Narrowing the discovery space of the cosmological 21-cm signal using multi-wavelength constraints

Jiten Dhandha

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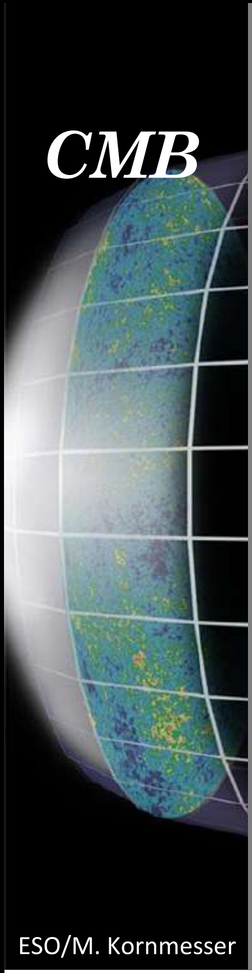
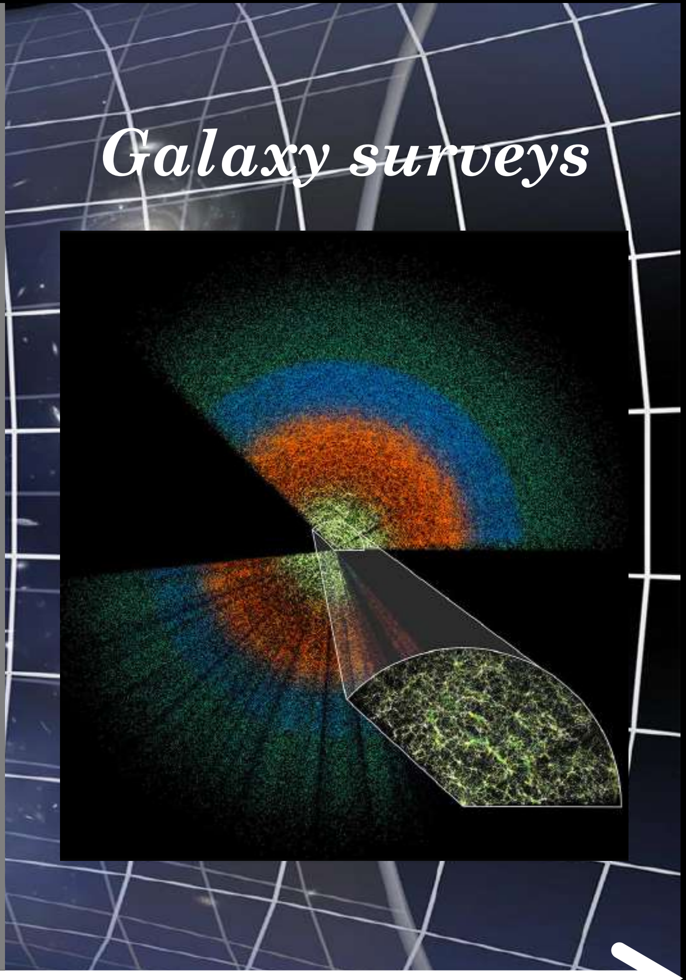
Introduction





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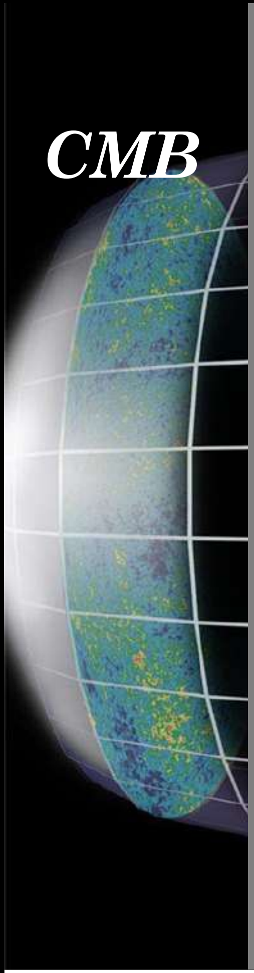
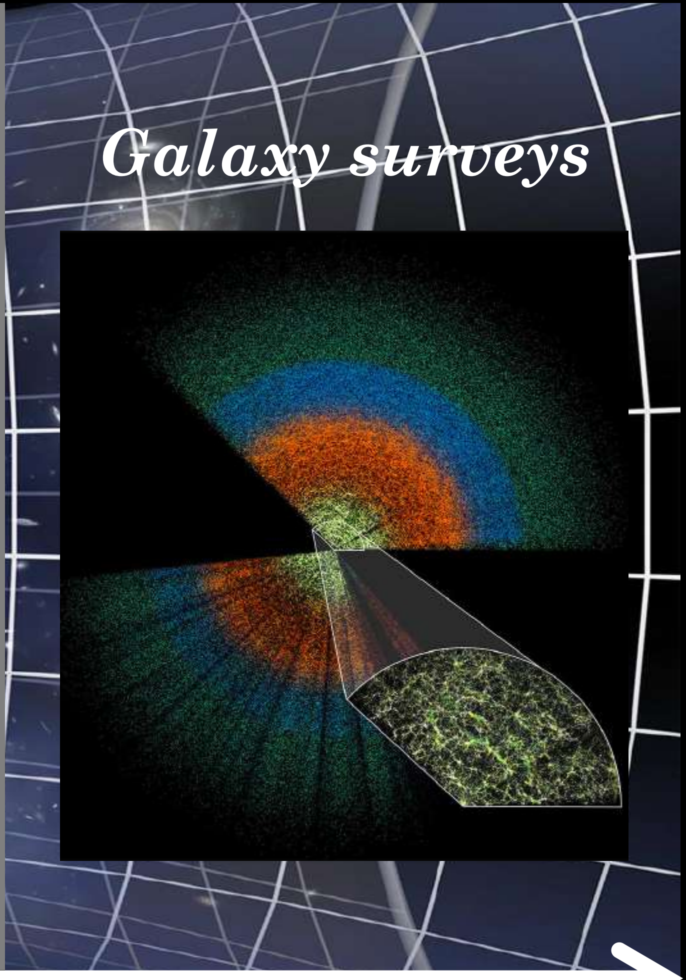


"[...] it's like missing your child's life from the moment of conception to the first day of school, apart from a single ultra-sound. If we don't have information about these formative years, what incorrect conclusions are we making about our Universe?"

— Emma Chapman (2022, UoM)



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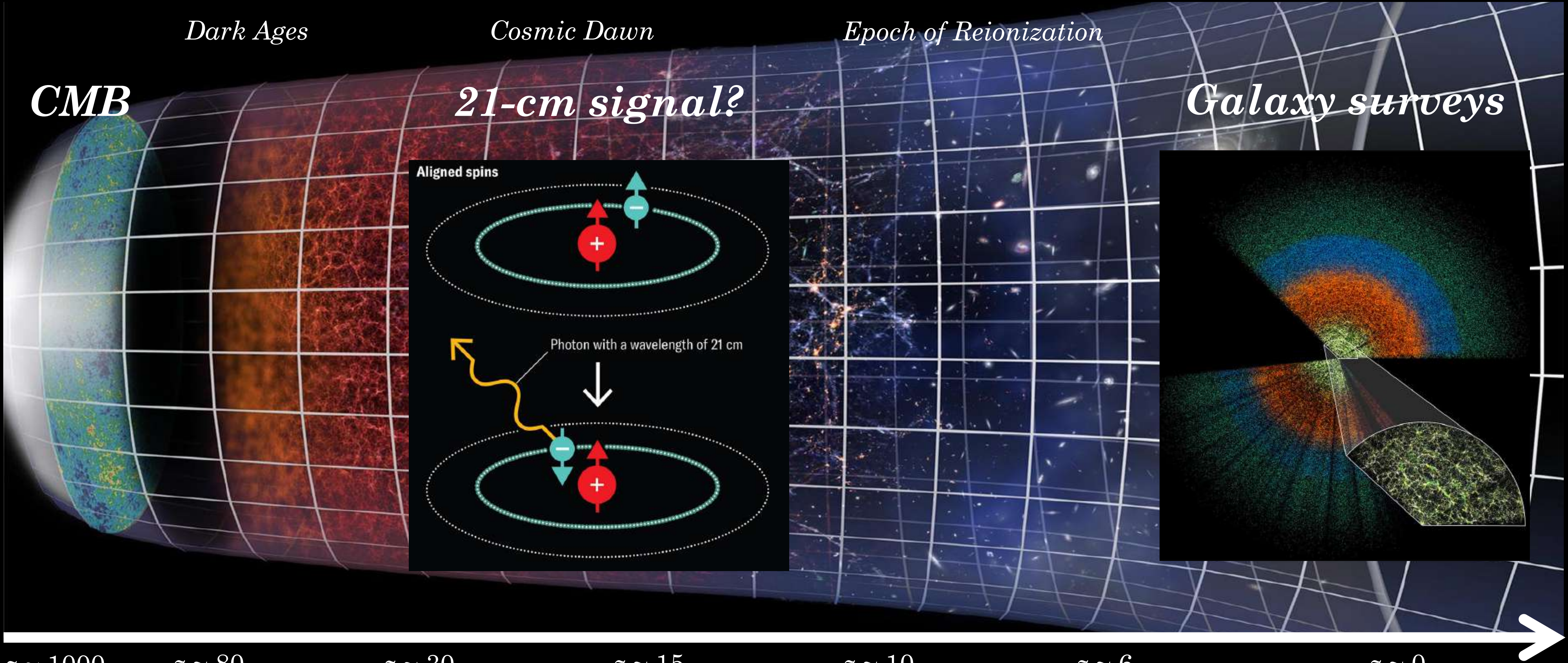

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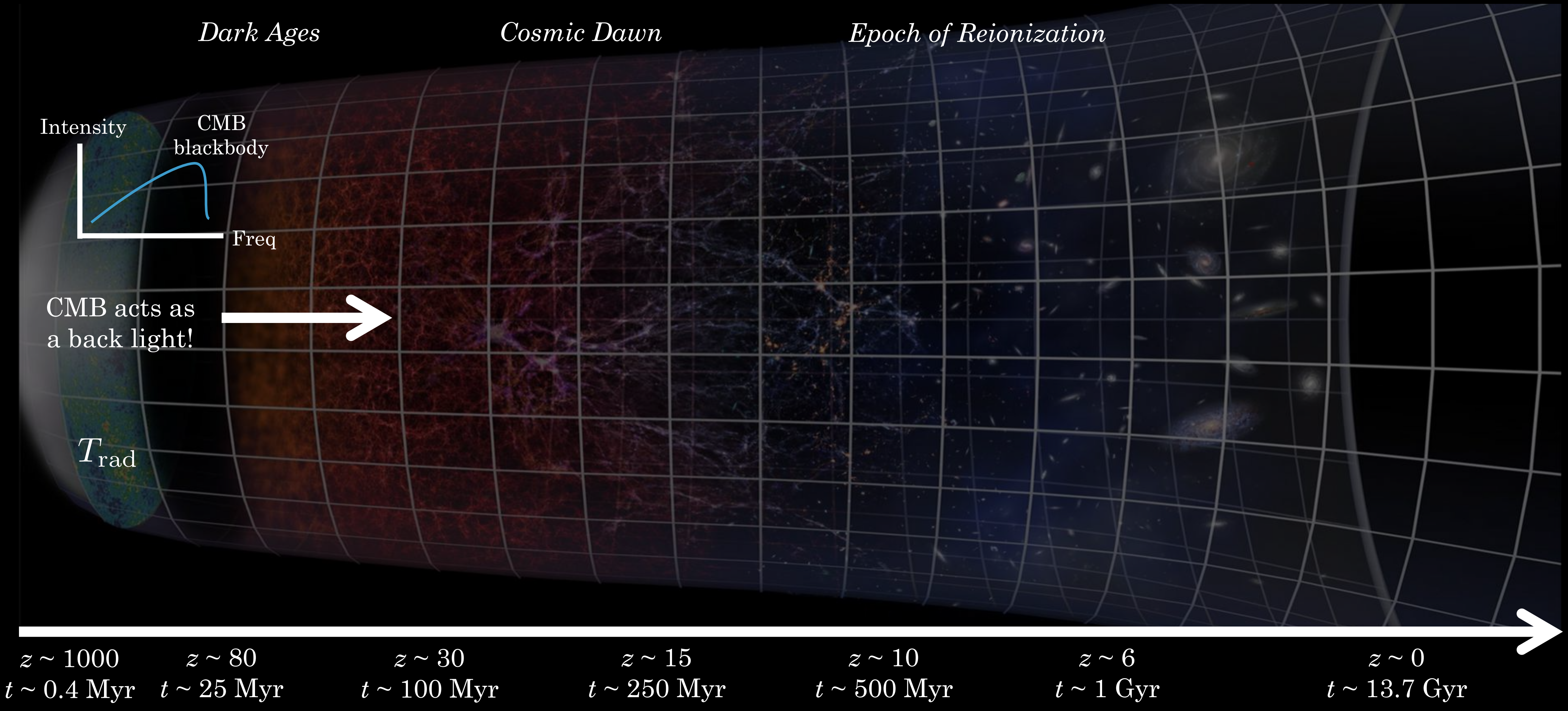
The 21-cm signal



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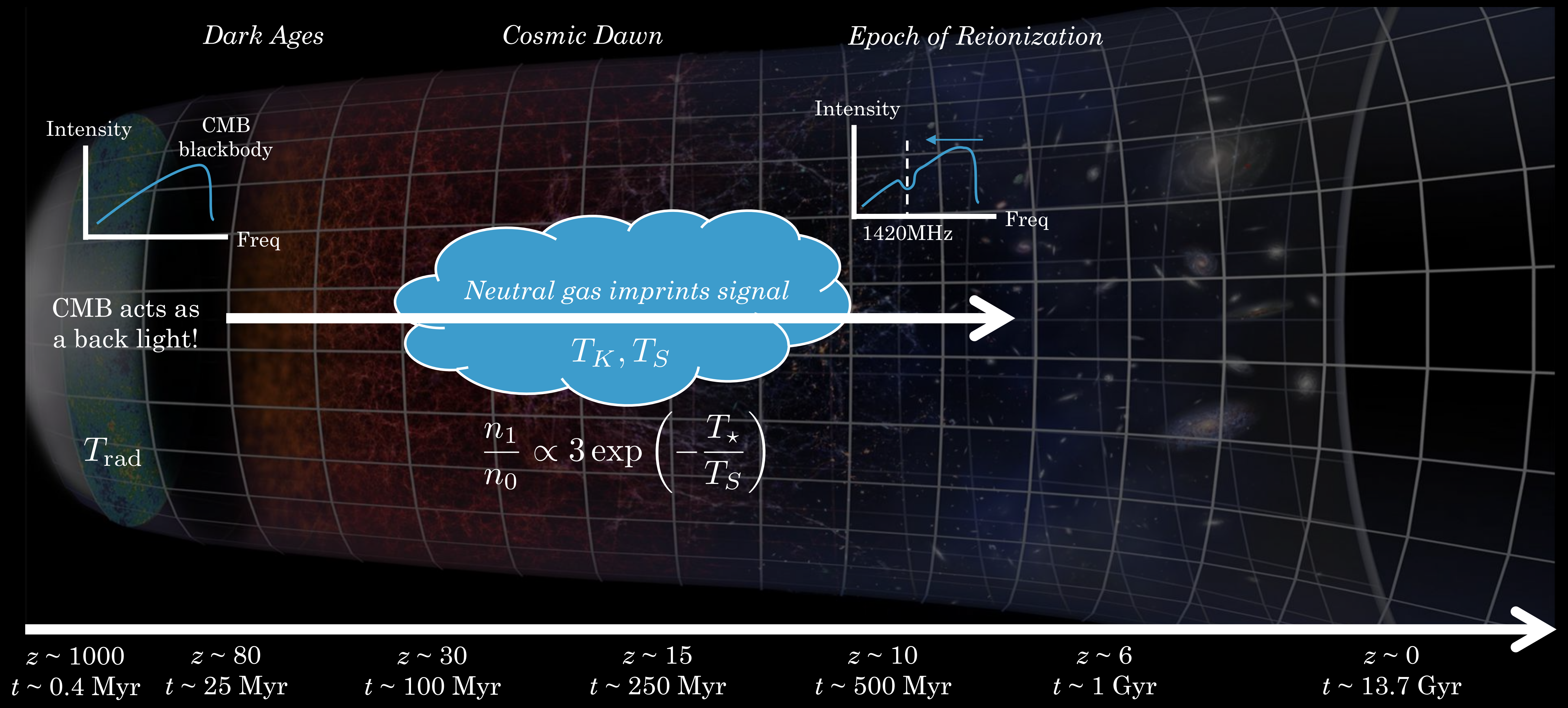

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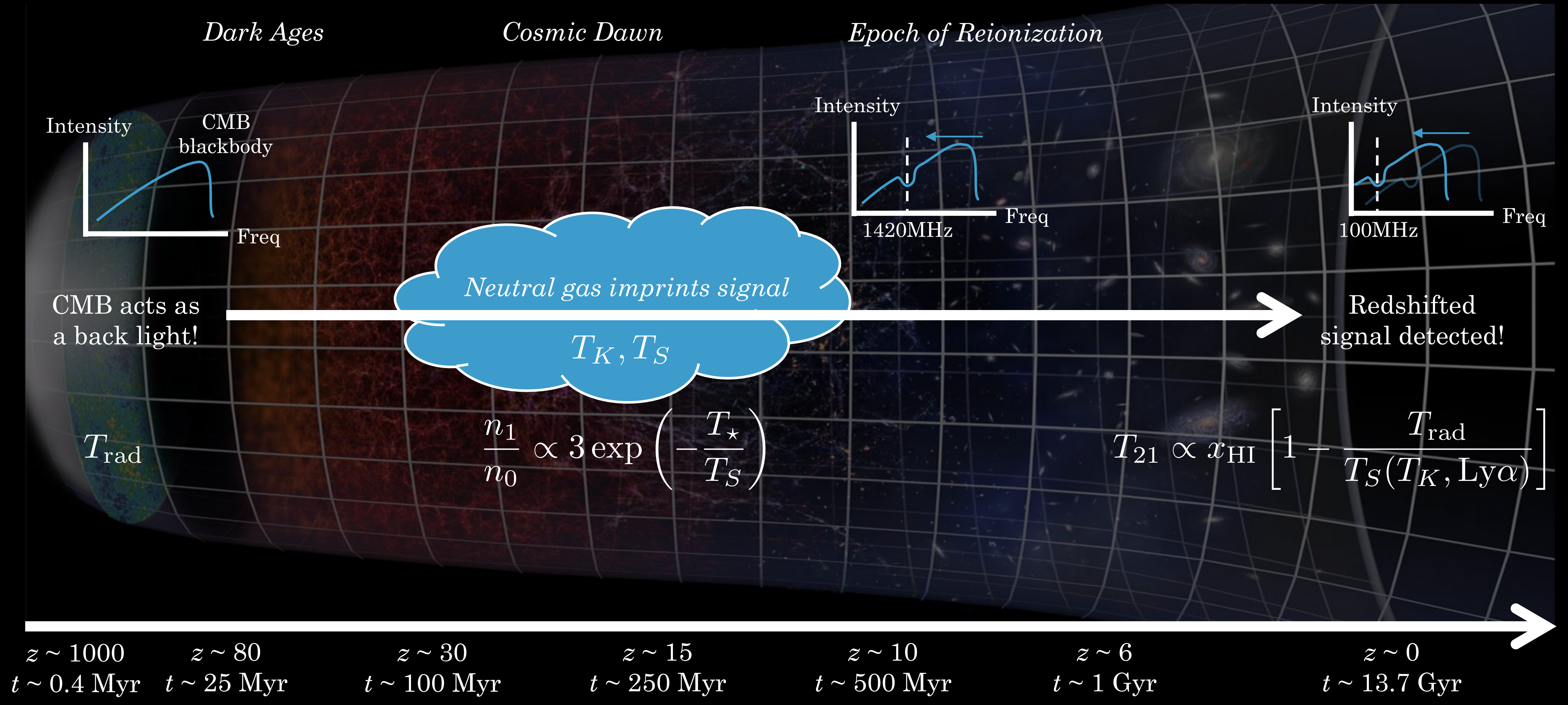

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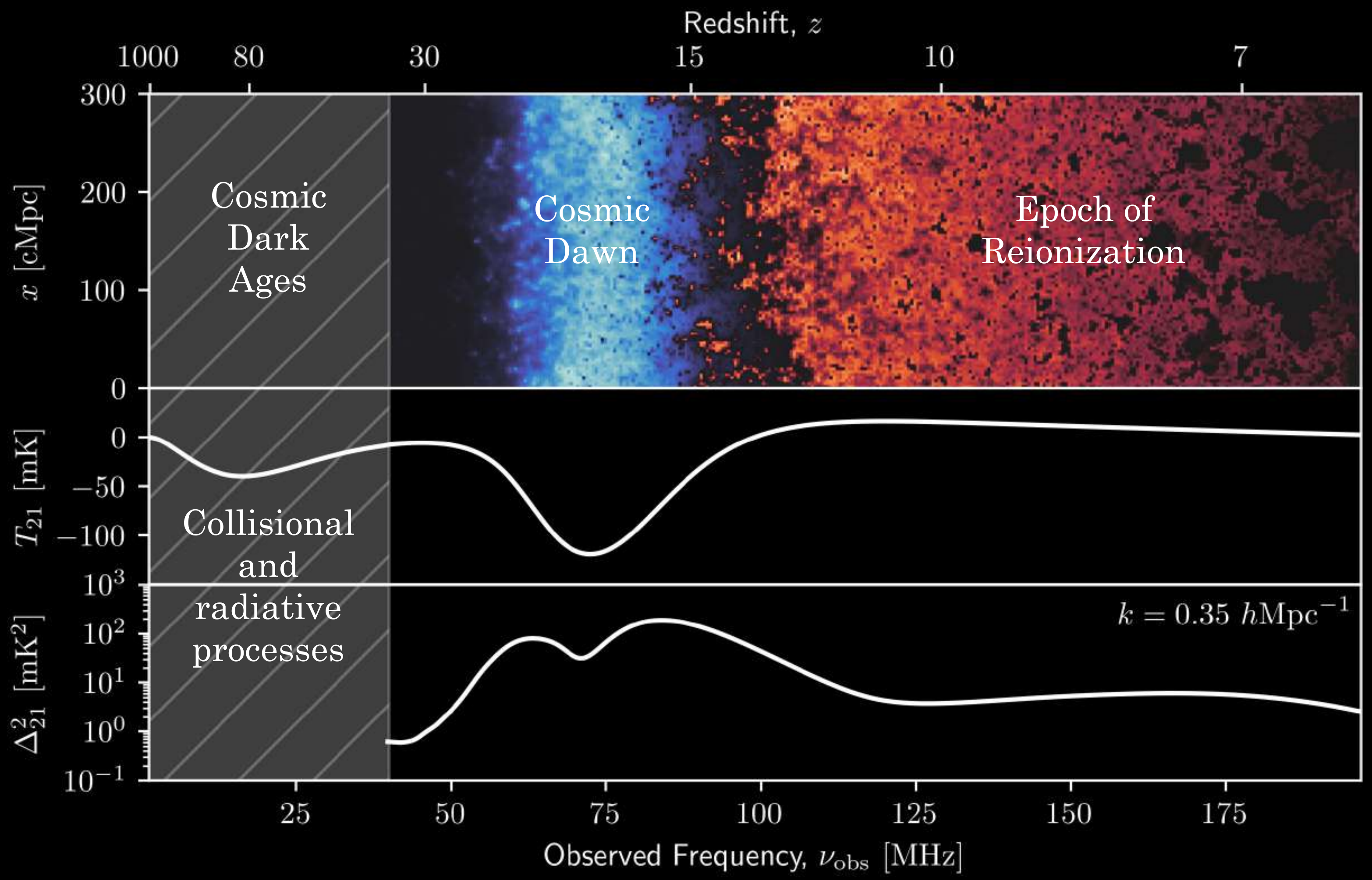
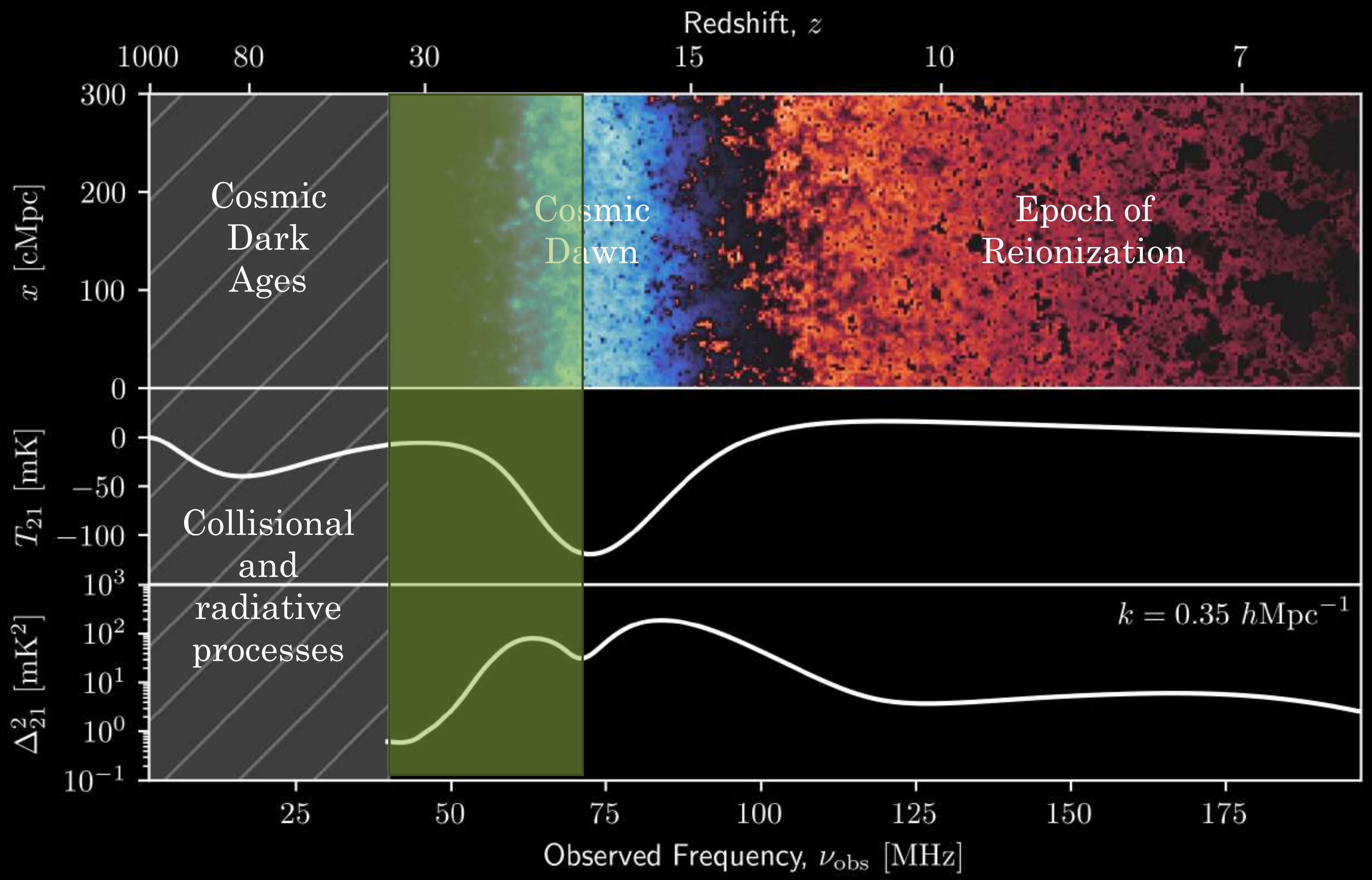


$$T_{21} \propto x_{\mathrm{HI}} \left[1 - \frac{T_{\mathrm{rad}}}{T_S(T_K, \mathrm{Ly}\alpha)} \right]$$

The 21-cm signal



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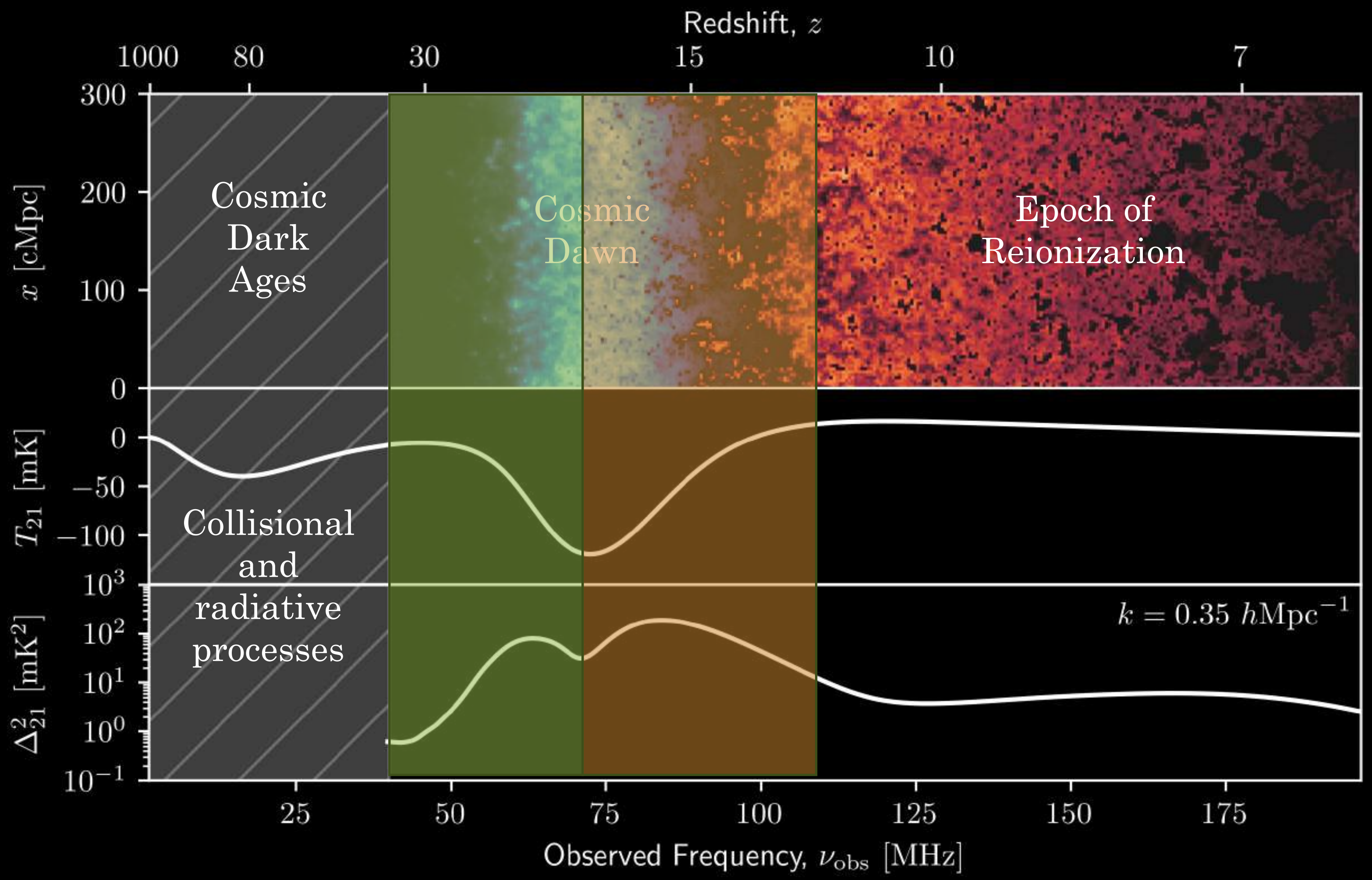
First luminous sources

The 21-cm signal



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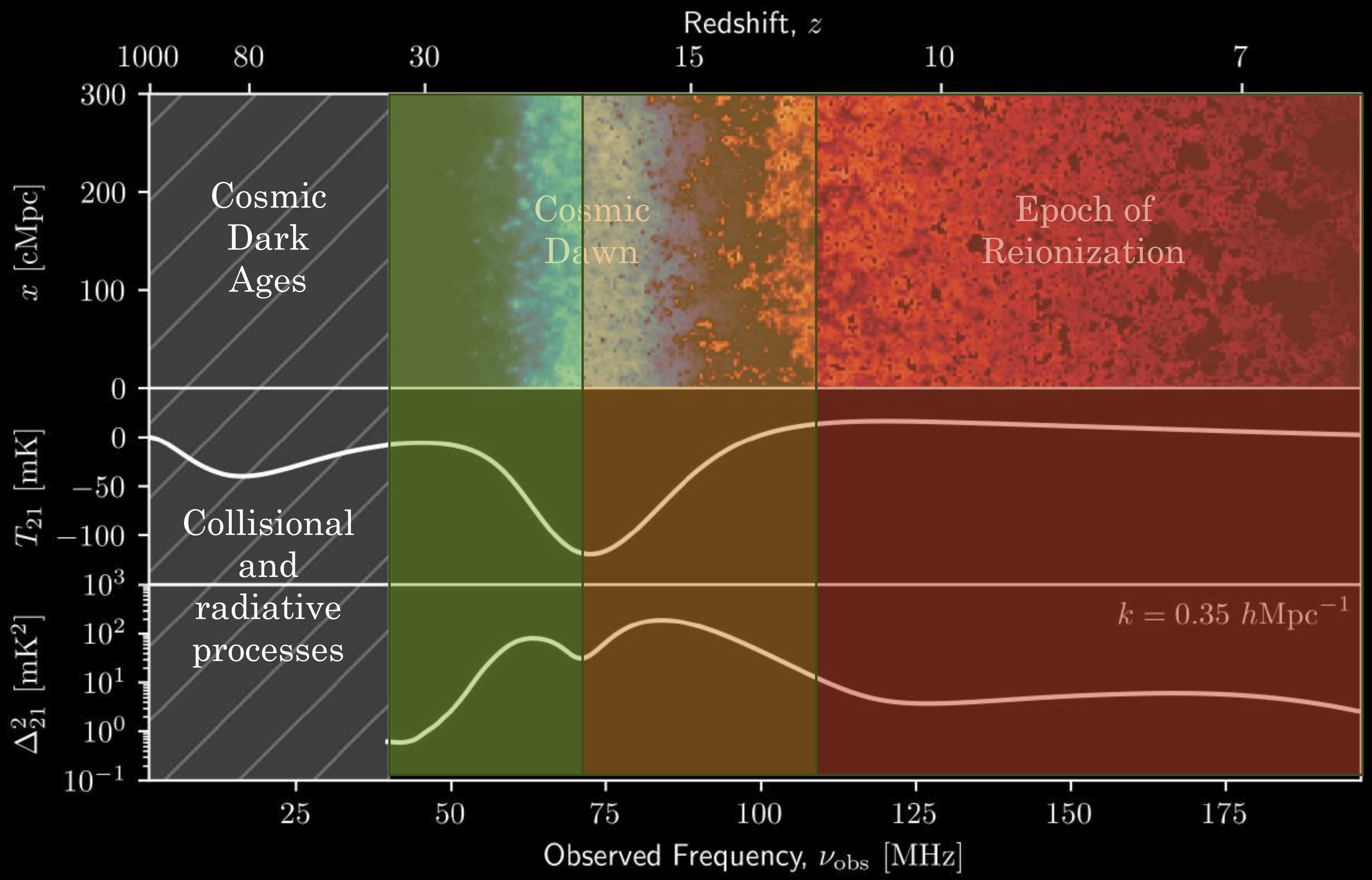
First luminous sources

IGM heating

The 21-cm signal



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- IGM heating
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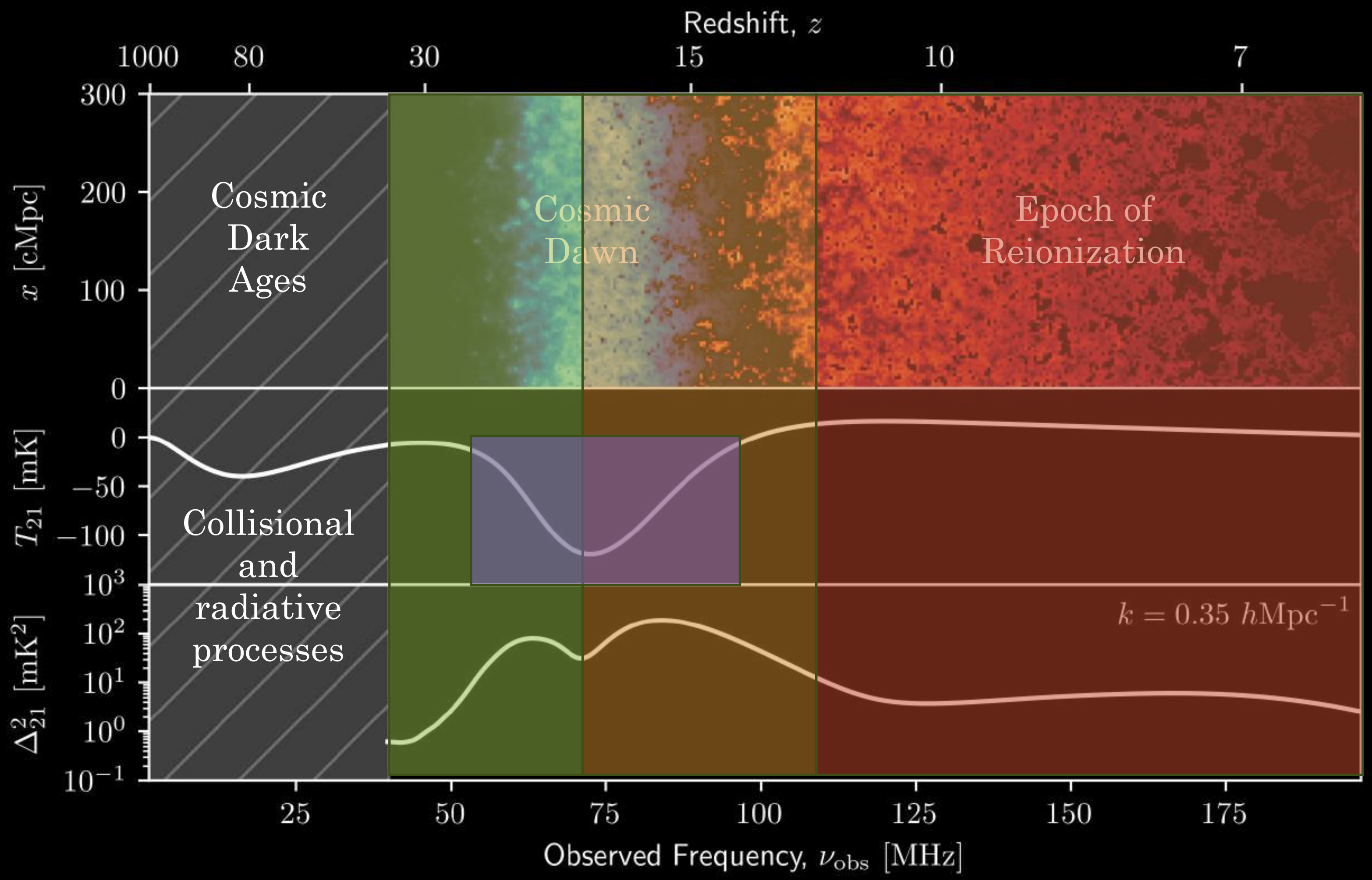
The 21-cm signal



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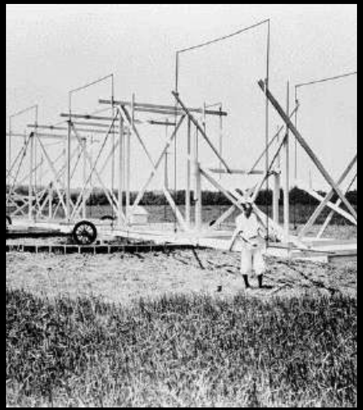
History of 21-cm cosmology

Radio waves outside the Solar System (Karl Jansky 1933)

First radio maps of the sky (1940, 1944, Grote Reber)



Prediction by van del Hulst (1945), Shklovskii 1949)

First discrete source Cyg-A (Hey et al. 1946) in UK

First optical counterparts (Bolton et al. 1949) in Australia

Cambridge 1C (Ryle et al. 1950)

1951: Ewen and Purcell (Harvard), Muller and Oort (Leiden), and Christiansen and Hindman (Sydney)

Radio stars ('stellar') sources vs synchrotron sources ('galactic')

Steady state vs Big Bang

21-cm: ISM in emission, and absorption against sources (e.g. Parkes survey of 1972)

21-cm: IGM in absorption against sources!

Detection of the CMB!

Cosmological leap with Zel'dovich (1970, 1972)

21-cm: IGM at high-z (Varshalovich and Khersonskii 1977, Hogan and Rees 1979)

First attempts: Jodrell, MRAO

More attempts: VLA, WSRT, Arecibo, etc.

Galaxy formation science with GMRT (Swarup and Subrahmanyan 1987, Scott and Rees 1990)

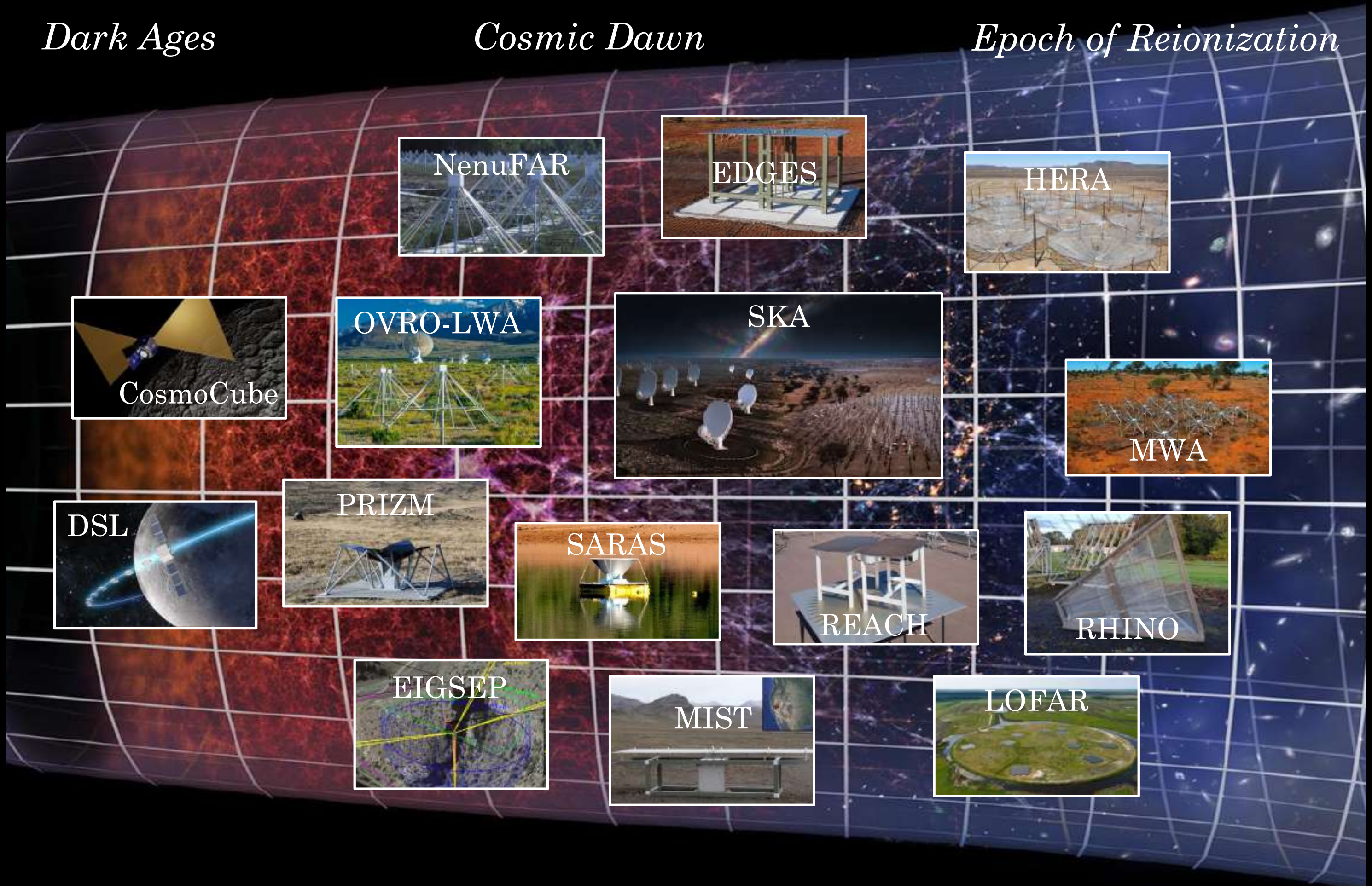
EoR science (Madau, Meiksin and Rees 1997)

> "This whole episode was a fine example of international cooperation, which has always been the hallmark of most of the relationships in radio astronomy" – Kerr (1984)

> "[…] by the way, radio astronomy can really become very important if there were at least one line in the radio spectrum. […]" – Oort to van del Hulst (1944)

1930s *1940s* *1950s* *1960s* *1970s* *1980s* *1990s*

Status of 21-cm observations



We are entering an exciting phase of 21-cm experimentation

$z \sim 1000$, $t \sim 0.4$ Myr | $z \sim 80$, $t \sim 25$ Myr | $z \sim 30$, $t \sim 100$ Myr | $z \sim 15$, $t \sim 250$ Myr | $z \sim 10$, $t \sim 500$ Myr | $z \sim 6$, $t \sim 1$ Gyr | $z \sim 0$, $t \sim 13.7$ Gyr

Status of 21-cm observations

bit.ly/21cmExperiments

An exhaustive public repository of 21-cm experiments

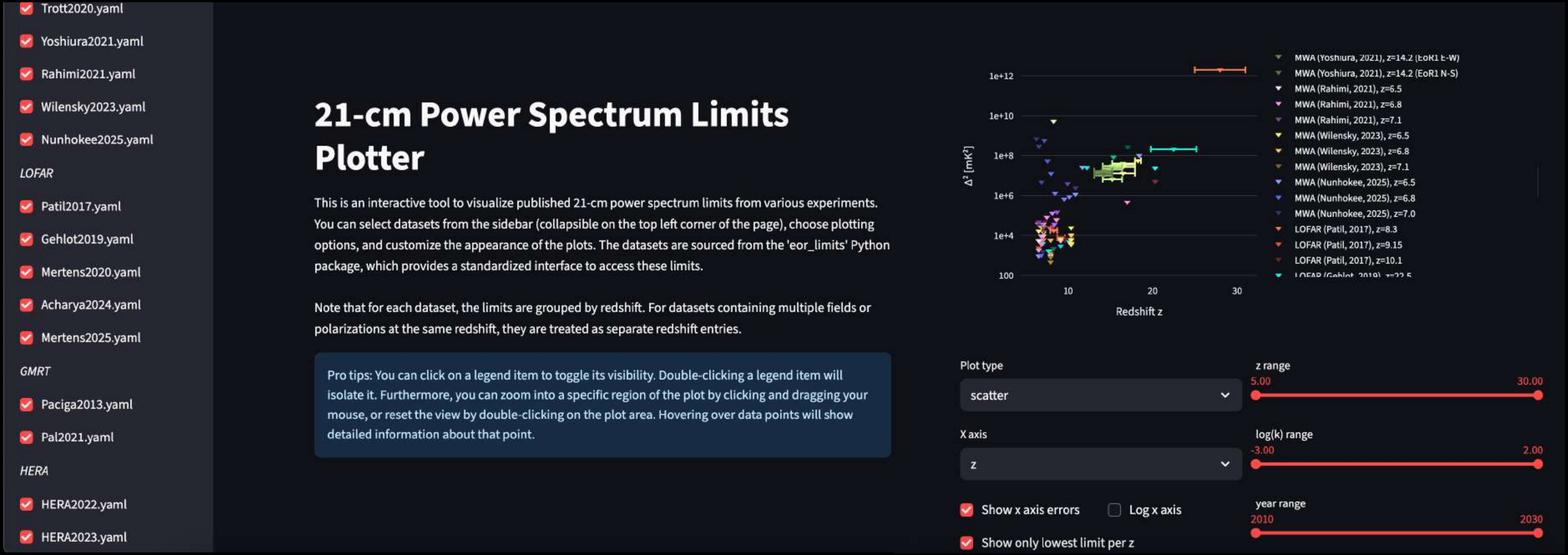
(see also bit.ly/21cmSimulators)

Experiment	Telescope	Publications	Location	Type	Antenna type	Frequency (MHz)
SARAS	SARAS1	2013ExA....36..319P	Gauribidanur Observatory (southern India)	global	Fat-dipole correlation spectrometer	87.5, 175
SARAS	SARAS2	2018ExA....45..269S, 2017ApJ...845L..12S	Timbaktu Collective (southern India)	global	Monopole	110, 200
SARAS	SARAS3	2021arXiv210401756N, 2020JAI.....950006G	Southern India	global	Monopole	40, 200
SCI-HI	SCI-HI	2014ApJ...782L...9V	Isla Guadalupe (Mexico)	global	HIBiscus	40, 130
BIGHORNS	BIGHORNS	2015PASA...32....4S	MRO (Western Australia)	global	Conical log-spiral	70, 200
EDGES	EDGES	2017ApJ...835...49M, 2017ApJ...847...64M, 2018Natur.555...67B	MRO (Western Australia)	global	Blade dipole	50, 100
PRIZM	PRIZM	2019JAI.....850004P	Marion Island (South Africa)	global	HIBiscus	30, 200
REACH	REACH	2022NatAs...6.1332D	Karoo desert (South Africa)	global	Hexagonal dipole (+4 more)	50, 170
MIST	MIST	2024MNRAS.530.4125M	McGill Arctic Research Station (Nunavut, Canada); Deep	global	Horizontal blade dipole	25, 105
GINAN	GINAN		Narrabri observatory (Western Australia)	global	SKA Low Antenna, on a blank SKA Low 40-m ground mesh	70, 350
EIGSEP	EIGSEP		Utah (USA)	global	3x Vivaldi feed (for now, new under development)	50, 250
RHINO	RHINO	2024arXiv241000076B	Jodrell Bank Observatory (Manchester, UK)	global	Horn antenna	60, 85
GMRT	GMRT	1991ASPC...19..376S, 2013MNRAS.433..639P	Maharashtra (India)	interferometer	30 parabolic 45m dishes	50, 1420
21CMA/PAST	21CMA/PAST	2004MPLA...19.1001P	Tianshan mountains (west China)	interferometer	81 pods x 127 log-spiral antennas	50, 200
NenuFAR	NenuFAR	2012sf2a.conf..687Z	Nançay (France)	interferometer	(96 core + 8 remote stations) x 19 cross-dipole antennas	10, 85
SKA	SKA-LOW	2009IEEEP..97.1482D	Karoo desert (South Africa); MRO (Western Australia)	interferometer	512 stations x 256 log-periodic antennas	50, 350
MWA	MWA	2013PASA...30....7T, 2018PASA...35...33W	MRO (Western Australia)	interferometer	4096 cross-dipole bowtie antennas	70, 300
PAPER	PAPER	2010AJ....139.1468P	PSA: Karoo desert (South Africa); PGB: Green Bank (Uni	interferometer	128 (PSA) + 32 (PGB) antenna array	120, 180
LOFAR	LOFAR	2013A&A...556A...2V	Netherlands and Europe	interferometer	Arrays of tiles with 16 crossed-bowtie dipoles each	120, 240
HERA	HERA	2017PASP..129d5001D	Karoo desert (South Africa)	interferometer	350 (planned) parabolic 14m wire mesh dishes	50, 250
OVRO-LWA/LEDA	OVRO-LWA/LEDA	2018MNRAS.478.4193P	Owens Valley (California)	interferometer	288 cross-dipole drooping antennas	27, 85
LCRT	LCRT	10.1109/AERO50100.2021.9438165	Lunar farside	global	1 km diameter parabolic mesh in a crater	4.7, 47
FARSIDE	FARSIDE	2021arXiv210308623B	Lunar farside	interferometer	128 dipole antennas across 10 km x 10 km area	0.1, 40
DALI	DALI	2007AAS...21113521L	Lunar farside	interferometer	1000 stations x 100 dipole antennas in 50 km diameter area	10, 100
ALO	ALO	2024AAS...24326401K	Lunar farside	interferometer		1, 80
FarView	FarView	2024AdSpR..74..528P	Lunar farside	interferometer	In-situ built 100,000 antennas over 200km2	5, 50
DAPPER	DAPPER	2021arXiv210305085B	Lunar orbit	global	Cross dipole antenna?	10, 100

Status of 21-cm observations

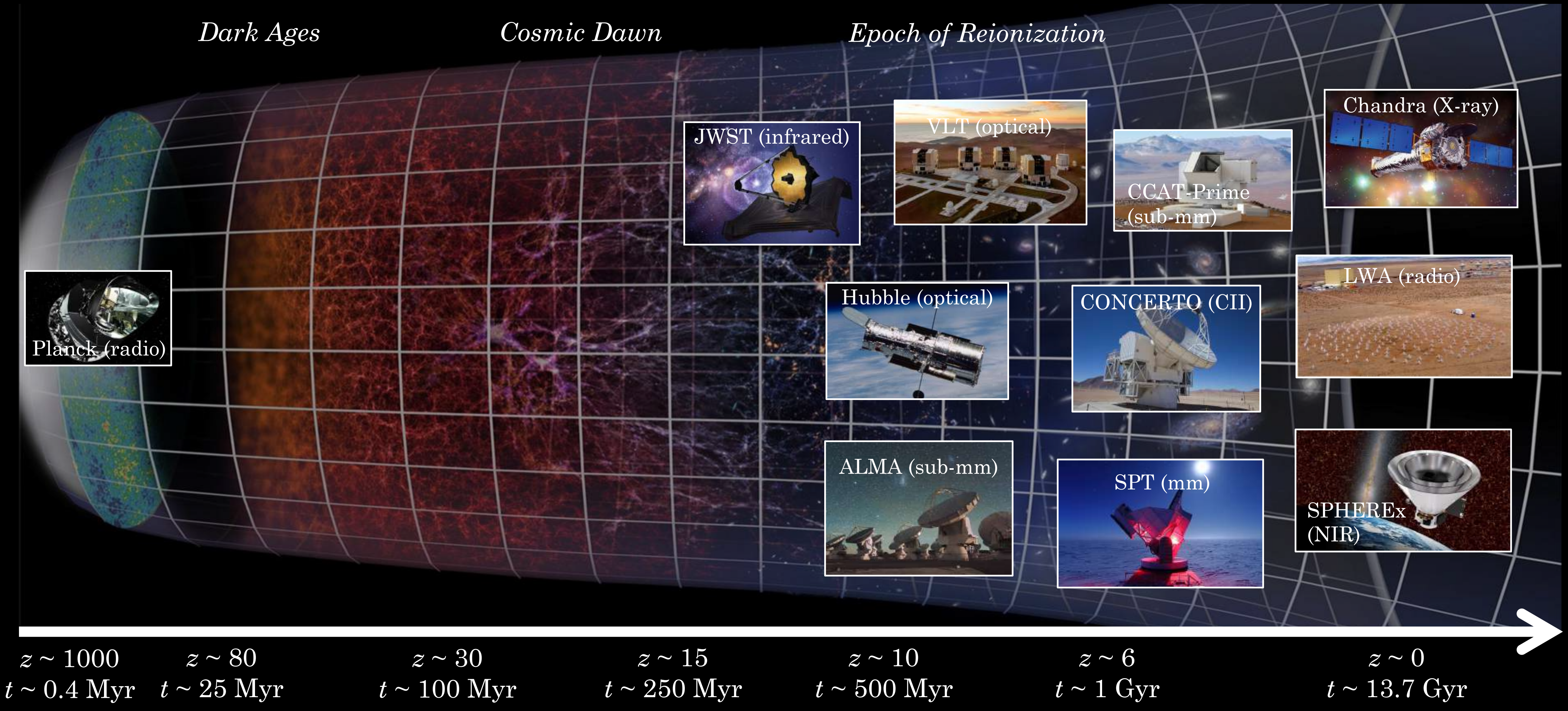
eorlimits.streamlit.app

A web-app to access* and plot latest power spectrum limits



*not pip-installable yet but stay tuned!

Multi-wavelength synergies?



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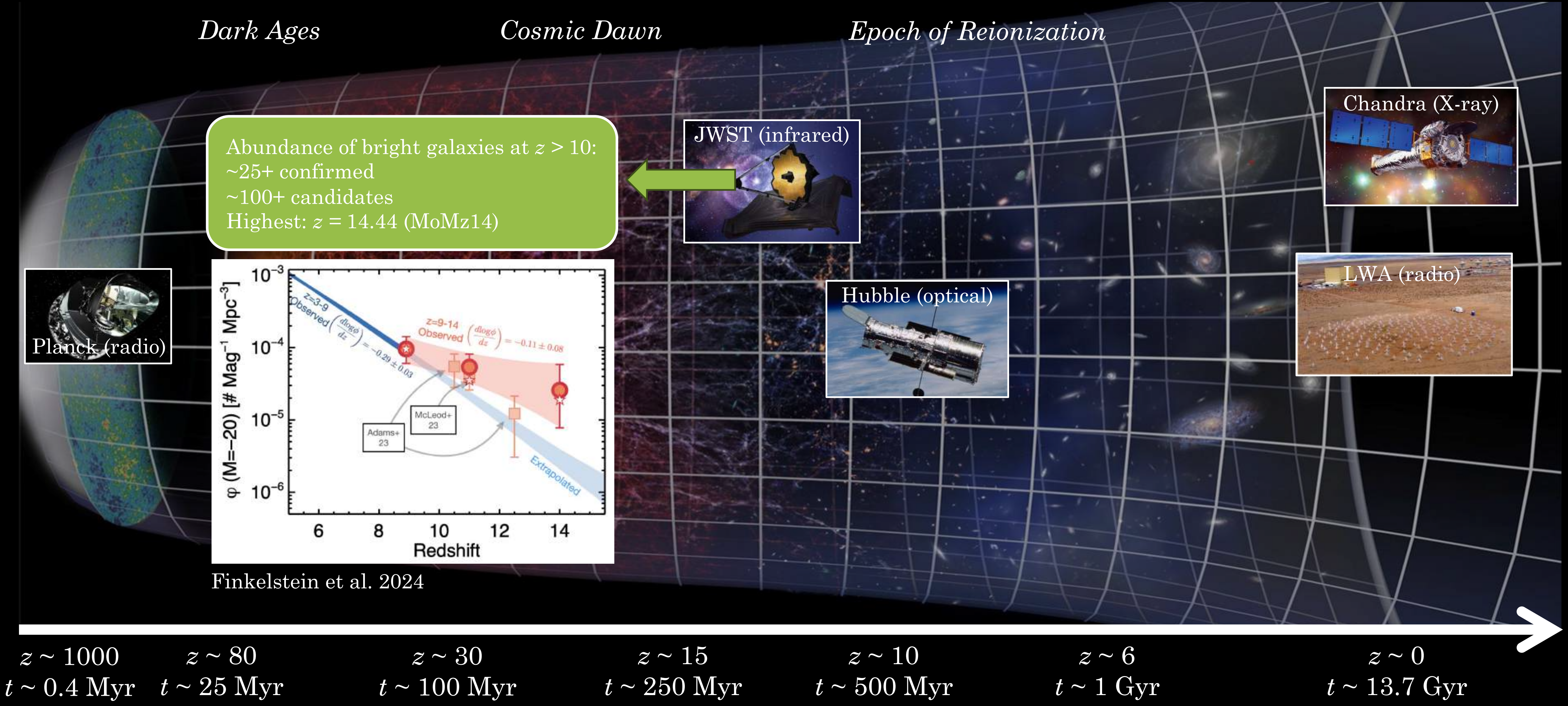

Towards a multi-wavelength picture

$$T_{21} \propto x_{\mathrm{HI}} \left[1 - \frac{T_{\mathrm{rad}}}{T_S(T_K, \mathrm{Ly}\alpha)} \right]$$

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21-cm signal
(SARAS3 non detection, HERA limits)

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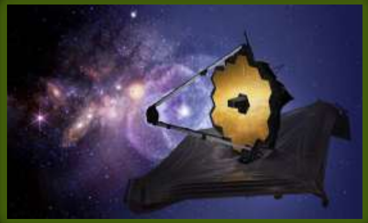

Galaxy UVLFs
(HST, JWST)

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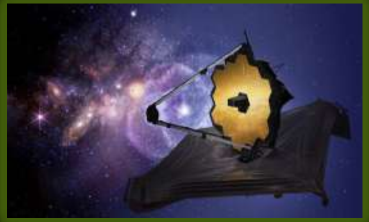

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Cosmic X-ray bg.
(Chandra, HEAO, Swift BAT, etc.)
(see e.g. Fialkov et al. 2017)

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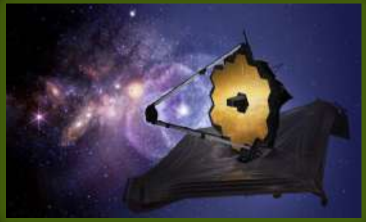

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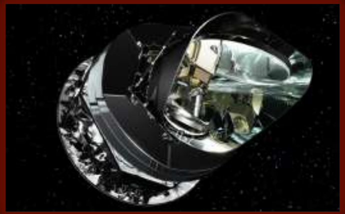

Neutral fraction
(Planck τ_{CMB} measurement)

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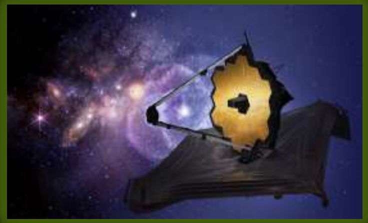

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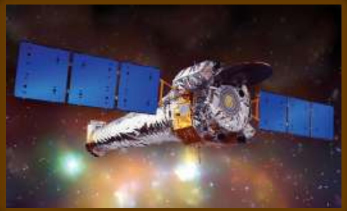

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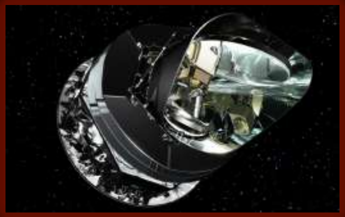
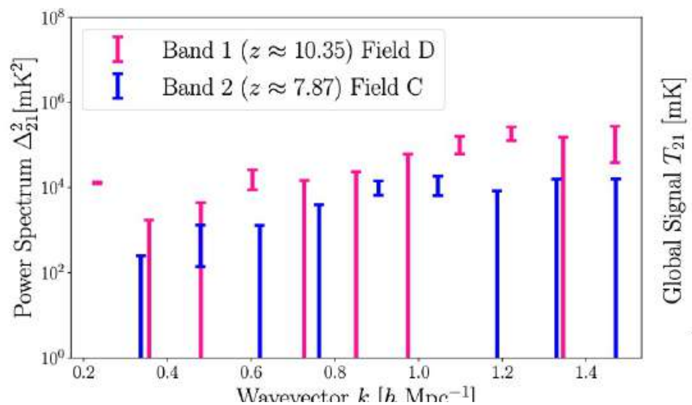


Neutral fraction
(Planck τ_{CMB} measurement)

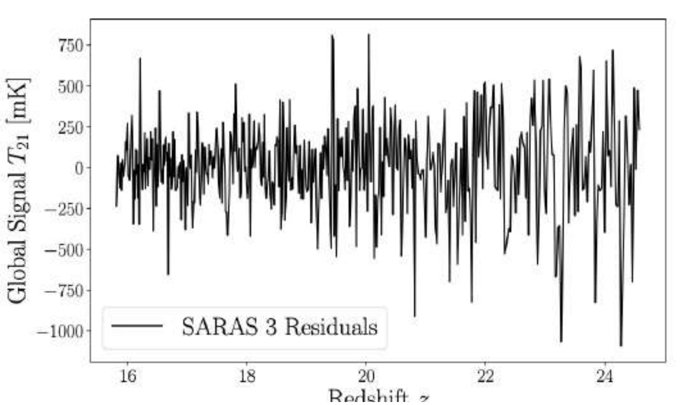
Cosmic radio bg.
(ARCADE2, LWA1, Haslam, etc.)

Multi-wavelength data

HERA Phase 1



SARAS 3 non detection

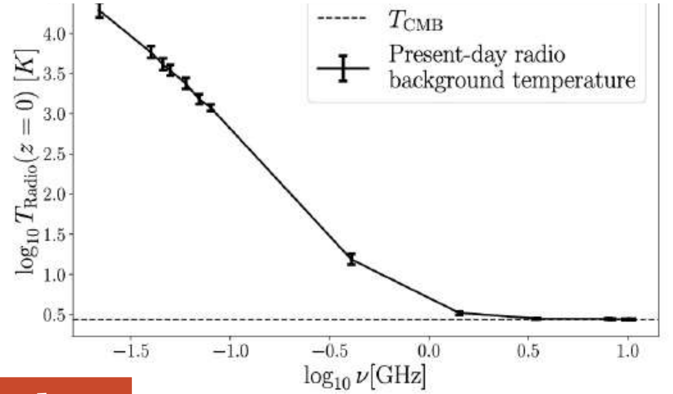


Chandra+

Data set	Integrated X-ray background S [erg cm^{-2} s^{-1} deg^{-2}]
1 – 2 keV Hickox & Markevitch (2006)	$(1.04 \pm 0.14) \times 10^{-12}$
2 – 8 keV Hickox & Markevitch (2006)	$(3.4 \pm 1.7) \times 10^{-12}$
8 – 24 keV Harrison et al. (2016)	$(1.832 \pm 0.042) \times 10^{-11}$
20 – 50 keV Harrison et al. (2016)	$(1.998 \pm 0.083) \times 10^{-11}$

(c)

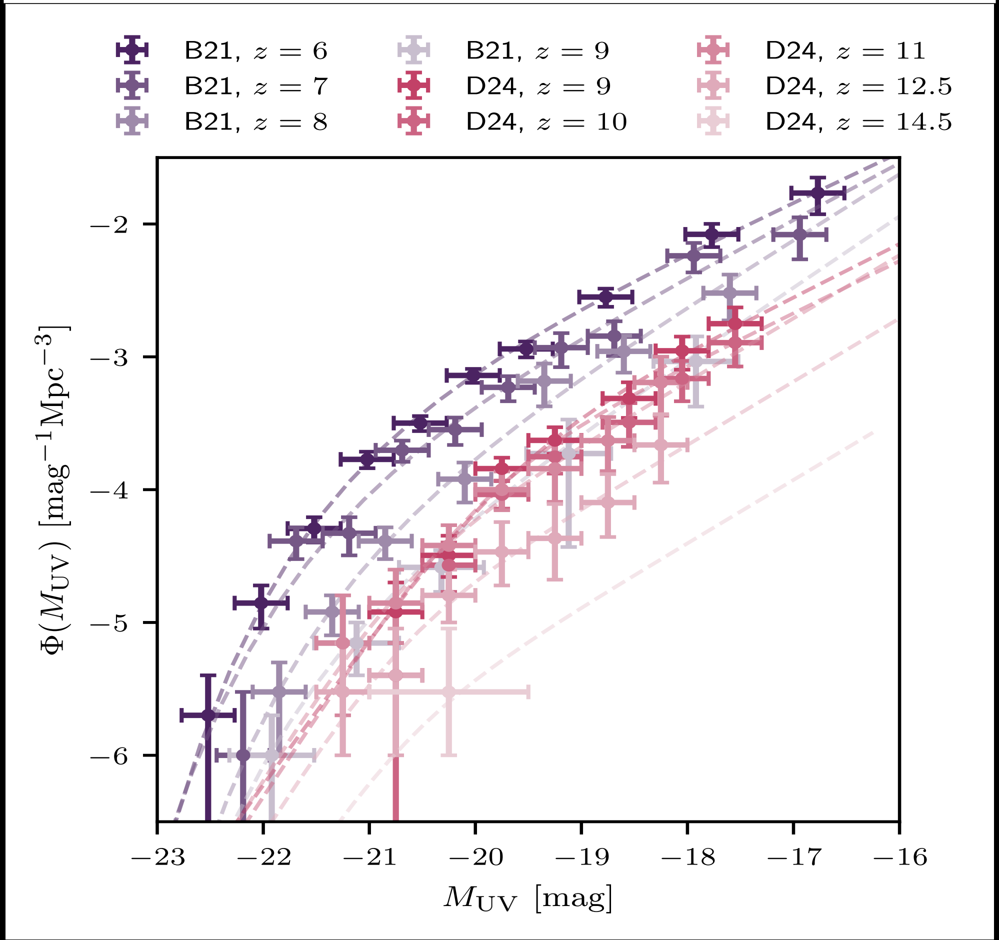
ARCADE2 / LWA1+



(d)

+ Planck τ

HST/JWST UVLFs at $z = 6 - 15$

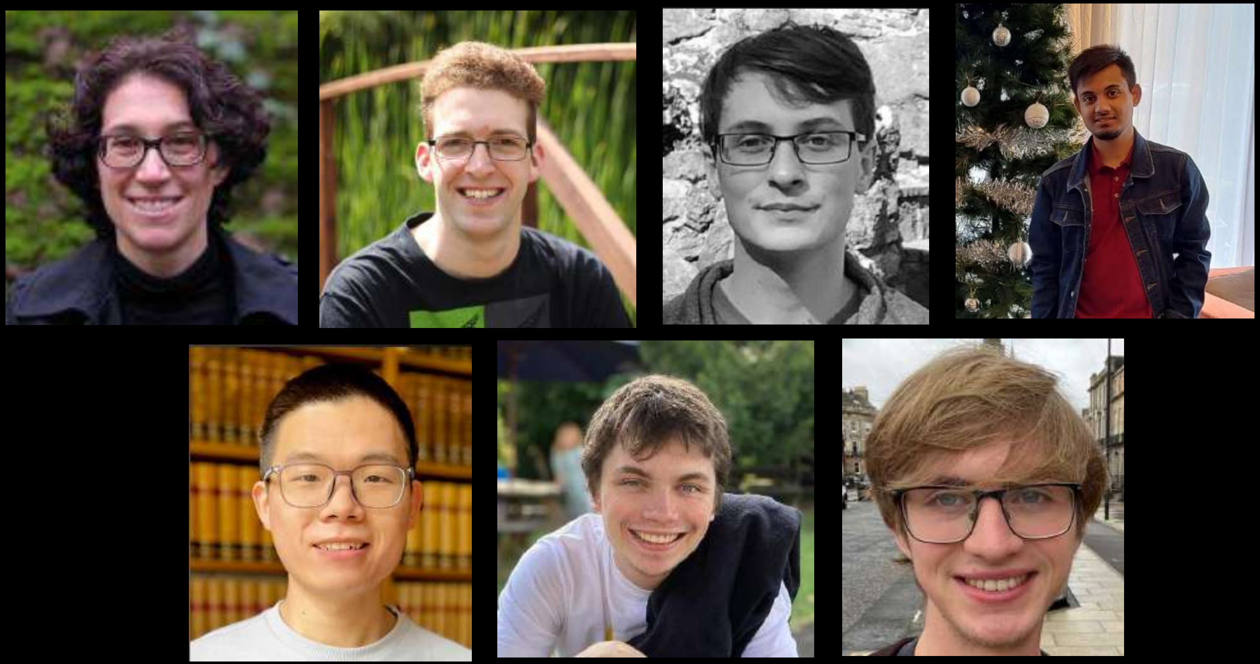


Pochinda et al. (2024; arXiv:2312.08095)

Dhandha et al. (2025a; arXiv:2503.21687)

The simulation

- **21cmSPACE** (**S**emi-numerical **P**redictions **A**cross **C**osmological **E**pochs)



- Faster than numerical simulations (~3hr) → Easy to explore parameter space!

Analytic halo and star-formation prescription + Numerical radiative transfer

The inference pipeline

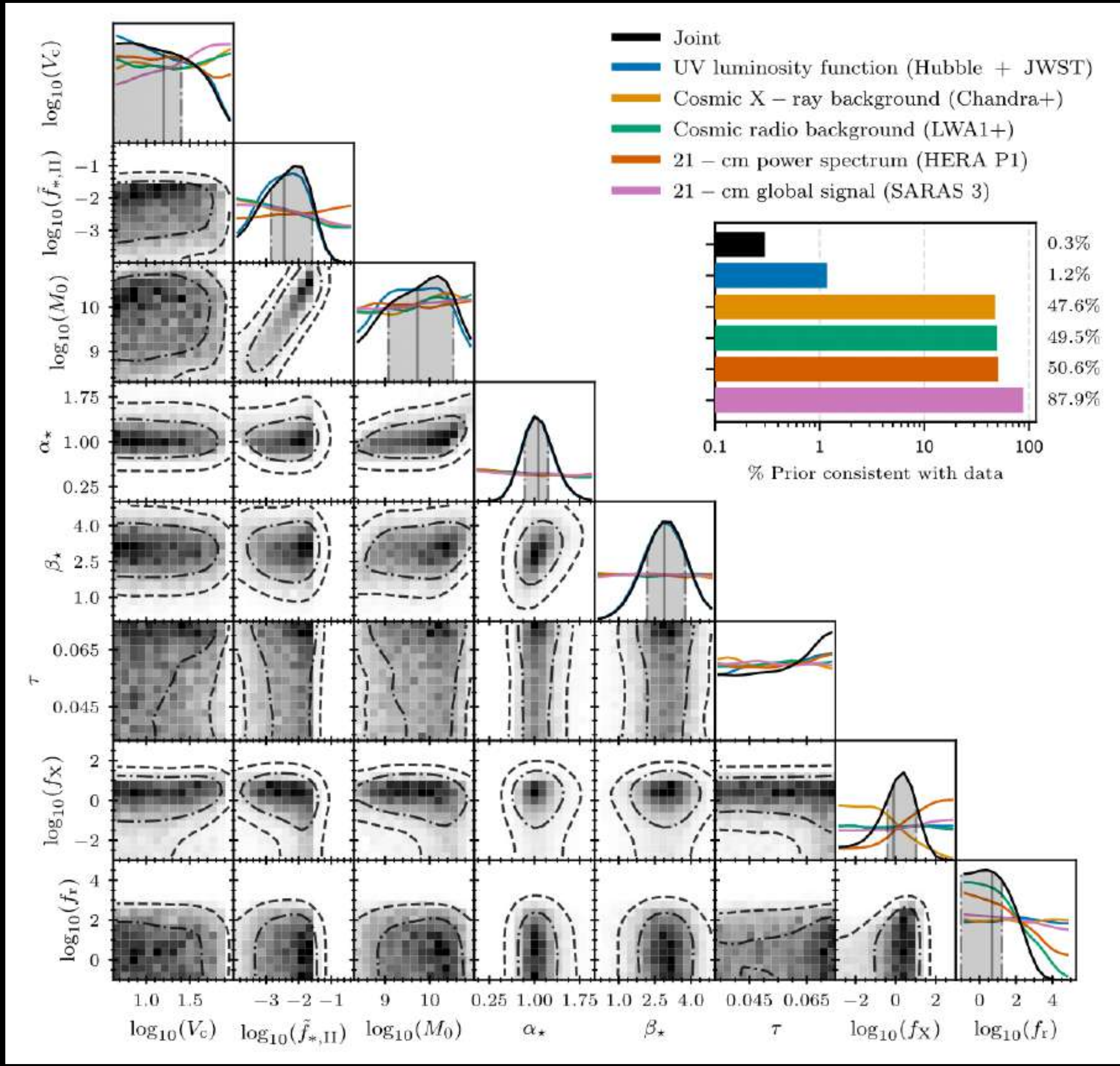
Construct 7D parameter space
$V_c, f_{\star,\mathrm{II}}, M_0, \alpha_\star, \beta_\star, f_X, f_{\mathrm{rad}}$

Extract 5 observables of interest:
X-ray background, radio background, 21-cm statistics, UVLFs

Train NNs to emulate the observables

Perform classical Bayesian inference to get your astrophysical constraints

Profit???



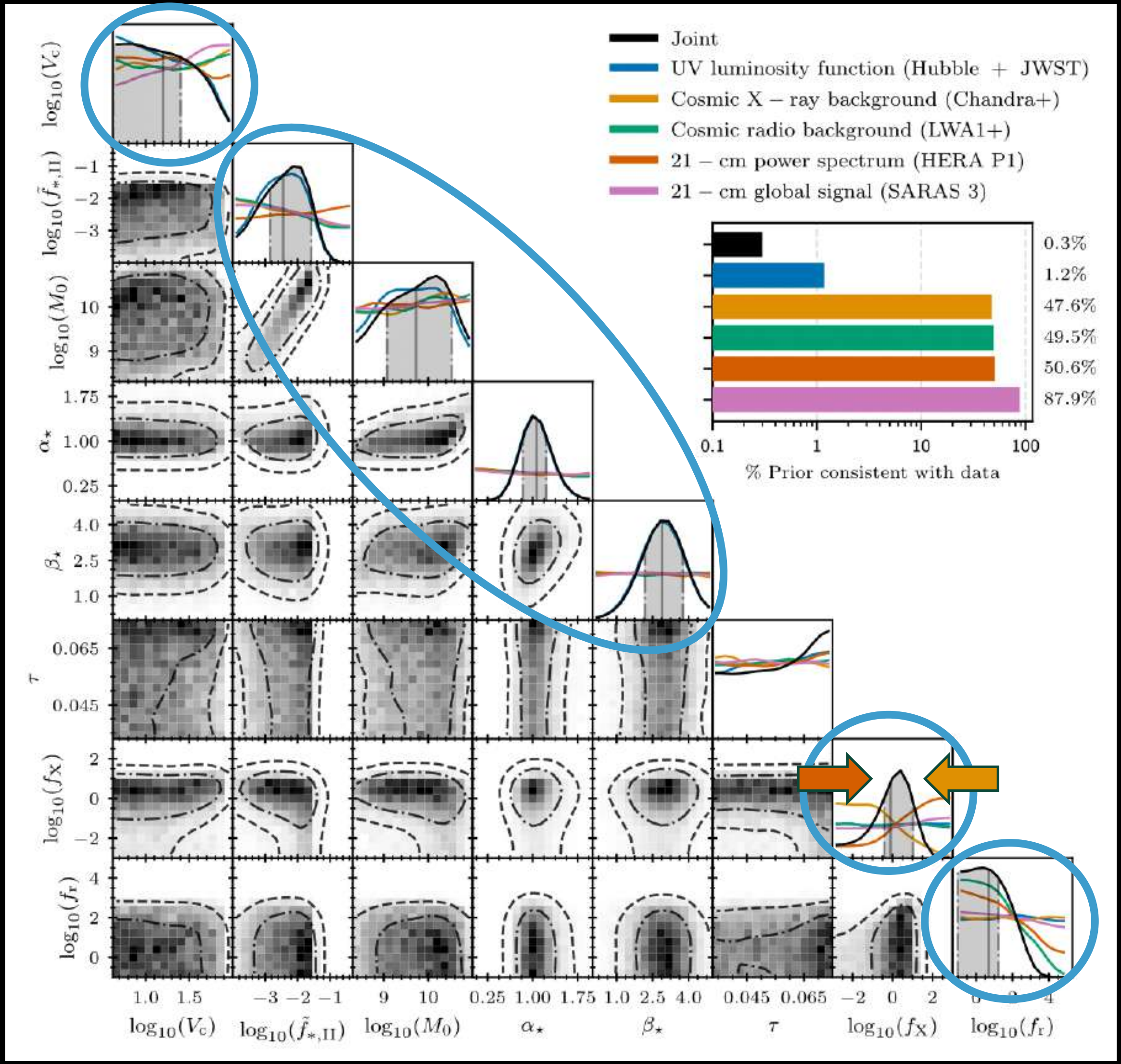
The inference pipeline

→ $V_c \lesssim 25\ km/s$
- SARAS3 prefers high threshold for star-forming halos
- UVLFs disfavours that by direct galaxy observation

→ $\tilde{f}_*, M_0, \alpha_*, \beta_*$
- SFE constrained by HST/JWST UVLFs

→ $f_X = 0.8^{+9.7}_{-0.4}$
- HERA disfavours weak IGM heating
- CXB disfavours strong IGM heating

→ $f_r \lesssim 17$
- HERA and CRB both strongly disfavour excess radio background



What can we learn?

Galactic properties

IGM properties

21-cm signal

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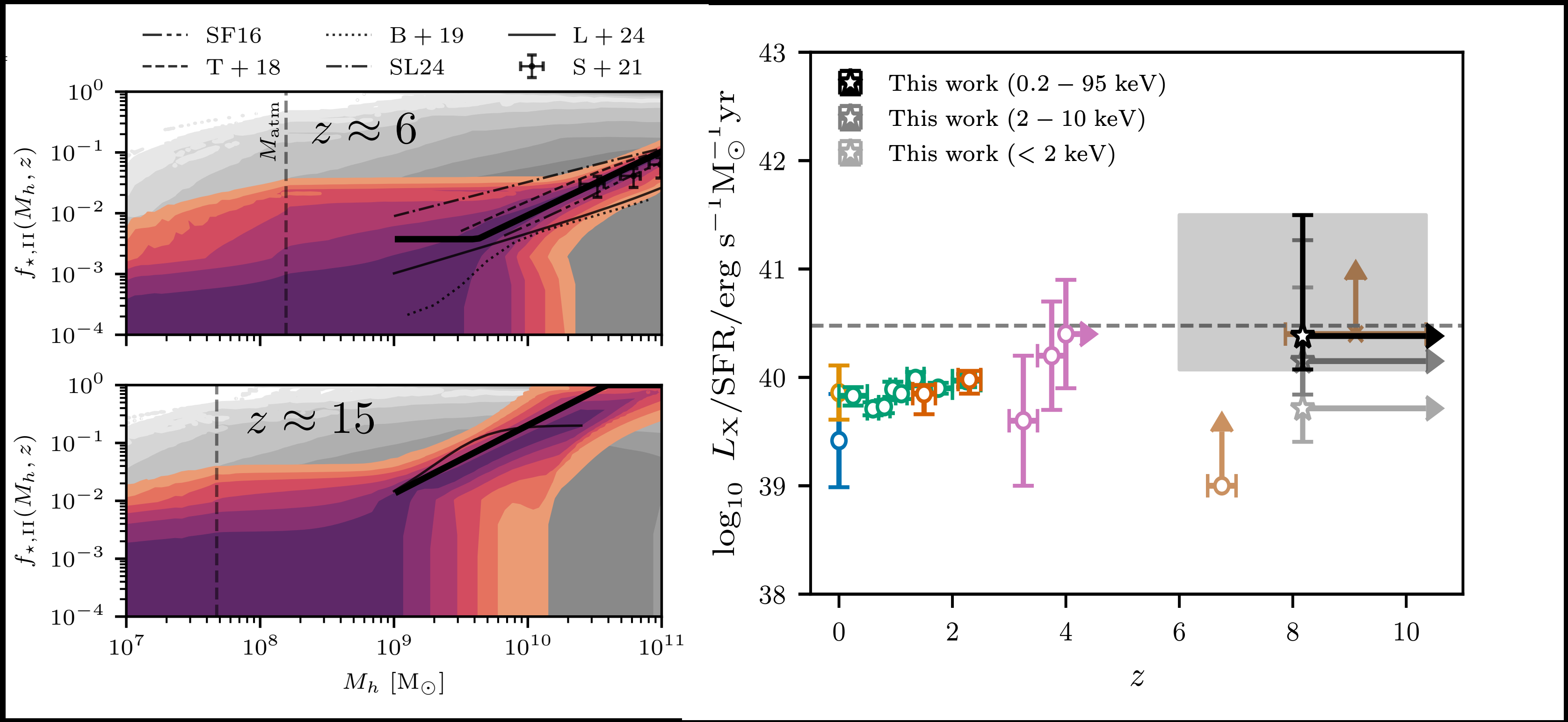
Galactic properties | IGM properties | 21-cm signal

- Star-formation efficiency increases with redshifts at z > 10
- X-ray efficiency ~ expected low-metallicity HMXBs



Star-formation efficiency:

$$f_{\star,\rm II} \approx \begin{cases} 2\% & z \lesssim 10 \\ 8\% & z \approx 12 \\ 21\% & z \approx 15 \end{cases}$$

X-ray efficiency:

$$\log L_X/{\rm SFR} = 40.4^{+1.1}_{-0.3}$$

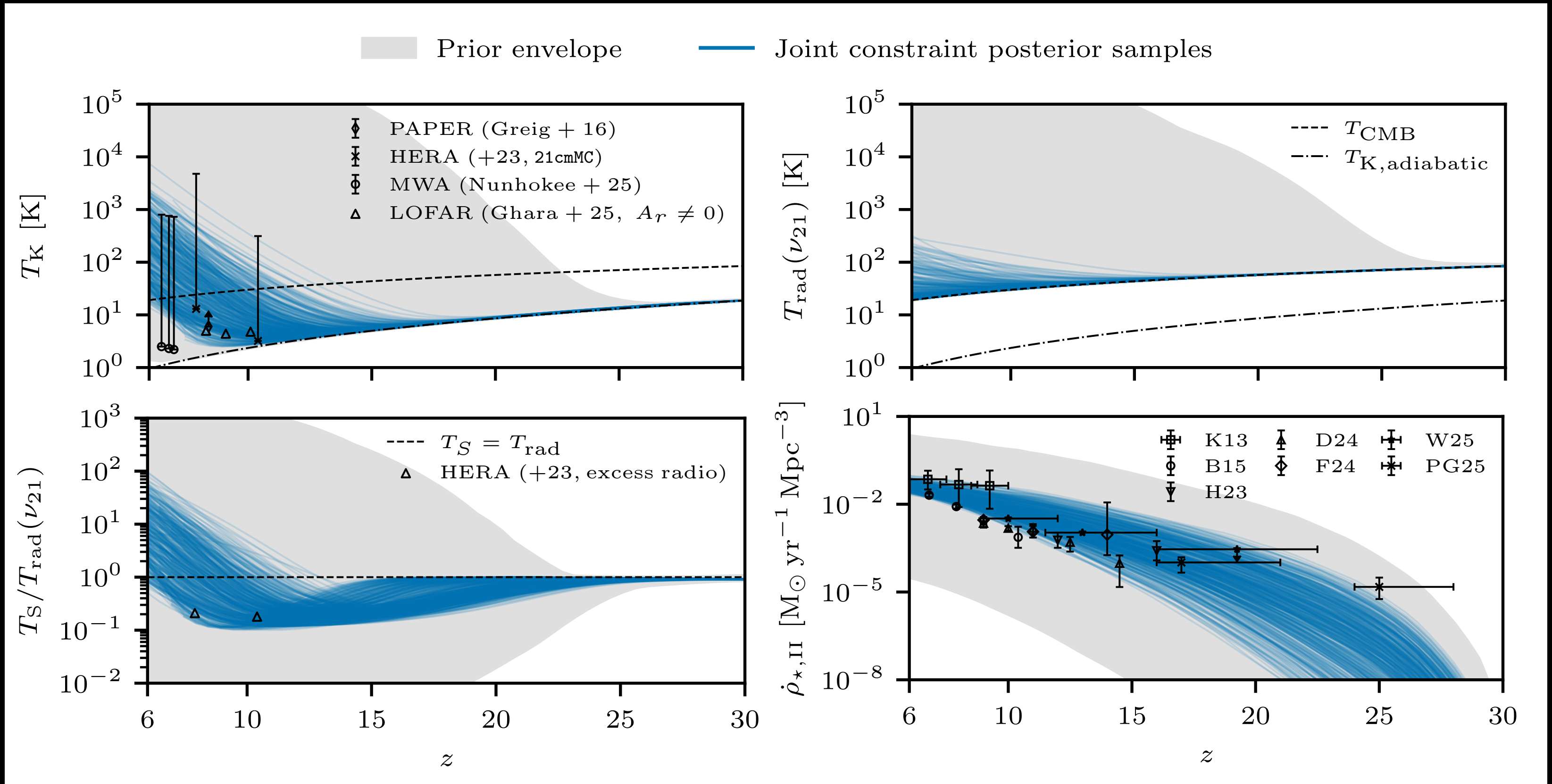
Radio efficiency:

$$\log L_r/{\rm SFR} \lesssim 23.2$$

What can we learn?

Galactic properties | **IGM properties** | 21-cm signal

- Matter temperature, radio temperature, spin temperature, SFRD



Matter temperature:

$T_{K,adb} \approx T_K(z=15) \sim 6\,K$

$T_{K,adb} < T_K(z=10) < 2T_{CMB}$

$T_{CMB} < T_K(z=6) \lesssim 2000\,K$

Radio temperature:

$T_{CMB} \leq T_{rad}(z=15) \lesssim 47\,K$

$T_{CMB} \leq T_{rad}(z=10) \lesssim 50\,K$

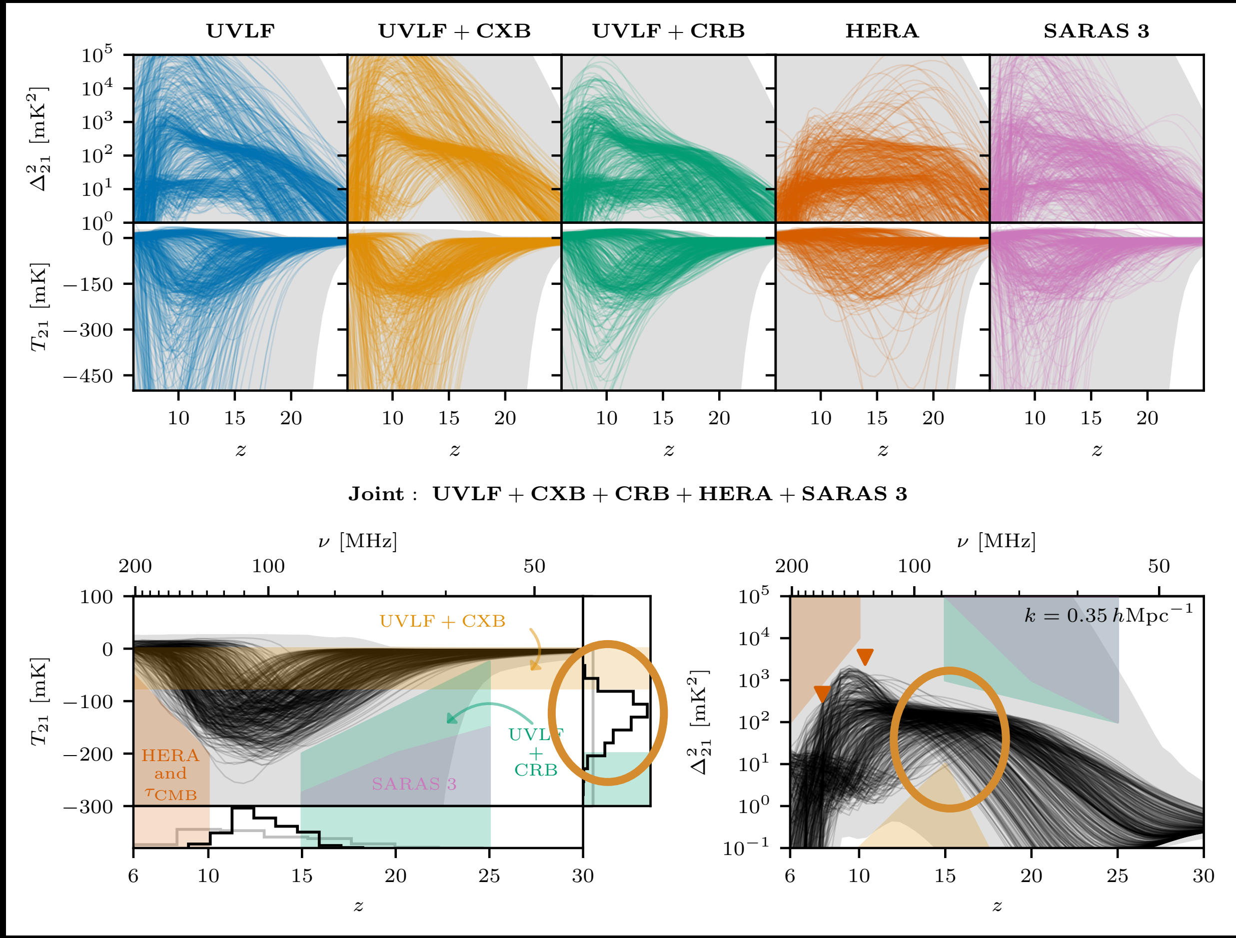
$T_{CMB} \leq T_{rad}(z=6) \lesssim 100\,K$

Spin temperature: !!!!

What can we learn?

Galactic properties | IGM properties | **21-cm signal**

- Promising 21-cm global signal and power spectrum limits!



21-cm global signal:

$$-200\,\mathrm{mK} \lesssim T_{21,\mathrm{min}} \lesssim -70\,\mathrm{mK}$$
$$10 \lesssim z_{\mathrm{min}} \lesssim 16$$
$$130\,\mathrm{MHz} \lesssim \nu_{\mathrm{min}} \lesssim 85\,\mathrm{MHz}$$

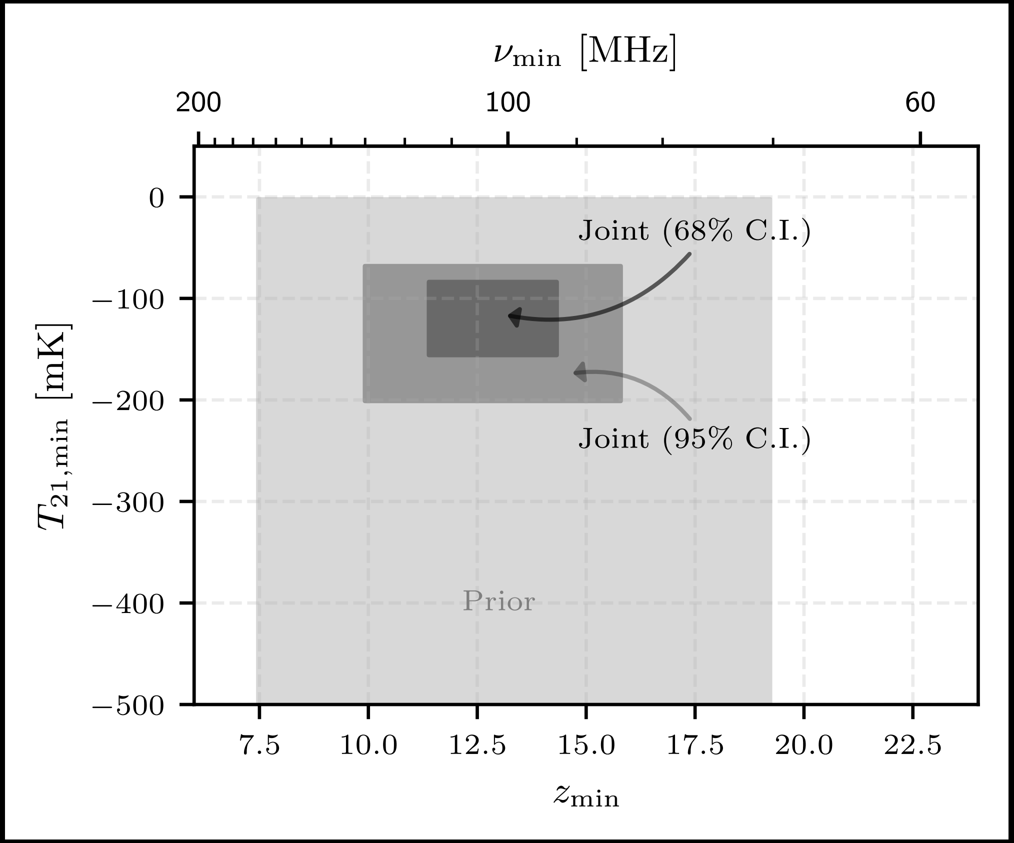
21-cm power spectrum:

$$9\,\mathrm{mK}^2 \lesssim \Delta^2_{21}(z=15) \lesssim 200\,\mathrm{mK}^2$$
$$\Delta^2_{21}(z=10) \lesssim 1000\,\mathrm{mK}^2$$
$$\Delta^2_{21}(z=8) \lesssim 180\,\mathrm{mK}^2$$

What can we learn?

Galactic properties | IGM properties | 21-cm signal

- A 'treasure-map' / discovery space for observers



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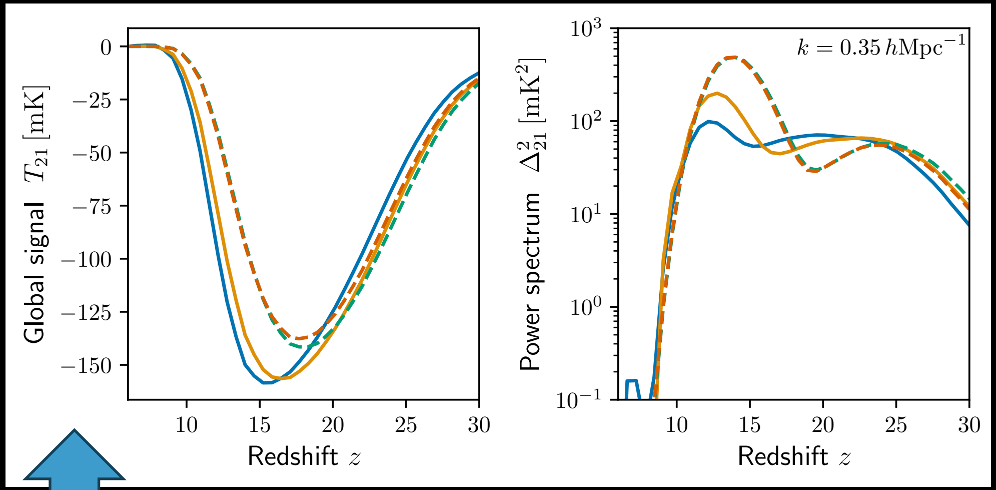
Caveats?

YES :(

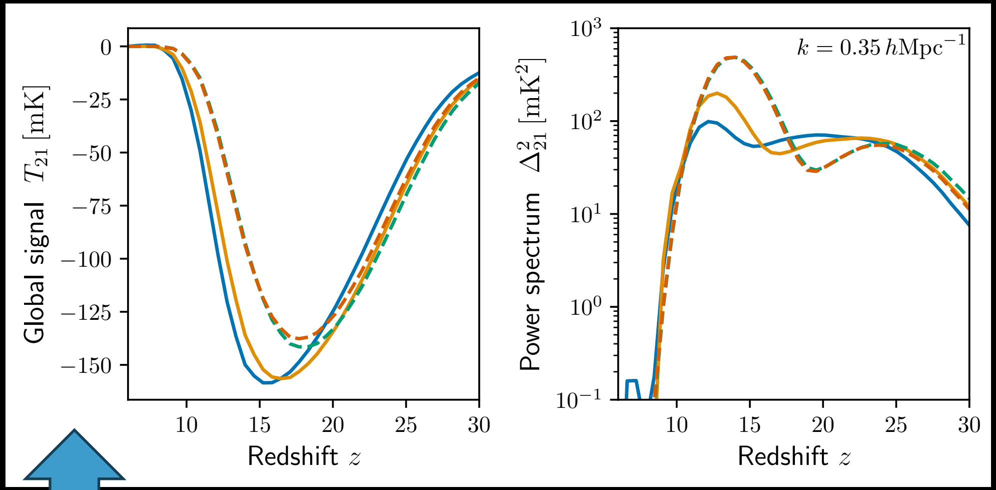
(everything is model dependent)

Caveats?



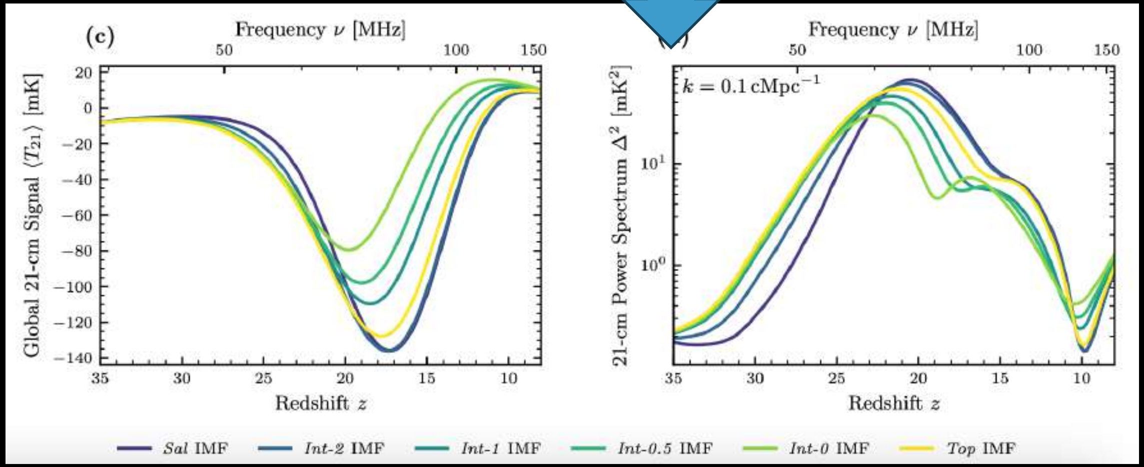
Rotating Pop III stars can ionize the Universe early!

Caveats?



Rotating Pop III stars can ionize the Universe early!

Some Pop III IMFs can heat the Universe early!



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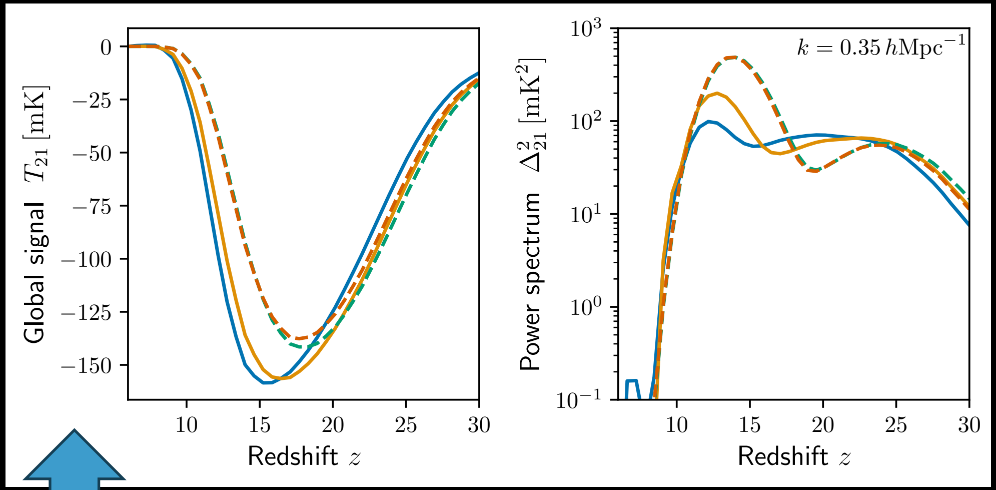

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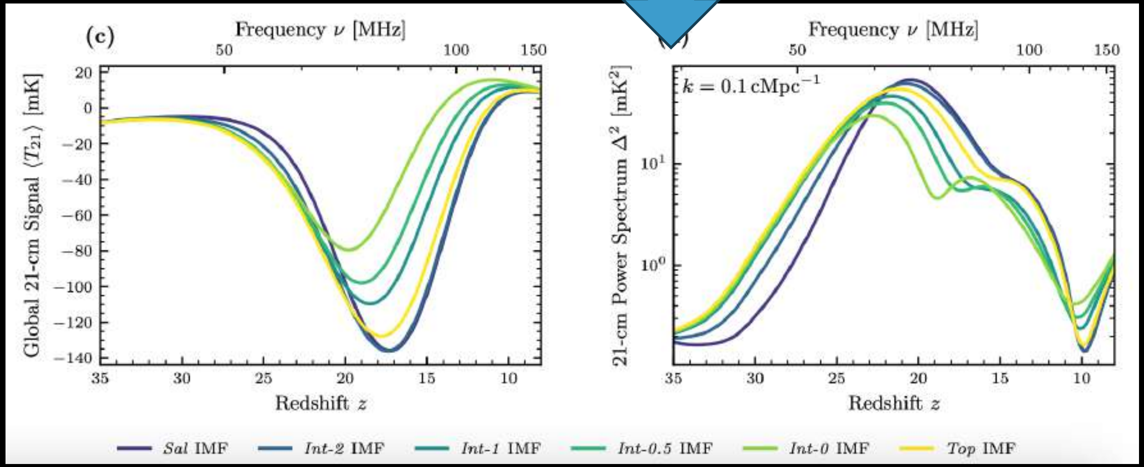

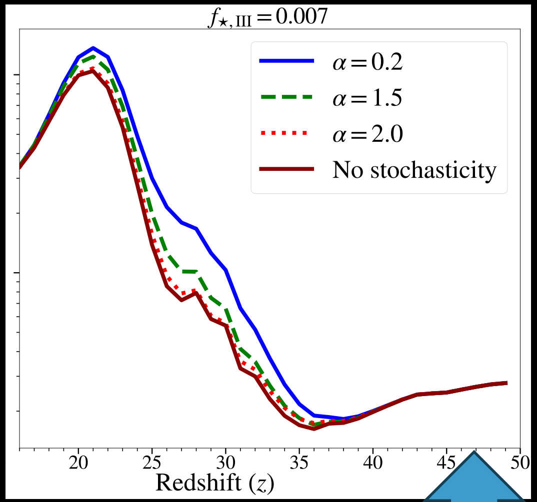

Pop III stochasticity can affect the PS!

Conclusions

Multi-wavelength constraints are cool and promising, but there's still lot to be done!

Star-formation efficiency:

$$f_{\star,\mathrm{II}} \approx \begin{cases} 2\% & z \lesssim 10 \\ 8\% & z \approx 12 \\ 21\% & z \approx 15 \end{cases}$$

X-ray efficiency:

$$\log L_X/\mathrm{SFR} = 40.4^{+1.1}_{-0.3}$$

Radio efficiency:

$$\log L_r/\mathrm{SFR} \lesssim 23.2$$

→

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Me realizing how much time I have to finish my PhD thesis (c. 2026)

I'll be at Kavli IPMU, Tokyo starting Sept 2026. I'd love to collaborate and start new projects, so please send me a message: **jitendhandha.com / jvd29@cam.ac.uk**.