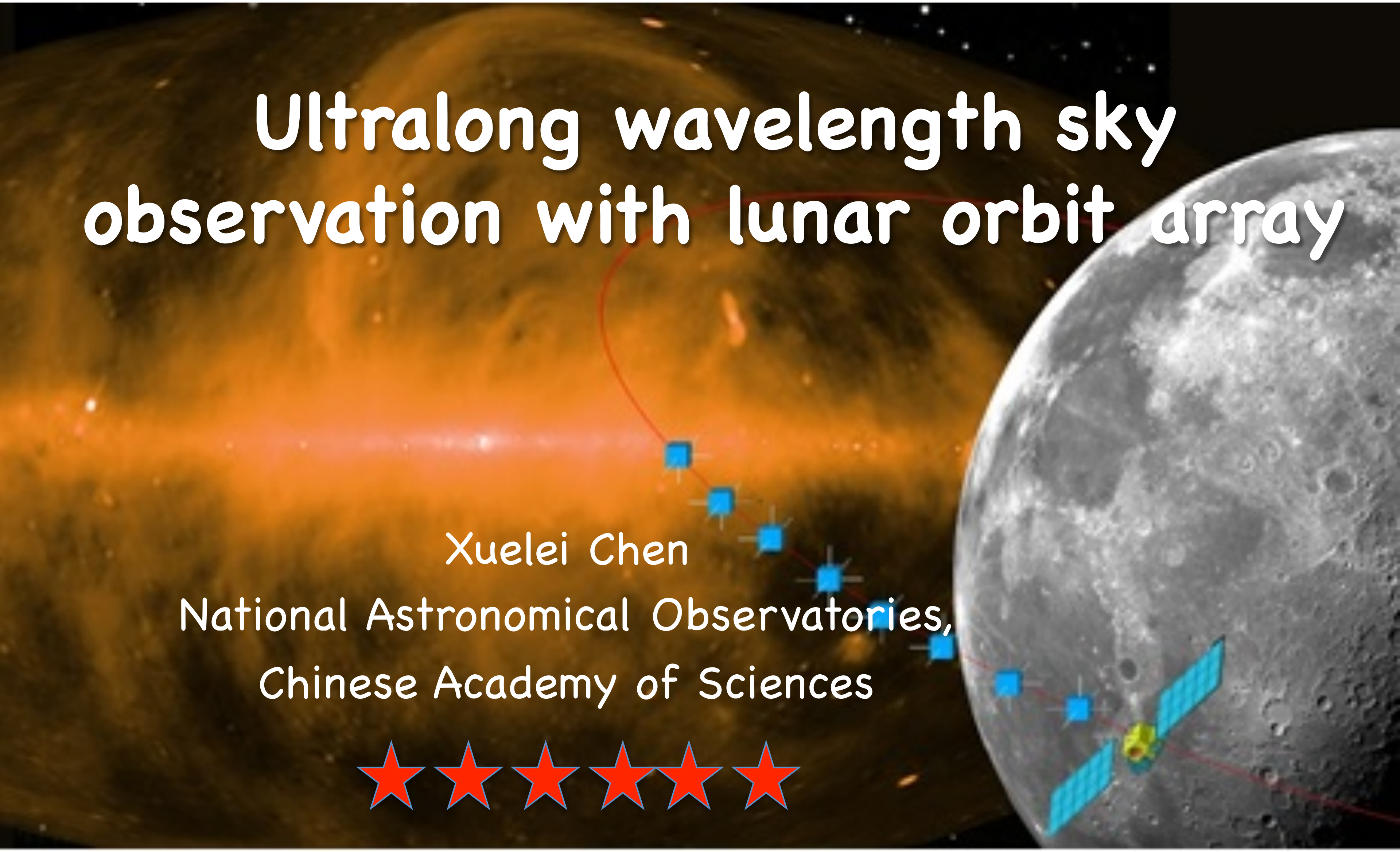
The 8th KIAS workshop on Cosmology & Structure Formation



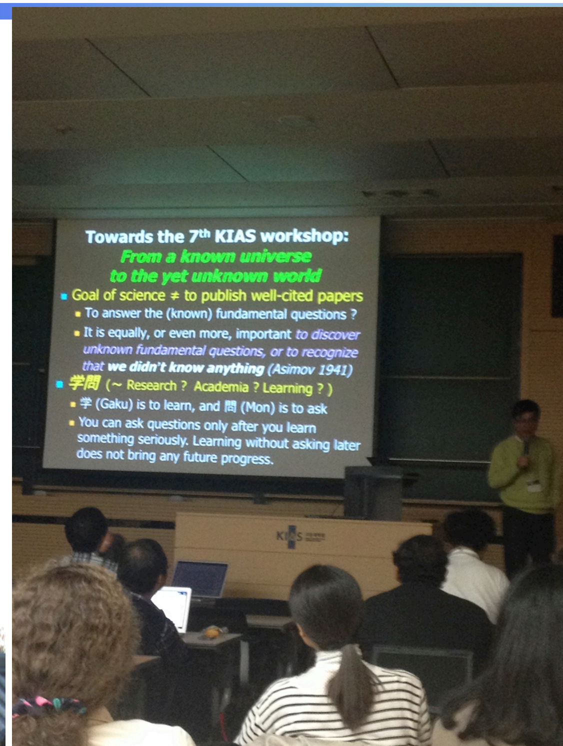
Ultralong wavelength sky observation with lunar orbit array

Xuelei Chen

National Astronomical Observatories,

Chinese Academy of Sciences

2018.11.08 KIAS

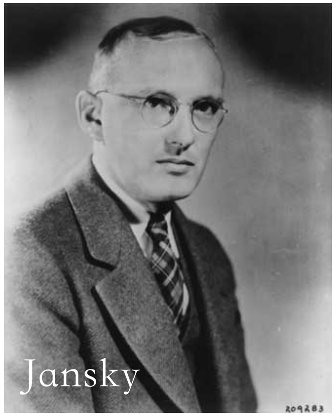

Towards the 7th KIAS workshop:
From a known universe
to the yet unknown world
Goal of science ≠ to publish well-cited papers
To answer the (known) fundamental questions ?
It is equally, or even more, important to discover unknown fundamental questions, or to recognize that we didn't know anything (Asimov 1941)
学問 (~ Research ? Academia ? Learning ?)
学 (Gaku) is to learn, and 問 (Mon) is to ask
You can ask questions only after you learn something seriously. Learning without asking later does not bring any future progress.

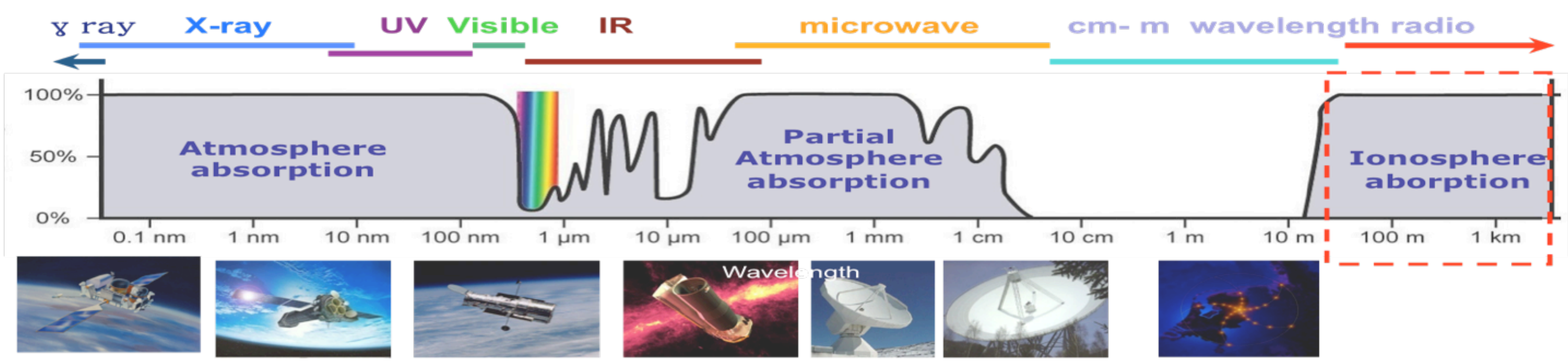
Astronomy at the lowest frequencies

- Radio astronomy started in low frequencies(Jansky, Reber)。
- But at low frequency the ionosphere has strong absorption and refraction
- Strong natural and artificial radio frequency interferences on Earth

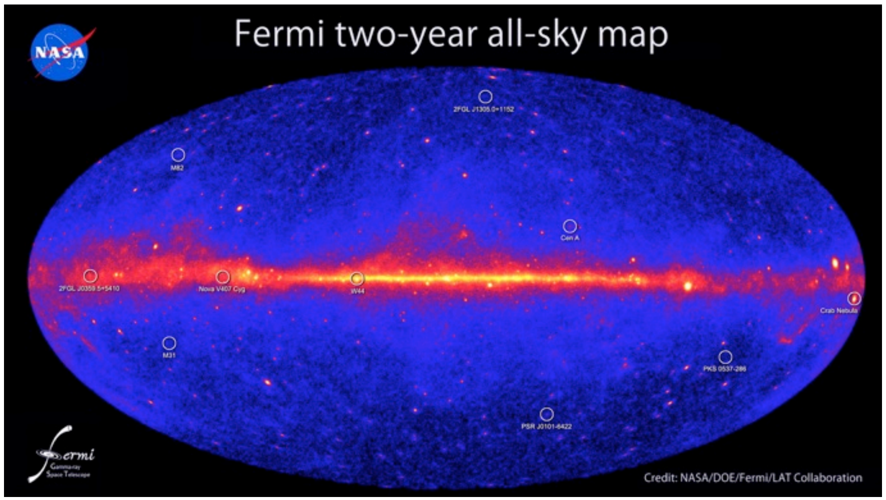
- **Low frequency observation strongly affected, lacking high quality observation data**

In radio communication,these are the MF, HF, VHF bands, but in astronomy these are low frequency, so we call it ultralong wavelength just to distinguish

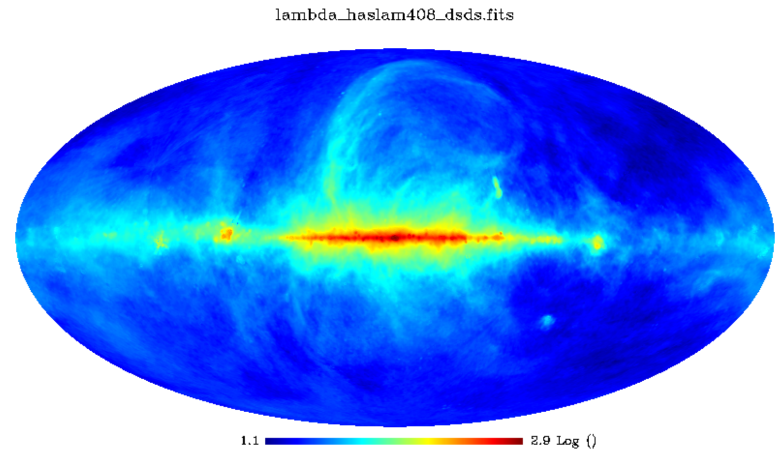




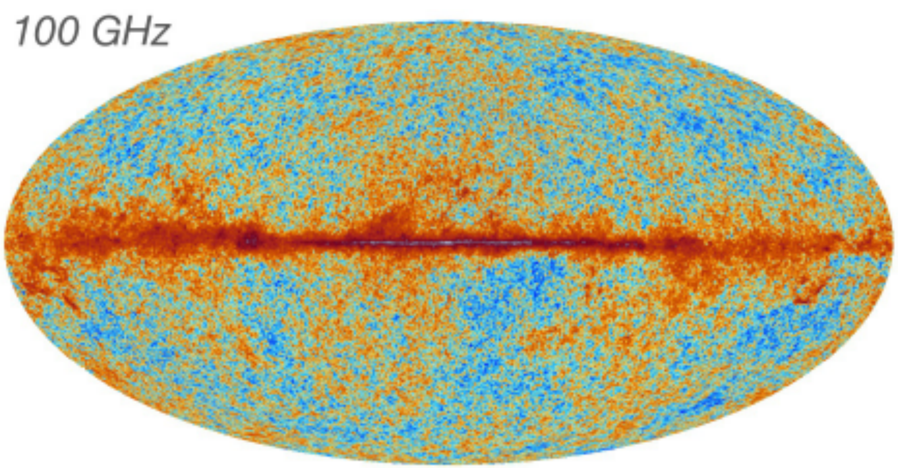
Sky in different wavelengths



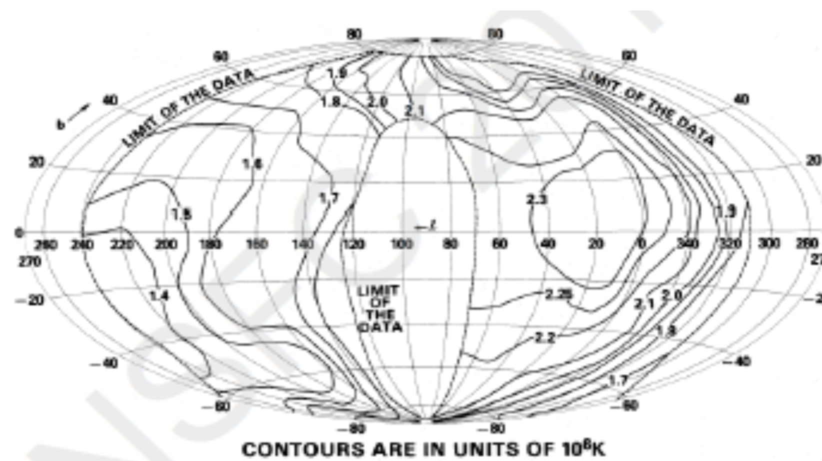
Gamma-ray Sky Map (Fermi Satellite)



408 MHz Sky Map

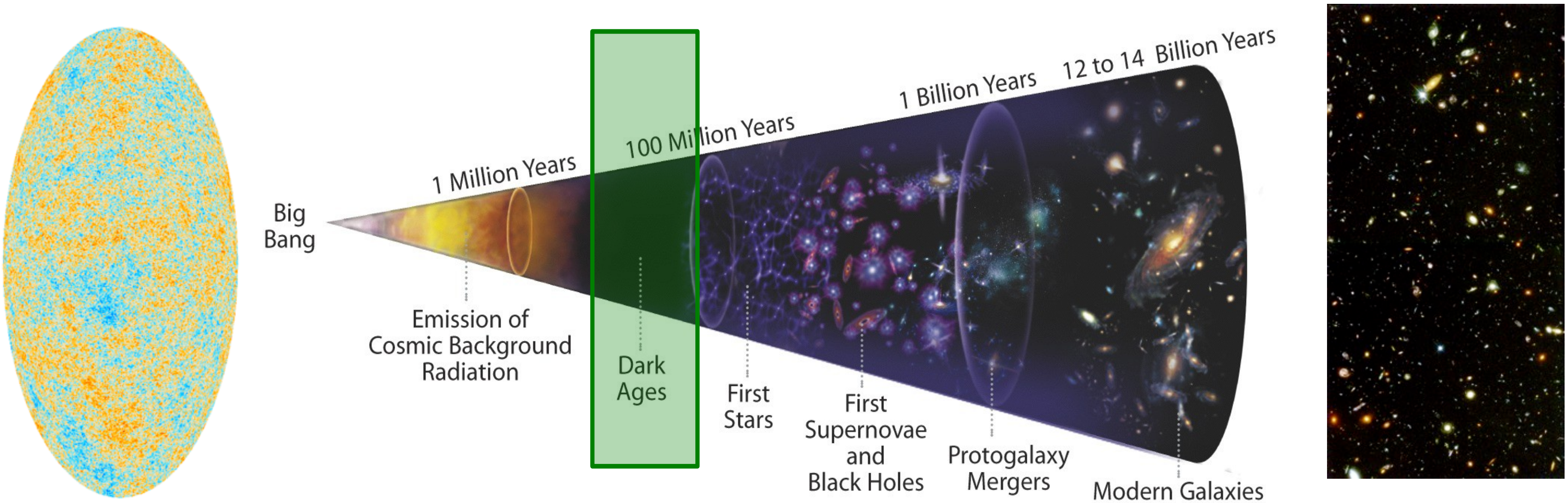


mm Sky Map (Planck Satellite)



Low Frequency (RAE-2 satellite)

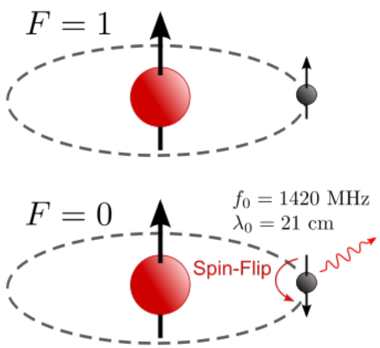
Cosmic Evolution History



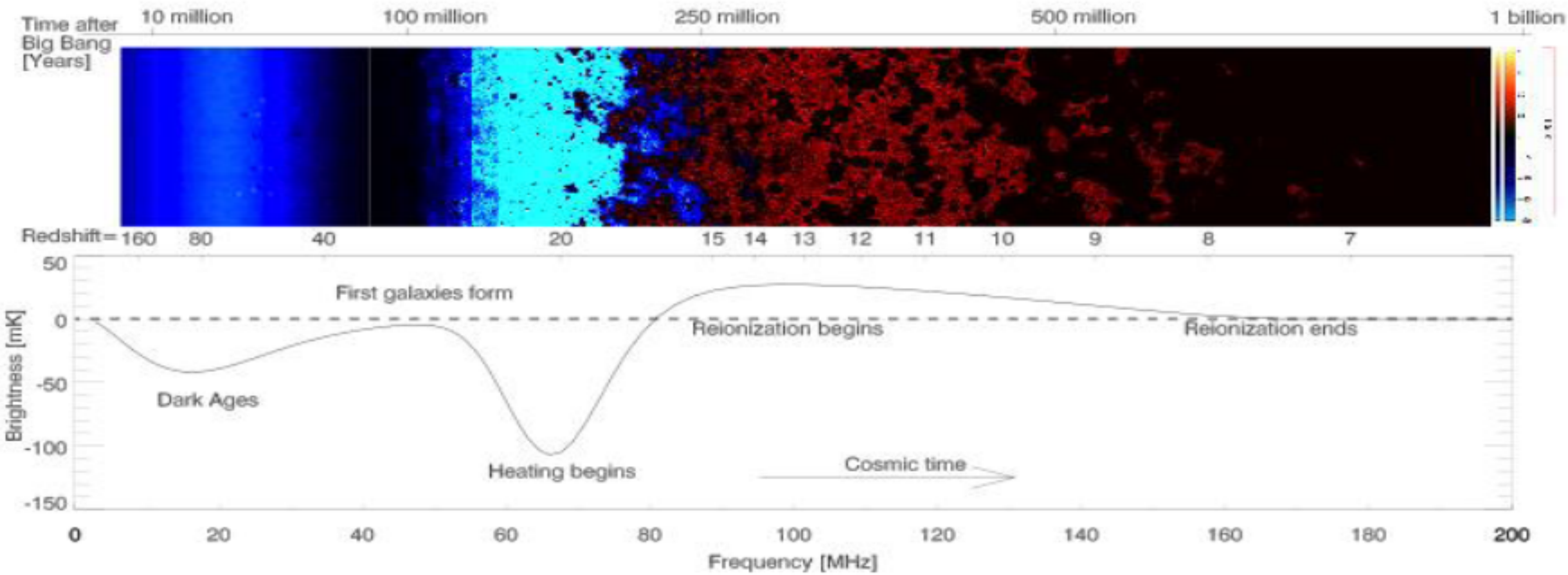
Big Bang Dark Age Cosmic Dawn Modern Universe

- Dark Age: After the Big Bang, the plasma recombined, photons last scattered and begin to propagate freely, stars and galaxies not formed yet
- cosmic dawn: As structures grow, first stars, galaxies and accreting black holes formed,produce first light
- Epoch of Reionization: The gas of the Universe gets ionized by energetic photons from stars and accretion disks

The Light in the dark age——21cm line

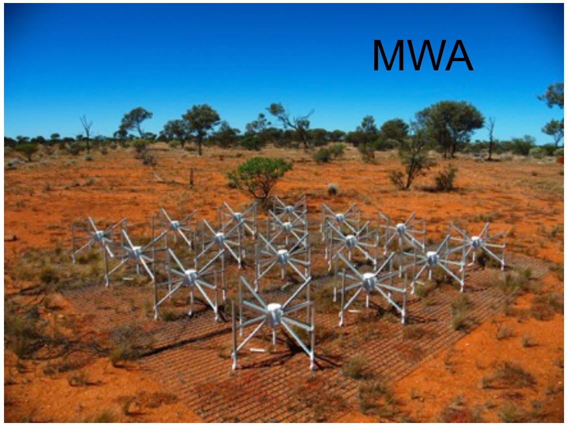


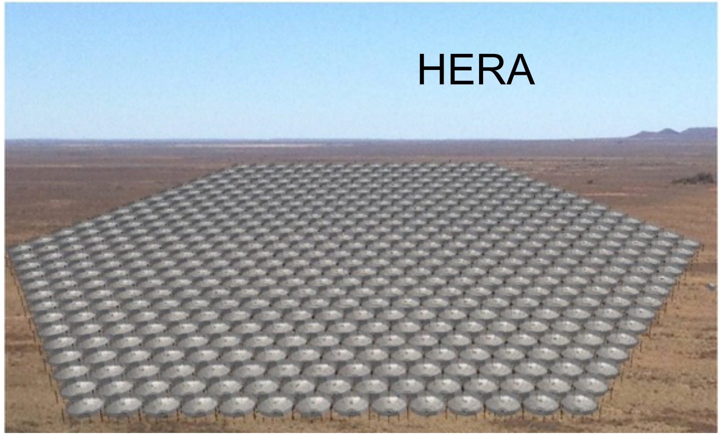
- **Neutral Hydrogen** (HI) produce spectral line of 1420MHz in Frequency or **21cm** in wavelength, superimposed on the radiation background
- **Strong Absorption line** can be produced by **Dark Age** and **Cosmic Dawn** (XC & J. Miralda-Escude 2004,2008)
- These are now redshifted to **low frequencies**

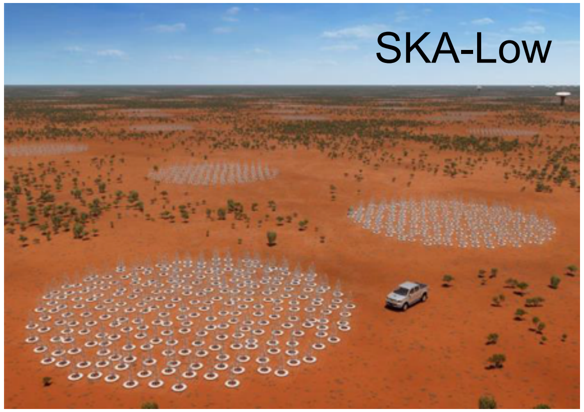


The Radio Astronomy at Low Frequencies

Driven by the Science of Cosmic Dawn and advances in the digital electronics, there is a revival of low frequency radio astronomy.

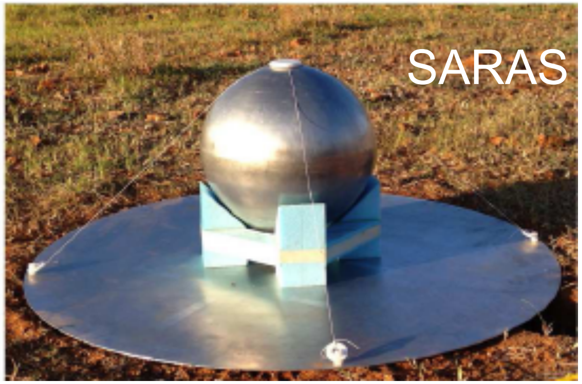






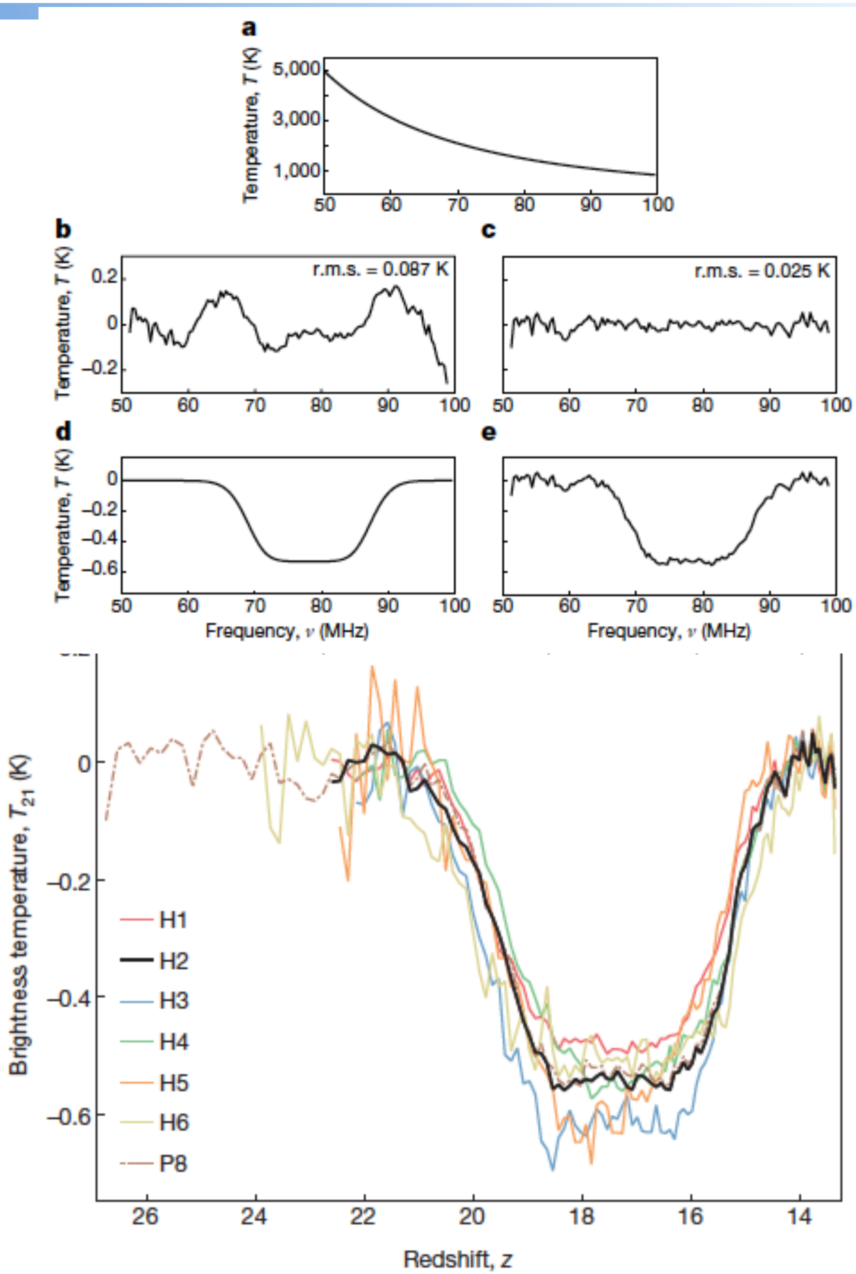
Ground-based Global Spectrum Experiments

Measure the average spectrum of a very large area of sky



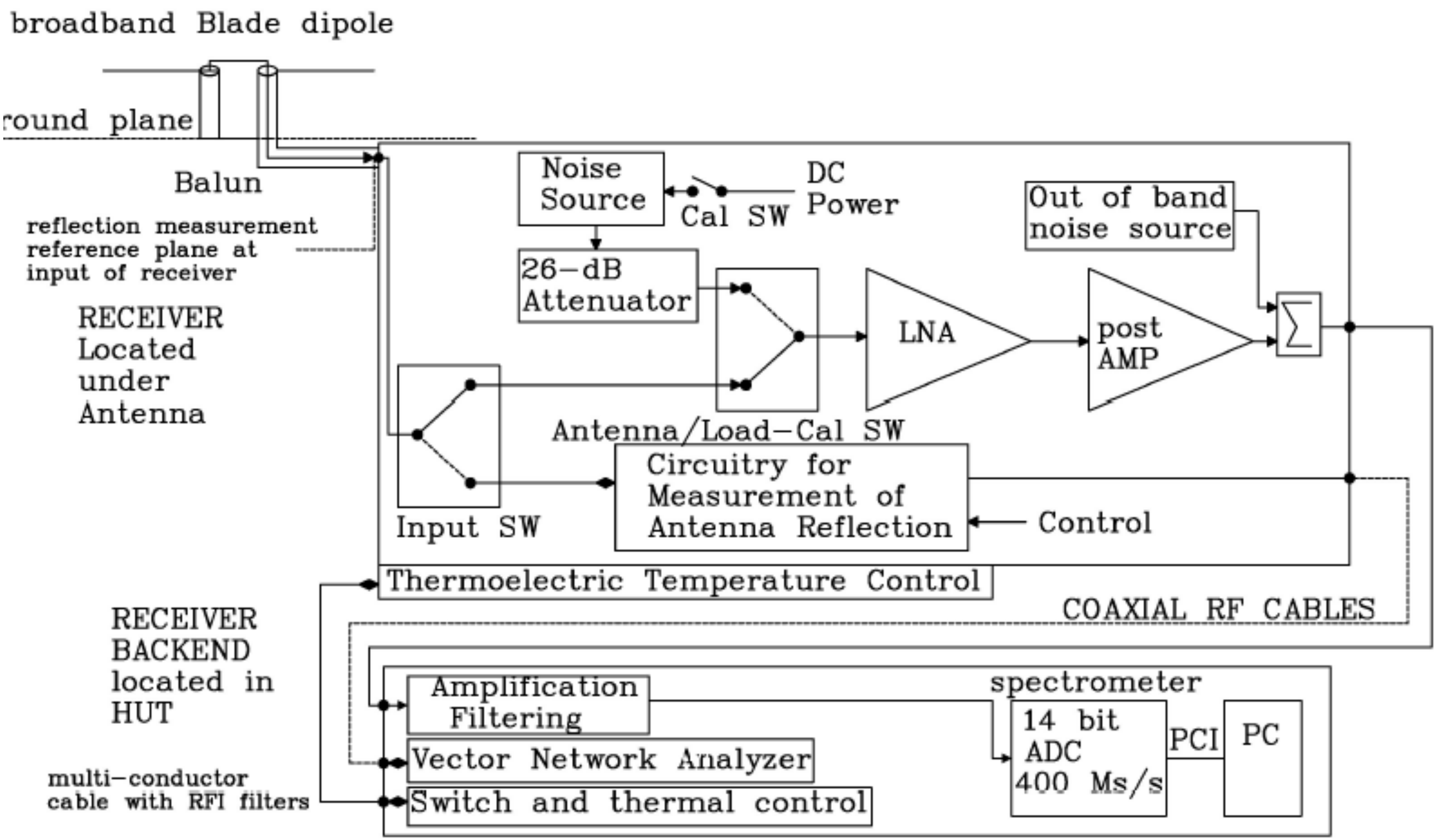
New Results from the EDGES Experiment

Bowman et al. 2018, Nature



EDGES Circuit

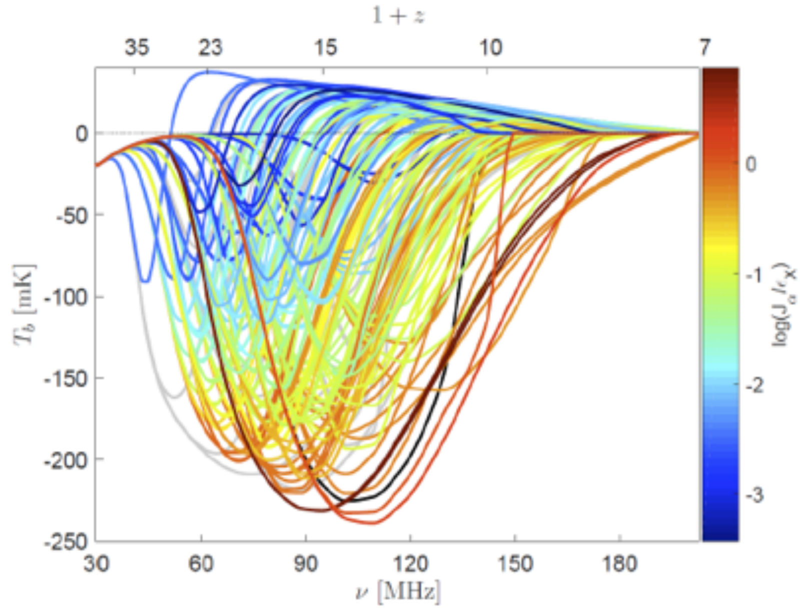
Careful calibration of the system response



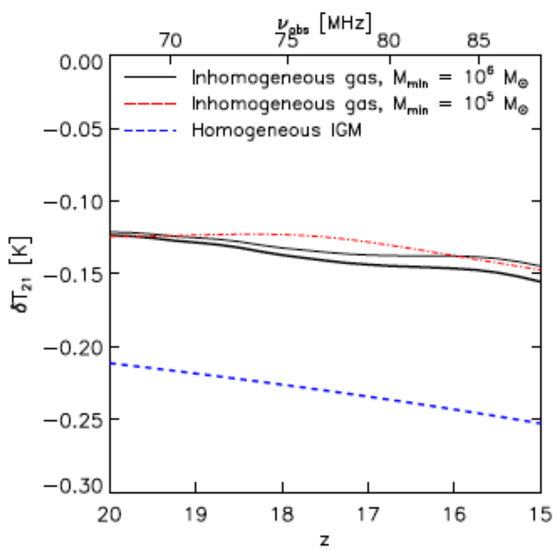
The Cosmic Dawn Signal

21cm absorption models

- The EDGES found an absorption signal of ~550mK, about twice the the theoretical maximum
- If considering the inhomogeneity of gas, the absorption signal may be even less (Xu, Yue, XC, 2018)
- Exotic milli-charged dark matter cooling the gas (Barkana 2018)?
- Extra Radio Background?



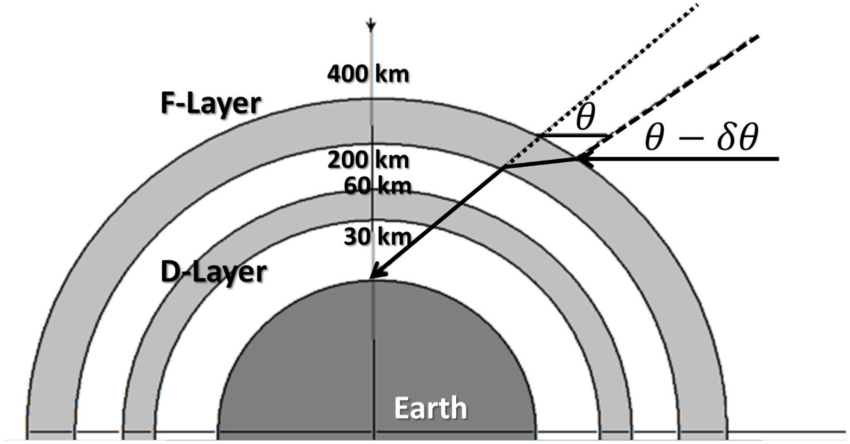
Cohen et al. (2017)

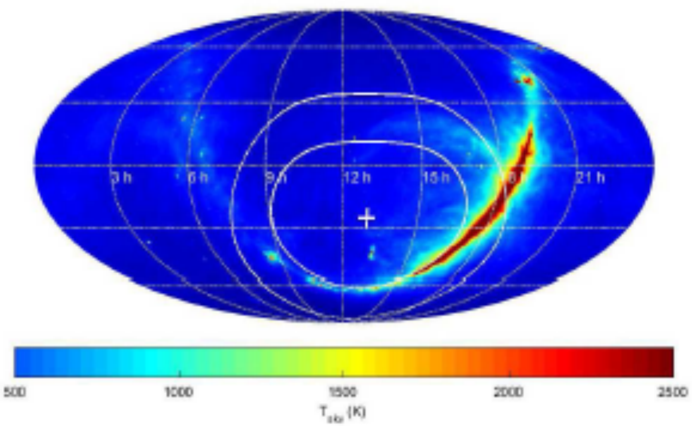


Xu et al., ApJ accepted
arxiv:1806.06080

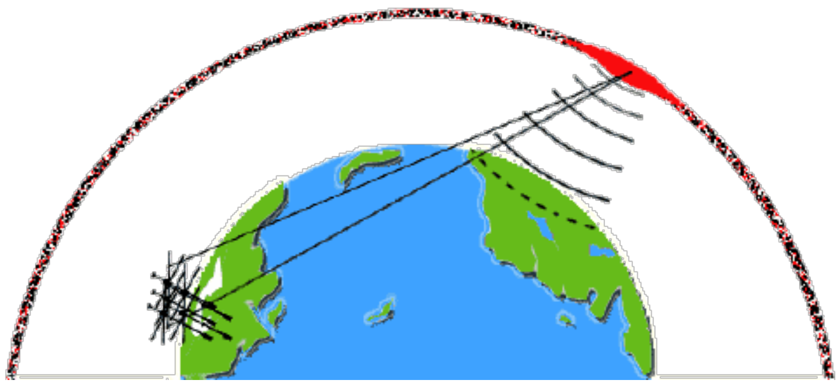
Problem in the experiment or Data Analysis?

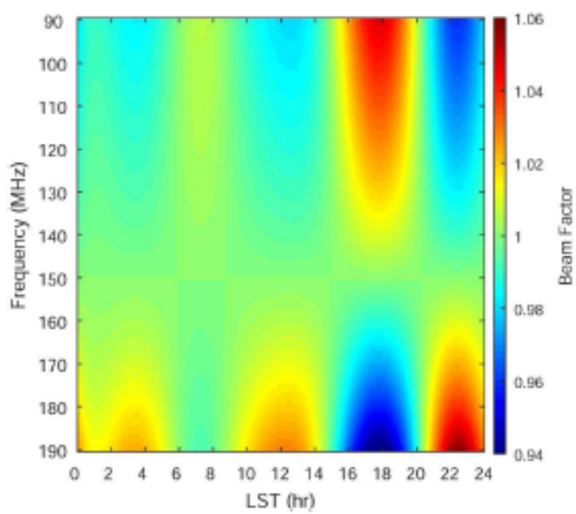
- Ionosphere Refraction and Absorption
- Radio Frequency Interference





Vedantham & Koopermans (2015)

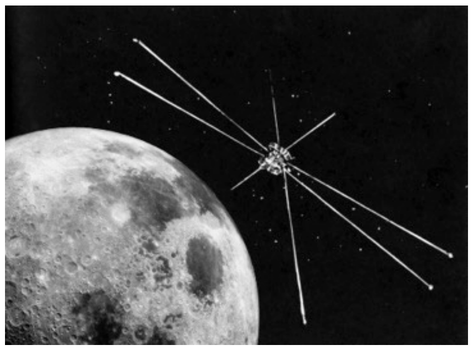




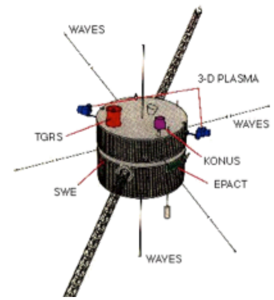
Spaceborne Low Frequency Experiments

- Since RAE-2，onky WIND/WAVES 、CASSINI did solar and planetary observations at ultra-long wavelengths
- Many proposals，but none realized
- During Chang’e-4 mission, there will be some experiments

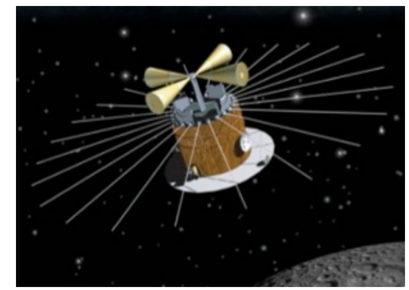
NASA RAE-1
launched 1968



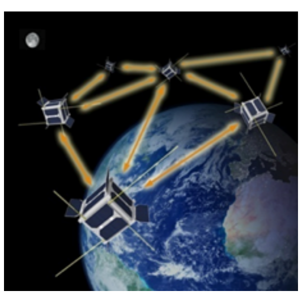
NASA RAE-2
launched 1973



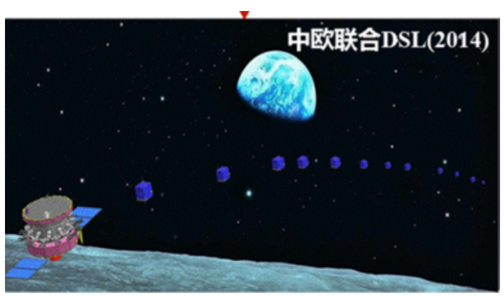
NASA WIND/WAVES
launched 1994



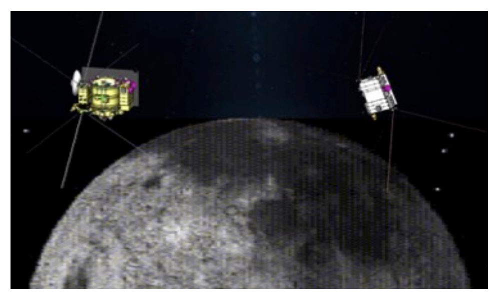
NASA DARE



Dutch OLFAR
proposed 2008

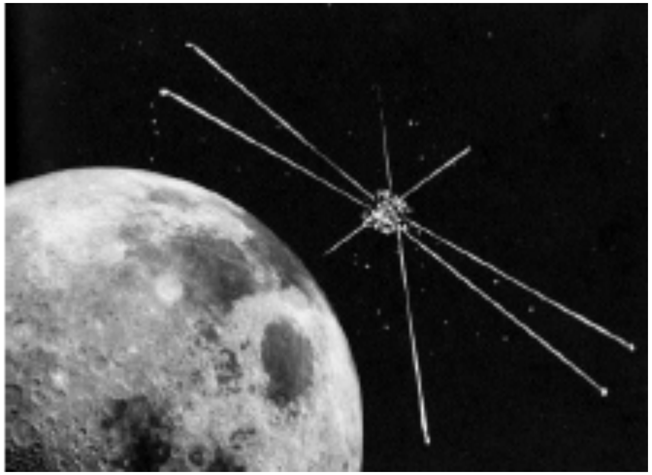


China-Dutch DSL
proposed 2014

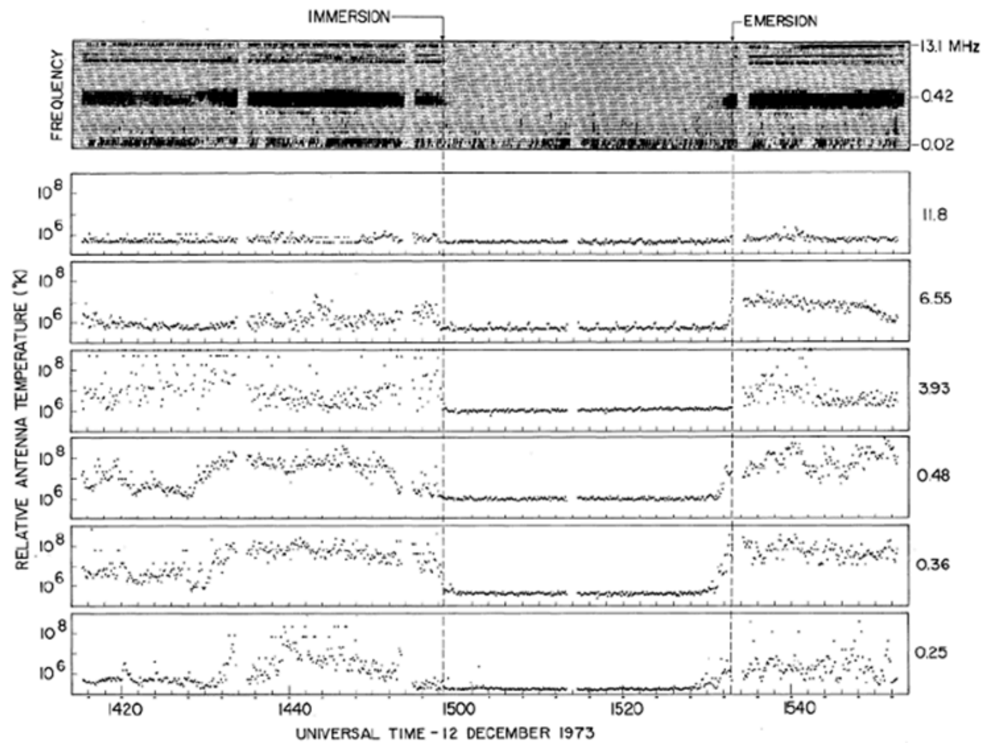


Chang’e-4 mission:Lander, Relay Satellite and Orbitor, launch 2018

The advantage of the Lunar Orbit



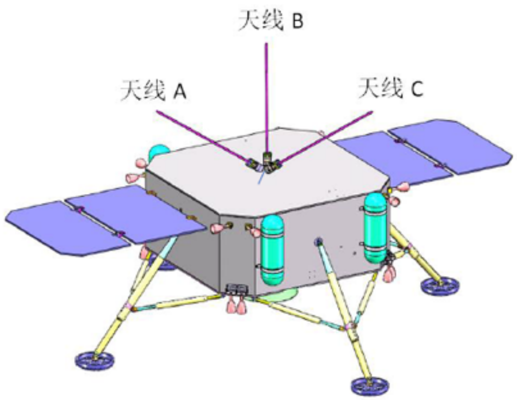
RAE-2 satellite and its spectrum measurement

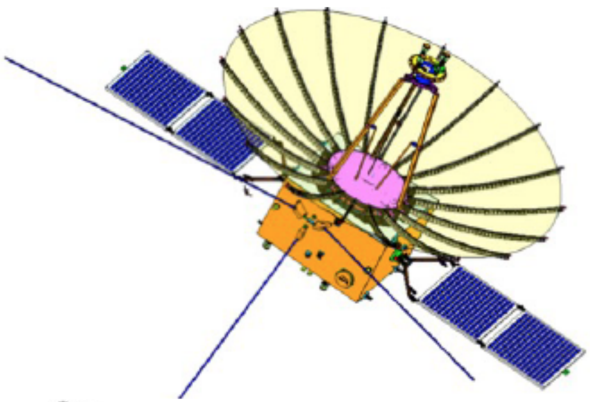


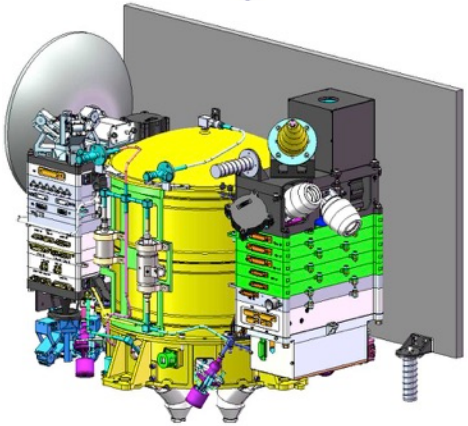
- The Moon can block the radiation from Earth
- Lunar surface—need to solve the problem of data transmission relay, and power supply during long lunar night
- lunar satellite: observe in the backside of moon, and transmit data back in front side
- Lunar orbit period is a few hours, can use solar power

Experiments during CE-4 mission

- CE-4 Lander
- Netherland-China Low frequency Experiment (Relay Satellite)
- Longjiang Orbiting satellites (piggy-back on relay satellite launch)

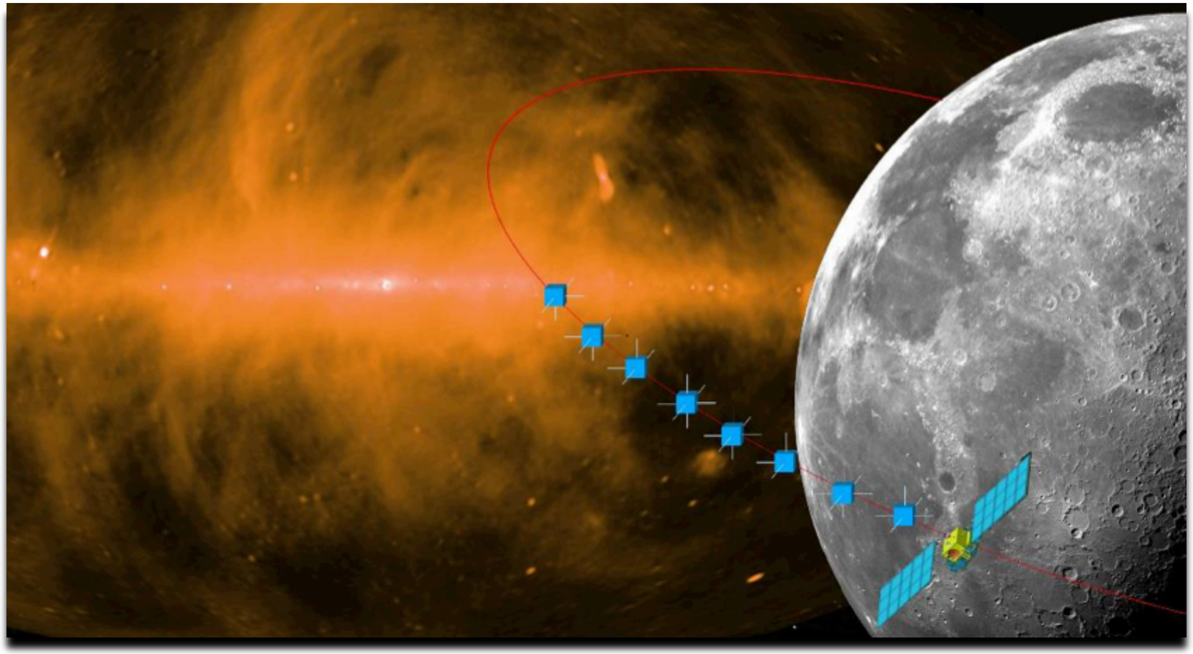






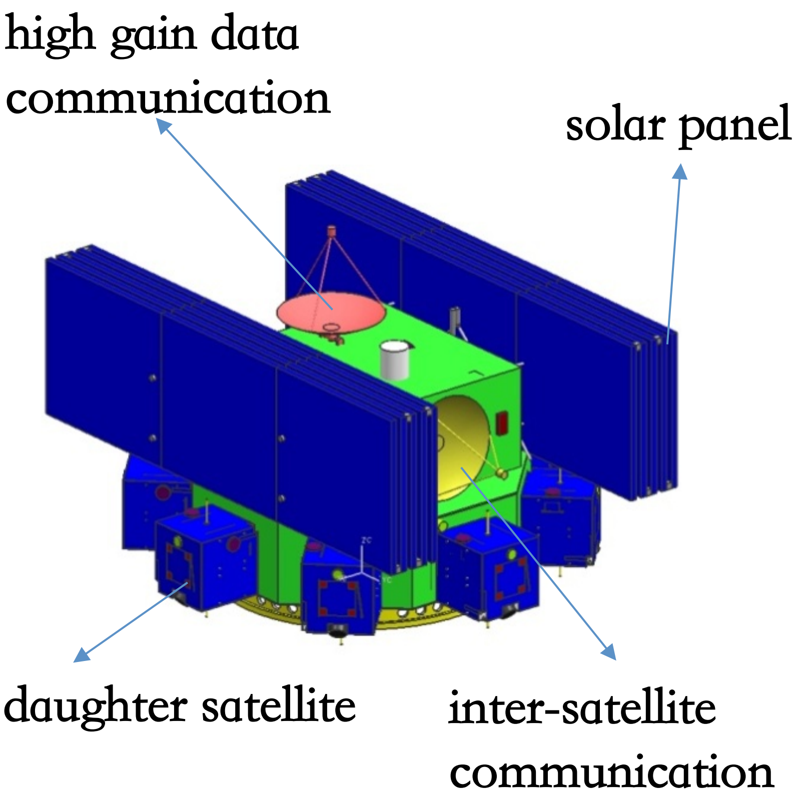
Lunar Orbit Array

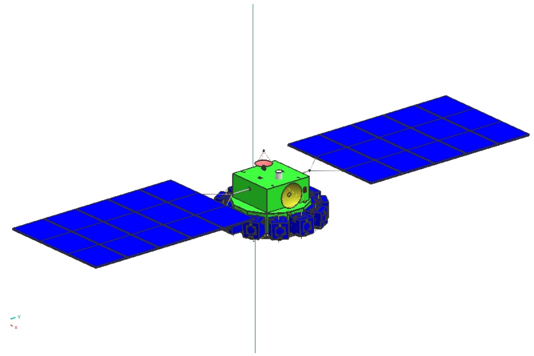
An interferometer array with one mother satellite and 5~8 daughter satellites, on a 300km circular orbit

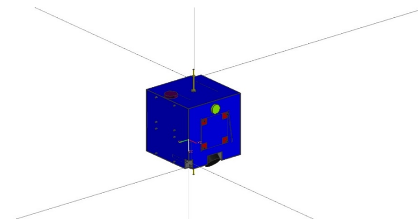


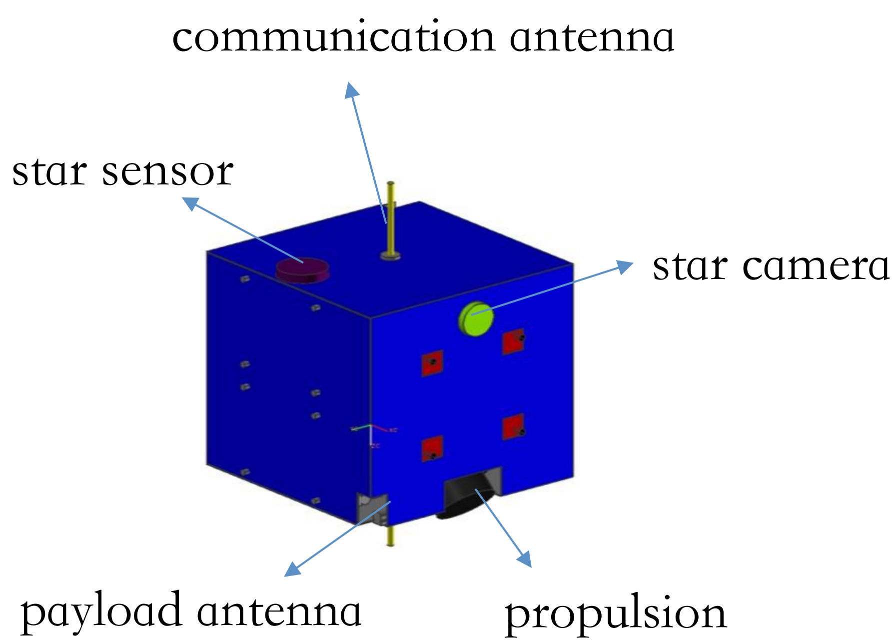
- **To obtain high resolution sky map at ultralong wavelength, openning up new window in eletromagnetic spectrum**
- **high precision measurement of global spectrum, to probe dark age and cosmic dawn**

Satellite System

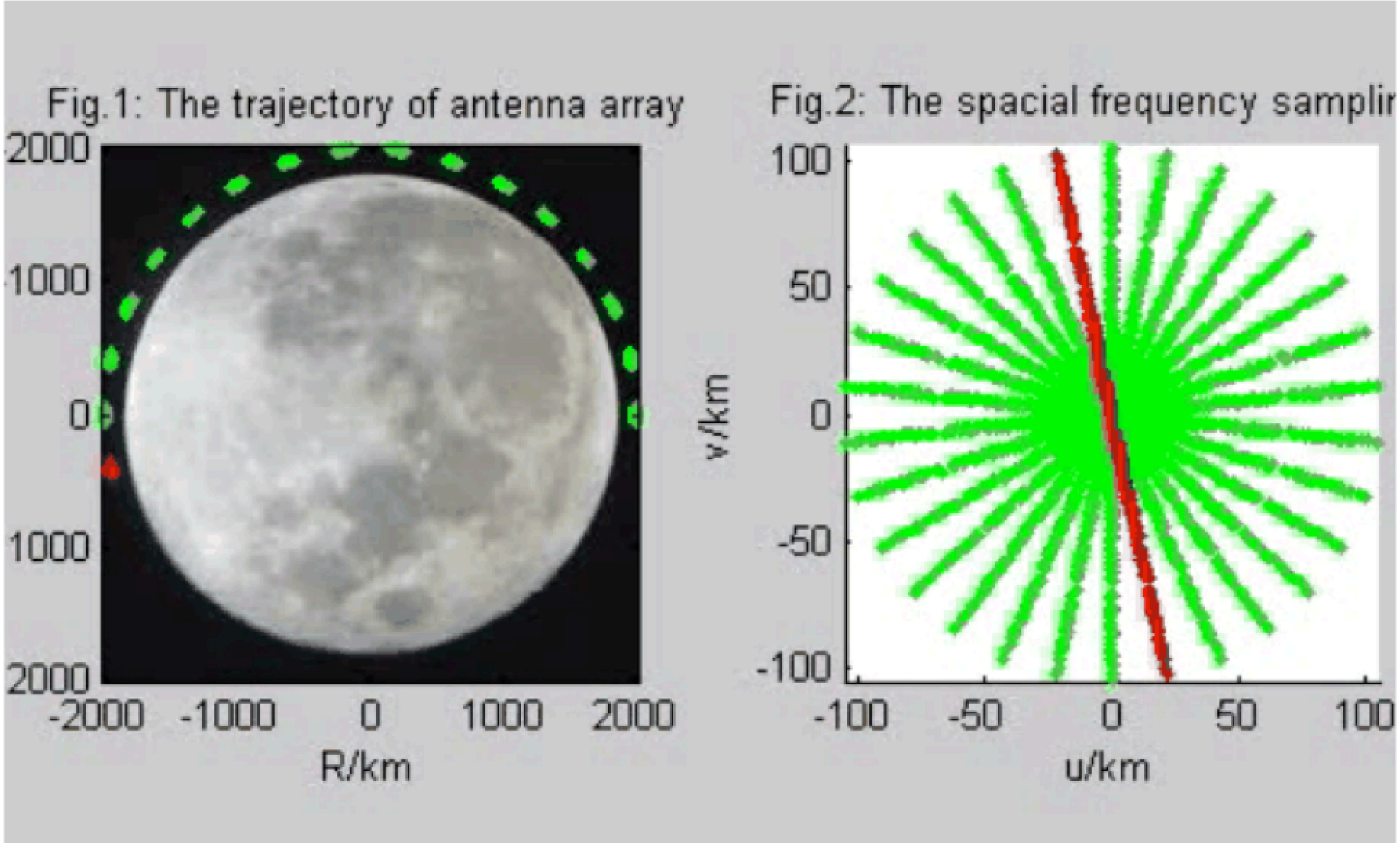






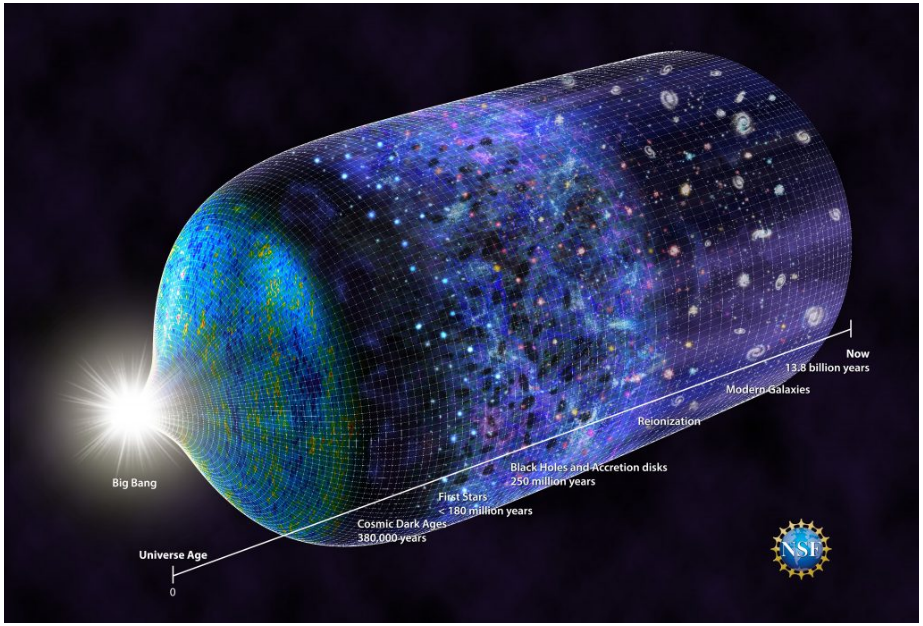


Baselines from Orbital motion

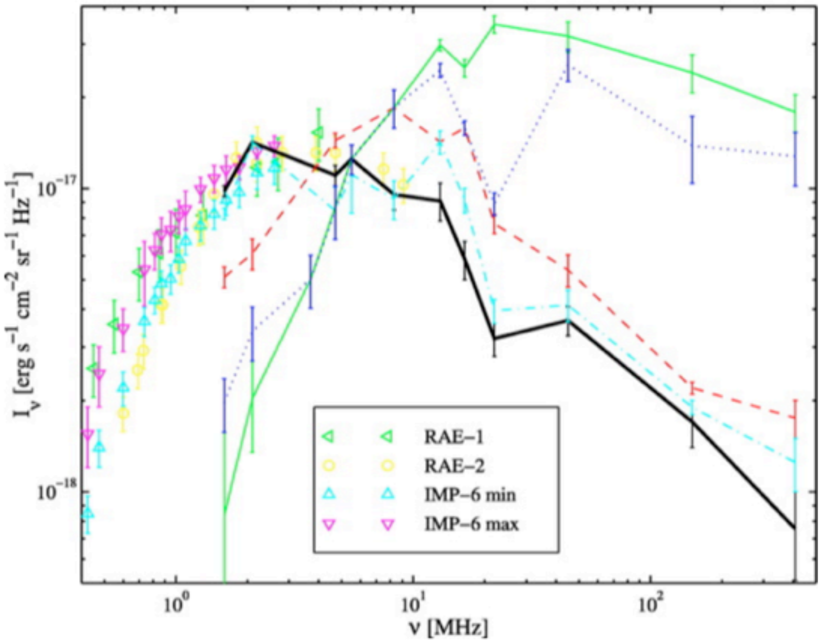


Science Objectives

- **Precision measurement of Global Spectrum, without the ionosphere refraction and absorption, to probe Cosmic Dawn and Dark Age**



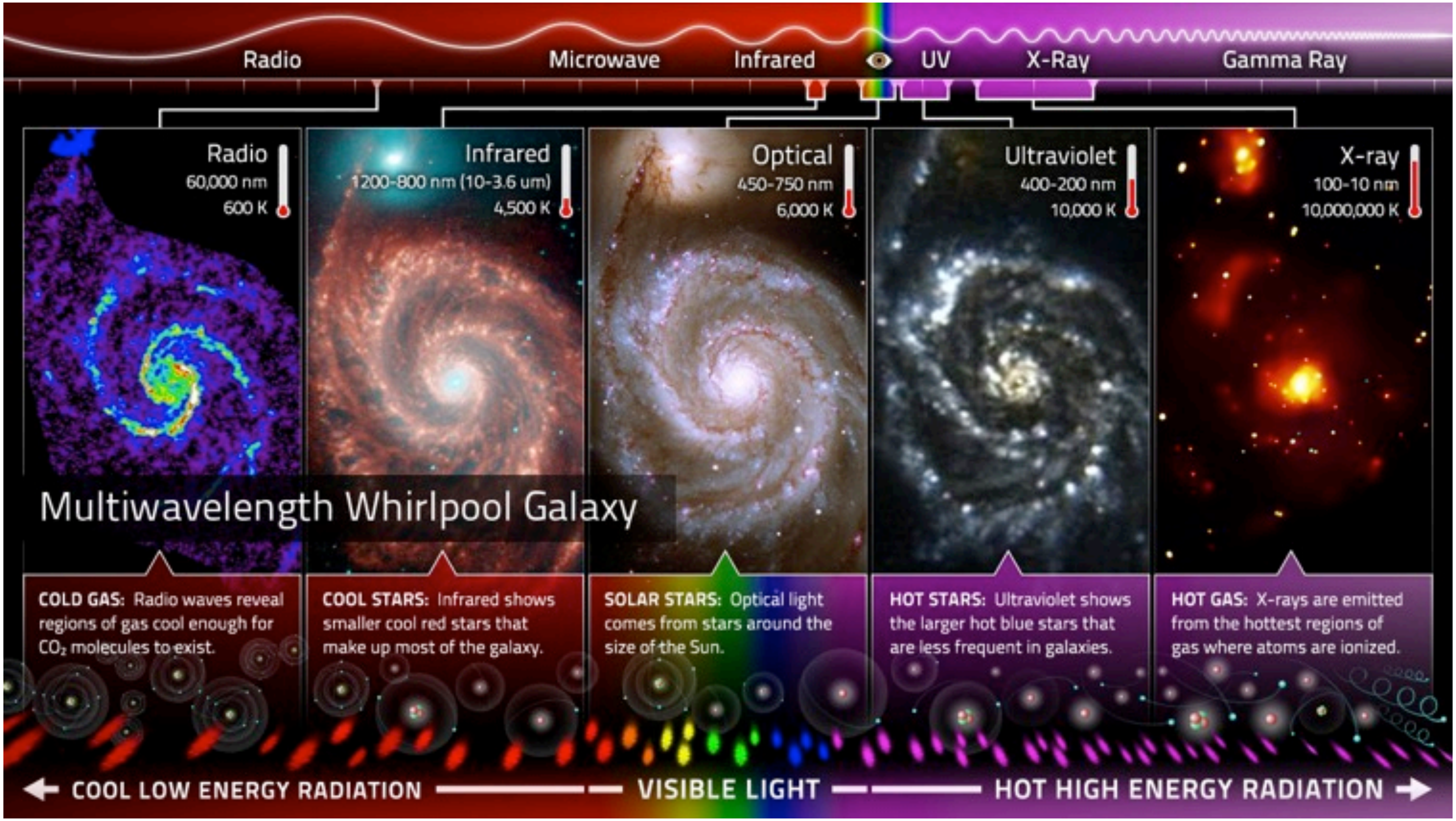
Low Frequency Global Spectrum



Keshet, Waxman & Loeb (2004)

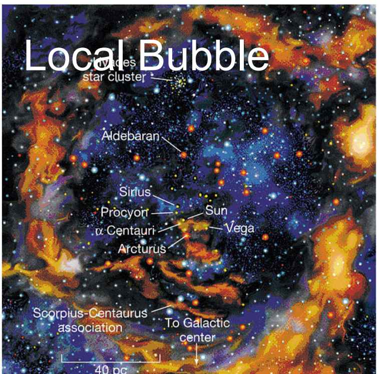
Science Objectives

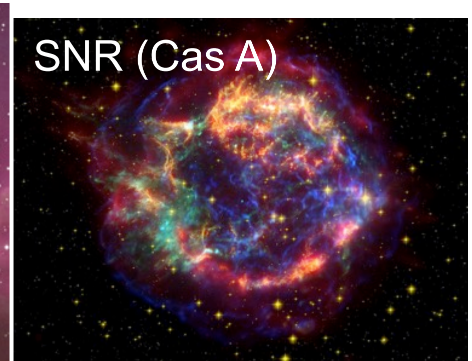
- ◆ **Open up the Low Frequency window, obtain sky map, discover the The Unknown Unknowns**

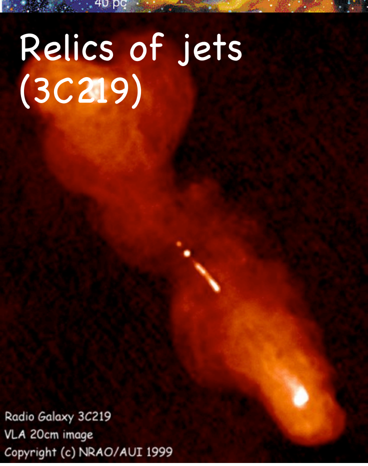


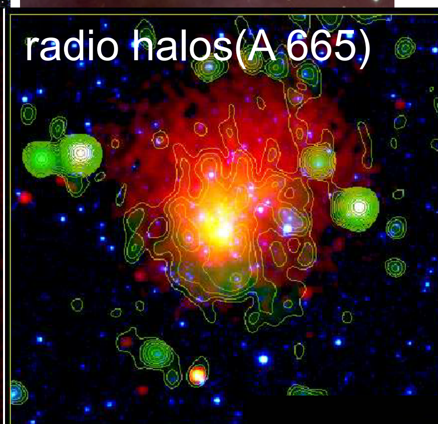
Science Objectives

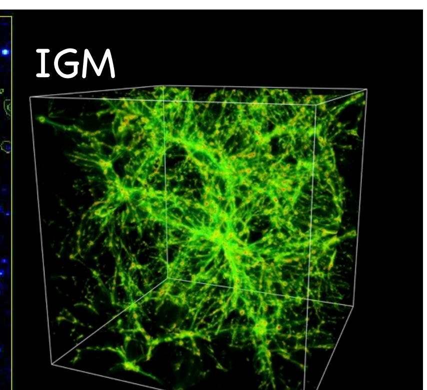
- **Provide new insights on ISM, Cosmic Ray, Supermassive Blackholes, Galaxy Clusters, IGM**

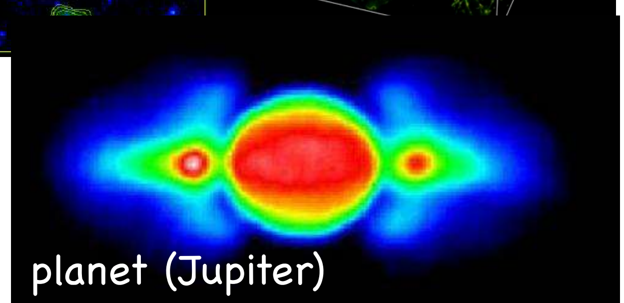




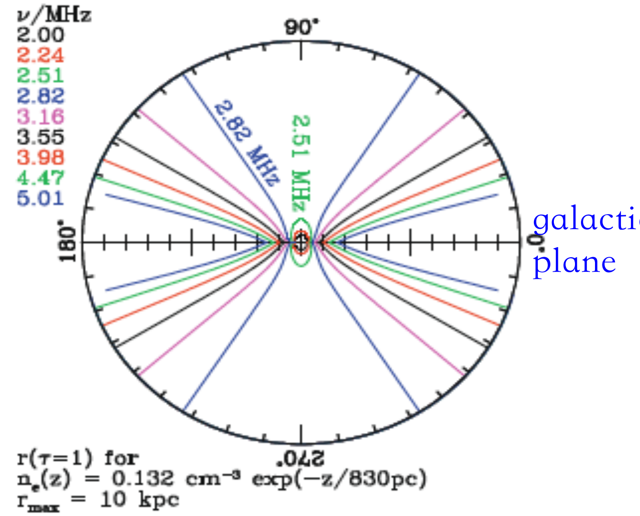




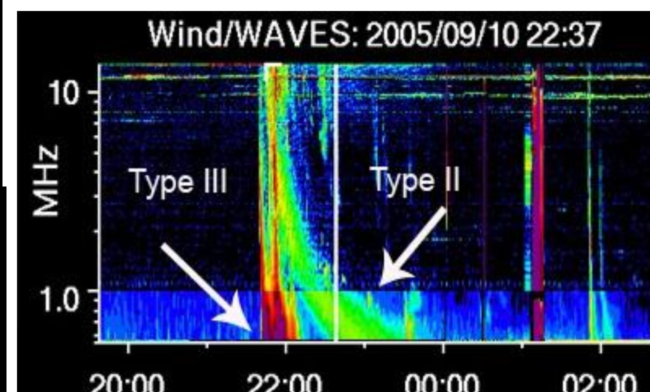




dark Galaxy at low f?



Critical Absorption (τ=1)
Jester & Falcke(2009)

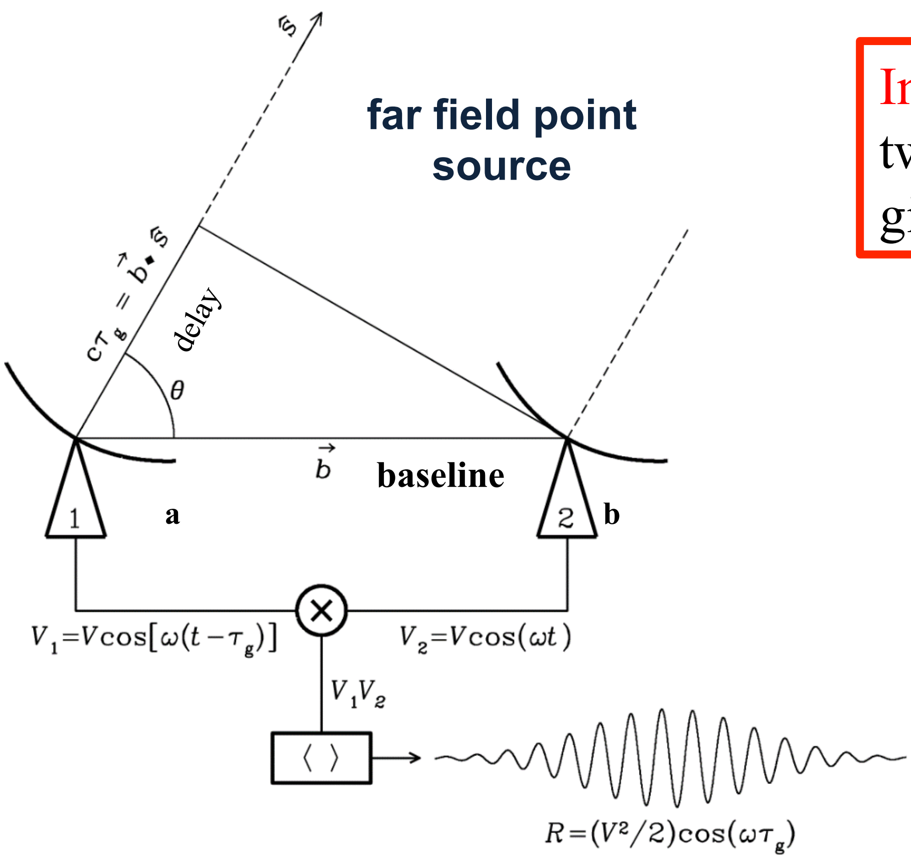


solar radio burst

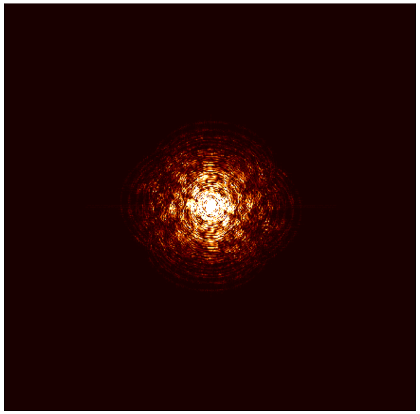
Interferometry

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

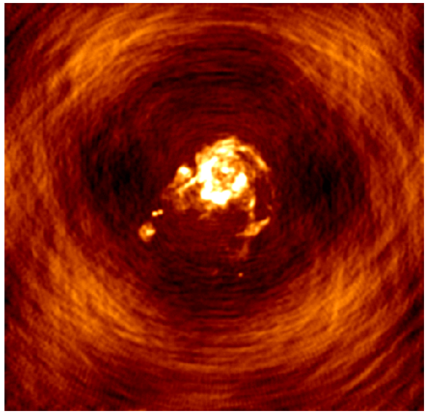
$\theta : \frac{\lambda}{D}$ → **θ <1°** → **10km aperture** { **real aperture X** / **vertual aperture ✓**



Interferometer measure cross-correlation of two units outputs, the resulting "visibility" gives Fourier components of sky intensity



Measured Visibilities



Image

Interferometer Array Realization

No need for high precision **adjustment** of satellite positions, but do **need** high precision of **relative position measurement**

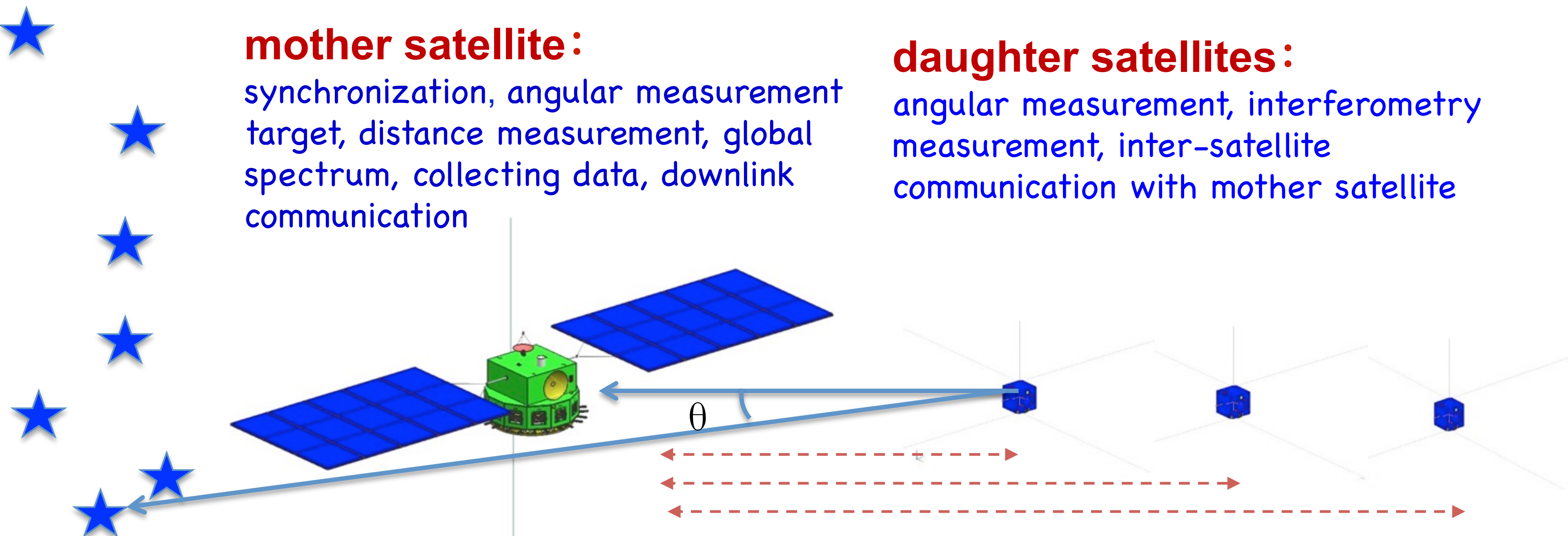
- Synchronization, Distance Measurement, Data Communication: microwave link between mother and daughter satellites
- Angular position: mother satellite carrying blinking LED lamp, daughter satellites use star sensor to determine position

mother satellite:

synchronization, angular measurement target, distance measurement, global spectrum, collecting data, downlink communication

daughter satellites:

angular measurement, interferometry measurement, inter-satellite communication with mother satellite



Star background for angle measurement

communication, ranging and synchronization through microwave link

Some Key Parameters

System	Parameter
Number of Satellites	1 mother + 5~8 daughters
Orbit	300km lunar cirlcular orbit, about 30^0 inclination
Baselines	0.1~100km
Sensitivity	＜0.1K@30MHz（1 year integration,1MHz BW）
angular resolution	＜0.2 degree@1MHz, 0.012 degree@30MHz
Individual	
Polarization	3 linear polarization
Frequency	1MHz~30MHz（interferometry incl. spectrum） 30MHz~120MHz（global spectrum）
Baseline prescision in each direction (1 σ)	＜ 1m
Synchronization	＜3.3ns
Inter-satellite data communication	＞20Mbps each daughter satellite

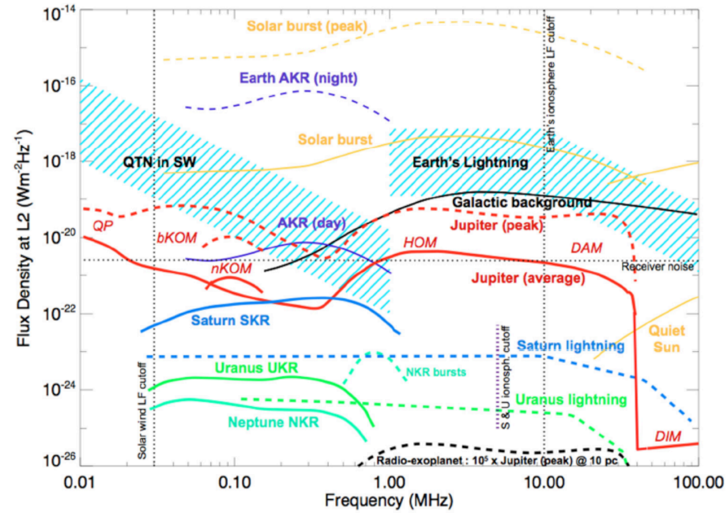
Sensitivity

- **Global Spectrum (3years，1/3 usable time)**

$$T_{rms} = \frac{T_{sys}}{\eta_Q \sqrt{\Delta \nu t}}$$

$$T_{sys}=T_{sky}+T_{rx}+T_{spill}$$

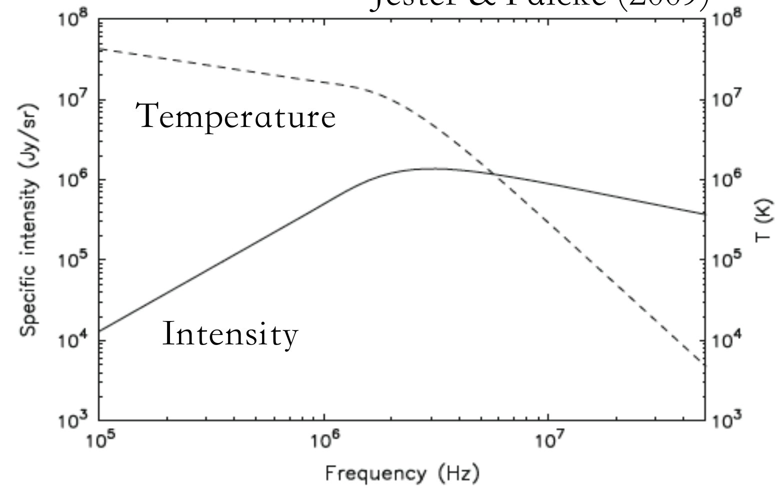
$$T_{sky} = \begin{cases} 16.3 \times 10^6 K (\frac{v}{2MHz})^{-2.53}, & v > 2MHz \\ 16.3 \times 10^6 K (\frac{v}{2MHz})^{-0.3}, & v \leq 2MHz \end{cases}$$



80 MHz $\quad T_{sky} = 1.44 \times 10^3$K, $\quad T_{rms} = 27.5$mK orbit, $\quad$ 0.26mK mission;

30 MHz $\quad T_{sky} = 1.7 \times 10^4$K, $\quad T_{rms} = 329$mK orbit, $\quad$ 3mK mission;

Jester & Falcke (2009)



- **Imaging（1/3 time，10 MHz, BW=1MHz, sky noise-dominated）**

$$S_{rms} = \frac{2kT_{sys}}{A\eta_Q\sqrt{n_a(n_a-1)n_{pol}\Delta\nu t}}$$

$S_{rms} = 27.8$Jy per orbit, $\qquad S_{rms} = 0.26$Jy mission;

$S_{rms} = 9.1$Jy per orbit, $\qquad S_{rms} = 0.086$Jy mission;

System Performance Analysis

- **Angular Resolution**

$$\theta \sim \frac{\lambda}{D}$$

ISM and IPM scattering

$$\vartheta_{\mathrm{ISM}} \approx \frac{30'}{(\nu/\mathrm{MHz})^{2.2}\sqrt{\sin b}},$$

$$\vartheta_{\mathrm{IPM}} \approx \frac{100'}{(\nu/\mathrm{MHz})^{2}}$$

Diffraction Limit

	10 km baseline	30 km baseline	100 km baseline
1 MHz	1.7°	0.57°	0.17°
10 MHz	0.17°	0.057°	0.017°
30 MHz	0.057°	0.019°	0.0057°

The angular resolution is limited by scattering, 100km baseline sufficient

- **Dispersion and Scattering**

$$\Delta t = 4.15 \times 10^3 \, \mathrm{DM} \, (\nu/\mathrm{MHz})^{-2} \, \mathrm{s}$$

Observing pulsars and FRBs would be hard due to very large dispersion delays

- **Depolarization**

$$\Delta\psi_{\mathrm{RMS}} = 2.6 \times 10^{-13} \, \lambda^2 \, \Delta N_e \, \lambda^2 a \, B_{\parallel} \sqrt{L/a} \, \mathrm{rad},$$

At this frequency, linear polarization is greatly reduced by depolarization. Circular polarization may be observable.

Key Technology and Challenges

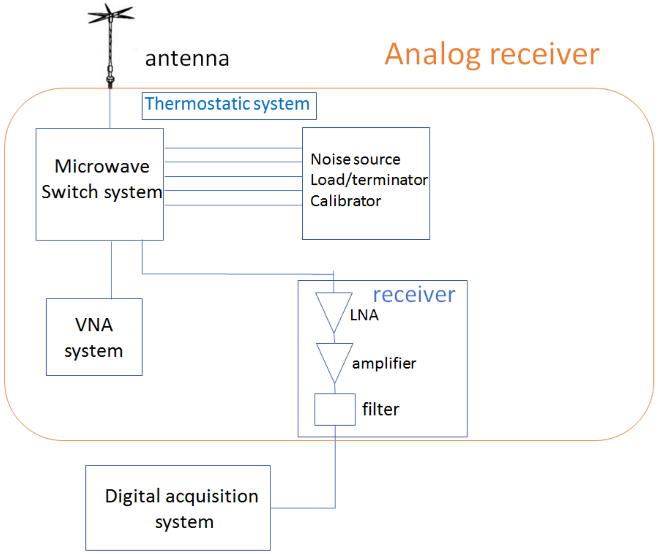
① Satellite Formation Fly in lunar orbit with large variation on scales

② Precision Measurement of Relative Positions and synchronization

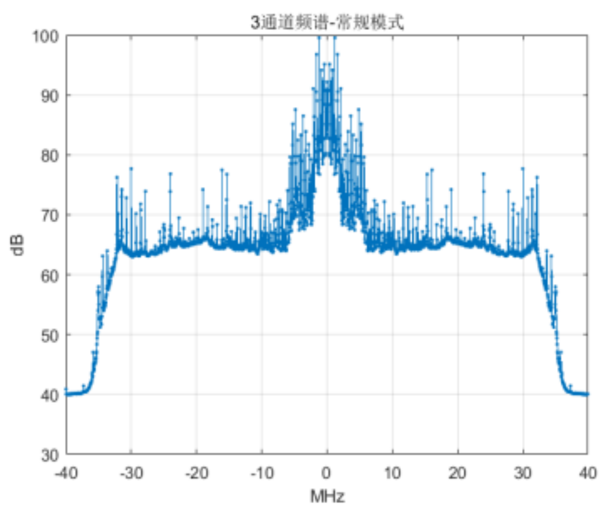
③ High precision calibration of phase and amplitude

④ Imaging algorithm with large field of view, 3D baseline distribution, and time-dependent blockage

⑤ Electromagnetic interference (EMI) suppresion and removal



Spectrometer



EMI

Synthesis Imaging with Lunar Array

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

- Conventional radio astronomy interferometer array: For nearly planar array, small field of view, small-w approximation: 2D FFT

$$V_{ij}(u,v,w) = \int \frac{\mathrm{d}l\,\mathrm{d}m}{n} A_{ij}(l,m)\, T(l,m)\, e^{-i2\pi[ul+vm+w(n-1)]}$$

$$\frac{A(x,y)I(x,y)}{\sqrt{1-x^2-y^2}} = \int\int dudv V(u,v) e^{-i2\pi(ux+vy)}$$

- For large FOV, or non-planar array, needs to take into account of the w-term:

3D Fourier transform: $V(u,v,w)e^{-i2\pi w} = \int \frac{I(l,m)\,\delta\sqrt{1-l^2-m^2}-n}{\sqrt{1-l^2-m^2}} e^{-i2\pi[ul+vm+wn]}\, dl\, dm\, dn$

w-projections: $V(u,v,w) \otimes \mathcal{K}^*(u,v,w) = V(u,v,0)$

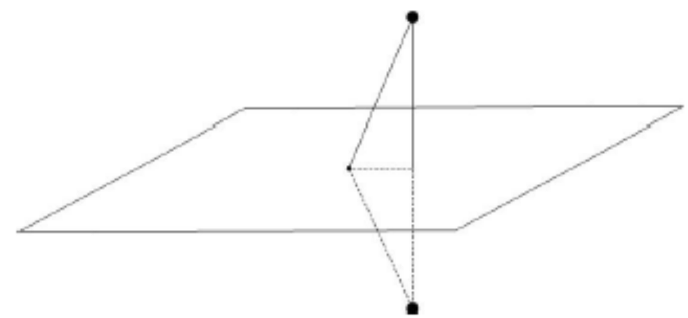
$$\mathcal{K}(u,v,w) = \int e^{-i2\pi w(\sqrt{1-l^2-m^2}-1)}\ e^{-i2\pi(ul+vm)}\ dl\, dm$$

w-stacking: $\frac{I(l,m)\ (w_{\max} - w_{\min})}{\sqrt{1-l^2-m^2}} = \int_{w_{\min}}^{w_{\max}} e^{i2\pi w(\sqrt{1-l^2-m^2}-1)}\ \mathcal{F}^{-uv}\ [V(u,v,w)]\, dw$

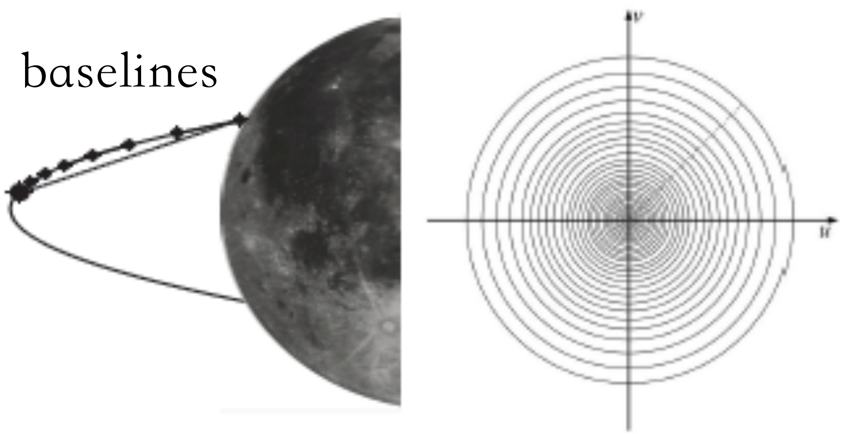
Problems

But here we face the following problems:

- whole sky field of view,
- problem of mirror symmetry,
- 3D distribution of baselines
- Position-dependent blockage



mirror symmetry



Kill two birds with one stone:
3D baselines actually solves the mirror symmetry problem

Position-dependent blockage by moon: visibility for each baseline has different part of sky blocked by the Moon!

Image Reconstruction

- Fundamentally, the relation between the sky intensity and visibility is a time-dependent (but known) linear map.

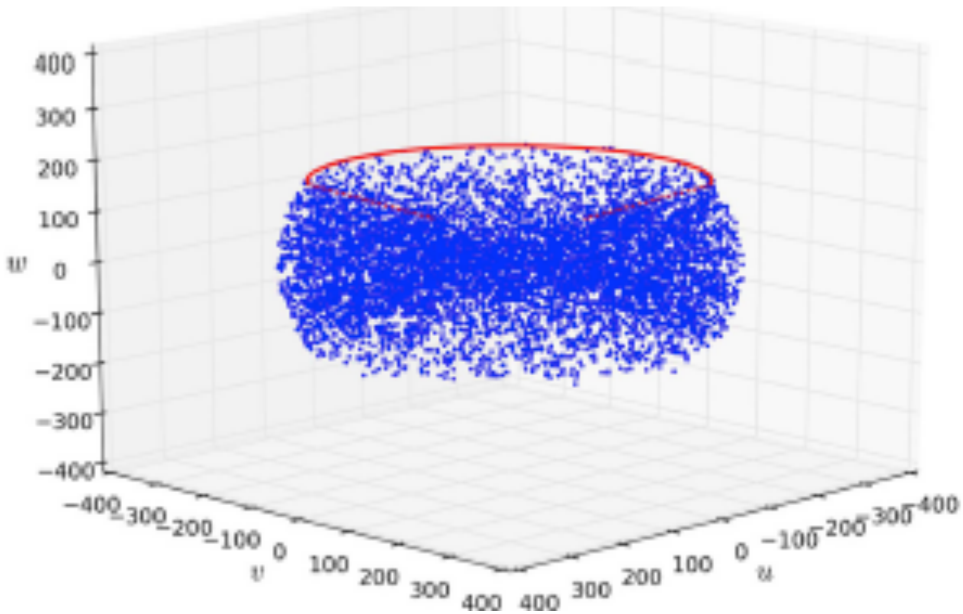
$$\mathbf{V} = \mathbf{B}\,\mathbf{I} + \mathbf{n}$$ B=A S(t) I, S: screening by Moon

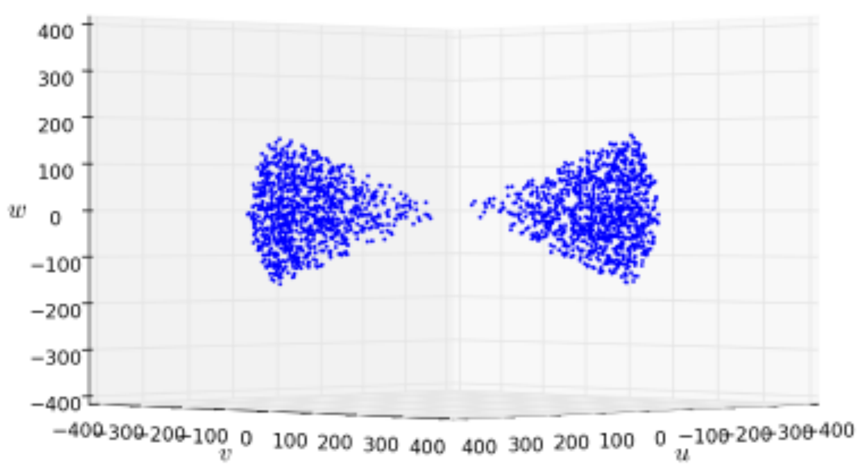
- So one can invert the map and obtain the image.

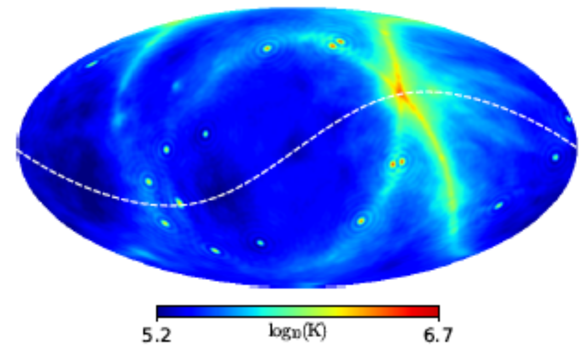
$$\hat{\mathbf{I}} = (\mathbf{B}^{\dagger}\mathbf{N}^{-1}\mathbf{B})^{-1}\mathbf{B}^{\dagger}\mathbf{N}^{-1}\mathbf{V}$$

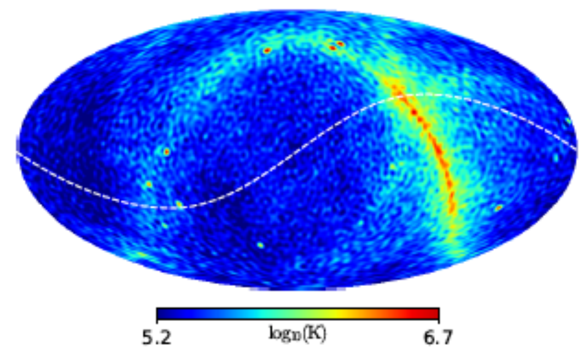
- Spherical Harmonic Expansion can be employed to reduce computation

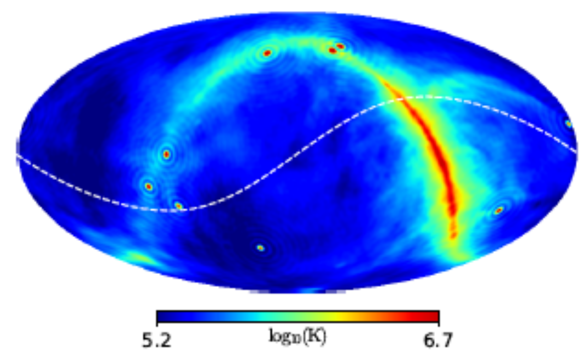
Break mirrow symmetry by 3D baselines







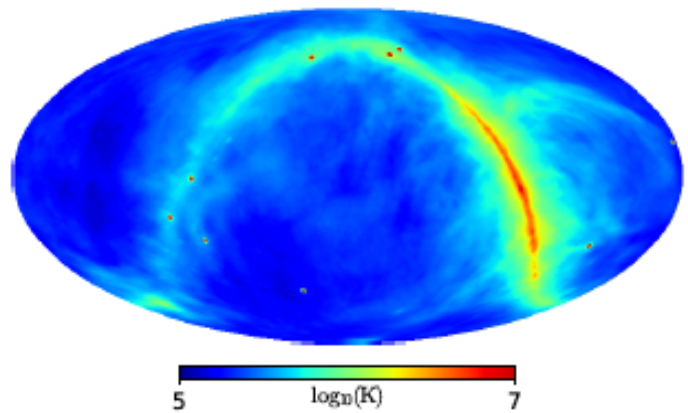




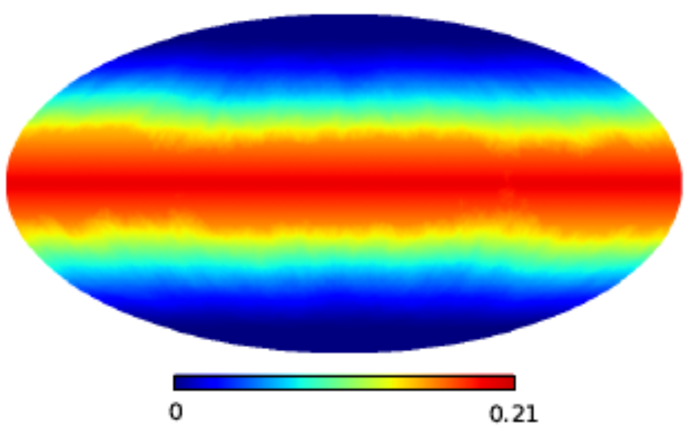
Reconstruction Results

input map

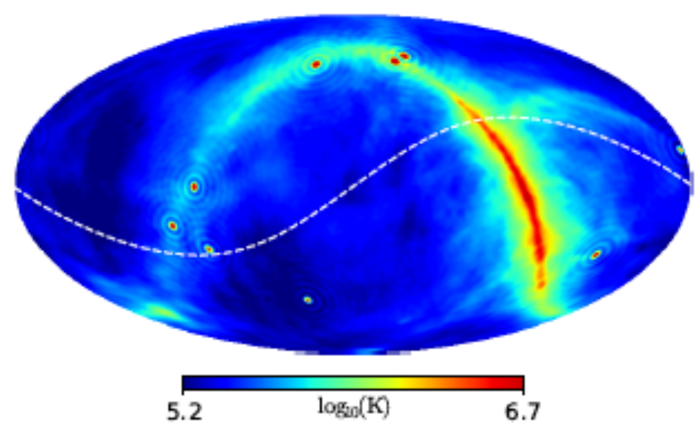
Q. Huang et al.:
AJ 156, 43 (2018)



blockage



reconstructed map

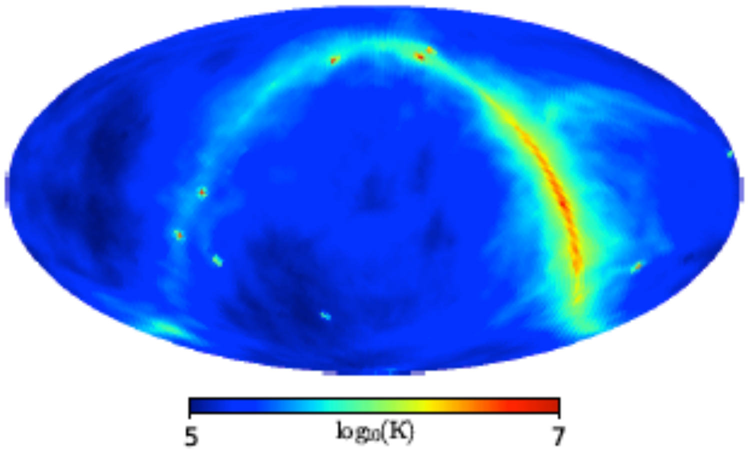


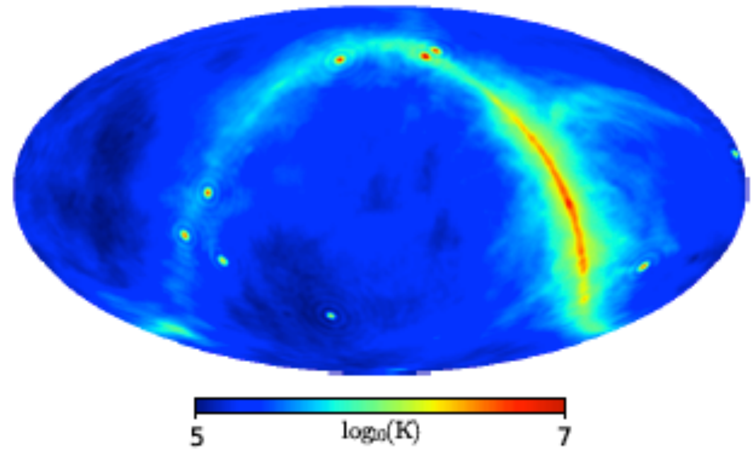
Errors in the reconstruction result

pixel space reconstruction

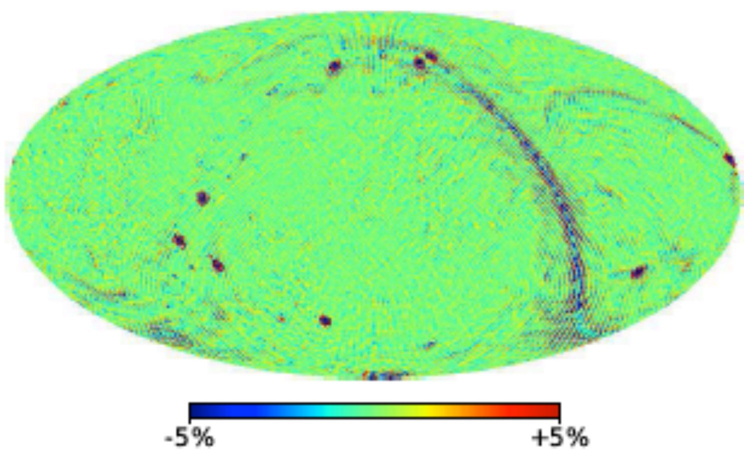
harmonic space reconstruction

Reconstructed Map





Relative Error



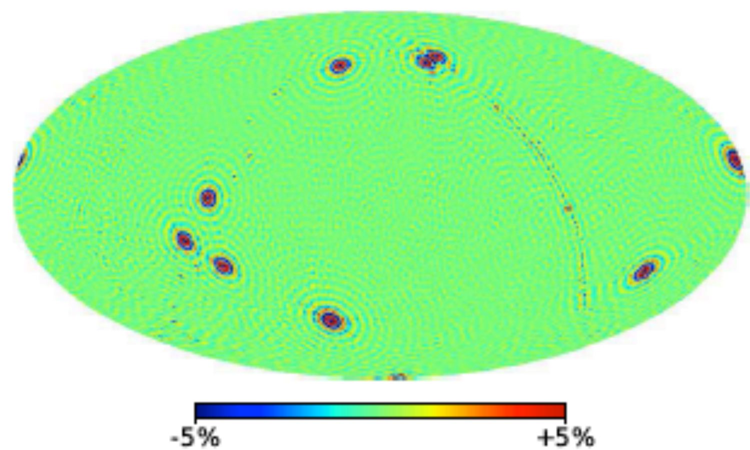
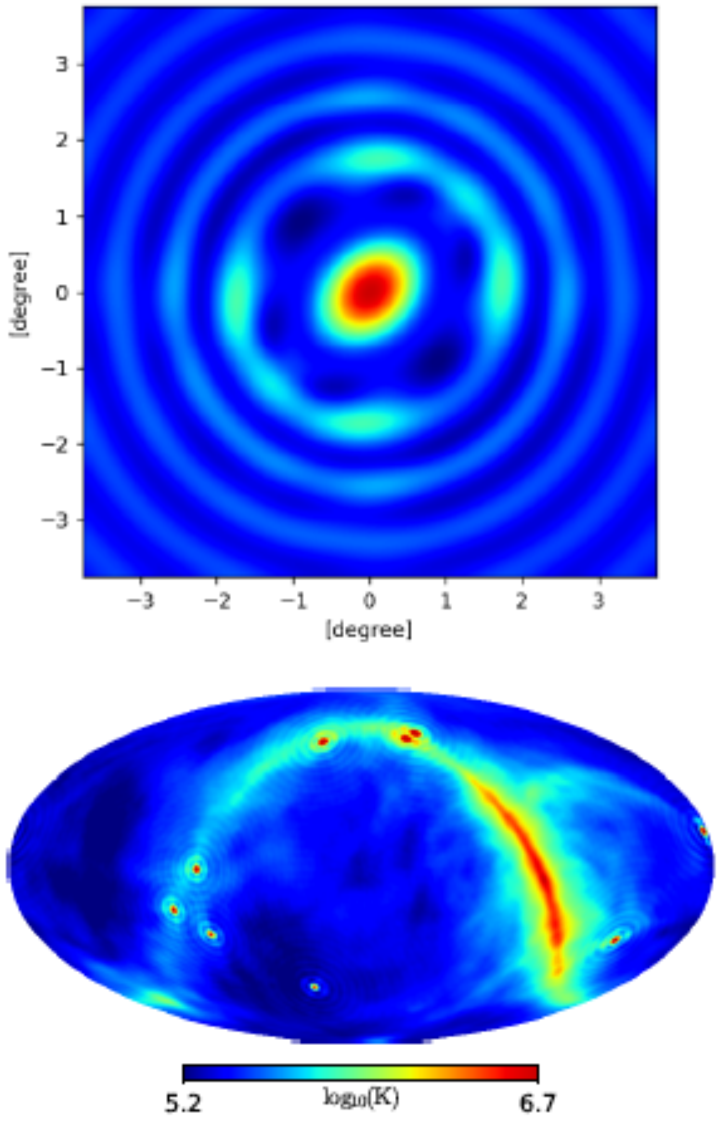
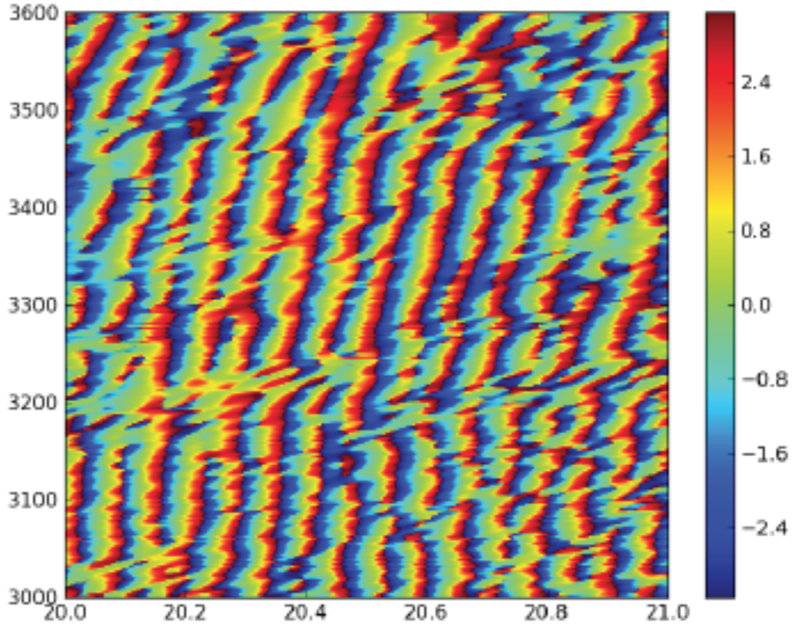


Image with asymmetric baselines



Problems to be solved

- Effect of noise and sensitivity
- Antenna Directionality
- Error in Position Measurement and Synchronization
- Calibration Method
- Reflection of the Moon
- Optimal Strategy

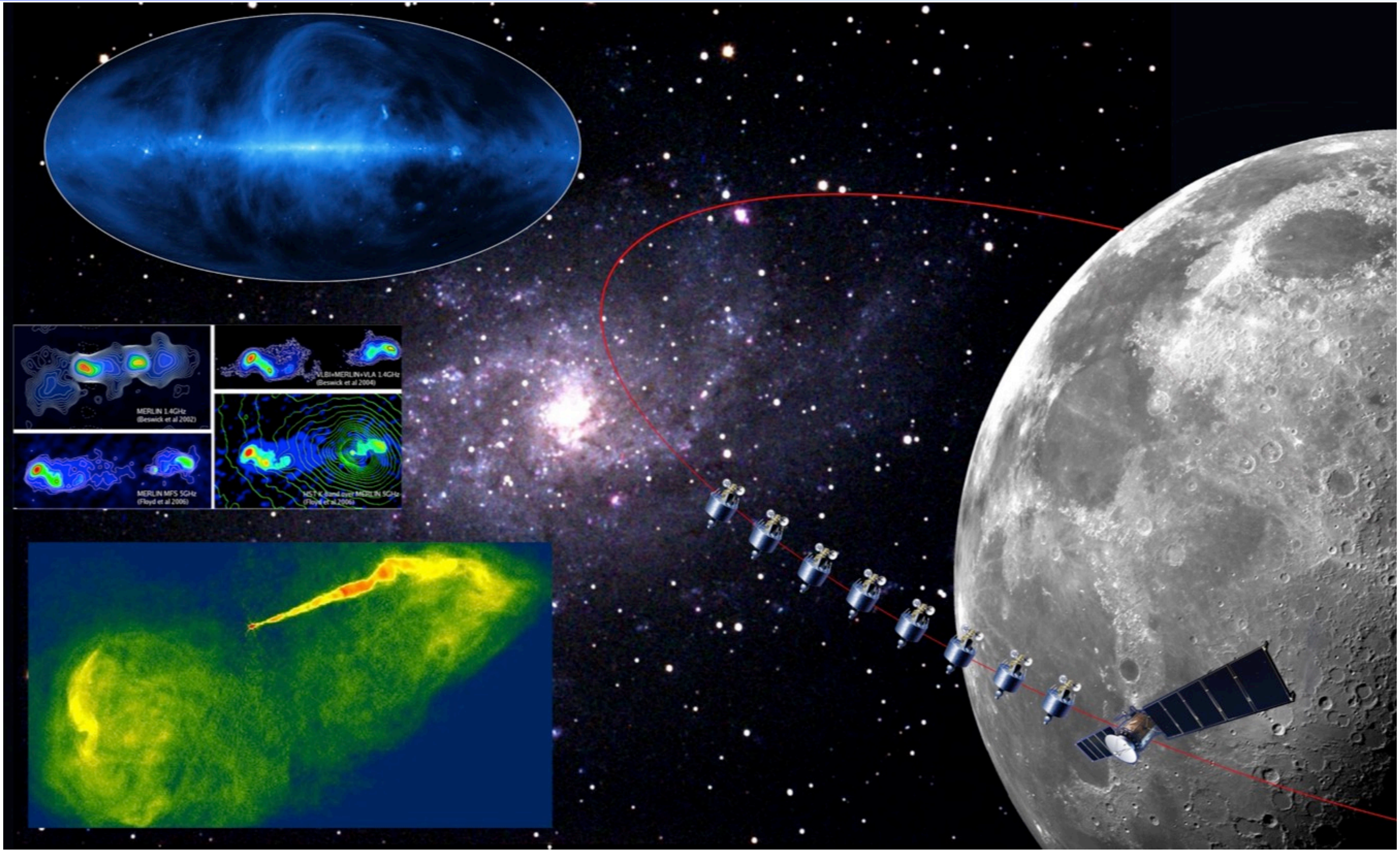


Simulated fringes (Zuo et al. in progress)

Project Status

- Currently undergoing intensive study.
- PI: Xuelei Chen (NAOC), Technology Chief: Jingye Yan (NSSC)
- NAOC team: Yidong Xu, Fengquan Wu, Maohai Huang, Linjie Chen, Mo Zhang, Shijie Sun
- NSSC team: Li Deng, Lin Wu, Fei Zhao, Li Zhou, Ailan Lan, Zhugang Wang, ...
- International Collaboration Welcome!
- Interested researchers welcome to join the Science Working Group, to discuss the science cases and key technologies
- A Science Whitepaper, first draft November this year, and continue to revise in the next two years

Thanks!


MERLIN 1.4GHz
(Beswick et al 2002)
VLBI+MERLIN+VLA 1.4GHz
(Beswick et al 2004)
MERLIN MFS 5GHz
(Floyd et al 2006)
(Floyd et al 2006)