Robust Extraction of Global 21 cm Spectrum from Experiments in Lunar Orbits

Yidong Xu (NAOC)

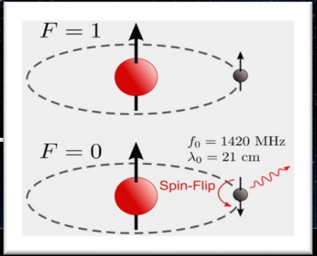
Collaborators: Haoran Li, Furen Deng, Meng Zhou, Xuelei Chen,
and the DSL collaboration :
-- National Astronomical Observatories, CAS
-- National Space Science Center, CAS
-- Innovation Academy for Microsatellites of CAS

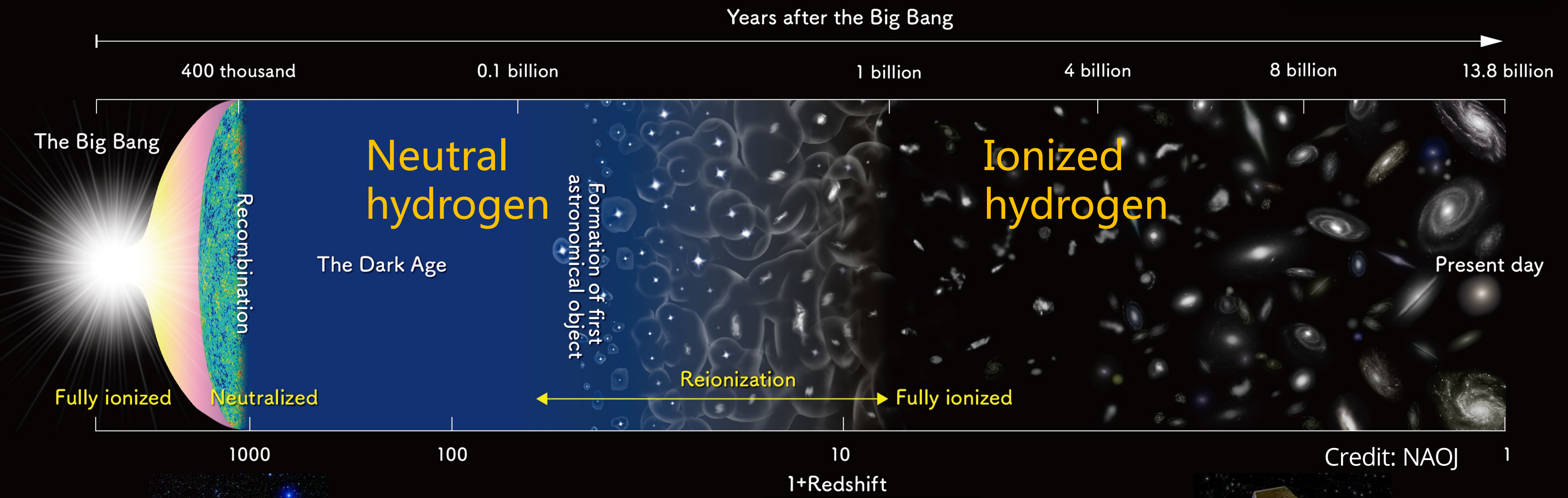
2026.3.17 Les Diablerets

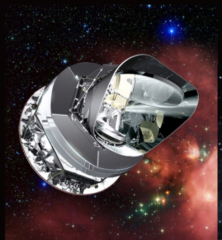
Discovering the Sky at the Longest wavelength

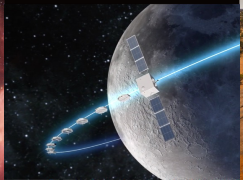
鸿蒙计划

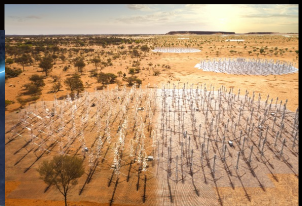
The 21 cm line of HI: Exploring the last desert in the observational universe

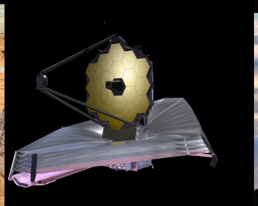


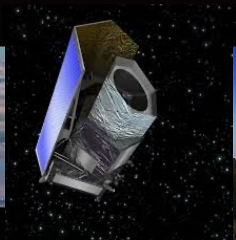


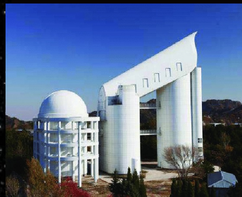












The 21 cm probes to CD/EoR

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

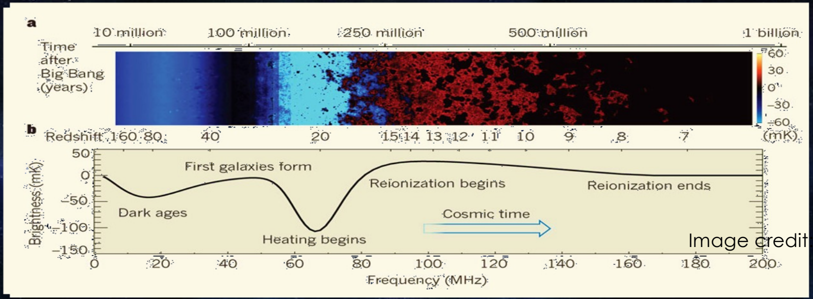
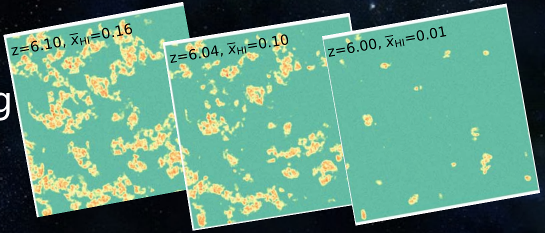


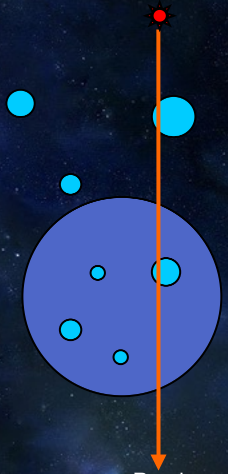
Image credit: Pritchard & Loeb 2012

  - → **2. 21 cm tomography**

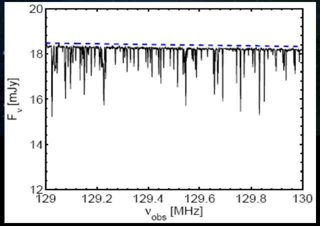
21 cm imaging



→ 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**)

The global 21cm spectrum from cosmic dawn (CD)

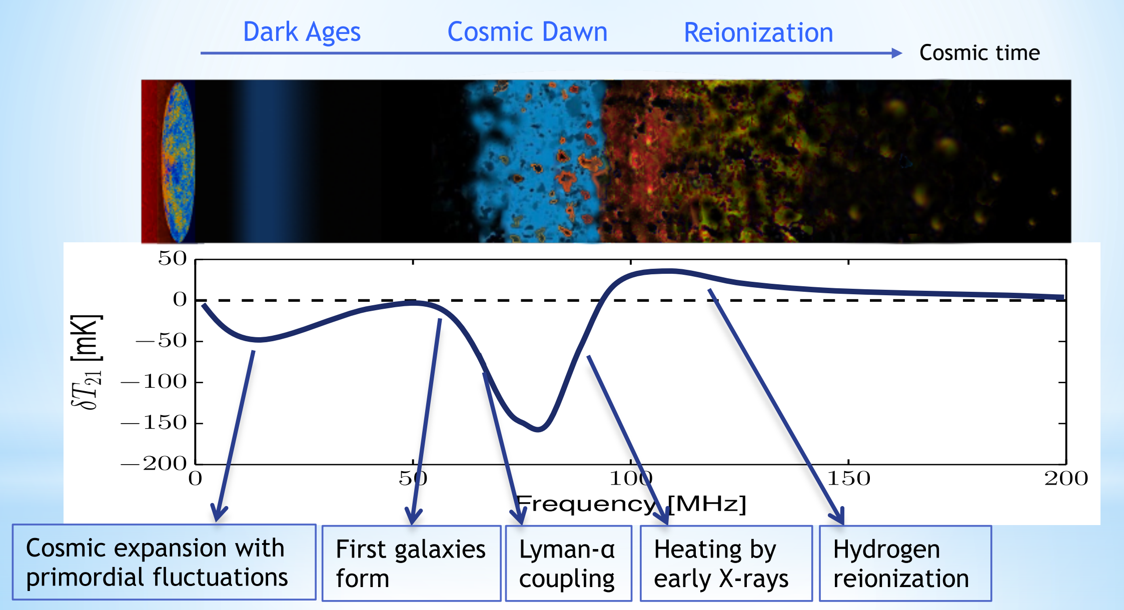
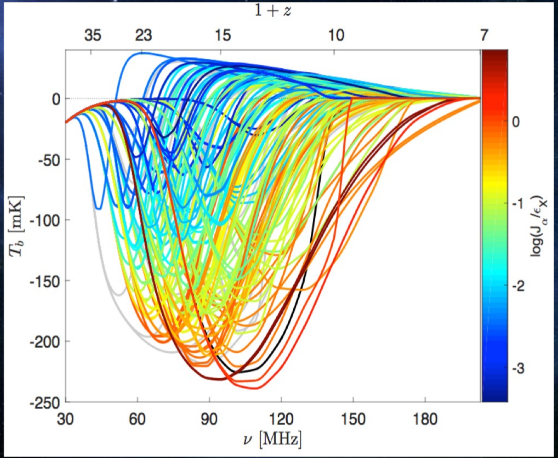


Image credit: Yuan Shi



(Cohen et al. 2018)

The global 21cm spectrum measurements

EDGES Low-band antennas

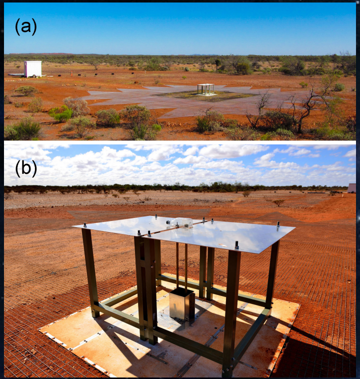
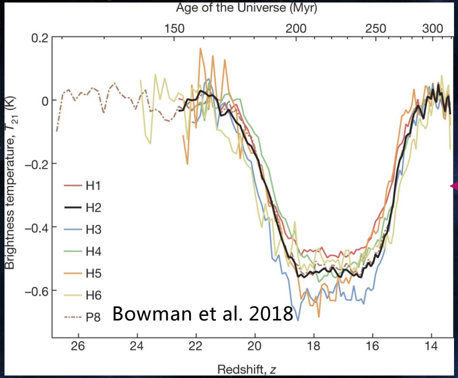
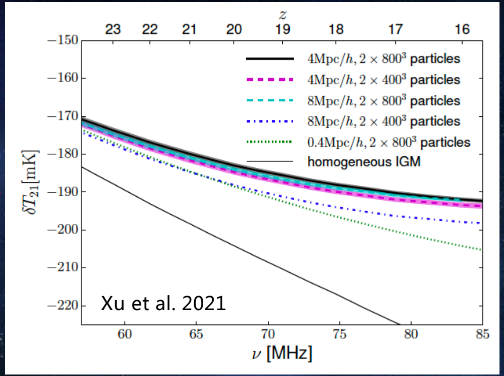


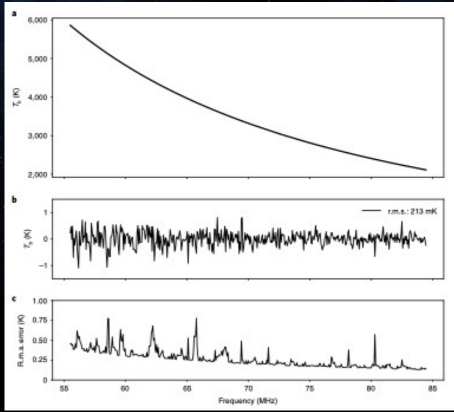
image credit: EDGES team

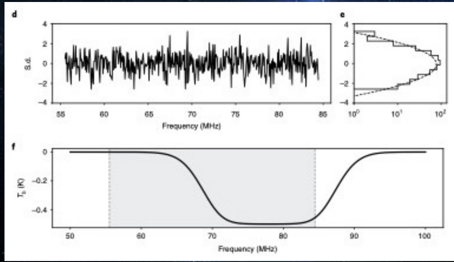


3.8 σ deviations



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)

NAOC

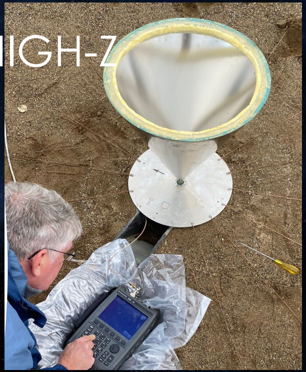
Other ground-based experiments

MIST

REACH

PRI^{Z}M

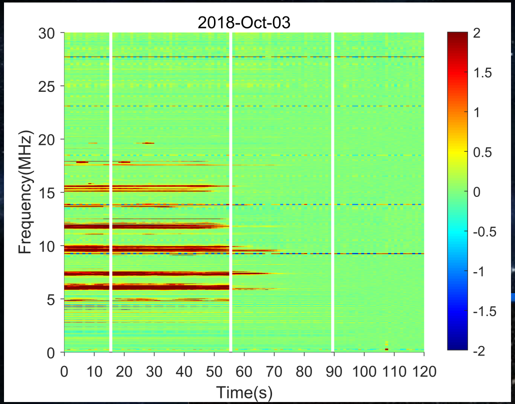
HIGH-Z



BIGHORNS:

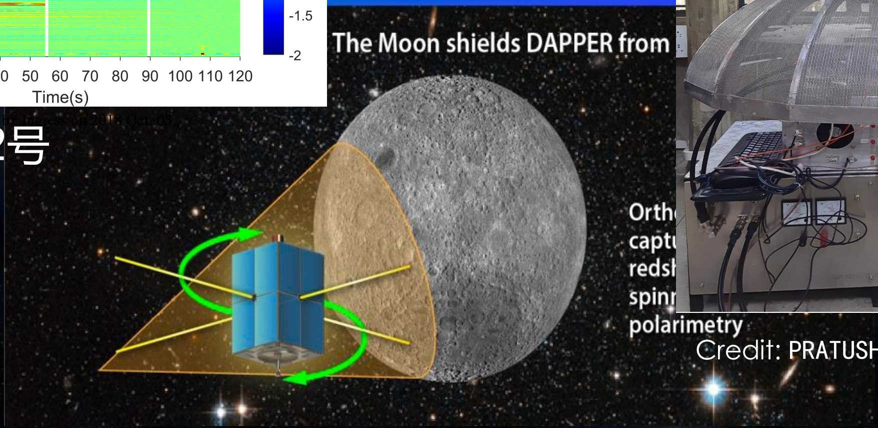
LEDA:

Going to the far side of the Moon …



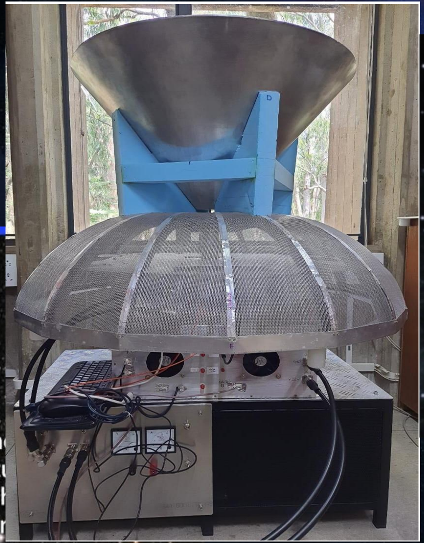
龙江2号

DAPPER



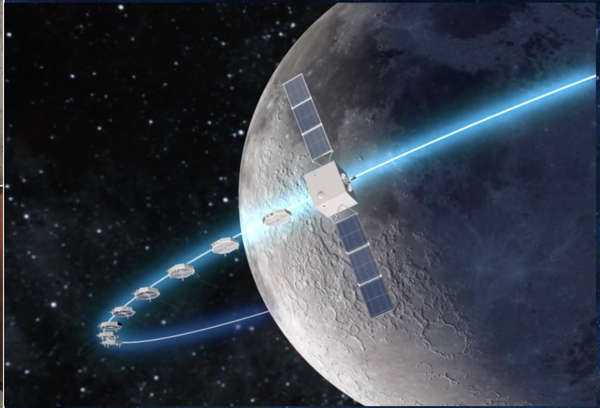
Credit: DAPPER collaboration

PRATUSH



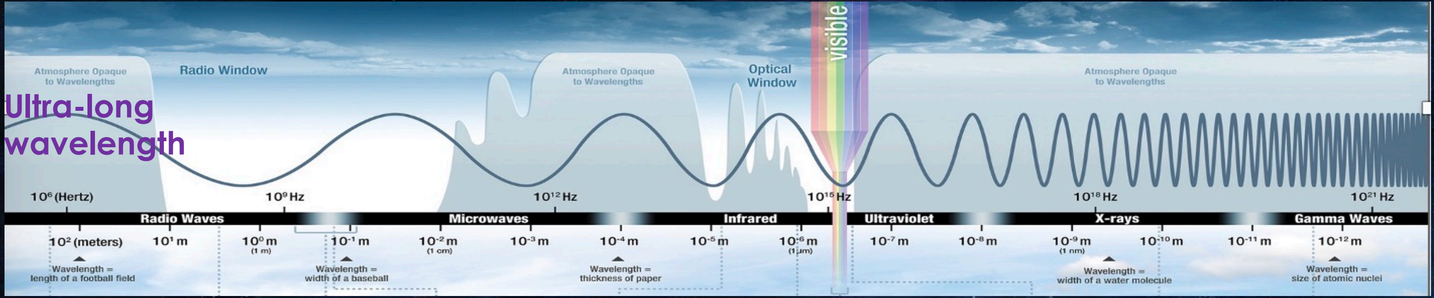
Credit: PRATUSH collaboration

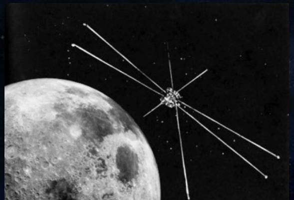
鸿蒙计划（**DSL**）



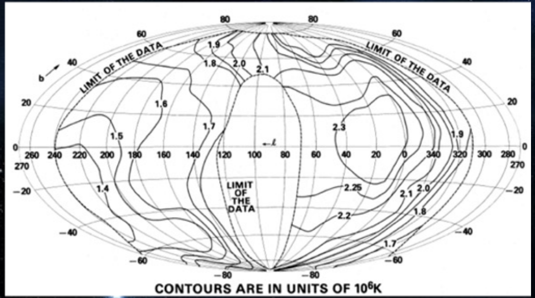
CosmoCube
(Eloy de Lera Acedo’s talk)

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

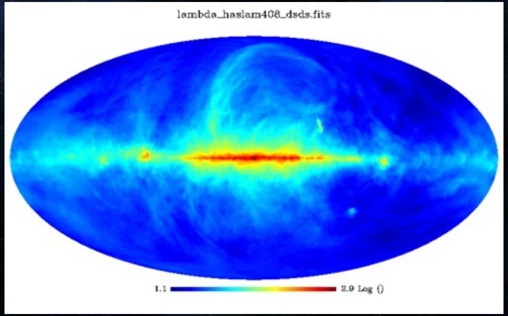




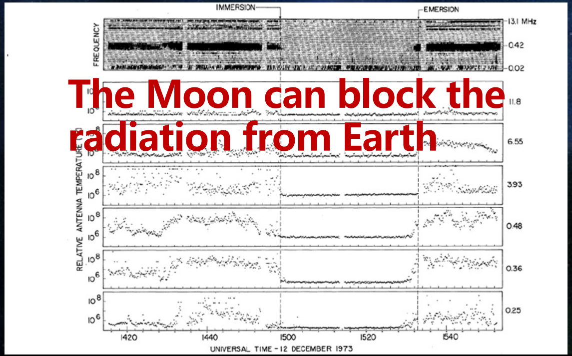
NASA RAE-2 launched 1973



RAE-2 satellite (1978)



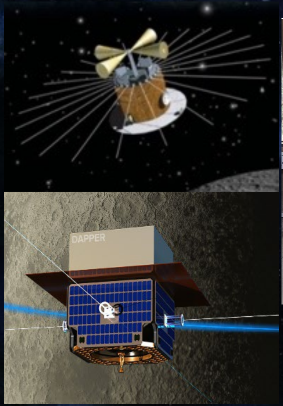
408 MHz Sky Map



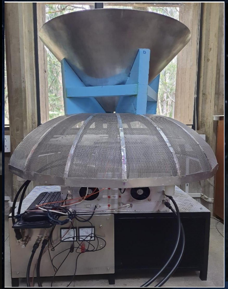
RAE-2 spectrum

Future experiments from the Moon

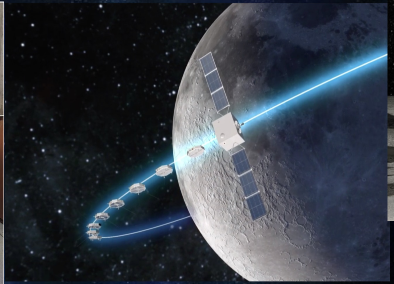
DARE/DAPPER



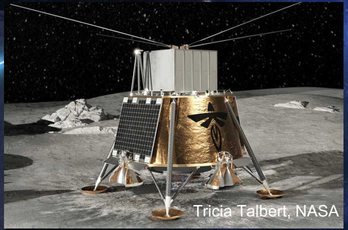
PRATUSH



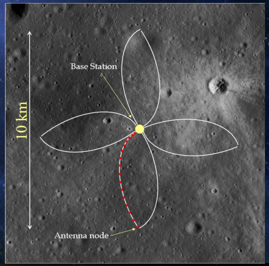
鸿蒙计划（DSL）

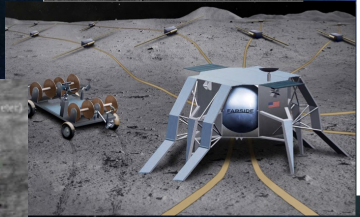


LuSEE ‘Night’

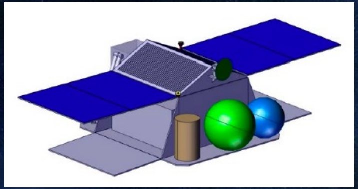


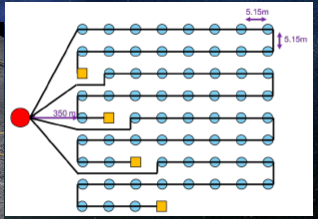
FARSIDE & FarView



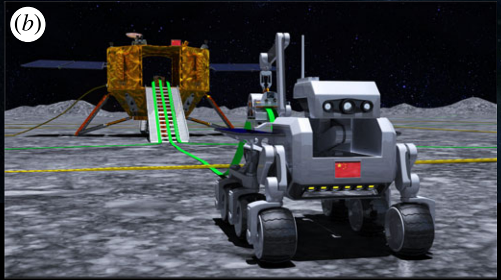


ALO & DEX

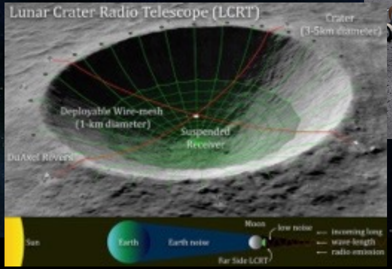




LARAF



LCRT



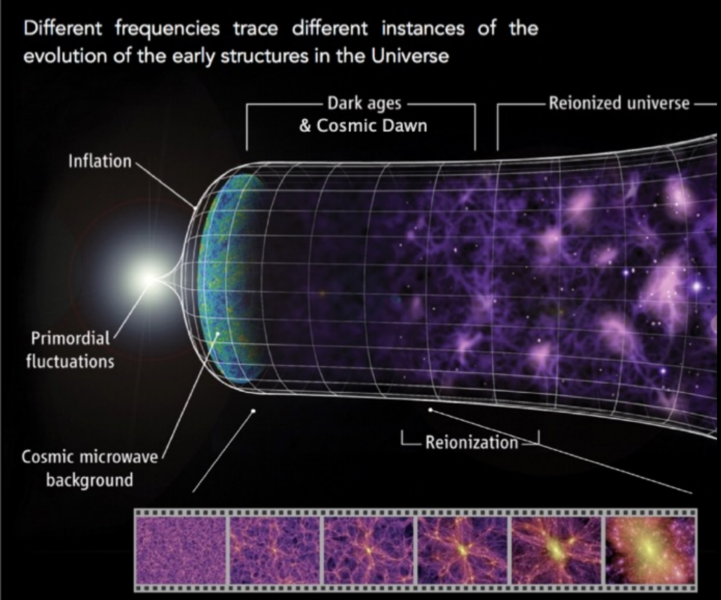
21 cm from the dark ages → the origin of cosmic structures

- Whether inflation occurred long ago?
- The non-Gaussianity (f_{NL}) of primordial density fluctuations

$\delta T/T\ (1 + f_{NL}\ \delta T/T)$

$f_{NL} \sim -5/12\ (n_s - 1) \sim 0.01 \quad n_s = 0.96\ (9\ \sigma)$

Maldacena 2003, Cabass + 2017; Mattarese + 2021



$N \sim 10^6$

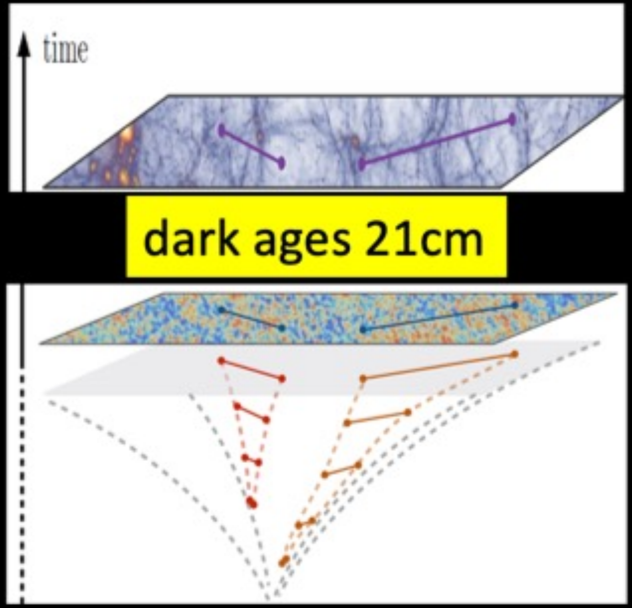
CMB pixels $f_{nl} \sim 10$

$N \sim 10^8$

galaxies $f_{nl} \sim 1$

$N \sim 10^{12}$

hydrogen clouds $f_{nl} \sim 0.01$

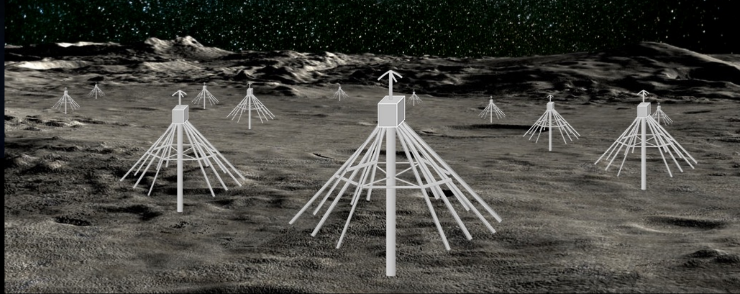


Slide by Joe Silk

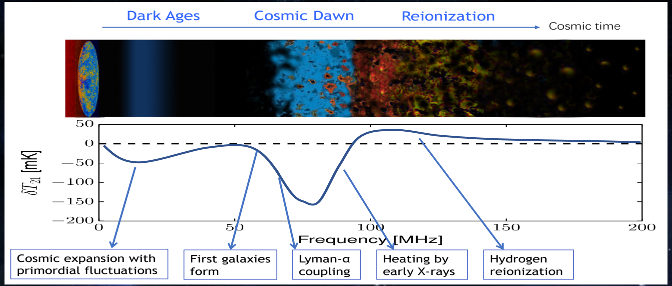
The radio array required to probe the Dark Ages

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 km²) 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 km²) 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 km²) 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

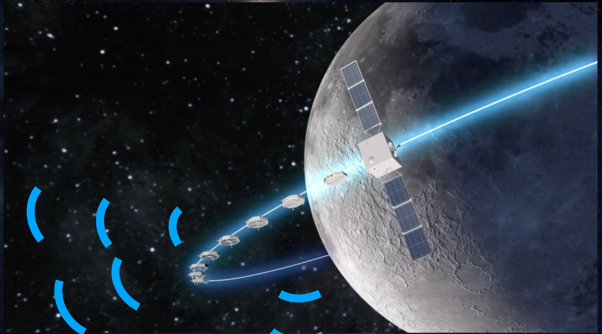
Koopmans et al., arxiv:1908.04296



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

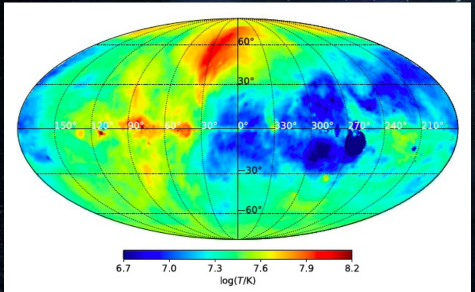


1. Reveal the dark ages and cosmic dawn with high-precision measurement of the global spectrum.

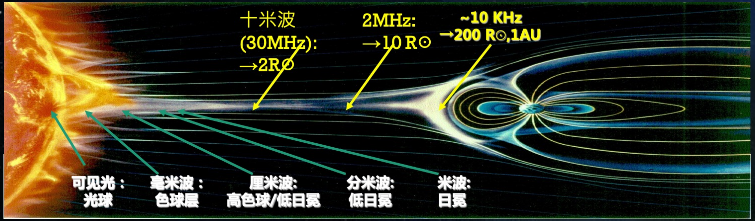


Chief Scientist: Xuelei Chen (NAOC)

Tech Chief: Jingye Yan (NSSC)



2. Open up the last unexplored electromagnetic window.

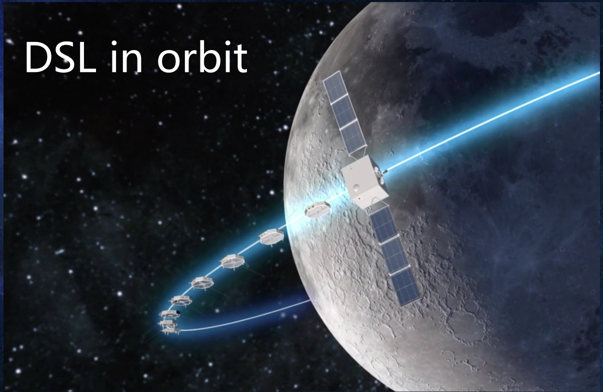


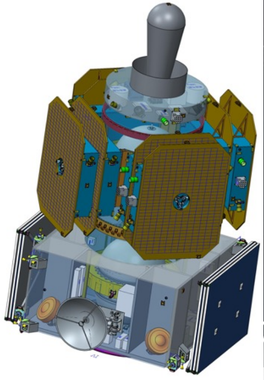
3. Observing the Sun and planets to uncover the dynamics of the interplanetary space.

Lunar Orbit Array DSL（鸿蒙计划）

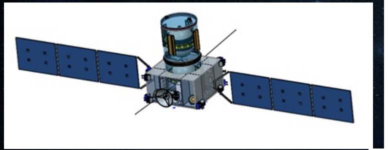
An interferometer array with 1 mother +9 daughter satellites in lunar orbit

- 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

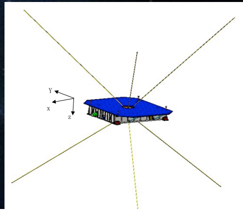




mother-daughter combo



mother satellite



8 x low freq. daughter

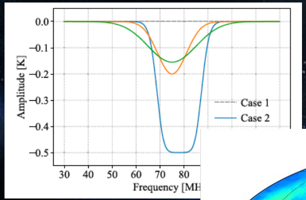
➔ **high resolution sky map at 1 – 30 MHz**

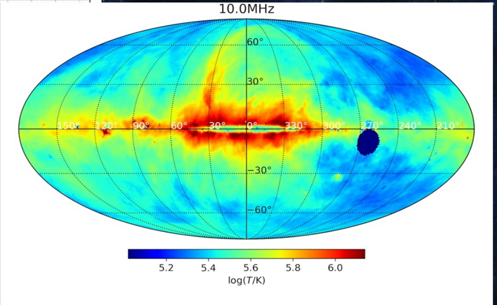
1 x high freq. daughter

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

Measuring the global 21 cm spectrum from CD on lunar orbit

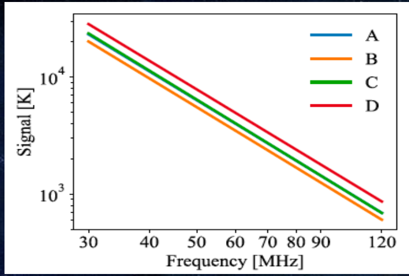
21cm signal model

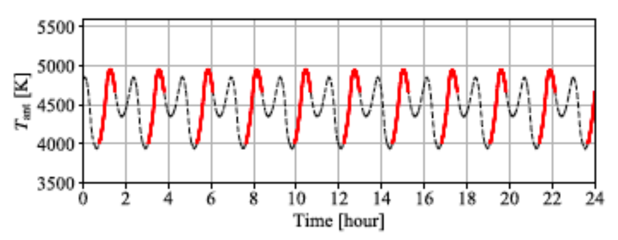


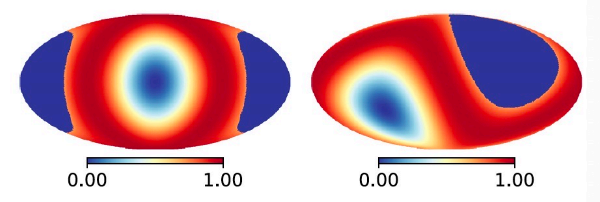


UltraLong wavelength Sky with
Absorption Model (**ULSA-1.0**)

- No ground
- With only limited RFI
- Foreground + chromaticity
- Fast-varying inhomogeneous sky







(a) A (b) B

Measuring the global 21 cm spectrum from CD on lunar orbit

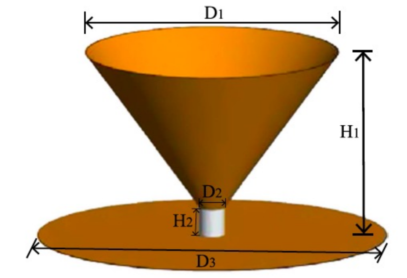
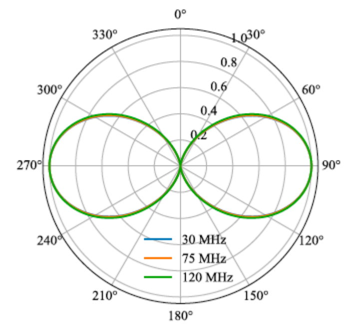
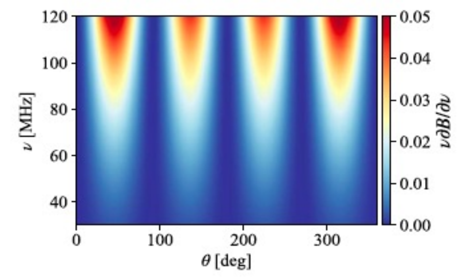


Figure 6. The disk-cone antenna. The size parameters are $D_1 = 40$ cm, $D_2 = 4$ cm, $H_1 = 30.5$ cm, and $H_2 = 4.5$ cm. The diameter of the optimal metallic reflector D_3 is 55 cm in our fiducial model.

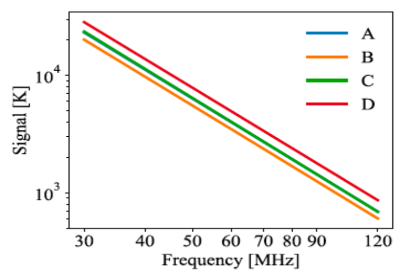
Beam pattern



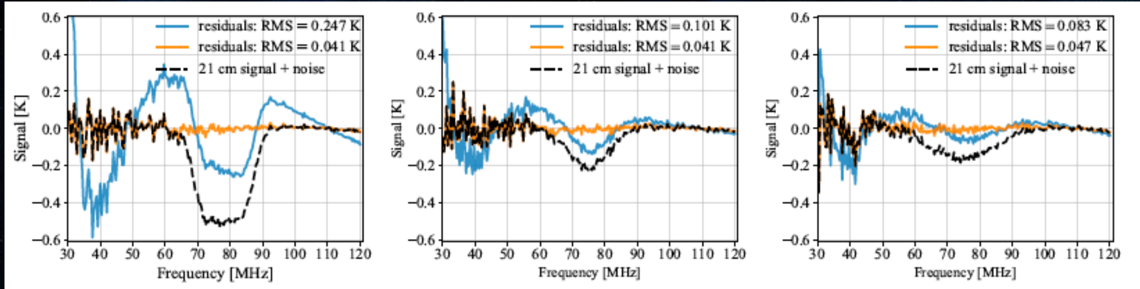
Frequency gradient of beam



Simulated spcetrum



Recovery of the global 21cm signal (Very low chromaticity required!)

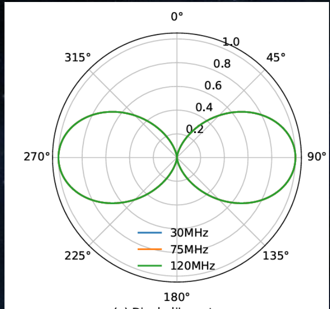


(a) Results for the EDGES 21 cm model. (b) Results for Gaussian 21 cm model ($A = 0.2$ K). (c) Results for Gaussian 21 cm model ($A = 0.155$ K).

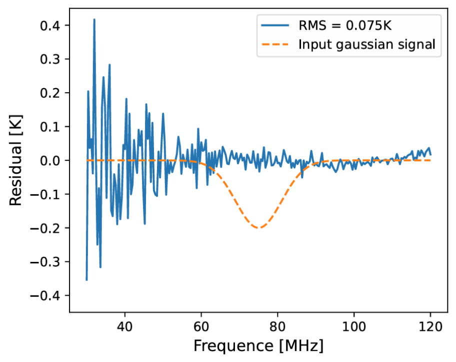
Shi, Deng, **YX** et al. 2022, ApJ, 929, 32.

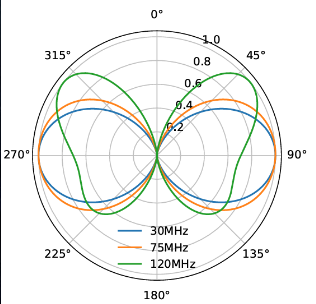
Measuring the global 21 cm spectrum from CD on lunar orbit

However, the simple polynomial fit would fail if there is a moderate level of chromaticity.

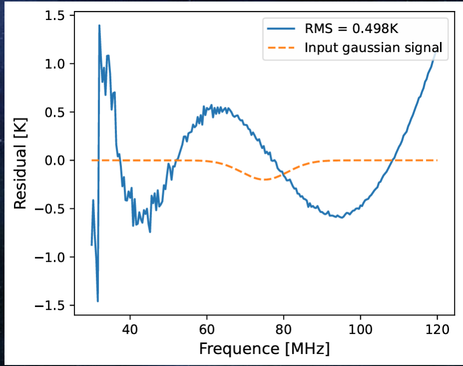


(a) Dipole-like antenna





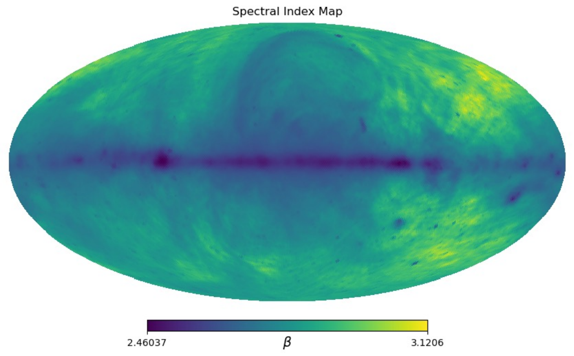
(c) chromatic disc-cone antenna

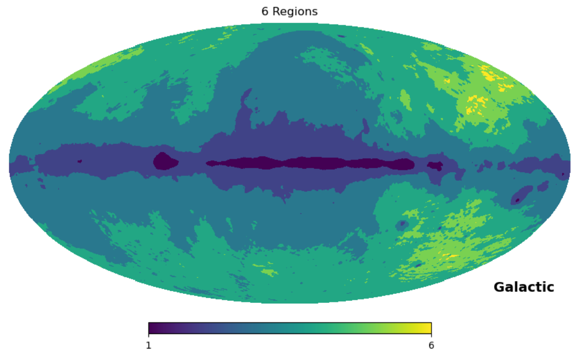


Inhomogeneous foreground spectrum ⊗ Chromatic beam response

To minimize the effect of foreground inhomogeneity

Forward modeling the sky — Divide the sky into N regions (Anstey et al. 2021, 2023)

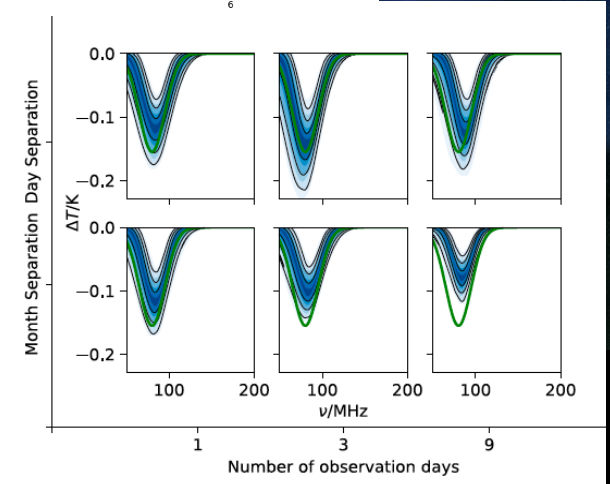




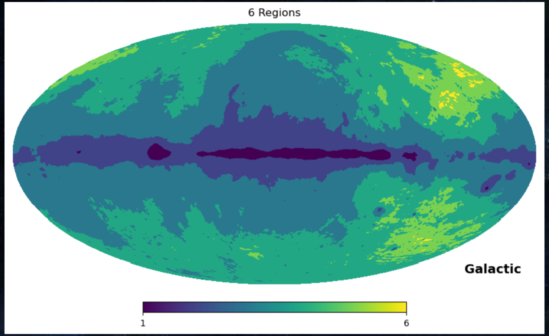
$$T_{\rm mock}(t,\nu) = \frac{\int B(t,\nu,\Omega)S(t,\Omega)T_{\rm sky}(\nu,\Omega)d\Omega + T_{\rm n}(t,\nu)}{\int B(t,\nu,\Omega)S(t,\Omega)d\Omega}$$

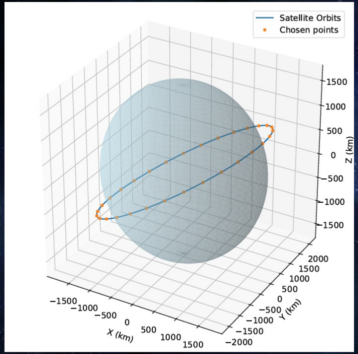
$$T_{\rm sky}(\nu,\Omega) = [T_{408}(\Omega) - T_{\rm CMB}]\left(\frac{\nu}{408}\right)^{-\beta(\Omega)} + T_{\rm CMB}$$

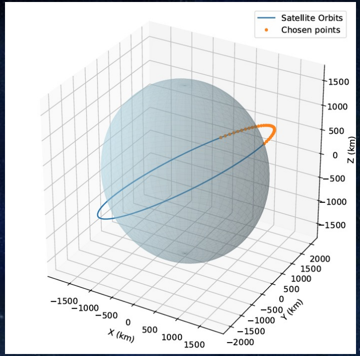
$$T_{\rm fgmd}(\nu,\Omega) = \sum_{i}^{N_r} M_i(\Omega)[T_{408}(\Omega) - T_{\rm CMB}]\left(\frac{\nu}{408}\right)^{-\beta_i} + T_{\rm CMB}$$



When applying this strategy to a lunar–orbit experiment ...

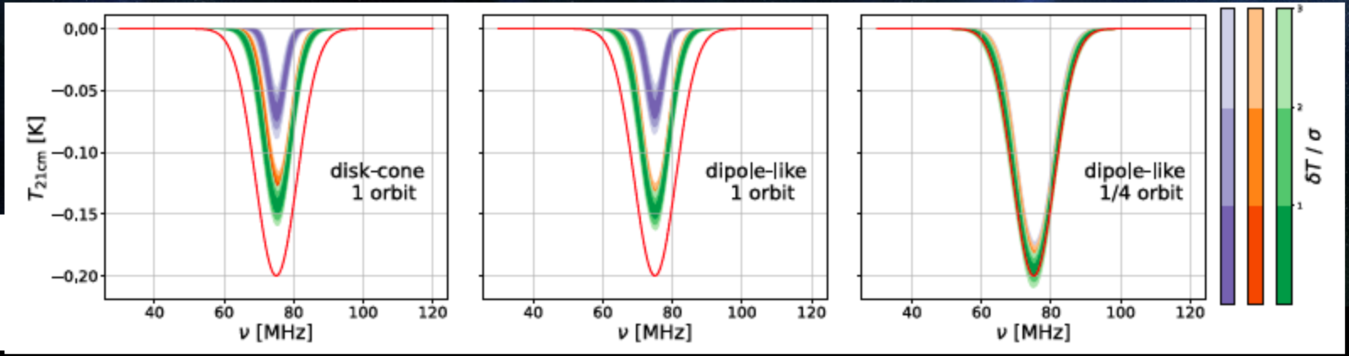






Fast moving satellite → Fast-varying sky

12 regions
15 regions
20 regions



Physics-motivated error modeling

Uncorrelated Modeling → Correlated Modeling

Uncorrelated Modeling

$$\ln \mathcal{L} = -\frac{1}{2}\sum_{i}^{N_t}\sum_{j}^{N_\nu}\left[\frac{T_{\rm model}(t_i, \nu_j) - T_{\rm mock}(t_i, \nu_j)}{\sigma_{\rm th}^{\rm eff}(t_i, \nu_j)}\right]^2$$

$$\sigma_{\rm th}^{\rm eff}(t_i, \nu_j) = \frac{\sigma_{\rm th}(t_i, \nu_j)}{\int B(t, \nu, \hat{\boldsymbol{n}})S(t, \hat{\boldsymbol{n}})d\hat{\boldsymbol{n}}}.$$

$$\boldsymbol{y} = (\boldsymbol{T}_{\rm model} - \boldsymbol{T}_{\rm mock})/\sigma_{\rm th}^{\rm eff}$$

$$\ln \mathcal{L} = -\frac{\boldsymbol{y}^T\boldsymbol{y}}{2}.$$

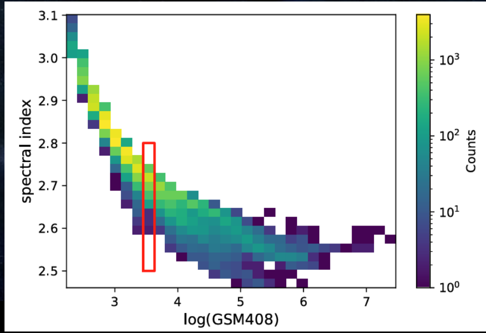
Correlated Modeling

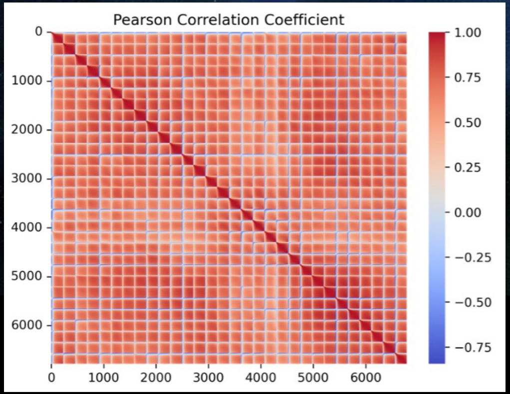
$$\ln \mathcal{L} = -\frac{\boldsymbol{y}^T(\boldsymbol{C}_{\rm model} + \boldsymbol{C}_{\rm th})^{-1}\boldsymbol{y}}{2},$$

$$\boldsymbol{C}_{\rm model} = \frac{\boldsymbol{R}^T \times \boldsymbol{R}}{1000},$$

Model errors:

- ➢ Inhomogeneous spectral index in sky regions;
- ➢ Correlation in residuals between data points at diff. t and at diff. υ;
- ➢ Correlation between T_{sky} and spectral index.

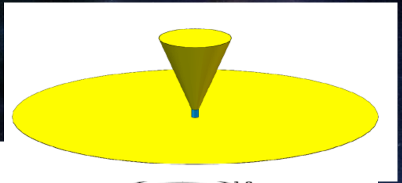


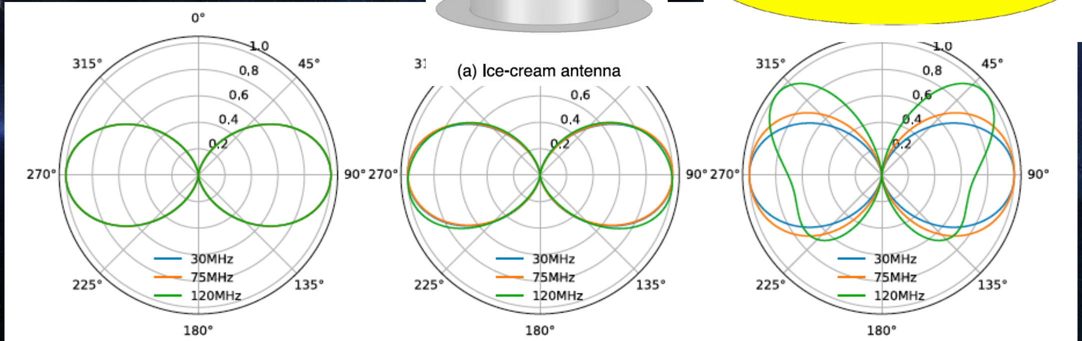


*Li, Deng, Zhou, **YX**, Chen, 2026, ApJ, 997, 4 (arXiv:2507.13102)*

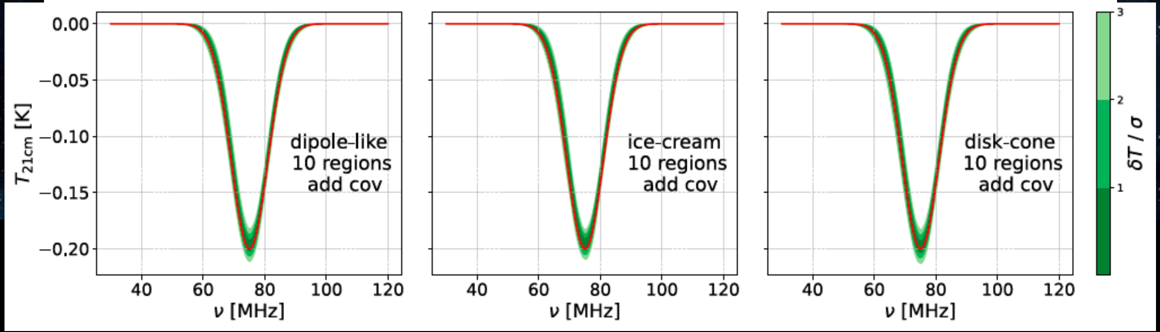
Unbiased extraction of 21cm signal with correlated error modeling

Ideal dipole





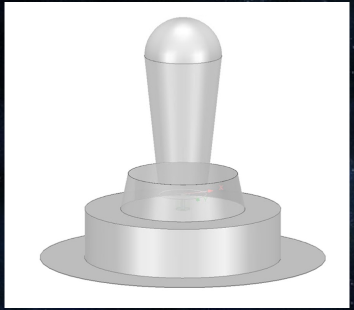
(a) Dipole-like antenna (b) Ice-cream antenna (c) Chromatic disk-cone antenna

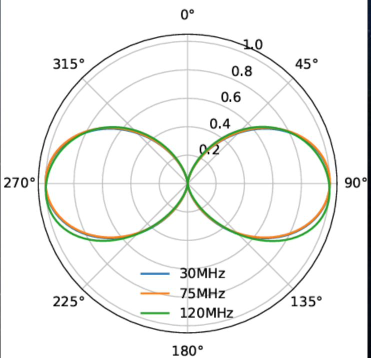


Unbiased extraction even for a testing antenna with a relatively high level of chromaticity, given that the beam can be measured precisely.

Li et al., 2026 (arXiv:2507.13102)

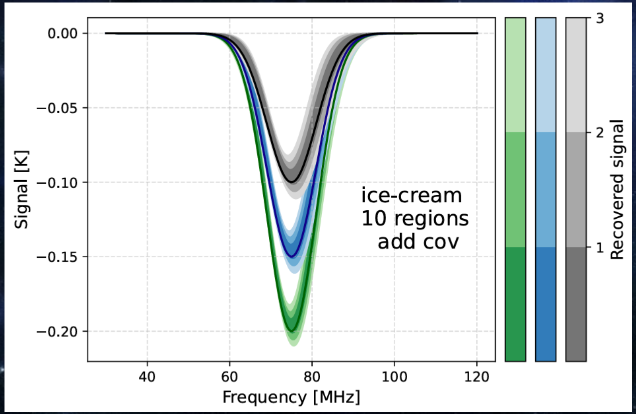
Unbiased extraction of 21cm signal with correlated error modeling



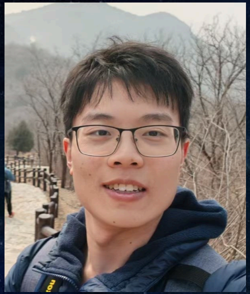


(b) Ice-cream antenna

21 cm signals of various amplitudes



- Robust against moderate beam chromaticity, significantly relaxes the stringent design and manufacturing requirements for the antenna



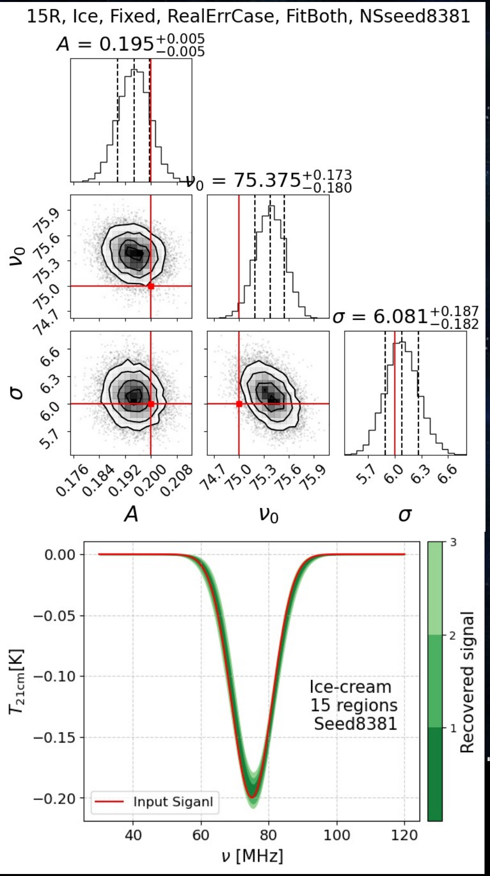
Haoran Li 李浩然

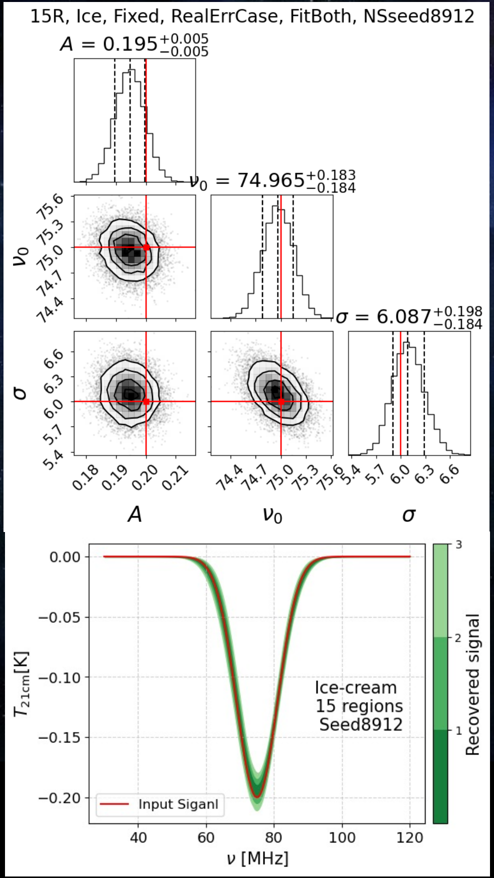
Furen Deng 邓辅仁

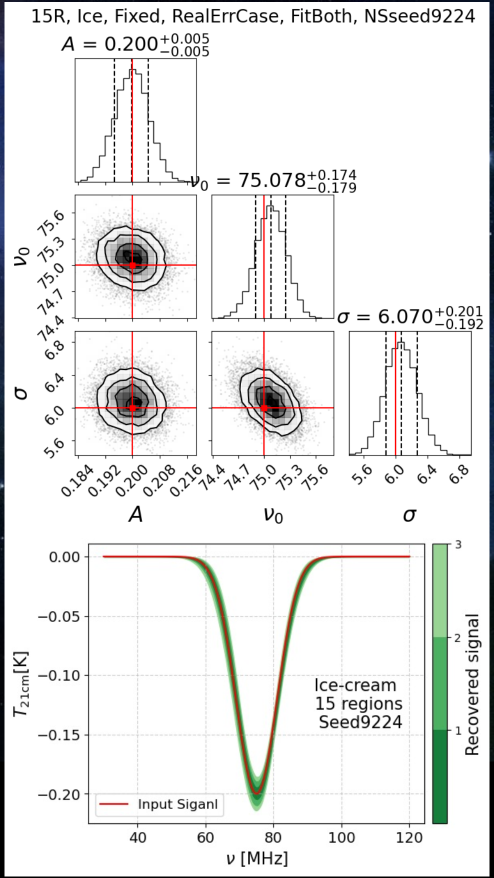
Provided that ** The beam can be measured precisely;
** Foreground basemap is know exactly.

Li et al., 2026 (arXiv:2507.13102)

Preliminary tests with foreground basemap errors (~ 15% T_{sky})







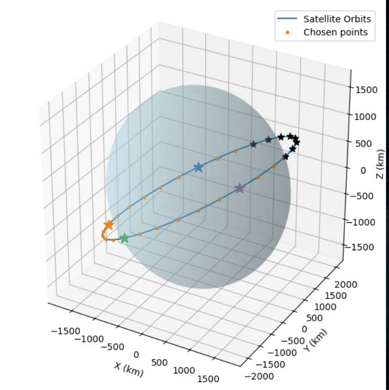

NAOC
中国科学院国家天文台
NATIONAL ASTRONOMICAL OBSERVATORIES, CAS
Thank you!

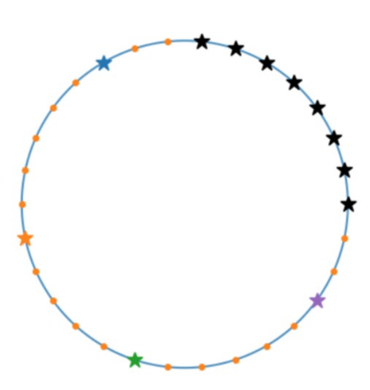
$$T_{\text{mock}}(t,\nu) = \frac{1}{\int B(t,\nu,\hat{\boldsymbol{n}})S(t,\hat{\boldsymbol{n}})d\Omega} \times \left\{T_{\text{th}}(t,\nu) + \int B(t,\nu,\hat{\boldsymbol{n}})S(t,\hat{\boldsymbol{n}})\left[T_{\text{sky}}(\nu,\hat{\boldsymbol{n}}) + T_{21\text{cm}}(\nu)\right]d\Omega\right\},$$

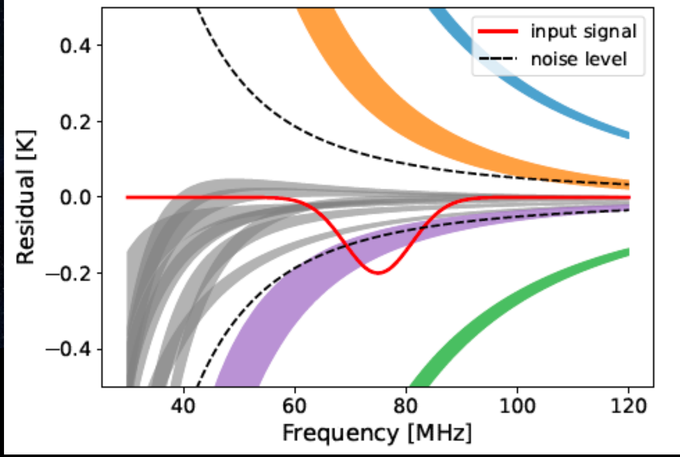
$$T_{\text{model}}(t,\nu) = \sum_{p}^{N_r} K_p(t,\nu)\left(\frac{\nu}{408}\right)^{-\beta_p} + T_{\text{CMB}} + T_{21\text{ cm}}(\nu),$$

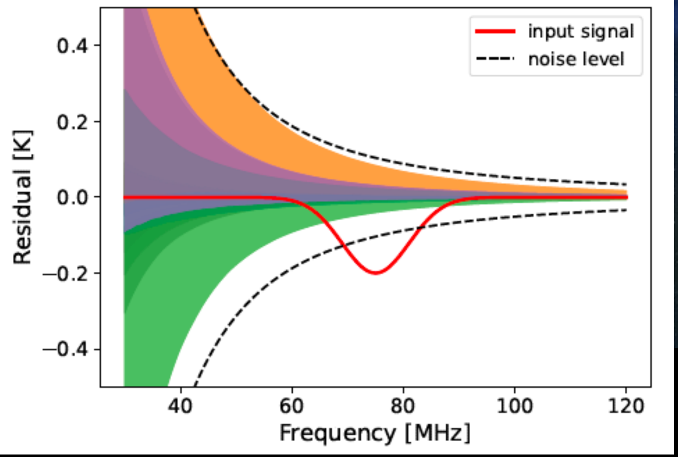
$$K_p(t,\nu) = \frac{1}{\int B(t,\nu,\hat{\boldsymbol{n}})S(t,\hat{\boldsymbol{n}})d\Omega} \times \int B(t,\nu,\hat{\boldsymbol{n}})S(t,\hat{\boldsymbol{n}})M_p(\hat{\boldsymbol{n}}) \times [T_{408}(\hat{\boldsymbol{n}}) - T_{\text{CMB}}]d\Omega.$$

Origin of the Fake Unbiasedness by Observations within a Quarter Orbit









Covariance with basemap errors

In 2000 times realizations:

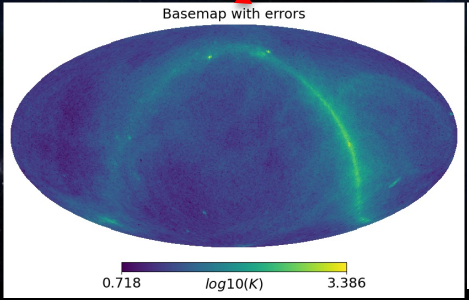
Res_i = $Mock_i$ - $Model_i$

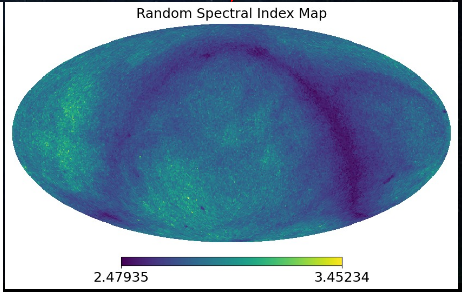
i: i-th realization

Mock

$$\int Beam\ Shade \ * T_{sky,i}\ d\Omega$$

$$T_{sky,i}(\Omega) = A_{\rm err}(\Omega) * \left(\frac{\nu}{\nu_c}\right)^{-\beta_i(\Omega)}$$





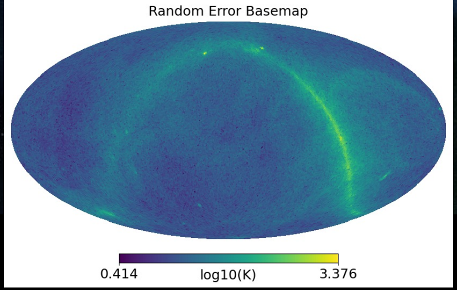
Model

Fit the mean spectra for $T_{sky,i}(\Omega)$

$$T_{\rm model}(t,\nu) = \sum_{p}^{N_r} K_p(t,\nu)\left(\frac{\nu}{408}\right)^{-\beta_p} + T_{\rm CMB} + T_{\rm 21cm}(\nu)\,, \quad (4)$$

where

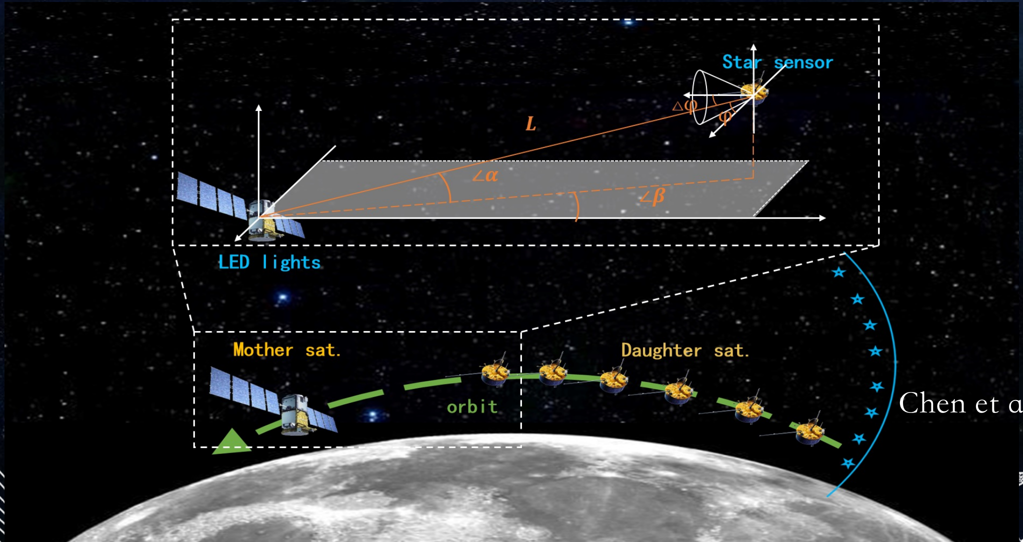
$$K_p(t,\nu) = \frac{1}{\int B(t,\nu,\hat{\boldsymbol{n}})S(t,\hat{\boldsymbol{n}})d\Omega} \times \int B(t,\nu,\hat{\boldsymbol{n}})S(t,\hat{\boldsymbol{n}})M_p(\hat{\boldsymbol{n}})[T_{408}(\hat{\boldsymbol{n}}) - T_{\rm CMB}]d\Omega\,. \quad (5)$$



使用随机实现的带误差的408天图

Interferometer Array Realization

- No need for high precision adjustment of satellite positions, but do need high precision of relative position measurement
- Synchronization, Distance Measurement (1 m), Data Communication: microwave link between mother and daughter satellites
- Angular position: mother satellite carrying blinking LED lamp, daughter satellites use star sensor to determine position (1 m)



Chen et al., arXiv:2007.15794