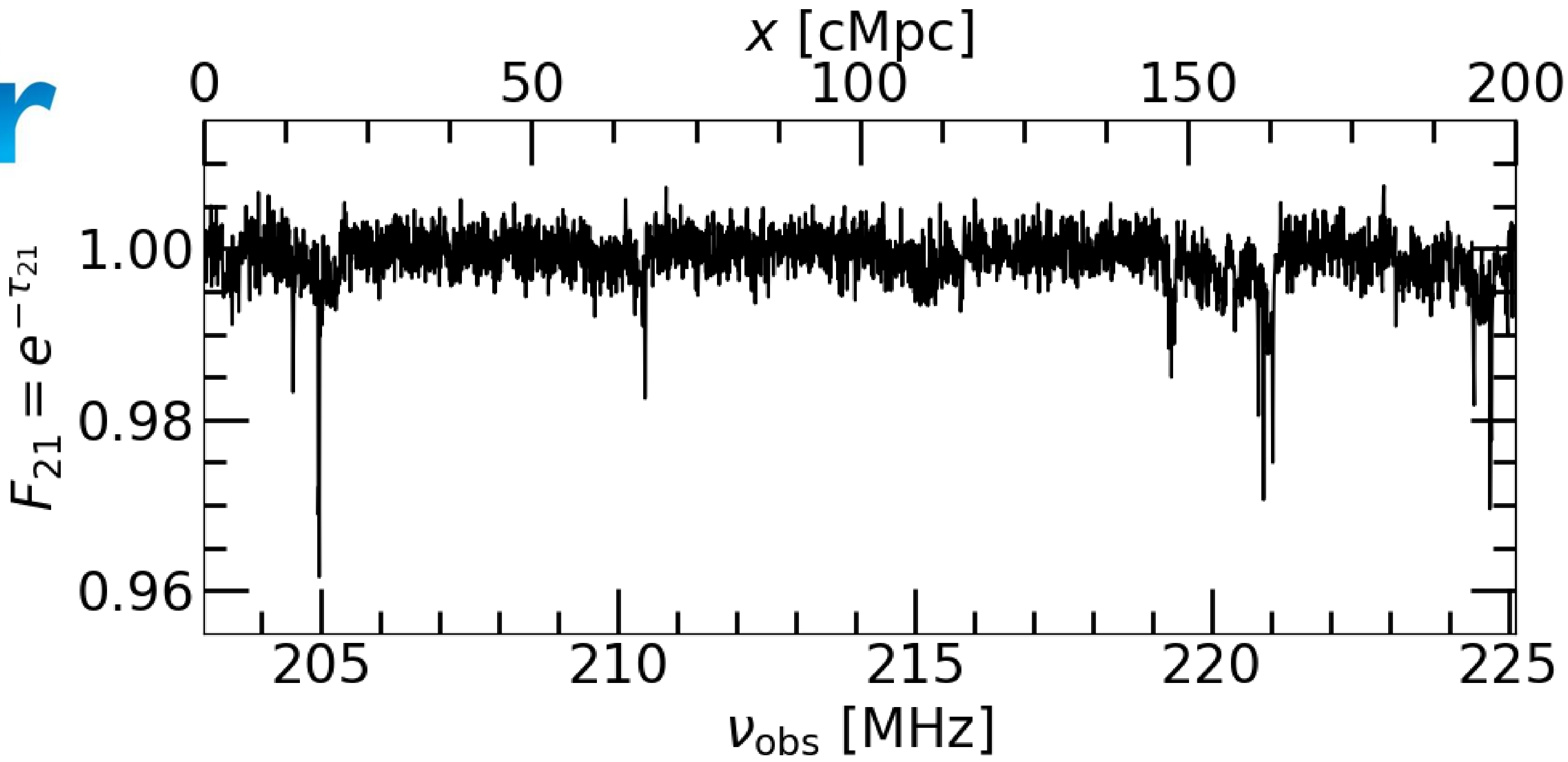
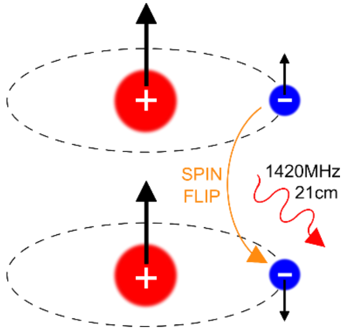


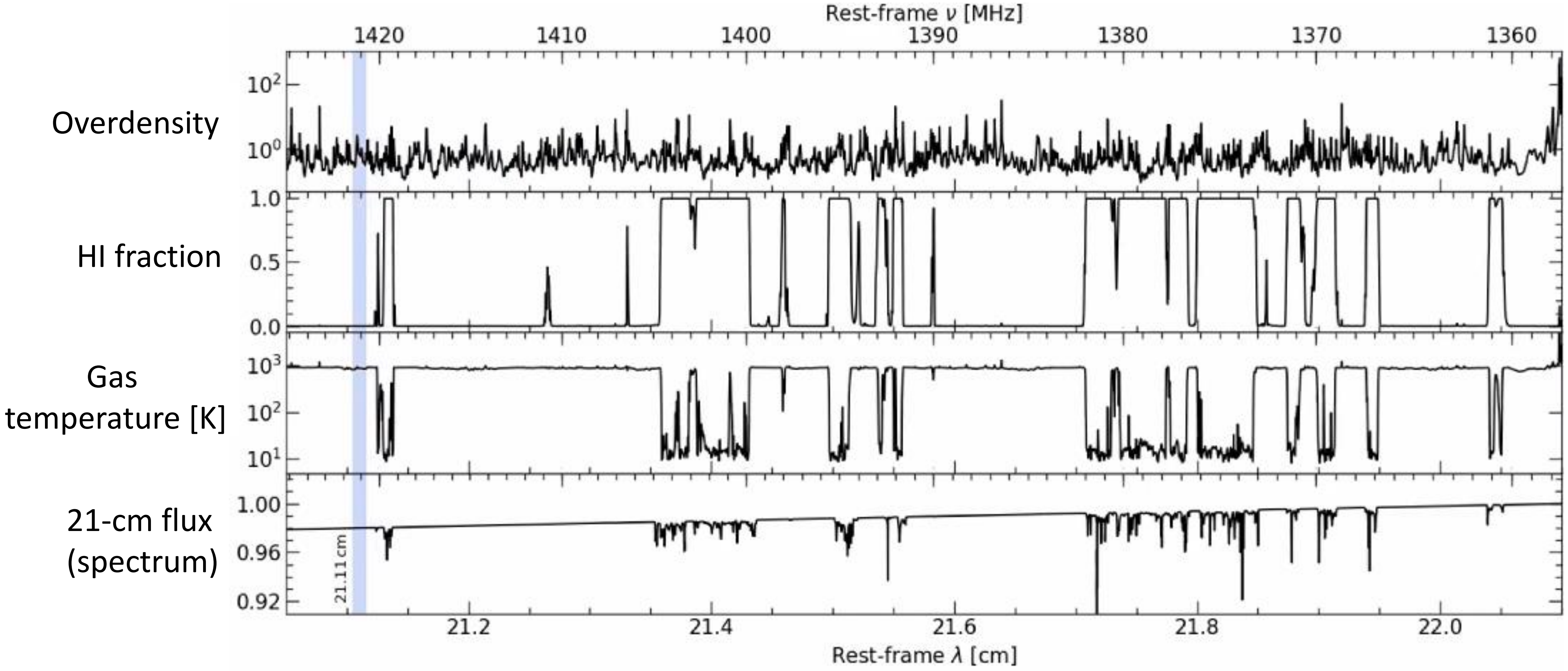
Prospects of a statistical detection of the 21-cm forest and its potential to constrain the cosmic heating and reionization history

TOMÁŠ ŠOLTINSKÝ, GIRISH KULKARNI, SHRIHARSH TENDULKAR, JAMES BOLTON

What is 21-cm forest?

21-cm forest


SPIN
FLIP
1420MHz
21cm


Overdensity
HI fraction
Gas temperature [K]
21-cm flux (spectrum)
Rest-frame ν [MHz]
1420
1410
1400
1390
1380
1370
1360
10^2
10^0
1.0
0.5
0.0
10^3
10^2
10^1
1.00
0.96
0.92
21.11 cm
21.2
21.4
21.6
21.8
22.0
Rest-frame λ [cm]

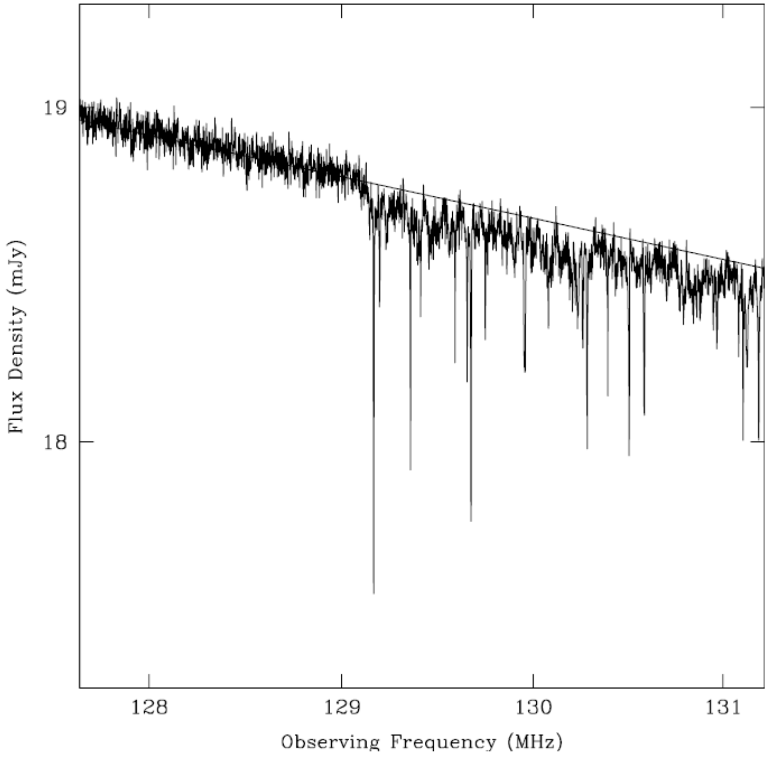
21-cm forest - complementary

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 neutral, dense and cold hydrogen
- z>6



Carilli et al. 2002
(Simulated spectrum)

21-cm forest - what can it probe?

Astroparticle – nature of dark matter (Shimabukuro et al. 2014, 2020, Shao et al. 2023)

– neutrino mass (Shimabukuro et al. 2014)

– primordial black holes (Villanueva-Domingo et al. 2021)

Structures – minihalos (Furlanetto et al. 2006, Meiksin 2011, Kadota et al. 2022)

Supermassive black hole growth models – quasar lifetimes (Šoltinský et al. 2023)

State of the IGM – ionization and thermal (Xu et al. 2011, Ciardi et al. 2013, Šoltinský et al. 2021)

Why now?

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

Reionization ends late

Motivated by Lyα observations

(Becker et al. 2015, Eilers et al. 2018)

↓

Seem to require reionization completed by z<5.5

(Kulkarni et al. 2019, Keating et al. 2020, Bosman et al. 2022, Zhu et al. 2023)

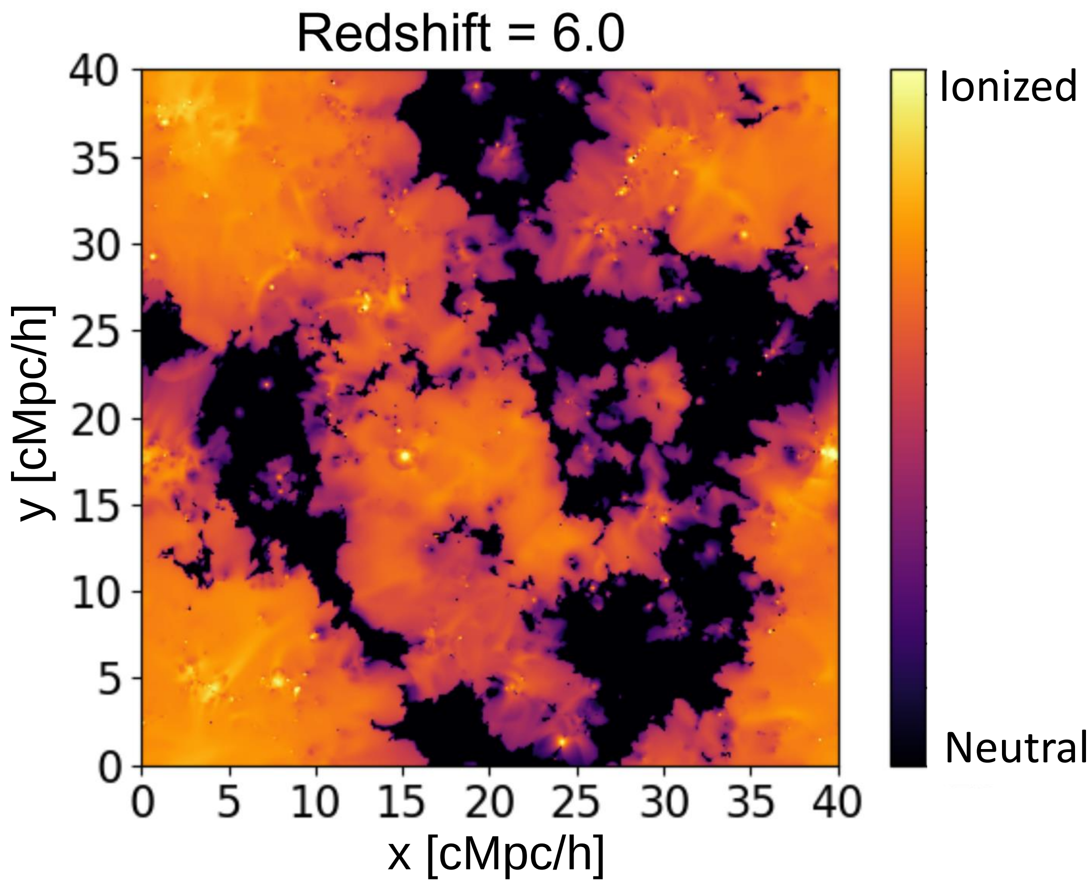
↓

Large islands of HI persist until z≈6

↓

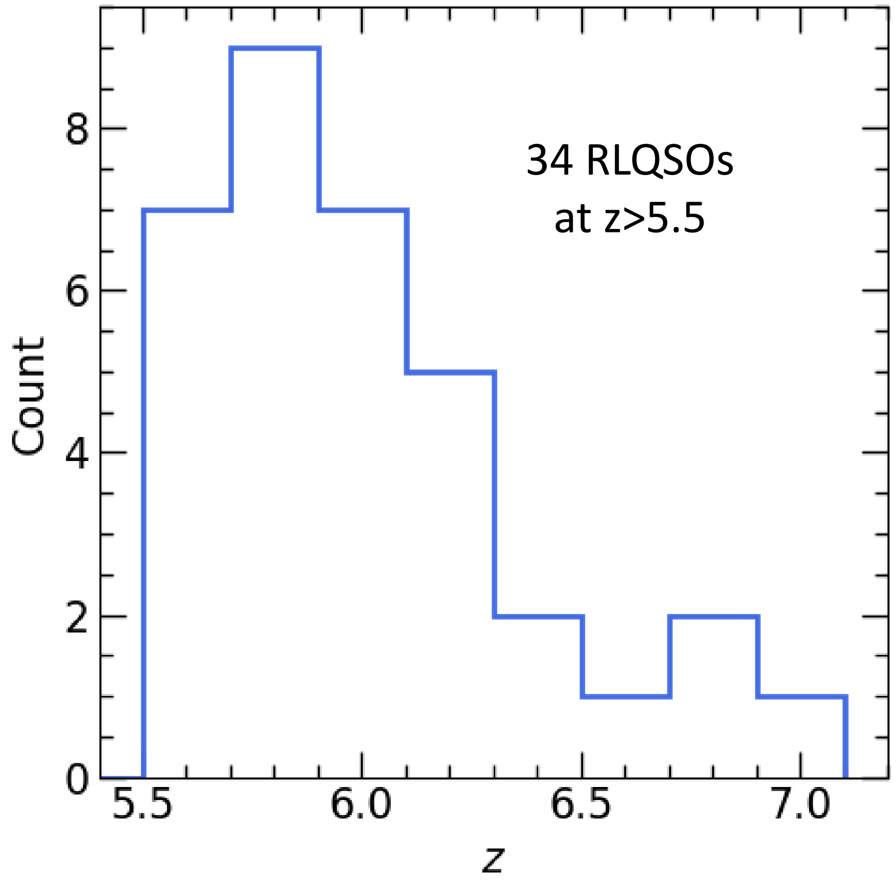
Possibility of detecting 21-cm forest

(Šoltinský et al. 2021)



New high-z radio-loud quasars detected

Šoltinský et al. in prep.

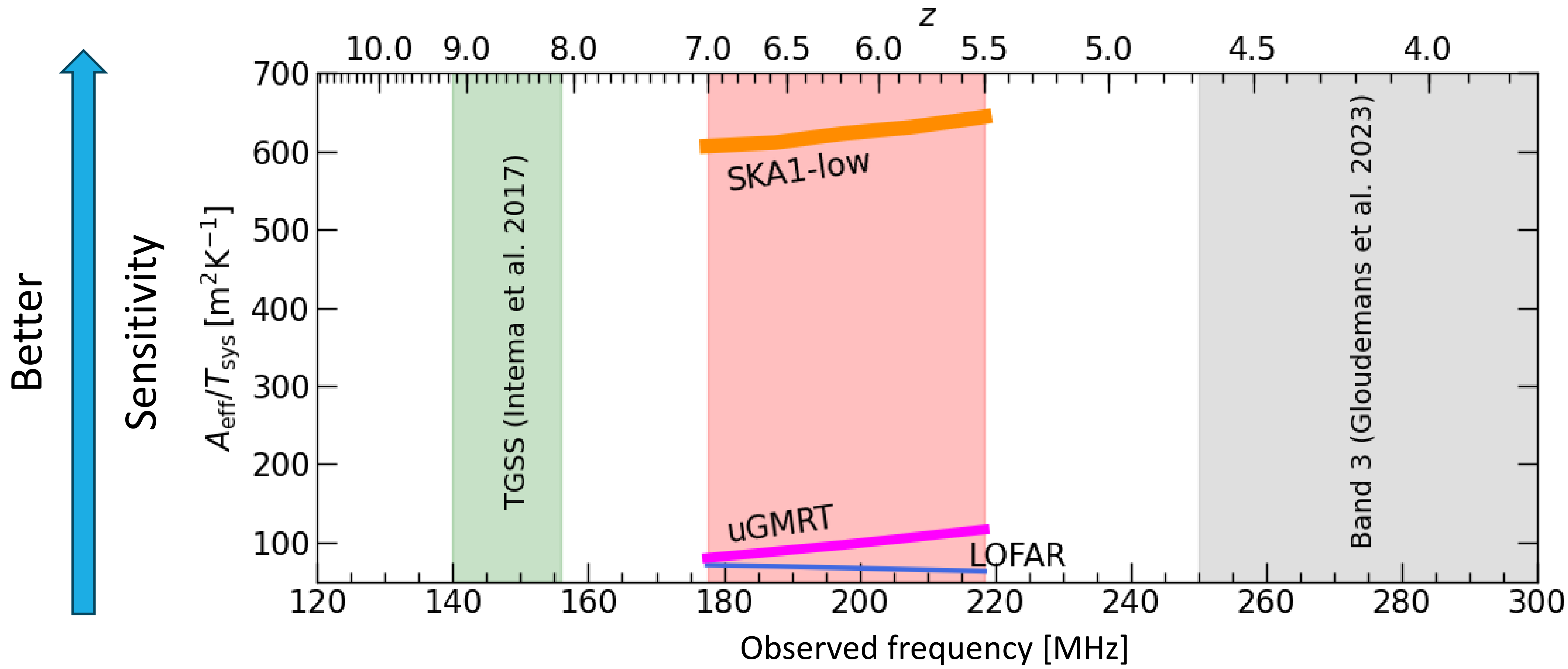


Wolf et al. 2024
Bañados et al. 2015,2018,2021,2023,2024
Ighina et al. 2021,2023,2024
Endsley et al. 2023
Gloudemans et al. 2022,2023
Shao et al. 2022
Connor et al. 2021
Liu et al. 2021
Belladitta et al. 2020
Frey et al. 2011
Zeimann et al. 2011
Willot et al. 2010
Jiang et al. 2009
McGreer et al. 2006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

WEAVE-LOFAR

spectroscopic z
(Smith et al. 2016)

Instrumentation improving and looking forward to SKA



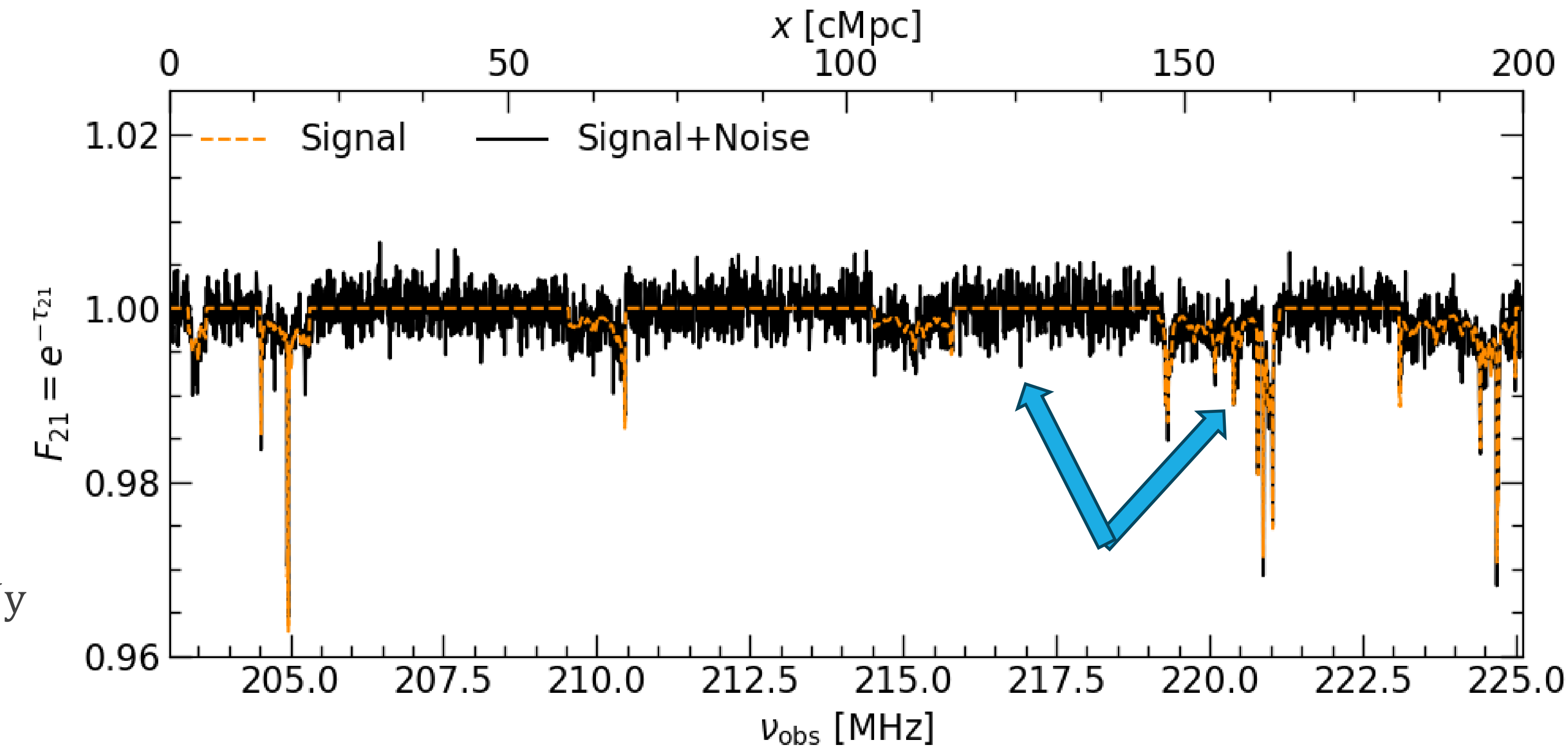
Braun et al. 2019

How?

21-cm forest spectrum

$z = 6$
21cmFAST

SKA1-low
AA4
$d\nu = 8\text{kHz}$
$t_{\text{int}} = 50\text{hr}$
$S_{147} = 64.2\text{mJy}$
$\alpha_R = -0.44$

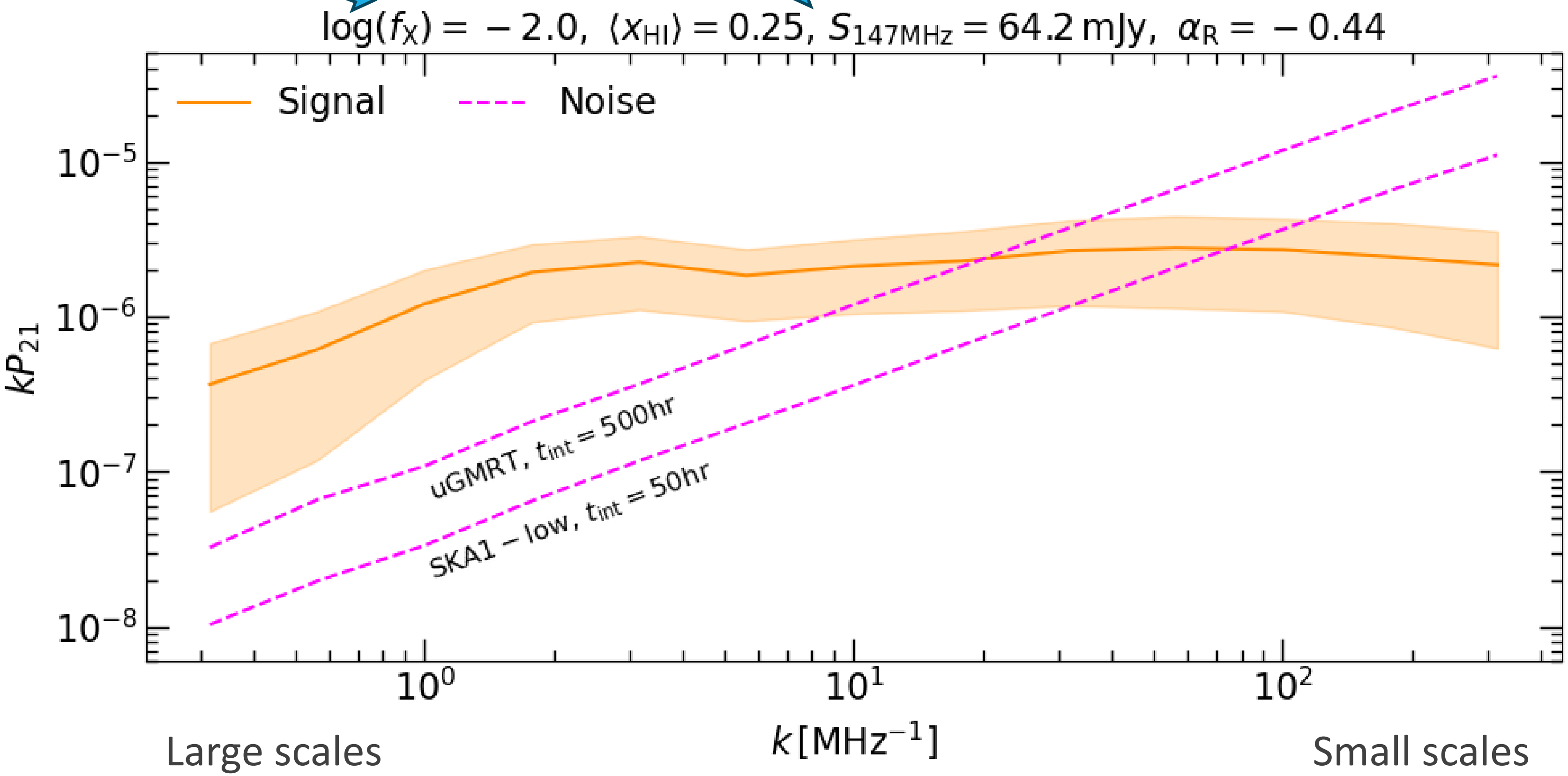


Šoltinský et al. in prep.

21-cm forest power spectrum

Thermal state of the IGM

Ionization state of the IGM



Large scales

Small scales

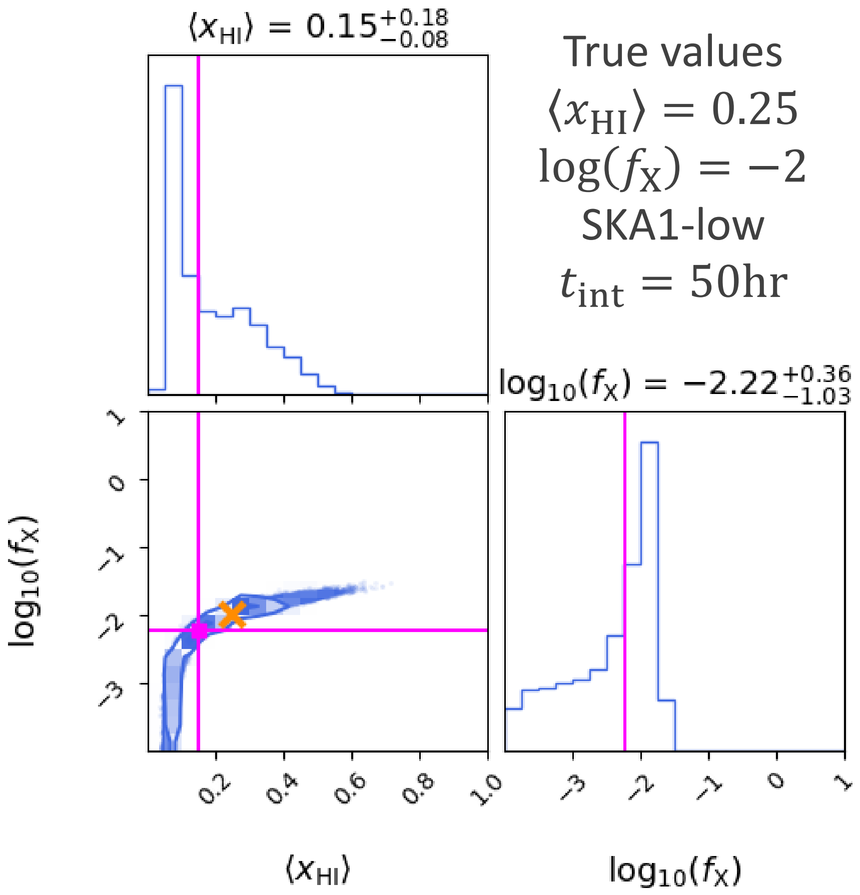
Šoltinský et al. in prep.

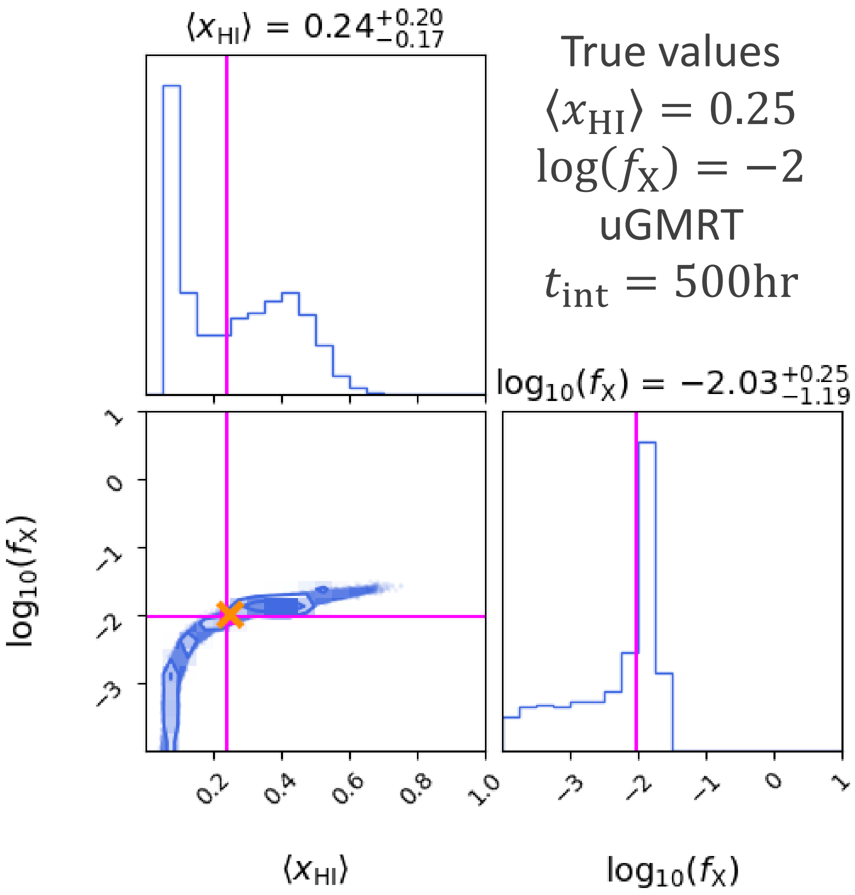
Constrain thermal and ionization state of the IGM at the same time

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

Limiting factor is
SAMPLE VARIANCE
not telescope noise

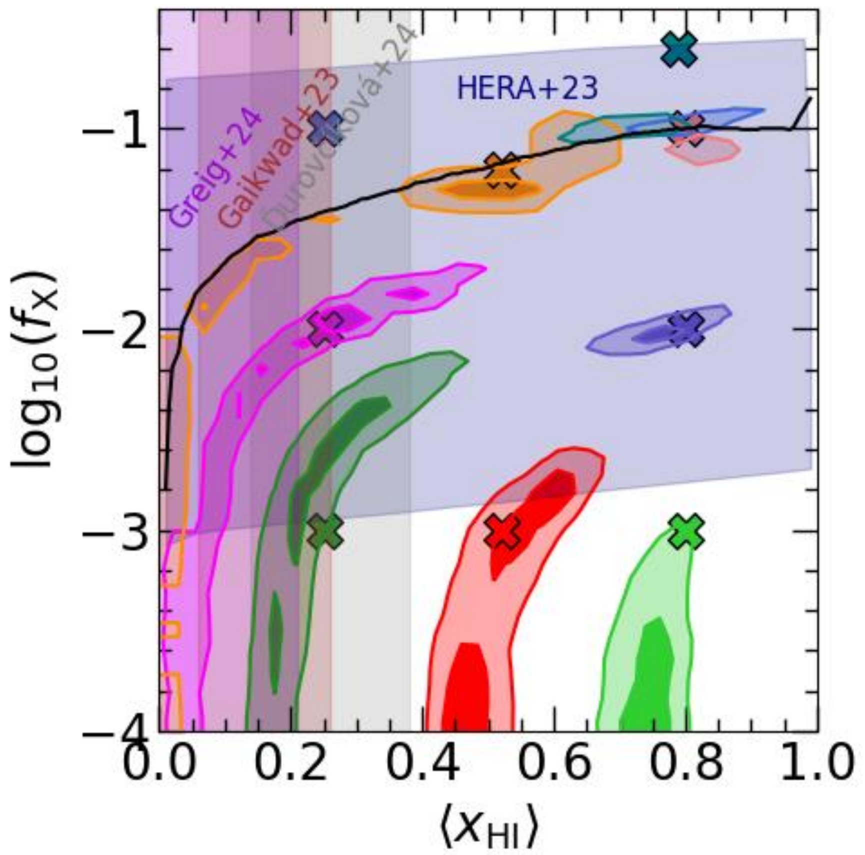
Šoltinský et al. in prep.





What about the rest of parameter space?

SKA1-low, $t_{\mathrm{int}} = 50\mathrm{hr}$



A null-detection disfavouring these regions in parameter space

Šoltinský et al. in prep.

Summary

Prospects of detecting the 21-cm forest are improving

➡ Sample variance dominates over the telescope noise

21-cm forest is a unique probe

➡ Possibility of constraining the thermal and ionization state of the IGM even with observations of 10 sources at $z \approx 6$ over 50hr each by SKA1-low (AA4)

APPENDIX

21-cm absorbers nature

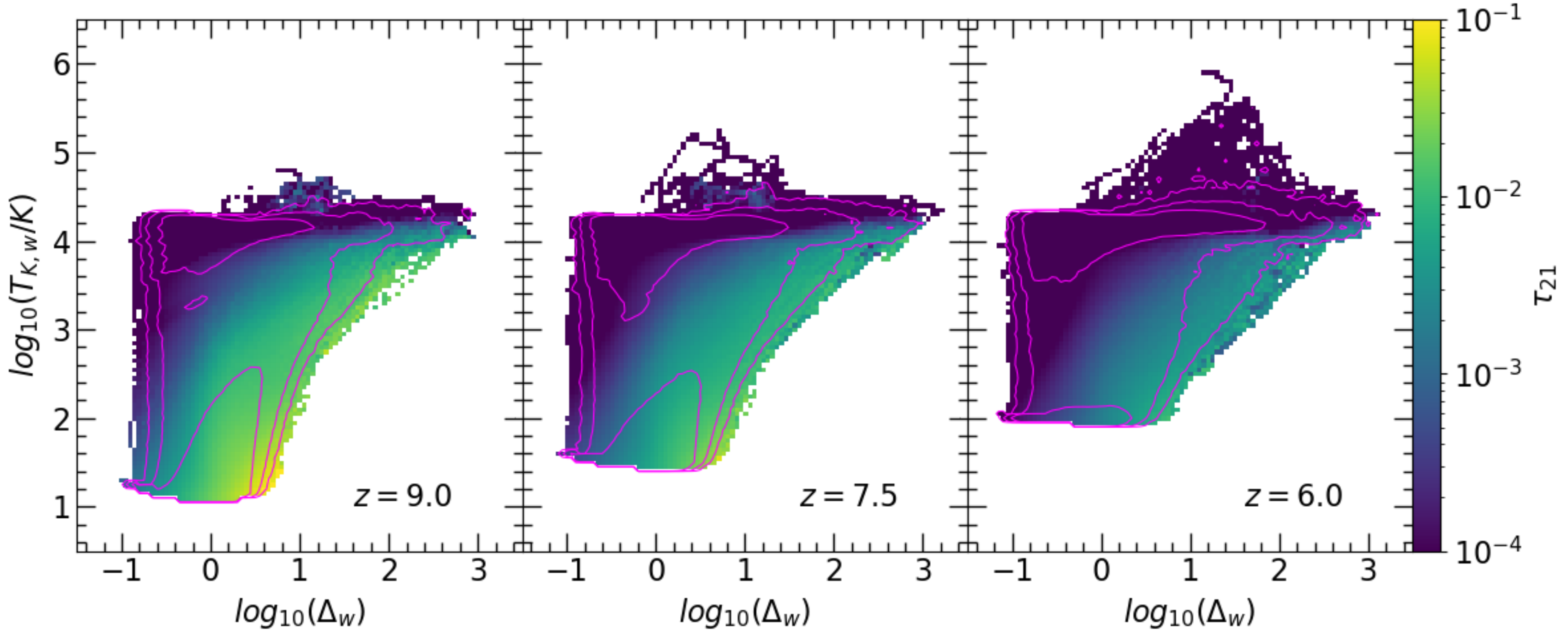
Cold diffuse IGM

T_K<100K

3<Δ<10

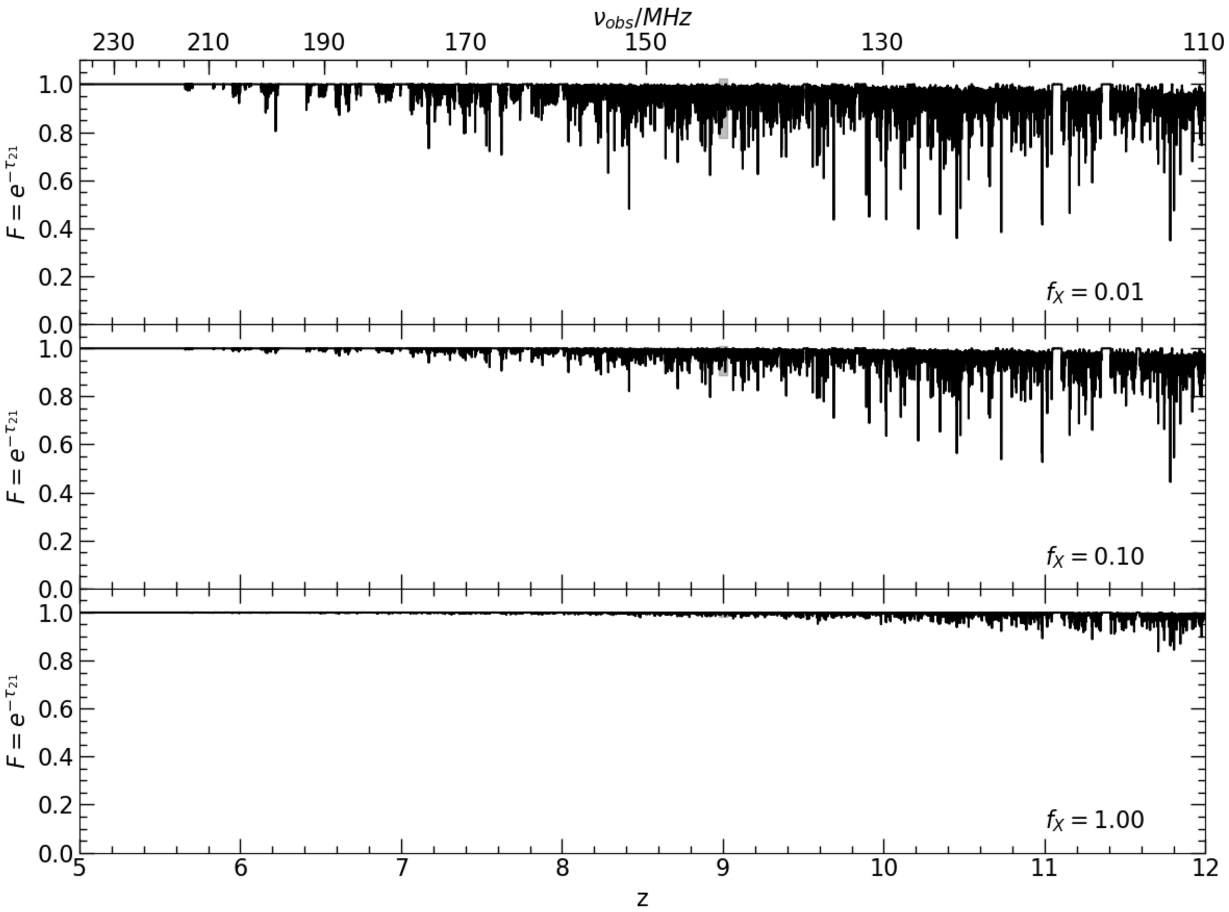
Strongest absorbers rare

~100 times less abundant than the bulk of cold, neutral gas



Šoltinský et al. 2021

X-ray background radiation suppresses the signal

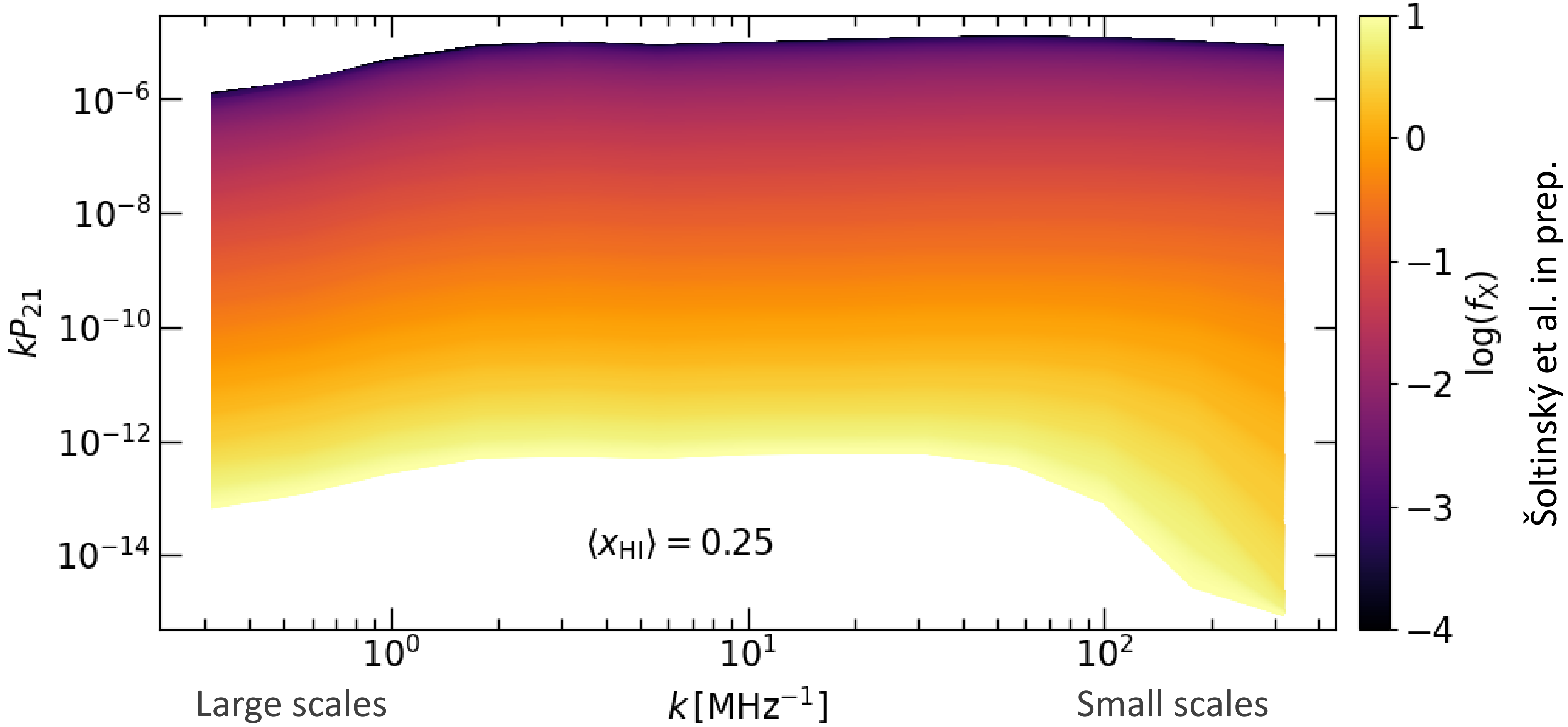


$L_X \propto f_X \times SFR$

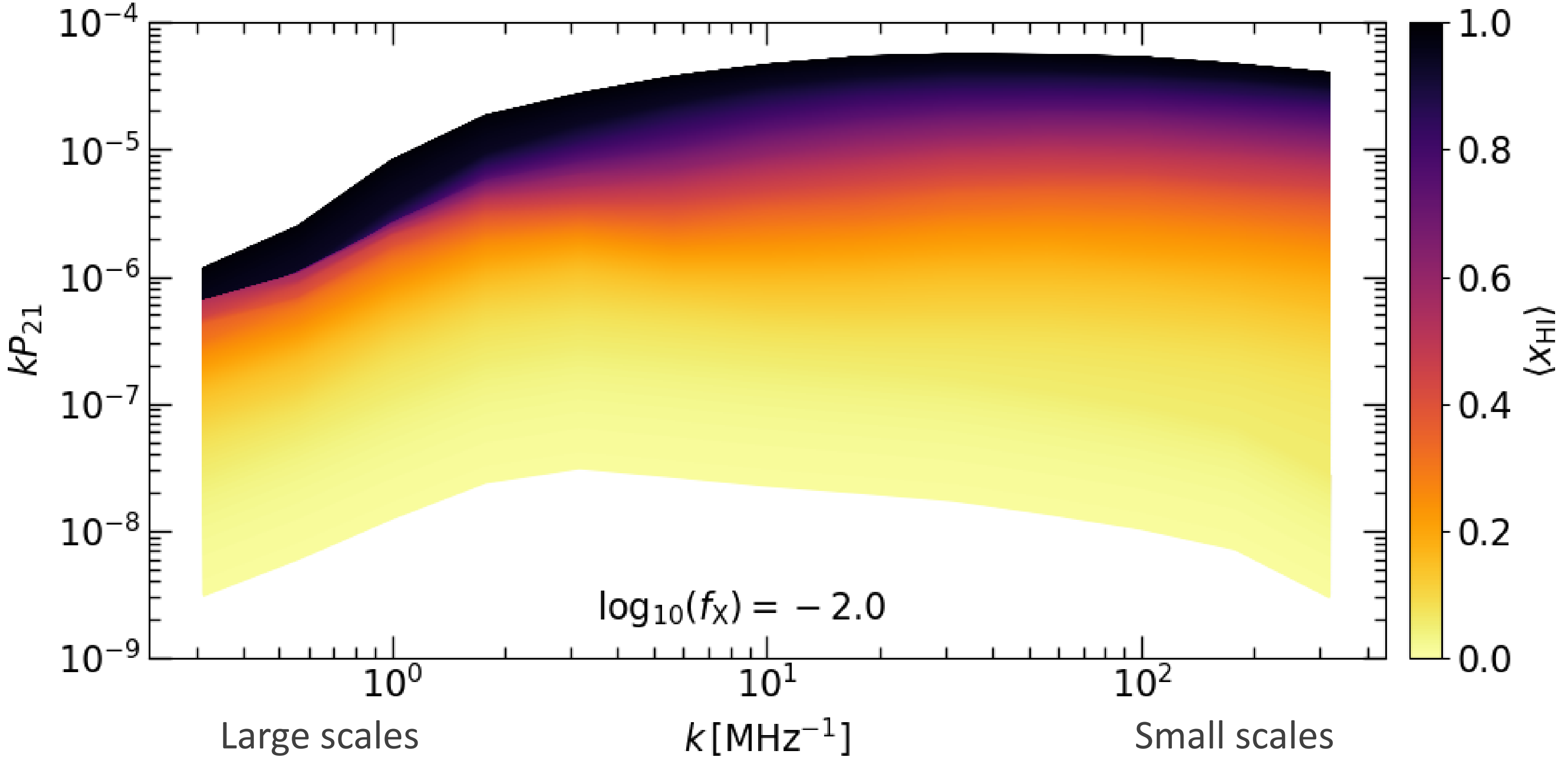
(Furlanetto 2006)

Šoltinský et al. 2021
(but see also Xu et al. 2011,
Mack & Wyithe 2012)

Sensitivity to X-ray background radiation

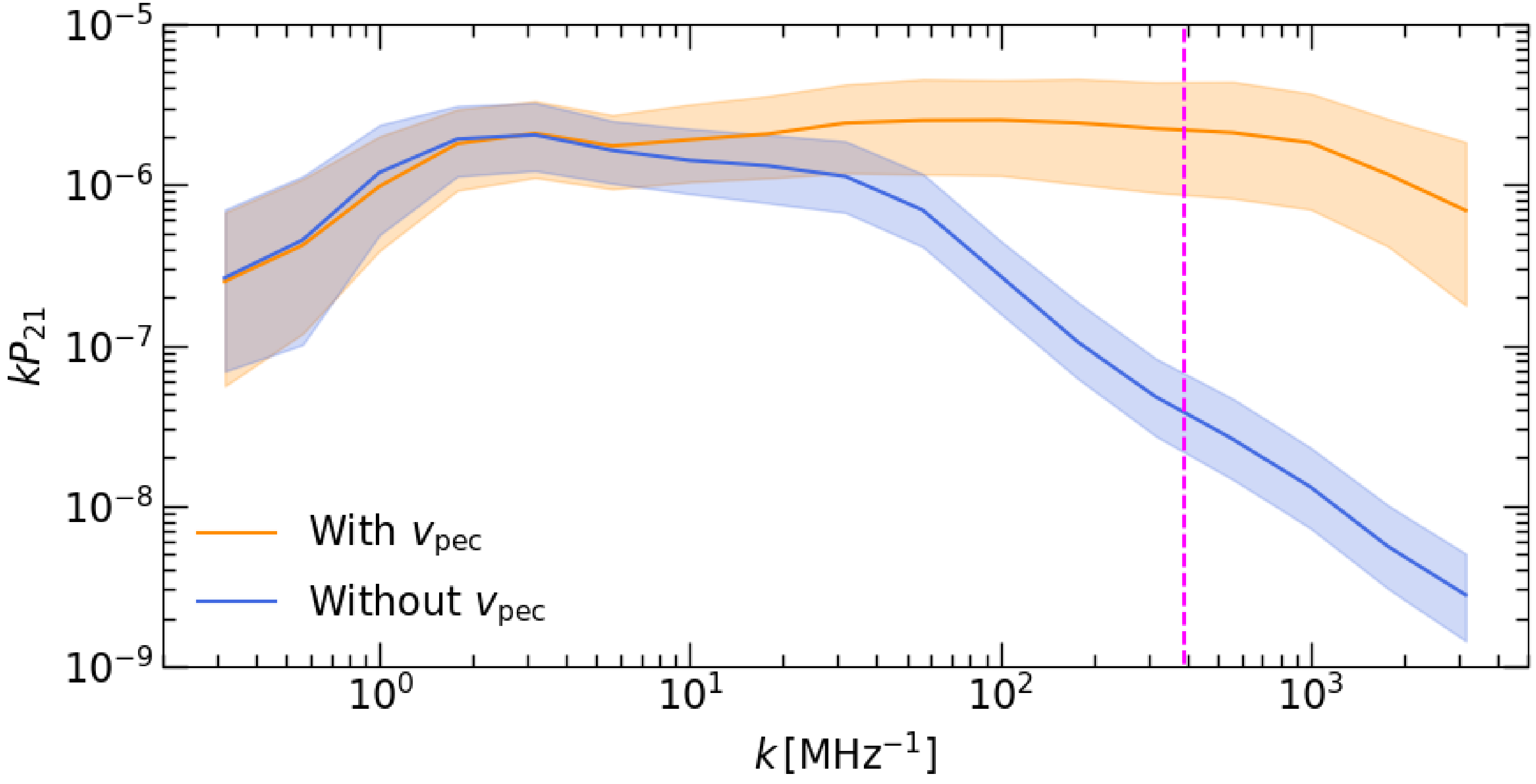


Sensitivity to HI fraction

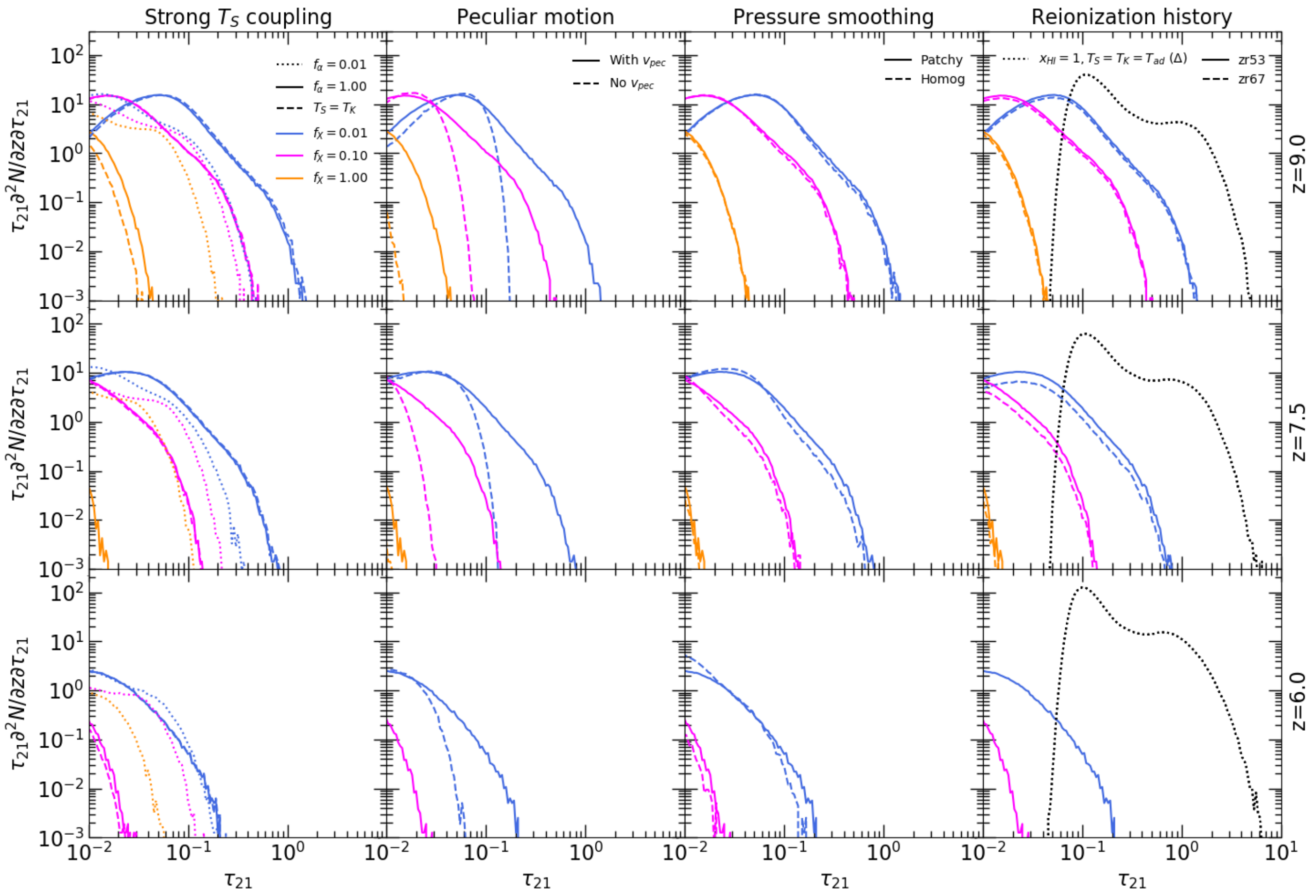


Šoltinský et al. in prep.

Effect of peculiar velocities



21-cm absorption lines distribution



Šoltinský et al. 2021

Reionization ends late

Large spatial fluctuations in the Lyα forest opacity at z>5
(Becker et al. 2015, Bosman et al. 2022)

Deficit of Lyα emitting galaxies around extended Lyα absorption troughs
(Kashino et al. 2020, Keating et al. 2020, Christenson et al. 2021)

Clustering of Lyα emitters (Weinberger et al. 2019)

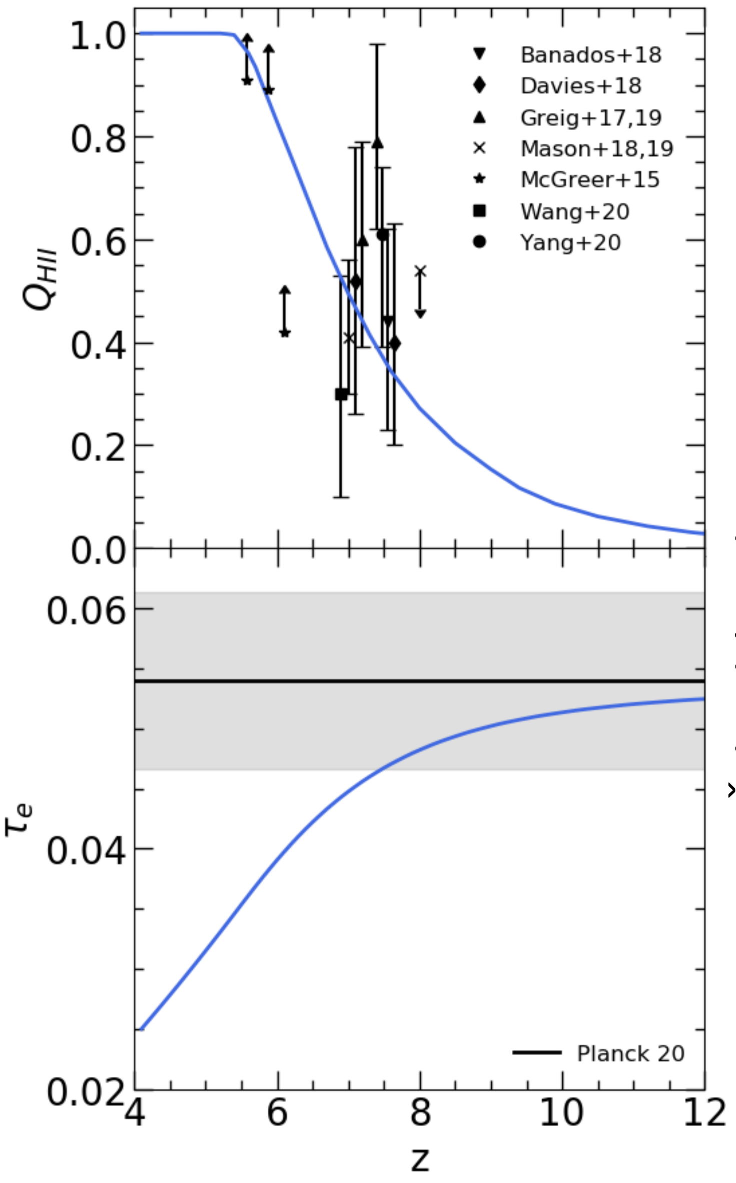
Thermal widths of Lyα forest transmission spikes at z>5 (Gaikwad et al. 2020)

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

Lyα equivalent widths (Nakane et al. 2023)

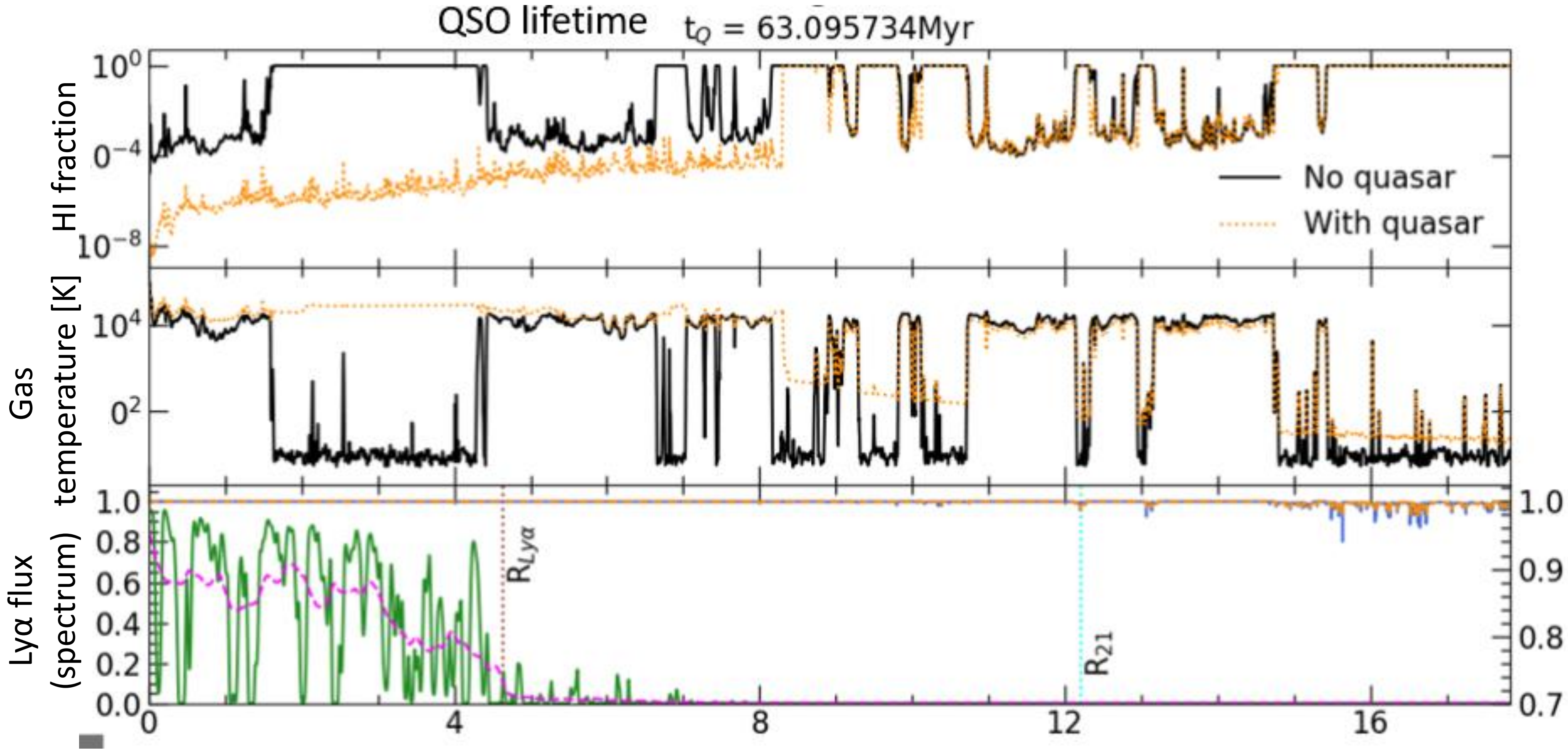
Long dark gaps in the Lyα (Zhu et al. 2021) and Lyβ forest (Zhu et al. 2022)

Damping wings in the Lyα forest at z<6
(Spina et al. 2024, Becker et al. 2024, Zhu et al. 2024)



Šoltinský et al. 2021

Time evolution



JV ➡ Ionises surrounding gas

⬇

Lyα forest observable

X-rays ➡ Heat up the gas

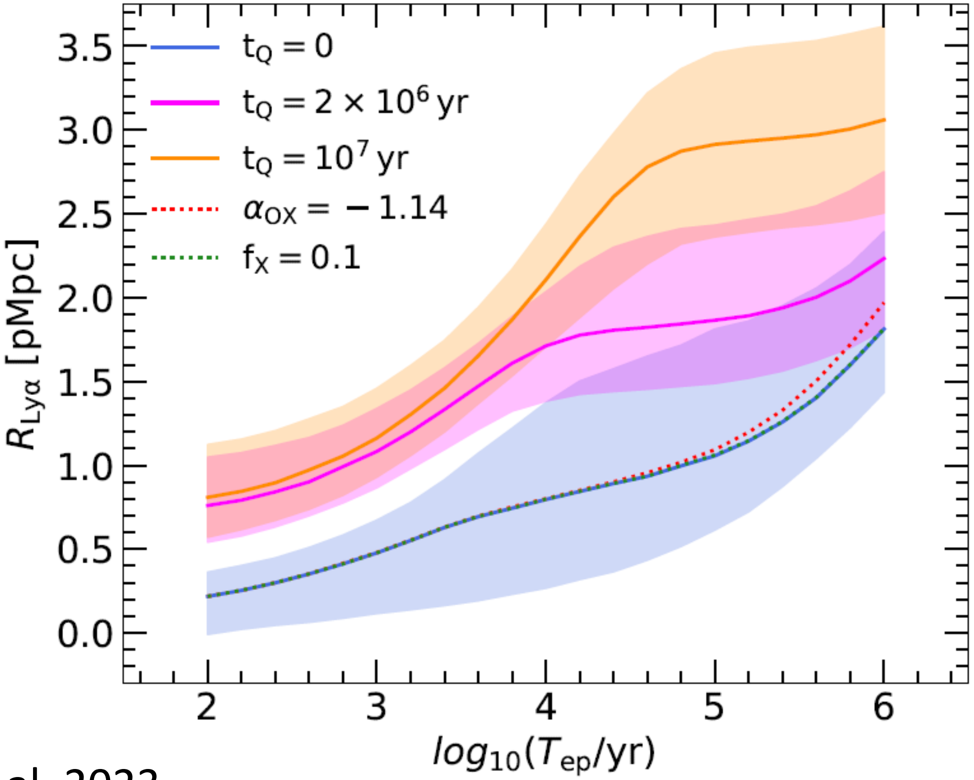
⬇

21-cm forest suppressed at larger distances

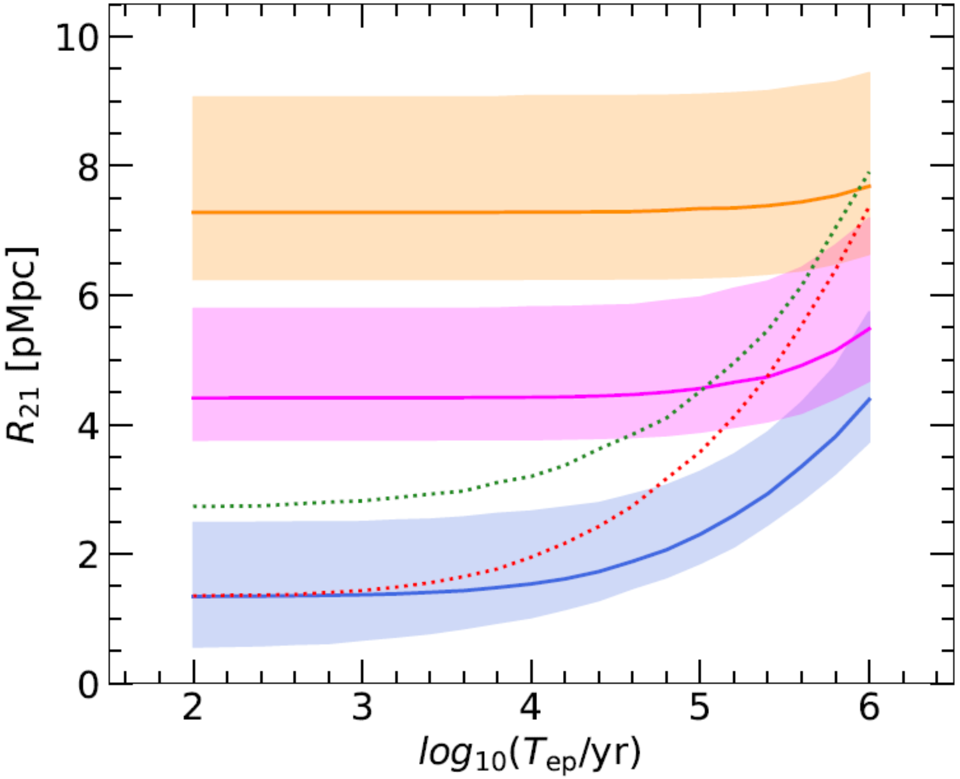
Šoltinský et al. 2023

Young vs flickering quasar

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



21-cm forest might discern between these cases



Šoltinský et al. 2023