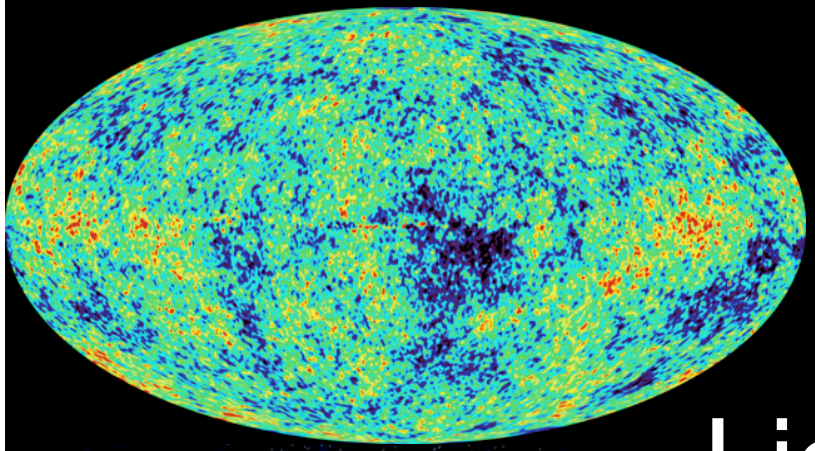
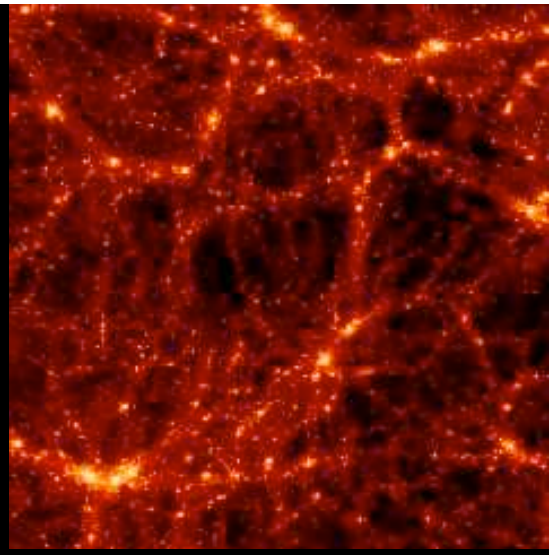
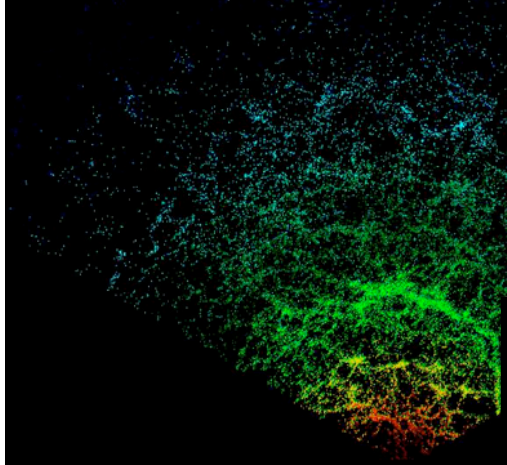
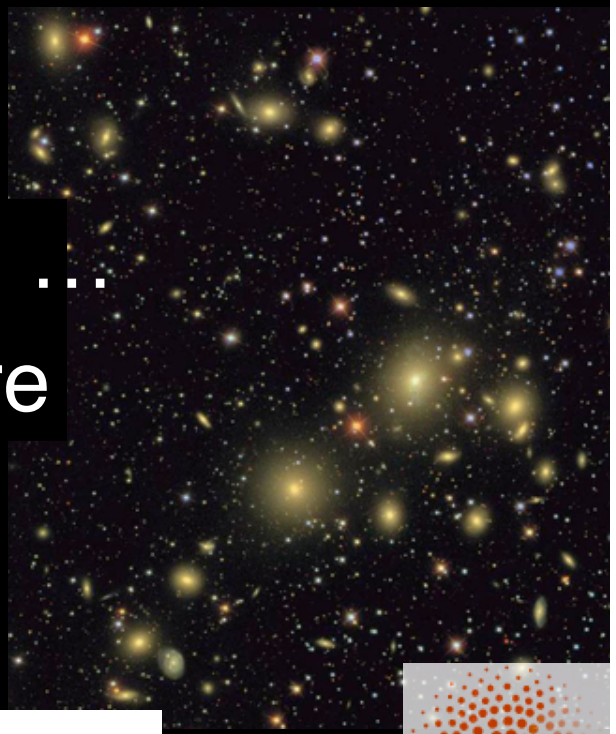




Licia Verde





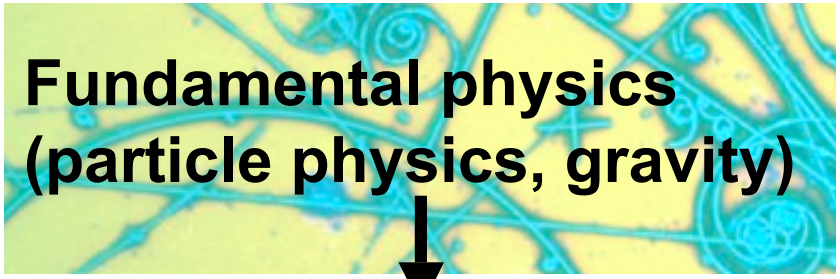
Unsolved problems in …

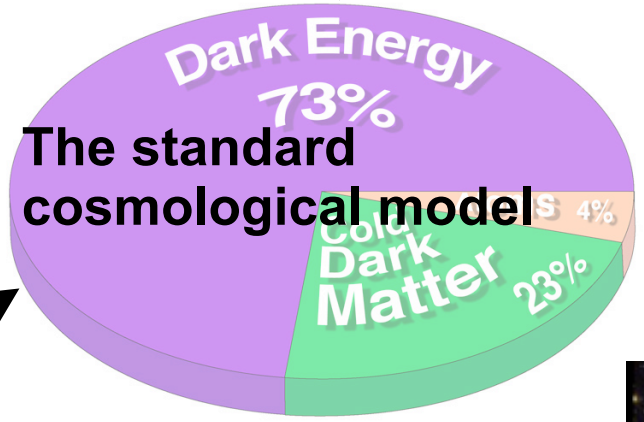
Large-scale structure

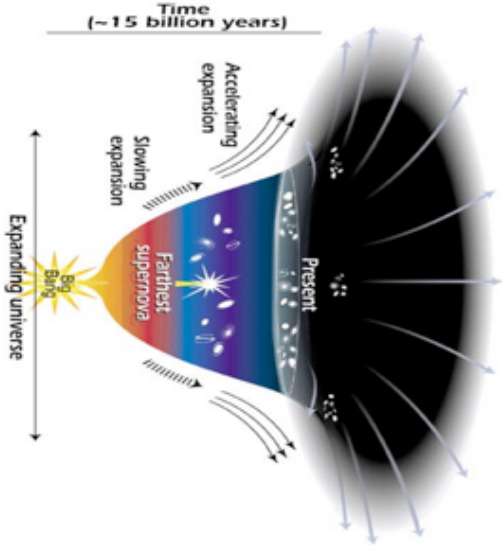
ICREA and ICC-UB IEEC
http://icc.ub.edu/~liciaverde/

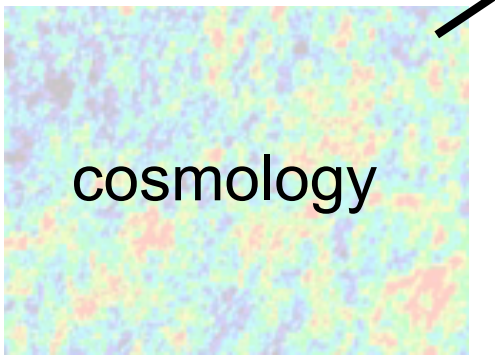
ICCUB Institut de Ciències del Cosmos
UNIVERSITAT DE BARCELONA
icrea Institució Catalana de Recerca i Estudis Avançats
erc

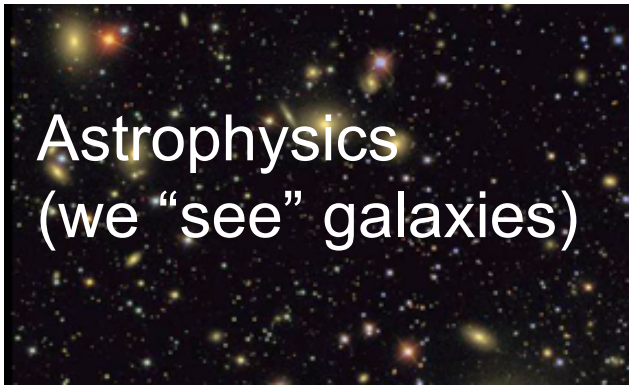
An extremely successful model for a preposterous Universe









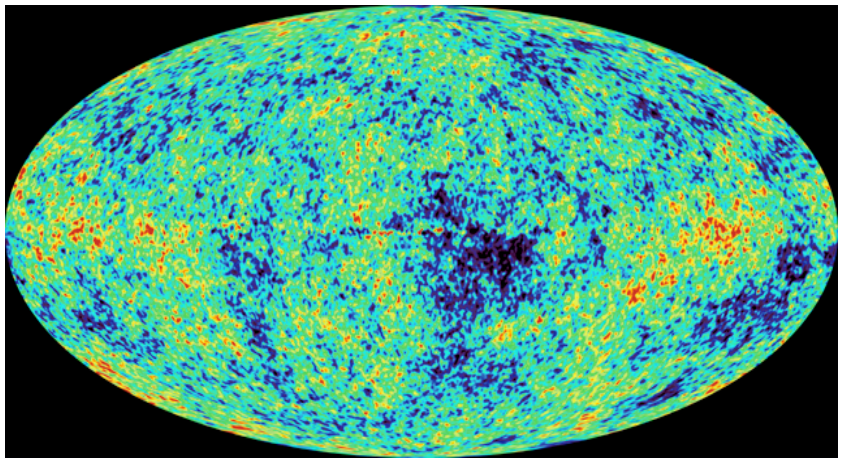


The status of cosmology

The status of LSS

Last Judgment, Vasari, Florence Duomo

Why large scale structure



CMB: Spectacular results
A snapshot of the Universe at recombination
Simple, clean physics
Perturbations are still linear, close to the initial conditions
Window into the early universe

BUT

13Gyr of Universe's history are just a "shadow" via secondary anisotropies

Physics happening
e.g., accelerated expansion, neutrinos properties,dark matter properties, etc.

The CMB gives mostly 2D info (snapshot), LSS add the third dimension and breaks degeneracies

The non-linearity of perturbations may have extra useful information

The catch is that things get much more

MESSY

Different probes:

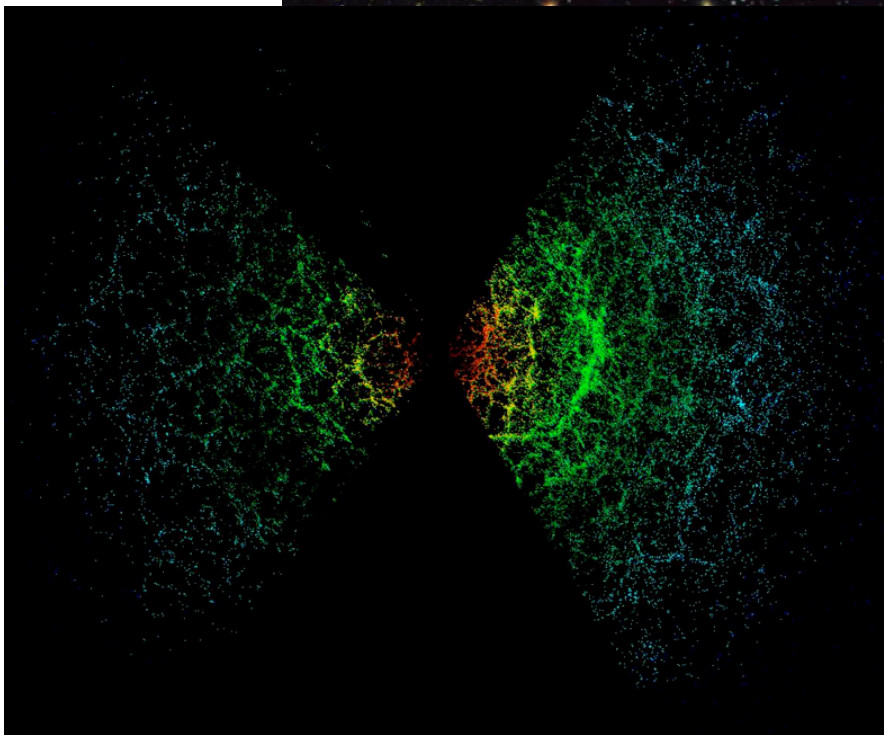
Weak gravitational lensing (A. Heavens)

Galaxy clustering

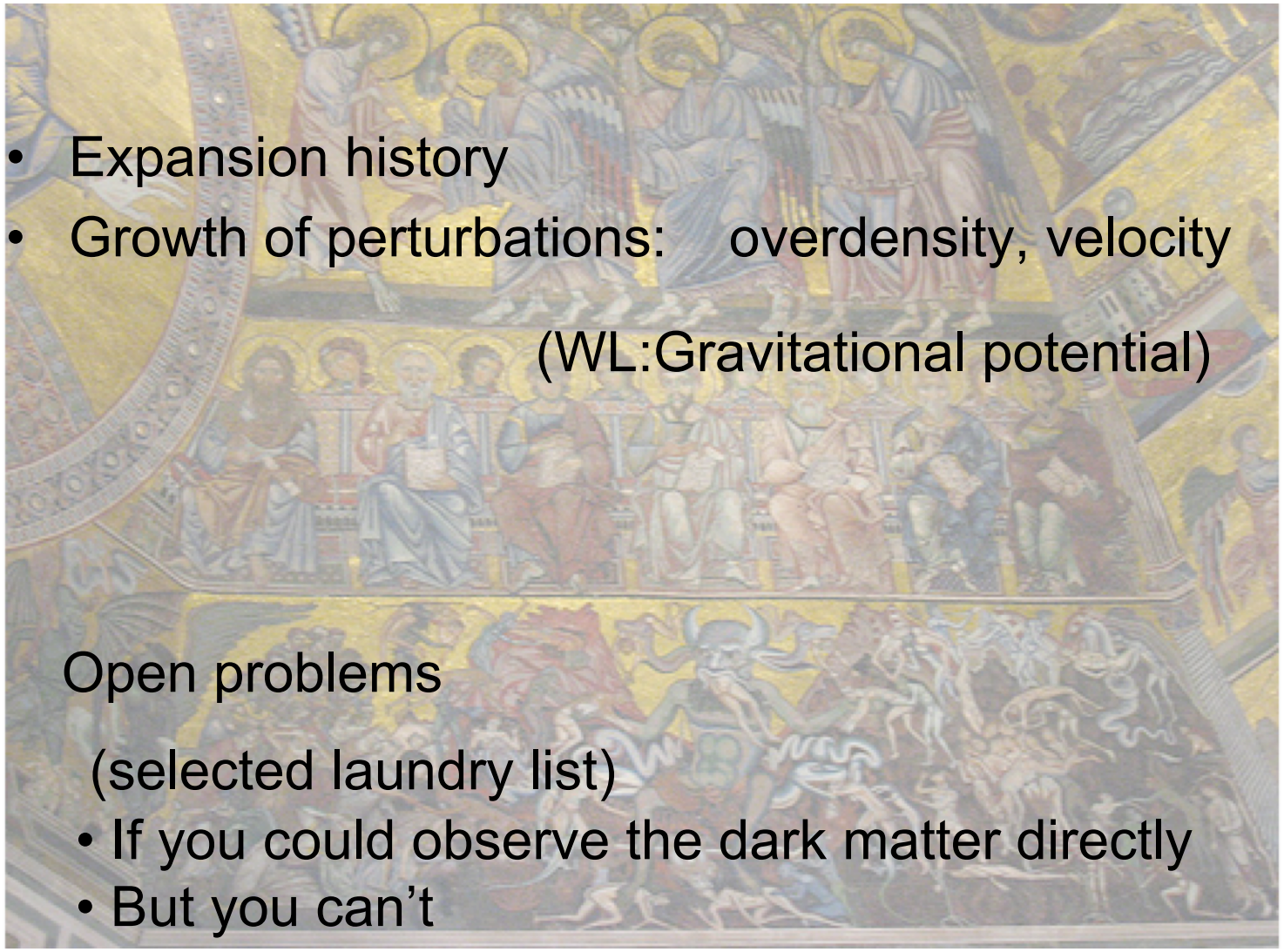
Galaxy clusters

Lyman-alpha forest

21 cm (A. Loeb, J. Hewitt)



What can LSS probe



- Expansion history
- Growth of perturbations: overdensity, velocity

(WL:Gravitational potential)

Open problems

(selected laundry list)

- If you could observe the dark matter directly
- But you can’t

Preliminaries: statistics

Real space

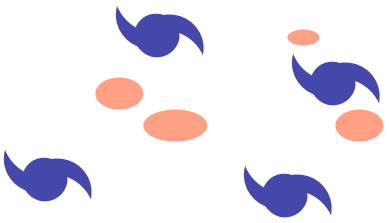
Correlation function

Localized in real space

Highly correlated errors

Not sensitive
to sky cuts/selection fn

Mix of linear-non linear scales



Fourier space

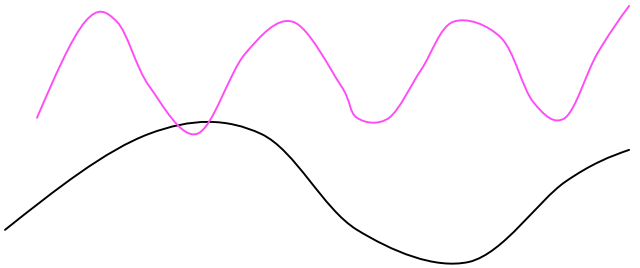
Power spectrum

not

Uncorrelated errors
in linear theory

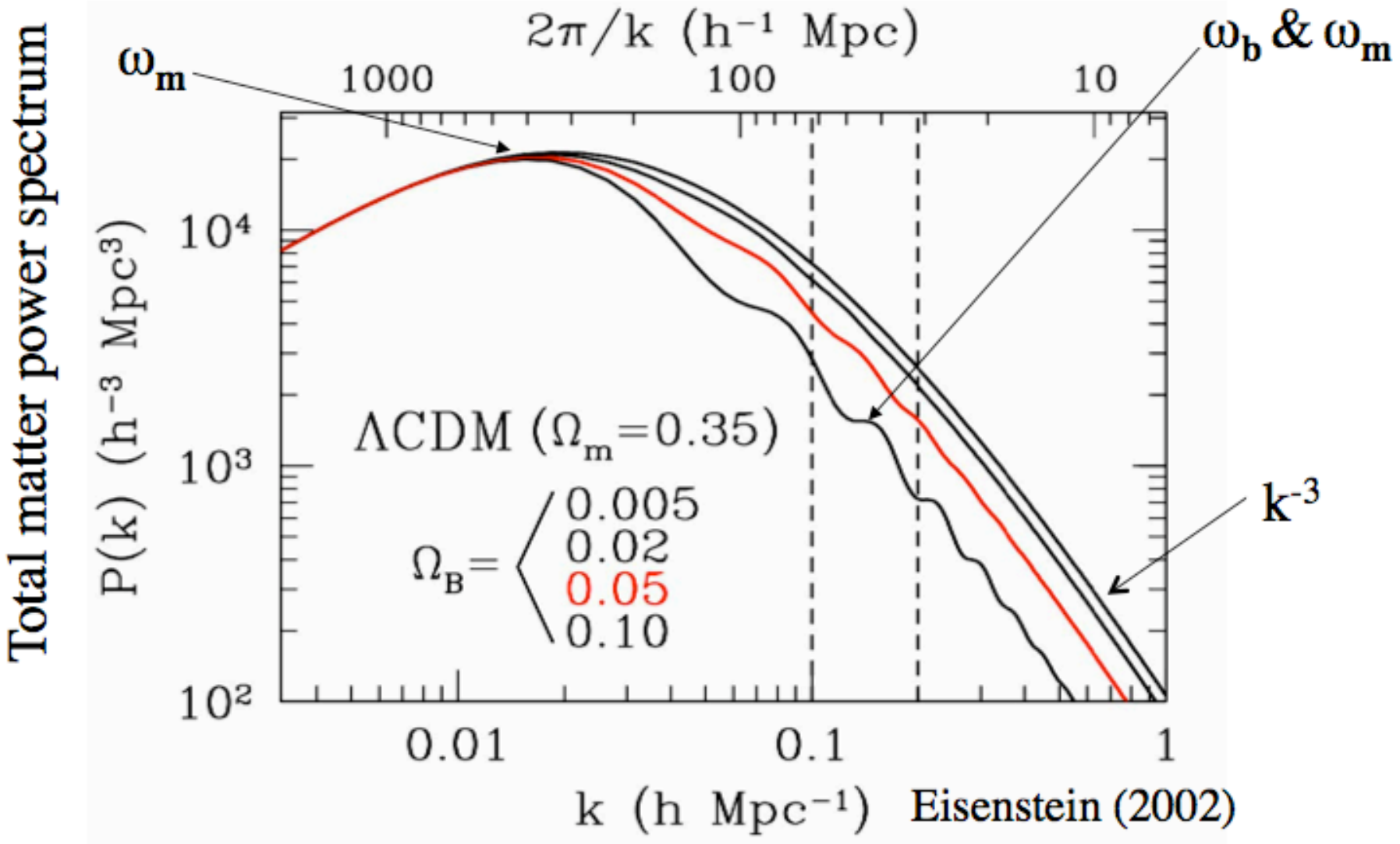
Very sensitive

Clear separation
linear-non linear scales

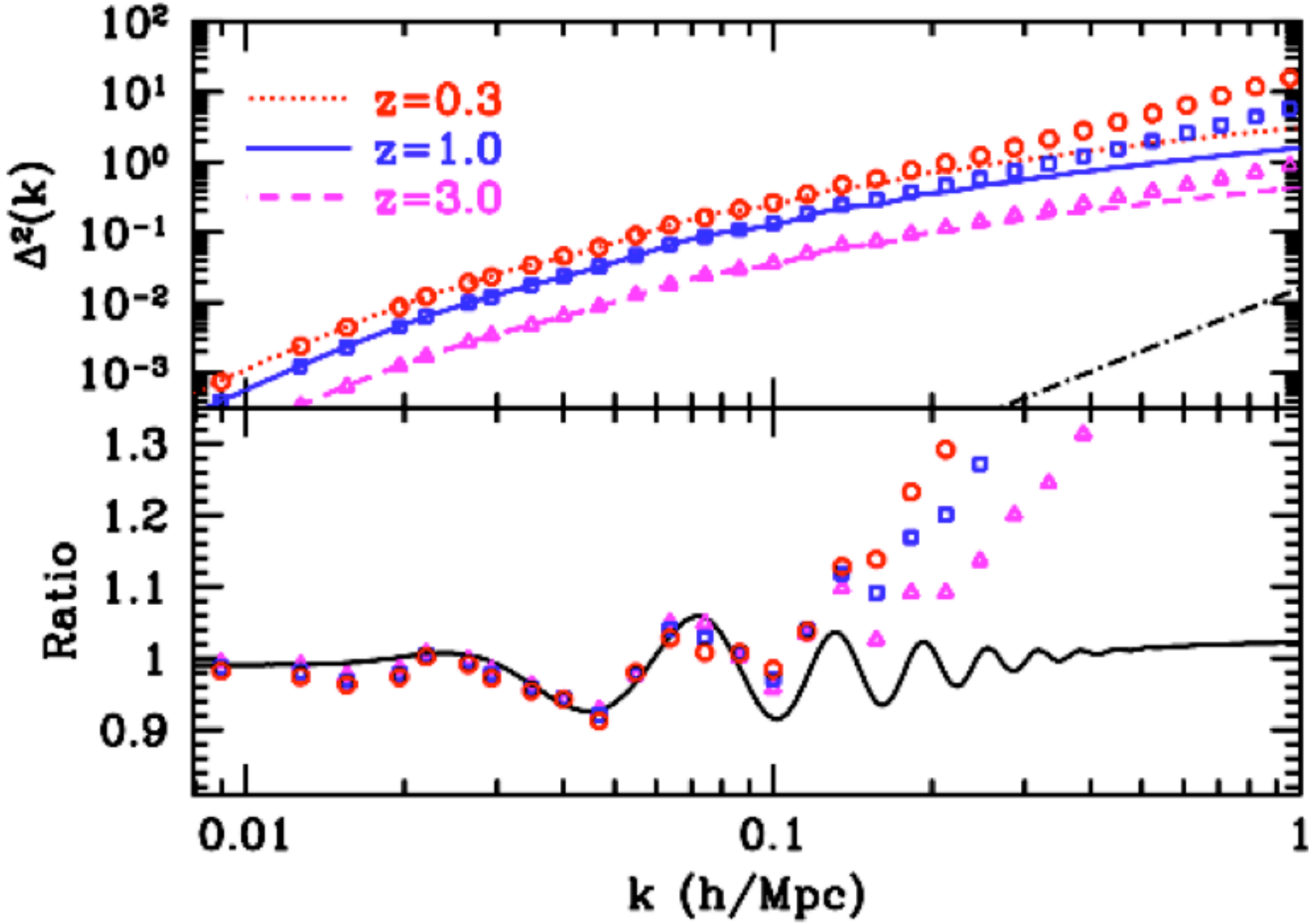


FT pairs!

Matter power spectrum: $P_L(k)$



Non-linearity



Non-linearity

Equations of motions (Ω_m=1)

Note: no GR

$$\begin{aligned} \frac{\partial \delta}{\partial \tau} + \vec{\nabla} \cdot [(1+\delta)\vec{v}] &= 0 \\ \frac{\partial \vec{v}}{\partial \tau} + \mathcal{H}\vec{v} + \left(\vec{v} \cdot \vec{\nabla}\right)\vec{v} &= -\vec{\nabla}\Phi \\ \nabla^2 \Phi &= \frac{3}{2}\mathcal{H}^2 \delta \end{aligned}$$

- Very familiar looking fluid equations
  - means we can borrow methods/ideas from other fields.
- Note the quadratic nature of the non-linearity.
- Since equations are now non-linear, can't use super-position of (exact) solutions even if they could be found!
- Proceed by perturbative expansion.

Aside
(what gauge?)

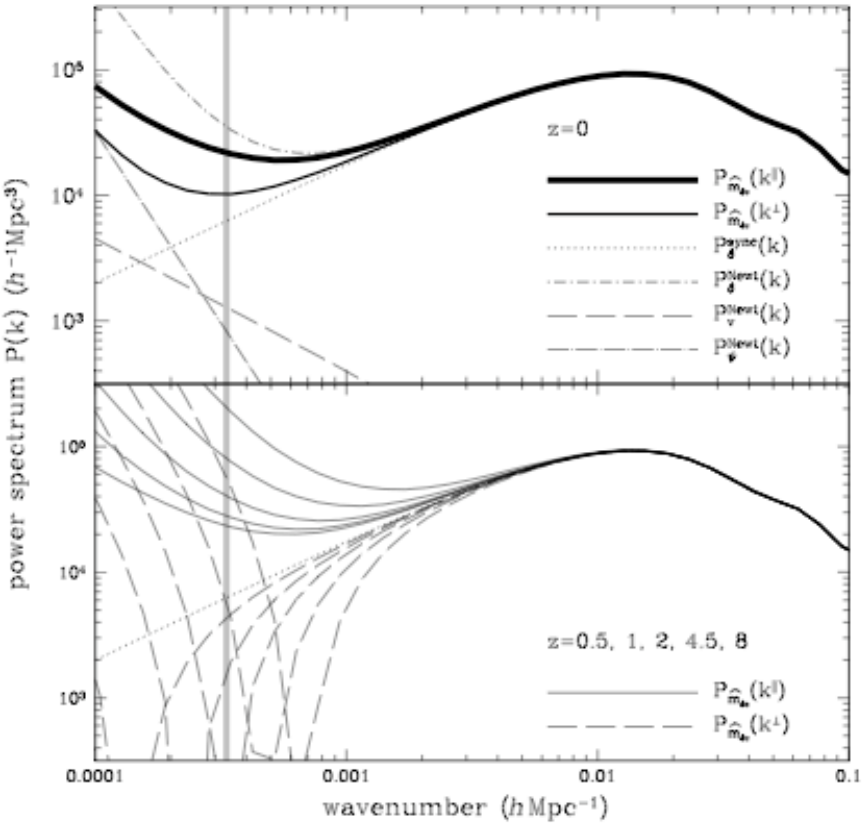


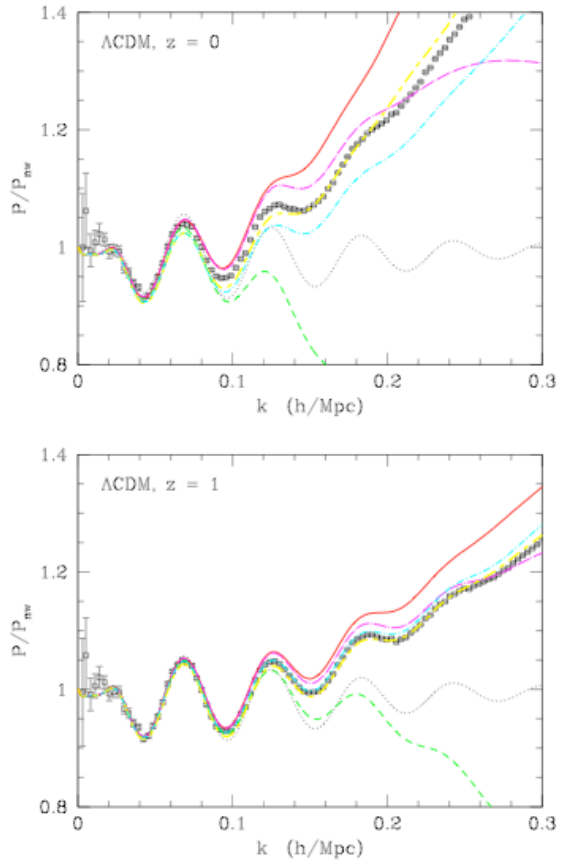
FIG. 1: Matter power spectrum $P_{\hat{m}_{\delta z}}(k, \mu_k)$ at various redshifts. Upper panel: Solid lines represent the matter power spectrum at $z = 0$, computed by using Eq. (7) along the line-of-sight direction ($\mu_k = 1$; thick) and along the transverse direction ($\mu_k = 0$; thin). For reference, various lines indicated in the legend show power spectra of perturbation variables in the conformal Newtonian gauge and the synchronous gauge. Bottom panel: matter power spectrum $P_{\hat{m}_{\delta z}}(k, \mu_k)$ at $z > 0$, but with its amplitude normalized to match $P_{\hat{m}_{\delta z}}(k, \mu_k)$ at $z = 0$. Solid and dashed lines represent $P_{\hat{m}_{\delta z}}(k, \mu_k)$ with $\mu_k = 1$ and $\mu_k = 0$, respectively. The horizon scale at $z = 0$ is shown as a vertical line.

- What are we actually measuring ?

On very large scales, not clear (Yoo 10)

Analytical tools to model non-linearities

- Perturbation theory
- Renormalized PT
- Lagrangian PT
- Renormalization group
- Time renormalization group



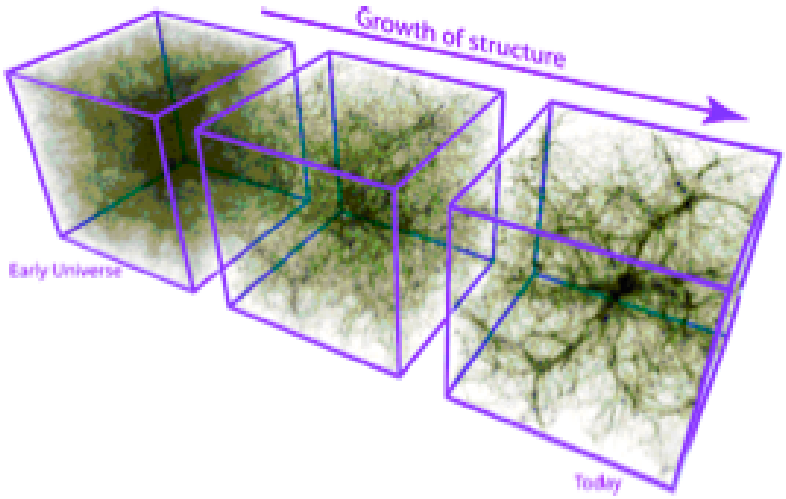
Open issues: which is best? In what regime? for what models?

Carlson et al 09 (and refs therein), Pietroni 08, S. Matarrese

Simulate the heck out of it

(G. Hinshaw)

If it is “just” gravity, N-body,DM-only simulations should do the trick (V. Springel)



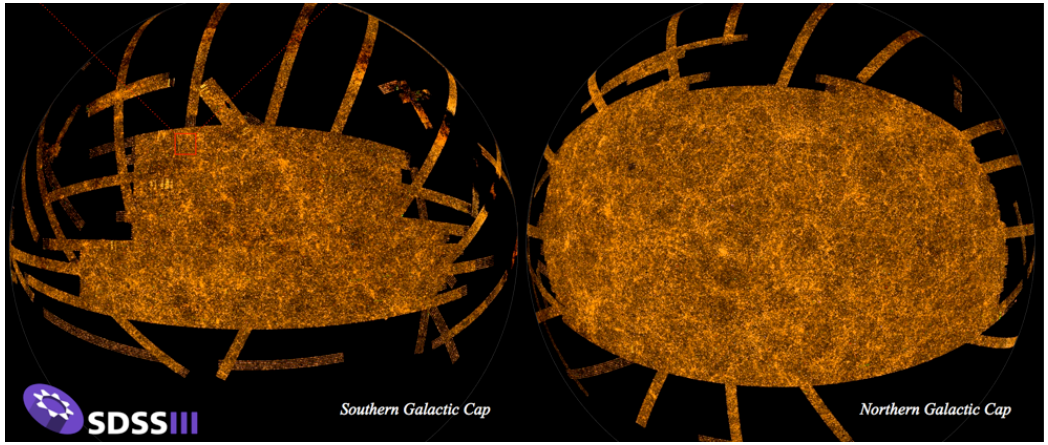
Issues: resolution, starting redshift, initial conditions…(Wagner)

In particular: computationally expensive
How to explore different cosmologies? “cosmic calibration” (LANL)

for future surveys: the entire survey volume cannot be simulated
What volume is needed? Would many small volumes do? (later)

ERRORS (covariances)

In the correlation function correlations are always large
--> Monte-Carlo simulate errors on mock Universes (surveys)



In the power spectrum:

Linear theory, infinite volume no correlations!!!

Effect of the mask (sky-cut) and selection function--> mode coupling

Non-linearities --> mode coupling

Relatively new effect: beat coupling

CAN'T simulate the full survey volume

Open issue!

Roland De Putter, Olga Mena for SDSS

Expansion history

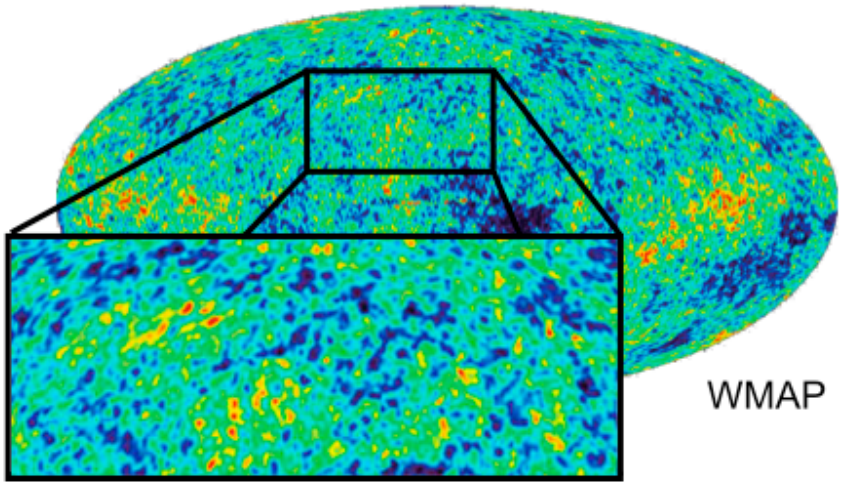
BAO

Baryon acoustic oscillations

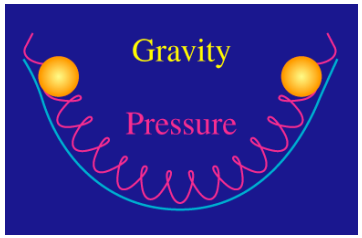
Sound horizon at decoupling

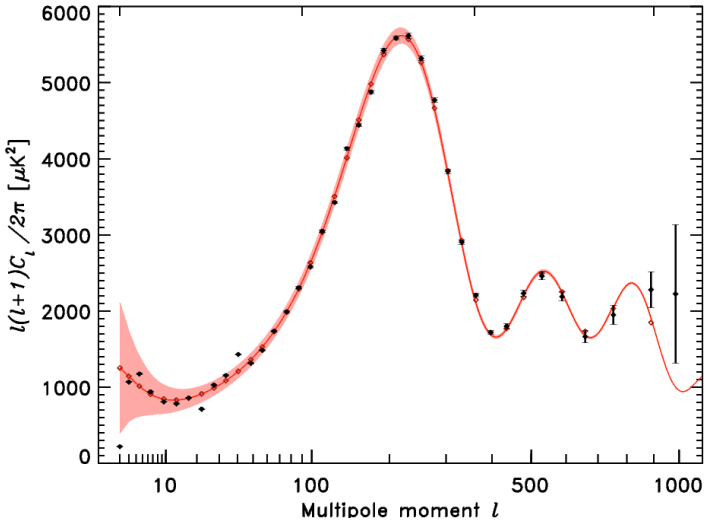
$$k_{\rm bao} = 2\pi/s$$

$$s = \frac{1}{H_0 \Omega_m^{1/2}} \int_0^{a_*} da \frac{c_s}{(a + a_{\rm eq})^{1/2}}$$

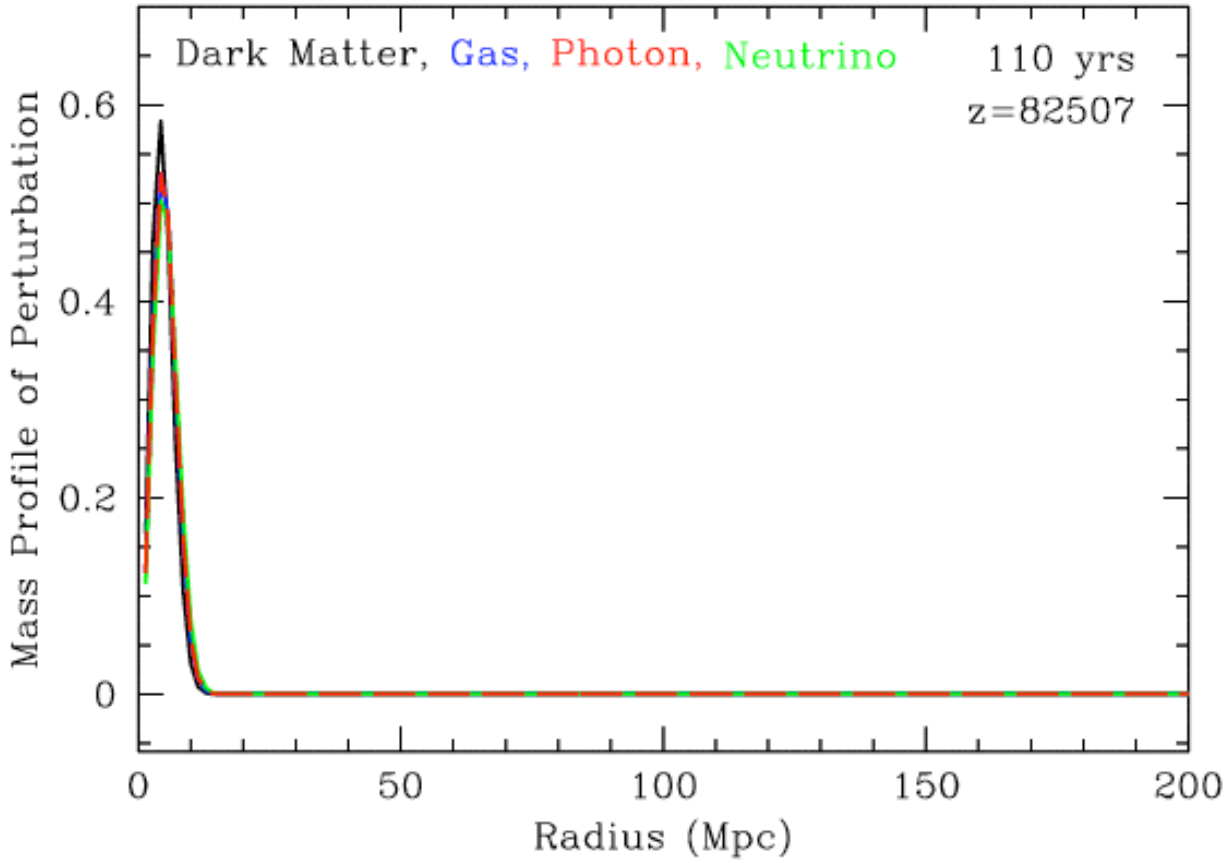


WMAP





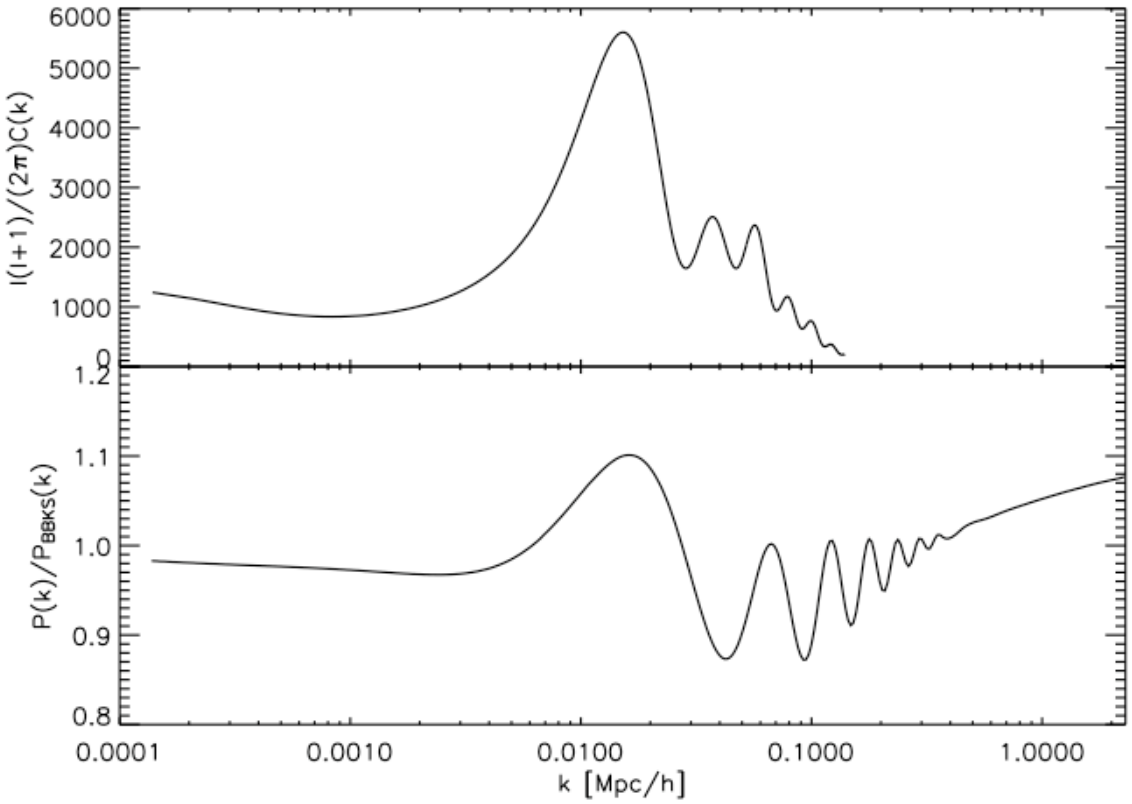
BAO



For those of you who think in Real space

Courtesy of D. Eisenstein

BAO



Observe photons

Photons coupled to baryons

“See” dark matter

If baryons are ~1/6 of the dark matter these baryonic oscillations should leave some imprint in the dark matter distribution (gravity is the coupling)

For those of you who think in Fourier space

BAO

Standard rulers at different redshifts

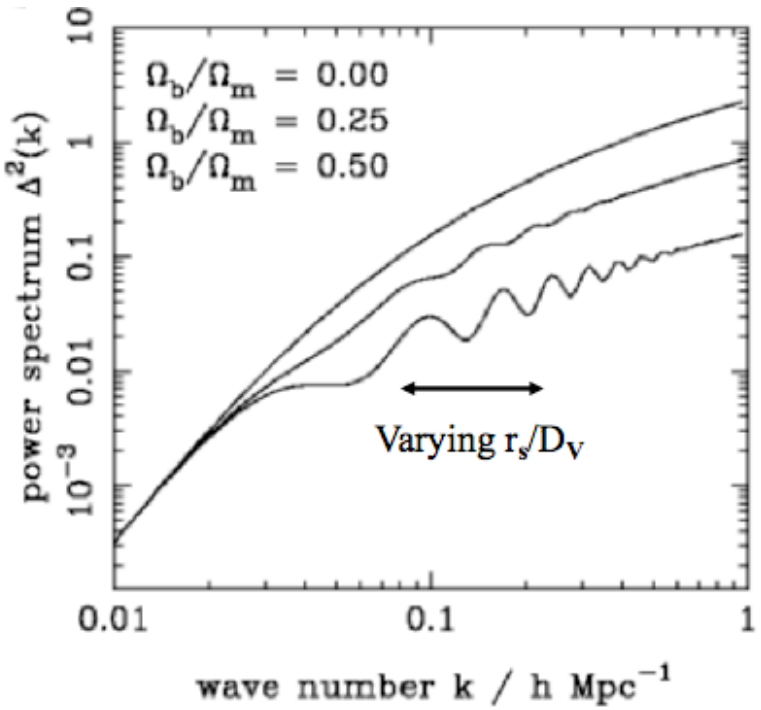
BAO measurements linked to physical BAO scale through:

Radial direction

$$\frac{c}{H(z)}\Delta z$$

Angular direction

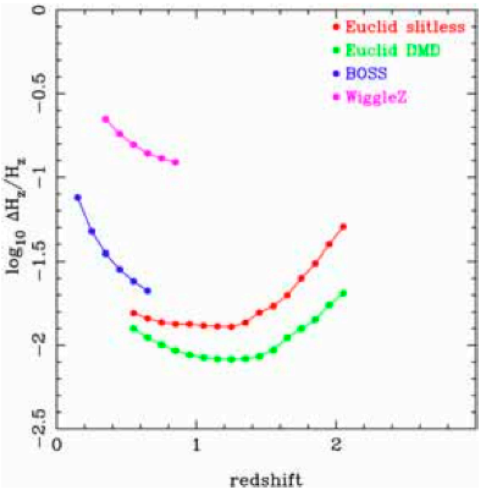
$$(1+z)D_A\Delta\theta$$

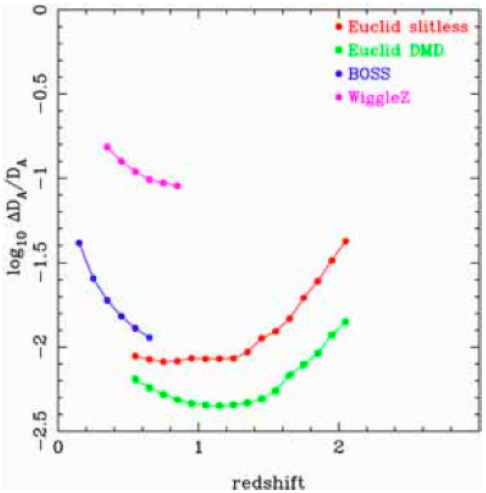


On Average:

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

Forecasts are great!





EUCLID yellow book

0912.0914

Open issues: how well is the standard ruler known?
Shall one also use the AP test?
Or just relative measurements?

BAO are on linear-mildly non-linear scale:
-non-linearities erase BAO feature: can they be un-done in part?
-can any residual bias be corrected? (see discussion on sims)

Reconstruction?

Velocity flows and non-linear collapse move matter in the Universe around by of order 10 Mpc relative to its initial comoving position. This tends to move pairs out of the 150 Mpc peak e.g. broaden the BAO.
On the large scales the bulk flows are generated by the density perturbations being surveyed, could one move particles (galaxies) back in time?

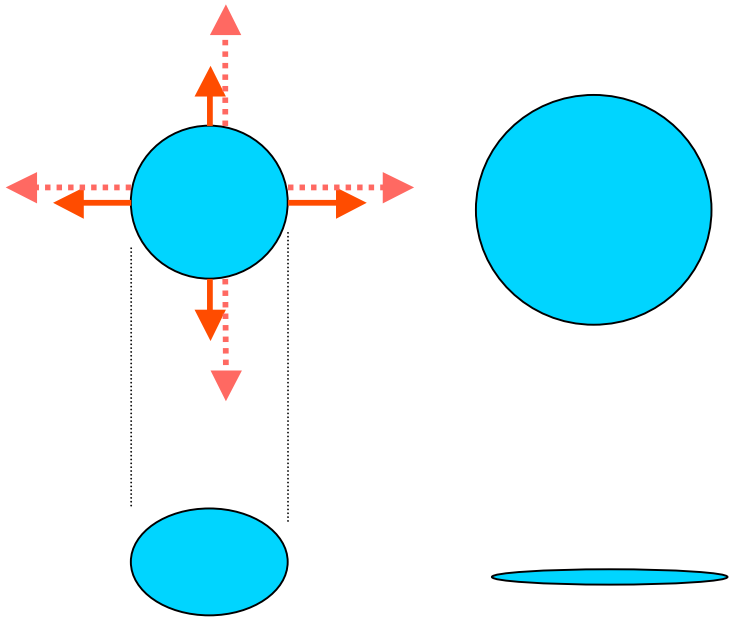
Issues: only applied on simulations so far…. (experts?)

WHAT ABOUT VELOCITIES?

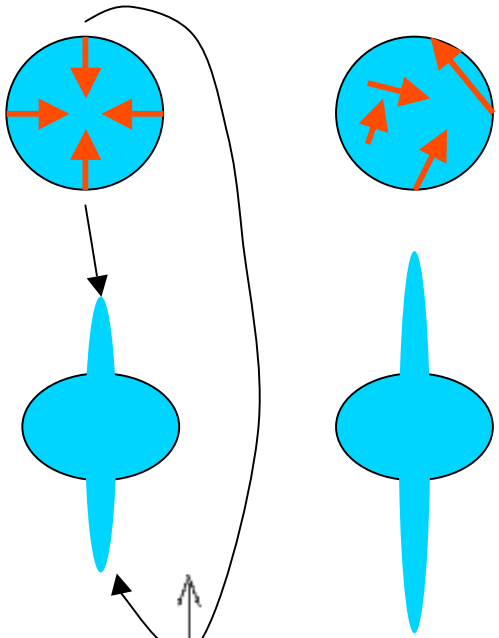
Redshift-space distortions (Kaiser 1987)

$z_{obs} = z_{true} + \delta v / c$ **δv prop. to** **d ln δ/dln a** **δρ/ρ**

shells



β

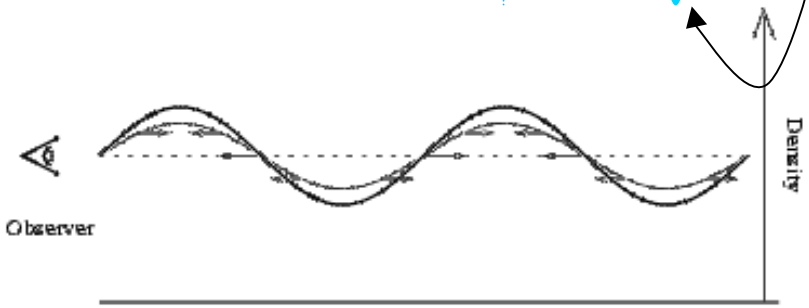


σ_p

linear

Non-linear

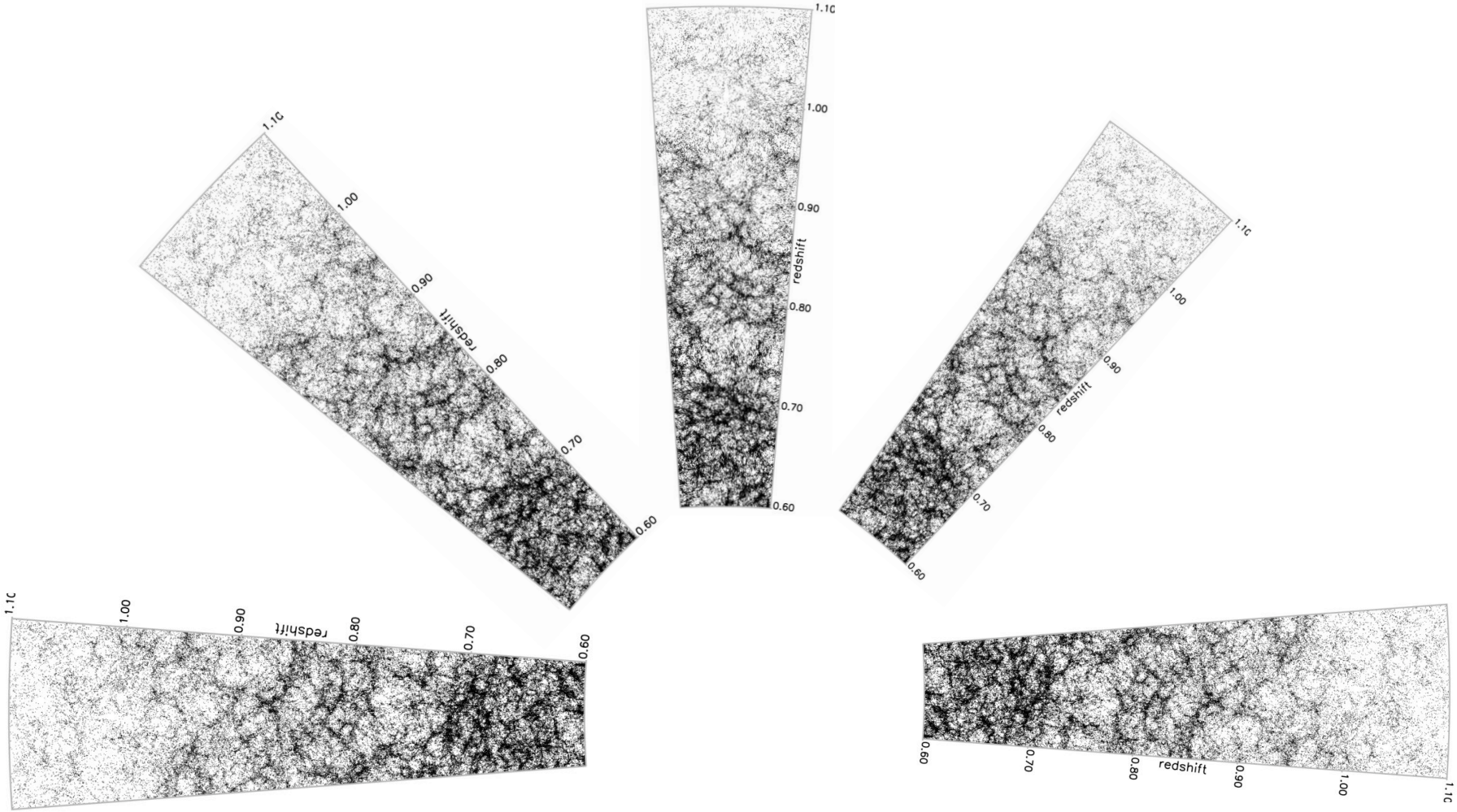
Fourier space



Unfortunately the sky is not flat

Affects Fourier-based analyses with a dependence on the LOS angle

BAO, redshift-space distortions



Unfortunately the sky is not flat

Affects Fourier-based analyses with a dependence on the LOS angle

BAO, redshift-space distortions

Open issue: options

Use correlation function (problems with error calculation)

Use small patches where LOS angle does not change (throw info)

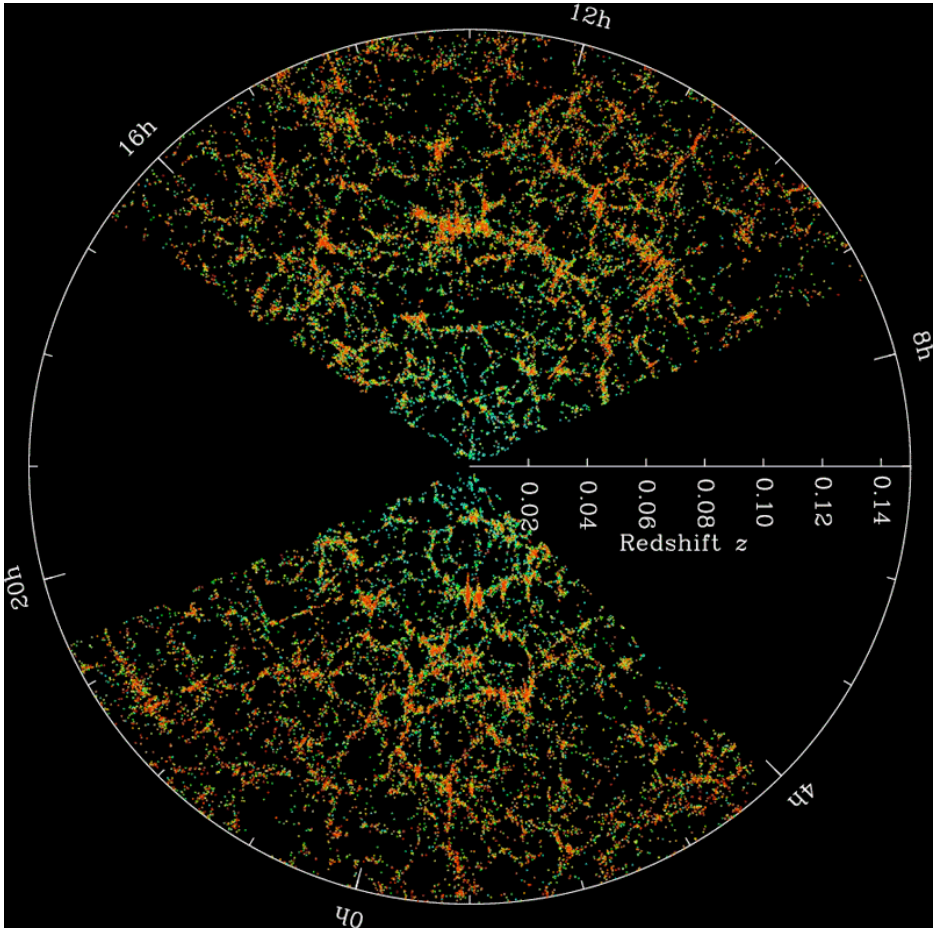
Use radial and angular expansion Sph. Harm+Bessel
(Heavens, Percival) NOT easy!

Use radial and angular eigenfunctions (not widely used)

Still open…

If you could see the DM, but you can't

Galaxies:
galaxy formation(B. Robertson)
Bias
Selection of galaxies



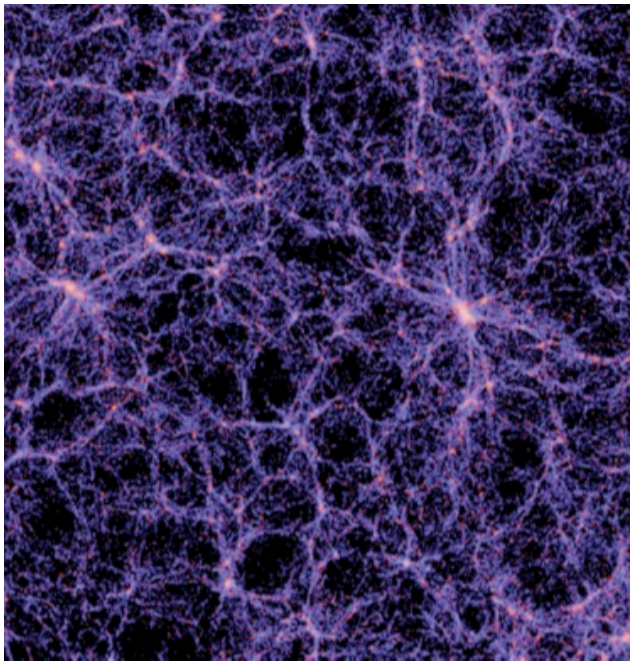
Baryons in the IGM (expected to be closer to the dark matter)

Challenges, examples

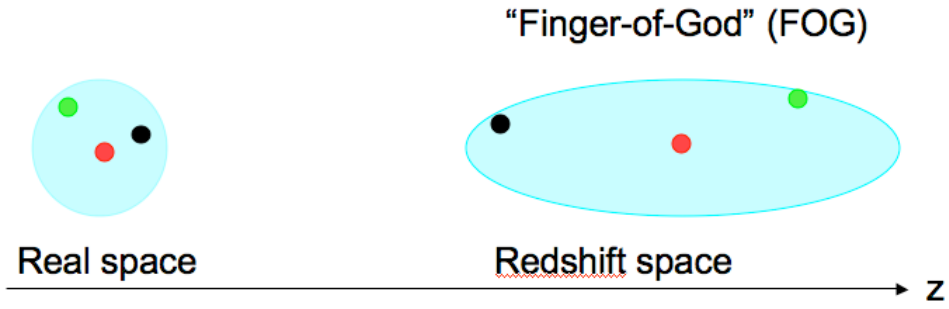
$$\delta = \frac{\delta\rho}{\rho}$$

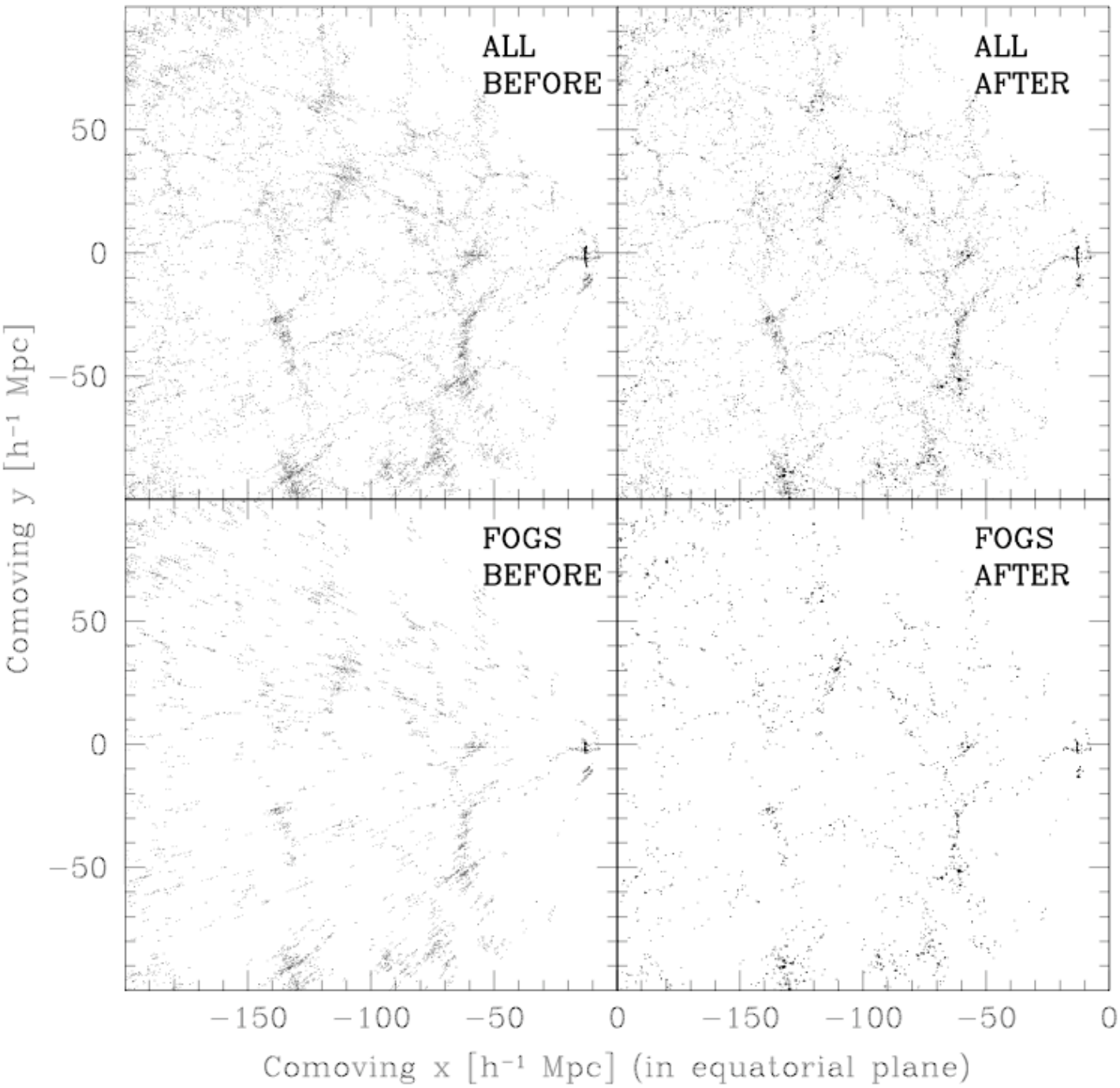
- density field δ goes nonlinear
- uncertainty in the mapping between the galaxy and matter density fields
- Galaxy positions observed in redshift space

LRG are “special”



From Croton et al.2005





From:
Tegmark et al 04

More about velocities

galaxy velocities only depend on the distribution of matter

Galaxies as test particles?

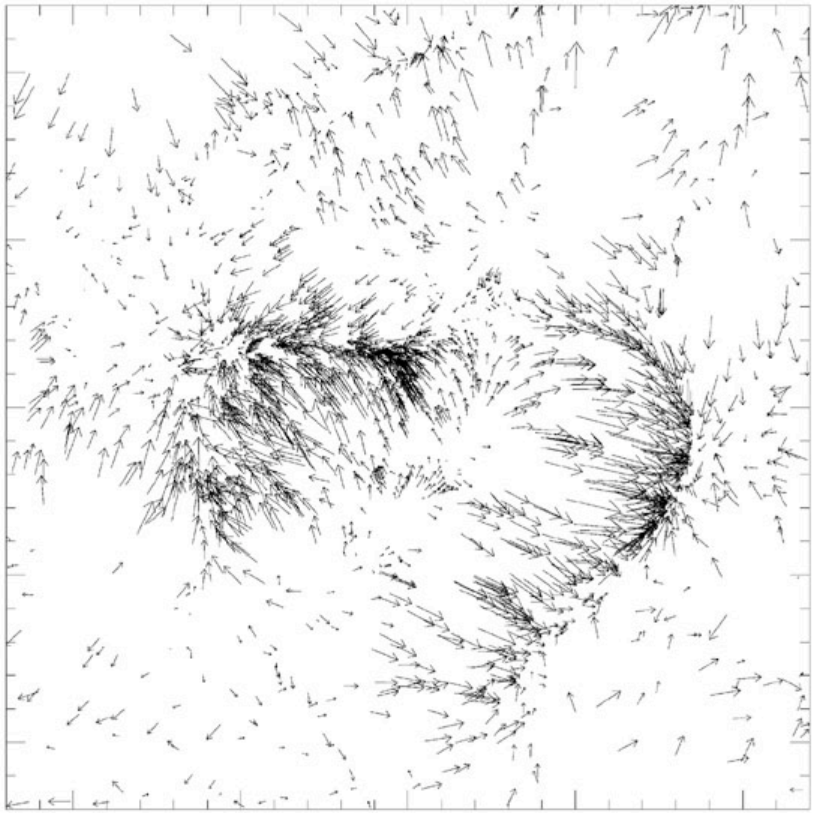
Probe temporal metric fluctuations (WL temporal and spatial)

Only LoS measurement

Linear order in perturbations

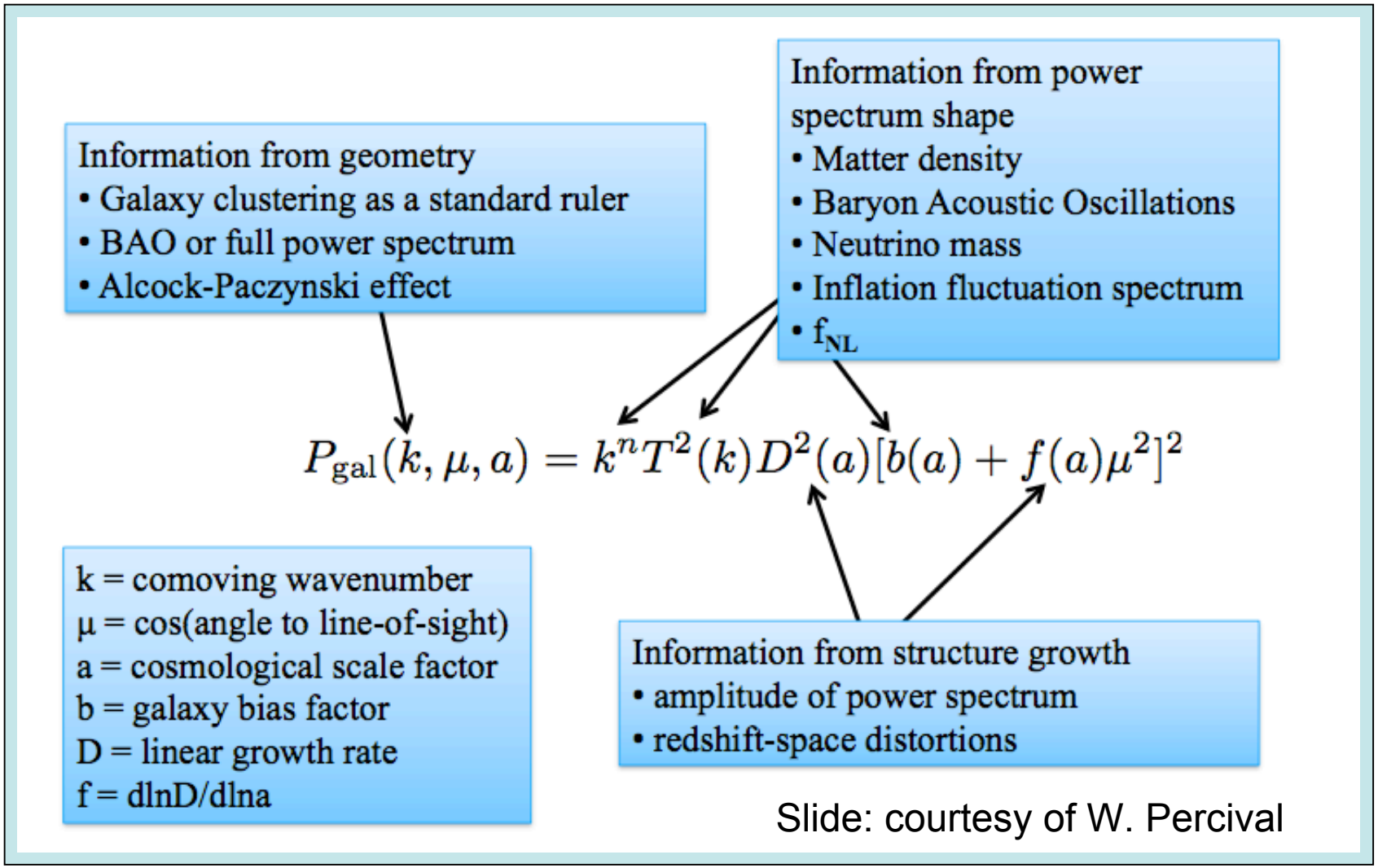
$$\theta \equiv \nabla \cdot \mathbf{u}, \qquad \delta_g^s(k) = \delta_g(k) - \mu^2\theta(k)$$

$$P_g^s(k,\mu,\mathrm{lin}) \equiv \langle|\delta_g^s(k,\mu)|^2\rangle,$$
$$= P_{gg}(k) - 2\mu^2 P_{g\theta}(k) + \mu^4 P_{\theta\theta}(k)$$



Yet to uncover full potential

Large-scale structure P(k) in equations



Large-scale structure P(k) in equations

Information from geometry
- Galaxy clustering as a standard ruler
- BAO or full power spectrum
- Alcock-Paczynski effect

Information from power spectrum shape
- Matter density
- Baryon Acoustic Oscillations
- Neutrino mass
- Inflation fluctuation spectrum
- f_{NL}

$$P_{\rm gal}(k,\mu,a) = k^n T^2(k) D^2(a$$  $$\mu^2]^2$$

k = comoving wavenumber
μ = cos(angle to line-of-sight)
a = cosmological scale factor
b = galaxy bias factor
D = linear growth rate
f = dlnD/dlna

Information from structure growth
- amplitude of power spectrum
- redshift-space distortions

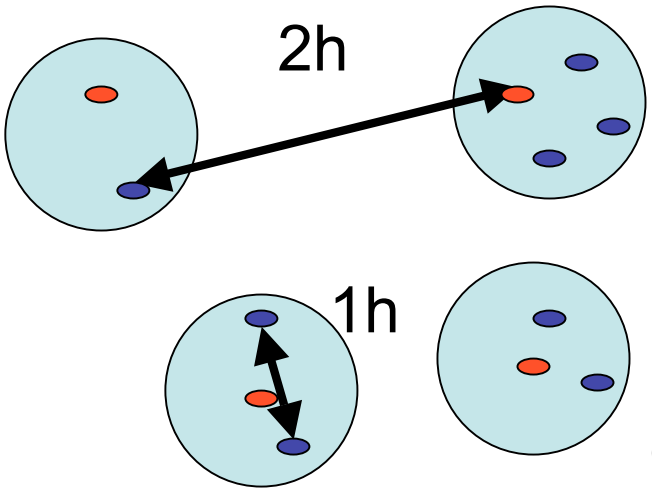
Slide: courtesy of W. Percival

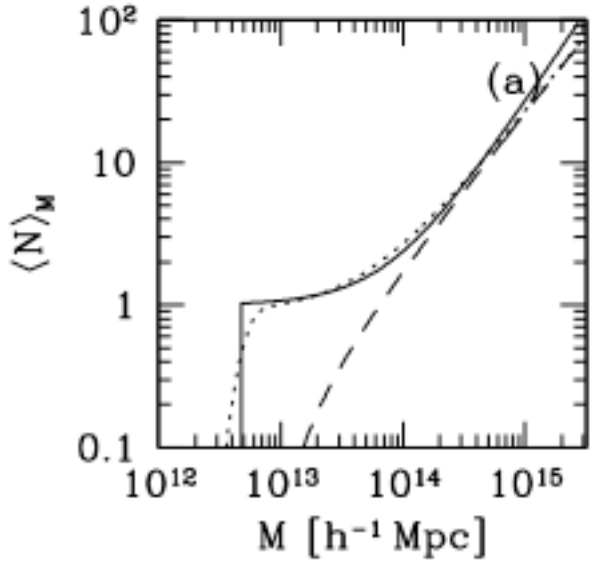
“bias” can be complicated

Not bias of halos which can be computed from first principles!

- HOD approach (e.g., Tinker, Zheng, Wechsler…)

Halo model framework





Can HOD be tuned to fit observations?

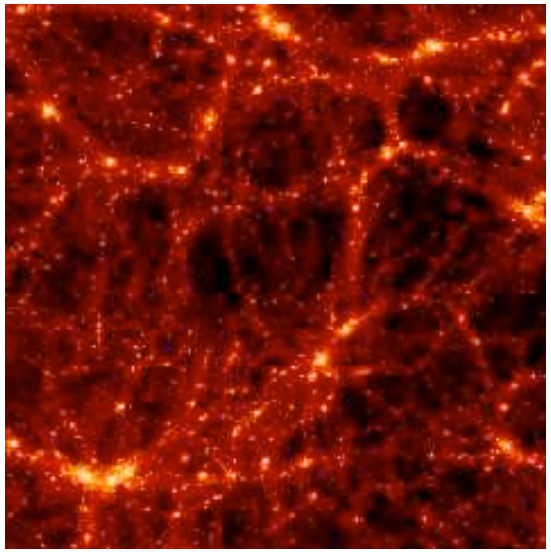
Higher-order correlations

- E.g., Bispectrum or three point function

bias

Initial conditions

Test of gravity



Modeling, error calculations,
computationally expensive just to compute the signal

Shot noise and stochasticity

What is shot noise? Depends on number density

Is is Poisson?

stochasticity $\begin{pmatrix} \langle\delta(\mathbf{x})\delta(\mathbf{x})\rangle & \langle\delta(\mathbf{x})\delta_g(\mathbf{x})\rangle \\ \langle\delta_g(\mathbf{x})\delta(\mathbf{x})\rangle & \langle\delta_g(\mathbf{x})\delta_g(\mathbf{x})\rangle \end{pmatrix} = \langle|\delta_{\rm mass}(\mathbf{x})|^2\rangle \begin{pmatrix} 1 & br \\ br & b^2 \end{pmatrix}$

Could be more complicated

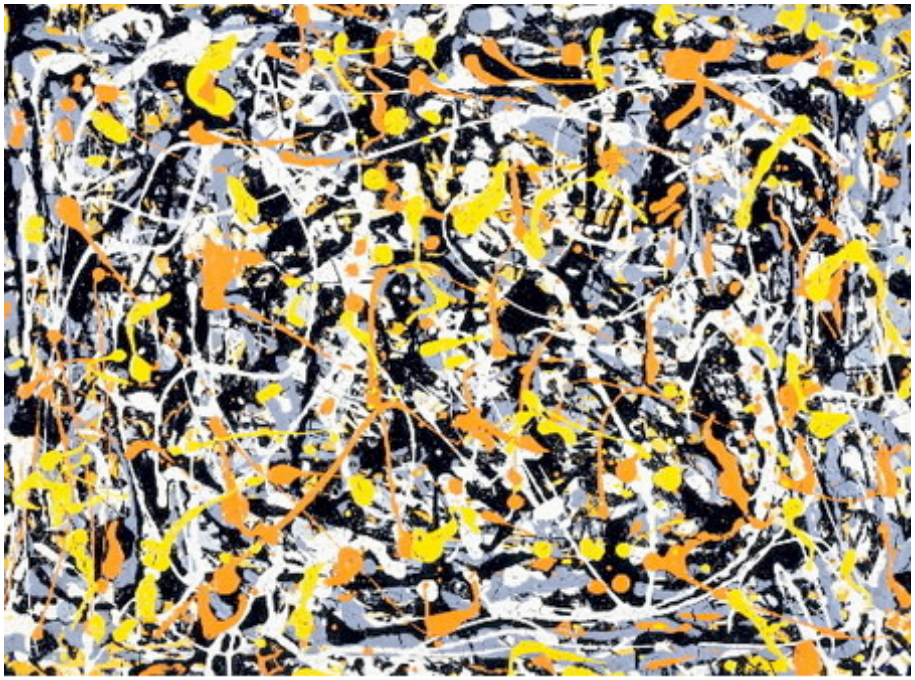
Local mass and momentum conservation ⟶ Optimal weighting

So far only for halos and in simulations

Seljak etal 09 Cai et al.10

Imperfect observations

- Missing galaxies
- Redshift errors
- Only photometry



Beyond the interest of most of the audience

NEUTRINOS: Physical effects

Total mass >~1 eV become non relativistic before recombination

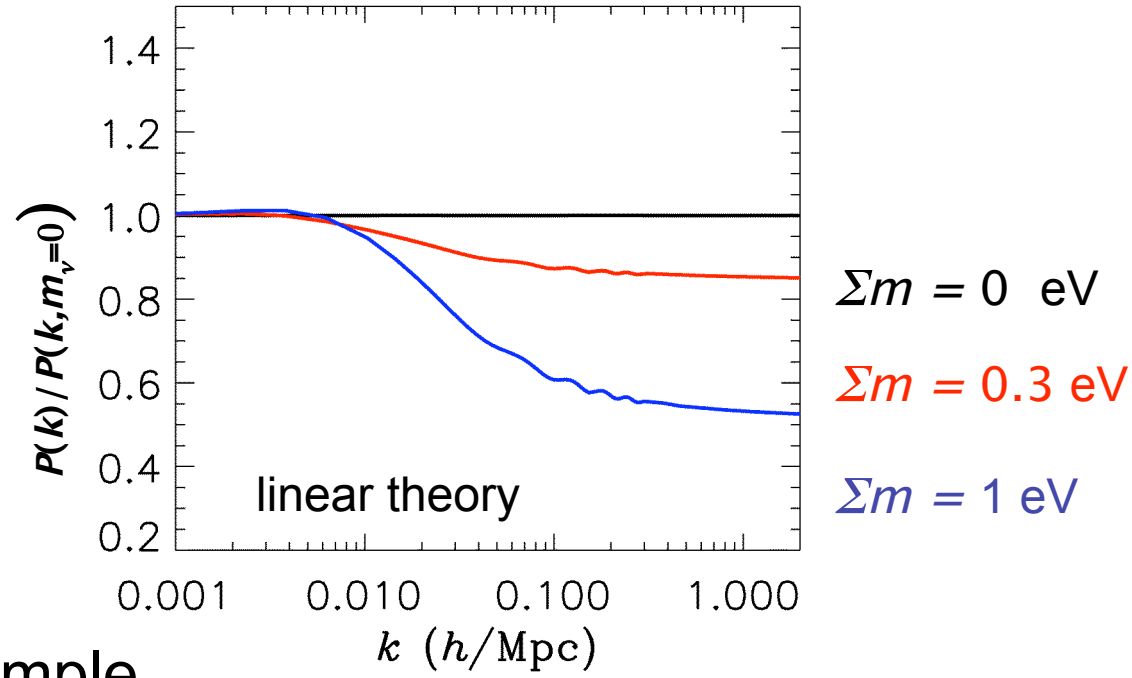
CMB

Total mass <~1 eV become non relativistic after recombination:
alters matter-radn equality but effect can be “cancelled”
by other parameters

Degeneracy

After recombination

FINITE NEUTRINO MASSES SUPPRESS THE MATTER POWER SPECTRUM ON SCALES SMALLER THAN THE FREE-STREAMING LENGTH



Discussion: worked example

C. Penya-G.

Clusters of galaxies

- Easier to identify clusters of galaxies with DM halos
- Left with 2h term
- If mass can be measured then bias is known (work from >20yrs ago)
- Extra bonus: number density

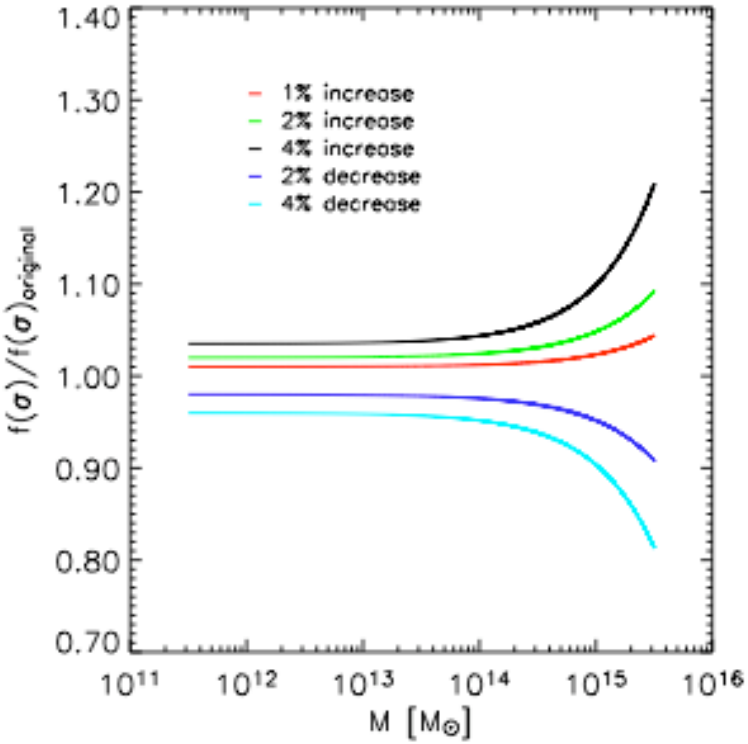
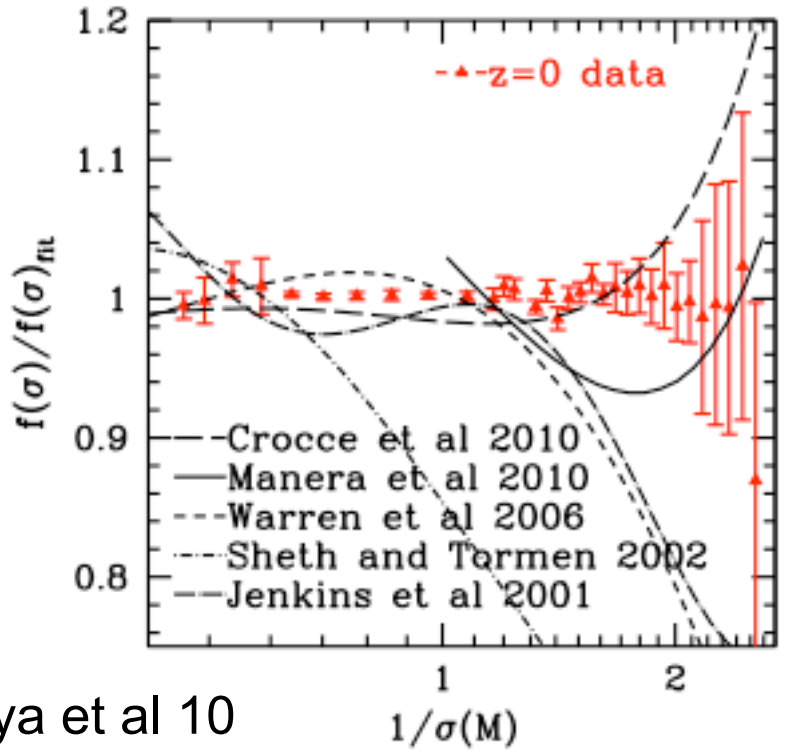


FIG. 1.— Sensitivity of the mass to systematic shifts in individual halo masses. Changes in the mass function are shown with respect to the baseline

Bhattacharya et al 10

Clusters of galaxies
open issues

- Ideally need a mass-limited sample: how?
- SZ surveys promised this but…
- What mass function?



Bhattacharya et al 10

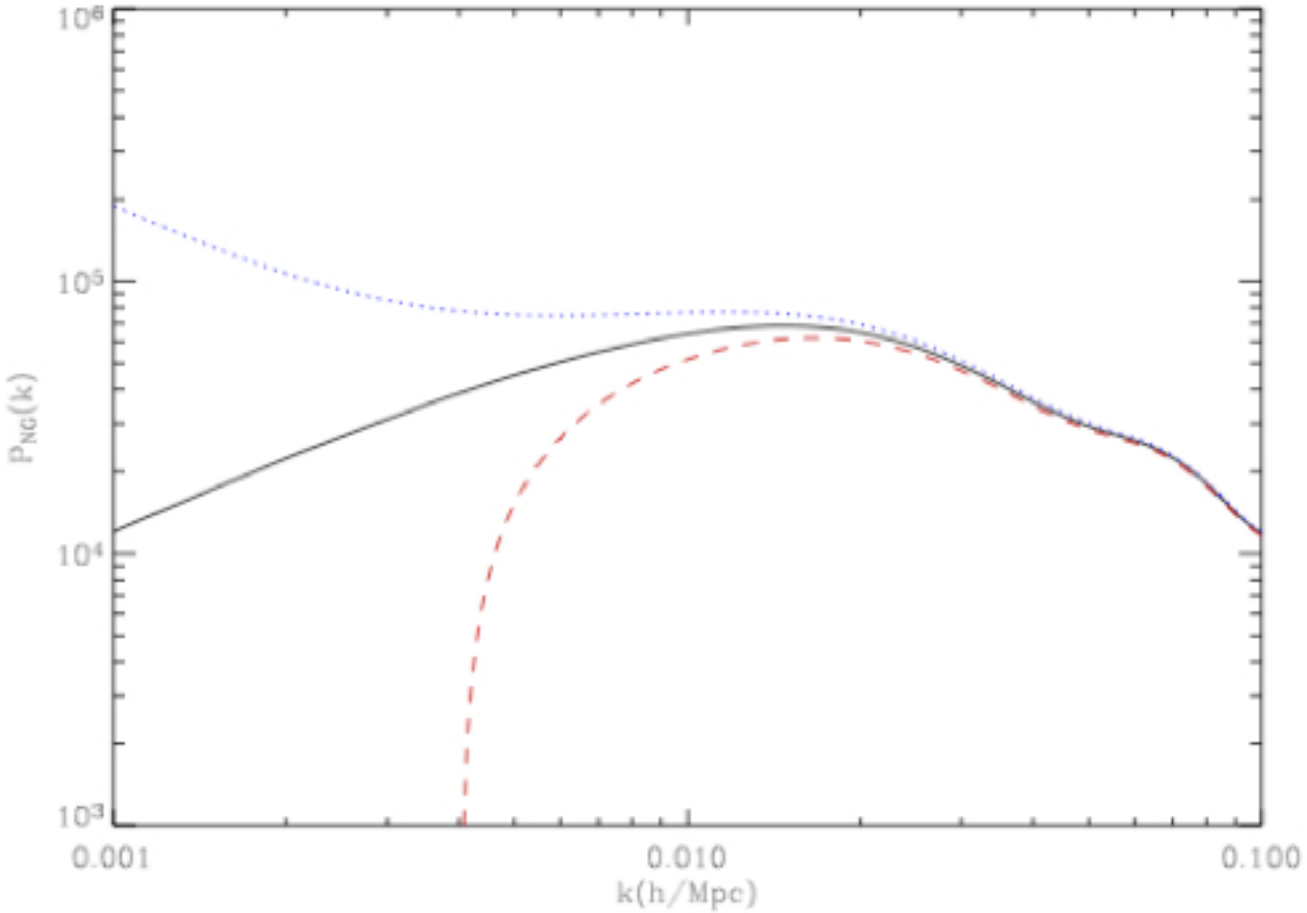
Halo bias

- A Gaussian field and a non-Gaussian field can have the same P(k)
- In a Gaussian field the P(k) of peaks is completely specified by the P(k)
- In a non-Gaussian field, however, the P(k) of the **peaks,** depends on all higher order correlations (i.e. f_{NL})

Non-Gaussian halo bias

- Gaussian IC and a non-Gaussian IC can have the same P(k) for the dark matter
- For Gaussian IC the P(k) of massive halos is completely specified by the dark matter P(k)
- For Non Gaussian IC, however, the P(k) of the halos, depends on all higher order correlations (i.e. f_{NL})

The effect



|fnl|=50, z=0, M>1.d13M_{Sun}

Extremely promising

survey	z range	sq deg	mean galaxy density $(h/Mpc)^3$	$\Delta f_{\rm NL}/q'$ LSS
SDSS LRG's	$0.16 < z < 0.47$	7.6×10^3	1.36×10^{-4}	40
BOSS	$0 < z < 0.7$	10^4	2.66×10^{-4}	18
WFMOS low z	$0.5 < z < 1.3$	2×10^3	4.88×10^{-4}	15
WFMOS high z	$2.3 < z < 3.3$	3×10^2	4.55×10^{-4}	17
ADEPT	$1 < z < 2$	2.8×10^4	9.37×10^{-4}	1.5
EUCLID	$0 < z < 2$	2×10^4	1.56×10^{-3}	1.7
DES	$0.2 < z < 1.3$	5×10^3	1.85×10^{-3}	8
PanSTARRS	$0 < z < 1.2$	3×10^4	1.72×10^{-3}	3.5
LSST	$0.3 < z < 3.6$	3×10^4	2.77×10^{-3}	0.7

Carbone, et al 08 & 09

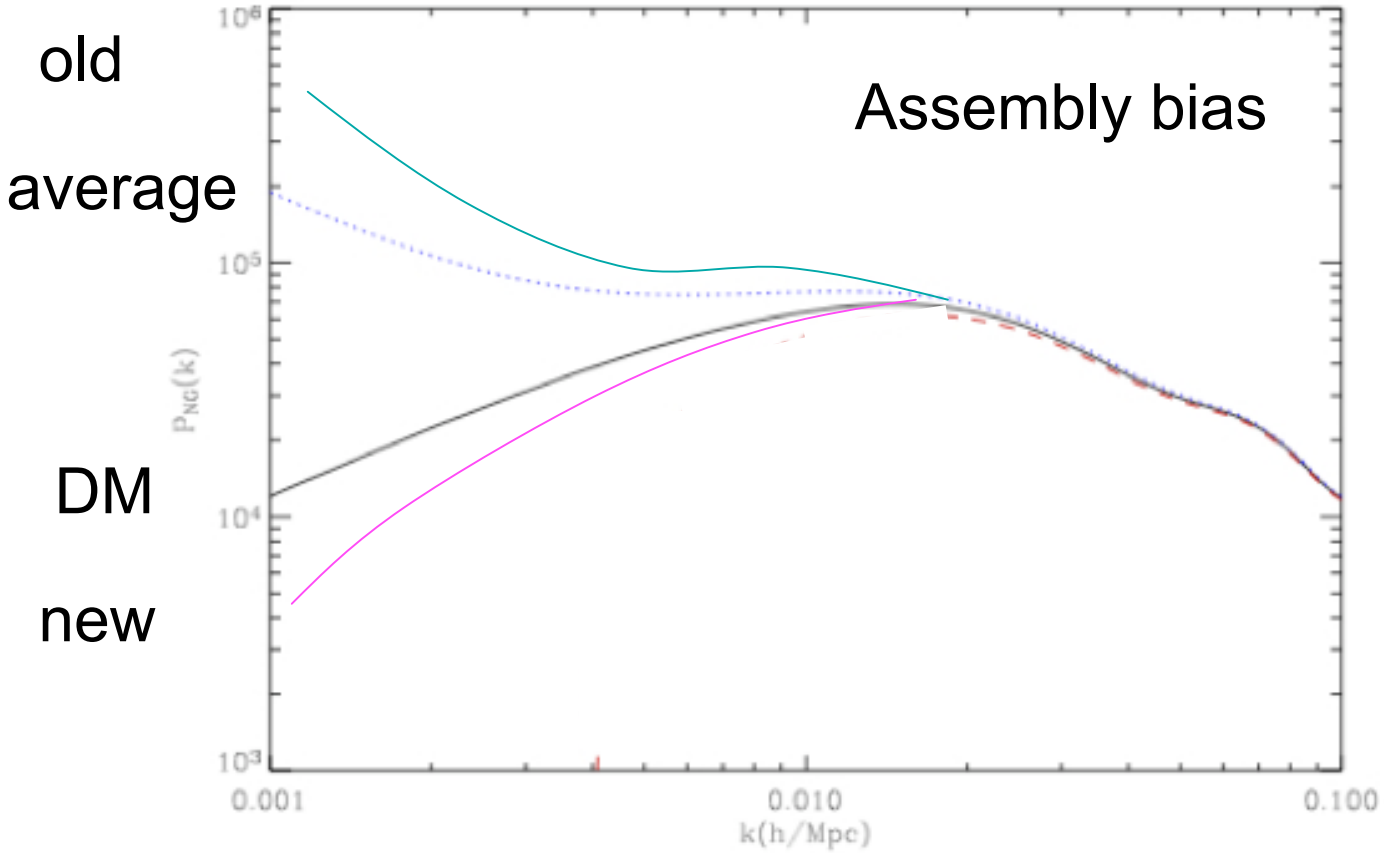
Open issues:

This is for the LOCAL shape, what about other shapes?

Simulations are key to calibrate the analytics,
can we simulate this?

Can shapes be distinguished?

Open issues



Effect of survey window.

Hints from current data (Matarrese)

What about the mass function (halos or voids)

Issues: what mass function? (LoVerde, Norena)

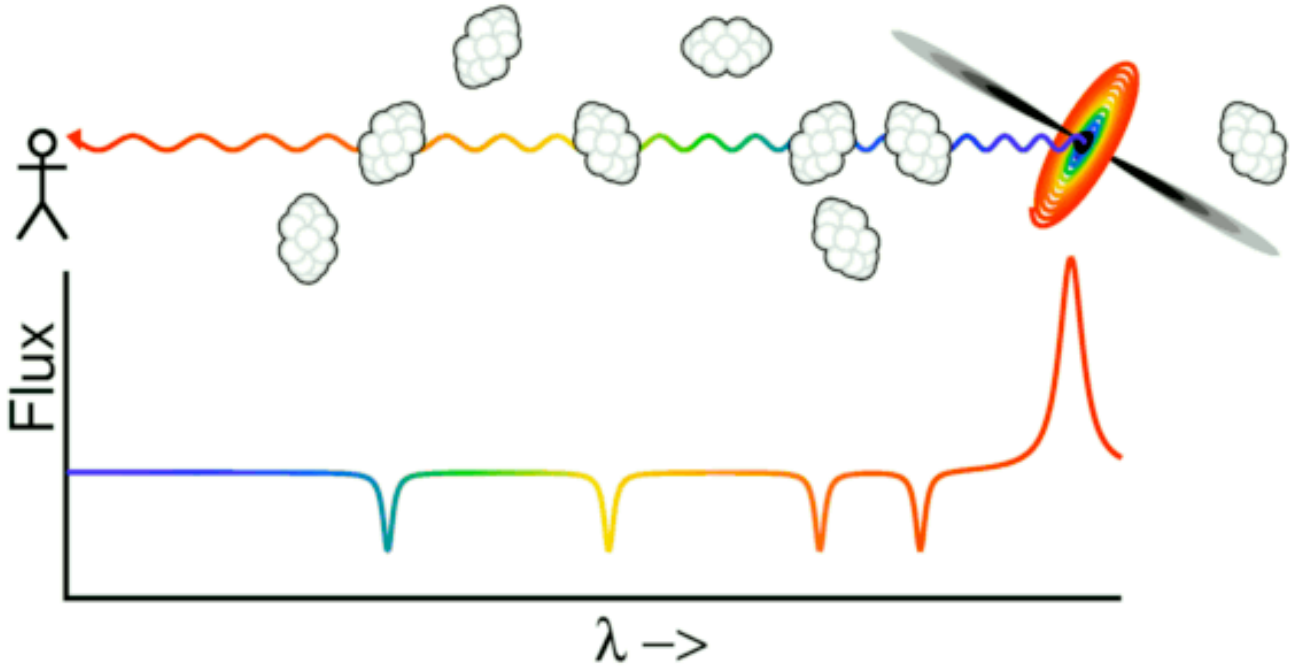
What non-gaussianity? (LoVerde)

What halo masses? (Hoyle)

Hints from current data… (Hoyle)

Lyman alpha forest

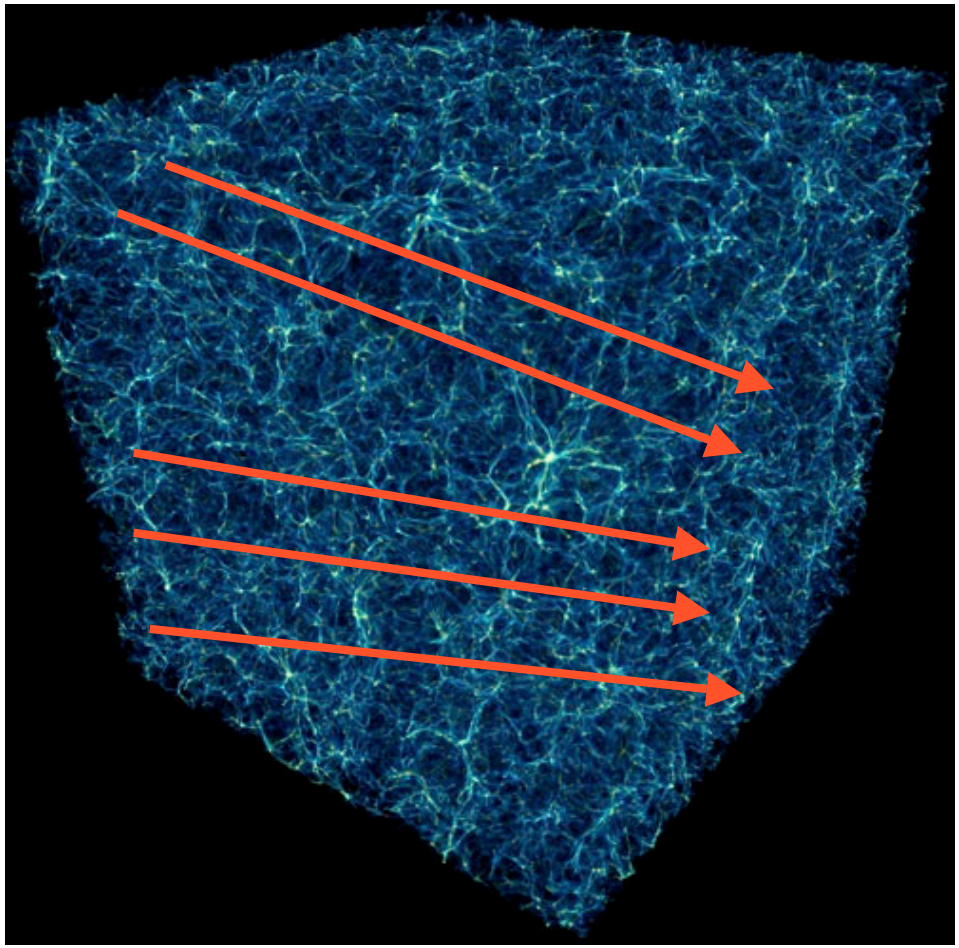
Lyman alpha line of hydrogen at a wavelength of 122 nm.



One sightline: 1D info

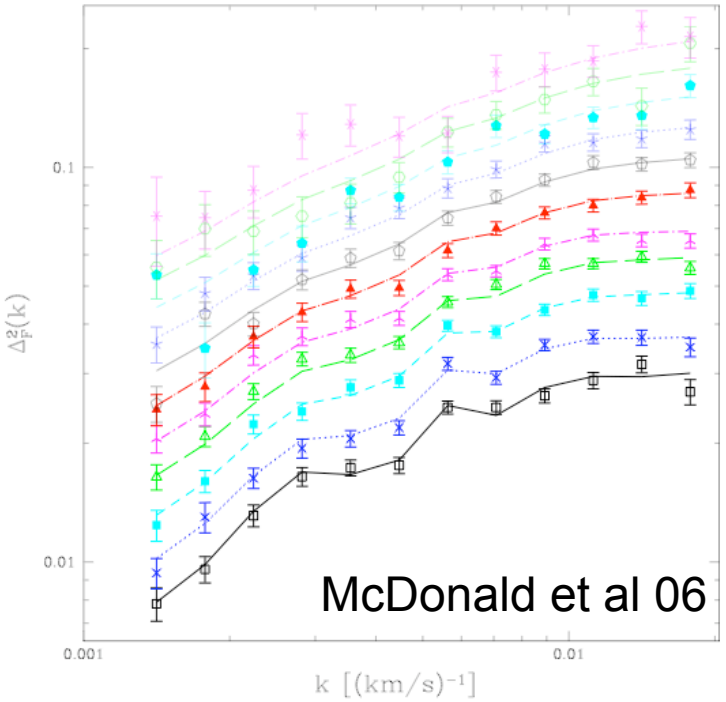
Lyman alpha forest

Getting 3D info

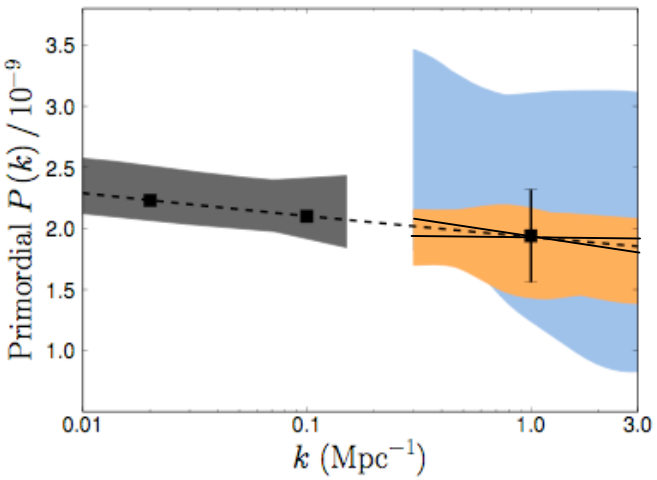


Lyman alpha: So far

- 1D info
- Small scales !!!
- High z still (almost) linear



McDonald et al 06



Bird et al 2010

Complications
(work in progress)

From gas density to flux and effect of peculiar velocity

Reminds you of bias

Rely heavily on simulations this time not DM only: hydrodynamical. Still assumptions must be made about ionization,IGM thermal history etc.

Back to the problem of how to interpolate between simulations

Open issues: it has not been done before!

Huge effort in SDSS3 Lyman alpha working group (J. Miralda)

Where LSS competitive?

- Dark energy
- DE vs tests of Gravity
- Neutrino properties
- Shape of the primordial power spectrum
- Primordial NG

On-going planned surveys

- SDSS3 (BOSS)
- DES
- EUCLID
- BigBoss
- Hetdex
- WFIRST
- Etc…

Open issues recap

- What are we really measuring? (and modeling?)
- Non-linearities, (analytical and numerical tools)
- Fourier space, real space, Sph Harm,…?
- Error-estimation
- Bias (galaxy formation)
- Velocity, reconstruction?
- Stochasticity
- What to simulate, how to interpolate
- Worked example: neutrinos
- Non-Gaussian halo bias, shapes? Assembly bias? Sims? (Worked example: hints from current data)
- Clusters: mass selected sample? Masses? What mass function?(Worked example: hints from high-z clusters)
- Lyman-alpha forest: open issues?