6th INPE Advanced School on Astrophysics
21cm Cosmology in the 21st Century

The Tianlai 21cm Intensity Mapping Experiment

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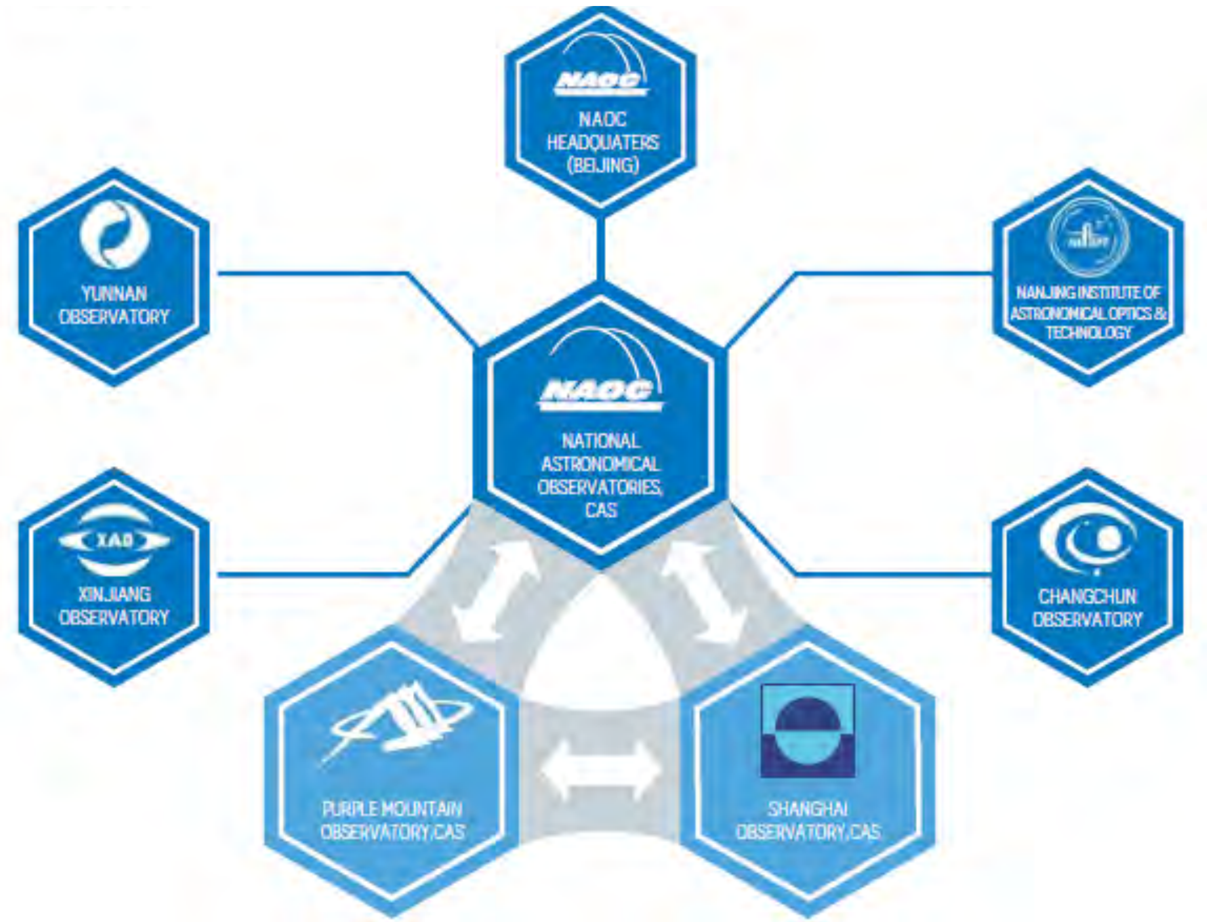
INPE, São José dos Campos, Brazil,
2018.08.15

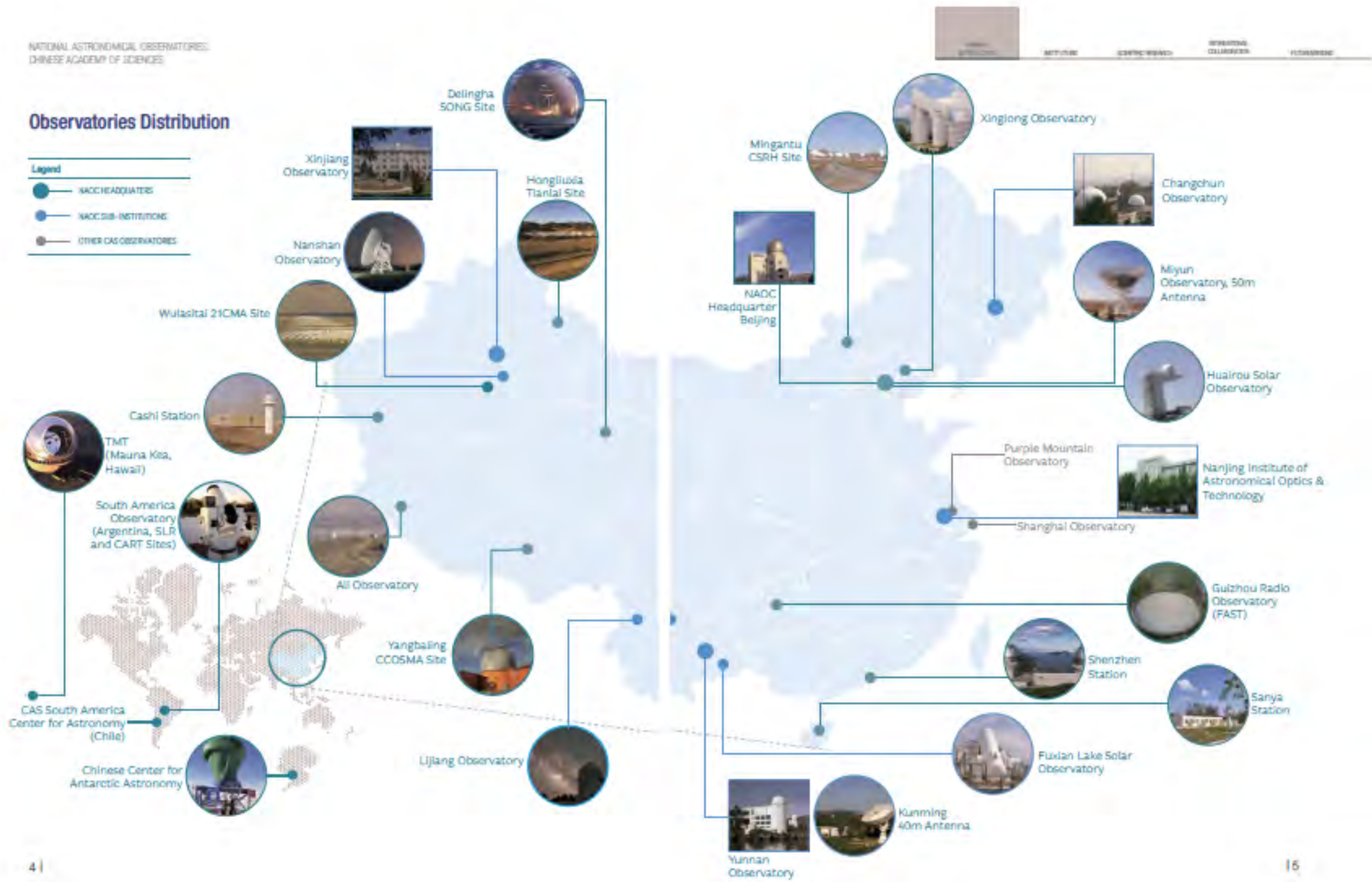
About NAOC

The Chinese Academy of Sciences comprises 12 branches, 104 research institutes, 3 universities (UCAS, USTC, SHTU), 11 supporting organizations, 20+ companies



FAST LAMOST

Astronomical Facilities in China



21cm Cosmology

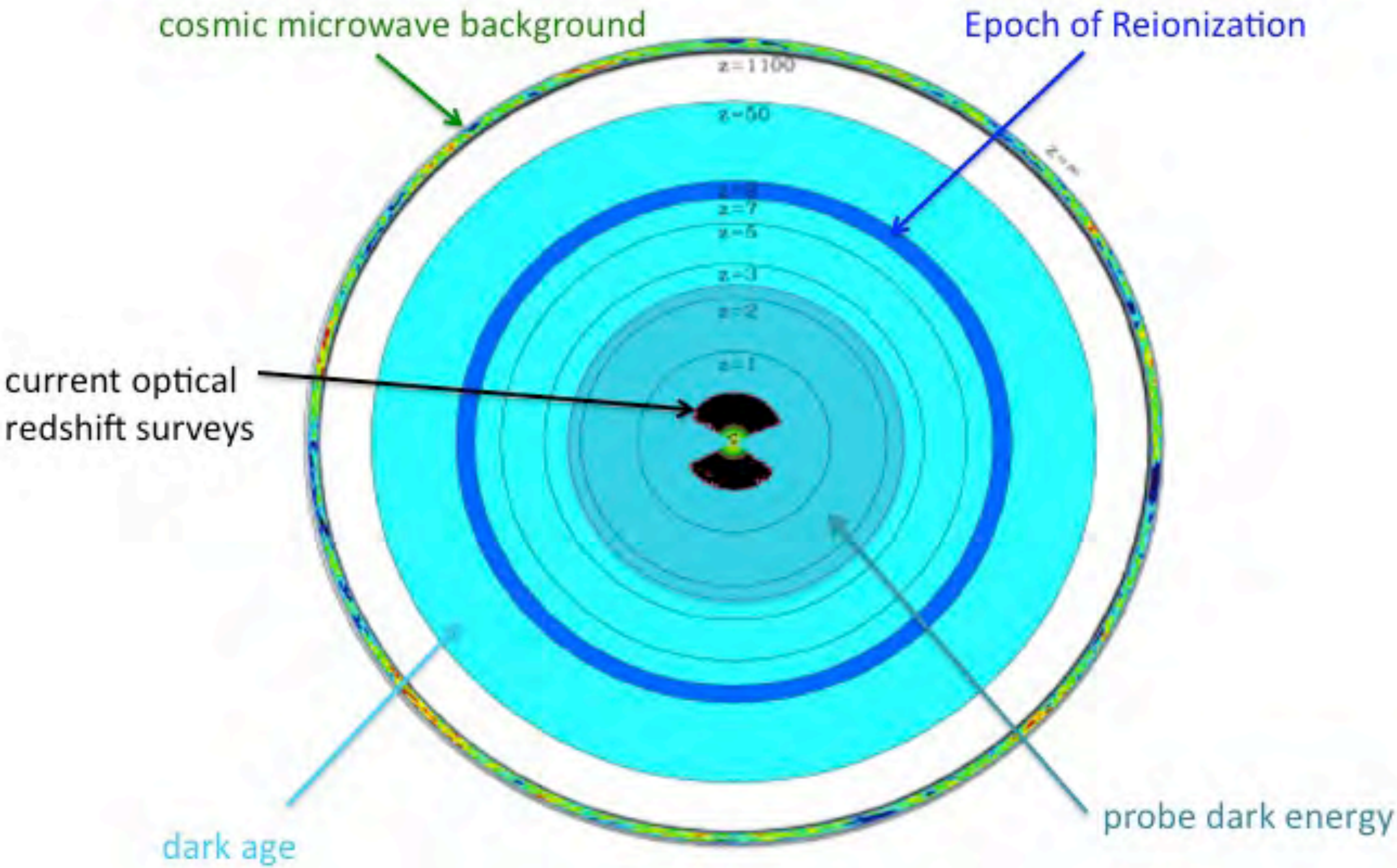
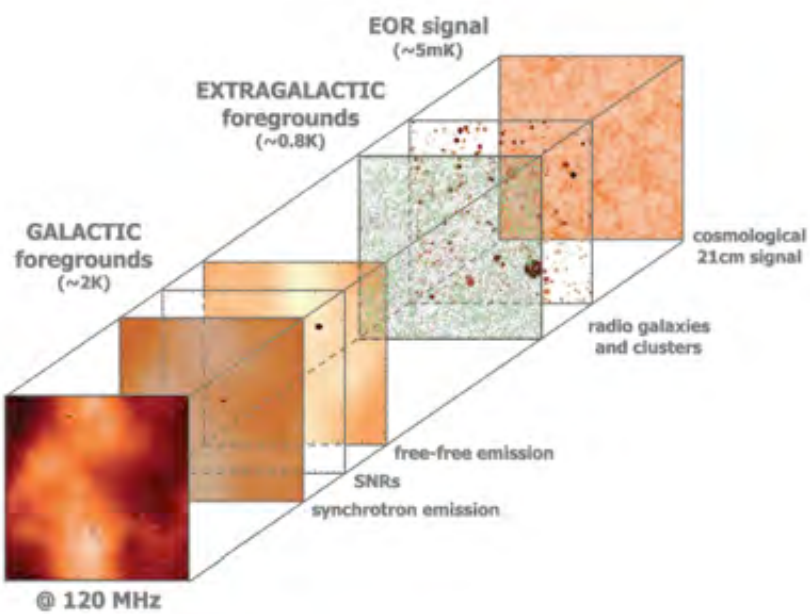


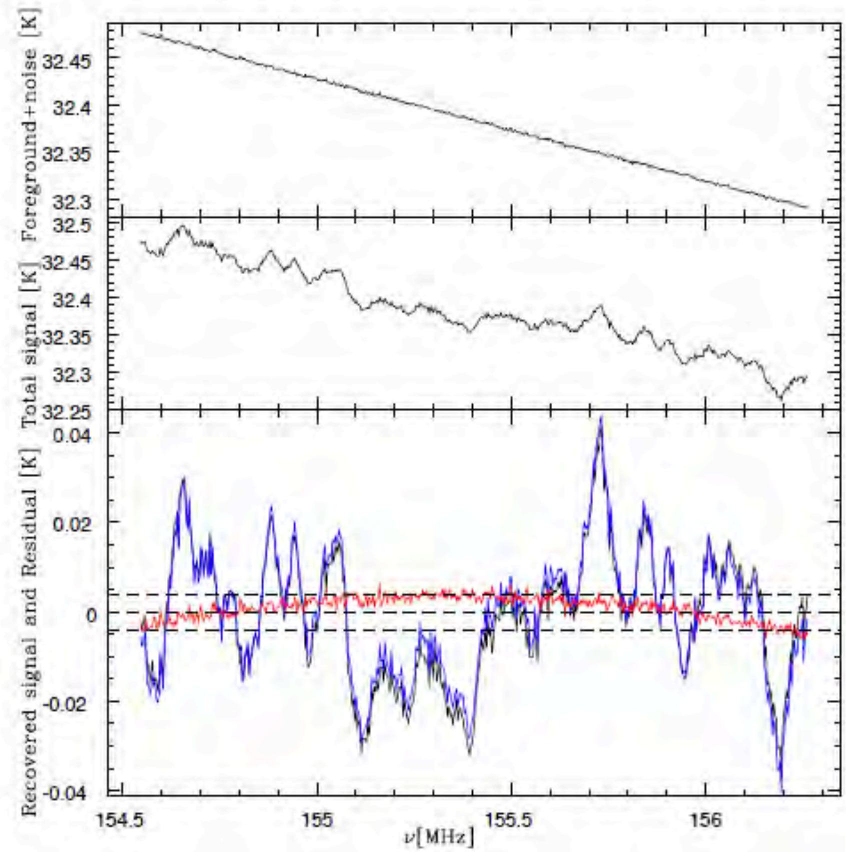
Figure inspired by Yi Mao & Max Tegmark

The challenge: strong foreground

raw signal to noise ration (SNR) ~ 10^{-5}



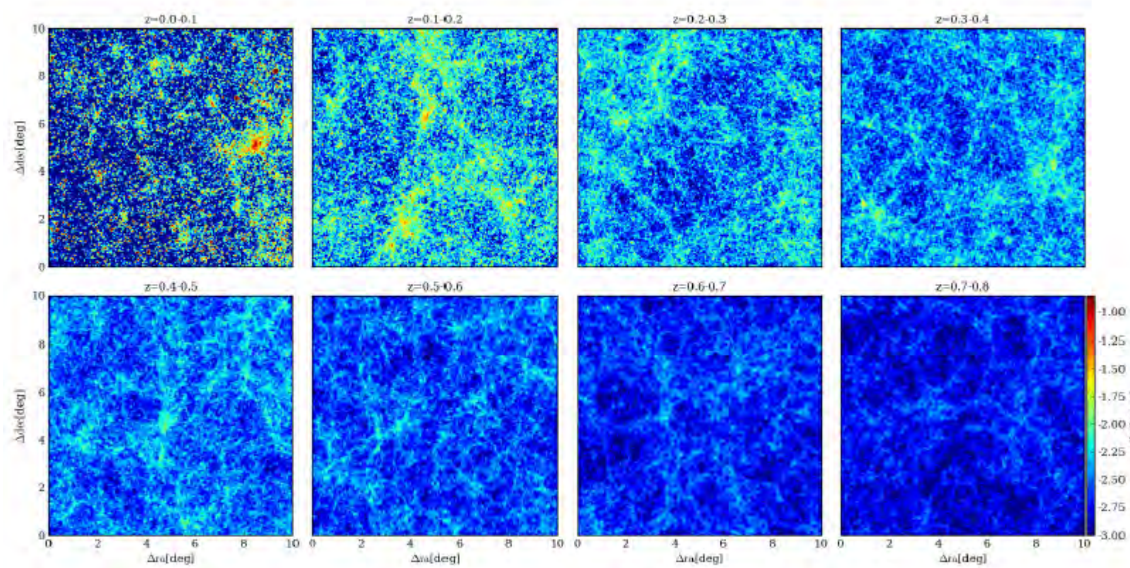
V. Jelic et al. (2010)



X. Wang et al. (2006)

FAST Intensity Mapping Survey

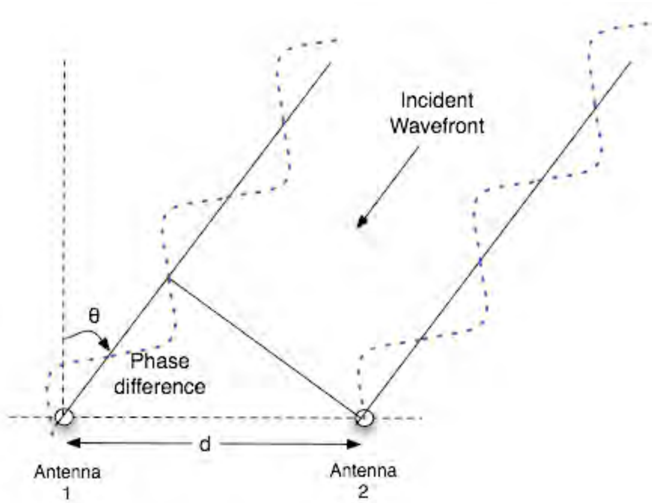
FAST

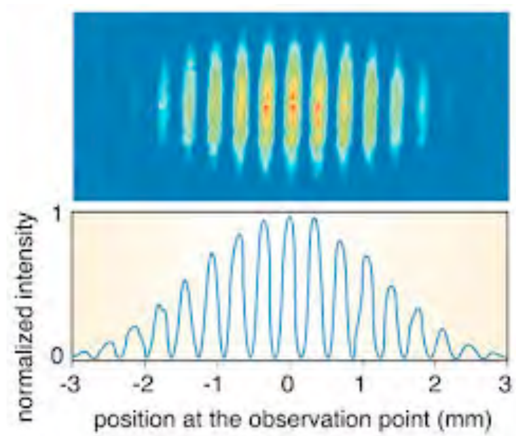


Hu et al. in preparation

Requirement for 21cm array

- interferometer array to get higher angular resolution
- Each array baseline (u,v) measures a Fourier mode





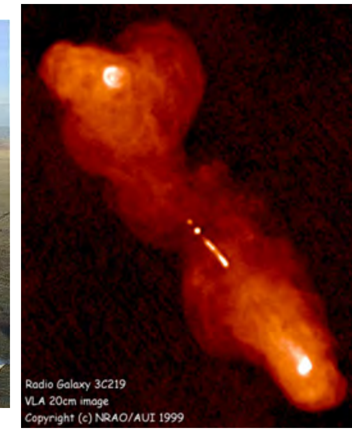
Visibility: $V_{ij} \equiv \langle s_i^* \times s_j \rangle$

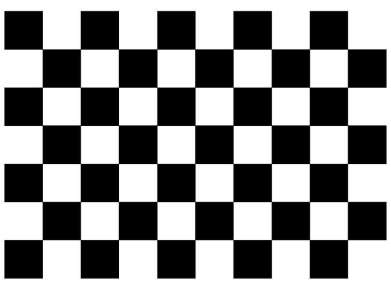
$$V(\mathbf{B}) = \int\int d\sigma A(\sigma) I(\sigma) \exp(i\frac{\omega}{c}\mathbf{B}\cdot\sigma)$$

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

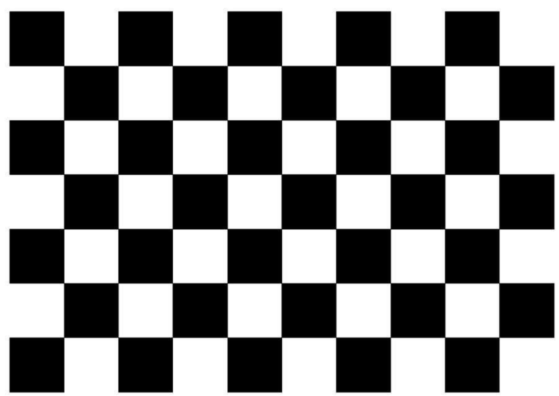
Requirement for 21cm array

- traditional array does NOT measure all modes, but good image can still be achived
- But to use frequency smoothness/ sparseness for foreground subtraction, we do need to sample the uv space completely





short wavelength



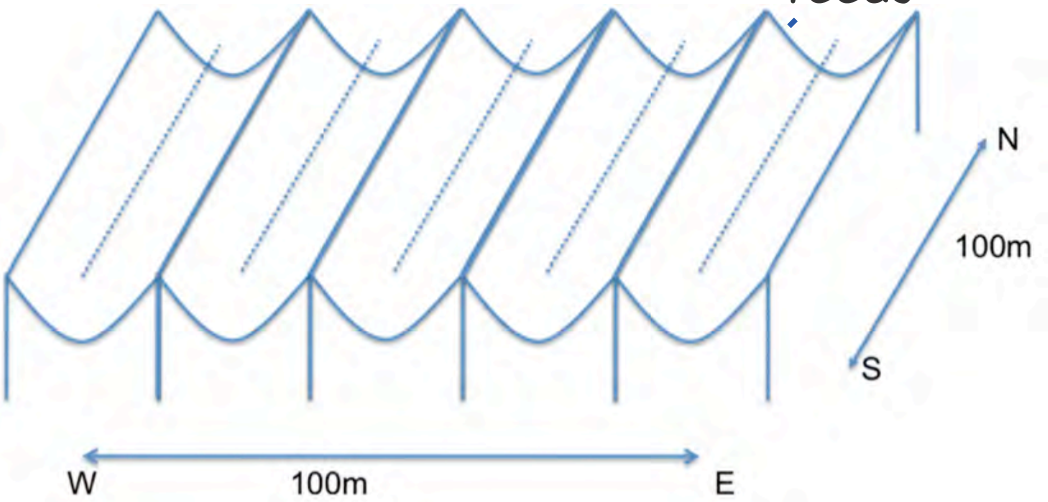
Long wavelength

Cylinder Arrays

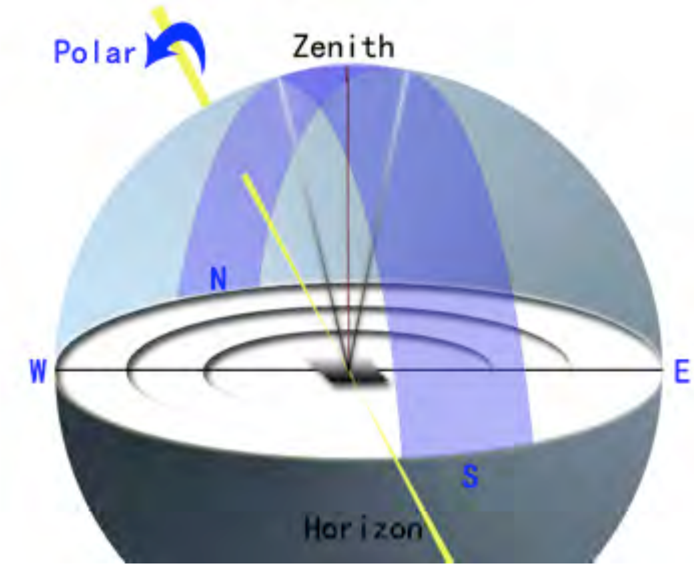
Drift Scan Cylinders (Peterson & Pen):

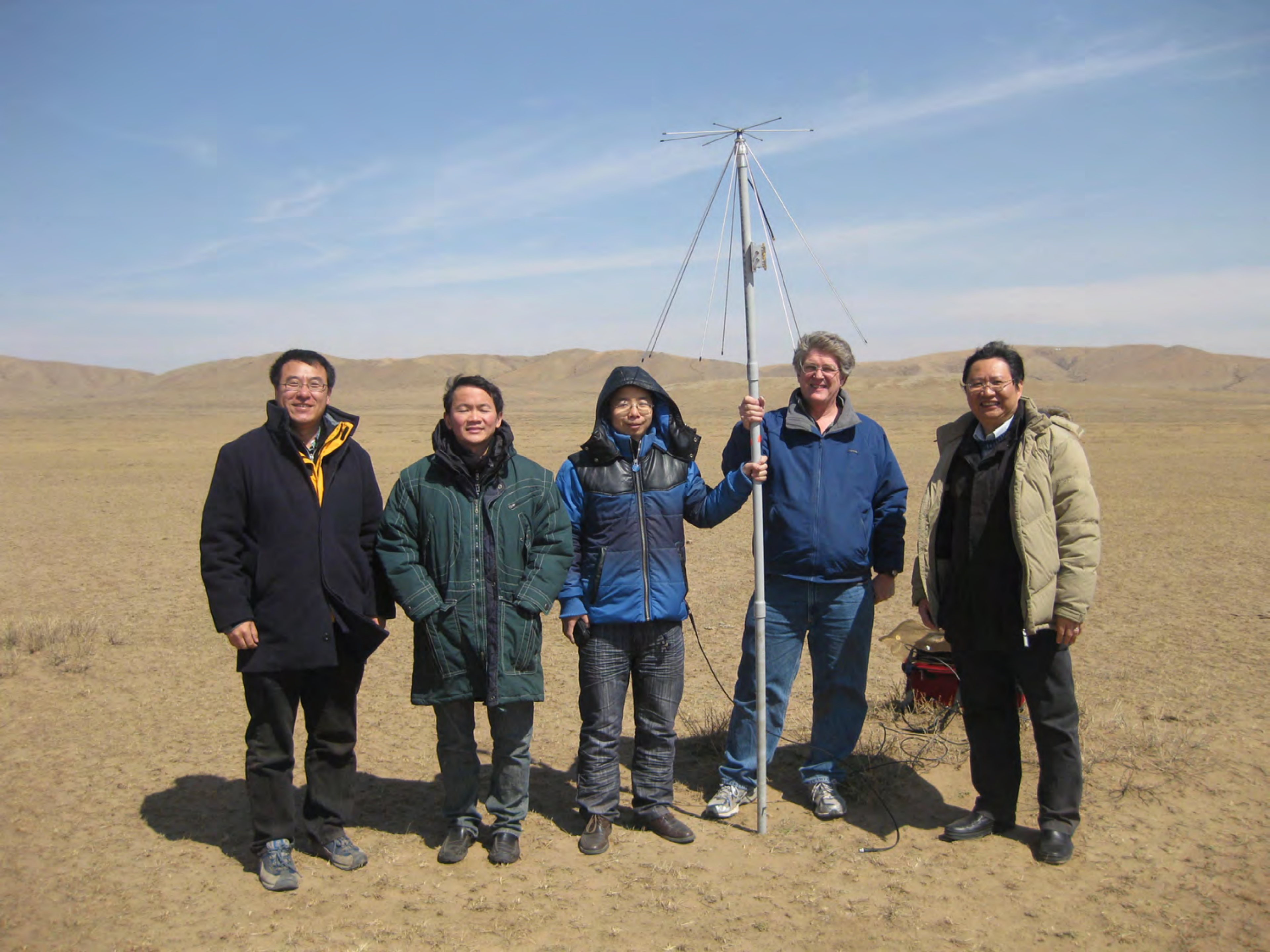
Canada: CHIME
China: Tianlai (heavenly sound)

feeds



instant field of view





The Tianlai (Heavenly Sound) Project

- NAOC, CETC-54, Institute of Automation, Hangzhou Dianzi U., XAO
- US: J. Peterson (CMU), P. Timbie & Das Santanu (Wisconsin), A. Stebbins (Fermilab)
- France: R. Ansari, J.E Campagne, M. Moniez (LAL/IN2P3), J.-M. Martin, P. Colom(Obs. Paris),
- Canada: Pen (CITA)

The concept of "tianlai"-- the heavenly sound was coined by ancient Chinese philosopher Zhuang-Zi (Chuang-Tzu, 369BC-286BC)

王桂松 耿京朝 **吴锋泉** 施浒立 李甜田 张巨勇 蒿杰 舒琳 李程程 宋亚芳

田海俊 王维侠 刘涛 **朱嘉炉** **王有刚** 左世凡 **徐怡冬** 张骄 刘东昊 **高长军**

黄启志 王鑫 李毅超 **孙士杰** 张兢予 **李吉夏** 陈志平 朱博勤 **牛晨辉** **岳斌**

程功 徐文啸 胡文凯 俞凯峰 王荣礼 丛艳平 巩岩 李佳威 曹烨 汪群雄 毛天翔

Tianlai pathfinder experiment

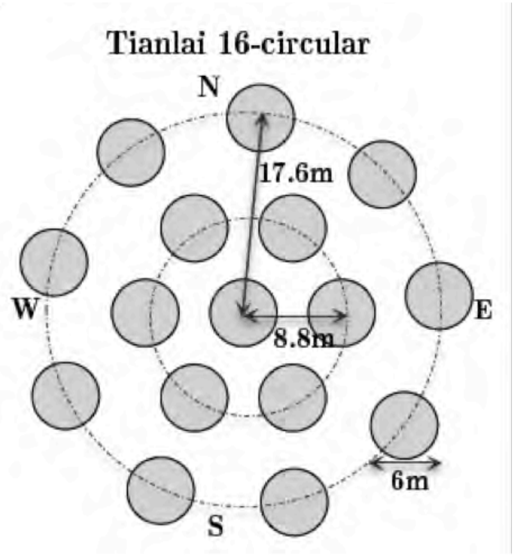
- A small pathfinder experiment to check the basic principles and designs, find out potential problems

- 3x15x40m cylinders, 96 dual polarization receiver units

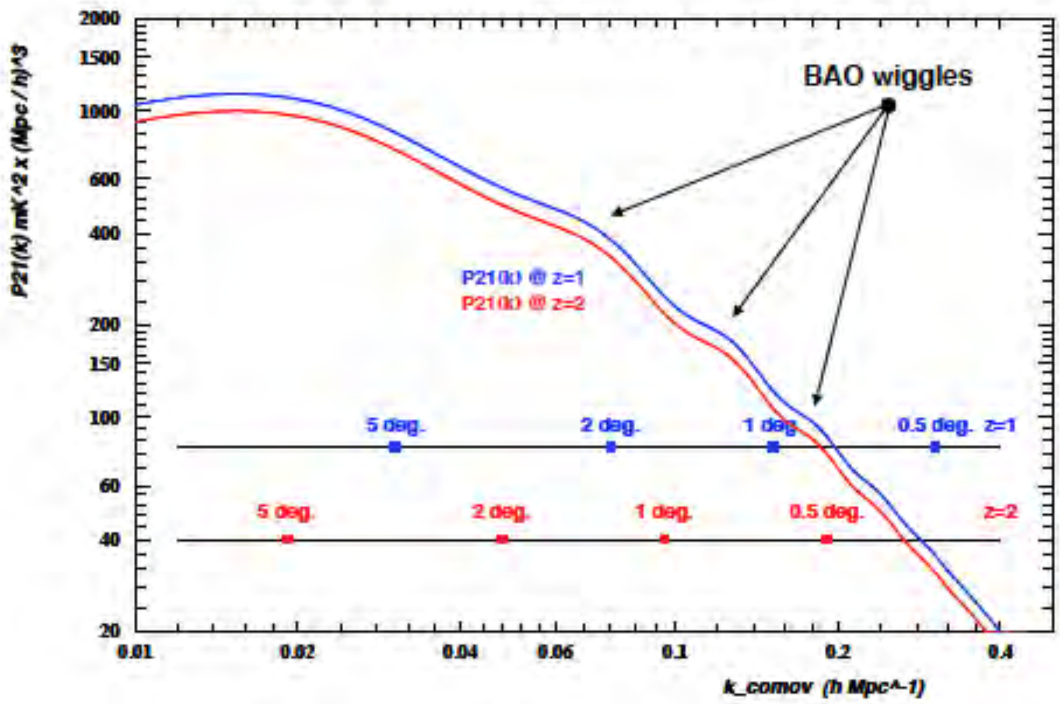
- 16 x 6m dishes

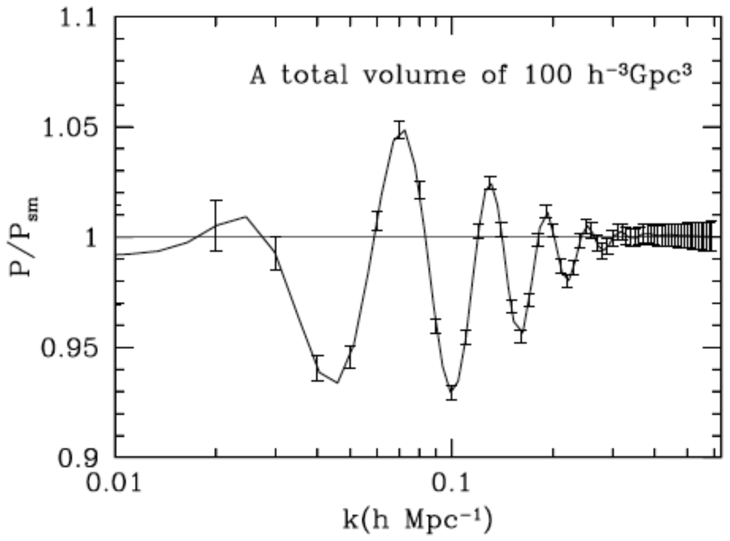
- observe 700-800MHz, can be tuned in 600-1420MHz

- If successful: expand to full scale 120mx120m, 2500 units



Array Size





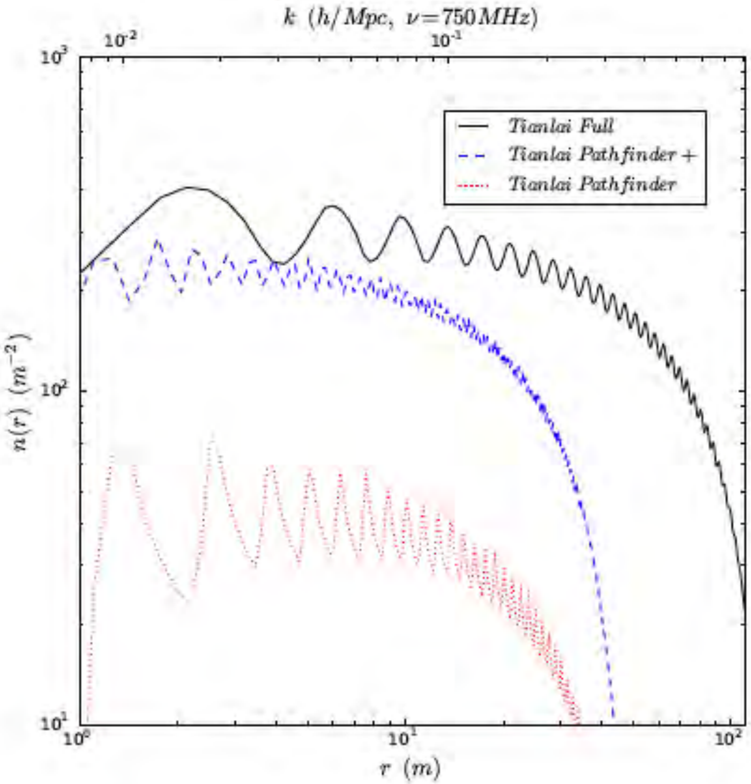
T. Chang et al. 2008, Seo et al. 2009, Ansari et al. 2012

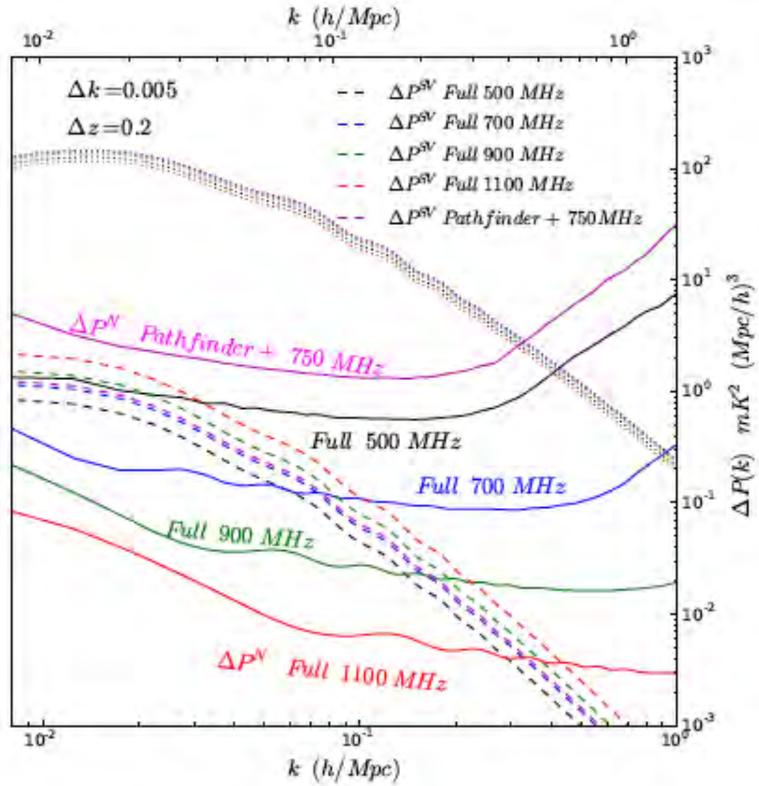
Tianlai performance

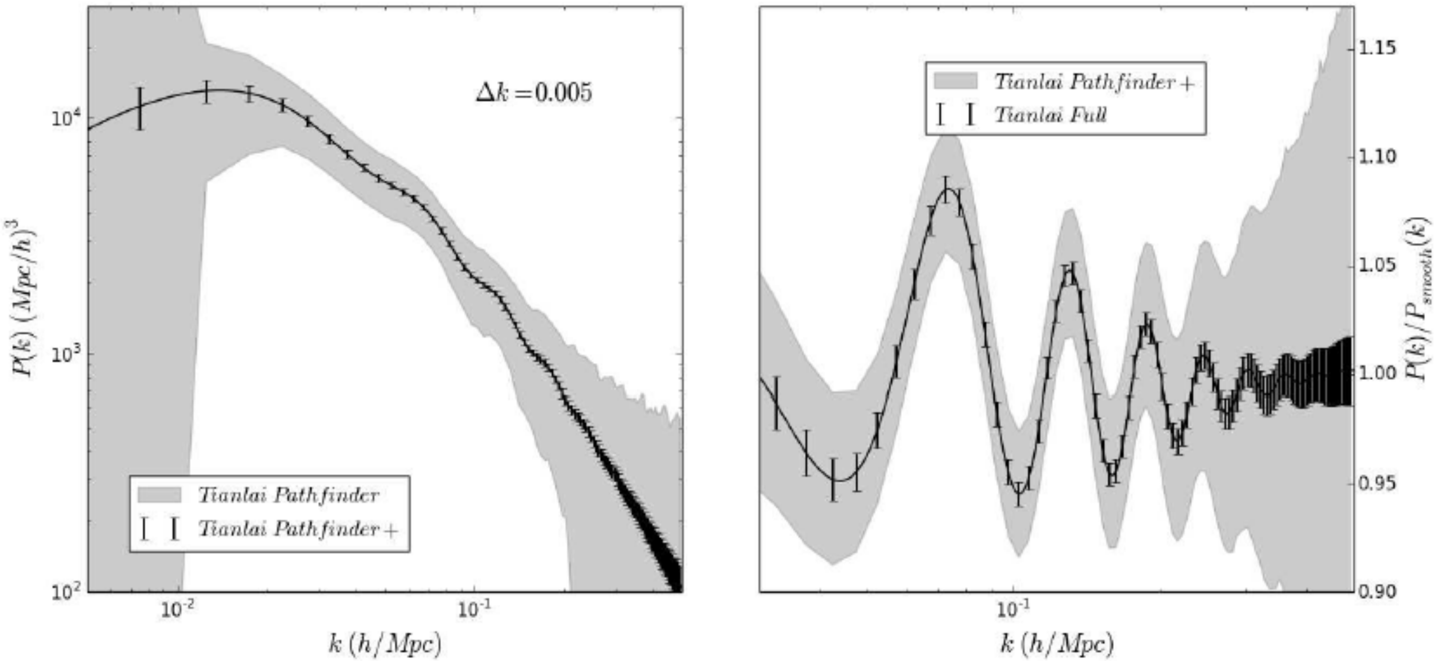
Xu et al. (2014)

$$\delta V_{\alpha\beta,[\mathrm{K}]}(\vec{u}_\perp,\nu) = \frac{\lambda^2 T_{\mathrm{sys}}}{A_e\sqrt{\Delta\nu t_{\vec{u}}}},$$

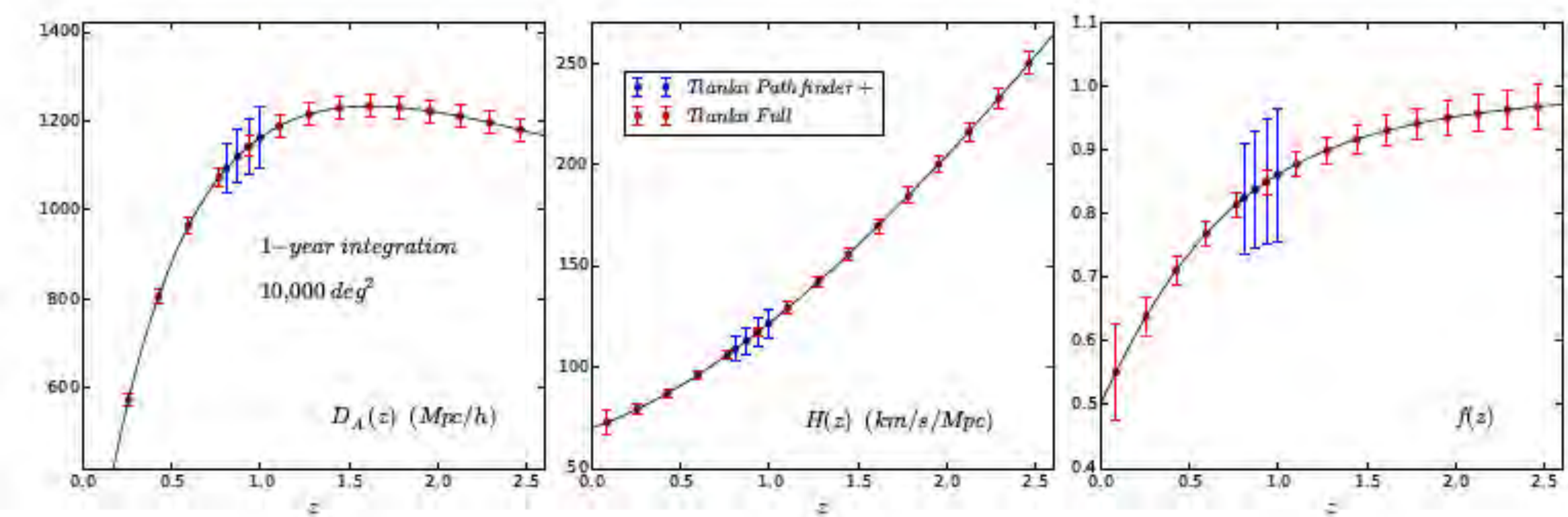
$$n(\vec{u}_\perp) = \sum_i^{n_b} R(\vec{u}_\perp - \vec{u}^i_\perp). \qquad R(\vec{u}_\perp) = \left(\frac{\lambda^2}{A_e}\right)\Lambda\left(\frac{u_L}{\Delta u_L}\right)\Lambda\left(\frac{u_W}{\Delta u_W}\right).$$





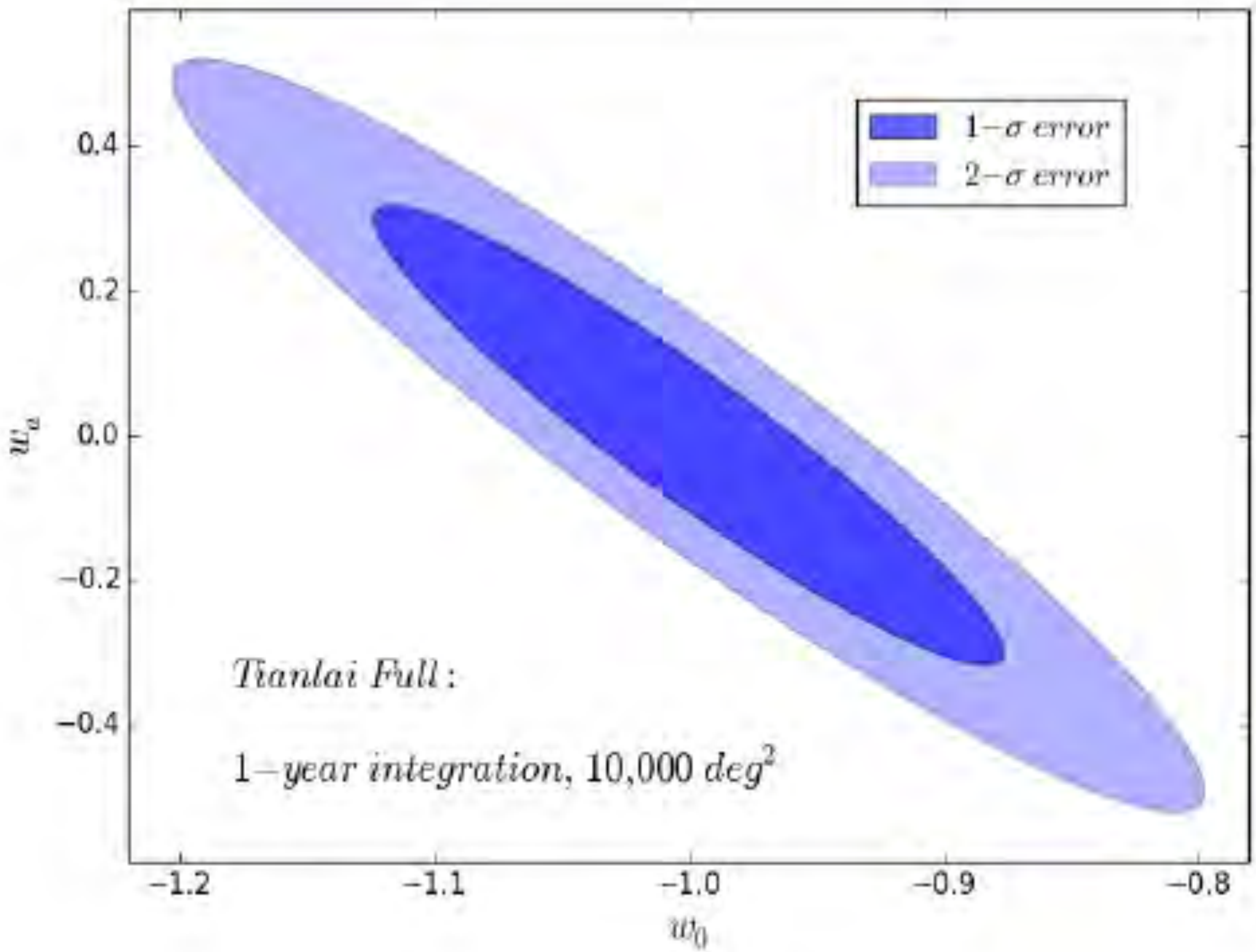


$\Delta k = 0.005$
$P(k)\ (Mpc/h)^3$
$k\ (h/Mpc)$
Tianlai Pathfinder
Tianlai Pathfinder+
Tianlai Pathfinder+
Tianlai Full
$P(k)/P_{smooth}(k)$
$k\ (h/Mpc)$



1−year integration
10,000 deg^2
$D_A(z)\ (Mpc/h)$
Tianlai Pathfinder+
Tianlai Full
$H(z)\ (km/s/Mpc)$
$f(z)$
z
z
z

Dark Energy Model

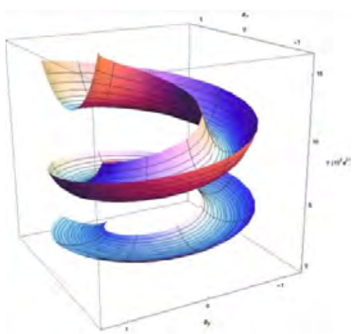


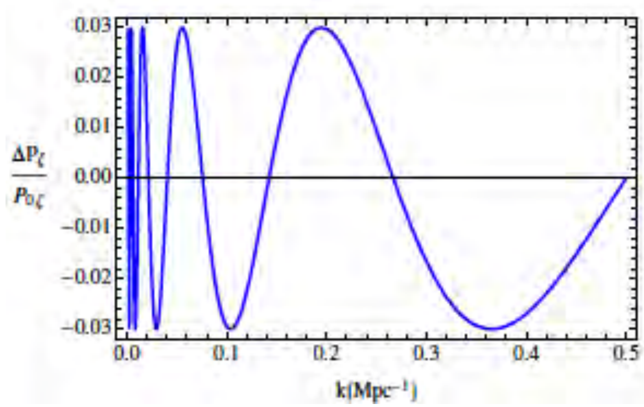
Probing the Origin of Universe

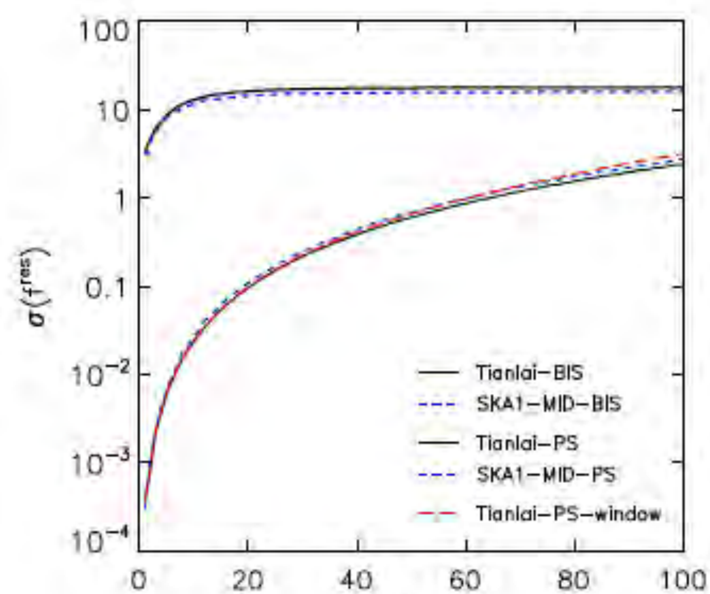
Current CMB (Planck) Constraints already very tight, can one do better?

$$f_{NL}^{local} = 0.8 \pm 5.0, \quad f_{NL}^{equil} = -4 \pm 43 \quad f_{NL}^{ortho} = -26 \pm 21$$

Features produced during inflation:





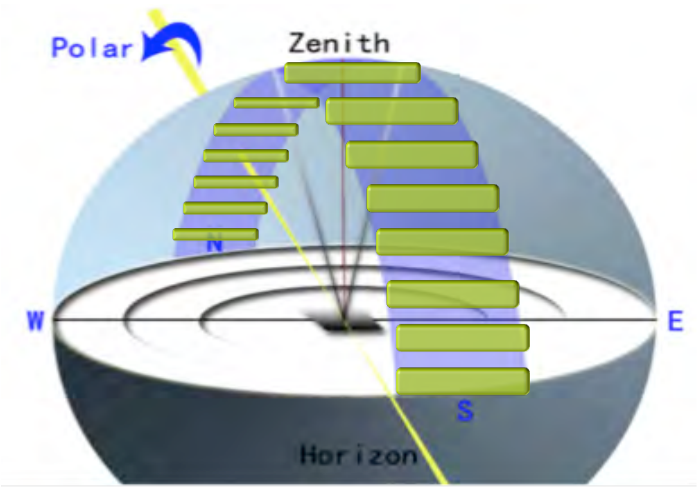


Xu, Hamann & Chen (2016)

inflation feautres: resonance model (e.g. axion monodromy inflation)

Collateral Sciences

- Continuum and Polarization Sky Survey
- Transients: Fast Radio Bursts, GRB & GWE radio afterglows
- Quasar activities
- 21cm absorbers
- …….

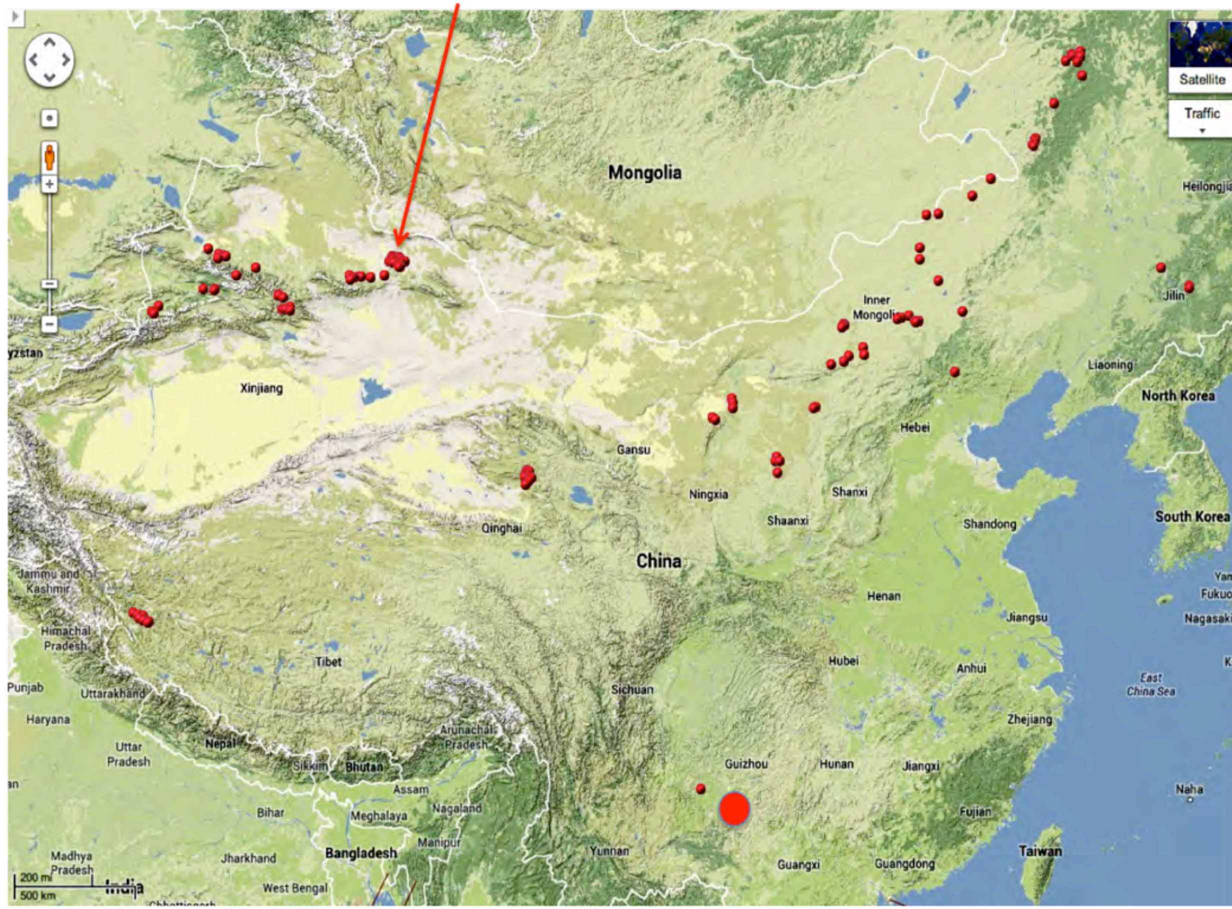


Site Selection

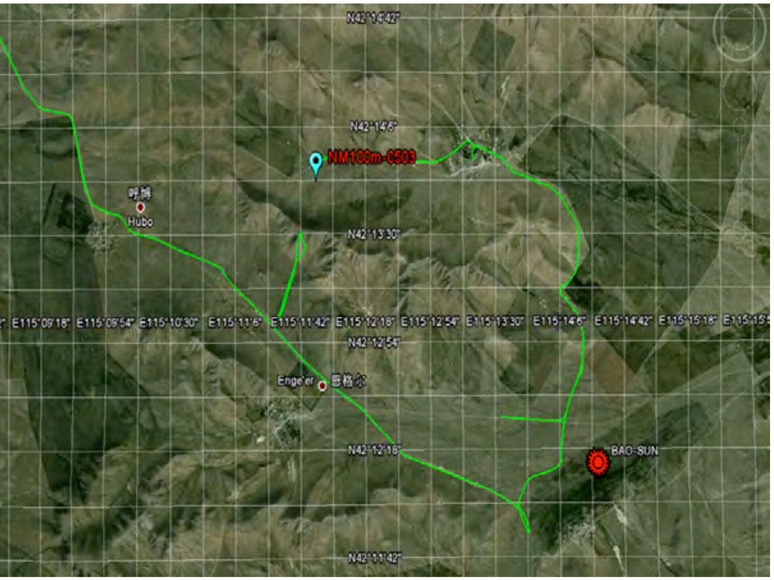
Site Requirements:

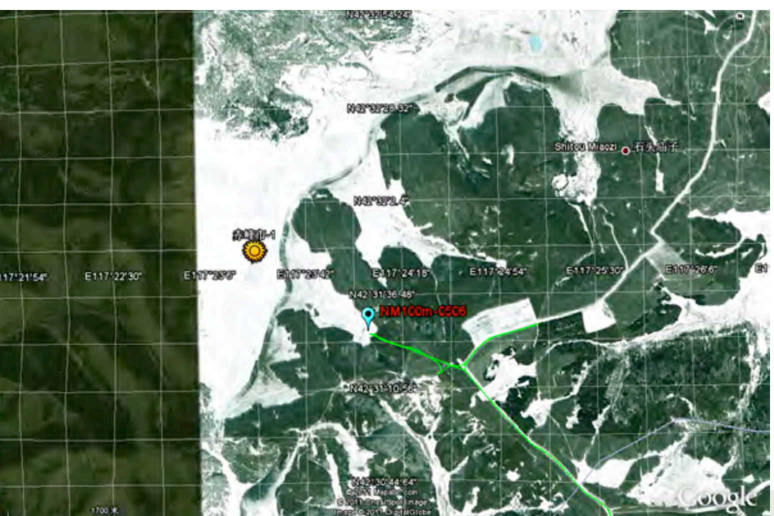
To minimize radio frequency interference (RFI), typically sparsely populated area, surrounded by mountains and hills

The Selected Site Hongliuxia

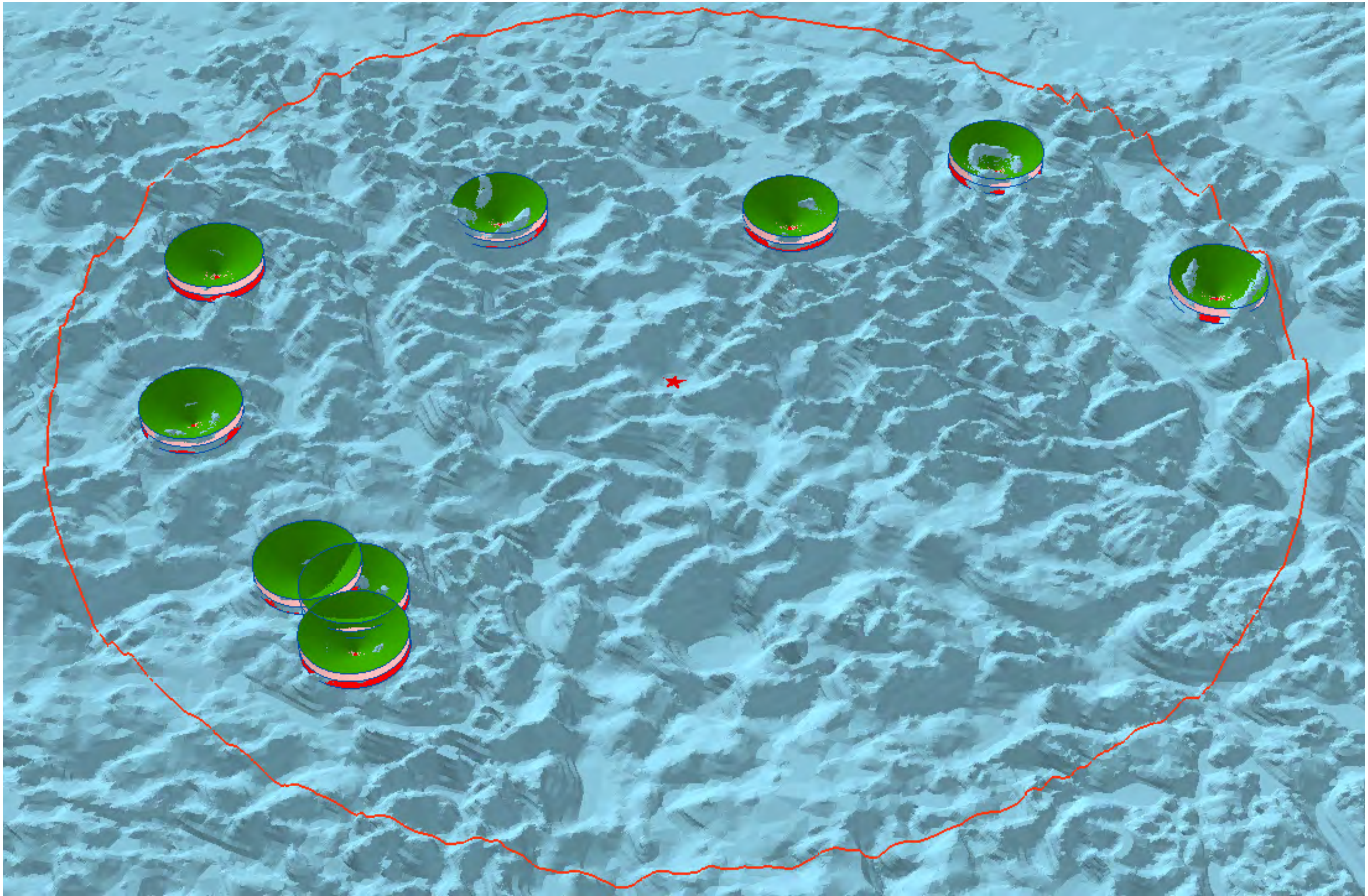


Candidate Sites near MUSER





Candidate Sites around FAST



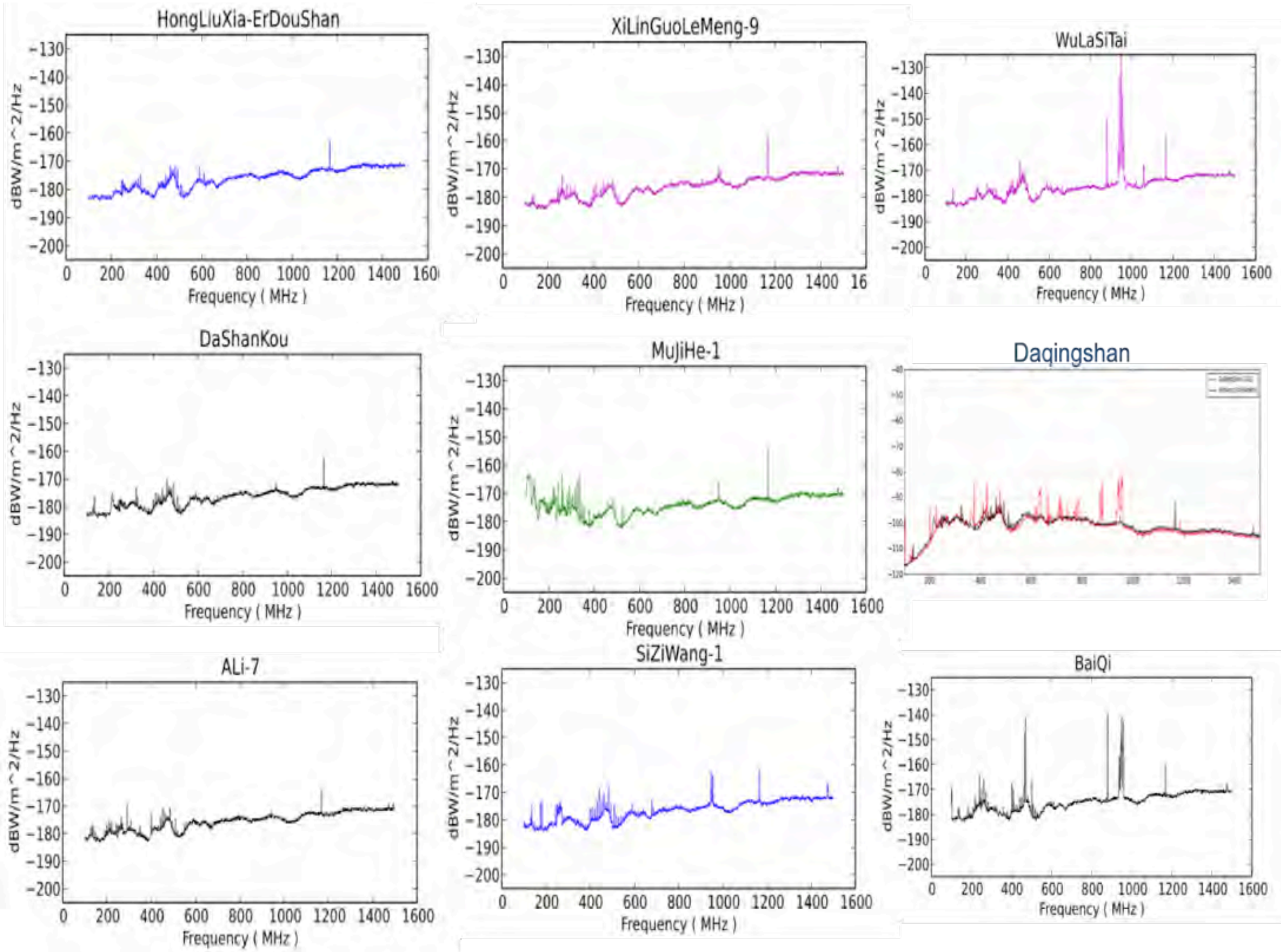

Inner Mongolia


Huadian, Jilin


Ali, Tibet


Pingtang, Guizhou

RFI spectrum for some sites



Hongliuxia （红柳峡）in Barkol （巴里坤）

Balikun (Barkol) town

Tianshan mountain

relic of ancient watch tower along silk road

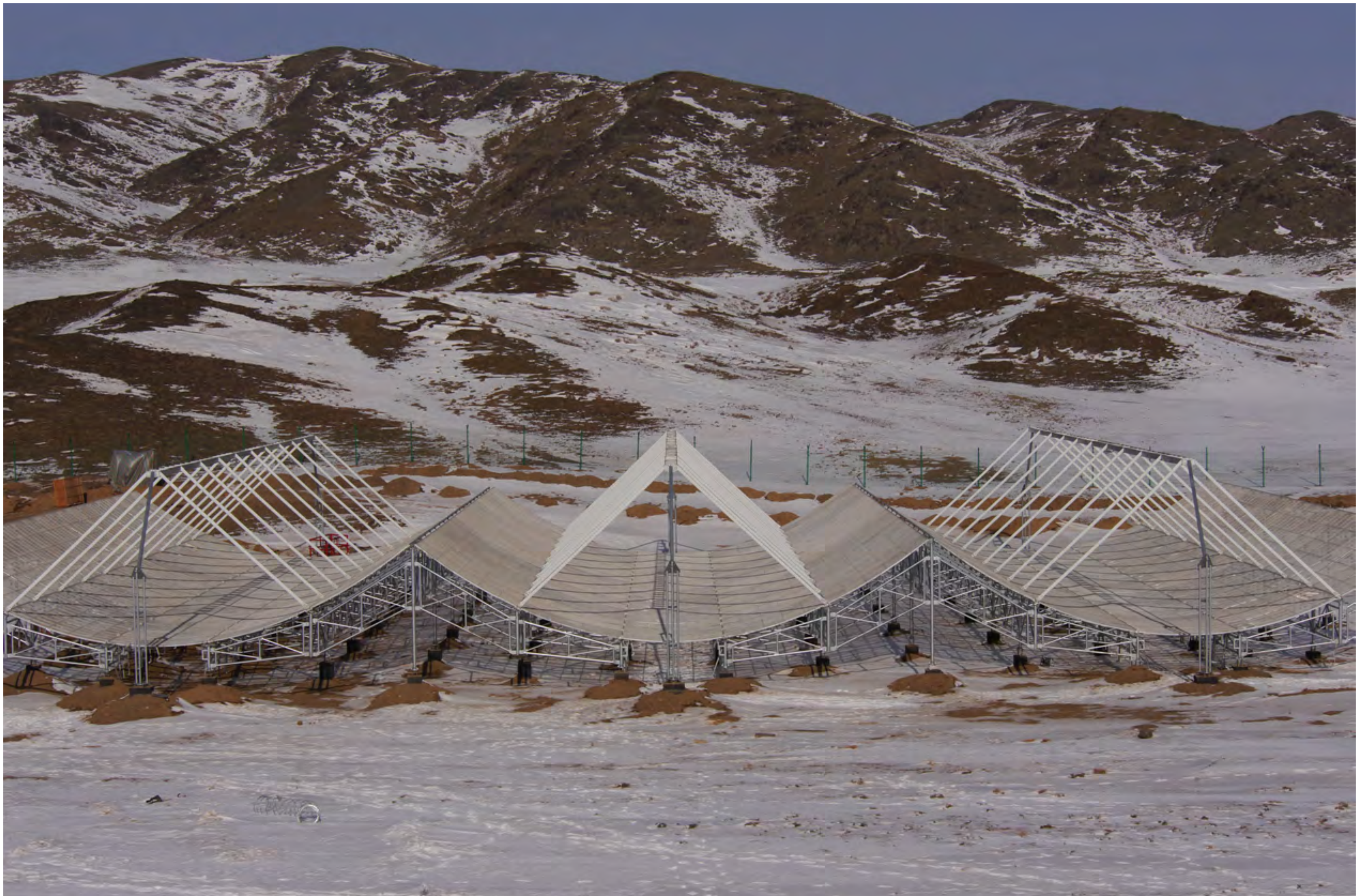
Site Arrangement

Station House

Construction of the Array

Tianlai Array

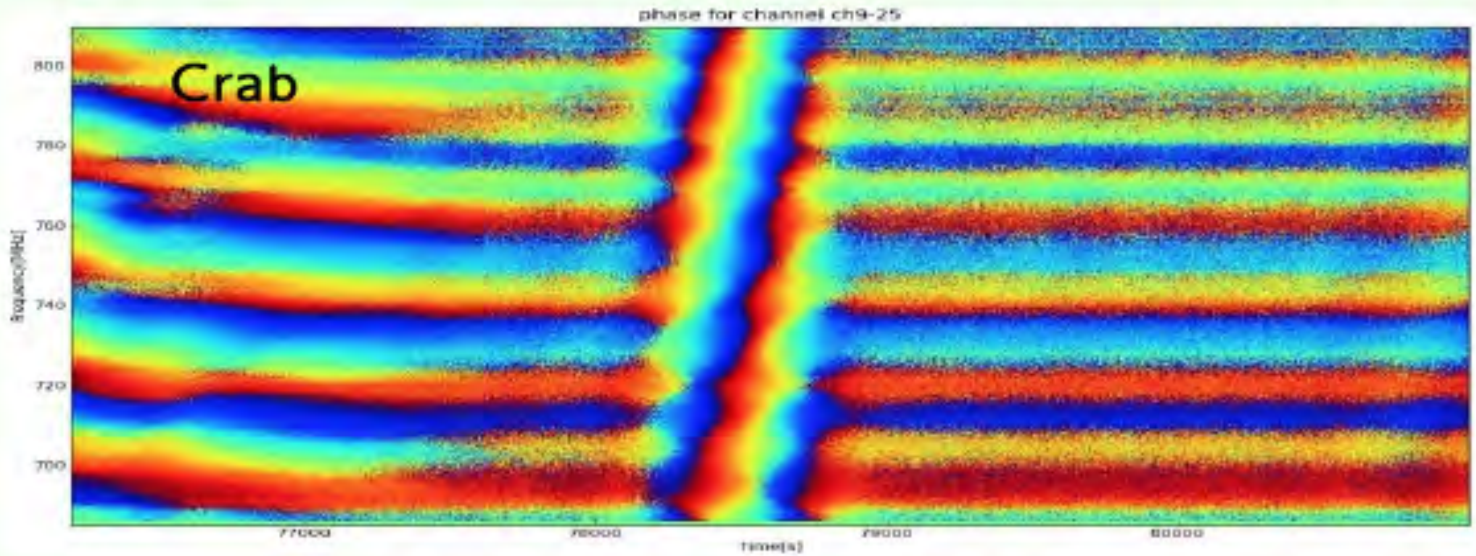
Cylinder Array

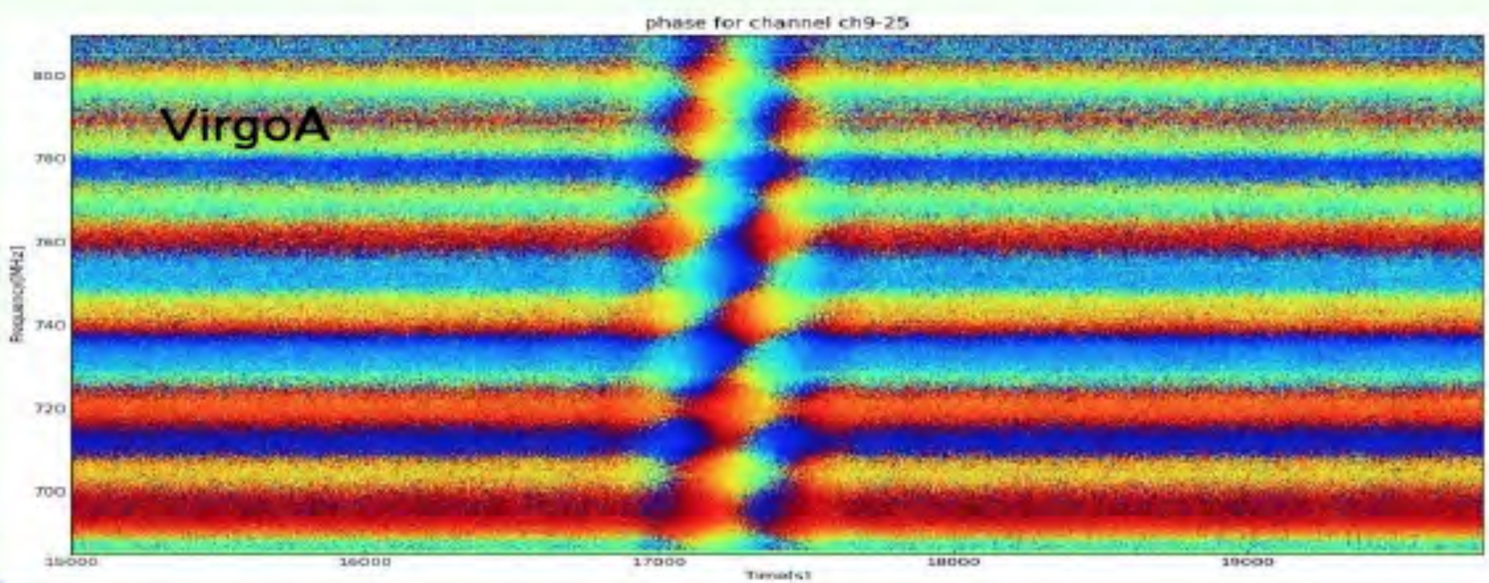


Dish Array

Receiver and Correlator

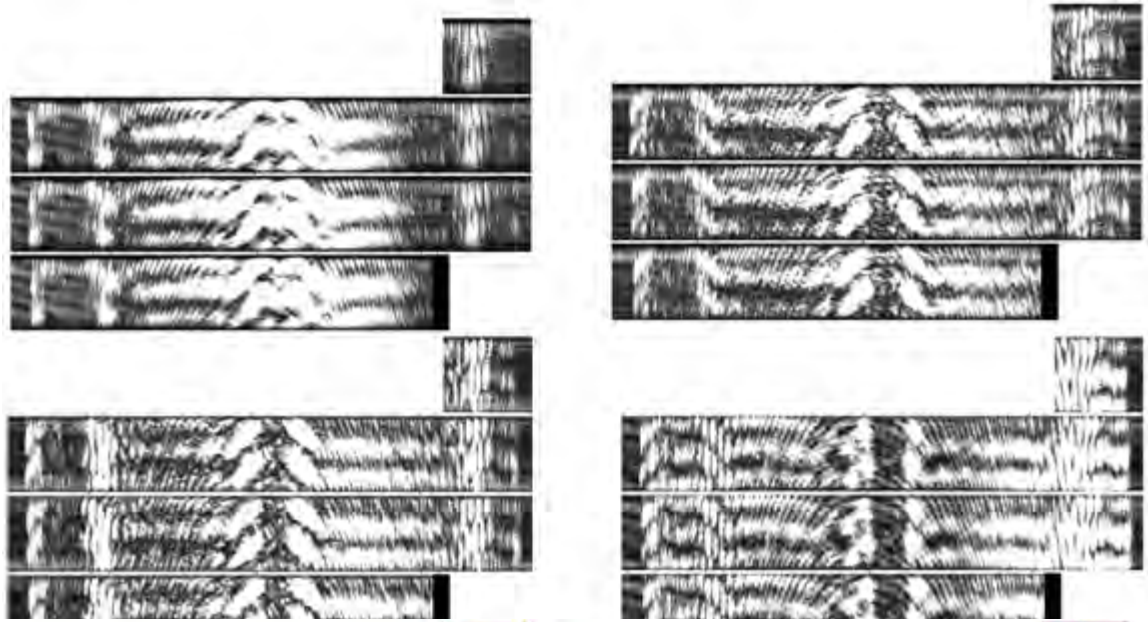
Experiment of Cylinder array



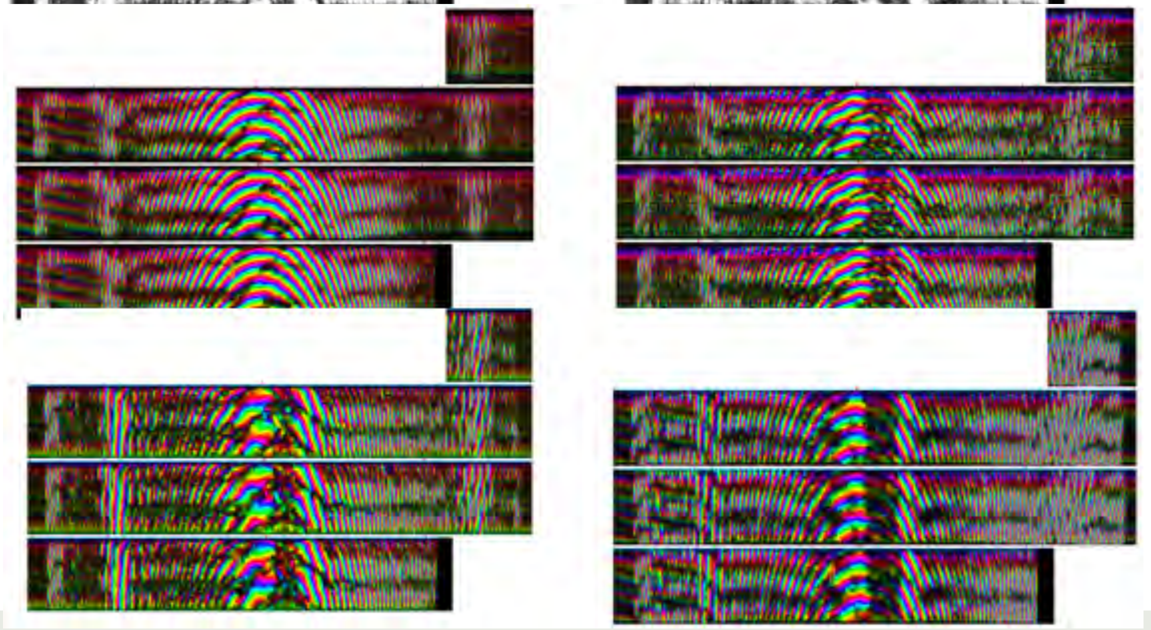


Tianlai First Light Data

amplitude:



phase:



Eigen-Vector Based Calibration

Zuo et al., arxiv:1807.04590

Each receiver's gain varies, phase delay—complex gain

$$F_i = g_i \int d^2\hat{n} A_i(\hat{n}) \mathcal{E}(\hat{n}) e^{-2\pi i \hat{\boldsymbol{n}}\cdot\boldsymbol{u}_i} + n_i \qquad \boldsymbol{u}_{ij} = (\boldsymbol{r}_i - \boldsymbol{r}_j)/\lambda$$

$$\begin{aligned} V_{ij} &\equiv \langle F_i F_j^* \rangle \\ &= g_i g_j^* \int d^2\hat{n}\, A_i(\hat{n}) A_j^*(\hat{n}) e^{-2\pi i \hat{\boldsymbol{n}}\cdot\boldsymbol{u}_{ij}} I(\hat{n}) + \langle n_i n_j^* \rangle, \end{aligned}$$

An eigenvector equation!

$$R_{ij} = V_{ij}^{\mathrm{obs}} / V_{ij}^{\mathrm{model}} = g_i g_j^* . \qquad \mathbf{R} = \boldsymbol{g}\boldsymbol{g}^\dagger, \quad \mathbf{R}\boldsymbol{g} = (\boldsymbol{g}\boldsymbol{g}^\dagger)\boldsymbol{g} = \boldsymbol{g}(\boldsymbol{g}^\dagger \cdot \boldsymbol{g})$$

Single Dominant point Source:

$$G_i = g_i A_i(\hat{\boldsymbol{n}}_0) e^{-2\pi i \hat{\boldsymbol{n}}_0 \cdot \boldsymbol{u}_i}; \qquad \mathbf{V}_0 = S_c G G^\dagger .$$

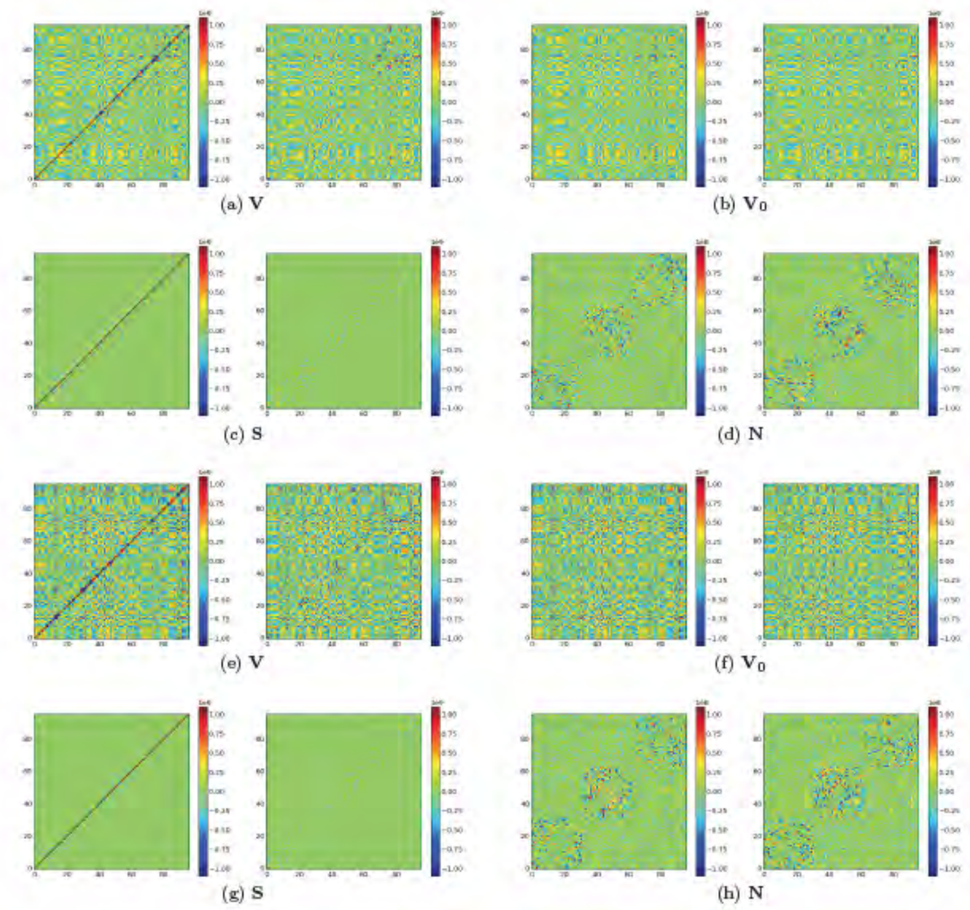
A refinement: SPCA

$$\mathbf{V} = \mathbf{V}_0 + \mathbf{S} + \mathbf{N},$$

$\mathbf{V}_0 = S_c G G^\dagger$ rank 1 matrix

S: sparse matrix (outliers)

N: noise, dense



Practical Application

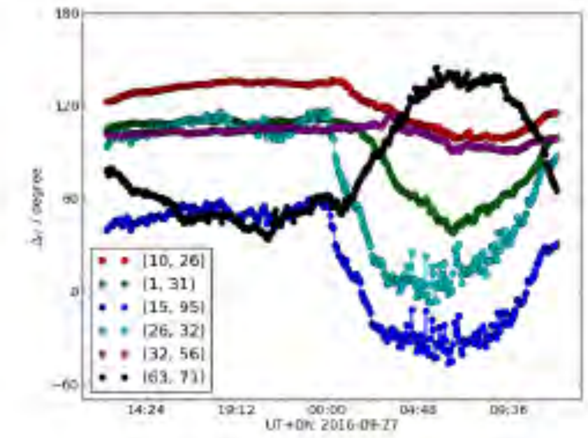
- RFI flagging

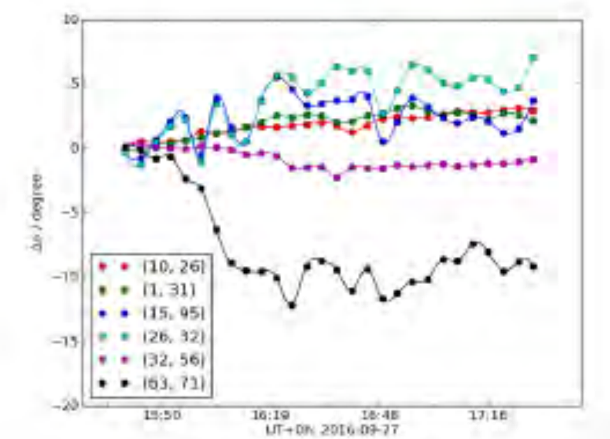
- relative phase calibration by noise source

$$V_{ij}^{\rm on} = G_{ij}(V_{ij}^{\rm sky} + V_{ij}^{\rm ns} + n_{ij})$$
$$V_{ij}^{\rm off} = G_{ij}(V_{ij}^{\rm sky} + n_{ij}),$$

$$\begin{aligned} V_{ij}^{\rm on} - V_{ij}^{\rm off} &= G_{ij}V_{ij}^{\rm ns} + \delta n_{ij} \\ &\approx C|G_{ij}|e^{-ik\Delta L_{ij}}e^{-ik(r_i - r_j)}, \end{aligned}$$

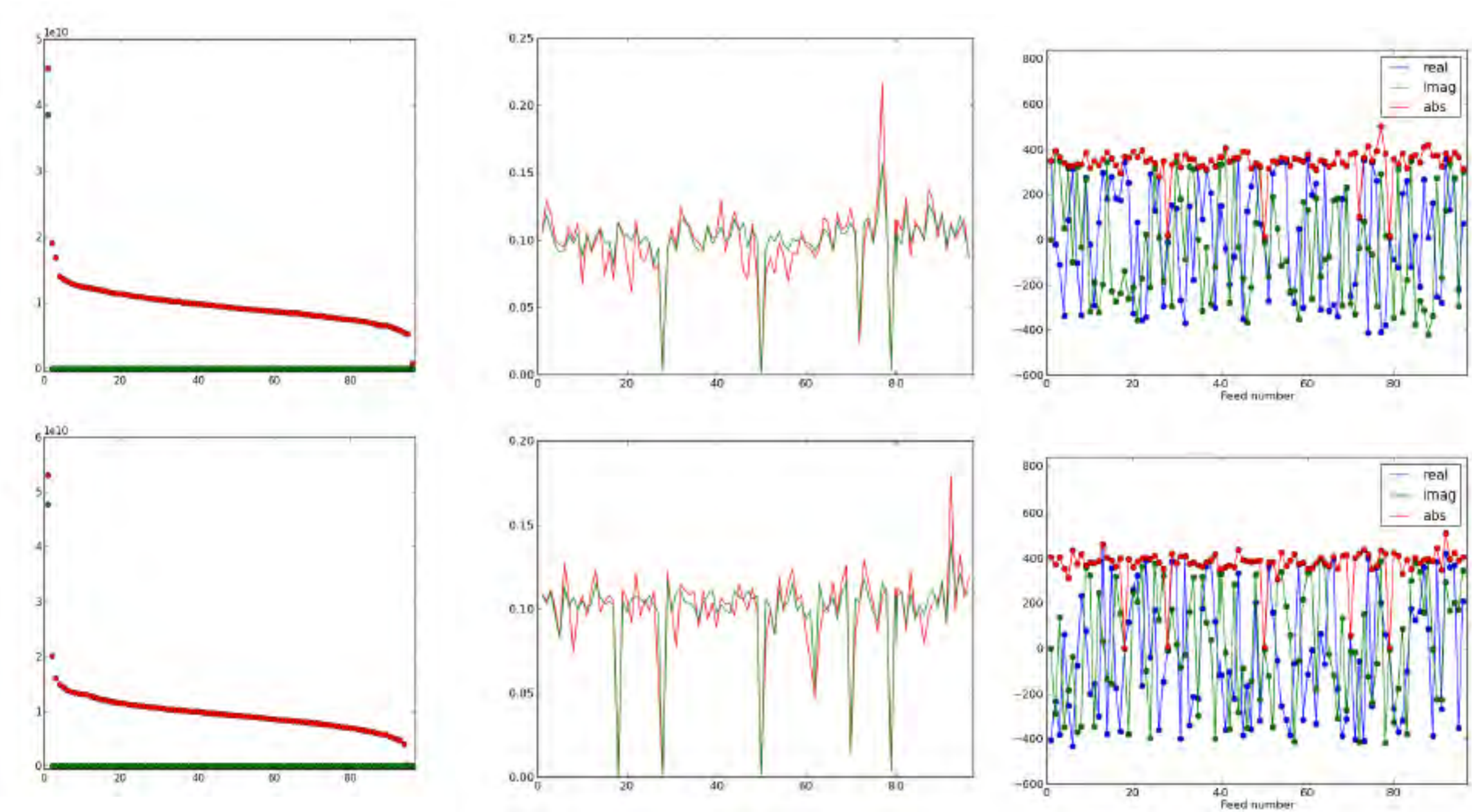
- absolute calibration with sky source





XX

YY

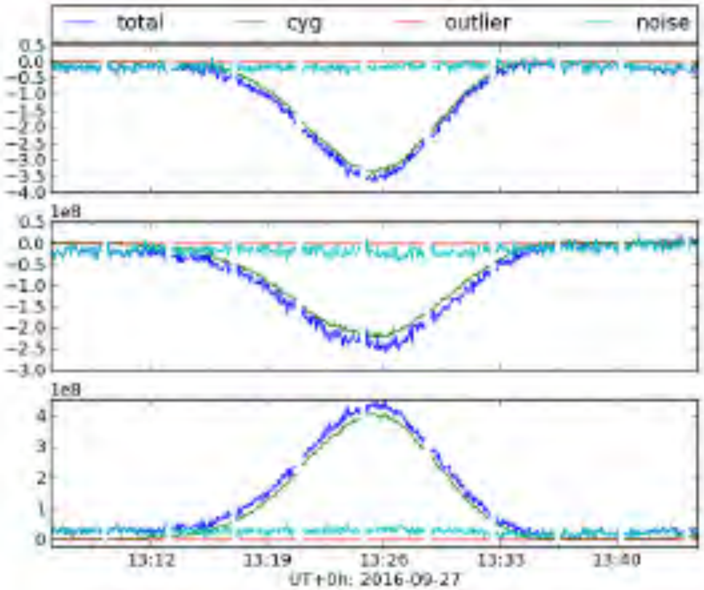


Eigenvalues

Eigenvector magnitude

solve G vector

Red: PCA (V), Green: SPCA (V_0)


total
cyg
outlier
noise
1e8
13:12
13:19
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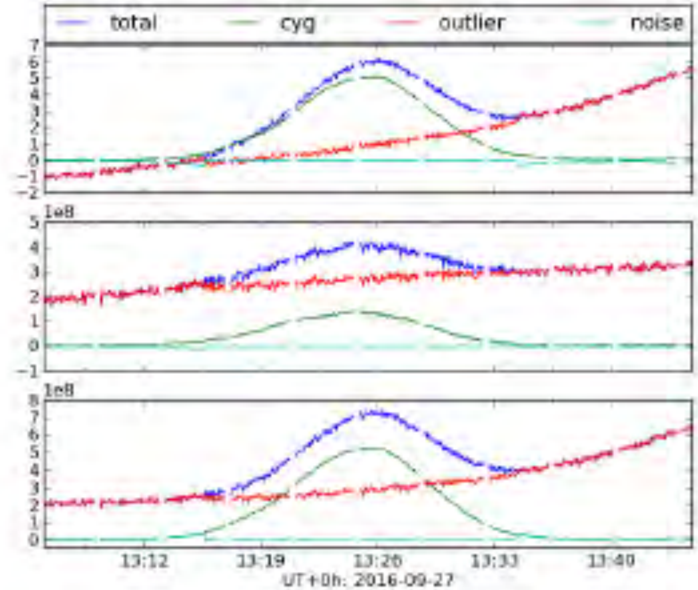
13:33
13:40
UT+0h: 2016-09-27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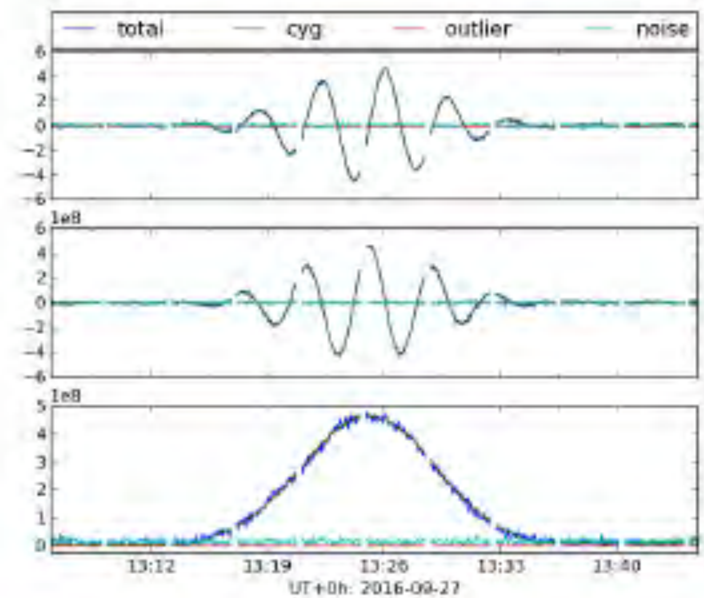
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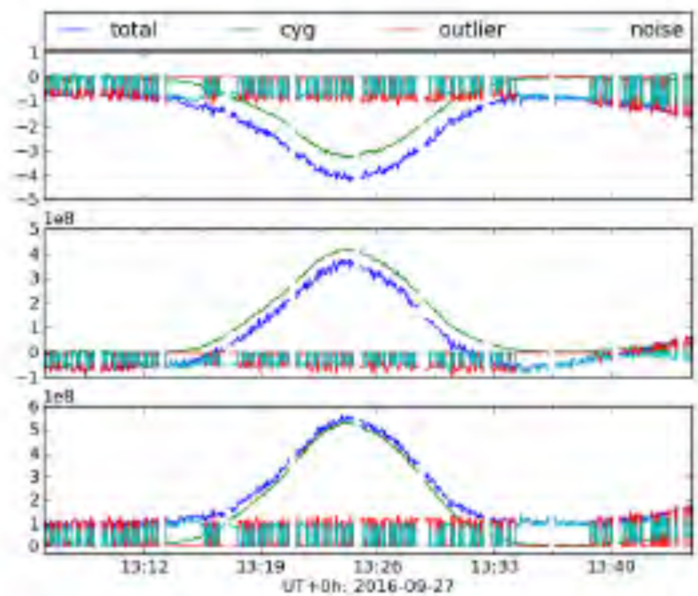
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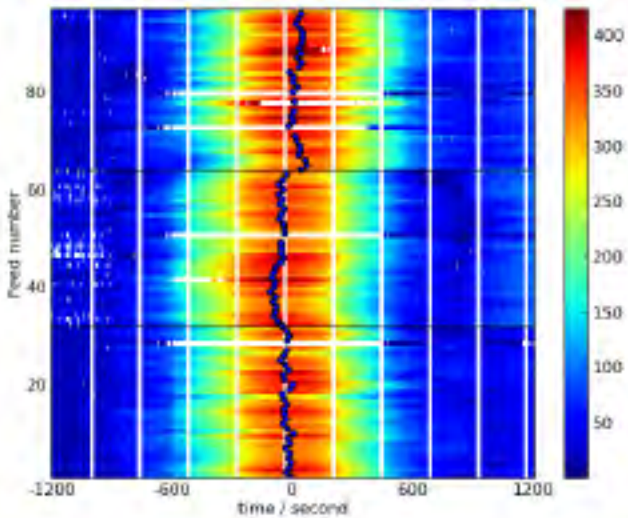
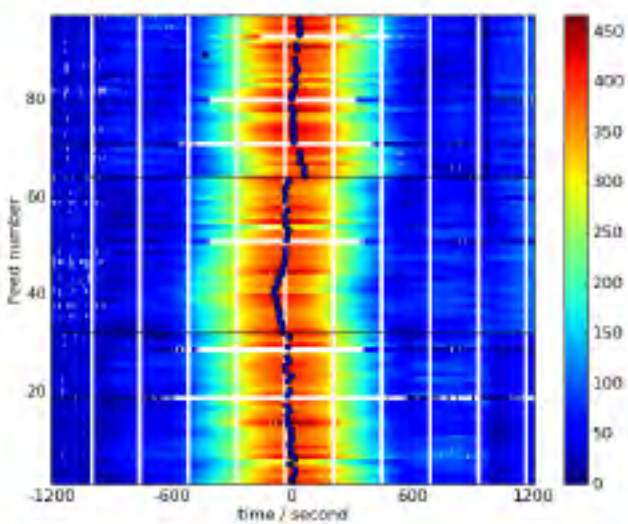
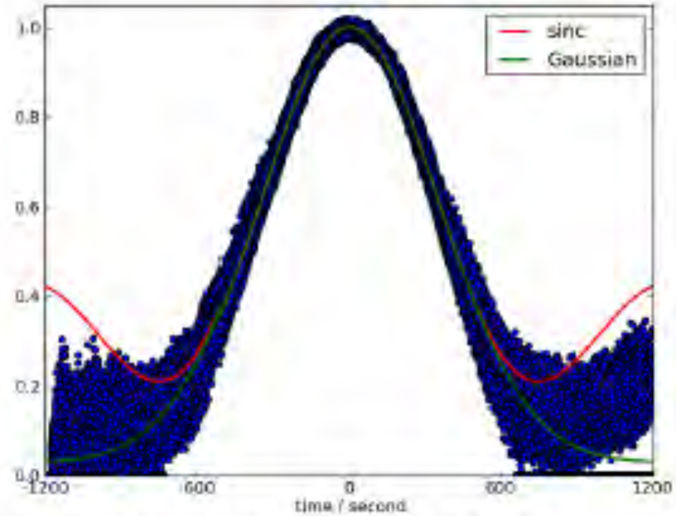


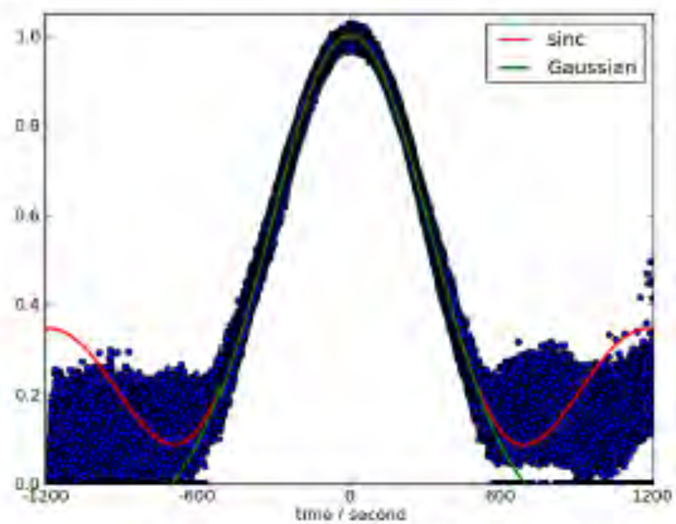
(a) East-West pol



(b) North-South pol



(a) XX polarization, FWHM = 3.6°

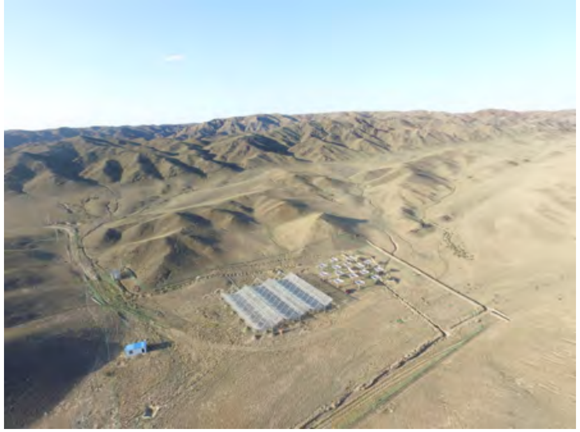


(b) YY polarization, FWHM = 3.15°

Figure 12. The fitted beam profile.

Problem: North-South Direction

Trying use drone for calibration



Map-making with m-modes

R. Shaw et al. (2014, 2015); Zhang et al. (2016a,b)

$$\mathcal{V}_{ij}(t) = \iint I(\hat{\boldsymbol{n}}) \boxed{L_{ij}(\hat{\boldsymbol{n}}, t)} d\hat{\boldsymbol{n}}$$

$$L_{ij}(\theta, \varphi' - \alpha_p(t))$$

$$I(\hat{\boldsymbol{n}}) = \sum_{\ell=0}^{+\infty} \sum_{m=-\ell}^{+\ell} \mathcal{I}_{\ell,m} Y_{\ell,m}(\hat{\boldsymbol{n}})$$

$$L_{ij}(\hat{\boldsymbol{n}}) = \sum_{\ell=0}^{+\infty} \sum_{m=-\ell}^{+\ell} \mathcal{L}_{ij}(\ell, m) Y_{\ell,m}(\hat{\boldsymbol{n}})$$

$$\tilde{V}_{ij}(m) = (-1)^m \sum_{\ell=|m|}^{+\ell_{max}} \mathcal{I}_{\ell,m} \mathcal{L}_{\ell,-m} + \text{noise}$$

$$\left[\tilde{V}\right]_m = \mathbf{L}_m \times [\mathcal{I}(\ell)]_m + [\tilde{\mathbf{n}}]_m$$

$$[\widehat{\mathcal{I}}]_m = \mathbf{L}_m^{-1} [\tilde{V}]_m$$

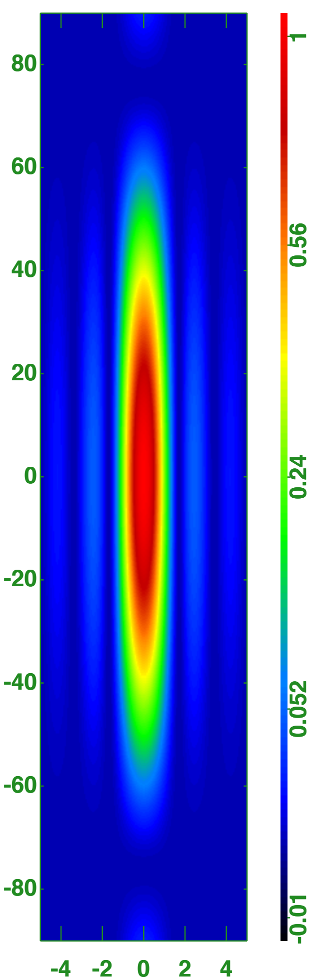
Invertion:

$$\mathbf{A} = \mathbf{U \Sigma Q}^{\dagger},$$

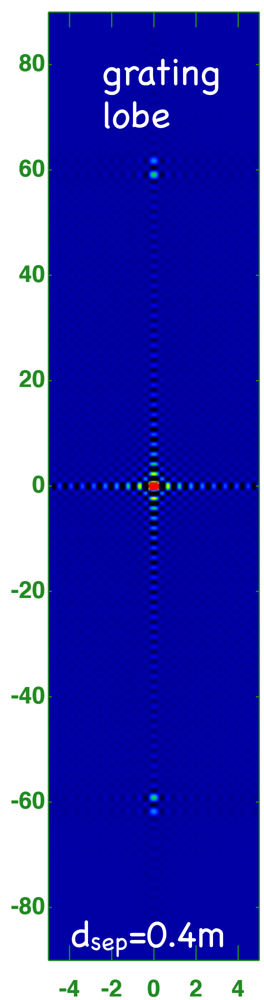
$$\tilde{\mathbf{A}}^{-1} = \mathbf{Q}\tilde{\mathbf{\Sigma}}^{-1}\mathbf{U}^{\dagger}$$

Cylinder Array simulation

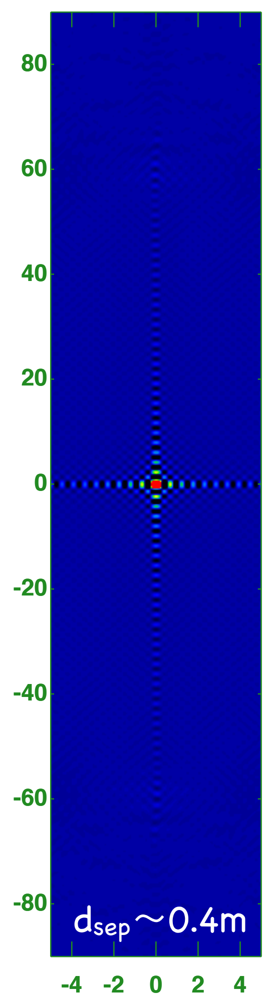
primary beam

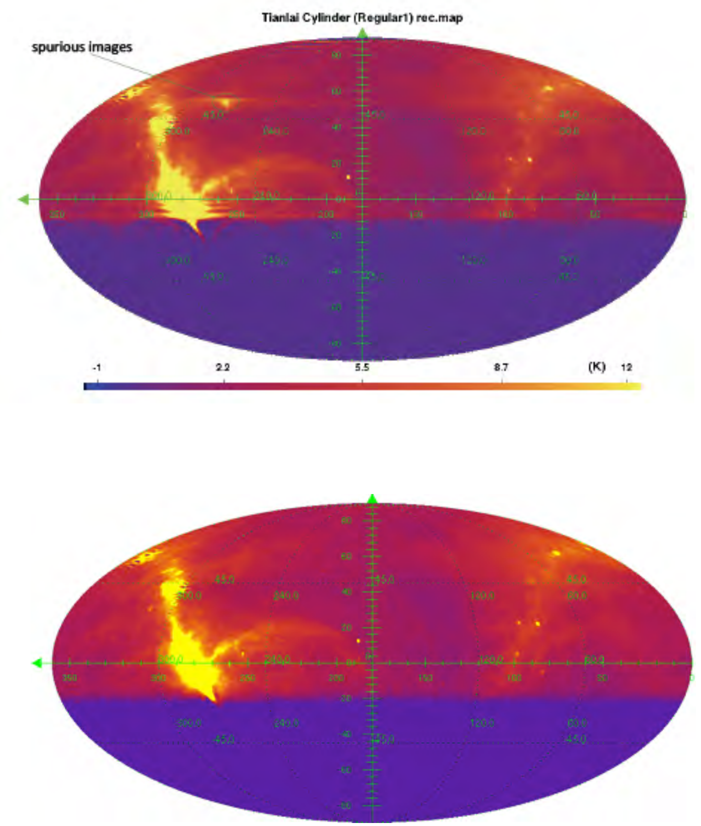


regular1 cylinder

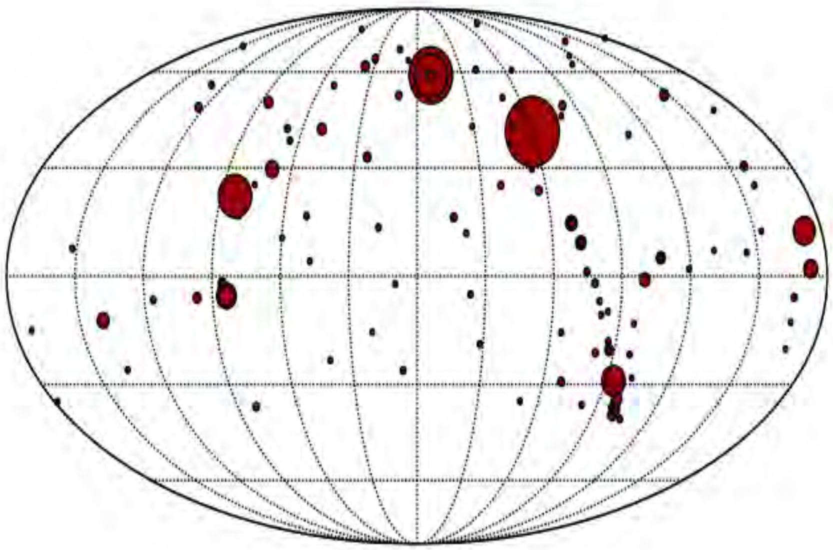


irregular1 cylinder

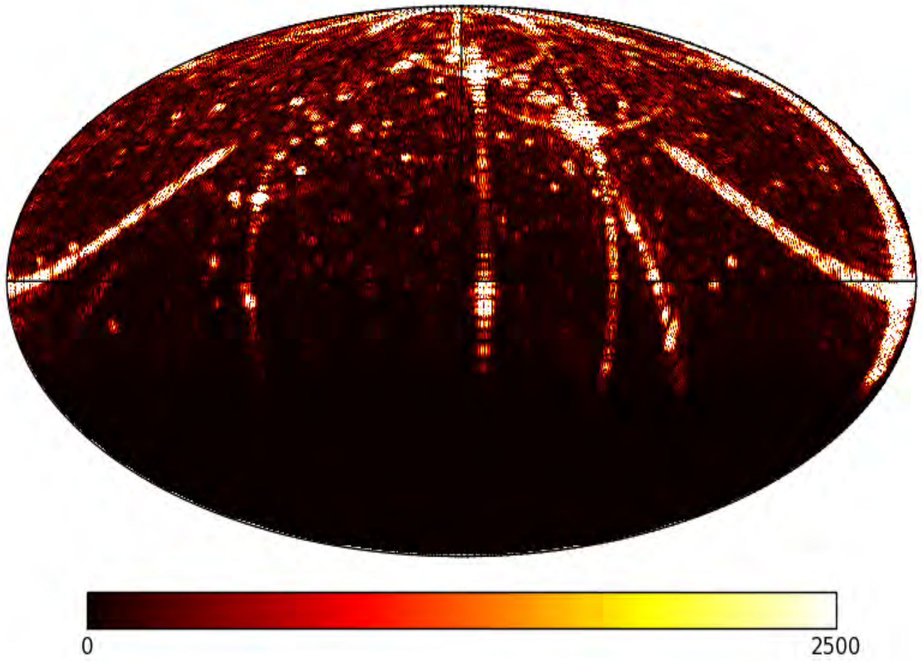




Sky Map



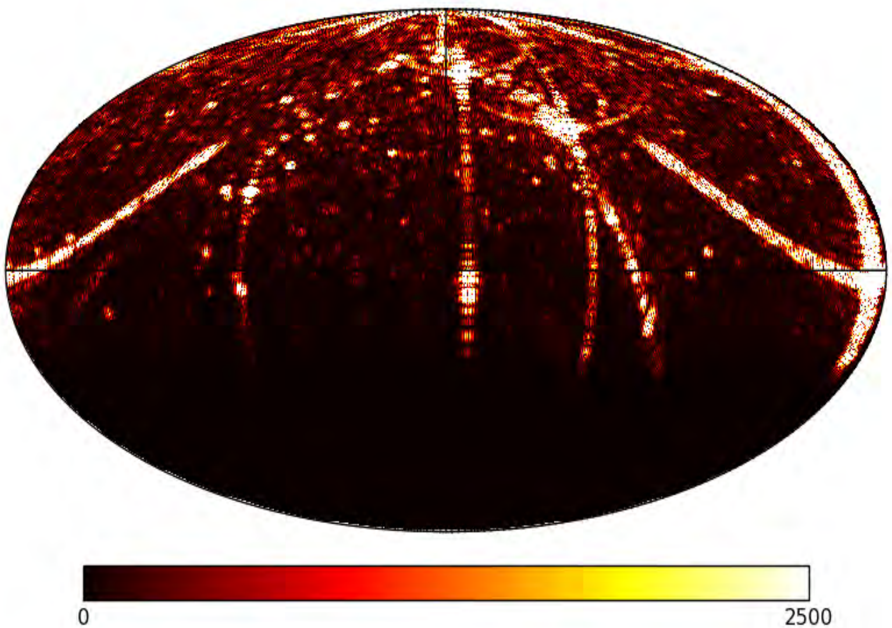
NVSS (1.4GHz) bright sources



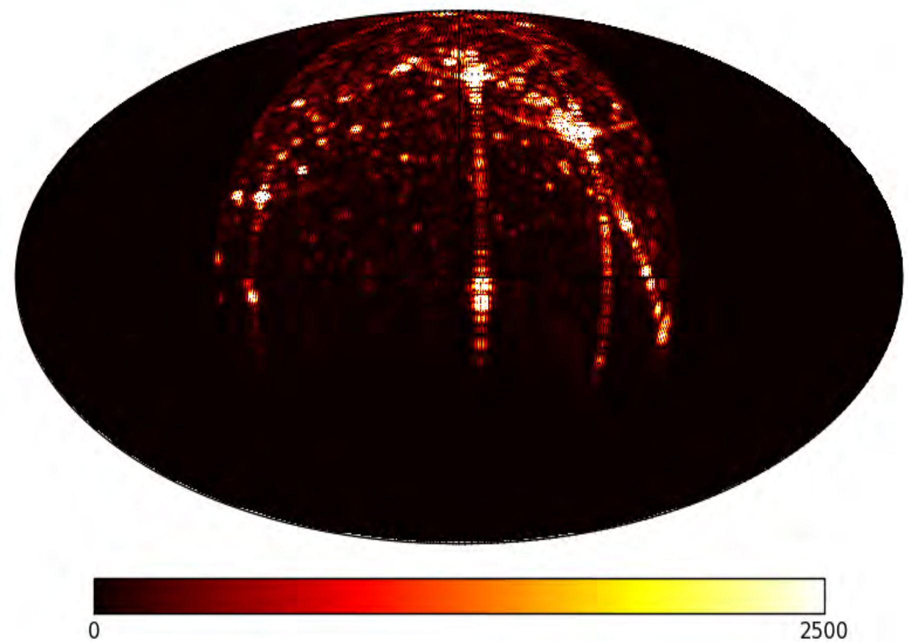
First light image with 5 frequency channels (0.1MHz each) from data taken during first light 2016.09.27-2016.09.30

S. Zuo et al., in preparation

Comparison of all-day vs. night data

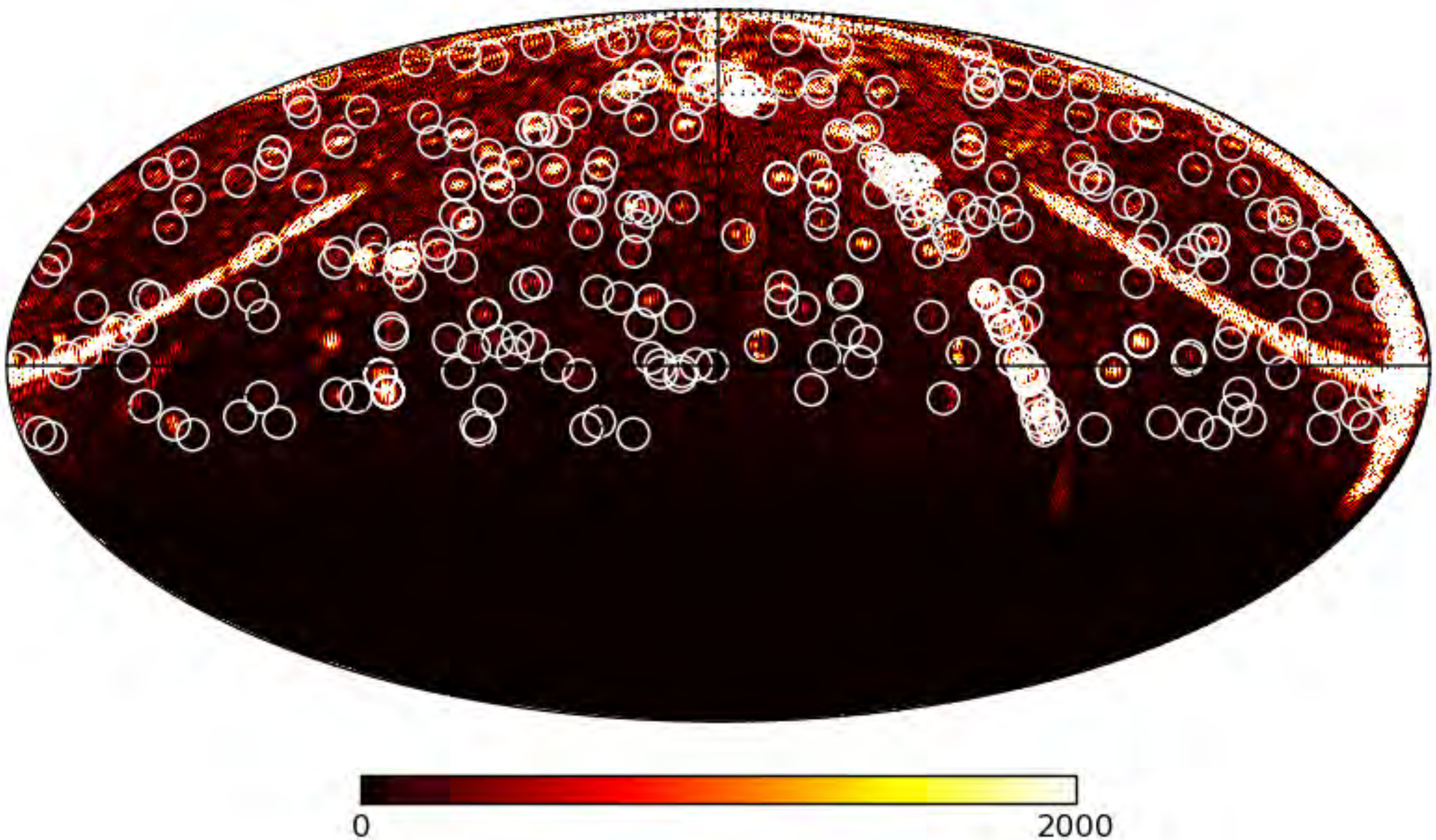


All Day



Night Only

Comparison with NVSS sources

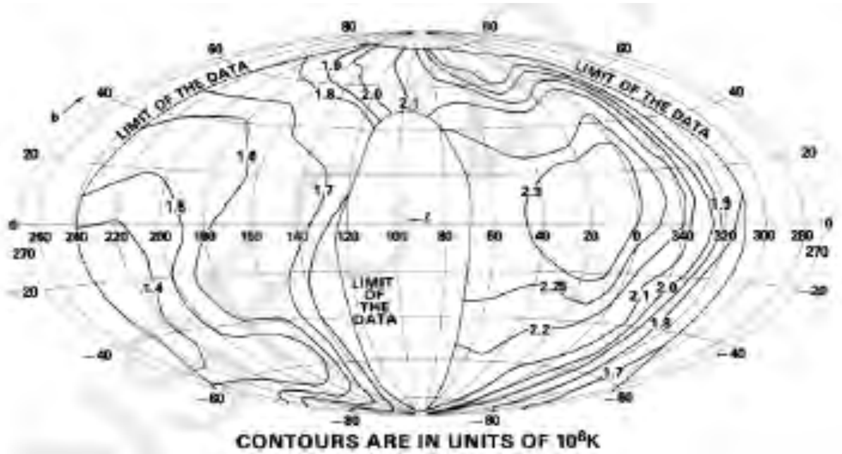


Summary

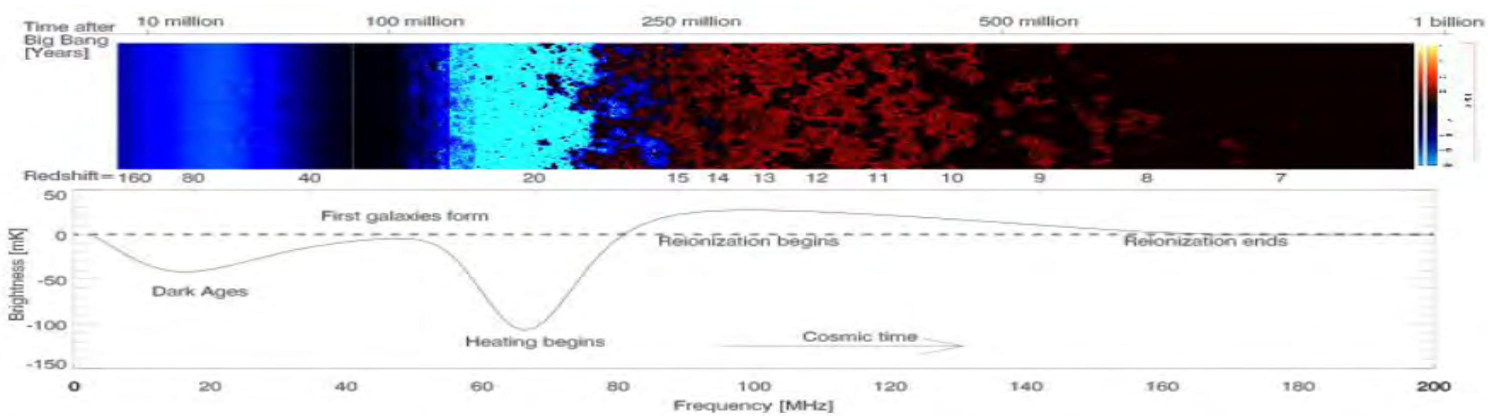
- 21cm Intensity mapping has great potential to become a very powerful tool for cosmology
- Foreground Subtraction remains a big challenge, may take at least a few years to overcome it
- A number of ongoing dedicated experiments, such as BINGO, CHIME, HERA, HIRAX, Tianlai, quite a few in BRICS countries!
- FAST and SKA may also conduct 21cm intensity observation
- Big Data Challenge!

Ultra-long wavelength satellite array

- Below 10MHz, due to ionosphere absorption, ground observation is nearly impossible.
- Dark Age & Cosmic Dawn may produce feature in 21cm global spectrum, but frequency-dependent ionosphere refraction introduce freatures in global spectrum



RAE-2 sky map (1979)

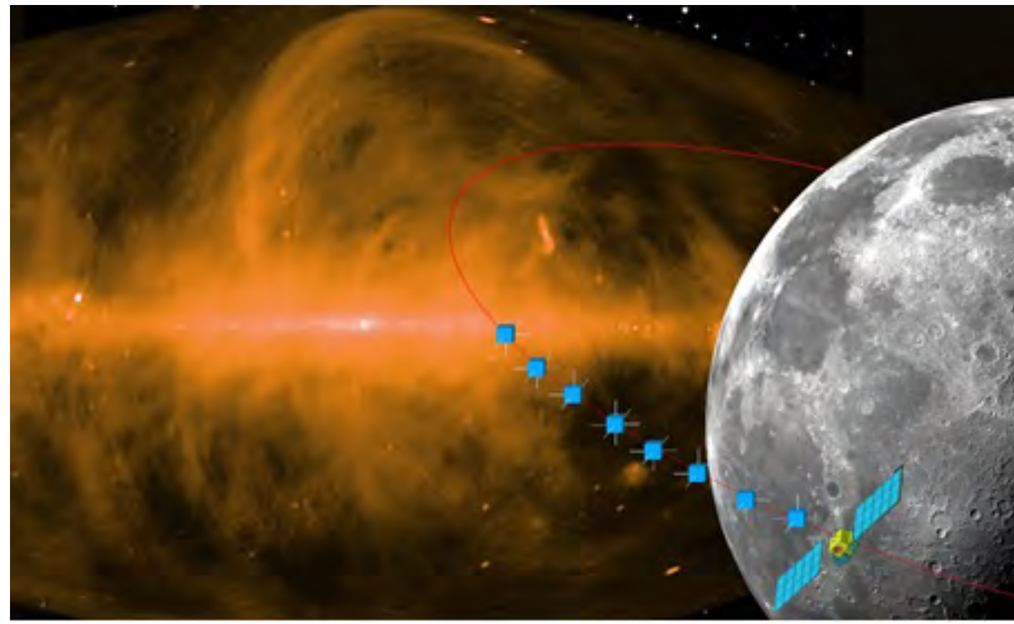


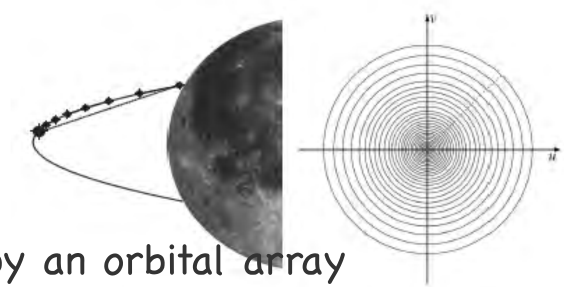
Discovering Sky at Longest (DSL) wavelength

- A linear array (5-8) of satellites moving around the moon, take observation at the backside of the moon, then transmit data back at the front side of the moon.

- A mother satellite measure the position of the daughter satellites

- Low frequency aims for imaging, high frequency aims to detect cosmic dawn signal by precise global spectrum measurement





baselines formed by an orbital array

Problems with Lunar Array

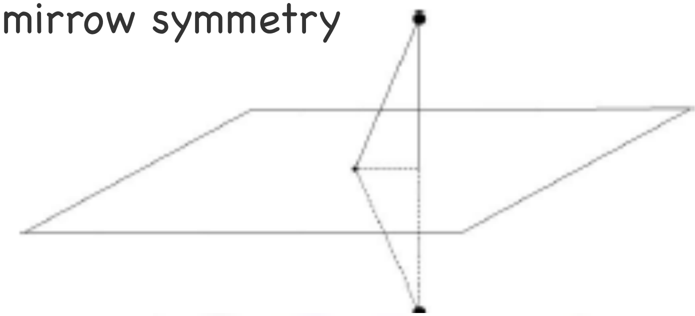
Traditional imaging algorithm can not work!

- short dipole ($l \ll \lambda$) antenna have very wide field of view (almost whole sky), traditional synthesis algorithm only for small field of view (flat sky, small w-term)
- A mirrow symmetry w.r.t. orbital plane, can be broken by 3D baselines (produced by orbital plane precession)
- Different baselines have different part of sky blocked by Moon

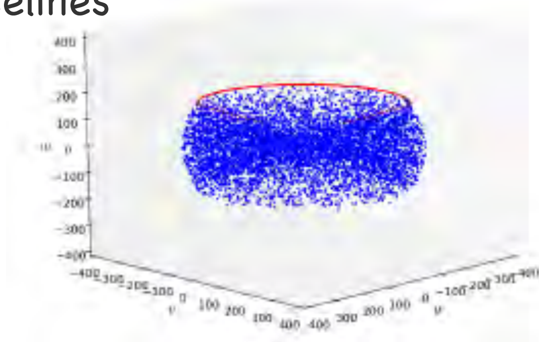
Brute force map-making (i.e. invertion)

$$\mathbf{V} = \mathbf{B}\,\mathbf{T} + \mathbf{n}. \qquad \hat{\mathbf{T}} = (\mathbf{B}^{\dagger}\mathbf{N}^{-1}\mathbf{B})^{-1}\mathbf{B}^{\dagger}\mathbf{N}^{-1}\mathbf{V} \equiv \mathbf{B}^{-1}\mathbf{V}.$$

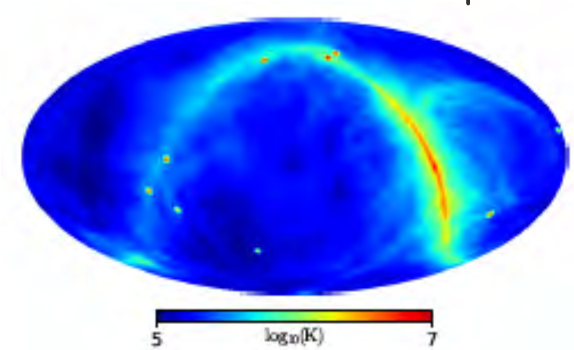
mirrow symmetry



3D baselines



simulated reconstruction map



Huang et al., arXiv:1805.08259

Thanks!