



Universiteit Leiden

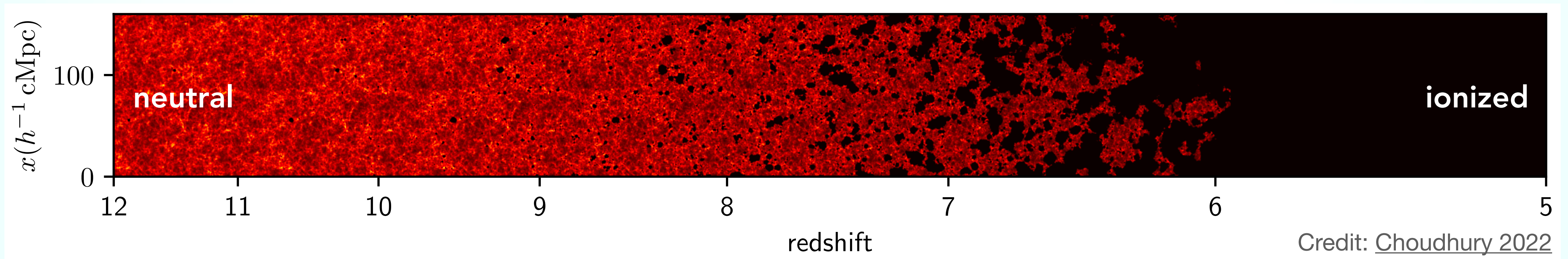


Towards precision constraints on reionization history with quasar IGM damping wings

Timo Kist, PhD candidate at Leiden Observatory
Supervisor: Joseph F. Hennawi

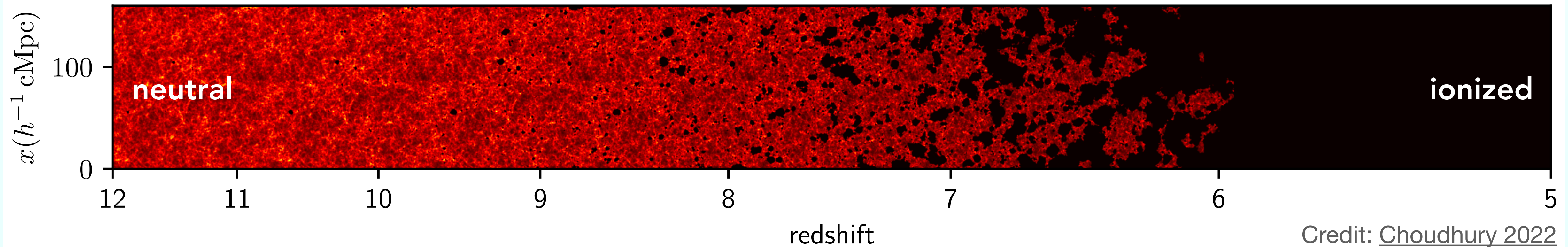
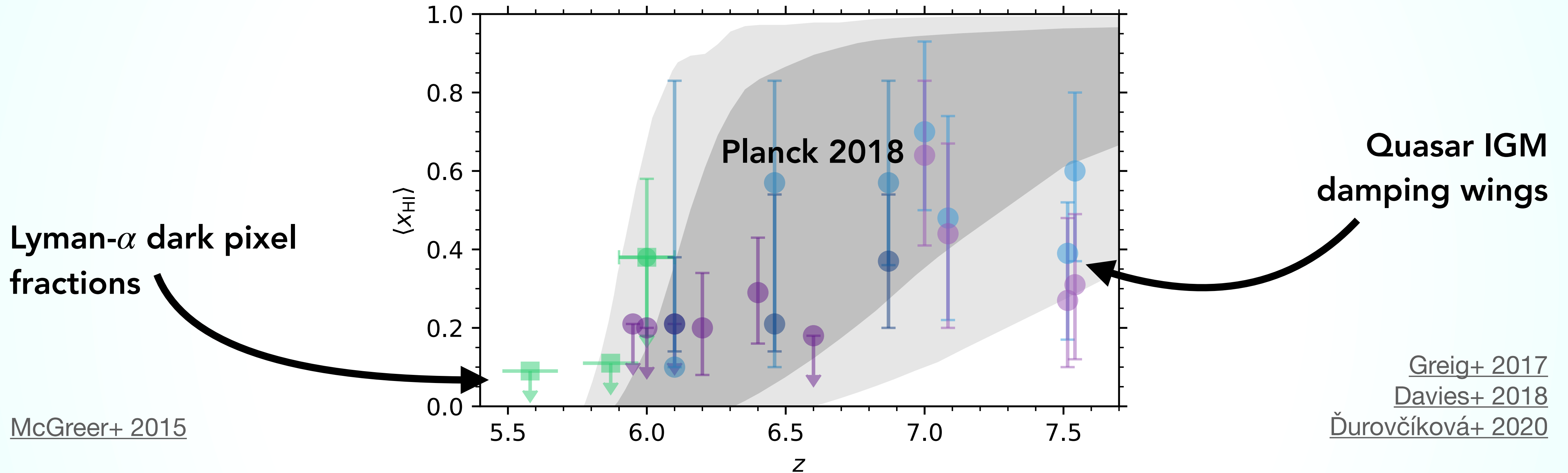
Quasars in a Reionizing Universe

Proximity Zones & IGM Damping Wings



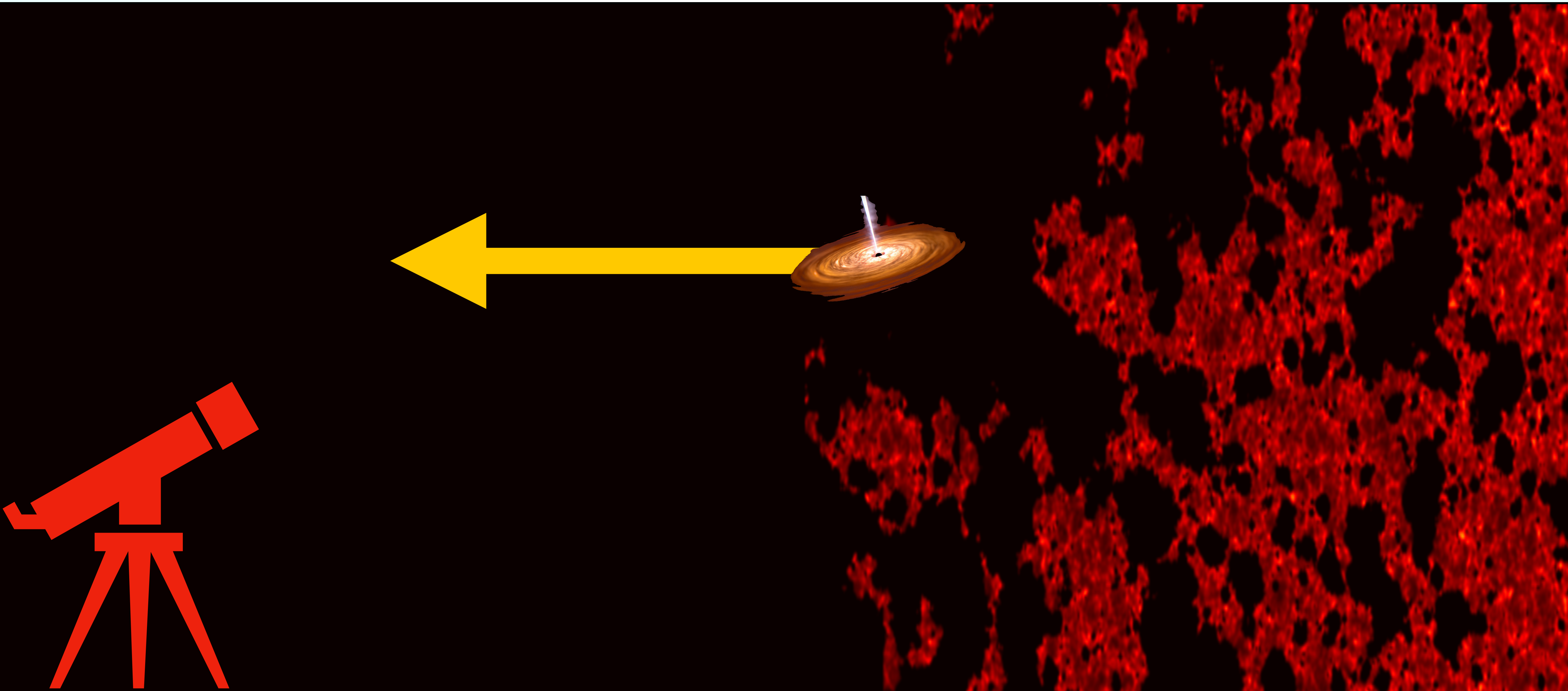
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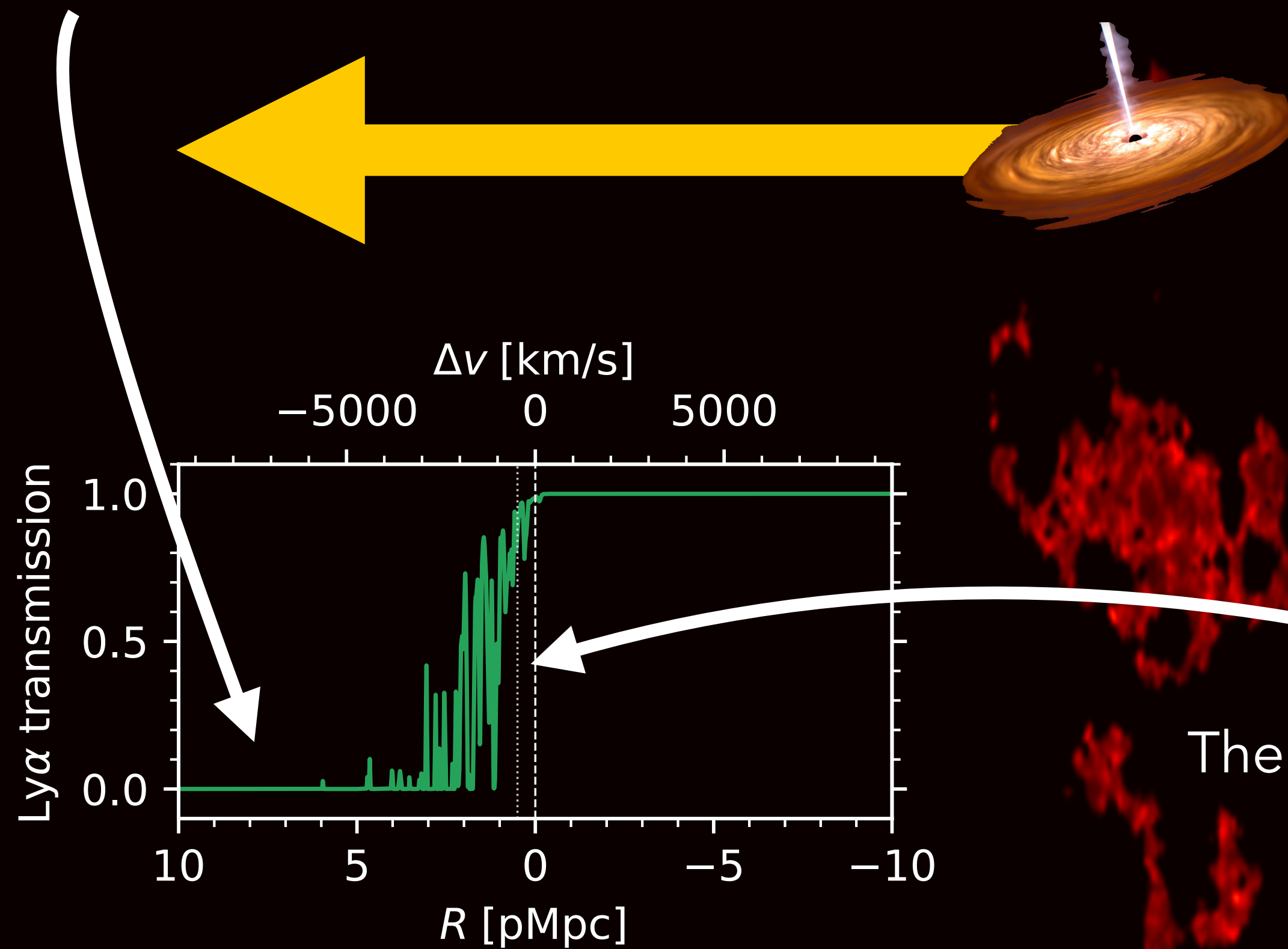
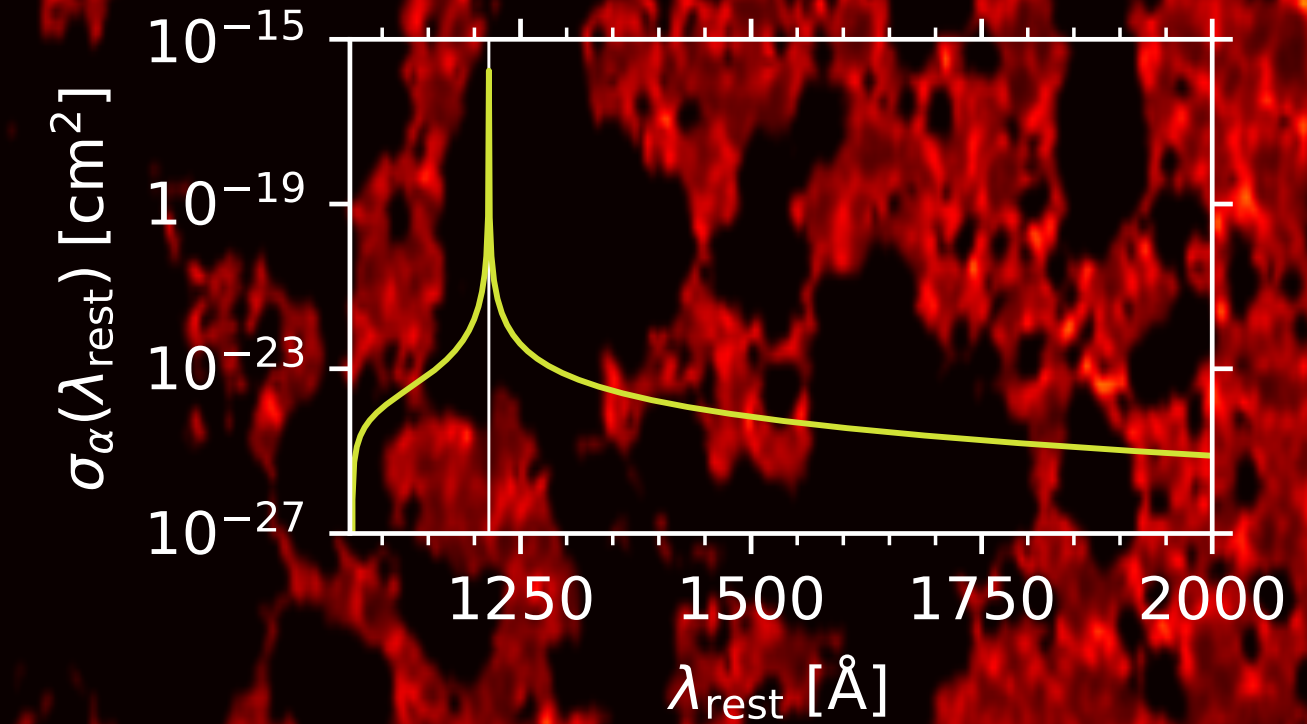


Quasars in a Reionizing Universe

Proximity Zones & IGM Damping Wings

Gunn-Peterson trough:

Complete absorption in the Ly- α forest region starting at IGM neutral fractions $\langle x_{\text{HI}} \rangle \gtrsim 10^{-4}$



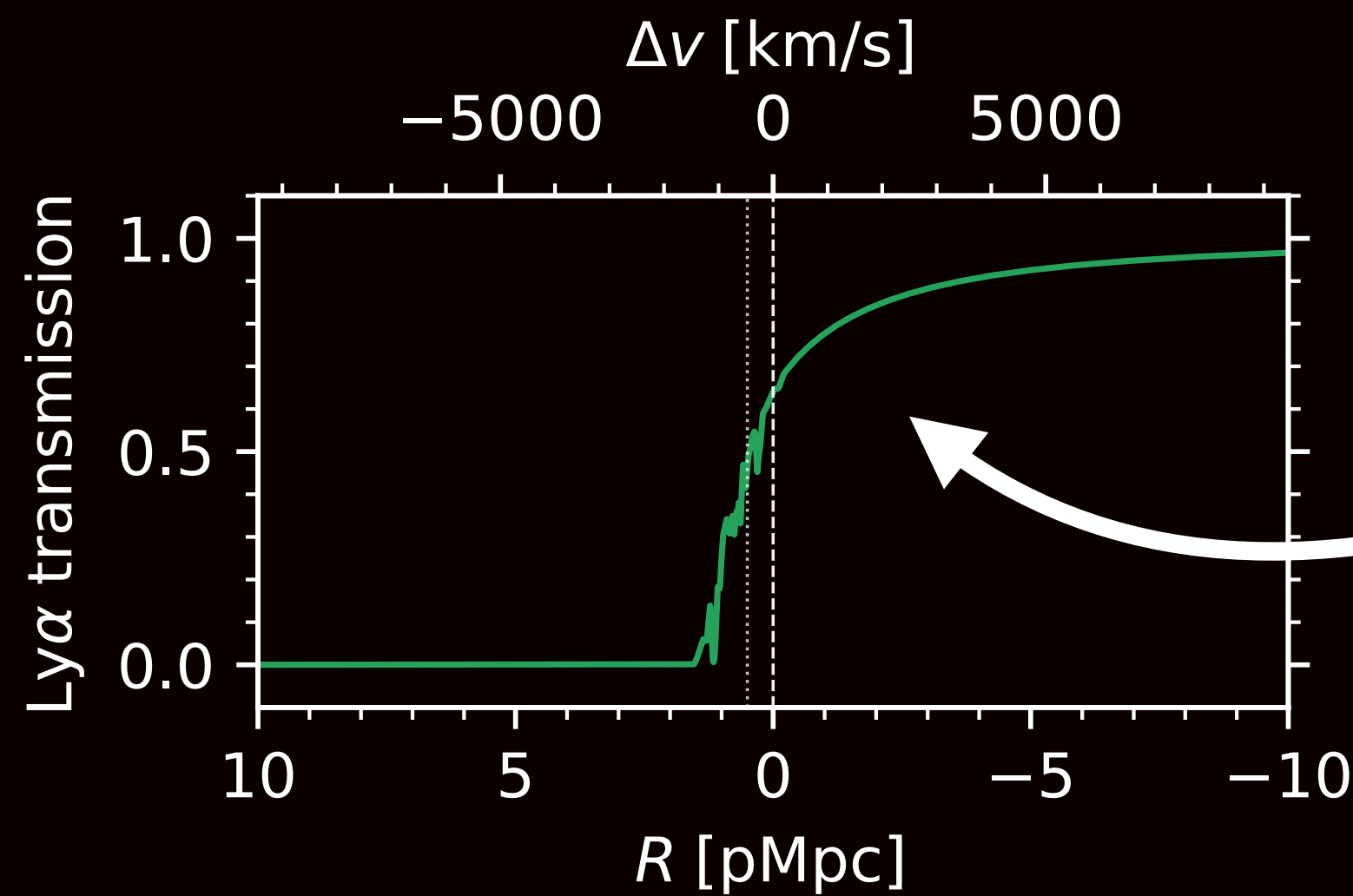
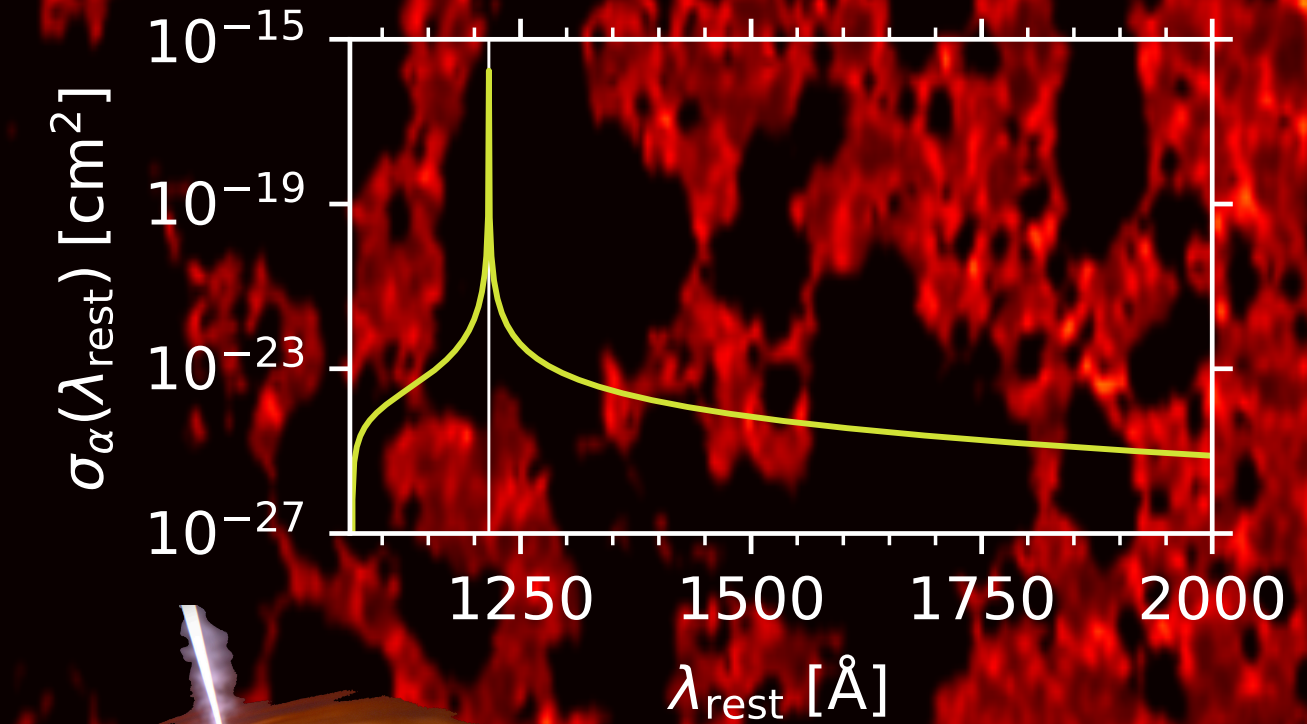
Quasar proximity zone:

The quasar carves out an ionized bubble whose size depends on its lifetime



Quasars in a Reionizing Universe

Proximity Zones & IGM Damping Wings



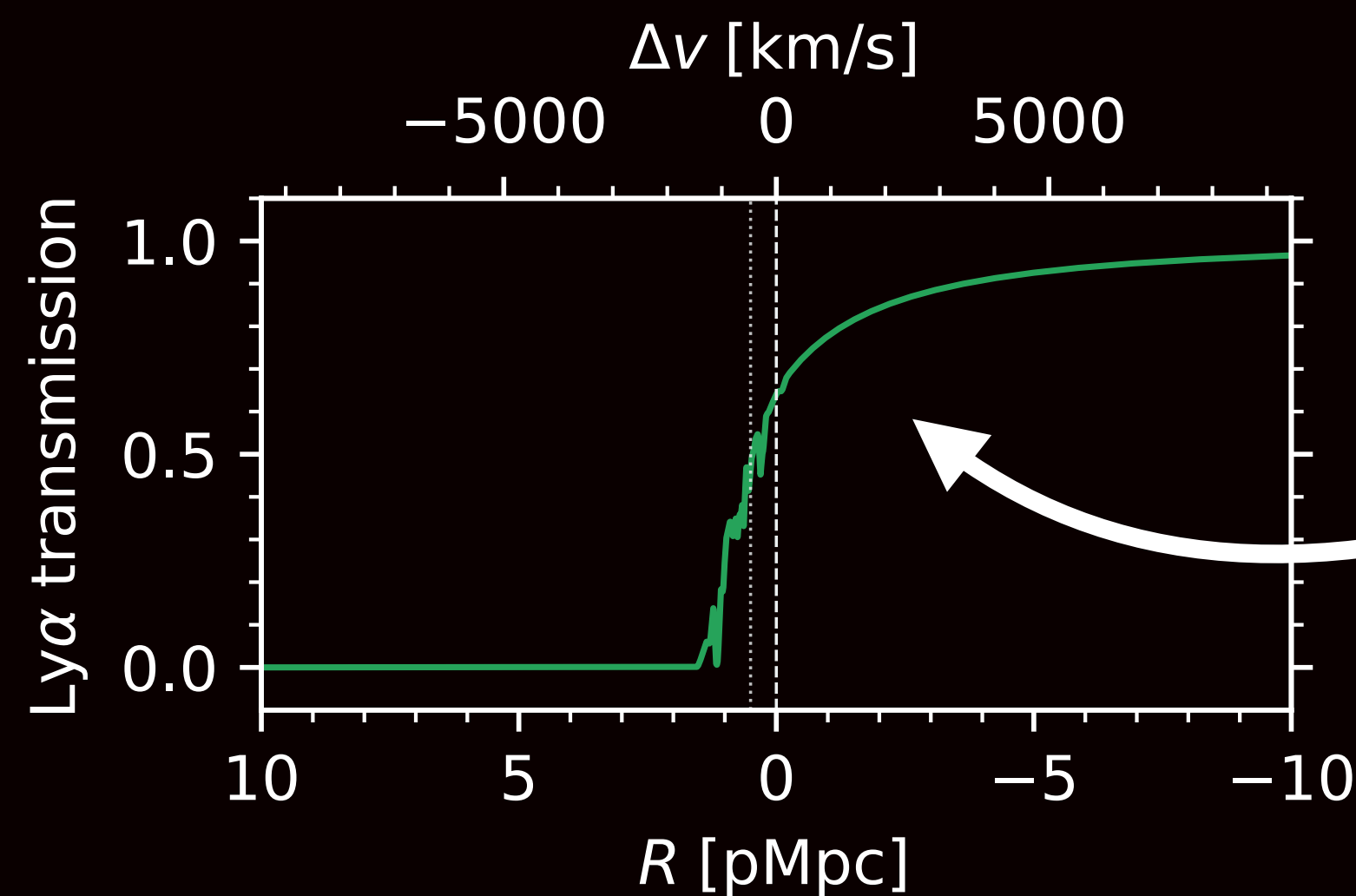
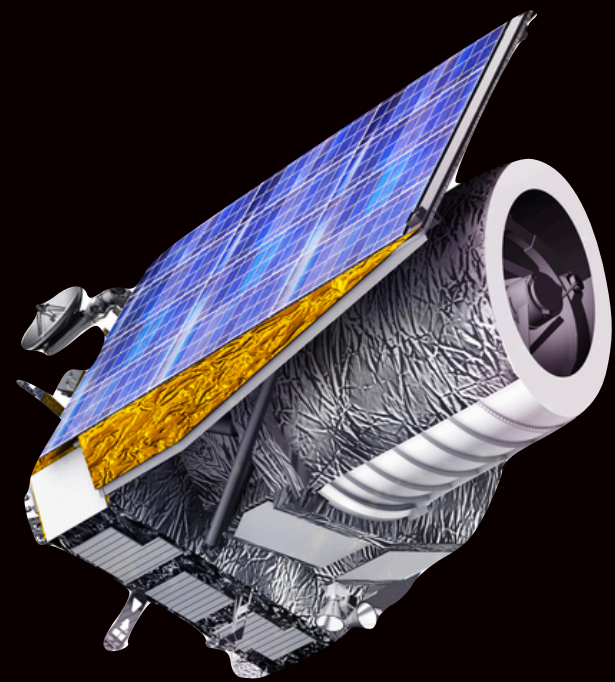
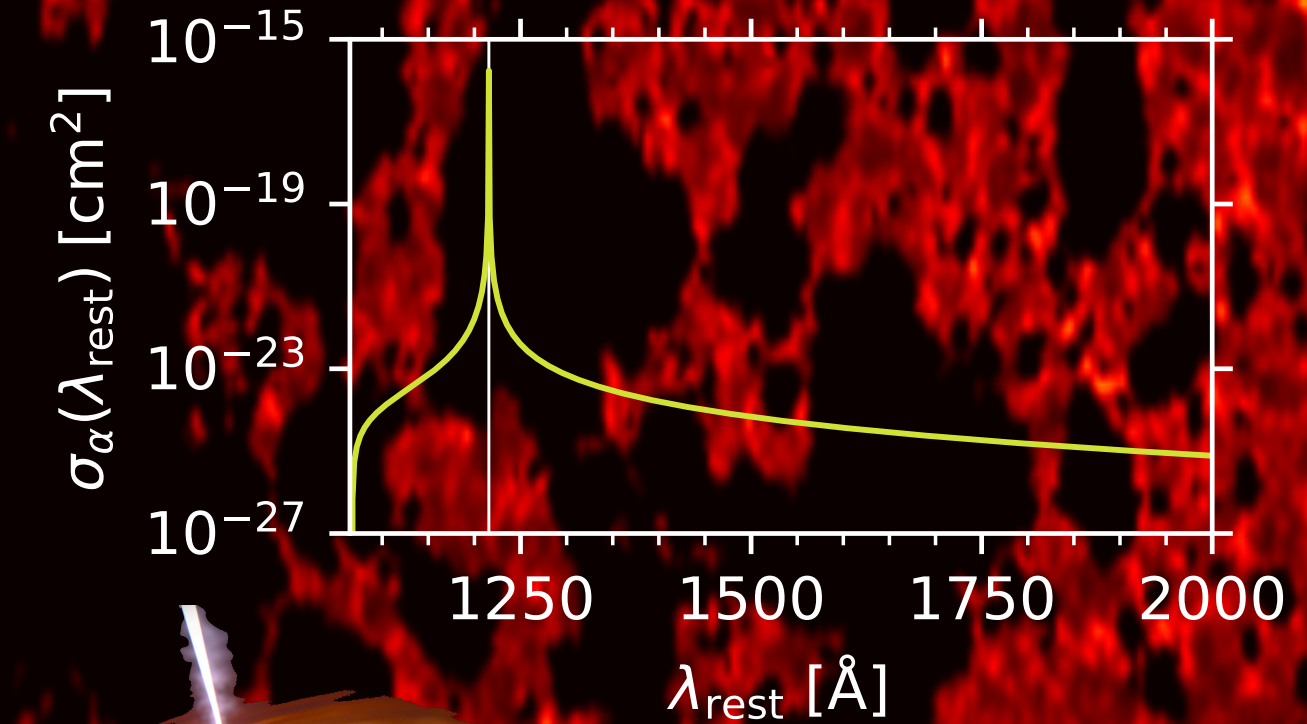
IGM damping wing:
 At $\langle x_{\text{HI}} \rangle = O(0.1)$, even the Lorentzian wing of the Lyman- α cross section becomes visible



Quasars in a Reionizing Universe

Proximity Zones & IGM Damping Wings

Euclid will find
hundreds of QSOs at $z > 6$



IGM damping wing:
At $\langle x_{\text{HI}} \rangle = O(0.1)$, even the Lorentzian wing
of the Lyman- α cross section becomes visible

Forward-Modelling Damping Wing Absorption

Constructing realistic skewers based on cosmological simulations

Nyx hydrodynamical simulations:

1200 density and temperature skewers around the most massive DM halos

21cmFast:

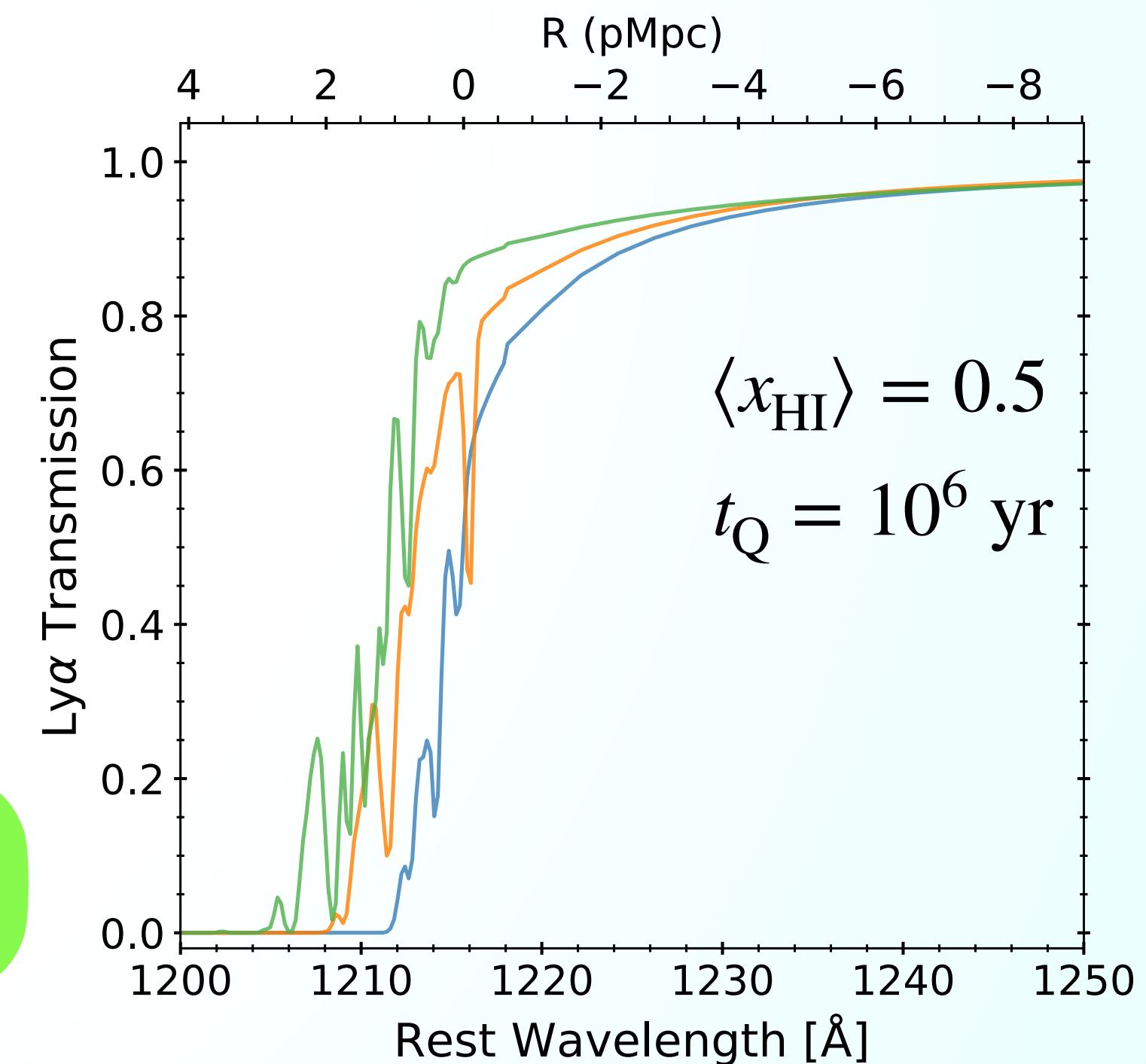
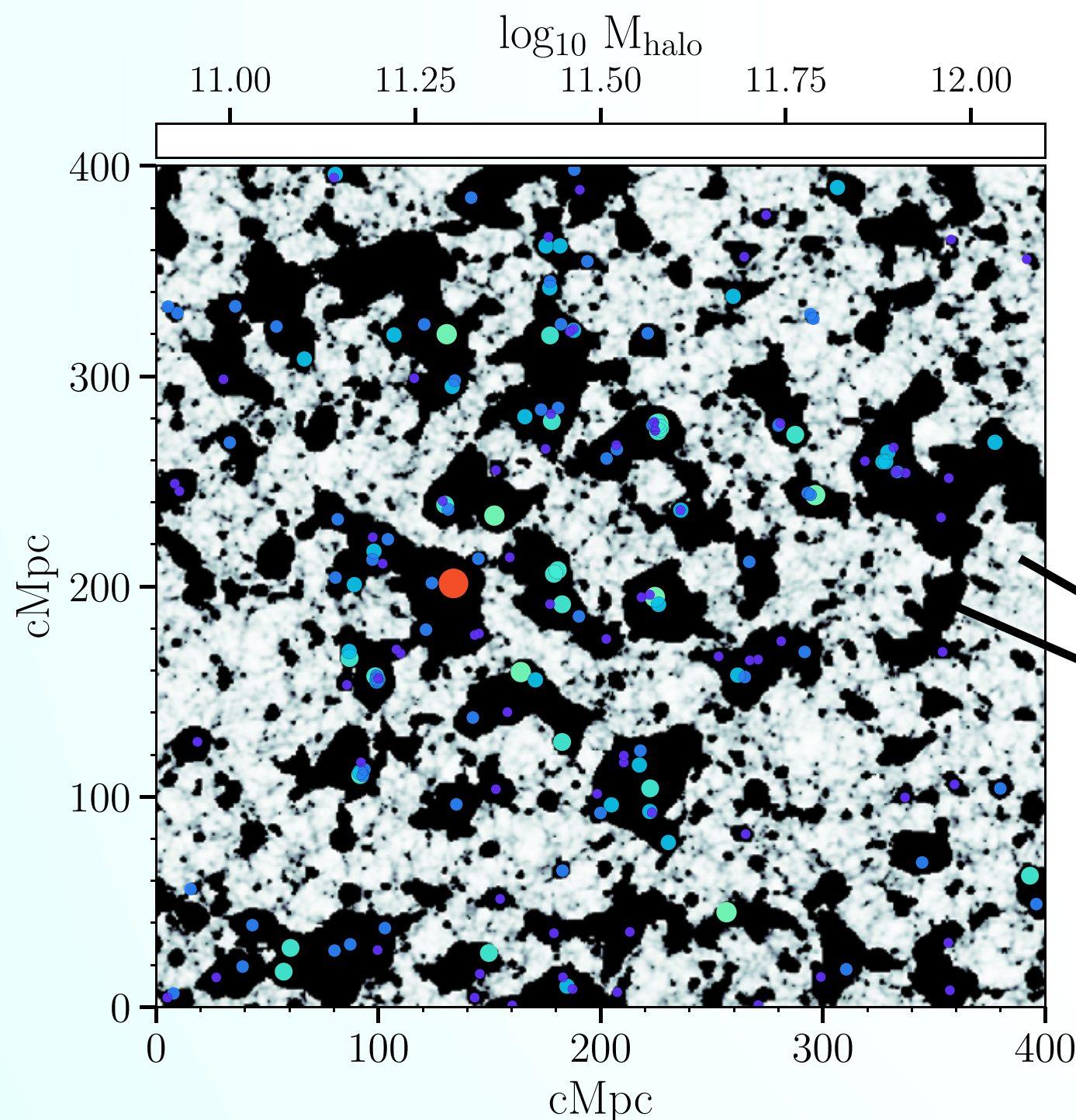
21 reionization topologies ($0 \leq \langle x_{\text{HI}} \rangle \leq 1$) with 10 000 x_{HI} skewers each

1D Radiative Transfer

51 quasar lifetimes between $10^3 \text{ yr} \leq t_Q \leq 10^8 \text{ yr}$

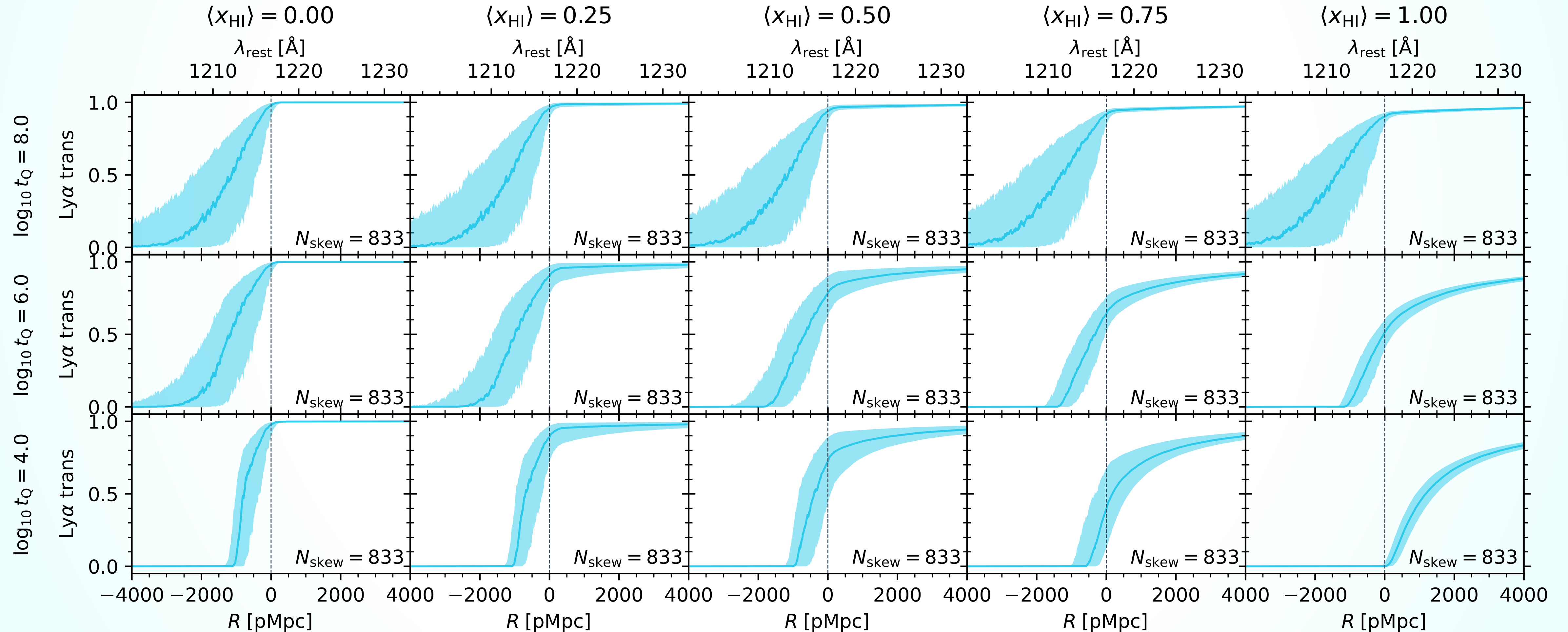
white: neutral
black: ionized

1200 x 21 x 51 grid of Ly- α transmission skewers



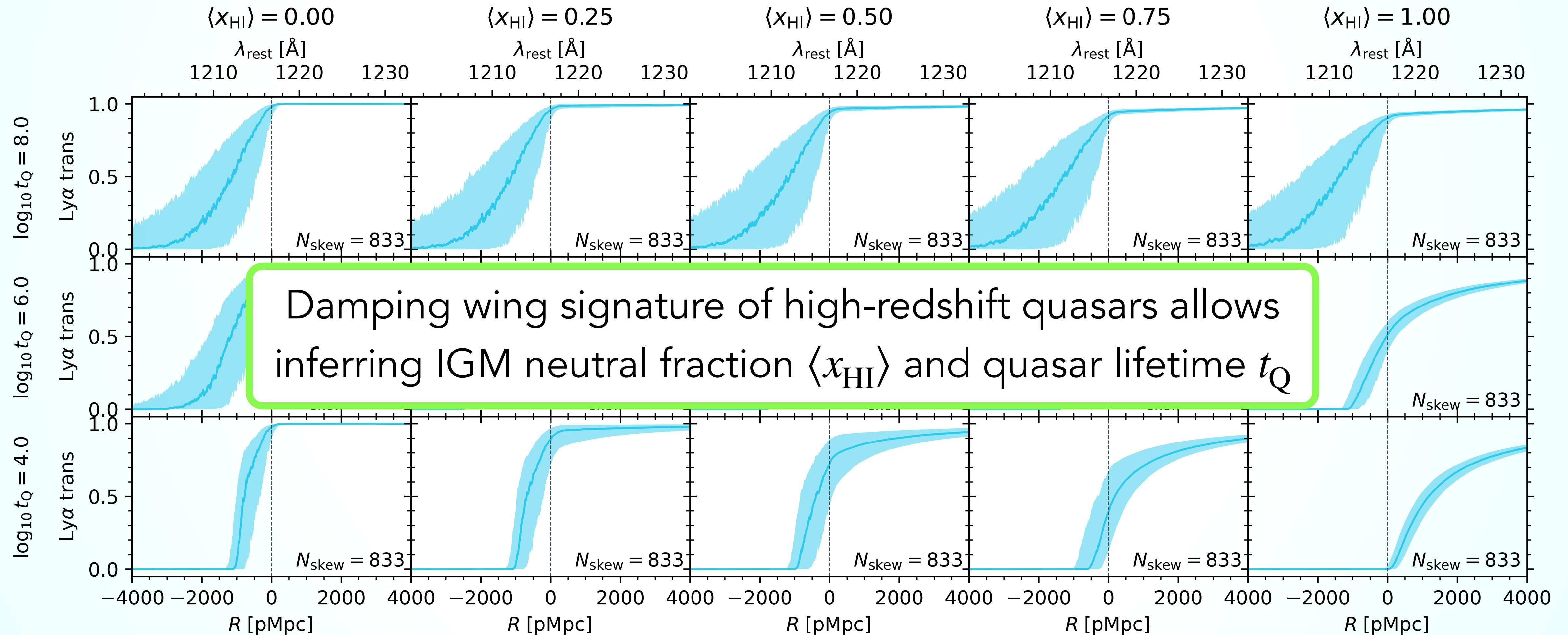
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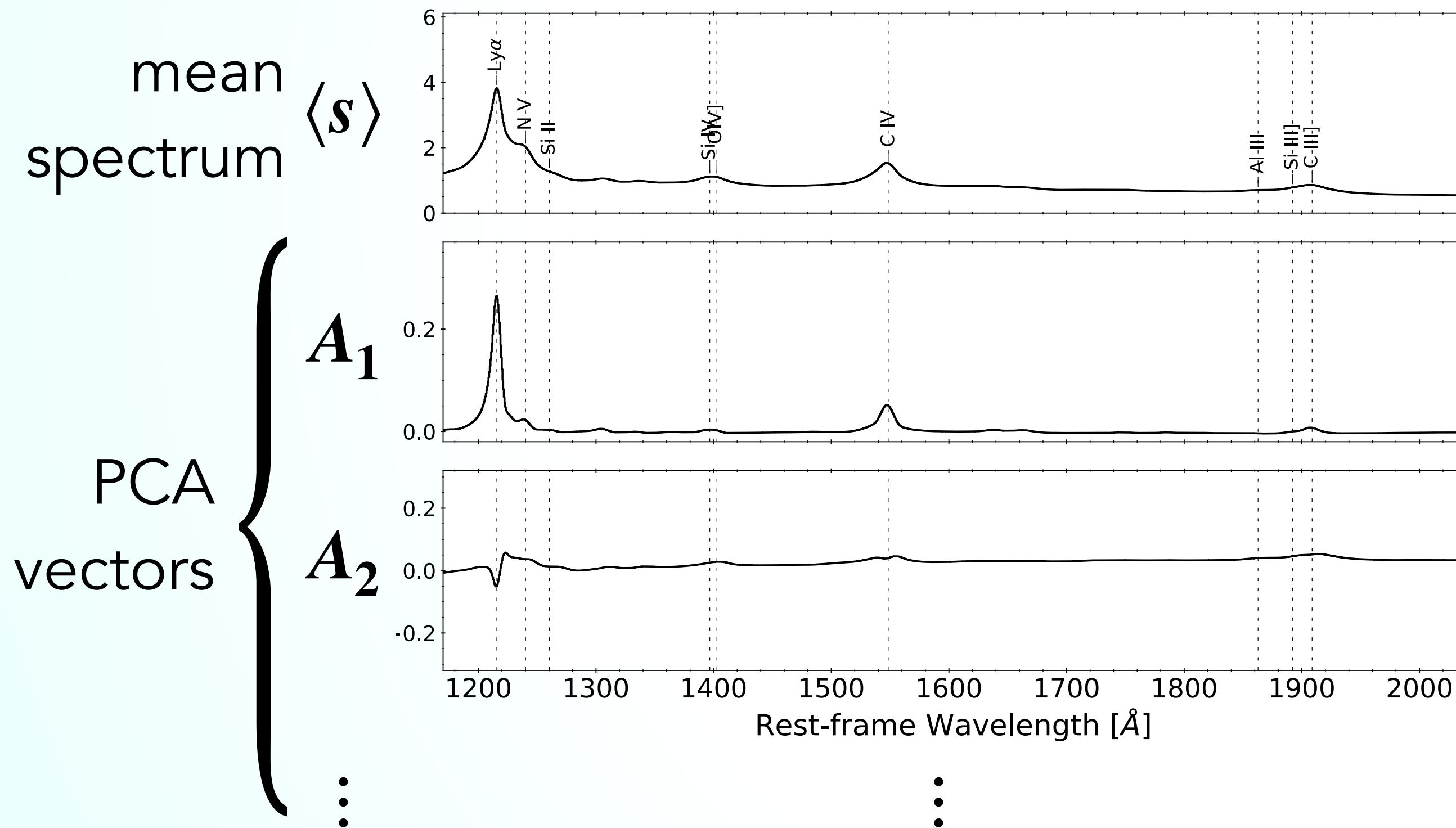


Predicting the Quasar Continuum

A PCA model for the entire spectral range

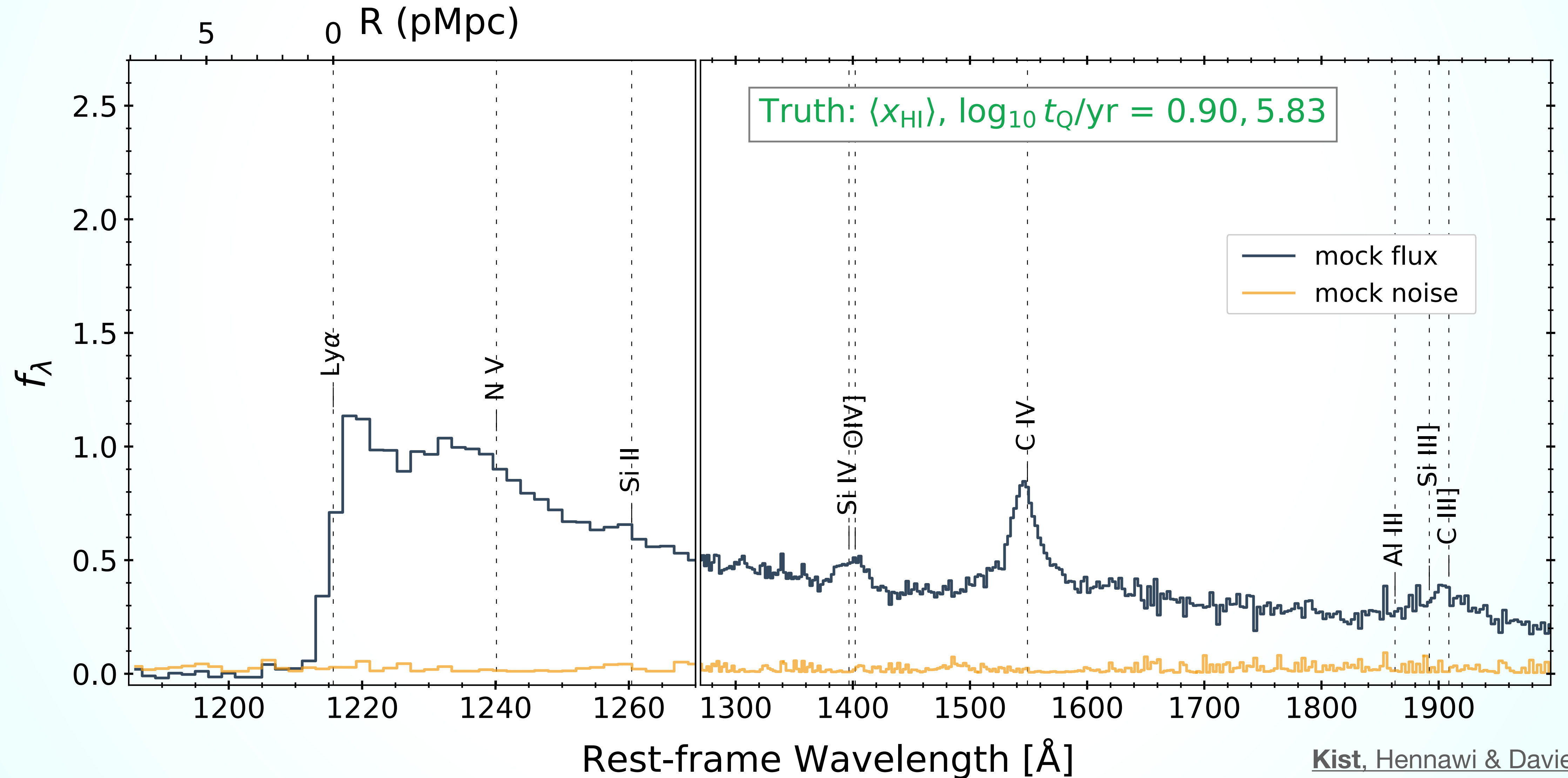
PCA decomposed continuum: $s_{\text{DR}}(\xi) = \langle s \rangle + \xi \cdot A$

- 15 559 SDSS-autofit spectra ($2.149 < z < 4$, $R \sim 2000$, $S/N > 10$)
- 95% - 5% training-test split:
 - Training set of 14 781 low-redshift spectra to build PCA model
 - Test set of 778 spectra to draw mock continua and estimate reconstruction error



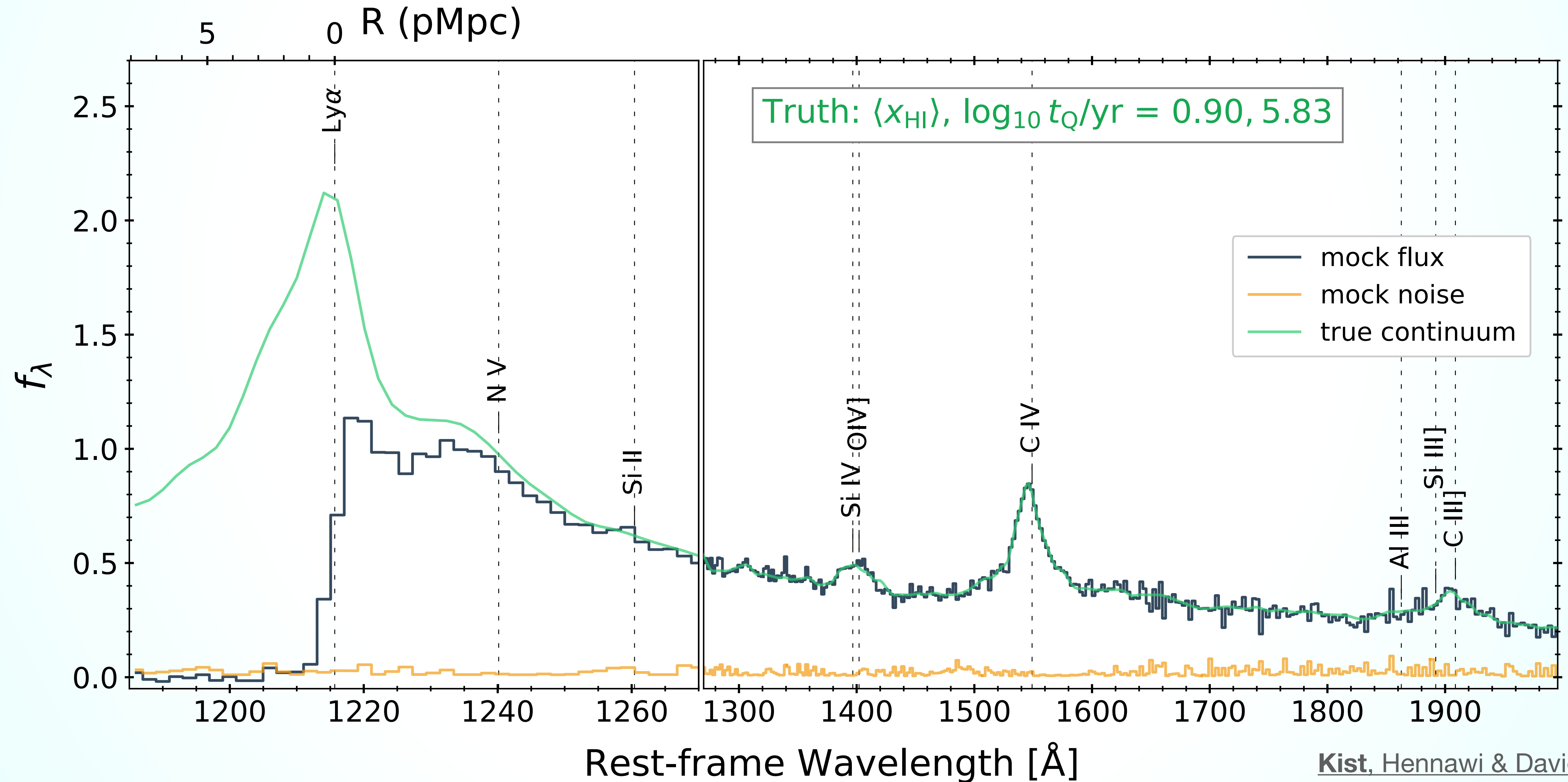
From an Observed Quasar Spectrum to $\langle x_{\text{HI}} \rangle$

A Quasar in a Neutral Environment



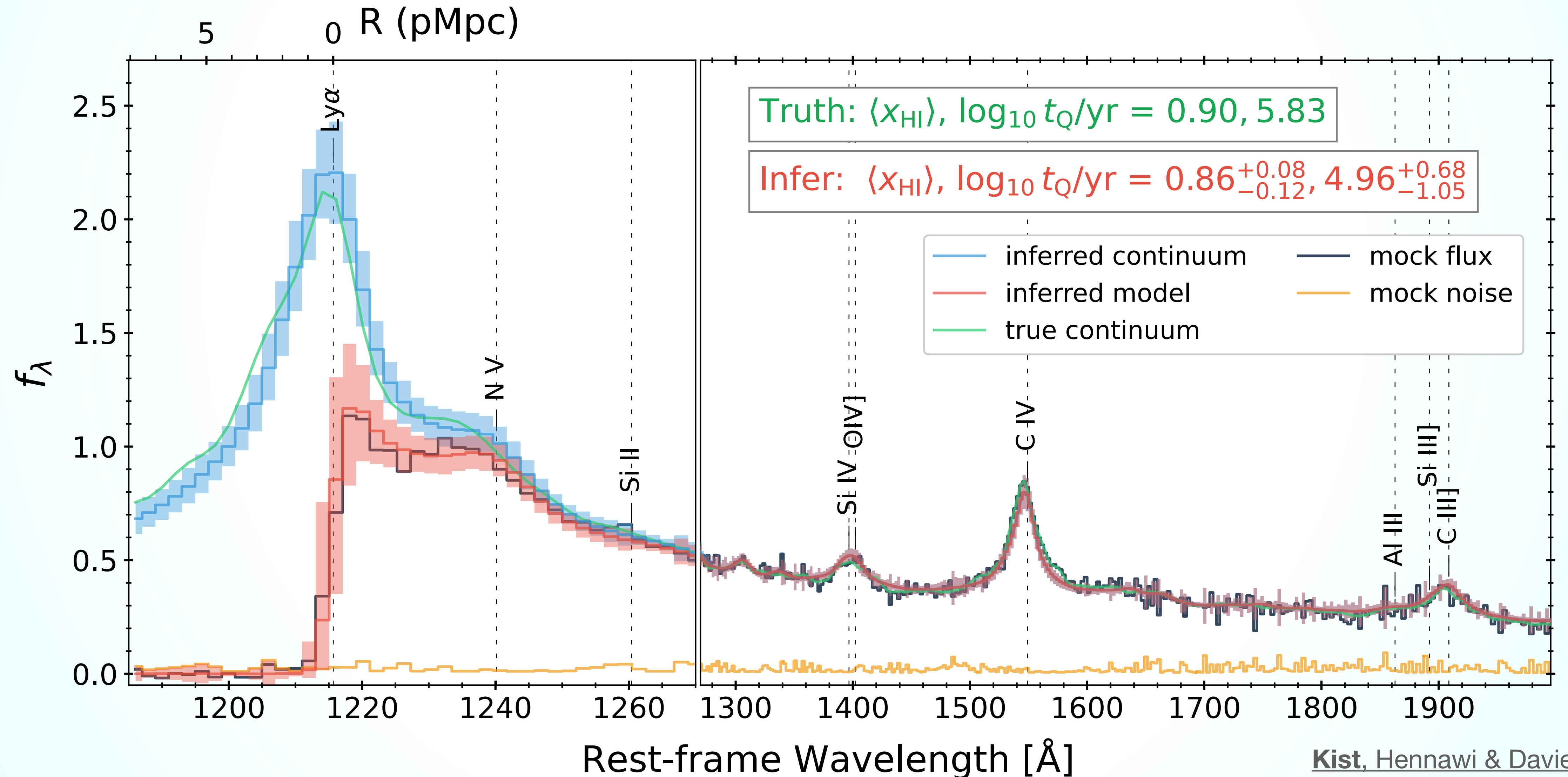
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A Quasar in a Neutral Environment



The new generation of QSO damping wing analysis

Joint HMC Parameter Inference

Hennawi, Kist, Davies & Tamanas 2024

Kist, Hennawi & Davies 2024a

DATA

Real (or mock) quasar spectrum with observational noise

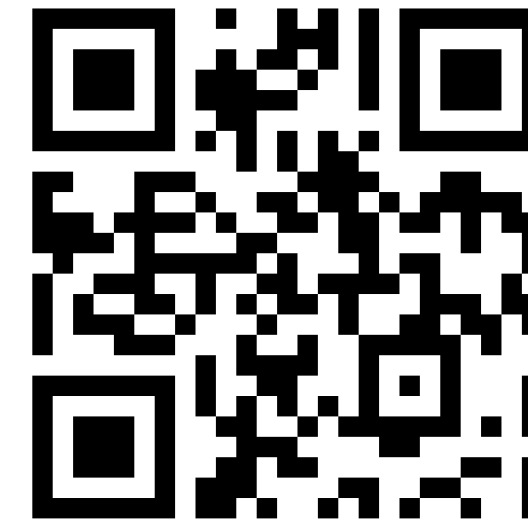
MODEL

Quasar continuum model

Reconstruction error stochastic process

+

IGM transmission field stochastic process

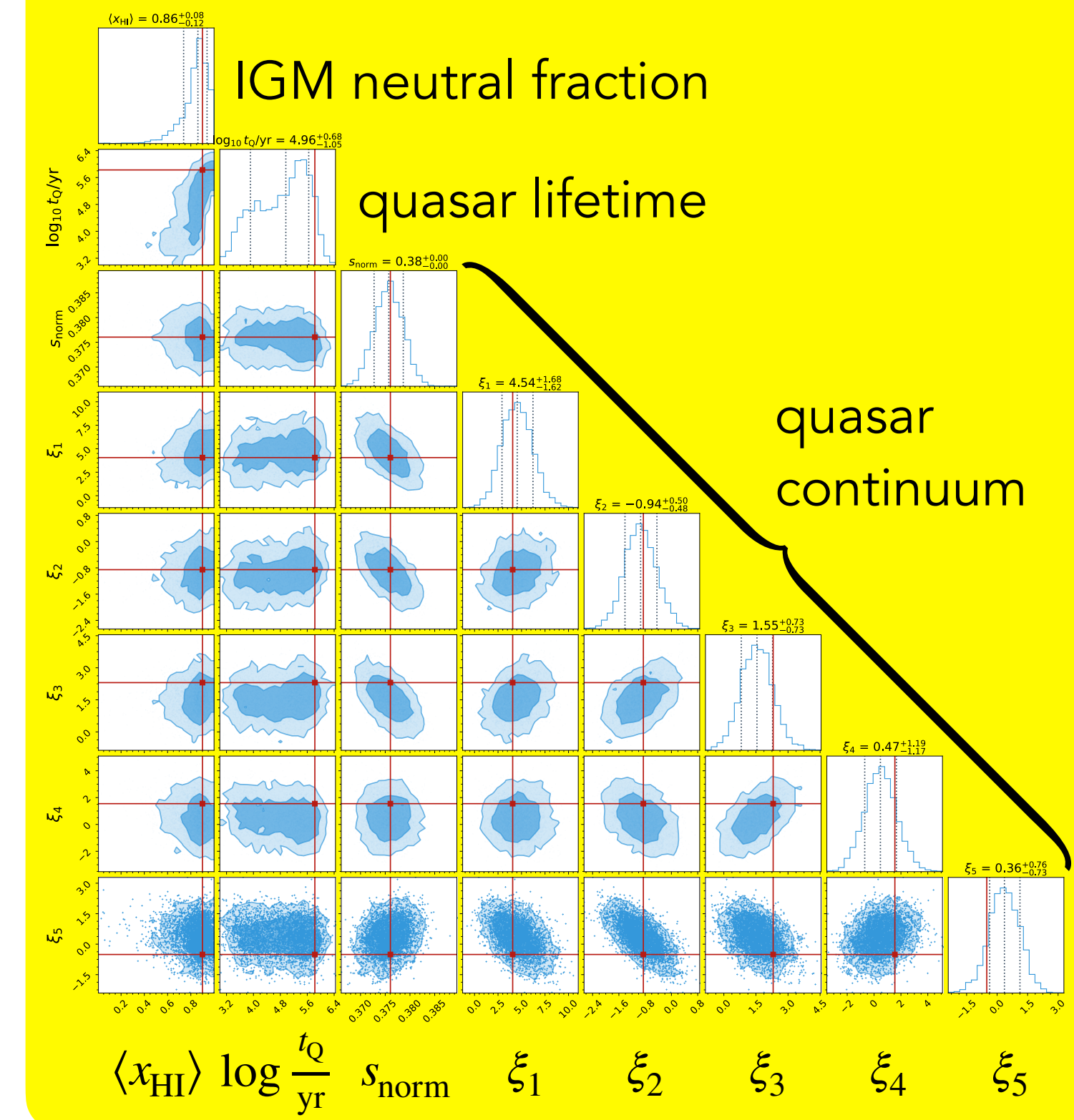


BAYESIAN INFERENCE

with a Gaussian likelihood approximation

- **Jointly** fitting the quasar continuum & IGM damping wing
- Likelihood operates on the **entire** spectrum (red- and blueward of Lyman- α)
- **Fast** GPU-accelerated JAX-based Hamiltonian Monte Carlo implementation (runtimes ~ 15 -30 min per object)

POSTERIOR



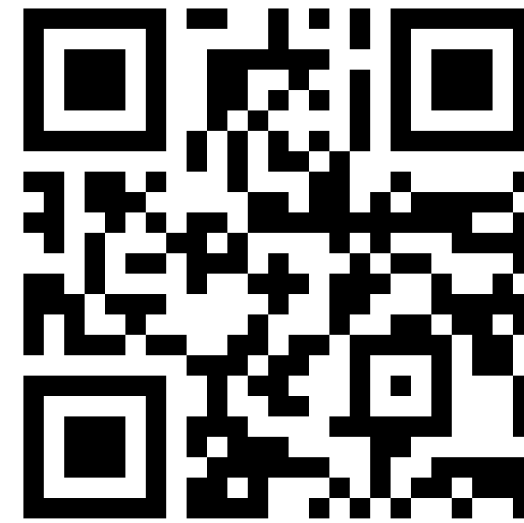
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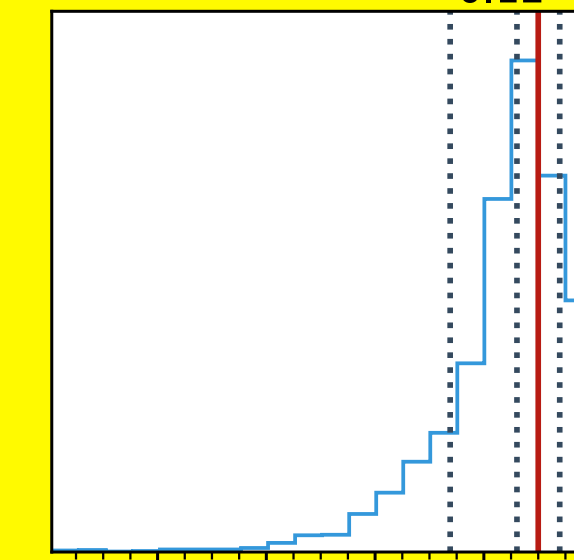
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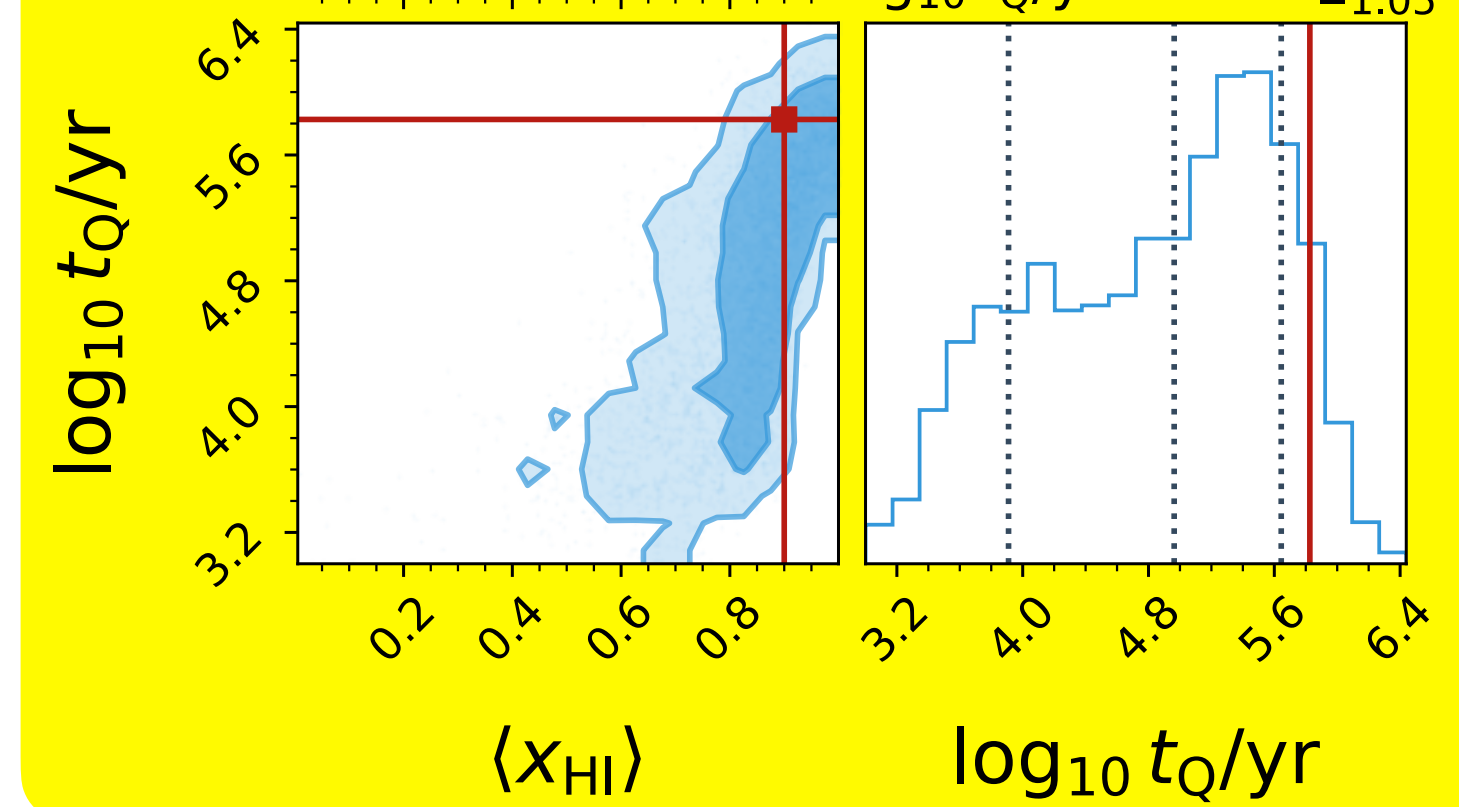
IGM neutral fraction

$$\langle x_{\text{HI}} \rangle = 0.86^{+0.08}_{-0.12}$$



quasar lifetime

$$\log_{10} t_Q/\text{yr} = 4.96^{+0.68}_{-1.05}$$



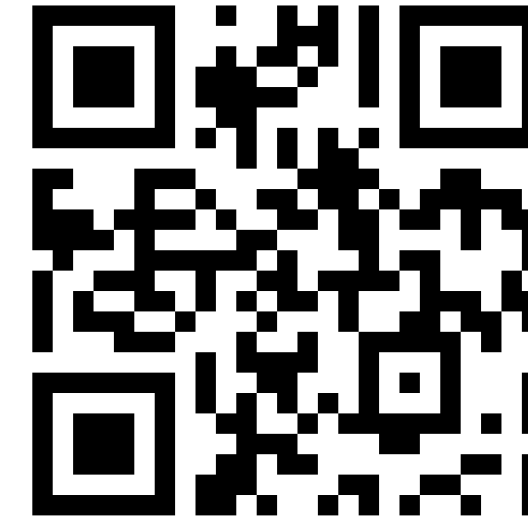
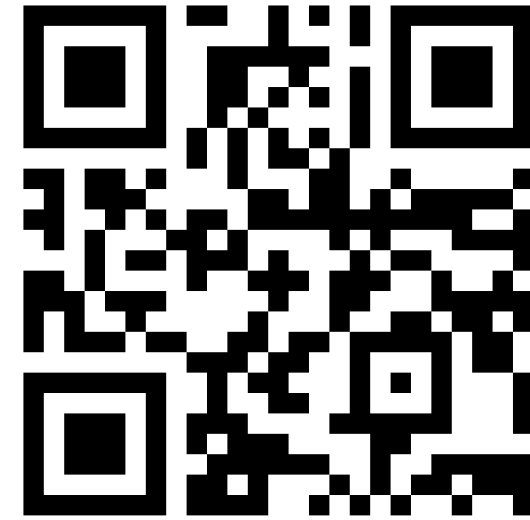
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[Hennawi, Kist, Davies
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Quasar
continuum
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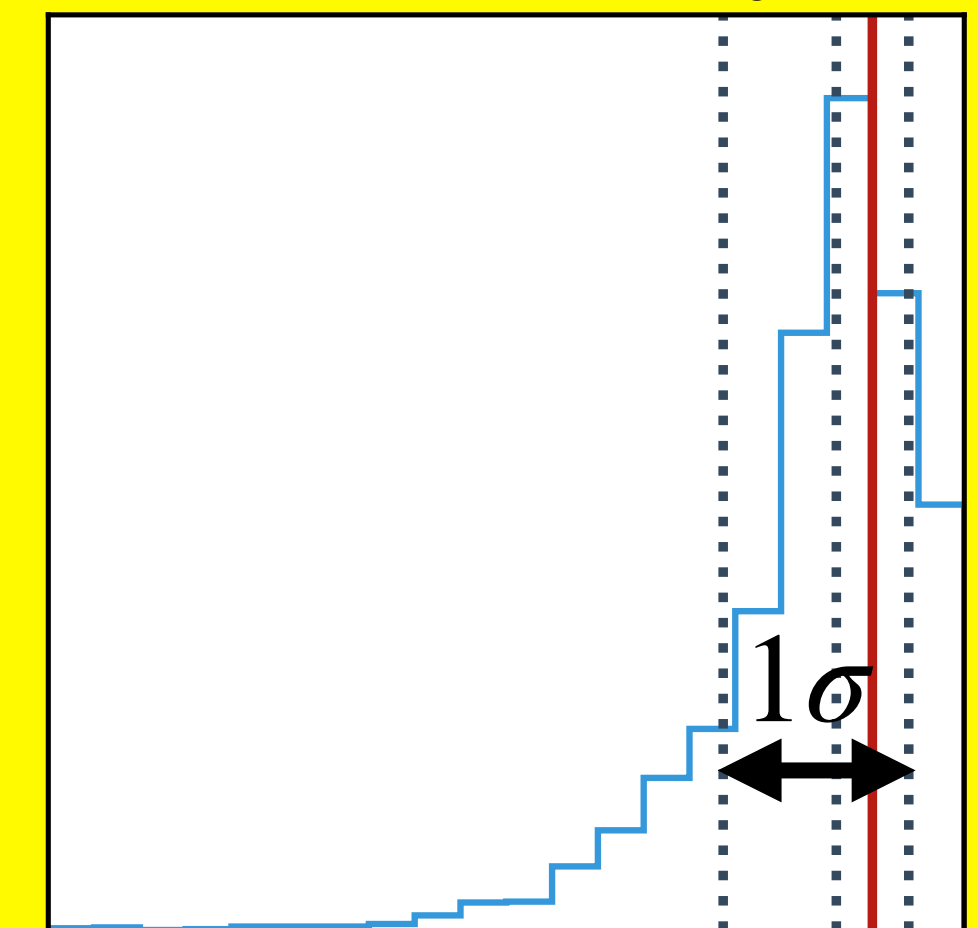
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POSTERIOR

$$\langle X_{\text{HI}} \rangle = 0.86^{+0.08}_{-0.12}$$

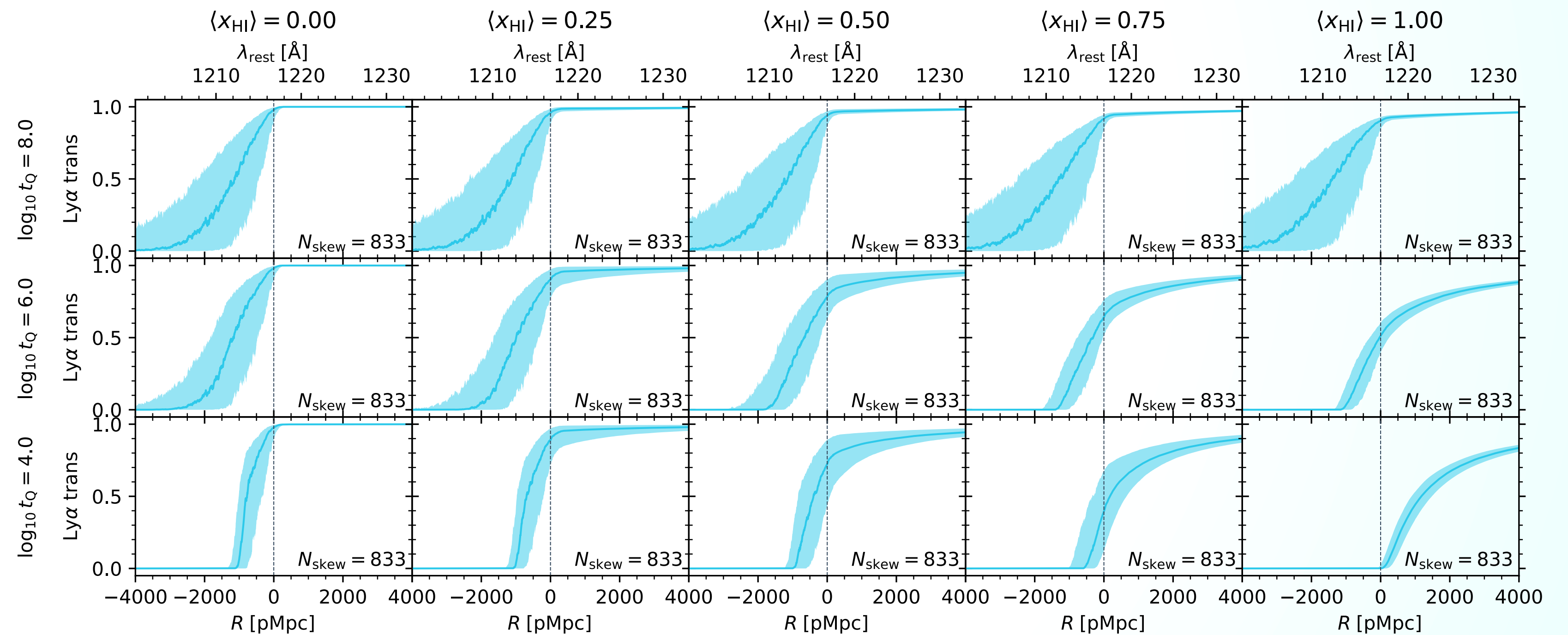
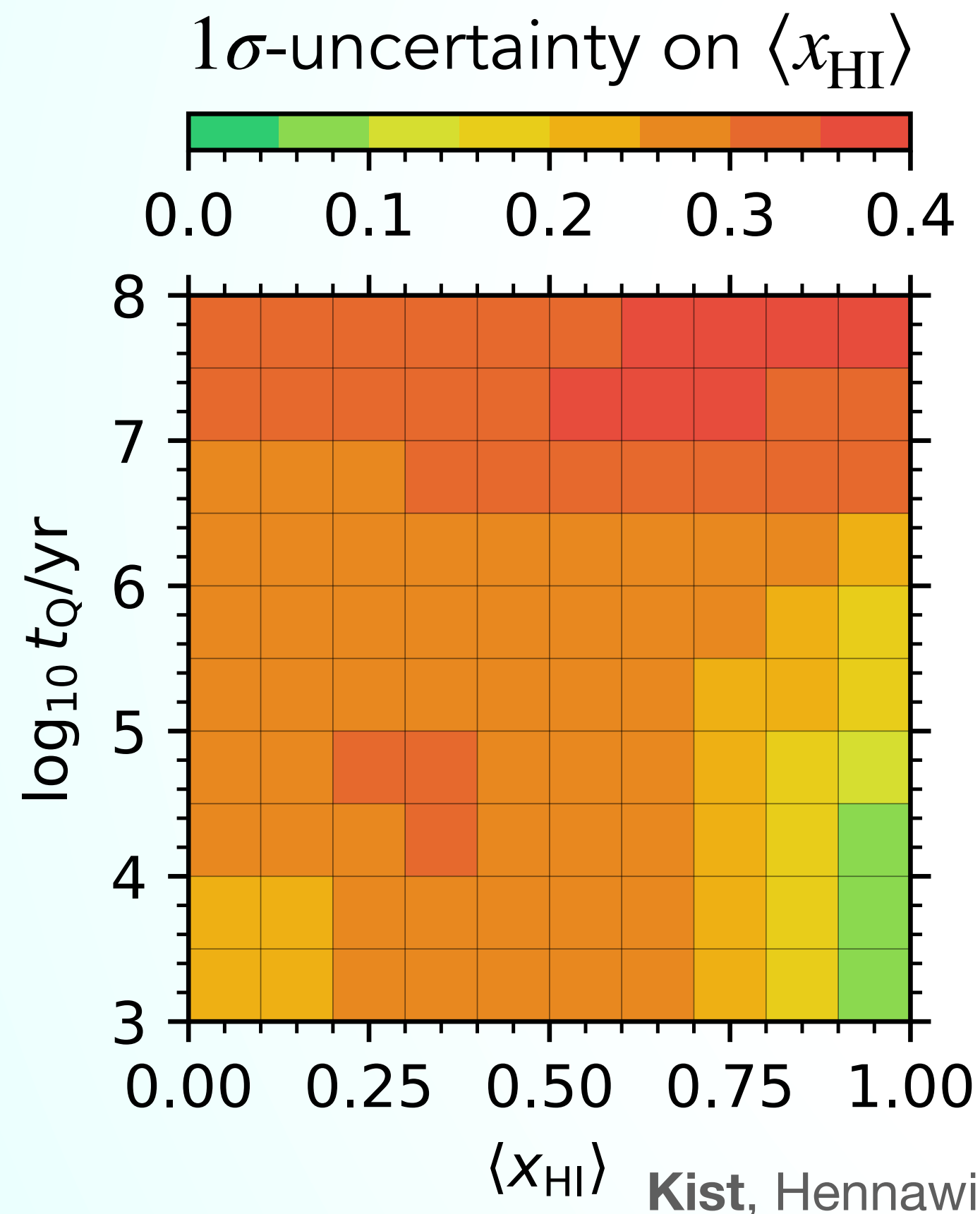


$\langle X_{\text{HI}} \rangle$



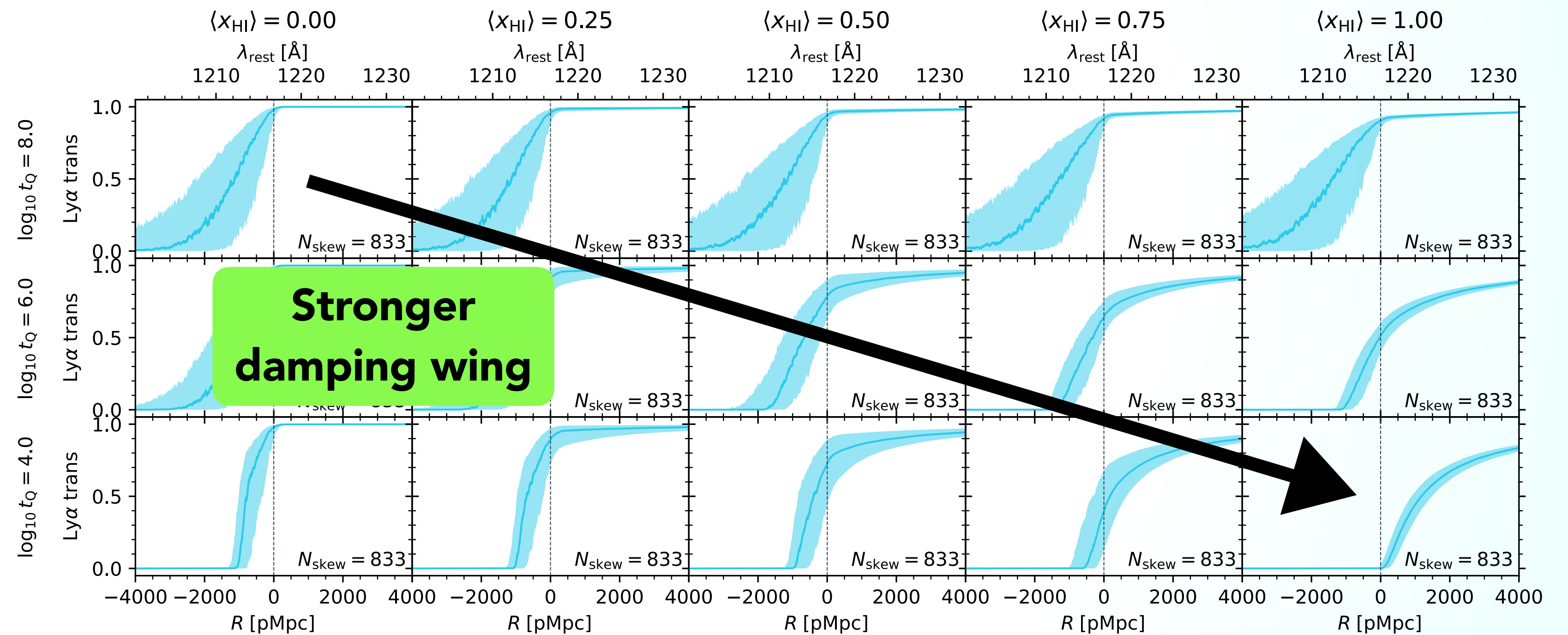
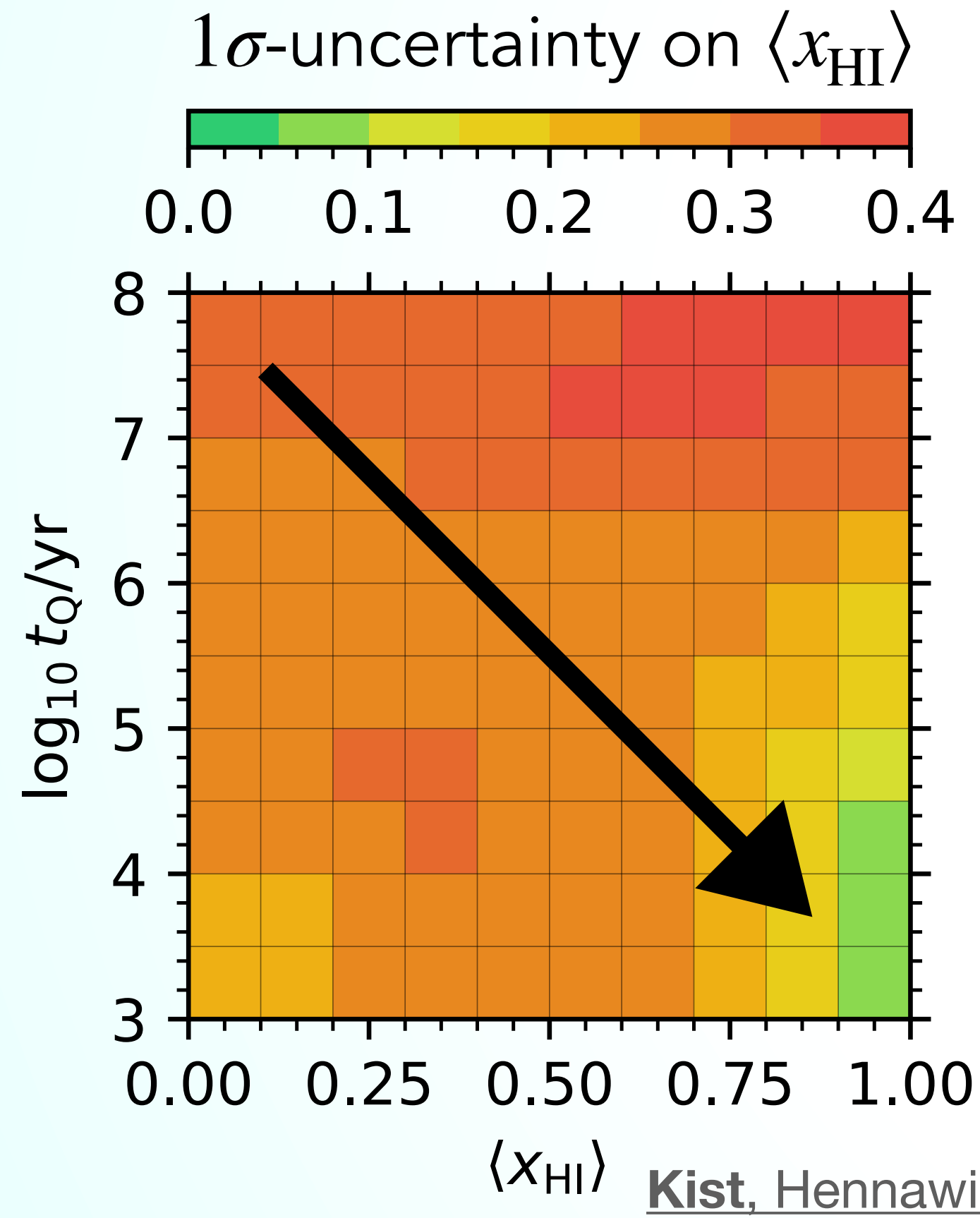
Quantifying $\langle x_{\text{HI}} \rangle$ Inference Precision

Variation across parameter space



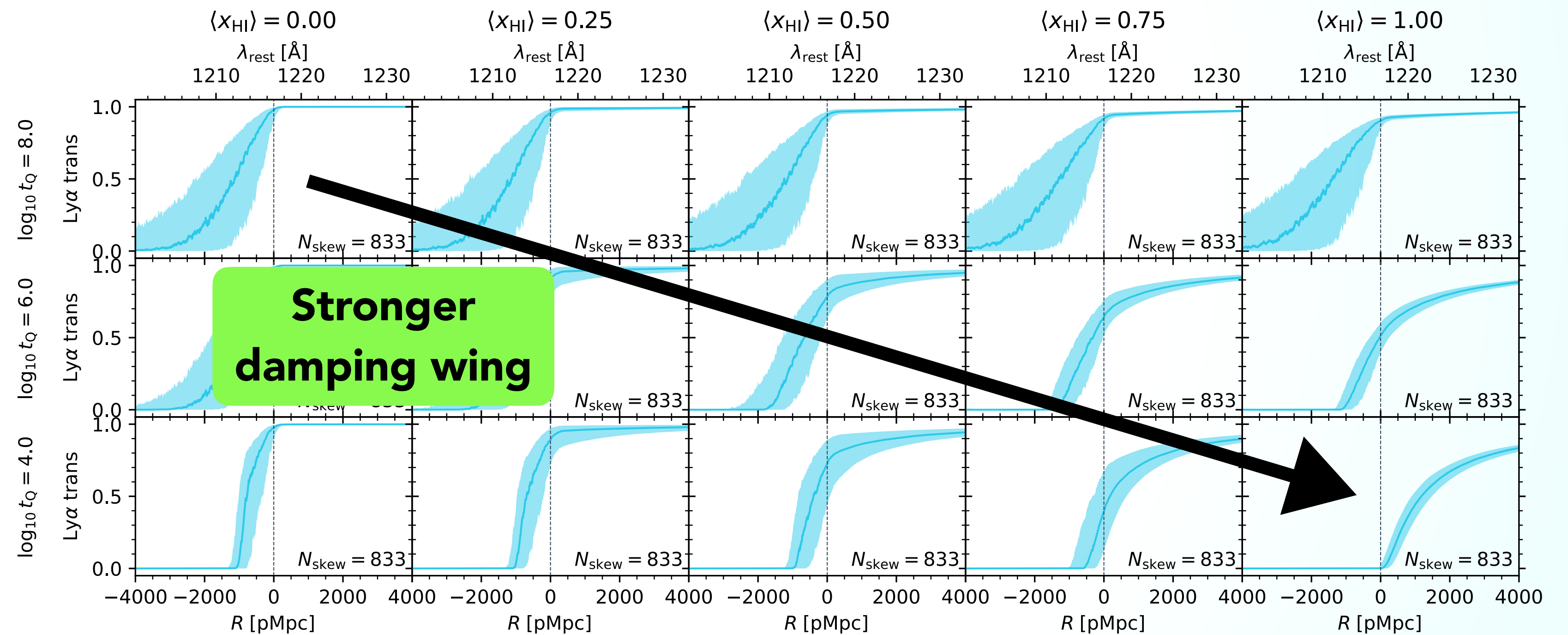
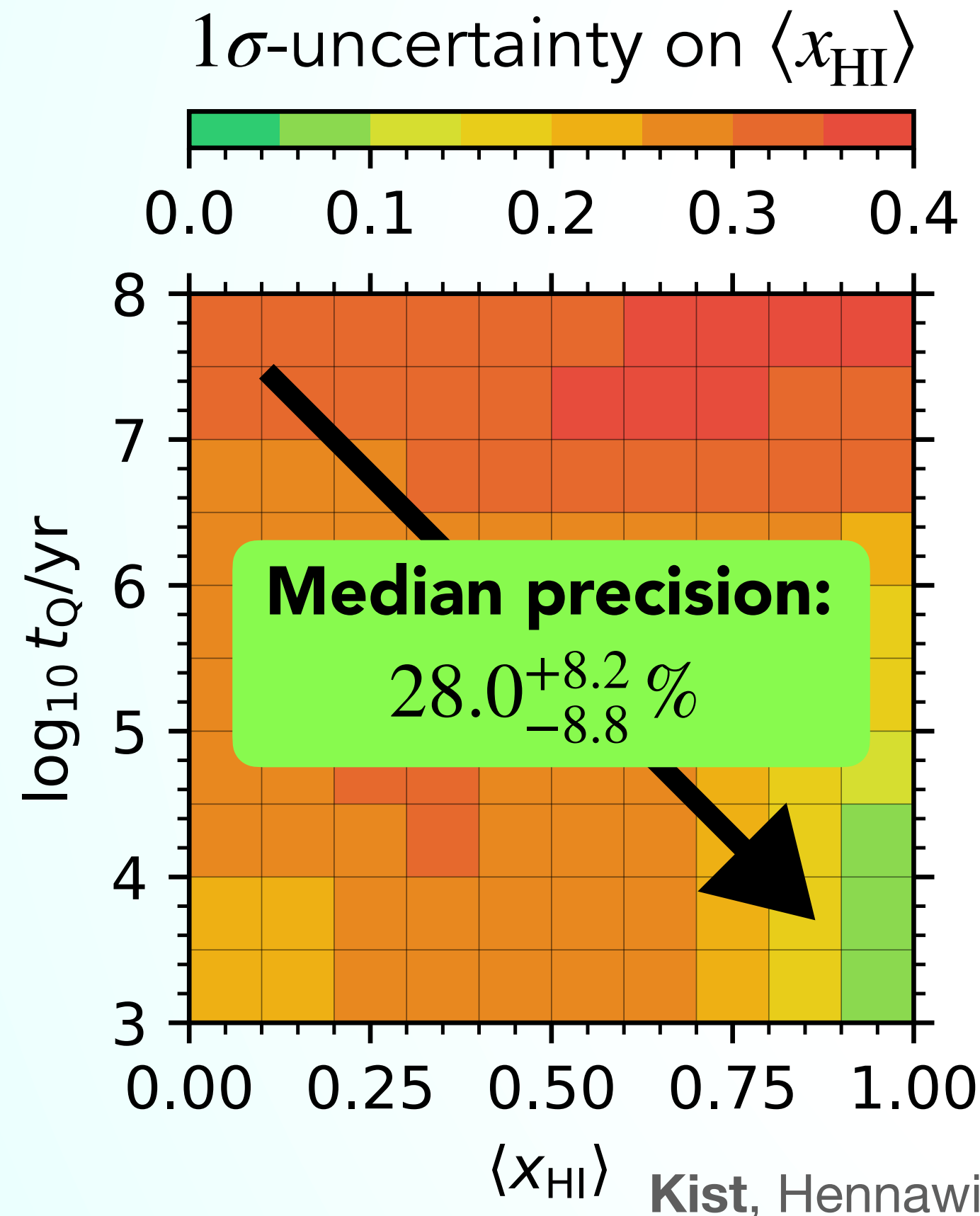
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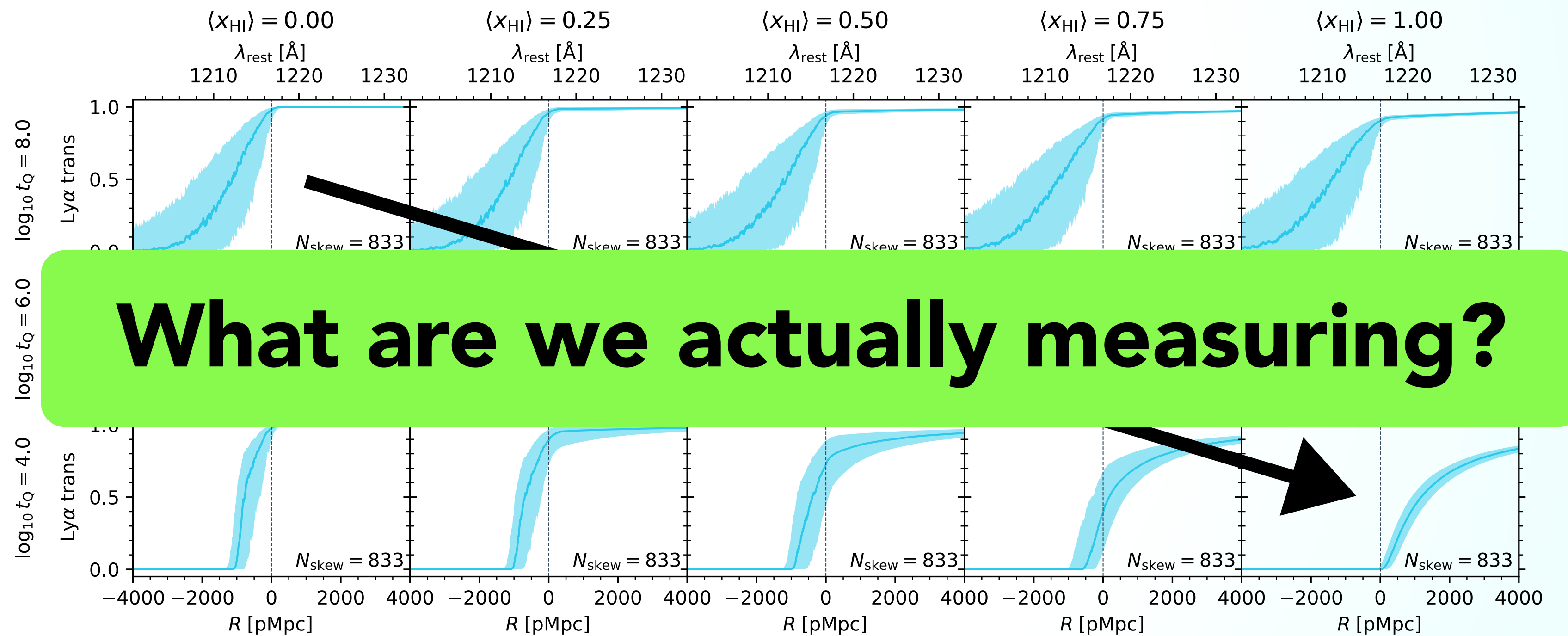
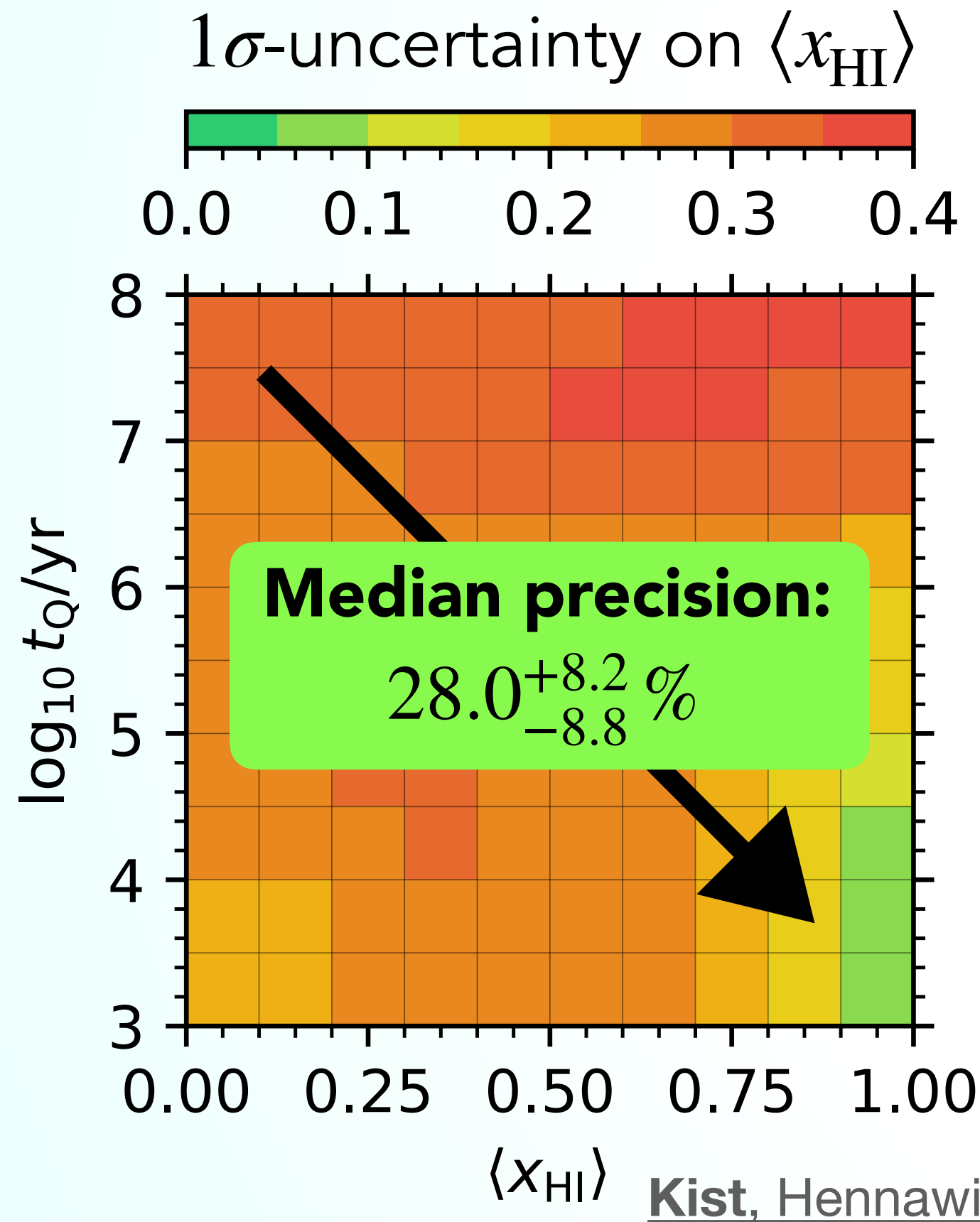
Variation across parameter space



Main sources of uncertainty: continuum reconstruction and **stochasticity of ionized bubble sizes**

Quantifying $\langle x_{\text{HI}} \rangle$ Inference Precision

Variation across parameter space



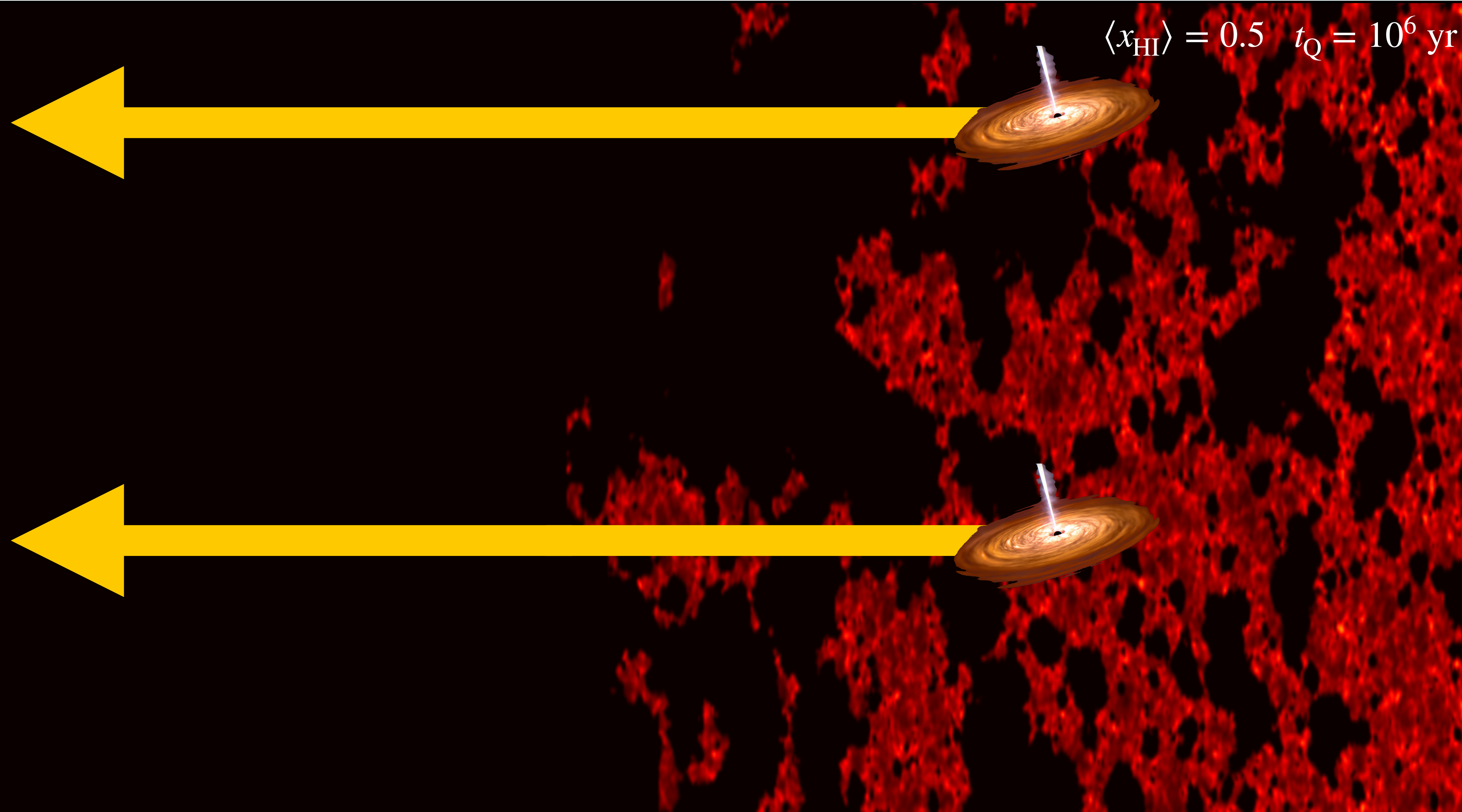
[Kist, Hennawi & Davies 2024a](#)

[Kist, Hennawi & Davies 2024b \(in prep.\)](#)

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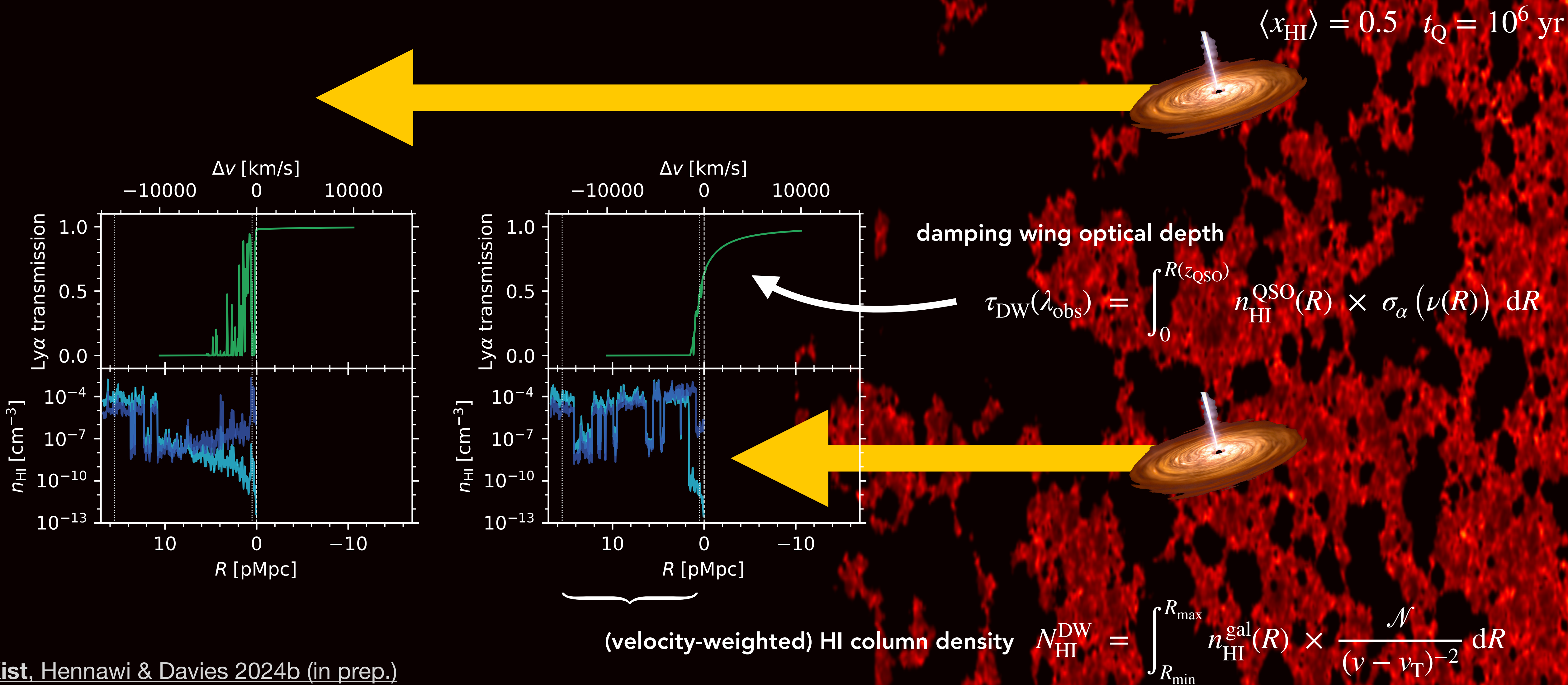
Measuring the local HI content in front of a quasar

Introducing a new label for the HI column density



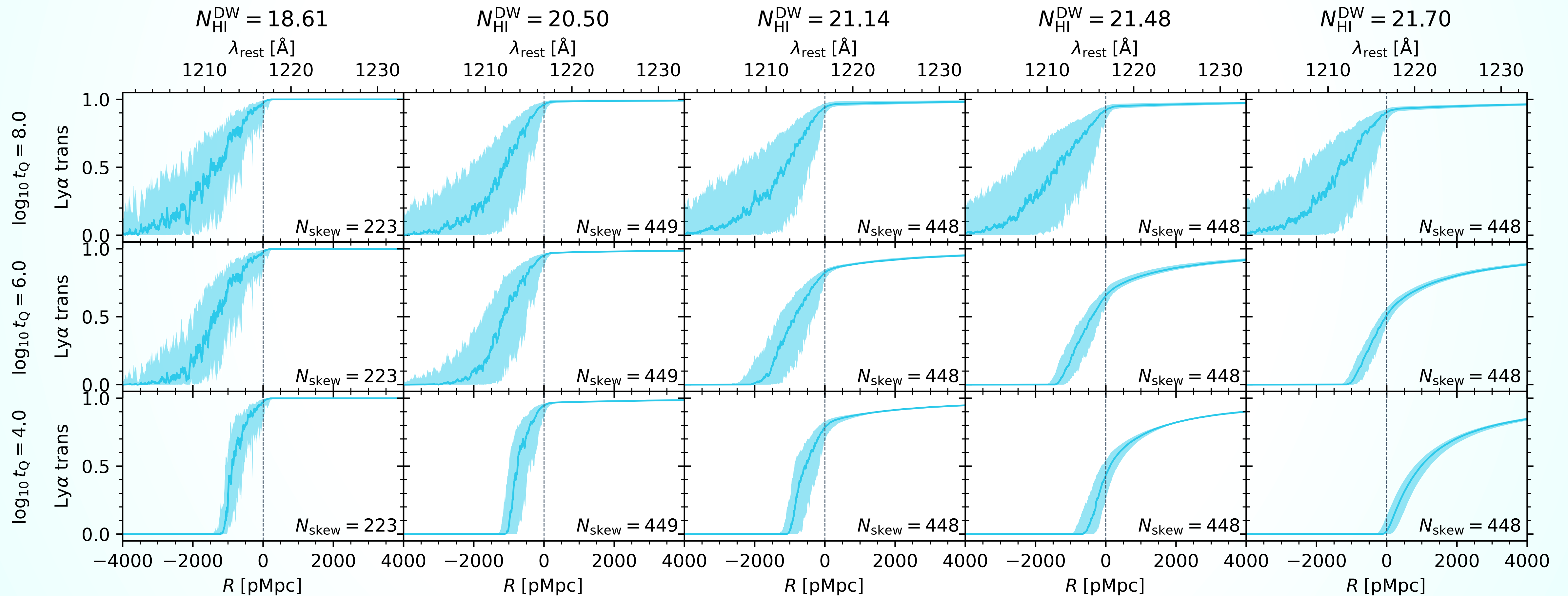
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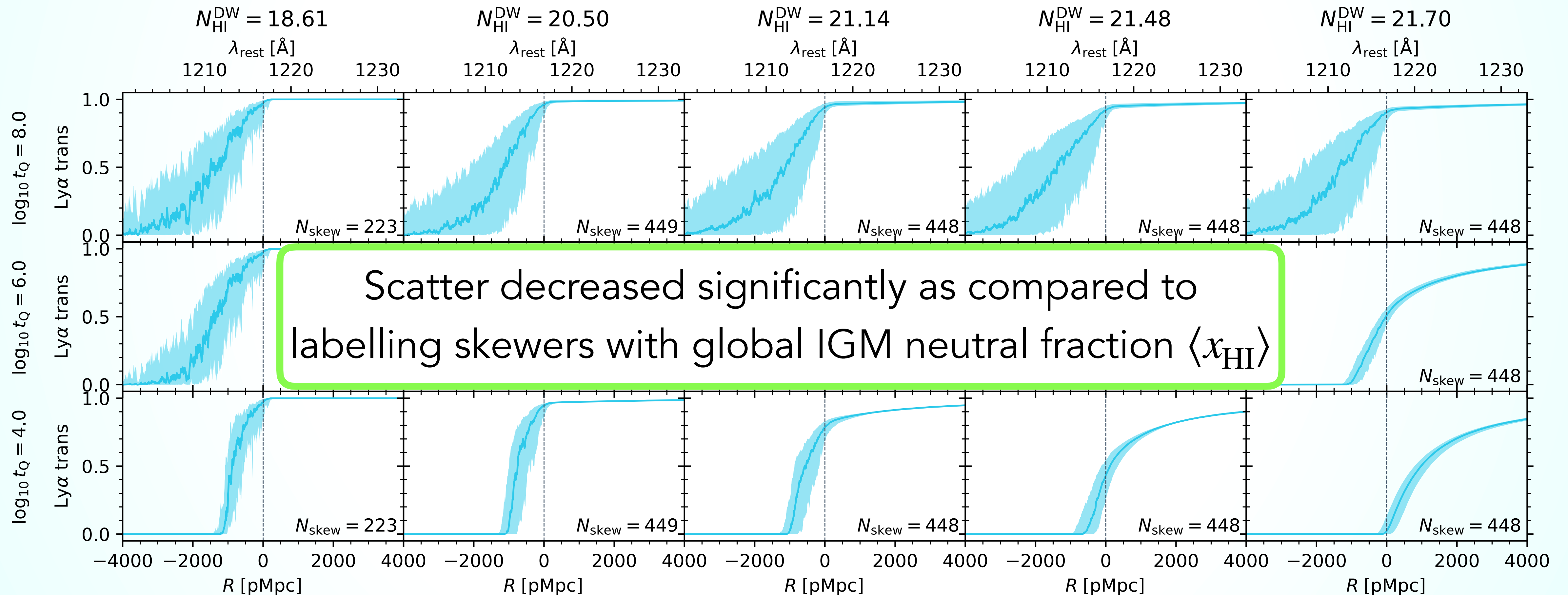
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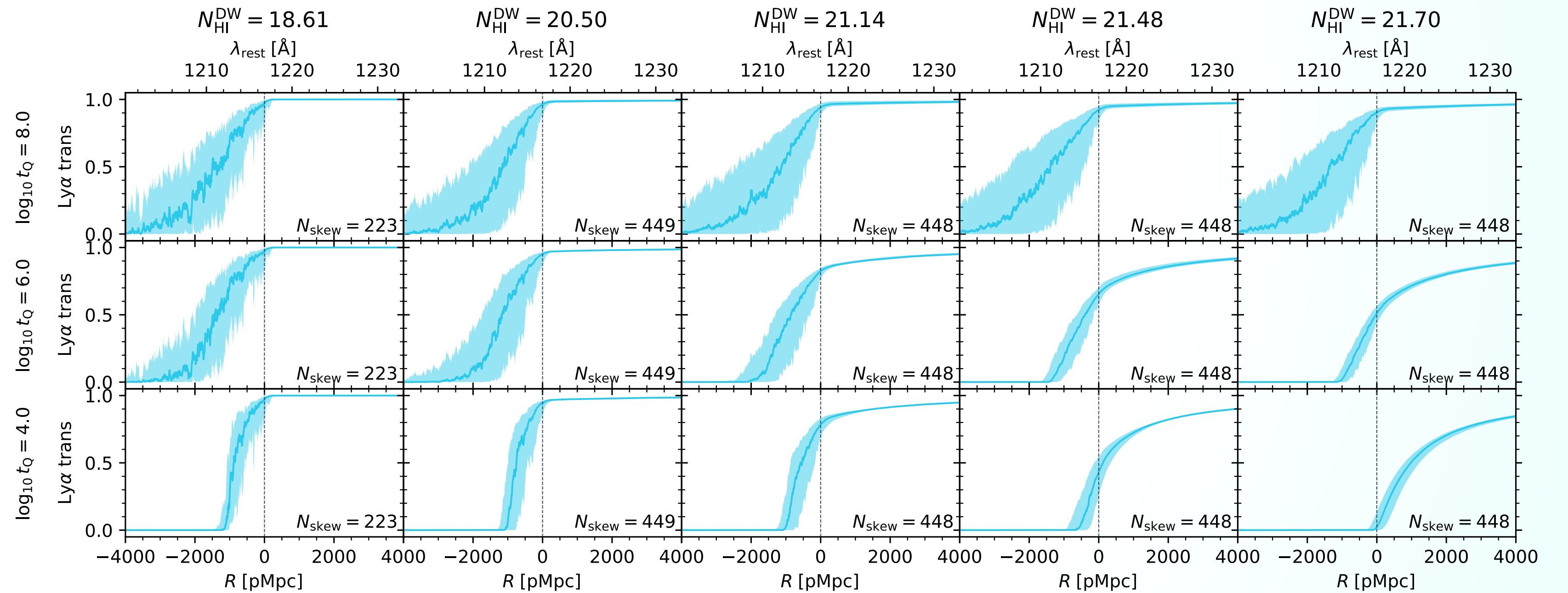
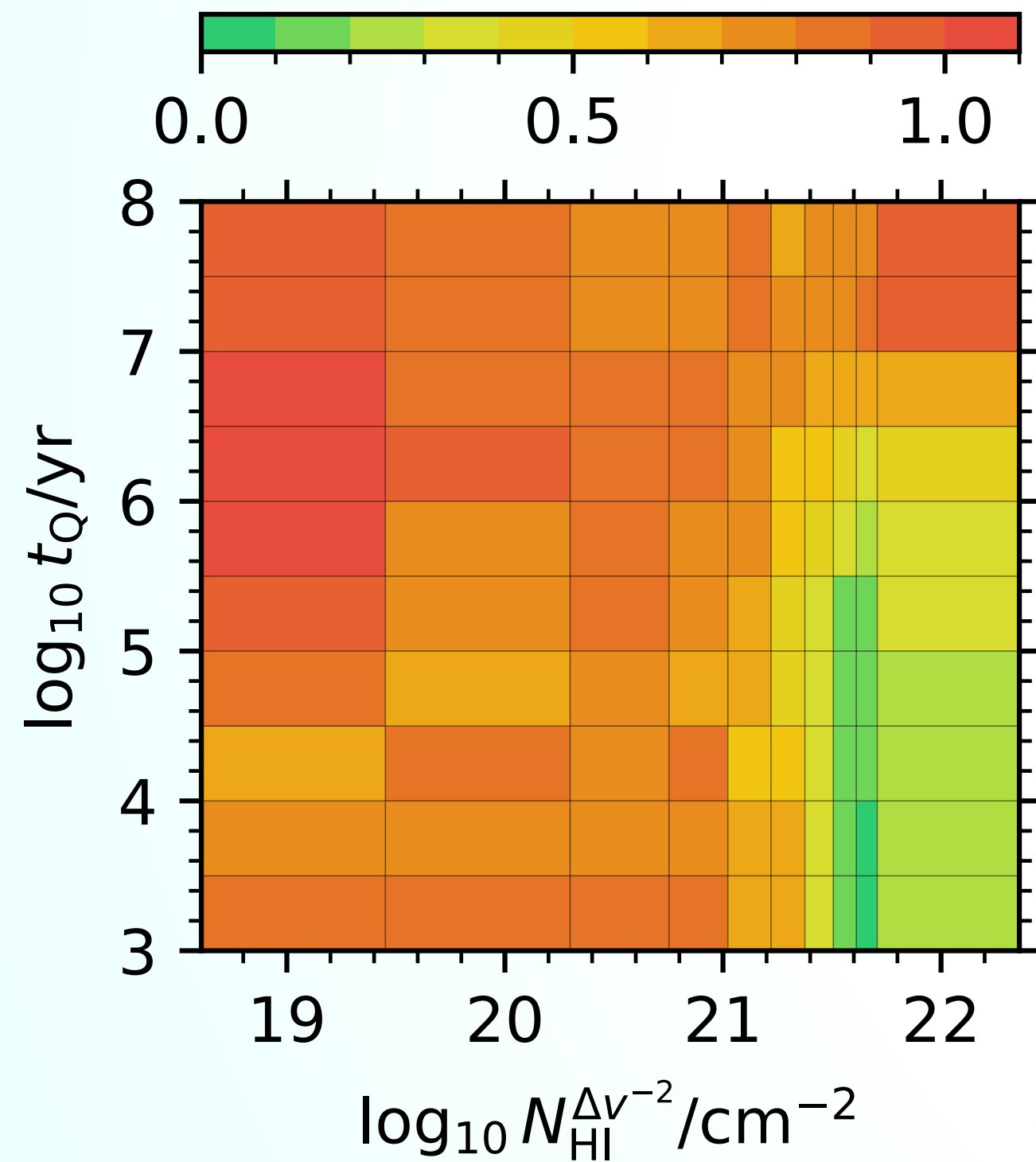
Introducing a new label for the HI column density



Quantifying $N_{\text{HI}}^{\text{DW}}$ Inference Precision

Variation across parameter space

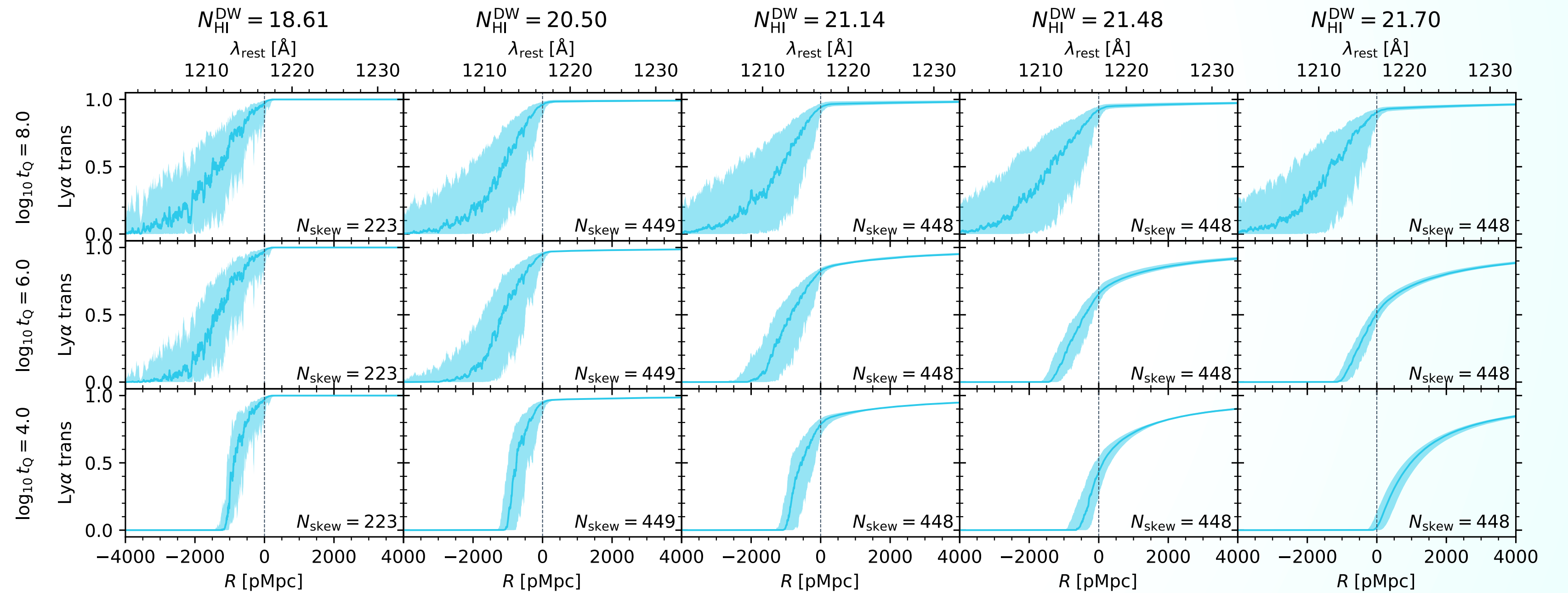
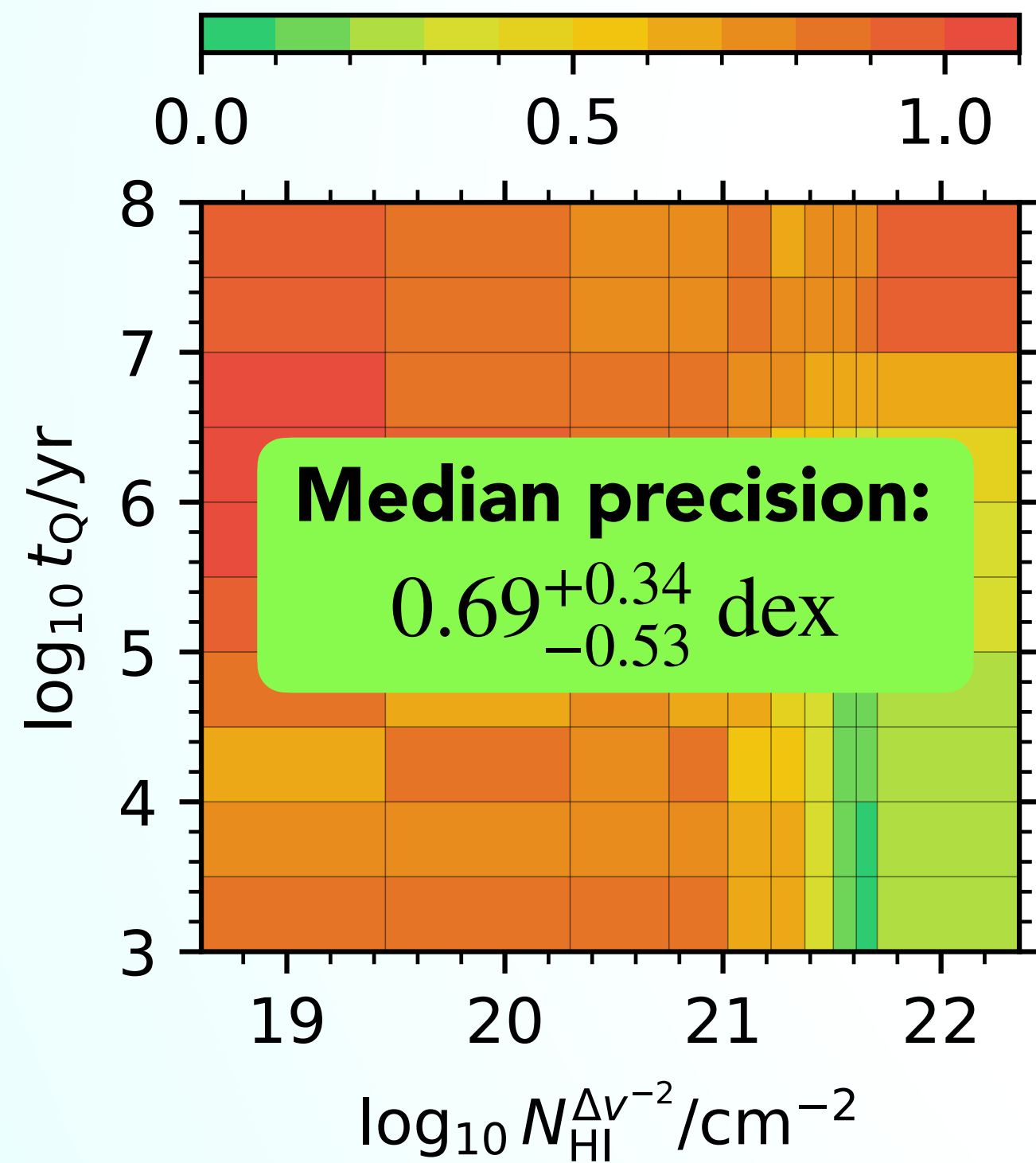
1σ -uncertainty on $\log_{10} N_{\text{HI}}^{\text{DW}}$



Quantifying $N_{\text{HI}}^{\text{DW}}$ Inference Precision

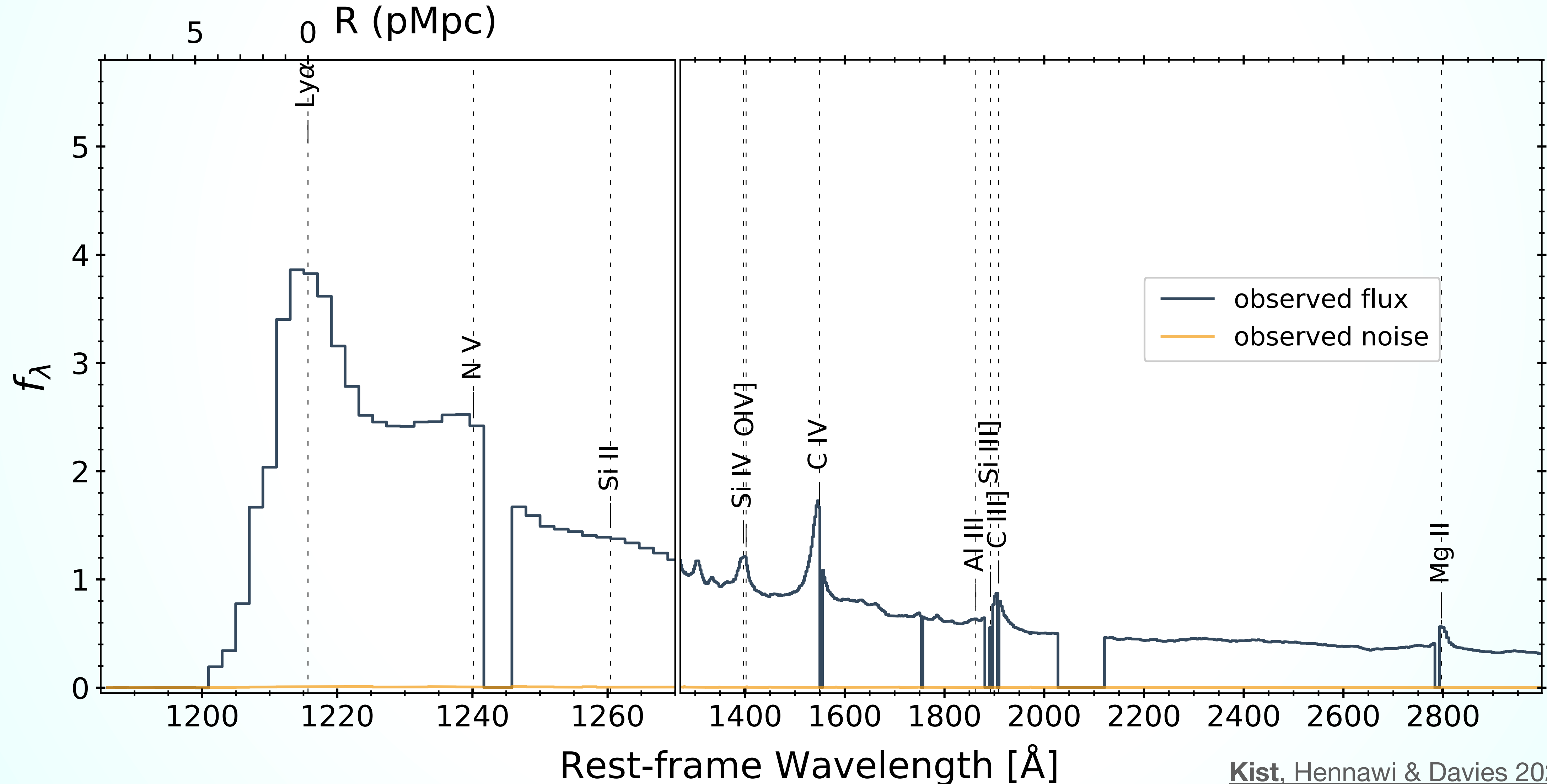
Variation across parameter space

1σ -uncertainty on $\log_{10} N_{\text{HI}}^{\text{DW}}$



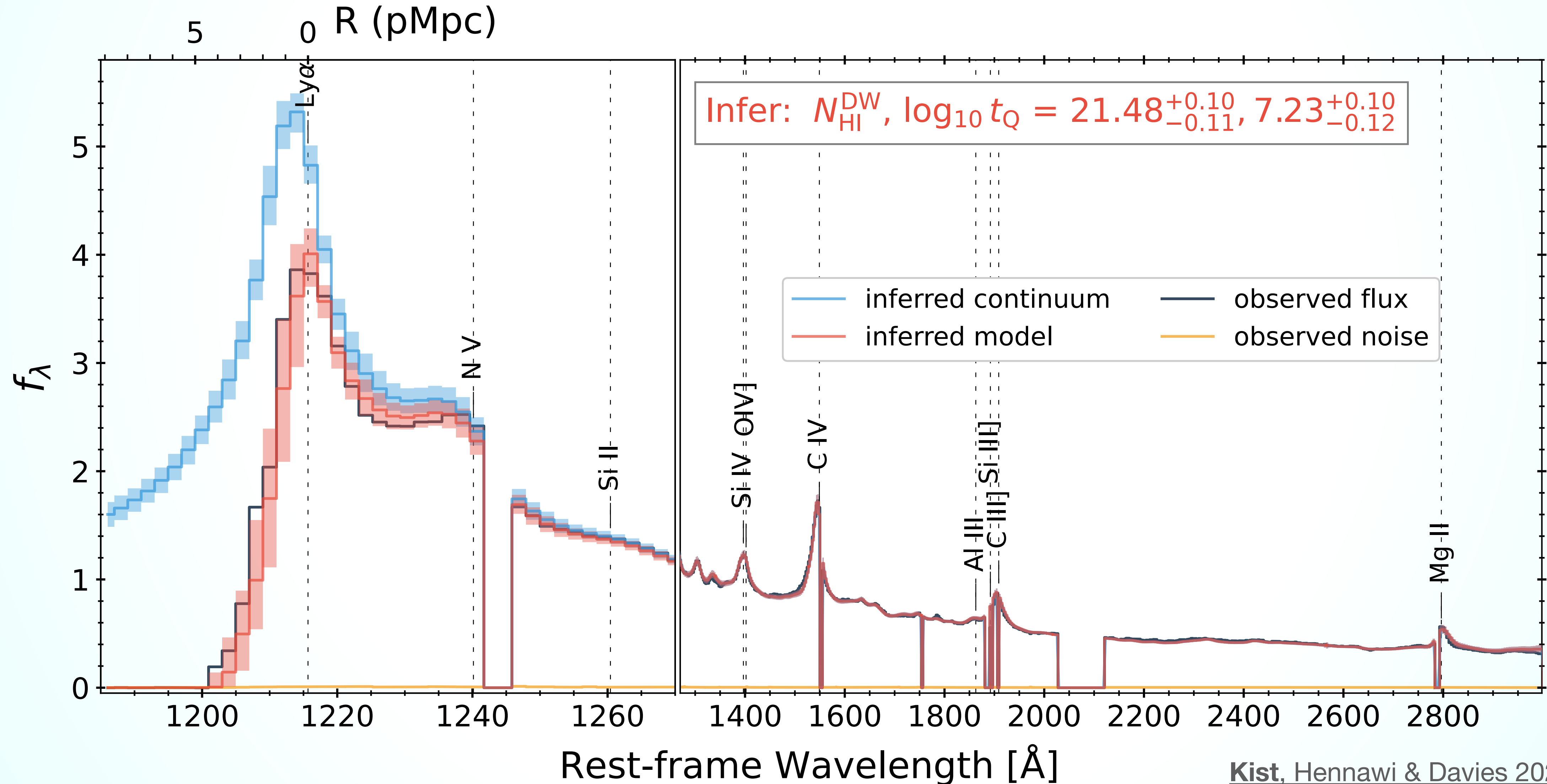
Inferring $N_{\text{HI}}^{\text{DW}}$ in front of a $z = 6.83$ quasar

A JWST spectrum of J0411-0907



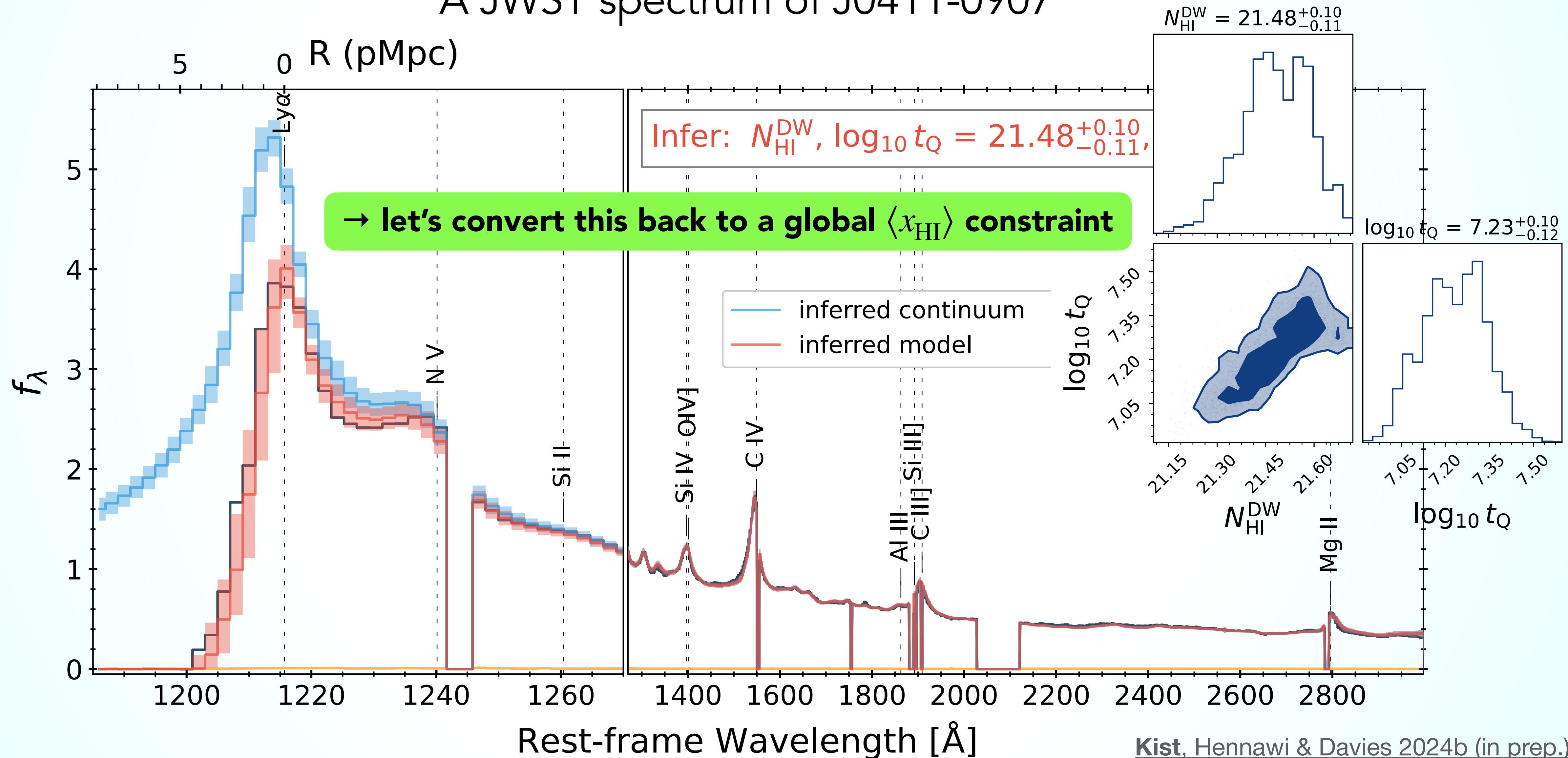
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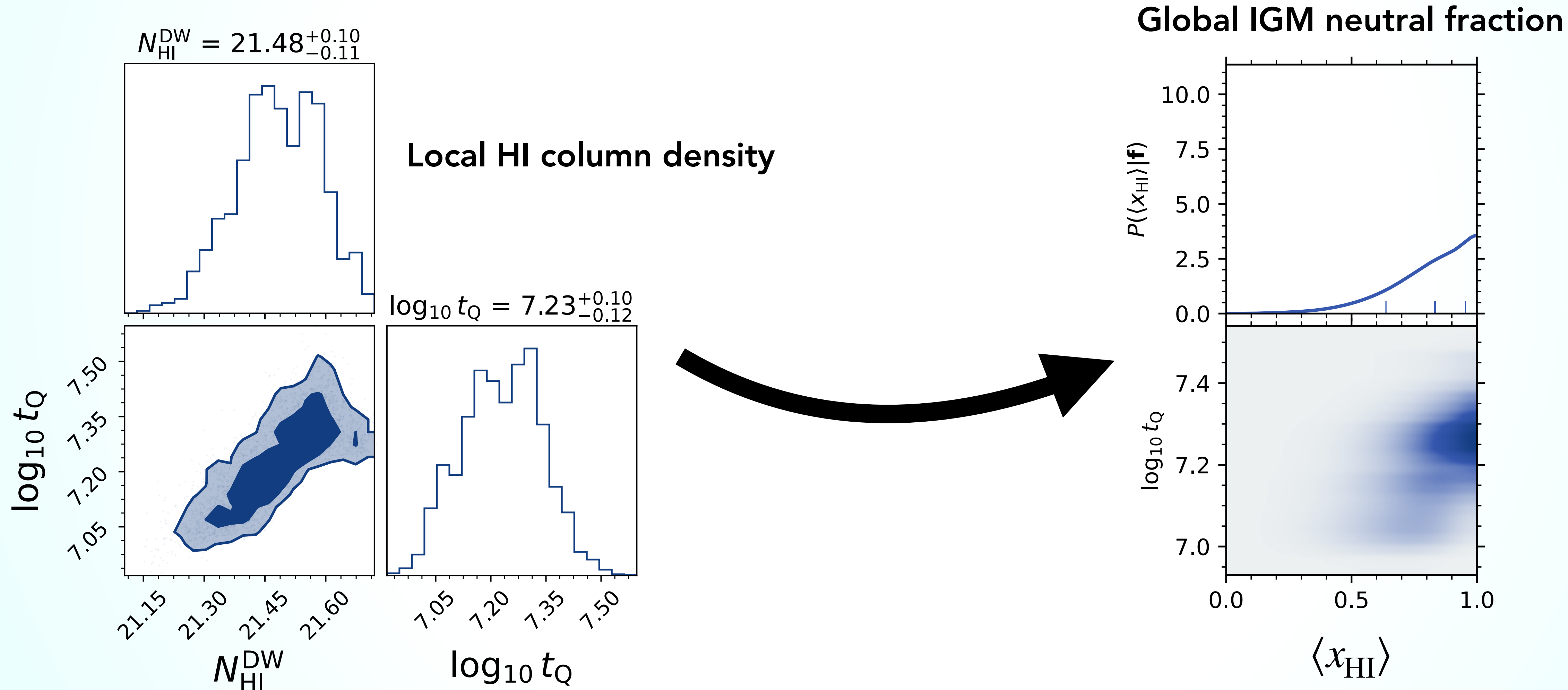
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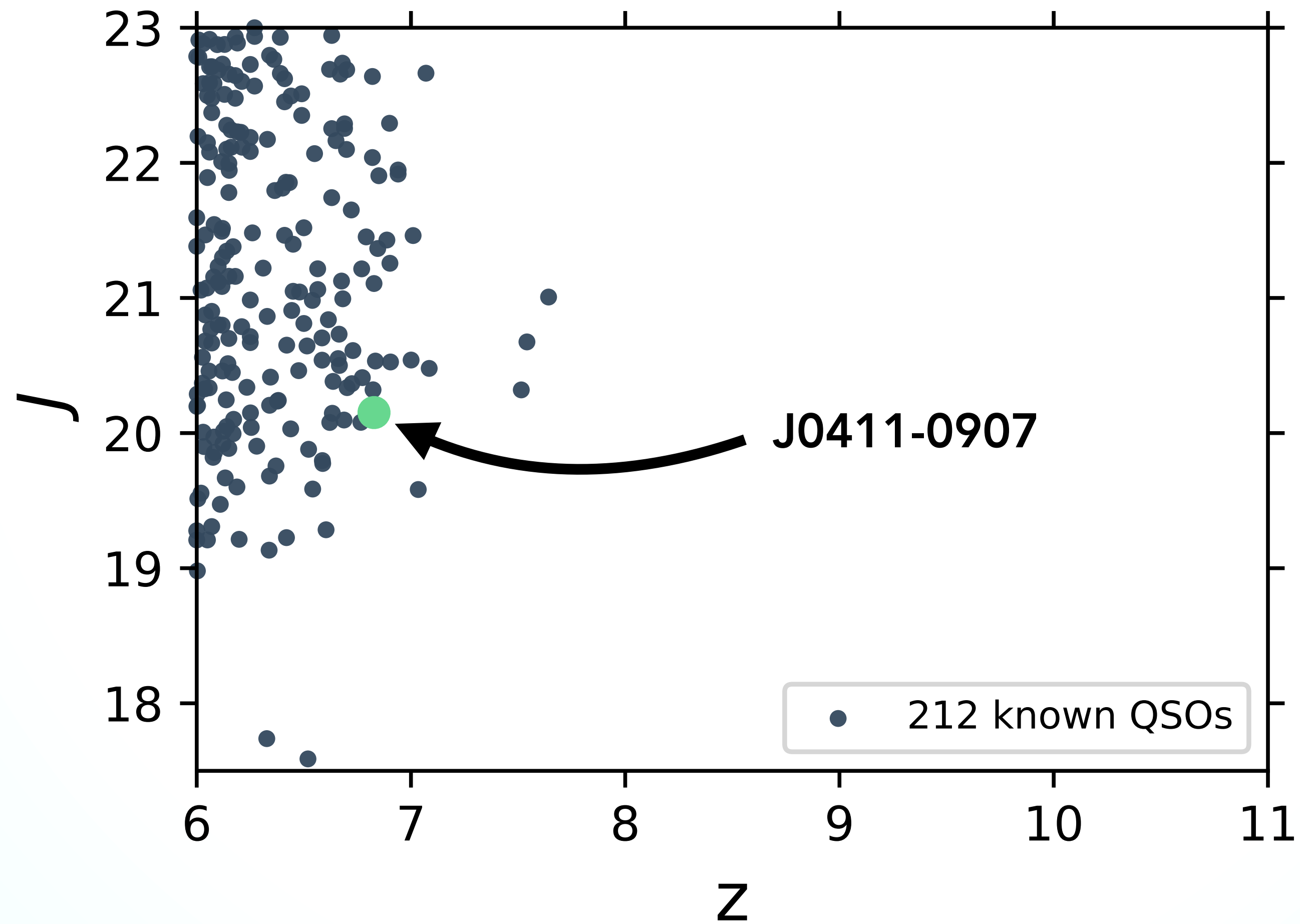
Converting the constraints

The *global* IGM neutral fraction inferred from J0411-0907



EUCLID

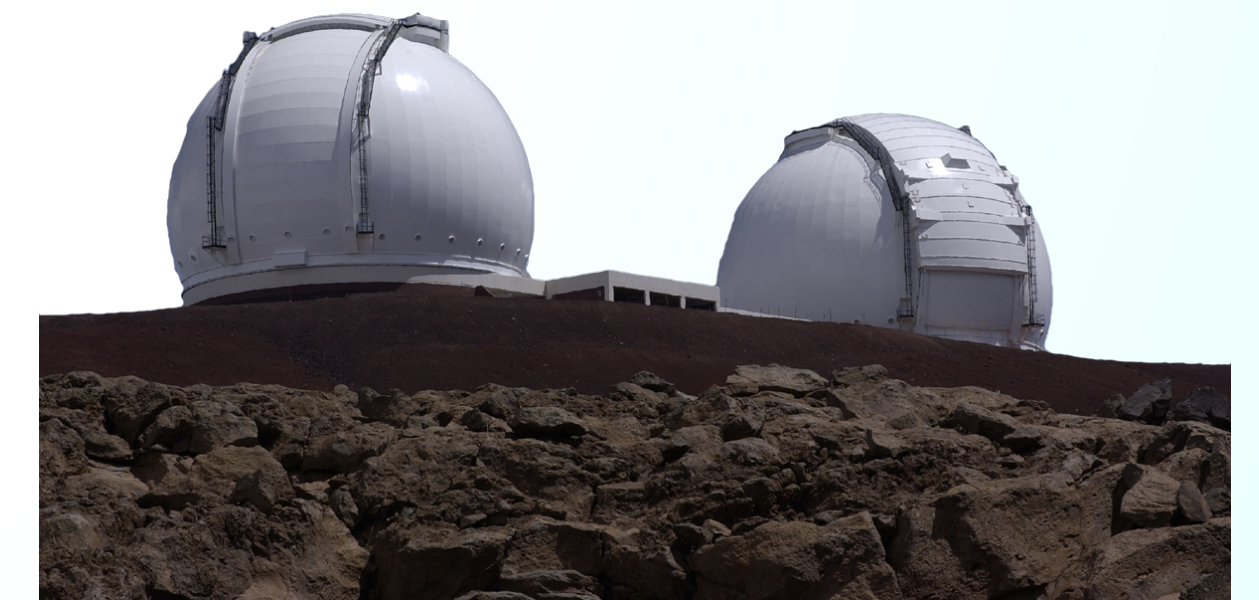
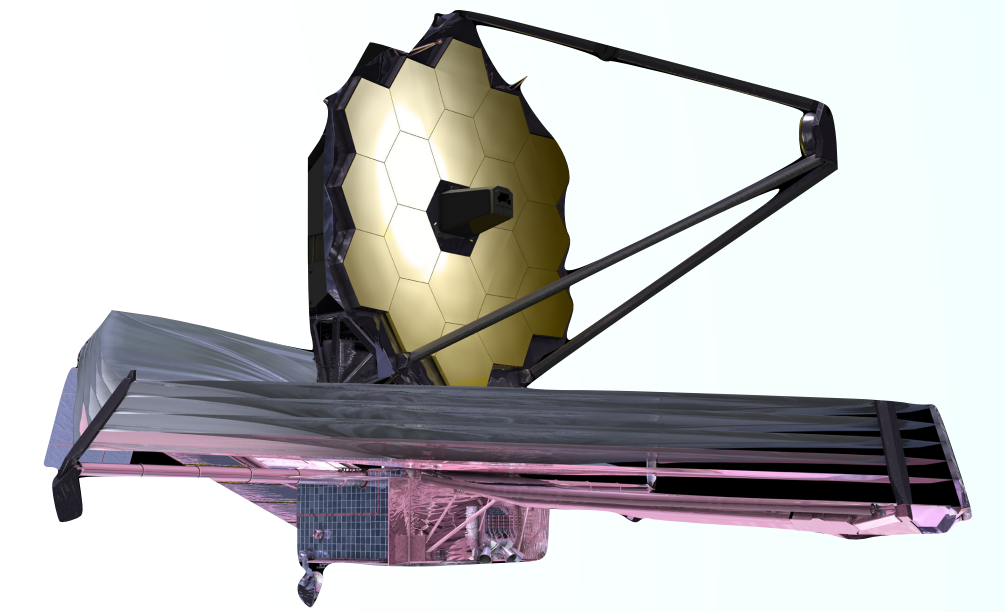
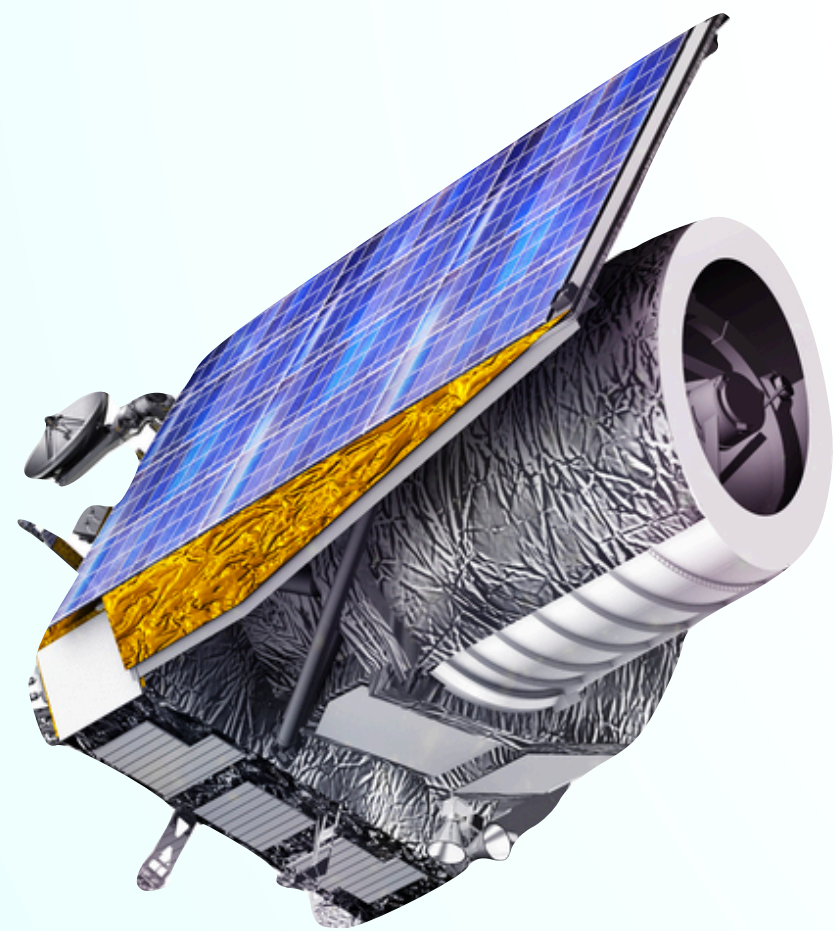
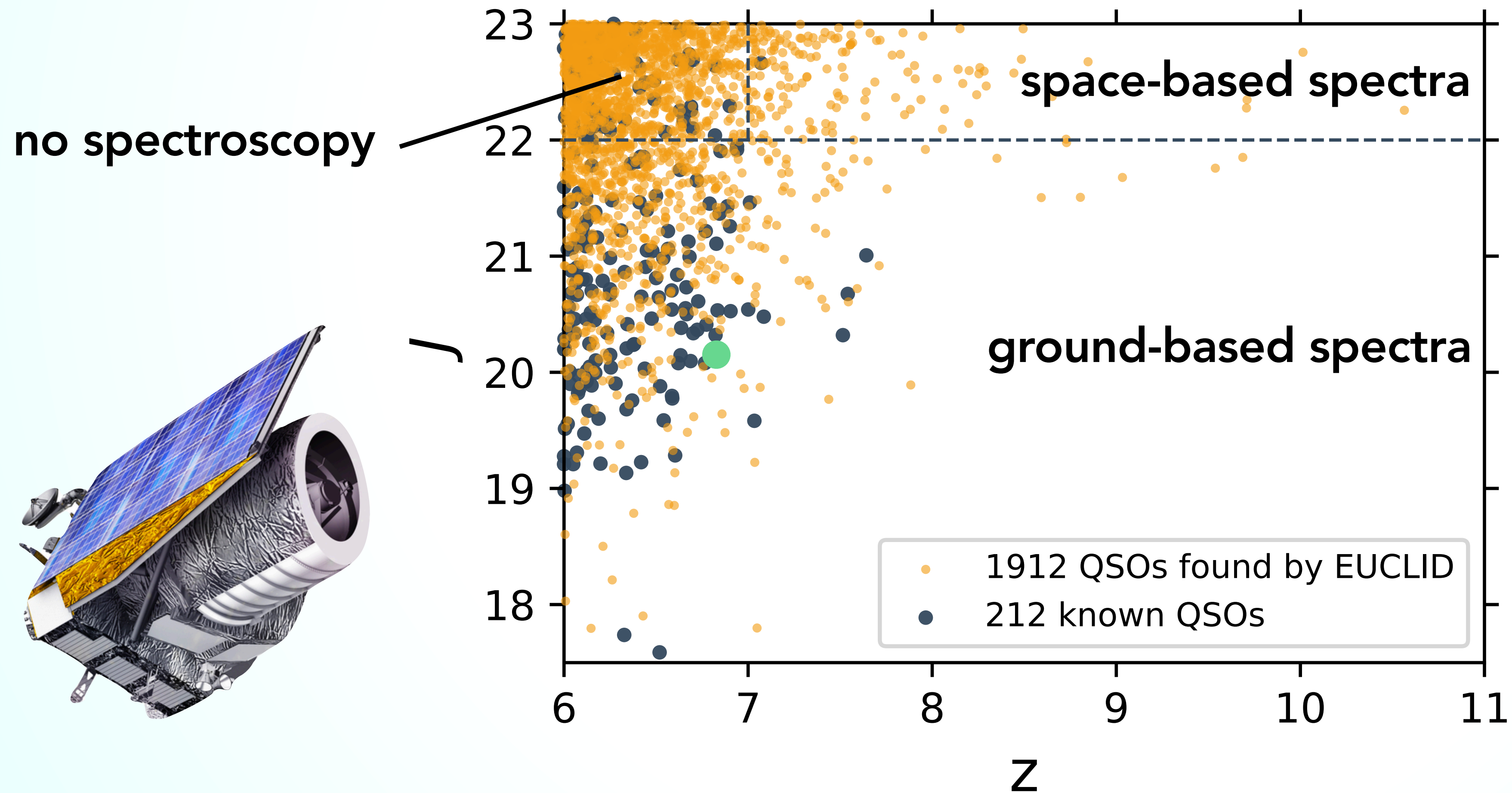
The Quasar Yield of the Wide-Field Survey



EUCLID

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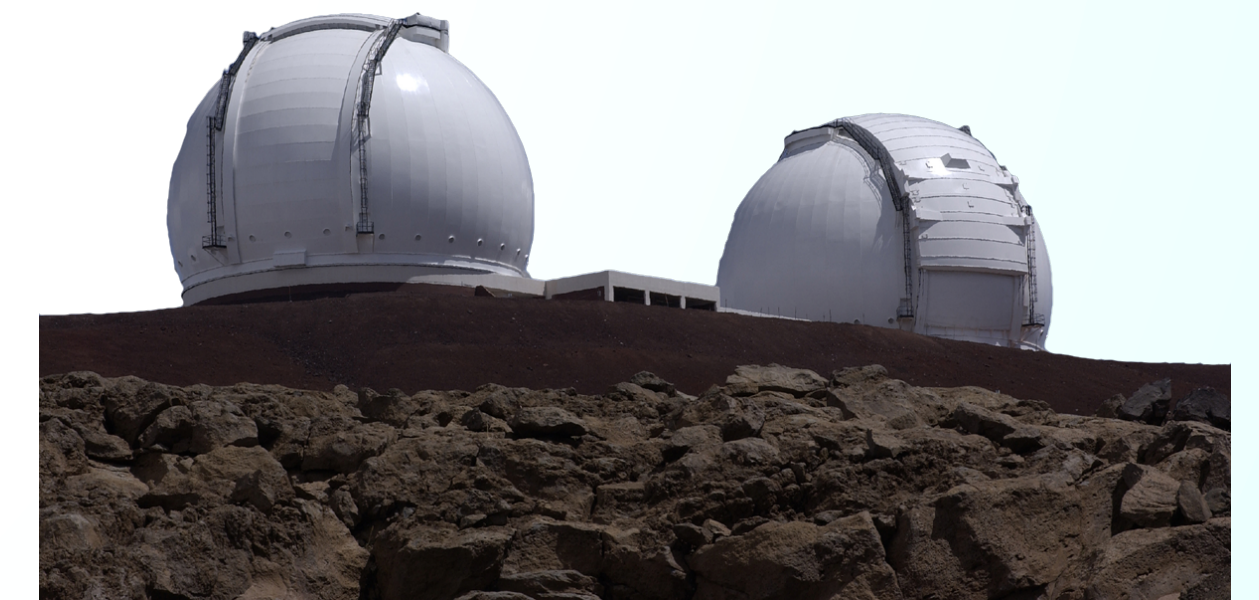
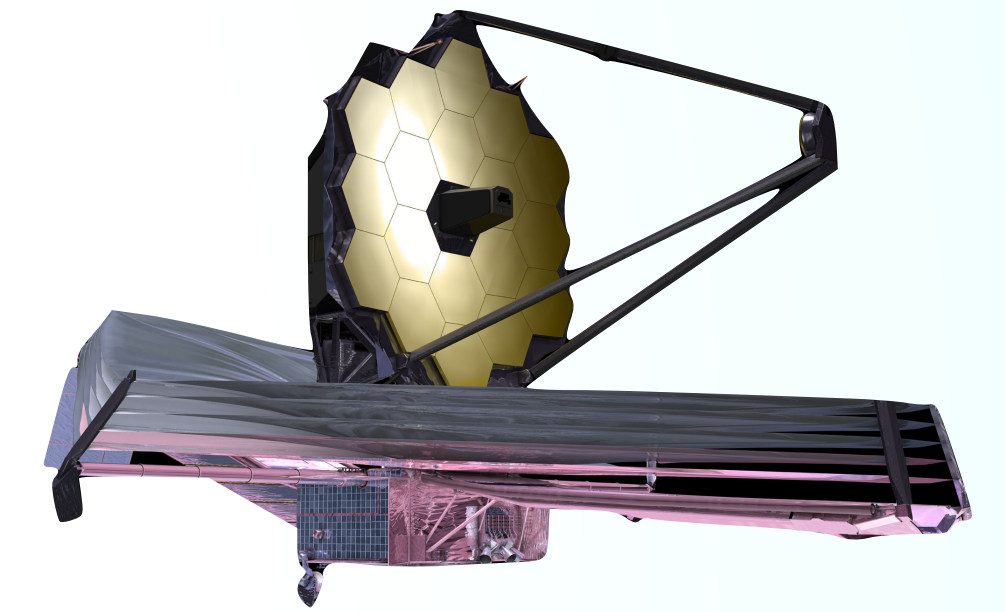
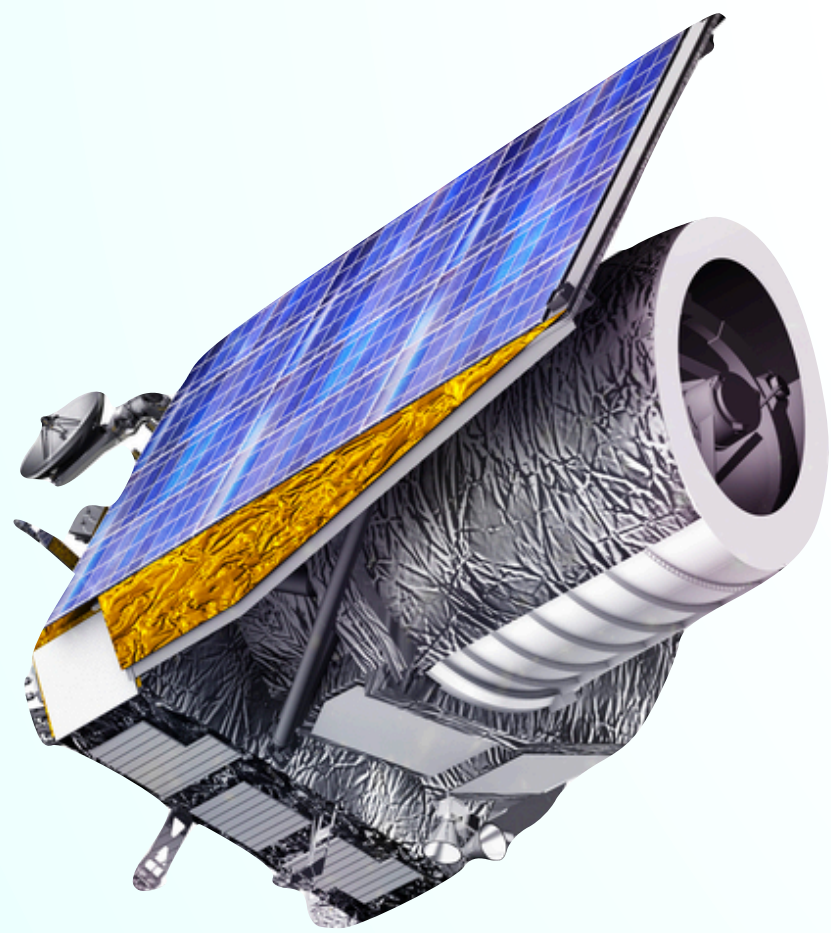
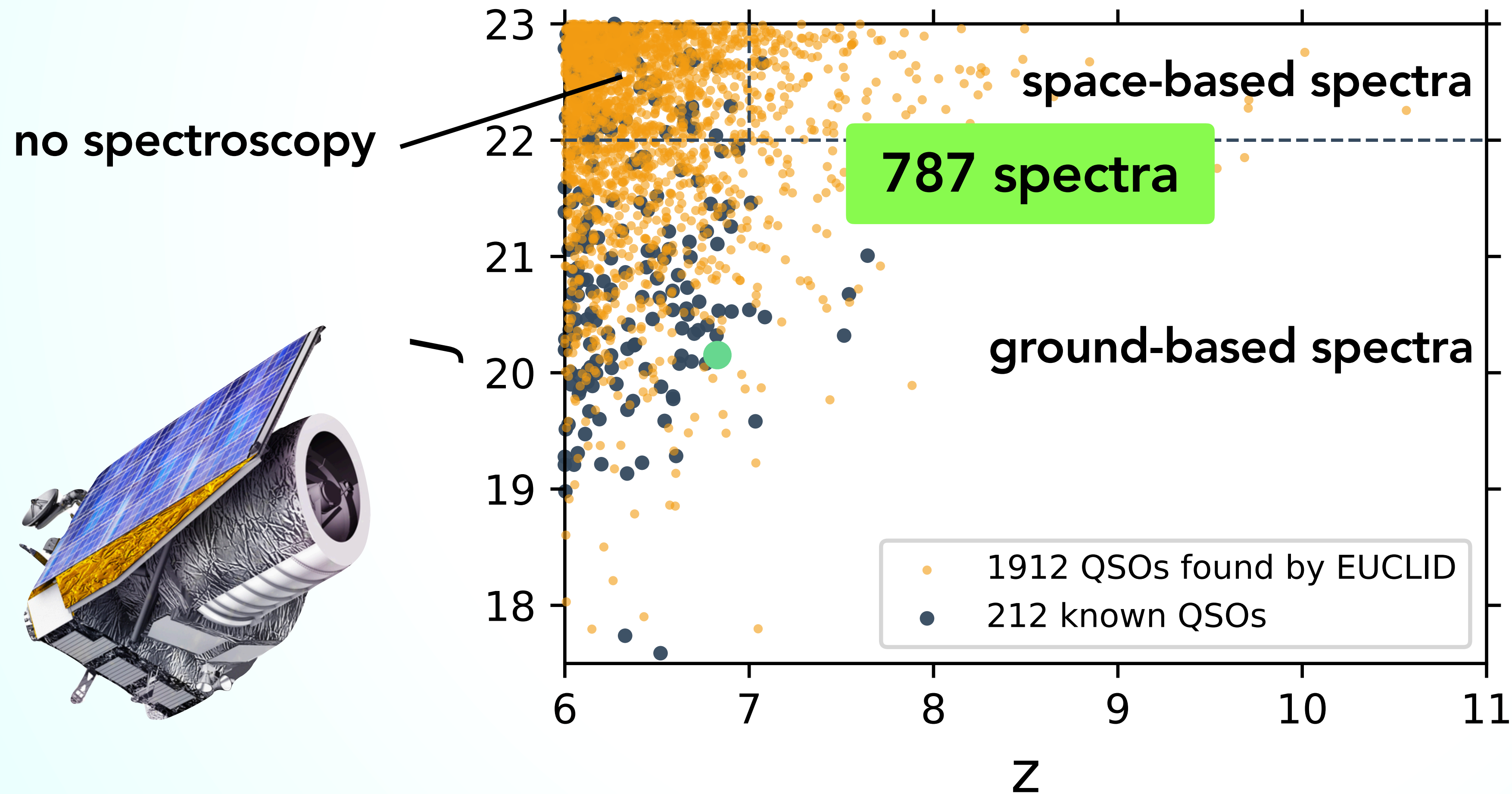
Samples from a Wang+2019 quasar luminosity function



EUCLID

The Quasar Yield of the Wide-Field Survey

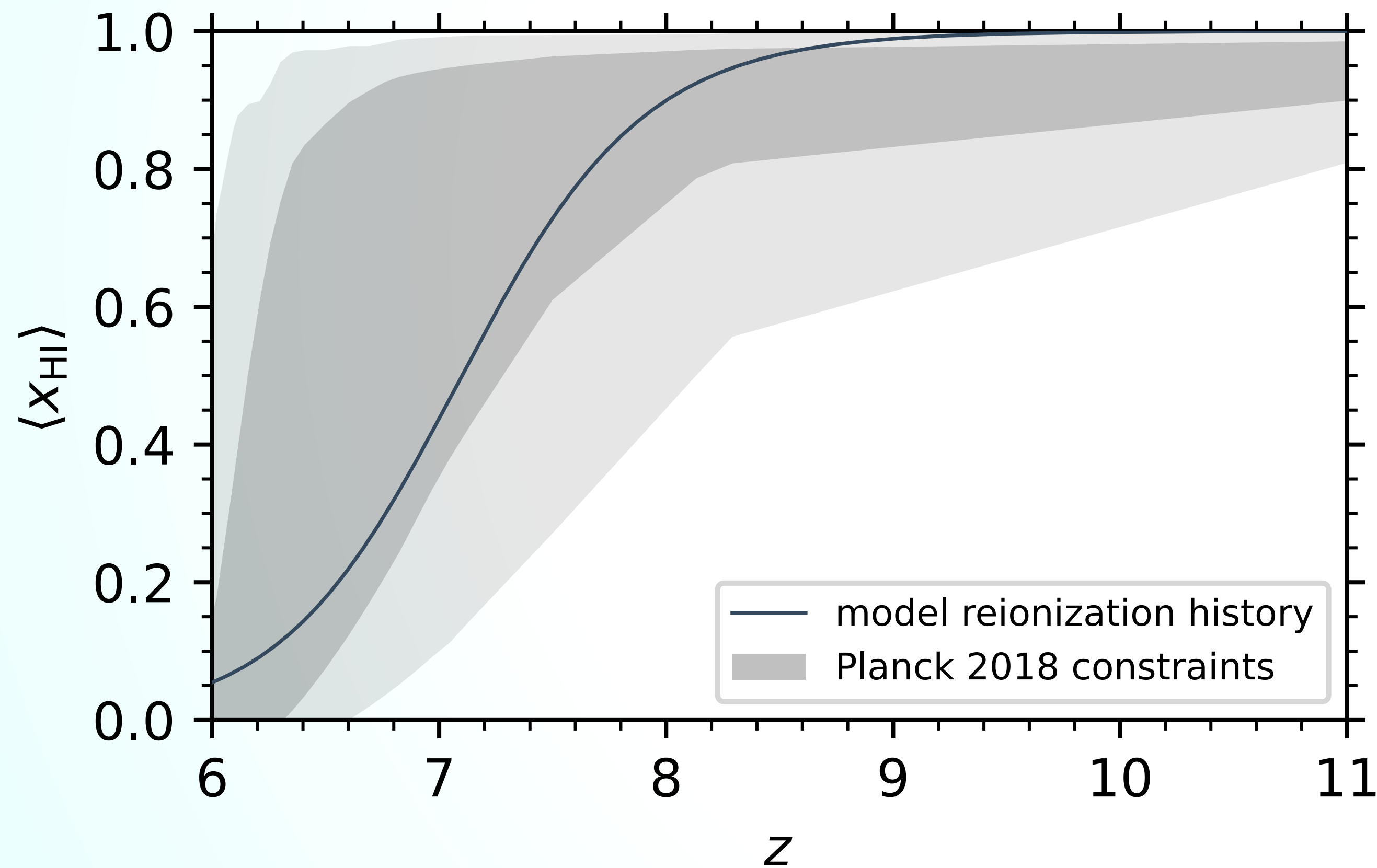
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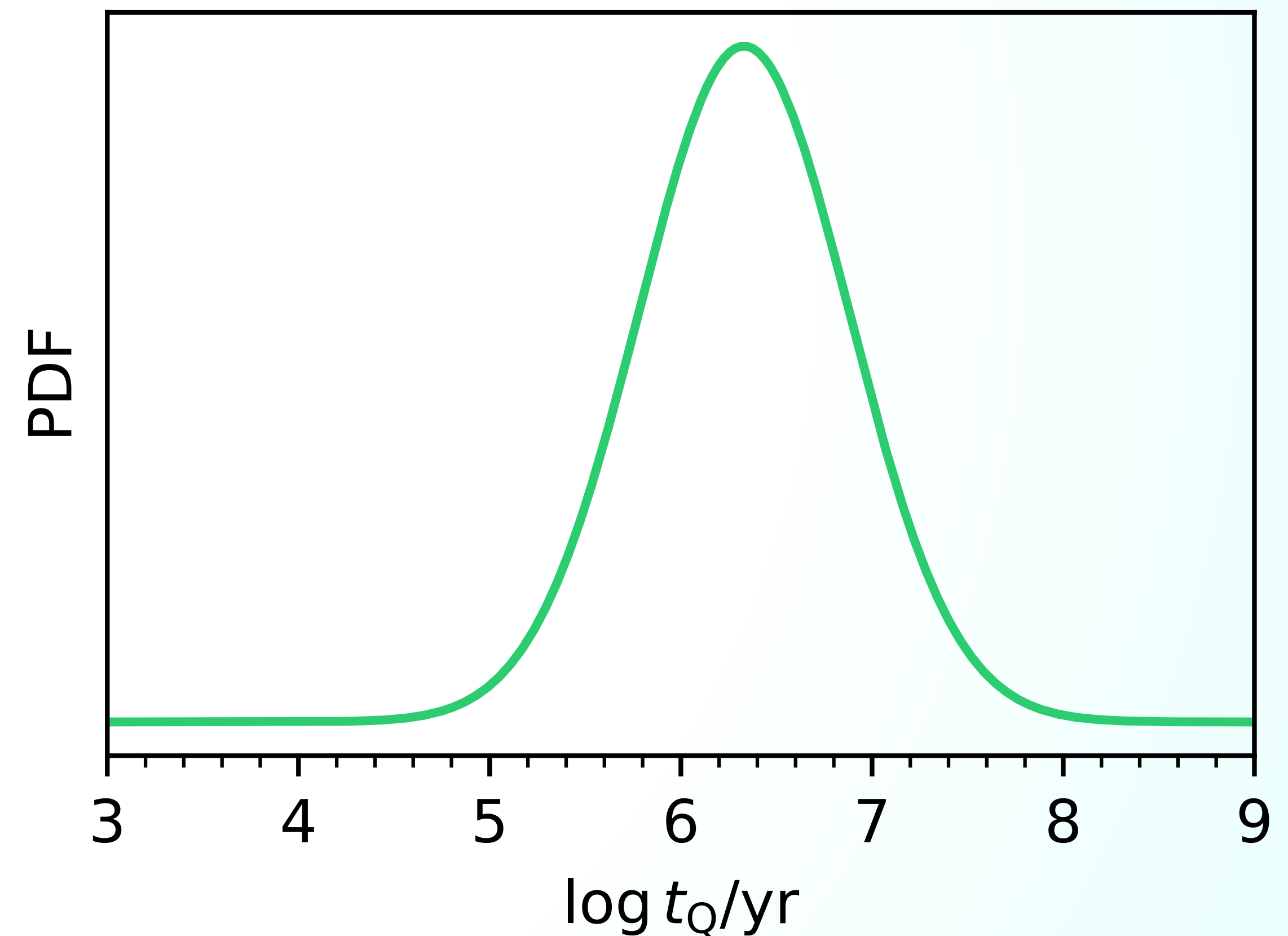
Constraining Reionization History with EUCLID & JWST

A forecast of upcoming IGM damping wing constraints

Toy model for $\langle x_{\text{HI}} \rangle(z)$

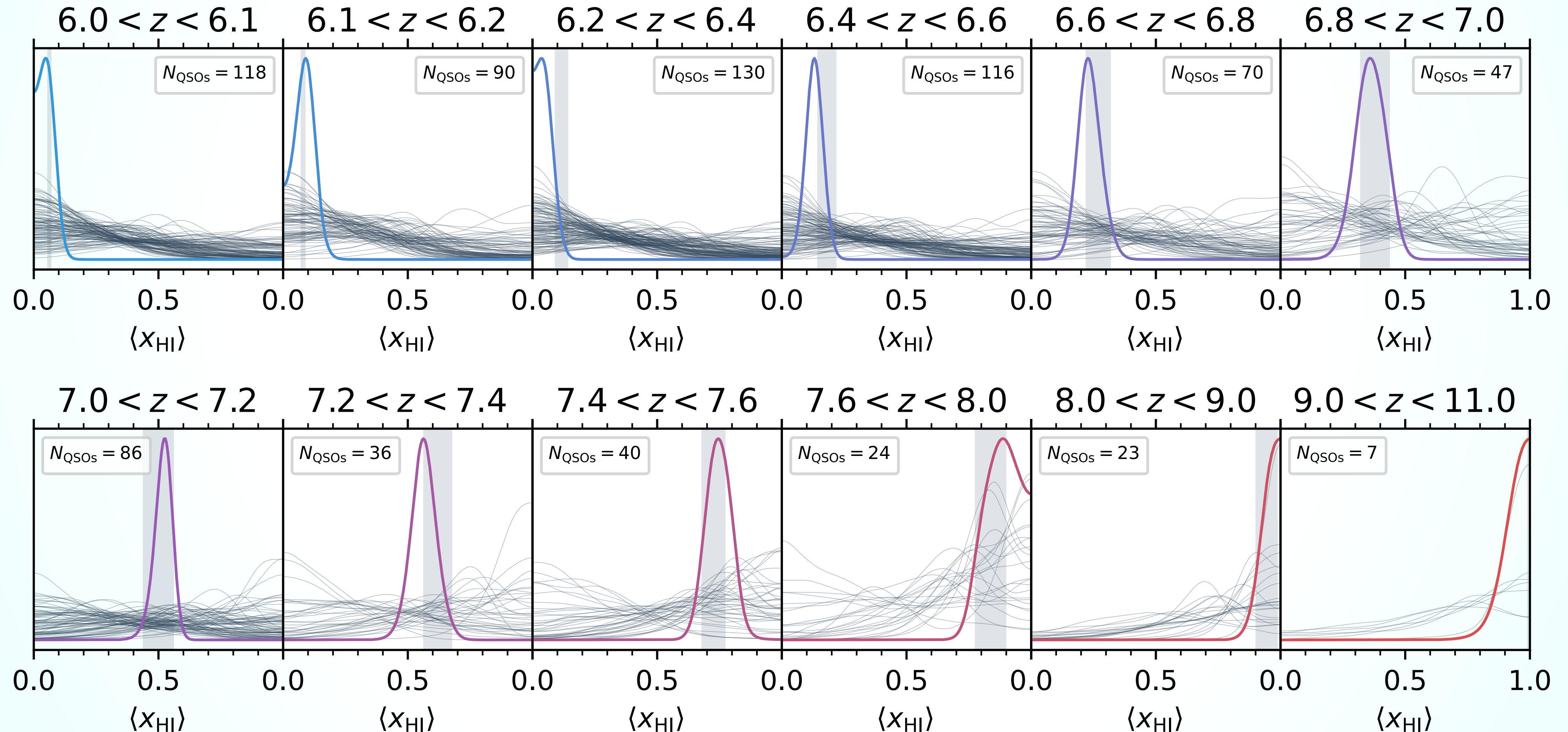


Lognormal t_Q distribution (Khrykin+ 2021)



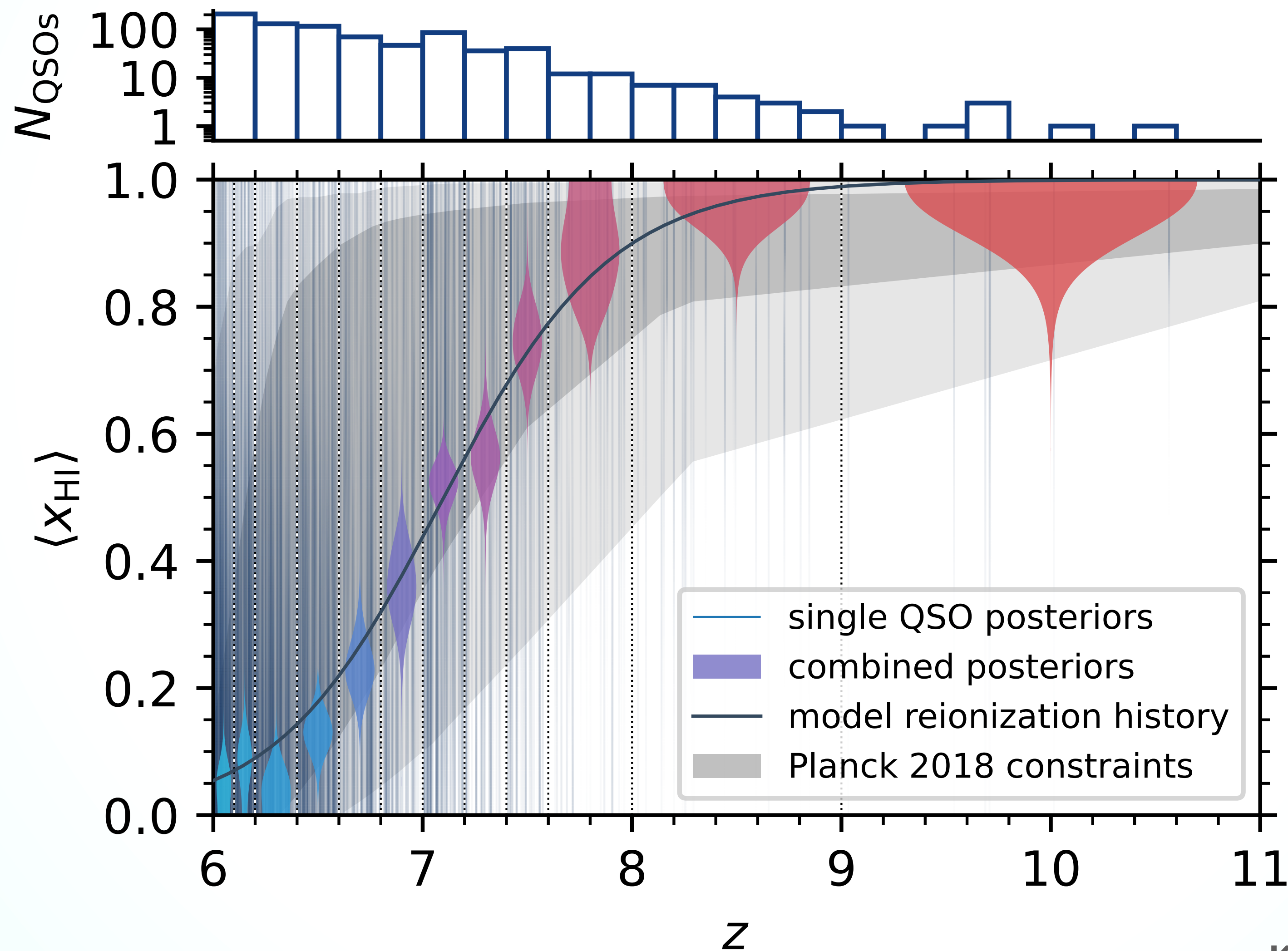
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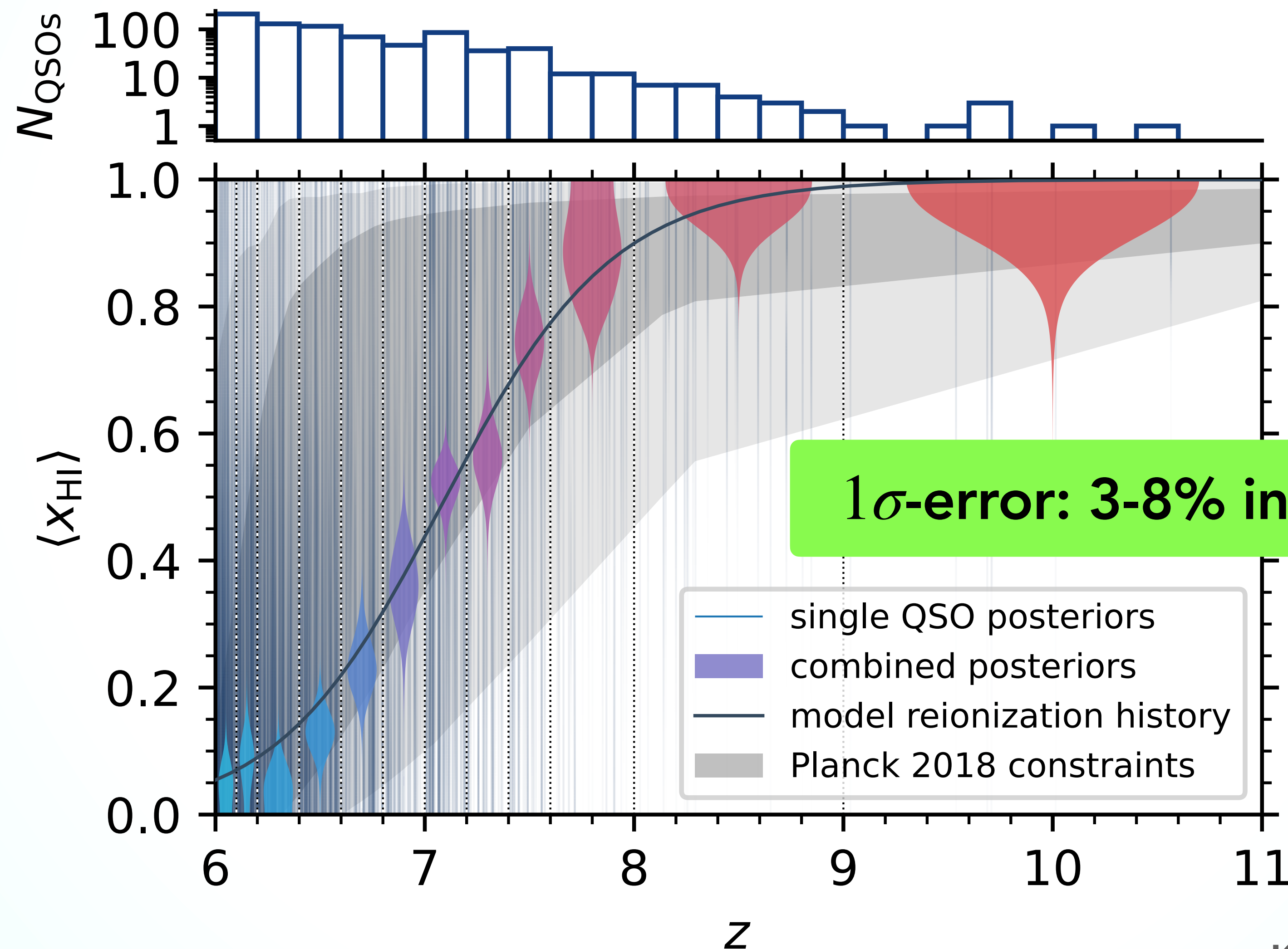
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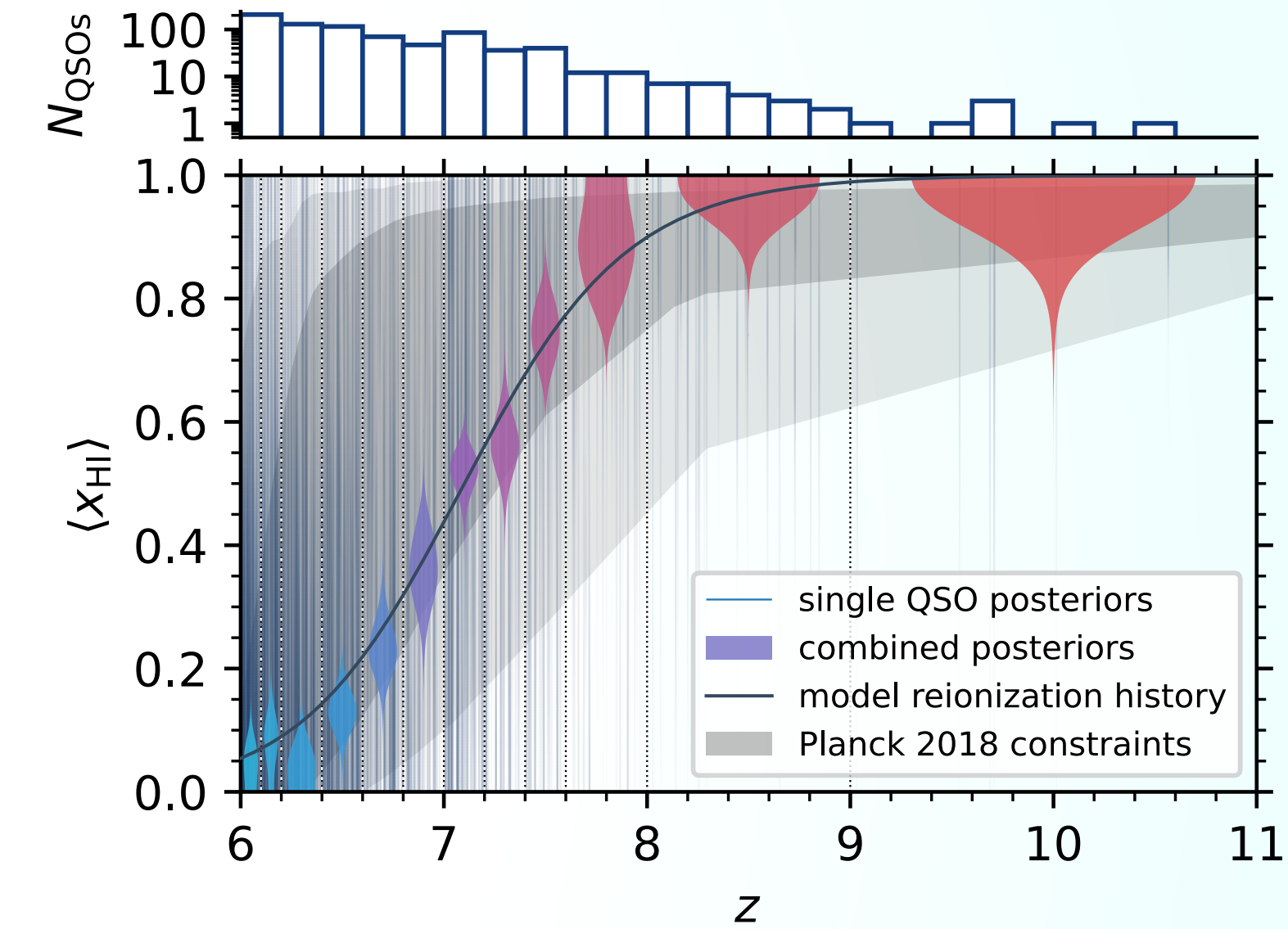
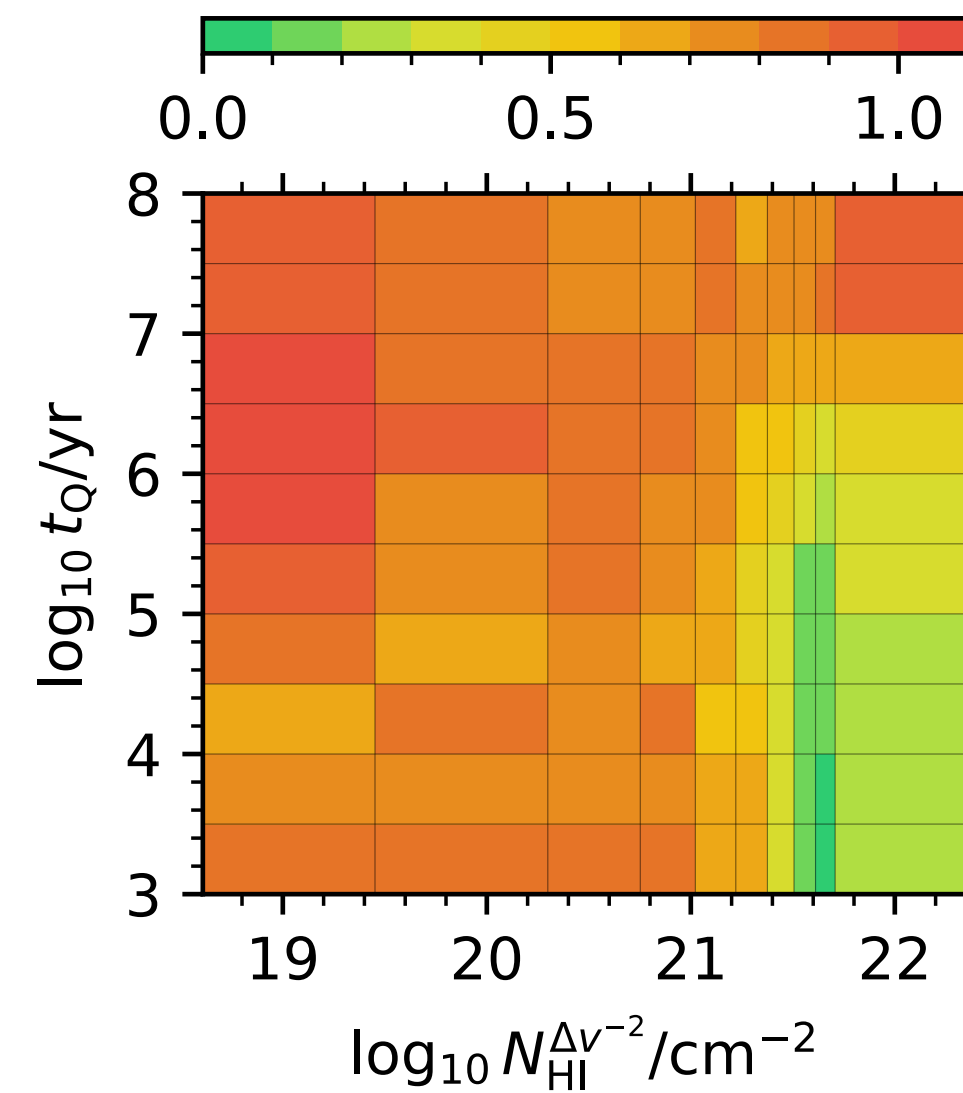
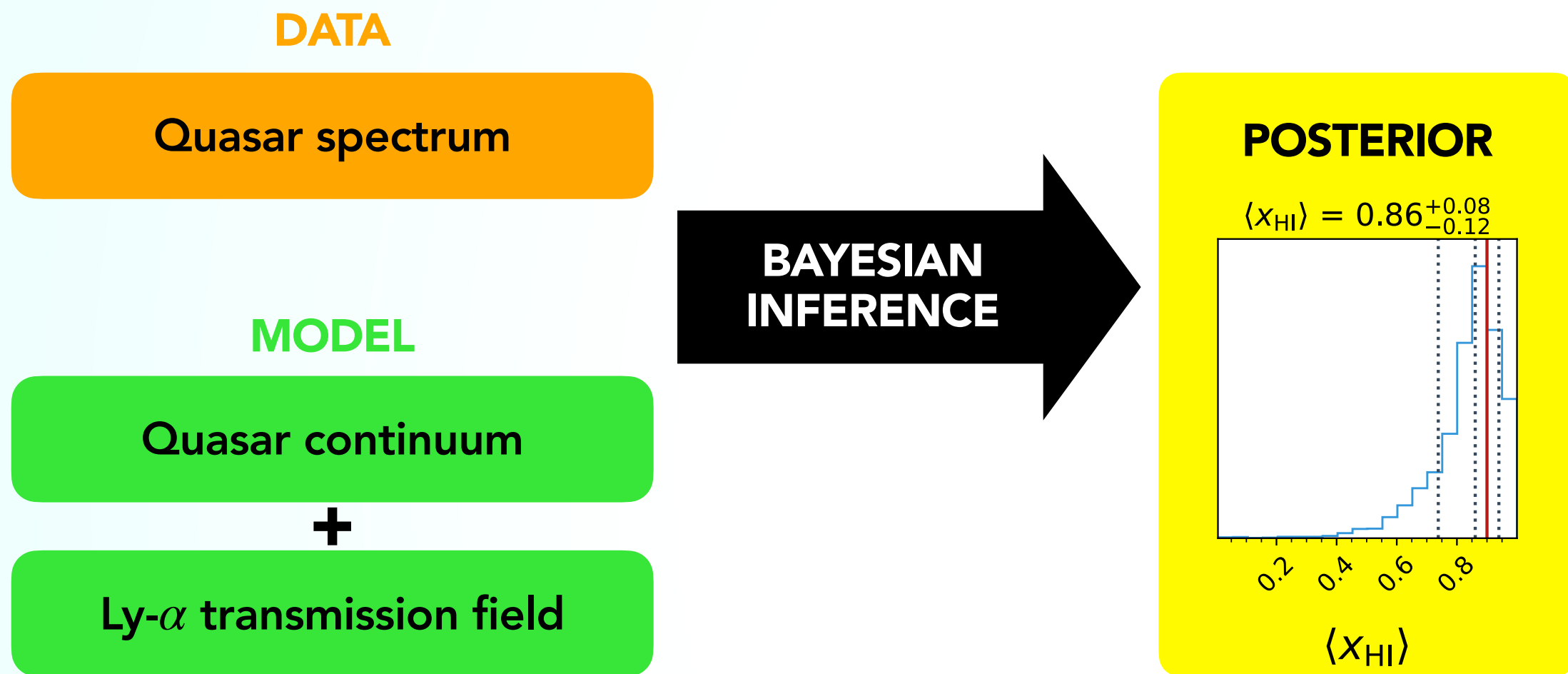


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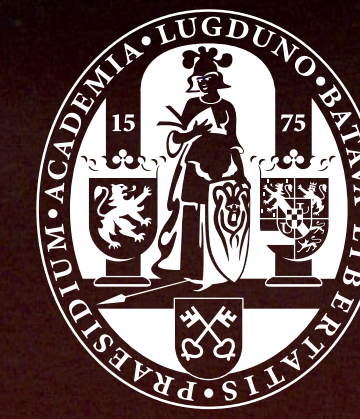
Summary



Fast HMC pipeline to infer $\langle x_{\text{HI}} \rangle / N_{\text{HI}}^{\text{DW}}$
and t_Q using the damping wing imprint
of high-redshift quasars

Inferring $\langle x_{\text{HI}} \rangle$ at $28.0^{+8.2}_{-8.8} \%$
precision, or even the local HI
column density at $0.69^{+0.34}_{-0.53}$ dex

EUCLID & JWST:
3-8% constraints on $\langle x_{\text{HI}} \rangle(z)$
between $6 \lesssim z \lesssim 11$



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Thank you!