Title: Cosmology with BOSS

Date: May 31, 2016 11:00 AM

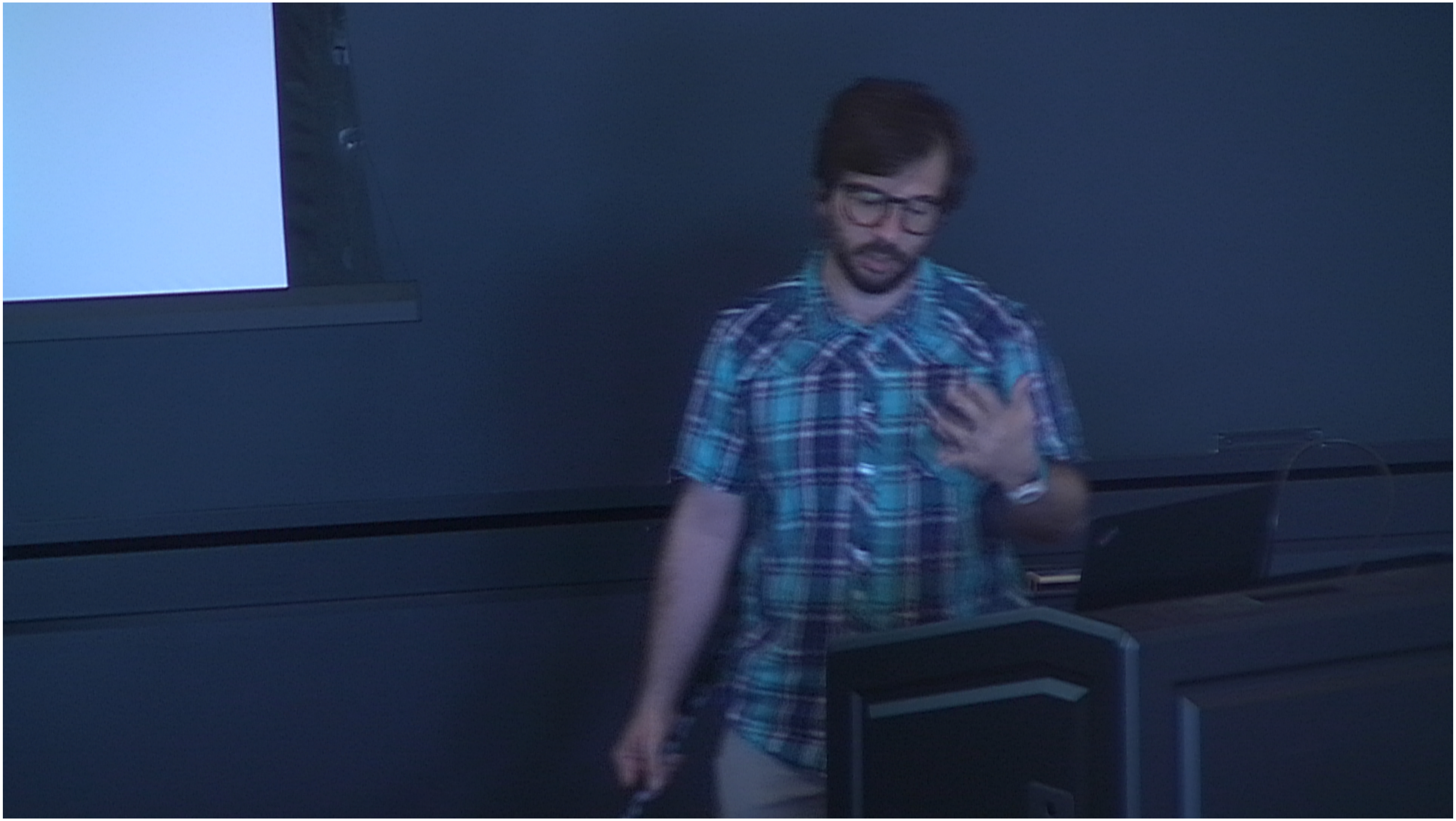
URL: http://pirsa.org/16050014

Abstract: <p>I will discuss how we constrain properties of the universe using two
 tracers of large scale structure measured by the BOSS (Baryon
 Oscillations Spectroscopic Experiment): galaxies and Lyman-alpha
 forest. I will show recent results from baryonic acoustic oscillations
 measured in both tracers and discuss cosmological implications. I
 will briefly mention other measurements and consider forecasts for
 quasar-forest bispectrum to constrain primordial non-Gaussianity.</p>

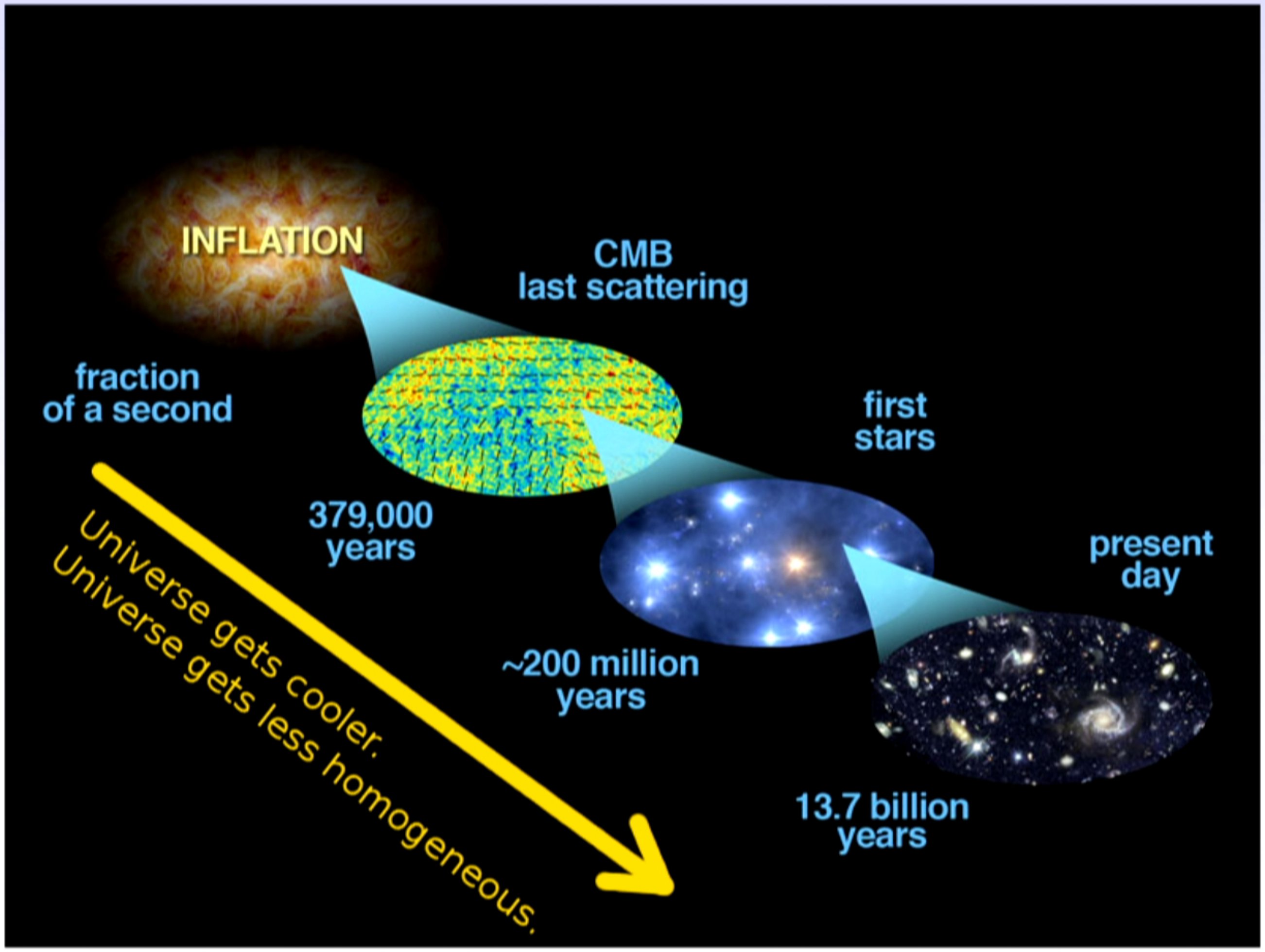
Cosmology with BOSS

Anže Slosar

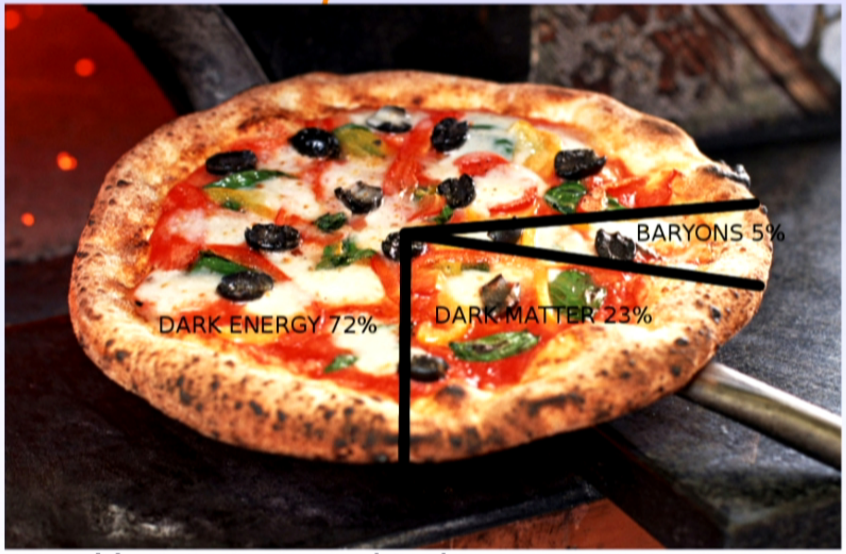
Perimeter Institute, 2016



Universe's timeline



Cosmic pizza



Smallest component of Universe:

- *Baryons:* Stuff we see that makes up the world around us: electrons, protons, neutrons, ...
- Stuff we know & love

However, we also have:

- *Dark Matter:*
  - Cold, pressureless, non-interacting stuff
  - Collapses under its own gravity
  - Without it, Universe wouldn't have time to form galaxies, stars, planets and us
- Dark Energy:
  - Drives accelerated expansion of the Universe - biggest surprise of the last decade

The Dark Sector

- *Macroscopic* behaviour well understood: we have many independent detections/confirmations of both dark components
- *Microscopic* understanding lacking:
  - How the dark sector fits with the standard model of particle physics?
  - Does gravity obey general relativity on all scales and at all energies?
  - How did it all begin? Is inflation an accurate description of the early universe?
- Dark Matter can be one of many postulated stable, weakly interacting particles – something you could see at LHC or detect directly
- Dark Energy much more mysterious. It behaves like energy density of a vacuum, but its energy scale does not relate to anything we know.

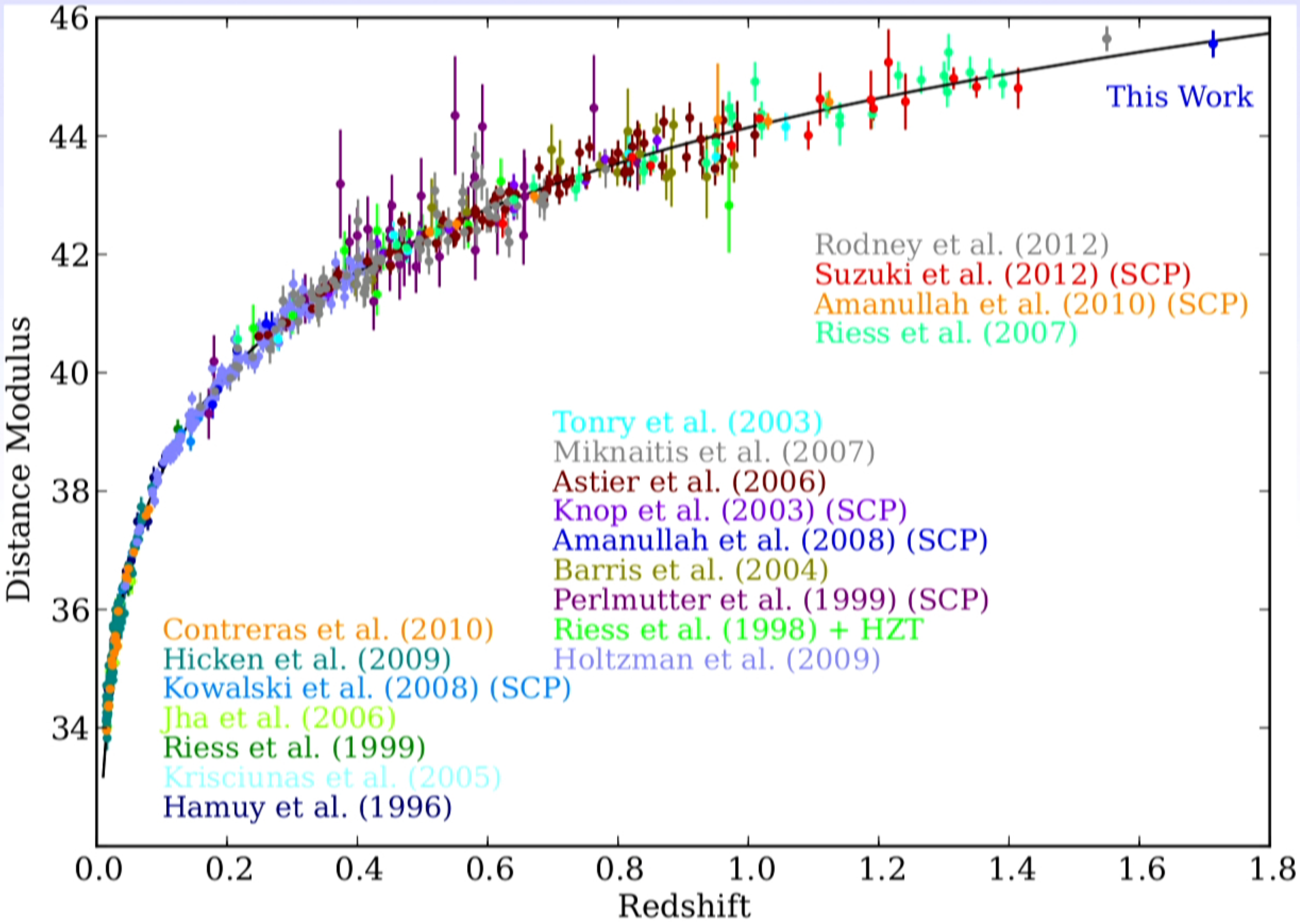
The Dark Sector

- *Macroscopic* behaviour well understood: we have many independent detections/confirmations of both dark components
- *Microscopic* understanding lacking:
  - How the dark sector fits with the standard model of particle physics?
  - Does gravity obey general relativity on all scales and at all energies?
  - How did it all begin? Is inflation an accurate description of the early universe?
- Dark Matter can be one of many postulated stable, weakly interacting particles – something you could see at LHC or detect directly
- Dark Energy much more mysterious. It behaves like energy density of a vacuum, but its energy scale does not relate to anything we know.

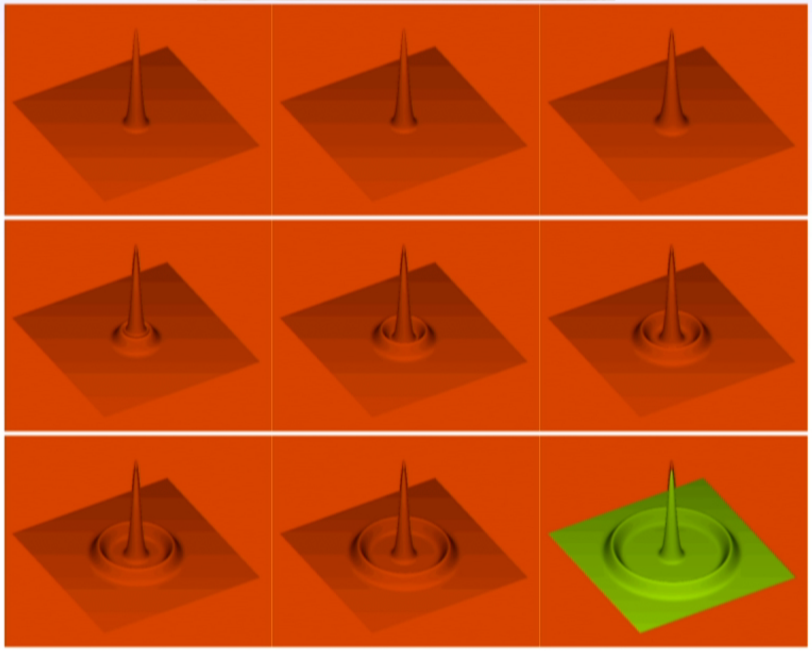
Expansion history

- We are essentially doing an adiabatic-expansion experiment on Universe's constituents
- This tells the equation of state of components ($w(a) = p/\rho$), but cannot directly inform us of microphysics
- It is nevertheless one of the basic properties of constituents of the Universe that we want to measure.

Hubble diagram from Supernovae

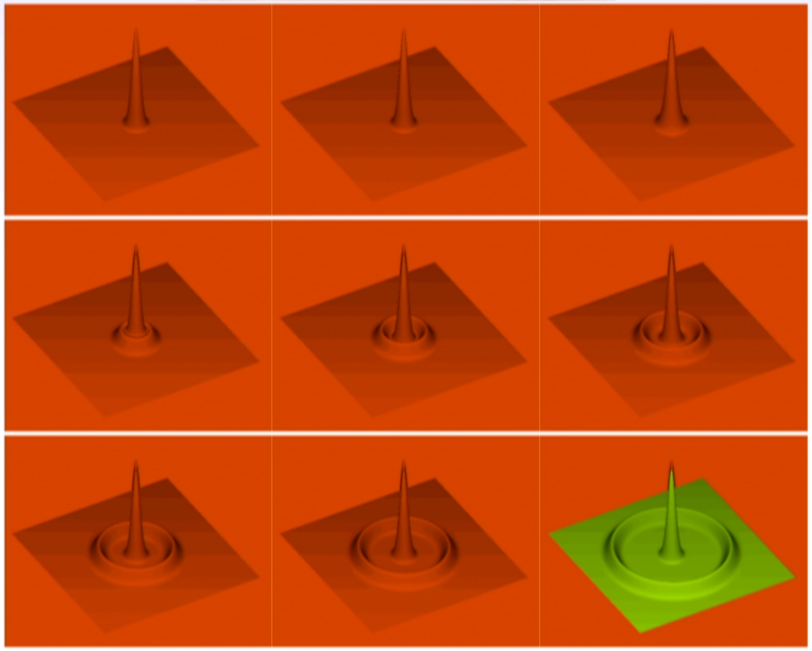


What is BAO?



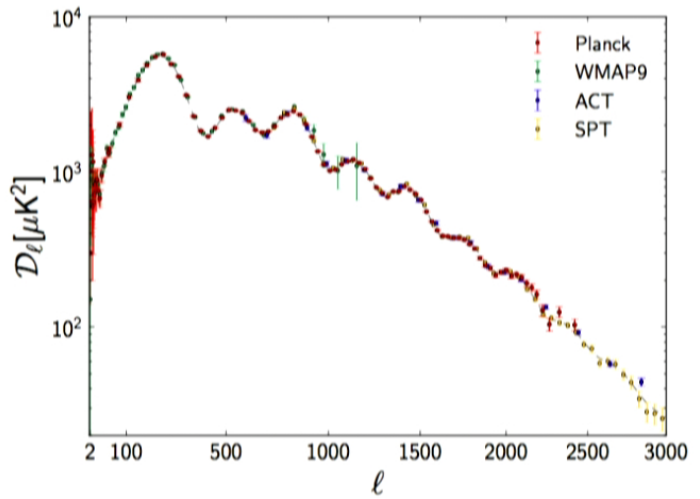
- Before recombination (i.e. formation of hydrogen atoms), primordial plasma supports acoustic waves
- Sound waves travel through Universe as long as it is in primordial plasma state
- We can see them in CMB power spectrum
- The characteristic scale is imprinted as a small bump into the correlation properties of dark matter
- It acts as a standard ruler, allowing very robust measurements of the expansion history of the universe.

What is BAO?

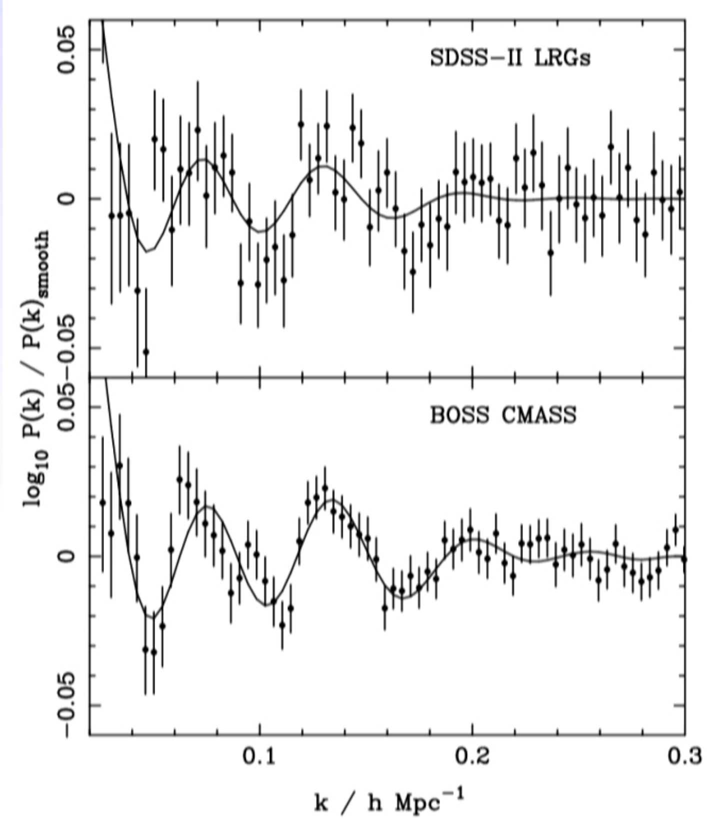


- Before recombination (i.e. formation of hydrogen atoms), primordial plasma supports acoustic waves
- Sound waves travel through Universe as long as it is in primordial plasma state
- We can see them in CMB power spectrum
- The characteristic scale is imprinted as a small bump into the correlation properties of dark matter
- It acts as a standard ruler, allowing very robust measurements of the expansion history of the universe.

What is BAO?

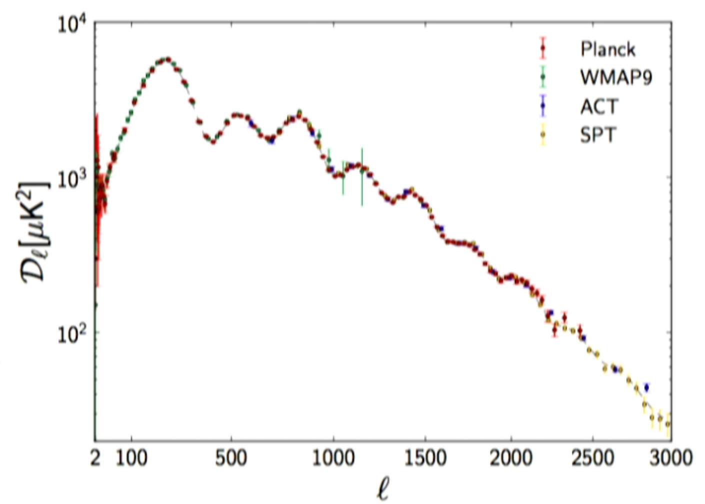


BAO in Cosmic Microwave Background

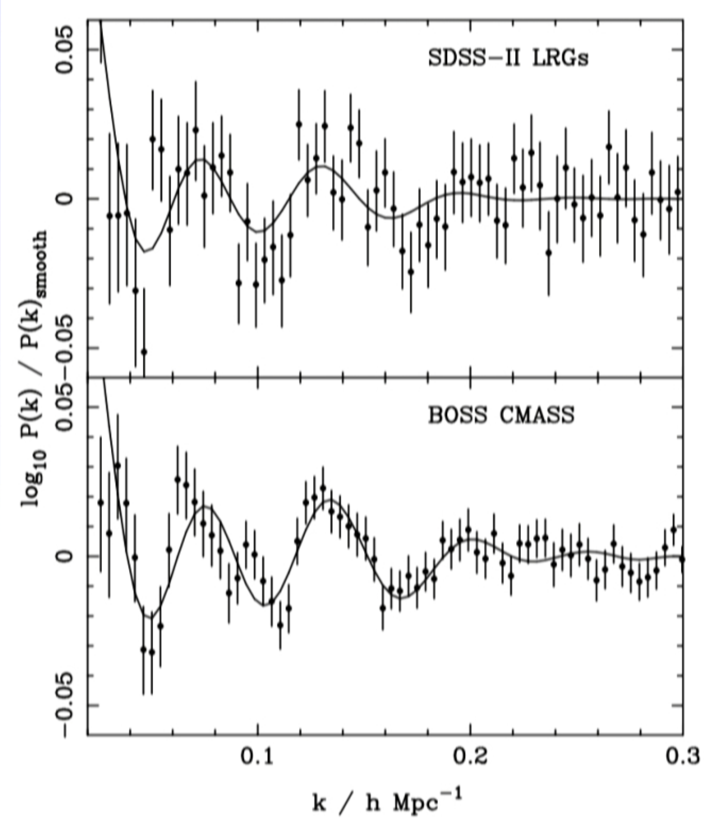


BAO in CMASS galaxies

What is BAO?

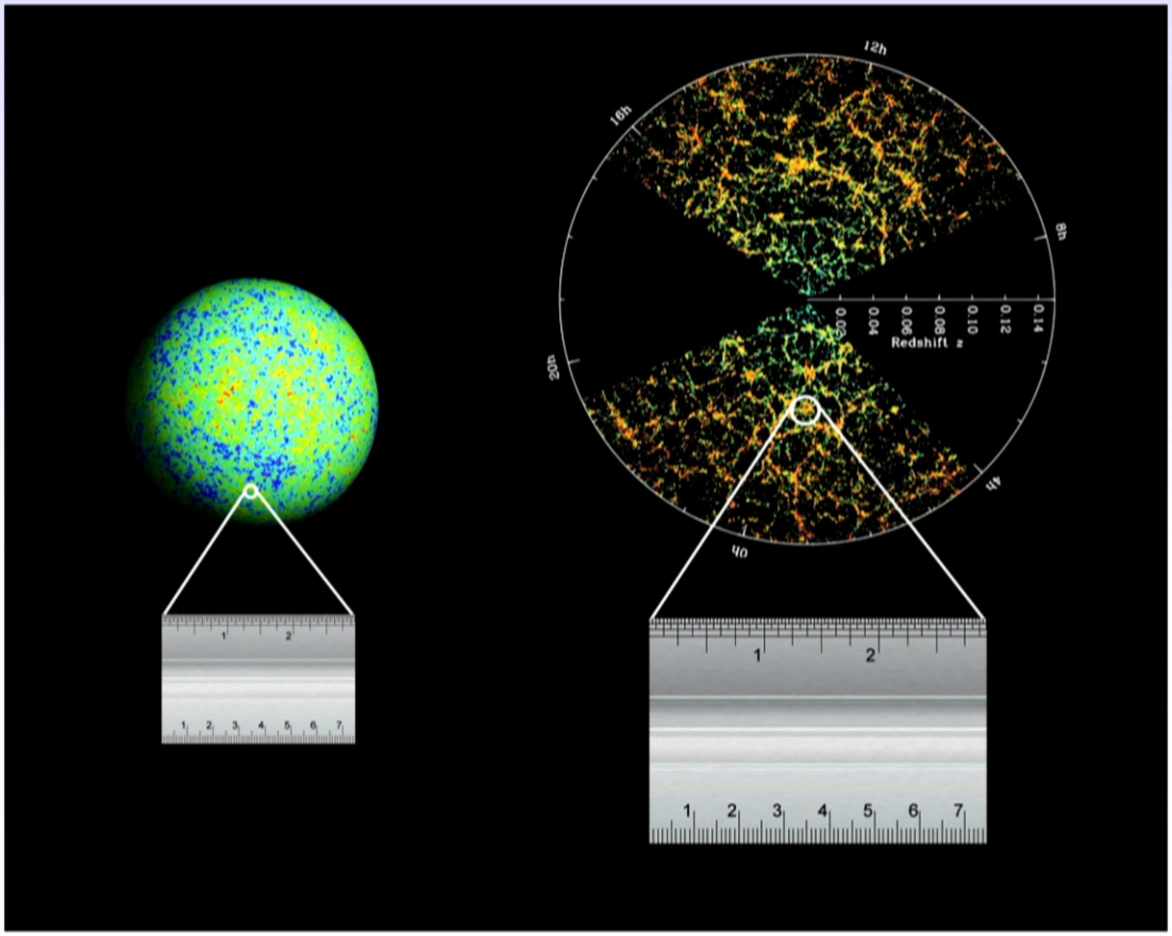


BAO in Cosmic Microwave Background

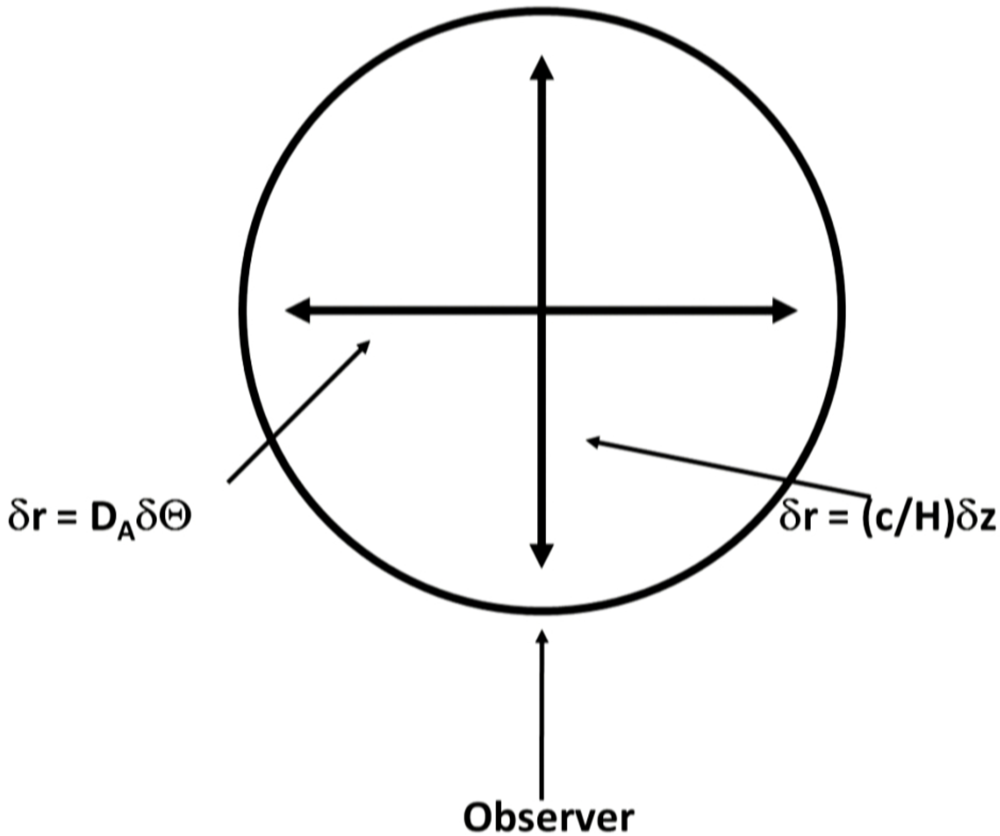


BAO in CMASS galaxies

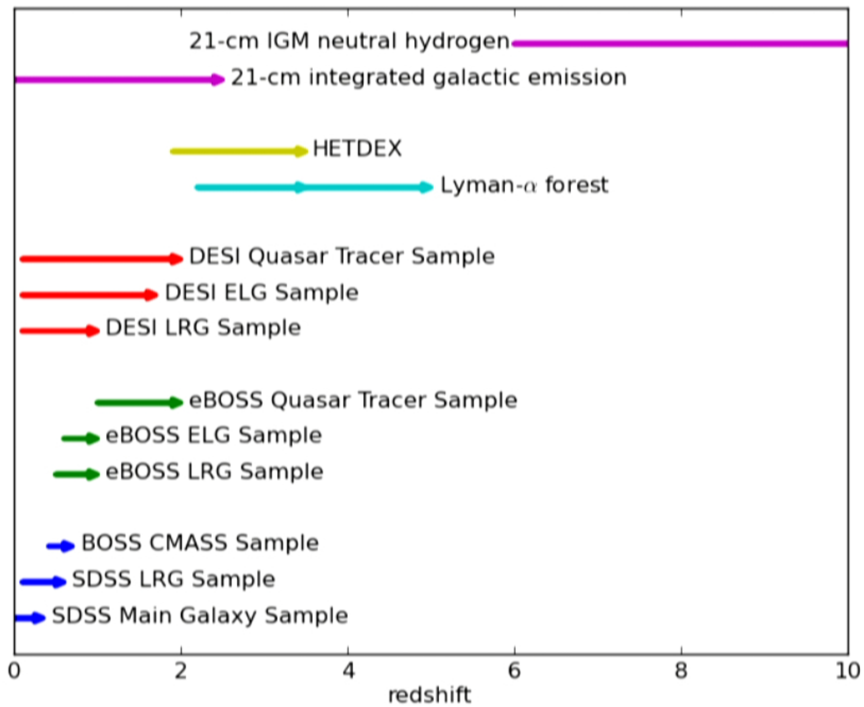
BAO is a statistical ruler



BAO is a statical ruler



From tracers to dark matter



- Disclaimer: plot does not show number densities and does not include photometric experiments
- At $z < 2$ galaxies are best tracers
- At $z > 2$ different techniques must be used: Lyman-α forest is one such probe used by BOSS
- Systematics very different from galaxies as tracers

Dark matter from galaxy clustering

Two very robust assumption about the galaxy formation process:

- The only field that matters on large scales are the fluctuations in the matter fluctuations $\rho_m = \bar{\rho}_m(1+\delta_m)$
- The galaxy formation process is local on some scale R:

$$\delta_g(\mathbf{x}) = F[\delta_m], \tag{1}$$

  where F is an arbitrary functional that, however has no contributions for distances larger than R from $\mathbf{x}$.

Under these assumptions, in the $k \to 0$ limit, galaxies in redshift-space must trace dark-matter following

$$\delta_g(\mathbf{k}) = (b_\delta + b_\eta f \mu^2)\delta_m(\mathbf{k}) + \epsilon, \tag{2}$$

where bs are bias parameters and ϵ is a white noise stochastic variable.

Galaxy clustering: relying on symmetries

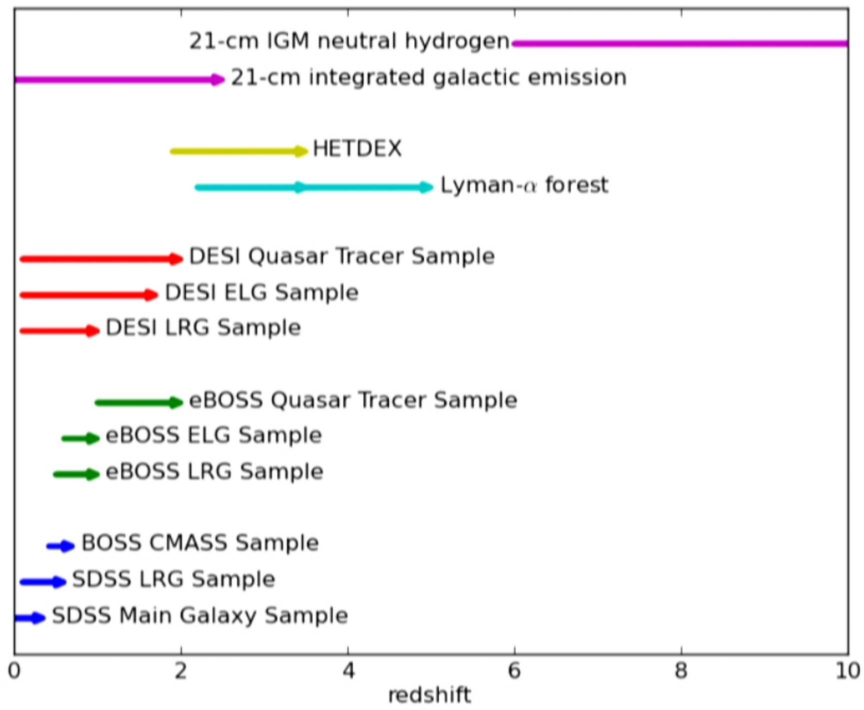
Under these assumptions, in the $k \to 0$ limit, galaxies in redshift-space must trace dark-matter following

$$\delta_g(\mathbf{k}) = (b_\delta + b_\eta f \mu^2)\delta_m(\mathbf{k}) + \epsilon, \tag{3}$$

This has all been derived with galaxies in mind (where one can show $b_\eta = 1$), but it is true for any local tracer and I am emphasizing the EFTish aspects.
Going to small scale gives:

- More bias parameters: quadratic terms b_2, tidal terms b_{s^2}, etc.
- $k^2 R^2$ series correction to each bias parameter
- Similar terms for redshift-space distortions
- Fingers of God!
- Number of papers: McDonald & Roy, Seljak & McDonald, Schmidt et al, Scoccimarro et al., Ferraro et al., and all the paper-trail following...

From tracers to dark matter

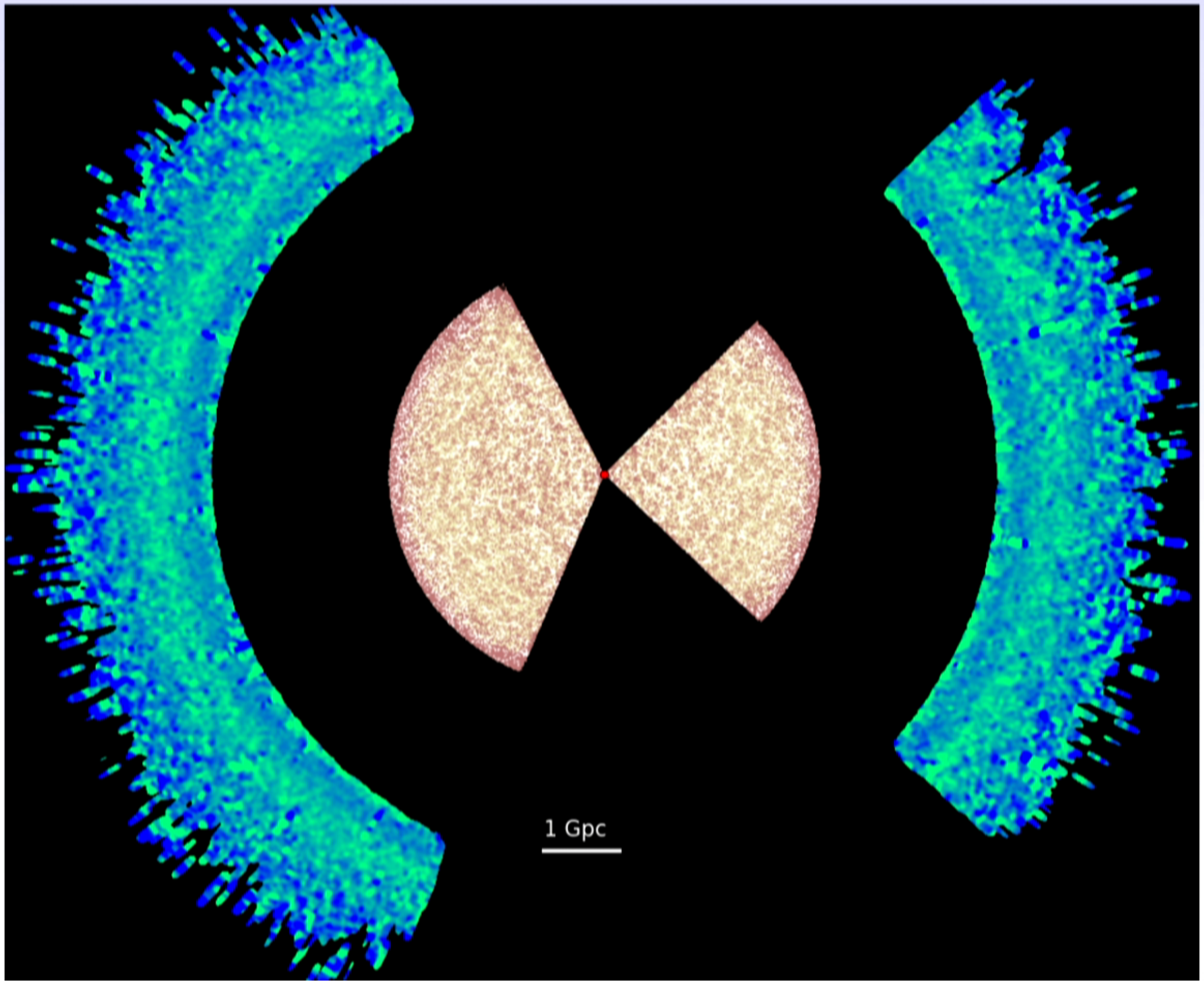


- Disclaimer: plot does not show number densities and does not include photometric experiments
- At $z < 2$ galaxies are best tracers
- At $z > 2$ different techniques must be used: Lyman-α forest is one such probe used by BOSS
- Systematics very different from galaxies as tracers

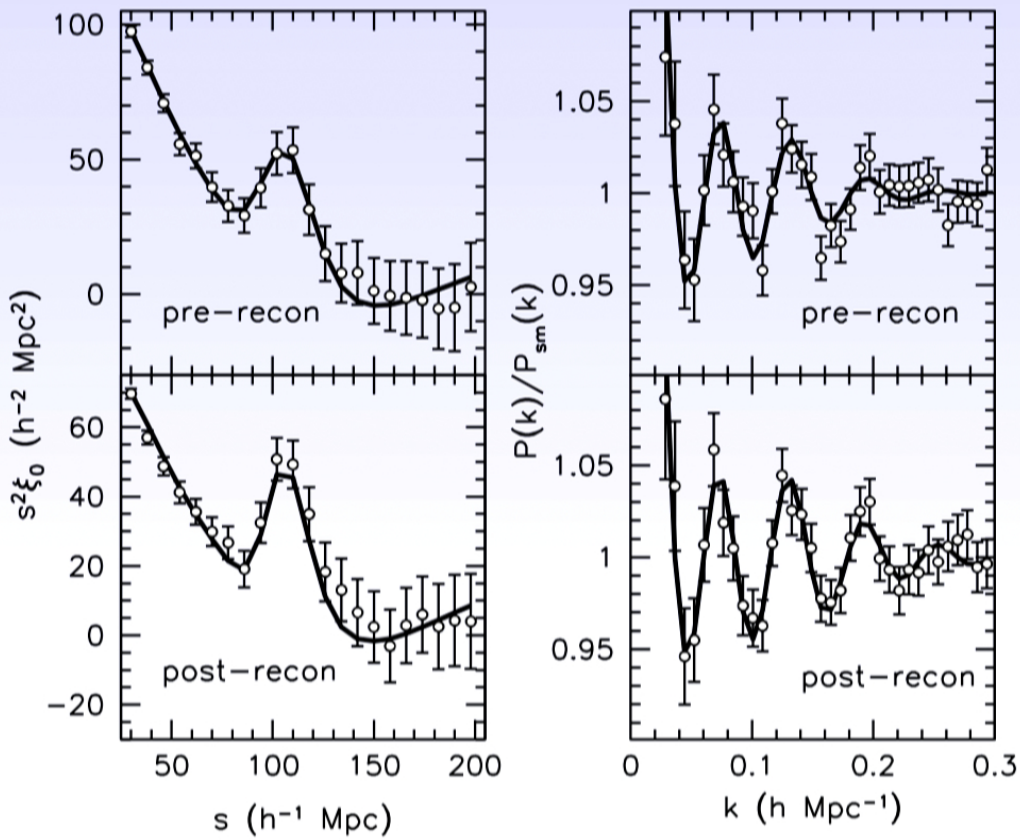
Baryon Oscillation Spectroscopic Survey (BOSS)

- BOSS ~~is~~ was one of 4 experiments making up SDSS3.
- Uses 2.5m SDSS telescope
- Large etendue
- Measuring:
  - mid resolution (R ∼2000) spectra
  - UV (∼3600Å)- mid IR (∼ 10,000Å)
  - 1000 spectra simultaneously
- Got spectra of
  - 1.5 million LRG ($z < 0.7$)
  - 160,000 QSOs with usable forest
- Survey completed June 2014
- Primary science goal is to measure dark energy through Baryonic Acoustic Oscillations.

BOSS maps

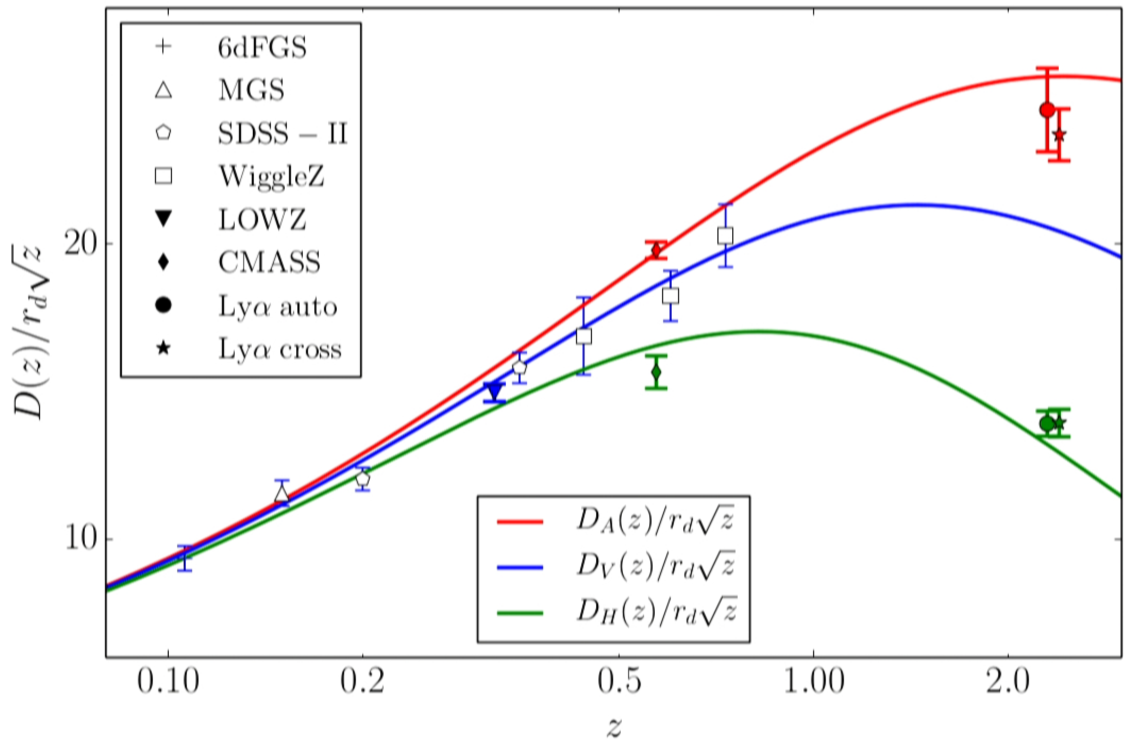


BOSS results: DR11 galaxy BAO

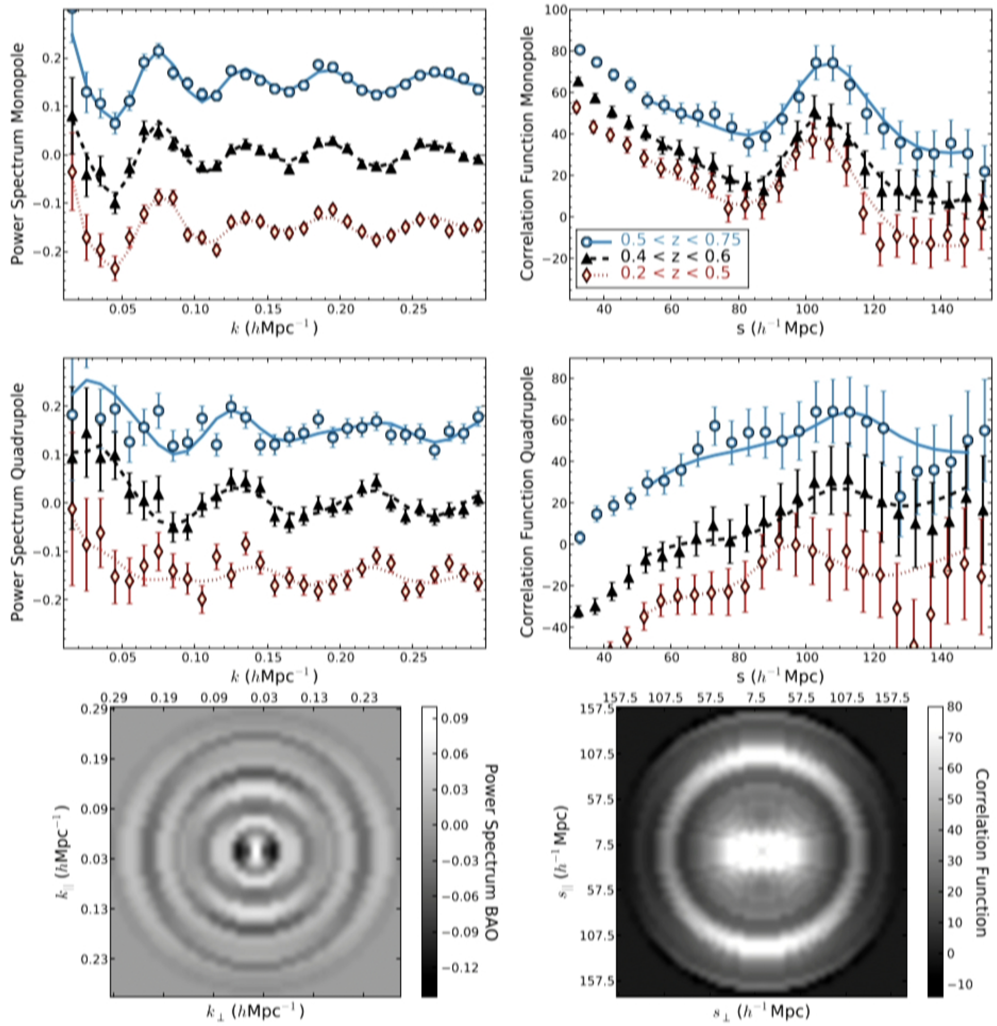


- Percent level distance to $z = 0.57$
- This is plot for isotropic measurements – CMASS results are anisotropic

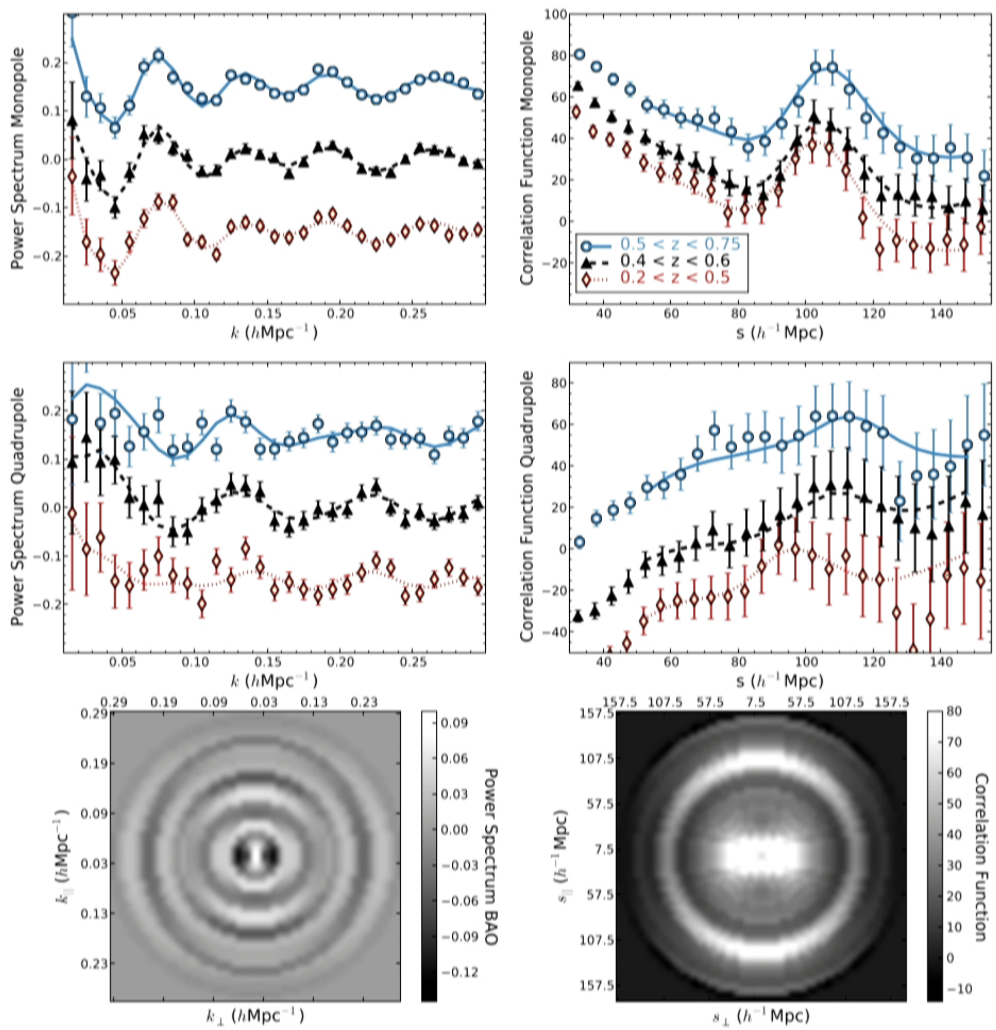
World BAO data



- Collection of world BAO data
- Lines are Planck best fit *predictions*

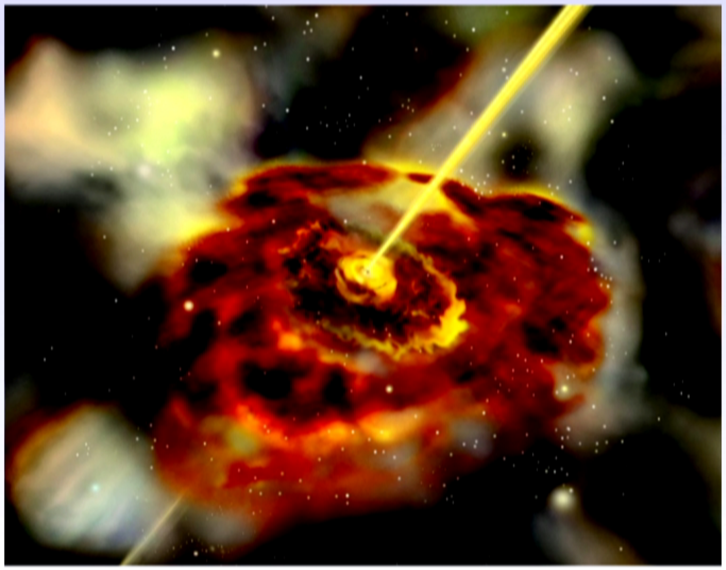


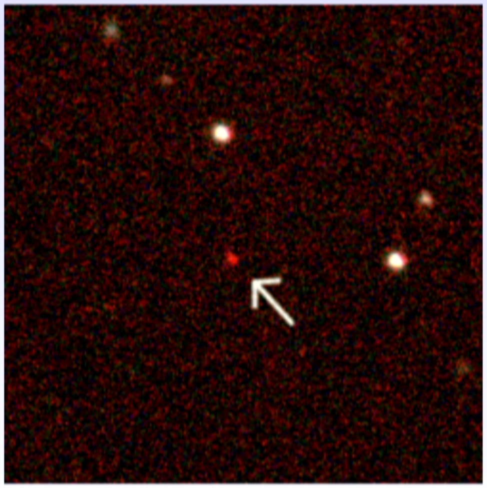
PRELIMIARY DR12 data



PRELIMIARY DR12 data

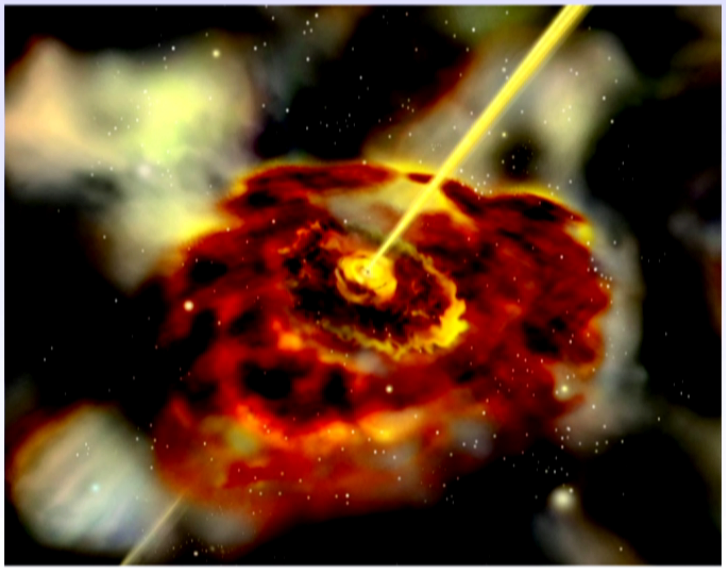
What are quasars

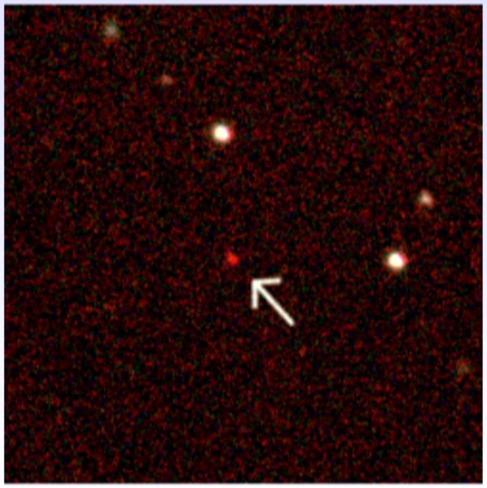




- Brightest things in the Universe
- Powered by energetic active galactic nuclei – can see them *very* far
- Featureless spectrum with a few broad emissions
- Understanding of underlying physics not important for our application.

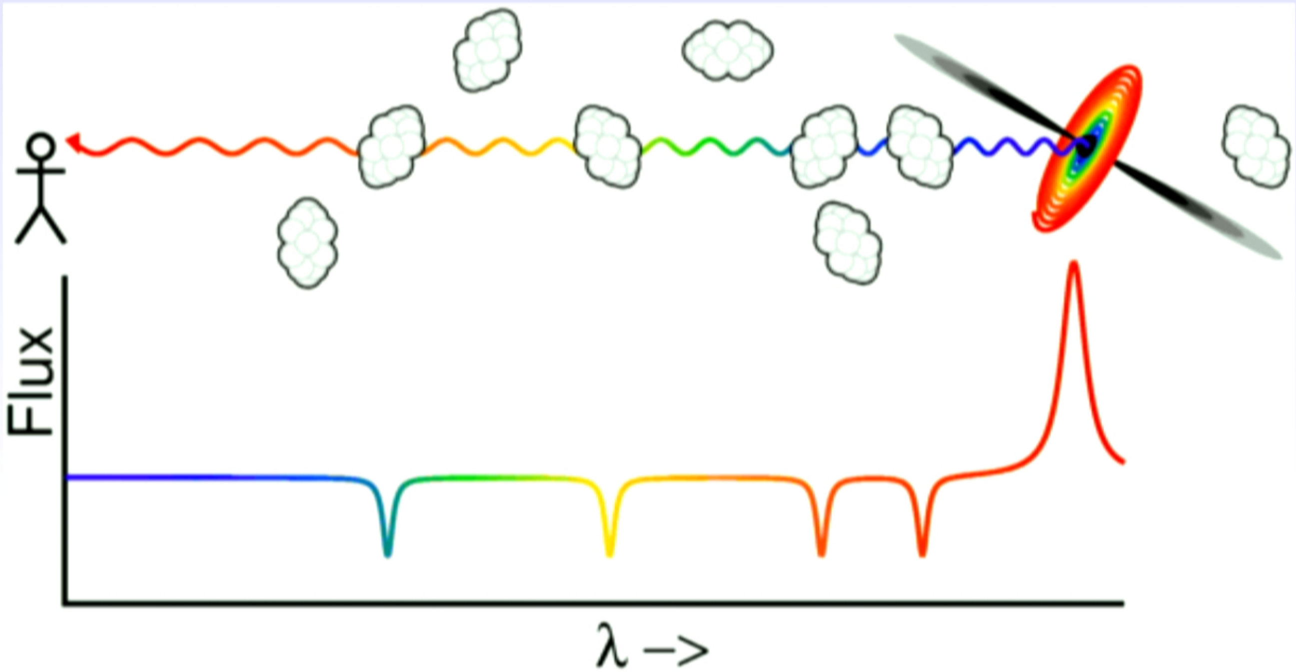
What are quasars





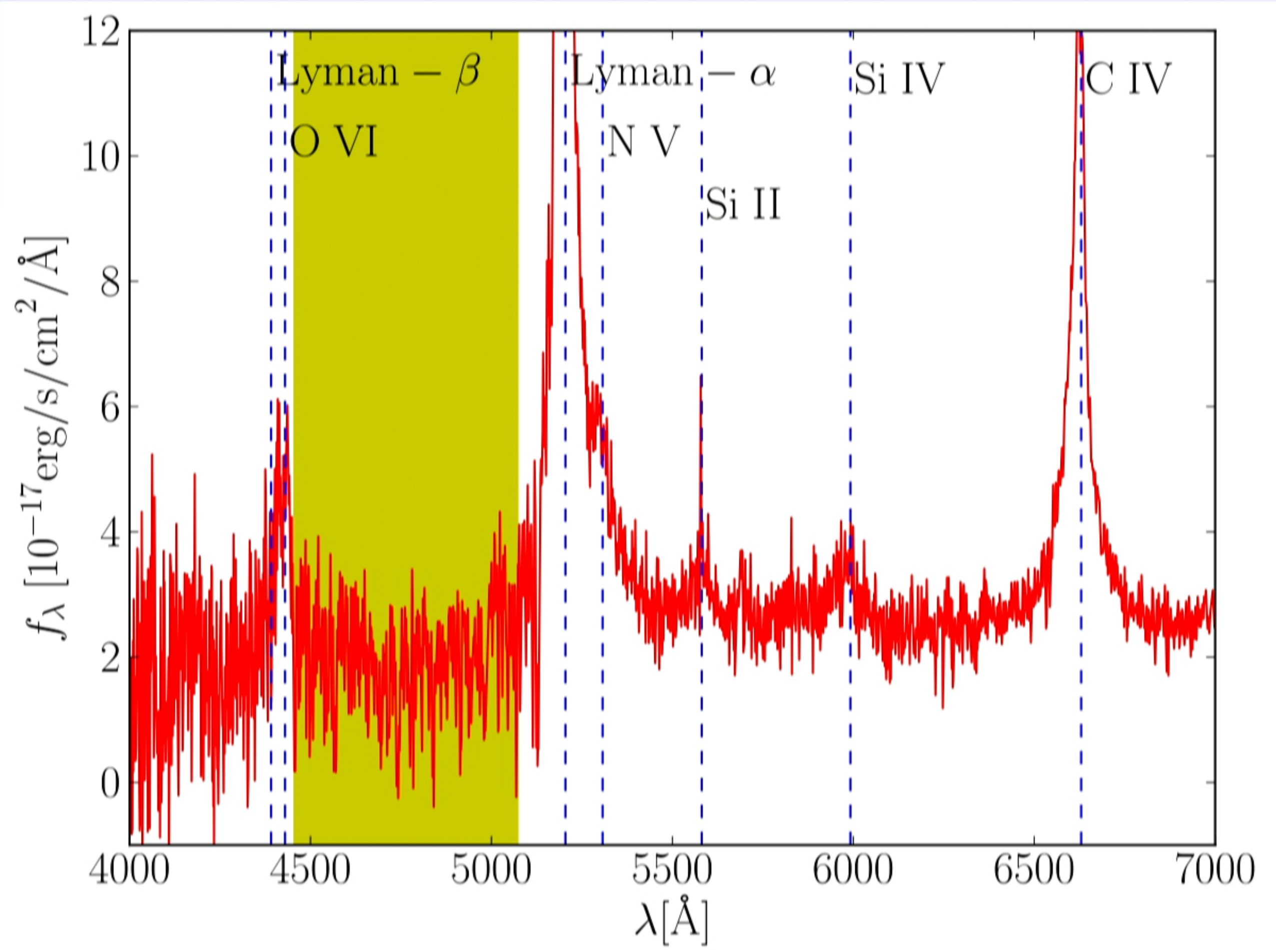
- Brightest things in the Universe
- Powered by energetic active galactic nuclei – can see them *very* far
- Featureless spectrum with a few broad emissions
- Understanding of underlying physics not important for our application.

Lyman-α forest

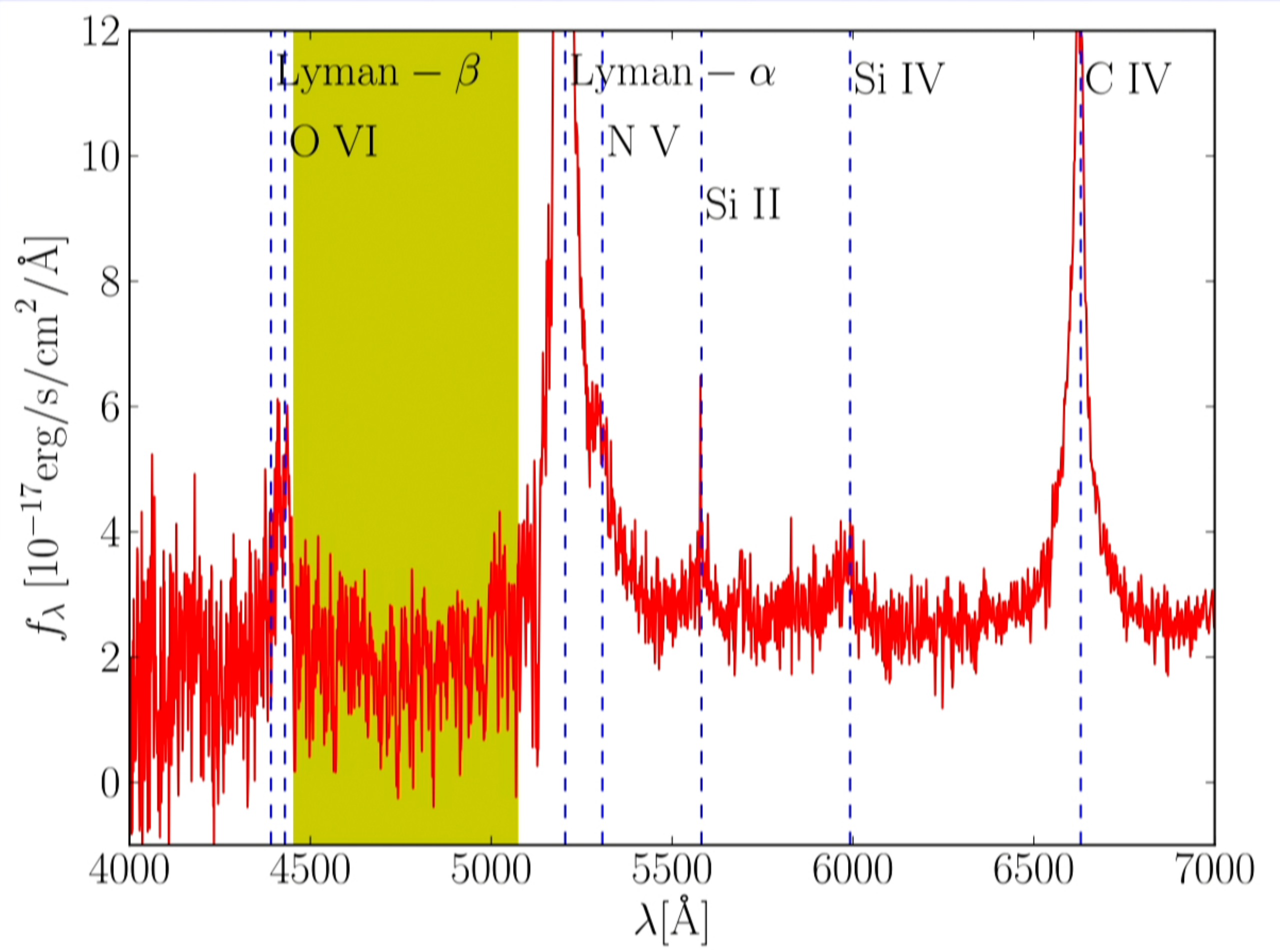


Neutral hydrogen absorbs light from distant quasars blue-ward of Lyman-α emission.

BOSS spectra



BOSS spectra



```
ALPINE 2.02(1266)   MESSAGE TEXT [A]              <RCF> archived                Msg   276 of 5,741 80% FWD +

Date: 9 Jan 2013 06:08:45 +0800
From: Am. J. Plant Sci. <ajps@elert-scirp.org>
Reply-To: ajps@scirp.org
To: anze@bnl.gov
Subject: Dr.An e Slosar, Special Issue on "The future of Forests" CFP

This message was sent to [anze@bnl.gov].Unsubscribe by clicking here [www.member.scirp.org].

Dear Dr.An e Slosar,

I am writing to let you know about our upcoming Special Issue on "The future of Forests", which will be
published in American Journal of Plant Sciences (AJPS, ISSN:2158-2750), an open access journal. The deadline
for submission is January 22nd, 2013, and the publication date is March 2013. You can find the Call for
Papers for this Special Issue at the following website: www.scirp.org/journal/ajps [www.scirp.org]. The
Special Issue is open to both original research articles as well as review articles.

I am contacting you about this Special Issue since I understand that you have published before in this area
and I wanted to invite you to submit your manuscripts. American Journal of Plant Sciences (AJPS) is an open
access journal, which means that all published articles are made freely available online without a
subscription.

Please read over the journal's Authors' Guidelines [www.scirp.org] for more information on the journal's
policies and the submission process [papersubmission.scirp.org]. Please include an indication of your
intention to publish within the special issue to be entitled "Special Issue- The future of Forests". If you
have any questions about this Special Issue, or about the journal, please do not hesitate to contact me.

Best regards,

On behalf of

? Help           < MsgIndex        P PrevMsg         - PrevPage     D Delete        R Reply
O OTHER CMDS     > ViewAttch       N NextMsg       Spc NextPage     U Undelete      F Forward
```

From baryons to flux

Absorption done by neutral hydrogen in photo-ionization equilibrium:

$$\Gamma n_{\rm HI} = \alpha(T) n_p n_e \quad (4)$$

$$n_{\rm HI} = \frac{\alpha(T)\rho_b^2}{\Gamma} \ll 1 \quad (5)$$

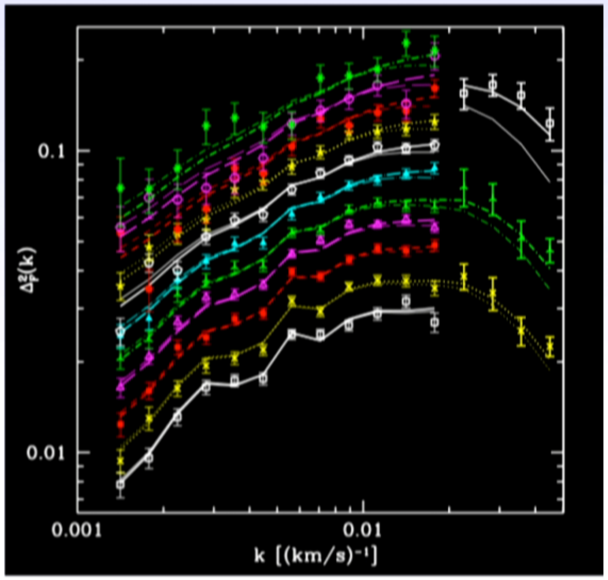
and so the absorbed flux fraction is given by

$$f = \exp\left(-\tau\right) \sim \exp\left(-A(1+\delta_b)^{1.7}\right) \quad (6)$$

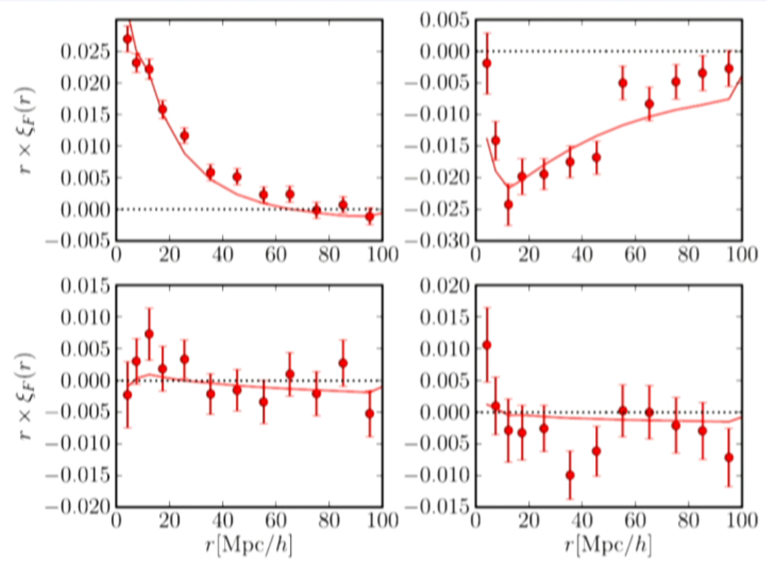
- We are observing a very non-linear transformation of the underlying density field.
- **On large scales, Lyman-α forest is simply a biased tracer.**
- **On small scales, physics can be understood from first principles.**

1D vs 3D

- Lyman-α forest is mapping the Universe through a very weird window function
- Historically: few and far apart high SNR measurements
- Quasars can be assumed independent in that limit: measure the 1D power spectrum of flux fluctuations
- With SDSS12: resolution down, noise up, quasar number up (from few tens to 15,000), but limited to 1D
- With SDSS3: noise further up, quasar number up (to 160,000): can finally measure correlations in three dimensions.

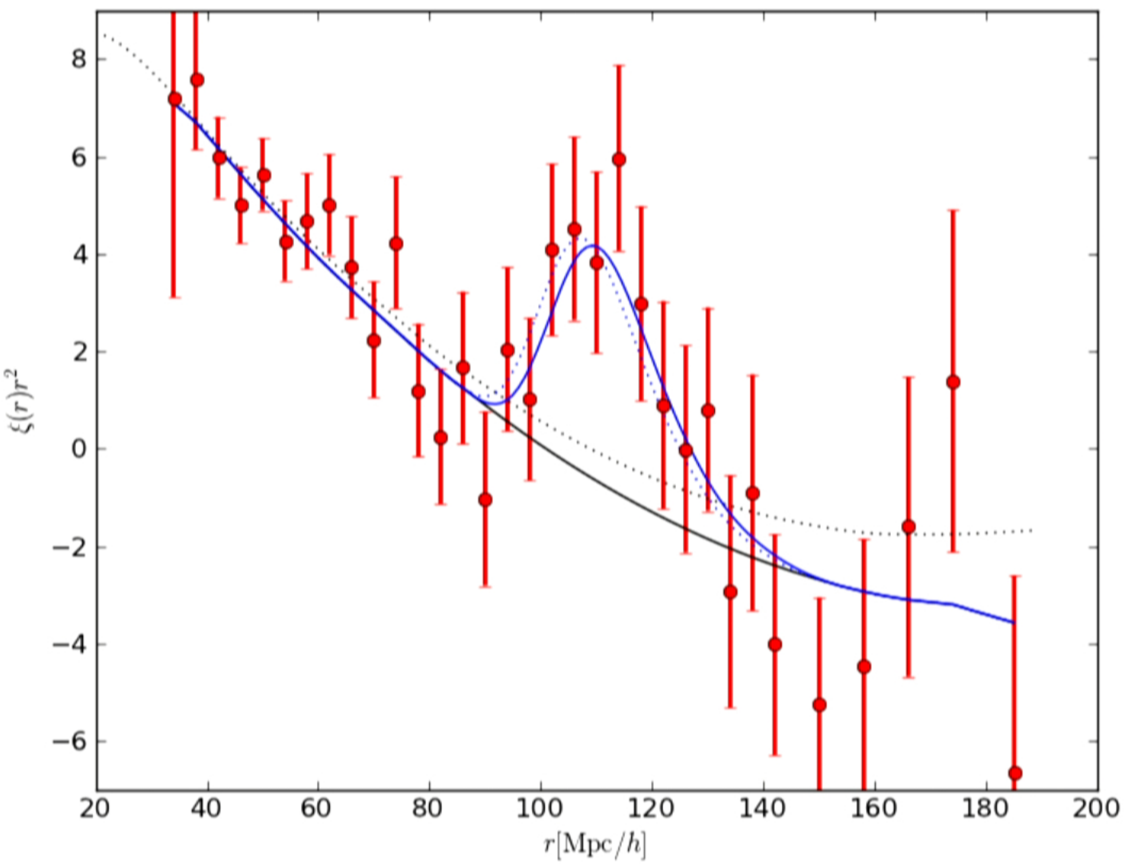


14k QSOs: ξ push

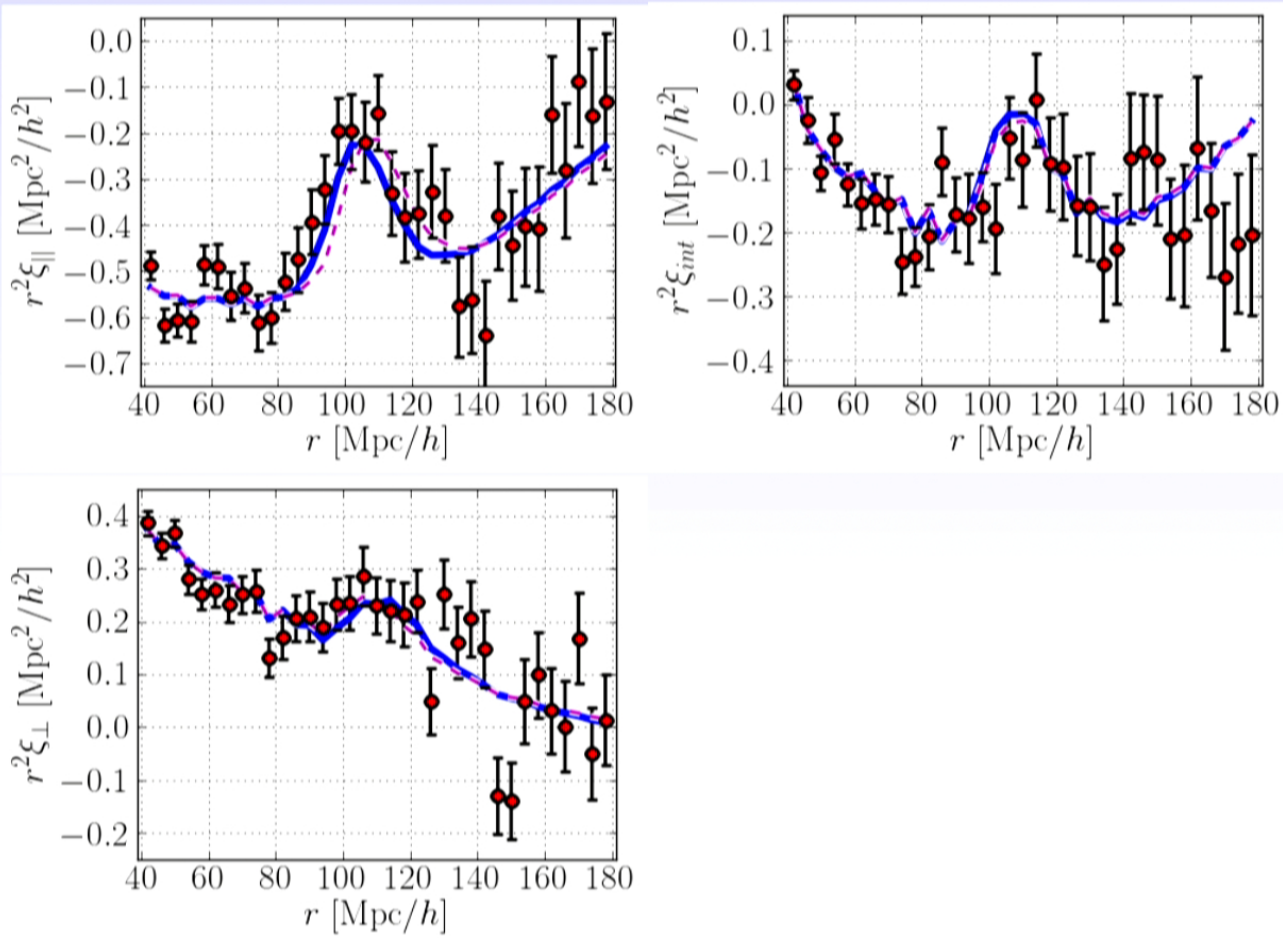


- Clear detection of correlations with no significant contamination
- The measured correlation function is distorted due to continuum fitting
- Analysis is harder than galaxy analysis:
  - Redshift-space distortions always matter
  - Redshift-evolution does matter

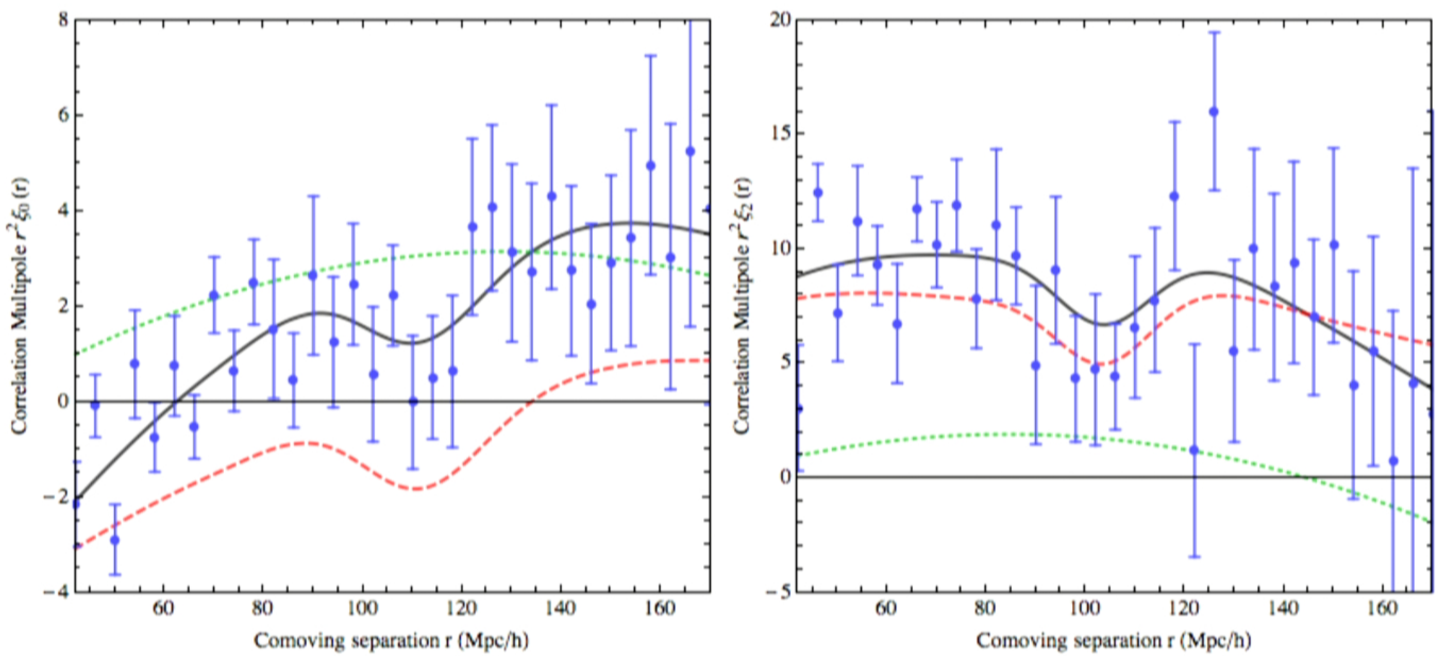
60k QSOs in DR9: BAO



140k QSOs in DR11: BAO

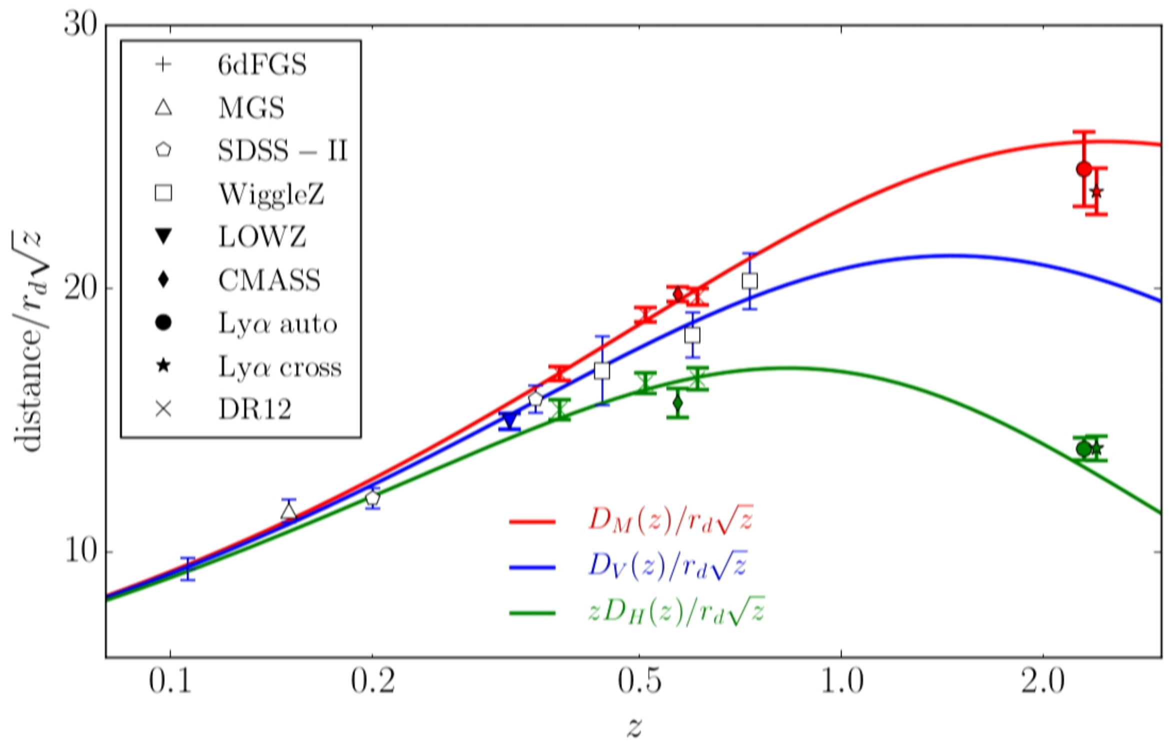


$\delta_F \delta_Q$ cross-correlation in BOSS



- Detection of the BAO in the cross-correlation between QSO and forest by Andreu Font & co.
- Ability for BOSS to do this has not been predicted, but constraining power nearly as powerful as with flux auto-correlation

World BAO data, post DR12

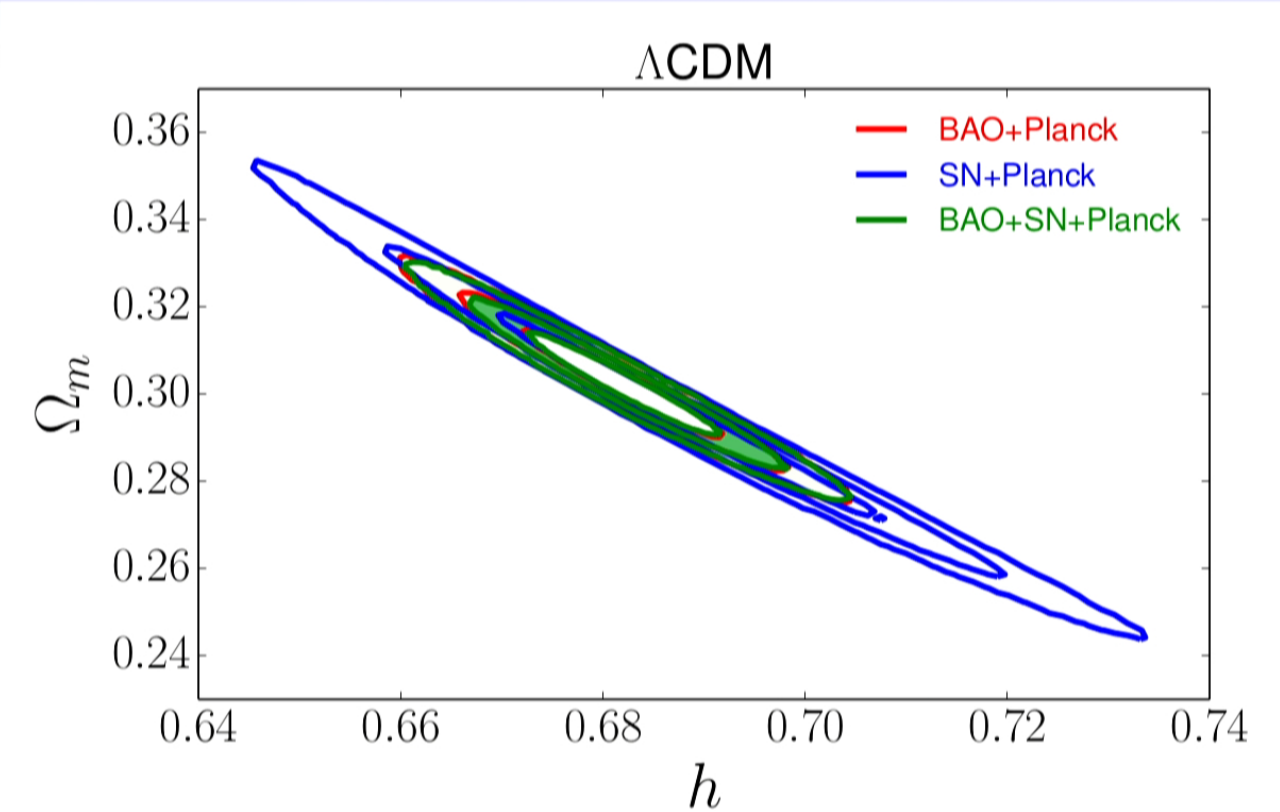


- Lyman-α forest measurements some $\sim 2.5\sigma$ away from minimal LCDM

Cosmology constraints

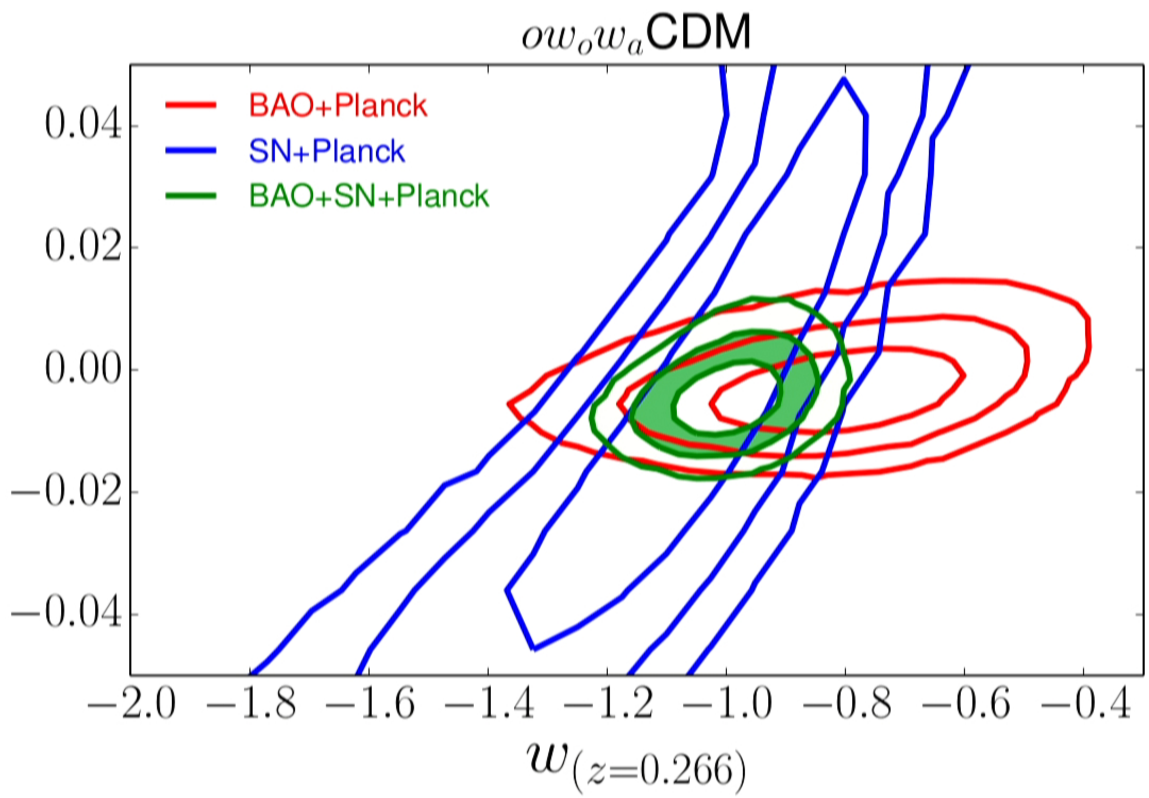
- See Aubourg et al, arXiv:1411.1074
- The minimal ΛCDM model fits great (even by eye).
- What is the story with relaxing other parameters?
  - As you relax the model, Ω_k and w_0 (at pivot) remain well constrained ($O(10^{-1})$)
  - w_1 is $O(1)$ unconstrained

DE models:



ΛCDM
BAO+Planck
SN+Planck
BAO+SN+Planck
Ω_m
0.36
0.34
0.32
0.30
0.28
0.26
0.24
0.64
0.66
0.68
0.70
0.72
0.74
h

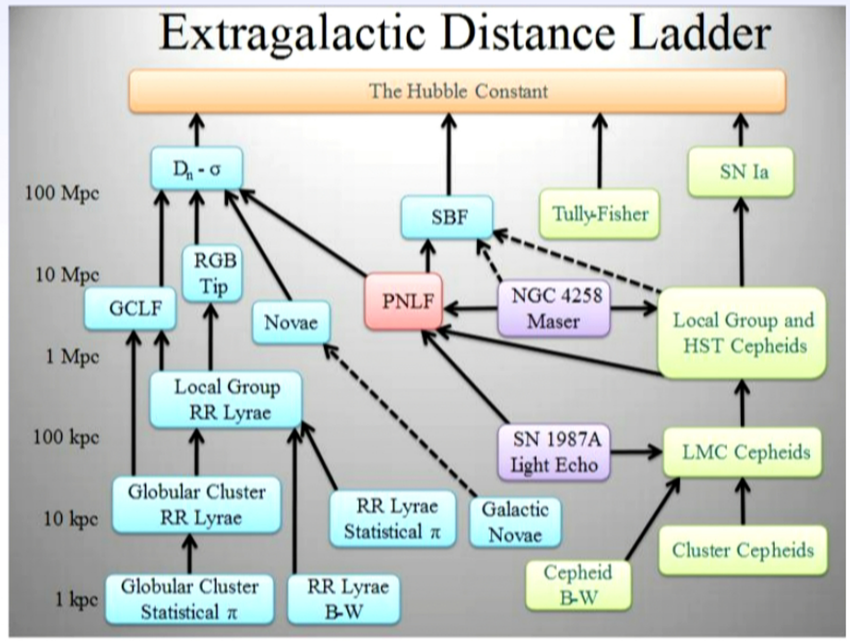
DE models:



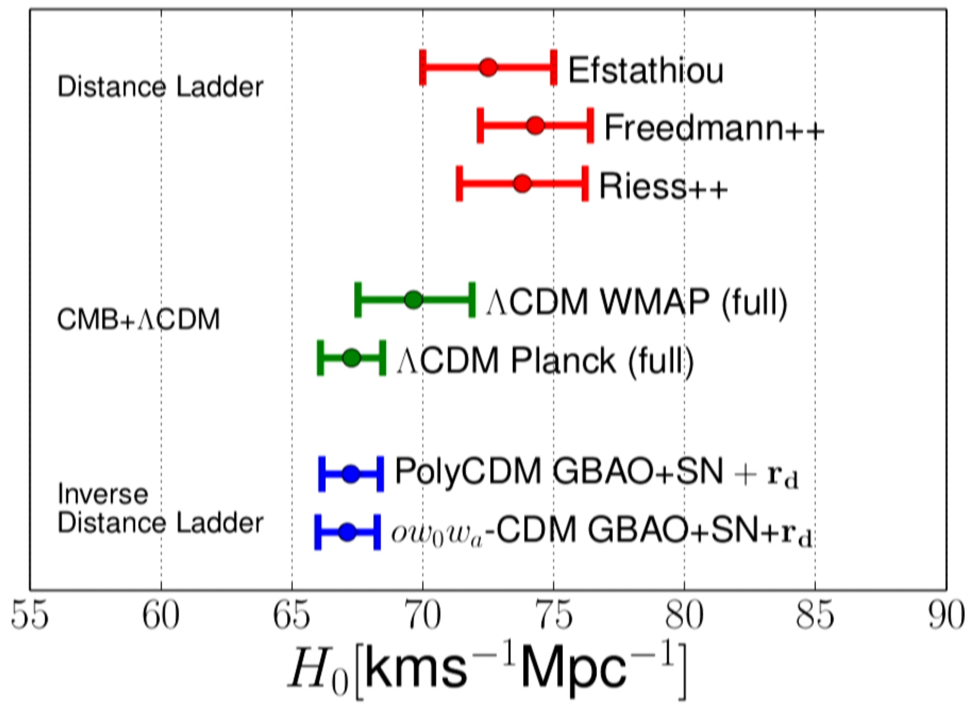
ow_ow_aCDM
BAO+Planck
SN+Planck
BAO+SN+Planck
0.04
0.02
0.00
−0.02
−0.04
Ω_k
−2.0
−1.8
−1.6
−1.4
−1.2
−1.0
−0.8
−0.6
−0.4
$w_{(z=0.266)}$

Distance Ladder

- Distance ladder starts with local measurements of the distance at kpc distances (RR Lyrae, Cepheids, etc.) to calibrate higher distance rulers.
- Once distance to object safely in the hubble flow is determined, we can measure Hubble parameter.

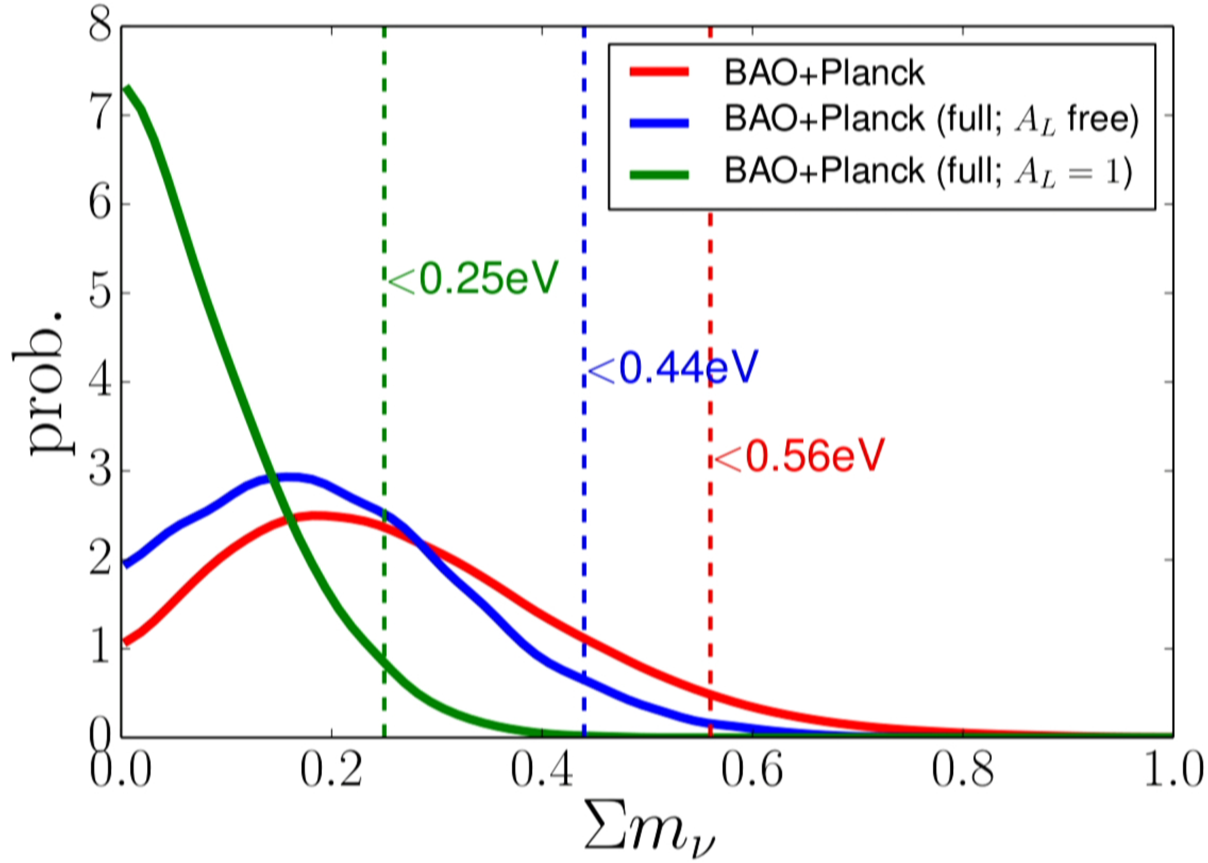


Inverse distance ladder

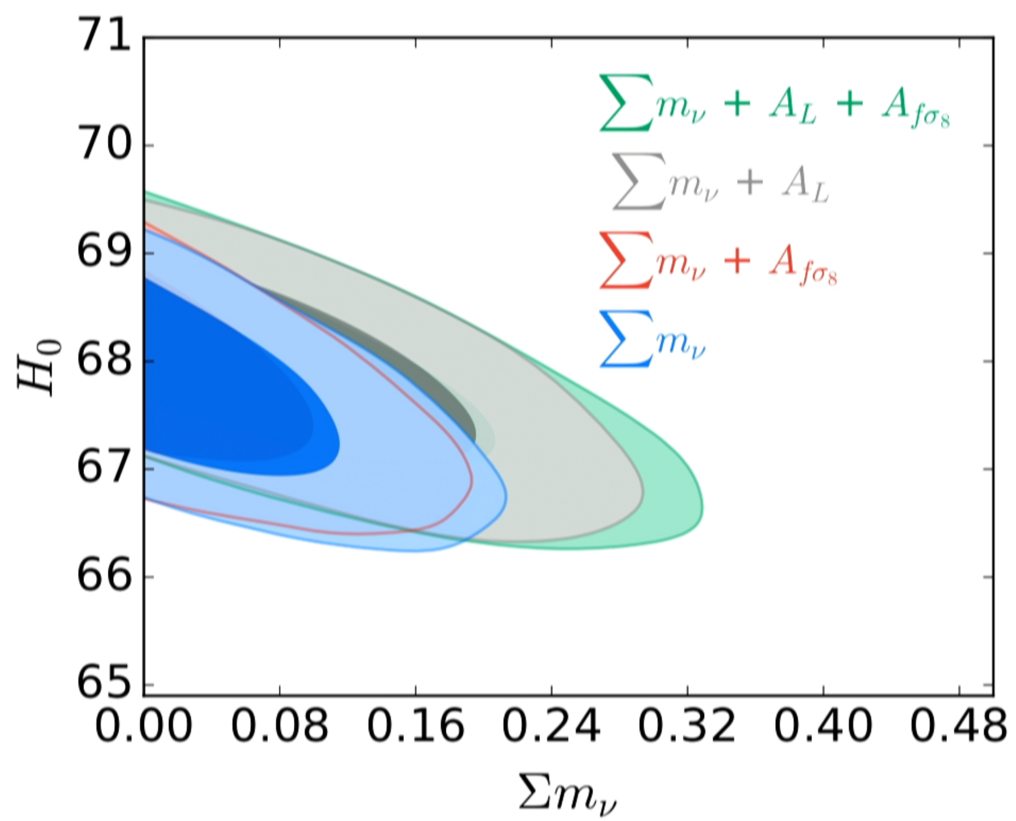


- BOSS prefers low-h Universe: $H = 68.1 \pm 1.2$

Neutrino mass from geometry:



Neutrino mass update:



PRELIMINARY, $\sum m_\nu < 0.16 eV$ from Planck+BAO+full $P(k)$

3pt function

- An age old idea many of us were considering
- Low k power spectrum of any tracer is limited by systematics in autocorrelation
- Cross-correlation between Lyman-α forest and quasar density would be great, but one cannot probe low k modes using Lyman-α forest due to astrophysical uncertainties
- Consider bispectrum of the kind in the squeezed limit $(k_l \ll k_{s_1} \sim k_{s_2})$

$$B_{qff}(k_l, k_{s_1}, k_{s_2}) = \langle \delta_q(k_l)\delta_F(k_{s_1})\delta_F(k_{s_2})\rangle \quad (7)$$

$$\sim \langle \delta_q(k_l) P_{FF}(k_s)\rangle \quad (8)$$

- Take the small scale power spectrum and treat is as another dynamical field to cross-correlate with large-scale field.
- Potentially systematically very clean!

3pt function

- An age old idea many of us were considering
- Low k power spectrum of any tracer is limited by systematics in autocorrelation
- Cross-correlation between Lyman-α forest and quasar density would be great, but one cannot probe low k modes using Lyman-α forest due to astrophysical uncertainties
- Consider bispectrum of the kind in the squeezed limit $(k_l \ll k_{s_1} \sim k_{s_2})$

$$
\begin{aligned}
B_{qff}(k_l, k_{s_1}, k_{s_2}) &= \langle \delta_q(k_l)\delta_F(k_{s_1})\delta_F(k_{s_2})\rangle && (7) \\
&\sim \langle \delta_q(k_l) P_{FF}(k_s)\rangle && (8)
\end{aligned}
$$

- Take the small scale power spectrum and treat is as another dynamical field to cross-correlate with large-scale field.
- Potentially systematically very clean!

Tracers

A general tracer will trace the dark matter on large scales as

$$t(\mathbf{x}) = \bar{t}\left(1 + \frac{\partial \log \bar{t}}{\partial \delta_L}\delta_L + \frac{\partial \log \bar{t}}{\partial \eta_L}\eta_L + \frac{\partial \log \bar{t}}{\partial \Phi_L}\Phi_L\right), \qquad (9)$$

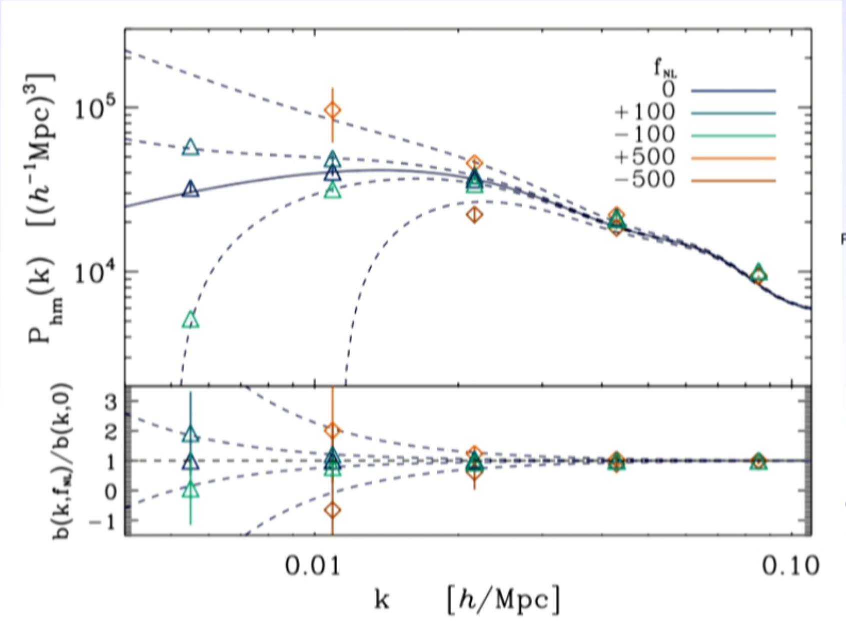
with $\eta = -Hdv_{||}/dr$ controlling RSD and Φ_L being potential fluctuations.

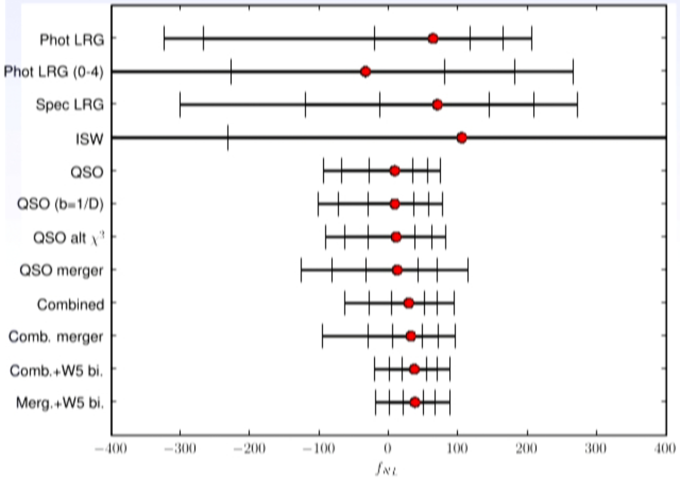
The beauty is that in the case of the local type non-Gaussianianity

$$\frac{\partial}{\partial \Phi_L} = 2f_{\rm NL}\frac{\partial}{\partial \log \sigma_{8,\rm local}} \qquad (10)$$

In other words, local non-Gaussianity will cause any tracer to pick up dependeny on Φ_L, allowing to detect the k^{-2} bias correction – the famous Dalal effect

Dalal's effect





Lyman-α forest $f_{\rm NL}$

	b_δ	b_η	b_{Φ_L}
quasars δ_q	b	b^{-1}	$2f_{\rm NL}(b-1)\delta_c$
$X_k = P_{FF}(k,\mu)$	$\frac{\partial \log P_{FF}}{\partial \delta_l}$	$\frac{\partial \log P_{FF}}{\partial \eta}$	$2f_{\rm NL}\frac{\partial \log P_{FF}}{\partial \log \sigma_8}$

- Derivatives in the case of Lyman-α forest need to be determined numerically, but we know how to do this.
- Note that one has in principle many X_k fields, one for each (k_s,μ) bin.

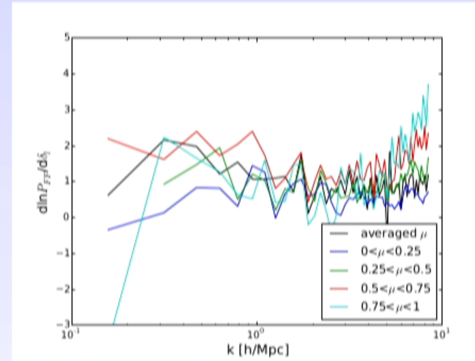
Lyman-α forest f_{NL}

	b_δ	b_η	b_{Φ_L}
quasars δ_q	b	b^{-1}	$2f_{\mathrm{NL}}(b-1)\delta_c$
$X_k = P_{FF}(k,\mu)$	$\frac{\partial \log P_{FF}}{\partial \delta_l}$	$\frac{\partial \log P_{FF}}{\partial \eta}$	$2f_{\mathrm{NL}}\frac{\partial \log P_{FF}}{\partial \log \sigma_8}$

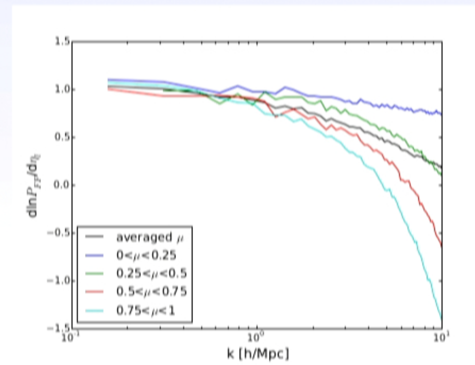
- Derivatives in the case of Lyman-α forest need to be determined numerically, but we know how to do this.
- Note that one has in principle many X_k fields, one for each (k_s,μ) bin.

Results

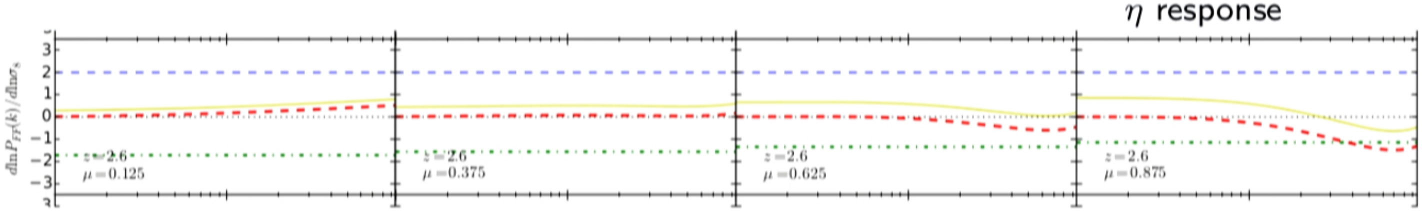
- Work done with **Chi-Ting Chang** (Stony Brook), **Agnieszka Cieplak** (BNL), Fabian Schmidt (MPI)
- σ_8 response just happens to be small
- Preliminary $\Delta f_{\mathrm{NL}} \sim 200$
- A bit disappointing. . .



δ_l response



η response



σ_8 response

Conclusions

- BOSS has changed the face of Cosmology and coming with a series of "best in the field" measurements with unprecedented systematic control
- The fire-hose will continue, the next decade bring DESI and LSST
- We expect at minimum to detect neutrino mass using at least two different tracers
- A much more interesting development would be one of the following:
  - detection of non-Gaussianity in LSS
  - detection of non-canonical N_{eff}
  - detection of dynamic dark energy
  - (tensor/scalar ratio, but that is CMB)