BRICS Astronomy Workshop 2016

Astronomical Data and Computation

Prospects of 21cm Cosmology

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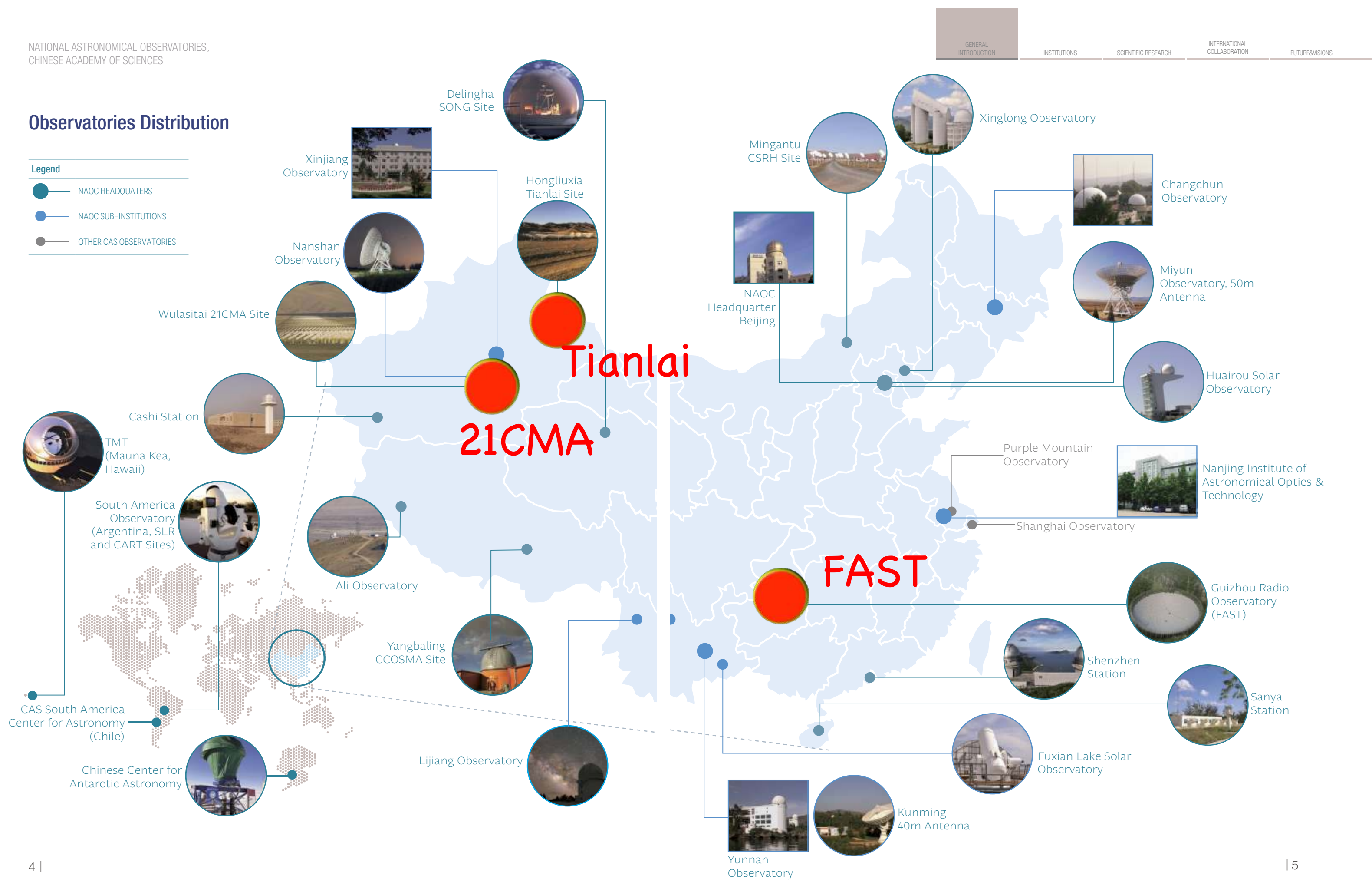
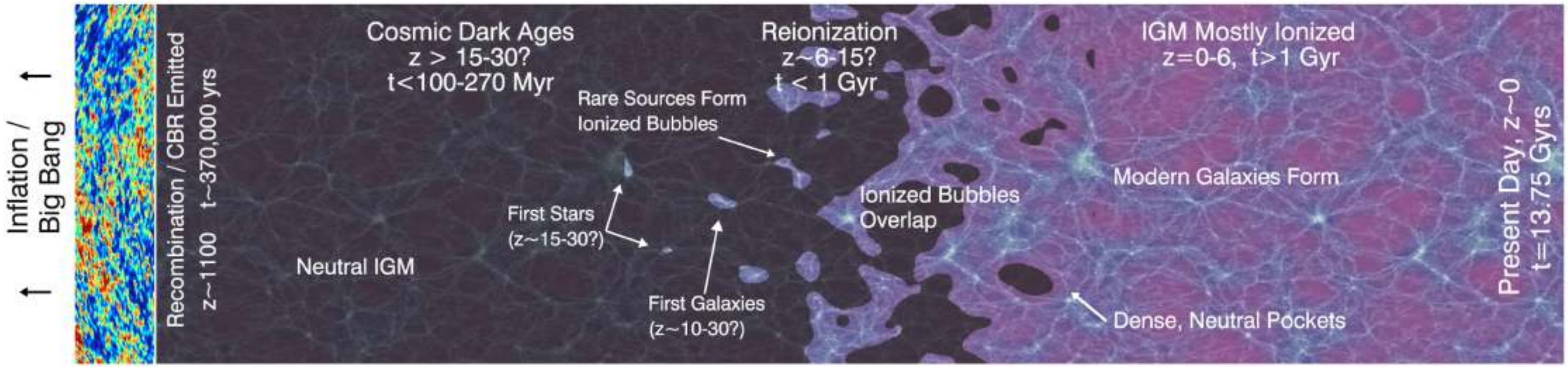
Astronomical Facilities of China



Neutral Hydrogen (HI) in the universe



coutesy B.E. Robertson et al., Nature

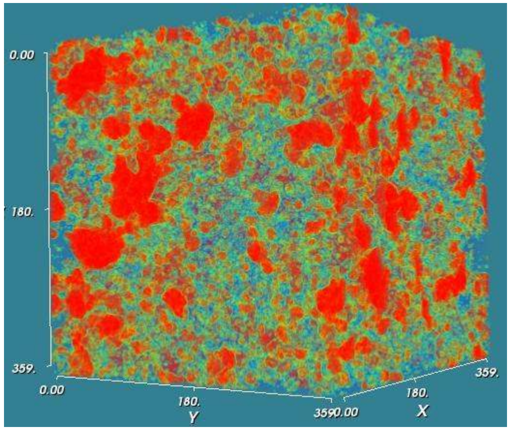
- interstellar medium

- nearby galaxies, kinematics (dark matter, Tully-Fisher relation determined distance), gas accretion

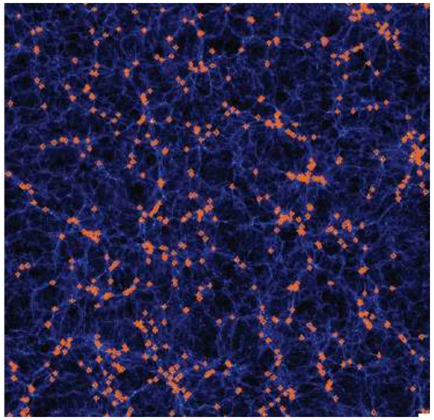
- large scale structure

- epoch of reionization

- dark age



Epoch of Reionization (EoR)



post-EoR

21cm Cosmology

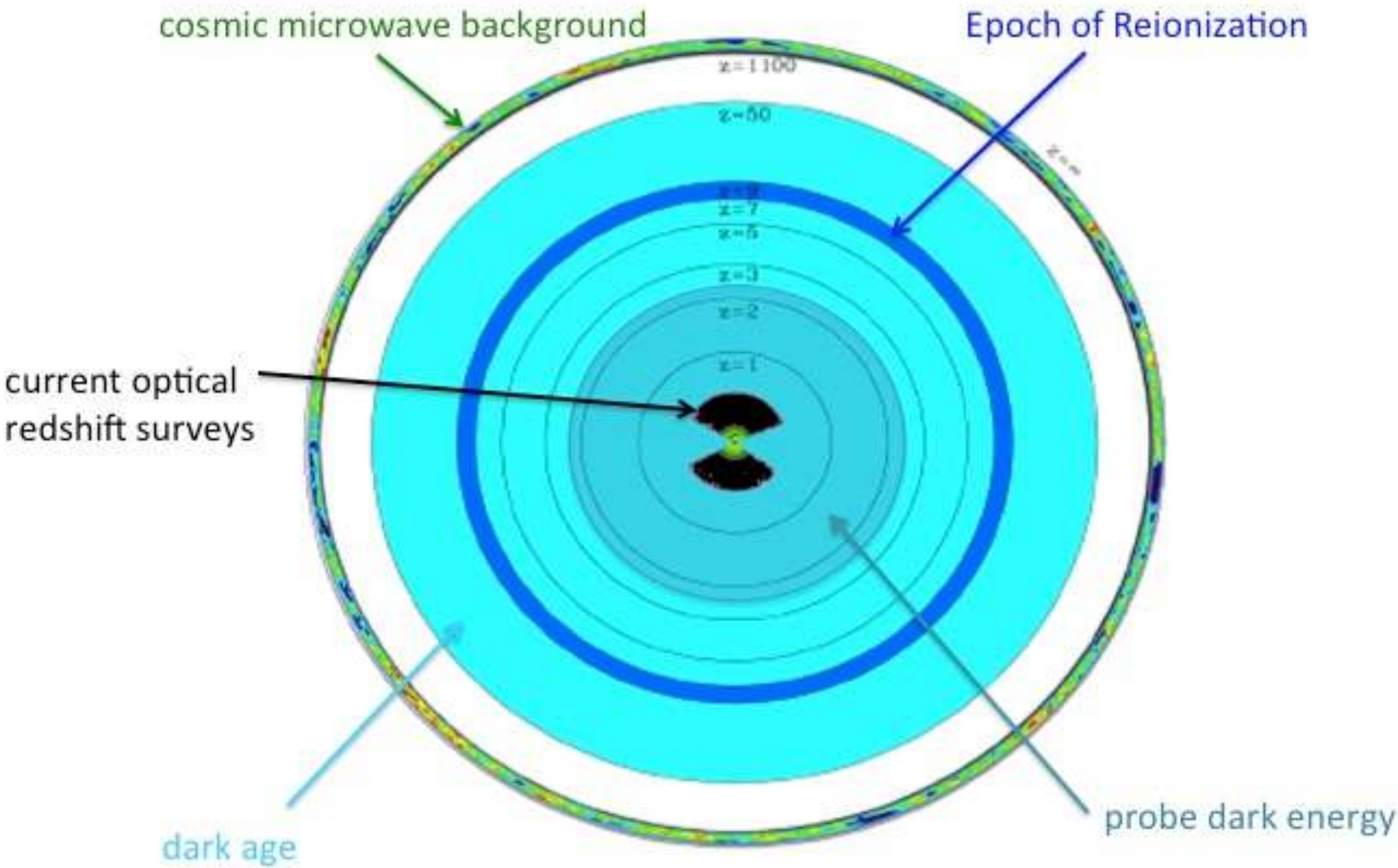
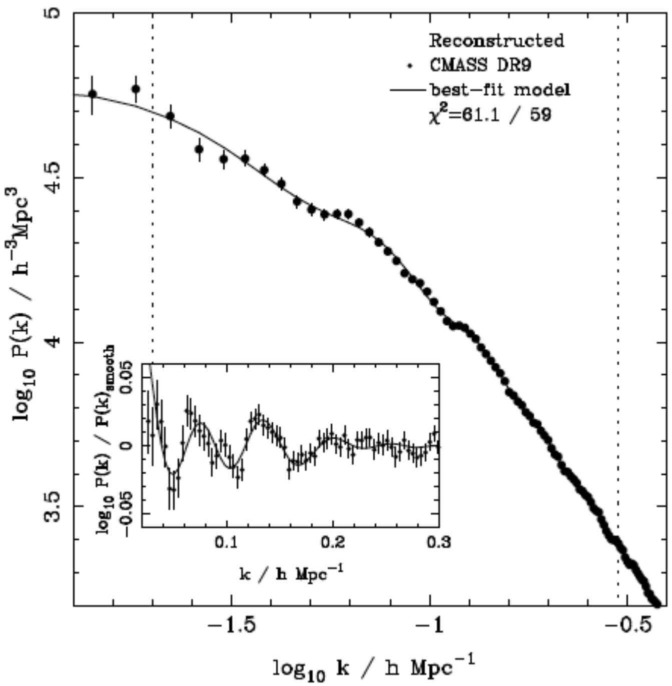
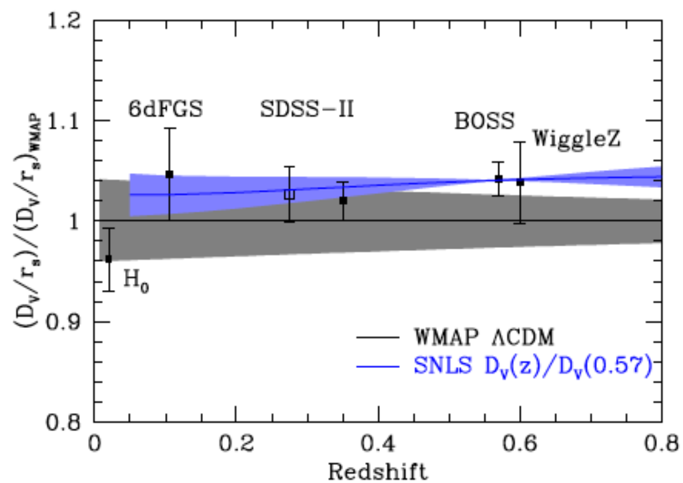


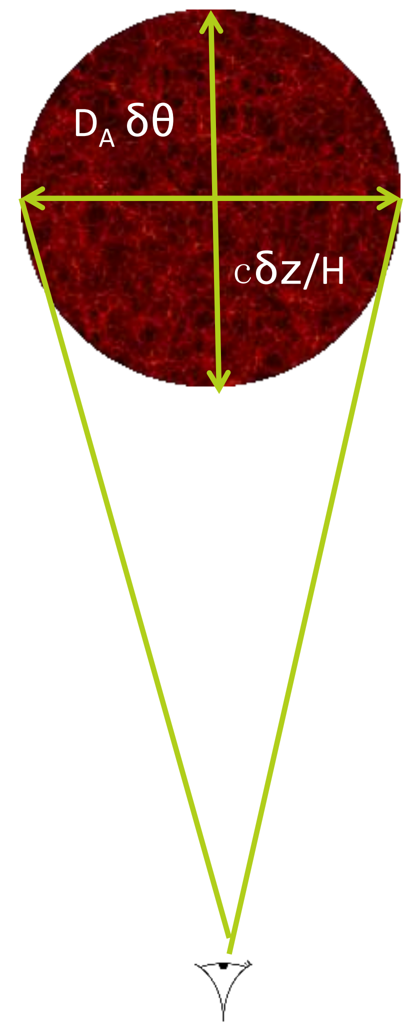
Figure inspired by Yi Mao & Max Tegmark

Baryon Acoustic Oscillation

Hubble expansion rate H(z)
angular diameter distance $d_A(z)$

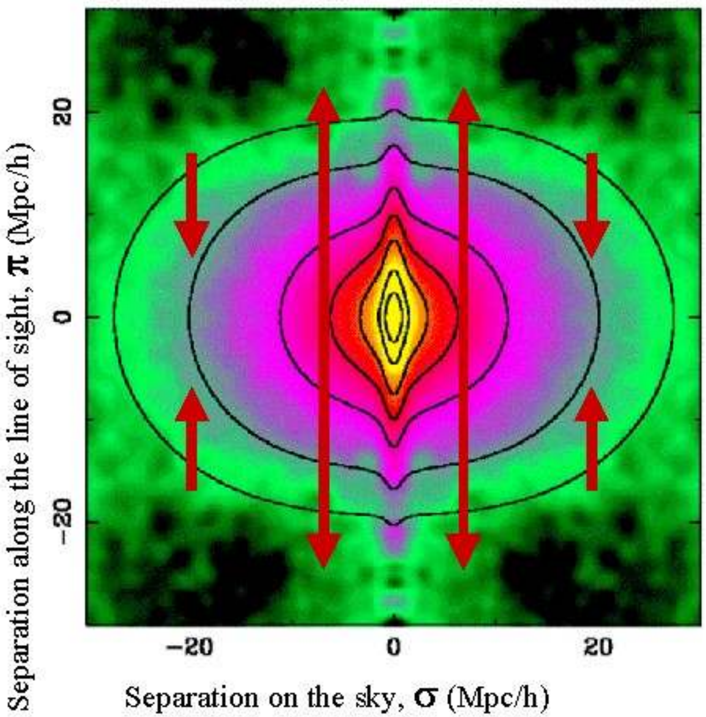


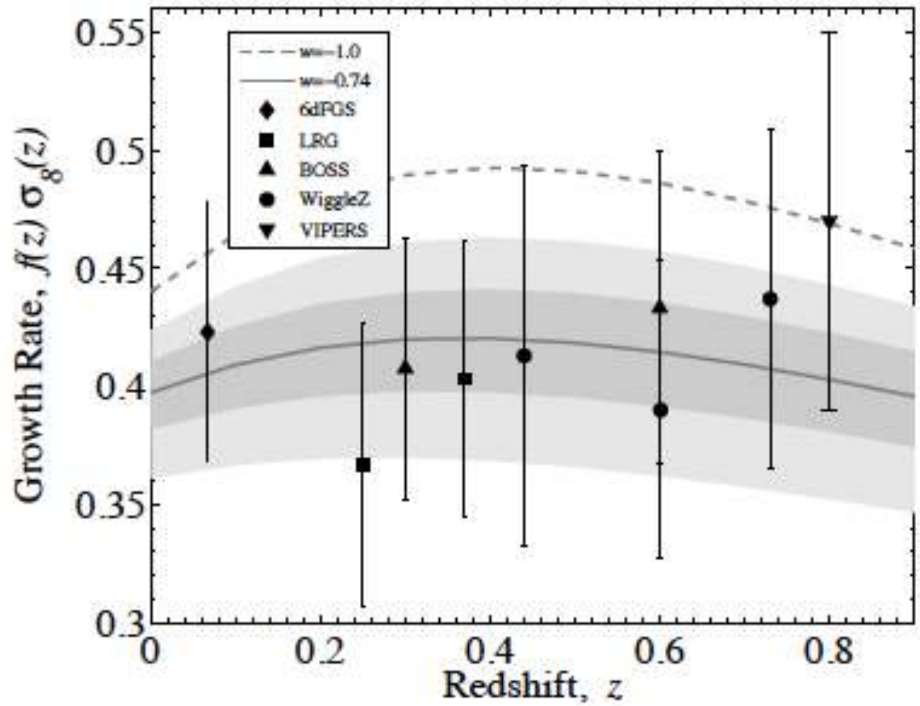




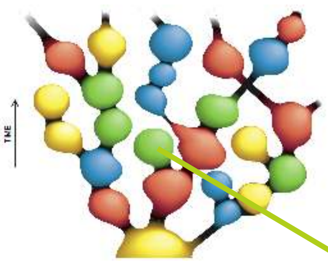
Redshift Distortion and Growth of Structure

$$P^s(\mathbf{k}) = P(\mathbf{k})[1 + 2\mu^2\beta^2 + \mu^4\beta^2]G\left[\frac{k^2\mu^2\sigma_v^2}{H^2(z)}\right],$$



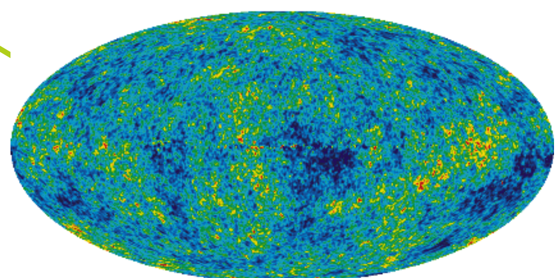


The ultimate cosmic information: Large Scale Structure



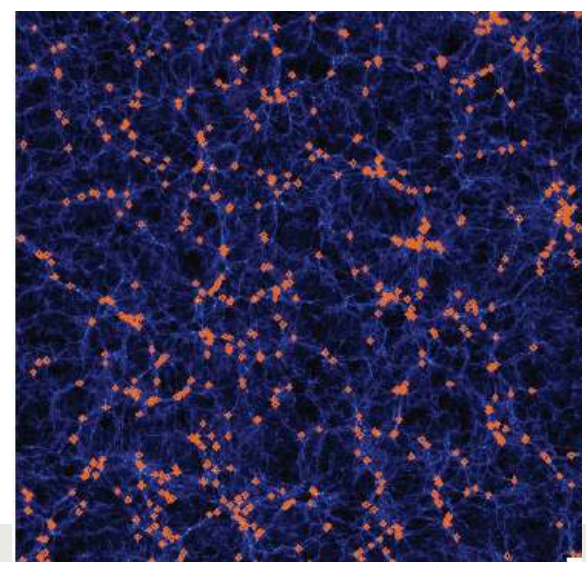
inflation

quantum fluctuations due to uncertainty principle



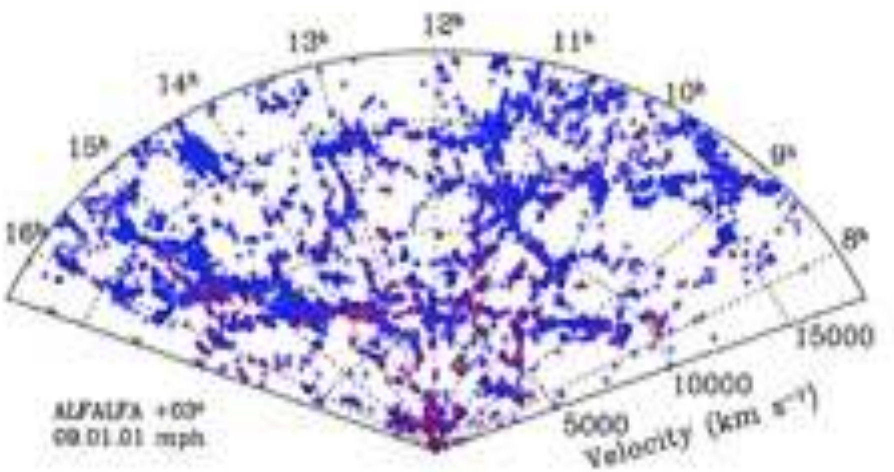
primordial fluctuations, CMB anisotropy

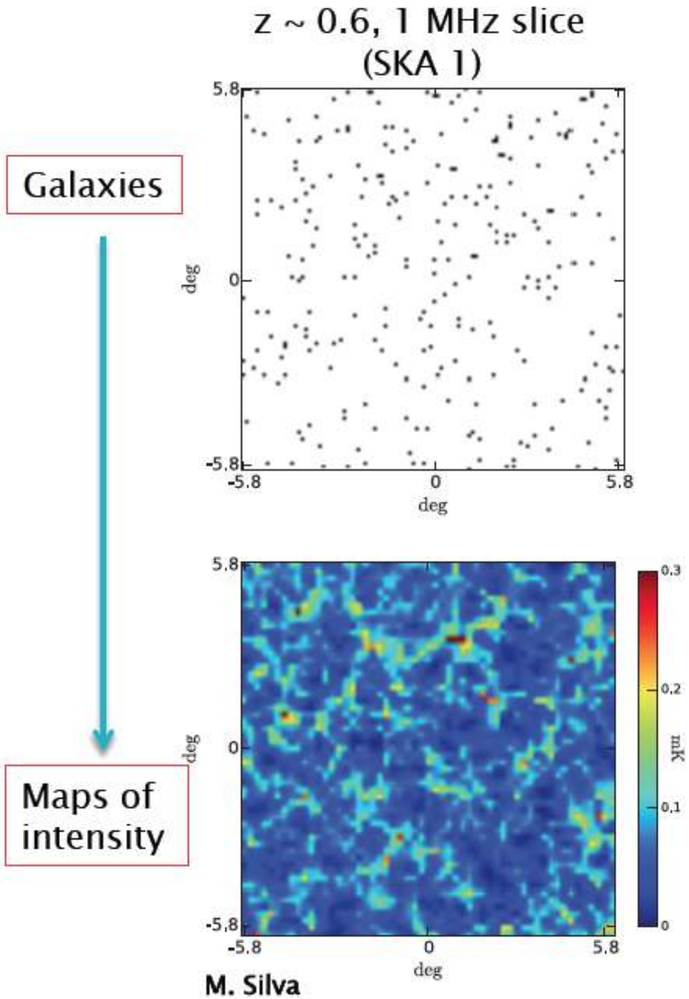
large scale structure probed by neutral hydrogen



Galaxy Survey & Intensity Mapping

HI galaxy survey





Advantage of 21cm for intensity mapping

Thompson, Moran & Swenson (2001)

Y. Gong et al. (ApJL 2011)

Intensity mapping may be contaminated by different spectral lines:

$$(1+z_1)\lambda_1 = (1+z_2)\lambda_2.$$

The low frequency 21cm does not have significant contaminants, we considered OH 18cm line. In such contamination, incoherent superposition (power spectra adds)

TABLE 1.1 Some Important Radio Lines

Chemical Name	Chemical Formula	Transition	Frequency (GHz)
Deuterium	D	$^2S_{\frac{1}{2}}, F = \frac{3}{2} \to \frac{1}{2}$	0.327
Hydrogen	HI	$^2S_{\frac{1}{2}}, F = 1 \to 0$	1.420
Hydroxyl radical	OH	$^2\Pi_{\frac{3}{2}}, J = \frac{3}{2}, F = 1 \to 2$	1.612[a]
Hydroxyl radical	OH	$^2\Pi_{\frac{3}{2}}, J = \frac{3}{2}, F = 1 \to 1$	1.665[a]
Hydroxyl radical	OH	$^2\Pi_{\frac{3}{2}}, J = \frac{3}{2}, F = 2 \to 2$	1.667[a]
Hydroxyl radical	OH	$^2\Pi_{\frac{3}{2}}, J = \frac{3}{2}, F = 2 \to 1$	1.721[a]
Methyladyne	CH	$^2\Pi_{\frac{1}{2}}, J = \frac{1}{2}, F = 1 \to 1$	3.335
Hydroxyl radical	OH	$^2\Pi_{\frac{1}{2}}, J = \frac{1}{2}, F = 1 \to 0$	4.766[a]
Formaldehyde	H_2CO	$1_{10} - 1_{11}$, six F transitions	4.830
Hydroxyl radical	OH	$^2\Pi_{\frac{3}{2}}, J = \frac{5}{2}, F = 3 \to 3$	6.035[a]
Methanol	CH_3OH	$5_1 \to 6_0 A^+$	6.668[a]
Helium	$^3He^+$	$^2S_{\frac{1}{2}}, F = 1 \to 0$	8.665
Methanol	CH_3OH	$2_0 \to 3_{-1} E$	12.179[a]
Formaldehyde	H_2CO	$2_{11} \to 2_{12}$, four F transitions	14.488
Cyclopropenylidene	C_3H_2	$1_{10} \to 1_{01}$	18.343
Water	H_2O	$6_{16} \to 5_{23}$, five F transitions	22.235[a]
Ammonia	NH_3	$1, 1 \to 1, 1$, eighteen F transitions	23.694
Ammonia	NH_3	$2, 2 \to 2, 2$, seven F transitions	23.723
Ammonia	NH_3	$3, 3 \to 3, 3$, seven F transitions	23.870
Methanol	CH_3OH	$6_2 \to 6_1, E$	25.018
Silicon monoxide	SiO	$v = 2, J = 1 \to 0$	42.821[a]
Silicon monoxide	SiO	$v = 1, J = 1 \to 0$	43.122[a]

$$\bar{I}_{OH}(z) = f_{OH}\int_{M_{min}}^{M_{max}} dM \frac{dn}{dM} f_{IR}(M) \frac{L_{OH}(M,z)}{4\pi D_L^2} y(z) D_A^2$$

The OH power is several orders of magnitude smaller than the 21cm power, so the contamination is insignificant

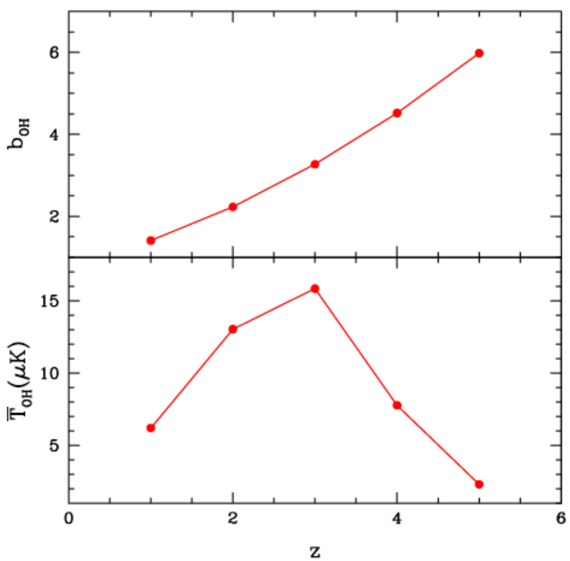
OH – IR relation (Darling & Giovanelli 2002):

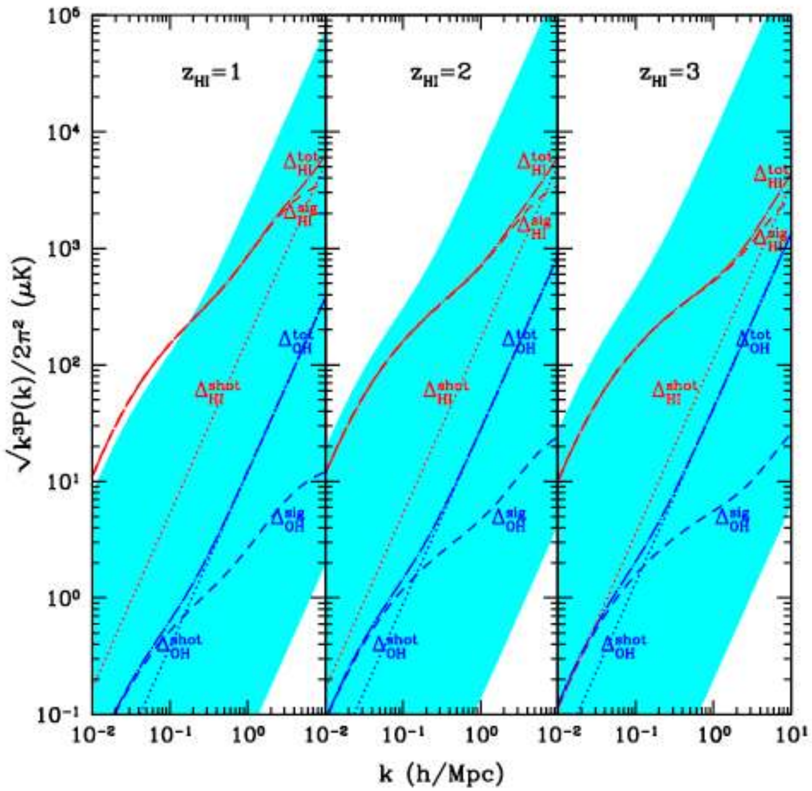
$$\log L_{OH} = (1.2 \pm 0.1)\log L_{IR} - (11.7 \pm 1.2).$$

IR-SFR relation （Magnelli et al. 2011)

$$L_{IR}\ [L_{\odot}] = 5.8 \times 10^9\ \mathrm{SFR}\ [\mathrm{M_{\odot} yr^{-1}}].$$

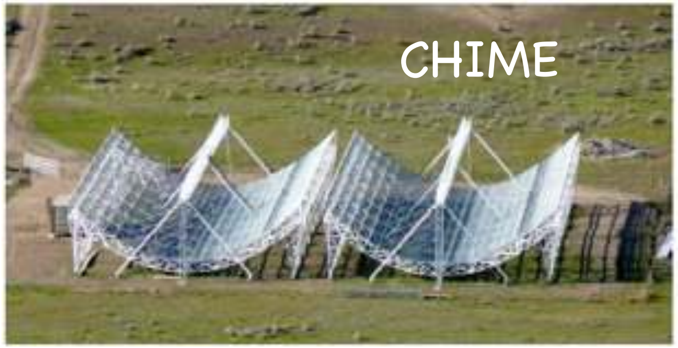
Using SKA sky simulation model to obtain halo and SFR(Obreschkow et al. 2009)

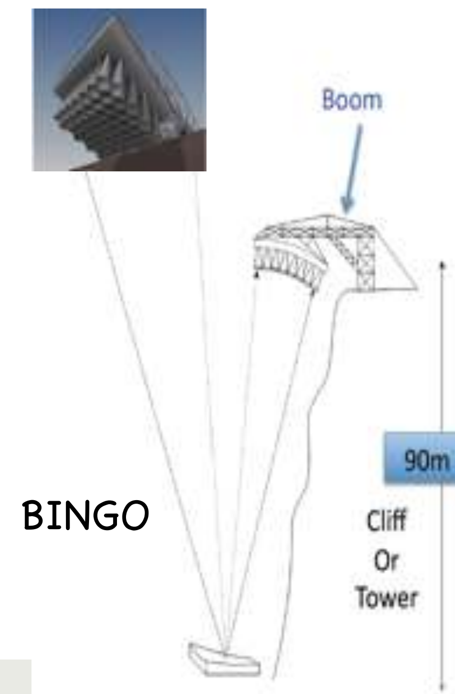




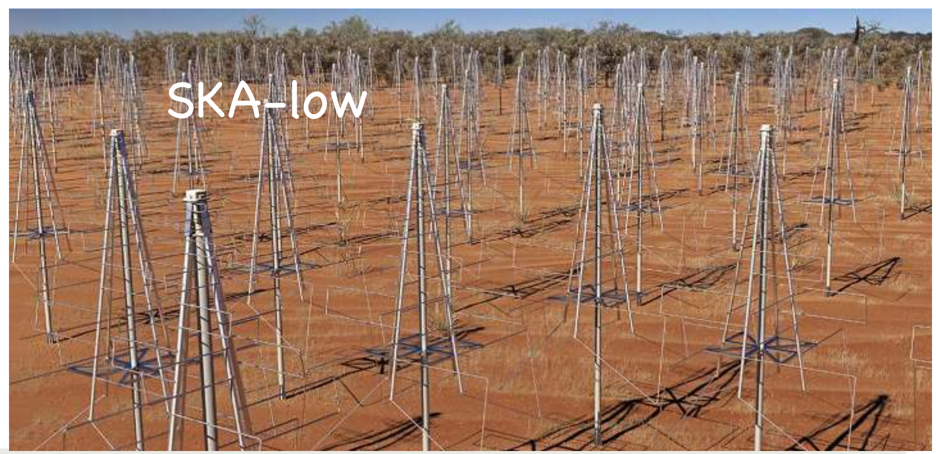
Some EoR 21cm experiments

Some 21cm Intensity Maping Experiments





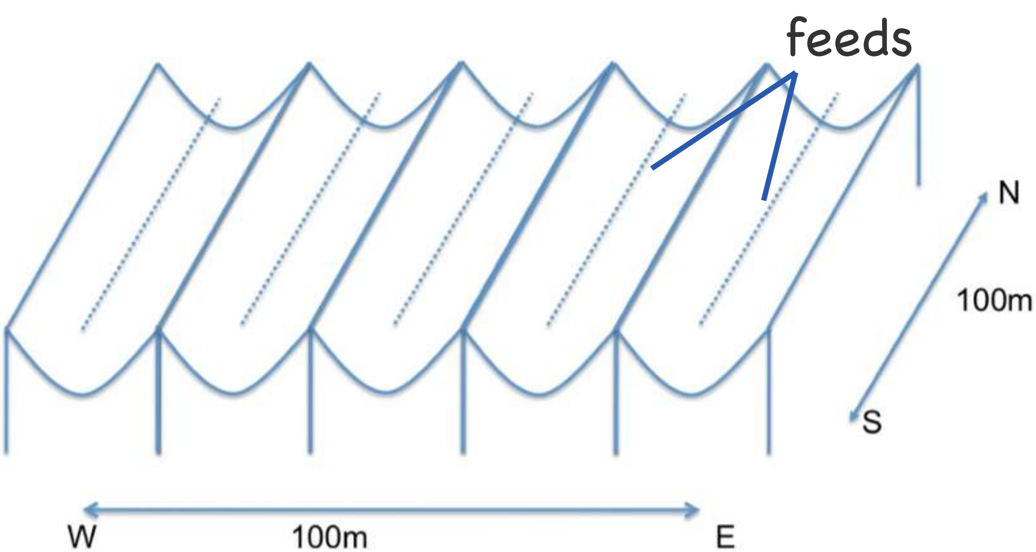
Big Telescopes



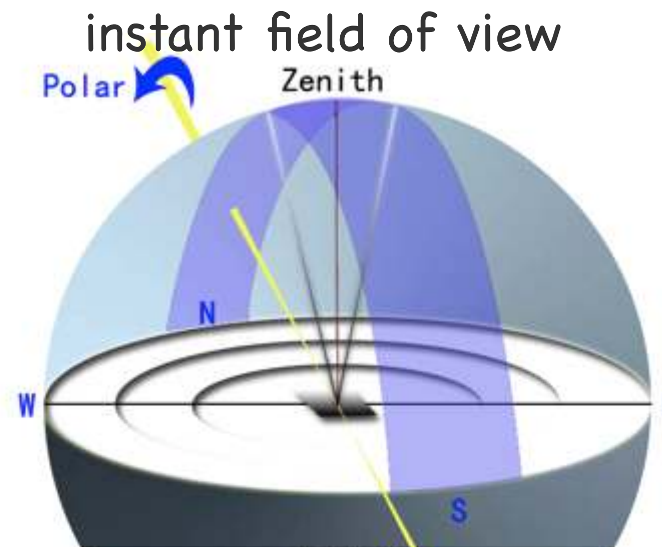
Intensity Mapping Arrays

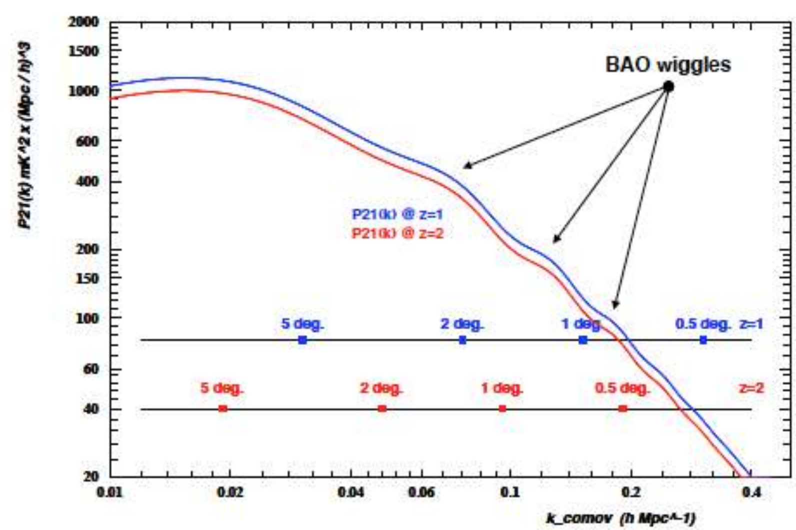
Drift Scan Cylinders (Peterson & Pen):

Canada: CHIME
China: Tianlai (heavenly sound)



Ansari et al., 1108.1474





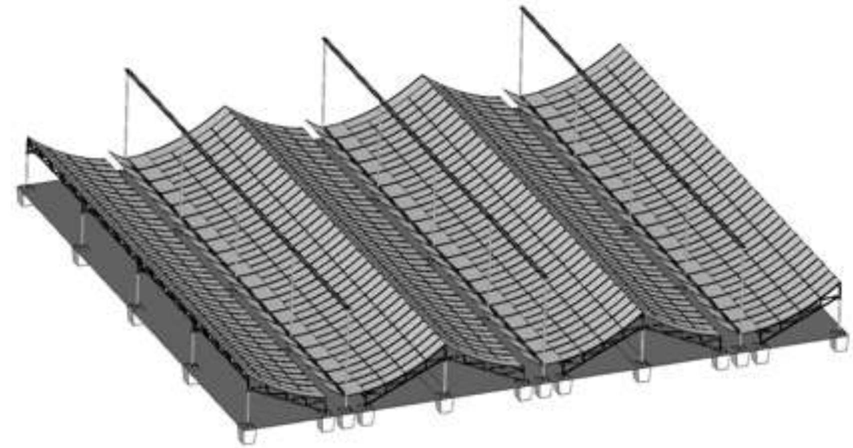
Tianlai pathfinder experiment

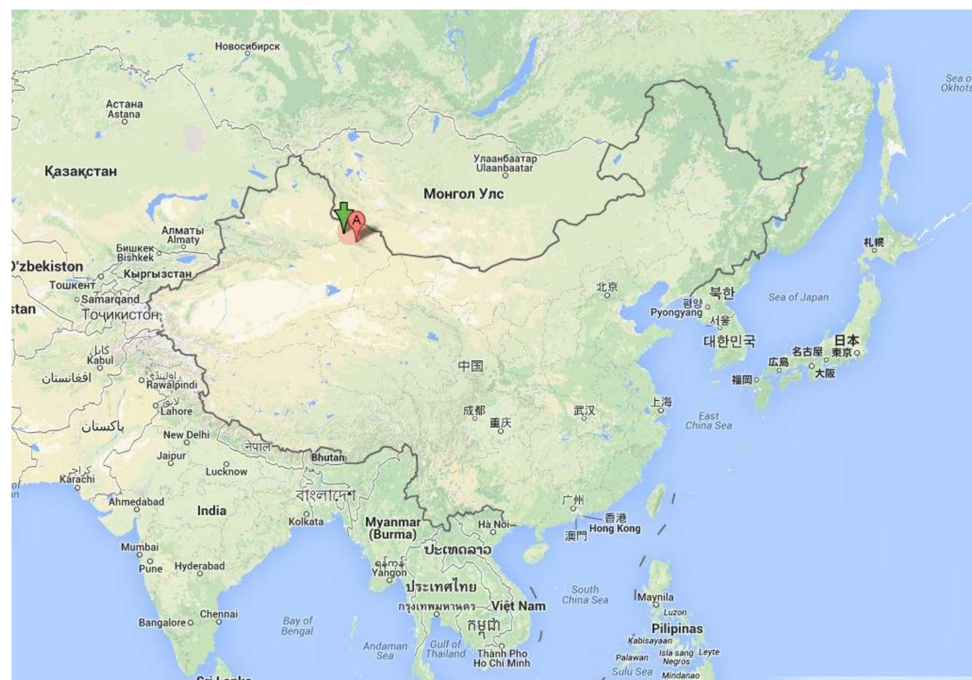
- A small pathfinder experiment to check the basic principles and designs, find out potential problems

- 3x15x40m cylinders, 96 dual polarization receiver units

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

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



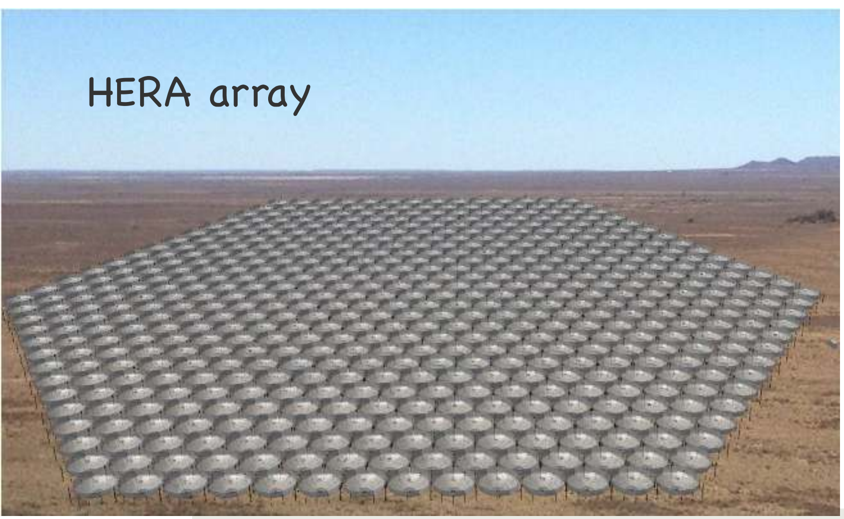


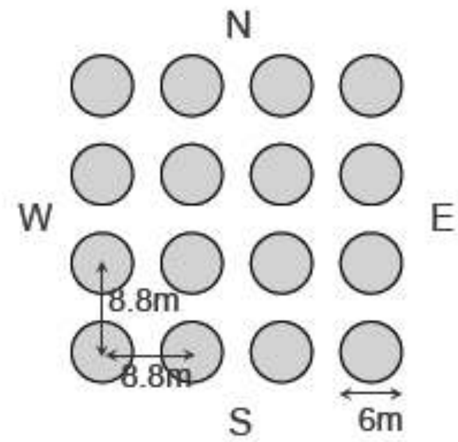
Another Idea: Array of Dishes

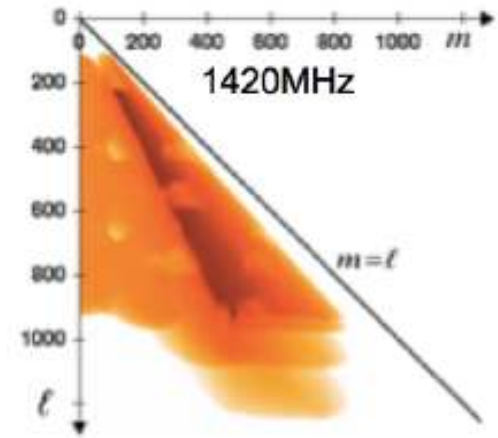
Dishes are better understood and have smaller sidelobes

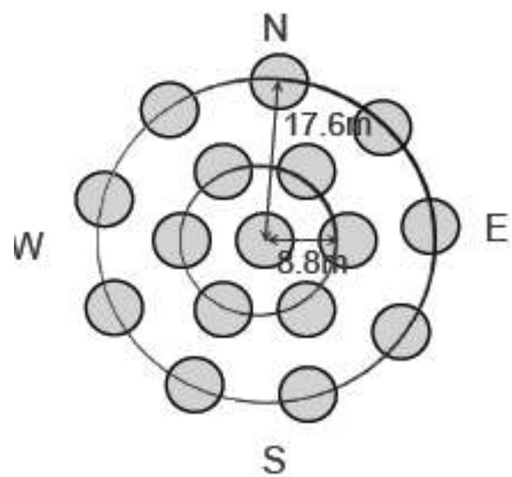
needs adjusting baseline for different declination

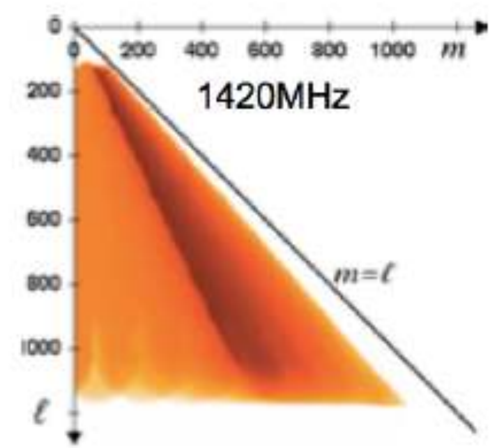
less responsive to large scale modes



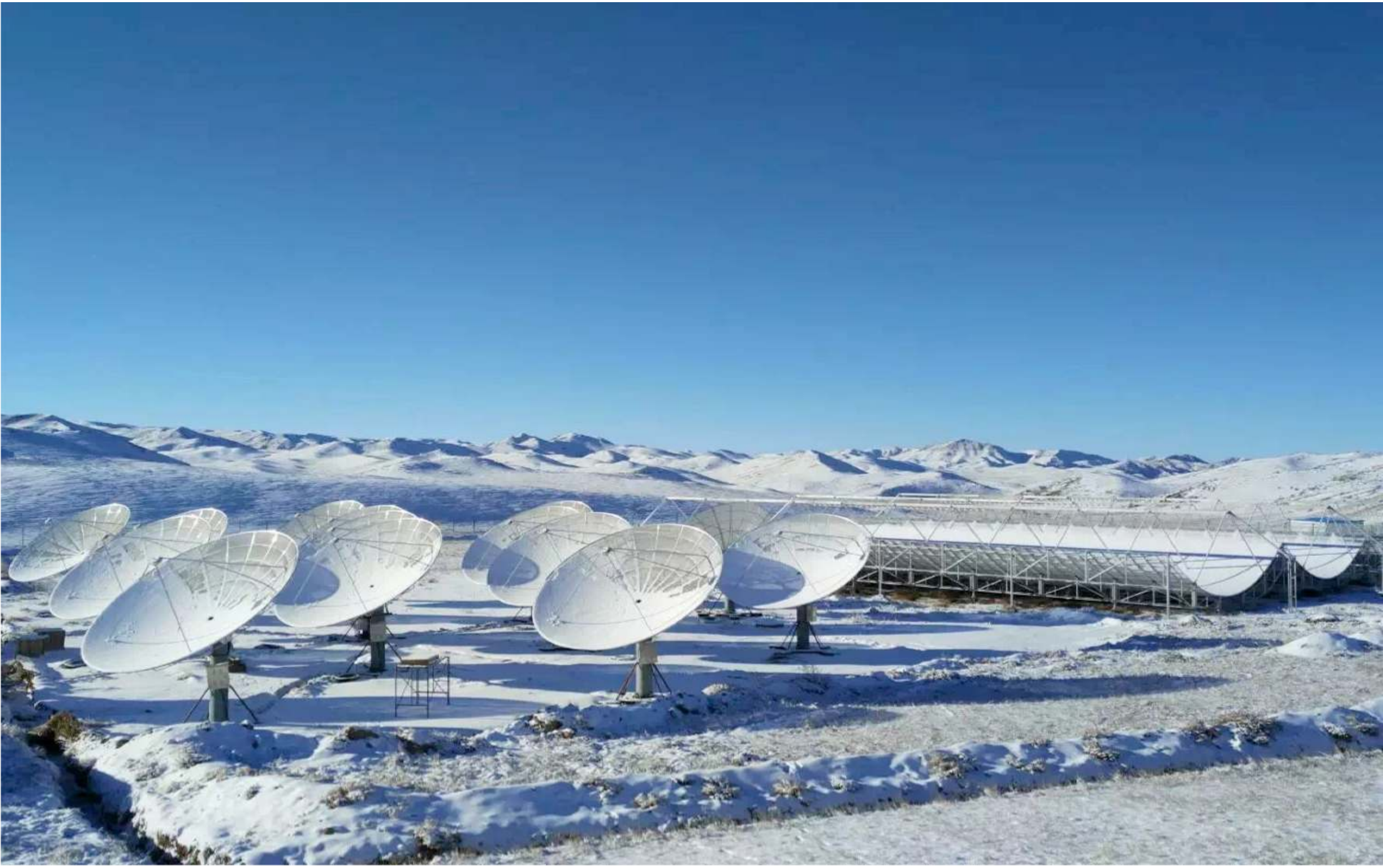


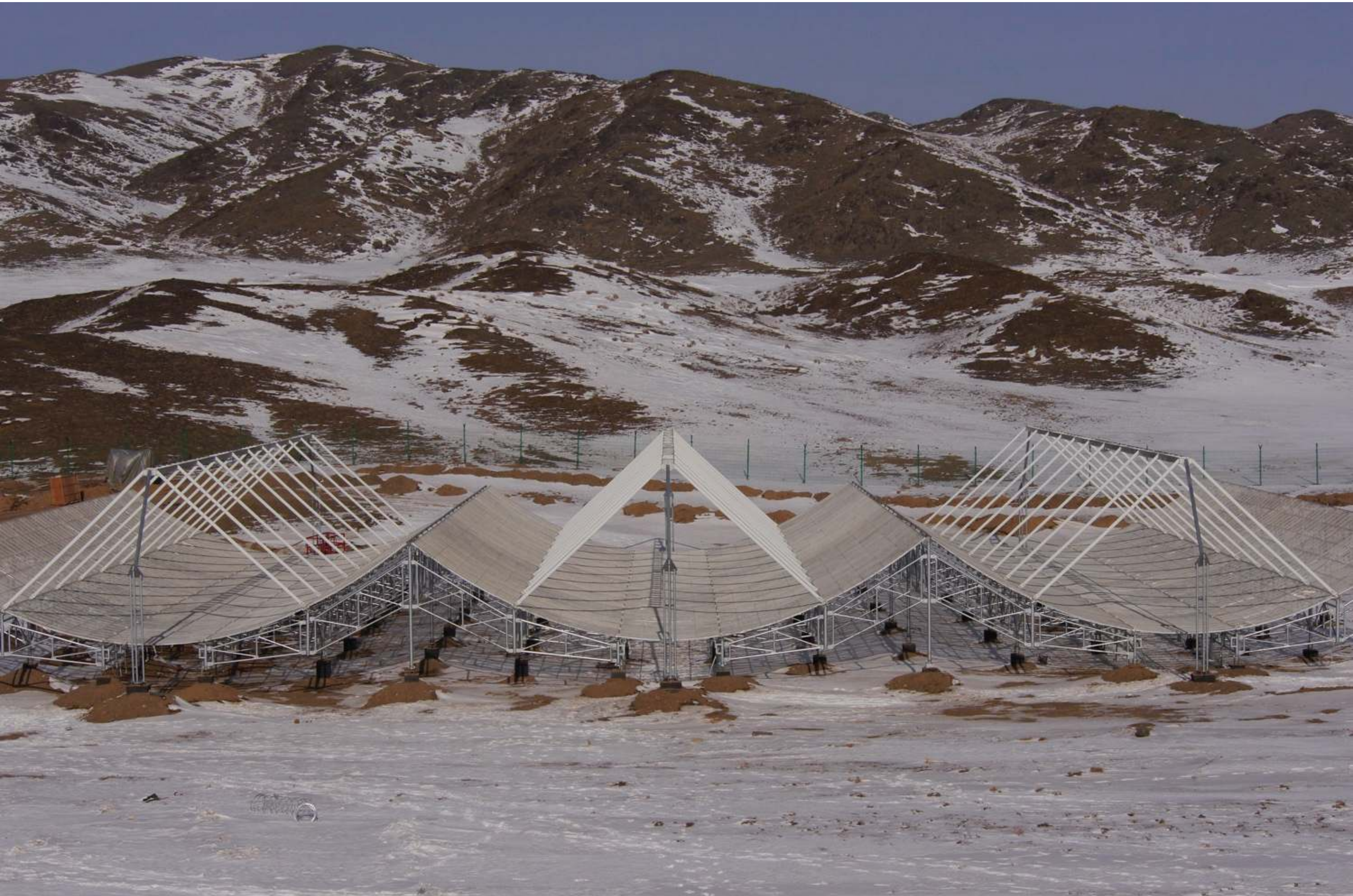






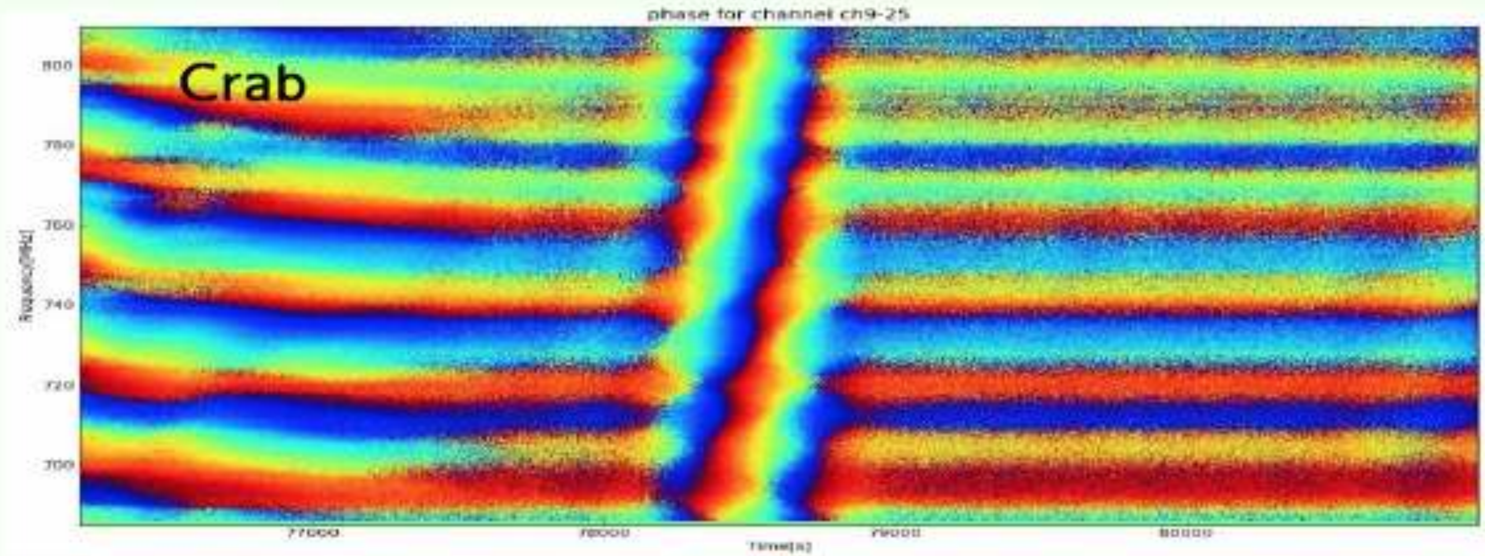
Site Arrangement

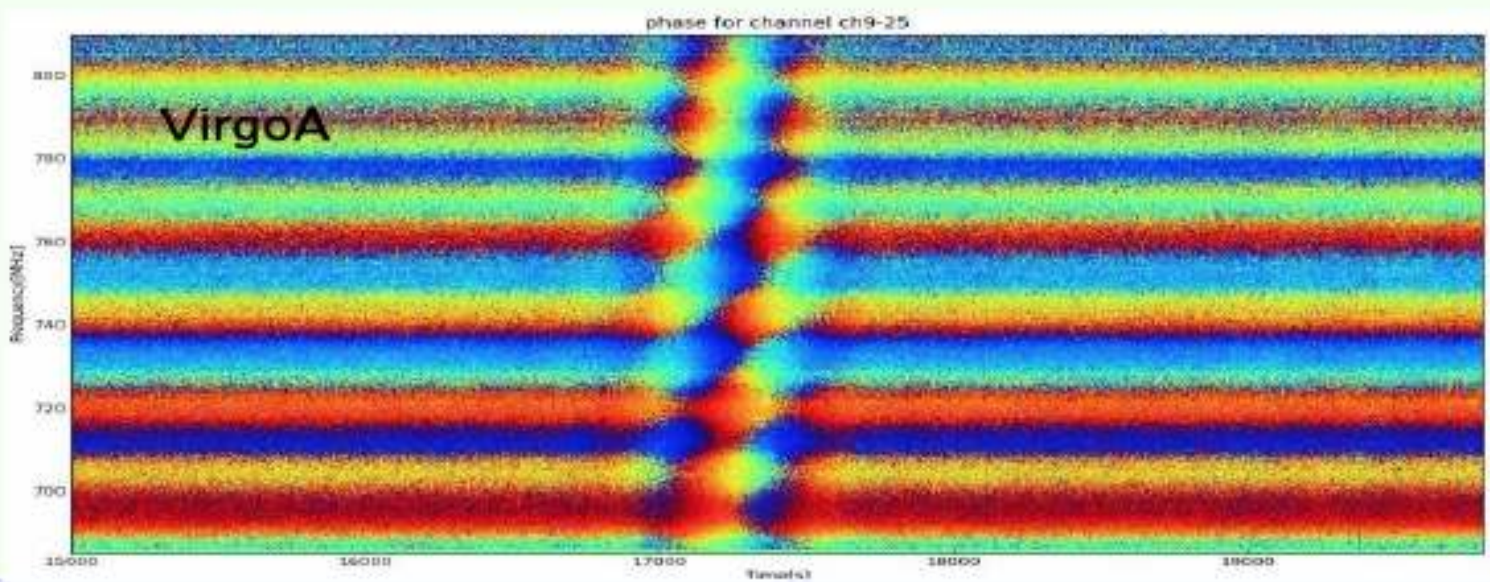




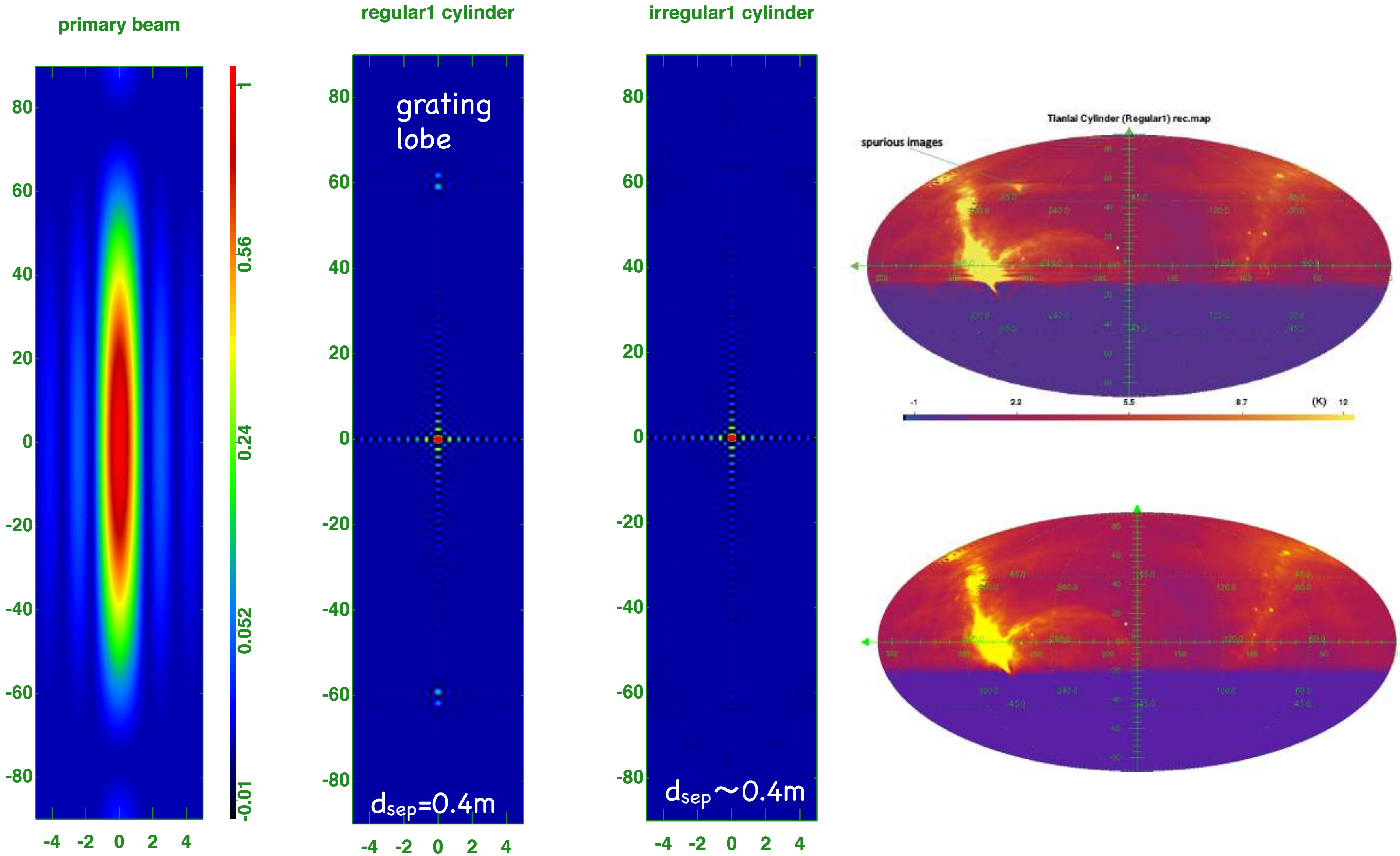
Receiver and Correlator

Experiment of Cylinder array





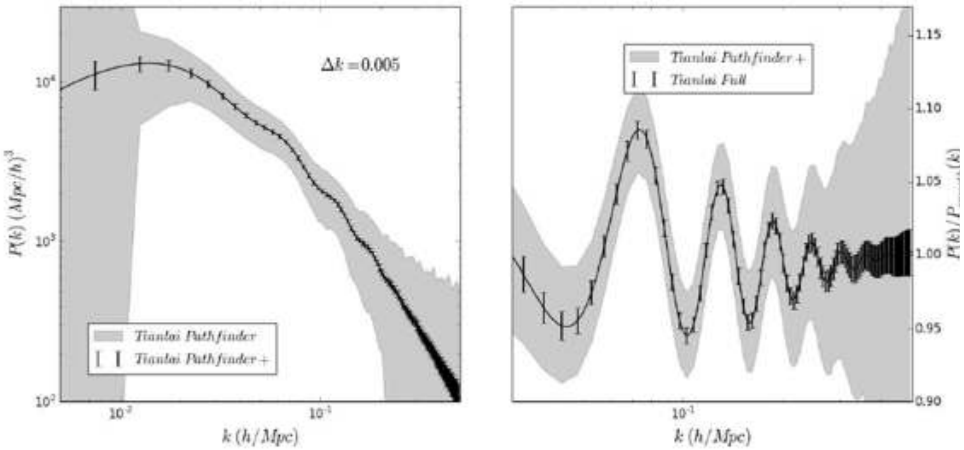
Cylinder Array simulation



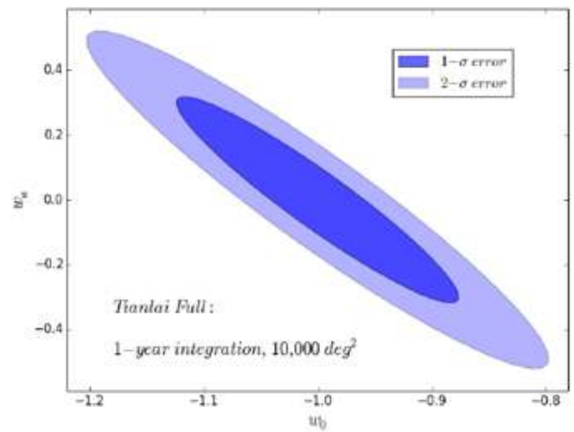
Performance Forecast

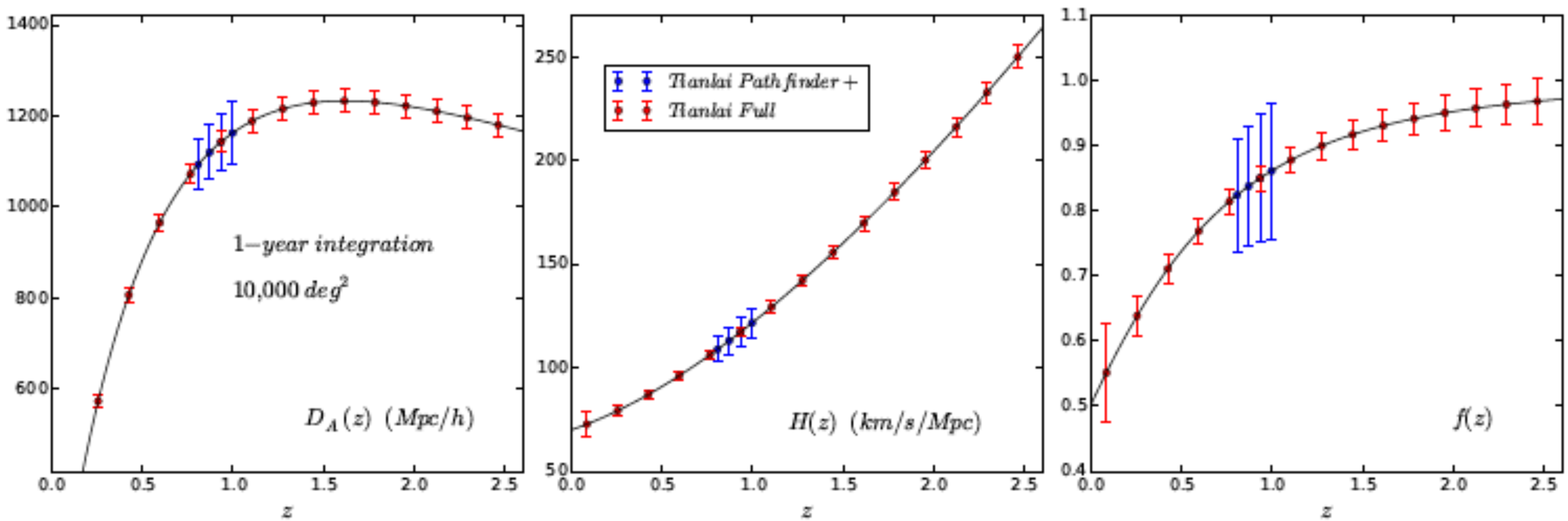
Xu, Wang & Chen, ApJ 2014,

power spectrum



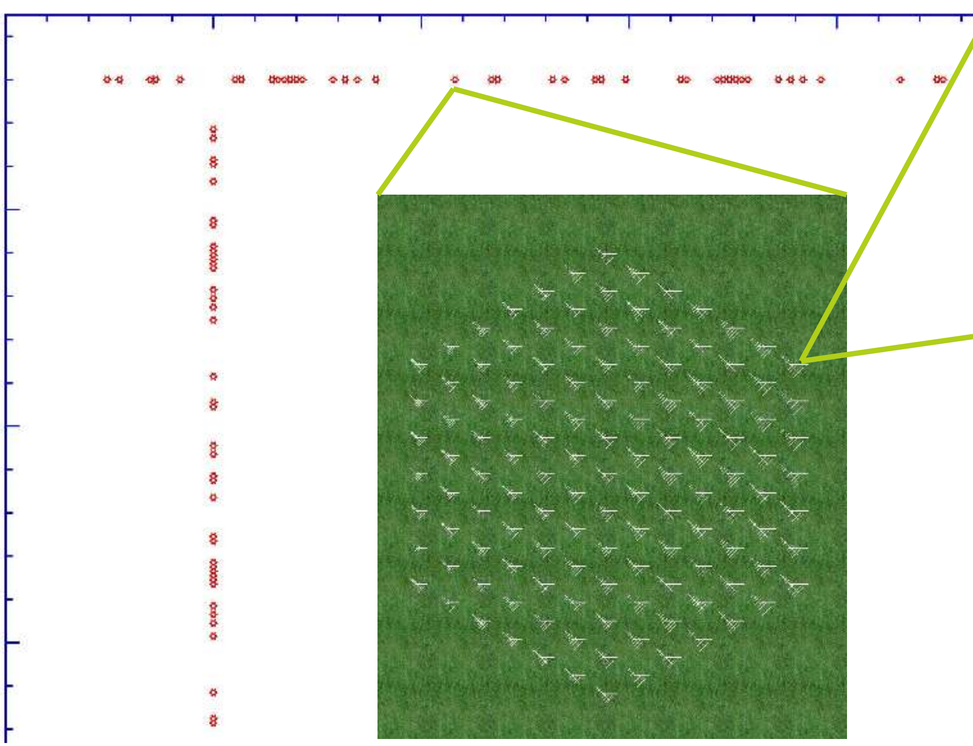
DE EoS





21CMA

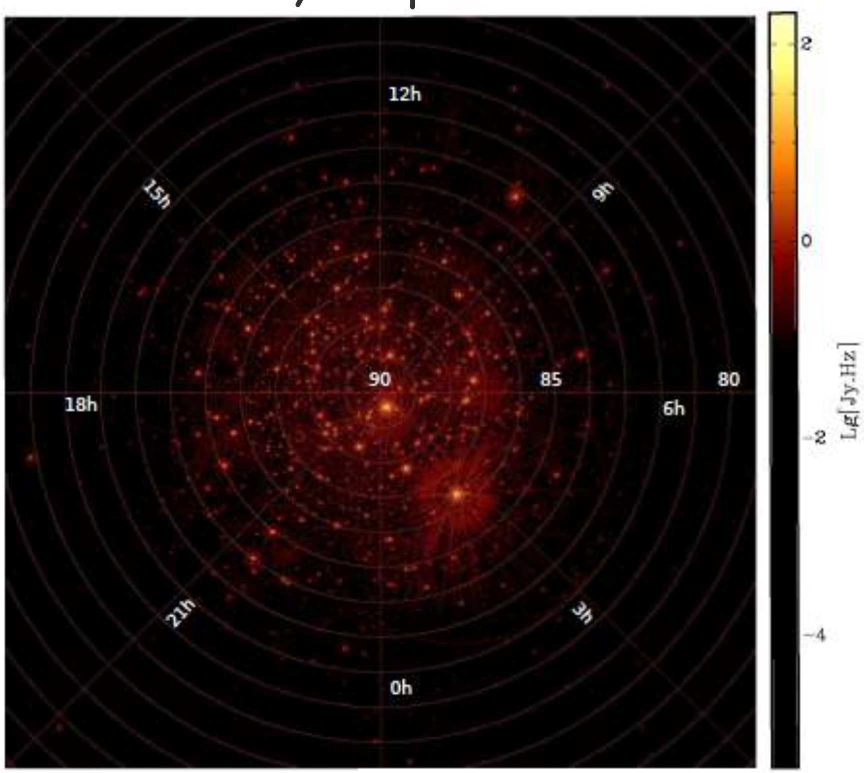
- project lead by Prof. Xiang-Ping Wu
- 81 pods along two arms (6km+4km), 10287 antenna (25,000m²), 50—200MHz



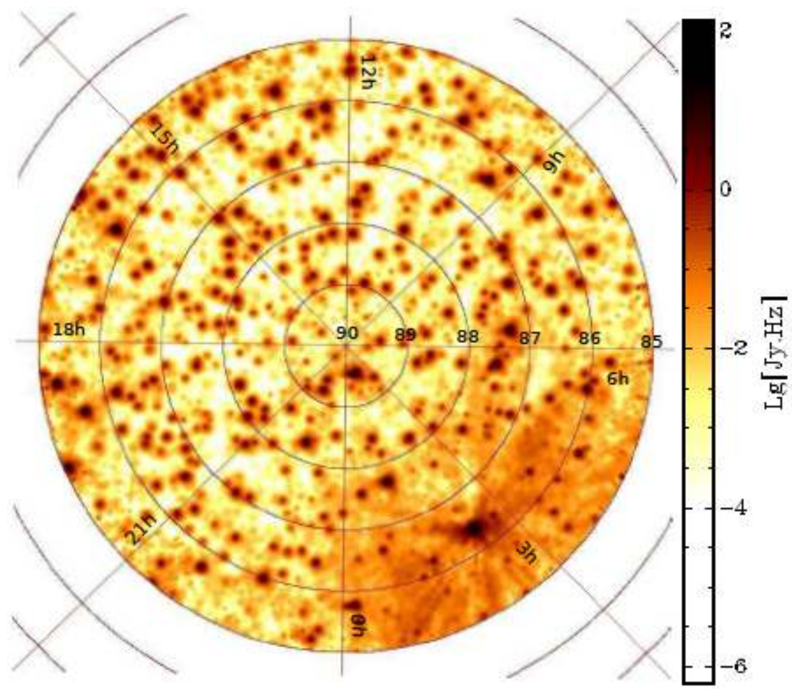
Some results

Q. Zheng et al., arxiv:1602.06624

dirty map



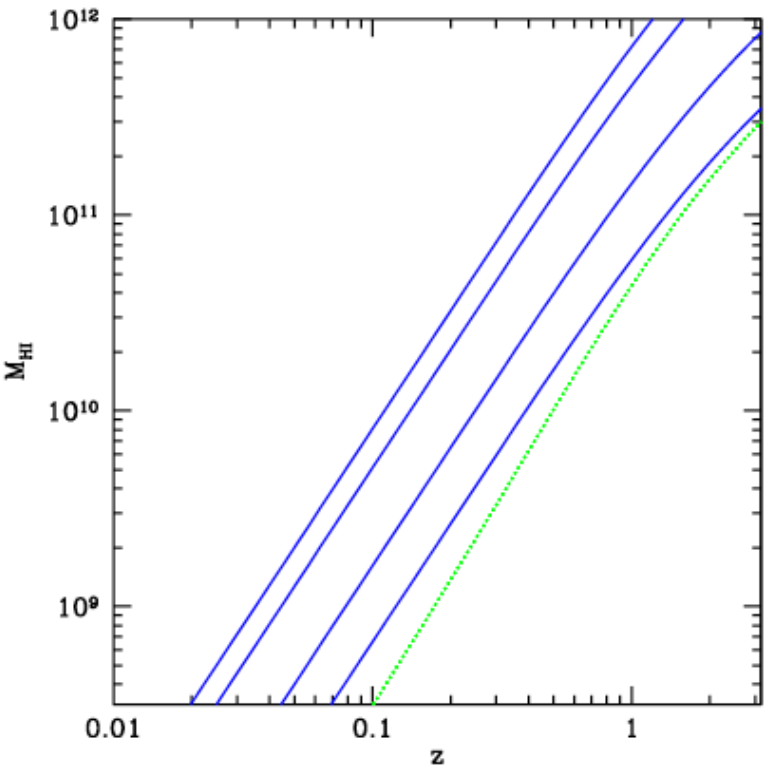
restored map

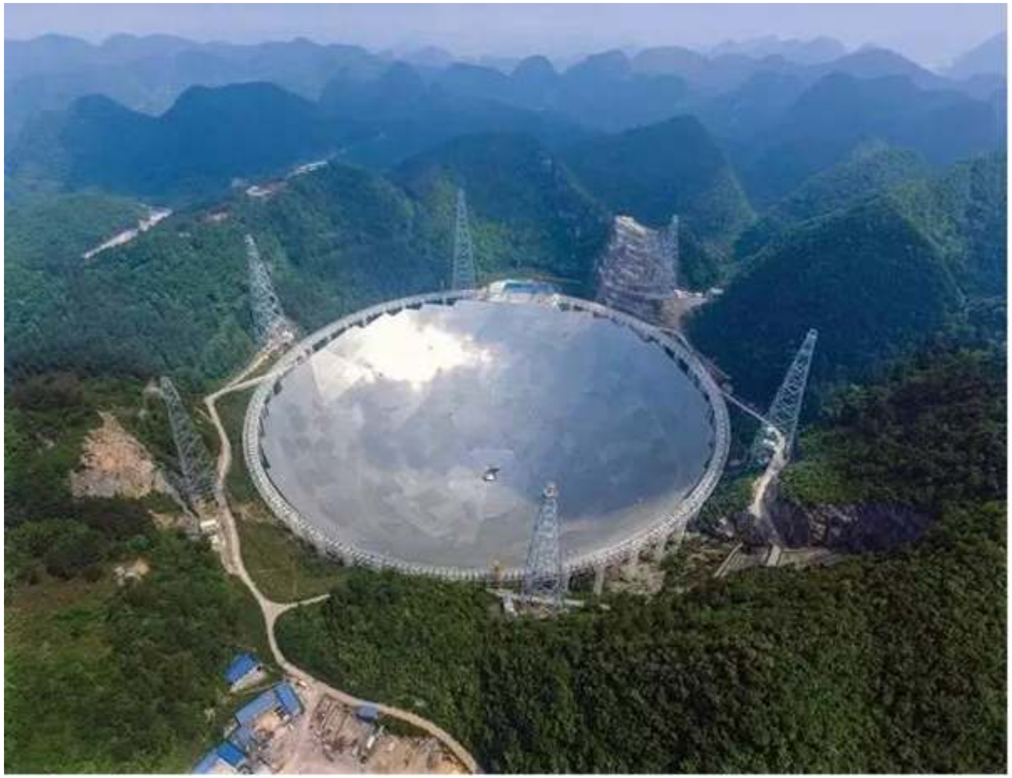


Five hundred meter Aperture Spherical Telescope (FAST)

$$\theta \sim \frac{21(1+z)\ \text{cm}}{30000\ \text{cm}} \sim 3(1+z)\,\text{arcmin}$$

lead by Prof. Rendong Nan

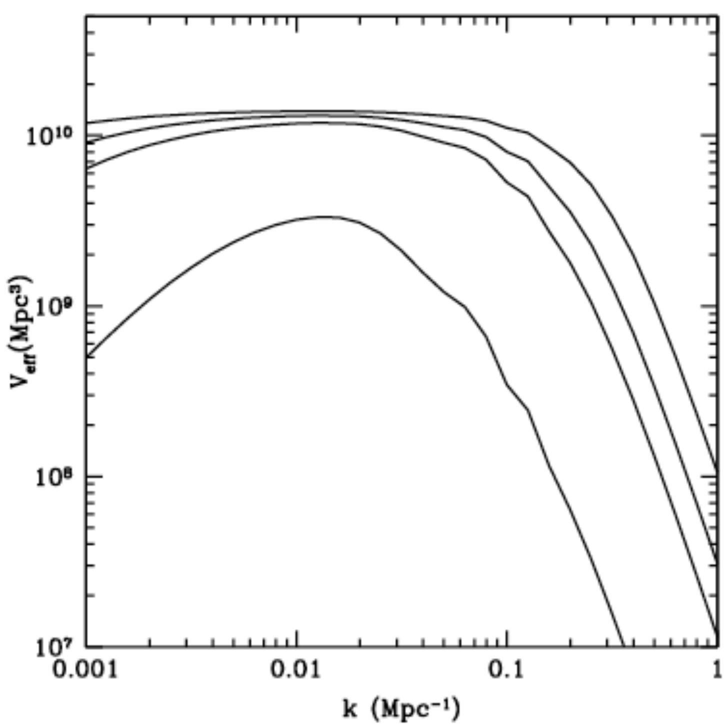




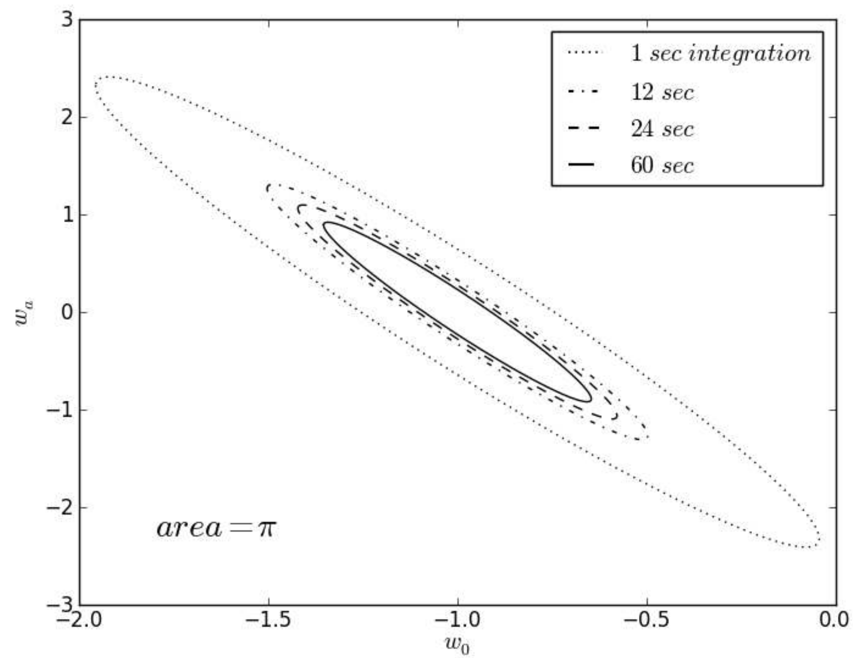
Expected Results for FAST

Effective Volume

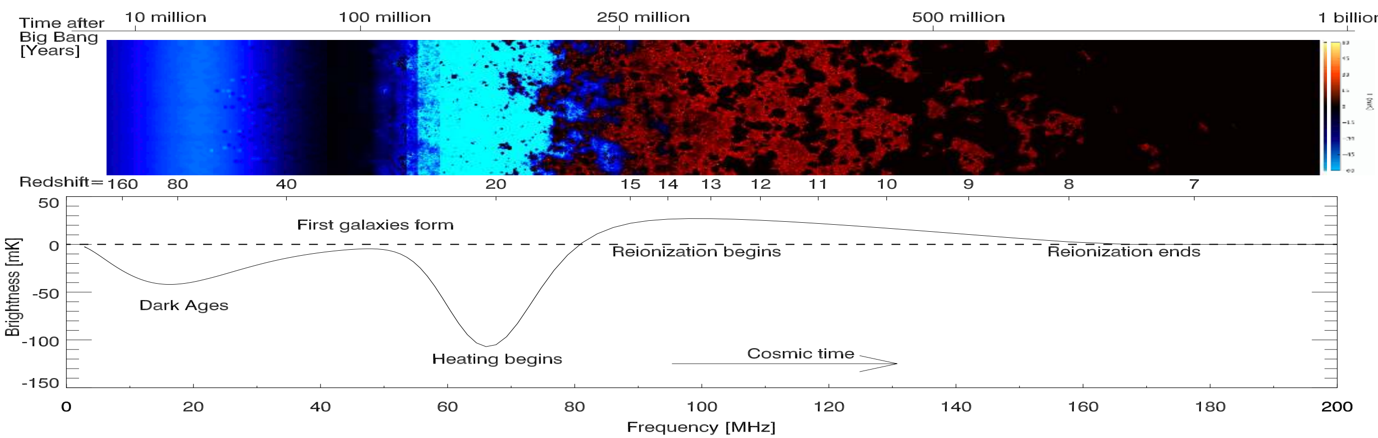
$$V_{eff}(\vec{k}) = \int d^3r \left[\frac{n_{eff}(r)W(k)P(k)}{n_{eff}(r)W(k)P(k)+1}\right]^2$$



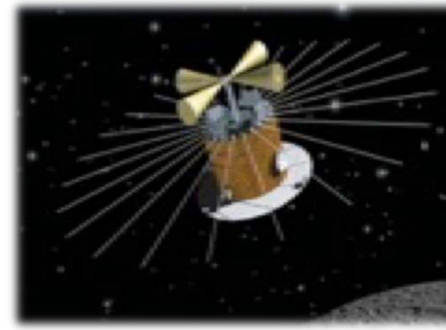
Forecast on Dark Eenergy Equation of State

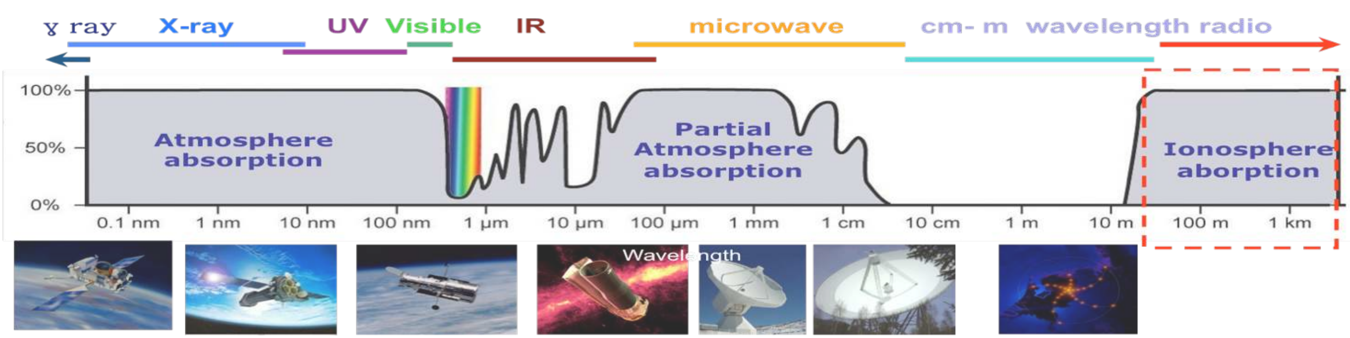


Probing the Dark Age with Global Spectrum



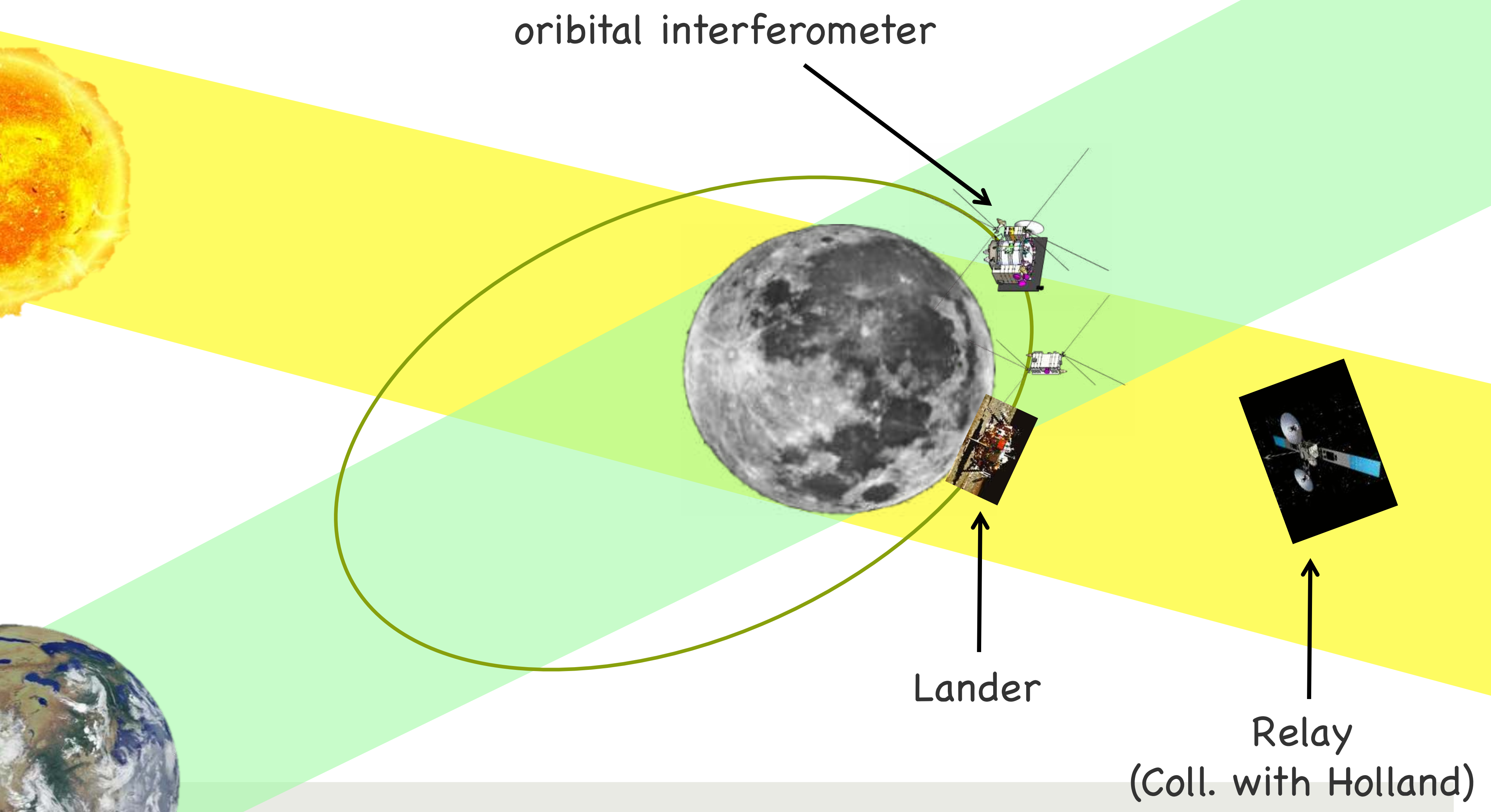
DARE experiment





SCI-HI experiment

Chinese Chang'e 4 program



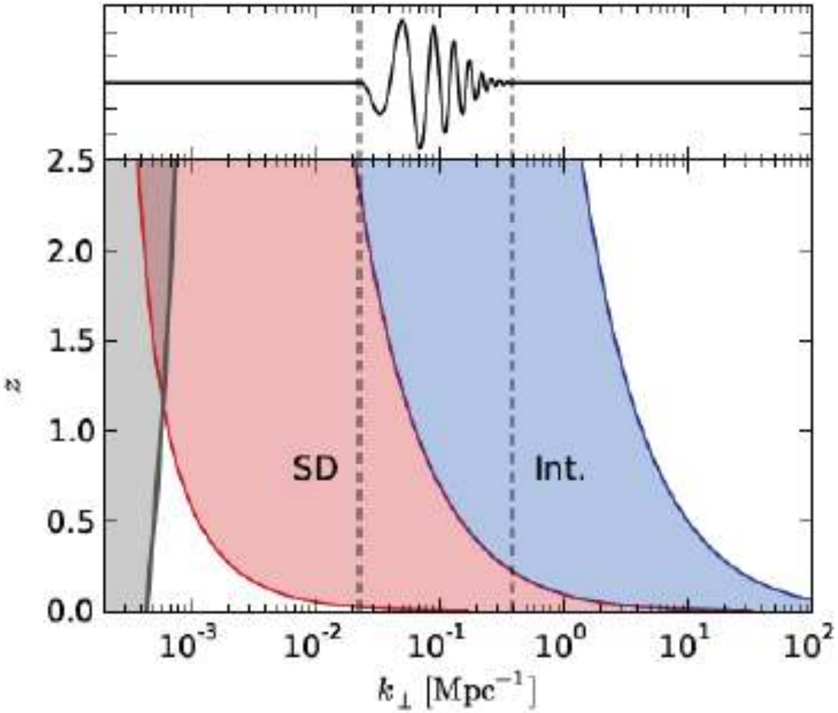
SKA

SKA SWG Cosmology Group wiki

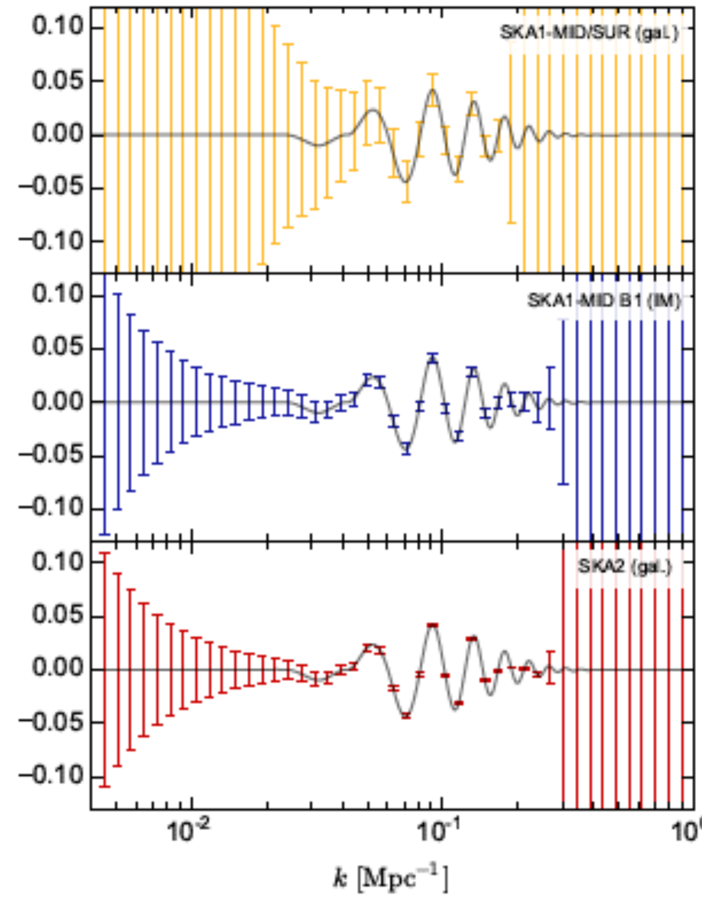
http://skacosmology.pbworks.com

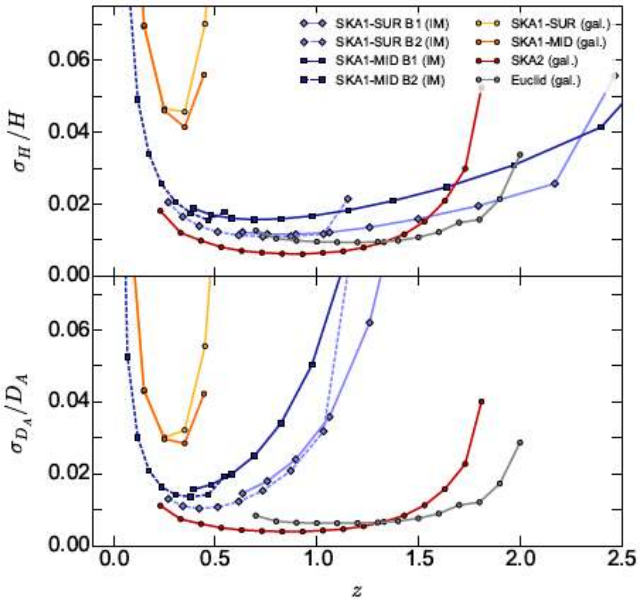
- HI galaxy survey
- HI Intensity Mapping
- Radio Continuum Survey
- Weak Lensing Survey

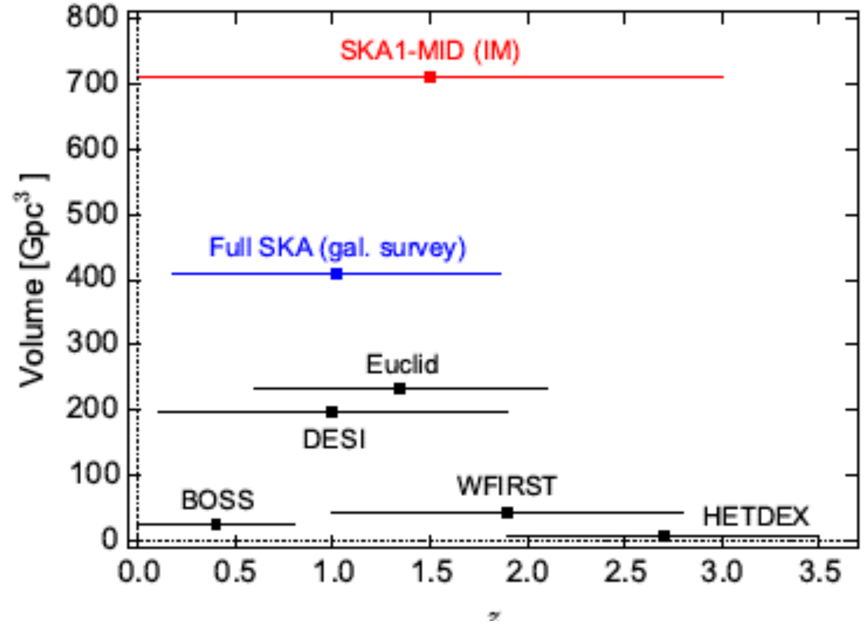
	All sky (10,000hr)	1000 **deg**^{2} (10,000hr)	10 **deg**^{2} (1,000hr)
SKA-low		HI intensity mapping survey	
SKA-mid B1	HI IM		
SKA-mid B2	HI IM+Gal, Continuum+WL	Weak Lensing	Weak Lensing Calibration

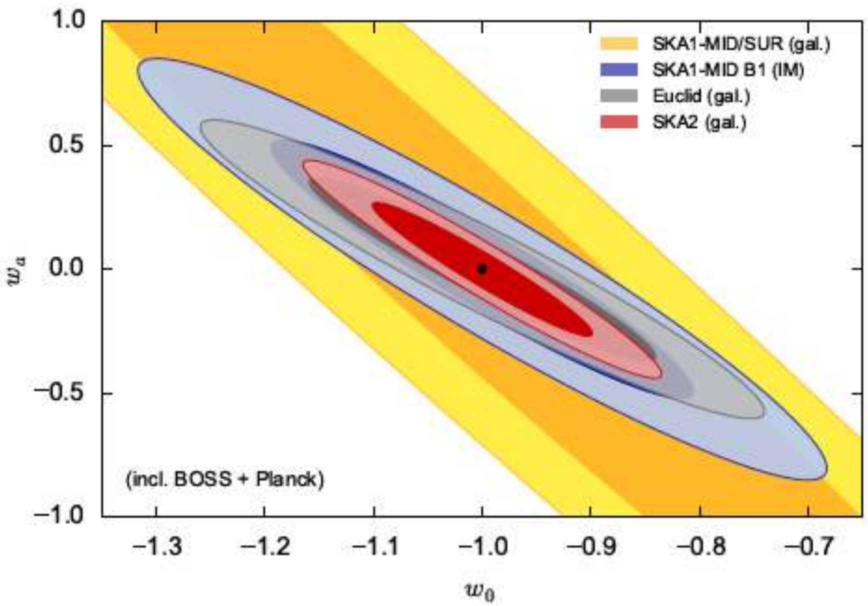


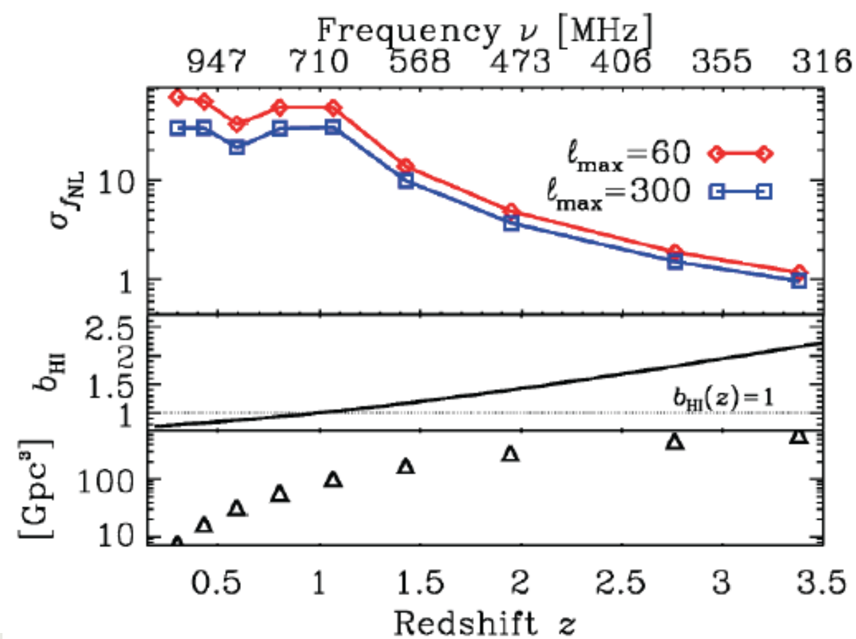
BAO scales probed by SKA1 – dish versus interferometer




SKA1-SUR B1 (IM)
SKA1-SUR B2 (IM)
SKA1-MID B1 (IM)
SKA1-MID B2 (IM)
SKA1-SUR (gal.)
SKA1-MID (gal.)
SKA2 (gal.)
Euclid (gal.)
σ_H/H
σ_{D_A}/D_A
0.00
0.02
0.04
0.06
0.0
0.5
1.0
1.5
2.0
2.5
z

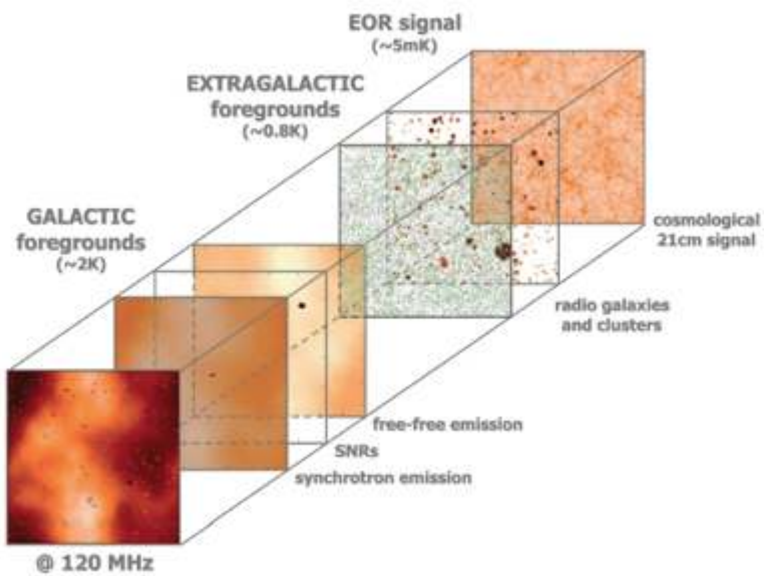

SKA1-MID (IM)
Full SKA (gal. survey)
Euclid
DESI
BOSS
WFIRST
HETDEX
Volume [Gpc^3]
0
100
200
300
400
500
600
700
800
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5


SKA1-MID/SUR (gal.)
SKA1-MID B1 (IM)
Euclid (gal.)
SKA2 (gal.)
(incl. BOSS + Planck)
w_a
w_0
1.0
0.5
0.0
−0.5
−1.0
−1.3
−1.2
−1.1
−1.0
−0.9
−0.8
−0.7


Frequency ν [MHz]
947
710
568
473
406
355
316
$\ell_{max}=60$
$\ell_{max}=300$
$\sigma_{f_{NL}}$
10
1
b_{HI}
2.5
2
1.5
1
$b_{HI}(z)=1$
[Gpc^3]
100
10
0.5
1
1.5
2
2.5
3
3.5
Redshift z

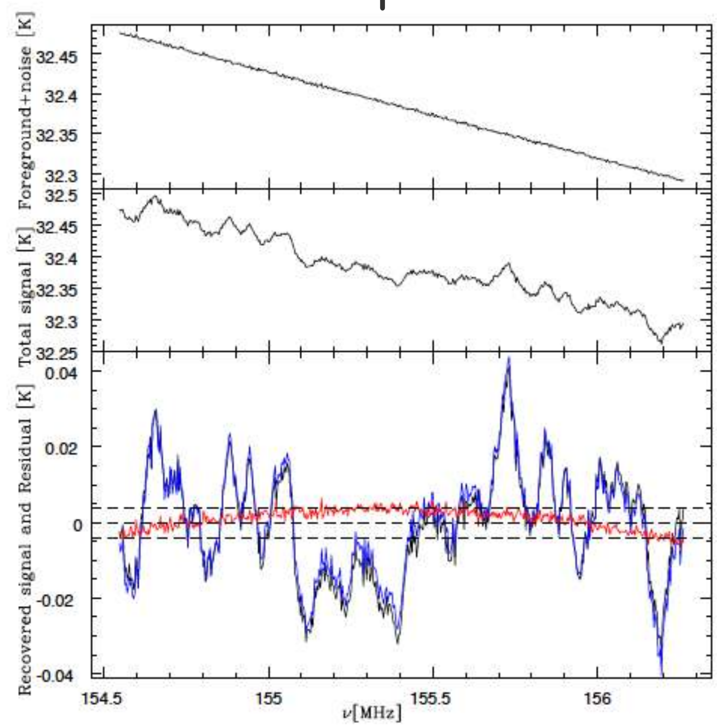
The challenge: strong foreground

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



V. Jelic et al. (2010)

removable: foreground smooth in spectrum



Wang et al. (2006)

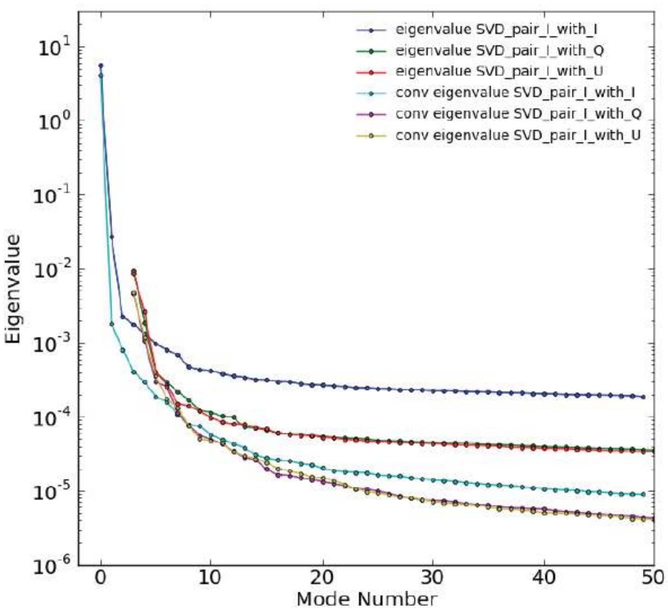
Apparent Foregrounds (Non-smooth)

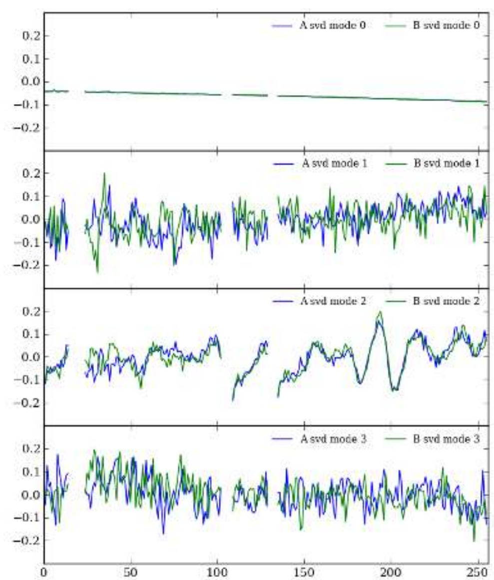
Foreground Principal Components

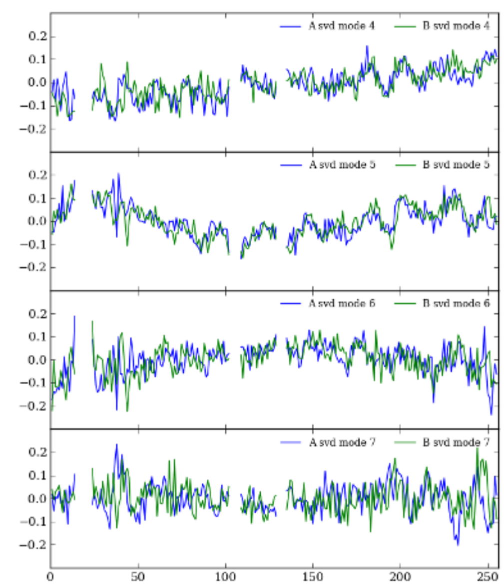
$$C = TT^{\dagger}$$

$$Cv_i = \lambda_i v_i$$

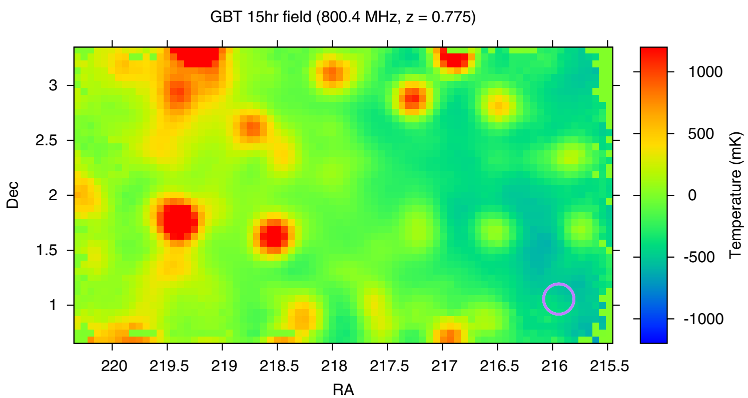
GBT intensity Mapping Data

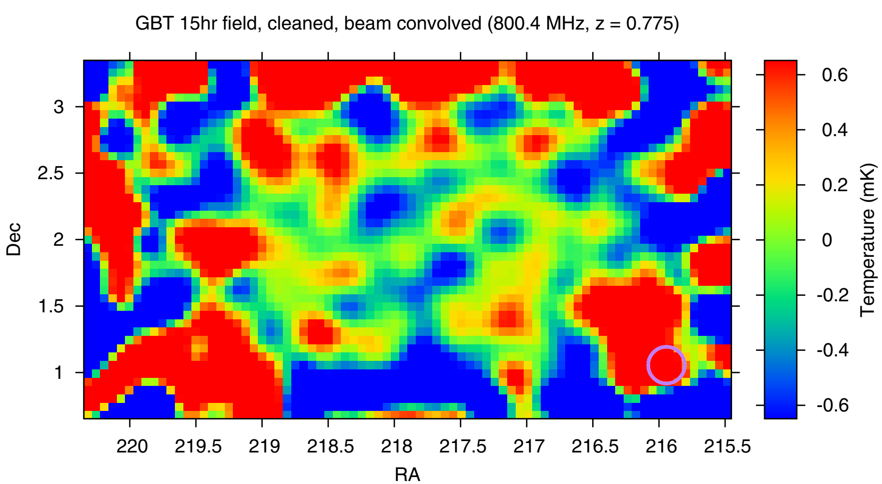


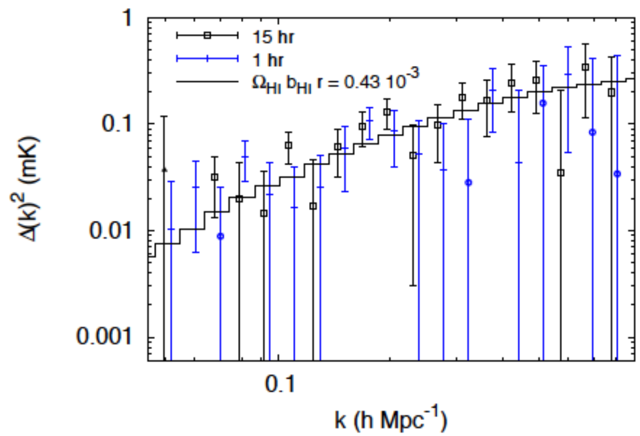


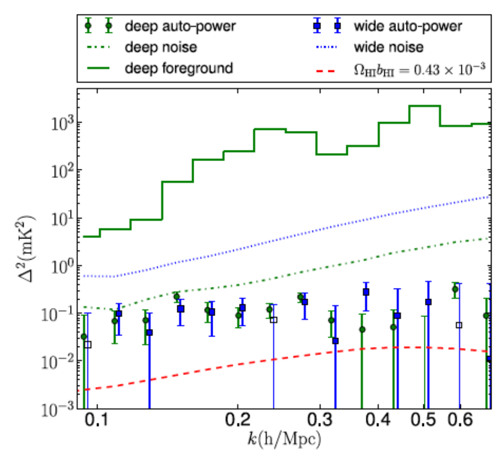


Foreground Subtraction



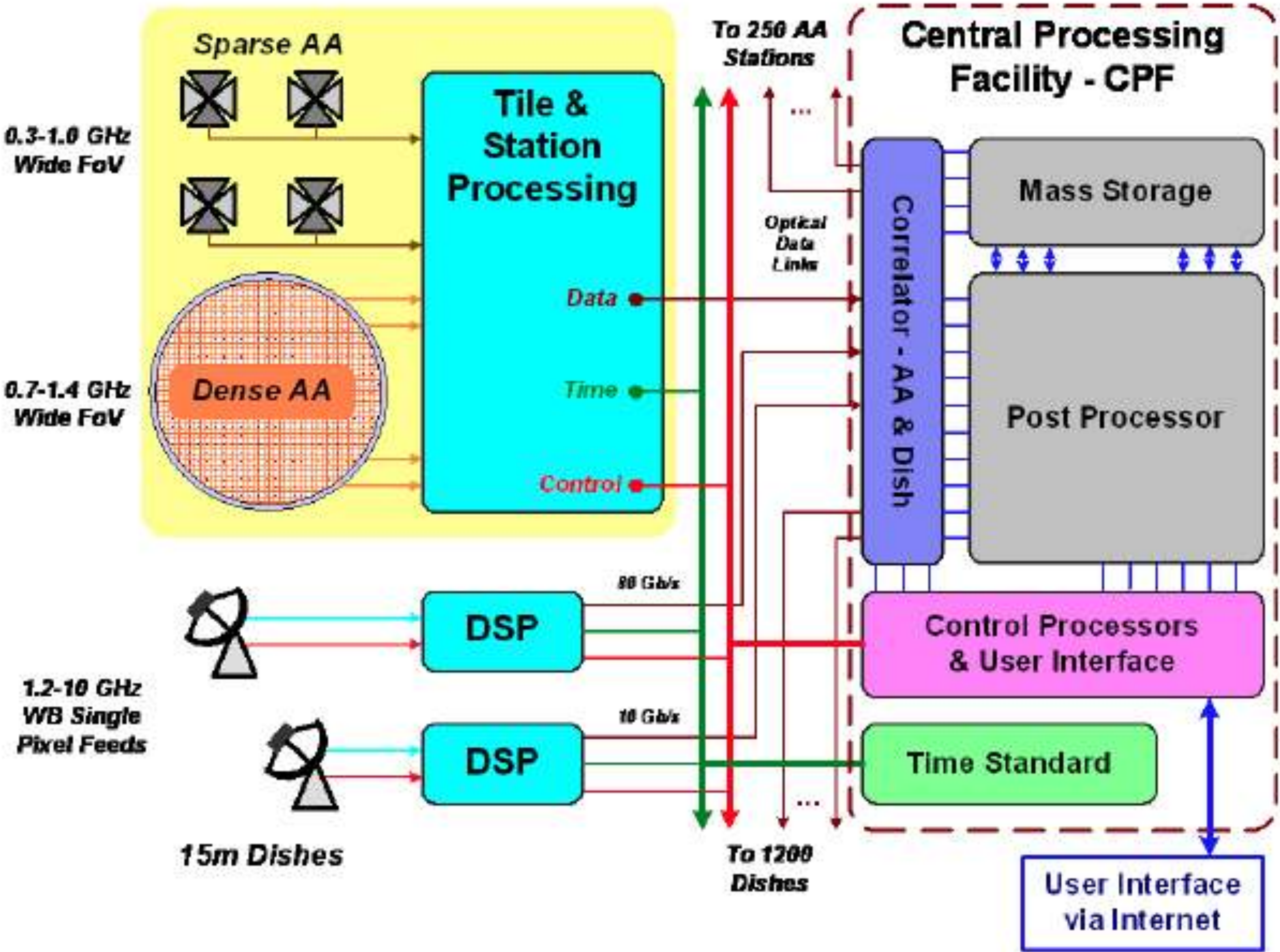






cross correlation with WiggleZ (Masui et al 2013)

auto correlation (Switzer et al. 2013)

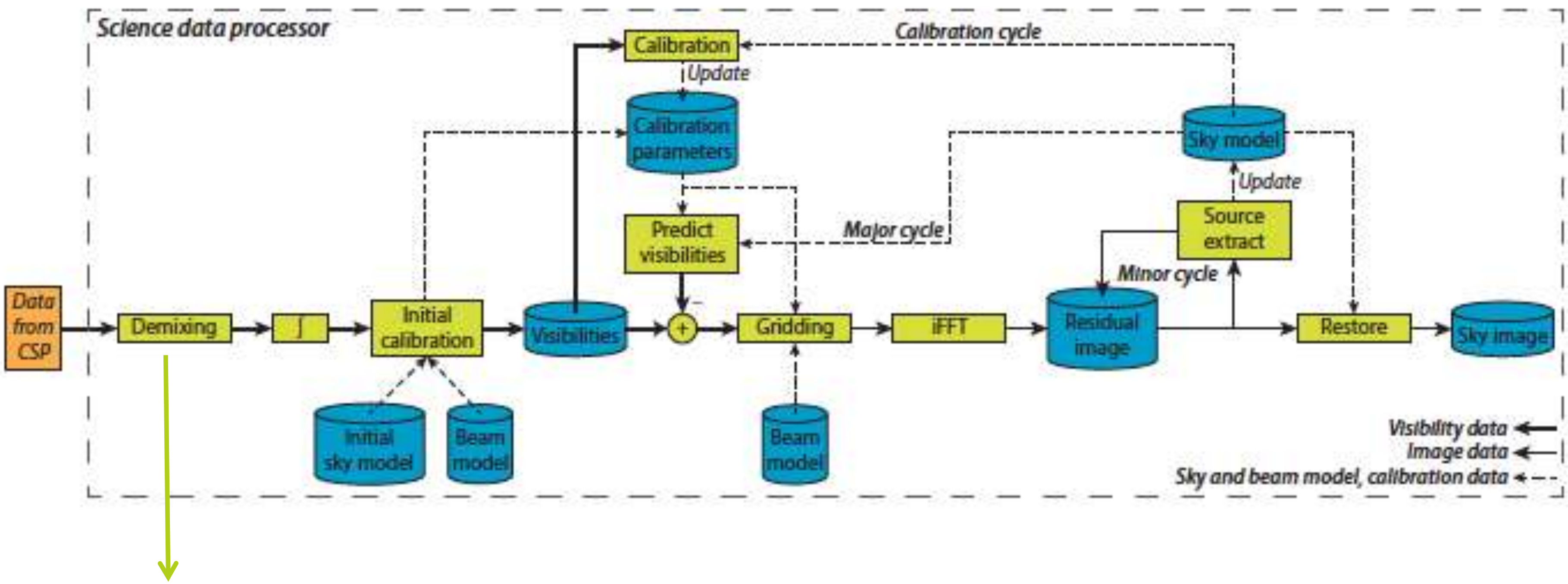


Sparse AA
0.3-1.0 GHz
Wide FoV
Tile &
Station
Processing
Data
Time
Control
Dense AA
0.7-1.4 GHz
Wide FoV
To 250 AA
Stations
...
Optical
Data
Links
Central Processing
Facility - CPF
Correlator - AA & Dish
Mass Storage
Post Processor
80 Gb/s
DSP
Control Processors
& User Interface
1.2-10 GHz
WB Single
Pixel Feeds
10 Gb/s
DSP
Time Standard
15m Dishes
To 1200
Dishes
User Interface
via Internet

Science Data Processing (SDP)

Jongerius et al.

Need very sophisticated and science-dependent processing, to be improved iteratively over time



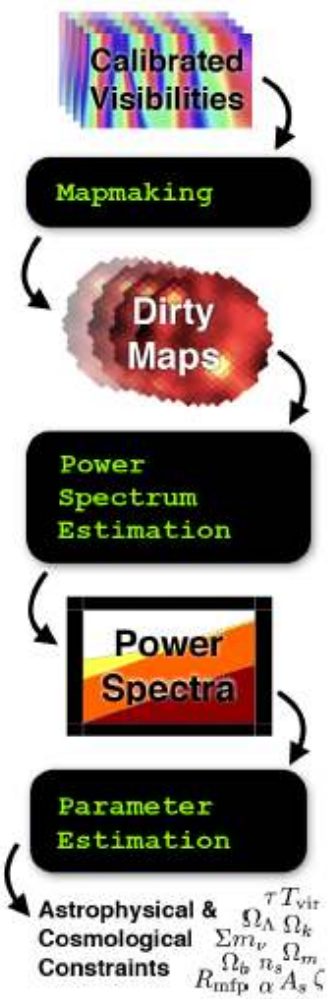
remove of bright source

Gridding with W-projection:

$$V(u,v,w) = \int I(\ell,m)G(\ell,m,w)\; e^{-2\pi i[u\ell+vm]} d\ell dm$$

$$G(\ell,m,w) = \frac{e^{-2\pi i[w(\sqrt{1-\ell^2-m^2}-1)]}}{\sqrt{1-\ell^2-m^2}}$$

Off-Site (Science) Data Processing



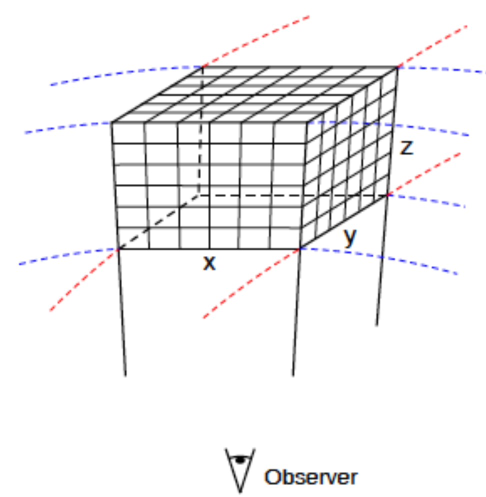
Foreground subtraction

Data Cube Volume:

Npix > 10^4 deg^2/(0.01 deg^2) ~10^6

Nfreq ~ 10^4

Nvox > 10^{10}, perhaps up to 10^{16}



Dillon et al. 2012, 2015

BRICS Project:

21cm Cosmology and Large Scale Structure

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(NAOC & Tsinghua U.)

T. R. Choudhury, N. Gupta, K. K. Datta, T.G.Sardar
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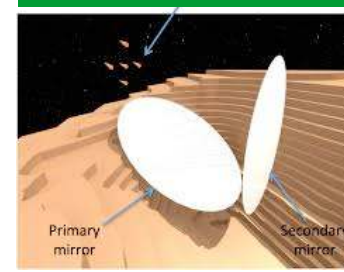
Y. Z. Ma, M. Santos, R. Dave, K. Moodley, J. Sievers
(UKZN & UWC)



Thanks!