21cm cosmology workshop and Tianlai Collaboration Meeting 2024

Low Frequency Astronomy from the Moon

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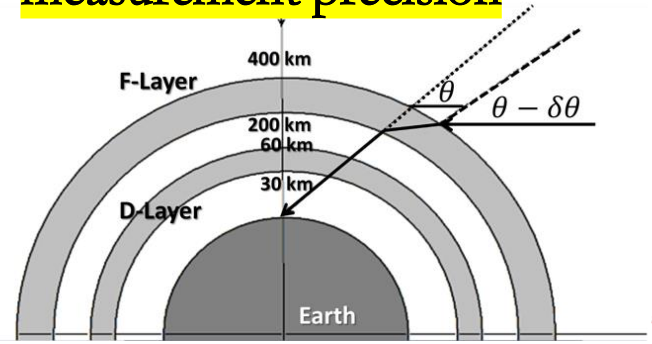
National Astronomical Observatories,
Chinese Academy of Sciences

Hangzhou, 2024.07.22

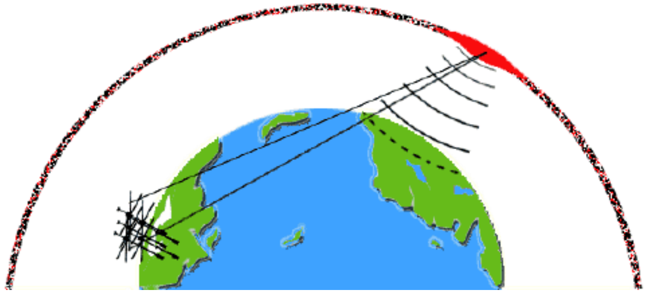
Difficulties of low frequency Ground Observation

Refraction and Absorption affects measurement precision

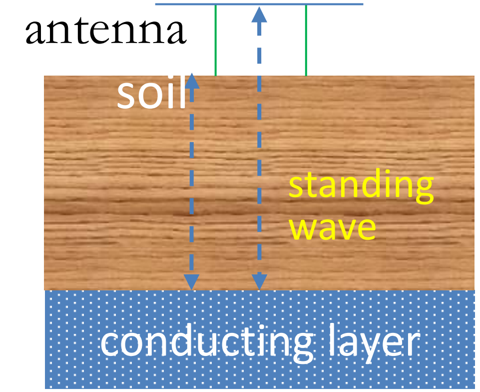


Vedantham & Koopermans (2015）,
Shen et al. (2021)

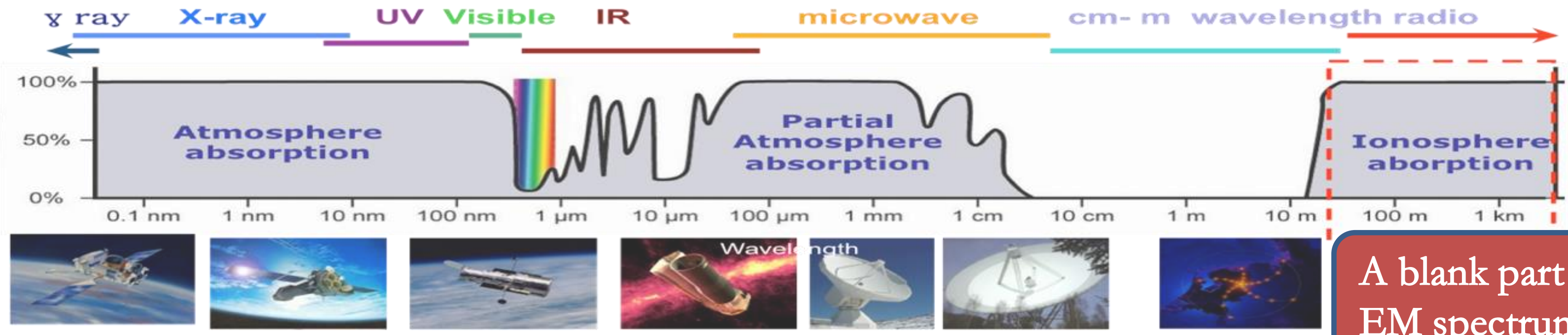
Reflection of RFI



Ground Reflection may generate false signal



Bradley et al. (2019)

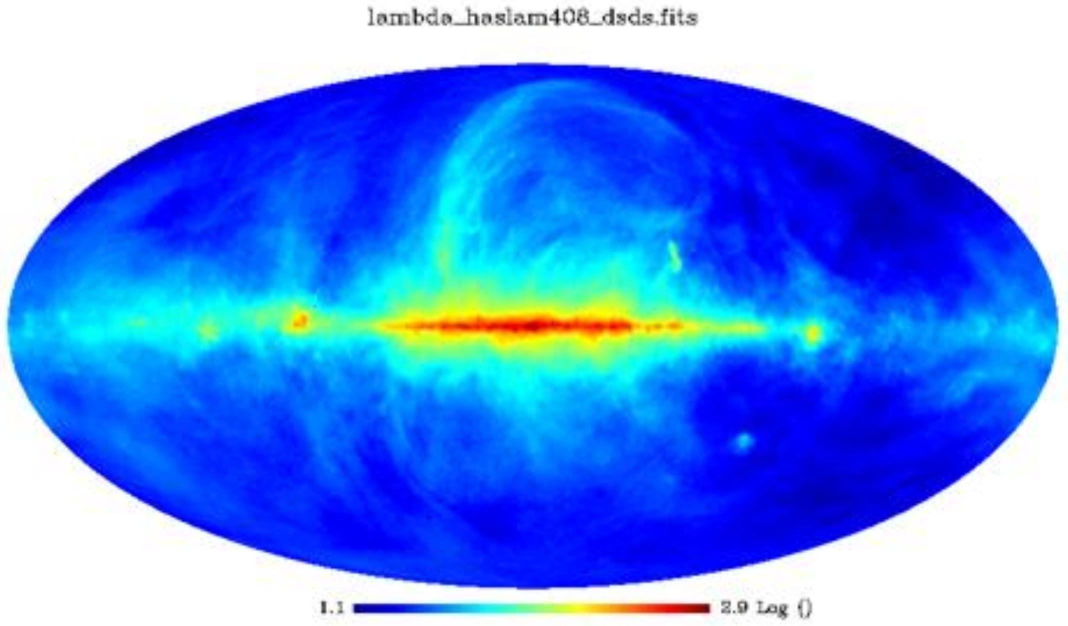


A blank part of EM spectrum

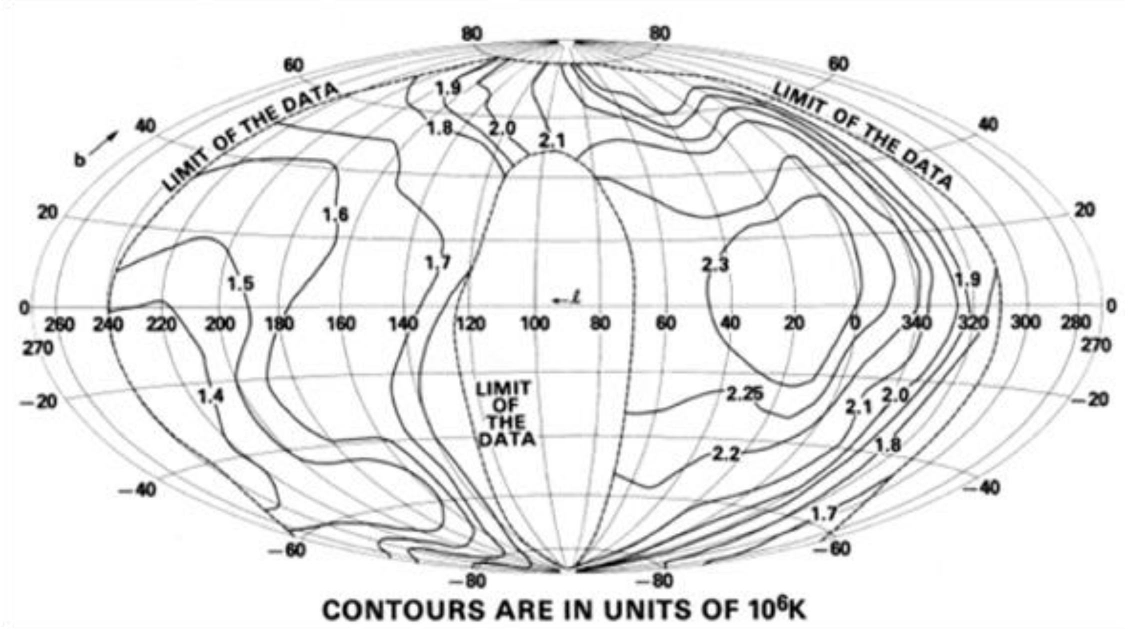
Space--avoid the ionosphere, RFI, ground reflection, and open up the last EM window

Low Frequency Radio – the last blank in EM spectrum

Due to ionosphere absorption, the sky below 30MHz is still largely unknown.
Compared with other frequencies, the map at this band is very crude

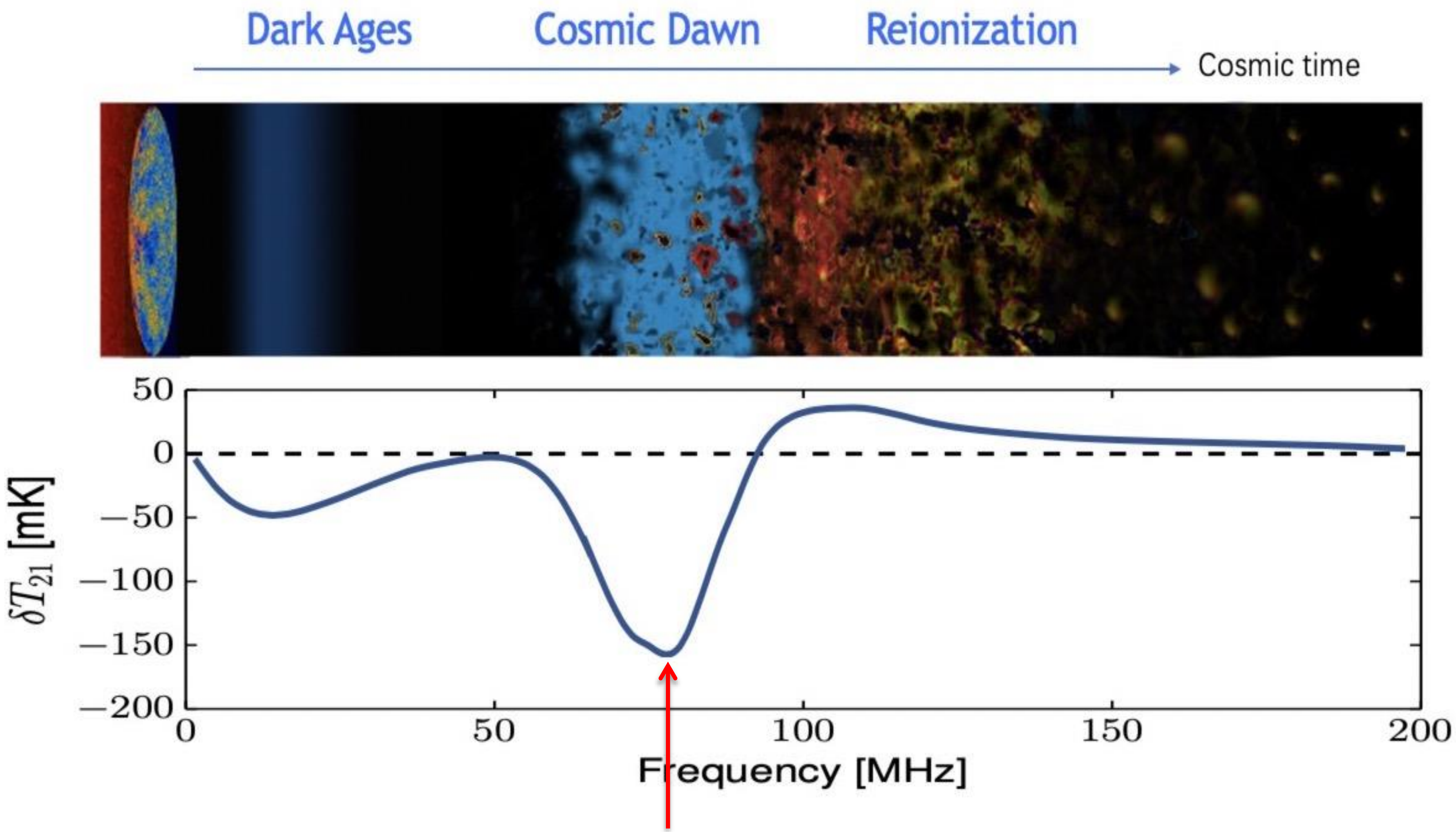


Haslam Map (408 MHz)



RAE-2 map (4.7 MHz)

The Light in the Dark Ages—21cm line

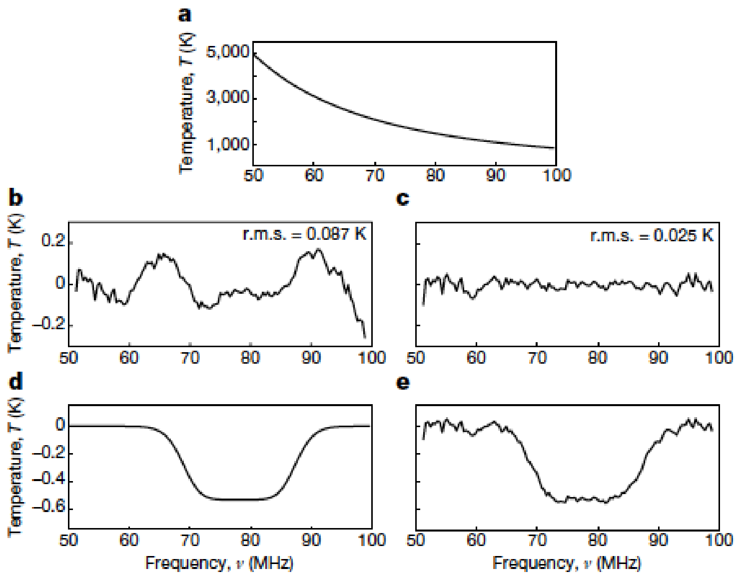


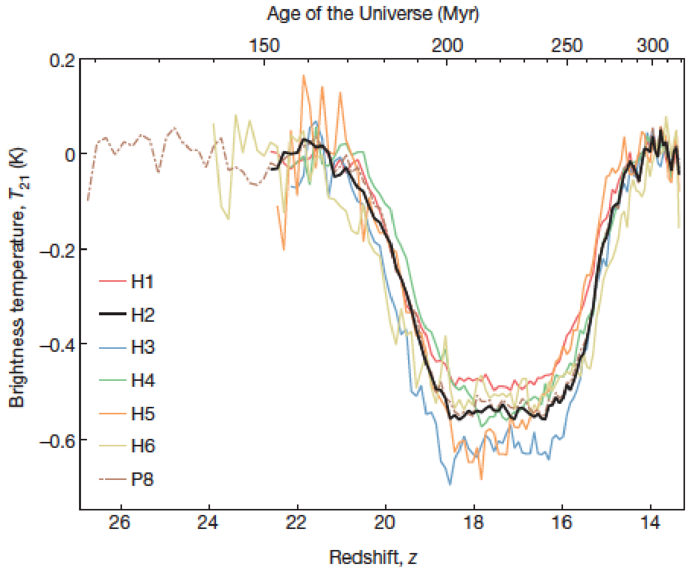
Cosmic Dawn signal
(XC& J. Miralda-Escude 2004, 2008)

EDGES vs. SARAS Results

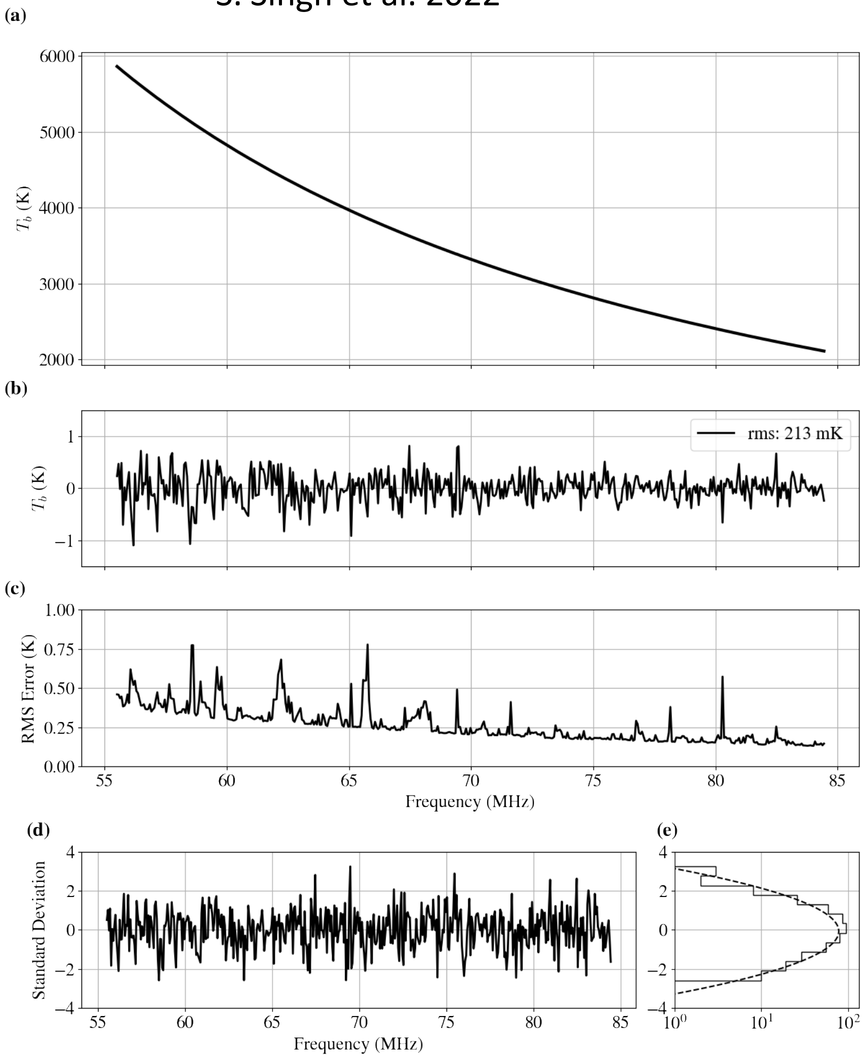
J. Bowman et al. 2018

see the talks in the global spectrum session

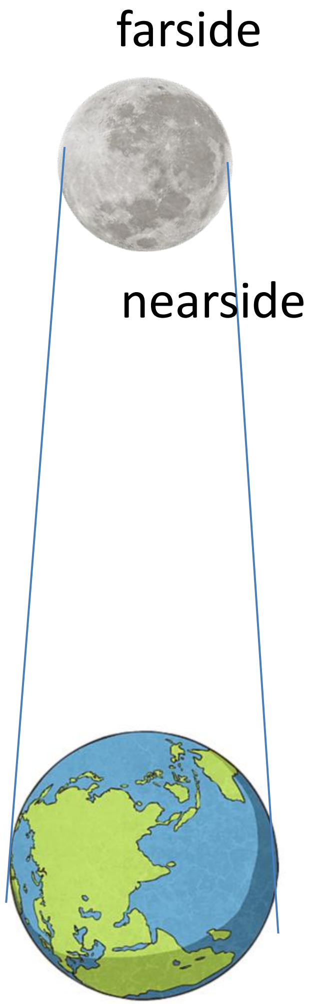


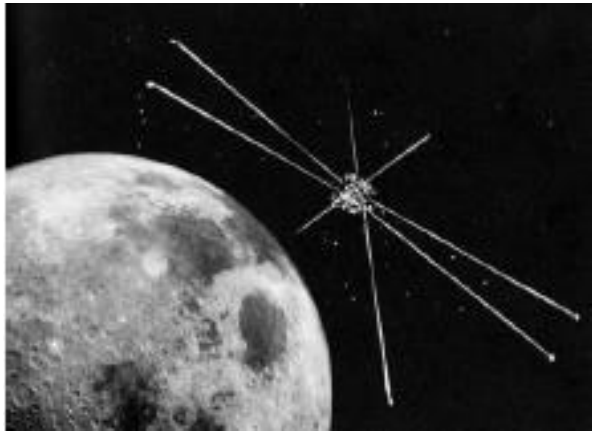


S. Singh et al. 2022

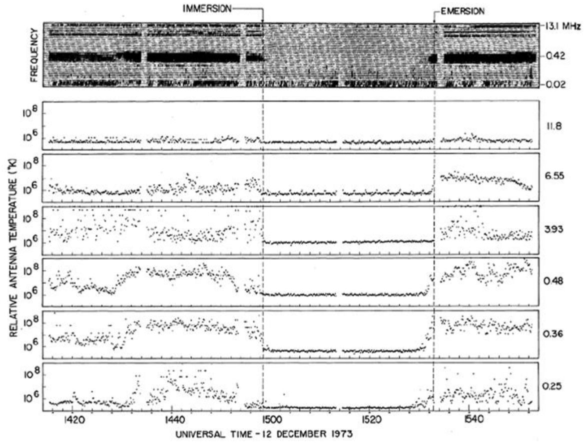


The Moon can shield RFI and provide ideal site

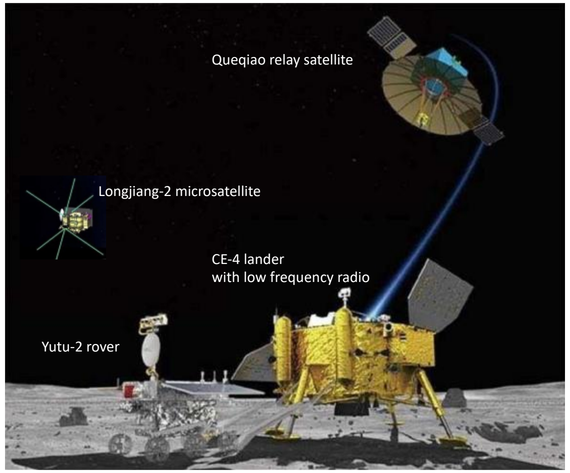




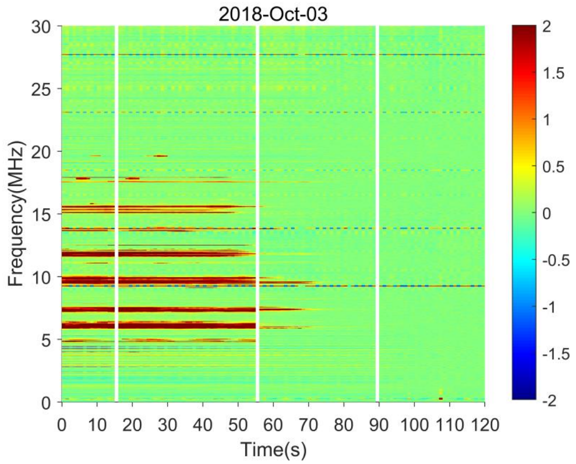
RAE-2 satellite



RAE-2 spectrum



low frequency radio experiments during Chang’e-4 mission



Longjiang-2 spectrum

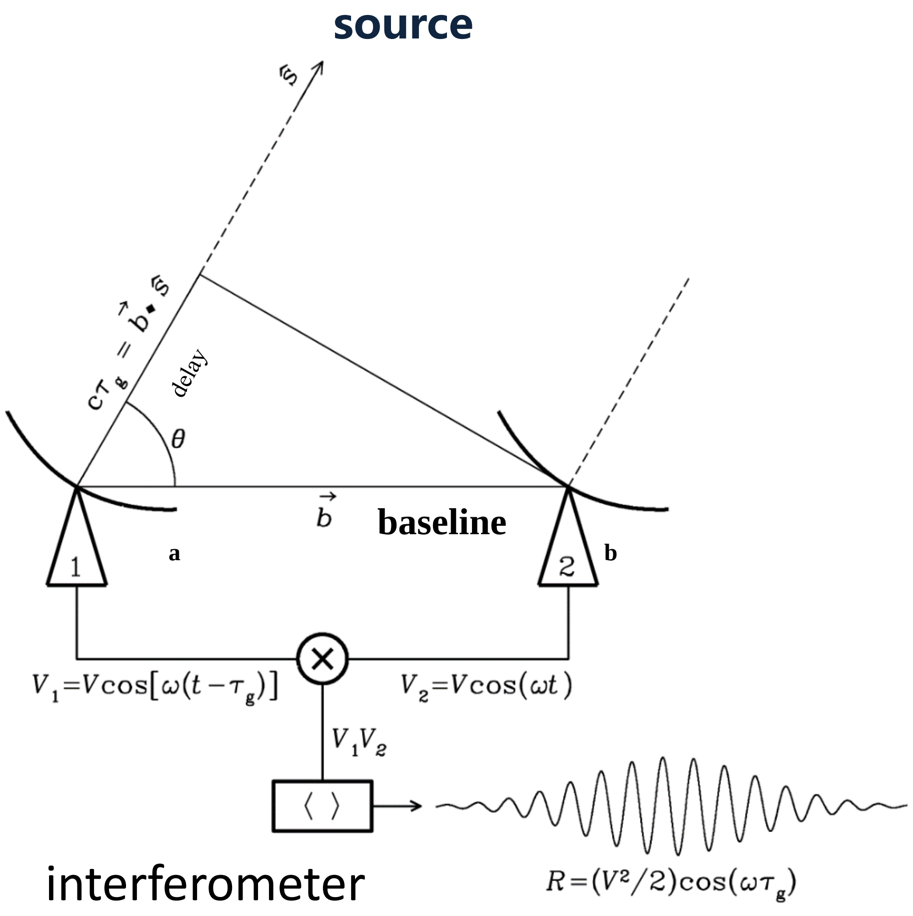
Low frequeny needs Interferometer

For the wavelength (10m~300m) of our interest, it is impractical to achieve good angular resolution with single antenna.

$$\theta : \frac{\lambda}{\mathrm{D}}$$

- **Interferometer produce cross-correlations (visibilities) of electrical signal at different space points, roughly corresponding to Fourier components of sky intensity**

$$V_{ij} = \int A_{ij}(\hat{k})T(\hat{k})\ e^{-i\vec{k}\cdot\vec{r}_{ij}}\, d^2\hat{k},$$



interferometer

array uvw coverage

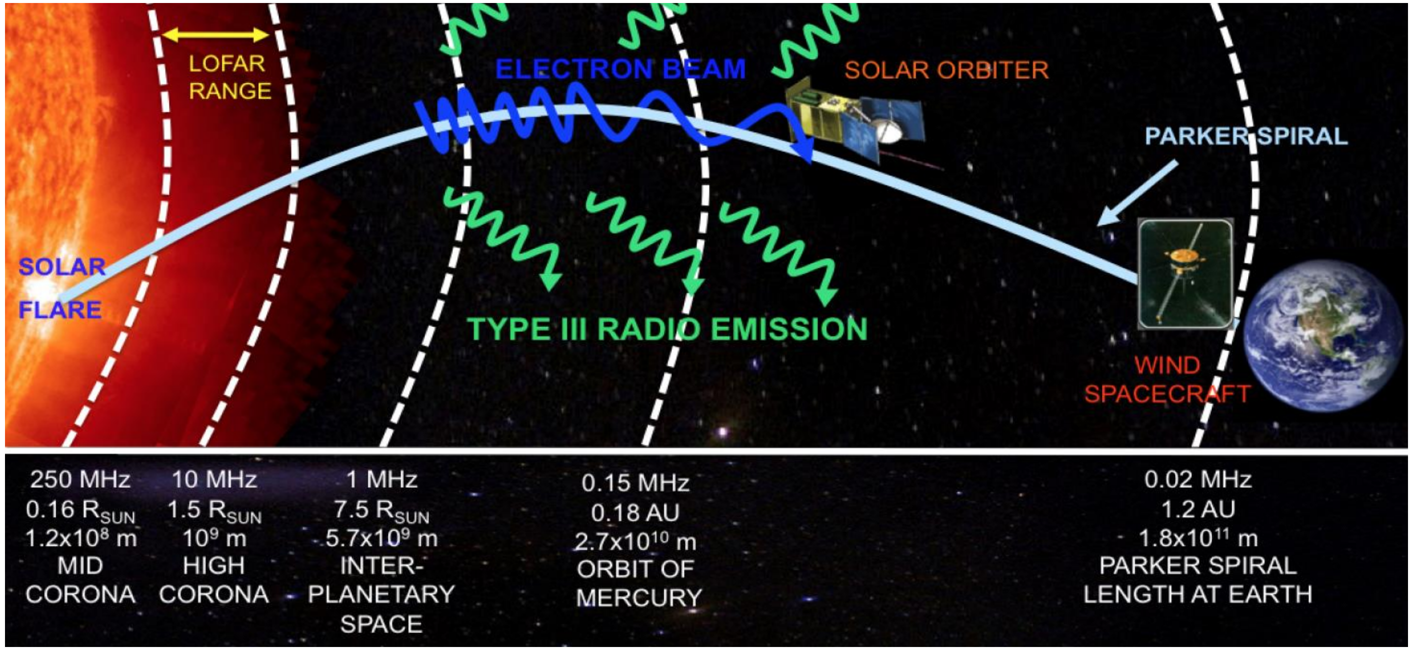
visibility

sampling in spatial frequency

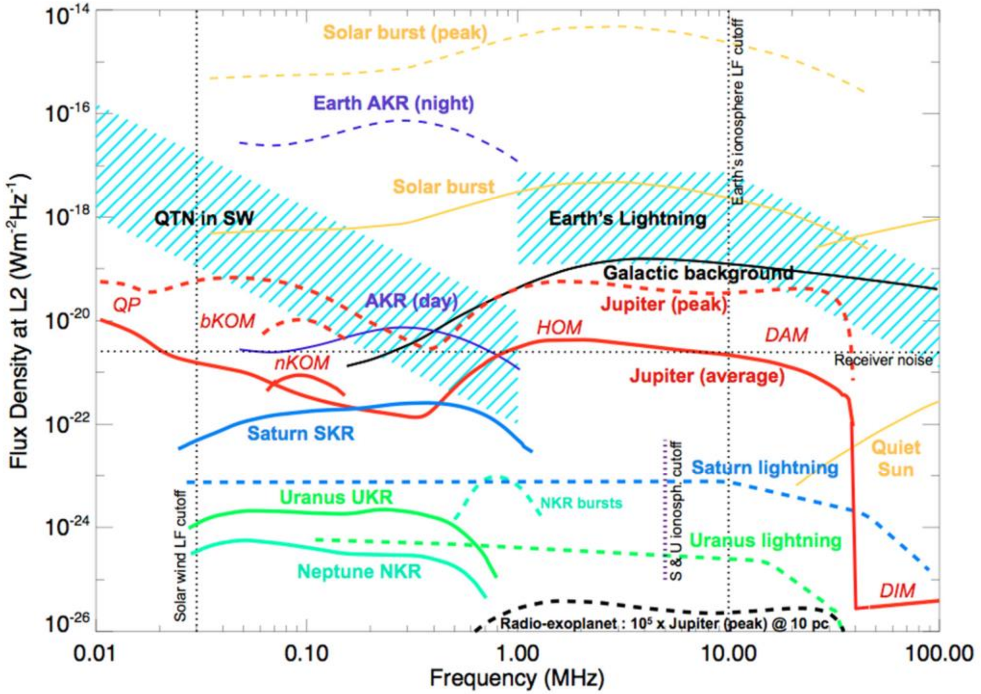
Image

Science Case for low-frequency: Observing the Sun and Planets

- Lower frequency observation traces solar burst emission at larger distance from the Sun
- low frequency emission from giant planets reveal magnetospheric dynamics, solar wind - magnetosphere coupling, and electrodynamic coupling of the magnetosphere with planet’s moons.
- A number of spacecrafts carried low frequency detectors

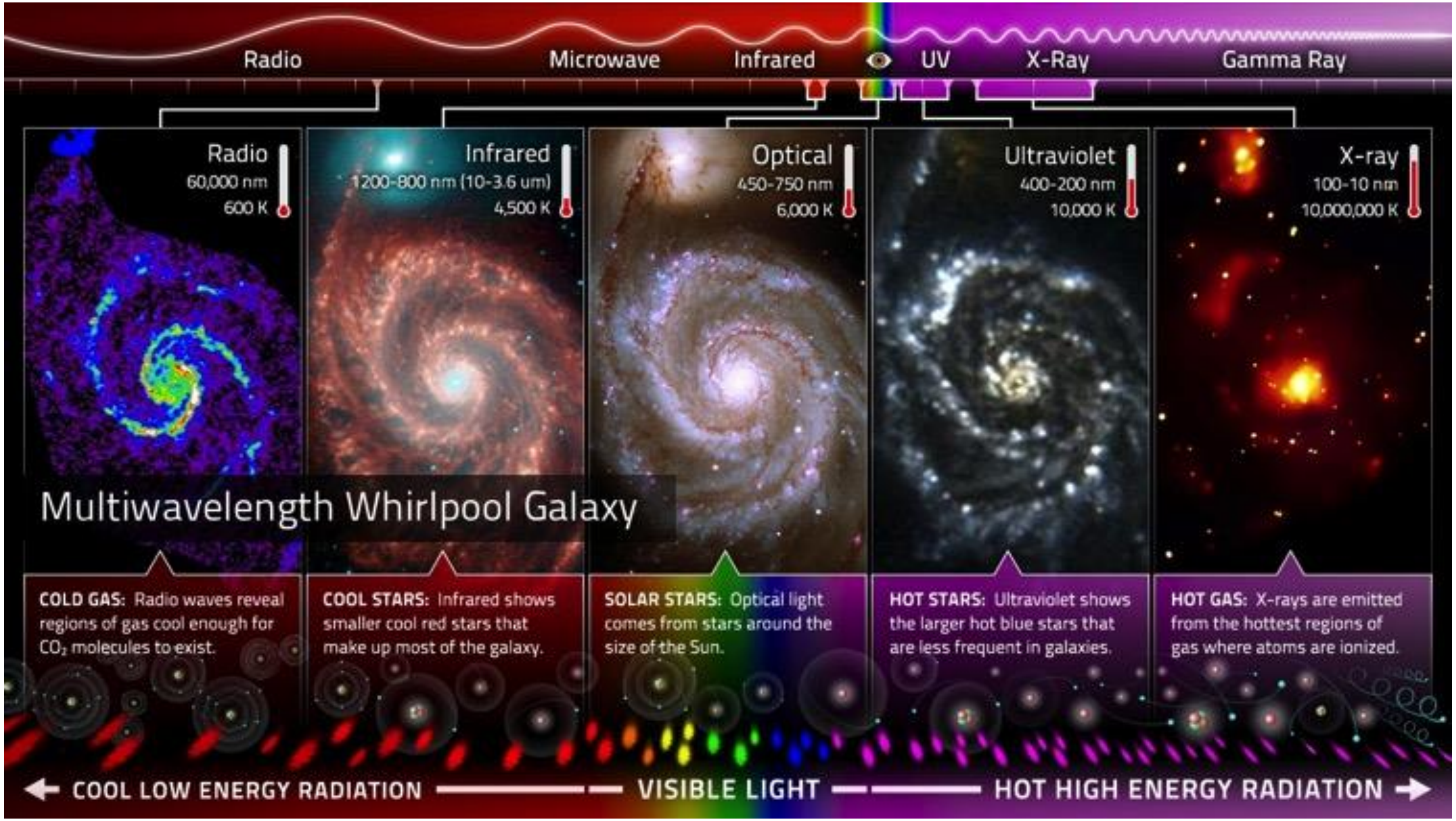


H.A.S. Reid (2015)



Mimoun et al.(2012)

Science Case: Open Up A New Observational Window



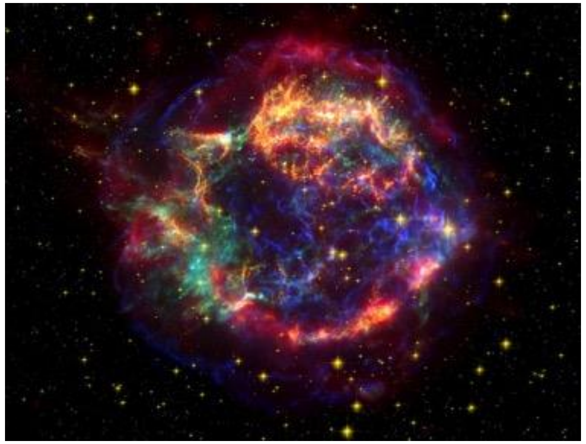
COLD GAS: Radio waves reveal regions of gas cool enough for CO_2 molecules to exist.

COOL STARS: Infrared shows smaller cool red stars that make up most of the galaxy.

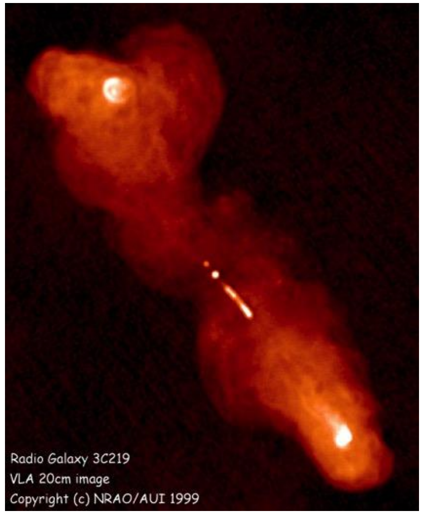
SOLAR STARS: Optical light comes from stars around the size of the Sun.

HOT STARS: Ultraviolet shows the larger hot blue stars that are less frequent in galaxies.

HOT GAS: X-rays are emitted from the hottest regions of gas where atoms are ionized.



supernova remnants



Radio Galaxy 3C219
VLA 20cm image
Copyright (c) NRAO/AUI 1999

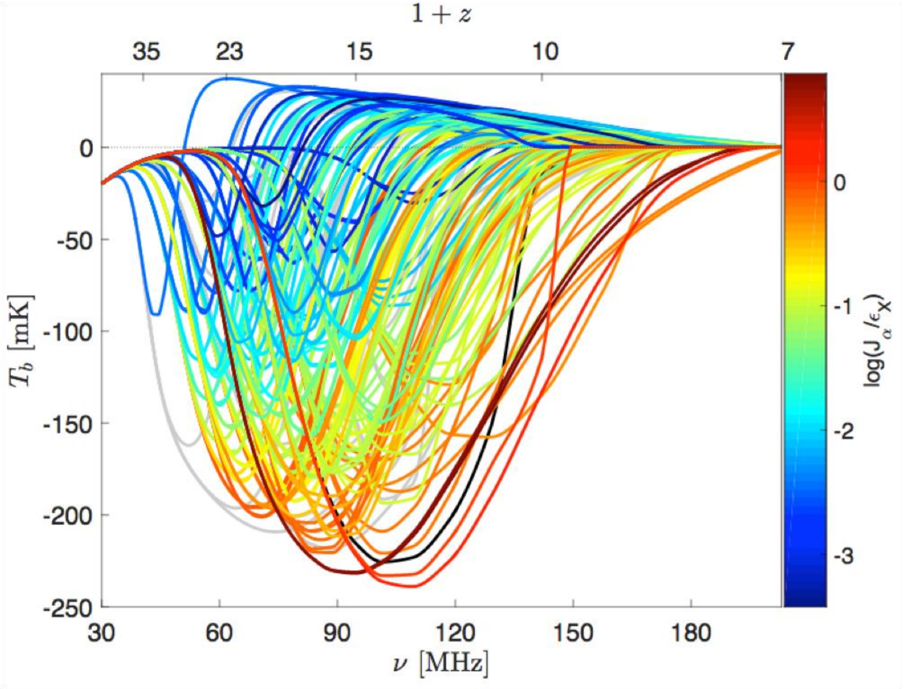
radio galaxies

What new objects will we see in the ultralong wavelength? What secret of the Nature will this observation reveal?

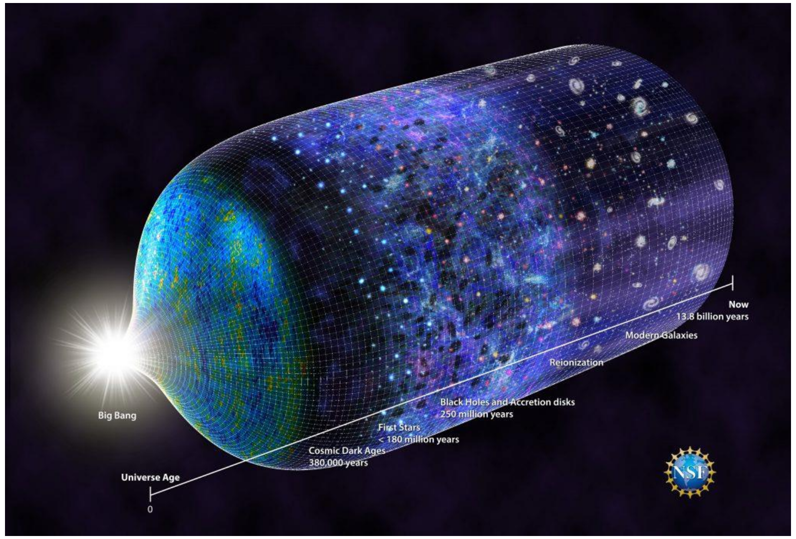
Science Case of low frequency: Dark ages and Cosmic Dawn

- The 21cm global specrtrum could be measured with single antenna and probe cosmic dawn and dark ages

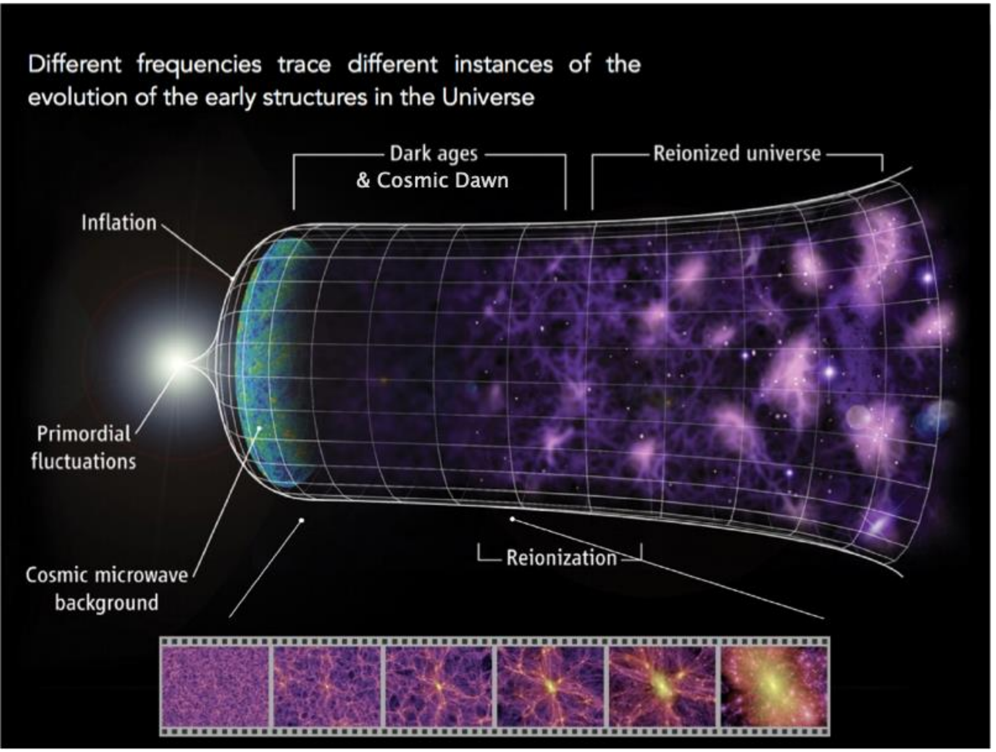
- In a lunar orbit global spectrum, ionosphere & external RFI can all be avoided, and ground reflection will not producing features at the relevant delay space



Cohen et al. (2018)



Lunar-based Ultralong wavelength Astronomy


Different frequencies trace different instances of the evolution of the early structures in the Universe

Observing 21cm fluctuations in the dark age requires extremely high sensitivity and large receiving area. Before that is realized, we need to first observe the 21cm global spectrum, and make some less demanding astronomical observations at ultralong wavelength.

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

Low Frequency Radio—Project Ideas

Lunar Orbit:

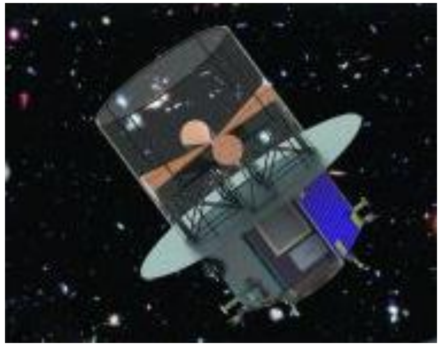
Engineeringly simpler, no need to land, and can use solar power

- single satellite: Dare/Dapper (USA), Pratush/SEAM (India), CosmoCube (UK)
- satellite array: DSL (China), MOIRE (Europe)

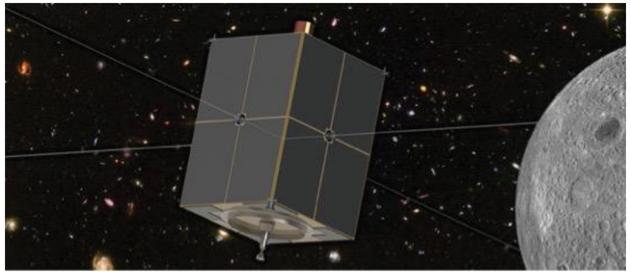
Lunar Surface:

Engineeringly more complex, but have stable platform

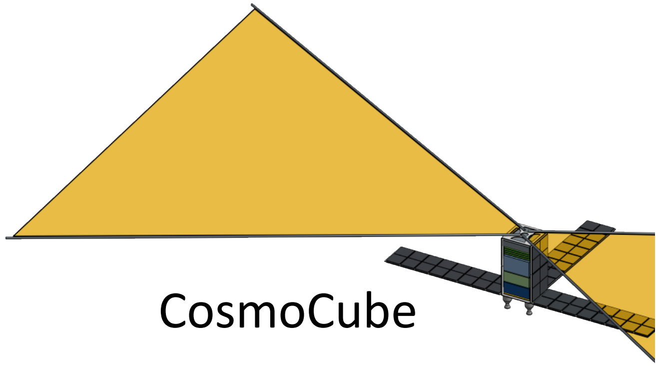
- small scale experiment: LuSee (USA)
- Farside: ALO (Europe), FARSIDE/FARVIEW (Europe), LARAF (China), LCRT (USA)



DARE



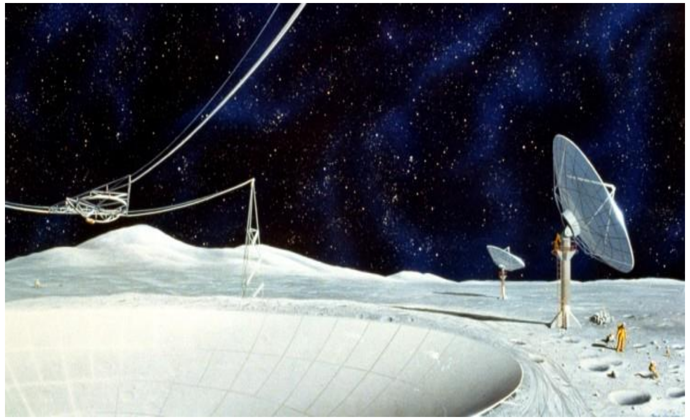
DAPPER



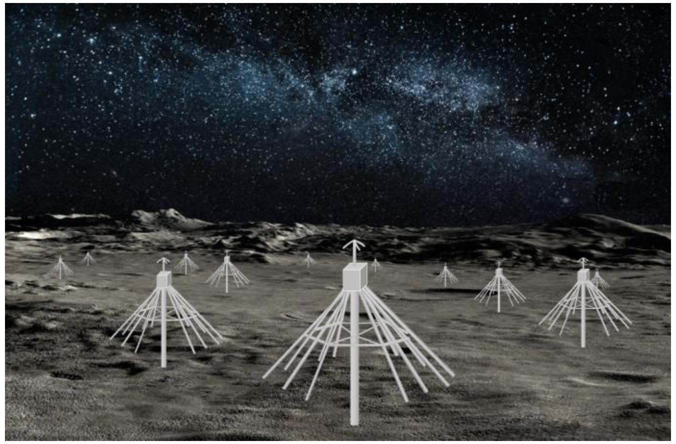
CosmoCube

Low Frequency Radio--antennas

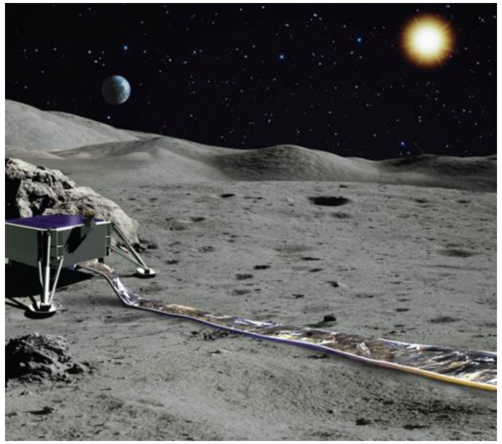
To minimize the weight to be carried, may need new antenna designs



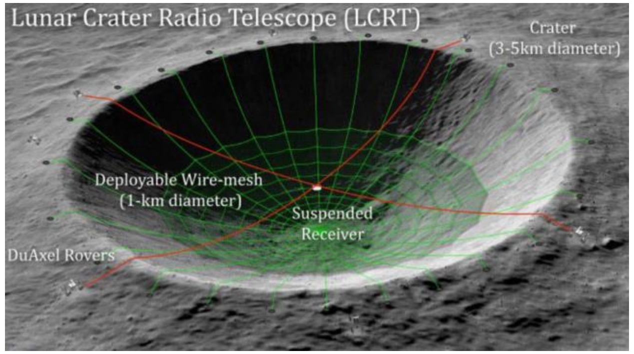
dish antenna (all frequencies)



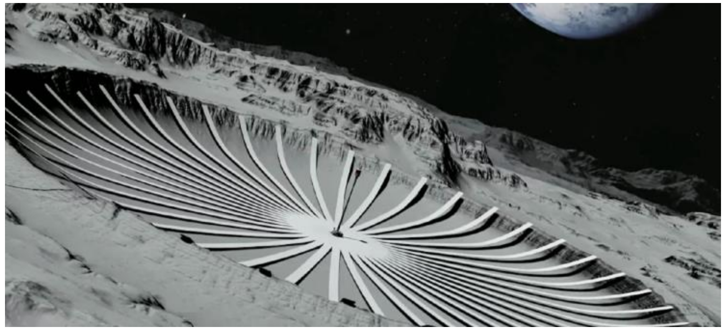
dipole antenna (low frequency)



membrane antenna
(lunar low frequency)



S. Bandyopadhya (2021)

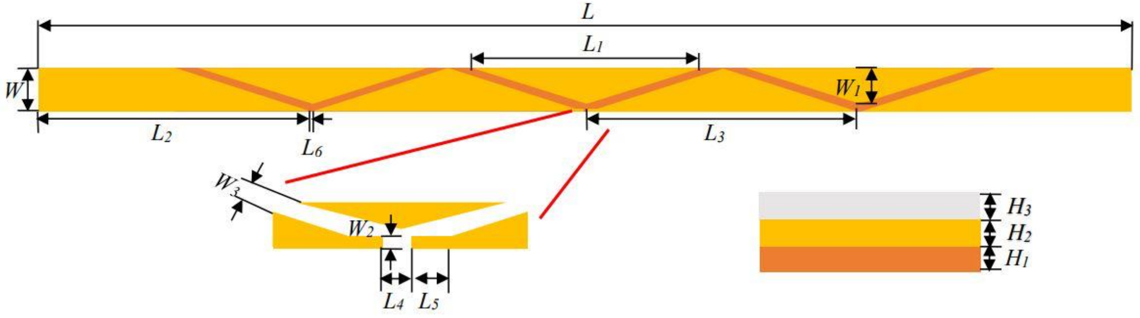


Prof. Huilong Zheng (private communication)

Maybe even antenna manufactured *in site* (e.g. FarView project, Polidan et al. 2024)

But: the membrane antenna remains to be tested

a piece of polyimide-based membrane test sample on ground



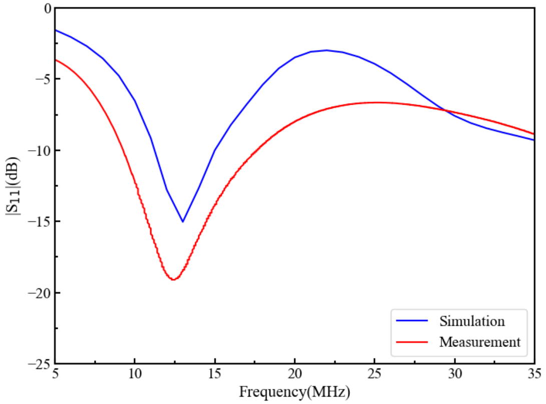
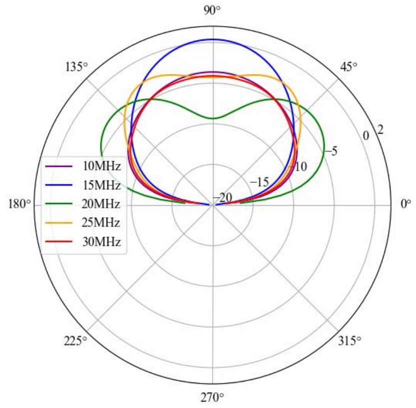
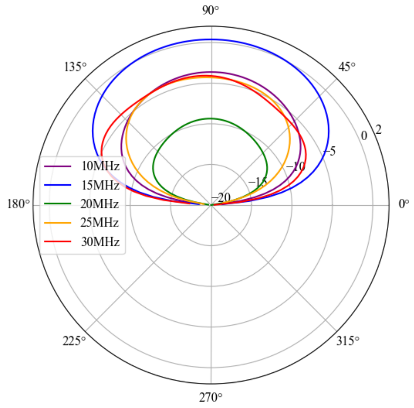


Fig. 10: The measured $|S_{11}|$ on the ground



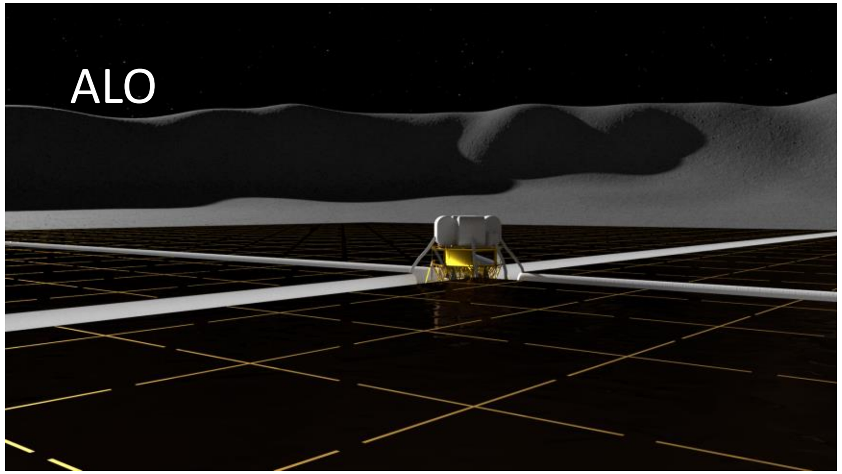
E-plane

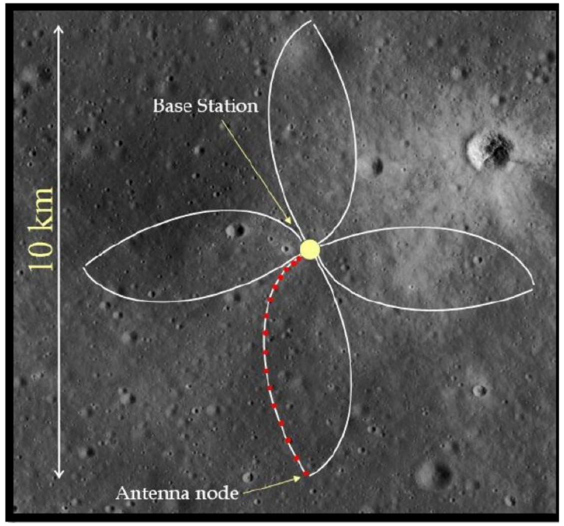


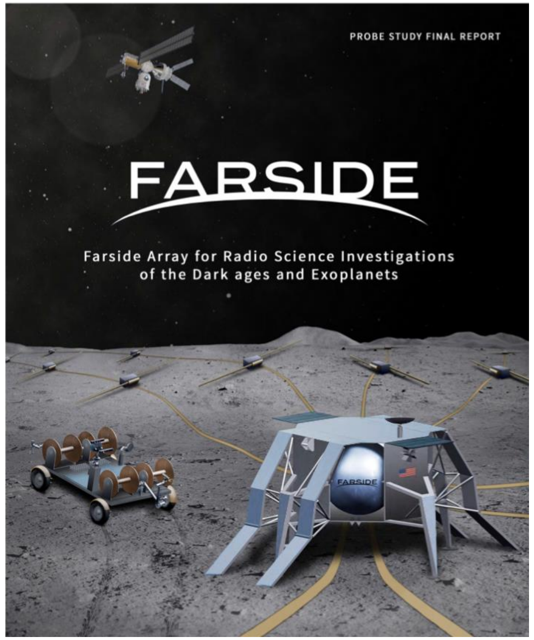
H-plane

Suonanben et al. 2024, to appear on ATI

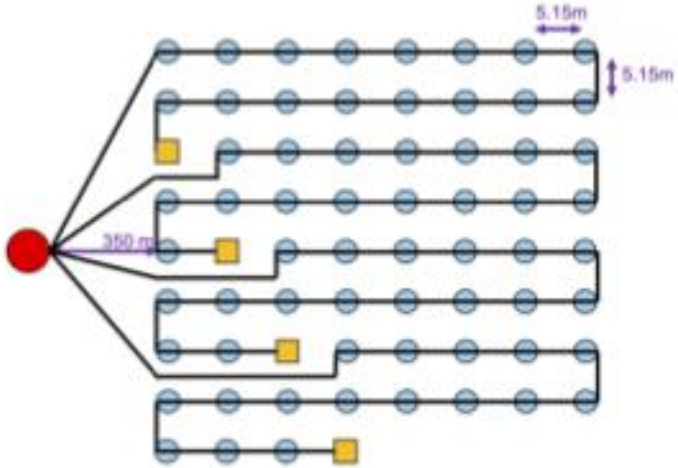
Lunar Surface Arrays



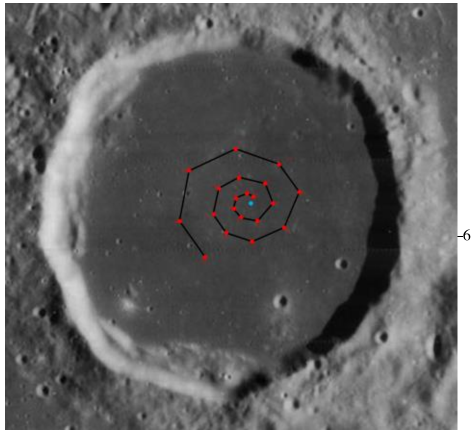


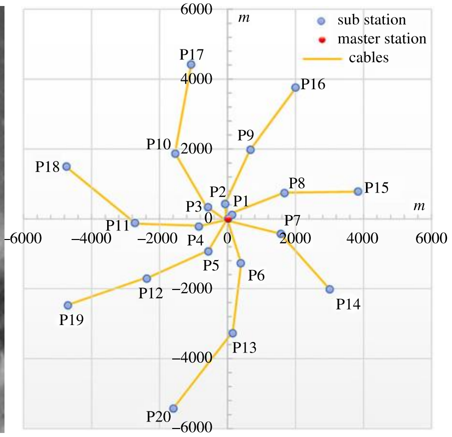


J. O. Burns et al. (2023)



M. Klein-Woit (2023)

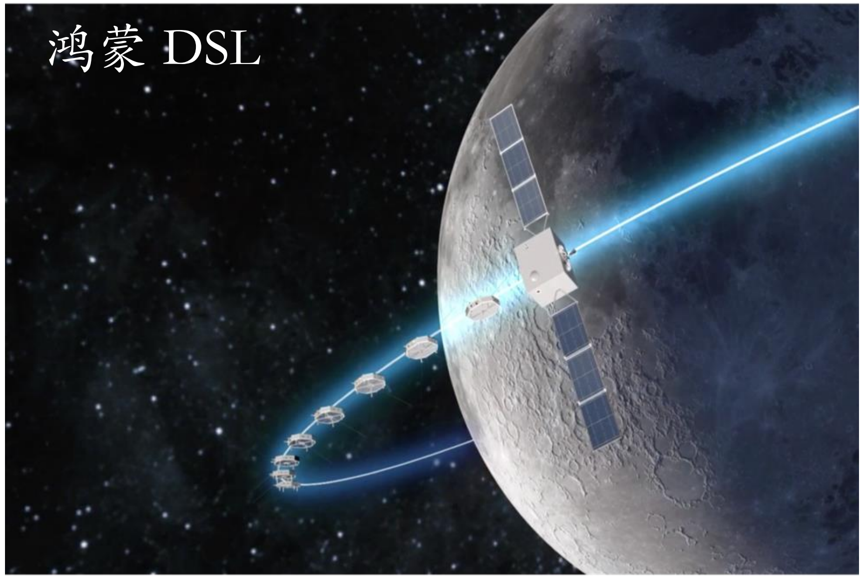




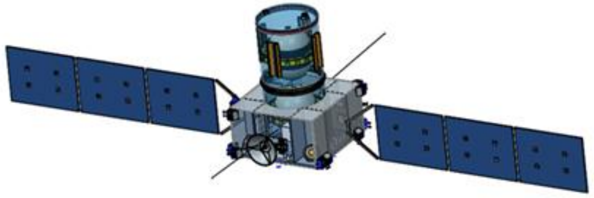
LARAF (Chen et al. 2023)

lunar orbit array (DSL--Hongmeng)

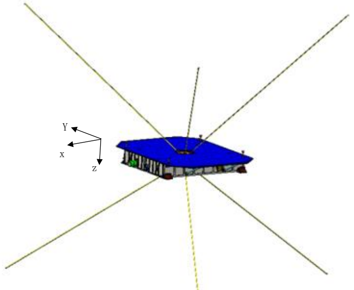
- lunar satellite: engineeringly simpler, no need for landing & deployment
- Lunar orbit period is about 2 hours, can use solar power
- Observe in the far side of the Moon, and transmit data back in the front side
- Launched by one rocket, all flying on the same orbit, easy to maintain and communicate



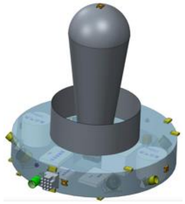
DSL:
1 mother satellite (communication & data processing)
+ 8 daughter satellite (0.1-30 MHz interferometry & global spectrum)
+ 1 daughter satellite (30-120 MHz global spectrum)



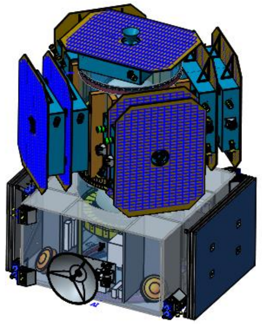
mother satellite



8 x low freq. daughter

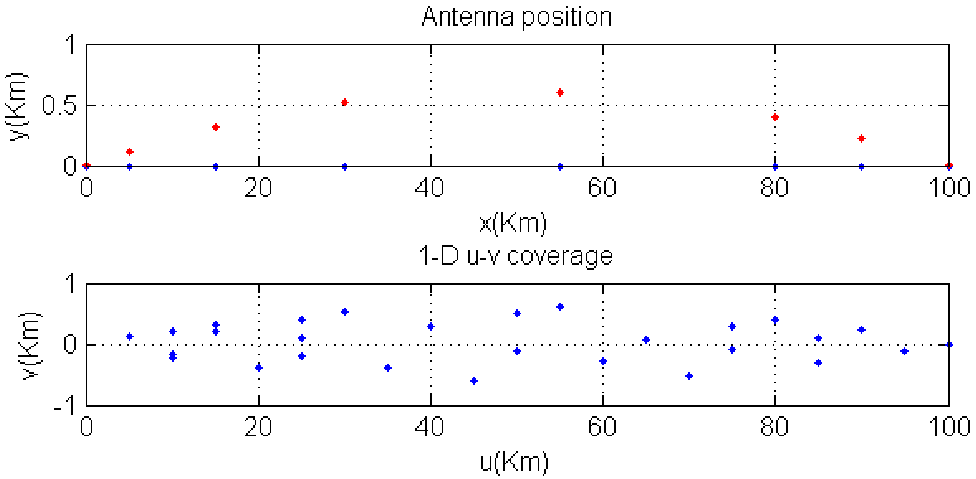


1 x high freq. daughter



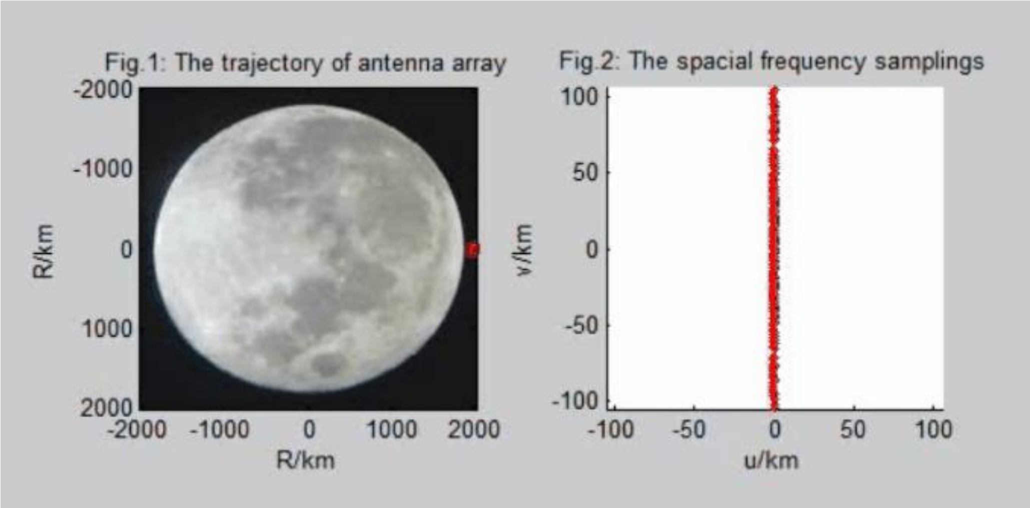
mother-daughter combo at launch

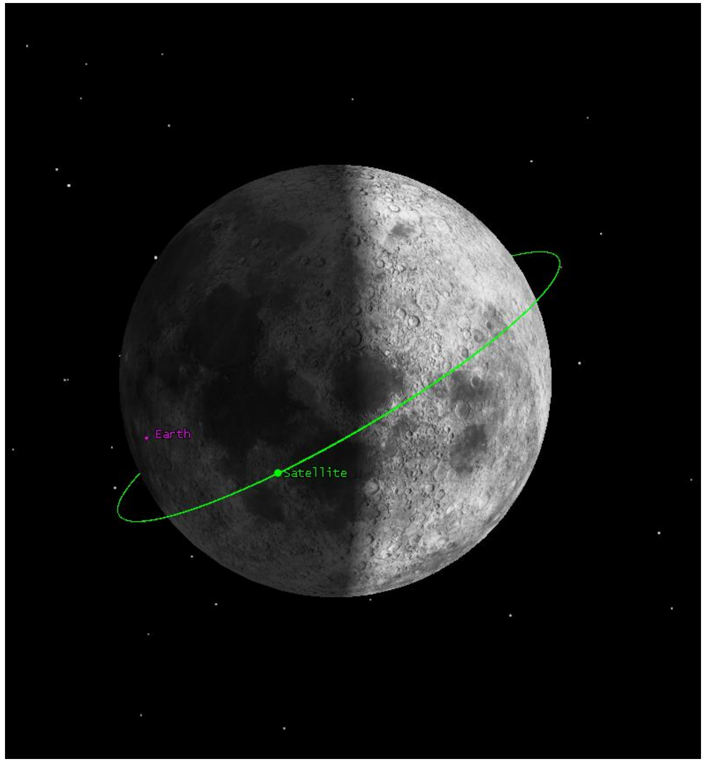
Collecting Baselines



instantaneous position & baseline for 8 units

one orbit cycle



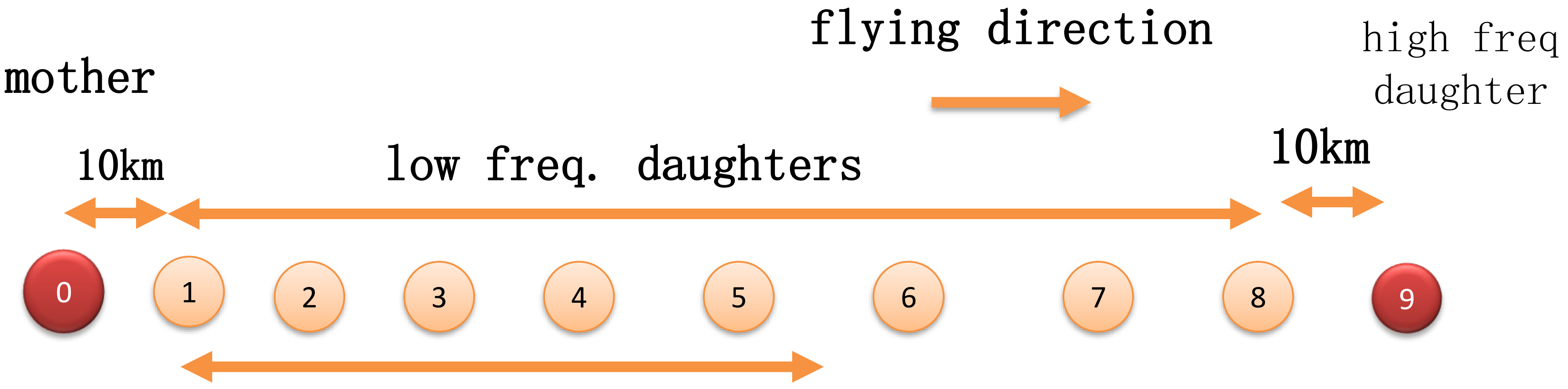


orbital plane precession

300km altitude, 30 degree inclination is chosen

Improving baseline distribution: breathing motion

to improve uvw coverage:



initial position S1 S2 S3 S4 S5 S6 S7 S8

compress S1 S2 S3 S4 S5 S6 S7 S8

extend S1 S2 S3 S4 S5 S6 S7 S8

compress S1 S2 S3 S4 S5 S6 S7 S8

extend S1 S2 S3 S4 S5 S6 S7 S8

Equal propellant; consumption for all daughter satellites

Requirements and Parameters Summary

Science	Observable	Measurement	Parameter	Payload
cosmic dawn and dark ages	21cm global spectrum (high precision 30-120 MHz, good precision 0.1-30 MHz)	30MHz–120MHz single antenna measurement	frequency band：30-120MHz sensitivity：<0.1K@80MHz (1MHz channel, 10 min integral) spectral resolution：<100kHz Antenna Beam non-chromatic: no sidelobe	**1 daughter satellite**
High Resolution whole sky survey, open up last window in EM spectrum	1-30MHz whole sky map and source catalogue	multi-satellite interferometry taken with daughter satellites, data communication and processing on mother satellite, Position determination by ranging and angular measurement. Downlink to Ground	band：0.1-30MHz spatial resolution：<0.18° @1MHz，0.012° @30MHz antenna: 3 polarization Tsys：＜120% Tsky（1-30MHz） gain stability < 0.02dB/°C Amplitude Error：0.5dB Phase error：50° baselines：100m–100km ranging error：≤1m angular error：≤2" clock synchronization error：3.3ns communication range：10km-120km	**8 daighter satellites with interferometric spectrometer, inter-sat communication, ranging and synchronization, star sensor; 1 mother satellite for communication system, correlator, calibration source**
solar and planet ultralong wave radiation	monitoring of continuum spectrum for solar radio burst and planetary radio	Time Allocation or Event triggering	frequency band：0.1-30MHz dynamic range：60dB time resolution：second spectral resolution：≥8192	

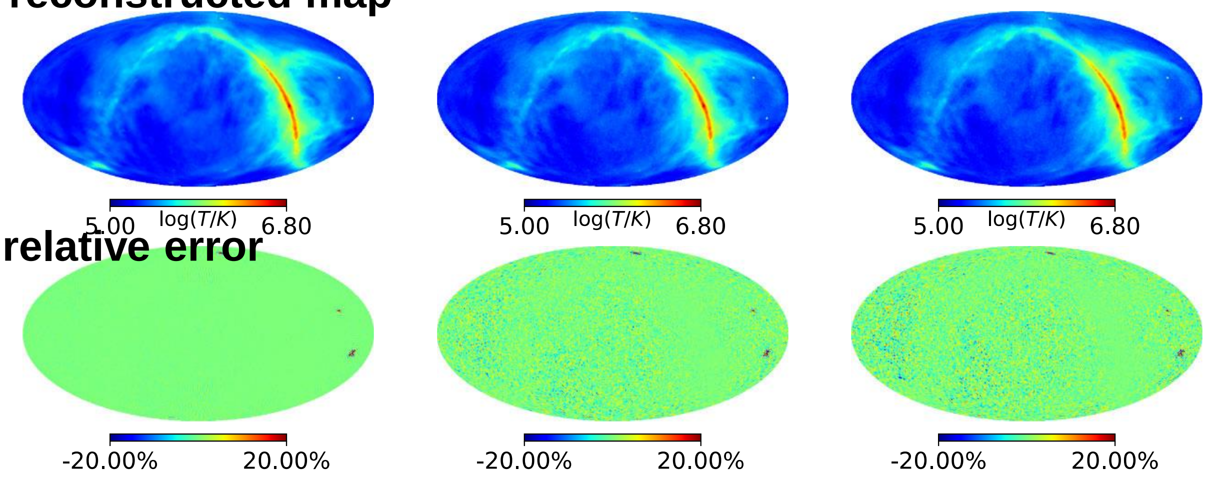
Noise & Sensitivities

$$T_{\rm sys} = T_{\rm rcv} + T_{\rm sky}.$$

$$T_{\rm rcv} = 6.61 \times 10^3 \left(\frac{\lambda}{10\,{\rm m}}\right)^2 \left(\frac{2.5\,{\rm m}}{l_{\rm eff}}\right)^2 \ {\rm K}.$$

reconstructed map

relative error



(a) 10 MHz: ideal situation.

(b) 10 MHz: with noise.

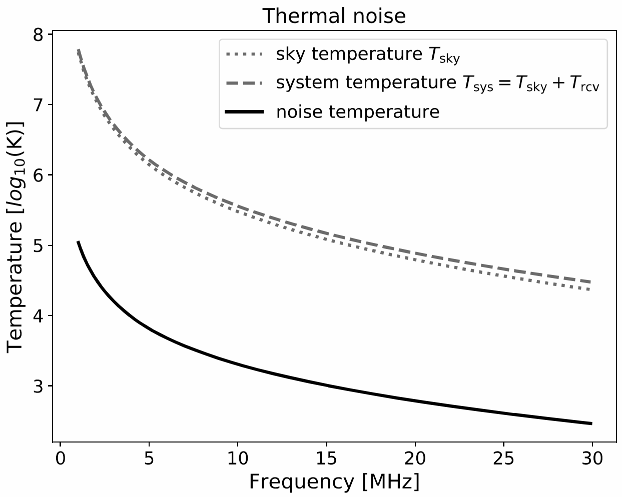
(c) 10 MHz: with Moon blockage and noise.

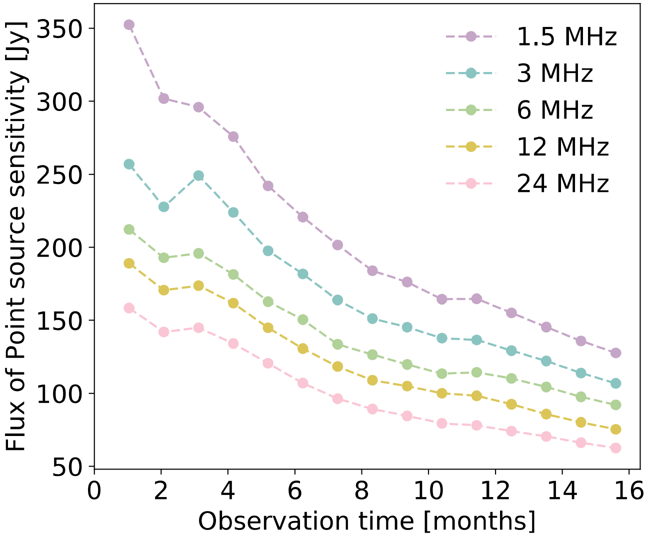
no noise

with noise

with noise & moon blocking

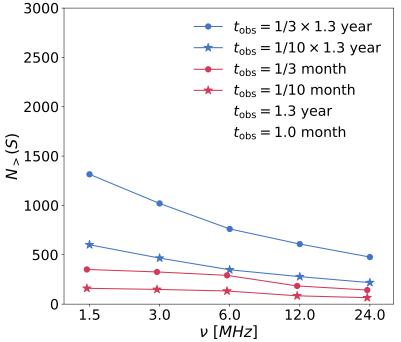
Huang et al. 2018, AJ 156, 43), Y. Shi et al. 2021, MNRAS 510, 3046



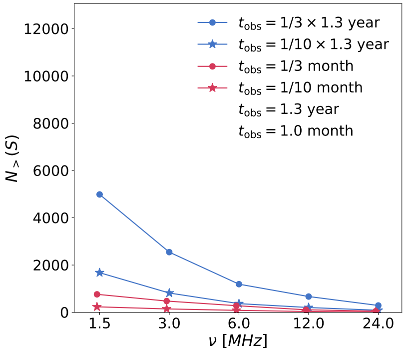


5 σ limit

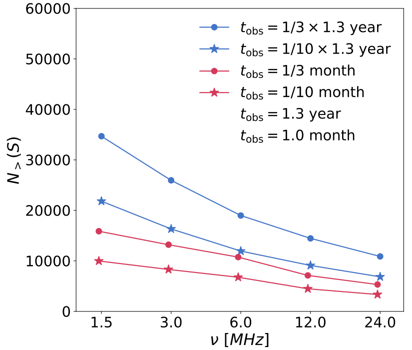
Detectable source (5σ, 8kHz)



VLSS model (Jester & Falck 2009)



GLEAM model (Franzen et al. 2019)



SSM model (Huang et al. 2019)

Subtle Issues

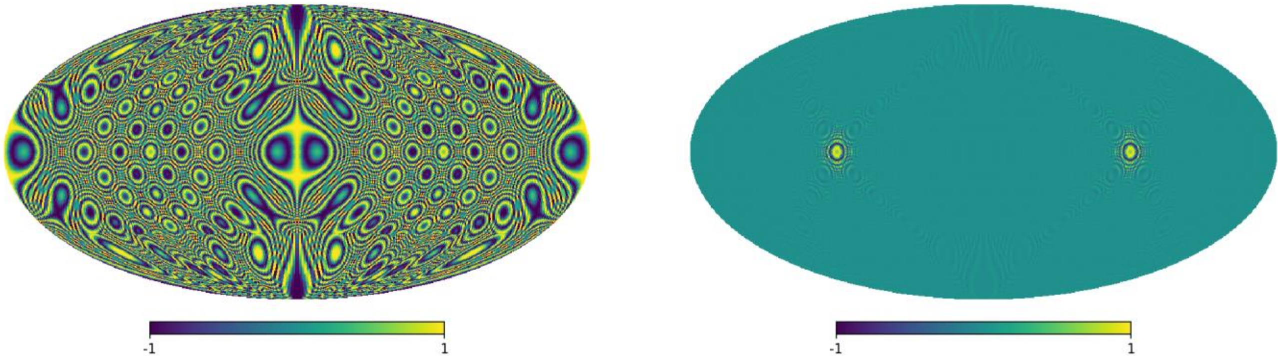
- **Doppler Effect: affect phase**

rotation around Sun: 30 km/s
rotation around Earth: 1 km/s
rotation around Moon: 1.7 km/s

Direction-dependent correction needs to be applied while doing reconstruction

$$
\begin{aligned}
V_{\mathrm{ab}}(t, \nu) &= \int \mathrm{d}^2\hat{\boldsymbol{k}}\, B_{\mathrm{ab}}(\nu, \hat{\boldsymbol{k}}) I(\nu', \boldsymbol{k}') \mathrm{e}^{-i\boldsymbol{k}'\cdot\boldsymbol{r}_{\mathrm{ab}}} \\
&\approx \int \mathrm{d}^2\hat{\boldsymbol{k}}\, B_{\mathrm{ab}}(\nu, \hat{\boldsymbol{k}}) I[\nu(1-\boldsymbol{\beta}\cdot\hat{\boldsymbol{k}}), \boldsymbol{k}/(1+\boldsymbol{\beta}\cdot\hat{\boldsymbol{k}})] \\
&\times\ \mathrm{e}^{-i(1-\boldsymbol{\beta}\cdot\hat{\boldsymbol{k}})(\boldsymbol{k}\cdot\boldsymbol{r}_{\mathrm{ab}})}. \\
&\approx \int \mathrm{d}^2\hat{\boldsymbol{k}}\, B(\nu, \hat{\boldsymbol{k}}) I[\nu, \hat{\boldsymbol{k}}] \mathrm{e}^{-i(1-\boldsymbol{\beta}\cdot\hat{\boldsymbol{k}})(\boldsymbol{k}\cdot\boldsymbol{r}_{\mathrm{ab}})}.
\end{aligned}
$$

- **Aliasing Effect (Moire pattern)**



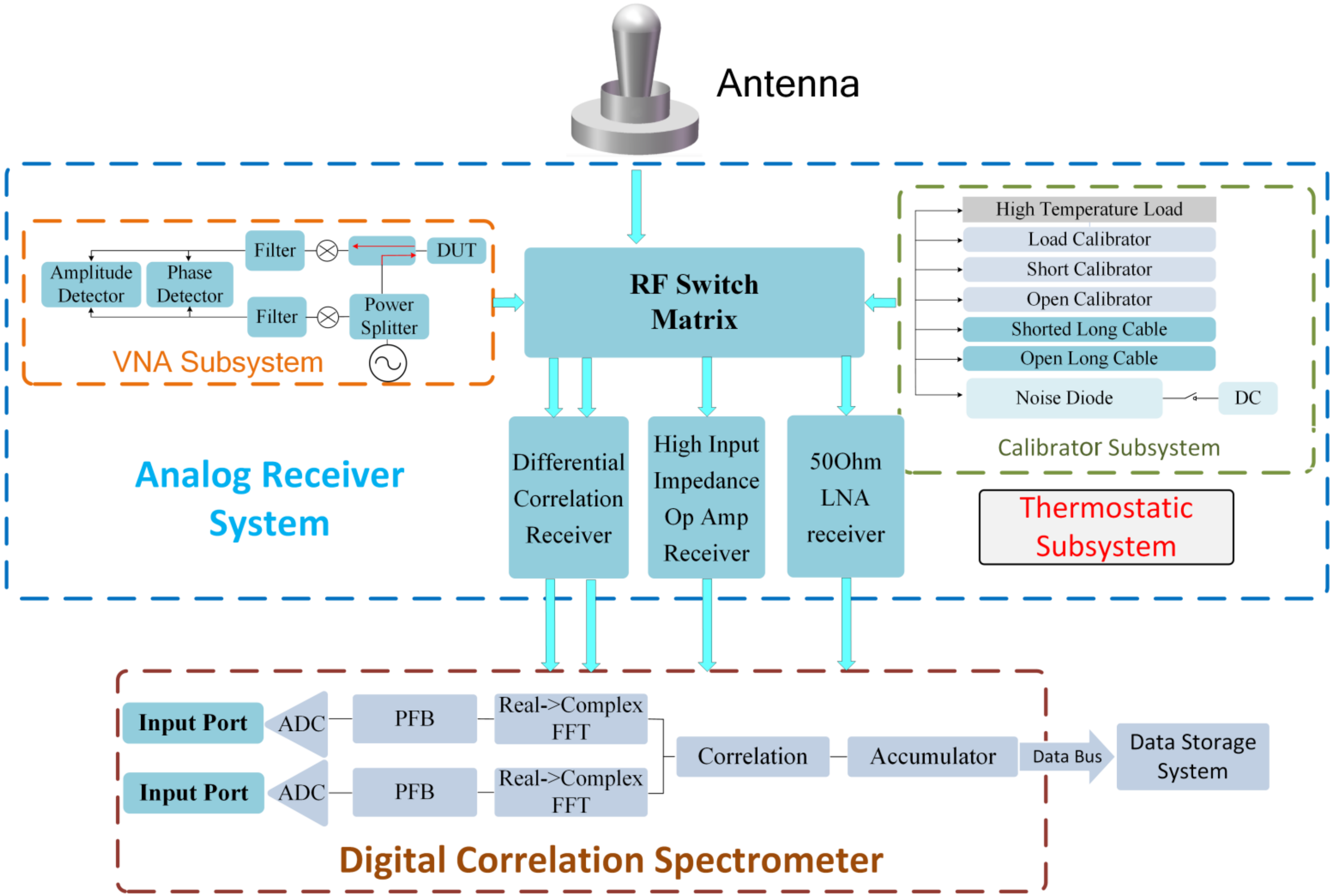
- **Reflections from the Moon**

- **Impact of Variable Sources**

Global Spectrum Measurement (HF)

see Fengquan Wu’s talk

design the antenna as the satellite



Antenna

VNA Subsystem

Amplitude Detector

Phase Detector

Filter

Filter

DUT

Power Splitter

RF Switch Matrix

High Temperature Load

Load Calibrator

Short Calibrator

Open Calibrator

Shorted Long Cable

Open Long Cable

Noise Diode

DC

Calibrator Subsystem

Analog Receiver System

Differential Correlation Receiver

High Input Impedance Op Amp Receiver

50Ohm LNA receiver

Thermostatic Subsystem

Input Port

ADC

PFB

Real->Complex FFT

Input Port

ADC

PFB

Real->Complex FFT

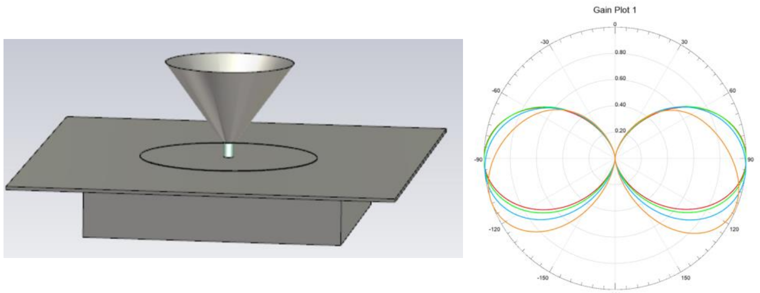
Correlation

Accumulator

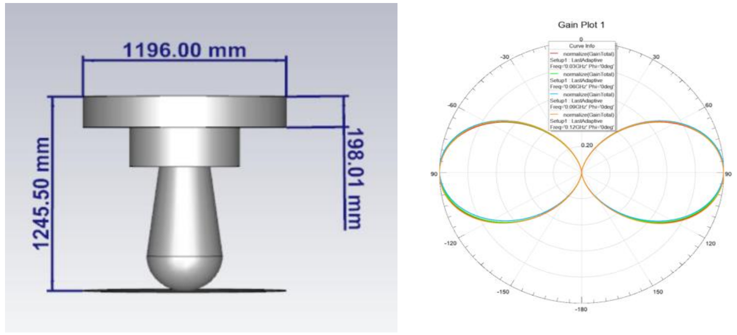
Data Bus

Data Storage System

Digital Correlation Spectrometer



The satellite body (thick box) affect beam pattern



Simulation & Error propagation analysis

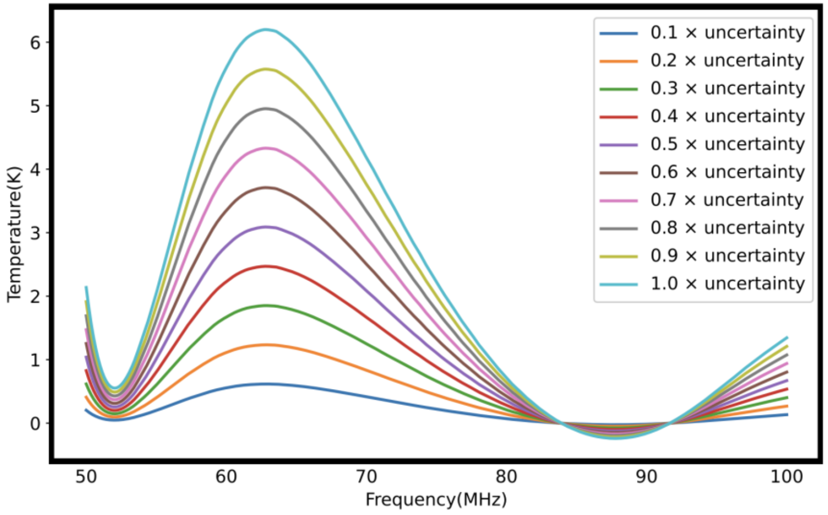
We use the error parameters given by VNA manufactures (e.g. Keysight) to estimate the error

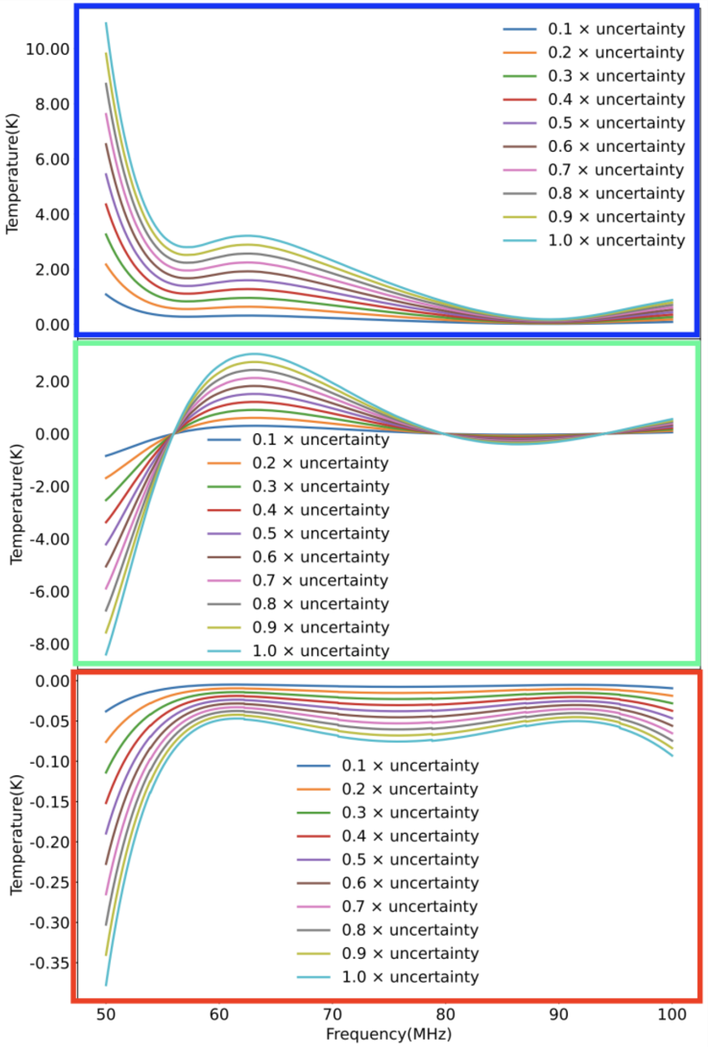
$$T_{\mathrm{sky}} = \frac{T_{\mathrm{ant}} - T_0}{(1-|\Gamma_{\mathrm{ant}}|^2)|F_{\mathrm{ant}}|^2} - \frac{T_u|\Gamma_{\mathrm{ant}}|^2}{1-|\Gamma_{\mathrm{ant}}|^2} - \frac{(T_c\cos(\phi) + T_s\sin(\phi))|\Gamma_{\mathrm{ant}}|}{(1-|\Gamma_{\mathrm{ant}}|^2)|F_{\mathrm{ant}}|} \qquad F_{\mathrm{ant}} = \frac{(1-|\Gamma_{\mathrm{rec}}|^2)^{\frac{1}{2}}}{1-\Gamma_{\mathrm{ant}}\Gamma_{\mathrm{rec}}}$$

$$\boxed{\delta T_{\mathrm{sky}}} = \boxed{\frac{\partial T_{\mathrm{sky}}}{\partial \Gamma_{\mathrm{ant}}}\delta\Gamma_{\mathrm{ant}}} + \boxed{\frac{\partial T_{\mathrm{sky}}}{\partial \Gamma_{\mathrm{rec}}}\delta\Gamma_{\mathrm{rec}}} + \boxed{\frac{\partial T_{\mathrm{sky}}}{\partial \Gamma_{\mathrm{open}}}\delta\Gamma_{\mathrm{open}}}$$

$$\frac{\partial T_{\mathrm{sky}}}{\partial \Gamma_{\mathrm{open}}} = \frac{\partial T_{\mathrm{sky}}}{\partial T_u}\frac{\partial T_u}{\partial \Gamma_{\mathrm{open}}} + \frac{\partial T_{\mathrm{sky}}}{\partial T_c}\frac{\partial T_c}{\partial \Gamma_{\mathrm{open}}} + \frac{\partial T_{\mathrm{sky}}}{\partial T_s}\frac{\partial T_s}{\partial \Gamma_{\mathrm{open}}}$$

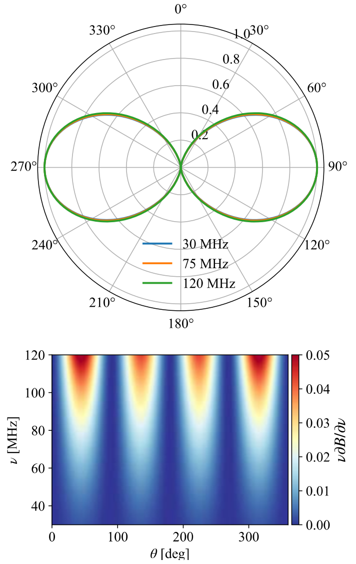
$$\frac{\partial T_{\mathrm{sky}}}{\partial \Gamma_{\mathrm{rec}}} = \left.\frac{\partial T_{\mathrm{sky}}}{\partial \Gamma_{\mathrm{rec}}}\right|_{\mathrm{direct}} + \frac{\partial T_{\mathrm{sky}}}{\partial T_u}\frac{\partial T_u}{\partial \Gamma_{\mathrm{rec}}} + \frac{\partial T_{\mathrm{sky}}}{\partial T_c}\frac{\partial T_c}{\partial \Gamma_{\mathrm{rec}}} + \frac{\partial T_{\mathrm{sky}}}{\partial T_s}\frac{\partial T_s}{\partial \Gamma_{\mathrm{rec}}} + \frac{\partial T_{\mathrm{sky}}}{\partial T_0}\frac{\partial T_0}{\partial \Gamma_{\mathrm{rec}}}$$

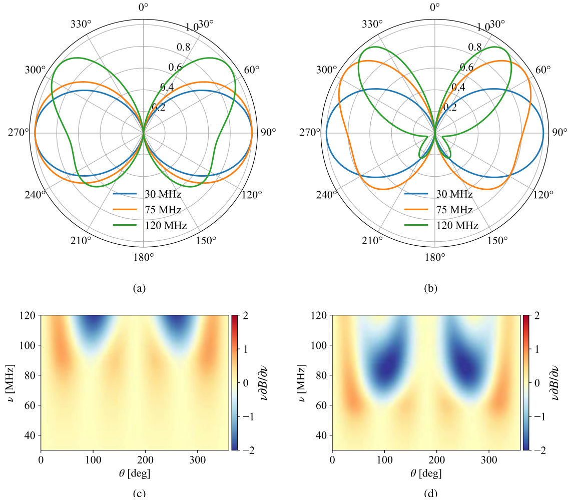




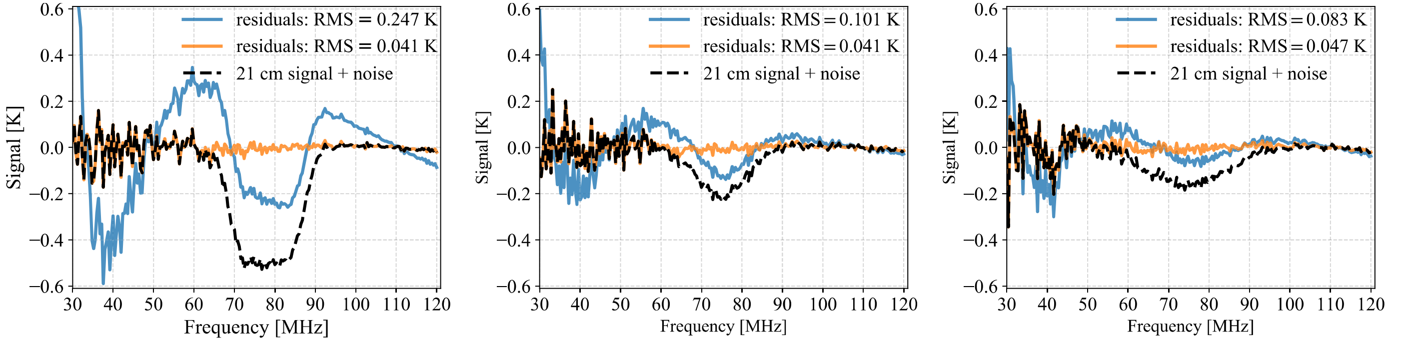
Calibration Error in 21-centimeter Global Spectrur Experiments
Shijie Sun et.al. Universe **2024**, *10*(6), 236

Antenna Chromaticity

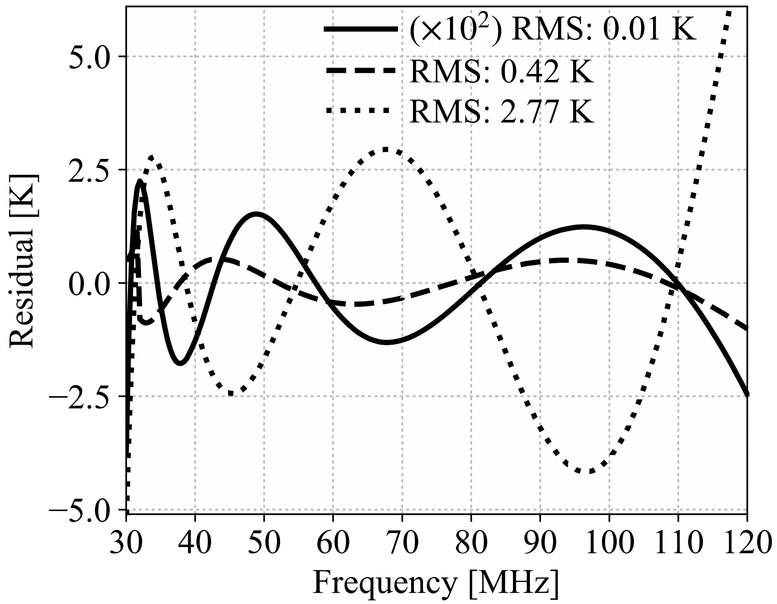




Fitting with a smooth foreground model

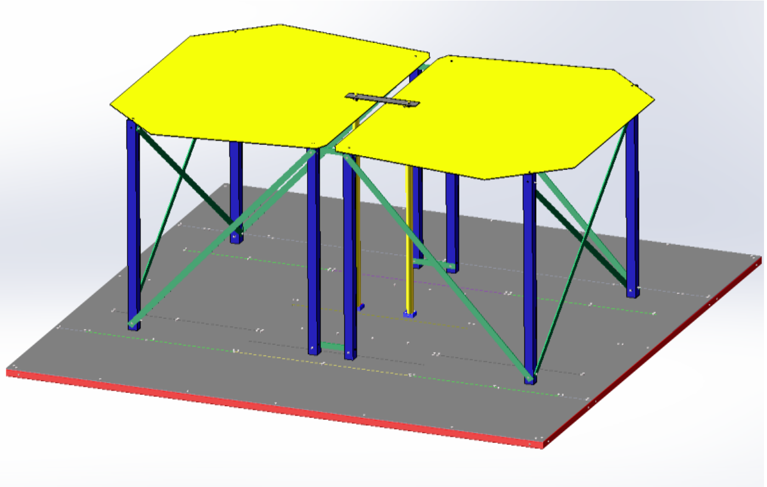


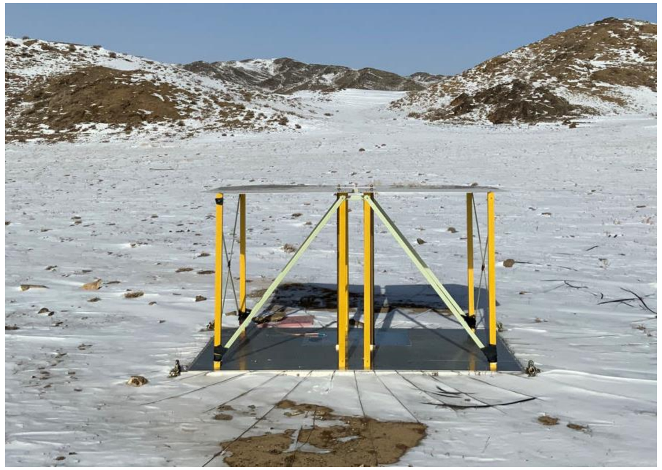
(a) Results for the EDGES 21 cm model. (b) Results for Gaussian 21 cm model (A = 0.2 K). (c) Results for Gaussian 21 cm model (A = 0.155 K).



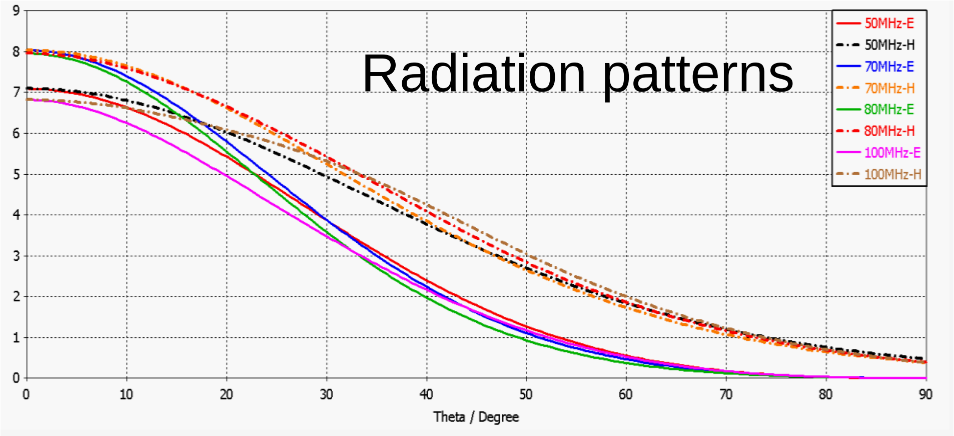
Y. Shi et al. (2022), ApJ 929, 32

Field Tests



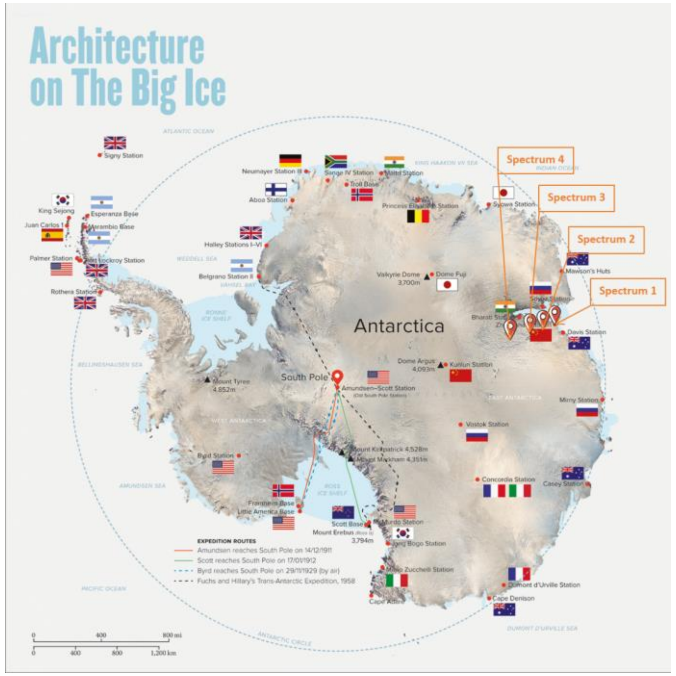


EDGES type, with hexgonal antenna

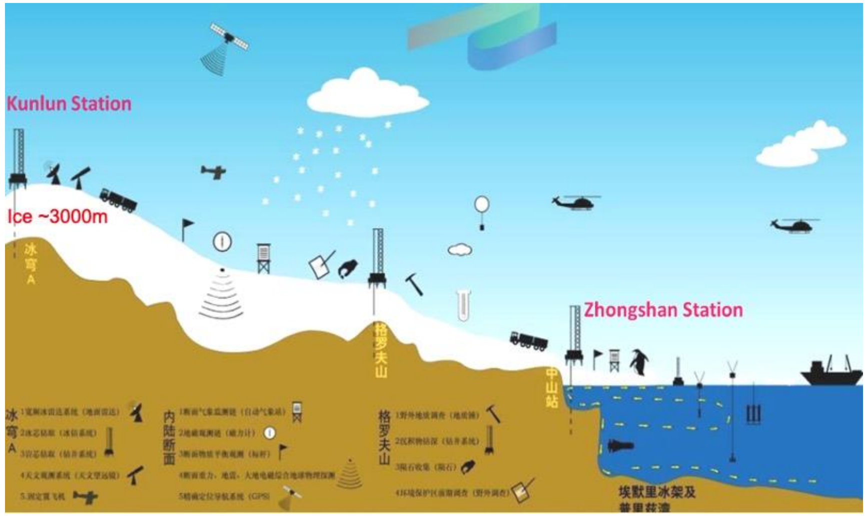


Radiation patterns

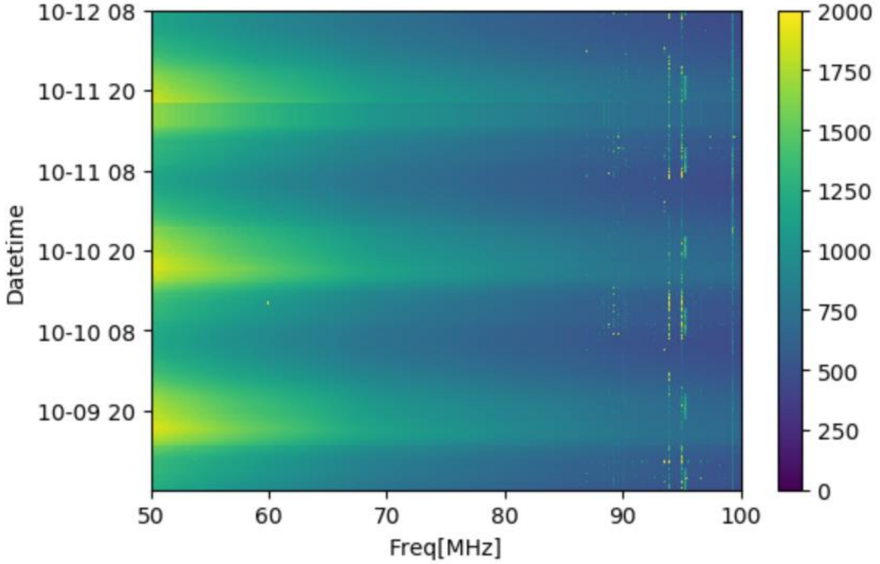
Antarctica Experiment

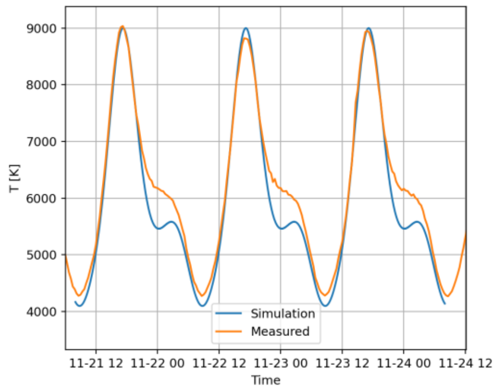


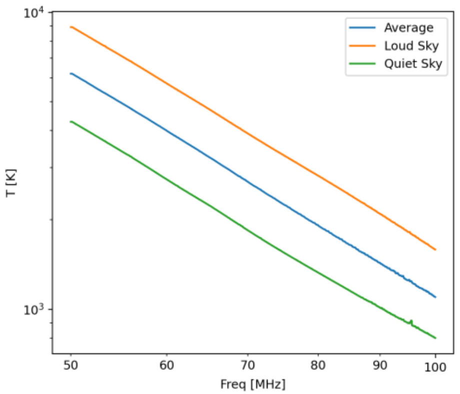
Shijie Sun with the solar panels



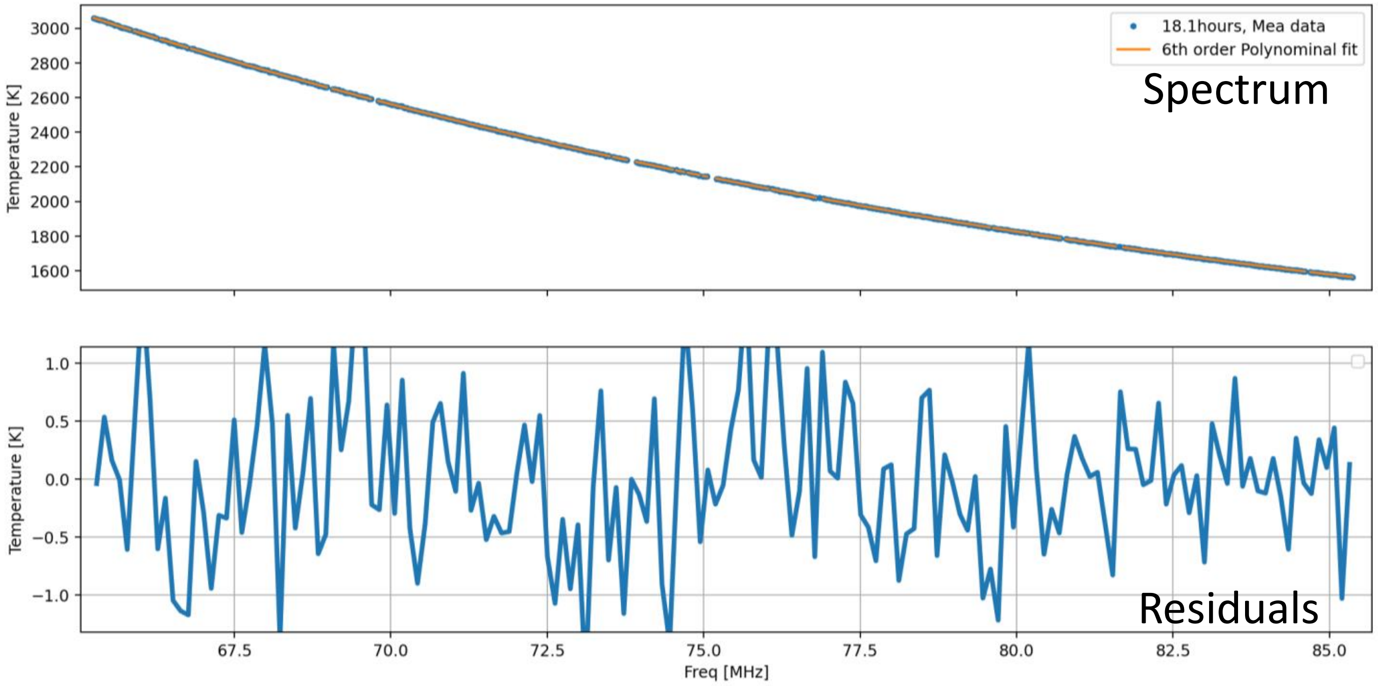
Field Test Result







Sky average spectrum (18 hr, RFI removed)



DSL Project Status

Chief Scientist: Xuelei Chen (NAOC)

Chief Engineer (payload): Jingye Yan (NSSC)

Satellite Platform: Xiaofeng Zhang (IAMC)

- **First proposed in 2015 as a China-Europe joint project**
- **Intensive Study (2018-2020) successfuly completed**
- **Aiming for a mission launch in 2027**

太空|TAIKONG

国际空间科学研究所 · 北京

ISSI-BJ Magazine

No. 14 July 2019

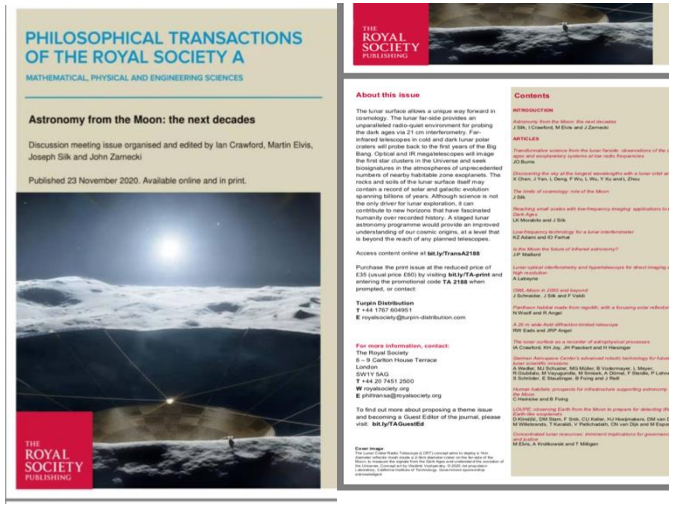
DISCOVER THE SKY BY LONGEST WAVELENGTH

WITH SMALL SATELLITE CONSTELLATION

太空|TAIKONG

Participants

X. Chen et al. arxiv:1907.10853



PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

MATHEMATICAL, PHYSICAL AND ENGINEERING SCIENCES

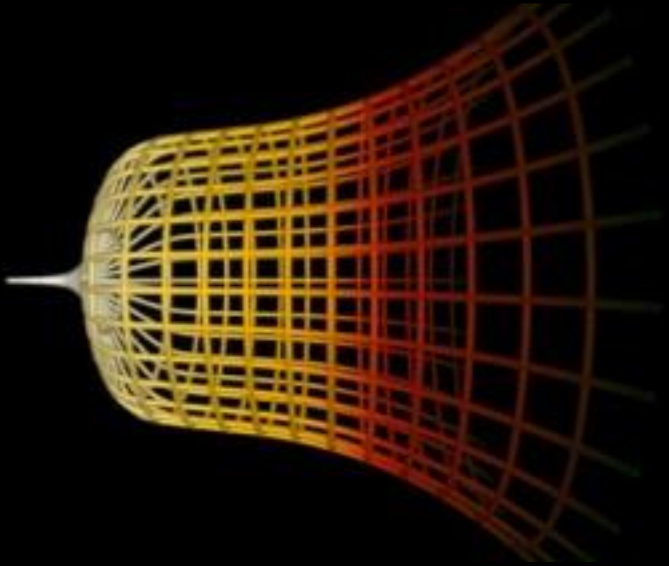
Astronomy from the Moon: the next decades

Discussion meeting issue organised and edited by Ian Crawford, Martin Elvis, Joseph Silk and John Zarnecki

Published 23 November 2020. Available online and in print.

Chen et al., arxiv:2007.15794

Summary



array with $10^3 \sim 10^4$ antennas on the farside, detect primordial fluctuations

2040-2050

array with 10^2 antennas to make astrophysical observations

2030-2040

first step experiments with $10^0 \sim 10^1$ antennas

2020-2030