The 6th Global 21-cm Workshop @ IFPU in Trieste, Italy

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

Yidong Xu/徐怡冬 (NAOC)

Collaborators: Yue Shao (NEU), Bin Yue (NAOC), Yougang Wang(NAOC), Wenxiu Yang (NAOC), Ran Li (NAOC), Xin Zhang (NEU), Xuelei Chen (NAOC)

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

The 21 cm probes to CD/EoR

- Using CMB as background

  → **1.** The sky-averaged 21-cm brightness -- the global 21cm spectrum

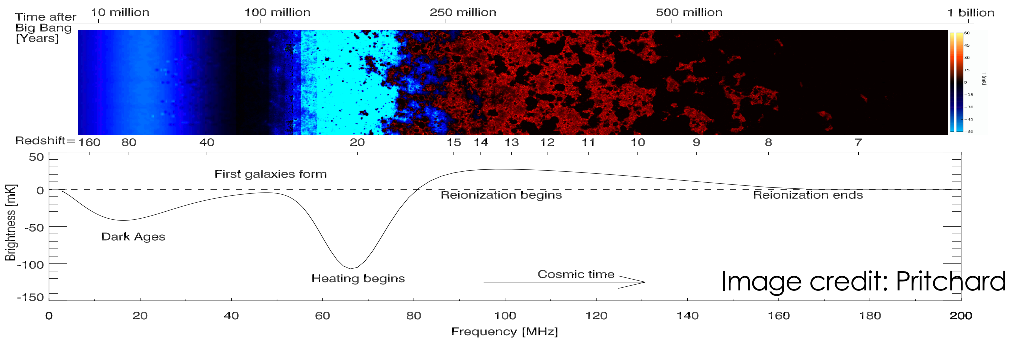
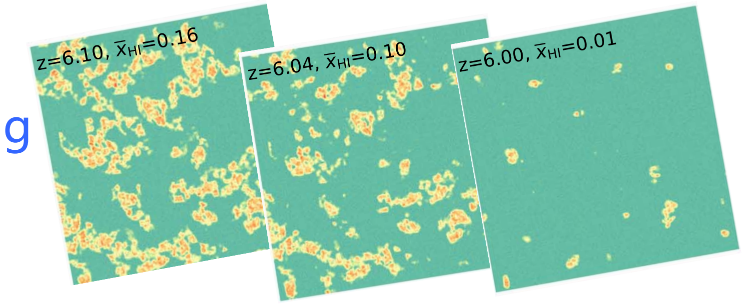


Image credit: Pritchard & Loeb 2012

  → **2.** 21 cm tomography

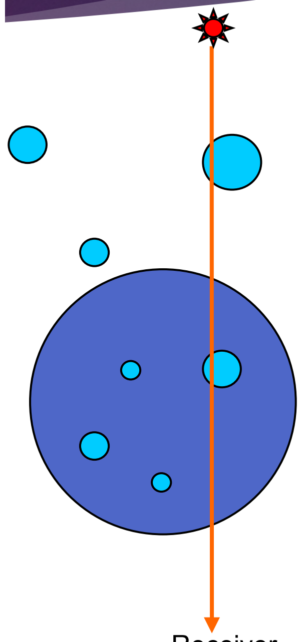
21 cm imaging



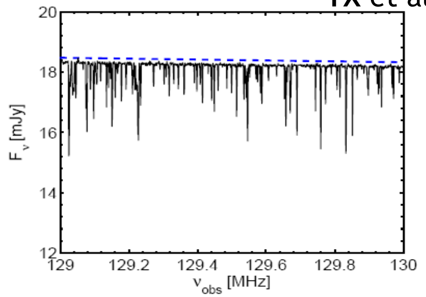
→ 21 cm statistics

- Using high-z radio point sources as background

  → **3.** 21 cm forest (absorption lines) (e.g. Carilli et al. 2002; **YX** et al. 2009, 2010, 2011)



YX et al. 2011 MNRAS



The global 21cm spectrum from cosmic dawn

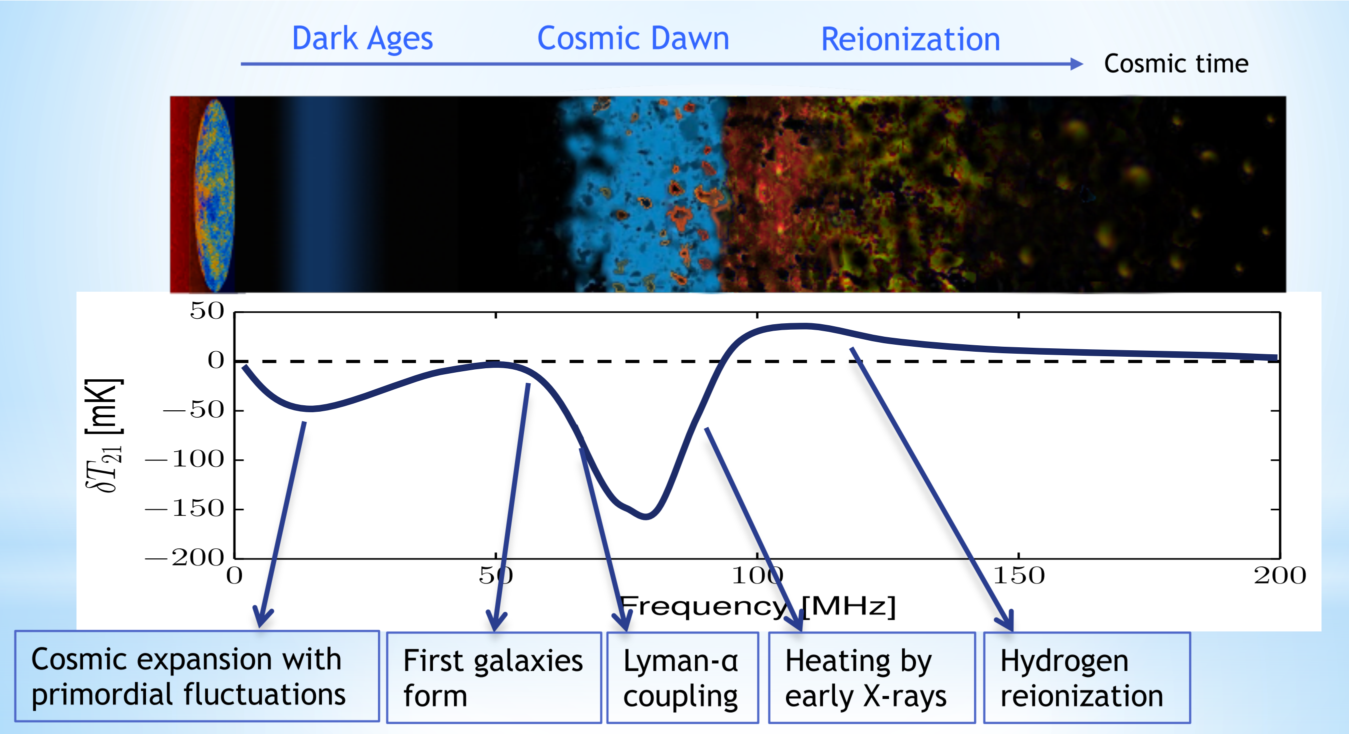
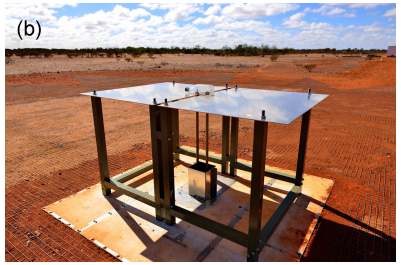
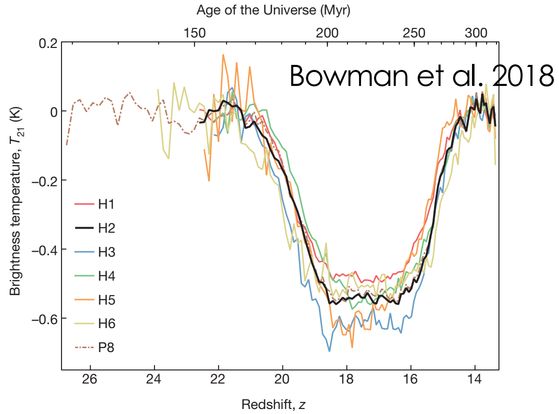
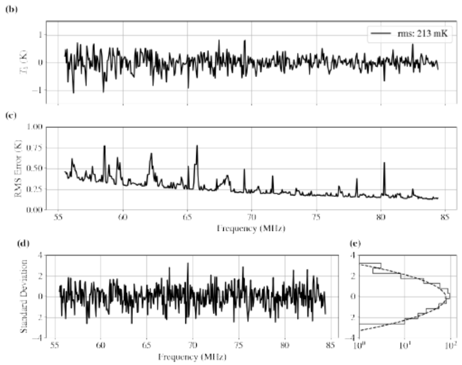


Image credit: Yuan Shi

EDGES-Low-band

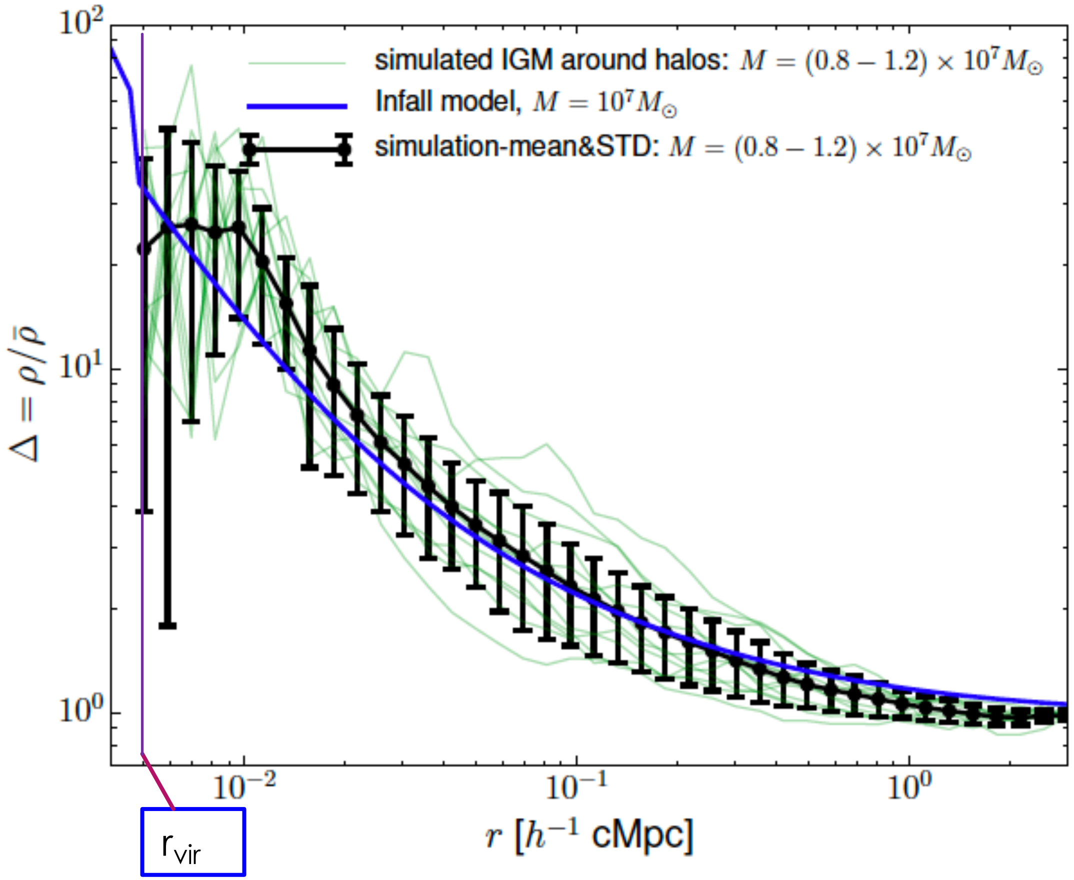






Singh et al. 2112.06778

The non-linear structure formation results in inhomogeneity in the IGM!

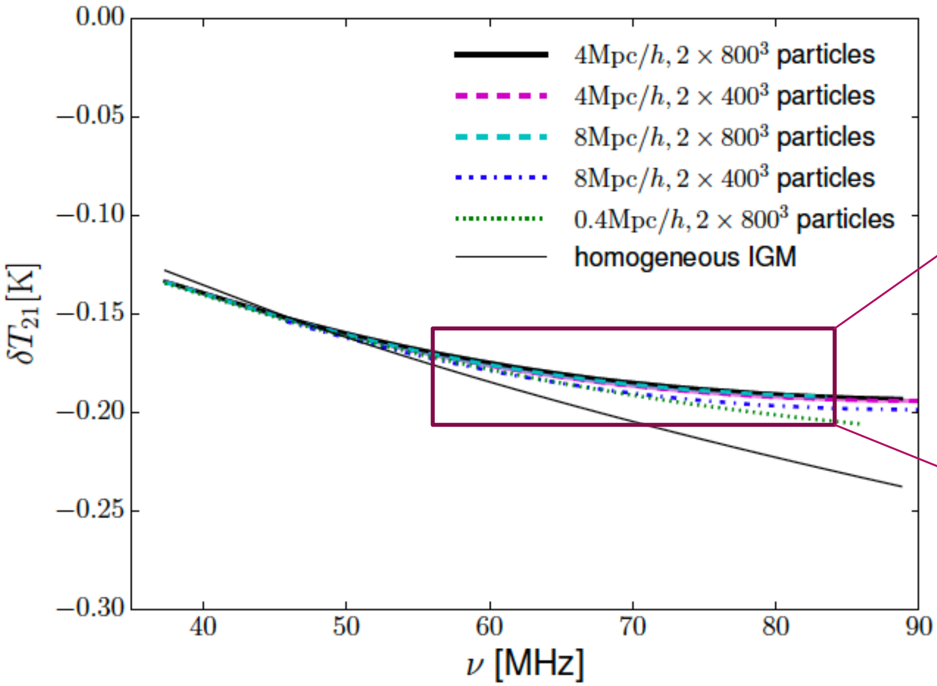


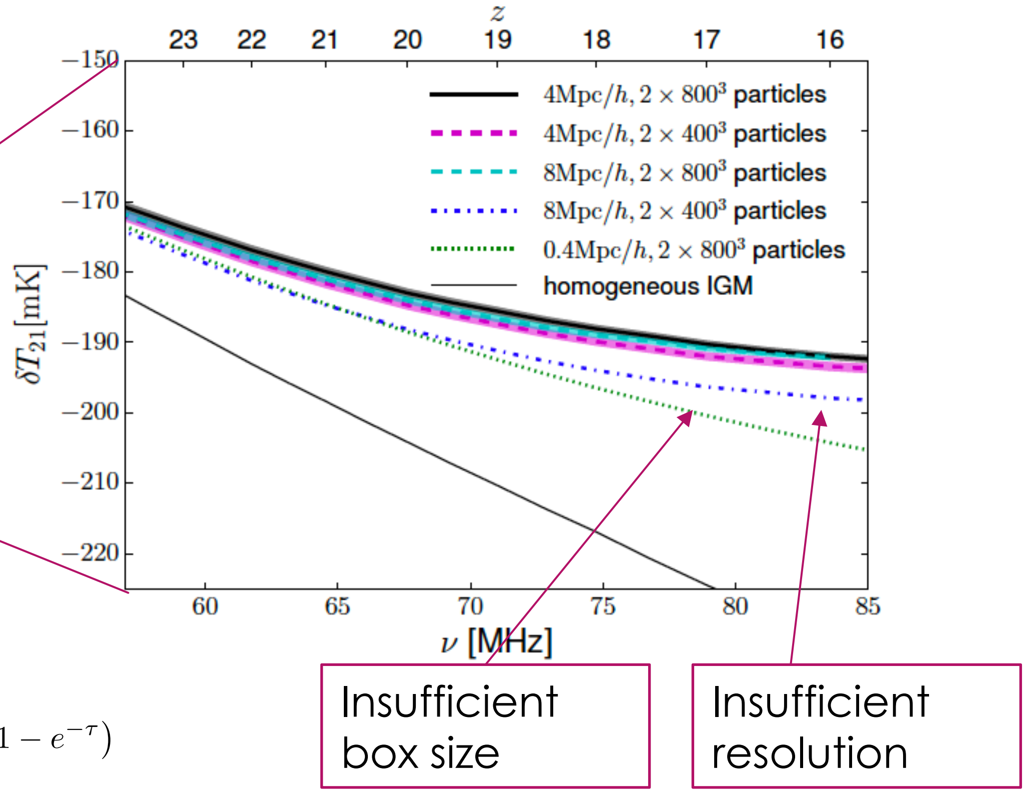
- Non-linear gas density fluctuations
- Peculiar velocities
- Adiabatic heating & cooling
- Shock heating
- Compton heating

Very high resolution hydrodynamic Simulation required!

The maximum global 21 cm signal

-- Effects of non-linear structure formation





$$dT_{21} = \frac{T_S - T_\gamma}{1+z}\left(1 - e^{-\tau}\right)$$

At z = 17, dT_{21} = −190 mK ~ **15% decrement** w.r.t. the homogeneous IGM case.

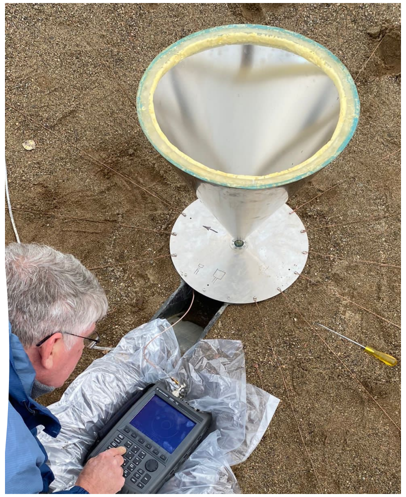
YX, Yue, Chen, 2021, ApJ

Other ground-based experiments for the global spectrum

REACH

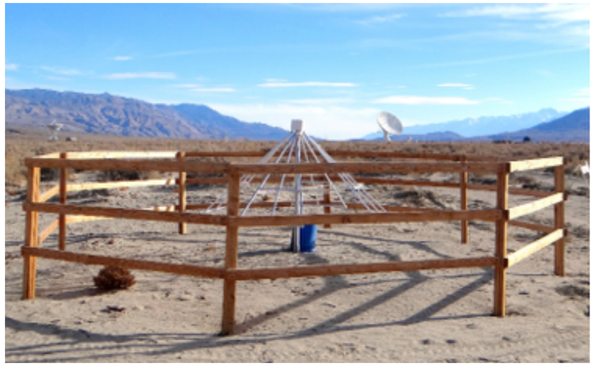
PRI^{Z}M

HIGH-Z

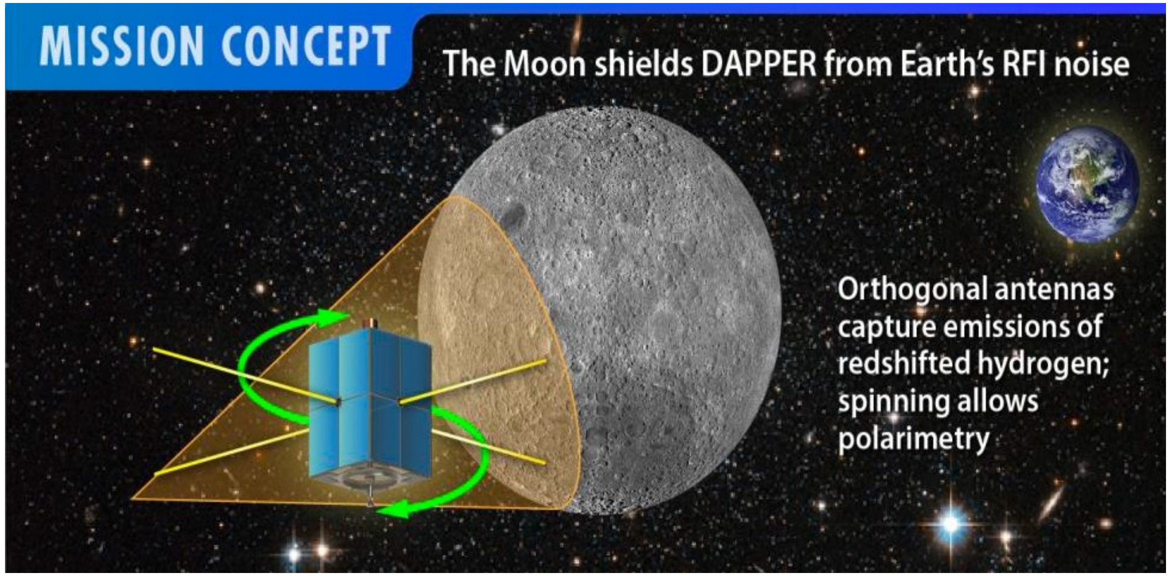


BIGHORNS:

LEDA:

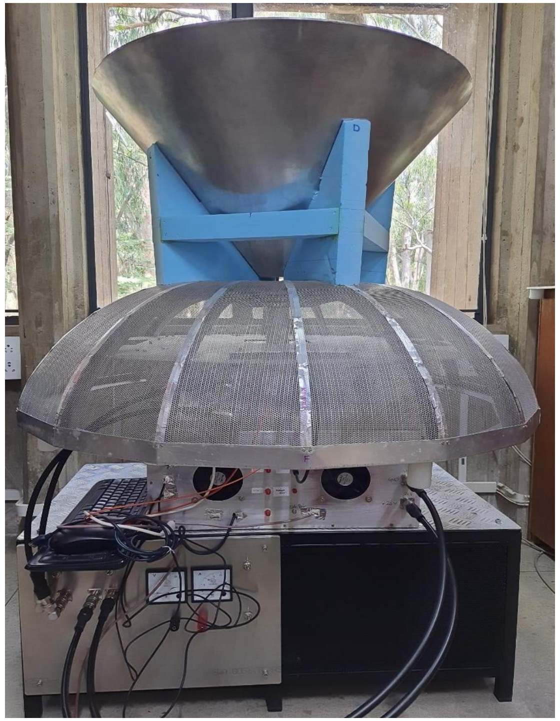


Going to the far side of the Moon …



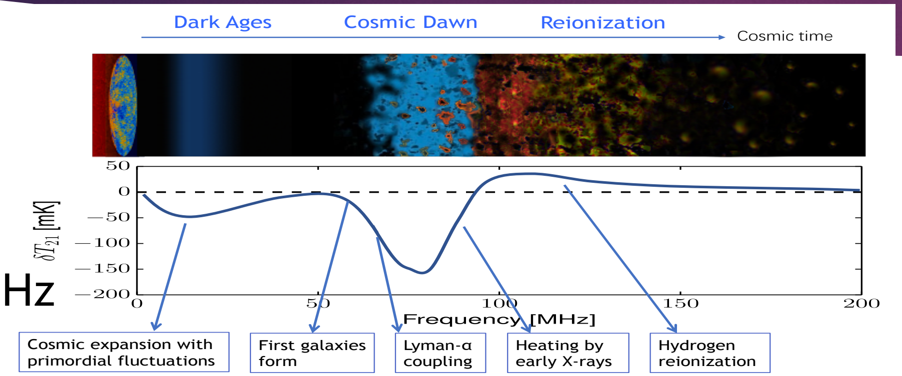
Credit: DAPPER collaboration

PRATUSH

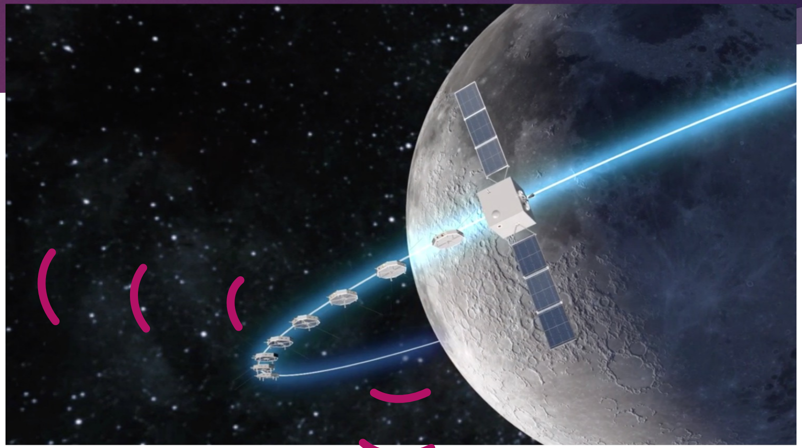


Credit: PRATUSH collaboration

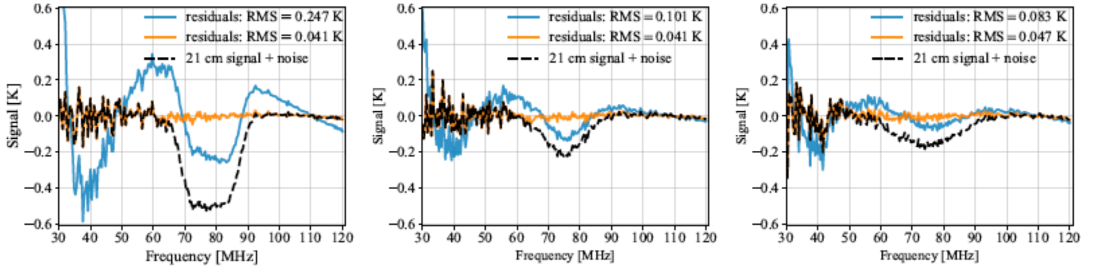
鸿蒙计划
Discovering the Sky at the Longest wavelength (DSL)



30 – 120 MHz

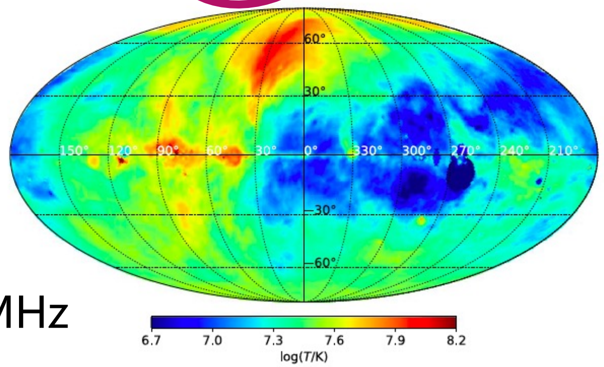


1. **Reveal the dark ages and cosmic dawn with high-precision measurement of the global spectrum.**



(a) Results for the EDGES 21 cm model. (b) Results for Gaussian 21 cm model (A = 0.2 K). (c) Results for Gaussian 21 cm model (A = 0.155 K).

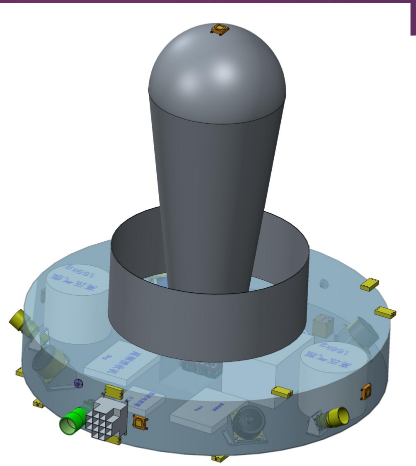
Shi, Deng, **YX** et al. 2022, ApJ, 929, 32.

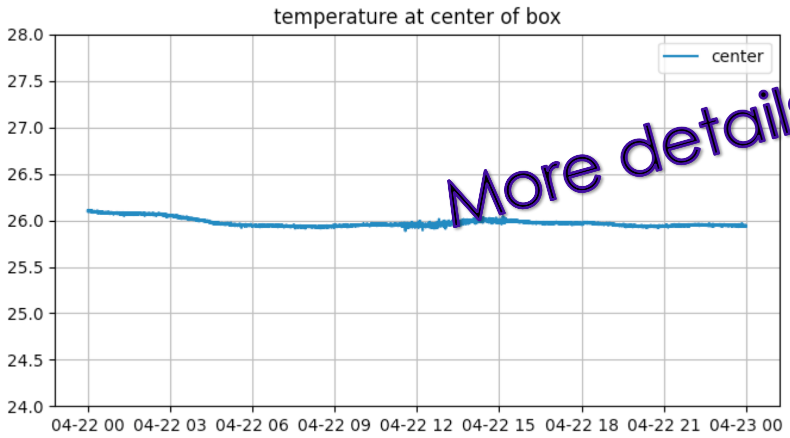


0.1 – 30 MHz

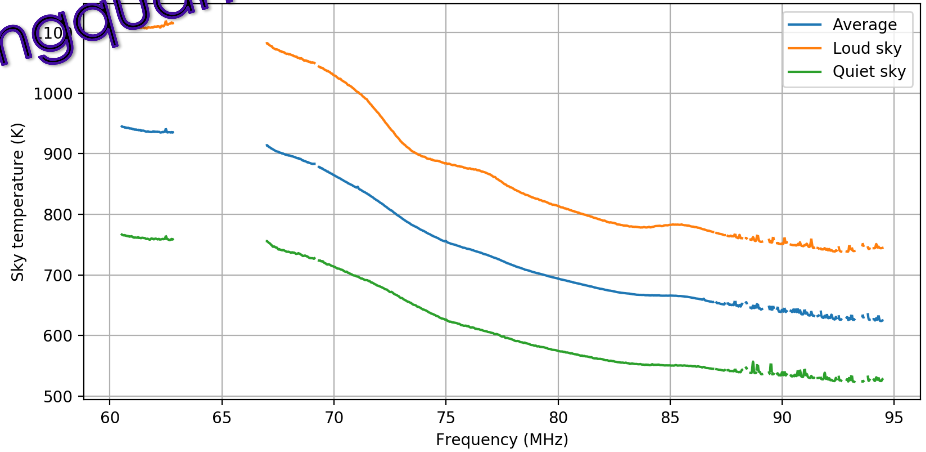
2. **Open up the last unexplored electromagnetic window.**

On-going works: Global Spectrum Field Test

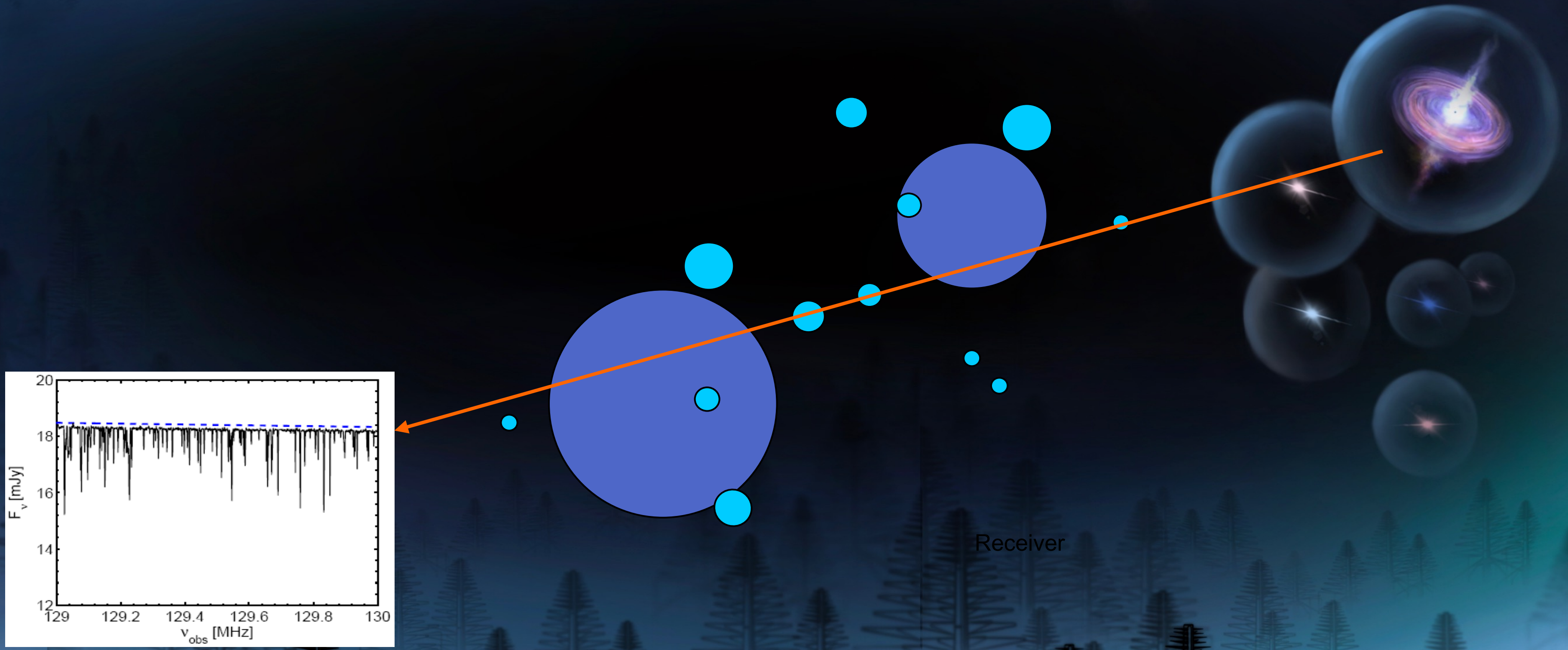




More details in Fengquan Wu's talk



21 cm Forest

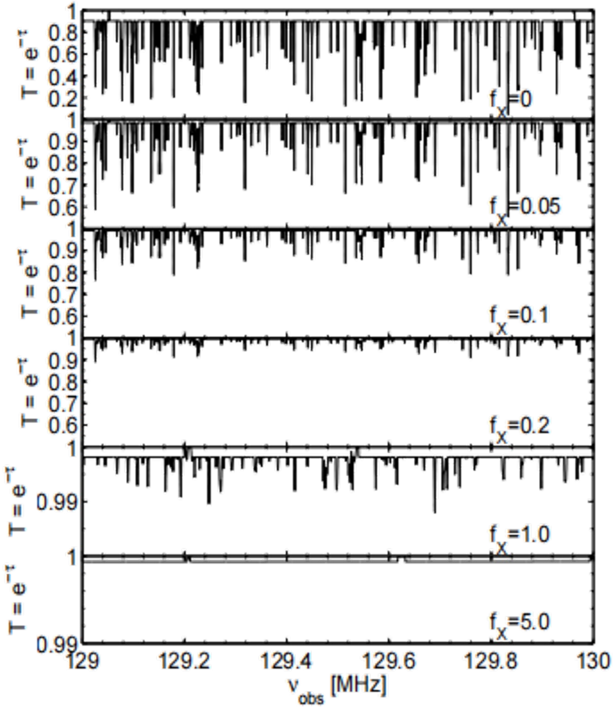


Receiver
20
18
16
14
12
129
129.2
129.4
129.6
129.8
130
F_ν [mJy]
ν_{obs} [MHz]

21 cm Forest

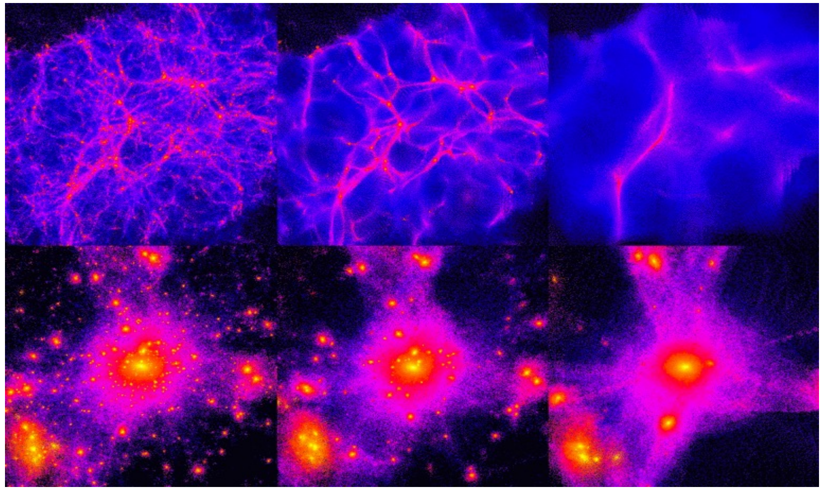
- Sensitive probe to **T_{IGM}**

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



Xu YD et al. 2009, 2010, 2011

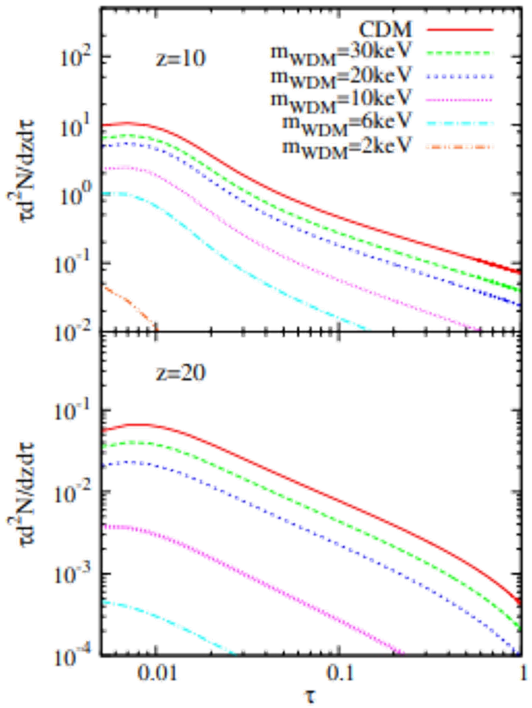
- Unique probe to **small –scale structures** at cosmic dawn (CD) → Dark Matter properties at CD



CDM
WIMP/AXION

WDM
Sterile Neutrino

HDW
3 Neutrinos

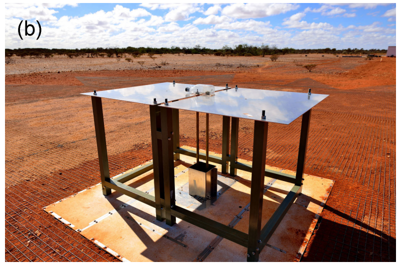


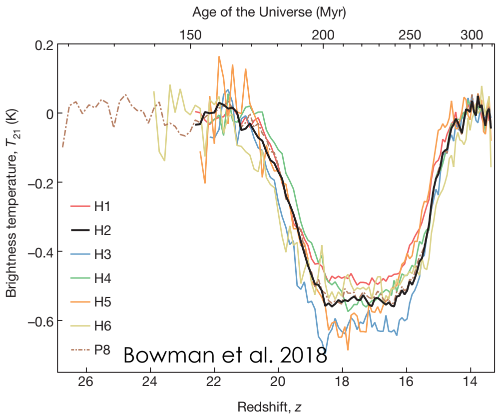
Shimabukuro et al. 2014

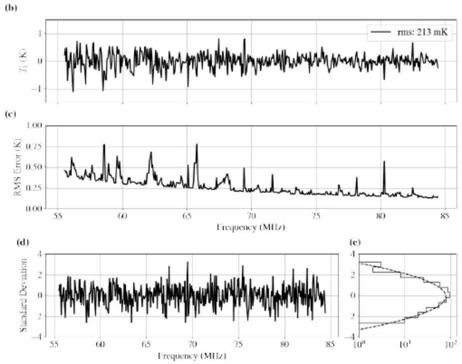
21 cm Forest: never even tried?!

1. 21 cm global spectrum

EDGES-Low-band



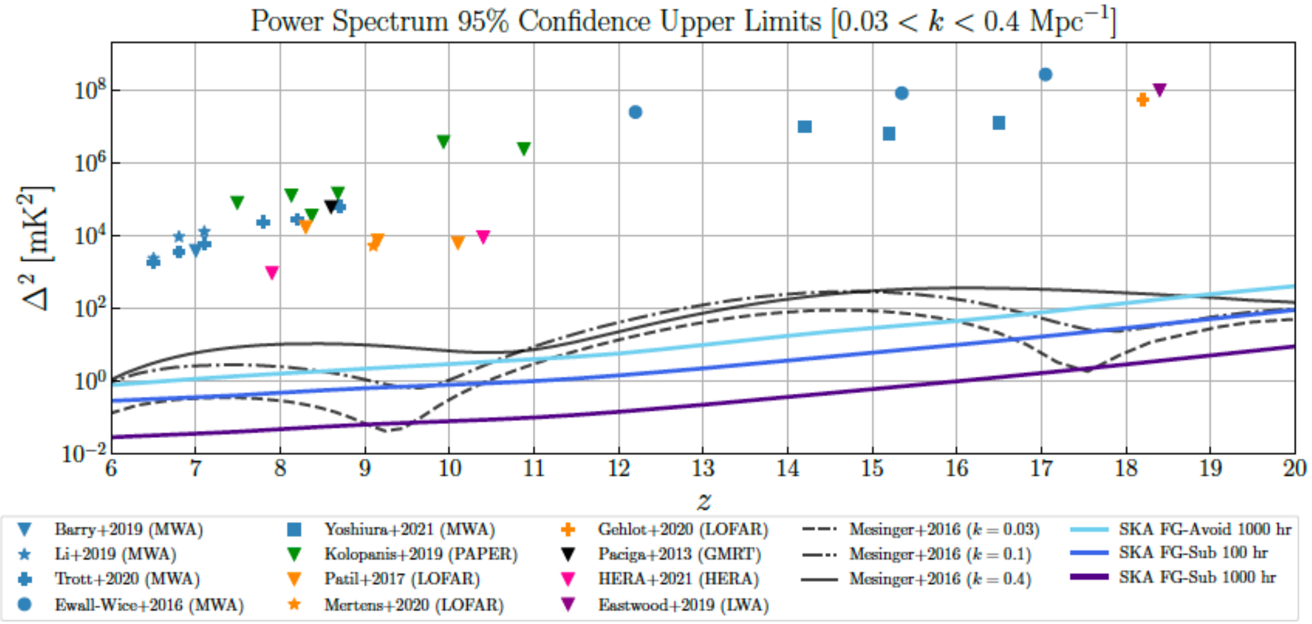




Singh et al. 2112.06778

2. 21 cm tomography

Interferometers

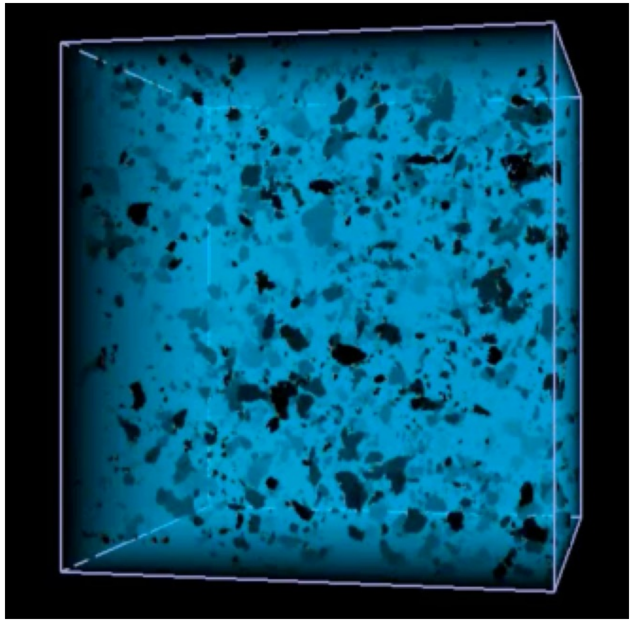


Barry et al. arXiv:2110.06173

21-cm Forest: theoretical challenges

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

1 Gpc



2×10^5

- Main contributor: minihalos & ambient IGM

6 kpc @ z=9

ρ & T_K profiles,
Local x_i & v,

T_S coupling

(collisional, Lyα, CMB)

……

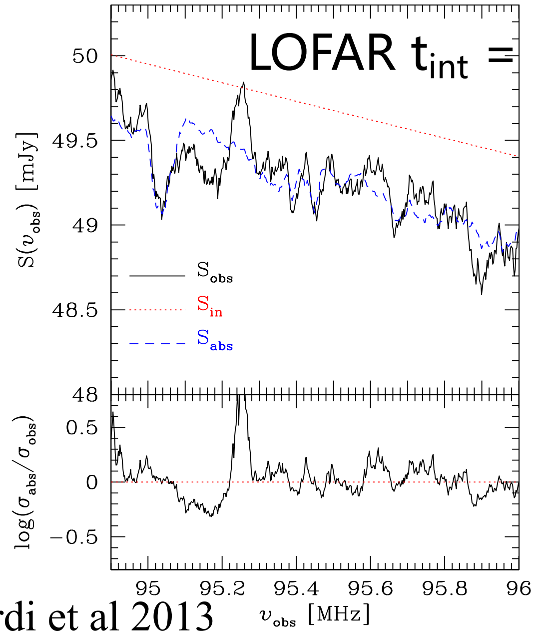
$$\tau_{\nu_0}(\hat{\boldsymbol{s}}, z) \approx 0.0085\,[1+\delta(\hat{\boldsymbol{s}}, z)]\,(1+z)^{3/2}\left[\frac{x_{\rm HI}(\hat{\boldsymbol{s}}, z)}{T_{\rm S}(\hat{\boldsymbol{s}}, z)}\right]\left[\frac{H(z)/(1+z)}{{\rm d}v_\parallel/{\rm d}r_\parallel}\right]\left(\frac{\Omega_{\rm b}h^2}{0.022}\right)\left(\frac{0.14}{\Omega_{\rm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

21-cm Forest: observational challenges

- Probing thermal history ⇔ easily suppressed (**weak**)

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

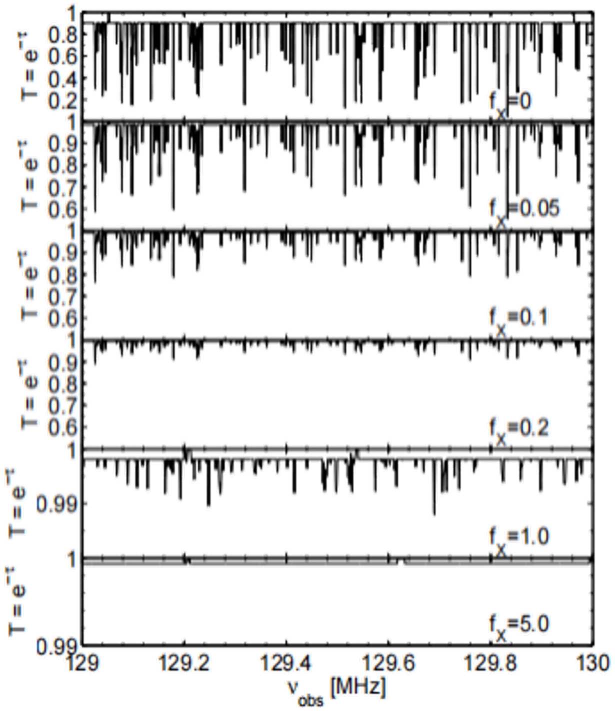
LOFAR t_{int} = 1000 hr



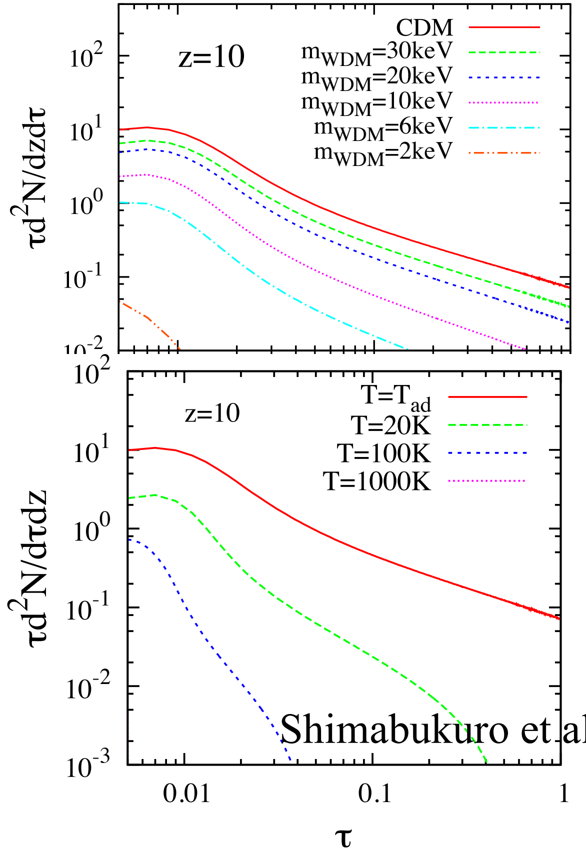
Ciardi et al 2013

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 Figure 10. Here we have assumed the noise σ_n given in eq. 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 $\mathcal{L}4.39$.

- Constraining DM: **degenerate** with astrophysics



Xu YD et al. 2011



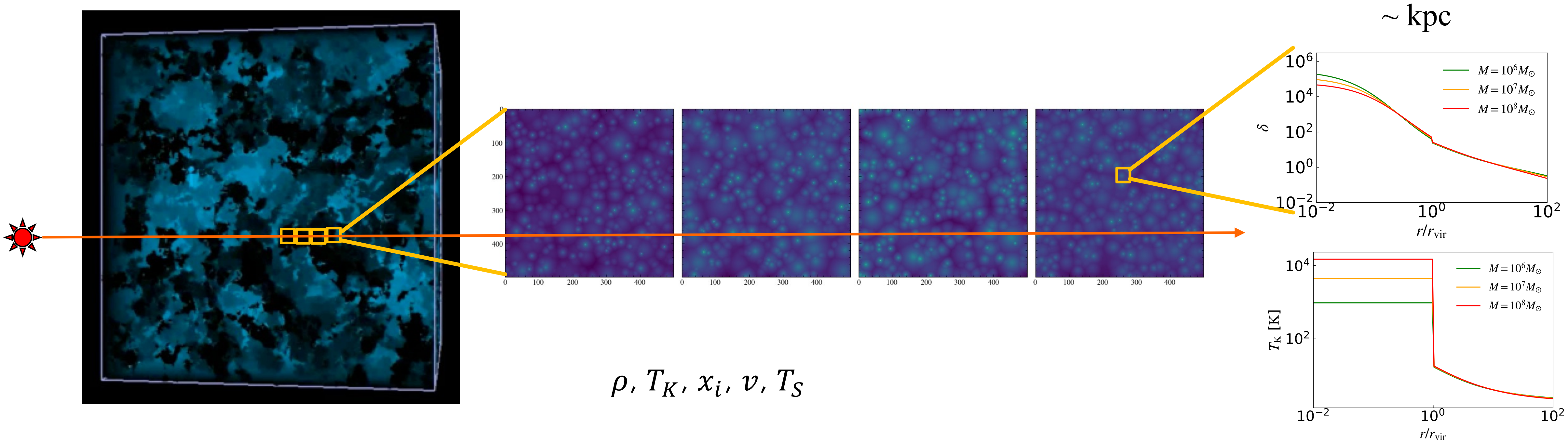
Shimabukuro et al. 2014

Key strategy #1: multi-scale hybrid modeling

- Large scales: semi-numerical simulation
- Small scales: analytic modeling

Box 1 Gpc → 500^3 Grids

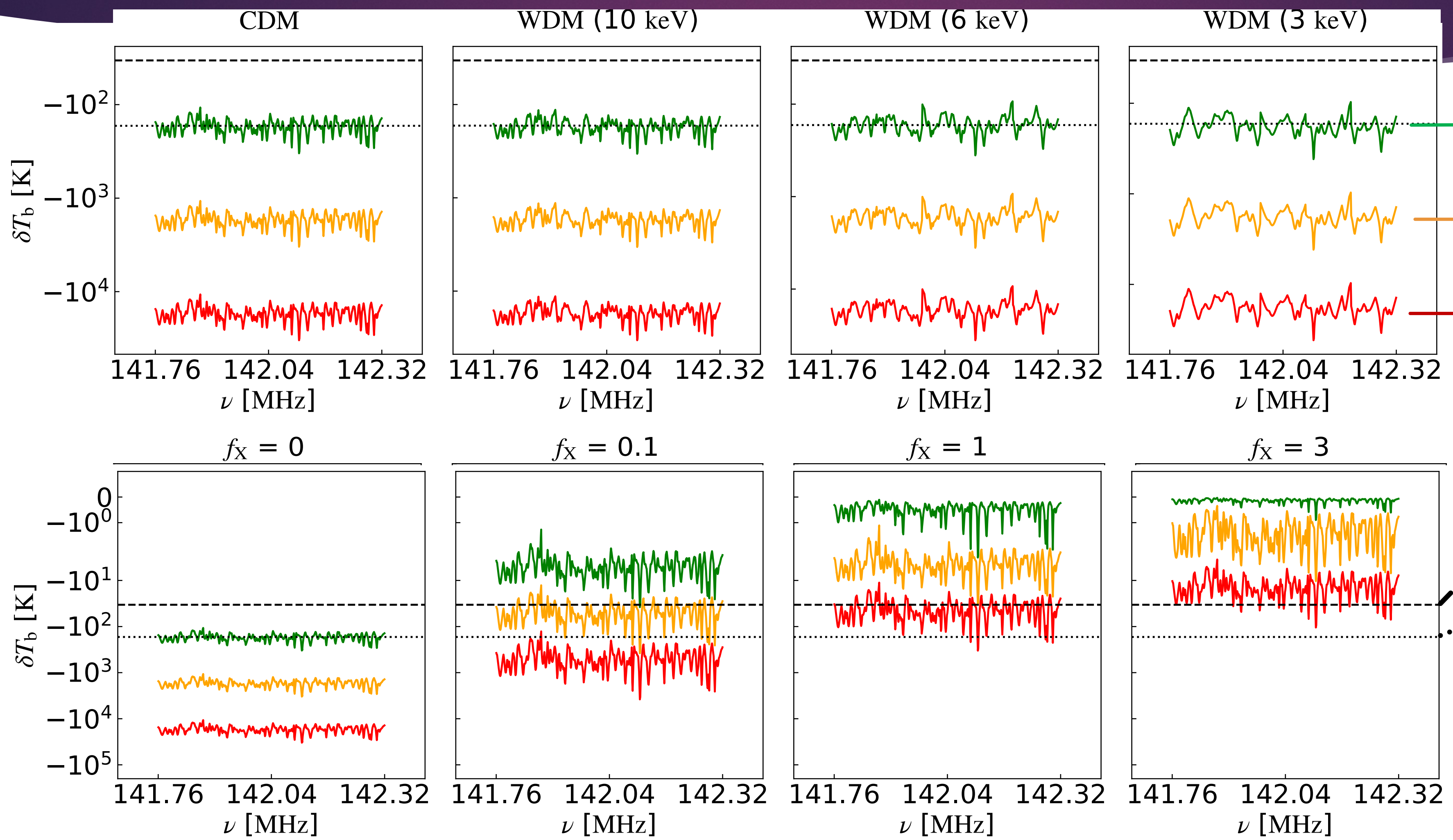
2 Mpc → 500^3 Voxels



21cmFAST (Mesinger+2010) /**islandFAST** (XuYD et al. 2017)

Shao Y., **XuYD***, et al. 2023

The mock 21 cm signals



S_{150} = 1 mJy

S_{150} = 10 mJy

S_{150} = 100 mJy

A_{eff}/T_{sys} =

SKA2-Low 4000 m² K⁻¹

SKA1-Low 800 m² K⁻¹

100 hr, 1 kHz

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

Key strategy #2: 1-D cross-power spectrum

- Cross-correlate two measurements to suppress the noise

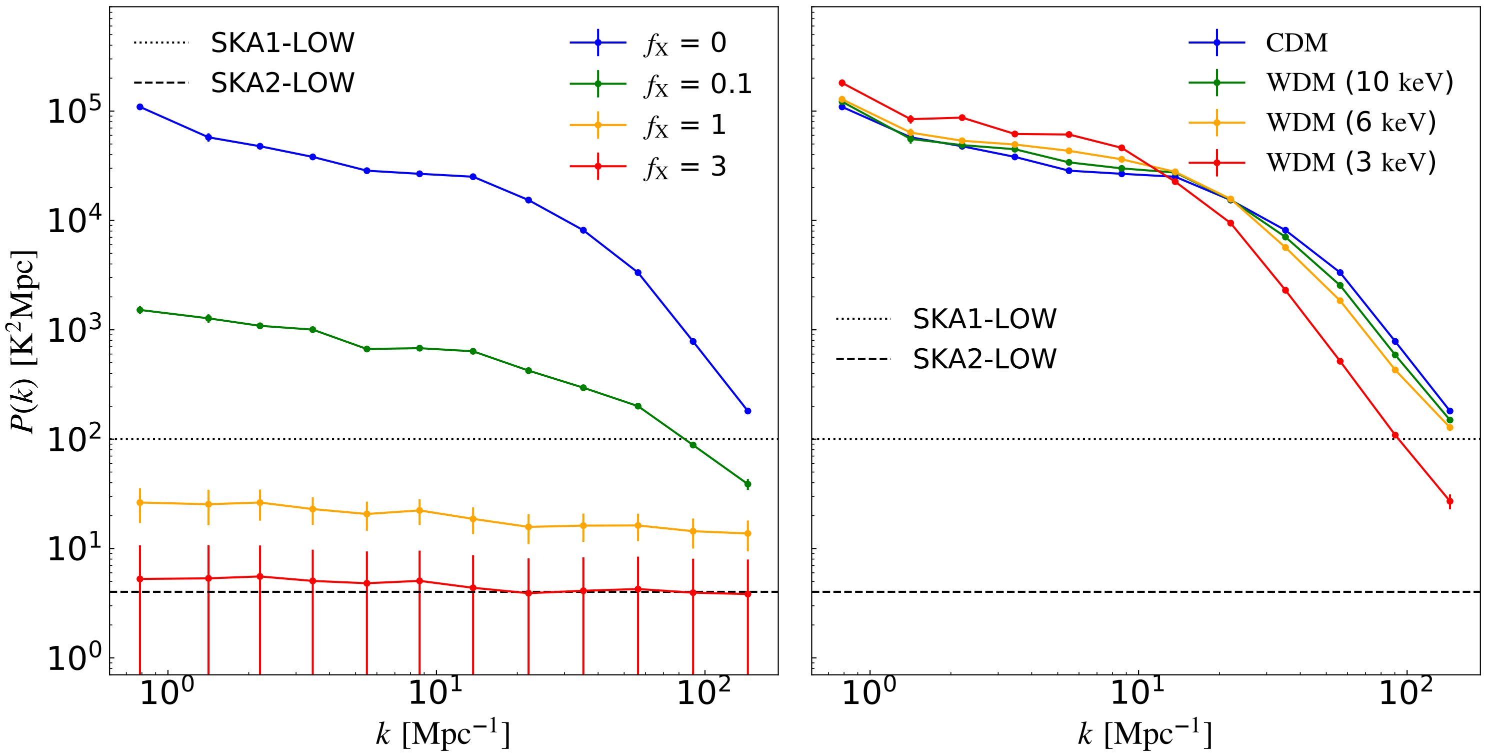
$$P\left(\hat{\boldsymbol{s}}, k_{\parallel}\right) = \left|\delta\widetilde{T}'\left(\hat{\boldsymbol{s}}, k_{\parallel}\right)\right|^2 \left(\frac{1}{\Delta r_z}\right)$$

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

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

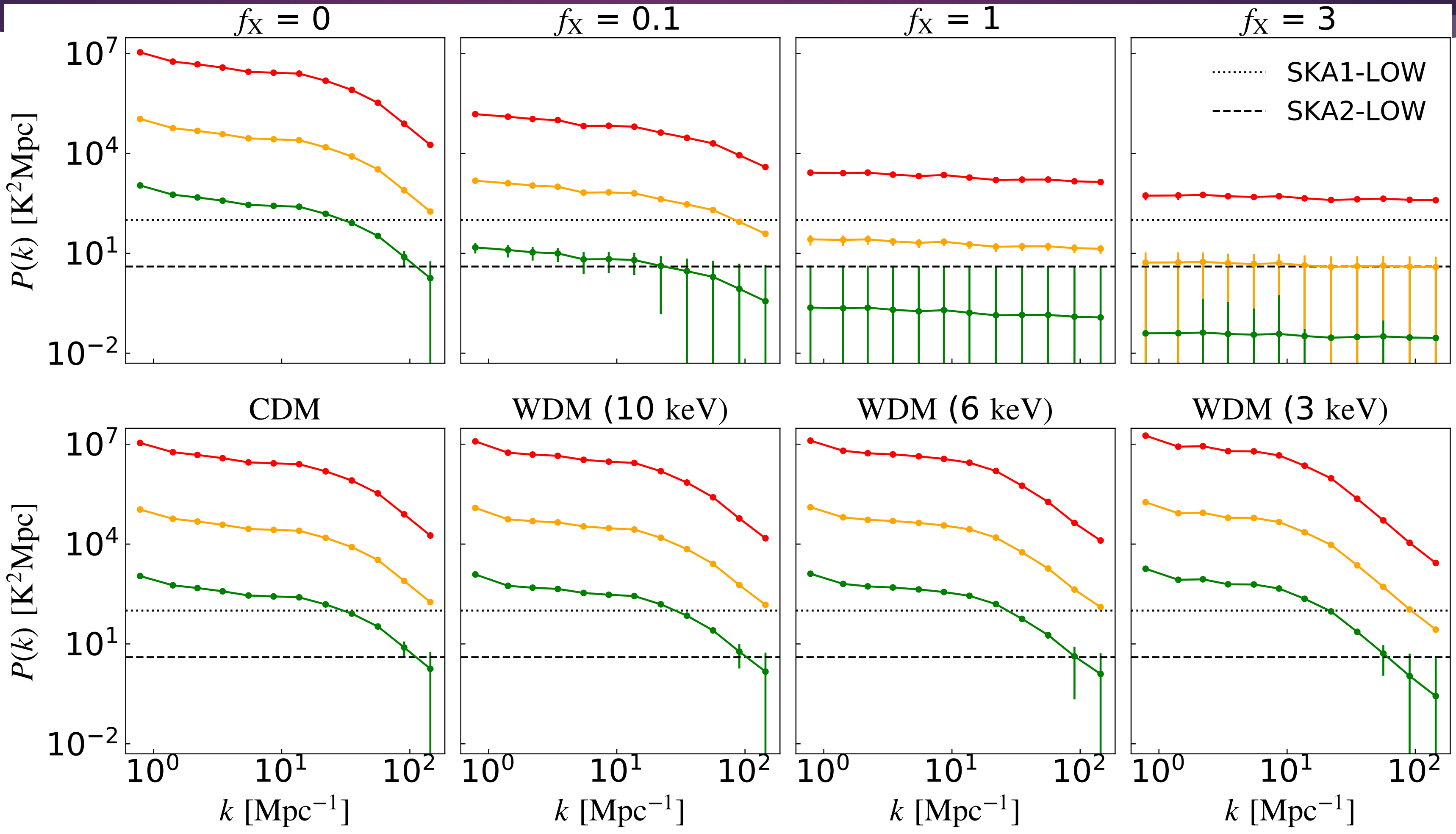
$t_{\rm int} = 2 * 50$ hr

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



Shao Y., **XuYD***, et al. 2023

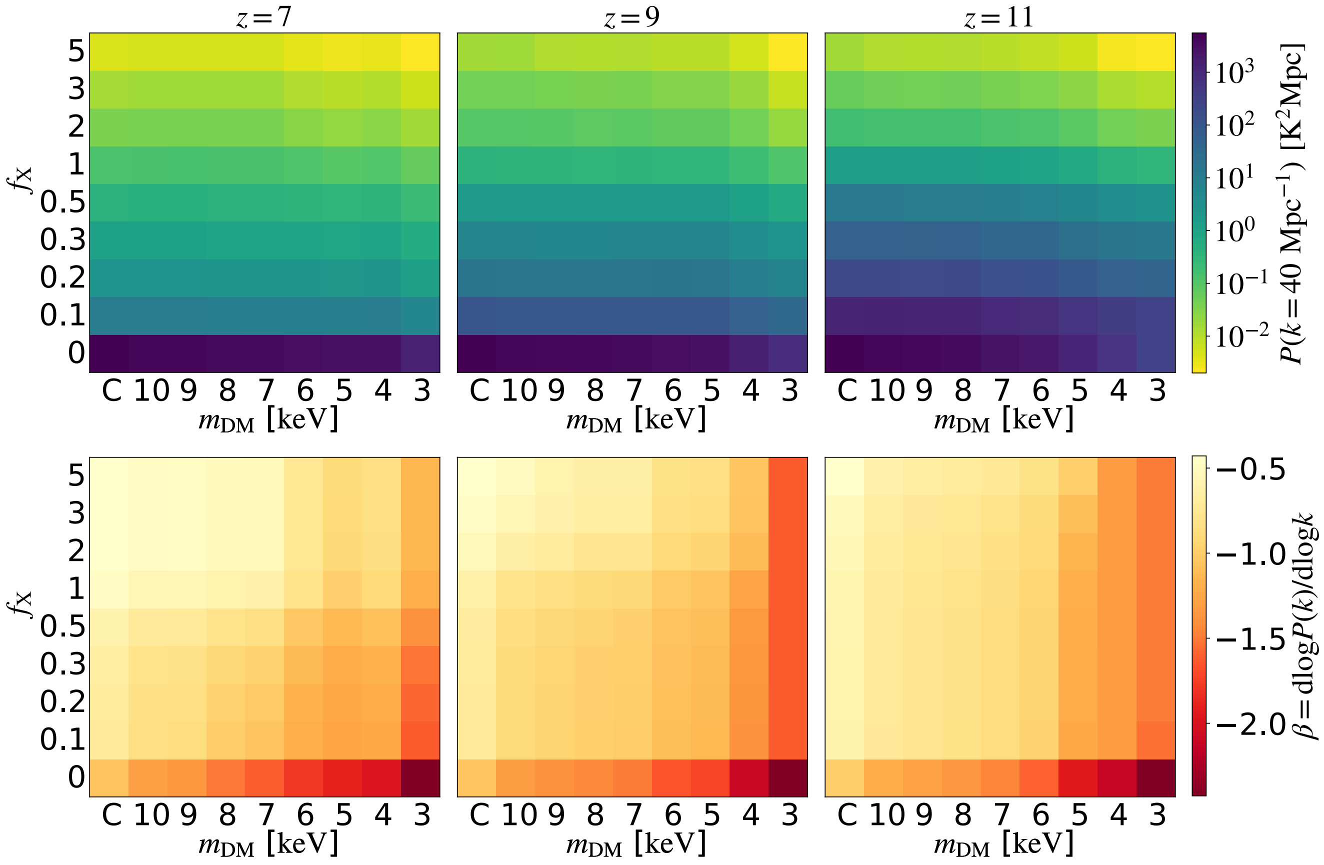
1-D cross-power spectrum



1-D cross-power spectrum
→ Two birds with one stone

Amplitude

Slope

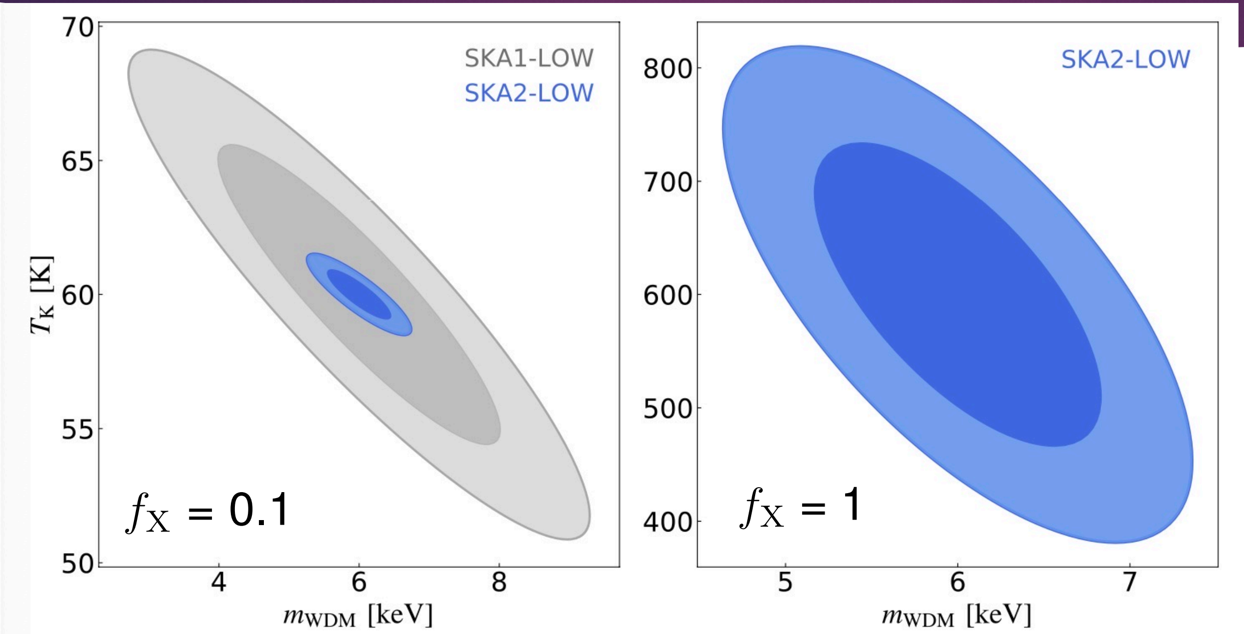


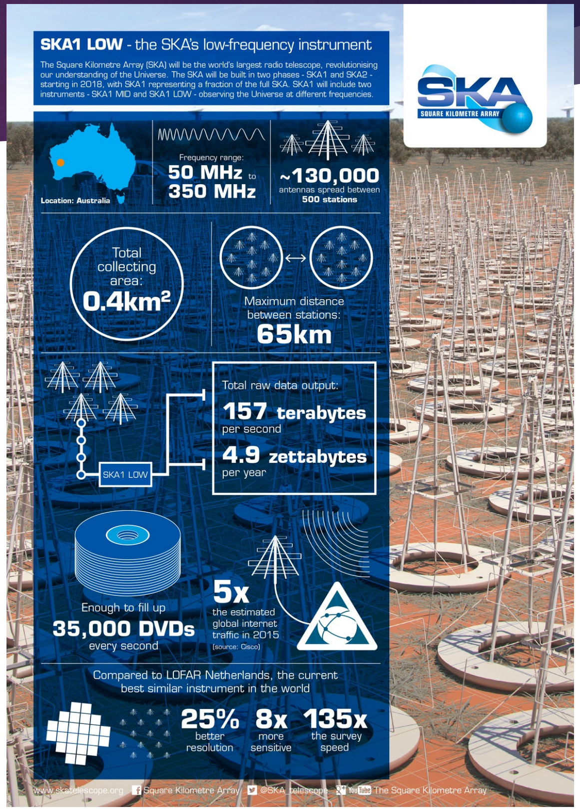
- Scientifically:
  1. DM particle mass
  2. Cosmic thermal history

- Technologically:
  1. Increase the sensitivity → feasible
  2. Breaking the degeneracy → simultaneous constraints

SKA forecasts

Using ~ 10 sources with S_{150} = 10 mJy at z = 9





- **For SKA1-Low:**

  $$\sigma_{m_{\rm WDM}} = 1.3\ \text{keV} \ \ \text{and} \ \ \sigma_{T_{\rm IGM}} = 3.7\ \text{K}$$

- **For SKA2-Low:**

  $$\sigma_{m_{\rm WDM}} = 0.3\ \text{keV} \ \ \text{and} \ \ \sigma_{T_{\rm IGM}} = 0.6\ \text{K}$$

- **For SKA2-Low:**

  $$\sigma_{m_{\rm WDM}} = 0.6\ \text{keV} \ \ \text{and} \ \ \sigma_{T_{\rm IGM}} = 88\ \text{K}$$

High-redshift radio sources?? Yes!

- High-z radio-loud quasars
  - ~ 250 quasars discovered at redshift z≥6
  - ~ 12 radio-loud quasars at z > 6

J1427+3312 at z = 6.12 (McGreer et al. 2006);
J1429+5447 at z = 6.18 (Willott et al. 2010);
J2318−3113 at z = 6.44 (Decarli et al. 2018; Ighina et al. 2021);
J0309+2717 at z = 6.10 (Belladitta et al. 2020, 2022);
J172.3556+18.7734 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;
ILTJ1133+4814 at z = 6.25;
ILTJ1650+5457 at z = 6.06;
ILTJ2336+1842 at z = 6.60 (Gloudemans+2022);
DES J0320−35 at z = 6.13 ± 0.05
DES J0322−18 at z = 6.09±0.05 (Ighina+2023).

➔ 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)

- Radio afterglows of high-z GRBs
  - GRB090423 at z = 8.1 (Salvaterra+2009)
  - GRB090429B at z = 9.4 (Cucchiara+2011)

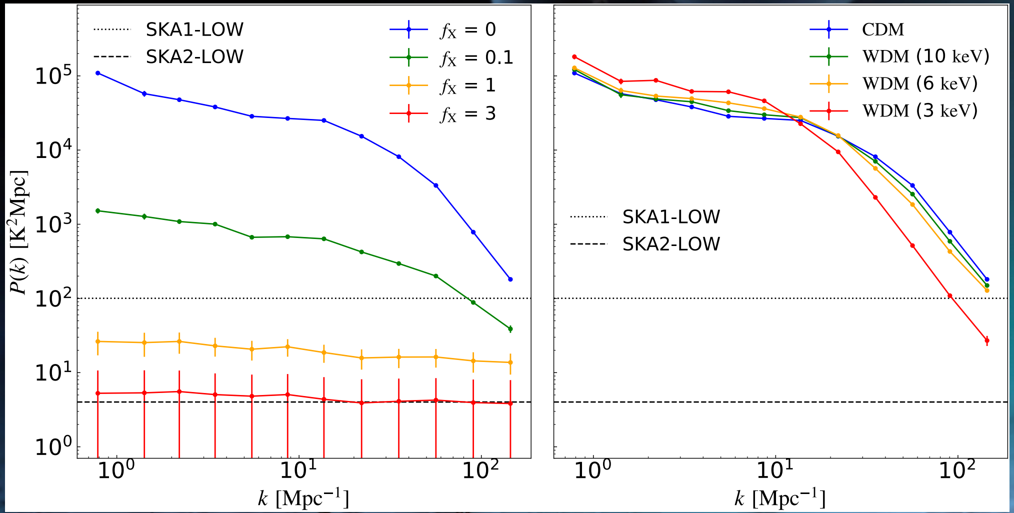
➔ The expected detection rate of luminous GRBs from Population III stars is **3 – 20 yr^{-1} at z > 8** (Kinugawa+2019)

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

Yue Shao (NEU)

- Multi-scale hybrid modeling
- 1-D cross-power spectrum ➔

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



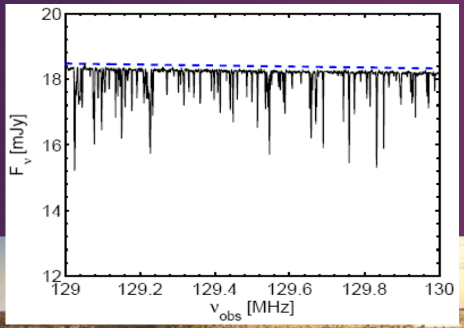
- Two birds with one stone ➔

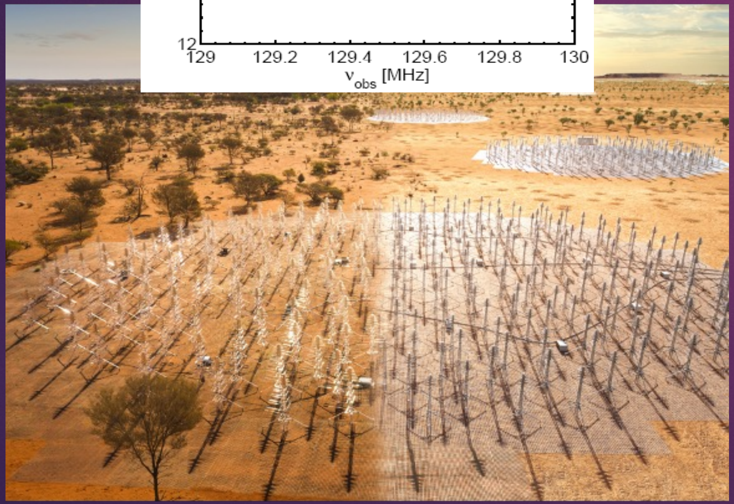
1. DM particle mass: to be probed **in an unexplored era** in the structure formation history
2. Cosmic heating history: probes the **first galaxies**

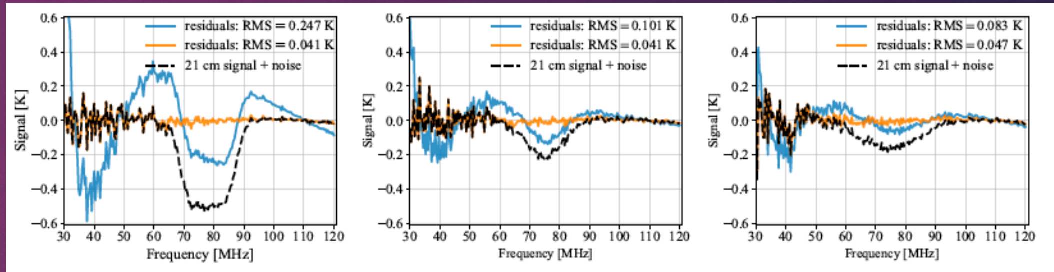
- Complement to global spectrum & 21 cm tomography

Shao Y., **XuYD**, et al. 2023 **Nature Astronomy**

Thank you!







(a) Results for the EDGES 21 cm model. (b) Results for Gaussian 21 cm model (A = 0.2 K). (c) Results for Gaussian 21 cm model (A = 0.155 K).