# Lyman-α Forest Cosmology

# Lecture 2: Physics of the Lyman-alpha forest

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# BAO in the LSS

Large-scale structures

Correlation function of matter overdensities: $\xi(\vec{r}) = \langle \delta(\vec{x})\delta(\vec{x}+\vec{r}) \rangle$

How to trace matter overdensities δ ?

**Galaxies**

Trace dense regions $\delta \gg 200$

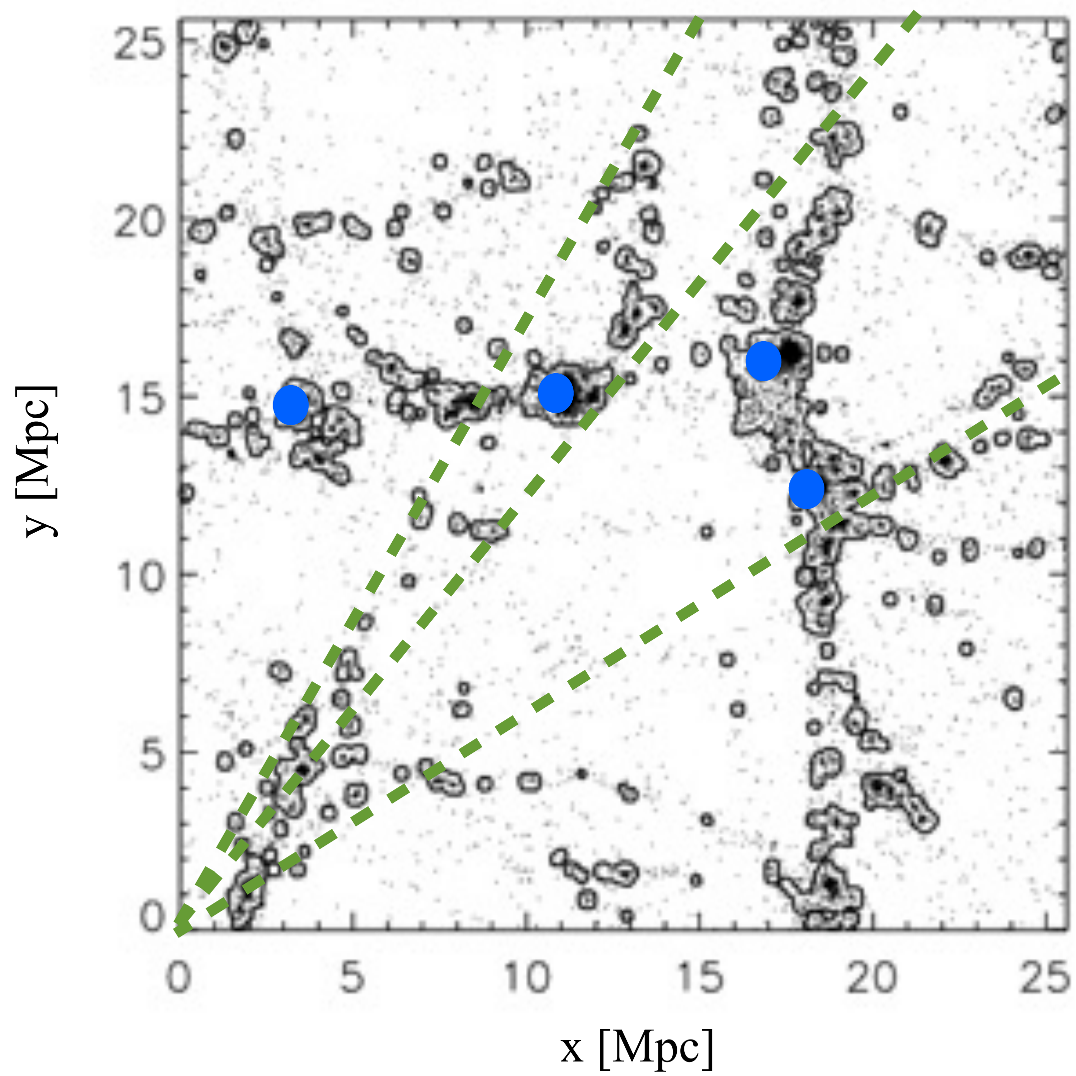
usually at low redshifts ($z < 1$)

**Lyman-α Forest**

Trace small over-densities $\delta \approx 1$

at high redshifts ($z > 2$)

(Petitjean et al. 1995)



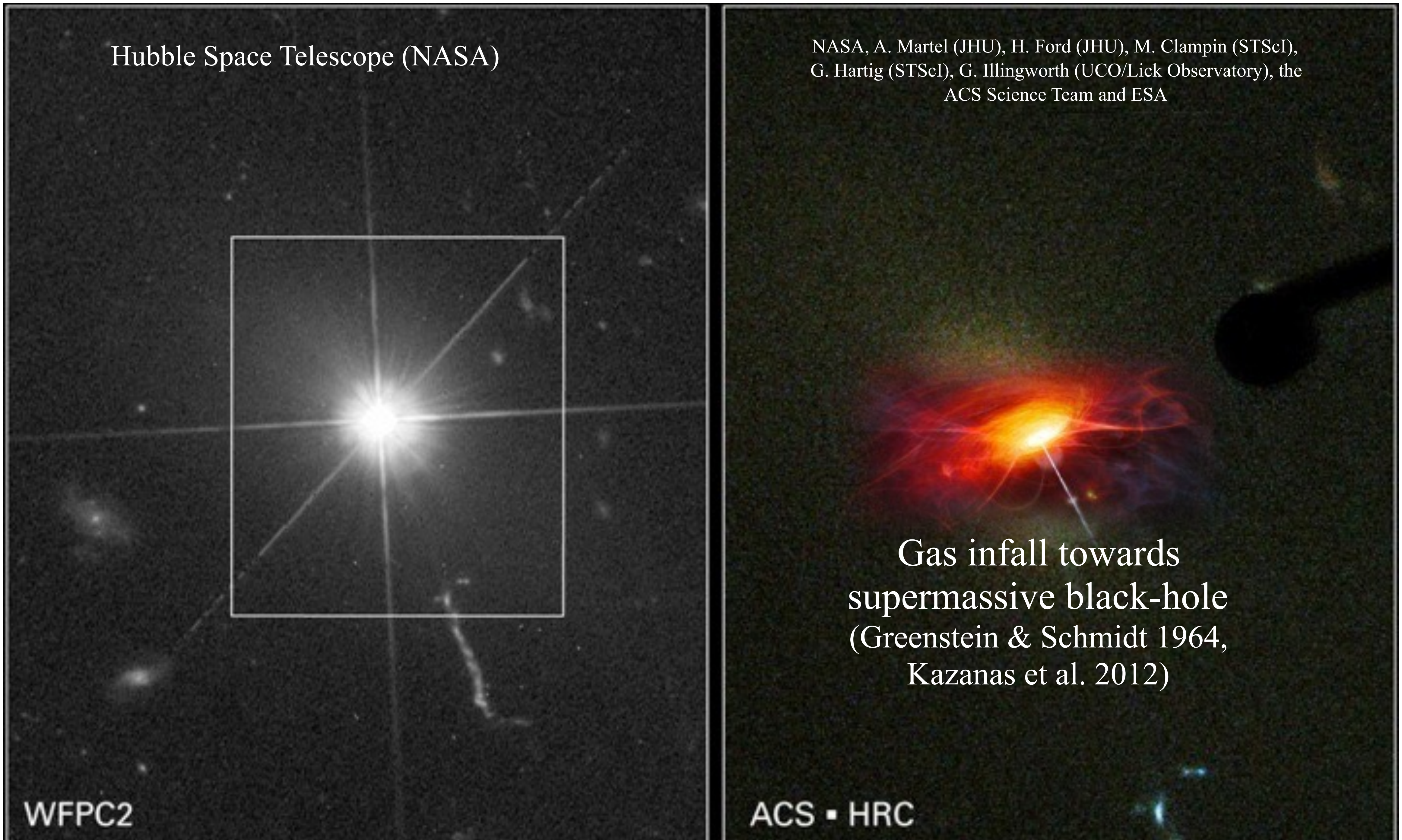
# Contents

- Physics of the Lyman-alpha forest
- Link to large-scale structures
- Three-dimensional clustering, BOSS and BAO

# Physics of the Lyman-alpha forest

# Quasars: the back light sources

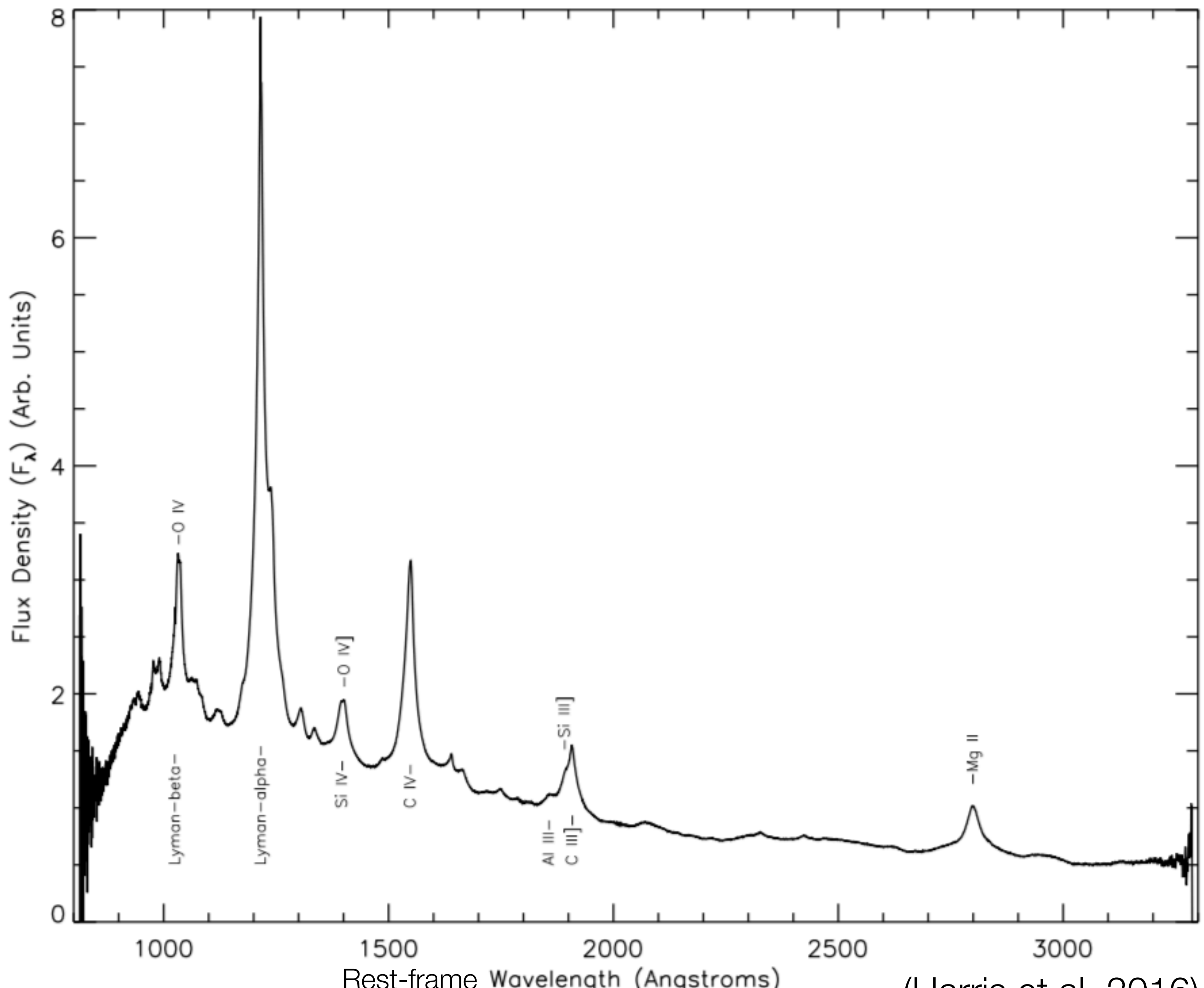
Quasar observed by the Hubble telescope




So bright that can be up to redshifts ~ 7 !

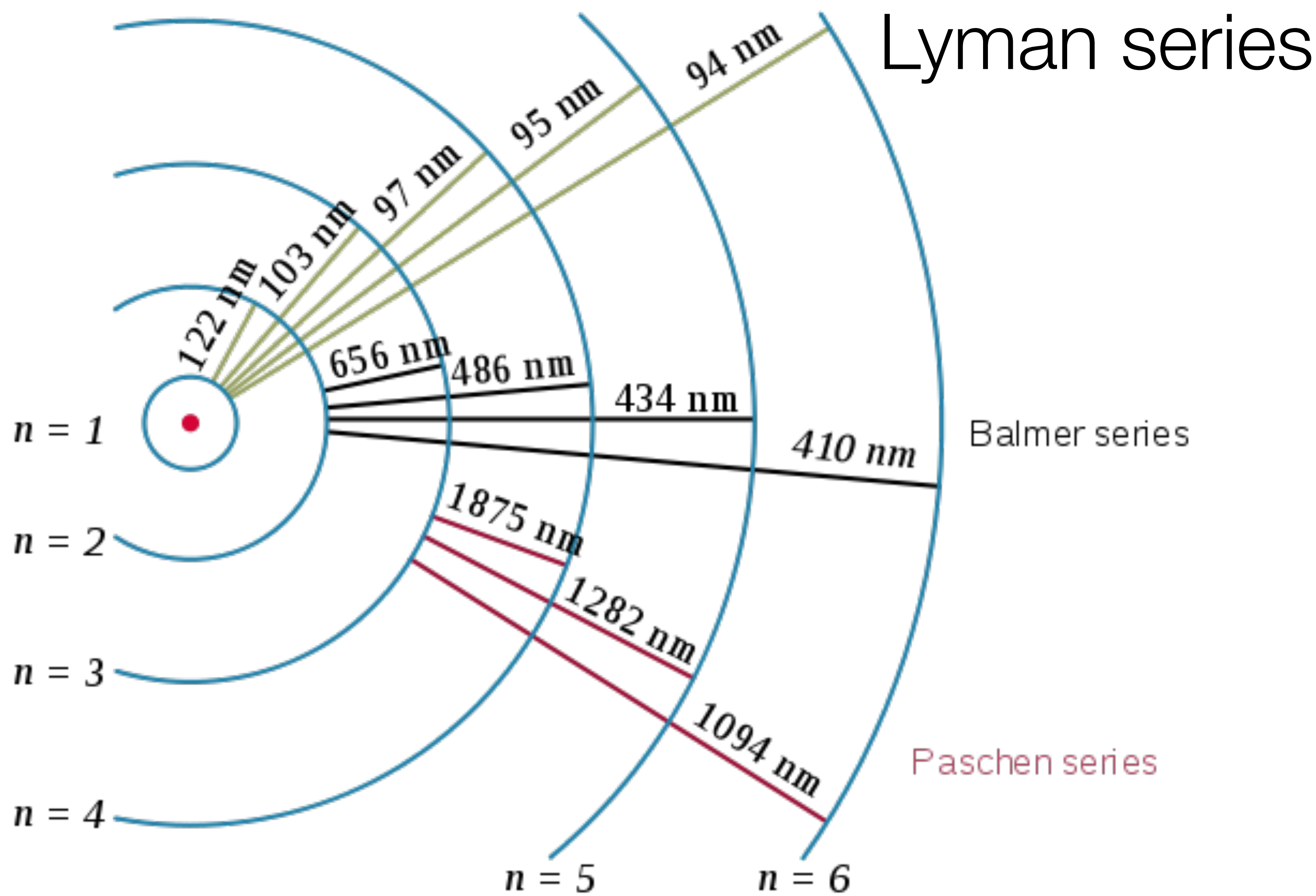
# Quasars: the back light sources

## Quasar ‘unabsorbed’ spectra




(Harris et al. 2016)

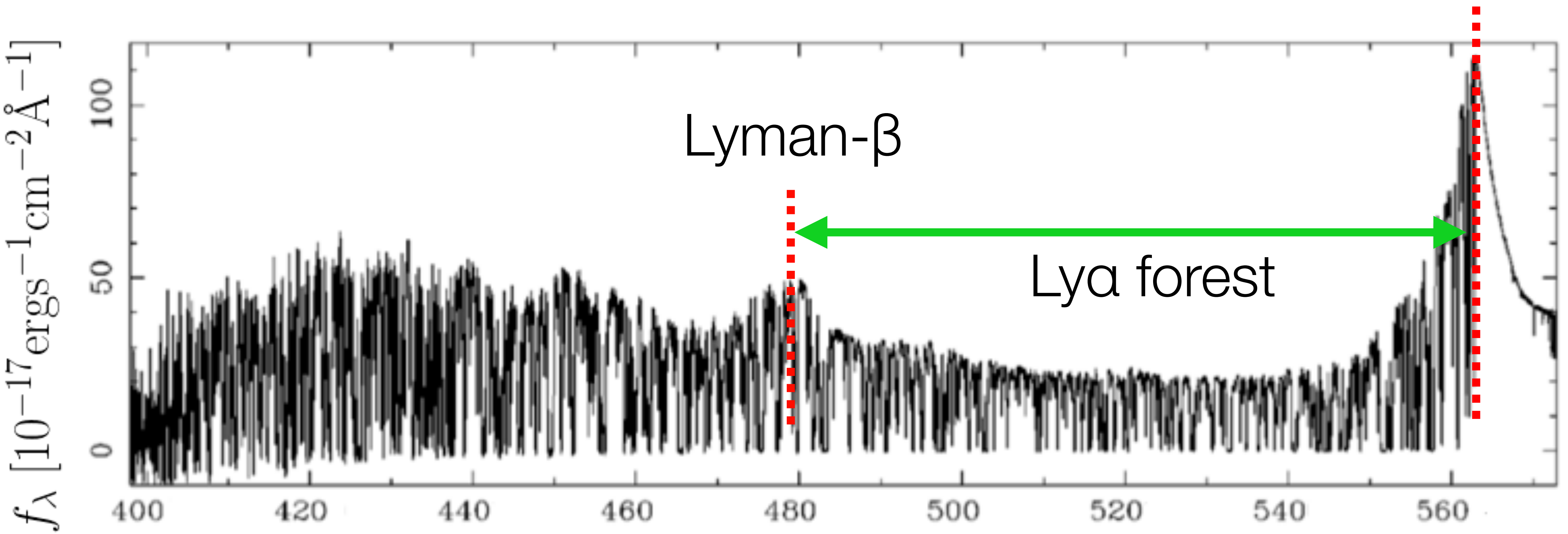
# Hydrogen atom transitions




Lyman limit : 91.2 nm or 13.6 eV

# The Lyman-α Forest

Quasar spectrum




(Womble et al. 1996)

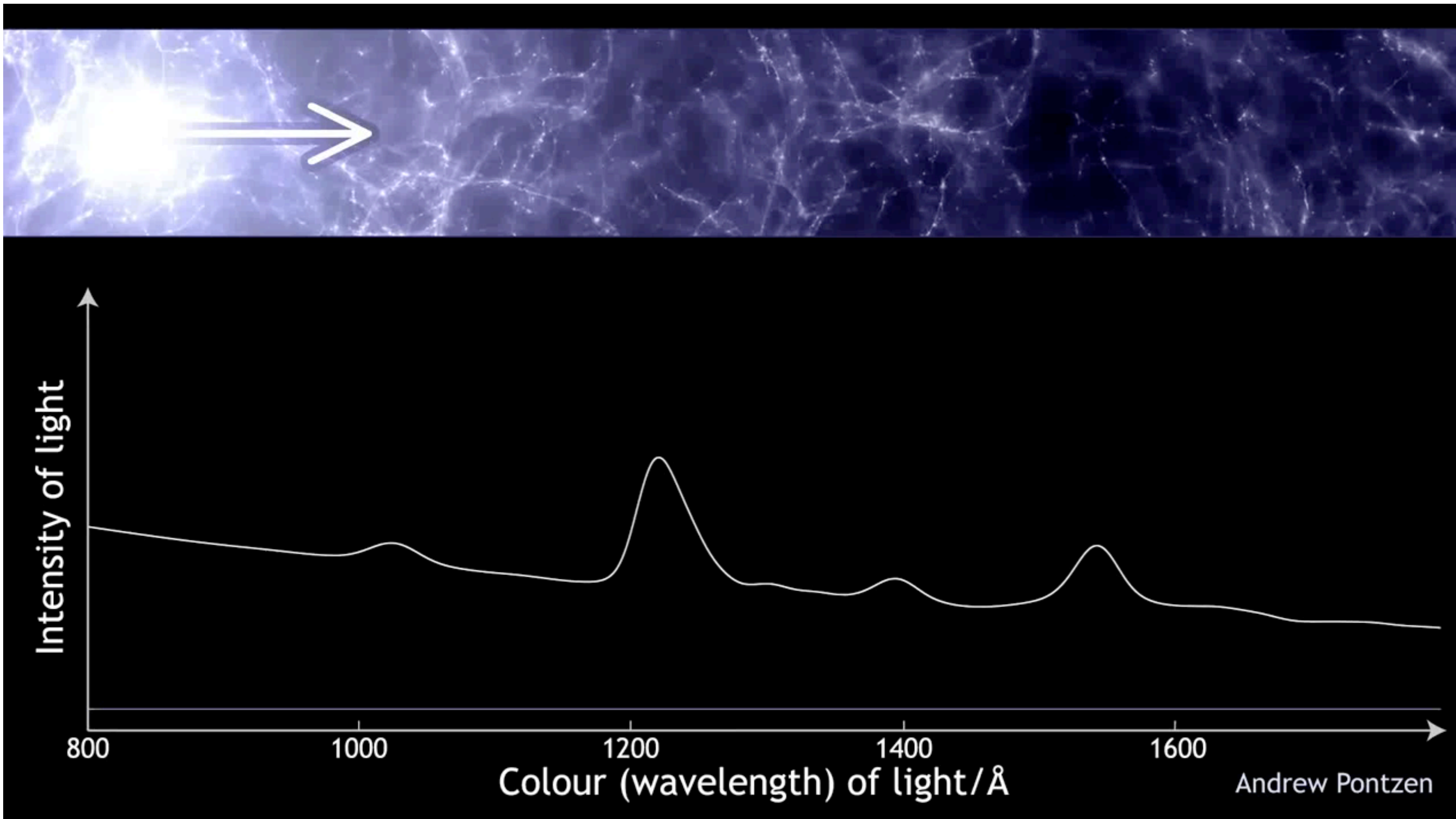
At rest-frame:

$$\lambda_{\mathrm{Ly}\alpha} = 121.6\ \mathrm{nm}$$

$$\lambda_{\mathrm{Ly}\beta} = 102.6\ \mathrm{nm}$$

$$\Rightarrow \quad z_{\mathrm{QSO}} = \frac{561.8\ \mathrm{nm}}{\lambda_{\mathrm{Ly}\alpha}} - 1 = 3.62$$

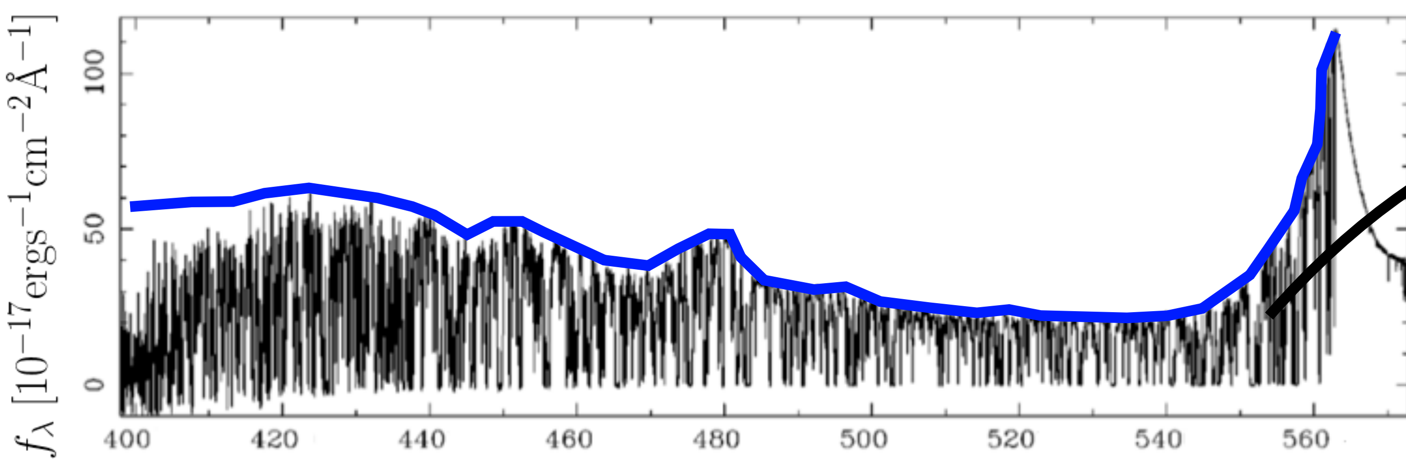
# The Lyman-α Forest: absorption by the IGM



# The Physics of the Lyman-α Forest: Gunn-Peterson

How much neutral hydrogen is need to explain observations?

Some definitions:




Flux

Optical Depth

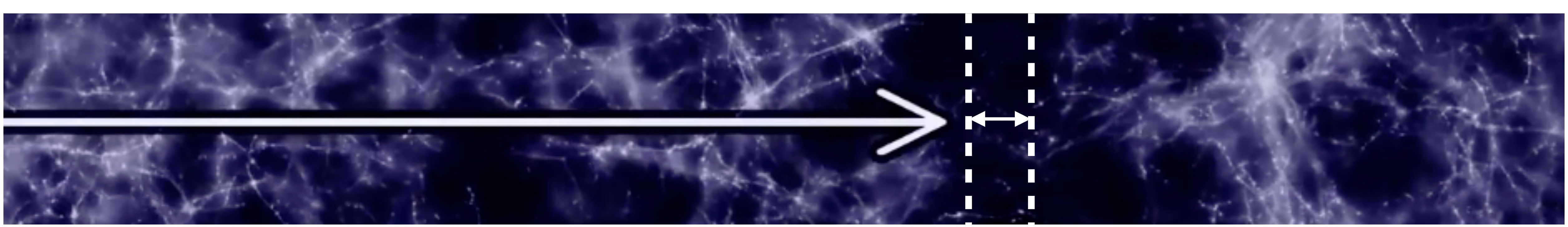
$$F(\lambda) = \frac{f(\lambda)}{C(\lambda)} = e^{-\tau(\lambda)}$$

Transmission

Continuum

$$\tau = \int_0^{z_0} \mathrm{d}\tau(z) = \int_0^{z_0} n_{\mathrm{HI}}(z)\sigma[\nu(1+z)]\frac{\mathrm{d}l}{\mathrm{d}z}\,\mathrm{d}z$$

($m^{-3}$) ($m^{-2}$) (m)



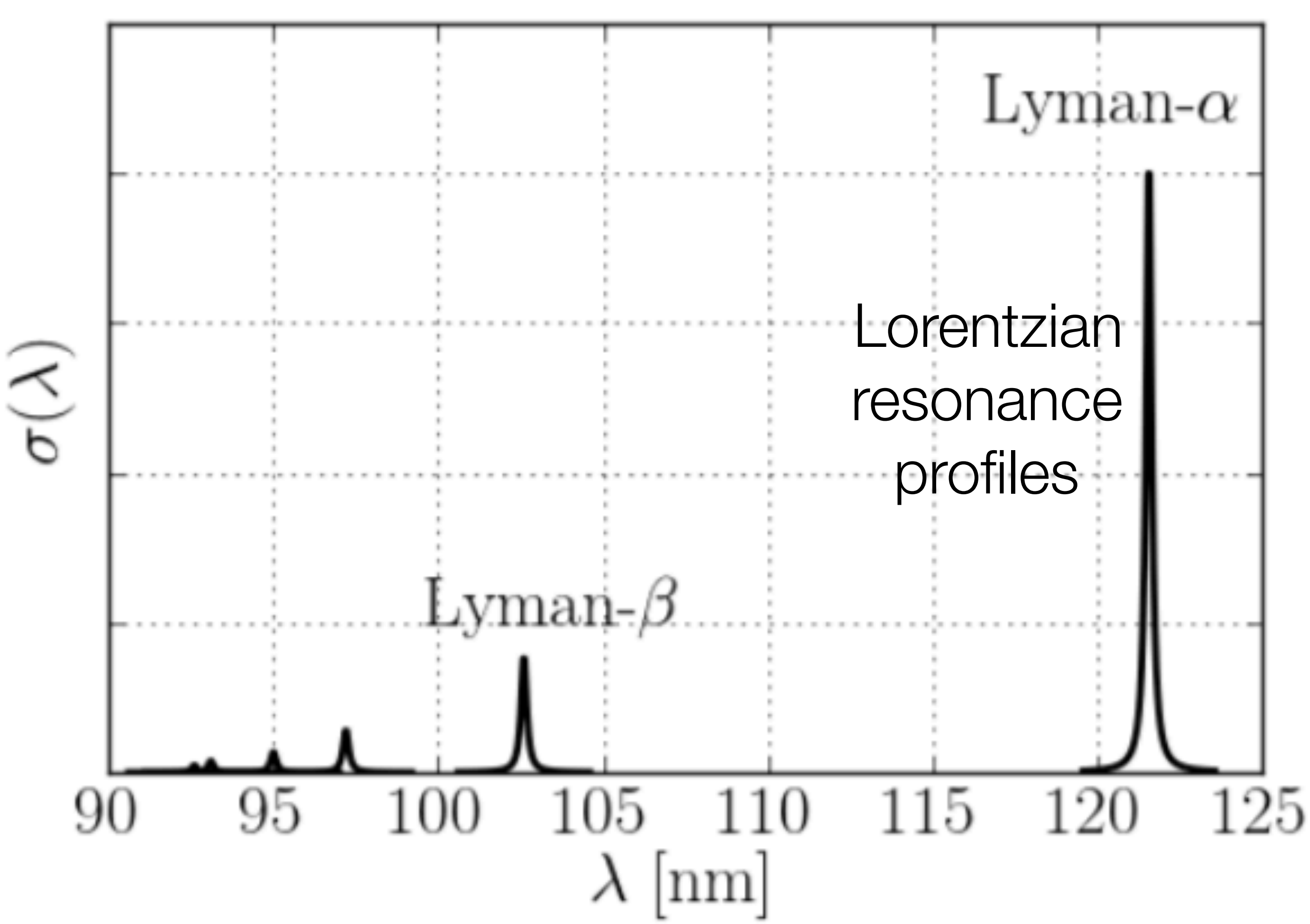
# How much neutral hydrogen is need to explain observations?

$$\tau = \int_0^{z_0} \mathrm{d}\tau(z) = \int_0^{z_0} n_{\mathrm{HI}}(z)\boxed{\sigma[\nu(1+z)]}\frac{\mathrm{d}l}{\mathrm{d}z}\,\mathrm{d}z$$

Cross-section:

$$\sigma(\nu) = \frac{\pi q^2}{m_e c} g(\nu)$$

q: electron charge
$m_e$: electron mass
c: speed of light



## How much neutral hydrogen is need to explain observations?

$$\tau = \int_0^{z_0} \mathrm{d}\tau(z) = \int_0^{z_0} \boxed{n_{\mathrm{HI}}(z)}\sigma[\nu(1+z)]\frac{\mathrm{d}l}{\mathrm{d}z}\,\mathrm{d}z$$

What is the density of neutral hydrogen $n_{\mathrm{HI}}(z)$?

1) density of baryons today (flat Universe): $\rho_{b0} = \Omega_b \rho_c = \Omega_b \dfrac{3H_0^2}{8\pi G}$

2) density of baryons in the past: $\rho_b(z) = \rho_{b0}(1+z)^3$

3) density of **hydrogen**: $\rho_{\mathrm{H}}(z) = \rho_b(1 - Y_{\mathrm{He}}) \sim 0.76\rho_b$

4) density of **neutral hydrogen**: $\rho_{\mathrm{HI}}(z) = X\rho_{\mathrm{H}}(z)$

5) number density of **neutral hydrogen atoms**:

$$n_{\mathrm{HI}}(z) = X\frac{3H_0^2}{8\pi G}\frac{\Omega_b}{m_p}(1 - Y_{\mathrm{He}})(1+z)^3$$

# How much neutral hydrogen is need to explain observations?

$$\tau = \int_0^{z_0} \mathrm{d}\tau(z) = \int_0^{z_0} n_{\mathrm{HI}}(z)\sigma[\nu(1+z)]\frac{\mathrm{d}l}{\mathrm{d}z}\mathrm{d}z$$

The last part: $$\mathrm{d}l = -c\mathrm{d}t = -c\frac{\mathrm{d}a}{\dot{a}} = \frac{c\ \mathrm{d}z}{(1+z)H(z)}$$

Assembling all terms:

$$\tau(\nu) = \int_0^{z_0} n_{\mathrm{HI}}(z)\frac{\pi q^2}{m_e c} f \delta^D[\nu(1+z) - \nu_\alpha]\frac{c}{H(z)(1+z)}\mathrm{d}z$$

where f = 0.416 is the oscillator strength of the Ly-alpha resonance.

Assuming: $$H_0 = 70\mathrm{km\ s^{-1}Mpc^{-1}}, \Omega_m = 0.27, \Omega_b = 0.045, z = 3$$

$$\boxed{\tau(z=3) \sim 10^5 X}$$

where X is the fraction of hydrogen in neutral form!

(Gunn & Peterson 1965)

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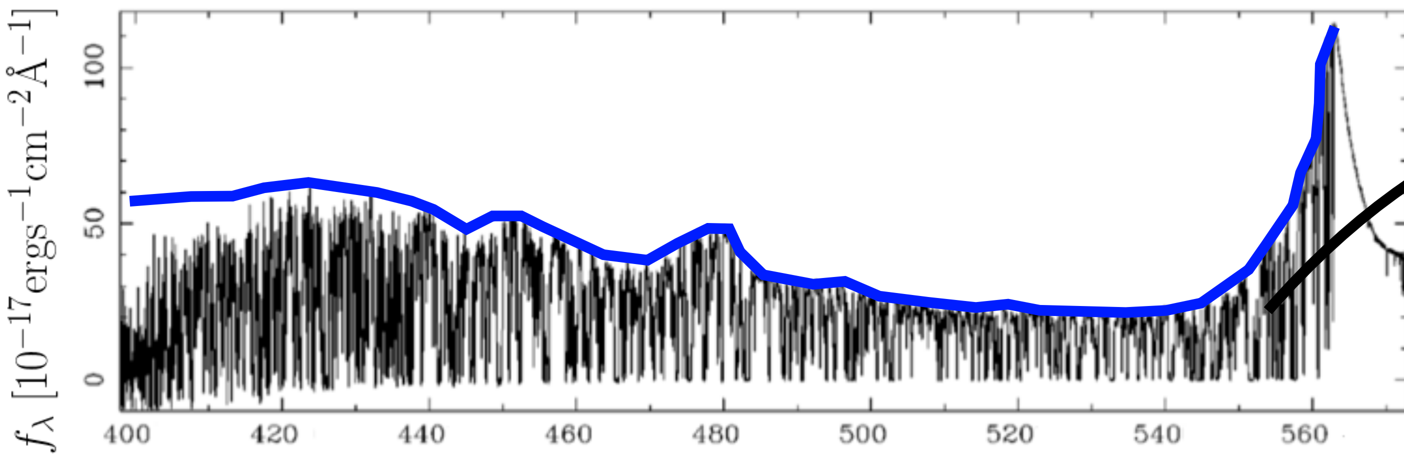
where X is the fraction of hydrogen in neutral form!




Flux

Optical Depth

$$F(\lambda) = \frac{f(\lambda)}{C(\lambda)} = e^{-\tau(\lambda)}$$

Transmission

Continuum

Observations show: $F(z=3) \sim 0.5X$

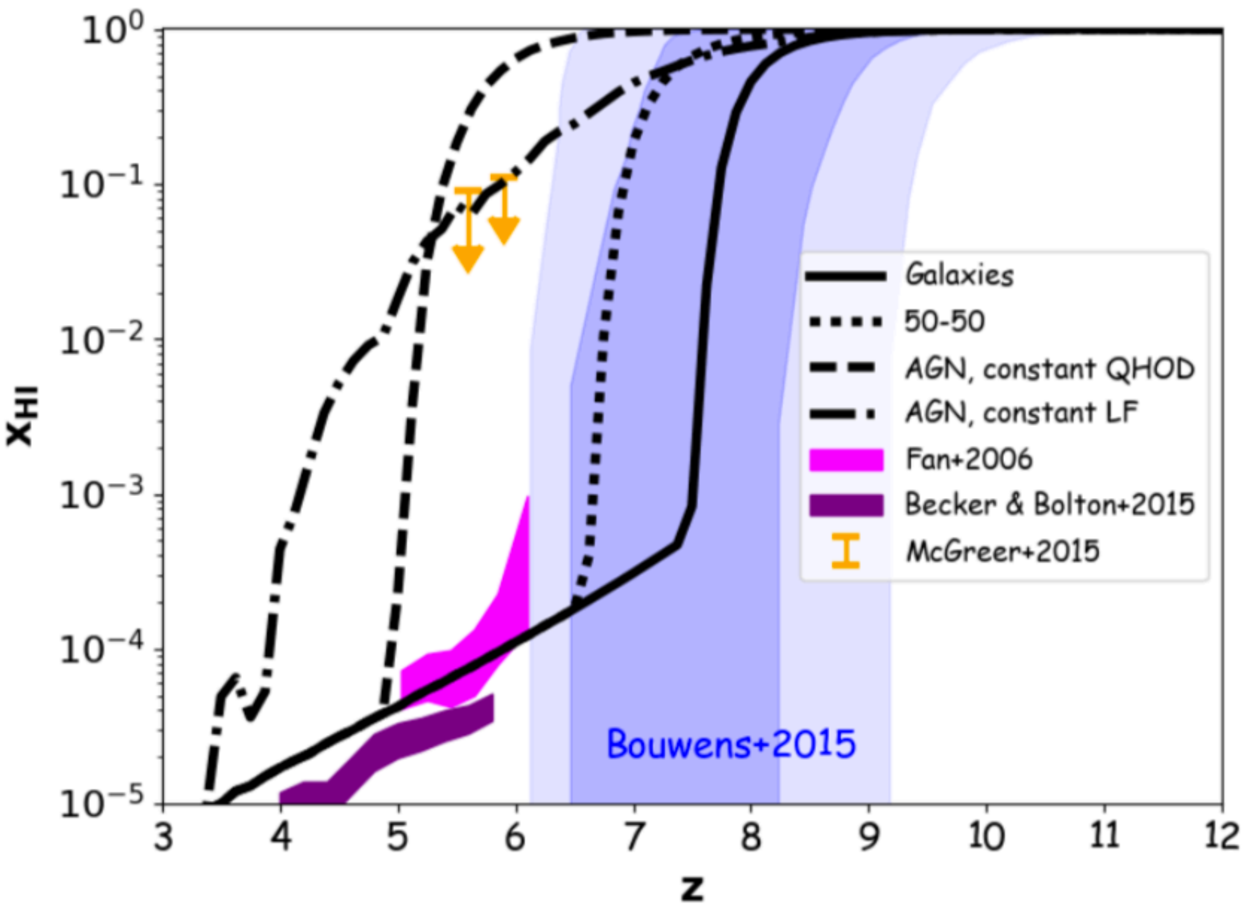
which leads to the conclusion: $X(z=3) \sim 10^{-5}$

**The Universe is mostly ionized at z ~ 3!**

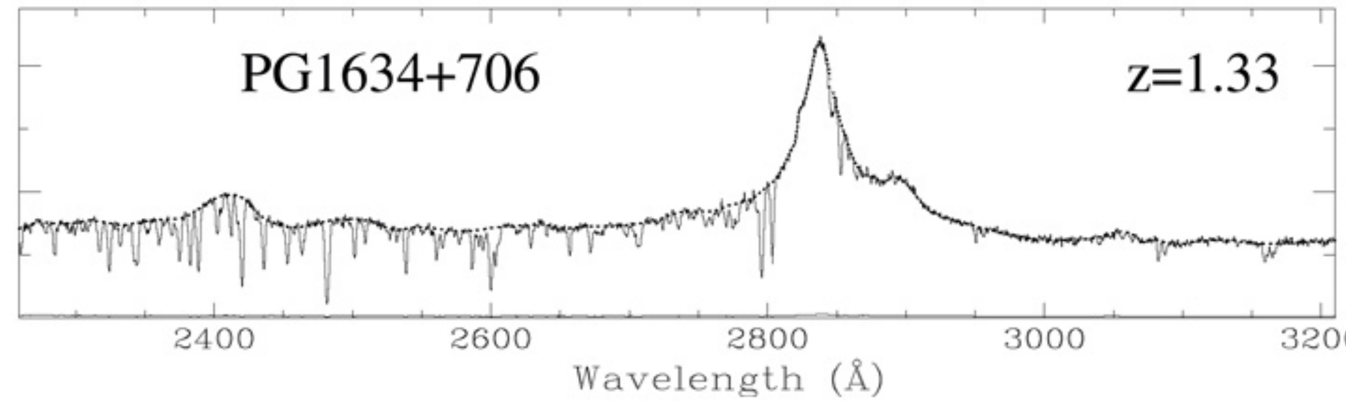
(Gunn & Peterson 1965)

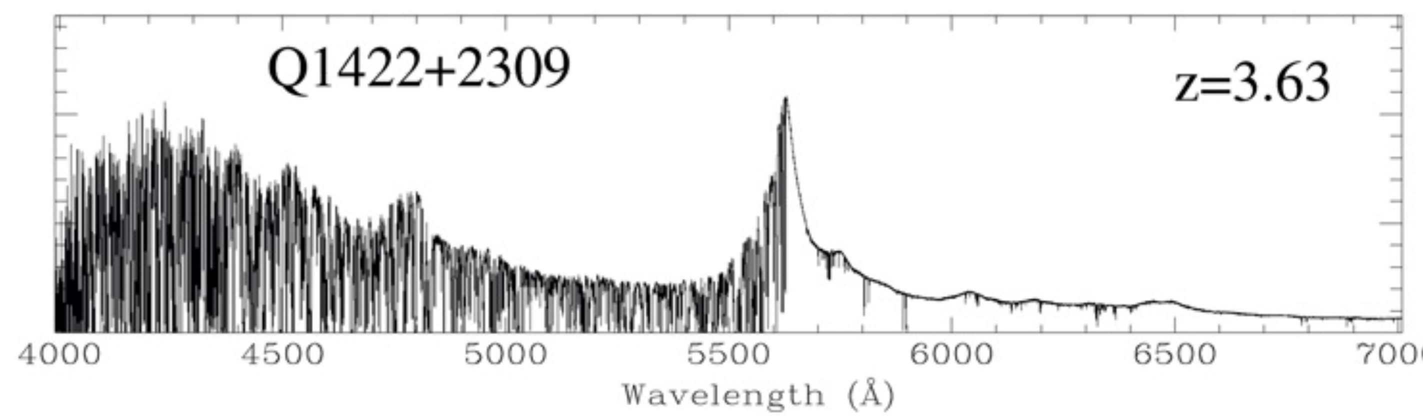
But the amount of neutral hydrogen is enough for Lyman-alpha forest observations!

# History of reionization

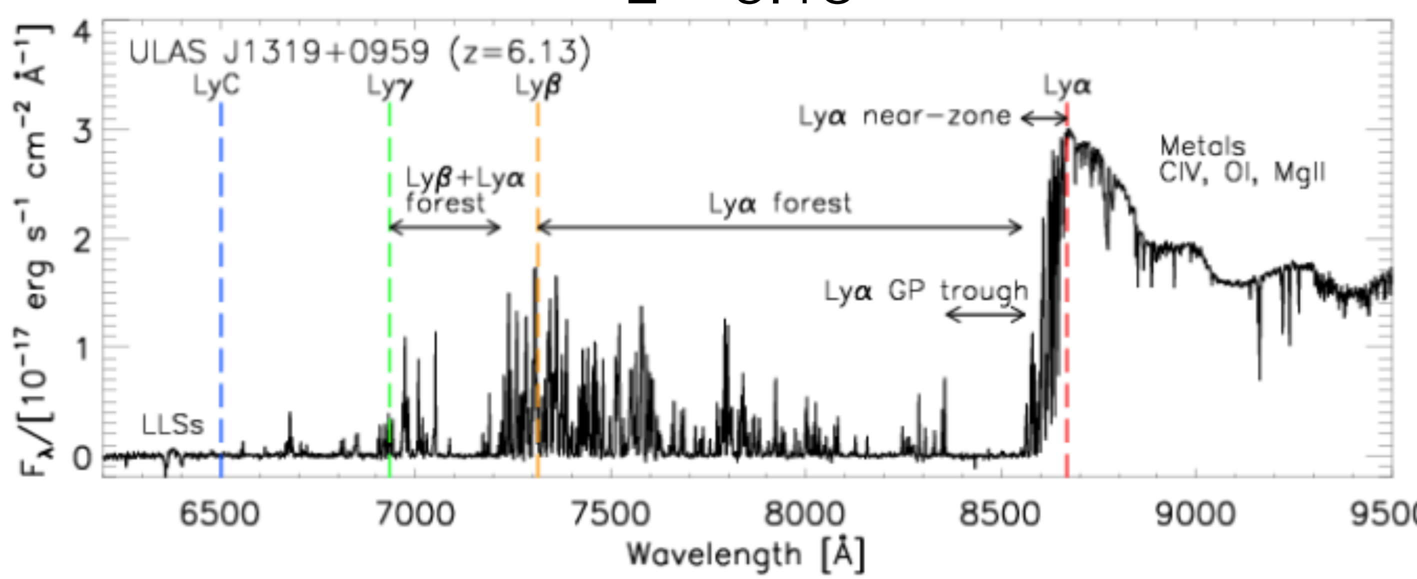



(Hassan et al. 2018)




z = 6.13




Becker et al. 2015

# Link to large-scale structures

# Link to large-scale structures

- Does the forest trace dark-matter fluctuations?
- Does it follow linear perturbation theory?
- What causes departure from linear theory?

Majority of forest is low density

$$\delta = \rho/\bar{\rho} - 1 \lesssim 1$$

Clustering mostly follows linear theory on large scales

Observable:

Optical Depth

Flux

$$\underbrace{F(\lambda)}_{\text{Transmission}} = \frac{f(\lambda)}{\underbrace{C(\lambda)}_{\text{Continuum}}} = e^{-\tau(\lambda)}$$

Fluctuations:

$$\delta_F = \frac{F}{\bar{F}} - 1$$

# Link to large-scale structures

$$F(\lambda) = \frac{f(\lambda)}{C(\lambda)} = e^{-\tau(\lambda)}$$

Density bias

$$b_F = \left.\frac{\partial \delta_F}{\partial \delta}\right|_{\eta}$$

Velocity bias

$$b_\eta = \left.\frac{\partial \delta_F}{\partial \eta}\right|_{\delta}$$

Because of non-linear transformation between F and density, the velocity bias is generally different than one (Seljak 2012)

The forest power-spectrum can be written as:

$$P_F(\vec{k}) = b_F^2(1 + \beta\mu^2)^2 P_{\rm lin}(k) D(\vec{k})$$

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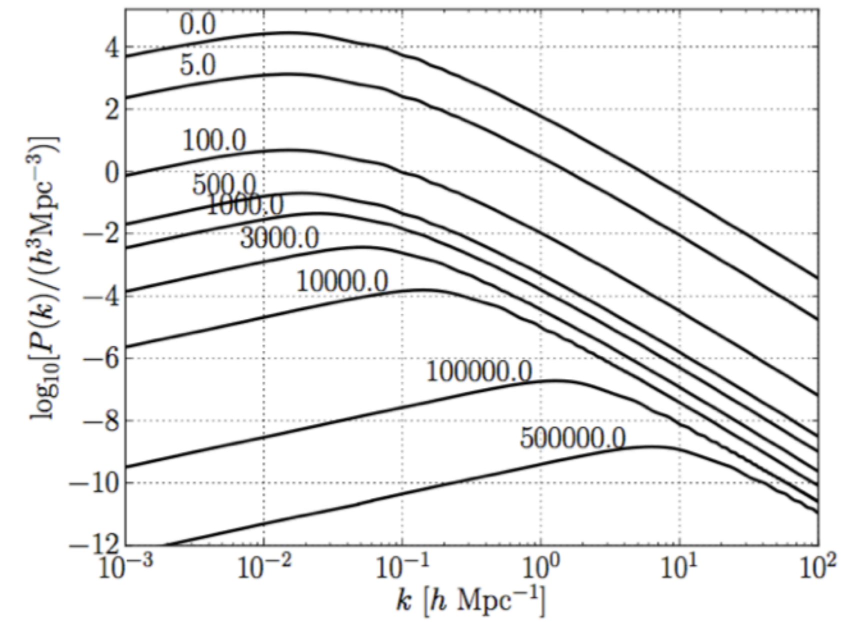
$$P_F(\vec{k}) = b_F^2 (1+\beta\mu^2)^2 P_{\rm lin}(k) D(\vec{k})$$

Kaiser redshift-space distortions

Linear matter-power spectrum




Non-linear contribution

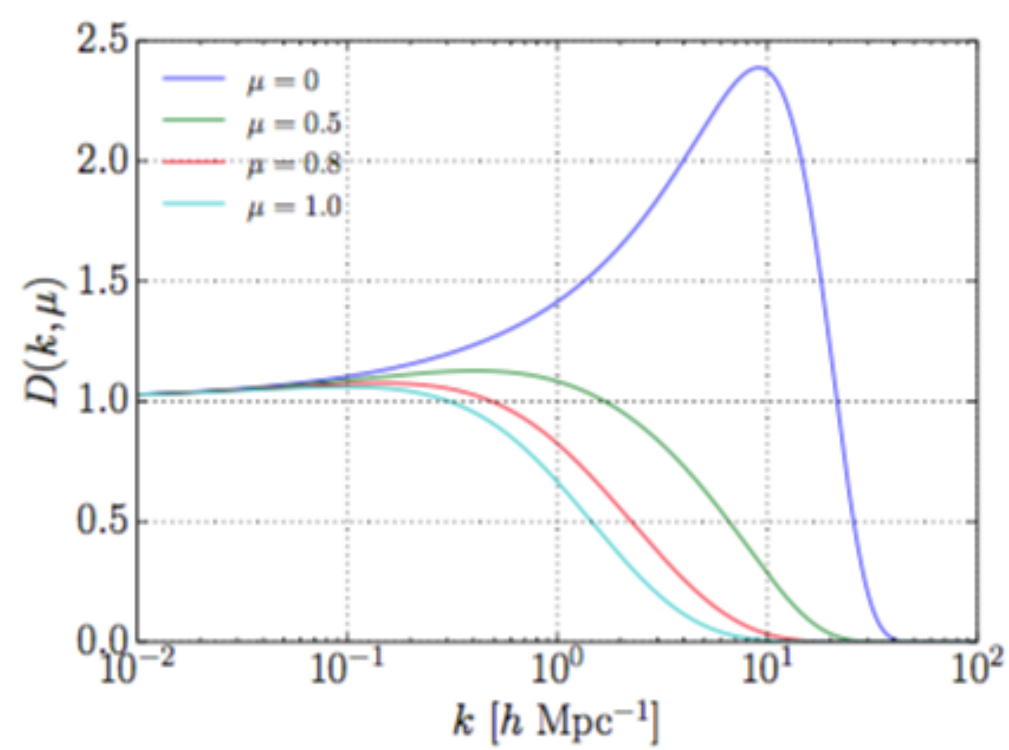
$$D(\vec{k}) = \exp\left\{\left[\frac{k}{k_{\rm NL}}\right]^{\alpha_{\rm NL}} - \left[\frac{k}{k_P}\right]^{\alpha_P} - \left[\frac{k_\parallel}{k_V(k)}\right]^{\alpha_V}\right\}$$

from hydro-sims

(McDonald 2003, Arinyo-i-Prats et al. 2015)

$$b_F = -0.131 \pm 0.017$$

$$\beta = b_\eta / b_F = 1.580 \pm 0.022$$



# Three-dimensional clustering measurements using BOSS forests

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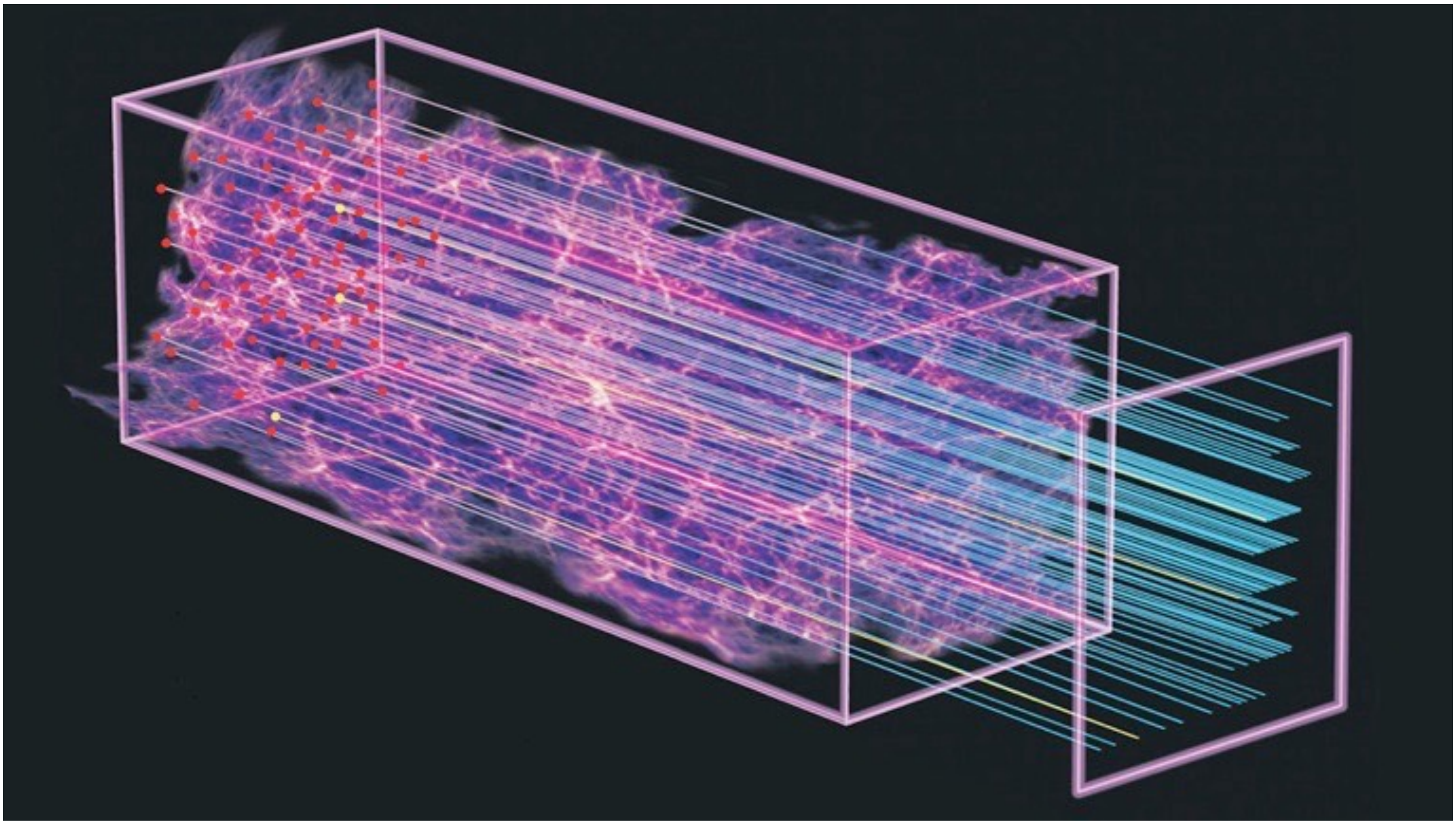
## Survey of forests

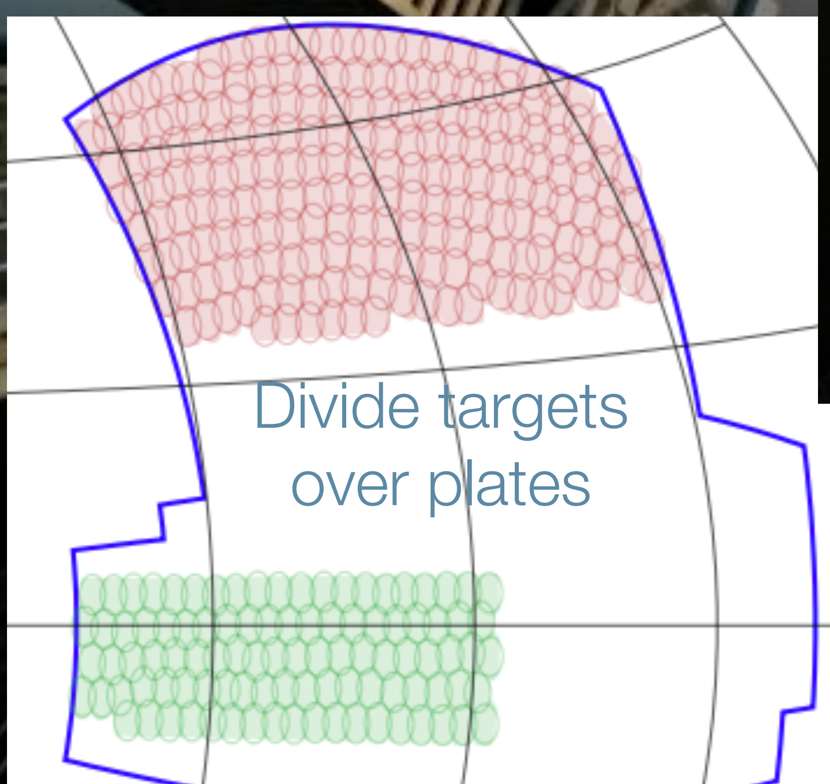


# (e)BOSS

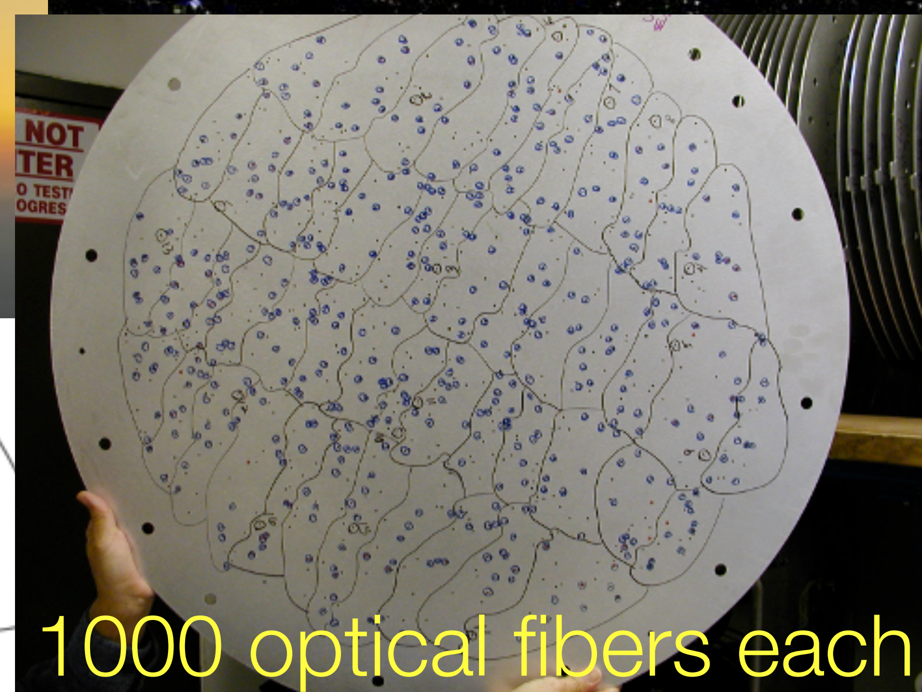
(Extended) Baryon Oscillation Spectroscopic Survey

Select galaxies and quasars from SDSS photometry

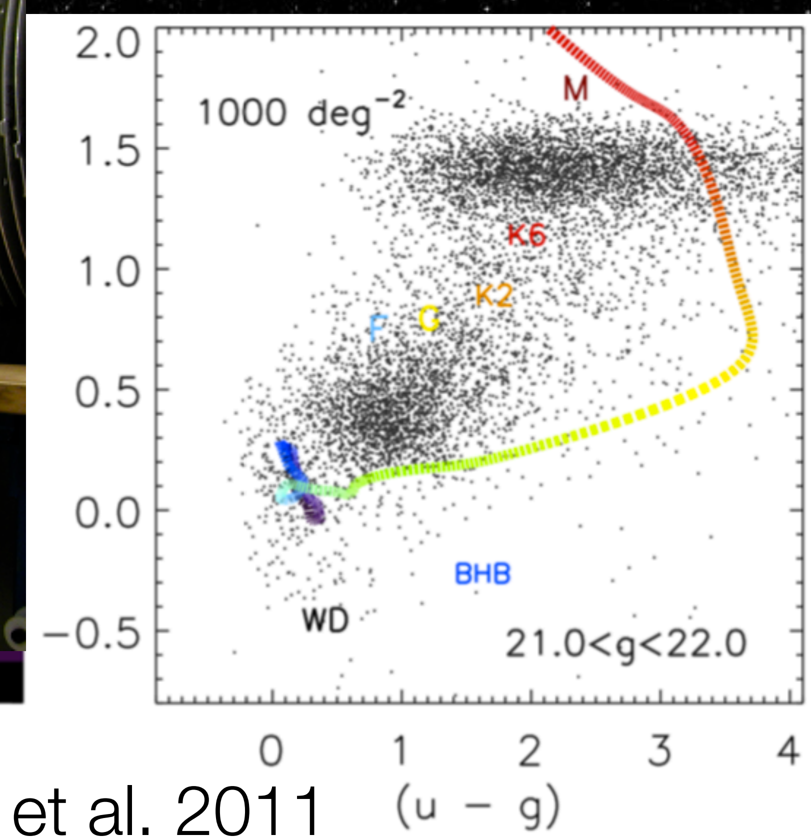
Quasars are harder because they look like stars!



Divide targets over plates



1000 optical fibers each




Ross et al. 2011

SDSS Telescope @ Apache Point Observatory, New Mexico, USA

# (e)BOSS

(Extended) Baryon Oscillation Spectroscopic Survey


Repeat that for 2400 plates during 5 years!

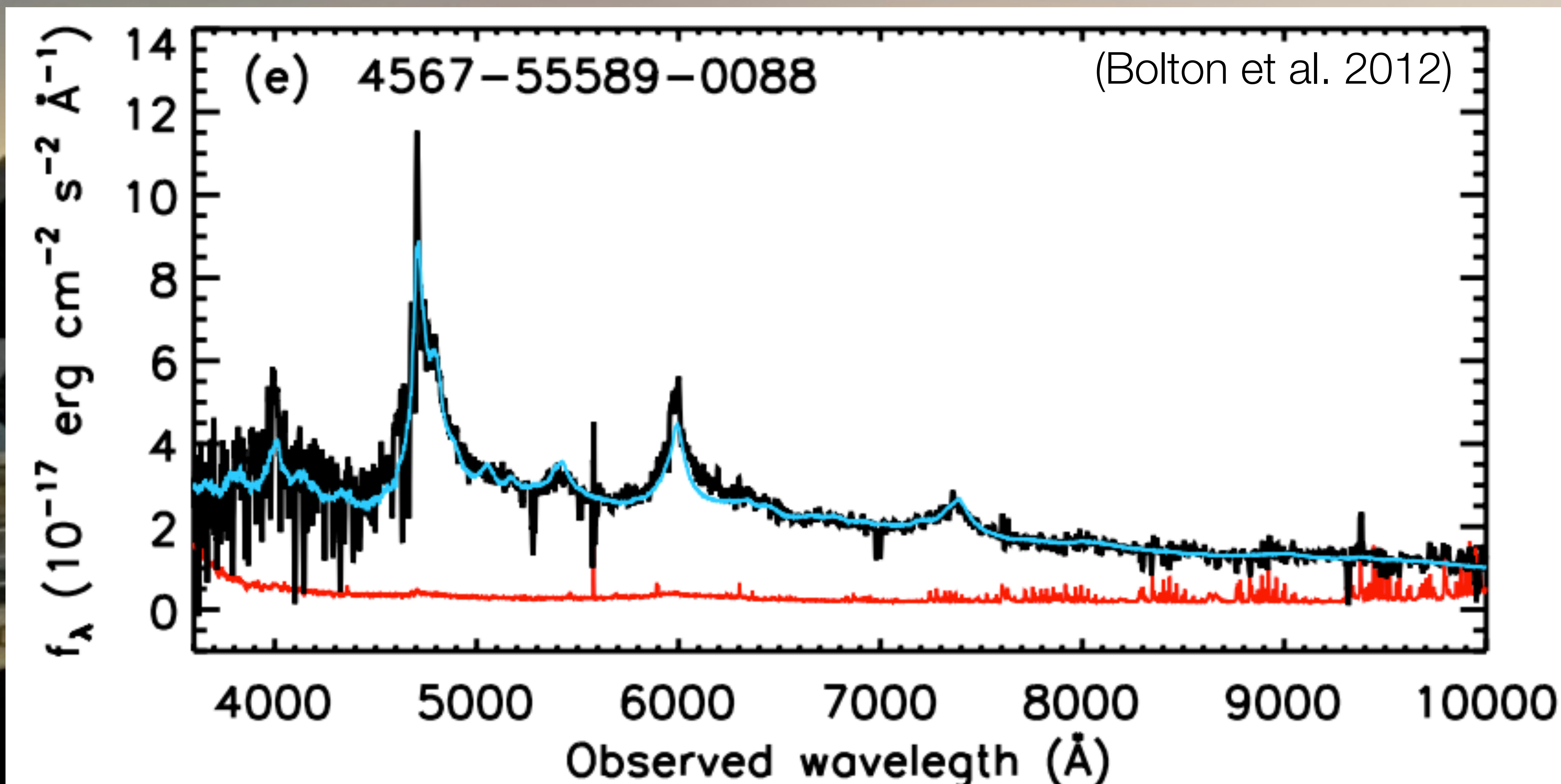
More than 1.3 million galaxies observed

More than 300 000 quasars observed

SDSS Telescope @ Apache Point Observatory, New Mexico, USA

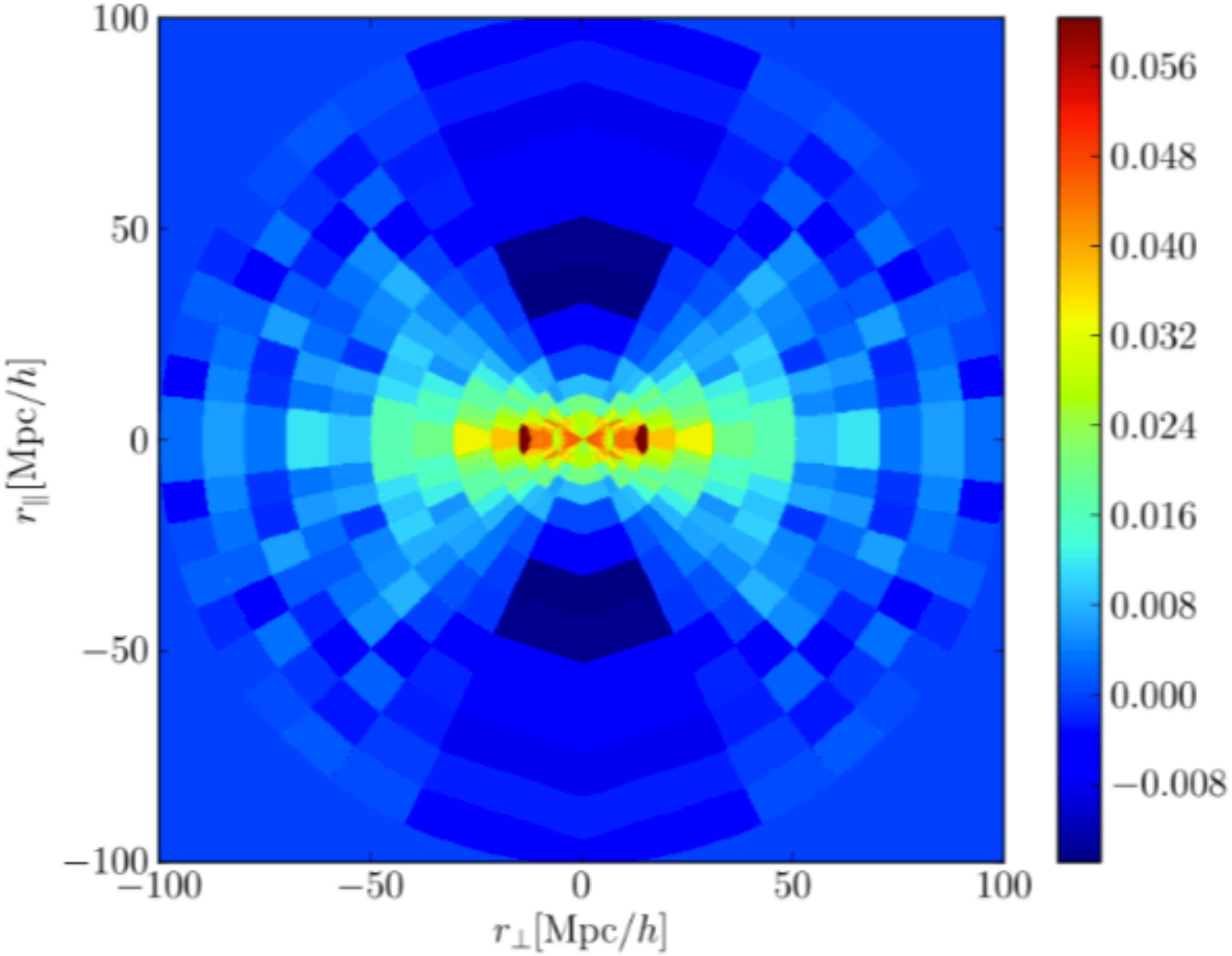
# (e)BOSS

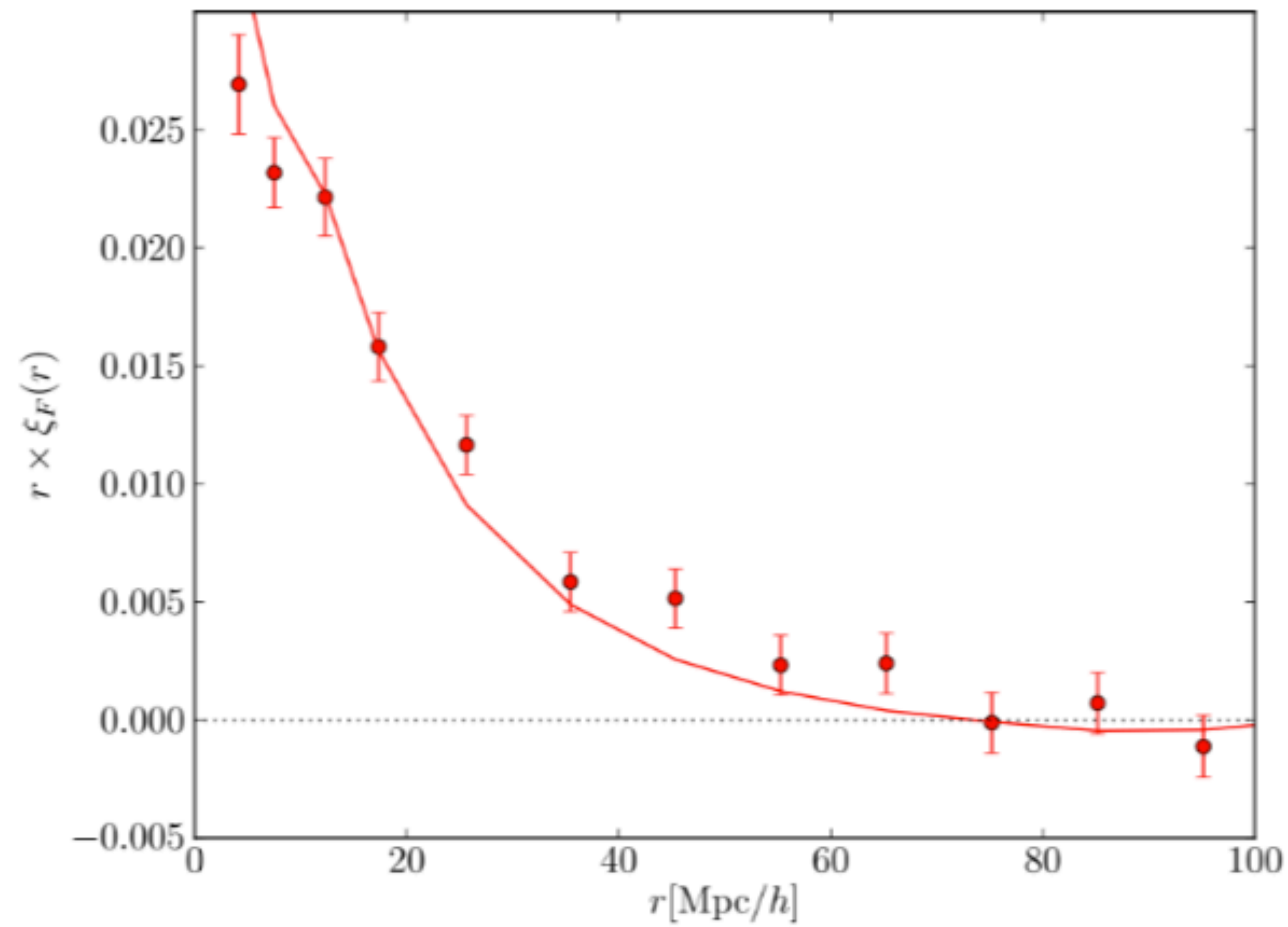
(Extended) Baryon Oscillation Spectroscopic Survey




SDSS Telescope @ Apache Point Observatory, New Mexico, USA

# First three-dimensional clustering measurement using 16k BOSS forests from 1st year




First evidence of large-scale correlations among different lines of sight, including redshift-space distortions

$-0.24 < b_F < -0.16$ and $0.44 < \beta_F < 1.20$ (95% confidence)

Slosar et al. 2011

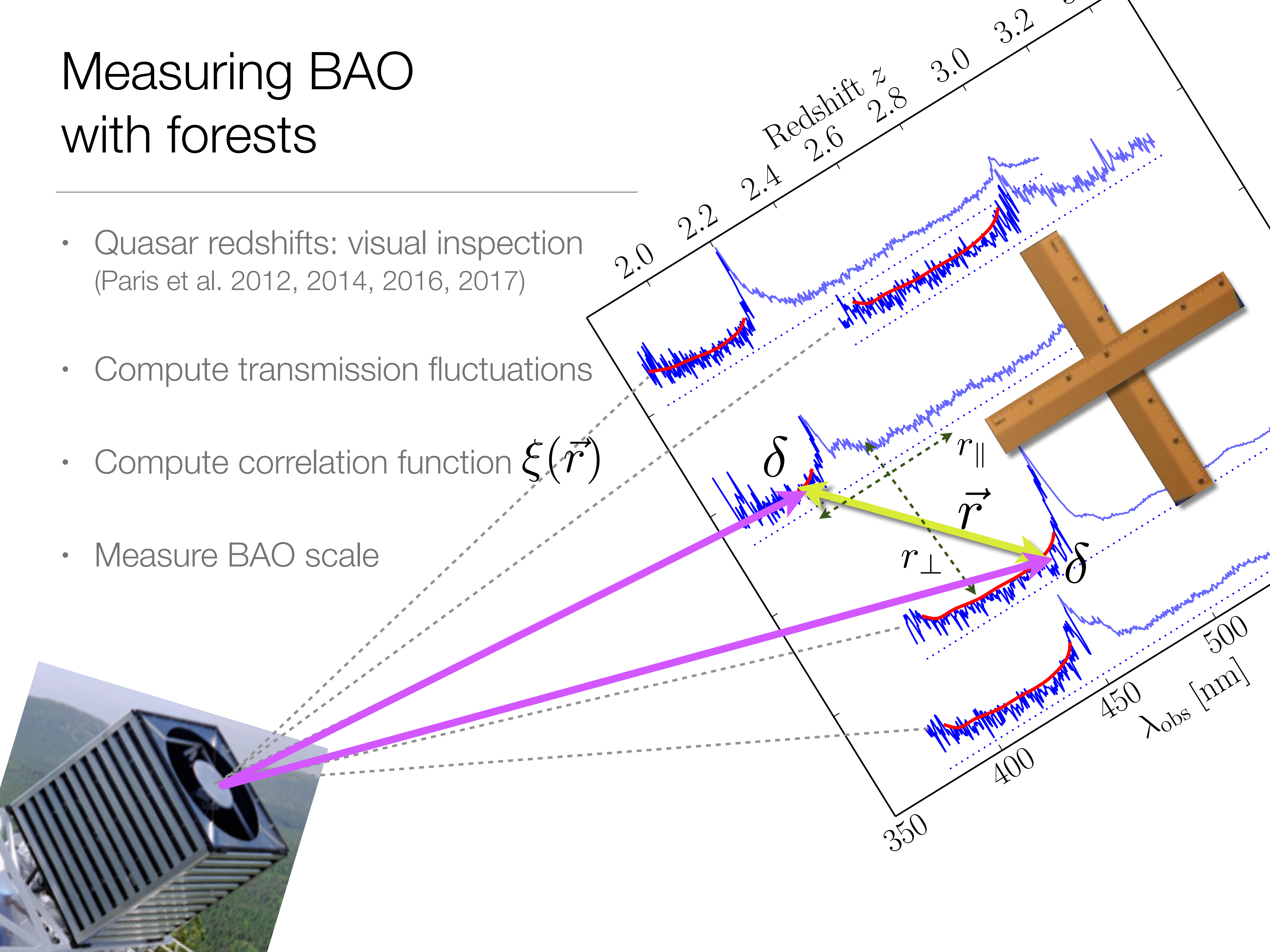
# How to perform three-dimensional clustering and **BAO** measurements

Busca et al. 2013
Slosar et al. 2013
Kirkby et al. 2013
Font-Ribera et al. 2013
Delubac, et al. 2014
Bautista et al. 2017
Du Mas des Bourboux et al. 2017
de Sainte Agathe et al. 2019
Blomqvist et al. 2019

github.com/igmhub/picca

# Measuring BAO with forests

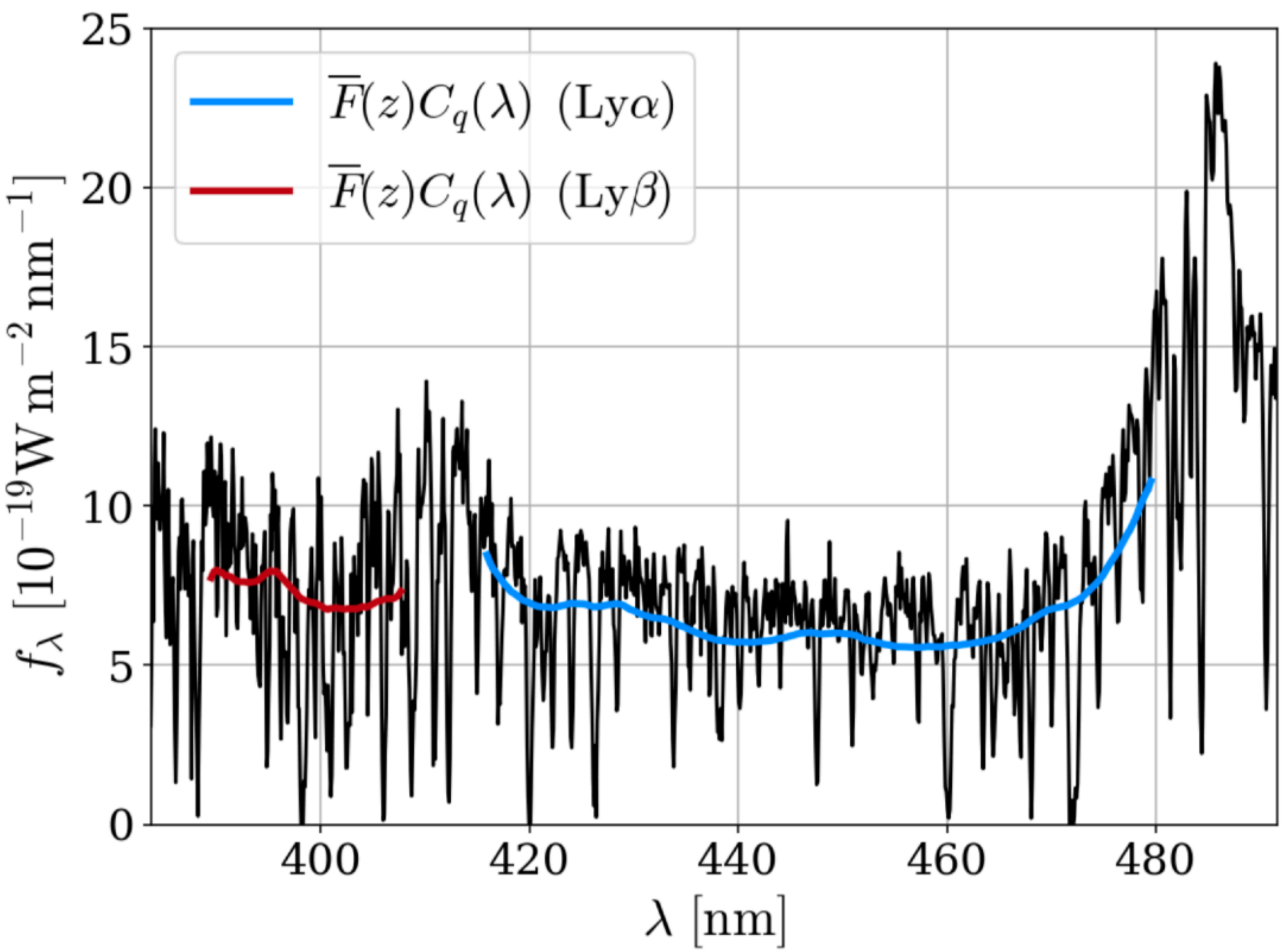
- Quasar redshifts: visual inspection (Paris et al. 2012, 2014, 2016, 2017)
- Compute transmission fluctuations
- Compute correlation function $\xi(\vec{r})$
- Measure BAO scale



# Computing fluctuations

Fit of continuum x mean absorption per quasar

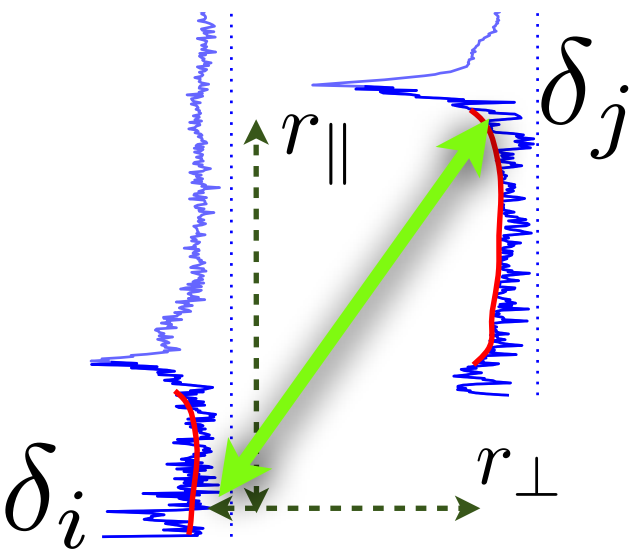
$$C_{\mathrm{q}}(\lambda)\overline{F}(\lambda) = \overline{f}(\lambda_{\mathrm{rf}})(a_{\mathrm{q}} + b_{\mathrm{q}} \log_{10}(\lambda))$$




$C_{\mathrm{q}}$ : stack in rest-frame
$\bar{F}$: stack in observed-frame

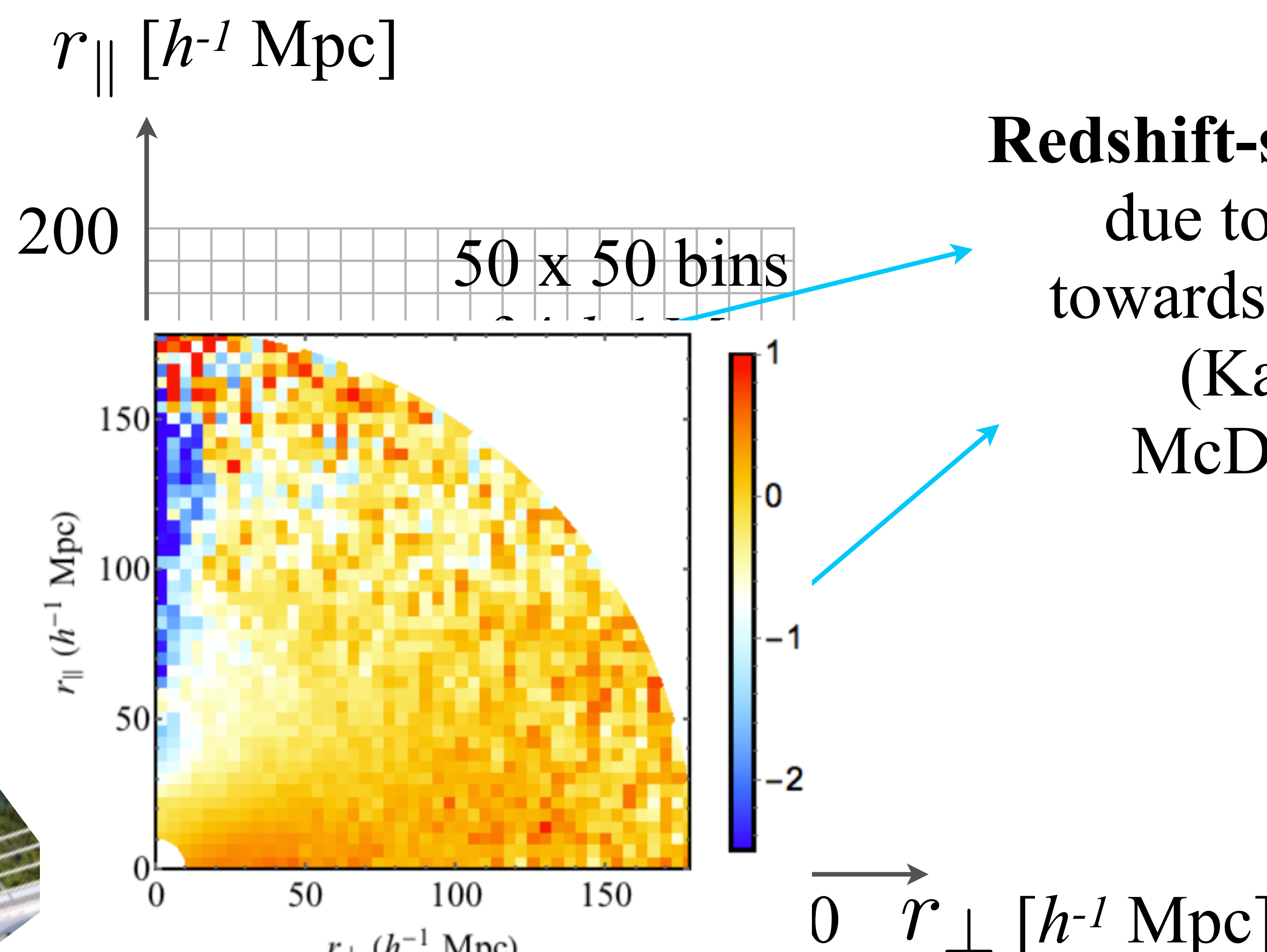
$$\delta_q(\lambda) = \frac{f_q(\lambda)}{C_q(\lambda)\bar{F}(z)} - 1$$

# Correlation function

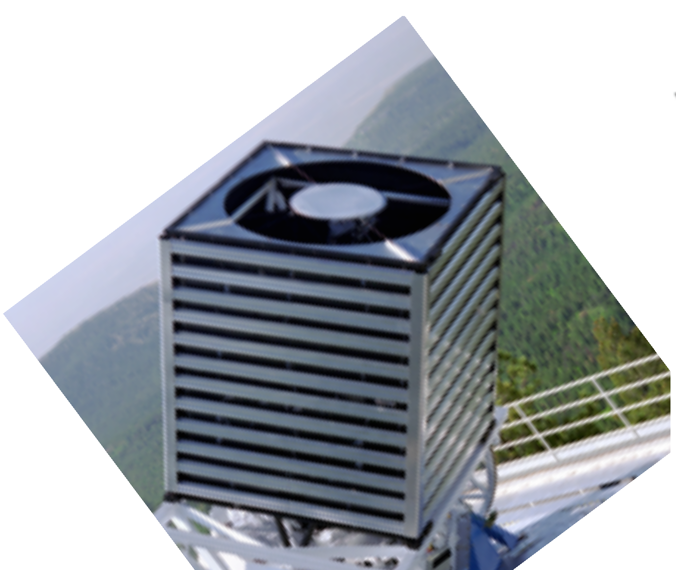



$$\delta_q(\lambda) = \frac{f_q(\lambda)}{C_q(\lambda)\bar{F}(z)} - 1$$

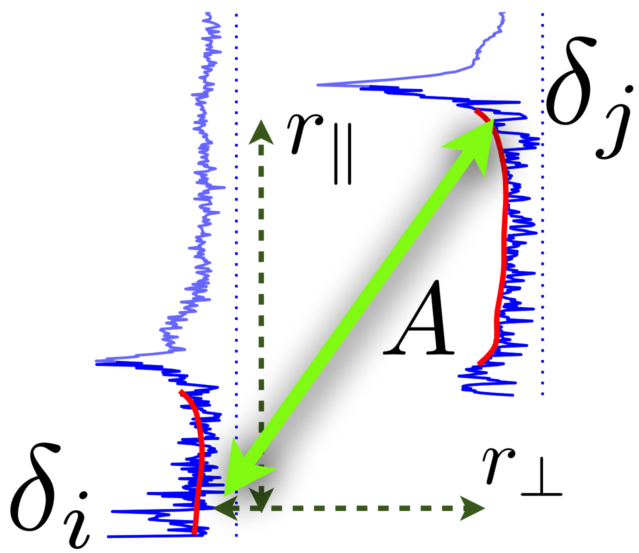
$$\hat{\xi}(r_{\perp}, r_{\parallel}) = \langle \delta_i \delta_j \rangle$$




**Redshift-space distortions**
due to matter infall
towards potential wells
(Kaiser 1987,
McDonald 2003)



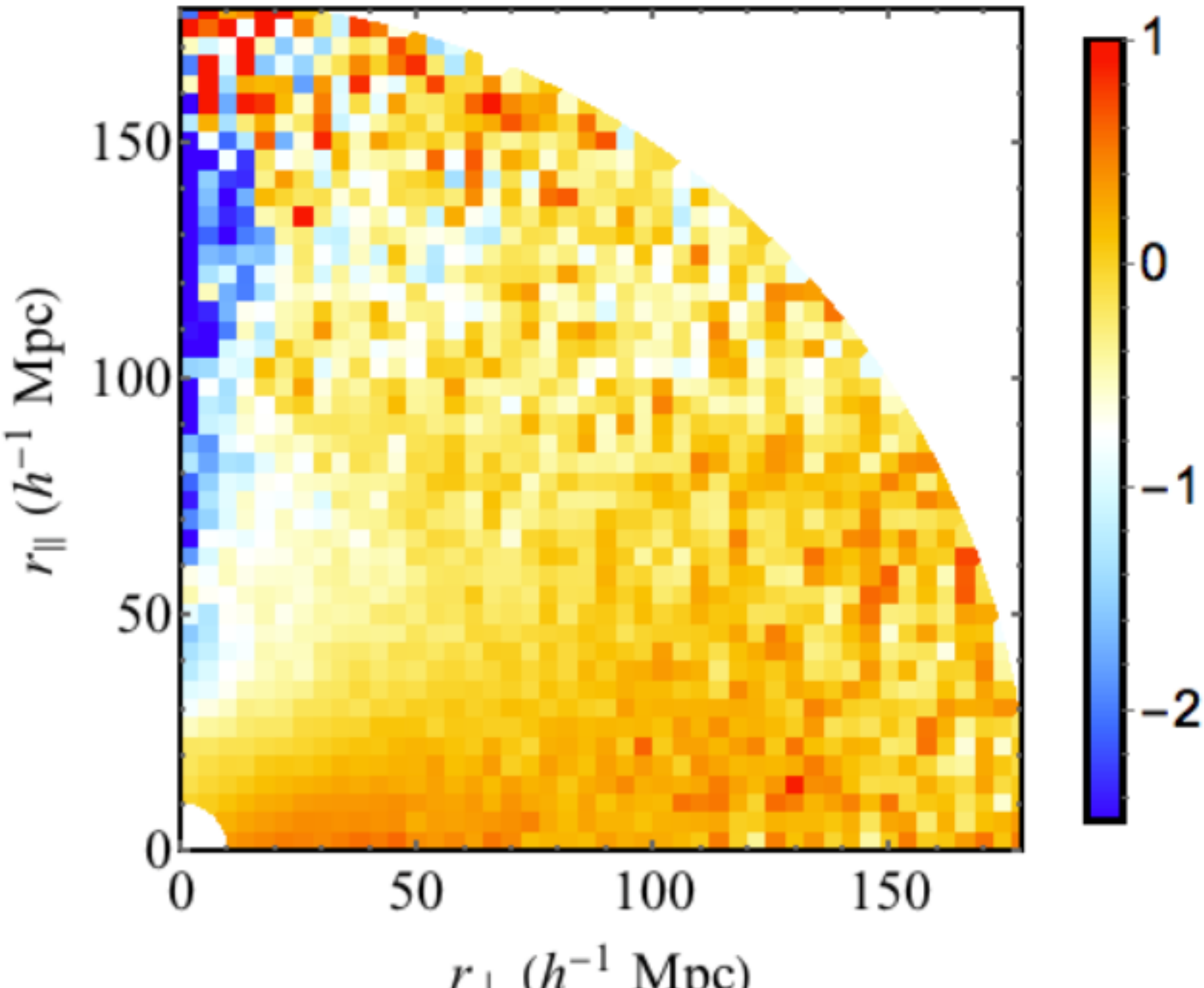
# Correlation function




$F_i$

$r_{\parallel}$

200



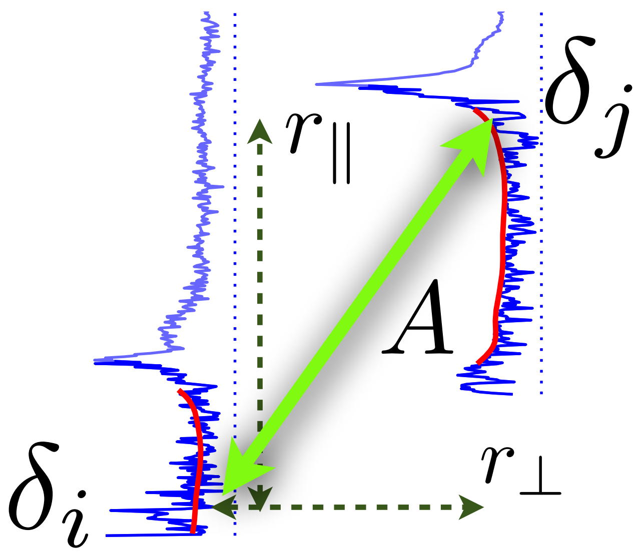

ions

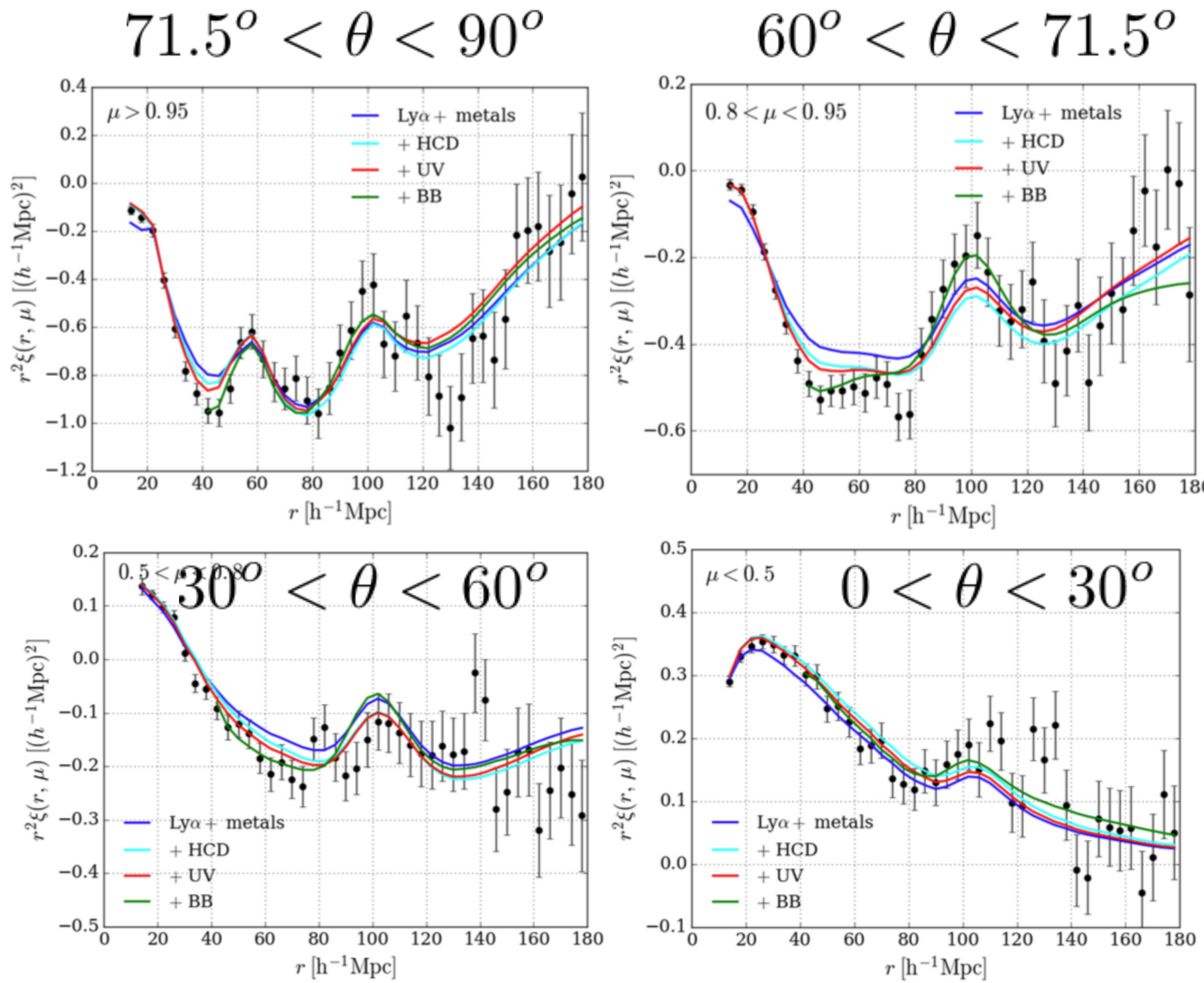
lls

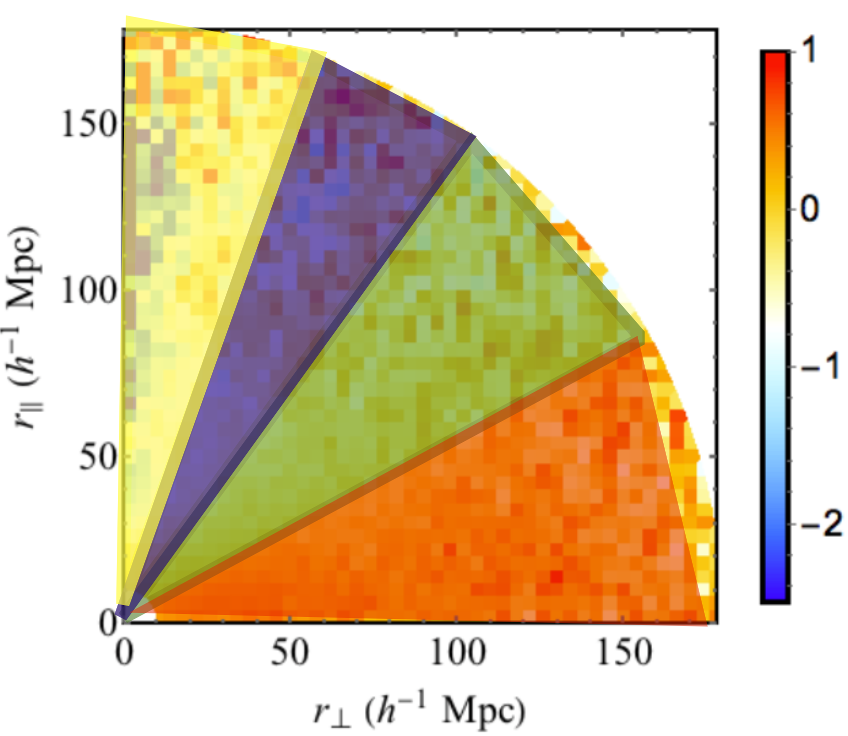
0

200 $r_{\perp}$ [$h^{-1}$ Mpc]

# Correlation function



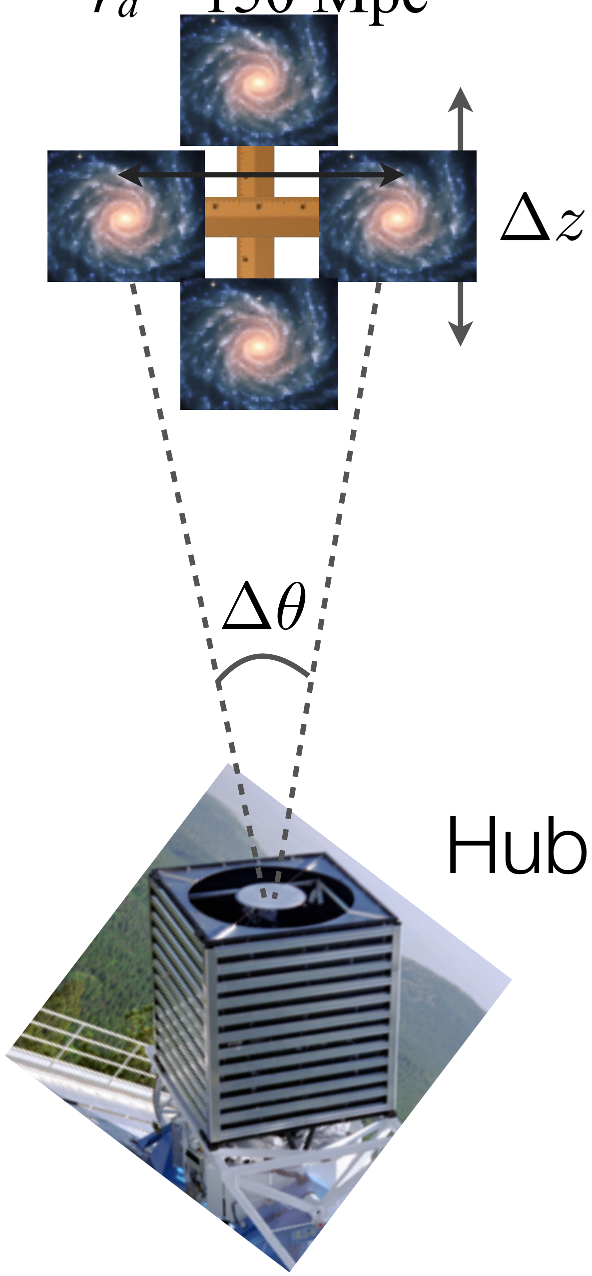

Bautista et al. 2017

# Measuring BAO Scale

Previously baofit (Kirkby++2013, Blomqvist++2015)
Currently github.com/igmhub/picca

## BAO scale

$r_d \sim 150$ Mpc

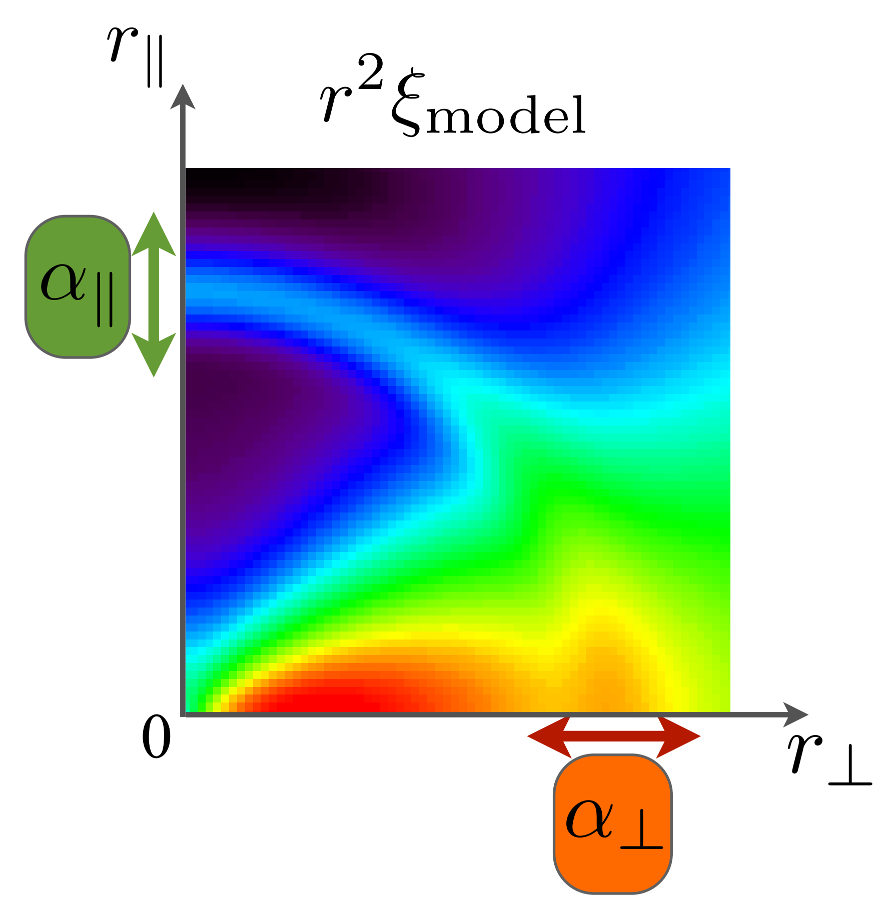



$$\xi_{\mathrm{model}}(\vec{r}, \alpha_{\parallel}, \alpha_{\perp}) = \xi_{\mathrm{cosmo}}(\vec{r}, \alpha_{\parallel}, \alpha_{\perp}) + \xi_{\mathrm{broadband}}(\vec{r})$$

$$\alpha_{\parallel} = \frac{D_H(\bar{z})/r_d}{[D_H(\bar{z})/r_d]_{\mathrm{fid}}} \quad \text{and} \quad \alpha_{\perp} = \frac{D_A(\bar{z})/r_d}{[D_A(\bar{z})/r_d]_{\mathrm{fid}}}$$

Radial BAO

Transverse BAO




## Distances

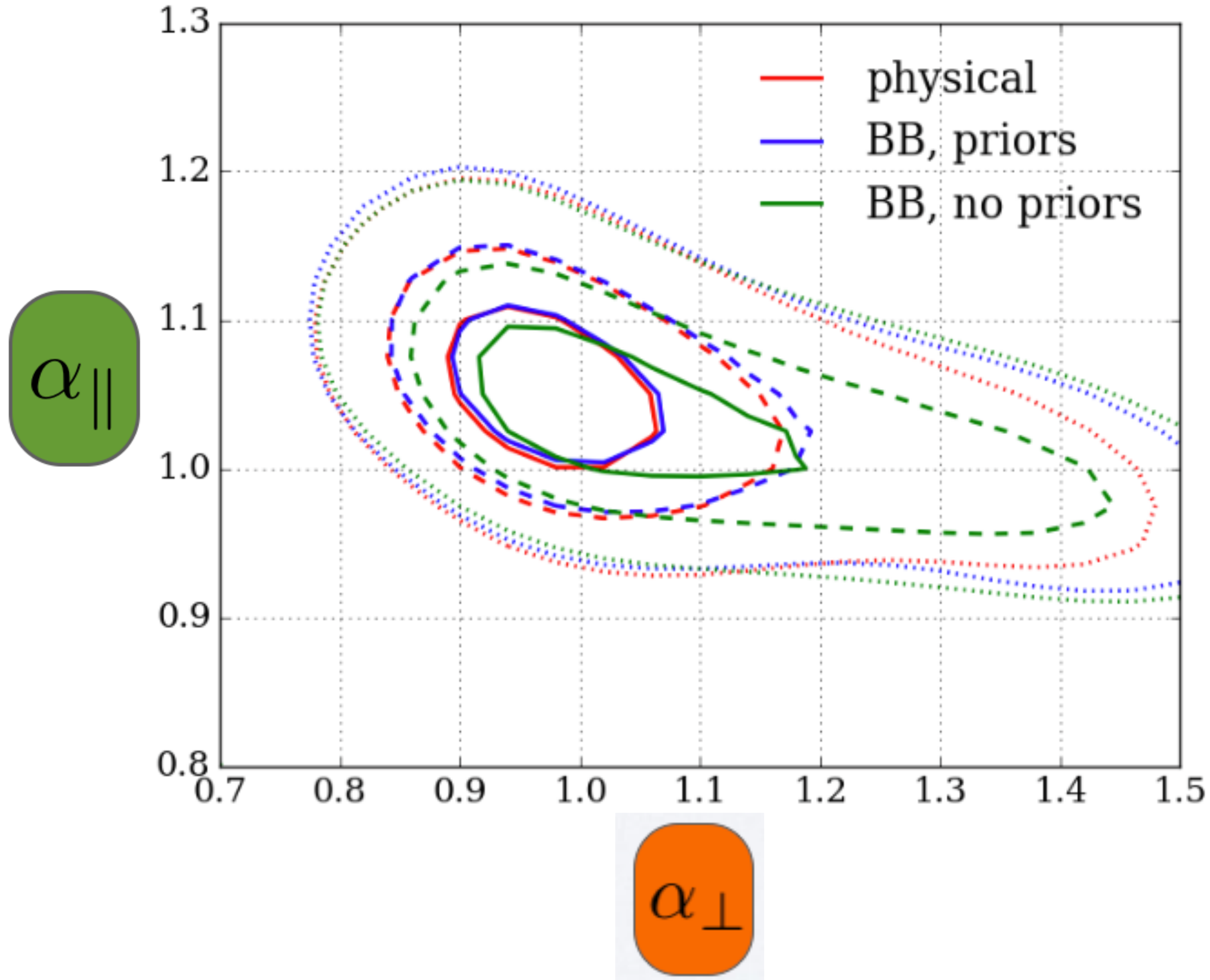
$$\Delta\theta \propto \frac{r_d}{D_A(z)}$$

## Hubble's law (in the past)

$$\Delta z \propto \frac{r_d}{D_H(z)}$$

# Measuring BAO Scale

Bautista et al. 2017




$$\alpha_{||} = \frac{D_H(\bar{z})/r_d}{[D_H(\bar{z})/r_d]_{\text{fid}}}$$ and $$\alpha_{\perp} = \frac{D_A(\bar{z})/r_d}{[D_A(\bar{z})/r_d]_{\text{fid}}}$$

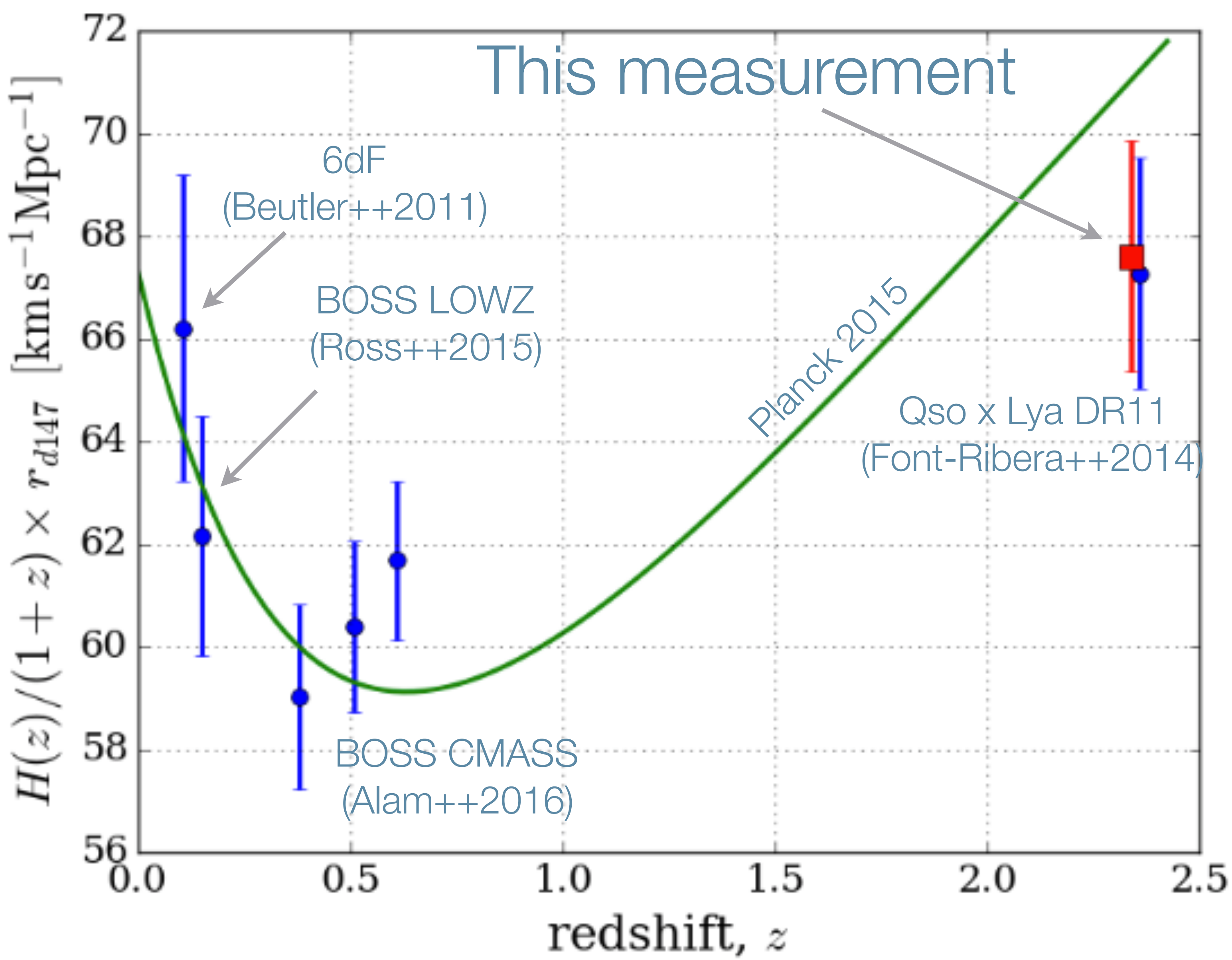
Radial BAO

Transverse BAO

# Expansion rate as measured with BAO

$$\alpha_{\parallel} = \frac{D_H(\bar{z})/r_d}{[D_H(\bar{z})/r_d]_{\rm fid}}$$

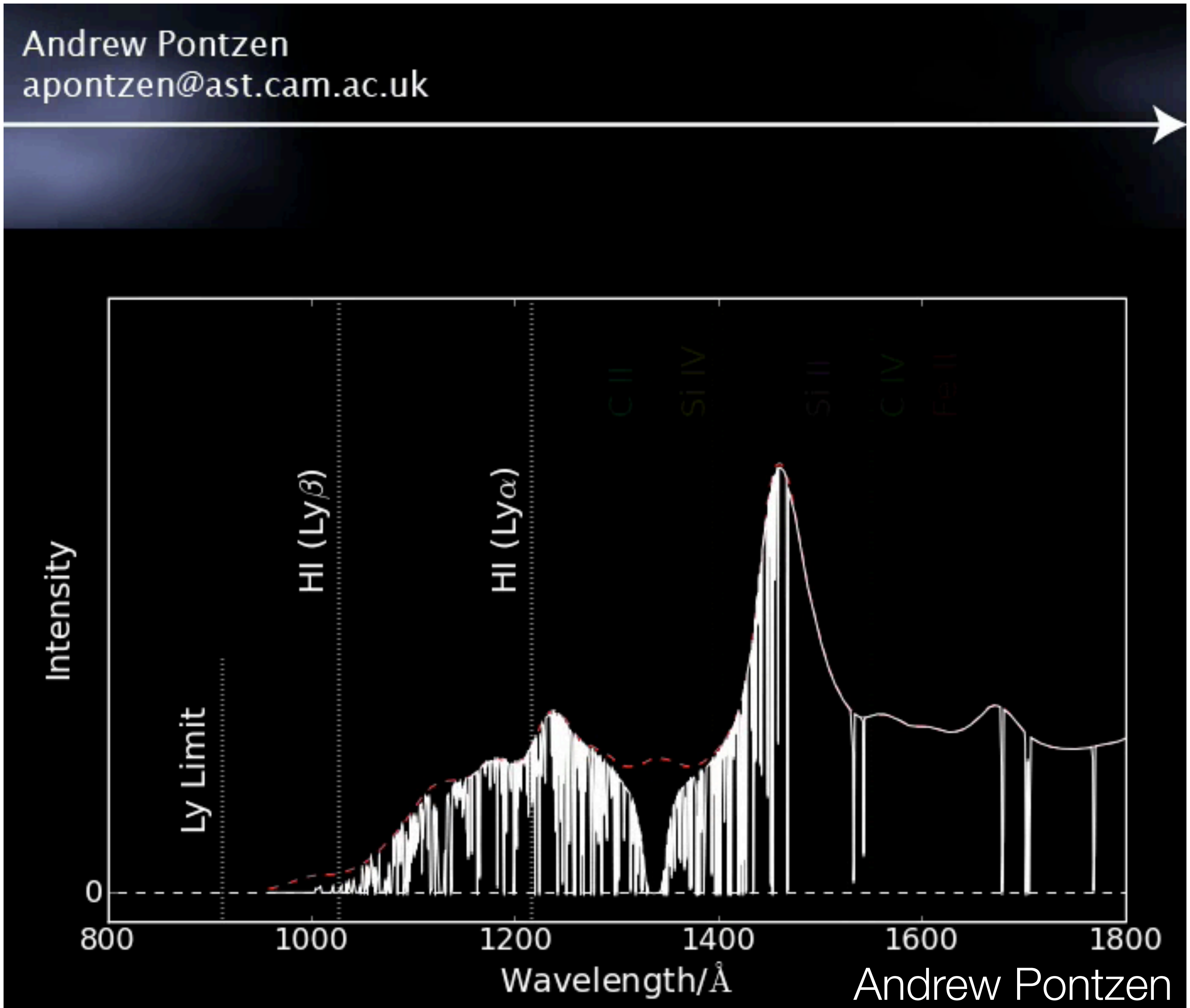
Radial BAO




Bautista et al. 2017

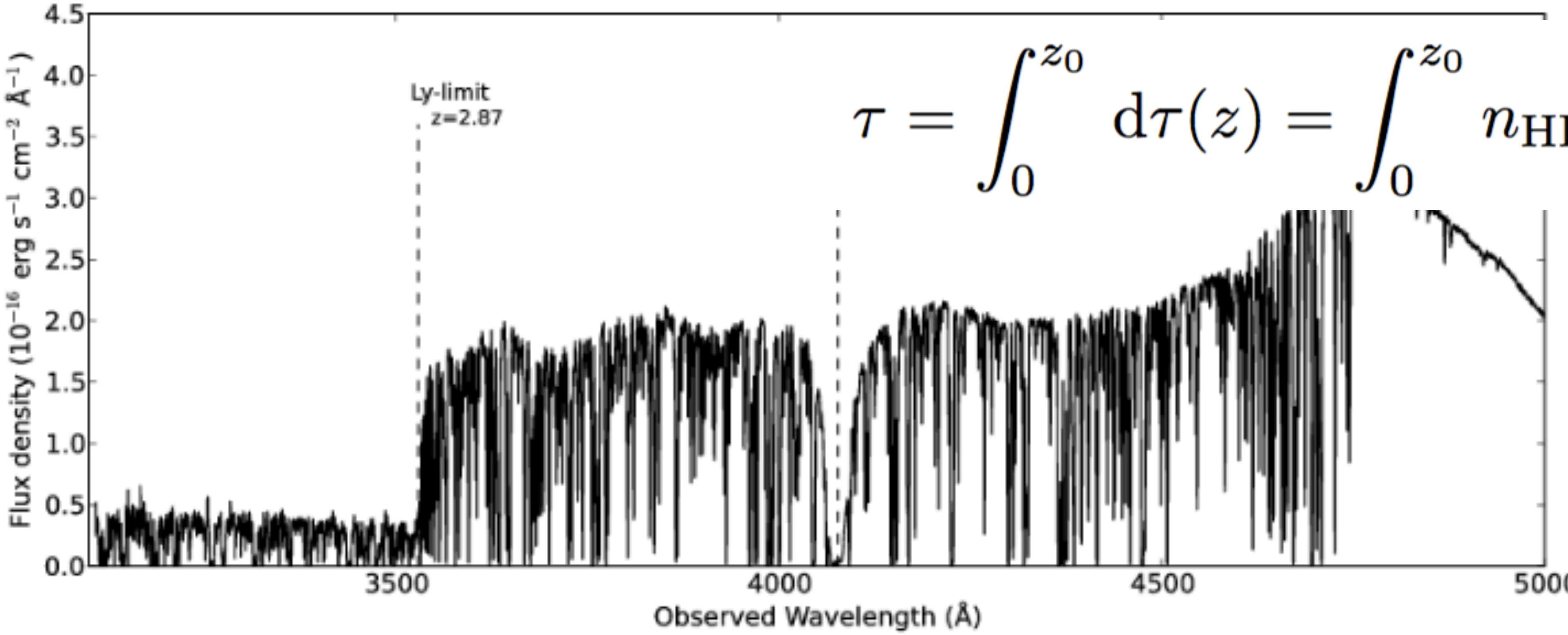
There is bonus cosmological information in this sample…

# There is bonus cosmological information in this sample…



There are at least 3 bonus tracers in that movie… which ones?

# Damped Lyman-alpha Systems (DLAs)



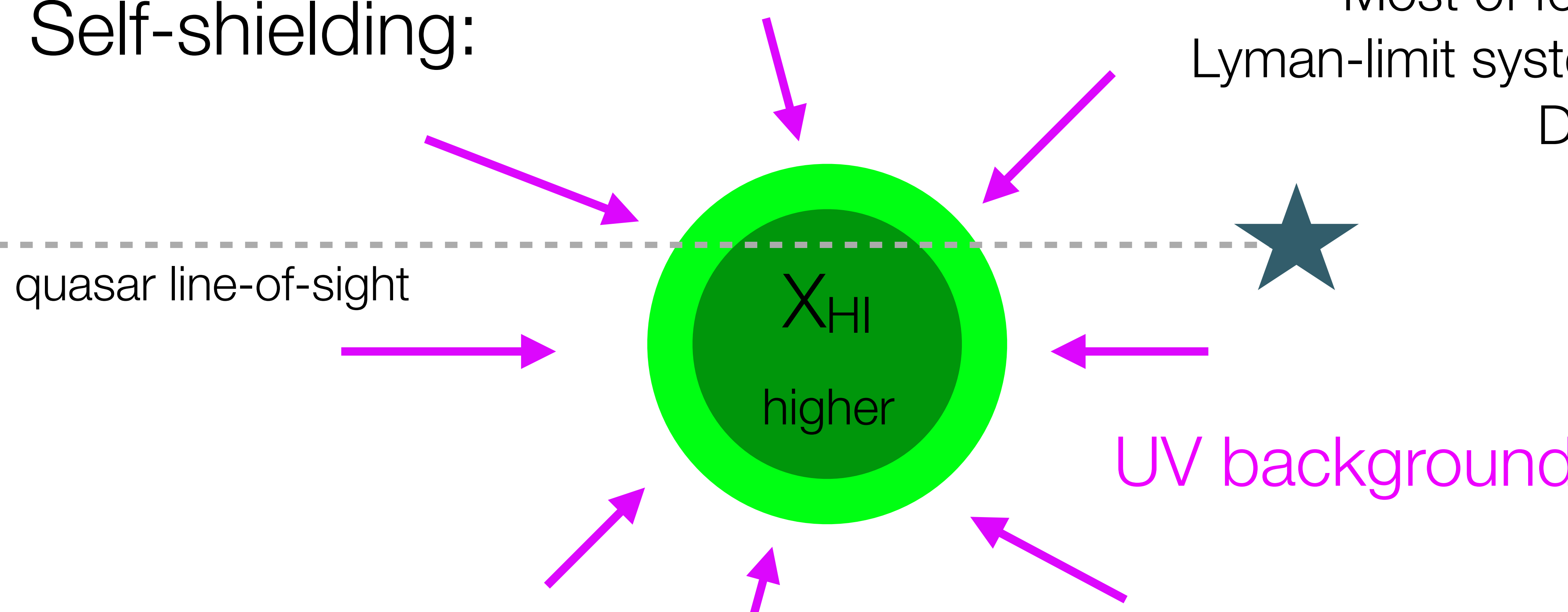

$$\tau = \int_0^{z_0} \mathrm{d}\tau(z) = \int_0^{z_0} n_{\mathrm{HI}}(z)\sigma[\nu(1+z)]\,\frac{\mathrm{d}l}{\mathrm{d}z}\,\mathrm{d}z$$

$$\tau(z) = \Sigma(z) N_{\mathrm{HI}}(z)$$

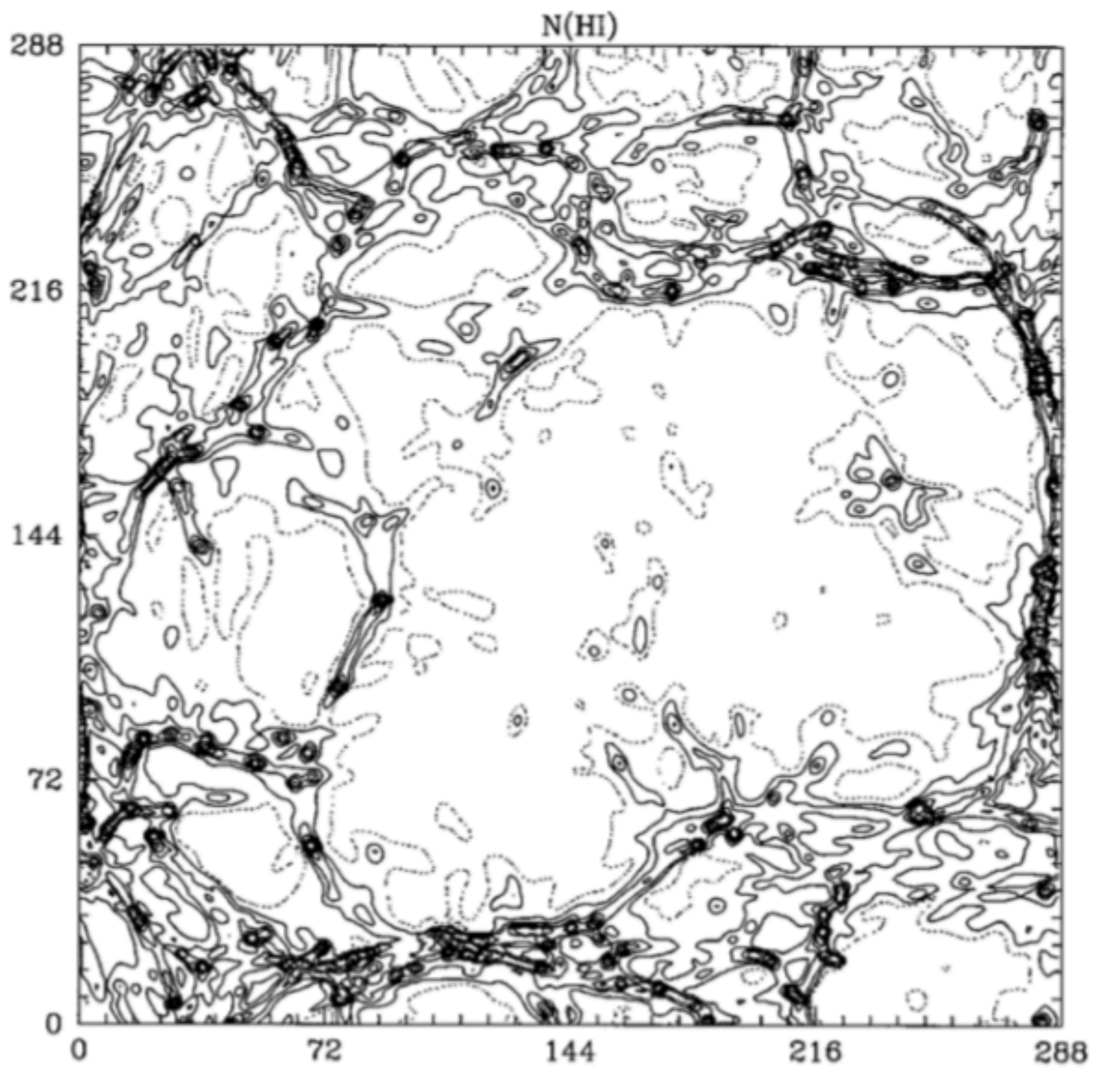
Column density [cm$^{-2}$]

Most of forest: $N_{\mathrm{HI}} \sim 10^{\mathbf{13\text{-}16}}$ cm$^{-2}$
Lyman-limit systems: $N_{\mathrm{HI}} \sim 10^{16\text{-}20}$ cm$^{-2}$
DLAs: $N_{\mathrm{HI}} \sim 10^{\mathbf{20\text{-}23}}$ cm$^{-2}$

## Self-shielding:



# Damped Lyman-alpha Systems (DLAs) as tracers of dark-matter field

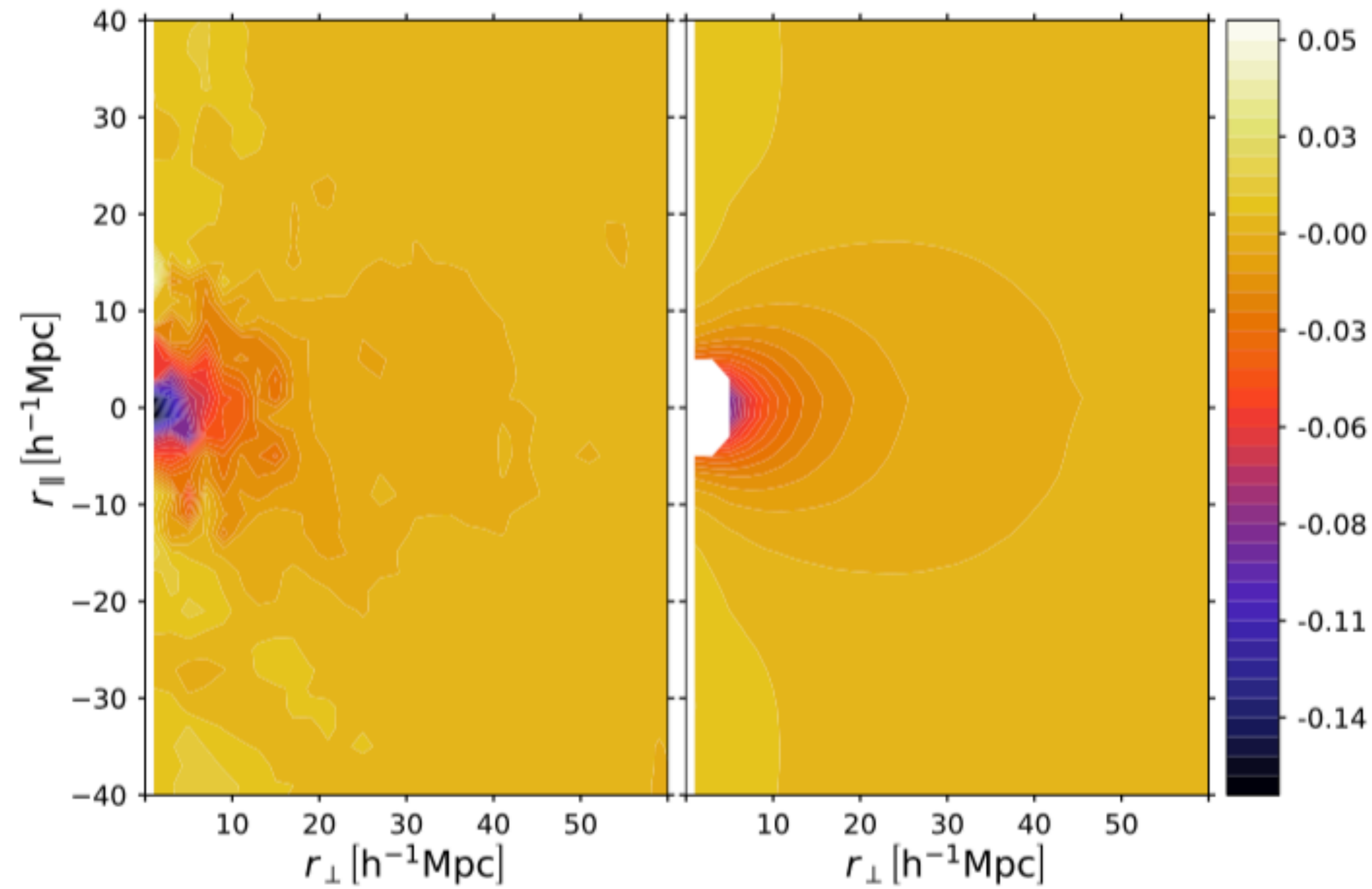



Contours = column densities

$10^{12+i*0.5}$ cm$^{-2}$ for i = 0, 1, 2, …

About 20% of forests contain DLAs

Cross-correlation with forests




Font-Ribera et al. 2012, Pérez-Ràfols et al. 2018

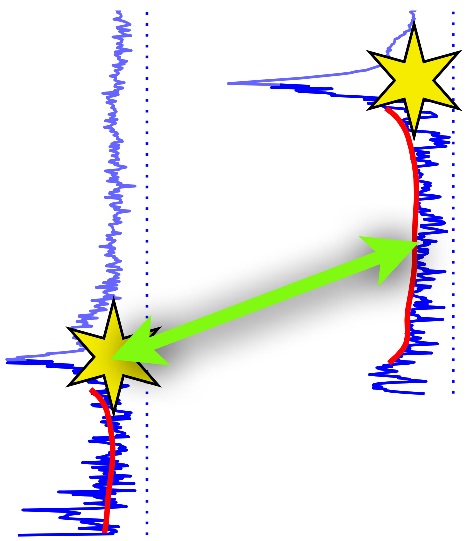
$b_{\mathrm{DLA}} = 2.00 \pm 0.19$

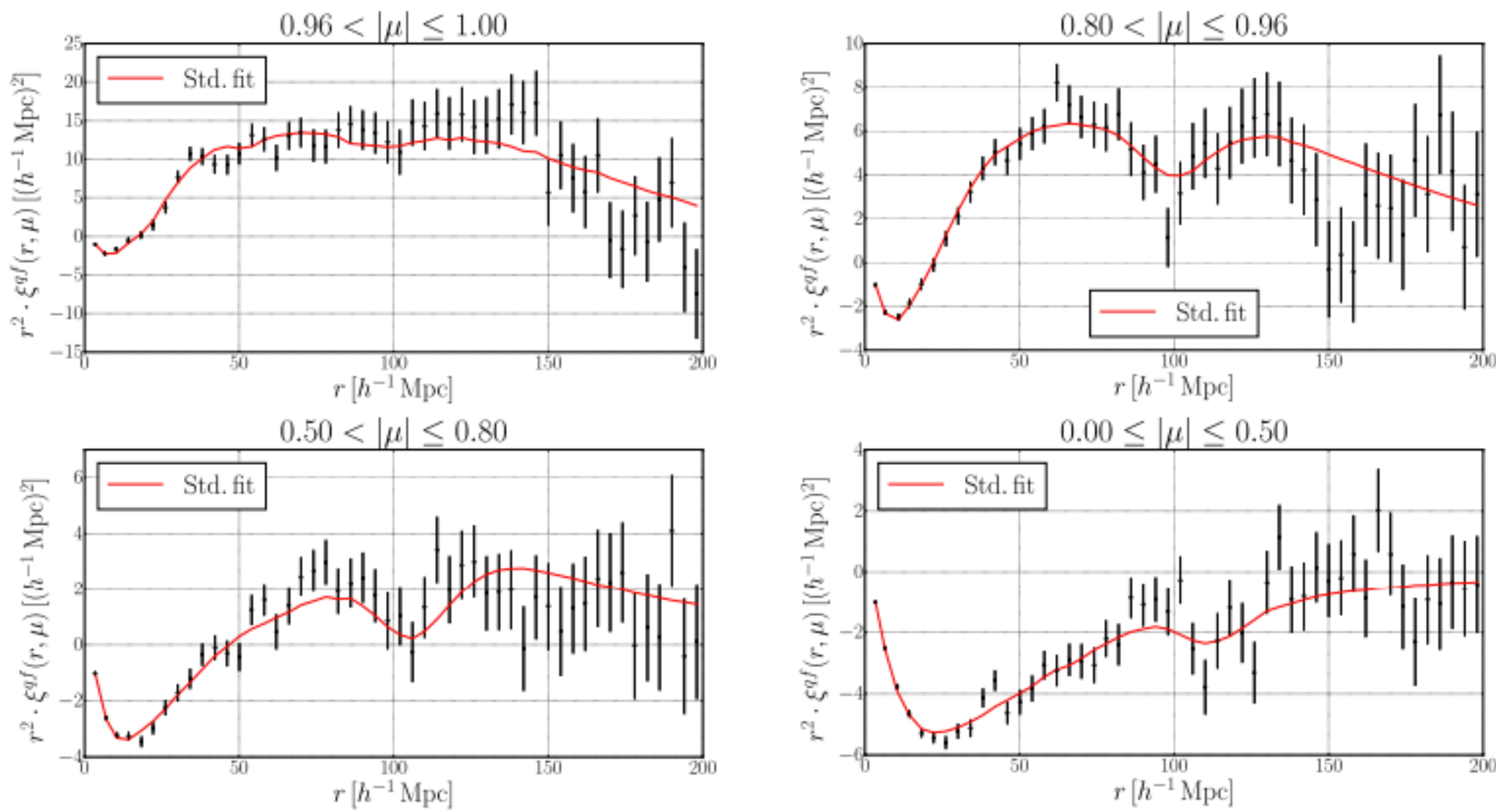
Host halo mass ~ $4 \cdot 10^{11}\, h^{-1}\mathrm{M}_\odot$

There are two left…

# Quasar-Forest Cross-Correlation

Provides complementary BAO information with the same sample!
(Font-Ribera et al. 2013, Du-Mas-des-Bourboux et al. 2017)






$$b_{\mathrm{QSO}}(z = 2.40) = 3.70 \pm 0.12$$

Agrees with Croom et al. 2005, Laurent et al. 2016

# Quasar-Forest Cross-Correlation

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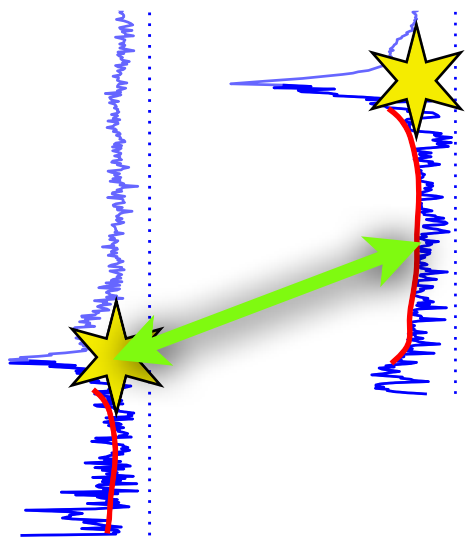
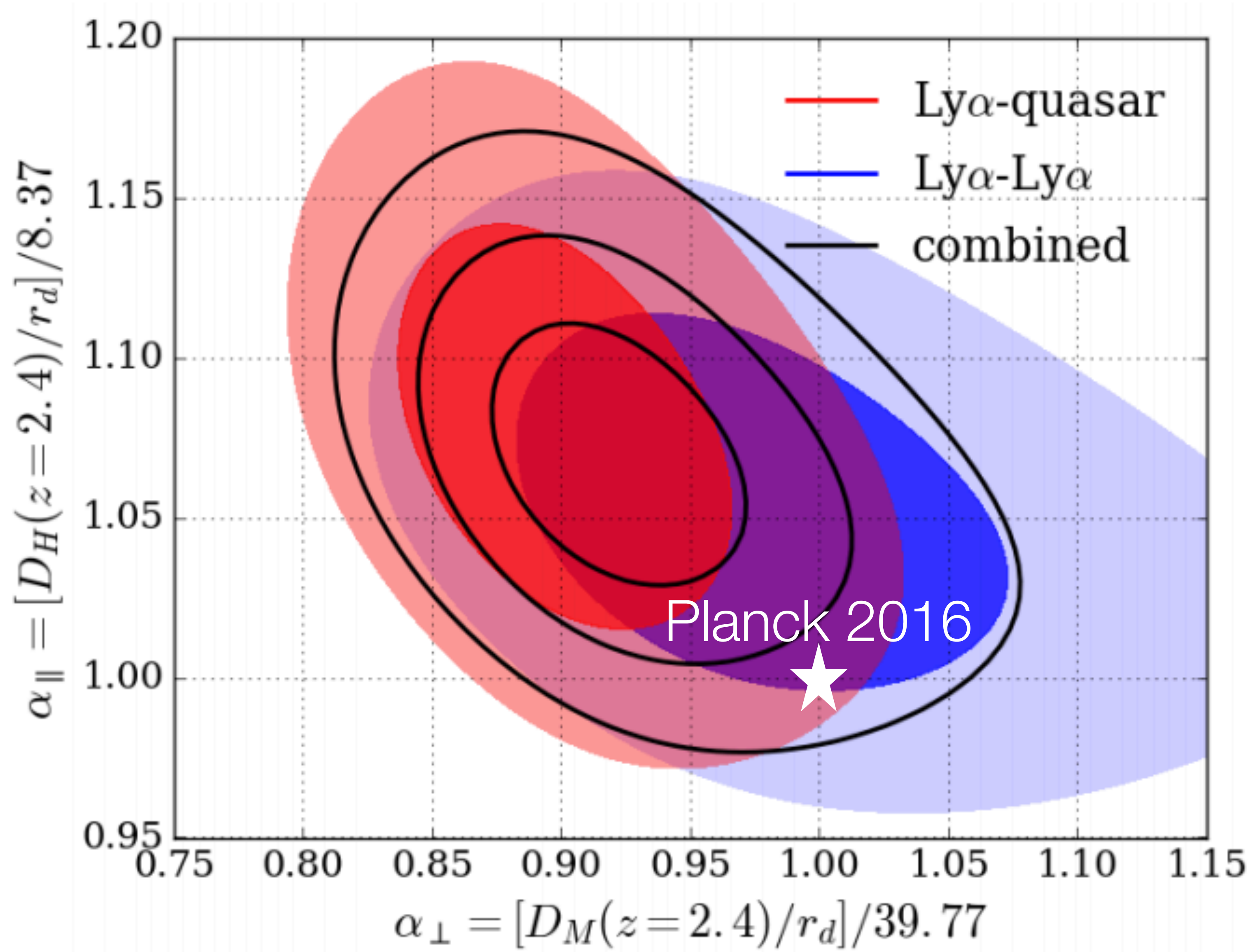
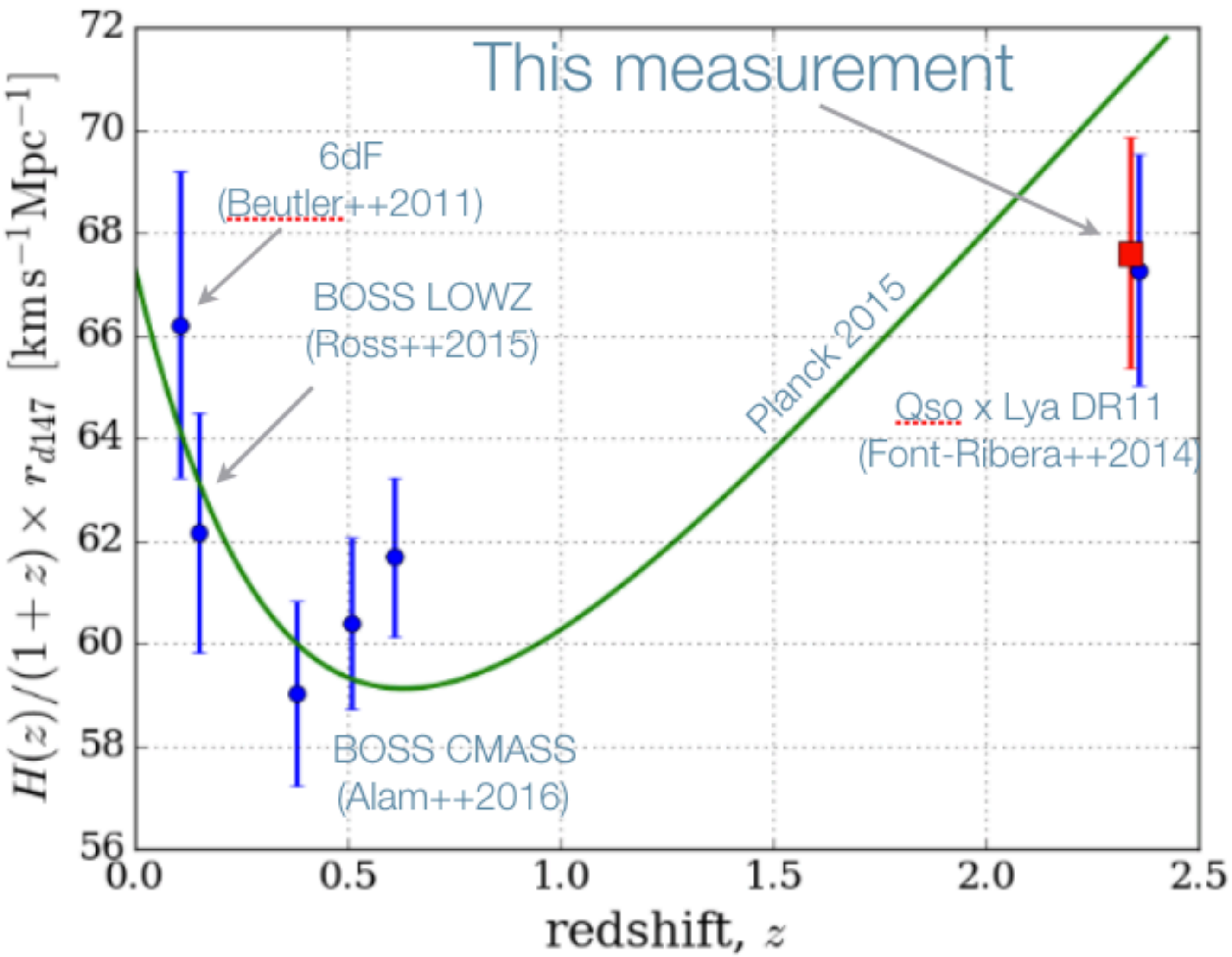


No significant correlation was found between the auto and cross measurements!

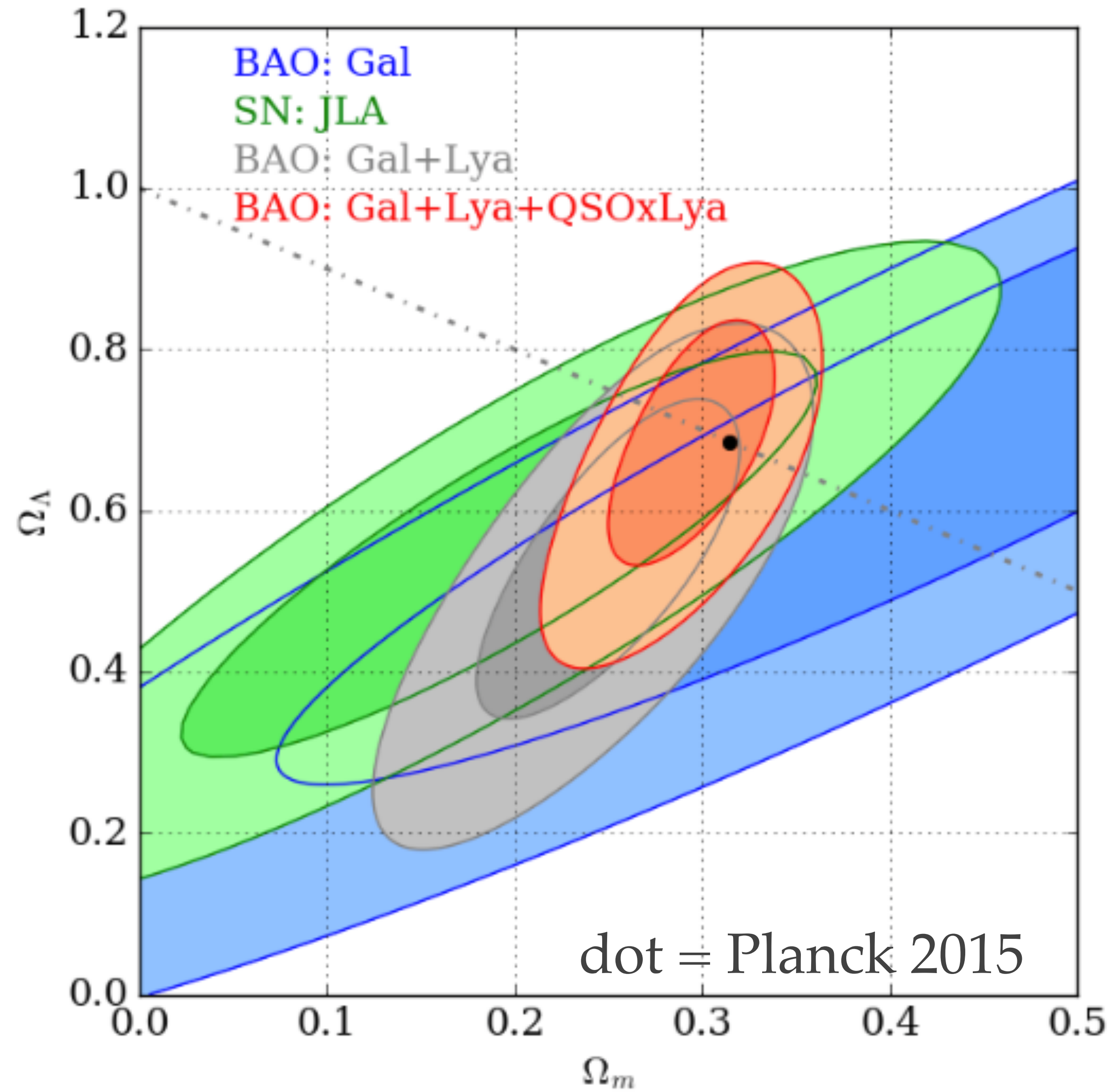



The combined measurement has 2.3 sigma difference with Planck prediction!

# BAO versus Supernovae

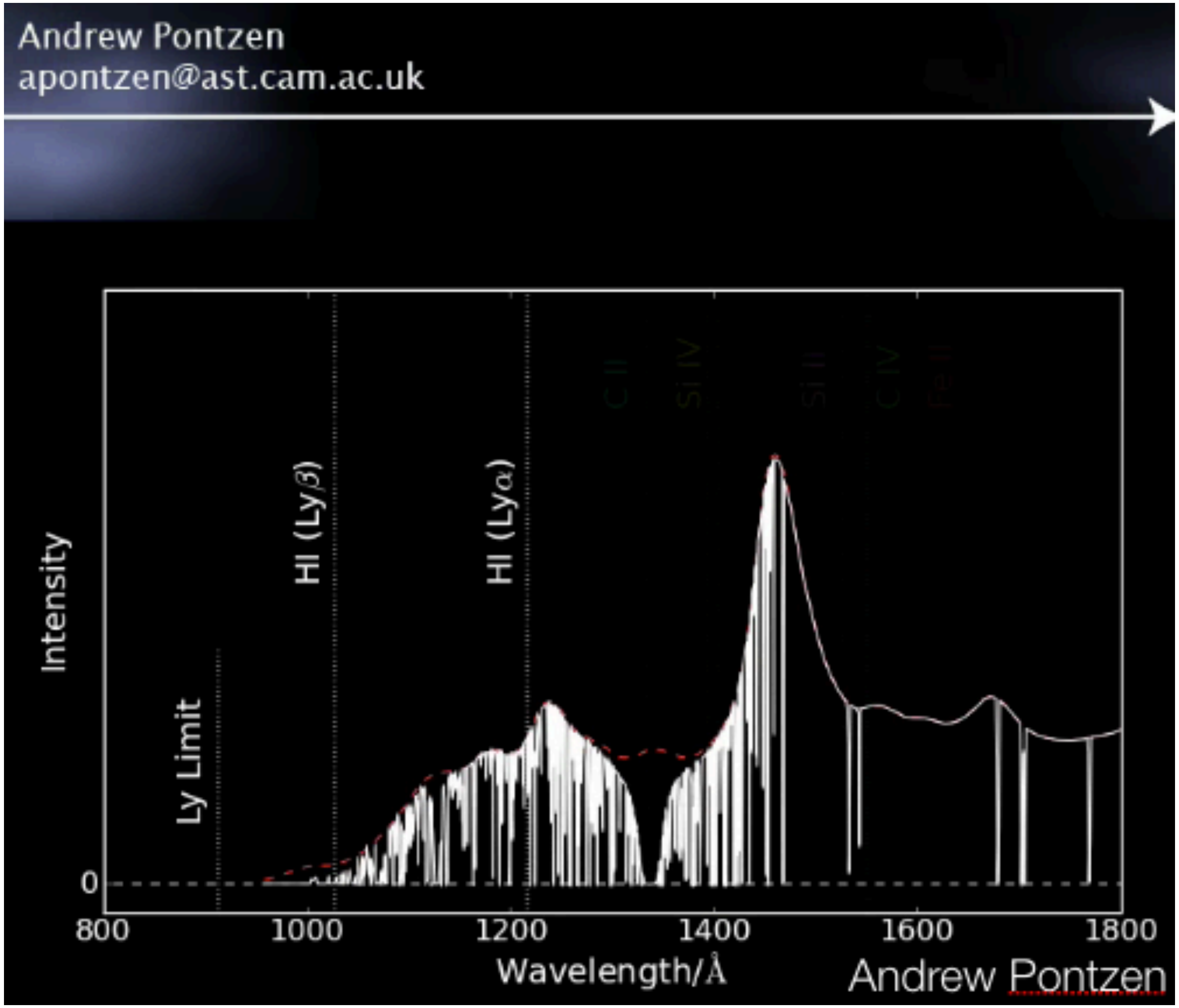



**BAO**
Beutler et al. 2011
Ross et al. 2015
Alam et al. 2017
Bautista et al. 2017
Du-Mas-Des-Bourboux et al. 2017

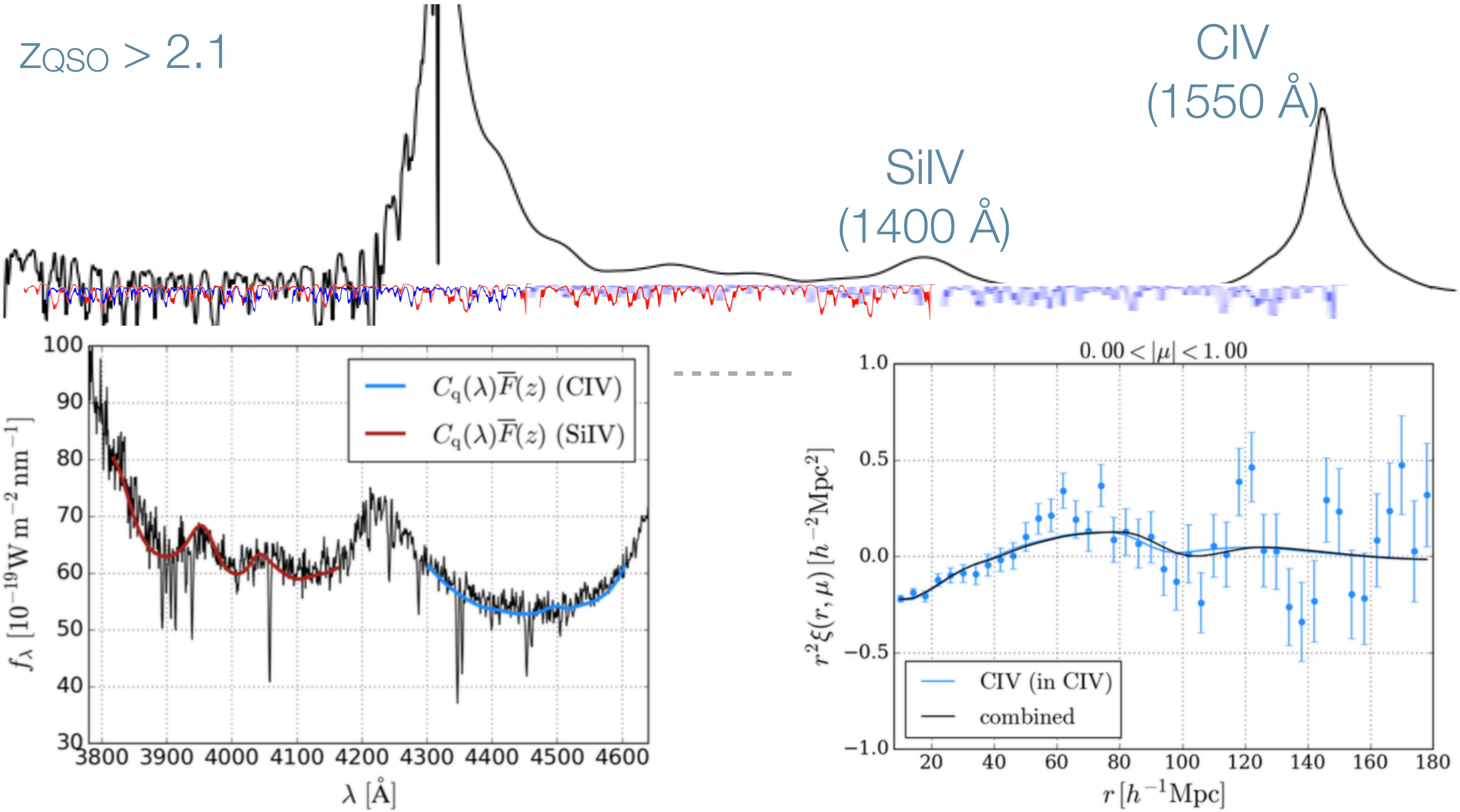



**Supernovae Ia**
Betoule et al. 2014

# Last tracer? This one is harder…



# Forest of Metals : CIV, SIV, MgII, etc

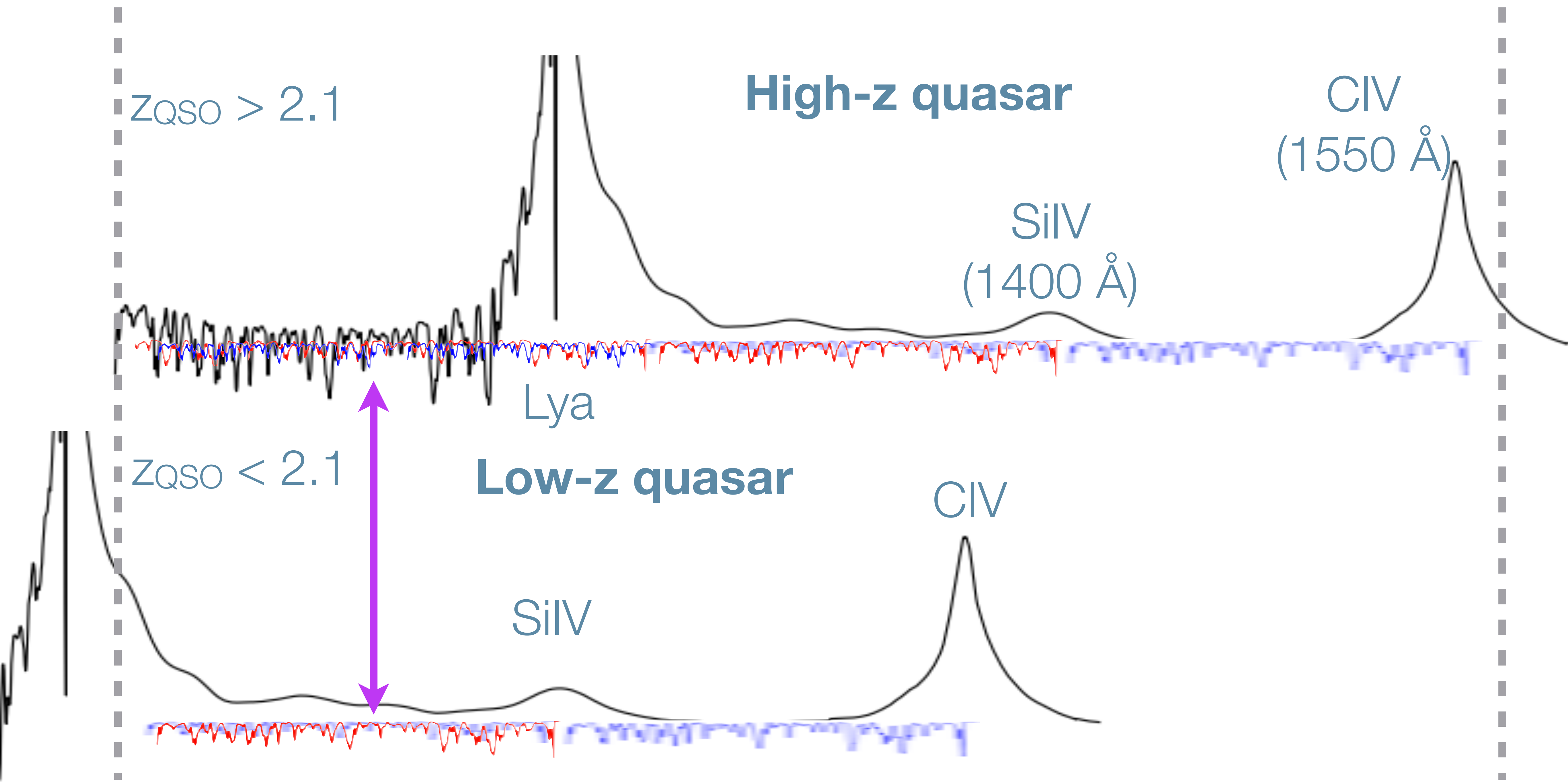



$$b_{\mathrm{CIV}}(z_{\mathrm{eff}} = 2.00) = -0.0144 \pm 0.0010$$

Blomqvist et al. 2018

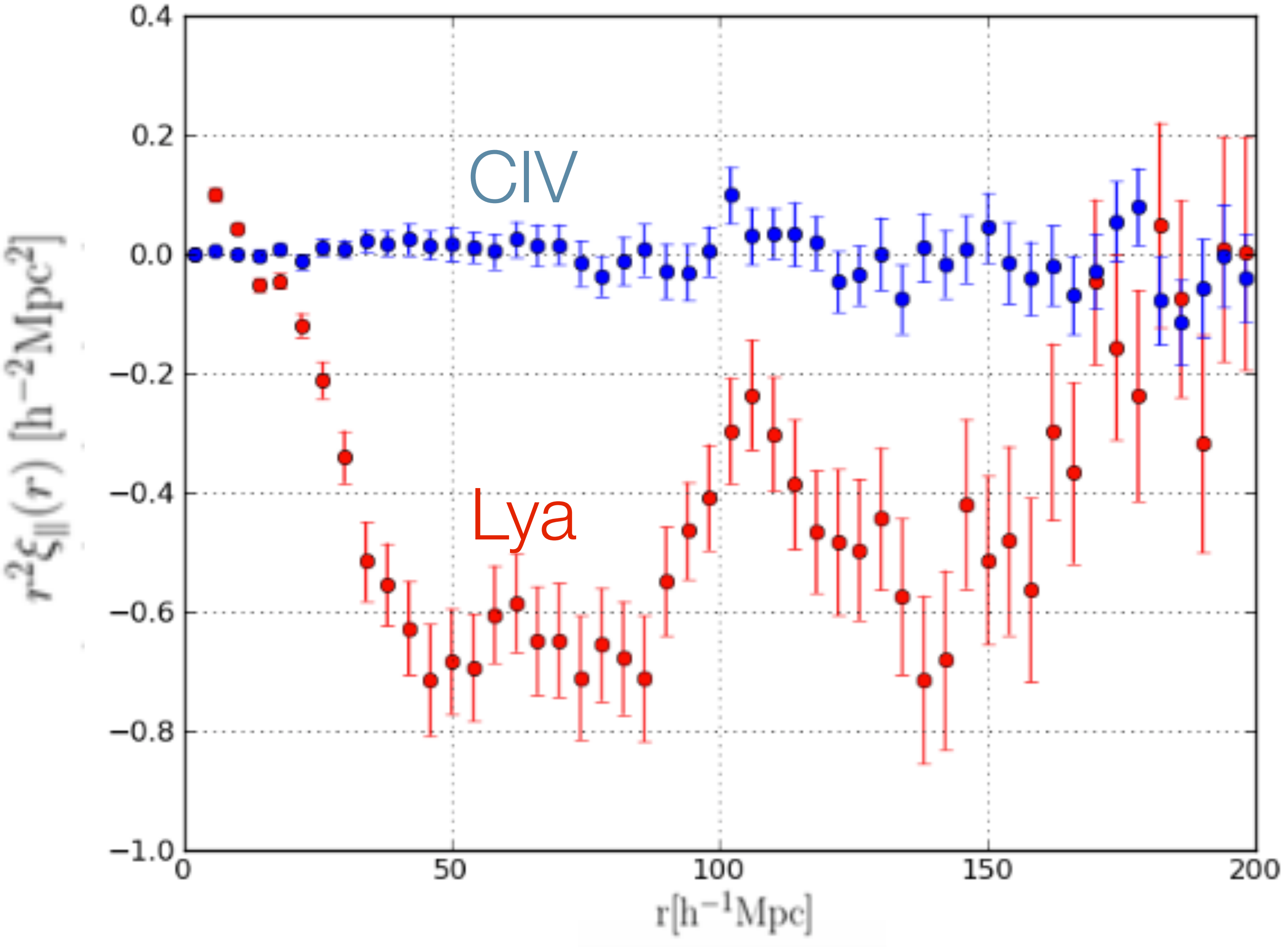
How about metals in the Lyman-alpha forest?

# Metals in the Lyman-alpha forest



# Metals in the Lyman-alpha forest

Radial 3D correlations



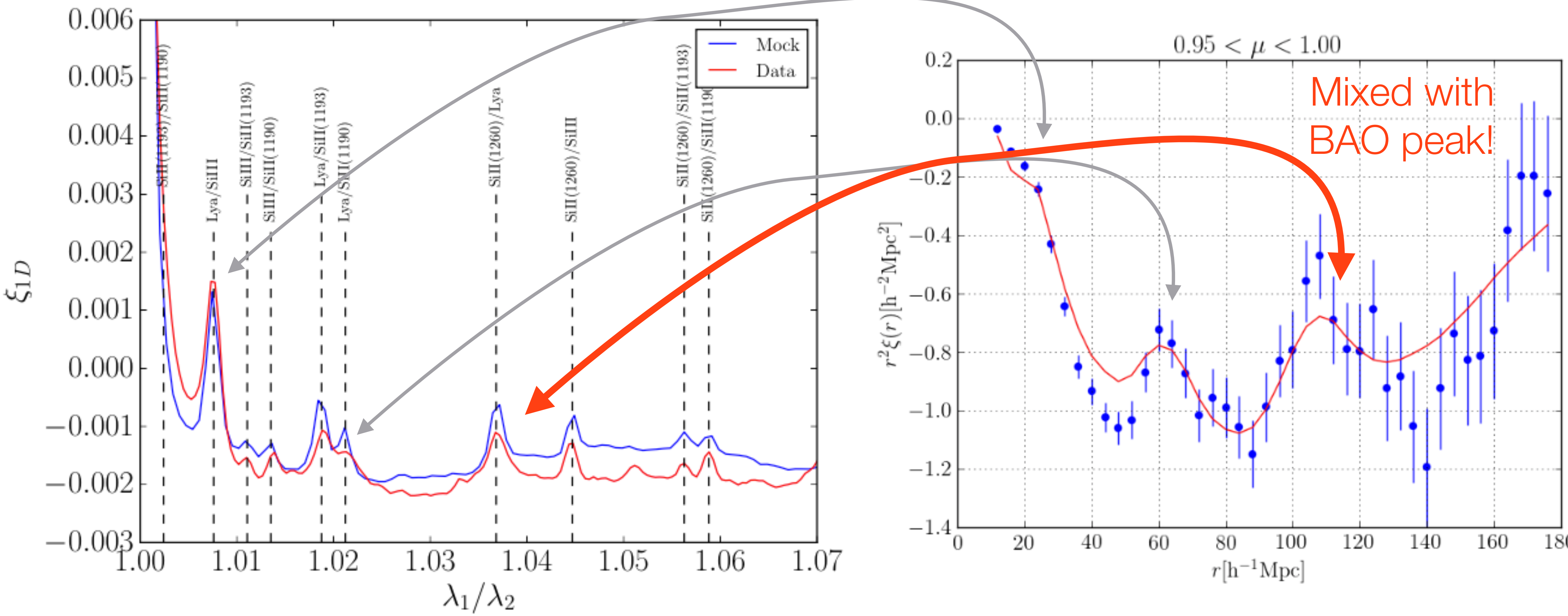

Impact of CIV in the Lyman-alpha forest clustering is negligible

That’s not all with metals…

# Metals in the Lyman-alpha forest

Same line-of-sight (or 1D) correlations

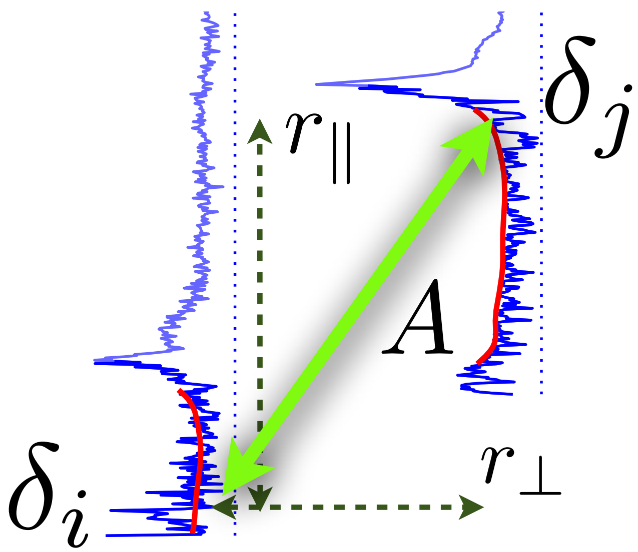
Different line-of-sight (or 3D) radial correlations

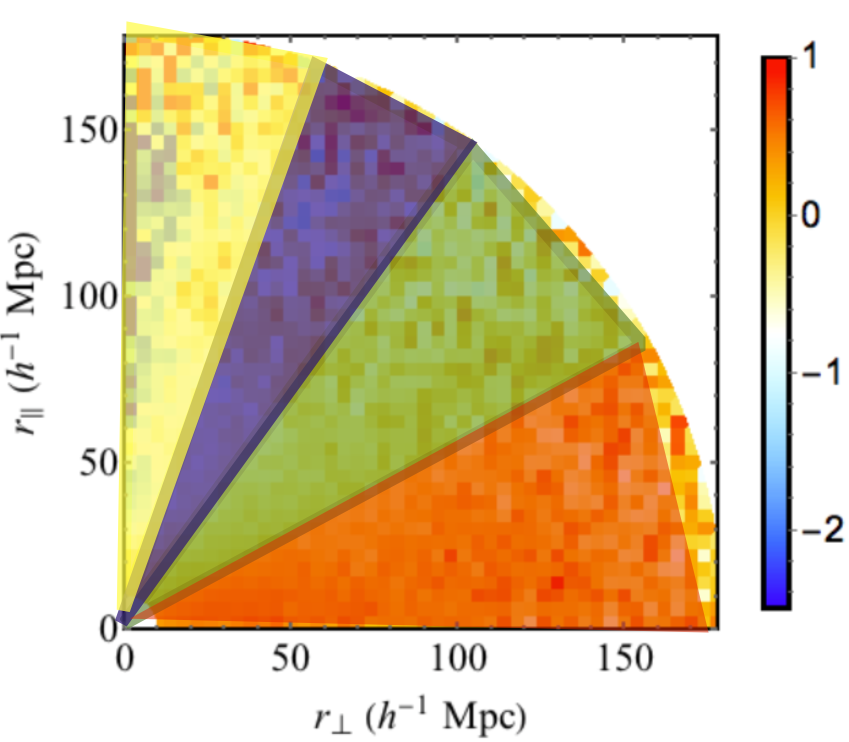


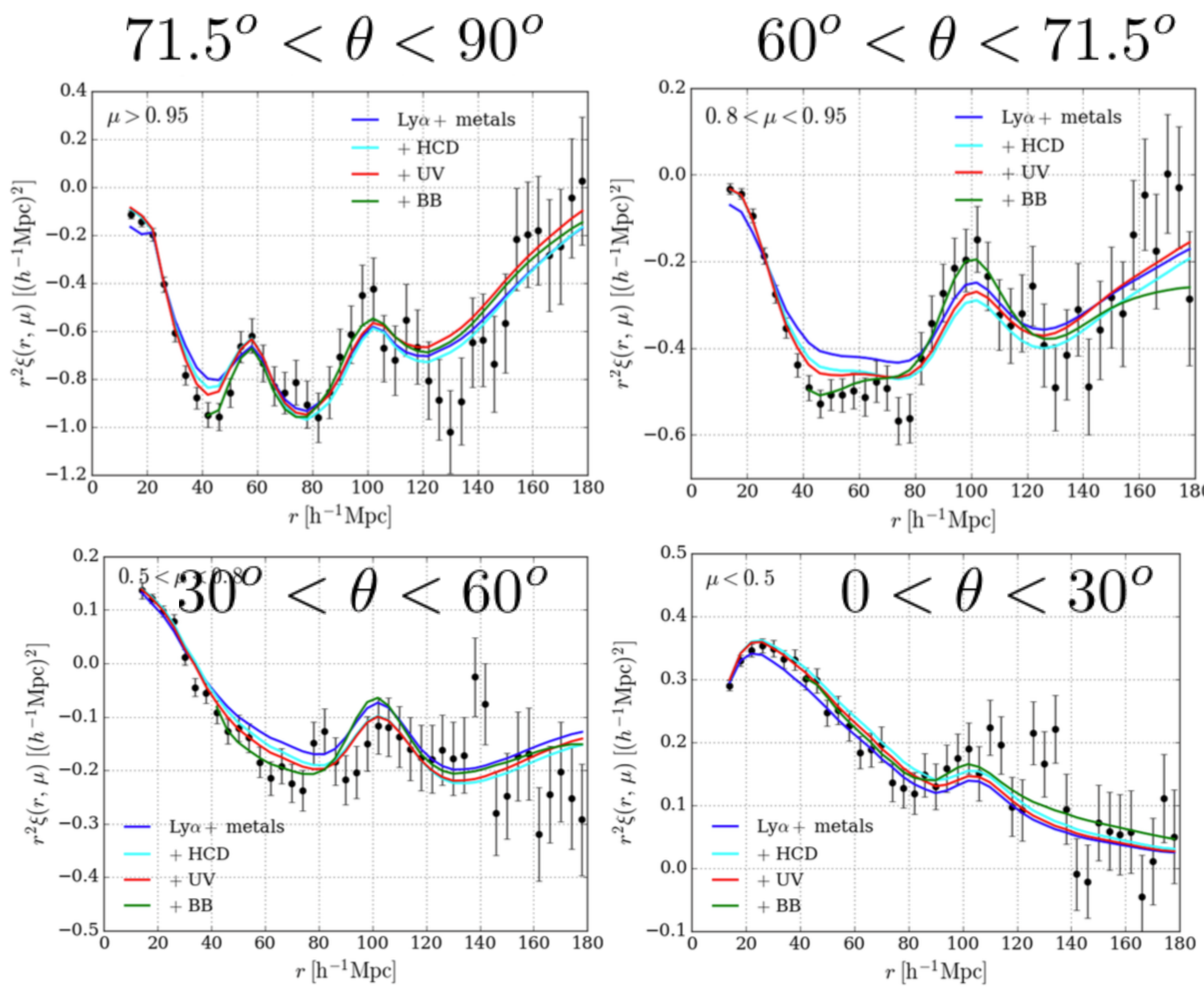

We marginalize over metal correlations (2 parameters per transition)

Impact on BAO: more robust + increase of errors by 25%

# Lyman-alpha Auto-Correlation function




Bautista et al. 2017

# UV background **fluctuations**

Gontcho A Gontcho et al. 2014

$$\frac{\mathrm{d}X}{\mathrm{d}t} \to 0$$

Photo-ionization Equilibrium

$$\frac{\mathrm{d}X}{\mathrm{d}t} = \alpha_{\rm rec} n_e (1 - X) - \gamma_c n_e X - \Gamma X$$

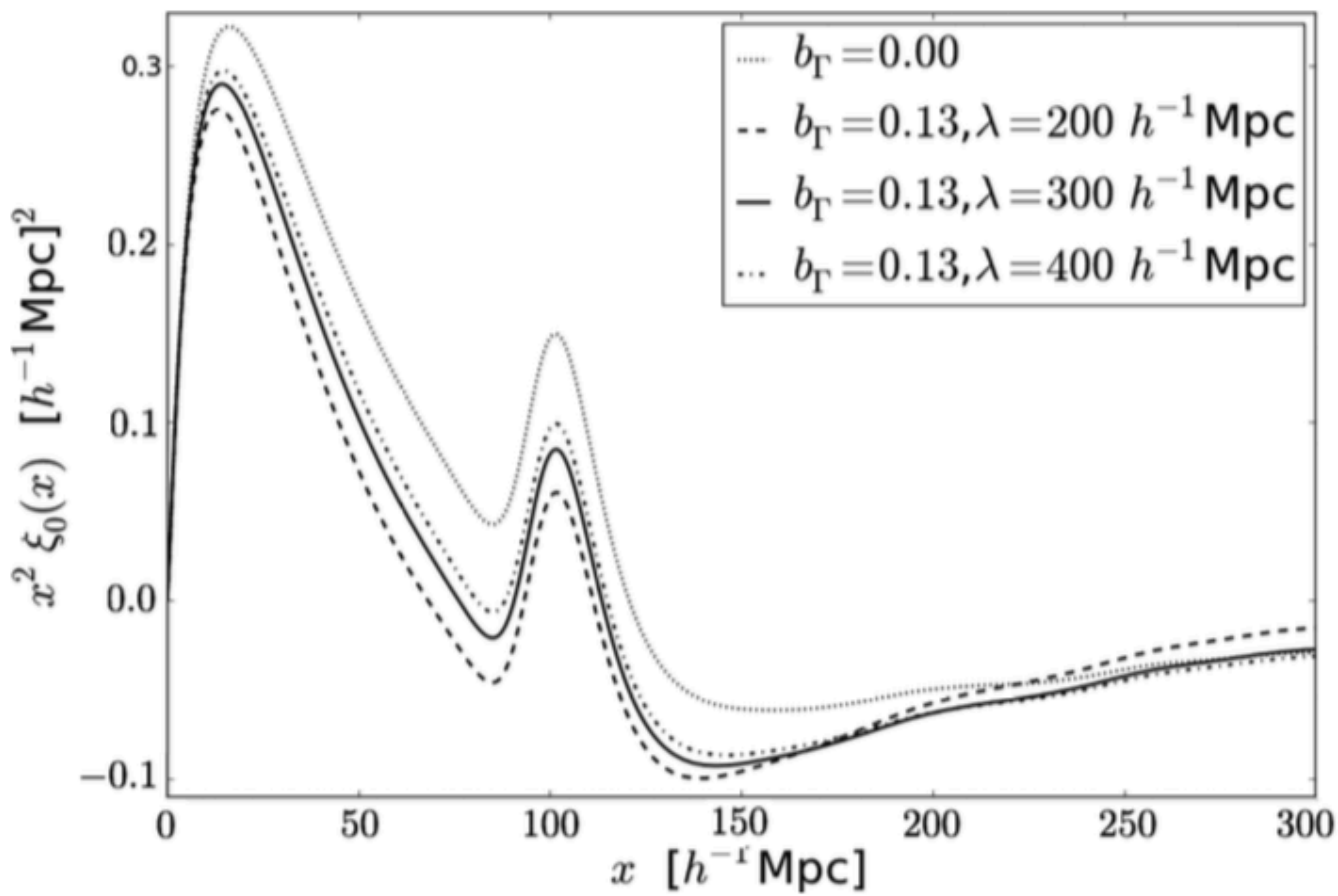
$$X \approx \frac{\alpha_{\rm rec} n_e}{\Gamma}$$

$$\delta_\alpha(\boldsymbol{x}) = b_\delta \delta(\boldsymbol{x}) + b_\Gamma \delta_\Gamma(\boldsymbol{x}),$$

$$\delta_\Gamma(\boldsymbol{x}) = \Gamma(\boldsymbol{x})/\bar{\Gamma} - 1$$

# UV background **fluctuations**

Gontcho A Gontcho et al. 2014



# List of tests on systematic errors

## Astrophysical systematics

- contamination by metals: Si, C
- contamination by DLAs, or BALs
- contamination by galactic absorption
- effect of UV background fluctuations
- effect of continuum fitting

## Instrumental systematics

- impact of flux calibration
- impact of sky residuals
- impact of fiber cross-talk
- impact of extraction

All tests were performed on data and mock catalogs

# Summary

- Lyman-alpha forest is a great tracer of the matter in the intergalactic medium
- The forest is caused by small amounts of neutral hydrogen in a post-reionization era
- BOSS and eBOSS observed hundreds of thousand forests
- Correlation function is affected by lots of interesting physics
- BAO can be measured to 3% precision