DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

1D Lyman-alpha forest power spectrum from DESI early data

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Overview

- Introduction to cosmology & Lyman-alpha forest
- P1D estimation
- Results from high-resolution spectra
- Results from DESI early data
- Metal properties through P1D
- Plans for Y1

Introduction

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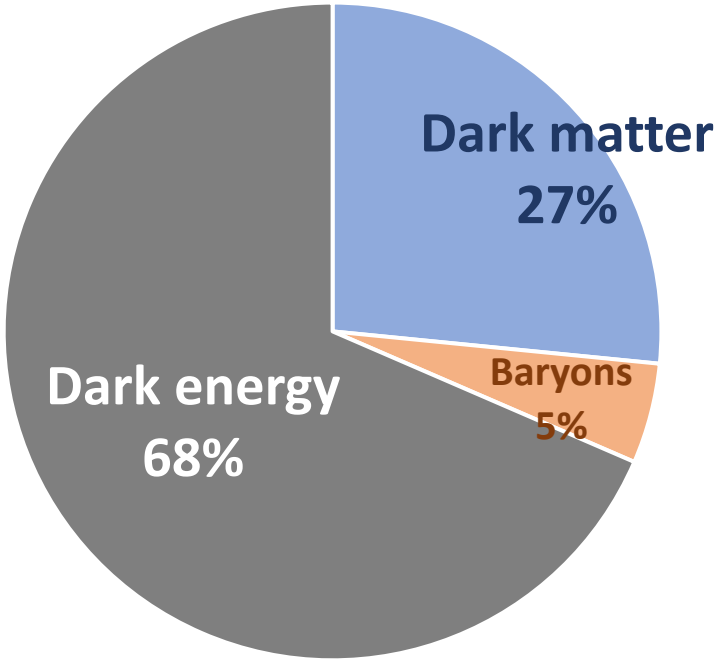
Current standard model of cosmology is based on:

- **Dark energy:** Accelerated expansion. What is its place in particle physics?
- **Dark matter:** Most of the matter in the universe. Not part of the standard model of particle physics.

ΛCDM model is successful in explaining observations

➔Beyond standard model physics



Introduction

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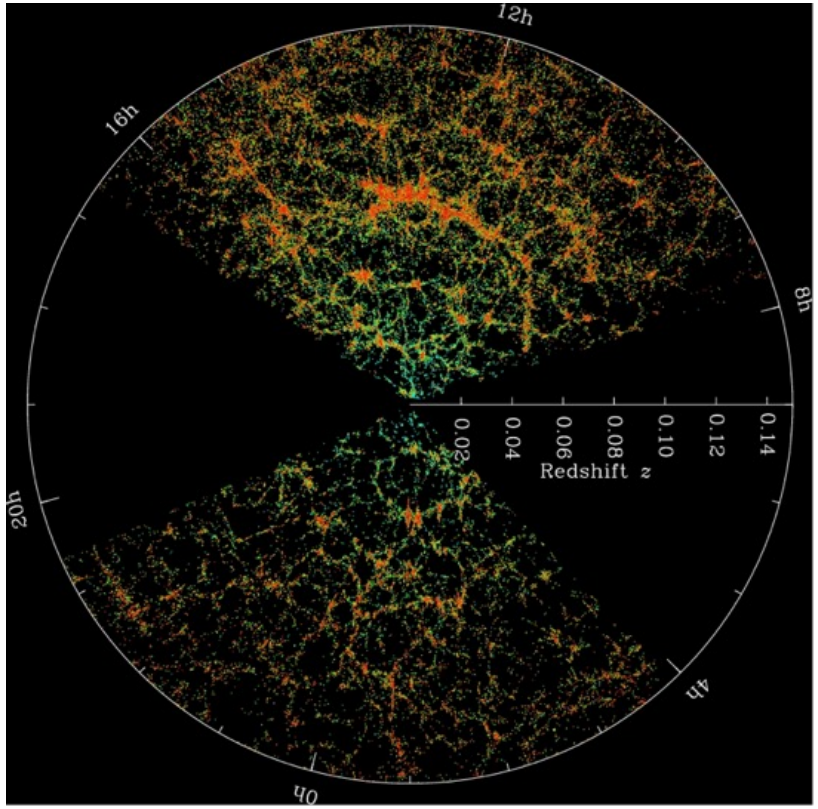
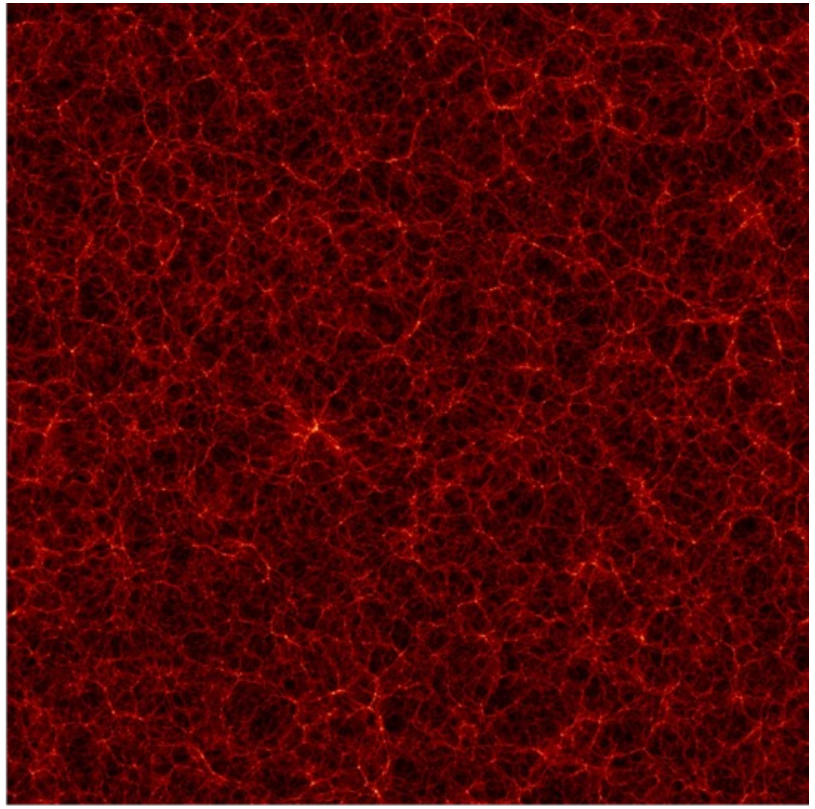


SDSS Galaxy Map



MultiDark Simulation

Lyman-alpha forest

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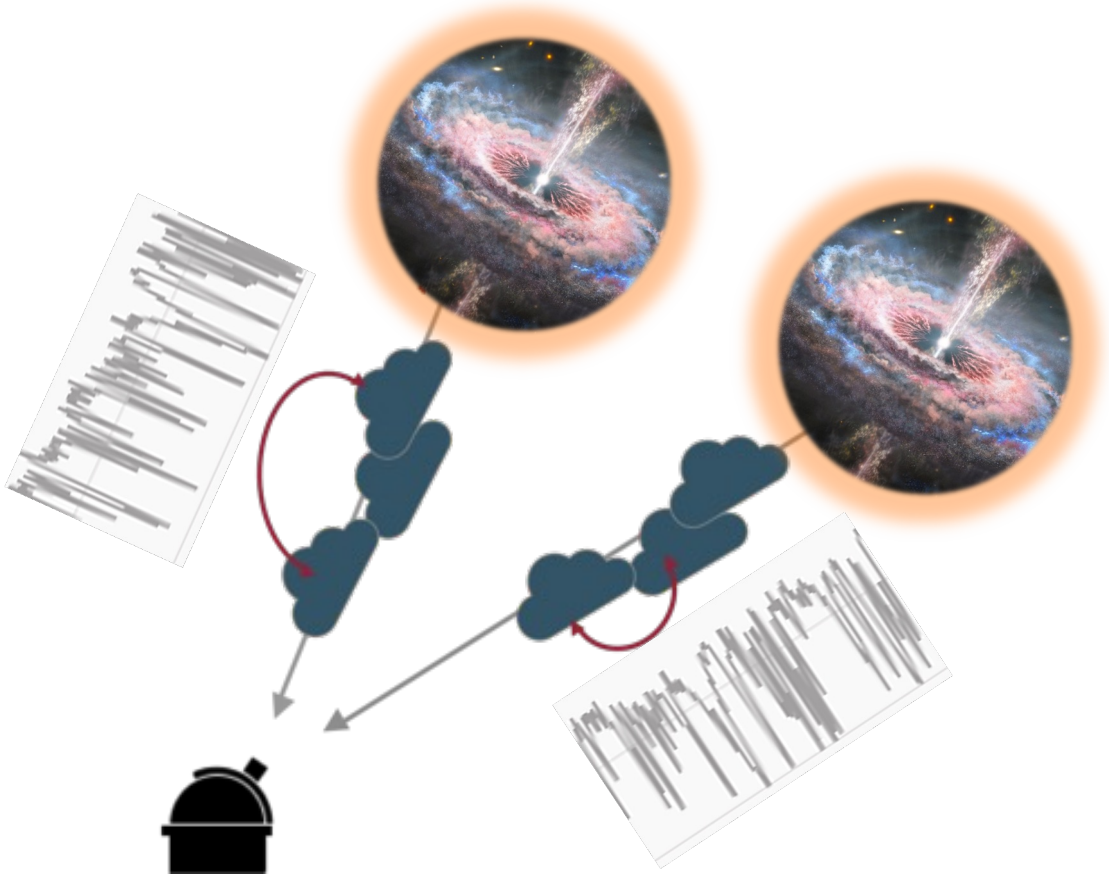
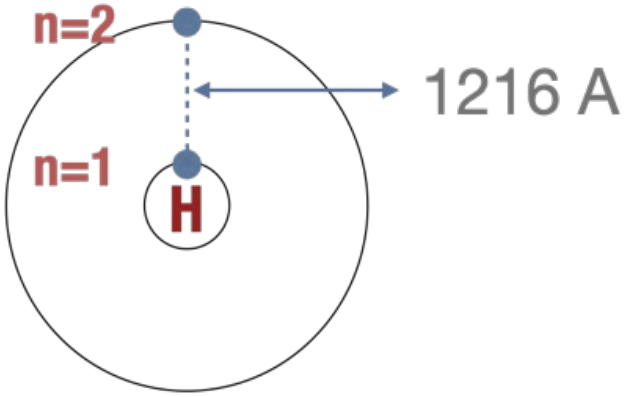


Image credits: NASA, ESA and J. Olmsted (STScI)

- A quasar is a very bright, distant and active supermassive black hole.
- The neutral hydrogen scatters the light emitted from quasars, which forms absorption lines.



Distances in cosmology

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- Cosmic expansion Doppler shifts both emission and absorption lines. Everything recedes, hence **redshifts.**

$$\lambda_{\text{obs}} = (1 + z)\lambda_{\text{true}}$$

- $z = \frac{v}{c}$ (Doppler shift)
- $v = H_0 d$ (Hubble's Law)

$$\left(d = \int_0^z \frac{c\,\mathrm{d}z'}{H(z')} \right)$$

Important redshifts:

- Now (Earth): z = 0
- Galaxies: z < 2
- Lya forest: 2 < z < 4.4
- CMB: z = 1100

Power spectrum

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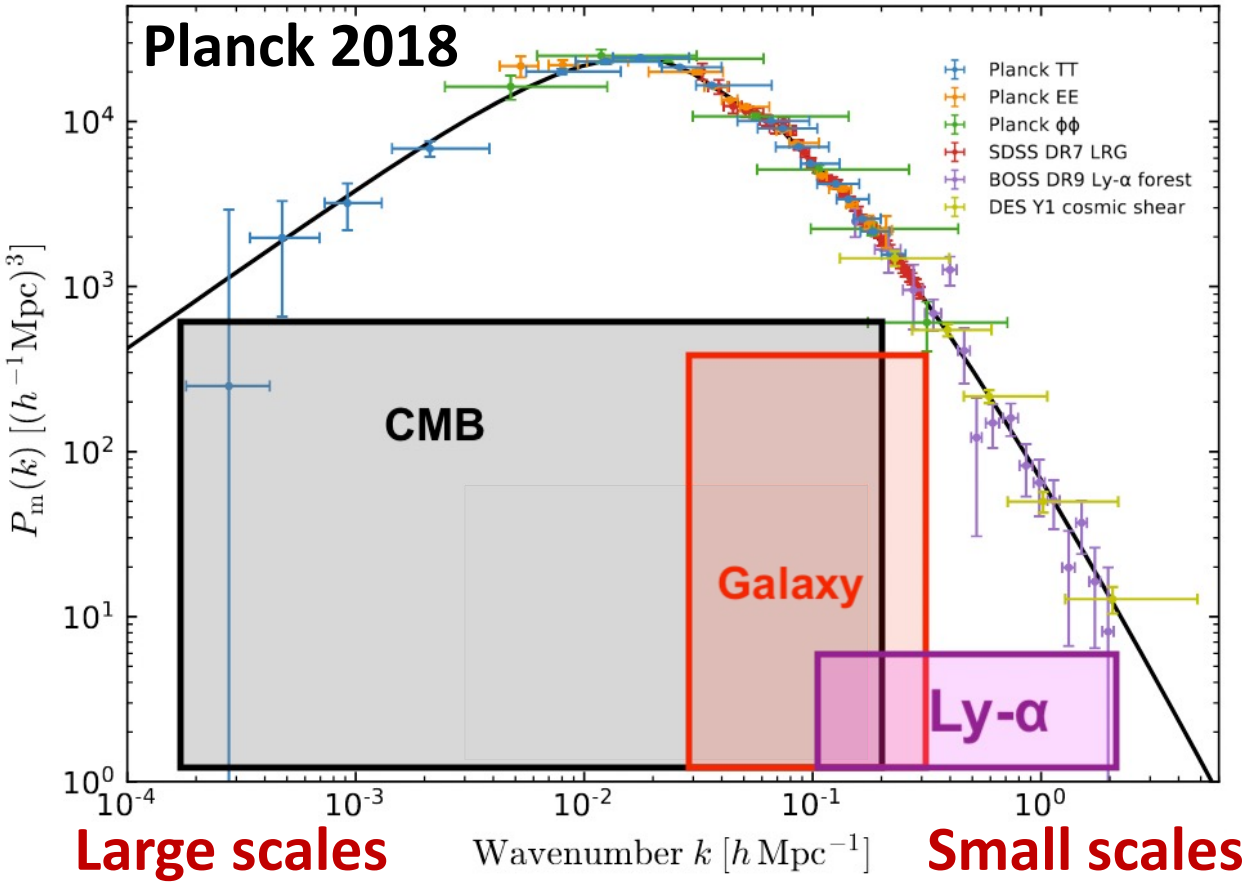


Power spectrum quantifies the amplitude of density fluctuations.

The model (black line) agrees with the data, which spans ~10 Gyr in time and 3 decades in scale.

- T_CMB: 370k years
- T_Lya: 1.5 -- 3 Gyr
- T_Galaxy: > 10 Gyr

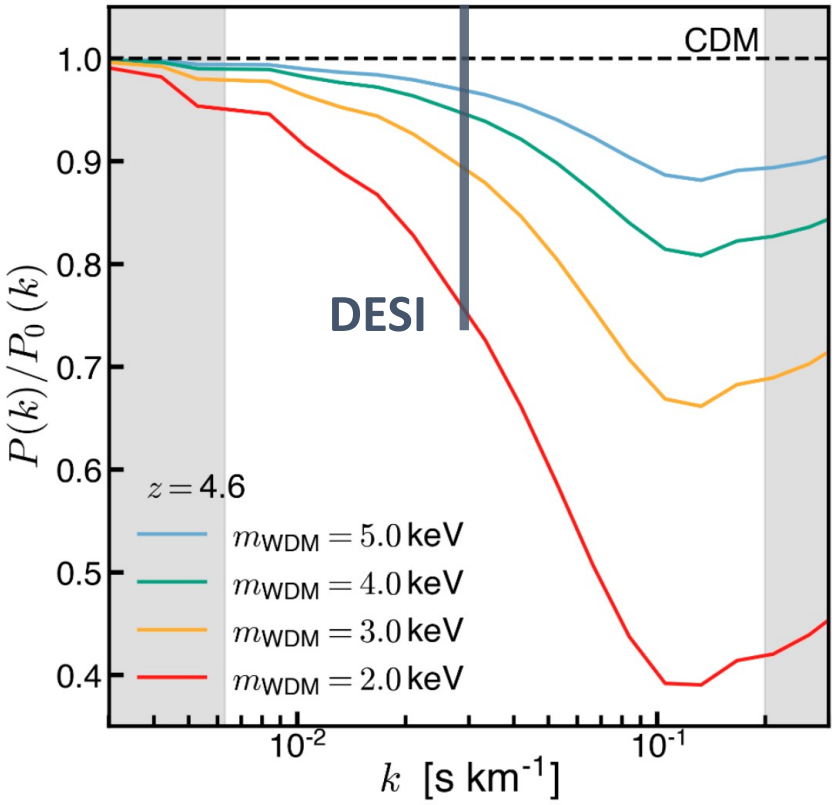
Lya forest is sensitive to small scales.

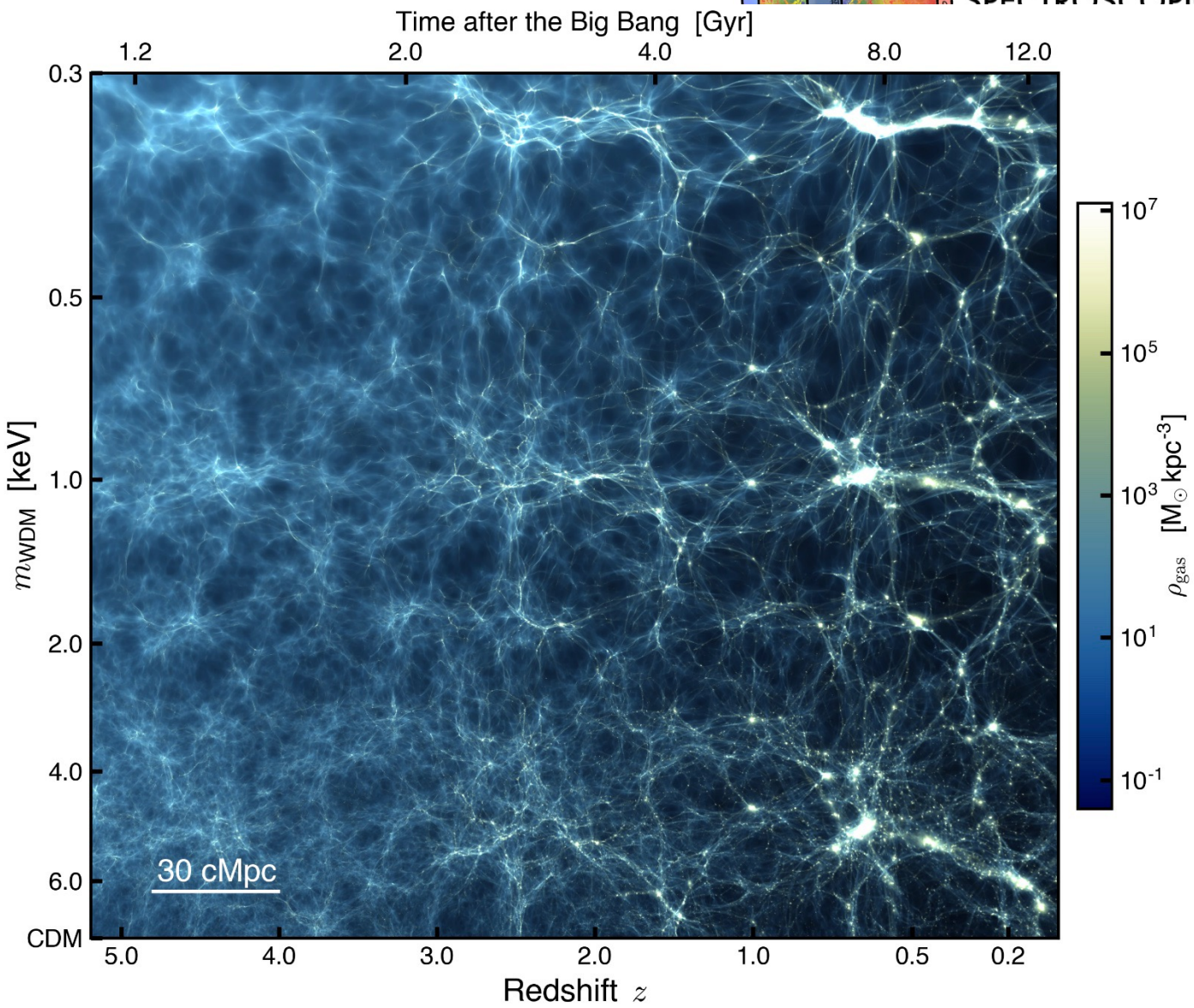
Warm dark matter

Villasenor et al. 2023

$m_{\mathrm{WDM}} > 3.1$ keV

- 4.2 < z < 5.2 from 15 quasars





The sum of the neutrino masses

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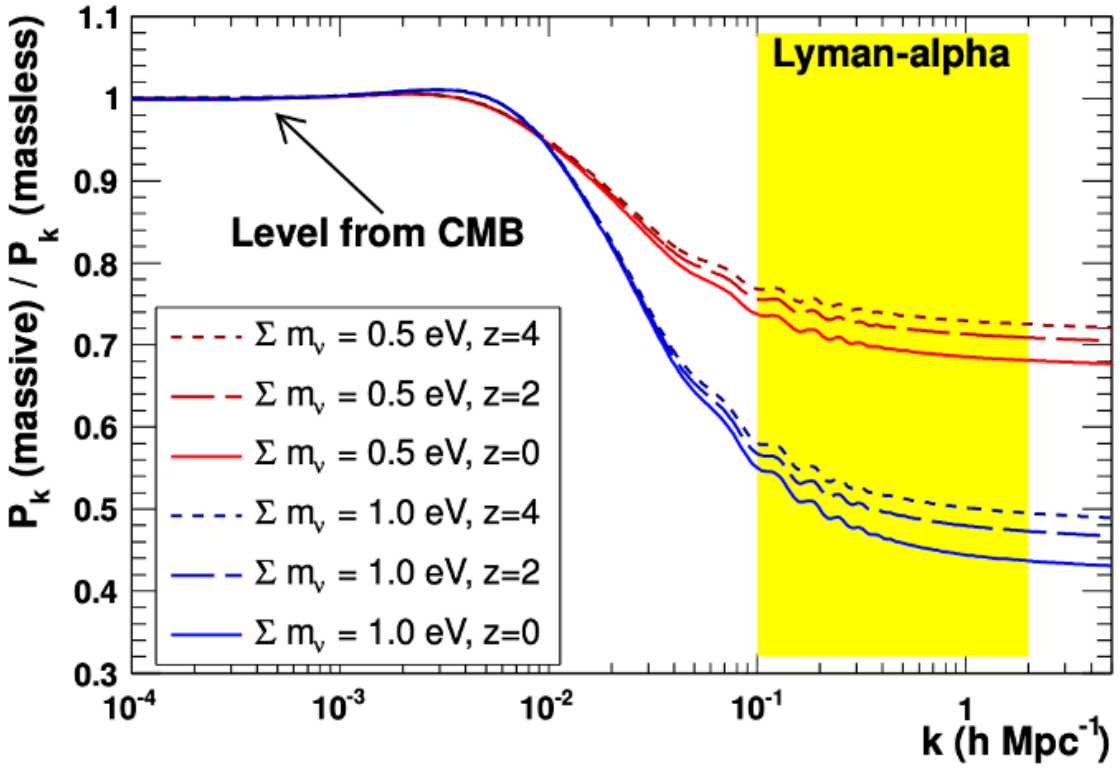
Palanque-Delabrouille et al. 2015

$\sum m_\nu < 0.12$ eV (BOSS + CMB)



Minimum mass

- Normal hierarchy: 0.057 eV
- Inverted hierarchy: 0.097 eV

DESI Forecast:

$$\sigma_{\sum m_\nu} = 0.02 \text{ eV}$$

Science, Targeting, and Survey Design: https://arxiv.org/abs/1611.00036 (2016)

DESI ~~will~~ is be the largest spectroscopic survey for dark energy. Each spectrum measures a galaxy redshift.

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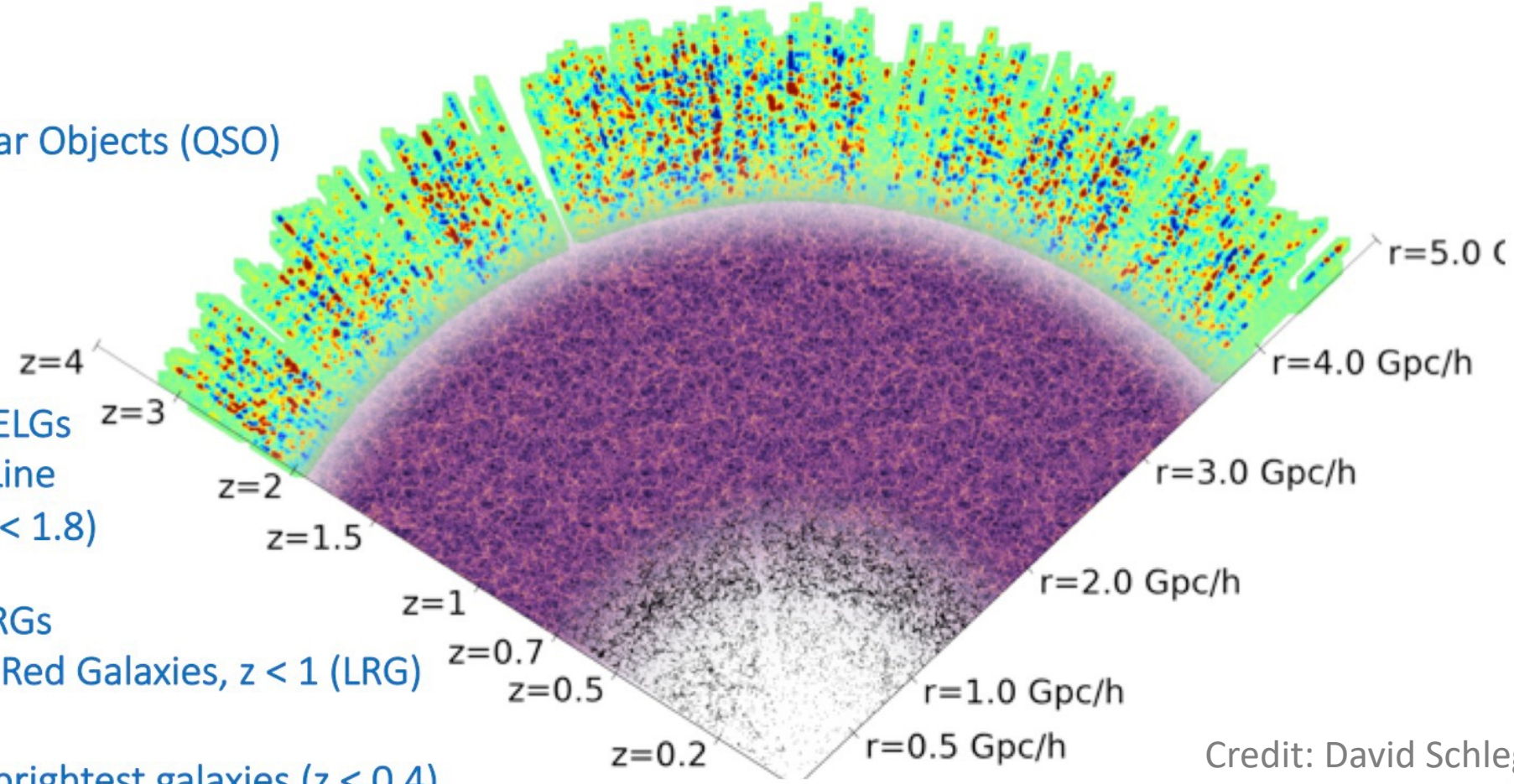
DESI will explore a x30 larger map over a x10 larger volume than SDSS

2.4 million
Quasi Stellar Objects (QSO)

17 million ELGs
(Emission Line
Galaxies, z < 1.8)

4 million LRGs
(Luminous Red Galaxies, z < 1 (LRG)

10 million brightest galaxies (z < 0.4)



Credit: David Schlegel, Aug 2019

DESI by the Numbers

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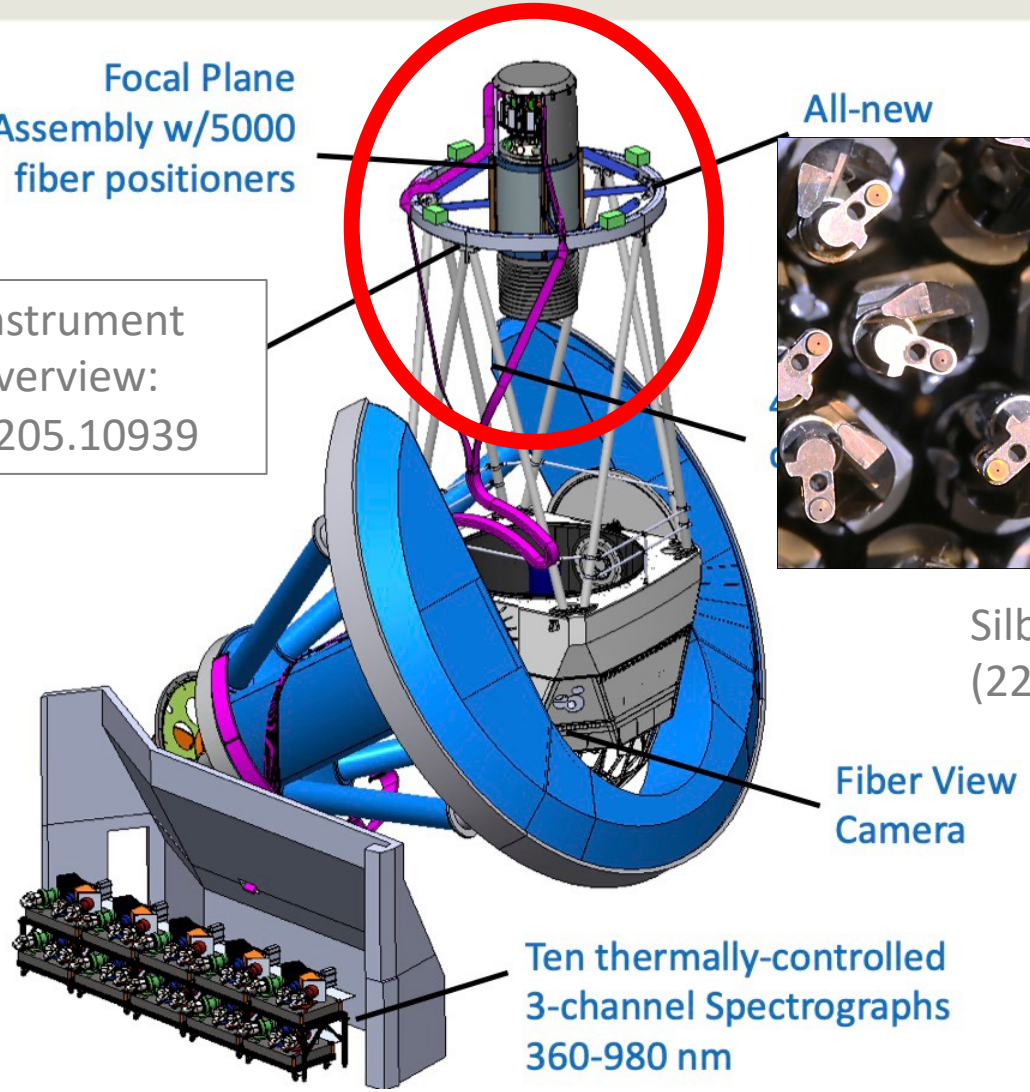
- DESI is a Fiber-fed multi-object spectrograph. It uses robotic control to position optical fibers onto the location of a known galaxy
- 5000 fiber positioner robots on the focal plane
- 8 sq. deg. FOV
- Ten 3-channel spectrographs
- Spectra of 35 million galaxies and quasars over 14,000 deg^2 in five years



All-new

Silber et al. 2022 (2205.09014)

Credit: Mike Levi, Aug 2019

- DESI will have the statistical power to tightly constrain the sum of the neutrino masses.

$$\sigma_{\sum m_\nu} = 0.02 \text{ eV}$$

- But we need to control the systematics on the measurement to realize that goal.
- Noise calibration errors, resolution correction errors…

Lyman-alpha forest

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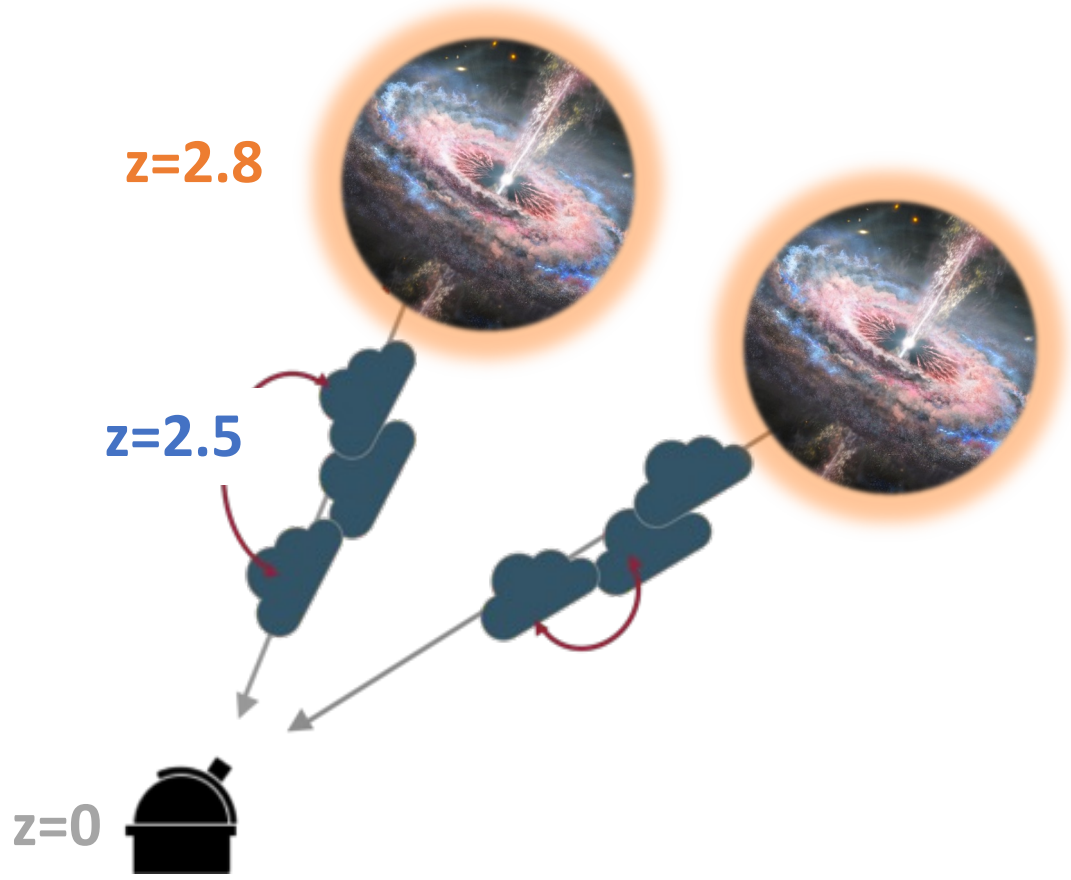

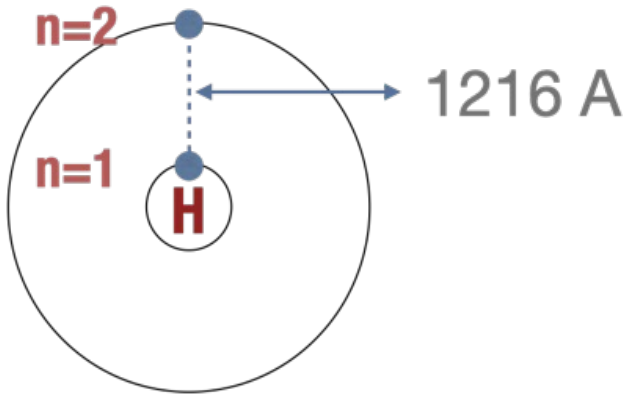

Image credits: NASA, ESA and J. Olmsted (STScI)

DESI Iron TARGETID: 39627785269943777

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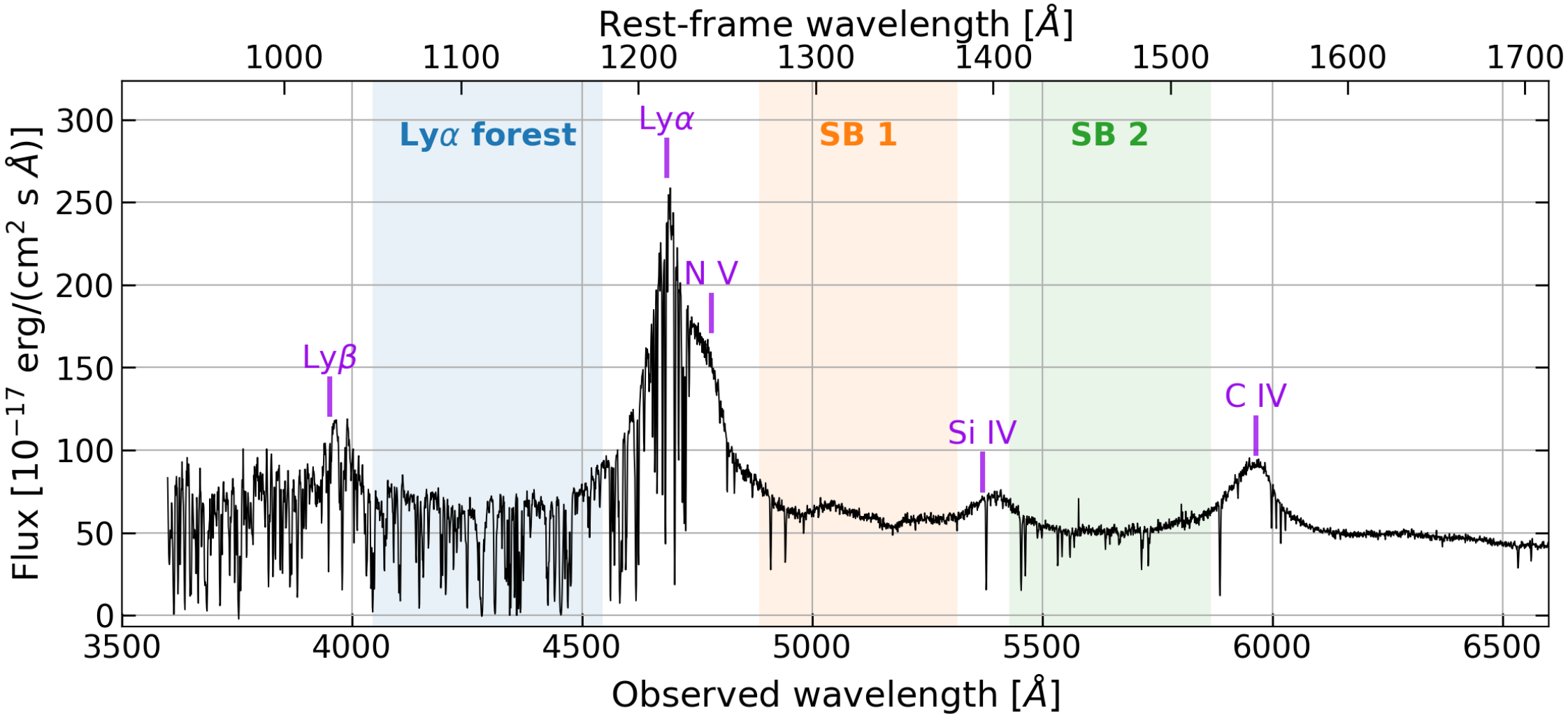

DESI Iron TARGETID: 39628488927348682

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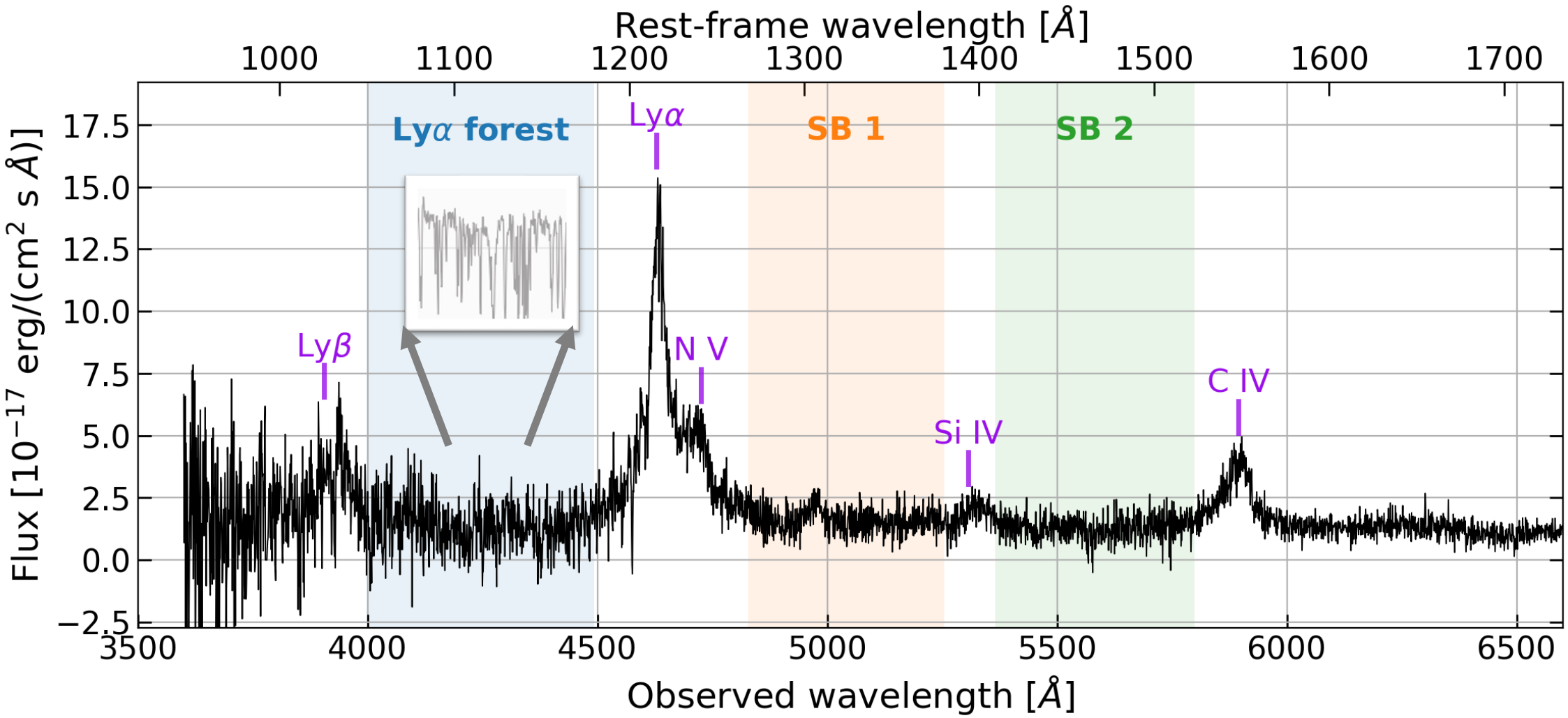

Components of P1D Estimation

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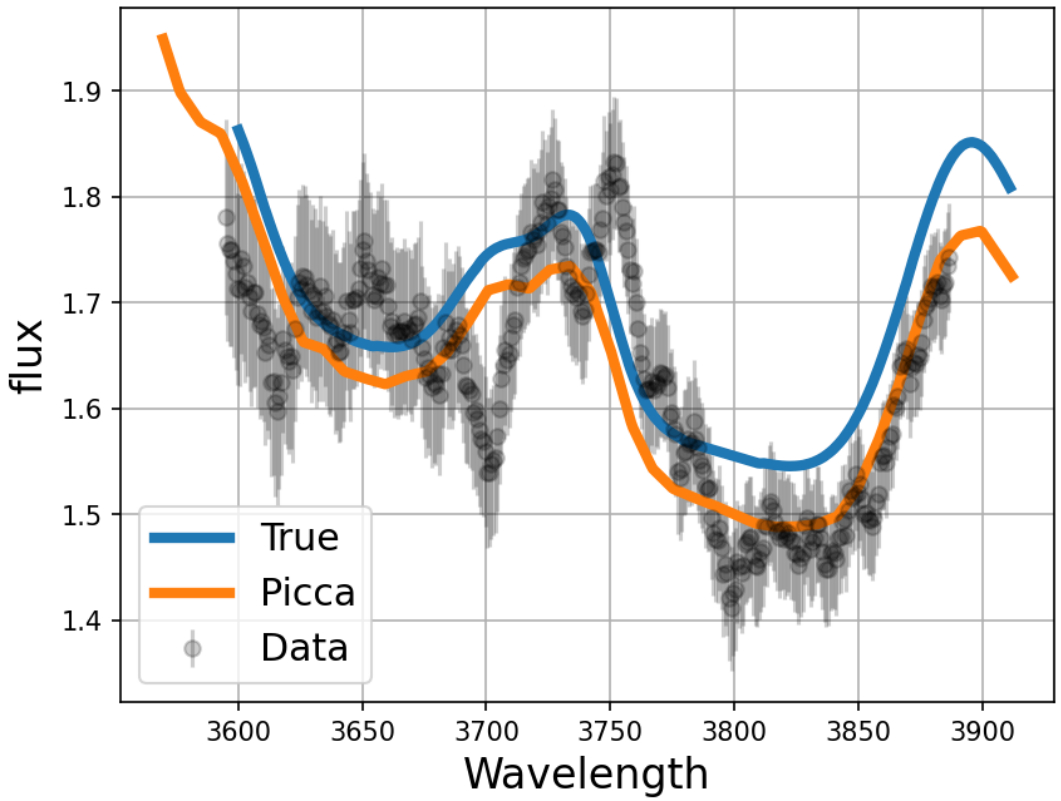
- Continuum fitting
- Masking bad/unwanted pixels

Data

- Power spectrum estimation
  - Methods: FFT, optimal quadratic estimator
- Noise subtraction
- Resolution correction
  - Deconvolving the spectrograph window function.
- Metal power subtraction



$$f(\lambda) = C(\lambda)F(\lambda)$$

Components of P1D Estimation

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- Continuum fitting
- Masking bad/unwanted pixels

$$P_F(k) = \langle |\widetilde{\delta_F}(k)|^2 \rangle$$

1. Raw power spectrum estimation
   - Methods: FFT, **optimal quadratic estimator**

$$P_{\rm raw}(k)$$

2. Noise subtraction

$$P_{\rm raw}(k) - P_N(k)$$

3. Resolution correction
   - Deconvolving the spectrograph window function.

$$\frac{P_{\rm raw}(k) - P_N(k)}{W^2(k; R, \Delta v)}$$

4. Metal power subtraction

$$P_{\rm Lya}(k) = \frac{P_{\rm raw}(k) - P_N(k)}{W^2(k; R, \Delta v)} - P_{\rm metal}(k)$$

Quadratic (maximum likelihood) estimator

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- Theoretically optimal.
- Robust against Lyα specific challenges: gaps, continuum errors, non-uniform noise
- Computationally expensive*
- Occasional convergence problems.

* 0.5 Node hours for EDR

Likelihood: $$2\mathcal{L} = \boldsymbol{\delta}_F^T \, \mathbf{C}^{-1} \boldsymbol{\delta}_F + \ln\det \mathbf{C}$$

Note $\mathbf{C} = \mathbf{C}\big(P(k)\big)$. Solve for $\frac{\partial \mathcal{L}}{\partial P_k}(\widehat{\boldsymbol{P}}) = 0$.

Newton-Raphson iterative solution:

$$\widehat{P}_k^{(i+1)} = \widehat{P}_k^{(i)} - \sum_{k'} \langle \mathcal{L}_{,kk'} \rangle^{-1} \Big|_{\widehat{\boldsymbol{P}}^{(i)}} \mathcal{L}_{,k'}(\widehat{\boldsymbol{P}}^{(i)})$$

Stack all spectra into one vector:

$$\delta_F = \begin{pmatrix} \delta_F^1 \\ \vdots \\ \delta_F^N \end{pmatrix}$$

A detour to high-resolution spectra

DESI vs KODIAQ

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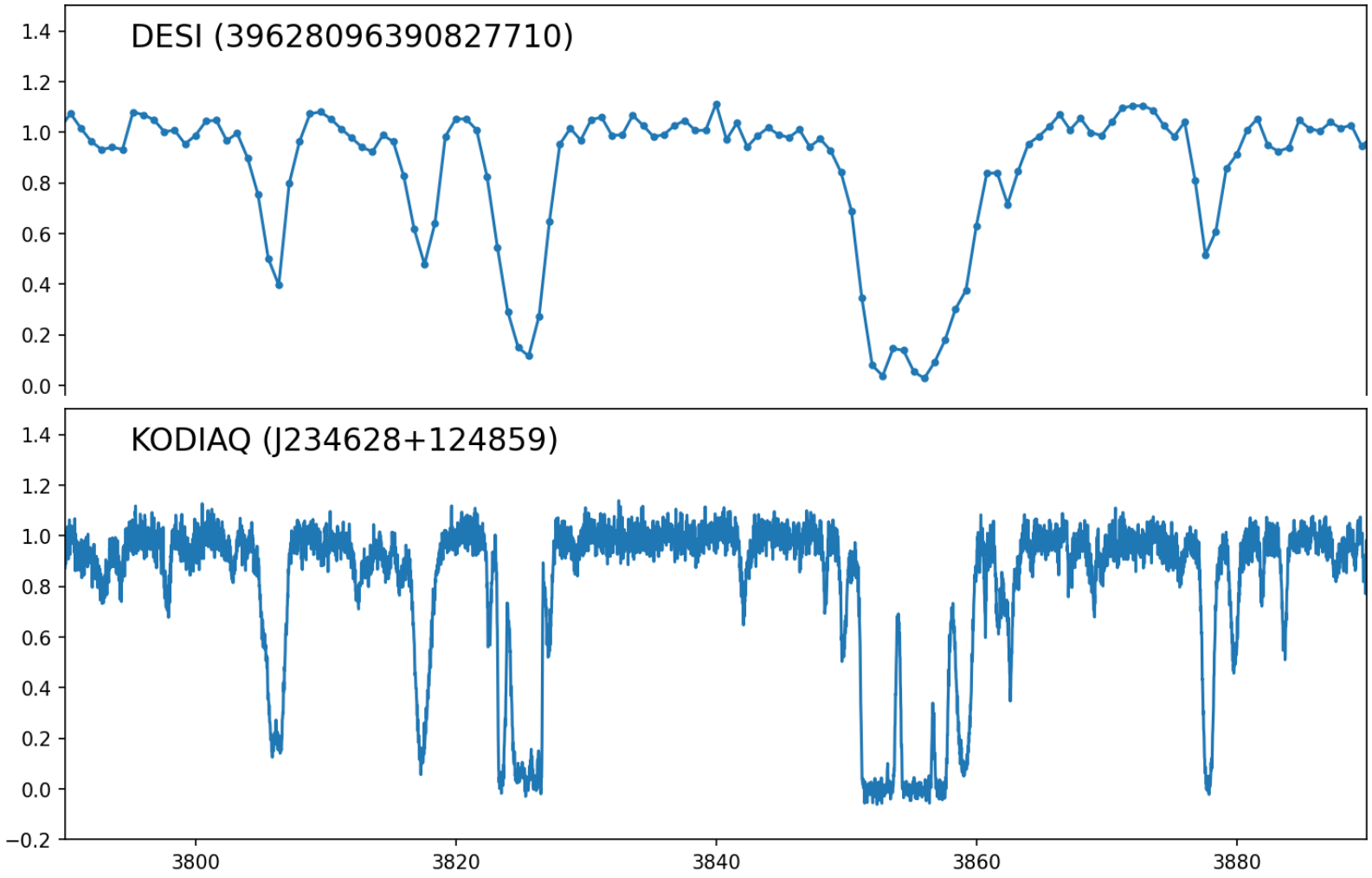
DESI:

- Low - Medium resolution
- 450,000 quasars

(Y1 Lya sample)

KODIAQ:

- 15 x DESI resolution
- 300 quasars
- Continuum is easier to fit



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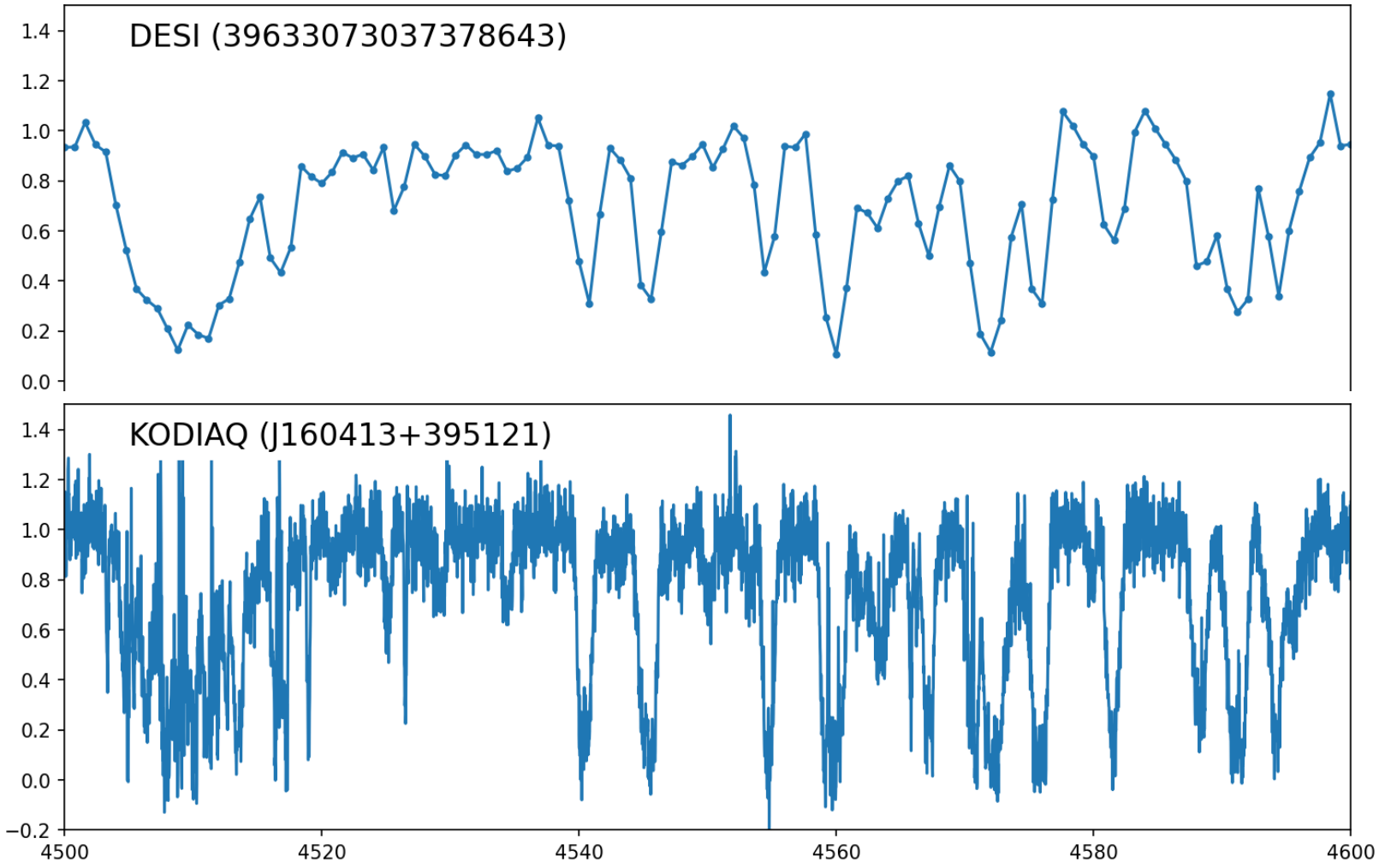

Application to high-resolution quasars

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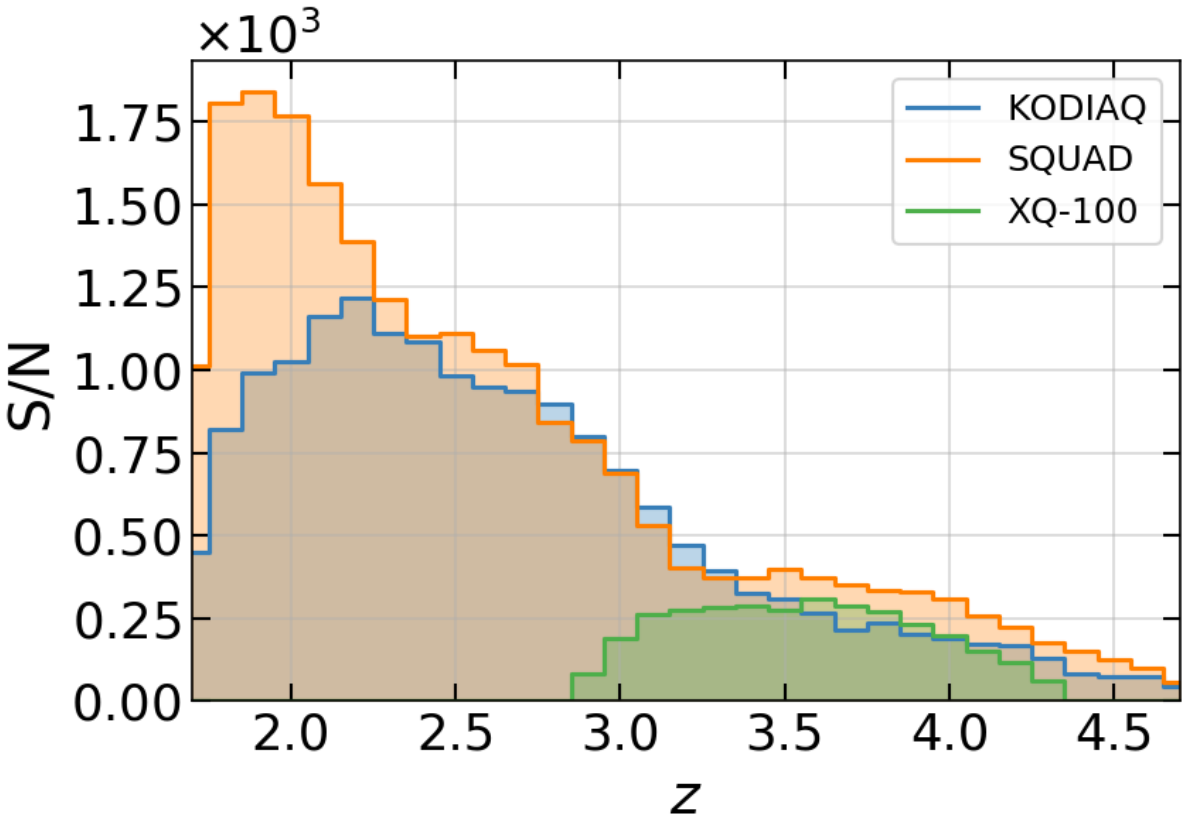
- KODIAQ/HIRES
  - 300 quasars with R > 36,000
- SQUAD/UVES
  - 467 quasars with R > 40,000
- XQ-100/X-shooter
  - 100 quasars with R ~ 6,000

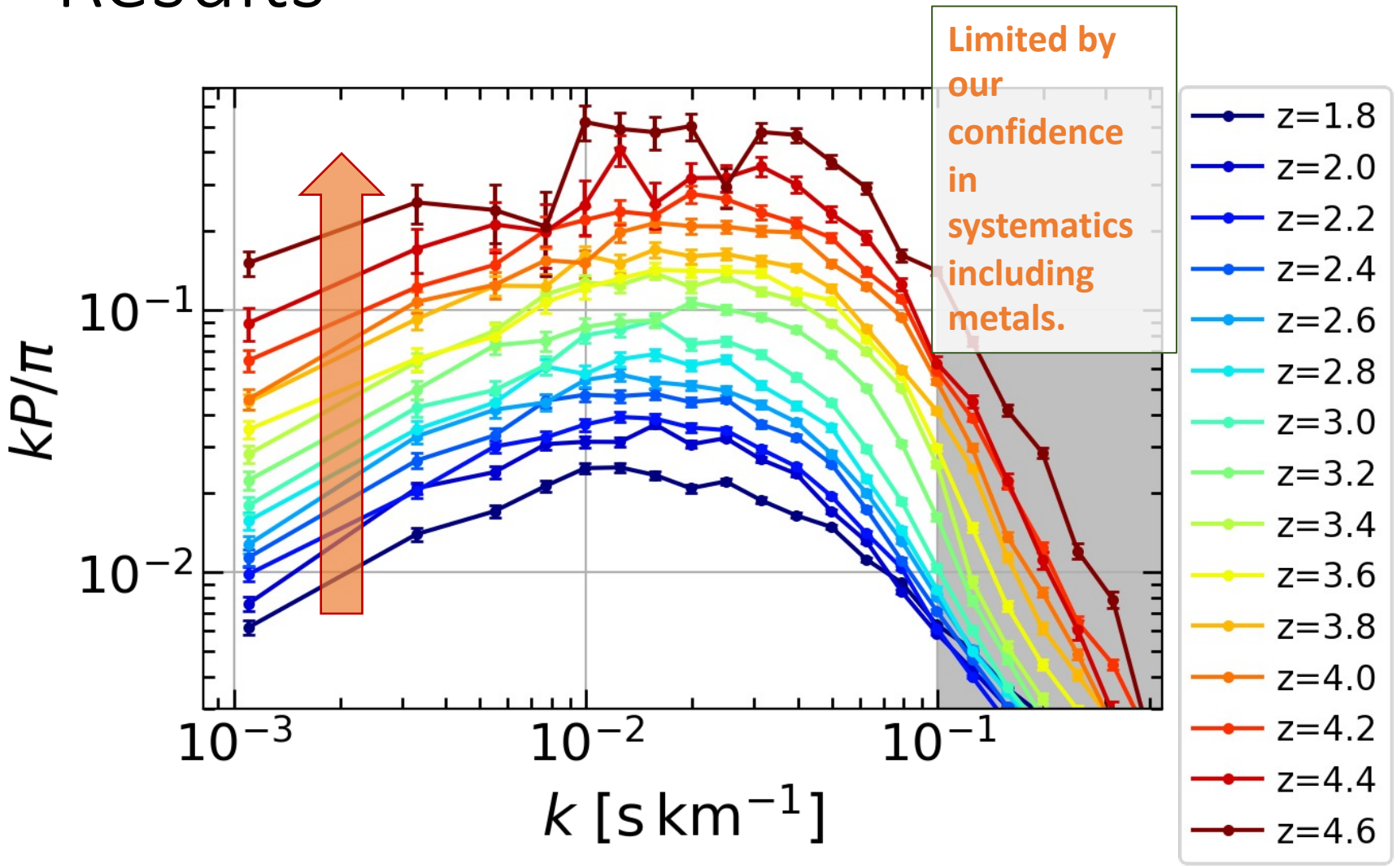
(DESI R ~ 3,000)

Total of **538** unique quasars.



Karaçaylı et al. 2022, MNRAS, 509, 2842

Results



Power increases with redshift because more HI at higher z.

Karaçaylı et al. 2022, MNRAS, 509, 2842

Results

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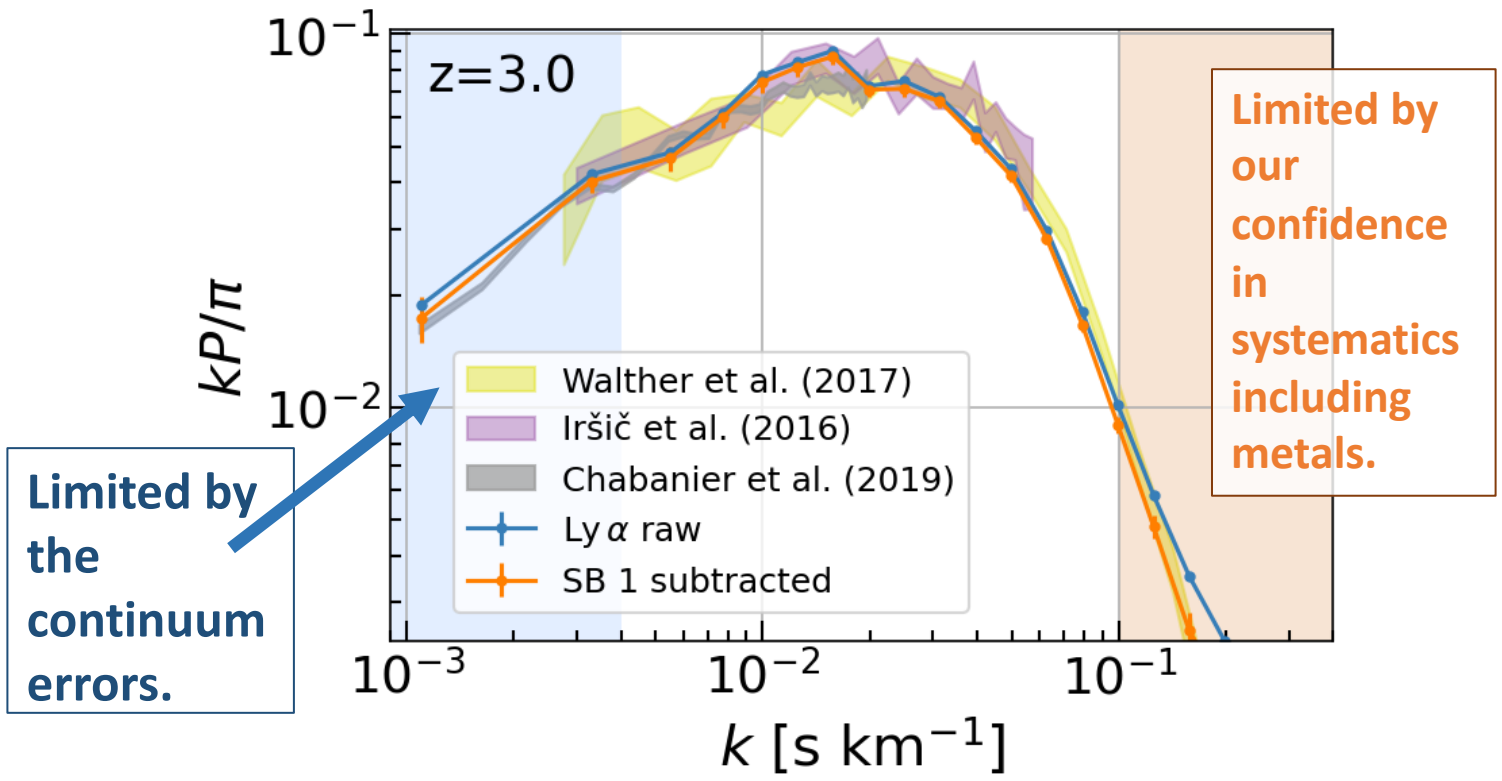

- Error bars are from 25,000 bootstrap realizations.
- They needed to be regularized for numerical stability.

Karaçaylı et al. 2022, MNRAS, 509, 2842

Statistical power

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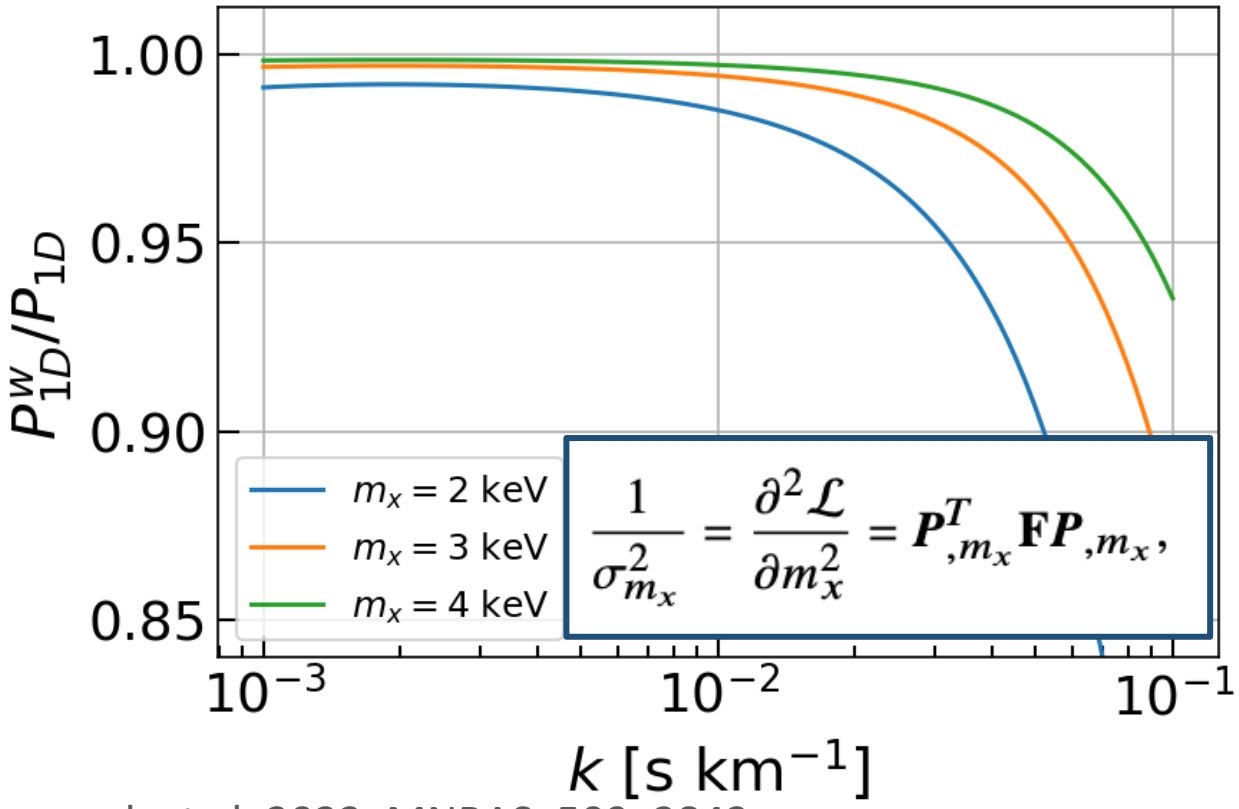
- A crude Fisher forecast analysis for warm dark matter mass using transfer function in Bode et al. (2001) assuming m_x=4 keV.



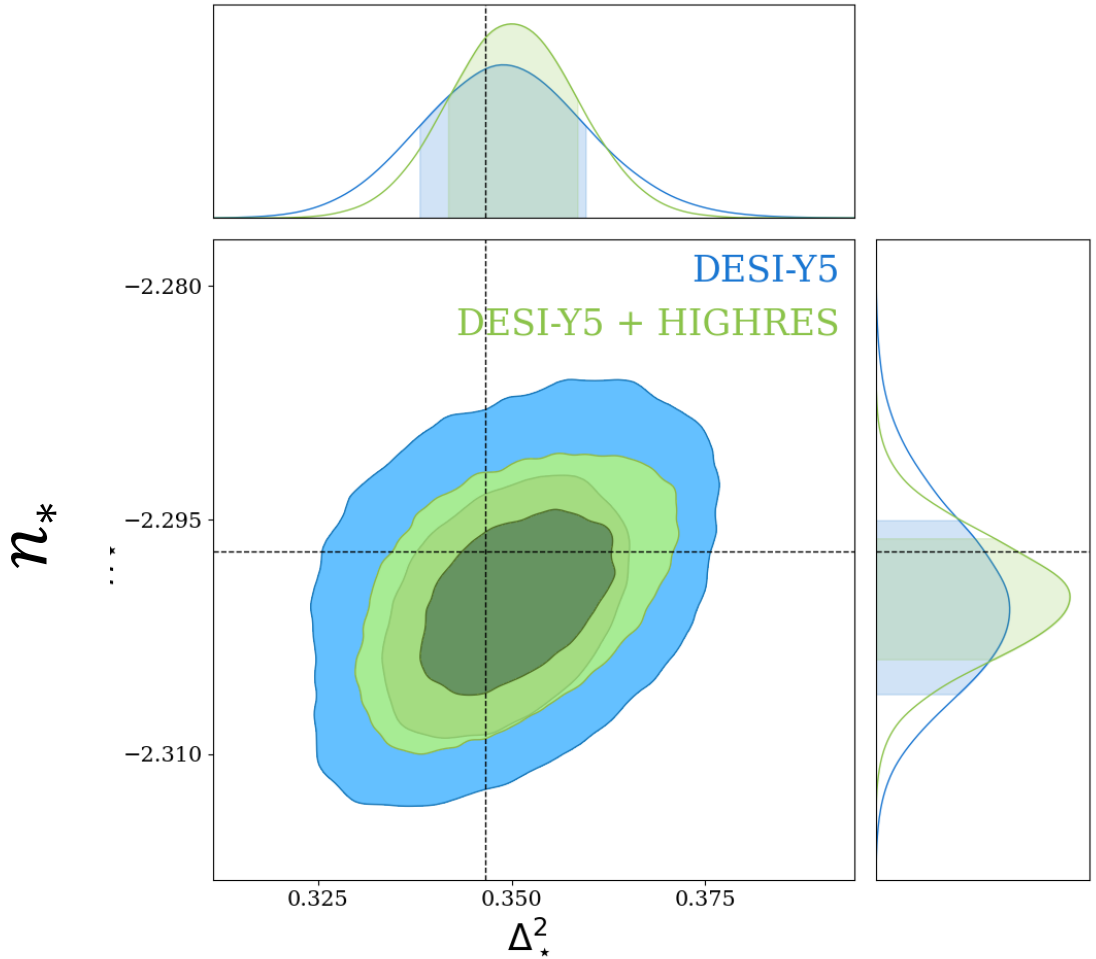
$$\frac{1}{\sigma^2_{m_x}} = \frac{\partial^2 \mathcal{L}}{\partial m_x^2} = \boldsymbol{P}^T_{,m_x} \mathbf{F} \boldsymbol{P}_{,m_x},$$

	σ_{m_x} [keV]
This work (stat. only)	0.36
This work (stat. + syst.)	0.38
Walther et al. (2017)	1.08
Chabanier et al. (2019)	1.44
Iršič et al. (2017c)	2.07

A factor of **>2** improvement on the error of the WDM mass

Karaçaylı et al. 2022, MNRAS, 509, 2842

Improves DESI constraints



Credit: Andreu Font-Ribera

n_*: Slope

Δ^2_*: Amplitude,

of the linear power spectrum

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Back to DESI

DESI Iron TARGETID: 39628488927348682

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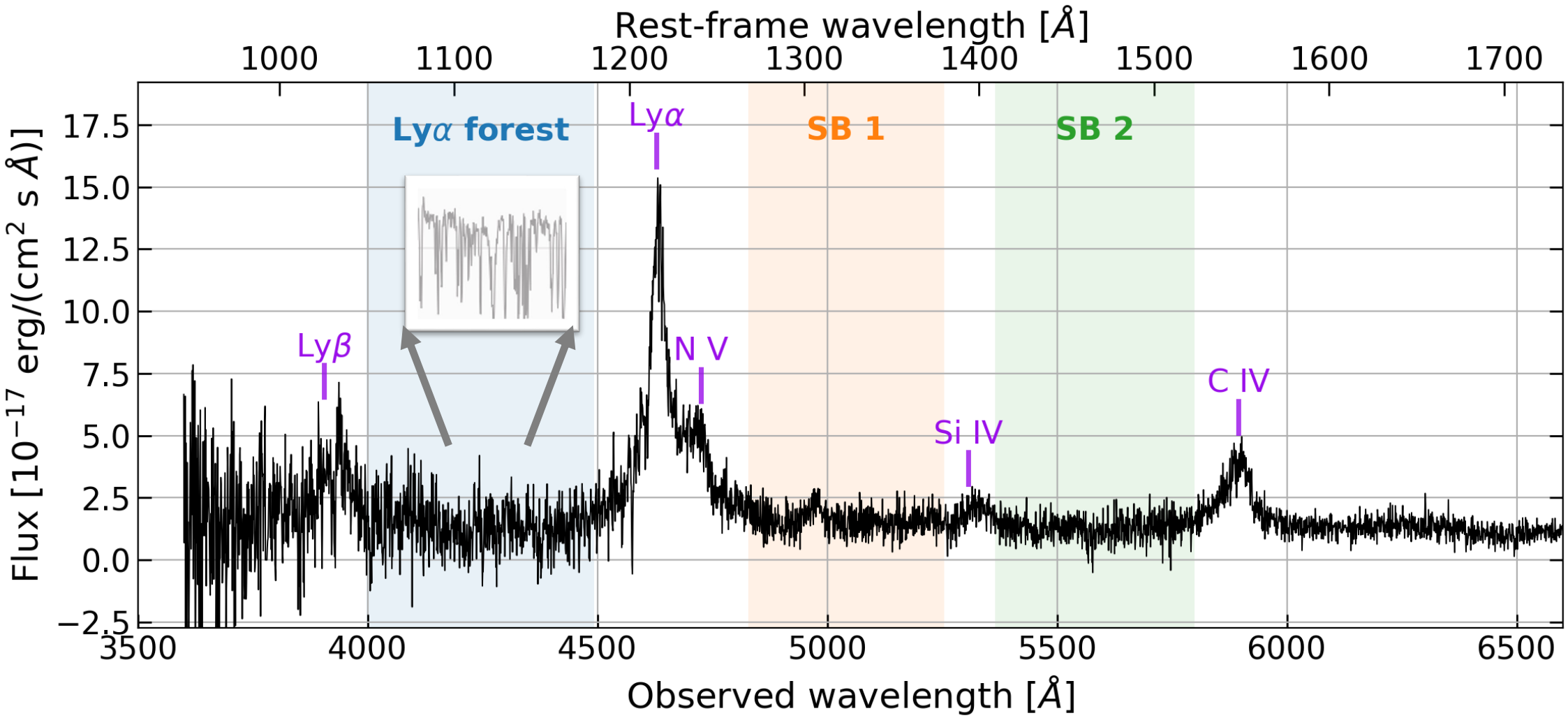

Two DESI challenges

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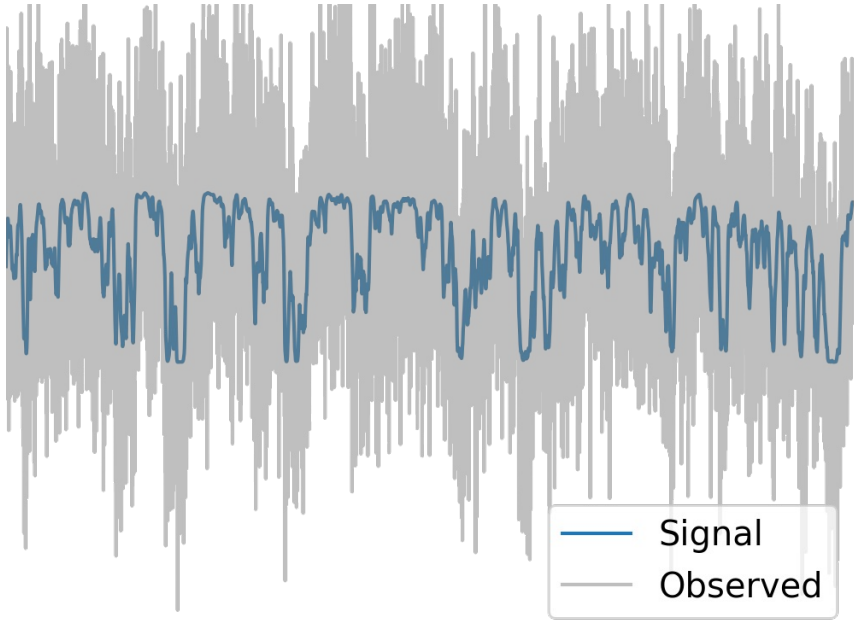
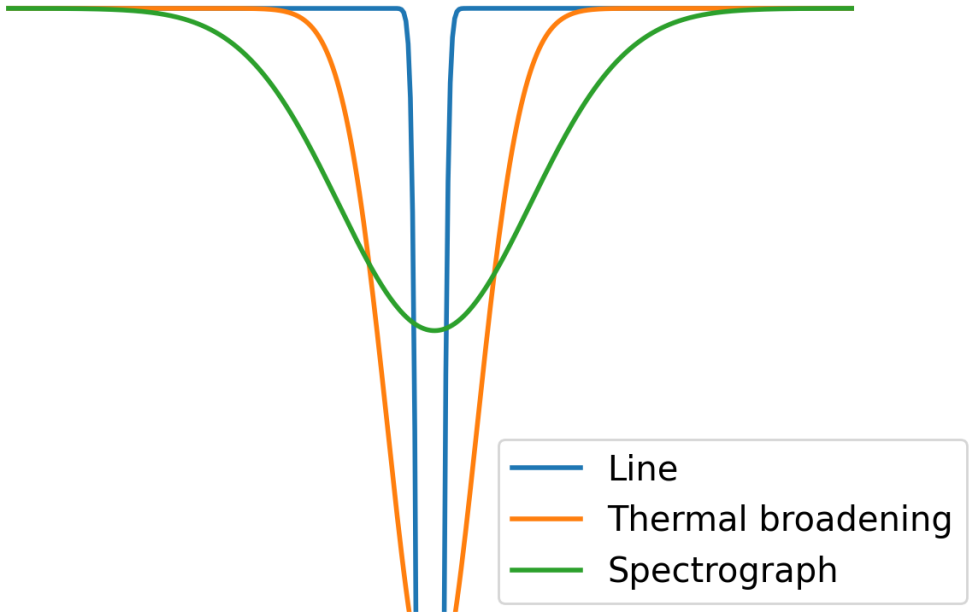
1. Signal is buried under noise. Accuracy of noise calibration is crucial.



2. Spectrograph resolution is comparable to thermal broadening.



DESI EDR Lya P1D

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- Data
  - No SV1 and SV2.
  - Removed quasars with BALs.
- Paper outline
  - Method – Optimal quadratic estimator
  - Validation – Tests on 1D and 2D simulations
  - Systematics
  - Results

1% Survey (SV3)	7,173
Main (Guadalupe)	47,427
Total	**54,600**

Karaçaylı et al. 2023, arXiv:2306.06316

Mock spectra for validation

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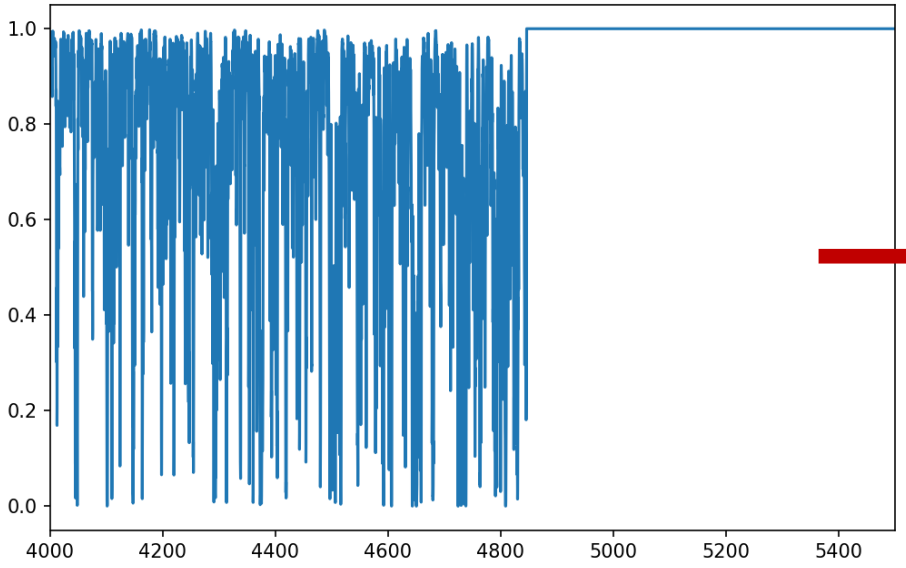

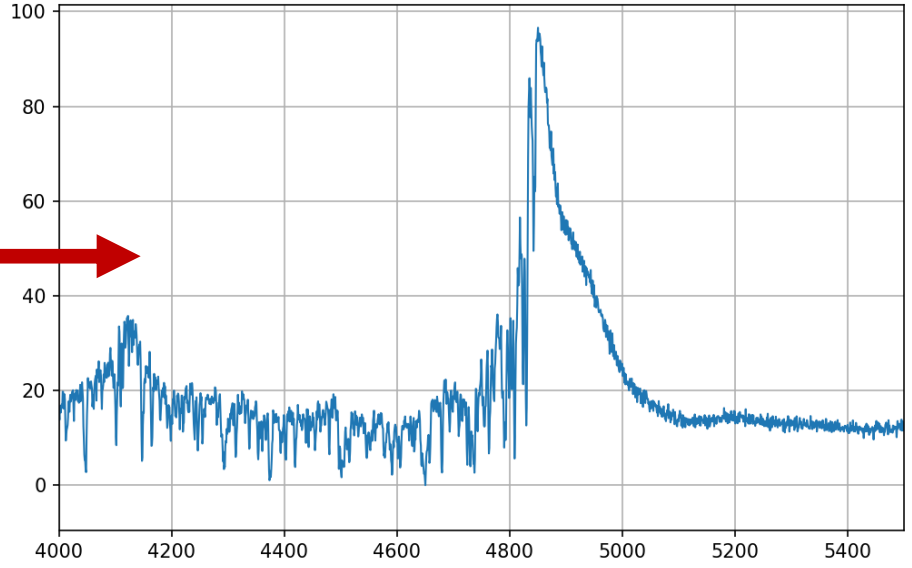

- Lognormal flux field with realistic power spectrum
- Uncorrelated in 3D

+ Quasar continuum
+ Instrument resolution
+ Noise

Validation – Tests on 1D simulations

(quickquasars)

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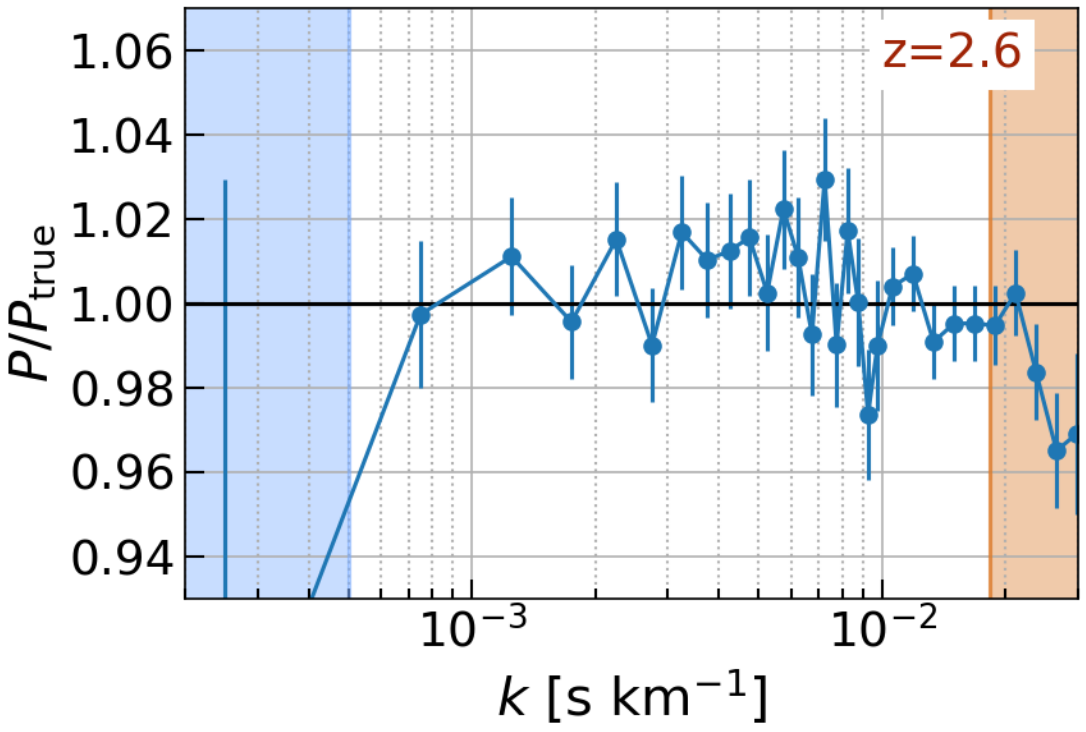
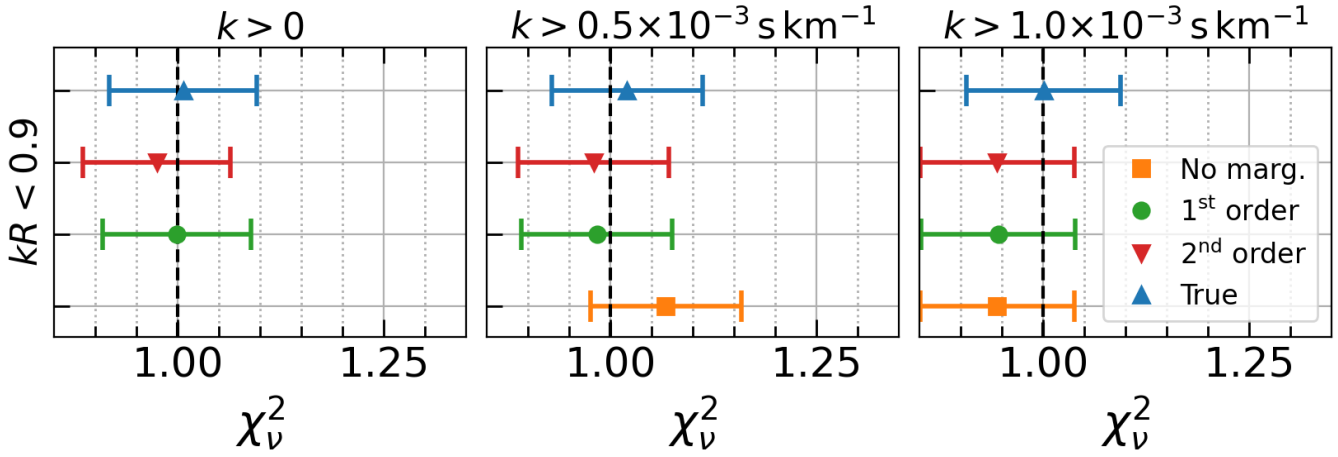


Large-scale cut



Karaçaylı et al. 2023, arXiv:2306.06316

Validation – Tests on 2D simulations

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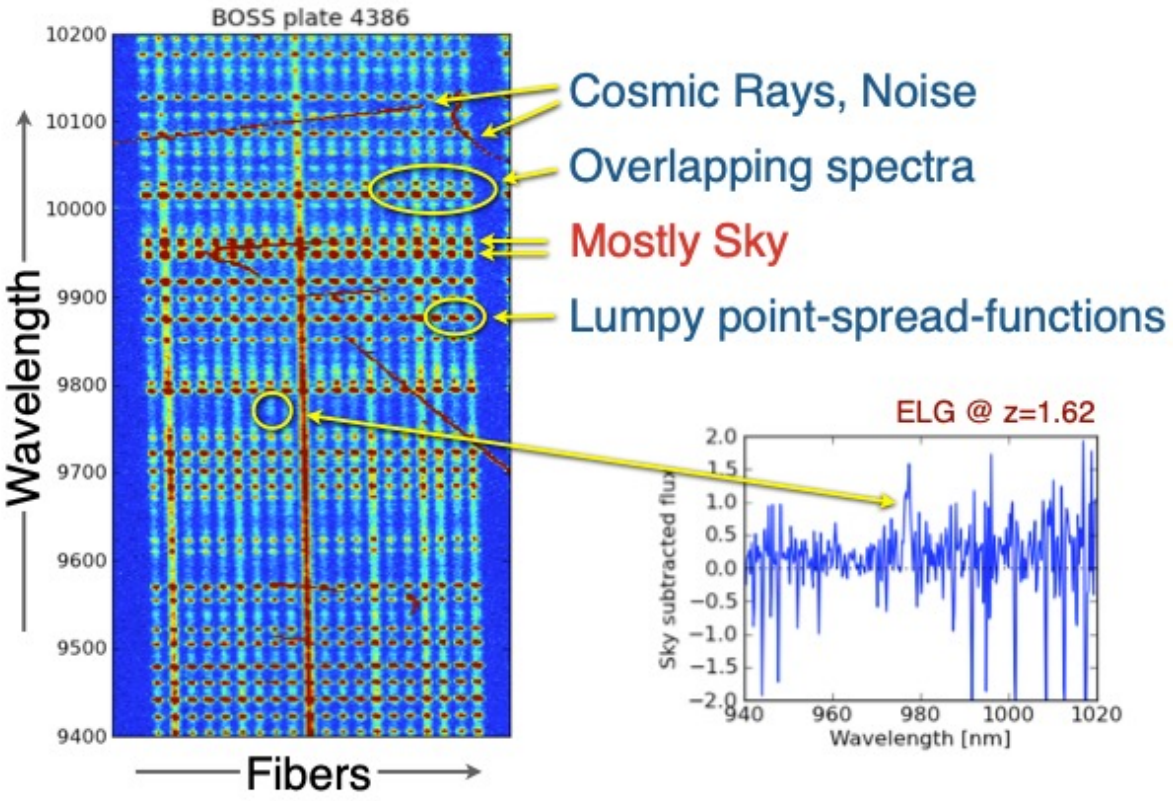
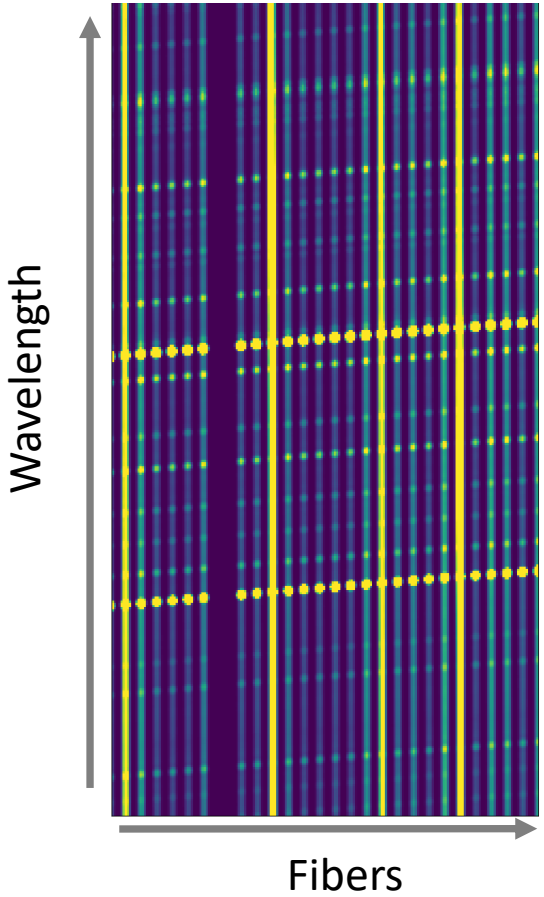
Spectral extraction is the process of turning a 2D image into N 1D spectra.

Raw data (credit: Stephen Bailey)



Simulations

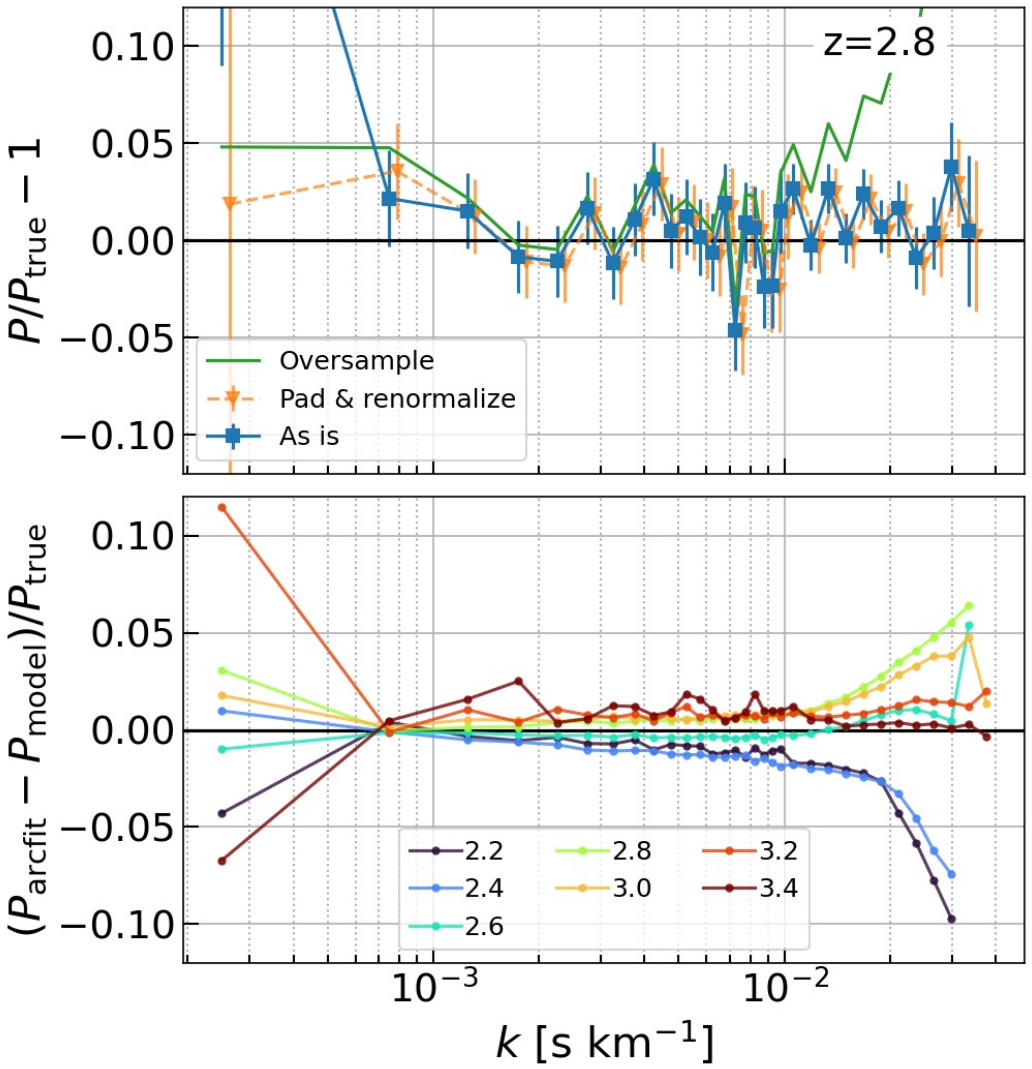


With
- Paul Martini
- Julien Guy

Resolution matrix

- 45 000 quasars, only B arm
- Uniform redshift distribution between 2.6 and 3.6

$$\delta_{\mathrm{obs}} = \mathbb{R}\,\delta_{\mathrm{model}}$$



Karaçaylı et al. 2023, arXiv:2306.06316

Recalibrate noise estimate

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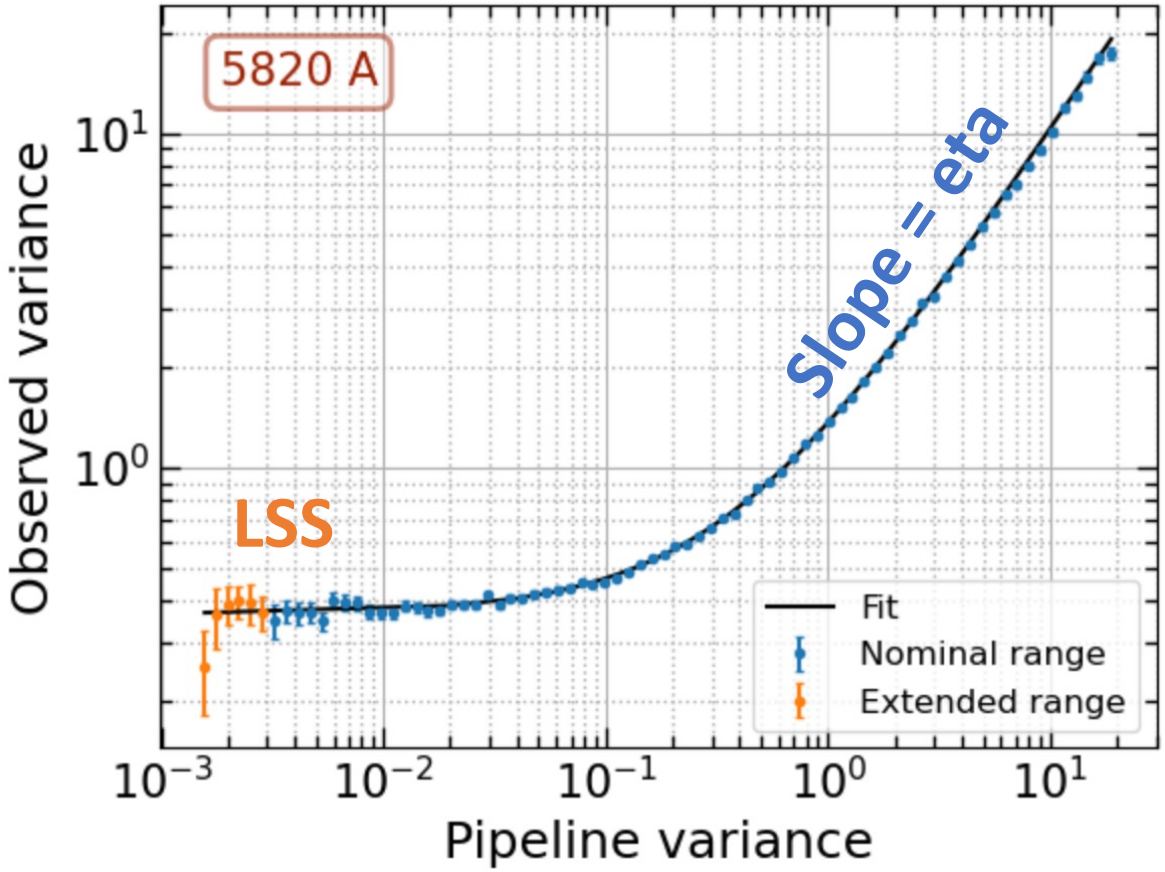
- Bin spectrum pixels with respect to reported pipeline variance.
- Compare the observed variance to pipeline variance.

$$\sigma^2(\lambda_p) = \eta(\lambda_p)\sigma^2_{\rm pipe}(\lambda_p) + \sigma^2_{\rm LSS}(\lambda_p)$$

- Pipeline noise correction, eta
- Large-scale structure variance



Recalibrate pipeline noise estimate

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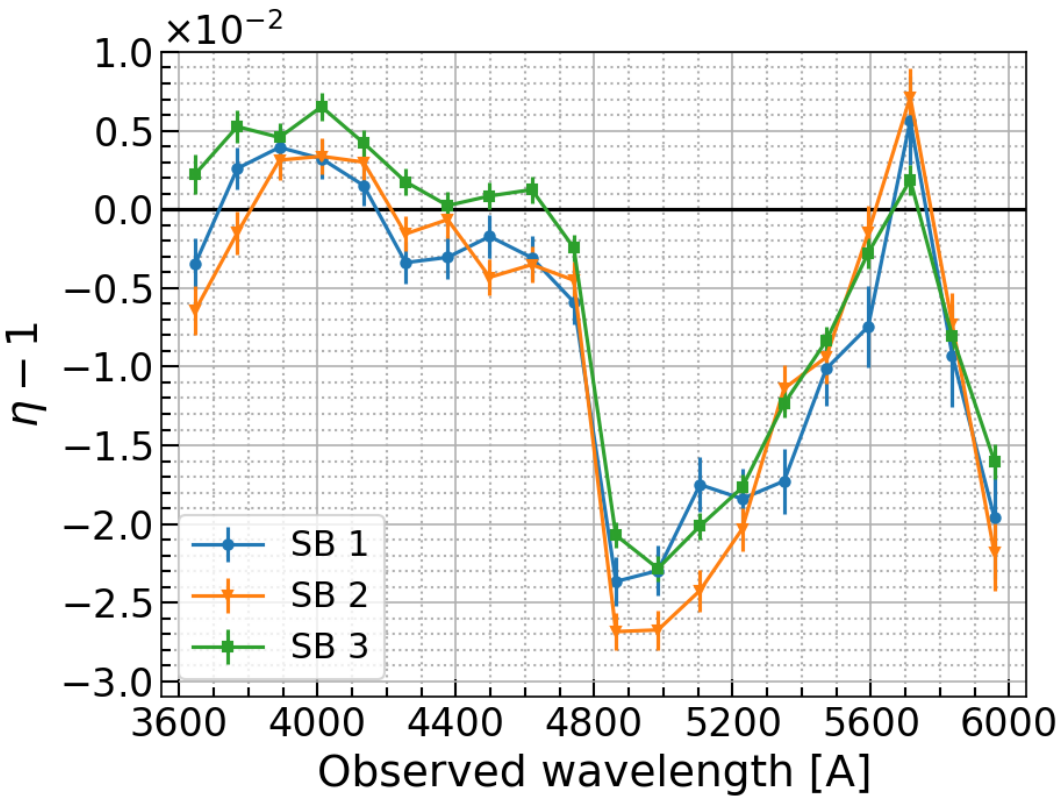
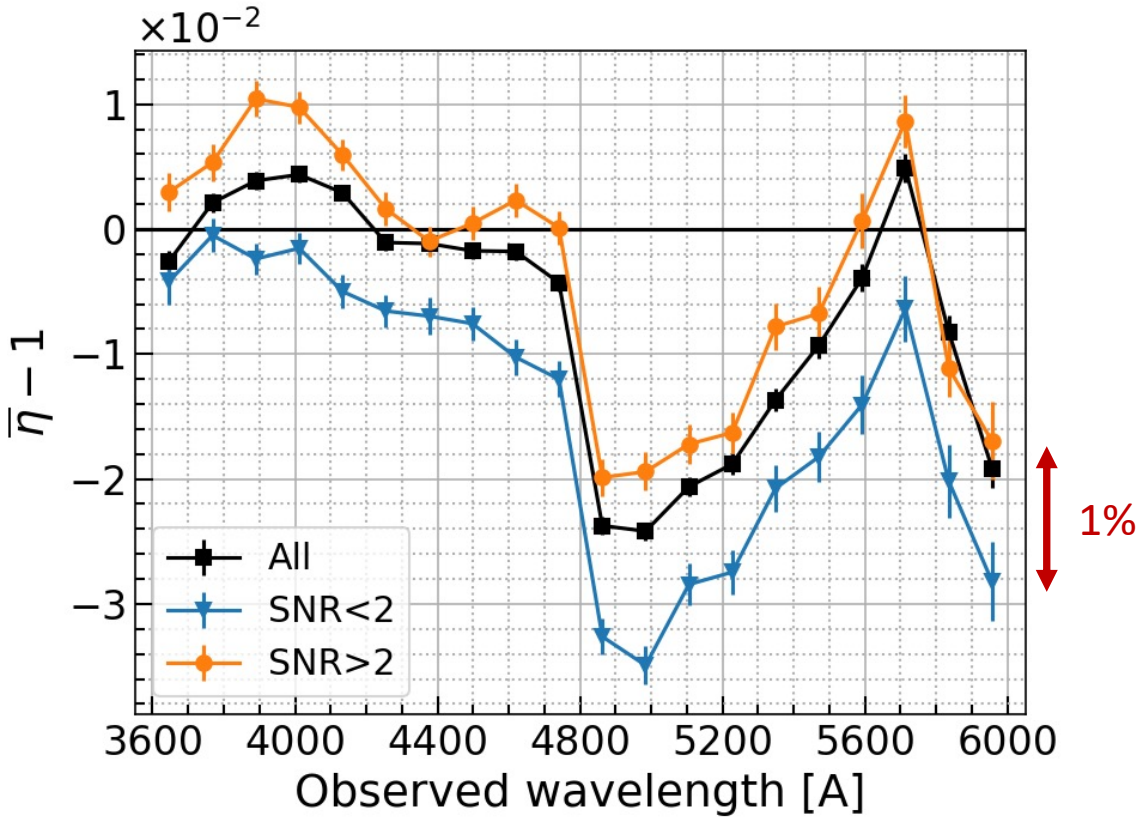
Noise calibration correction

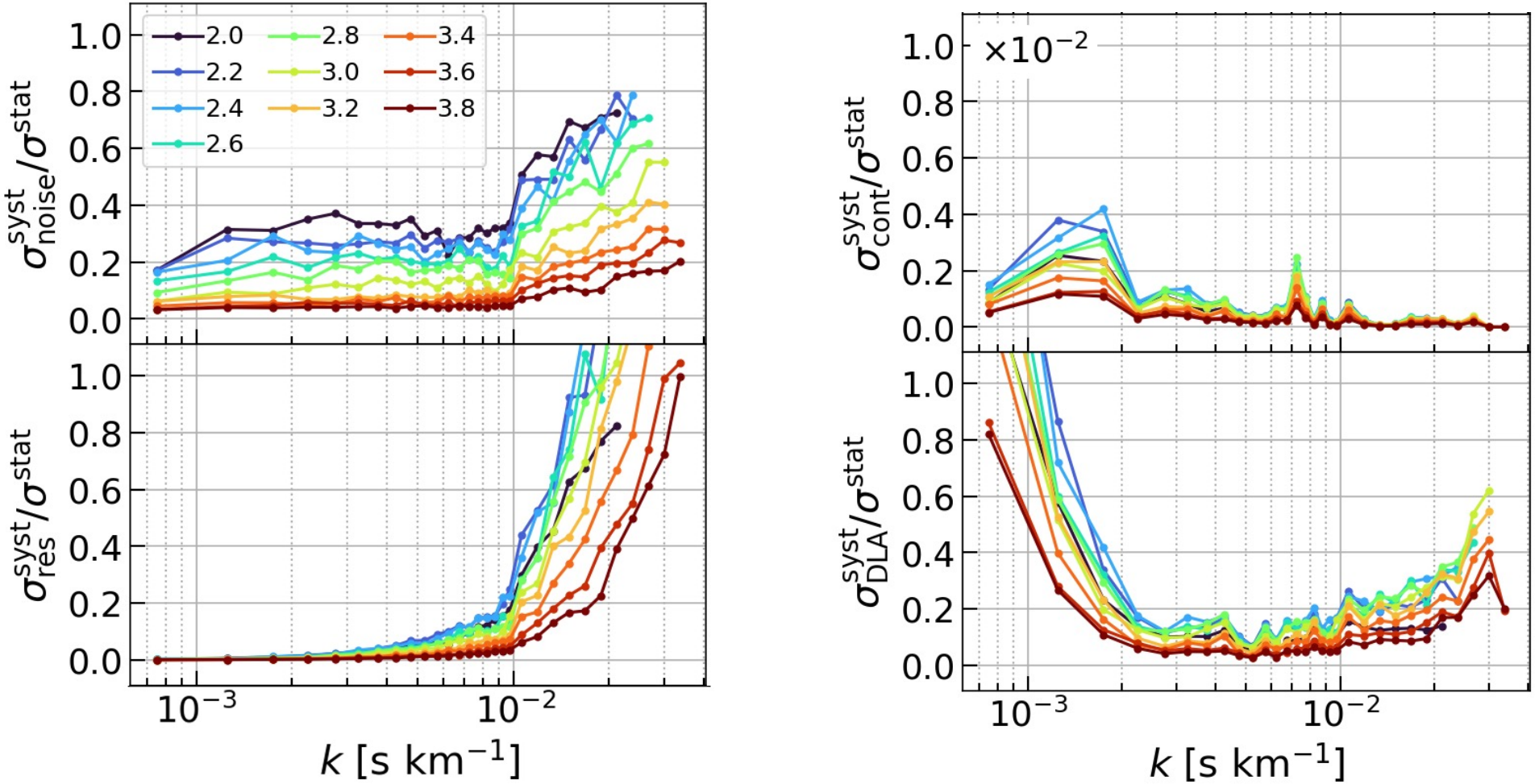


SNR dependence of this correction



Karaçaylı et al. 2023, arXiv:2306.06316

Systematics



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Effects on parameters

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Need work for Year 1 to take full advantage of data!

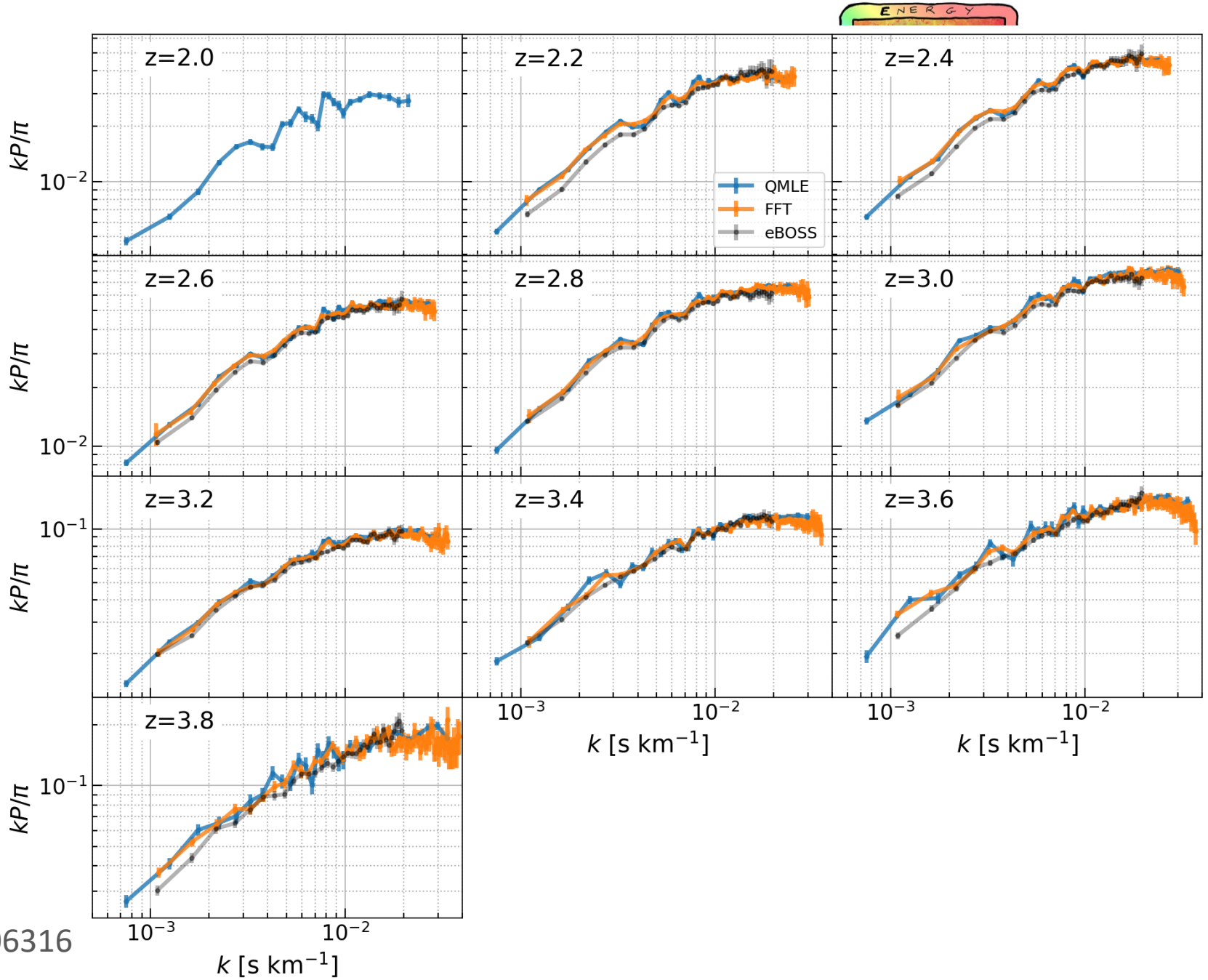
Systematics	Increase in error A	n	α
Noise	49.8%	6.9%	0.7%
Resolution	34.0%	89.1%	26.5%
DLA	0.9%	2.8%	30.5%
All	74.3%	99.9%	62.5%

Table 2. Percentage increase in error given by the minimizer for each systematics at $z = 2.8$. The precision of the amplitude A is nearly equally affected by noise and resolution systematics, whereas for n, it is thoroughly affected by resolution systematics.

$$P_{\rm base}(k) = \frac{A\pi}{k_0}\left(\frac{k}{k_0}\right)^{2+n+\alpha \ln k/k_0}$$

Karaçaylı et al. 2023, arXiv:2306.06316

Comparison with eBOSS, FFT



Good agreement with the FFT result, which is on similar data and a different analysis pipeline!

Karaçaylı et al. 2023, arXiv:2306.06316

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Metals properties through P1D

What is in the side bands?

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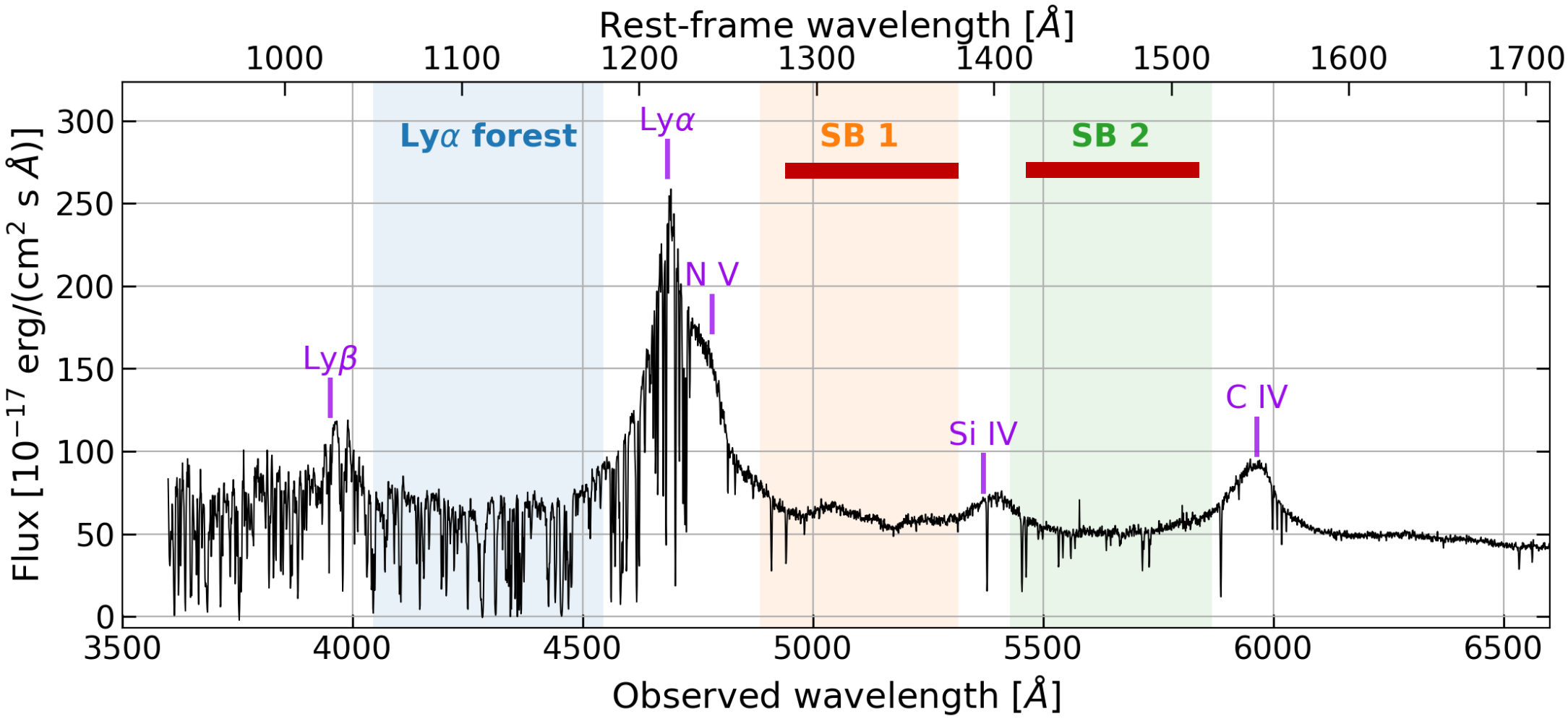

What is in the side bands?

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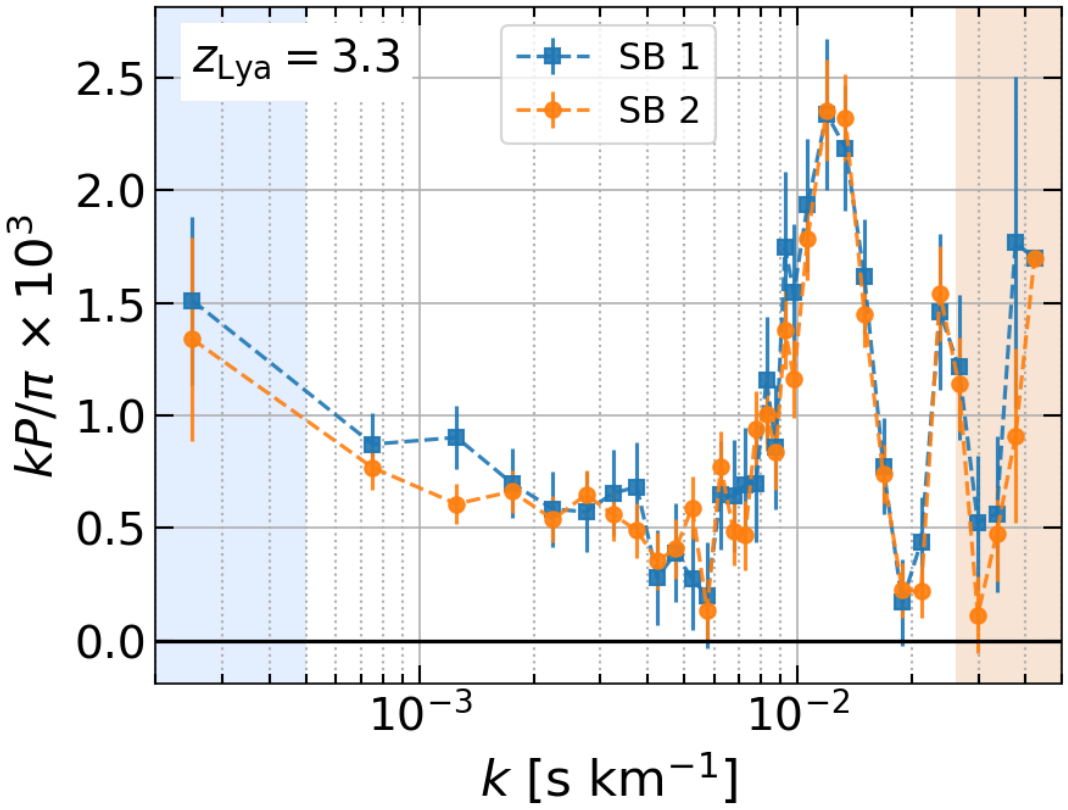
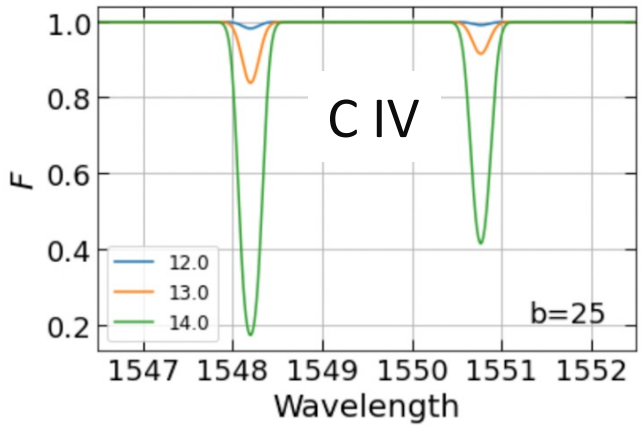


- Strong metal transitions such as
  C IV, Si IV and Mg II.
- They have a clear signal in DESI power spectrum!
- Most common method in literature is identification using high-resolution, high-SNR spectra.



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Metal abundance model

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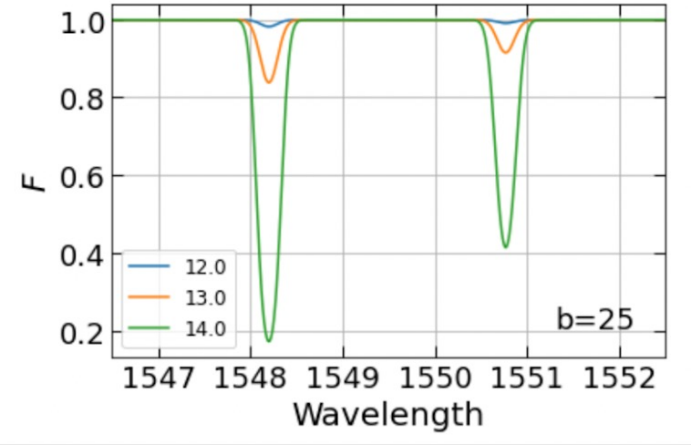
We can analytically describe metal P1D using three quantities:

- Abundance (column density distribution)
- Temperature (effective Doppler parameter)
- Clustering (cloud-cloud correlation function)

$$\langle K_{\rm tot} K_{\rm tot} \rangle = \sum_i \langle K_i K_i \rangle + \sum_{i \neq j} \langle K_i K_j \rangle .$$

K is the absorption profile.



Karaçaylı et al. 2023, MNRAS, 522, 5980

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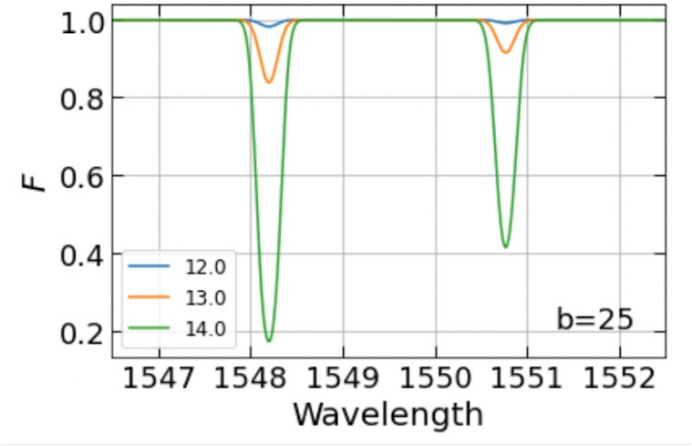
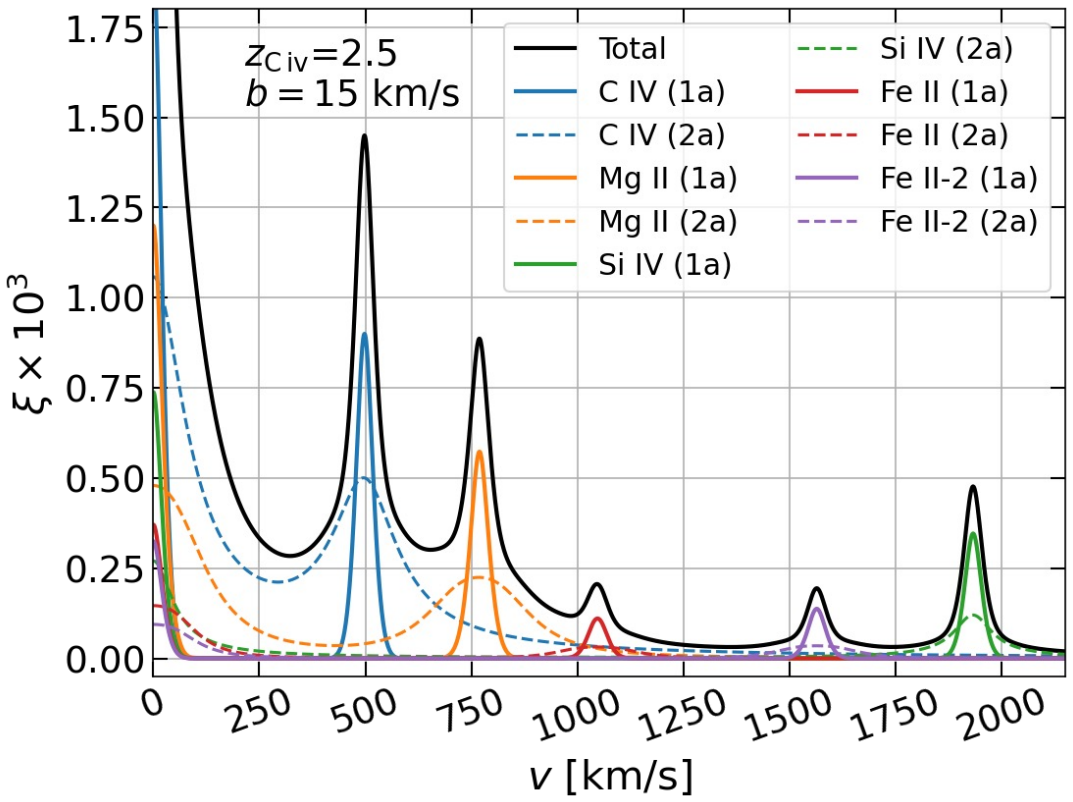
$$\xi_{1a}(v) = \int \mathrm{d}N_i f(N_i) \int \mathrm{d}v' K_i(v') K_i(v'+v) \tag{11}$$

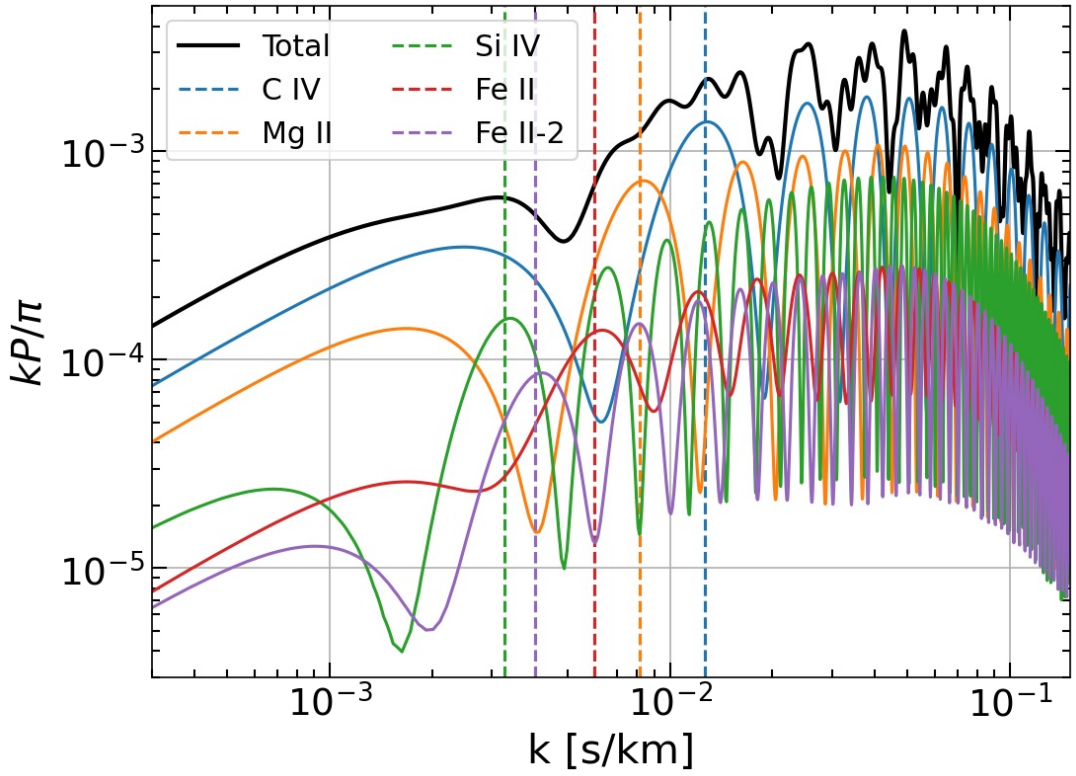
$$\xi_{2a}(v) = \int \mathrm{d}N_i \mathrm{d}N_j f(N_i) f(N_j) \times \int \mathrm{d}x \mathrm{d}v' K_i(v') K_j(v'+x+v) \xi_{cc}(x; N_i, N_j), \tag{12}$$



Karaçaylı et al. 2023, MNRAS, 522, 5980

Metal abundance model





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Time evolution of ion abundance

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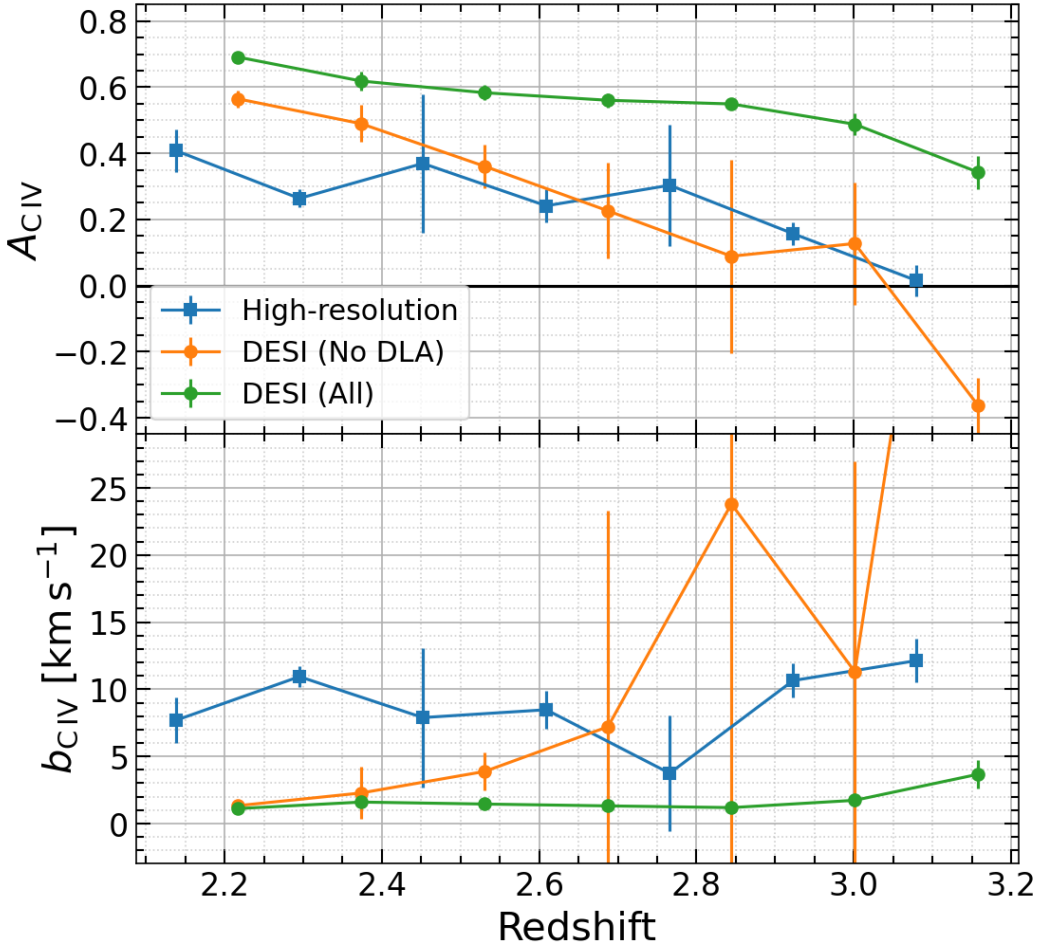

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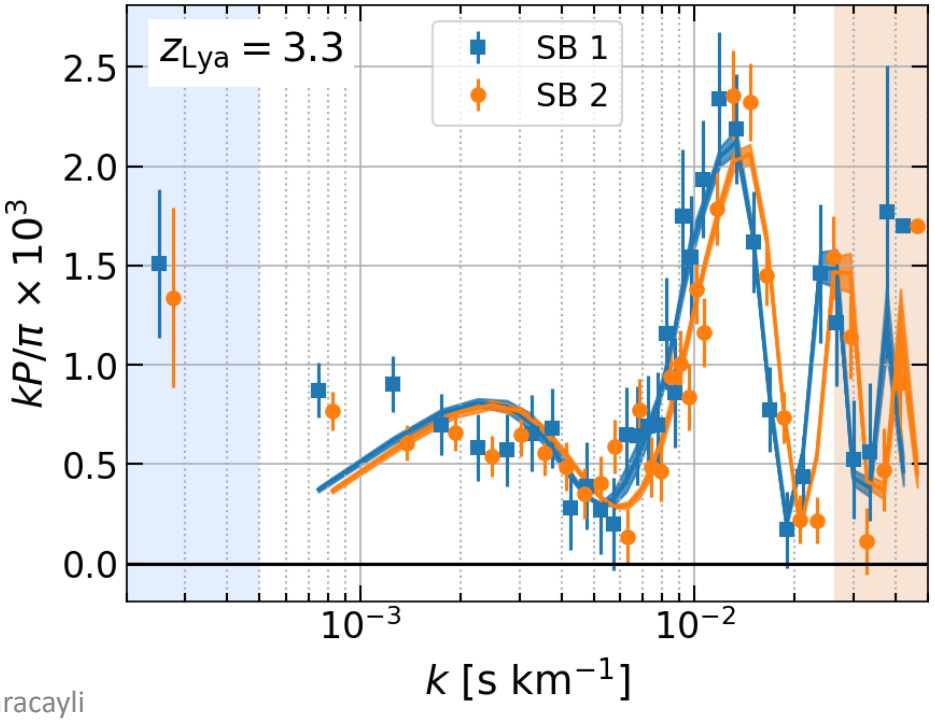
We can investigate time evolution of abundance (column density distribution).

$$f(N) = 10^{-12.7+A}\left(\frac{N}{10^{13}\ \mathrm{cm}^{-2}}\right)^{-1.8}$$



Plans for Y1

Plans for Y1

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450,000 Lya quasars! -> More work into systematics

We identified possible solutions to noise and resolution systematics.

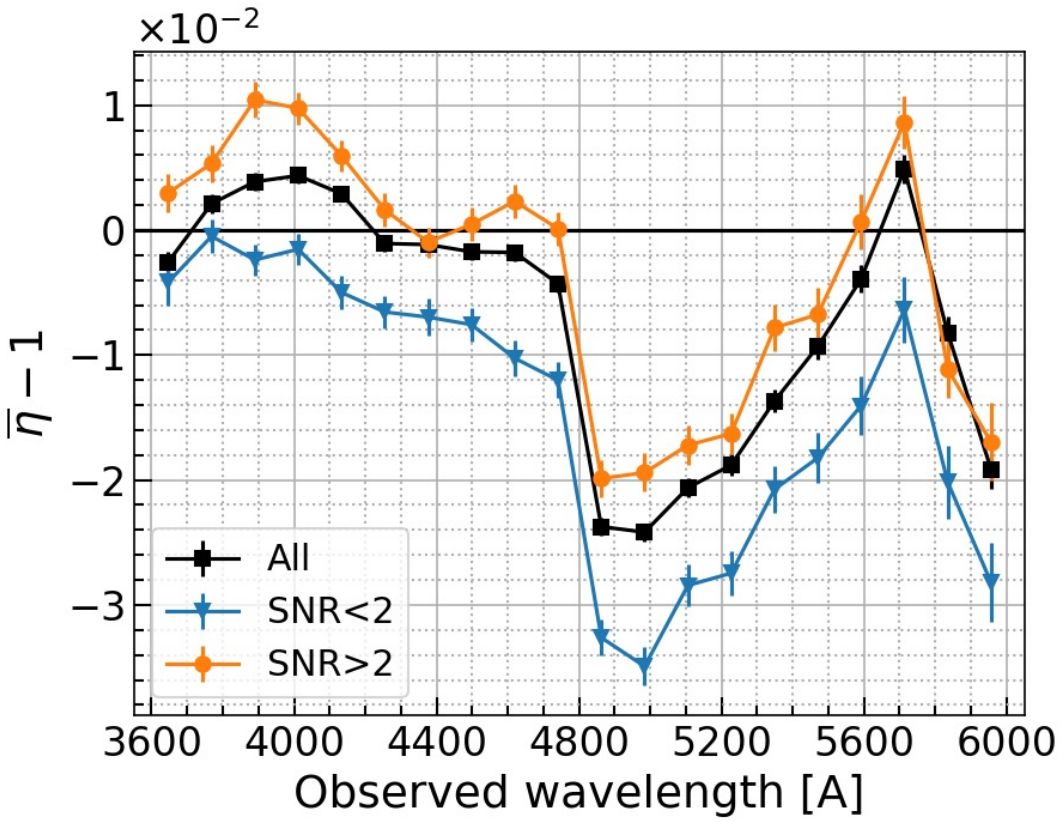
+ DLA finder.
+ Mask BAL features and recover those spectra.
+ Version control.
+ Coordination with FFT.

Other projects for Y1:

- CMB lensing x P1D
- Repeat metal model analysis

GPUs

Noise calibration SNR dependence

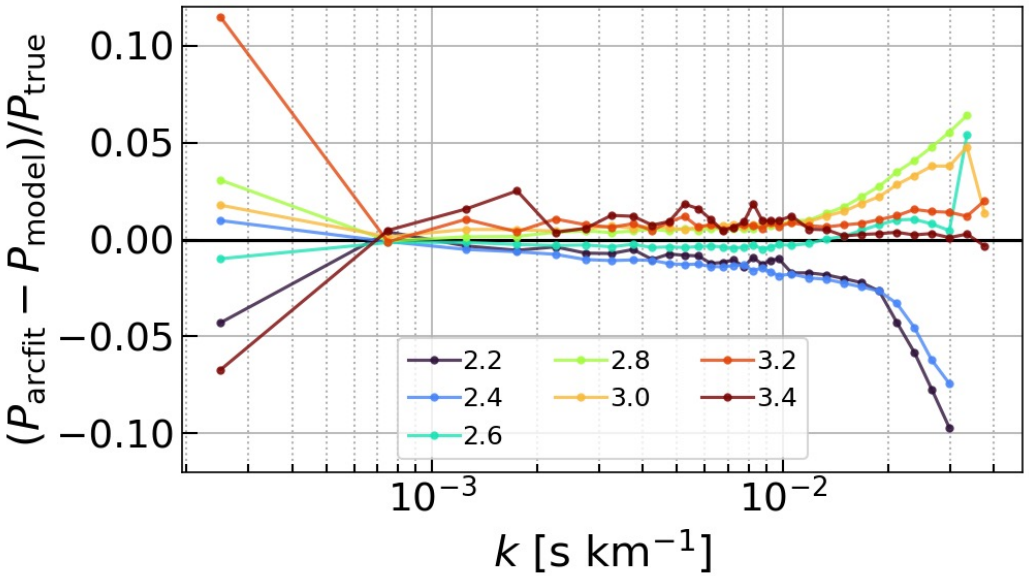


$$\sigma^2(\lambda_p) = \eta(\lambda_p)\sigma^2_{\rm pipe}(\lambda_p) + \sigma^2_{\rm LSS}(\lambda_p)$$

- ~ 1 million quasars in Y1 for eta analysis
- Quantify eta in multiple SNR bins

$$\eta = \eta(\lambda, \mathrm{SNR})$$

Resolution systematics



Model fit to ARC lamp exposure vs true PSF

- Accurately quantify the bias due to model with more simulations.
- (Difficult) change the model.
- Can be helpful in noise calibration errors too.

Summary

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- DESI will have the statistical power to tightly constrain the sum of the neutrino masses. $\sigma_{\sum m_\nu} = 0.02$ eV
- P1D from DESI EDR+ (54,600 quasars).
- We identified the major systematics error sources, noise and resolution. The systematics are comparable to statistical errors.
- There is a plan to reduce these errors.

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We are honored to be permitted to conduct scientific research on Iolkam Du'ag (Kitt Peak) in Arizona, a mountain with particular significance to the Tohono O'odham Nation.

Thanks to our sponsors and 69 Participating Institutions!