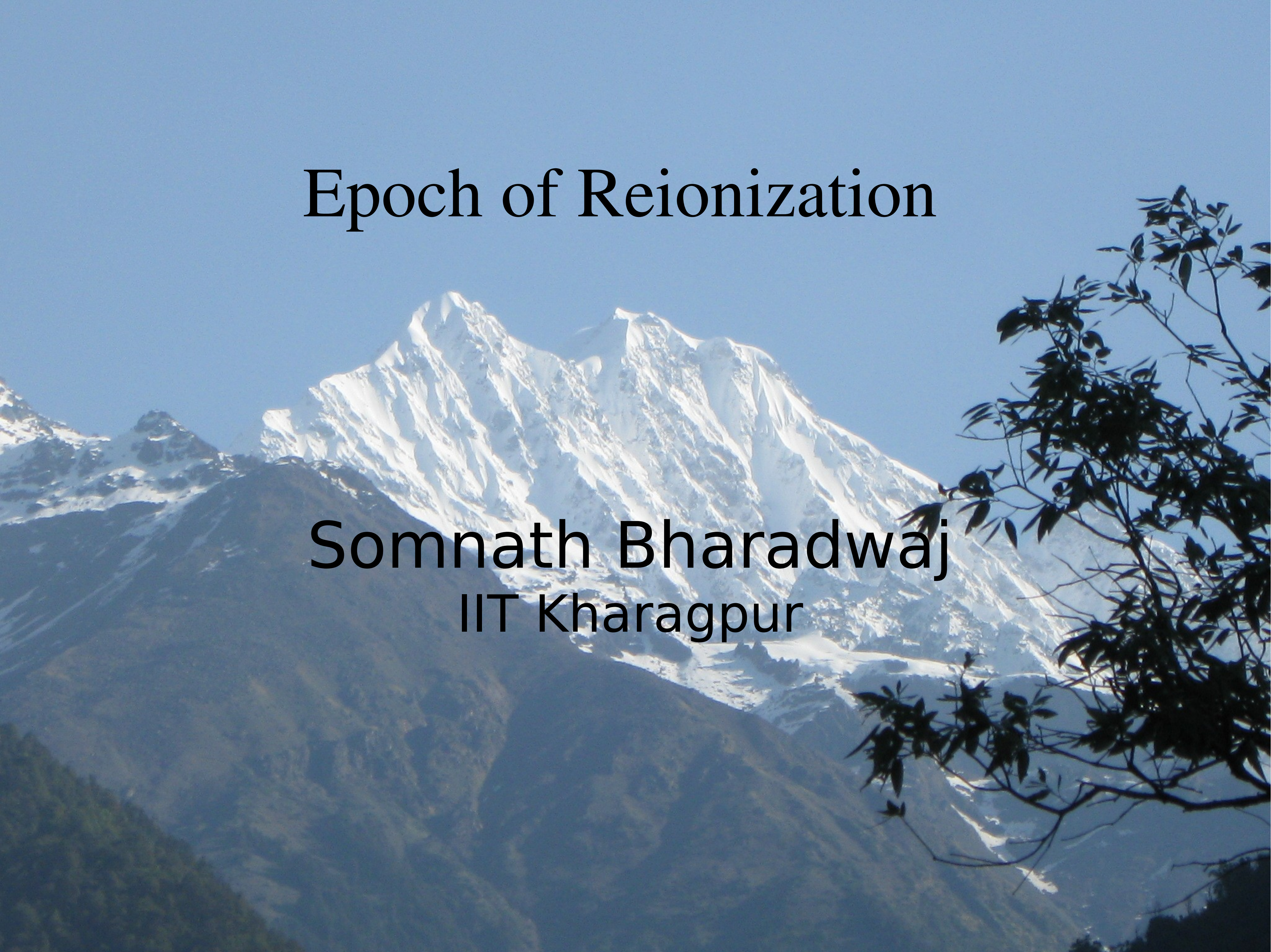
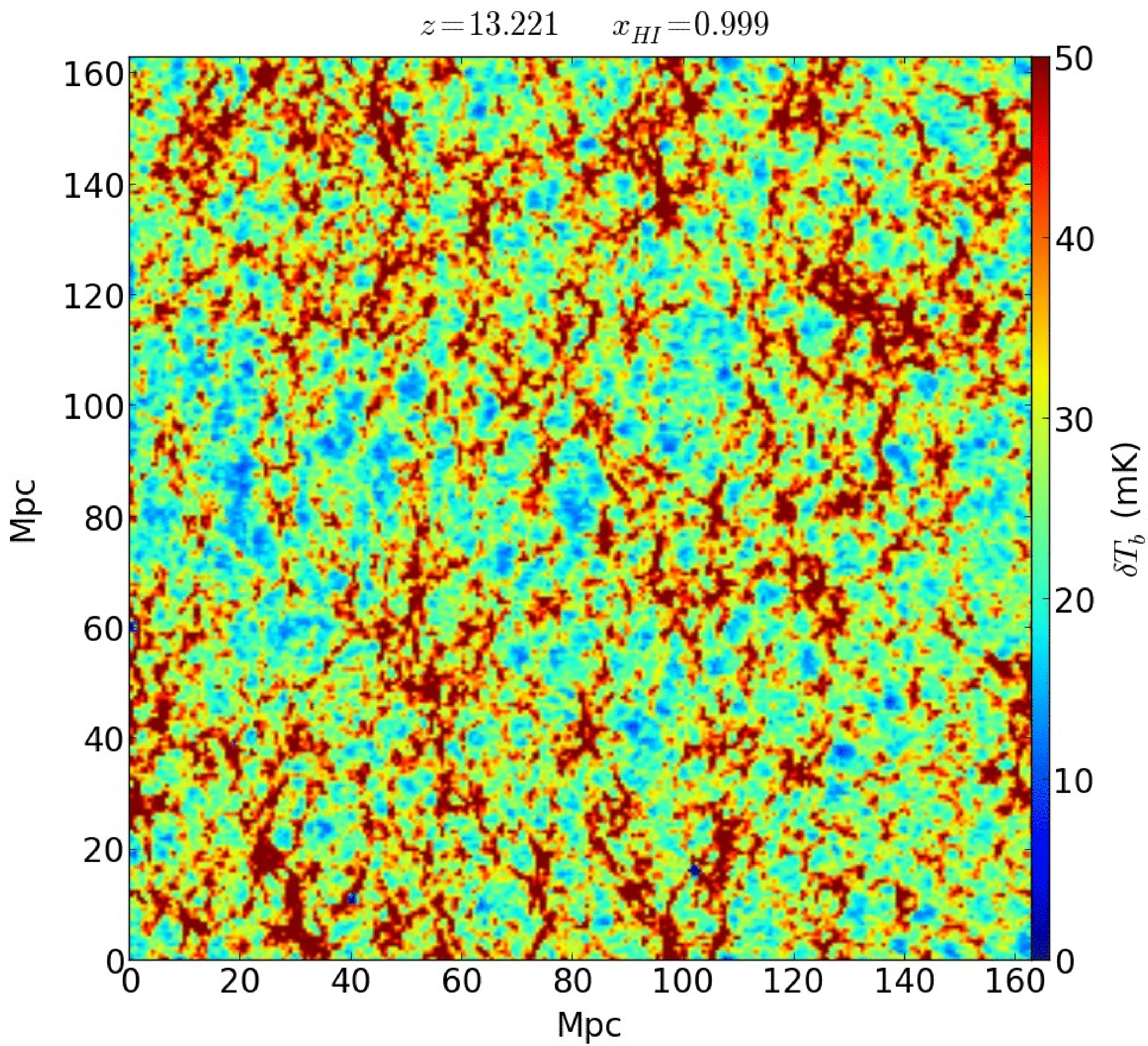
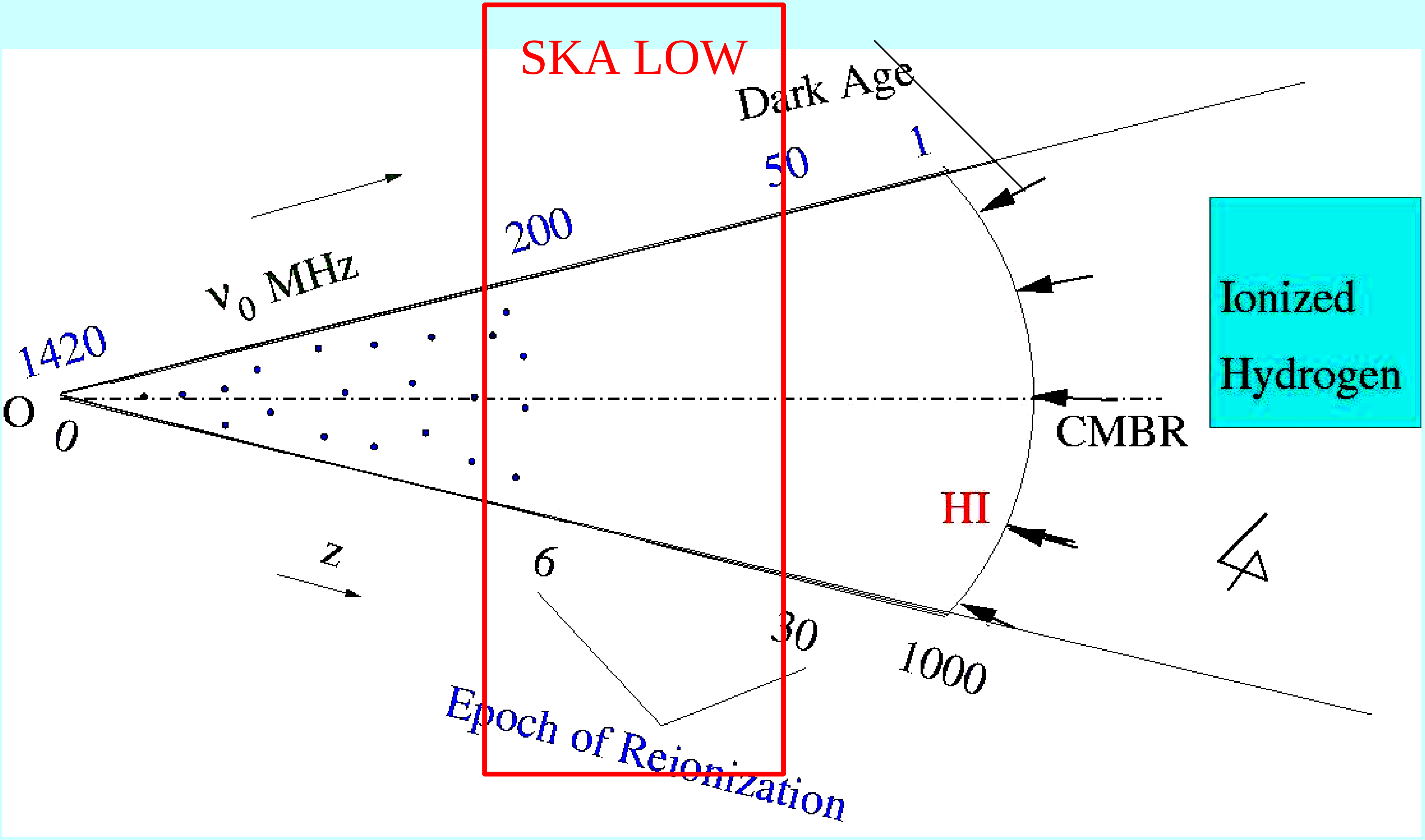


Epoch of Reionization

Somnath Bharadwaj
IIT Kharagpur


$z = 13.221 \quad x_{HI} = 0.999$
Mpc
Mpc
δT_b (mK)
0
20
40
60
80
100
120
140
160
0
10
20
30
40
50

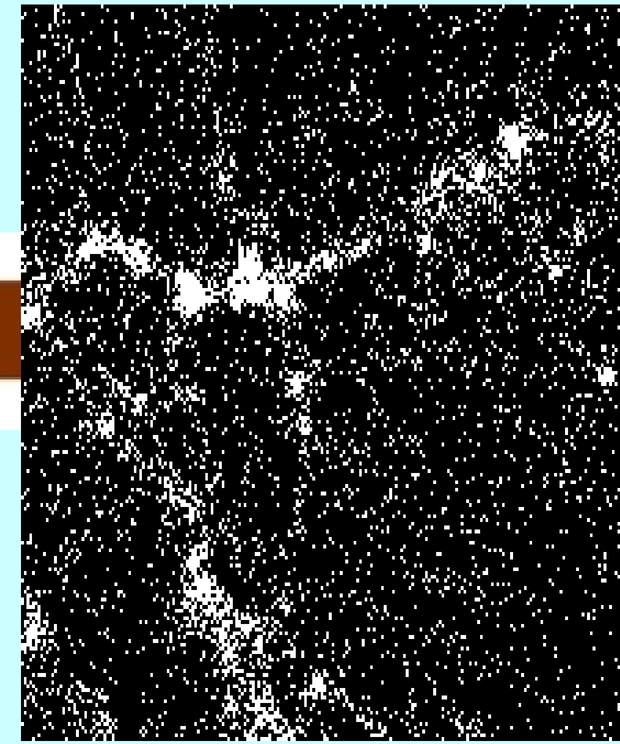
HI Evolution

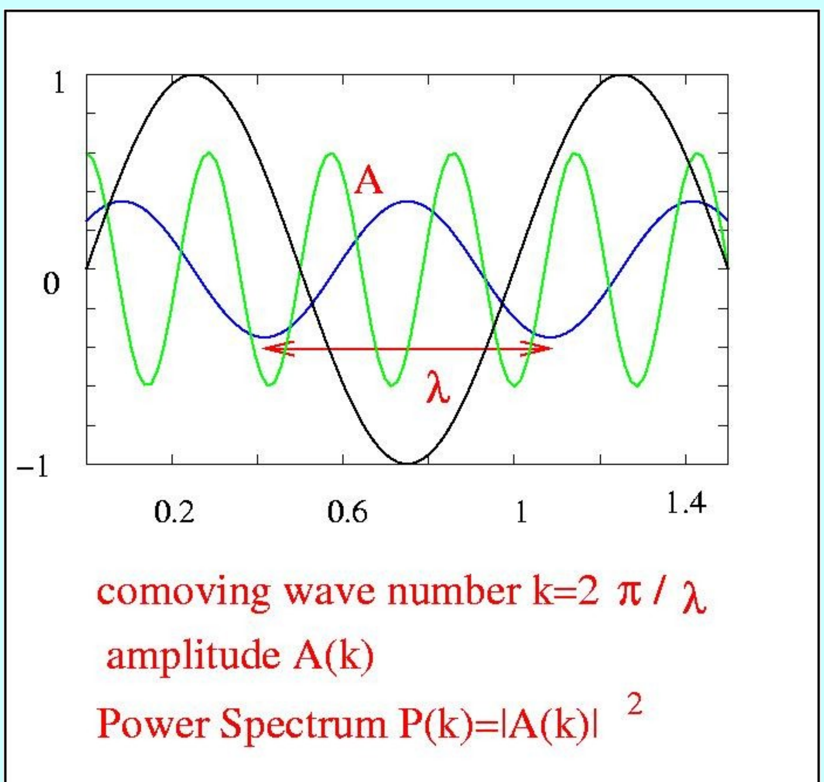


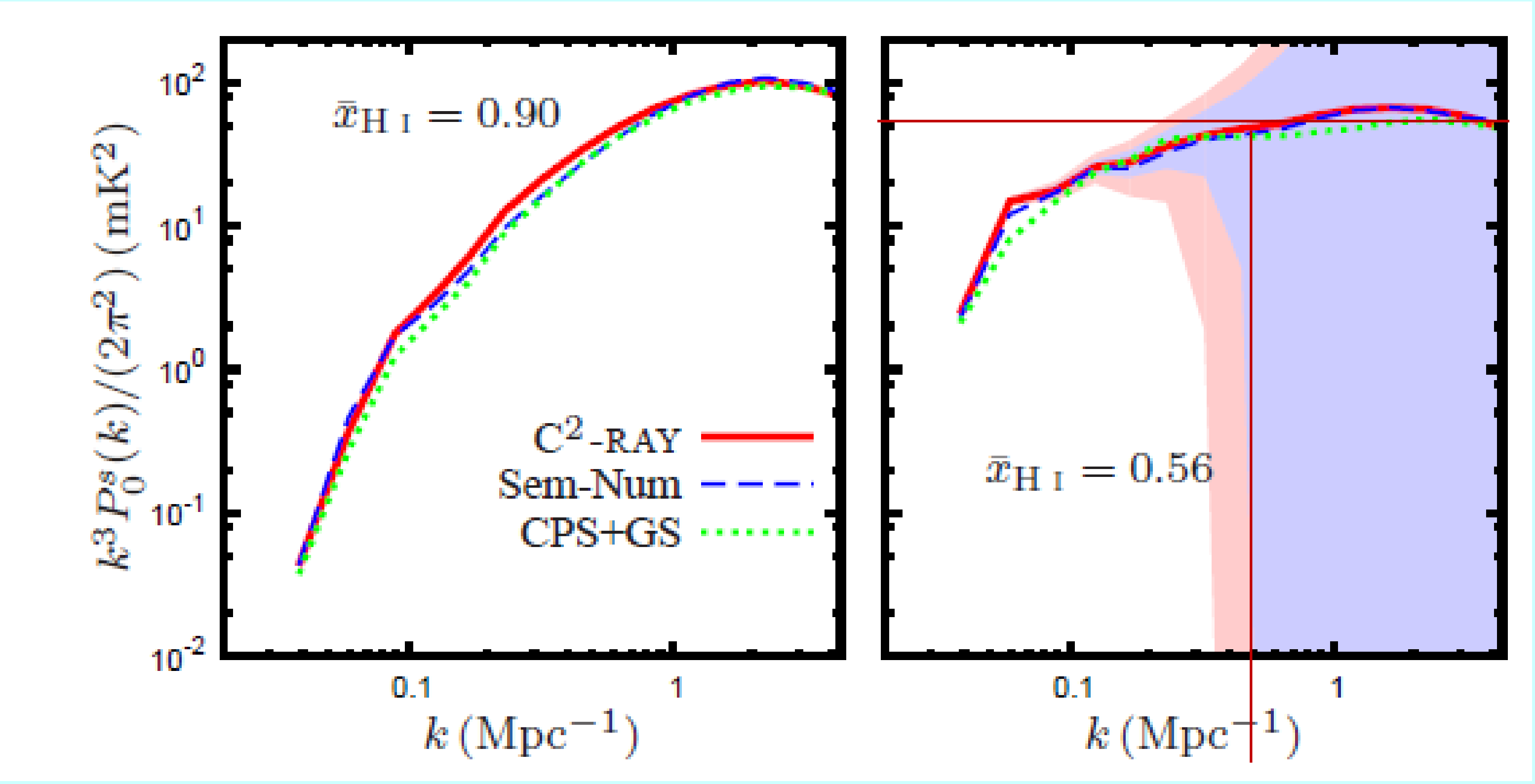
Bharadwaj, S. and Ali, Sk.S., 2005, MNRAS, 356, 151

What do we observe?

Fluctuations in the 21-cm Brightness Temperature
In the sky and in frequency







Signal Predictions

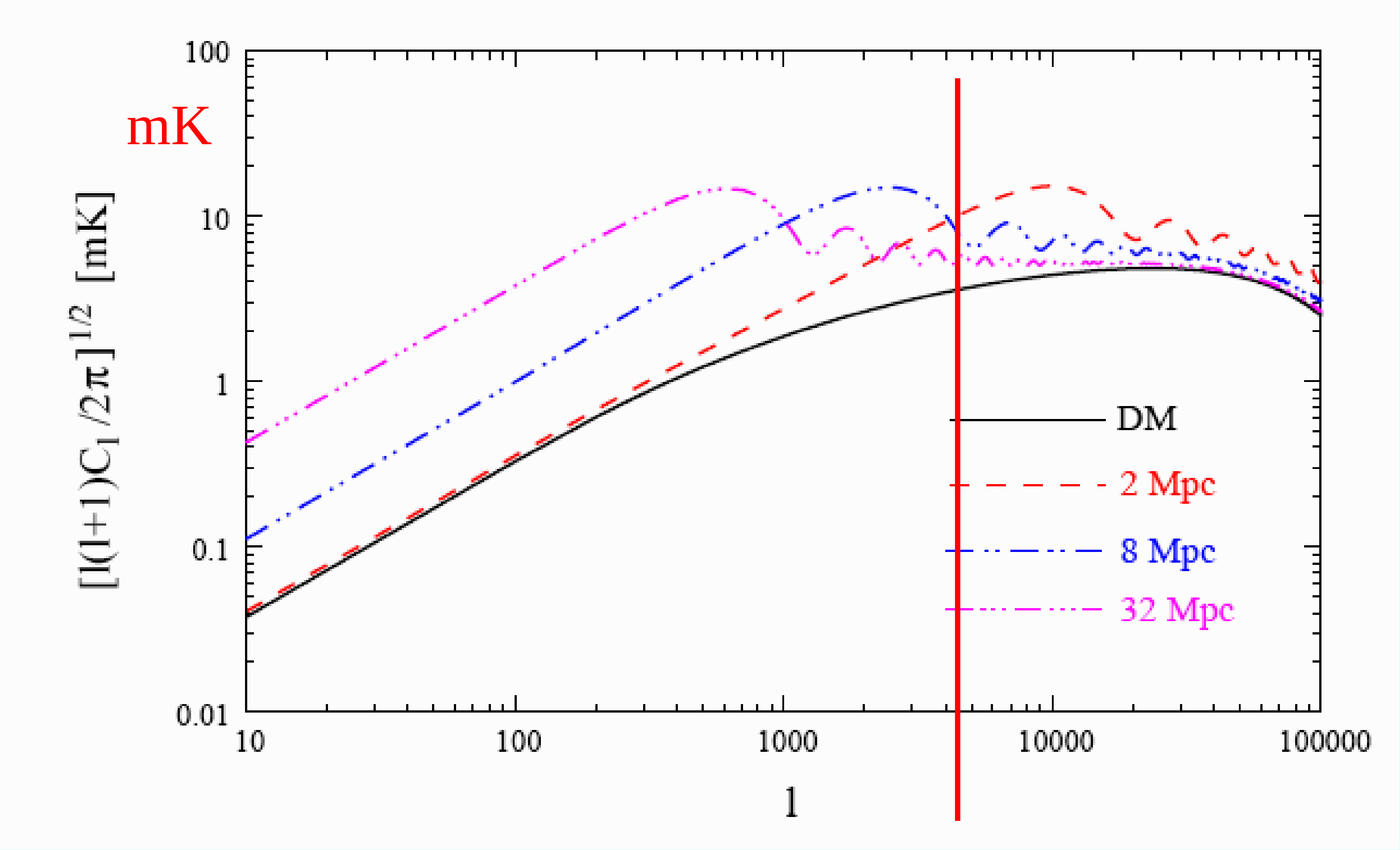
Brightenss Temperature Fluctuations $\delta T \sim$ 5-10 mK at k=0.5 Mpc $^{-1}$

Corresponds to $\theta \sim 5'$ and $\Delta\nu \sim 0.7$ MHz

Majumdar, S., Mellemam G.,**Datta, K.K.,**Jensen,H., **Roy Choudhury, T., Bharadwaj,S**. and Friedrich, M., 2014, arxiv:1403.0941, Submitted to MNRAS

Signal Prediction

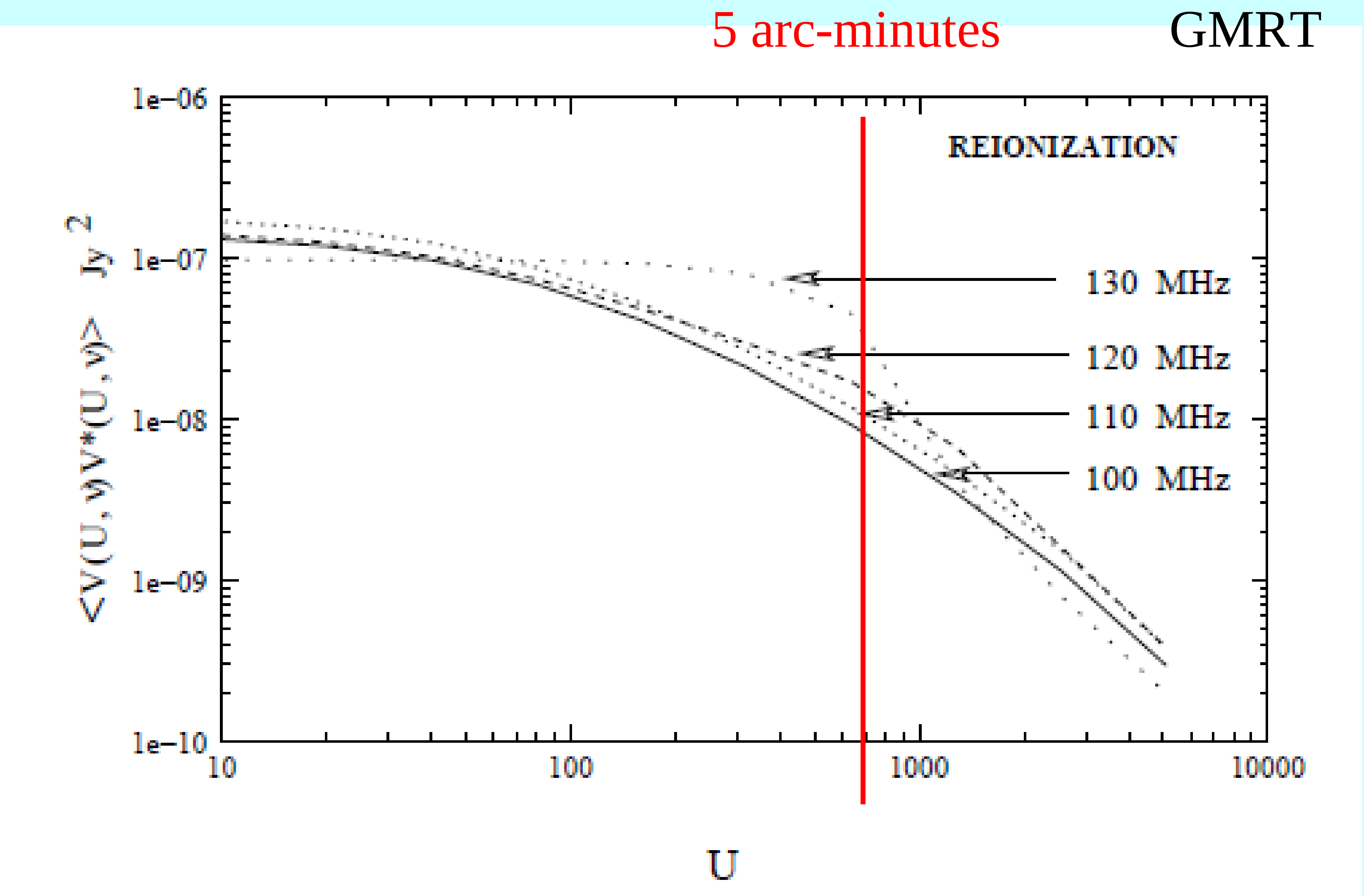
z=10, x=0.5



5 arc-minutes

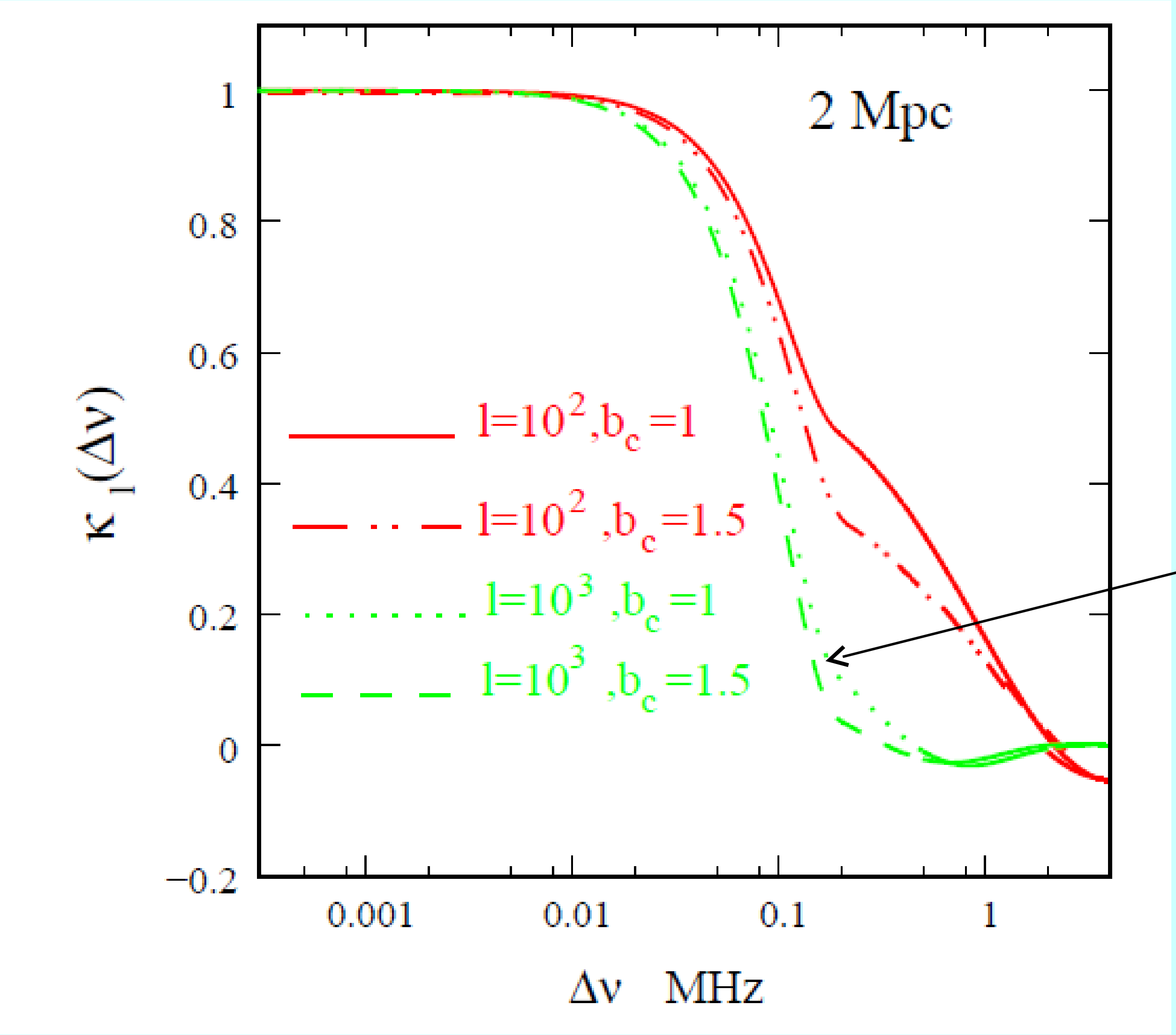
Datta, Roy Choudhury & Bharadwaj 2007, 387,767

Signal Prediction



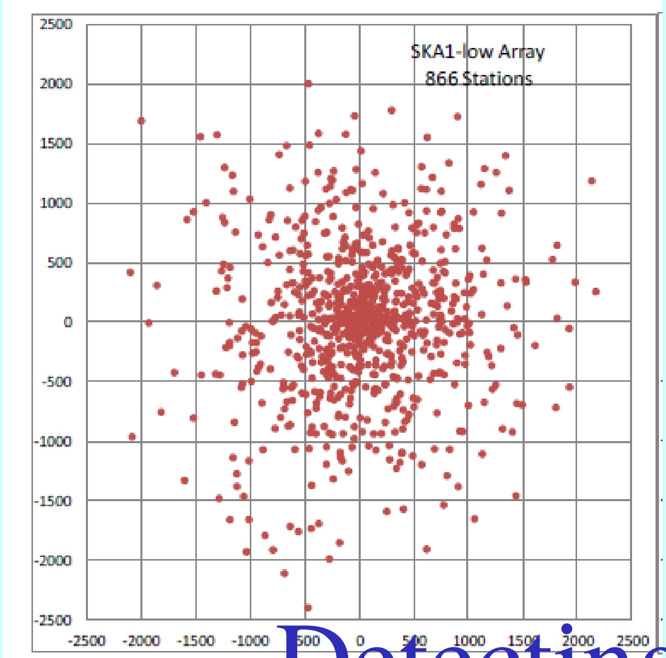
Bharadwaj, S. and Ali, Sk.S., 2005, MNRAS, 356, 151

Signal Prediction



20 arc-minutes

Datta, Roy Choudhury & Bharadwaj 2007, 387,767



Detecting the EOR signal is one of the key scientific goals of SKA low

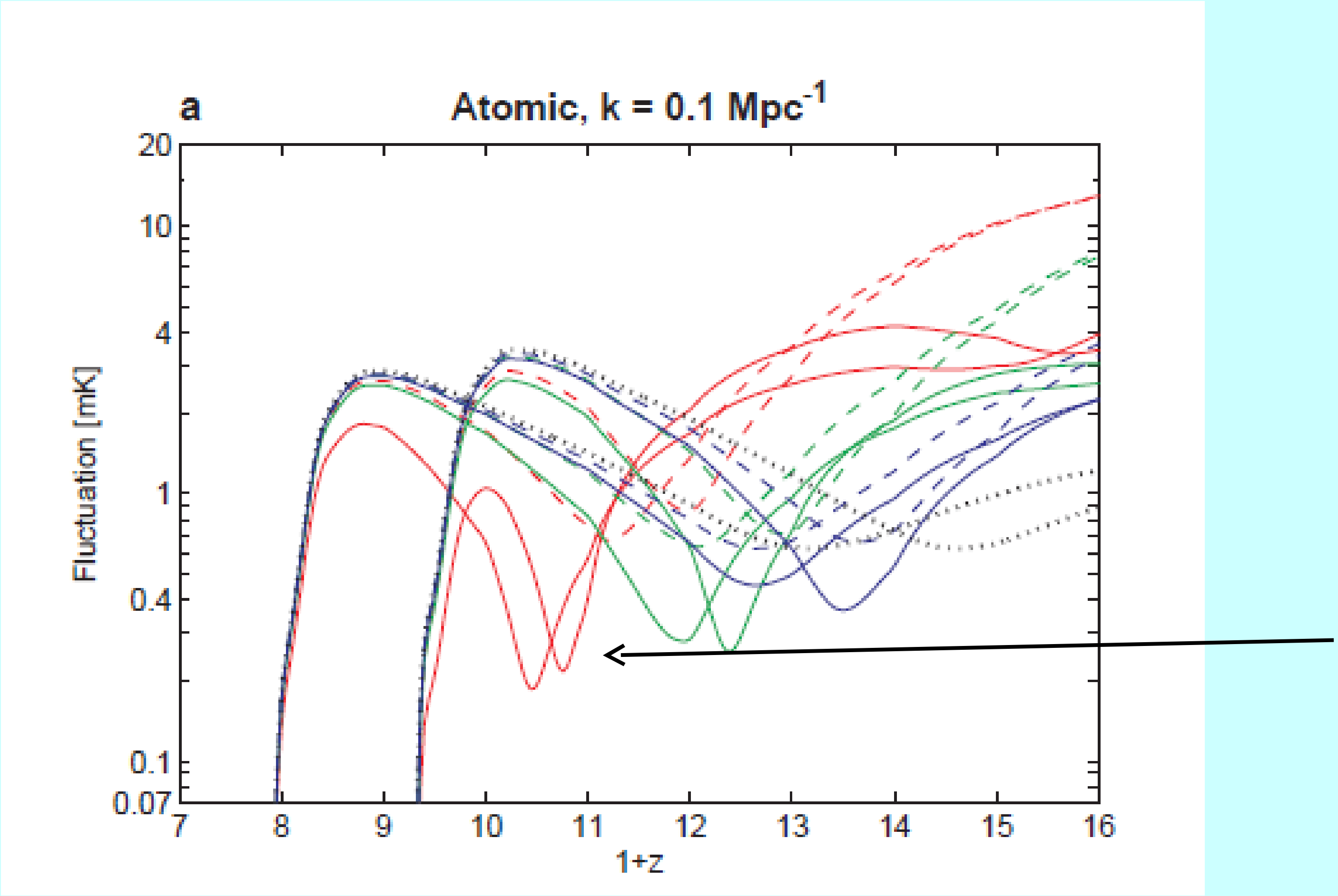
Frequency Range 50 – 350 MHz, full polarization

250,000 antennas (2 dipoles) grouped in 911 stations - 35 m

Field of view ~20 deg^2 , 650 stations within 1 km radius core

Resolution 5′, rms. $\delta T \sim 1$ mK with $\Delta\nu = 100$ KHz, 1000 hr

Signal could be smaller



Fialkov, Barkana & Visbal, 2014, Nature, 506, 197

Issues

- Model Based Signal Predictions
- Telescope and Observations
- Signal Detection
- Reionization History (from detected signal)
- First Stars and Galaxies, Cosmology,…

- Foreground Modeling and Removal

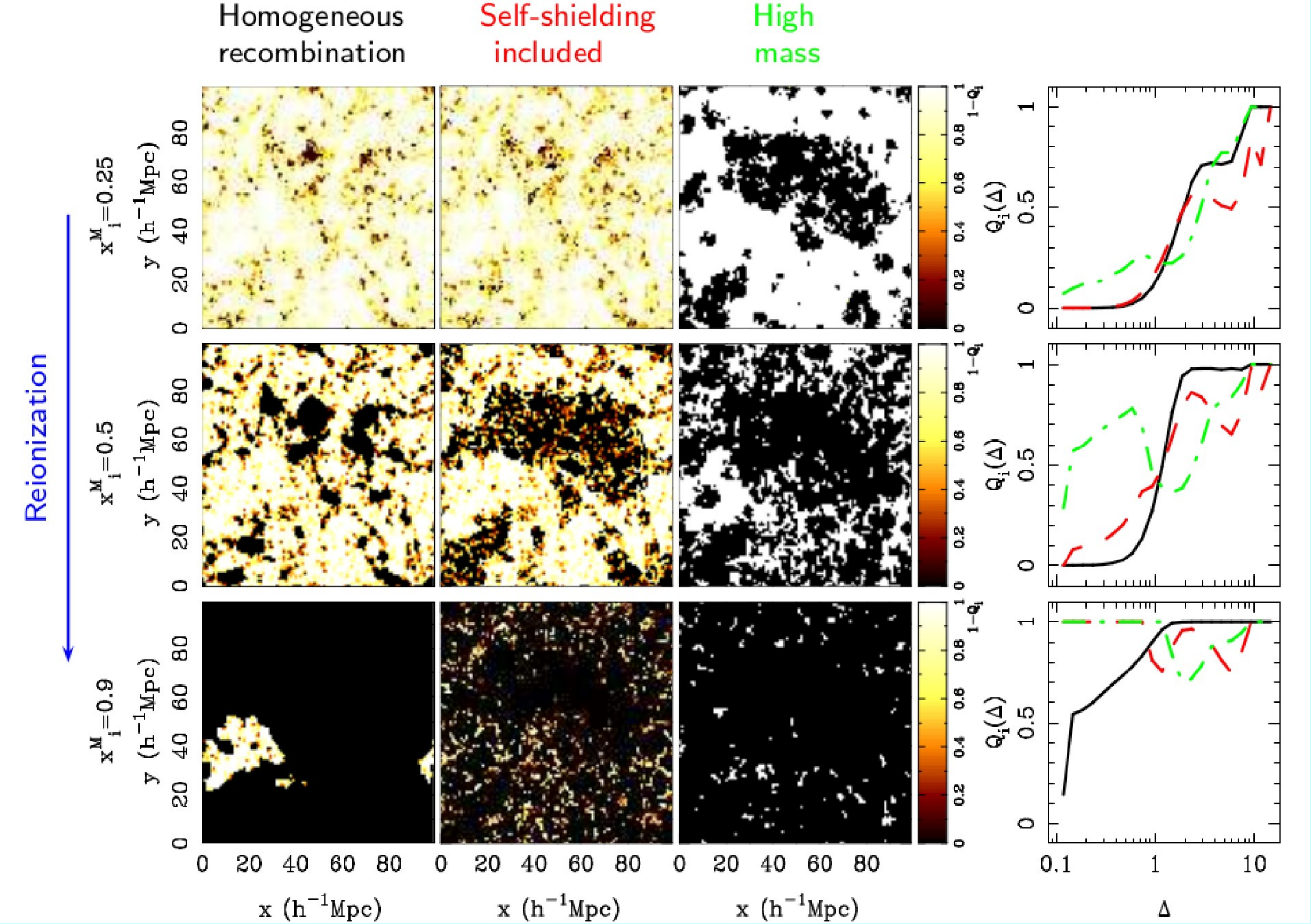
Model Based Signal Predictions

Tirthankar Roy Choudhury
Kanak K Datta

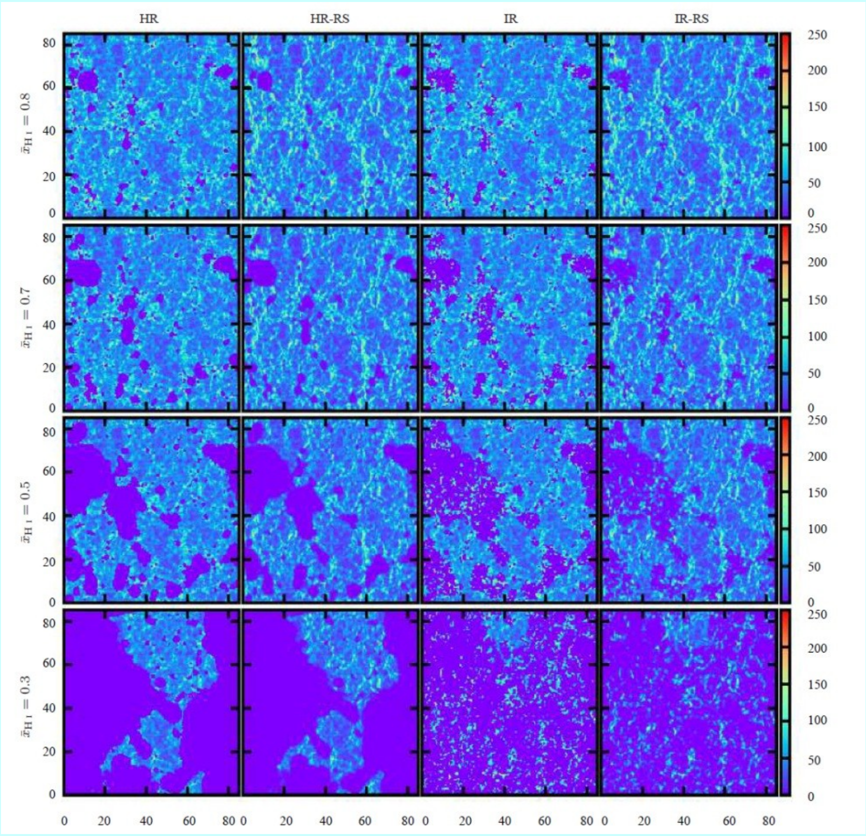
Semi-numerical models

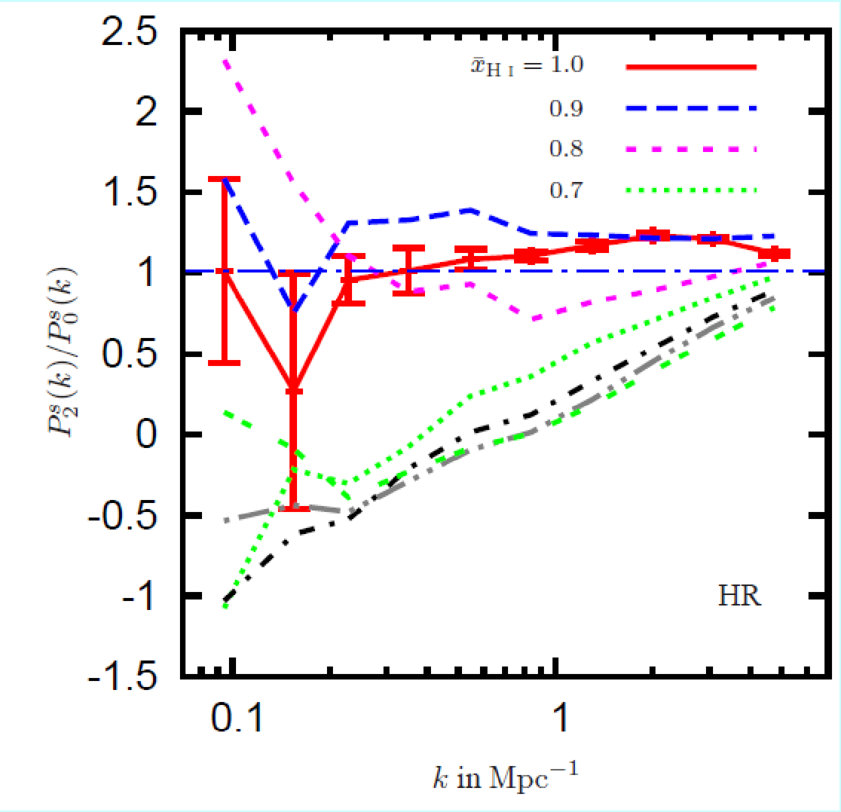
- Physical processes at high redshift highly unknown, so we need to explore the parameter space efficiently.
- Impossible with numerical simulations.
- Semi-numerical models: approximations made regarding the radiative transfer of photons, but they are very fast
- Conventional models do not account for inhomogeneous recombination in high-density regions (self-shielding).
- Model developed by **Choudhury**, Haehnelt & Regan (2009) quantifies the effect of self-shielding.

HI maps with self-shielding



Effect of Peculiar Velocities

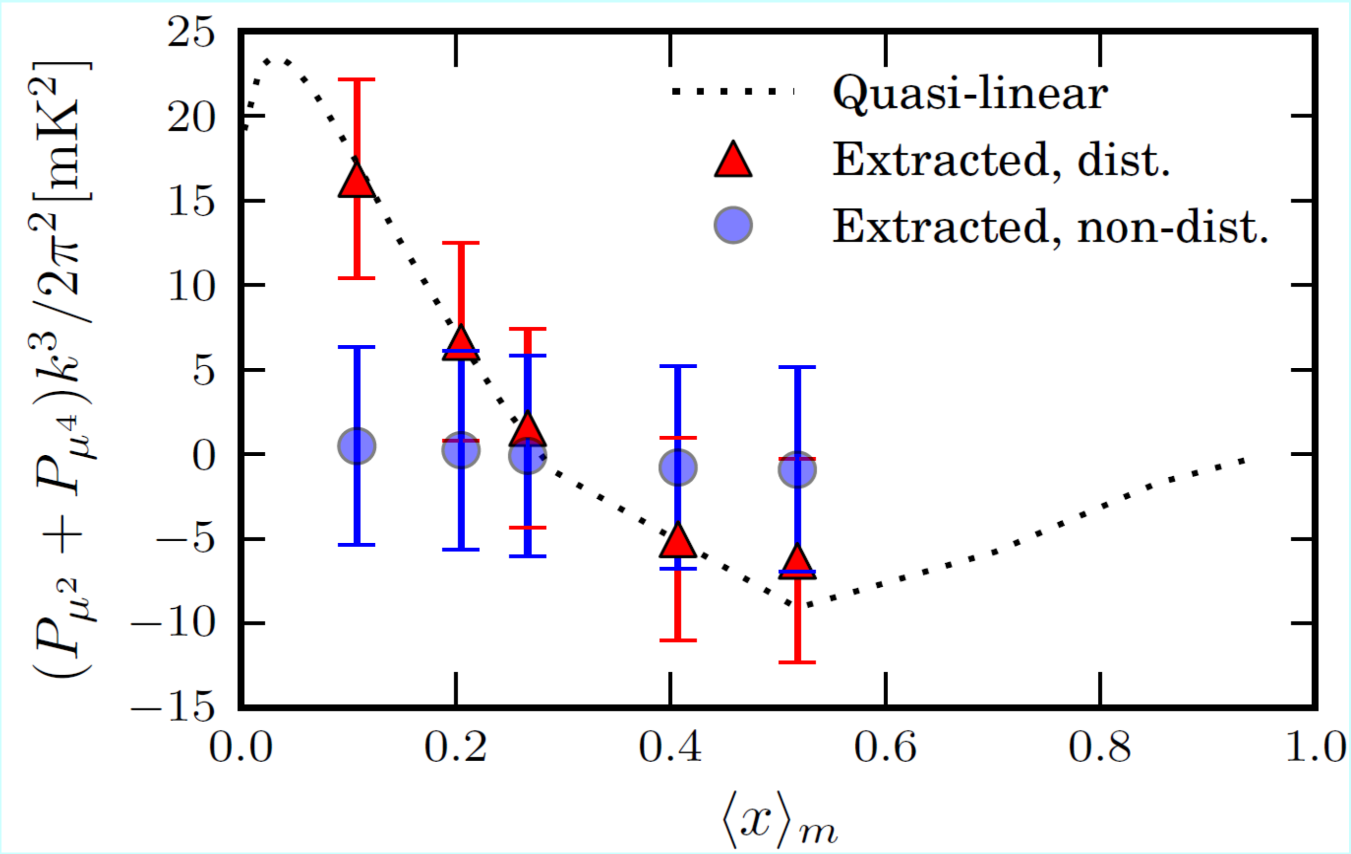




Quadrupole moment becomes negative as reionization proceeds

Majumdar, Bharadwaj and Choudhury, 2013,MNRAS, 434, 1978

Detectability of anisotropies using LOFAR

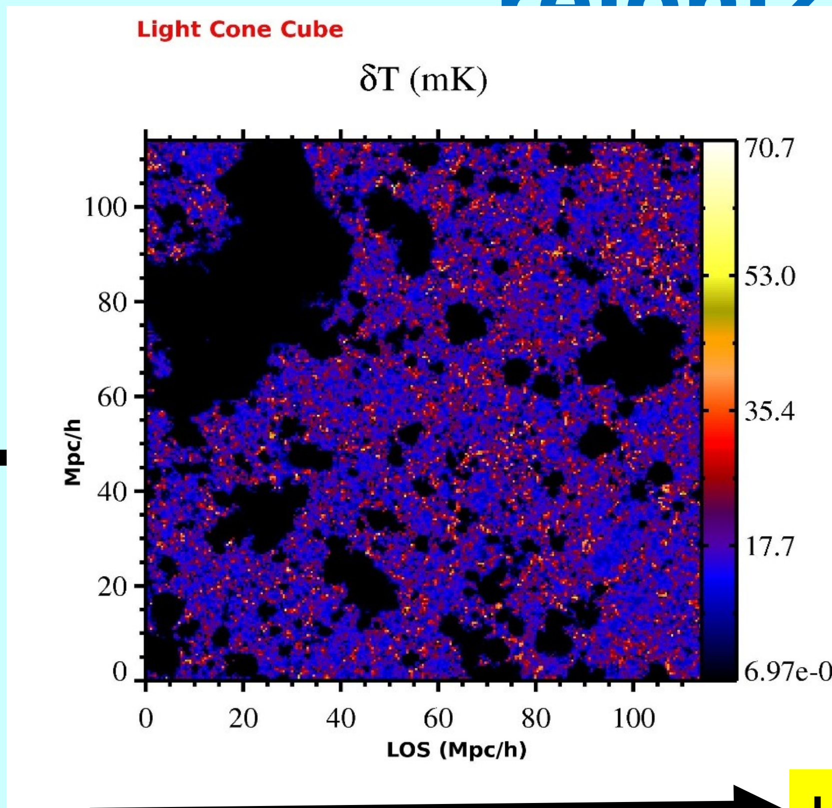


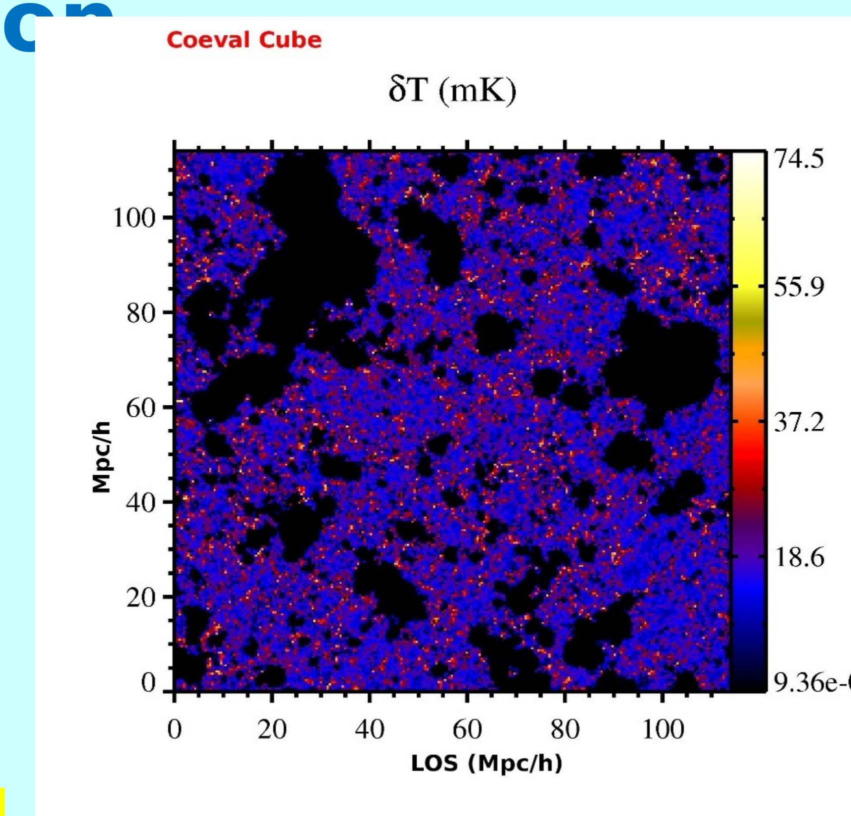
- The range of scales around k~0.007 – 0.02 /Mpc seems most promising for detection with LOFAR

- A 2000 hrs observation with LOFAR should detect anisotropies in the signal.

Jensen, Datta et al 2013, MNRAS, 435,460

Light cone effect on the HI signal during reionization





Observ
er

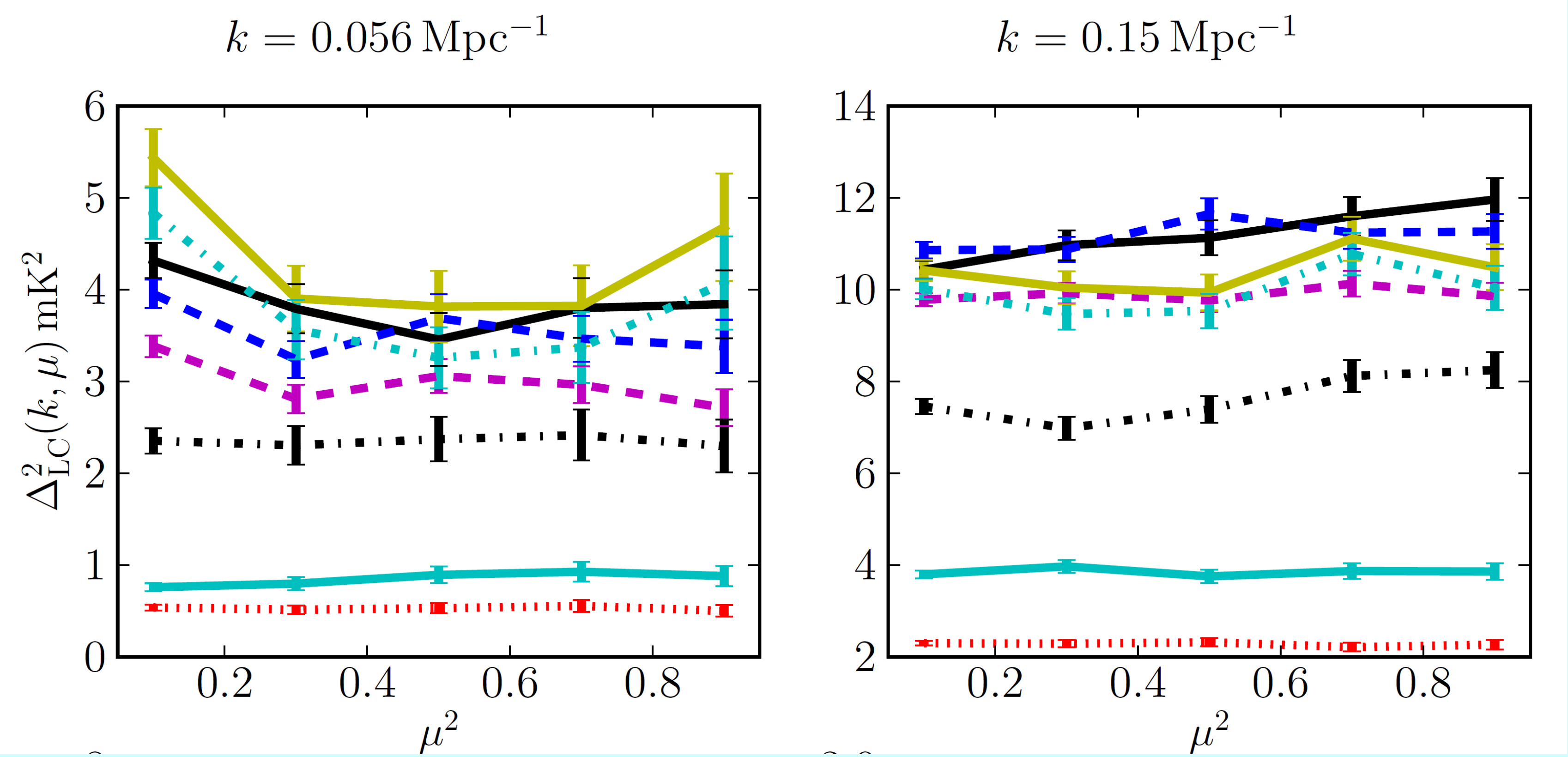
LOS

nized bubble sizes and HI fluctuations evolve along the LOS.

power spectrum of ‘light cone’ volume differs from ‘snapshot’ vol

Datta et al 2012 MNRAS, 424, 1877

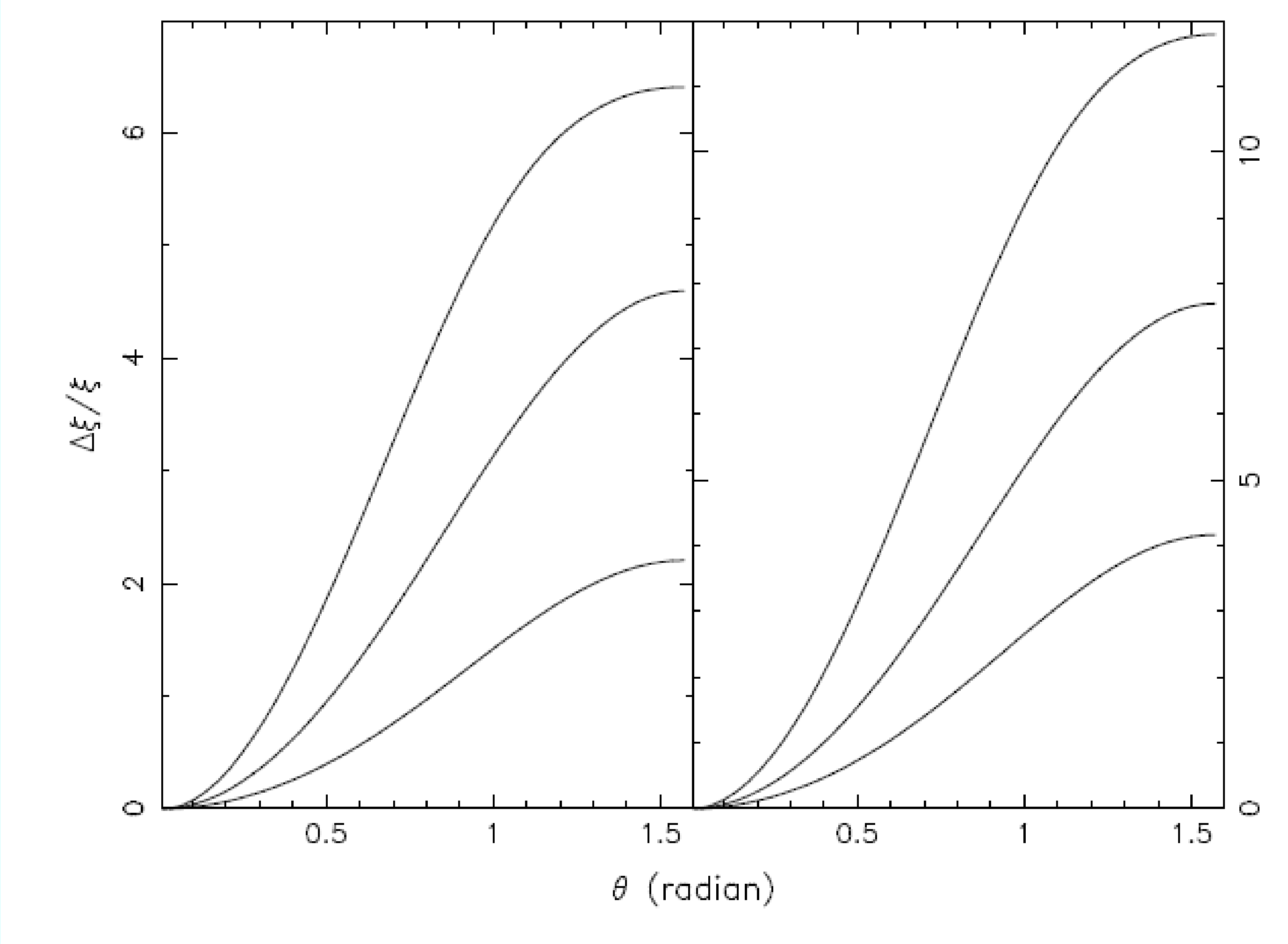
Light cone anisotropy in the 3D HI power spectrum



- Surprisingly, we do not observe any significant anisotropy in the HI power spectrum.
- Systematic change in the bubble size as a function of the LOS while individual bubbles remain spherical is not enough to make the power spectrum anisotropic.

Datta et al 2014, arxiv: 1402:0508

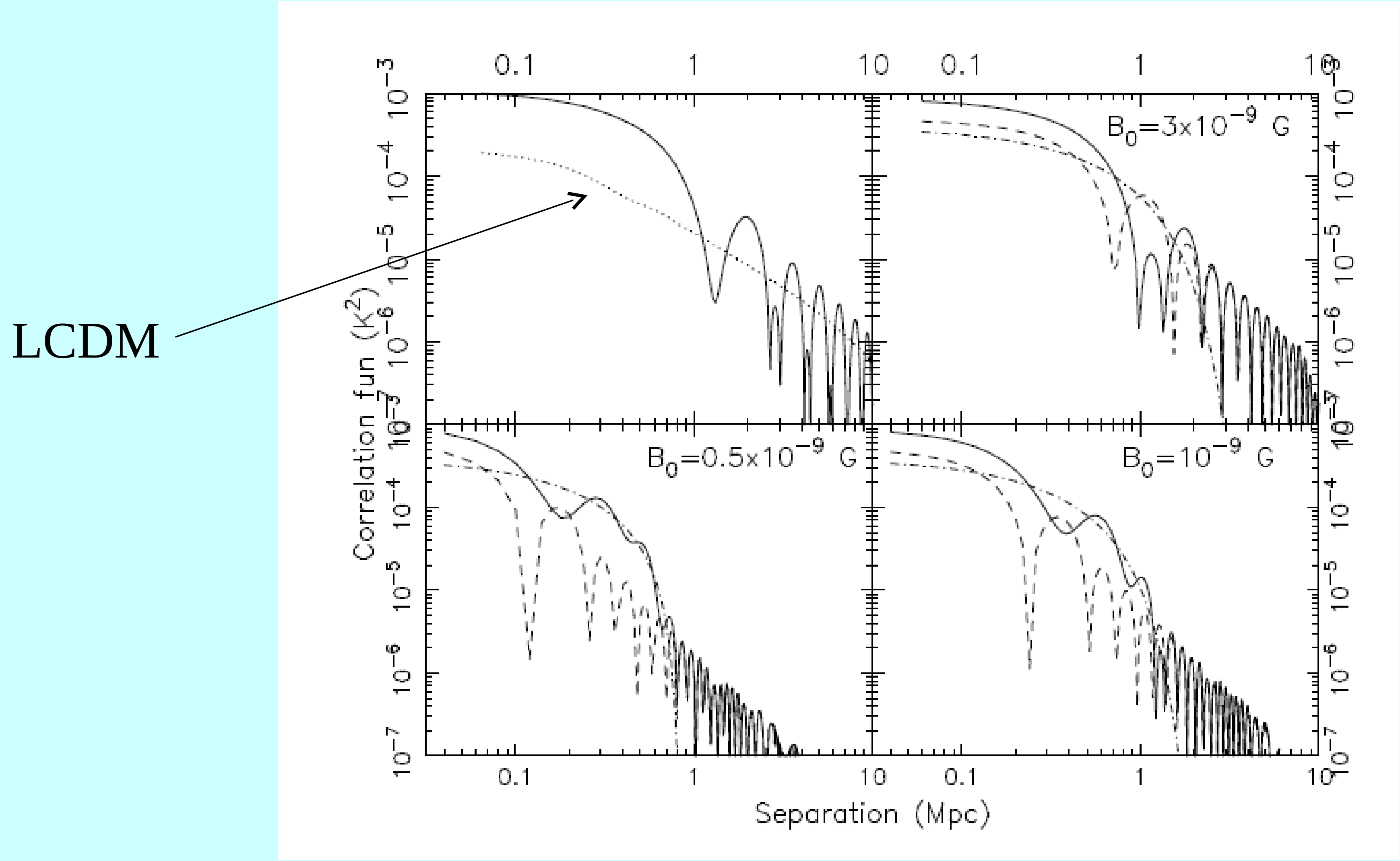
Light-cone Anisotropies in Quasar Bubbles



z=7

Sethi, S.K. & Haiman, Z., 2008, Apj, 673,1

Primordial Magnetic Fields

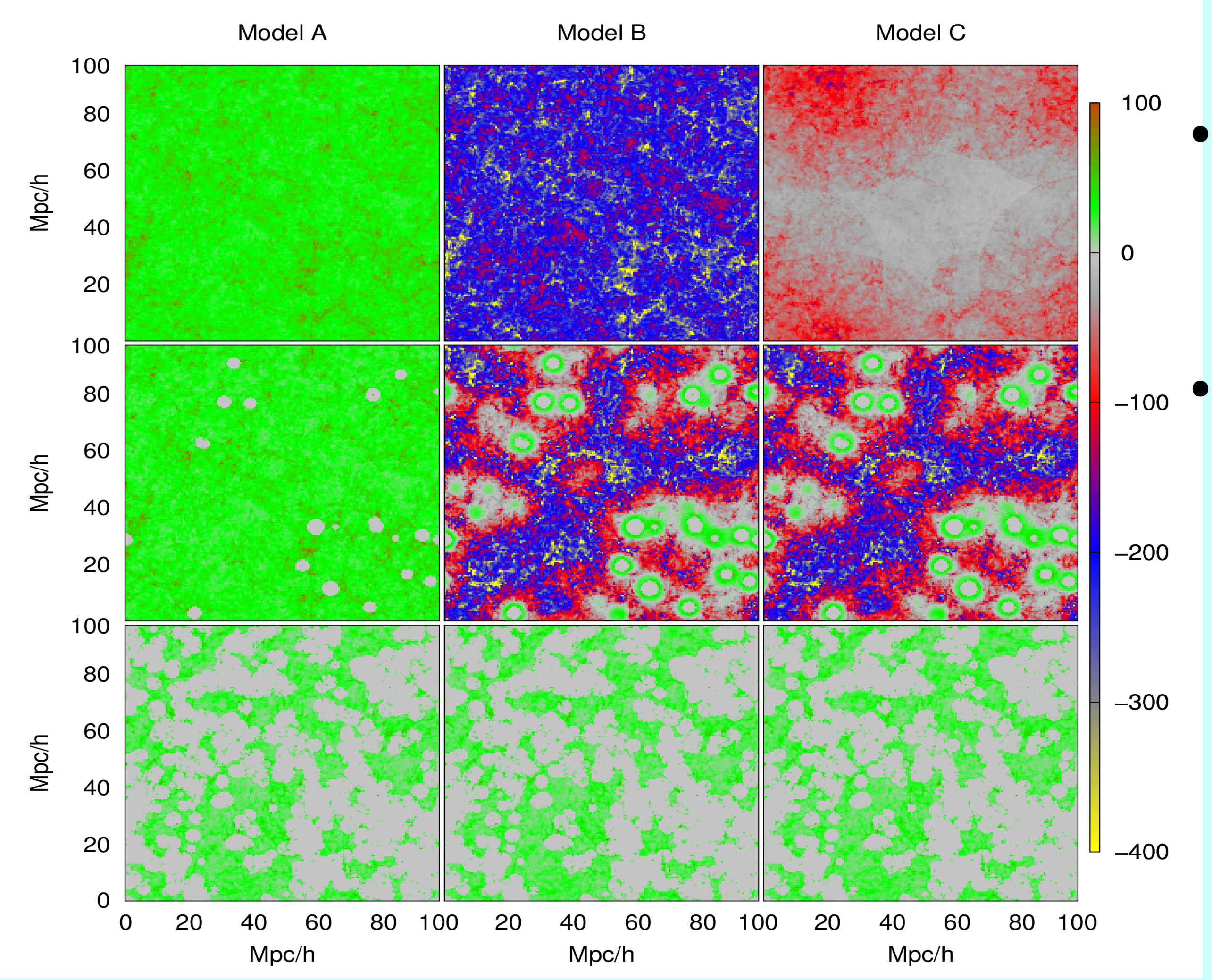


Sethi,S.K. & Subramanian,K., 2009,JCAP,11,021

Effect of X-rays on HI signal

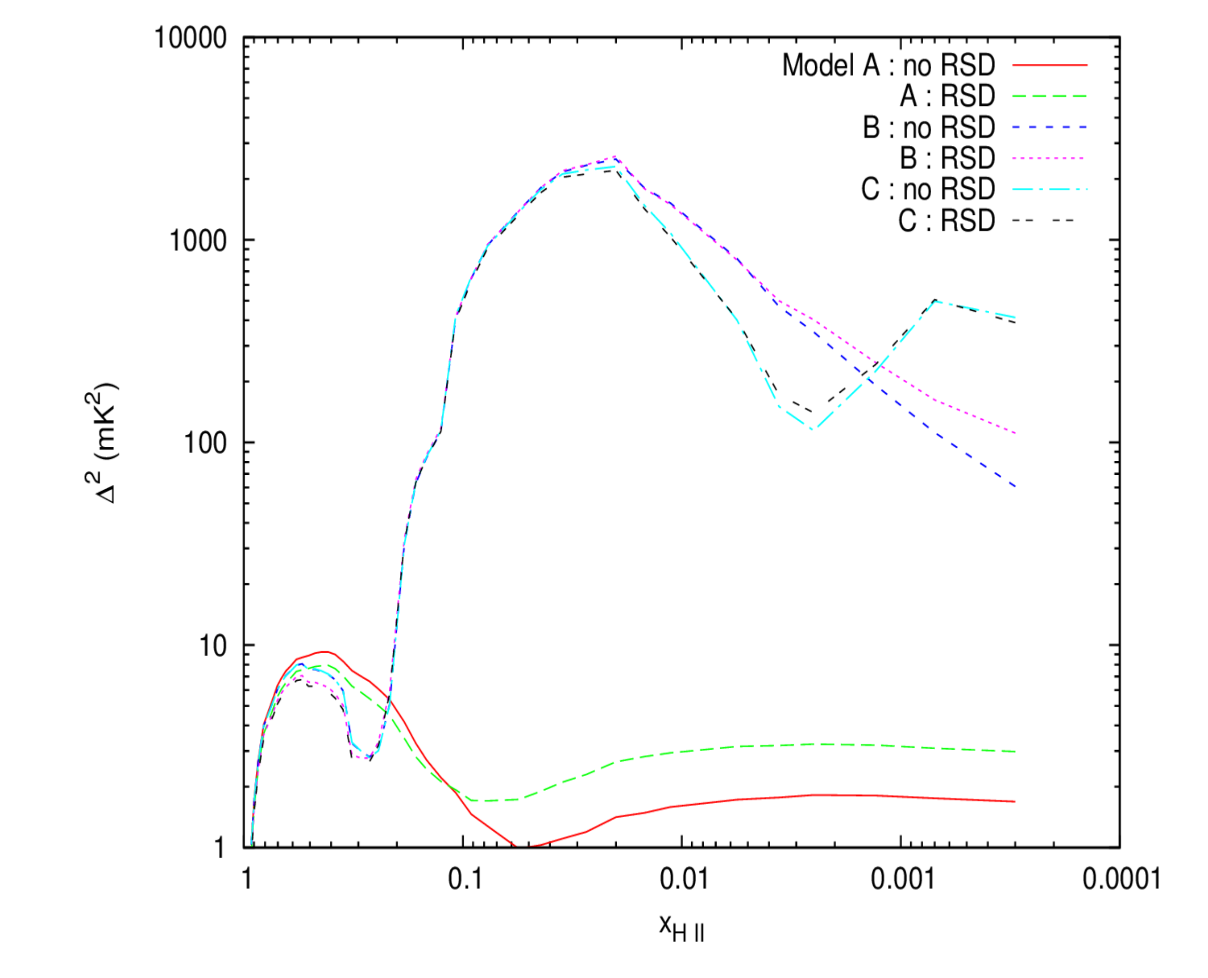
- X-ray heating is important while modelling the HI signal at early stages of reionization
- Also important to understand the effect of Lya coupling so that Ts is coupled to Tk.
- Developed a detailed numerical model to study these effects (Ghara, Choudhury & Datta in prep)

Effect of X-rays on HI signal



- Brightness temperature maps at z = 20, 16, 8.
- Treatment of heating and Lya coupling differs between three models.

Effect of X-rays on HI signal



- Power spectrum of brightness temperature at a scale k = 0.1/Mpc
- Effect of redshift-space distortion shown. Effect is less when heating and Lya coupling are treated self-consistently (Models B and C)

Detection Techniques

Uday Shankar N., RRI

Raman Research Institute

A STUDY OF FUNDAMENTAL LIMITATIONS TO STATISTICAL DETECTION OF REDSHIFTED HI FROM THE EPOCH OF REIONIZATION

Nithyanandan Thyagarajan
Udaya Shankar. N
Ravi Subrahmanyan

MWA collaboration

arXiv:1308.0565

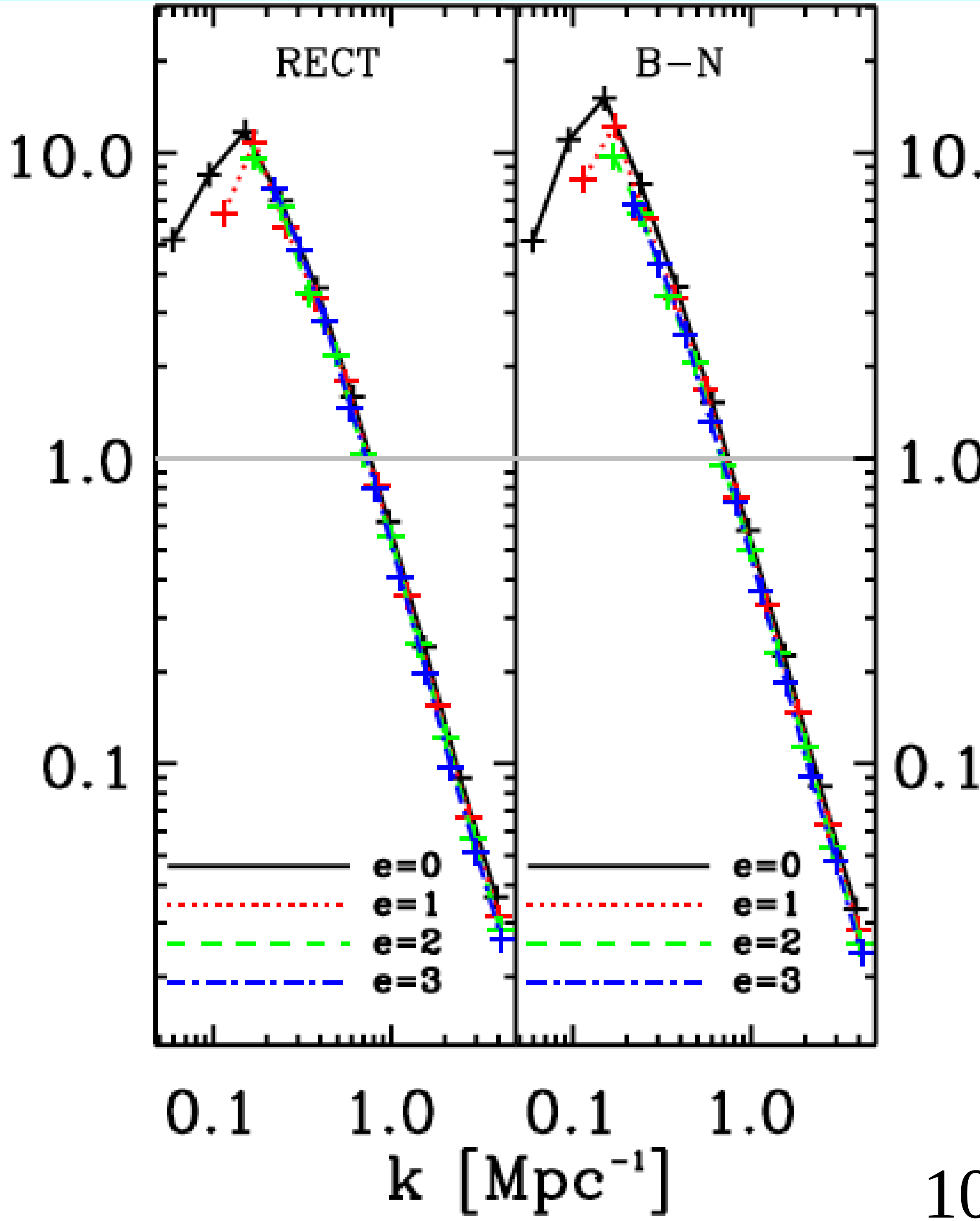
MWSKY Conference

Objectives of the presentation

1. Unified framework to estimate three fundamental sources of Uncertainty in the estimation of the EoR power spectra:
   – Foreground Contamination
   – Thermal Noise
   – Sample Variance
2. Methods to reduce foreground contamination
   – Shaping the Bandpass window
   – Refining EoR window
3. Sensitivity of Radio Interferometer (MWA)
   - signal estimated → instrumental Transfer Function

Assumptions

- Only extragalactic point-like sources.
- Extended emission from Galaxy and beyond not considered.
- Ignored non-coplanar baseline effects.
- Perfect subtraction of foregrounds and sidelobes down to a threshold.
- Flux density of residuals does not vary across frequency band.



With observing mode 1 using 128-tile MWA, the S/ N > 1 For **k** < 0. 8 Mpc^{-1}.

There is no improvement in overall sensitivity as e is varied.

1000 hrs of observation

Telescope and Observations

Yashwant Gupta

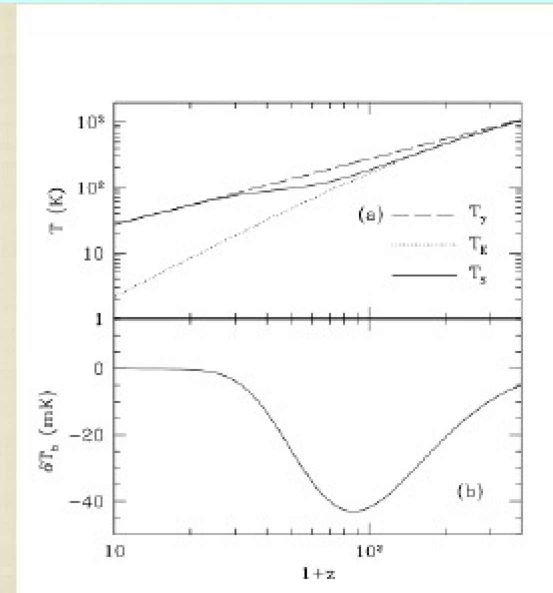
Global EOR Signal

Team "SARAS"

- Nipanjana Patra.
- Ravi Subrahmanyan.
- A. Raghunathan.
- N. Udaya Shankar.

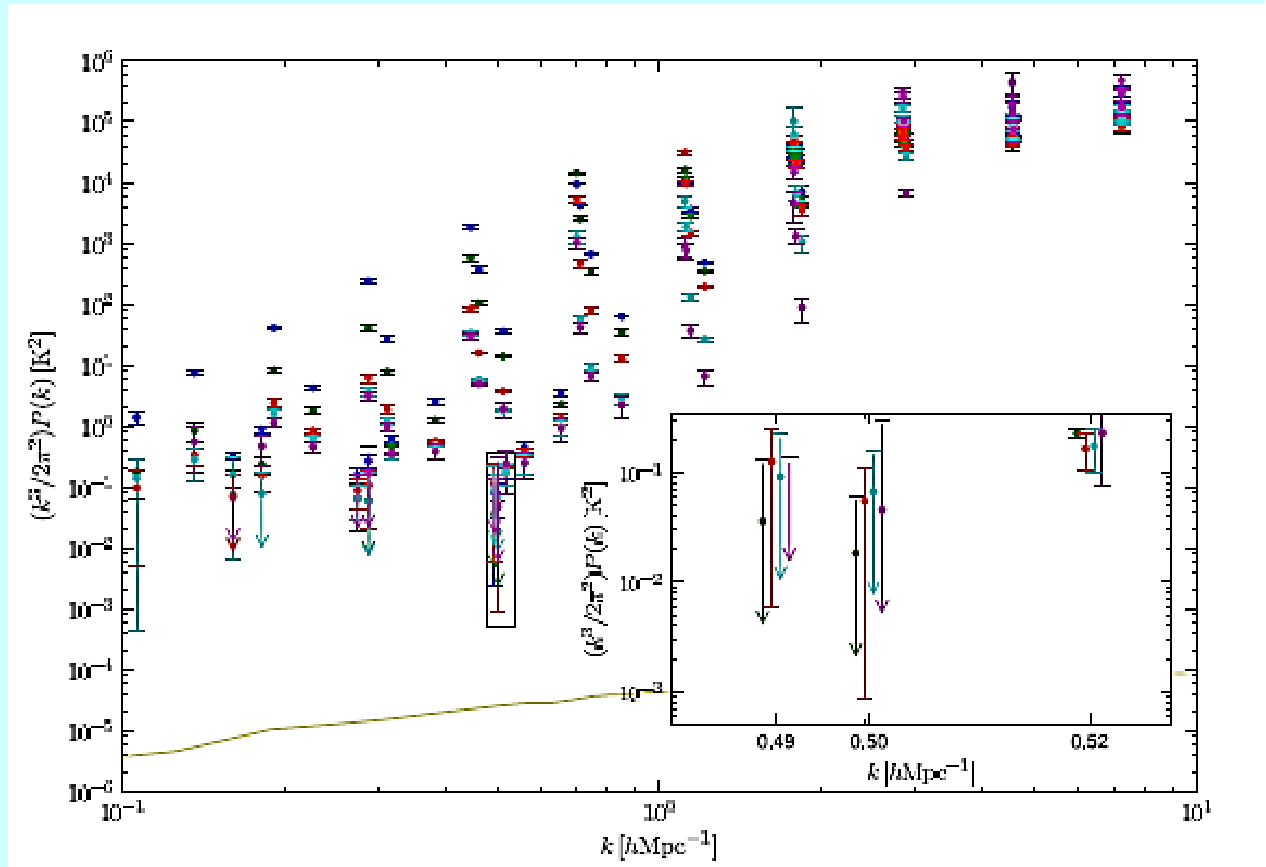
System Description:

Antenna : A frequency independent (fat) Shaped Dipole antenna Raghunathan et al. 2012,(In preparation)



EoR Experiment at the GMRT

- EoR project at the GMRT led by Ue-Li Pen (CITA)
- Uses a field with a pulsar at the phase centre as the calibrator !
- Works off a special mode of the GSB with real-time pulsar gating
- First published results establish interesting new limits on EoR signal strength



Paciga et al, 2011 & 2013

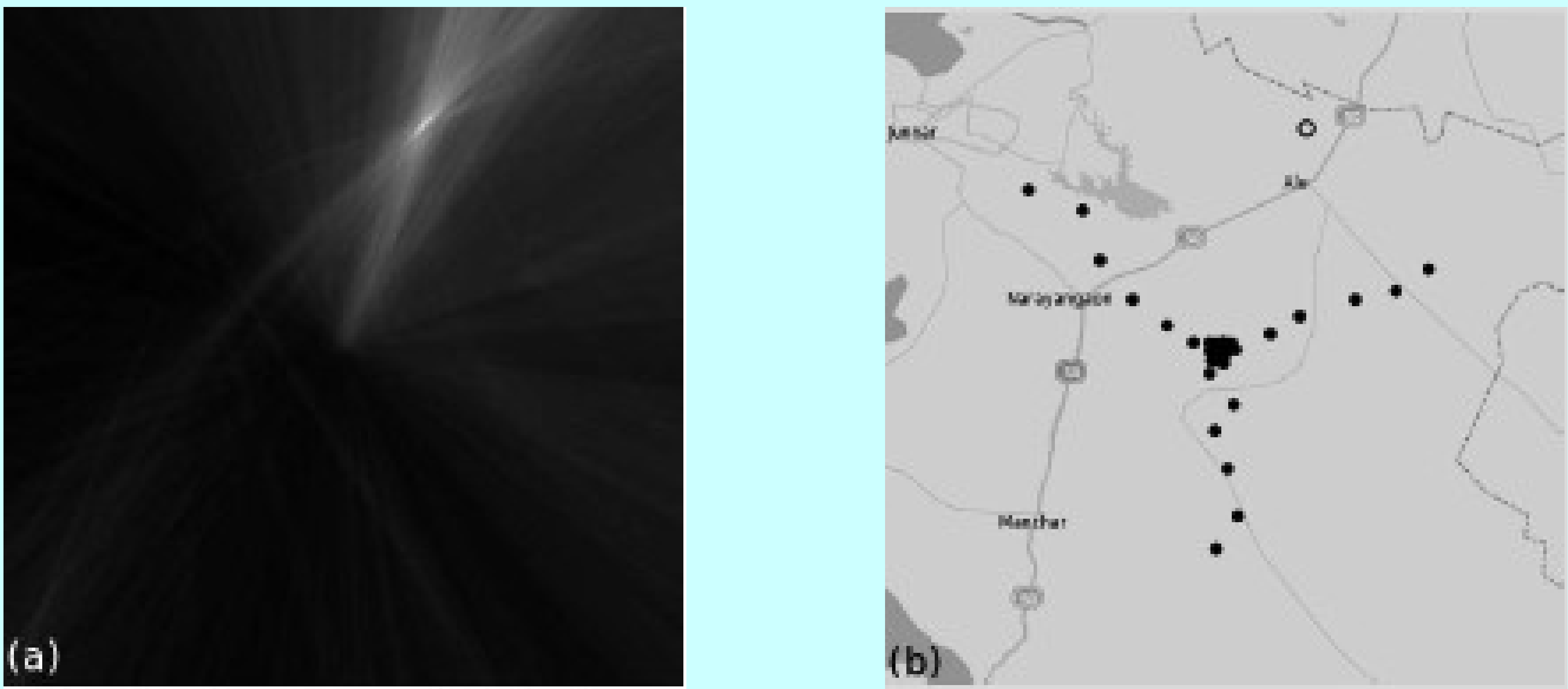
(Gupta, Y., Ray, J).

2-sigma upper limit at (248 mK)^2 for k=0.50 h/Mpc. While this revised limit is larger than previously reported, we believe it to be more robust and still represents the best current constraints on reionization at z=8.6.

Paciga et al, 2013

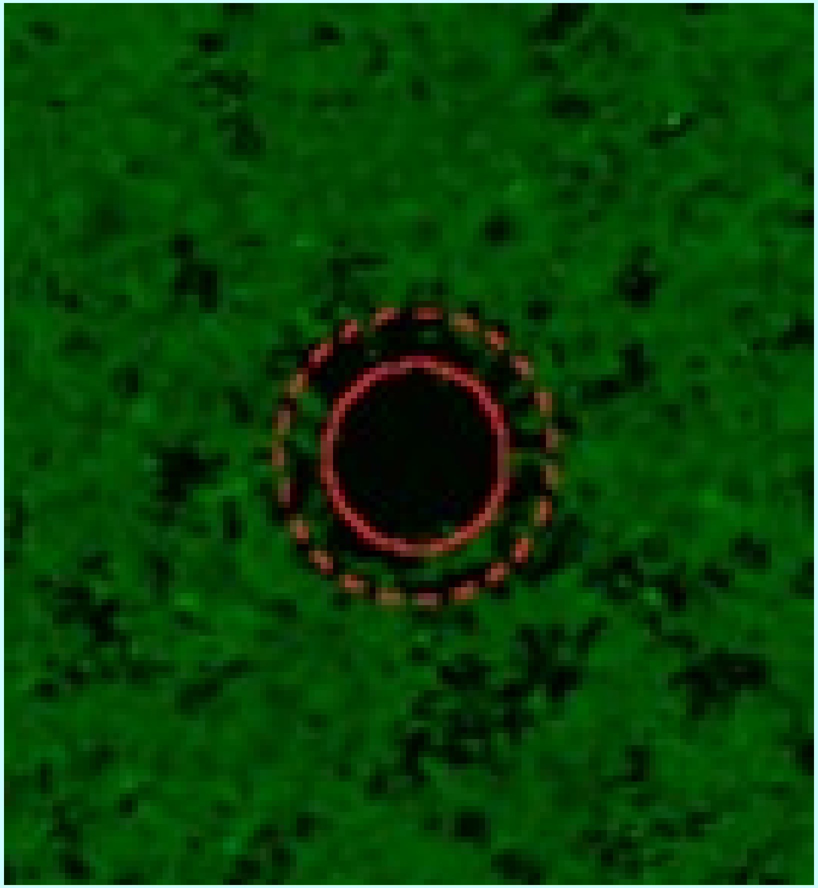
New capabilities : finding RFI sources

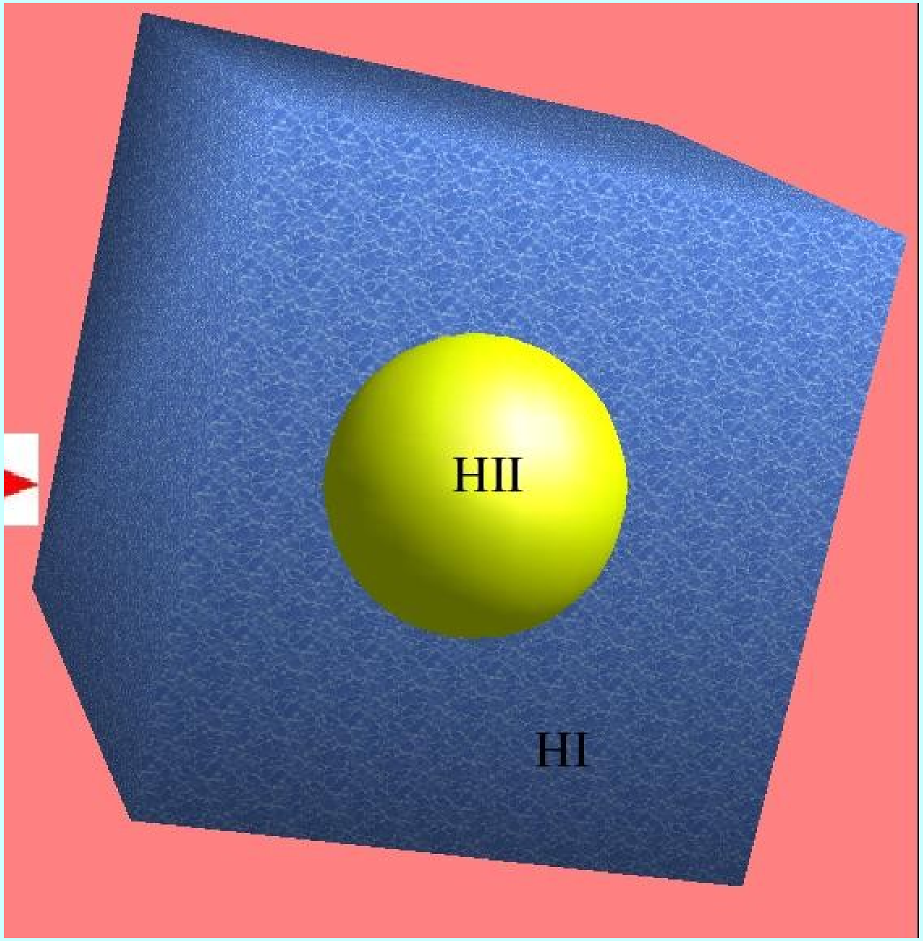
•Imaging RFI sources on the ground, using SVD to separate sources on the ground and the sky -- work done by the GMRT EoR group (Ue-Li Pen et al)



Paciga et al, 2011

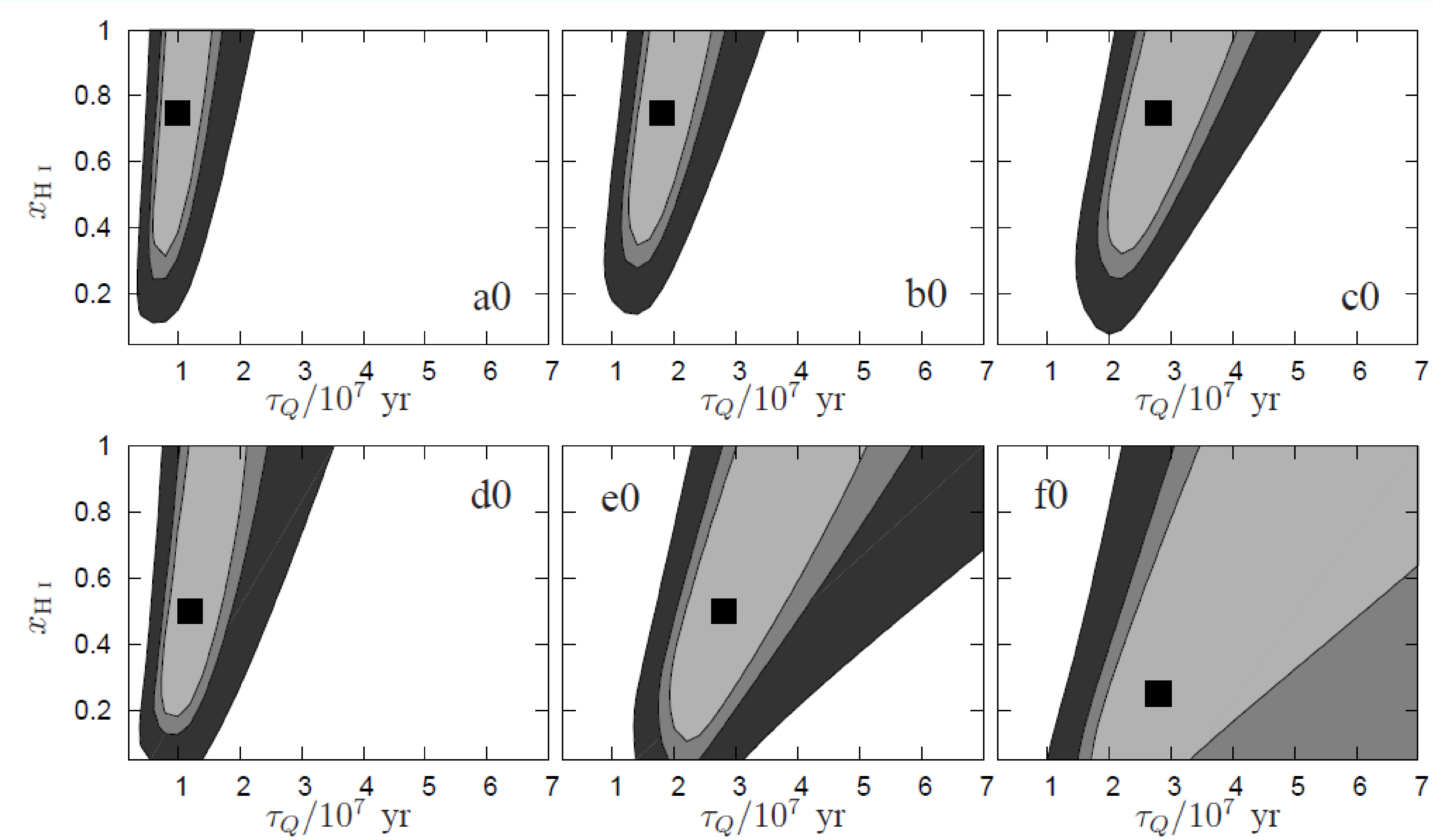
Matched Filter Ionized Bubble Detection





Datta, Bharadwaj, & Choudhury,, 2007

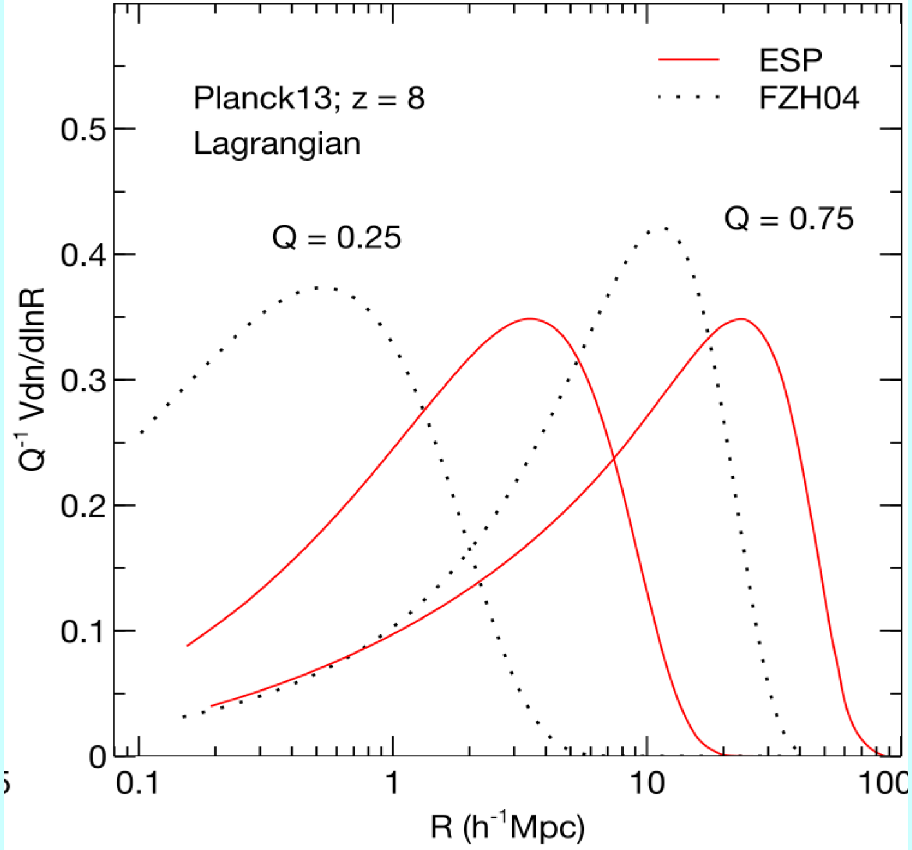
Constraining IGM and Quasar



Majumdar, Bharadwaj and Choudhury, 2013

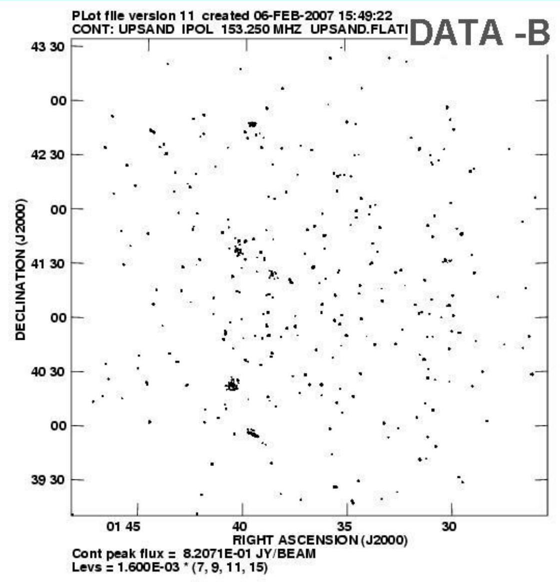
Analytic calculations for bubble size distribution

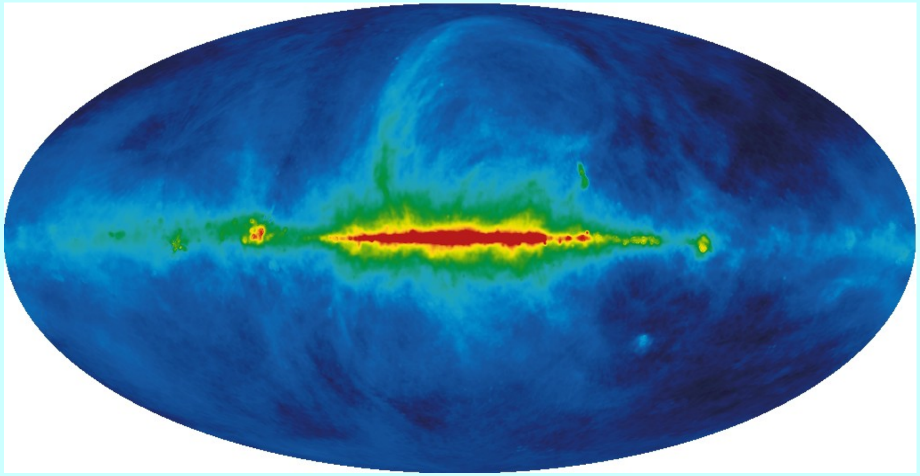
The size distribution of ionized regions during the epoch of reionization can be modelled analytically using the excursion set formalism (Paranjape & Choudhury 2014). Possible to constrain source properties using such models and data from SKA.



Foregrounds

Foregrounds



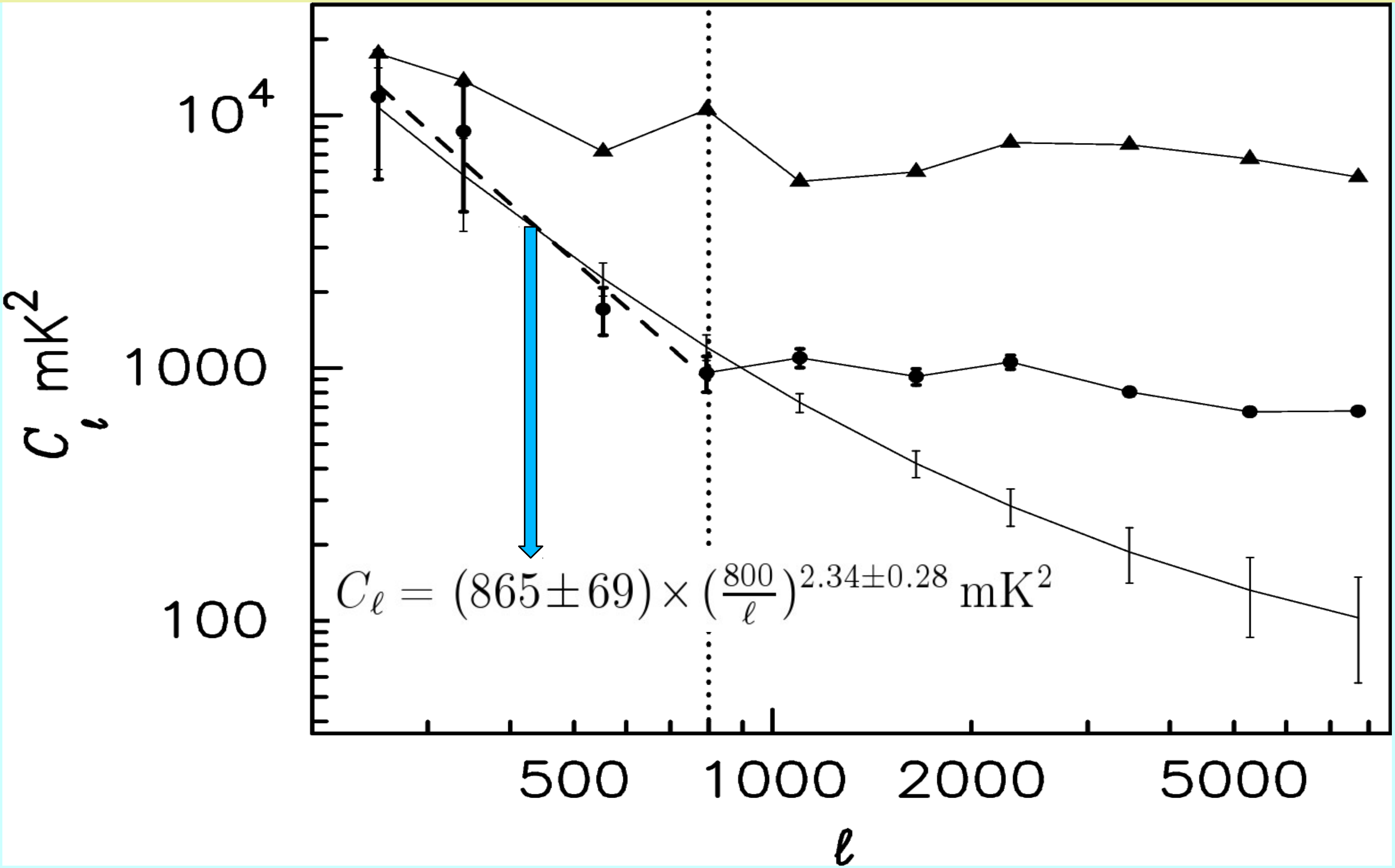


Point Sources

Diffuse

Removal is Biggest Challenge

Angular Power spectrum of Galactic Synchrotron Radiation :



- The power spectrum of the Diffuse emission was fitted by a power-law down to ℓ = 800 (θ ≈ 10'):

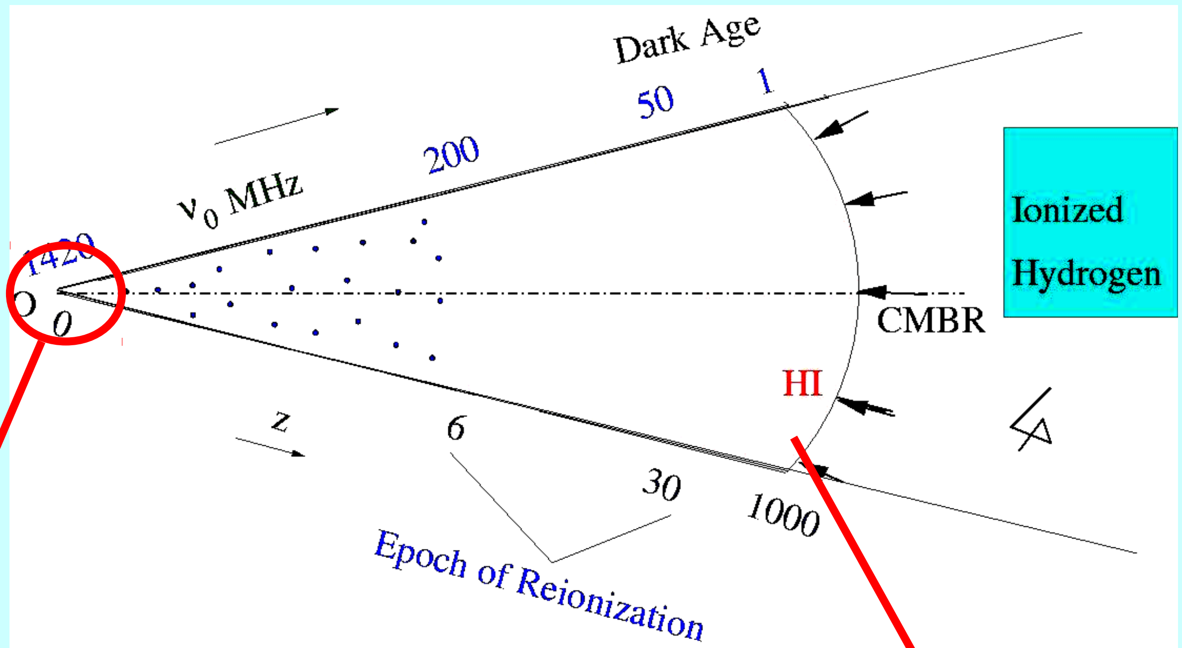
Ghosh, Prasad, Bharadwaj, Ali & Chengalur 2012

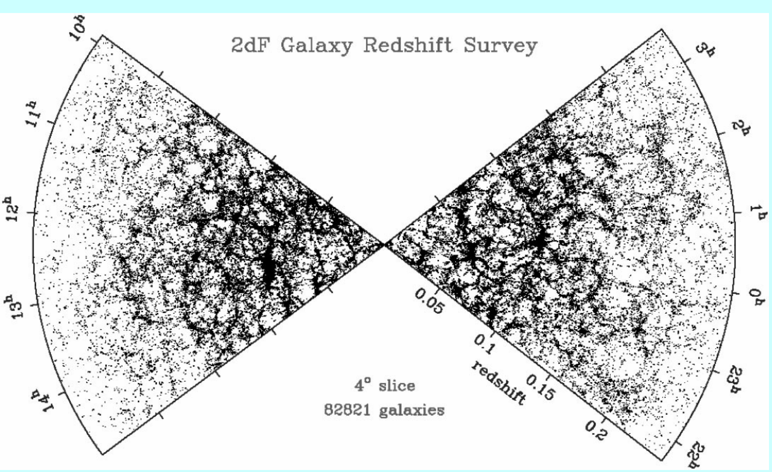

Thank You

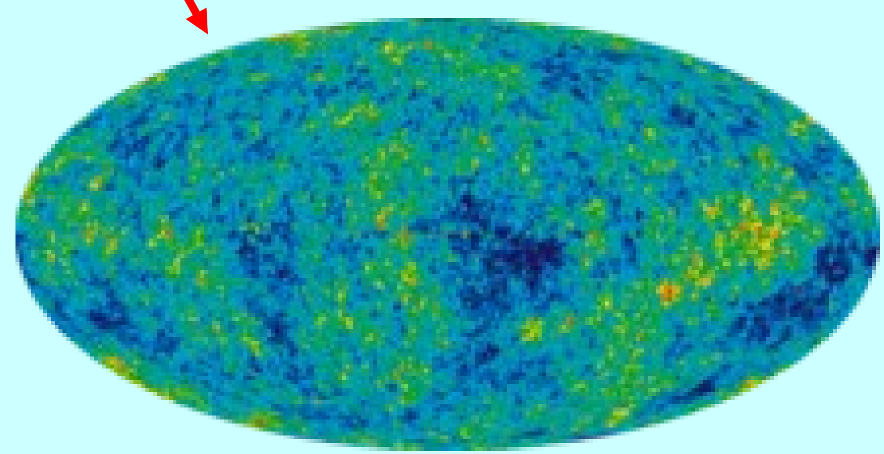
Concluding Remarks

- Probe Dark Ages, First Luminous Objects, reionization, post-reionization
- Potential Probe of Dark Energy
- Challenge Foregrounds, RFI

Evolution of the Universe

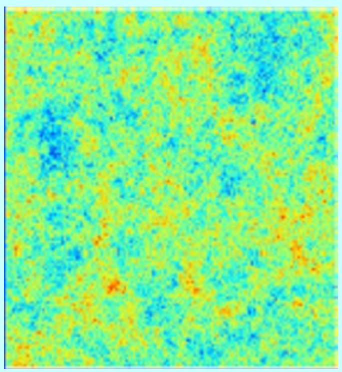


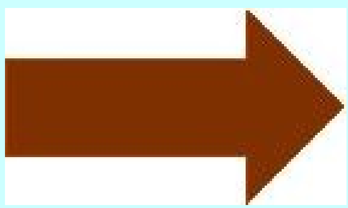




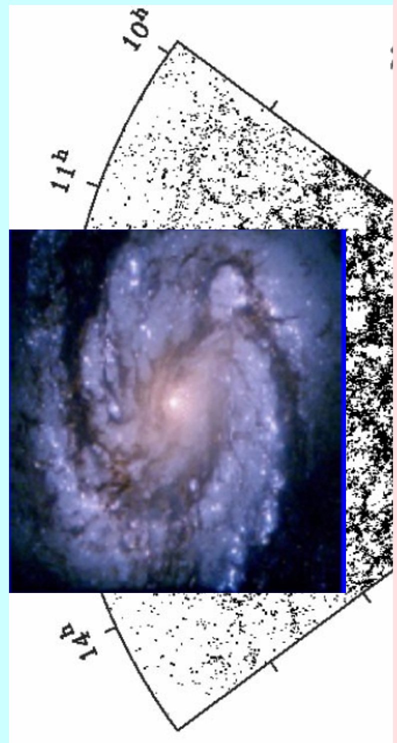
Structure Formation

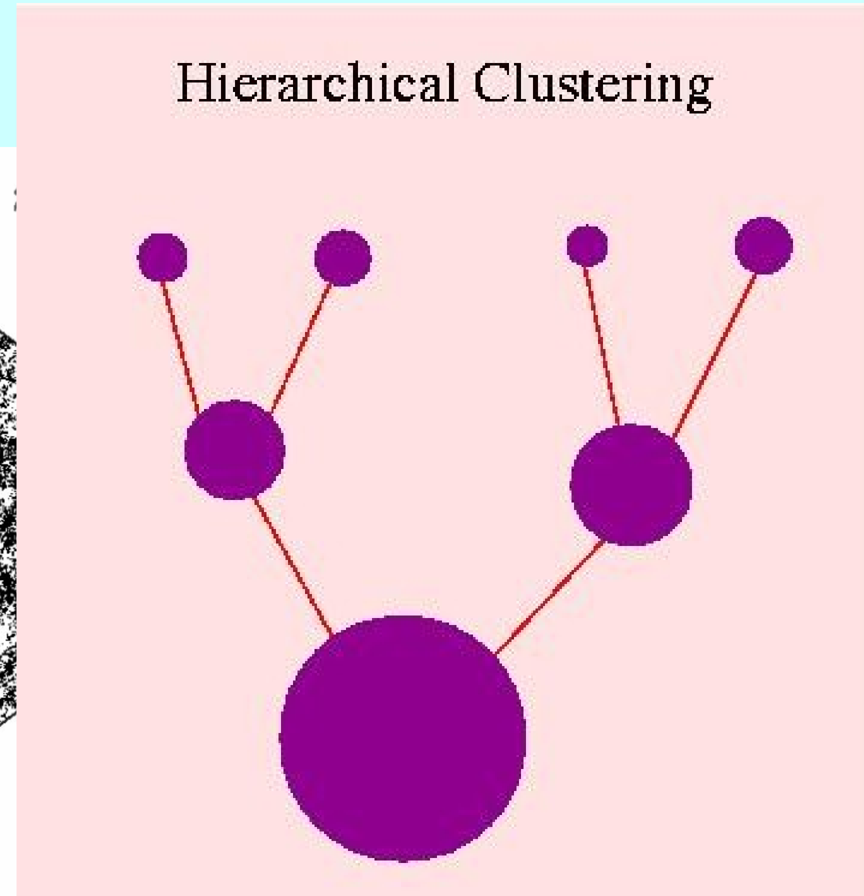
Z=1000





Z=0





Gravitational Instability

Dark matter dominates the dynamics

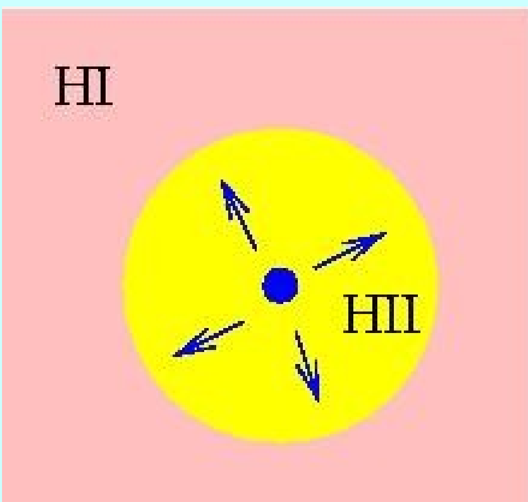
Rionization

Dark Matter Halos
Baryons Condense Within Halos

Galaxies

Photoionization

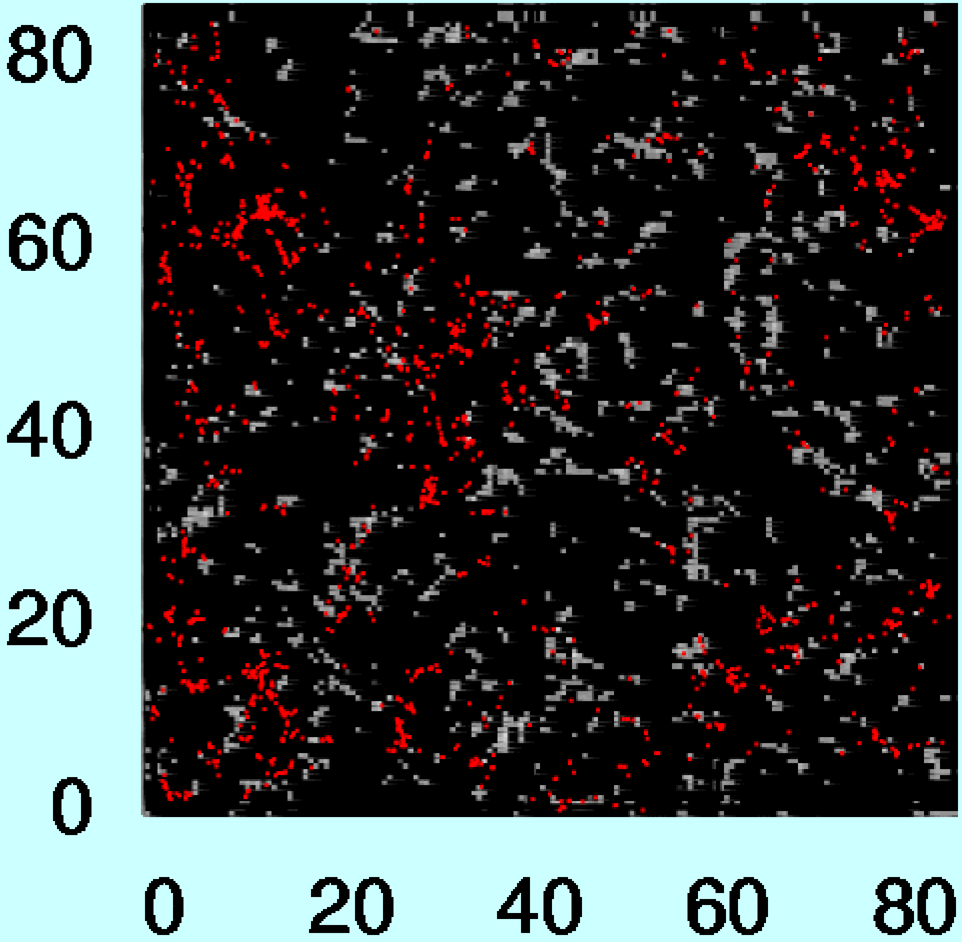
First Luminous Objects z~30



Massive Stars
Quasars - Accreting Black Holes
Emit Photons with E > 13.6 eV
Bubbles of Ionized Gas - HII Regions
Bubbles Grow - Overlap
Reionization Complete by z ~ 6

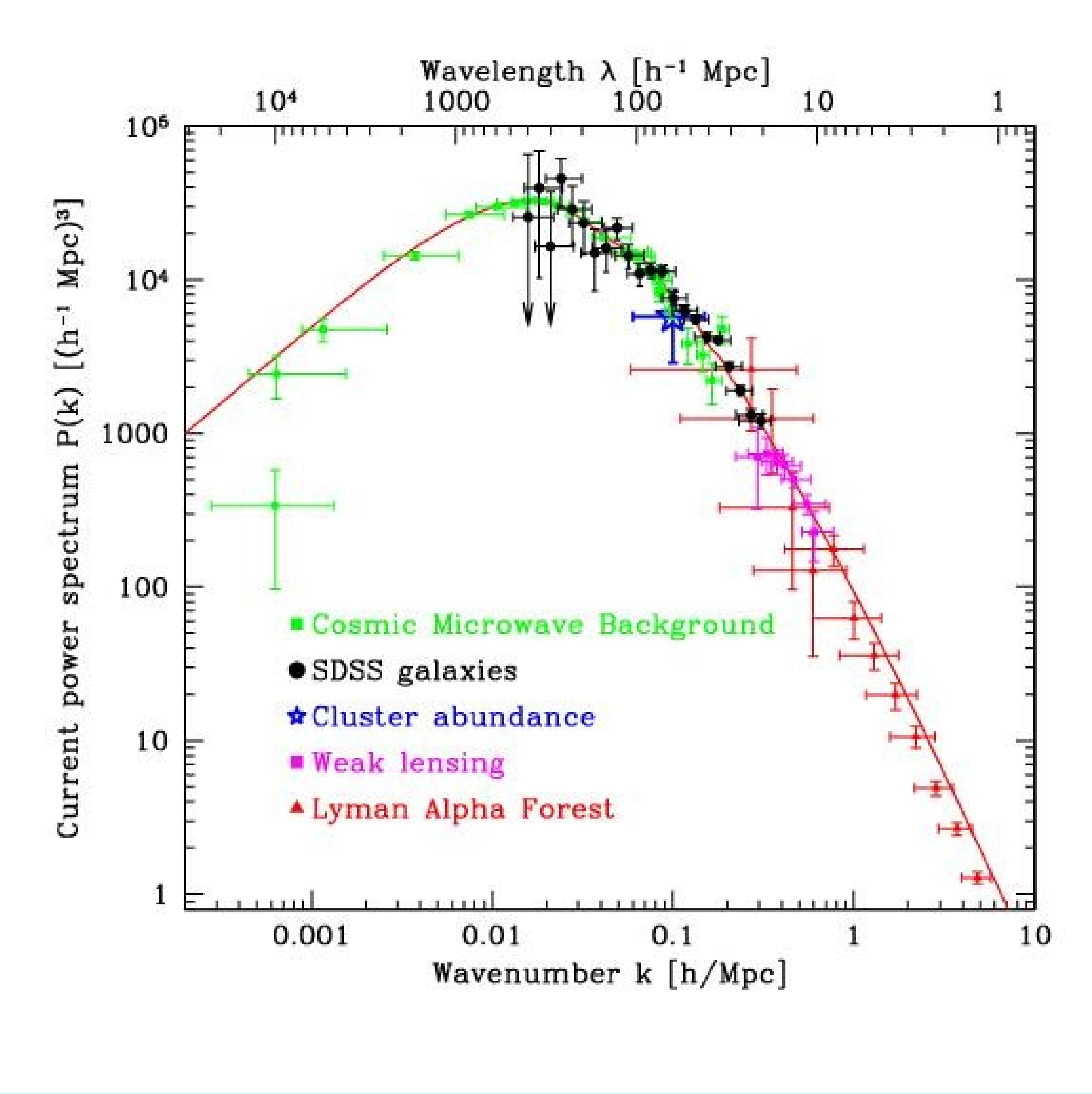
$15 > z > 6$

Simulation



Majumdar, Bharadwaj& Roy Choudhury 2012,MNRAS, Submitted

The Dark Matter Power Spectrum



Mini-Summary

- Redshifted 21-cm radiation fluctuates with frequency and angle on sky
- Observations can be used to study:
  - Universe at z ~ 50 (Dark Age) – only possible probe
  - Formation of the first luinous objects
  - Reionization
  - Structure formation after reionization

J. Astrophys. Astr. (2001) **22**, 21–34

Our Efforts Started With

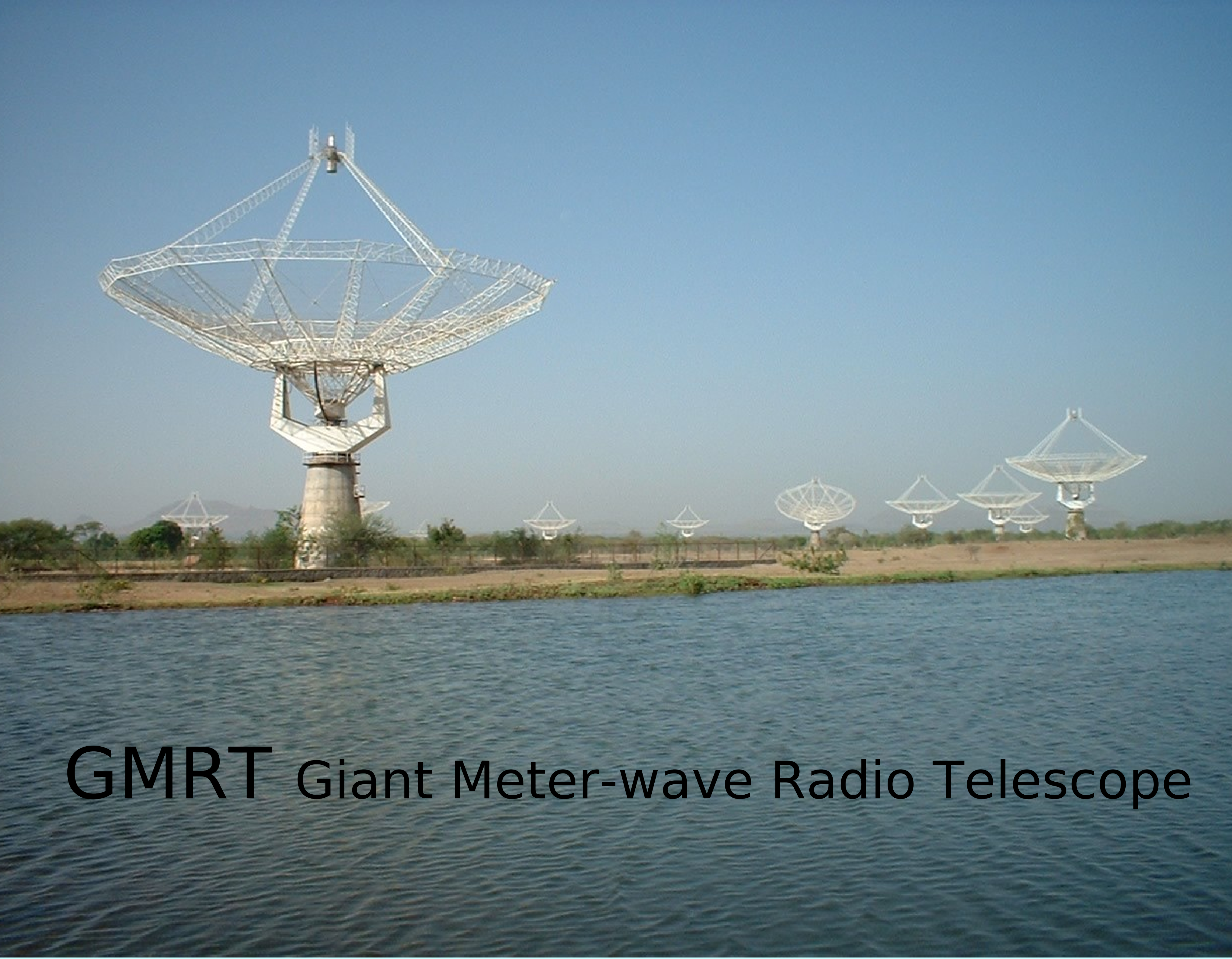
Using HI to Probe Large Scale Structures at z ~ 3

Somnath Bharadwaj [1*], Biman B. Nath [2†] & Shiv K. Sethi [3‡]
[1] *Department of Physics and Meteorology & Center for Theoretical Studies, I.I.T. Kharagpur, 721 302, India*
[2] *Raman Research Institute, Bangalore 560 080, India*
[3] *Harish-Chandra Research Institute, Chhatnag Road, Jhusi, Allahabad 211 019, India*

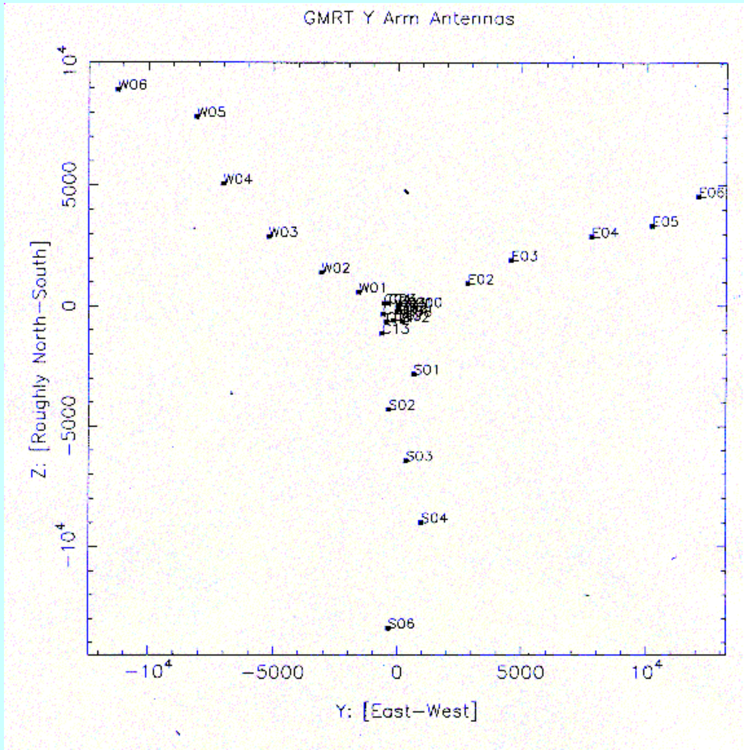
Received 2000 March 14; accepted 2000 October 21.

Abstract. The redshifted 1420 MHz emission from the HI in unresolved damped Lyman-α clouds at high z will appear as a background radiation in low frequency radio observations. This holds the possibility of a new tool for studying the universe at high-z, using the mean brightness temperature to probe the HI content and its fluctuations to probe the power spectrum. Existing estimates of the HI density at $z \sim 3$ imply a mean brightness temperature of 1 mK at 320 MHz. The cross-correlation between the temperature fluctuations across different frequencies and sight lines is predicted to vary from $10^{-7}\,K^2$ to $10^{-8}\,K^2$ over intervals corresponding to spatial scales from 10 Mpc to 40 Mpc for some of the currently favoured cosmological models. Comparing this with the expected sensitivity of the GMRT, we find that this can be detected with $\sim$ 10 hrs of integration, provided we can distinguish it from the galactic and extragalactic foregrounds which will swamp this signal. We discuss a strategy based on the very distinct spectral properties of the foregrounds as against the HI emission, possibly allowing the removal of the foregrounds from the observed maps.

Key words: Cosmology: theory, observations, large scale structures—diffuse radiation.


GMRT Giant Meter-wave Radio Telescope

Radio Interferometric Array



GMRT

30 antennas 45 diameter

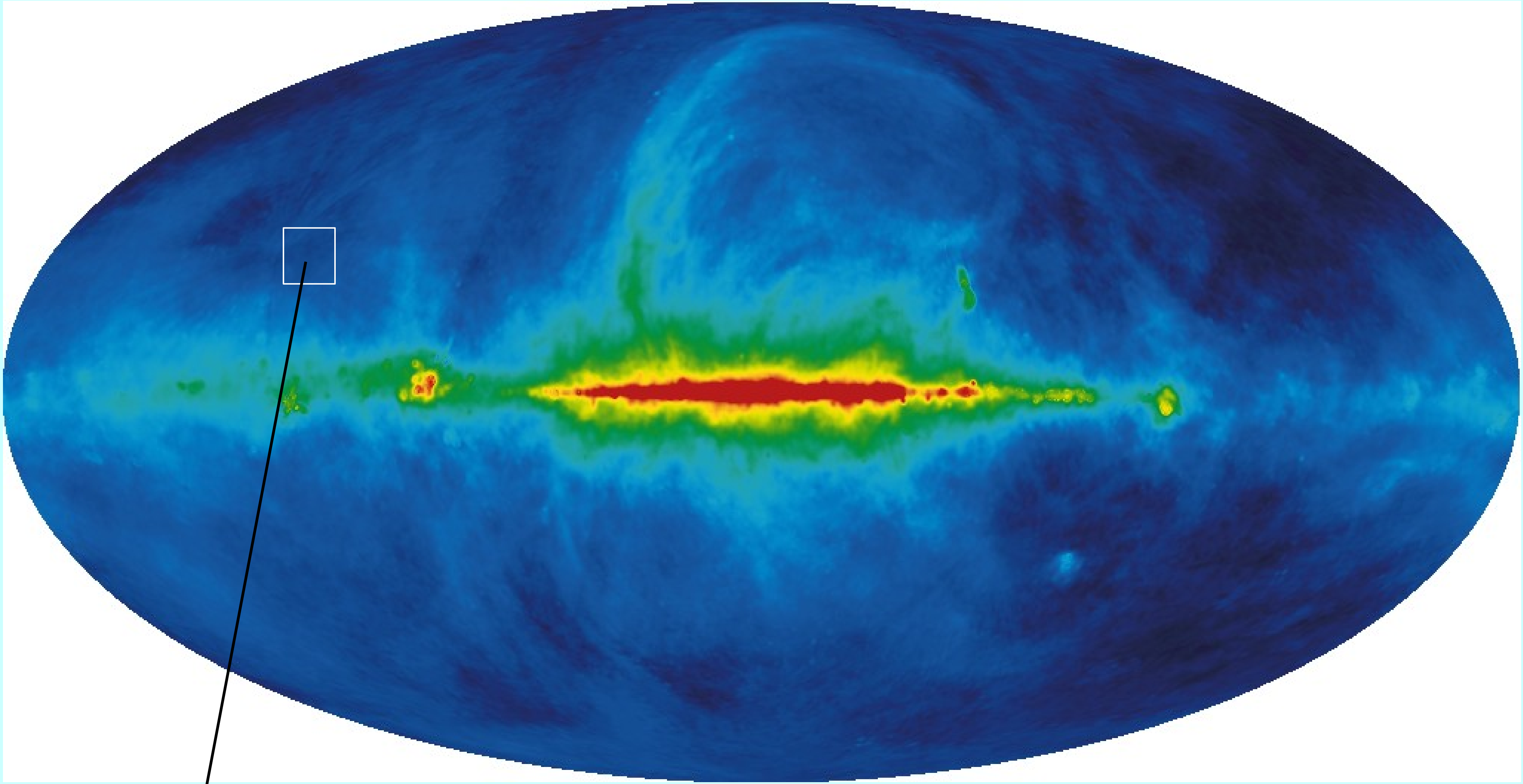
Frequency MHz	153	235	325	610	1420
z	8.3	5.0	3.4	1.3	0

32 MHz bands with 128 separate channels

Have we observed the cosmological 21-cm radiation?

No!

Haslam Map - 408 MHz All-Sky Survey)

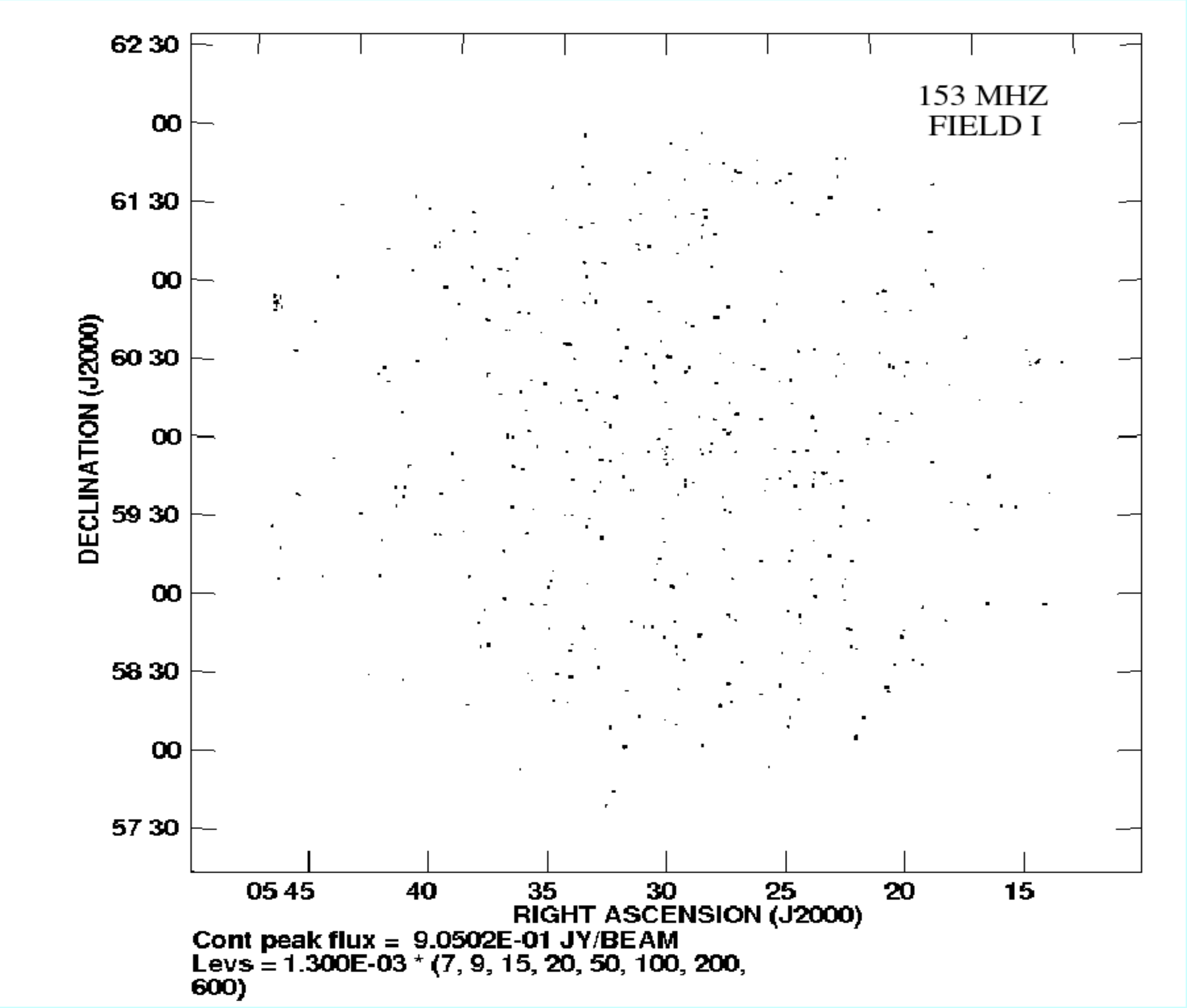


≈ 4^0 Angular scales (off-galactic)

Galactic coordinates (l, b) 151.80°, 13.89°

Synchrotron Radiation
180K – 70,000K at 150 MHz

GMRT Observations

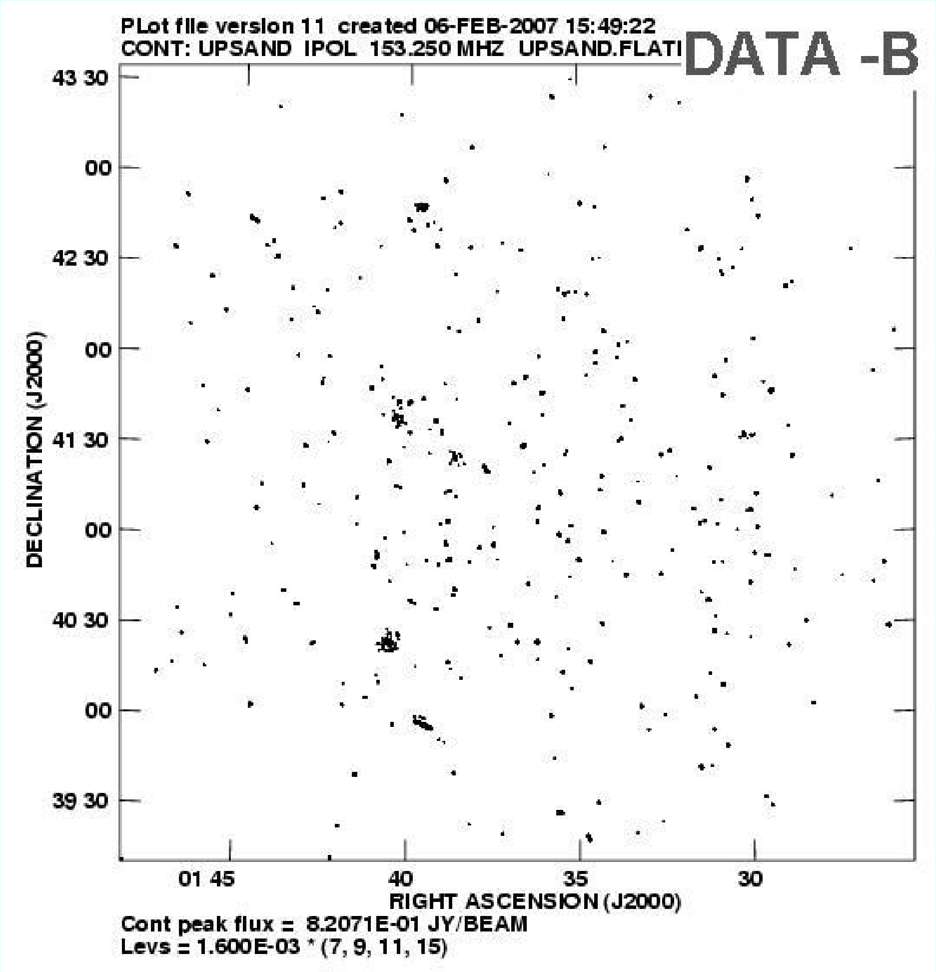


FIELD I

Ghosh, Prasad, Bharadwaj, Ali & Chengalur 2012, MNRAS, In Press

14 hrs GMRT Observations

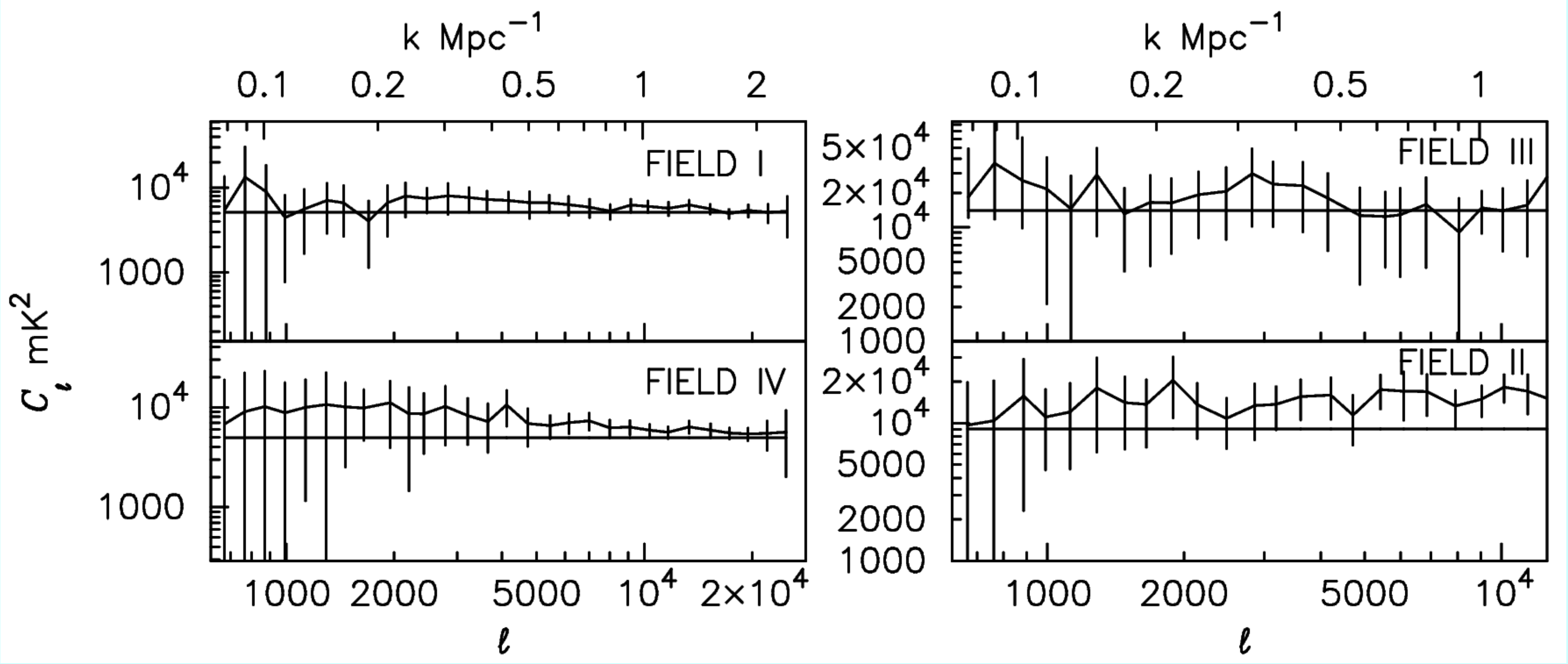
RA 01 36 46 DEC 41 24 23



FIELD IV

Ali, Bharadwaj & Chengalur 2008,MNRAS,385,2166

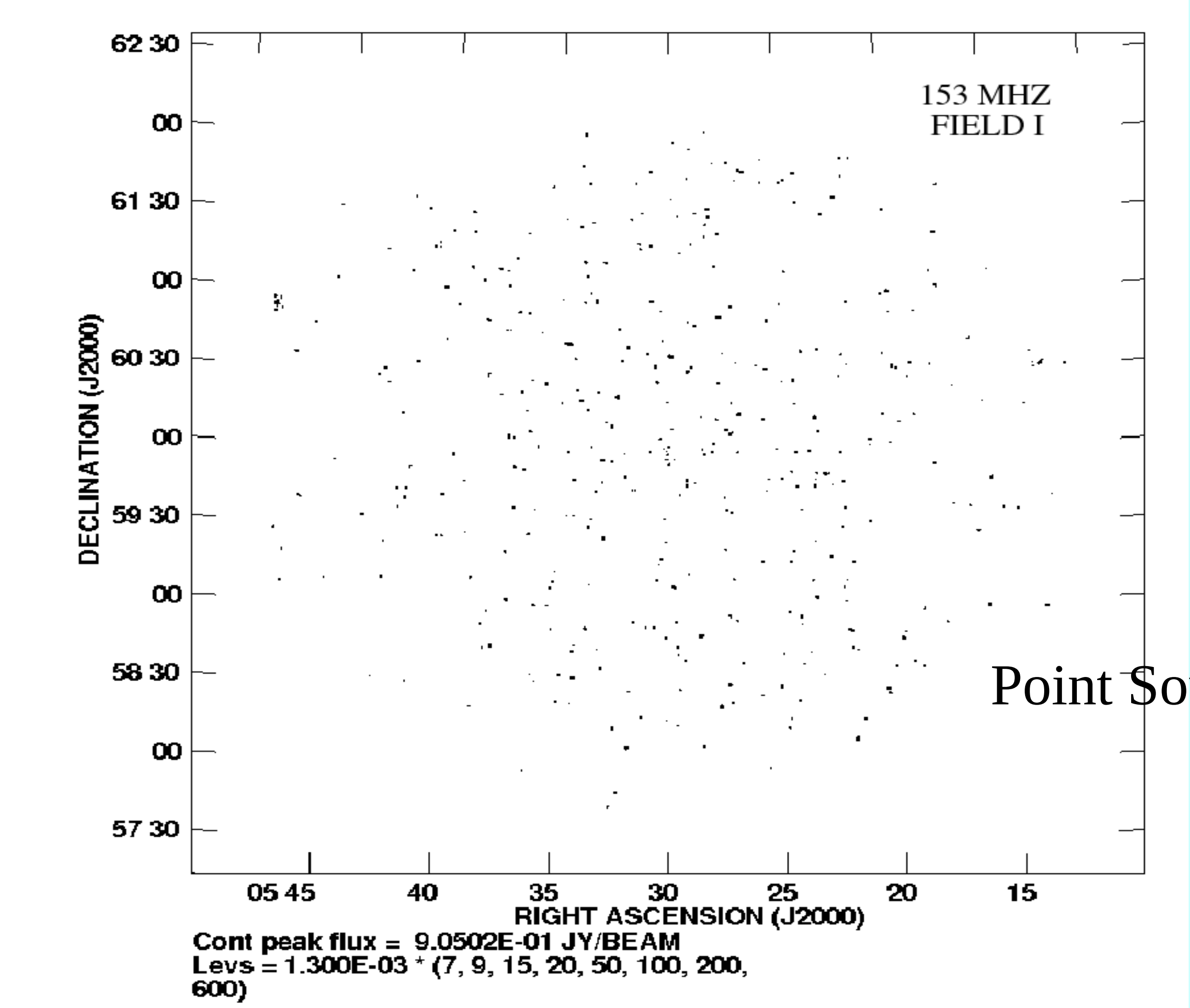
Measured C_ℓ



Expected 21-cm Signal $C_\ell \sim 10^{-3} – 10^{-4}$ mK^2

Ghosh, Prasad, Bharadwaj, Ali & Chengalur 2012, MNRAS, In Press

GMRT Observations



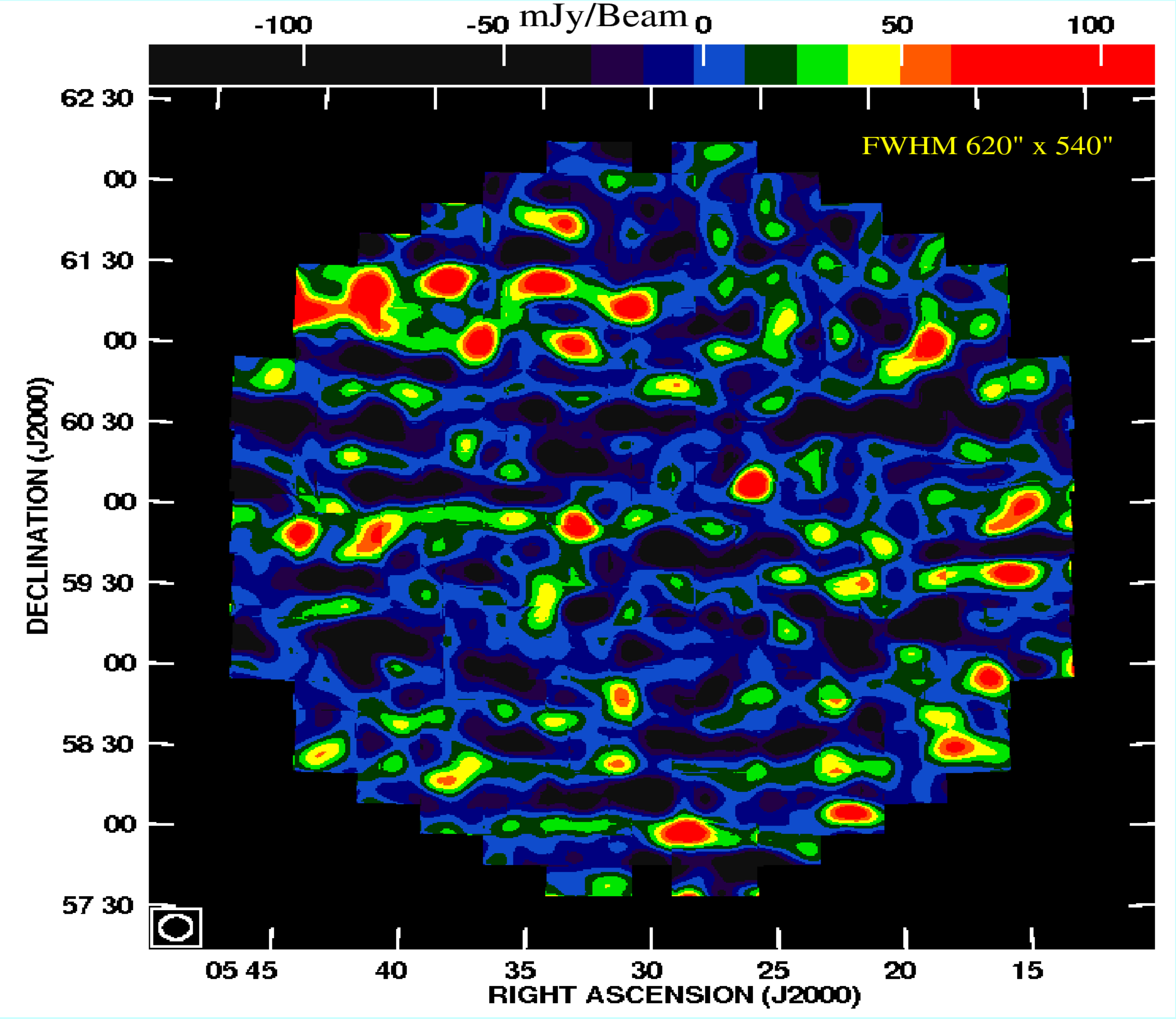
FIELD I

Point Source Dominated

Ghosh, Prasad, Bharadwaj, Ali & Chengalur 2012, MNRAS, In Press

Low resolution Residual Map. Taper @ |U|=170

The brightest structures in this map are at 5σ level compared to the local rms value ~ 23.5 mJy/Beam.

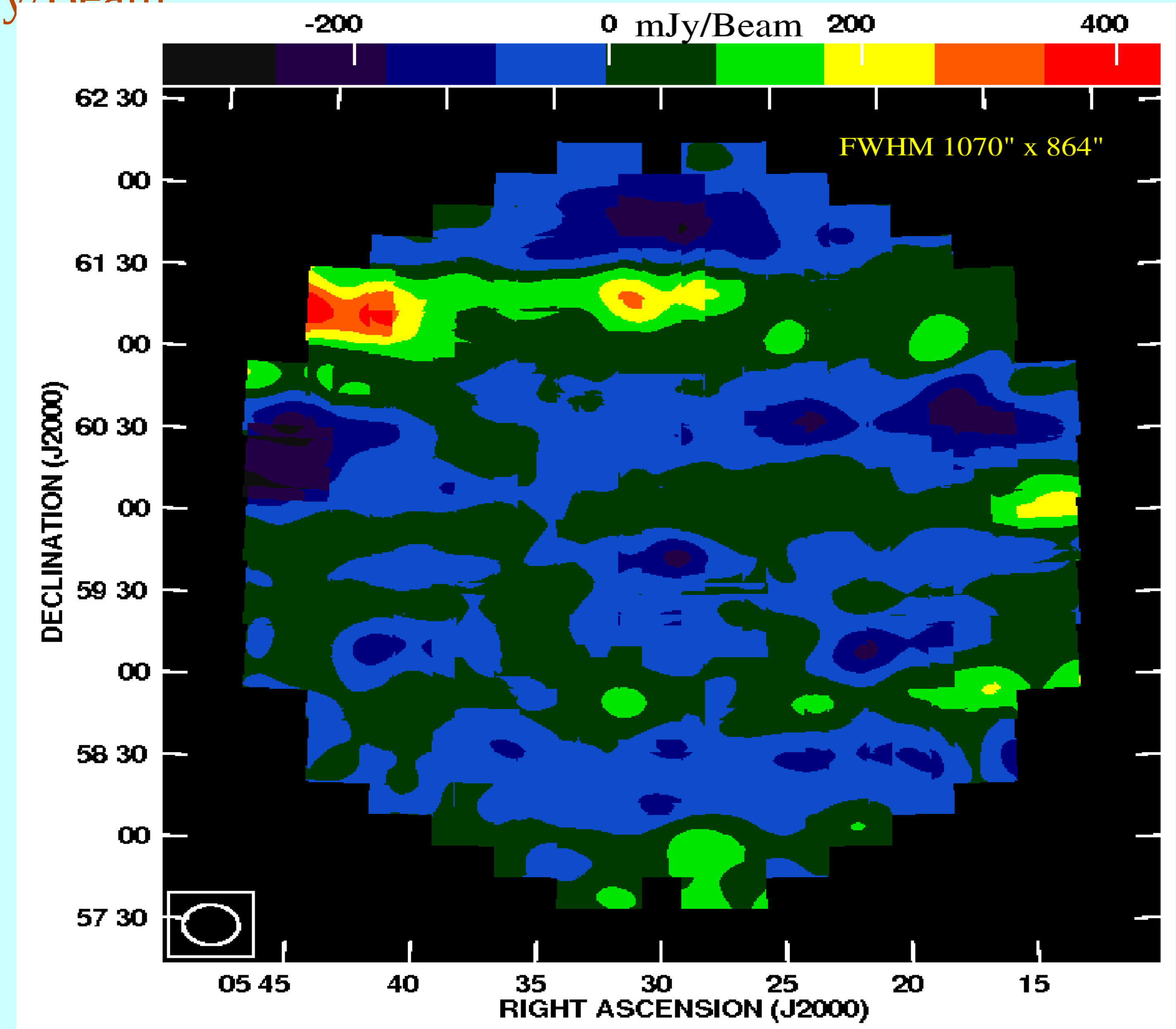


Diffuse Structure Appearing On the Map on Scales > 10 arcmin

Angular resolution	rms (mJy/Beam)	Conversion factor (mJy/Beam) to (K)	rms (K)
$620'' \times 540''$	23.50	0.17	4.00

The brightest structures in this map are at 10σ level compared to the local rms value ~ 35 mJy/Beam

Taper @ |U|=100

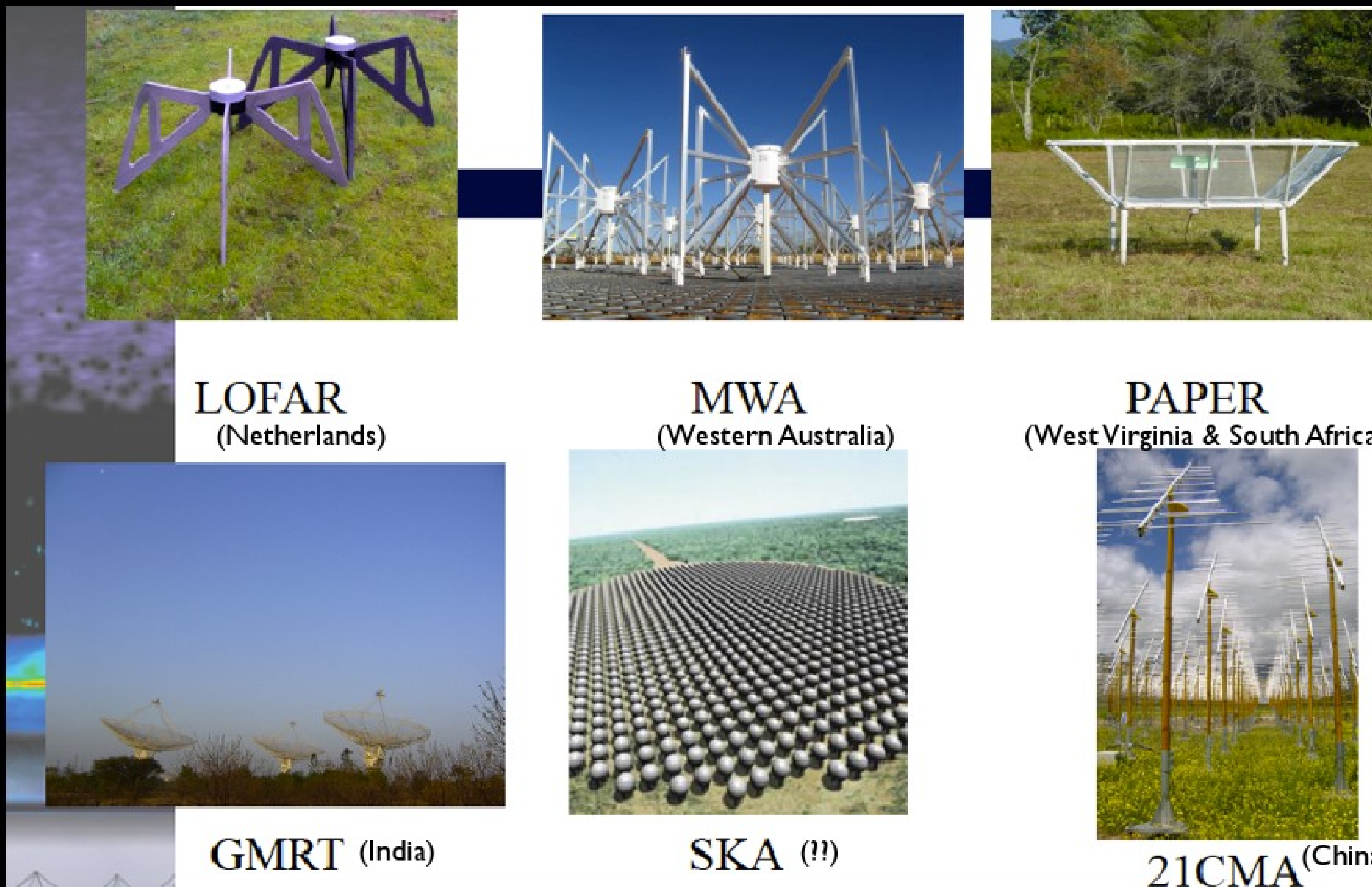


Angular resolution	rms (mJy/Beam)	Conversion factor (mJy/Beam) to (K)	rms (K)
1070″ × 864″	35.00	0.06	2.1

Currently working on

- Theoretical Predictions of Expected 21-cm Signal
- Detection Strategies
- Quantify and Remove Foregrounds

Efforts to Detect the Spatially Fluctuating 21cm Signal from Reionization




Thank You

Concluding Remarks

- Probe Dark Ages, First Luminous Objects, reionization, post-reionization
- Potential Probe of Dark Energy
- Challenge Foregrounds, RFI

21 cm radiation

Neutral Hydrogen - HI

Ground state