Probing Cosmic Dawn from the ground to the lunar orbit

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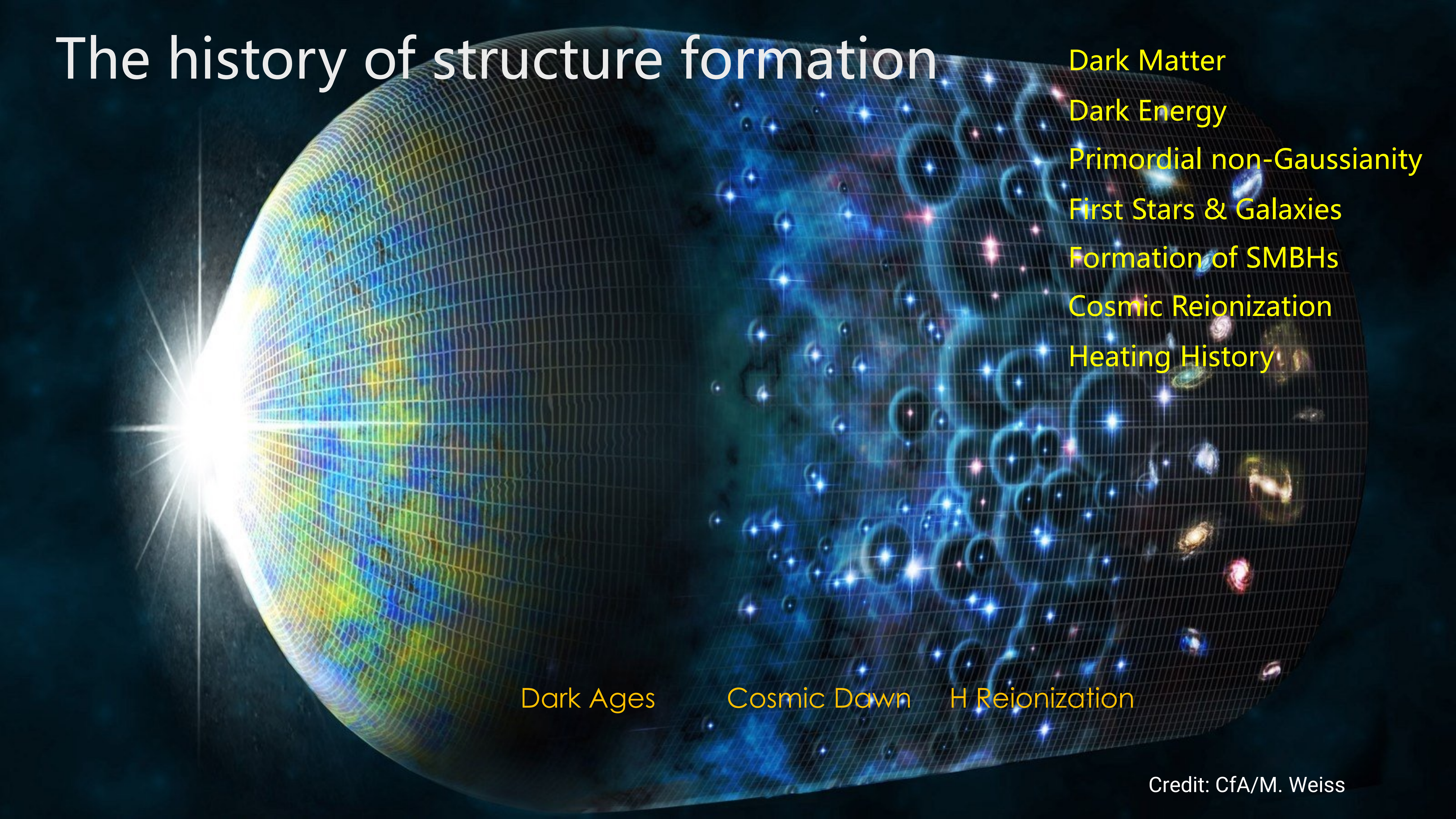
2023.10.13 TIFR on line

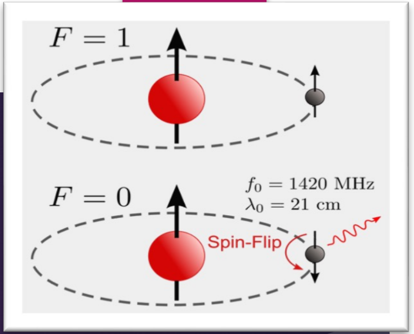
The history of structure formation

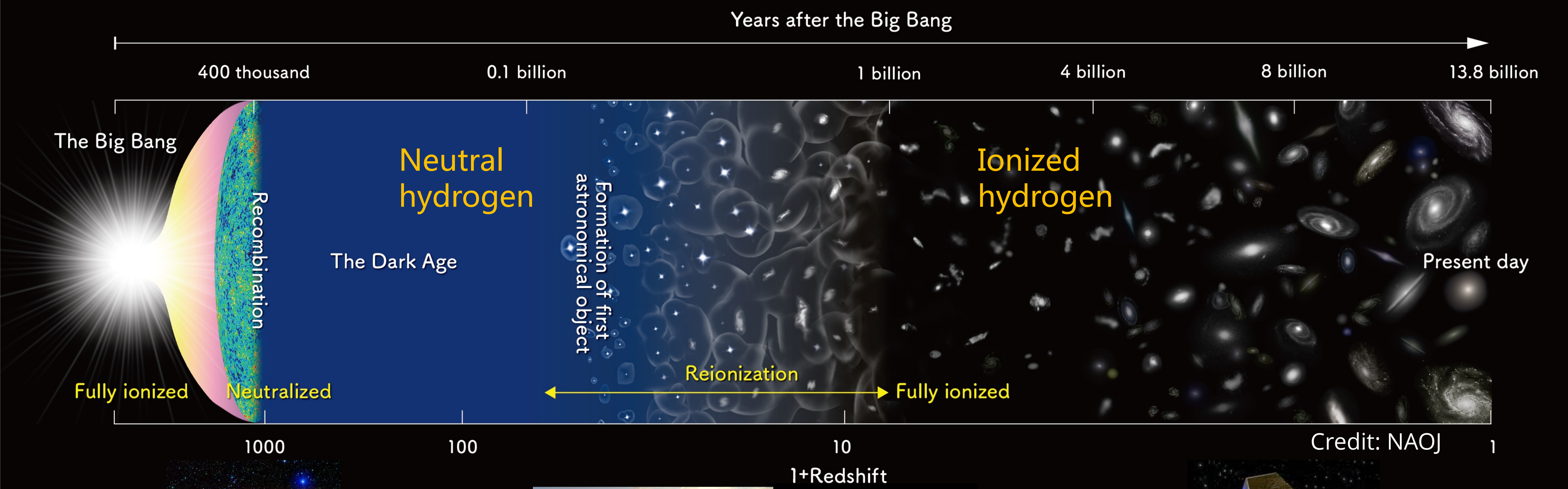
- Dark Matter
- Dark Energy
- Primordial non-Gaussianity
- First Stars & Galaxies
- Formation of SMBHs
- Cosmic Reionization
- Heating History

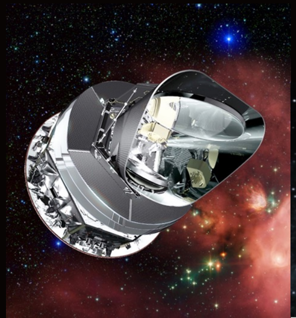
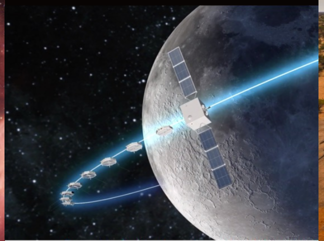
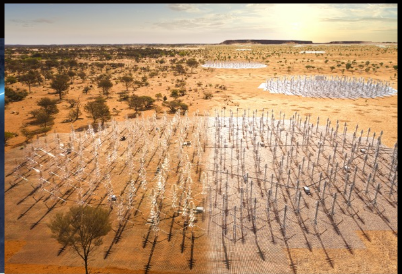
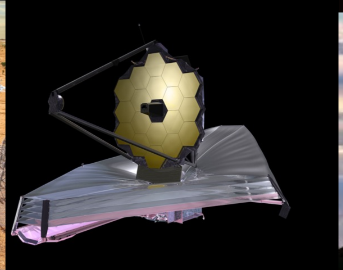


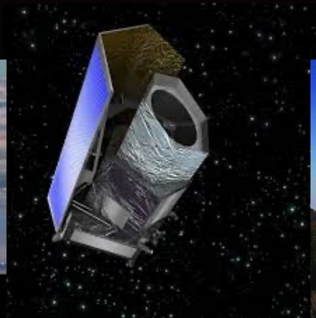
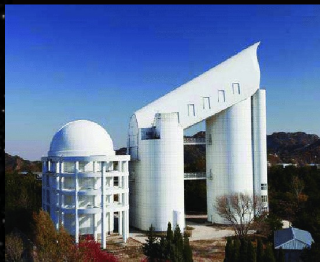
Credit: CfA/M. Weiss

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



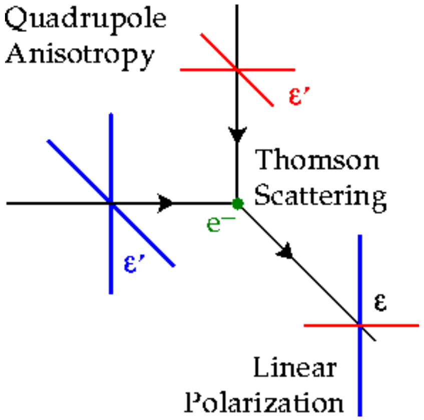


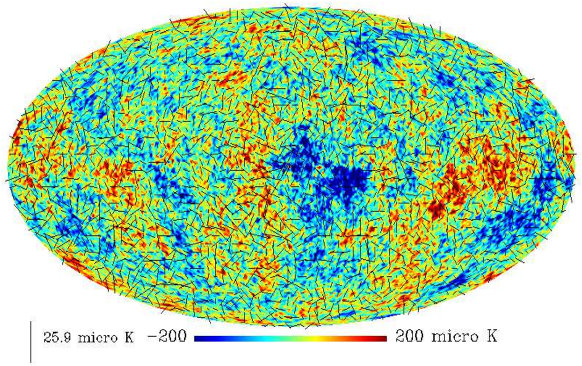



What we know to inform the 21cm observations

- The Thomson scattering optical depth measured on CMB polarization map



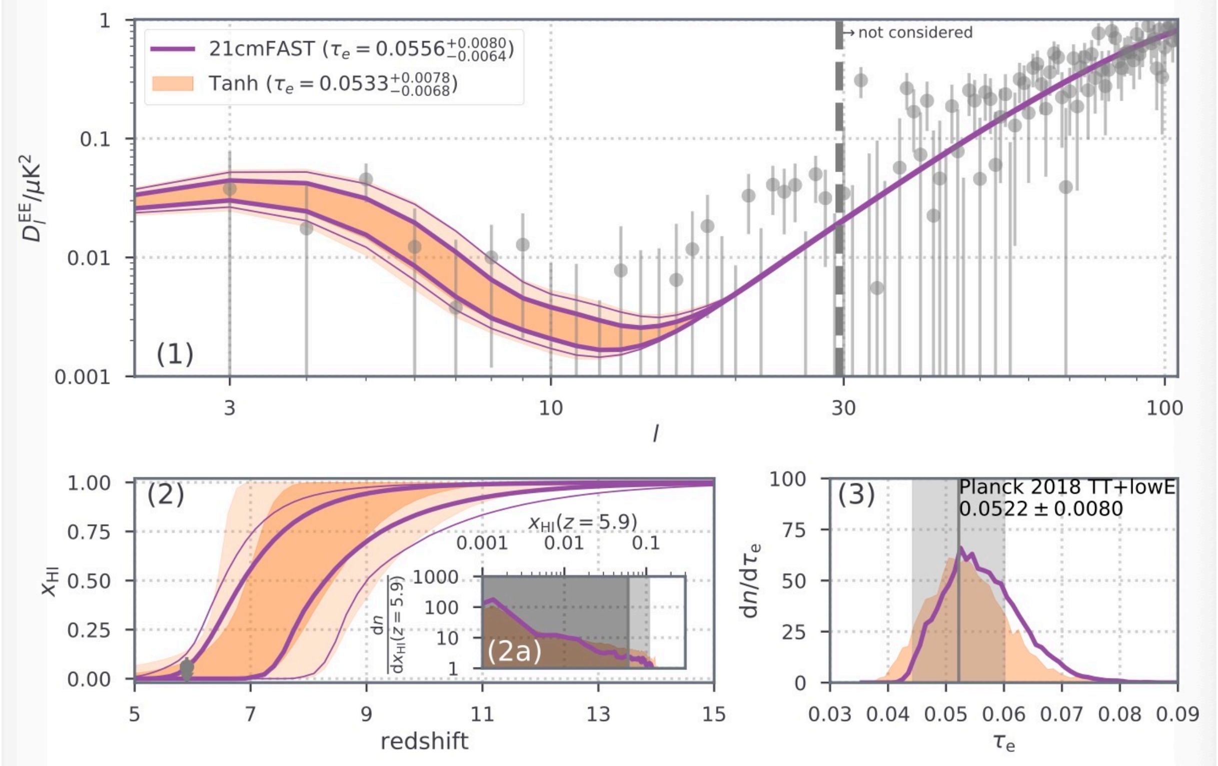
$$\tau = \int_0^{z_{\rm reion}} dz \sigma_T n_e(z) \frac{d\ell}{dz}.$$



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

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

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

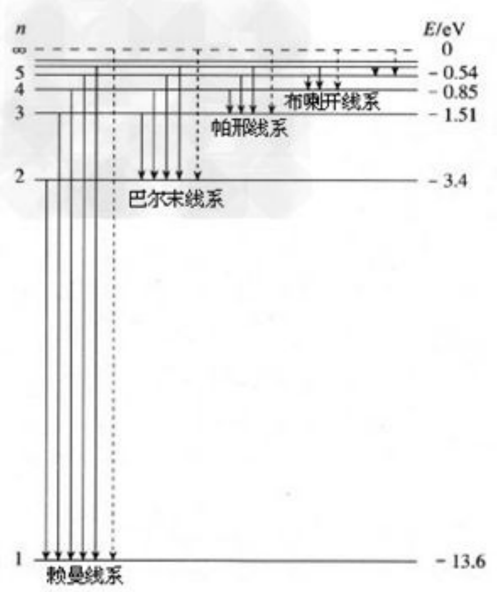


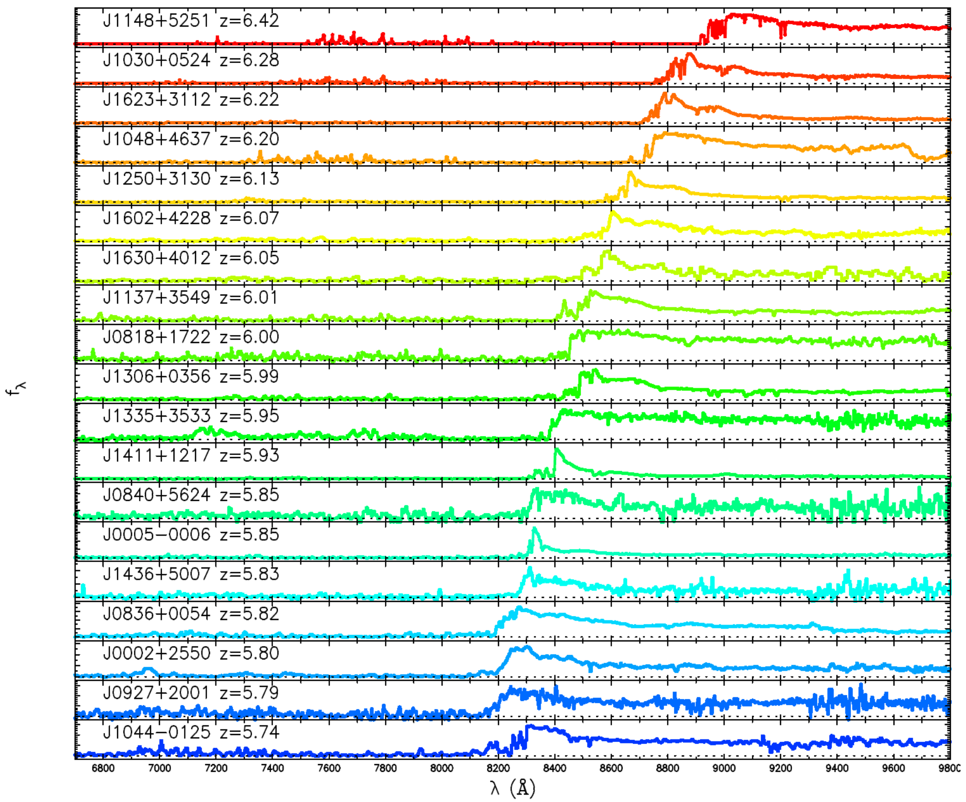
Qin et al. 2006.16828

What we know to inform the 21cm observations

- The Gunn-Peterson tests on high-z QSO spectra → very nearly complete by z ~ 6

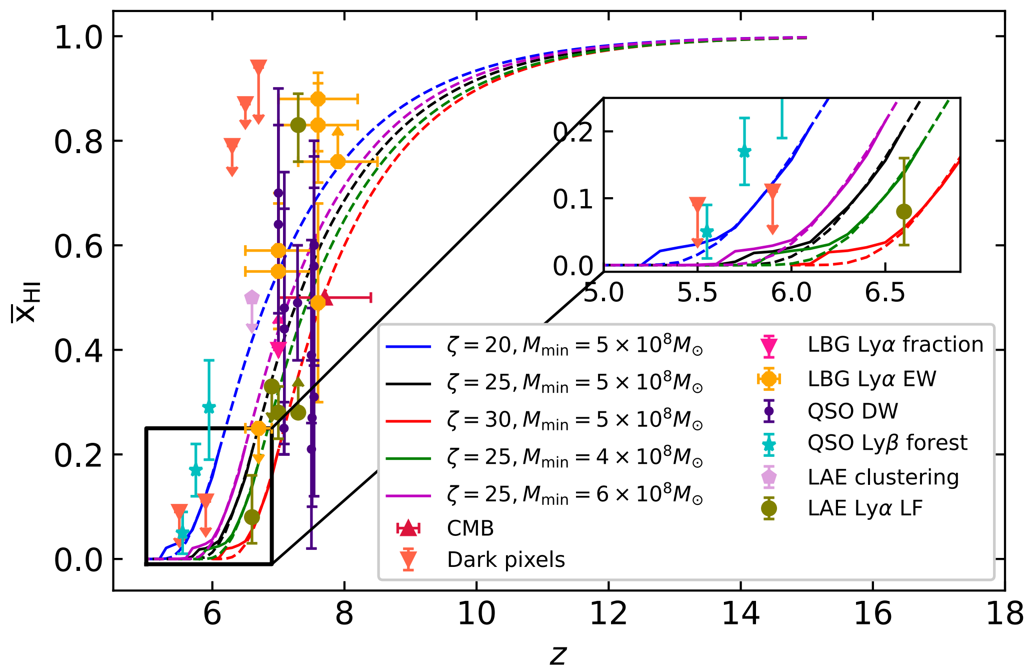
The Ly-a resonant absorption





Fan et al. (2006)

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

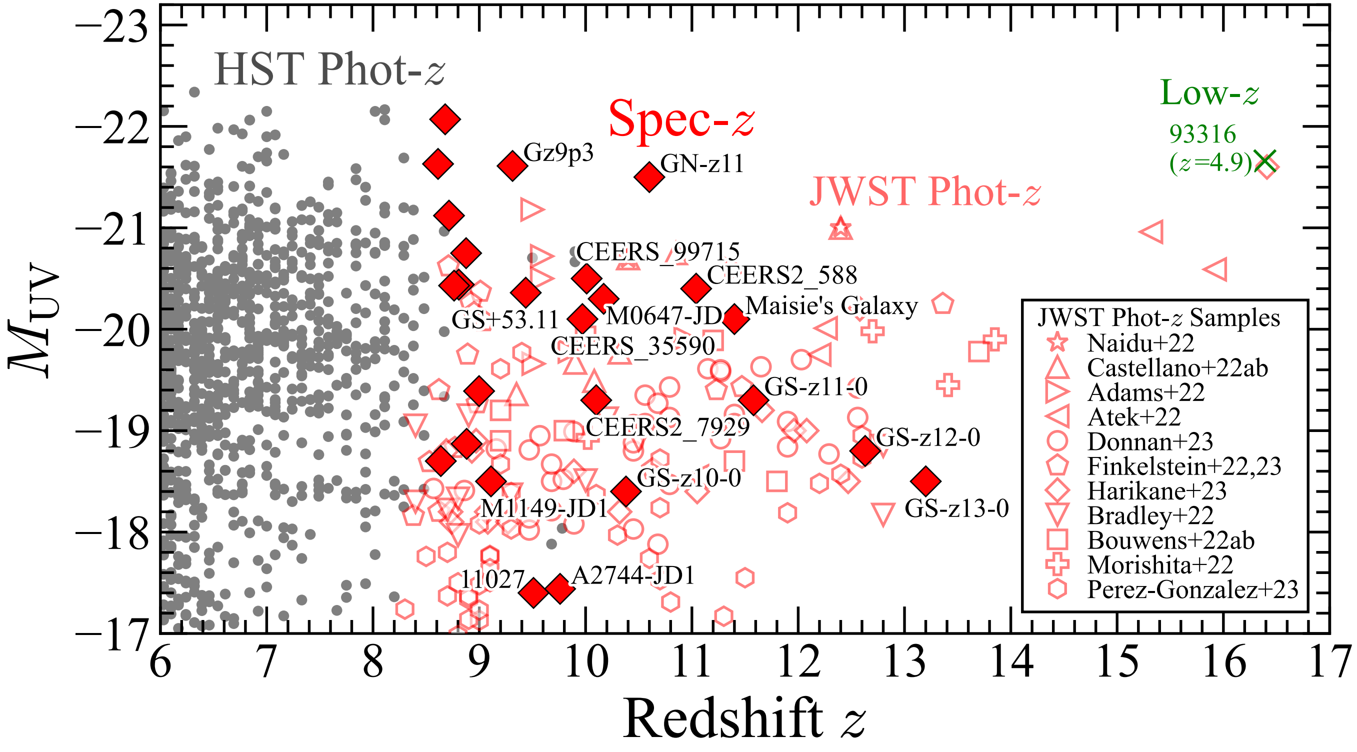


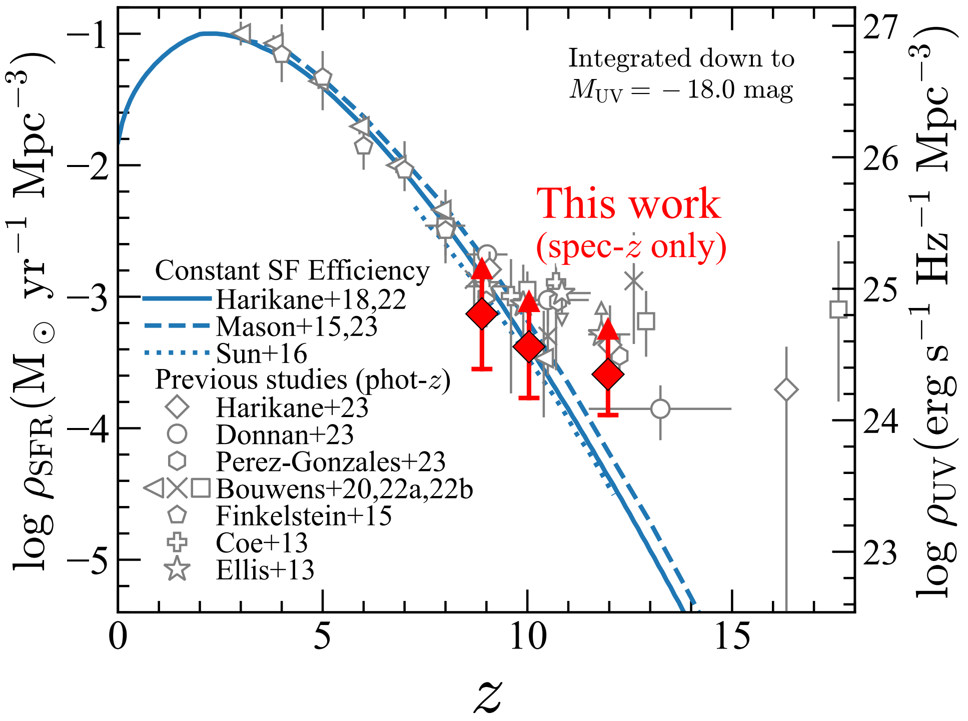
Zhu, **YX** et al. 2023, RAA

- Thomson τ 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. Ban˜ados+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

- 25 Galaxies at z_{spec} = 8.61 – 13.20 Confirmed with JWST/NIRSpec





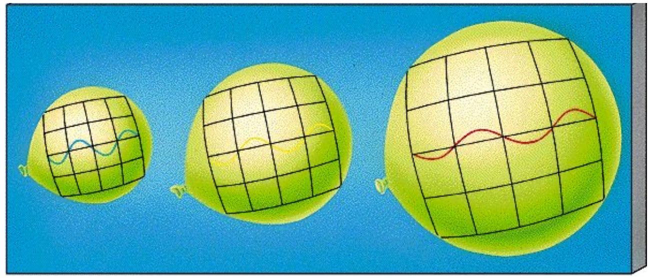
Harikane et al. 2304.06658

The 21cm transition of HI

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

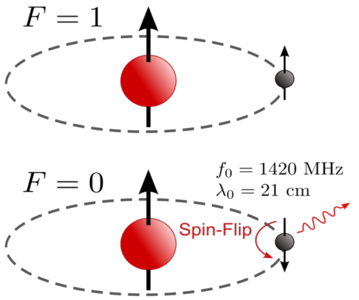
$$\delta T_b(\nu) = \frac{T_S - T_\gamma(z)}{1+z}(1 - e^{-\tau_{\nu_0}}) \approx \frac{T_S - T_\gamma(z)}{1+z}\tau_{\nu_0}$$

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



21cm → 21cm*(1+z)

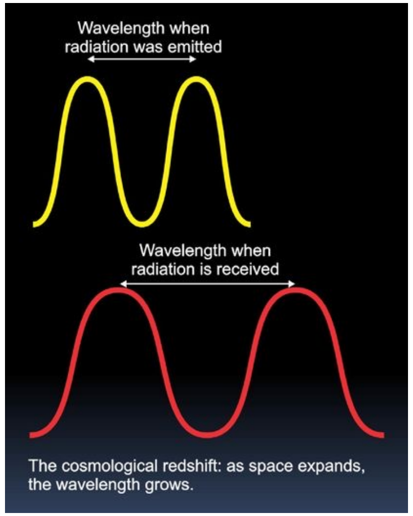
- Signal level: determined by **T_S (spin temperature)**



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

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

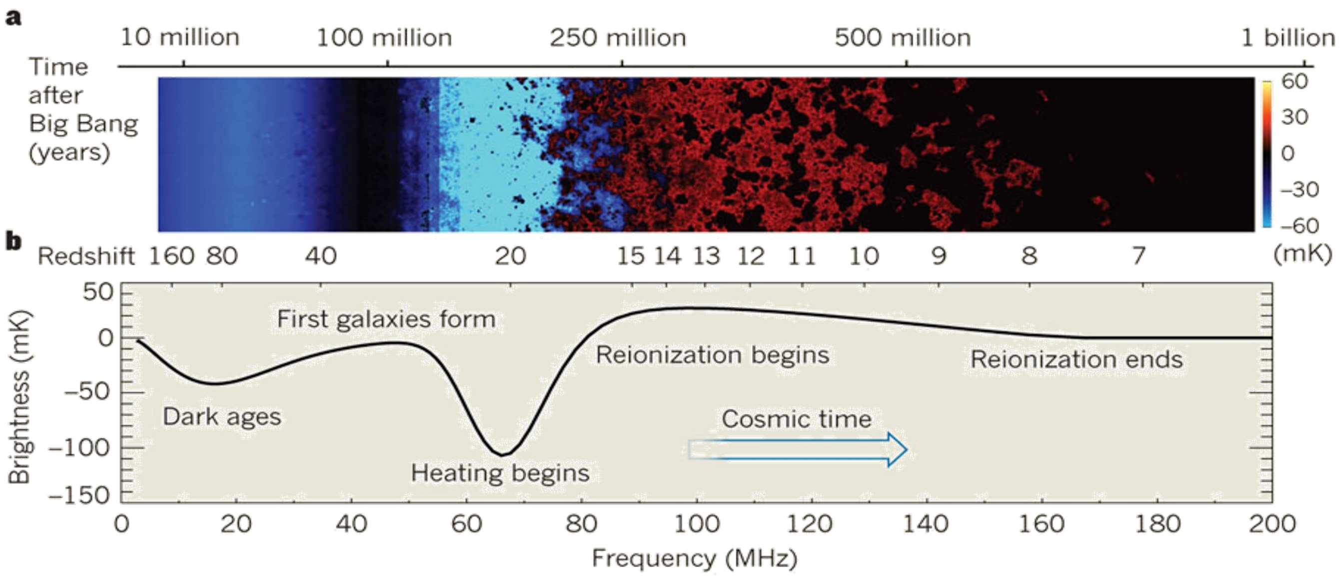
$2.876 * 10^{-15} s^{-1}$ (11 million years)



Probing cosmic dawn with 21cm signals

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

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



- Rough timing → Target band:

50 MHz ~< ν <~ 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

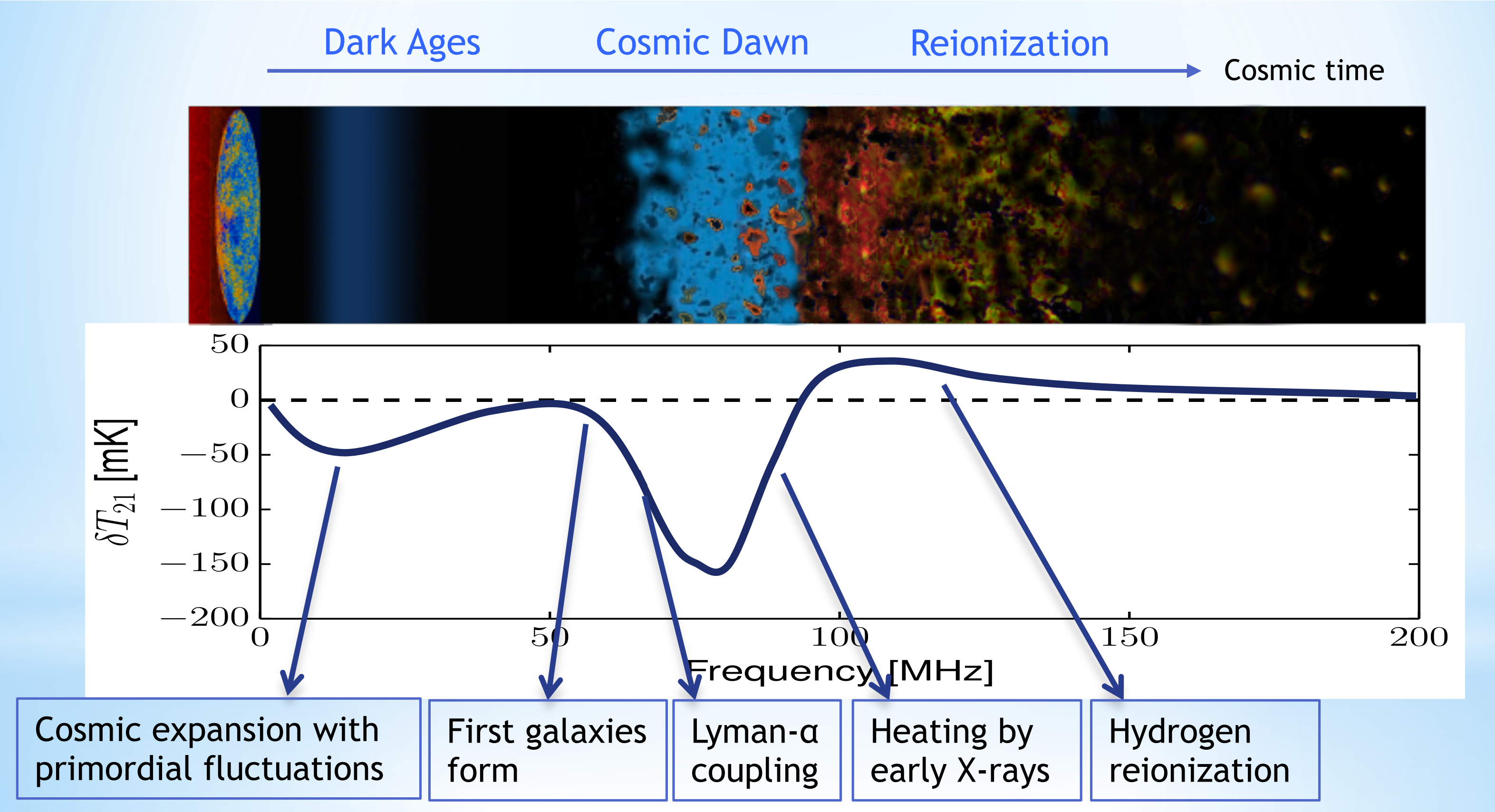


Image credit: Yuan Shi

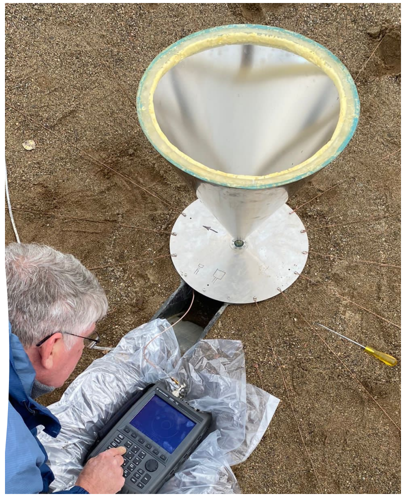
Single-antenna experiments for the global spectrum

MIST

REACH

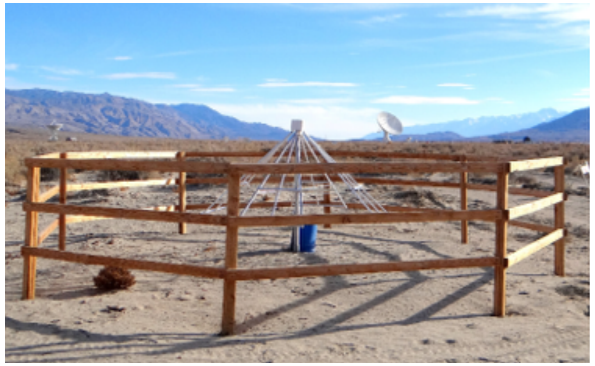
PRI^{Z}M

HIGH-Z



BIGHORNS:

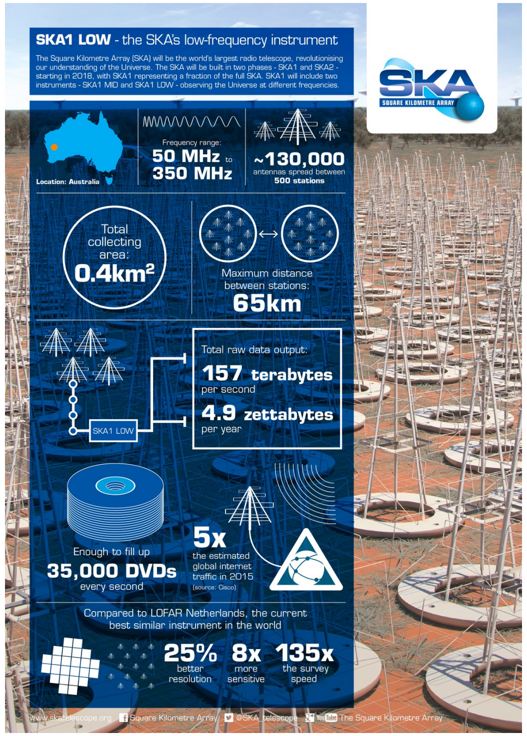
LEDA:



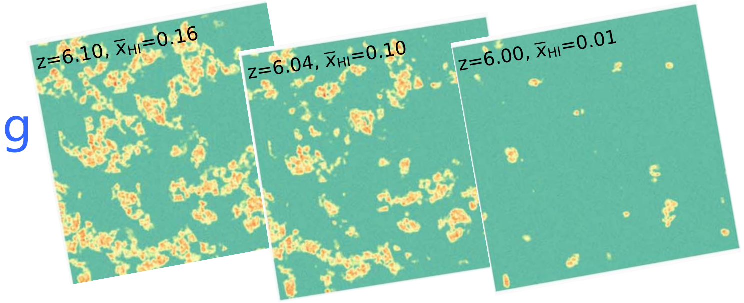
The 21 cm probes to CD/EoR

- Using CMB as background

  → **2.** 21 cm tomography

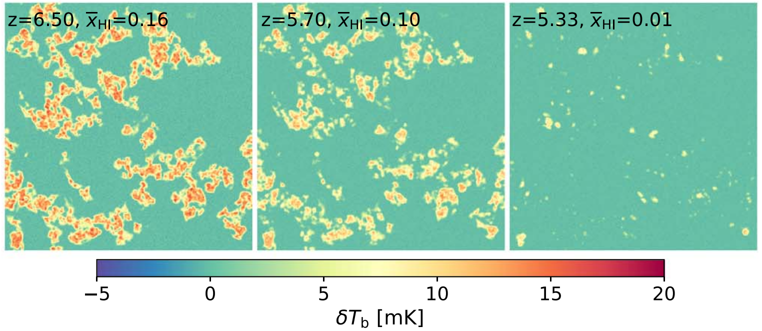


21 cm imaging



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

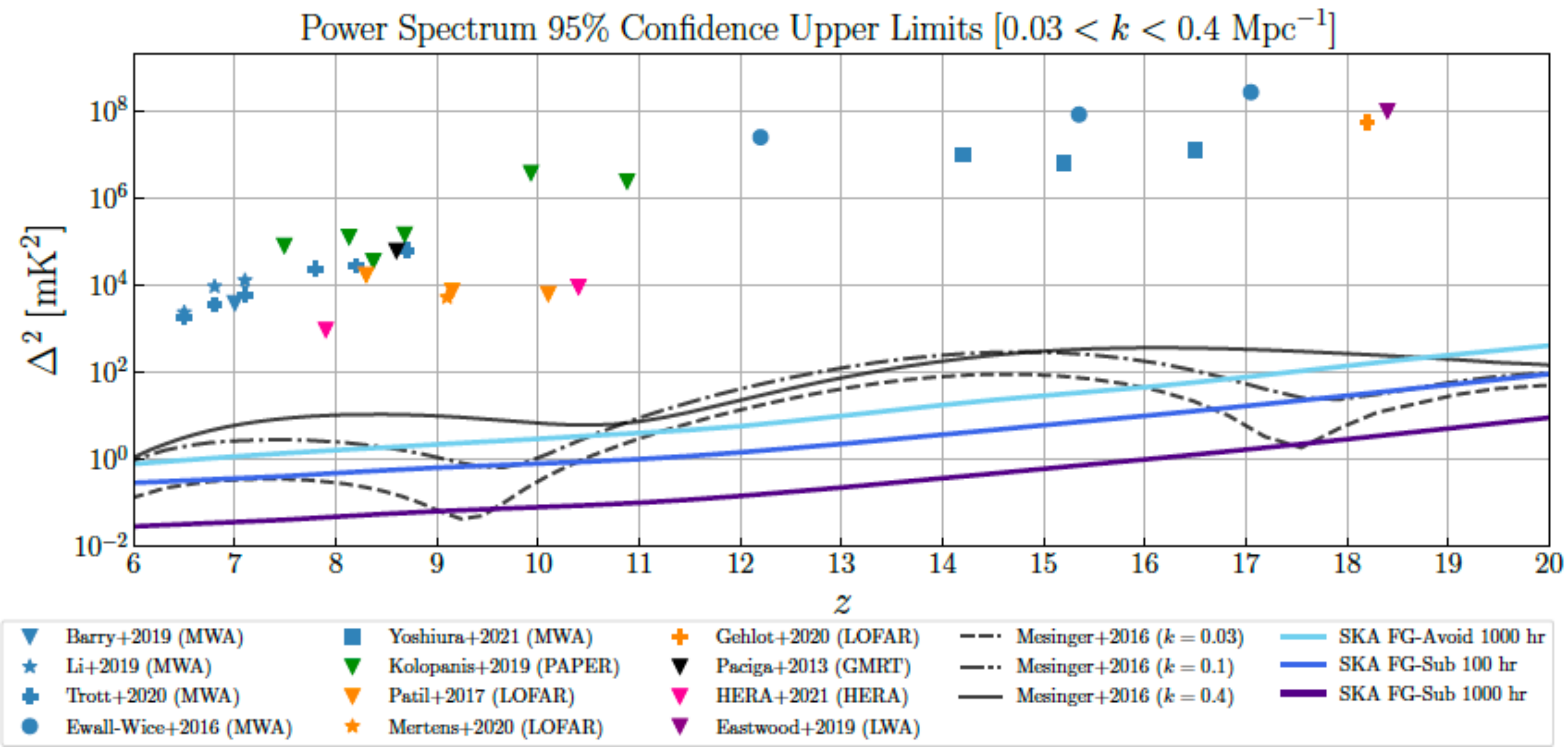
High z → Low z



B = 1 MHz

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

2– 21 cm Tomography – power spectrum upper limits



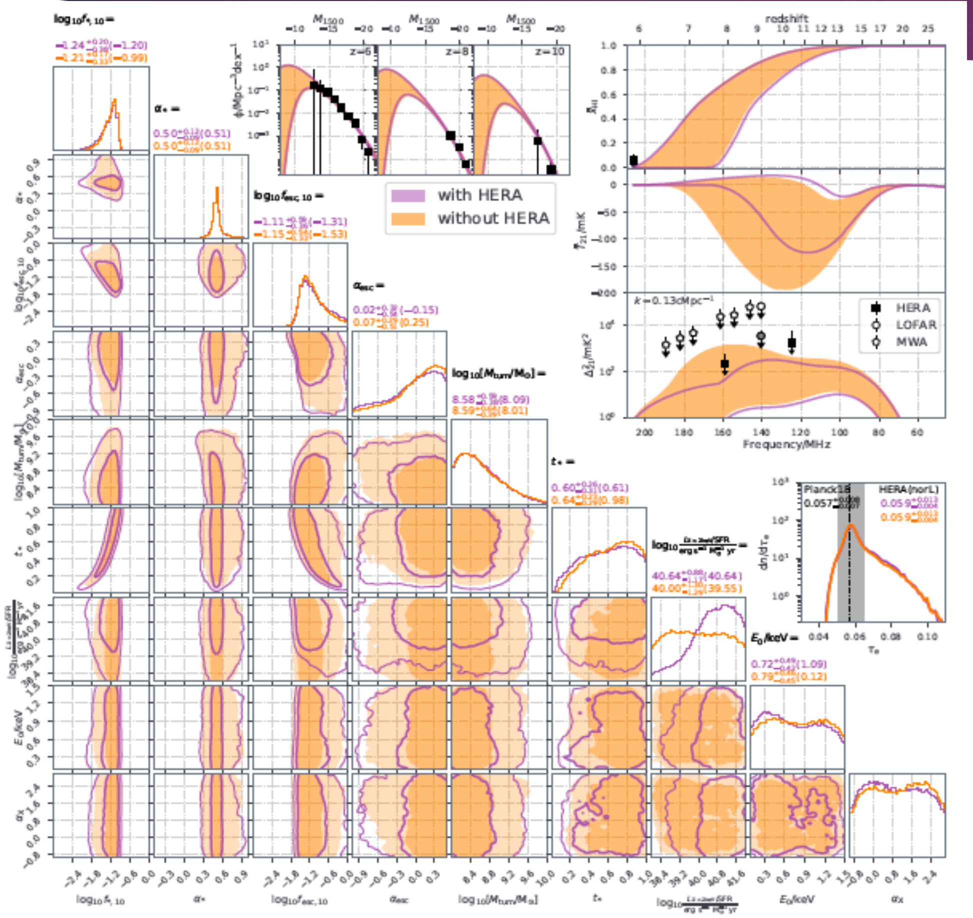
Barry et al. arXiv:2110.06173

PAPER

LOFAR

HERA

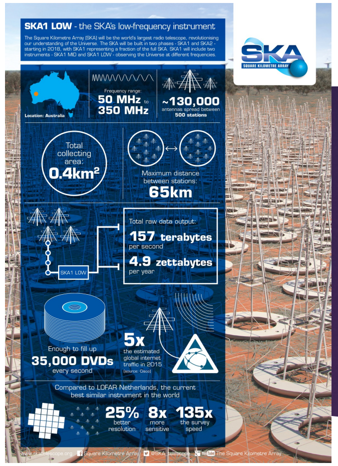
Inferring the EoR physics

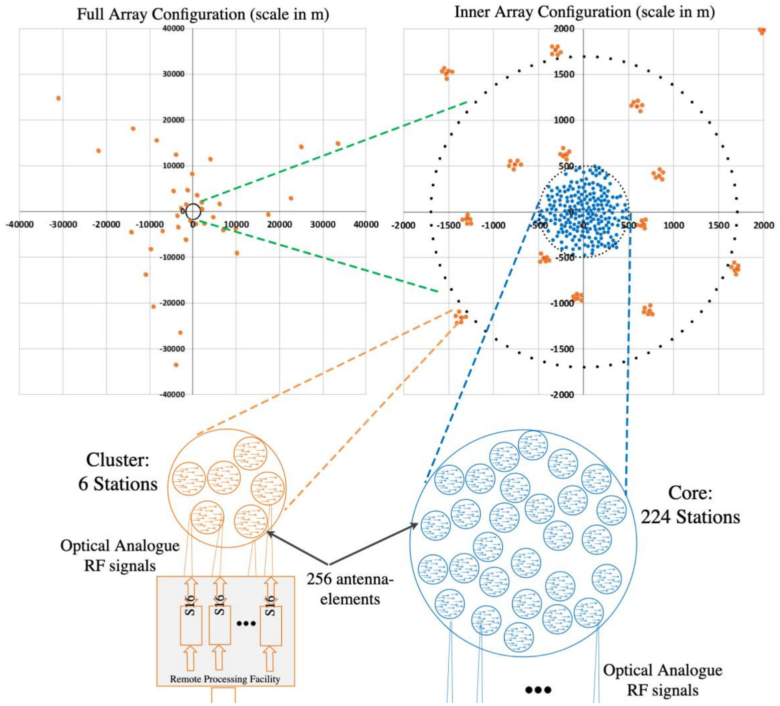


The HERA Collaboration, 2022, ApJ, 924, 51

- **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



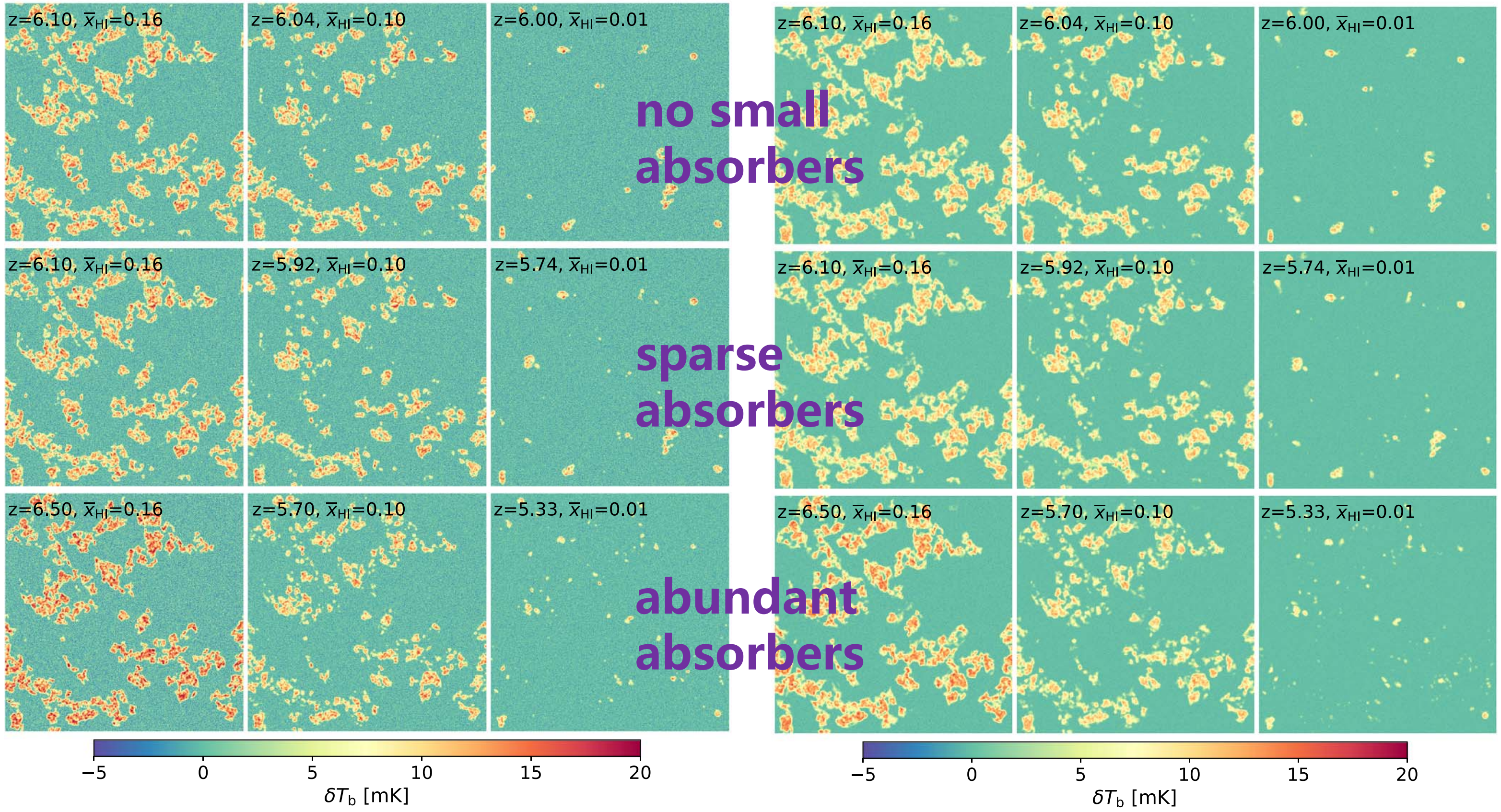


Credit: SKAO (SKA-TEL-SKO-0001075)

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

B = 0.1 MHz

B = 1 MHz



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

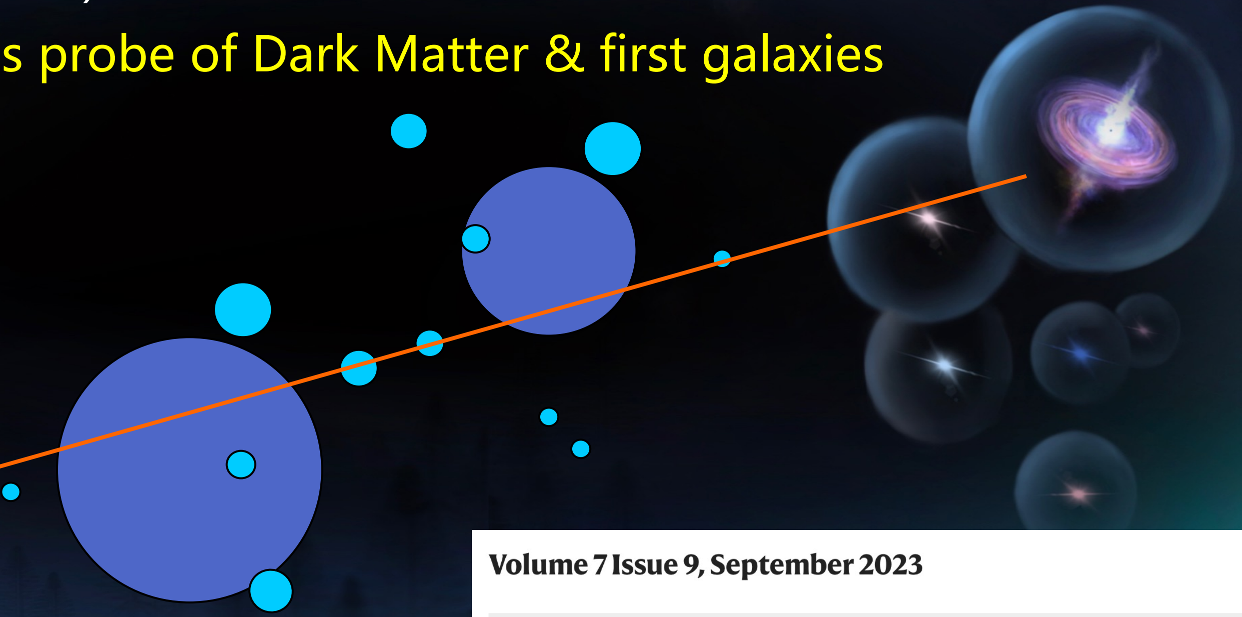
Using high-z radio point sources as the background:

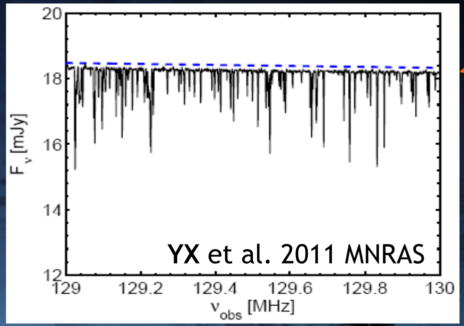
3. 21 cm Forest (absorption lines)

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

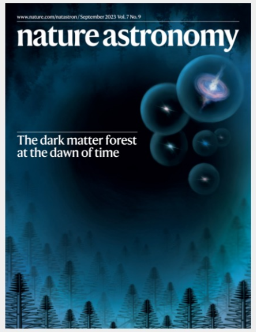
Statistical measurement: a simultaneous probe of Dark Matter & first galaxies

See Yue Shao's talk days later...





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.

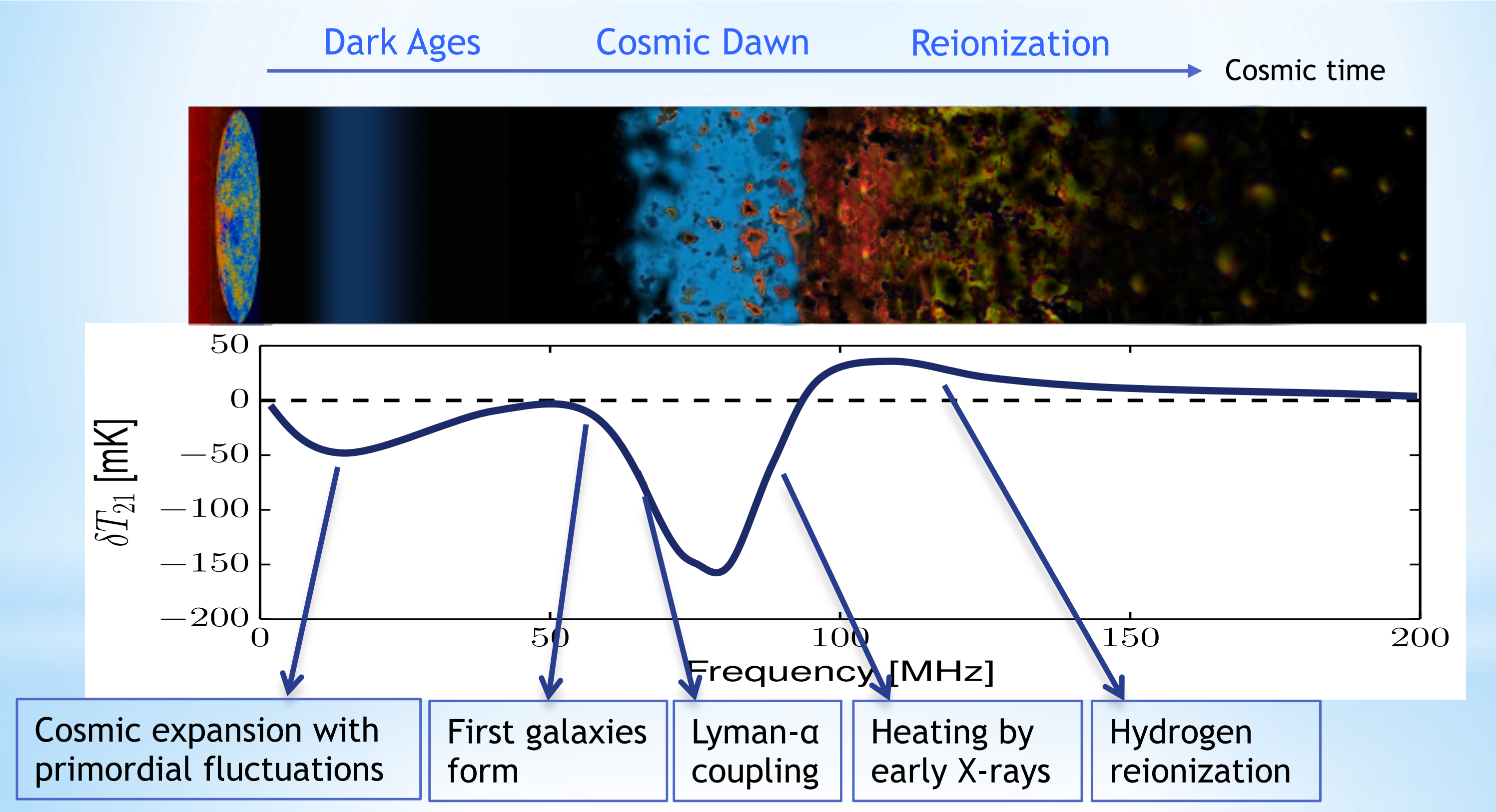
See Shao et al.

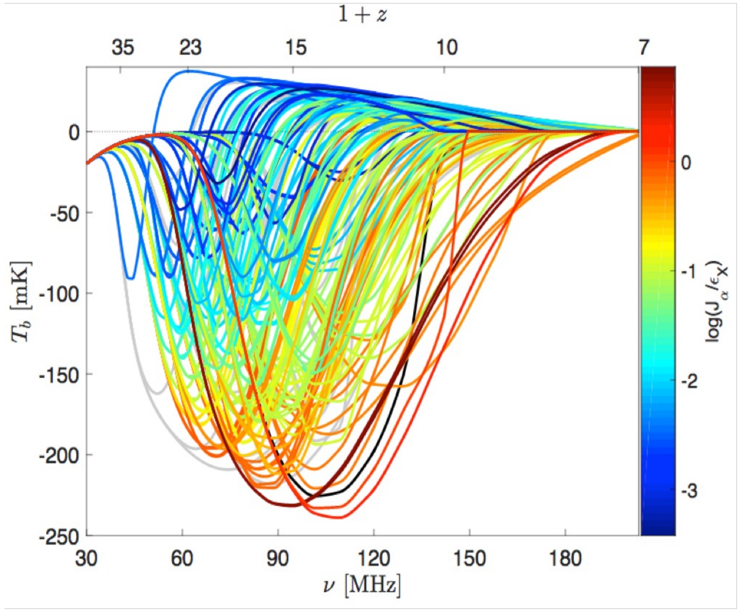
Image: Xin Zhang, Northeastern University, Shenyang, China and Yidong Xu, National Astronomical Observatories, Chinese Academy of Sciences. Cover design: Bethany Vukomanovic.

Subscribe

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

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

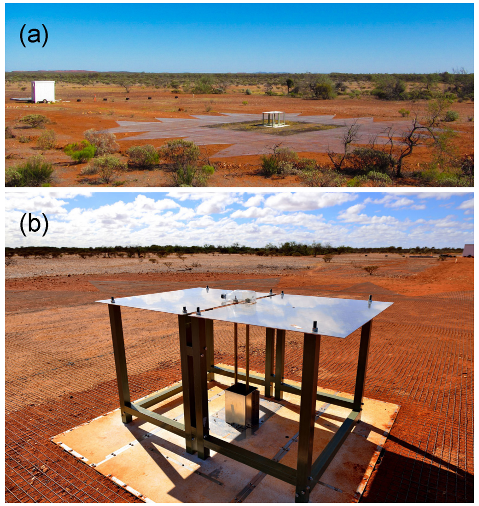
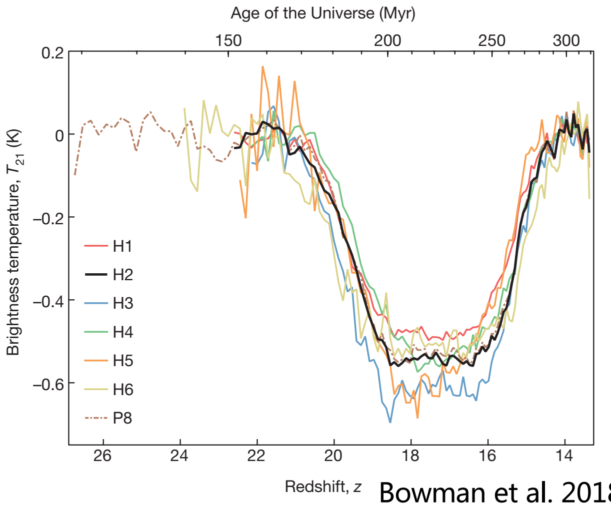
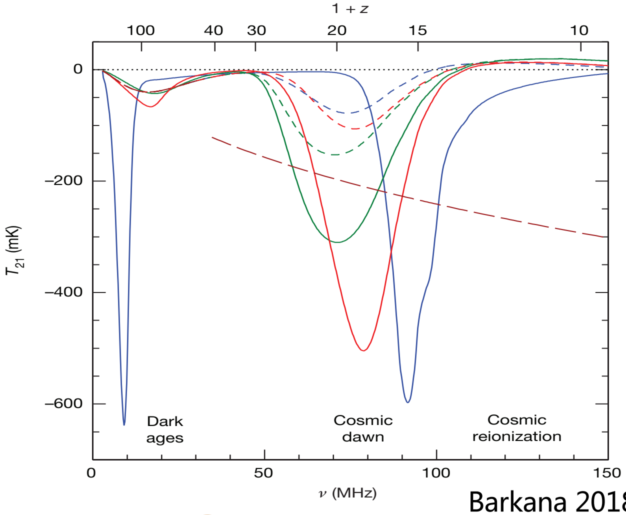


image credit: EDGES team



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?

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

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

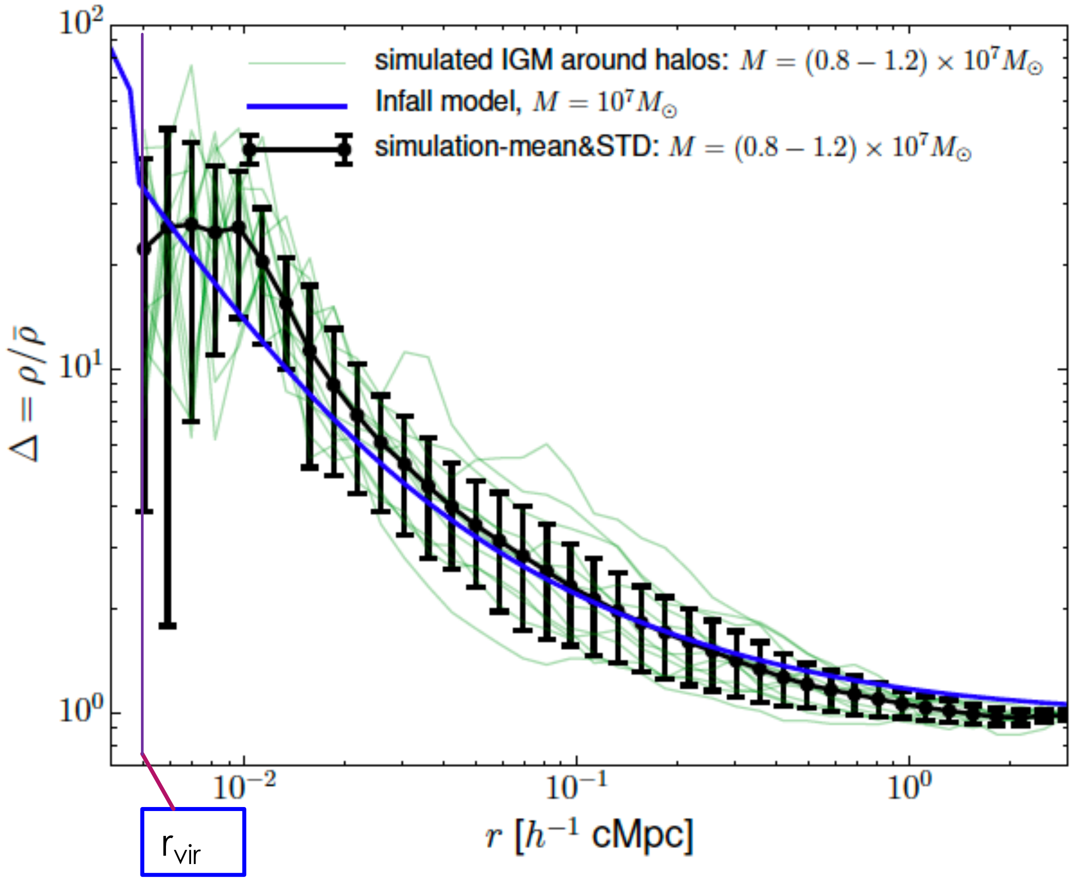
HI density

Gas temperature

Velocity gradient

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 cosmic hydrodynamic simulation

- High-resolution GADGET-2

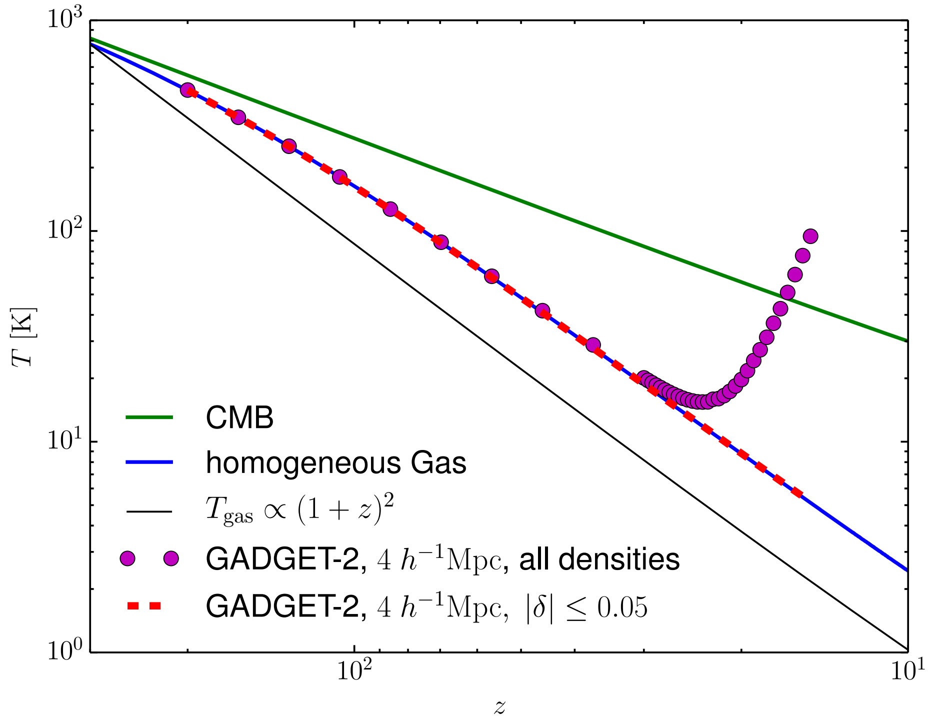
+ collisional ionization & recombination,

+ collisional excitation & deexcitation,

+ Compton scattering

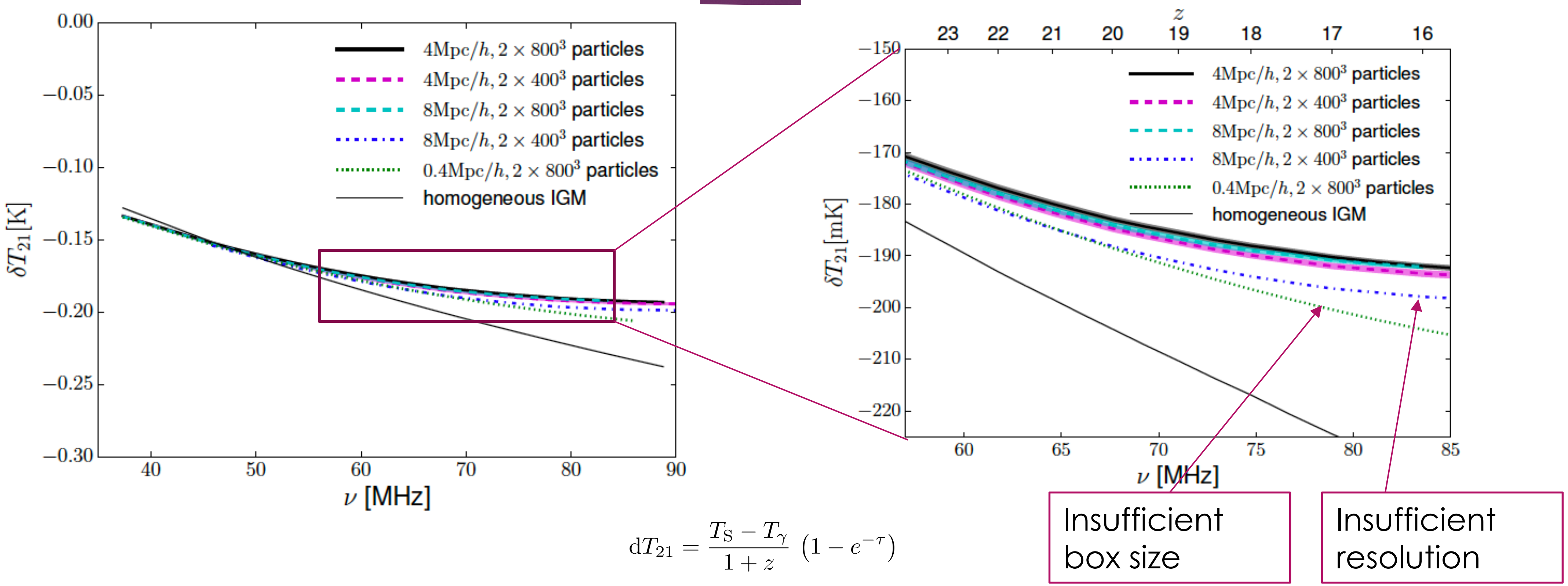
- Assuming saturated coupling between T_S and T_K

- Compton heating and shock heating only, NO extra heating process



The maximum global 21 cm signal

High resolution cosmic hydrodynamic simulation



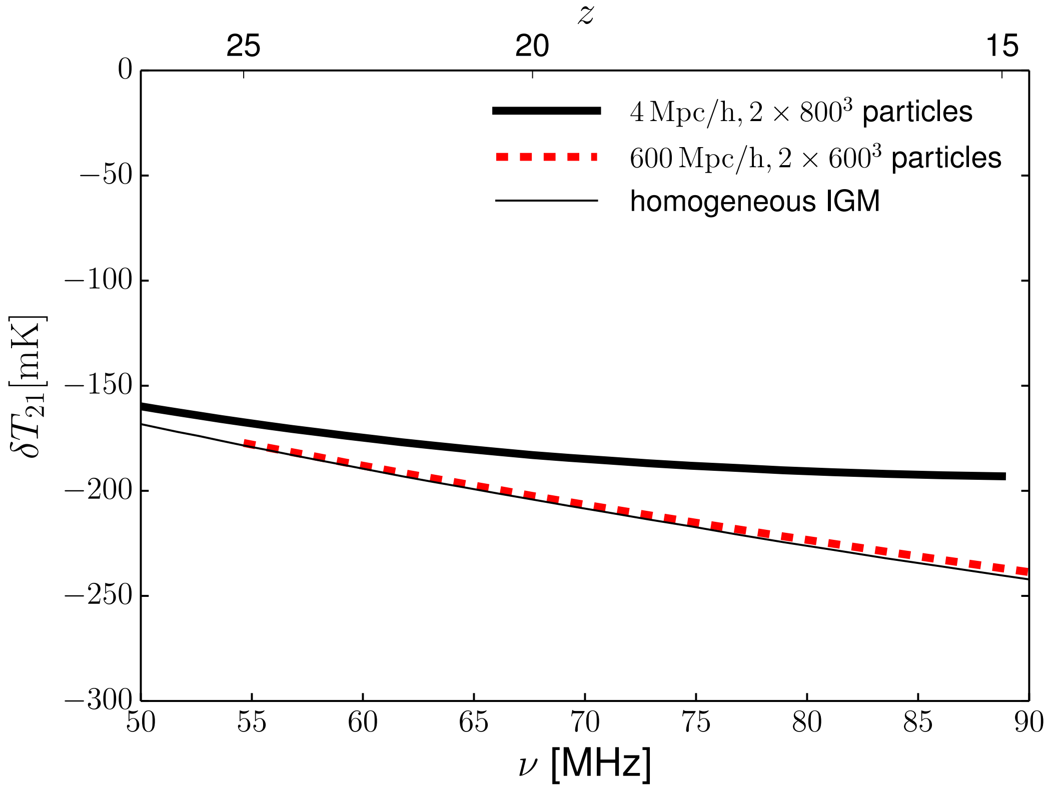
$$dT_{21} = \frac{T_S - T_\gamma}{1+z}\left(1 - e^{-\tau}\right)$$

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

YX, Yue, Chen, 2021, ApJ

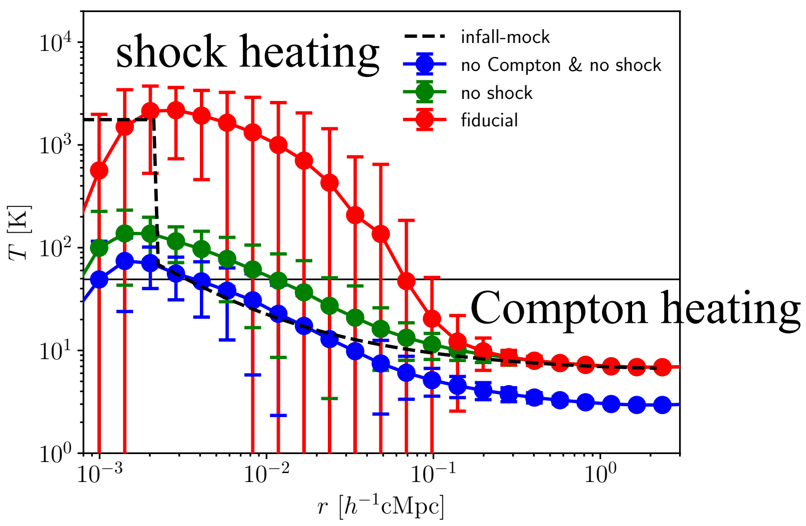
Under-resolved signal

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

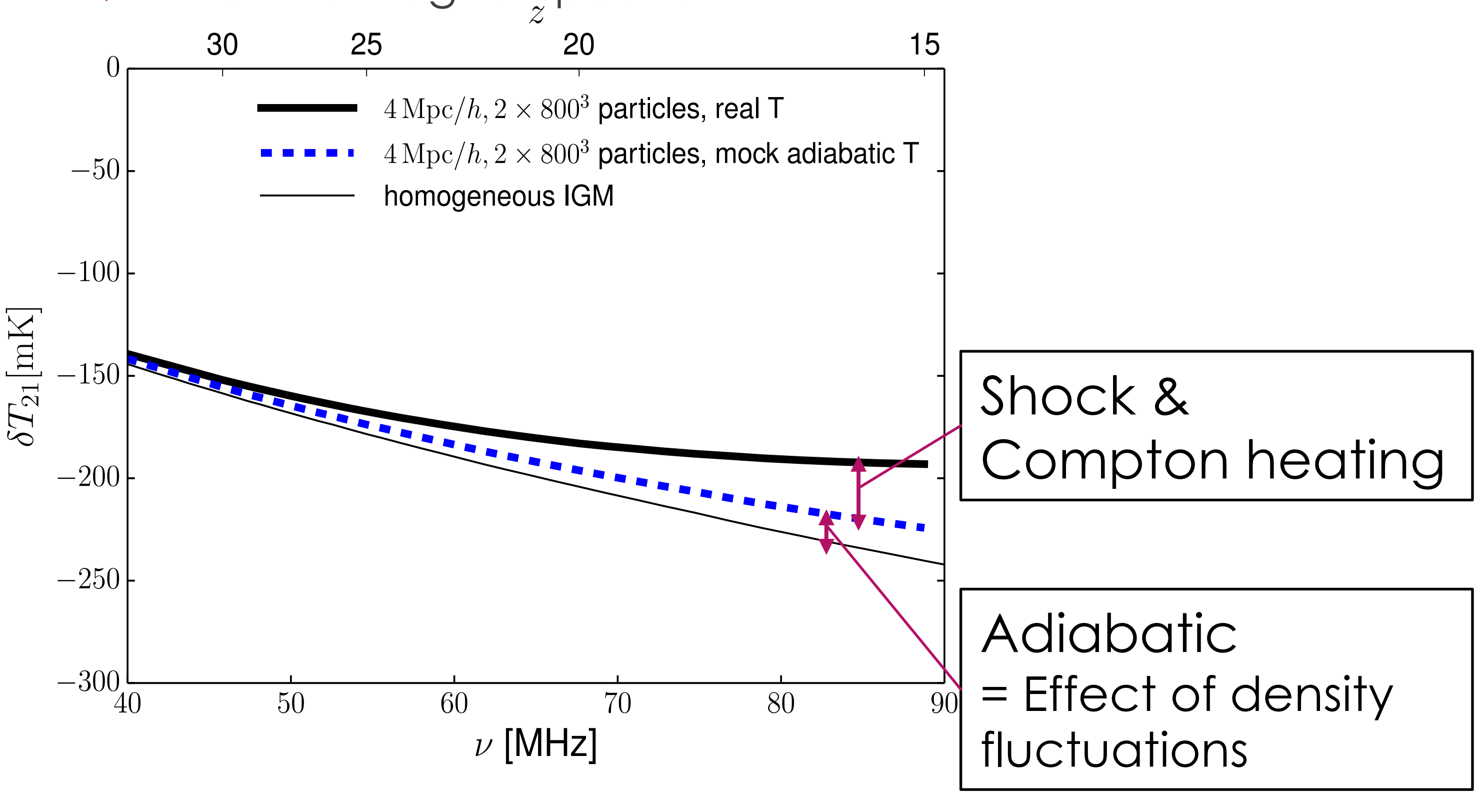


The effect of shock heating & Compton heating

- T_K profile around halos



- Maximum signal spectrum



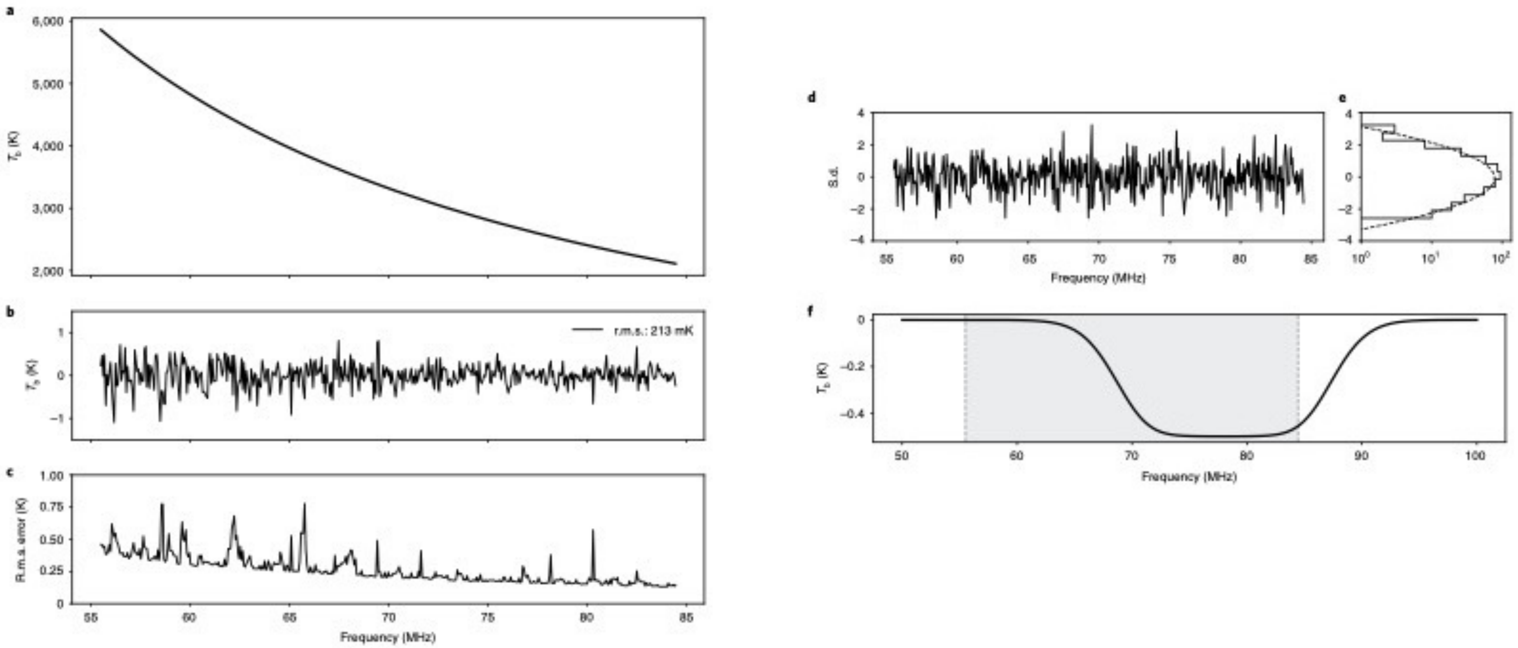
Take-home message: global 21 cm spectrum

- 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!

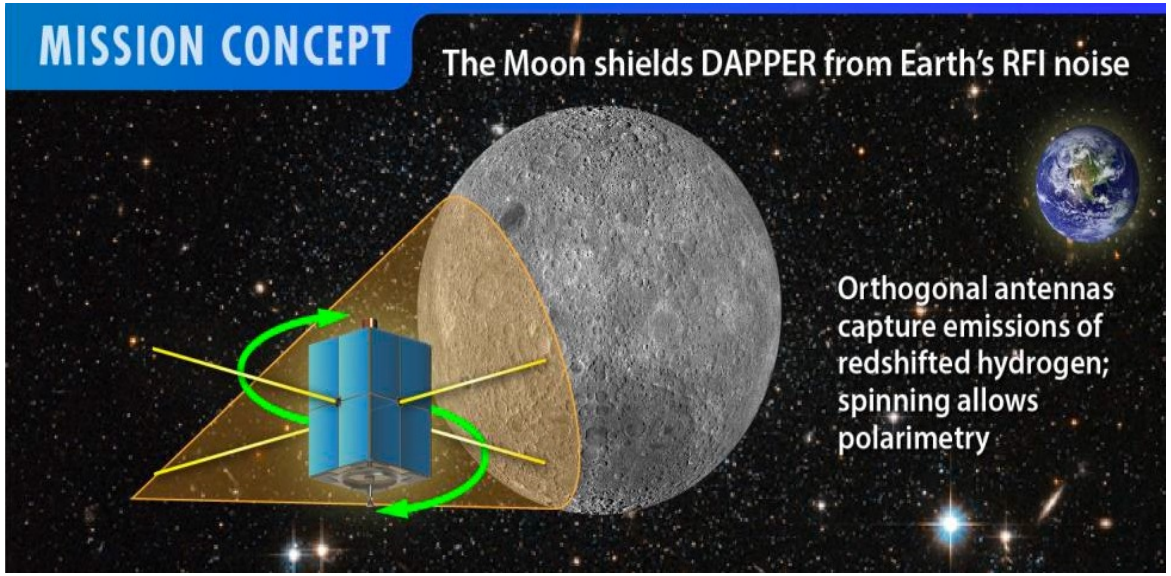
- Enlarged discrepancy between theory and EDGES signal!

The SARAS-3 measurement



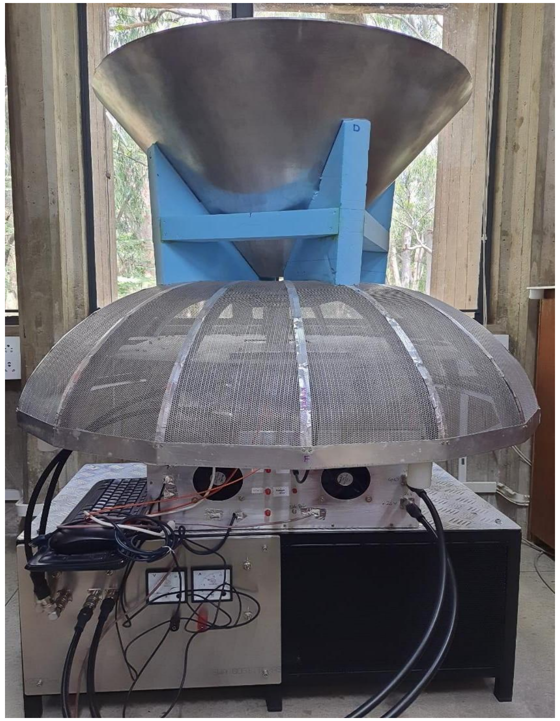
Reported a **non-detection** of the EDGES absorption feature at 95.3% confidence using 15 hrs of observations between 55 – 85 MHz (z = 15 – 25)
(S. Singh et al. 2022)

Going to the far side of the Moon …



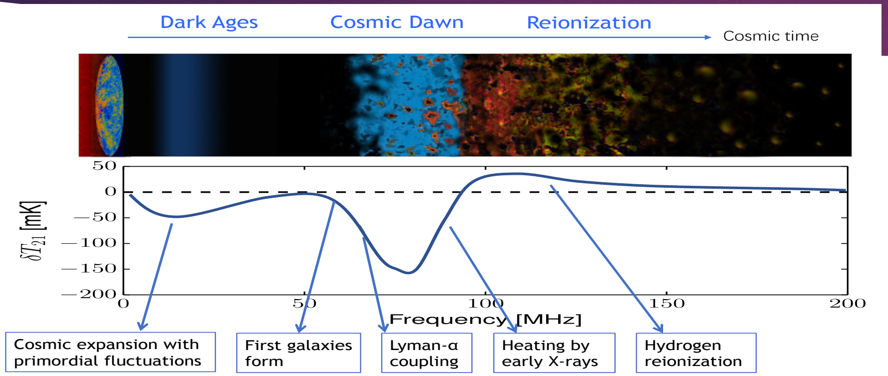
Credit: DAPPER collaboration

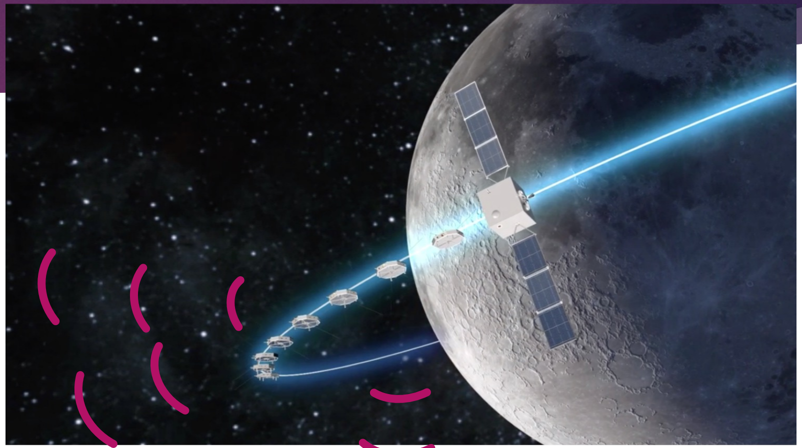
PRATUSH



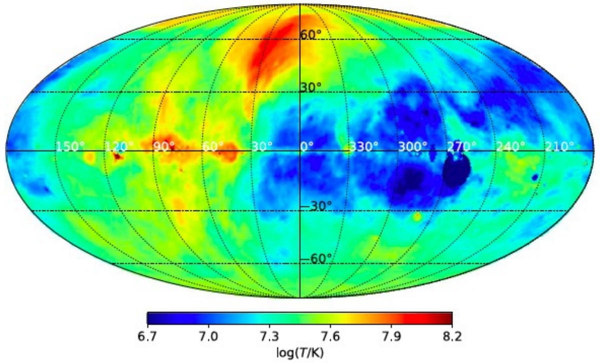
Credit: PRATUSH collaboration

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

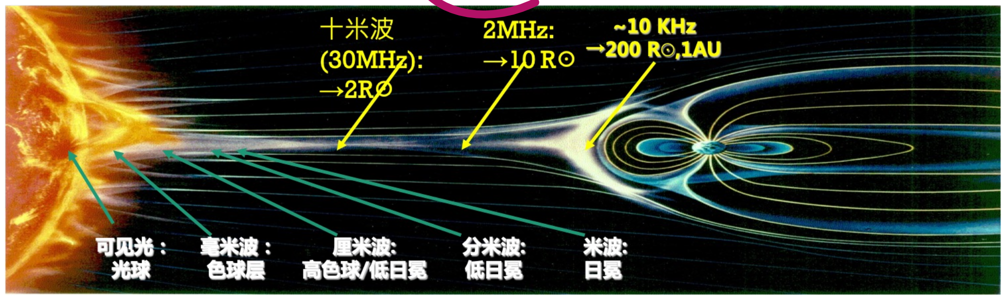




1. Reveal the dark ages and cosmic dawn with high-precision measurement of the global spectrum.

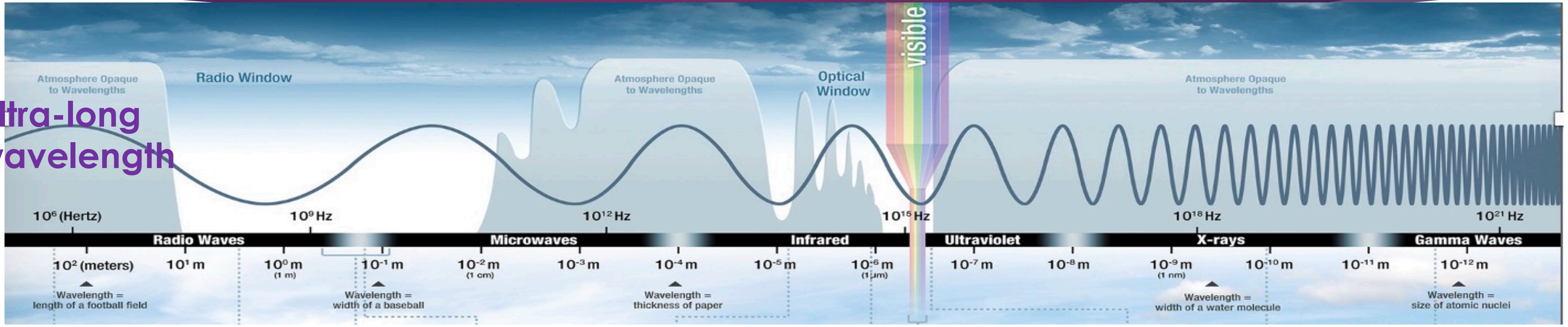


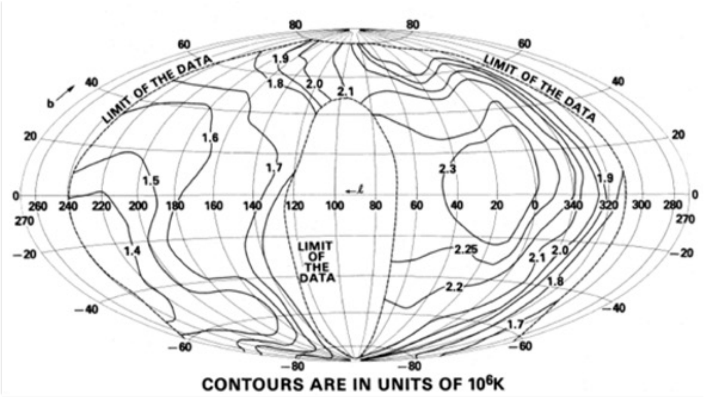
2. Open up the last unexplored electromagnetic window.



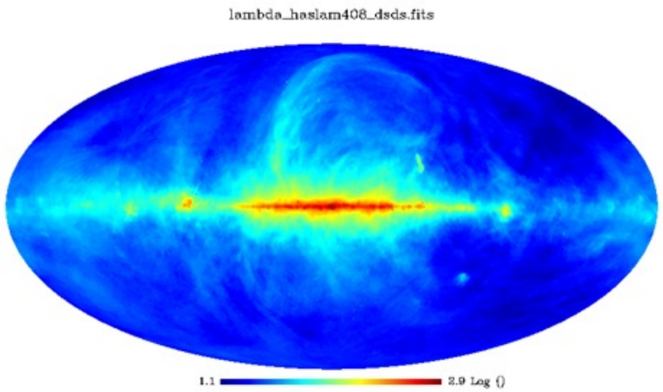
3. Observing the Sun and planets to uncover the dynamics of the interplanetary space.

Ultra-long wavelengths (ν < 30 MHz) – the last unexplored electromagnetic window

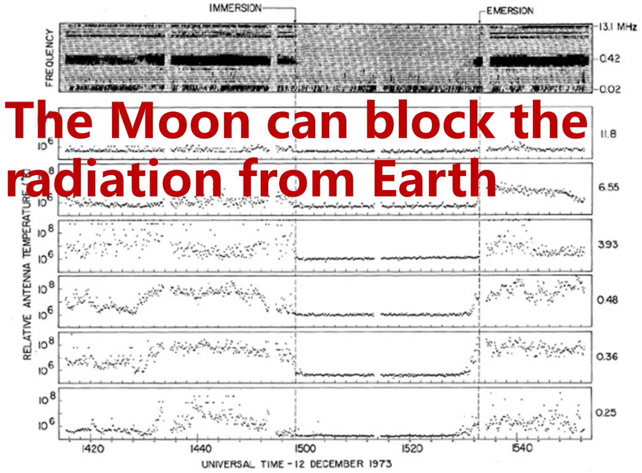




RAE-2 satellite (1978)



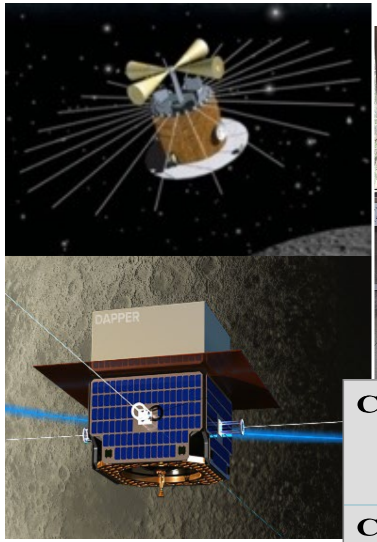
408 MHz Sky Map



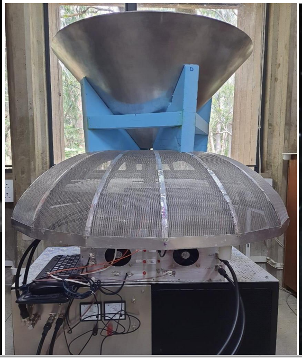
RAE-2 spectrum

Lunar-based ultralong wavelength astronomy

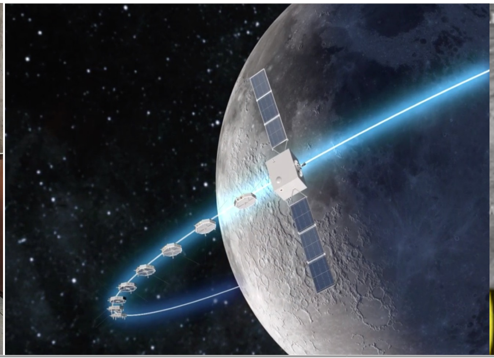
US:
DARE/DAPPER



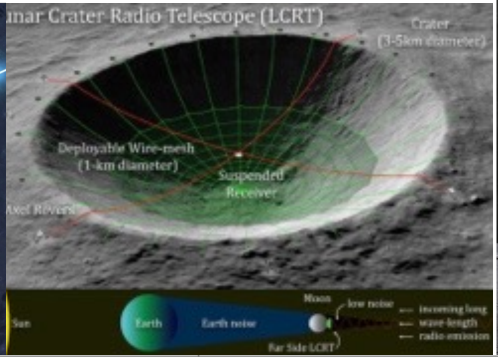
India:
PRATUSH



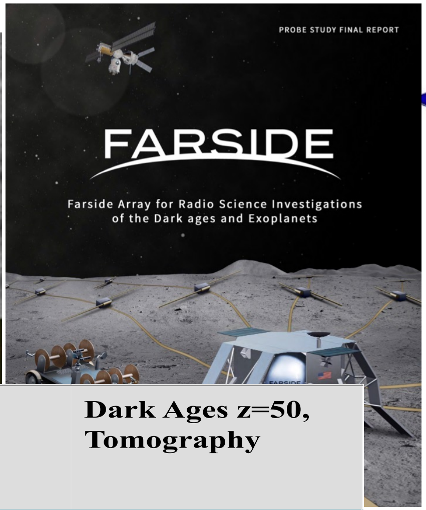
China:
鸿蒙计划（DSL）



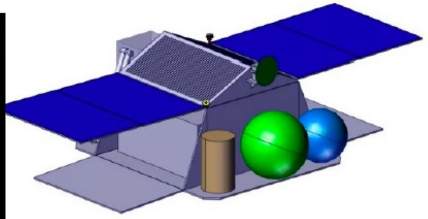
US:
LCRT

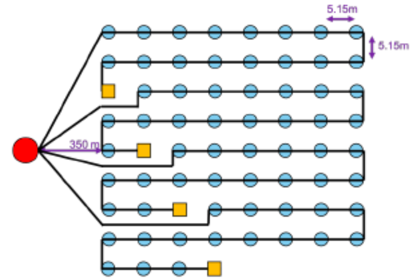


US:
FARSIDE



Europe:
ALO





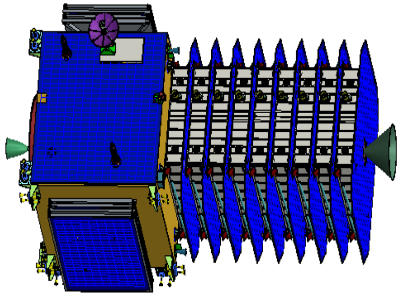
CoDEX Mission	Dark Ages z=30, Power Spectra	Dark Ages z=30, Tomography	Dark Ages z=50, Power Spectra	Dark Ages z=50, Tomography
CoDEX ($1\ km^2$) M-class	S/N~10 for k~0.01-0.1	S/N~5 for k=0.01	S/N<1	S/N<1
CoDEX ($10\ km^2$) L-class	S/N~10-100 for k~0.01-1.0	S/N~10-100 for k~0.01-0.1	S/N>10 for k~0.01-1	S/N>10 for k~0.01
CoDEX ($100\ km^2$) L-class	S/N~100-1000 for k~0.01-1.0	S/N~10-1000 for k~0.01-0.4	S/N>100 for k~0.01-1	S/N~10-100 for k~0.01-0.1

Koopmans et al., arxiv:1908.04296

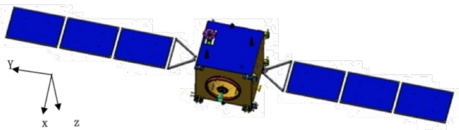
Discovering the Sky at the Longest wavelengths (DSL/鸿蒙计划)

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

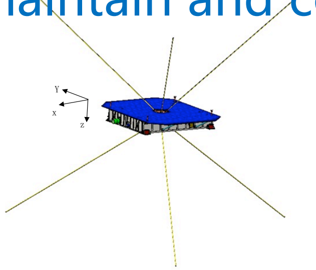
- lunar satellite: no need for landing
- Lunar orbit period is a few hours, can use solar power
- Observe on the far side of the Moon, and transmit data back on the front side
- All flying on the same orbit, easy to maintain and communicate



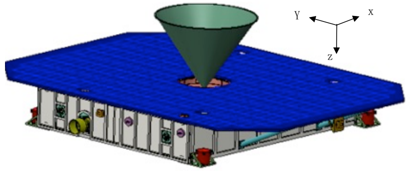
mother-daughter combo



mother satellite



8 x low freq. daughter



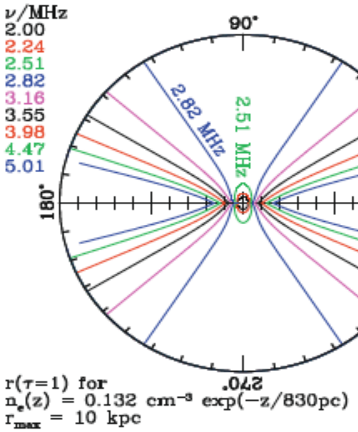
1 x high freq. daughter

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

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

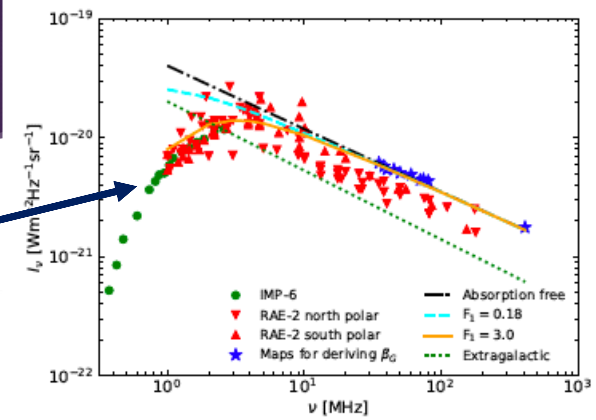
What to expect for the ultra-long wavelength sky?

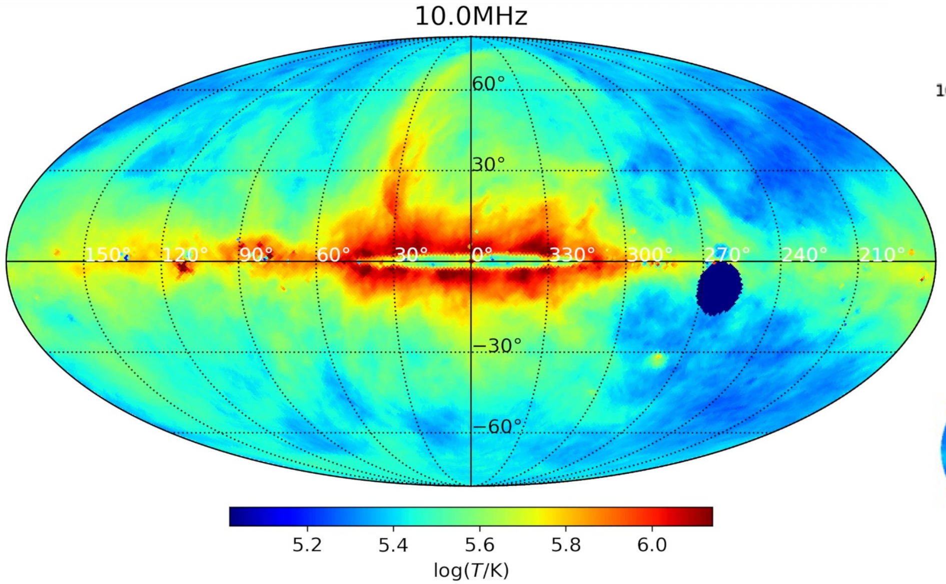
Free-free absorption by the ISM

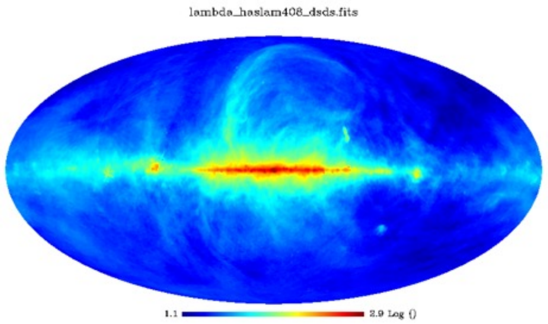


distance to τ=1 due to free-free absorption of ISM (Jester & Falcke 2009)

The absorption becomes significant at ultra-long wavelengths



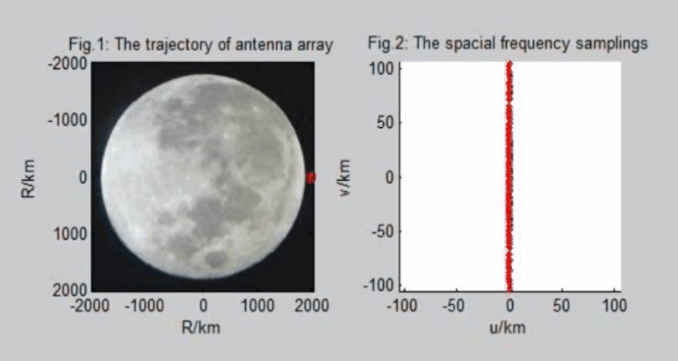




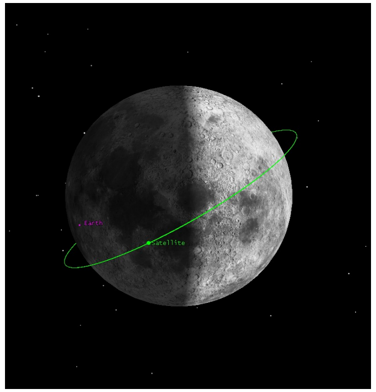
Ultra-Long wavelength Sky with Absorption Model (**ULSA**)

(Cong, Y et al. 2021, ApJ, 914, 128)

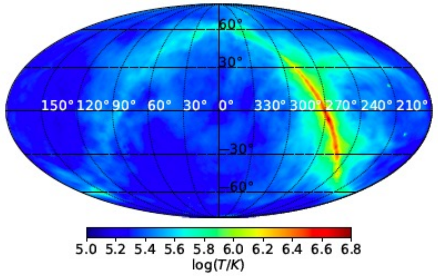
Wide-field imaging simulation with a 3-D moving array



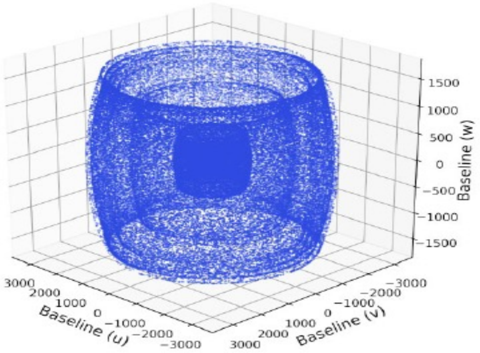
一个轨道周期的空间频率覆盖



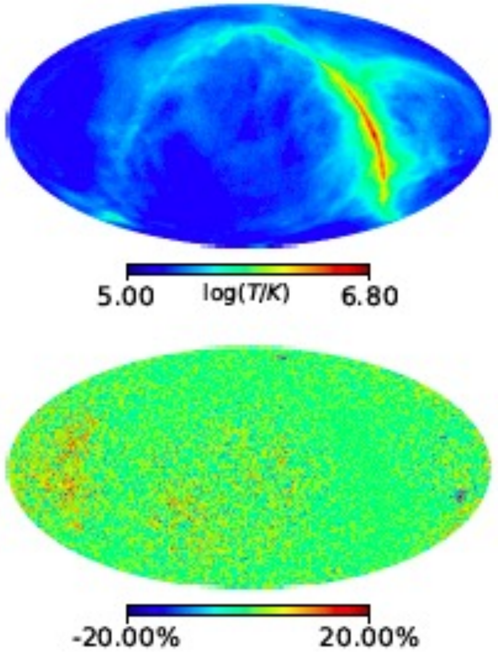
Input sky at 10 MHz



(b) 10.0 MHz



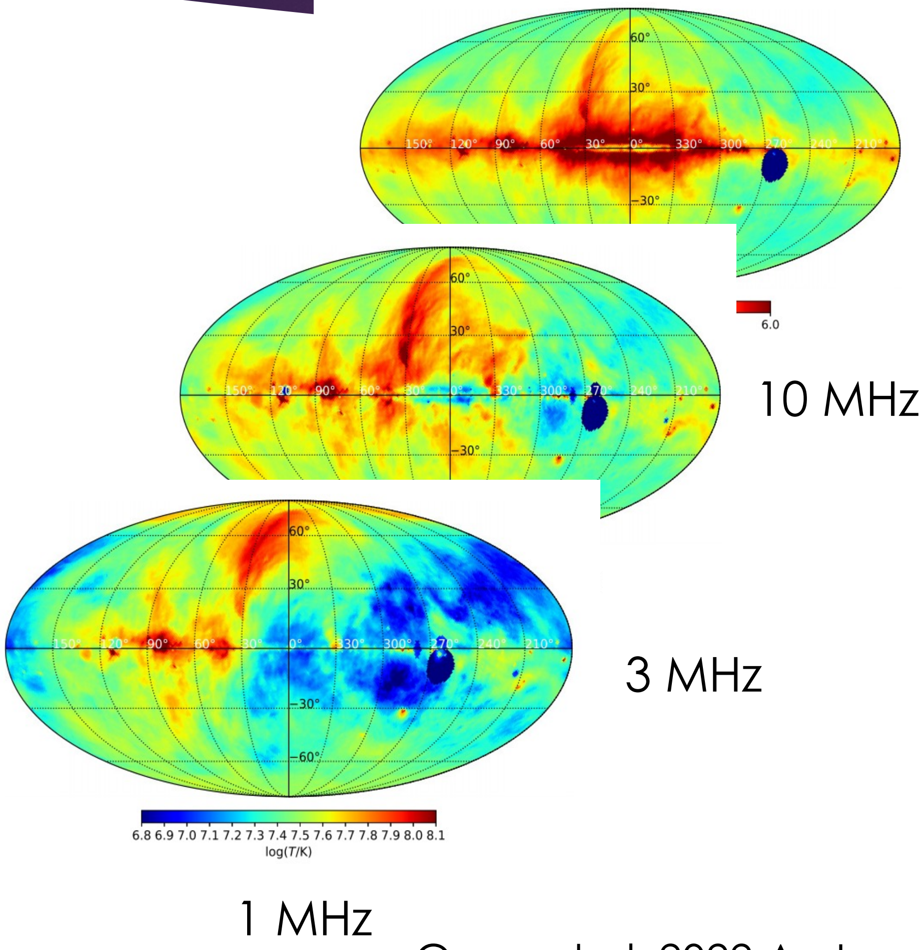
Imaging with 5 satellites for one precession period (1.3 yr)



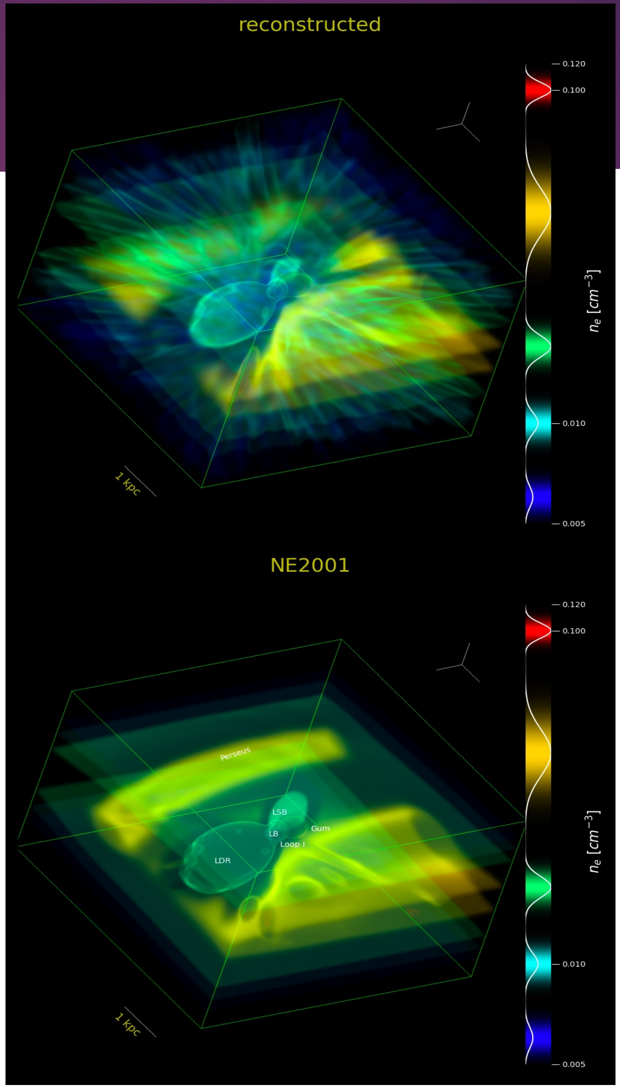
Y. Shi et al. 2022, MNRAS 510, 3046

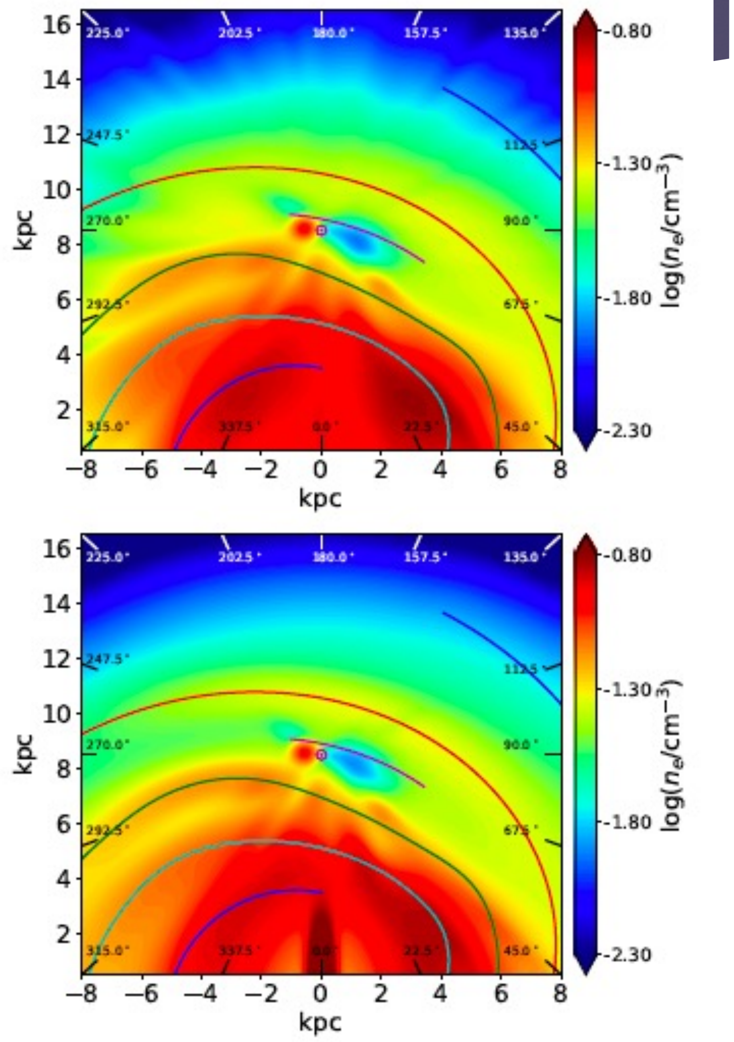
(d) 10 MHz: with Moon blockage, noise, antenna response and digital correlation limit.

What can we do?
– reconstructing Galactic 3-D structures from ultra-long wavelength sky maps

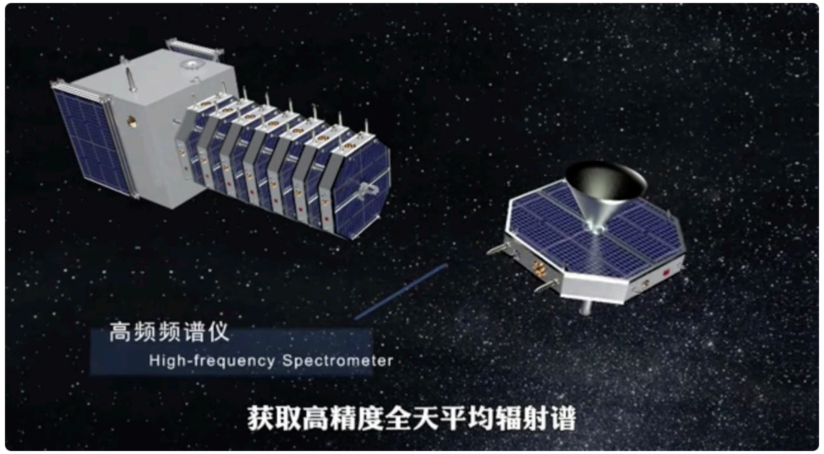


Cong et al. 2022 ApJ.

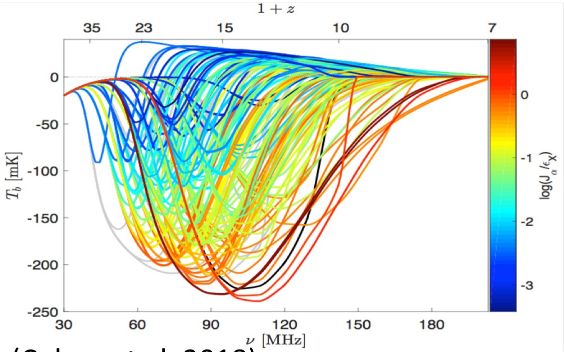




What can we do?
– Measuring the global 21 cm spectrum on lunar orbit

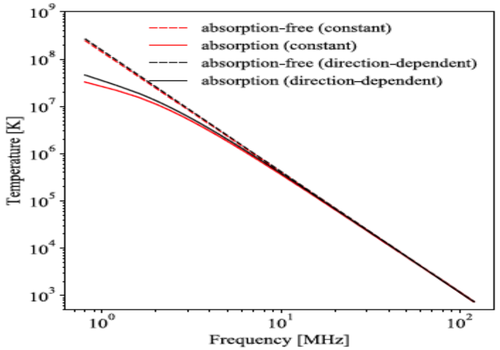


21cm signal ~ 0.1 – 0.2 K



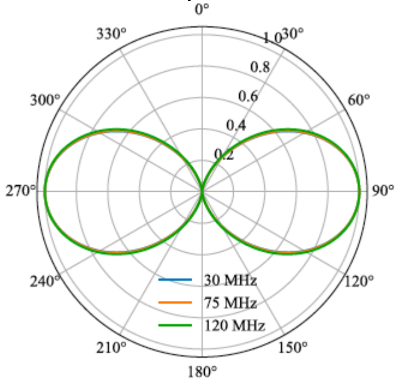
(Cohen et al. 2018)

Foreground ~ 10^4 K

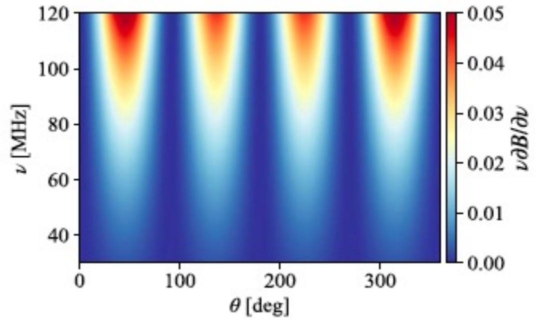


Very low chromaticity required!

Beam pattern

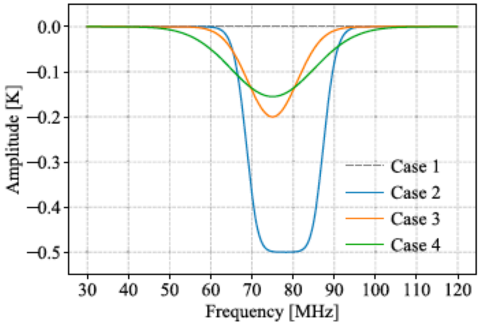


Frequency gradient of beam

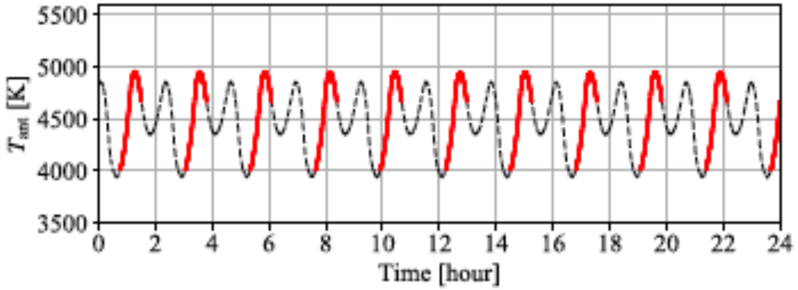


Measuring the global 21 cm spectrum from Cosmic Dawn on lunar orbit

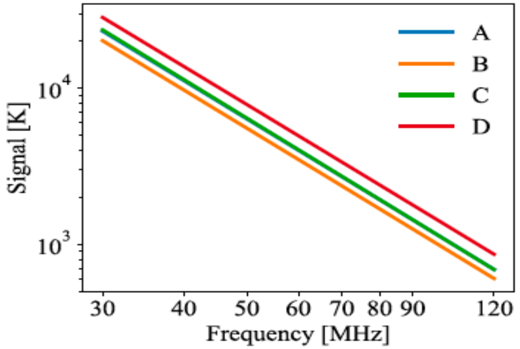
21cm signal model



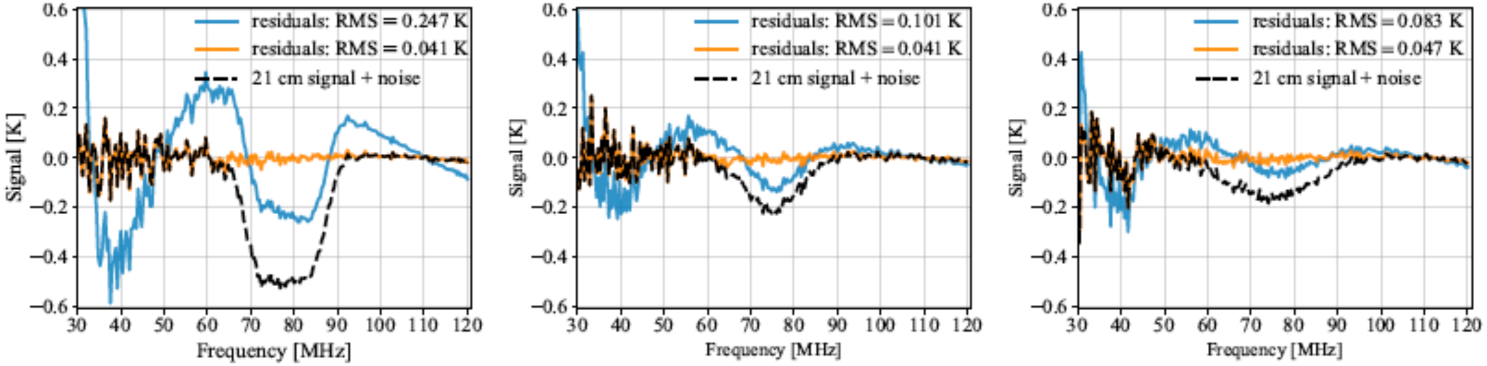
Mock observation（60 MHz）



Simulated spcetrum



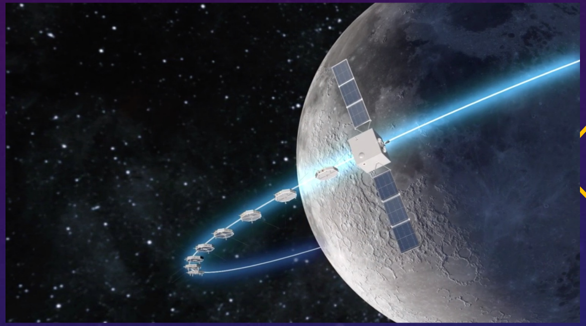
Recovery of the global 21cm signal

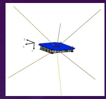


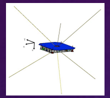
(a) Results for the EDGES 21 cm model. (b) Results for Gaussian 21 cm model (A = 0.2 K). (c) Results for Gaussian 21 cm model (A = 0.155 K).

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

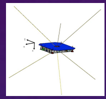
On-going works: End-to-End simulation





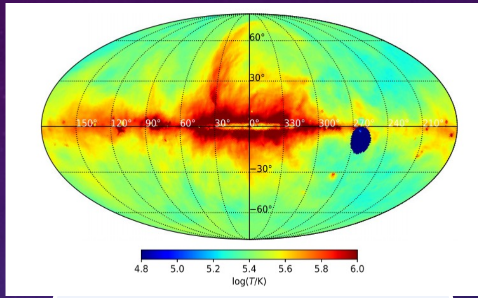


……

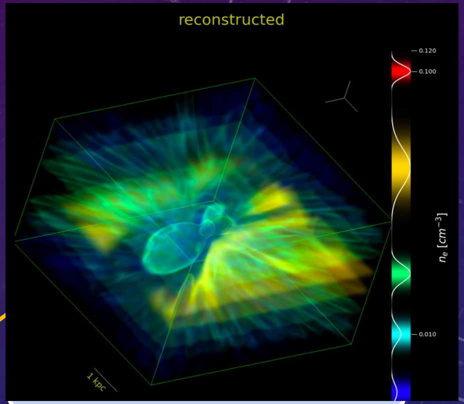


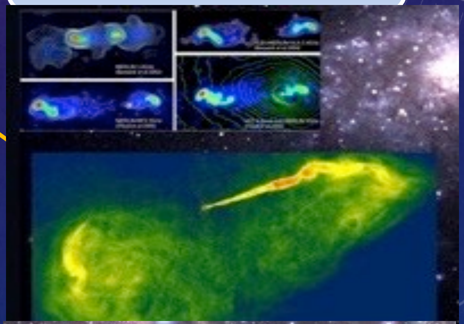
Interferometer imaging

(1 – 30 MHz)



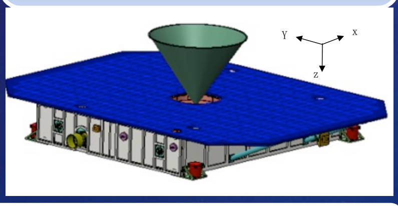
High resolution maps & source catalog



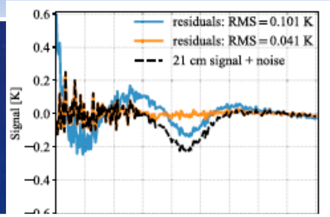


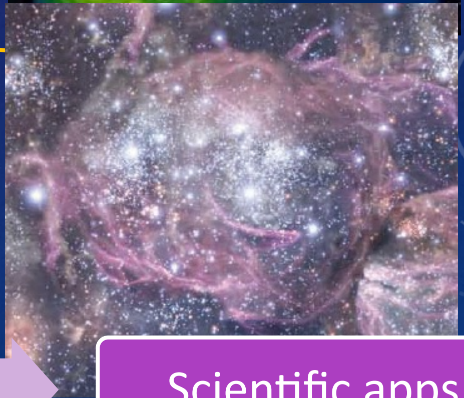
Global spectrum measurement

(30 – 120 MHz)



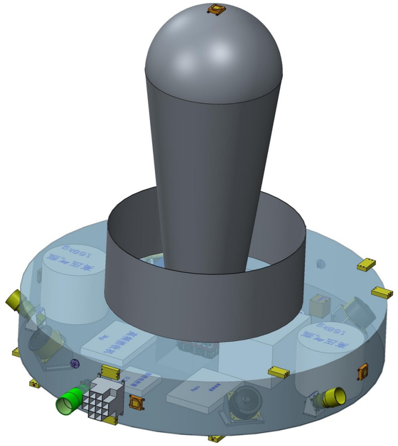
21cm global spectrum from DAs and CD

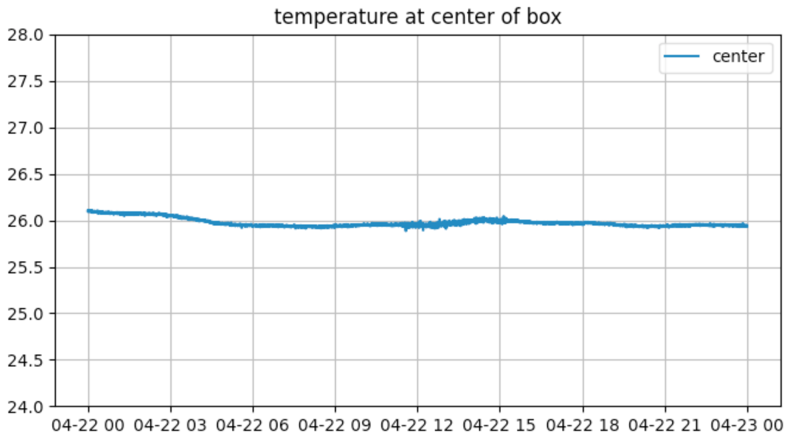


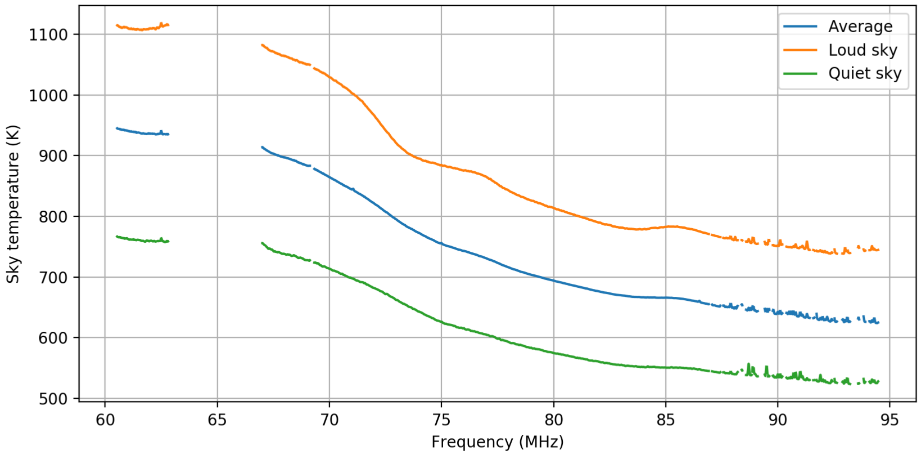


Input sky model → Mock observations → Data analysis → Scientific apps.

On-going works: Global Spectrum Field Test





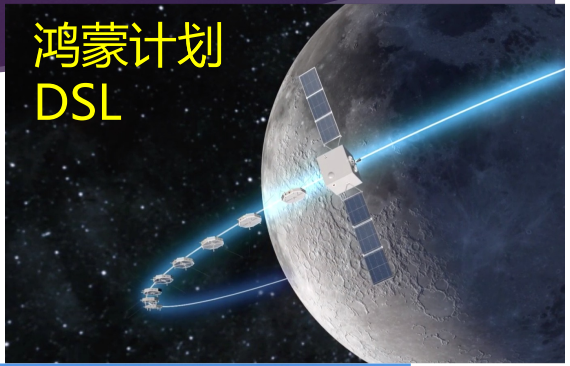


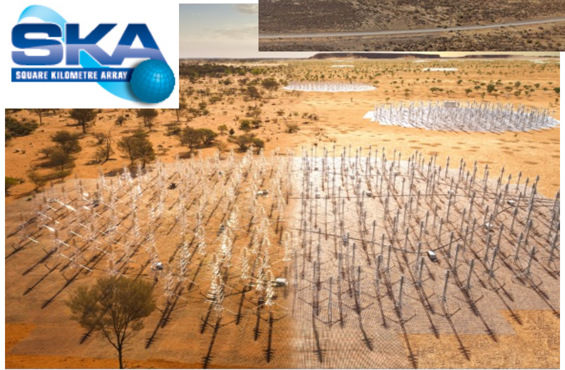
21 cm probes: challenging but intriguing!

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

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

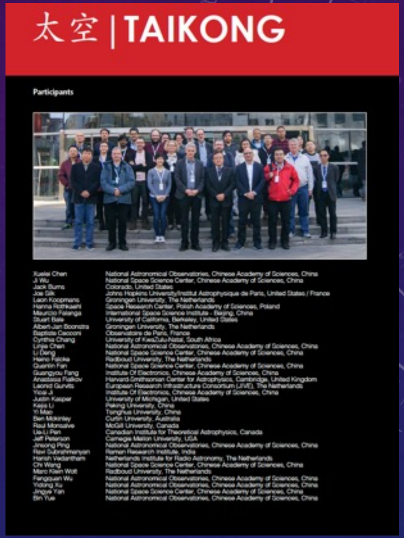
- 21 cm forest: a ***simultaneous probe*** of DM & first galaxies



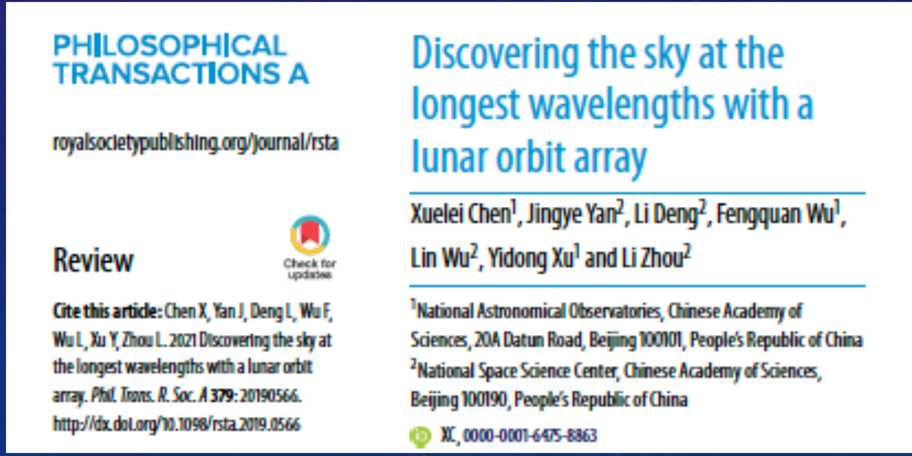


Project Status

- 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



PHILOSOPHICAL TRANSACTIONS A

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Review

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

Xuelei Chen[1], Jingye Yan[2], Li Deng[2], Fengquan Wu[1], Lin Wu[2], Yidong Xu[1] and Li Zhou[2]

[1]National Astronomical Observatories, Chinese Academy of Sciences, 20A Datun Road, Beijing 100101, People's Republic of China
[2]National Space Science Center, Chinese Academy of Sciences, Beijing 100190, People's Republic of China

XC, 0000-0001-6475-8863

Chen X, et al. 2021, Phil. Trans. R. Soc. A 379: 20190566. http://dx.doi.org/10.1098/rsta.2019.0566

Thank you!