Lyman-α forest cosmology & recent BOSS results

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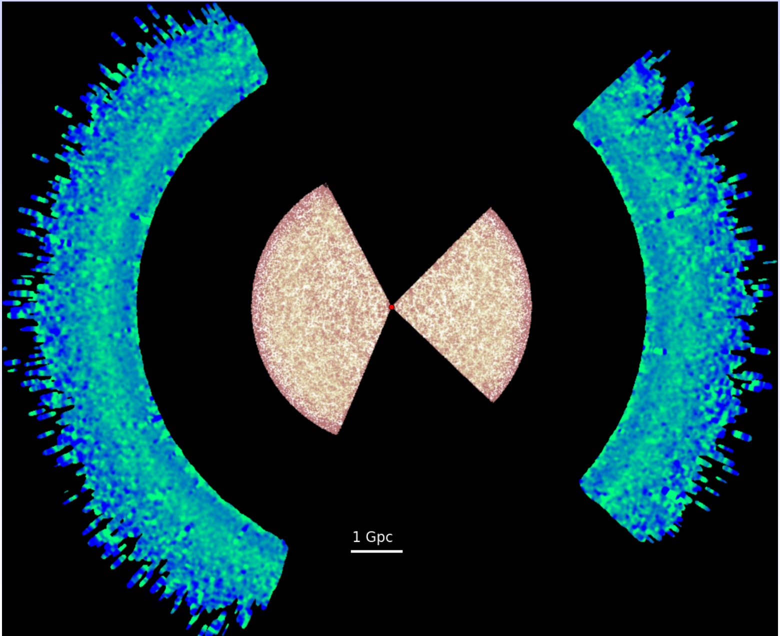
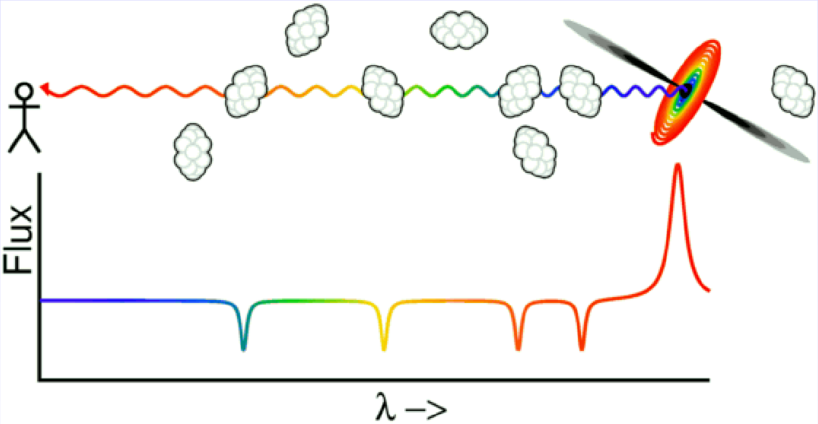
Baryon Oscillation Spectroscopic Survey (BOSS)

- BOSS ~~is~~ was one of 4 experiments making up SDSS3.
- Uses 2.5m SDSS telescope
- Large etendue
- Measuring:
  - mid resolution ($R \sim$2000) spectra
  - UV ($\sim$3600Å)- mid IR ($\sim$ 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

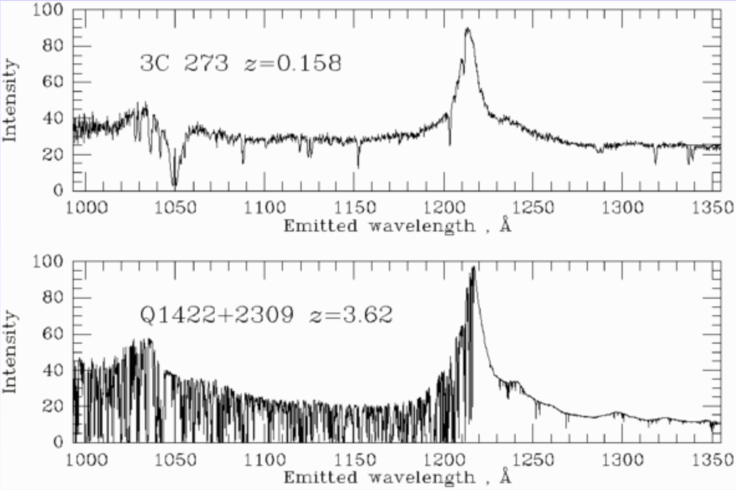


Lyman-α forest



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

Lyman-α forest



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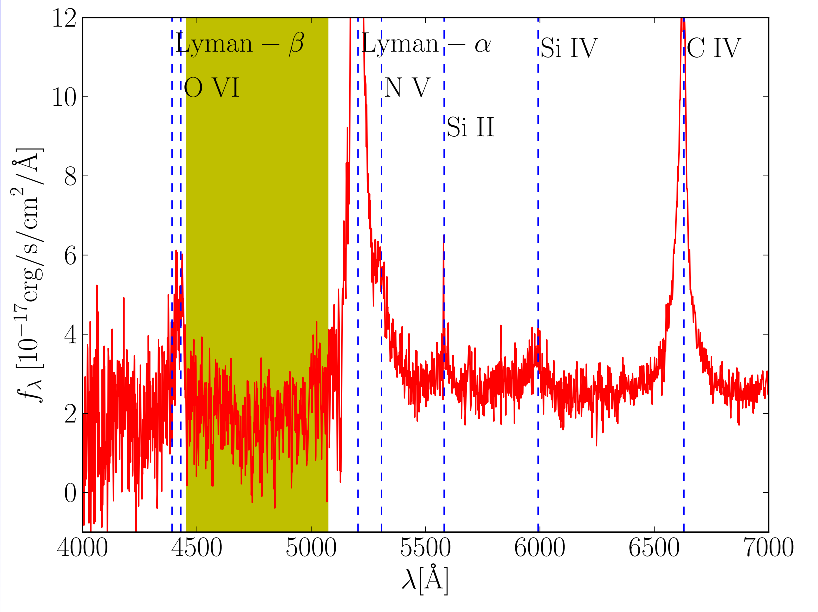
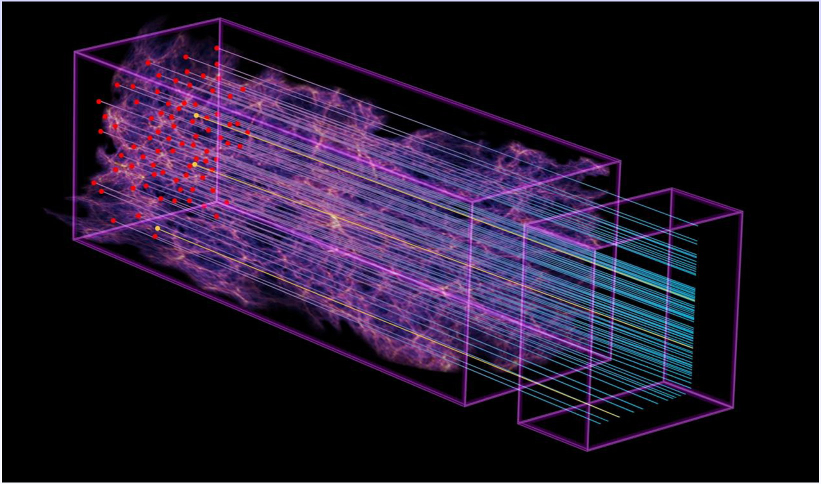
BOSS spectra



3D sampling of the universe



From baryons to flux

Absorption done by neutral hydrogen in photo-ionization equilibrium:

$$\Gamma n_{\rm HI} = \alpha(T) n_p n_e \tag{1}$$

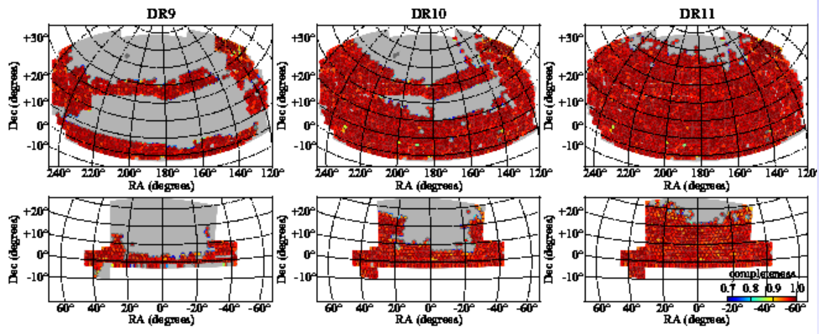
$$n_{\rm HI} = \frac{\alpha(T)\rho_b^2}{\Gamma} \ll 1 \tag{2}$$

and so the absorbed flux fraction is given by

$$f = \exp\left(-\tau\right) \sim \exp\left(-A(1+\delta_b)^{1.7}\right) \tag{3}$$

- 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.**

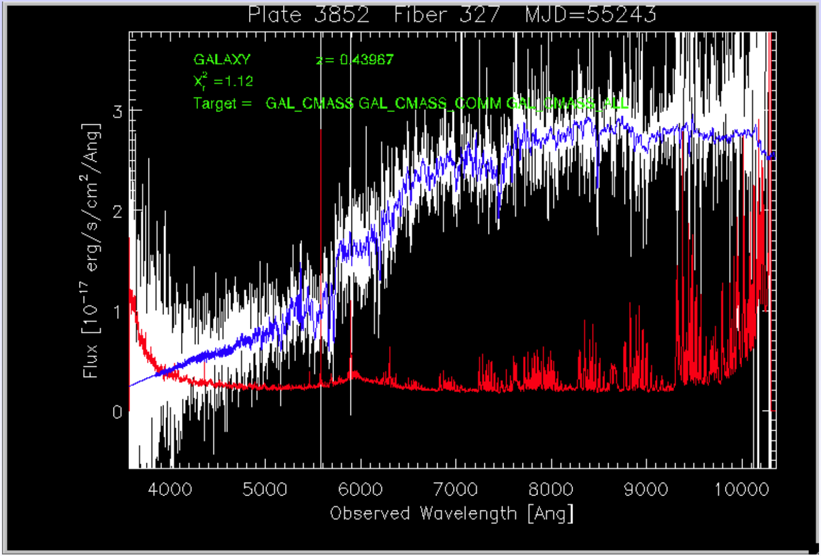
Data Releases



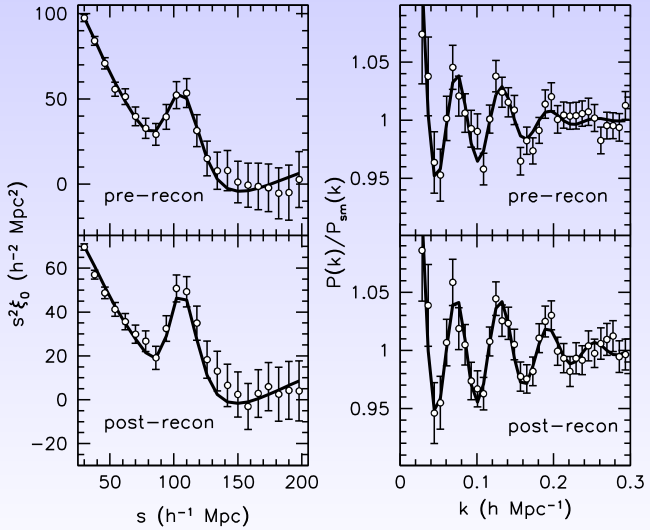
- DR 12: 2.3 million galaxies, 300k QSOs
- DR 11 (internal release): 90% of DR12
- DR10 : 75% DR12
- DR9 : 60% DR12

Bottom line: majority of papers published with DR11 datasets – no real statistical gain in DR12, but can improve systematics

BOSS spectra

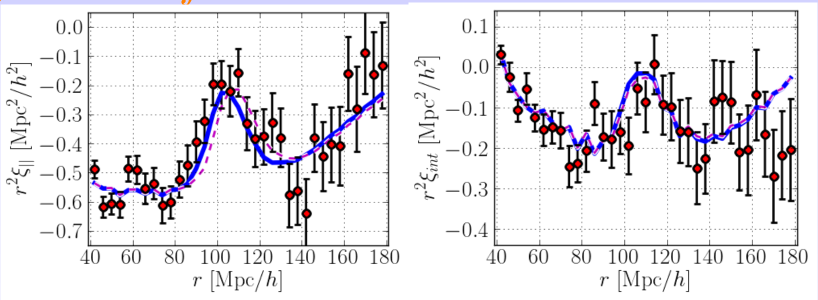


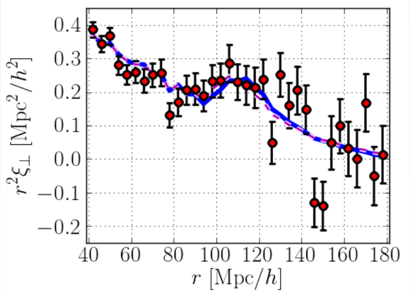
BOSS results: DR11 galaxy BAO



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

Lyman-α forest BAO

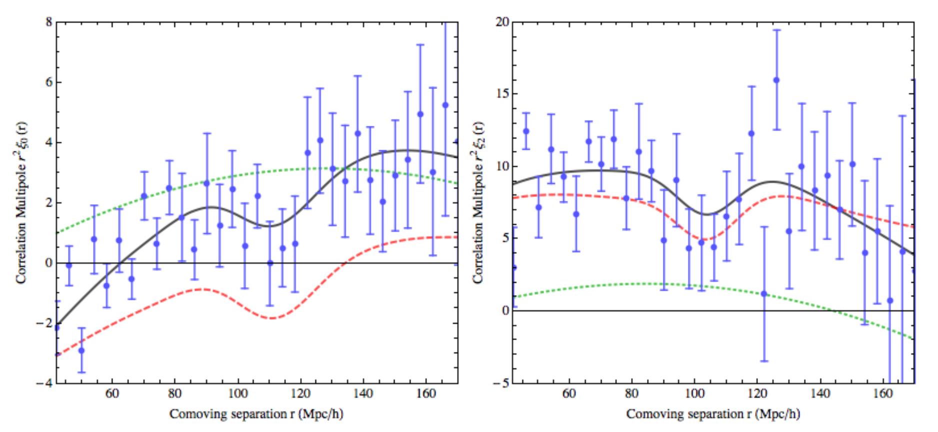




from de Lubac et al, 2014

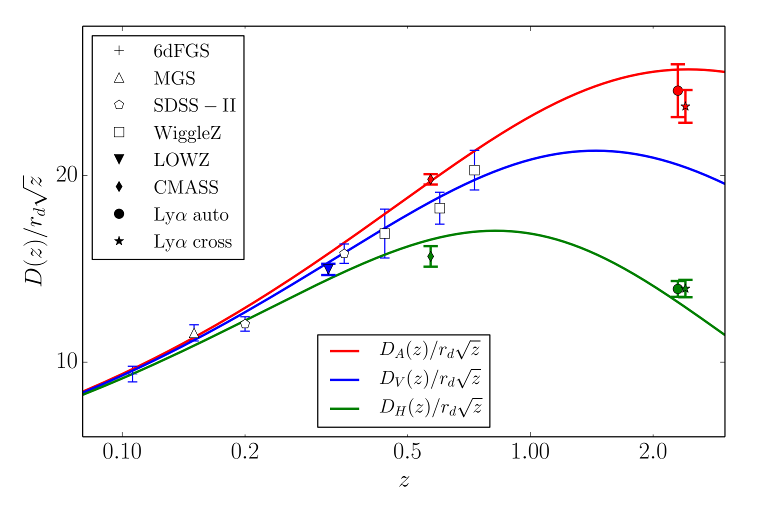
Measurements of BAO at $z = 2.4$

$\delta_F \delta_Q$ 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

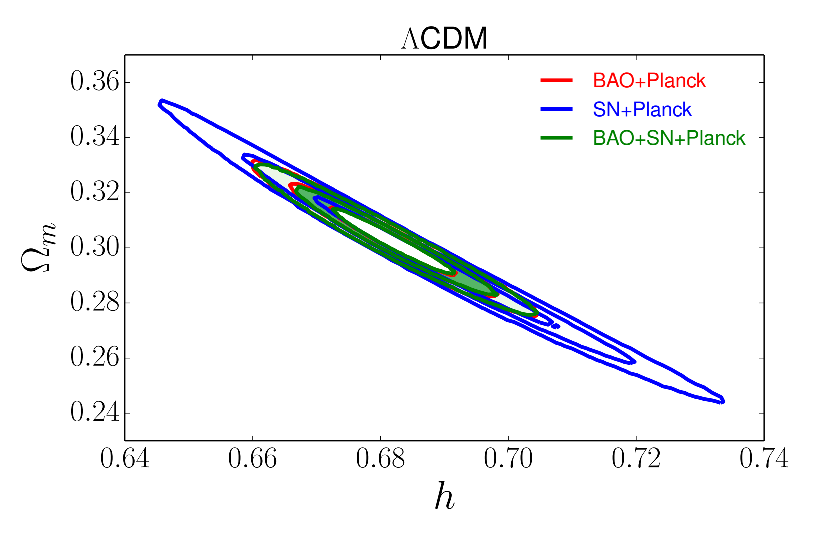


- Collection of world BAO data
- Lines are Planck best fit *predictions*

Cosmology constraints

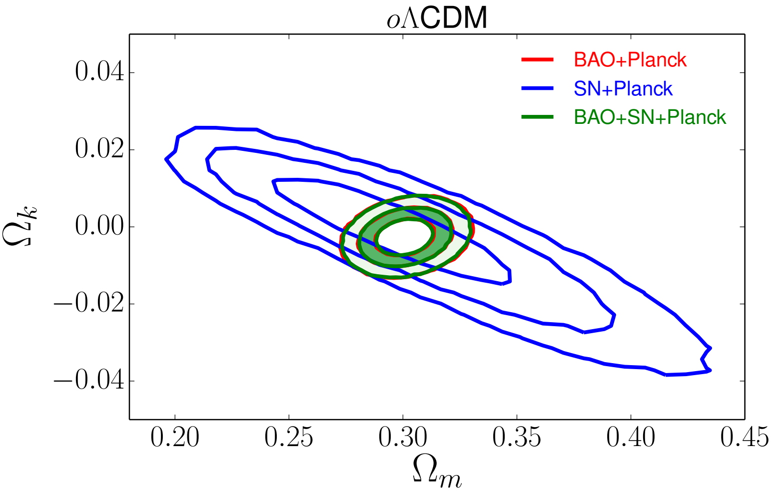
- The minimal ΛCDM model fits great (even by eye).
- The high-z points are at 2.5 σ, but overall χ^2 is fine
- What is the story with relaxing other parameters?
  - As you relax the model, Ω_k and w_0 (at pivot) remain well constrained ($O(10^{-1})$)
  - w_1 is $O(1)$ unconstrained

DE models:



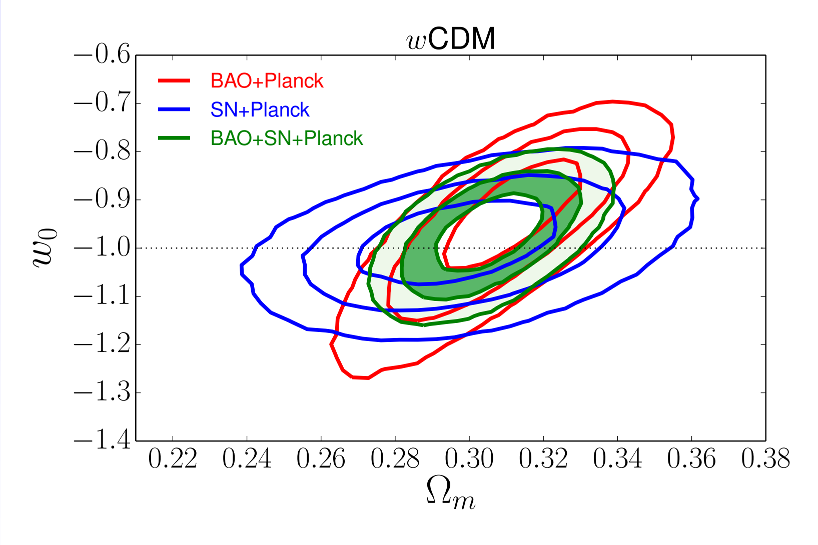
ΛCDM
BAO+Planck
SN+Planck
BAO+SN+Planck
0.36
0.34
0.32
0.30
0.28
0.26
0.24
Ω_m
0.64
0.66
0.68
0.70
0.72
0.74
h

DE models:



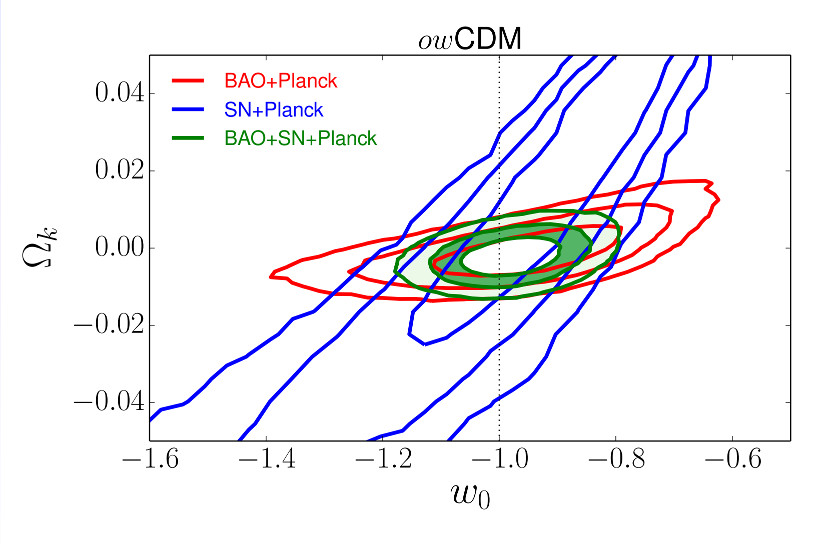
$o\Lambda$CDM
BAO+Planck
SN+Planck
BAO+SN+Planck
0.04
0.02
0.00
−0.02
−0.04
Ω_k
0.20
0.25
0.30
0.35
0.40
0.45
Ω_m

DE models:



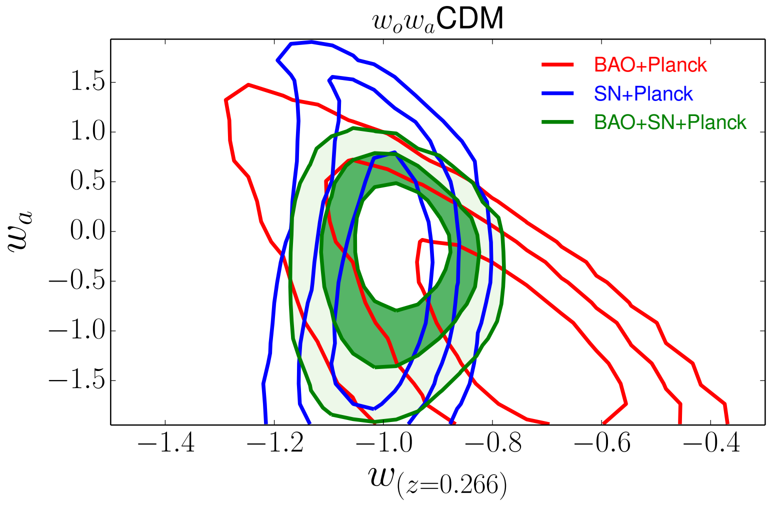
wCDM
BAO+Planck
SN+Planck
BAO+SN+Planck
−0.6
−0.7
−0.8
−0.9
−1.0
−1.1
−1.2
−1.3
−1.4
w_0
0.22
0.24
0.26
0.28
0.30
0.32
0.34
0.36
0.38
Ω_m

DE models:



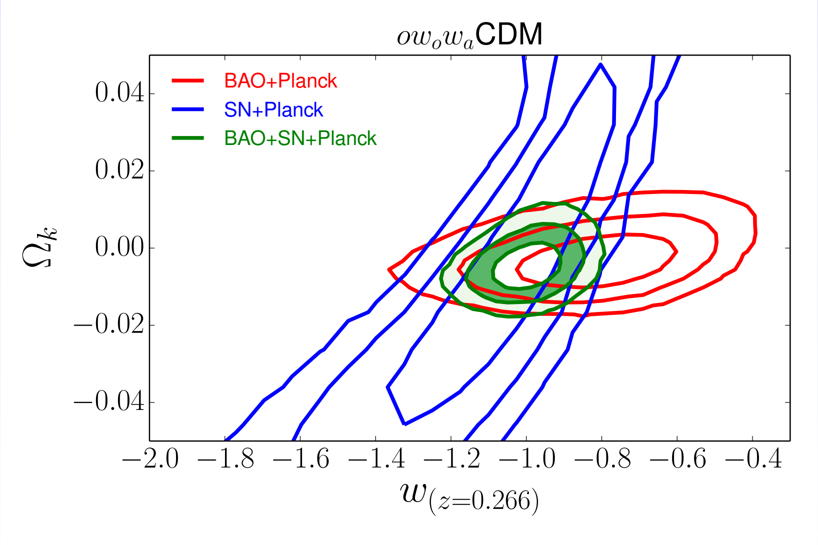
owCDM
BAO+Planck
SN+Planck
BAO+SN+Planck
0.04
0.02
0.00
−0.02
−0.04
Ω_k
−1.6
−1.4
−1.2
−1.0
−0.8
−0.6
w_0

DE models:



$w_o w_a$CDM
BAO+Planck
SN+Planck
BAO+SN+Planck
w_a
$w_{(z=0.266)}$
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−1.4
−1.2
−1.0
−0.8
−0.6
−0.4

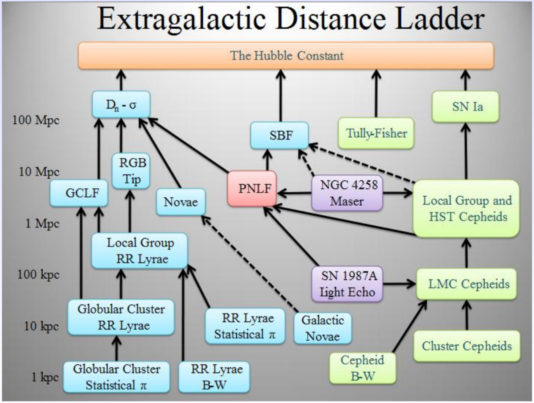
DE models:



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
$w_{(z=0.266)}$

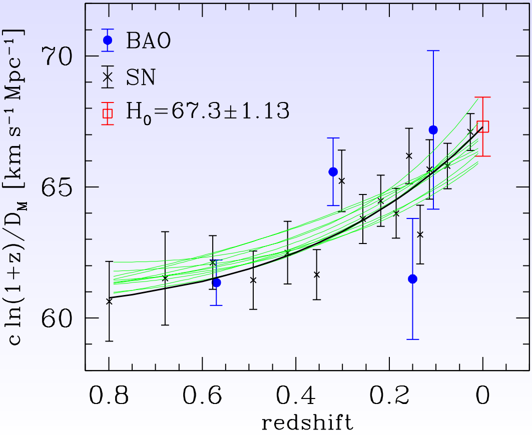
Distance Ladder

- 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.

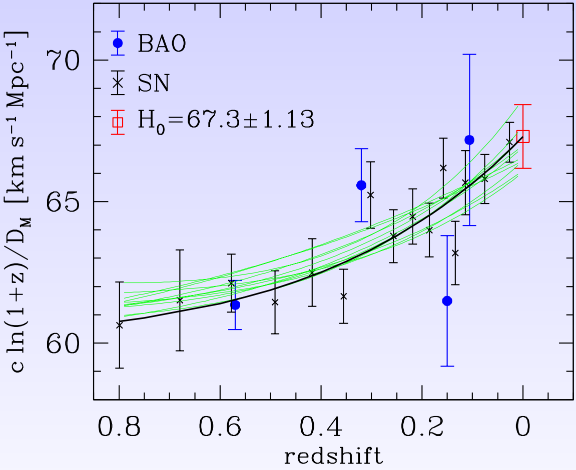


Inverse Distance Ladder

- In inverse distance ladder measurements we start with high-*z* measurements of the Hubble parameter from BAO and bring them down using SN data.
- This is done in a way that marginalizes over all possible smooth expansion histories.

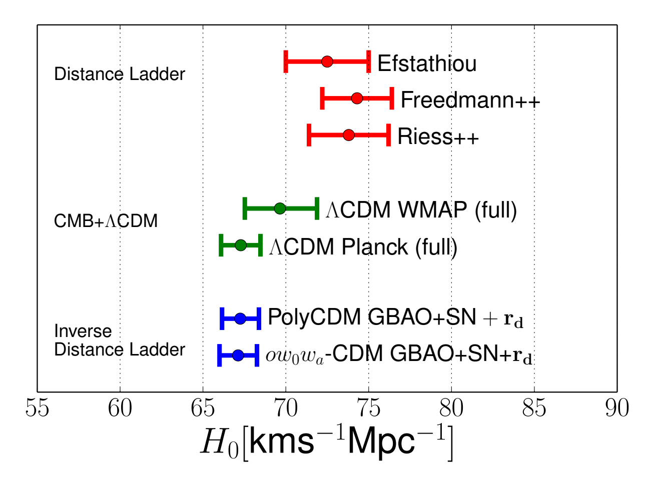


Inverse distance ladder



- Inverse distance ladder transfer H_0 measurement from redshift of observation to $z = 0$ using Supernovae Type Ia

Inverse distance ladder



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

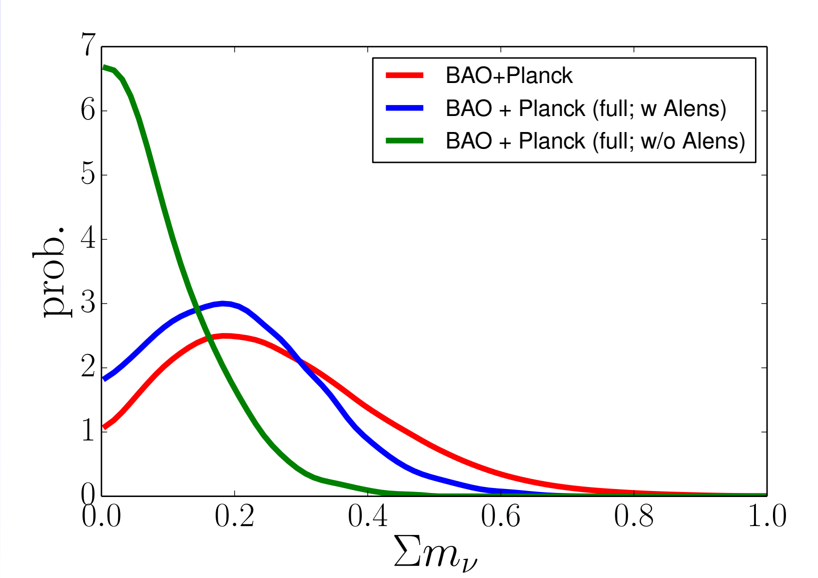
Neutrino mass

- Ratio of numbers of neutrino/photon is determined by thermodynamics in the early universe
- Light neutrinos become non-relativistic at redshift

$$z \sim 2000 \frac{m_\nu}{1\mathrm{eV}}$$

- There are subtle expansion history effects:
  - Distance to the last scattering surface is affected by m_ν
  - CMB determination of Ω_m does not include neutrinos, while BAOs do.
- Our compressed limit is $\sum m_\nu < 0.56eV$ at 95% c.l. from expansion history alone!
- Including the effects on growth of perturbations tightens the bound to < 0.22eV

Neutrino mass from geometry:



Side rants on $\sum m_\nu$

First:

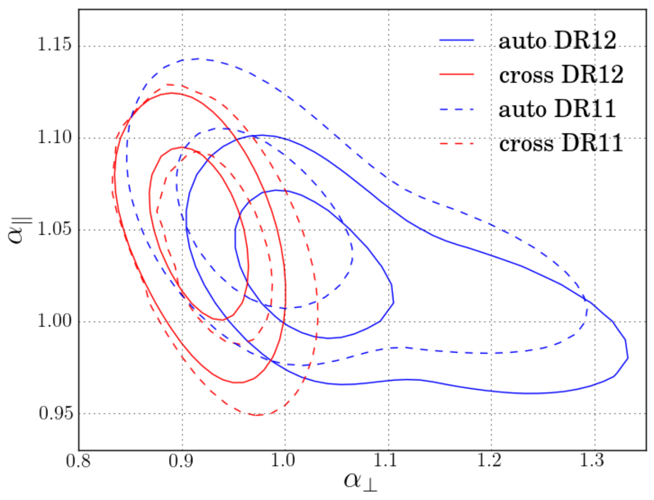
- At the edge of detection, experiments with downward noise fluctuations will claim upper limits and those with upward noise fluctuations detections.
- E.g. say true value $\sum m_\nu = 0.15$eV.
- This completely consistent with $\sum m_\nu < 0.2$eV at 95 c.l AND $\sum m_\nu = 0.33 \pm 0.1$eV

Second:

- Standard lore says that LSS measures neutrino mass by measuring scale-dependent suppression in the matter power spectrum as traced by galaxies
- However, Font-Ribera et all show that for e.g. Planck+DESI give $\sigma \sum m_\nu = 0.021$eV, dropping to $\sigma \sum m_\nu = 0.1$eV when marginalizing over Linder's γ parameter (c.f. drop to $\sigma \sum m_\nu = 0.038$eV when marginalising over DETF model)
- Evidence that RSD play a major role through $f\sigma_8$, but more work needs to be done

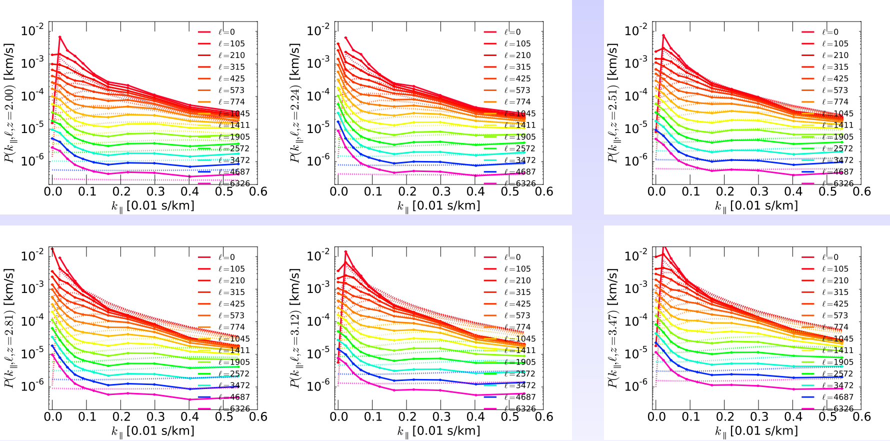
Updates to Lyman-α forest

Using existing pipeline with improvements to systematics:



- A completely different pipeline based on power-spectrum measurement in the works

New power-spectrum code



- Completely new code, developed by Pat McDonald, Andreu Font Ribera and myself
- Took three years, but things coming together
- Power-spectrum measurement
- Basis for all experiments and majority of analysis

Future

- eBOSS: covering the full redshift range to $z = 2$ using ELG, QSOs as tracers, more Lyα forest
- DESI: 35 million redshifts at $z < 1.5$
- Euclid: 50 million redshifts at $z > 1$