Large scale structures with Lyman-α forests

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SDSS

Contents

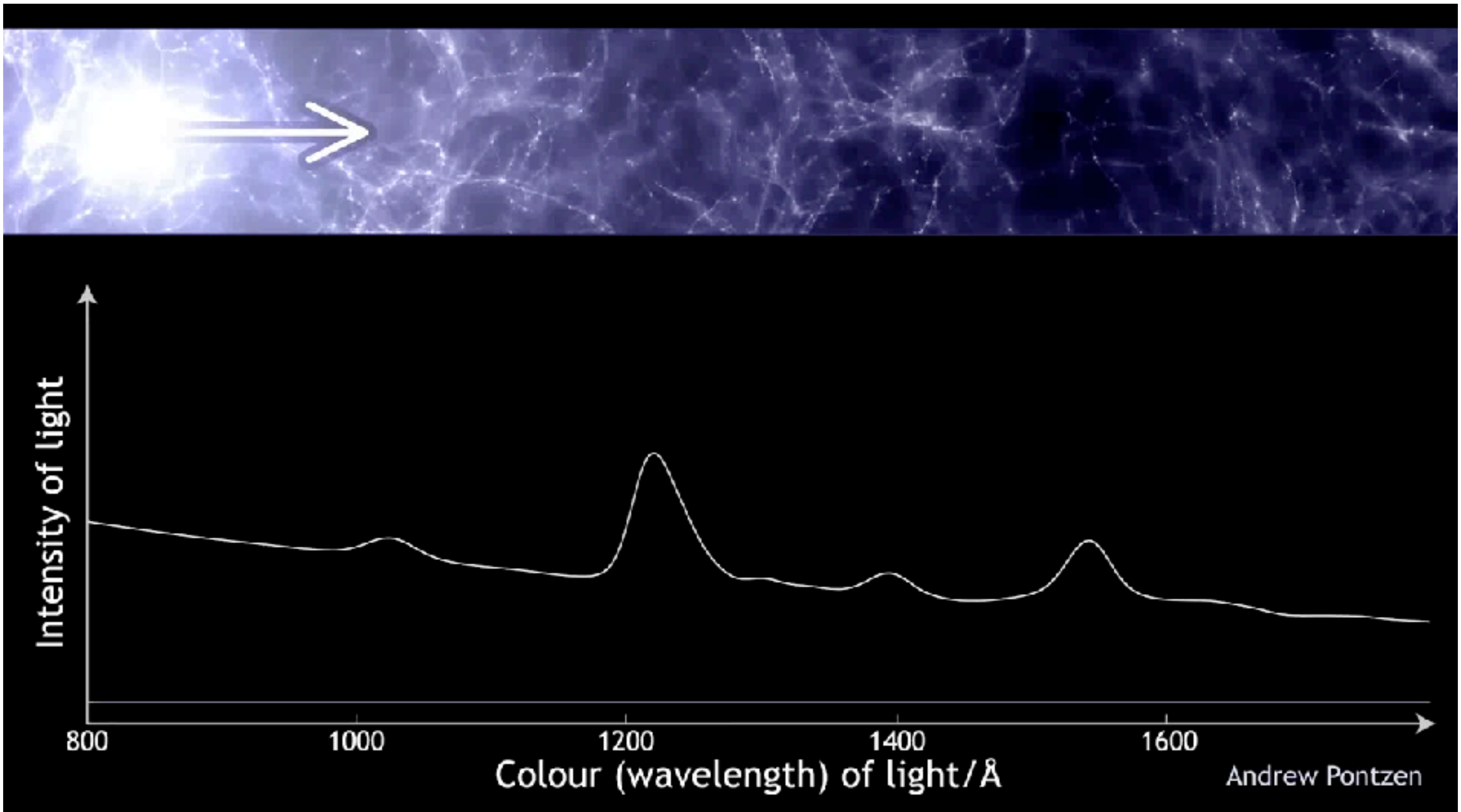
- Quick summary
- Physics of the Lyman-alpha forest
- Simulating forests in a cosmological context
- Link to large-scale structures
- One-dimensional clustering and neutrino masses
- Three-dimensional clustering, BOSS and BAO
- Near future

Overview of clustering using Lyman-alpha forests

(in 10 min?)

Overview of clustering using Lyman-alpha forests

Quasar spectrum



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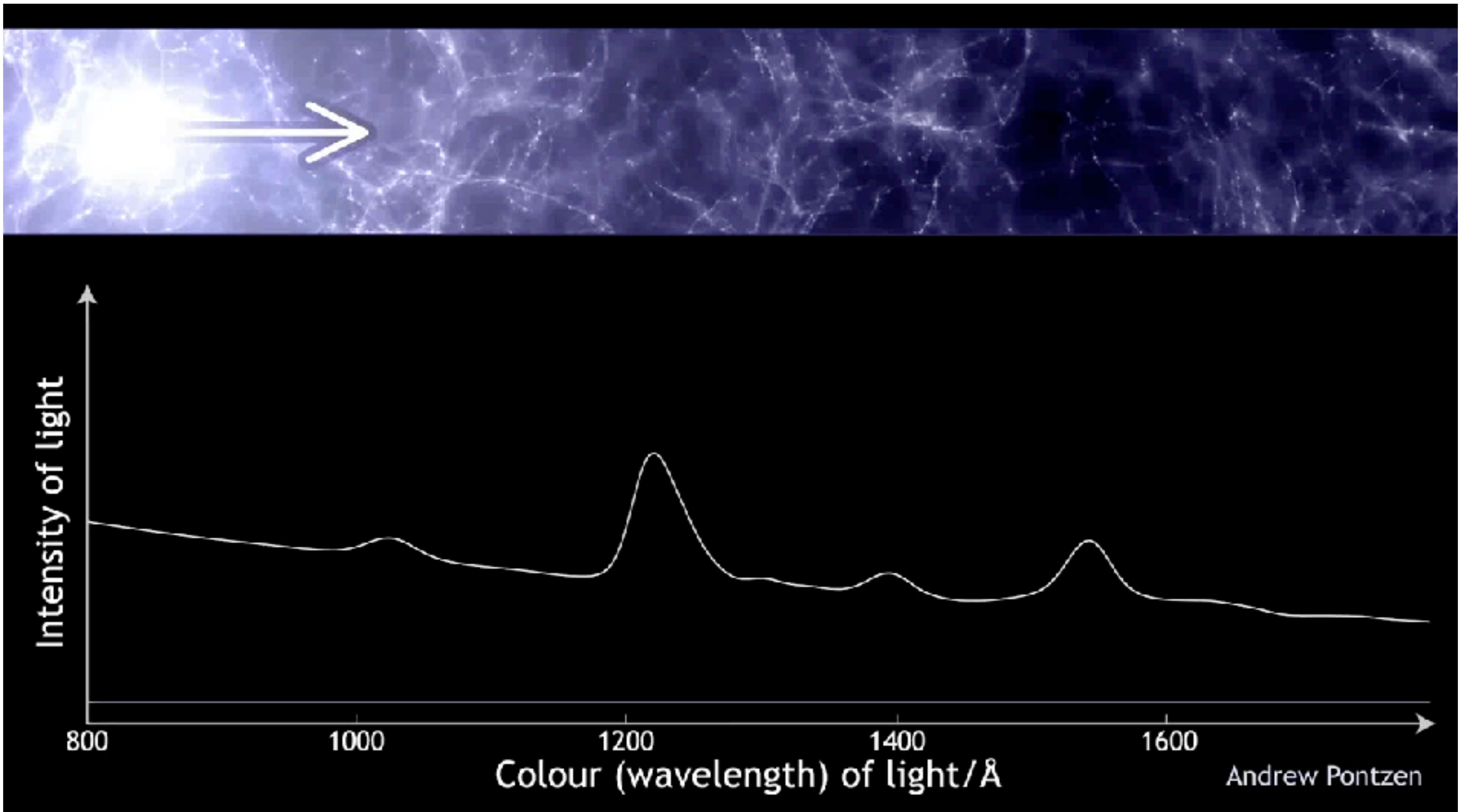
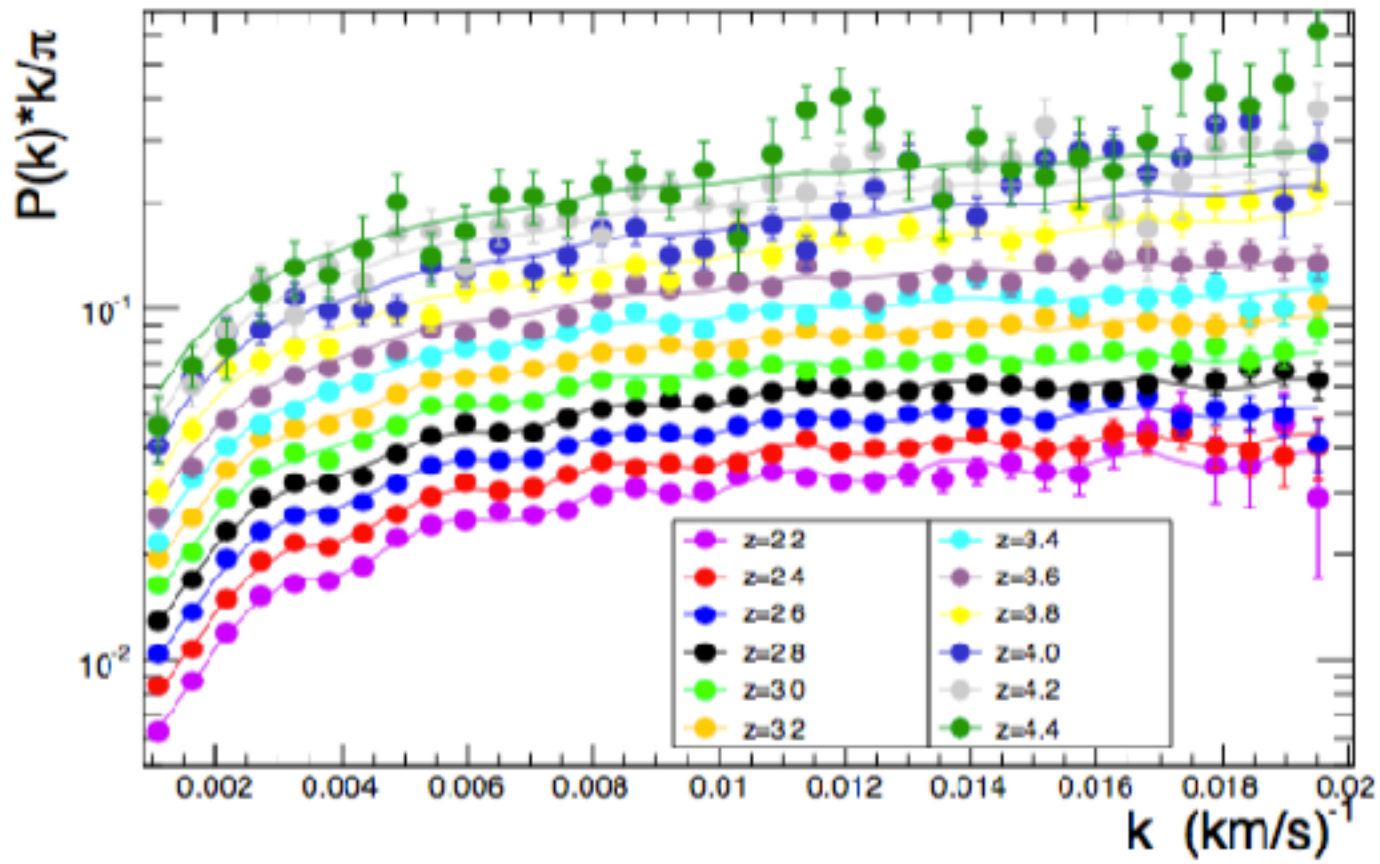
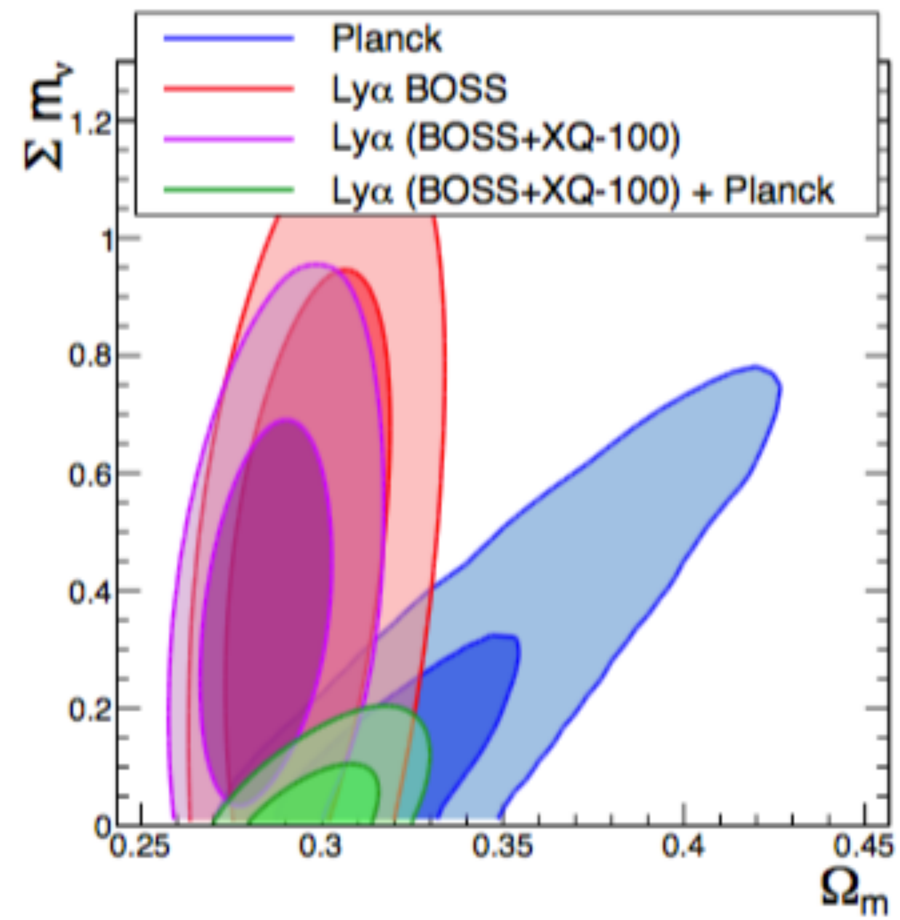


Overview of clustering using Lyman-alpha forests

1D flux power-spectrum



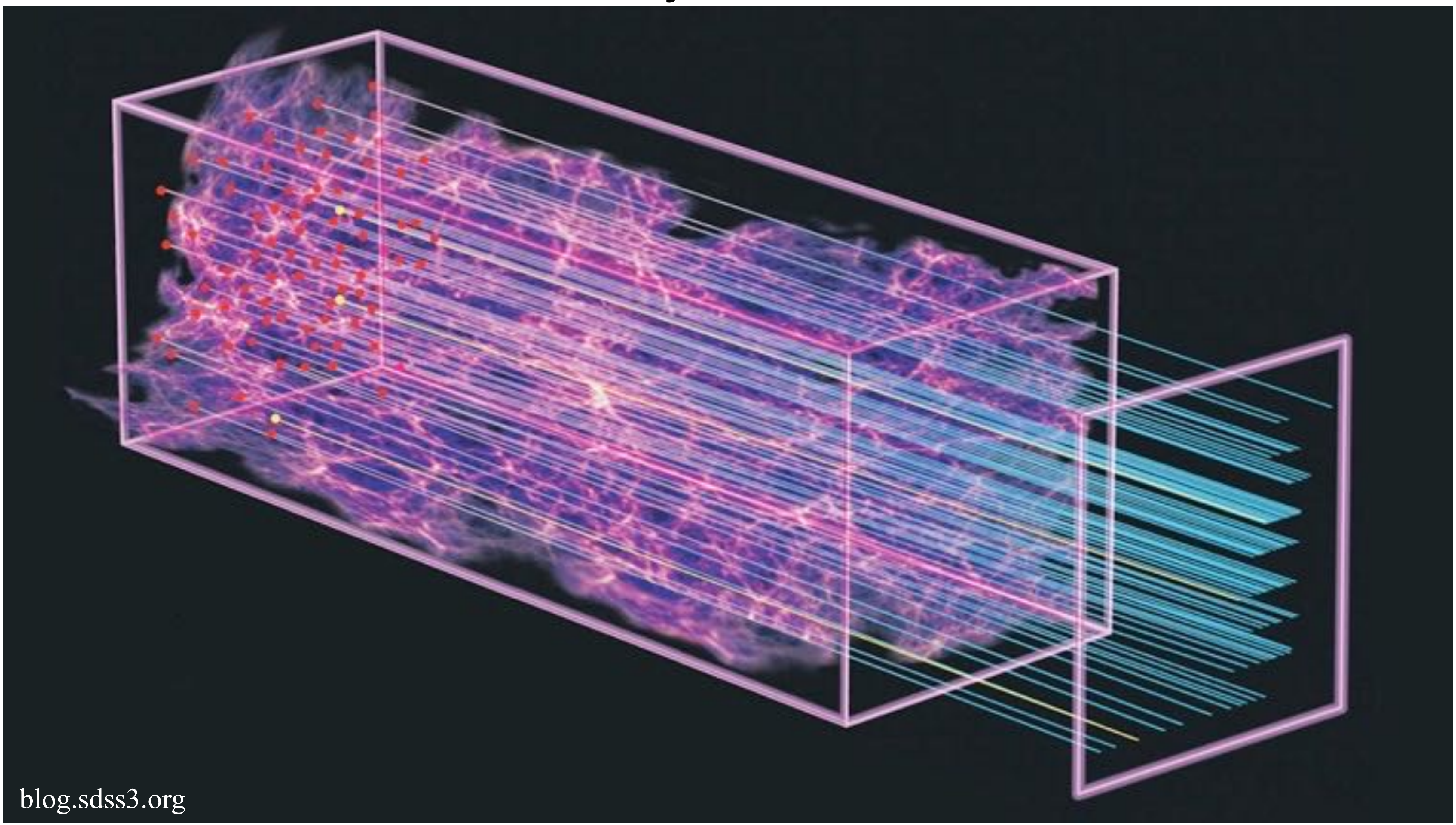
Neutrino masses



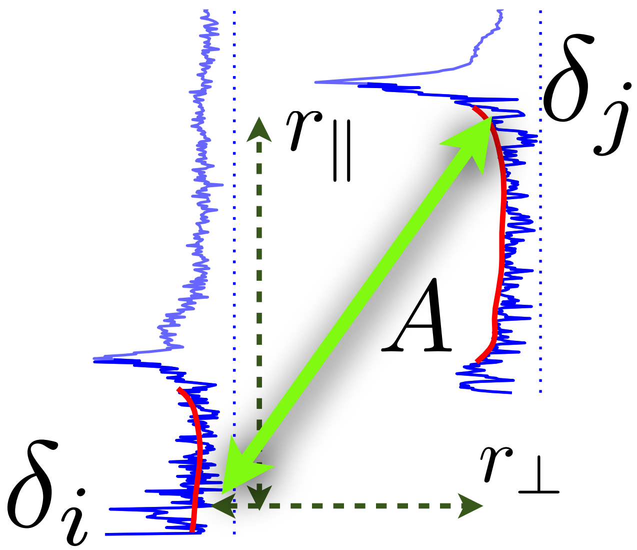
Yèche et al. 2017

Overview of clustering using Lyman-alpha forests

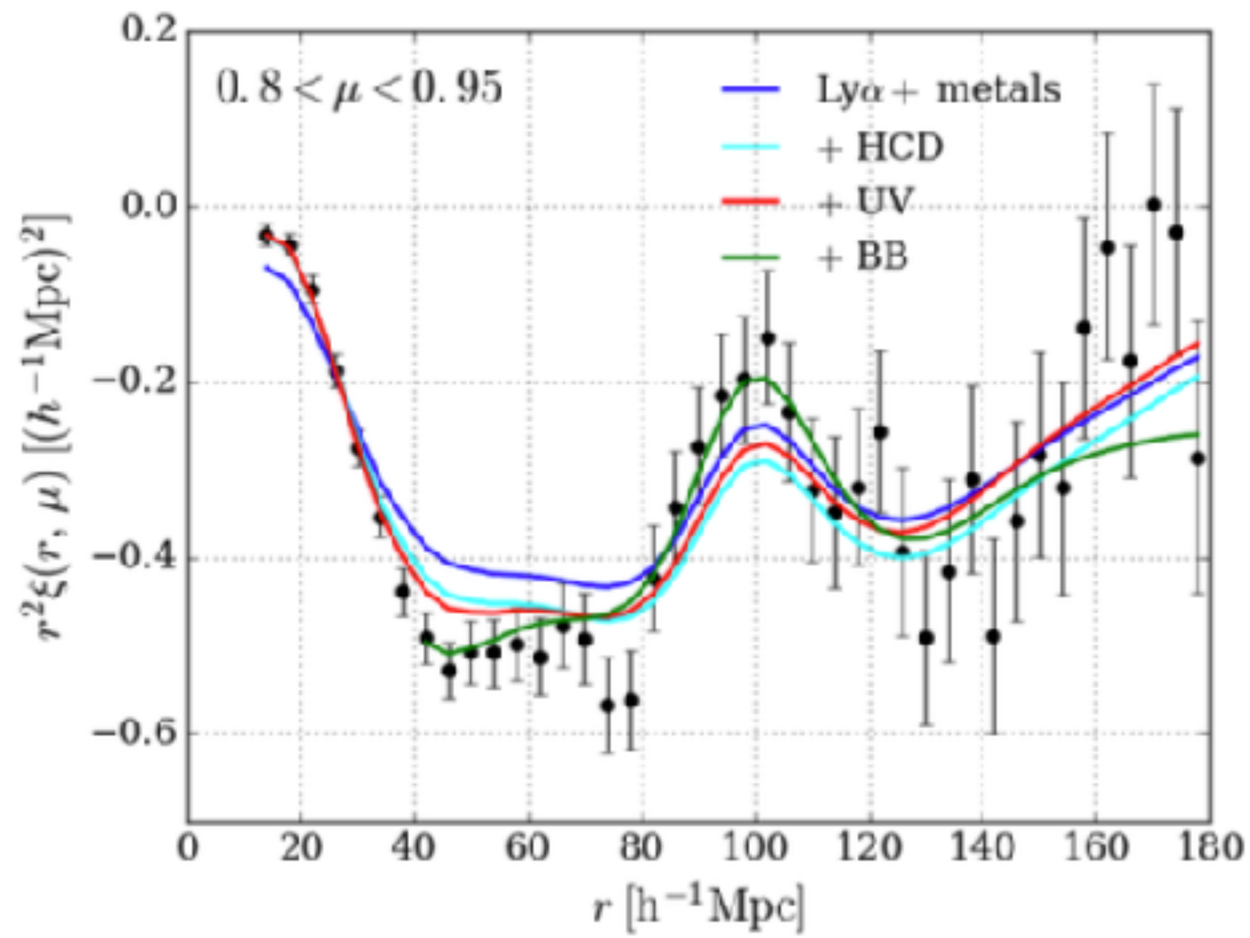
Survey of forests

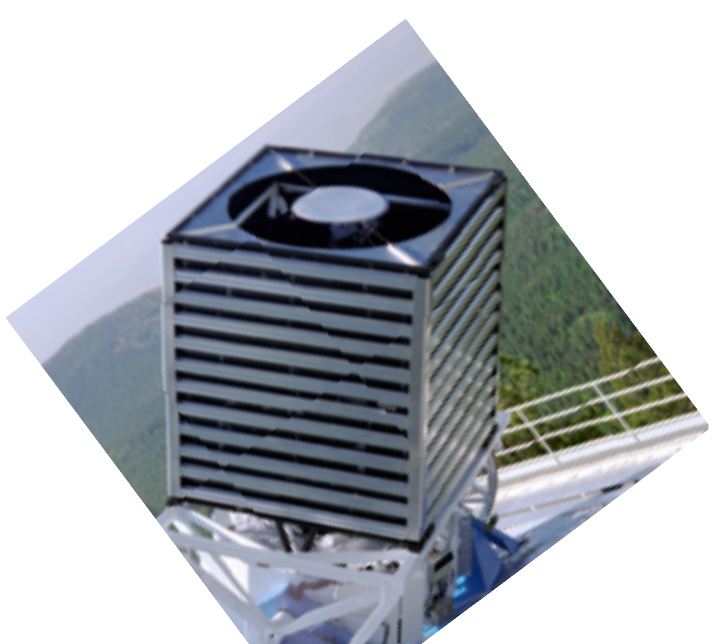


Overview of clustering using Lyman-alpha forests



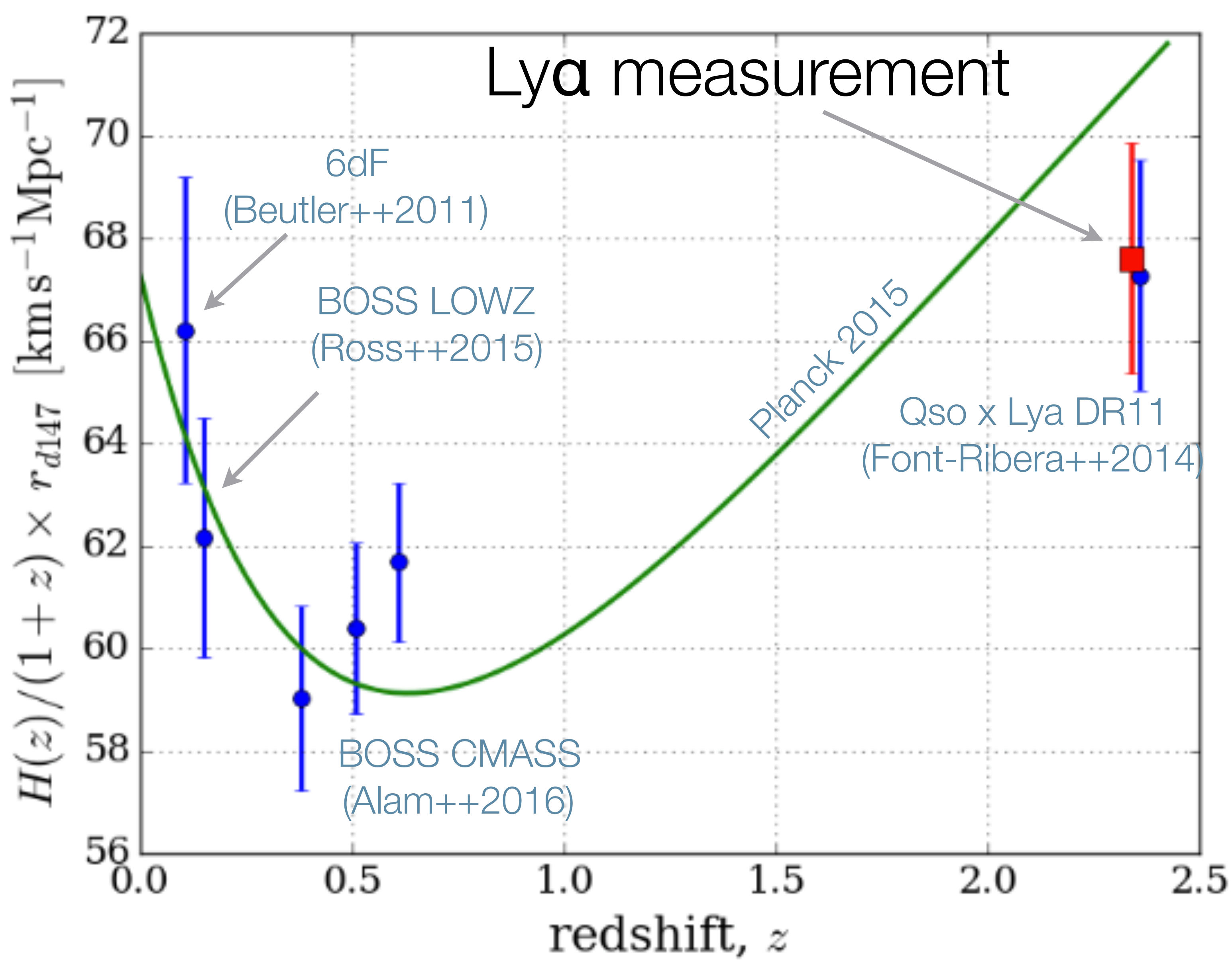
Correlation function $\hat{\xi}(r_\perp, r_\parallel) = \langle \delta_i \delta_j \rangle$





Overview of clustering using Lyman-alpha forests

Expansion rate with BAO



Overview of clustering using Lyman-alpha forests

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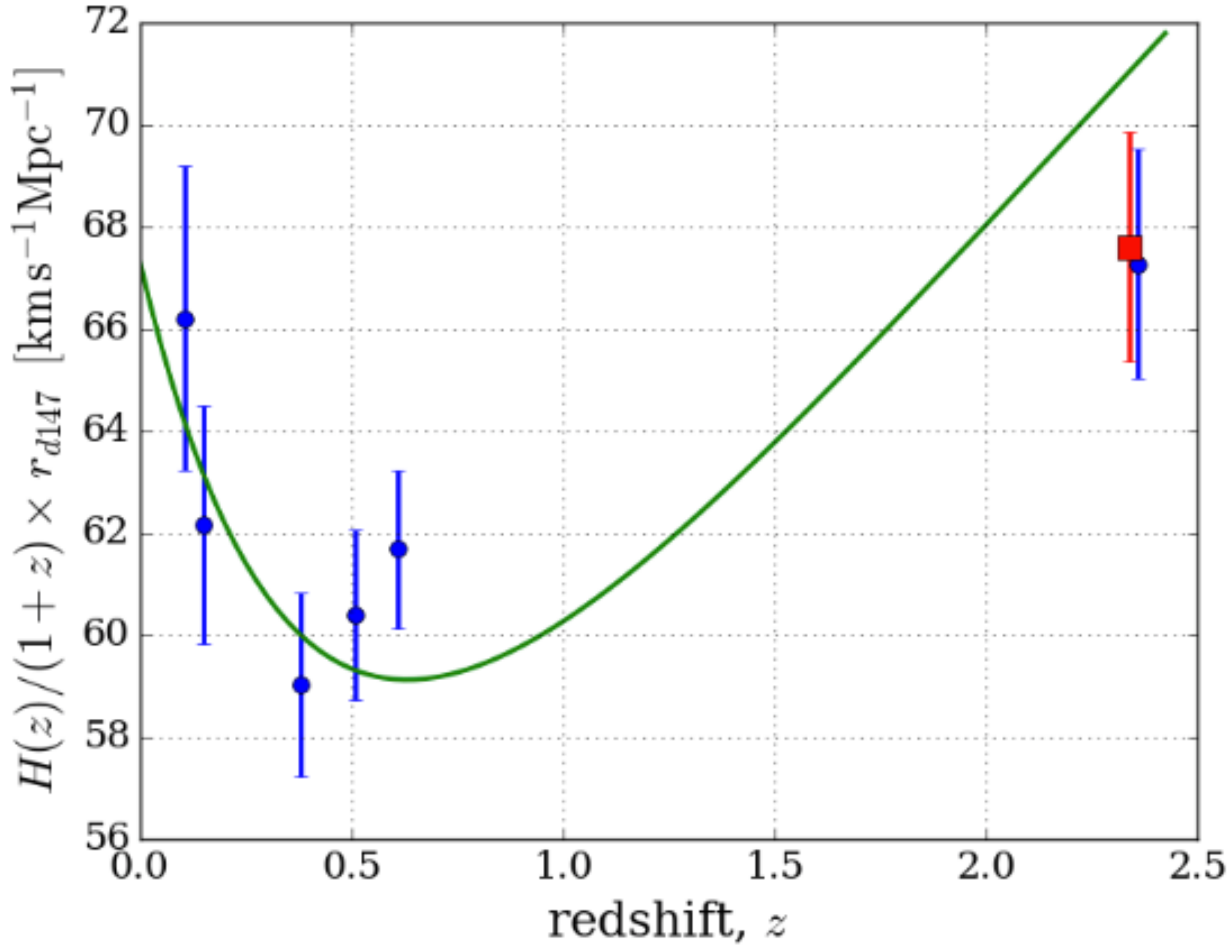

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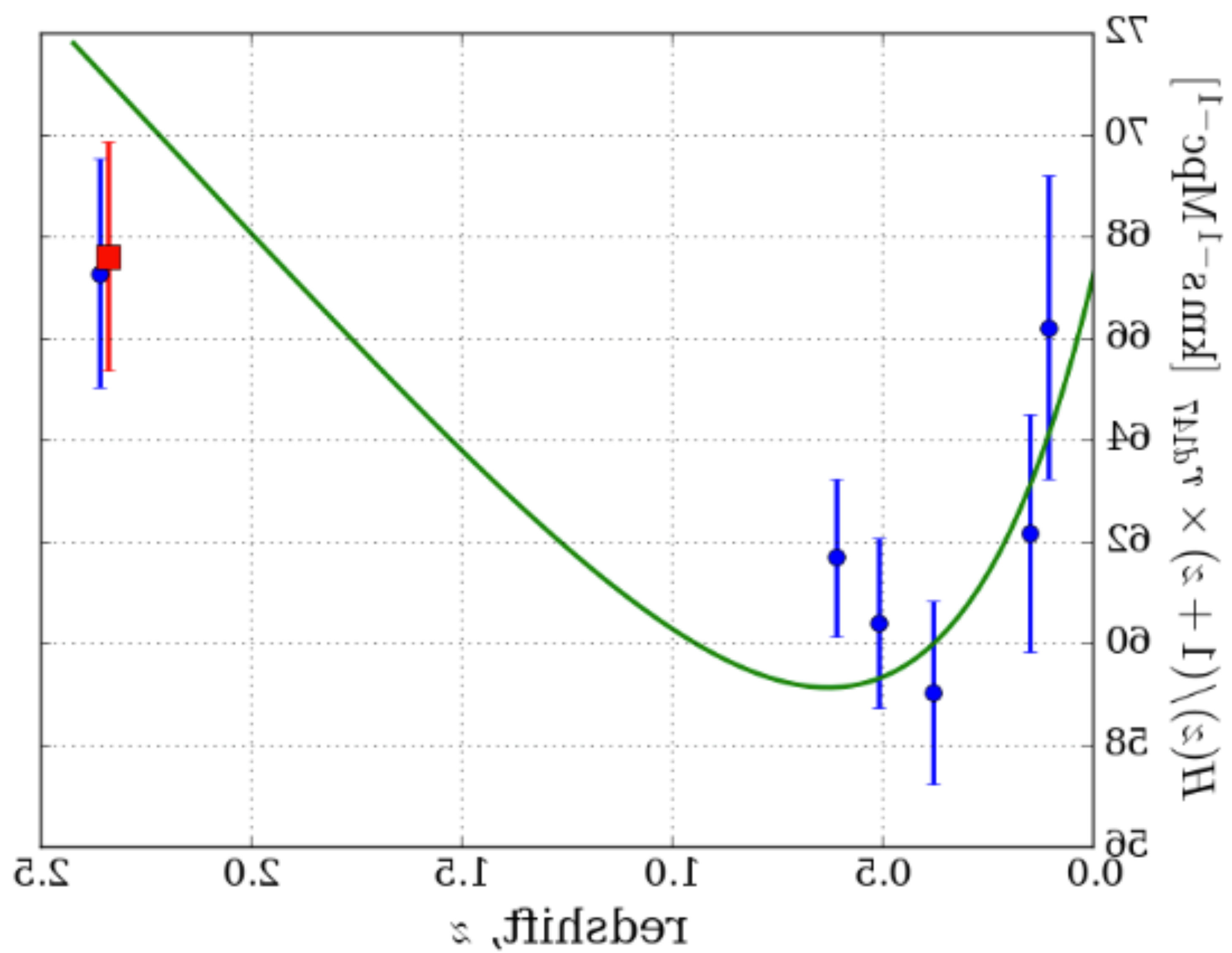

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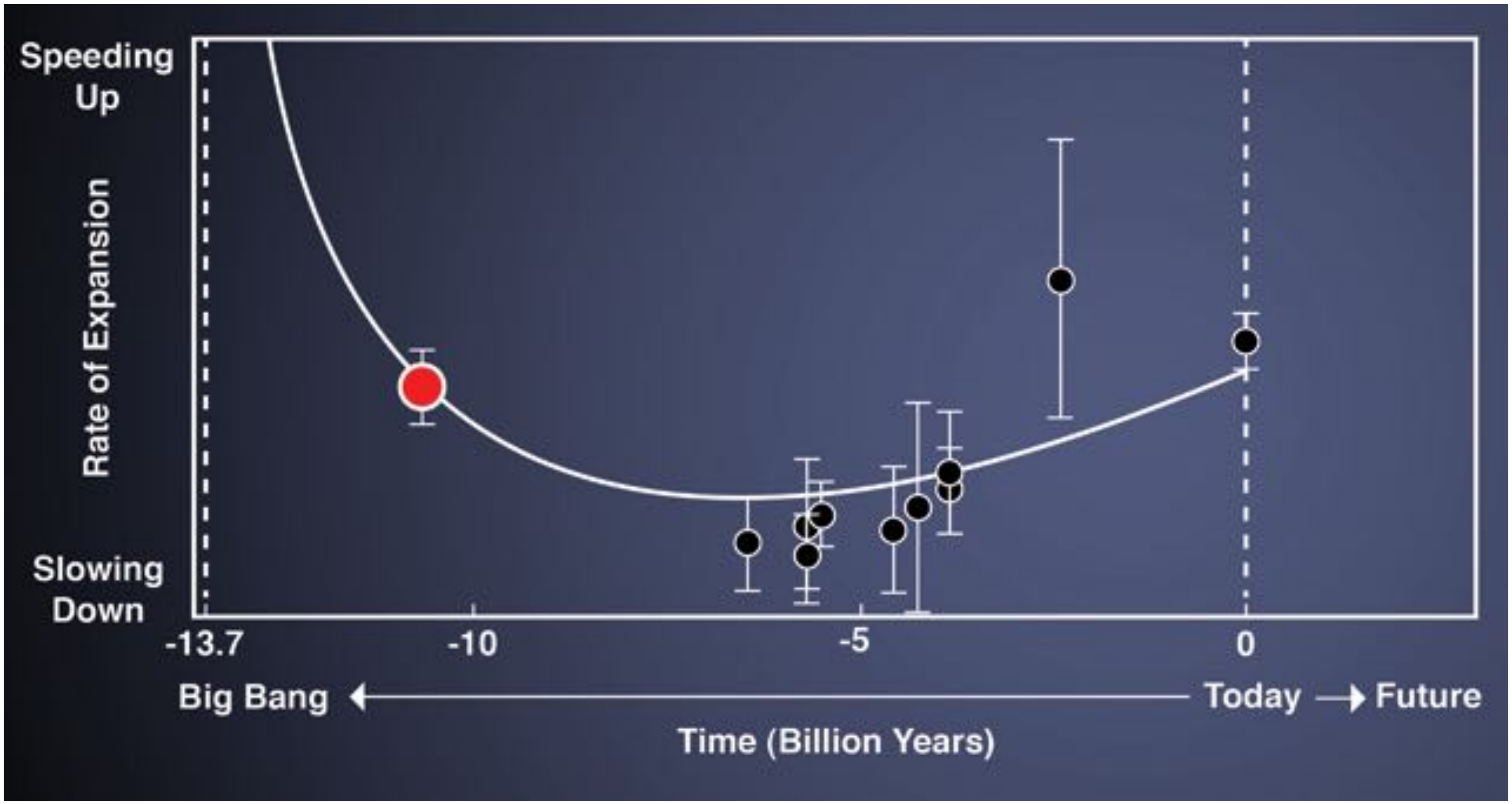

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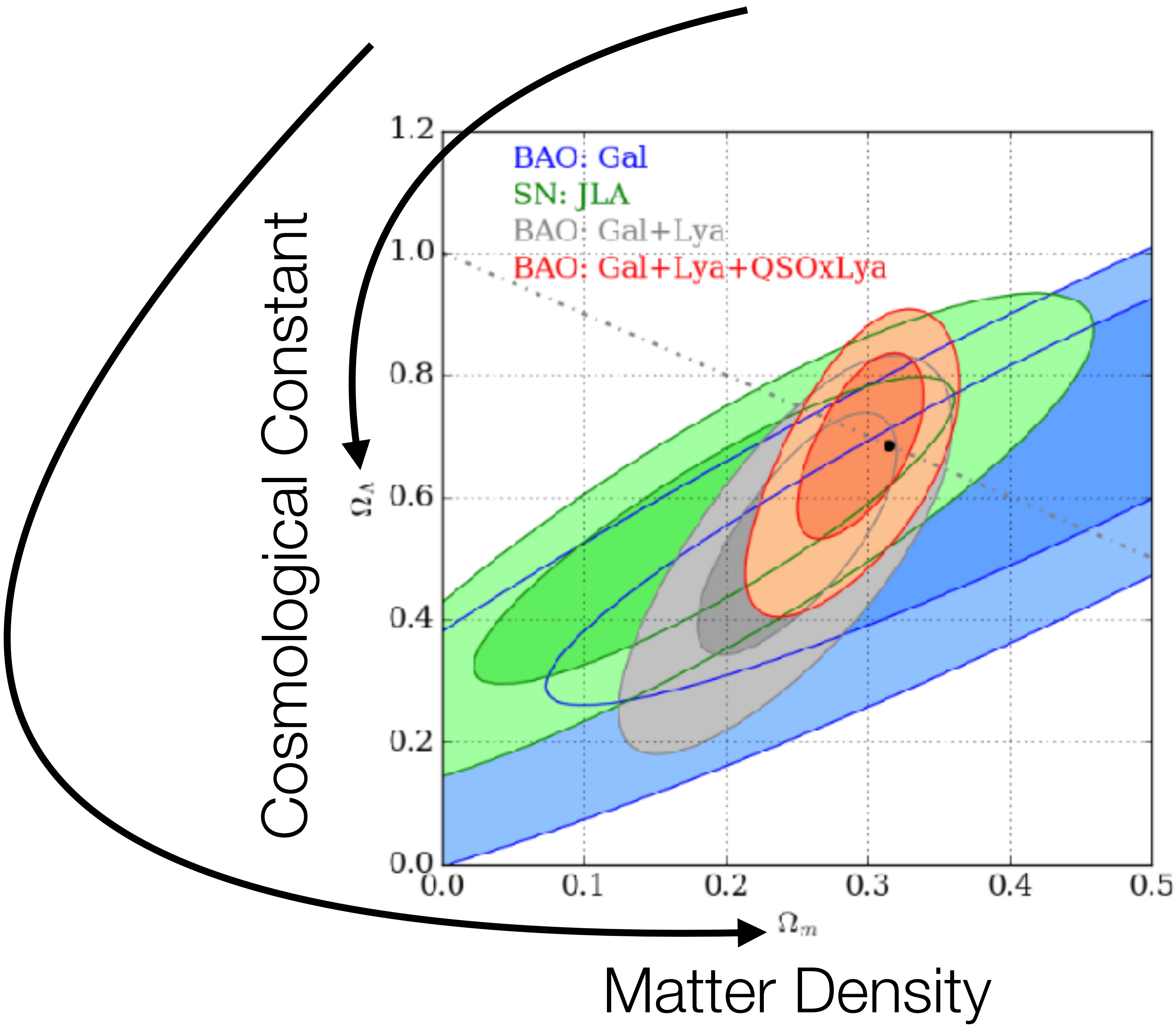
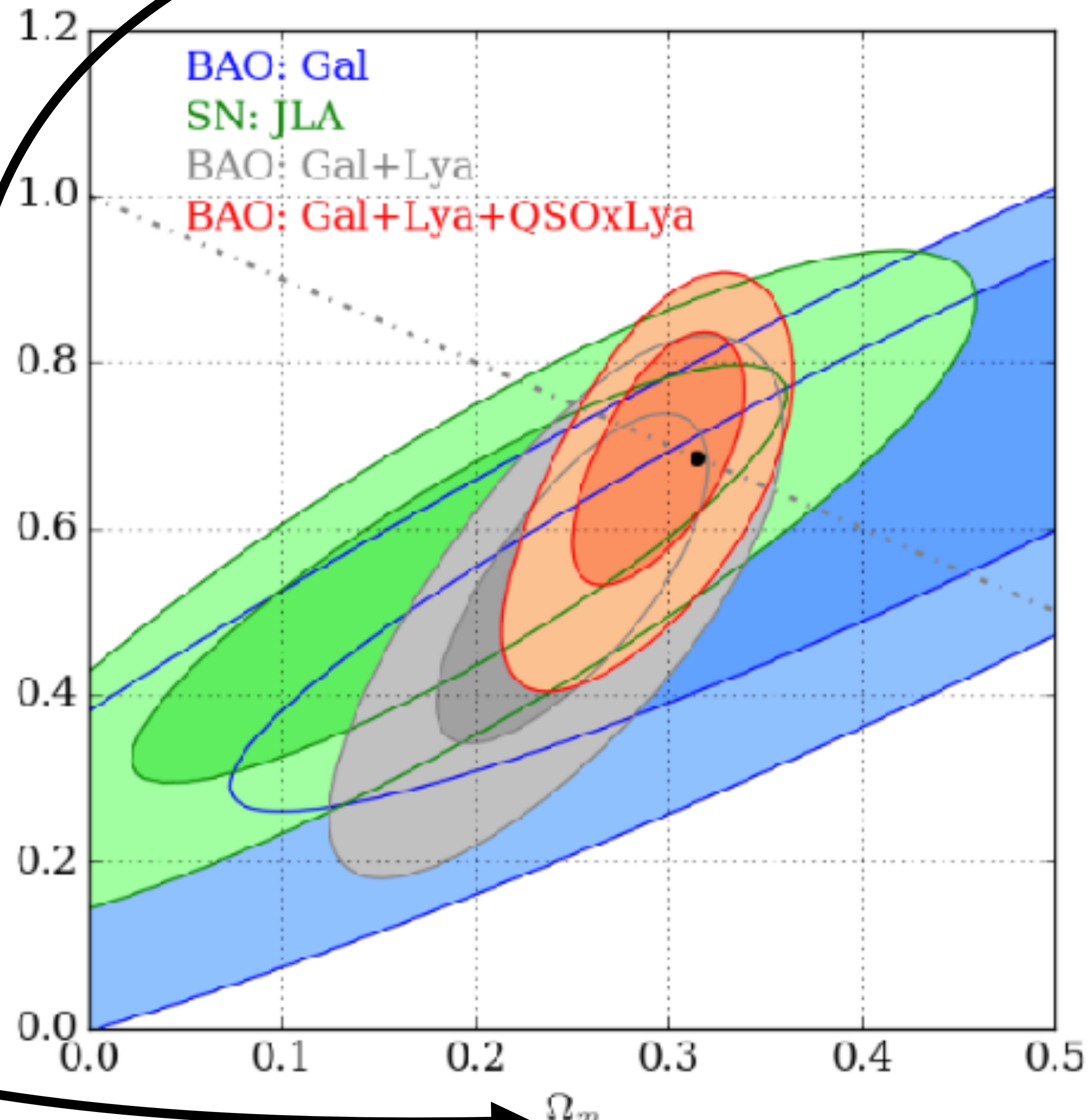


Overview of clustering using Lyman-alpha forests

$$H^2(z) = H_0^2\left[\Omega_m(1+z)^3 + \Omega_\Lambda + \Omega_k(1+z)^2 + \Omega_r(1+z)^4\right]$$

Cosmological Constant

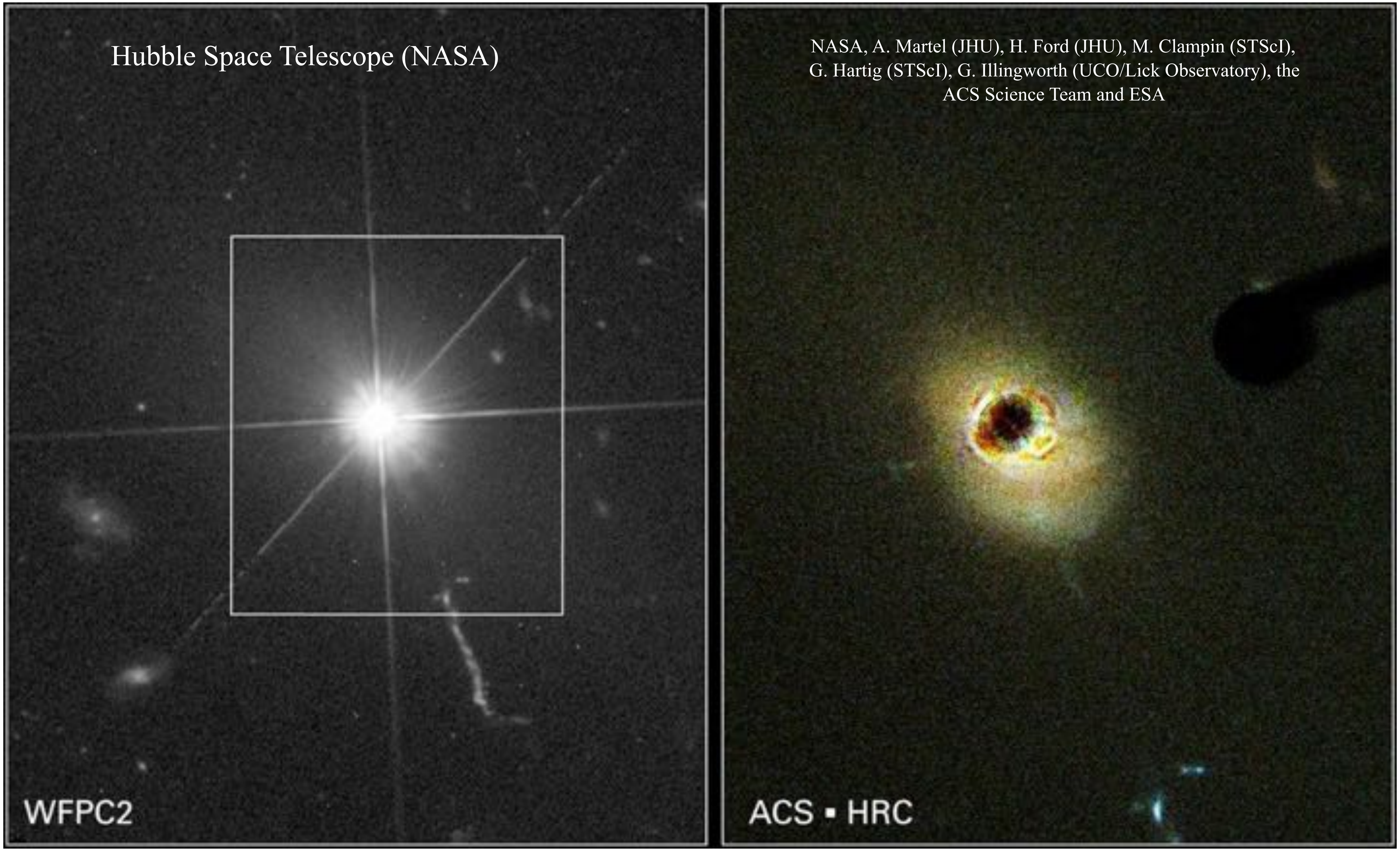


Matter Density

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 !

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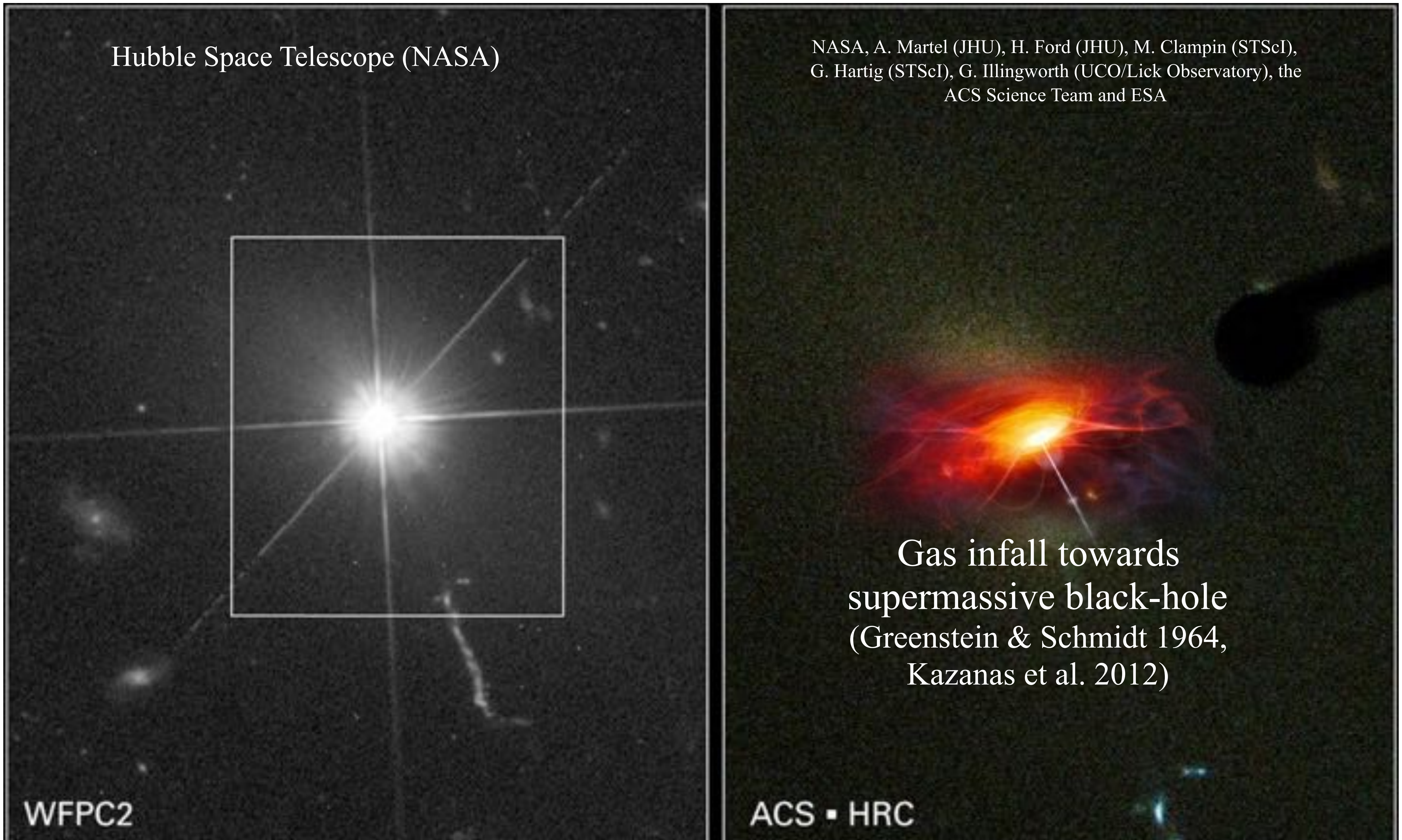

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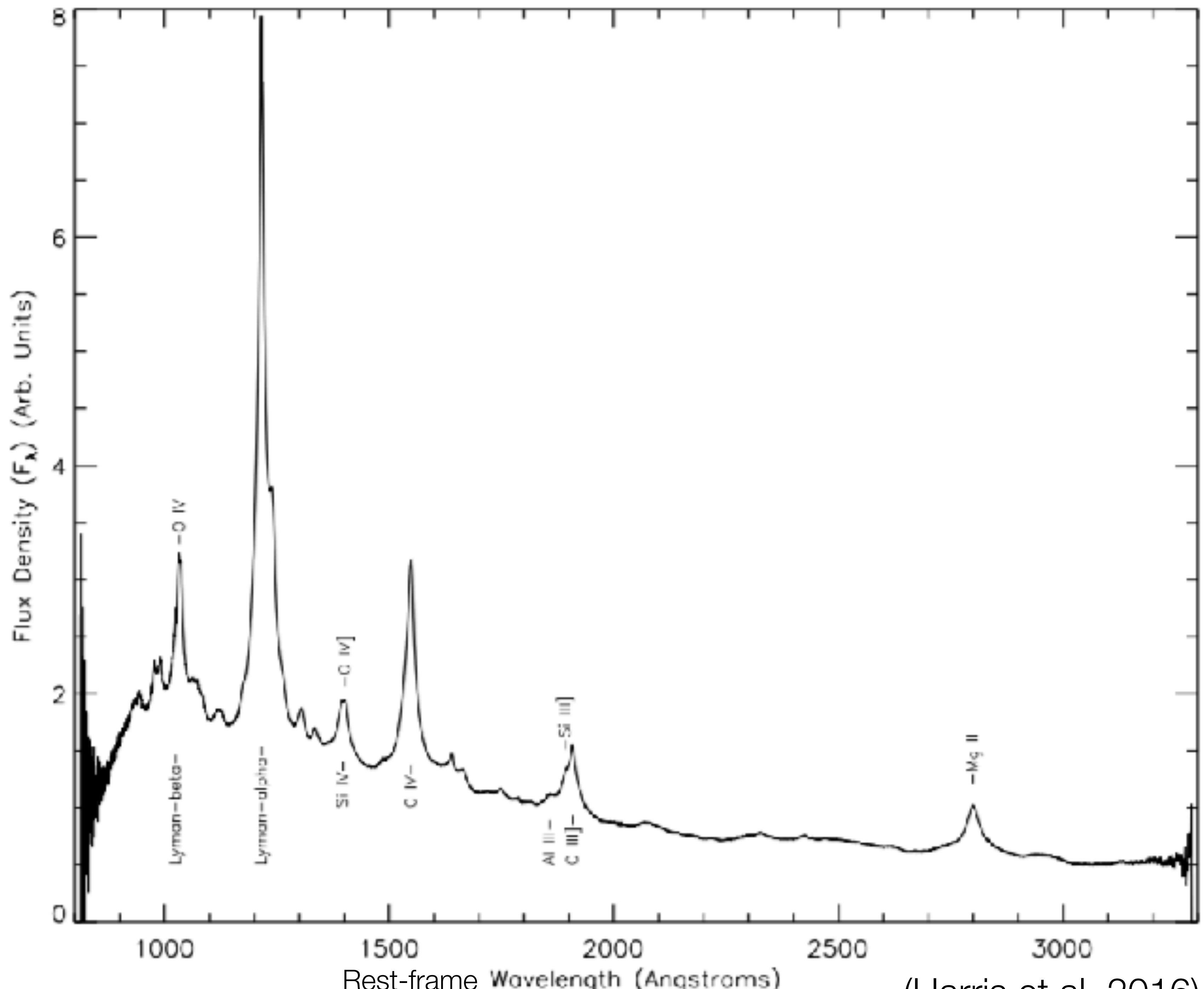
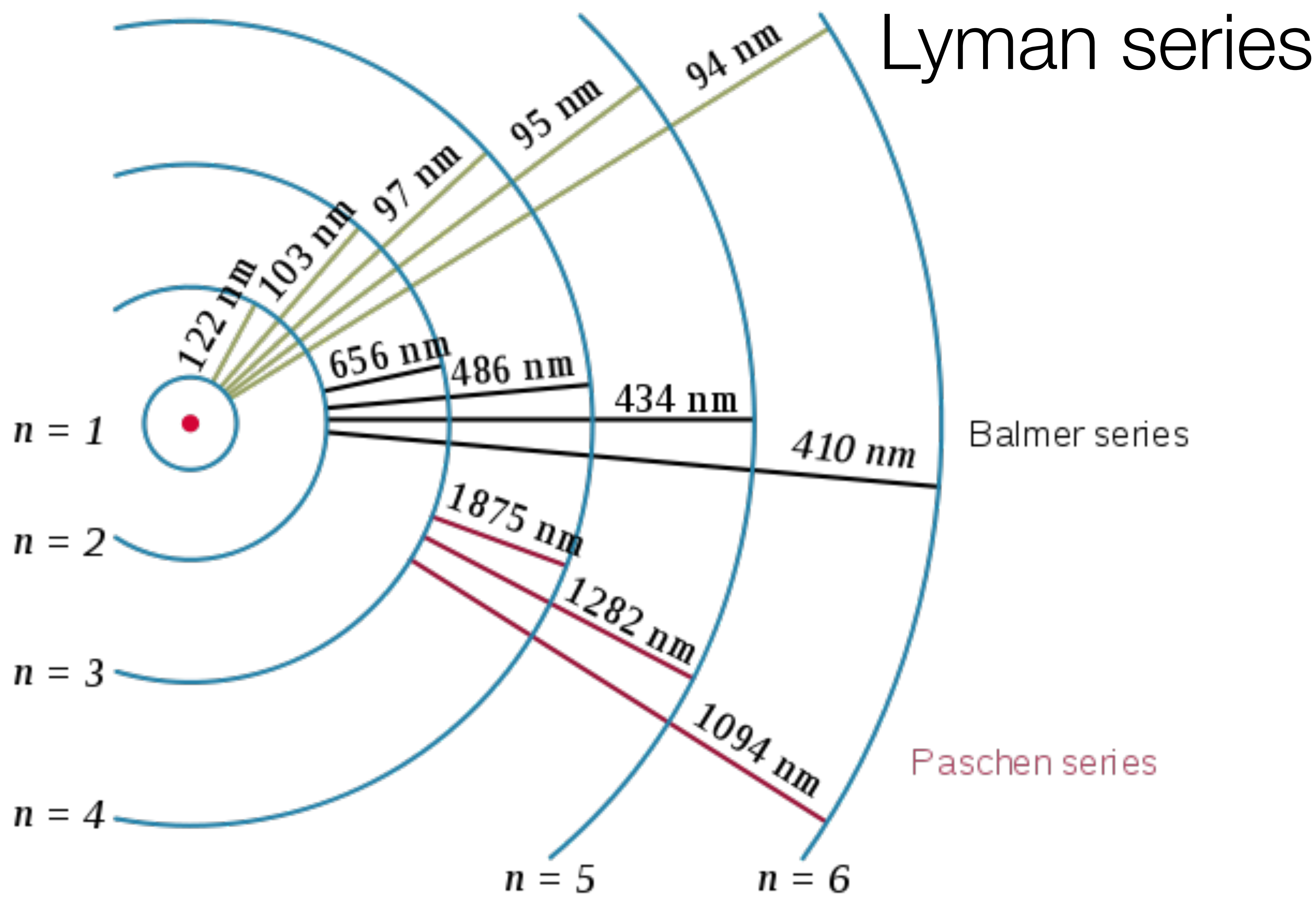
Quasars: the back light sources

Quasar ‘unabsorbed’ spectra



(Harris et al. 2016)

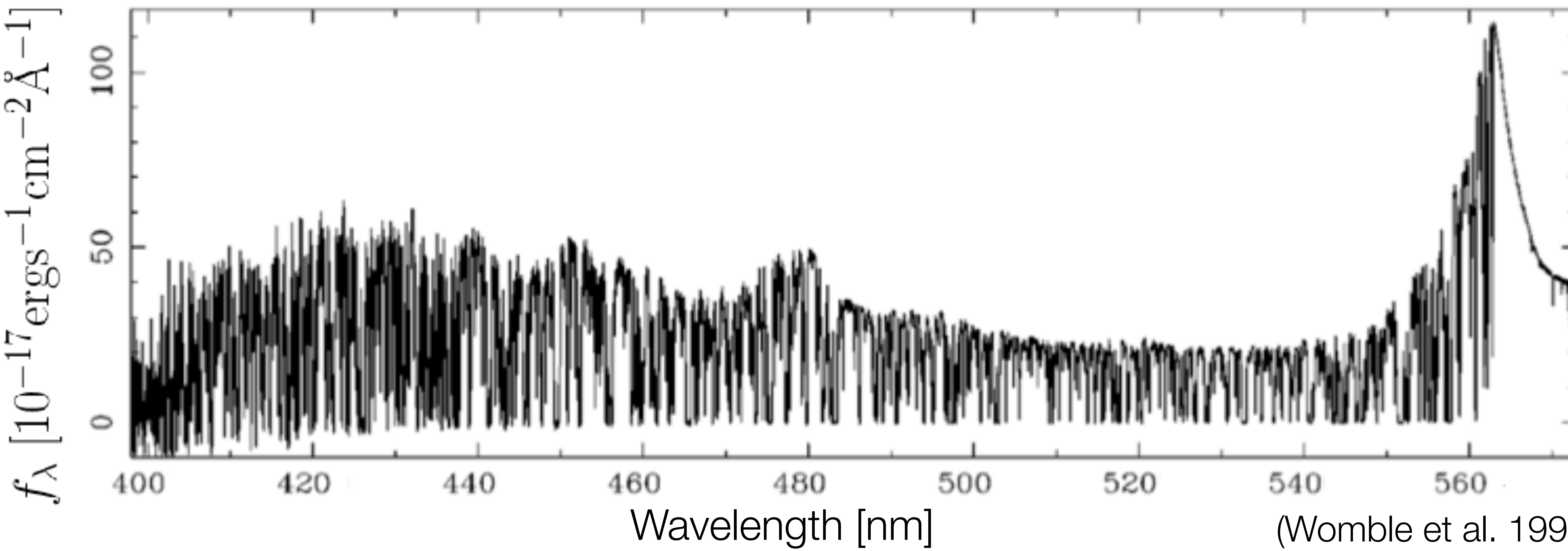
Hydrogen atom transitions



Lyman limit : 91.2 nm or 13.6 eV

The Lyman-α Forest

Quasar spectrum



(Womble et al. 1996)

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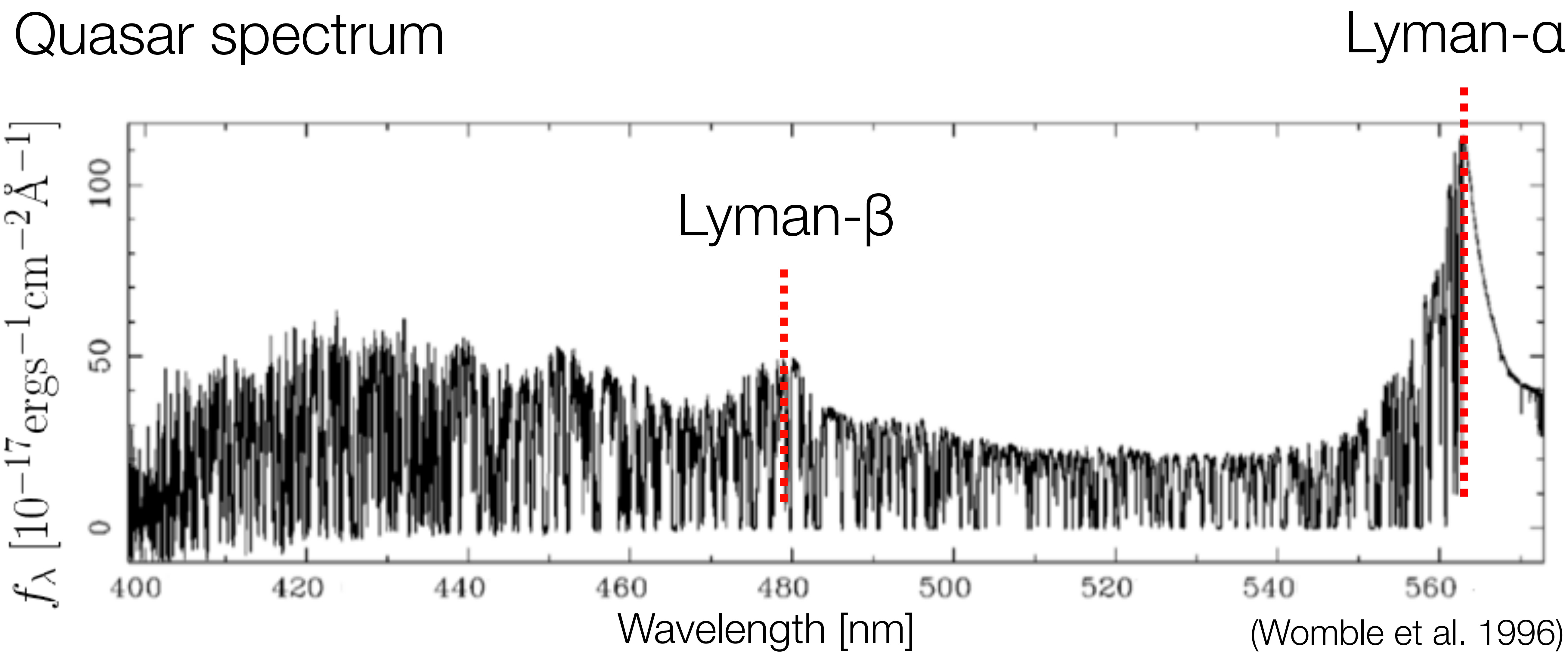

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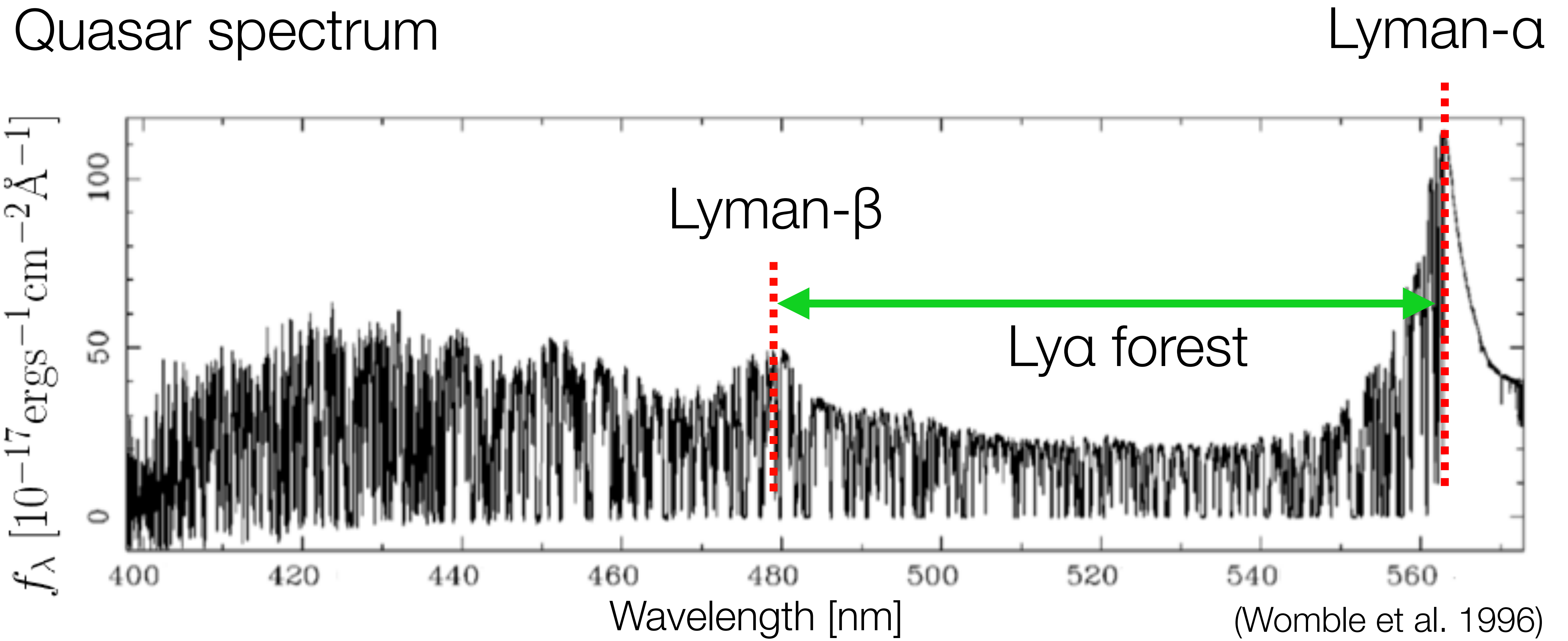

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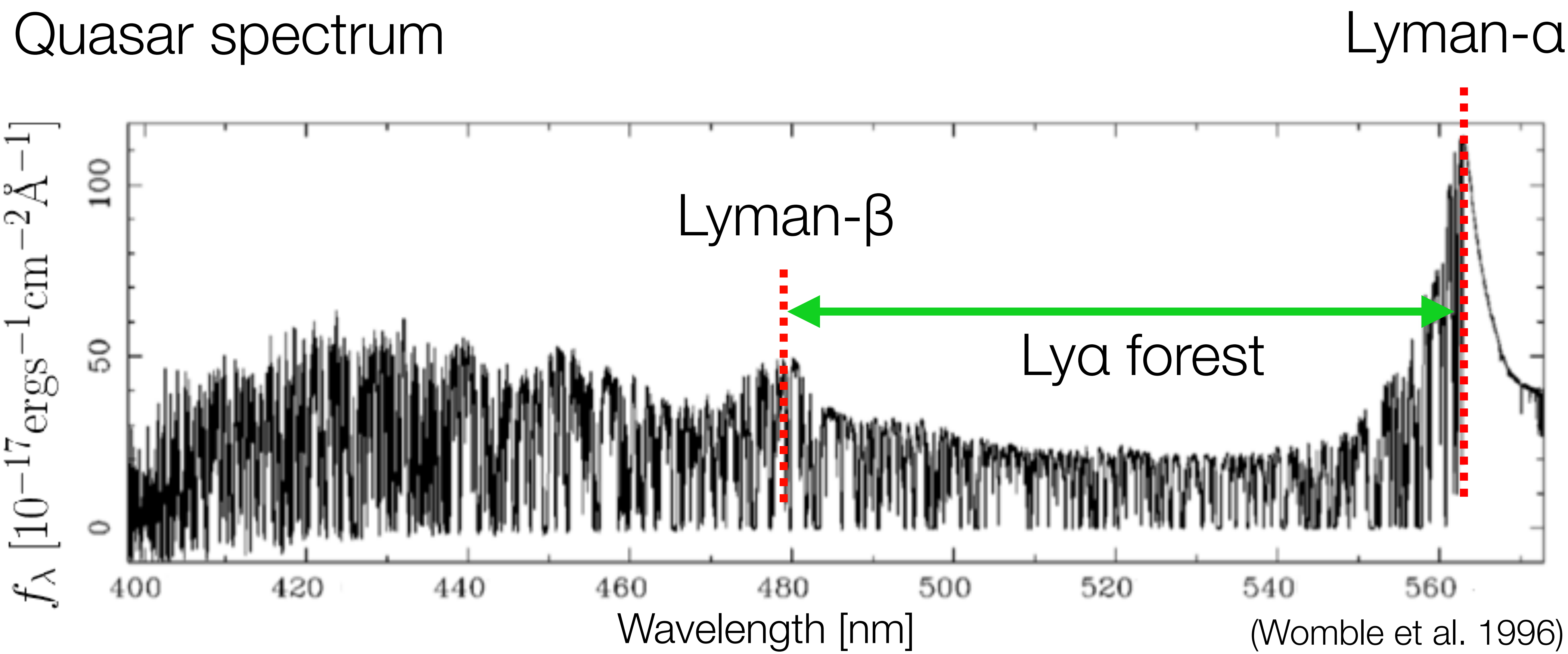


(Womble et al. 1996)

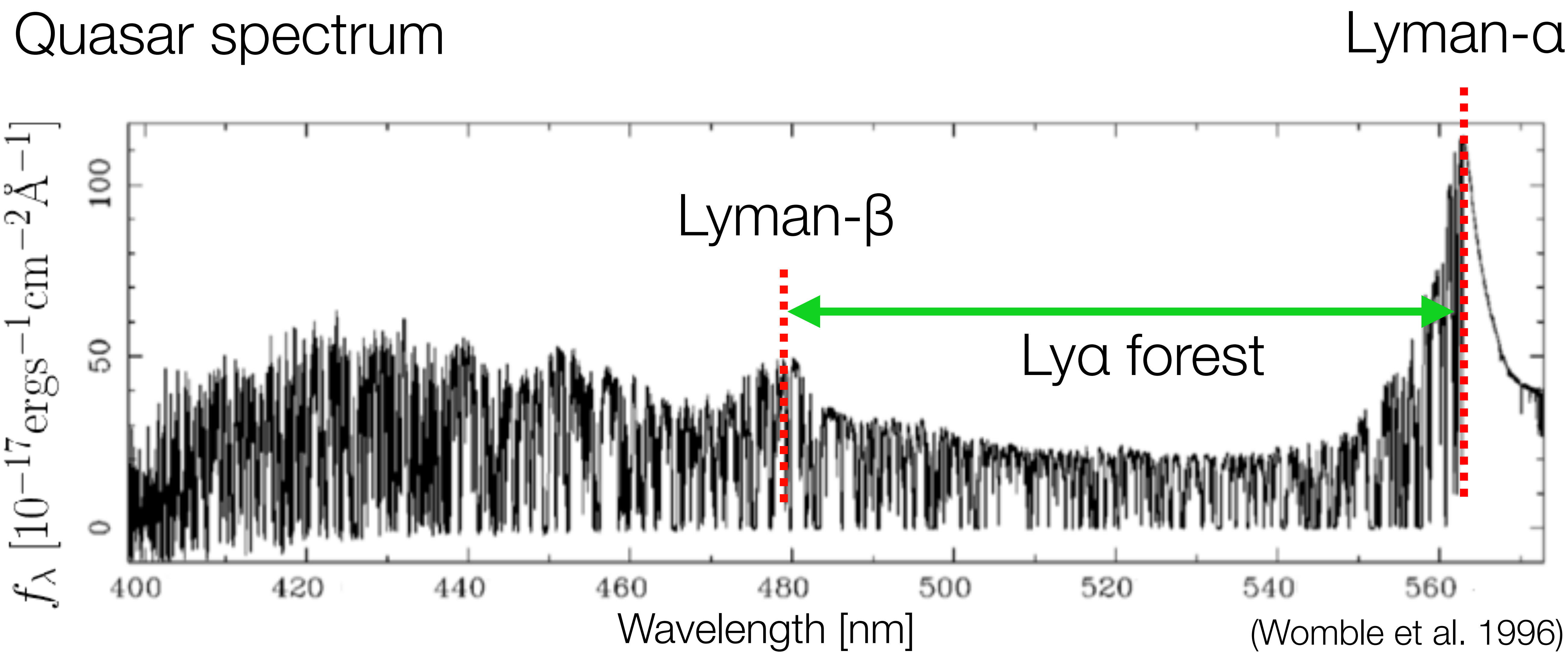
At rest-frame:

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

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

The Lyman-α Forest

Quasar spectrum



(Womble et al. 1996)

At rest-frame:

$$\lambda_{\mathrm{Ly}\alpha} = 121.6 \text{ nm} \quad \rightarrow \quad z_{\mathrm{QSO}} = \frac{561.8 \text{ nm}}{\lambda_{\mathrm{Ly}\alpha}} - 1 = 3.62$$

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

The Lyman-α Forest: absorption by the IGM

Isn't it material ejected from quasar?

- huge momentum requirements (Goldreich and Scoville, 1976)
- detection of galaxies at same redshifts as some metal absorbing systems (Bergeron, 1986)
- detecting of low metallicity systems in systems far from the quasar (Petitjean and Bergeron, 1994)

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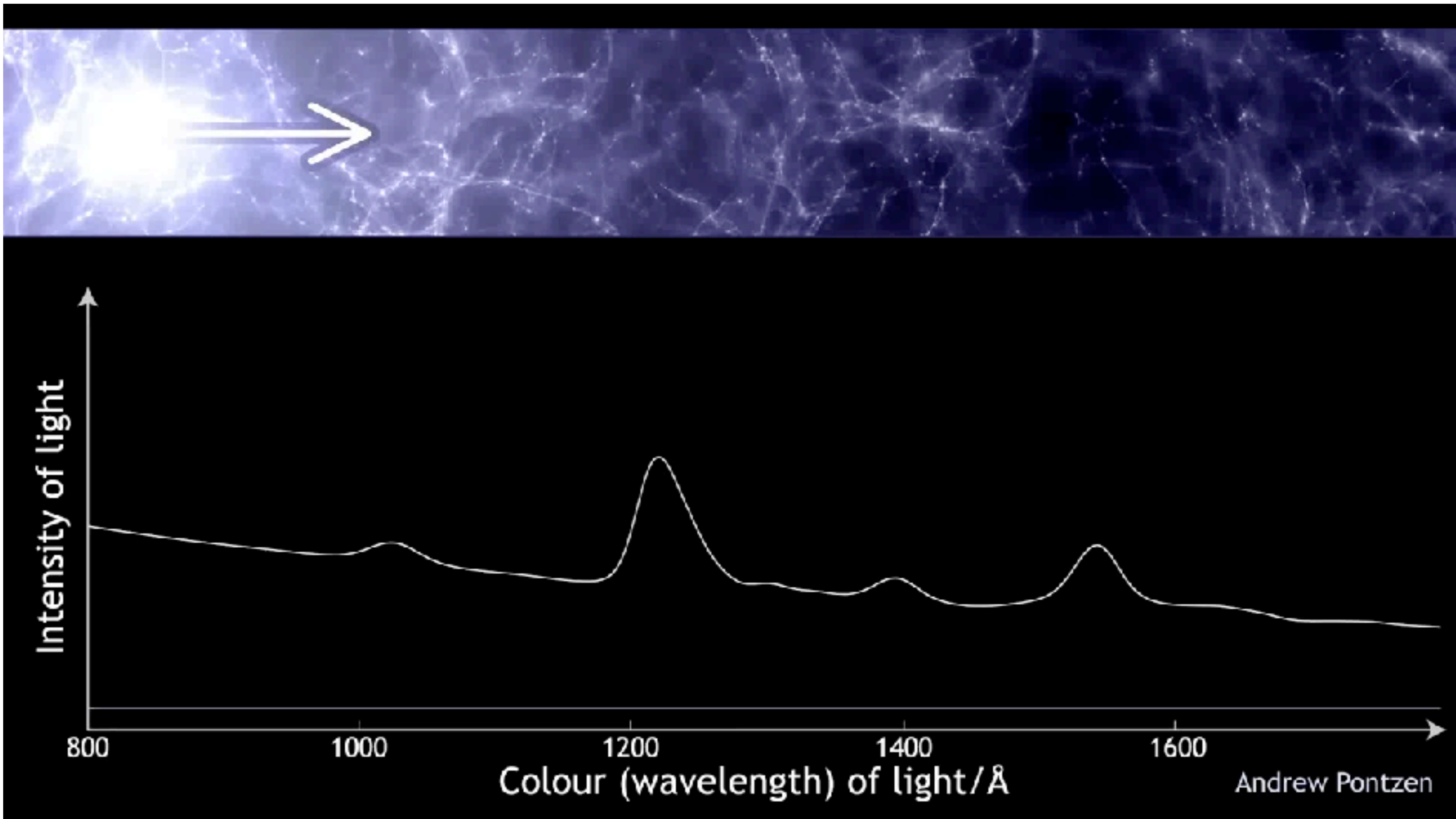
Therefore, the Lyman-alpha absorption is caused by hydrogen in the InterGalactic Medium (IGM)

The Lyman-α Forest: absorption by the IGM



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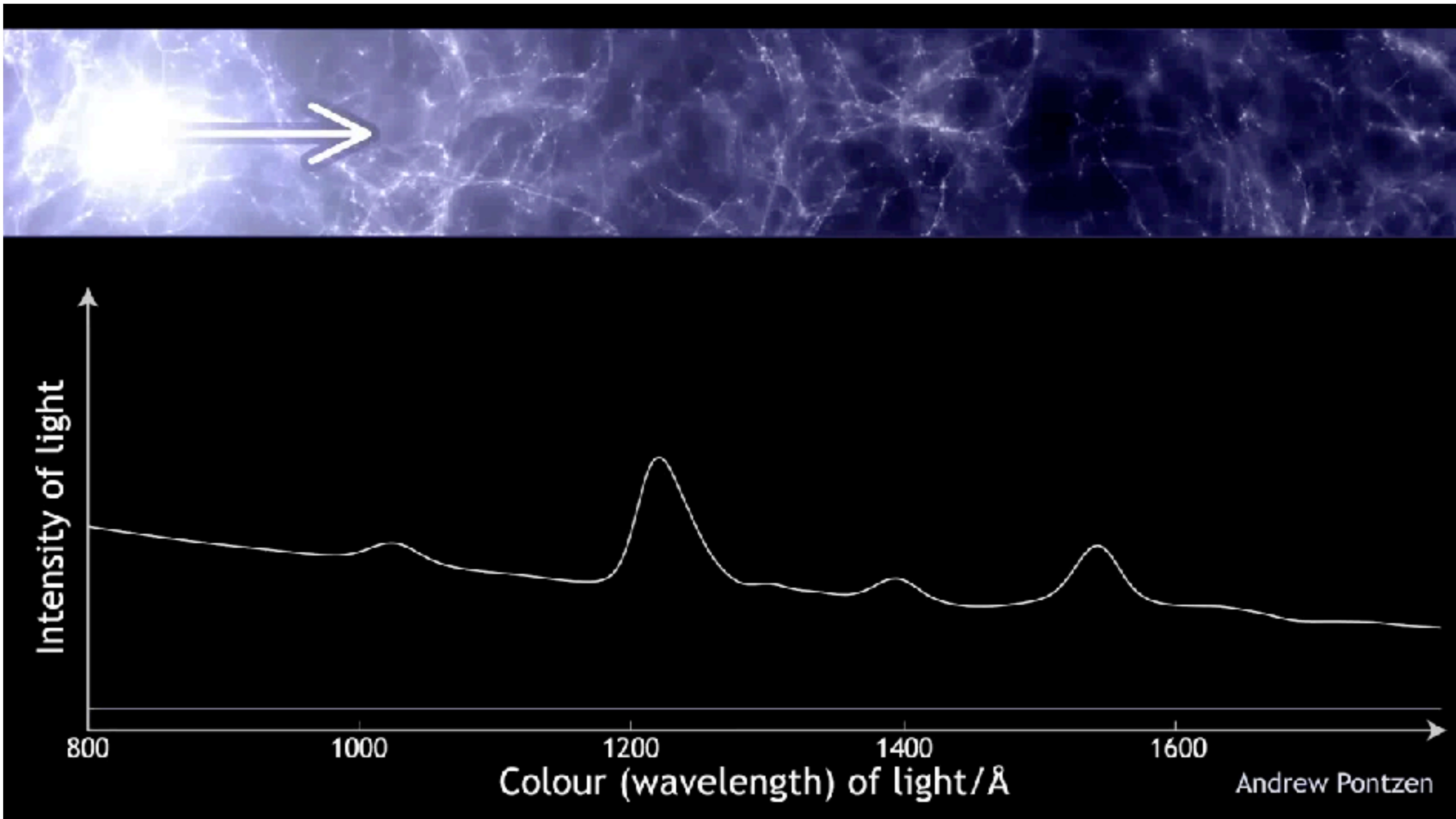
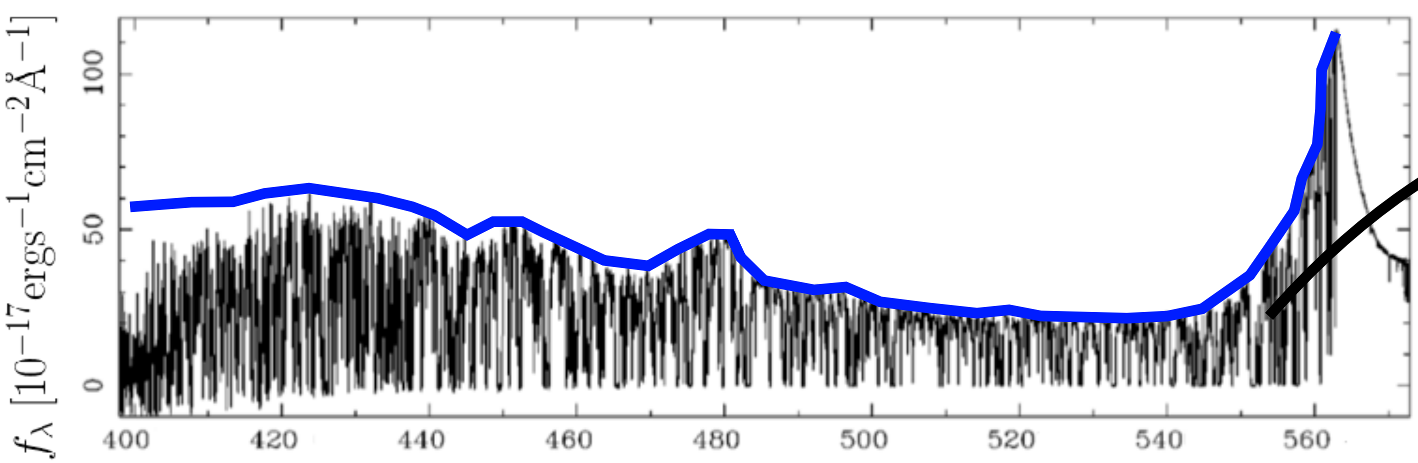


The Physics of the Lyman-α Forest: Gunn-Peterson

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

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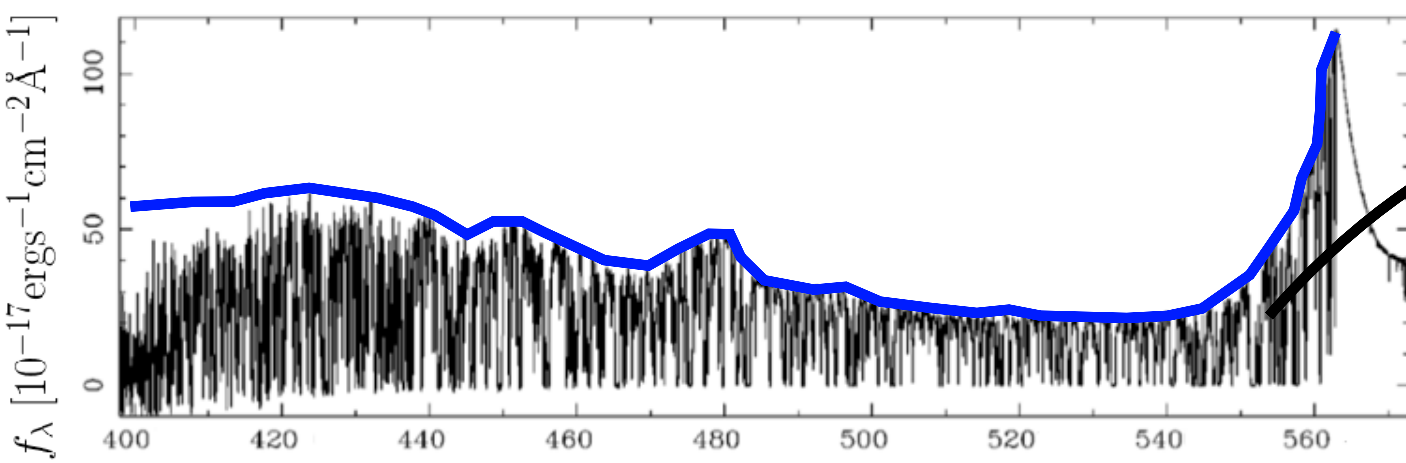

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Continuum

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

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

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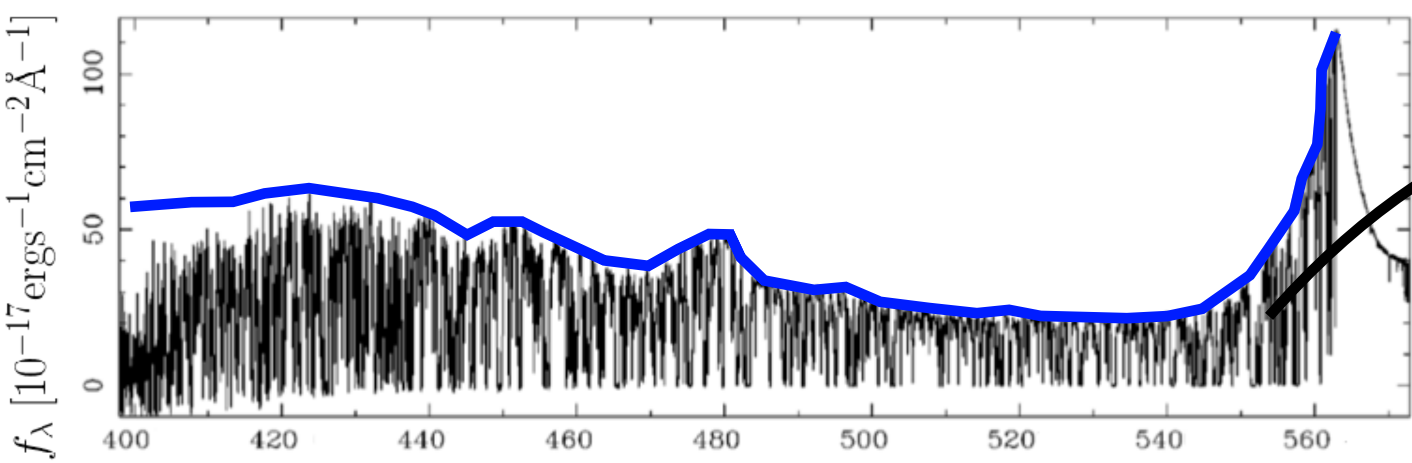

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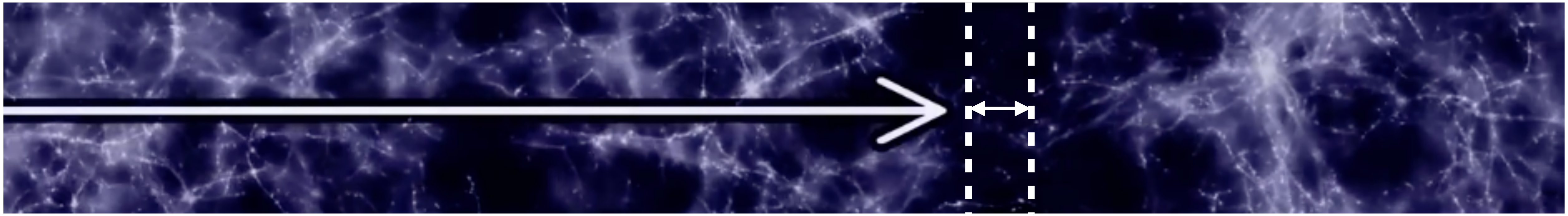

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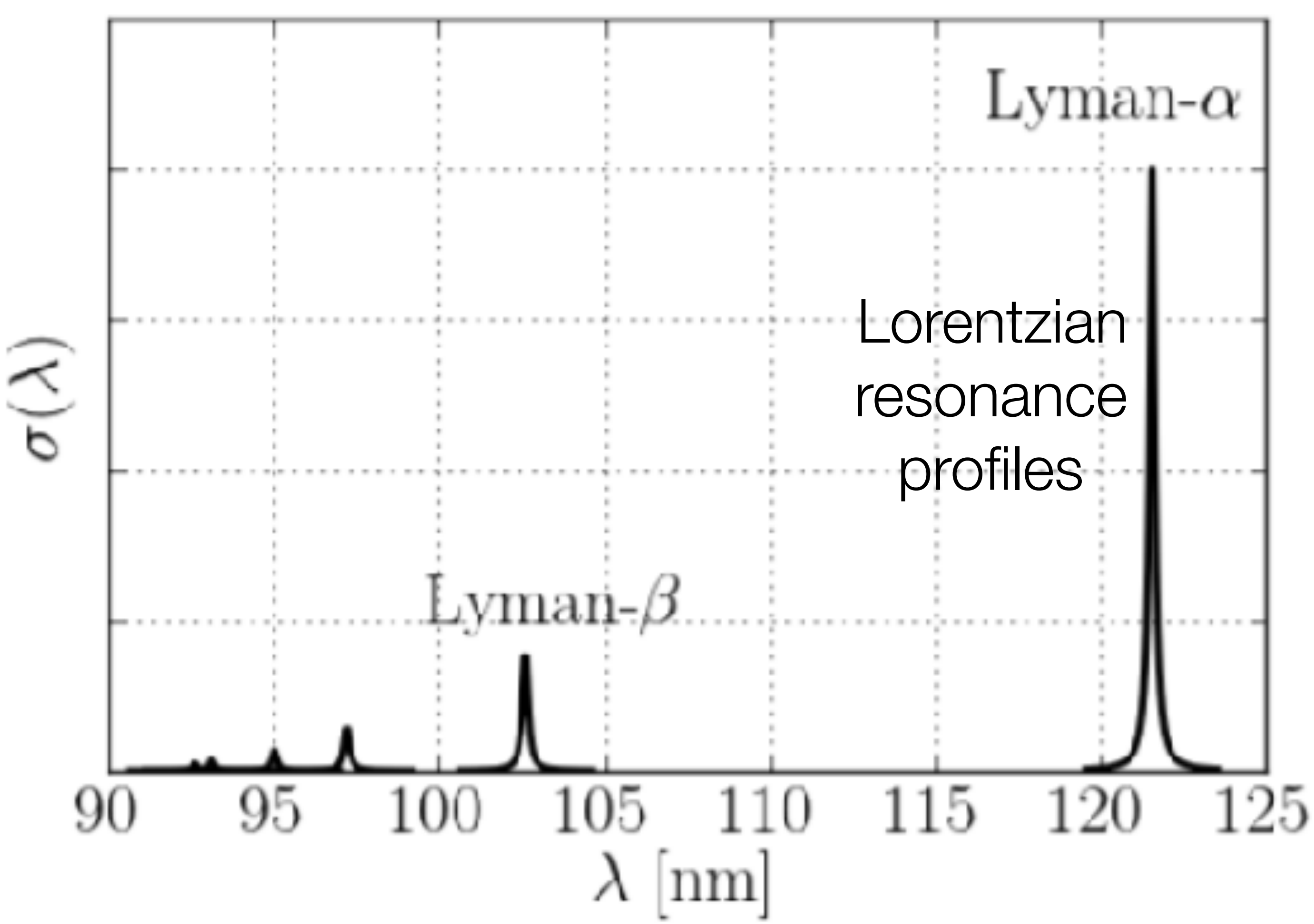
Cross-section:

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

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



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

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

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

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

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

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

(Gunn & Peterson 1965)

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Approximating the cross-section by a Dirac delta function:

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

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

(Gunn & Peterson 1965)

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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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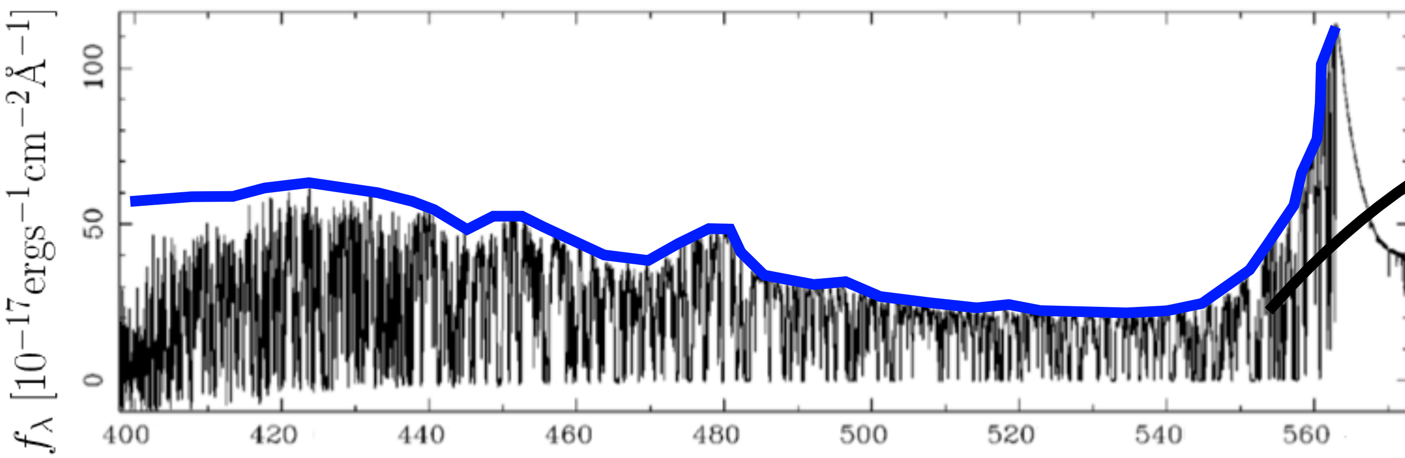

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Continuum

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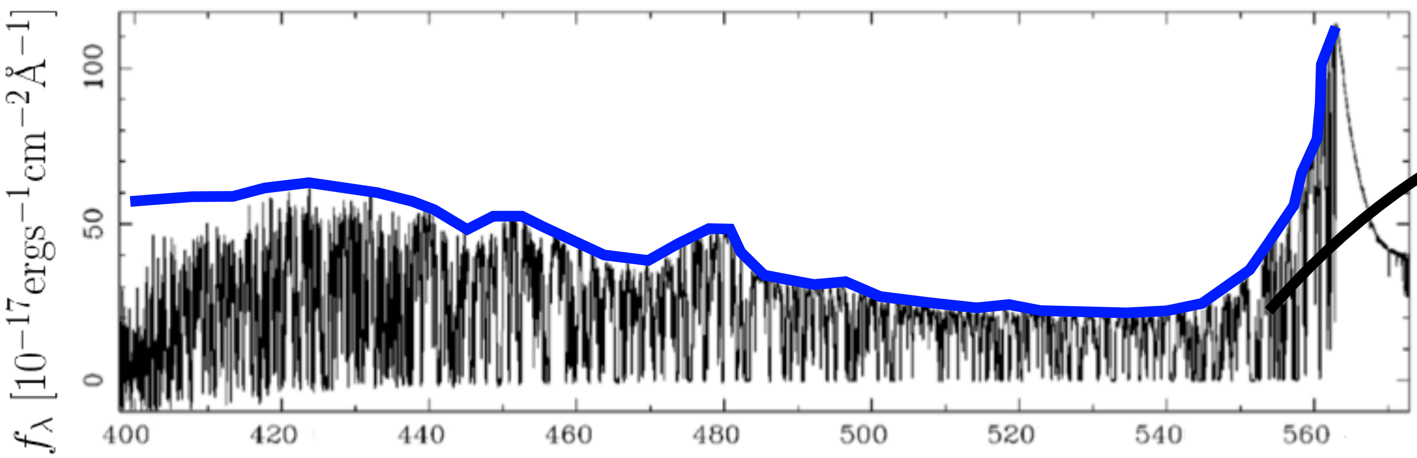

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Observations show: $F(z=3) \sim 0.5X$

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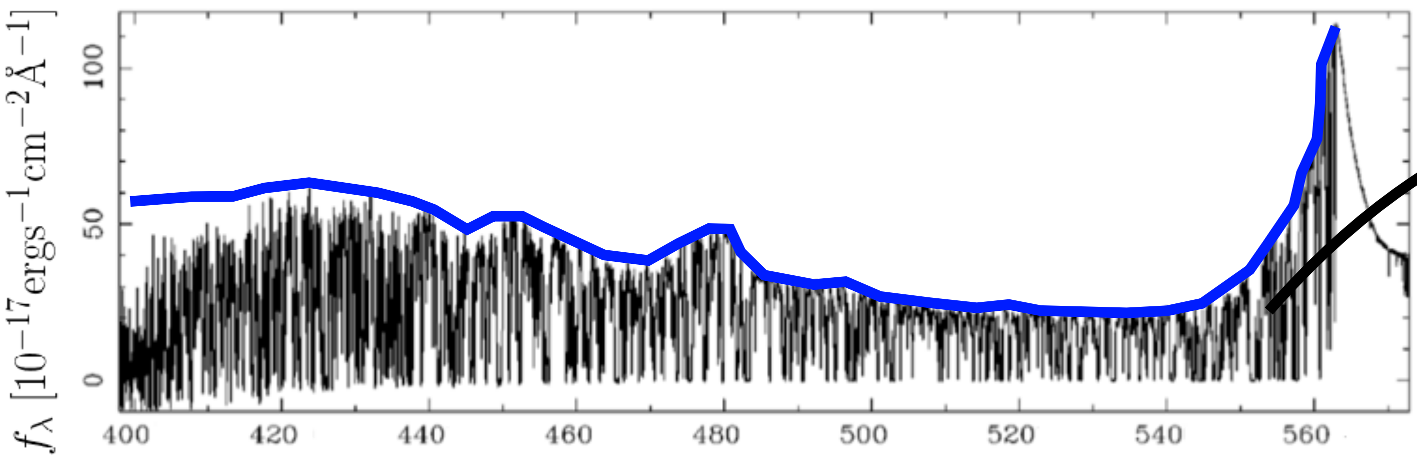

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which leads to the conclusion: $X(z=3) \sim 10^{-5}$

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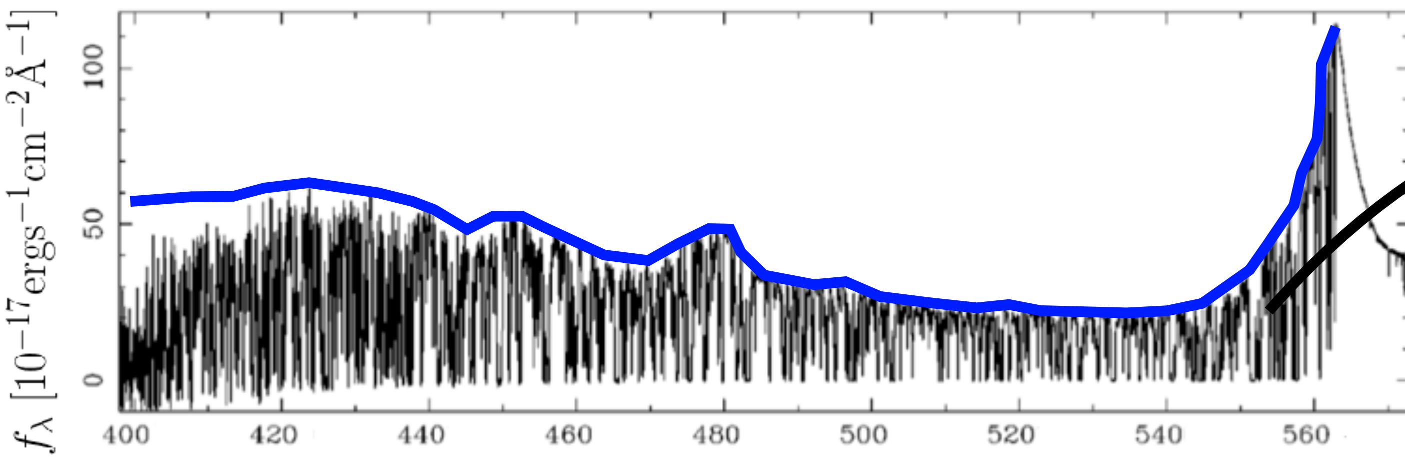

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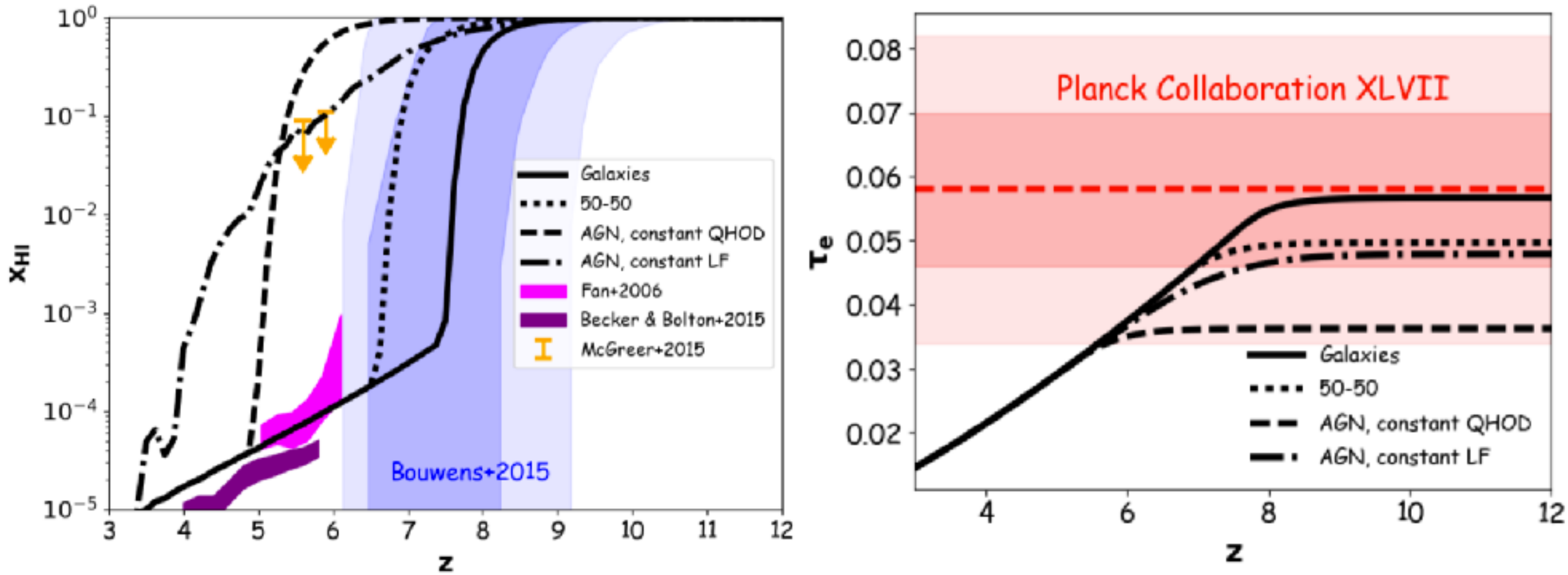
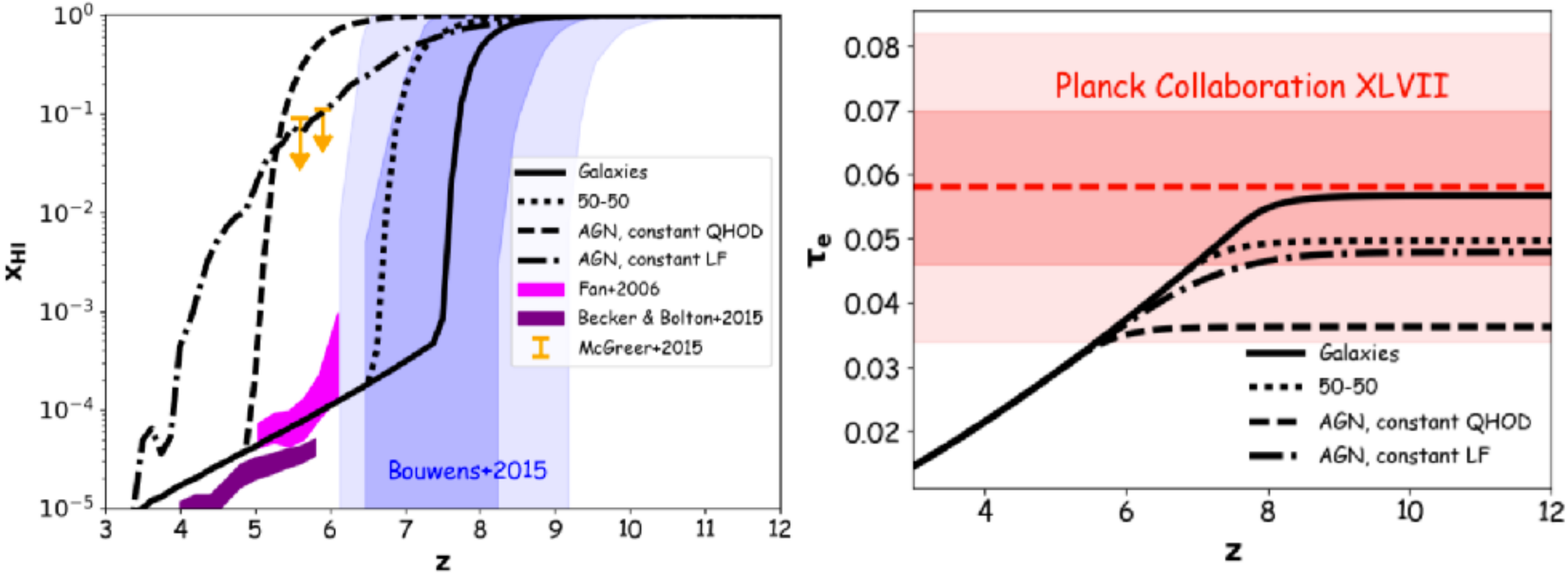
The Universe is mostly ionized at z ~ 3!

(Gunn & Peterson 1965)

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



(Hassan et al. 2018)



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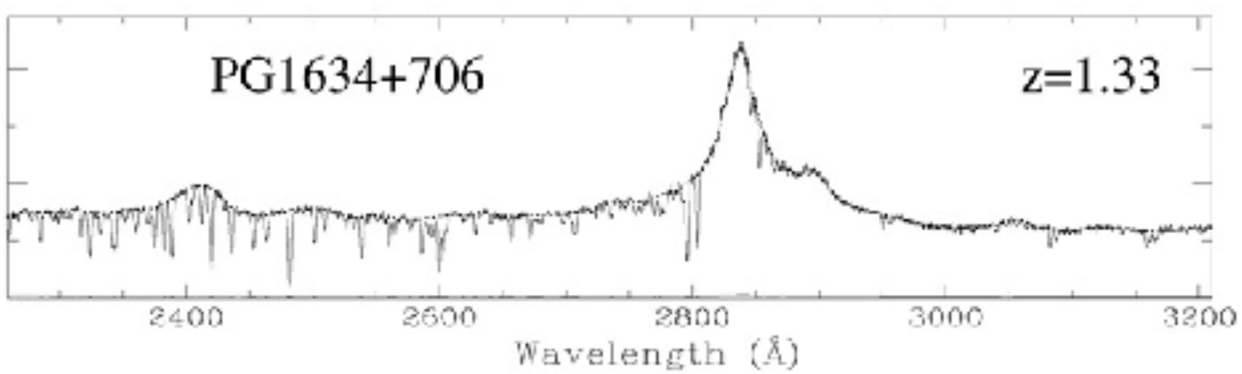

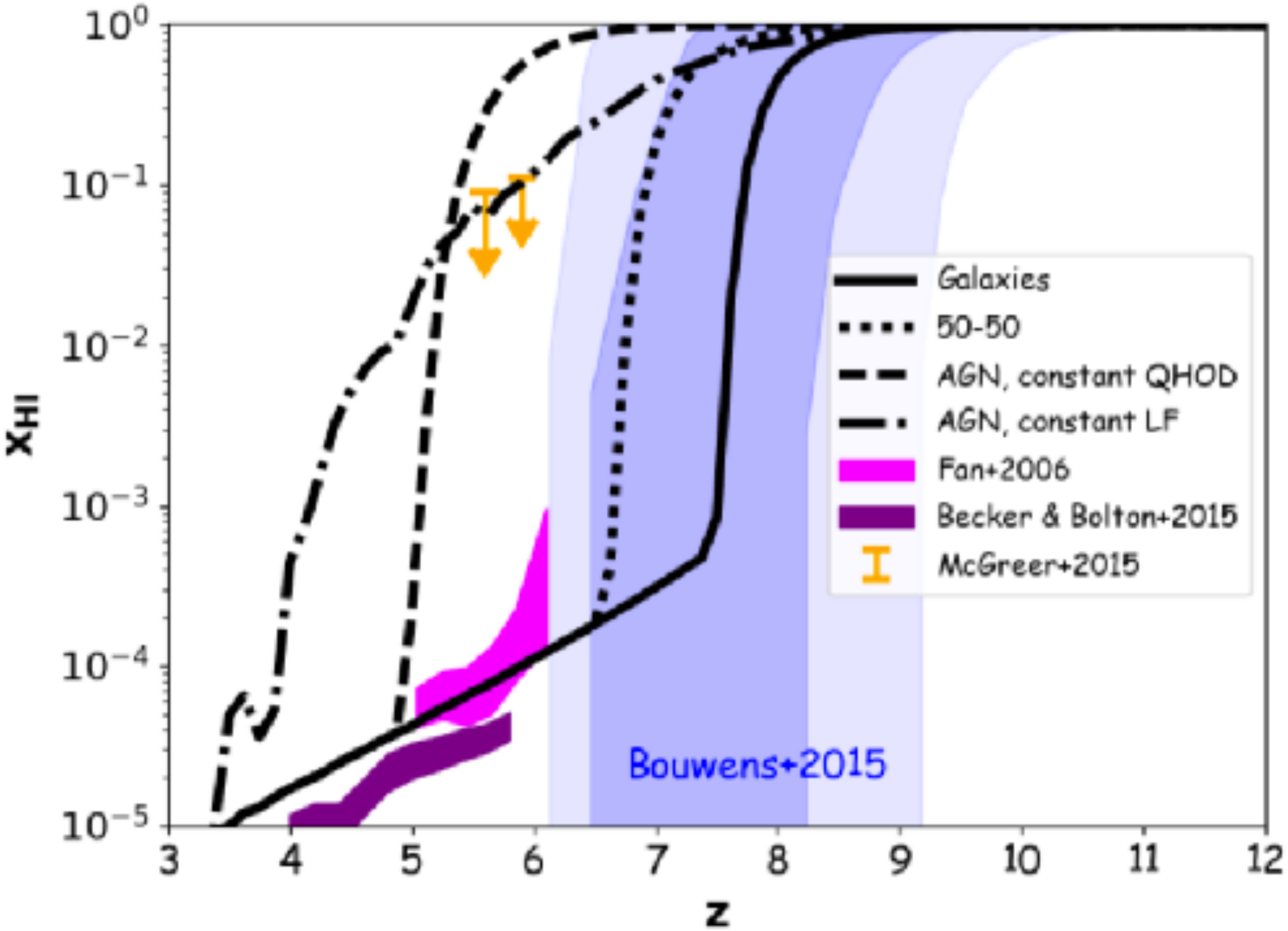

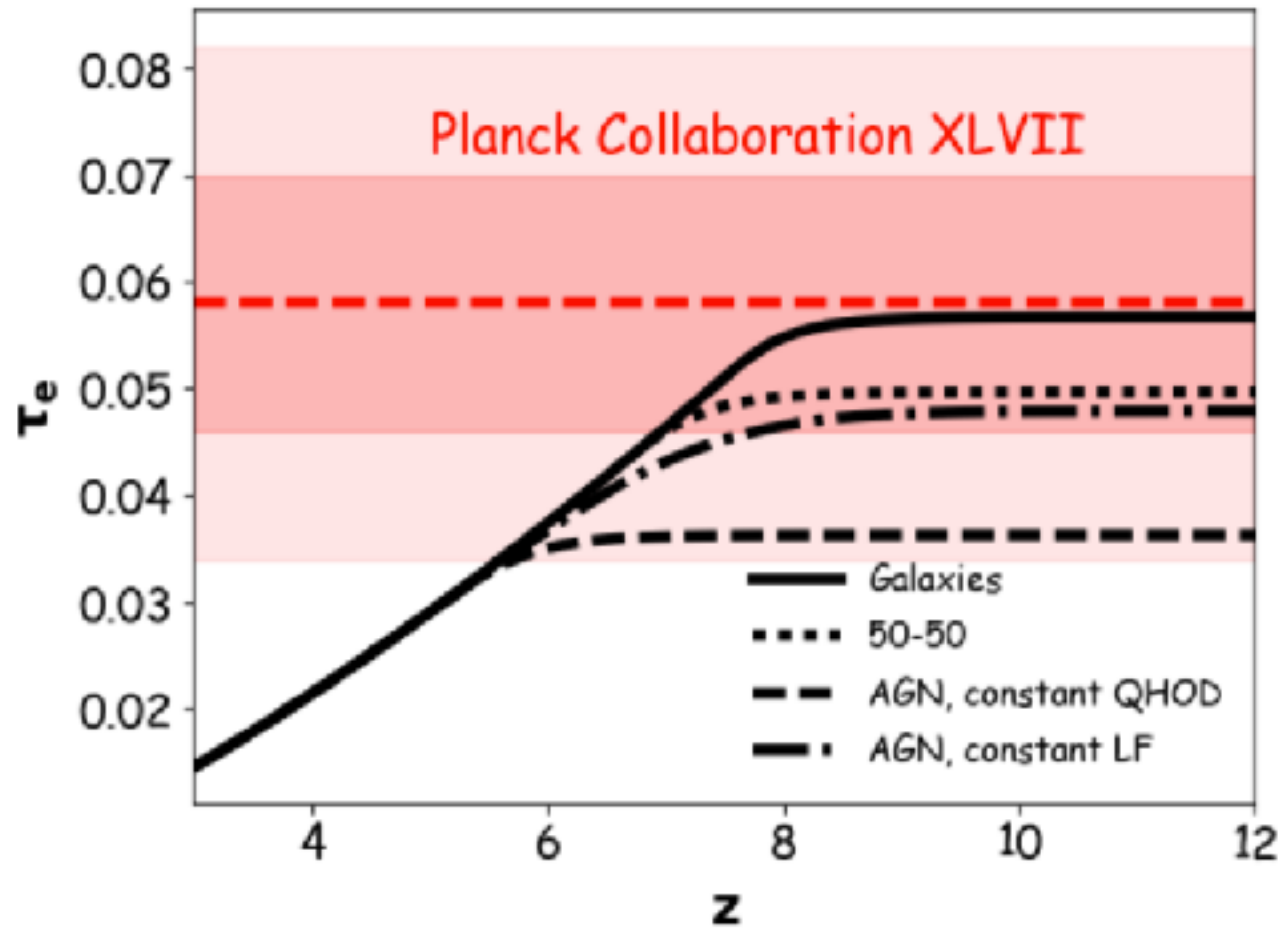

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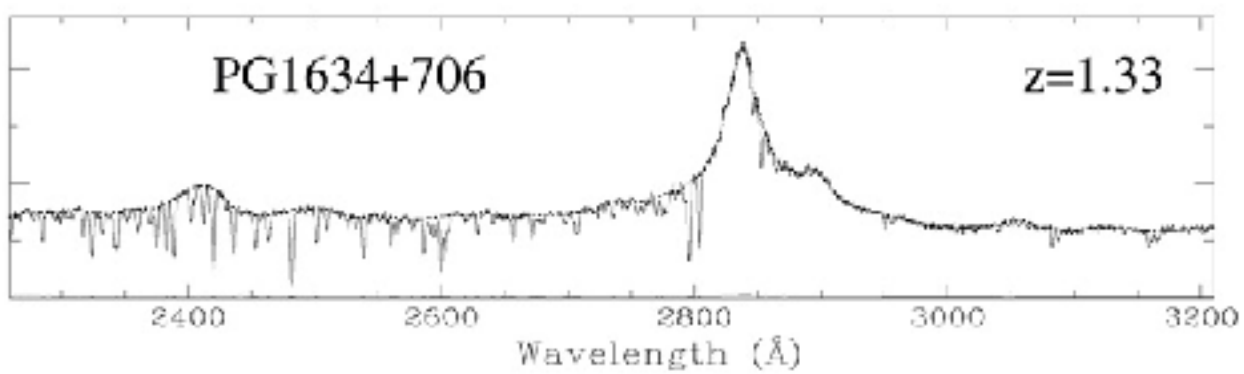

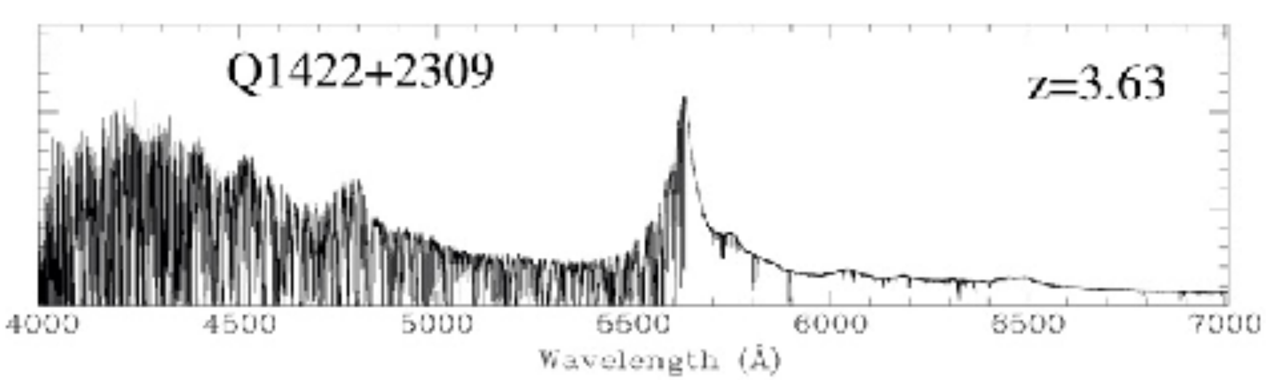

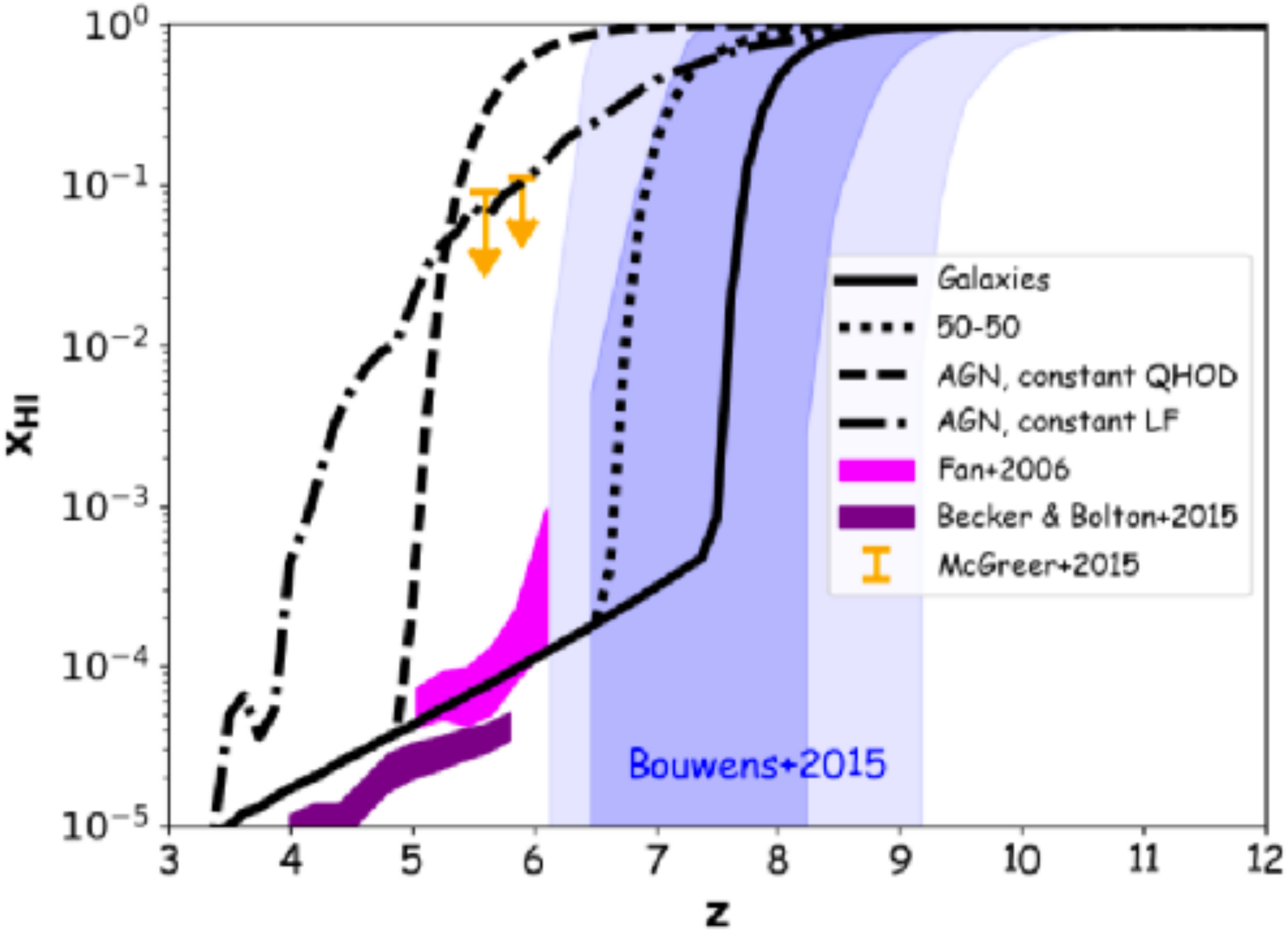

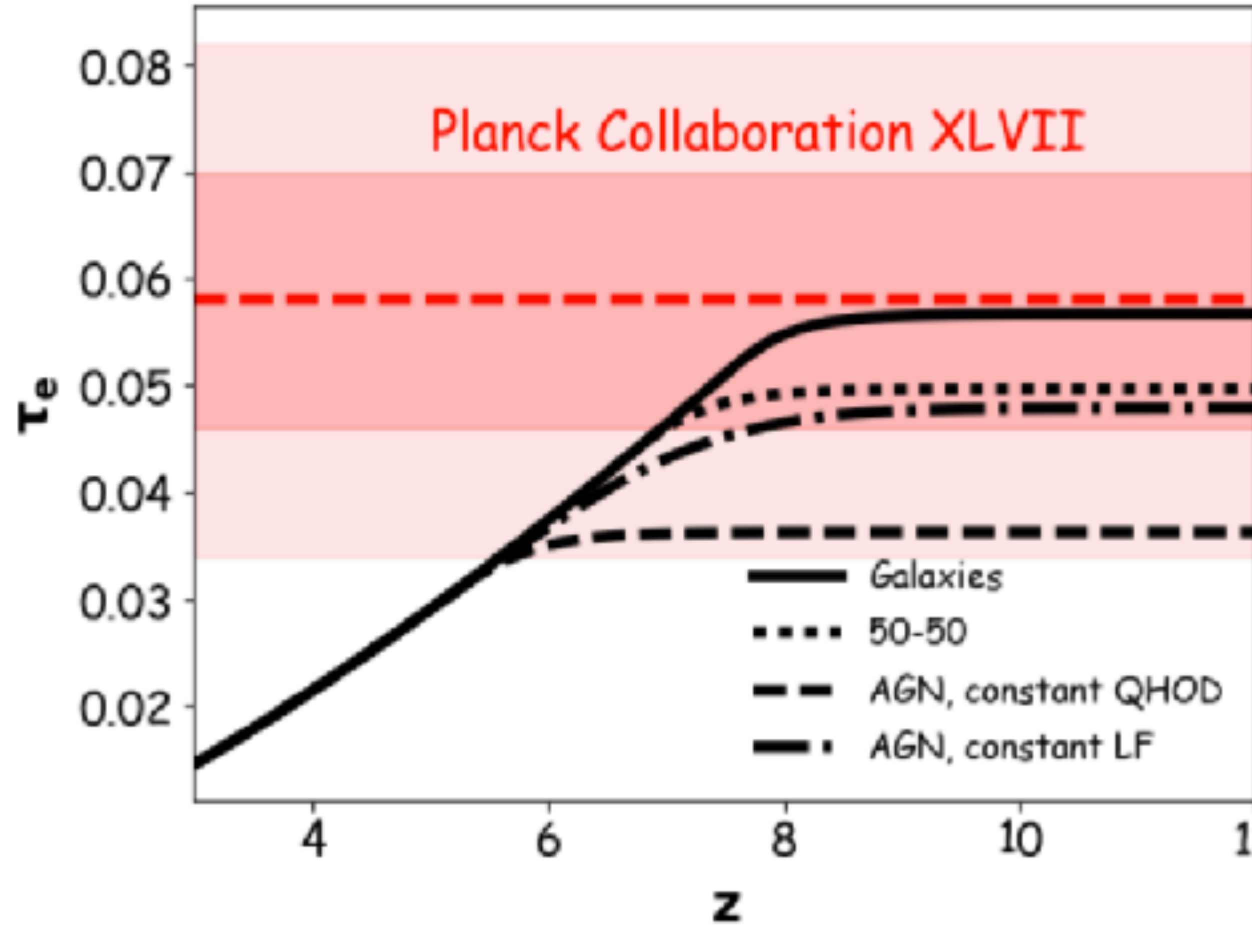

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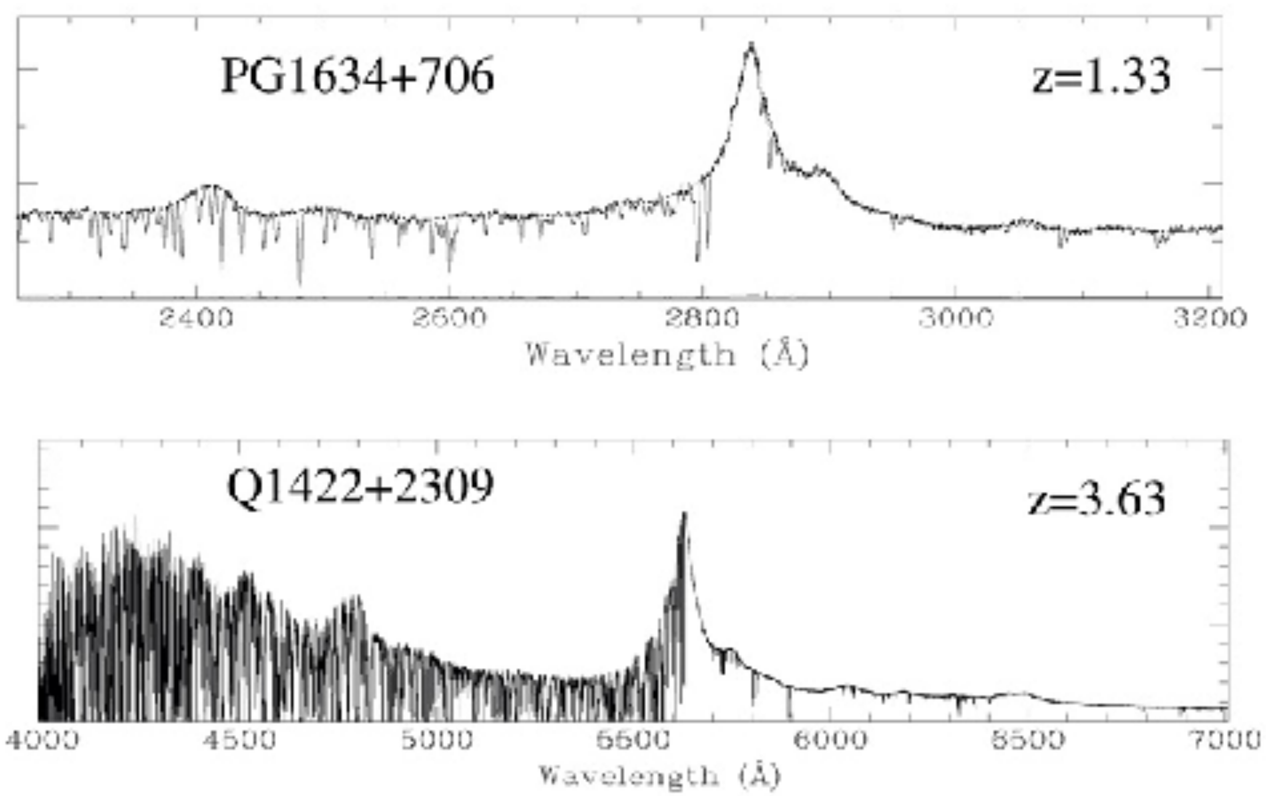

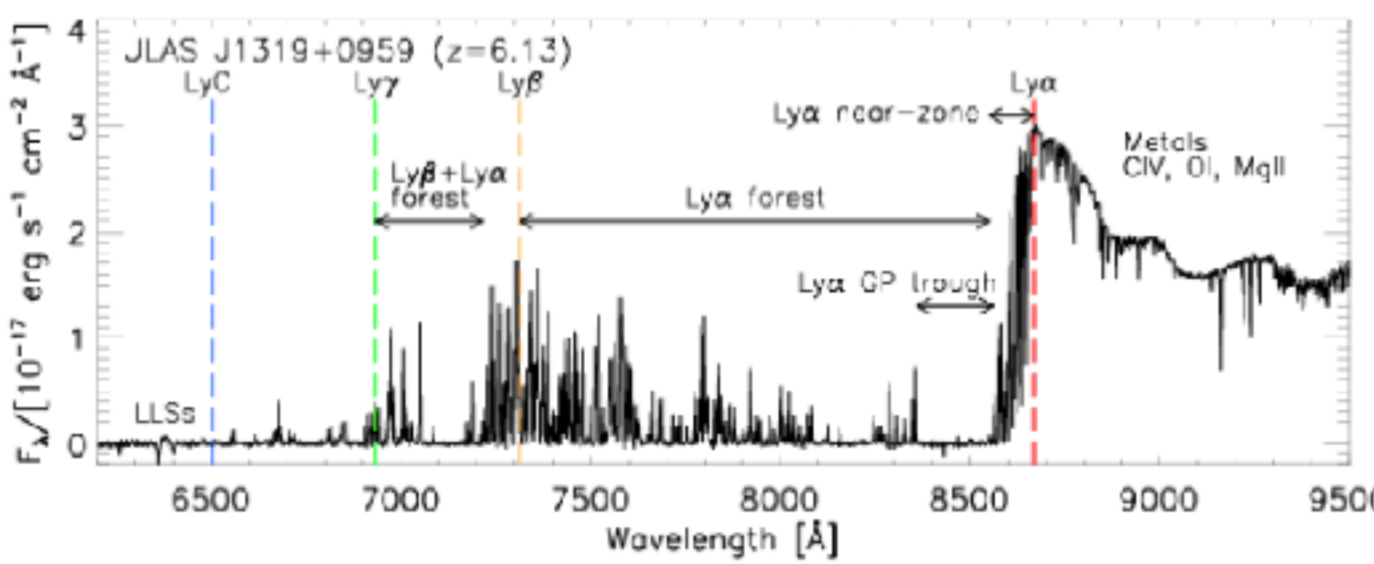

Becker et al. 2015

The Physics of the Lyman-α Forest: Photo-ionization Equilibrium

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Writing Boltzmann equation for the neutral fraction X:

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The evolution of X is a battle between these processes

- At z ~ 1000, CMB photons cool down such that recombination dominates

$$X \to 1$$

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- At z ~ 20-100, the first stars and galaxies form, increasing the UV background around them.

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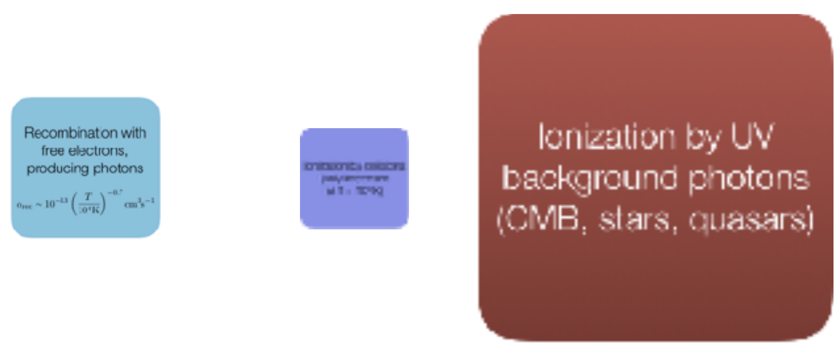

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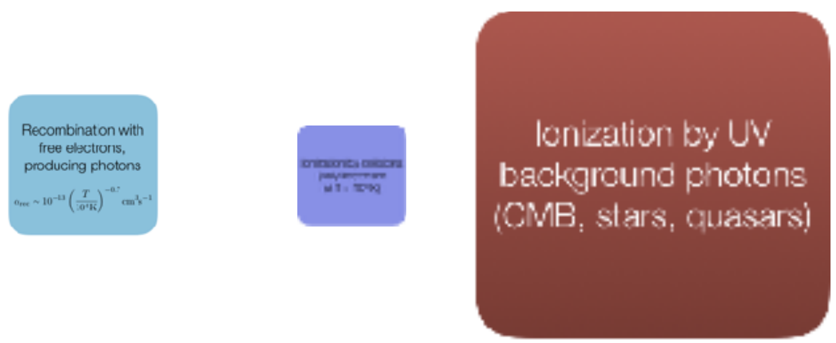

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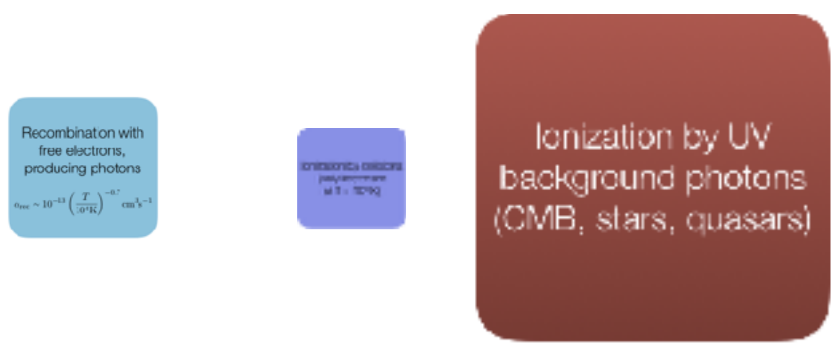

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$$X \approx \frac{\alpha_{\mathrm{rec}} n_e}{\Gamma}$$

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Simulating Lyman-alpha forests

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Eulerian dark-matter N-body simulations
+ gas hydrodynamics
+ galaxy formation
+ cosmological constant:
IGM properties **weakly** dependent on
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(Cen et al., 1994, Petitjean et al., 1995,
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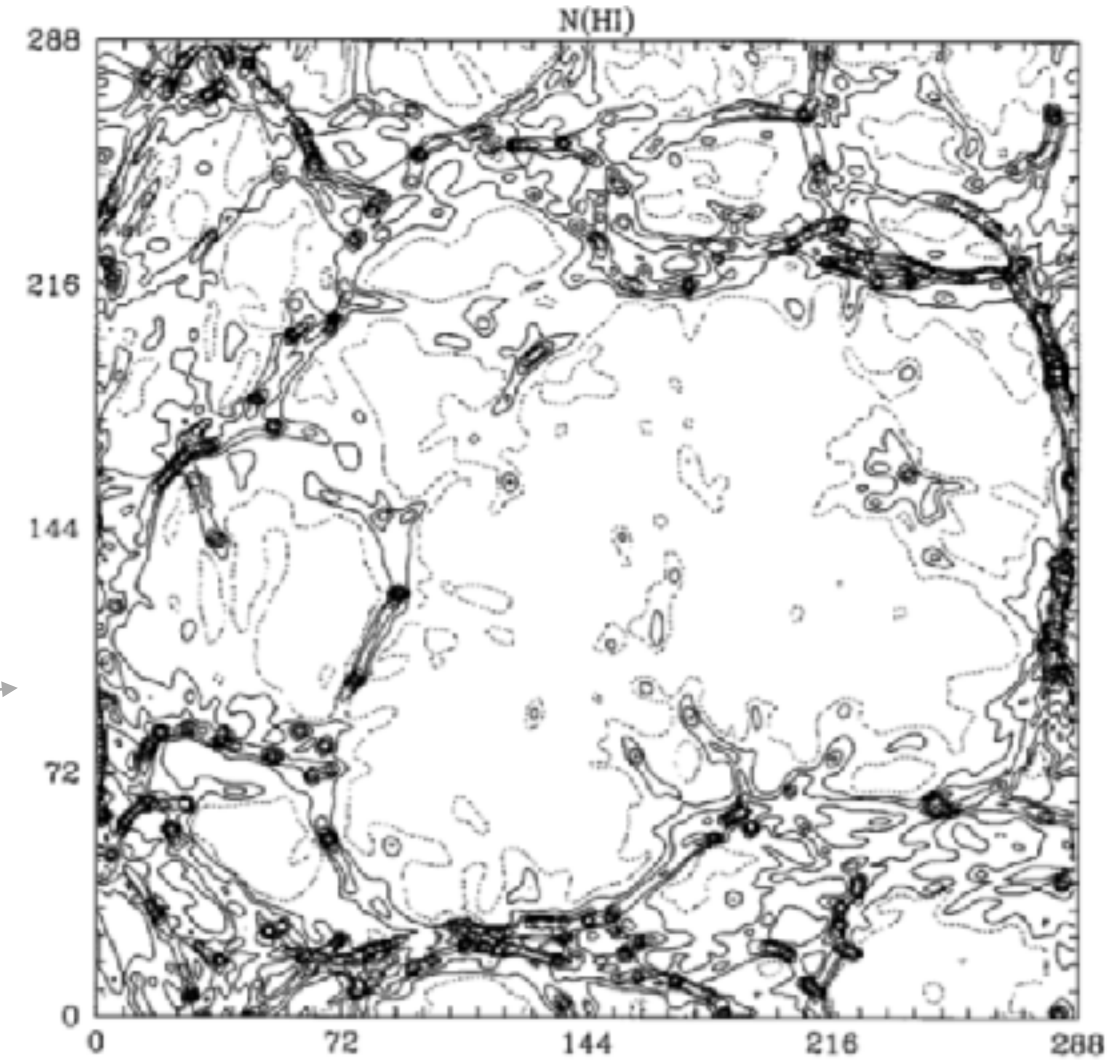

Contours = column densities $10^{12+i*0.5}$ cm^{-2} for i = 0, 1, 2, …

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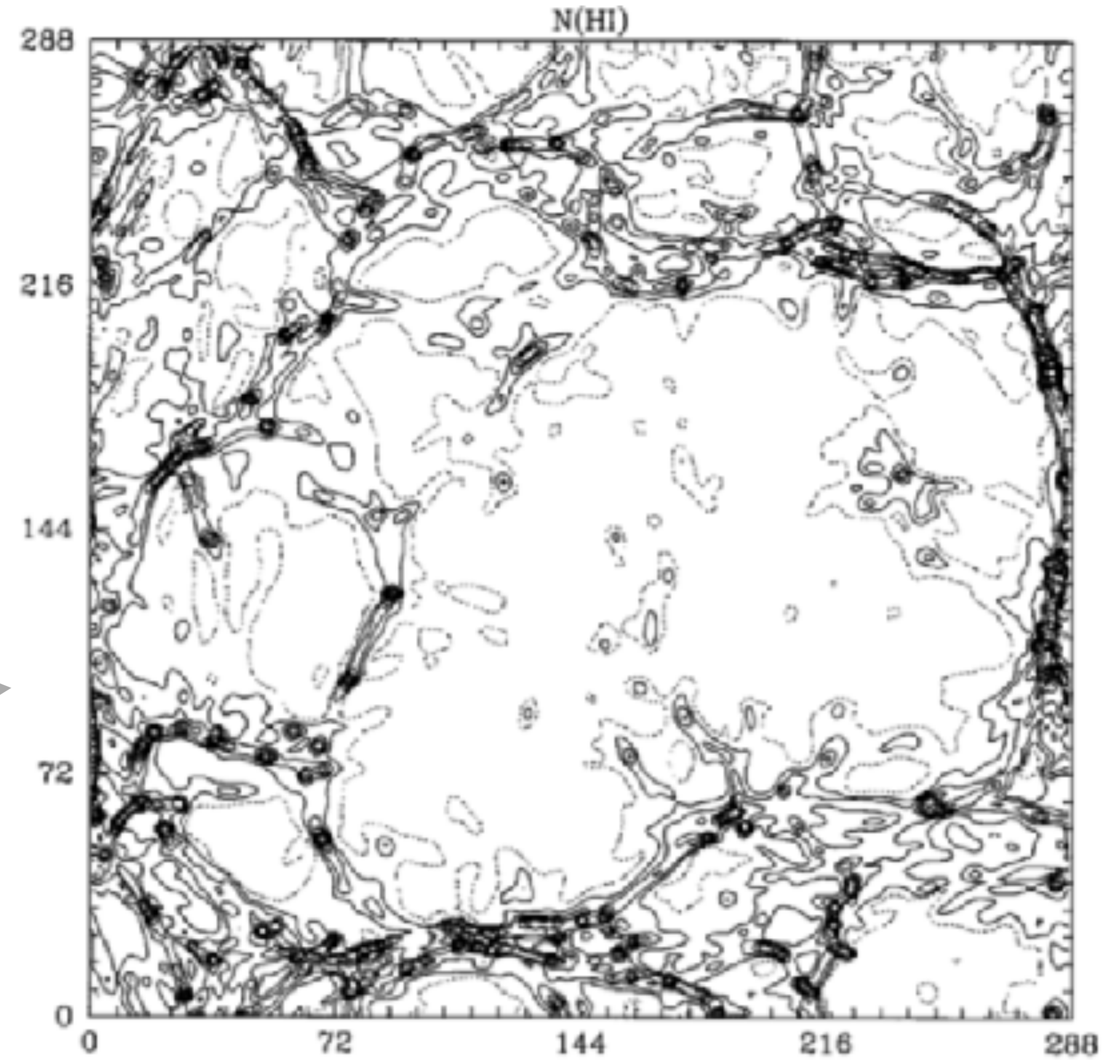

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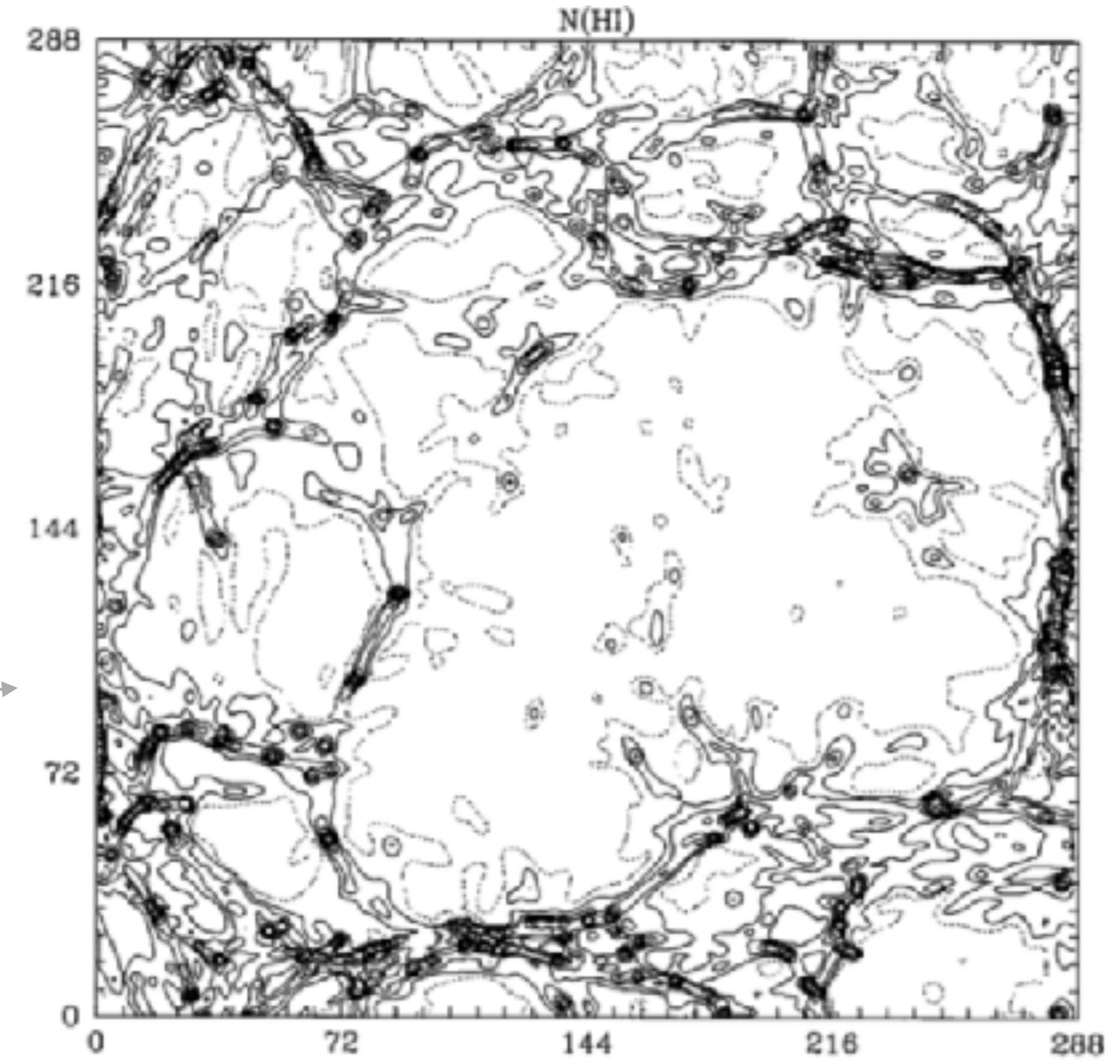

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80-90% of the forests come from low density sheet/filament-like gas structures ("Cosmic Web"). Higher density structures follow dark-matter halos

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Temperature-density relation from SPH simulation

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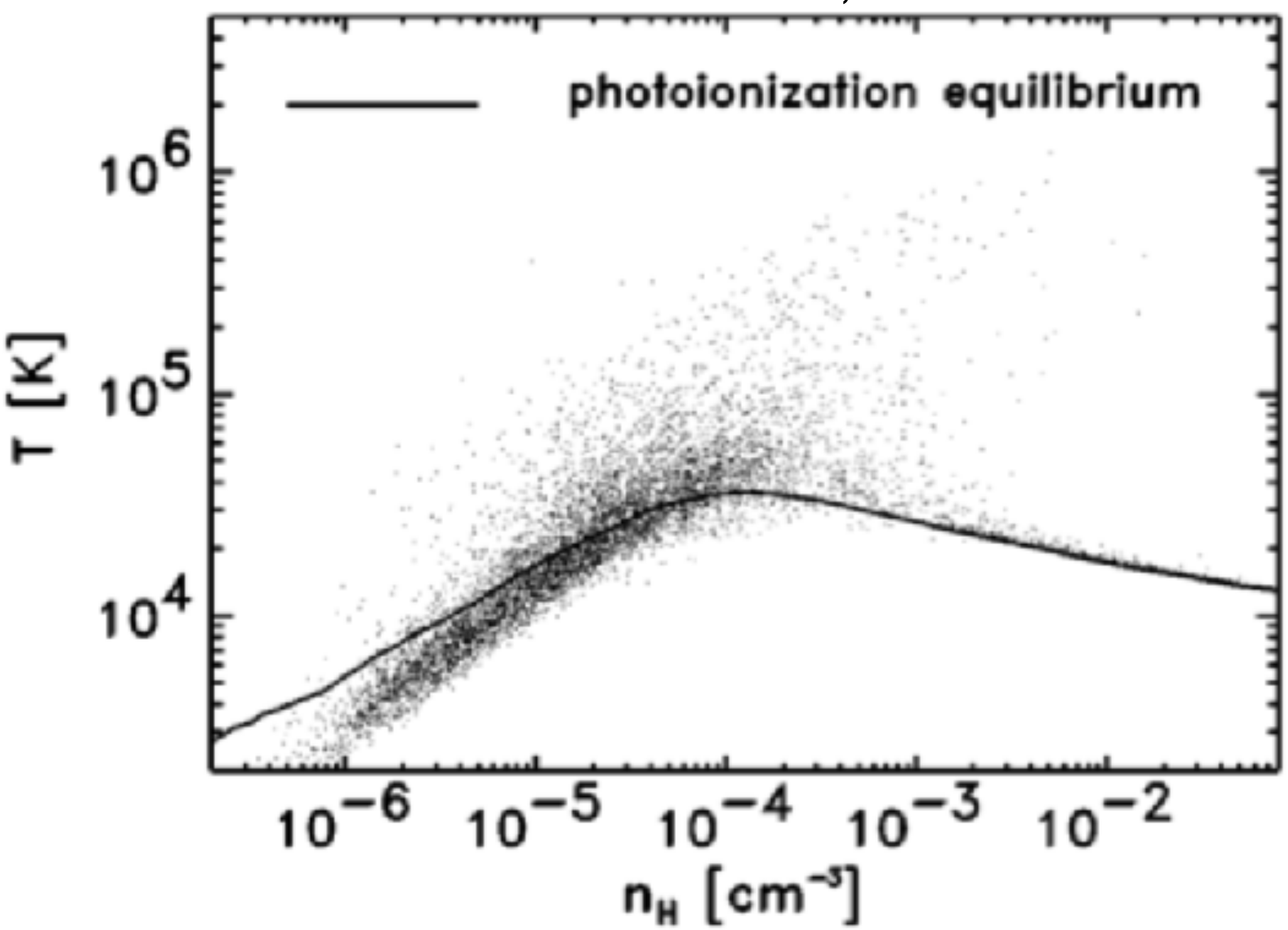
Haehnelt et al., 1996



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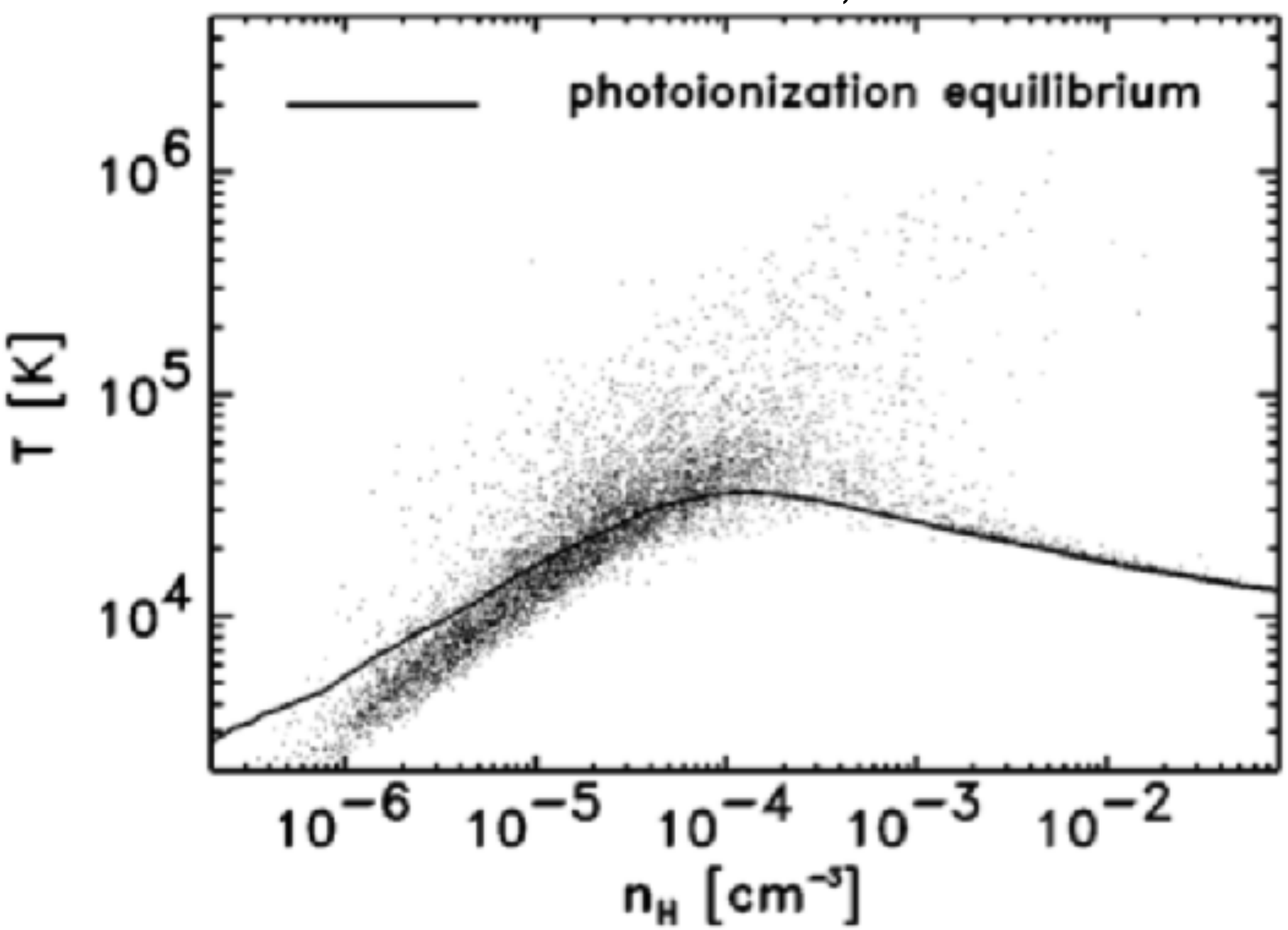

Departure from equilibrium:

- cooling due to expansion
- adiabatic compression
- shock heating
- other non-linear processes

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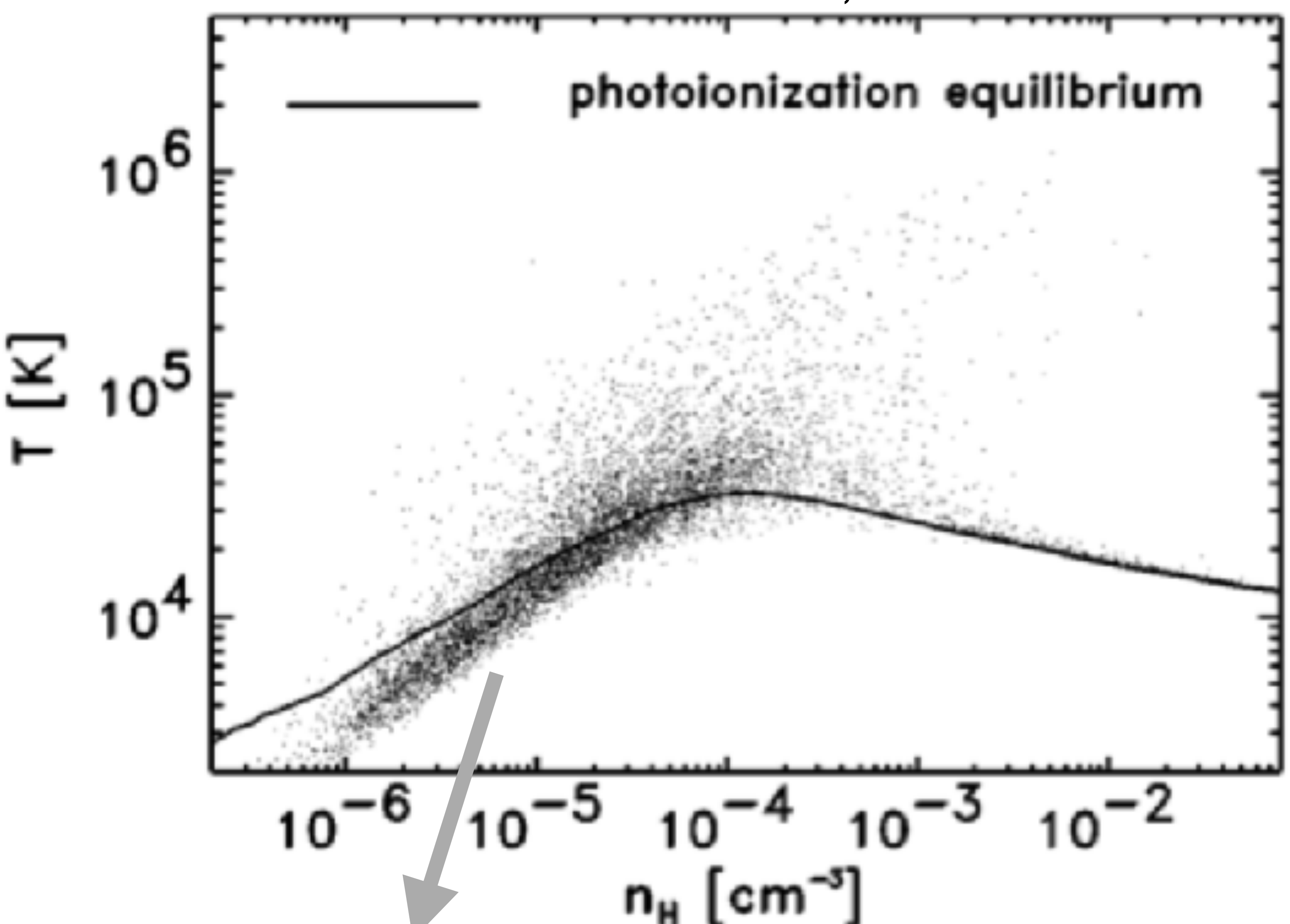

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$$T = T_0 \left(\frac{\rho_b}{\bar{\rho}_b} \right)^{\gamma}$$

$$0.3 < \gamma < 0.6$$

(Hui & Gnedin, 1997)

Very useful for semi-analytical simulations!

Link to large-scale structures

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

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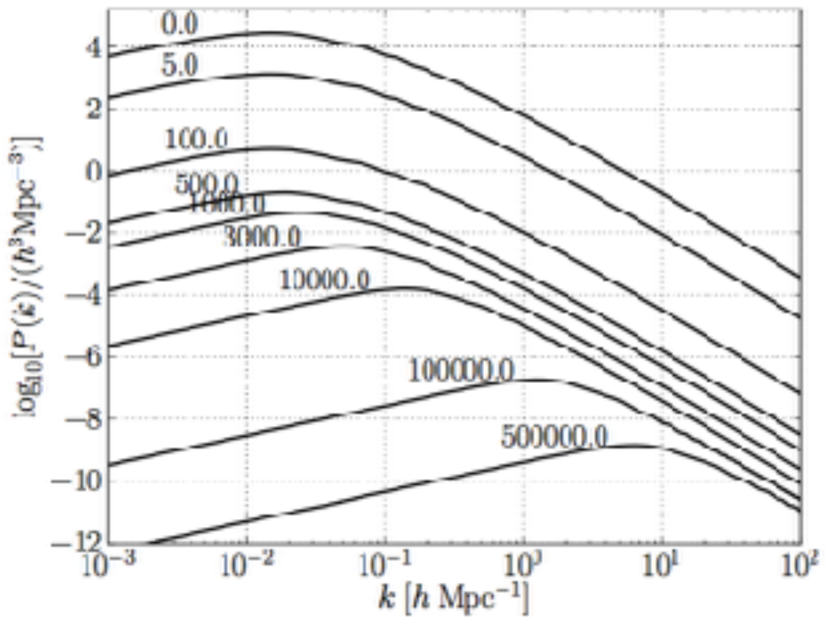

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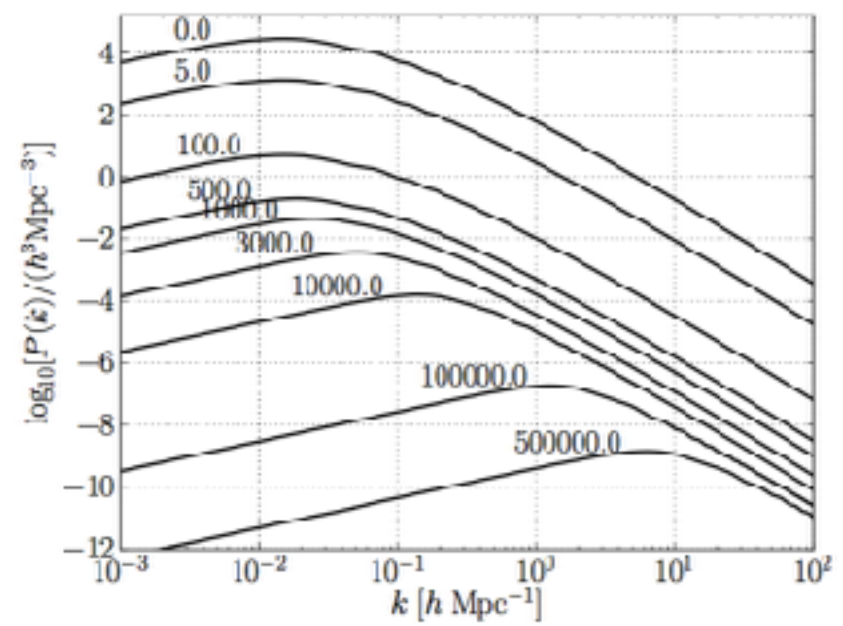

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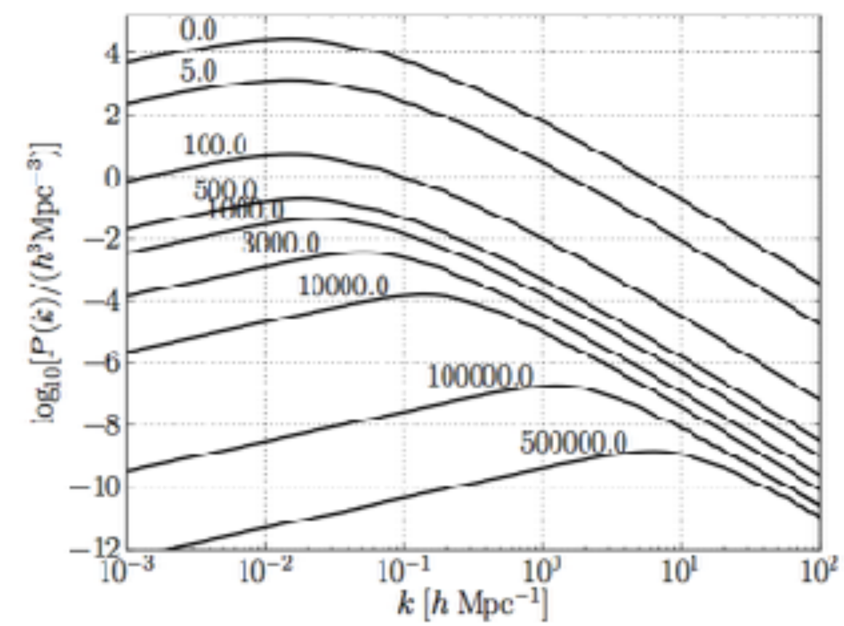

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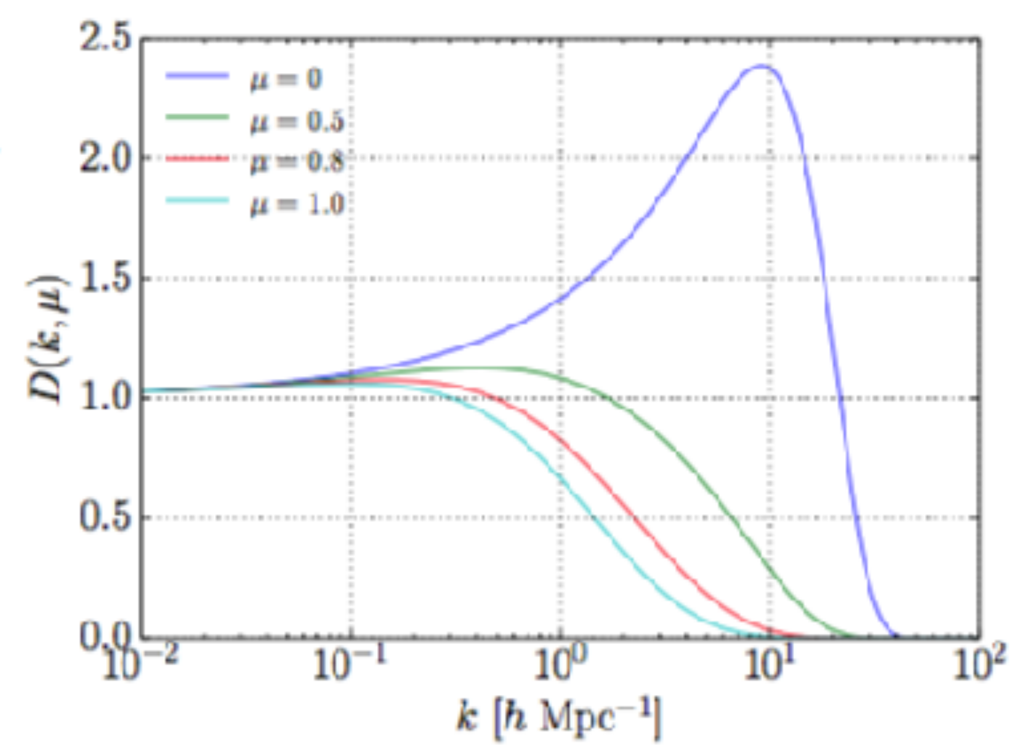
$$D(\vec{k}) = \exp\left\{ \left[\frac{k}{k_{\rm NL}}\right]^{\alpha_{\rm NL}} - \left[\frac{k}{k_P}\right]^{\alpha_P} - \left[\frac{k_\parallel}{k_V(k)}\right]^{\alpha_V} \right\}$$

from hydro-sims (McDonald 2003)



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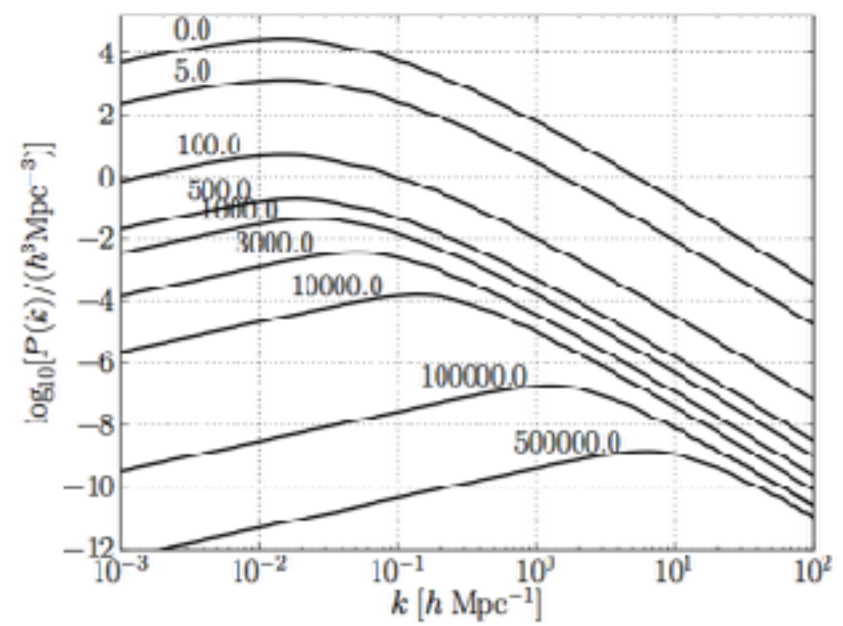

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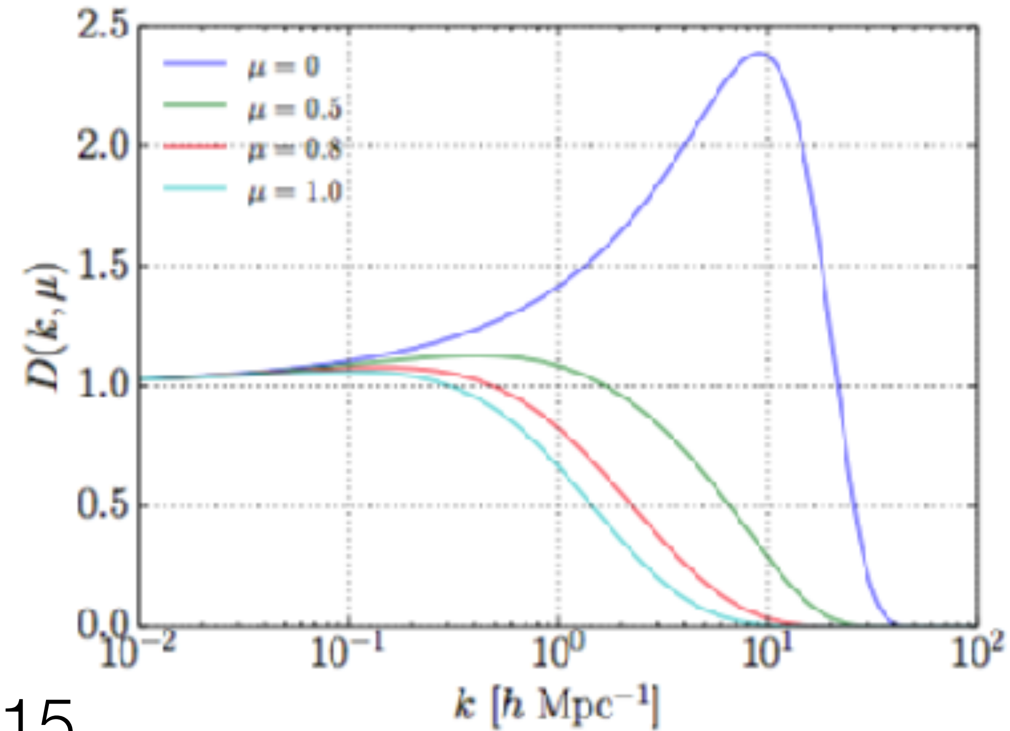

$$b_F = -0.131 \pm 0.017$$
$$\beta = b_\eta / b_F = 1.580 \pm 0.022$$

Alternate functions determined by Arinyo-i-Prats et al. 2015

First clustering measurements using forests

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Few forests available

Measurements of line-of-sight correlations/power spectrum

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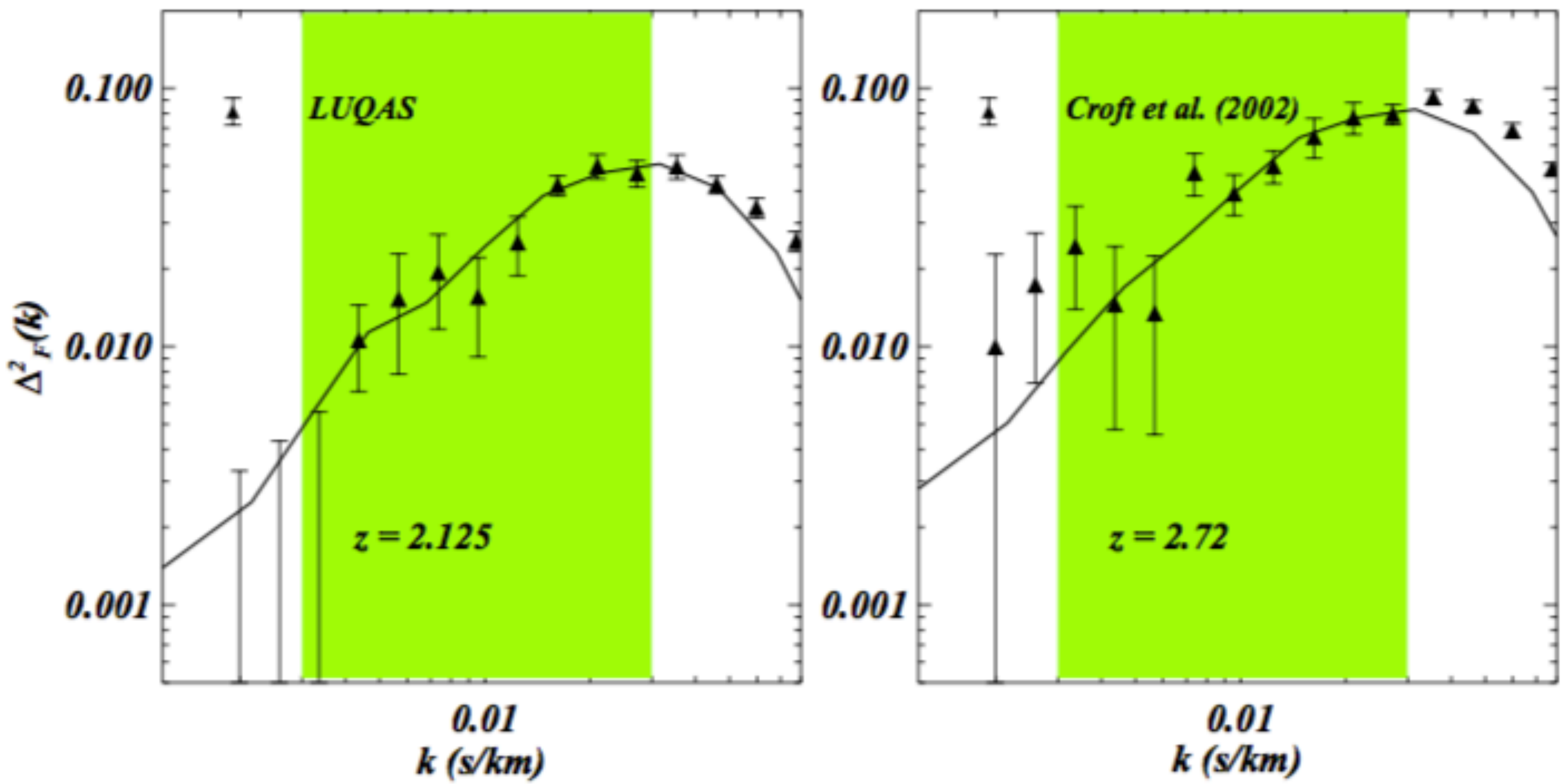

Viel et al. 2004

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Constraints on n_s, σ_8, warm dark matter and **neutrino masses**
McDonald et al. 2006, Palanque-Delabrouille et al. 2013, Yèche et al. 2017

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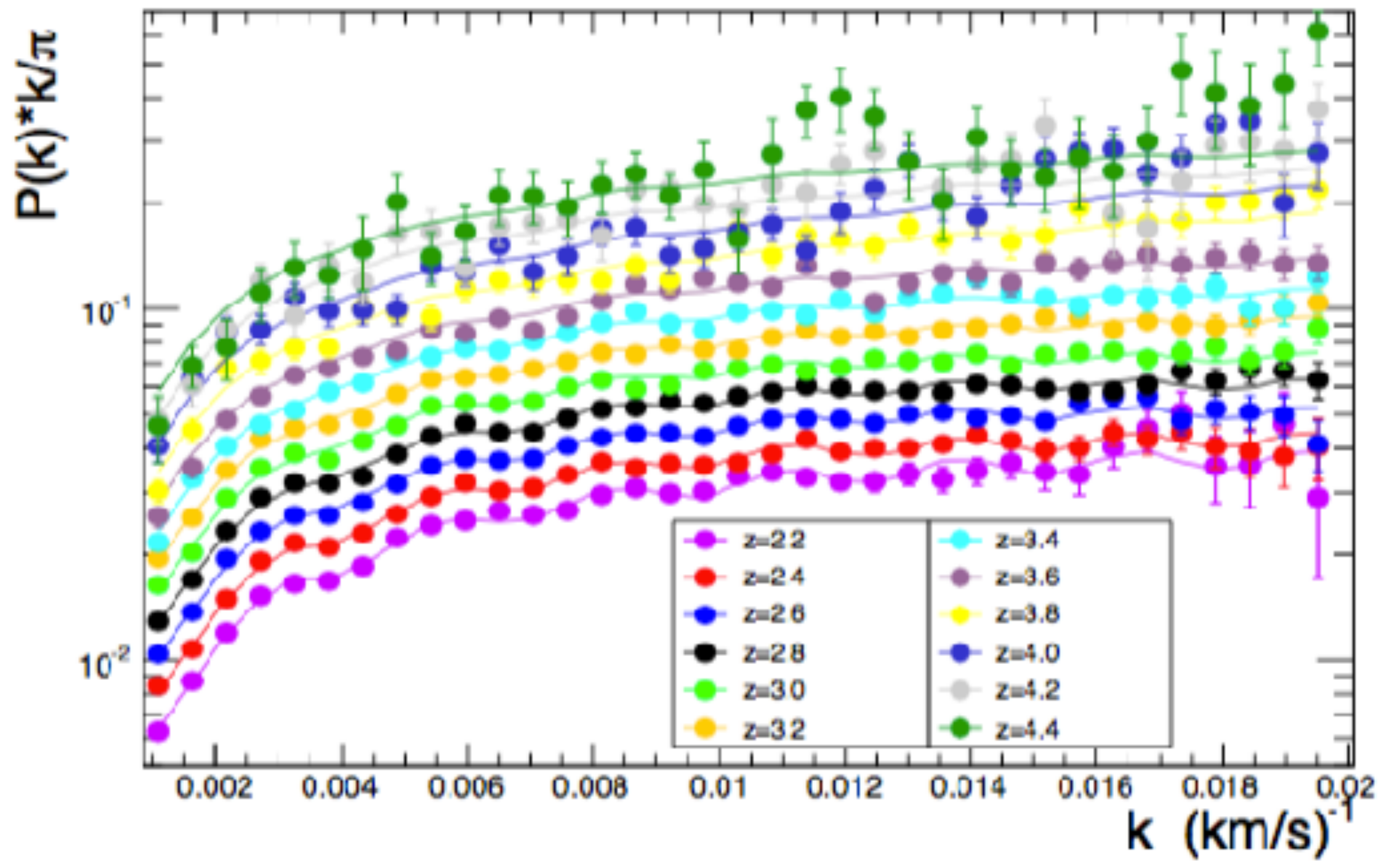

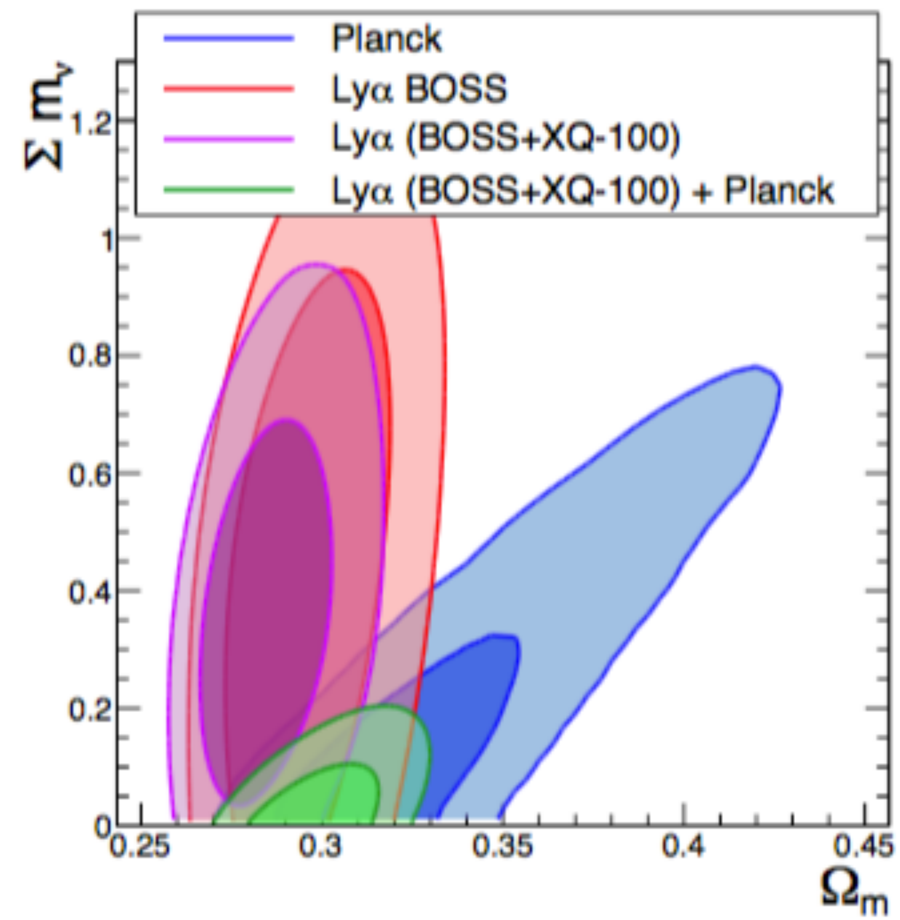

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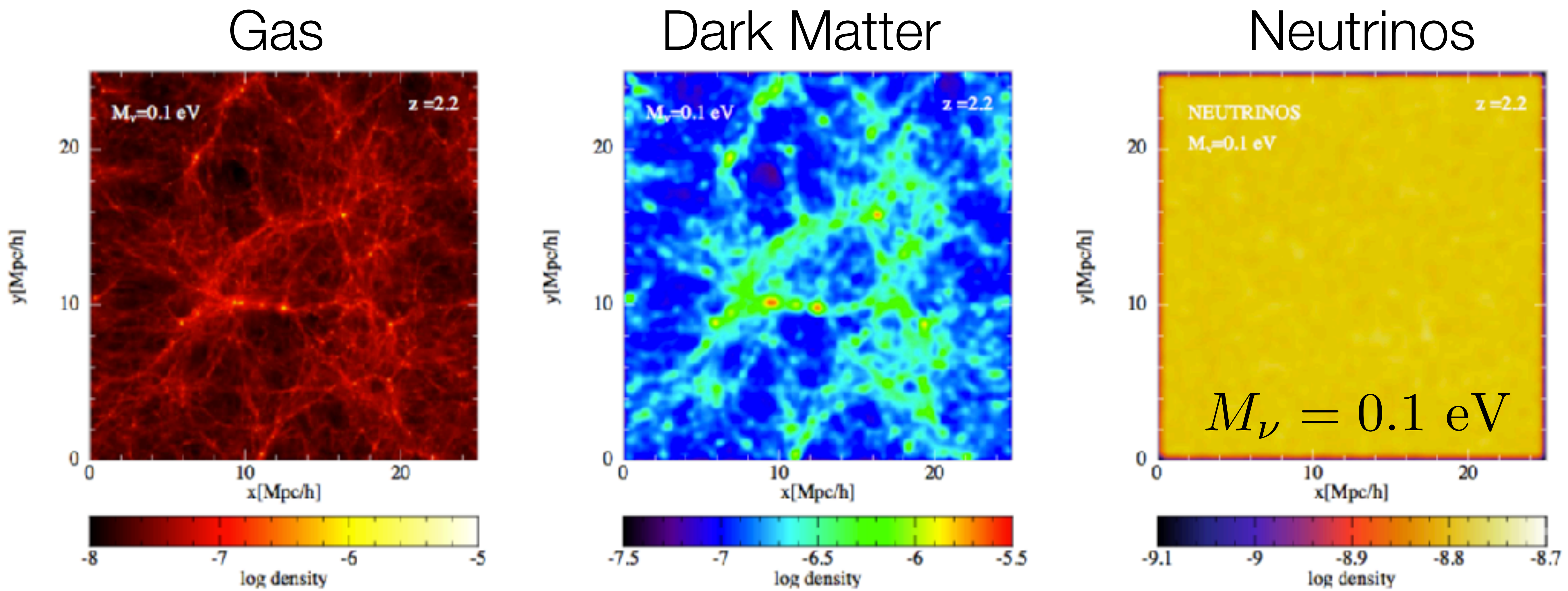
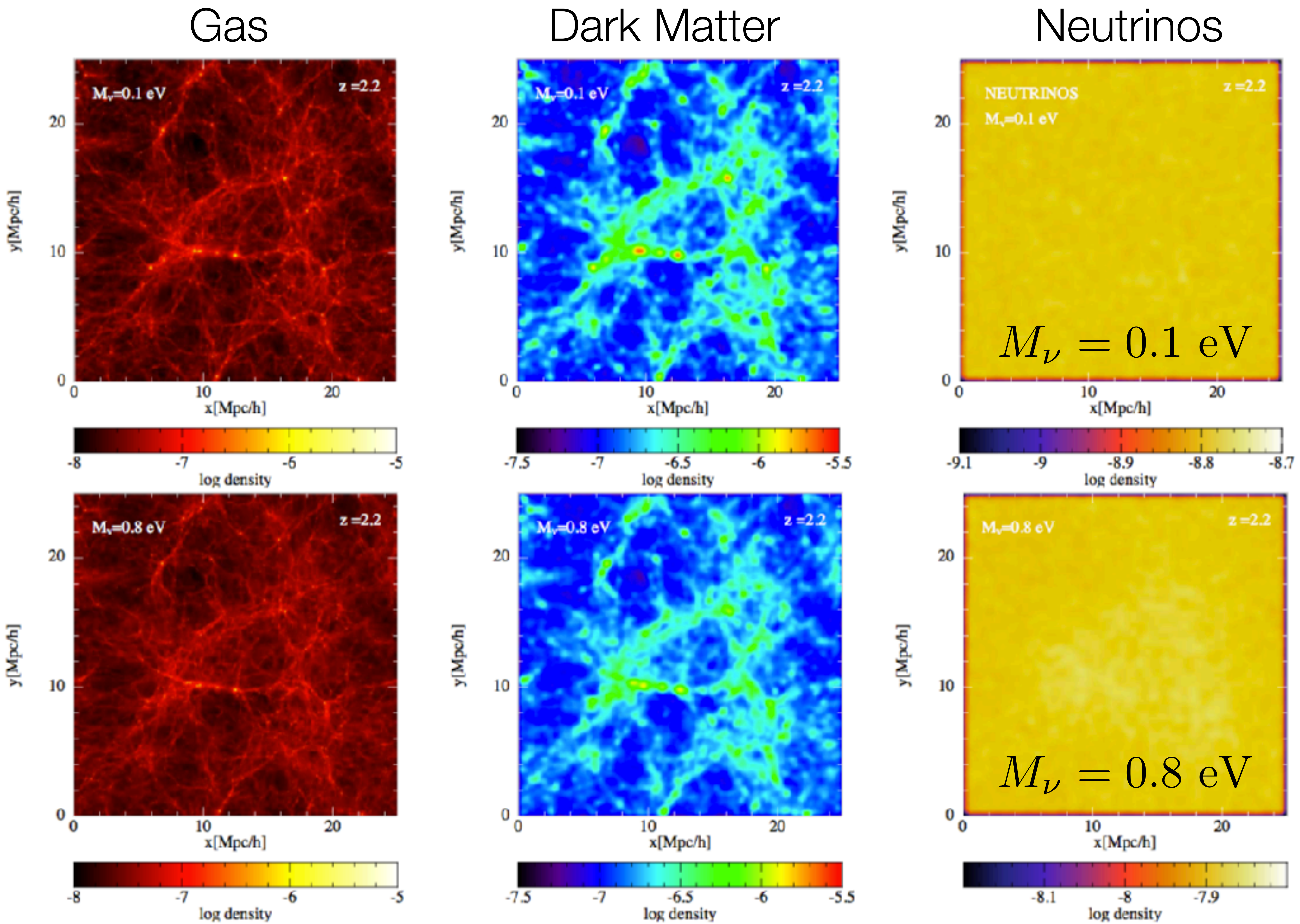
Any attempt to measure the shape of the power-spectrum need simulations to understand the signal

Yeche et al. 2017 use a series of simulations for many combinations of cosmological and IGM parameters (Borde et al. 2014, Rossi et al. 2014, Baur et al. 2016)

Parameter	Value
$\sigma_8(z=0)$	0.83
n_s	0.96
H_0 [km s^{-1}Mpc^{-1}]	67.5
Ω_m	0.31
Ω_b	0.044
Ω_Λ	0.69
$T_0(z=3)[K]$	15000
$\gamma(z=3)$	1.3
Starting redshift	30



Rossi et al. 2014



Rossi et al. 2014

End of lecture 1

Large scale structures with Lyman-α forests

Julián Bautista - Institute of Cosmology and Gravitation
University of Portsmouth, United Kingdom

UNIVERSITY OF PORTSMOUTH

THE UNIVERSITY OF UTAH

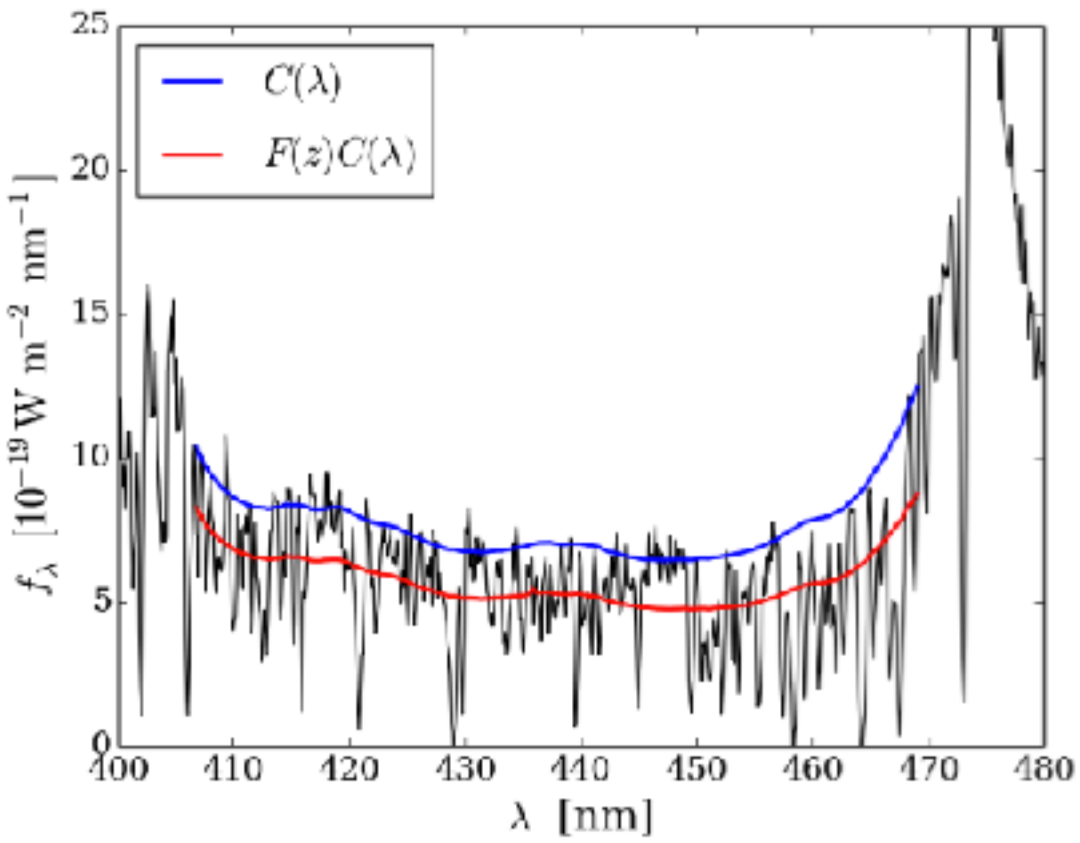
SDSS

Questions from yesterday

- units of k:

$$z_i = \frac{\lambda_i}{\lambda_\alpha} - 1 \qquad \Delta v = c\frac{\Delta\lambda}{\lambda} \text{ [km/s]} \qquad k \equiv \frac{2\pi}{\Delta v} \text{ [s/km]}$$

- what quantity do you correlate in 1D power-spectrum?



$$\delta_F^q(\lambda_i) = \frac{F_i}{\bar{F}} - 1$$

Many of these per forest!
One delta per pixel

$$\hat{\delta}^q(k_i) = \mathrm{FFT}[\delta^q(\lambda_i)]$$

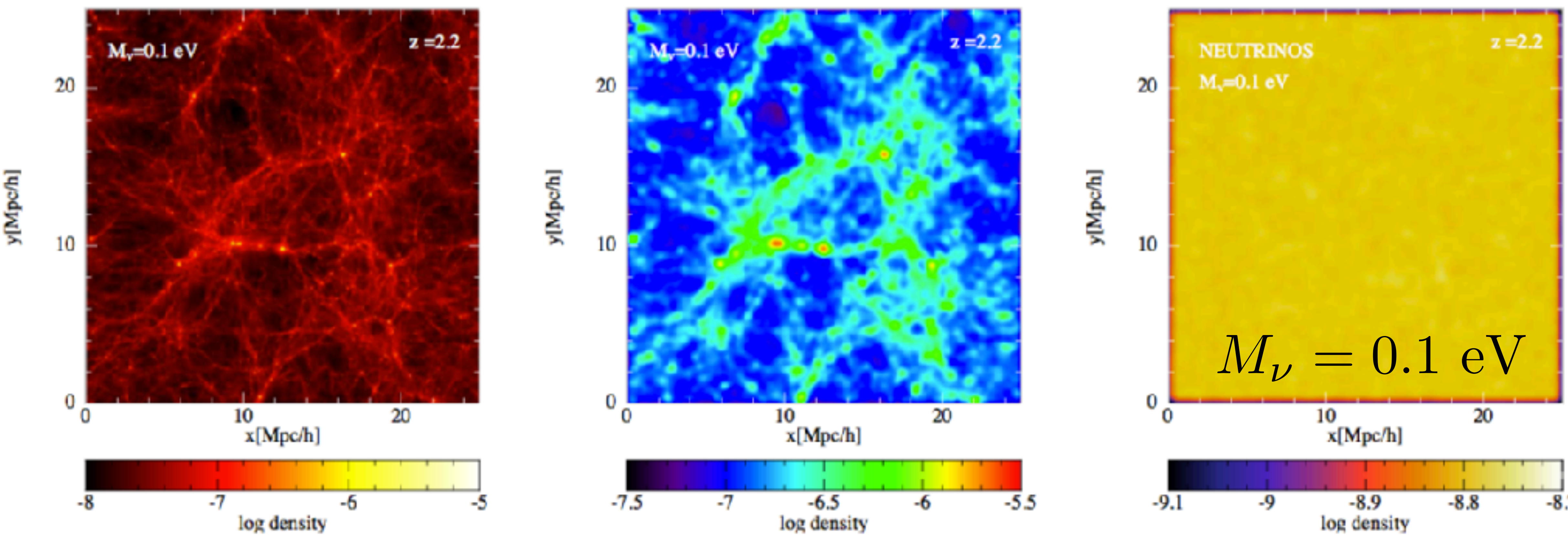
$$P_F(k_i) = \langle \hat{\delta}_F^q(k_i)\bar{\hat{\delta}}_F^q(k_i)\rangle_q$$

Questions from yesterday

- The forests, do they trace the dark matter field or not?

Yes! And much better at low density regions than galaxies!

Gas Dark Matter Neutrinos



- What is the constraint on warm dark-matter from Yeche et al. 2017?

Early decoupled thermal relics:

$$m_X \gtrsim 2.08\ \mathrm{keV}\ (95\%\ \mathrm{C.L.})$$

Non-resonantly produced right-handed neutrinos

$$m_s \gtrsim 10.2\ \mathrm{keV}\ (95\%\ \mathrm{C.L.})$$

Questions from yesterday

- Do you fit a model to $P_{1D}(k)$ in Yeche et al 2017?

You use the predicted $P_{1D}(k)$ directly from the simulations and compare to the data!

Grid of simulations varying:
cosmo parameters
IGM parameters
neutrino masses
And interpolate between results to find best-fit

Three-dimensional clustering measurements using BOSS forests

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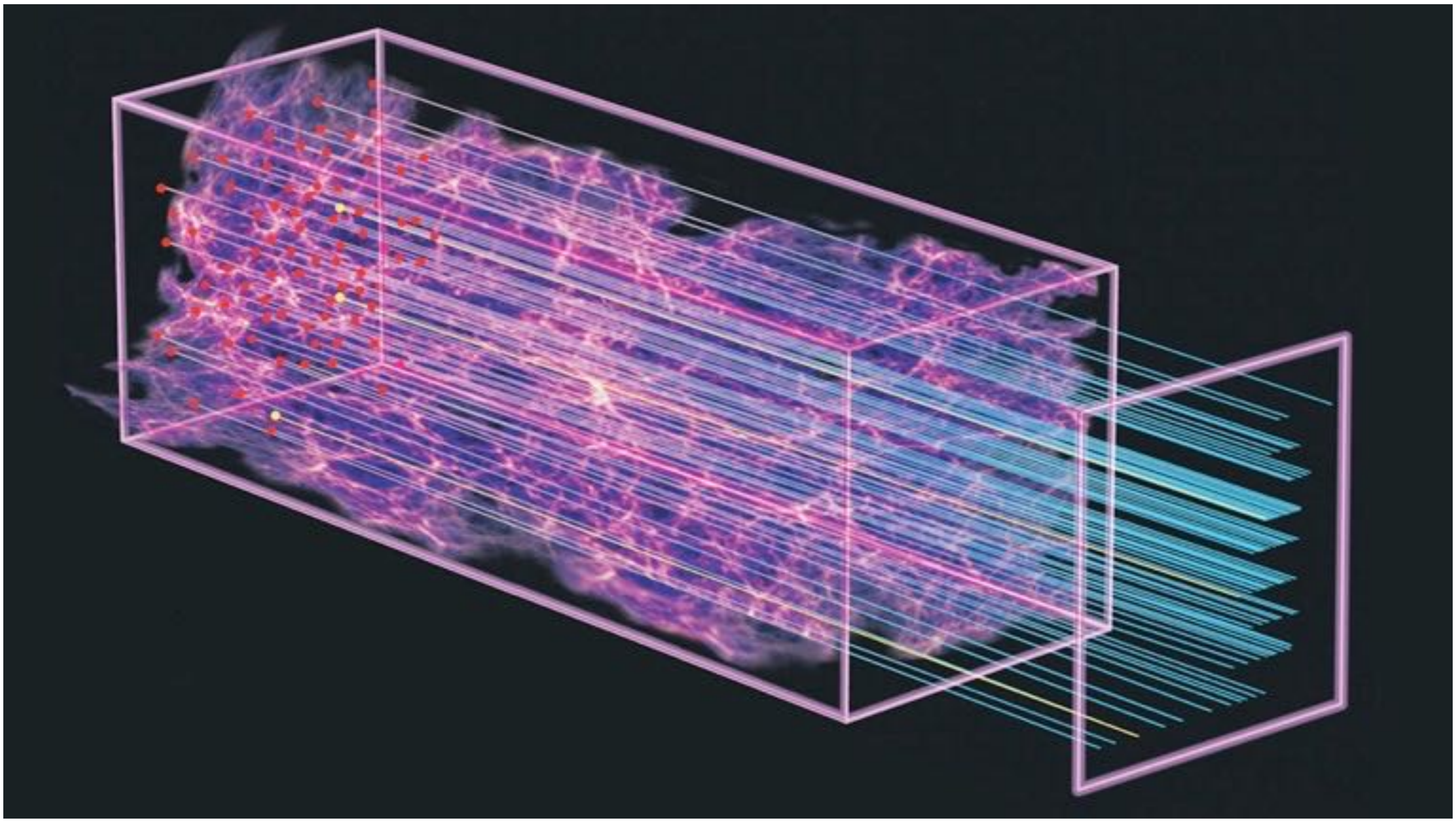
Survey of forests



(e)BOSS

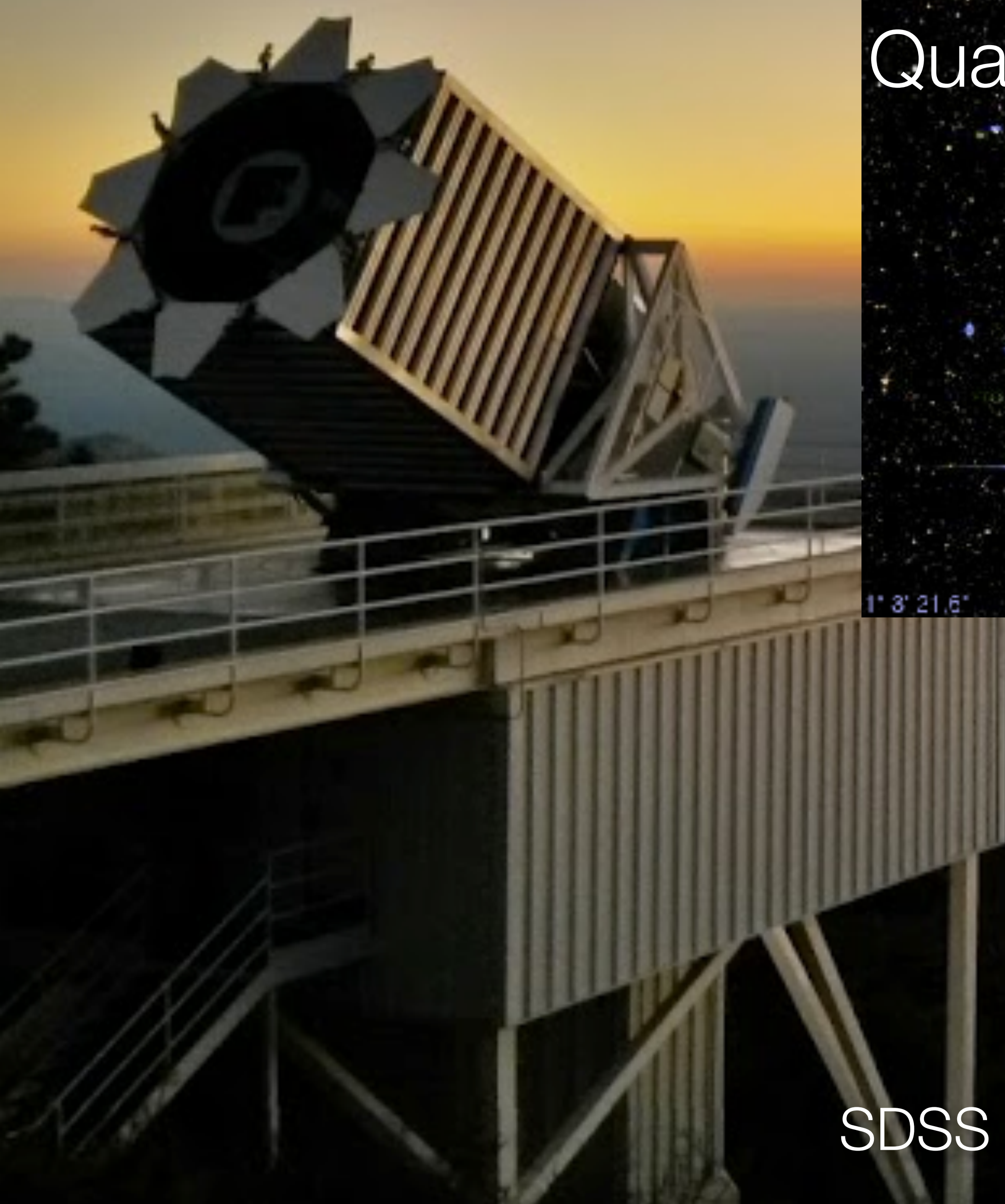
(Extended) Baryon Oscillation Spectroscopic Survey

SDSS Telescope @ Apache Point Observatory, New Mexico, USA

(e)BOSS

(Extended) Baryon Oscillation Spectroscopic Survey

Select galaxies and quasars from
SDSS photometry
Quasars are harder because they look like stars!



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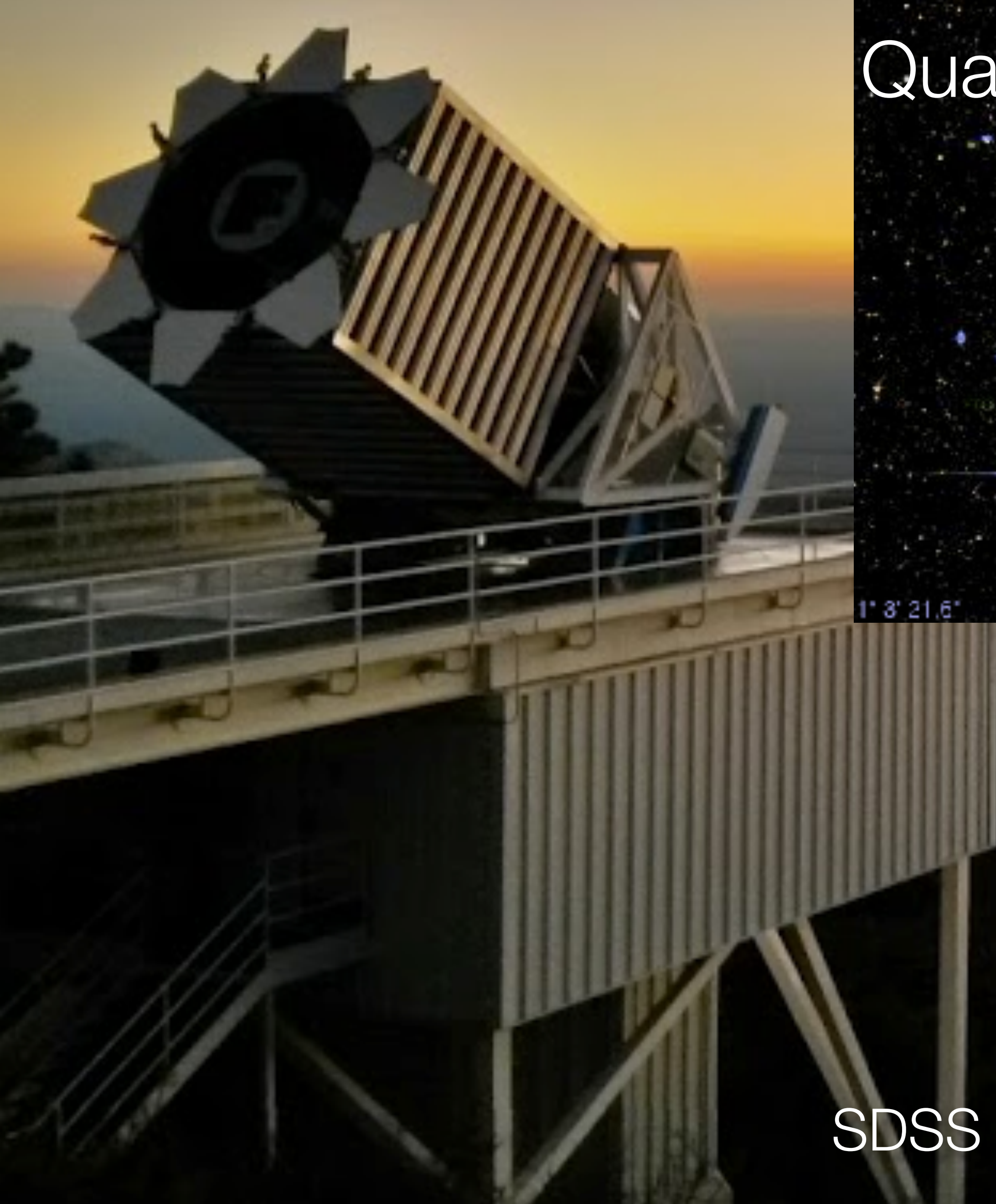

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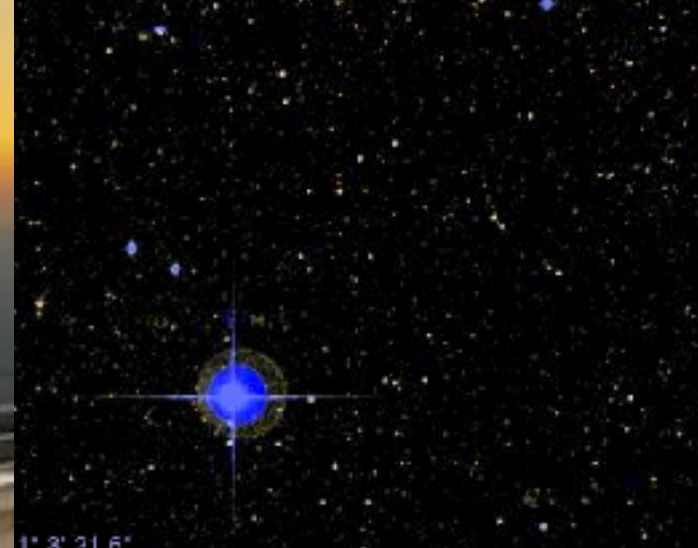
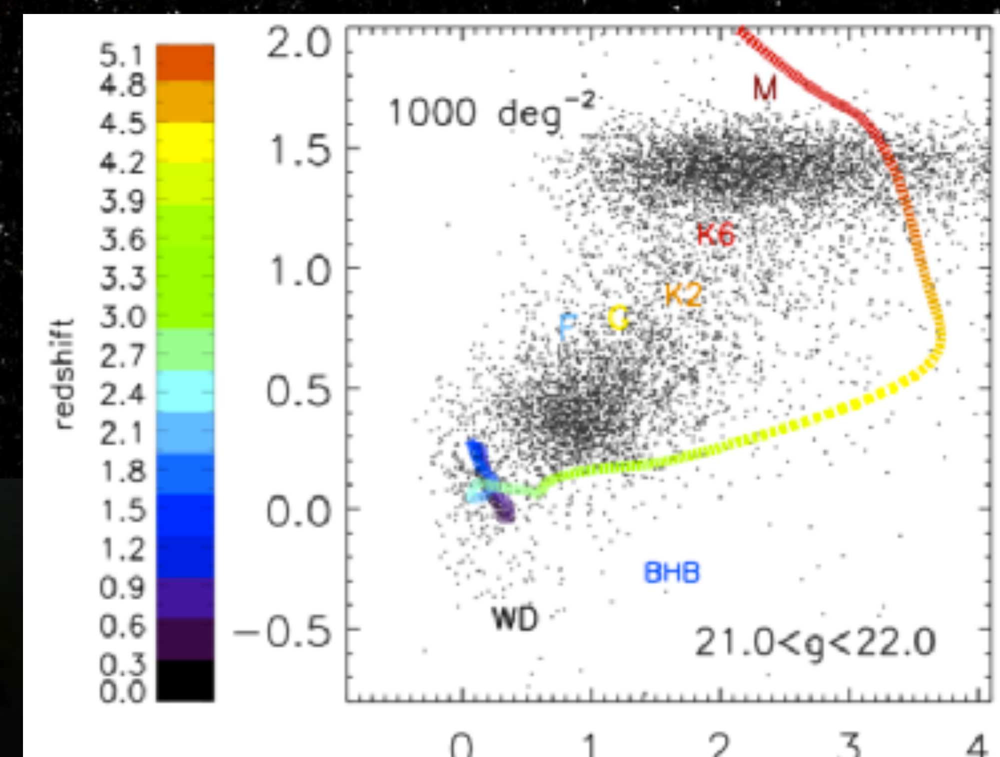
Quasars are harder because they look like stars!





Ross et al. 2011

SDSS Telescope @ Apache Point Observatory, New Mexico, USA

(e)BOSS

(Extended) Baryon Oscillation Spectroscopic Survey

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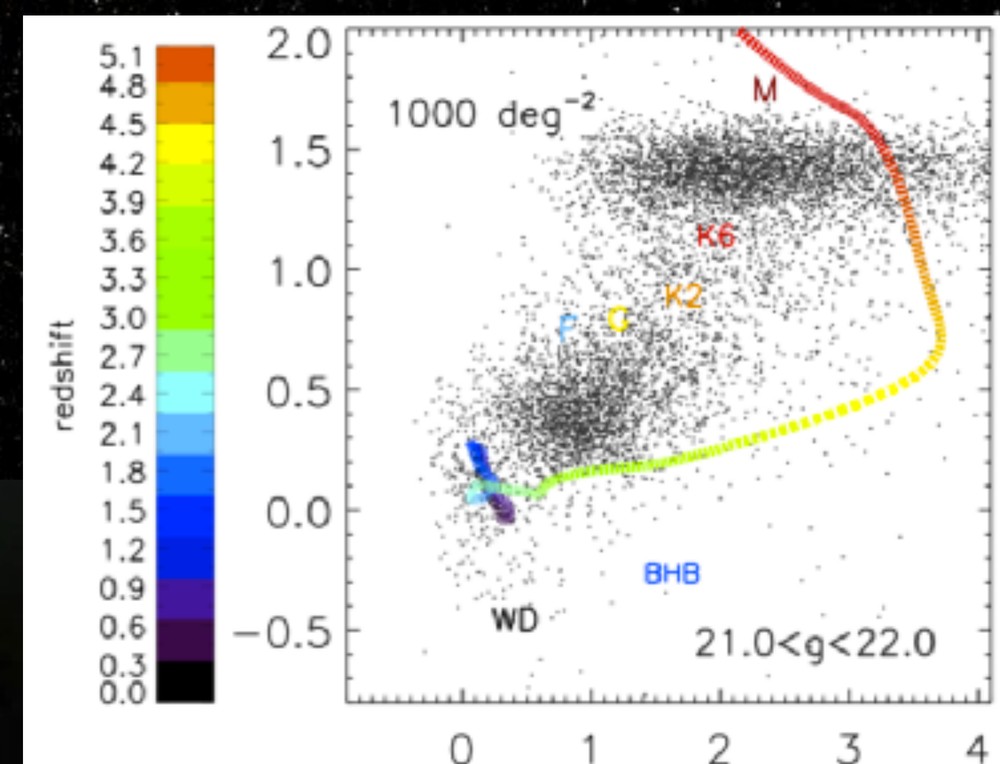
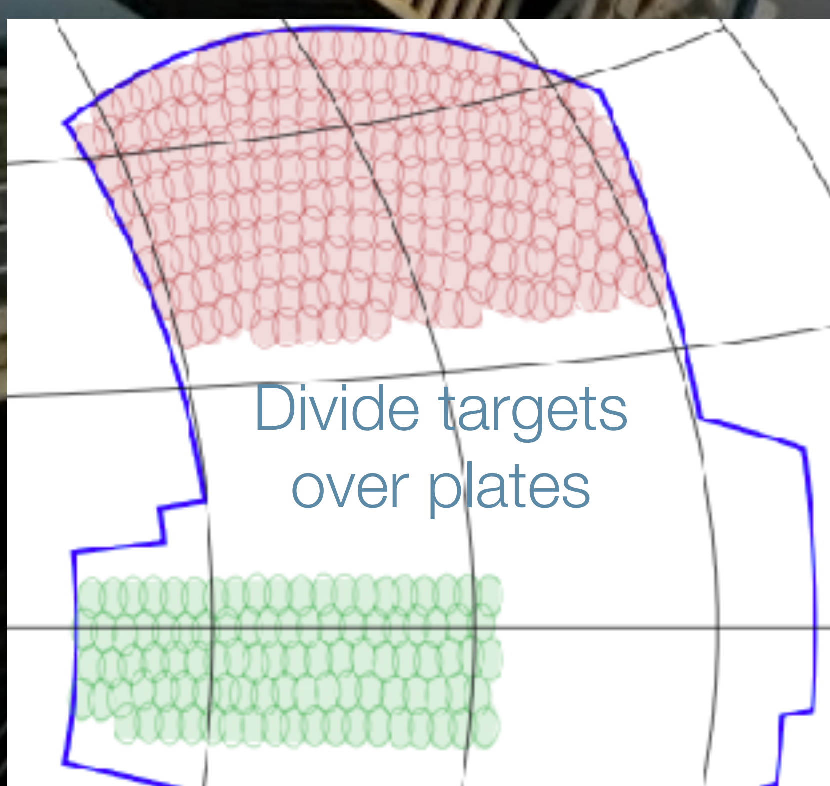


Ross et al. 2011



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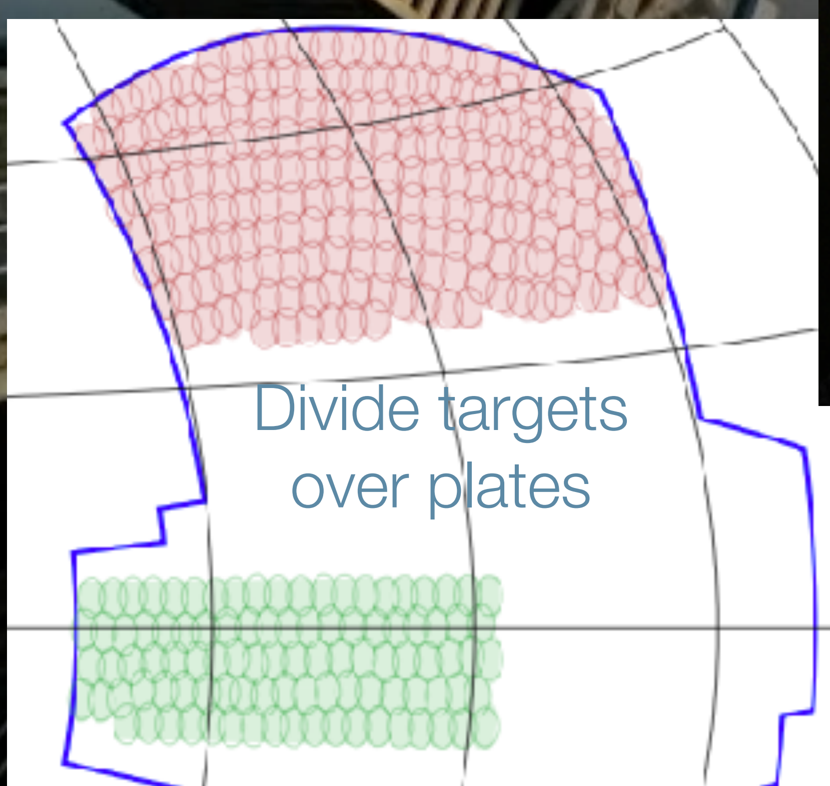

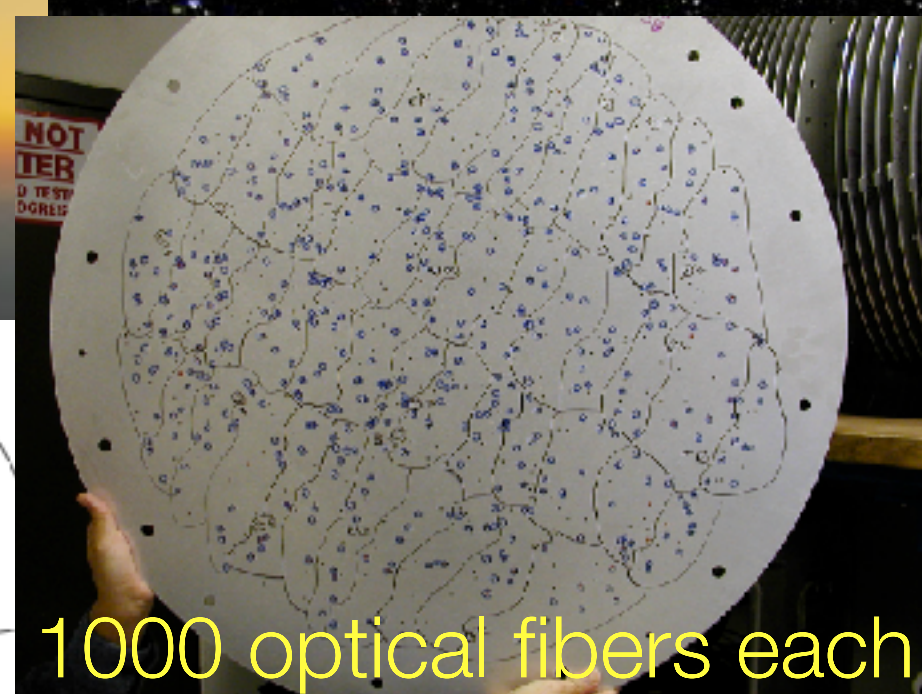

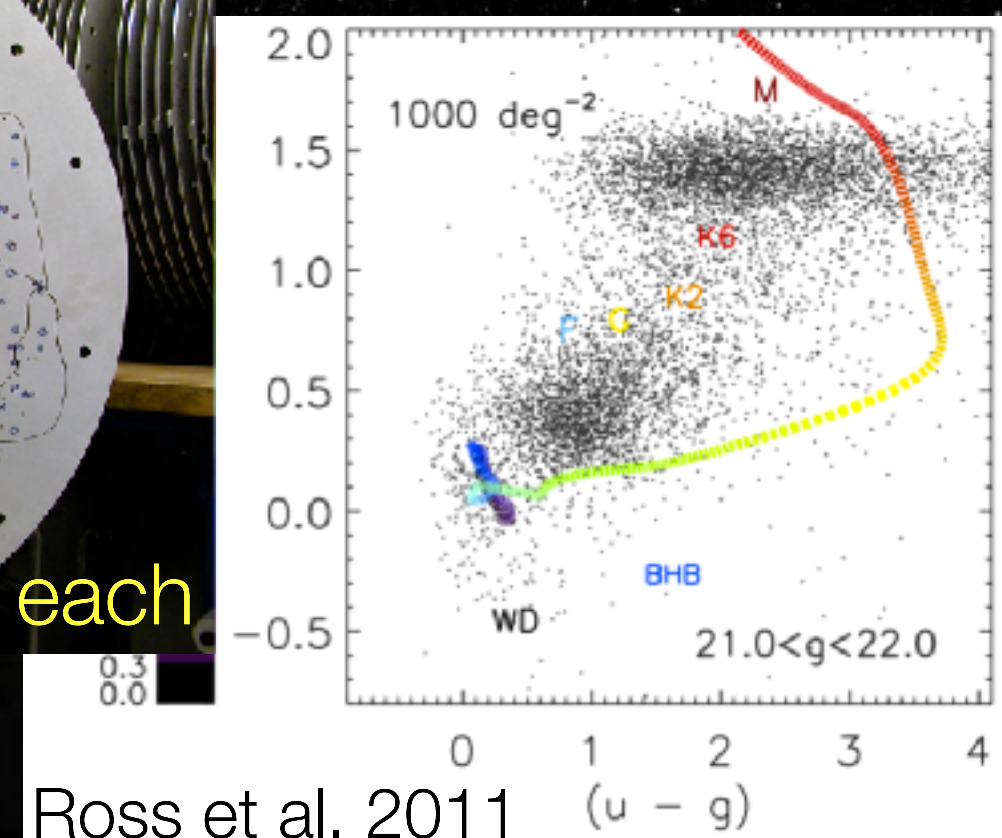

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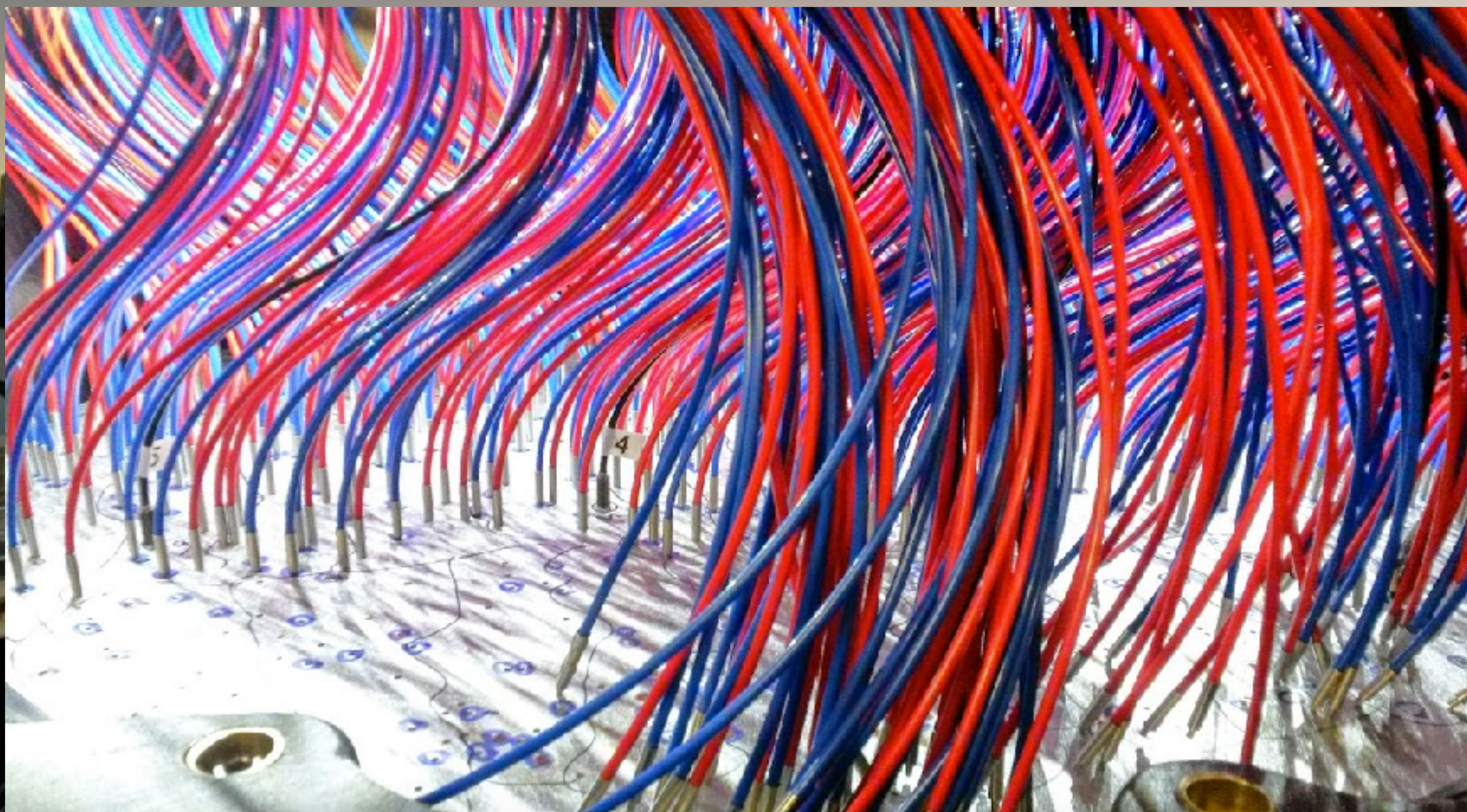

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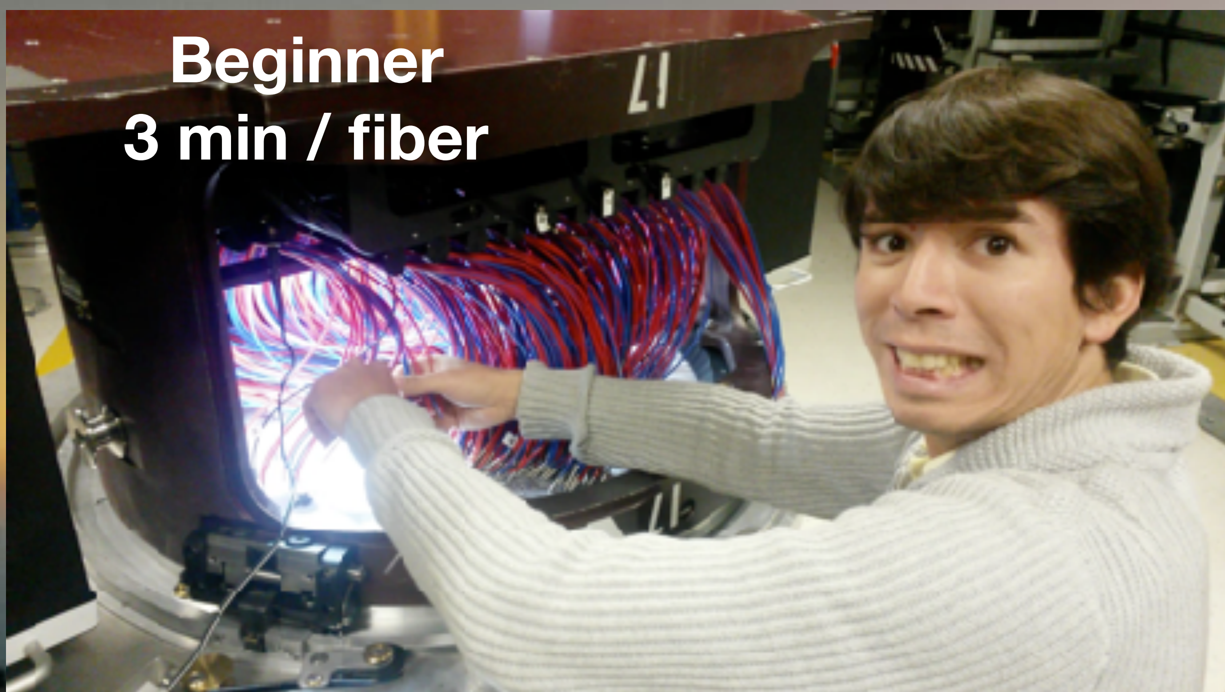

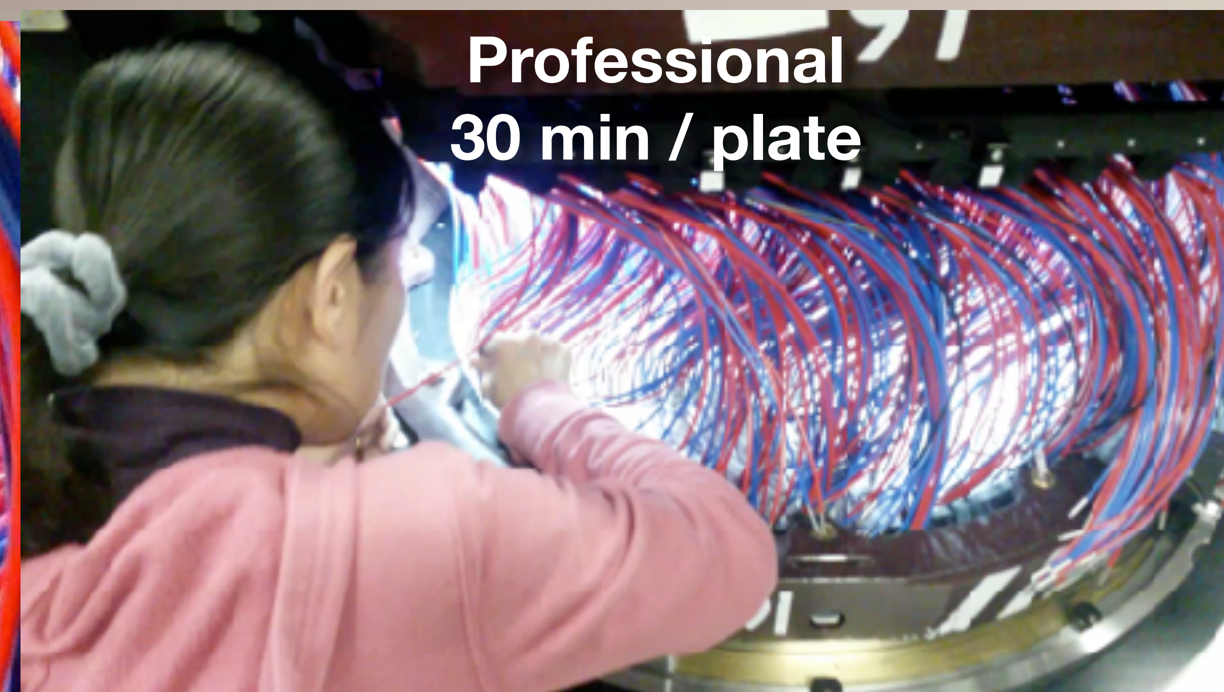

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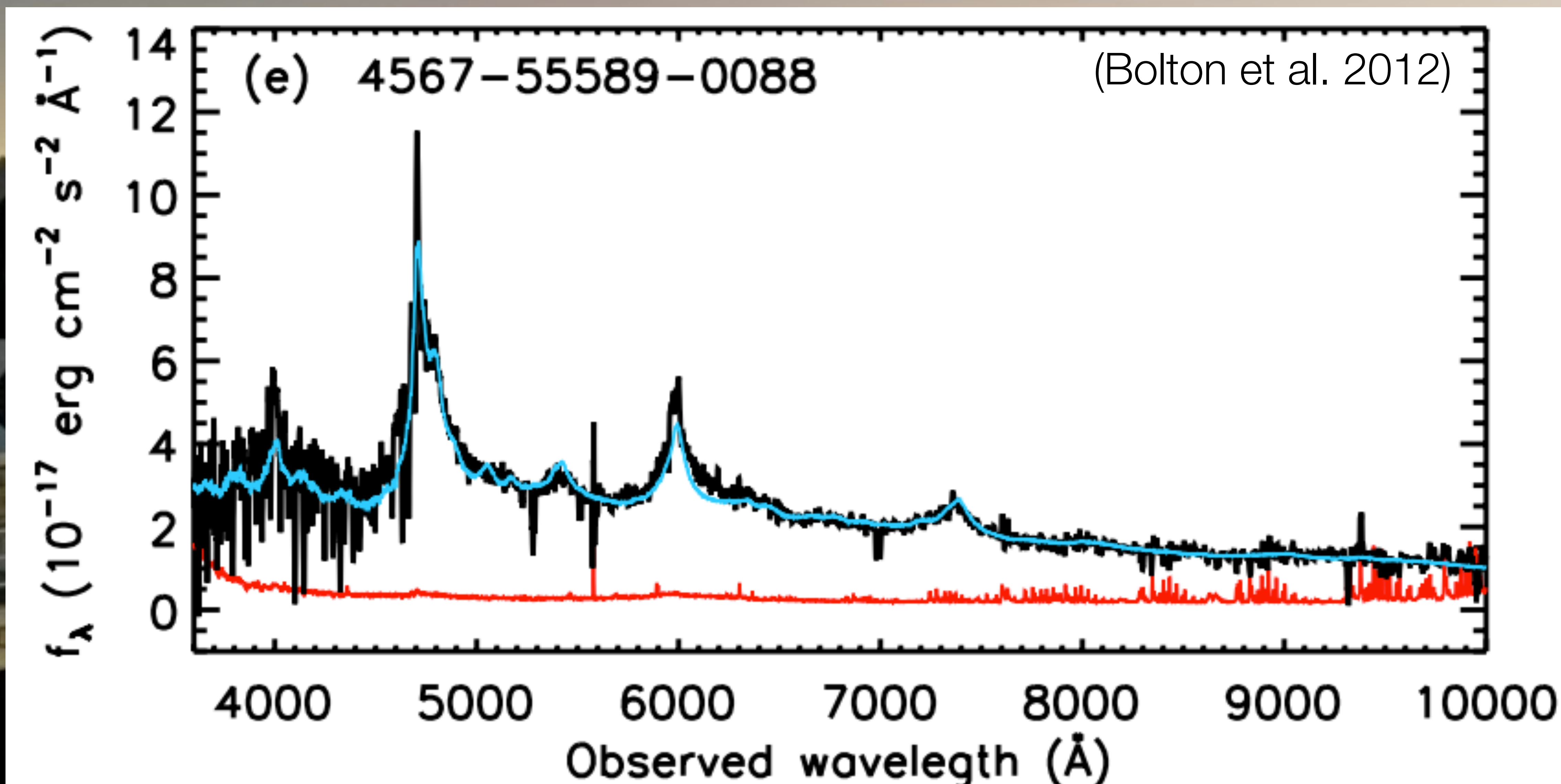
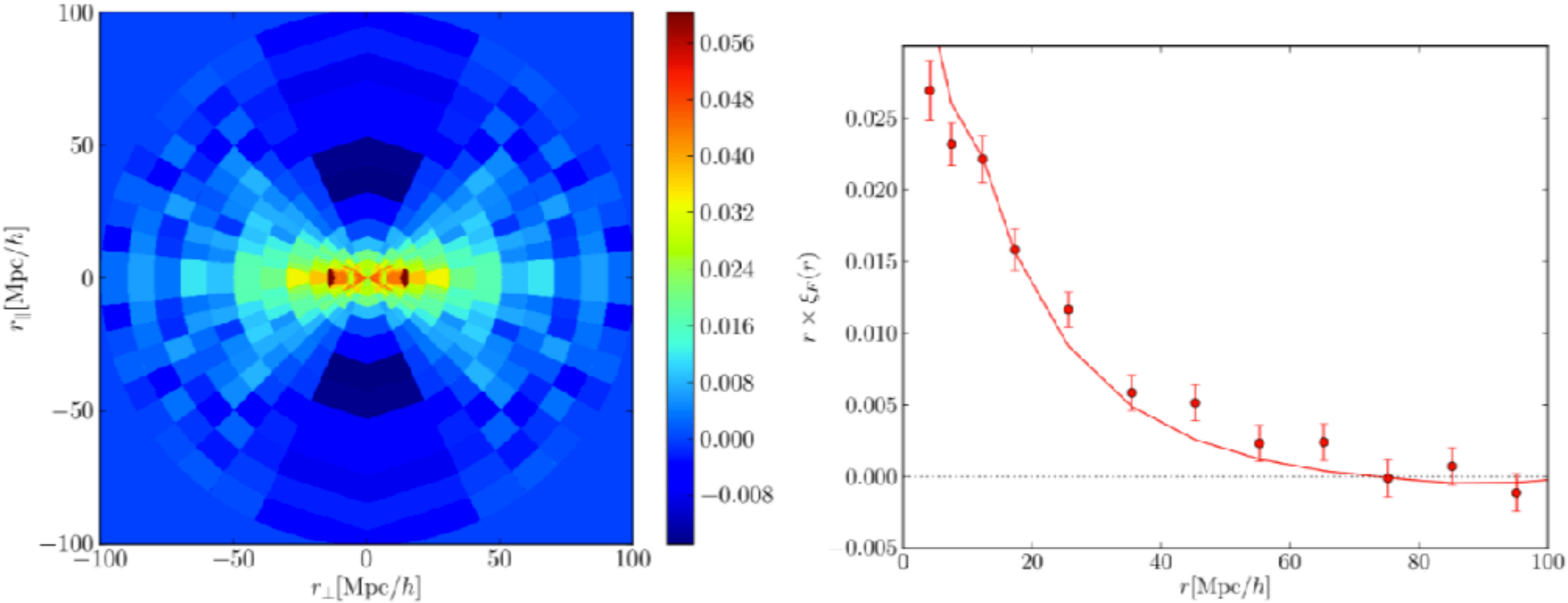


SDSS Telescope @ Apache Point Observatory, New Mexico, USA

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

Slosar et al. 2011

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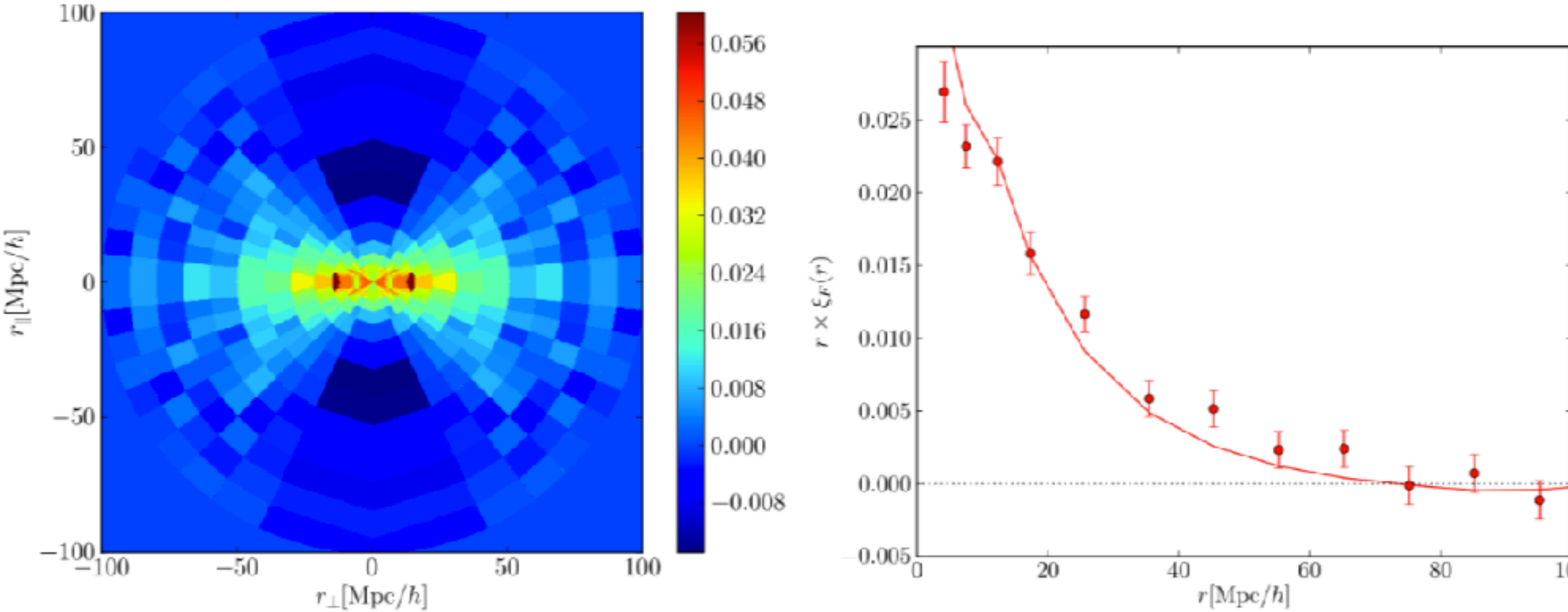

First evidence of large-scale correlations among different lines of sight, including redshift-space distortions

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

Slosar et al. 2011

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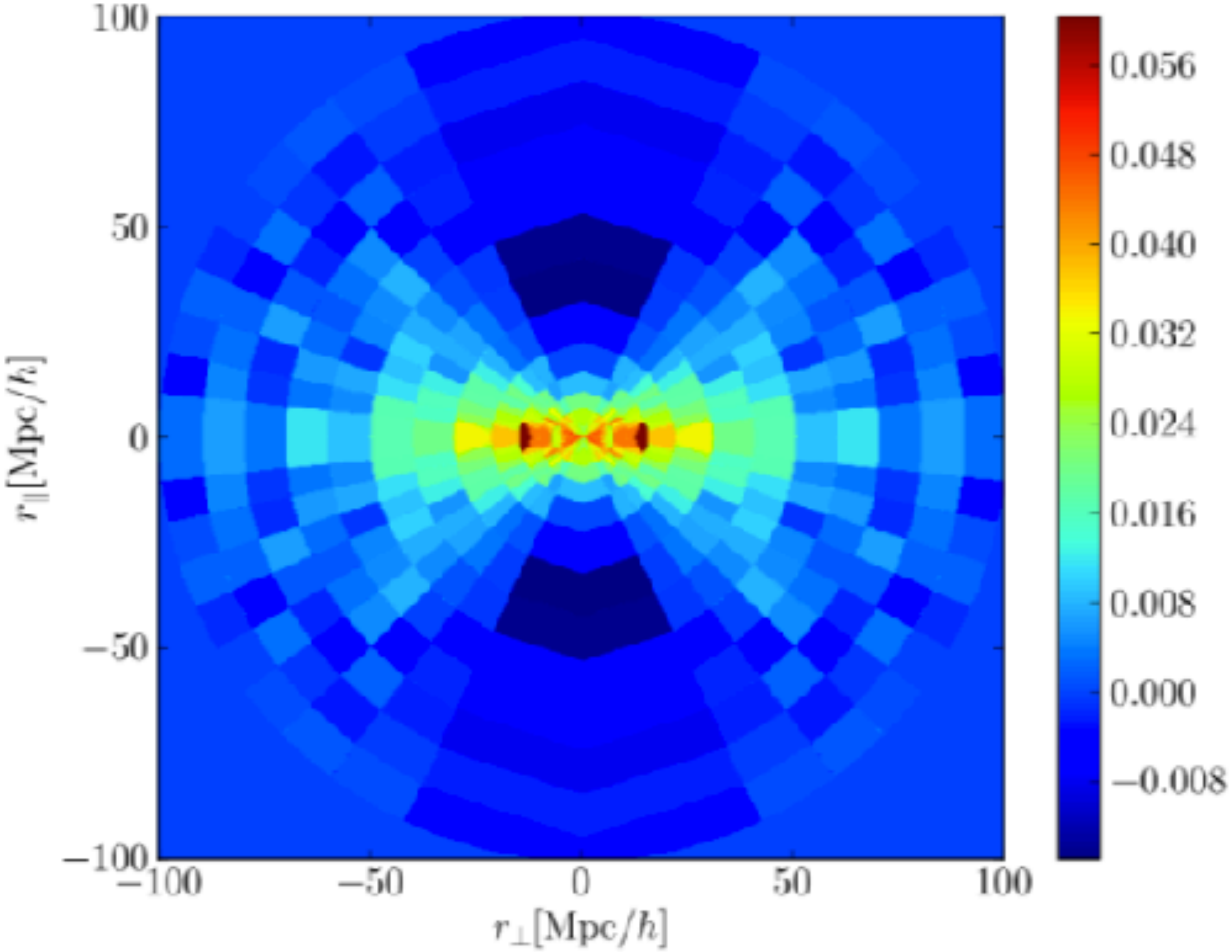
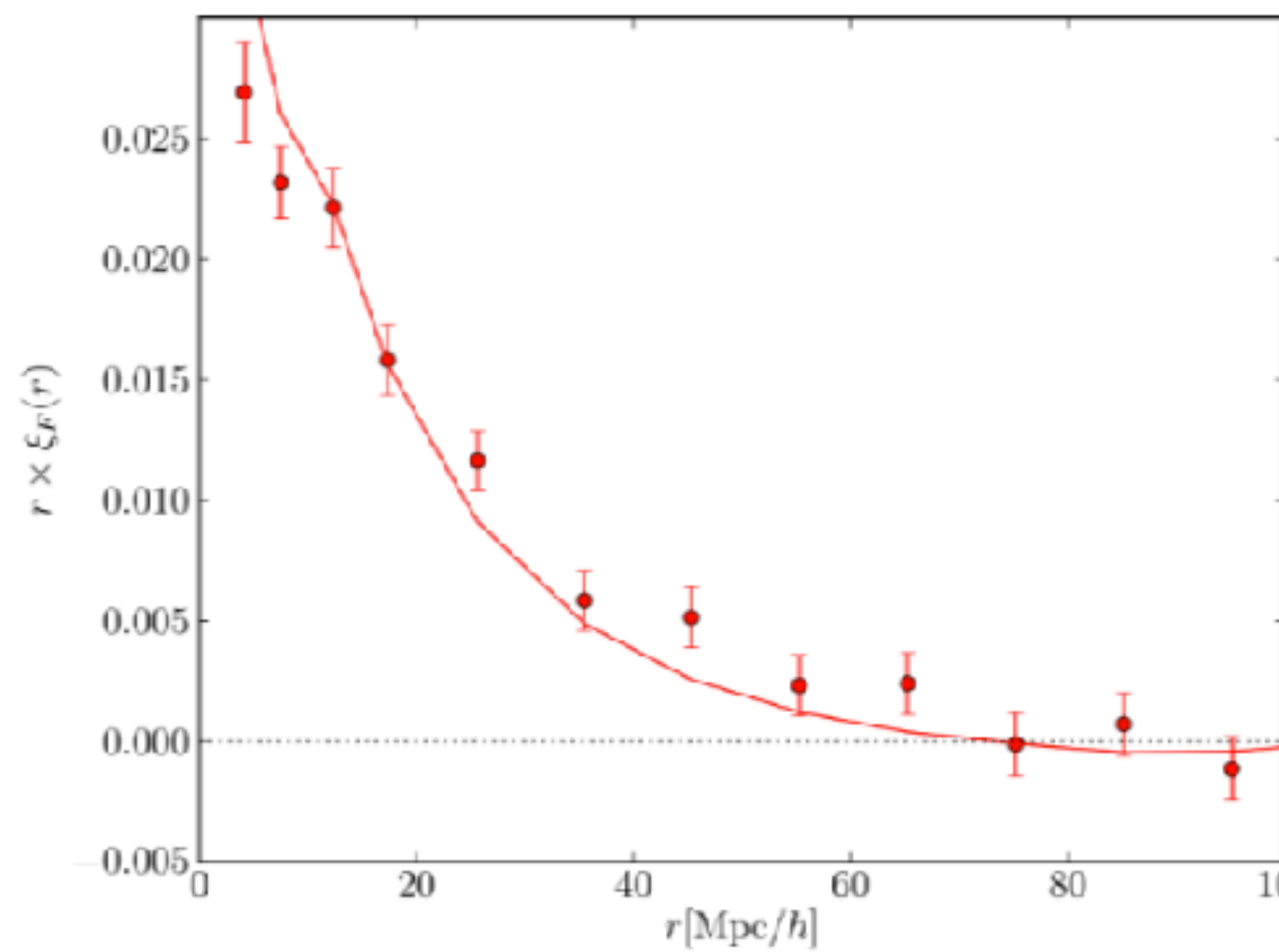




First evidence of large-scale correlations among different

$b_F = -0.131 \pm 0.017$

ncludir

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

ons

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

Consistent with hydro-simulations!

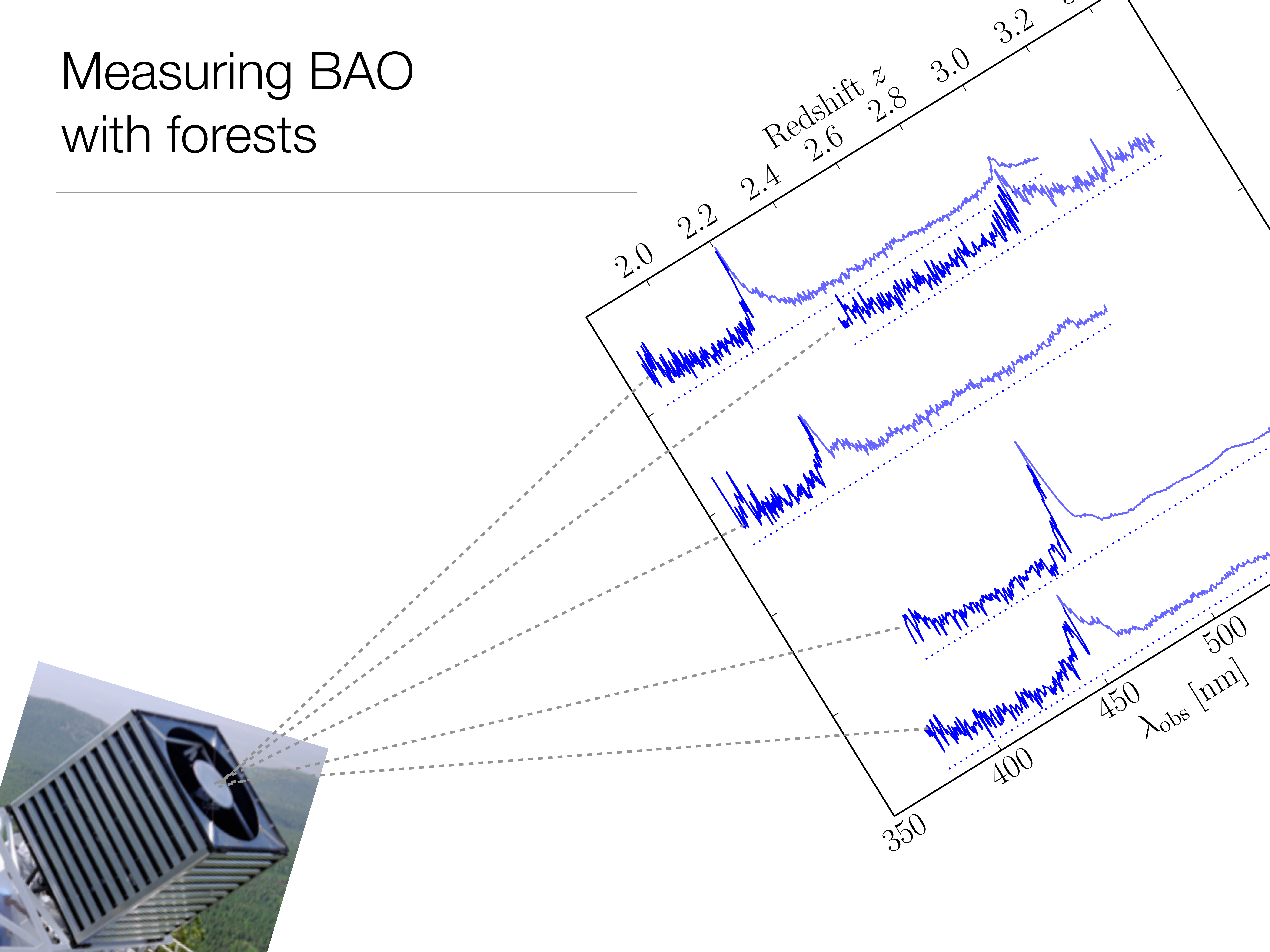
Slosar et al. 2011

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, JB, et al. 2014
JB et al. 2017
Du Mas des Bourboux et al. 2017

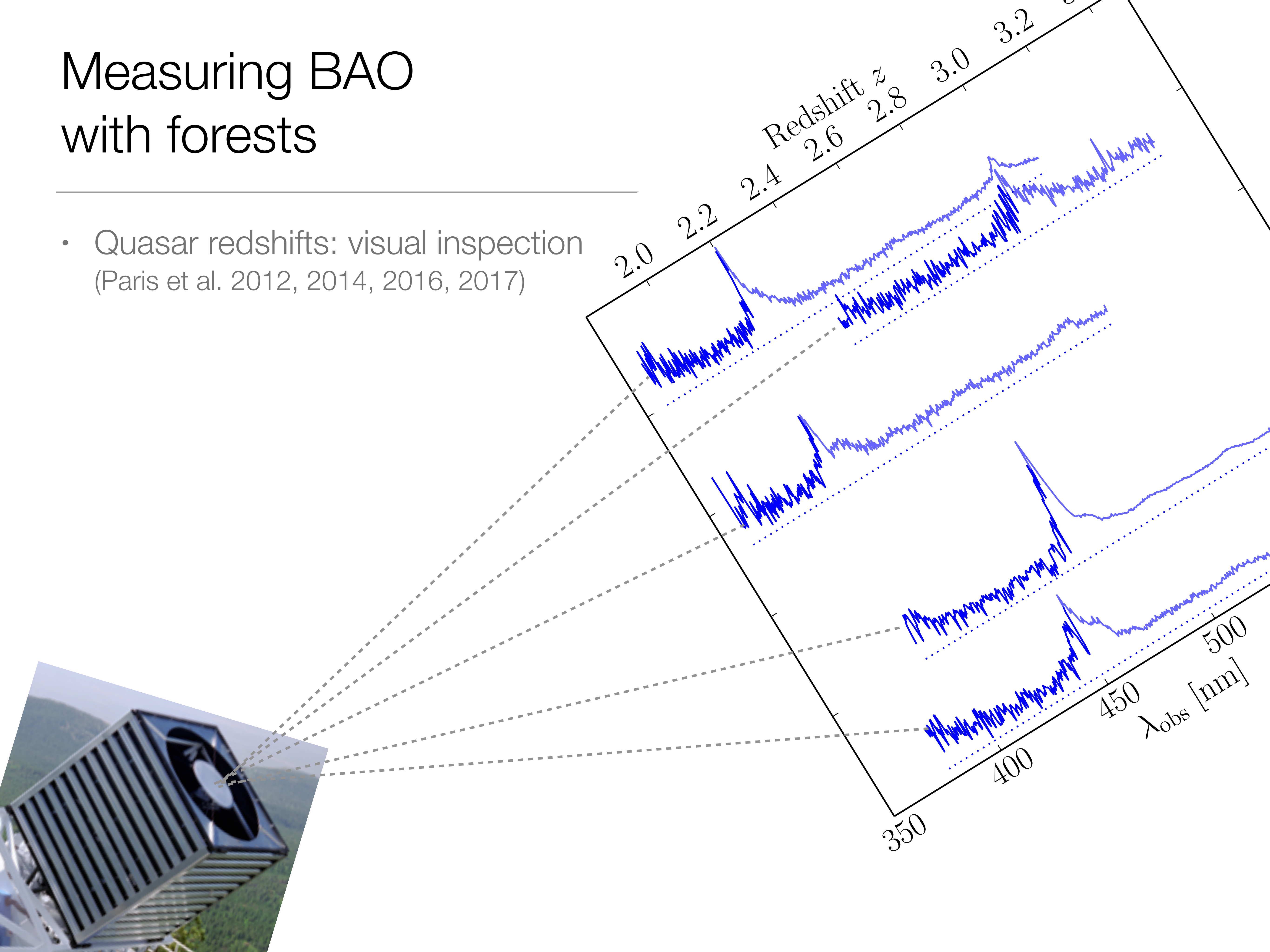
github.com/igmhub/picca

Measuring BAO with forests



Measuring BAO with forests

- Quasar redshifts: visual inspection
  (Paris et al. 2012, 2014, 2016, 2017)



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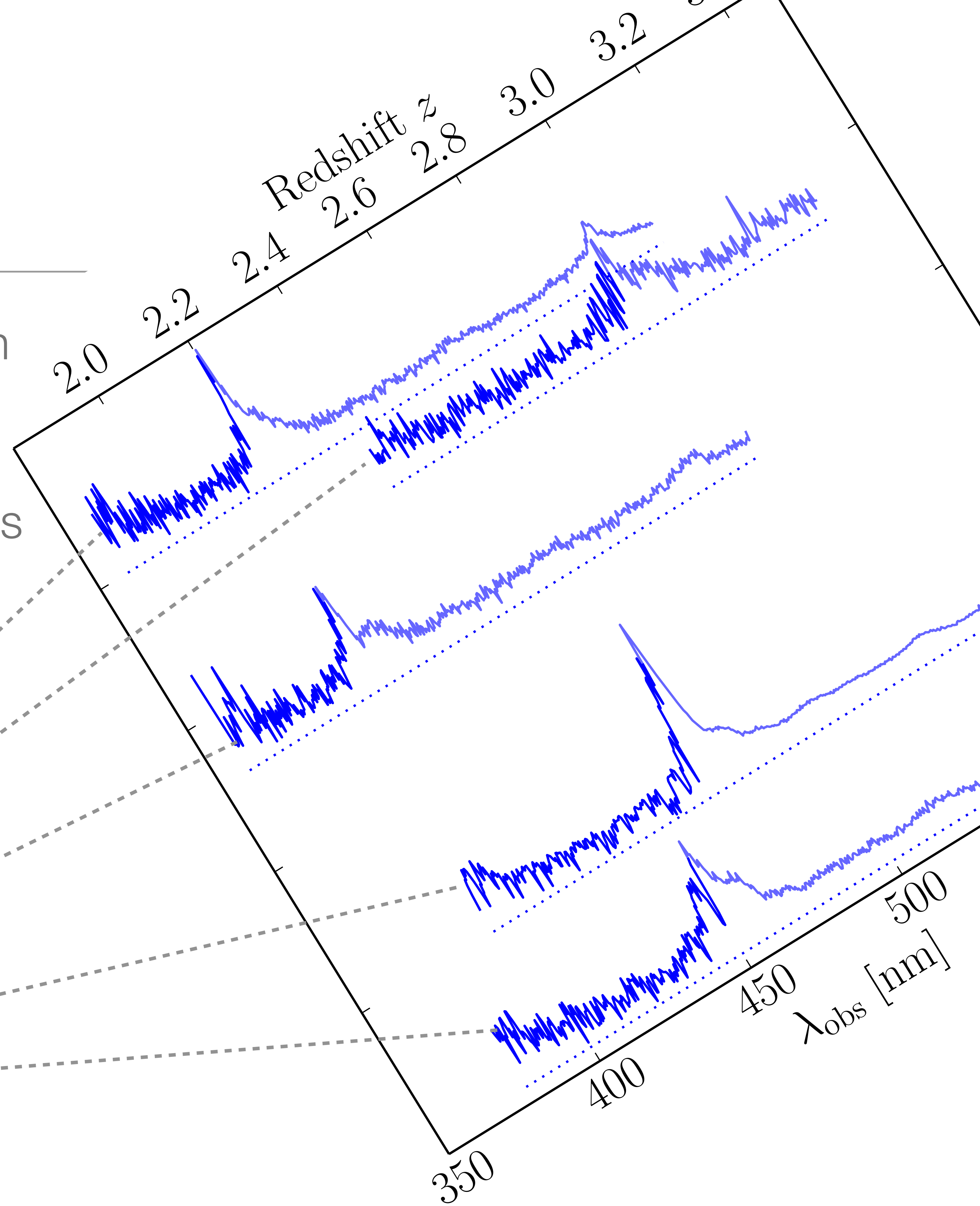

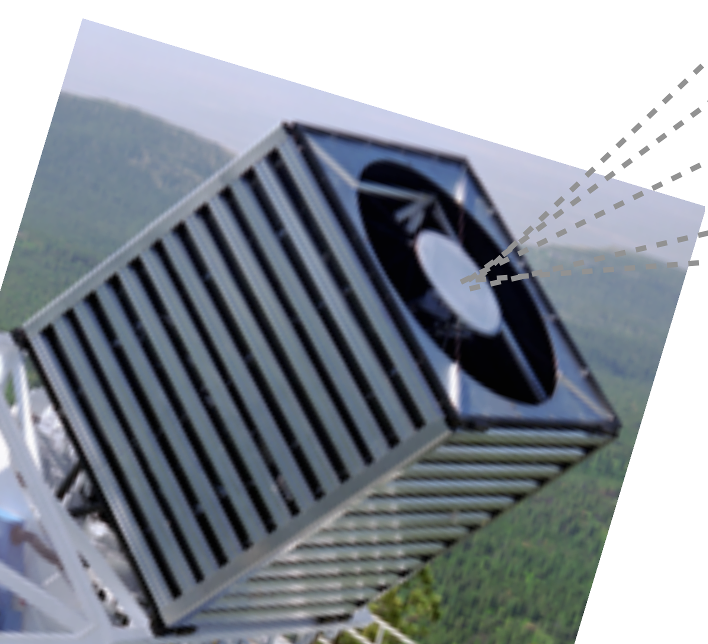

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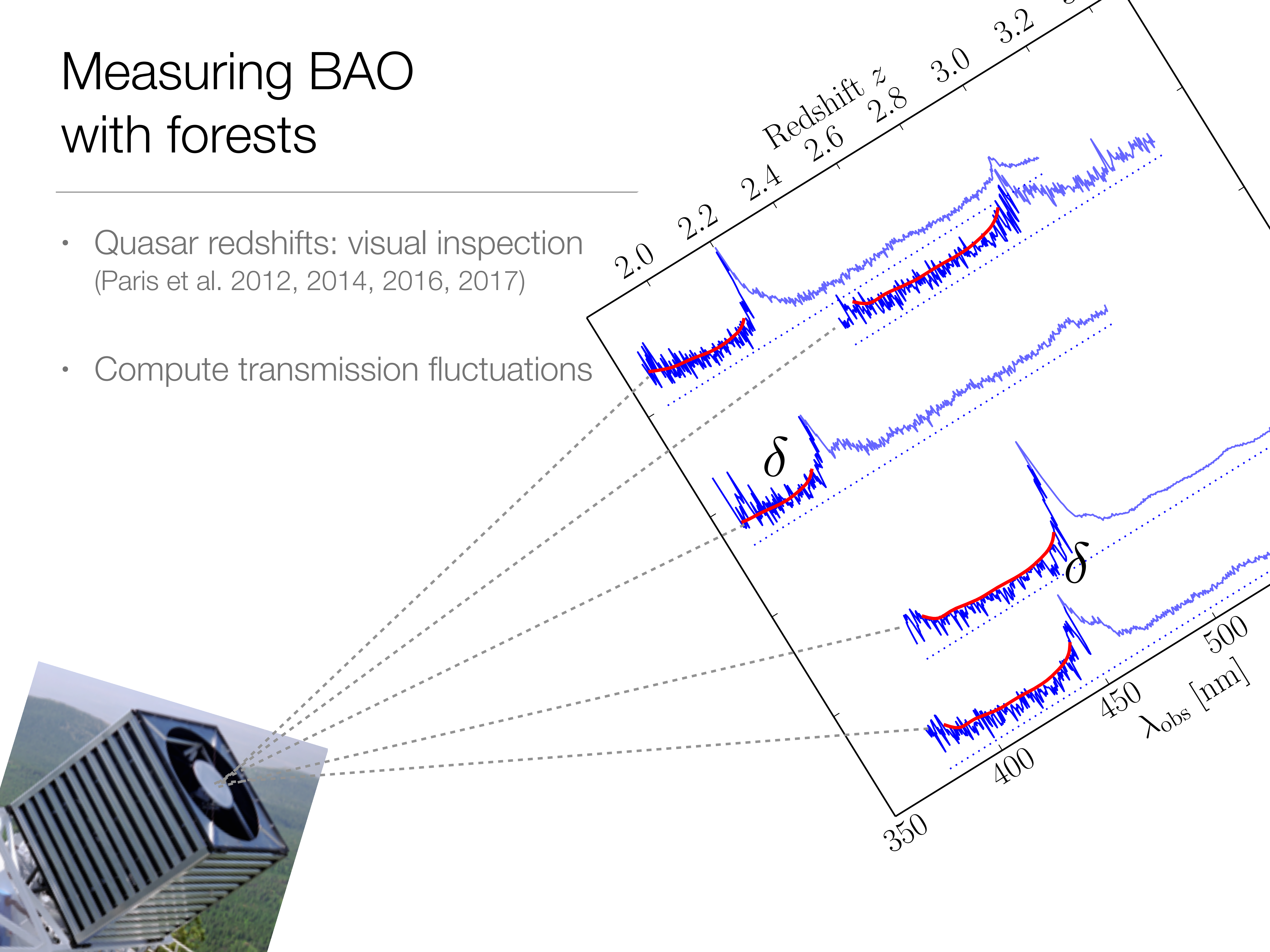

Measuring BAO with forests

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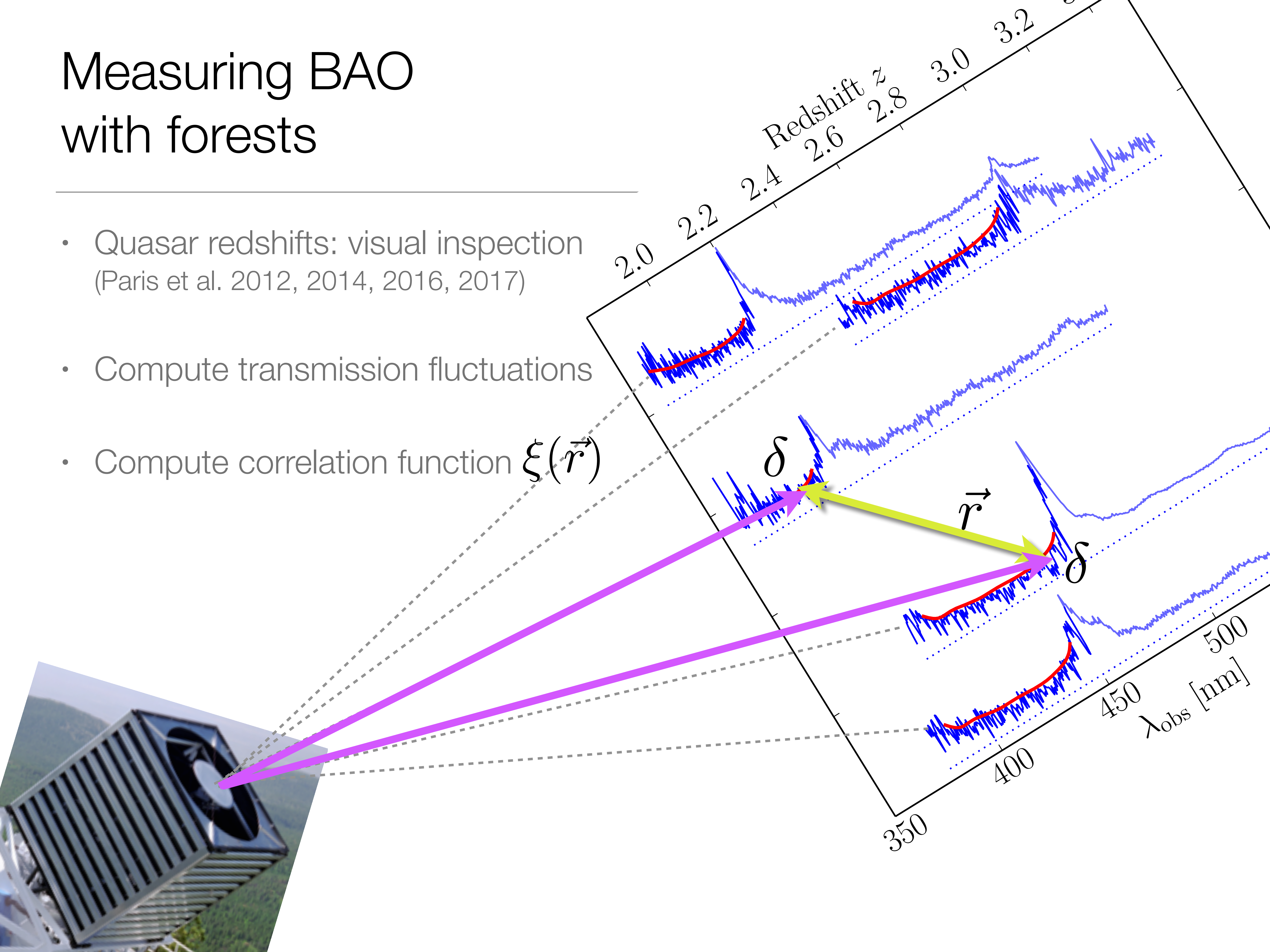

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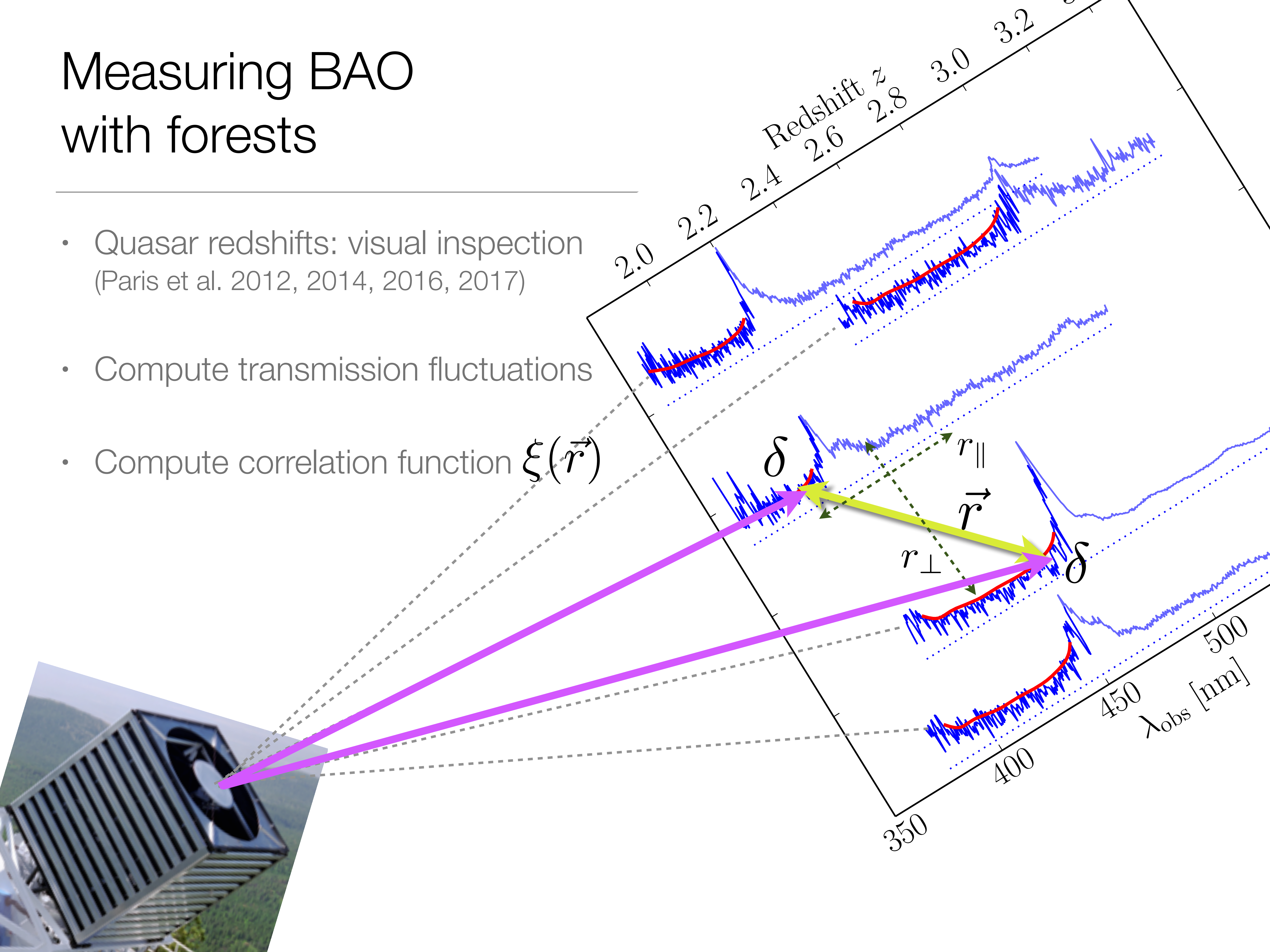

Measuring BAO with forests

- Quasar redshifts: visual inspection
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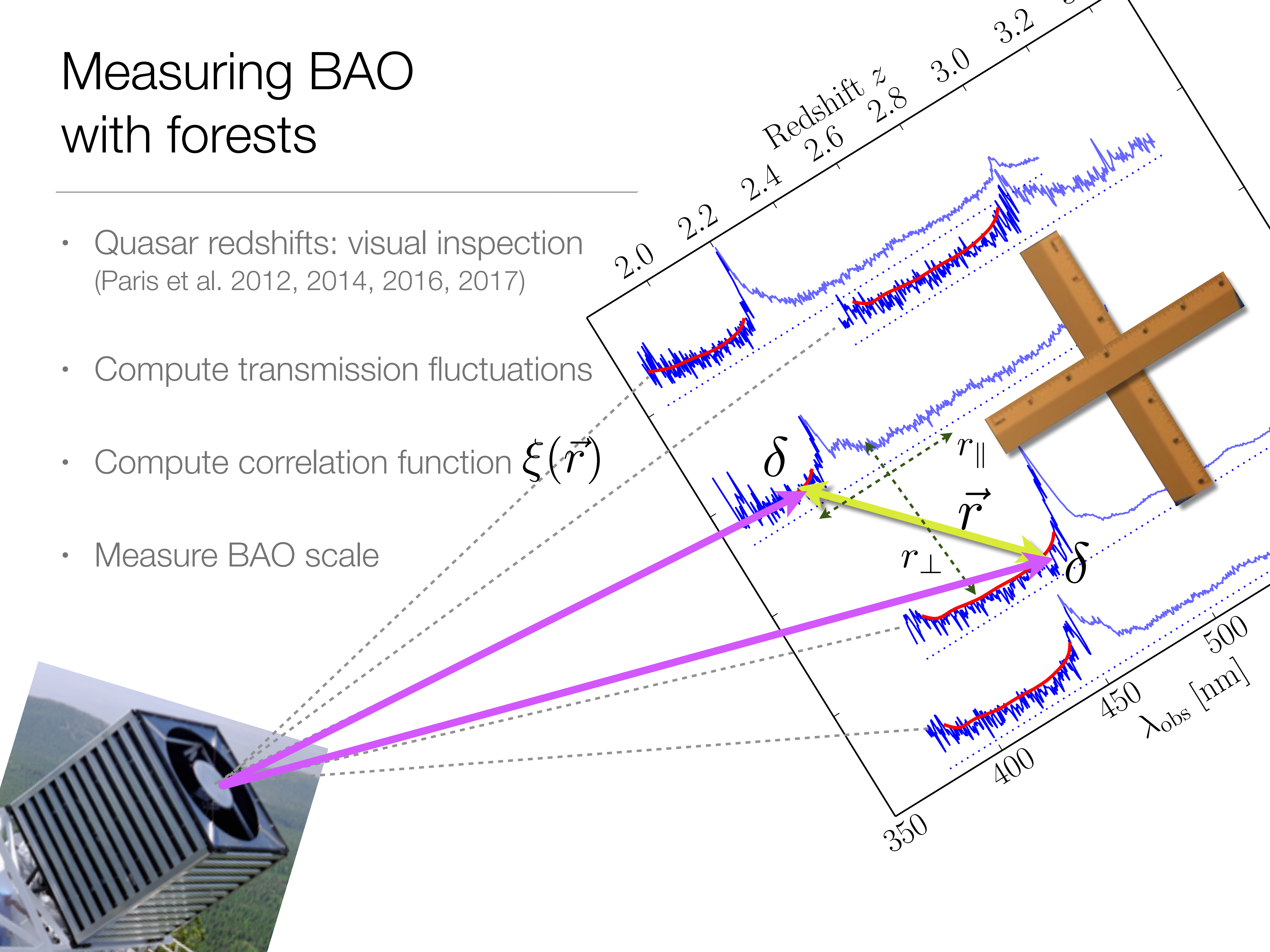
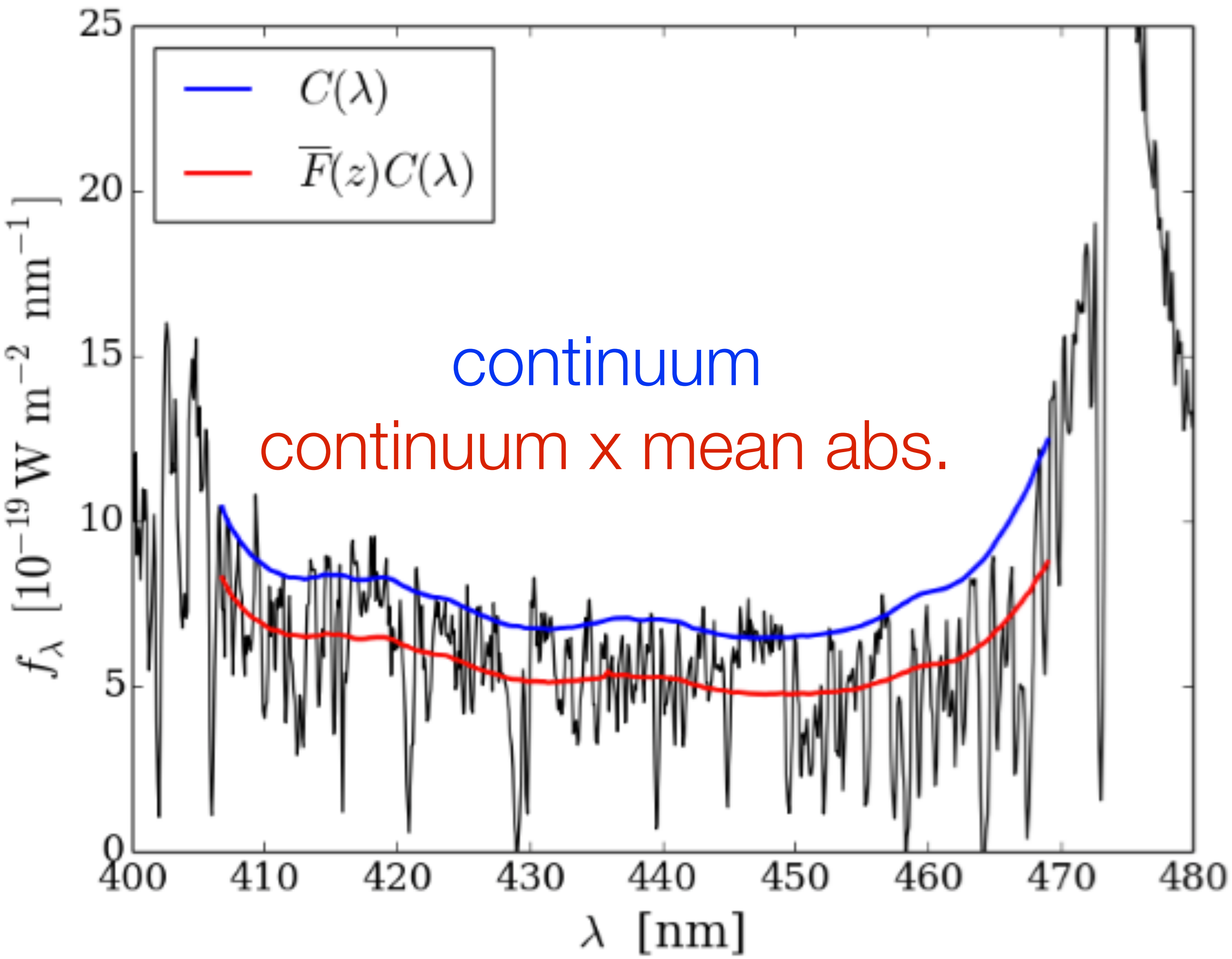
- Compute transmission fluctuations
- Compute correlation function $\xi(\vec{r})$
- Measure BAO scale



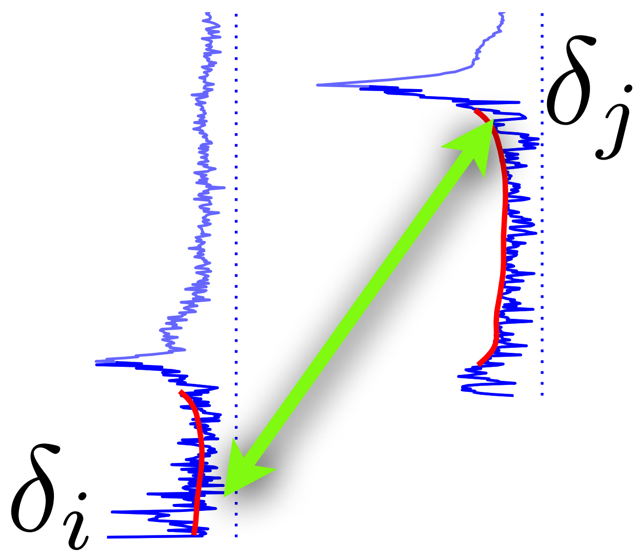
Computing fluctuations



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

C_q : stack in rest-frame
$\bar{F}$: stack in observed-frame

Correlation function



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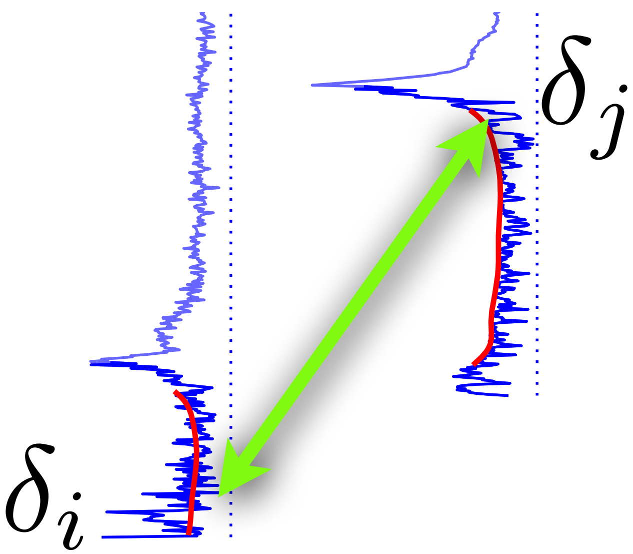

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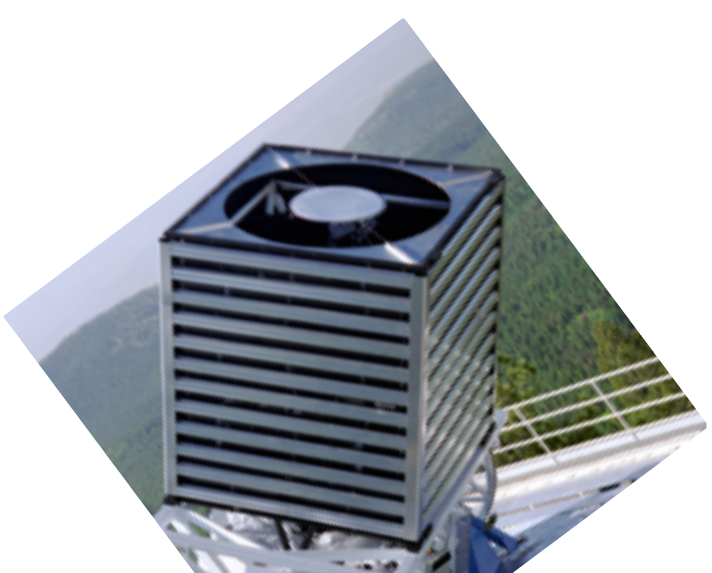

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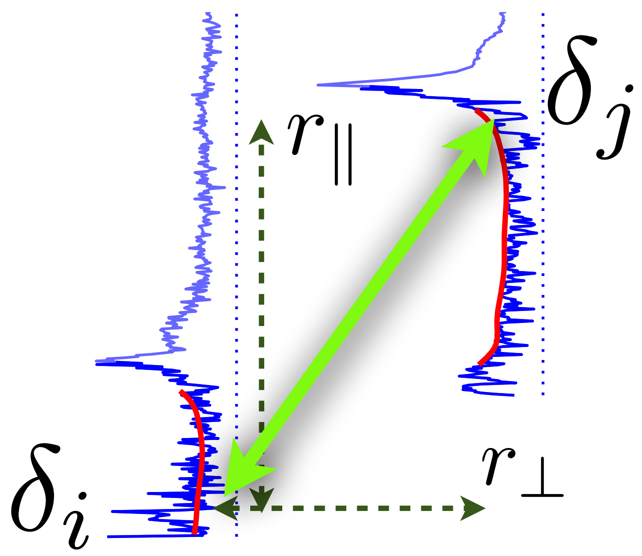

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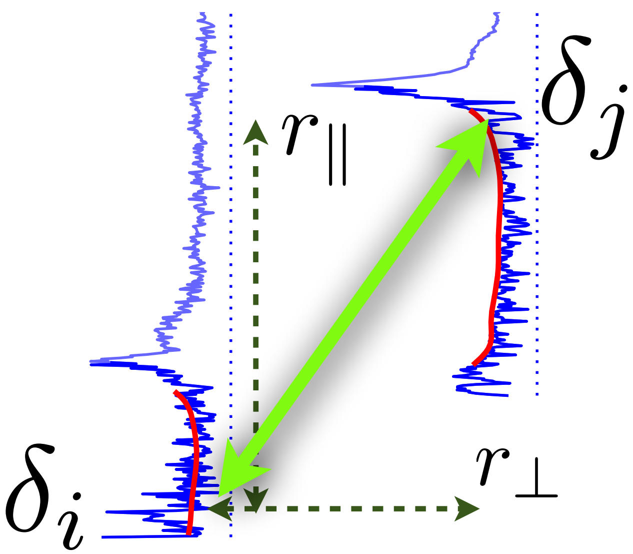

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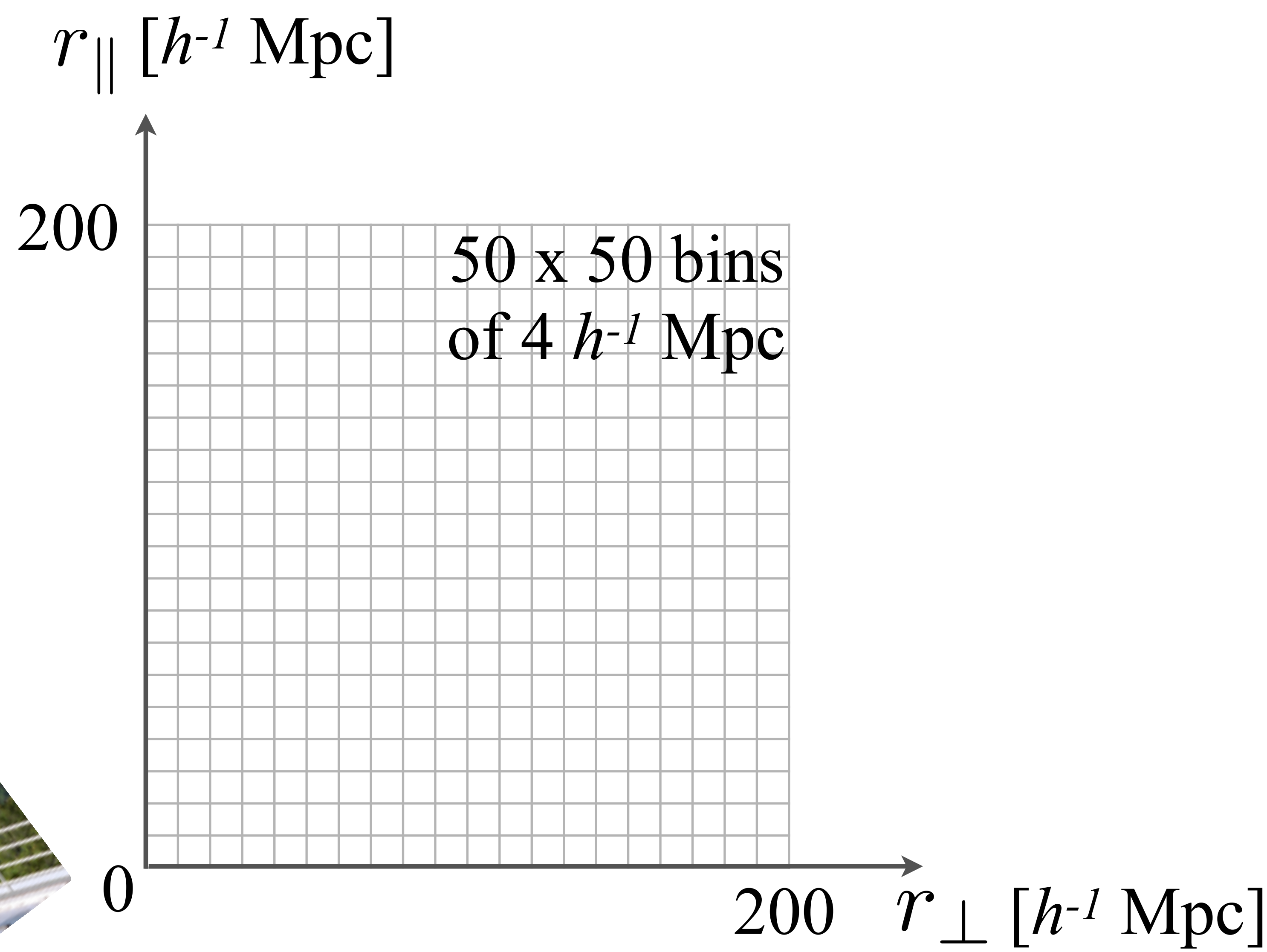

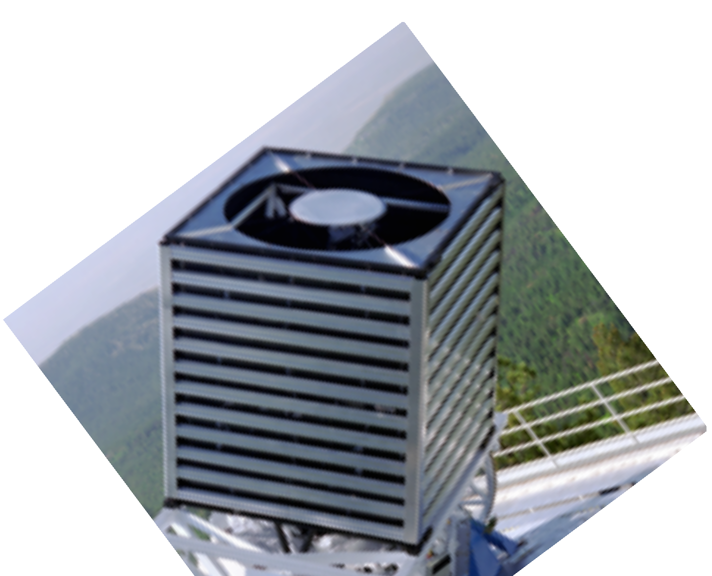

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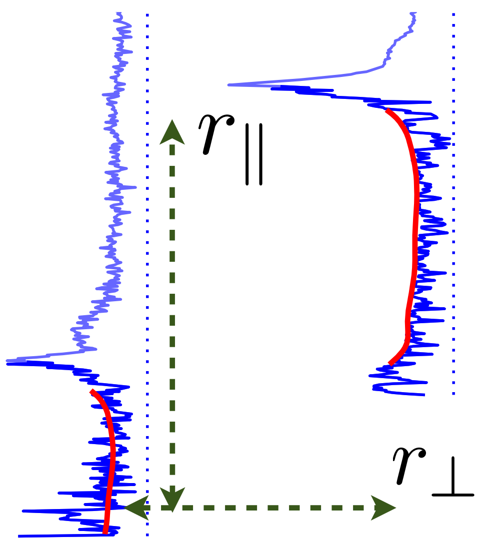

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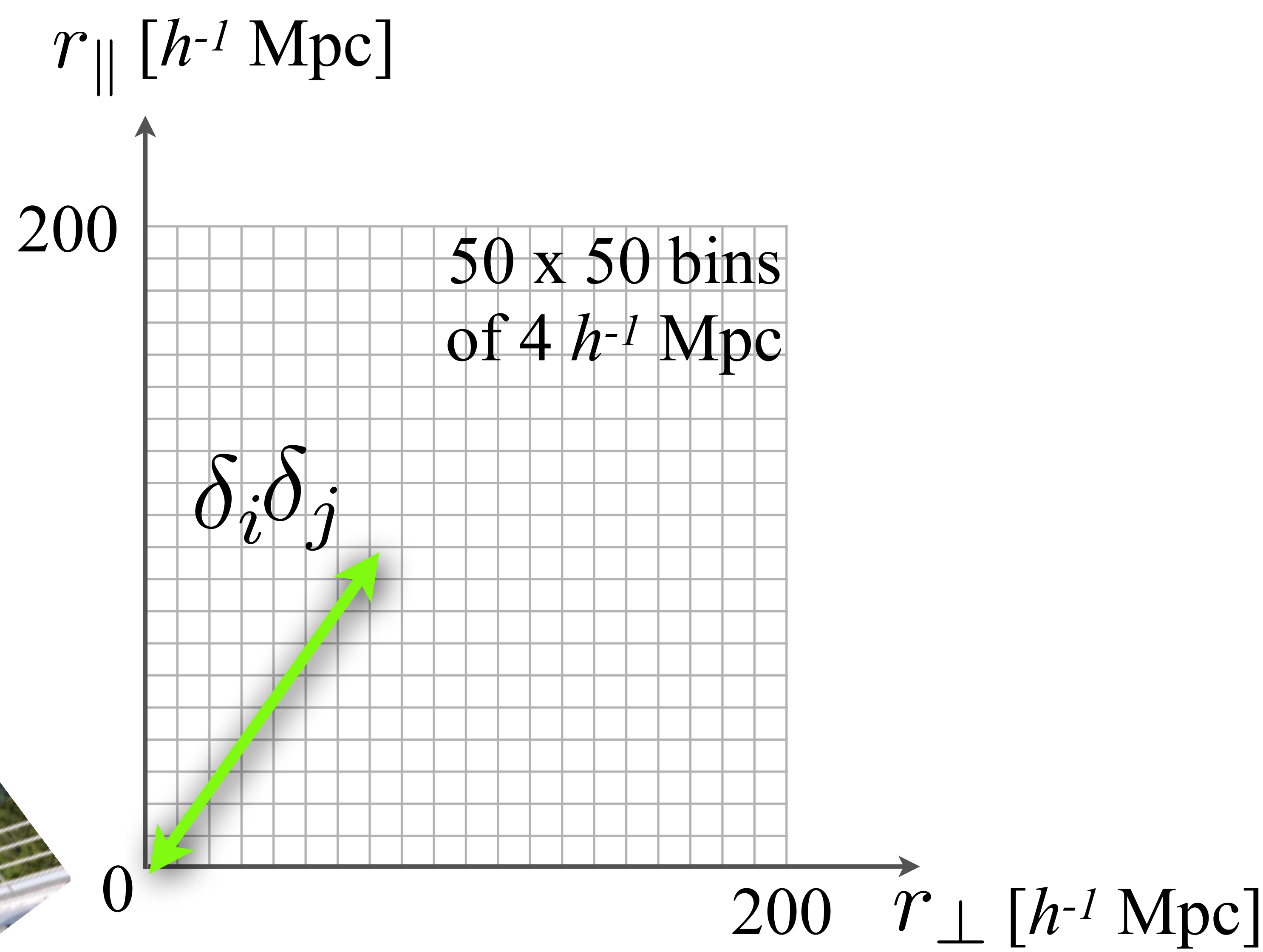

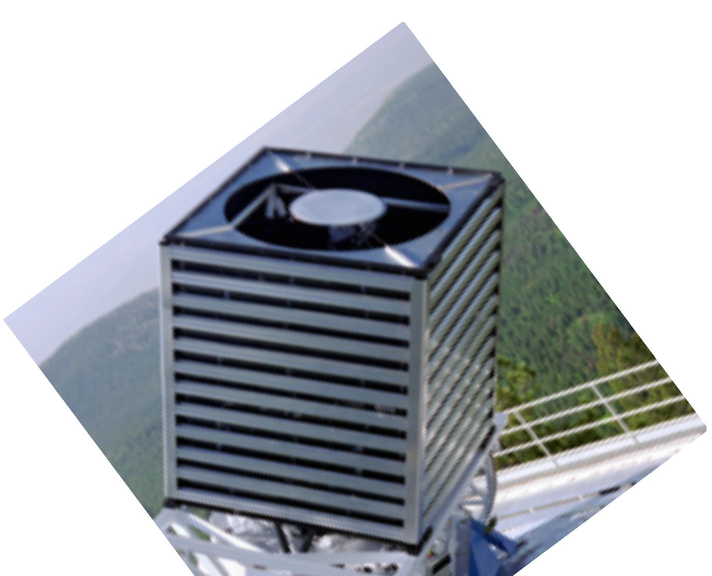

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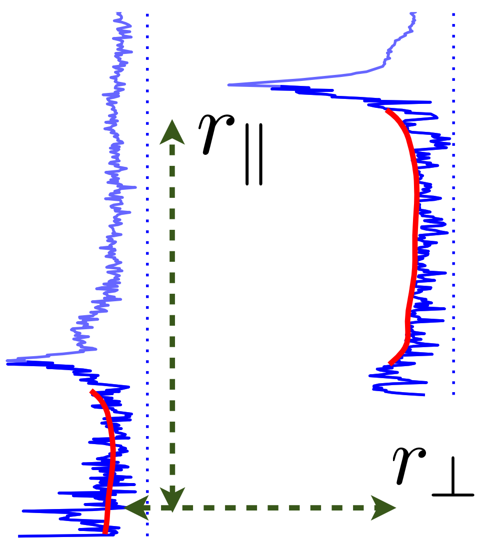

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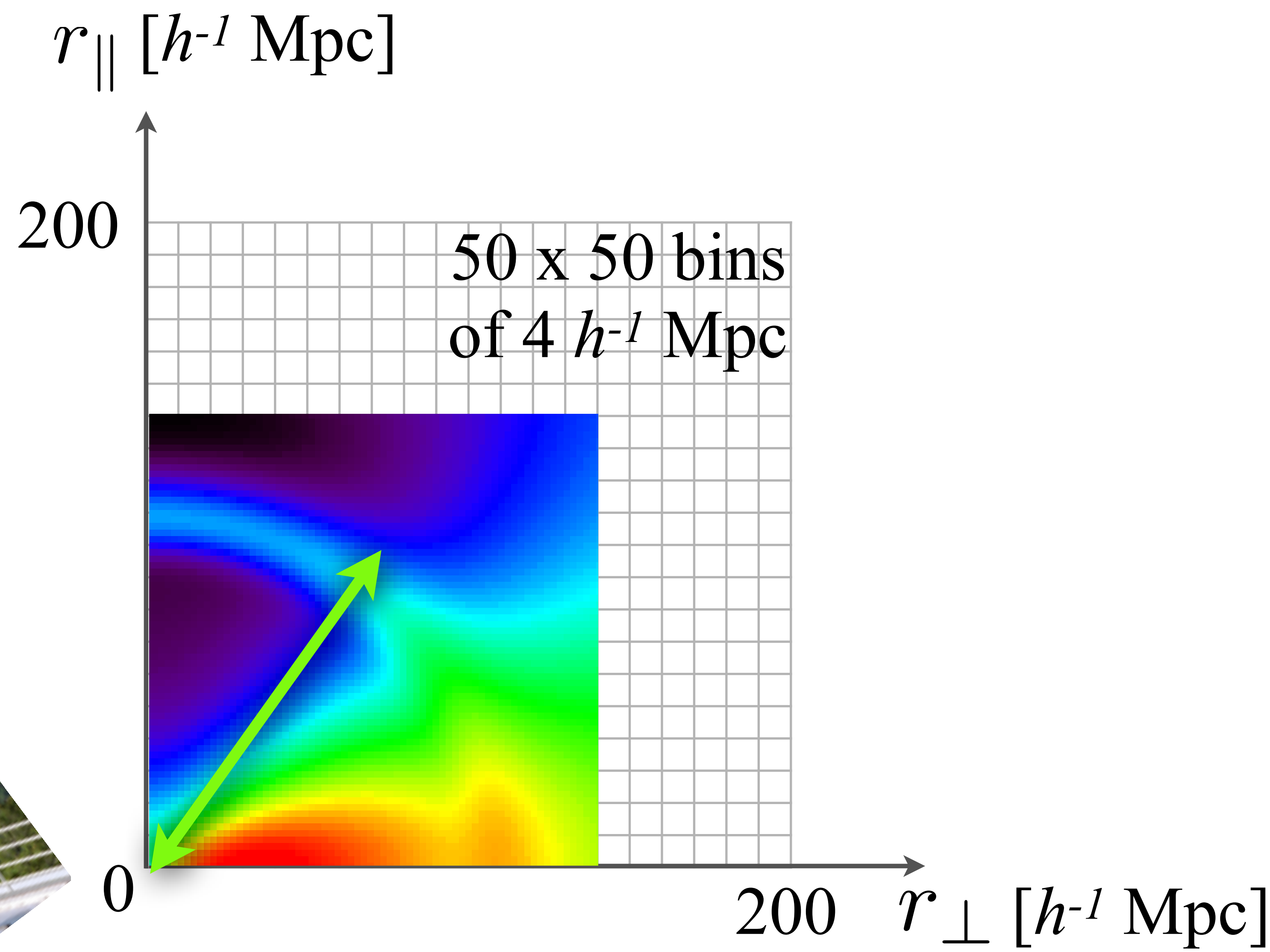

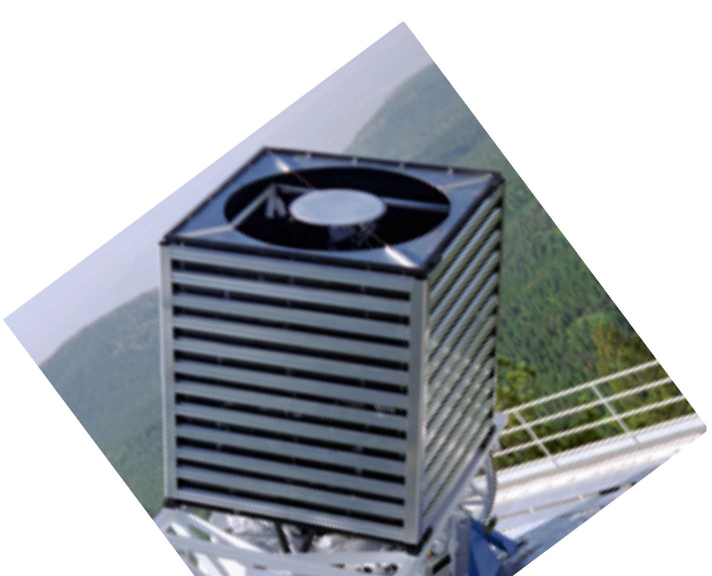

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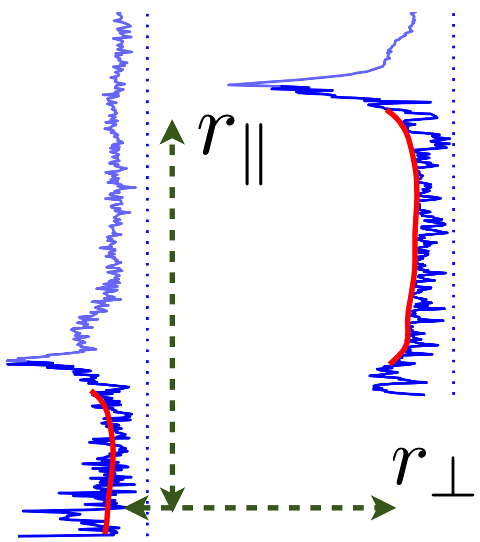

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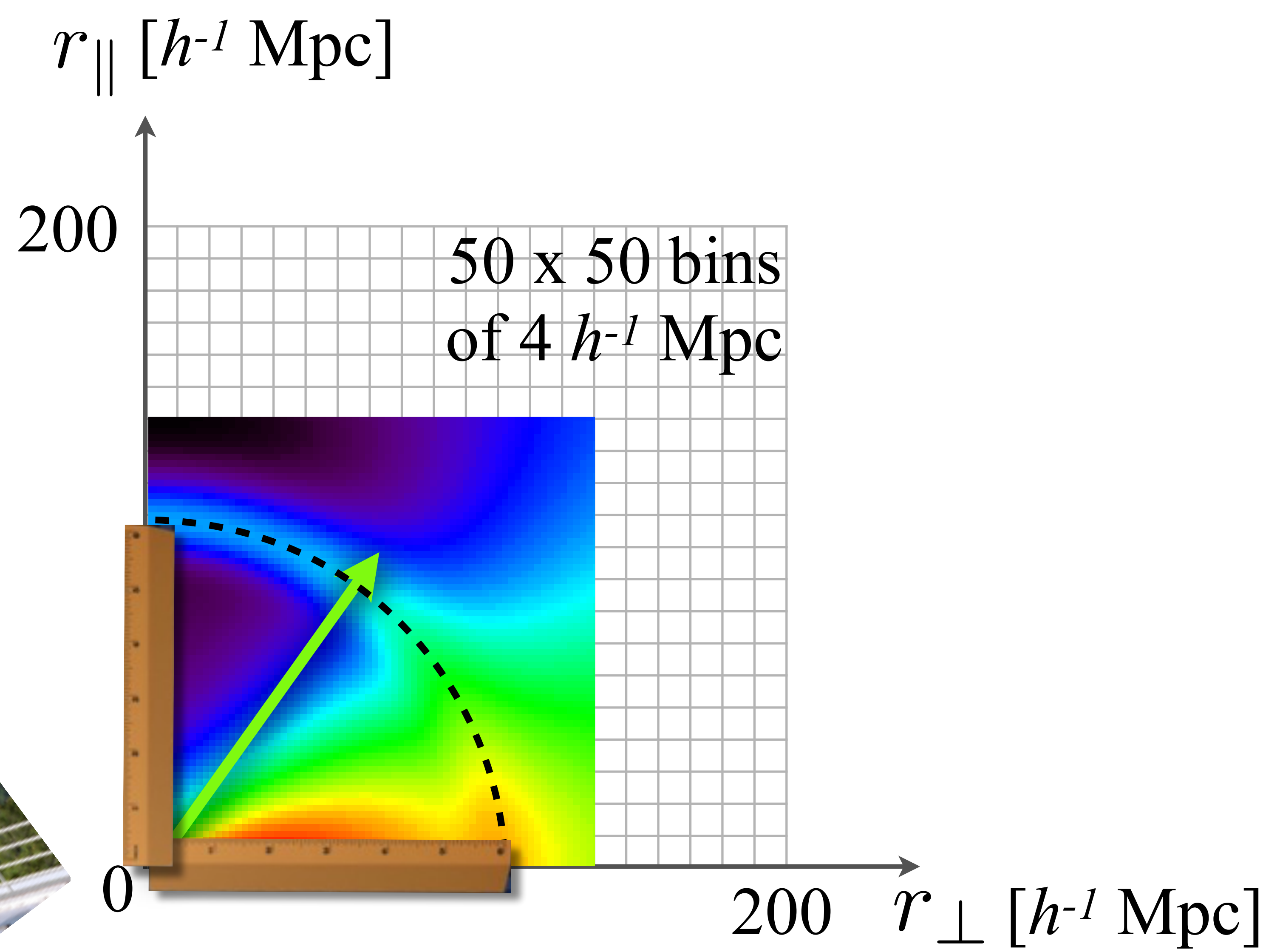

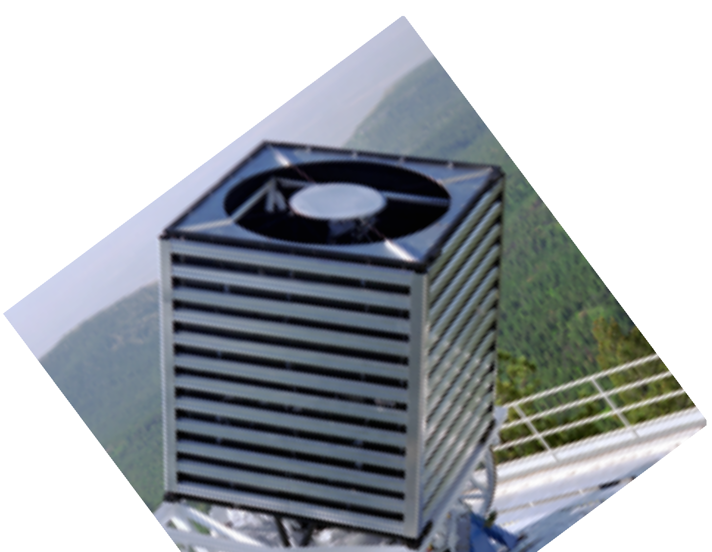

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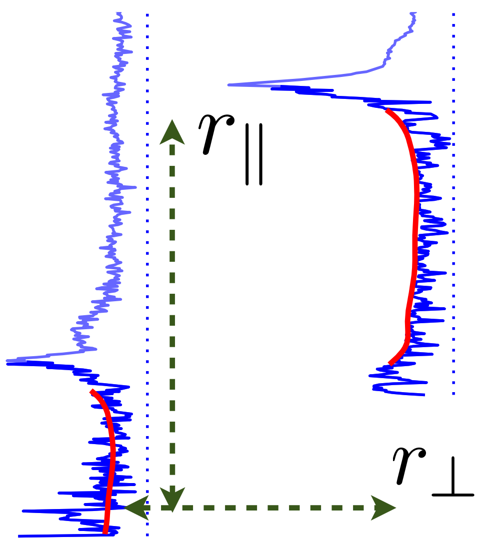

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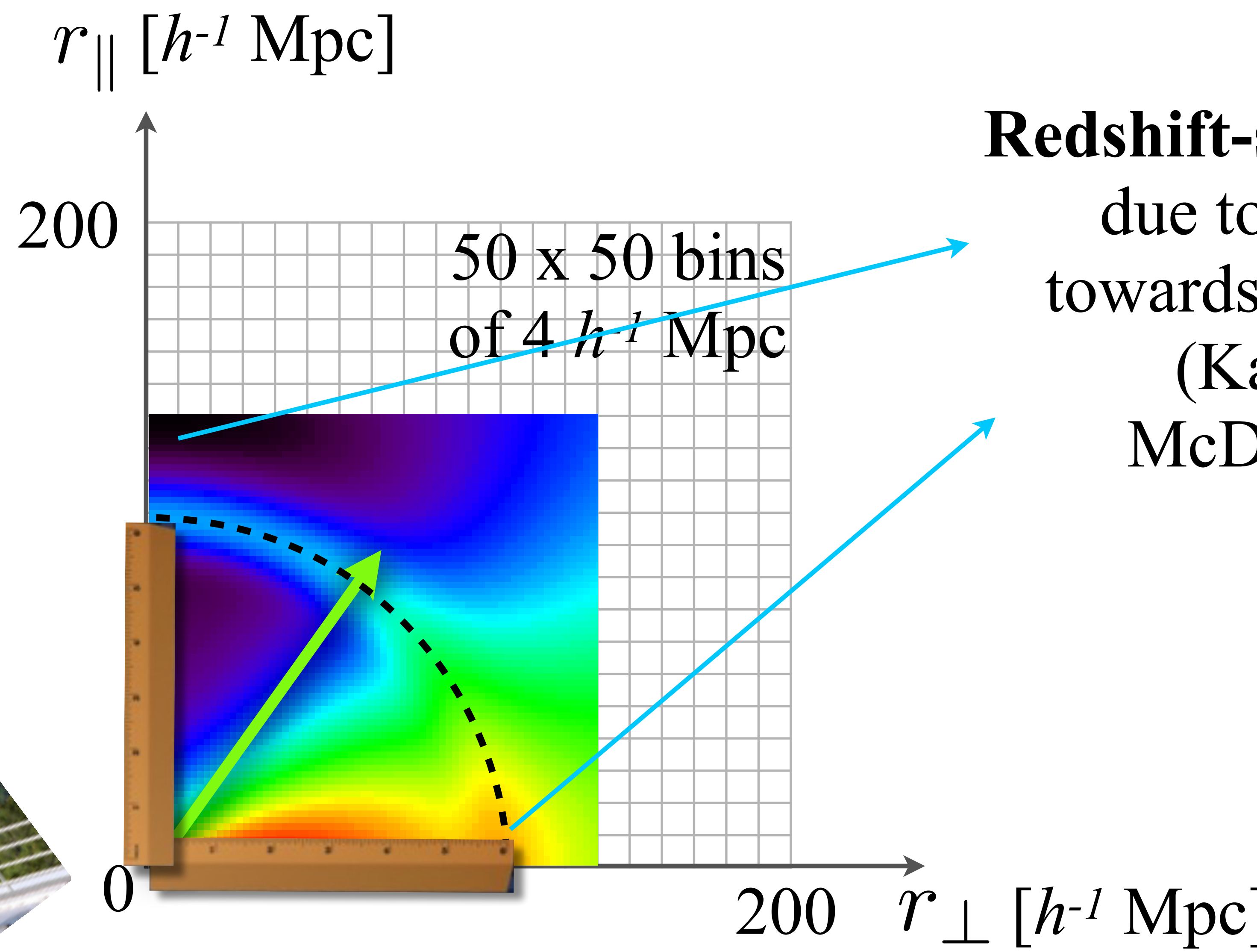
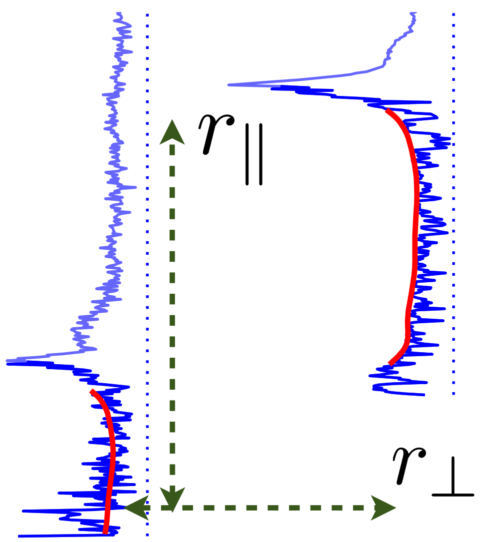


Redshift-space distortions
due to matter infall
towards potential wells
(Kaiser 1987,
McDonald 2003)

Correlation function



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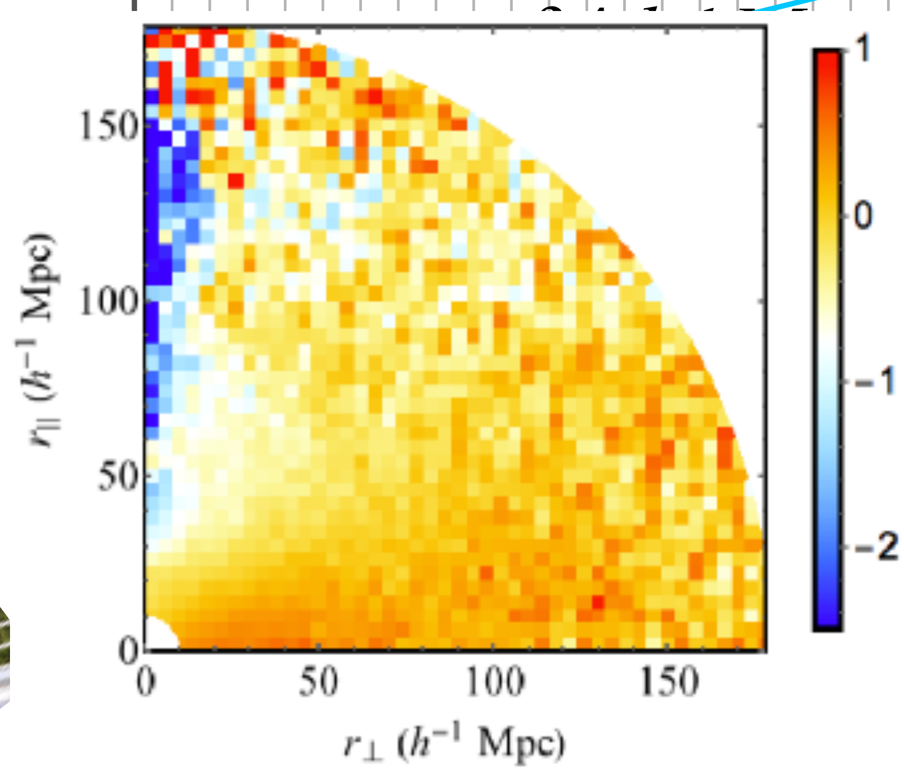
$r_{\parallel}$ [h^{-1} Mpc]

200

50 x 50 bins



0 $r_{\perp}$ [h^{-1} Mpc]

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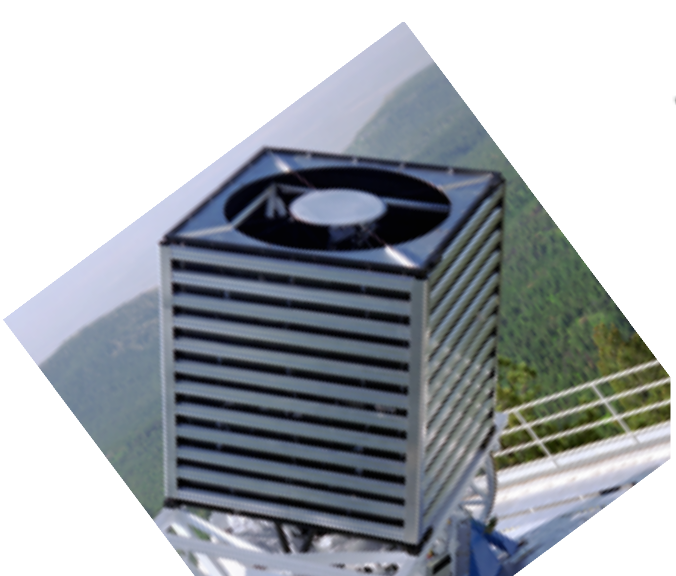
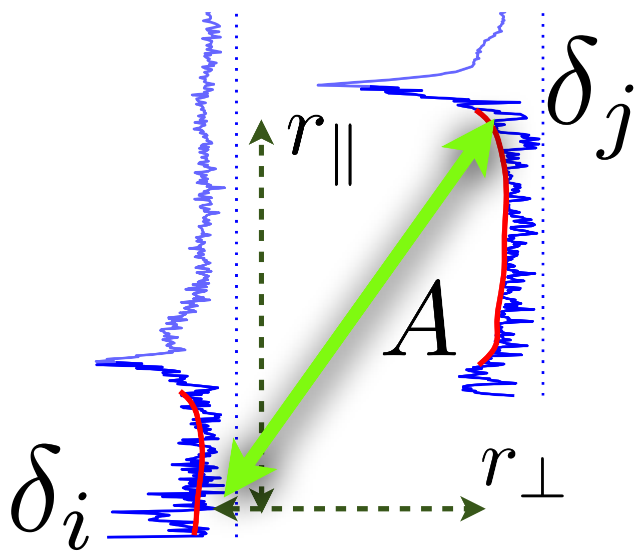


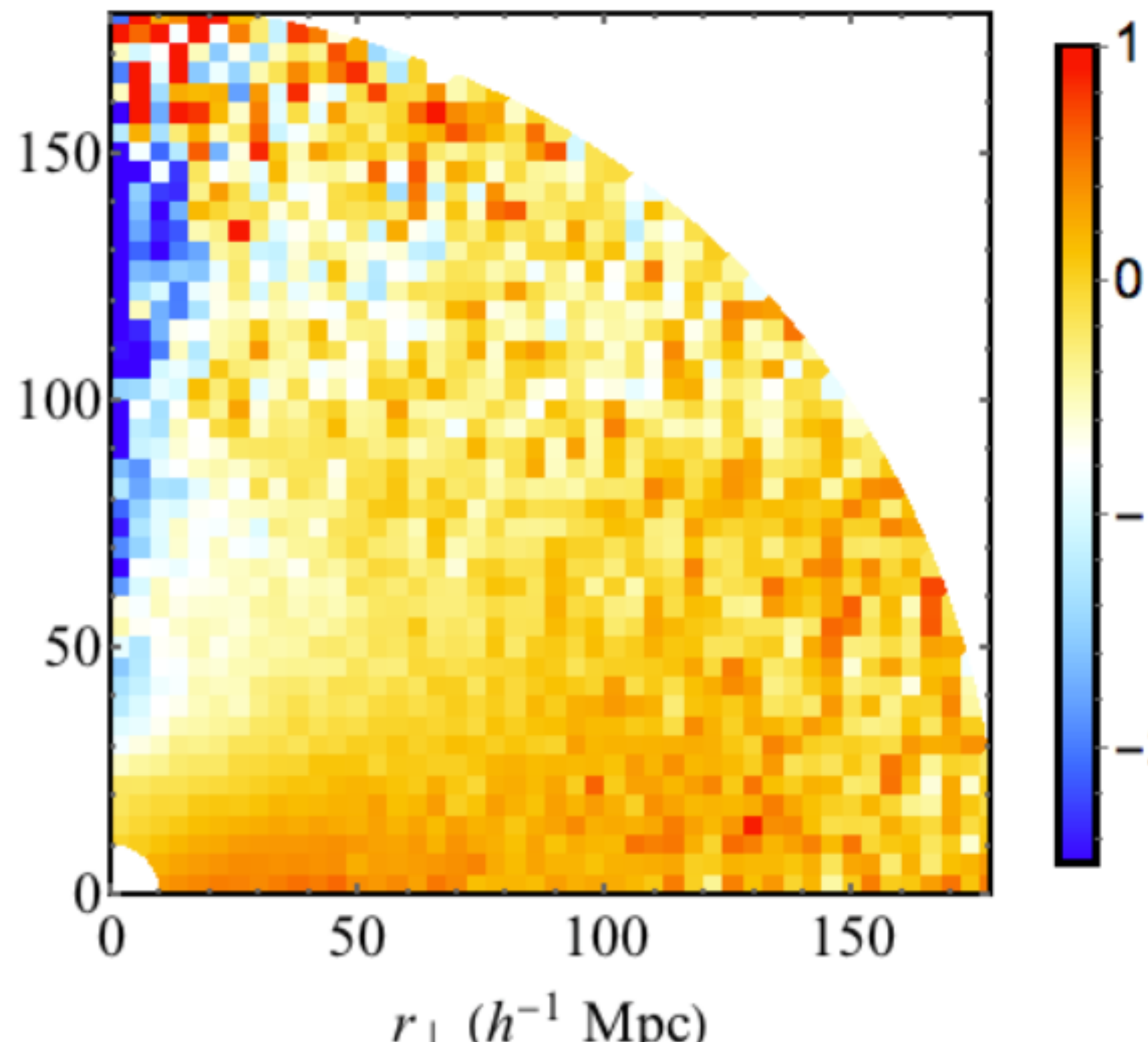
Correlation function



F_i

$r_\parallel$

200



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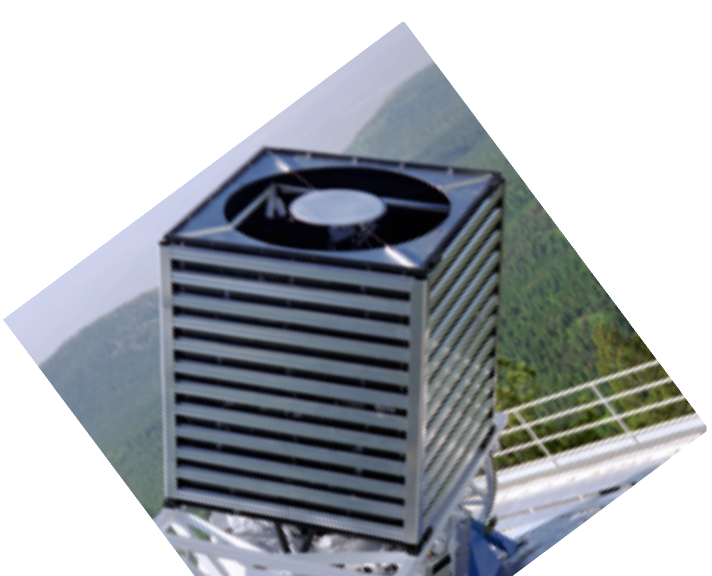
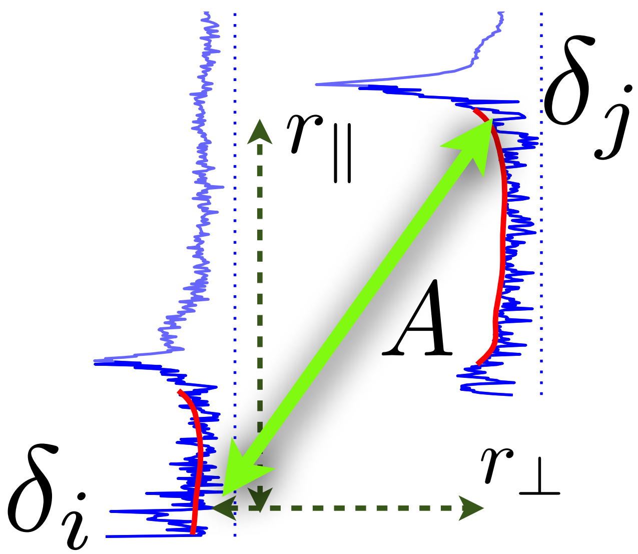
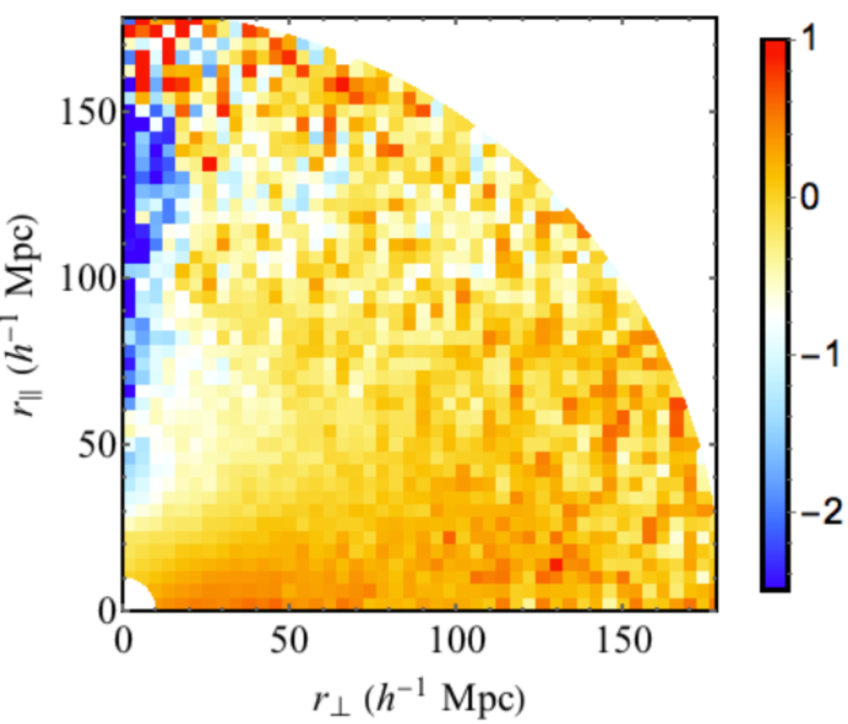


0

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

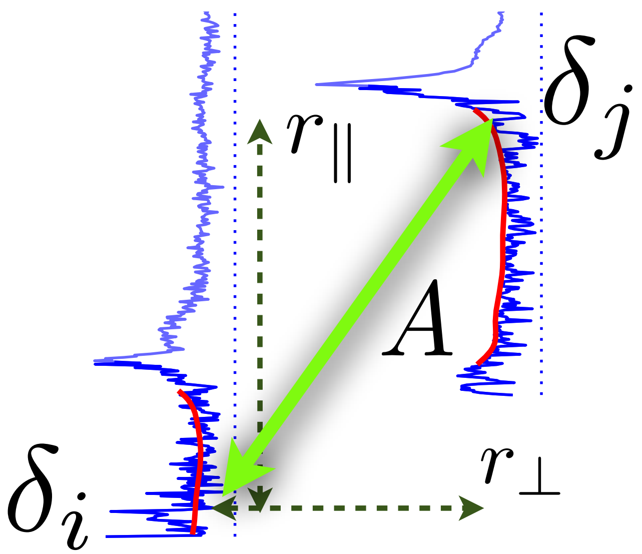
Correlation function

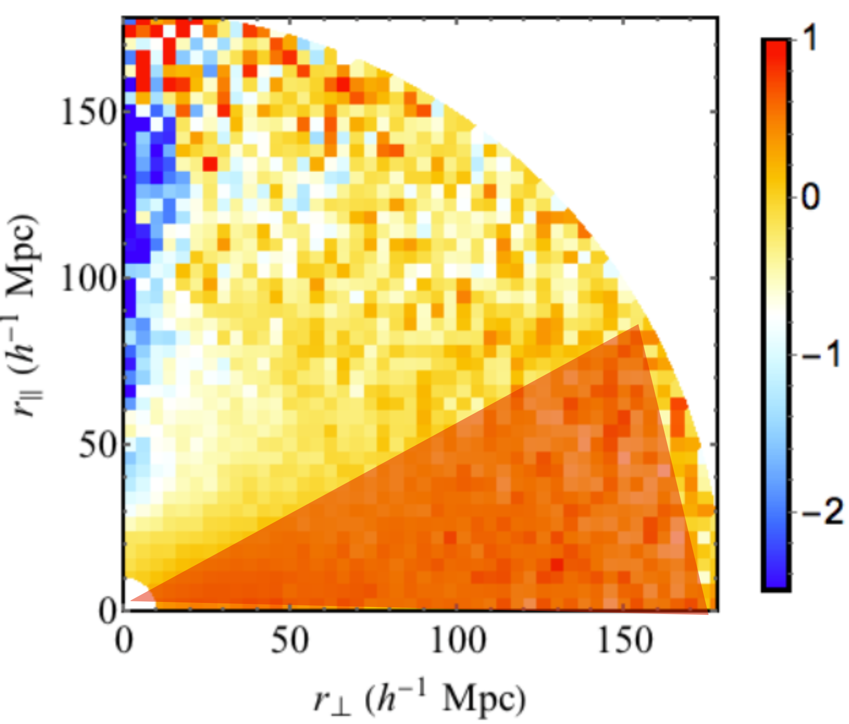


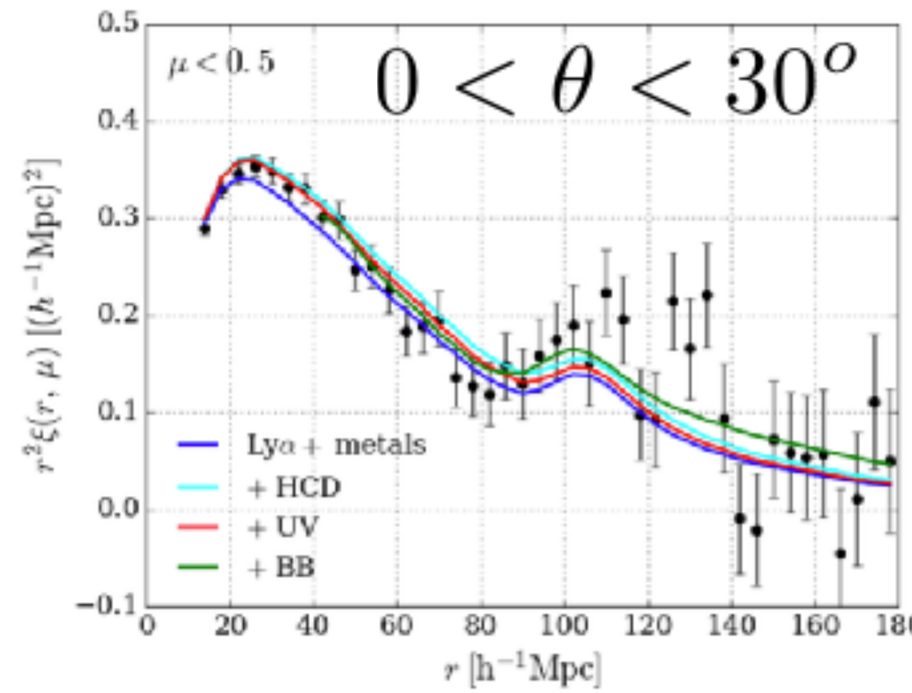


Bautista et al. 2017

Correlation function







Bautista et al. 2017

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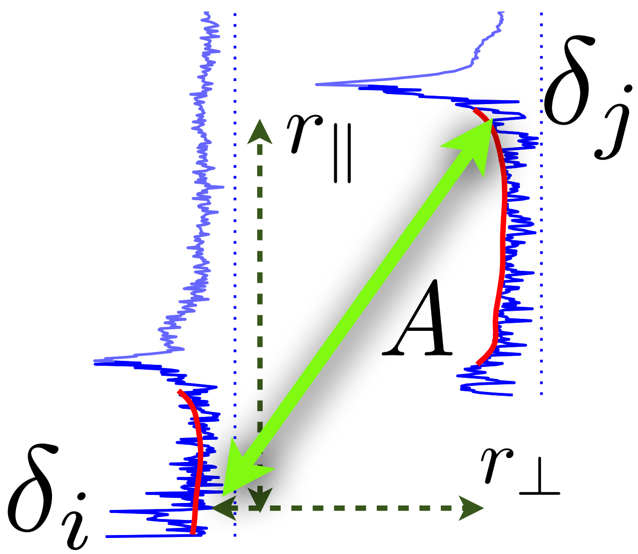

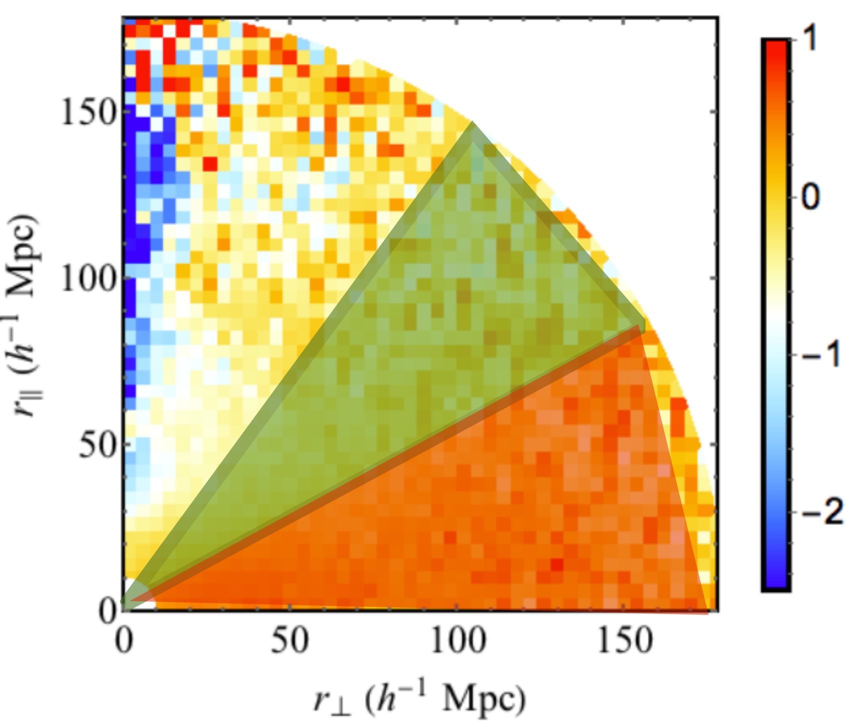

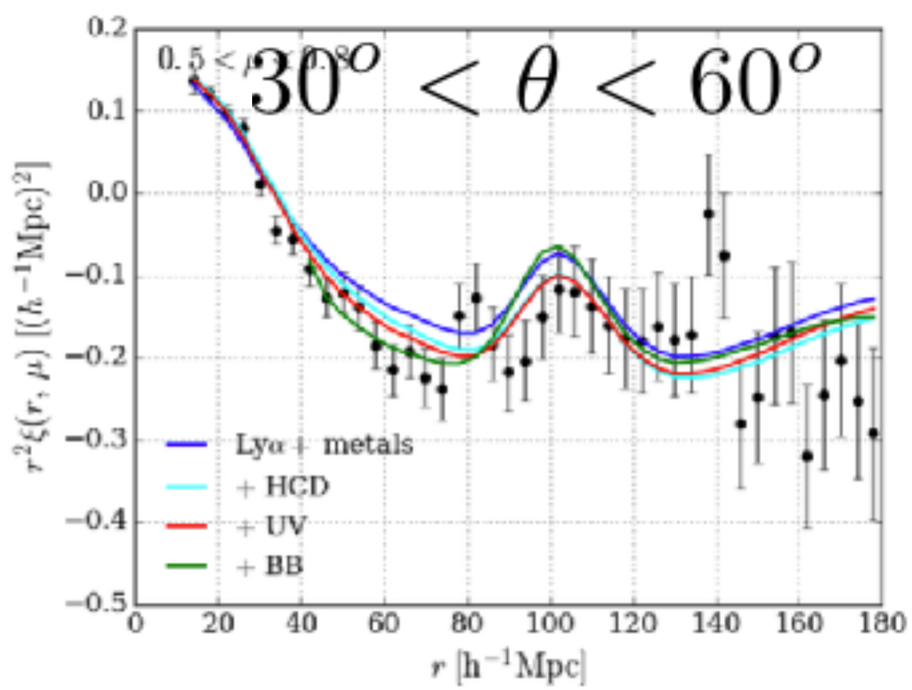

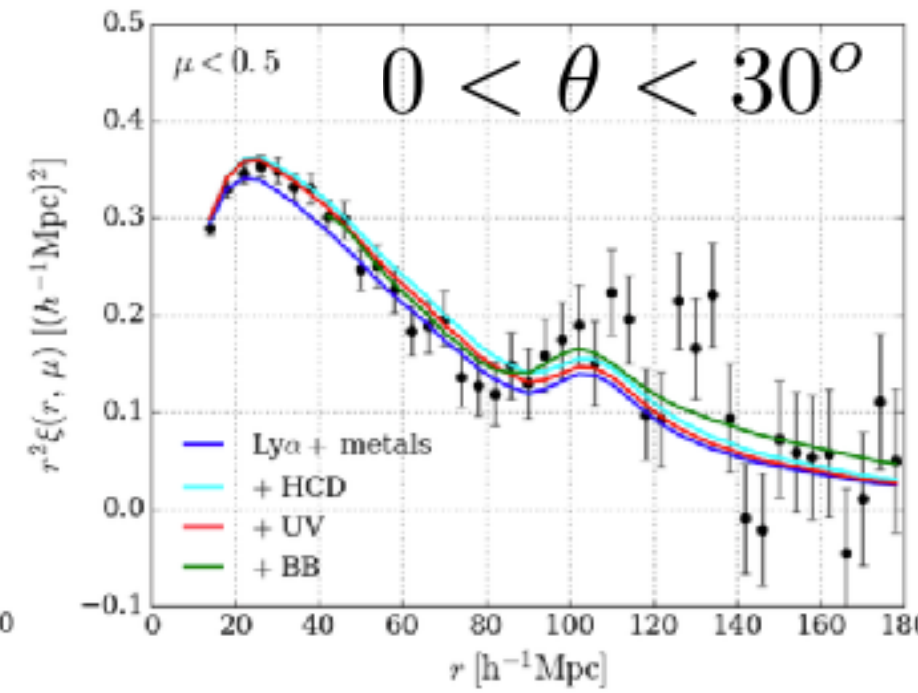

Bautista et al. 2017

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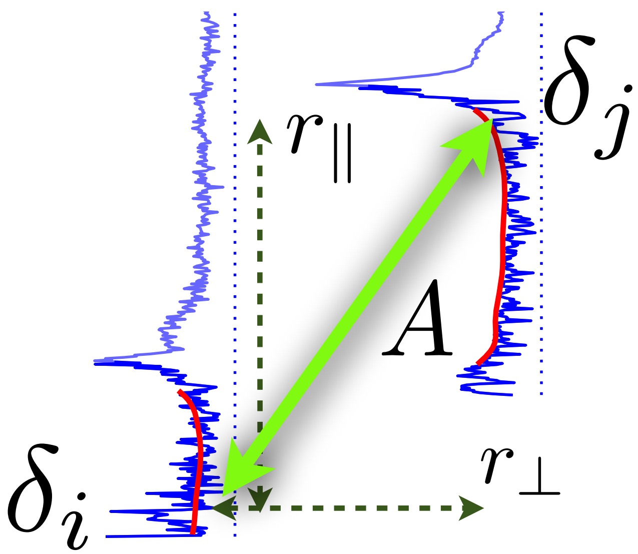
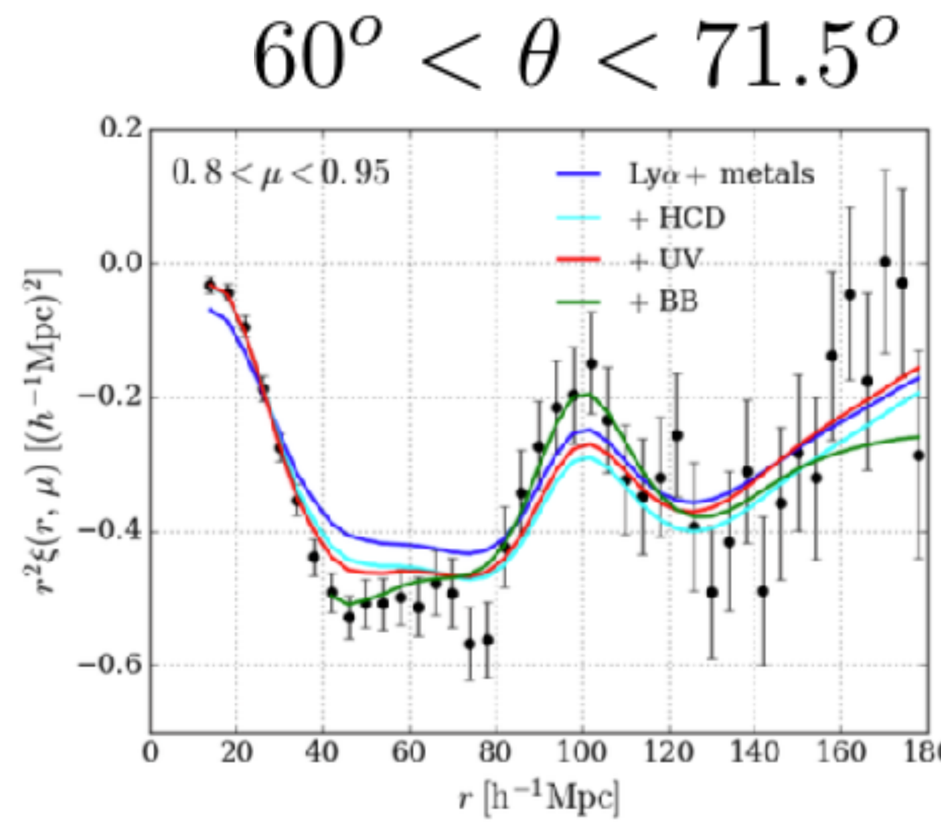
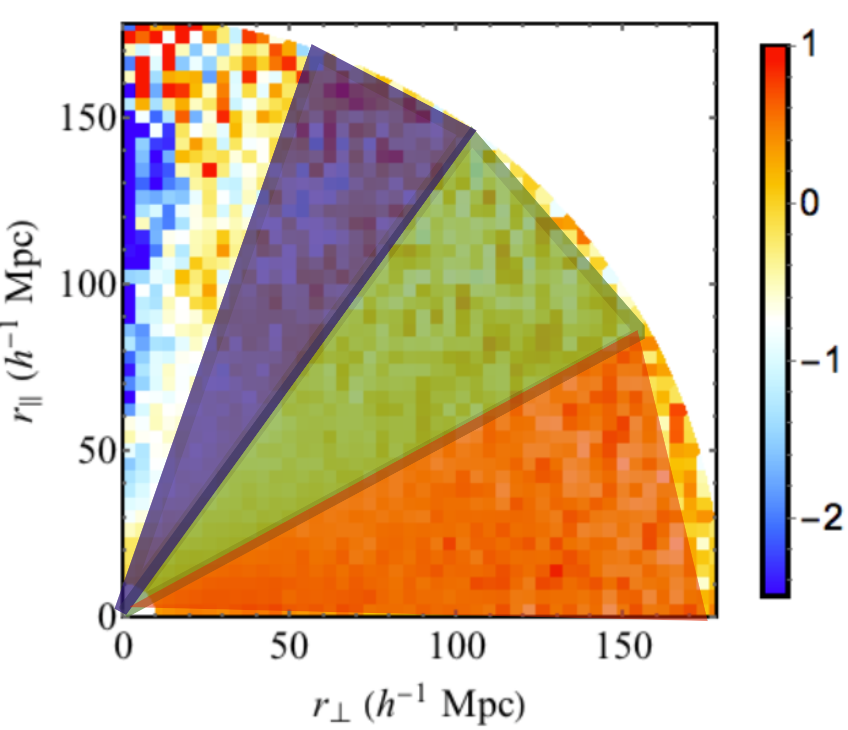
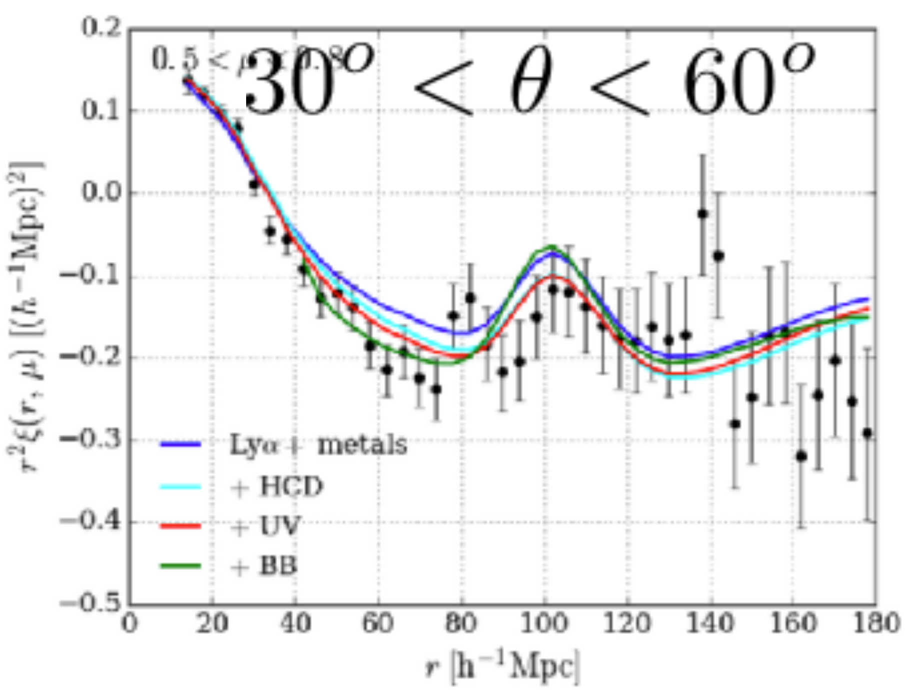
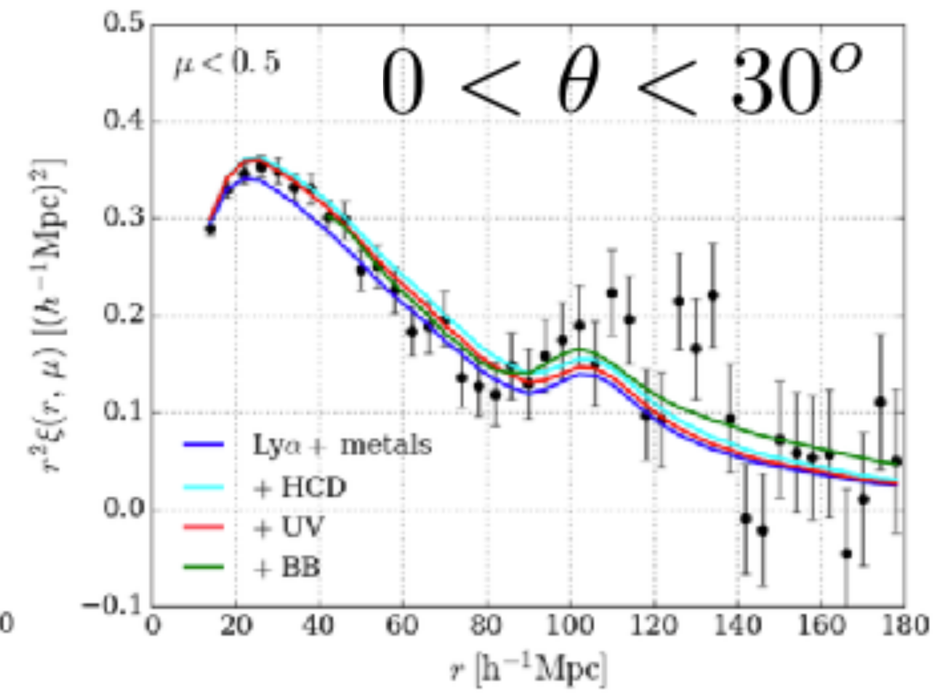




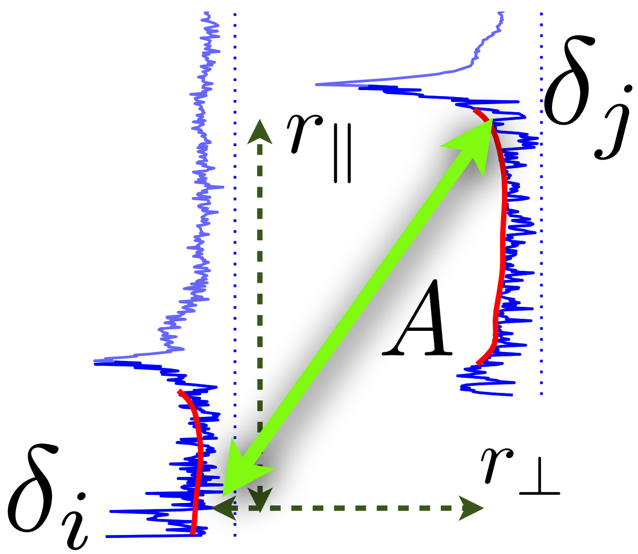


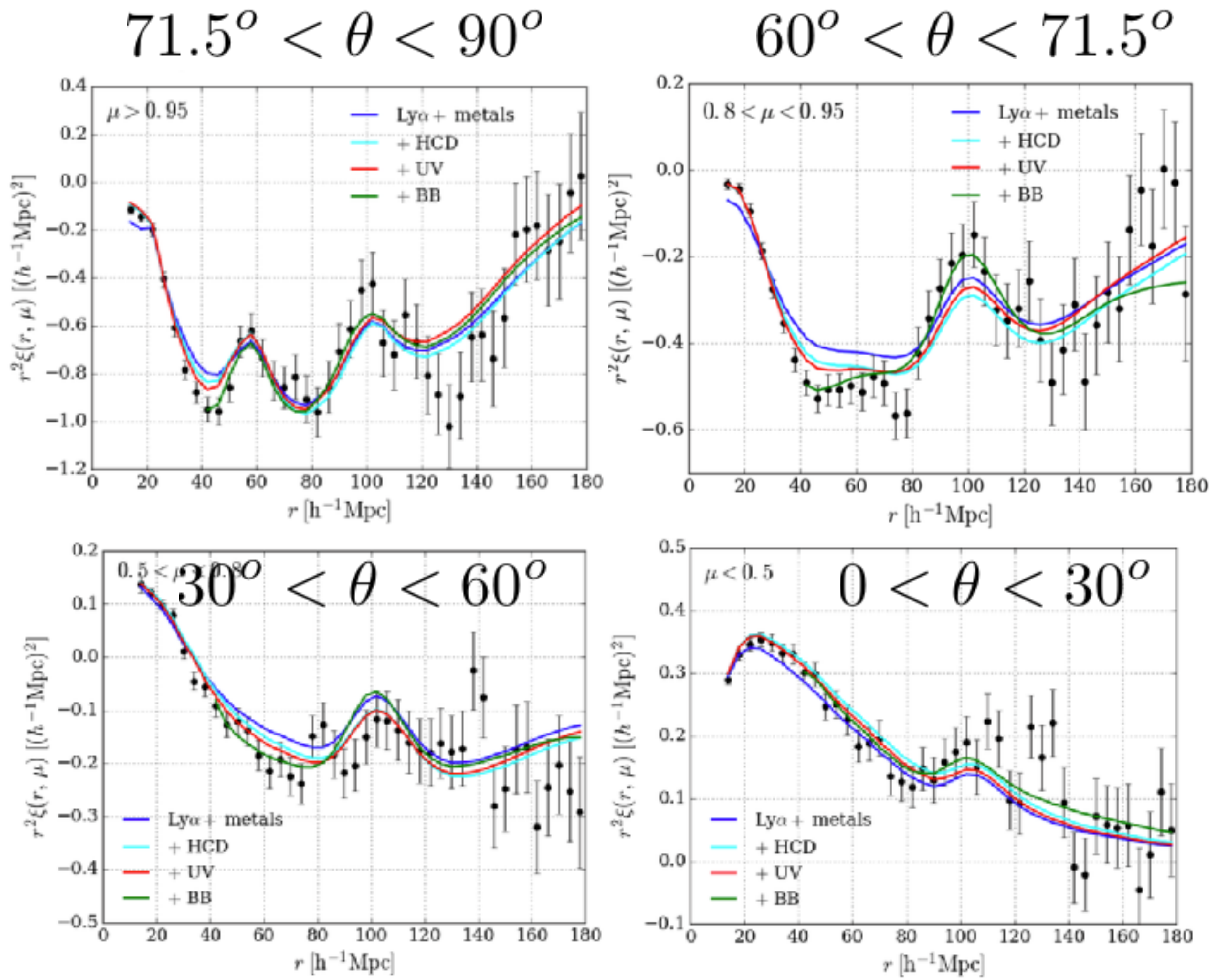


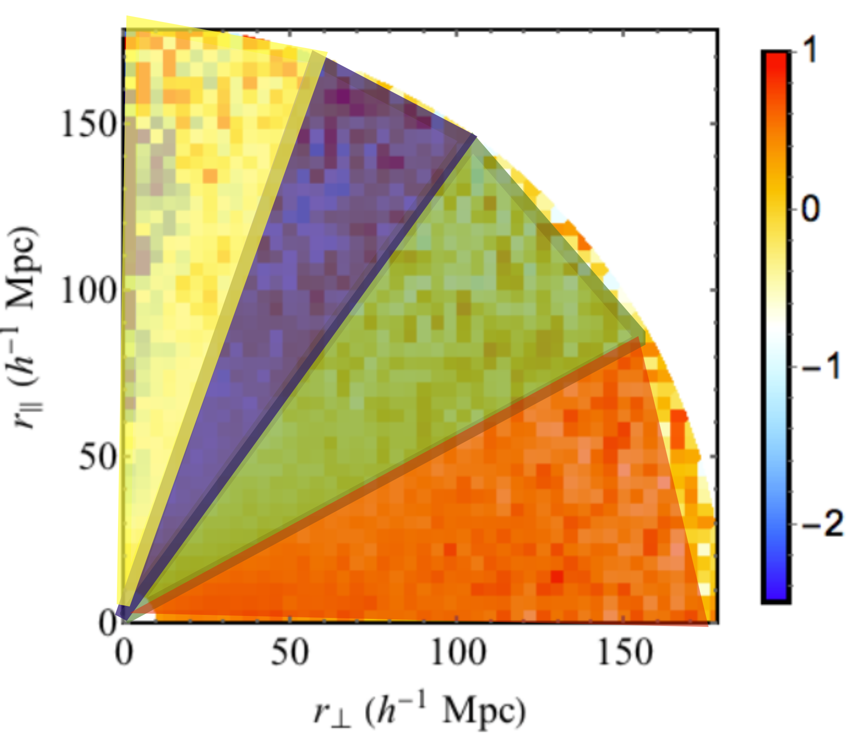


Bautista et al. 2017

Correlation function







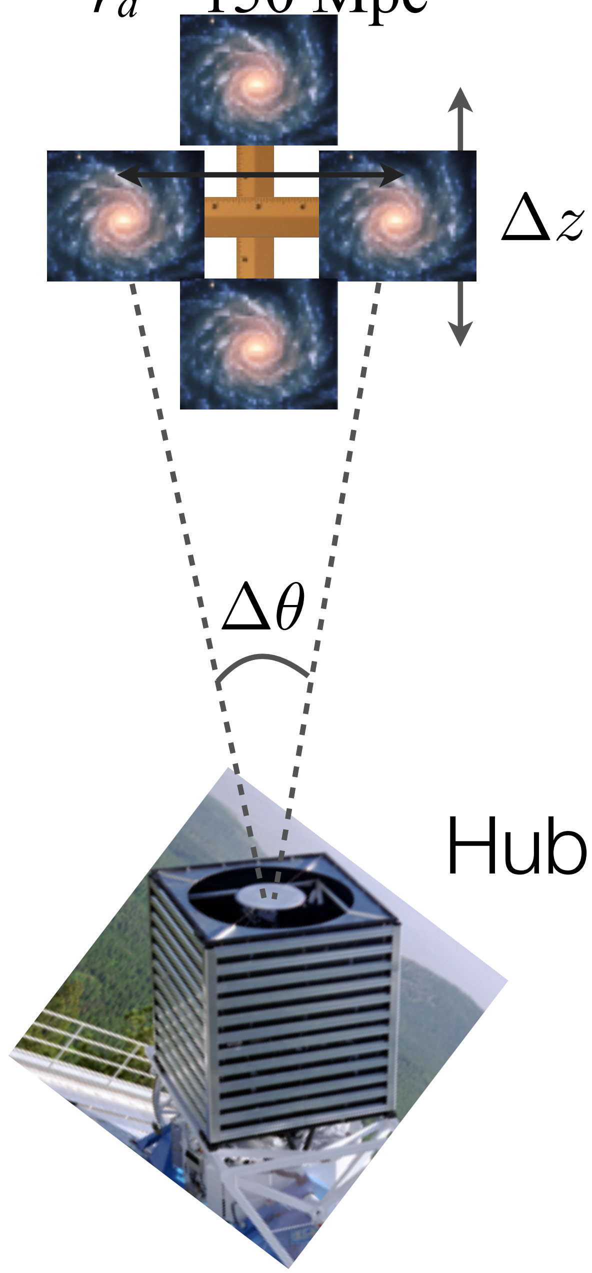
Bautista et al. 2017

Measuring BAO Scale

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

BAO scale

$r_d \sim 150$ Mpc



Distances

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

Hubble's law (in the past)

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

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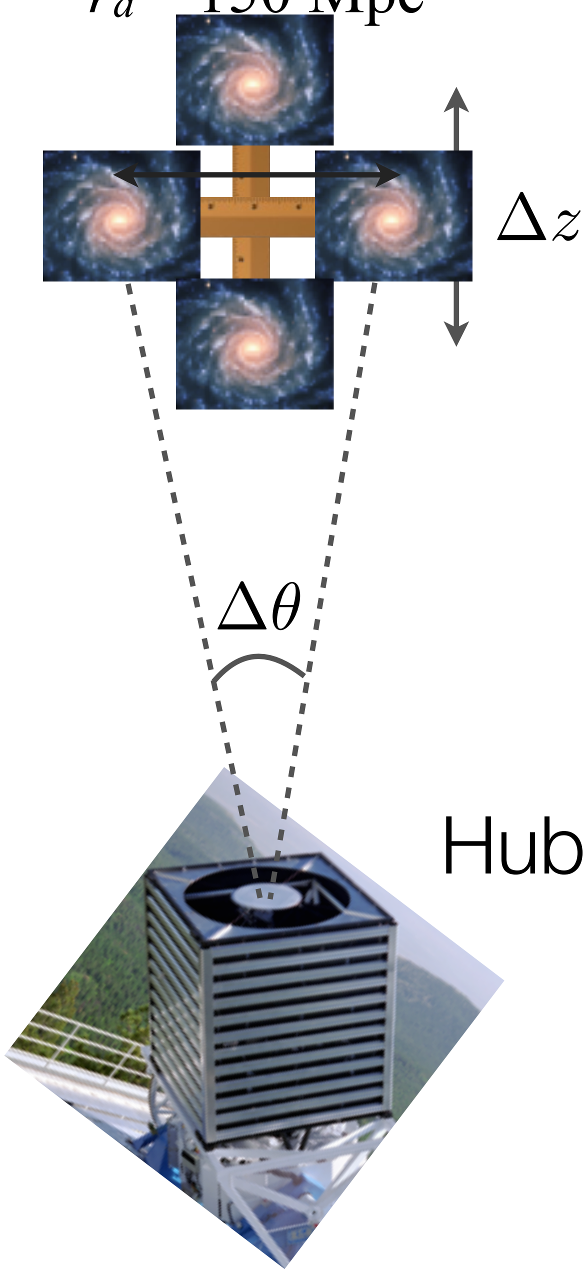
$$\xi_{\mathrm{model}}(\vec{r}, \alpha_{\parallel}, \alpha_{\perp}) = \xi_{\mathrm{cosmo}}(\vec{r}, \alpha_{\parallel}, \alpha_{\perp}) + \xi_{\mathrm{broadband}}(\vec{r})$$



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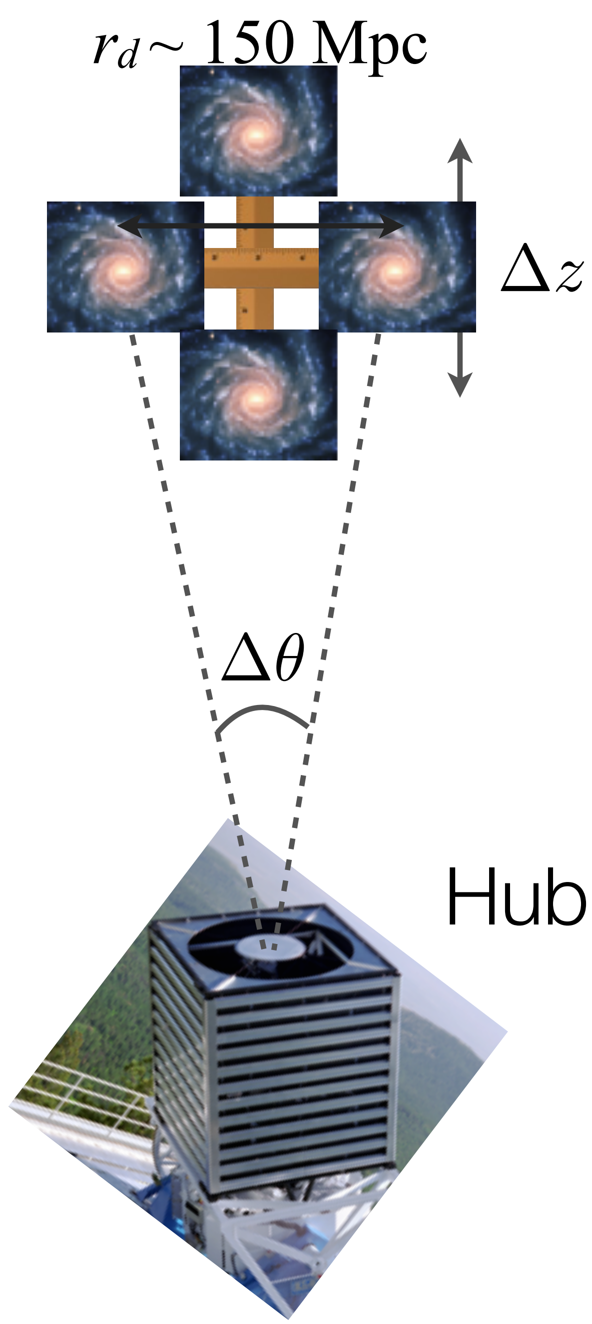

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$$\alpha_{\parallel} = \frac{D_H(\bar{z})/r_d}{[D_H(\bar{z})/r_d]_{\text{fid}}} \quad \text{and} \quad \alpha_{\perp} = \frac{D_A(\bar{z})/r_d}{[D_A(\bar{z})/r_d]_{\text{fid}}}$$

Radial BAO

Transverse BAO

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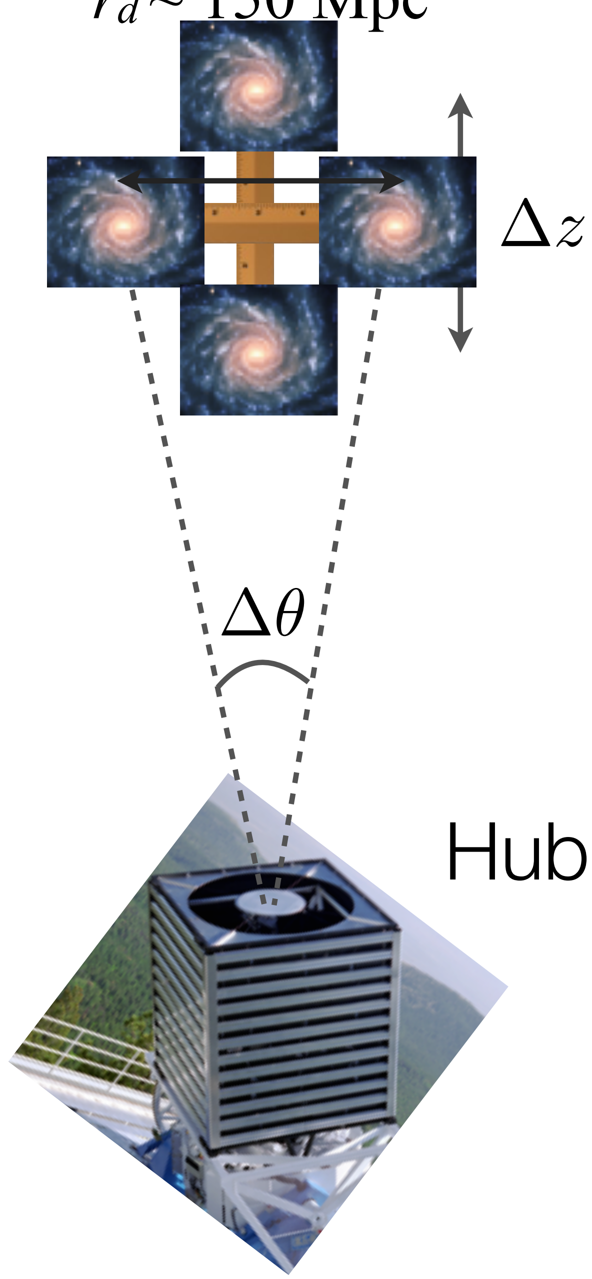

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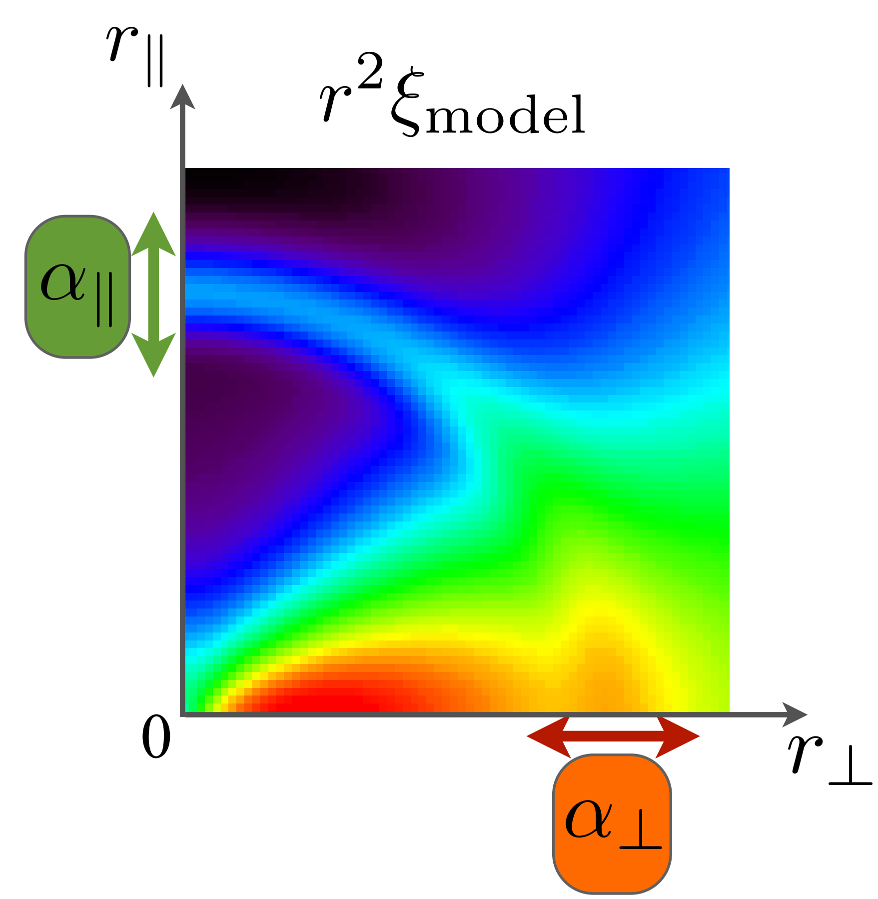
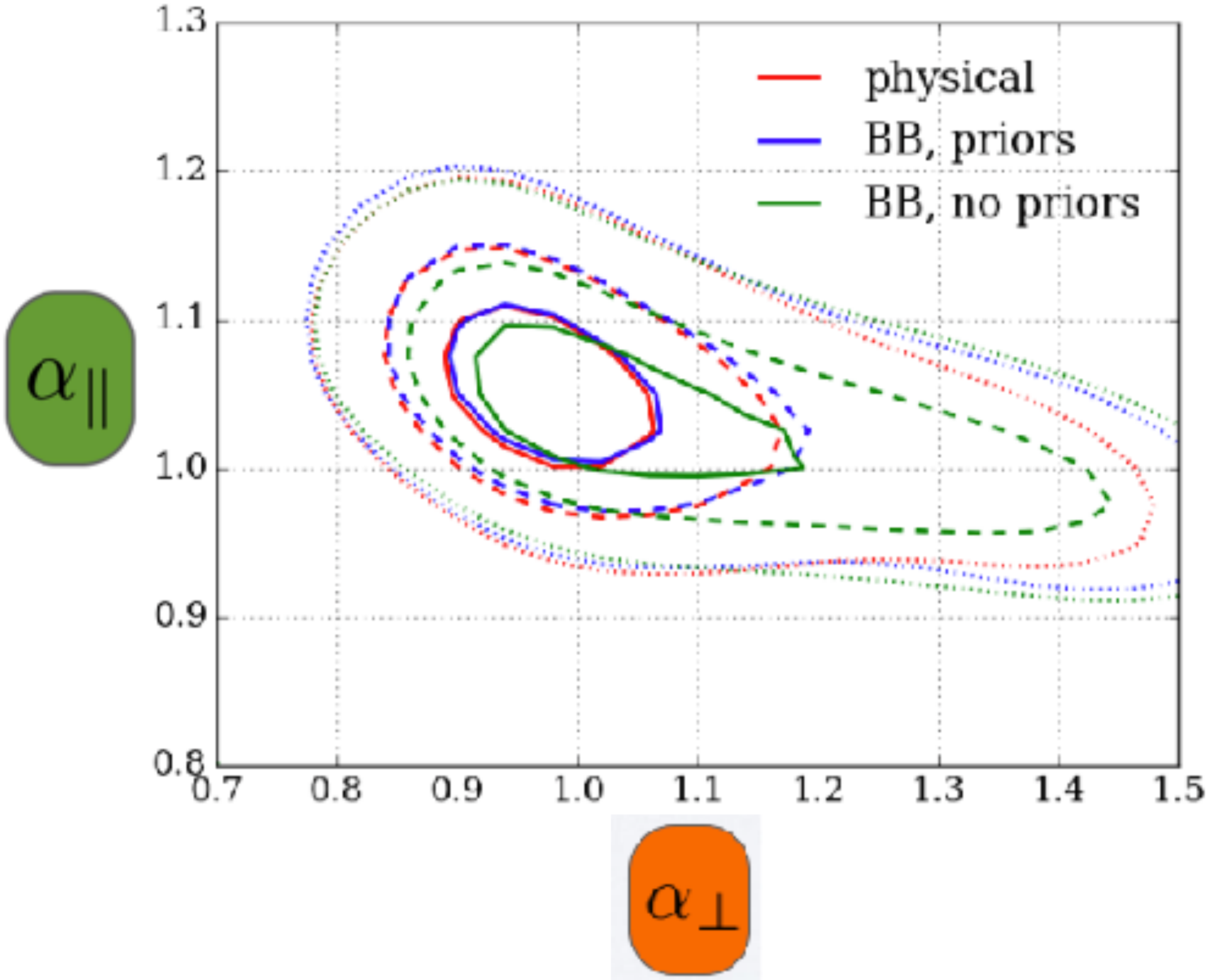


Measuring BAO Scale

Bautista et al. 2017



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

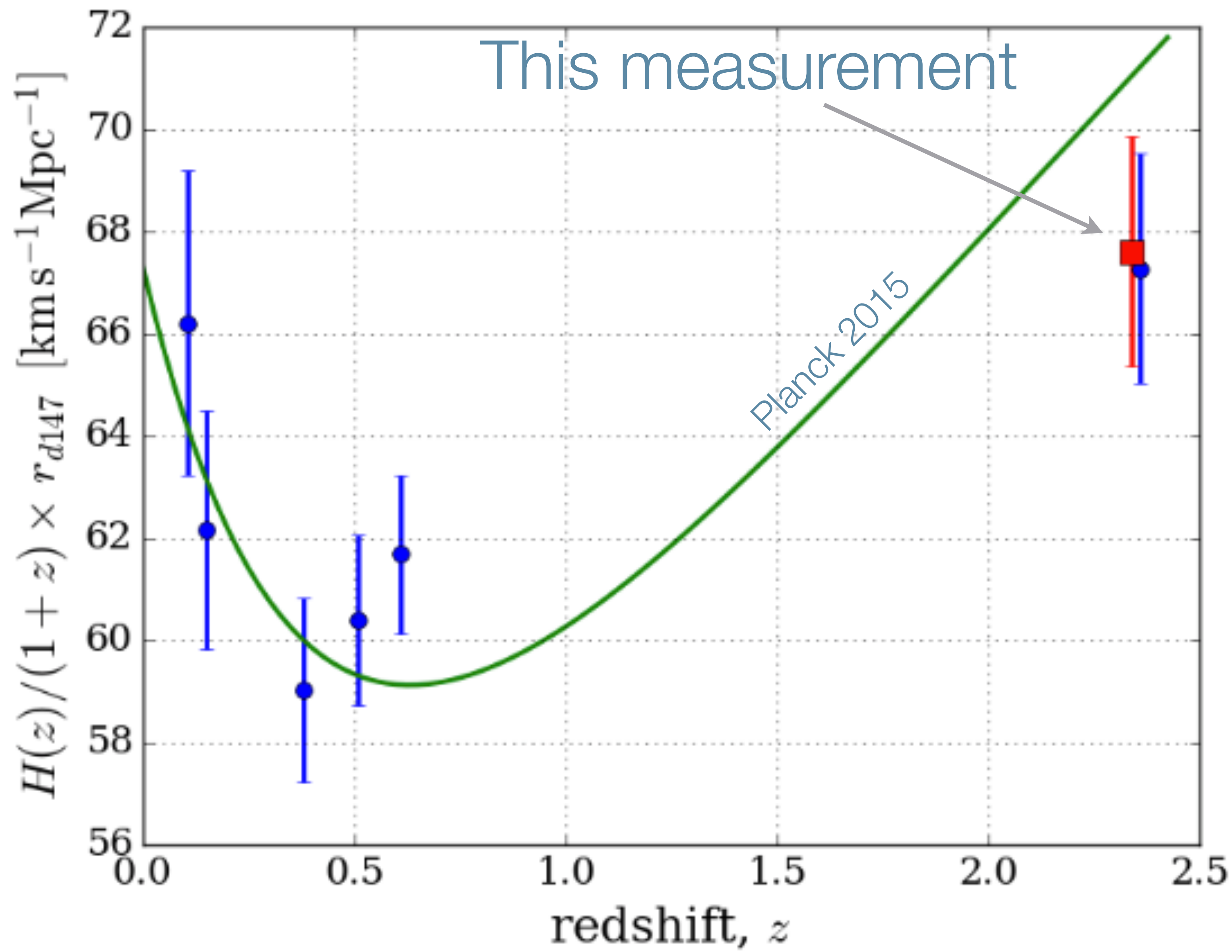
Radial BAO

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

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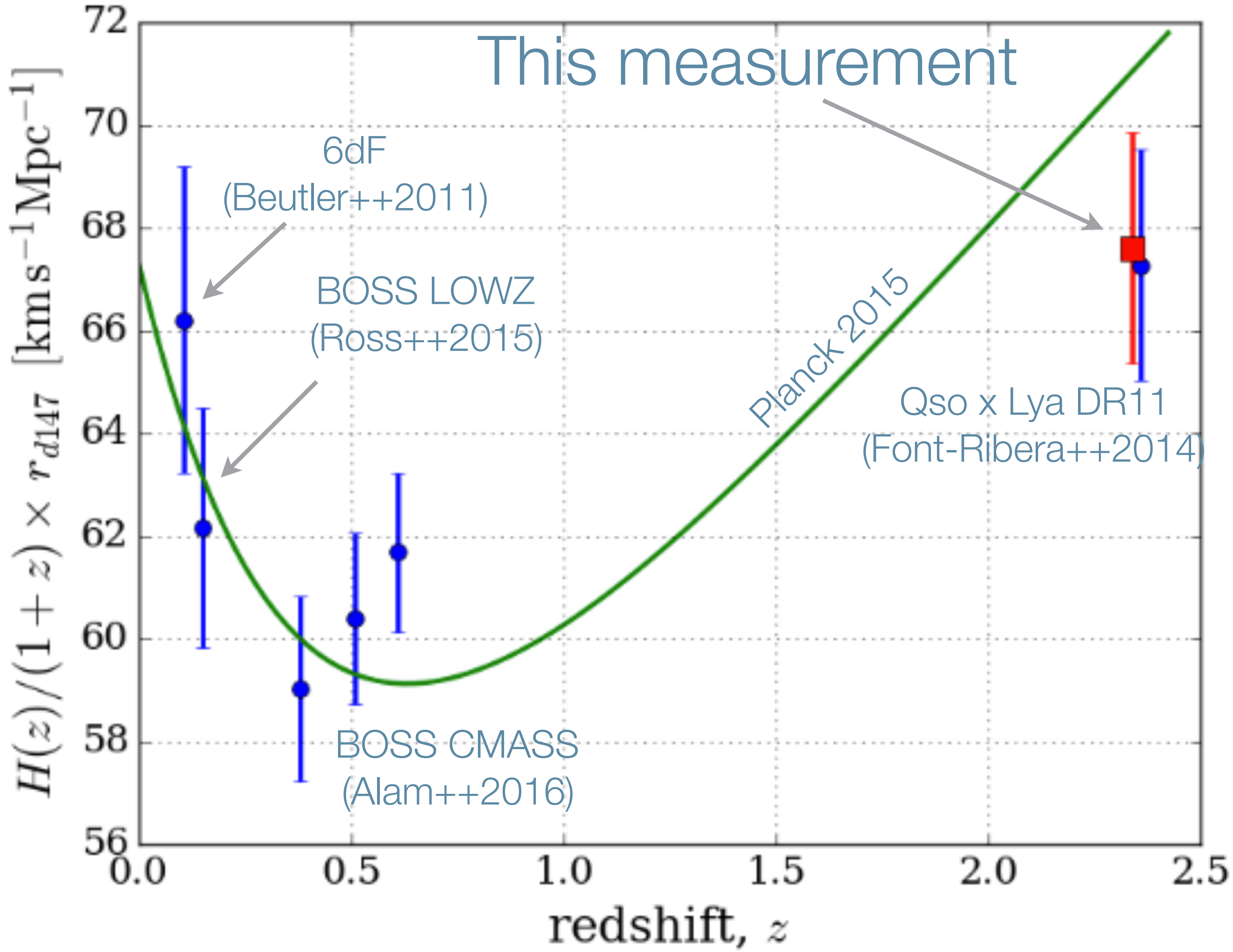

Bautista et al. 2017

There is bonus cosmological information in this sample…

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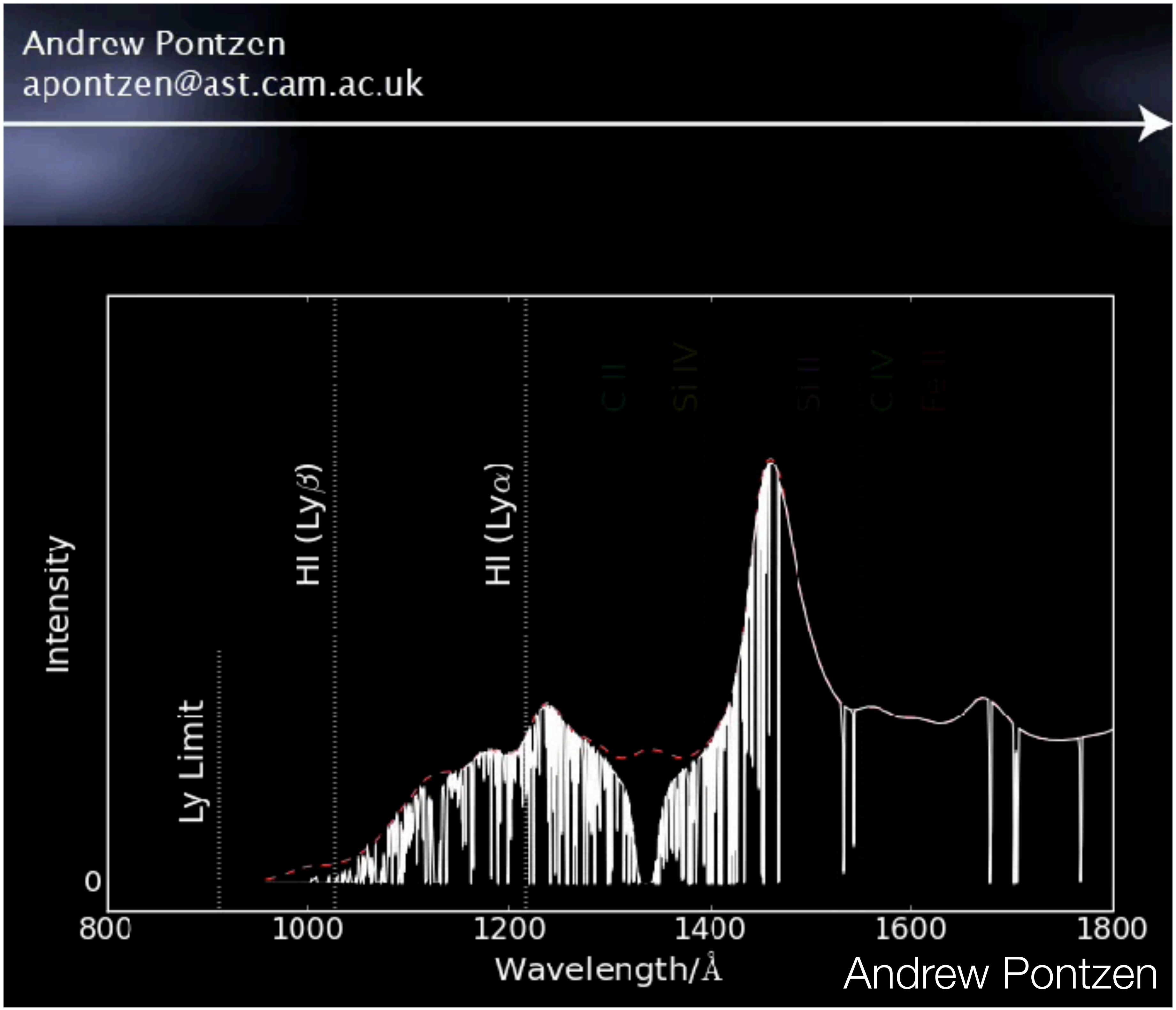
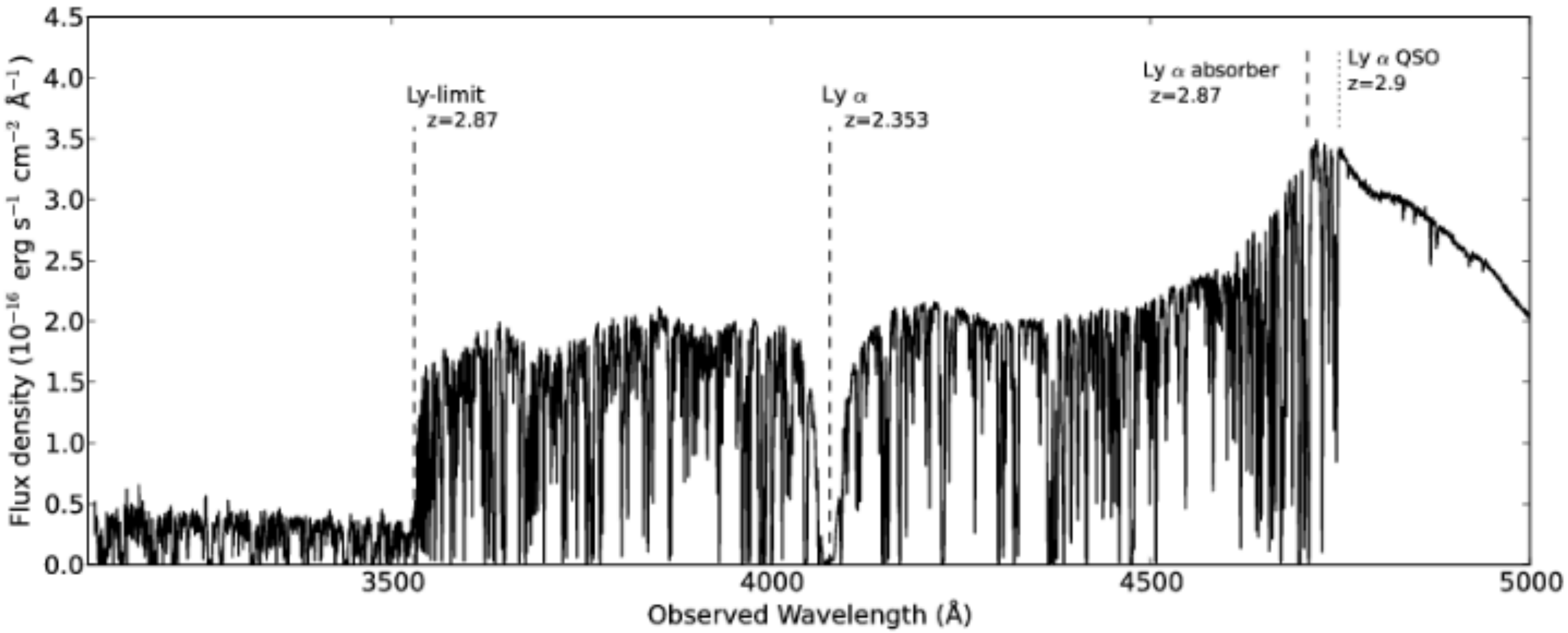


There are at least 3 bonus tracers in that movie… which ones?

Damped Lyman-alpha Systems (DLAs)



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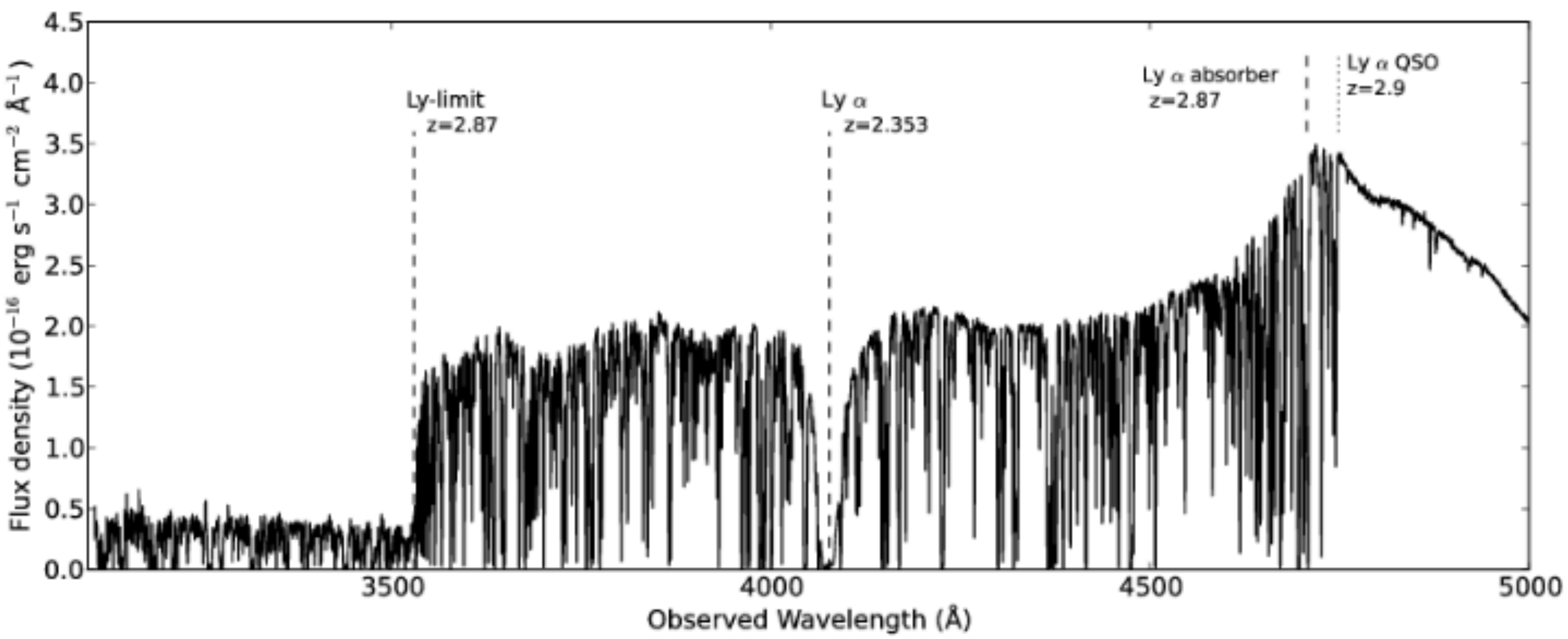
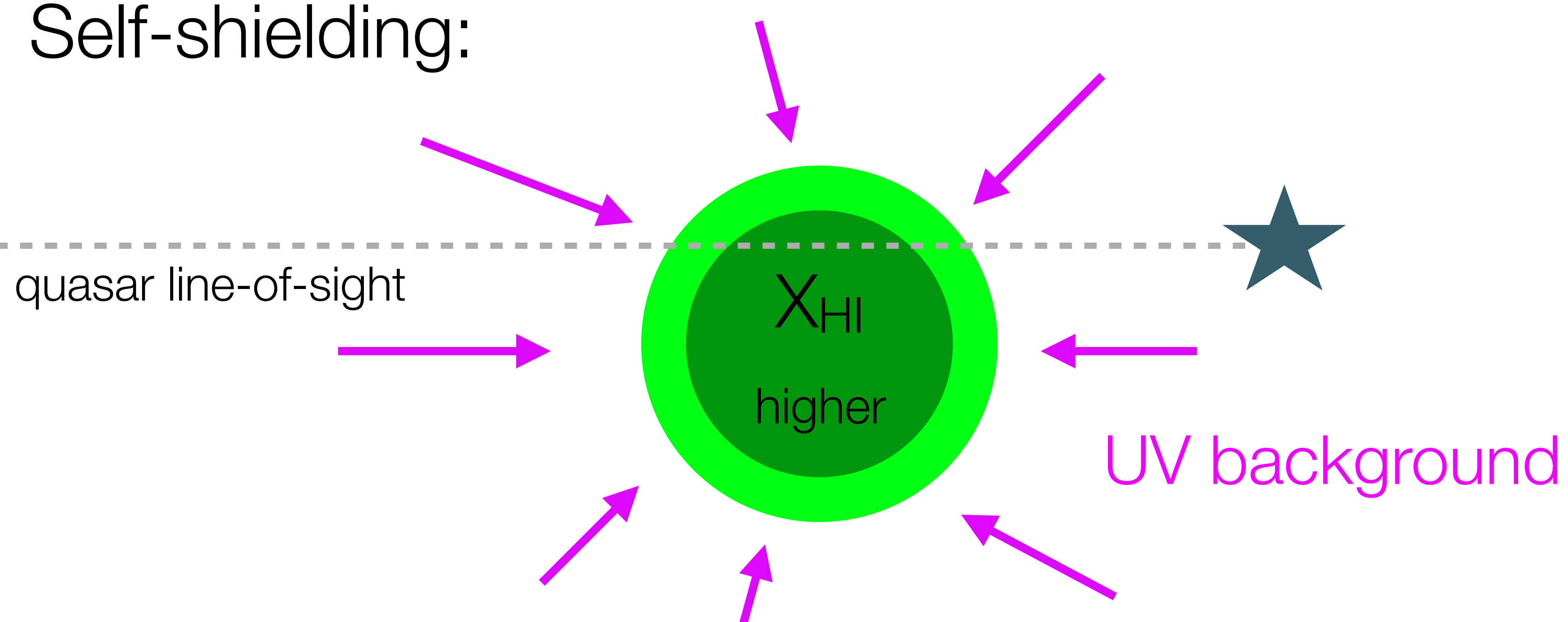


Self-shielding:



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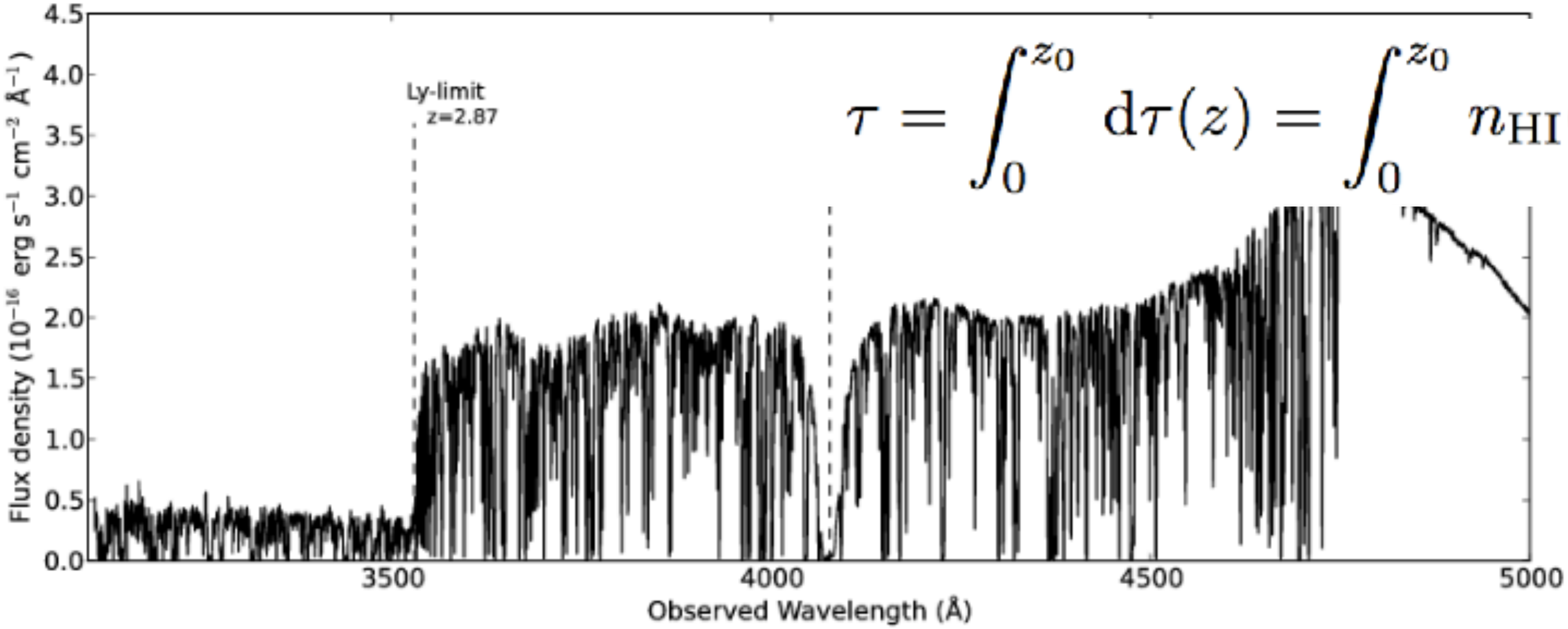

$$\tau = \int_0^{z_0} \mathrm{d}\tau(z) = \int_0^{z_0} n_{\mathrm{HI}}(z)\sigma[\nu(1+z)]\,\frac{\mathrm{d}l}{\mathrm{d}z}\,\mathrm{d}z$$

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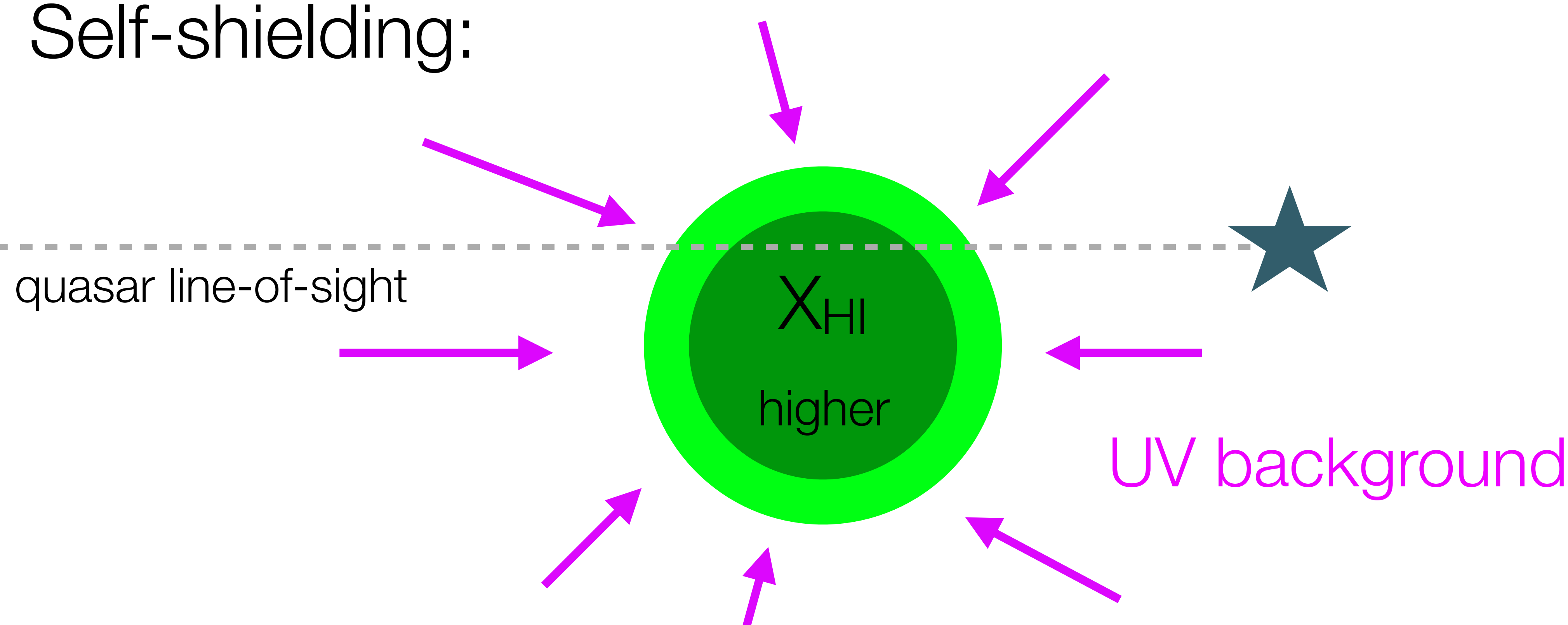

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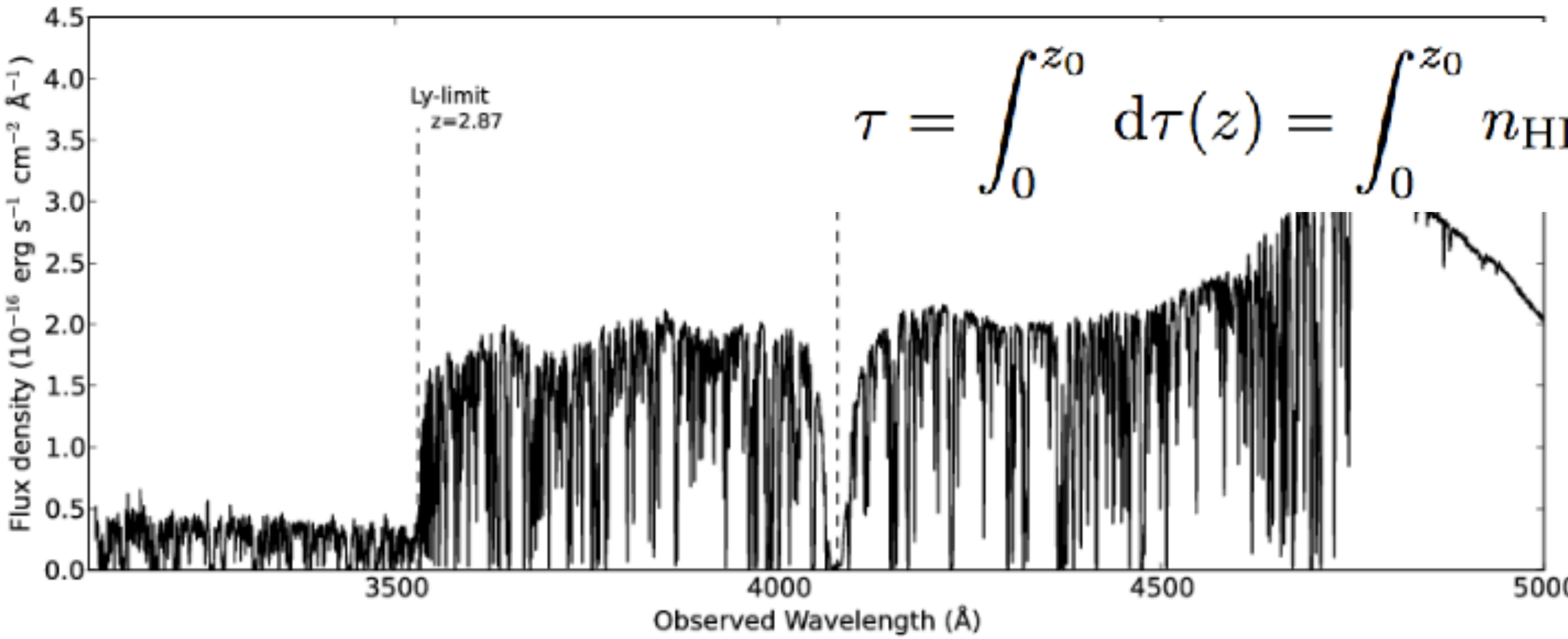

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$$\tau(z) = \Sigma(z) N_{\mathrm{HI}}(z)$$

Column density [cm^{-2}]

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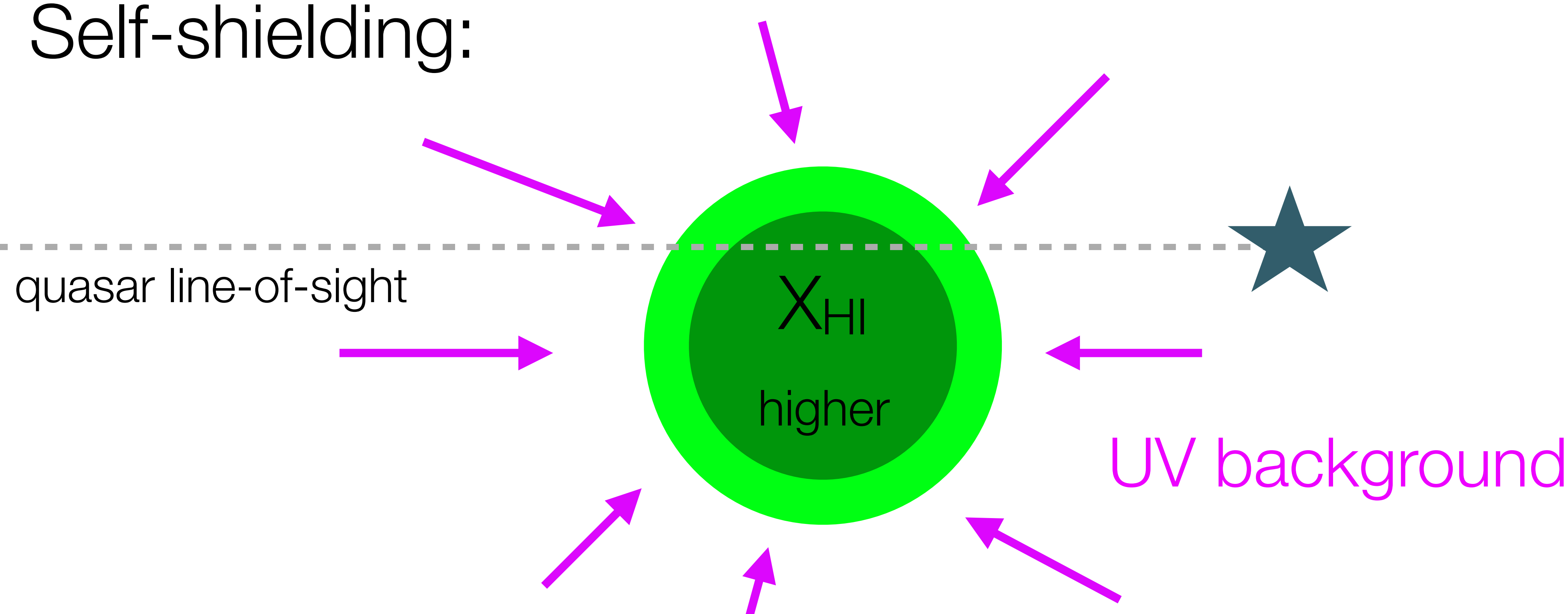

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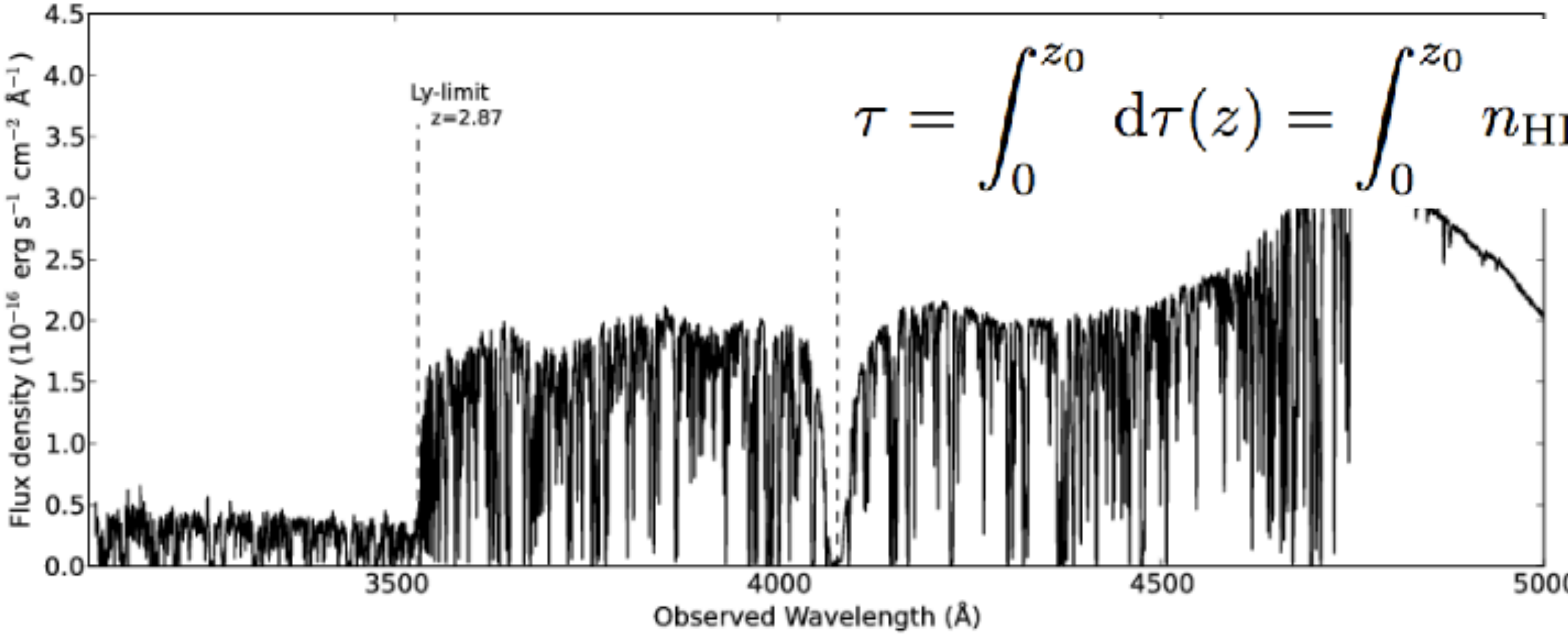

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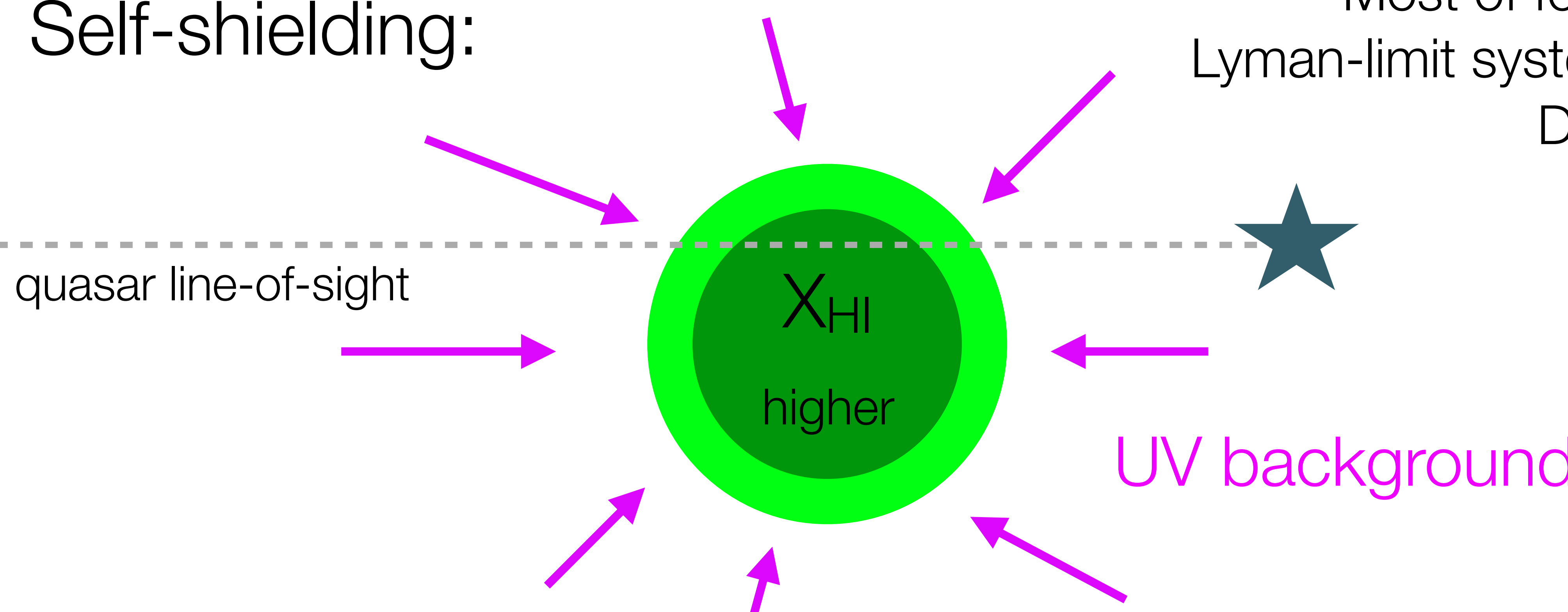
Column density [cm^{-2}]

Most of forest: $N_{HI} \sim 10^{\mathbf{13\text{-}16}}$ cm^{-2}

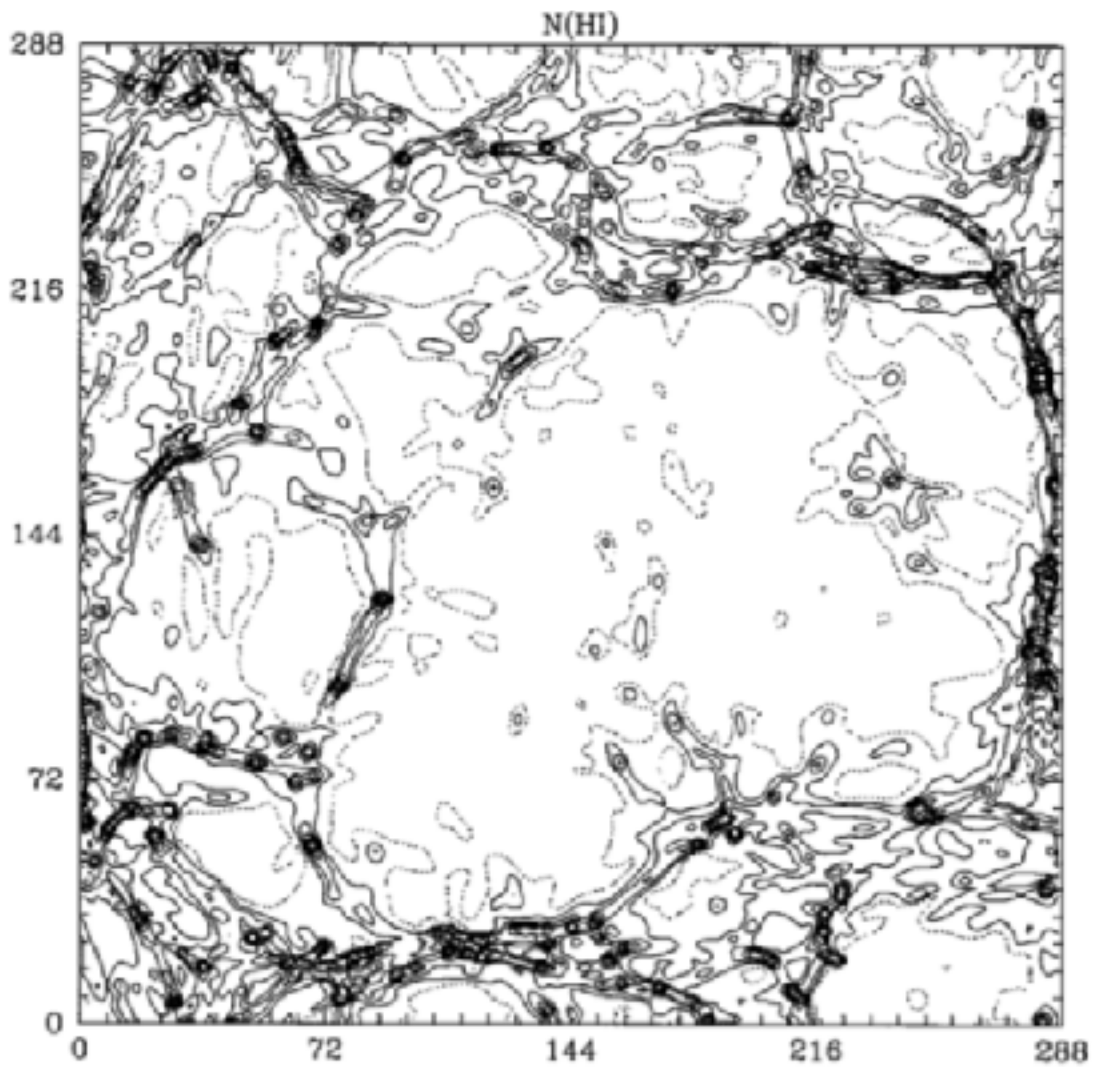
Lyman-limit systems: $N_{HI} \sim 10^{\mathbf{16\text{-}20}}$ cm^{-2}

DLAs: $N_{HI} \sim 10^{\mathbf{20\text{-}23}}$ 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

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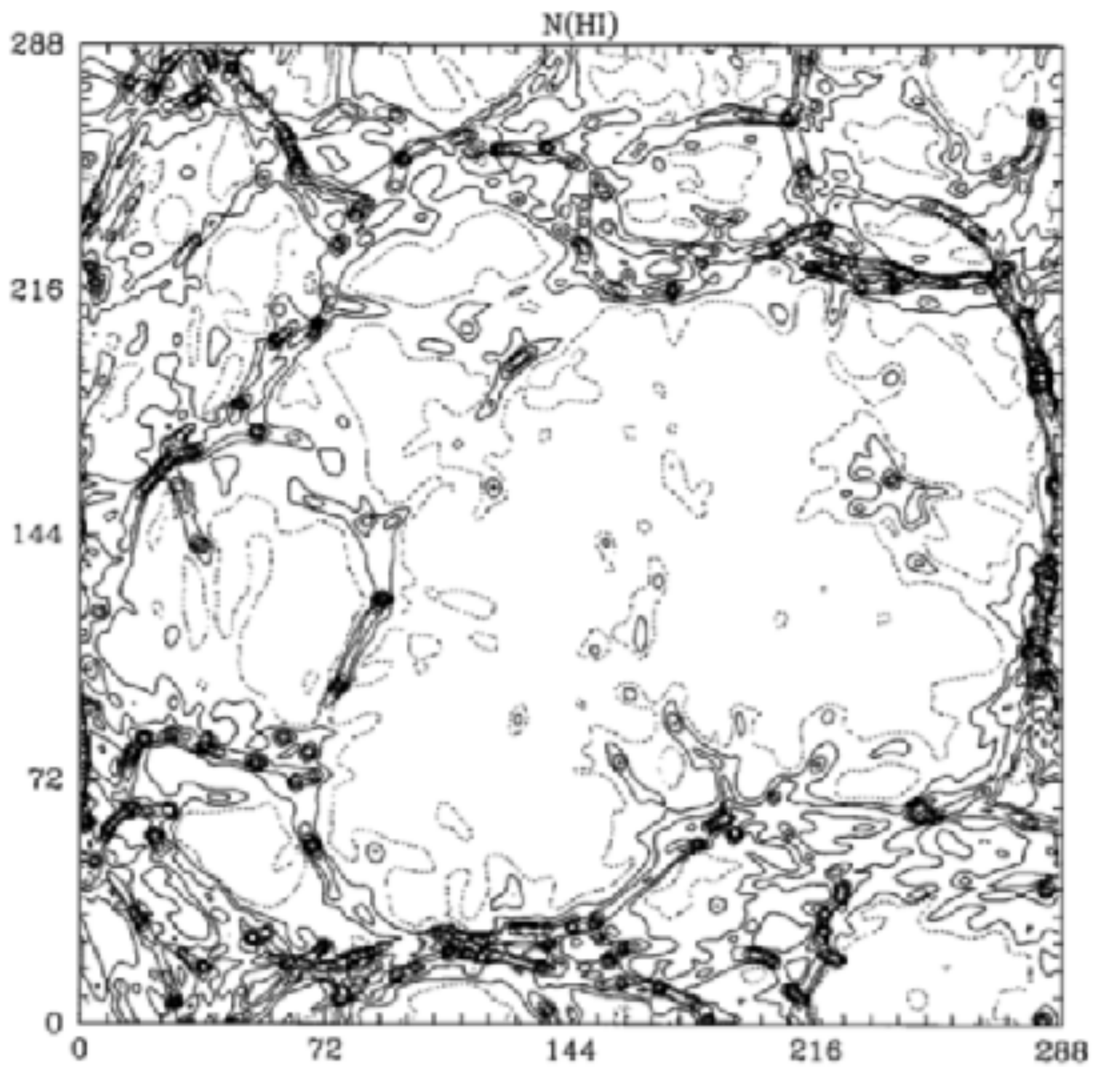

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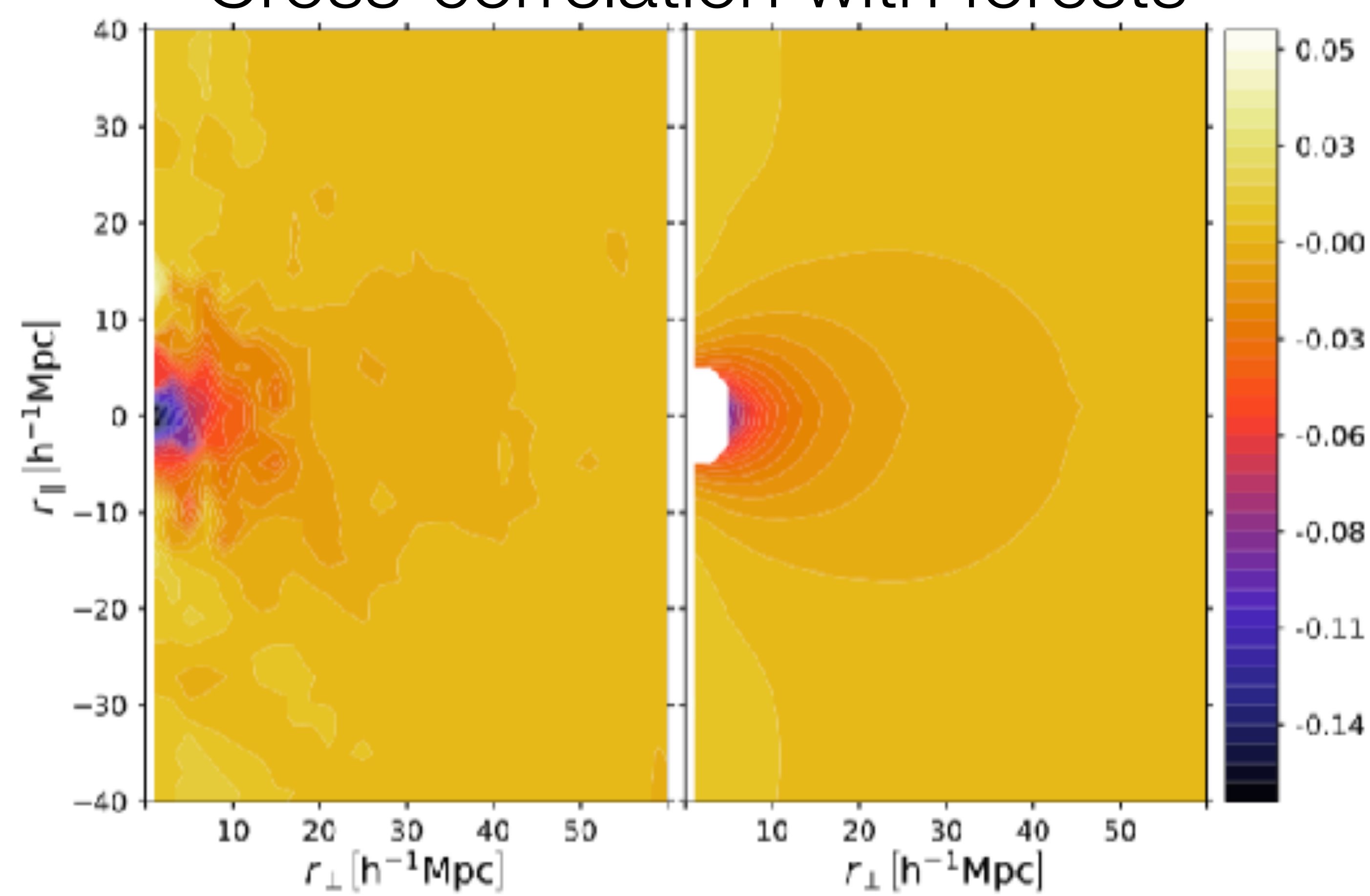
Cross-correlation with forests



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

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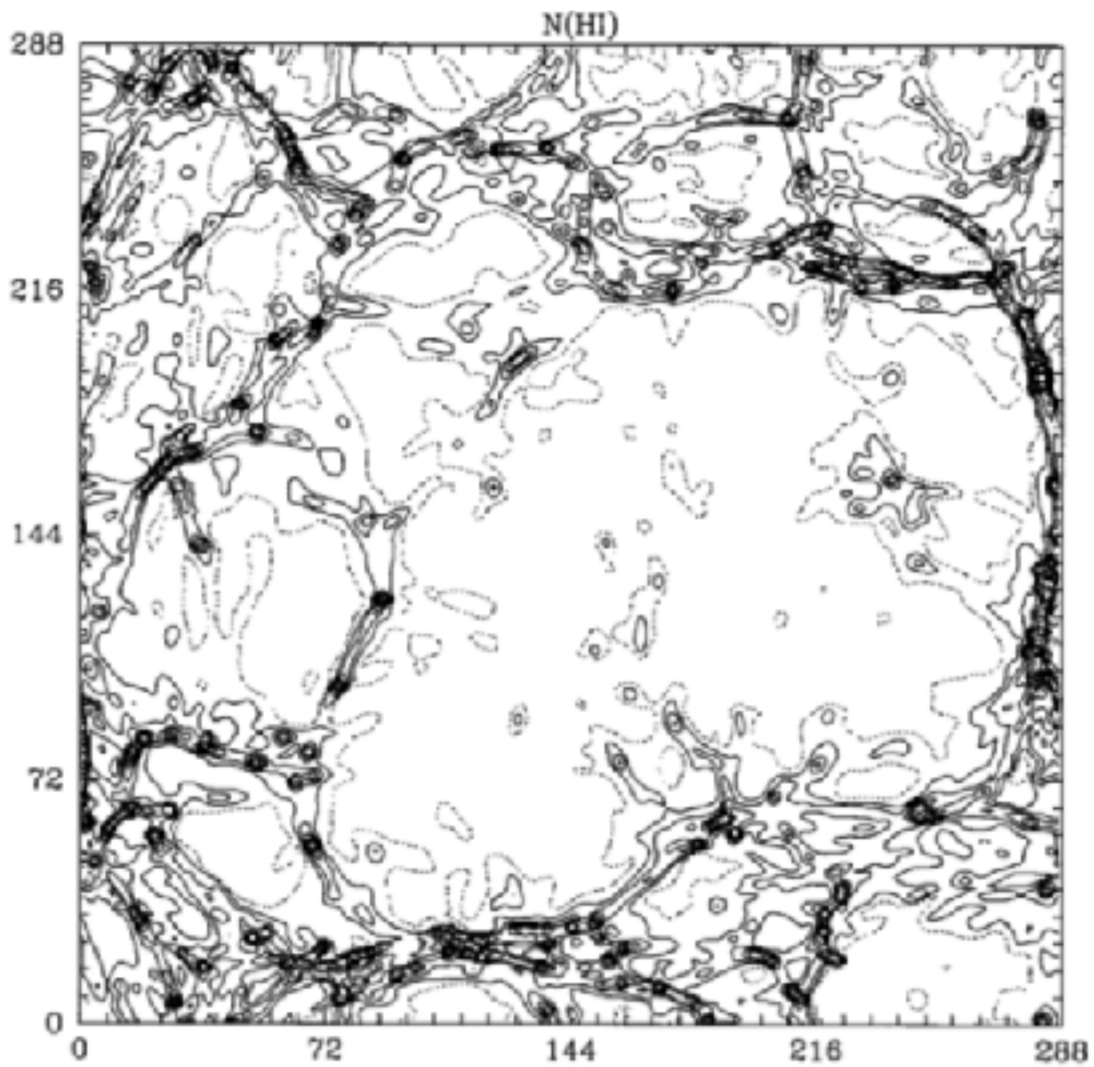

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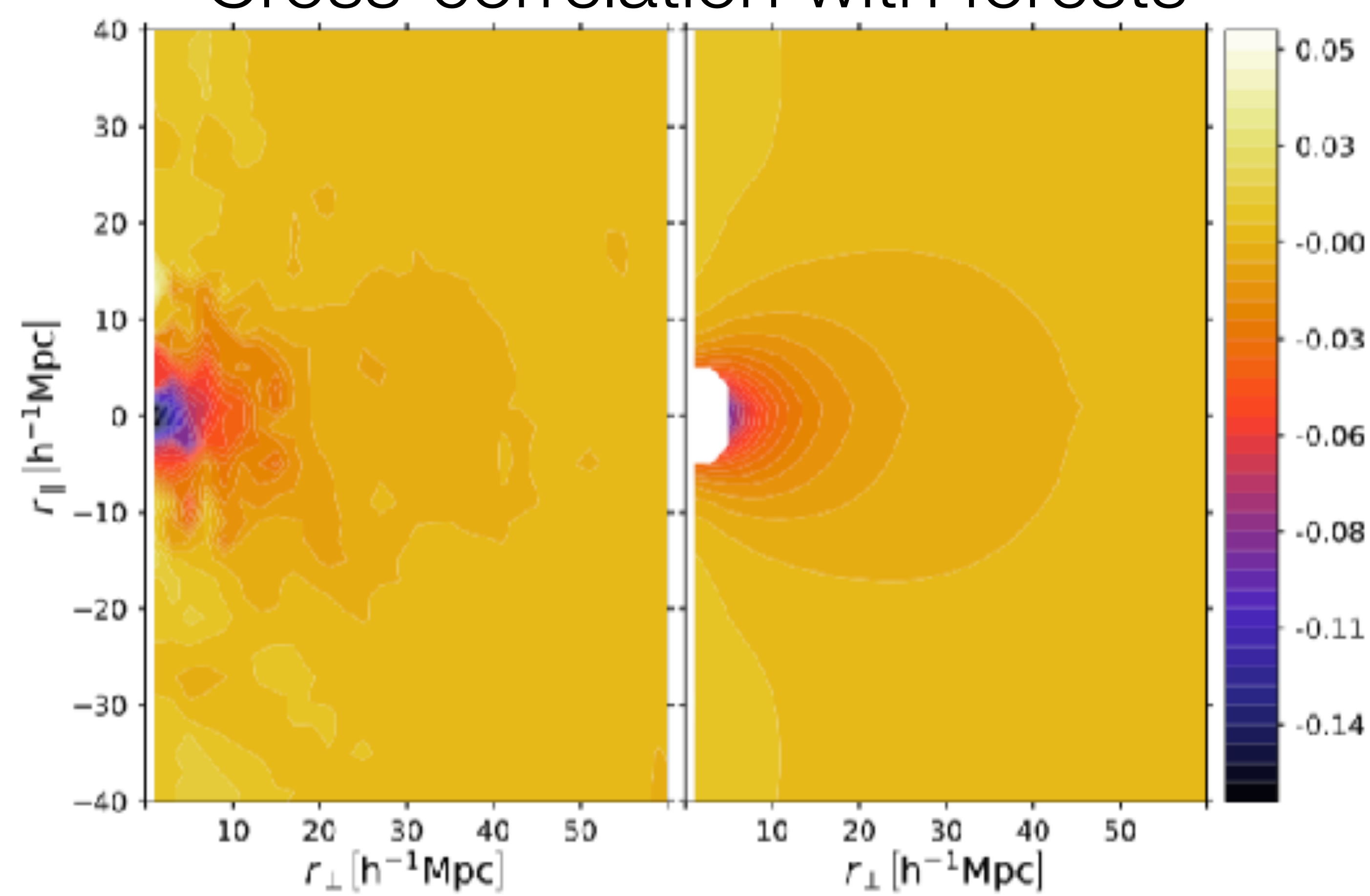


Font-Ribera et al. 2012, Pérez-Ràfols et al. 2018

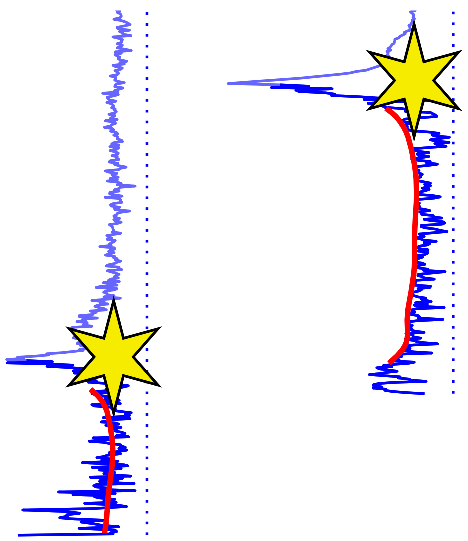
$b_{\rm DLA} = 2.00 \pm 0.19$ Host halo mass ~ $4 \cdot 10^{11}\, h^{-1}{\rm M}_{\odot}$

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)



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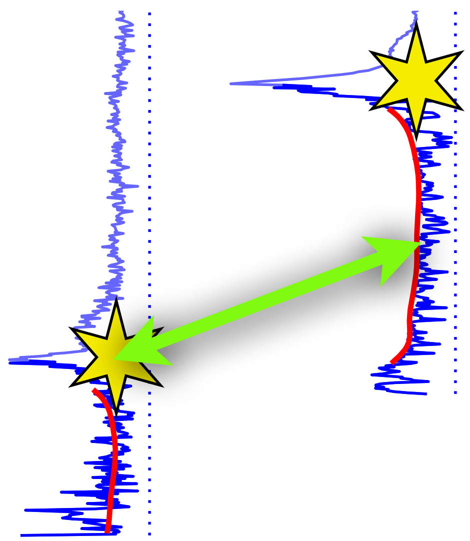

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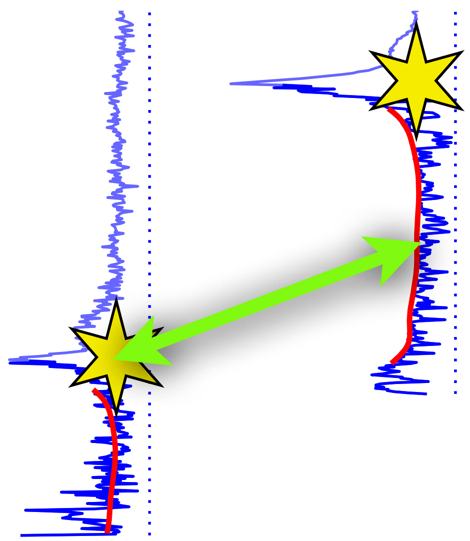

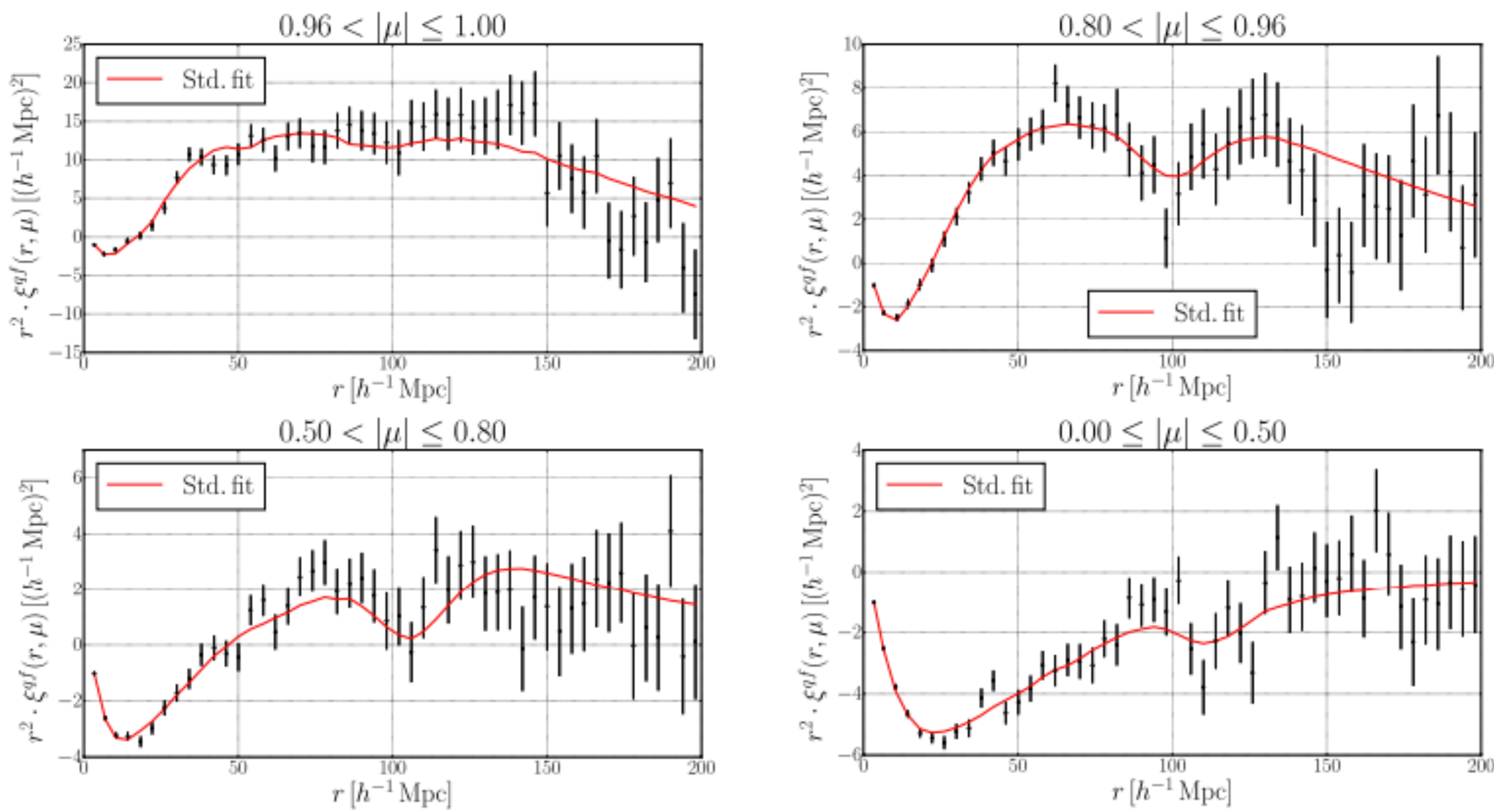

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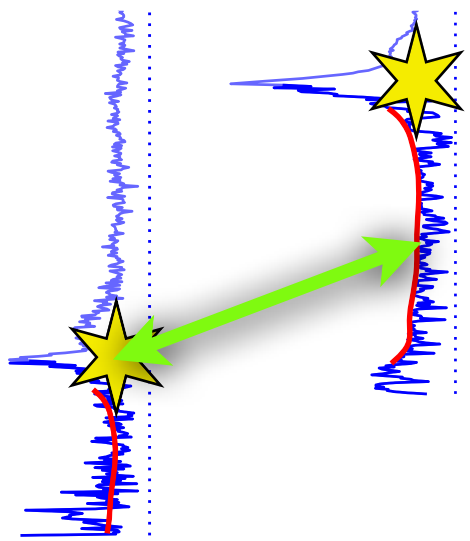

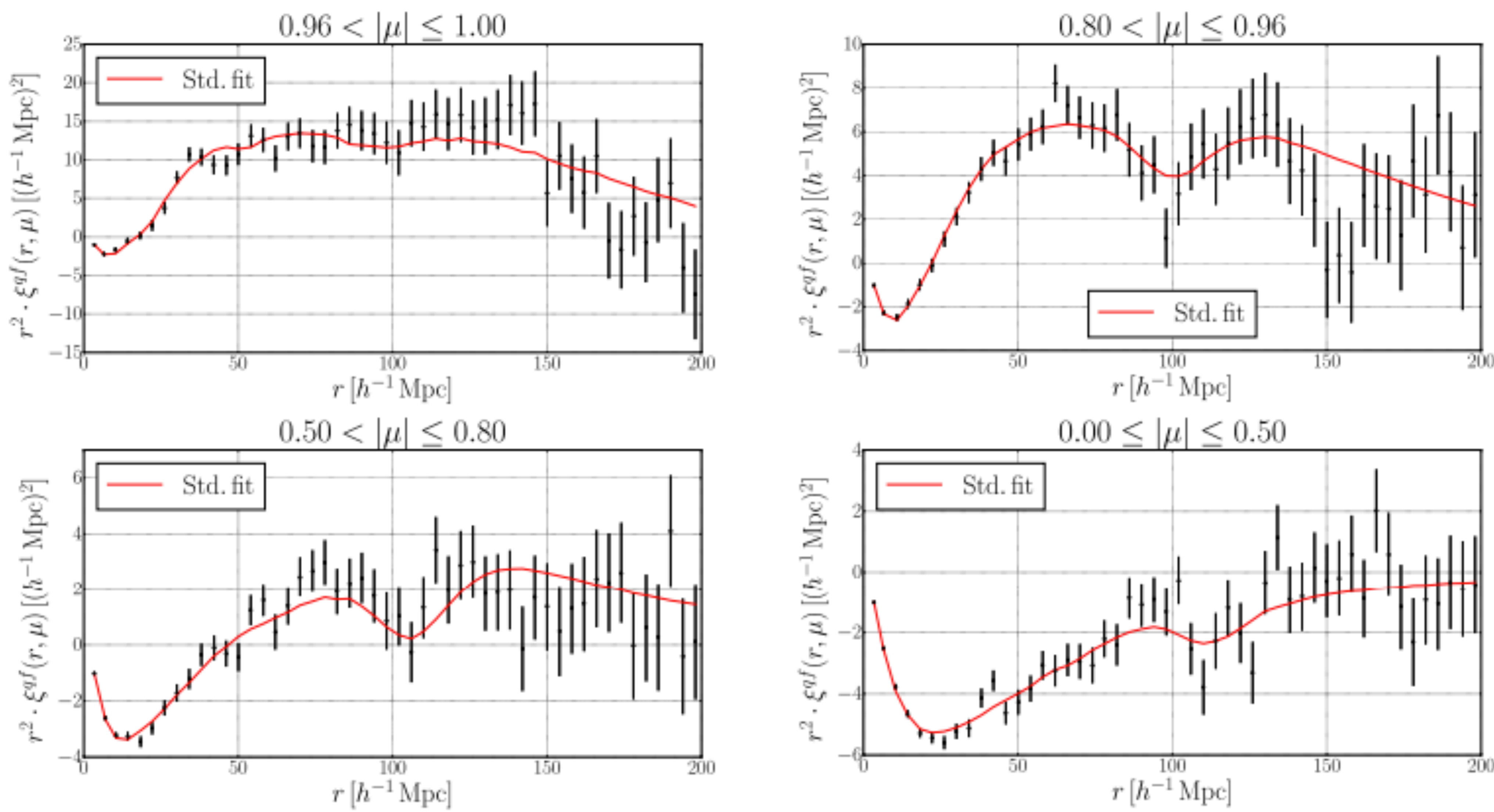

$$b_{QSO}(z = 2.40) = 3.70 \pm 0.12$$

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

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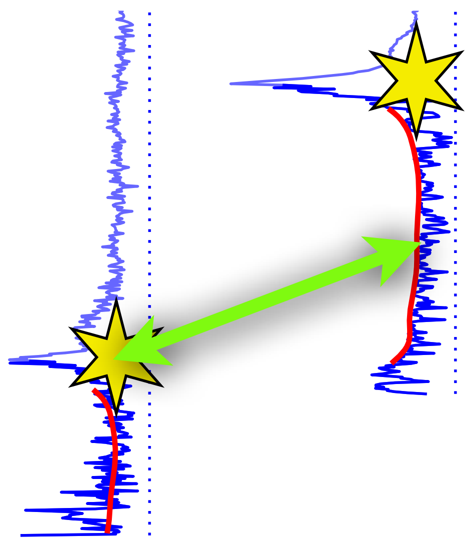
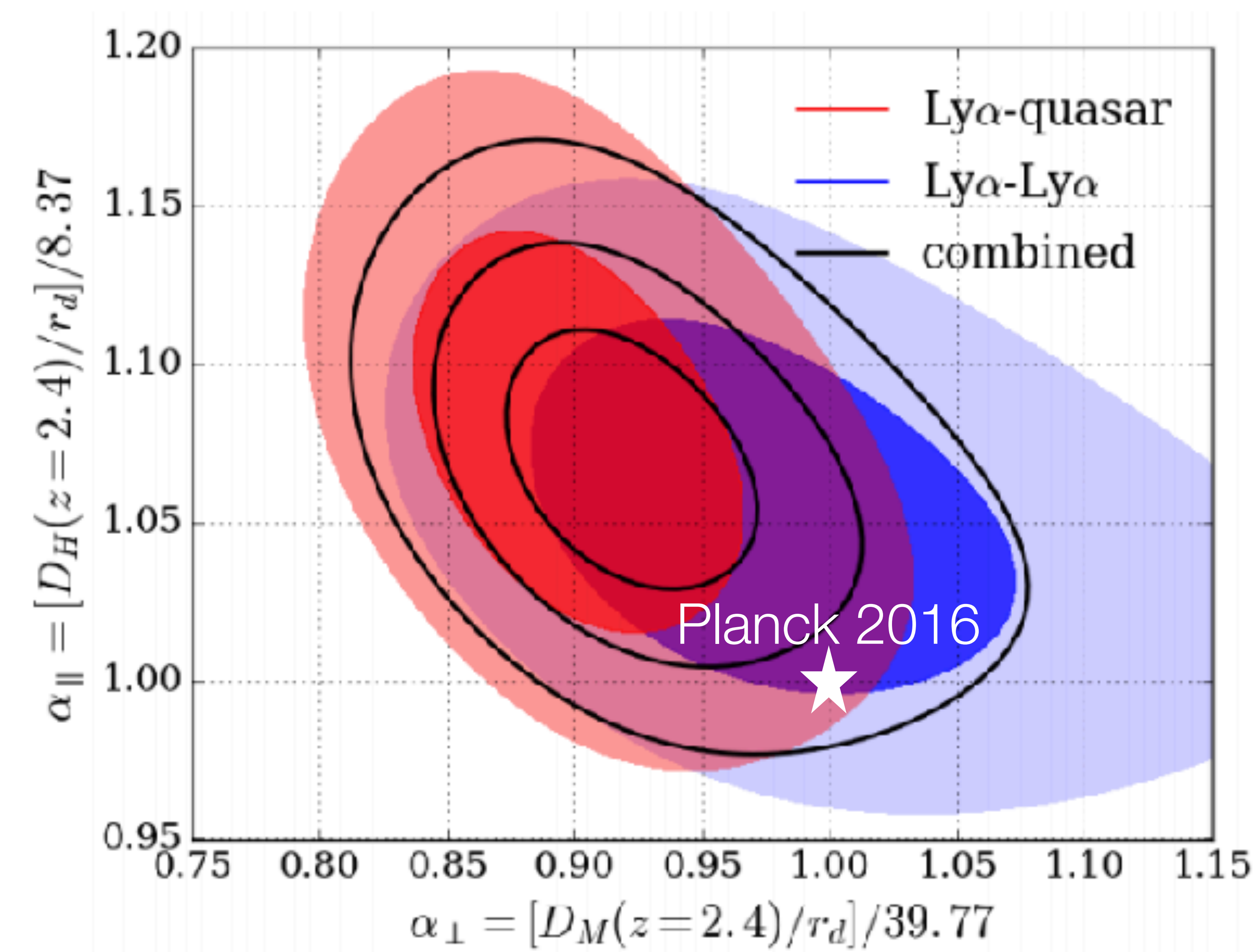
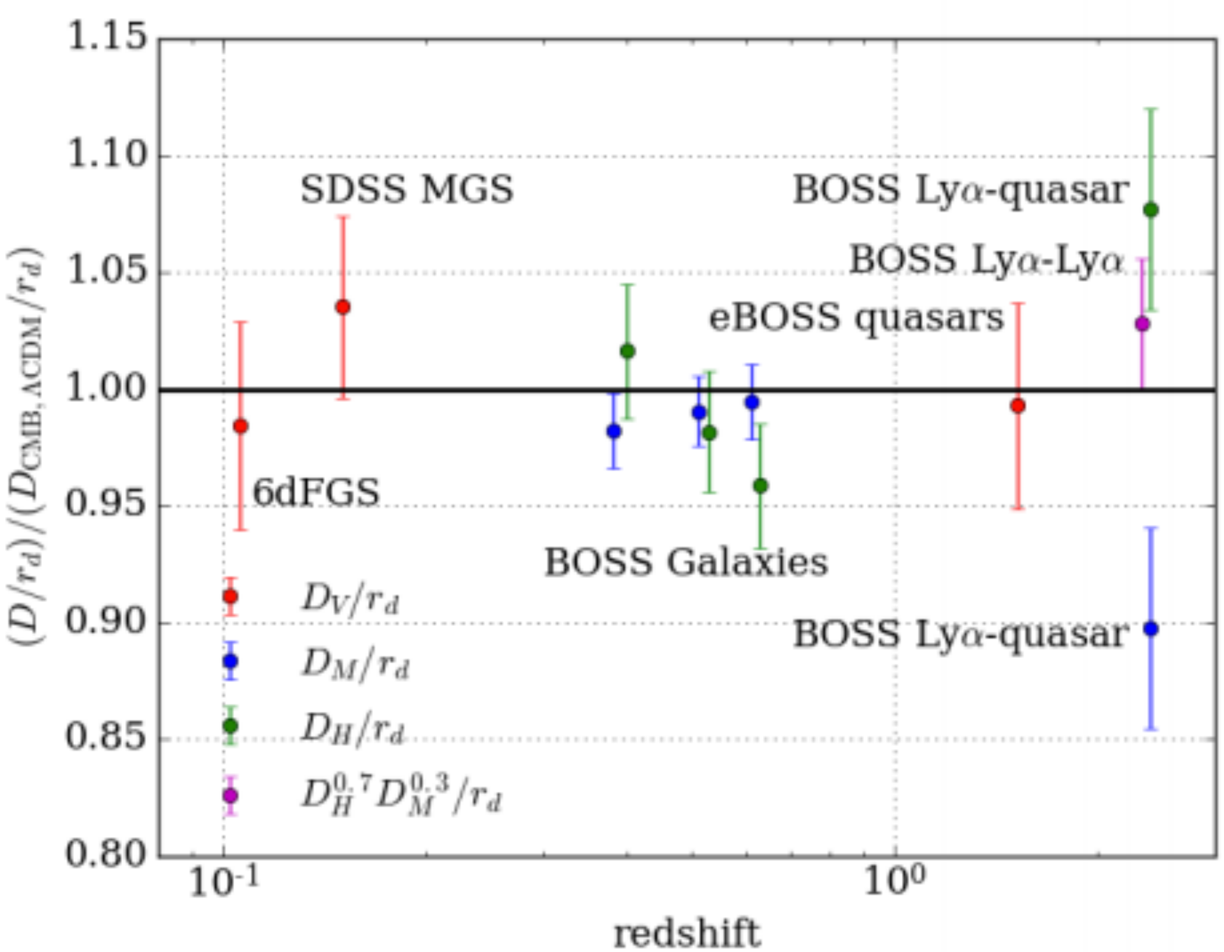


No significant correlation was found between the auto and cross measurements!



The combined measurement has 2.3 sigma difference with Planck prediction!

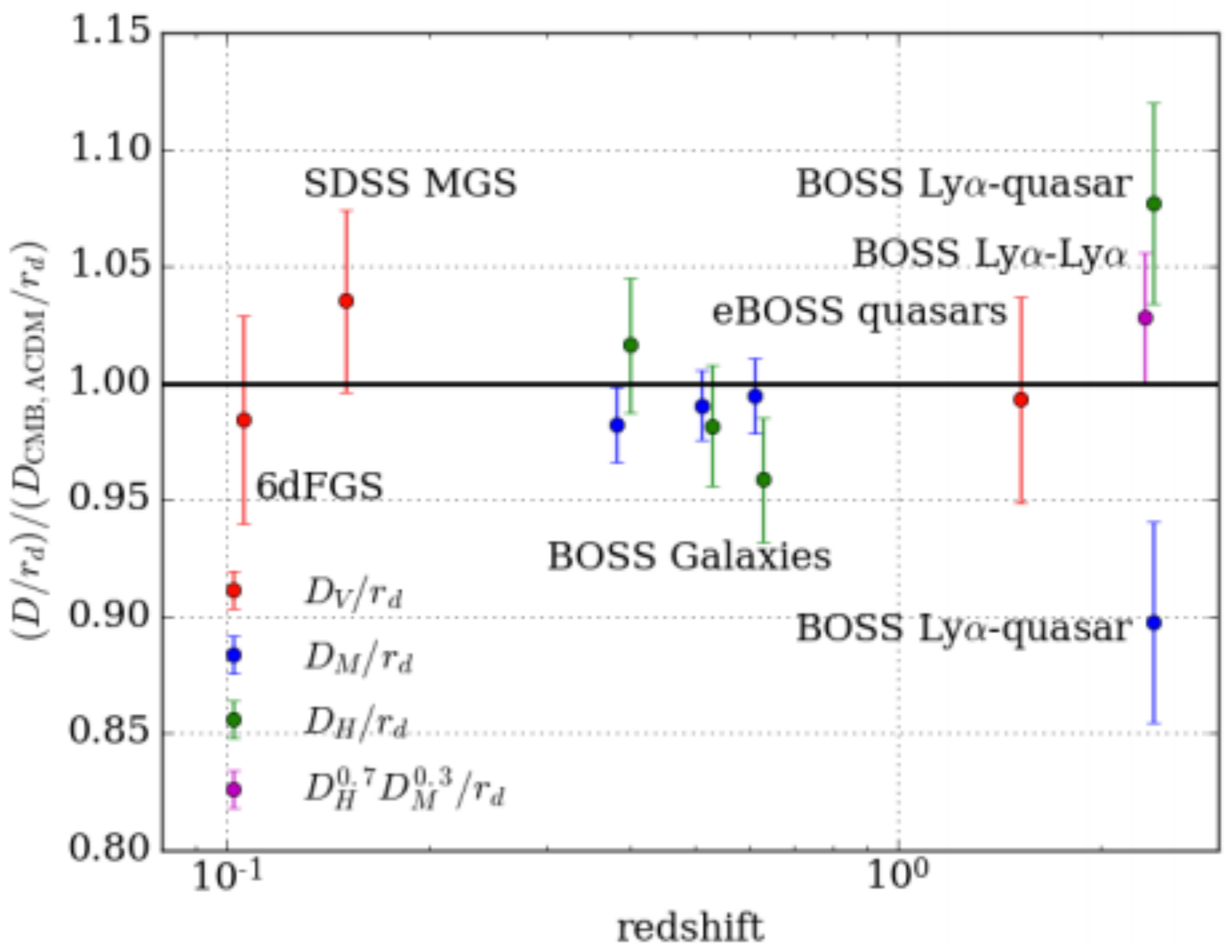
BAO versus Supernovae



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

BAO versus Supernovae



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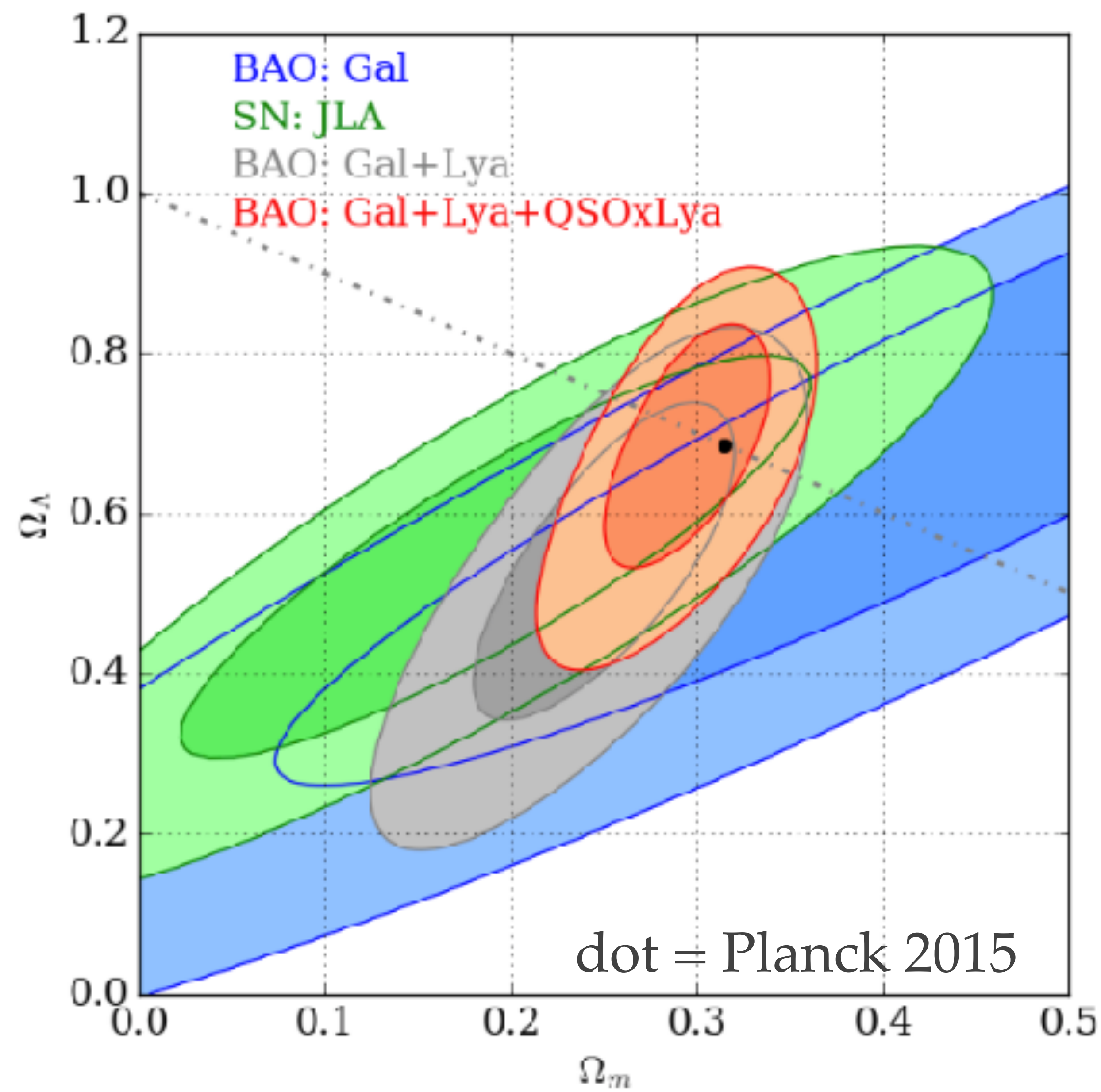

Supernovae Ia

Betoule et al. 2014

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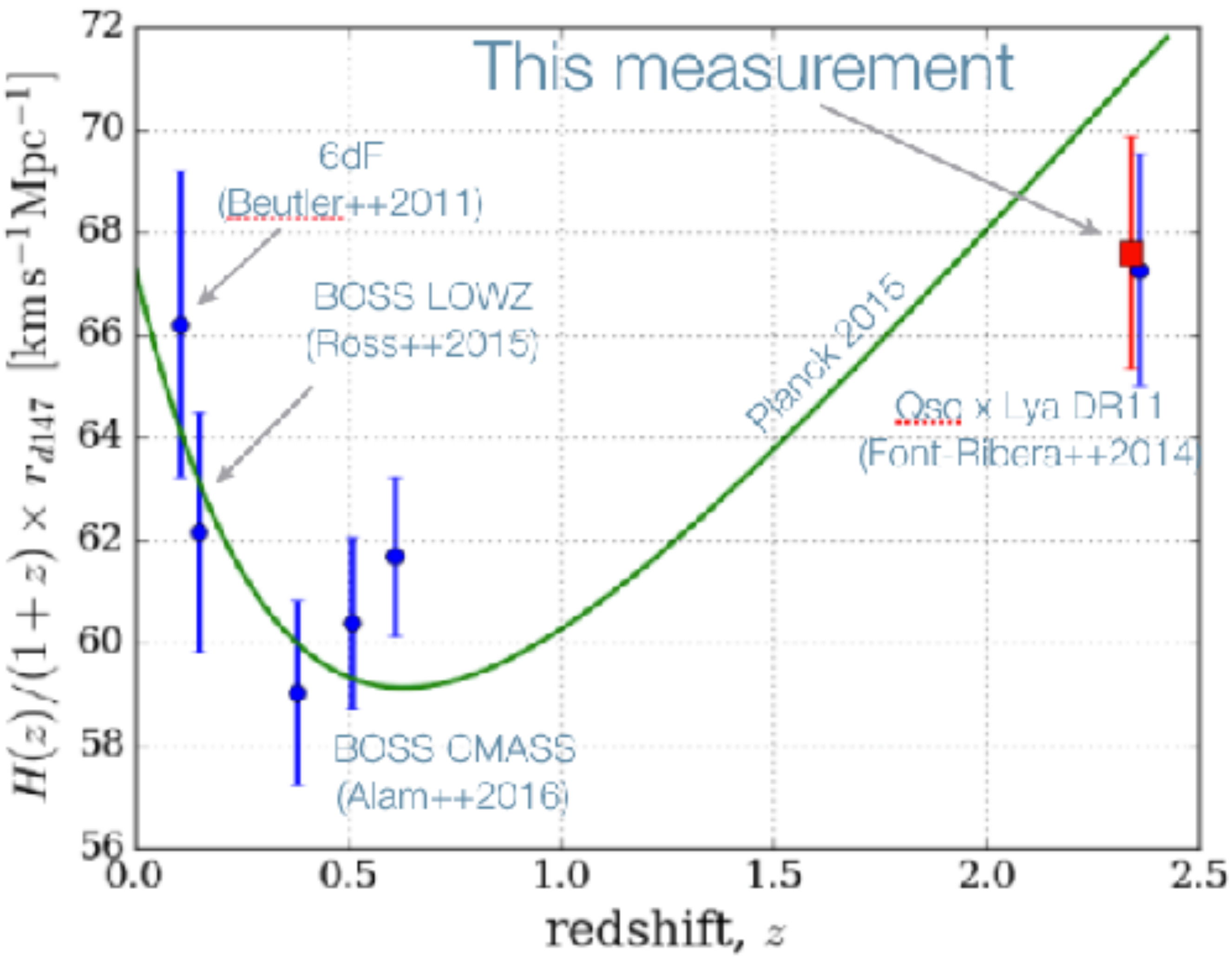

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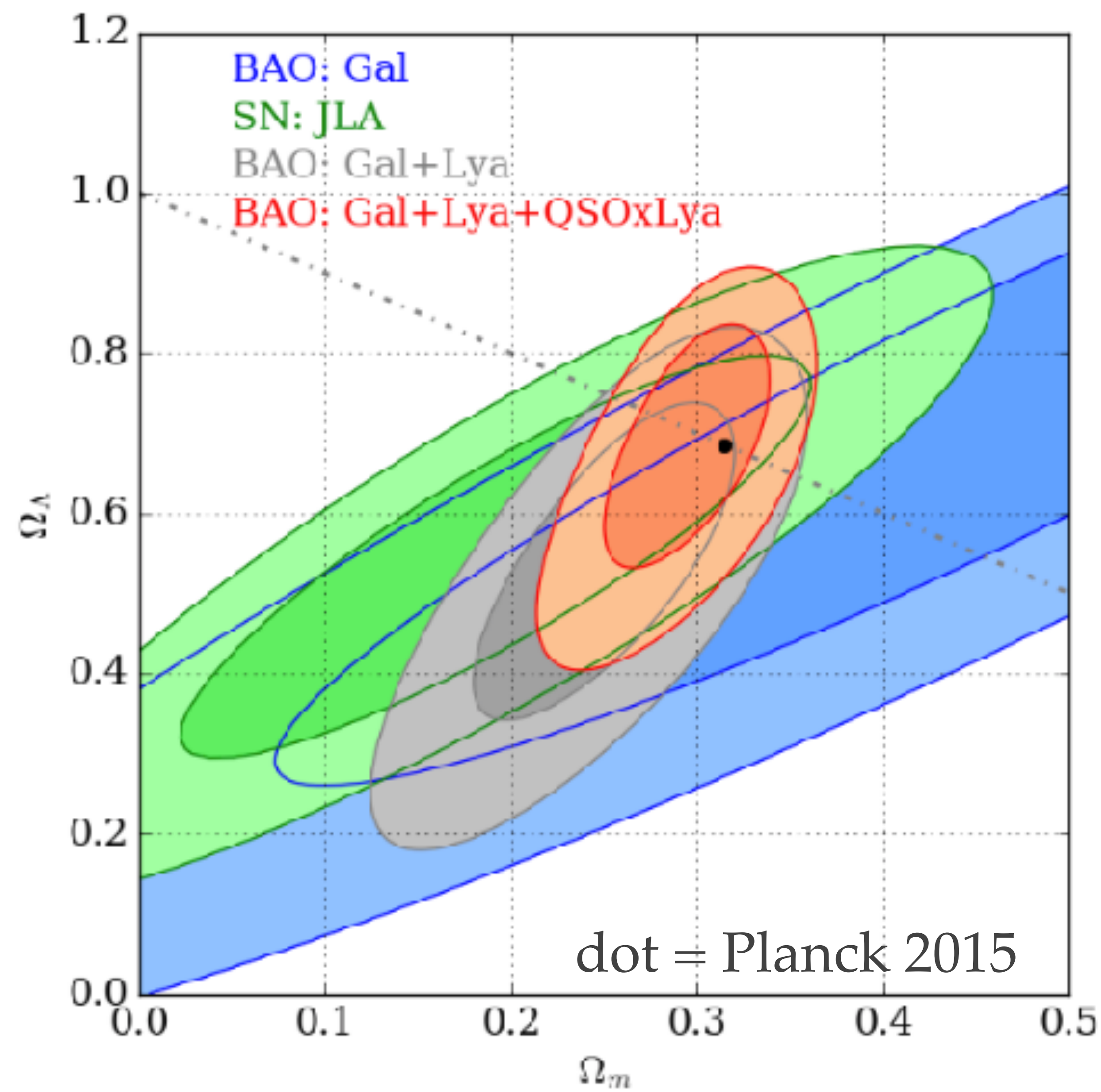
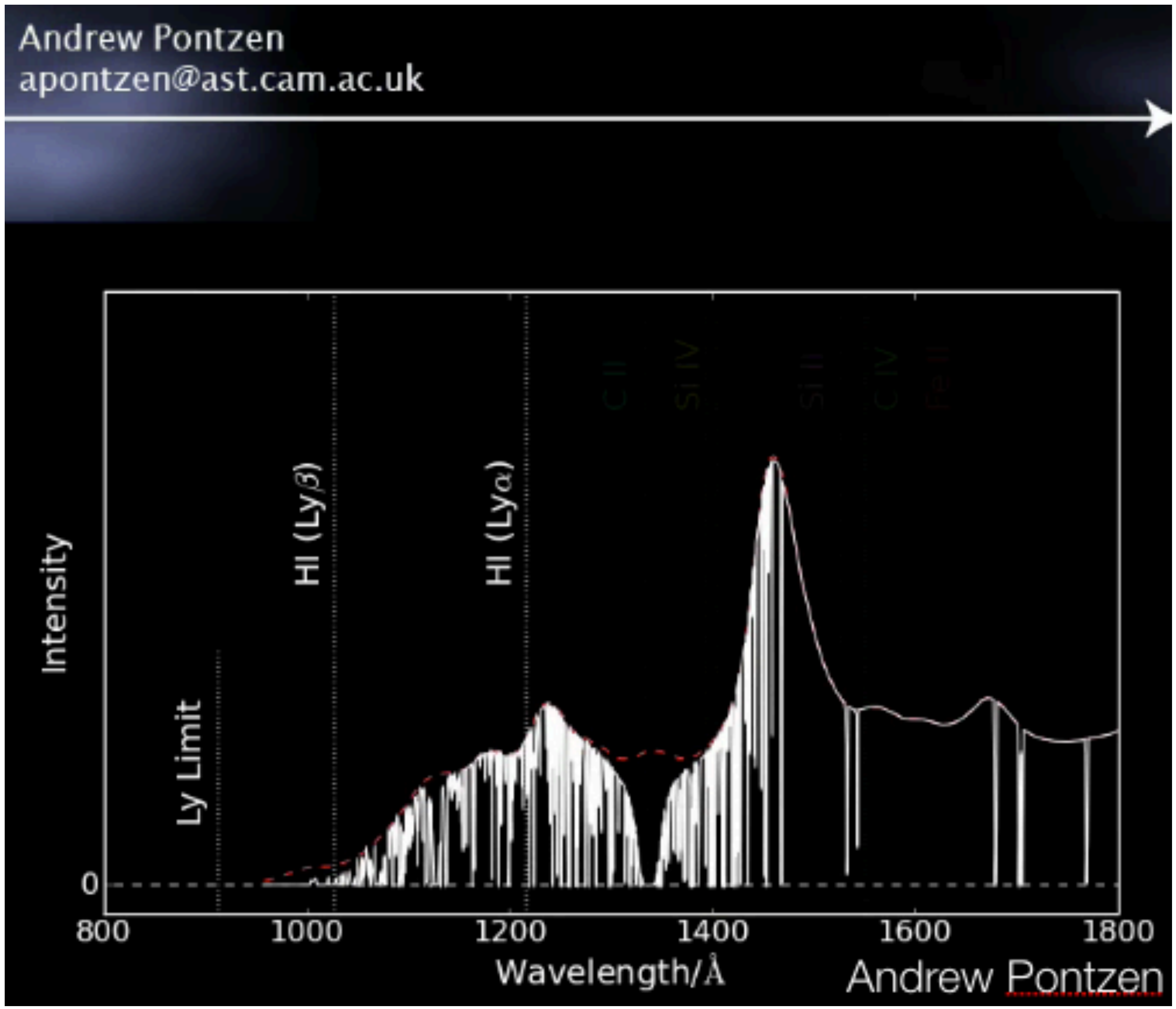


Supernovae Ia

Betoule et al. 2014

Last tracer? This one is harder…



Forest of Metals : CIV, SIV, MgII, etc

Blomqvist et al. 2018

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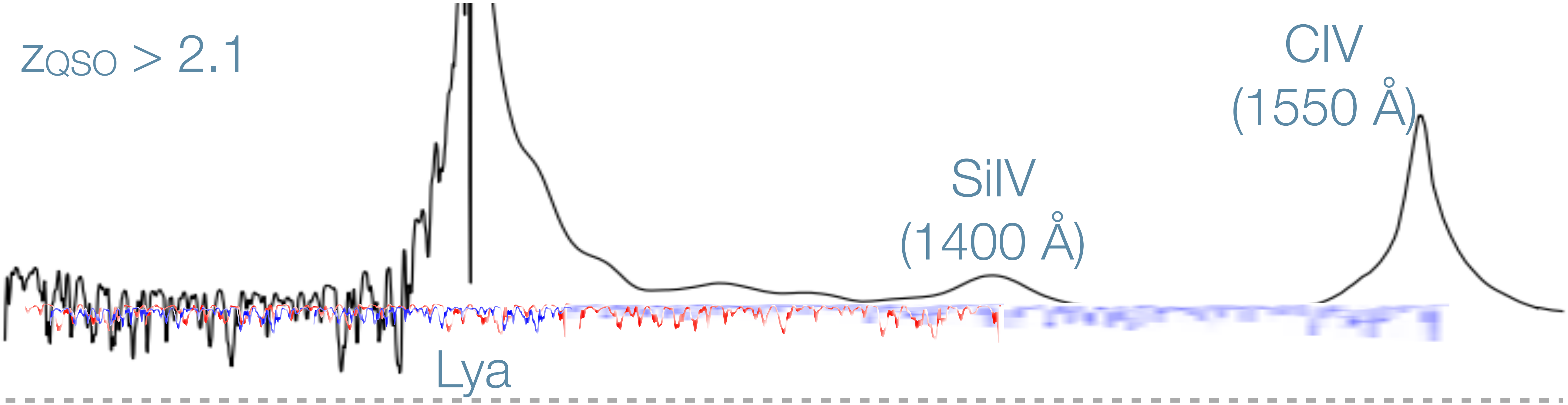

Blomqvist et al. 2018

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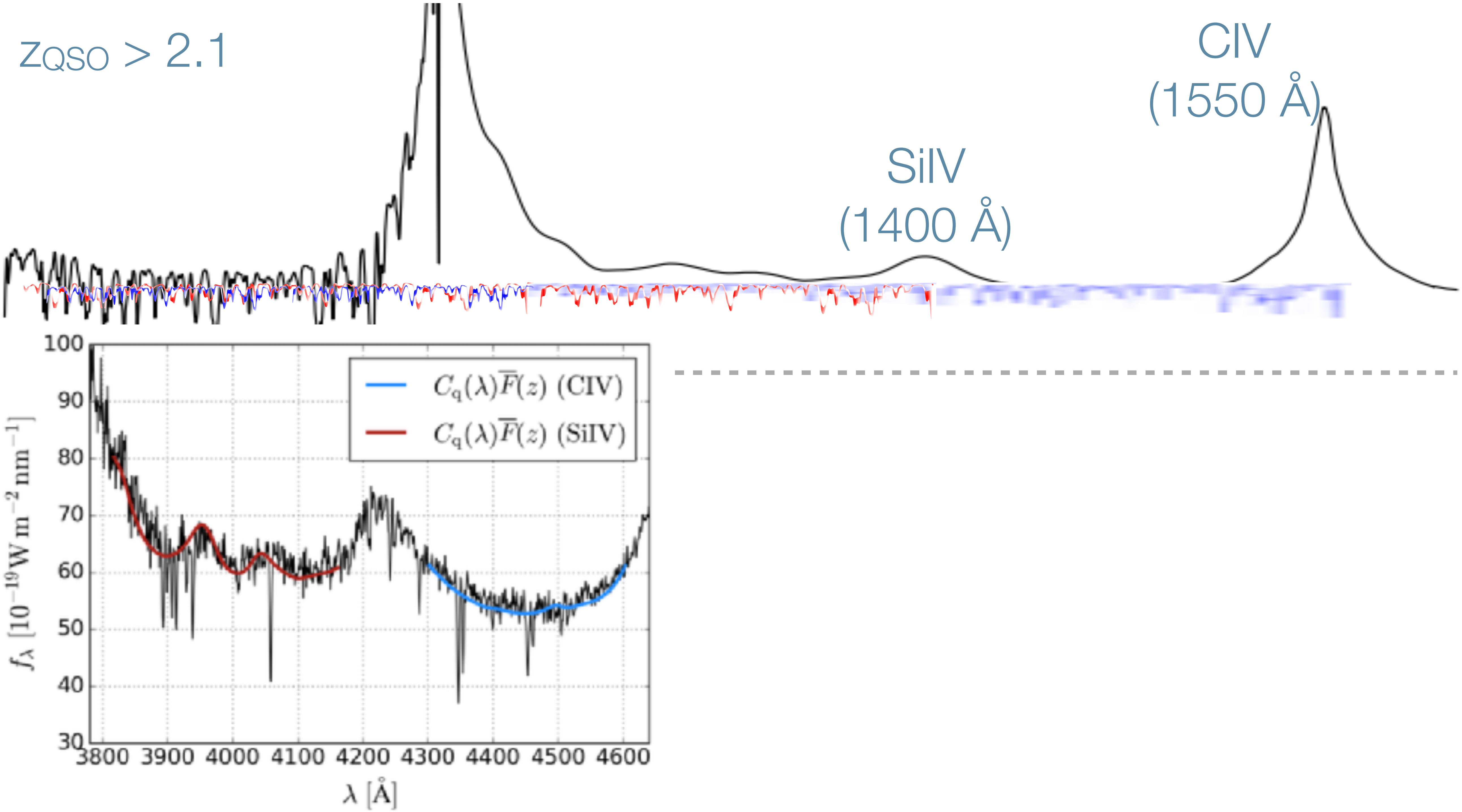

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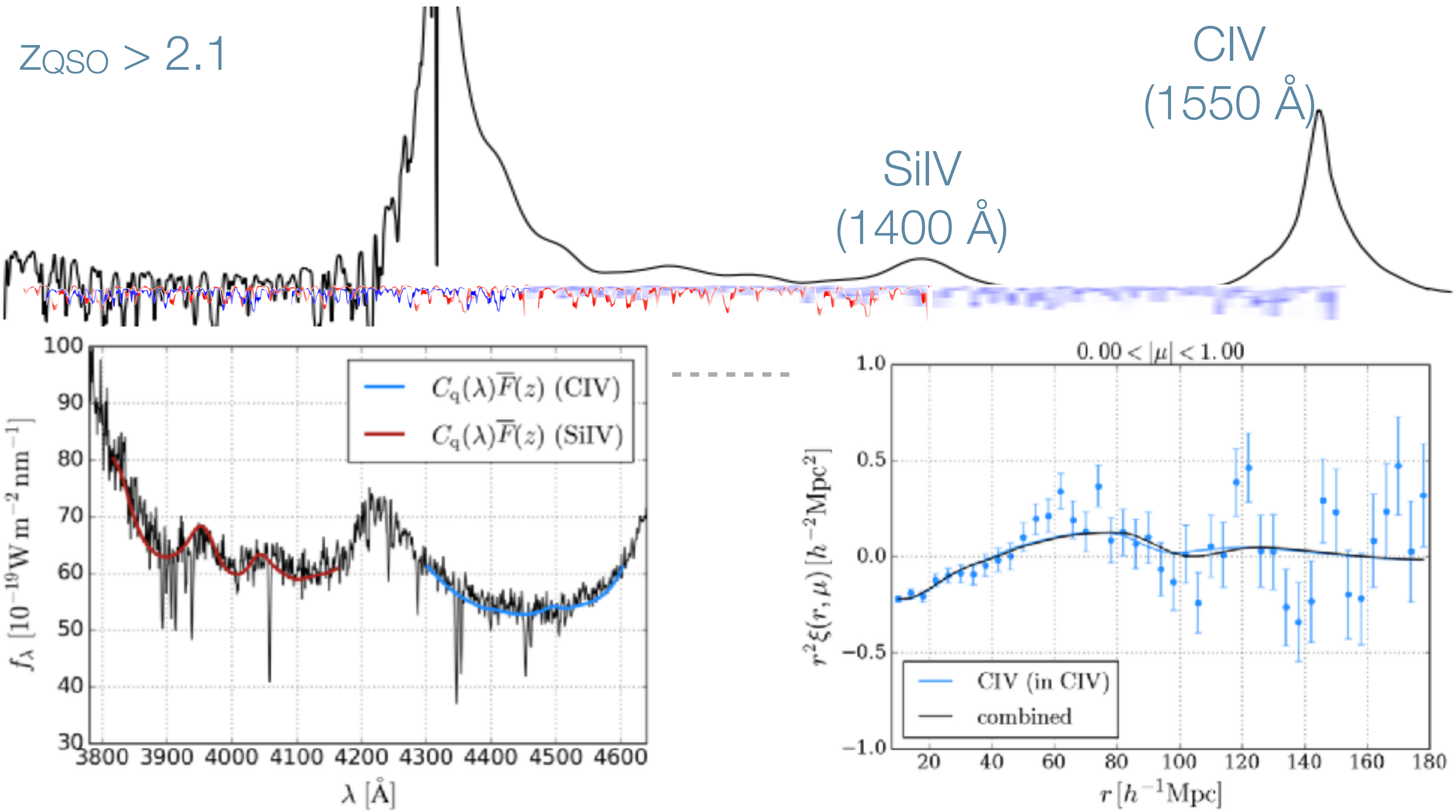

Blomqvist et al. 2018

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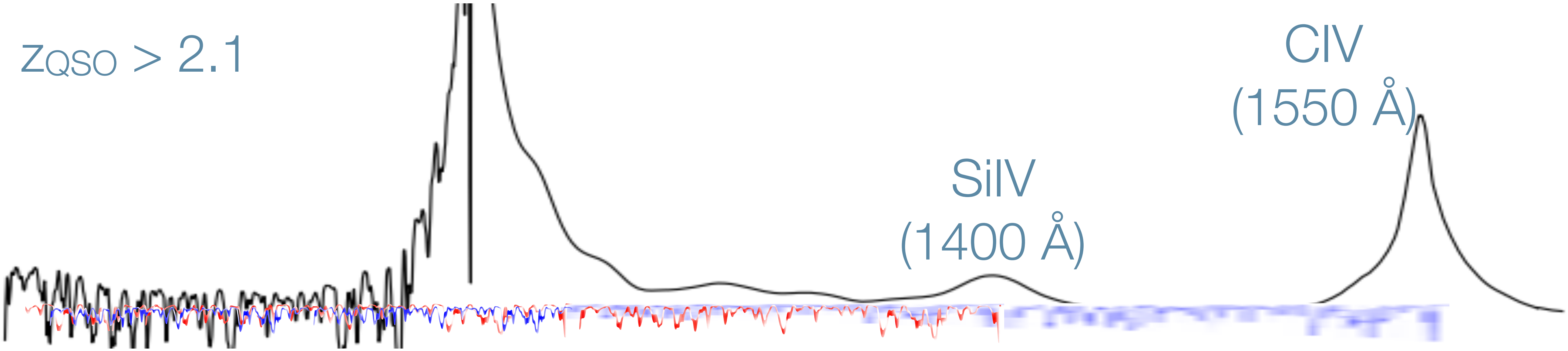
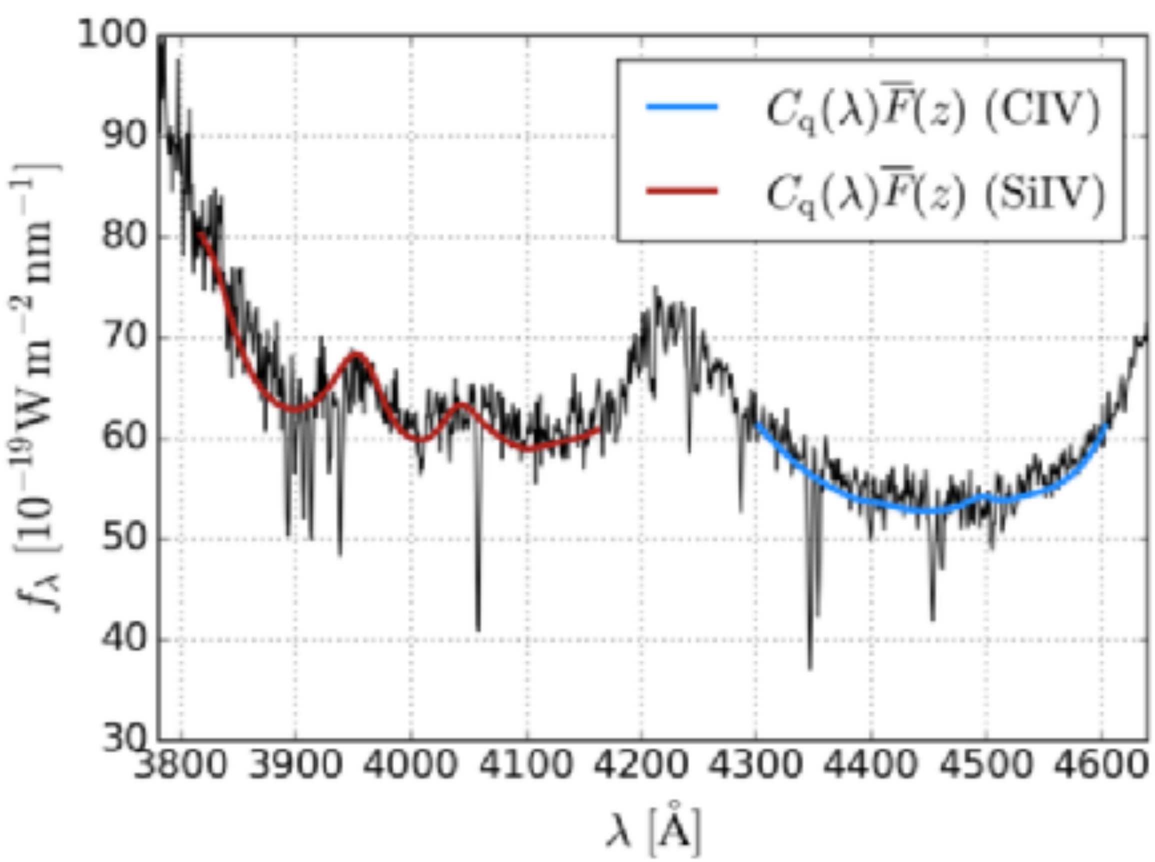
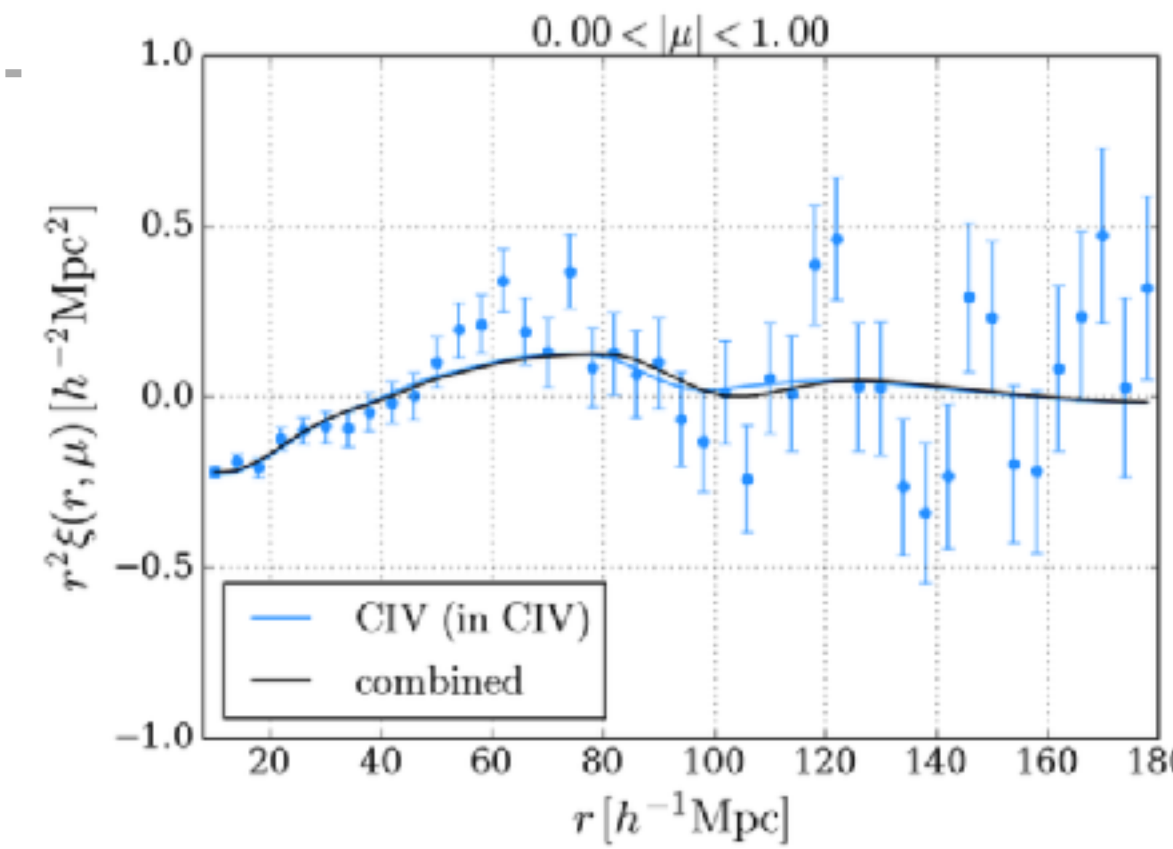






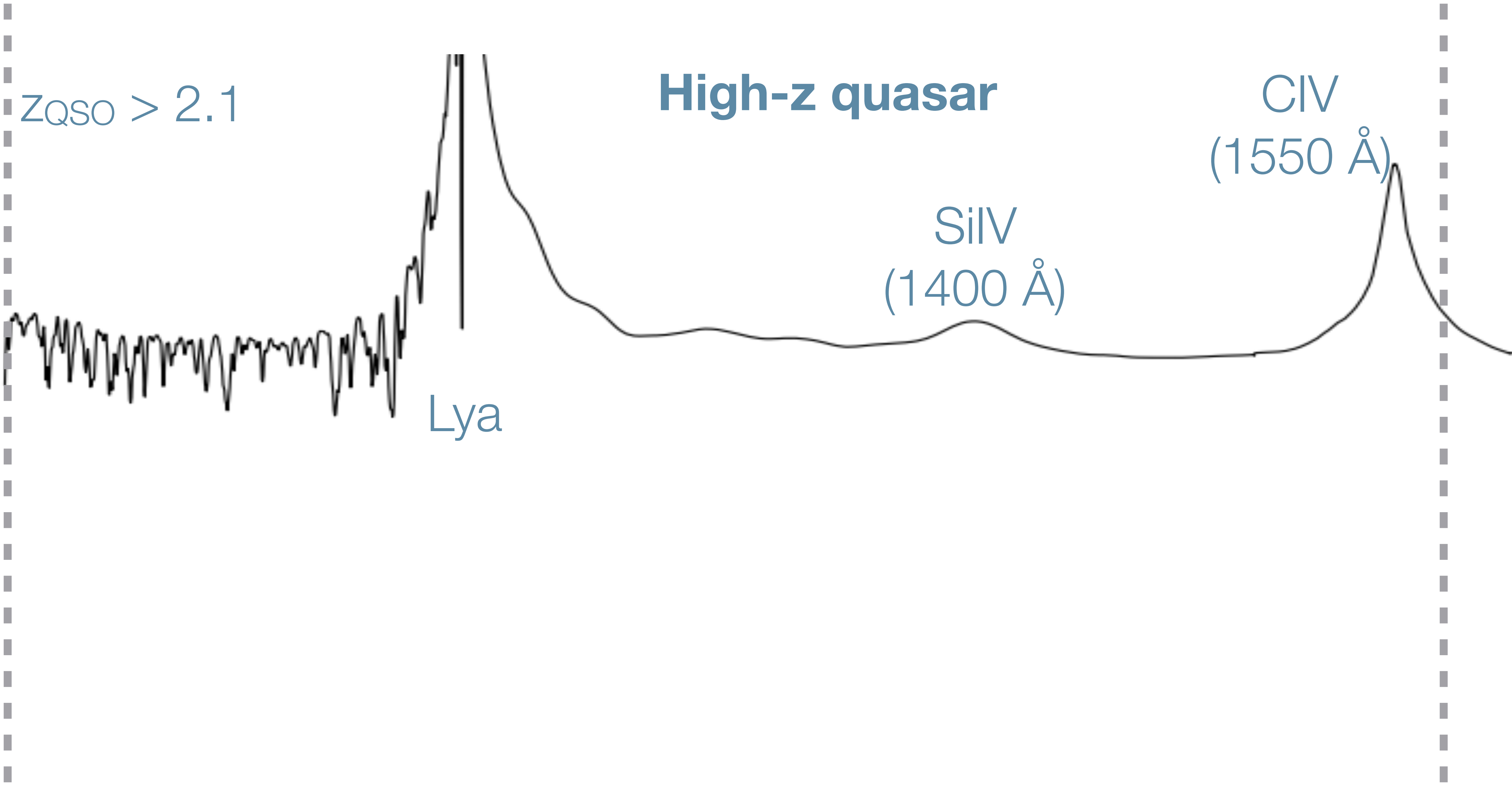
$$b_{\mathrm{CIV}}(z_{\mathrm{eff}} = 2.00) = -0.0144 \pm 0.0010$$

Blomqvist et al. 2018

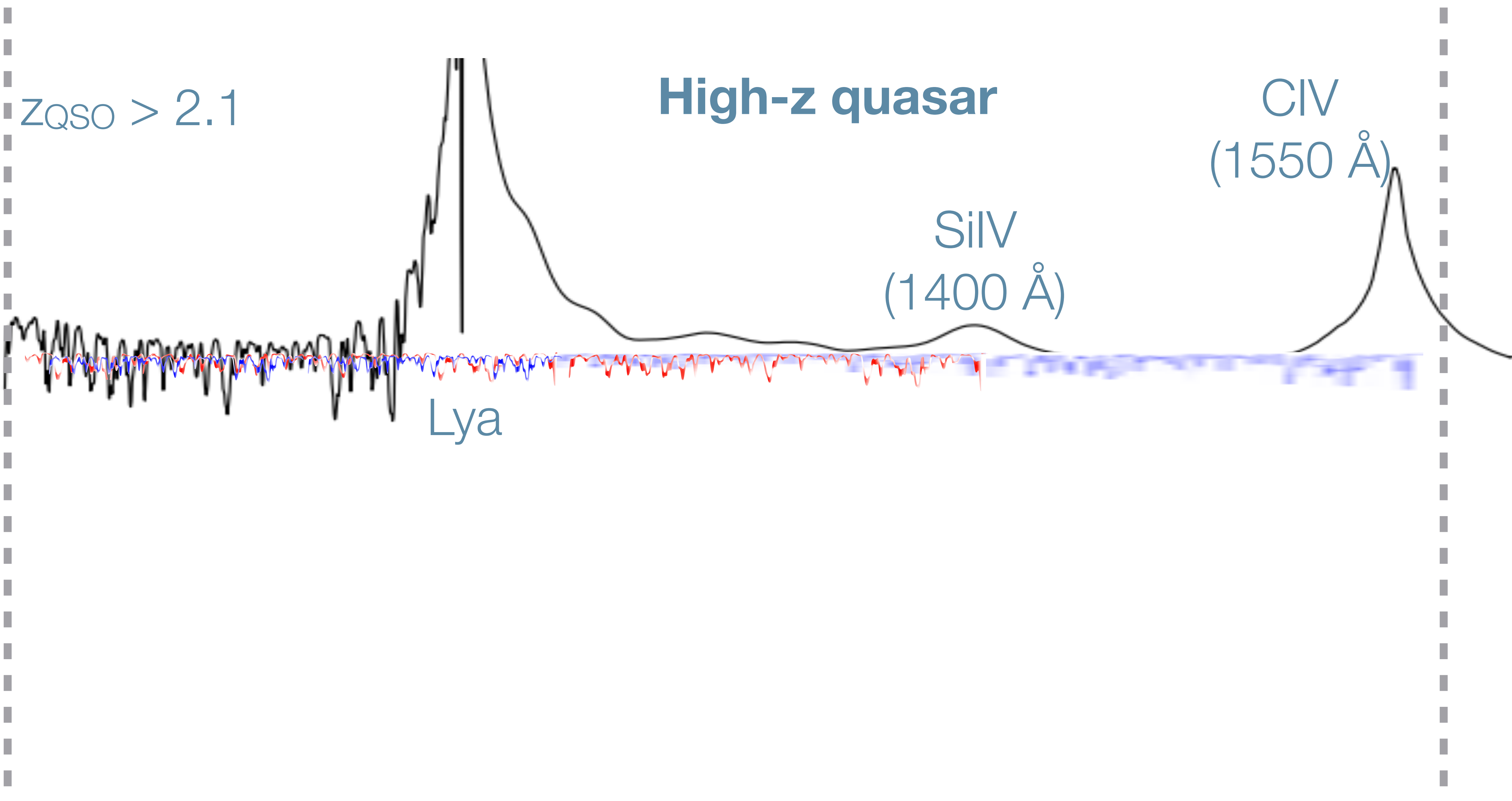
How about metals in the Lyman-alpha forest?

Metals in the Lyman-alpha forest

Metals in the Lyman-alpha forest



Metals in the Lyman-alpha forest



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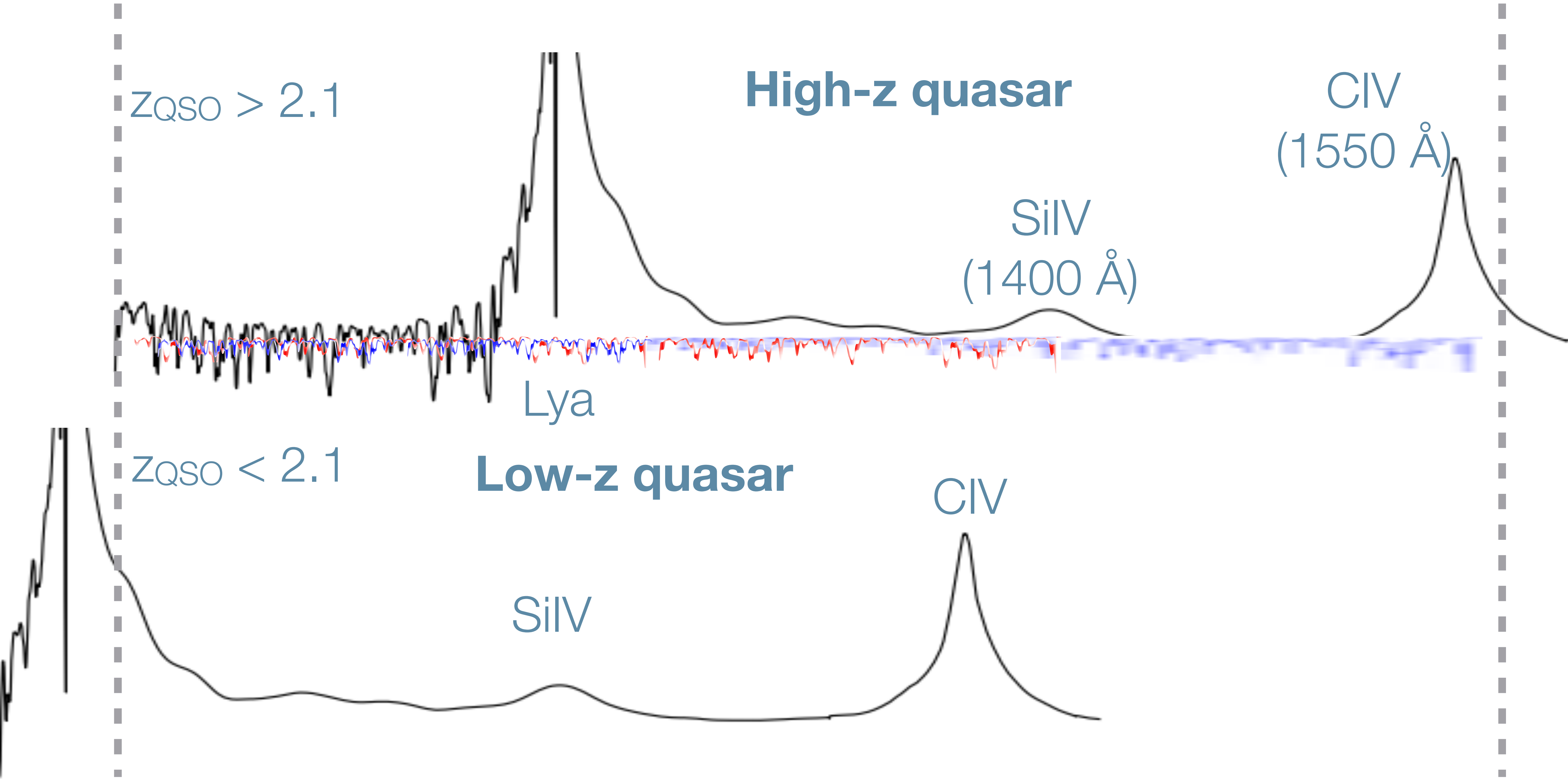

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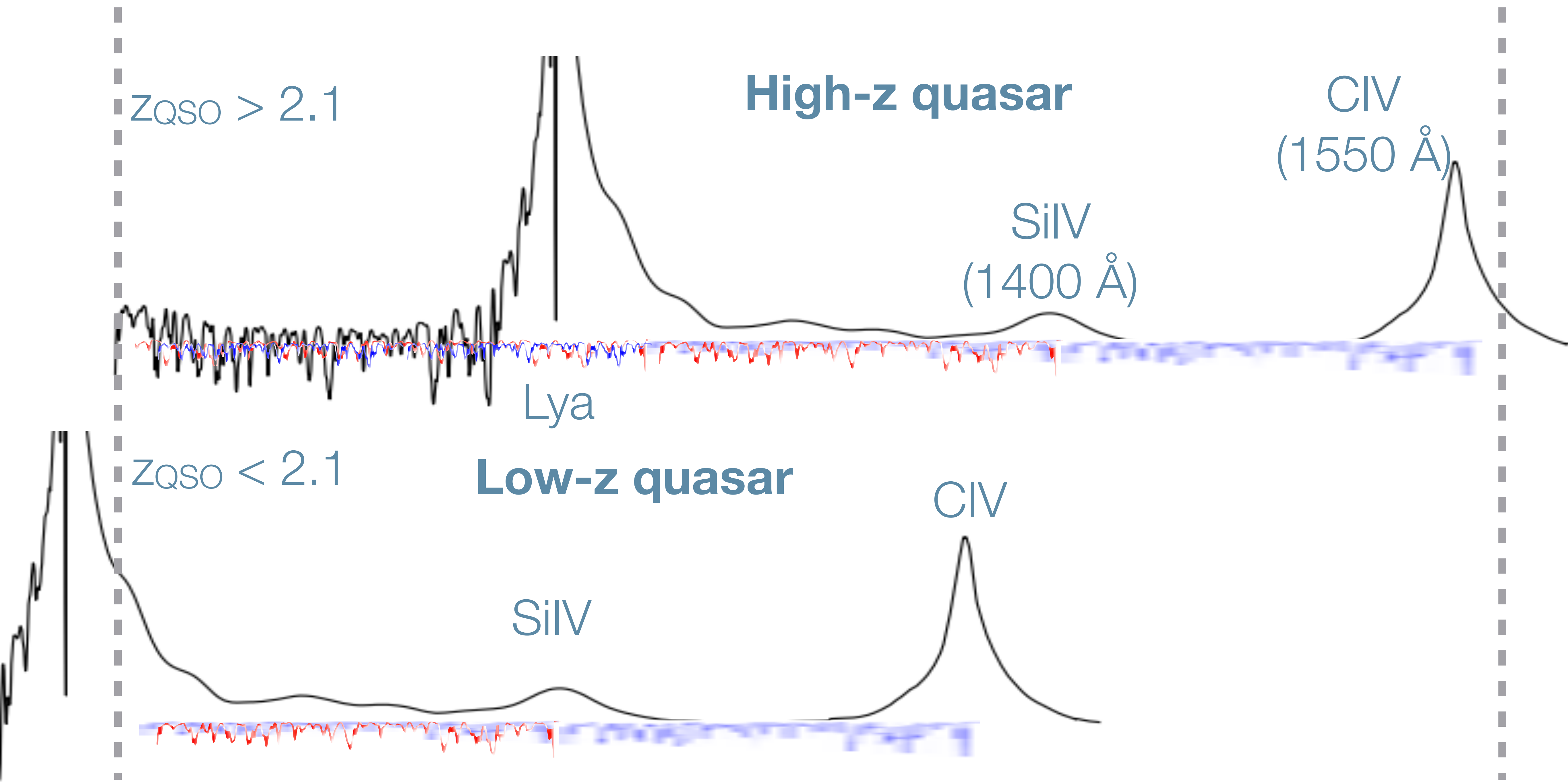

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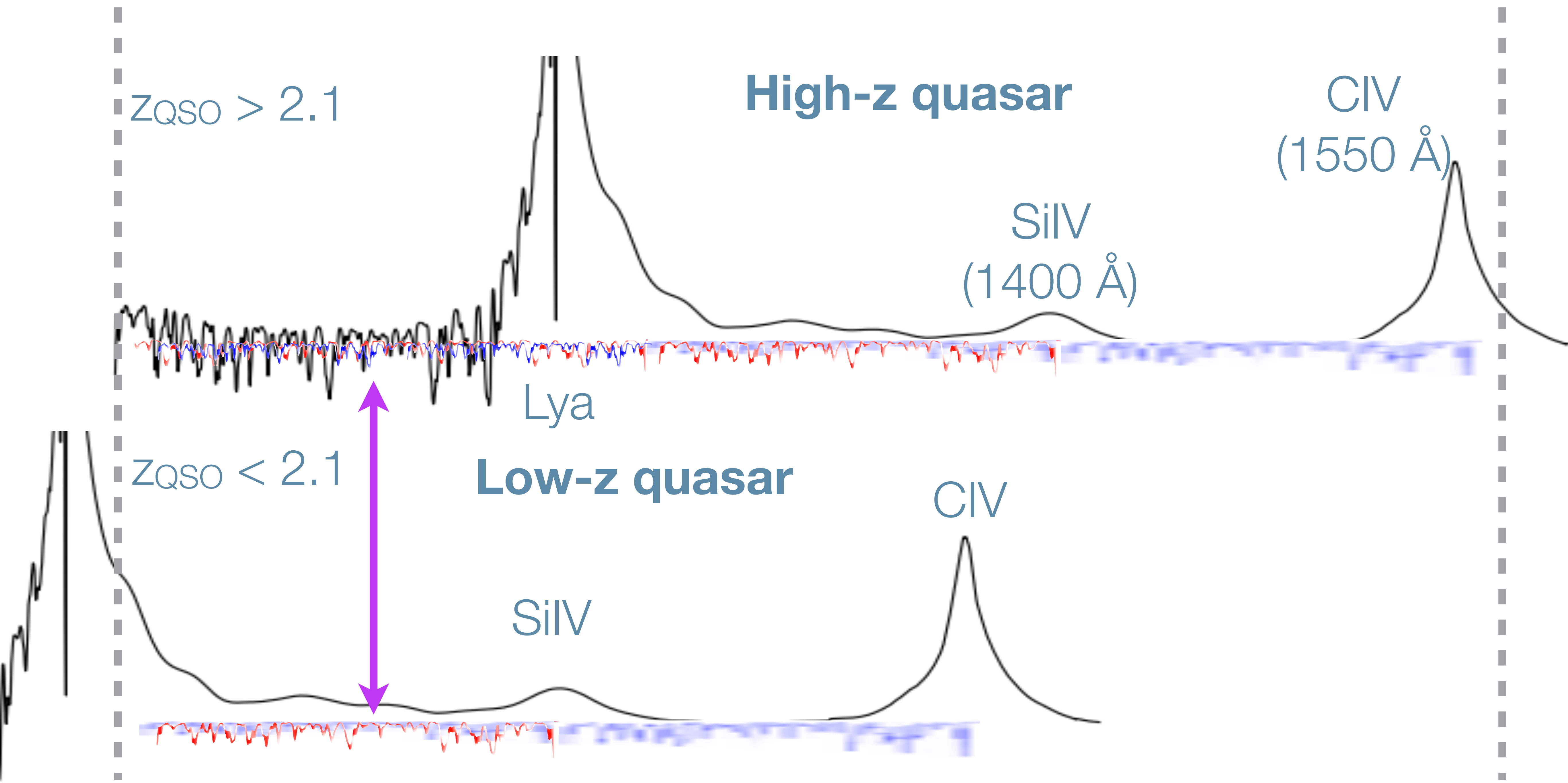
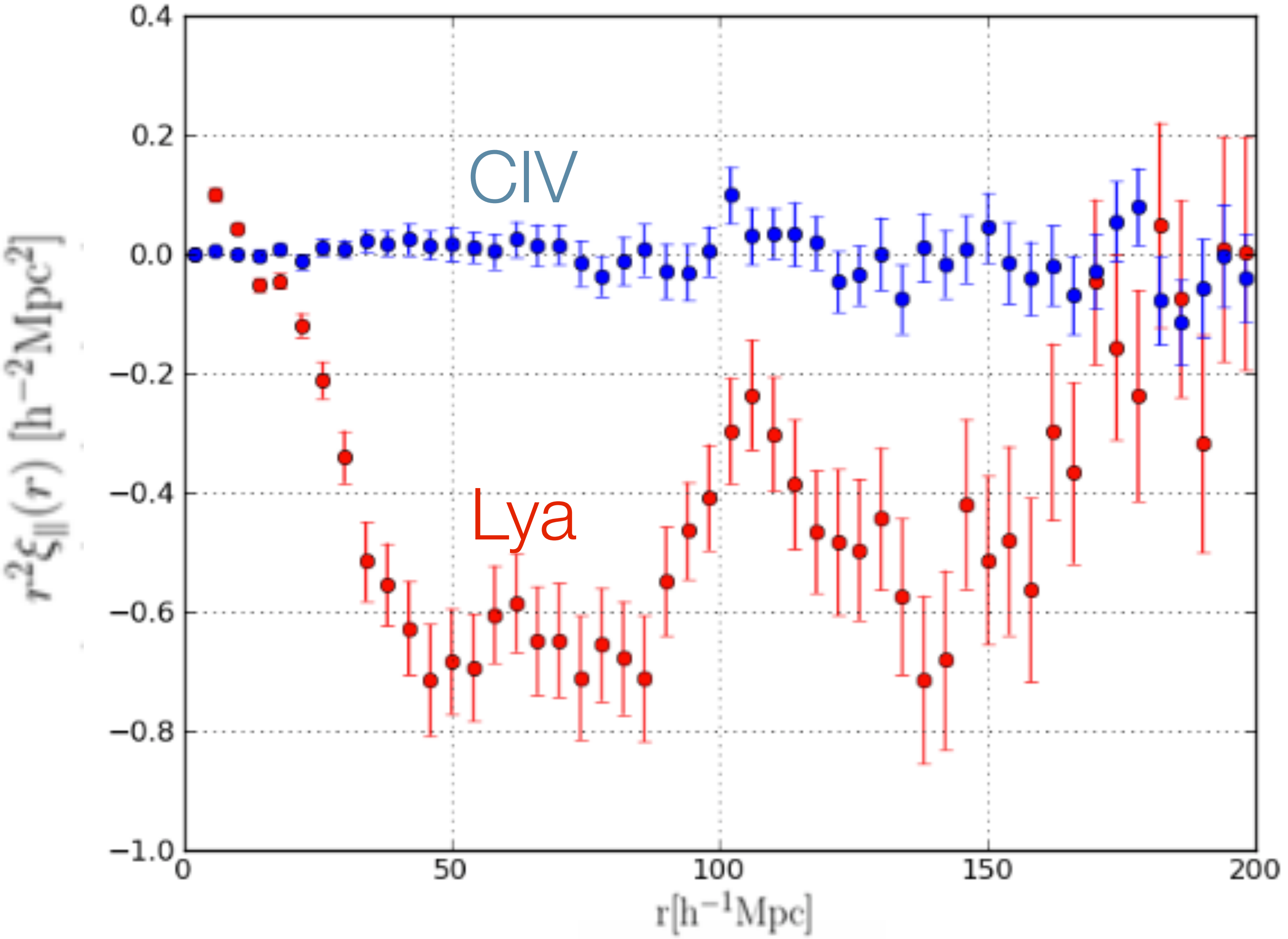


Metals in the Lyman-alpha forest

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

Metals in the Lyman-alpha forest

Radial 3D correlations



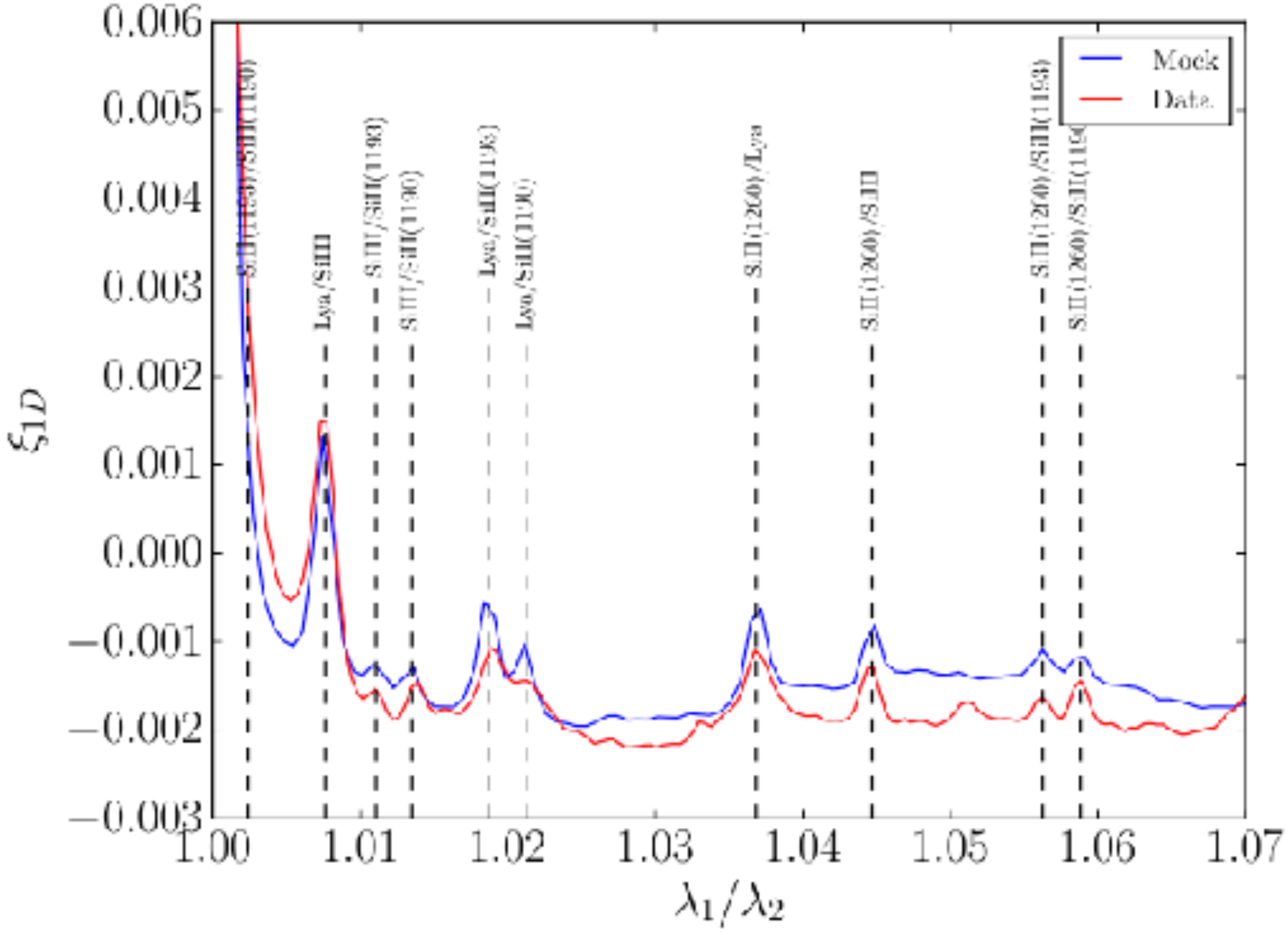
Impact of CIV in the Lyman-alpha forest clustering is negligible

That’s not all with metals…

Metals in the Lyman-alpha forest

Metals in the Lyman-alpha forest

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



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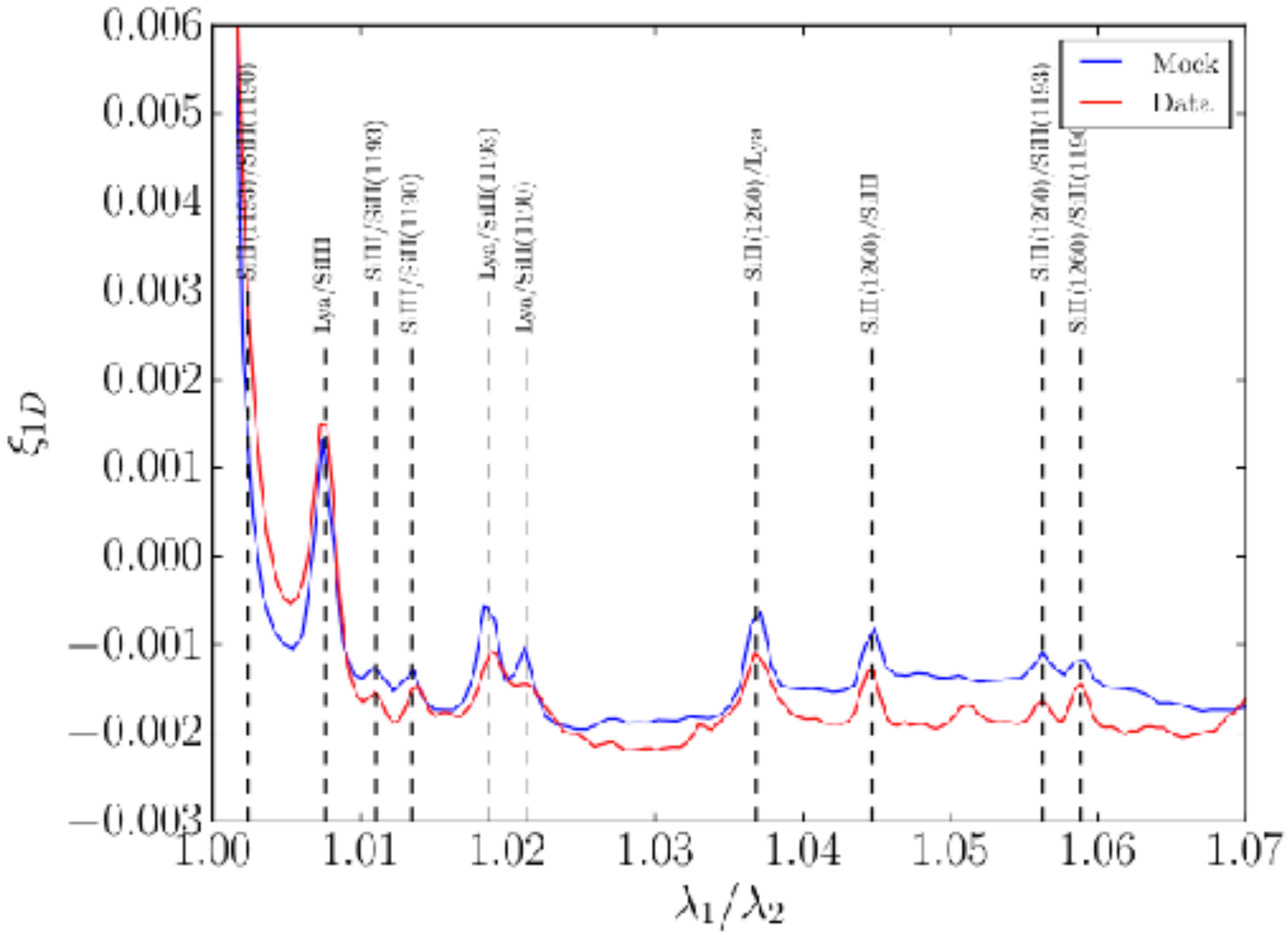
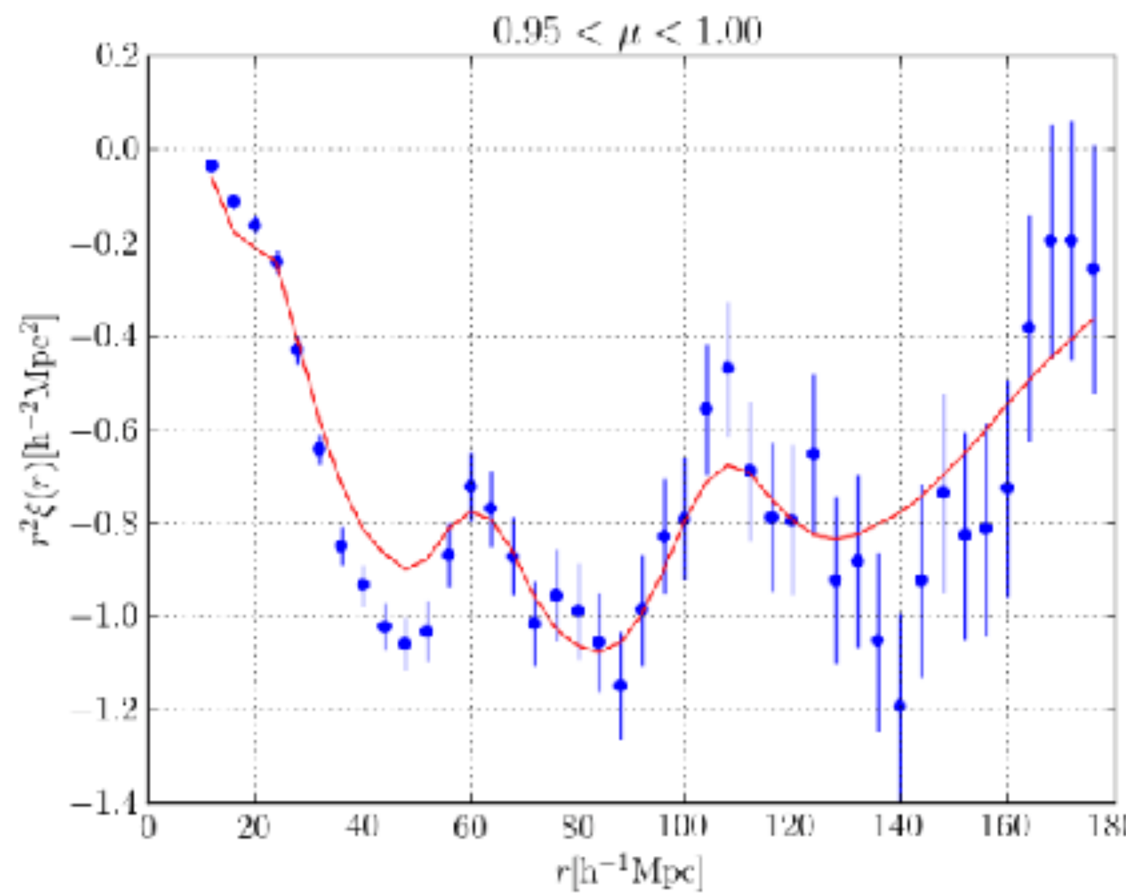


Different line-of-sight (or 3D) radial correlations



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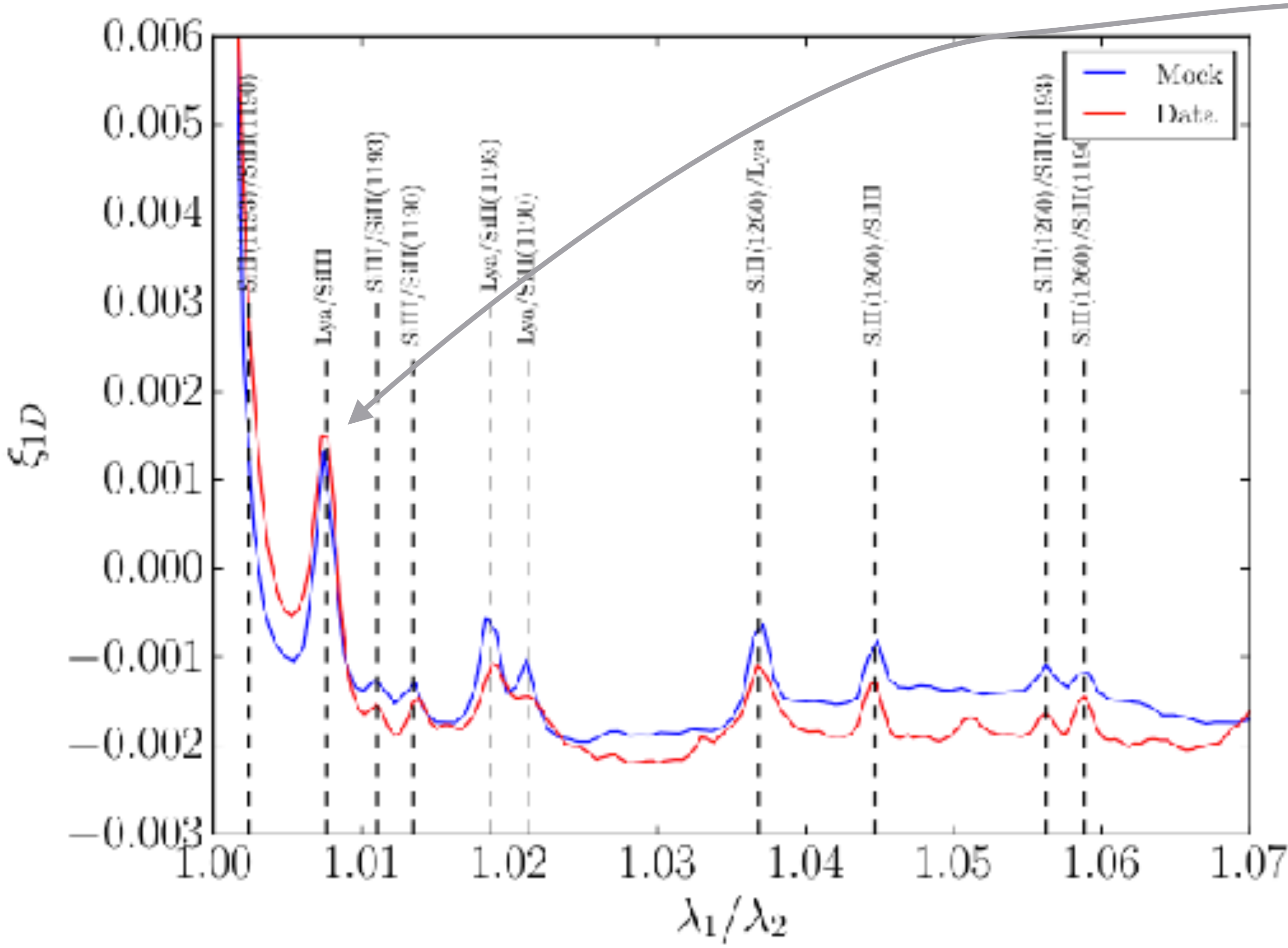

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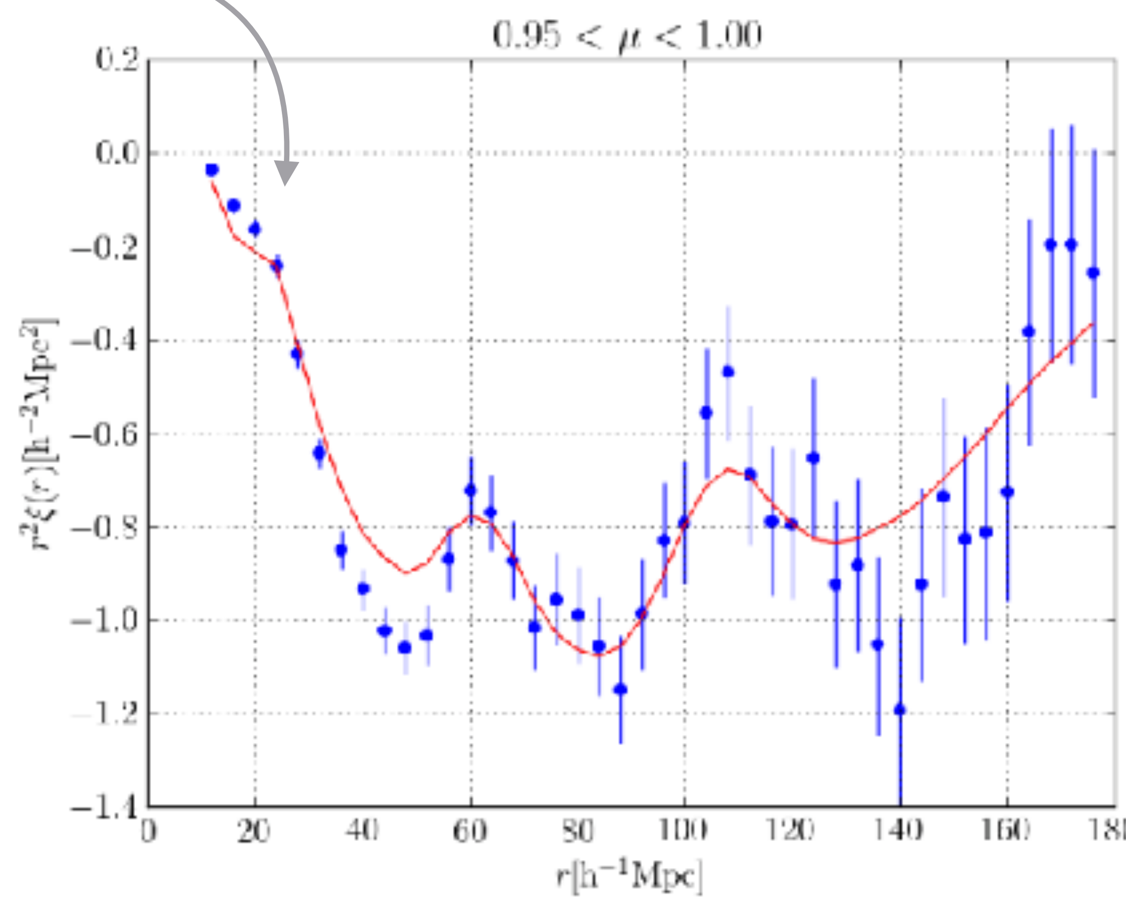

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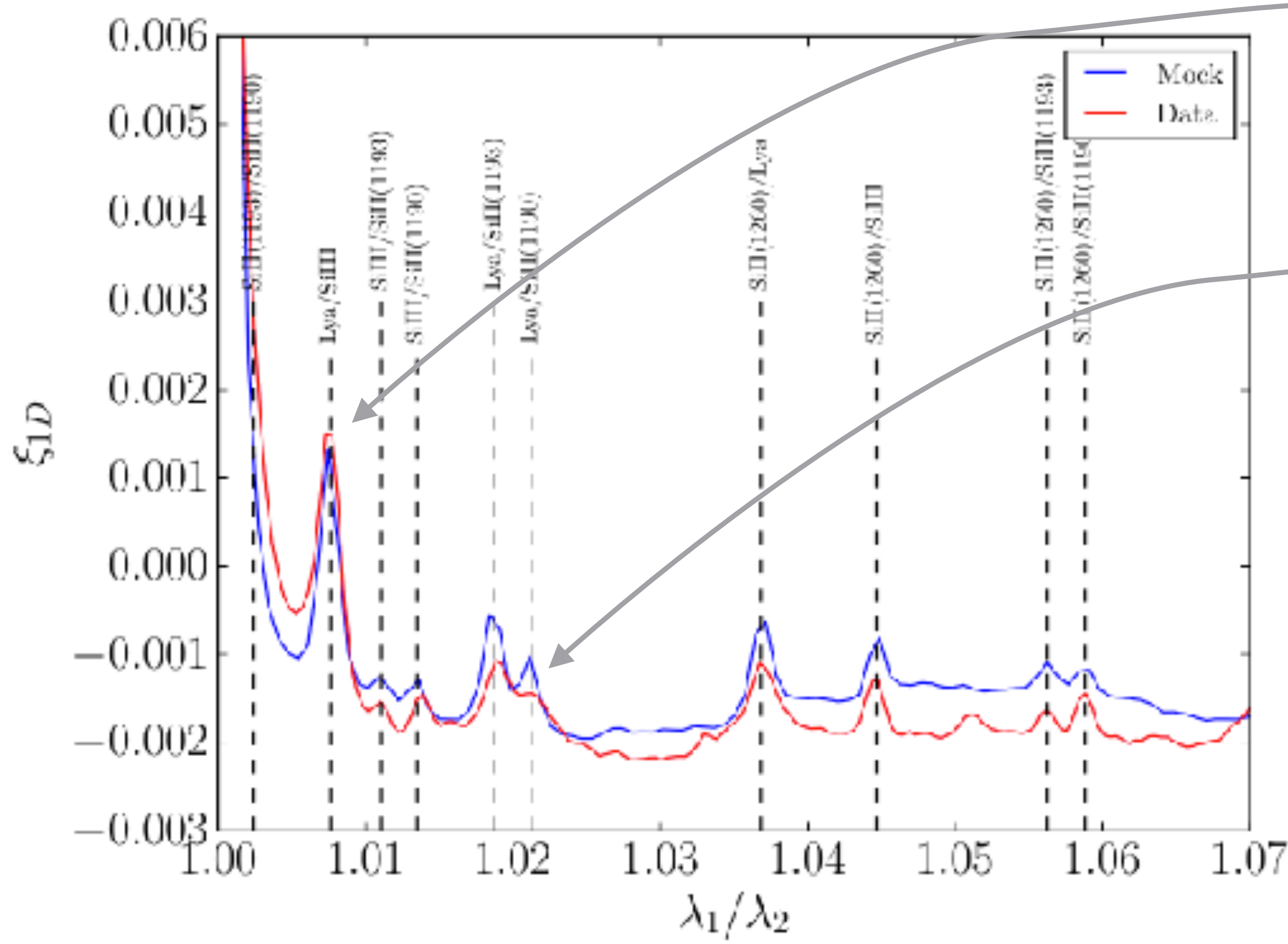

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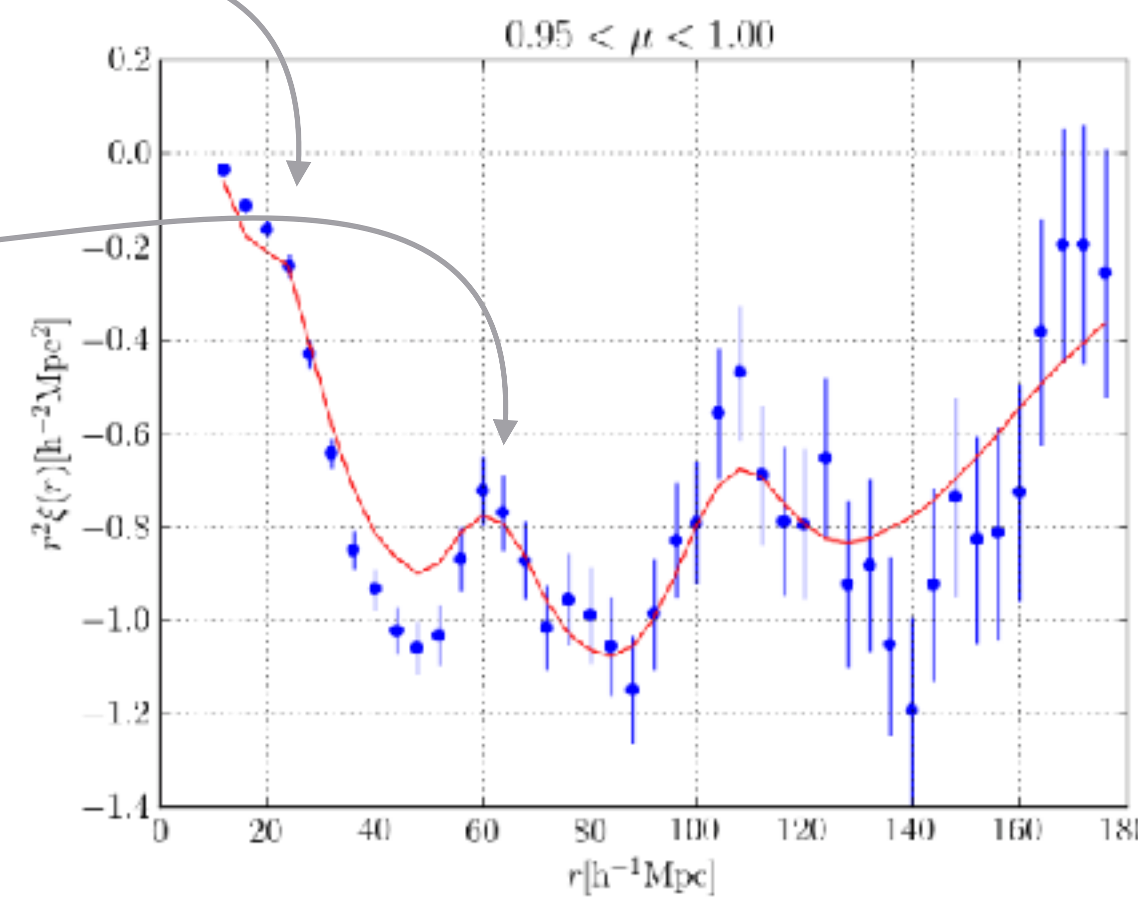

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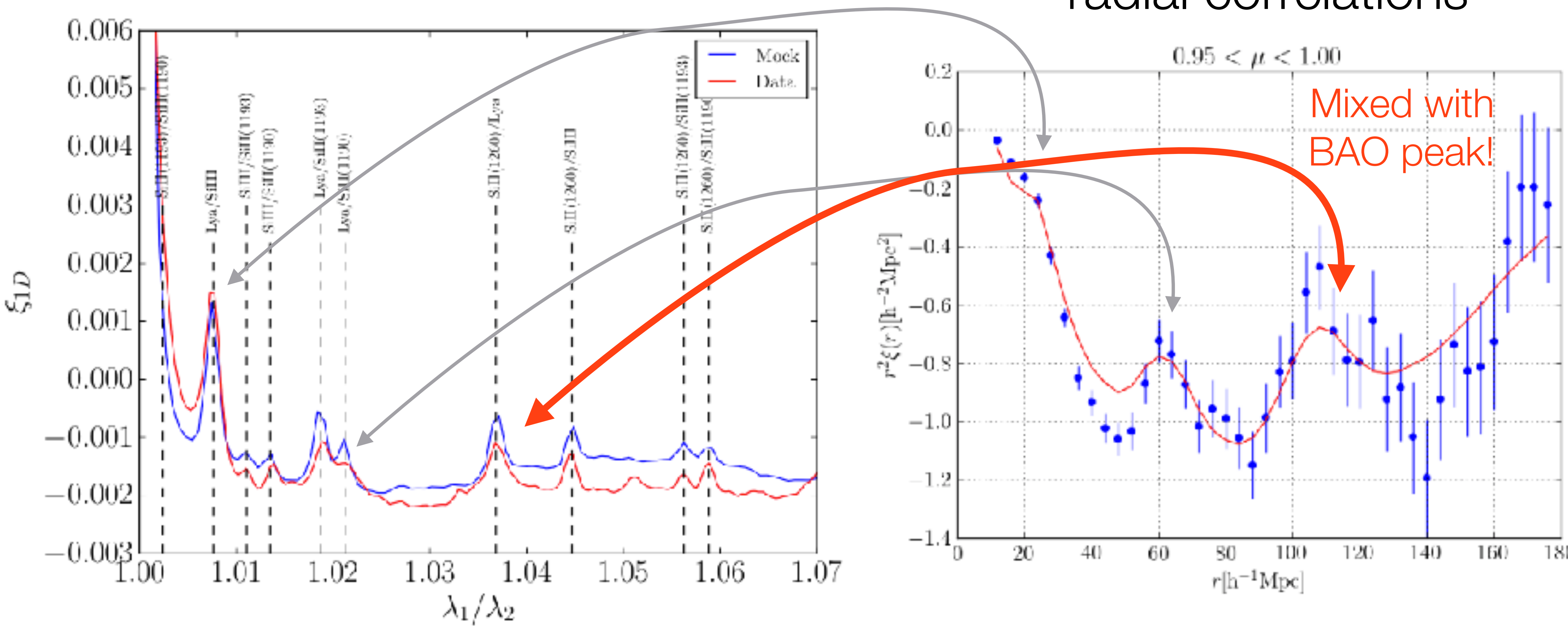

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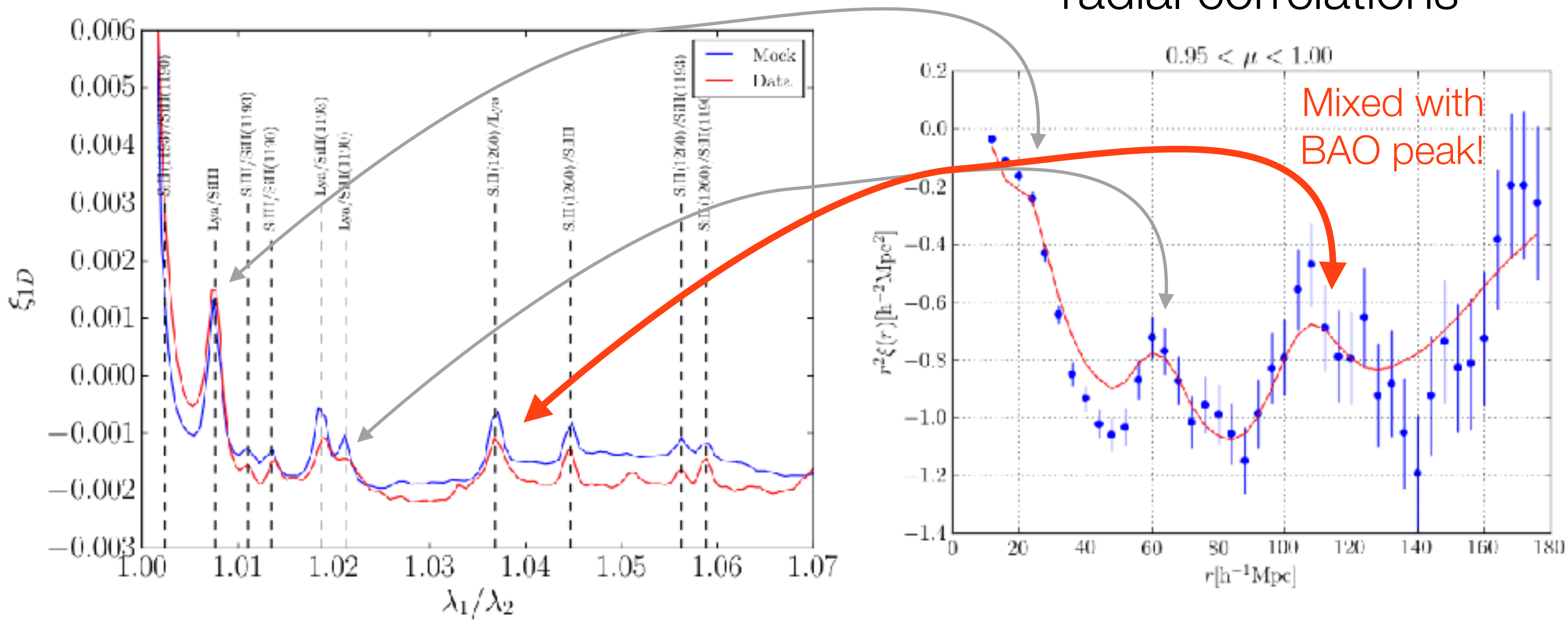

We marginalize over metal correlations (2 parameters per transition)

Metals in the Lyman-alpha forest

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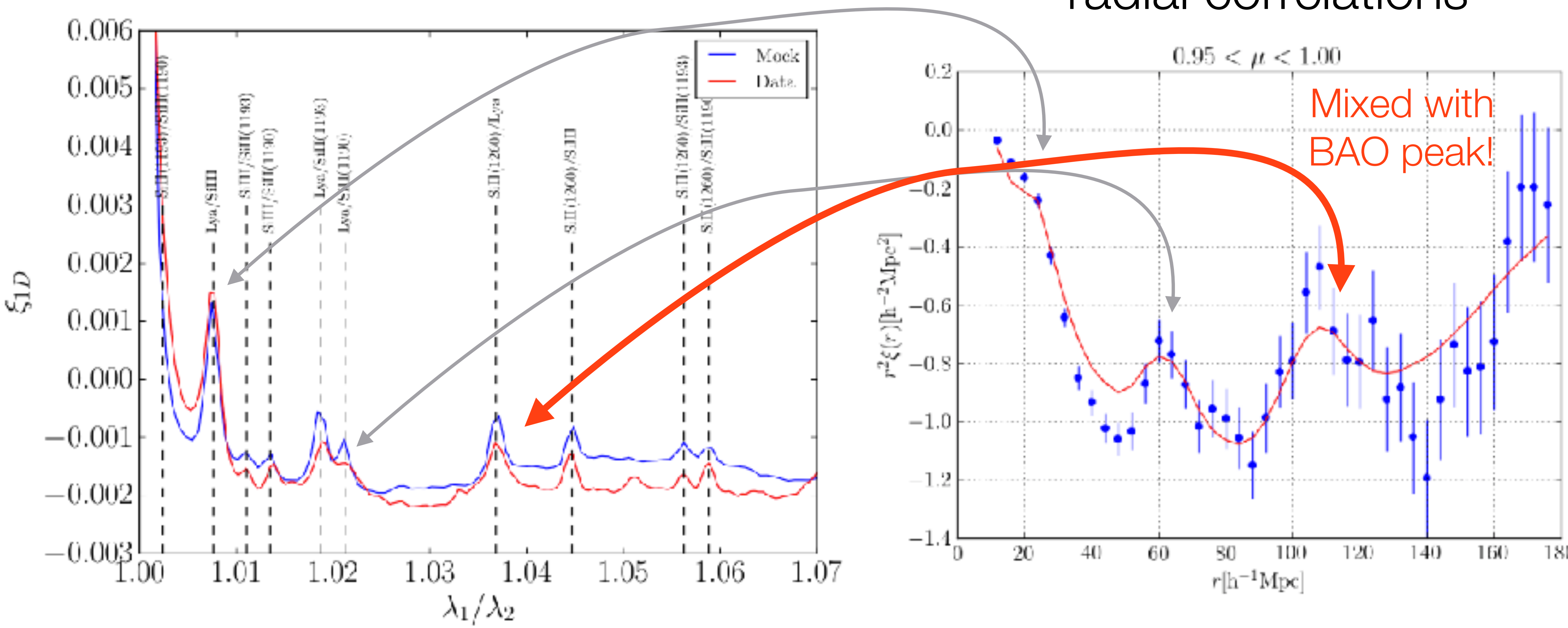
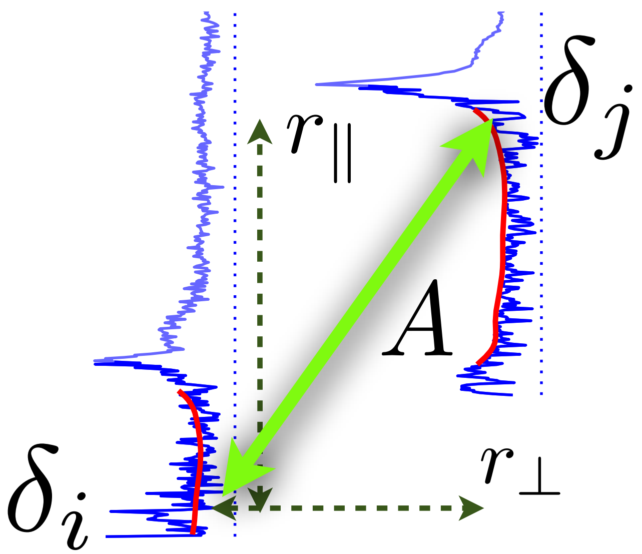
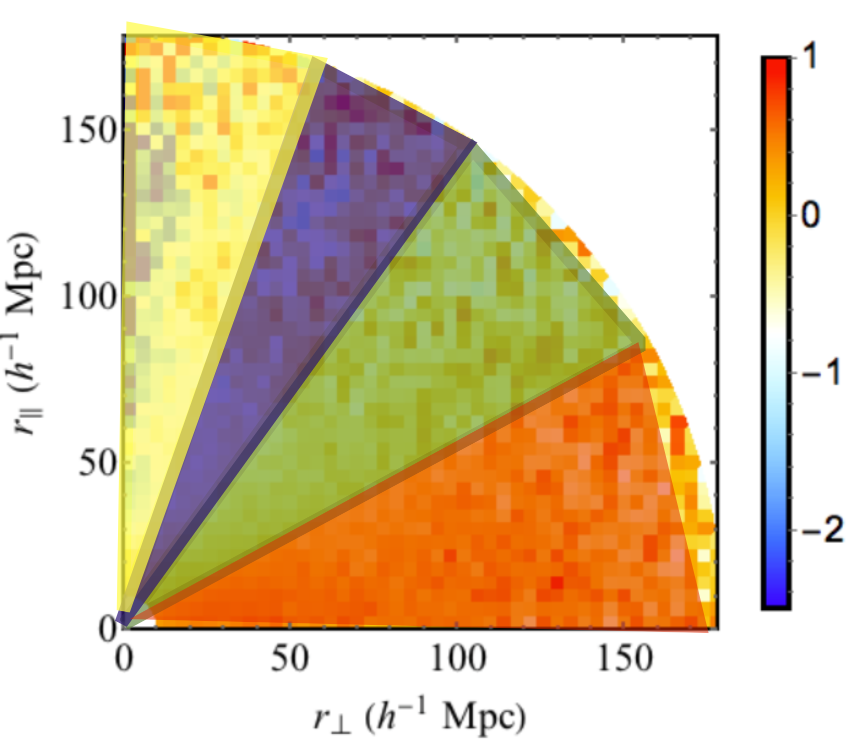


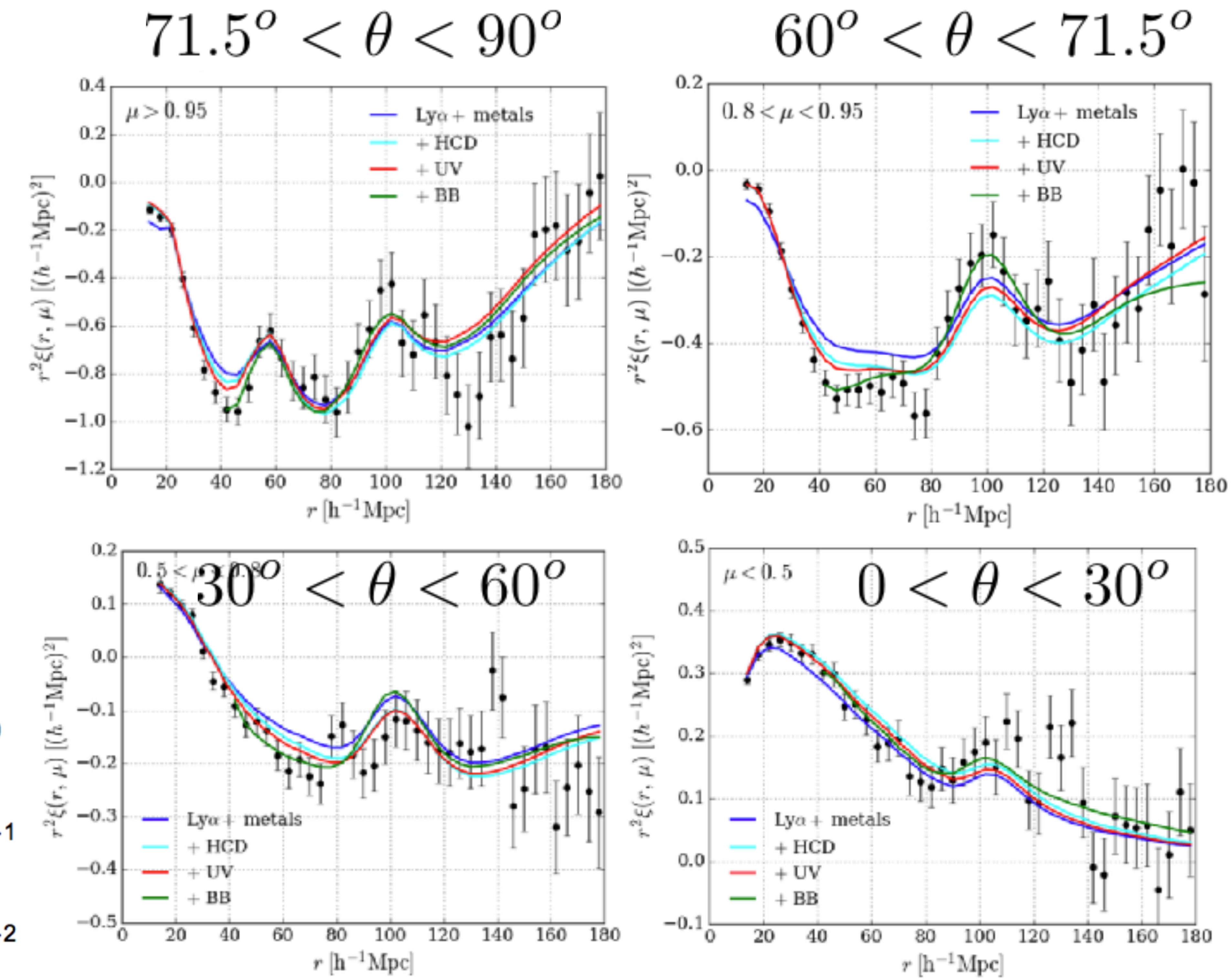
We marginalize over metal correlations (2 parameters per transition)

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

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

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

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

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Photo-ionization Equilibrium

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$$\Downarrow$$

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

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

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

UV background **fluctuations**

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UV background **fluctuations**

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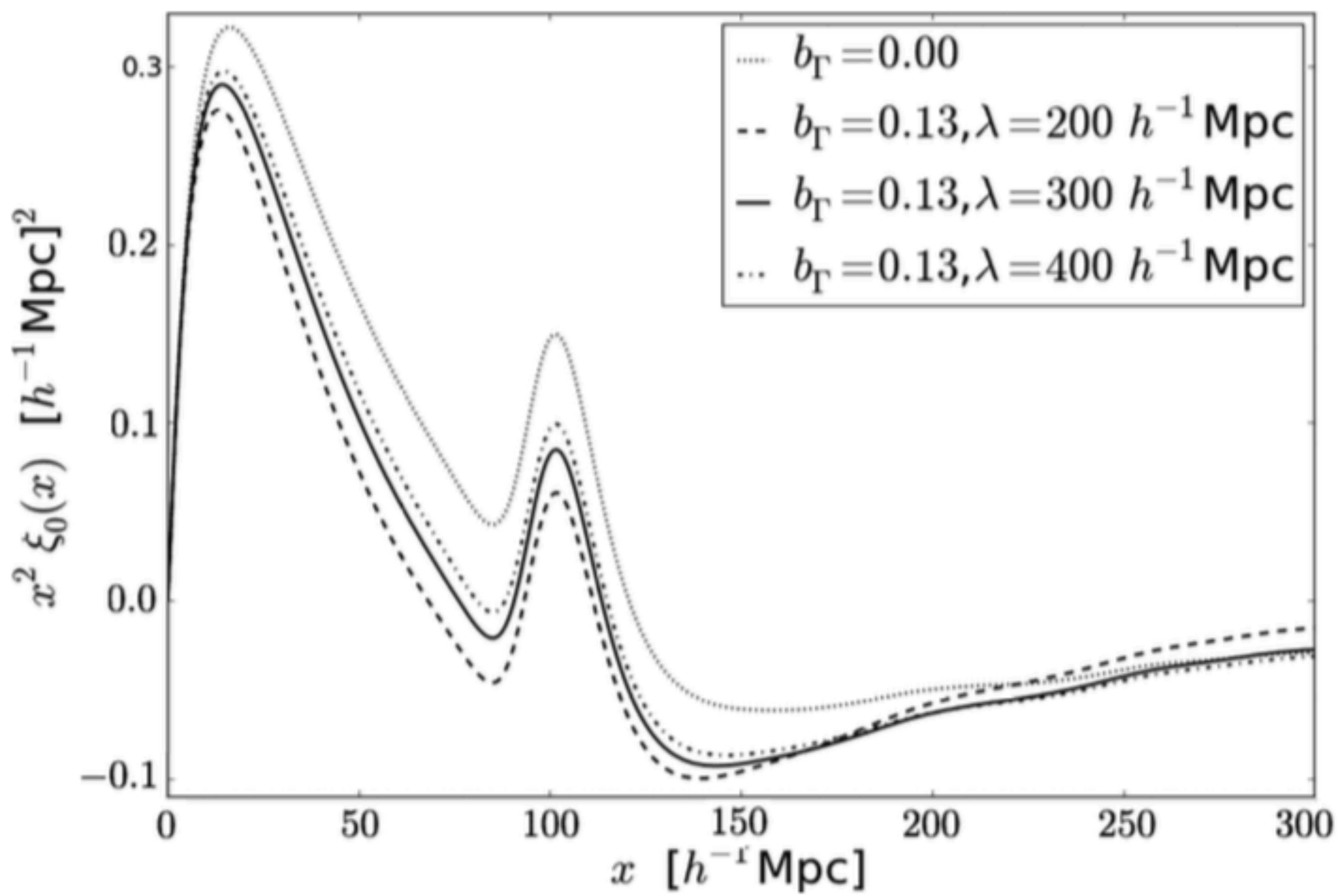


List of tests on systematic errors

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

Mock catalogs for BAO with Lyman-alpha forests

Hydro-sims are not feasible:
we need **hundreds** of realizations of
large volumes while resolving **small**-scales

We use log-normal mock forests generated though

$$P_F(k,\mu) = P_0^2(1+\beta\mu^2)^2 P_{\rm lin}(k) D(k,\mu)$$

(Font-Ribera et al. 2012, Bautista et al. 2015)

Run quick dark-matter only N-body and "paint" forests using

$$T = T_0 \left(\frac{\rho_b}{\bar{\rho}_b}\right)^{\gamma} \qquad X \approx \frac{\alpha_{\rm rec} n_e}{\Gamma}$$

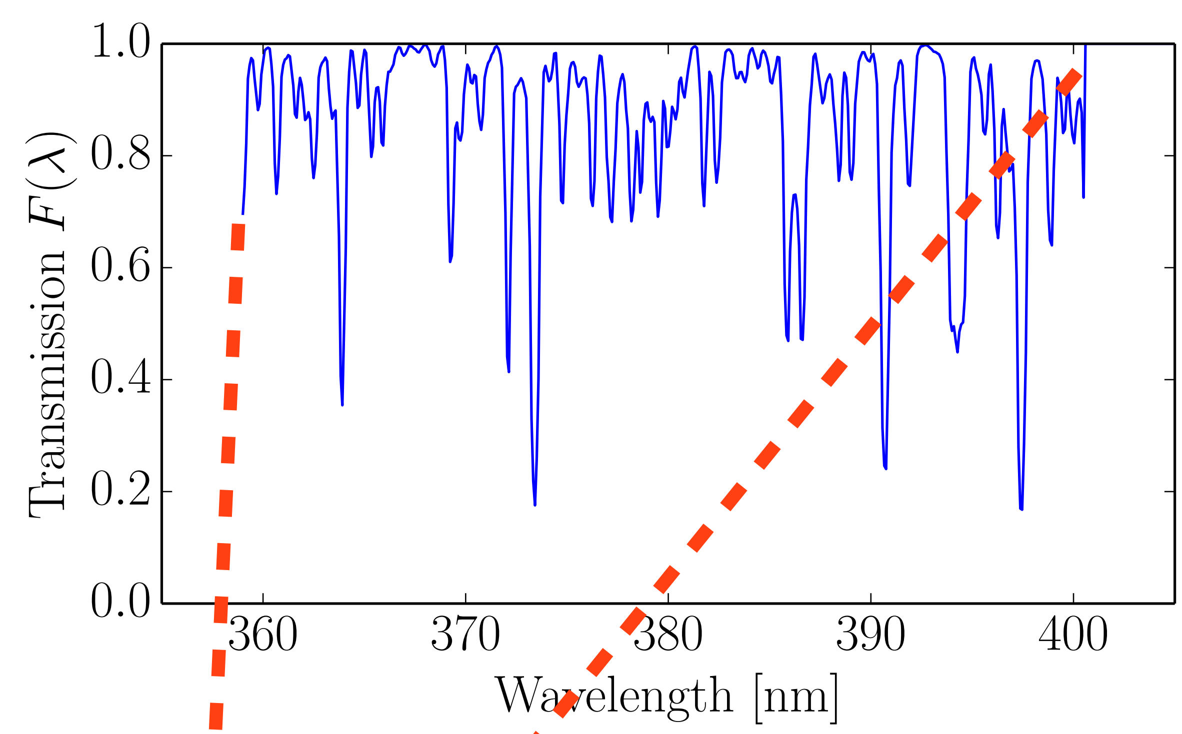
Very useful for semi-analytical simulations!

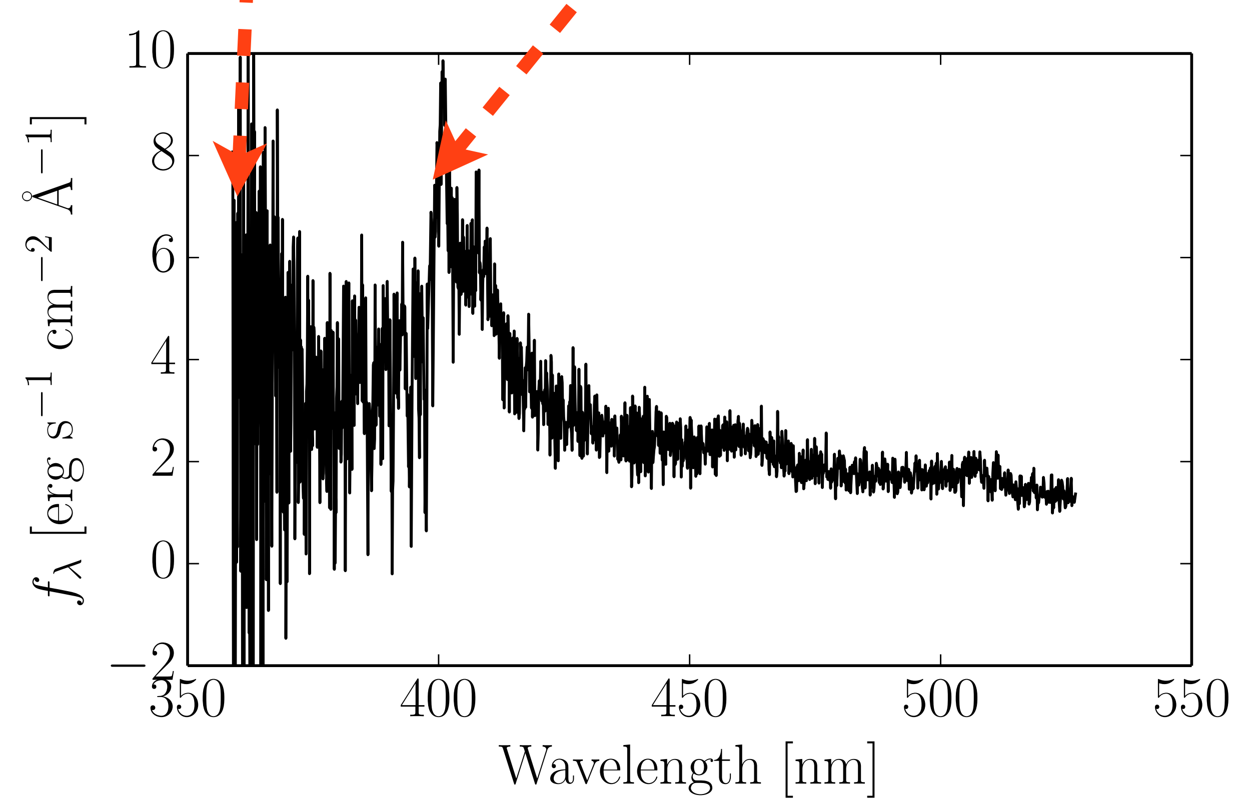
These include quasar-forest correlations (LeGoff et al. 2011)

Mock catalogs for BAO with Lyman-alpha forests

Absorption field

Create realistic quasar spectra





Create realistic quasar spectra

- Resolution, binning
- High column density systems
- Metals
- Continuum
- Noise
- Sky subtraction residuals
- Observational errors

Bautista et al. (2015)

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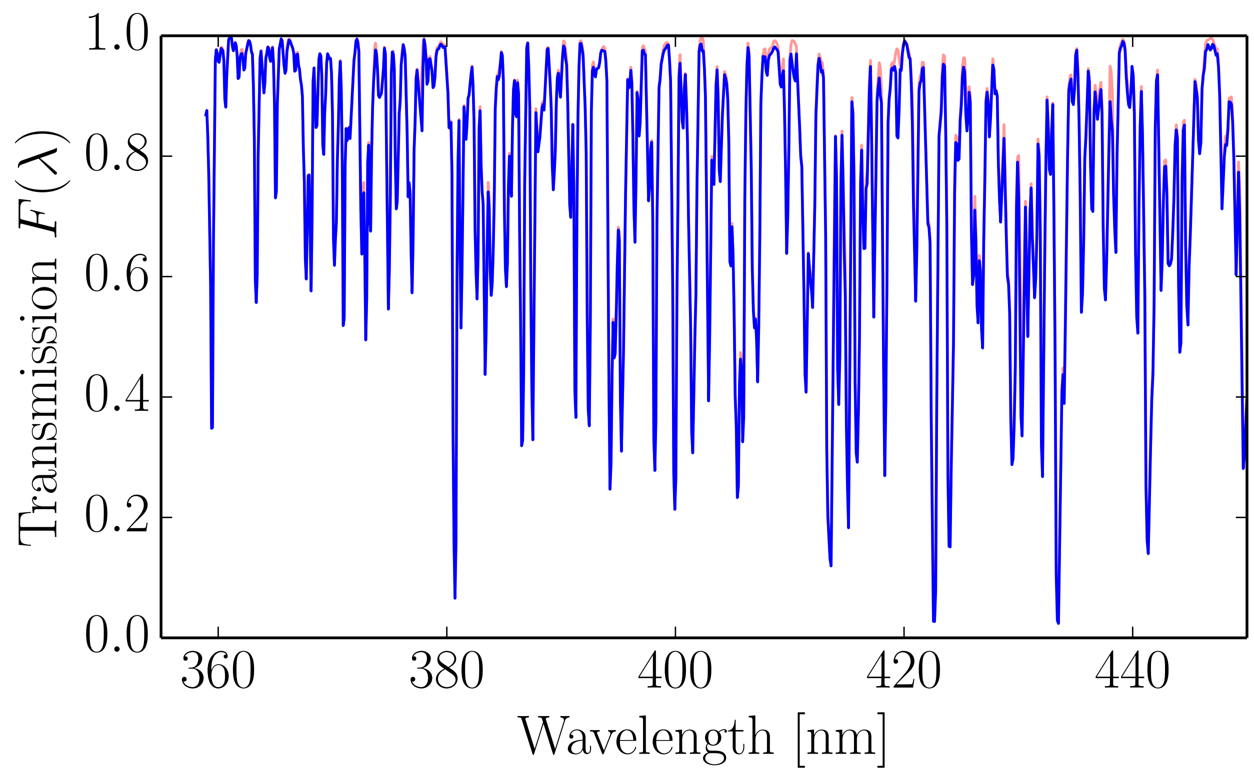

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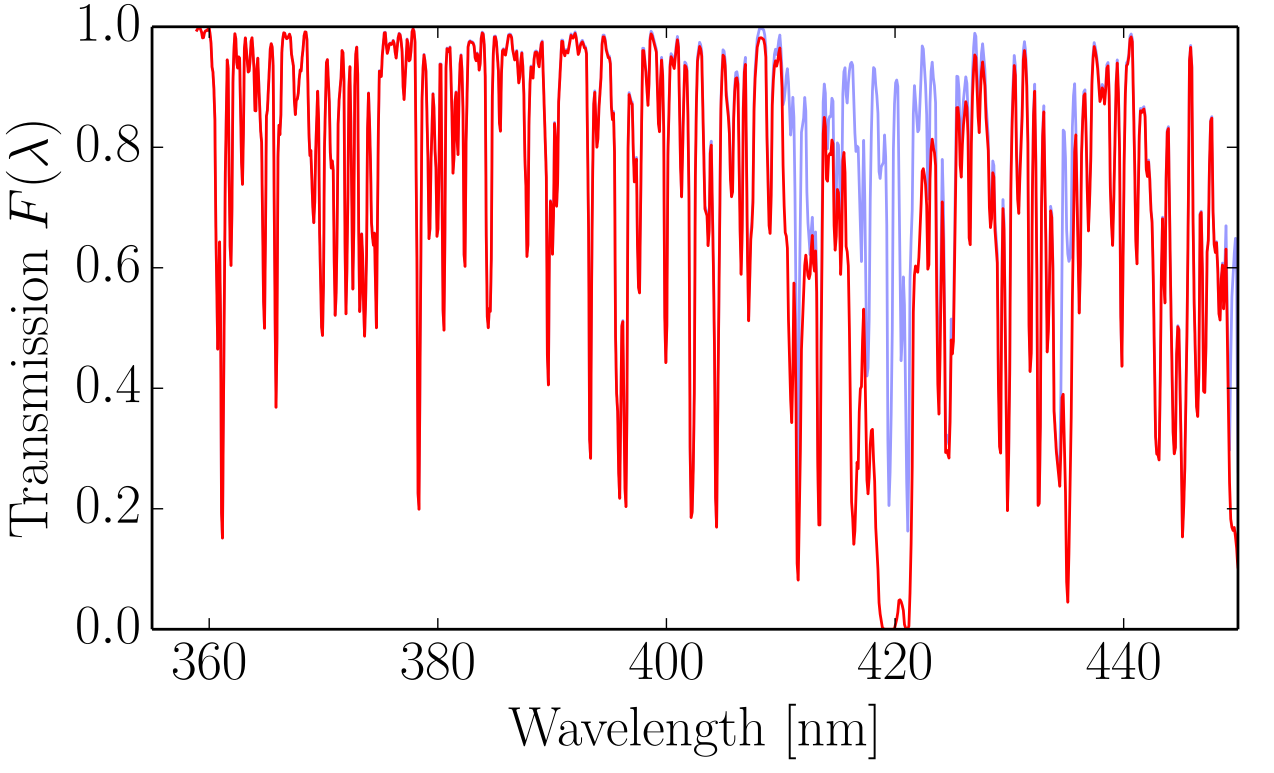

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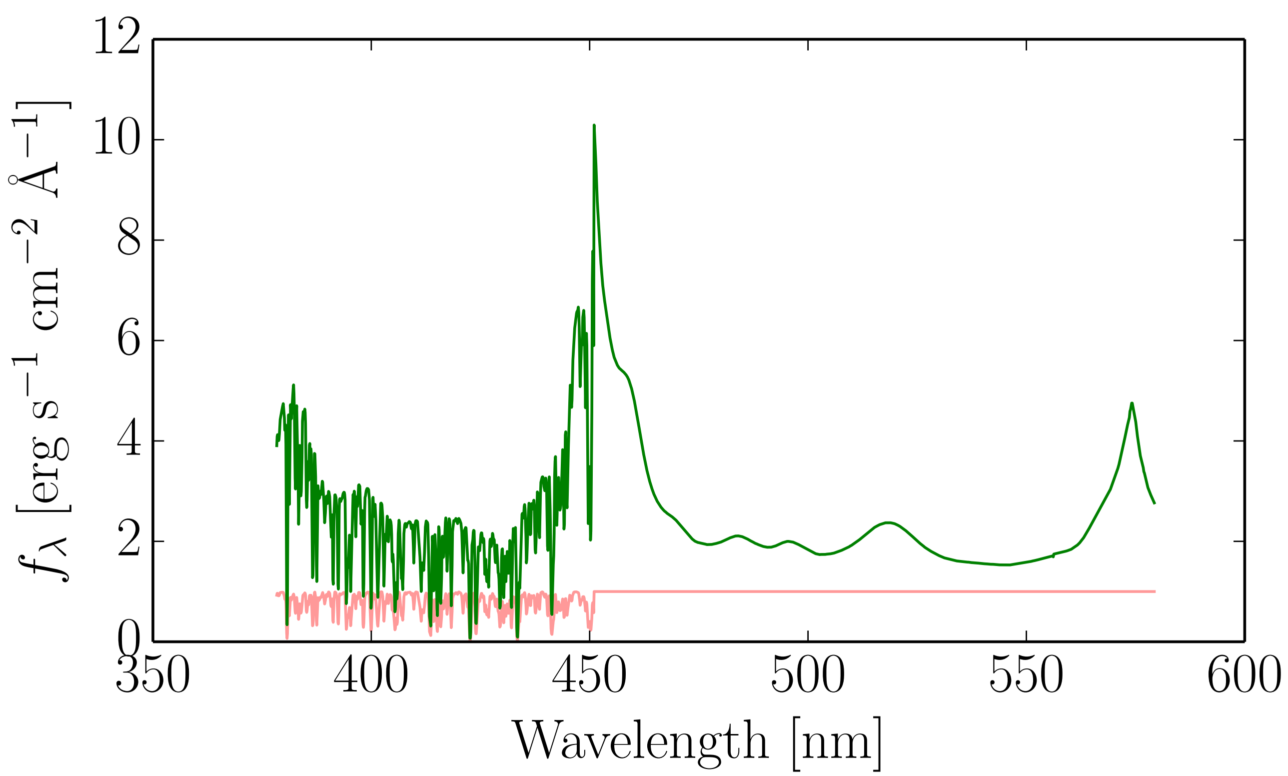

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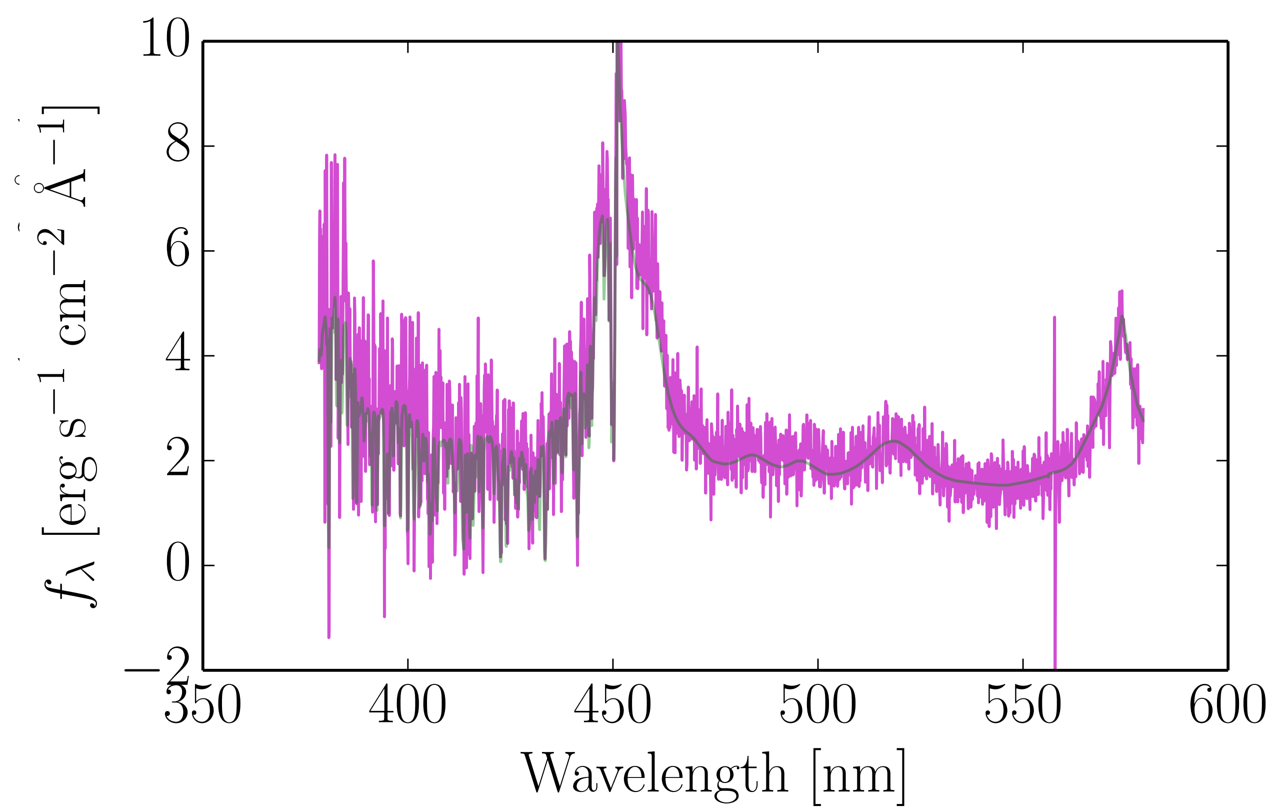


Bautista et al. (2015)

The future

Future

- DESI
- HETDEX
- PFS
- 4MOST
- Euclid
- WFIRST

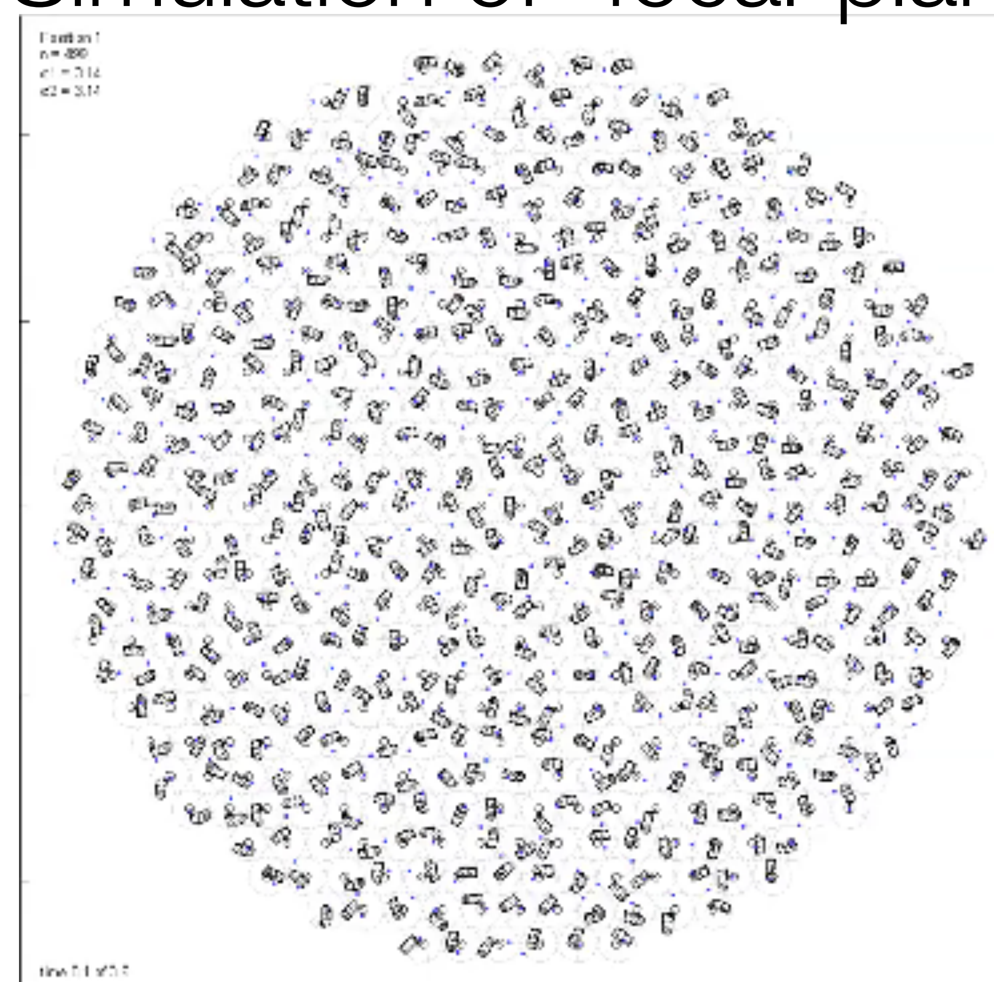
DESI

Dark Energy Spectroscopic Survey
will start operations in 2020

2.5 meters -> 4.0 meters
7500 deg^2 -> 14000 deg^2
1000 fibers -> 5000 fibers
fibers plugged by human -> fibers plugged by robot
similar final spectral S/N

Fiber positioner

Simulation of “focal-plane”



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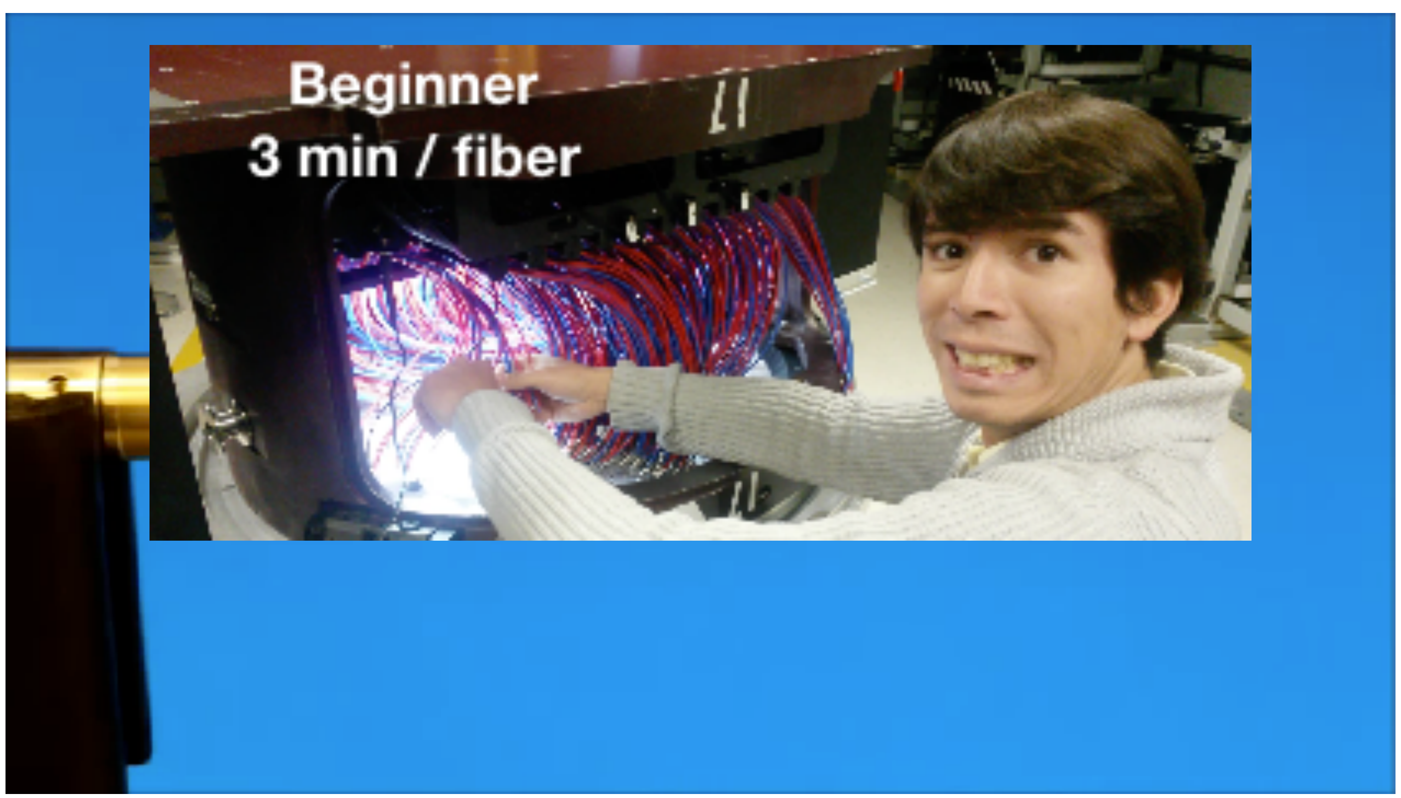

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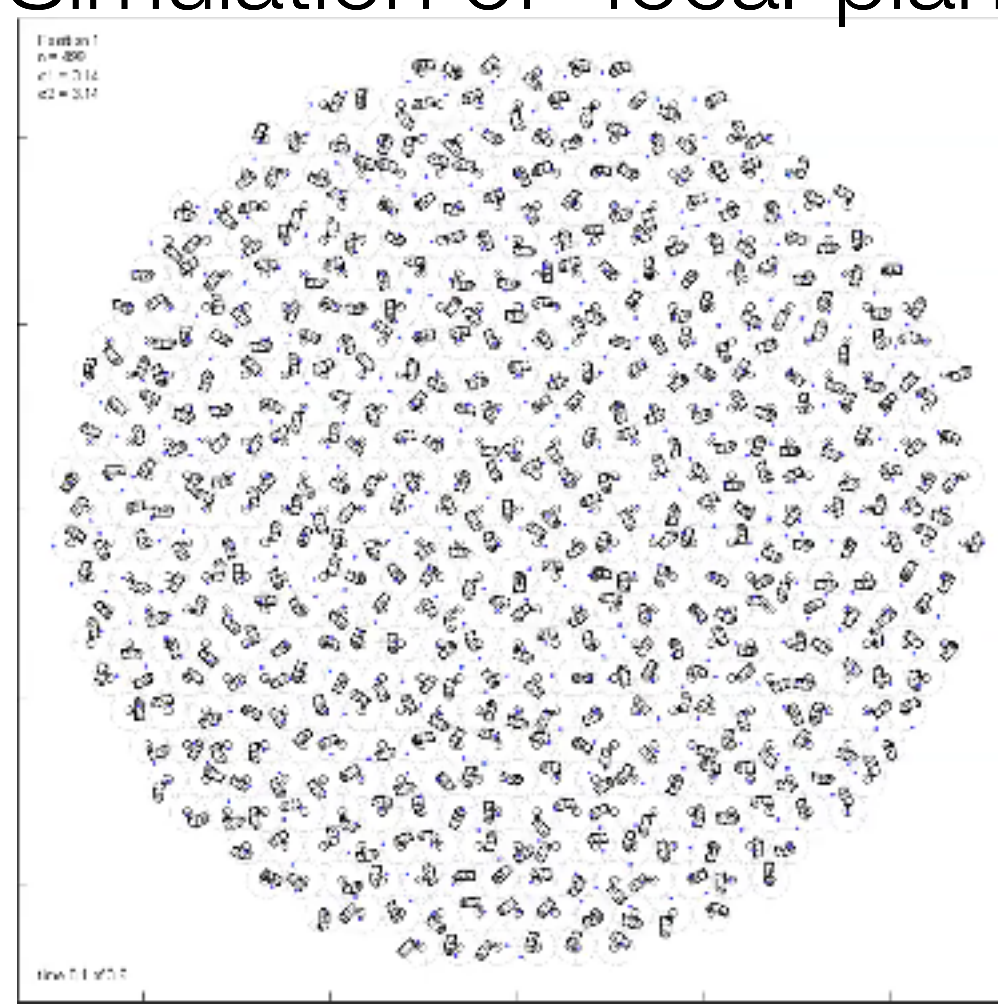

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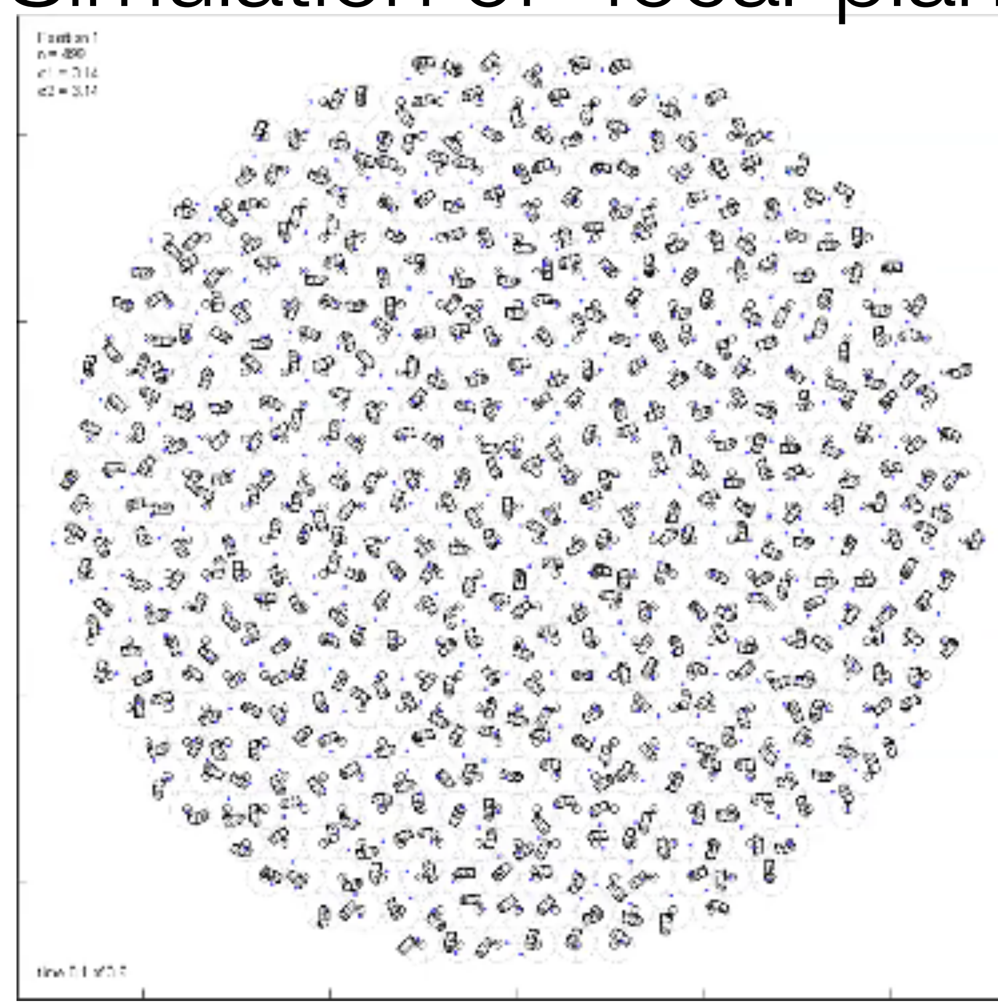

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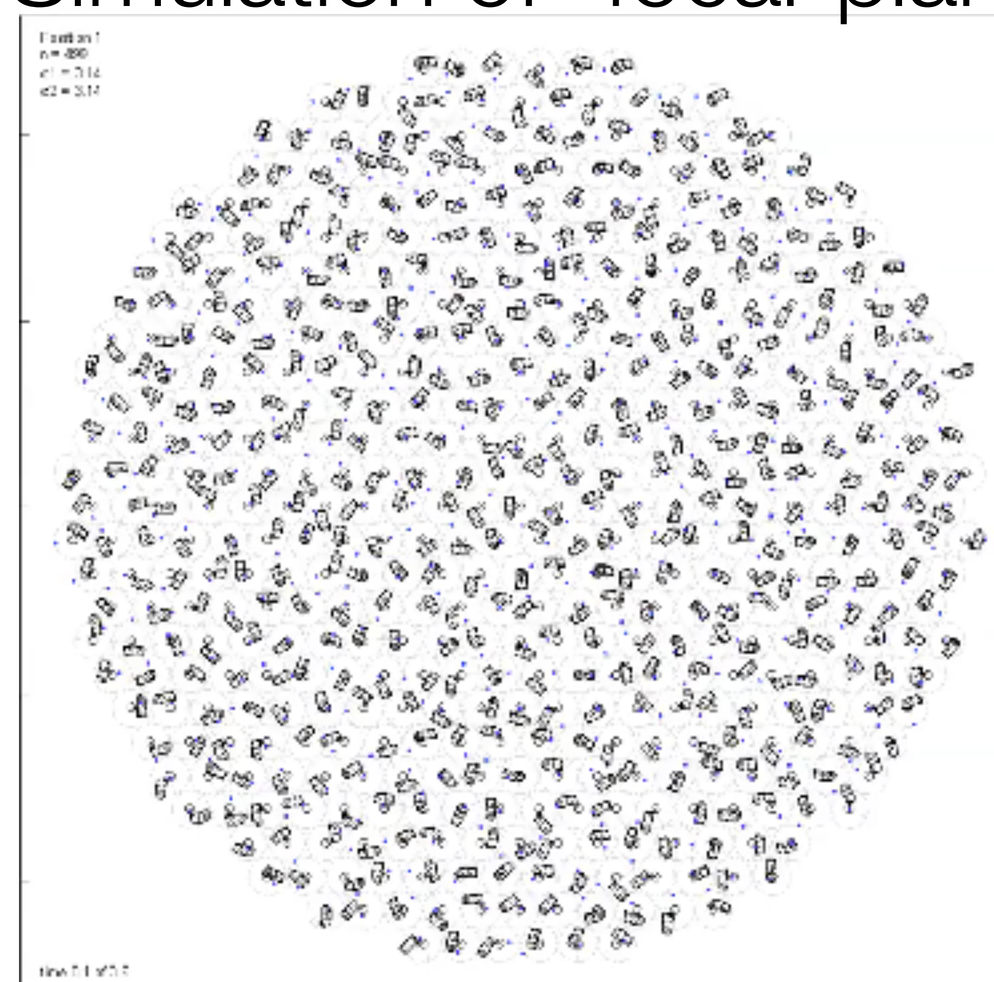

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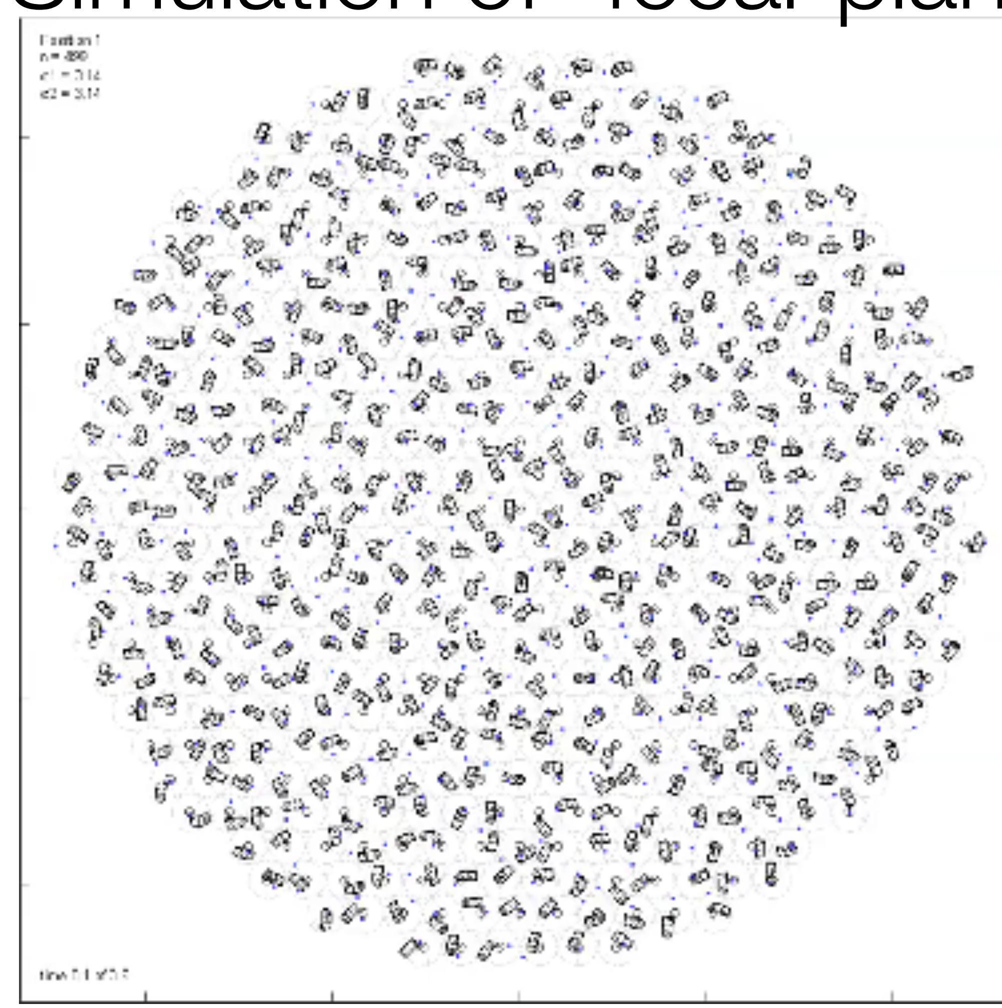

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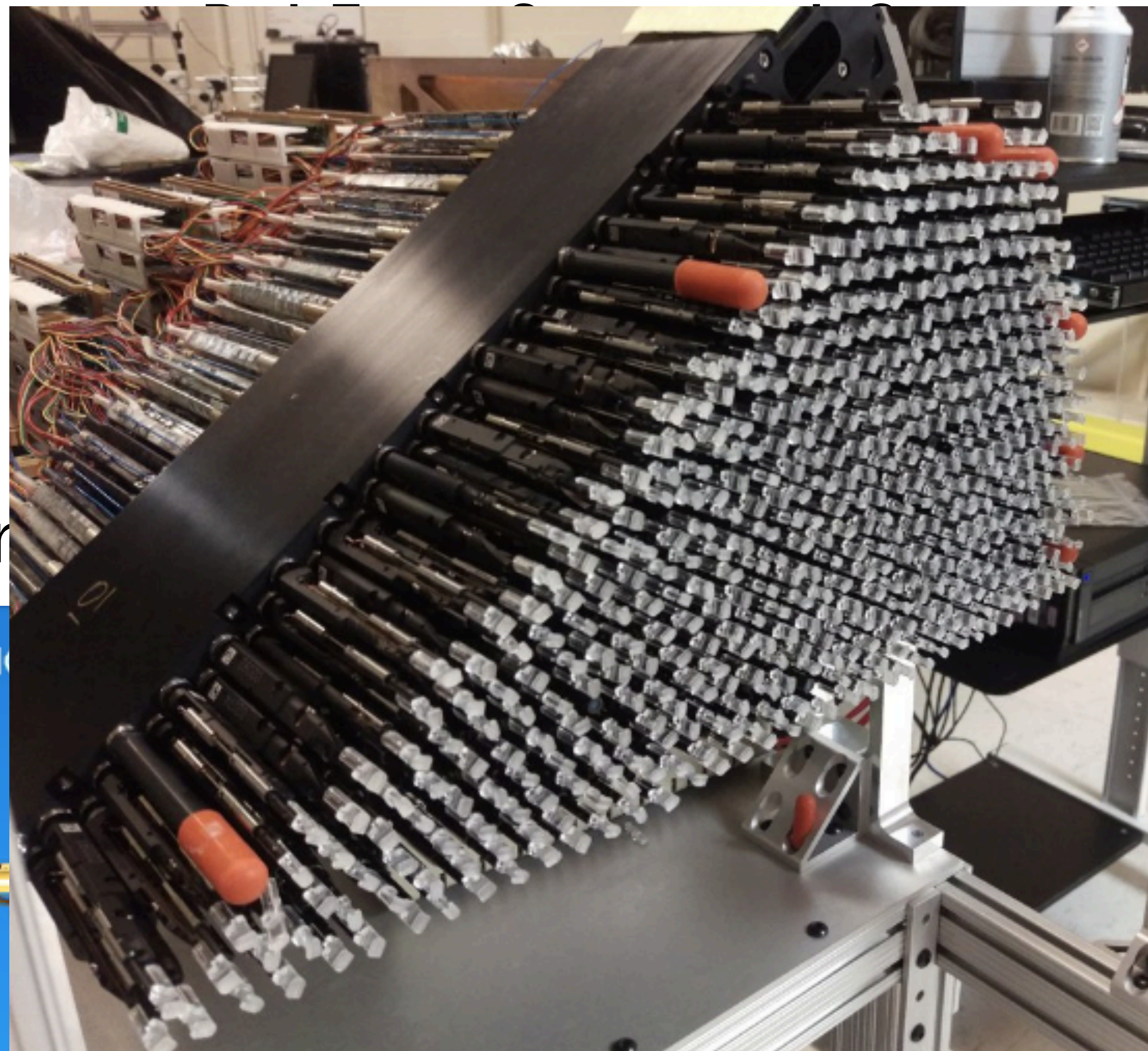

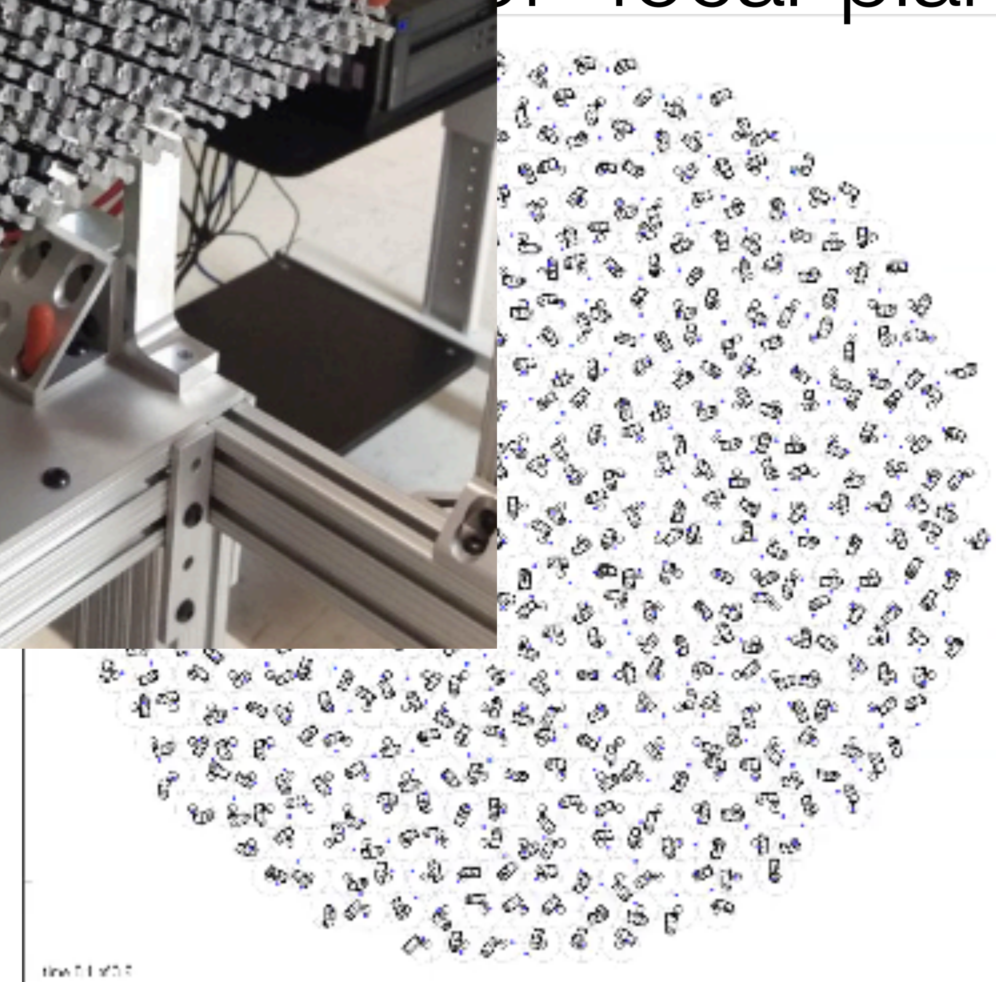

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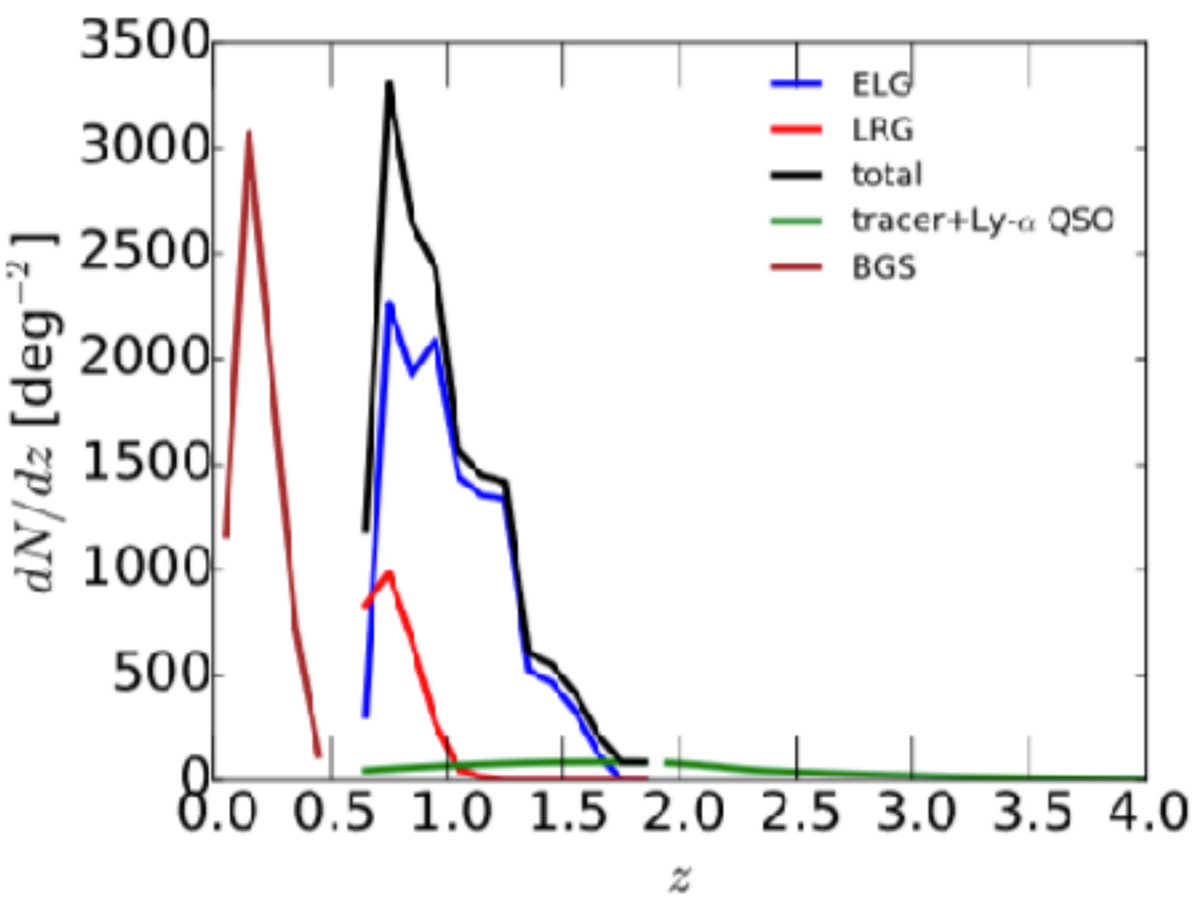
Mostly ELGs, LRGs and QSOs



DESI

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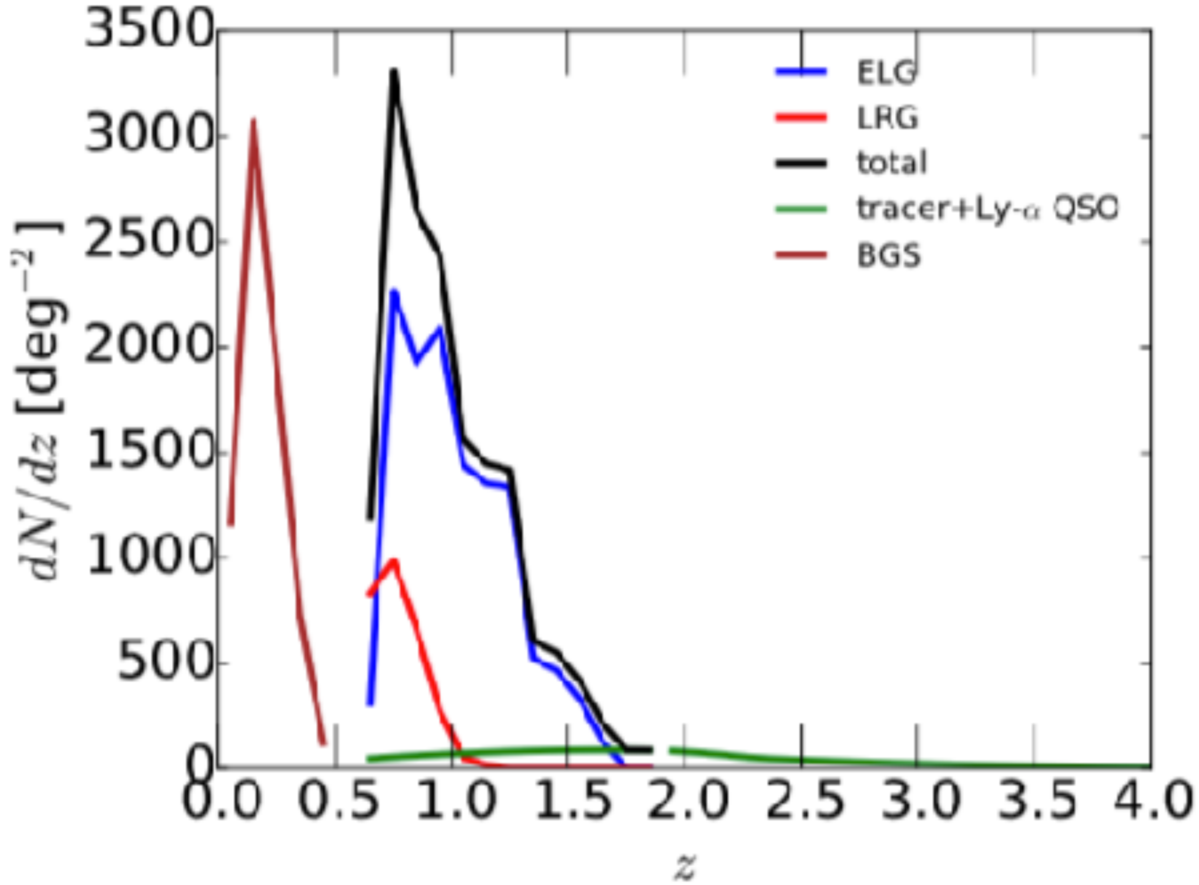

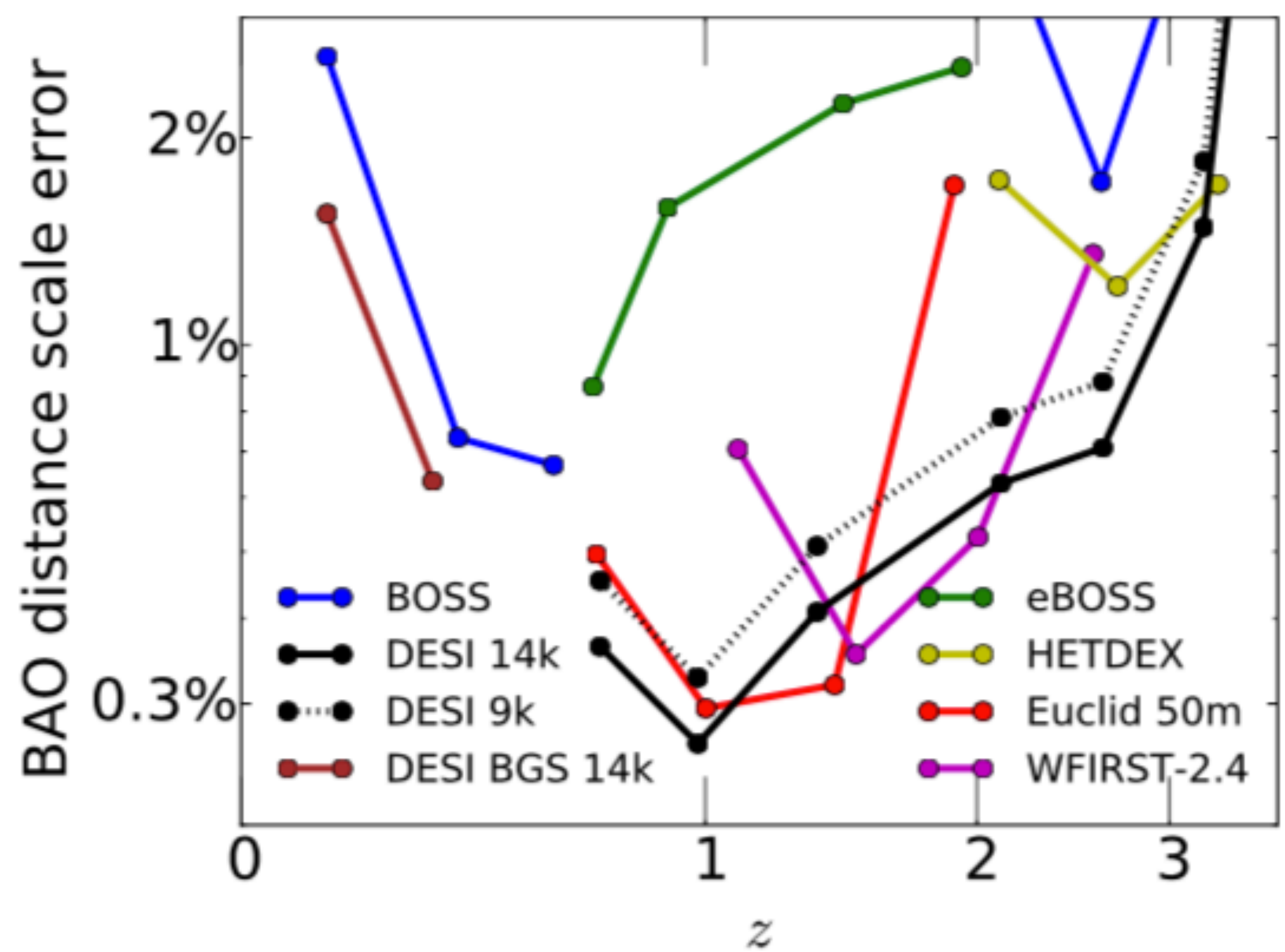

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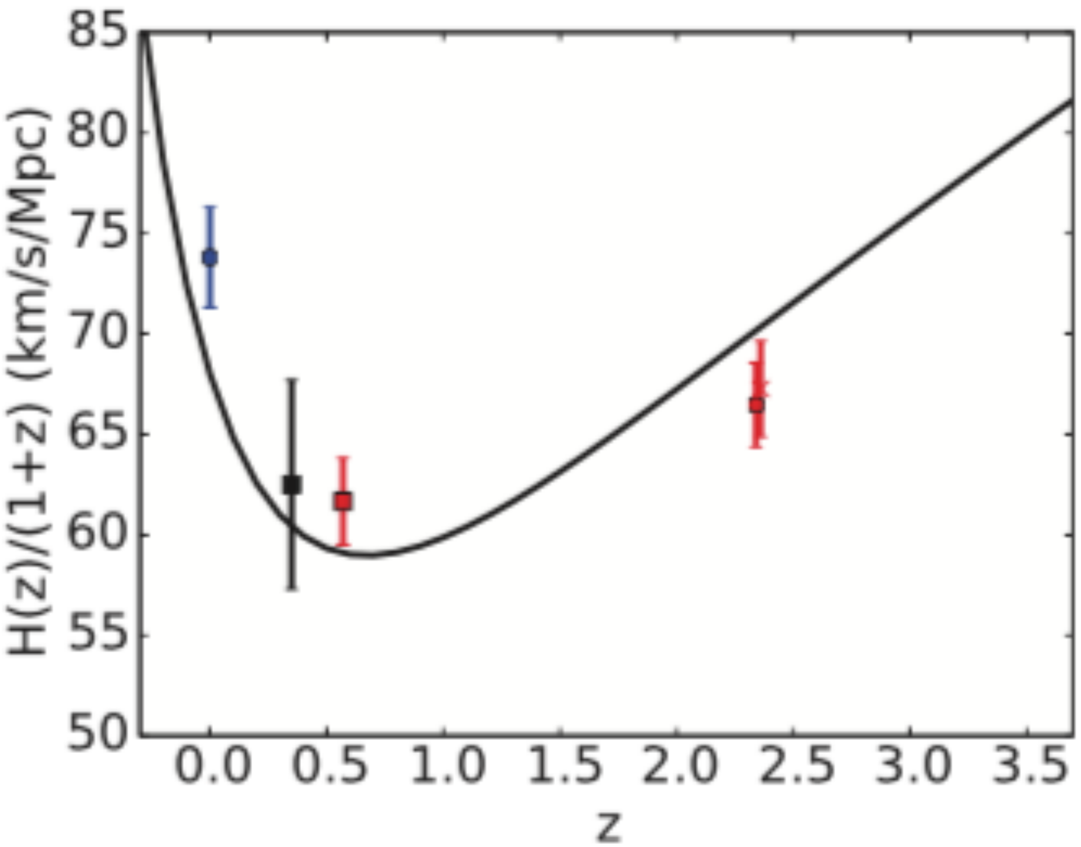

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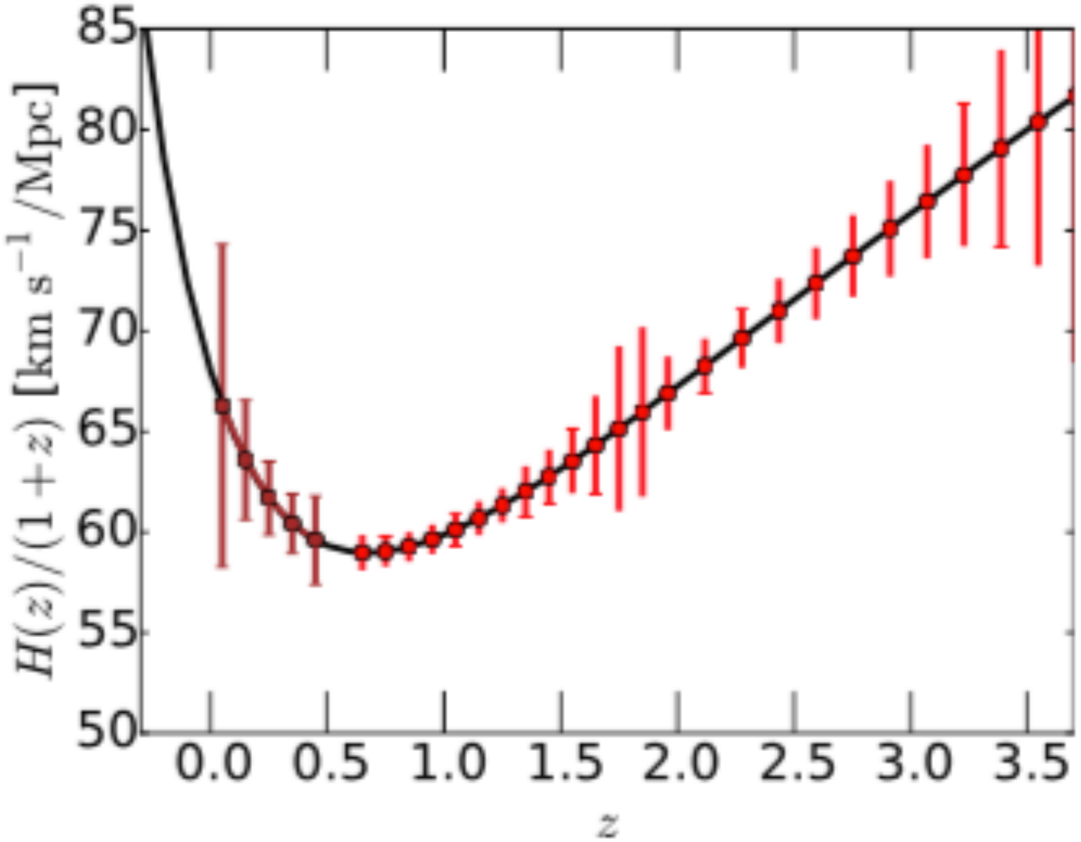

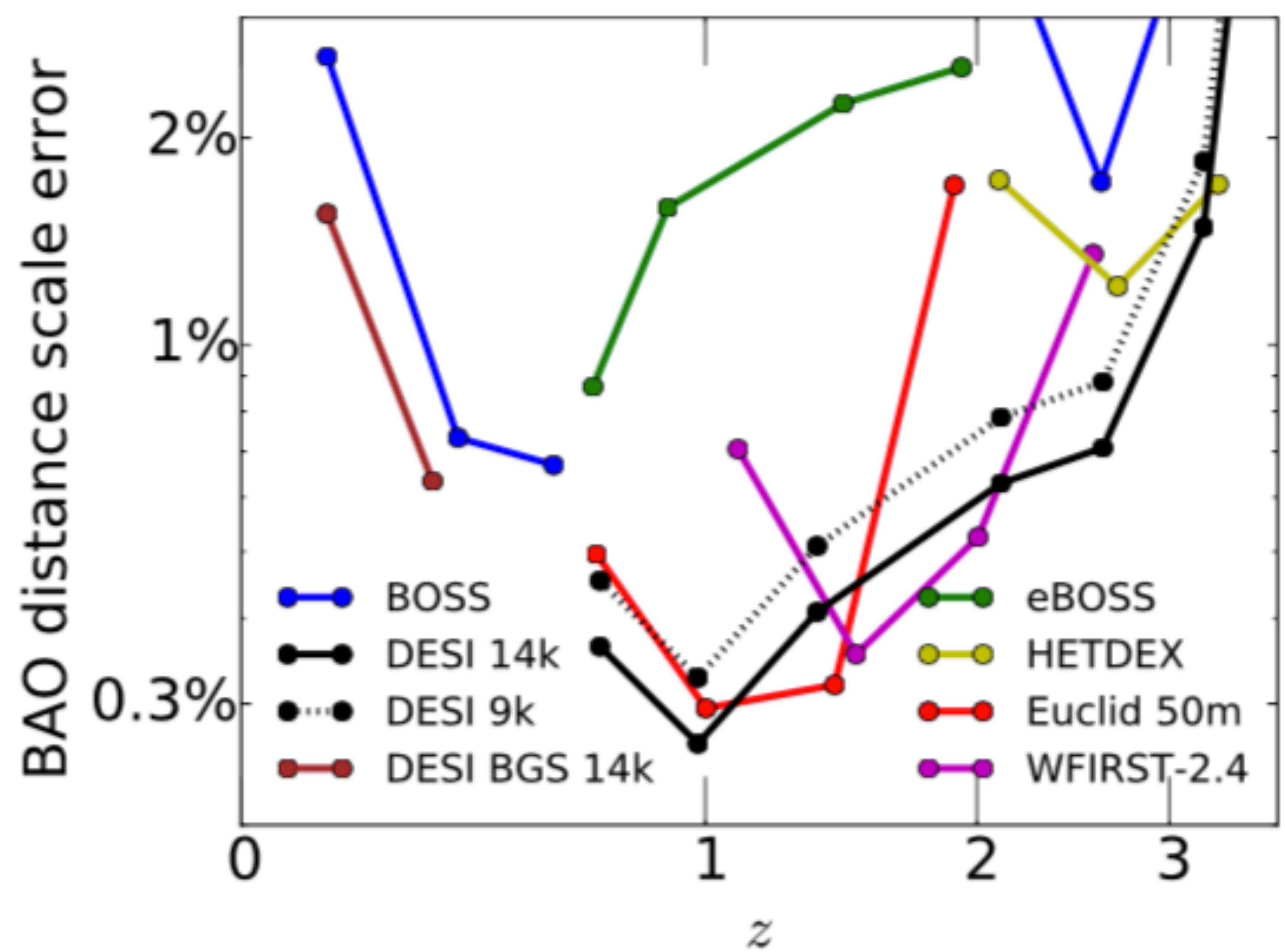

Conclusions

Conclusions

- The forest traces the “few” neutral hydrogen atoms at high redshift
- The neutral hydrogen traces the dark matter field even at low densities and it is mostly a linear tracer
- The access to small-scale clustering yields very interesting constraints on neutrino masses
- With a large survey of forests, BAO can be measured at higher redshift than galaxies, constraining dark-energy models
- DESI will start next year and increase volume and number of quasars
- Dark Energy and Neutrinos: here we come!