Universiteit Leiden

Sterrewacht Leiden

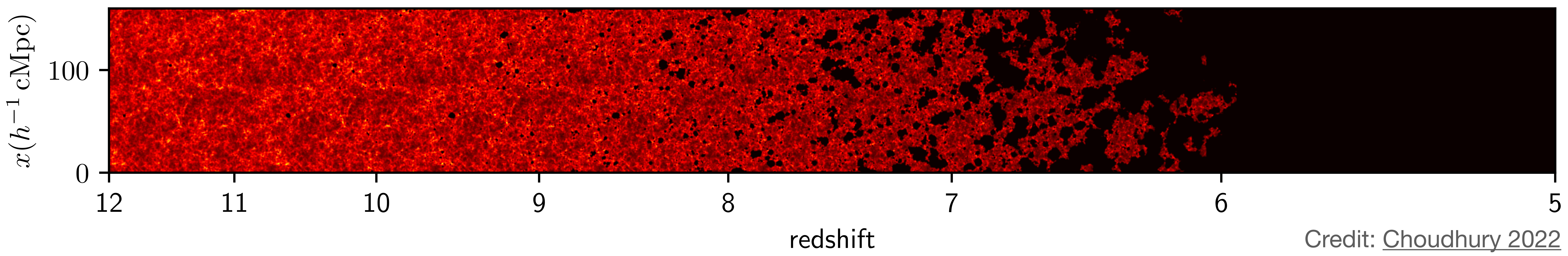
Constraining the Reionization History with High-z Quasar Damping Wings

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

Timo Kist, Leiden Observatory, kist@strw.leidenuniv.nl

Quasars in a Reionizing Universe

Proximity Zones & IGM Damping Wings

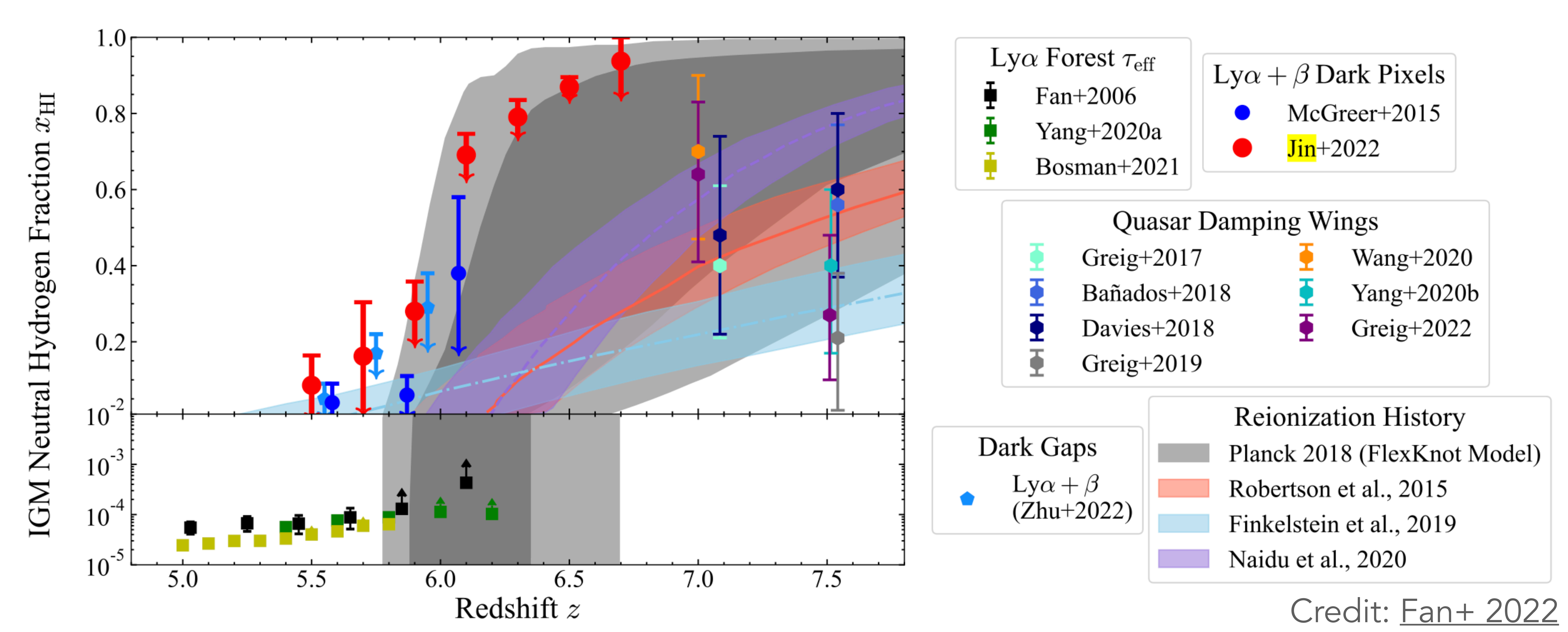


Credit: Choudhury 2022

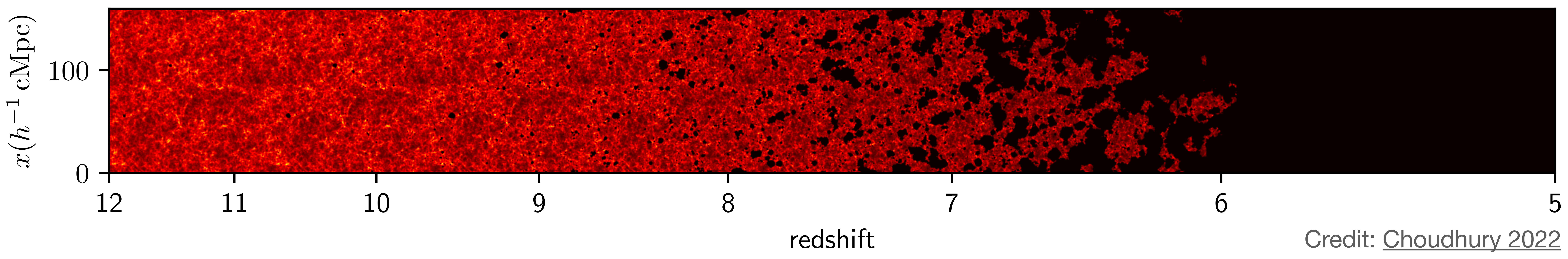
Timo Kist, Leiden Observatory, kist@strw.leidenuniv.nl

Quasars in a Reionizing Universe

Proximity Zones & IGM Damping Wings



Credit: Fan+ 2022



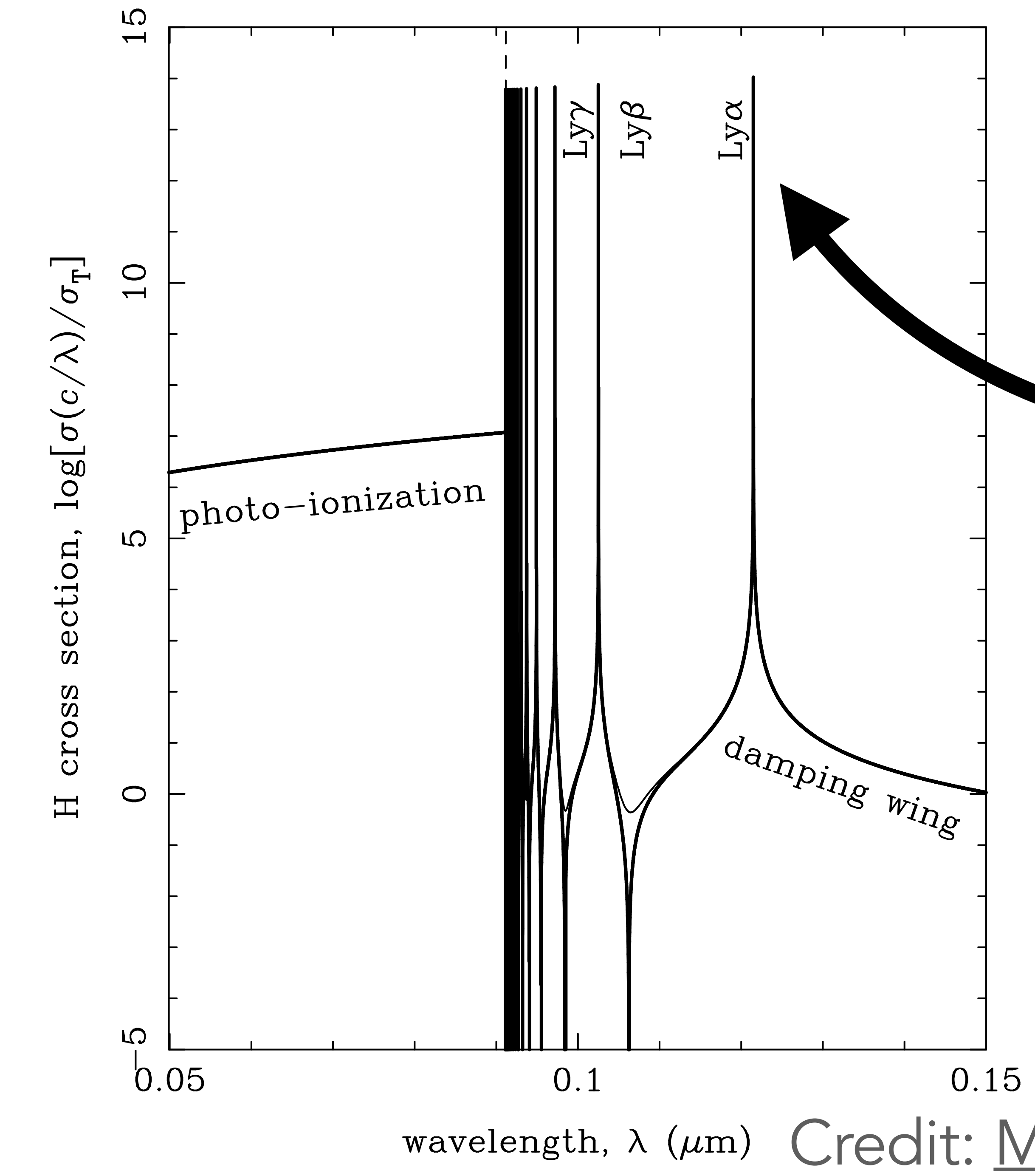
Credit: Choudhury 2022

Timo Kist, Leiden Observatory, kist@strw.leidenuniv.nl

Quasars in a Reionizing Universe

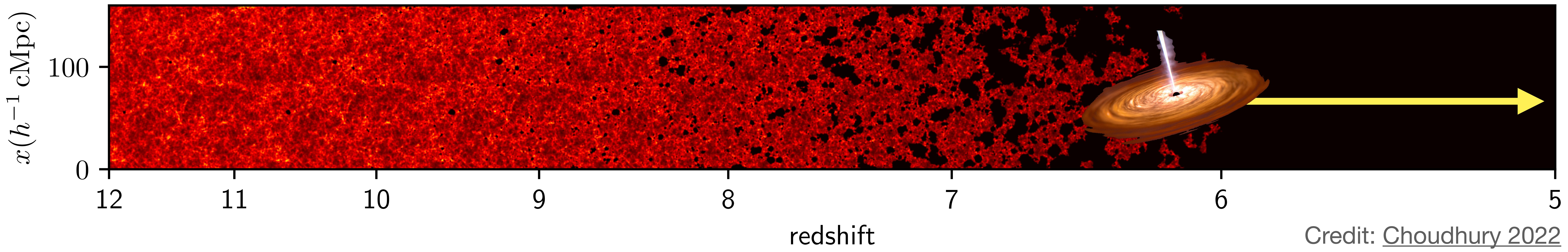
Proximity Zones & IGM Damping Wings

HI cross section



Credit: Mortlock 2016

Lyα cross section so high that neutral fractions of $\langle x_{\rm HI} \rangle \gtrsim 10^{-5}$ are enough to cause complete absorption in the Lyα forest (Gunn-Peterson trough)



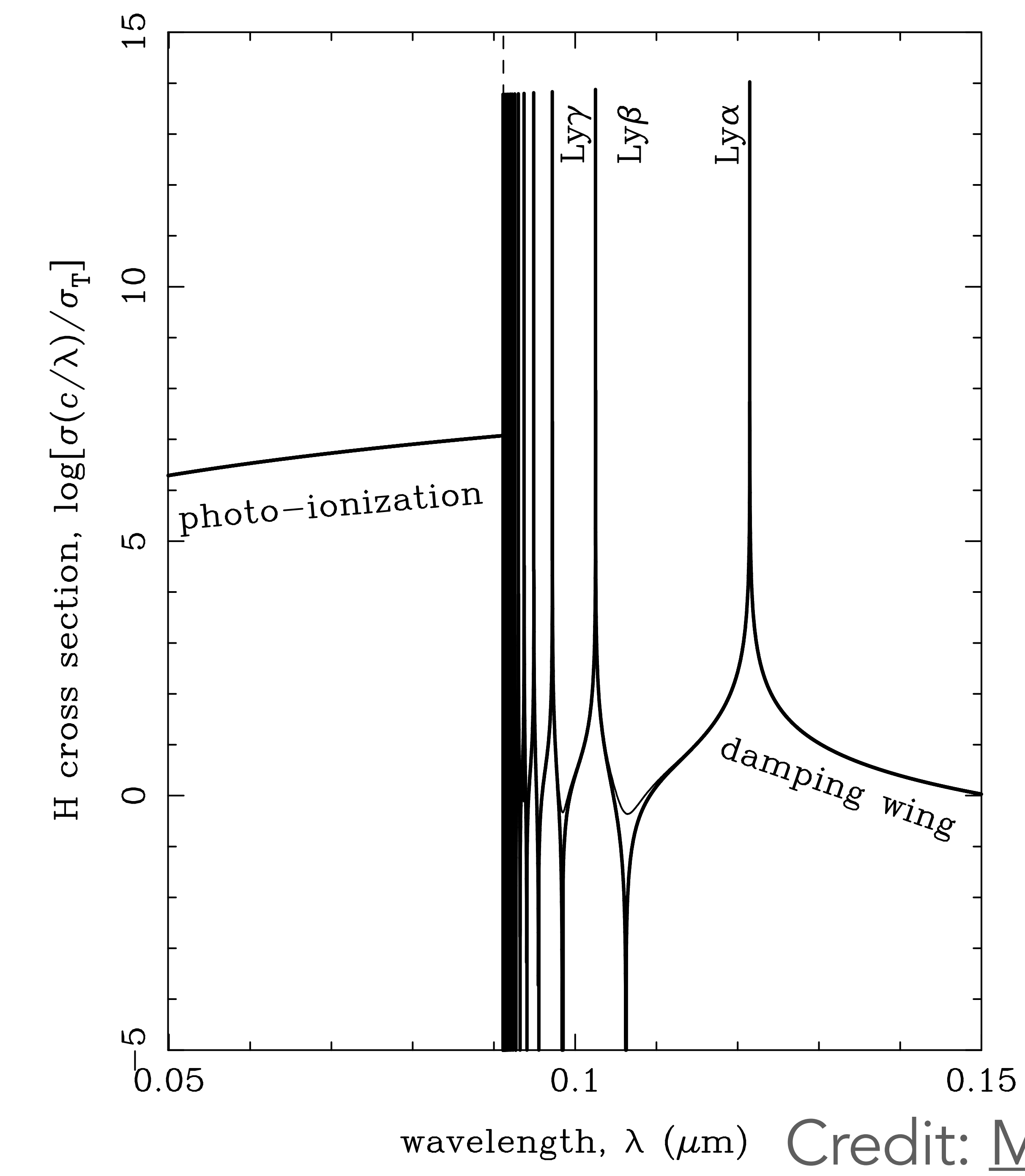
Credit: Choudhury 2022

Timo Kist, Leiden Observatory, kist@strw.leidenuniv.nl

Quasars in a Reionizing Universe

Proximity Zones & IGM Damping Wings

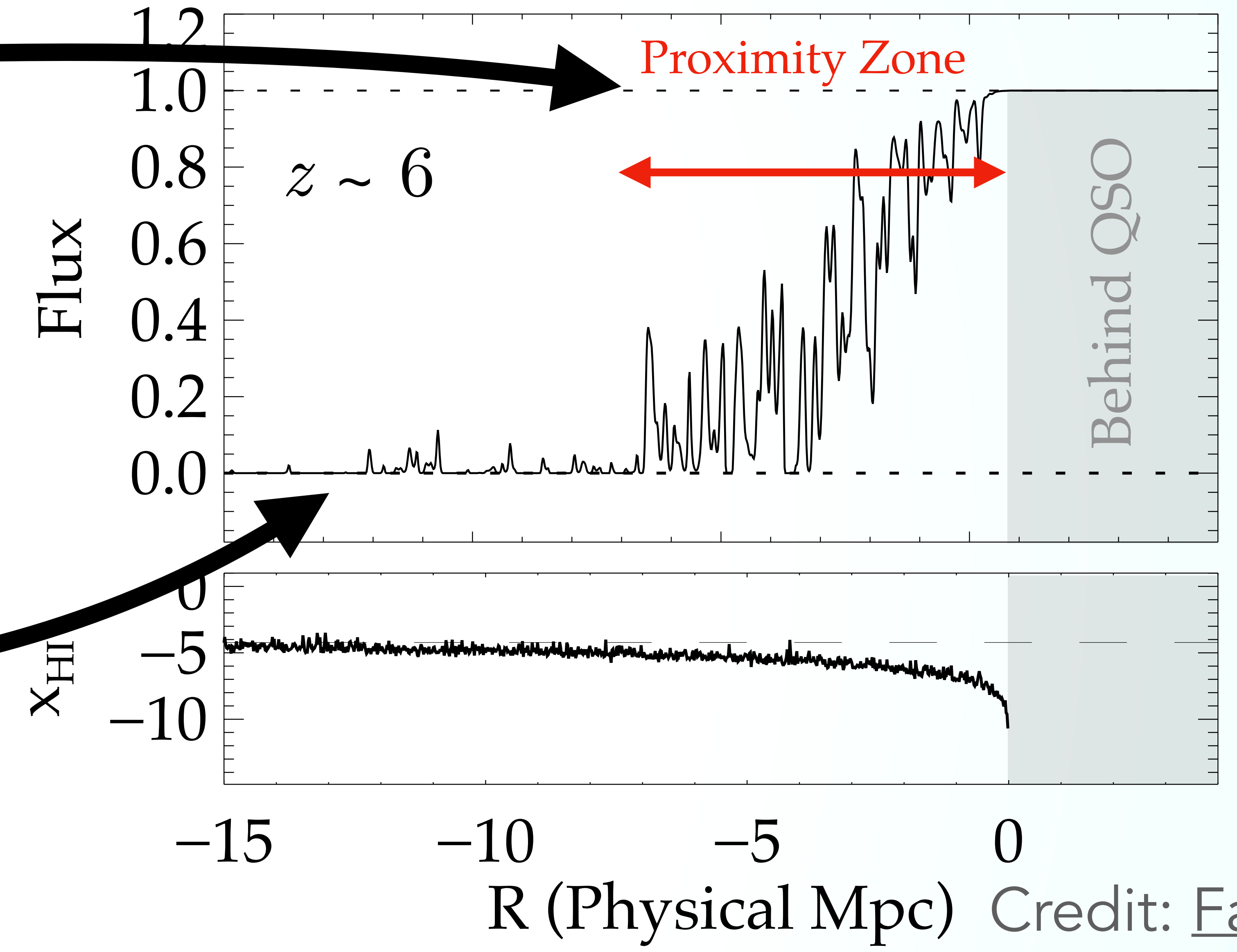
HI cross section



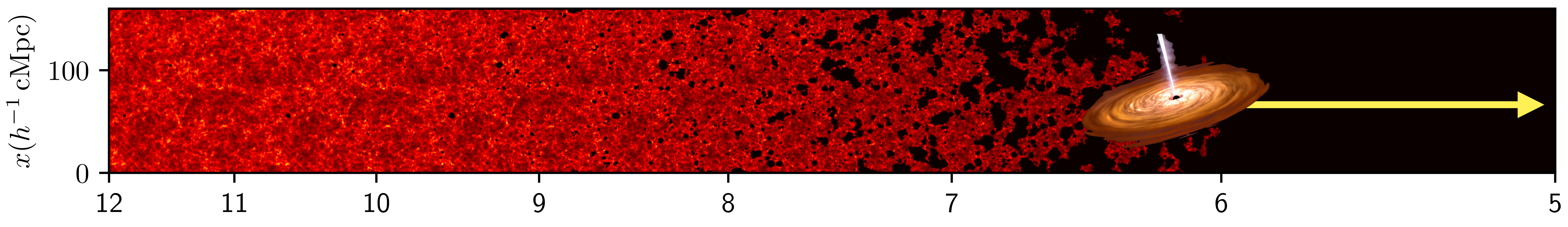
Credit: Mortlock 2016

Proximity zone:
Non-zero transmission in the quasar's proximity due to its strong ionizing radiation

Gunn-Peterson trough



Credit: Fan+ 2022



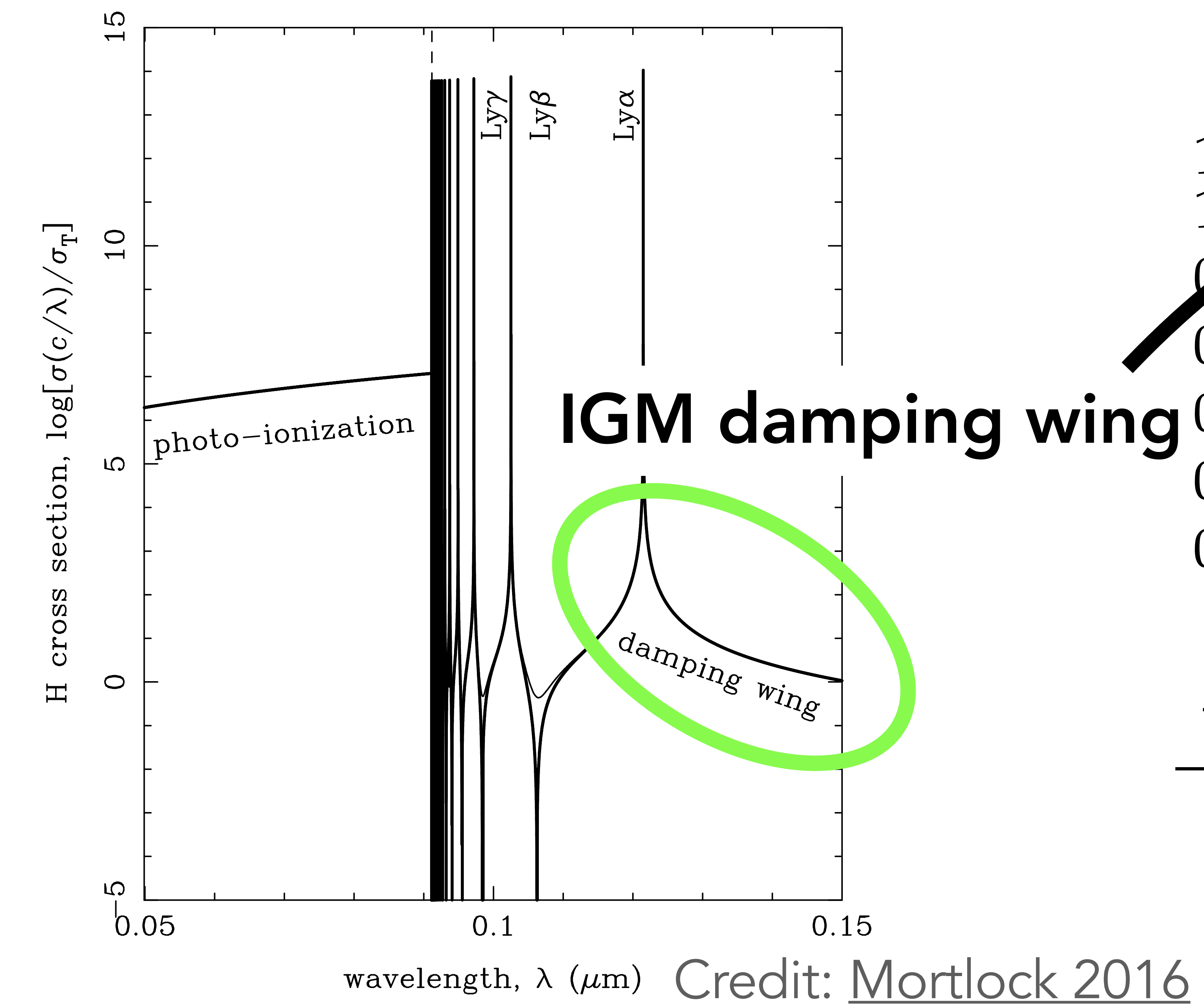
Credit: Choudhury 2022

Timo Kist, Leiden Observatory, kist@strw.leidenuniv.nl

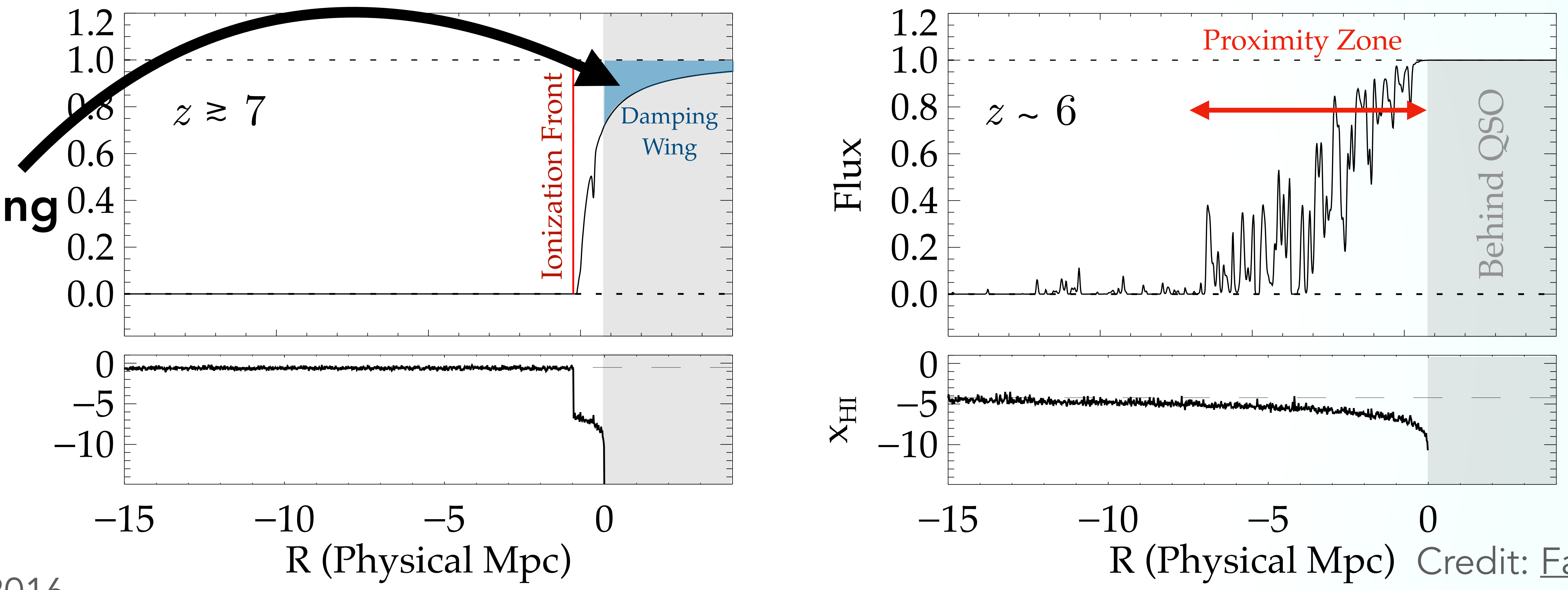
Quasars in a Reionizing Universe

Proximity Zones & IGM Damping Wings

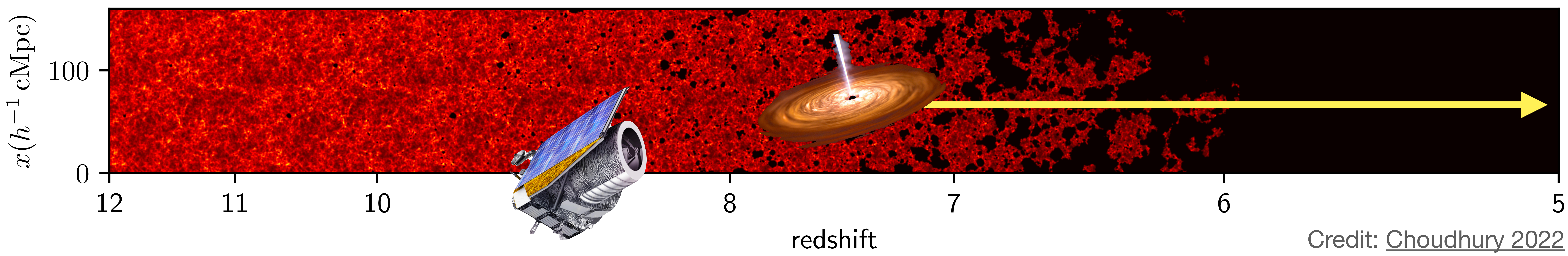
HI cross section



Credit: Mortlock 2016



Credit: Fan+ 2022



Credit: Choudhury 2022

Timo Kist, Leiden Observatory, kist@strw.leidenuniv.nl

Forward-Modelling Damping Wing Absorption

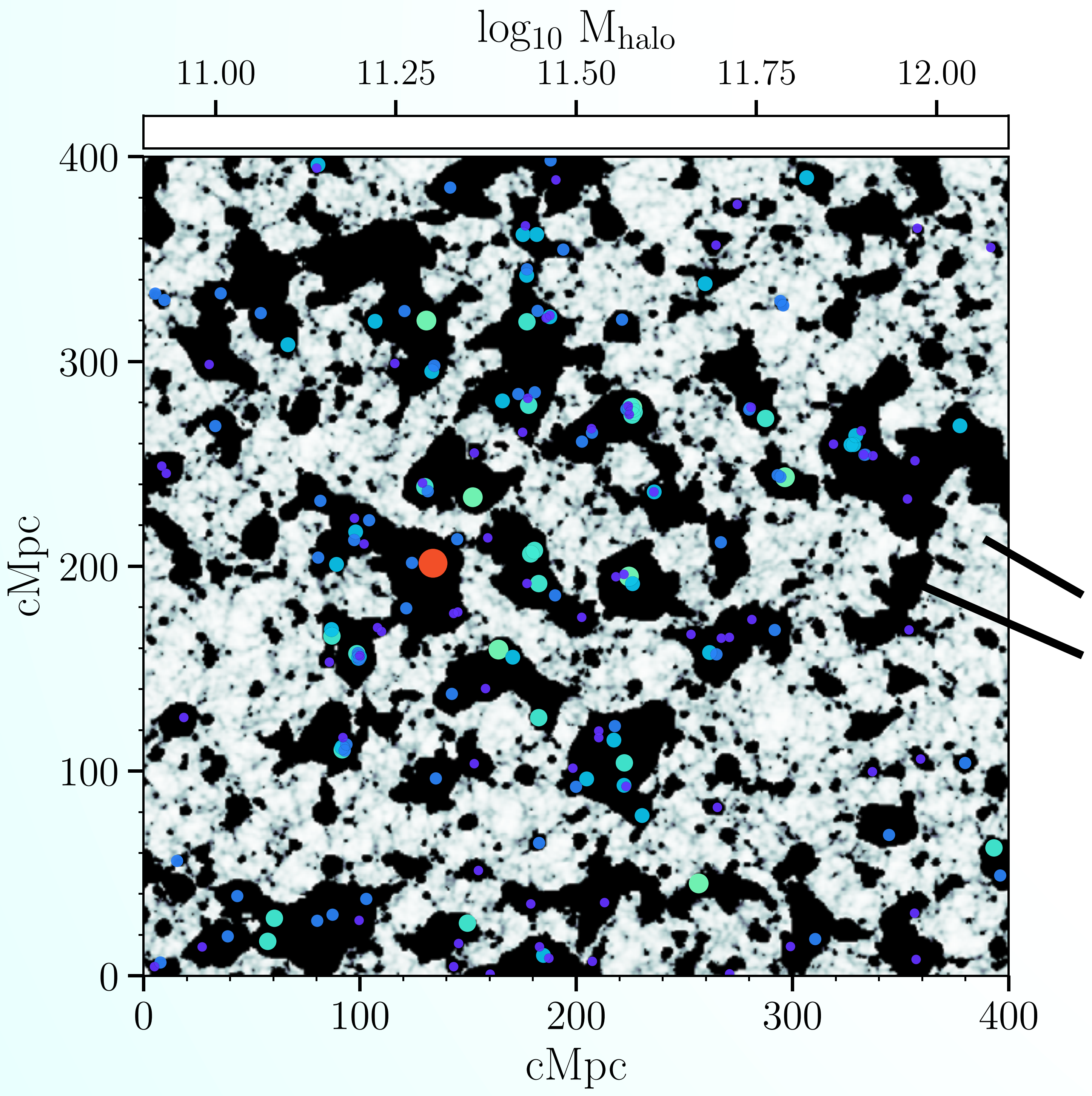
Constructing realistic skewers based on cosmological simulations

Nyx hydrodynamical simulations:

1200 density and temperature skewers around the most massive DM halos

`21cmFast:`

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

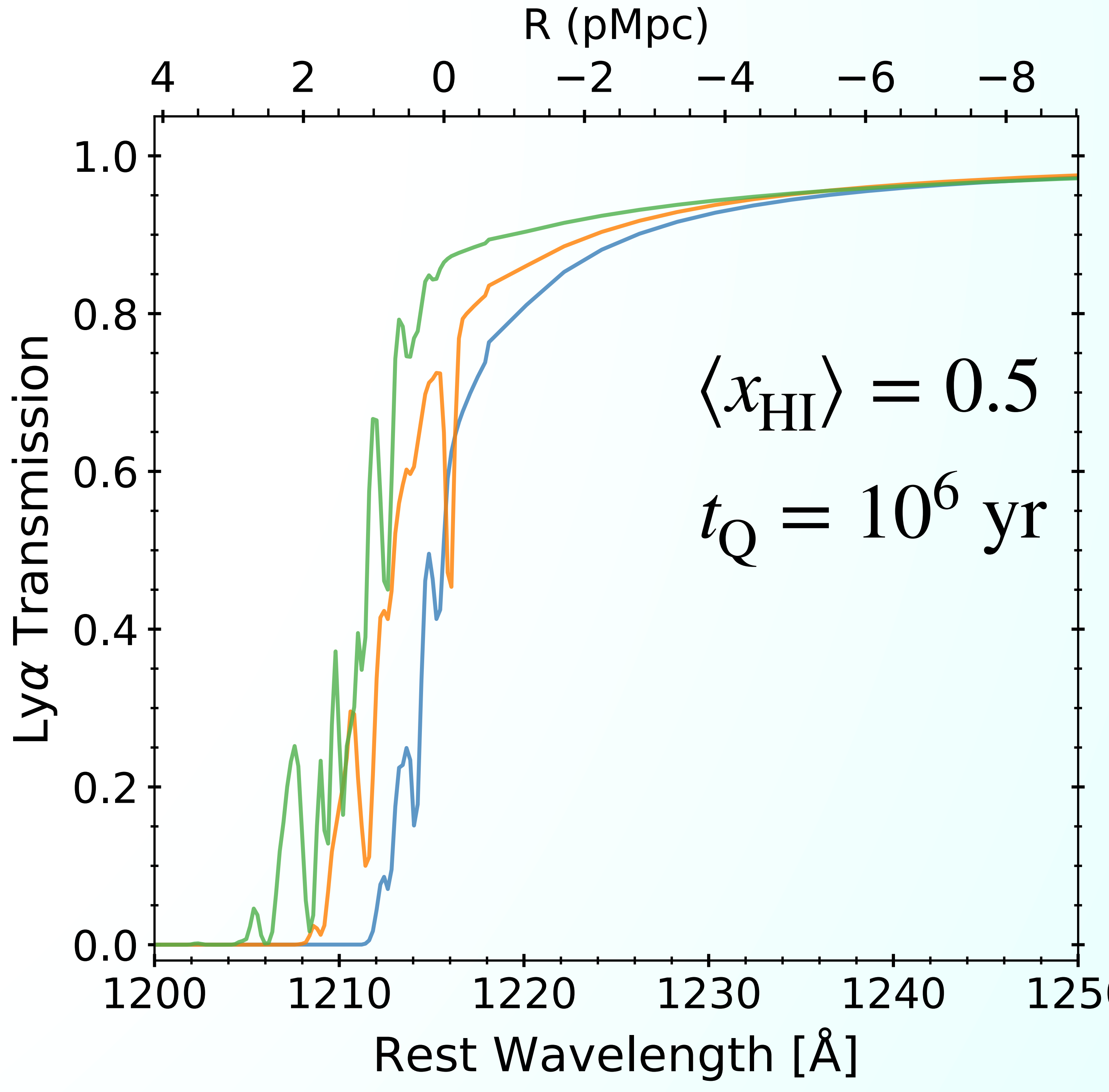


1D Radiative Transfer

51 quasar lifetimes between

$10^3\,{\rm yr} \leq t_{\rm Q} \leq 10^8\,{\rm yr}$

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



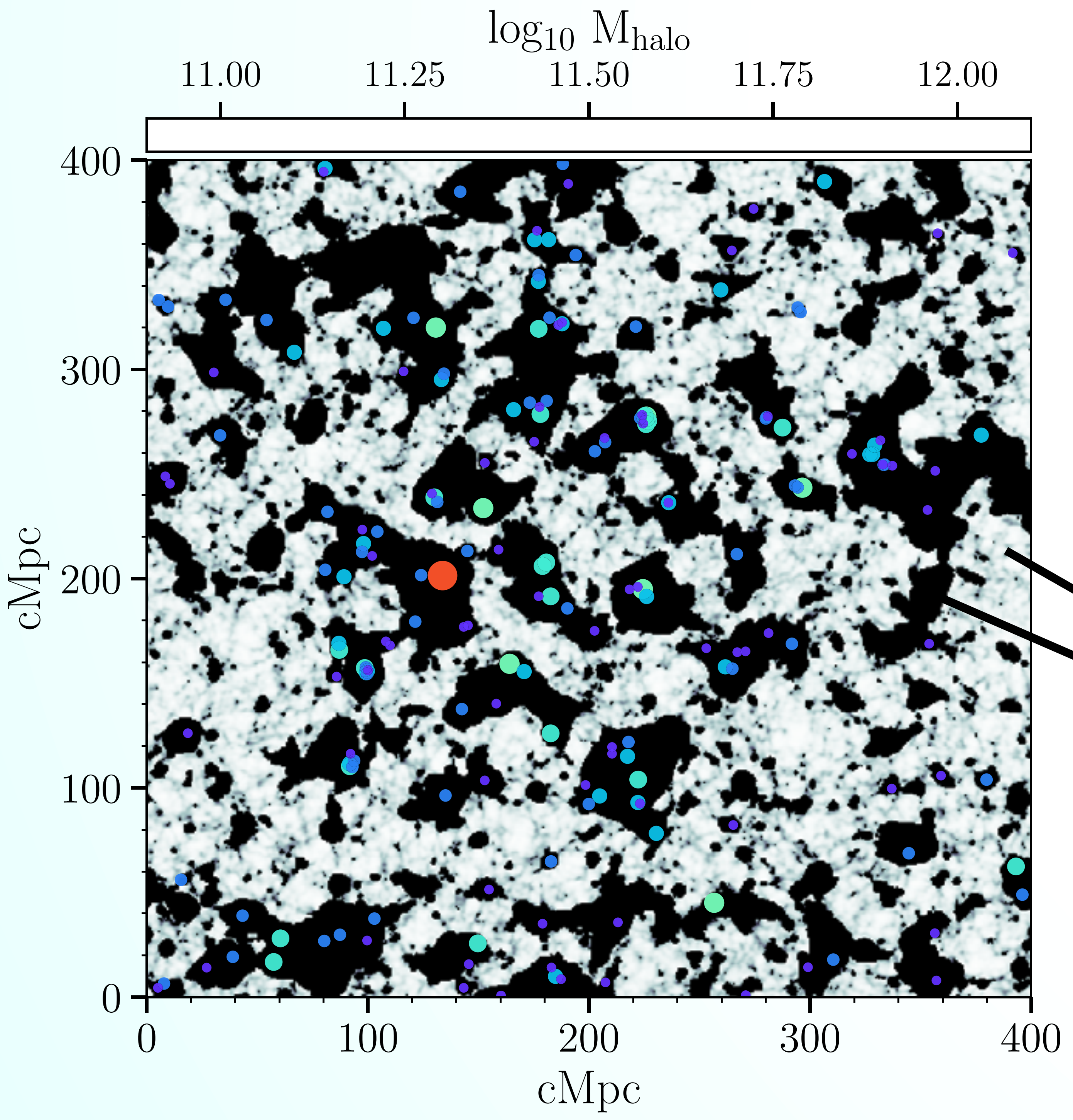
Credit: Davies+ 2018

Kist, Hennawi, Davies+ 2023a (in prep.)

Timo Kist, Leiden Observatory, kist@strw.leidenuniv.nl

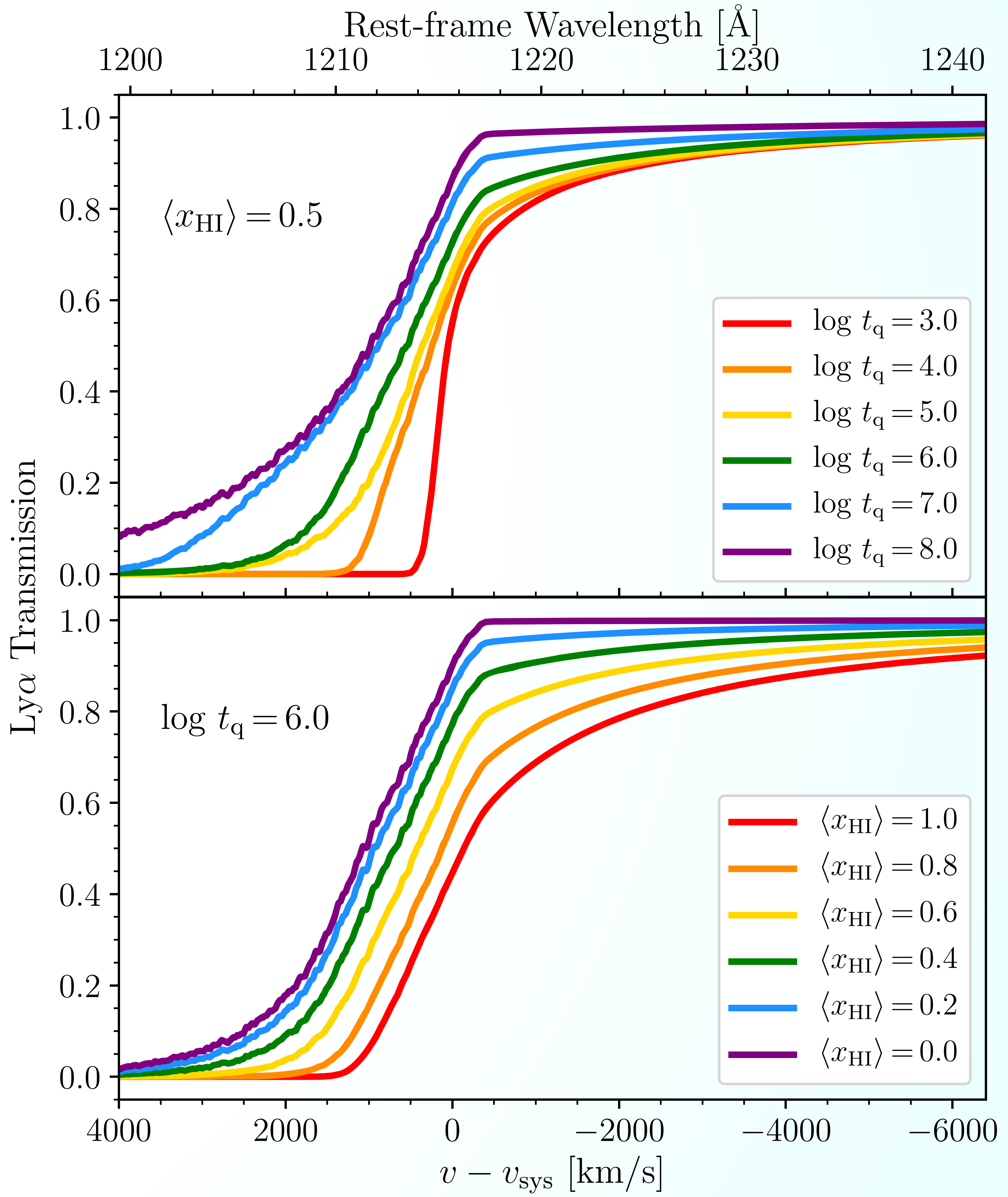
Forward-Modelling Damping Wing Absorption

Constructing realistic skewers based on cosmological simulations



Credit: Davies+ 2018

Damping wing signature of high-redshift quasars allows inferring IGM neutral fraction $\langle x_{HI} \rangle$ and quasar lifetime t_Q



Credit: Davies+ 2018

Timo Kist, Leiden Observatory, kist@strw.leidenuniv.nl

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

Astrophysical Parameter Inference

DATA

Real or mock quasar spectrum with observational noise

MODEL

Quasar continuum model

Reconstruction error stochastic process

+

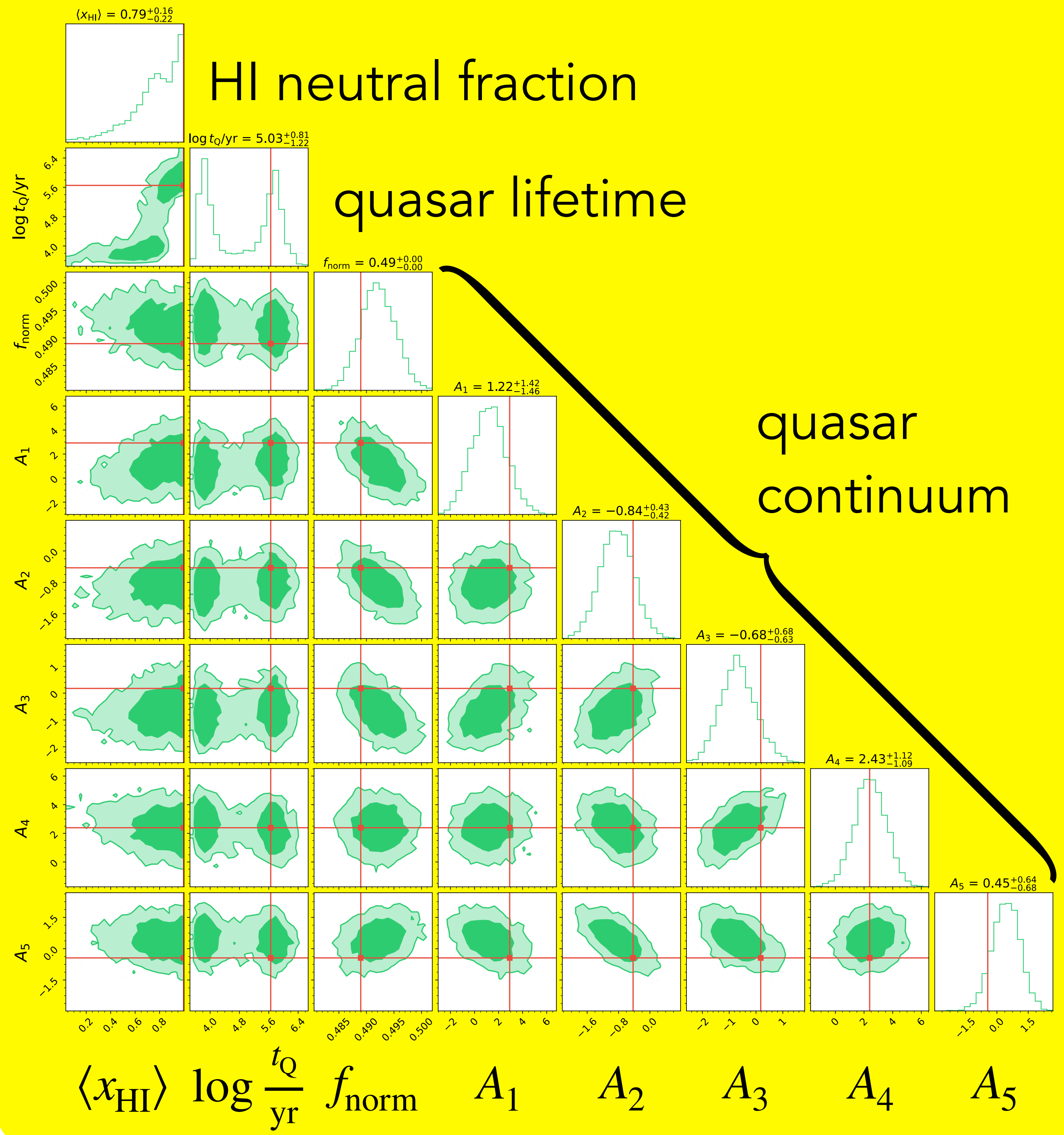
Ly-α transmission field stochastic process

BAYESIAN INFERENCE

with an analytical Gaussian likelihood approximation

- Likelihood operates on the **entire** spectrum (no red-blue split)
- Fast GPU-accelerated HMC implementation (runtimes $\lesssim$ 1 hour)

POSTERIOR



Hennawi, Kist, Davies+ 2023a (in prep.)

Timo Kist, Leiden Observatory, kist@strw.leidenuniv.nl

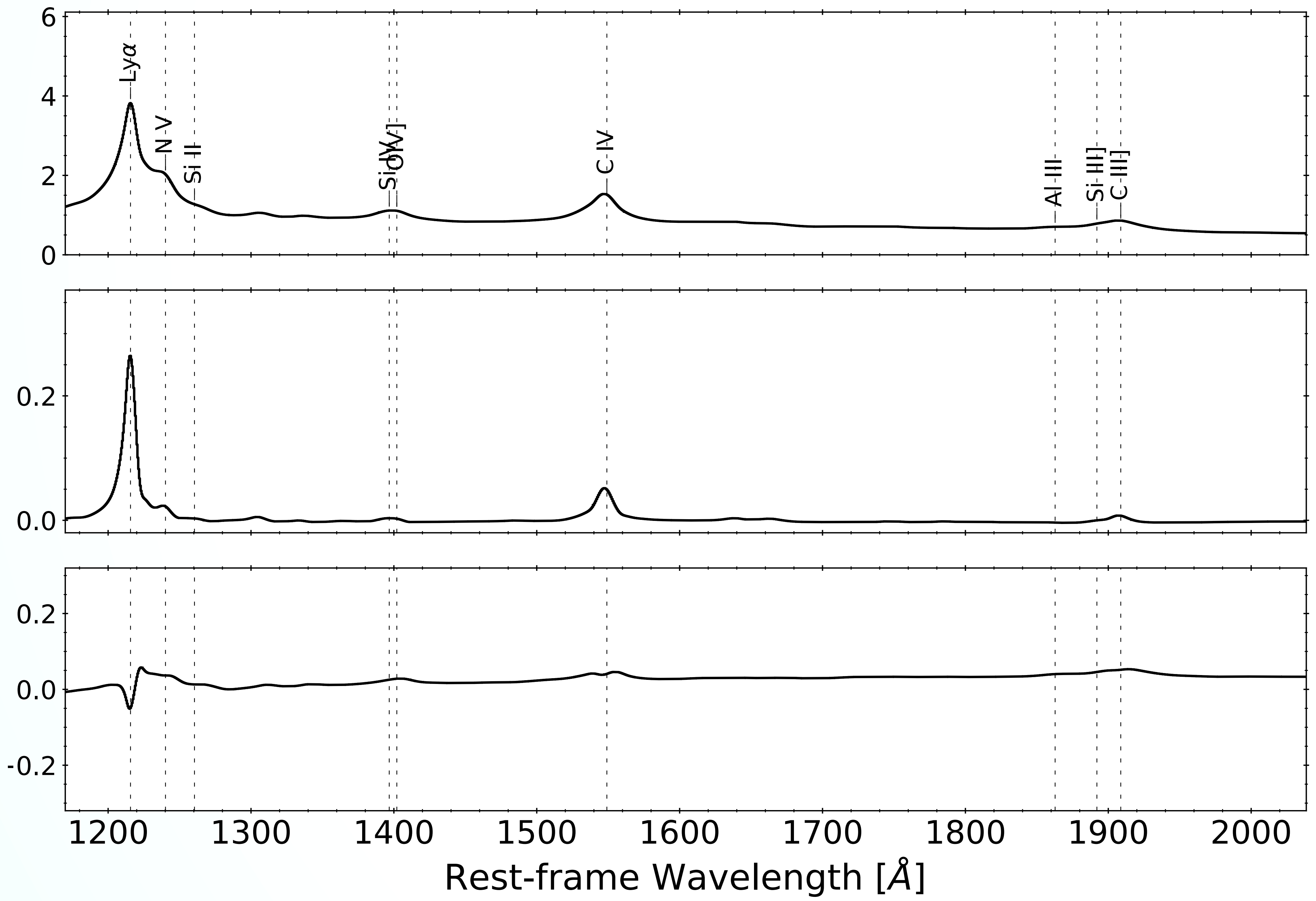
A PCA Model for the Quasar Continuum

Old-fashioned Dimensionality Reduction

PCA decomposed spectrum $s_{\mathrm{DR}}(\boldsymbol{\alpha}) = \langle s \rangle + \boldsymbol{\alpha} \cdot \boldsymbol{A}$

mean spectrum $\langle s \rangle$

PCA vectors $\boldsymbol{A}_1$, $\boldsymbol{A}_2$, ⋮



⋮

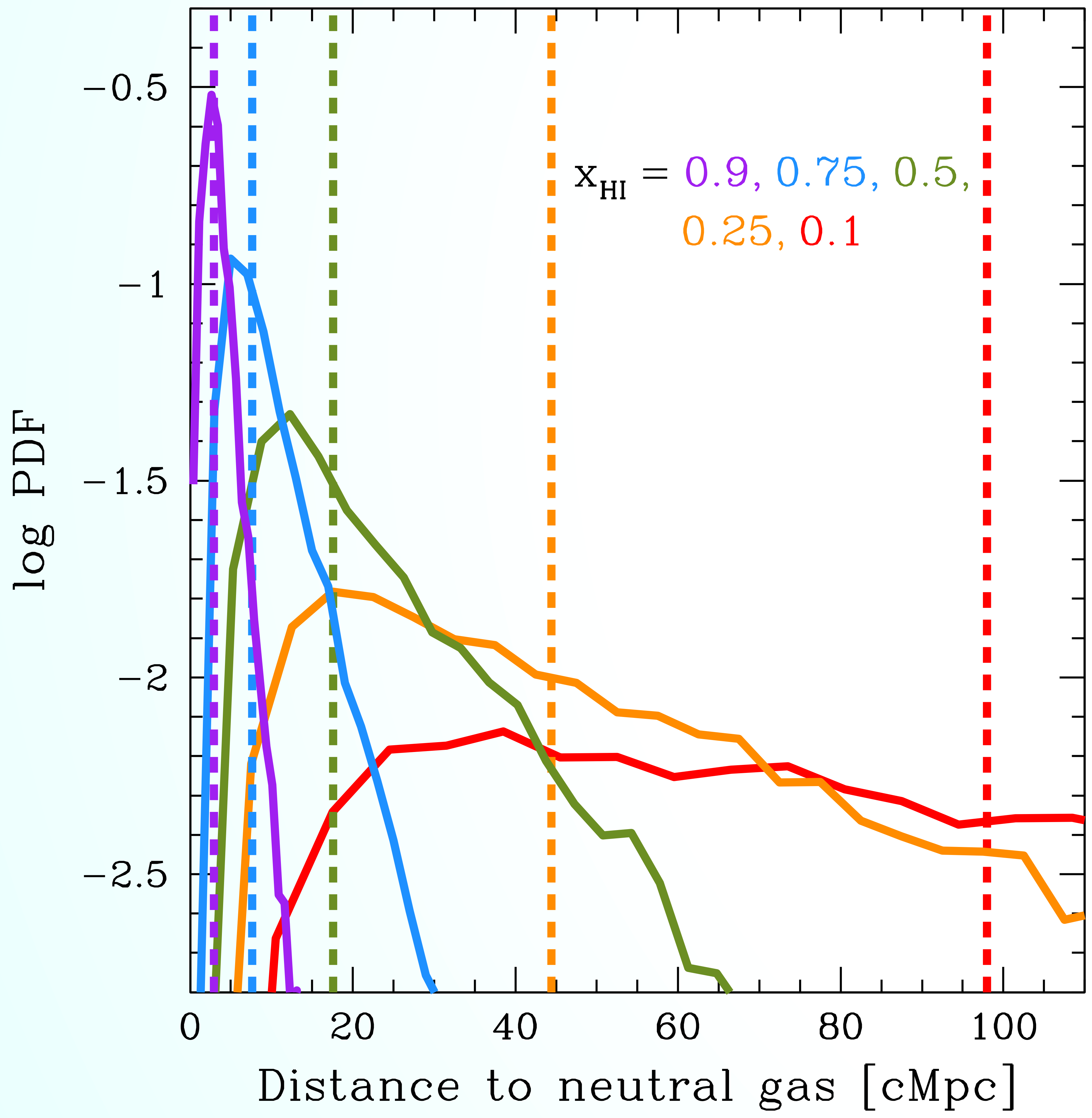
- 15 559 SDSS-autofit continua (2.149 < z < 4, R ~ 2000, S/N > 10)
- 95% - 5% training-test split:
  - Training set of 14 781 continua to build PCA model
  - Test set of 778 continua to draw mock continua and estimate reconstruction error

Hennawi, Kist, Davies+ 2023a (in prep.)

Timo Kist, Leiden Observatory, kist@strw.leidenuniv.nl

Forward-Modelling Damping Wing Absorption

Eliminating the stochasticity of the bubble size distribution



Credit: Davies+ 2018

- Ionised bubble sizes in simulation model depend stochastically on $\langle x_{\rm HI} \rangle$

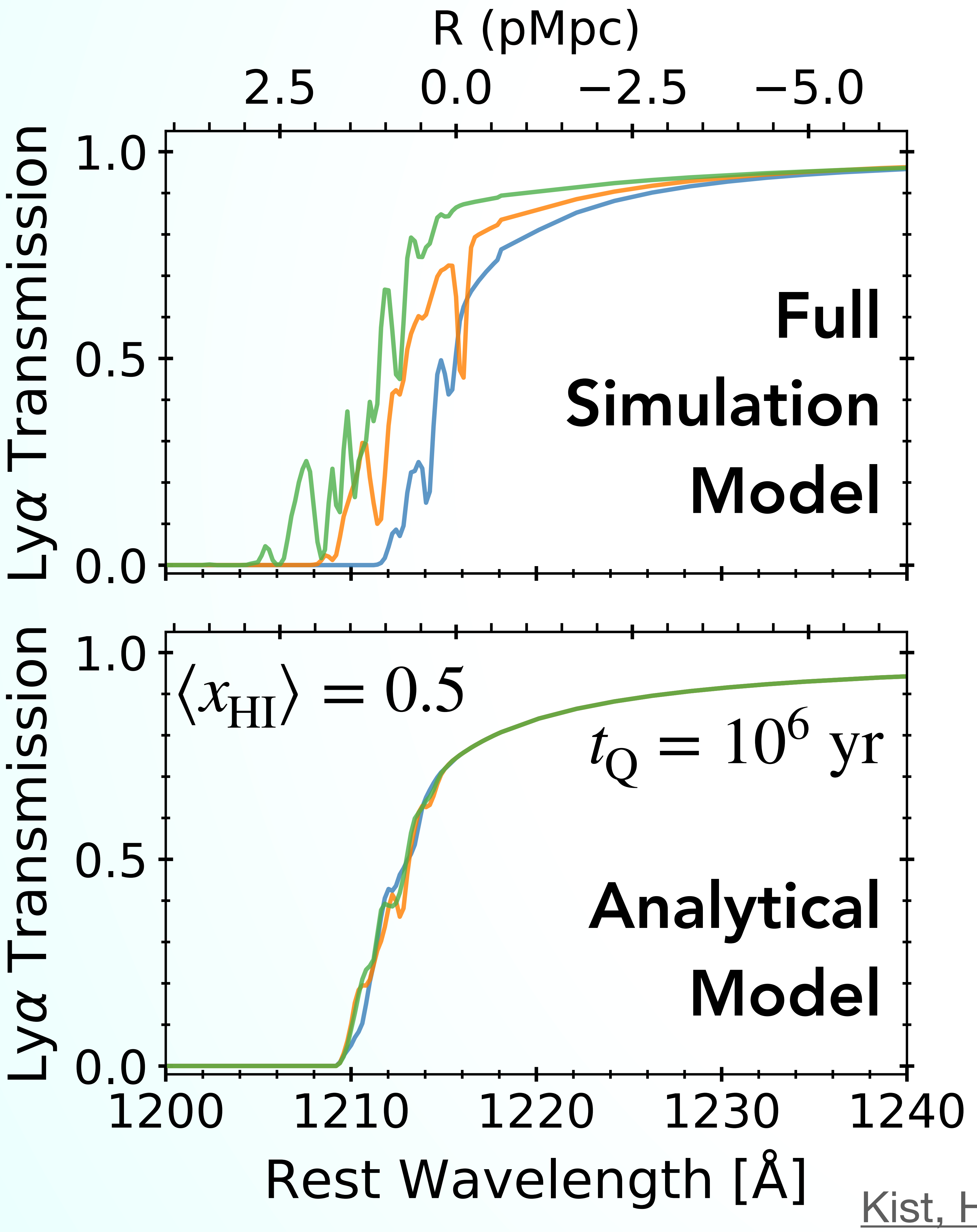
→ For analysis purposes, eliminate this stochasticity by building a simple analytic model (c.f. Mortlock 2016):

  - Radius of the ionisation front:
    $R_{\rm ion} \simeq 12.0\,{\rm cMpc} \times (t_{\rm Q}/{\rm Myr})^{1/3} \langle x_{\rm HI} \rangle^{-1/3}$
  - Damping wing optical depth determined deterministically in terms of $R_{\rm ion}$ (c.f. Miralda-Escudé 1998)

Timo Kist, Leiden Observatory, kist@strw.leidenuniv.nl

Forward-Modelling Damping Wing Absorption

Eliminating the stochasticity of the bubble size distribution



Kist, Hennawi, Davies+ 2023a (in prep.)

- Ionised bubble sizes in simulation model depend stochastically on $\langle x_{\rm HI} \rangle$

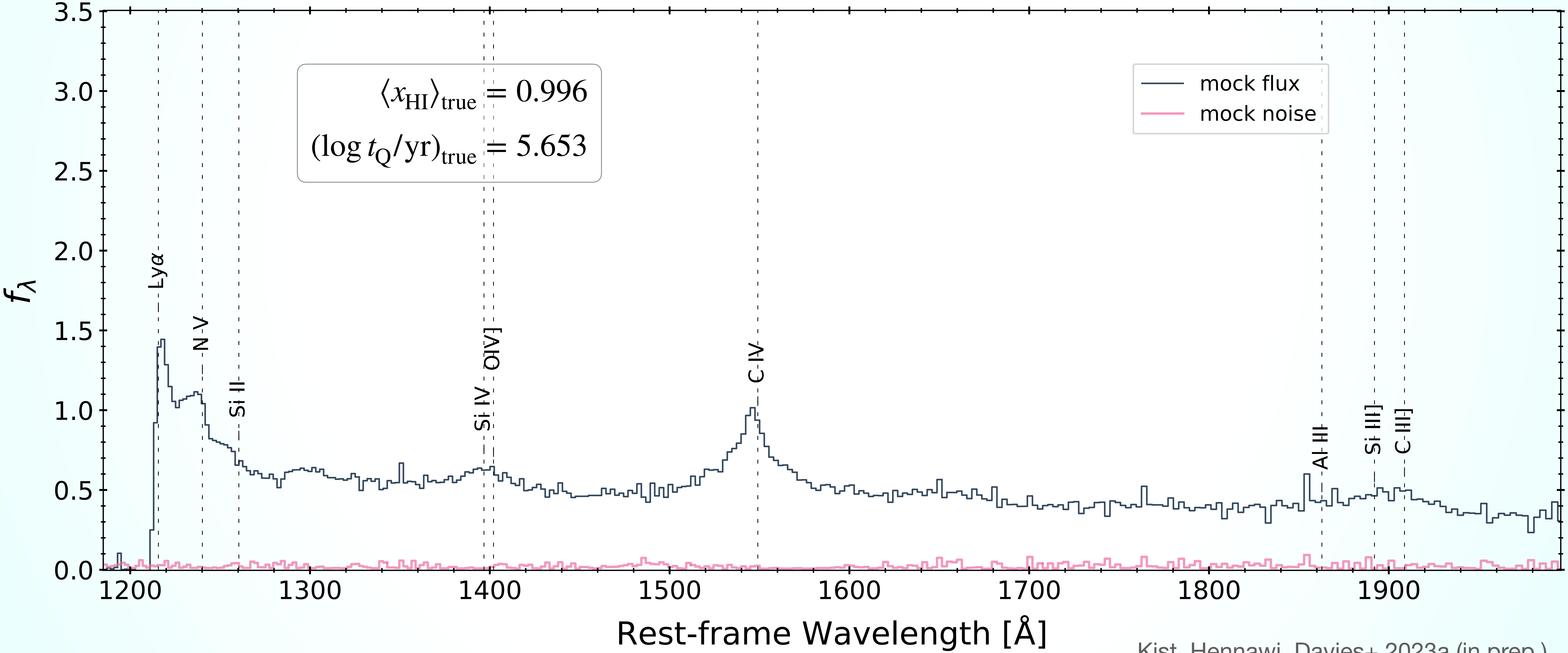
→ For analysis purposes, eliminate this stochasticity by building a simple analytic model (c.f. Mortlock 2016):

  - Radius of the ionisation front: $R_{\rm ion} \simeq 12.0\,{\rm cMpc} \times (t_{\rm Q}/{\rm Myr})^{1/3} \langle x_{\rm HI} \rangle^{-1/3}$
  - Damping wing optical depth determined deterministically in terms of $R_{\rm ion}$ (c.f. Miralda-Escudé 1998)

Timo Kist, Leiden Observatory, kist@strw.leidenuniv.nl

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

A Quasar in a Neutral Environment

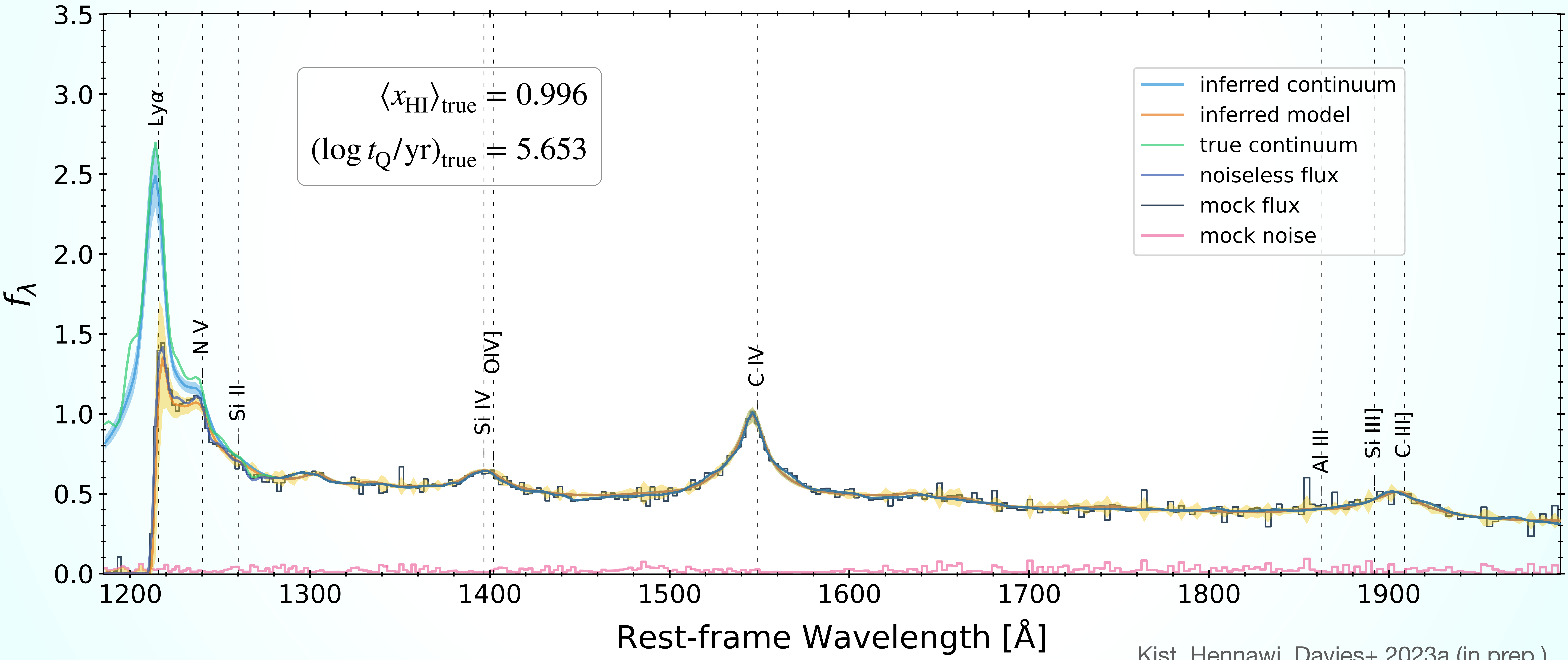


Kist, Hennawi, Davies+ 2023a (in prep.)

Timo Kist, Leiden Observatory, kist@strw.leidenuniv.nl

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

A Quasar in a Neutral Environment



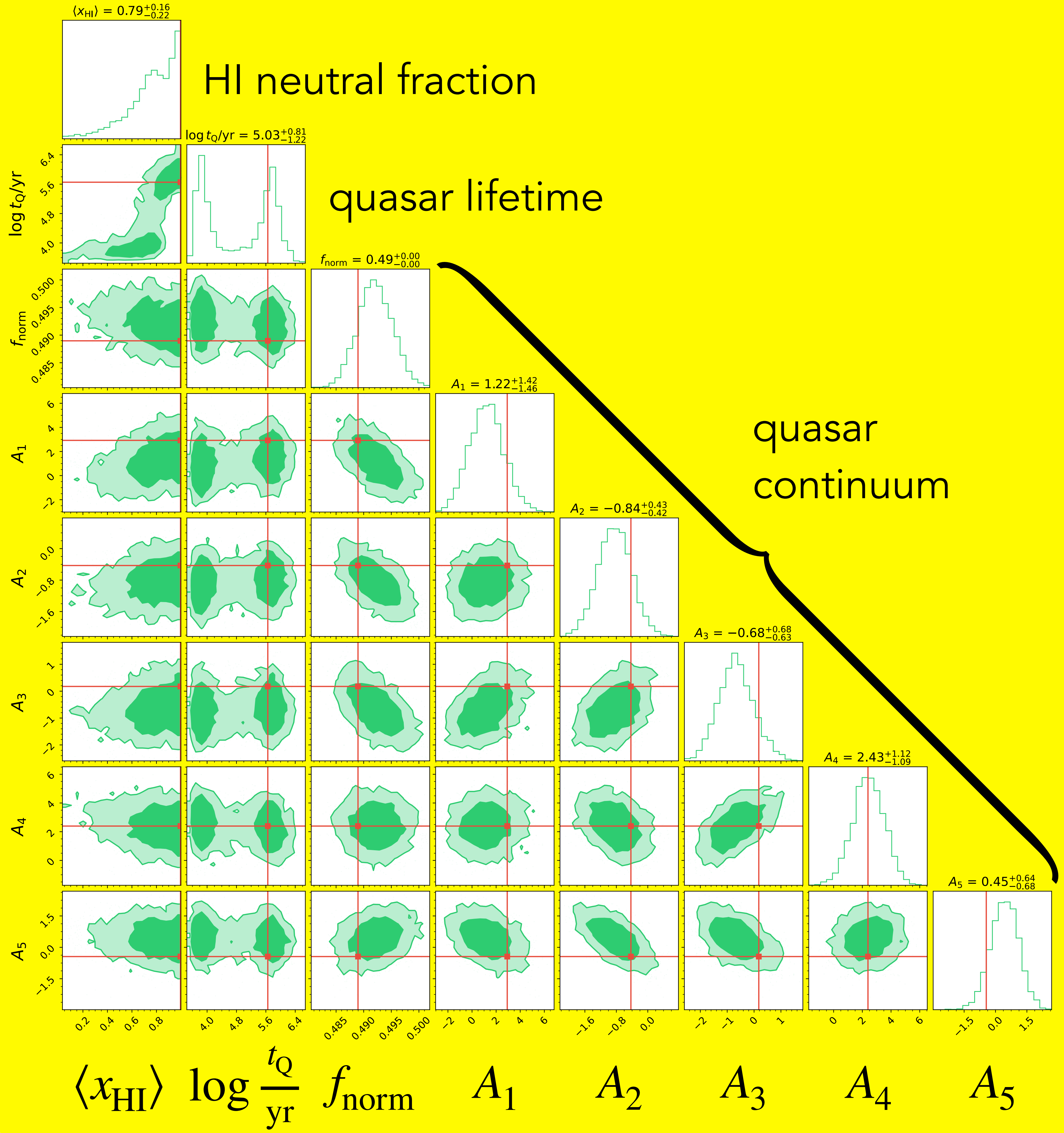
Kist, Hennawi, Davies+ 2023a (in prep.)

Timo Kist, Leiden Observatory, kist@strw.leidenuniv.nl

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

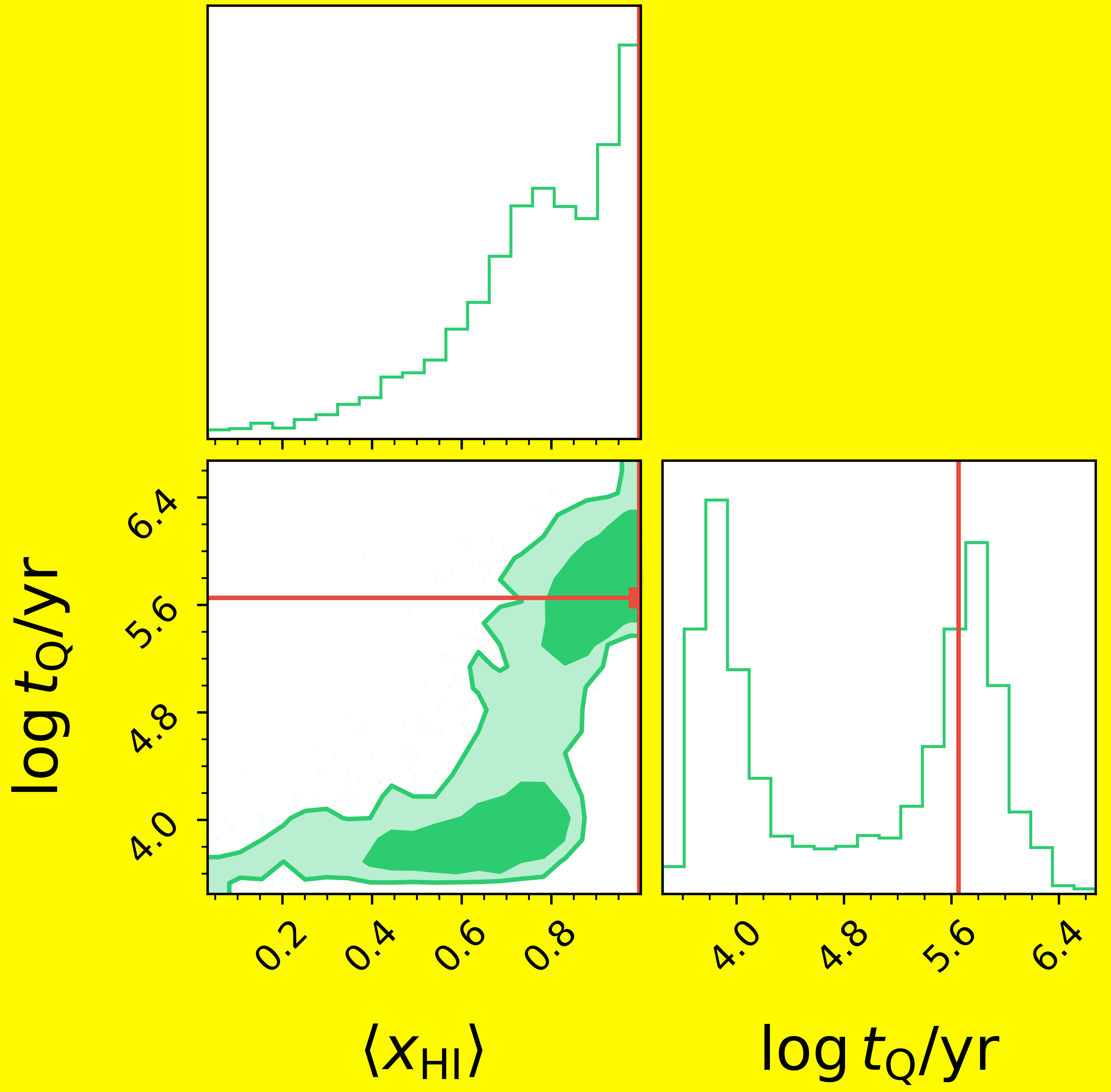
Posterior Distribution

Full 2+6-dimensional posterior distribution



Marginalizing over 6 continuum nuisance parameters

Marginal $(\langle x_{\rm HI} \rangle, t_{\rm Q})$-posterior distribution



Kist, Hennawi, Davies+ 2023a (in prep.)

Timo Kist, Leiden Observatory, kist@strw.leidenuniv.nl

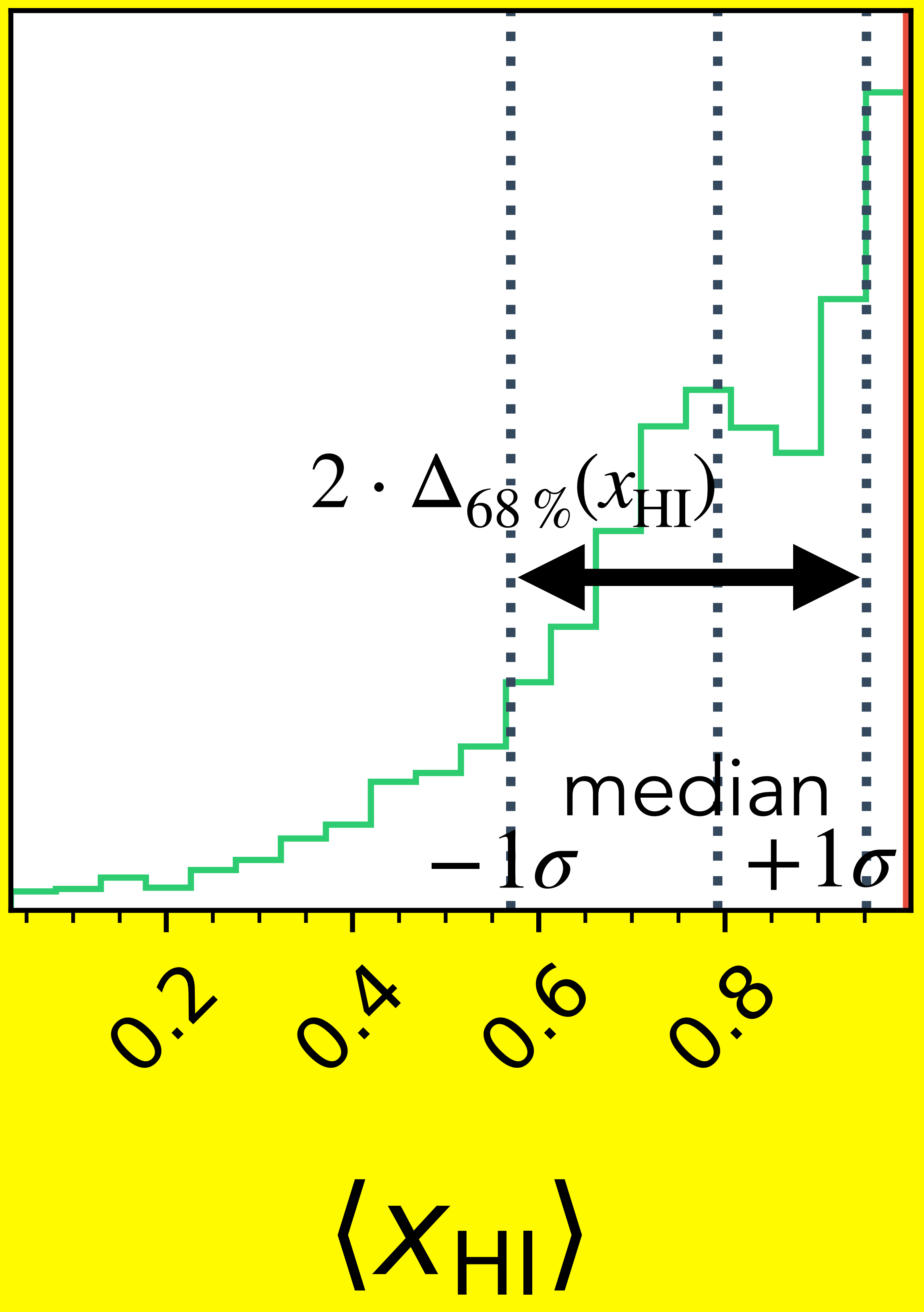
From an Observed Quasar Spectrum to $\langle x_{\mathrm{HI}} \rangle$

Posterior Distribution

How does inference precision vary across parameter space?

What are the dominant contributions to the error budget?

Marginal $\langle x_{\mathrm{HI}} \rangle$-posterior distribution



Kist, Hennawi, Davies+ 2023a (in prep.)

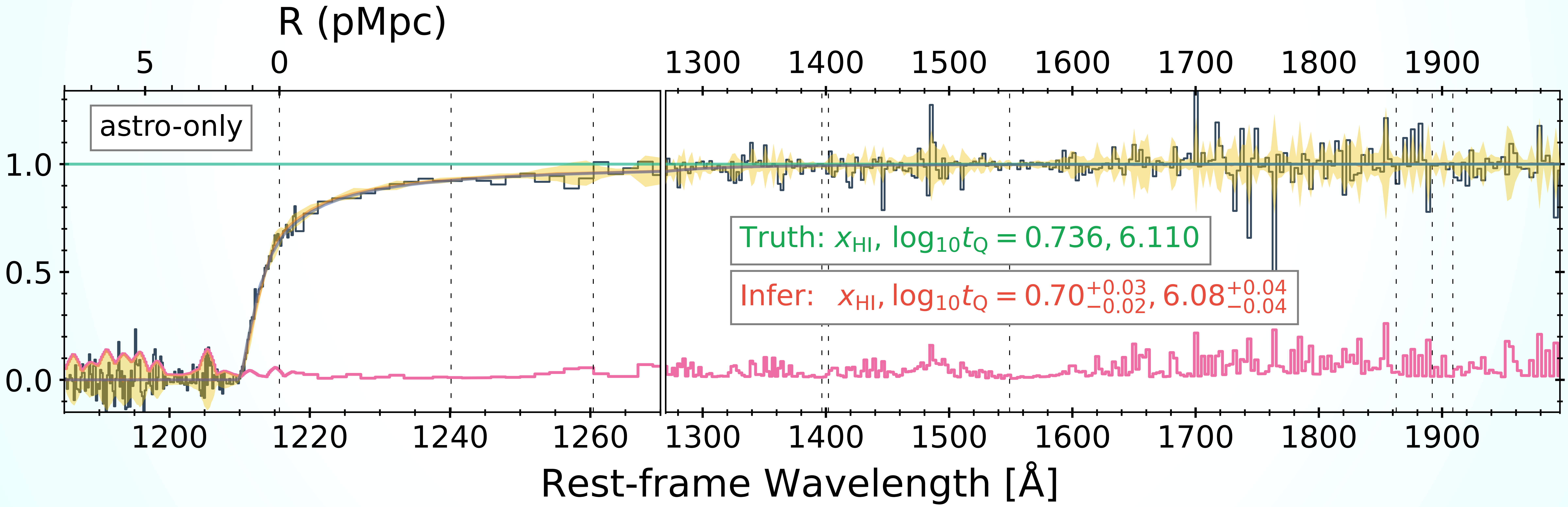
Timo Kist, Leiden Observatory, kist@strw.leidenuniv.nl

The PCA Continuum Model

Impact on Inference Precision

Continuum-normalized spectrum:

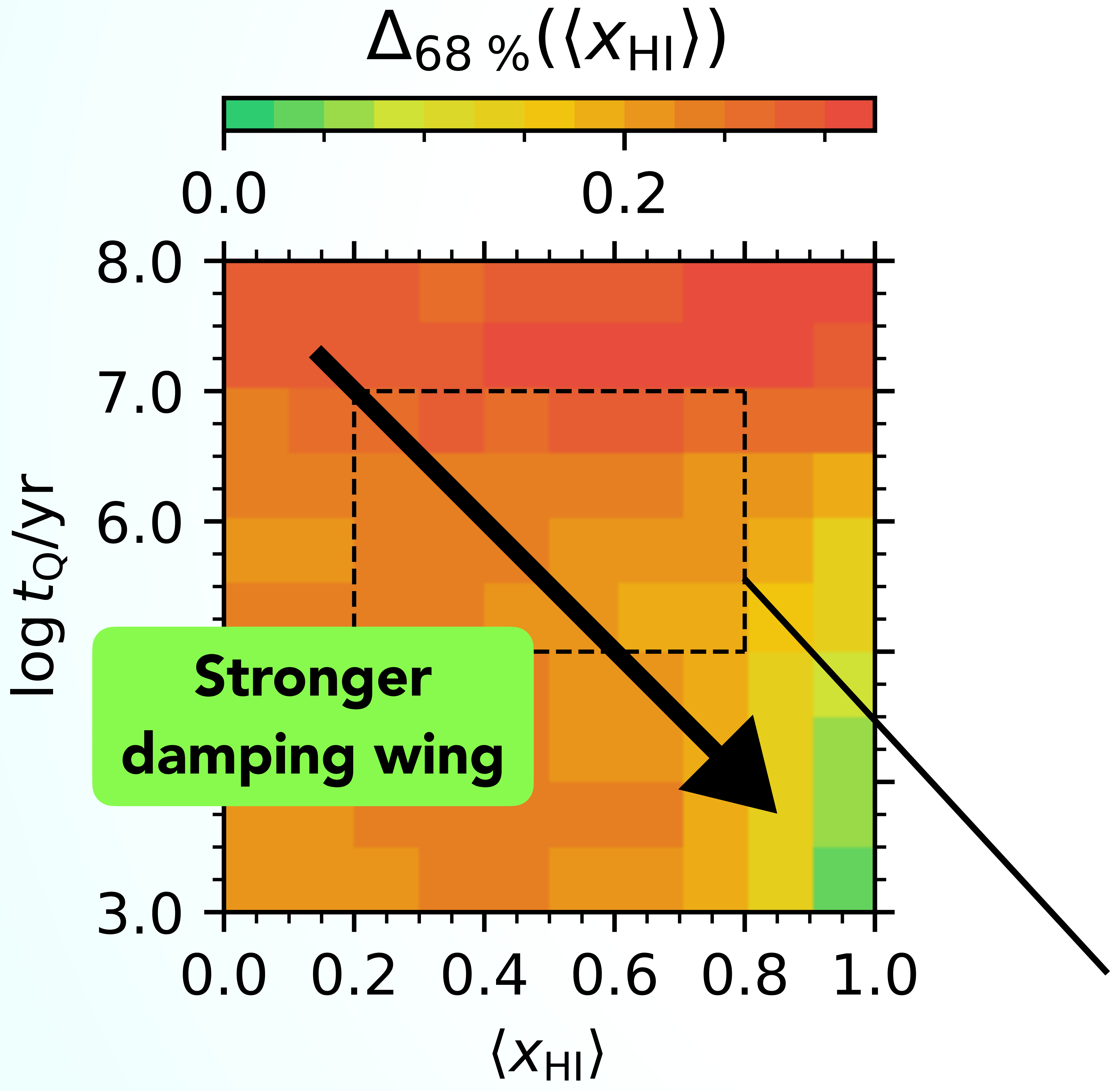
→ optimal bound on inferring $\langle x_{\rm HI} \rangle$ and $t_{\rm Q}$ without nuisance parameters



Hennawi, Kist, Davies+ 2023a (in prep.)

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

Variation across Model Components and Parameter Space



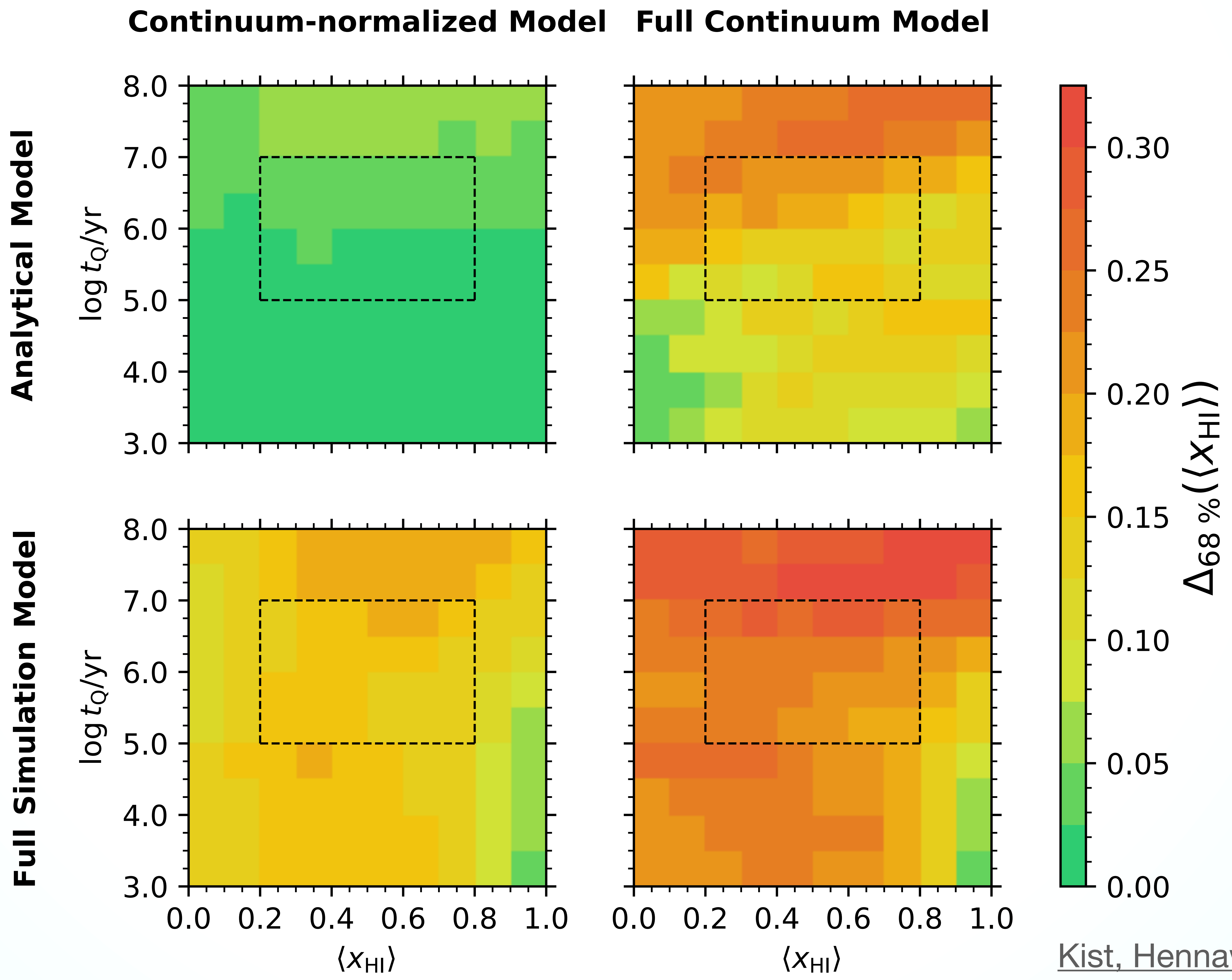
- Precision varies significantly across parameter space (between 2.6% and 39.3%)
- Median precision: 23.4%
- Stronger damping wing imprint (higher $\langle x_{\mathrm{HI}} \rangle$, lower t_{Q}) improves precision

"Fiducial" region of parameter space

Kist, Hennawi, Davies+ 2023a (in prep.)

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

Variation across Model Components and Parameter Space



Overall median: 2.2%
Fiducial median: 2.4%

Overall median: 13.9%
Fiducial median: 15.8%

Overall median: 14.9%
Fiducial median: 15.3%

Overall median: 23.4%
Fiducial median: 23.4%

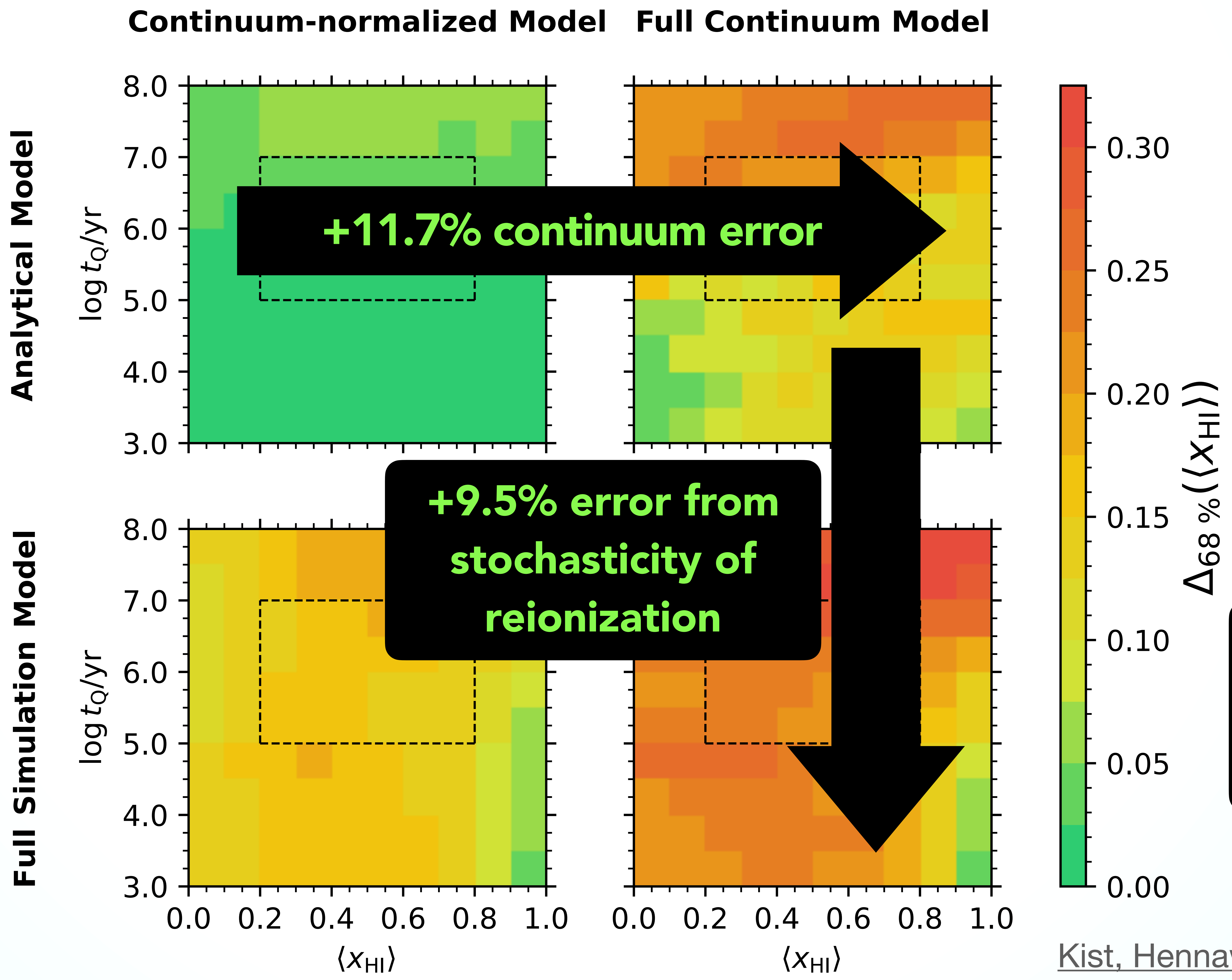
Kist, Hennawi, Davies+ 2023a (in prep.)

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

Variation across Model Components and Parameter Space

Overall median: 2.2%
Fiducial median: 2.4%

Overall median: 14.9%
Fiducial median: 15.3%



Overall median: 13.9%
Fiducial median: 15.8%

23.4% total 1σ-uncertainty

Kist, Hennawi, Davies+ 2023a (in prep.)

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

Variation across Model Components and Parameter Space

Ove

Fiduc

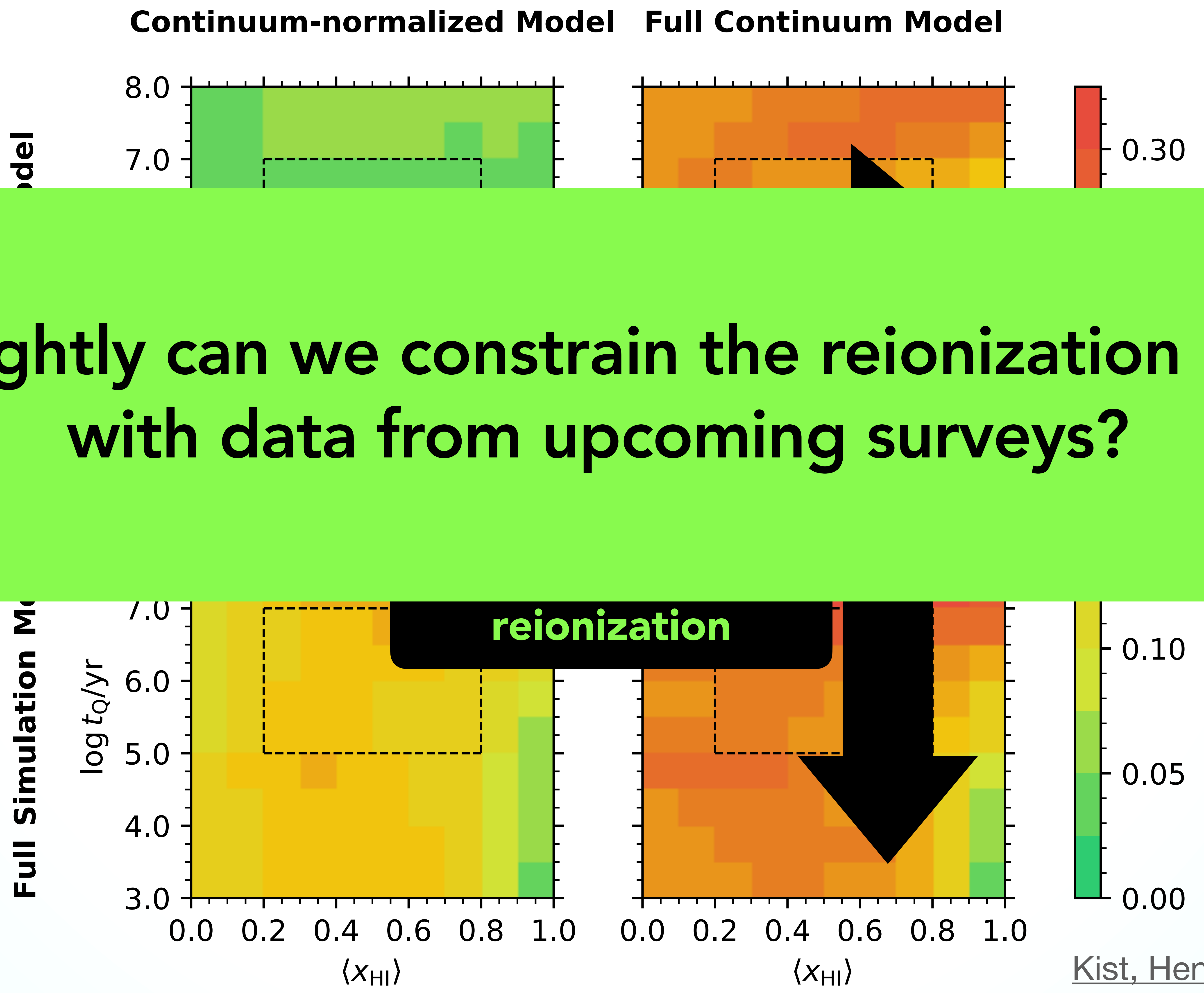
13.9%

15.8%

How tightly can we constrain the reionization history with data from upcoming surveys?

Overall median: 14.9%

Fiducial median: 15.3%



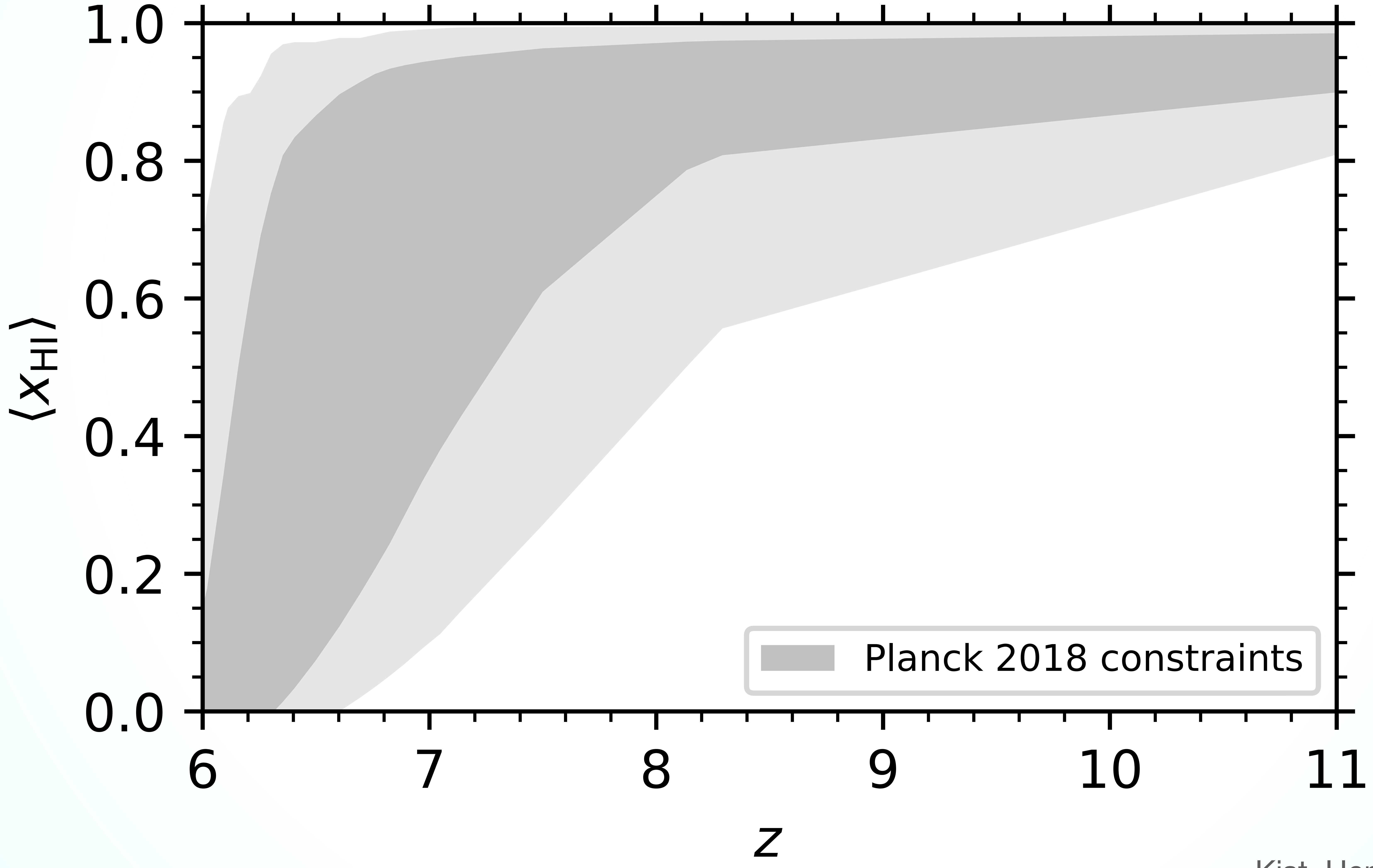
23.4% total 1σ-uncertainty

Kist, Hennawi, Davies+ 2023a (in prep.)

Timo Kist, Leiden Observatory, kist@strw.leidenuniv.nl

Constraining Reionization History

Current CMB constraints



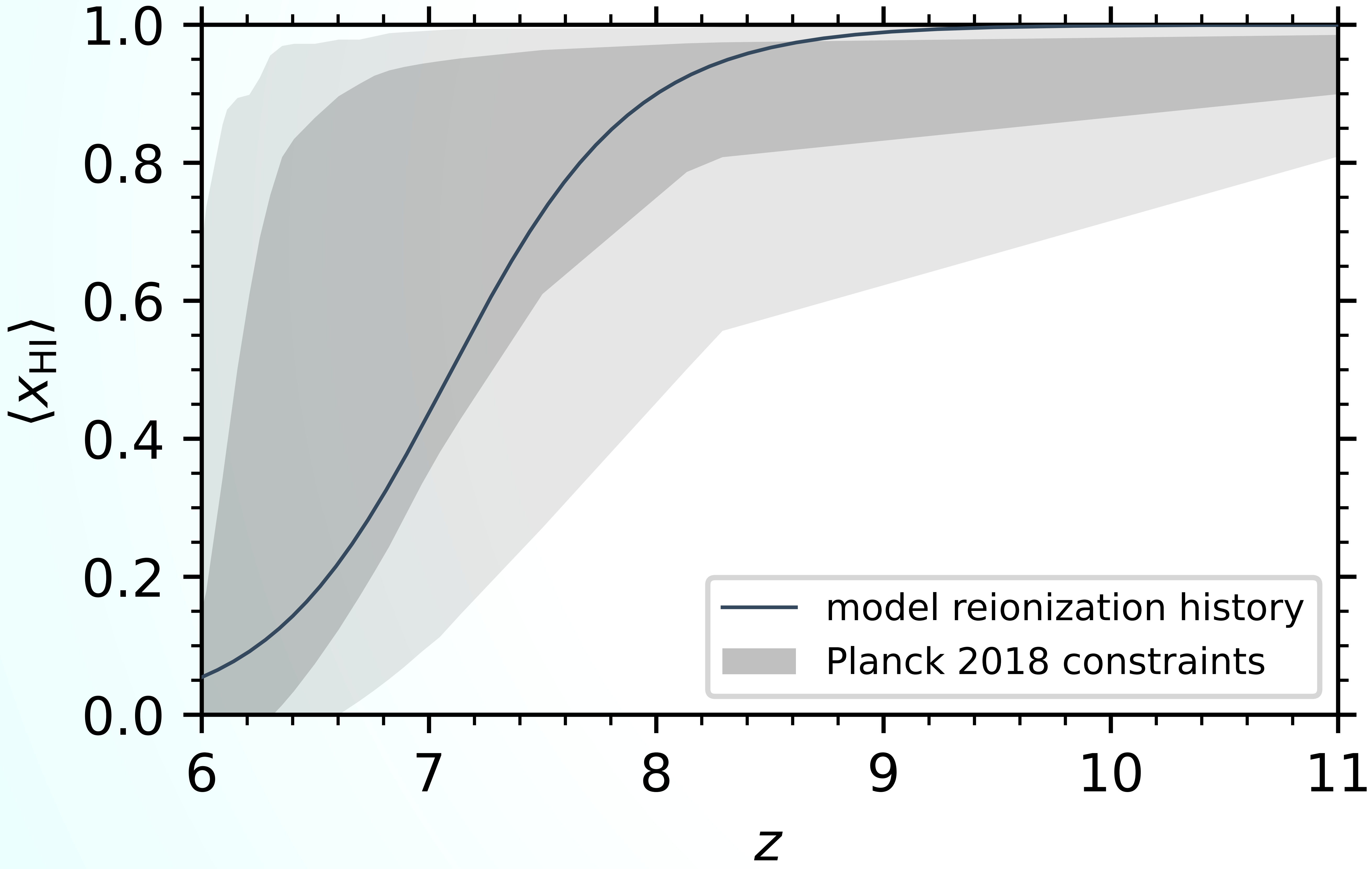
Kist, Hennawi, Davies+ 2023b (in prep.)

Timo Kist, Leiden Observatory, kist@strw.leidenuniv.nl

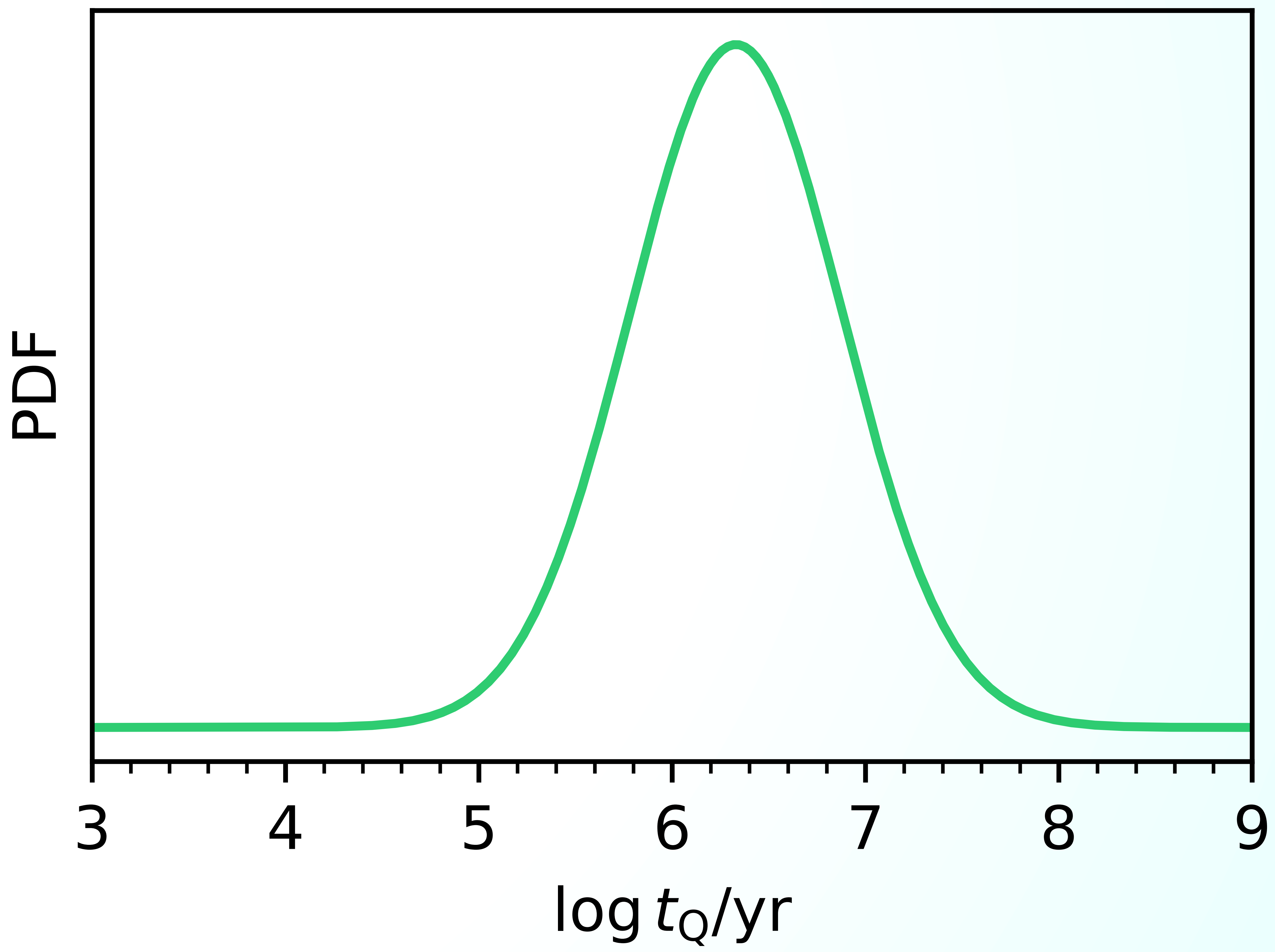
Constraining Reionization History

A forecast of upcoming EUCLID constraints

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



Lognormal $t_{\rm Q}$ distribution (Khrykin+ 2021)

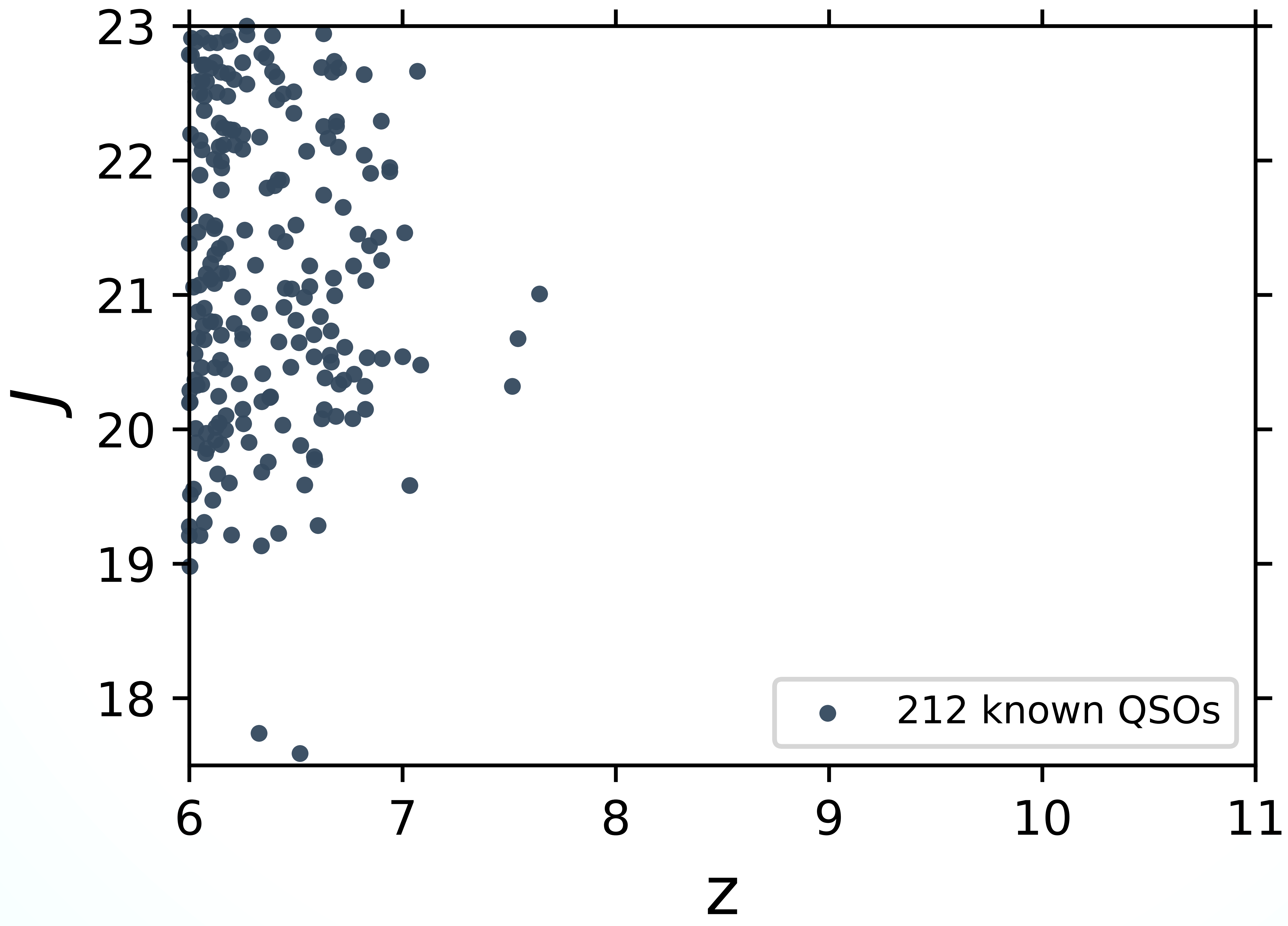


Kist, Hennawi, Davies+ 2023b (in prep.)

Timo Kist, Leiden Observatory, kist@strw.leidenuniv.nl

EUCLID

The Quasar Yield of the Wide-Field Survey



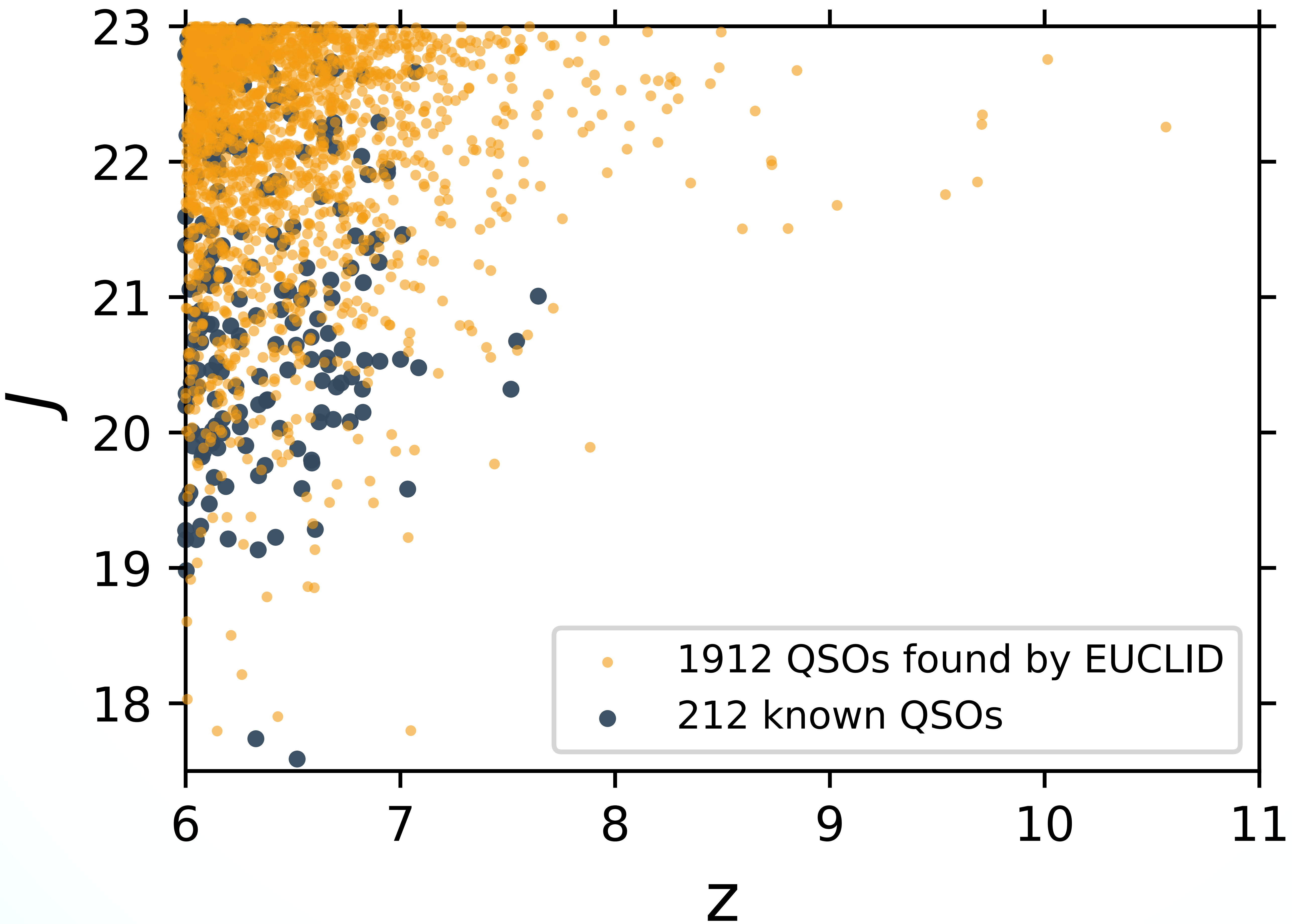
Kist, Hennawi, Davies+ 2023b (in prep.)

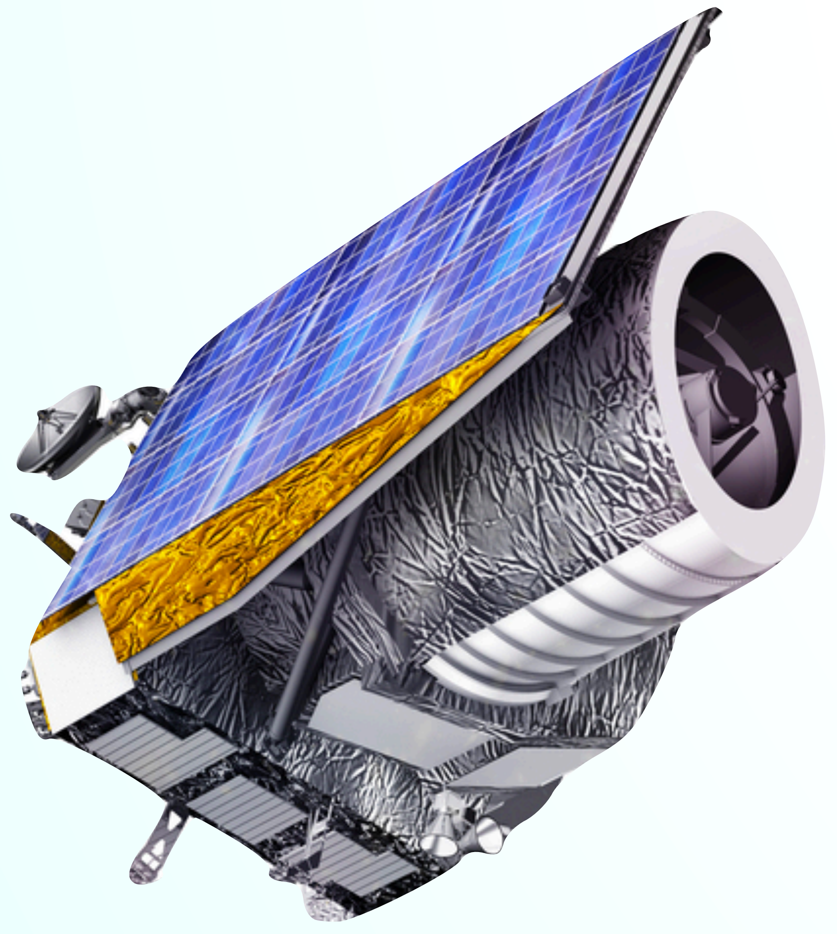
Timo Kist, Leiden Observatory, kist@strw.leidenuniv.nl

EUCLID

The Quasar Yield of the Wide-Field Survey

Samples from a Wang+2019 quasar luminosity function





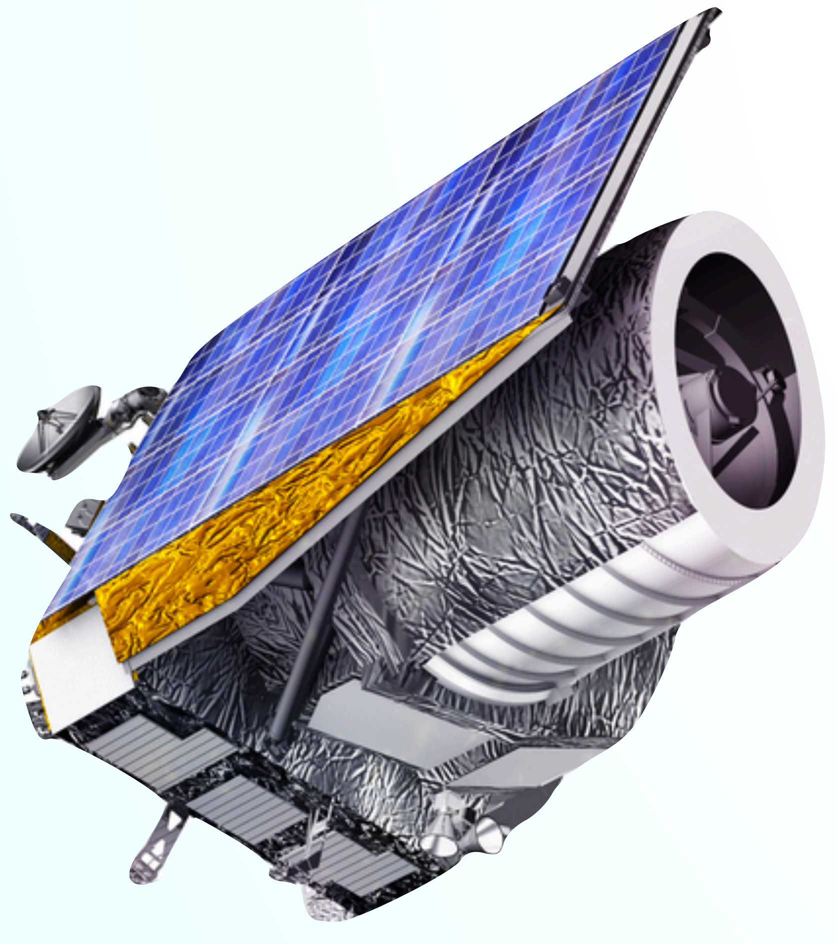
Kist, Hennawi, Davies+ 2023b (in prep.)

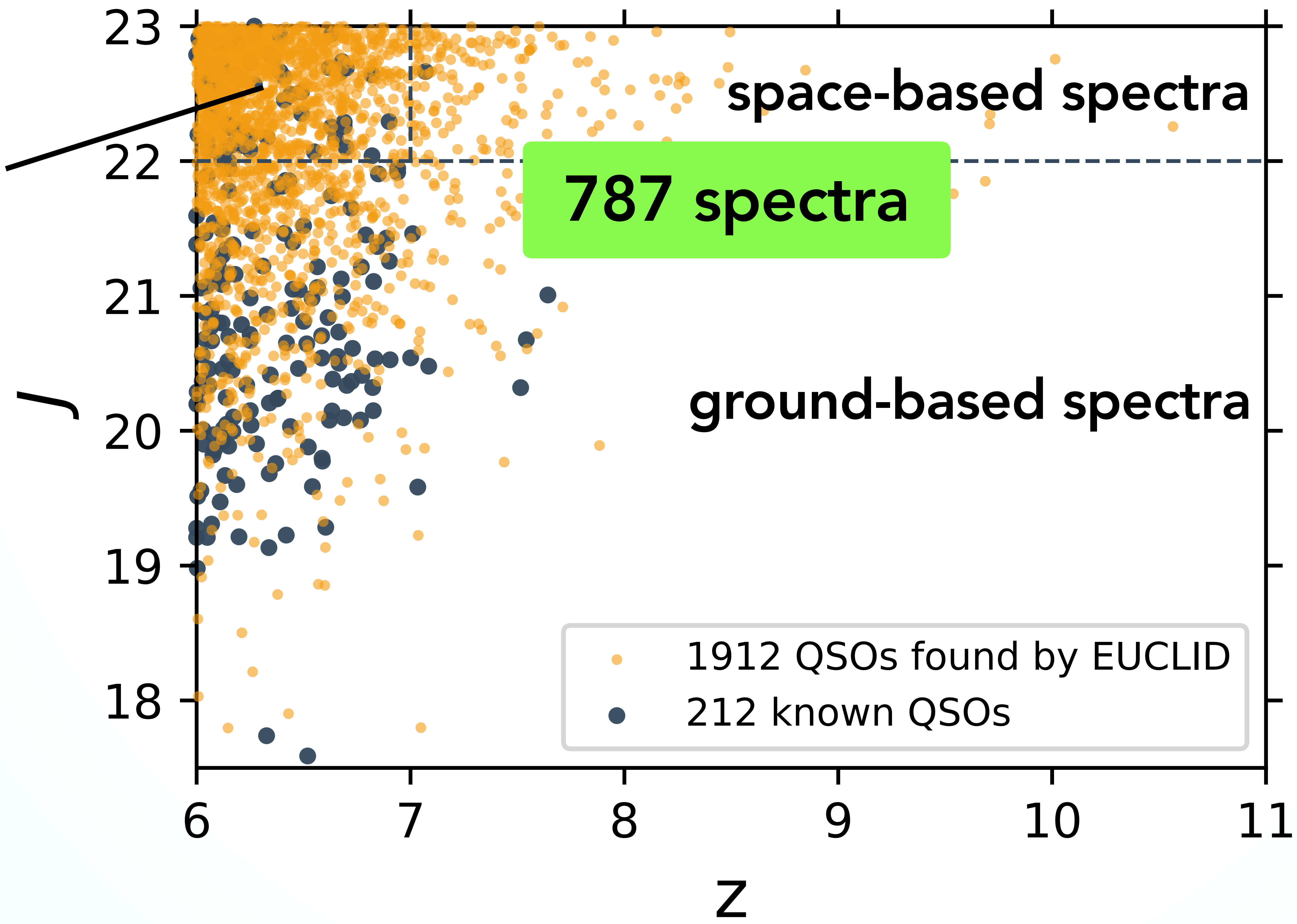
Timo Kist, Leiden Observatory, kist@strw.leidenuniv.nl

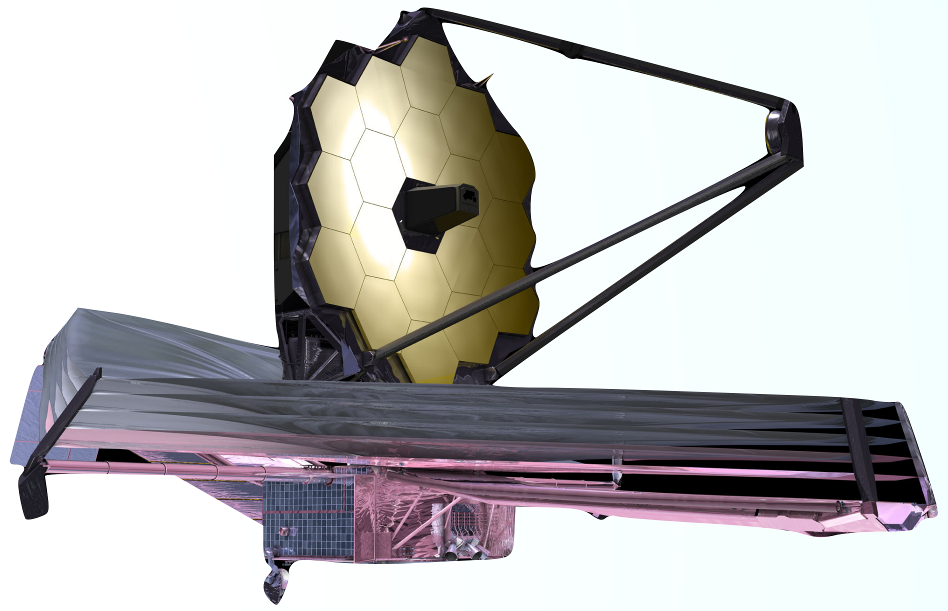
EUCLID

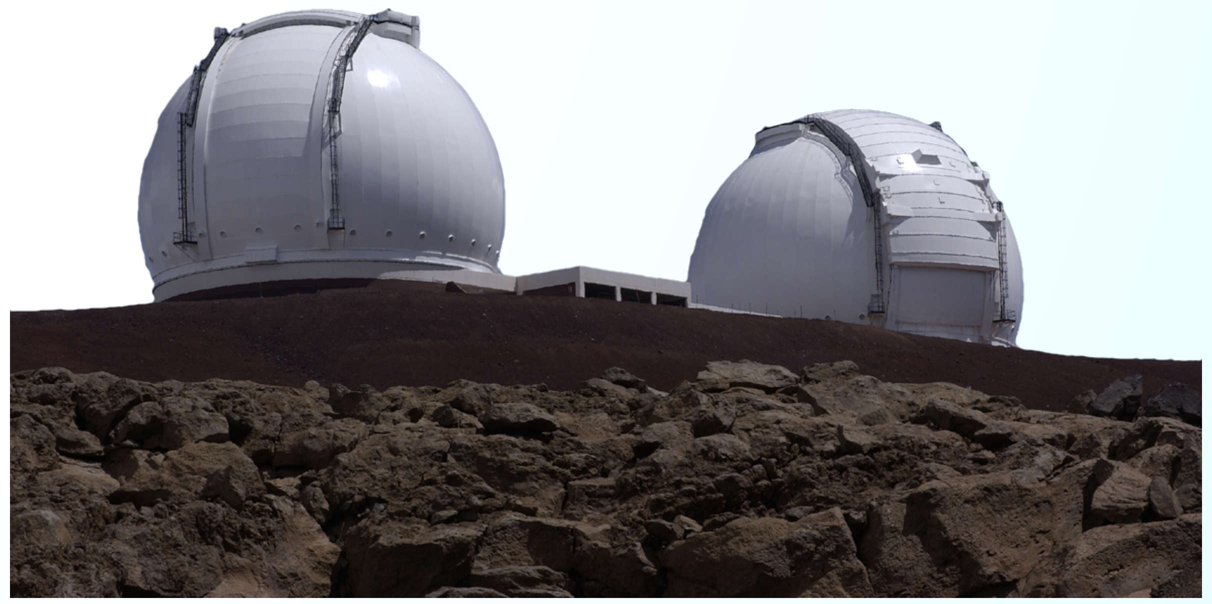
The Quasar Yield of the Wide-Field Survey

Samples from a Wang+2019 quasar luminosity function







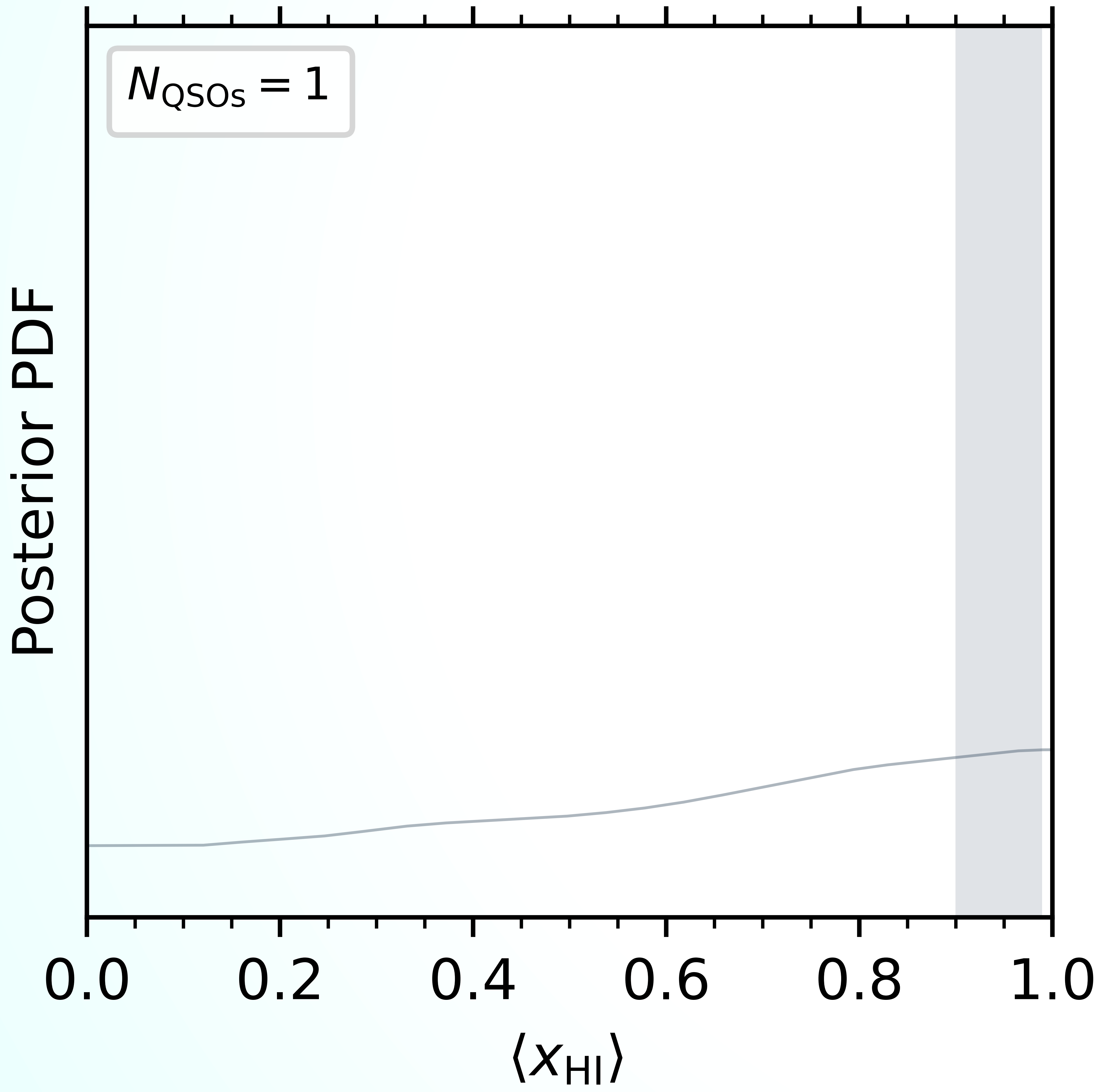


Kist, Hennawi, Davies+ 2023b (in prep.)

Timo Kist, Leiden Observatory, kist@strw.leidenuniv.nl

Ensemble inference

Combining $\langle x_{\mathrm{HI}} \rangle$ Posteriors



KDE of a single marginal $\langle x_{\mathrm{HI}} \rangle$-posterior inferred from a realistic mock observational spectrum:

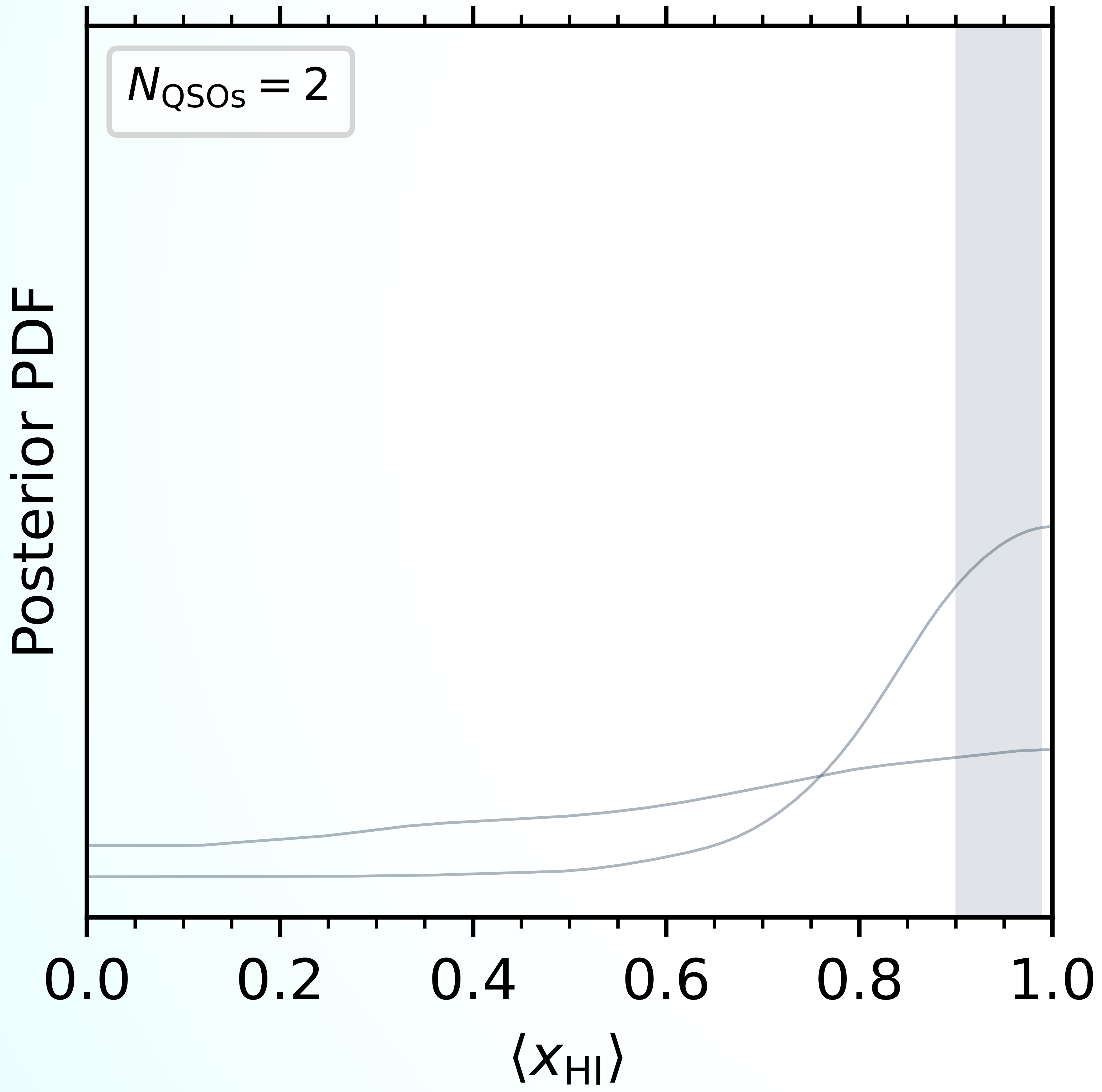
- Full simulation model
- Latent PCA dimension 5
- Wavelength coverage up to 2000 Å, S/N = 10, FWHM = 100 km/s (rebinned to a 500 km/s pixel scale)

Kist, Hennawi, Davies+ 2023b (in prep.)

Timo Kist, Leiden Observatory, kist@strw.leidenuniv.nl

Ensemble inference

Combining $\langle x_{\mathrm{HI}} \rangle$ Posteriors



KDE of two marginal $\langle x_{\mathrm{HI}} \rangle$-posteriors inferred from realistic mock observational spectra:

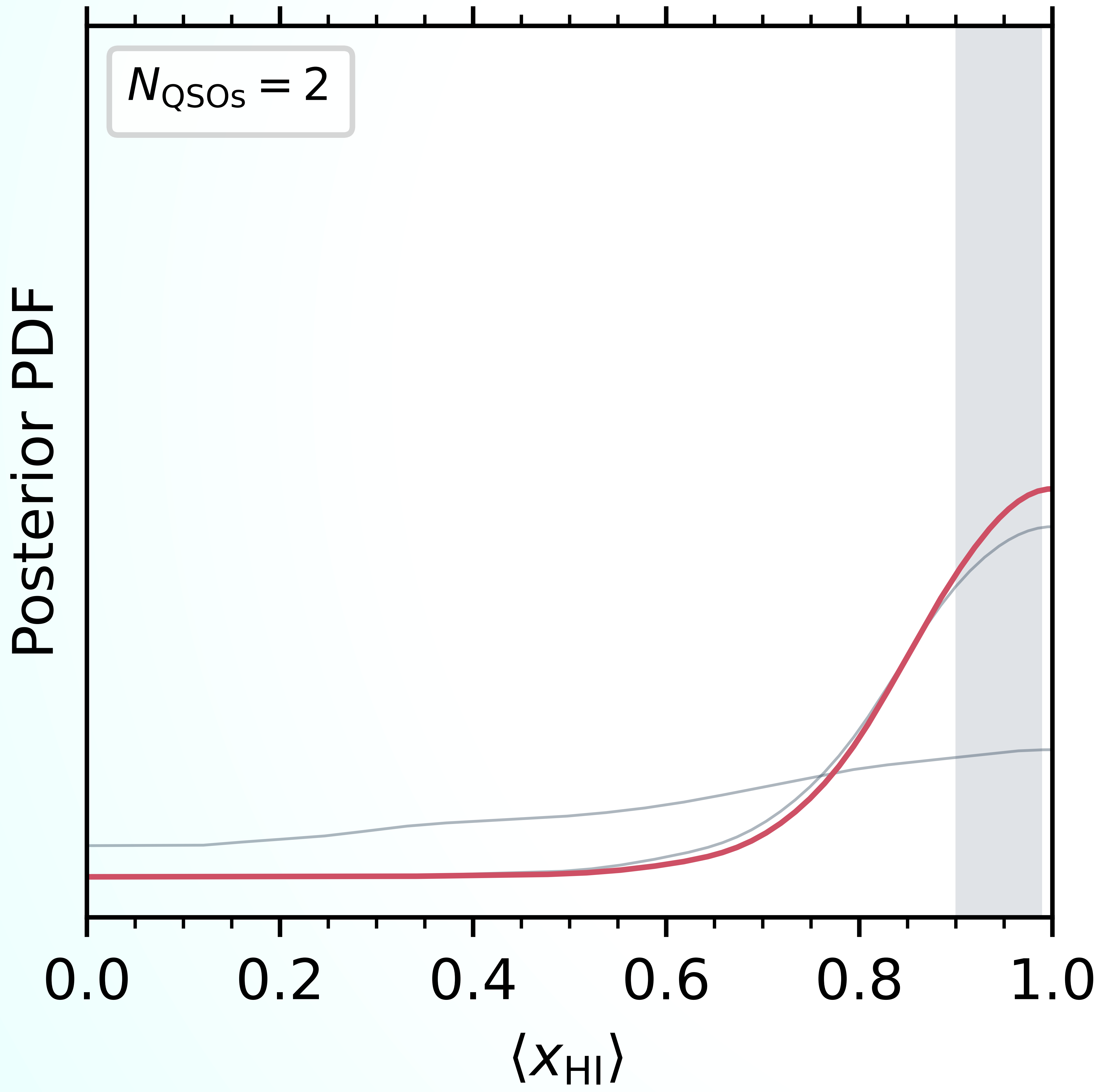
- Full simulation model
- Latent PCA dimension 5
- Wavelength coverage up to 2000 Å, S/N = 10, FWHM = 100 km/s (rebinned to a 500 km/s pixel scale)

Kist, Hennawi, Davies+ 2023b (in prep.)

Timo Kist, Leiden Observatory, kist@strw.leidenuniv.nl

Ensemble inference

Combining $\langle x_{\mathrm{HI}} \rangle$ Posteriors



KDE of two marginal $\langle x_{\mathrm{HI}} \rangle$-posteriors inferred from realistic mock observational spectra:

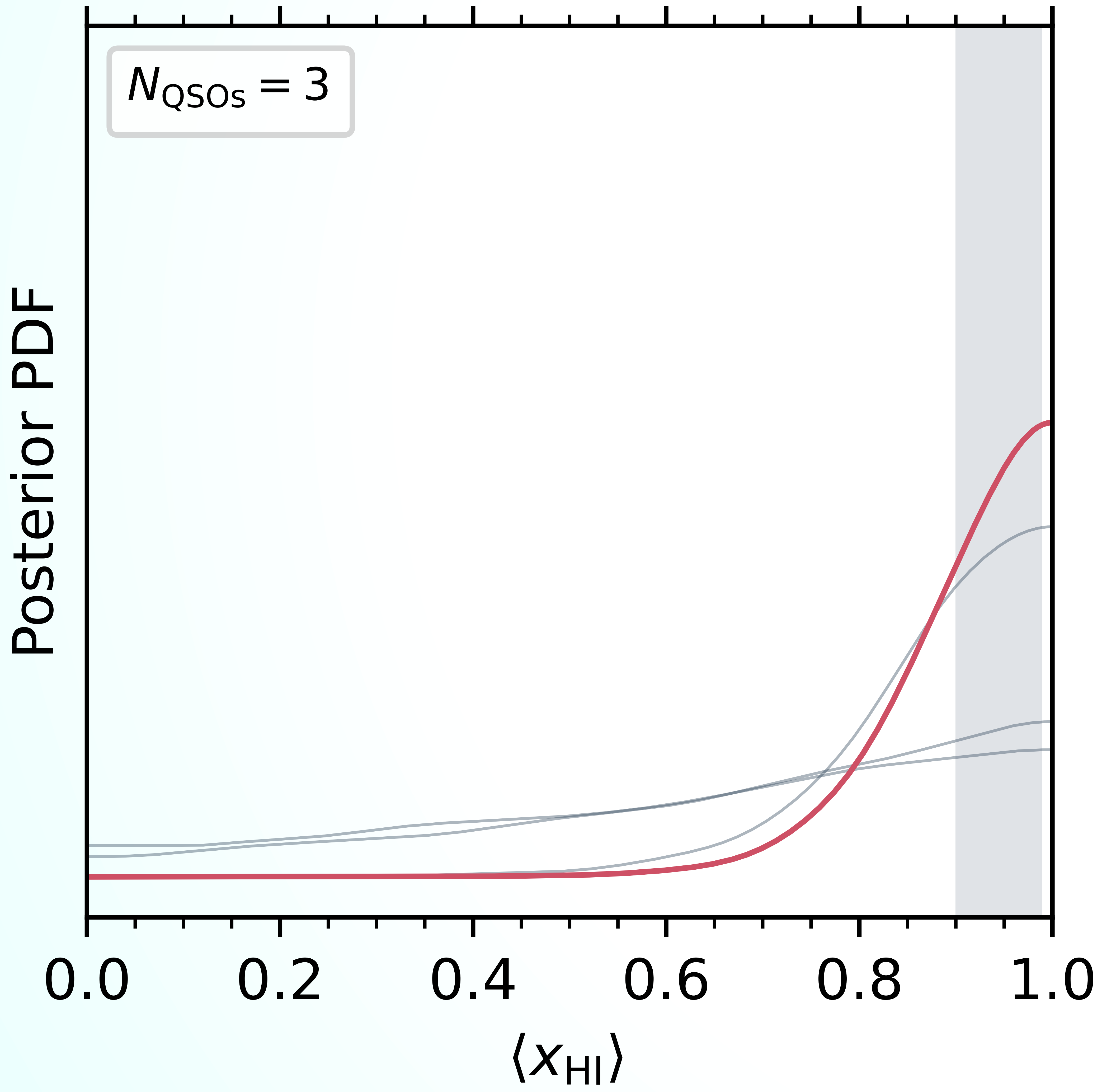
- Full simulation model
- Latent PCA dimension 5
- Wavelength coverage up to 2000 Å, S/N = 10, FWHM = 100 km/s (rebinned to a 500 km/s pixel scale)

Kist, Hennawi, Davies+ 2023b (in prep.)

Timo Kist, Leiden Observatory, kist@strw.leidenuniv.nl

Ensemble inference

Combining $\langle x_{\mathrm{HI}} \rangle$ Posteriors



KDE of marginal $\langle x_{\mathrm{HI}} \rangle$-posteriors inferred from realistic mock observational spectra:

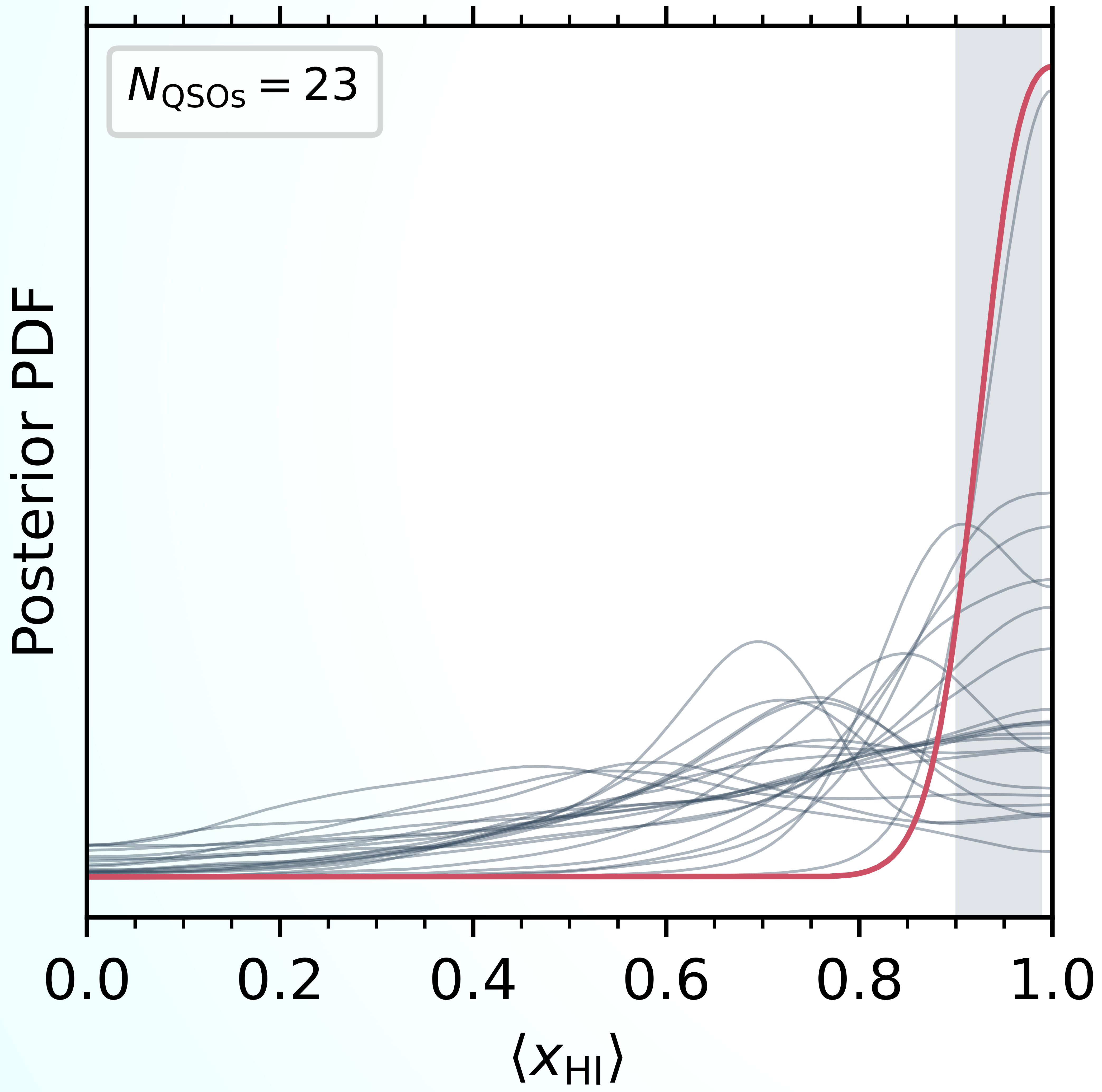
- Full simulation model
- Latent PCA dimension 5
- Wavelength coverage up to 2000 Å, S/N = 10, FWHM = 100 km/s (rebinned to a 500 km/s pixel scale)

Kist, Hennawi, Davies+ 2023b (in prep.)

Timo Kist, Leiden Observatory, kist@strw.leidenuniv.nl

Ensemble inference

Combining $\langle x_{\mathrm{HI}} \rangle$ Posteriors



KDE of marginal $\langle x_{\mathrm{HI}} \rangle$-posteriors inferred from realistic mock observational spectra:

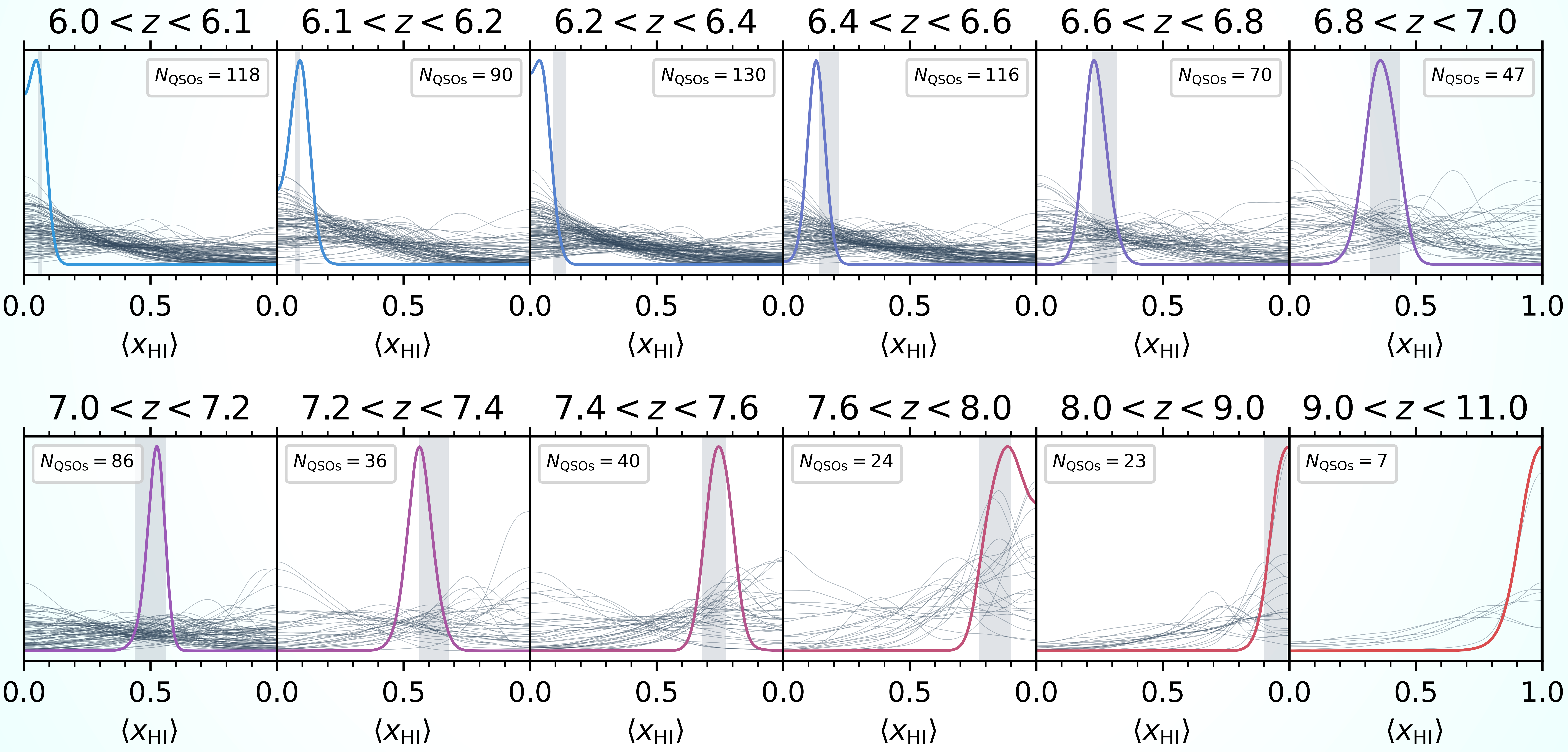
- Full simulation model
- Latent PCA dimension 5
- Wavelength coverage up to 2000 Å, S/N = 10, FWHM = 100 km/s (rebinned to a 500 km/s pixel scale)

Kist, Hennawi, Davies+ 2023b (in prep.)

Timo Kist, Leiden Observatory, kist@strw.leidenuniv.nl

Ensemble inference

Constraining reionization history at the ~5% level with EUCLID & JWST

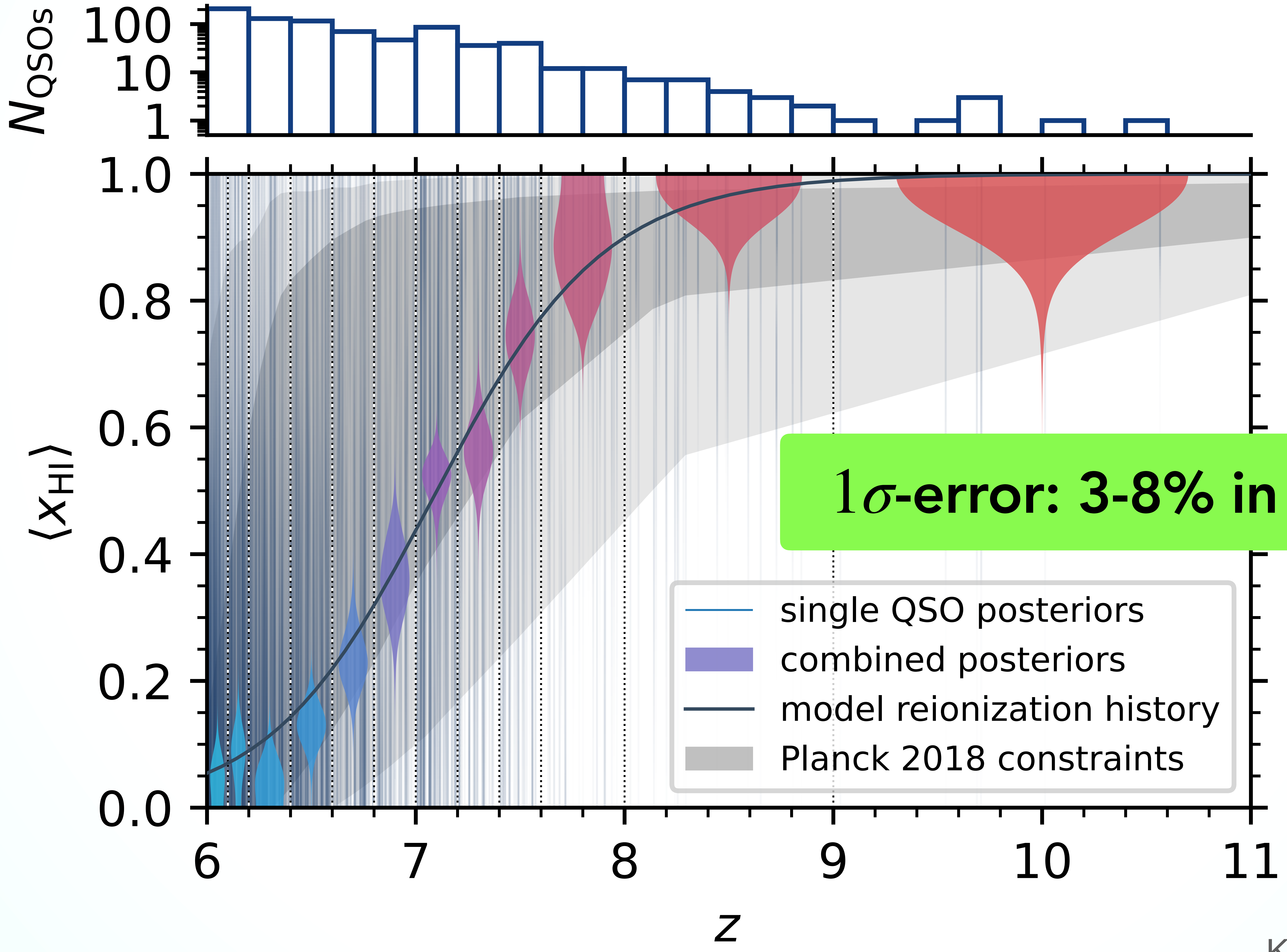


Kist, Hennawi, Davies+ 2023b (in prep.)

Timo Kist, Leiden Observatory, kist@strw.leidenuniv.nl

Ensemble inference

Constraining reionization history at the ~5% level with EUCLID & JWST

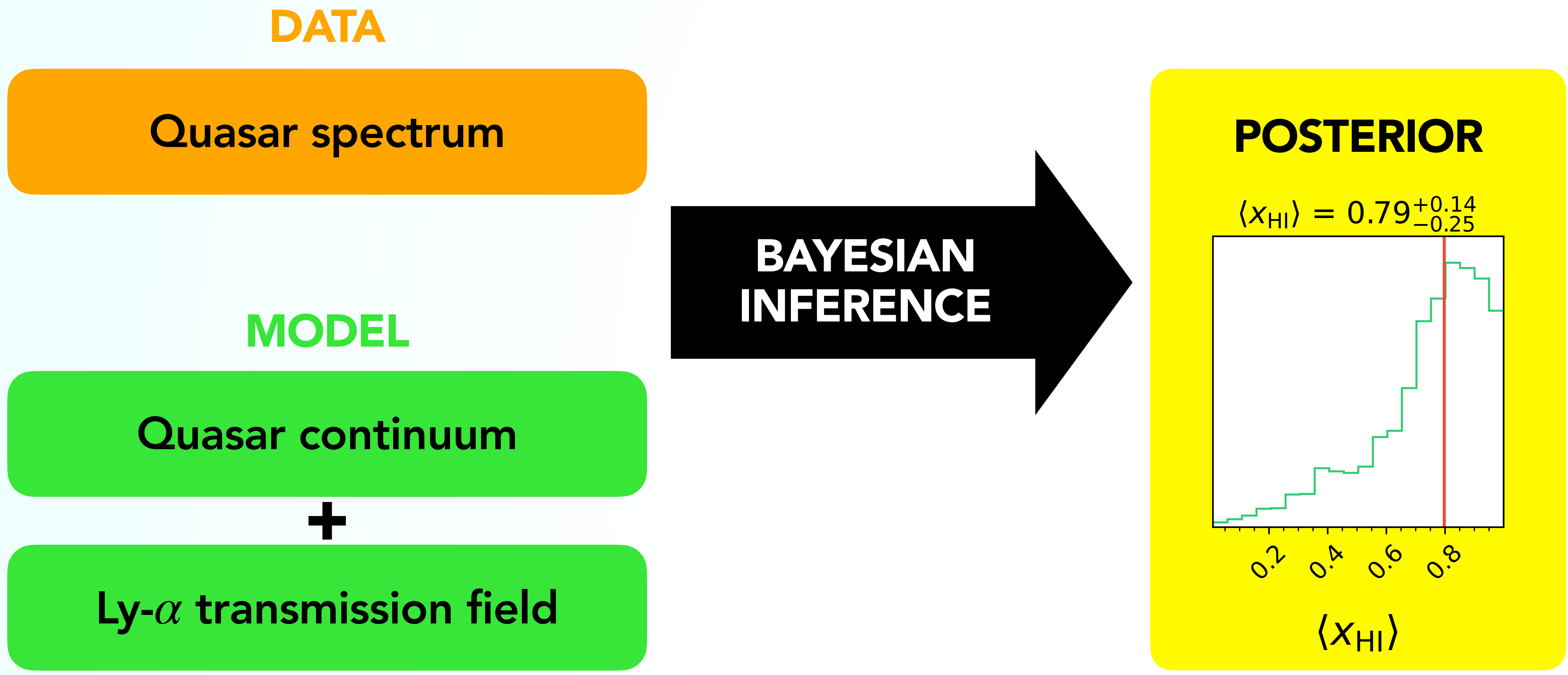


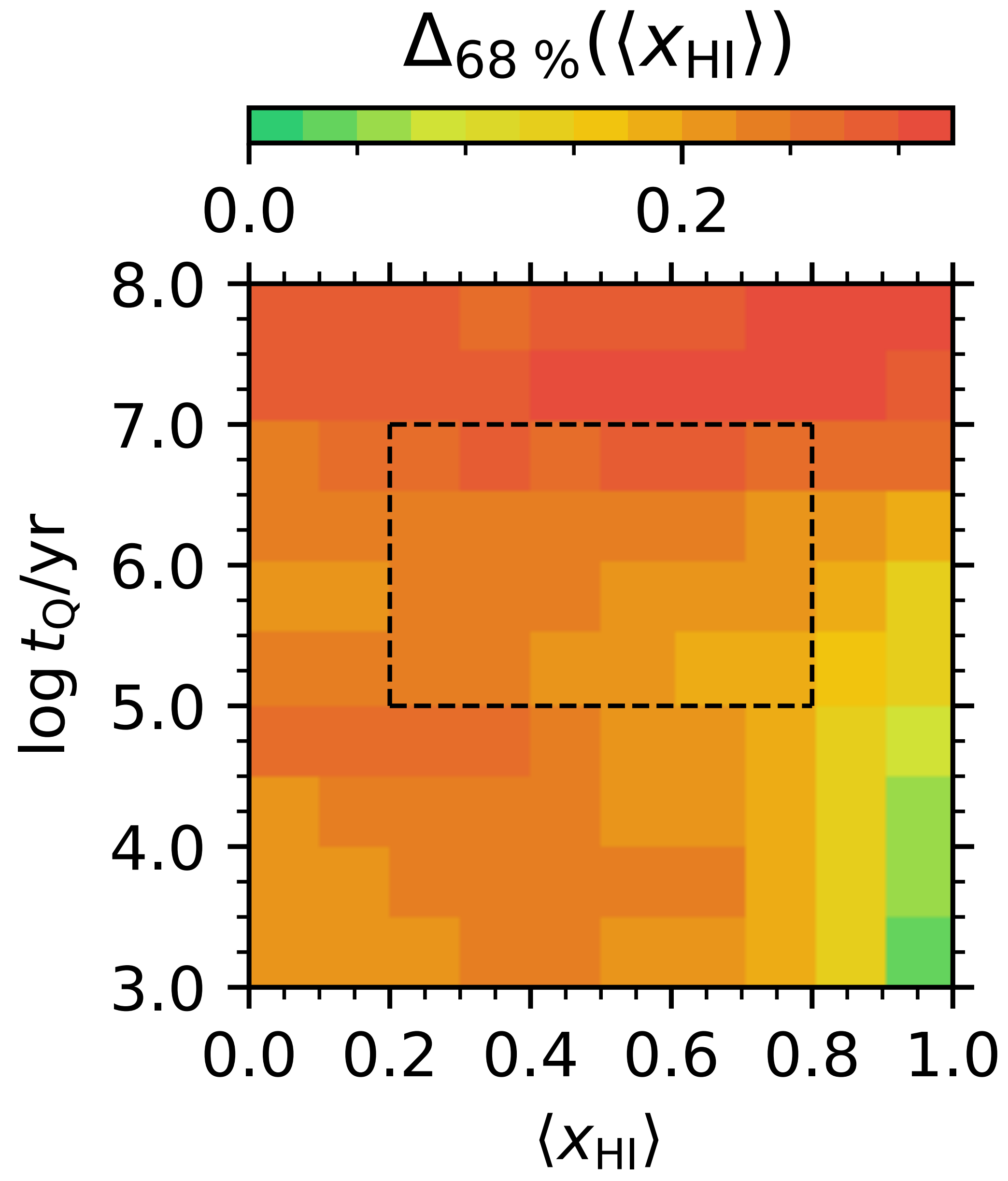
1σ-error: 3-8% in each redshift bin!

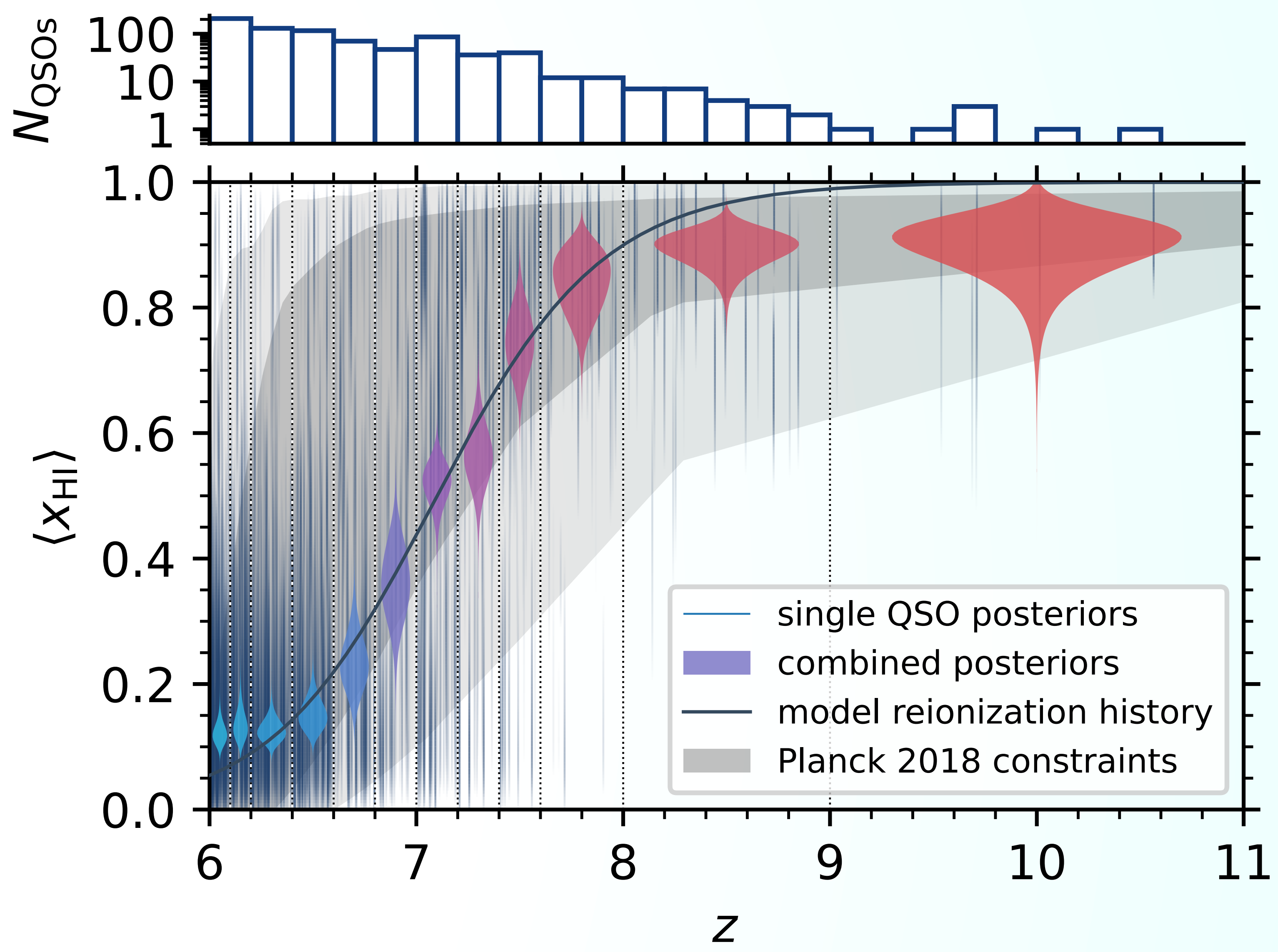
Kist, Hennawi, Davies+ 2023b (in prep.)

Timo Kist, Leiden Observatory, kist@strw.leidenuniv.nl

Summary







Fast Hamiltonian Monte-Carlo inference scheme to infer $\langle x_{\rm HI} \rangle$ and $t_{\rm Q}$ using the damping wing signature of high-redshift quasars

Sensitivity analysis: Apart from continuum reconstruction, stochasticity of reionization dominates the error budget

EUCLID forecast: 3-8% constraints on $\langle x_{\rm HI} \rangle (z)$ throughout the Epoch of Reionization

Kist, Hennawi, Davies+ 2023 a/b (in prep.)