

Cosmology With The Ly α Forest

David Weinberg, Ohio State Astronomy and CCAPP

Results from the SDSS-III BOSS Ly α 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 $z = 2 - 4$

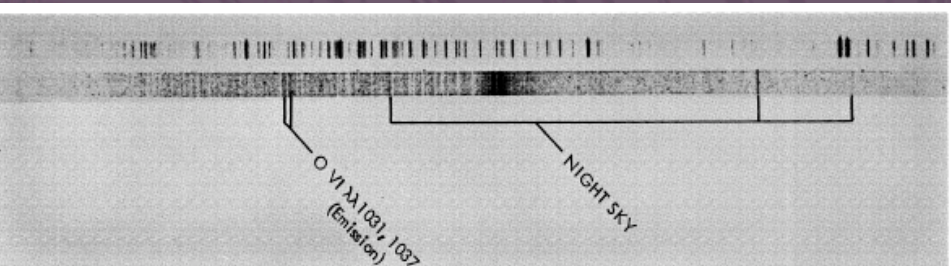
(together with CMB lensing)

- Observational accessibility
- Simplicity of first-order physical interpretation

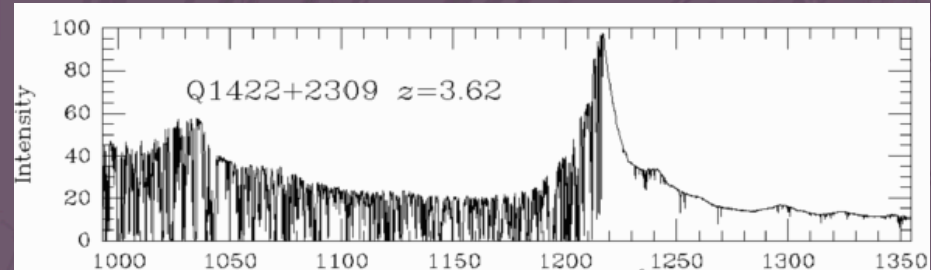
Best probe of primordial power spectrum on \sim Mpc scales

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

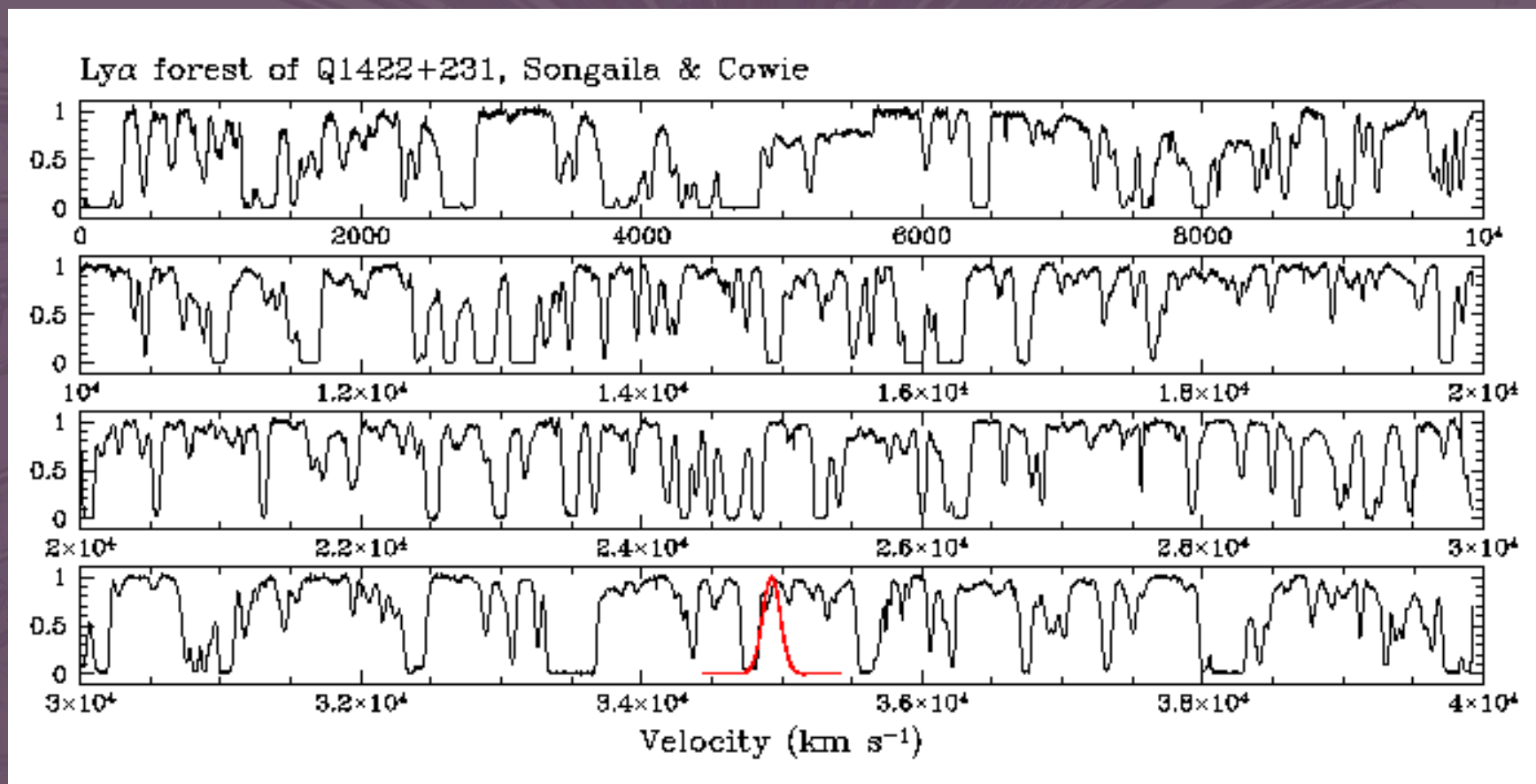
- Primordial structure not erased by non-linearity
- Neutrino masses, warm dark matter



Lynds 1971, Kitt Peak 2.2m



Songaila & Cowie 1994, Keck 10m



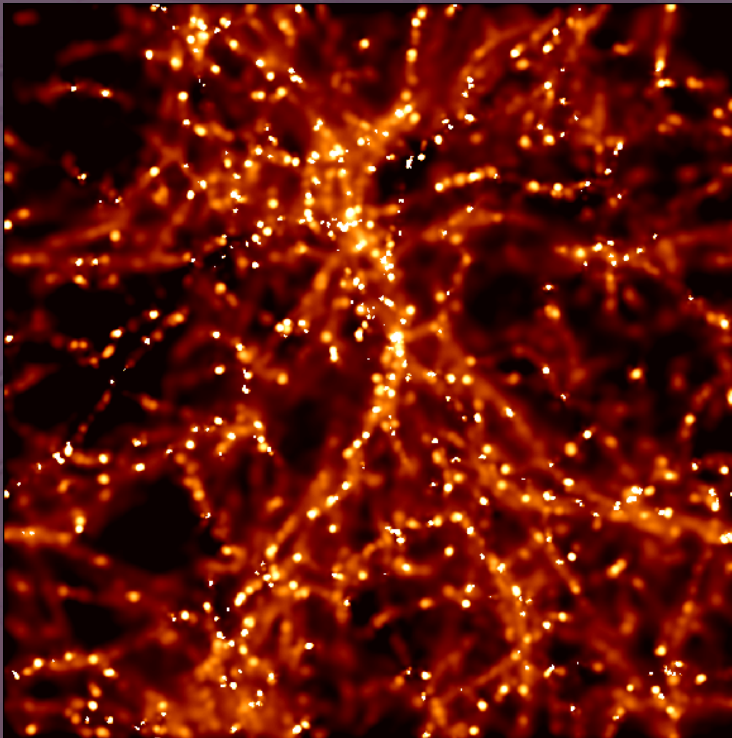
Mid-1990s: Properties of Ly α forest well explained by 3-d cosmological hydro simulations

Cen, Miralda-Escudé, Ostriker, Rauch 1994

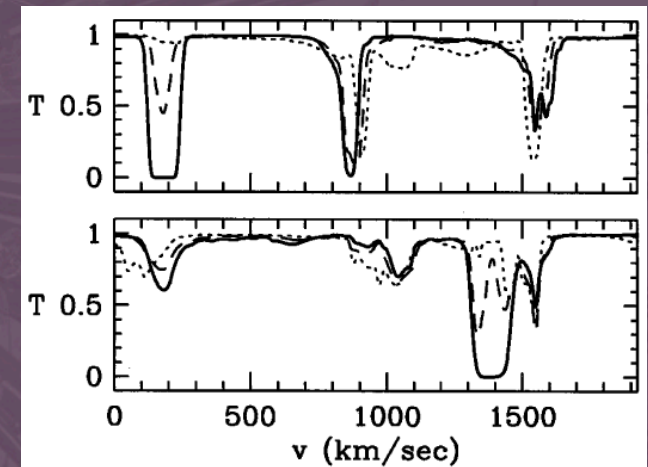
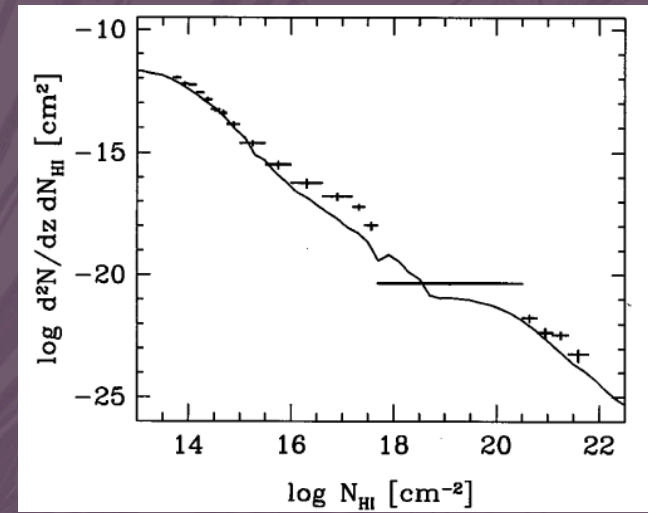
Zhang, Anninos, Norman 1995

Hernquist, Katz, Weinberg, Miralda-Escudé 1996

Bi & Davidsen 1997; Hui & Gnedin 1997



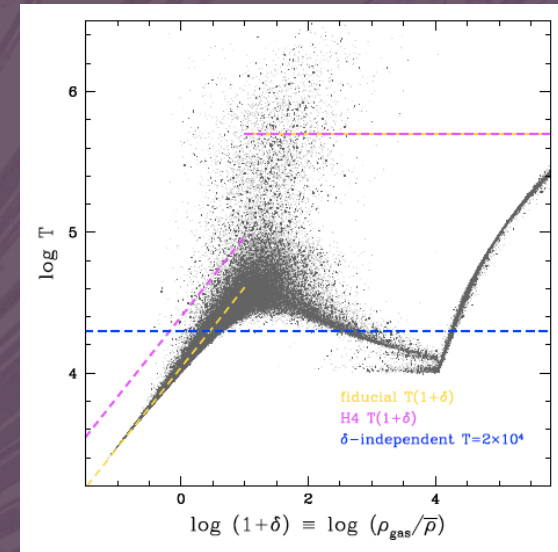
Katz et al. 1996



Hernquist et al. 1996

Power-law temperature-density relation
 \Rightarrow Ly α absorption is a local non-linear
 map of baryonic matter density

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



Fluctuating Gunn-Peterson Approximation (FGPA)

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

- Density & velocity fields
- IGM parameters
- Cosmological parameters

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

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

R. Croft, Weinberg, Katz, Hernquist ++

P. McDonald, Miralda-Escudé, Seljak ++

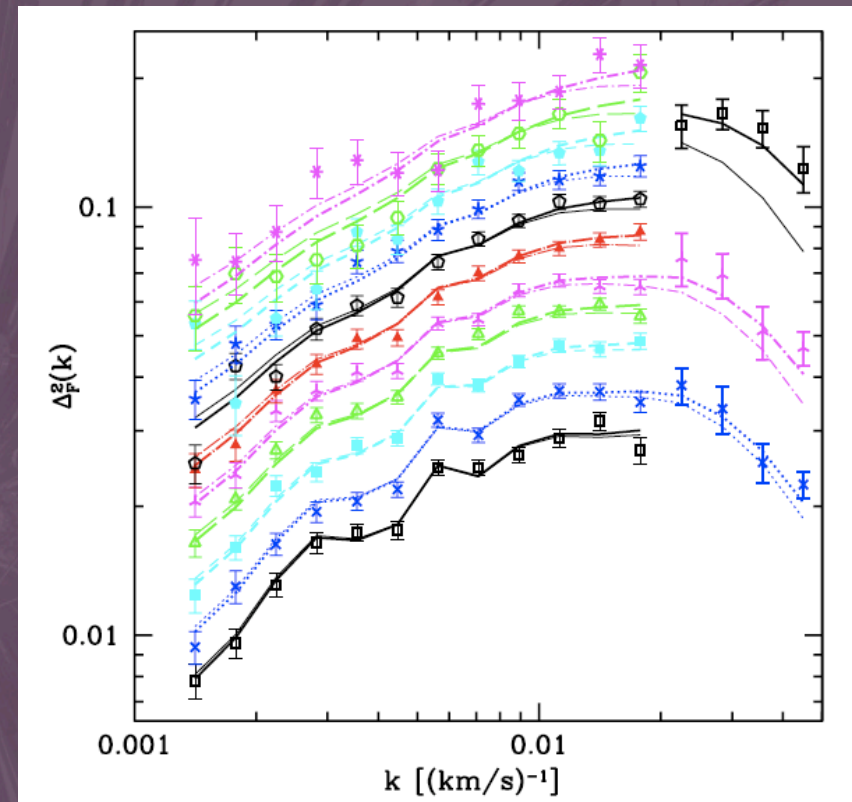
With a sufficiently large, dense
survey, one can measure 3-d
structure and BAO in the Ly α forest

M. White 2003

McDonald & Eisenstein 2007

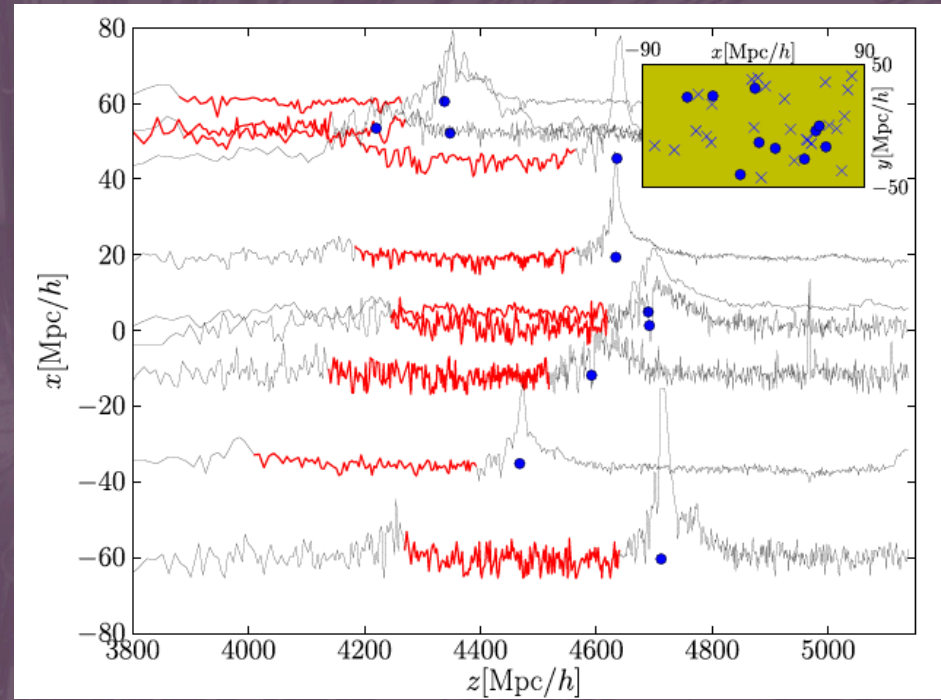
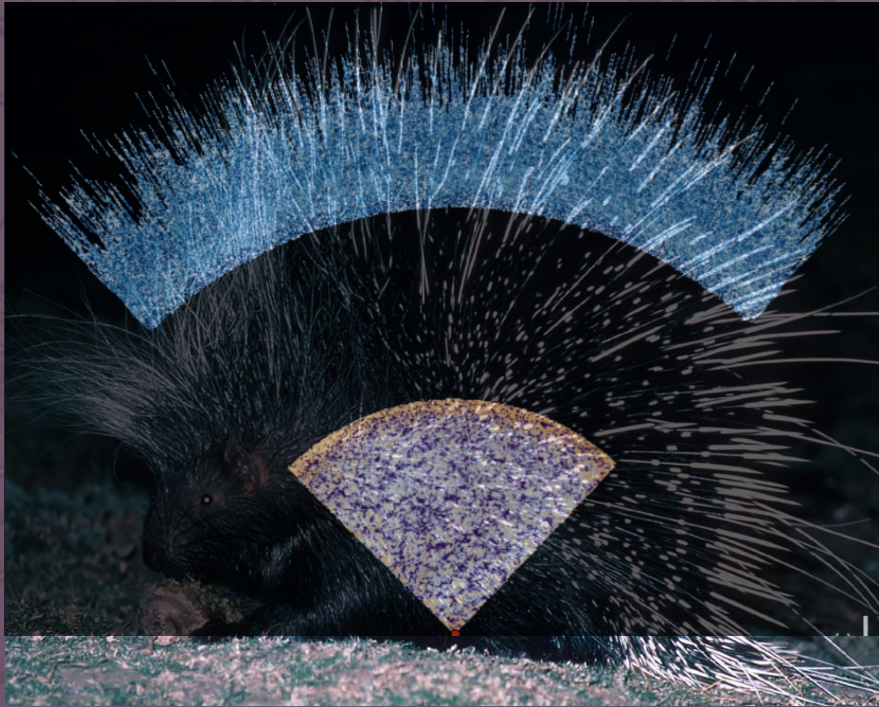
And in QSO-Ly α cross-correlations

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

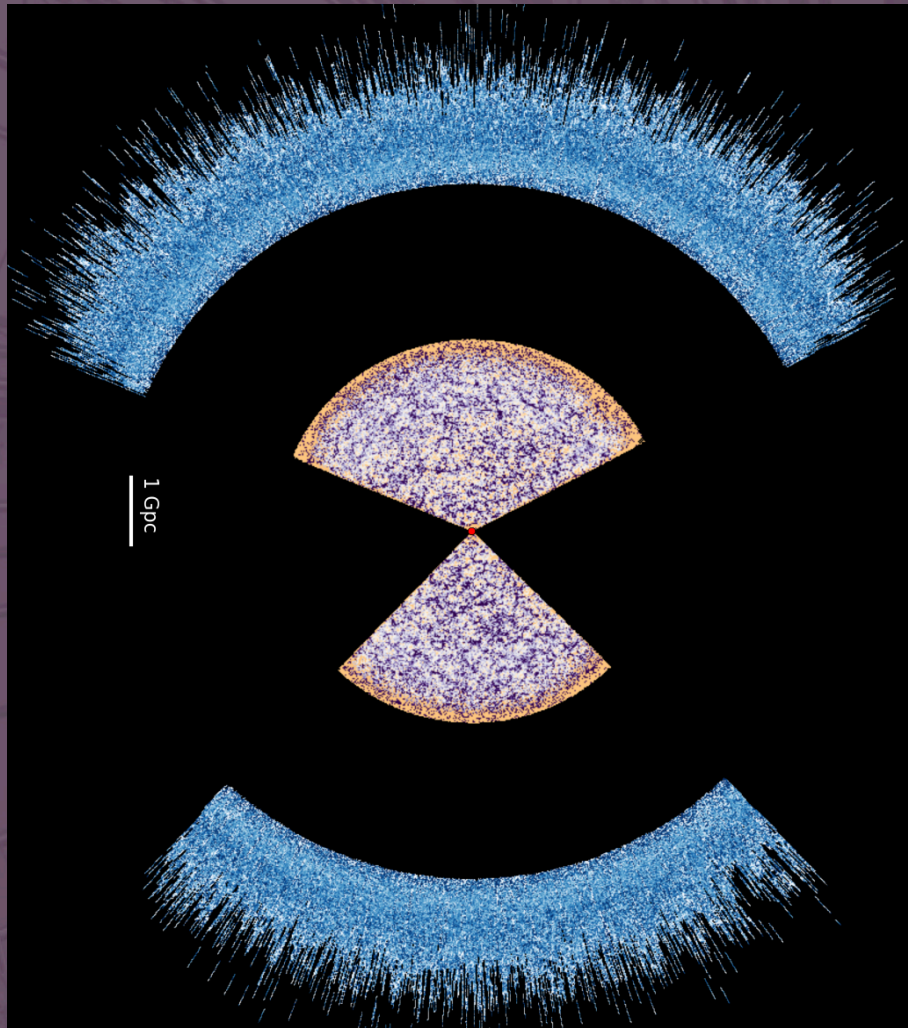


Figure: A. Slosar

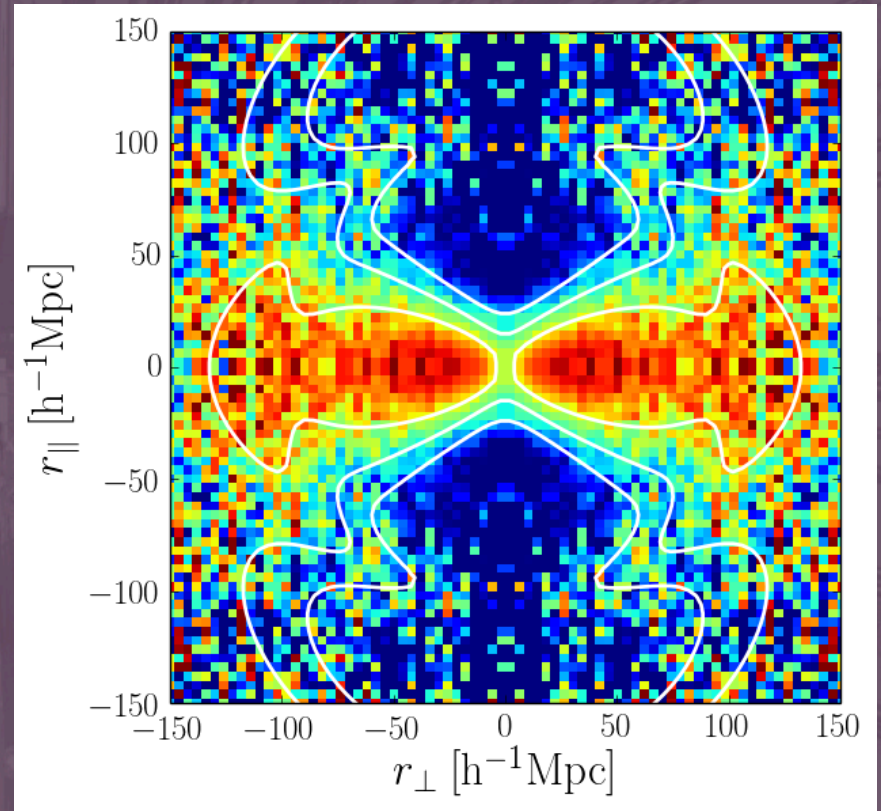
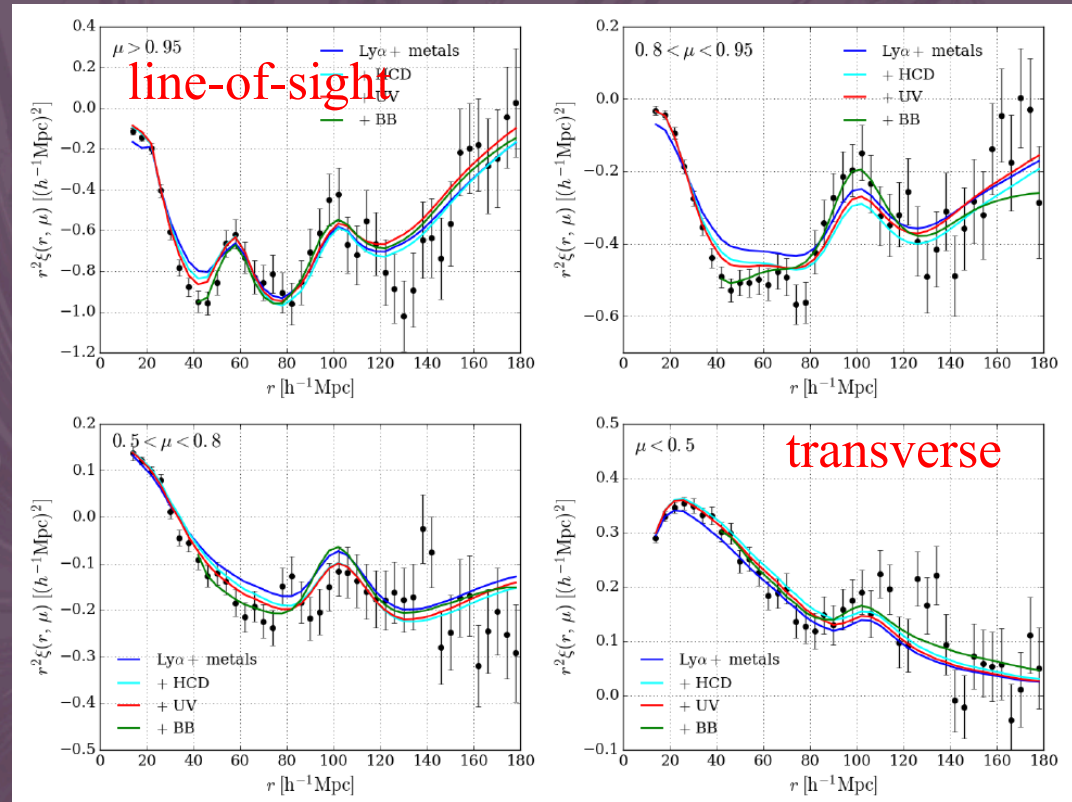


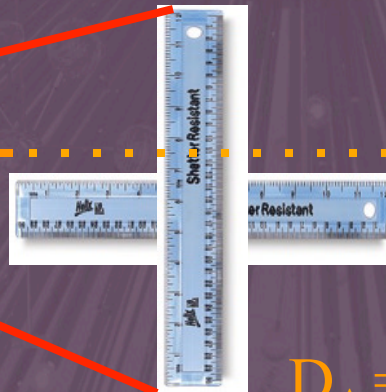
Figure: N. Busca

BAO in BOSS DR12 Ly α 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
- Ly α cross-correlation sharpens
precision to

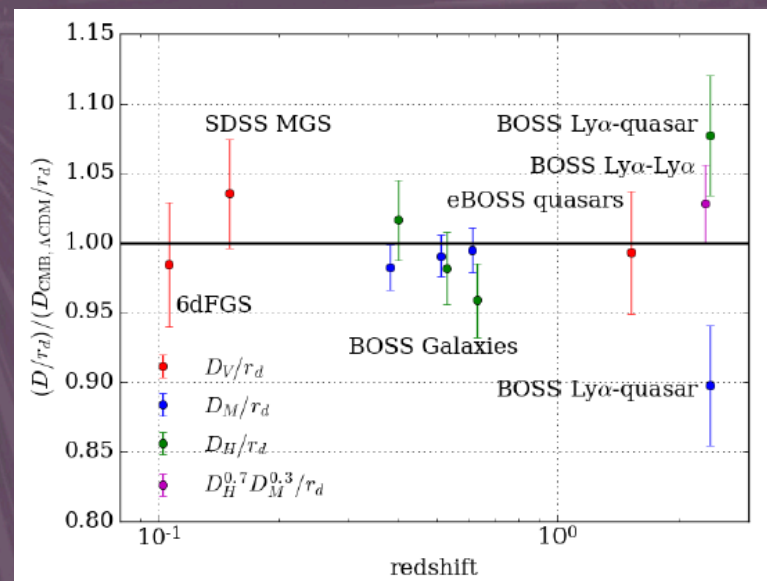
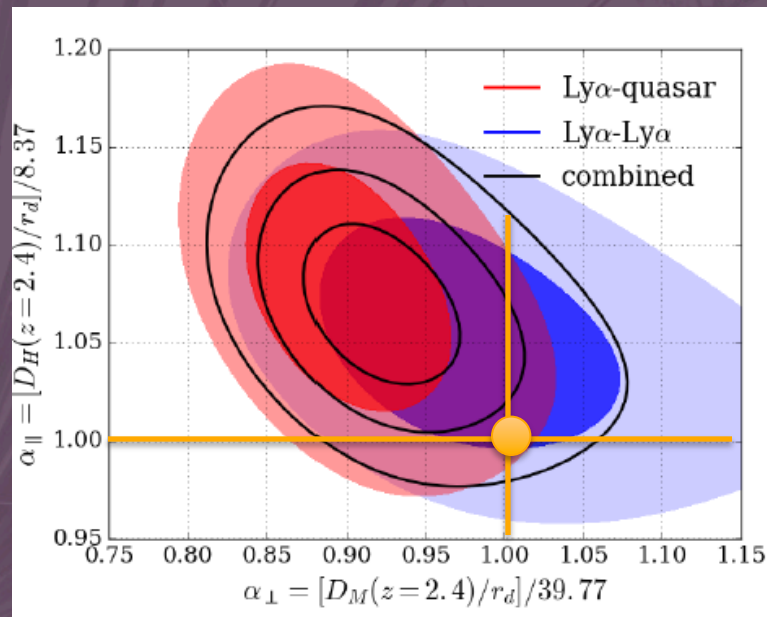
2.5% on $H(z)$

3.3% on $D_A(z)$

Combined constraint is $\sim 2.3\sigma$
from best Planck Λ CDM model.

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

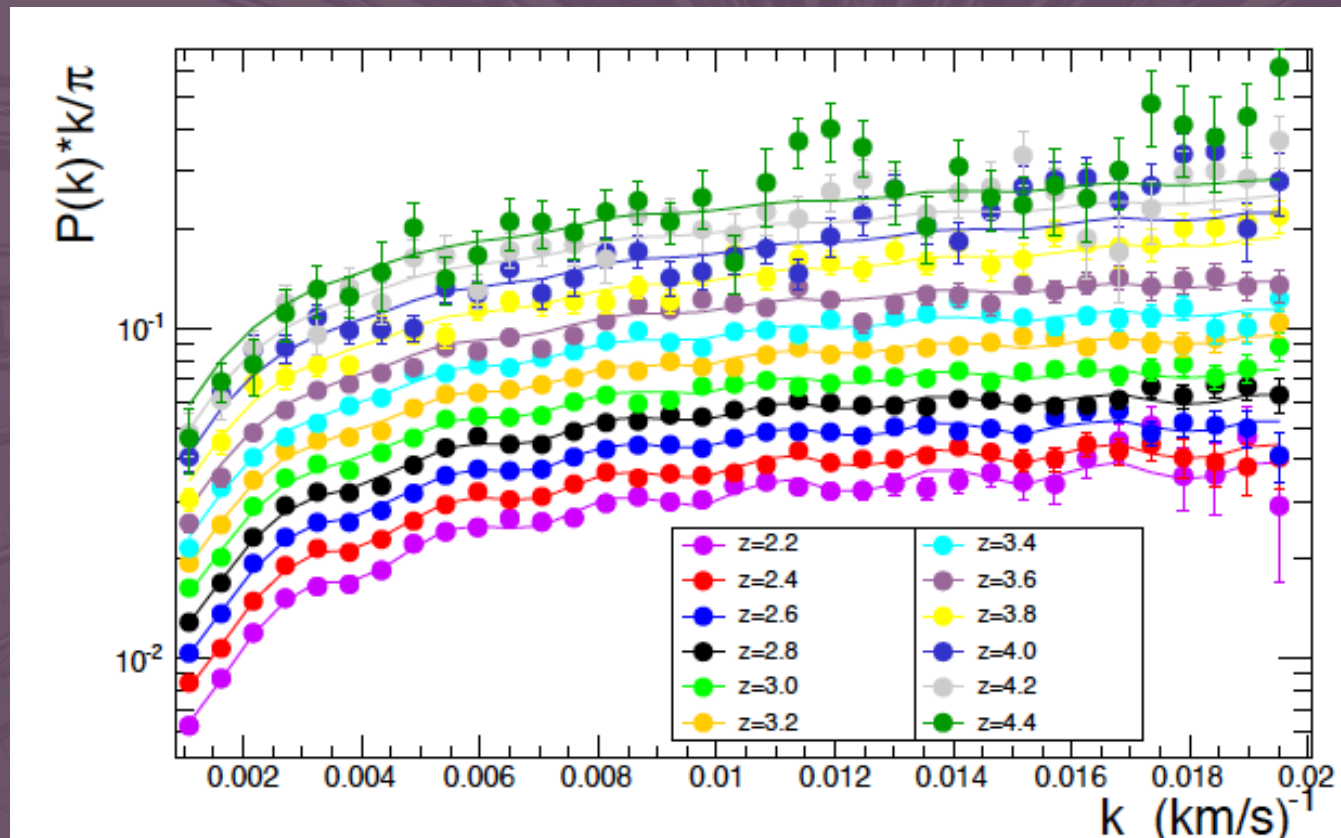
Ensemble of BAO data consistent
with Planck Λ CDM.



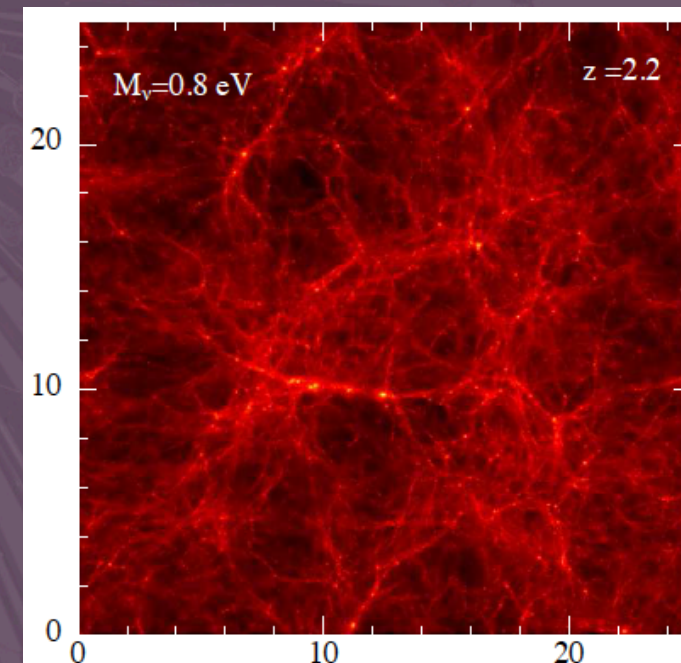
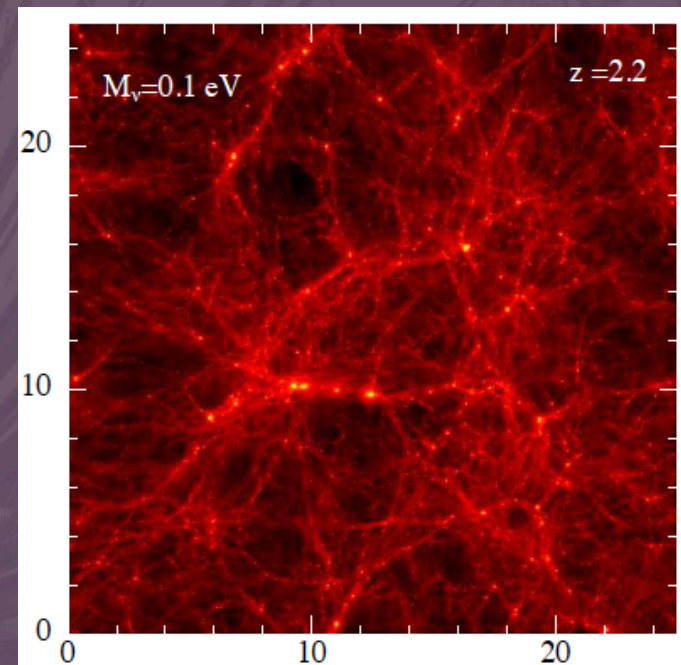
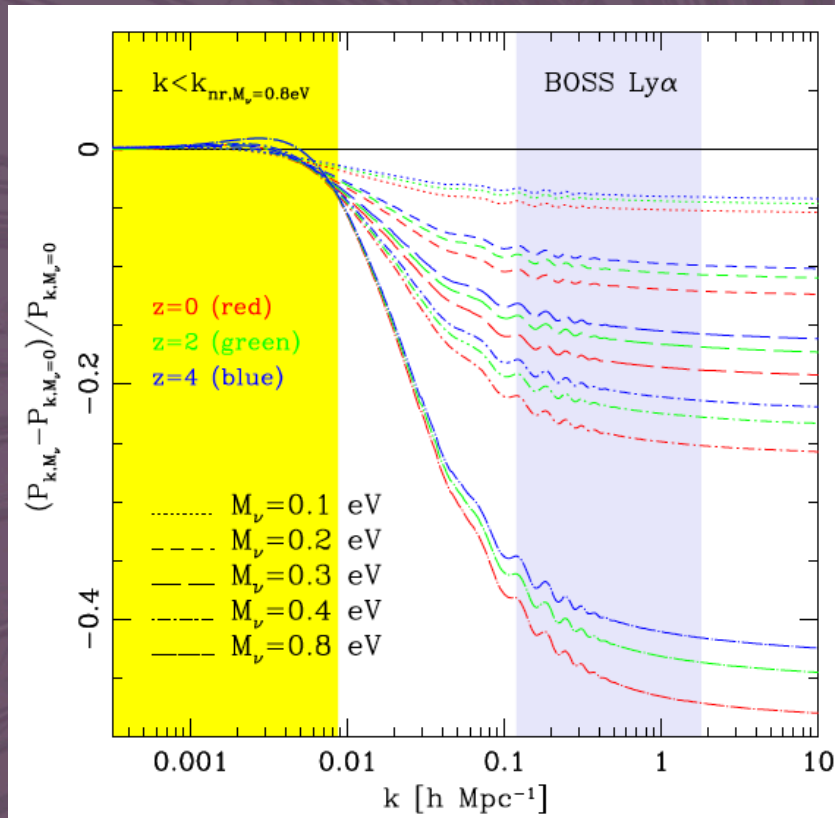
du Mas des Bourboux, Le Goff,
Blomqvist et al. 2017

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

Palanque-Deslauriers, Yèche, Borde et al. 2013

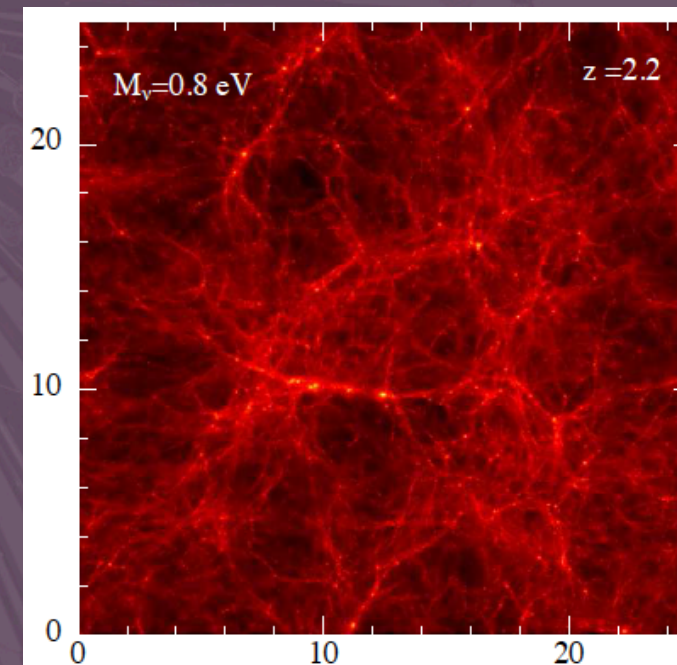
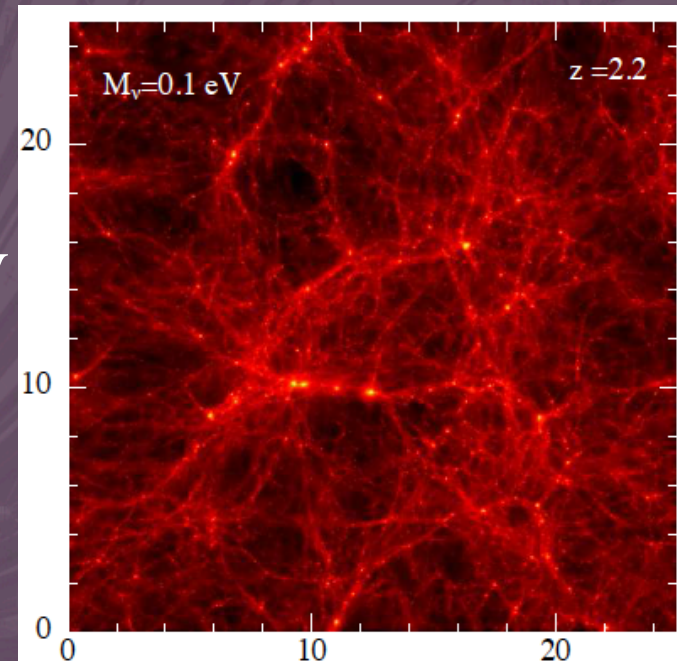
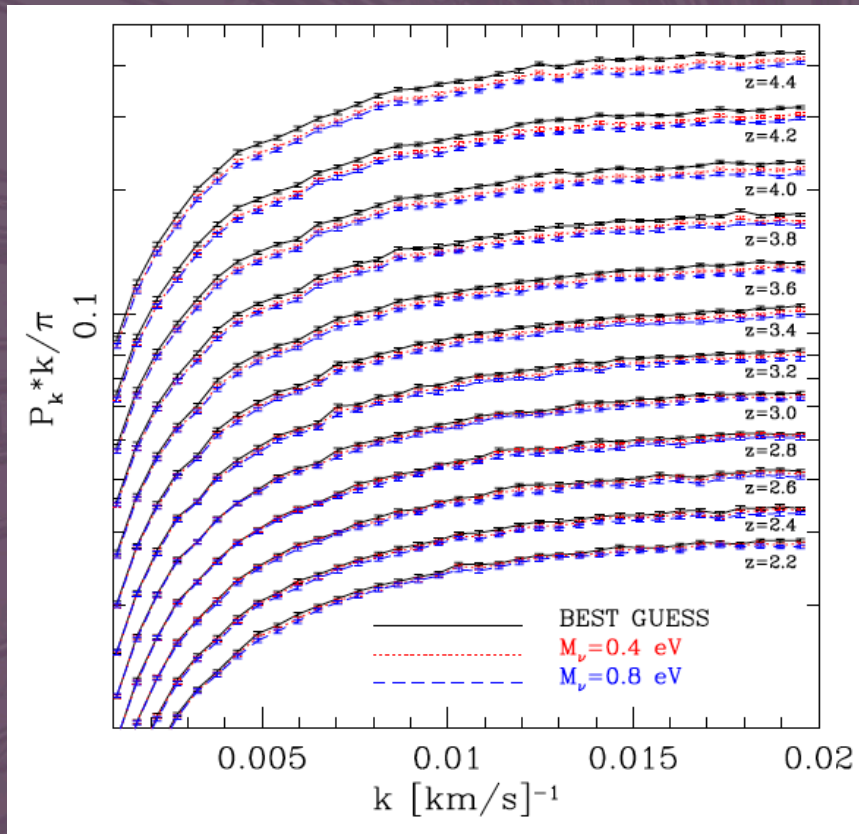


Non-zero neutrino mass suppresses linear $P(k)$ on Ly α forest scales relative to CMB.

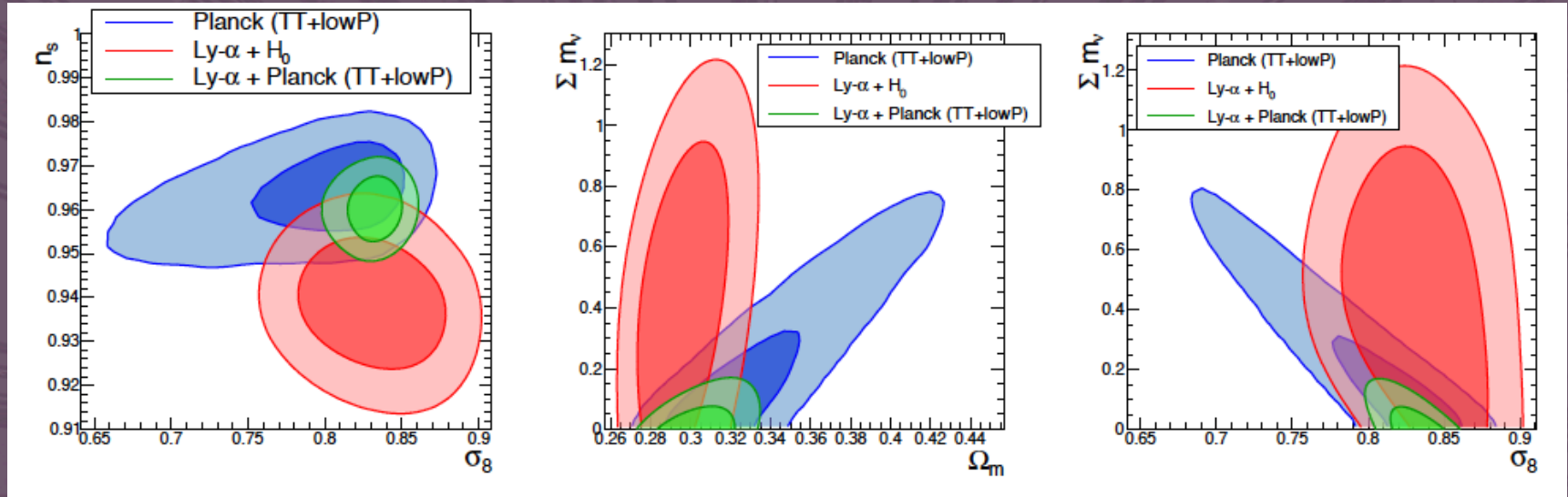


Rossi, Palanque-Delabrouille, Borde et al. 2015

Non-zero neutrino mass suppresses linear $P(k)$ on Ly α 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



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

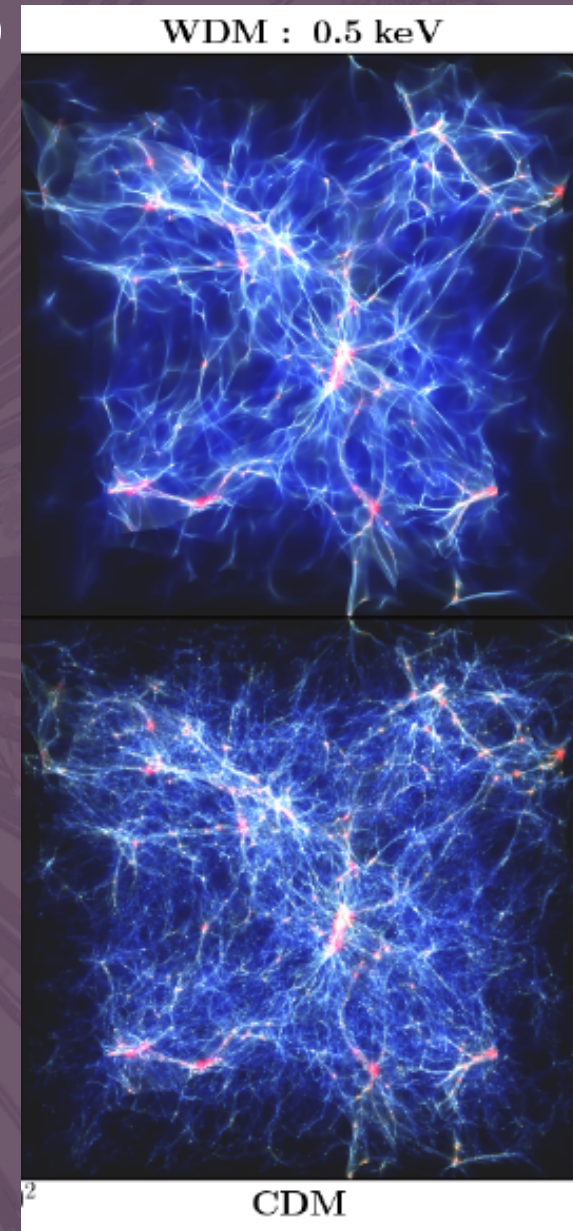
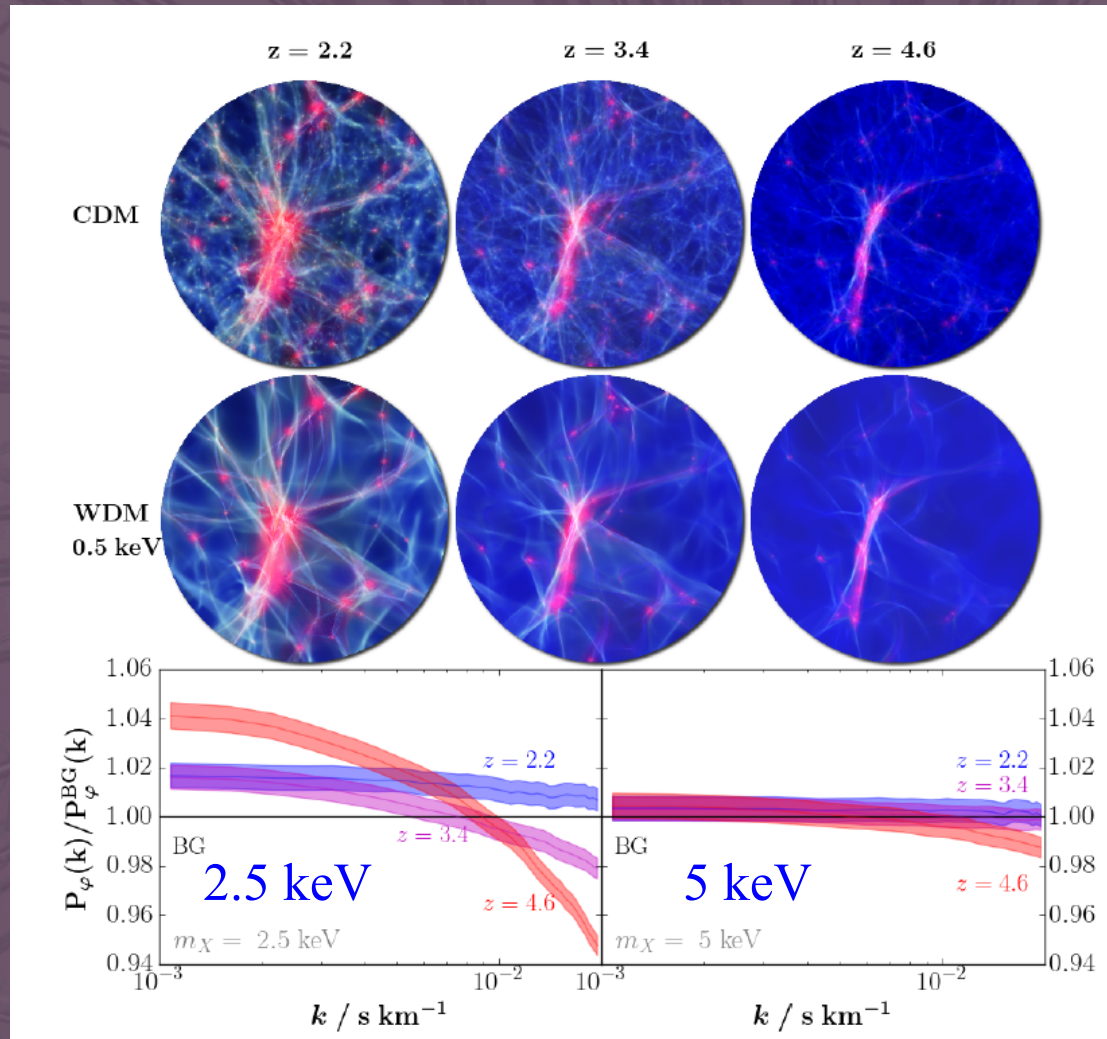
Ly α P(k) measures these independent of CMB.

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

Some tension between CMB and Ly α value of n_s .

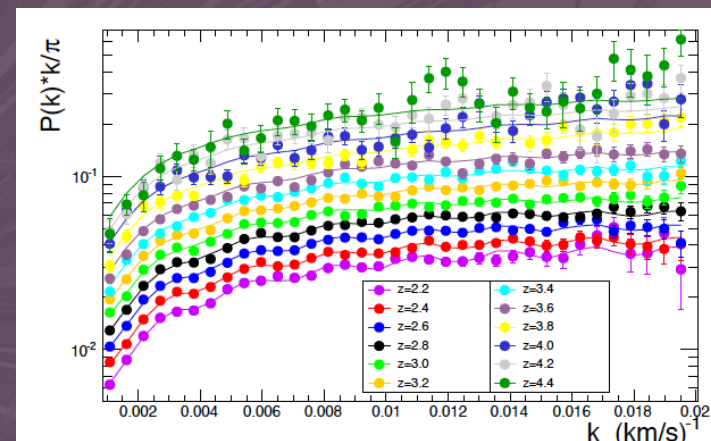
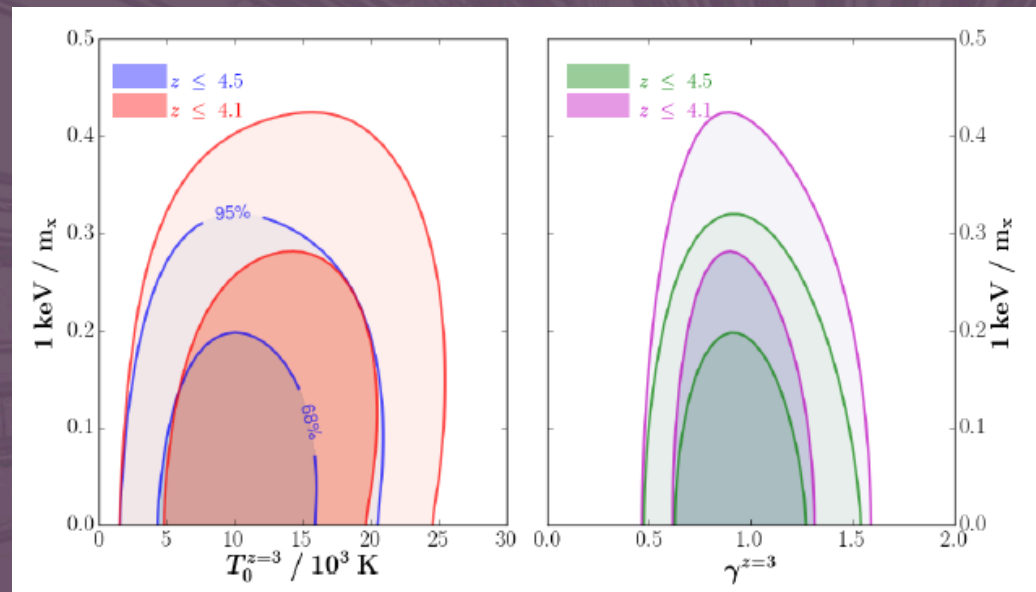
Warm dark matter suppresses small scale $P(k)$

Larger suppression at higher redshift



BOSS DR9 1-d P(k):

Thermal relic 95% C.L. lower limit of 3.0 keV



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

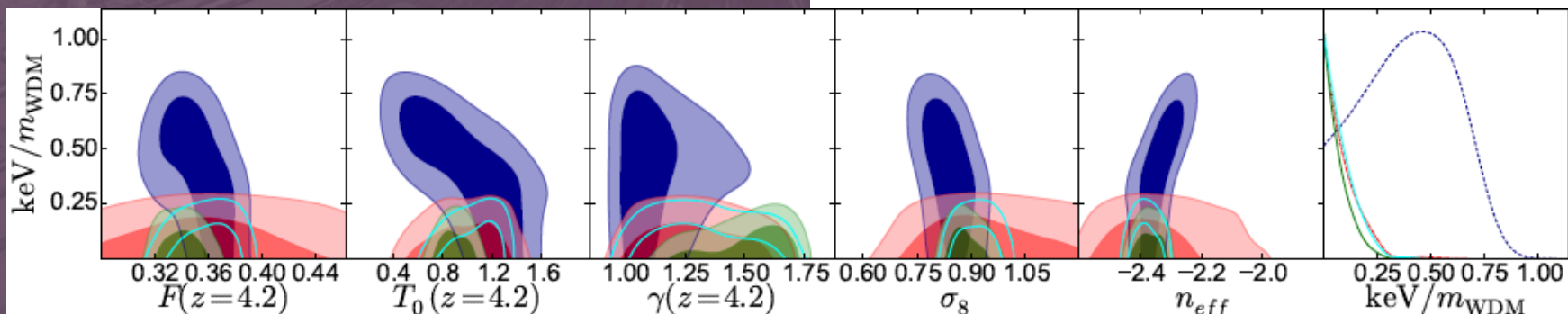
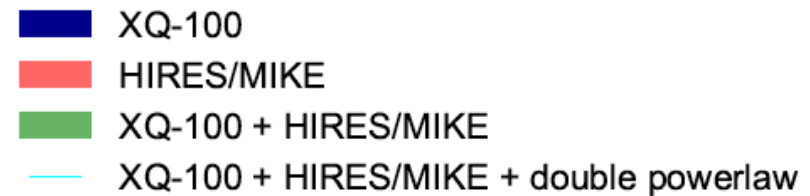
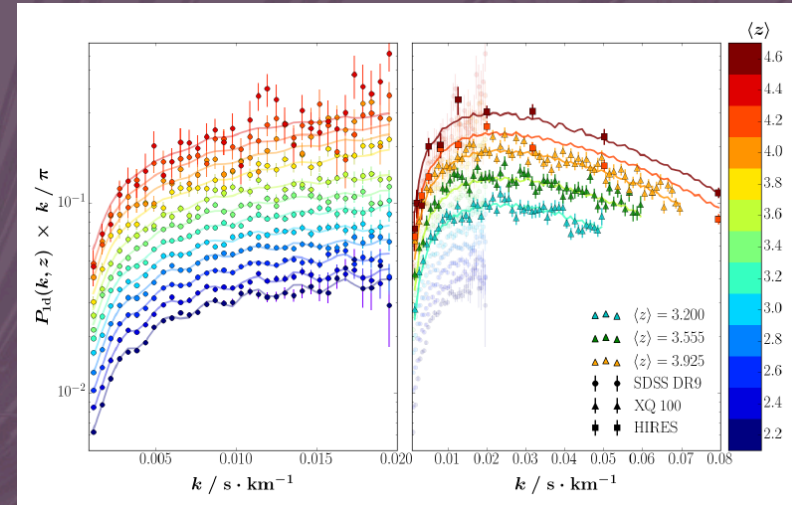
Higher resolution data provide greater leverage on WDM, especially at high z .

Iršič, Viel, Haehnelt++ 2017:

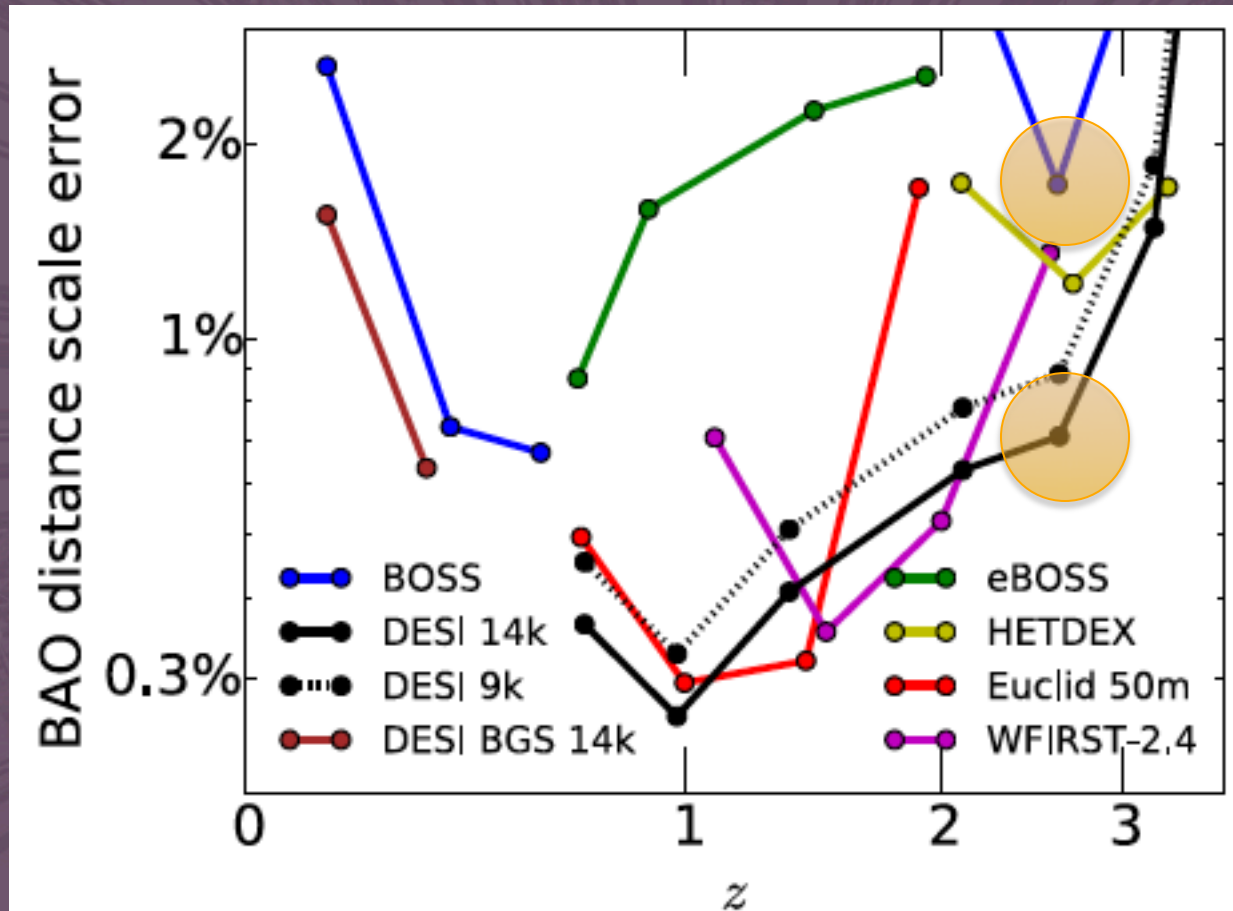
High-res data $\Rightarrow m_{\text{wdm}} > 5.3 \text{ keV}$

Baur, P.-D., Yèche++ 2017:

Compared to BOSS, high-res data show suppression, could be WDM or IGM physics



DESI: 700,000 Ly α 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 Ly α forest

$$\tau_{\text{HI}} = 1.54 \times \underbrace{\left(\frac{T_0}{10^4 \text{ K}} \right)^{-0.7}}_{\text{IGM parameters}} \underbrace{\left(\frac{10^{-12} \text{ s}^{-1}}{\Gamma_{\text{UV}}} \right)}_{\text{IGM parameters}} \underbrace{\left(\frac{1+z}{1+3} \right)^6}_{\text{Cosmological parameters}} \underbrace{\left(\frac{0.7}{h} \right)}_{\text{Cosmological parameters}} \\ \times \underbrace{\left(\frac{\Omega_{b,0} h^2}{0.02156} \right)^2}_{\text{Cosmological parameters}} \underbrace{\left[\frac{4.0927}{H(z)/H_0} \right]}_{\text{Density \& velocity fields}} \underbrace{(1 + \delta)^{2-0.7\alpha}}_{\text{Density \& velocity fields}} \underbrace{\left[1 + \frac{1}{H(z)} \frac{dV_{\text{los}}}{dx} \right]^{-1}}_{\text{Density \& velocity fields}}$$

- Density & velocity fields
- IGM parameters
- Cosmological parameters

Cosmology With The Ly α 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/ Λ CDM, probably statistical fluke

Best probe of primordial power spectrum on \sim Mpc scales

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

Challenges

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