
# Probing Cosmic Dawn from the ground to the lunar orbit


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- NEU collaborators: Yue Shao, Pengju Wu, Xin Zhang
- The DSL collaboration

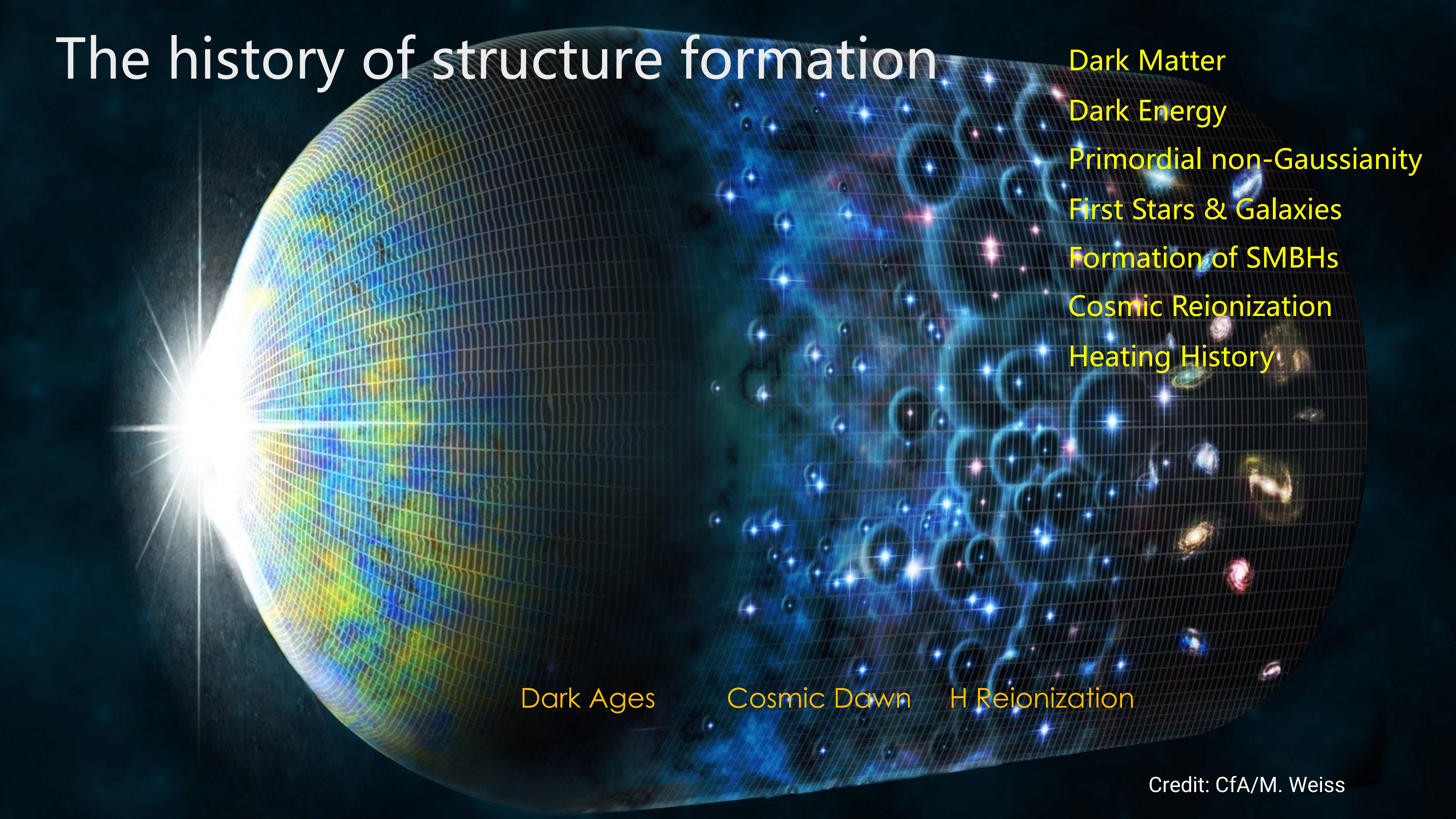
2023.11.16 Tsinghua University

NAOC

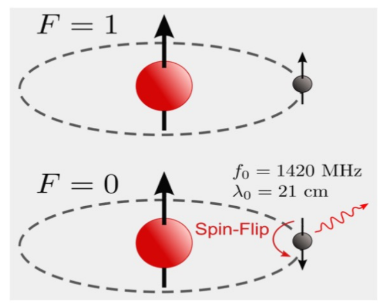
# Outline

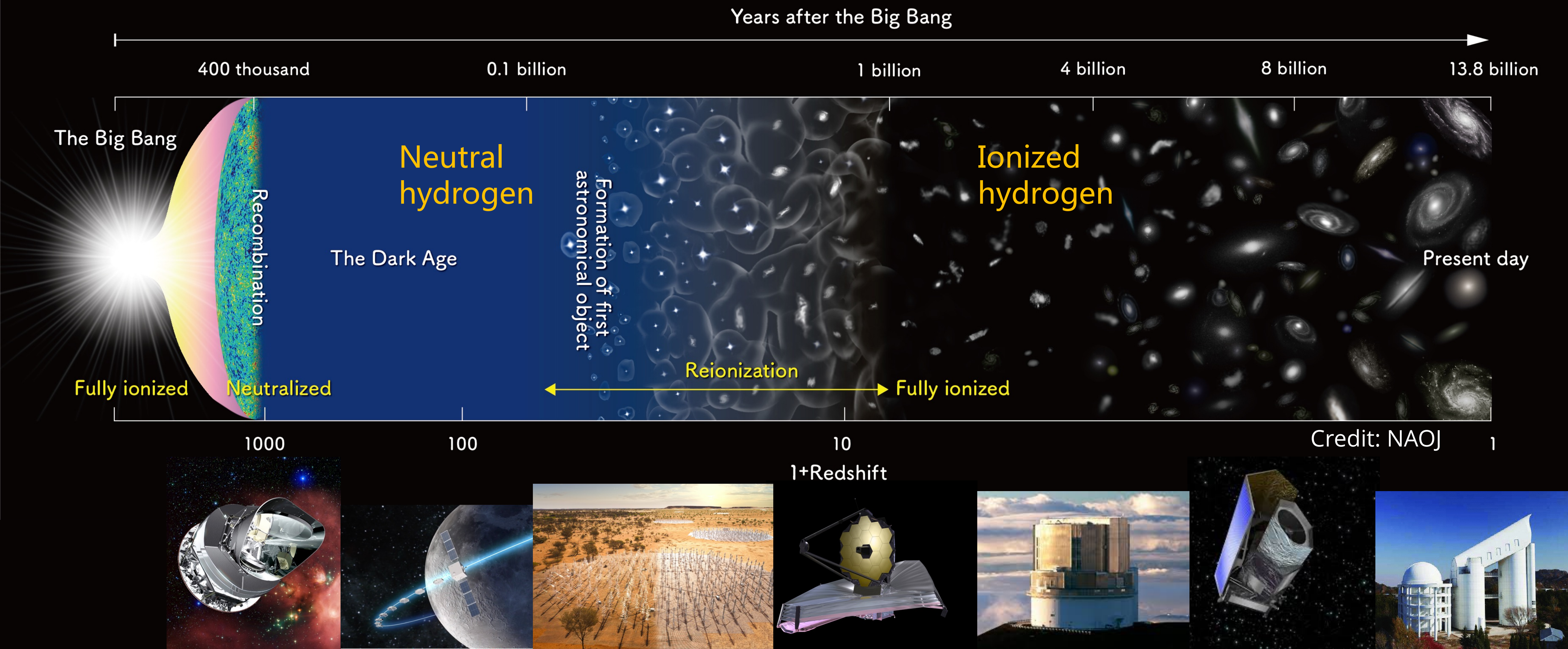
- Background: Cosmic dawn and various probes
- 1. The global 21cm spectrum
- 2. The 21cm tomography
- 3. The 21cm forest
- Summary

# The history of structure formation



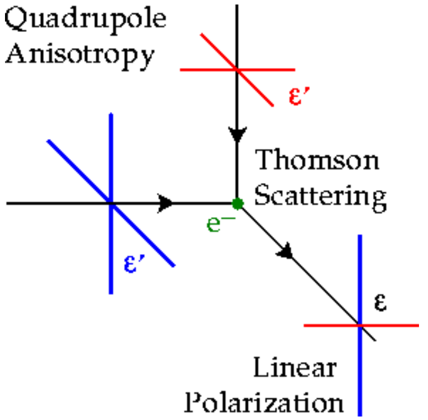
# The 21cm line of HI:
# Exploring the last desert in the observational universe



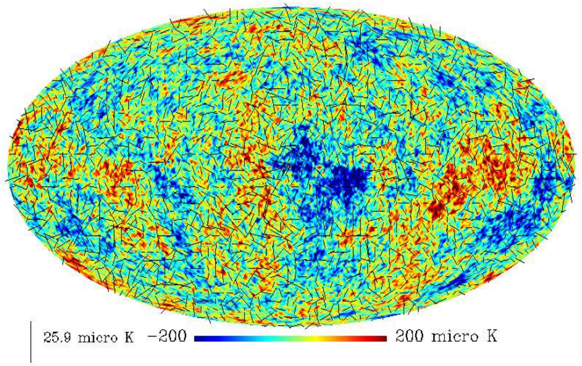



# What we know to inform the 21cm observations

- The Thomson scattering optical depth measured on CMB polarization map



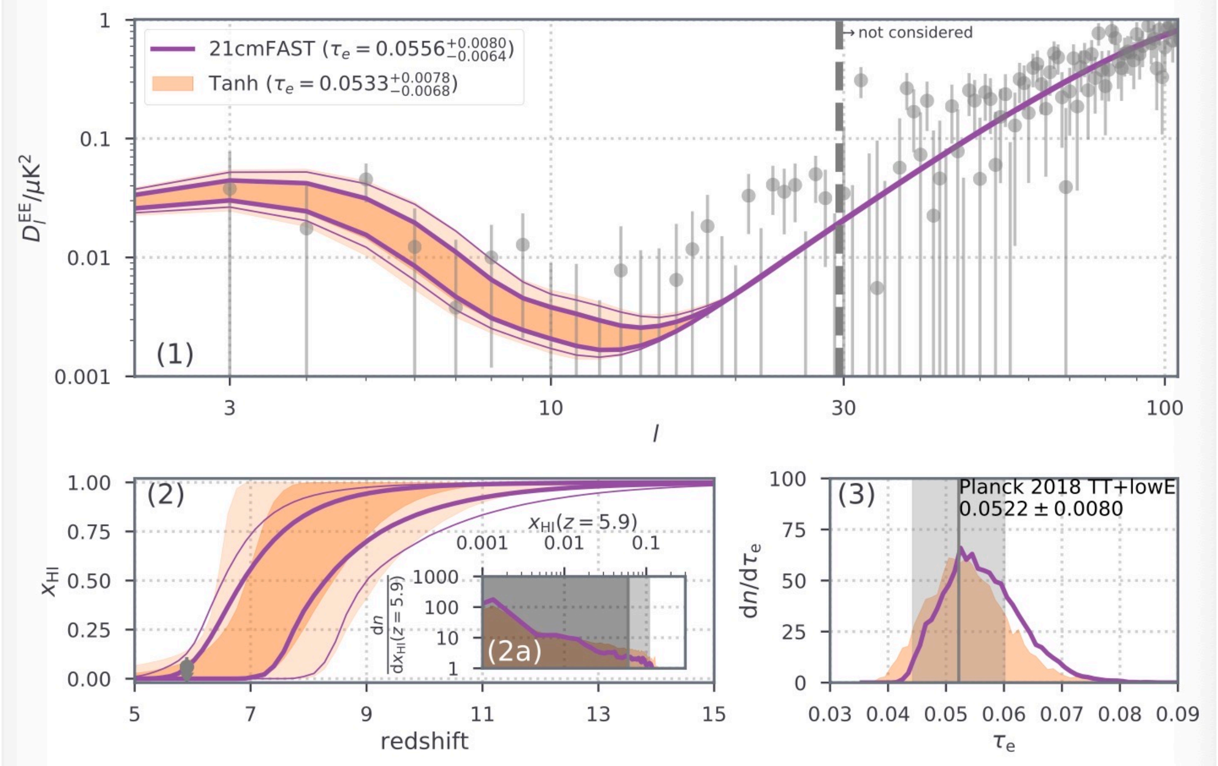

$$\tau = \int_0^{z_{\rm reion}} dz \sigma_T n_e(z) \frac{d\ell}{dz}.$$




Planck 2018 results VI. A&A 641, A6 (2020)

$$\tau = 0.0544^{+0.0070}_{-0.0081} \quad (68\%, \text{TT,TE,EE+lowE}).$$

$$\boxed{z_{\rm re} = 7.68 \pm 0.79 \quad (68\%, \text{TT,TE,EE+lowE}),}$$

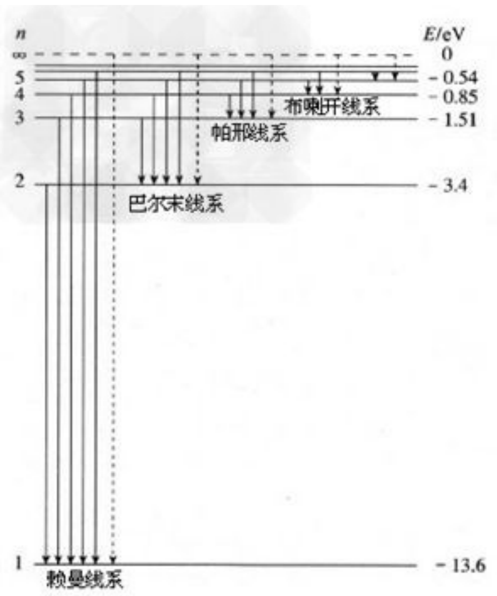


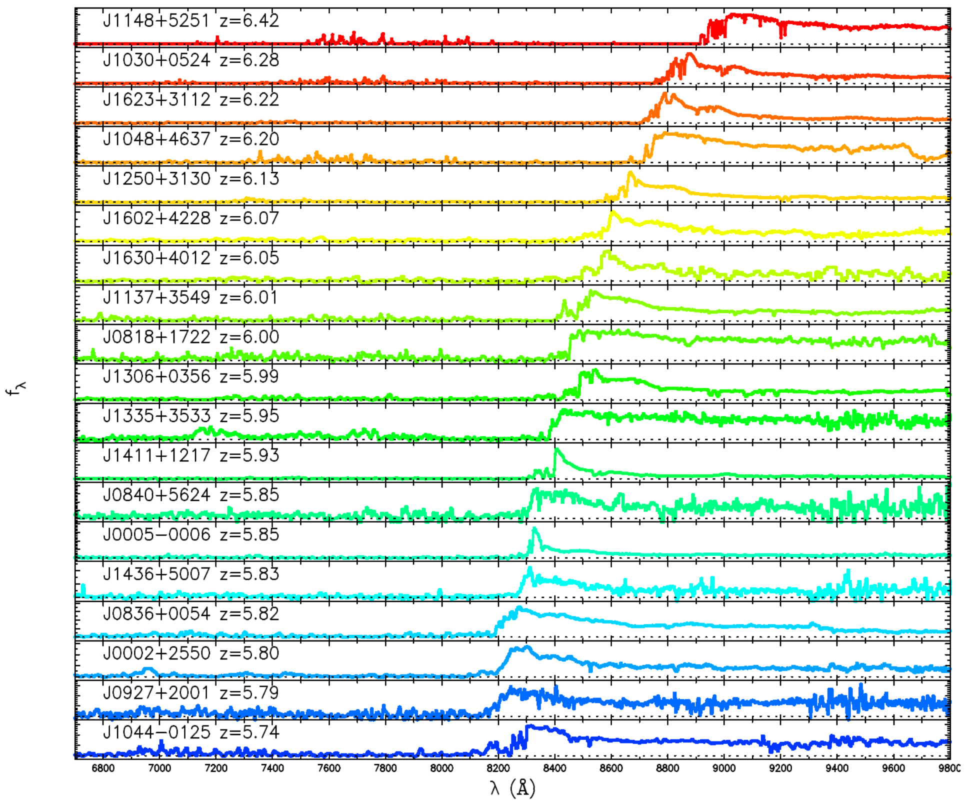

Qin et al. 2006.16828

# What we know to inform the 21cm observations

- The Gunn-Peterson tests on high-z QSO spectra → $\boxed{\text{very nearly complete by } z \sim 6}$

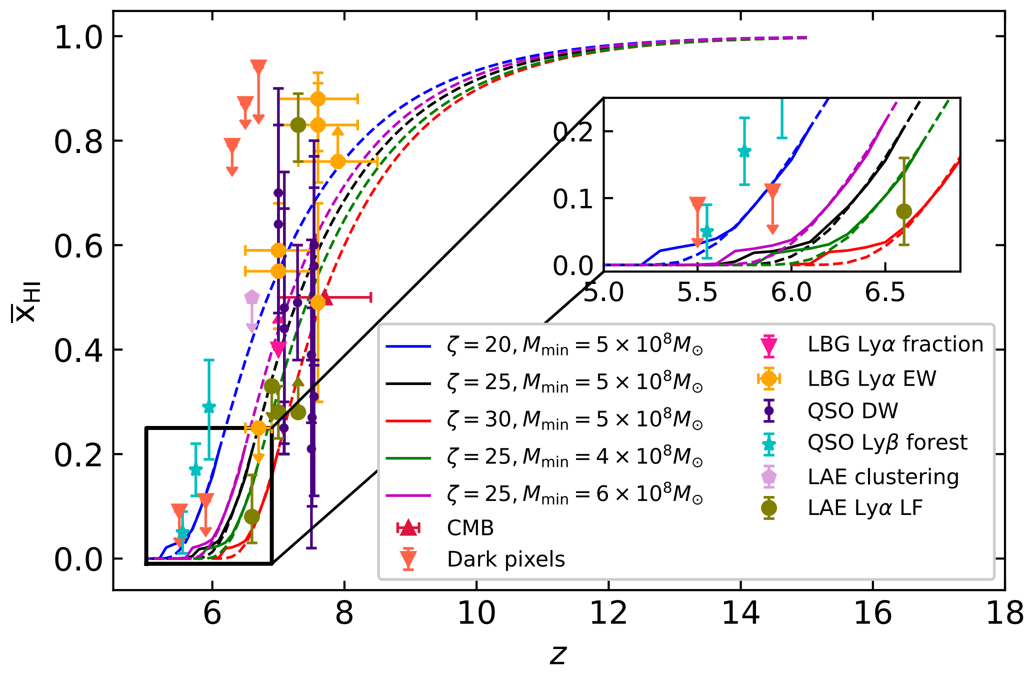
The Ly-a resonant absorption




Fan et al. (2006)

# Current Constraints on $x_{HI}(z)$

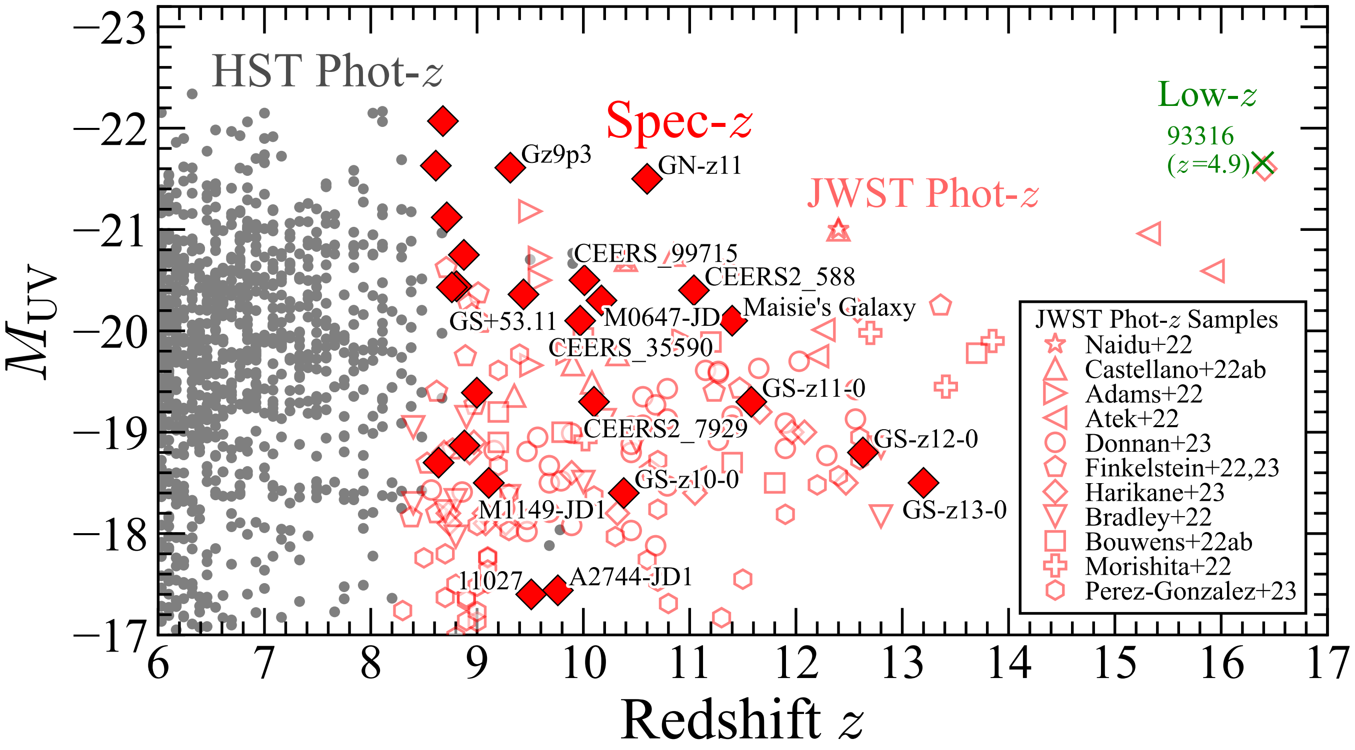


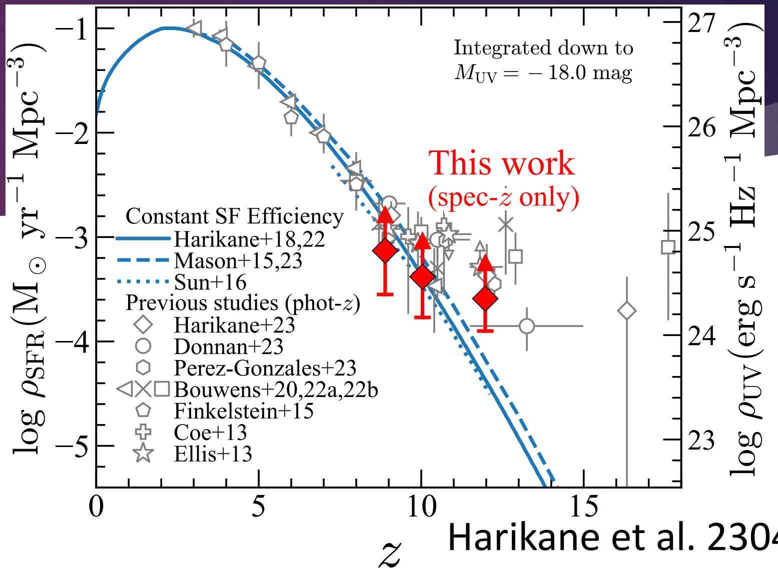

Zhu, **YX** et al. 2023, RAA

- Thomson $\tau$ to CMB (Planck Collaboration+2020);
- Dark pixels statistics (McGreer+2015; Jin+2023);
- Lya fraction (Mesinger+2015);
- Lya EW distribution of LBGs (e.g. Mason+2018, 2019; Bolan+2022),
- Lya damping wings (e.g. Bañados+2018; Greig+2019, 2022; Yang+2020);
- Dark gaps in Lyβ forest (Zhu+2022);
- Clustering of LAEs (Sobacchi & Mesinger 2015);
- Lya LFs (e.g. Morales+2021; Goto+2021; Wold+2022).

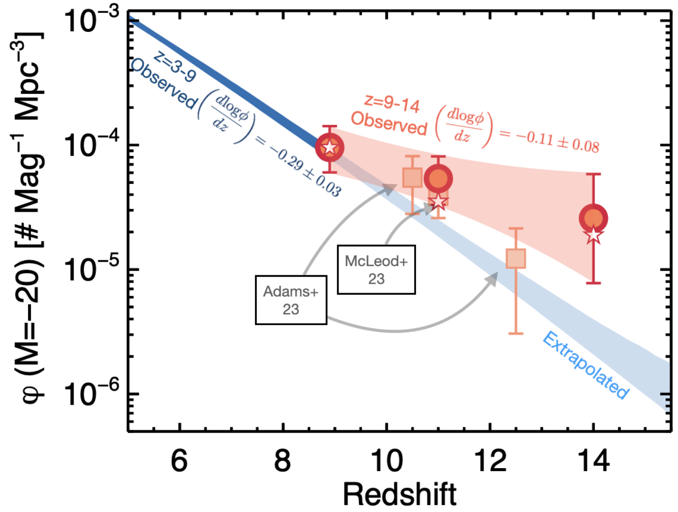
# Pieces collected by JWST

- 88 candidates at z ~ 8.5–14.5 with JWST/NIRCam
- 25 Galaxies at $z_{spec}$ = 8.61 – 13.20 Confirmed with JWST/NIRSpec




Harikane et al. 2304.06658



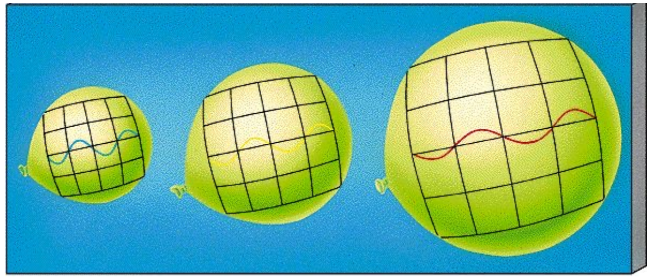

Complete CEERS (Finkelstein et al. 2311.04279)

# The 21cm transition of HI

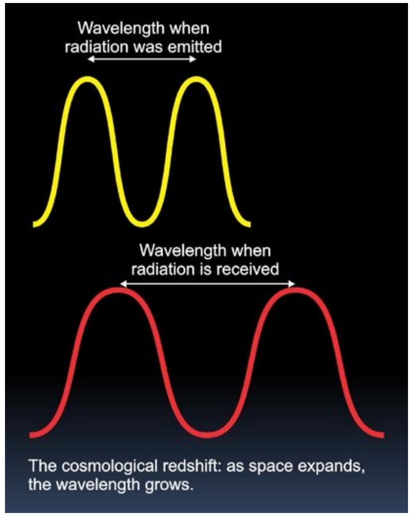
- Observable: **differential brightness** against a background source

$$\delta T_b(\nu) = \frac{T_S - T_\gamma(z)}{1+z}(1 - e^{-\tau_{\nu 0}}) \approx \frac{T_S - T_\gamma(z)}{1+z}\tau_{\nu 0}$$

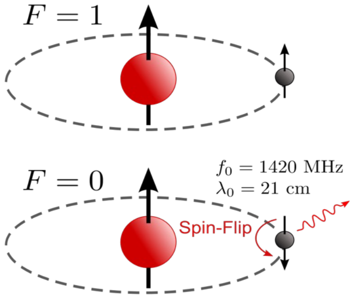
$$\approx 9 x_{\rm HI}(1+\delta)(1+z)^{1/2}\left[1 - \frac{T_\gamma(z)}{T_S}\right]\left[\frac{H(z)/(1+z)}{\mathrm{d}v_\parallel/\mathrm{d}r_\parallel}\right]\,\mathrm{mK}.$$



21cm → 21cm*(1+z)




- Signal level: determined by **$T_S$ (spin temperature)**




$$\frac{n_1}{n_0} = \frac{g_1}{g_0}\exp\left(-\frac{T_\star}{T_S}\right)$$

- Ts > Tγ → emission
- Ts < Tγ → absorption

$\mathbf{2.876 * 10^{-15} s^{-1}}$ **(11 million years)**

# Probing cosmic dawn with 21cm signals

$$\delta T_b(\nu) = \frac{T_S - T_\gamma(z)}{1+z}(1 - e^{-\tau_{\nu_0}}) \approx \frac{T_S - T_\gamma(z)}{1+z}\tau_{\nu_0}$$

$$\approx 9 x_{\mathrm{HI}}(1+\delta)(1+z)^{1/2}\left[1 - \frac{T_\gamma(z)}{T_S}\right]\left[\frac{H(z)/(1+z)}{\mathrm{d}v_\parallel/\mathrm{d}r_\parallel}\right]\boxed{\mathrm{mK}.}$$

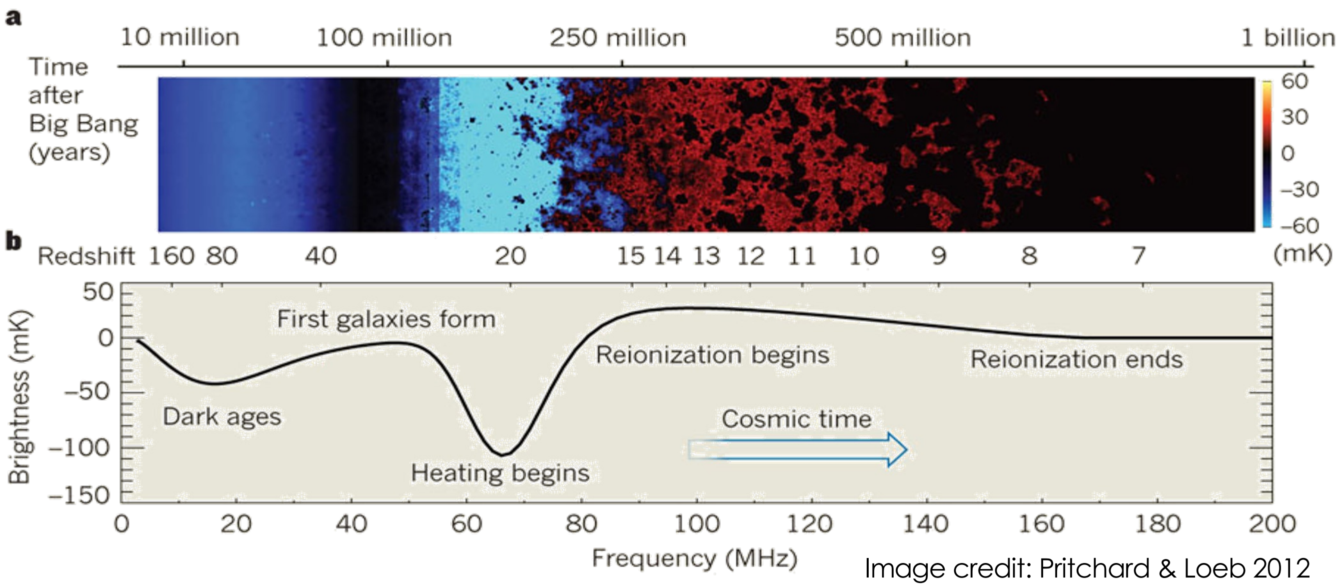



Image credit: Pritchard & Loeb 2012

- Rough timing → Target band:

50 MHz ~< $\nu$ <~ 200 MHz

- Bright foreground VS. Weak signal

- Unknown temperature
- Unknown signal level

# The 21 cm probes to CD/EoR

- Using CMB as background
  - → **1.** The sky-averaged 21-cm brightness -- the global 21cm spectrum

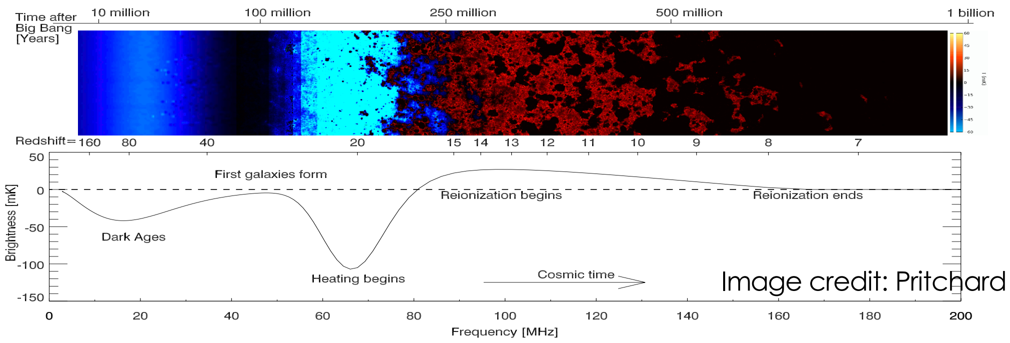
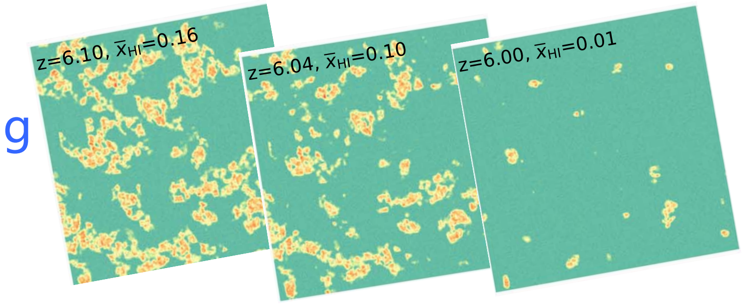


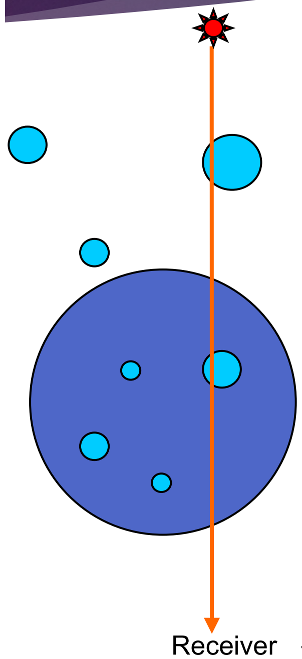

Image credit: Pritchard & Loeb 2012

  - → **2.** 21 cm tomography

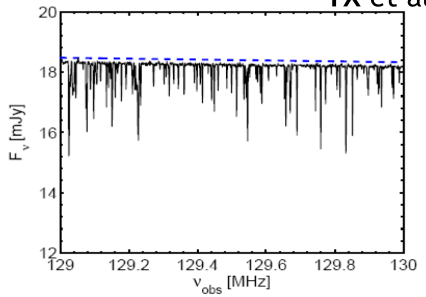
21 cm imaging




21 cm statistics




YX et al. 2011 MNRAS




- 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)

# Outline

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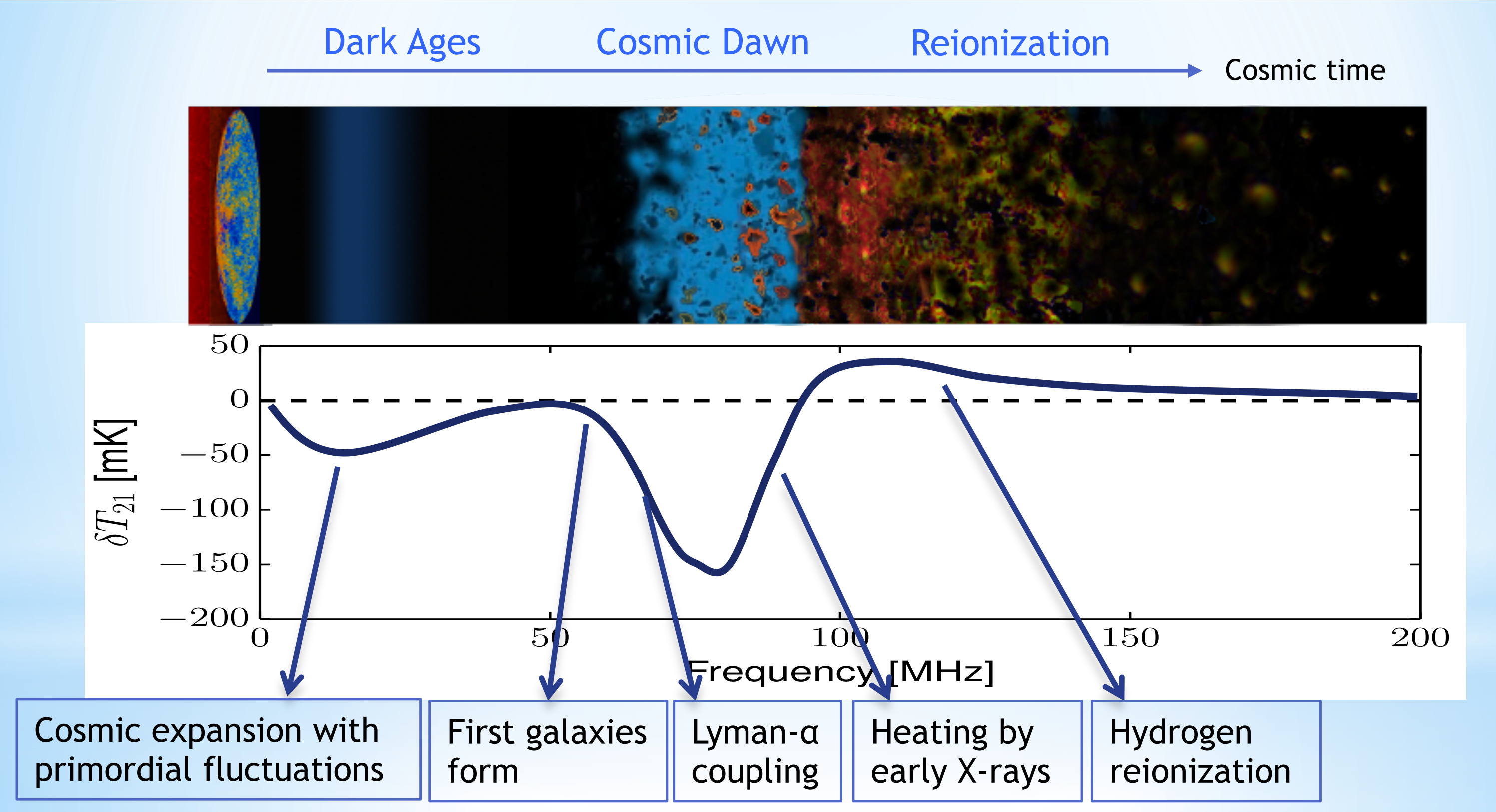
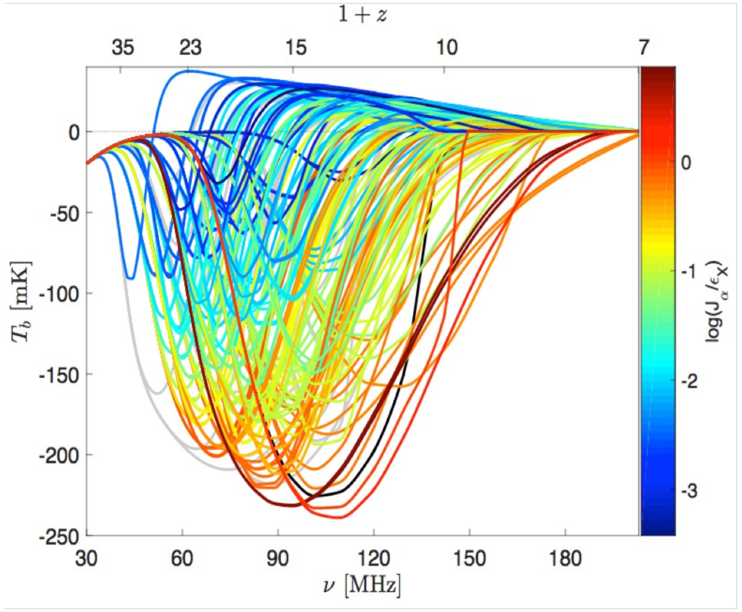
# The global 21cm spectrum from cosmic dawn




(Cohen et al. 2018)

Image credit: Yuan Shi

# The UNEXPECTED spectrum measured by EDGES

EDGES Low-band antennas

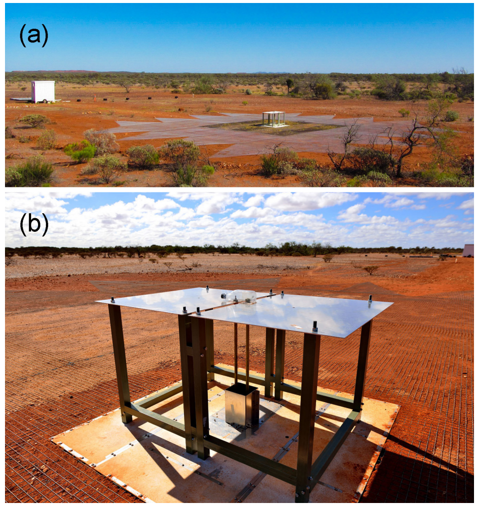
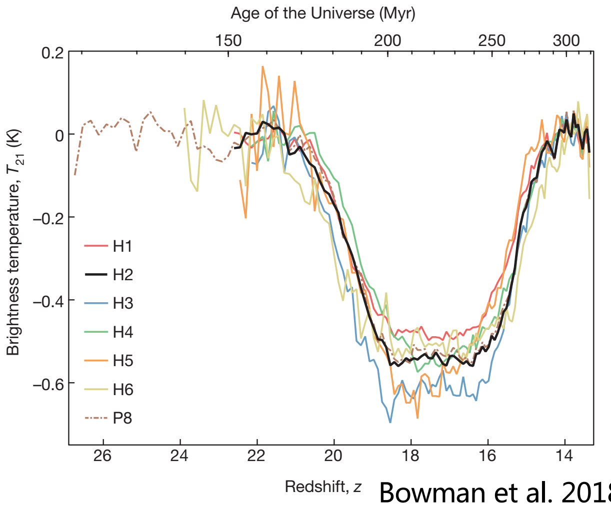
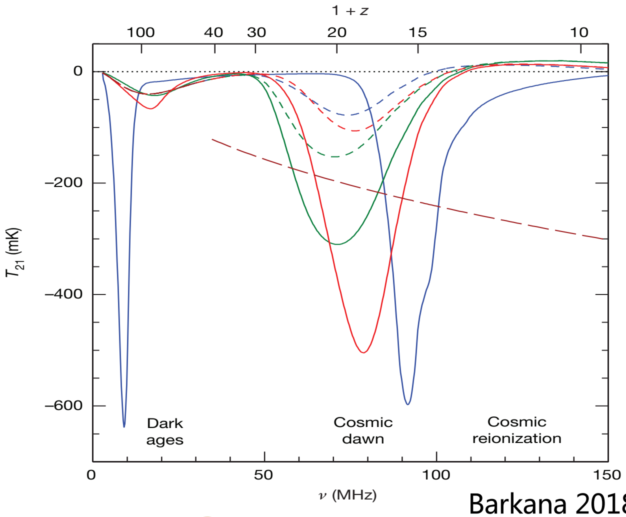



image credit: EDGES team




Bowman et al. 2018

*3.8 σ deviations*




Barkana 2018

$$T_{21}(z) \approx 0.023\ \mathrm{K} \times x_{\mathrm{HI}}(z)\left[\left(\frac{0.15}{\Omega_{\mathrm{m}}}\right)\left(\frac{1+z}{10}\right)\right]^{\frac{1}{2}}\left(\frac{\Omega_{\mathrm{b}}h}{0.02}\right)\left[1-\frac{T_{\mathrm{R}}(z)}{T_{\mathrm{S}}(z)}\right]$$

*Implications*

➔ **Higher $T_R$ ?** ($T_R$ > 104 K) (e.g. Feng & Holder 2018; Ewall-Wice et al. 2018; Fraser et al. 2018)

➔ **Lower $T_S$ ?** ($T_S$ < 3.2 K) (e.g. Barkana 2018; Fialkov et al. 2018; Barkana et al. 2018; Slatyer & Wu 2018; Hirano & Bromm 2018; Munoz et al. 2018)

➔ Modified cosmology (largely constrained by the CMB)

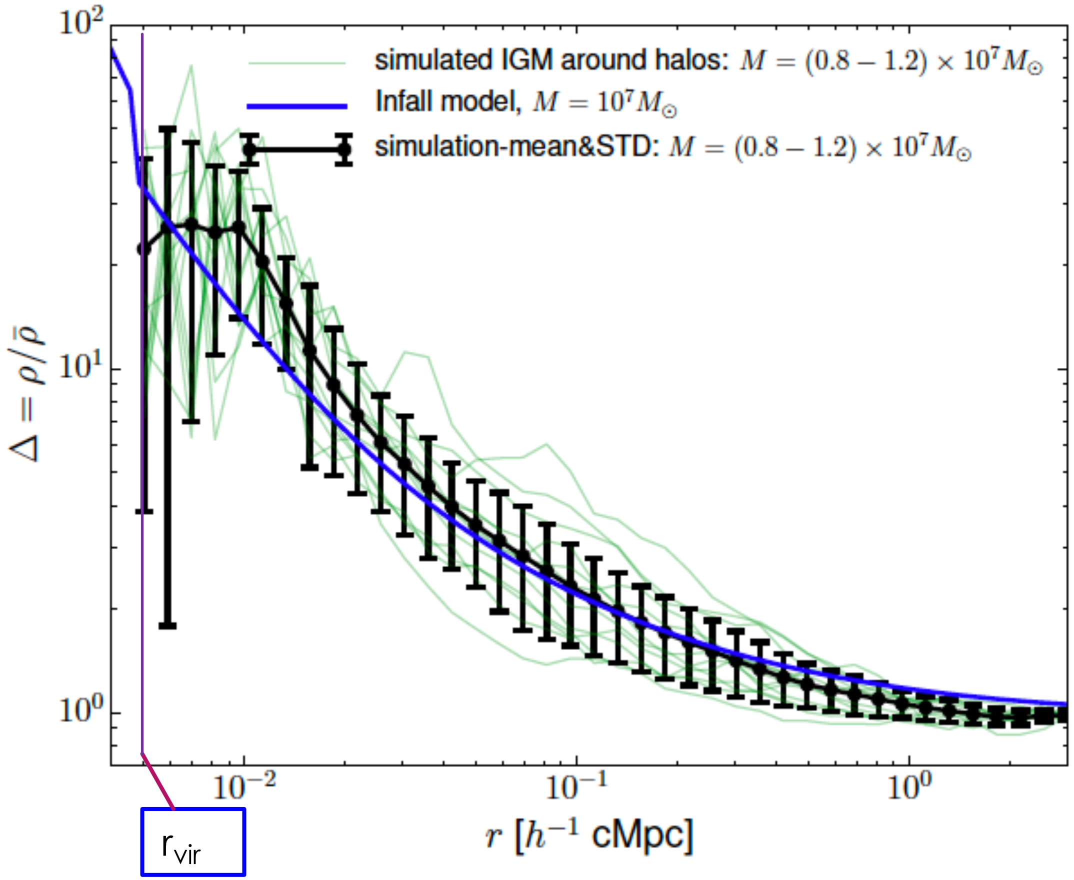
# Any neglected effects within the framework of standard model?

$$\delta T_b(\nu) = \frac{T_S - T_\gamma(z)}{1+z}(1 - e^{-\tau_{\nu 0}}) \approx \frac{T_S - T_\gamma(z)}{1+z}\tau_{\nu 0}$$

$$\approx 9 \underbrace{x_{\rm HI}(1+\delta)}_{\text{HI density}}(1+z)^{1/2}\left[1 - \frac{T_\gamma(z)}{\underbrace{T_S}_{\text{Gas temperature}}}\right]\left[\frac{H(z)/(1+z)}{\underbrace{\mathrm{d}v_\parallel/\mathrm{d}r_\parallel}_{\text{Velocity gradient}}}\right] \mathrm{mK}.$$

*Does the non-linear structure formation have an overall effect?*

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

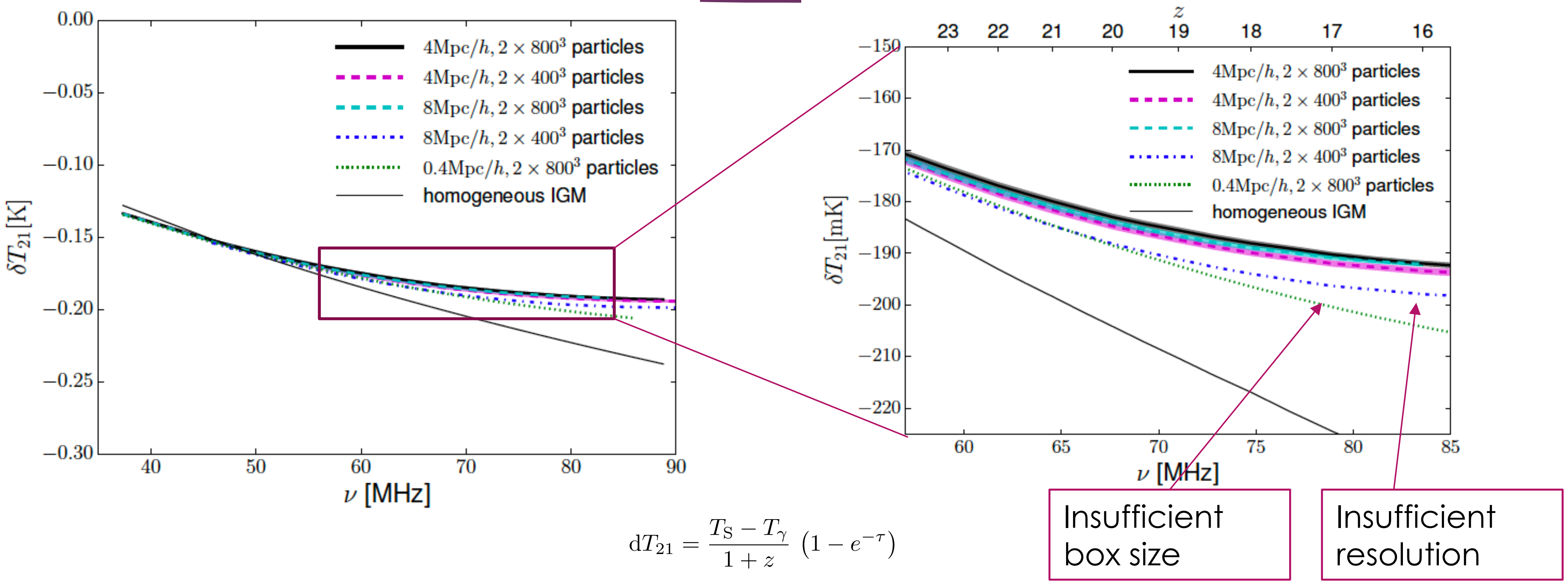



- Non-linear gas density fluctuations
- Peculiar velocities
- Adiabatic heating & cooling
- Shock heating
- Compton heating

***Very high resolution hydrodynamic Simulation required!***

# The maximum global 21 cm signal

## High resolution cosmic hydrodynamic simulation




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

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

**YX**, Yue, Chen, 2021, ApJ

# Take-home message for the global 21 cm spectrum

- The non-linear structure formation ***reduces the maximum*** 21 cm absorption signal ***by 15% at $z = 17$***!

- Necessary to take into account the non-linear structure formation when interpreting the upcoming data, and looking for new physics!

- Enlarged discrepancy between theory and EDGES signal!

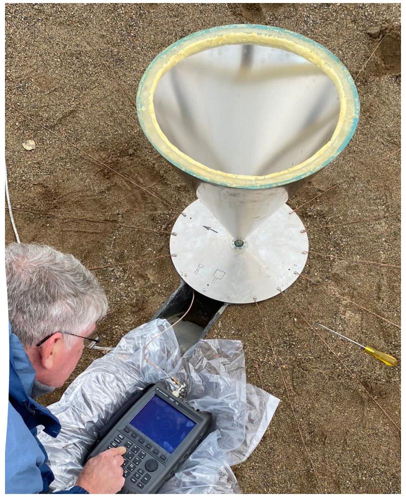
# Other ground-based experiments for the global spectrum

MIST

REACH

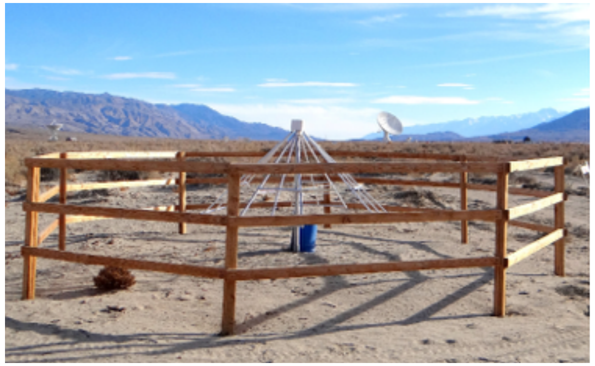
PRI$^{Z}$M

HIGH-Z

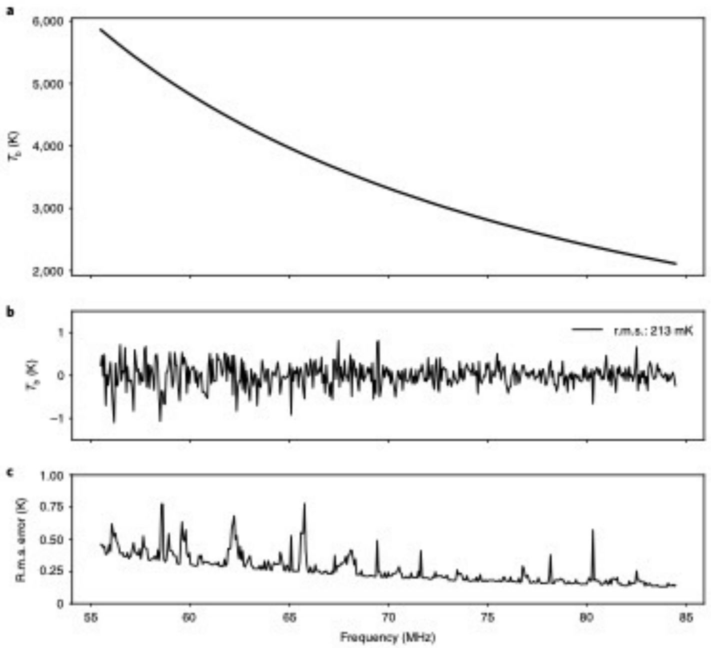


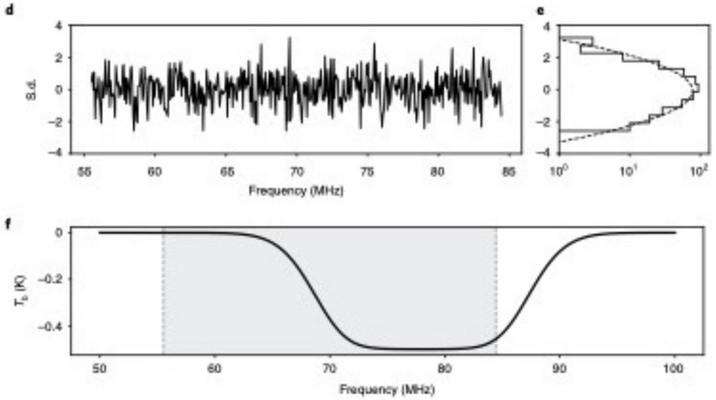
BIGHORNS:

LEDA:



# The SARAS-3 measurement

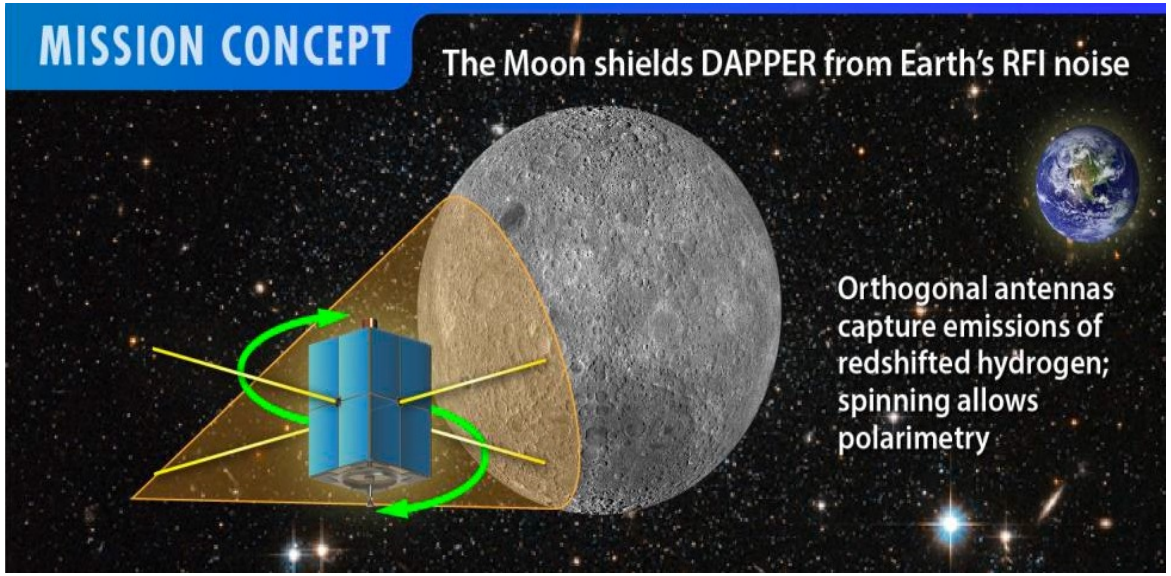


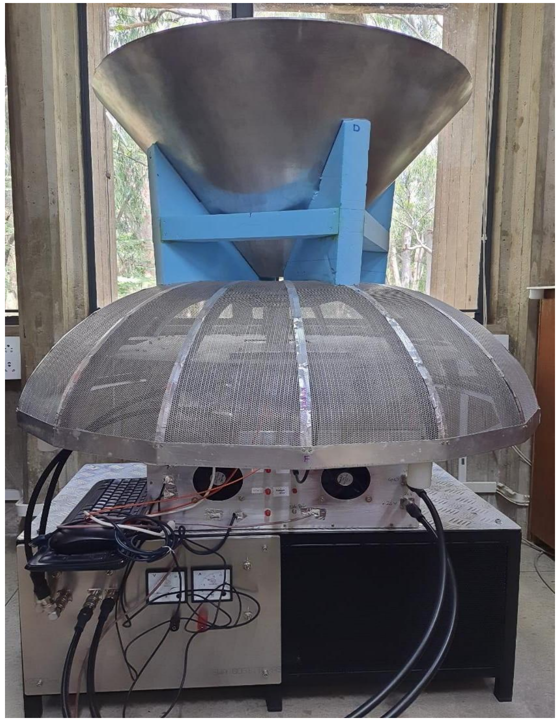

Reported a **non-detection** of the EDGES absorption feature at 95.3% confidence using 15 hrs of observations between 55 – 85 MHz (z = 15 – 25)
(S. Singh et al. 2022)

# Going to the far side of the Moon …

**PRATUSH**




Credit: DAPPER collaboration

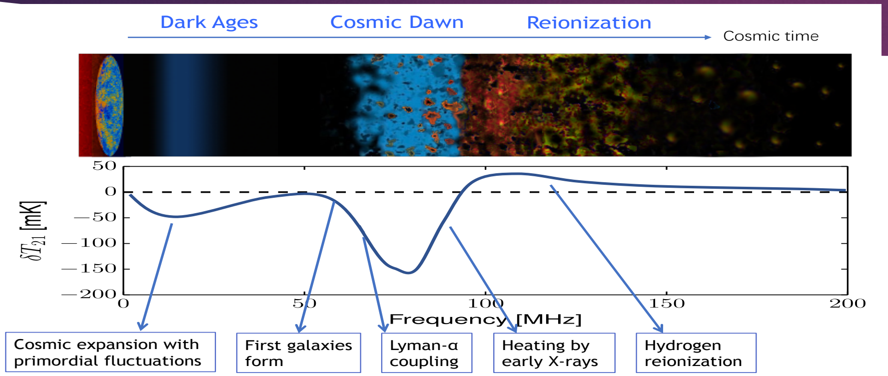


Credit: PRATUSH collaboration

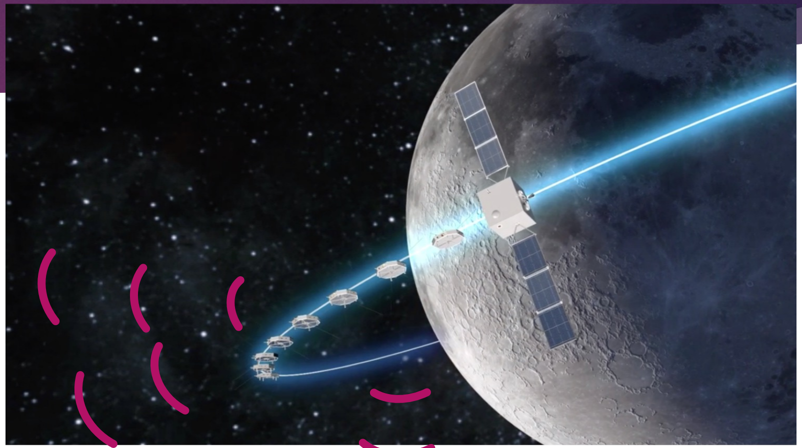
# 鸿蒙计划
# Discovering the Sky at the Longest wavelength (DSL)

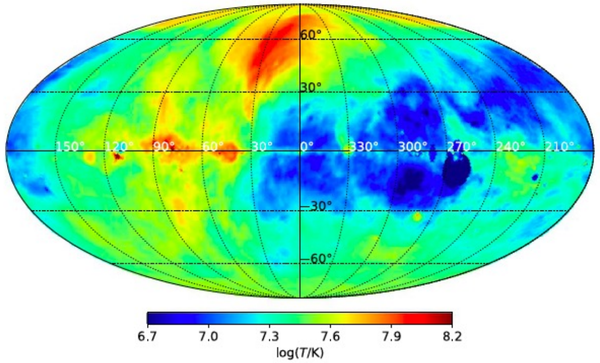
PI: Xuelei Chen (NAOC)

Tech Chief: Jingye Yan (NSSC)

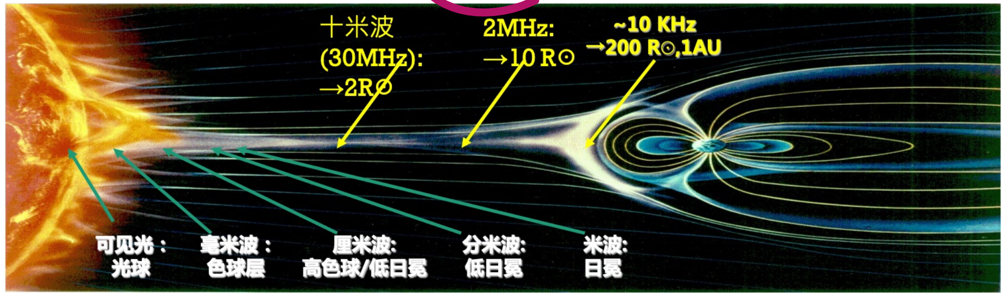



1. Reveal the dark ages and cosmic dawn with high-precision measurement of the global spectrum.





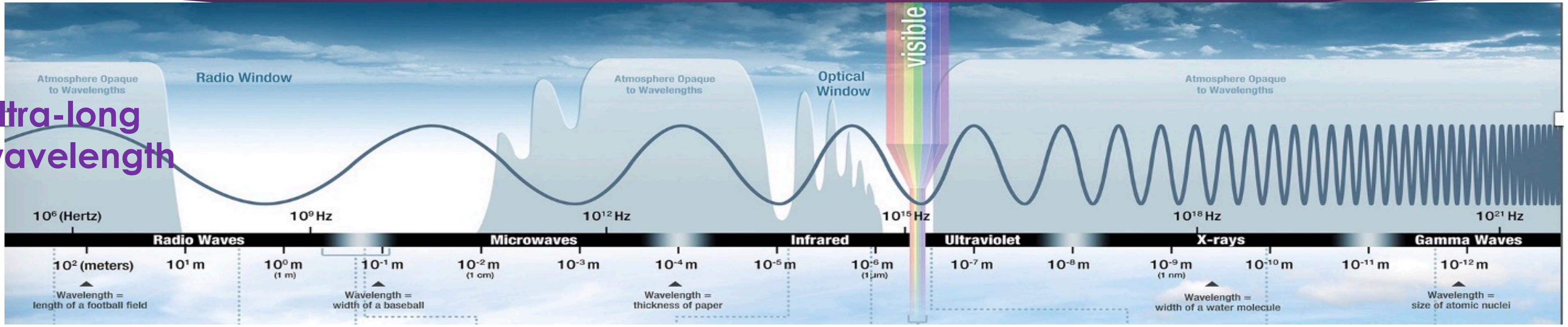

2. Open up the last unexplored electromagnetic window.

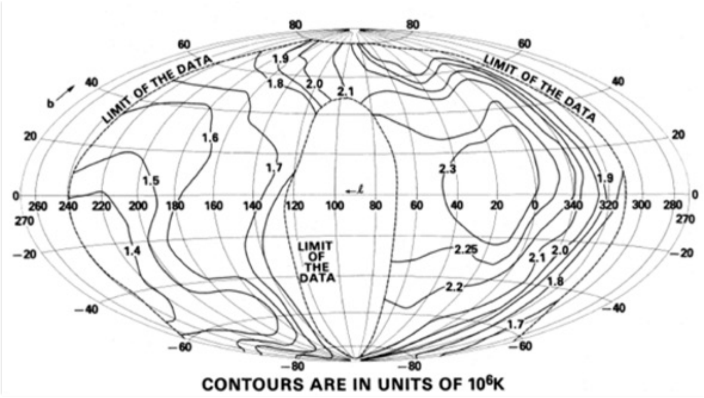



3. Observing the Sun and planets to uncover the dynamics of the interplanetary space.

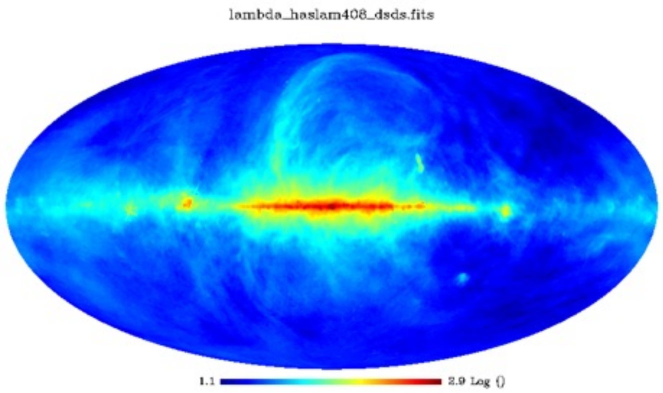
# Ultra-long wavelengths ($\nu$ < 30 MHz) – the last unexplored electromagnetic window

Ultra-long wavelength

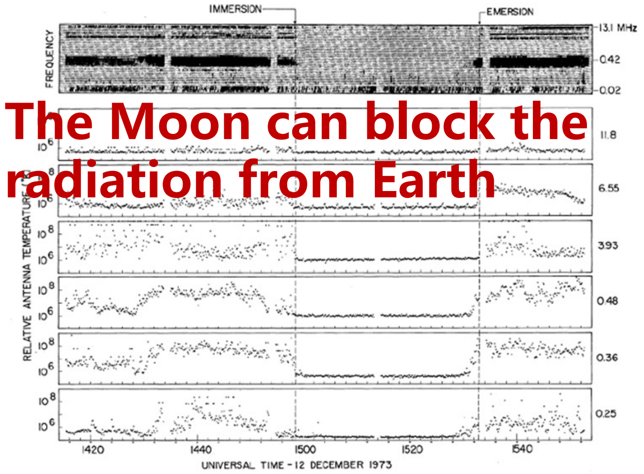



RAE-2 satellite (1978)




408 MHz Sky Map

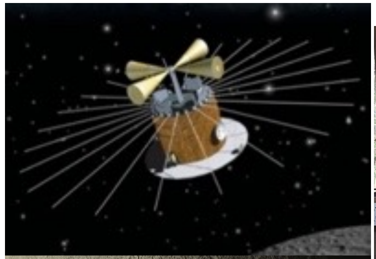


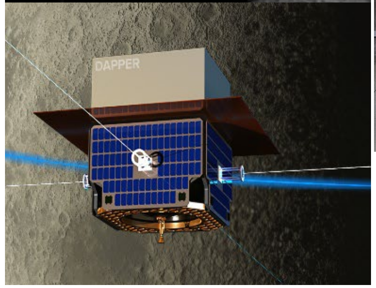

The Moon can block the radiation from Earth

RAE-2 spectrum

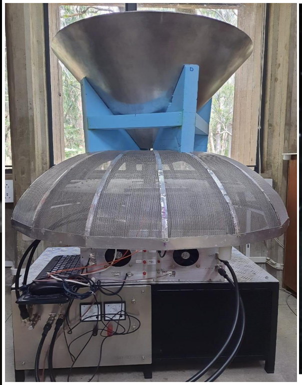
# Lunar-based ultralong wavelength astronomy

美国：
DARE/DAPPER

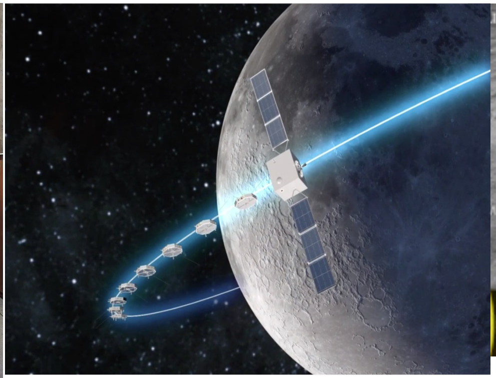




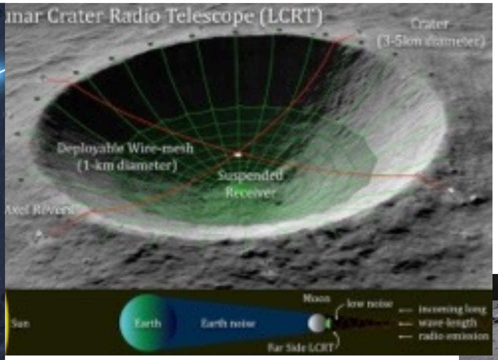

印度：
PRATUSH



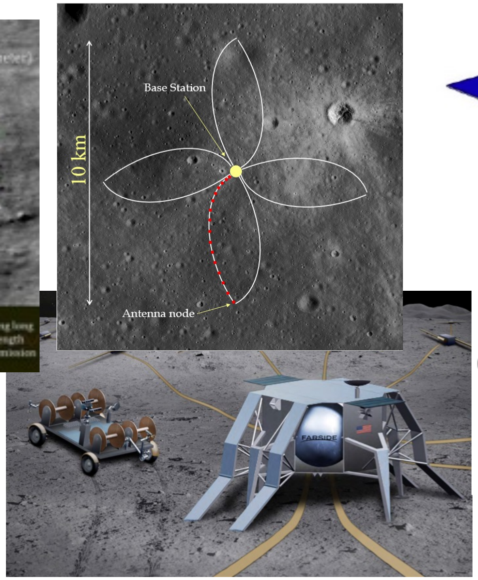
中国：
鸿蒙计划（DSL）



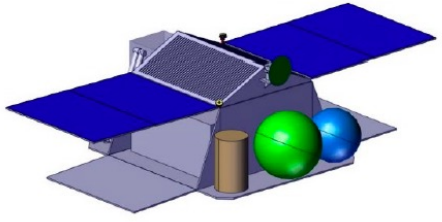
美国：
LCRT

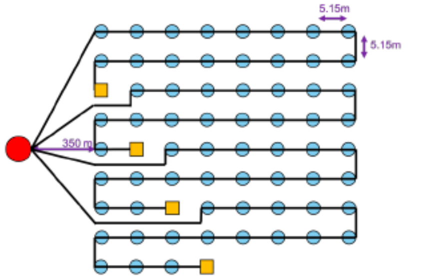



美国：
FARSIDE




欧洲：
ALO

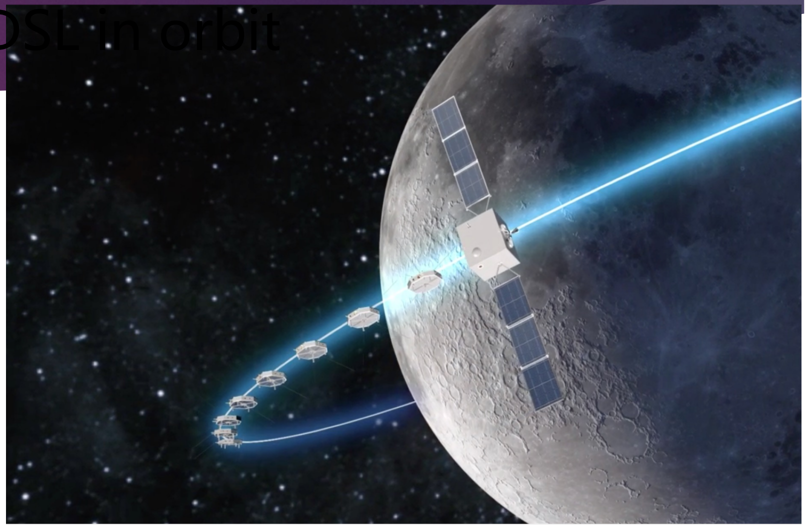




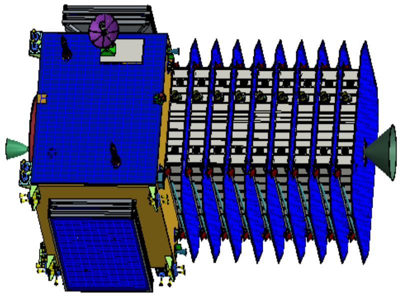
# Lunar Orbit Array DSL（鸿蒙计划）

An interferometer array with 1 mother +9 daughter satellites in lunar orbit

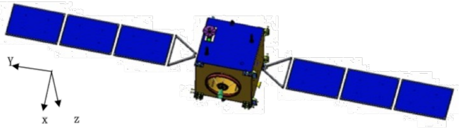
DSL in orbit



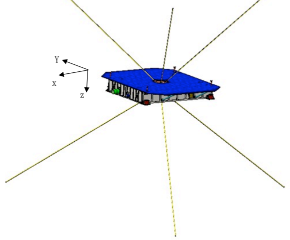
- lunar satellite: no need for landing
- Lunar orbit period is a few hours, can use solar power
- Observe on the far side of the Moon, and transmit data back on the front side
- All flying on the same orbit, easy to maintain and communicate



mother-daughter combo

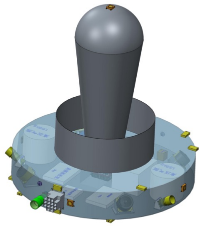


mother satellite



8 x low freq. daughter

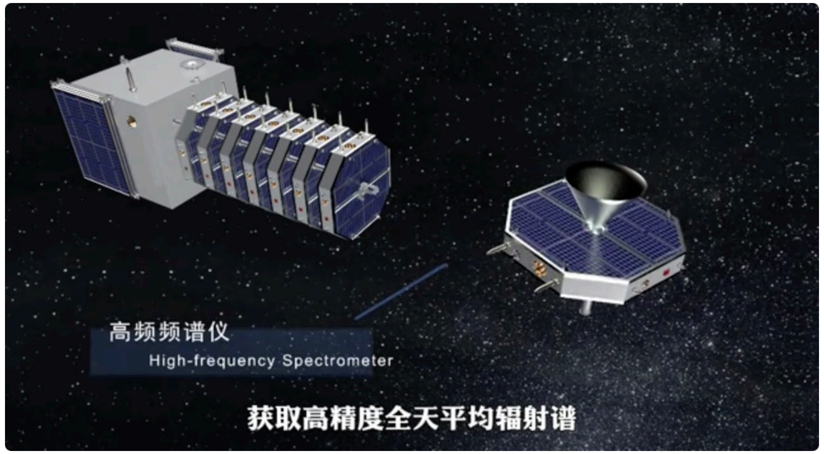
➔ **high resolution sky map at 0.1 – 30 MHz**



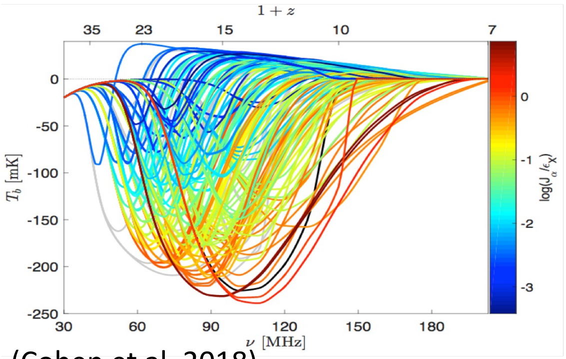
1 x high freq. daughter

➔ **high precision measurement of global spectrum at 30 – 120 MHz**

# What can we do?
# – Measuring the global 21 cm spectrum on lunar orbit

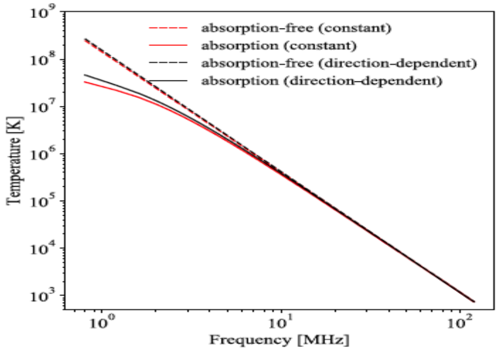



21cm signal ～ 0.1 – 0.2 K



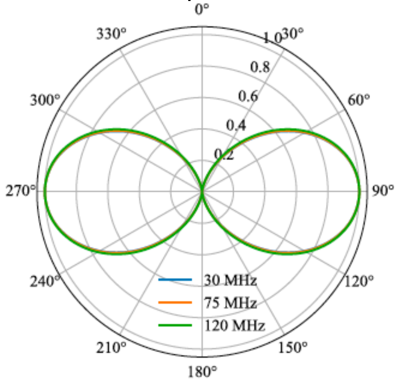

(Cohen et al. 2018)

Foreground ～ $10^4$ K

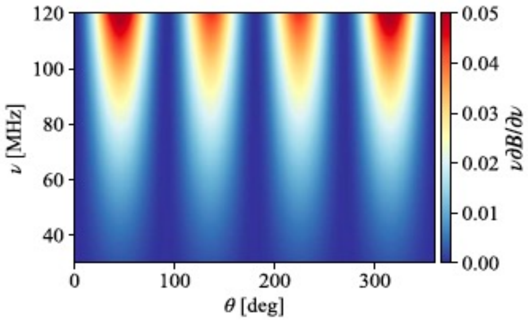



**Very low chromaticity required!**

Beam pattern

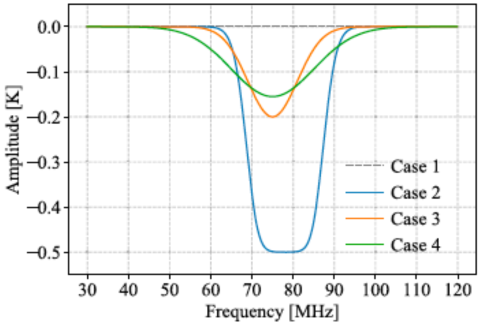



Frequency gradient of beam

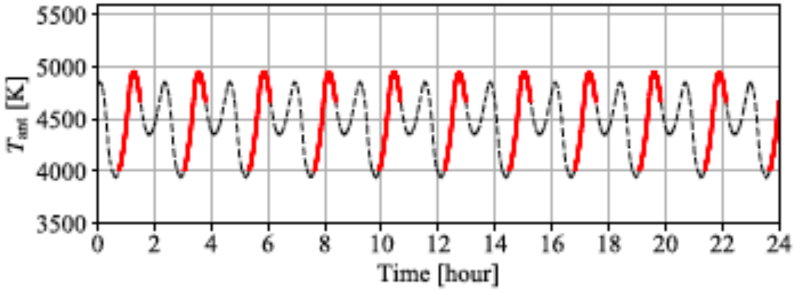


# Measuring the global 21 cm spectrum from Cosmic Dawn on lunar orbit

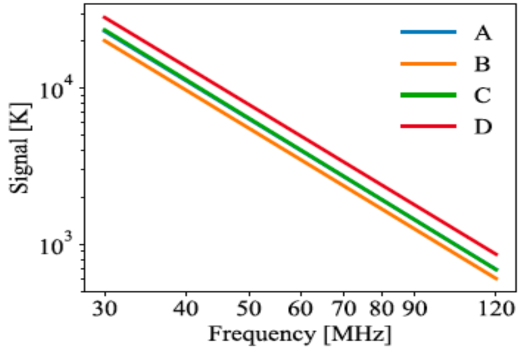
21cm signal model




Mock observation（60 MHz）

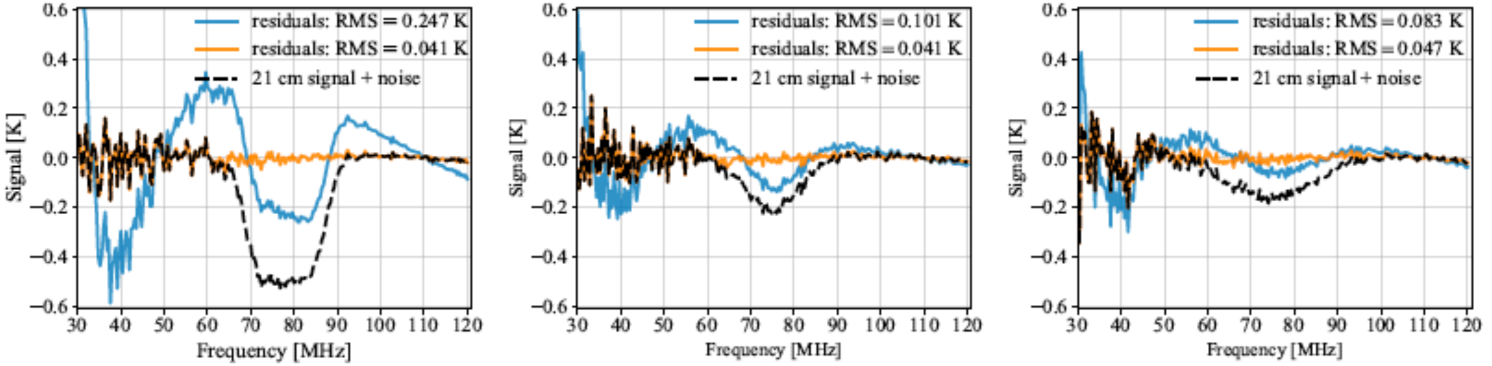



Simulated spcetrum




施媛(SJTU)

## Recovery of the global 21cm signal



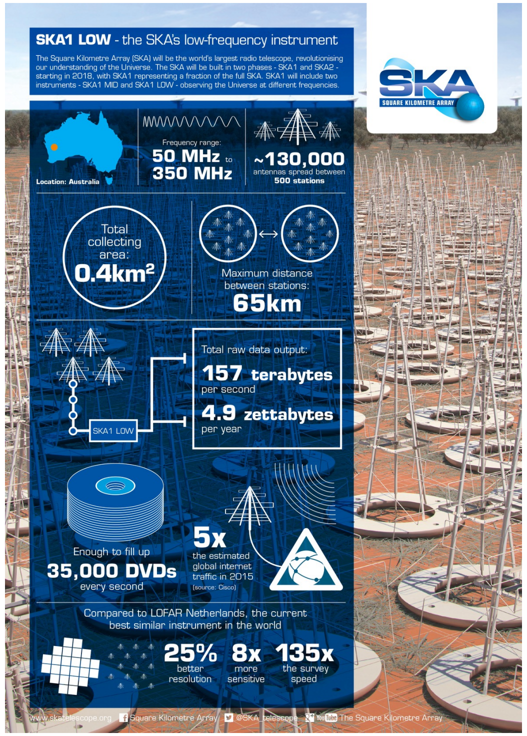

(a) Results for the EDGES 21 cm model. (b) Results for Gaussian 21 cm model ($A$ = 0.2 K). (c) Results for Gaussian 21 cm model ($A$ = 0.155 K).

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

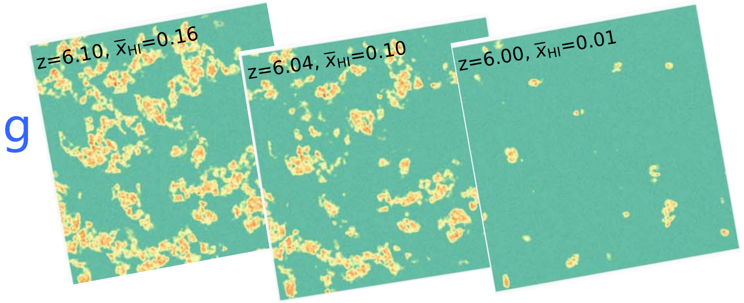
# Outline

- Background: Cosmic dawn and various probes
- 1. The global 21cm spectrum
- **2. The 21cm tomography**
- 3. The 21cm forest
- Summary

# 21 cm Tomography – imaging

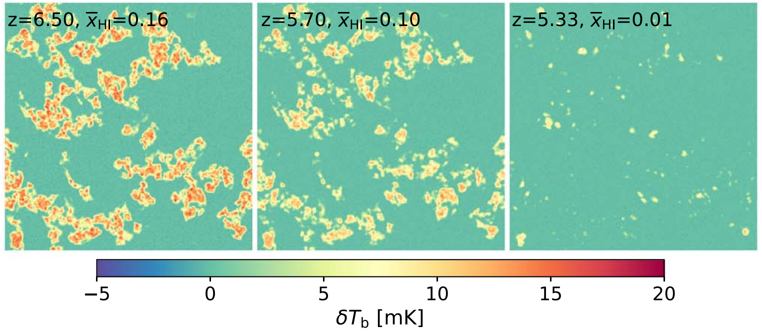



21 cm imaging




21 cm statistics (power spectrum, bispectrum, skewness, ...)

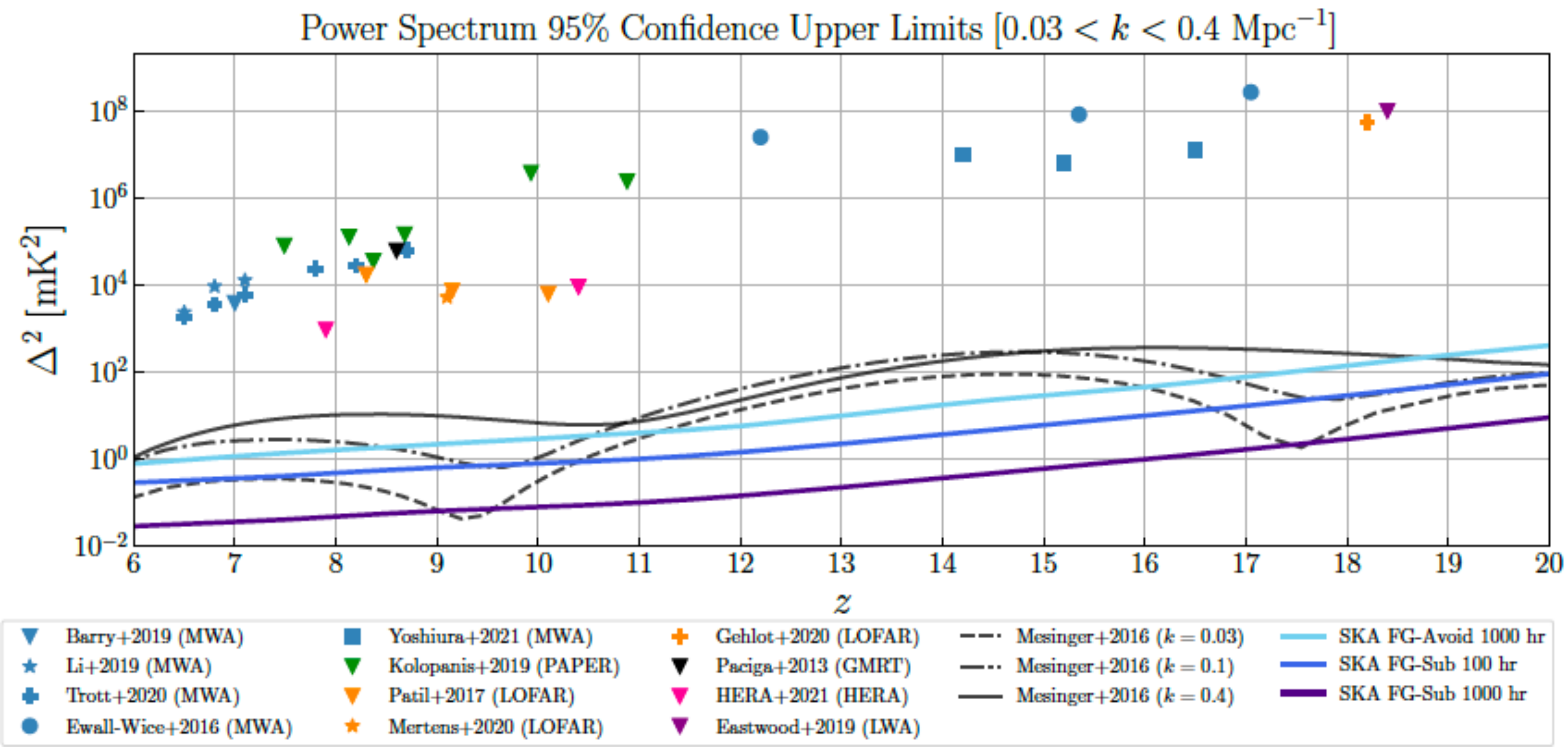
High z → Low z




B = 1 MHz

Wu, **YX** et al. 2022, ApJ

# 21 cm Tomography – power spectrum upper limits



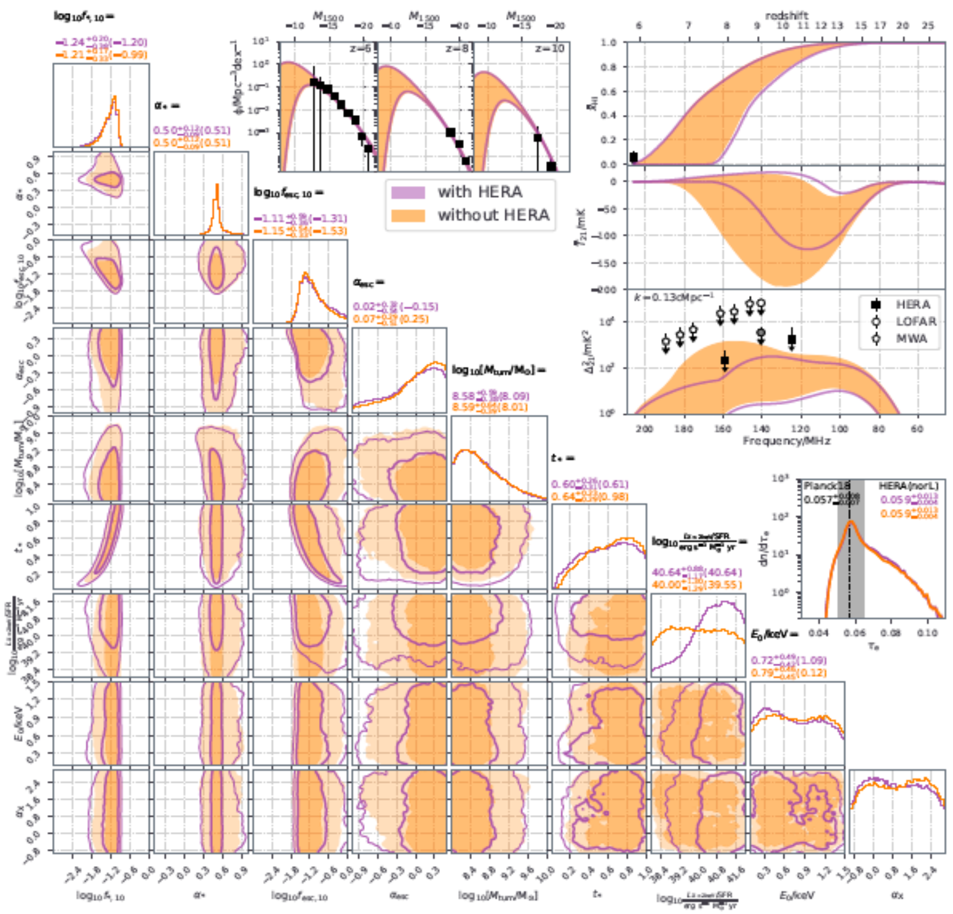

Barry et al. arXiv:2110.06173

PAPER

LOFAR

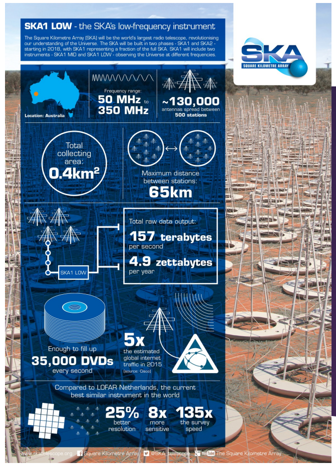

HERA

# Inferring the EoR physics

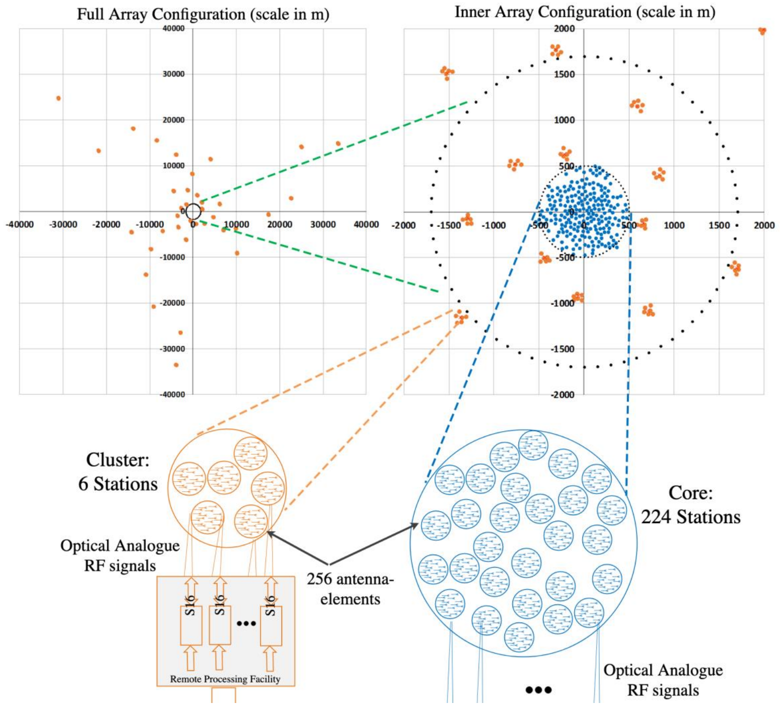



The HERA Collaboration, 2022, ApJ, 924, 51

- **Complex** physical processes interplaying
- **Fast** realization of 3-D lightcone → parameter inference
  - 21CMMC (Greig+15, 18)
  - 21cmDELFI-PS (Zhao et al. 2022)
- Model-dependent → possible bias → **accurate** modeling required

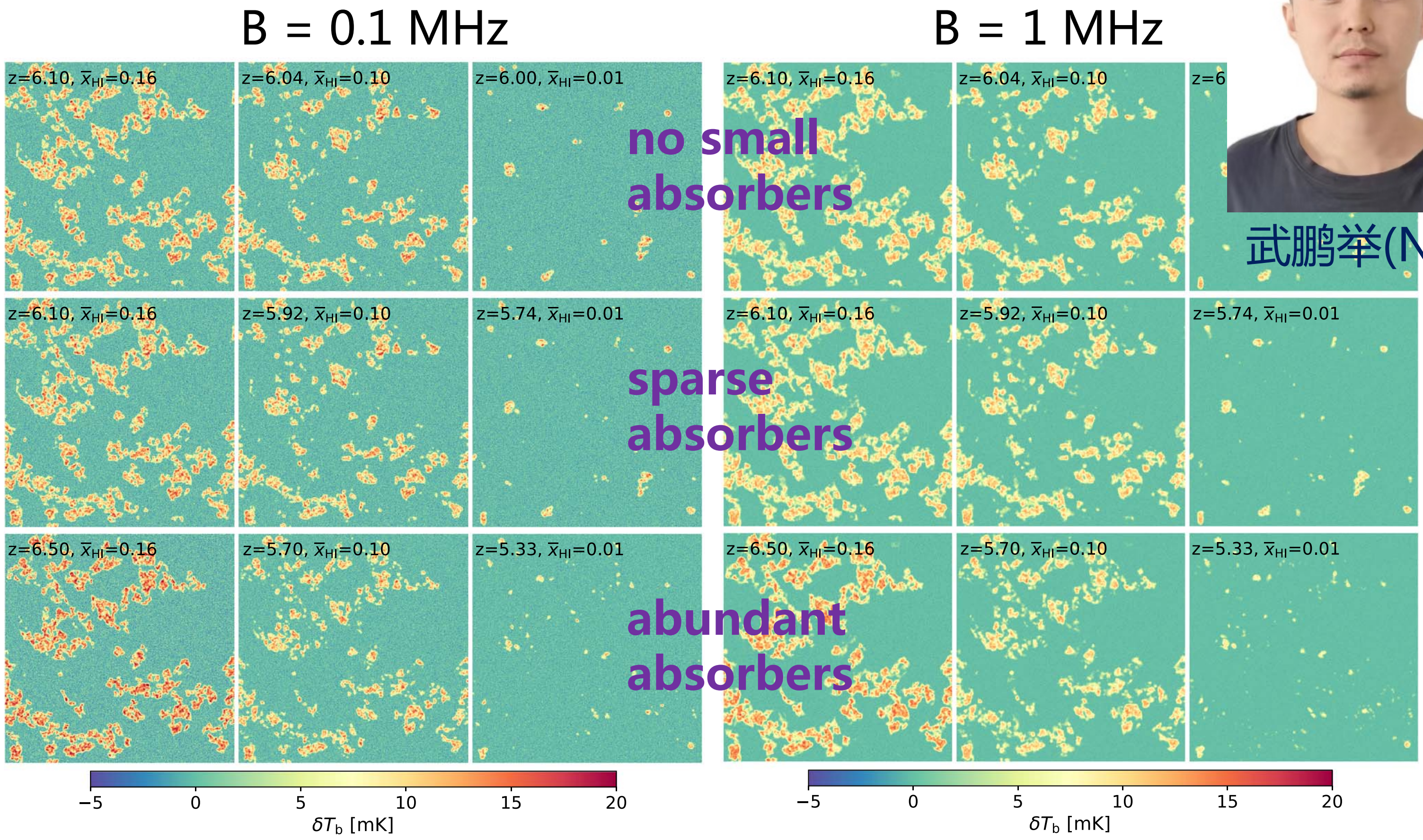



# The 21 cm images as observed by the SKA1-Low core array




Credit: SKAO (SKA-TEL-SKO-0001075)

$$\sigma_T = \frac{k_\perp}{2\pi}(D_c^2 \times \Omega_{\rm FoV})^{1/2}\,\frac{T_{\rm sys}}{\sqrt{B\,t_{\rm int}}}\,\sqrt{\frac{A_{\rm core}A_{\rm eff}}{A_{\rm coll}^2}}$$




武鹏举(NEU)

Wu, **YX** et al. 2022, ApJ

# Outline

- Background: Cosmic dawn and various probes
- 1. The global 21cm spectrum
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- **3. The 21cm forest**
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# 21 cm Forest

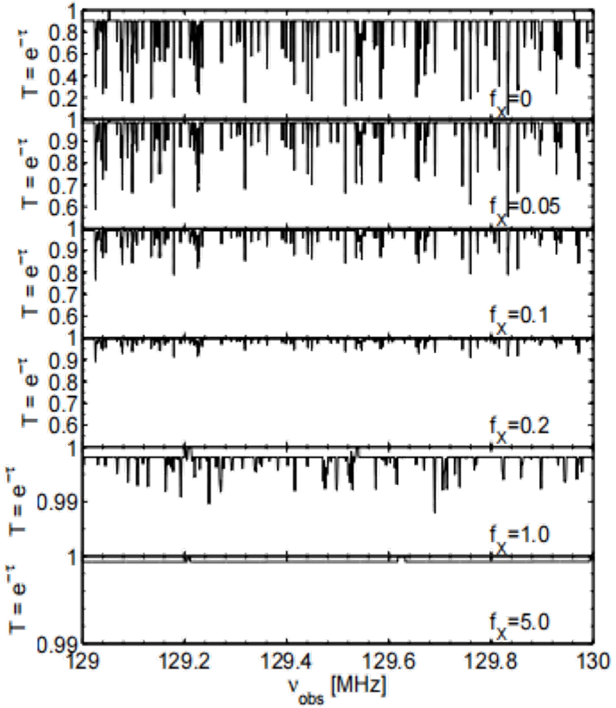
# -- absorption lines against high-z radio point sources

(e.g. Carilli et al. 2002; YX et al. 2009, 2010, 2011)

# 21 cm Forest

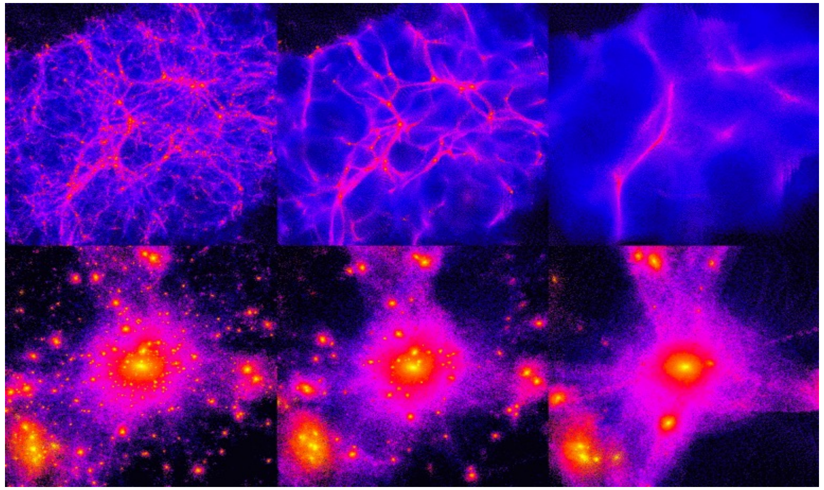
- Sensitive probe to $T_{IGM}$

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




**Xu YD** et al. 2009, 2010, 2011

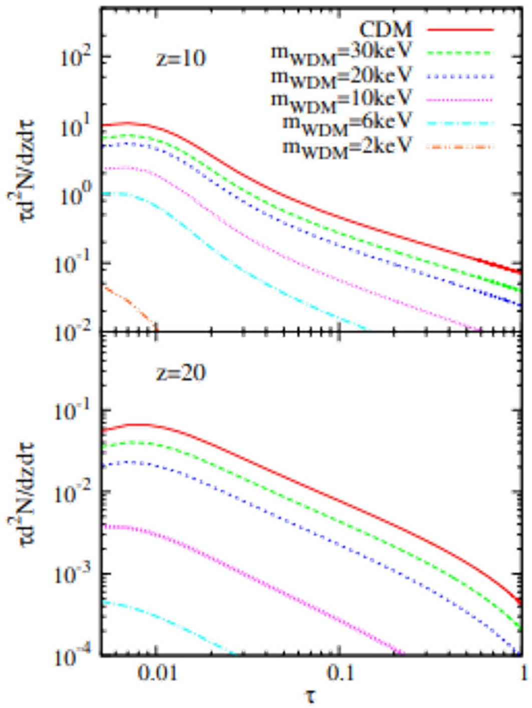
- Unique probe to small –scale structures at cosmic dawn (CD) → Dark Matter properties at CD



CDM
WIMP/AXION

WDM
Sterile
Neutrino

HDW
3 Neutrinos

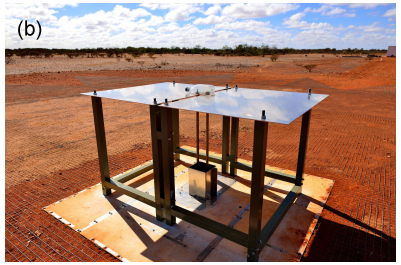


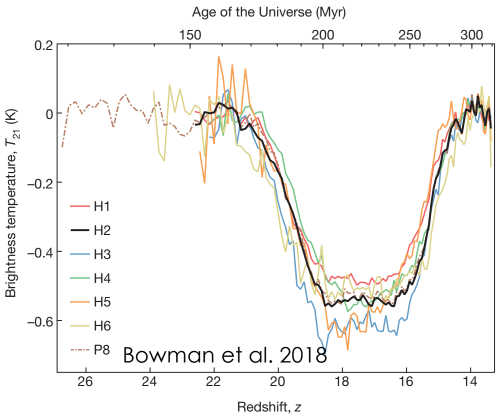

Shimabukuro et al. 2014

# 21 cm Forest: never even tried?!

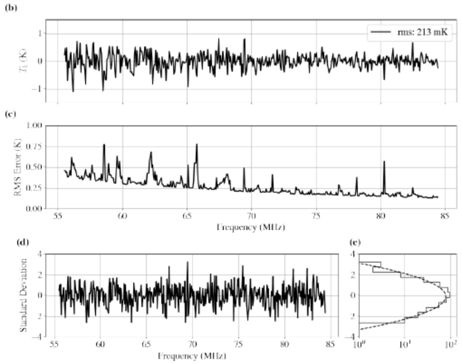
1. 21 cm global spectrum

EDGES-Low-band



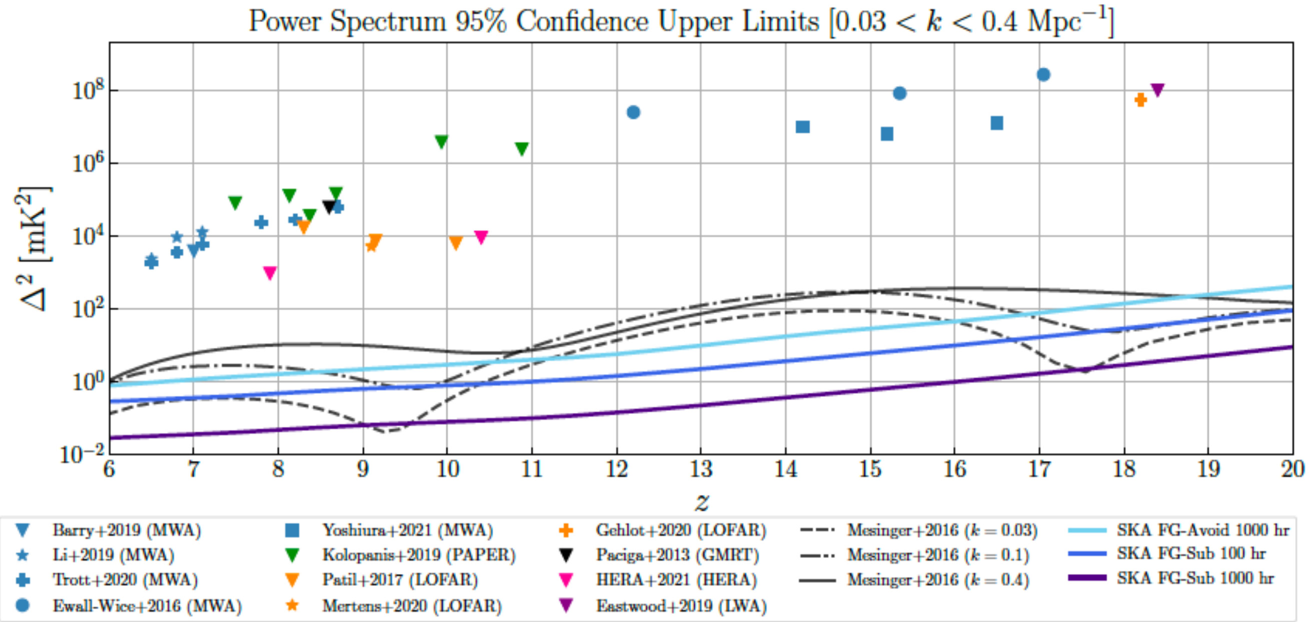

SARAS 3




Singh et al. 2112.06778

2. 21 cm tomography


Interferometers

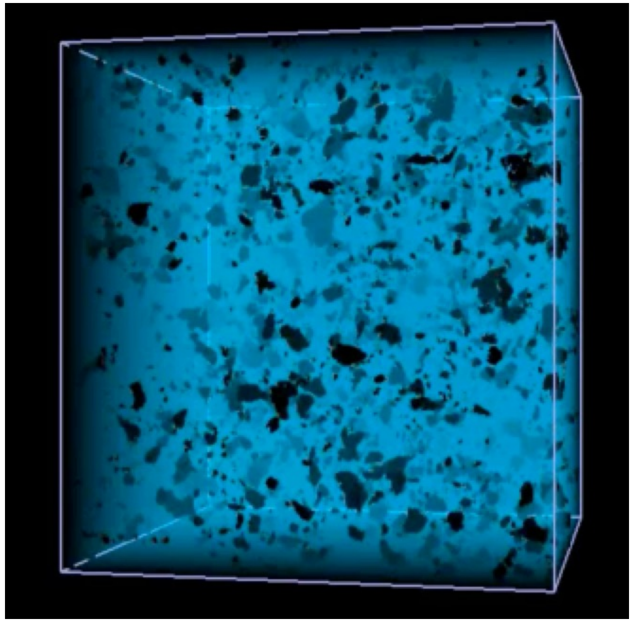



Barry et al. arXiv:2110.06173

# 21-cm Forest: theoretical challenges

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

1 Gpc



**islandFAST**, **XuYD** et al. 2017

2✖10[5]

- Main contributor: minihalos & ambient IGM

6 kpc @ z=9


$\rho$ & $T_K$ profiles,
Local $x_i$ & $v$,
$T_S$ coupling
(collisional, Ly$\alpha$,
CMB)
……

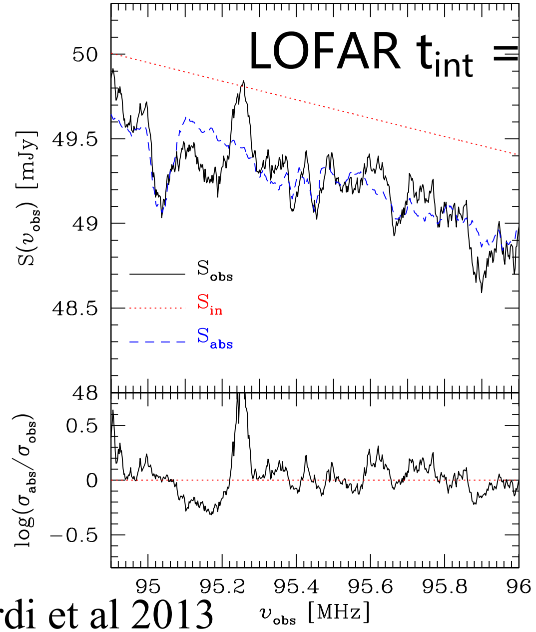
$$\tau_{\nu_0}(\hat{\boldsymbol{s}}, z) \approx 0.0085\,[1+\delta(\hat{\boldsymbol{s}}, z)]\,(1+z)^{3/2}\left[\frac{x_{\rm HI}(\hat{\boldsymbol{s}}, z)}{T_{\rm S}(\hat{\boldsymbol{s}}, z)}\right]\left[\frac{H(z)/(1+z)}{{\rm d}v_\parallel/{\rm d}r_\parallel}\right]\left(\frac{\Omega_{\rm b}h^2}{0.022}\right)\left(\frac{0.14}{\Omega_{\rm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

# 21-cm Forest: observational challenges

- Probing thermal history ⇔ easily suppressed

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

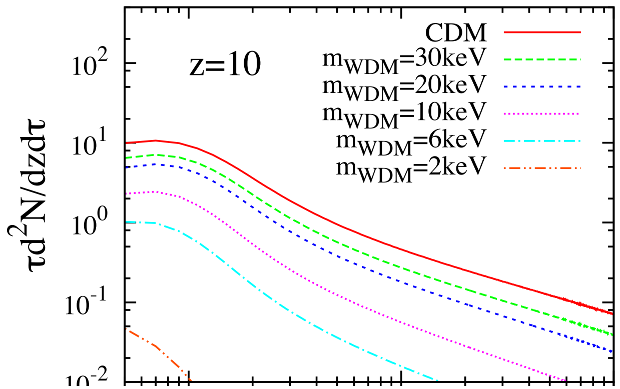
LOFAR $t_{int}$ = 1000 hr

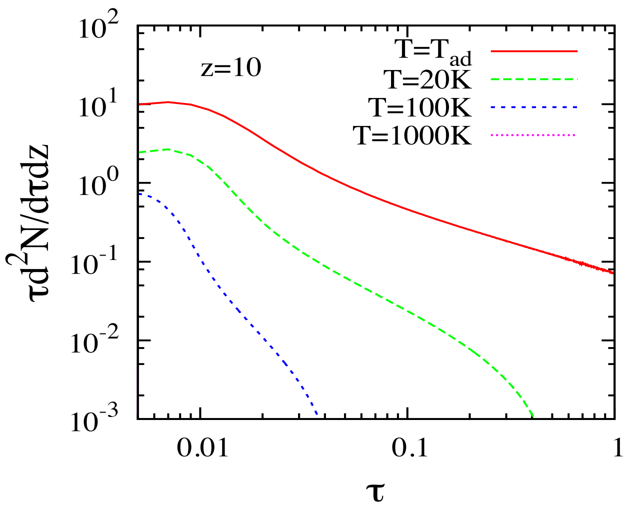



Ciardi et al 2013

**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 $S_{\rm in}(z_s) = 50$ mJy. The lines are the same as those in Figure 10. Here we have assumed the noise $\sigma_n$ 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

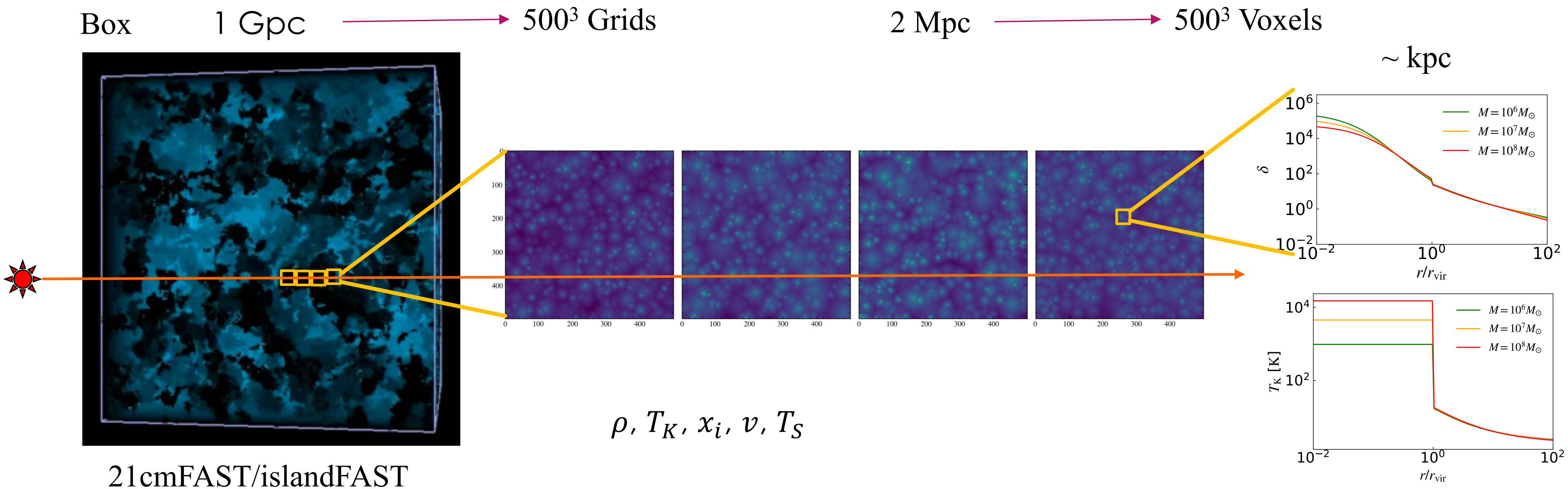



Shimabukuro et al. 2014

# Key strategy #1: multi-scale hybrid modeling

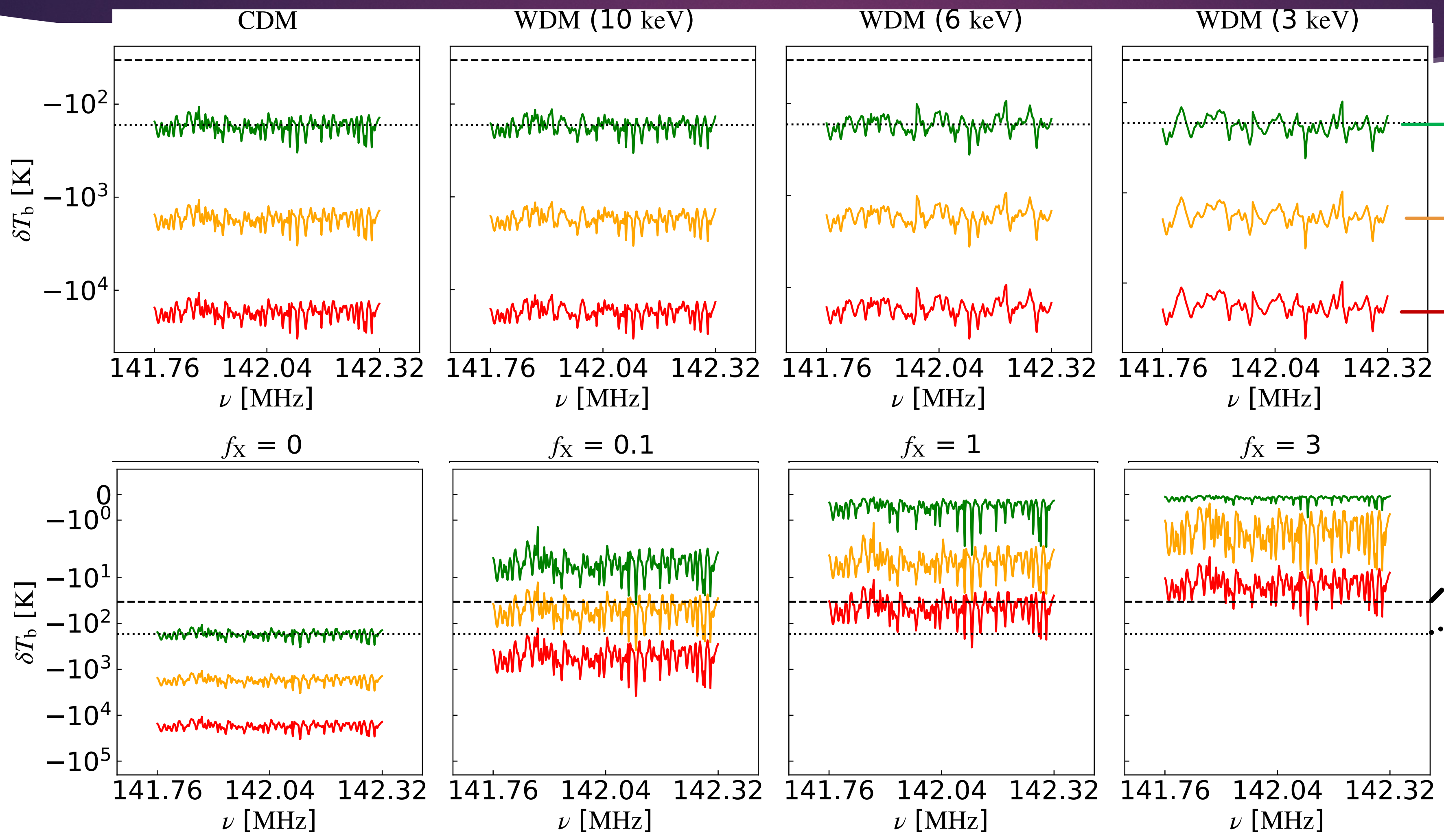
- Large scales: semi-numerical simulation
- Small scales: analytic modeling




**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

$A_{\rm eff}/T_{\rm sys}$ =

SKA2-Low 4000 m$^2$ K$^{-1}$

SKA1-Low 800 m$^2$ 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

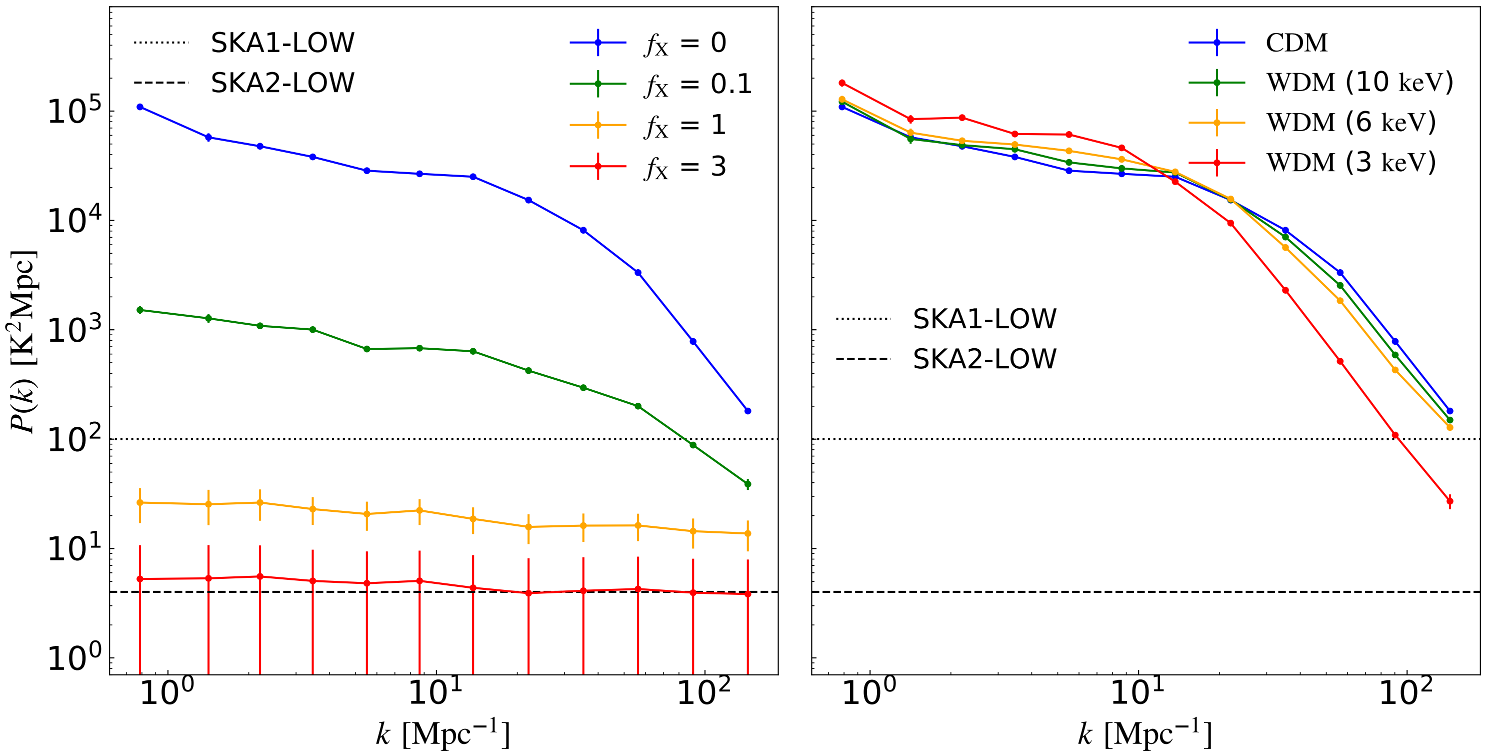
$$P\left(\hat{\boldsymbol{s}}, k_{\|}\right)=\left|\delta \widetilde{T}'\left(\hat{\boldsymbol{s}}, k_{\|}\right)\right|^2\left(\frac{1}{\Delta r_z}\right)$$

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

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

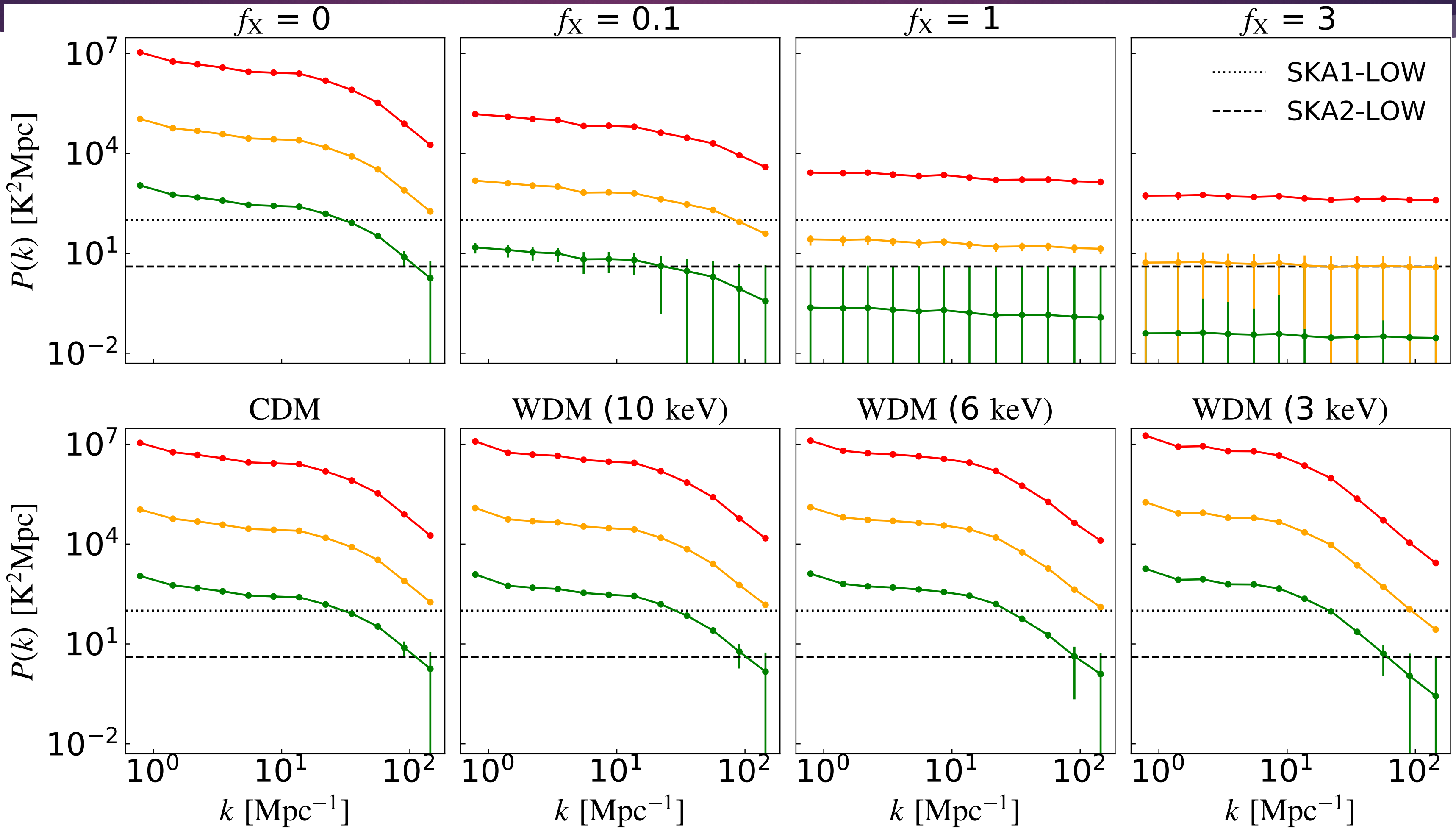
$t_{int}$ = 2 * 50 hr

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




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

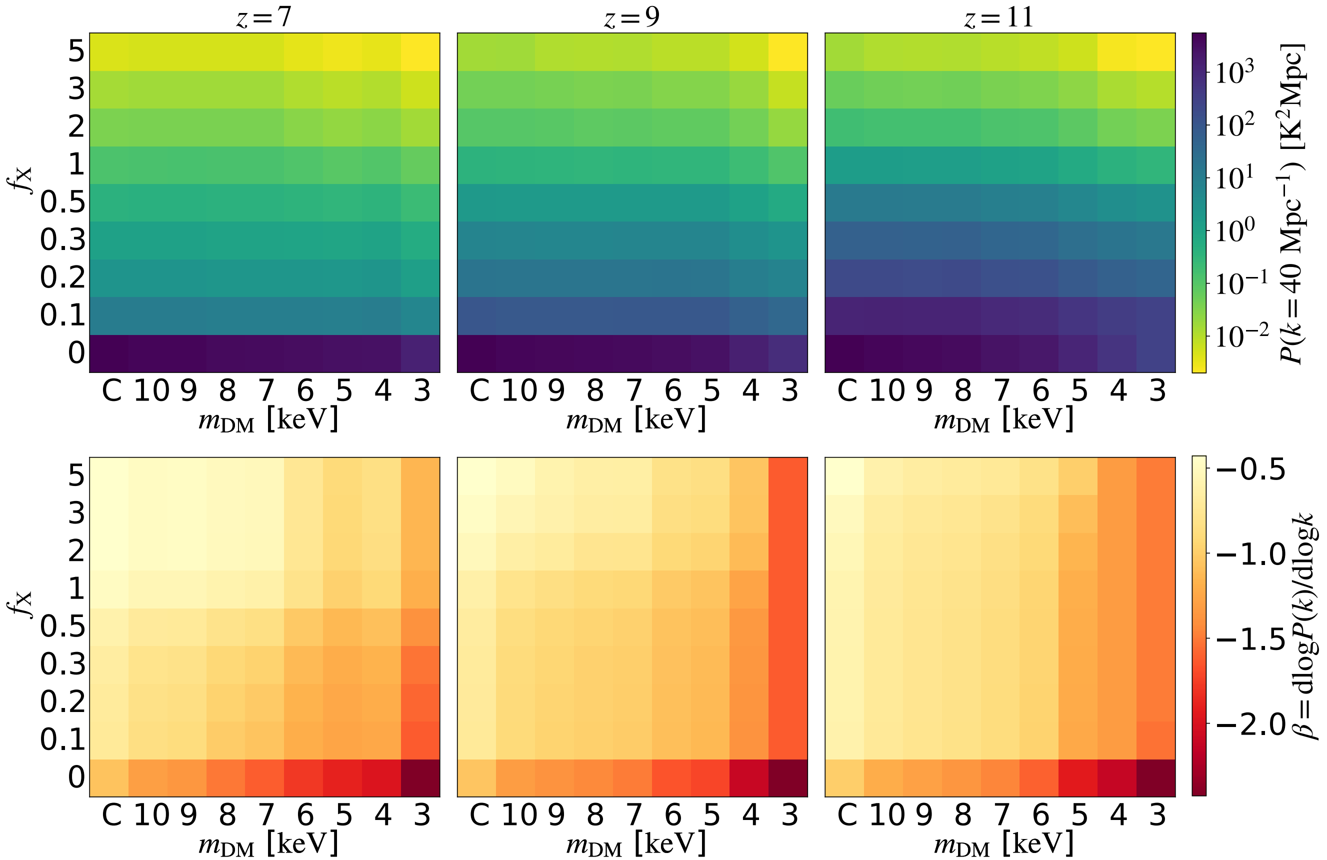
# 1-D cross-power spectrum



# 1-D cross-power spectrum
# ➔ Two birds with one stone

Amplitude

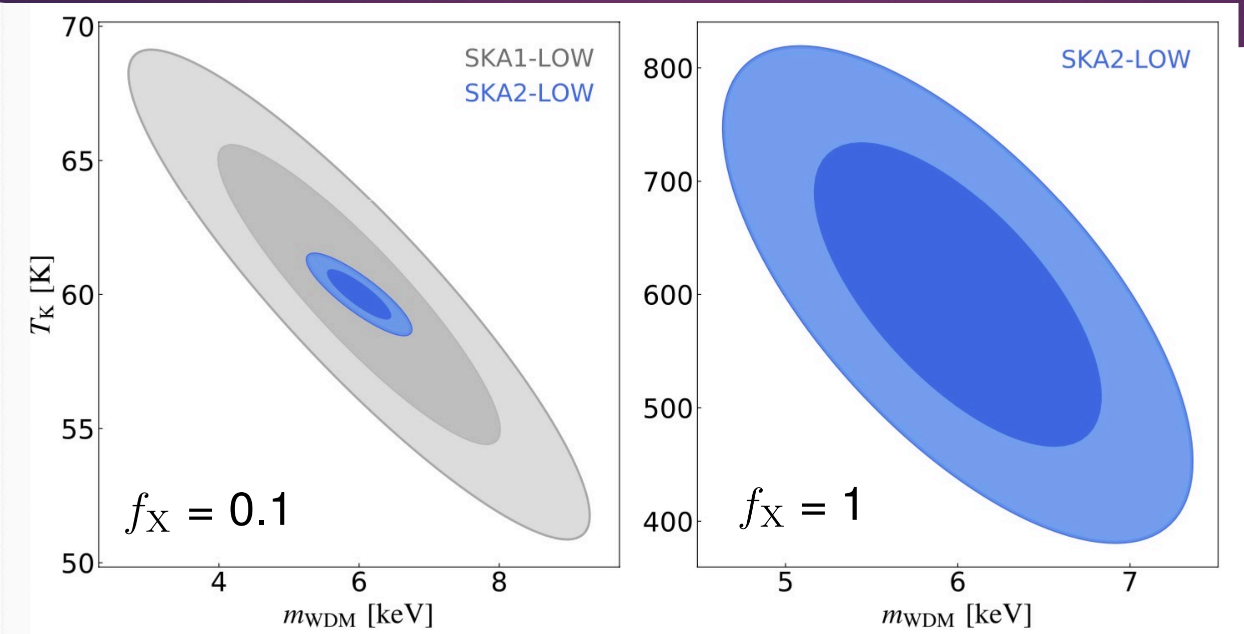
Slope

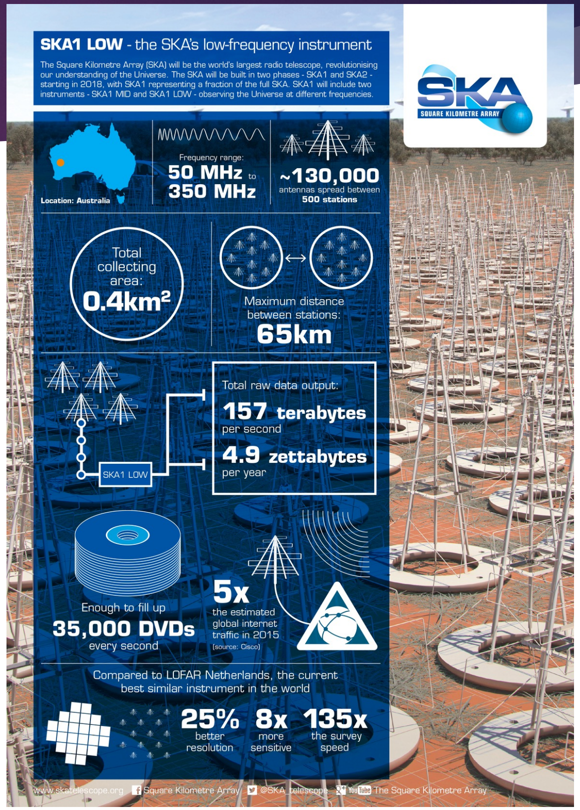



- Scientifically:
  1. DM particle mass
  2. Cosmic thermal history
- Technologically:
  1. Increase the sensitivity → feasible
  2. Breaking the degeneracy → simultaneous constraints

# SKA forecasts

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




- **For SKA1-Low:**

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

- **For SKA2-Low:**

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

- **For SKA2-Low:**

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

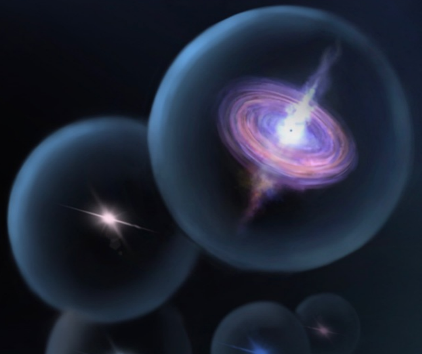
# High-redshift radio sources?? Yes!

- High-z radio-loud quasars
  - ~ 250 quasars discovered at redshift $z \geq 6$
  - ~ 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 $z = 6.13 \pm 0.05$
DES J0322−18 at $z = 6.09 \pm 0.05$ (Ighina+2023).

➔ A few hundred radio quasars with > 8 mJy at $z \sim 6$ 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


邵悦(NEU)

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

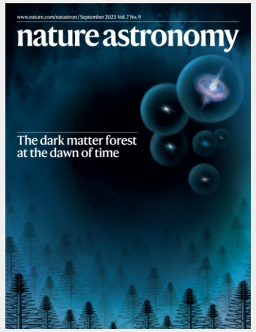
1. Make the probe actually feasible by increasing sensitivity
2. Constrain simultaneously DM & thermal history as it breaks the degeneracy

- 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

**Volume 7 Issue 9, September 2023**




**The dark matter forest at the dawn of time**

The 21-cm forest — absorption lines of atomic hydrogen against a background high-redshift radio source — can be used to probe small-scale structures in the early Universe. When observed at scale with the upcoming Square Kilometre Array, statistical analysis of these lines will be able to constrain the properties of dark matter at that epoch.

See Shao et al.

Image: Xin Zhang, Northeastern University, Shenyang, China and Yidong Xu, National Astronomical Observatories, Chinese Academy of Sciences. Cover design: Bethany Vukomanovic.

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NAOC 東北大學 Northeastern University

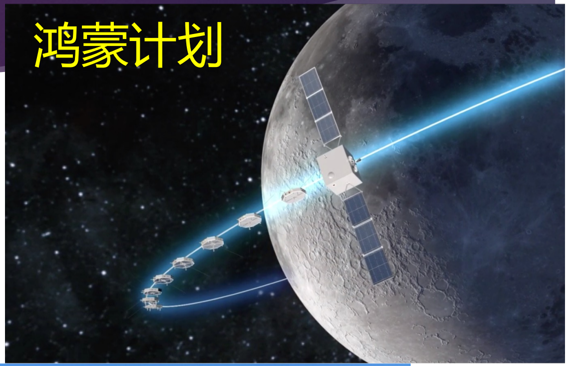
Shao Y., **XuYD**, et al. 2023 **Nature Astronomy**

# 21 cm probes: challenging but intriguing!

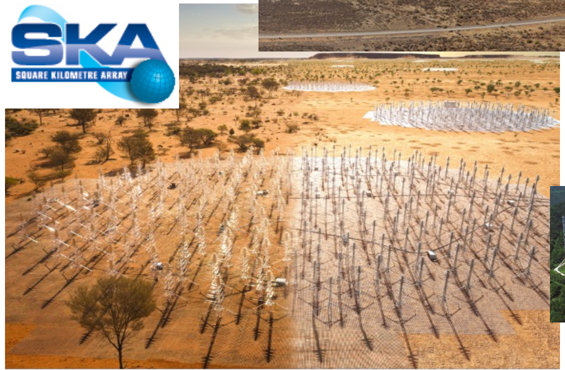
- <u>21 cm global spectrum</u>: the non-linear structure formation ***reduces the maximum*** 21 cm absorption signal ***by 15% at z = 17*** !

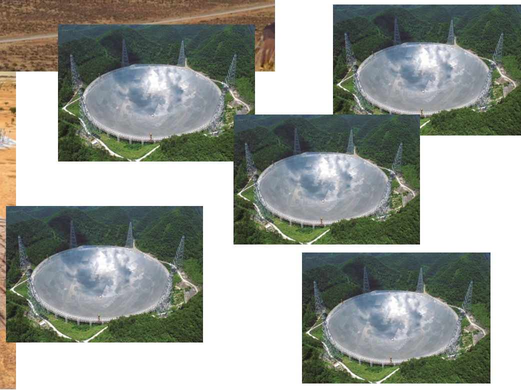
- <u>21 cm tomography</u>: ***upper limits*** on the 21 cm power spectrum start to constrain the ionizing sources & absorbers.

- <u>21 cm forest</u>: a ***simultaneous probe*** of DM & first galaxies

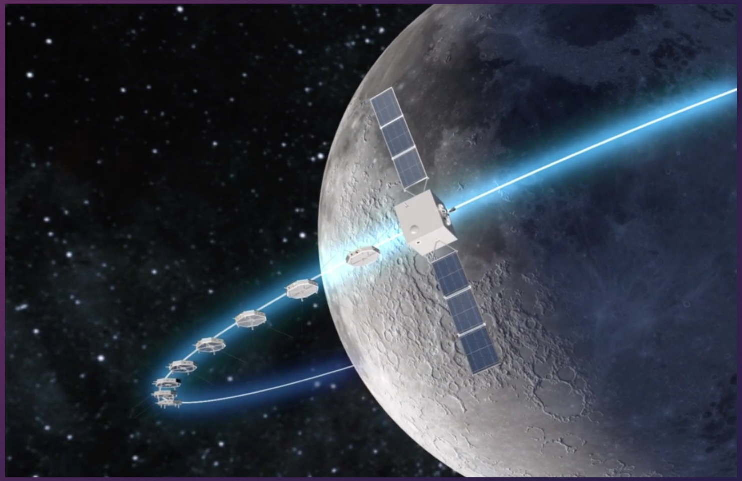






# Thank you!



# The cosmic hydrodynamic simulation

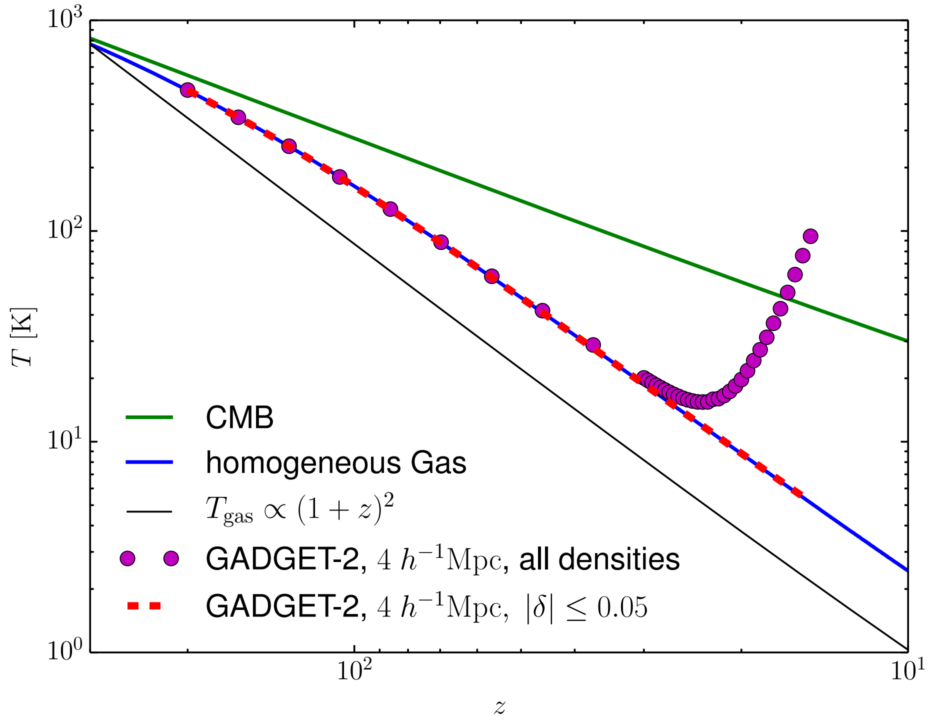
- High-resolution GADGET-2

+ collisional ionization & recombination,

+ collisional excitation & deexcitation,

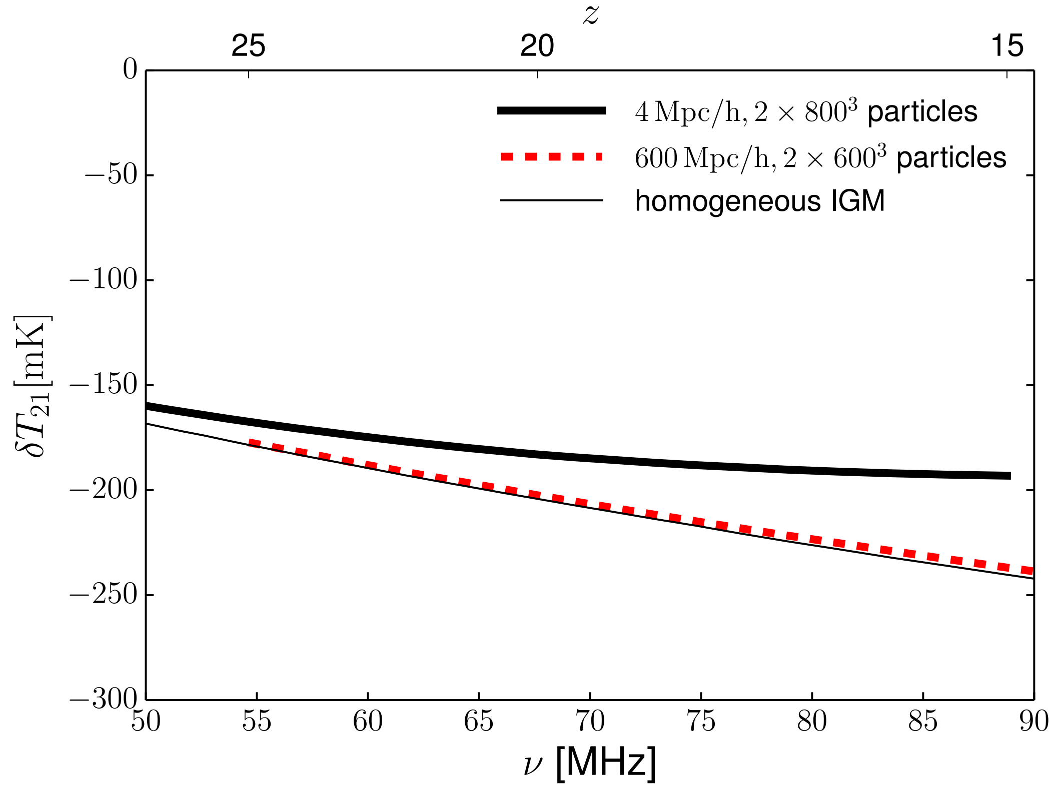
+ Compton scattering

- Assuming saturated coupling between $T_S$ and $T_K$
- Compton heating and shock heating only, NO extra heating process



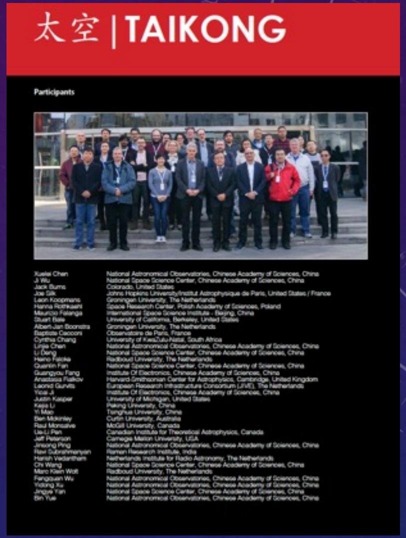
# Under-resolved signal

- The expected 21 cm spectrum for a typical semi-numerical simulation



# Project Status

- PI: Xuelei Chen (NAOC), Technology Chief: Jingye Yan (NSSC)
- Completed intensive study, applying for entering Engineering Phase
- International Collaboration Welcome!
- Interested researchers welcome to join the Science Working Group, to discuss the science cases and key technologies


X. Chen et al. arxiv:1907.10853

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Review

Check for updates

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## Discovering the sky at the longest wavelengths with a lunar orbit array

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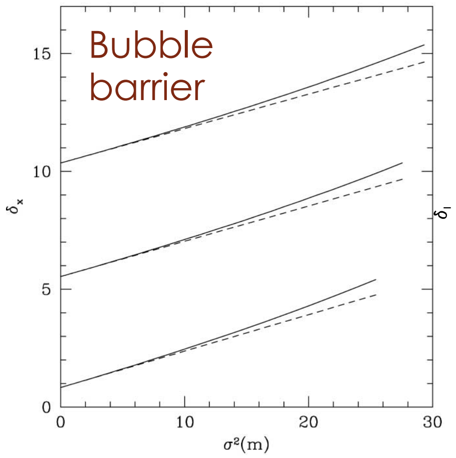
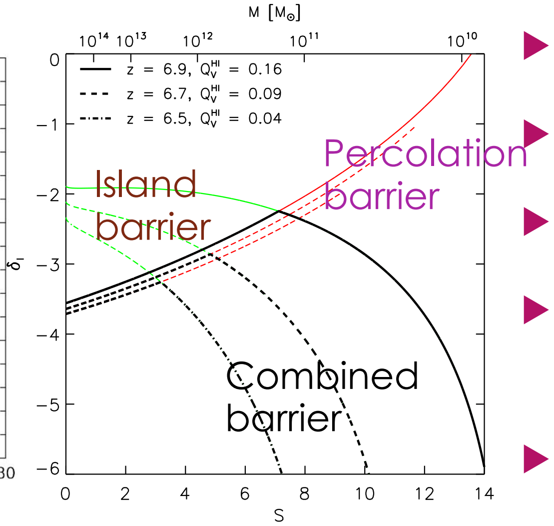
# Bubble model vs. Island model

## Before percolation

- Early EoR
- Growing ionized bubbles
- No UVB in model
- First-up-crossing distribution
- Linear-fitted barrier with analytical solution



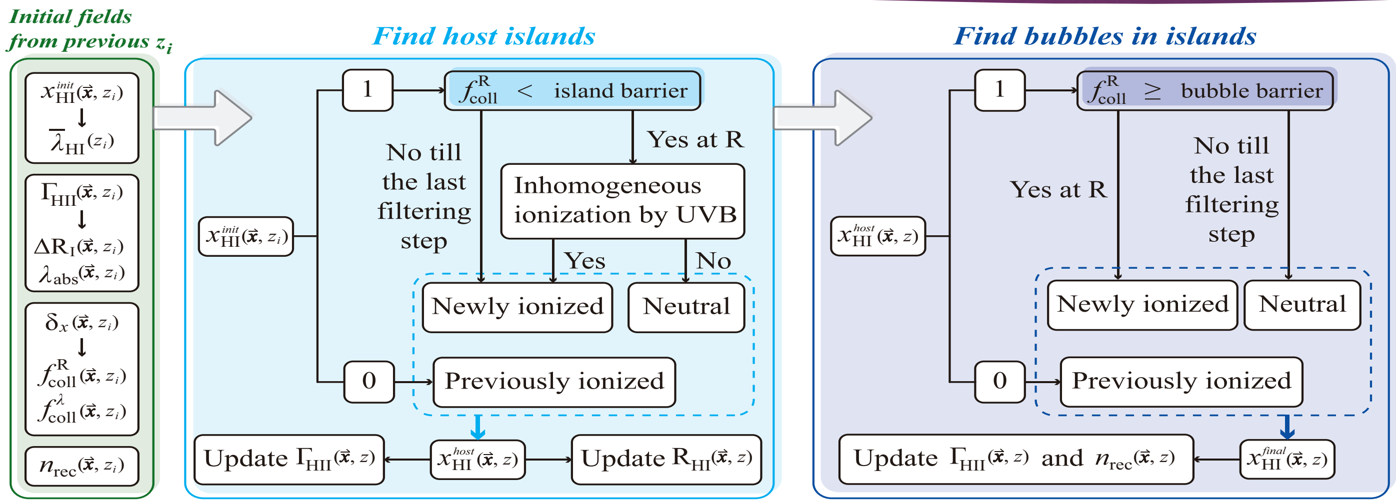



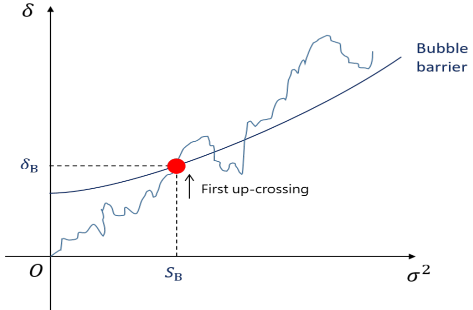

## After percolation

- Late EoR
- Shrinking neutral islands
- With UVB
- First-down-crossing distribution
- Arbitrary shaped barriers with numerical solution
- Bubbles-in-island effect

# Semi-numerical simulation – islandFAST

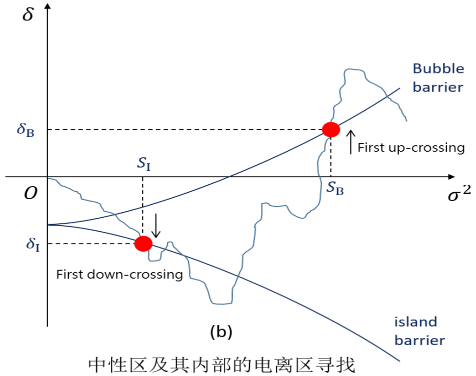
(Xu et al. 2017)



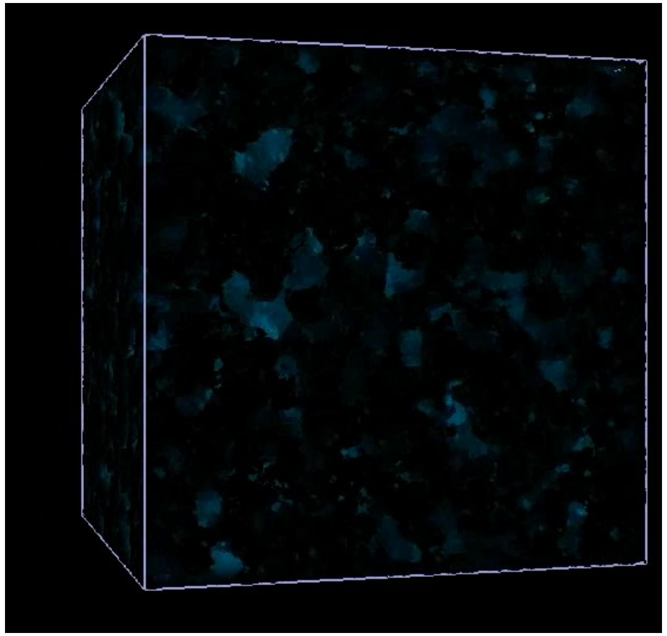

(a)

电离区的寻找（再电离早期）




(b)

中性区及其内部的电离区寻找
（再电离晚期）



Credit: Xu et al. (NAOC)
& Yang Gao (CNIC)

Zhu, **YX** et al. 2023, RAA