Cosmology with Lyα forests from BOSS

James Rich

DPhP-IRFU
CEA-Saclay
91191 Gif-sur-Yvette

james.rich@cea.fr

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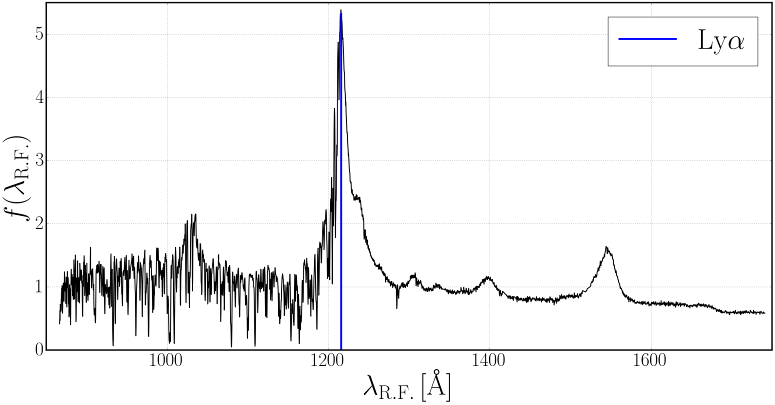
Outline

- The Lyα forest
- BOSS
  "Baryon Oscillation Spectroscopy Survey"
- Baryon Acoustic Oscillations in the forest
  Cosmological parameters from BAO
- Reconstructing the linear power spectrum
  Constraints on neutrino masses
  Warm dark matter
  Fuzzy dark matter
- Future projects

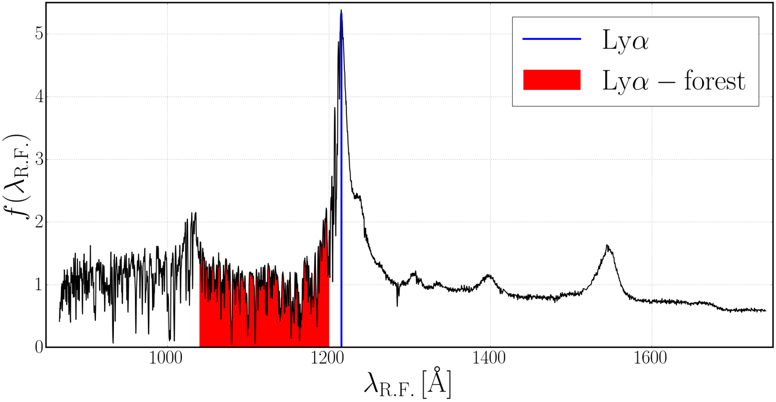
Quasar = Black hole accreting hot gas

Spectrum: power-law + emission lines



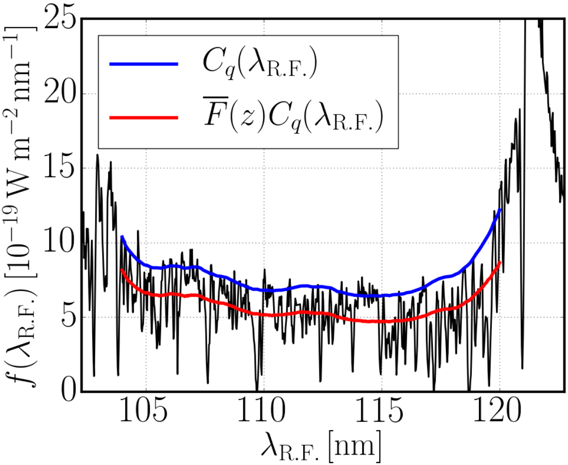
Quasar = Black hole accreting hot gas

Absorption by atomic hydrogen (HI) blueward of Lyα emission



Absorption at $\lambda_{observed}$ depends on n_{HI} at $z + 1 = \lambda_{obs}/1215$.

Need to model the smoothed forest spectrum

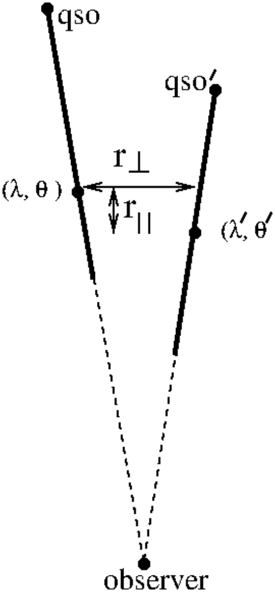


$$1+\delta(\lambda,\vec{\theta}) = \frac{\textit{observed flux}}{\textit{expected flux}}$$

Fluctuations of n_{HI} and of radial-velocity gradiant

$\Rightarrow$ Fluctuations of $\delta(\lambda,\vec{\theta})$

Correlate forests to find $\xi(r_\perp, r_\parallel)$



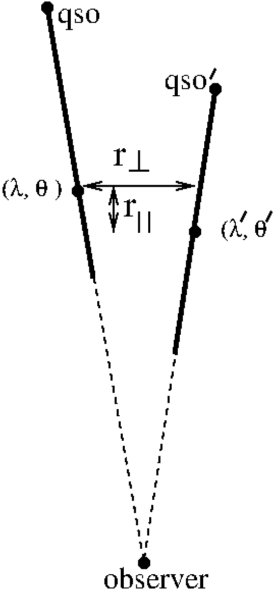
$$\xi(r_\perp, r_\parallel) = \frac{\sum w_i w_j \delta_i \delta_j}{\sum w_i w_j}$$

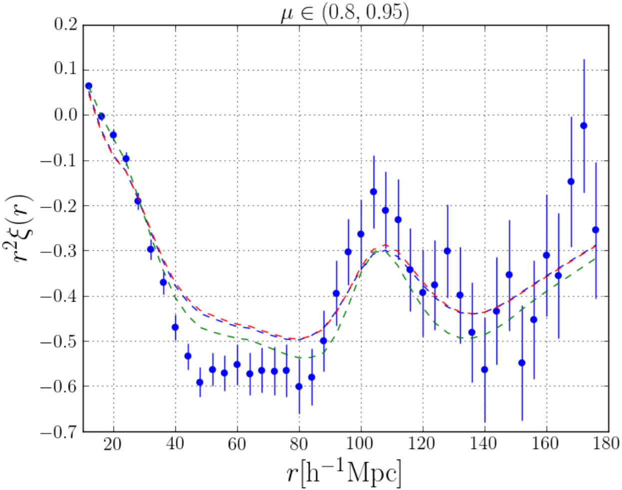
.

Sums over pixel pairs (i, j) separated by $(r_\perp, r_\parallel)$

Weight, w_i, is chosen to minimize variance of ξ.

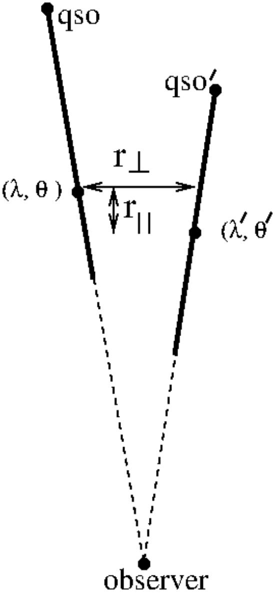
BOSS results: Bautista et al. (2017)





BAO peak at $r = r_d$ (sound horizon)

Measured quantities $(\Delta\theta, \Delta z)$



$$\Delta\theta = \frac{r_\perp}{D_M(z)} \qquad \Delta z = \frac{r_\parallel}{D_H(z)}$$

$\Rightarrow$ BAO peak position determines

$r_d/D_M(z)$ (transverse)

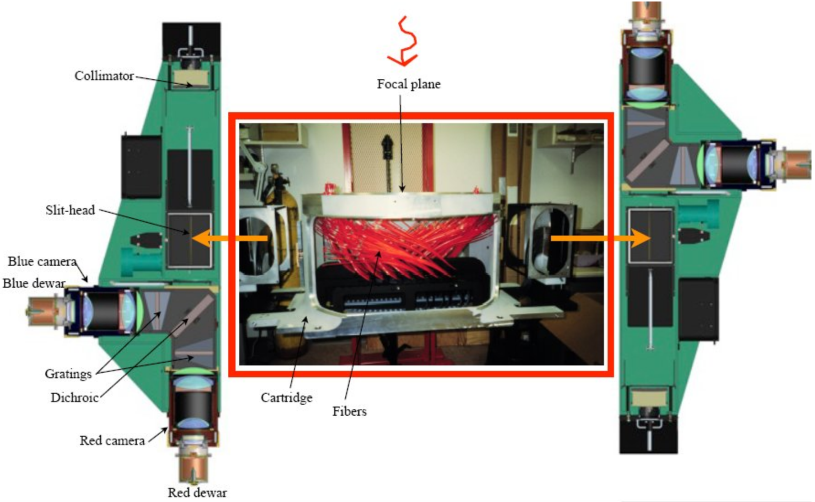
$r_d/(c/H(z))$ (radial)

BOSS: Baryon-Oscillation Spectroscopy Survey

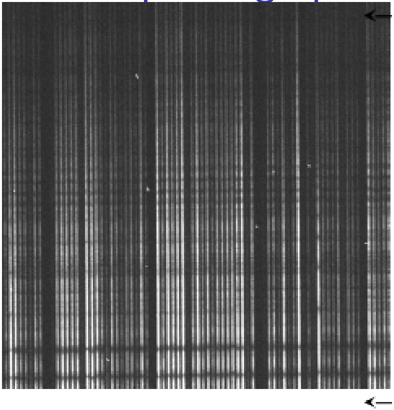
2.5meter Sloan telescope
Apache Point, New Mexico

$7deg^2$ focal plane
connected to spectrograph
via 1000 optical fibers

BOSS Spectrograph



BOSS Spectrograph,CCD



2 BOSS surveys ($10^4 deg^2$ 5 years)

- 6×10^5 Large Red Galaxies (LRG)
  $\sim$ 500 fibers per plate
  (candidates from SDSS-I photometry)
  $\langle z \rangle \sim 0.6$, $n \sim 10^{-4} Mpc^{-3}$
  BAO results: arXiv:1607.03155
- 1.6×10^5 quasars with Lyα absorption
  $\sim$ 280 fibers per plate
  (candidates from SDSS-I photometry)
  $\langle z \rangle \sim 2.4$
  BAO results: arXiv:1702.00176; 1708.02225

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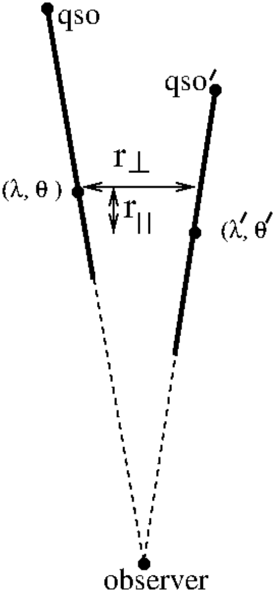
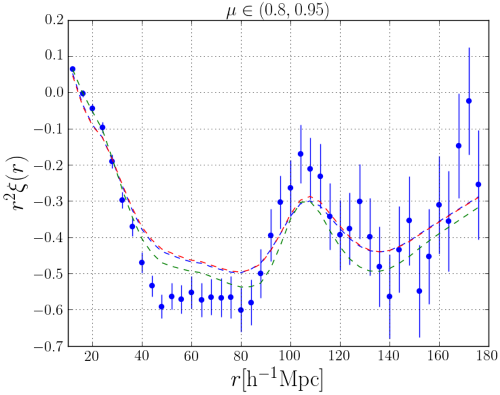
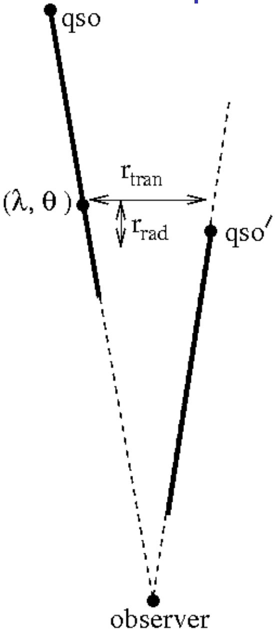
Correlate forests



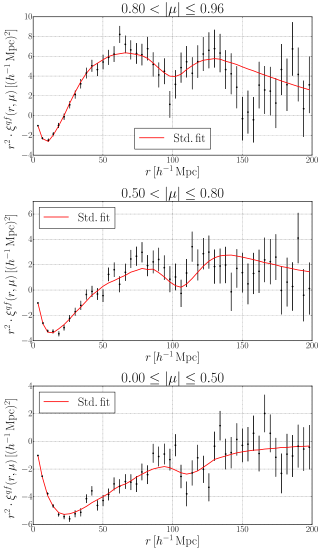
Bautista et al. (2017)
Nearly radial direction:



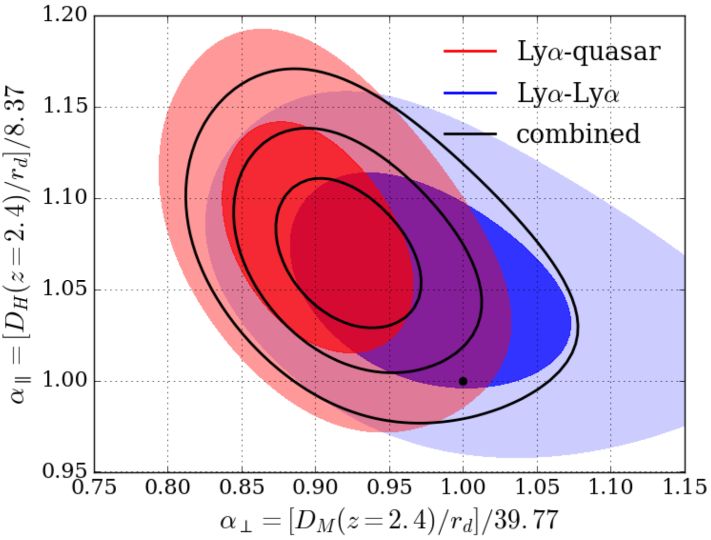
Correlate quasars and forests



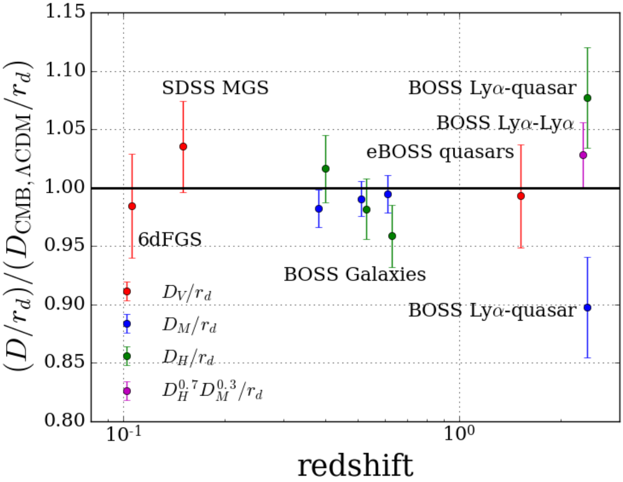
du Mas des Bourboux et al. (2017)



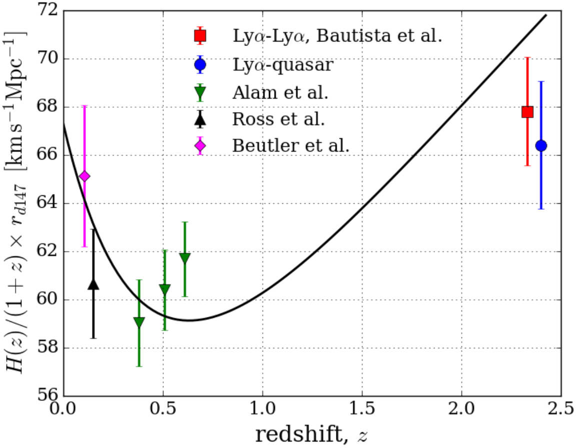
Constraints on $(D_M/r_d, D_H/r_d)$ at $z = 2.4$



Summary of BAO measurements of D/r_d

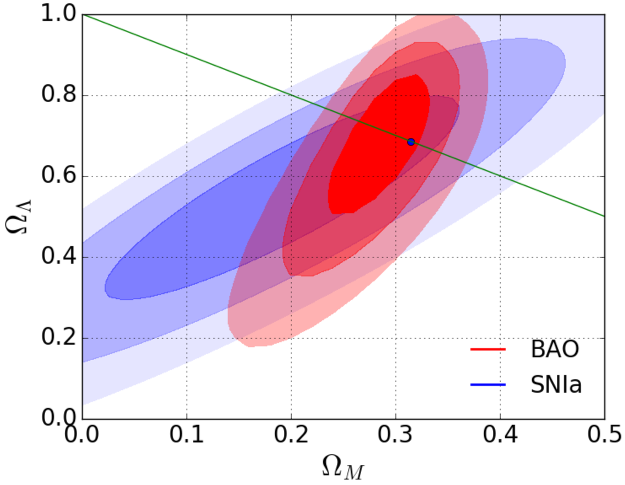


BAO $H(z) \Rightarrow$ deceleration$\rightarrow$acceleration



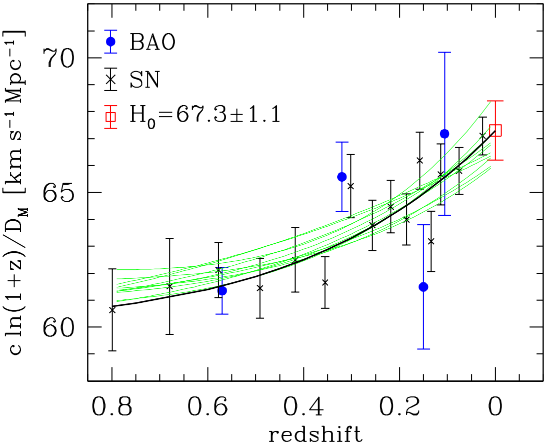
ΛCDM prediction

BAO $(D_M(z)/r_d, D_H(z)/r_d) \Rightarrow (\Omega_\Lambda, \Omega_M, r_d H_0)$



Top-down: the BAO and SNIa Hubble diagram

Aubourg et al. arXiv:1411.1074



Calibrate SNIa luminosity by requiring $D_M(z = 0.57)$ from SNIa agree with $D_M(z = 0.57)$ from BAO

$\Rightarrow H_0 = 67.3 \pm 1.1$

Distance ladder: $H_0 = 73.24 \pm 1.74$, arXiv:1604.01424

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Lyα flux transmission power spectrum

$$P_F(\vec{k}) = P_{lin}(k) b_F^2 (1 + \beta\mu_{\vec{k}}^2) F_{NL}(\vec{k})$$

Bias parameters (b_f, β).

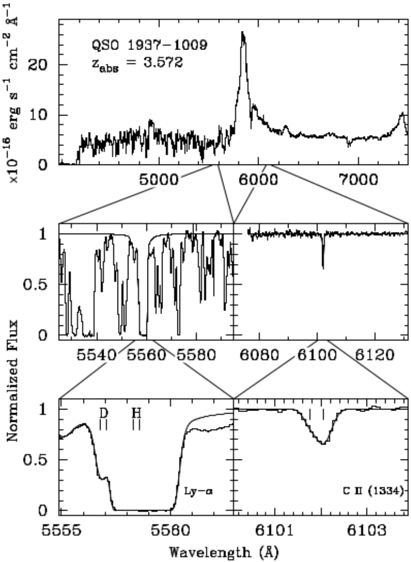
$F_{NL}(\vec{k})$ describes "non-linear" effects.

Galaxy power spectrum depends on unknown astrophysics of galaxy and star formation.

Lyα power spectrum depends on complicated but mostly understood hydrodynamics of the inter-galactic medium.

$\Rightarrow$Use simulations of IGM to find $(b_F, \beta, F_{NL}(\vec{k}))$ to derive $P_{lin}(k)$ from measured $P_F(\vec{k})$

The Lyα forest: $1A \sim 1$Mpc

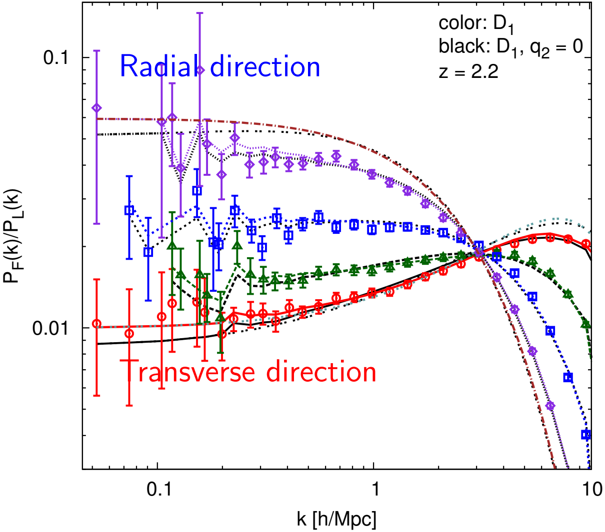


Low-resolution (BOSS)

High-resolution spectrum (Keck).
Simulations must resolve
Jeans-length of IGM ($\sim$ 100kpc).

Complications from non-HI
absorbers

Predicted $P_{F3d}(\vec{k})/P_L(k)$ (Arinyo et al.,2016)

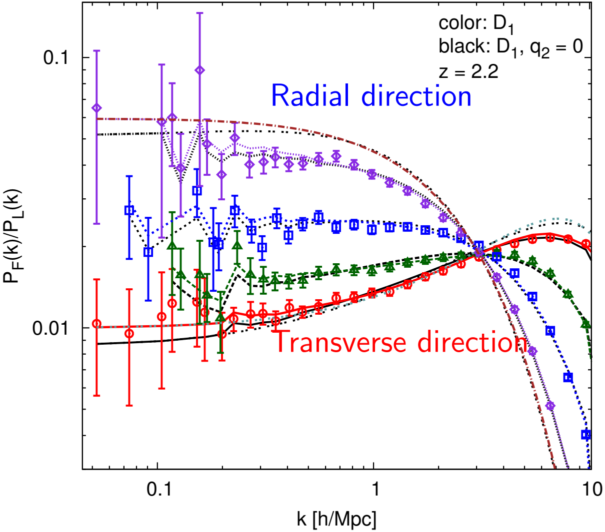


At small k

$P_{radial} \gg P_{transverse}$

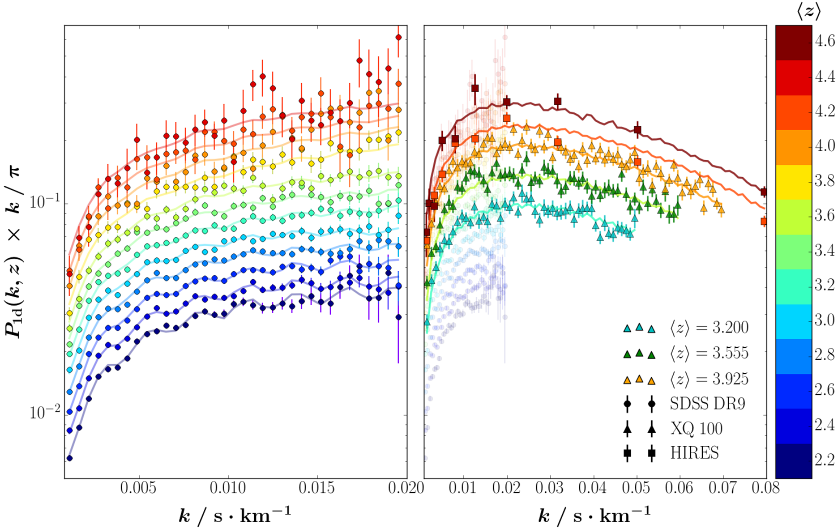
(because $b \ll 1$)

Predicted $P_{F3d}(\vec{k})/P_L(k)$ (Arinyo et al.,2016)

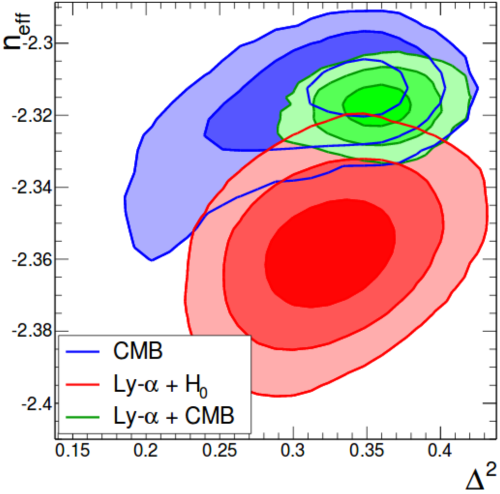


At large k
P_{radial} suppressed
(thermal broadening,
chaotic velocity
field)

Radial Power: BOSS, VLT, Keck



Deduced $P_L(k)$ (Palanque-Delabrouille et al 1410.7244)



Normalization of power spectrum Δ^2
Predicted by Planck ΛCDM
in agreement with
Observed in Lyαforest

⇒No room for extra free streaming effects of neutrinos

Suppression of power by massive neutrinos.

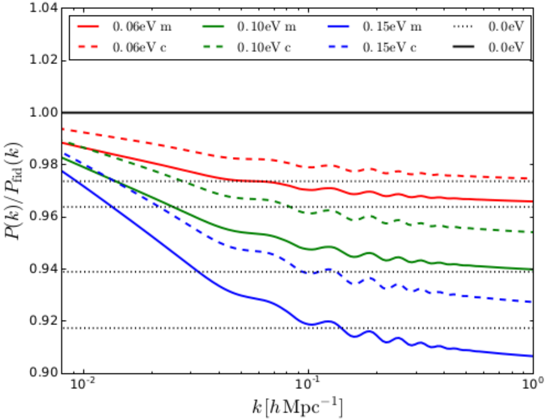


Figure 1. We carry out our analysis using simulations for different cosmologies with massive and massless neutrinos. In the plot we show the linear power spectrum of each model, normalized by the power spectrum of the fiducial cosmology (solid black line), at $z = 0$. The dotted black lines show the models with massless neutrinos and lower value of σ_8 than the fiducial model. The solid/dashed colored lines show the matter/CDM+baryons power spectrum of the models with massive neutrinos.

Villaescusa et al.
arXiv:1708.01154

Lyα $P_{1d}(k_{\parallel})$
$0.2 < k_{\parallel} < 4$

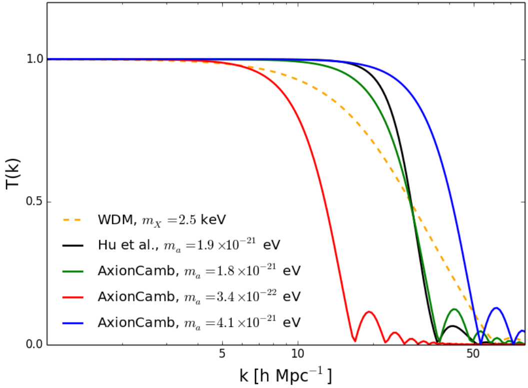
$P_{galaxy}(k)$
$0.01 < k < 1$

Limits on $\sum m_\nu$ from Lyα -CMB comparison

- Seljac, Slosar & McDonald (2006) $\sum m_\nu < 0.17$ eV
  SDSSI + WMAP-3yr
- Palanque-Delabrouille et al. (2015) $\sum m_\nu < 0.15$ eV
  BOSS+Planck 1yr
- Yeche et al. (2017) $\sum m_\nu < 0.14$ eV
  BOSS+VLT+Planck 2015

All assume n_s not running.
DESI limit goal: $\sigma(\sum m_\nu) = 0.02eV$
$\sum m_\nu = 0.06$ (0.11) for normal (inverted) mass ordering

Warm or Fuzzy DM cuts off the power spectrum



WDM: free-streaming

$$k_c \sim 6\ Mpc^{-1} \left(\frac{m_{wdm}}{keV}\right)^{1.1}$$

FDM: deBroglie wavelength

$$k_c \sim 5\ Mpc^{-1} \left(\frac{m_{fdm}}{10^{-22} eV}\right)^{0.46}$$

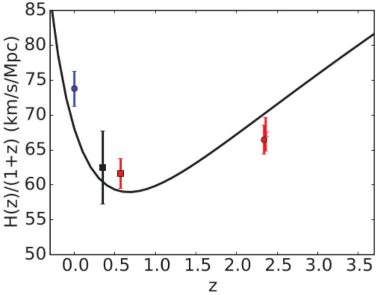
Observed large-k power consistent with expected thermal effects

BOSS,VLT,Keck Lyαpower

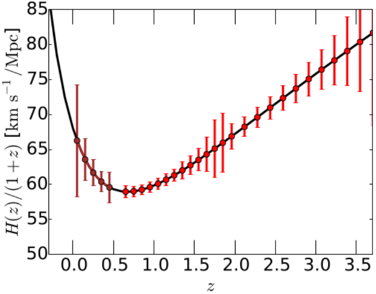
$\Rightarrow m_{wdm} >\sim$ 5keV [arXiv:1706.03118, 1702.03314]

$\Rightarrow m_{fdm} >\sim 3 \times 10^{-21}$eV [arXiv:1703.09126]

Future: Dark Energy Spectroscopy Survey (DESI)

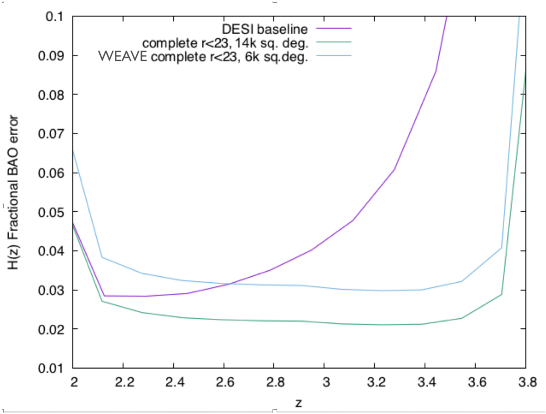


. BOSS $H(z)$



DESI $H(z)$:
arXiv:1611.00036
2.5M Sloan Telescope→4M Mayall
1000fibers → 5000 fibers

WEAVE



DESI: H(z) precision

WEAVE: precision with improved quasar selection using J-PAS narrow-band photometry

Lyα cosmology summary

Large CCD arrays and fiber-optic-fed spectrometers have allowed (will allow) BOSS$\rightarrow$eBOSS$\rightarrow$DESI to

- Constrain parameters of homogeneous cosmology with a well-understood standard ruler from BAO
- Study the small-scale power spectrum to place constaints on massive neutrinos, warm dark matter, and fuzzy dark matter.