Search for Cosmic Reionization with the HI 21cm Signal

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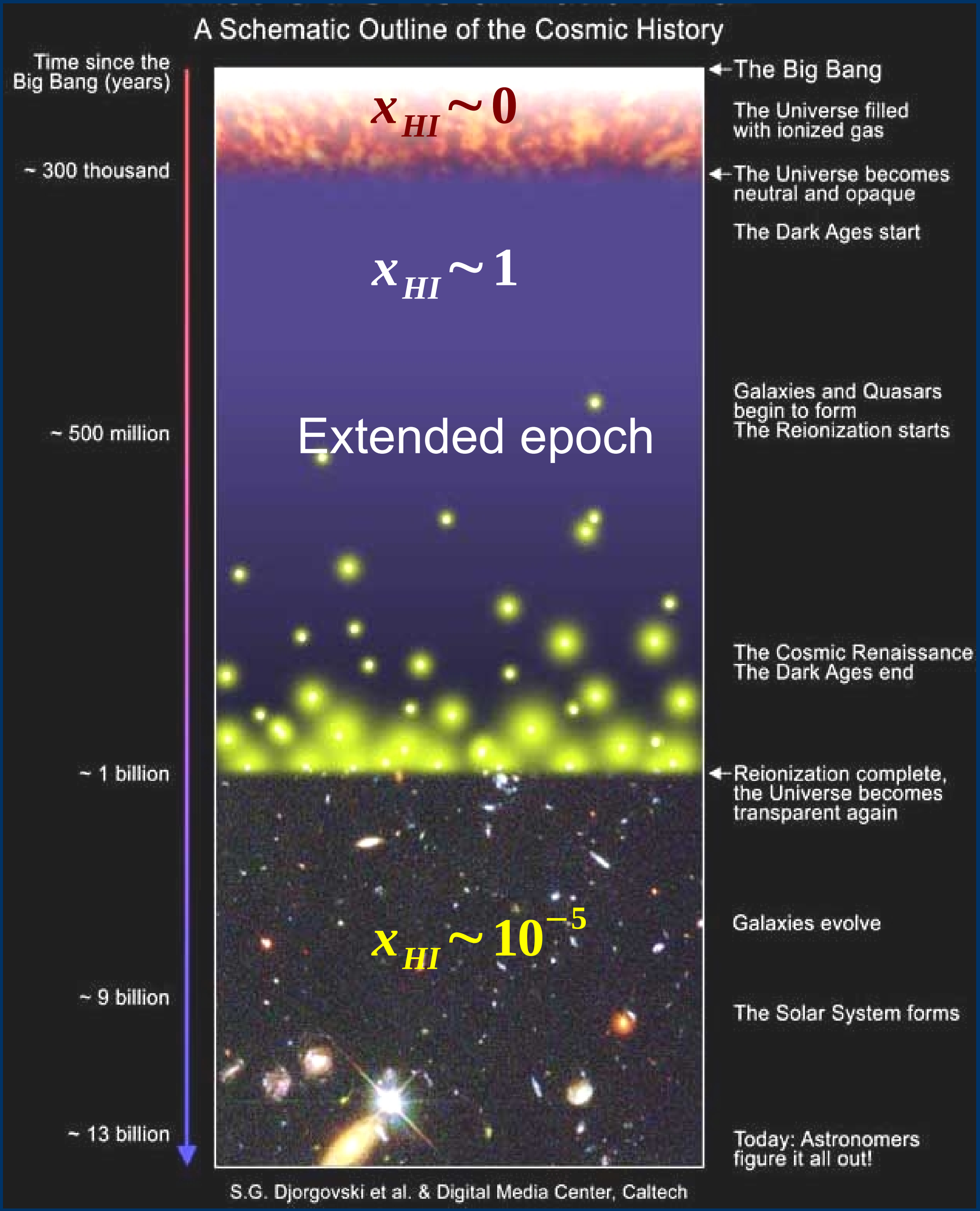
Lunar Workshop, Boulder, October 5, 2010

Outline

- Epoch Of Reionization – Overview
  - Signatures, Constraints
  - Challenges of Low Frequency Observations

- Bright Foreground Removal
  - Image Domain
  - Power Spectrum

Reasons to study EoR

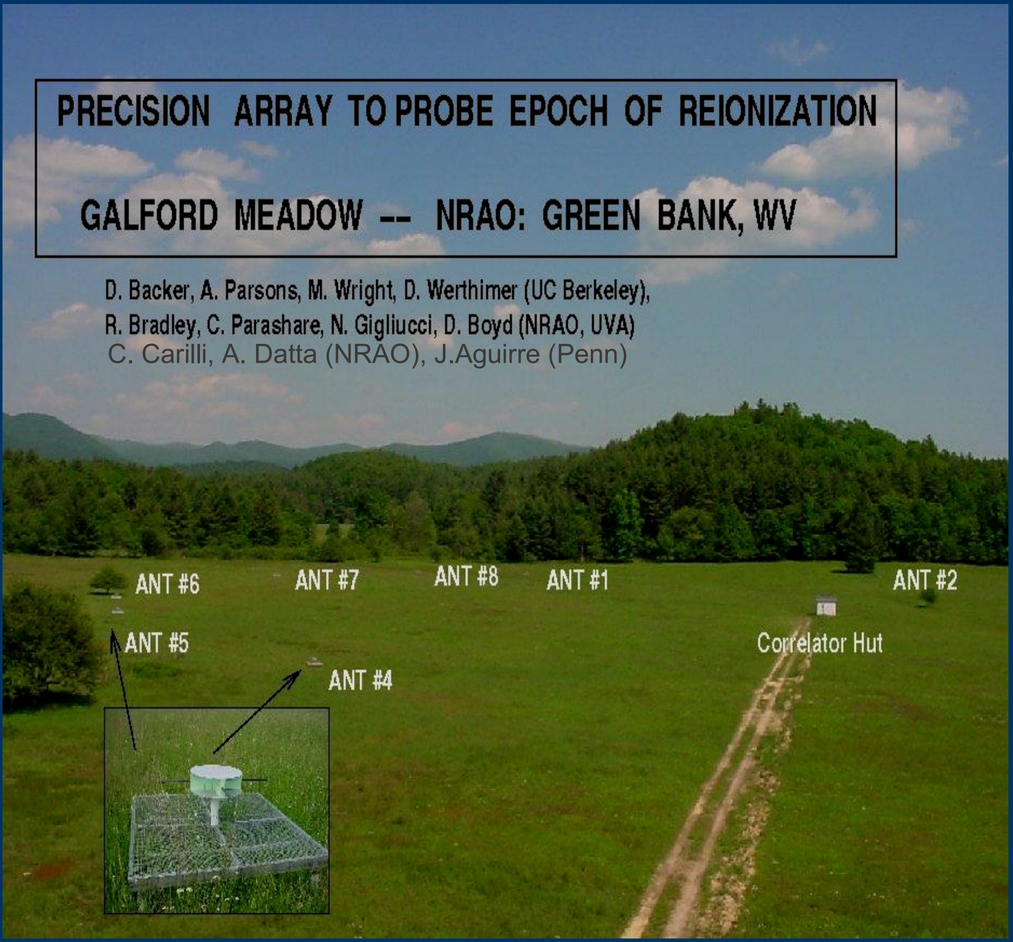


- First probe to Dark ages
- When did reionization occur ?
- Sources responsible ? First sources that appear – population ?
- Gives us a handle on the Star Formation history of the Universe
- IGM Feedback processes – photoionization heating.
- Clustering of the sources in the history of structure formation.

Next Generation Telescopes

MWA **21 CMA** **LOFAR**

Next Generation Telescopes



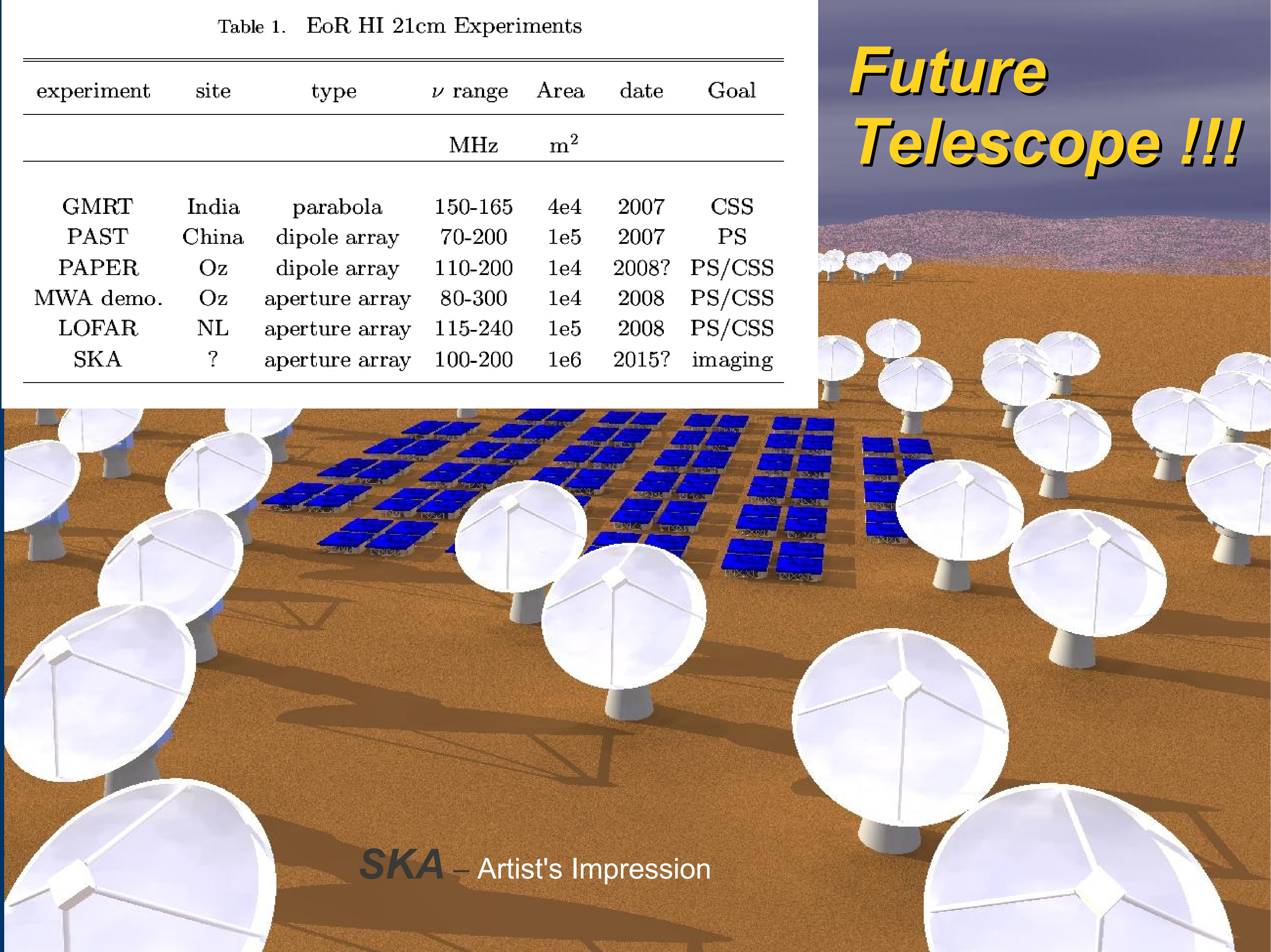
PAPER

GMRT

Future Telescope !!!

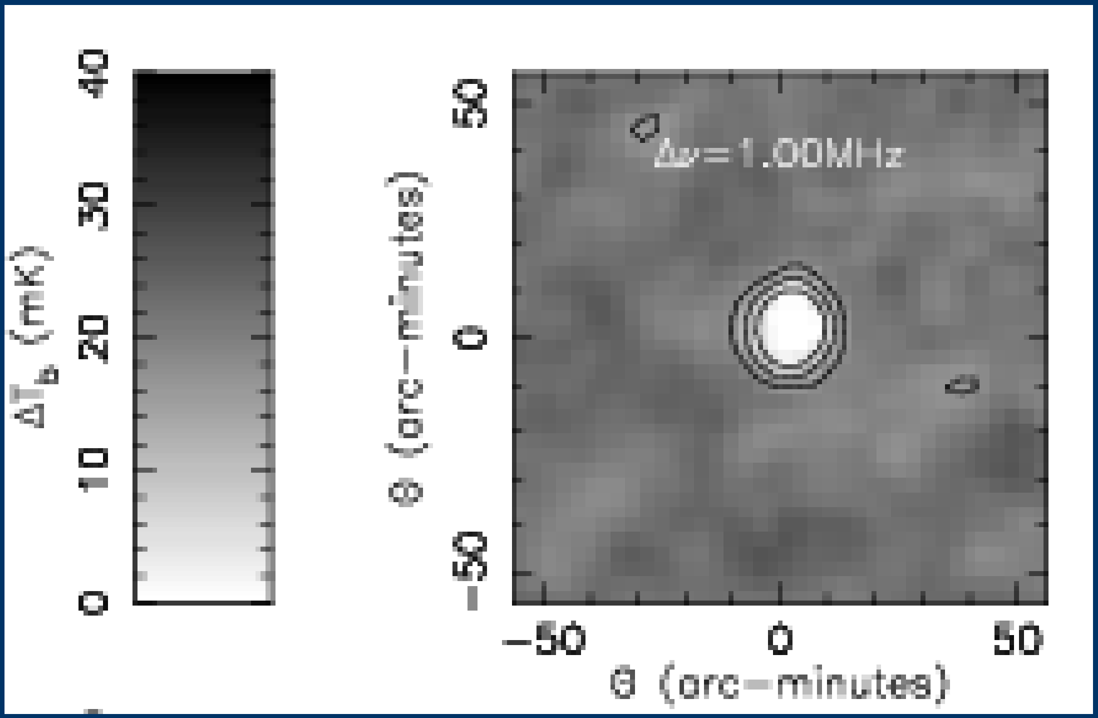
Table 1. EoR HI 21cm Experiments

experiment	site	type	ν range	Area	date	Goal
			MHz	m^2		
GMRT	India	parabola	150-165	4e4	2007	CSS
PAST	China	dipole array	70-200	1e5	2007	PS
PAPER	Oz	dipole array	110-200	1e4	2008?	PS/CSS
MWA demo.	Oz	aperture array	80-300	1e4	2008	PS/CSS
LOFAR	NL	aperture array	115-240	1e5	2008	PS/CSS
SKA	?	aperture array	100-200	1e6	2015?	imaging



SKA – Artist's Impression

Signal I: Cosmic Stromgren spheres @z > 6 QSOs



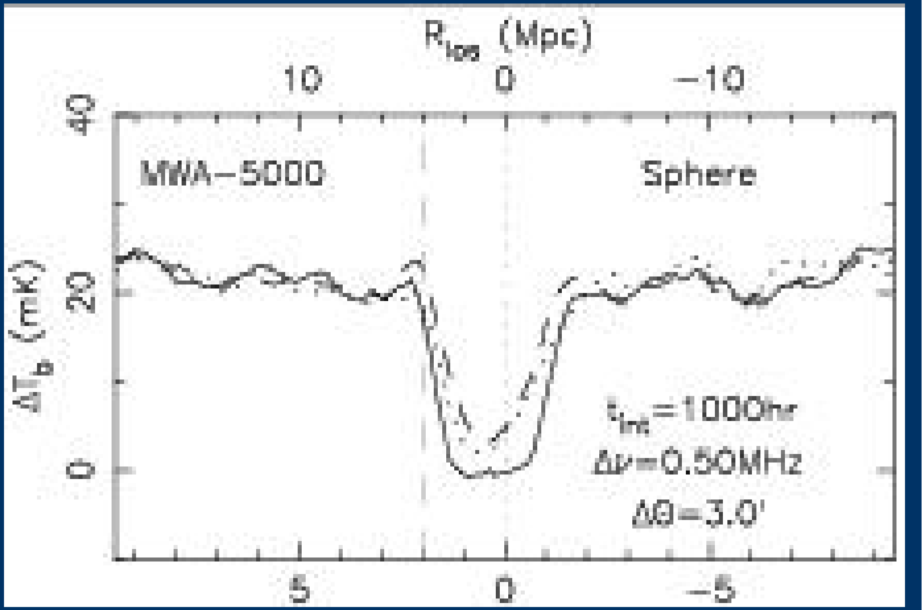
Simulated LOFAR 'observation':

20mK x_{HI}, 15',1000km/s

=> 0.24 mJy x_{HI}

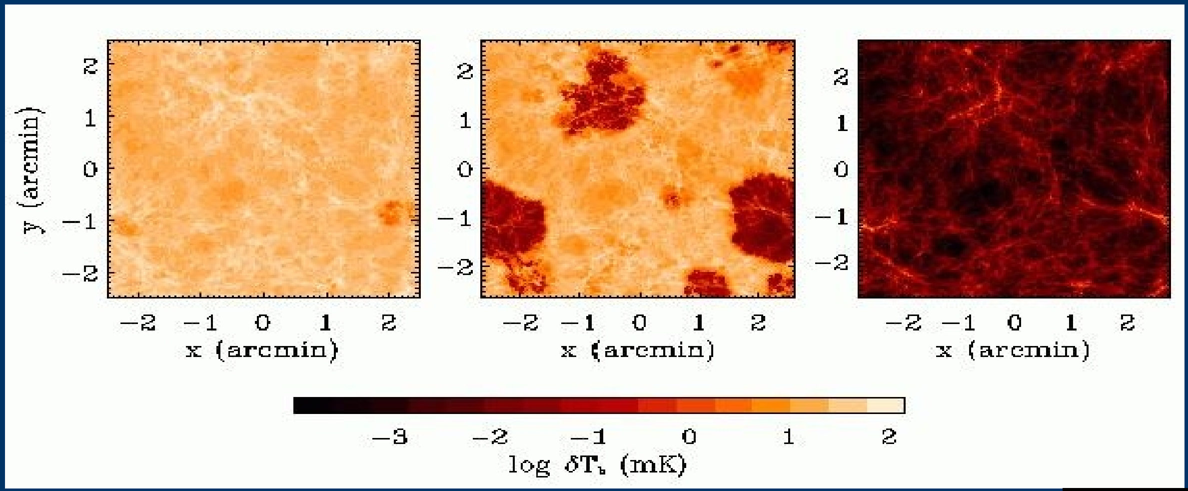
Pathfinders: Set first hard limits on

x_{HI} at end of cosmic reionization



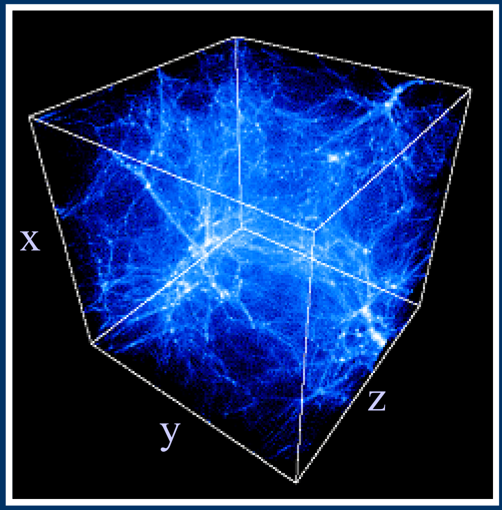
neutral fraction :- $x_{HI} = \frac{n_{HI}}{n_H}$

Signal II: 3D Power spectrum analysis

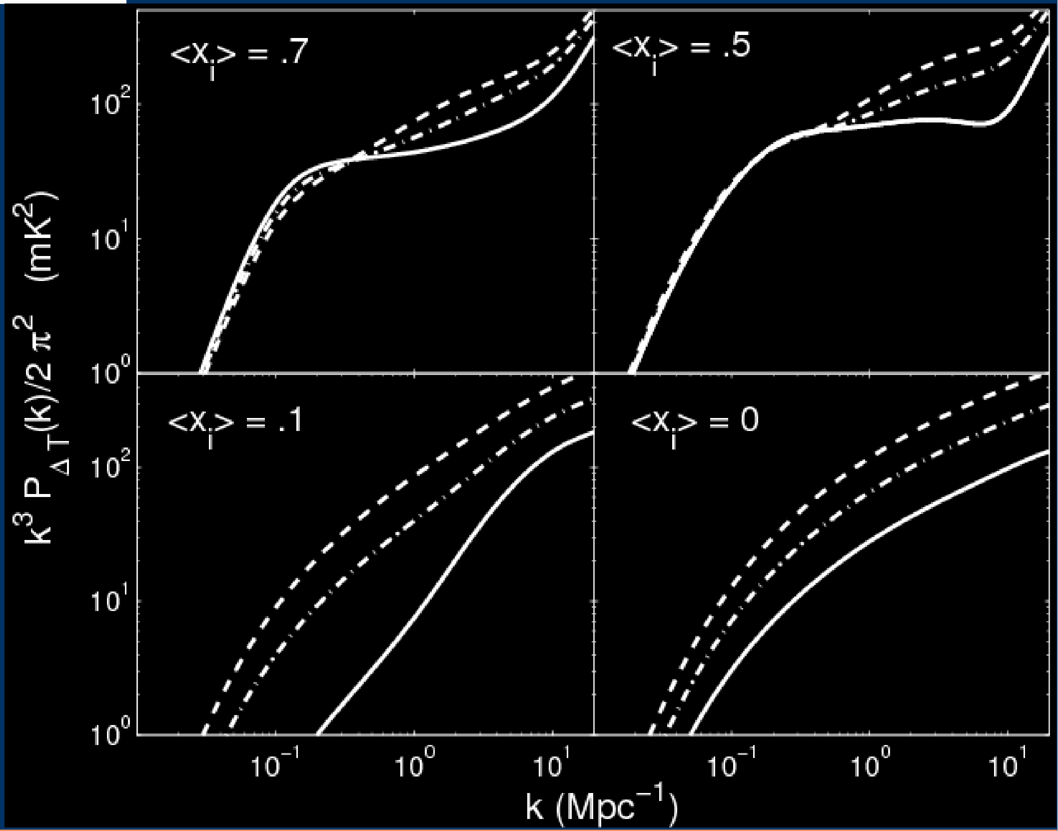


3D tomography of IGM

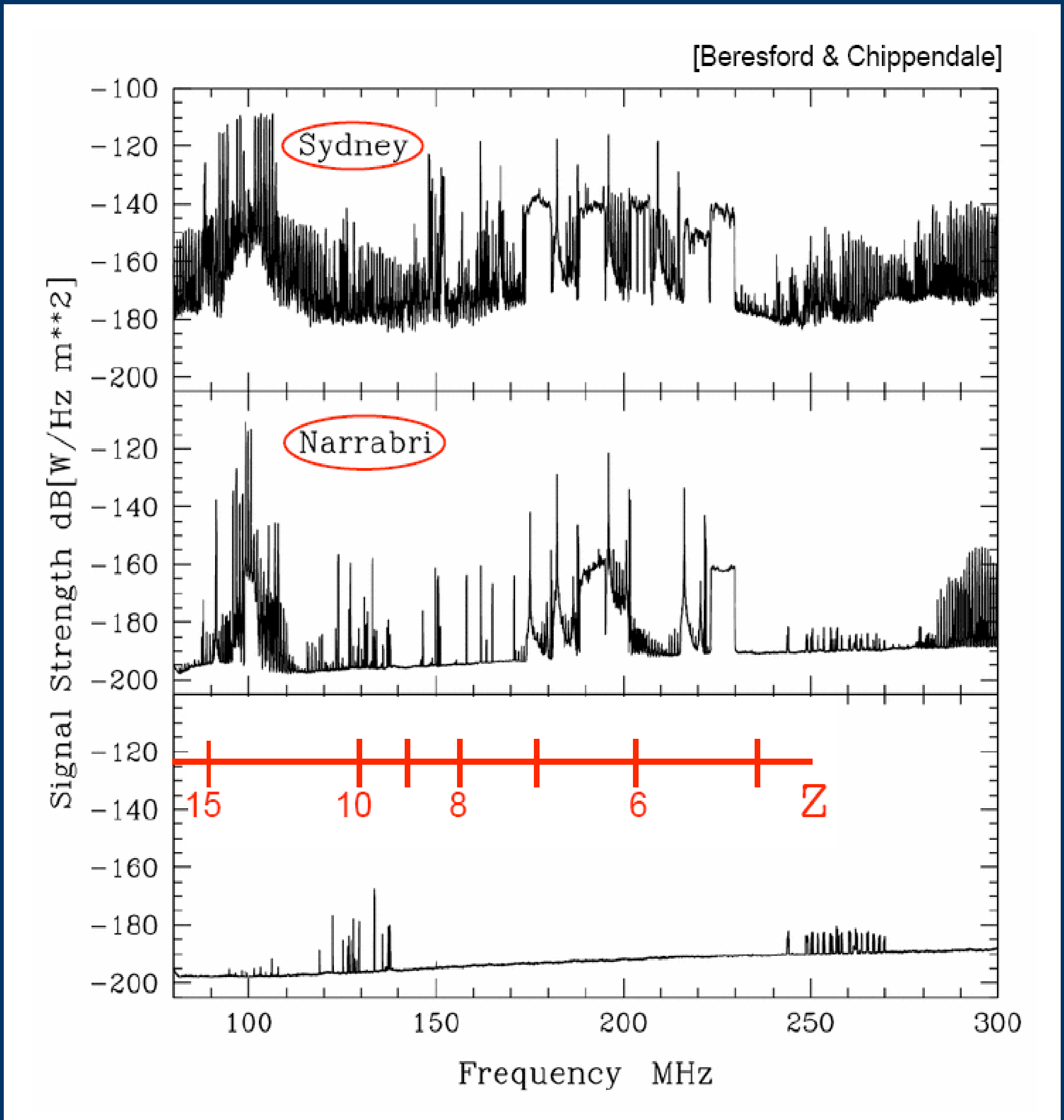
McQuinn, Zahn, Hernquist, & Furlanetto (2006)

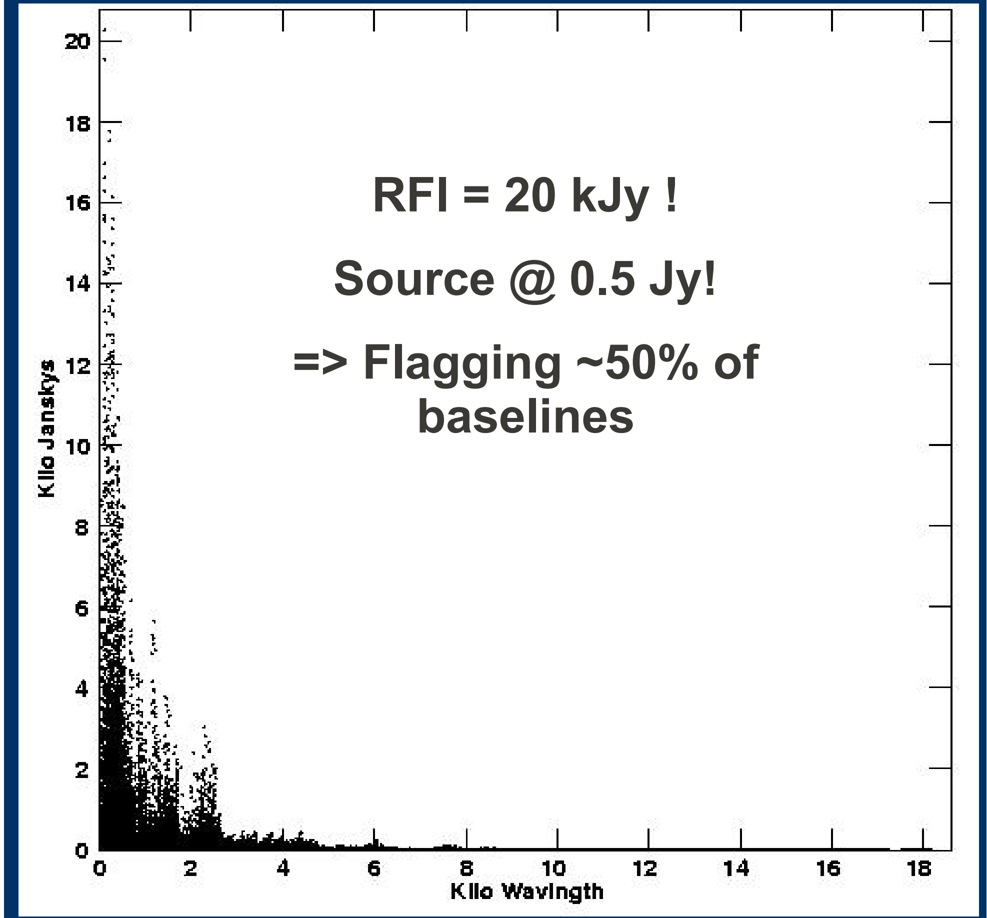


F.T.



Challenges: Radio Frequency Interference

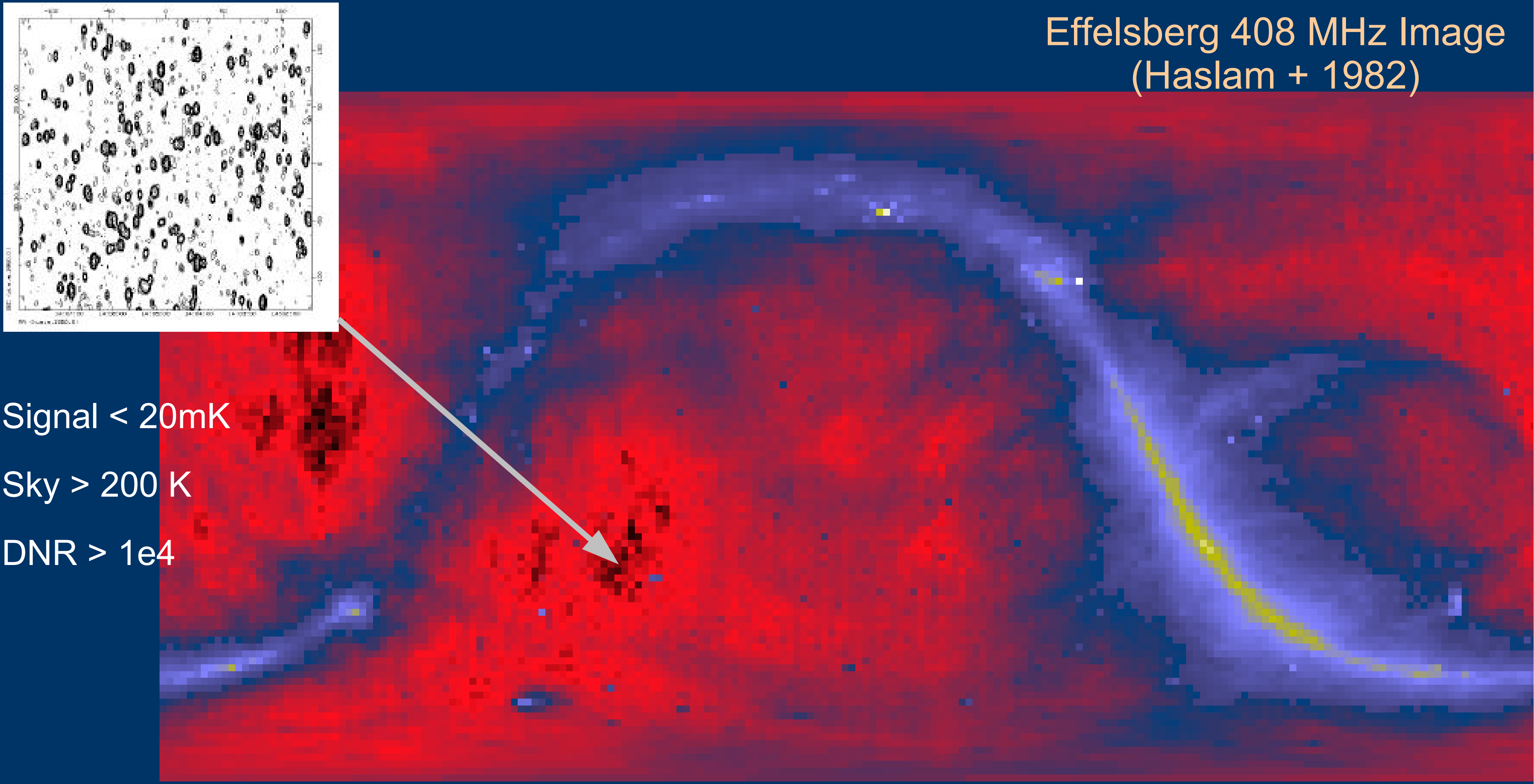




GMRT Observation at 233 MHz
(Datta et al. 2010 (in prep)

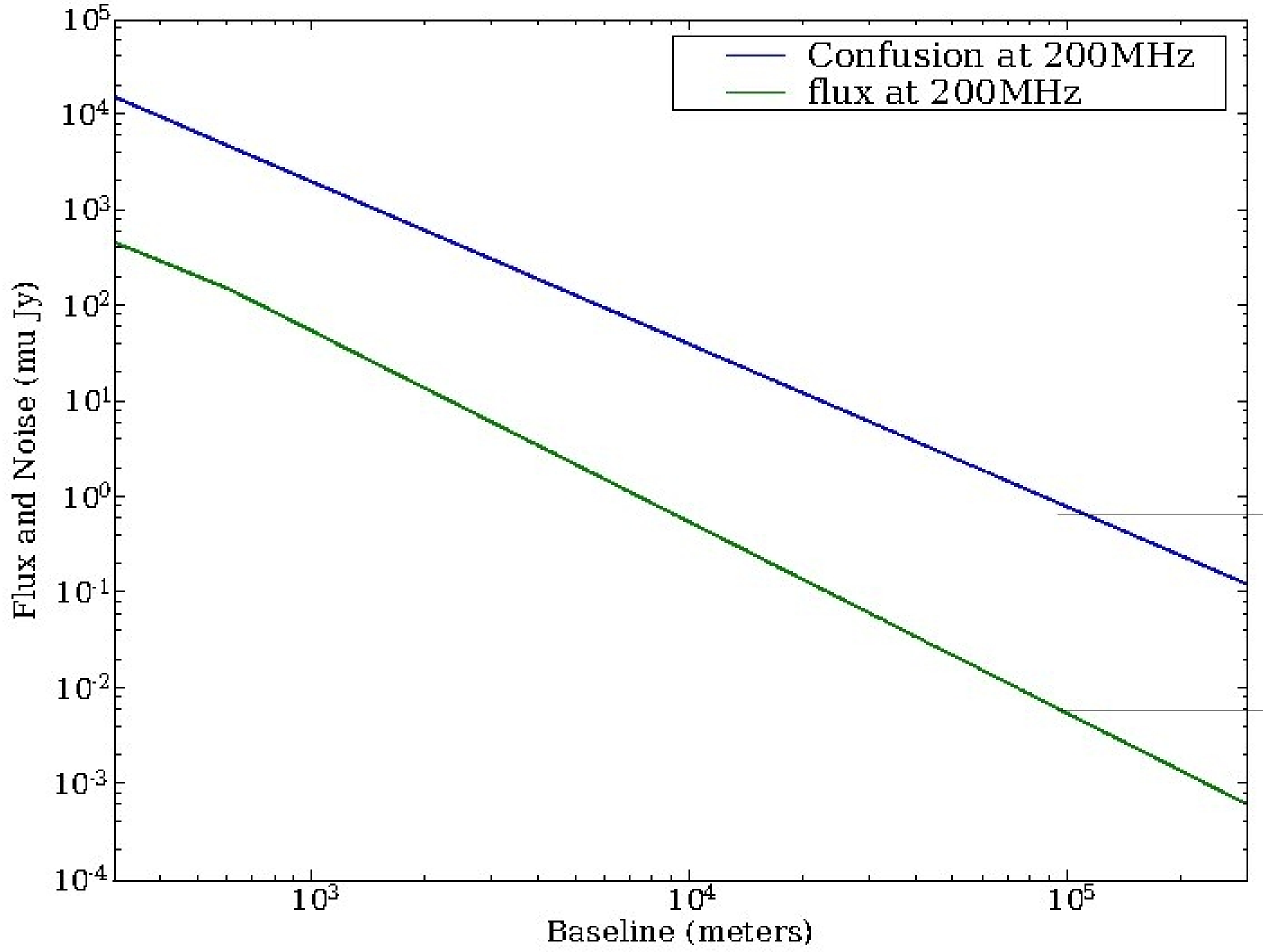
Challenges: Low–Frequency Foregrounds

Effelsberg 408 MHz Image
(Haslam + 1982)



- Coldest regions: T ~ 180 $(\nu/180\ \mathrm{MHz})$^-2.6 K
- 90% = Galactic foreground (~200-1000K, 99% Synchrtron, 1% Free-free),
  10% = Egal. radio sources (~50K) , Galactic RRLs (< 1K), Sun

Challenges: Confusion Noise



$$S_c = 40\,\theta^{1.7} f_{GHz}^{-0.7}\,\mu Jy$$

Subhramanyan, R. 2002

Confusion Noise @ 200MHz

Surface brightness of CSS

Outline

- Epoch Of Reionization – Overview
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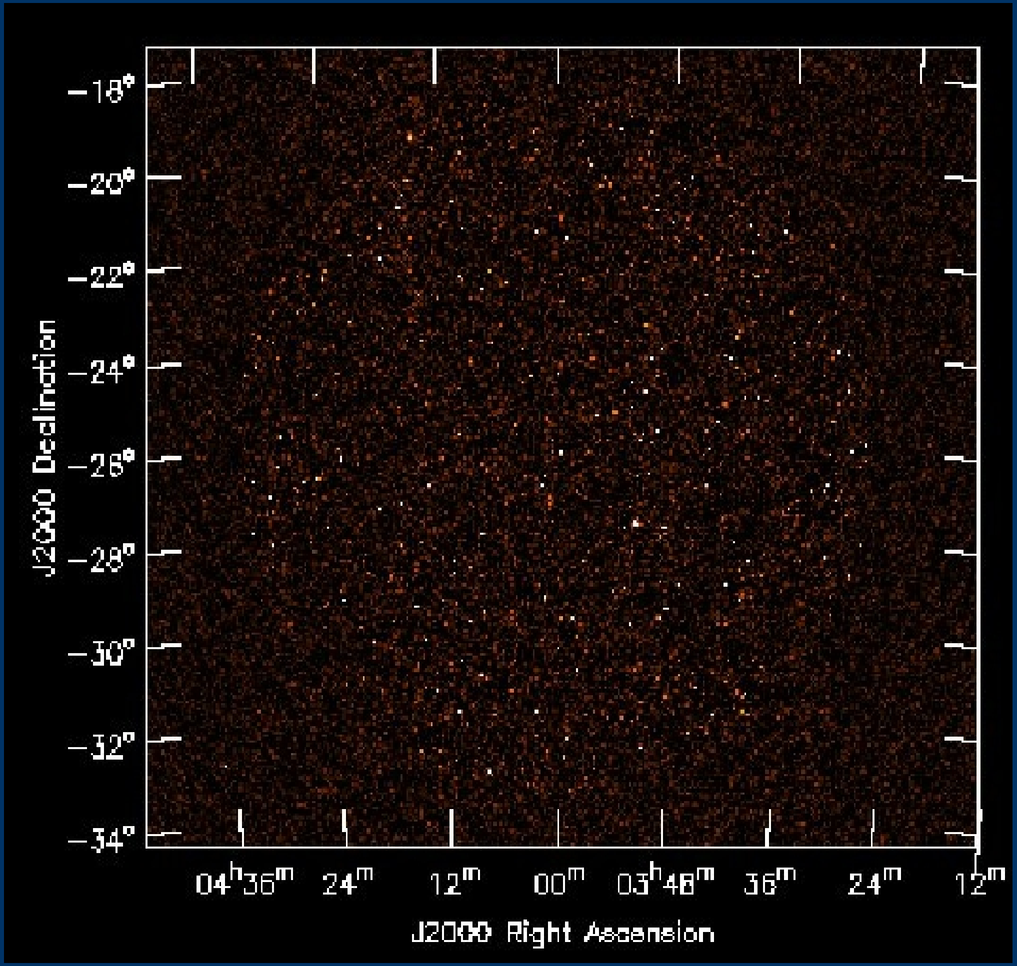
  - Challenges of Low Frequency Observations
- Bright Foreground Removal
  - Image Domain
  - Power Spectrum

NVSS Sky
@ 158MHz

Motivation for this project

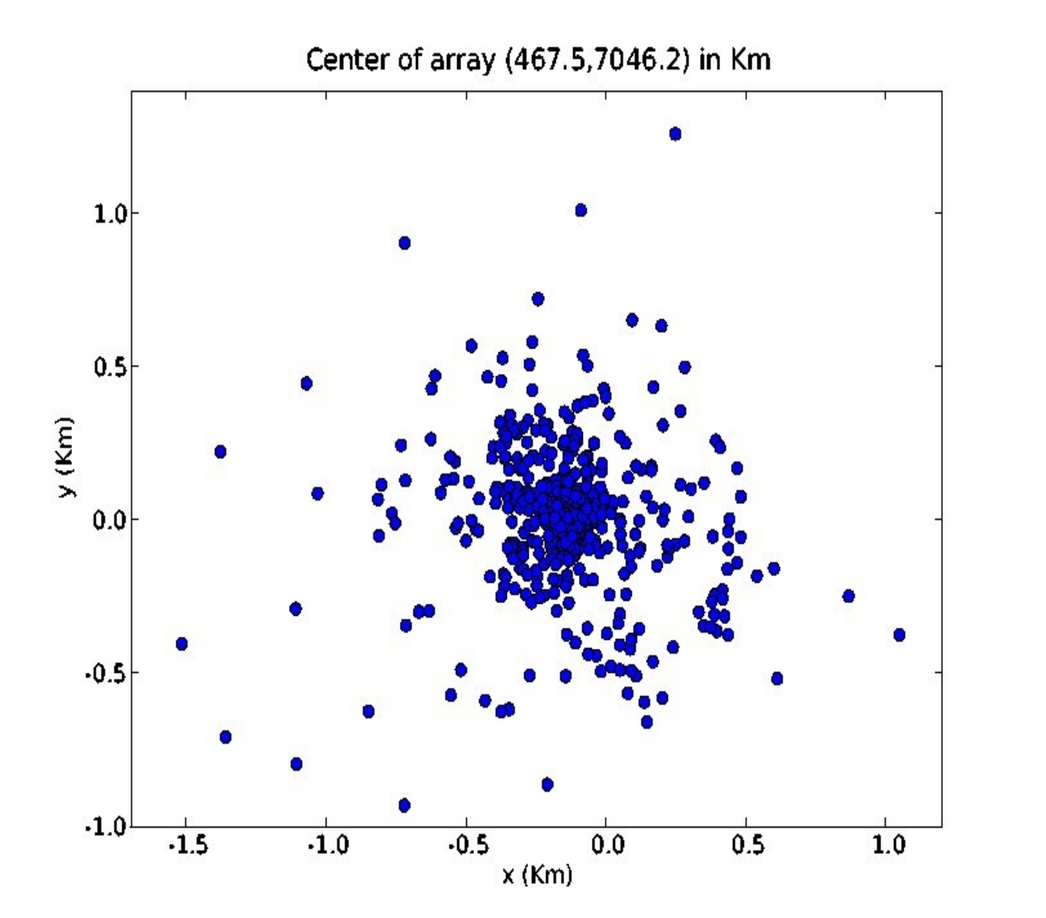


- Lots of recent research on the foreground source subtraction schemes deals with only sub-Jy sources (e.g. Liu et al. 2008).
- They implicitly assume that these sources can be removed perfectly.
- The main aim of our project is to demonstrate the accuracy with which these > 1Jy sources need to be removed in order to extract the reionization signal from the datasets of the upcoming radio telescopes (MWA, PAPER, etc).

Brightest source ~ 14 Jy/bm, rms ~ 33 mJy/bm

source count ~ 8590! Pixelation and confusion!!

MWA Array Configuration & Specifications



MWA -512

512 elements, 1.5 Km baseline

ARRAY SPECIFICATIONS

Parameters	Values
No. of Tiles	512
Central Frequency	158 MHz ($z \sim 8$)
Field of View	$\sim 15^o$ at 158 MHz. ($\propto \lambda$)
Synthesized beam	$\sim$ 4.5' at 158 MHz. ($\propto \lambda$)
Effective Area per Tile	$\sim 17\ m^2$
Maximum Baseline	$\sim$ 1.5 km.
Total Bandwidth	32 MHz
T_{sys}	$\sim$ 250 K
Channel Width	$\sim$ 32 kHz
Thermal Noise	$\sim 15.4\ \mu$ Jy/beam ($5x10^3$ hours & 2.5 MHz)

32 MHz bandwidth,
central frequency – 158 MHz (z ~ 8)

Response of Array Configuration - Point Spread Function

Sidelobes for 512 elements

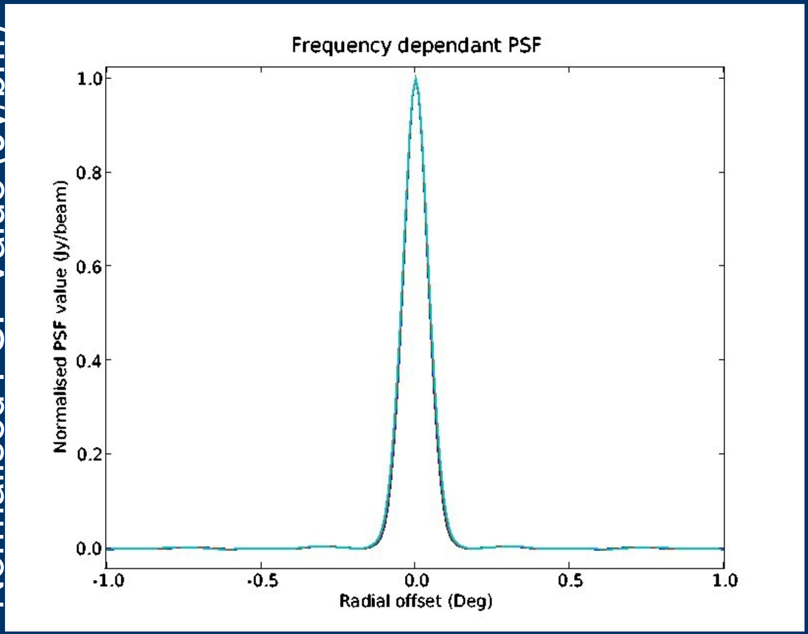
With Natural Weighting

RMS sidelobe noise level between 512 and 128 is just a scaling!!!!!!

Frequency dependent sidelobe levels vary across the entire band of observations.

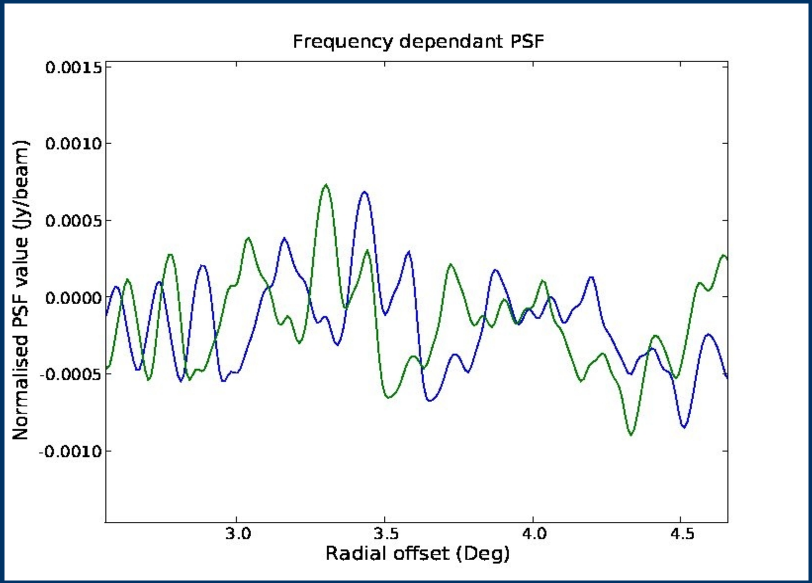
This is only frequency dependent part in array-response itself.

Normalised PSF Value (Jy/bm)



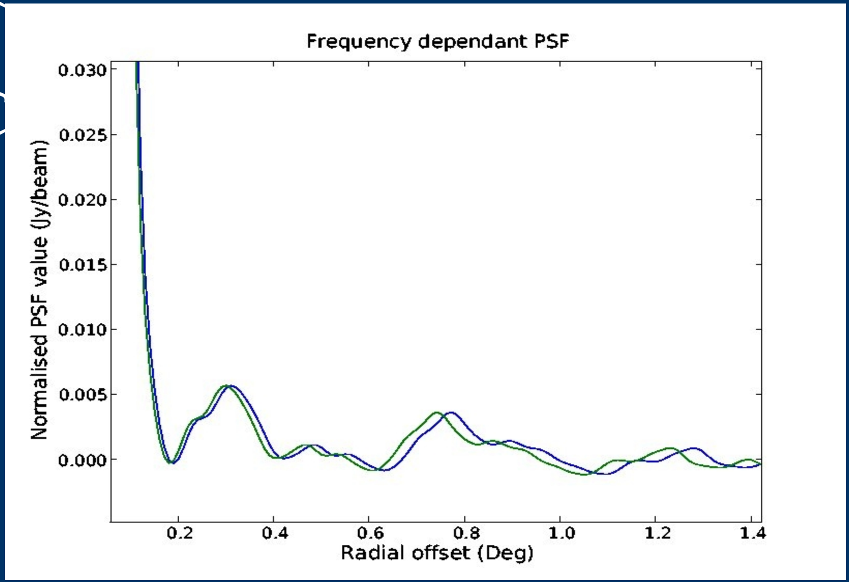
Radial Offset (Deg)

Normalised PSF Value (Jy/bm)



Radial Offset (Deg)

Normalised PSF Value (Jy/bm)



Radial Offset (Deg)

CALIBRATION Scheme

Same as adapted for next generation low-frequency telescopes

- UV data rate is really high for the telescopes
  -- estimated 19 GB/s or a few peta-bytes a day (MWA: Mitchell 2008)

- Need to remove few strongest sources in the FOV before compressing the data and forming image-cubes.

- Find out first few strong sources in the field of view on the basis of some Global Sky Model (GSM).

- Run position self-cal and calibration on them and remove them

- Image the residual data sets and store the resultant image cubes

- Run different polynomial fitting routines to extract the residual foreground from the image cubes (Furlanetto, Briggs, Oh 2006).

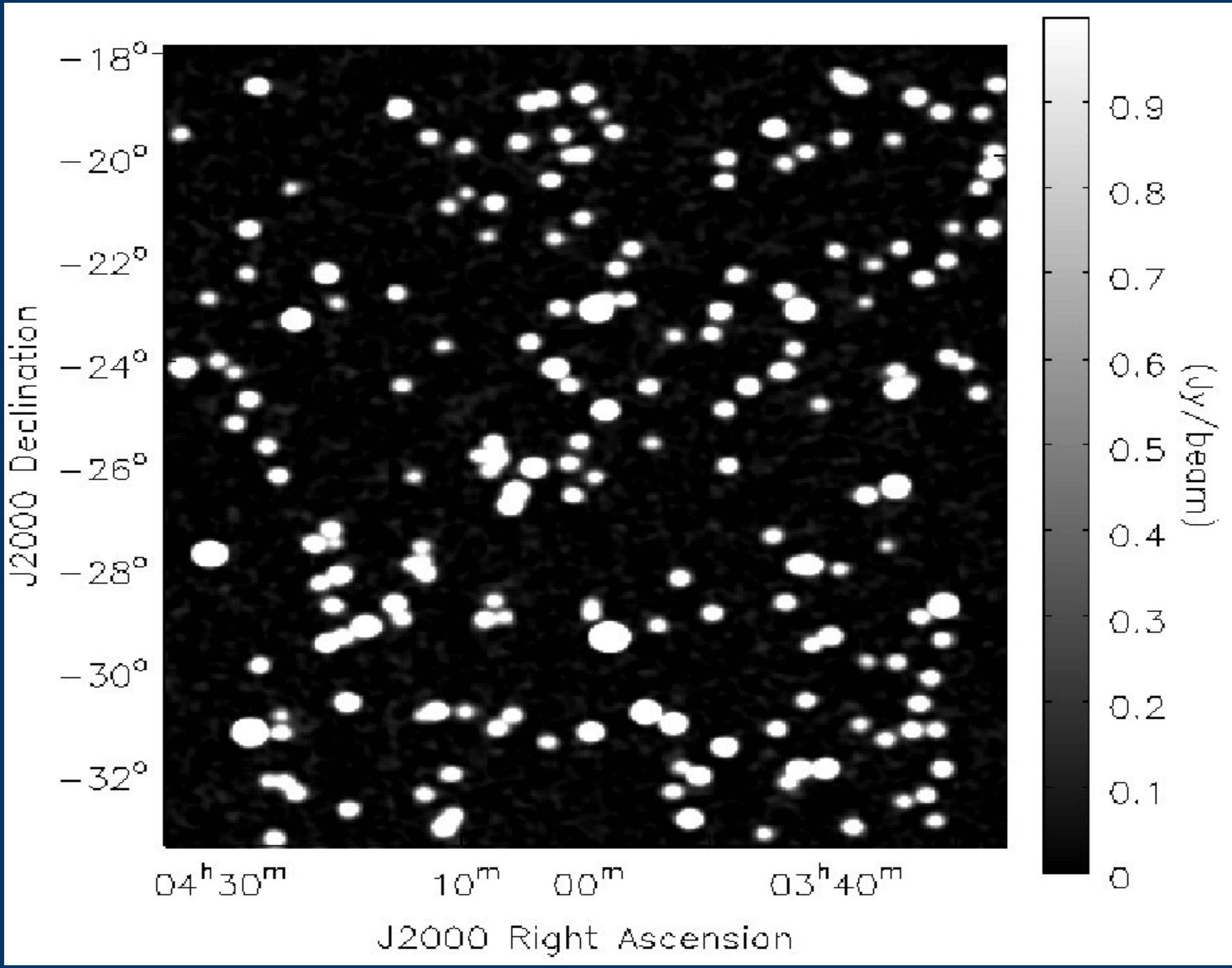
Simulation - Procedure

- Simulate Visibilities using the **GSM => (1)**
- Predict Model Visibilities with GSM position error or Calibration errors.
- Subtract the model visibilities from the simulated visibilities => **UVSUB (2)**
- Image the residual visibilities !!!!!

$$V_{ij}^{R} = g_i g_j^* V_{ij}^{Ideal} - \left(V_{ij}^{Ideal} + \Delta V_{ij} \right)$$

- Fit a 3rd order polynomial to the residual image cube => **IMLIN (3)**

Simulated Sky - LogN-LogS



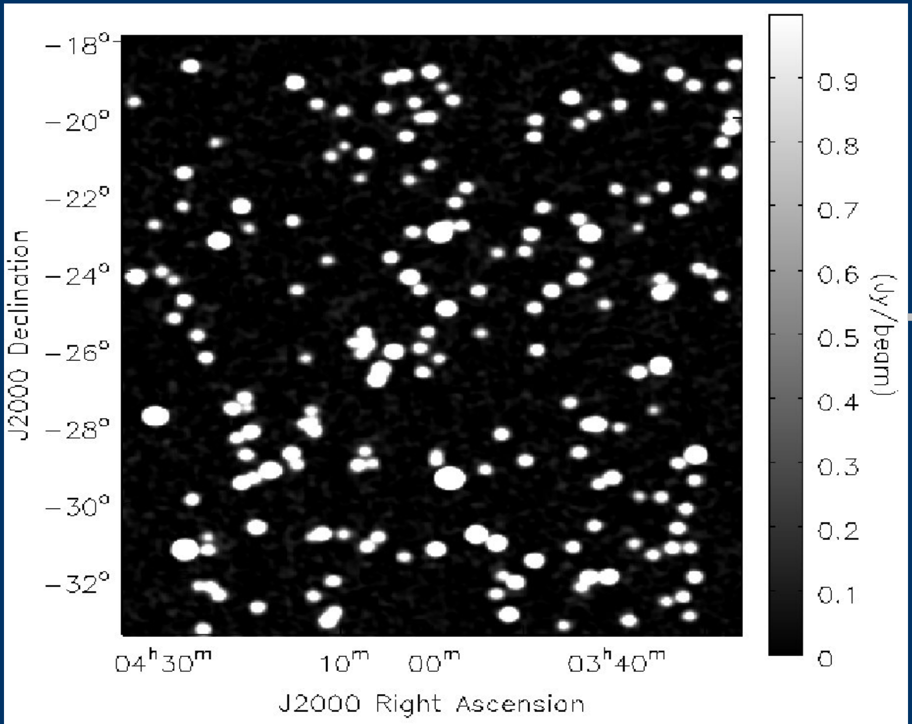
Sources above 1 Jy flux density

Source count matches that from 6C survey from Hale et al.

This forms our Global Sky Model (GSM)

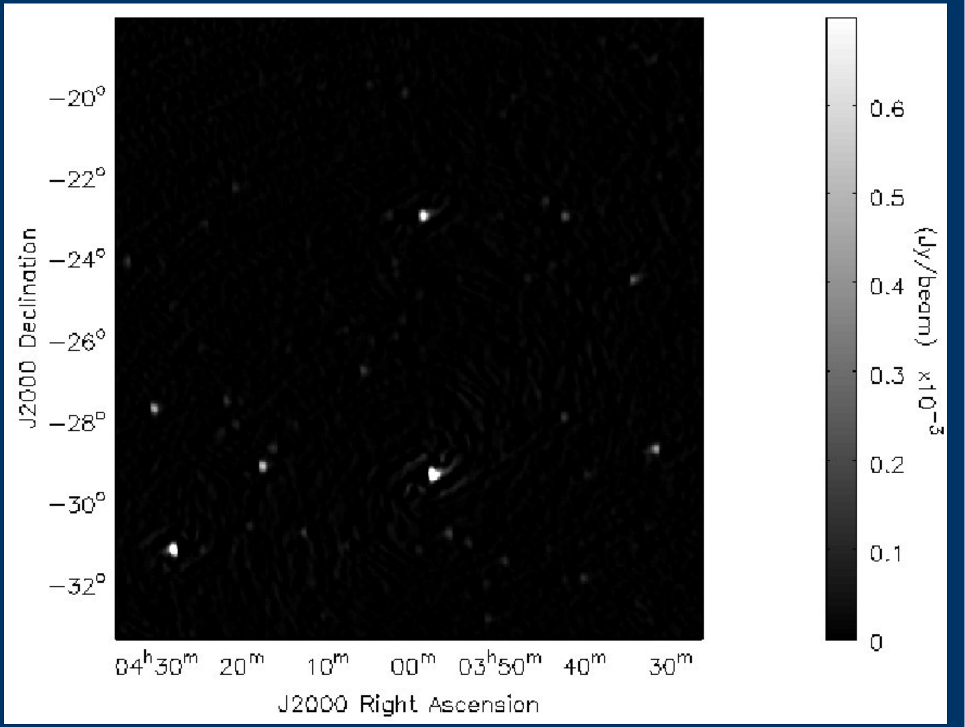
Datta et al. 2009 (ApJ)

Simulation - Procedure

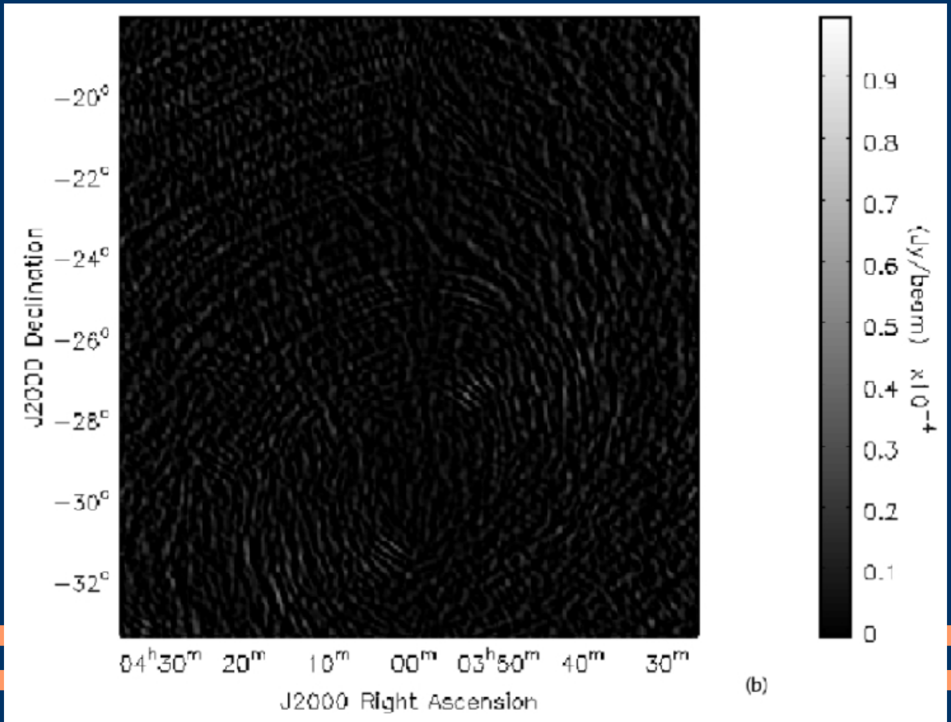


(1) GSM

(2) UVSUB



(3) IMLIN



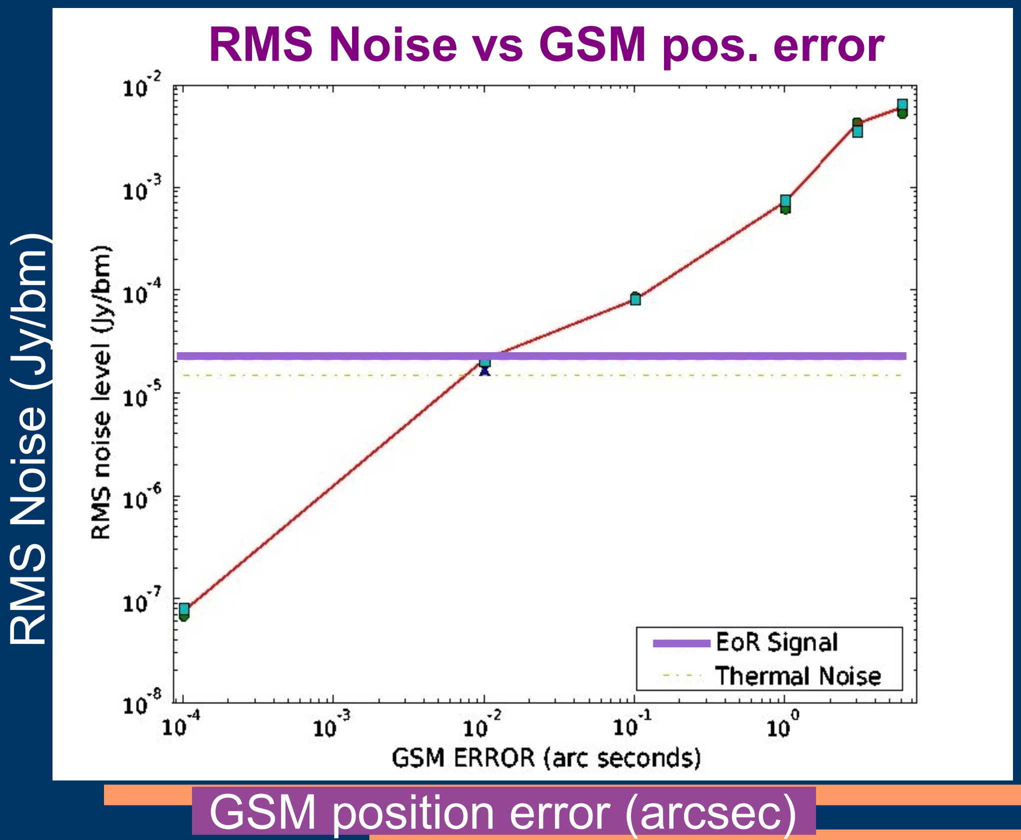
GSM position Errors :-

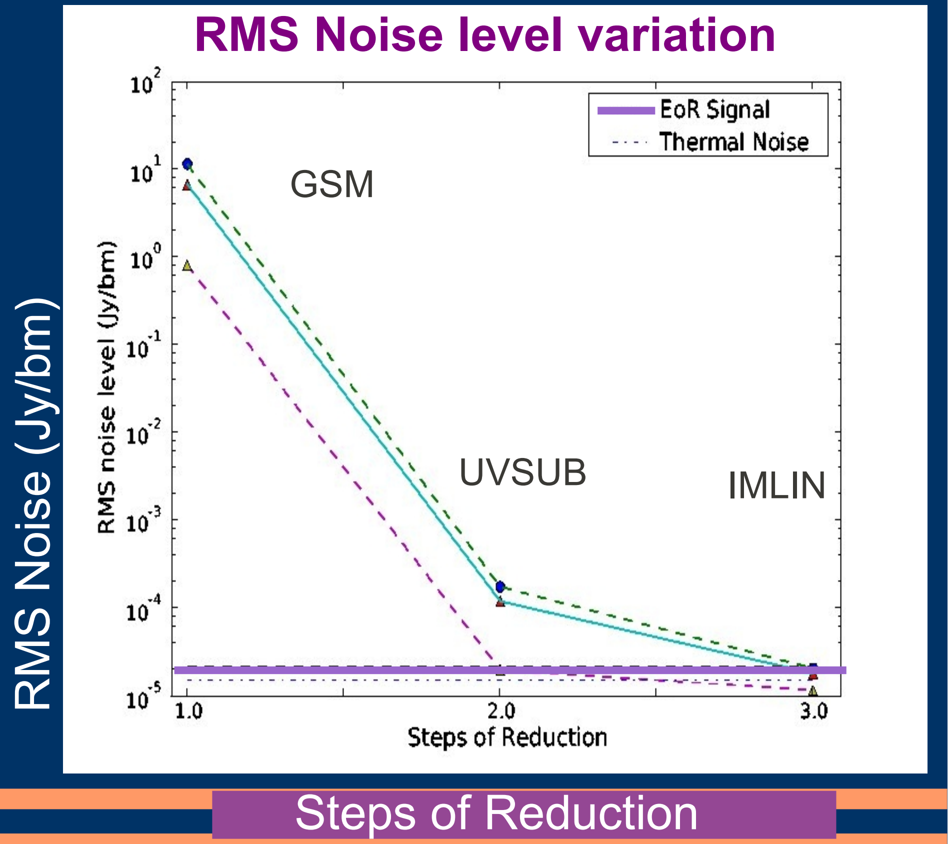
Datta et al. 2009 (ApJ)

REQUIRE :

~ 0.1 arcsec accuracy in source position

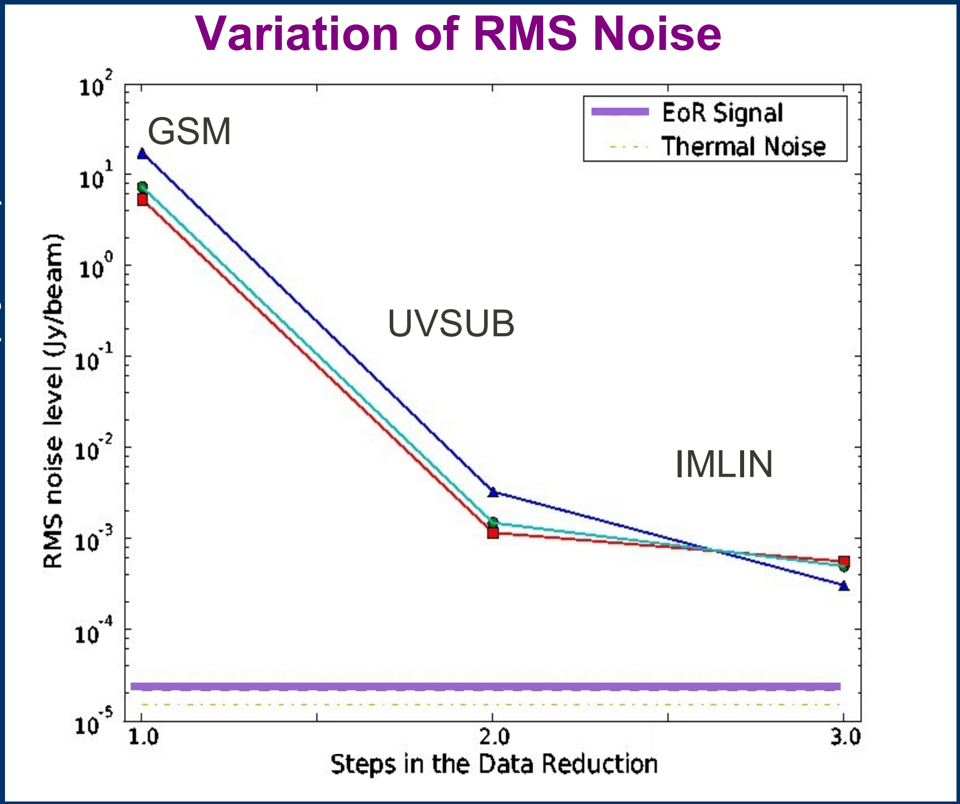
The GSM position error is assumed to be same over the entire duration of observations (5000 hrs) and hence systematic to the datasets.





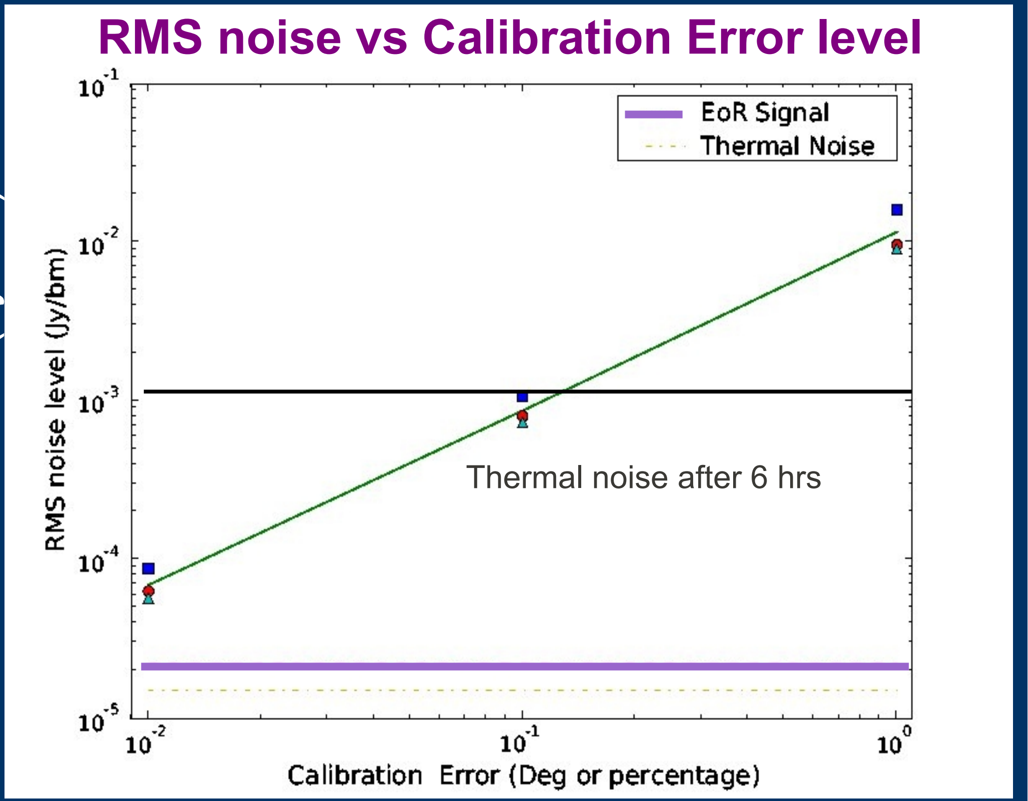
Calibration Errors: $V_{ij}(t) = g_i(t)\,g_j^*(t)\,V_{ij}^o(t) + \epsilon_{ij}(t)$

RMS Noise (Jy/bm)



Steps in Reduction

RMS Noise (Jy/bm)



Calibration Error

REQUIRE:-

0.1% amplitude gain error
0.1deg phase gain error

to reach the RMS noise for 512 elements

The mean value of the residual calibration error remains the same over the entire duration of observations (5000 hrs) !!

Datta et al. 2009 (ApJ)

Power Spectra Analysis:

Datta et al. 2010 (ApJ)

Convert the Residual Images from **UVSUB (2) & IMLIN (3)** into :

- Angular Power Spectra:

$$C_\ell = \frac{\sum_{2\pi|\mathbf{u}|=\ell} W(\mathbf{u})|V(\mathbf{u})|^2}{\sum_{2\pi|\mathbf{u}|=\ell} W(\mathbf{u})}$$

- 1D Spherically-Averaged power Spectra:

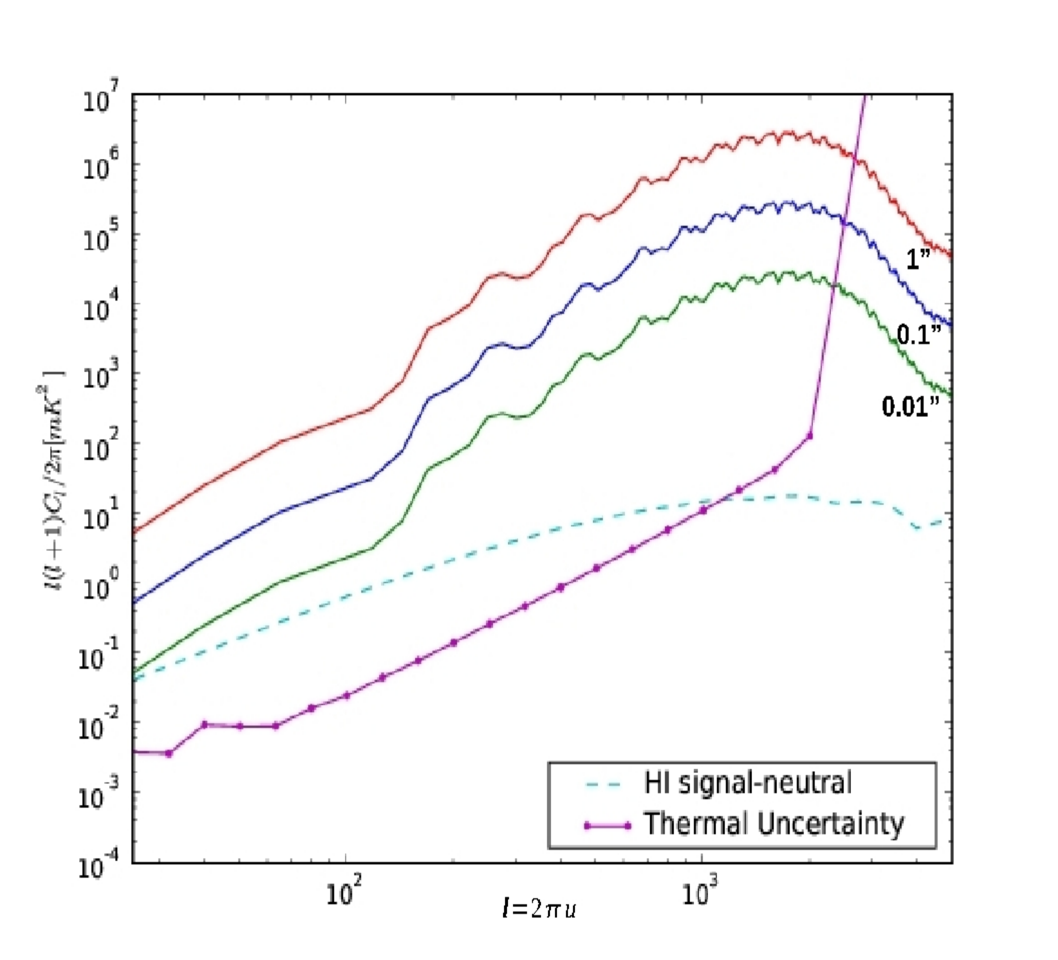
$$P(\tilde{\mathbf{k}}) = \frac{\sum_{|\mathbf{k}|=\tilde{\mathbf{k}}} W_u(\mathbf{k})\,|V(\mathbf{k})|^2}{\sum_{|\mathbf{k}|=\tilde{\mathbf{k}}} W_u(\mathbf{k})}$$

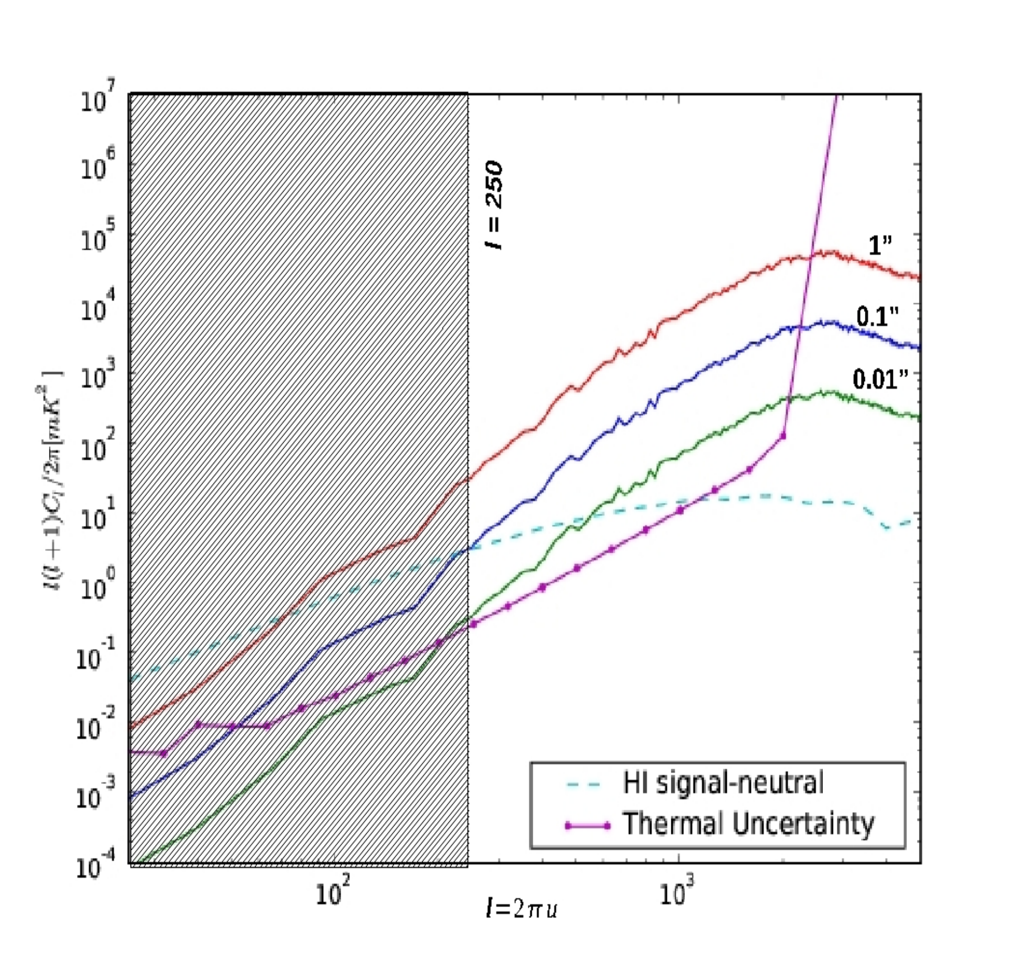
- 2D Power Spectra :

$$P(\tilde{k_\perp}, \tilde{k_\parallel}) = \frac{\sum_{|\mathbf{k}_\perp|=\tilde{k_\perp}} \sum_{|k_\parallel|=\tilde{k_\parallel}} W_u(k_\perp, k_\parallel)\left|V(k_\perp, k_\parallel)\right|^2}{\sum_{|\mathbf{k}_\perp|=\tilde{k_\perp}} \sum_{|k_\parallel|=\tilde{k_\parallel}} W_u(k_\perp, k_\parallel)}$$

Angular PS: GSM position Errors :-

$$C_\ell = \frac{\sum_{2\pi|\mathbf{u}|=\ell} W(\mathbf{u})|V(\mathbf{u})|^2}{\sum_{2\pi|\mathbf{u}|=\ell} W(\mathbf{u})}$$





After UVSUB

After IMLIN

REQUIRE :

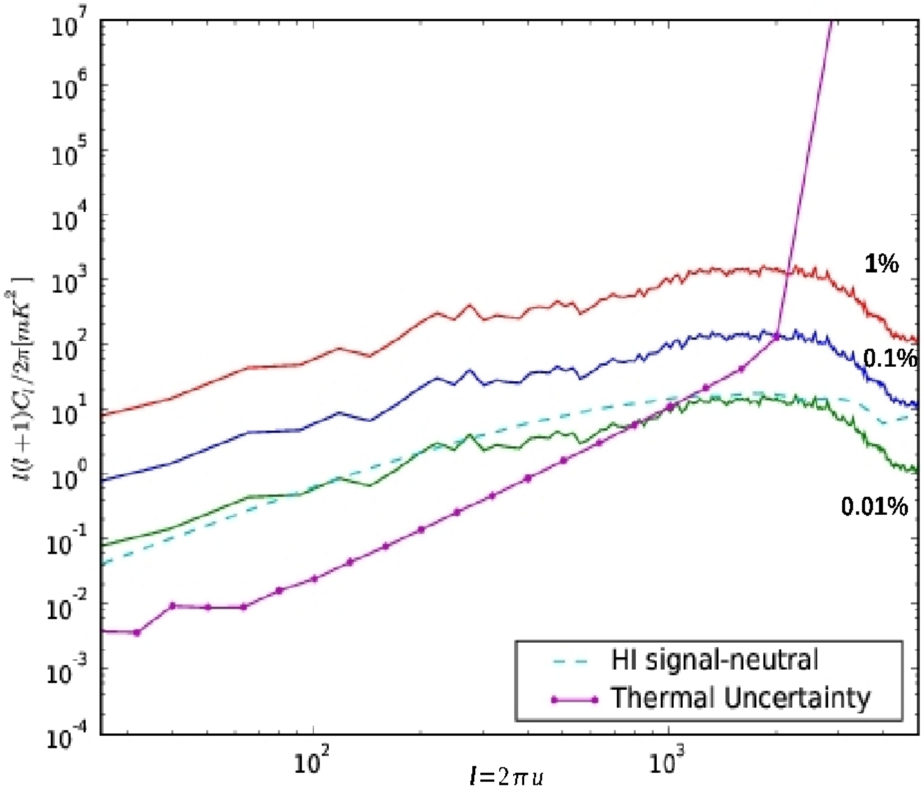
< ***0.1 arcsec*** accuracy in source position

Thermal sensitivity @ 5000hrs

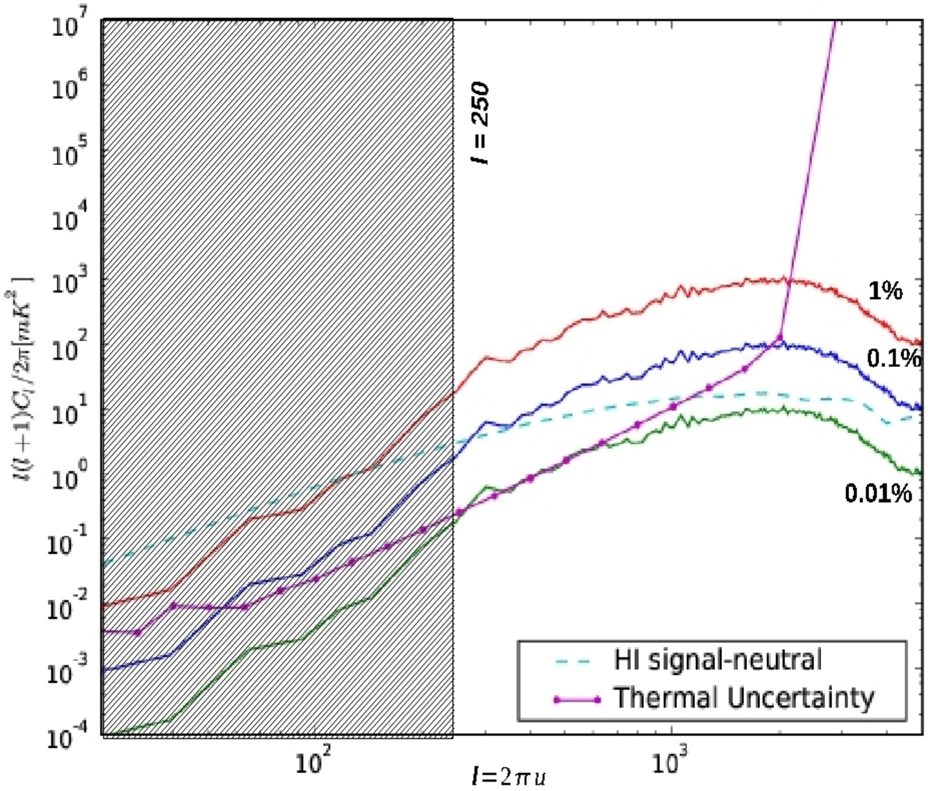
Datta et al. 2010 (ApJ)

Angular PS: Calibration Errors

$$C_\ell = \frac{\sum_{2\pi|\mathbf{u}|=\ell} W(\mathbf{u})|V(\mathbf{u})|^2}{\sum_{2\pi|\mathbf{u}|=\ell} W(\mathbf{u})}$$



After UVSUB



After IMLIN

REQUIRE :
< *0.05%* accuracy in calibration

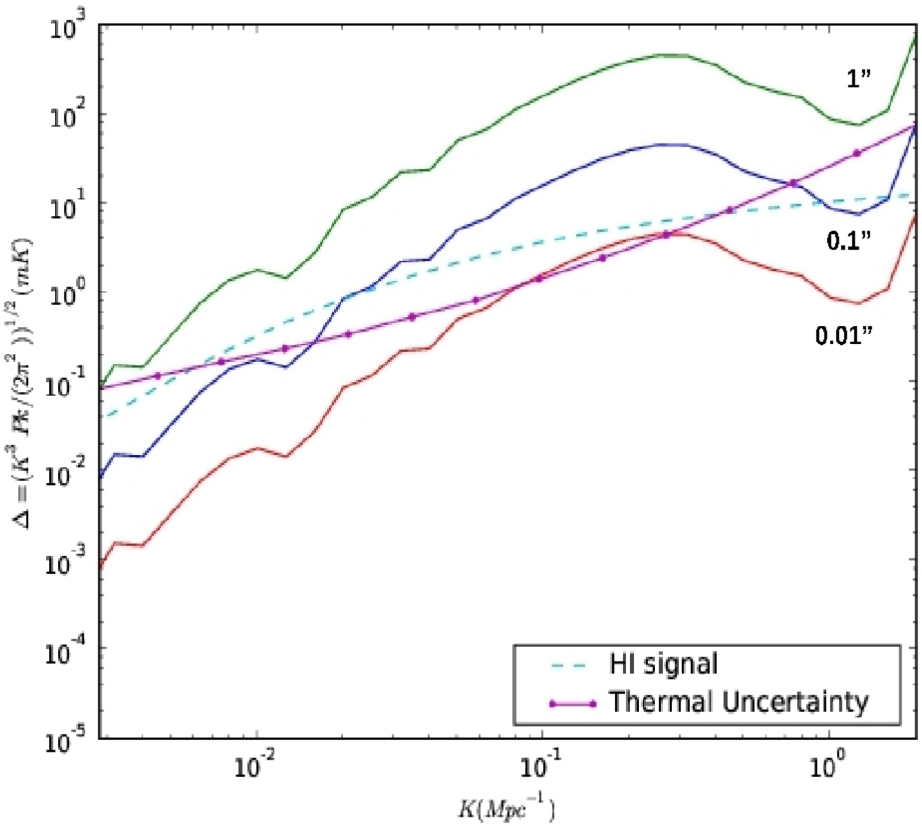
Thermal sensitivity @ 5000hrs

Datta et al. 2010 (ApJ)

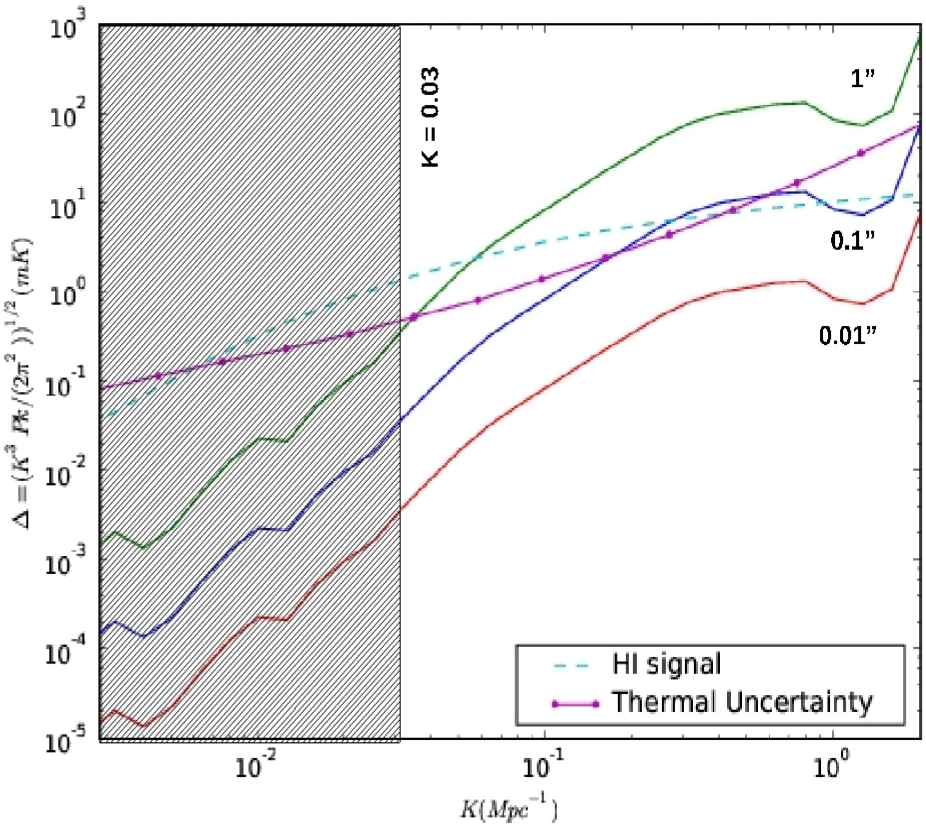
1D PS: GSM position Errors

$$P(\tilde{\mathbf{k}}) = \frac{\sum_{|\mathbf{k}|=\tilde{\mathbf{k}}} W_u(\mathbf{k}) \, |V(\mathbf{k})|^2}{\sum_{|\mathbf{k}|=\tilde{\mathbf{k}}} W_u(\mathbf{k})}$$

Higher Sensitivity than Angular PS.



After UVSUB



After IMLIN

REQUIRE :

< ***0.1 arcsec*** accuracy in source position

Thermal sensitivity @ 300hrs

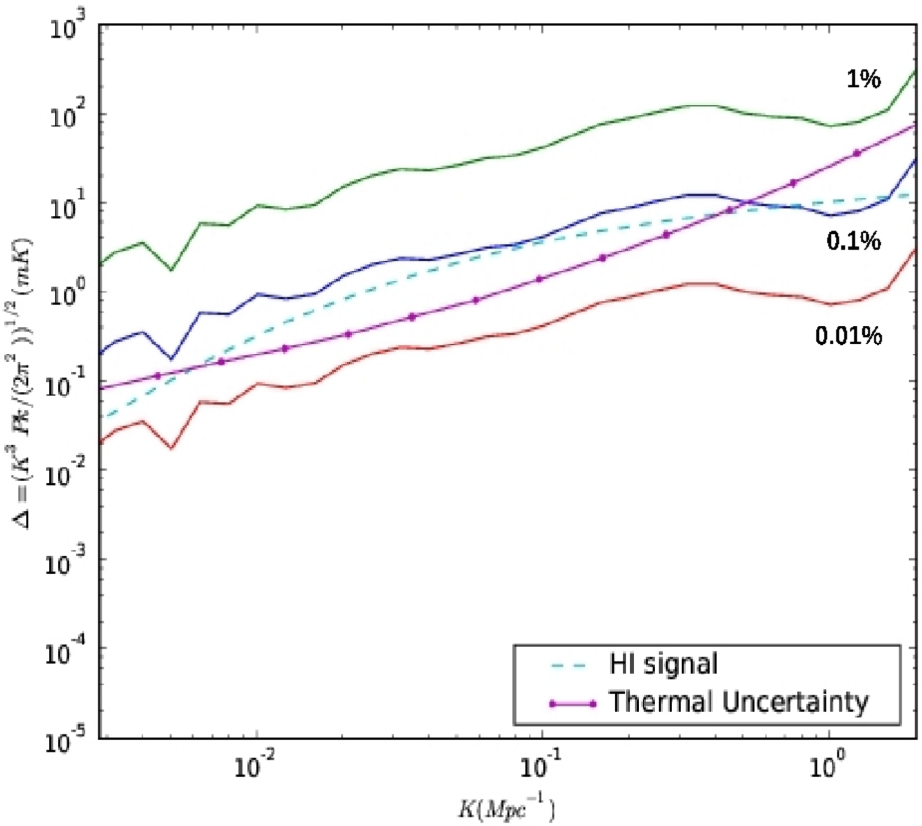
Datta et al. 2010 (ApJ)

$$\Delta^2 = k^3 P(k) / (2\pi^2)$$

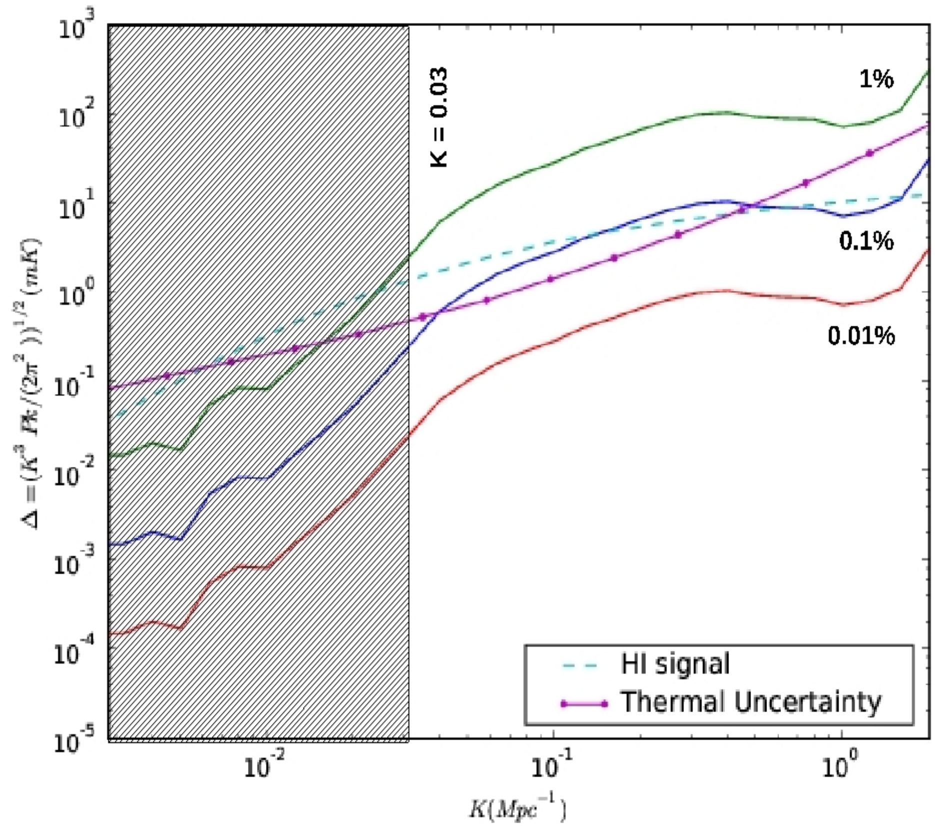
1D PS: Calibration Errors

$$P(\tilde{\mathbf{k}}) = \frac{\sum_{|\mathbf{k}|=\tilde{\mathbf{k}}} W_u(\mathbf{k}) \, |V(\mathbf{k})|^2}{\sum_{|\mathbf{k}|=\tilde{\mathbf{k}}} W_u(\mathbf{k})}$$

Higher Sensitivity than Angular PS.



After UVSUB



After IMLIN

REQUIRE :

< ***0.05%*** accuracy in calibration

$$\Delta^2 = k^3 P(k) / (2\pi^2)$$

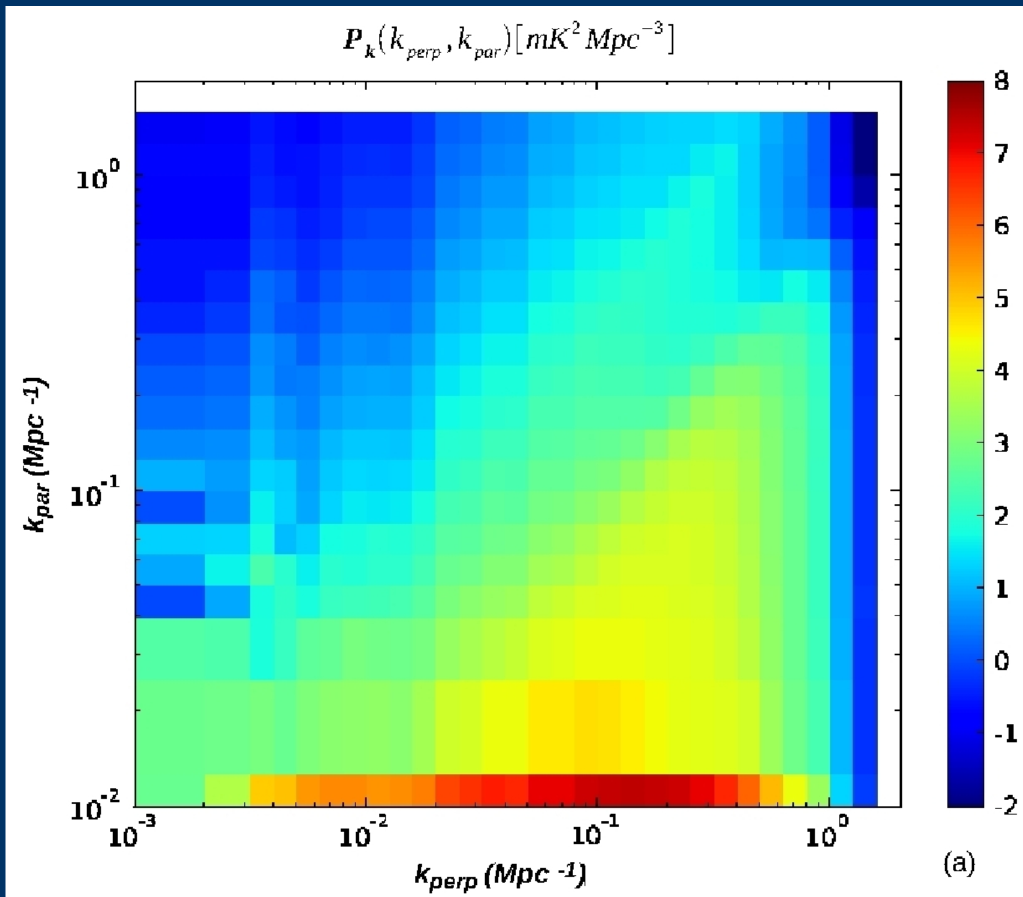
Thermal sensitivity @ 300hrs

Datta et al. 2010 (ApJ)

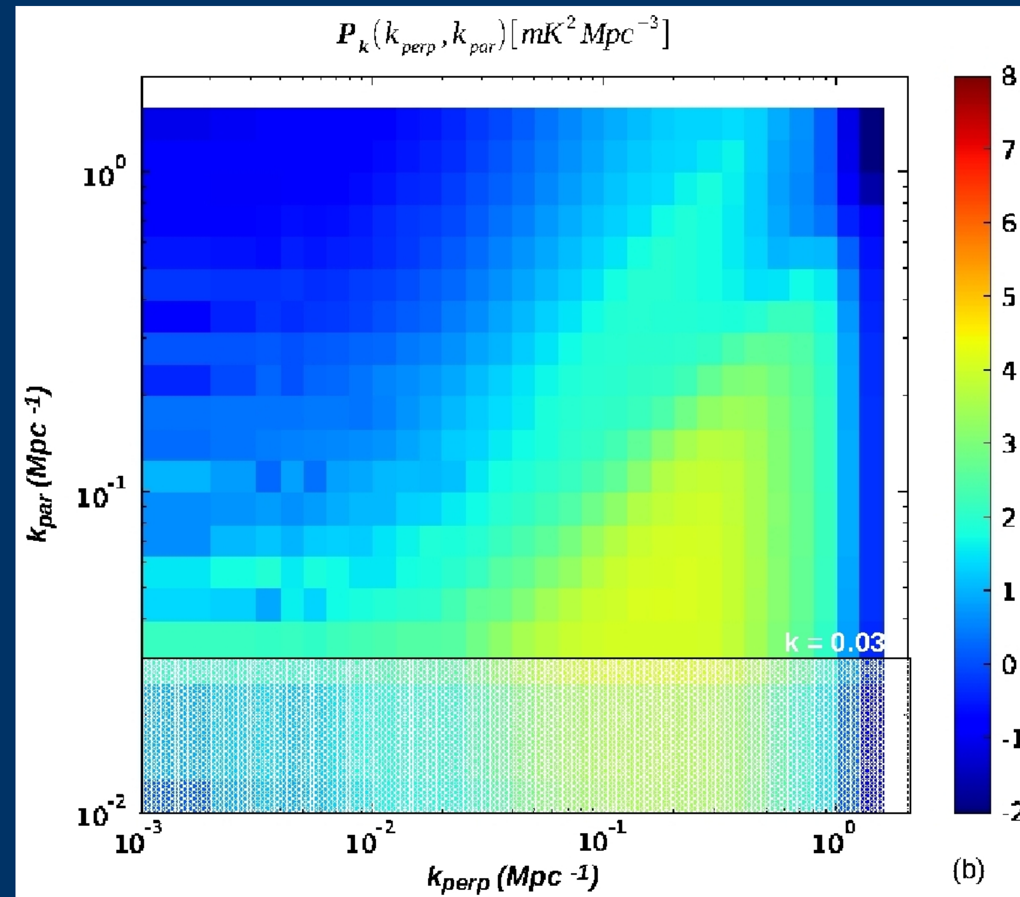
2D PS: GSM position Errors

$$P(\tilde{k}_{\perp}, \tilde{k}_{\parallel}) = \frac{\sum_{|\mathbf{k}_{\perp}|=\tilde{k}_{\perp}} \sum_{|k_{\parallel}|=\tilde{k}_{\parallel}} W_u(k_{\perp}, k_{\parallel}) \left| V(k_{\perp}, k_{\parallel}) \right|^2}{\sum_{|\mathbf{k}_{\perp}|=\tilde{k}_{\perp}} \sum_{|k_{\parallel}|=\tilde{k}_{\parallel}} W_u(k_{\perp}, k_{\parallel})}$$

0.1”



After UVSUB

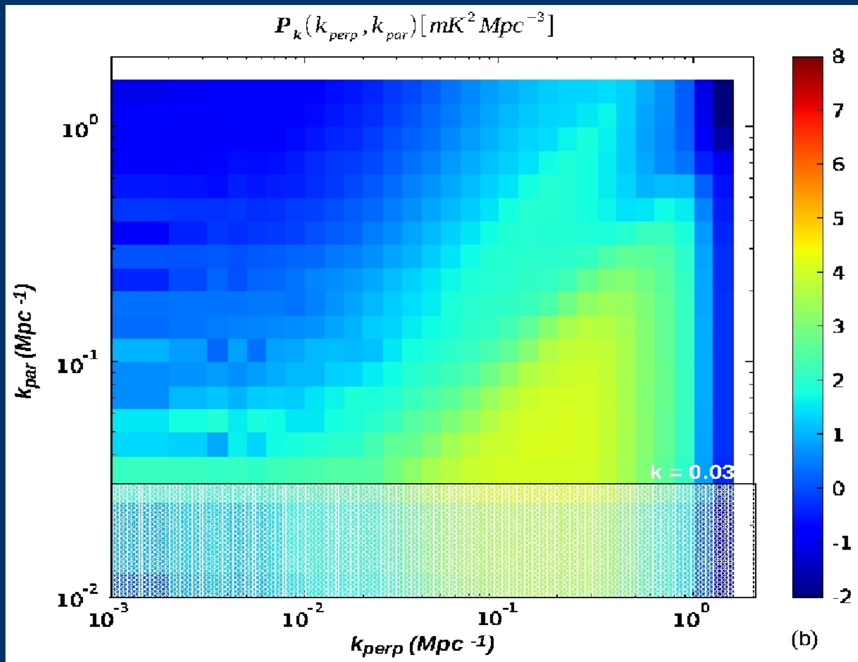


After IMLIN

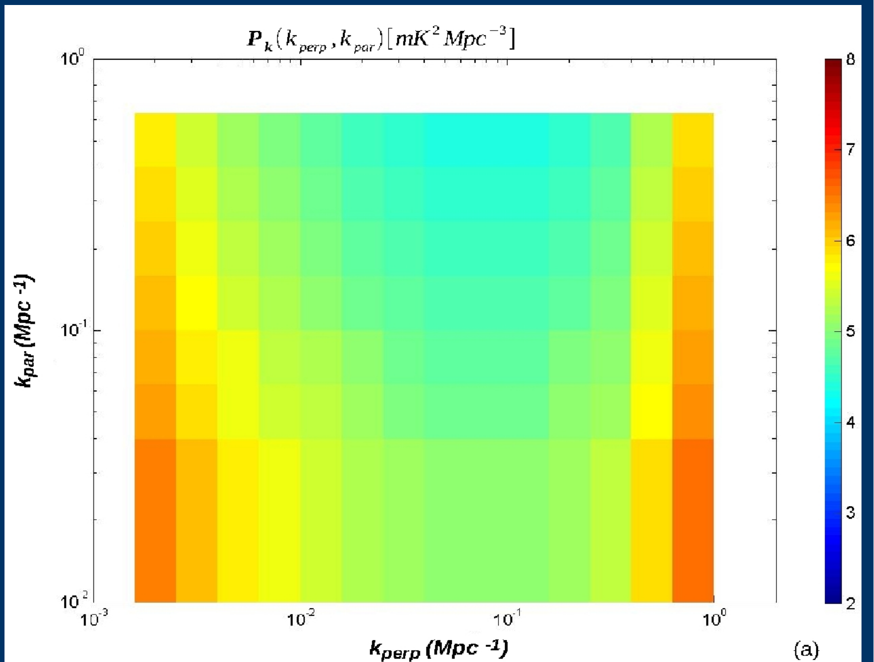
Contributions are decoupled along two axes

Errors localized at higher K values > 0.05

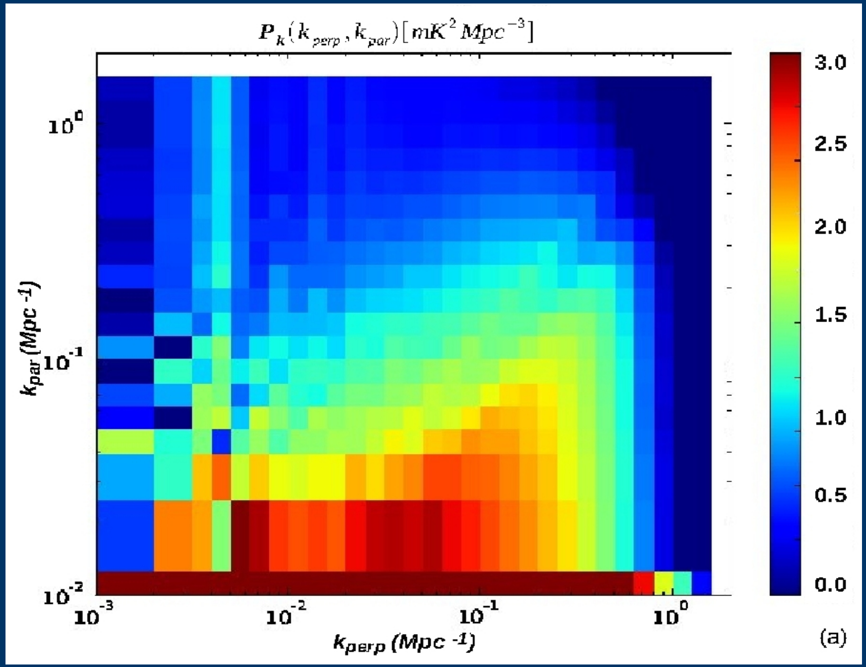
Datta et al. 2010 (ApJ)



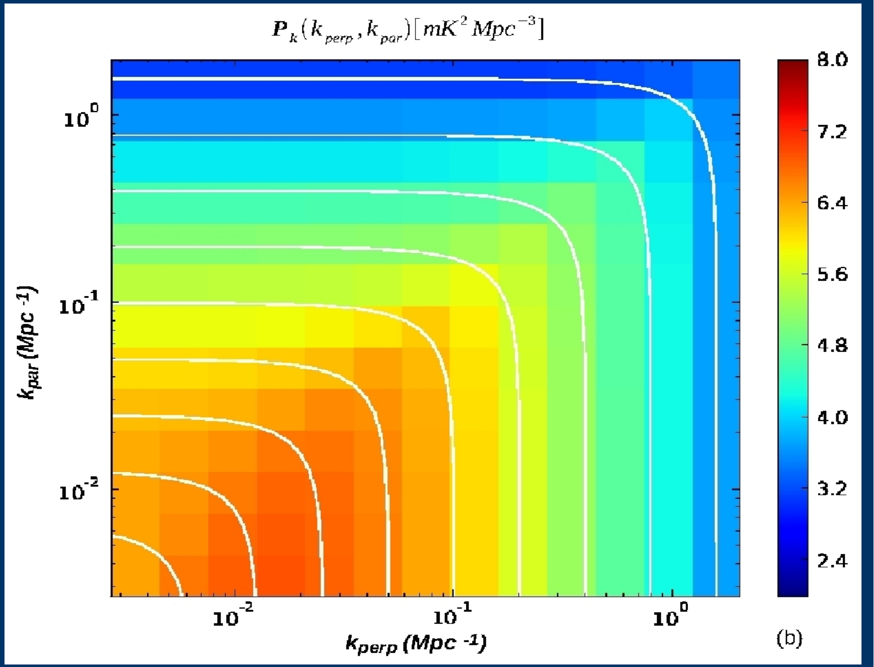
GSM 0.1” after IMLIN



Thermal Uncertainty MWA (300hr)



2D PS of MWA-512 PSF

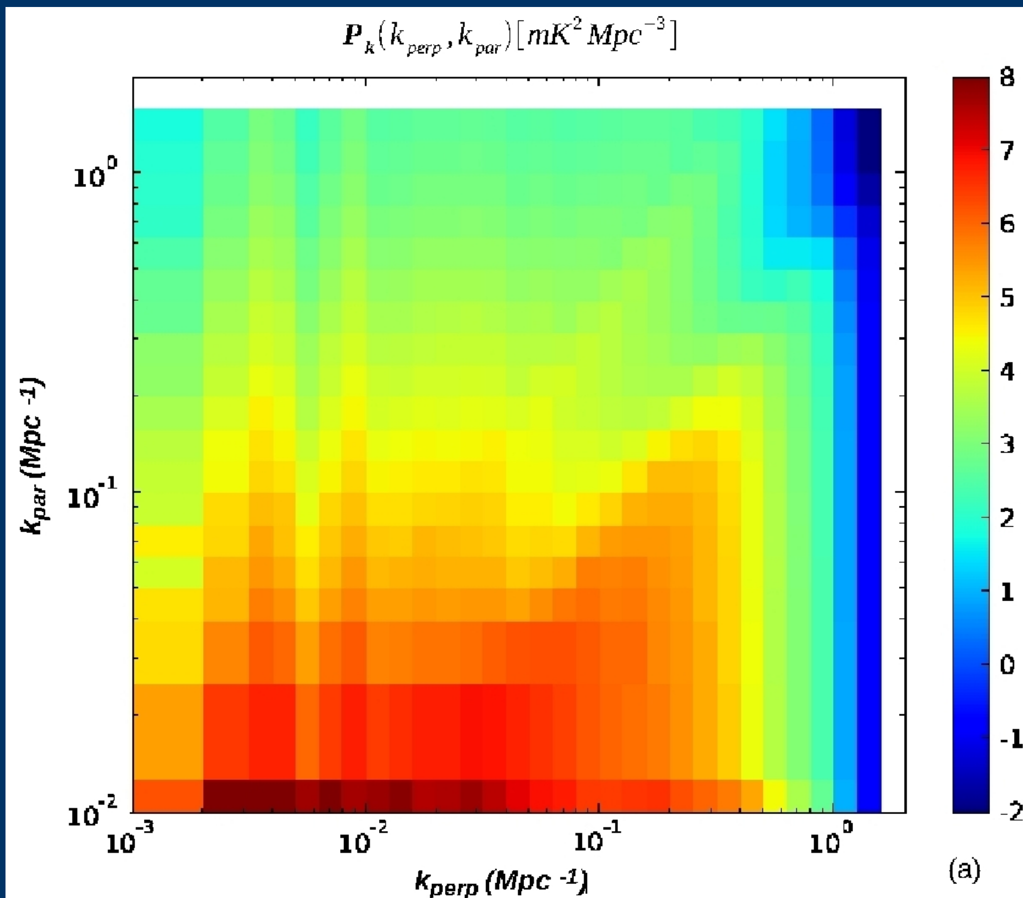


HI power spectra

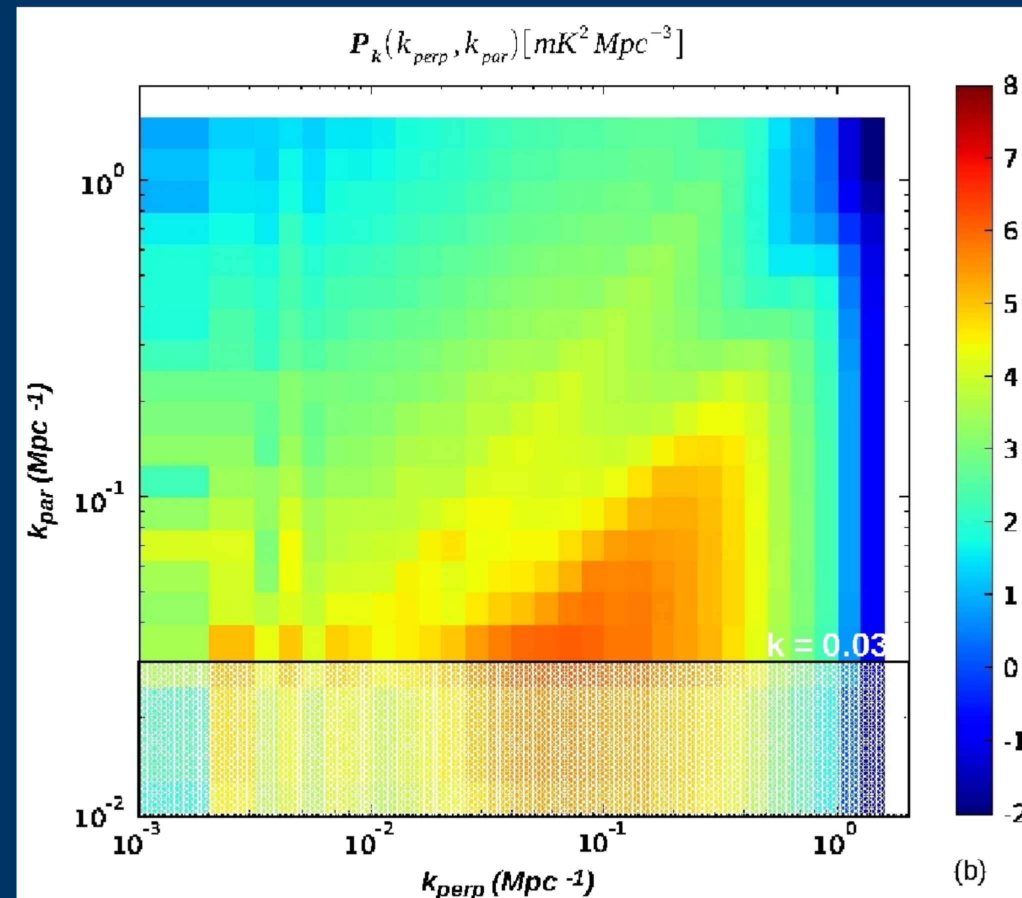
2D PS: Calibration Errors

$$P(\tilde{k_\perp}, \tilde{k_\parallel}) = \frac{\sum_{|\mathbf{k}_\perp|=\tilde{k_\perp}} \sum_{k_\parallel|=\tilde{k_\parallel}} W_u(k_\perp, k_\parallel) \left| V(k_\perp, k_\parallel) \right|^2}{\sum_{|\mathbf{k}_\perp|=\tilde{k_\perp}} \sum_{|k_\parallel|=\tilde{k_\parallel}} W_u(k_\perp, k_\parallel)}$$

0.1%



After UVSUB



After IMLIN

Contributions are decoupled along two axes

Errors localized at higher K values > 0.05

Datta et al. 2010 (ApJ)

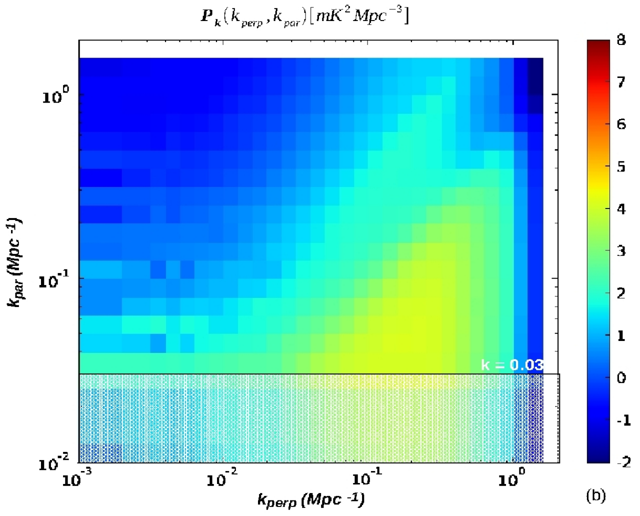
Important Results: Scope of development

Q. Do we have a handle on the accuracies?

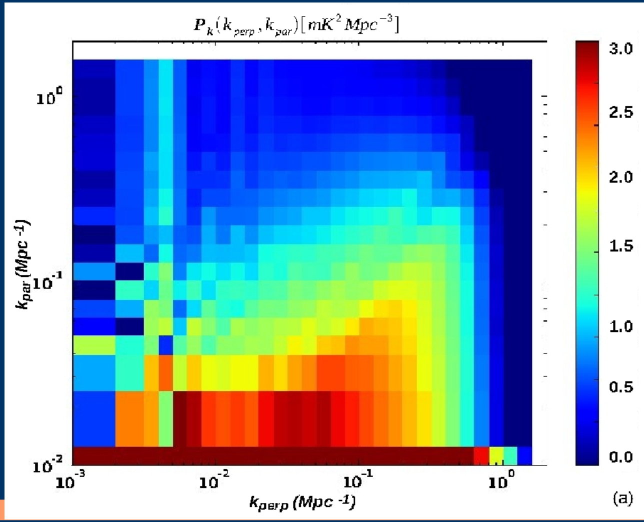
A. Yes! Power spectrum requires more accuracies than Image Domain!

Q. Do we have a template for the source subtraction?

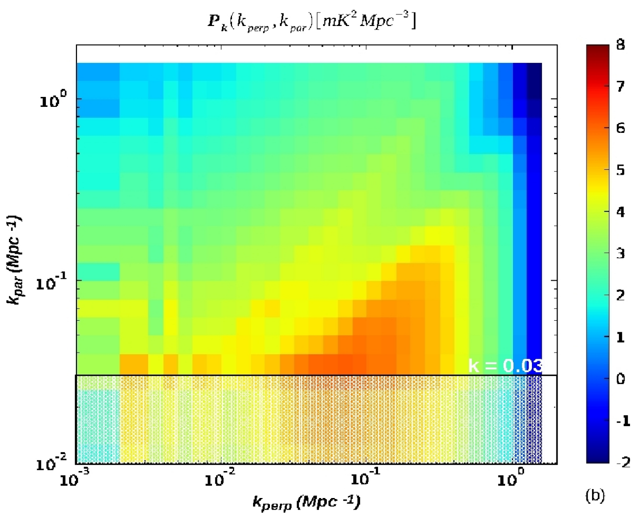
A. Yes (?) The PSF structure from the array creates a major template for the source subtraction !



GSM source position (0.1")



MWA-512 PSF



Calibration error (0.1%)

Results – Extrapolating to other Experiments

	# of elements	Position error	Calibration error
MWA	512	< 0.1”	<0.05%
PAPER	128	< 0.02”	< 0.01%
SKA	5000	<1”	< 0.5%
LRA	10000	<2”	<1%

More corrupting Terms :-

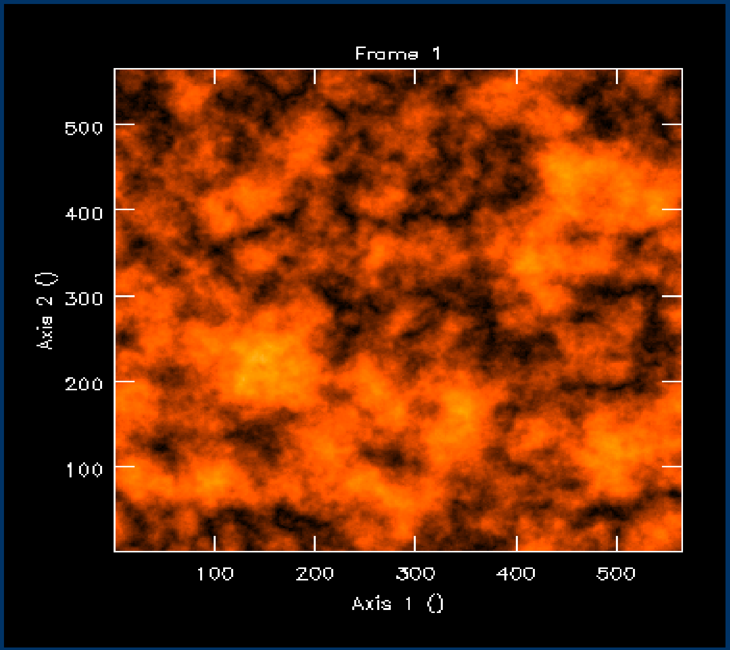
Frequency Dependant Gains :-

- Bandpass Shape (introduce frequency dependent calibration errors)

- Residual Spectral Index Variation

Direction Dependant Gains :-

- Ionosphere !!
  (which acts as a phase screen and introduces gain errors)



Kolmogorov Phase screen, 2006

Thank You !