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21cm Cosmology Workshop 2023 & Tianlai Collaboration Meeting

The 21-cm forest as a simultaneous probe of dark matter and cosmic heating history

Yue Shao

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Shao et al. 2023, Nature Astronomy (arXiv:2307.04130)

https://www.nature.com/articles/s41550-023-02024-7

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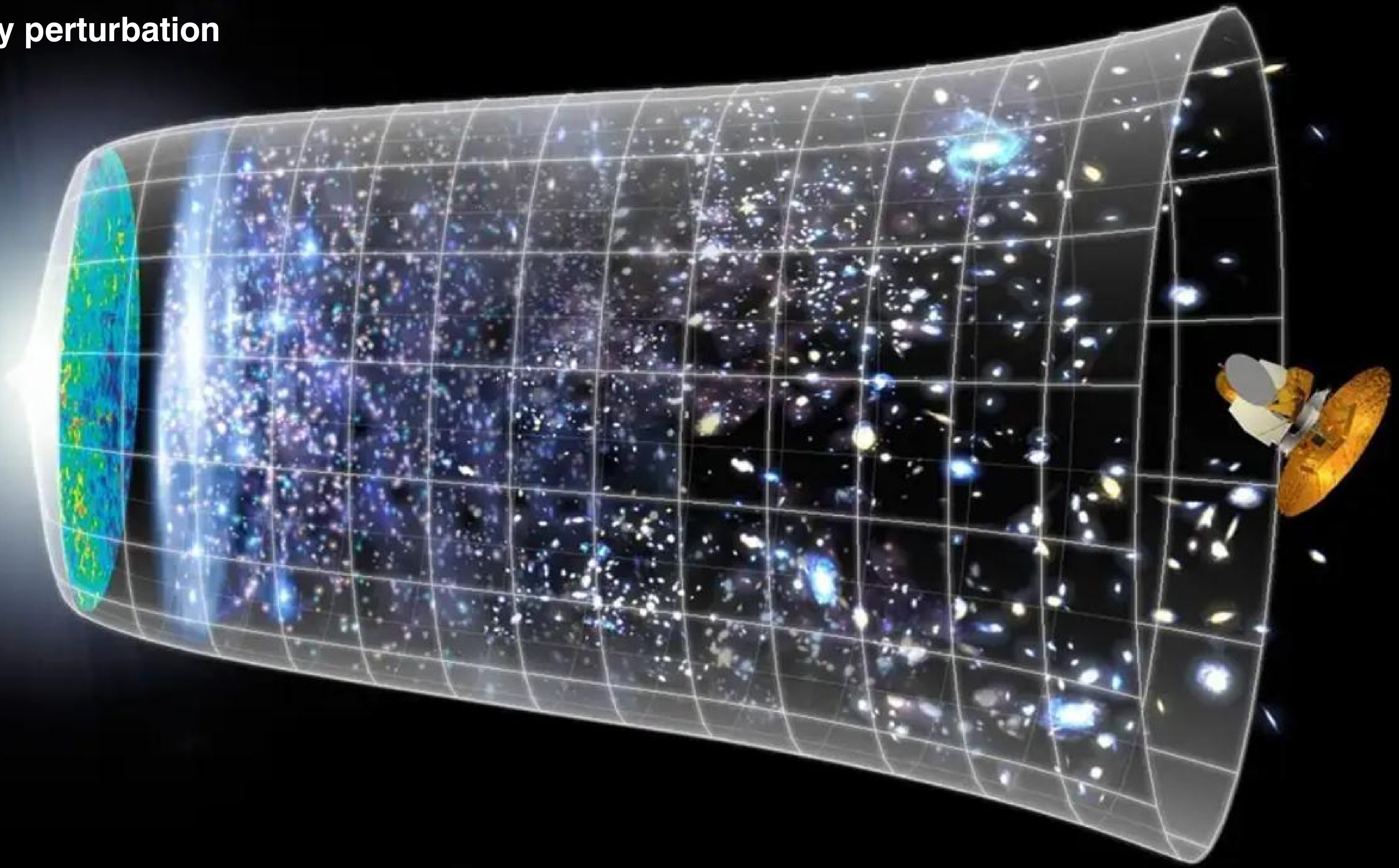
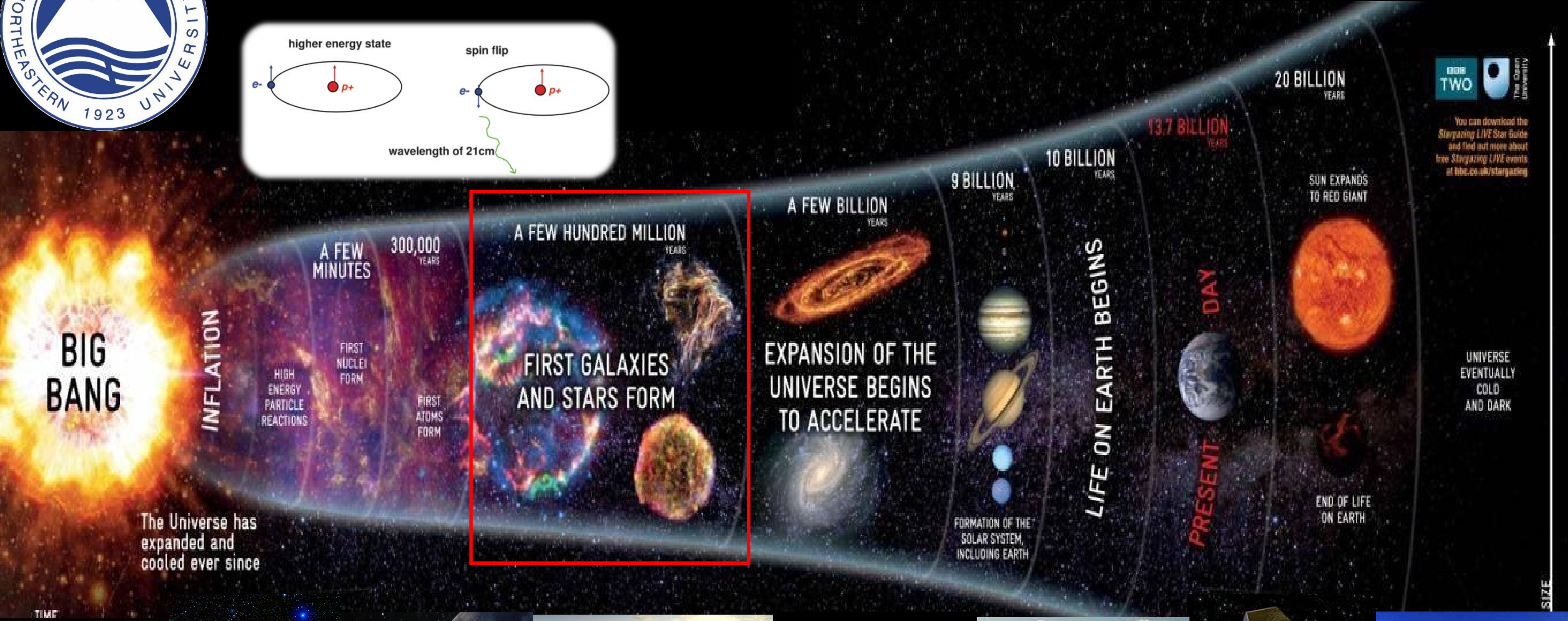
Dark matter
Dark energy
Primordial density perturbation
First galaxies
First black holes
Thermal history
Ionization history

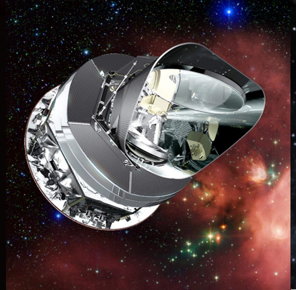
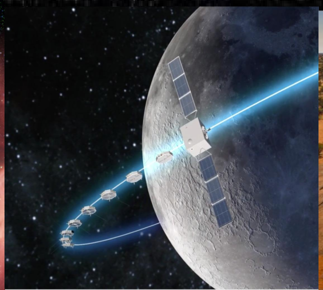
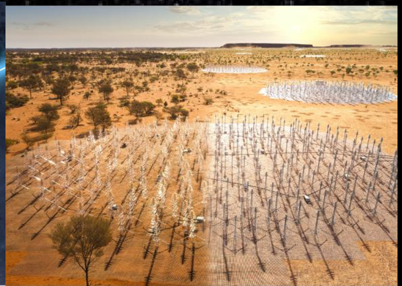
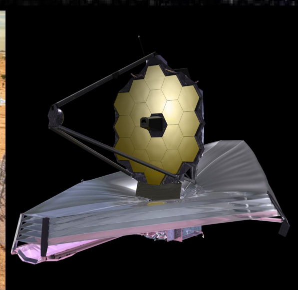
The origin and evolution of the structure of the universe

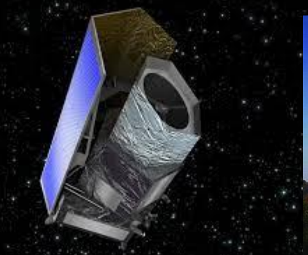
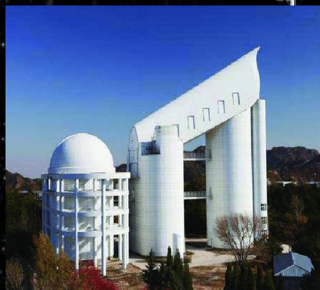


Credit: Wesson 1999

The 21-cm line: Exploring the first billion years



21-cm probe of the cosmic dawn

CMB as background

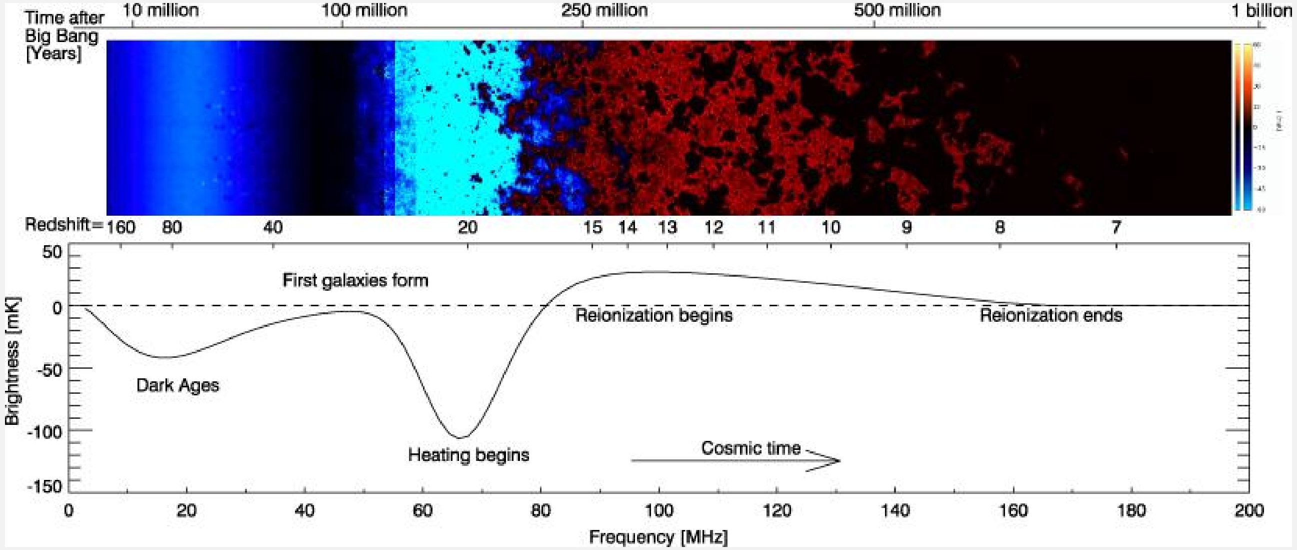
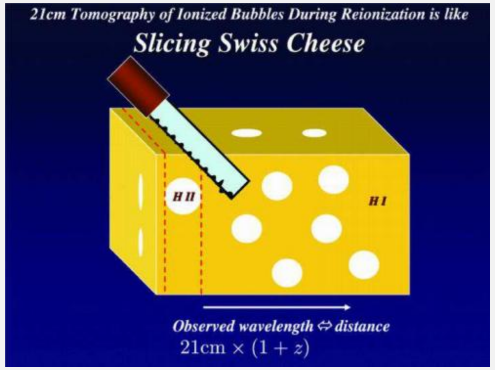


Image credit: Pritchard & Loeb 2012

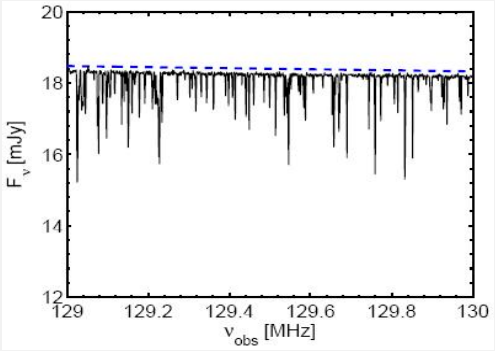
- all-sky averaged spectrum
- **21-cm tomography**



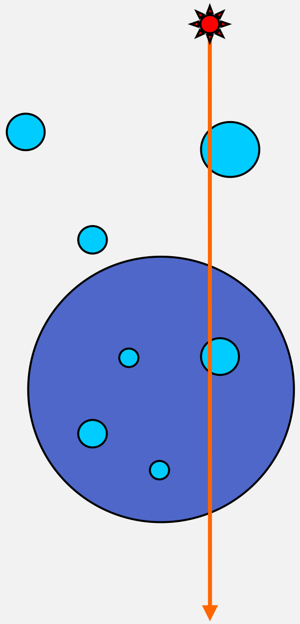
Loeb 2009

Point source as background

- **21-cm forest**



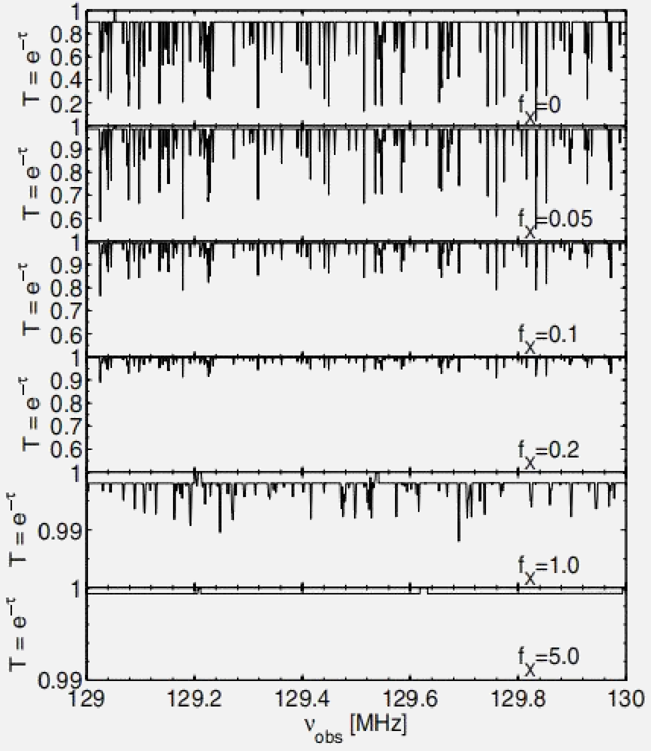
Xu et al. 2011 MNRAS



21-cm Forest

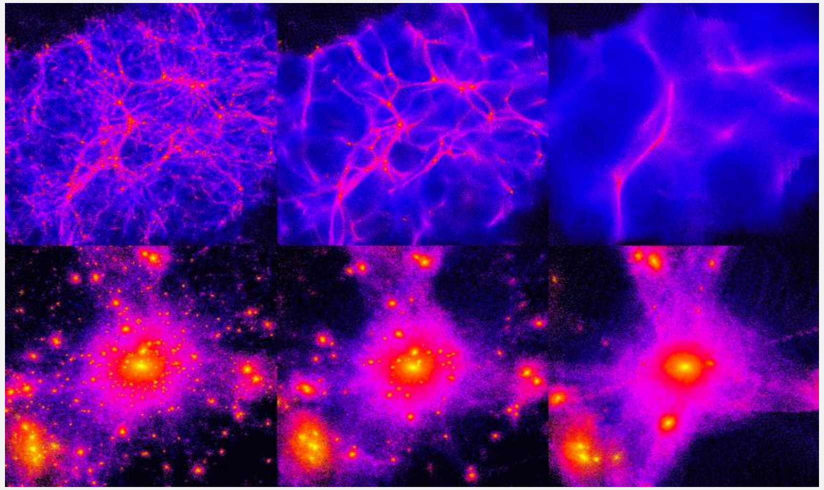
- **Sensitive probe to T_{IGM}**

$$\tau \propto \frac{1}{T_S}$$

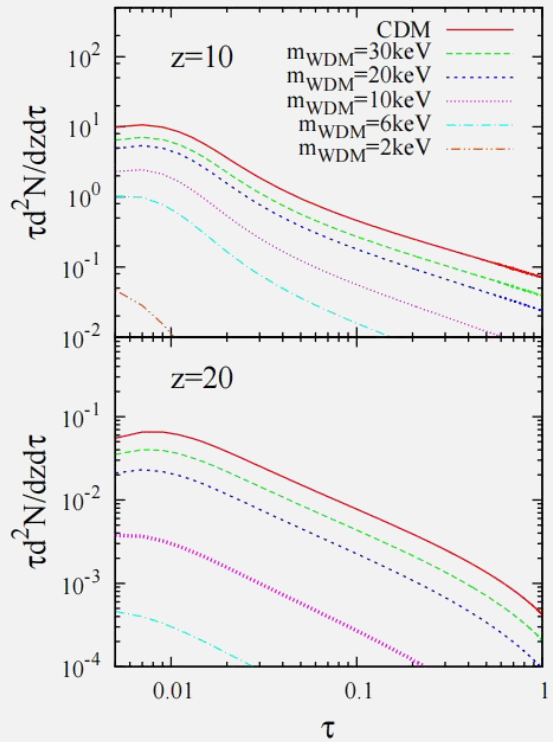


Xu et al. 2009, 2010, 2011

- **Unique probe to small–scale structures at cosmic dawn → Dark Matter properties**



CDM WIMP/AXION — WDM Sterile Neutrino — HDW 3 Neutrinos



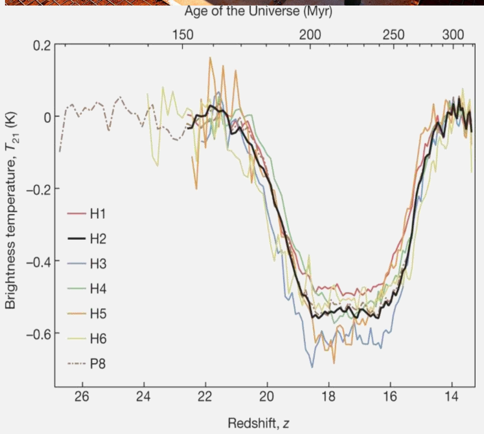
Shimabukuro et al. 2014

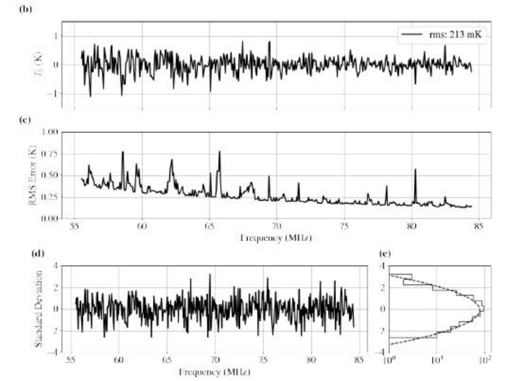
21-cm Forest: never even tried

- **21-cm global spectrum**

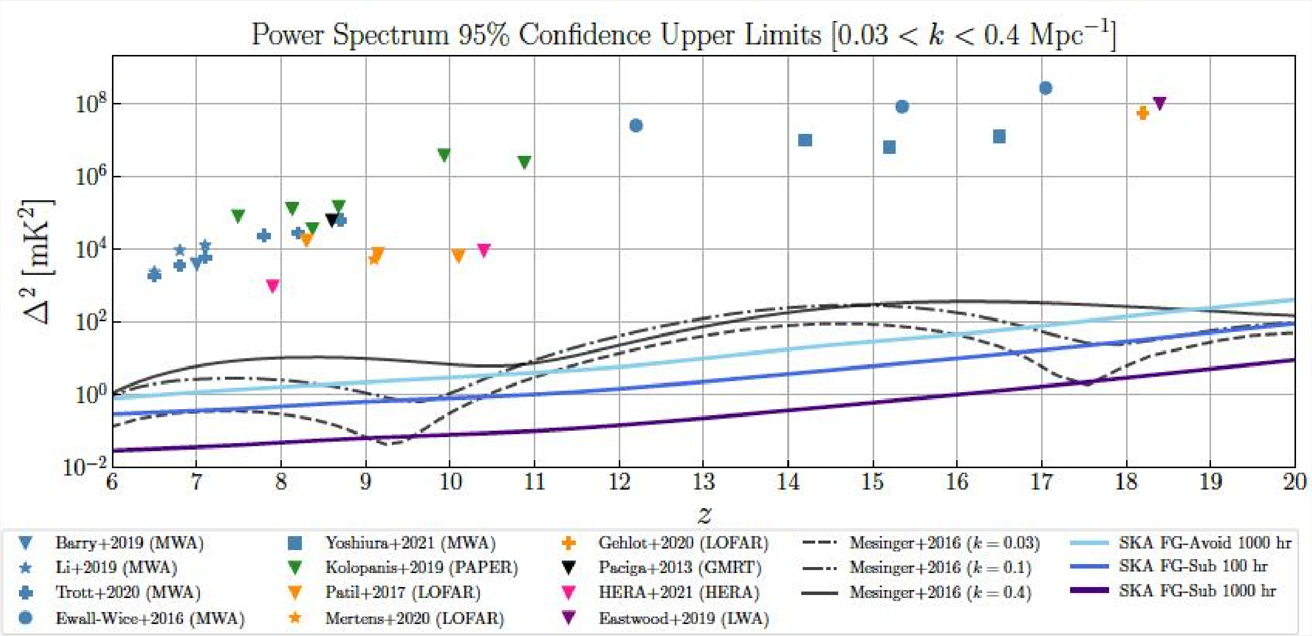
EDGES-Low-band

SARAS 3





- **21-cm tomography**



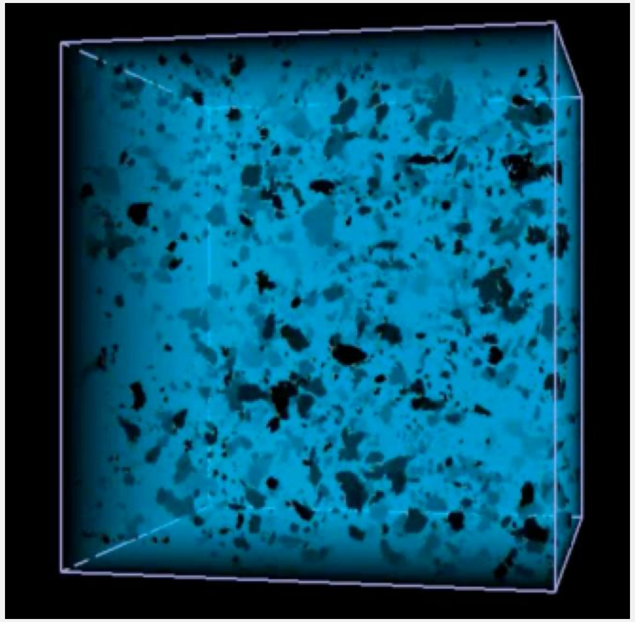
Barry et al. arXiv:2110.06173

Theoretical challenges

Large-scale environment: $\rho(\vec{x})$, $x_i(\vec{x})$, $T(\vec{x})$.

Main contributor: minihalos & ambient IGM

1 Gpc



islandFAST, Xu et al. 2017

Over 5 orders of magnitude

6 kpc (z=9)

10^6 M$_\odot$

ρ & T_K profiles,

Local x_i & v,

T_S coupling

(collisional, Lyα, CMB)

……

$$\tau_{\nu_0}(\hat{\boldsymbol{s}}, z) \approx 0.0085[1+\delta(\hat{\boldsymbol{s}}, z)](1+z)^{3/2}\left[\frac{x_{\mathrm{HI}}(\hat{\boldsymbol{s}}, z)}{T_{\mathrm{S}}(\hat{\boldsymbol{s}}, z)}\right]\left[\frac{H(z)/(1+z)}{\mathrm{d}v_{\|}/\mathrm{d}r_{\|}}\right]\left(\frac{\Omega_{\mathrm{b}} h^2}{0.022}\right)\left(\frac{0.14}{\Omega_{\mathrm{m}} h^2}\right)$$

Observational challenges

Probing thermal history: easily suppressed

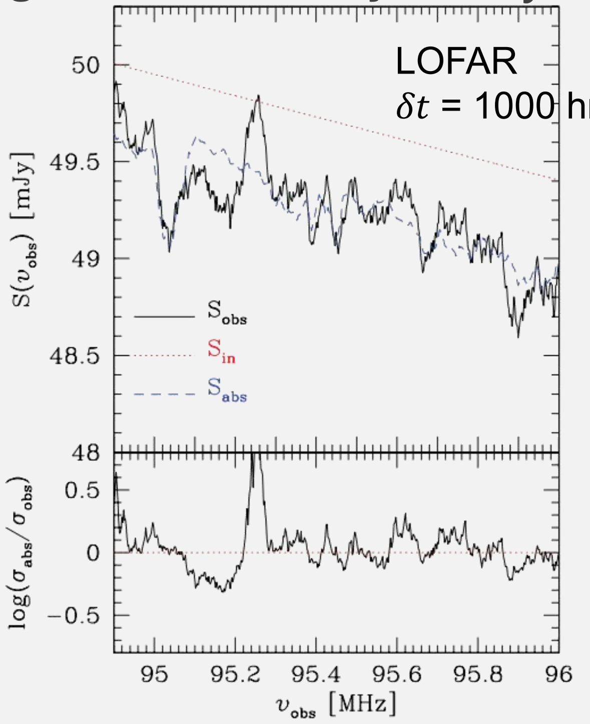
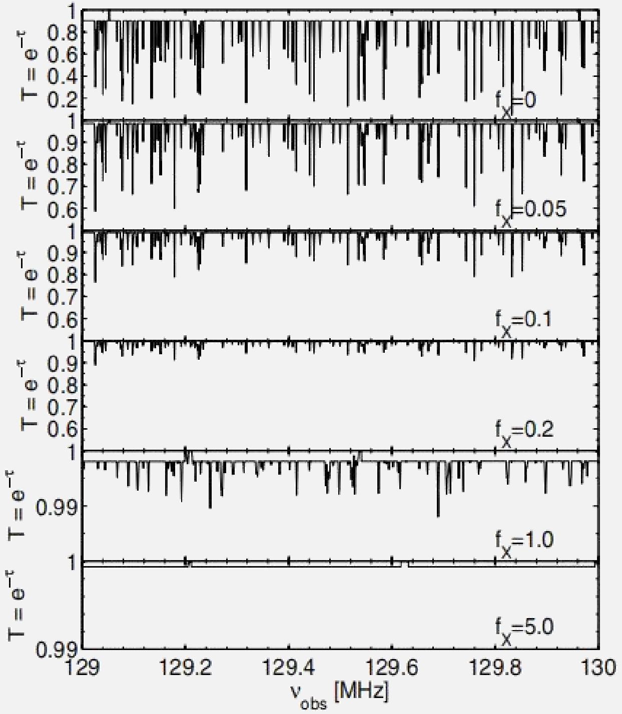


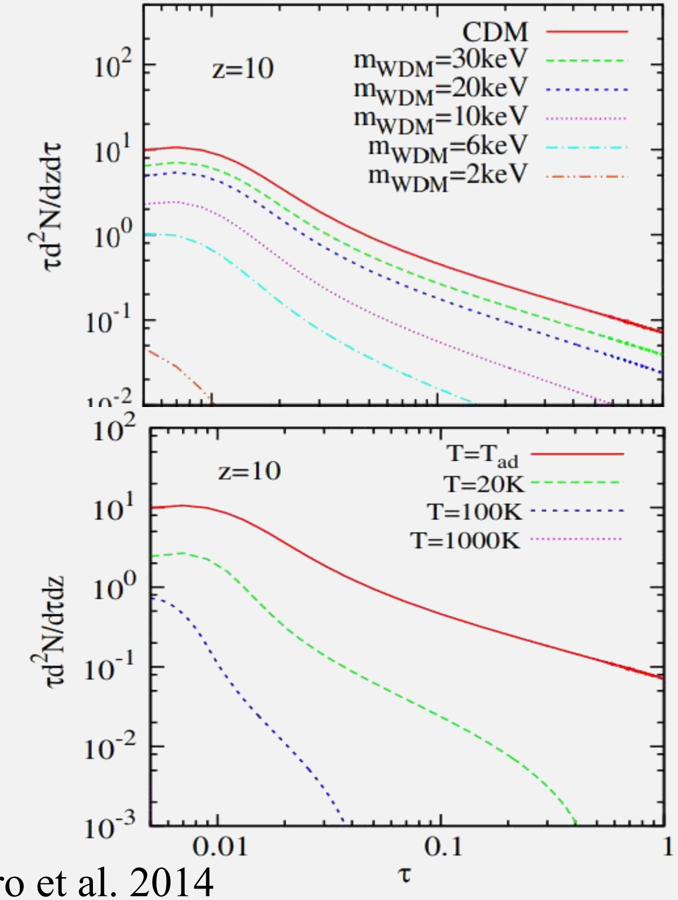
Figure 13. Upper panel: spectrum of a source positioned at $z = 14$ (i.e. $\nu \sim 95$ MHz), with an index of the power law $\alpha = 1.05$ and a flux density $S_{in}(z_s) = 50$ mJy. The lines are the same as those in Fig. 10. Here we have assumed the noise σ_n given in equation (3), a bandwidth $\Delta\nu = 20$ kHz, smoothing over a scale $s = 20$ kHz and an integration time $t_{int} = 1000$ h. The IGM absorption is calculated from the reference simulation $\mathcal{L}4.39$.

Ciardi et al 2013



Xu et al. 2011

Constraining DM: degenerate with astrophysics



Shimabukuro et al. 2014

Key strategy #1: multi-scale hybrid modeling

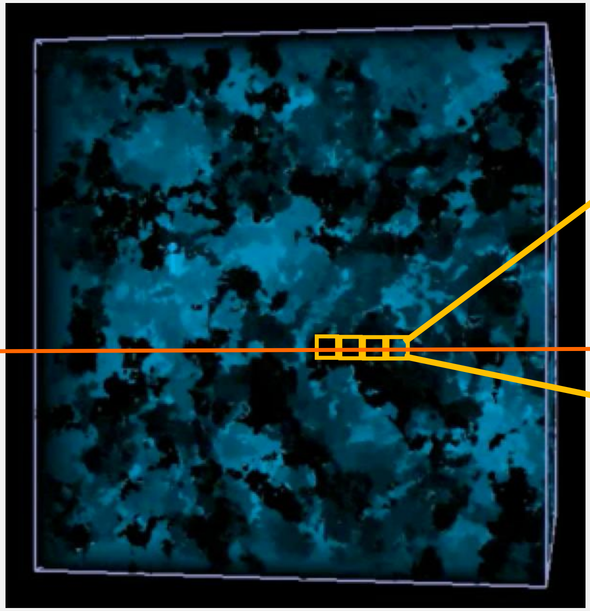
Large scales: semi-numerical simulation

Small scales: analytic modeling

Box $(1\ \text{Gpc})^3$ → Grid $(2\ \text{Mpc})^3$ → Voxel $(4\ \text{kpc})^3$

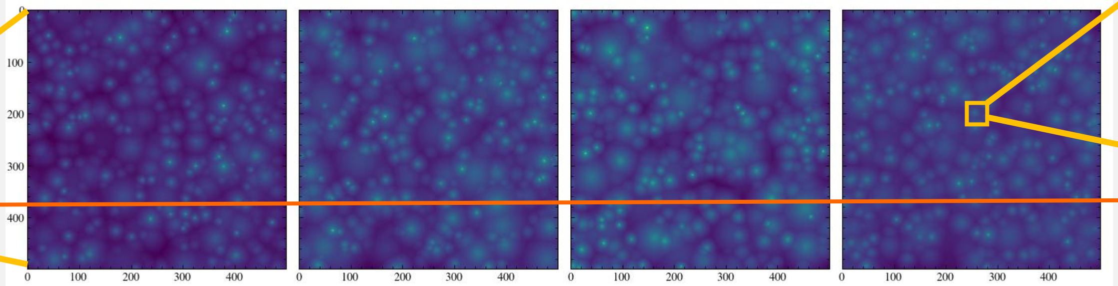
~ kpc

Conditional halo mass function

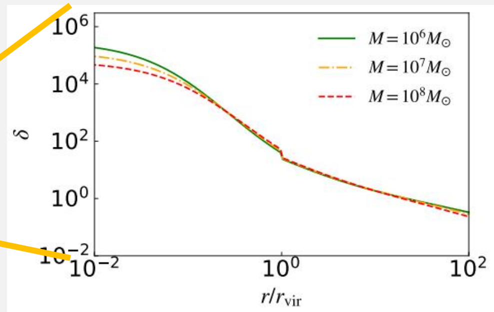


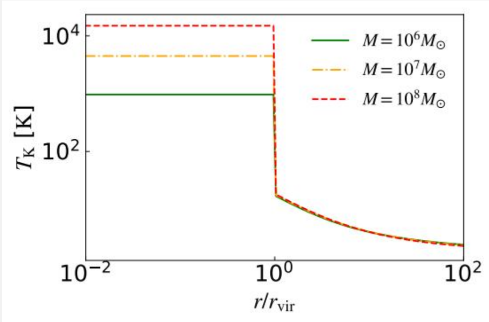
21cmFAST/islandFAST

Xu et al. 2017



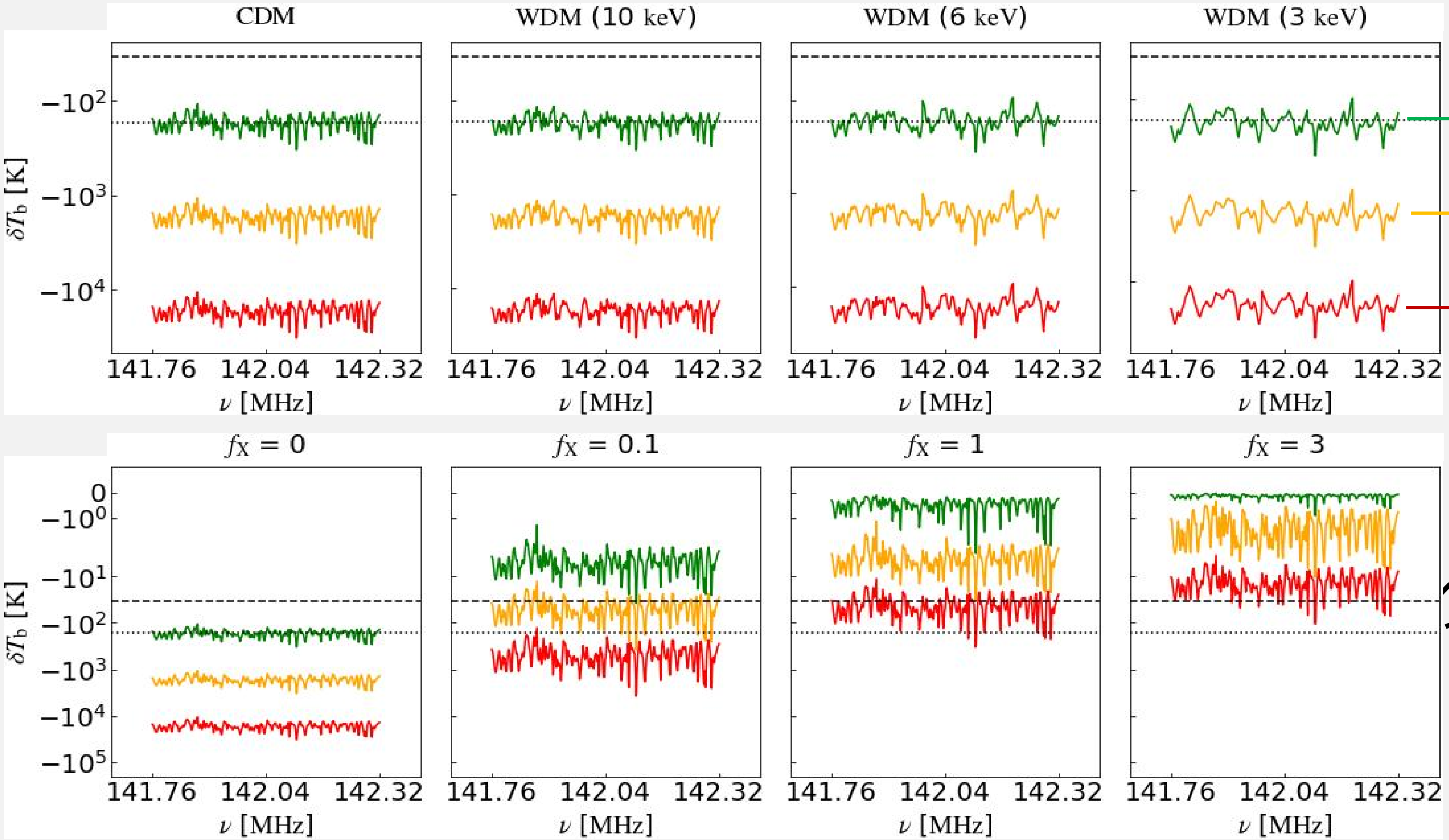
ρ, T_K, x_i, v, T_S





The mock 21-cm signals

$$\delta T^{\mathrm{N}} = \delta S^{\mathrm{N}} \left(\frac{\lambda_z^2}{2k_{\mathrm{B}}\Omega} \right) \approx \frac{\lambda_z^2 T_{\mathrm{sys}}}{A_{\mathrm{eff}}\Omega\sqrt{2\delta\nu\delta t}}$$



S_{150} = 1 mJy

S_{150} = 10 mJy

S_{150} = 100 mJy

Aeff /Tsys =

SKA2-LOW 4000 m^2 K^{-1}

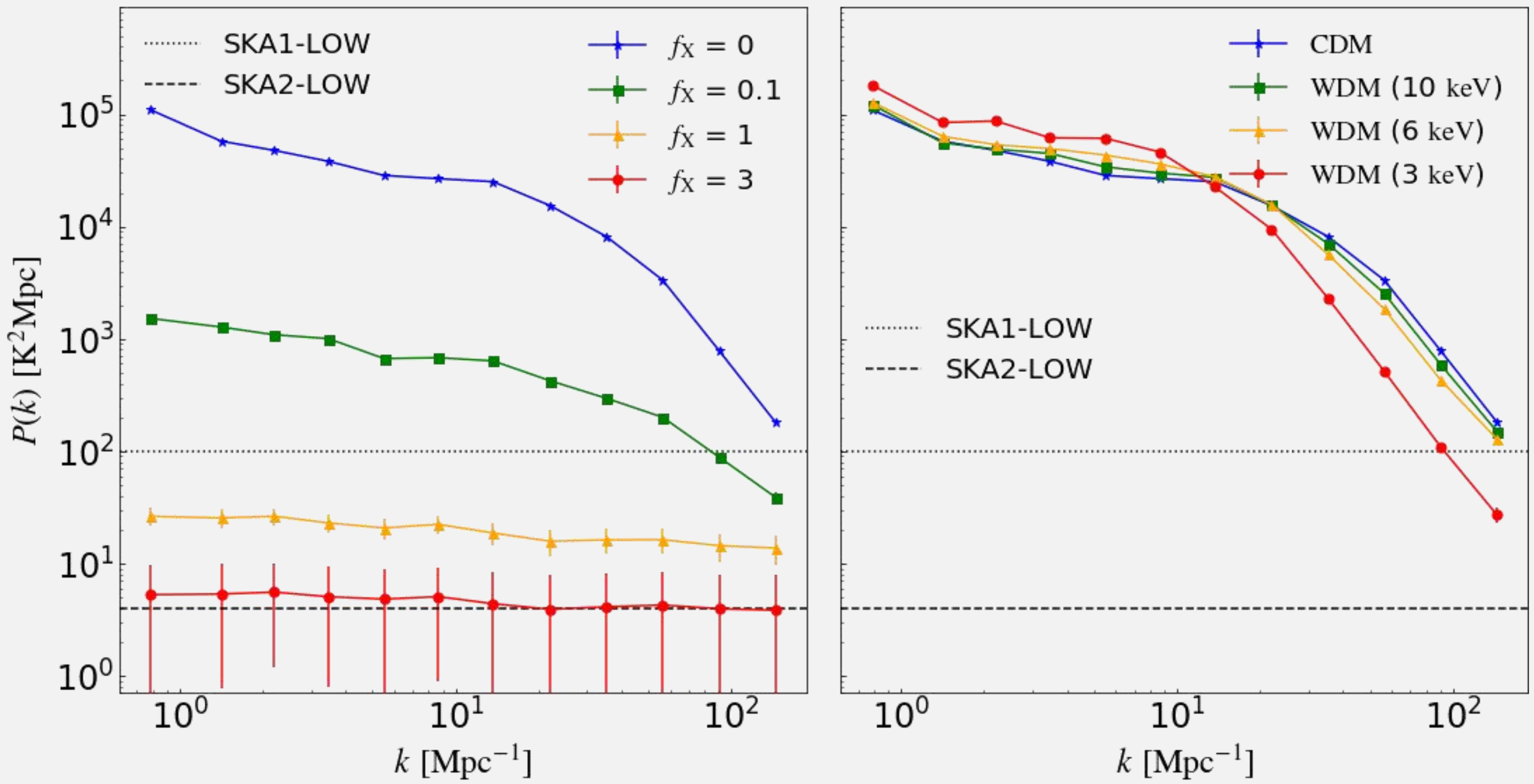
SKA1-LOW 800 m^2 K^{-1}

δt = 100 hr

$\delta\nu$ = 1 kHz

Key strategy #2: 1D power spectrum

10 sources with S_{150} = 10 mJy at z = 9 δt = 2 * 50 hr



Shao et al. 2023 ***Nature Astronomy***

Cross-correlate two measurements to suppress the noise

$$P(\hat{s}, k_\parallel) = \left|\delta\widetilde{T'}(\hat{s}, k_\parallel)\right|^2 \left(\frac{1}{\Delta r_z}\right)$$

Thermal Noise:

$$P^N = \frac{1}{\sqrt{N_s}} \left(\frac{\lambda_z^2 T_{\rm sys}}{A_{\rm eff}\Omega}\right)^2 \left(\frac{\Delta r_z}{2\Delta\nu_z \delta t_{0.5}}\right)$$

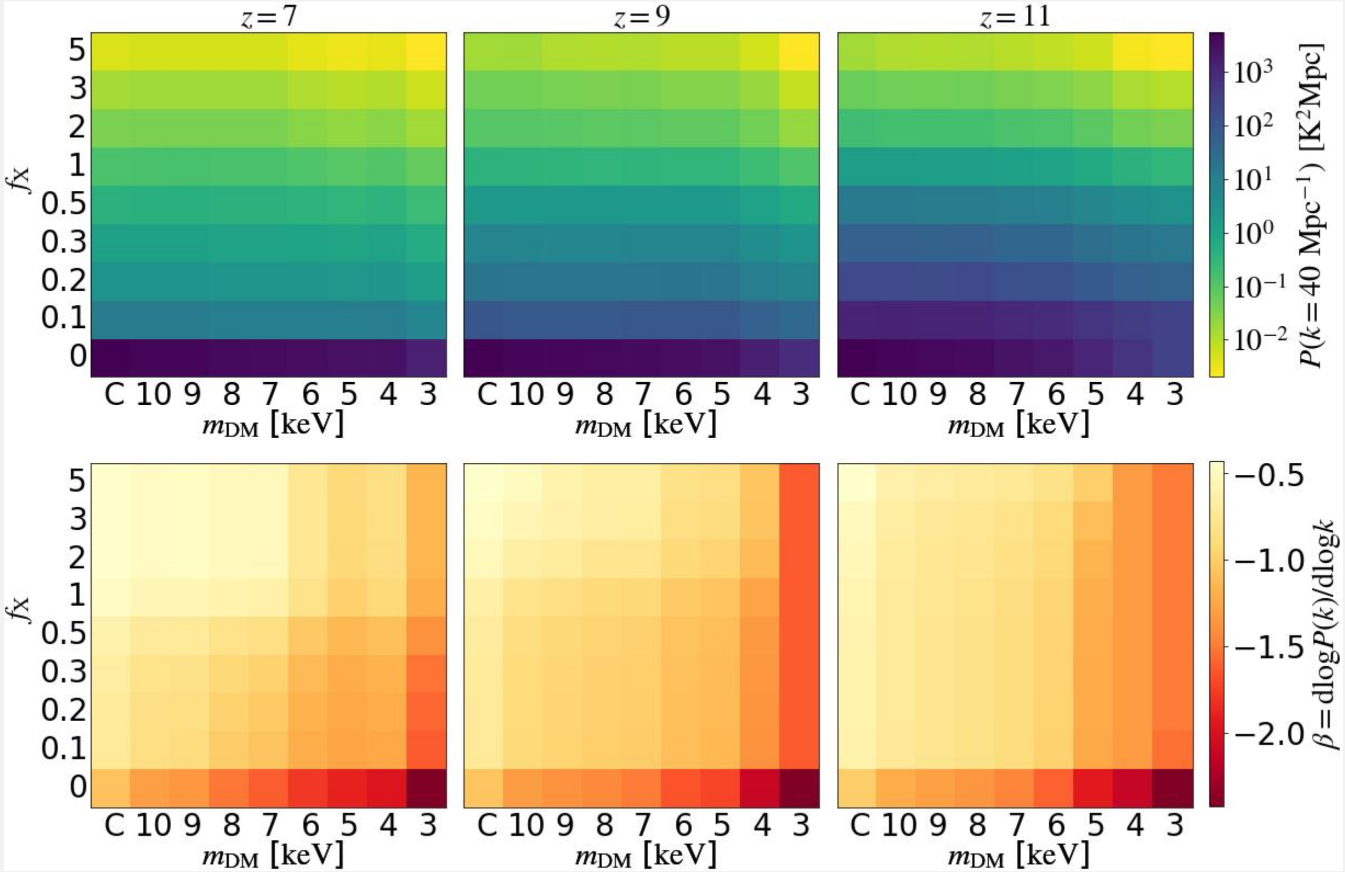
Statistical error:

$$P^S = \sigma_P(k)/\sqrt{N_s \cdot N_m}$$

1D power spectrum: Two birds with one stone

Amplitude

Slope



Scientifically:

- DM particle mass
- Cosmic thermal history

Technologically:

- Increase the sensitivity
- Breaking the degeneracy

SKA forecasts

(10 sources with S_{150} = 10 mJy at z = 9)

SKA1-LOW:

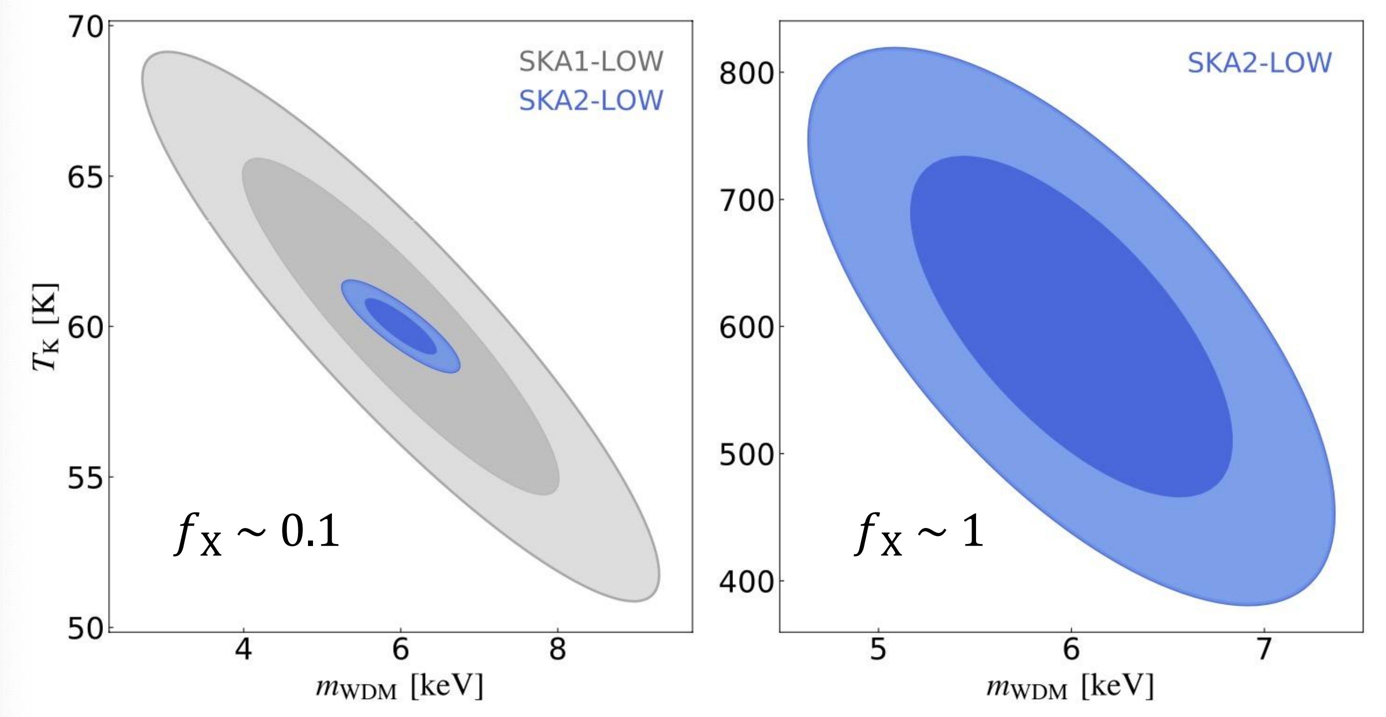
$\sigma_{m_{\rm WDM}} = 1.3$ keV

$\sigma_{T_{\rm K}} = 3.7$ K

SKA2-LOW:

$\sigma_{m_{\rm WDM}} = 0.3$ keV

$\sigma_{T_{\rm K}} = 0.6$ K



SKA2-LOW:

$\sigma_{m_{\rm WDM}} = 0.6$ keV

$\sigma_{T_{\rm K}} = 88$ K

High-redshift radio sources

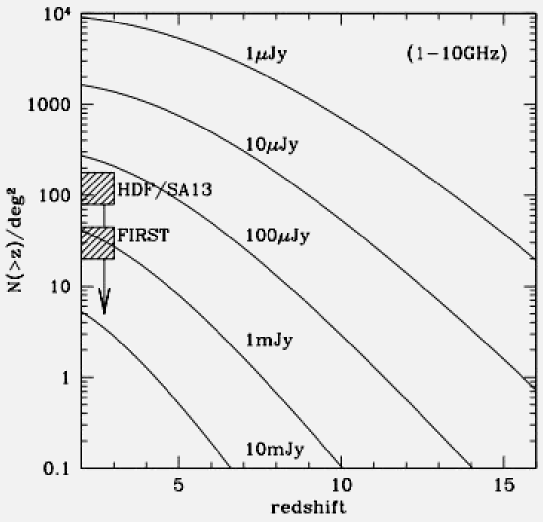
High-z radio-loud quasars

- **J1427+3312 at z = 6.12** (McGreer et al. 2006)
- **J1429+5447 at z = 6.18** (Willott et al. 2010)
- **J0309+2717 at z = 6.10** (Belladitta et al. 2020)
- **VIK J2318–3113 at z = 6.44** (Ighina et al. 2021)
- **P172+18 at z = 6.82** (Bañados et al. 2021)
- **J233153.20+112952.11 at z = 6.57** (Koptelova & Hwang 2022)
- **ILTJ1037+4033 at z = 6.07** (Gloudemans et al. 2022)
- **ILTJ1133+4814 at z = 6.25** (Gloudemans et al. 2022)
- **ILTJ1650+5457 at z = 6.06** (Gloudemans et al. 2022)
- **ILTJ2336+1842 at z = 6.60** (Gloudemans et al. 2022)
- **DES J0320−35 at z = 6.13** (Ighina+2023)
- **DES J0322−18 at z = 6.09** (Ighina+2023)

Radio afterglows of high-z GRBs

- **GRB090423** at z = 8.1 (Salvaterra+2009)
- **GRB090429B** at z = 9.4 (Cucchiara+2011)

- **A few hundred** radio quasars with **> 8 mJy at z ~ 6** are expected (Gloudemans+2021)
- **~ 2000 sources with > 6 mJy at 8 < z < 12** (Haiman+2004)
- The expected detection rate of luminous GRBs from Population III stars is **3 – 20 yr−1 at z > 8** (Kinugawa+2019)



Haiman et al. 2004

21-cm forest: a simultaneous probe of DM & first galaxies

nature astronomy

Article

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The 21-cm forest as a simultaneous probe of dark matter and cosmic heating history

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Check for updates

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The absorption features in spectra of high-redshift background radio sources, caused by hyperfine structure lines of hydrogen atoms in the intervening structures, are known collectively as the 21-cm forest. They provide a unique probe of small-scale structures during the epoch of reionization, and can be used to constrain the properties of the dark matter (DM) thought to govern small-scale structure formation. However, the signals are easily suppressed by heating processes that are degenerate with a warm DM model. Here we propose a probe of both the DM particle mass and the heating history of the Universe, using the one-dimensional power spectrum of the 21-cm forest. The one-dimensional power spectrum measurement not only breaks the DM model degeneracy but also increases the sensitivity, making the probe actually feasible. Making 21-cm forest observations with the upcoming Square Kilometre Array has the potential to simultaneously determine both the DM particle mass and the heating level in the early Universe, shedding light on the nature of DM and the first galaxies.

Multi-scale hybrid modeling

1D power spectrum

- Make the probe actually feasible by increasing sensitivity
- Constrain simultaneously DM & thermal history as it breaks the degeneracy

Two birds with one stone

- DM particle mass: to be probed in an unexplored era in the structure formation history
- Cosmic heating history: probes the first galaxies

Complement to global spectrum & 21 cm tomography

Thank you!

The 21-cm forest as a simultaneous probe of dark matter and cosmic heating history

https://www.nature.com/articles/s41550-023-02024-7