Cosmology With The Lyα Forest

David Weinberg, Ohio State Astronomy and CCAPP

Results from the SDSS-III BOSS Lyα Forest

Baryon acoustic oscillations (BAO):

J. Bautista, M. Blomqvist, N. Busca, T. Delubac, H. du Mas des Bourboux
A. Font-Ribera, J. Guy, D. Kirkby, P. McDonald, J. Miralda-Escude,
M. Pieri, J. Rich, A. Slosar

1-d power spectrum:

N. Palanque-Delabrouille, C. Yèche, J. Baur, A. Borde, J.-M. Le Goff,
C. Magneville, G. Rossi, M. Viel

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Best probe of expansion and matter clustering at $z = 2 – 4$

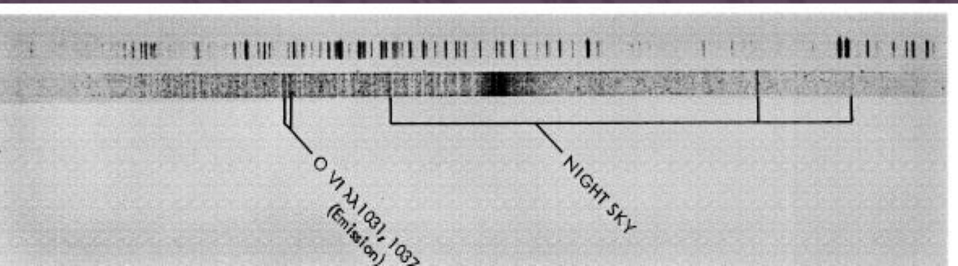
(together with CMB lensing)

- Observational accessibility
- Simplicity of first-order physical interpretation

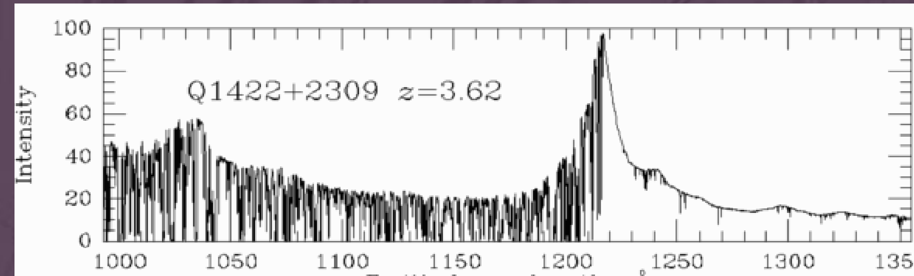
Best probe of primordial power spectrum on ~ Mpc scales

(together with dwarf galaxies/strong lensing/tidal streams)

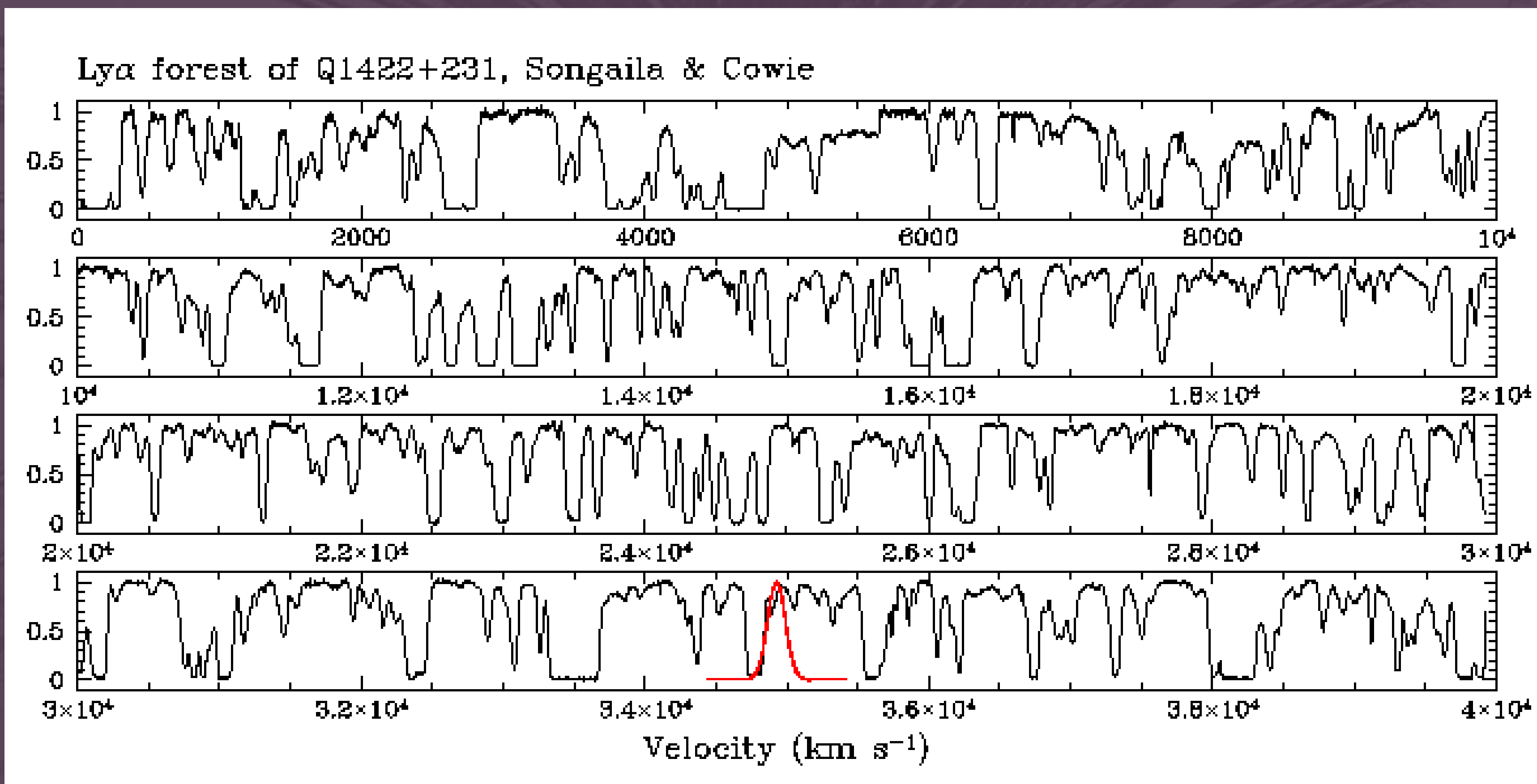
- Primordial structure not erased by non-linearity
- Neutrino masses, warm dark matter



Lynds 1971, Kitt Peak 2.2m



Songaila & Cowie 1994, Keck 10m



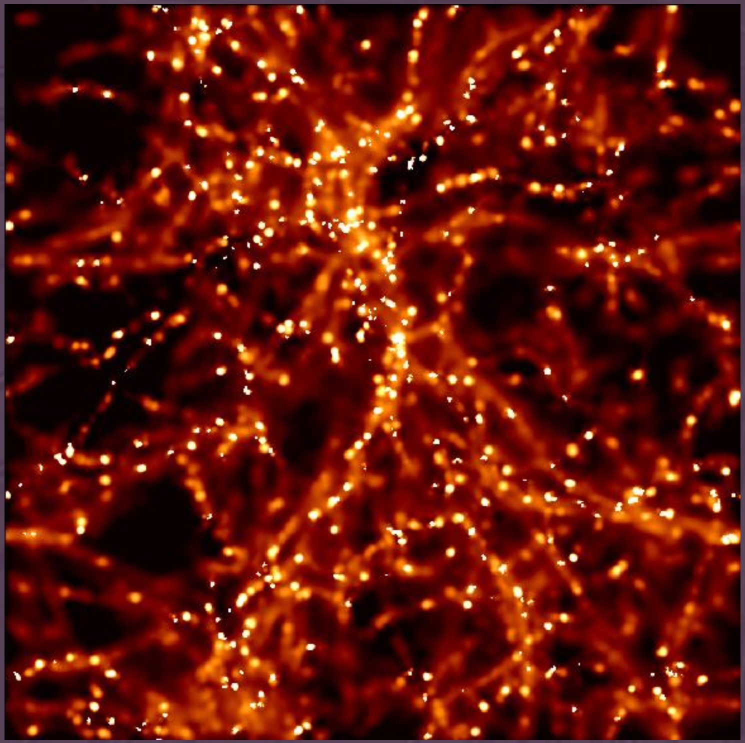
Mid-1990s: Properties of Lyα forest well explained by 3-d cosmological hydro simulations

Cen, Miralda-Escudé, Ostriker, Rauch 1994

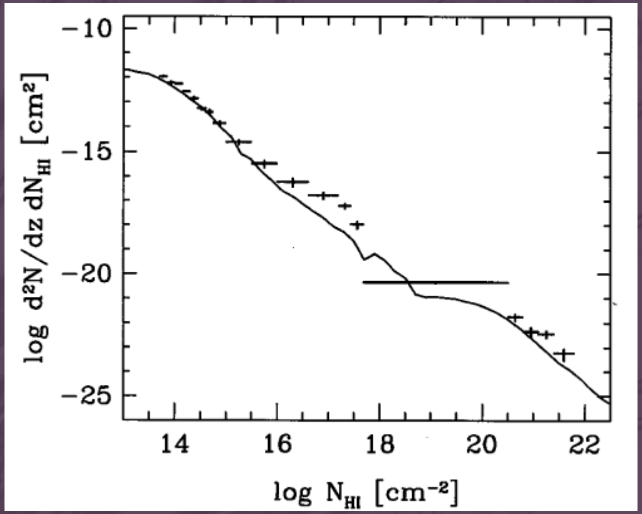
Zhang, Anninos, Norman 1995

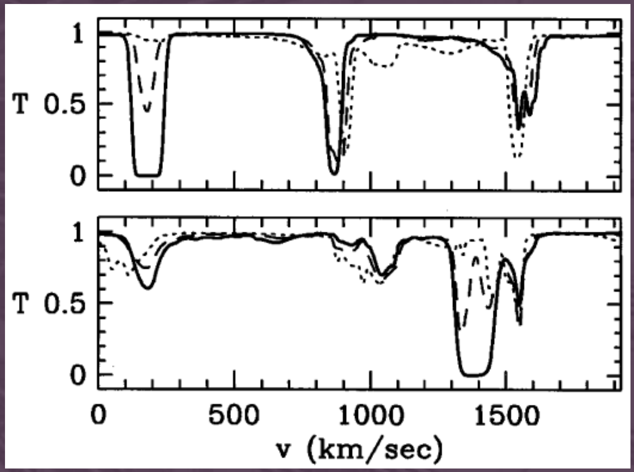
Hernquist, Katz, Weinberg, Miralda-Escudé 1996

Bi & Davidsen 1997; Hui & Gnedin 1997



Katz et al. 1996

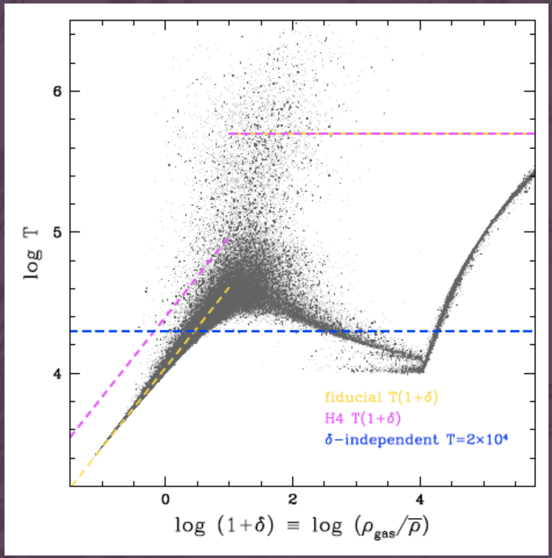




Hernquist et al. 1996

Power-law temperature-density relation
=> Lyα absorption is a local non-linear map of baryonic matter density

$F \approx \exp[-A(1+\delta)^{1.6}]$



Fluctuating Gunn-Peterson Approximation (FGPA)

$$\tau_{\rm HI} = 1.54 \times \left(\frac{T_0}{10^4\,\mathrm{K}}\right)^{-0.7} \left(\frac{10^{-12}\,\mathrm{s}^{-1}}{\Gamma_{\rm UV}}\right) \left(\frac{1+z}{1+3}\right)^6 \left(\frac{0.7}{h}\right) \times \left(\frac{\Omega_{b,0}h^2}{0.02156}\right)^2 \left[\frac{4.0927}{H(z)/H_0}\right] (1+\delta)^{2-0.7\alpha} \left[1 + \frac{1}{H(z)}\frac{\mathrm{d}V_{\rm los}}{\mathrm{d}x}\right]^{-1}$$

- Density & velocity fields (red)
- IGM parameters (green)
- Cosmological parameters (blue)

Weinberg, Katz, & Hernquist 1997
Croft, Weinberg, Katz & Hernquist 1998

Line-of-sight Lyα power spectrum is proportional to 1-d matter P(k)

R. Croft, Weinberg, Katz, Hernquist ++

P. McDonald, Miralda-Escudé, Seljak ++

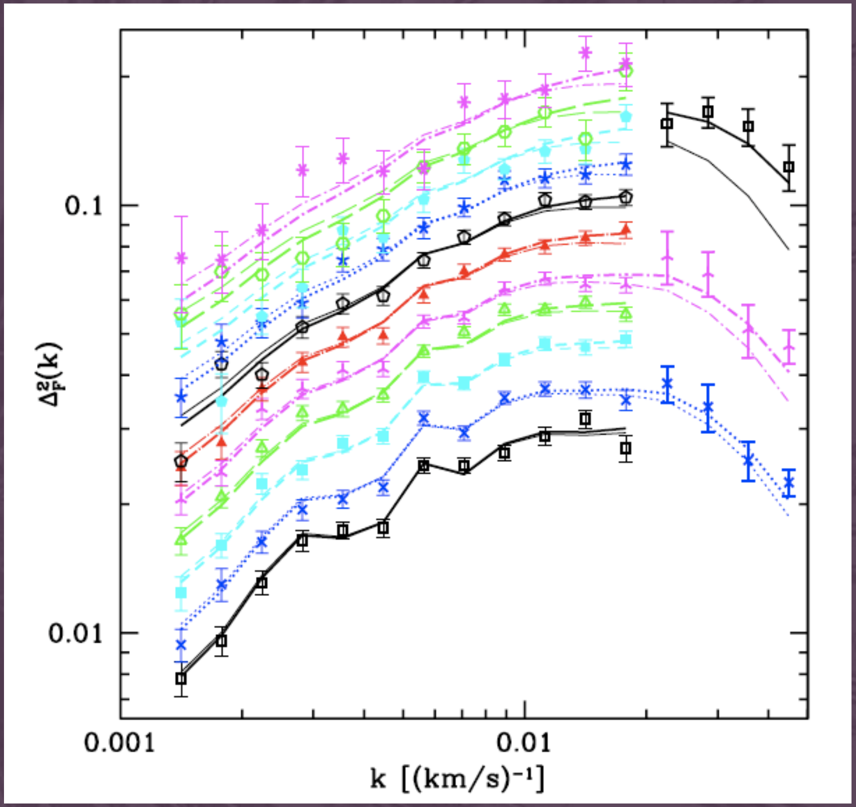
With a sufficiently large, dense survey, one can measure 3-d structure and BAO in the Lyα forest

M. White 2003

McDonald & Eisenstein 2007

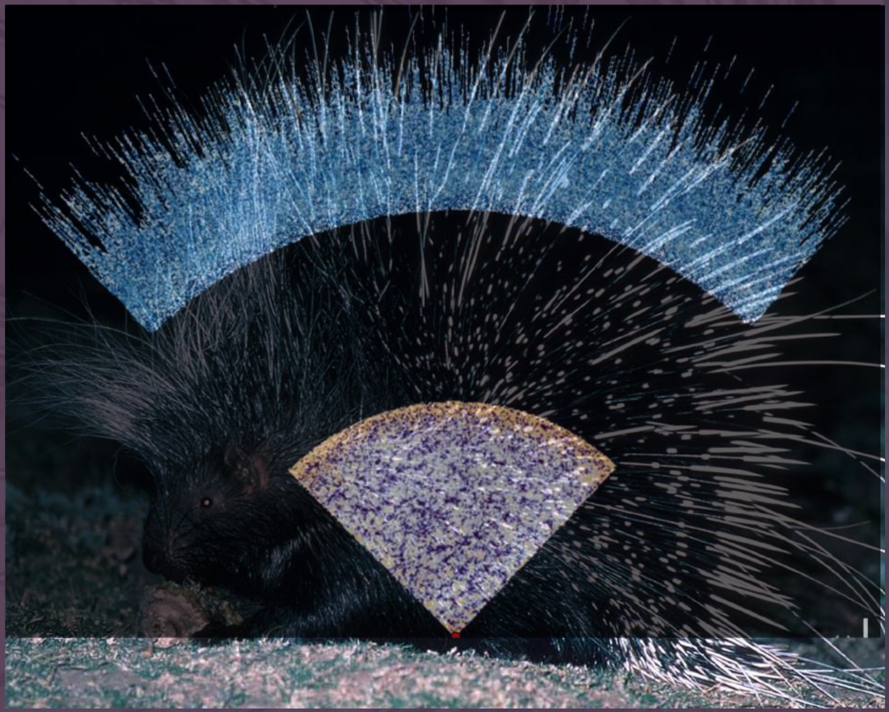
And in QSO-Lyα cross-correlations

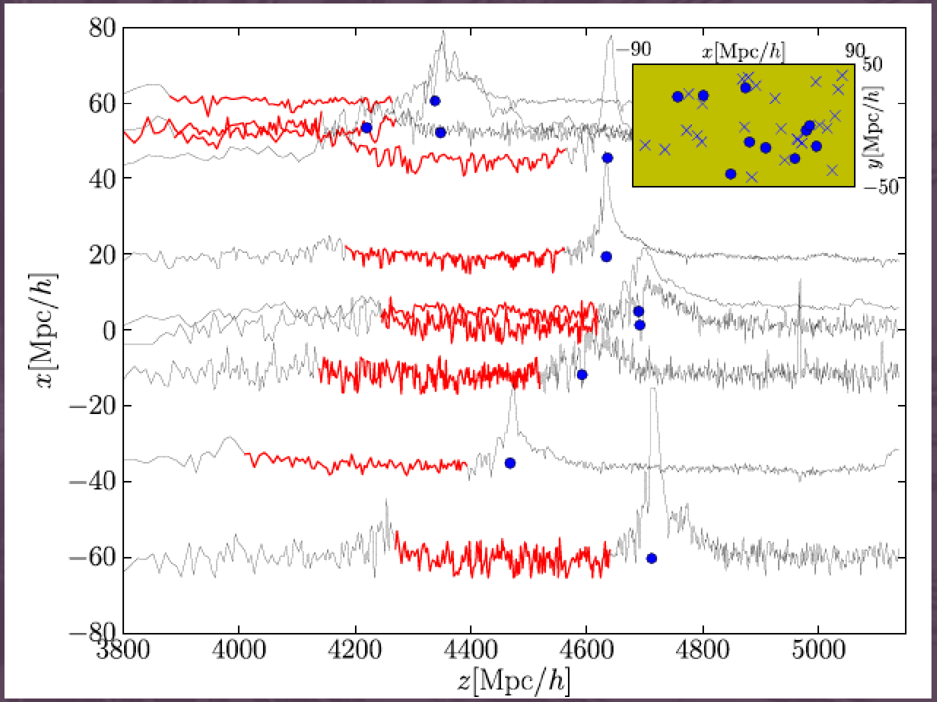
Font-Ribera, Kirkby, Busca et al. 2014



Seljak, Makarov, McDonald, Trac 2006

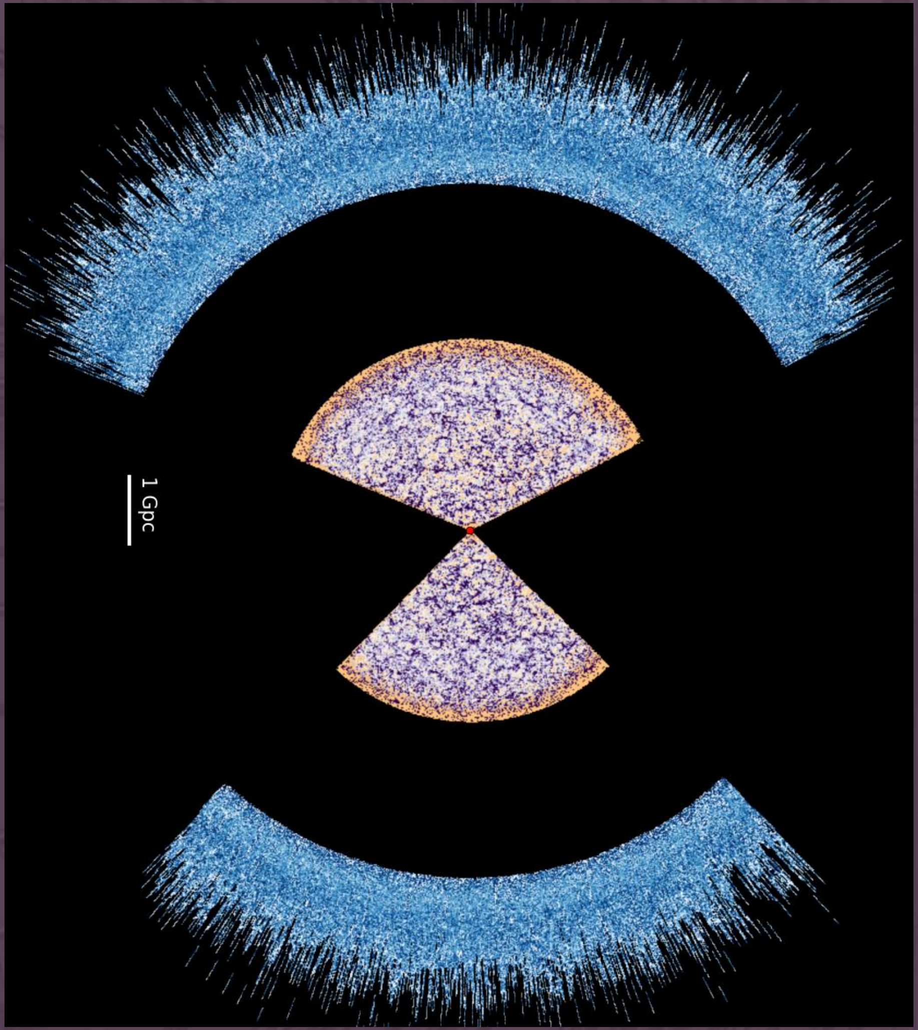
SDSS-III BOSS: 3-d correlations in the Lyman-α forest





Slosar, Font-Ribera, Pieri et al. 2011

SDSS-III BOSS: 3-d correlations in the Lyman-α forest



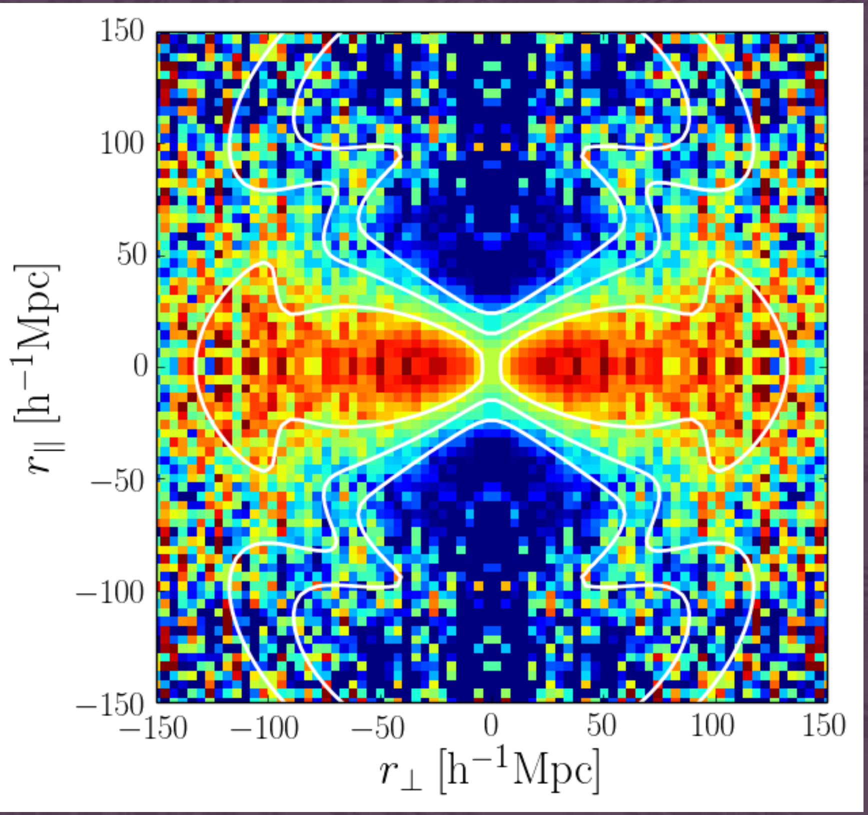


Figure: N. Busca

Figure: A. Slosar

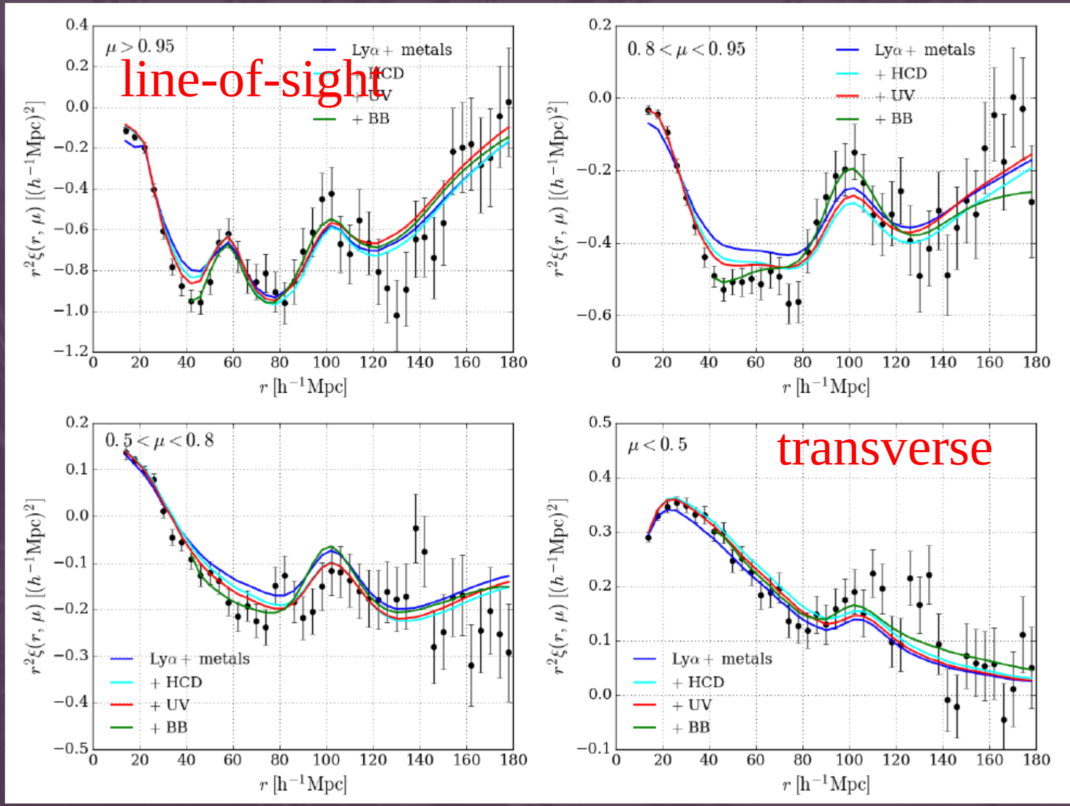
BAO in BOSS DR12 Lyα forest auto-correlation

Measures H(z) to 3.4%

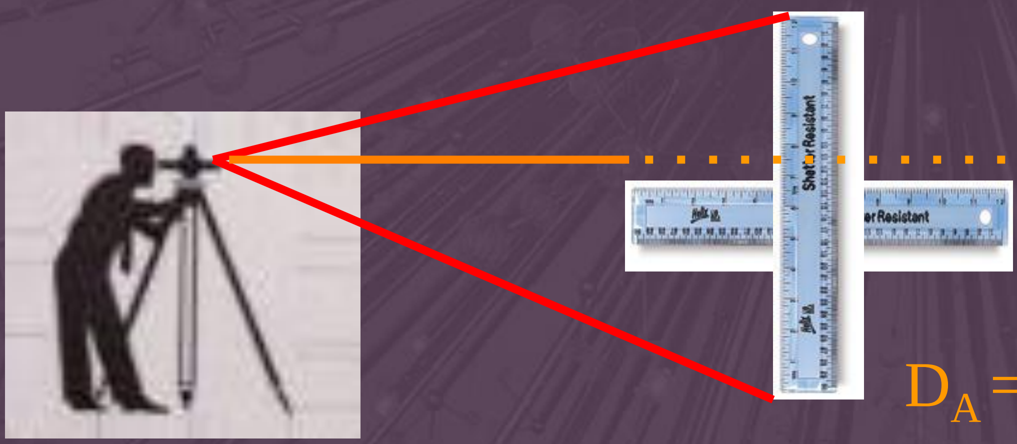
$D_A(z)$ to 5.7%

Best combo to 2.5%

At effective z = 2.3



Bautista, Busca, Guy et al. 2017



$D_A = L / \theta$; $H = c\,\Delta z / L$

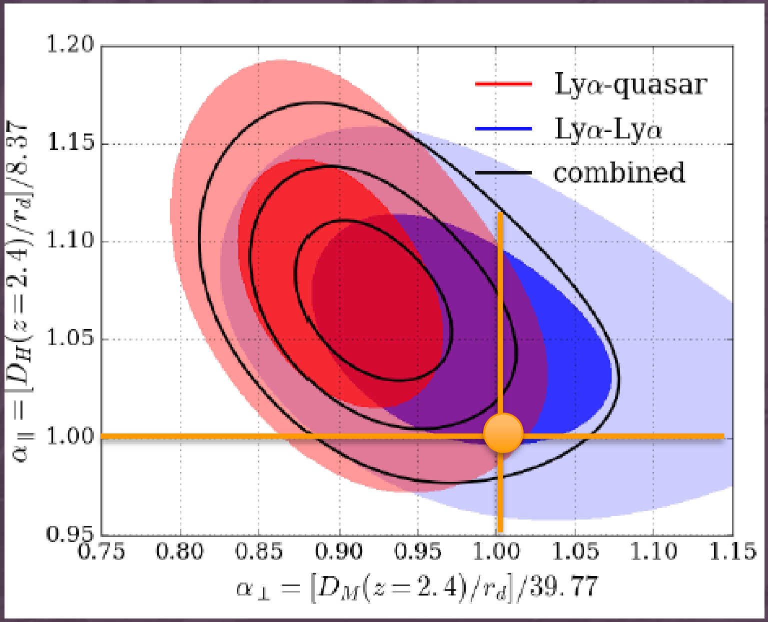
Combined with BOSS DR12 QSO - Lyα cross-correlation sharpens precision to

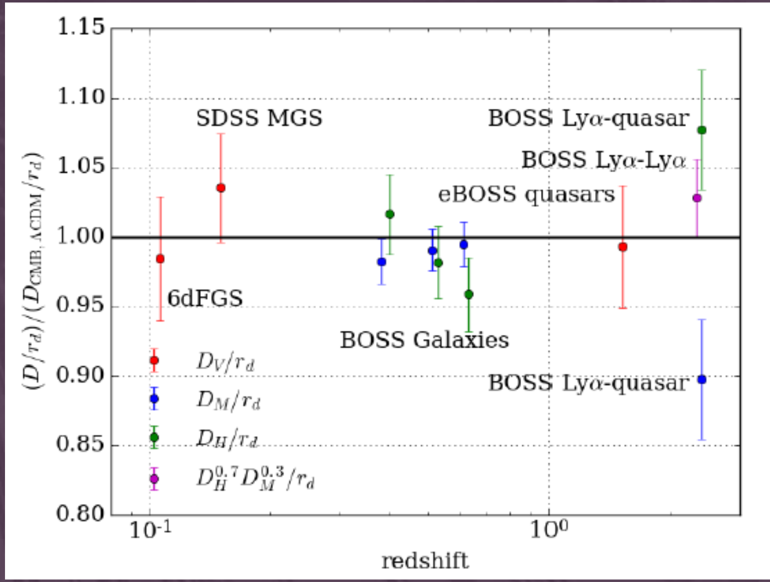
2.5% on H(z)
3.3% on D_A(z)

Combined constraint is ~ 2.3σ from best Planck ΛCDM model.

Hard to explain with new physics: D_A and (cz/H) off in opposite directions.

Ensemble of BAO data consistent with Planck ΛCDM.

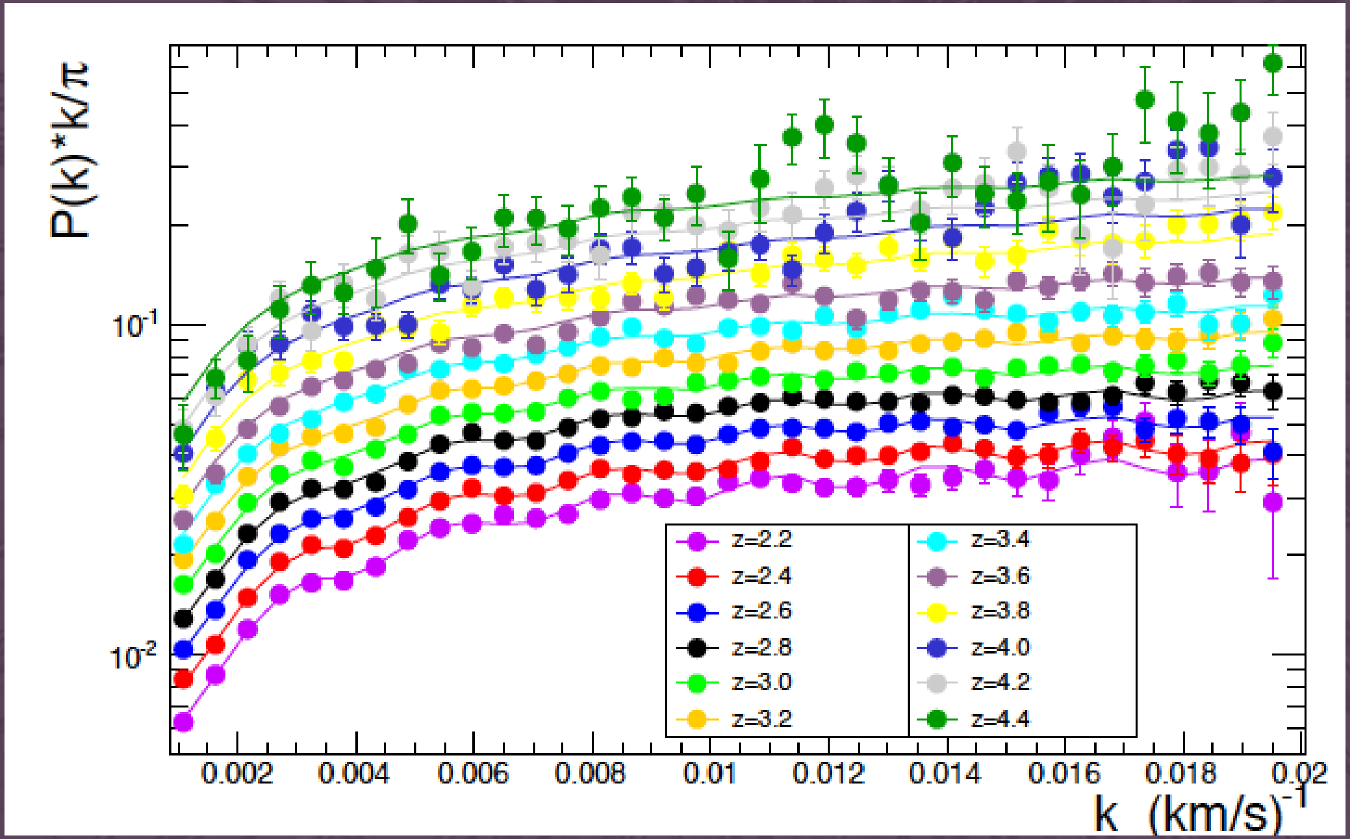




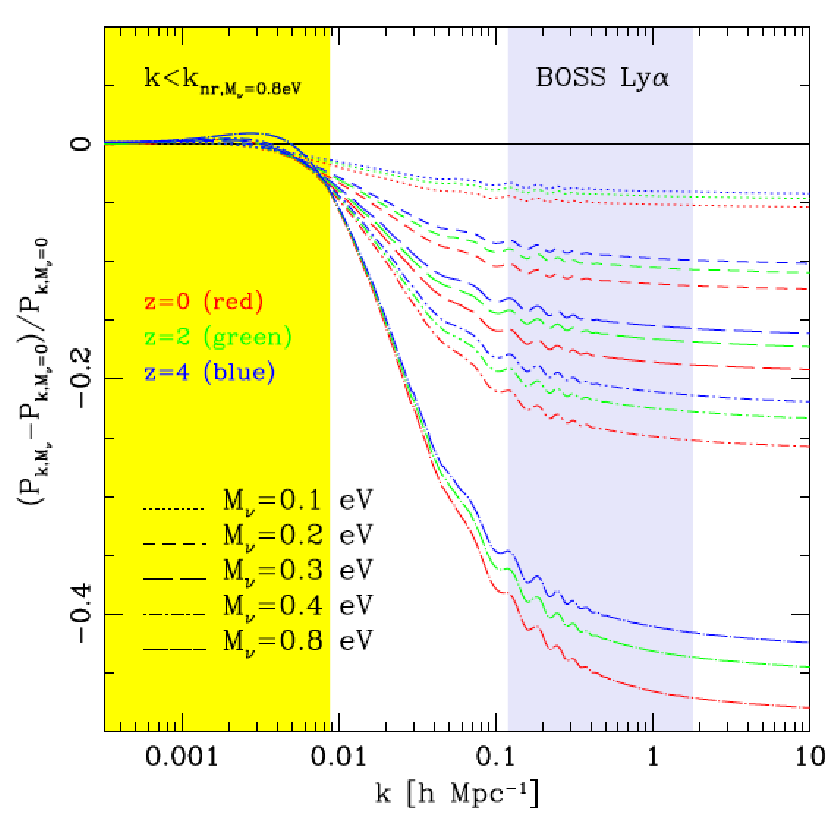
du Mas des Bourboux, Le Goff, Blomqvist et al. 2017

High-precision measurement of 1-d P(k) from ensemble of BOSS spectra, z = 2.2 – 4.4

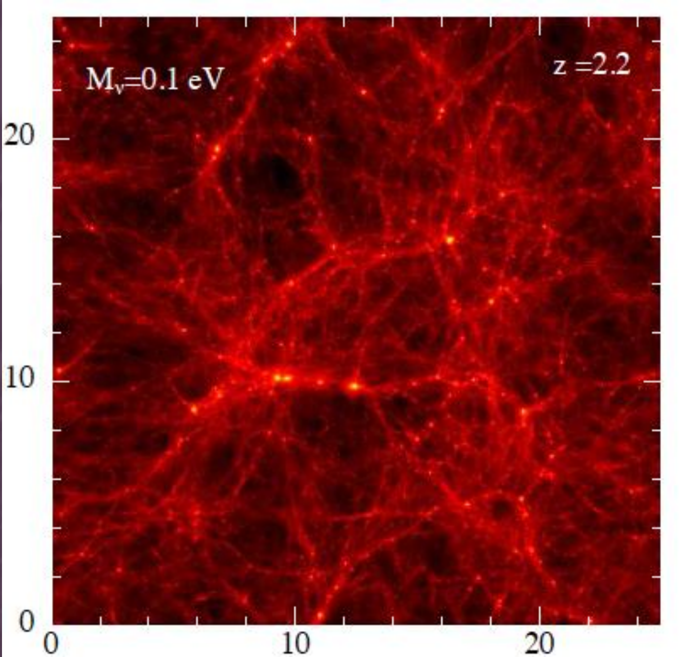
Palanque-Delabrouille, Yèche, Borde et al. 2013

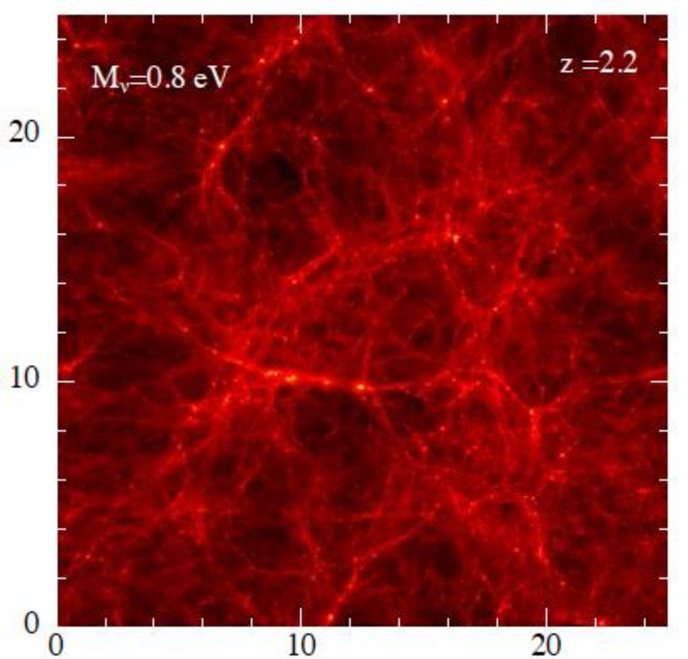


Non-zero neutrino mass suppresses linear P(k) on Lyα forest scales relative to CMB.

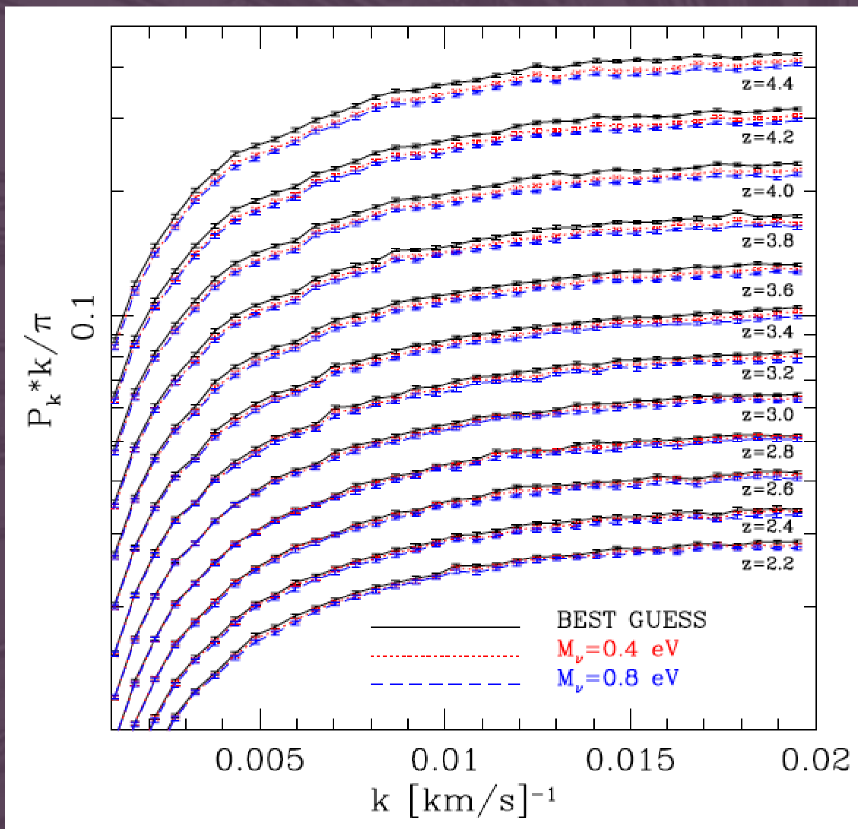


Rossi, Palanque-Delabrouille, Borde et al. 2015

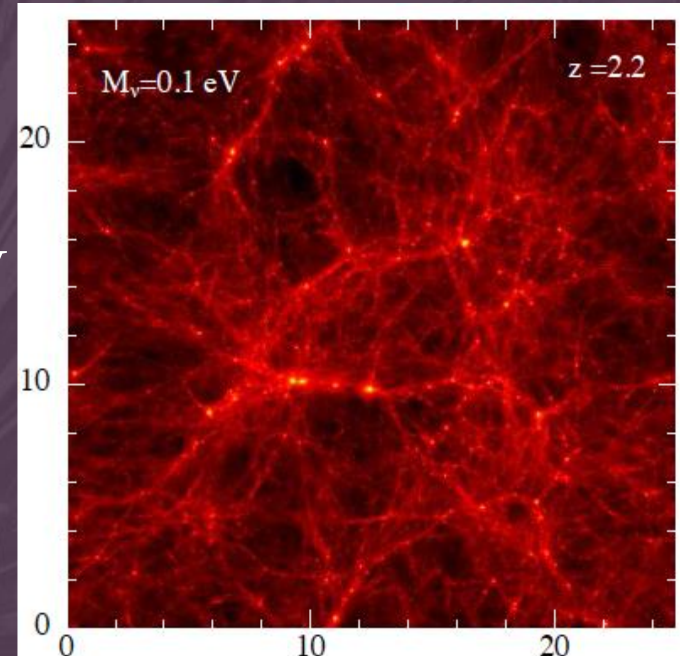


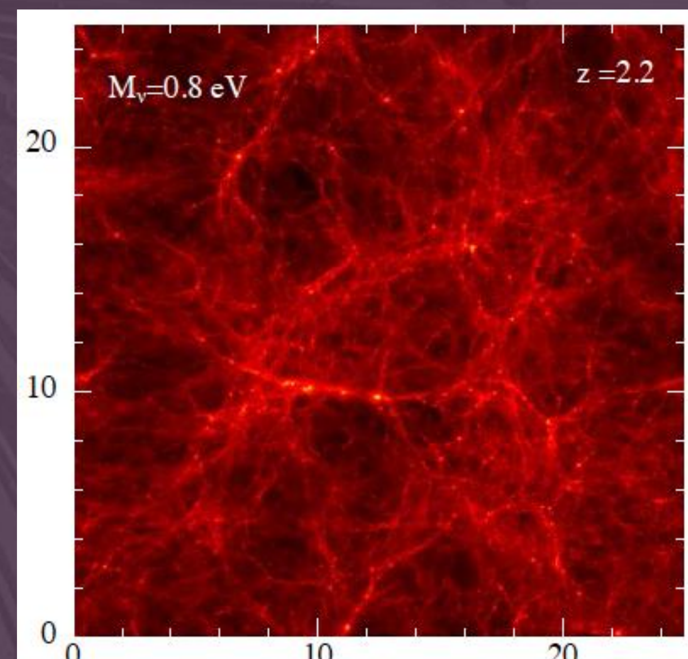


Non-zero neutrino mass suppresses linear P(k) on Lyα forest scales relative to CMB. Impact on flux P(k) is few % for $m_\nu \sim 0.5$ eV



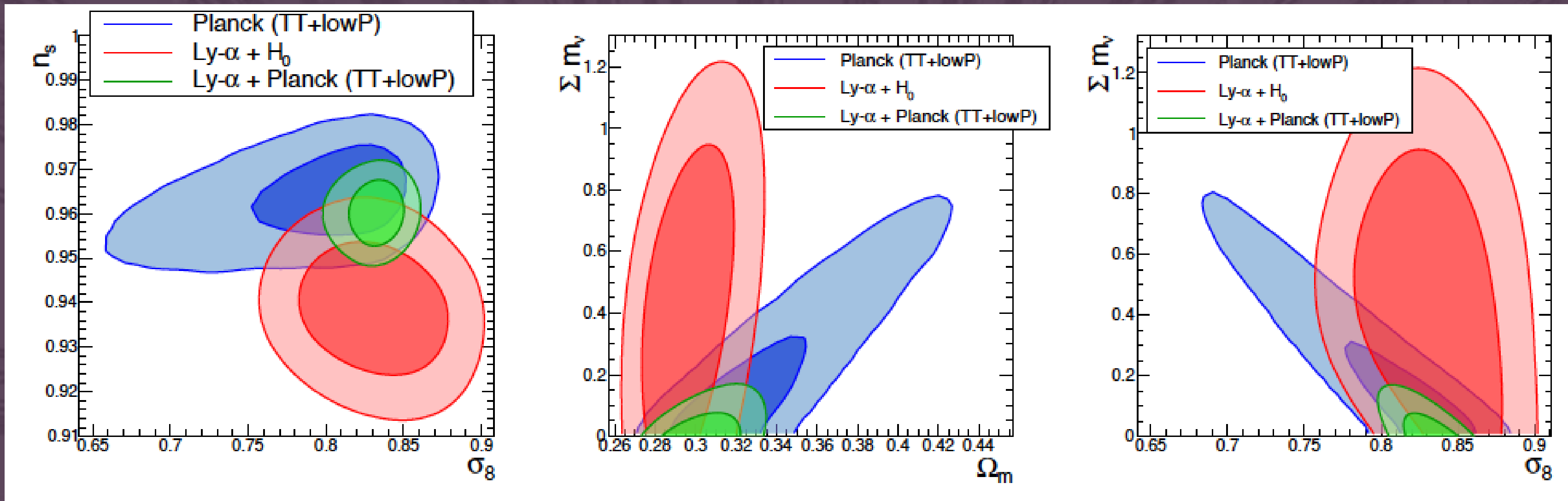
Rossi, Palanque-Delabrouille, Borde et al. 2015





Palanque-Delabrouille, Yèche, Baur et al. 2015

Blue = CMB
Red = Lyα



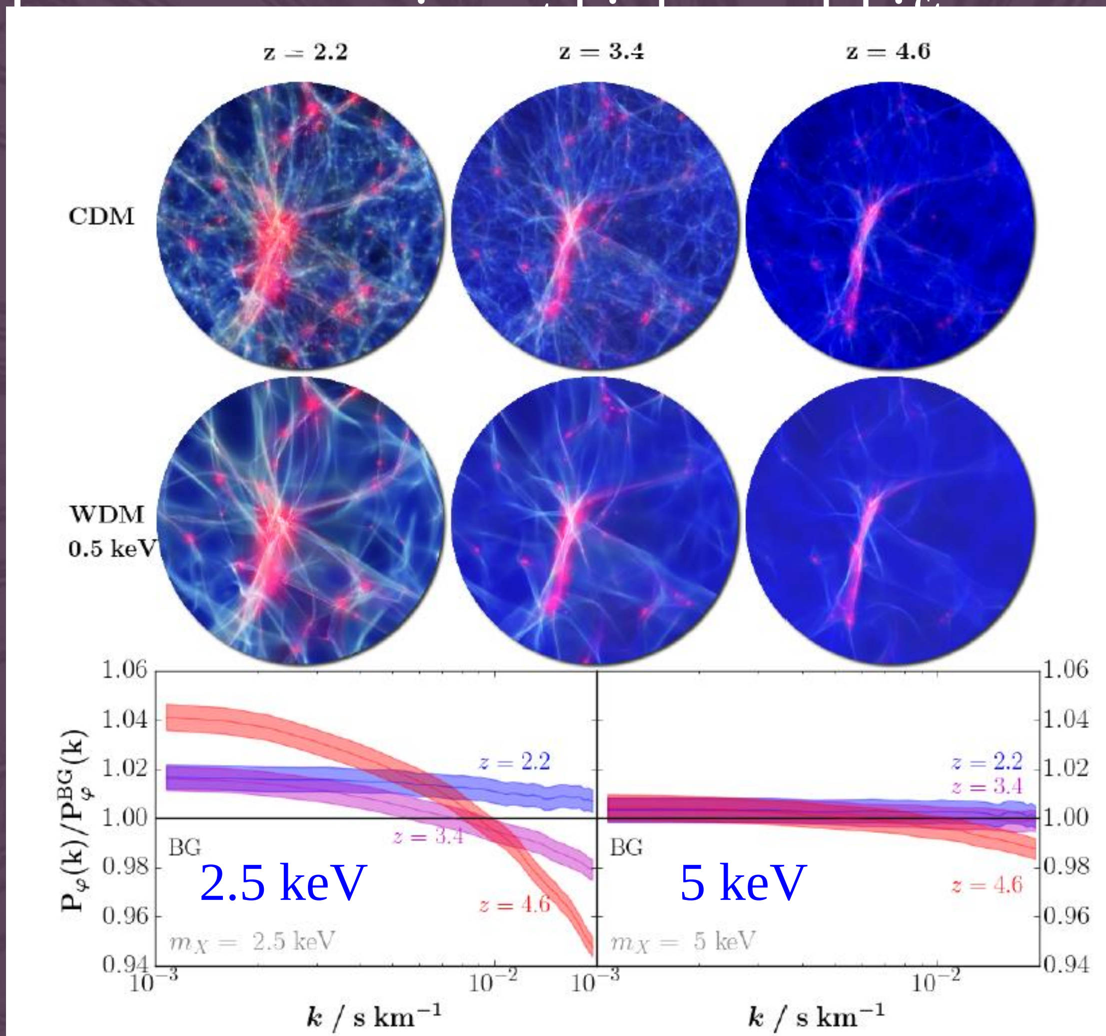
For Planck CMB, high Σm_ν implies low σ_8, high Ω_m.

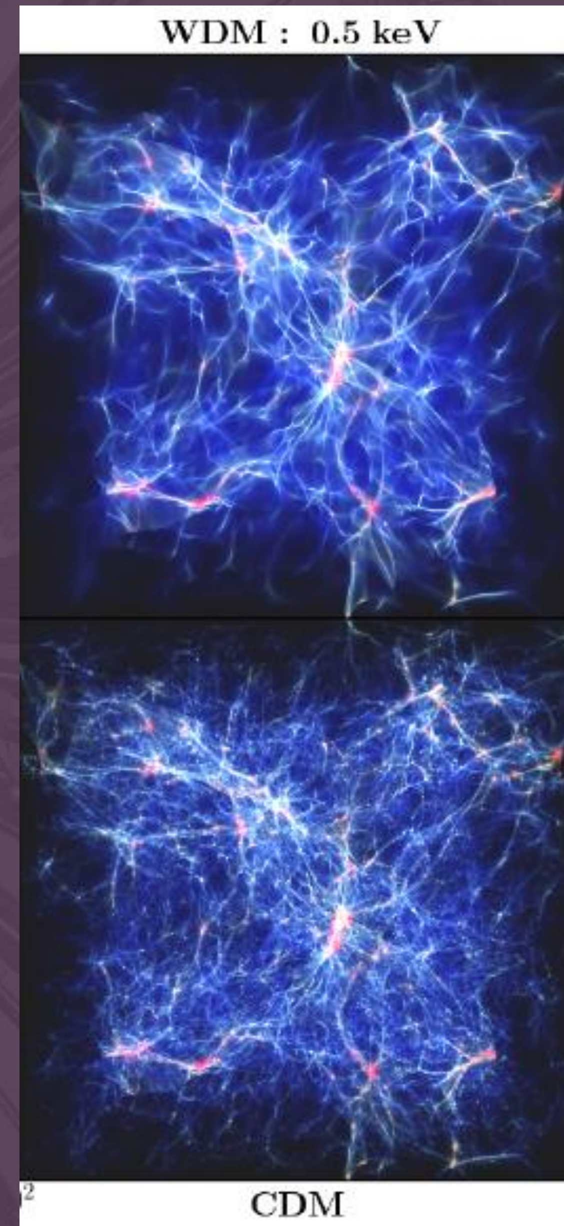
Lyα P(k) measures these independent of CMB.

Combined 95% C.L. constraint is $\Sigma m_\nu < 0.12$ eV.

Some tension between CMB and Lyα value of n_s.

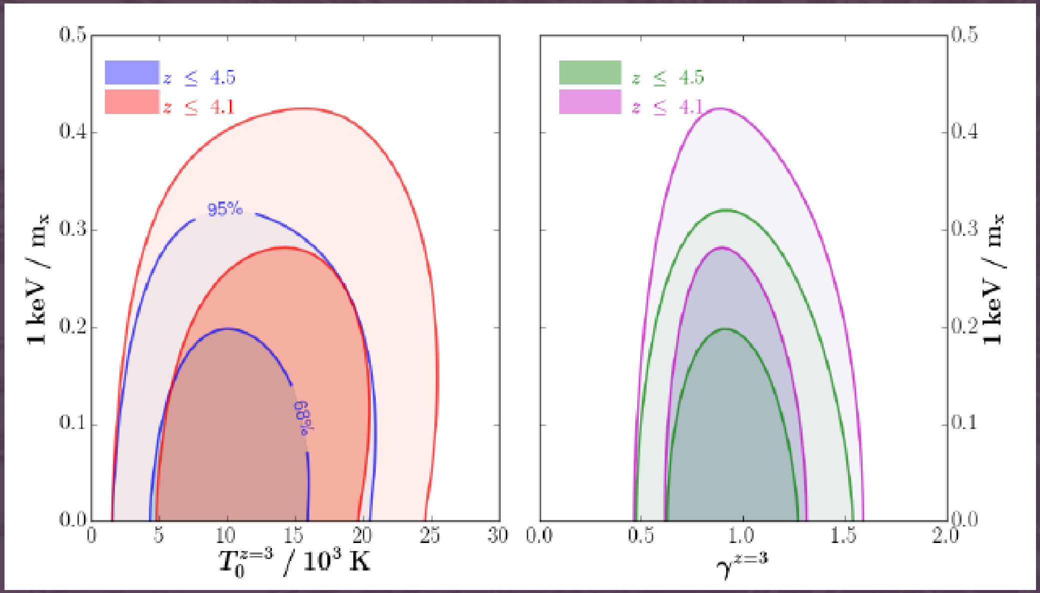
Warm dark matter suppresses small scale P(k)

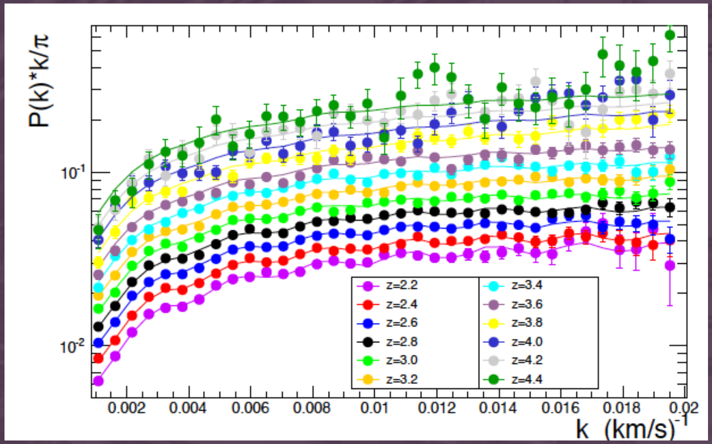




Baur, Palanque-Delabrouille, Yeche, Magneville, Viel 2016

BOSS DR9 1-d P(k):
Thermal relic 95% C.L. lower limit of 3.0 keV





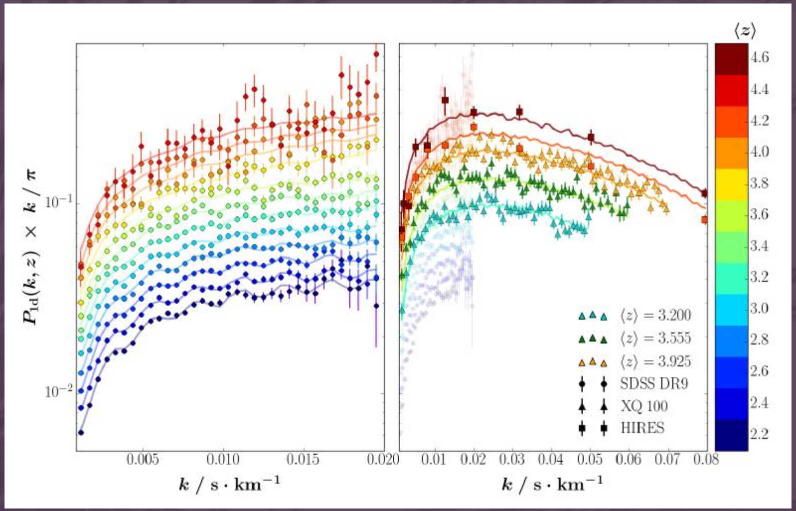
Baur, Palanque-Delabrouille, Yèche, Magneville, Viel 2016

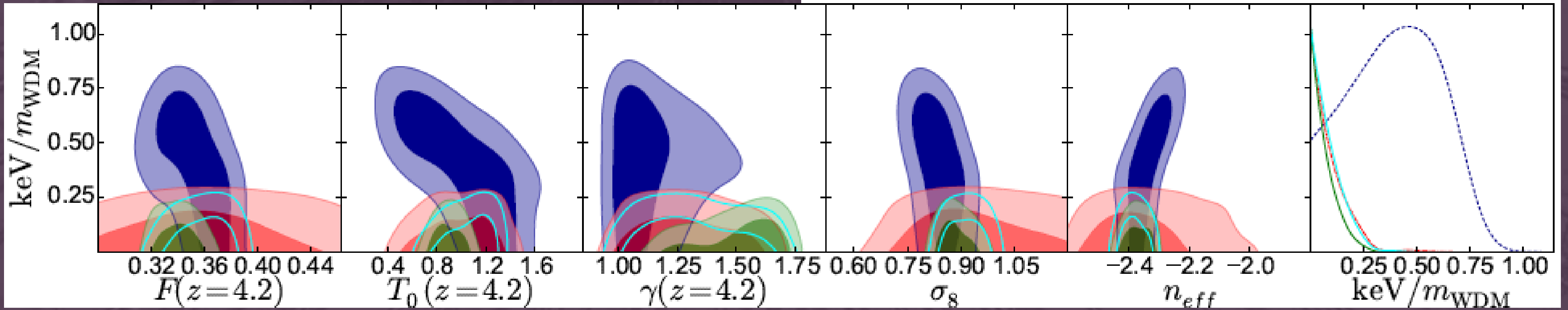
Higher resolution data provide greater leverage on WDM, especially at high z.

Iršič, Viel, Haehnelt++ 2017:
High-res data => m_{wdm} > 5.3 keV

Baur, P.-D., Yèche++ 2017:
Compared to BOSS, high-res data show suppression, could be WDM or IGM physics

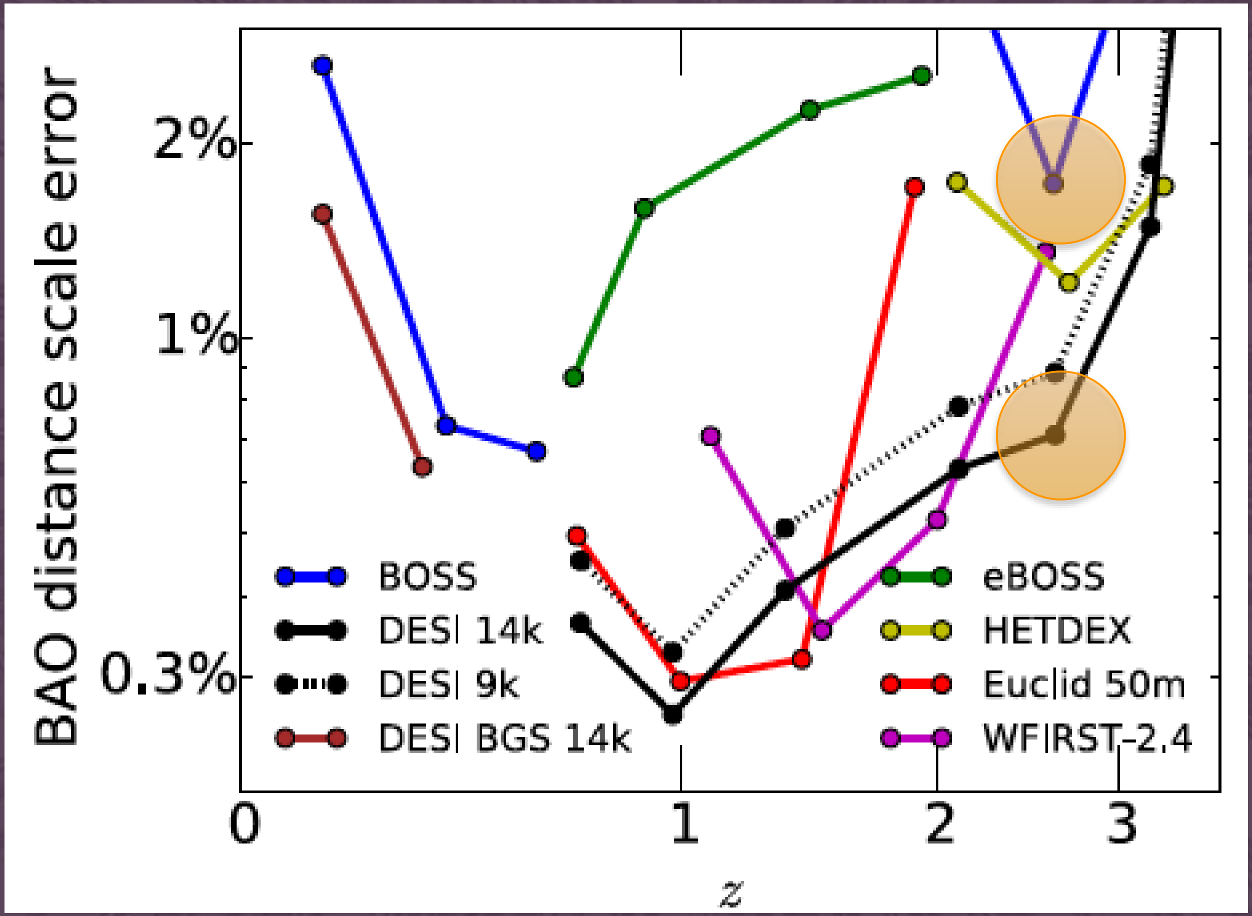
Baur, P.-D., Yèche++ 2017





Iršič, Viel, Haehnelt++ 2017

DESI: 700,000 Lyα QSOs (z > 2.1)
(vs. 158,000 for BOSS)



DESI Collaboration 2016

The “nuisance parameters” are astrophysically interesting:

Hydrogen and helium reionization

Sources of the ionizing background radiation

Heating mechanisms of the diffuse intergalactic medium

Nature of high column density absorbers & metal-line systems

Influence of CDM-baryon streaming velocities on Lyα forest

$$\tau_{\mathrm{HI}} = 1.54 \times \left(\frac{T_0}{10^4\,\mathrm{K}}\right)^{-0.7} \left(\frac{10^{-12}\,\mathrm{s}^{-1}}{\Gamma_{\mathrm{UV}}}\right) \left(\frac{1+z}{1+3}\right)^{6} \left(\frac{0.7}{h}\right)$$
$$\times \left(\frac{\Omega_{b,0}h^2}{0.02156}\right)^{2} \left[\frac{4.0927}{H(z)/H_0}\right] (1+\delta)^{2-0.7\alpha} \left[1 + \frac{1}{H(z)}\frac{\mathrm{d}V_{\mathrm{los}}}{\mathrm{d}x}\right]^{-1}$$

Density & velocity fields (red)

IGM parameters (green)

Cosmological parameters (blue)

Cosmology With The Lyα Forest

Best probe of expansion and matter clustering at $z = 2 - 4$

- Observational accessibility
- Simplicity of first-order physical interpretation
- BAO in slight tension w/ ΛCDM, probably statistical fluke

Best probe of primordial power spectrum on ~ Mpc scales

- Primordial structure not erased by non-linearity
- Consistent w/ΛCDM, limits neutrino or WDM suppression

Challenges

- Removal of instrumental/observational signatures
- Highly accurate modeling of IGM physics