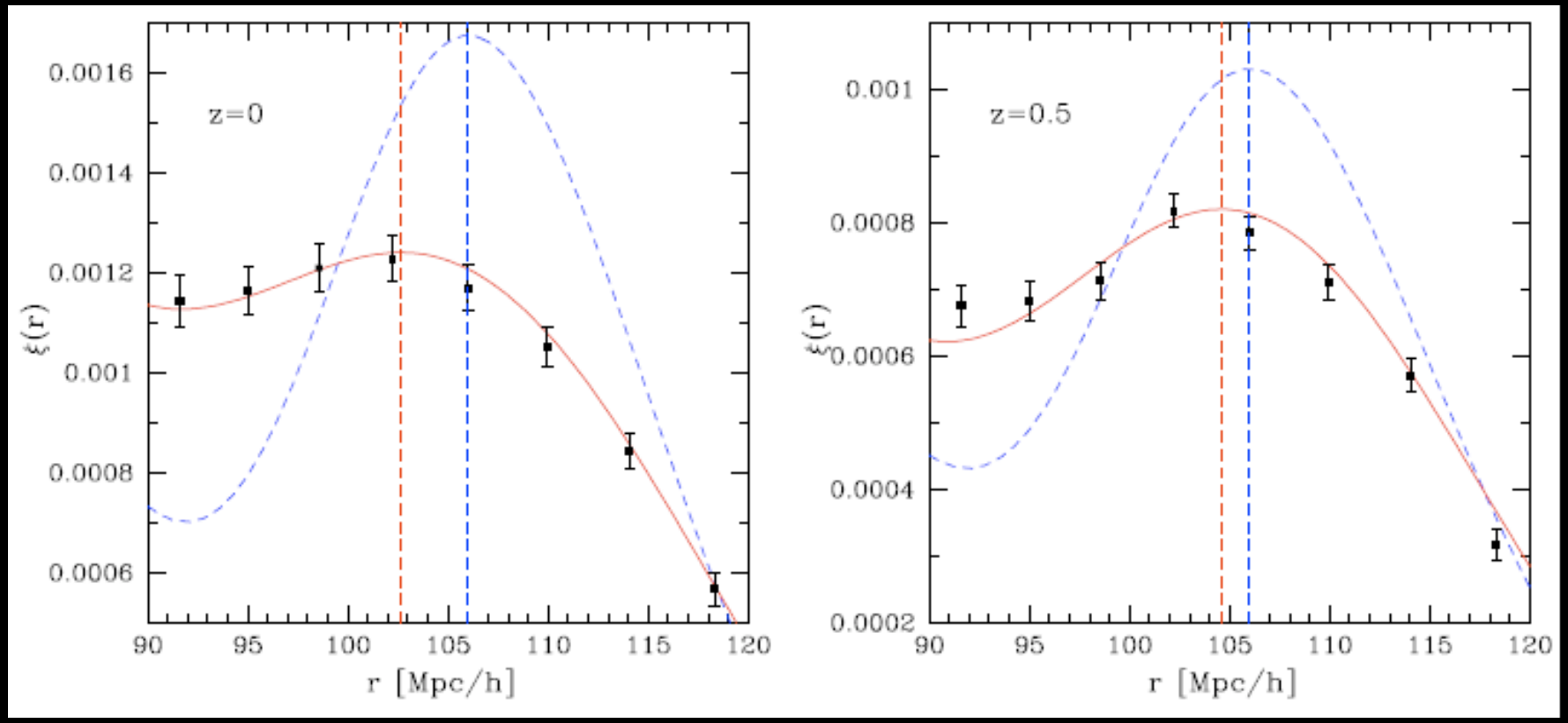
Crocce & Scoccimarro 2006, 2007; Matarrese & Pietroni 2007; McDonald 2006, 2007; Jeong & Komatsu 2007

Renormalized Perturbation Theory



Crocce & Scoccimarro 2007

The peak moves (a little) …

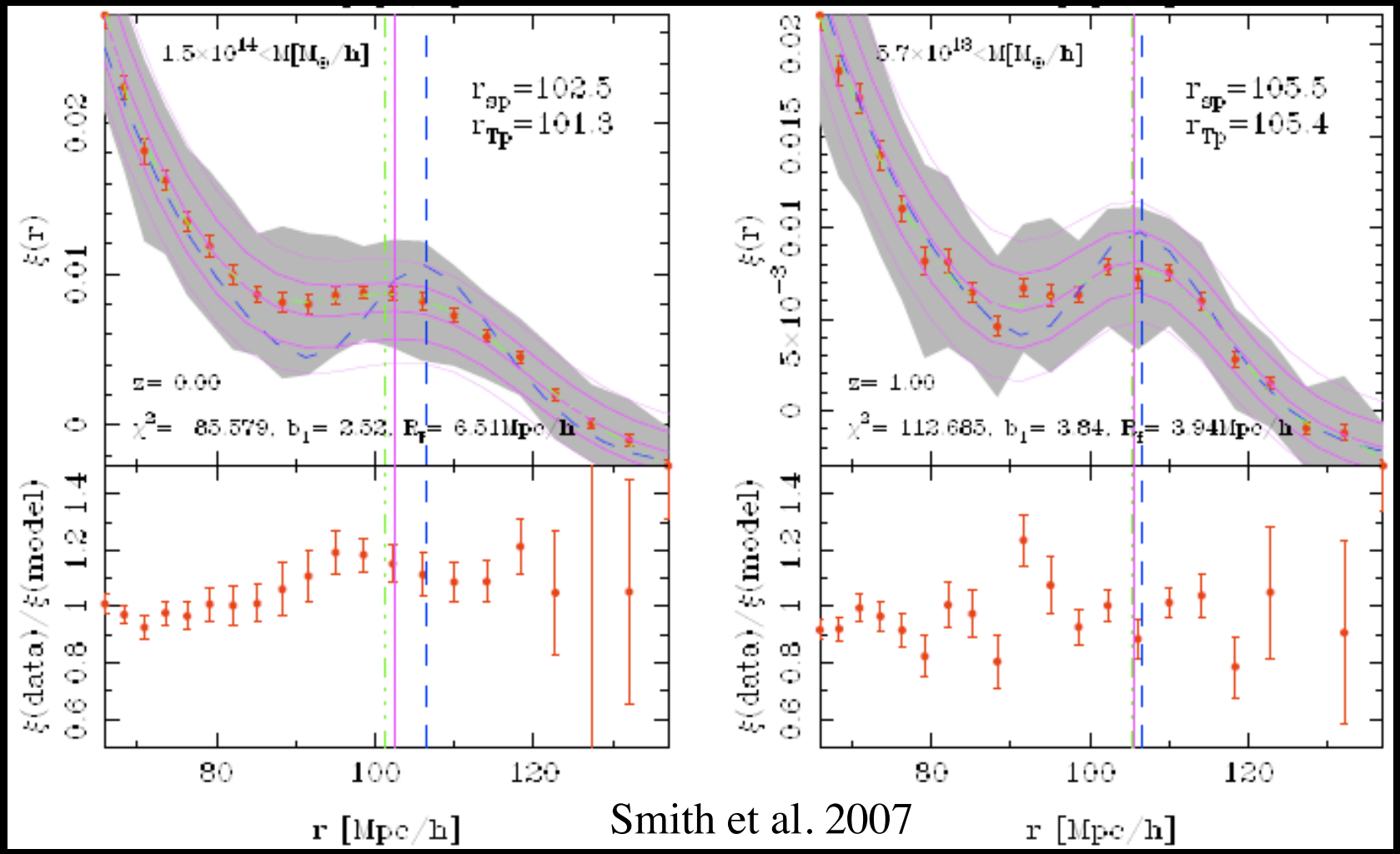


…because of smoothing (benign) and MC (pernicious)

What about halos (and galaxies)?

- RPT good to better than 1% for dark matter; no RPT for halos yet
- Accounting for nonlinear smoothing is necessary, but insufficient
- Smoothing likely to depend only weakly on halo mass (because velocities are approximately unbiased)
- Mode-coupling likely to be stronger for more biased tracers

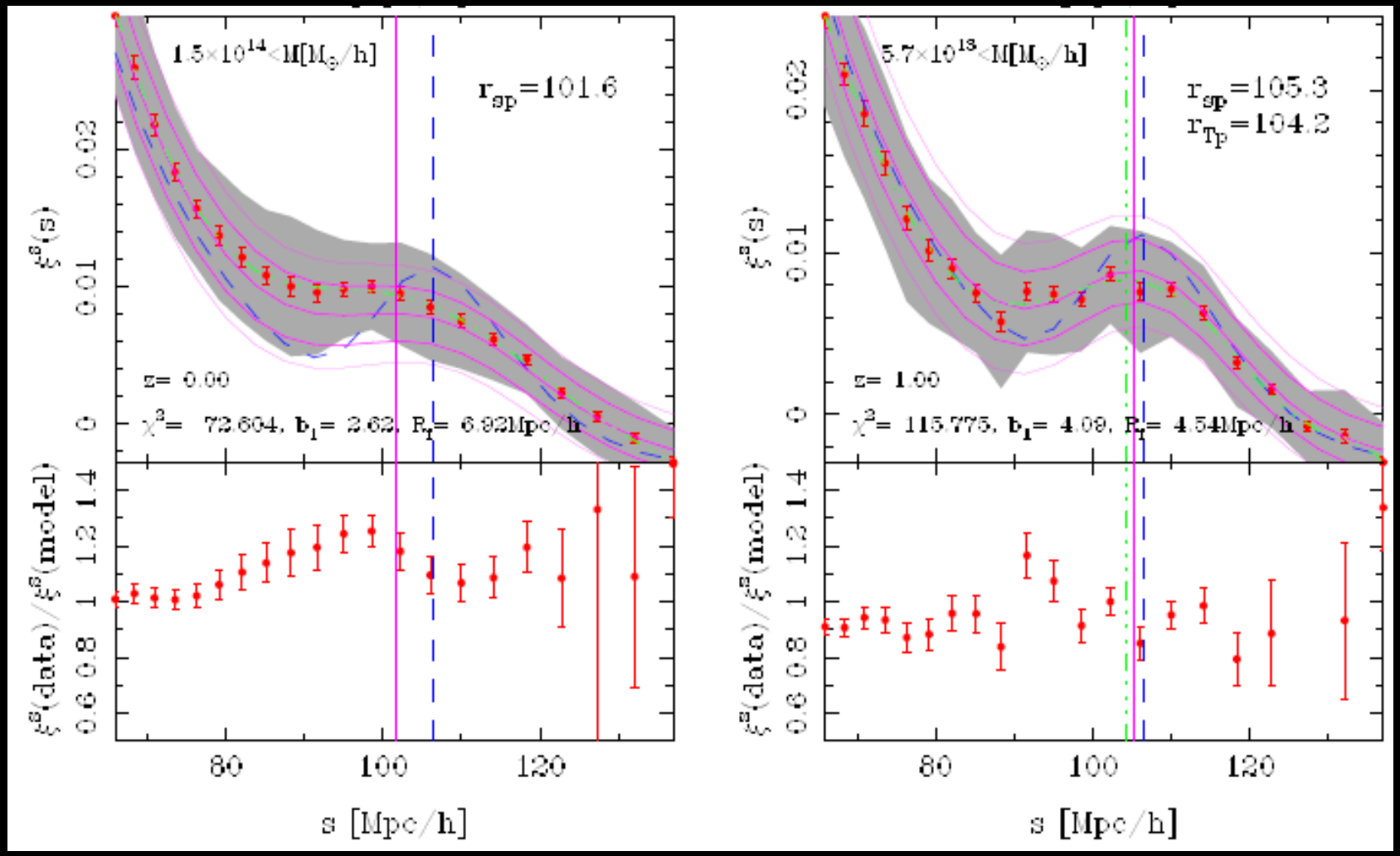
Methods with $\xi = G^2$ Ä $\xi_0 + \xi_{MC}$ with ξ_{MC} smooth …



Smith et al. 2007

N.B. Errors approximately, but not exactly, Gaussian + Poisson noise

… are not sufficiently accurate



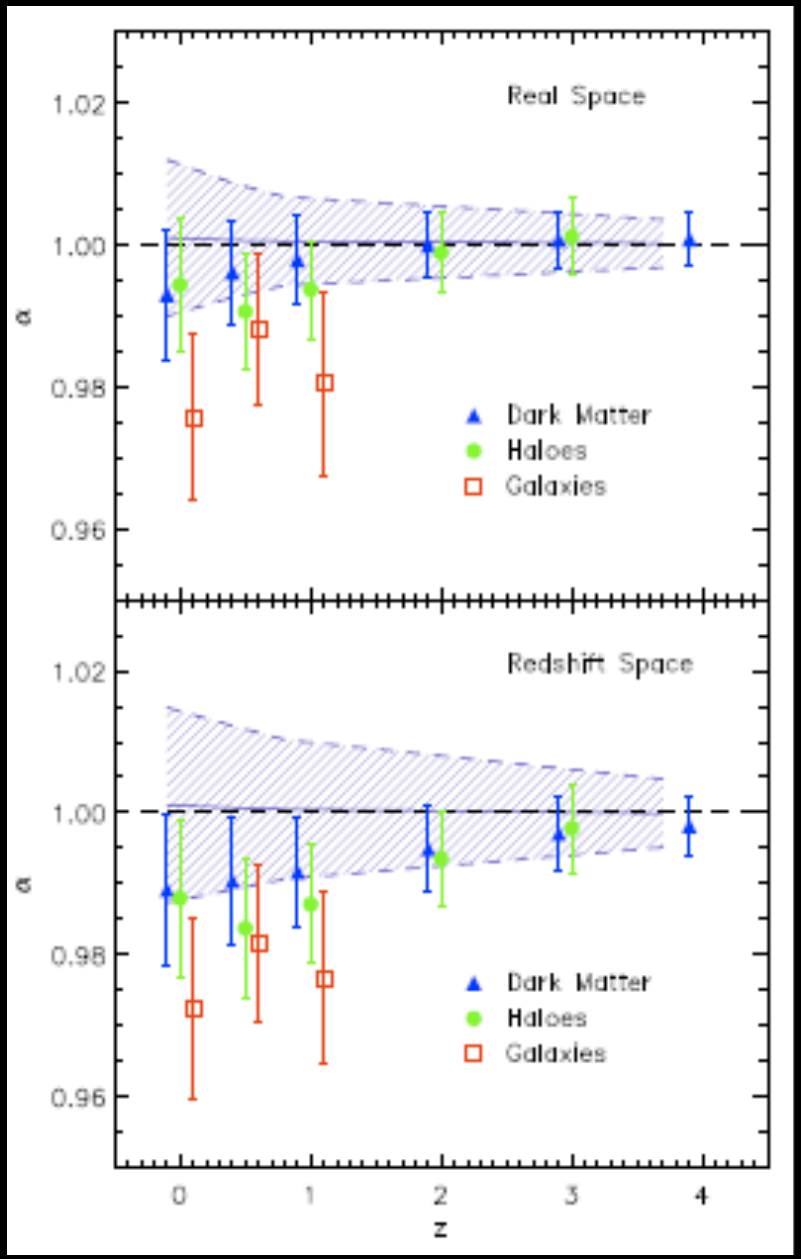
(note structure in residuals)

Smith et al. 2007

Shift is larger …

- At late times
- For more biased tracers
- In redshift space

- Crude model:
  - $P(k) \therefore P(\alpha k)$ and fit for α
  - Allow for nonlinear `smoothing' scale to be different along vs perpendicular to line of sight



Angulo et al. 2007

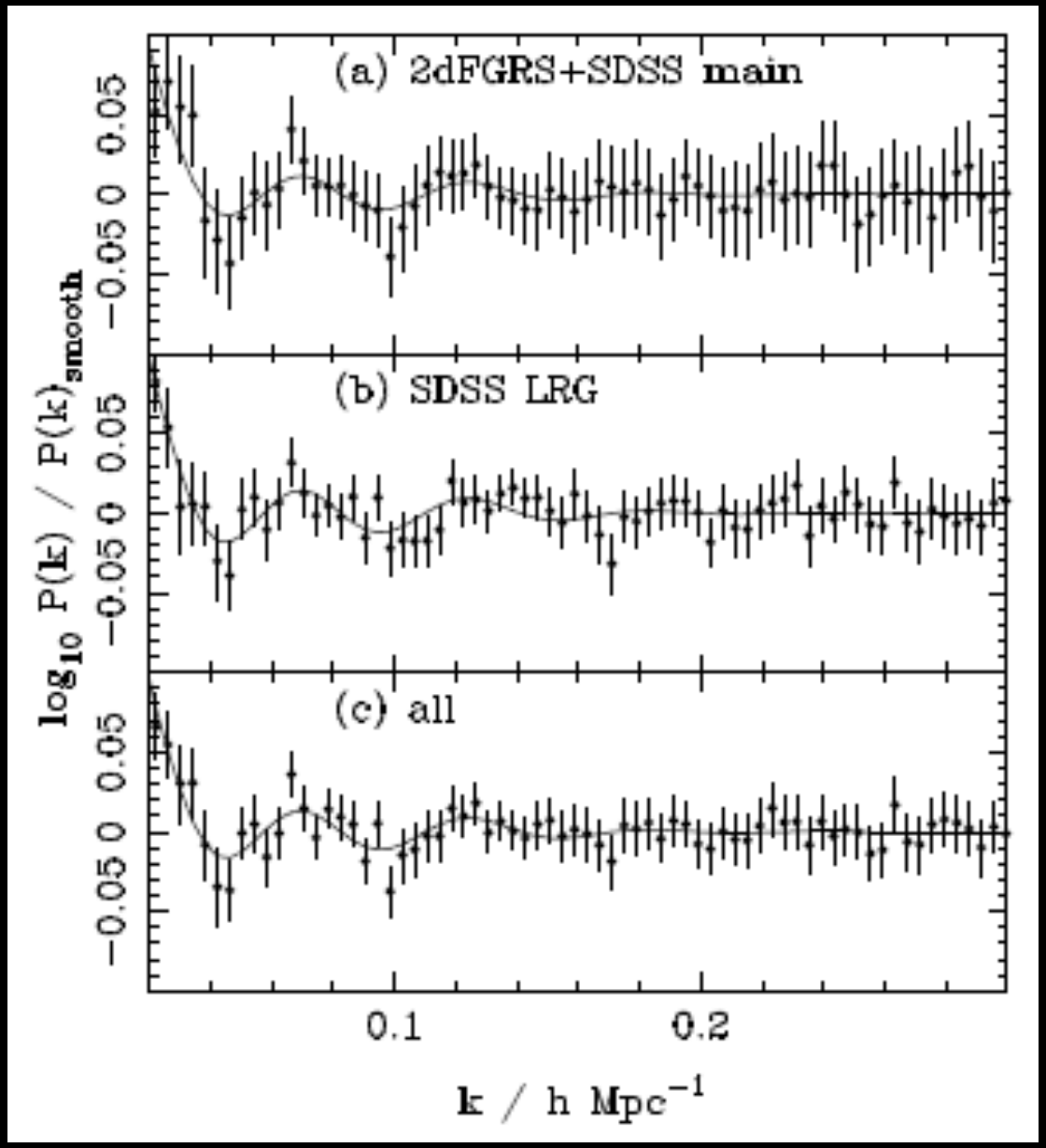
WARNING!

- The following content is of an explicit nature and may be offensive to some viewers.

Whose rod stays rigid longer?

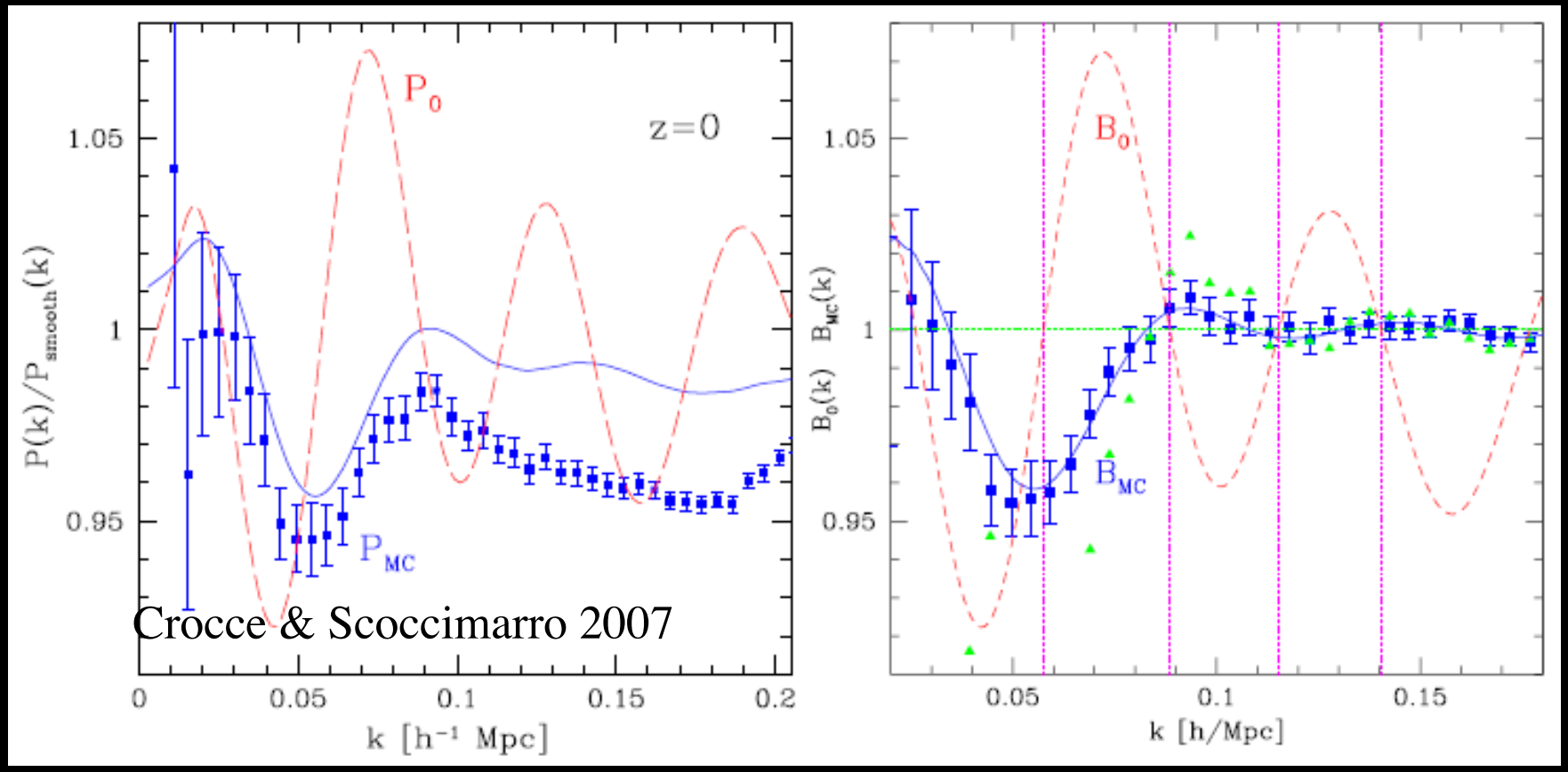
(Herbal supplements vs Viagra?)

- Rod is NOT location of maximum in measured $\xi(r)$
- Rod is NOT location of first (or first few) maxima and minima in $P(k)$
- Rod is first few zero crossings of this carefully defined ratio…?



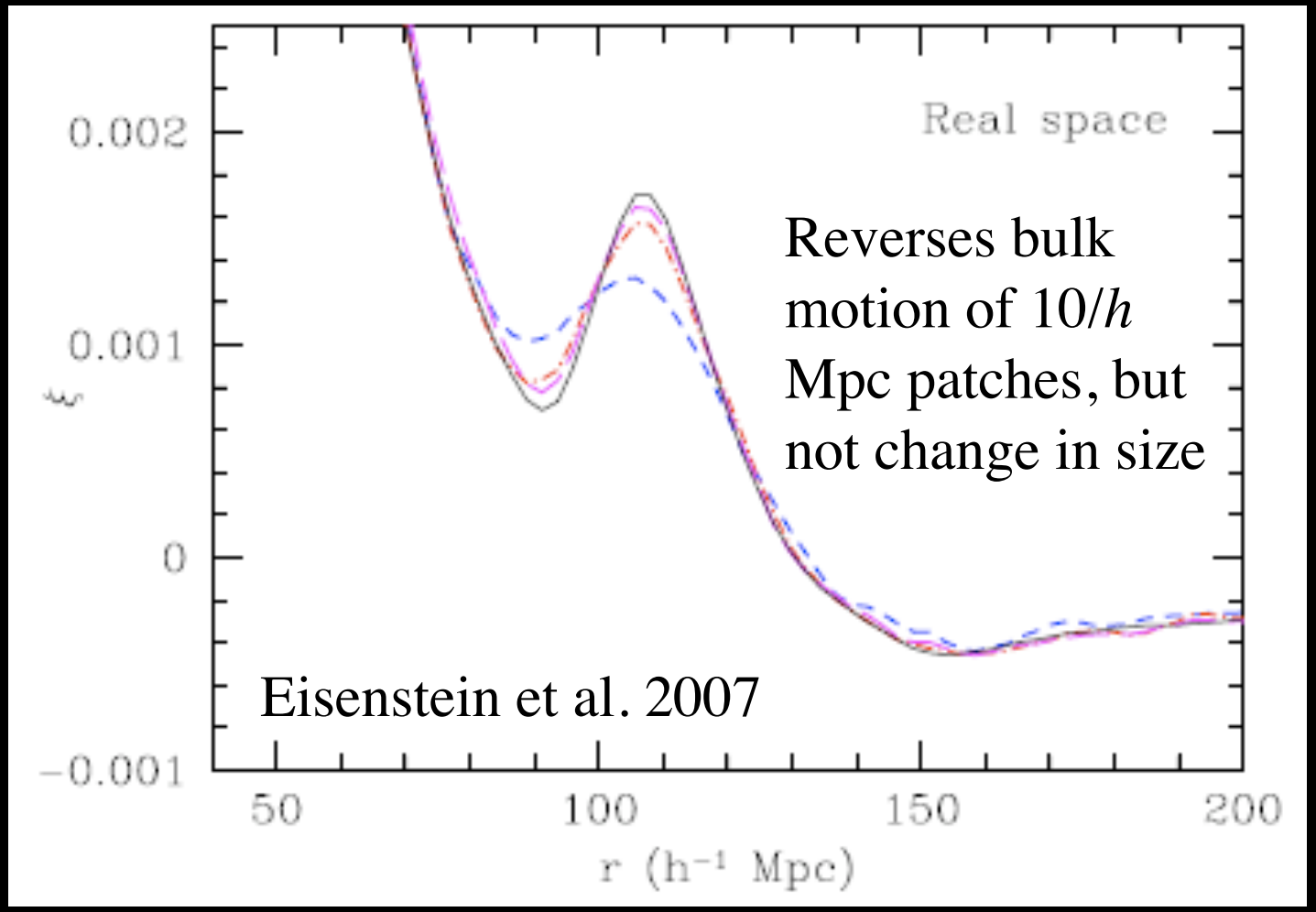
Percival et al. 2007

OR IS IT…???



MC terms show 90 degree phase shift: all previous methods miss this contribution

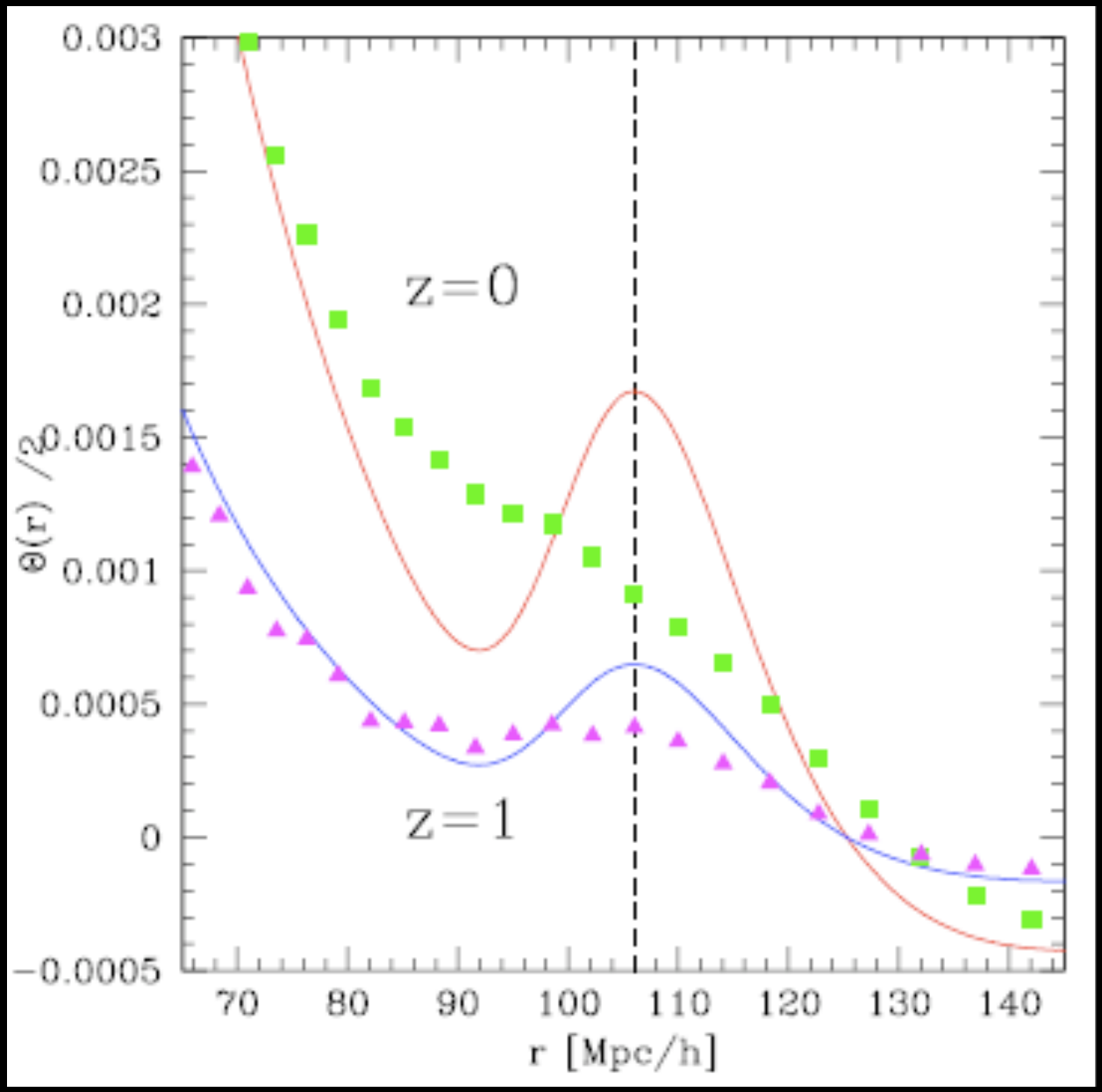
Reconstruction using linear theory



Must suppress fingers of god before applying in z-space

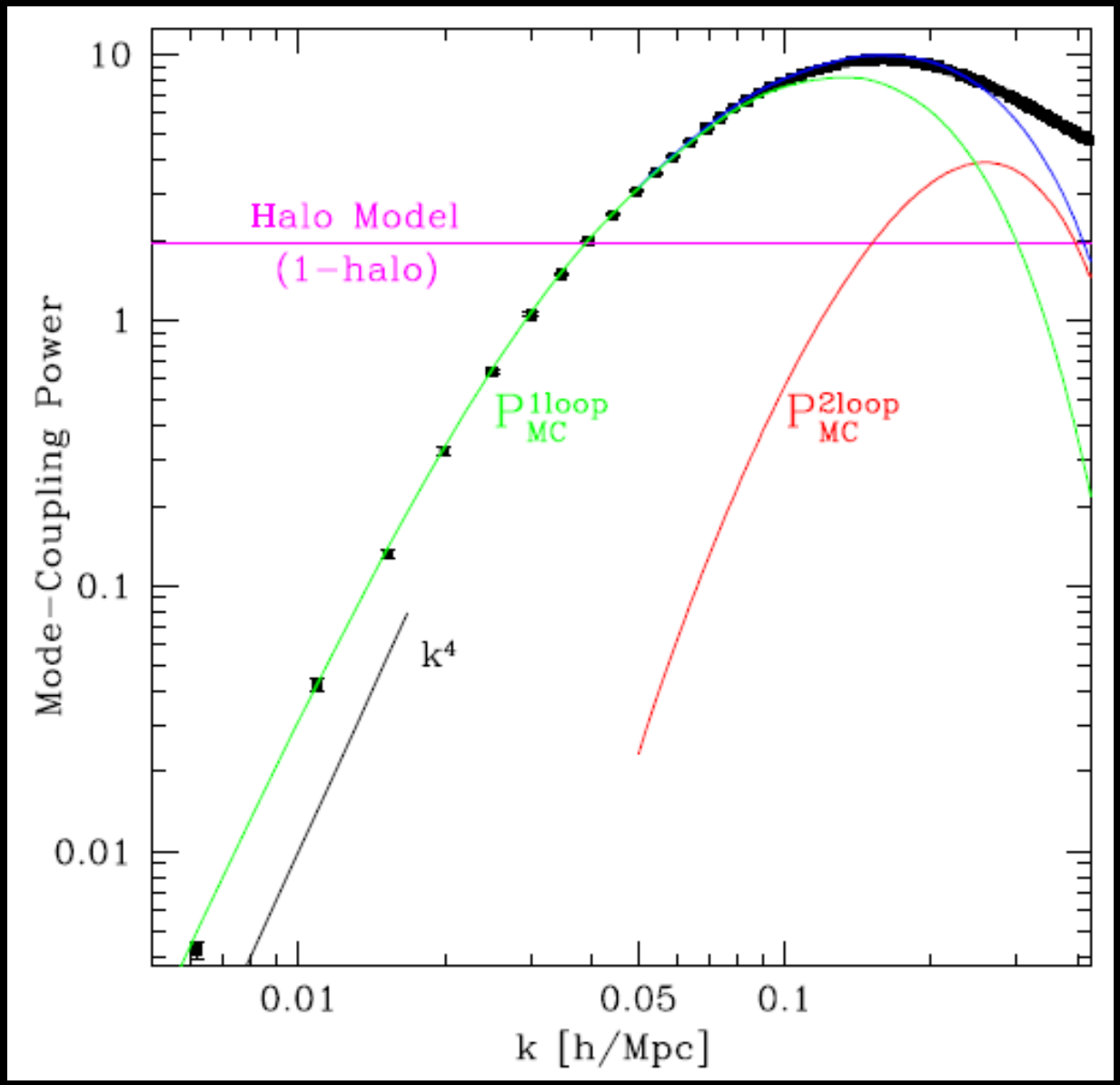
Error analysis more complicated

- Note that on these scales (divergence of) velocities *in*-consistent with linear theory, *even at z=1*



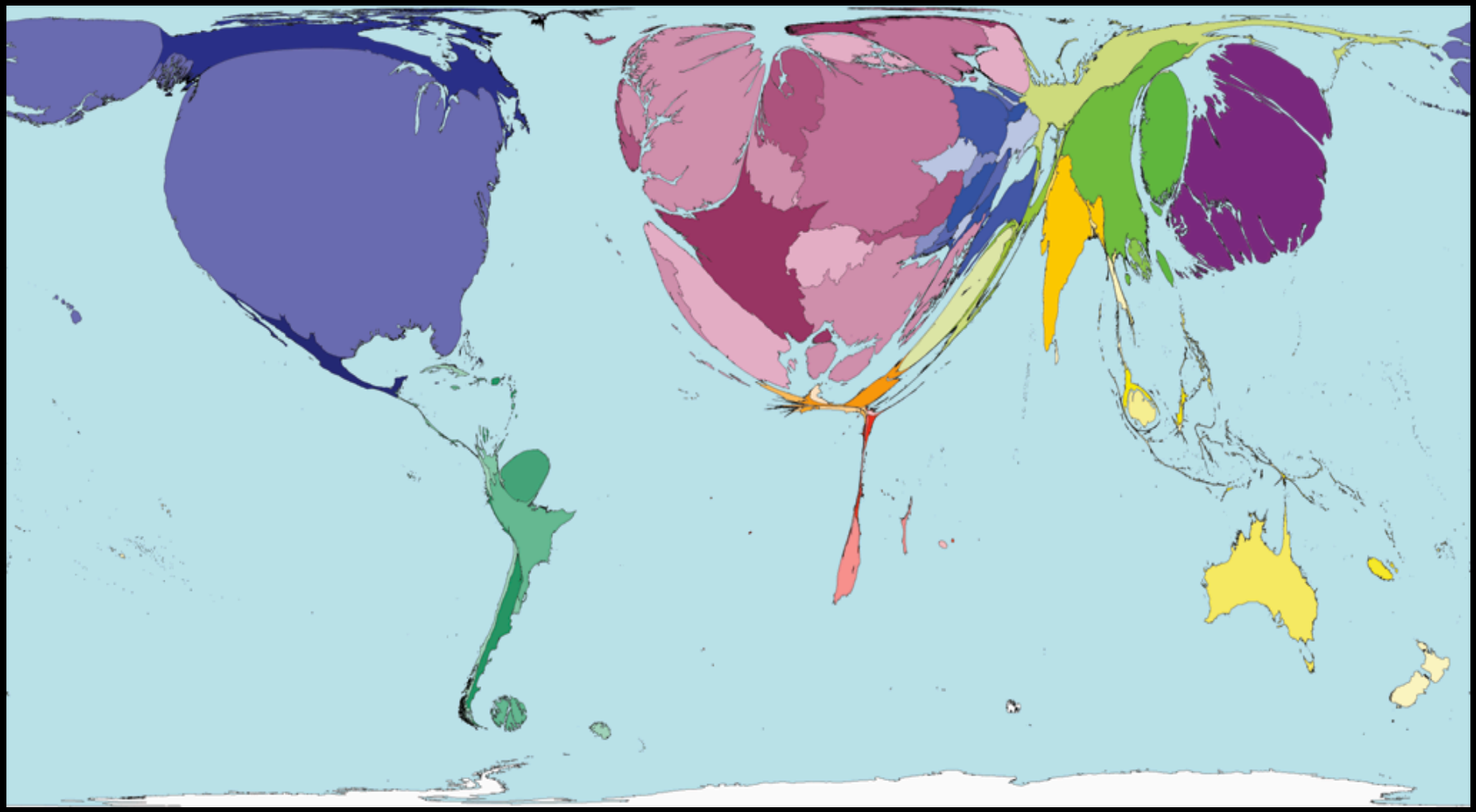
- RPT and halo model descriptions VERY different!

- More work needed

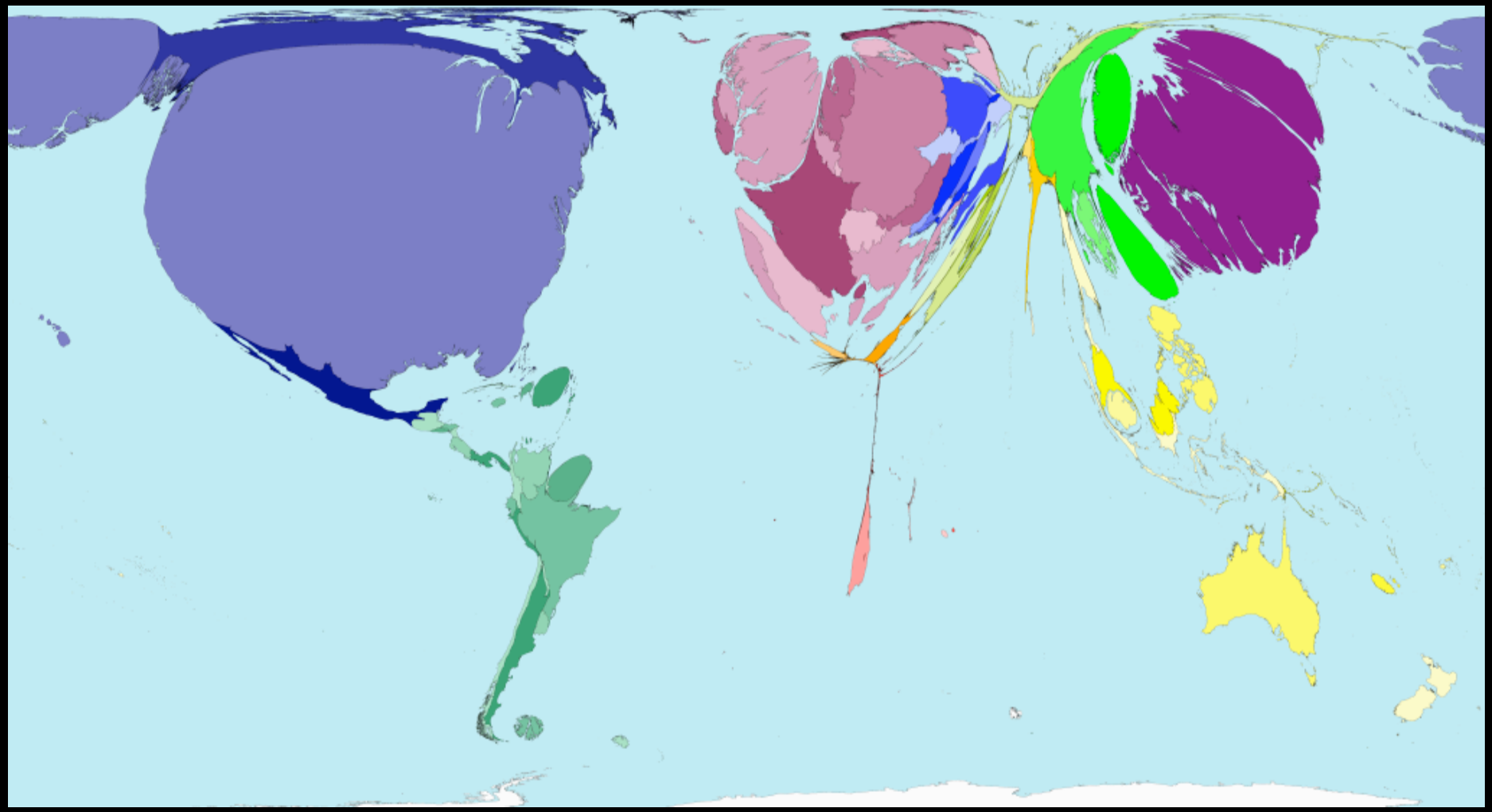


Summary

- Next decade will see 1% precision measurements in spectroscopic galaxy distribution to z~1, and Ly-alpha forest at z~3, and in photometric datasets.
- Should also see it in 21cm measurements.
- At this level of precision, BAO rod must be standardized, but this is quickly becoming a problem of known unknowns.
- RPT predicts consistency check from *B(k)*
- Least action based methods for reconstruction? (Croft & Gaztanaga 1997; Branchini, Eldar & Nusser 2002)



Research papers published in 2001



One world, One food: McDonalds outlets