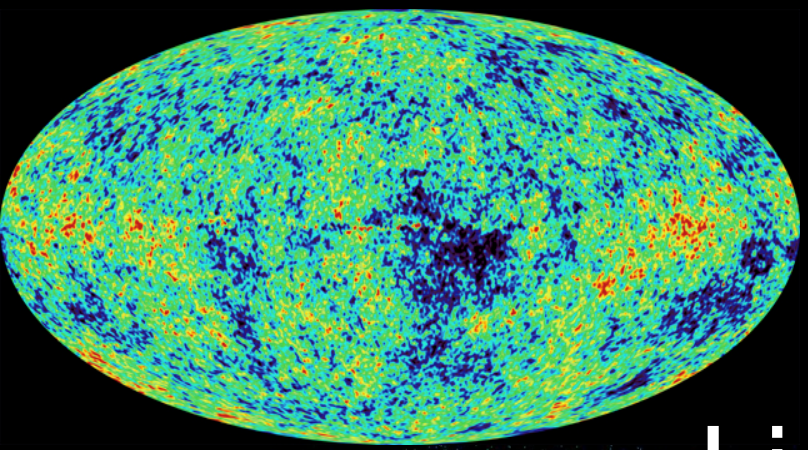
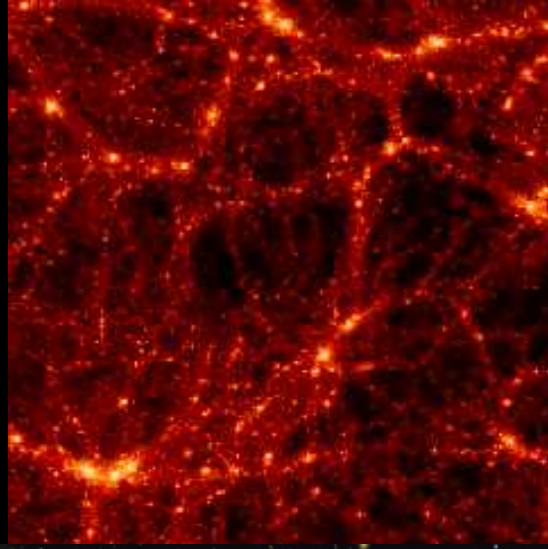




Licia Verde

What BAO can do for you
or rather what can we do for BAO

http://icc.ub.edu/~liciaverde

CERN

icrea
Institució Catalana de Recerca i Estudis Avançats

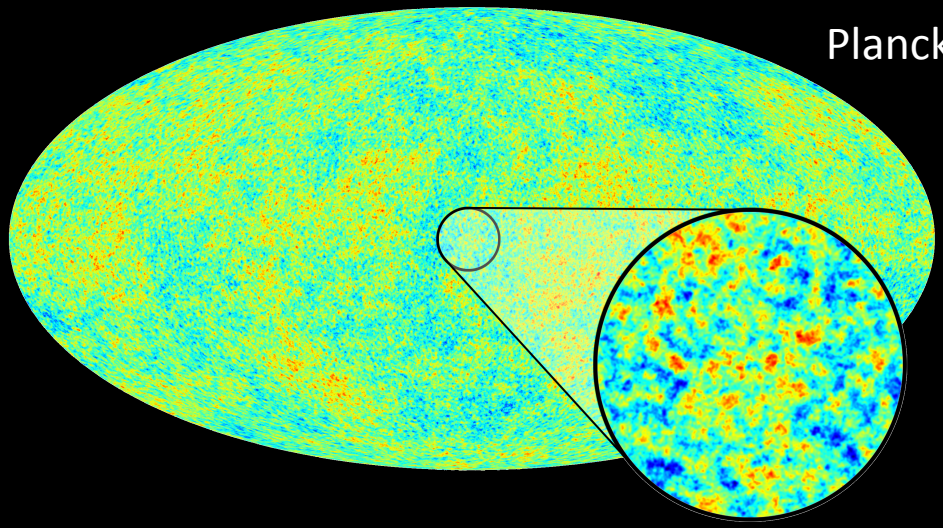
ICCUB
Institut de Ciències del Cosmos

UNIVERSITAT DE BARCELONA

IEEC

erc

Baryon acoustic oscillations

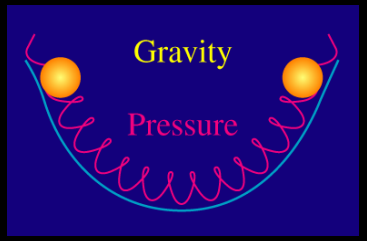


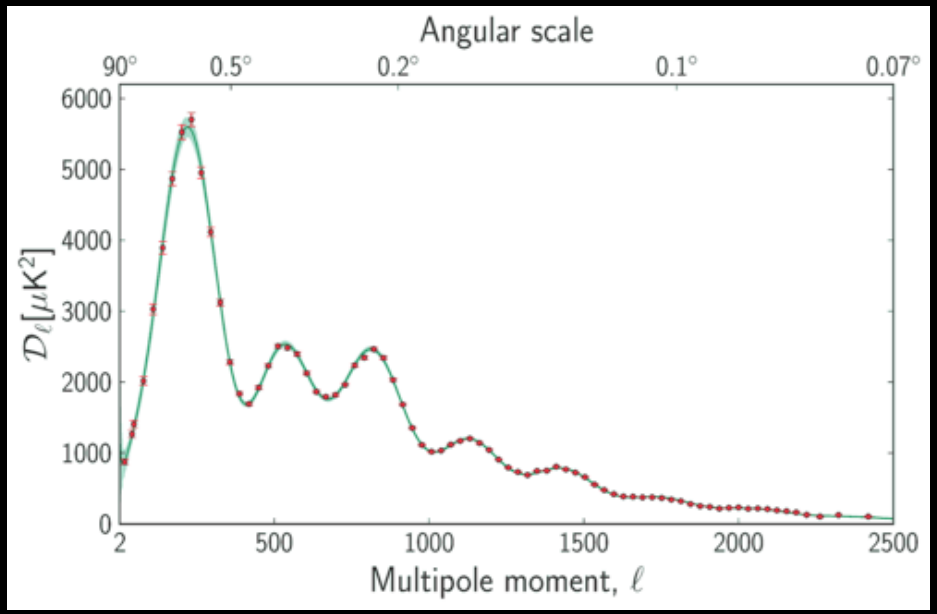
Planck

Sound horizon at decoupling

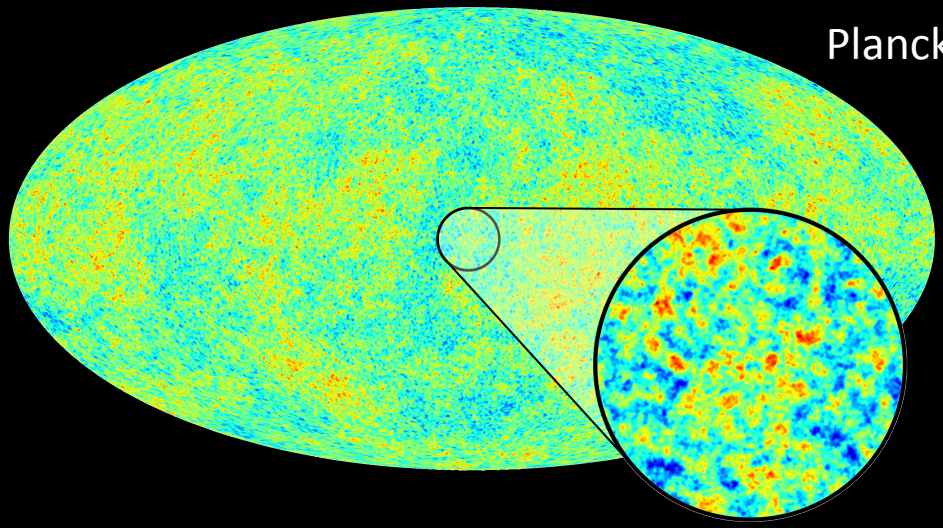
$$k_{\rm bao} = 2\pi/s$$

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





Baryon acoustic oscillations



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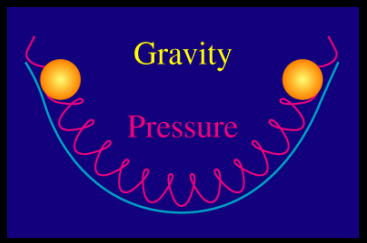
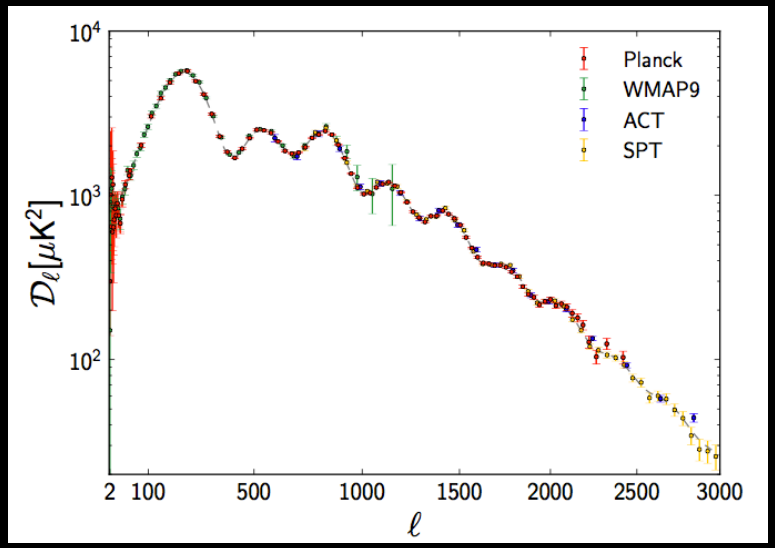
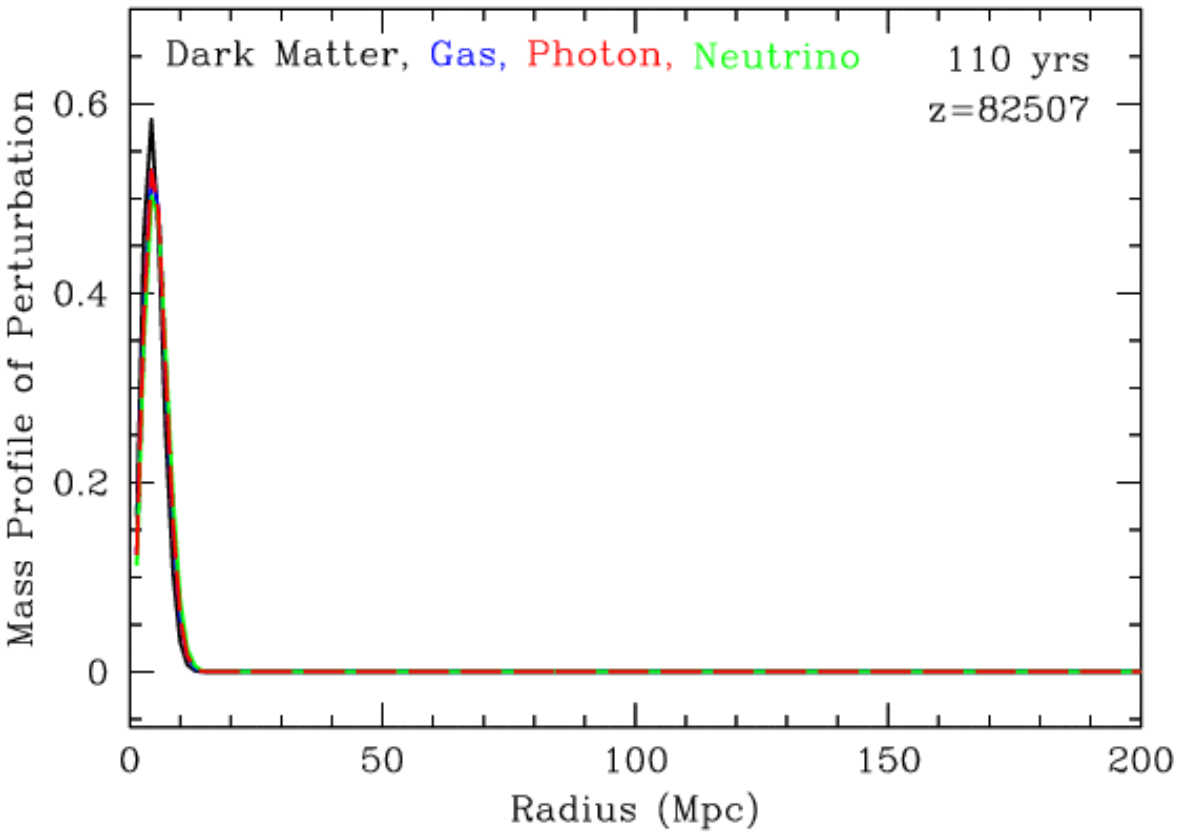




what's BAO?

Baryonic Acoustic Oscillations



Evolution of a single perturbation,

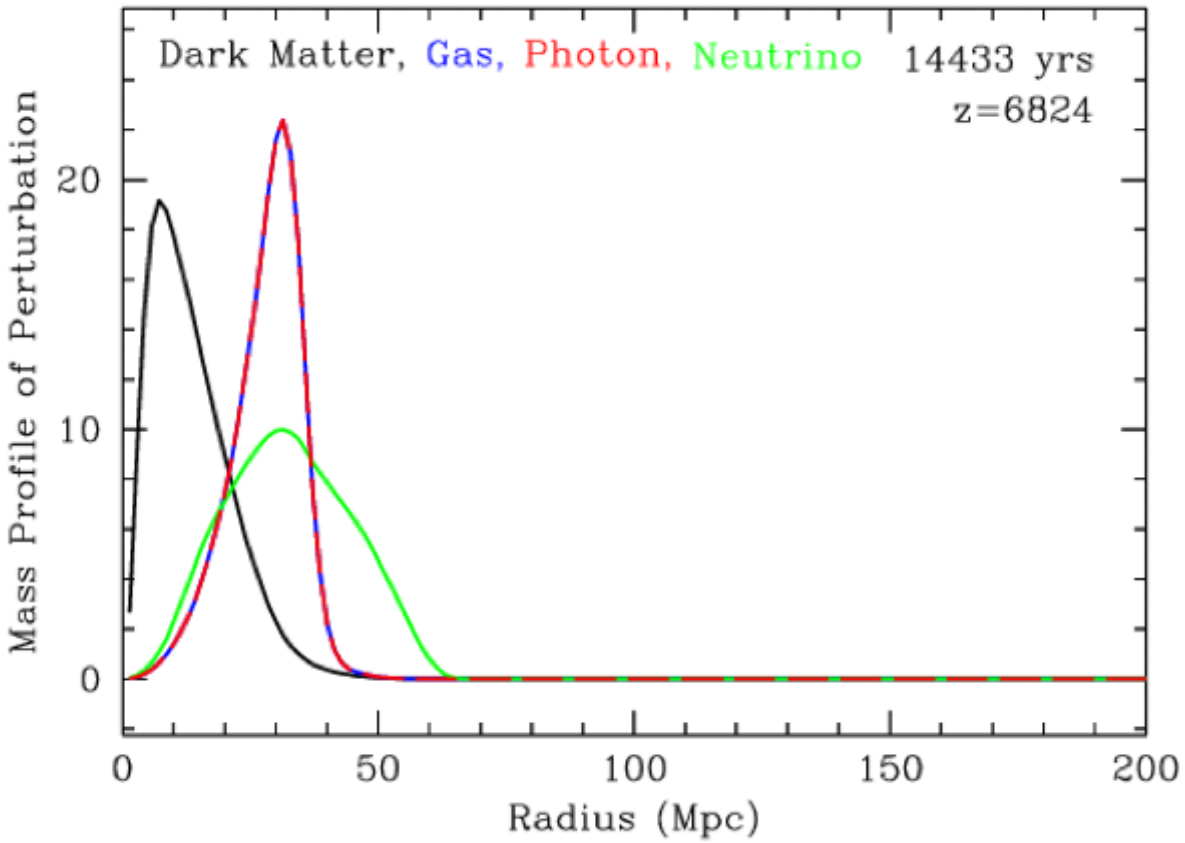
Imagine a superposition

For those of you who think in Real space

Courtesy of D. Eisenstein

what's BAO?

Baryonic Acoustic Oscillations



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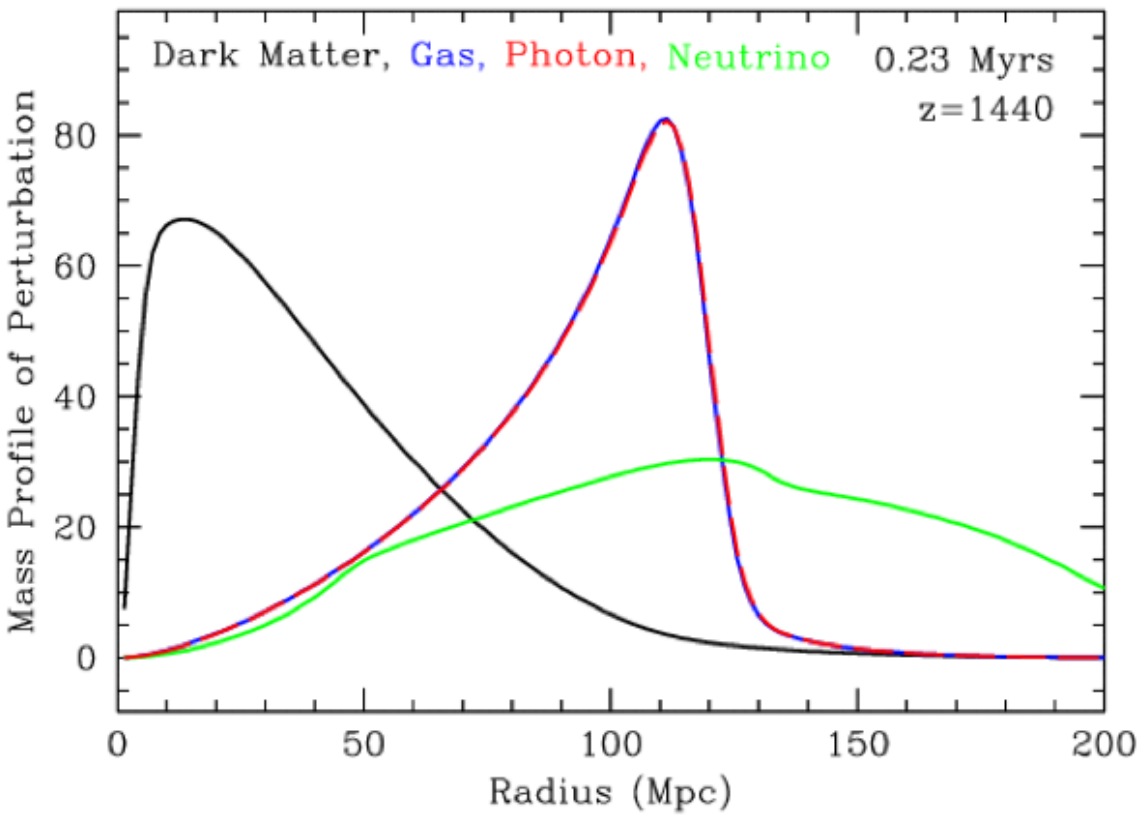

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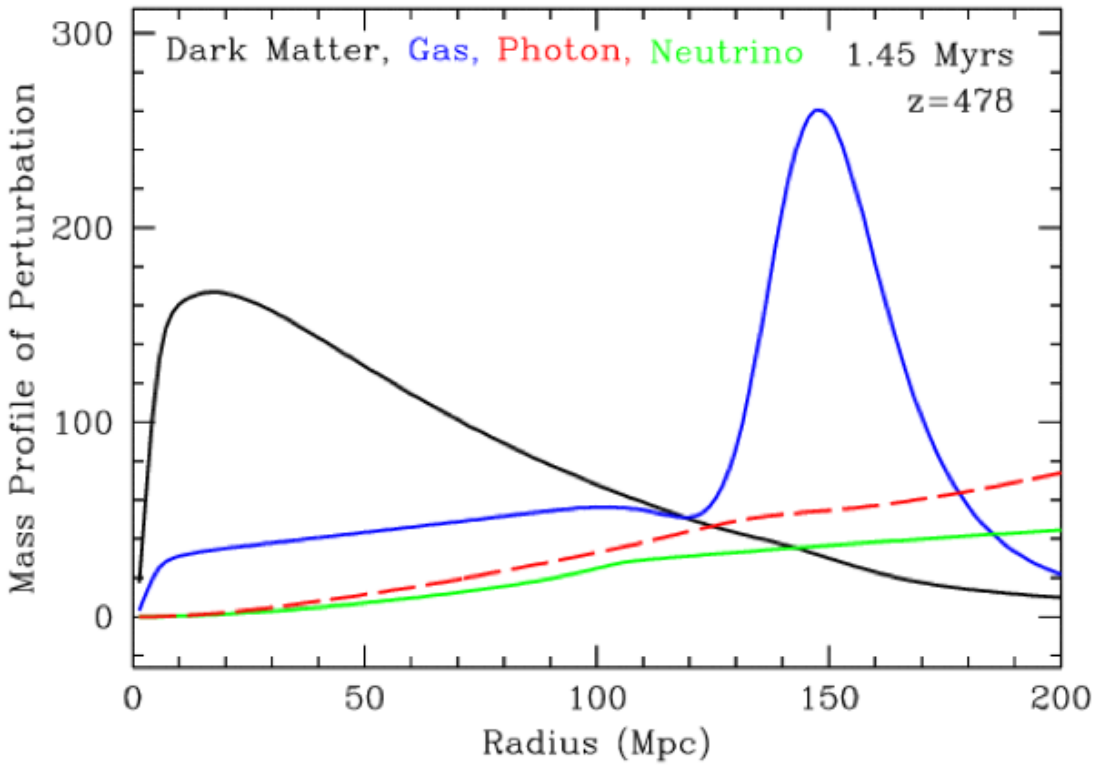

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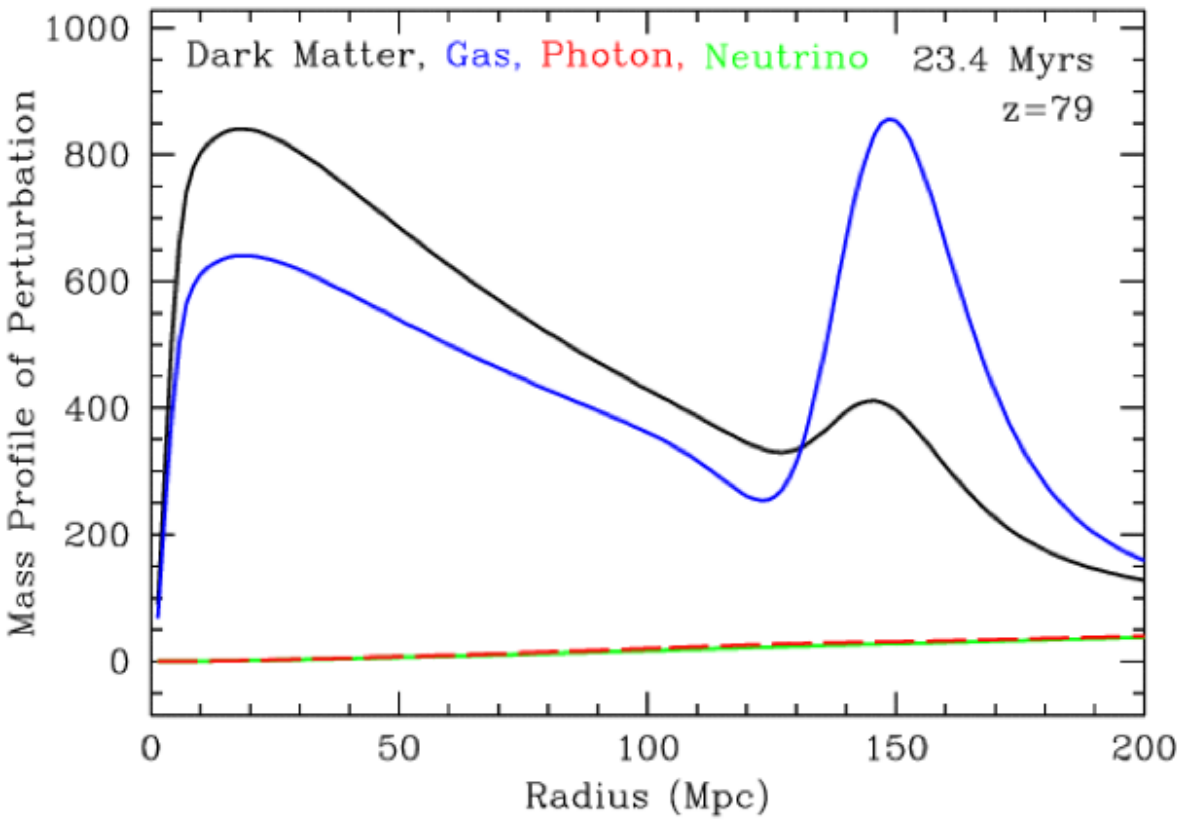

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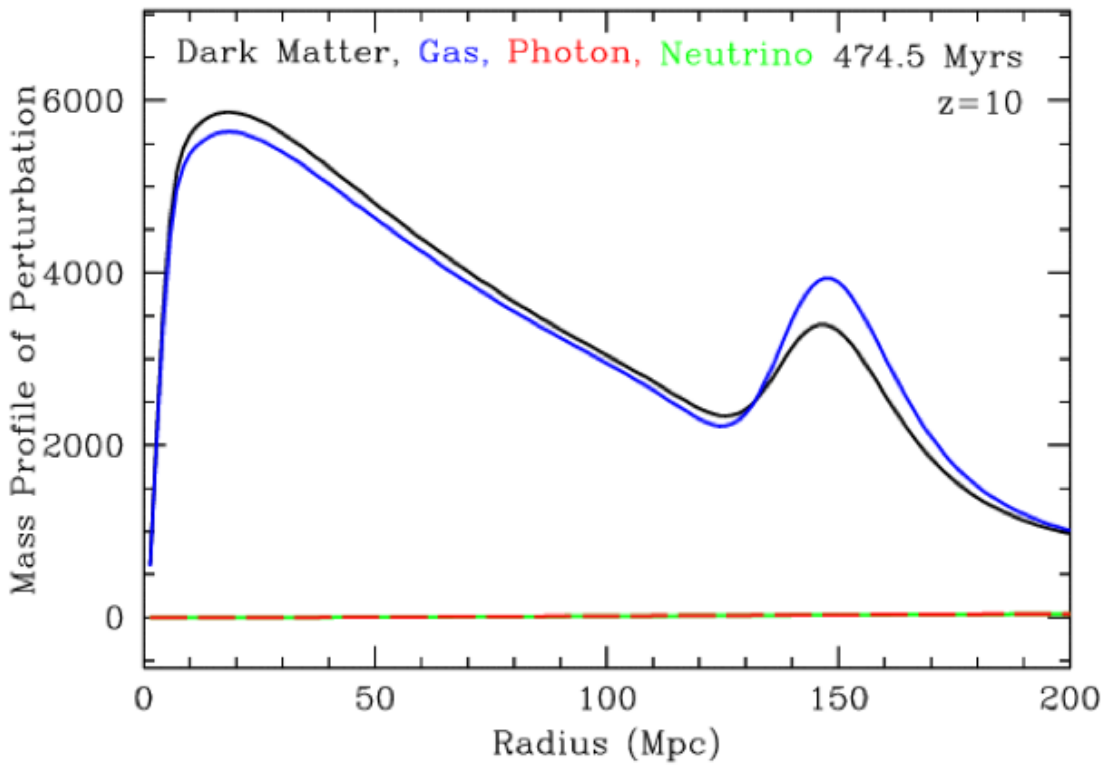


Evolution of a single perturbation,

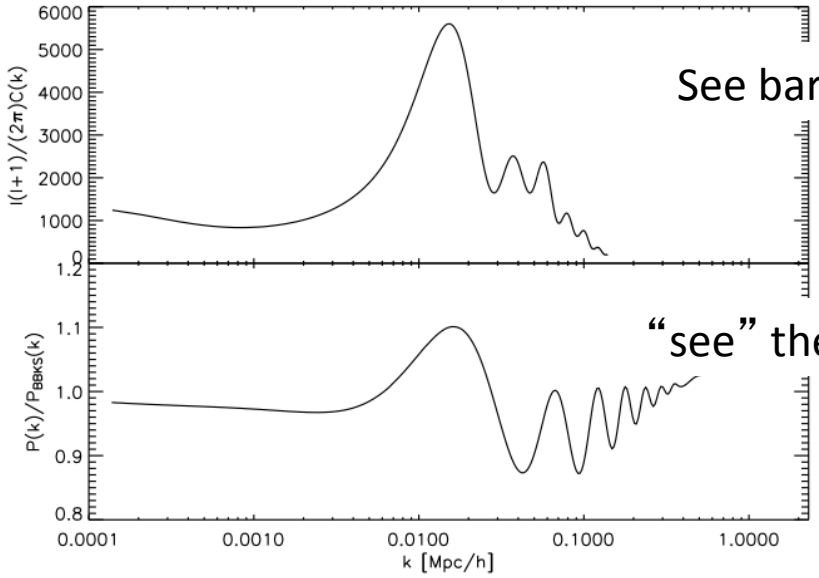
Imagine a superposition

For those of you who think in Real space

Courtesy of D. Eisenstein

what's BAO?

For those of you who think in Fourier space



See baryons

"see" the 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)

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

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

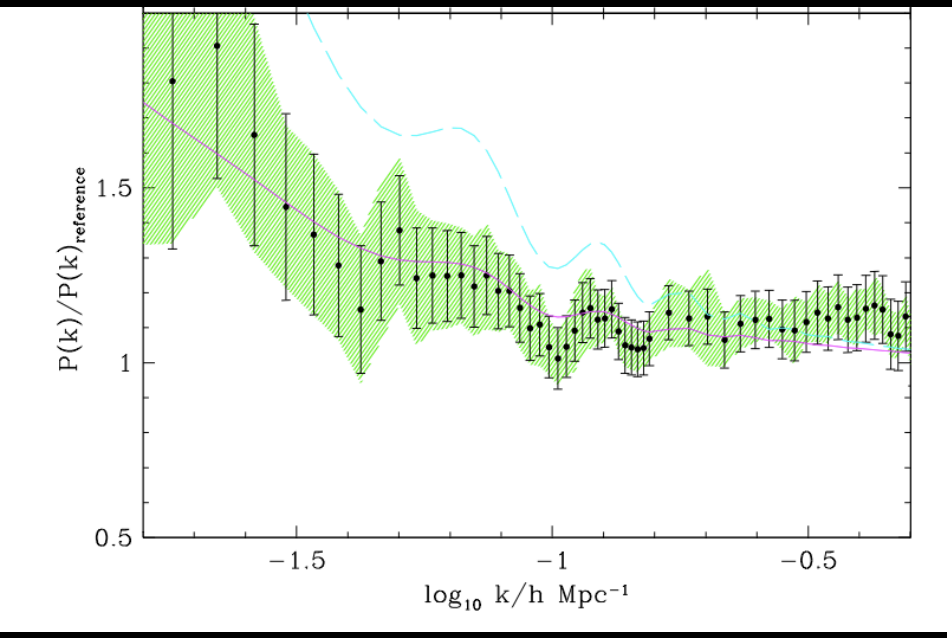
Not new

- Predicted in the 1990ies, but realization one oculd do cosmology with (I think) is 1997 paper by Eisenstein & Hu
- First detected in 2005:

  2dF Cole et al 2005; SDSS Eisenstein et al 2005
- But extremely, excruciatingly low signal-to-noise

Not new

2dF



SDSS

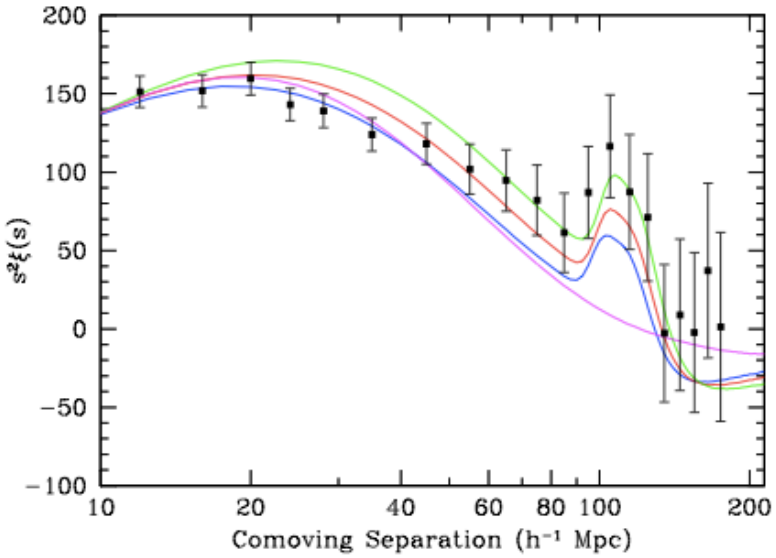
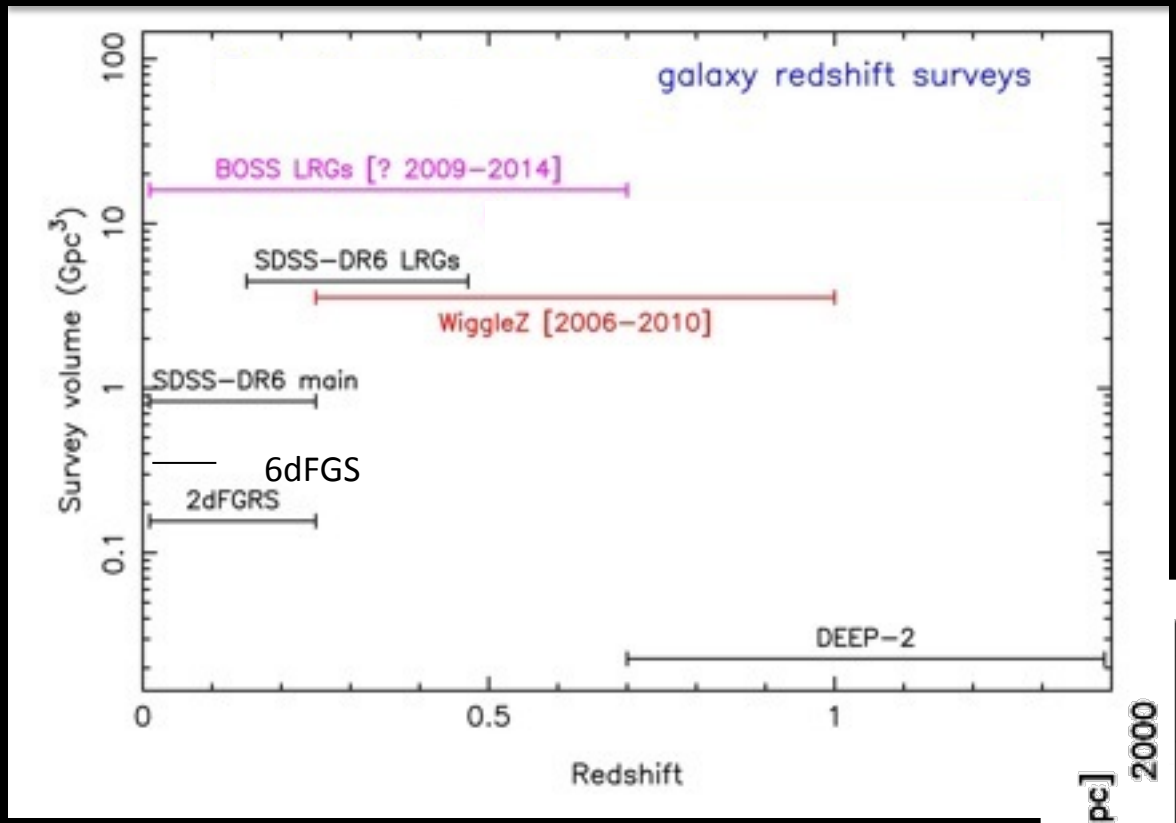


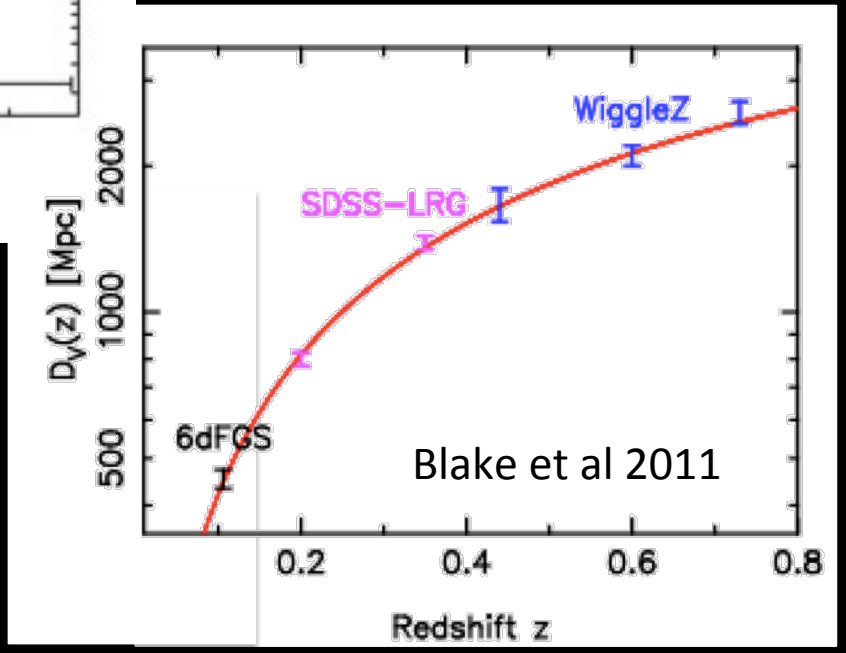
FIG. 3.— As Figure 2, but plotting the correlation function times s^2. This shows the variation of the peak at $20h^{-1}$ Mpc scales that is controlled by the redshift of equality (and hence by $\Omega_m h^2$). Varying $\Omega_m h^2$ alters the amount of large-to-small scale correlation, but boosting the large-scale correlations too much causes an inconsistency at $30h^{-1}$ Mpc. The pure CDM model (magenta) is actually close to the best-fit due to the data points on intermediate scales.

But extremely, excruciatingly low signal-to-noise

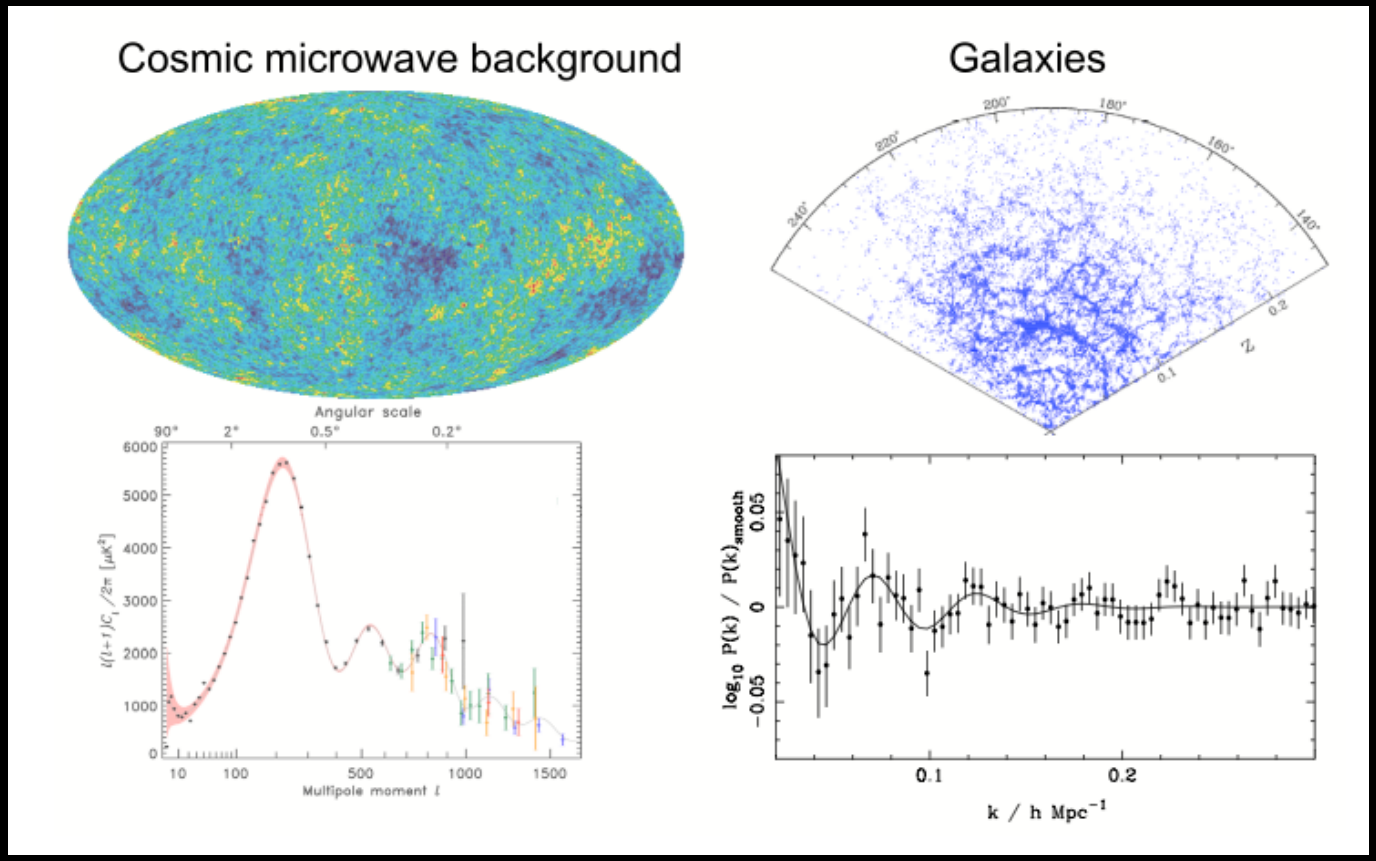
Some surveys



Adapted from WiggleZ web page

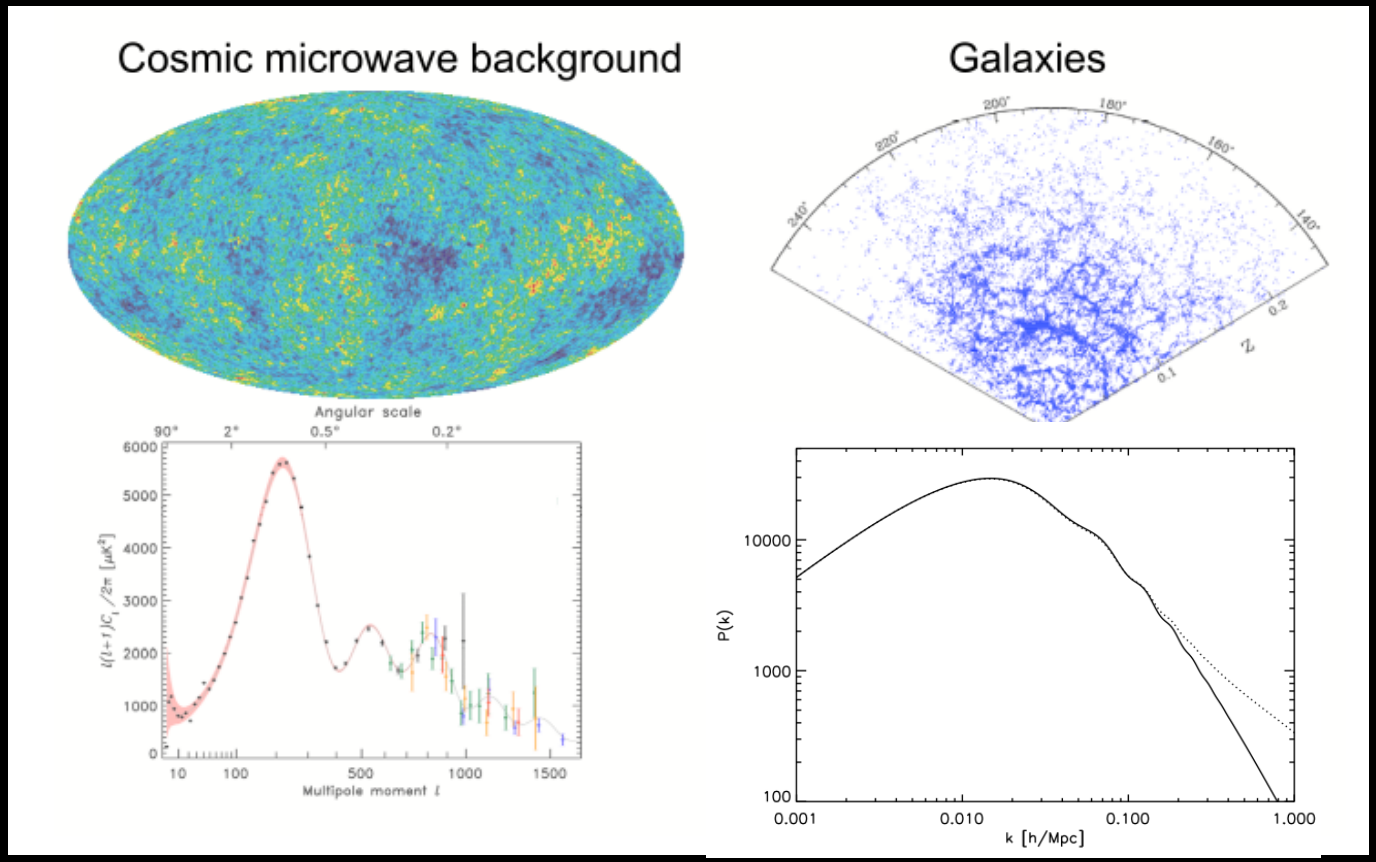


What surveys aim to measure



But there is <u>much more</u> cosmological information

What surveys aim to measure



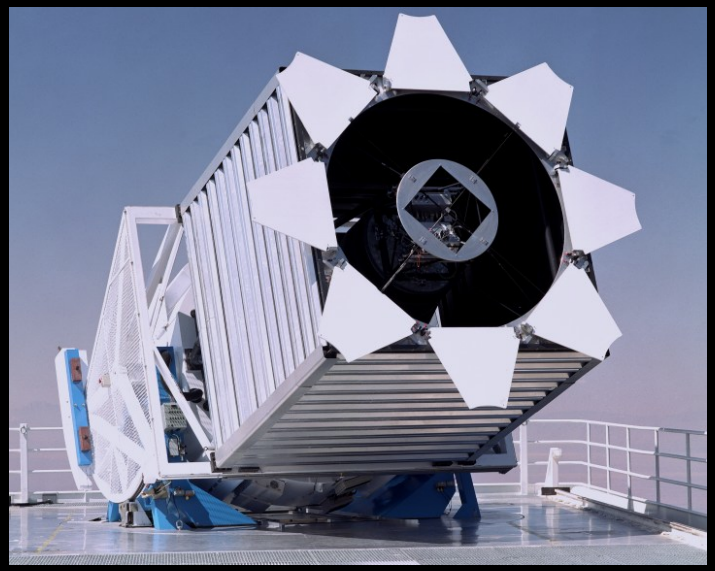
But there is <u>much more</u> cosmological information

And there is the challenge!

SDSSIII (BOSS)

Sloan Digital Sky Survey Telescope

2.5 meters in New Mexico



Photometry + spectroscopy

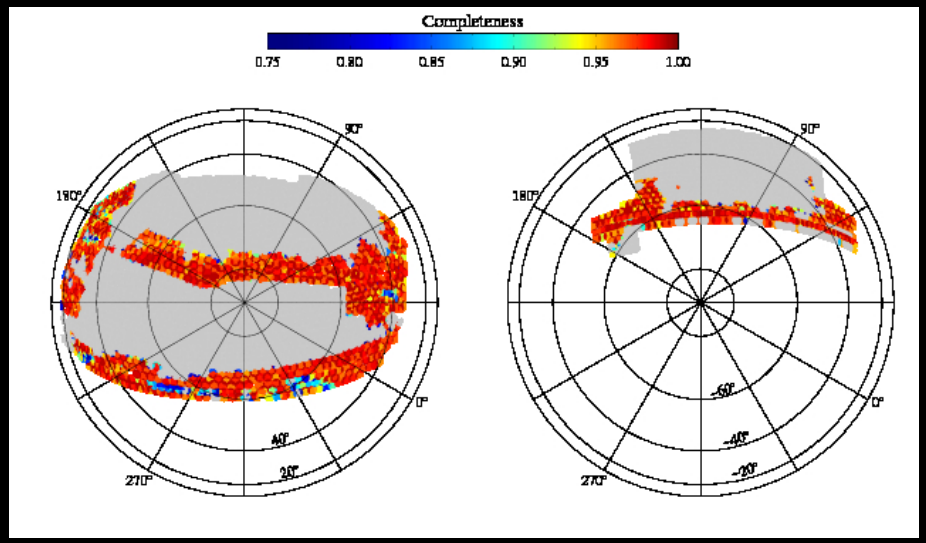
SDSS used by over 5000 refereed papers

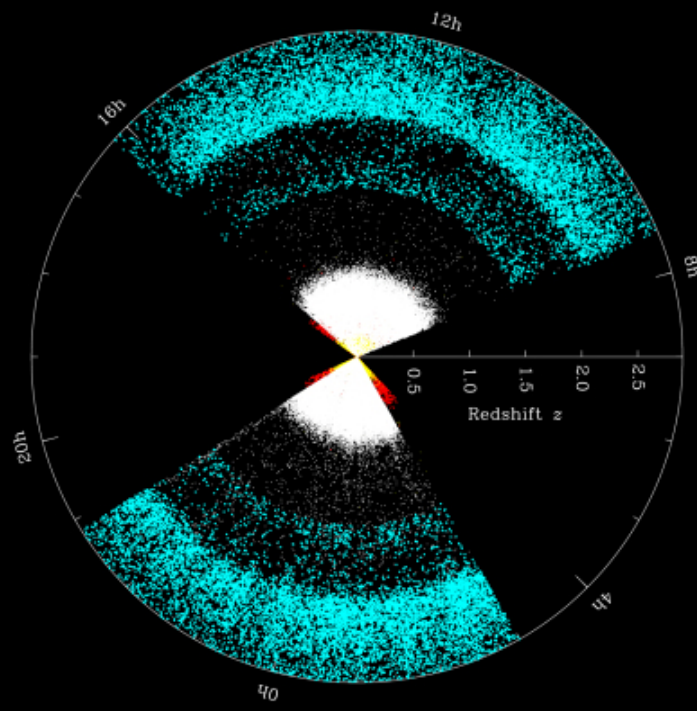
SDSSIII BOSS

Baryon Oscillation Spectroscopic Survey

1000 fibers spectrograph 2 M spectra!

Luminous red galaxies (LRG) Quasars





DR9 survey footprint galactic coordinates (Sanchez et al. 2012)

400K galaxy spectra

WHY LRG? Luminous and highly biased

Who is BOSS

Funding for SDSS-III has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, and the U.S. Department of Energy Office of Science. The SDSS-III web site is http://www.sdss3.org/.

SDSS-III is managed by the Astrophysical Research Consortium for the Participating Institutions of the SDSS-III Collaboration including the University of Arizona, the Brazilian Participation Group, Brookhaven National Laboratory, University of Cambridge, Carnegie Mellon University, University of Florida, the French Participation Group, the German Participation Group, Harvard University, the Instituto de Astrofisica de Canarias, the Michigan State/Notre Dame/JINA Participation Group, Johns Hopkins University, Lawrence Berkeley National Laboratory, Max Planck Institute for Astrophysics, Max Planck Institute for Extraterrestrial Physics, New Mexico State University, New York University, Ohio State University, Pennsylvania State University, University of Portsmouth, Princeton University, the Spanish Participation Group, University of Tokyo, University of Utah, Vanderbilt University, University of Virginia, University of Washington, and Yale University.

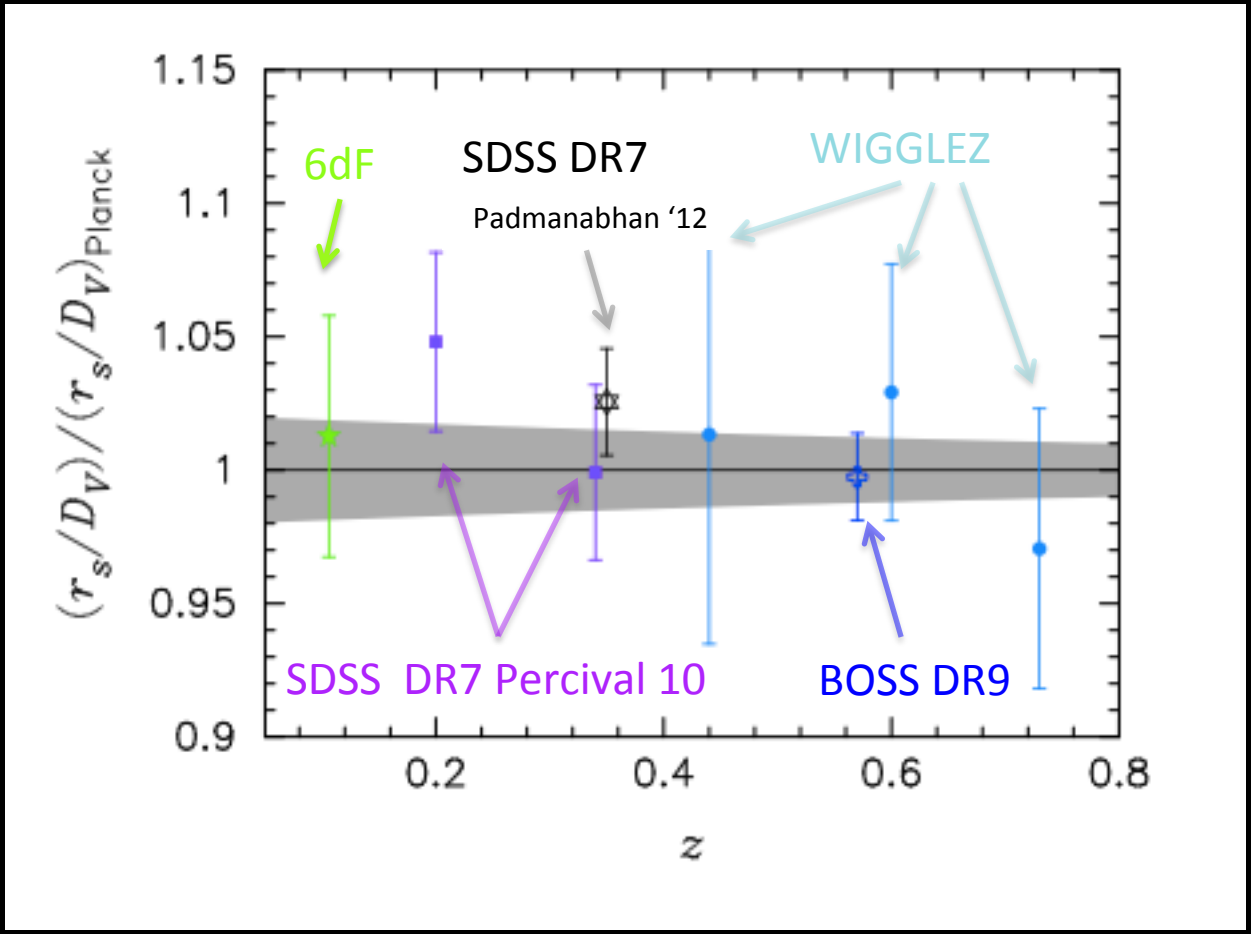
The Spanish participation group is comprised of three associate members: ICC-UB (Barcelona), IFIC (Valencia), and Multidark IFT-UAM/CSIC (Madrid) & IAA-CSIC (Granada), composed of the following people:

Olga Mena, Jordi Miralda Escude, Francisco Prada, Licia Verde

Sorry I am listing only the faculty members

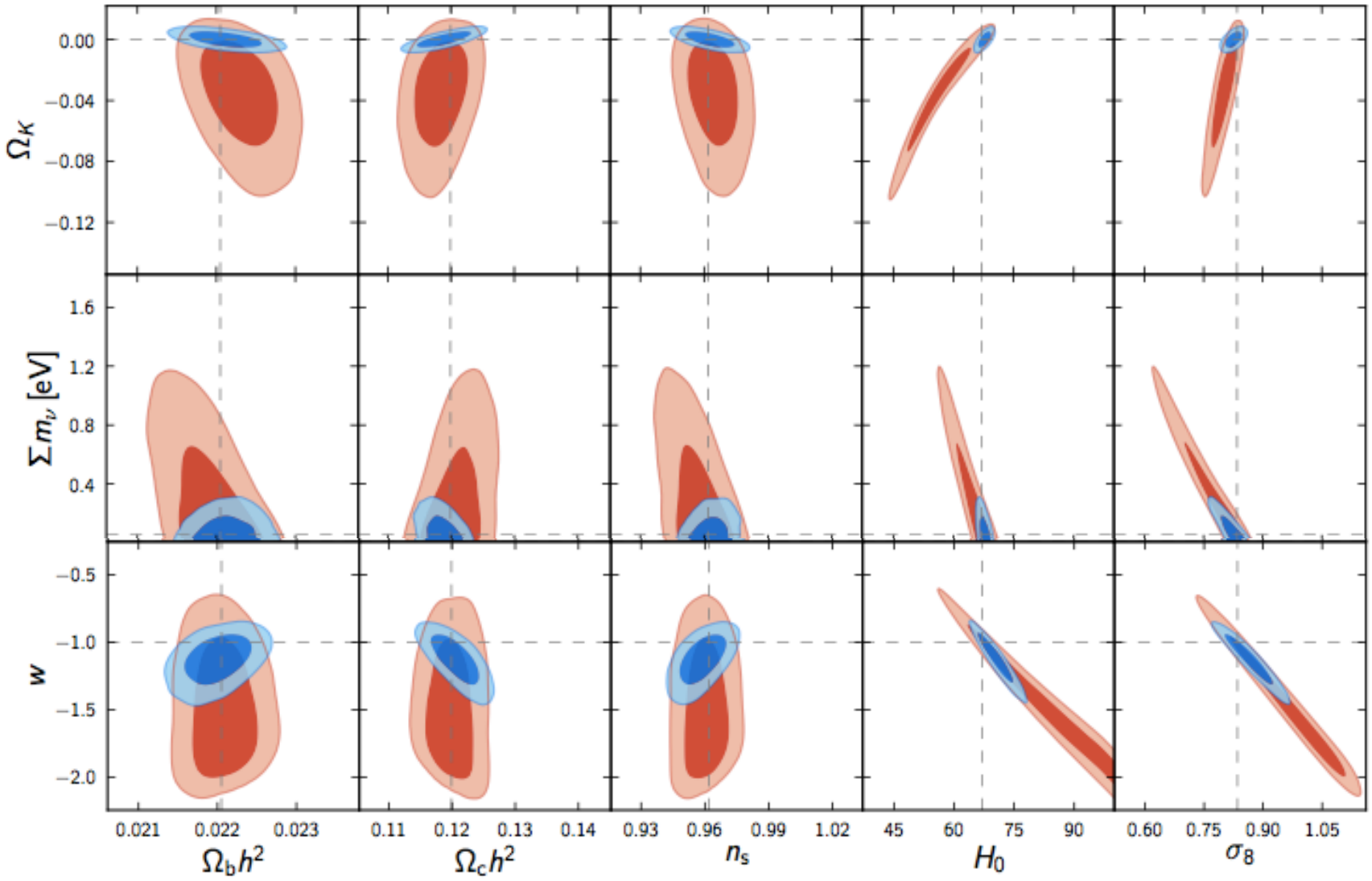
The power of BAO

From the Planck cosmological parameters paper: almost the state of the art

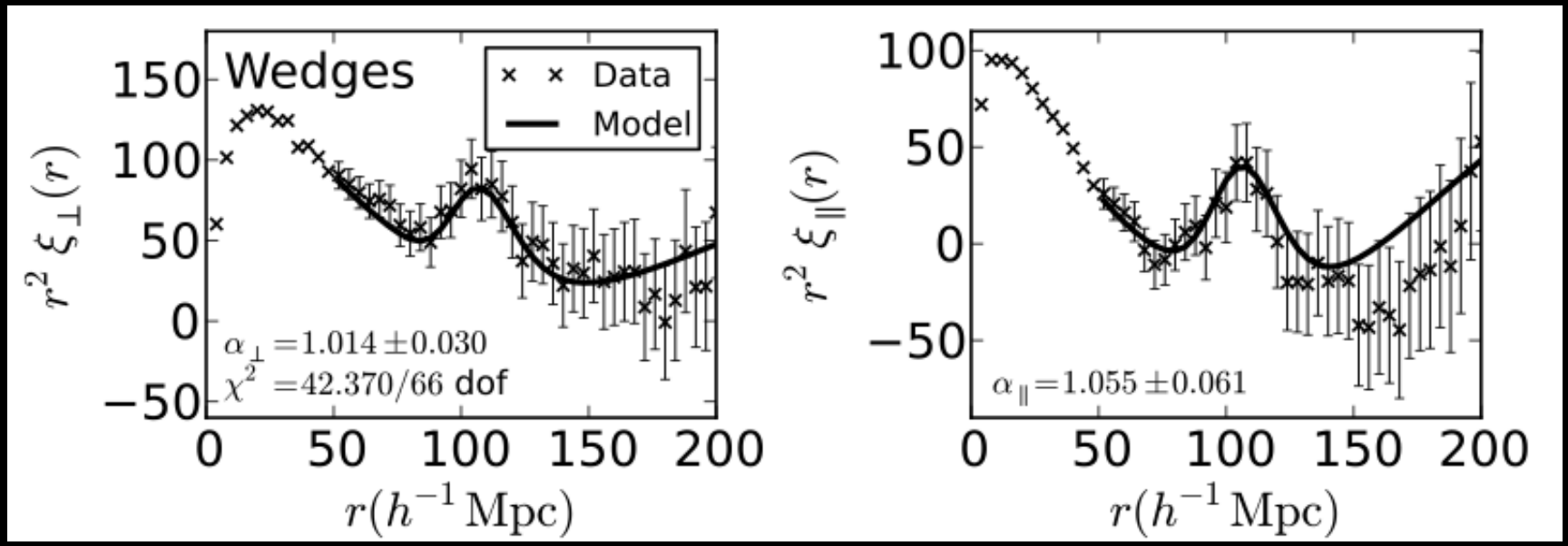


The power of BAO

From the Planck cosmological parameters paper Planck+WP +BAO



Hot off the press



$$\alpha_\perp = \frac{D_A(z) r_s^{\rm fid}}{D_A^{\rm fid} r_s},$$

$$\alpha_{||} = \frac{H^{\rm fid}(z) r_s^{\rm fid}}{H(z) r_s}.$$

$$\alpha = \alpha_\perp^{2/3} \alpha_{||}^{1/3}$$

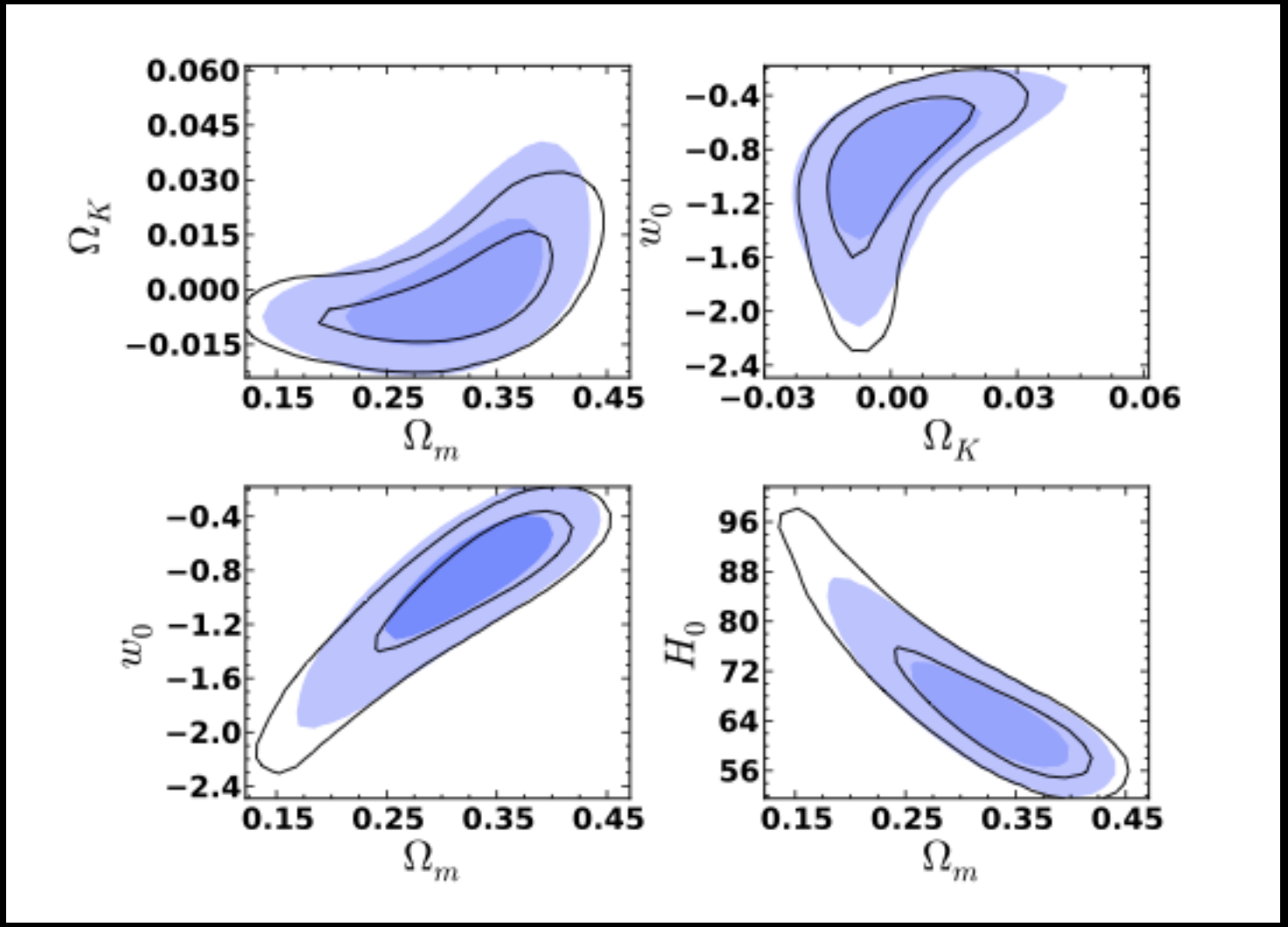
Isotropic shift

$$1 + \epsilon = \left(\frac{\alpha_{||}}{\alpha_\perp} \right)^{1/3}$$

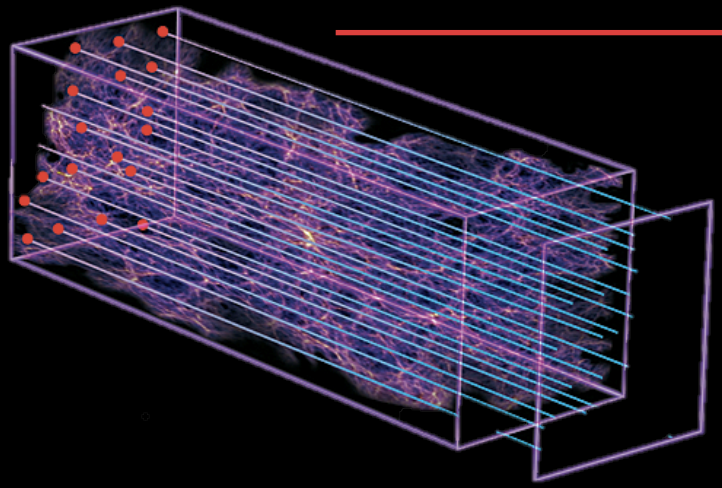
Anisotropic shift

Anderson et al 2013

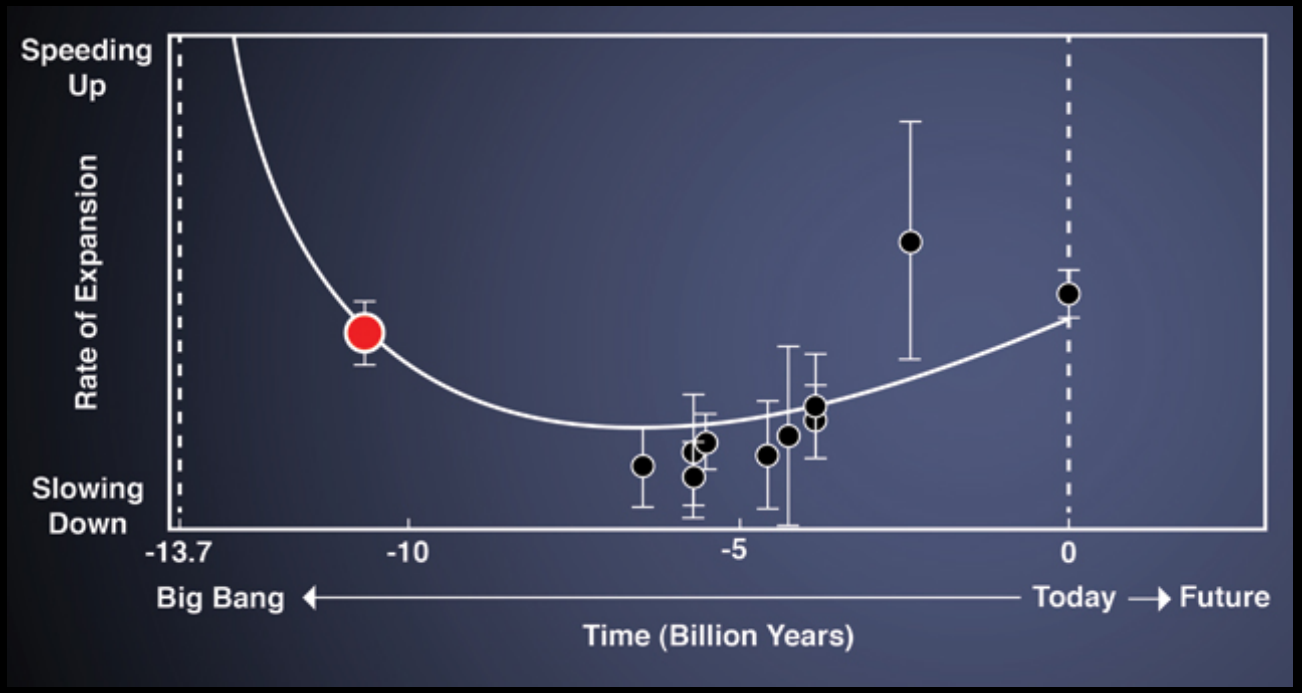
Hot off the press



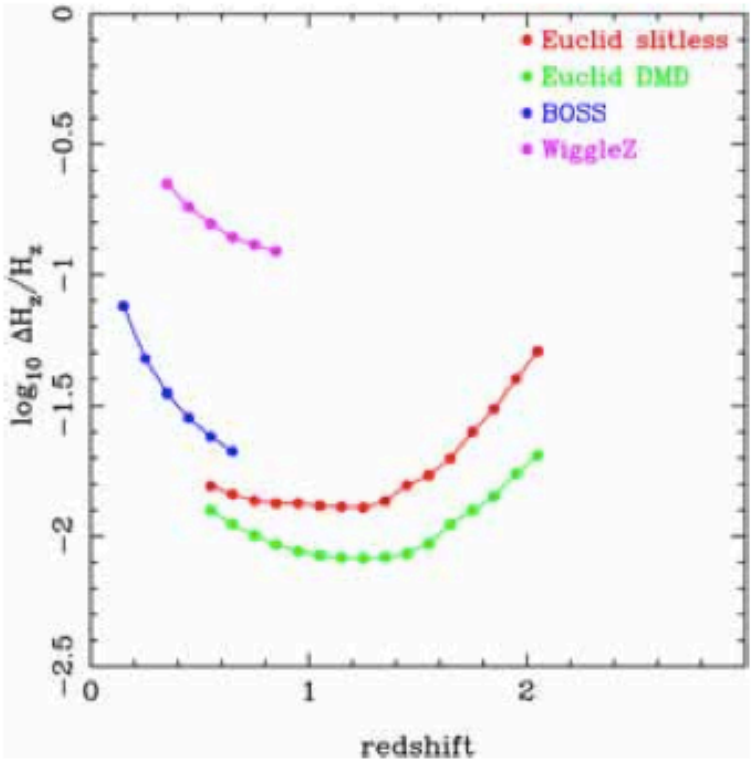
A new window….

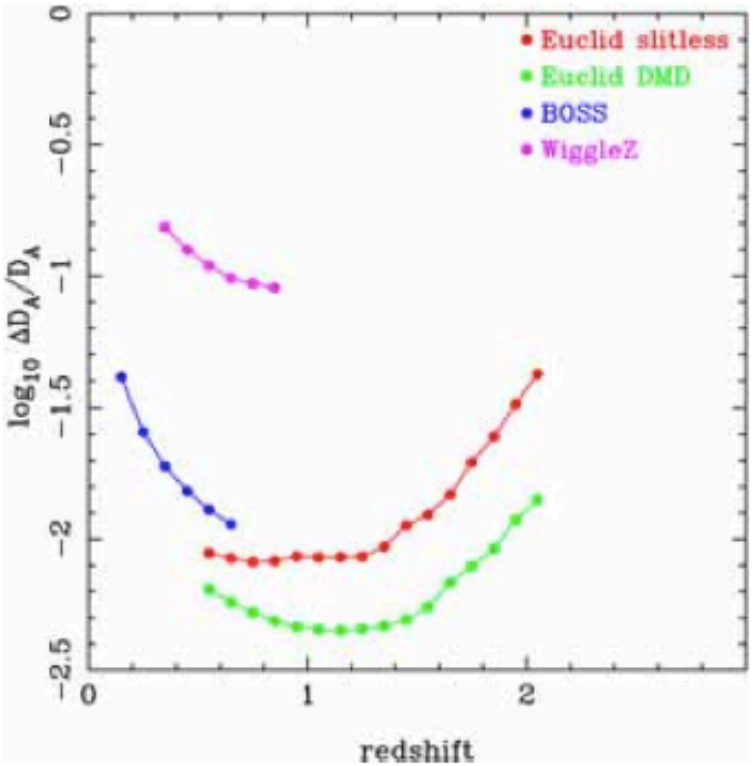


Lyman alpha forest



What's coming…



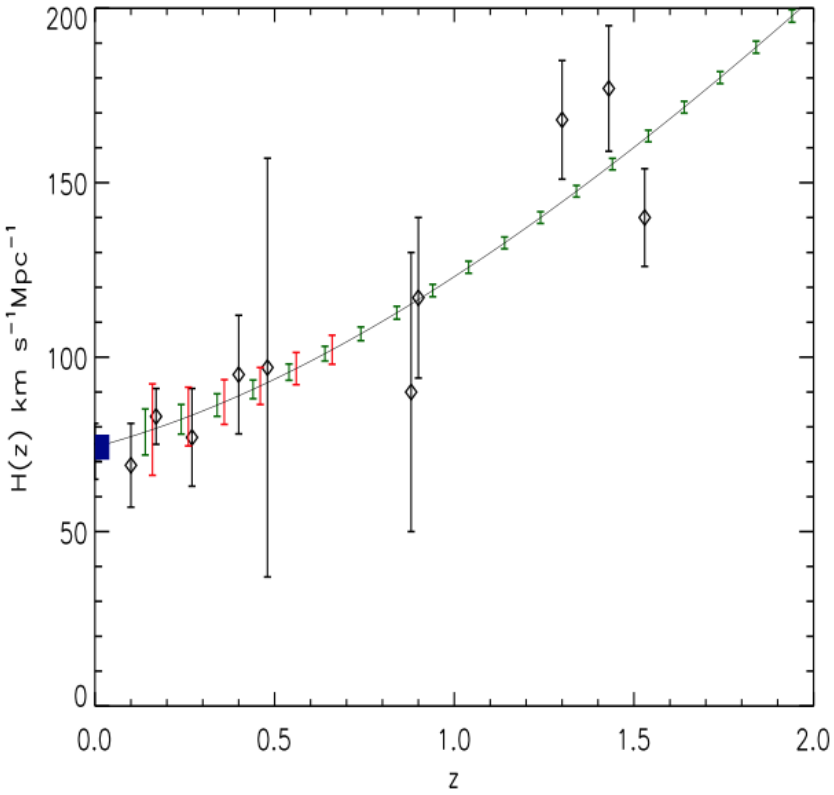


Laurejis et al 09

ULTIMATE EXPERIMENT, what I call "legacy"

What's coming…

BOSS (SDSSIII) survey-on going



Euclid

ULTIMATE EXPERIMENT, what I call "legacy"

What I had in mind when preparing this talk: Bleak situation

- Highly competitive, big money-big survey world, technology driven, large collaborations (eBOSS, BigBOSS… $$$$)
- Southern Europe disastrous financial situation and disastrous funding for science, even worst for basic science
- What can we do???
- Possibility : find a niche of relatively low cost, interesting problems to work on. Have the luxury of thinking long(-er) term, while weathering the economic storm.

The (BAO) challenges/open problems

- Non-linearities
- Bias
- Other modeling challenges
- Error-bars
- Algorithm and statistics
- Theoretical uncertainties

All that is available is just OK for the current survey size (sometimes not even that).

Even more:

- There is more info in these surveys than BAO:
- The P(k) shape state-of-the-art measure is more than three years old (and came out of BCN ☺)
- Peculiar velocities have quite useful cosmological information they are not just nuisance
- Non-linearities also have in principle useful info.
- If you think beyond simple LCDM extensions, the interpretation of cosmological data is… largely unexplored

About initial conditions….

BAO science relies on
the measurement of the sound horizon at radiation drag $r_s(z_d)$ from CMB
Which in turn relies on knowing well what was going on up to decoupling

2 examples on how this can fail

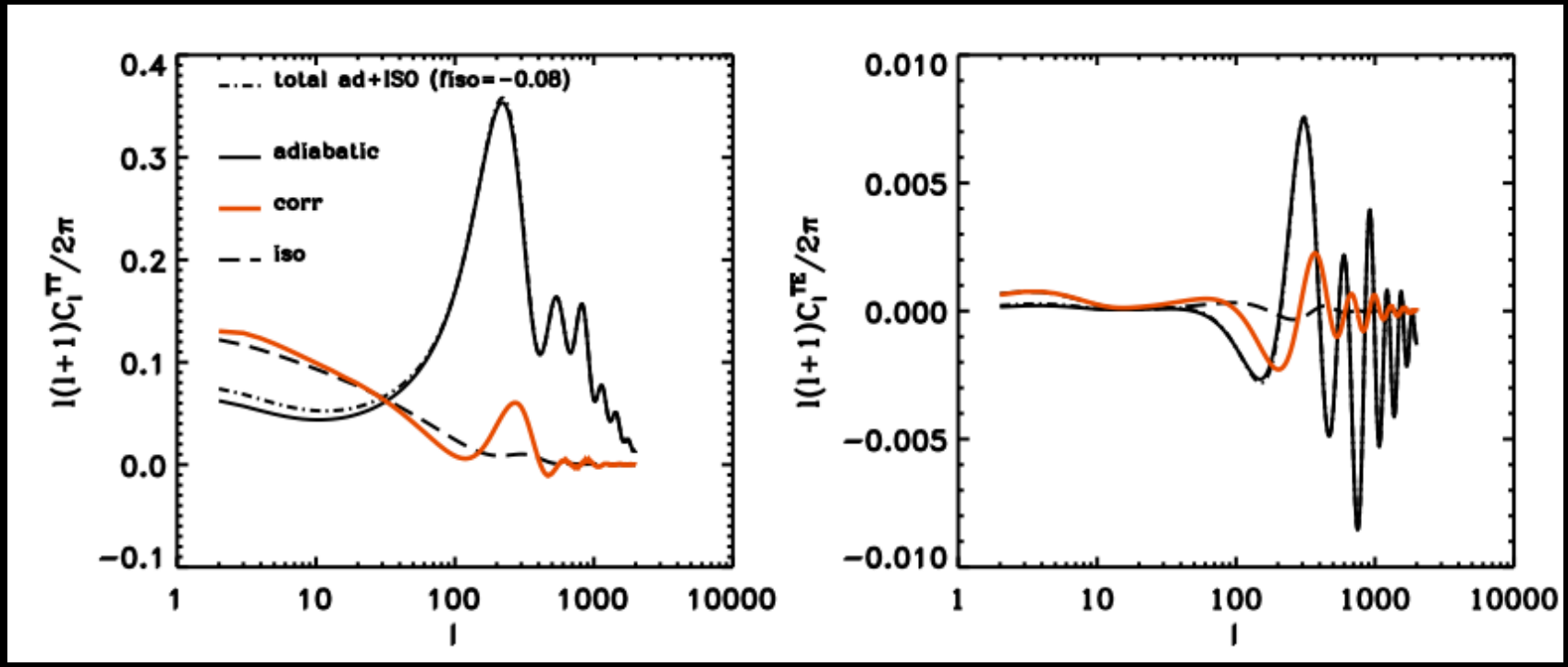
1: Isocurvature modes and Baryon Acoustic Oscillations

Anna Mangilli, LV, M. Beltran 2010

What's dark energy got to do with the nature of the initial perturbations?

Current data allow for a mix of adiabatic+isocurvature contributions to the initial conditions;.

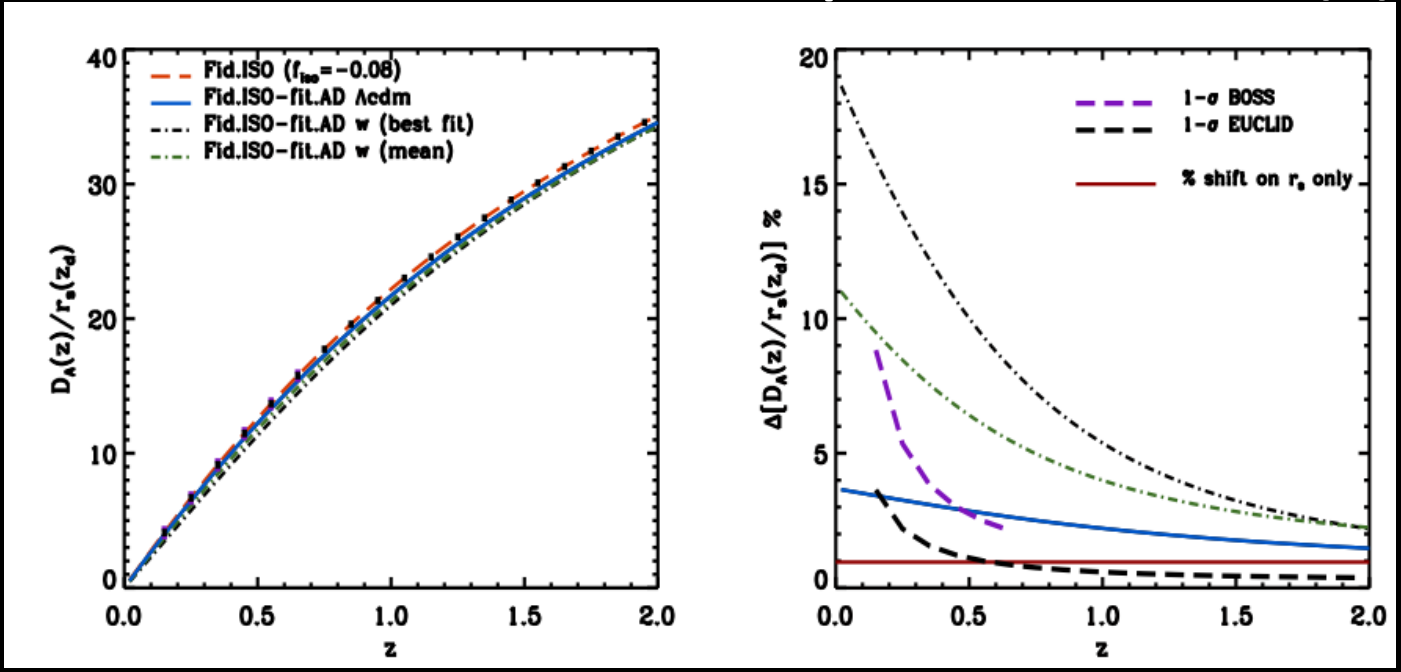
Effect of isocurvature



$$C_\ell = \langle \mathcal{R}^2_{rad} \rangle [C^{ad}_\ell + f^2_{iso} C^{iso}_\ell + 2 f_{iso} \cos \Delta_{k_0} C^{cor}_\ell].$$

Neglecting isocurvatures in parameter fit, can introduce systematic shifts in estimated parameters, including $r_s(z_d)$

Effects on BAO quantities Da(z)



In order to recover an *unbiased determination for the sound horizon* and dark energy parameters, a component of isocurvature perturbations must be included in the model when analyzing CMB data. Fortunately, doing so does not increase parameter errors significantly.

On the other hand this is saying that by doing a joint fit CMB+BAO the constraints on primordial isocurvature modes can be improved (compared to CMB-only constraints)

2. Delayed recombination:

a CMB measure of rs relies on:

accurate determination of photon to baryon ratio and matter radiation equality

e.g. extra light degrees of freedom, neutrinos or injection of resonant photons…

z	$\delta D/D$	$\delta H/H$
0.35	−3.0%	3.0%
0.6	−3.4%	3.3%
0.8	−3.6%	3.6%
1.0	−3.1%	3.0%
1.2	−3.4%	3.3%
2.8	−4.5%	4.5%

TABLE V: relative shift in the measure of $D_A(z)$ and $H(z)$ for the mean redhsift of each bin as computed from (18) assuming $\epsilon_\alpha = 0$ in the hypothesis that true value is $\epsilon_\alpha = 0.05$.

deBernardis et al 09

A possible way out: relative BAO

Say you have BAO measurements in N redshift bins

Take:

$D_{As}(z_i)/D_A(z_1)$
$Hs(z_i)/Hs(z_1)$

And $D_{as}(z1)H_s(z_1)$

If you have more than few bins in redshift the errors do not grow to much.

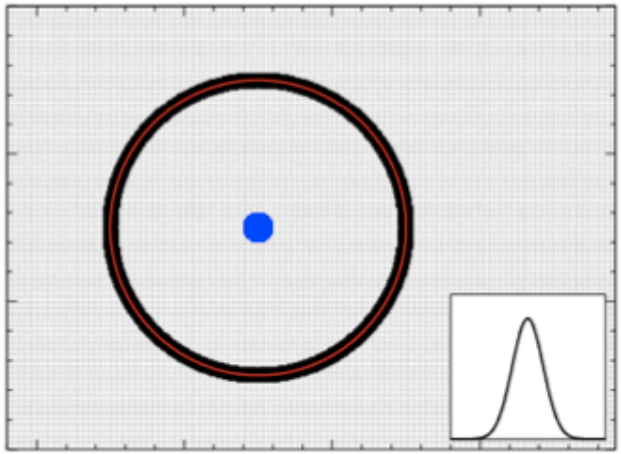
Noreña et al 2011

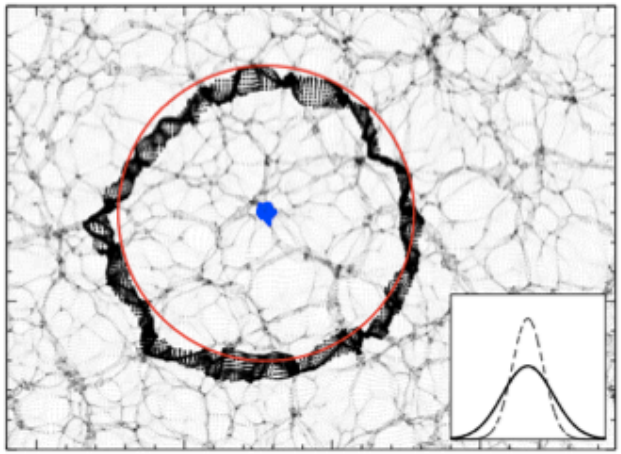
Non-linearities

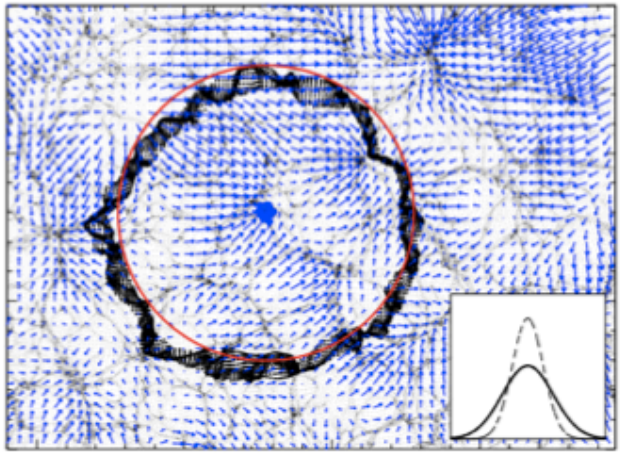
- Ignore
- Model
- Undo
- Other fancy approaches not yet tested

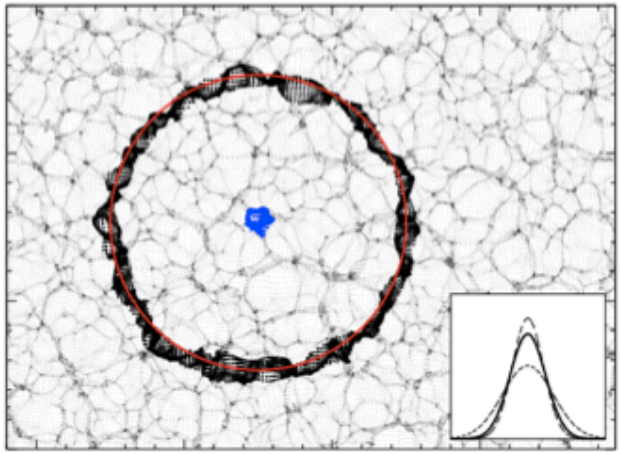
Undo:

Particularly cute:









Uses Lagrangian Perturbation theory

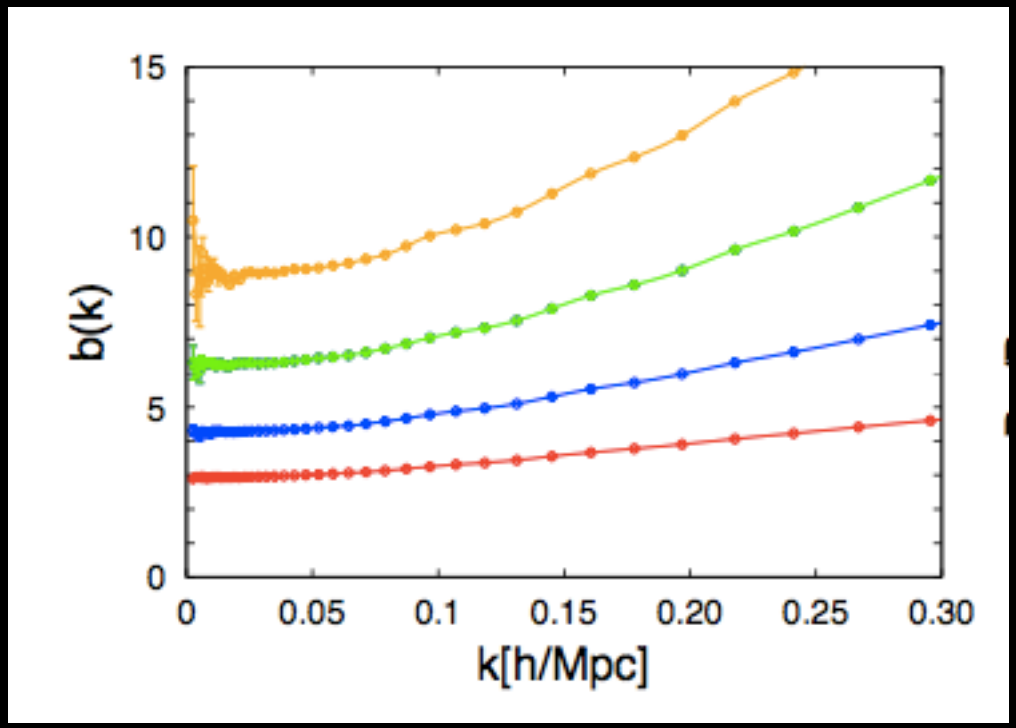
Fig. from Padmanabhan et al 12 but reconstruction has a longer history…

HALOS (still not galaxies…)

Say that we know the bias (from simulations)

160 independent runs,

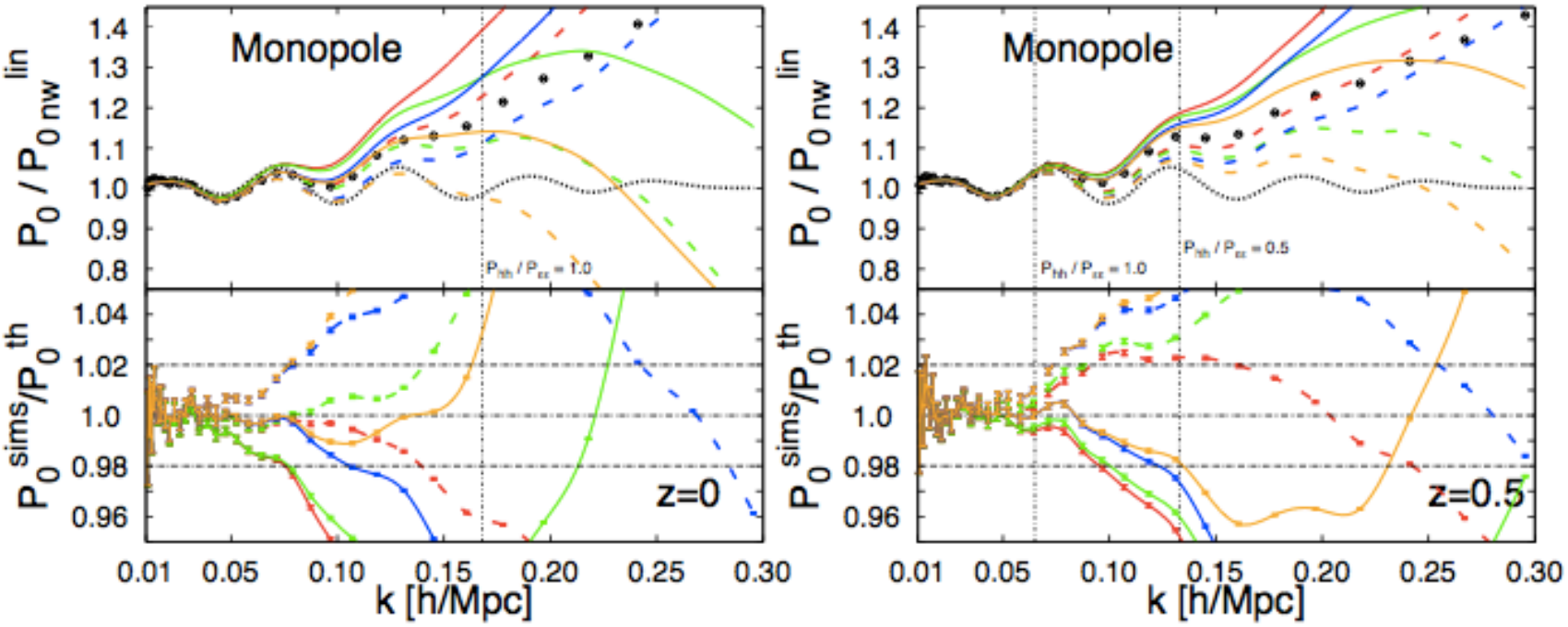
768^3 particles, 2.4Gpc/h box side



M>10^{14} Msun

Gil-Marín, Héctor ; Wagner, Christian; Verde, Licia; Porciani Cristiano, Jimenez, Raul 2012

HALOS (still not galaxies…) multipoles



Kaiser

Scoccimarro

Taruya

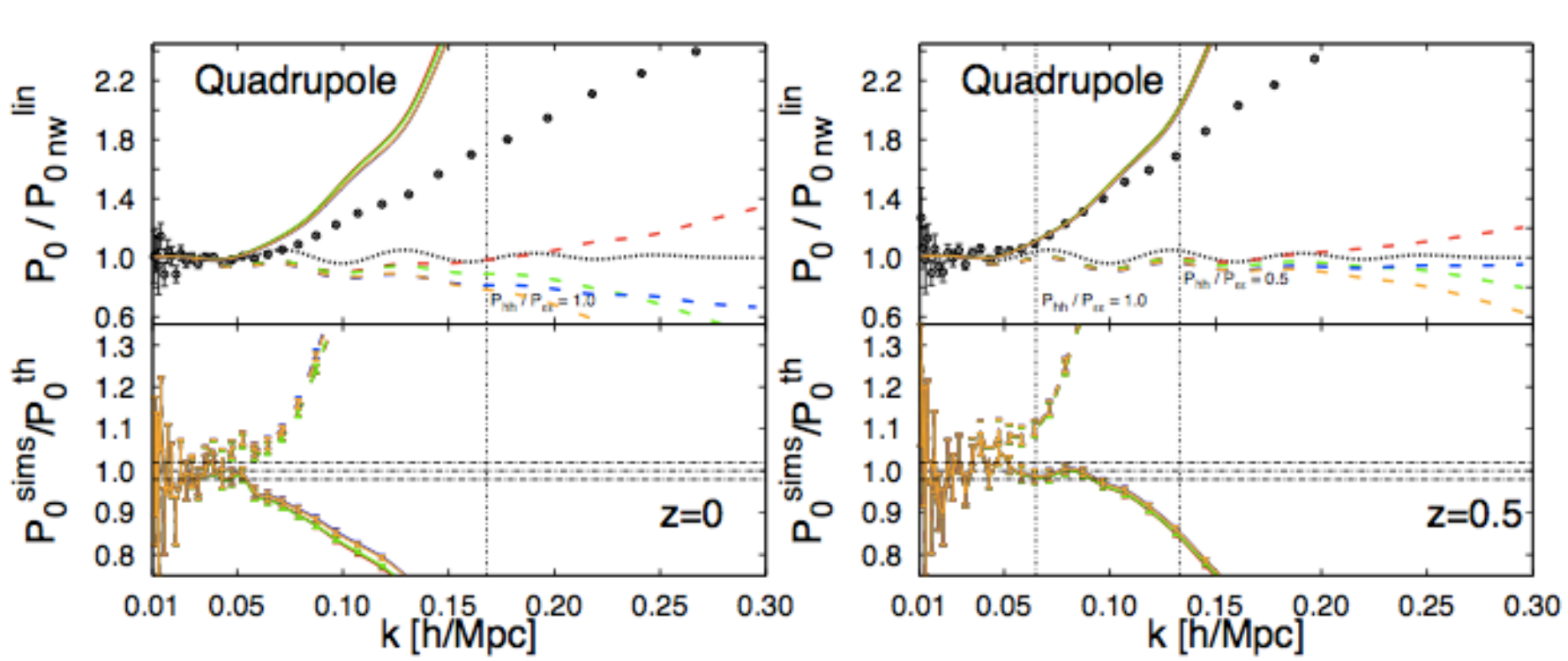
SPT 1loop

SPT 2 loops

2 loops RPT N_1

2 loops RPT N_2

HALOS (still not galaxies…) multipoles



Kaiser

Scoccimarro

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SPT 1loop

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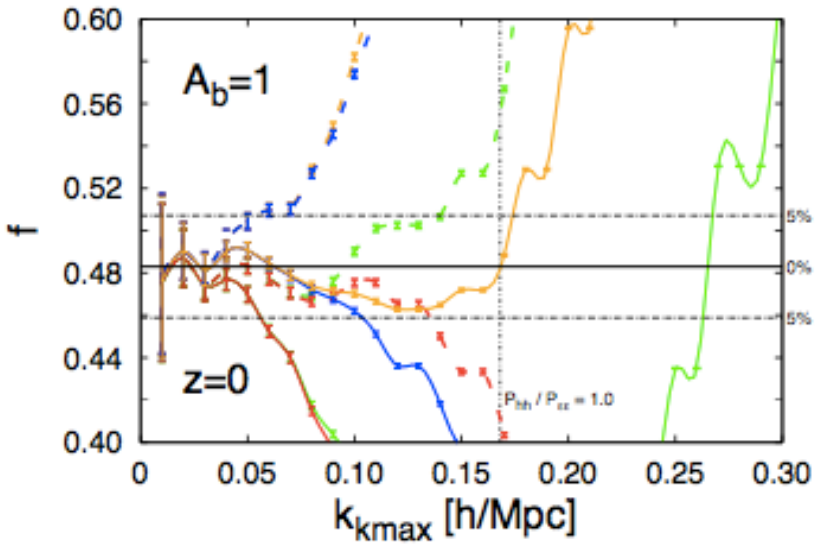
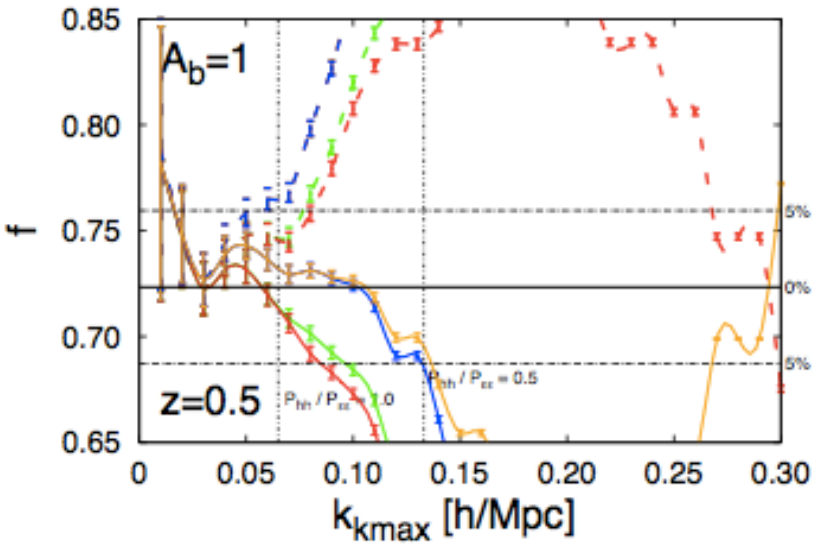
2 loops RPT N_1

2 loops RPT N_2

Recovering f…





If you know bias

Kaiser

Scoccimarro

Taruya

SPT 1loop

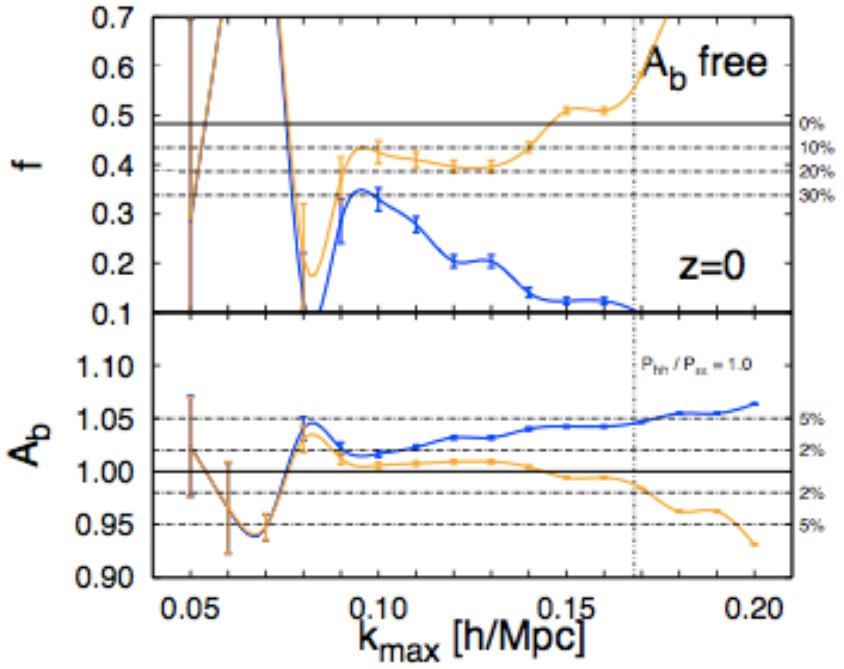
SPT 2 loops

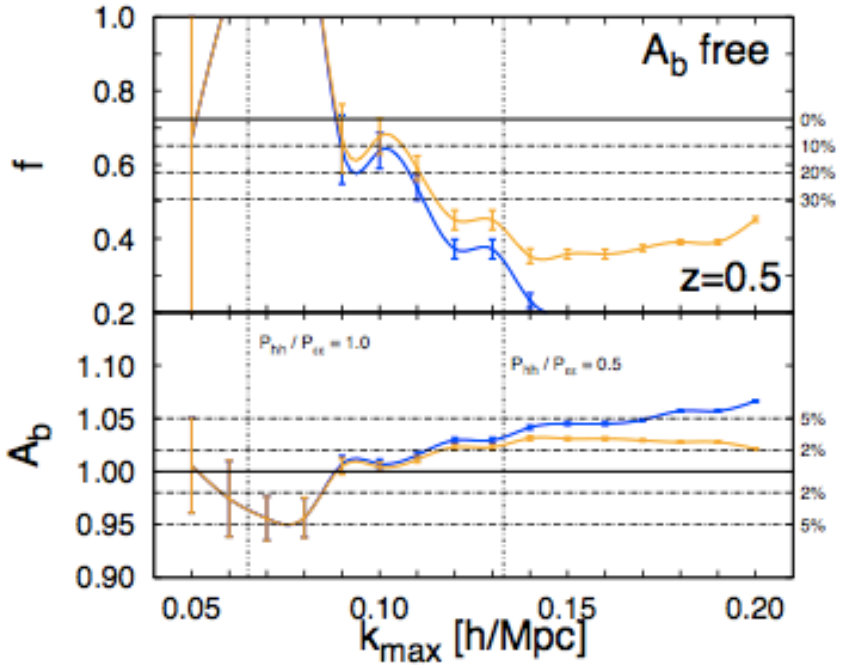
2 loops RPT N_1

2 loops RPT N_2

Recovering f…

But if you don't…..





Taruya+2loops SPT

Taruya+2 loops RPT N_2

To summarize…

- Dark matter real space under control: 2 loops RPT N2 works quite well…. % accuracy up to k=0.2h/Mpc
- Redshift space distortions complicate things but for dark matter f is unbiased (at % level)
- Halos are a problem even if you know bias
- A small error on b propagates into a large error on f

Diclaimer: We used massive halos, for less massive ones things might be different.

The (BAO++) challenges/open problems

- Non-linearities
- Bias
- Other modeling challenges
- Error-bars
- Algorithm and statistics
- Theoretical uncertainties

All that is available is just OK for the current survey size (sometimes not even that).

Summary, conclusions

- Simple physics gives a fundamental (BAO) scale
- Imprinted on the dark matter, seen on the galaxy distribution
- Clean direct way to track expansion history
- Need large surveys
- Still open problems
- One man's trash is another man's treasure
- Treasure trove…