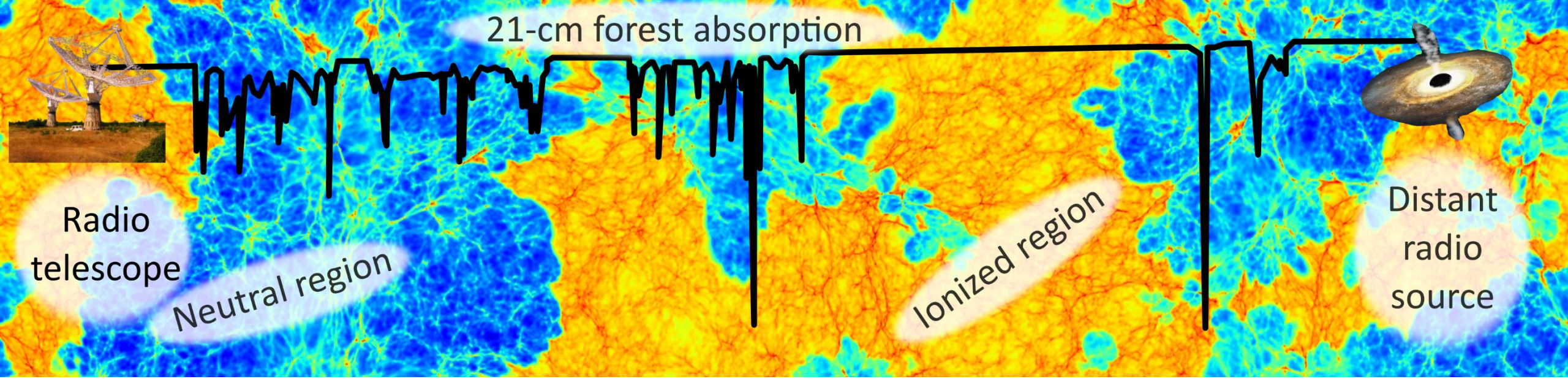


https://arxiv.org/abs/2607.15341

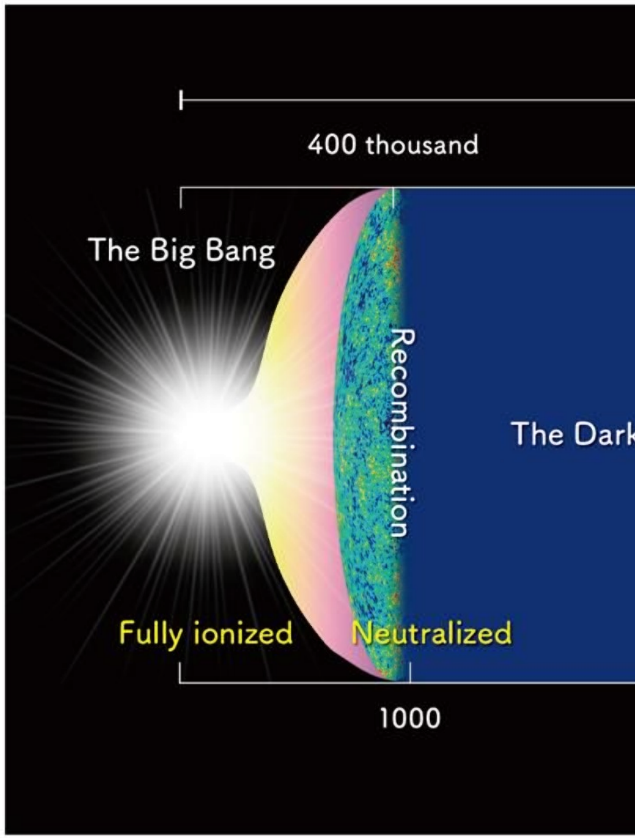
Forest without Trees is still Fruitful:

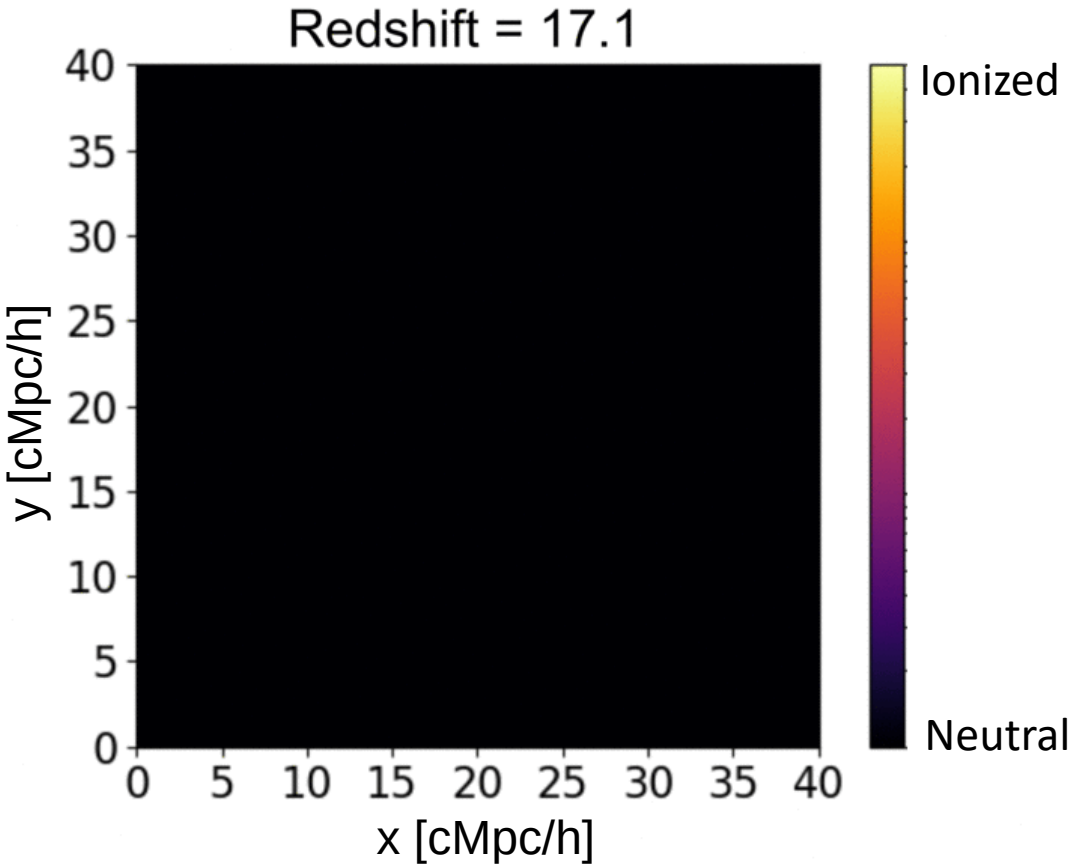
Constraining the Thermal State of Neutral Intergalactic Medium at z~5.6 with the 21-cm Forest 1D Power Spectrum Observations

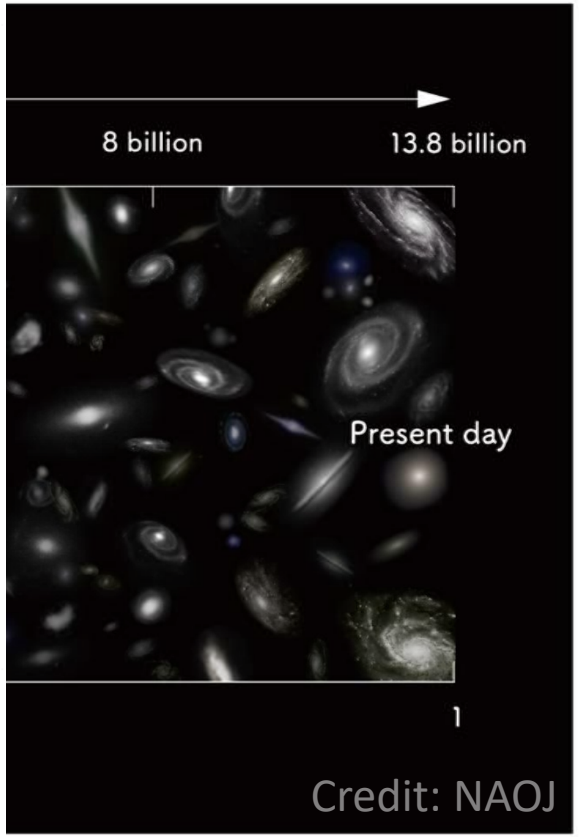
Tomáš Šoltinský

Arnab Chakraborty, Girish Kulkarni, Matteo Viel, Cathryn Trott, Rashmi Sagar, Nithyanandan Thyagarajan, James Bolton, Benedetta Ciardi, Emma Ryan-Weber, Soumak Maitra, Abhirup Datta , Nirupam Roy, Sameer Patil

Epoch of Reionization







Spin flip

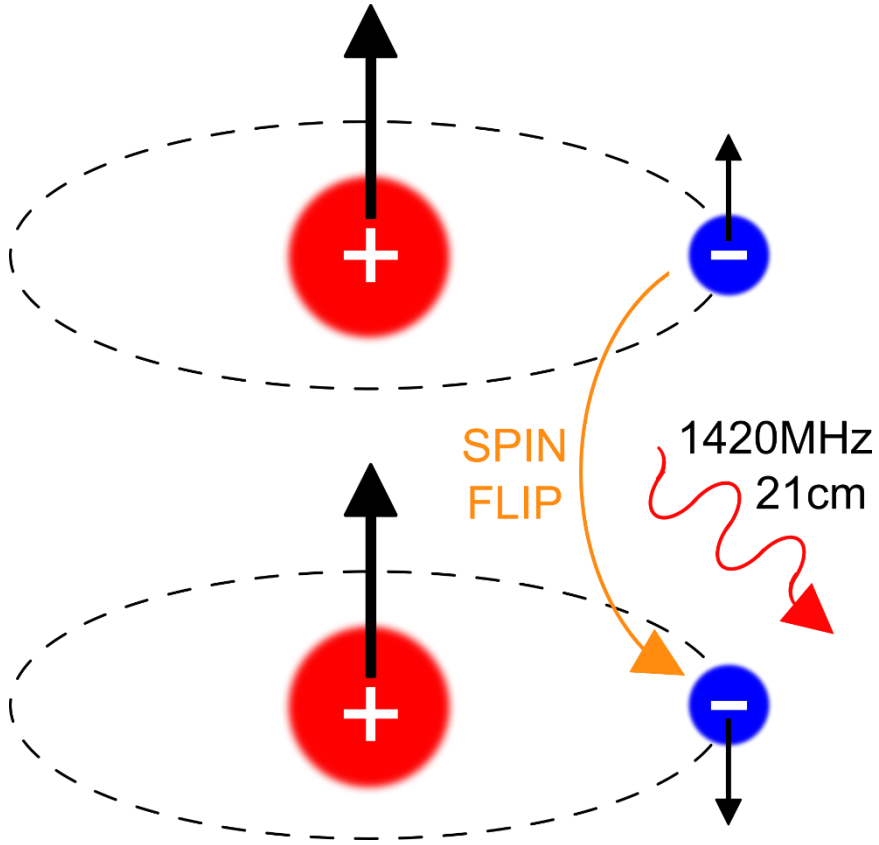
Most of baryonic matter is Hydrogen

and most of it is in IGM

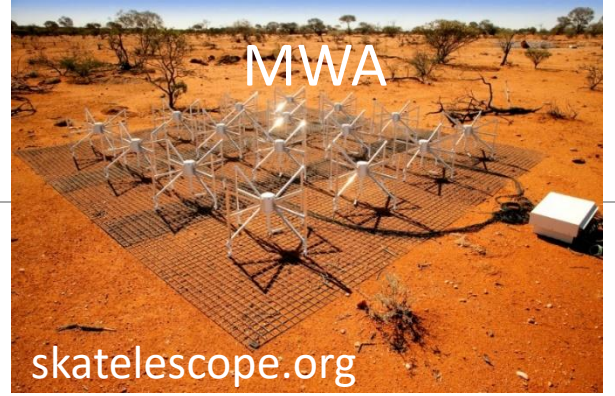
Hyperfine structure

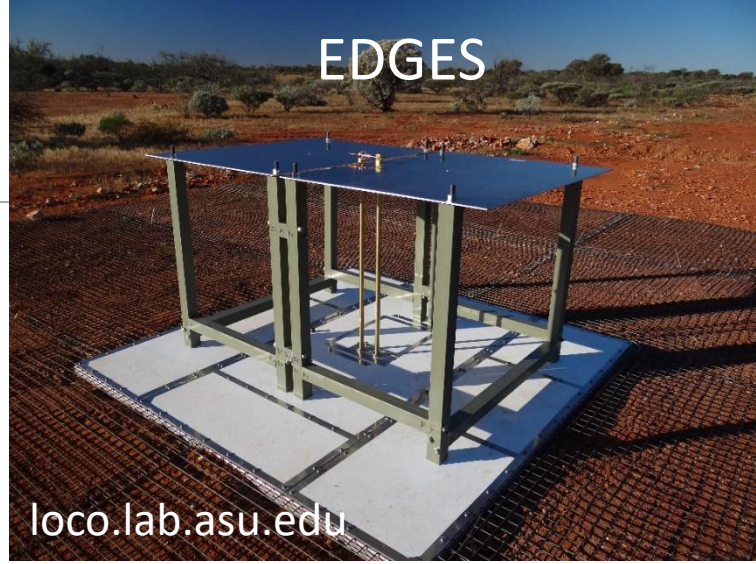
Distinctive 21-cm line

$$\sigma_{21} \ll \sigma_{Ly\alpha}$$



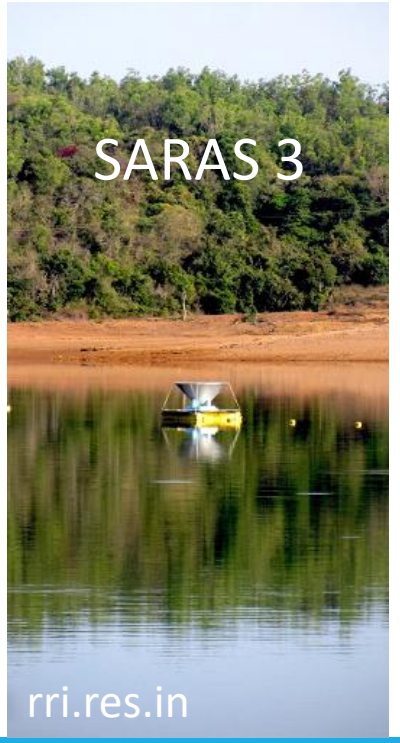
Observatories











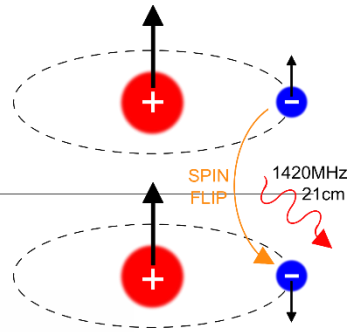


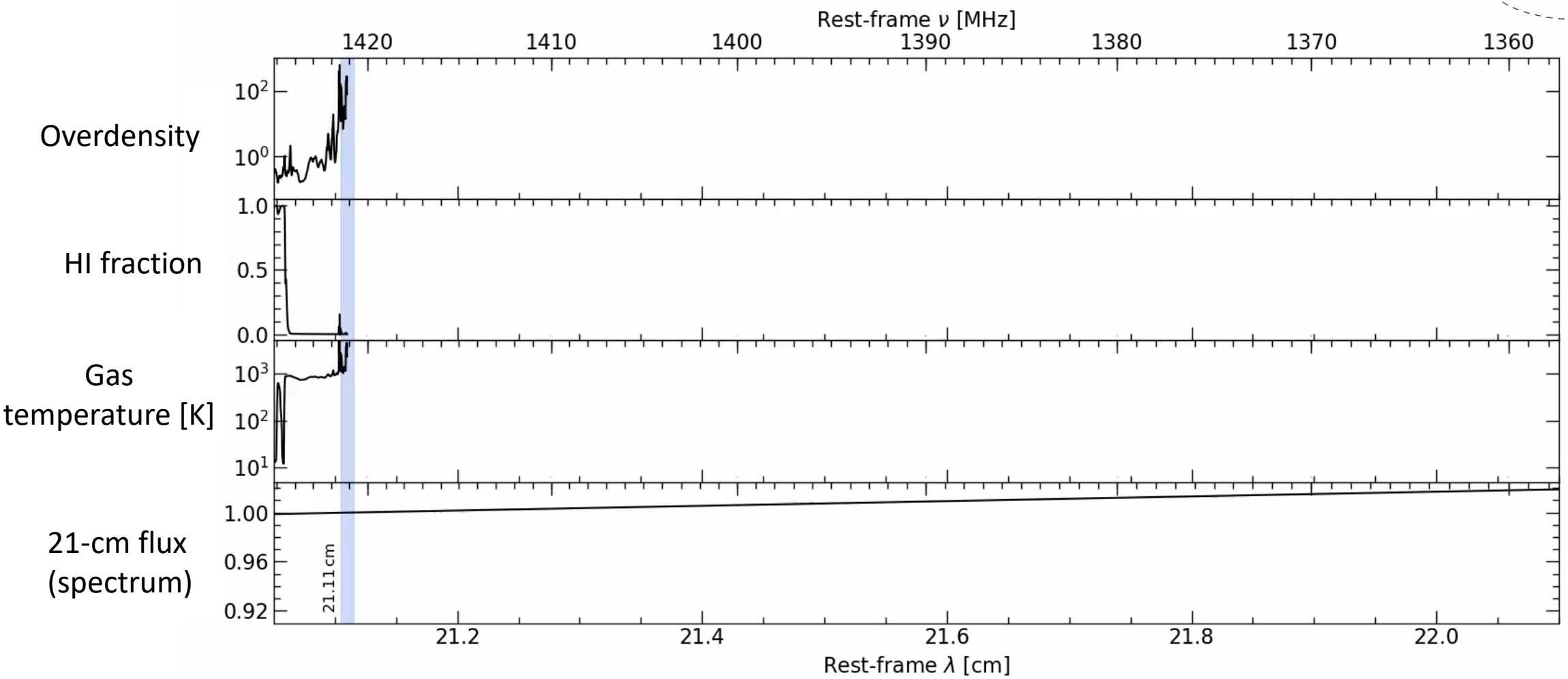




What is 21-cm forest?

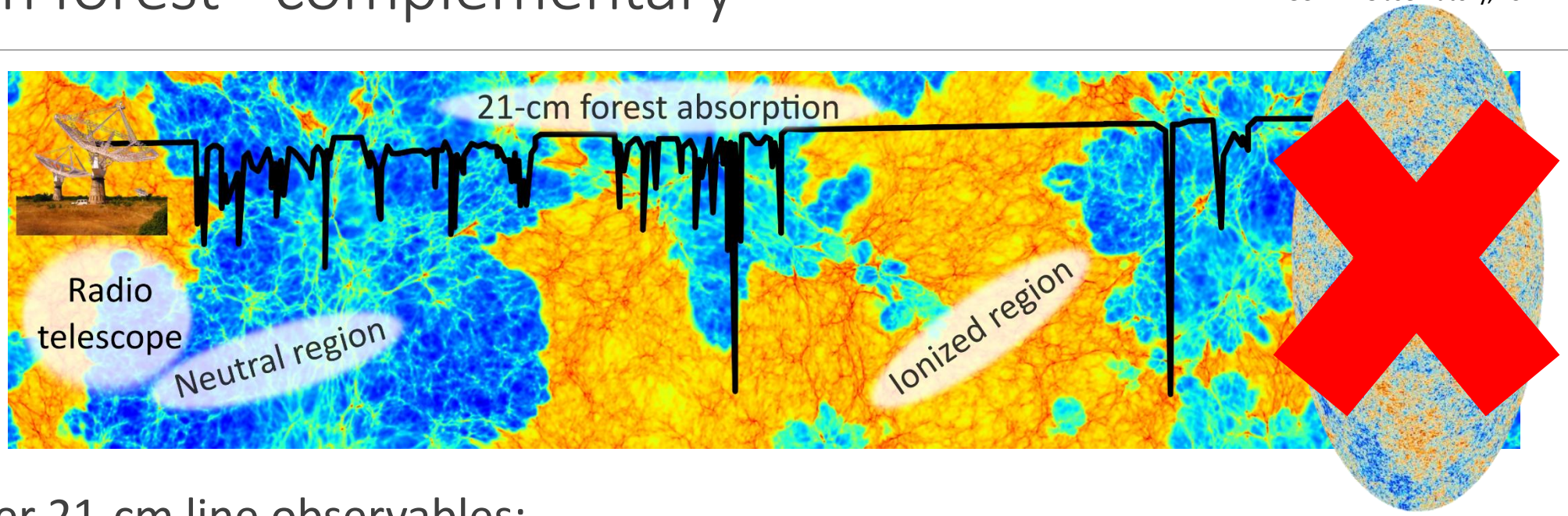
21-cm forest


SPIN
FLIP
1420MHz
21cm


Rest-frame ν [MHz]
1420
1410
1400
1390
1380
1370
1360
Overdensity
HI fraction
Gas temperature [K]
21-cm flux (spectrum)
21.11 cm
21.2
21.4
21.6
21.8
22.0
Rest-frame λ [cm]

21-cm forest - complementary

Credit: SKAO, International Gemini Observatory, ESA



To other 21-cm line observables:

- only requirement is a high signal-to-noise spectrum
- in principle less complicated to detect
- challenge is the abundance of radio-bright sources

To the Lyα forest:

- unique probe of cold and neutral hydrogen at z>6

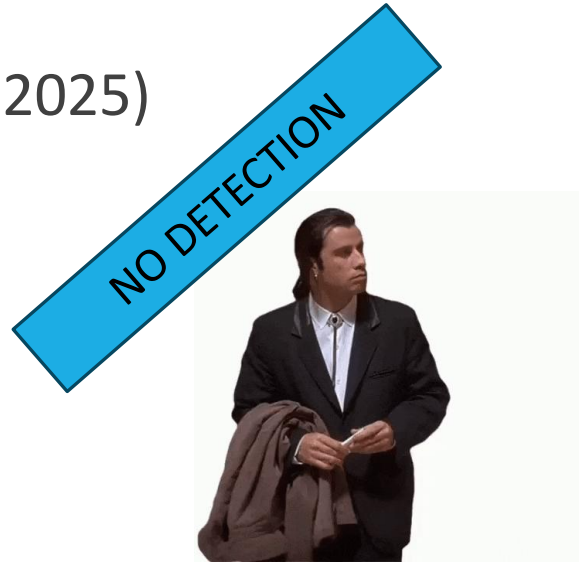
21-cm forest - what can it probe?

State of the IGM – ionization and thermal (Xu+2009,2011, Mack & Wyithe 2012, **Šoltinský+2021,2025**)

Structures – minihalos (Furlanetto+2006, Xu+2010 Meiksin 2011, Kadota+2022)

Astroparticle – nature of dark matter (Shimabukuro+2014, 2020, 2025, Shao+2023,Sun+2024)
– neutrino mass (Shimabukuro+2014, Shao+2025)
– primordial black holes (Villanueva-Domingo+2021, Zhao+2025)

AGN – RLQSO population (Ewall-Wice+2014)
– Supermassive black hole growth models (**Šoltinský+2023**)



Why now?

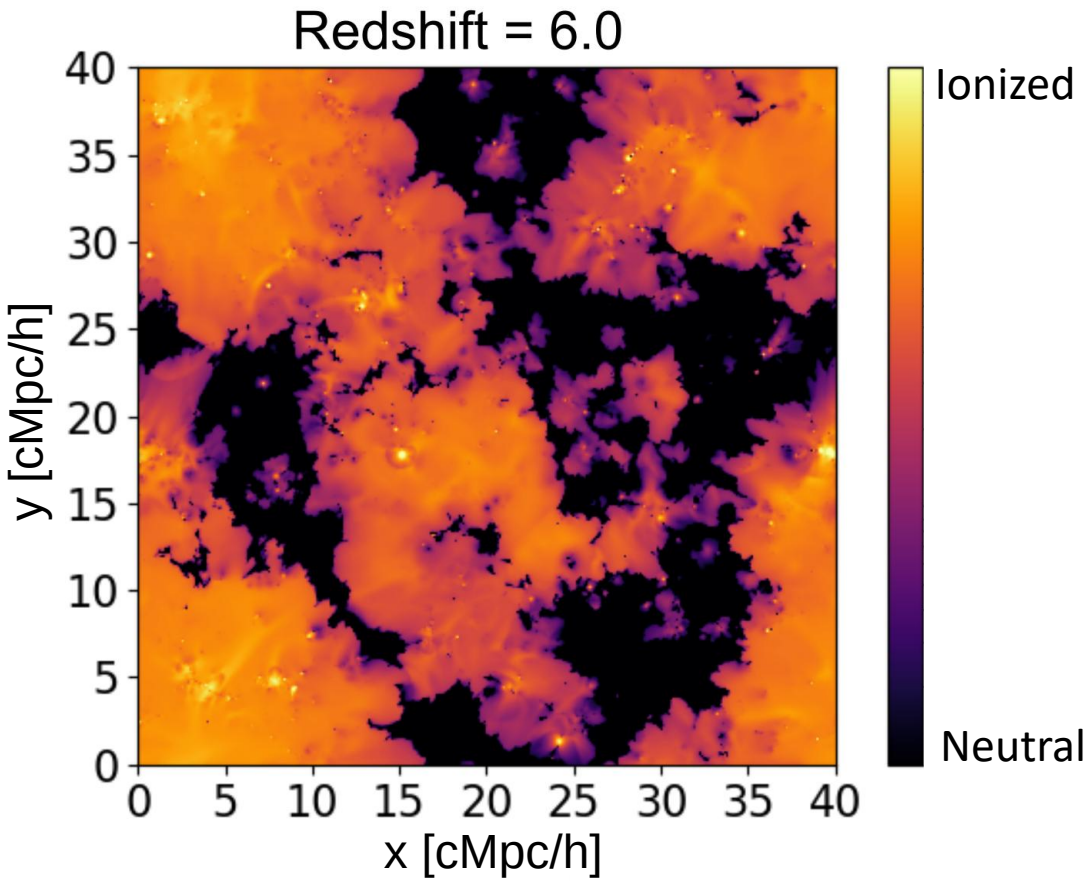
Reionization ends late

Motivated by Lyα observations
(Becker+2015, Eilers+2018)

Seem to require reionization completed by z<5.6
(Kulkarni+2019, Keating+2020, Bosman+2022,
Zhu+2024, Sawyer+2025)

Large islands of HI persist until z≈6

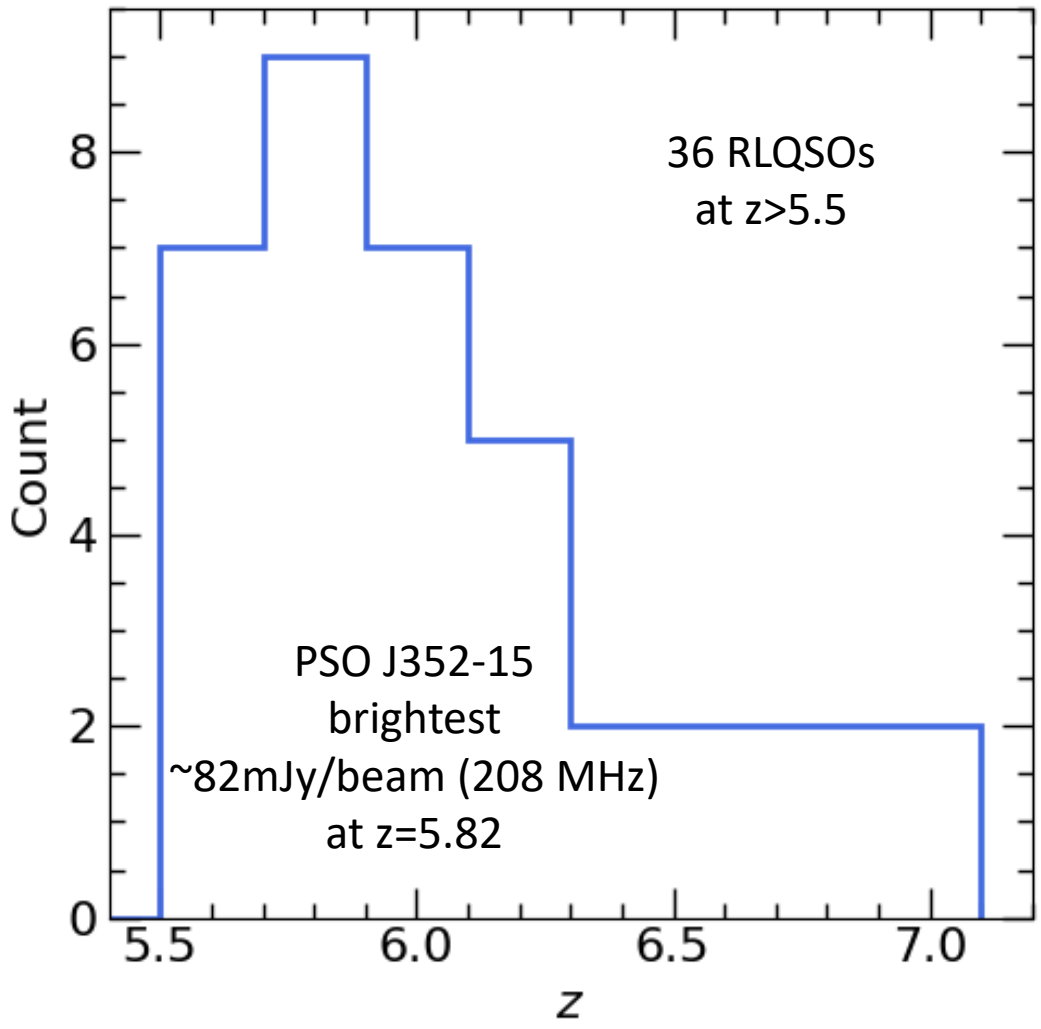
Possibility of detecting 21-cm forest
(**Šoltinský+2021**)



https://www.nottingham.ac.uk/astronomy/sherwood-relics/
Puchwein+2023

New high-z radio-loud quasars detected

Šoltinský+2025



Yang+2026
Wolf+2024
Bañados+2015,2018,2021,2023,2025
Ighina+2021,2023,2024
Endsley+2023
Gloudemans+2022,2023
Shao+2022
Connor+2021
Liu+2021
Belladitta+2020
Frey+2011
Zeimann+2011
Willot+2010
Jiang+2009
McGreer+2006
Fan+2001

www.tomassoltinsky.github.io

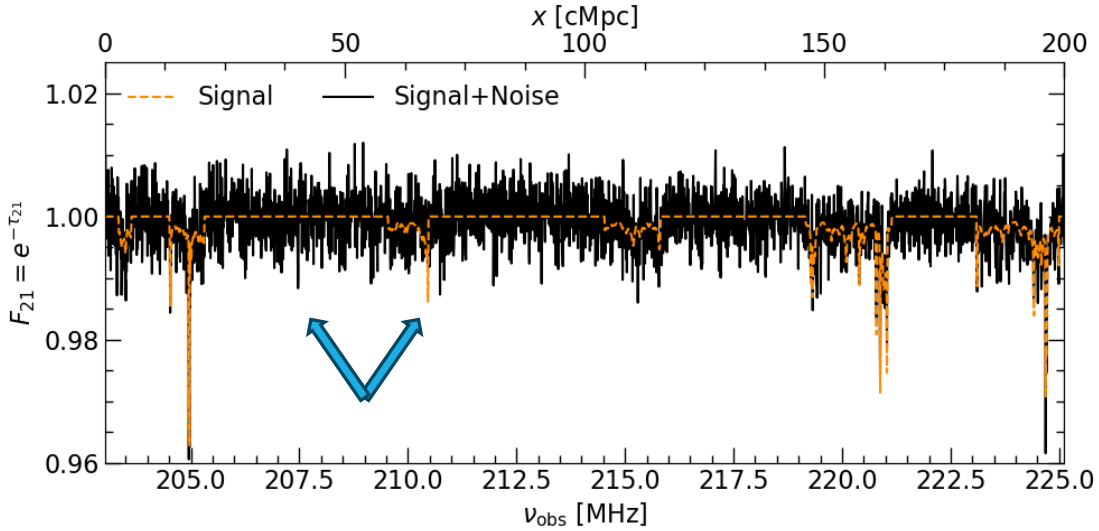
+few radio galaxies at z>5.5
(Drouart+2020, Varadaraj+2026)

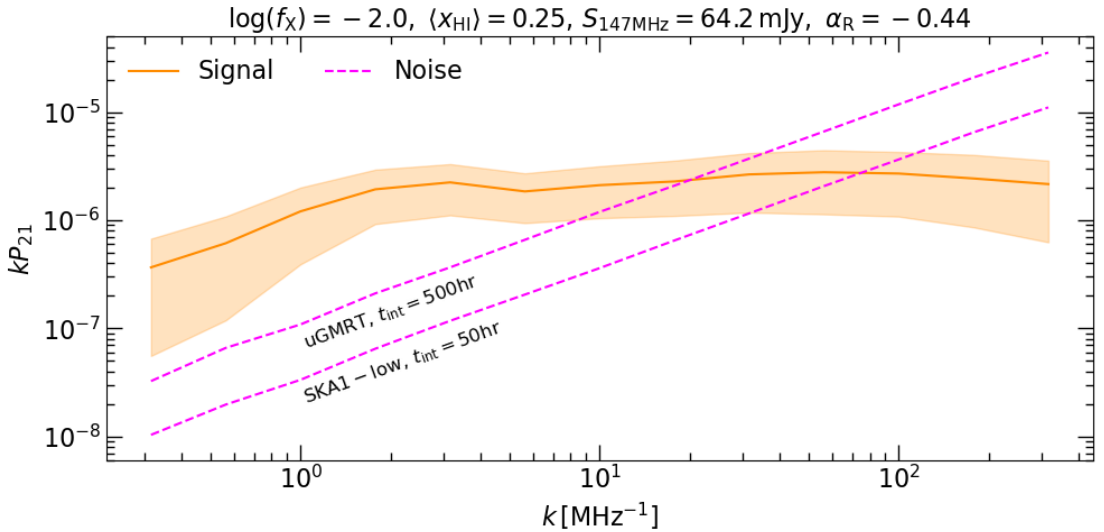
Statistical observables and machine learning

- Wavelet Scattering Transforms, Topological signatures, Differential number density distribution of frequency channels (Shimabukuro+2025a, b, **Šoltinský+2025**)

- 1D power spectrum (Thyagarajan 2020, Shao+2023, 2024, 2025, **Šoltinský+2025**)

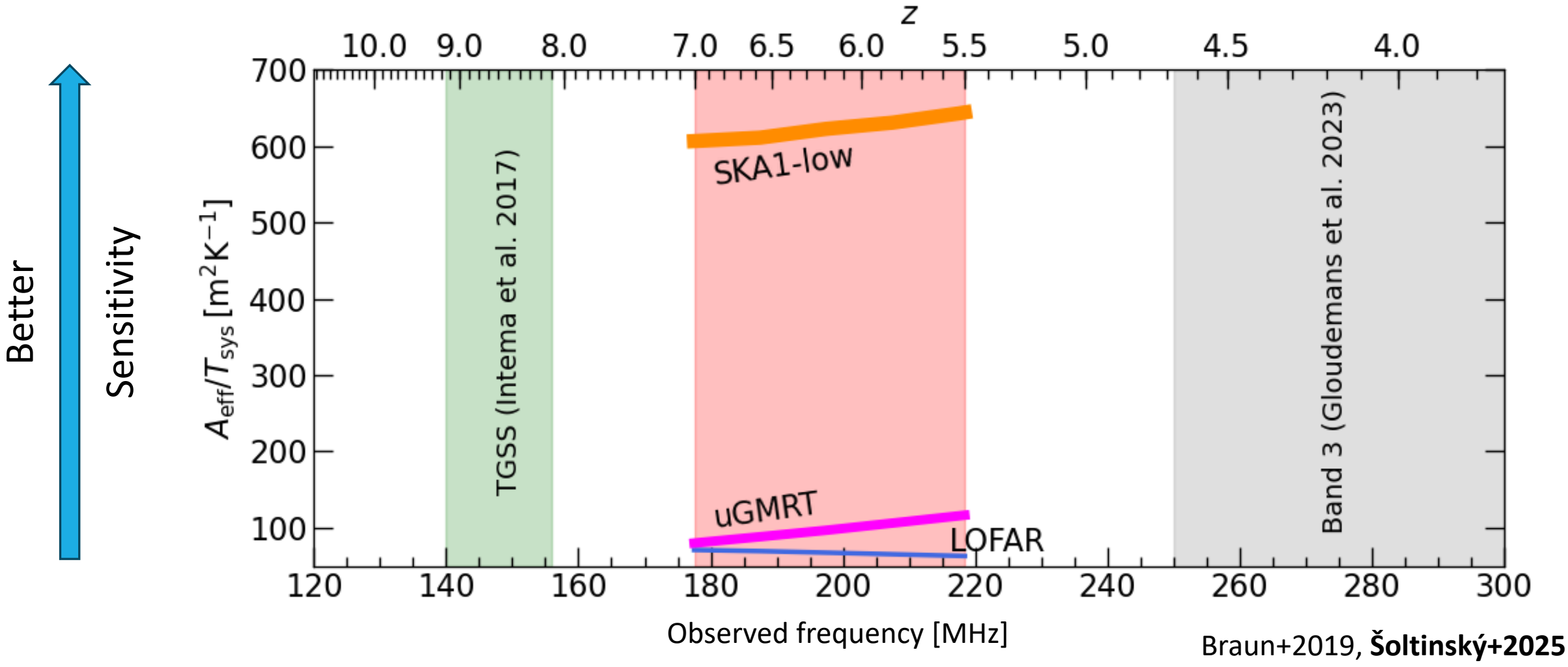
- U-net denoising + XGBoost (**Patil+2026**) and other (Sun+2024)





Šoltinský+2025
https://arxiv.org/abs/2412.06879

Instrumentation improving and looking forward to SKA



Braun+2019, **Šoltinský+2025**

uGMRT archival observations



uGMRT – 21-cm forest 1D power spectrum measurement

17.5 hr of data - PSO J352-15 at z=5.82

Target selection (Bañados+2018)

Usable spectral modes (Thyagarajan 2020)

RFI mitigation

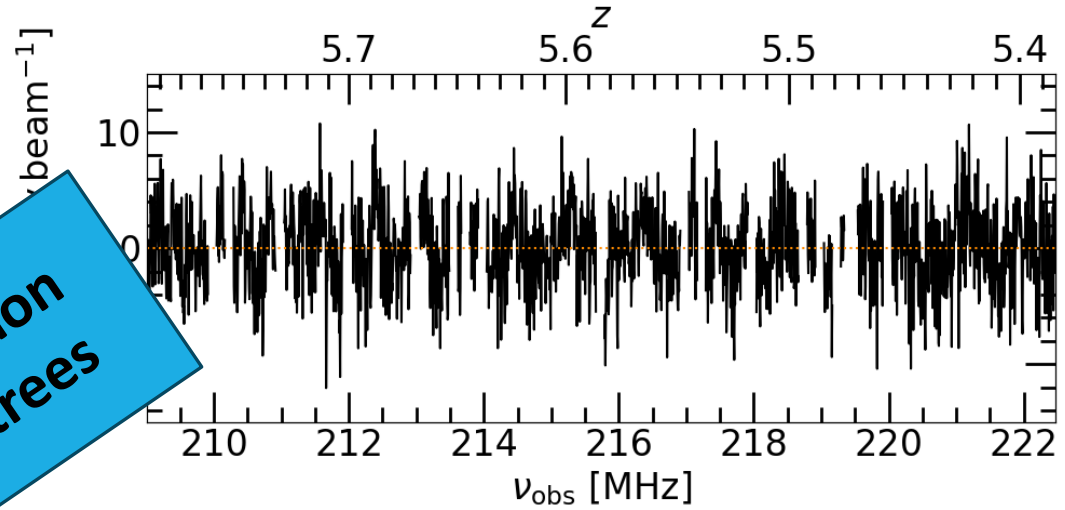
Calibration (self, DD, bandpass sub.)

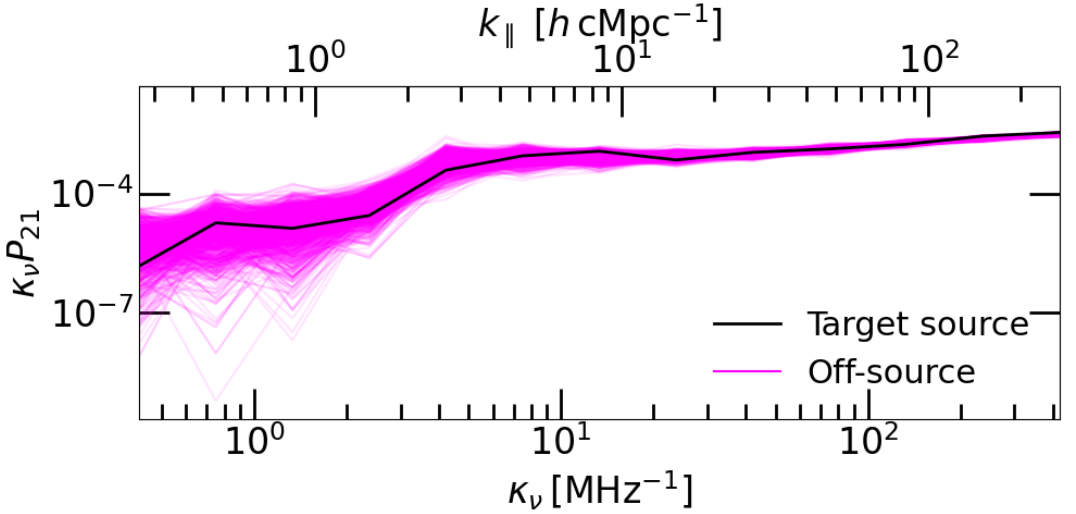
Noise rms of ~3.6 mJy/beam per 6.1

Measured flux density spectrum

and the first 1D power spectrum of 21 forest

No statistical detection
Forest is without trees





Šoltinský+2026
https://arxiv.org/abs/2607.15341

uGMRT – constraining IGM properties

Completed 60hr programme on uGMRT!

J352-15 – 40hr

The deepest targeted observations at ~200MHz

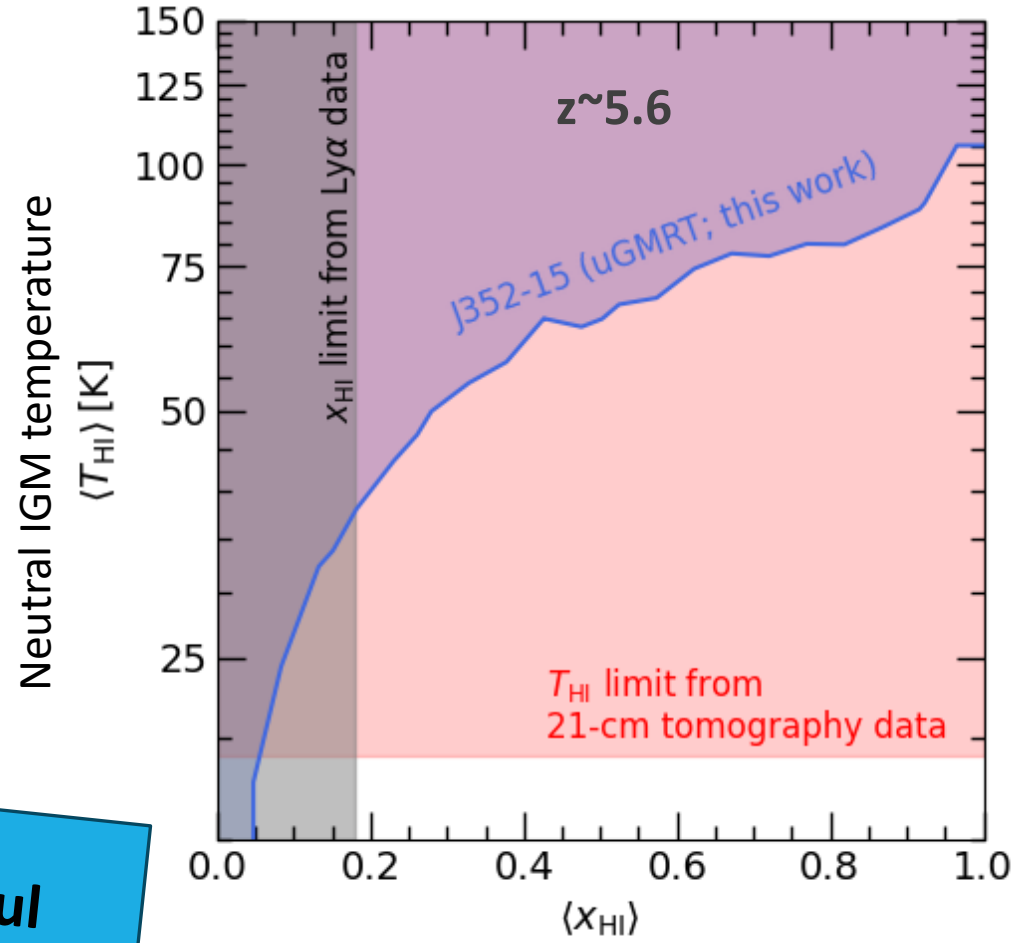
Goal – improving sensitivity and constraints

J0309+27 – 20hr

Goal – pilot study to explore the field

– building multi-source sample

– decrease effect of sample variance



Forest without trees is still fruitful

Šoltinský+2026

https://arxiv.org/abs/2607.15341

(Gaikwad+2023, Qin+2025, Umeda+2025, Dhadha+2025)

Summary

21-cm forest now possible to detect

- Late-end reionization, increasing number of high-z RLQSO, improving sensitivity of radio telescopes, statistical observables, ML

21-cm forest is a unique probe of the cold, neutral IGM

- Even in the case of a null-detection

The 1st measurement of 21-cm forest 1D power spectrum

- Disfavouring the coldest and most neutral IGM models

21-cm forest studies - from theoretical → observationally informative

New observations with uGMRT finished recently!

tomas.soltinsky@inaf.it
www.tomassoltinsky.github.io



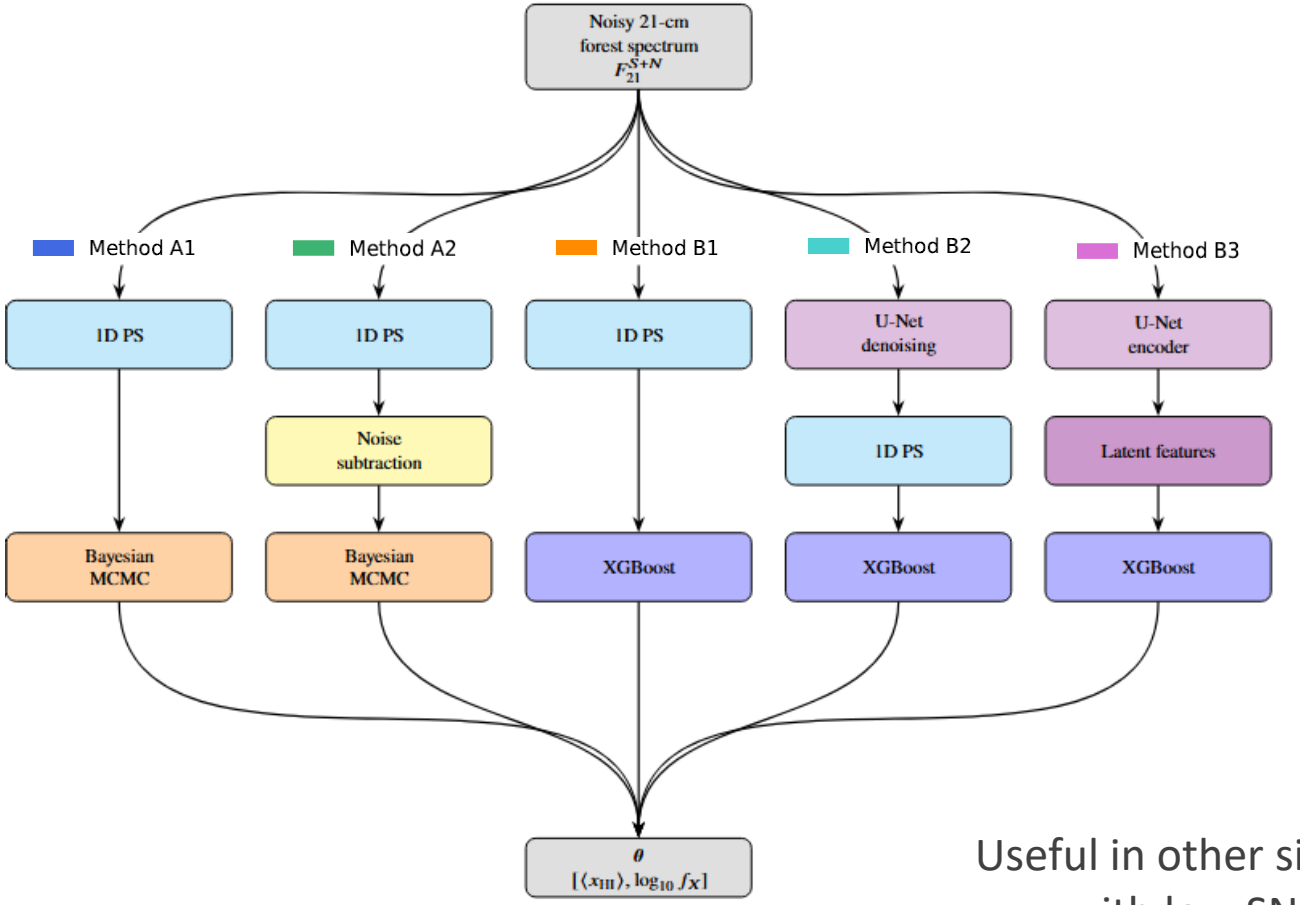
Acknowledgements

TŠ is supported by the Istituto Nazionale di Astrofisica - Osservatorio Astronomico di Trieste (INAF-OATs) under the Theory grant ‘Cosmological Investigation of the Cosmic Web’ (C93C23006820005).

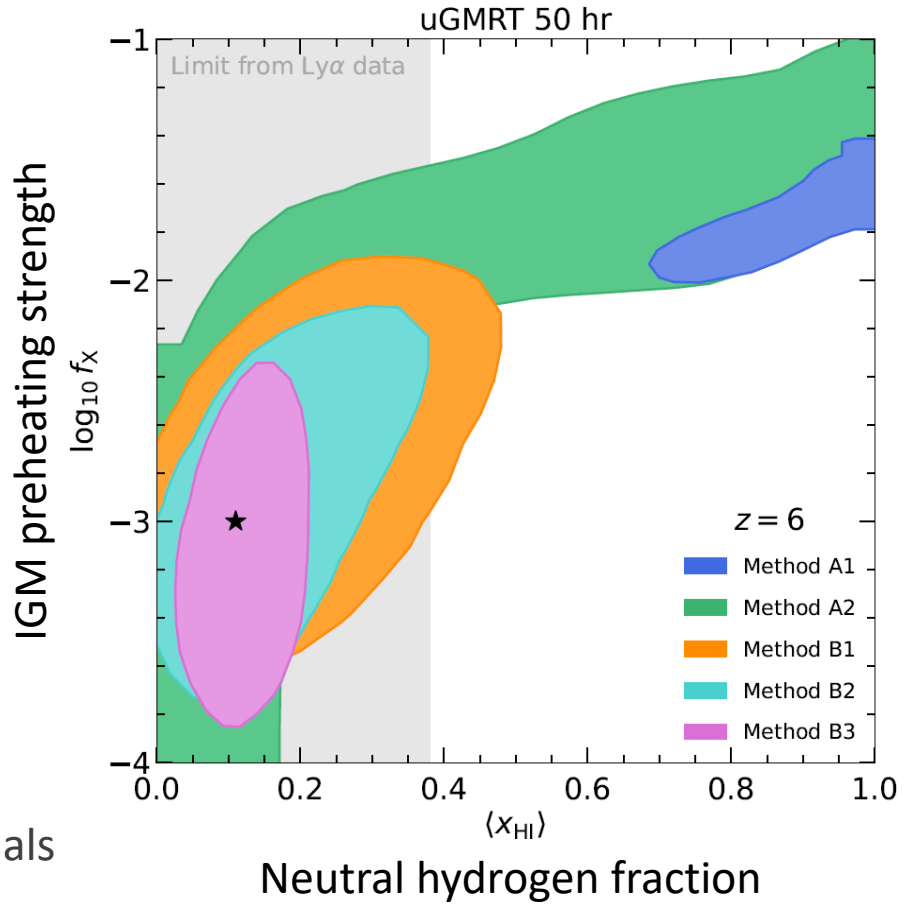
TŠ is also supported by the Istituto Nazionale di Fisica Nucleare (INFN) INDARK grant.

Appendix

Improving parameter inference with ML



Useful in other signals with low SNR



Patil et al. 2026
https://arxiv.org/abs/2507.11611

See also Sun et al. 2024 (Generative + inference normalizing flows)

Where do strong 21-cm forest absorbers come from?

Minihalos

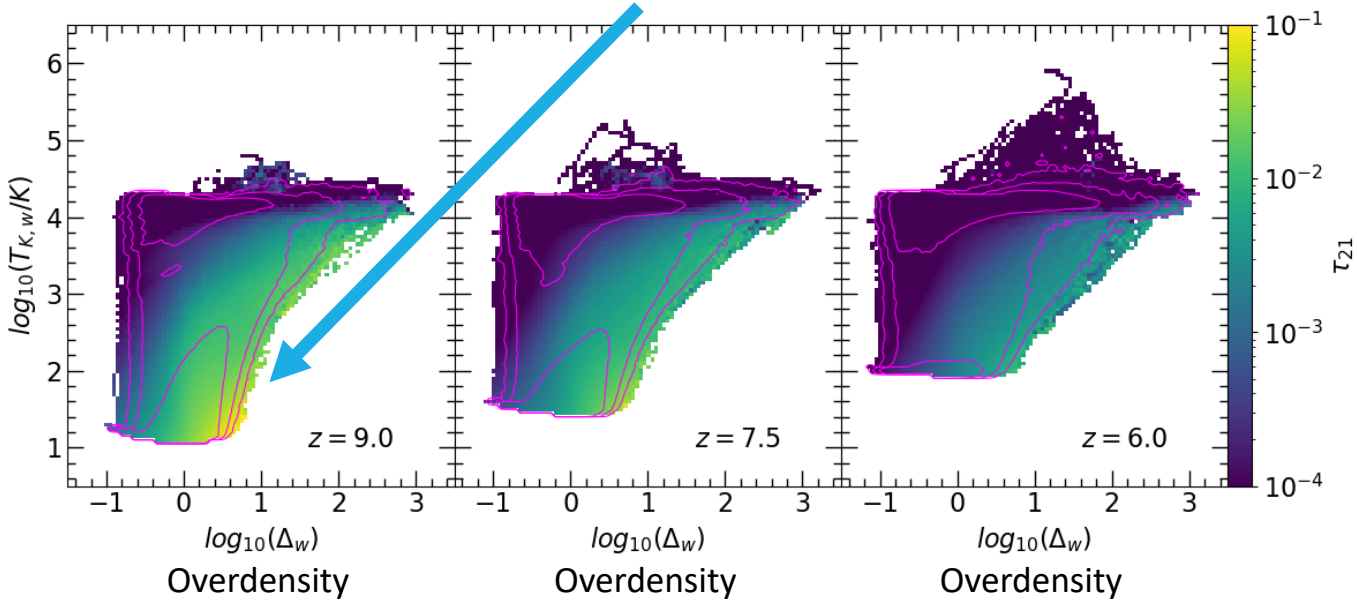
(e.g. Furlanetto & Loeb 2002, Meiksin 2011, Xu+2011, Shimabukuro+2014, Naruse+2024, Shao+2024)

VS

Diffuse IGM

(Carilli+2002, Ciardi+2013, Bhagwat+2022, Thyagarajan 2020, Šoltinský+2021)

Cold diffuse IGM - T_K<100K, 3<Δ<10



Šoltinský+2021

https://arxiv.org/abs/2105.02250

Reionization ends late

At z<5.6

-Large spatial fluctuations in the Lyα forest opacity at z>5 (Becker+2015, Kulkarni+2019, Nasir & D'Aloisio 2021, Choudhury+2021, Bosman+2022, Qin+2024)

-Deficit of Lyα emitting galaxies around extended Lyα absorption troughs (Kashino+2020, Keating+2020, Christenson+2021)

-Clustering of Lyα emitters (Weinberger+2019)

-Thermal widths of Lyα forest transmission spikes at z>5 (Gaikwad+2020)

-Lyα equivalent widths (Nakane+2024)

-Mean free path of ionizing photons at z=6 (Becker+2021, Cain+2021, Zhu+2023, Gaikwad et a. 2023)

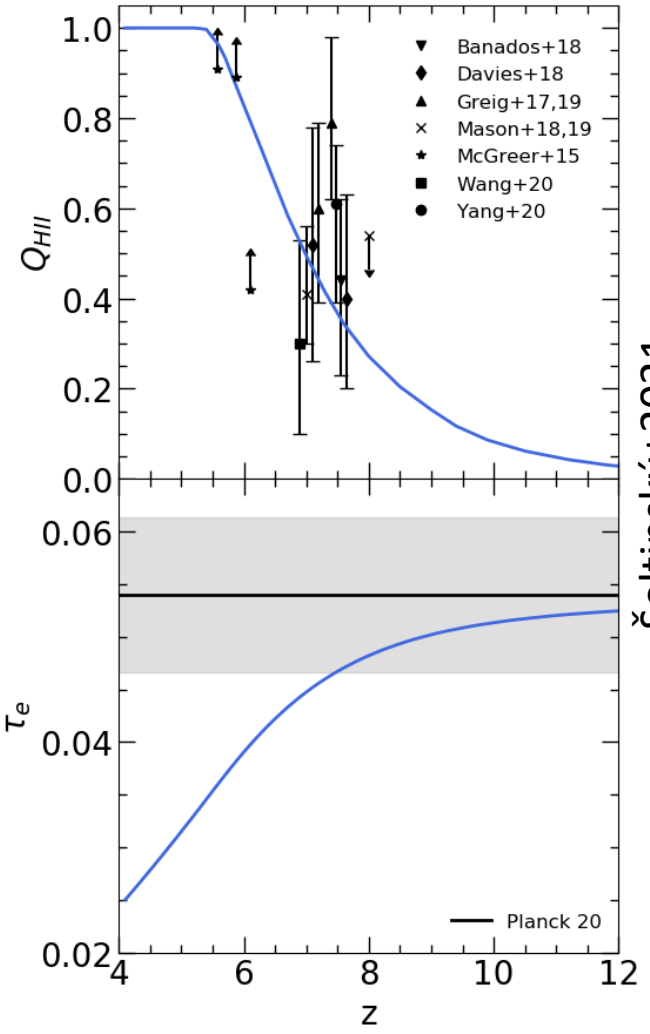
-Long dark gaps in the Lyα and Lyβ forest (Zhu+2021, 2022, Maity+2026)

-Dark pixels fraction in the Lyα and Lyβ forest (Davies+2025)

-Damping wings in the Lyα forest at z<6 (Spina+2024, Becker+2024, Zhu+2024, Sawyer+2025)

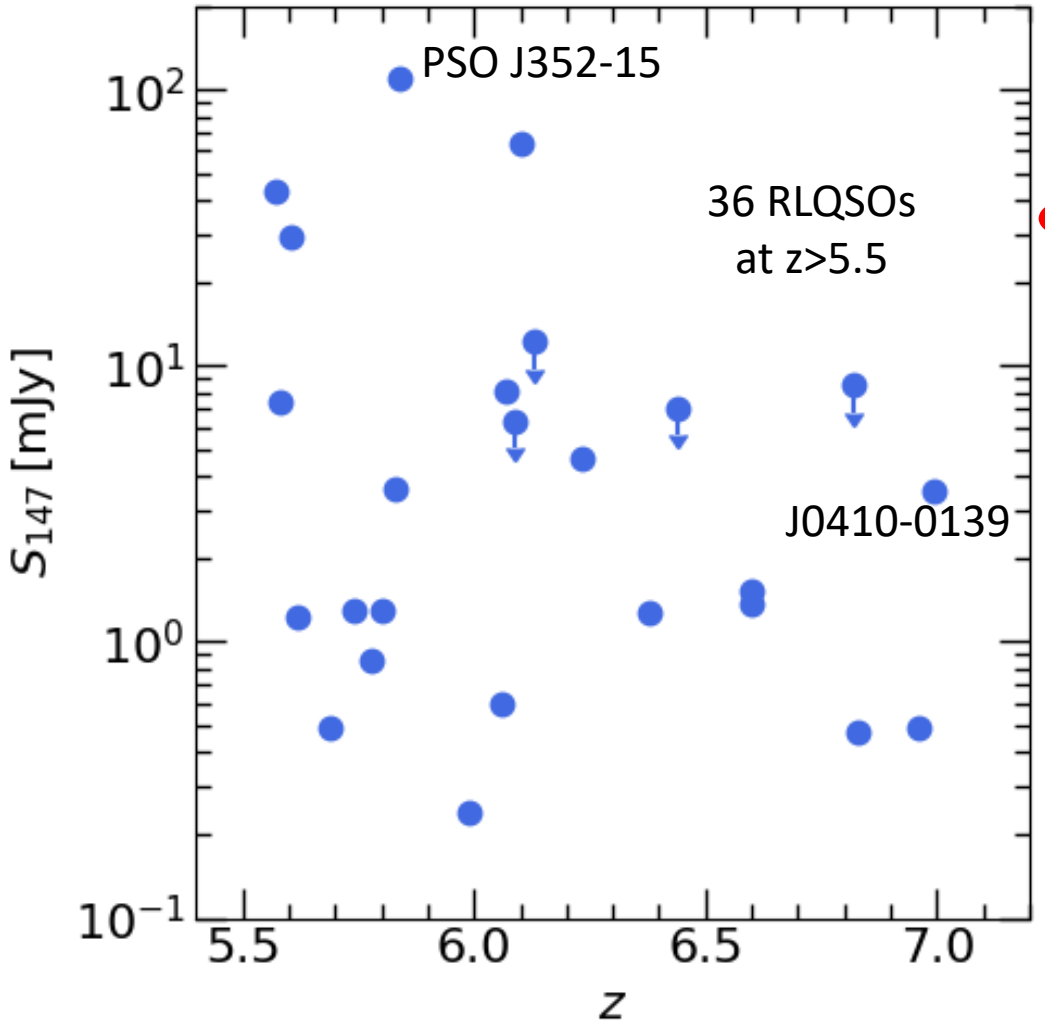
-Cross-correlation of the Lyα forest-[O III] emitters (Kakiichi+2025)

-Upturn of OI absorbers line density at z>5.5 (Becker+2019, Sebastian+2024)



Šoltinský+2021

New high-z radio-loud quasars detected



Šoltinský+2025

Wolf+2024
Bañados+2015,2018,2021,2023,2025
Ighina+2021,2023,2024
Endsley+2023
Gloudemans+2022,2023
Shao+2022
Connor+2021
Liu+2021
Belladitta+2020
Frey+2011
Zeimann+2011
Willot+2010
Jiang+2009
McGreer+2006
Fan+2001

LOFAR
+
DESI

www.tomassoltinsky.github.io

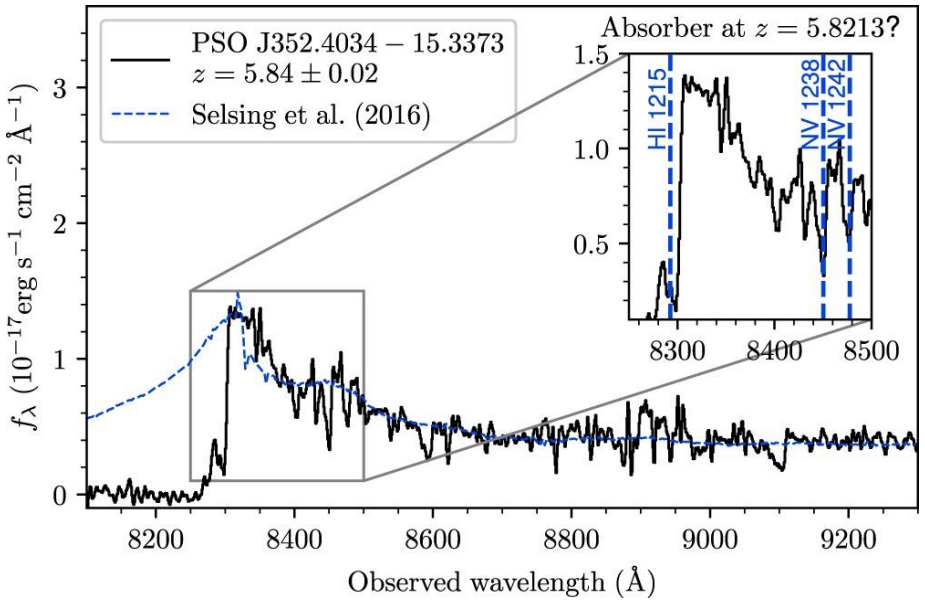
+radio galaxies at z>5.5 (Drouart+2020, Varadaraj+2026)

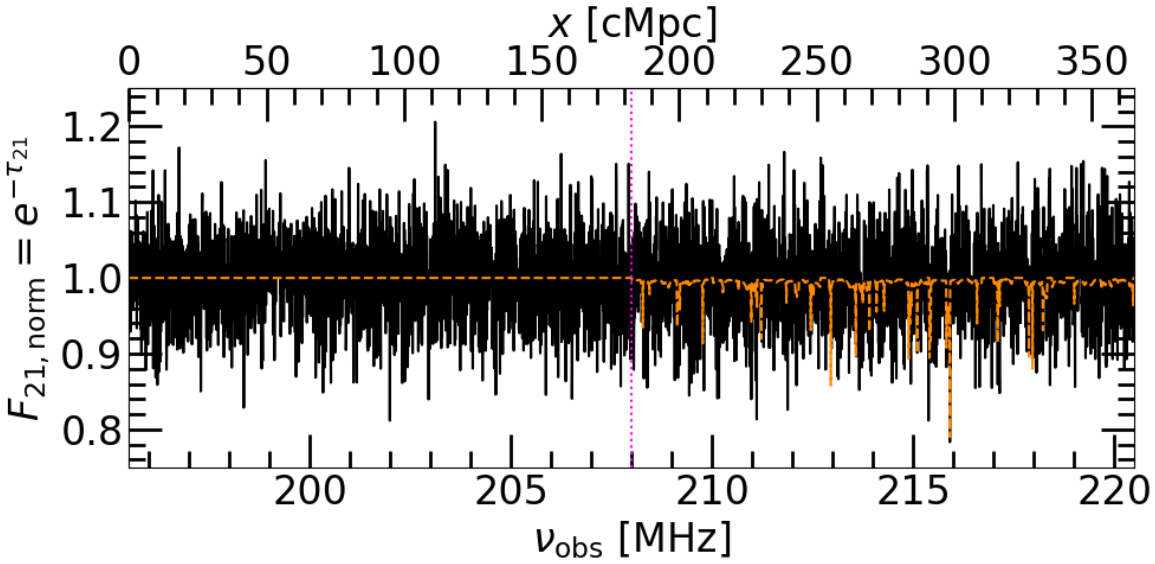
Predicted ~50 RLQSO of >100mJy at z>5.5 (Niu+2024)

Target selection

Target	z	RA	DEC	S_{200MHz} [mJy] (computed)	S_{147MHz} [mJy]	α_R (1.4GHz-147MHz)	Ref.
PSO J352-15	5.82	23.494	-15.337	84.09	110.6	-0.89	Bañados+2018
PSO J0309+27	6.10	3.163	27.299	56.07	64.2	-0.44	Belladitta+2020
VIK J2318-3113	6.44	23.305	-31.229	5.18	7	-0.98	Ighina+2021
J0410-0139	7.00	4.169	-1.656	3.28	3.5	0.21	Bañados+2025

(Bañados+2018)





Sidelobe-induced mode-mixing

Thyagarajan 2020 - highest k dominated by sidelobes → $k_{\parallel,\mathrm{w}} \simeq \frac{2\pi H_0 E(z)}{c(1+z)} \frac{\sin(\frac{\theta_\mathrm{p}}{2})}{\theta_\mathrm{s}}$

GMRT System parameters and current status 2026 →
θ_P= 120’ (187.5MHz/ν) = 1.8°
θ_S= 17.3’’ (187.5MHz/ν) = 15.6’’

J352-15: z=5.82, ν_T=208MHz
Conversion MHz^{-1} = c(1+z)^{2}h/2$\pi\nu_{21}$H(z) → **k_{SL} = 0.63h cMpc^{-1} = 1MHz^{-1}**

MWA: θ_P= 18.8° B_{max}=3km —> θ_S= 1.65’ → k_{SL} = 1.00h cMpc^{-1} = 1.6MHz^{-1}

LOFAR: θ_P= 2.11° B_{max}=100km —> θ_S= 0.04’ → k_{SL} = 4.72h cMpc^{-1} = 7.4MHz^{-1}

uGMRT observational data reduction

RFI - AOFLAGGER (Offringa+2012) + CASA

Calibrators - 3C 48 (v), 2321-163 (t)

Self-calibration - Imaging with WSCLEAN (Offringa+2014)

Direction-dependent calibration - Approach from Heywood+2020,2022

DDFacet (Tasse+2018) – image of target field

CUBICAL (Kenyon+2018) – differential gains per source

Continuum subtraction - CASA+2nd order polynomial

Barycentric correction - Doppler shift due Earth's motion

Channel averaging - 1.5kHz to 6.1kHz

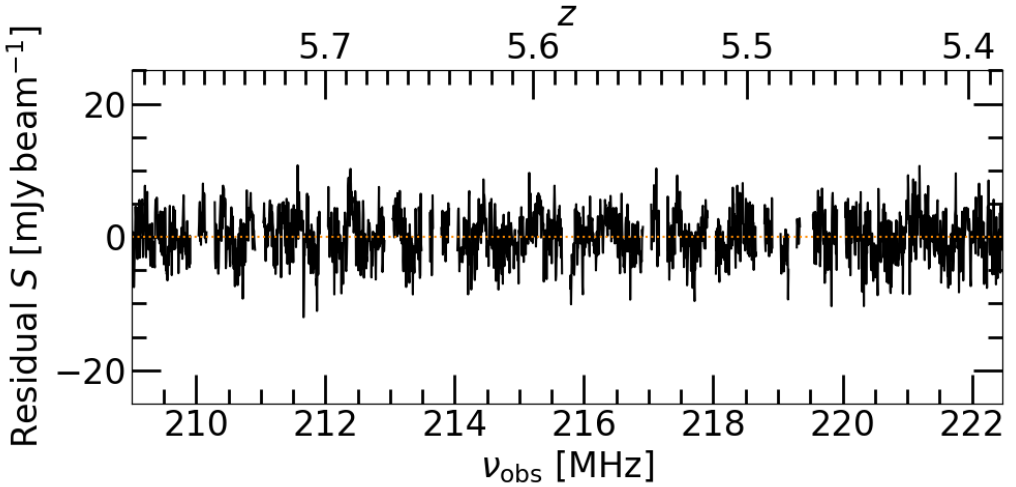
uGMRT observational data reduction

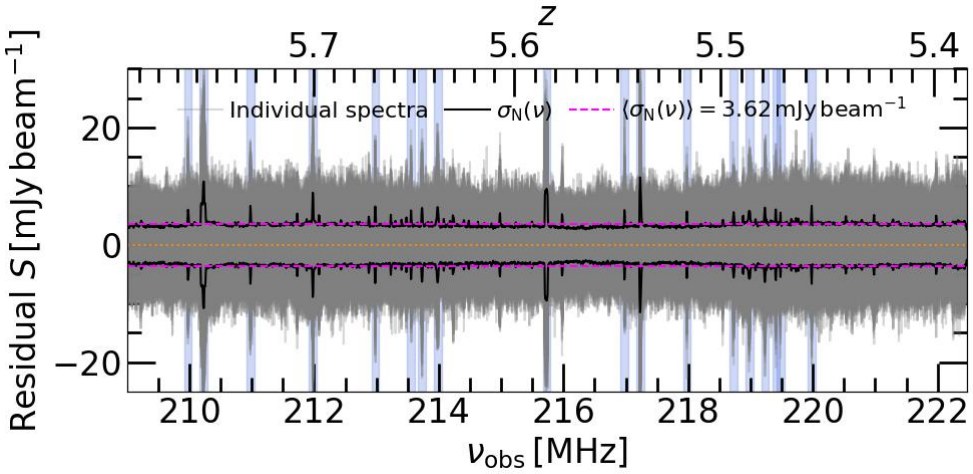
Residual bandpass structure subtraction

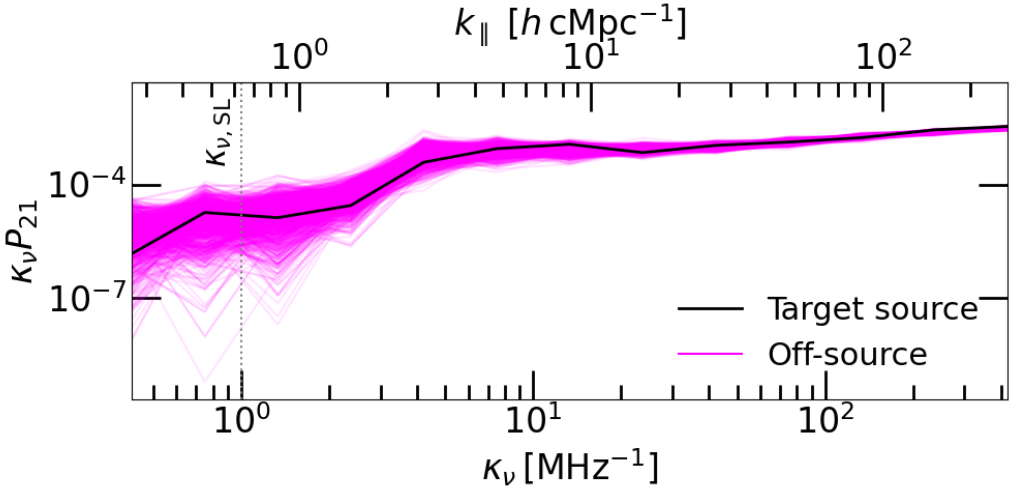
Wavelet decomposition

- coarsest component, Daubechies 9

Flagging bad channels



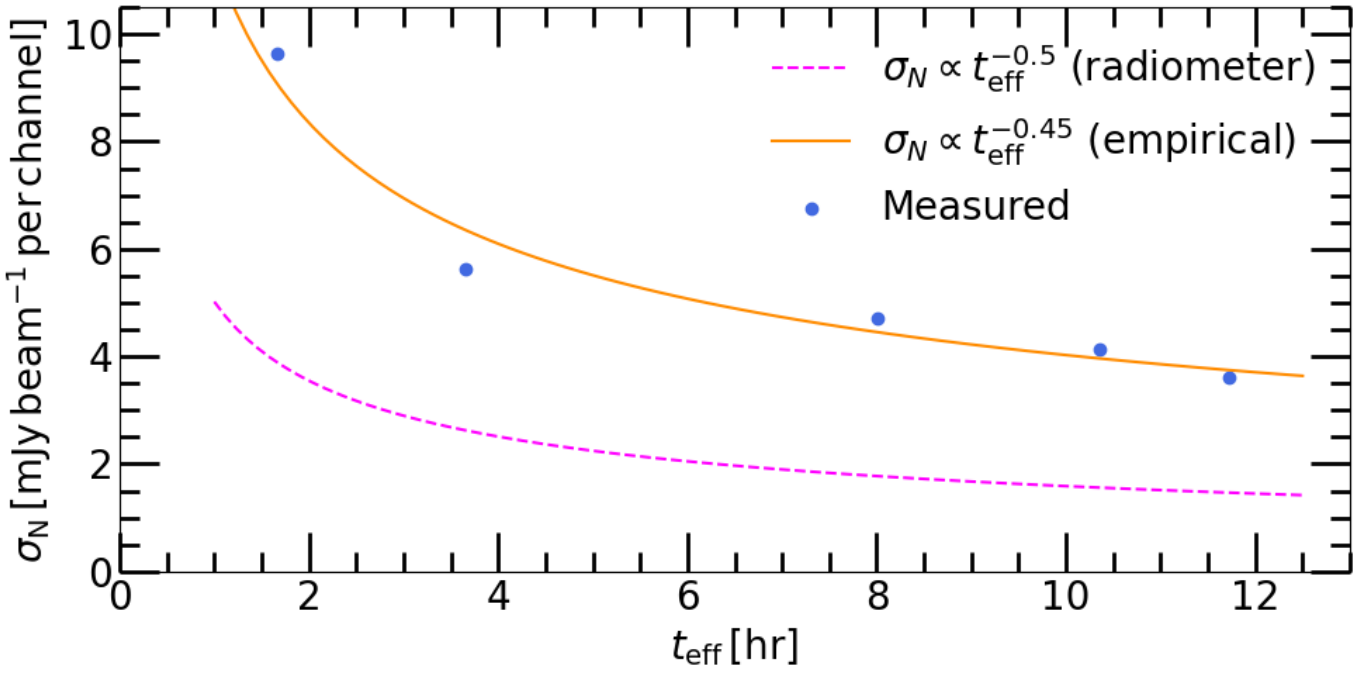




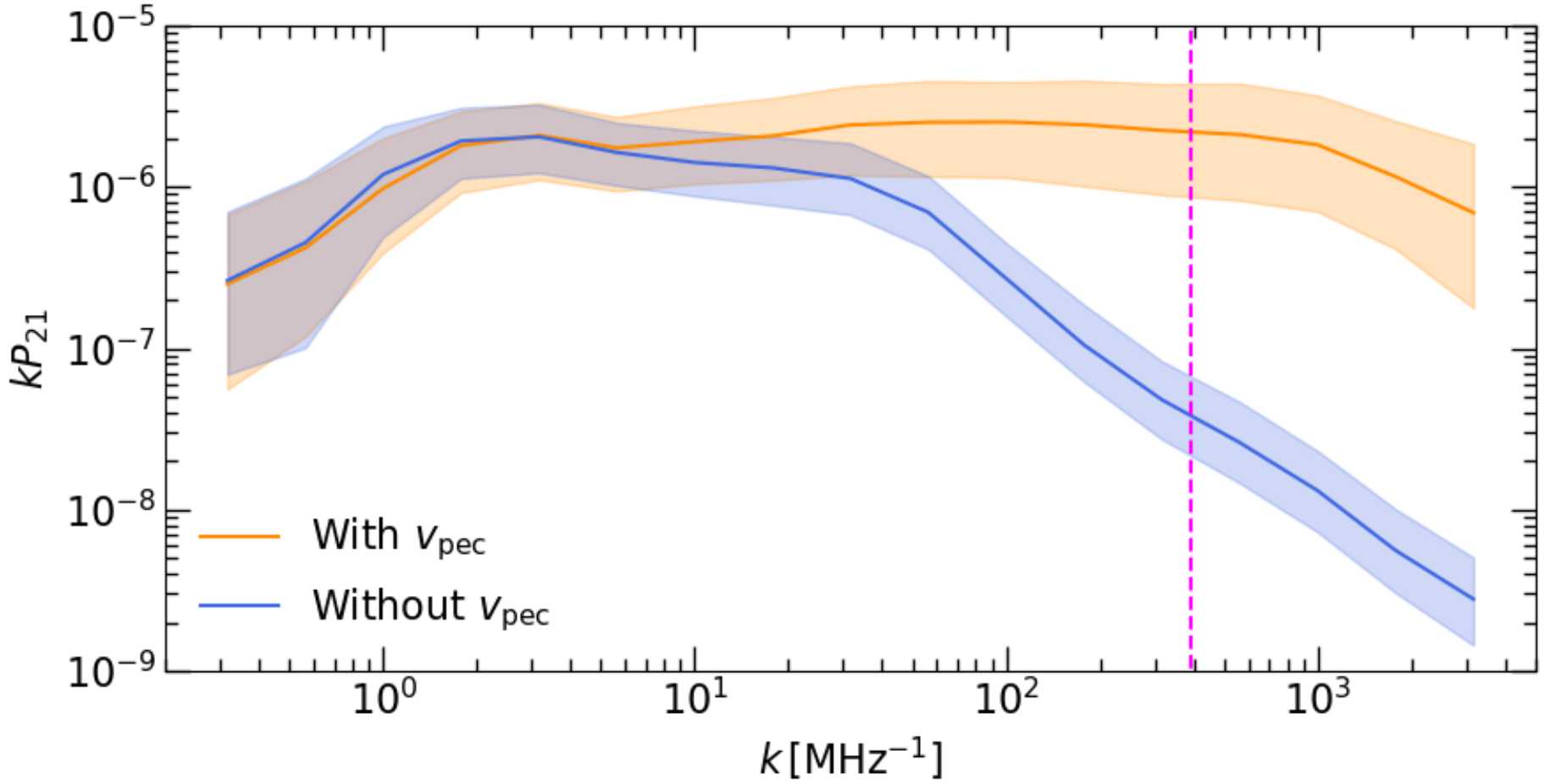
uGMRT observational data reduction

Empirical noise-level estimation

Std of 1000 randomly selected LOS close to the target



Effect of peculiar velocities

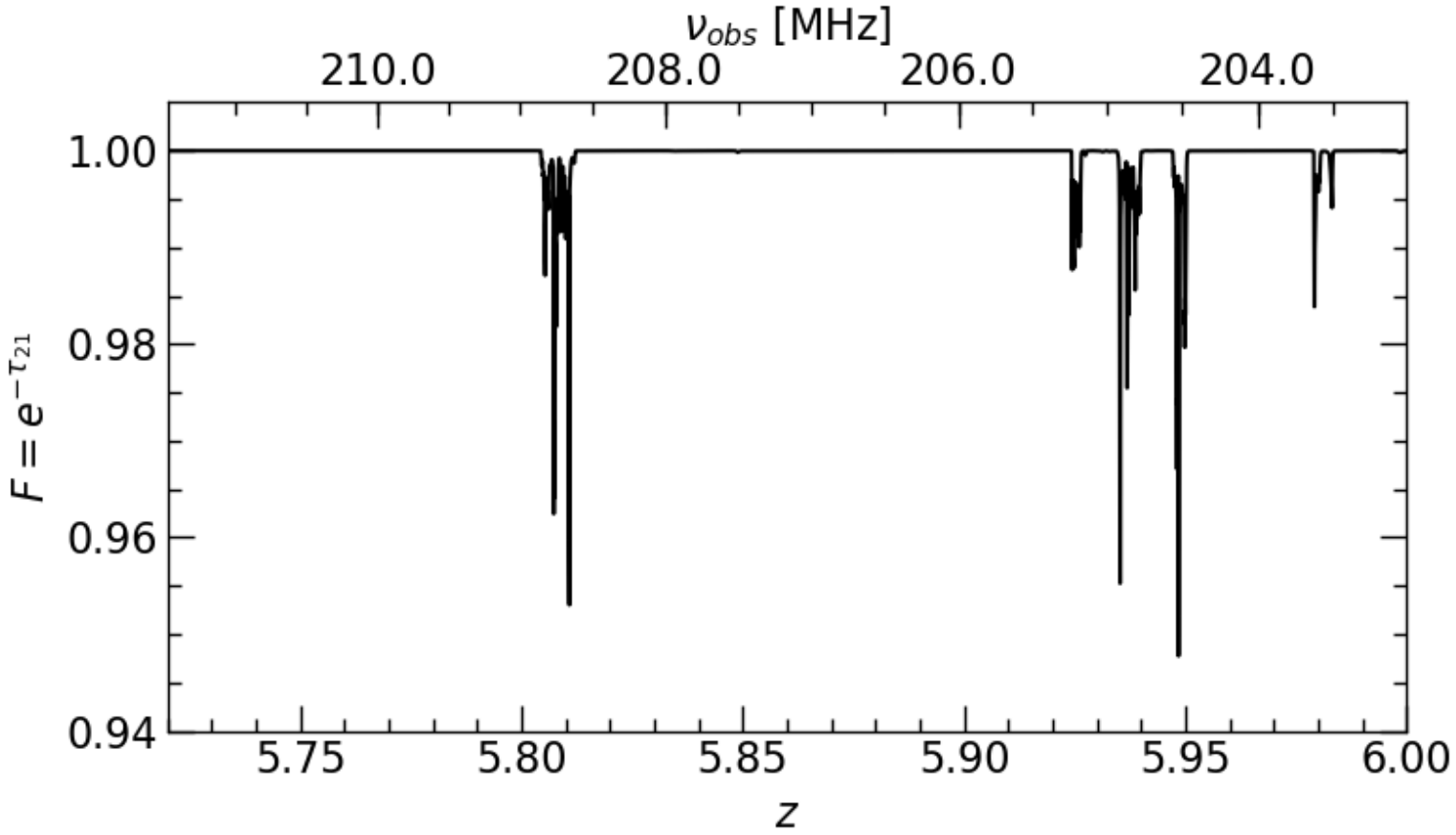


Šoltinský+2025

21-cm forest spectrum

$$\tau_{21,i} = \frac{3h_{\rm p}c^3A_{10}}{32\pi^{3/2}\nu_{21}^2k_{\rm B}}\frac{\delta v}{H(z)}\sum_{j=1}^{N}\frac{n_{{\rm HI},j}}{b_jT_{{\rm S},j}}\exp\left(-\frac{(v_{{\rm H},i}-u_j)^2}{b_j^2}\right)$$

z = 6



Šoltinský+2021

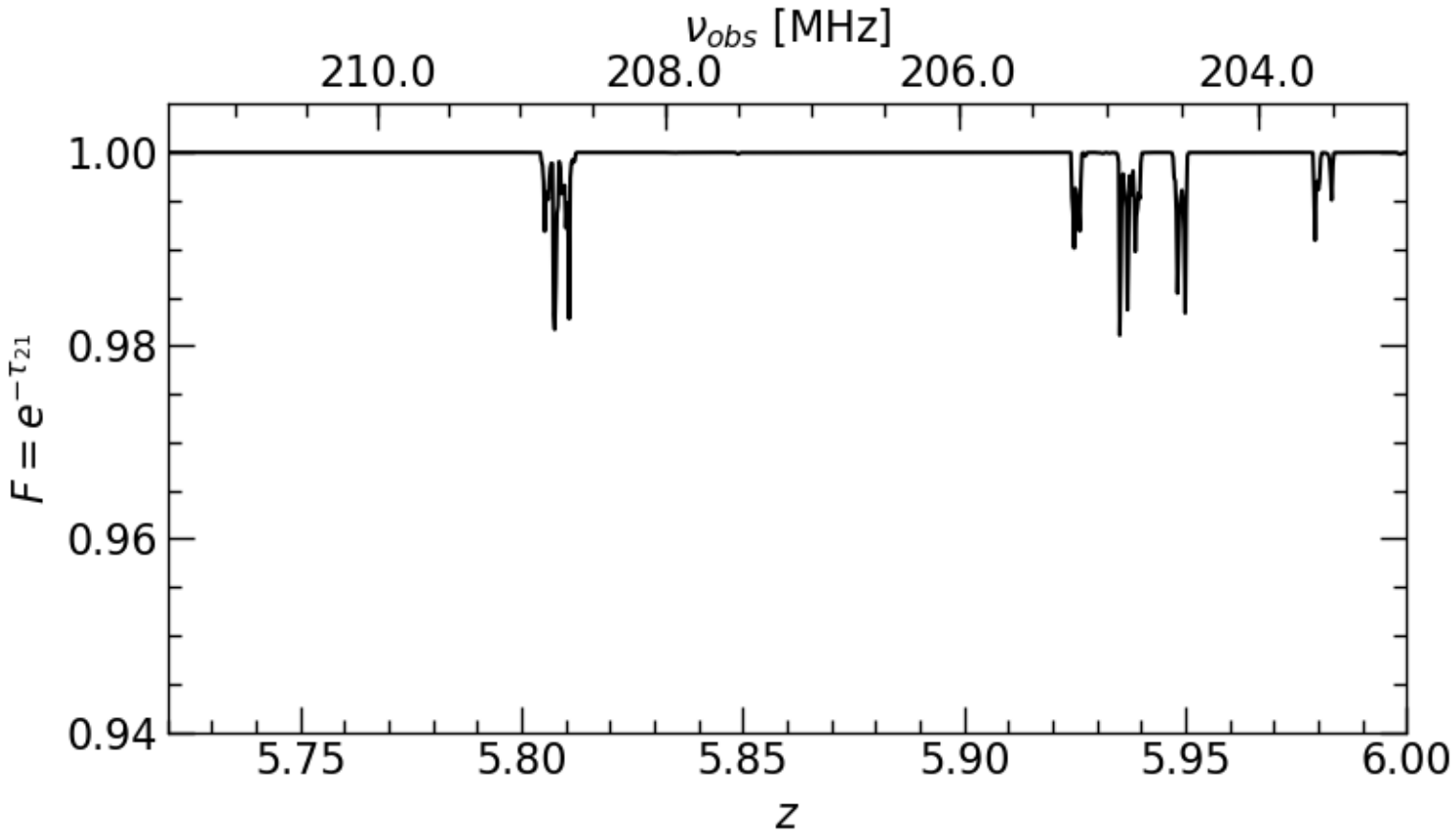
21-cm forest spectrum - Spectral resolution

z = 6

$\Delta\boldsymbol{\nu}$ = 8kHz

Convolution over fixed boxcar function

Reduces number of pixels



Šoltinský+2021

21-cm forest spectrum - Telescope noise

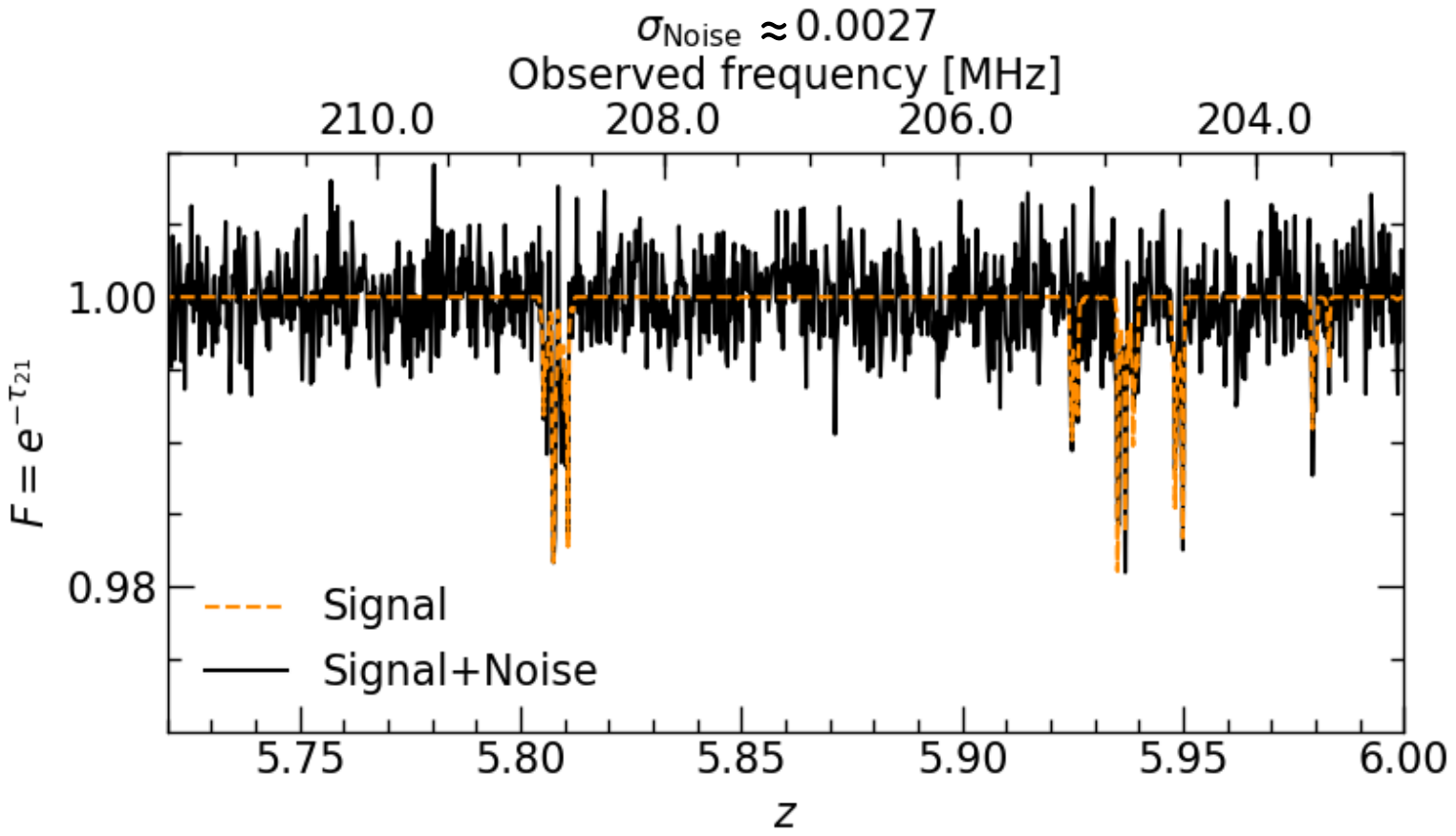
$$\sigma_{\mathrm{N}} = \frac{\sqrt{2} k_B T_{\mathrm{sys}}}{A_{\mathrm{eff}} \sqrt{N_{\mathrm{d}}(N_{\mathrm{d}} - 1)\Delta\nu t_{\mathrm{int}}}} \ \mathrm{mJy}$$

(Modified Datta+2007)

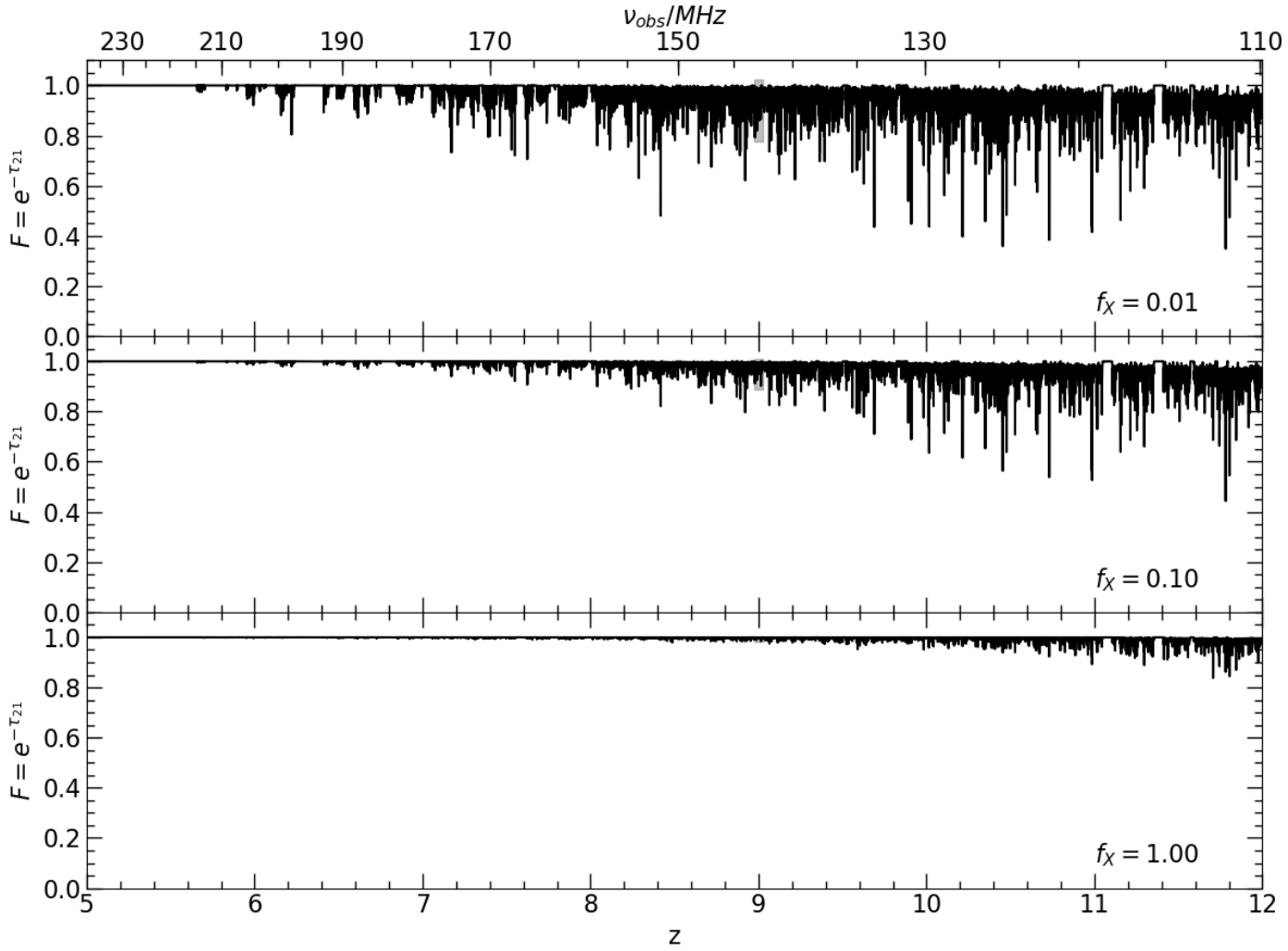
z = 6

Gaussian white noise

Included also intrinsic RLQSO radio spectrum as a single power law



X-ray background radiation suppresses the signal

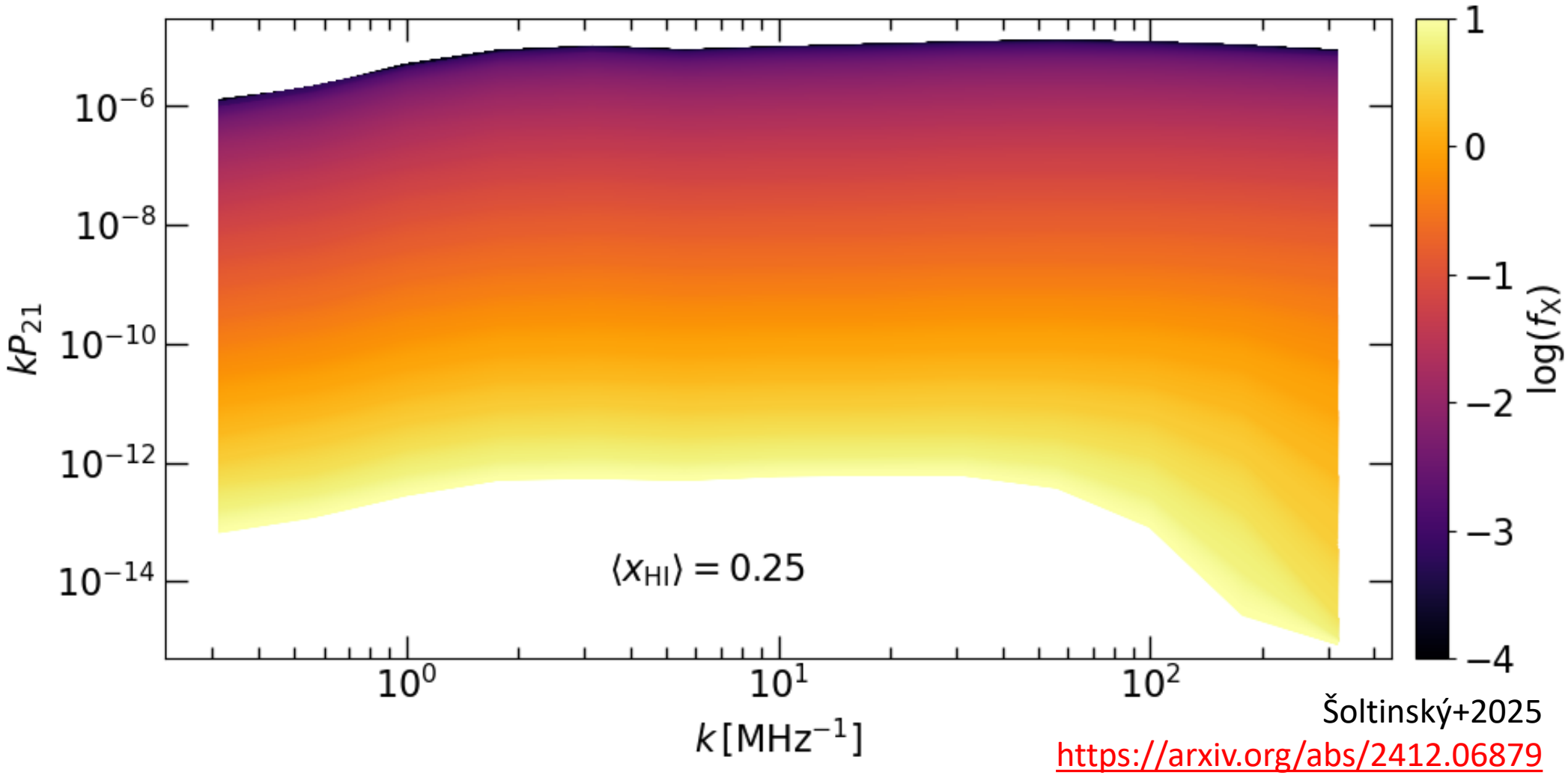


$$L_{\mathrm{X}} \propto f_{\mathrm{X}} \times SFR$$

(Furlanetto 2006)

Šoltinský+2021
https://arxiv.org/abs/2105.02250
(but see also Xu+2011,
Mack & Wyithe 2012)

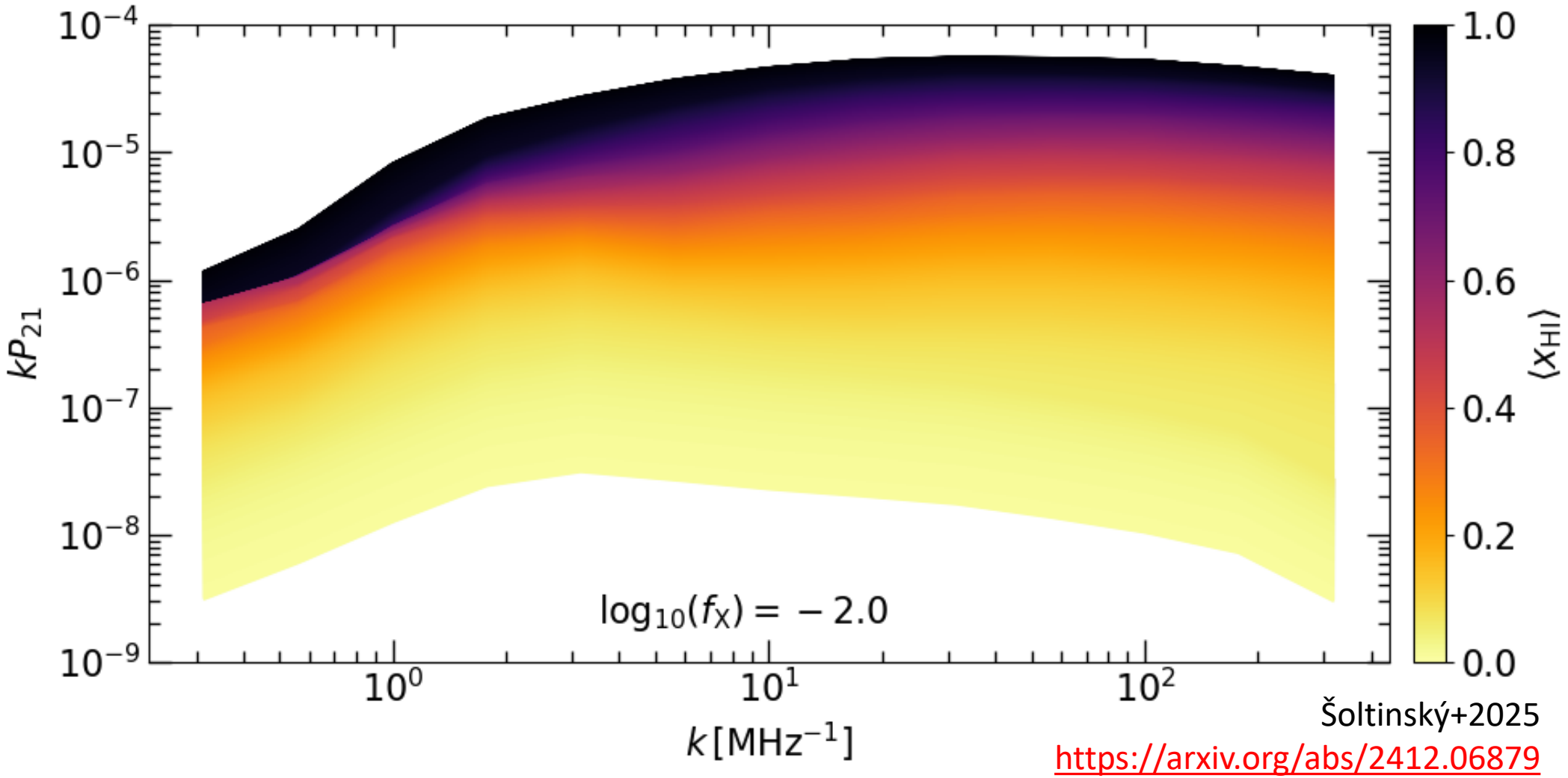
Sensitivity of P_{21} to X-ray background radiation



Šoltinský+2025

https://arxiv.org/abs/2412.06879

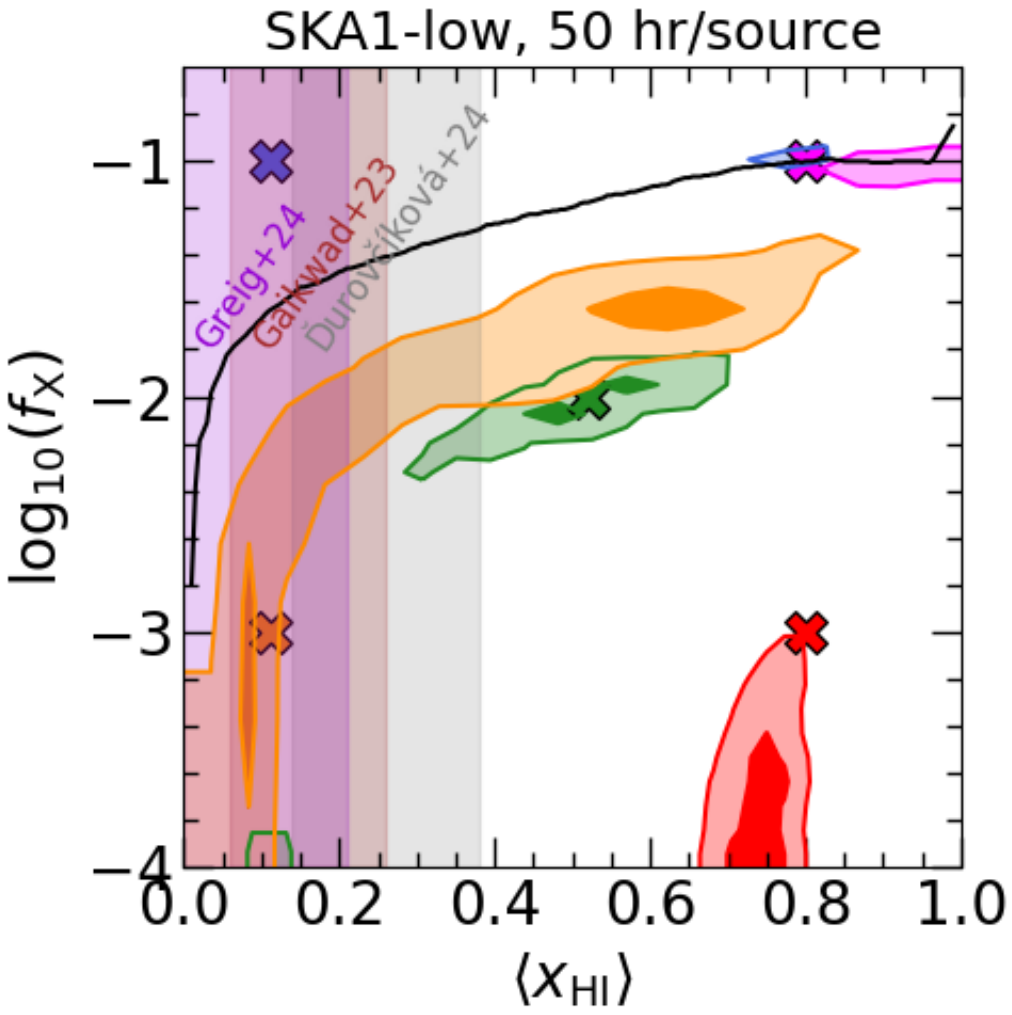
Sensitivity of P_{21} to HI fraction



Šoltinský+2025

https://arxiv.org/abs/2412.06879

Constrain thermal and ionization state of the IGM at the same time

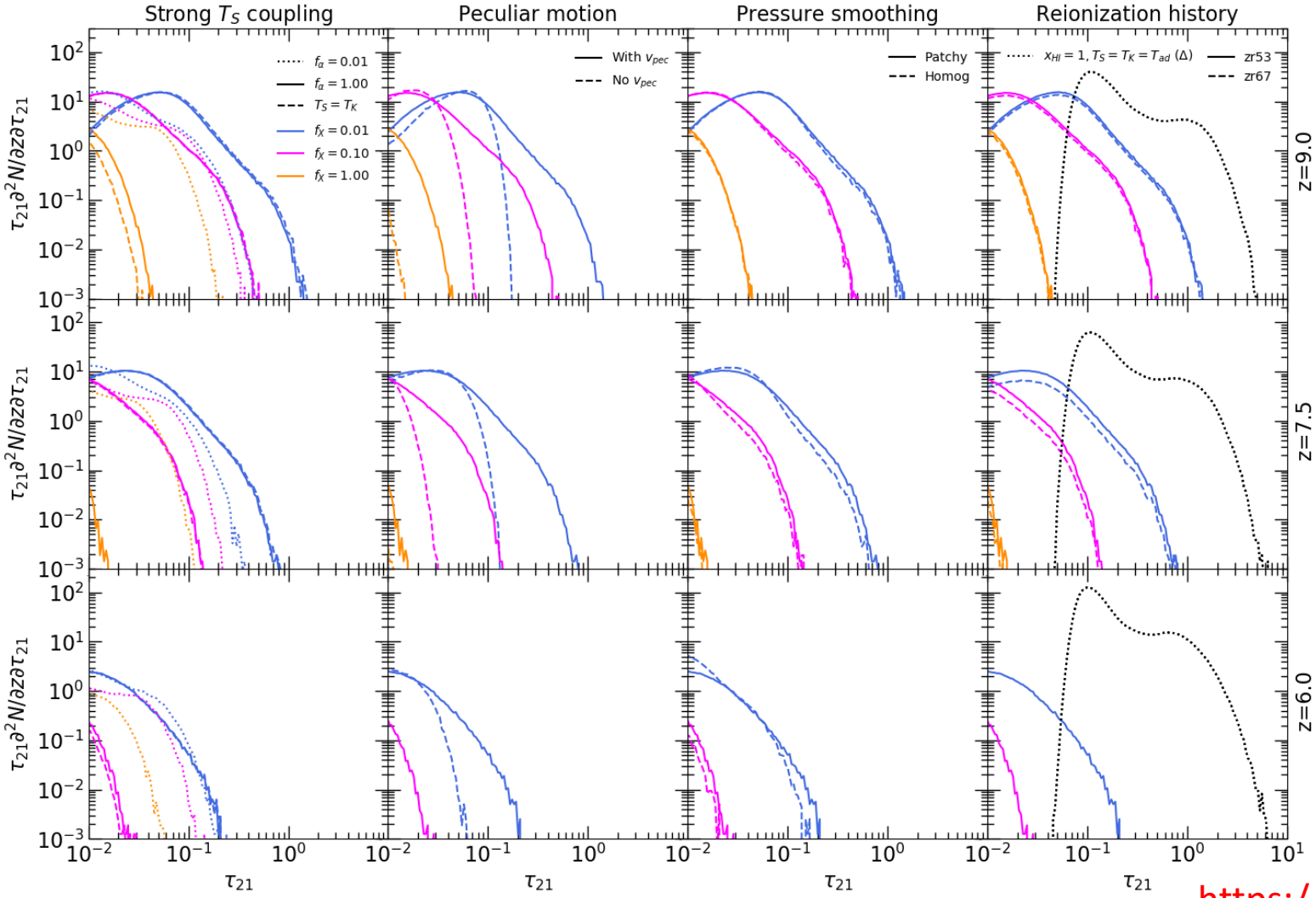


Observation of
10 spectra
of 200cMpc at z=6
Δν=22.1MHz

A null-detection disfavouring
these regions in parameter space

Šoltinský+2025
https://arxiv.org/abs/2412.06879

21-cm absorption lines distribution



Šoltinský+2021
https://arxiv.org/abs/2105.02250

Sherwood-relics simulation suite

Hydrodynamics + Radiative transfer

Base P-GADGET-3 grid

⬇

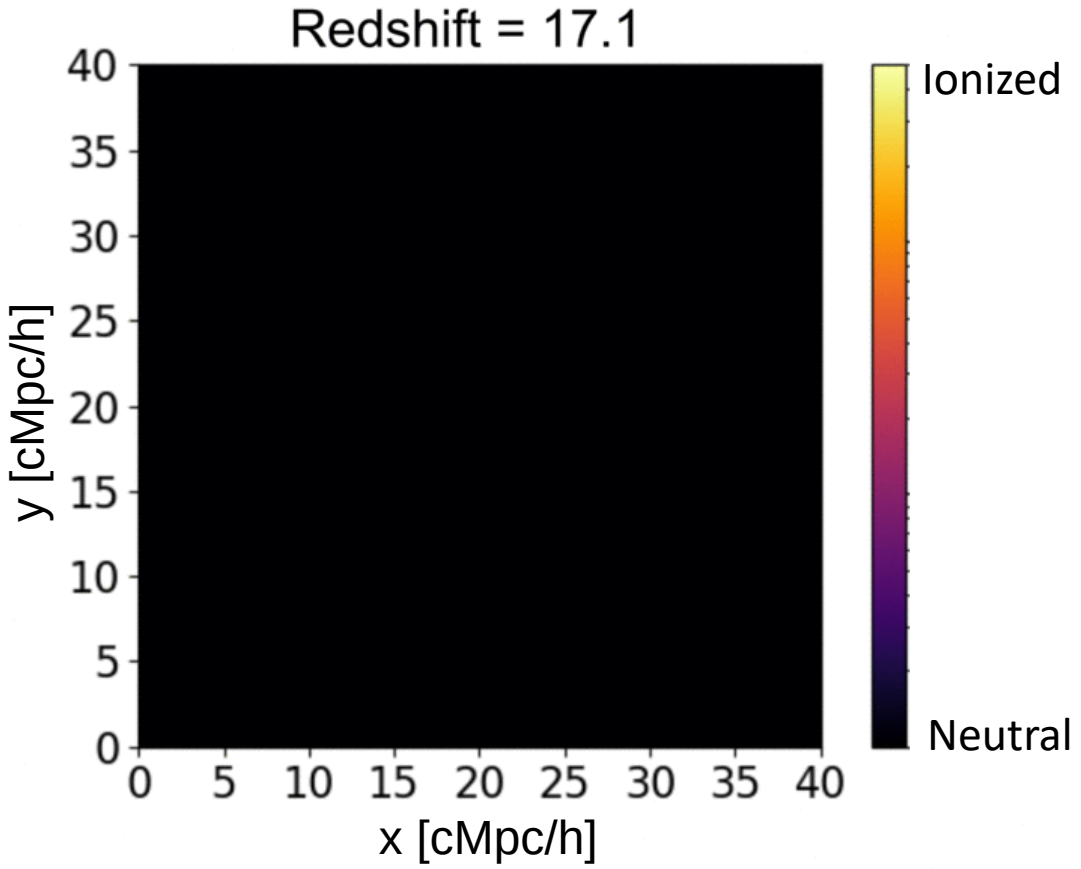
Run ATON
Obtain photo-ionization maps

⬇

Re-run P-GADGET-3

⬇

HD response to the reionization
Calibrate to observational data

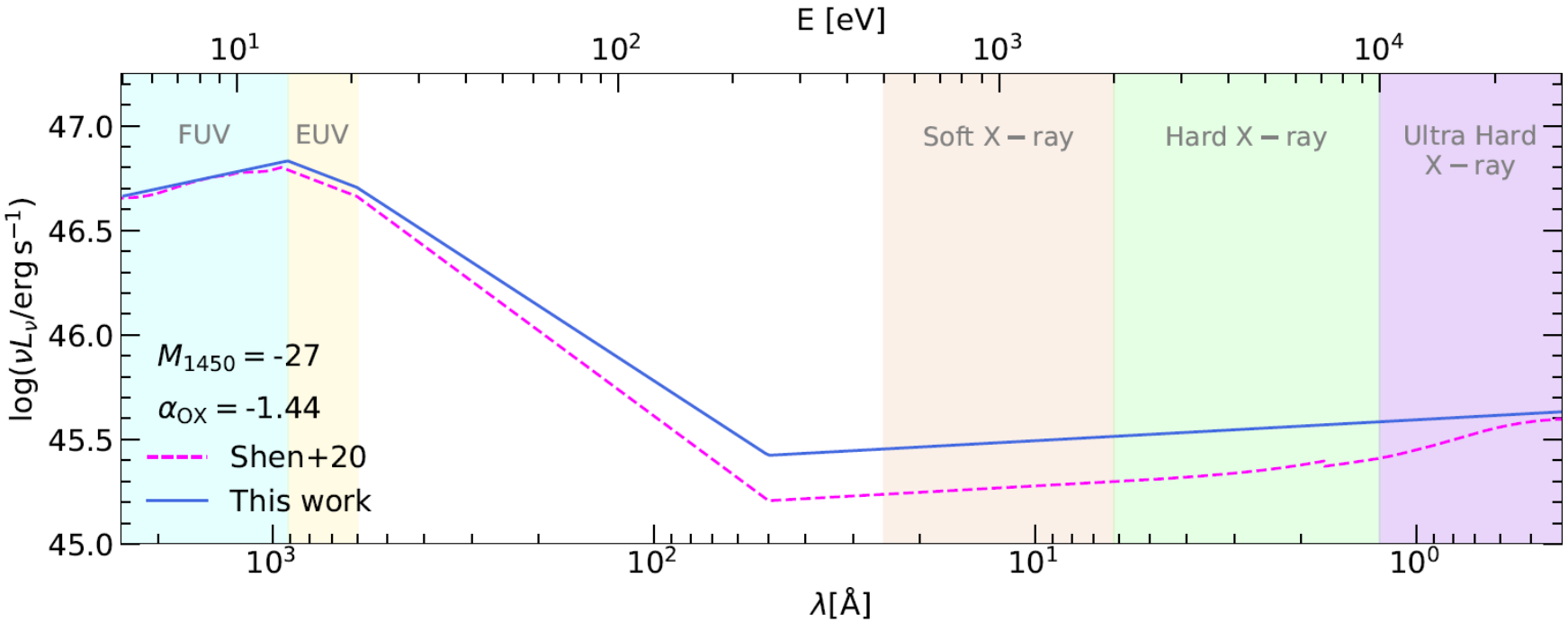


1DRT for quasar radiation

Sherwood-relics – 40cMpc/h, 2048, z_r=5.3

The effect of quasar radiation on the 21-cm forest

1D multifrequency radiative transfer (Bolton & Haehnelt 2007)



Šoltinský+2023

https://arxiv.org/abs/2211.07655

Lyα and 21-cm forest in quasar near zone

Turn on the quasar for 10Myr - 1D multifrequency RT (Bolton & Haehnelt 2007)

Without quasar - IGM+reionization models from Sherwood-relics simulations (Puchwein+2023)

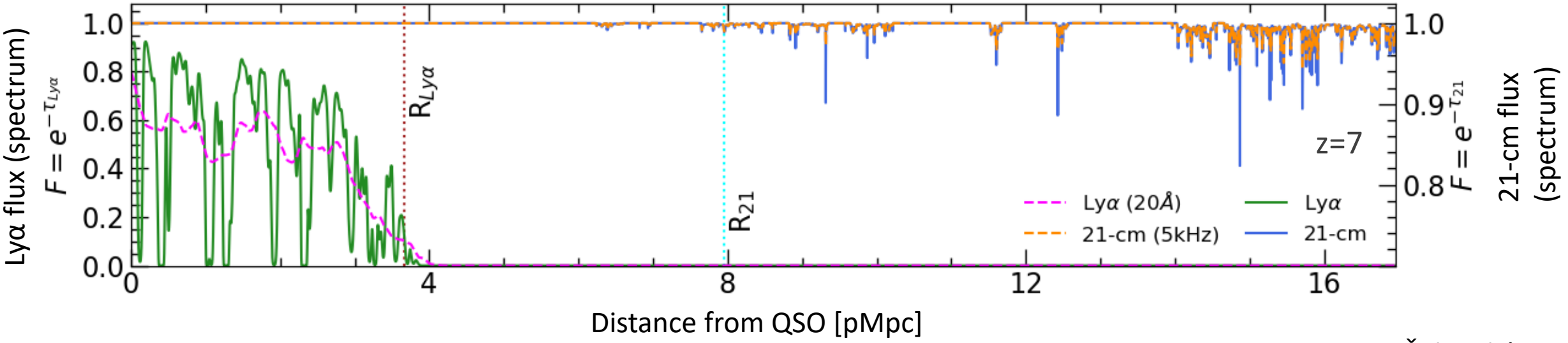
Smooth Lyα forest spectrum with boxcar of width 20Å (Fan+2006)

Smooth 21-cm forest spectrum with boxcar of width 5kHz

https://www.nottingham.ac.uk/astronomy/sherwood-relics/

Lyα near-zone size where smoothed spectrum falls below 10%

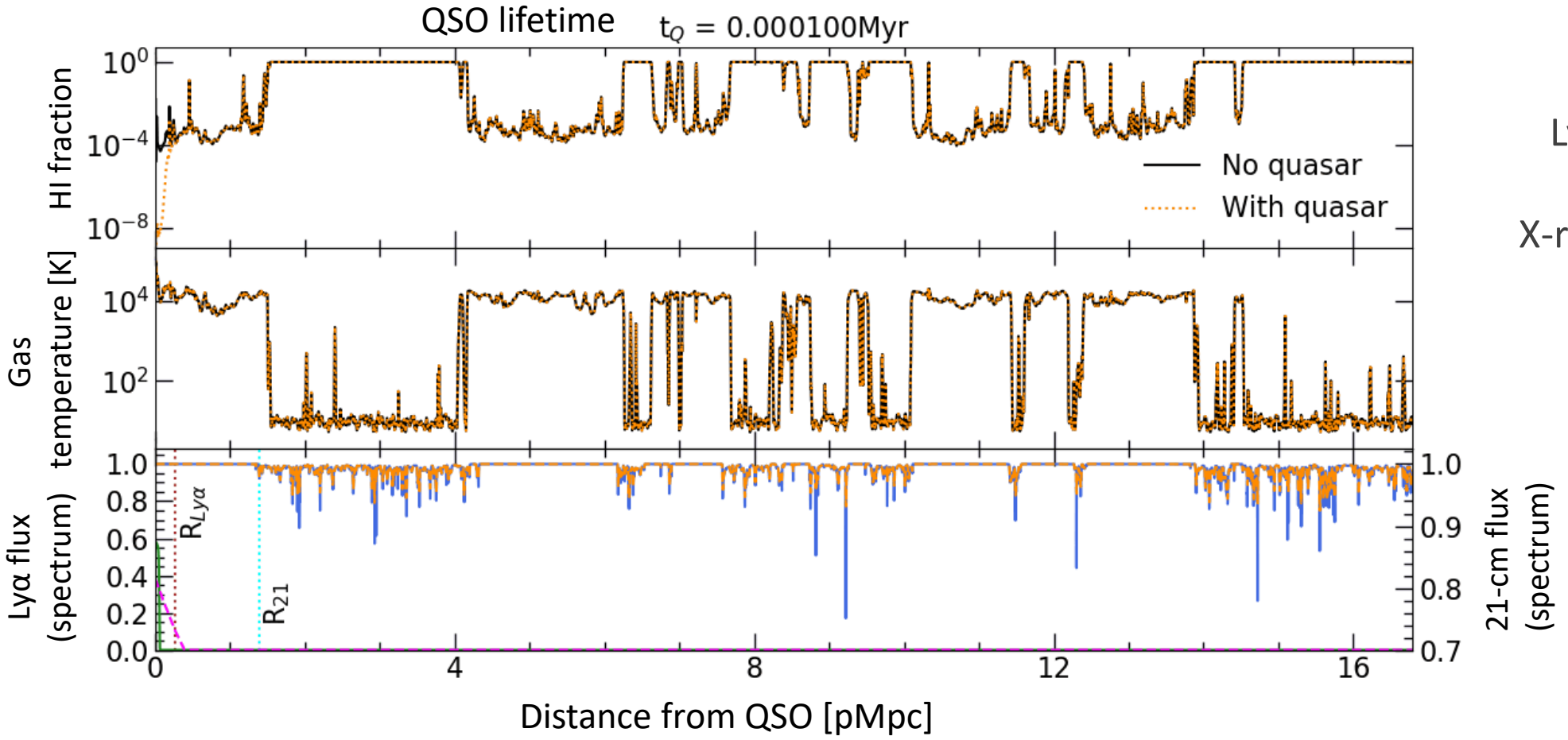
21-cm near-zone size where smoothed spectrum falls below 99%



Šoltinský+2023

https://arxiv.org/abs/2211.07655

Lyα and 21-cm forest in quasar near zone



UV ➡ Ionises surrounding gas

⬇

Lyα forest observable

X-rays ➡ Heat up the gas

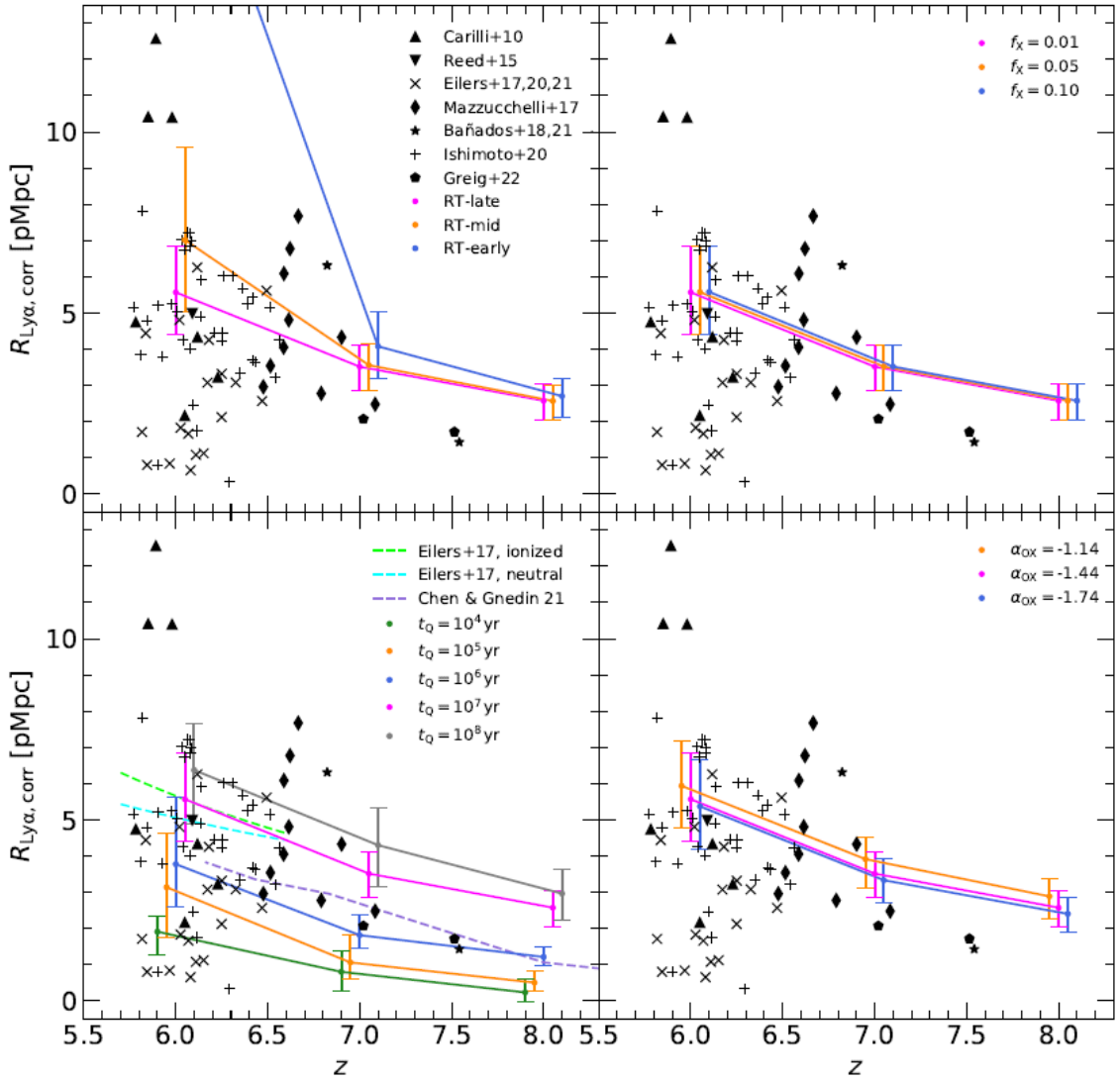
⬇

21-cm forest suppressed at larger distances

Šoltinský+2023

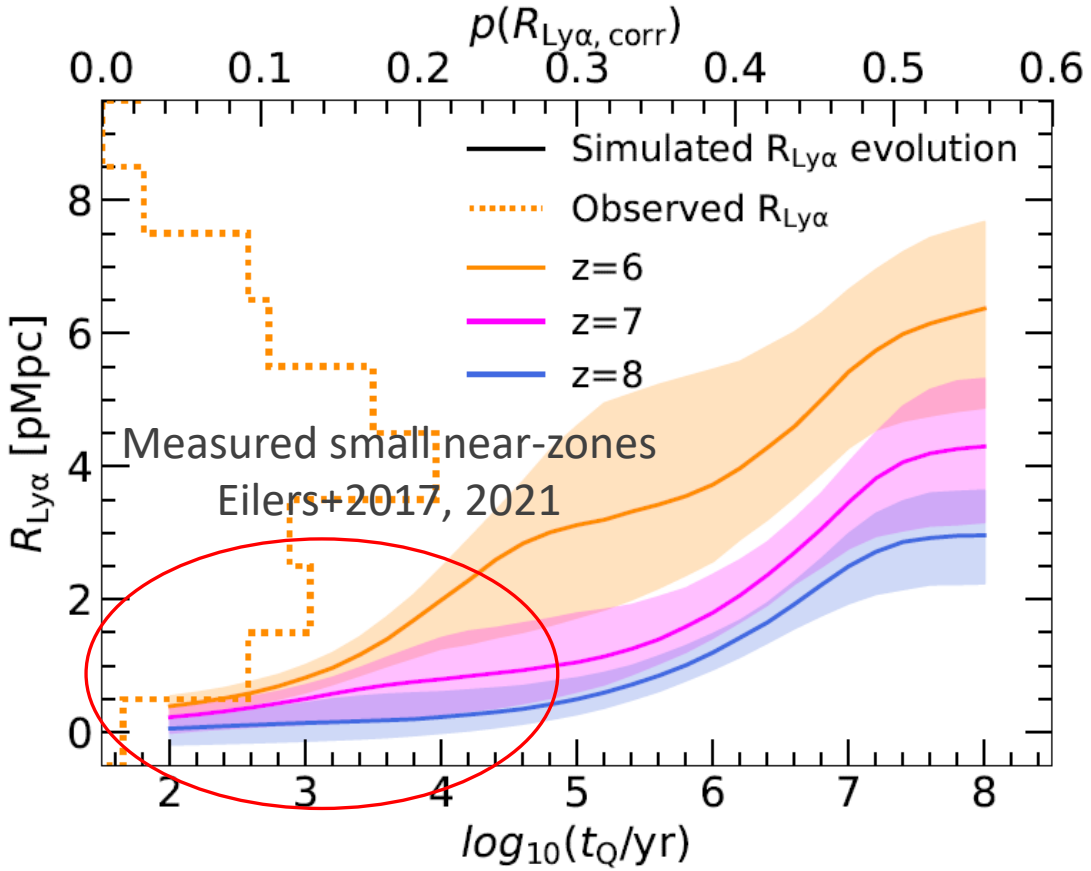
https://arxiv.org/abs/2211.07655

Lyα forest simulated vs observed

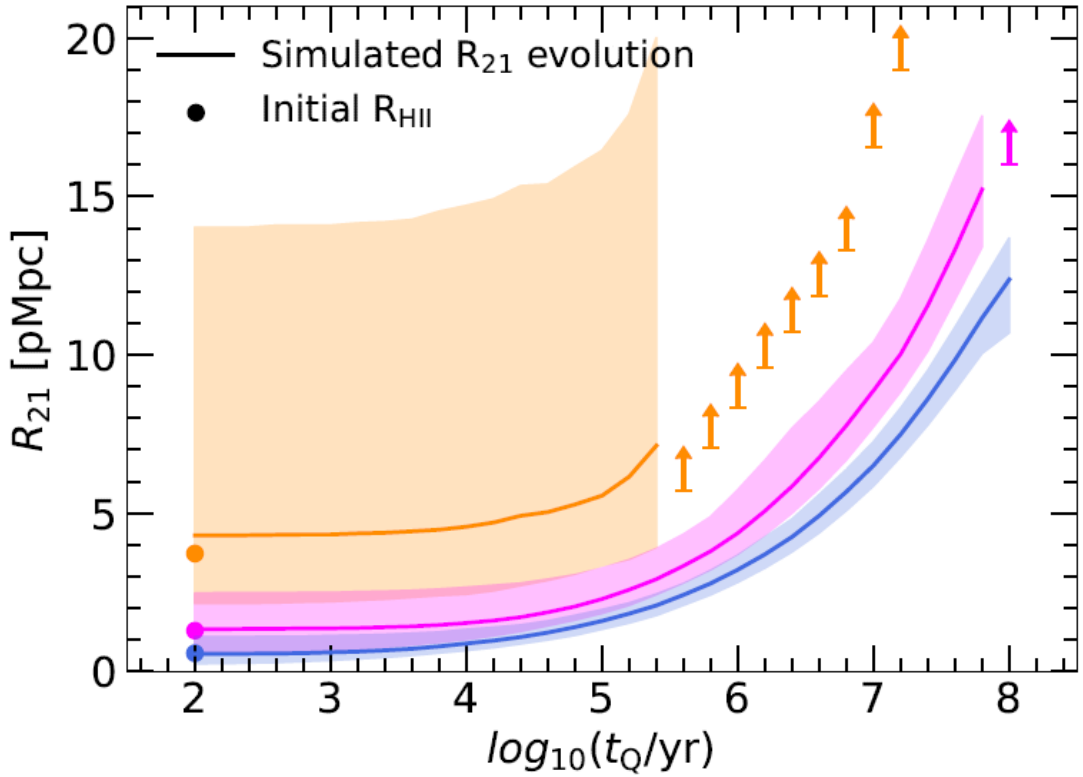


Šoltinský+2023
https://arxiv.org/abs/2211.07655

Time evolution



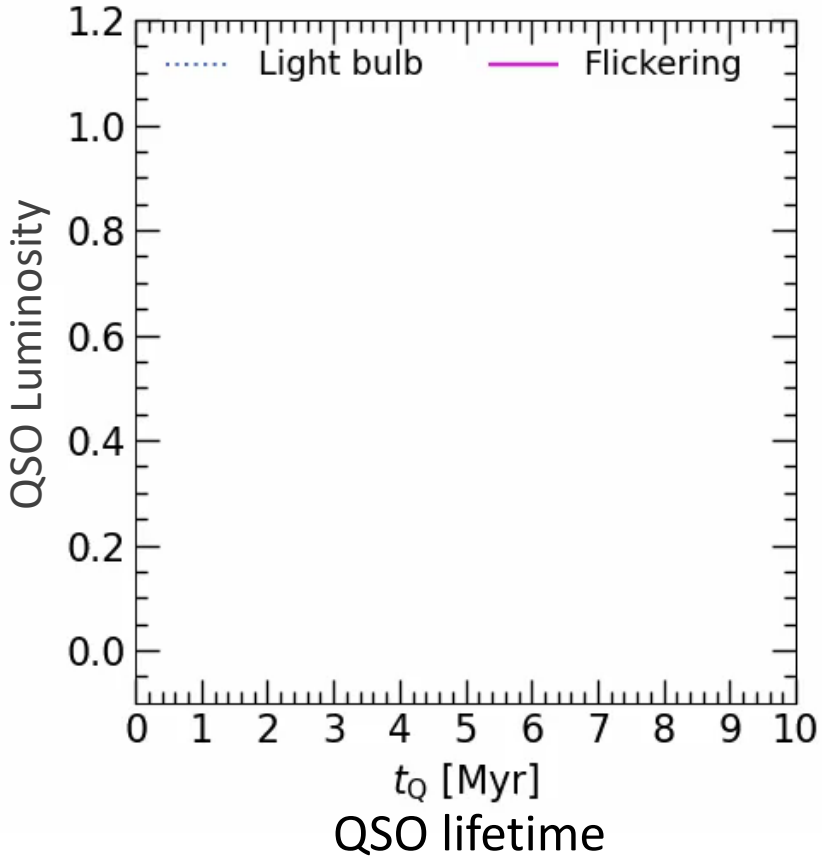
QSO lifetime



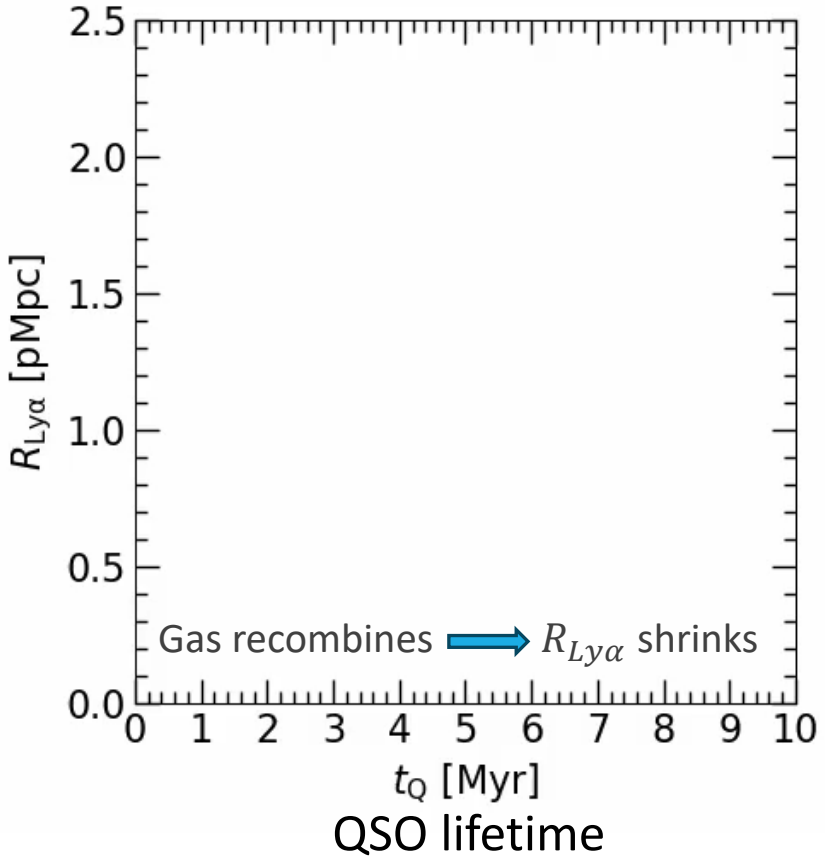
QSO lifetime

Šoltinský+2023
https://arxiv.org/abs/2211.07655

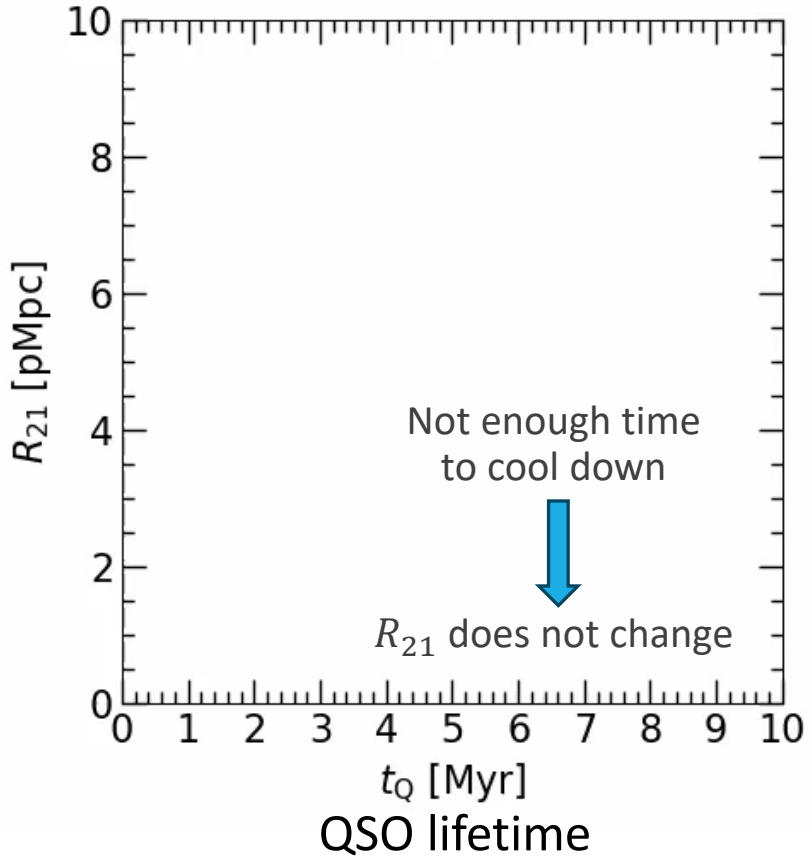
Flickering quasar



QSO lifetime



QSO lifetime

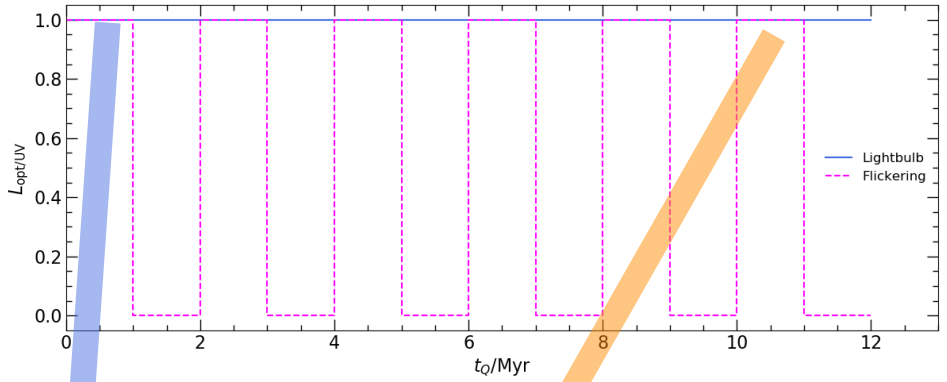


QSO lifetime

Šoltinský+2023 https://arxiv.org/abs/2211.07655
See also Davies+2020,
Satyavolu+2023, Zhou+2024

R_{21} sensitive to the integrated lifetime of the quasar

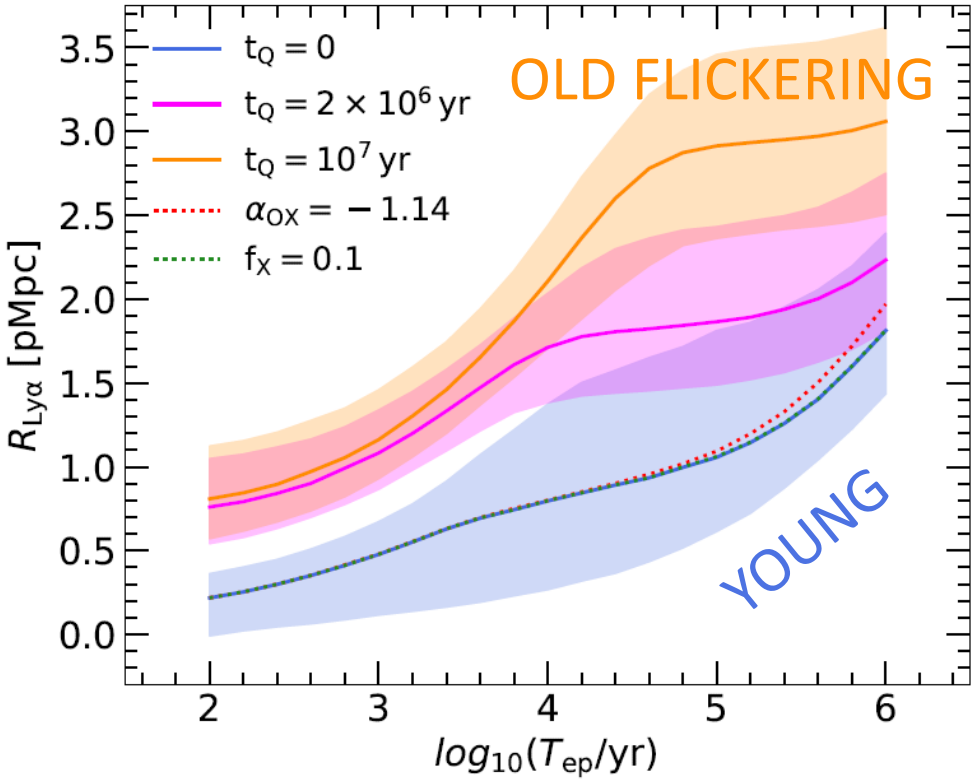
Young vs old flickering quasar

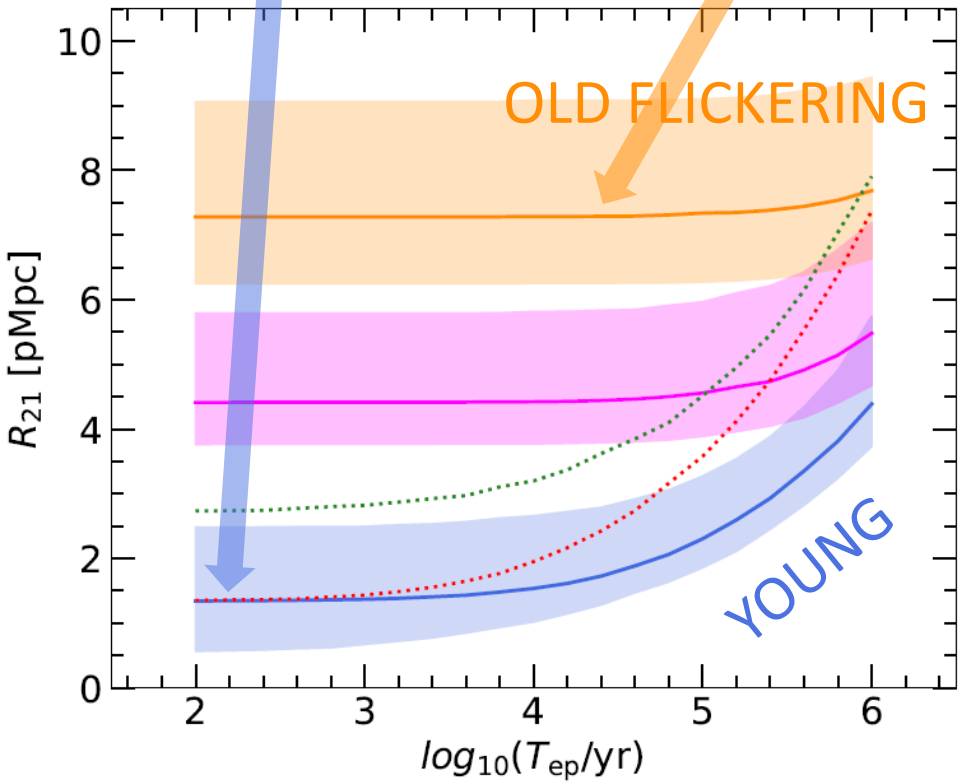


Can reproduce small $R_{Ly\alpha}$ in both cases

21-cm forest might discern between these cases

z=7





Šoltinský+2023

https://arxiv.org/abs/2211.07655

Current episodic time

Current episodic time