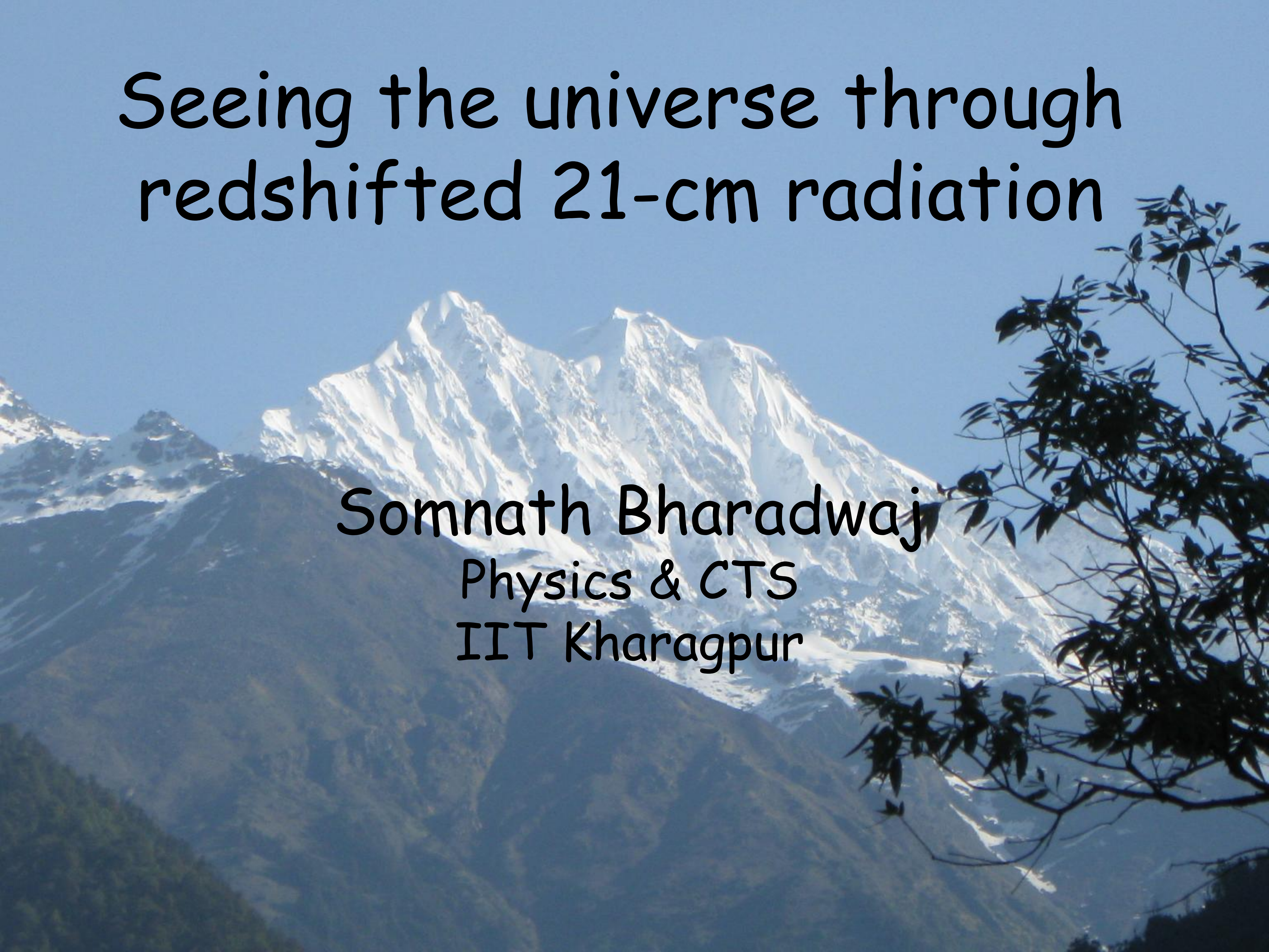

Seeing the universe through redshifted 21-cm radiation

Somnath Bharadwaj

Physics & CTS

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Collaborators

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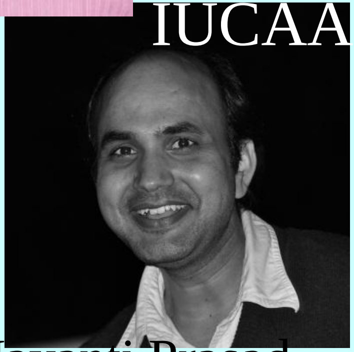


IUCAA

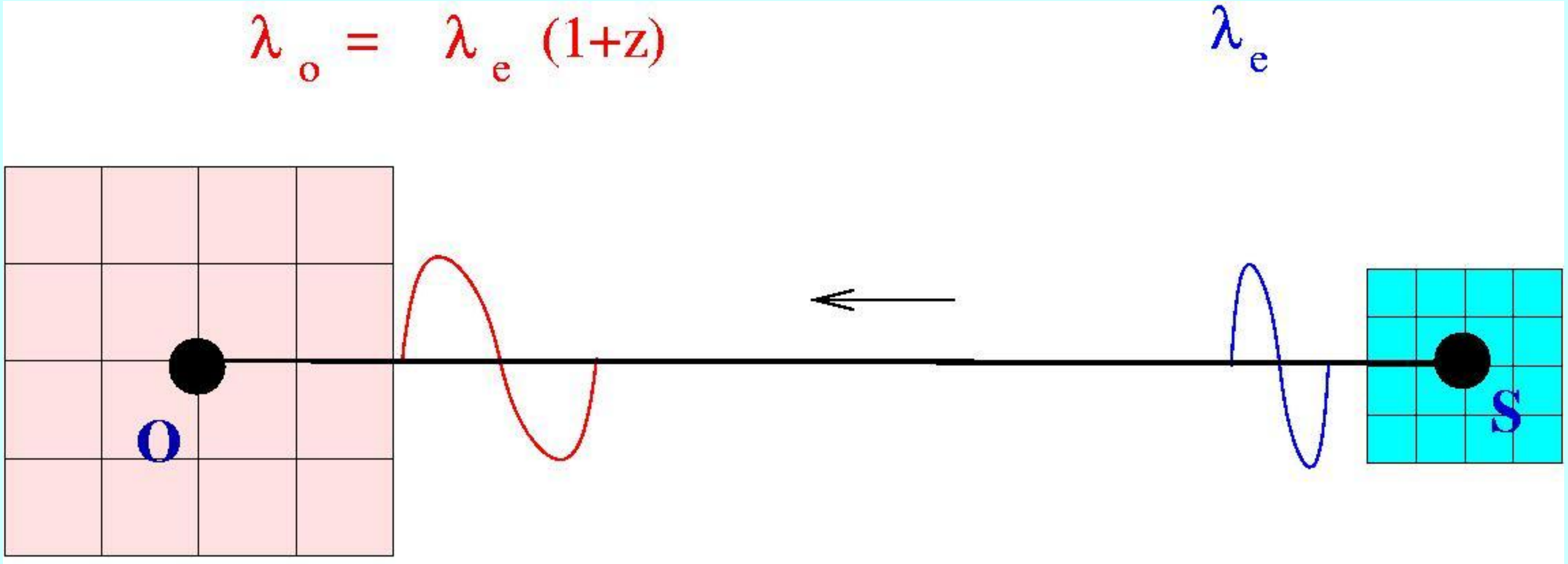
Jayanti Prasad

Stockholm

Kanan Datta

Suman Majumdar

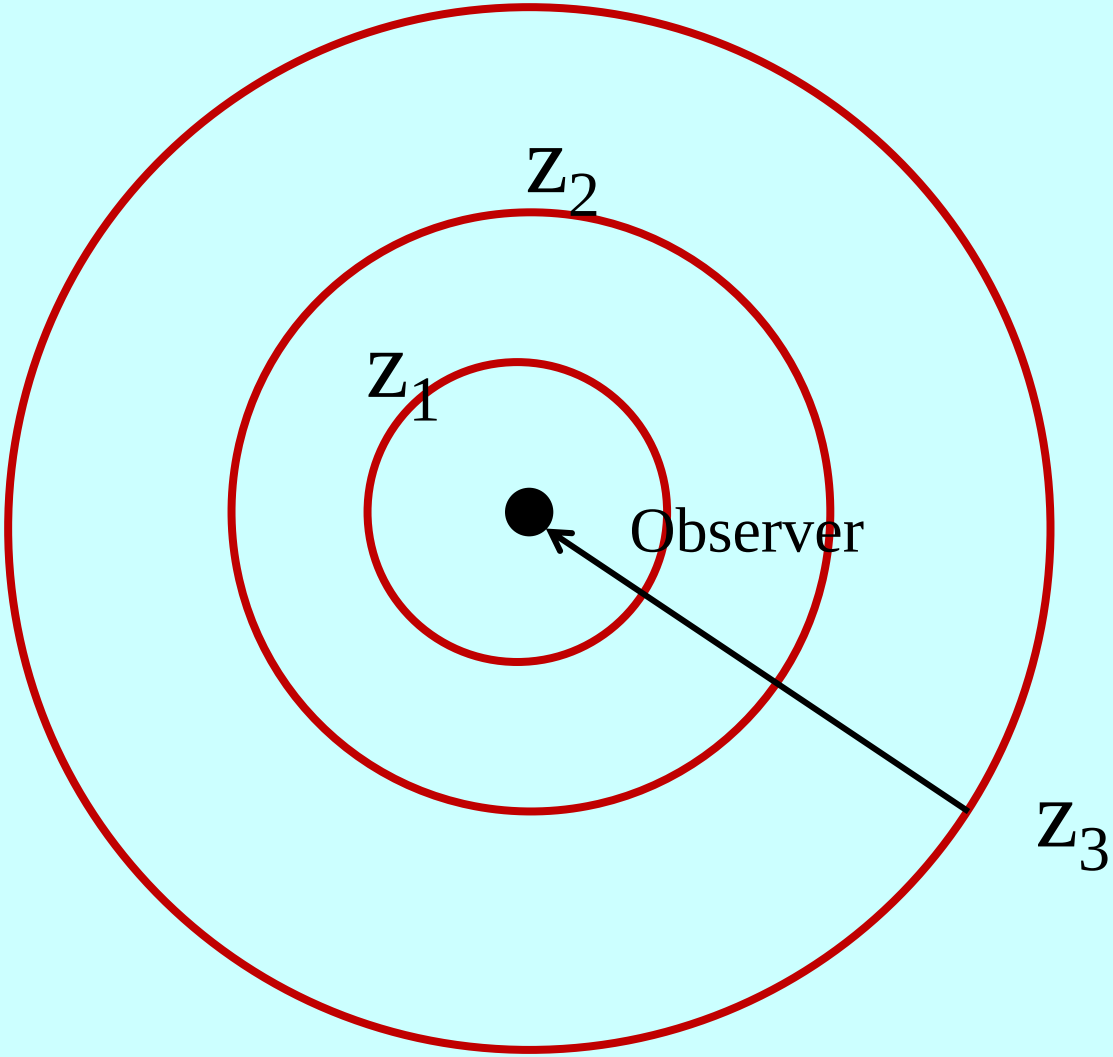
The Expanding Universe



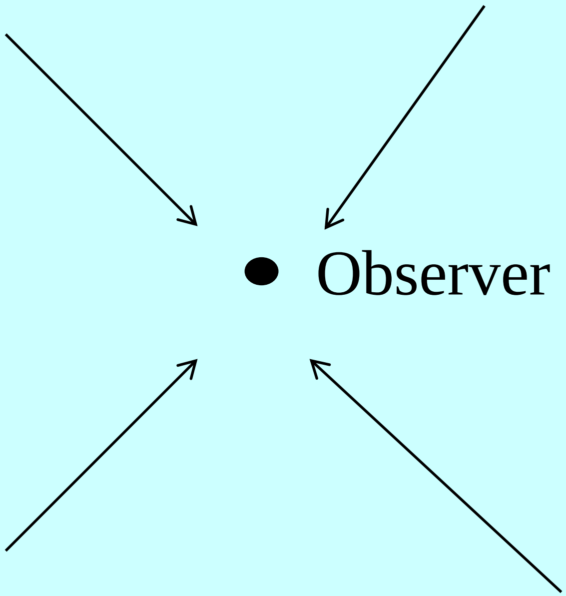
1 Mpc = 3.08×10^{22} m

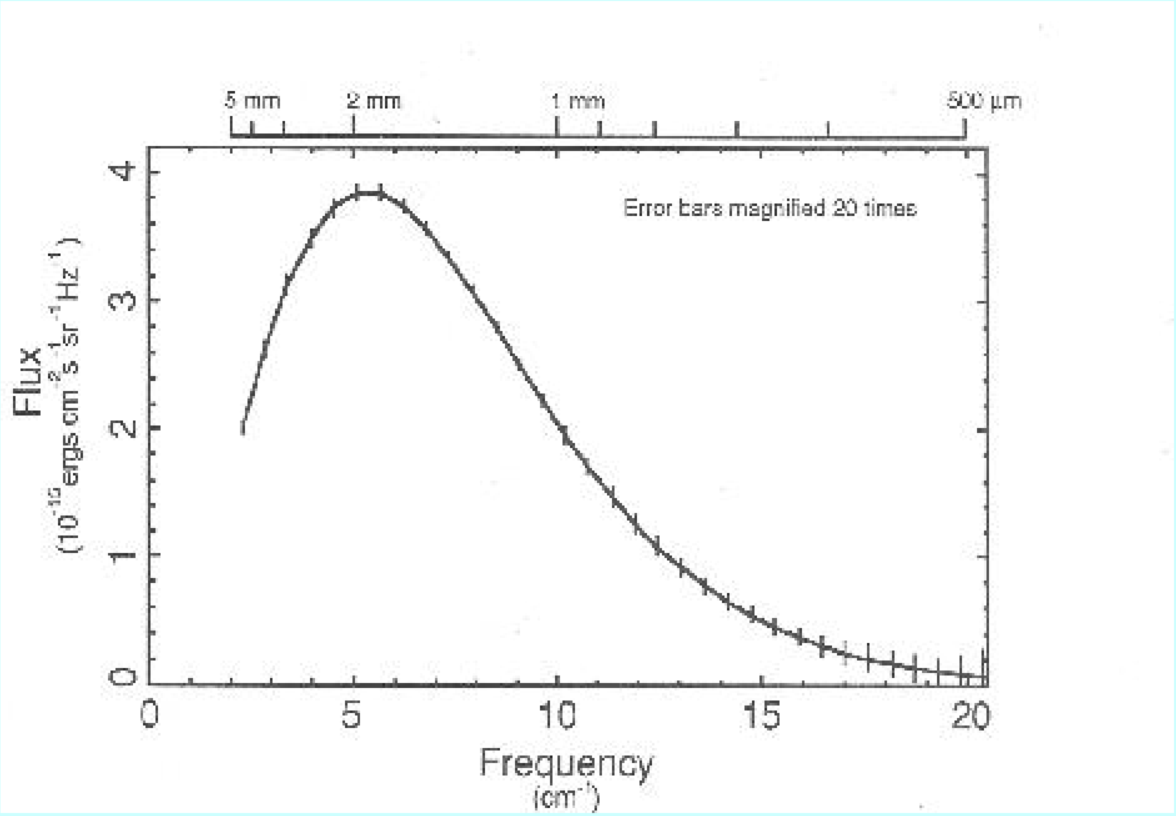
H_0= 70 km / s / Mpc

Redshift - distance - time



Cosmic Microwave Background Radiation (CMBR)

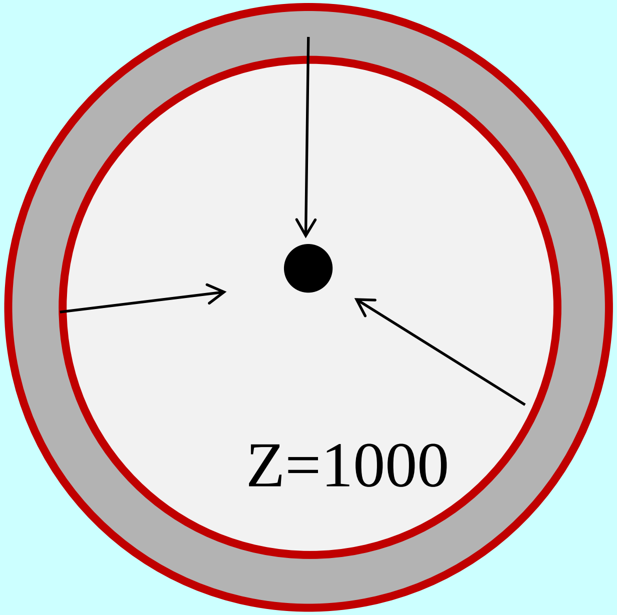




T=2.725 K

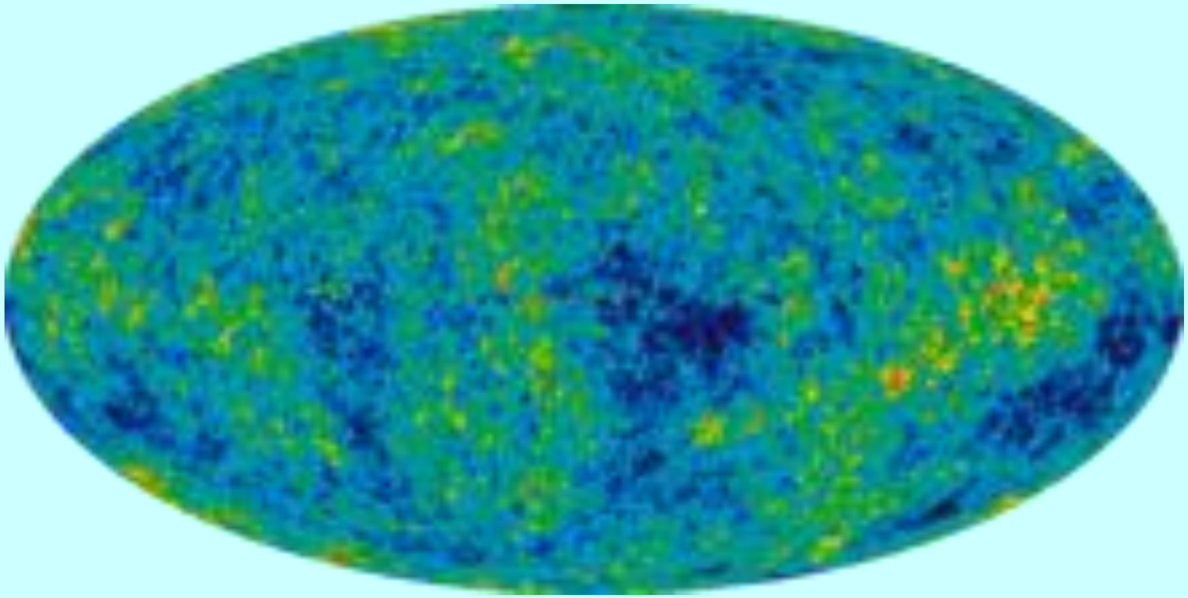
CMBR anisotropies

Universe ionized and opaque at z >1000



Z=1000

WMAP NASA

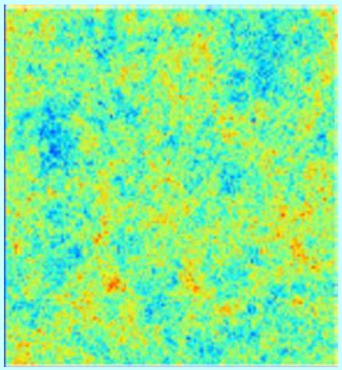


T=2.725 K

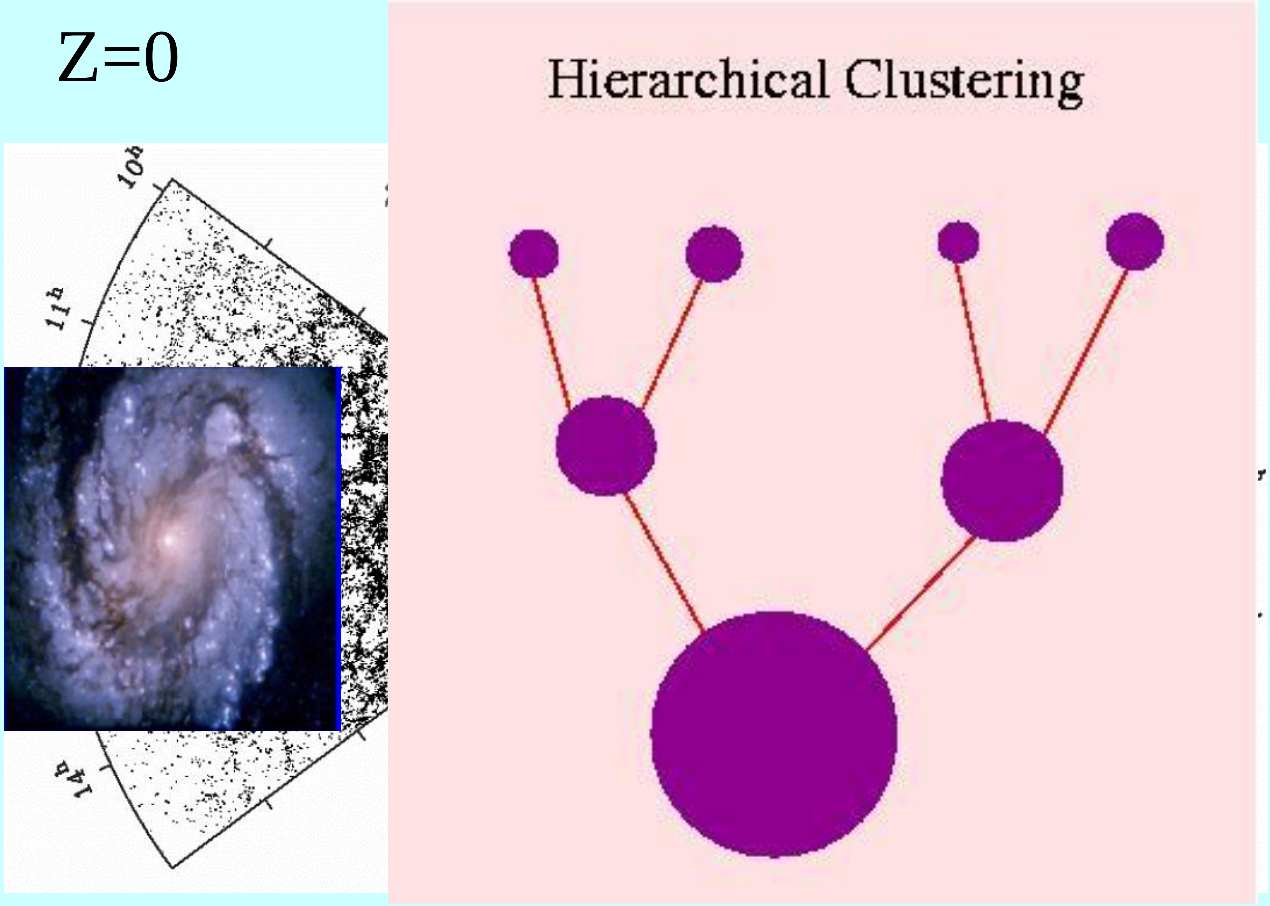
Nearly isotropic ΔT ~ 10 micro K

Structure Formation

Z=1000



Z=0

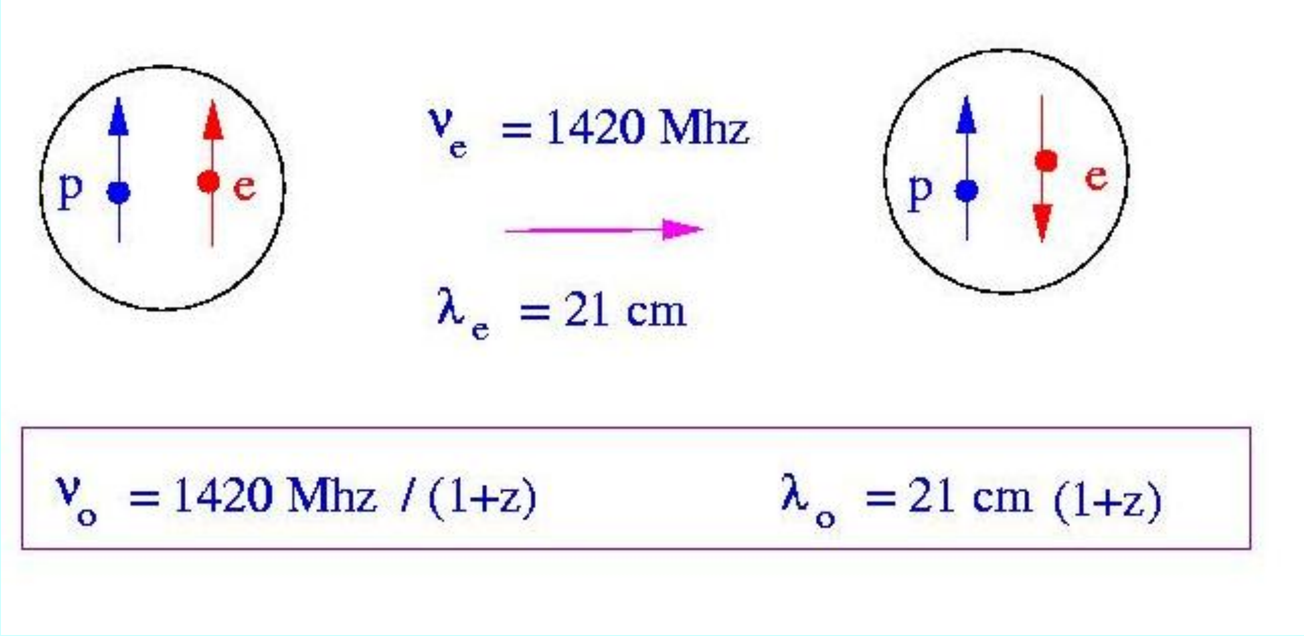


Gravitational Instability

Dark matter dominates the dynamics

21-cm radiation

Neutral Hydrogen - HI
Ground state

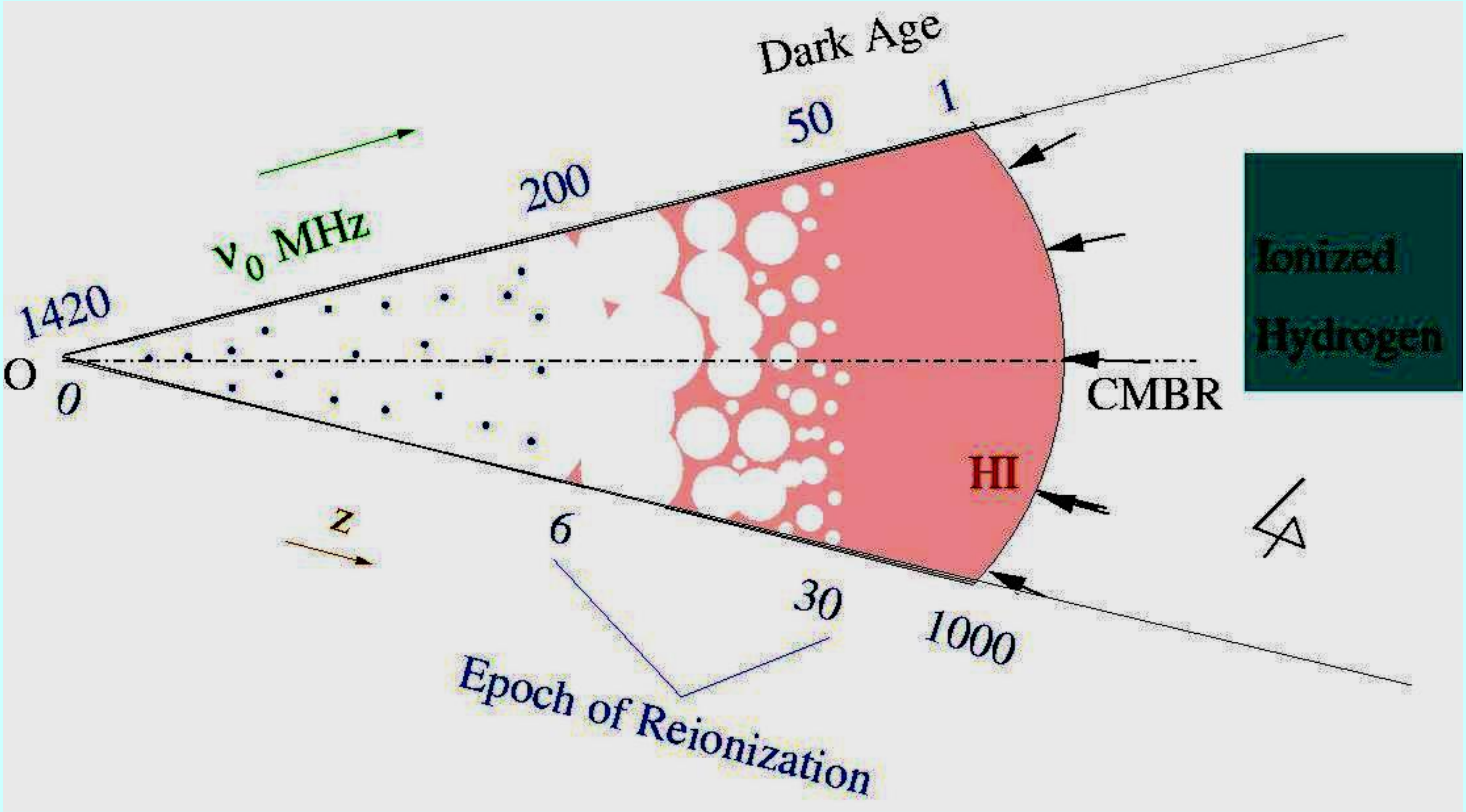


Spin Temperature

$$\frac{n_1}{n_0} = \frac{g_1}{g_0} e^{-T_\star/T_s}$$

$$T_\star = h_p \nu_e / k_B = 0.068 \text{ K}$$

HI Evolution

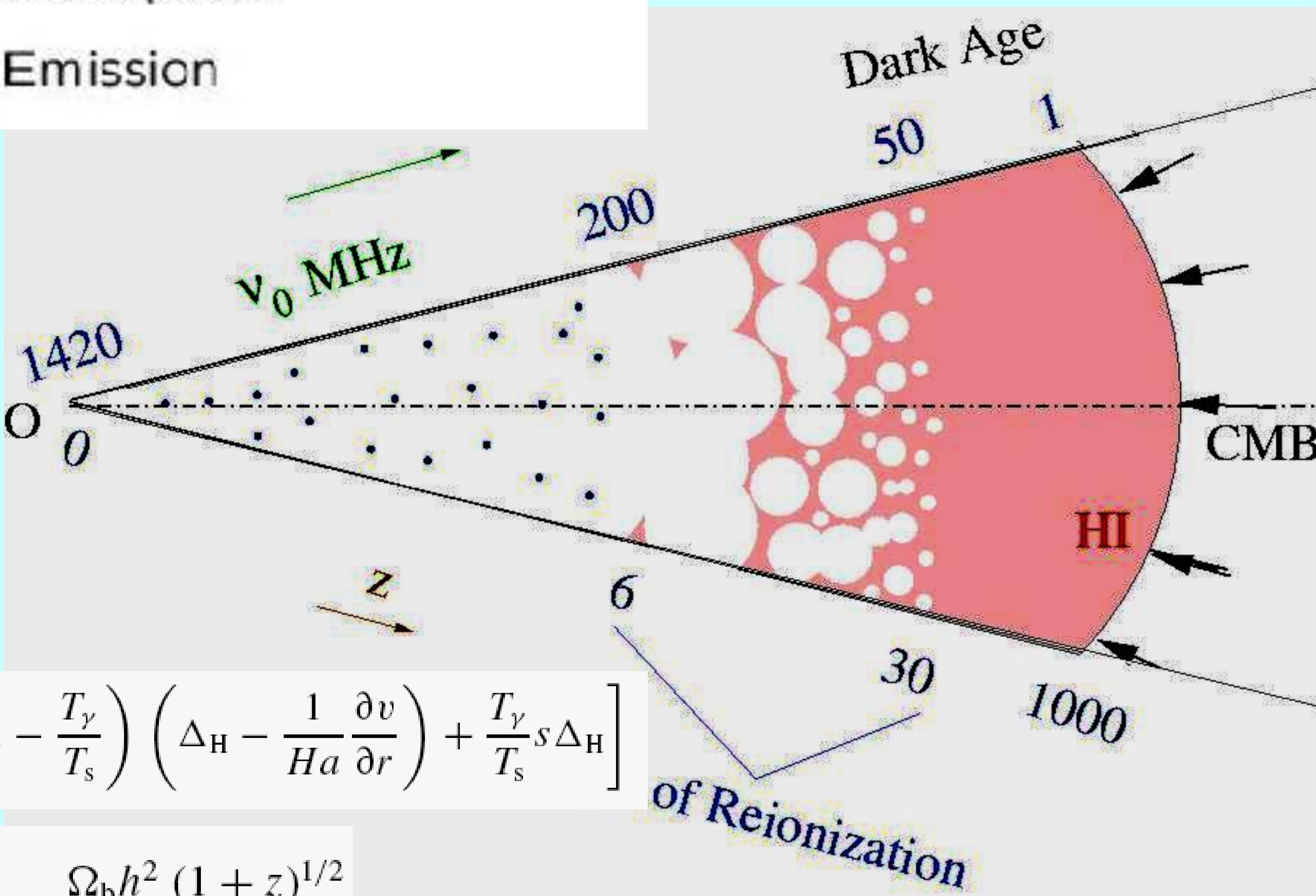


21-cm signal

$$T_b \propto \left(1 - \frac{T_\gamma}{T_s}\right) n_{\rm HI}$$

$T_s < T_\gamma$ Absorption

$T_s > T_\gamma$ Emission

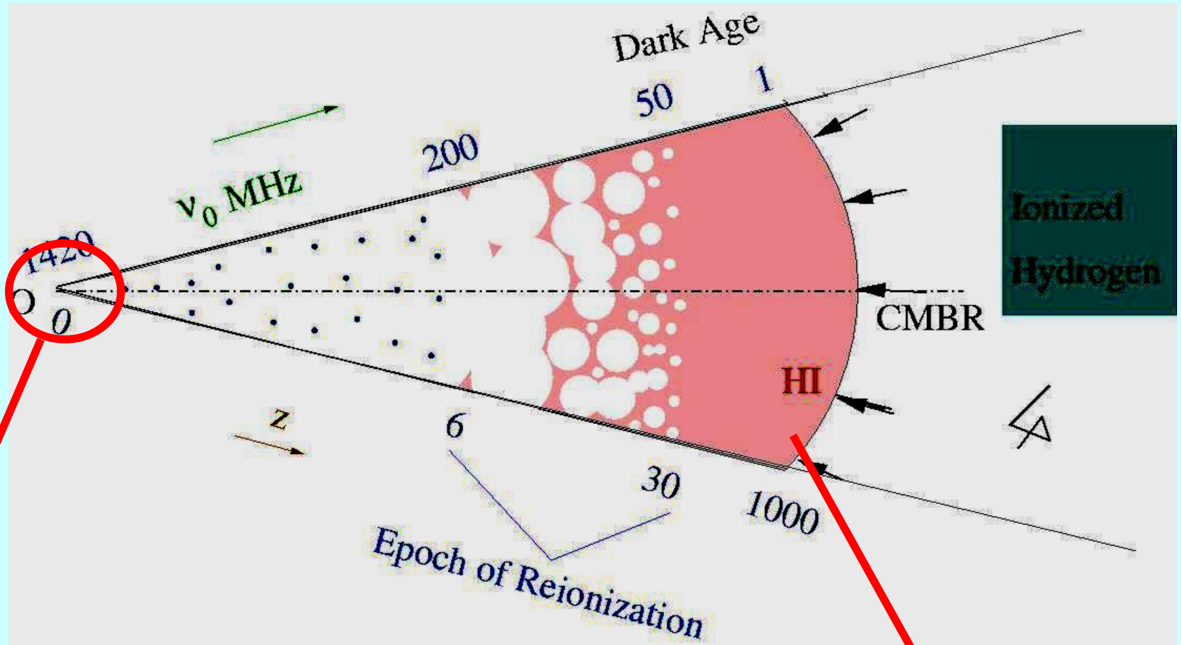


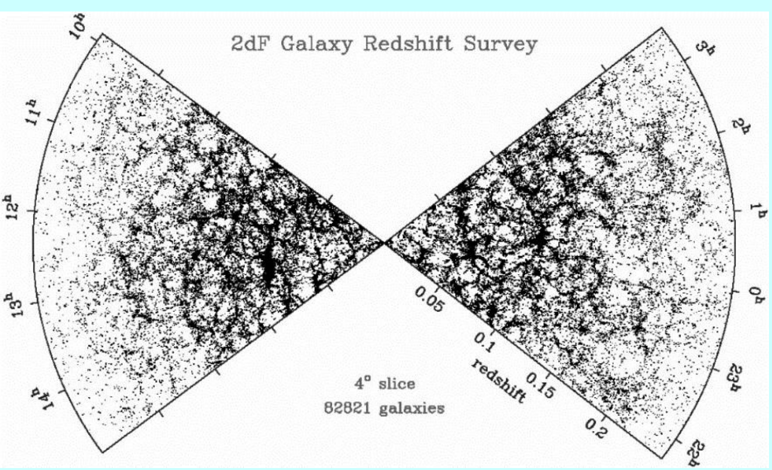
$$\delta T_{\rm b}(\boldsymbol{n}, \nu) = \bar{T}\left[\left(1 - \frac{T_\gamma}{T_{\rm s}}\right)\left(\Delta_{\rm H} - \frac{1}{Ha}\frac{\partial v}{\partial r}\right) + \frac{T_\gamma}{T_{\rm s}} s\,\Delta_{\rm H}\right]$$

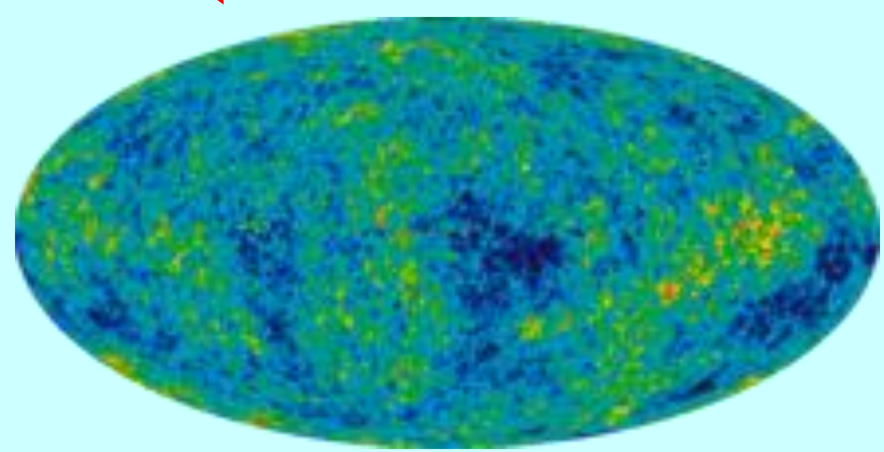
$$\bar{T} = 2.67 \times 10^{-3}{\rm K}\ \frac{\Omega_{\rm b}h^2}{0.02}\frac{(1+z)^{1/2}}{\Omega_{\rm m0}^{1/2}h}$$

Bharadwaj & Ali, 2004

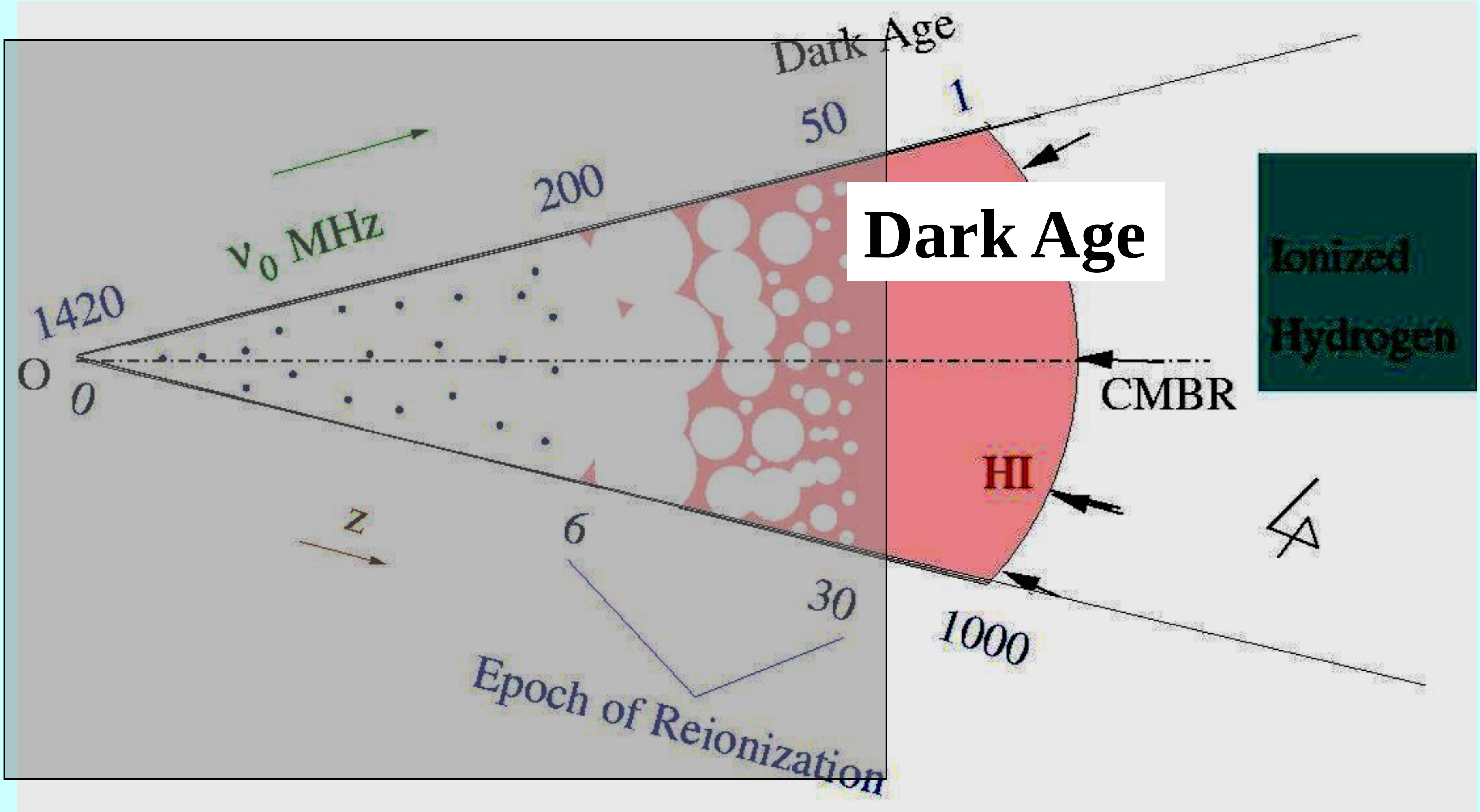
Evolution of the Universe







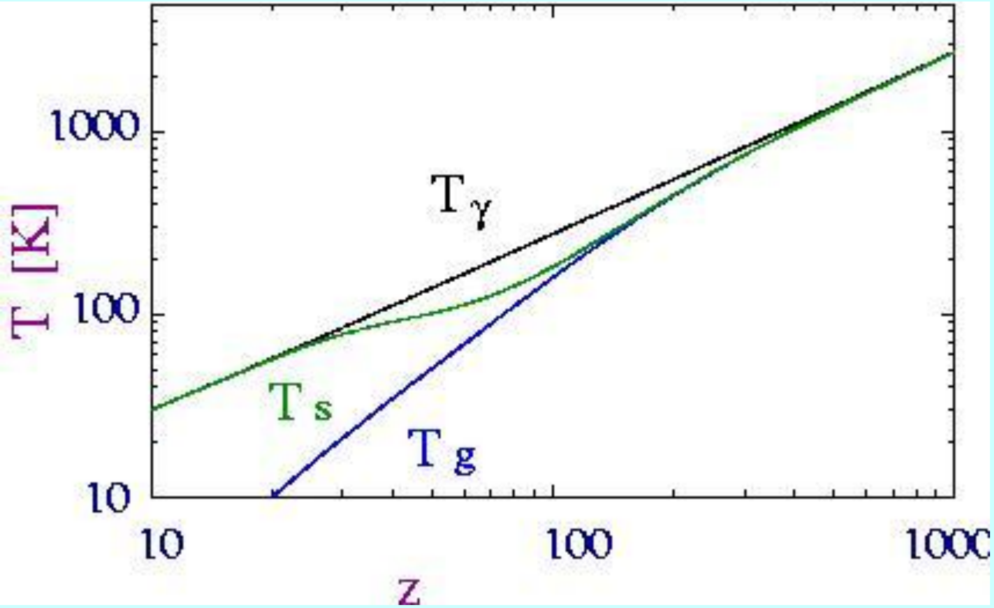
HI Evolution



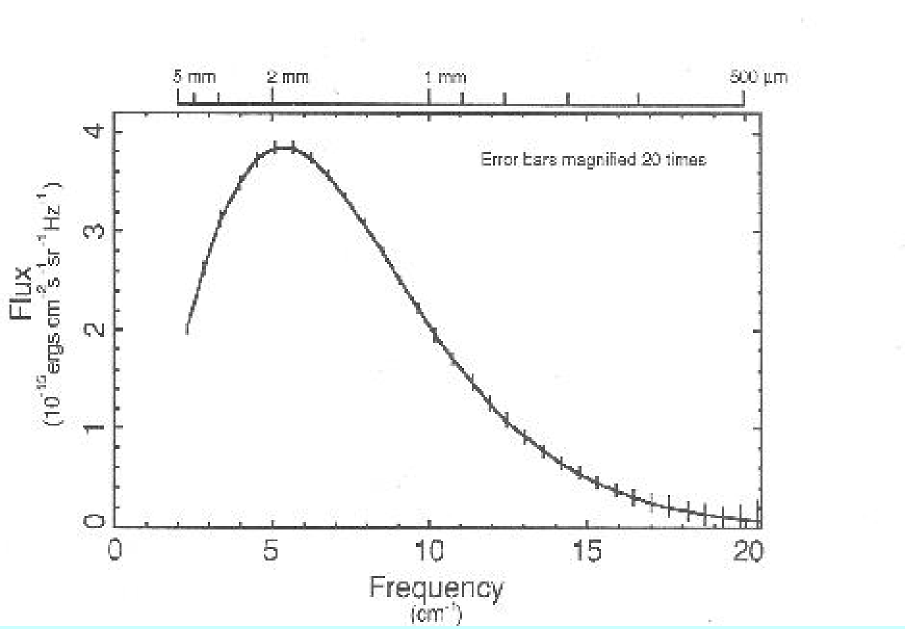
HI seen in absorption against CMBR

The Dark Ages

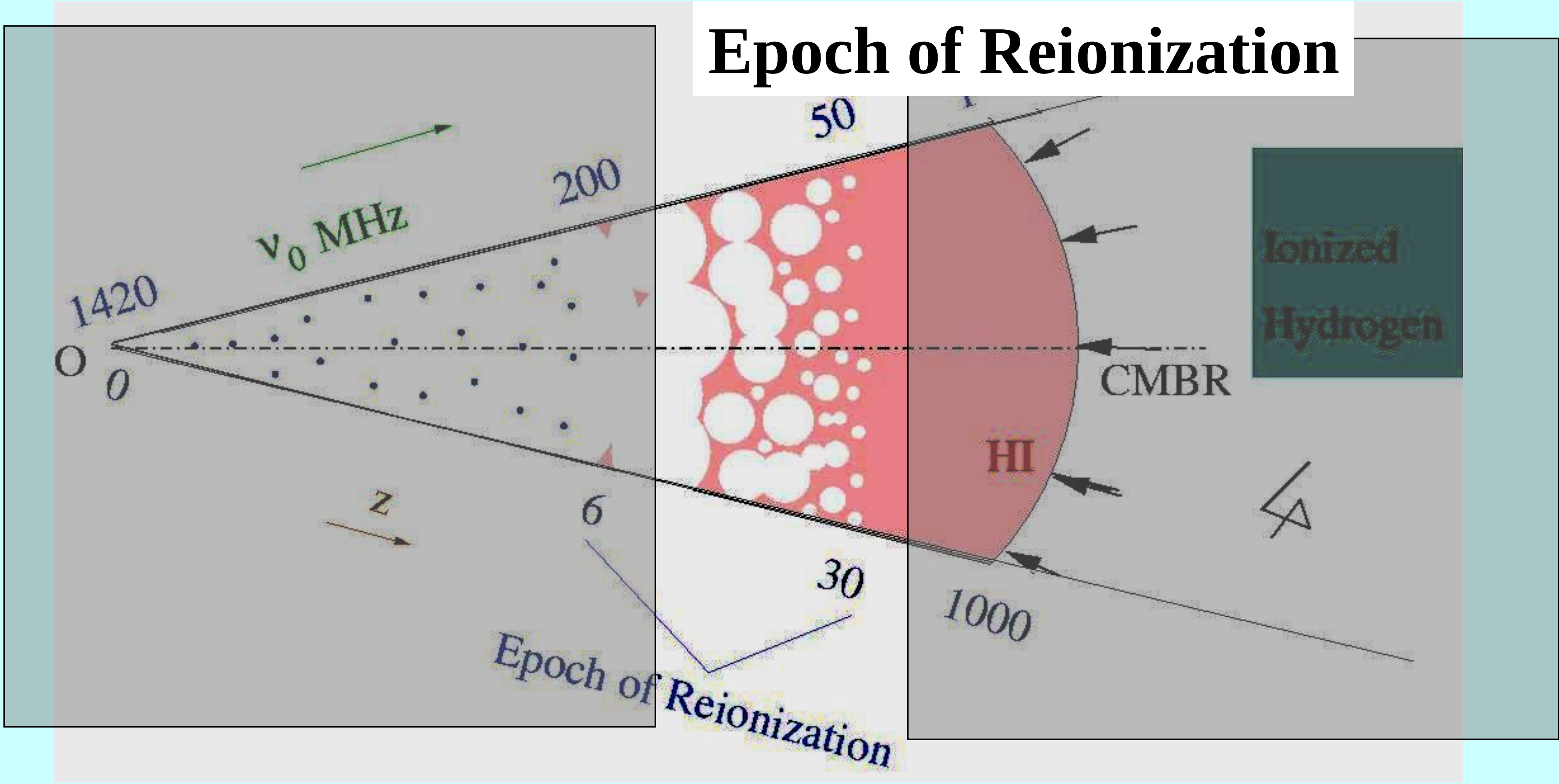
No luminous sources
HI traces dark matter
Will be seen in absorption against CMBR 200 > z > 30



$Ts < T\gamma$



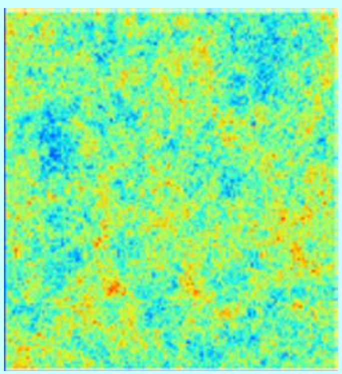
HI Evolution



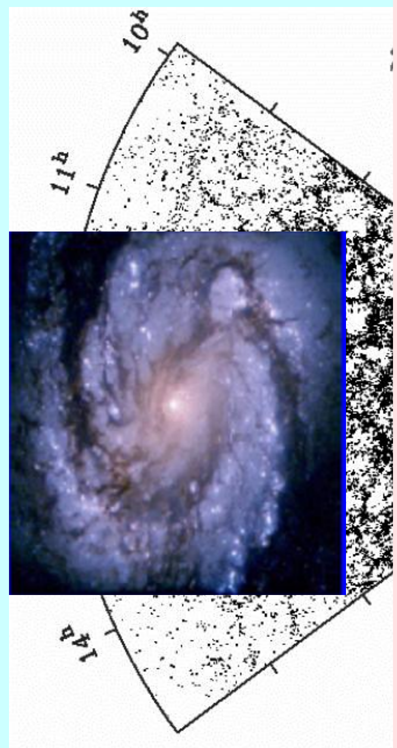
HI seen in emission

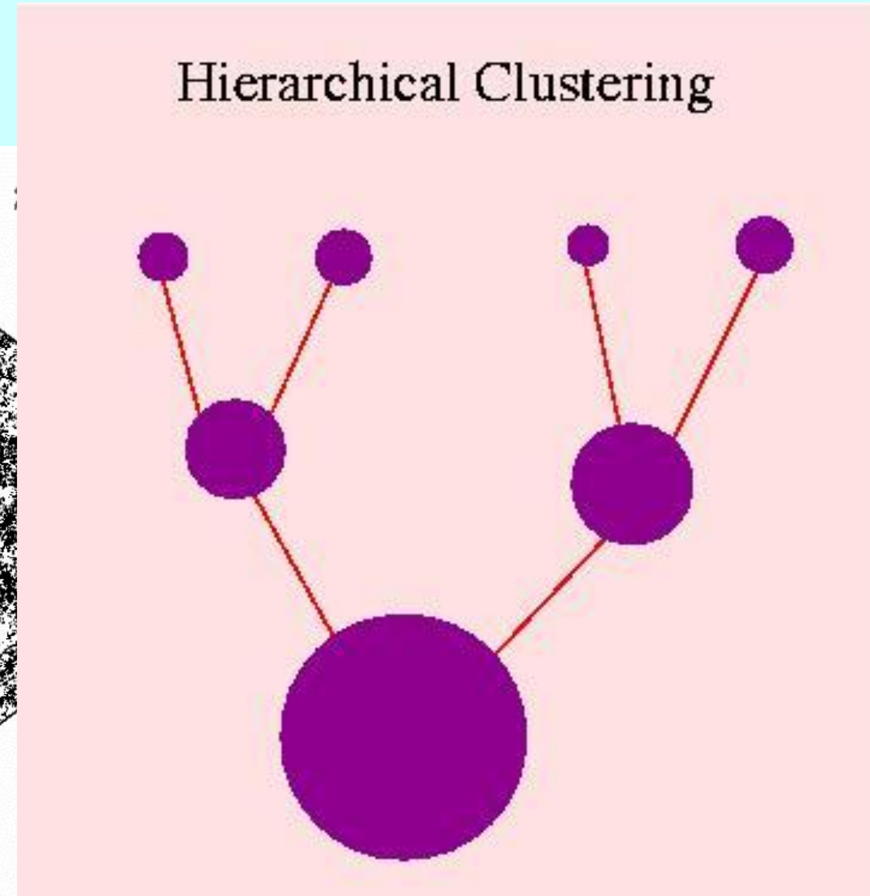
Structure Formation

Z=1000



Z=0





Gravitational Instability

Dark matter dominates the dynamics

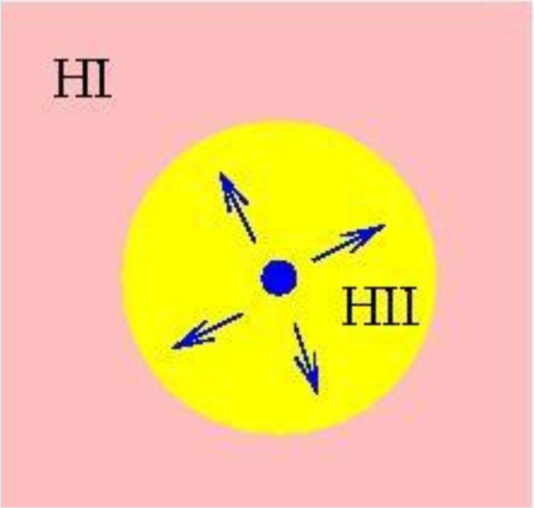
Rionization

Dark Matter Halos
Baryons Condense Within Halos

→ Galaxies

Photoionization

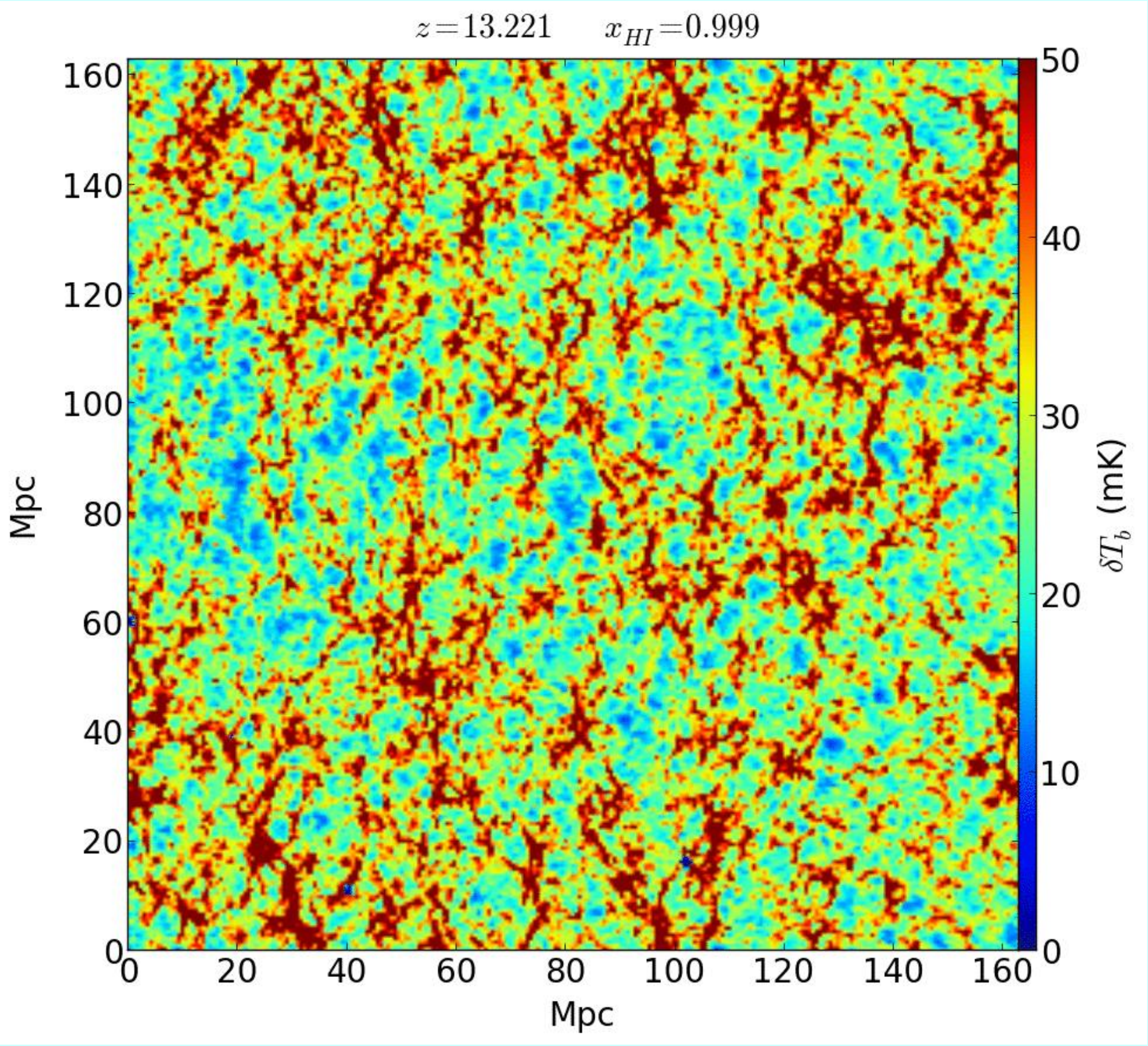
First Luminous Objects z~30



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

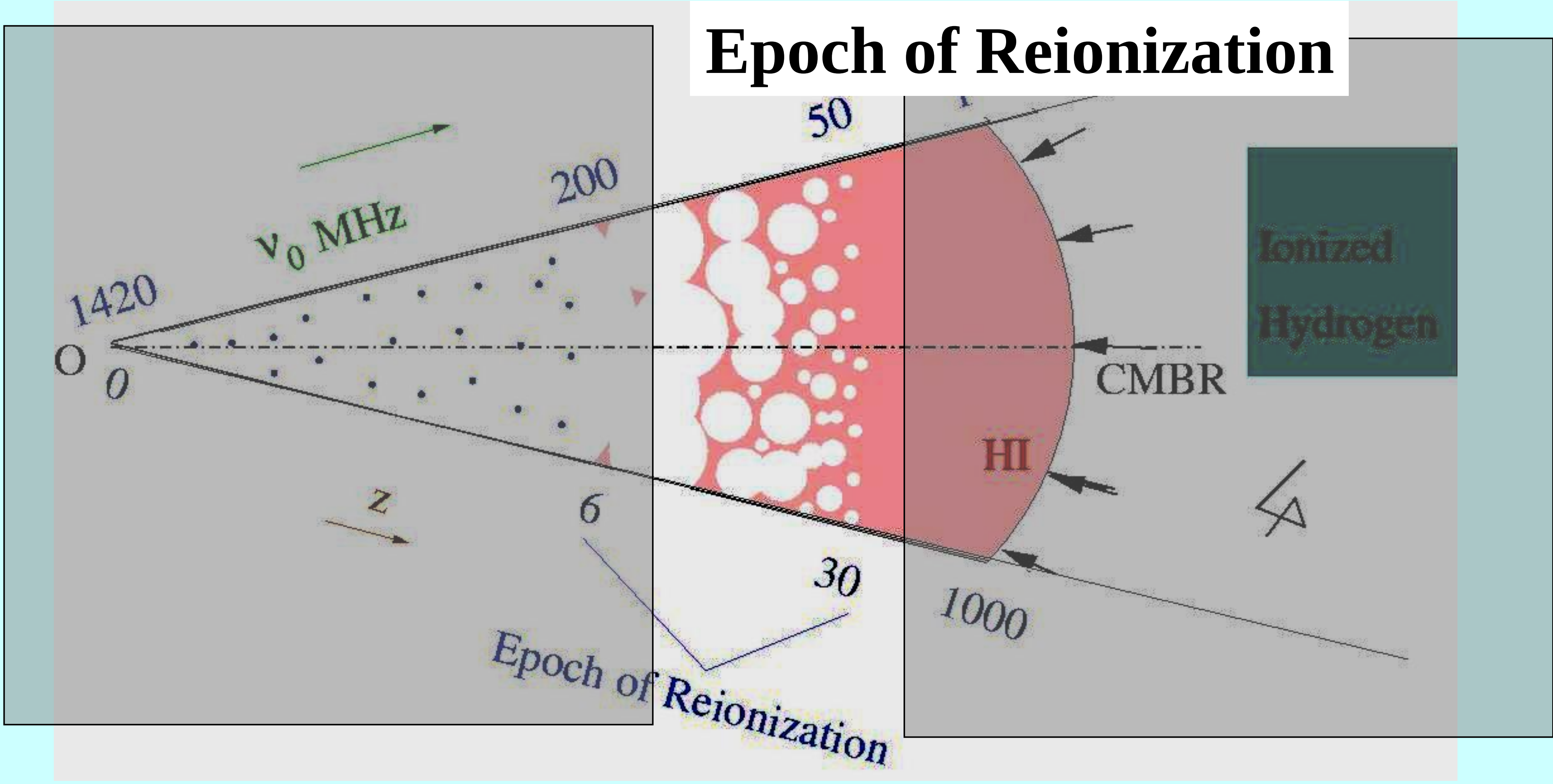
$15 > z > 6$

Simulation



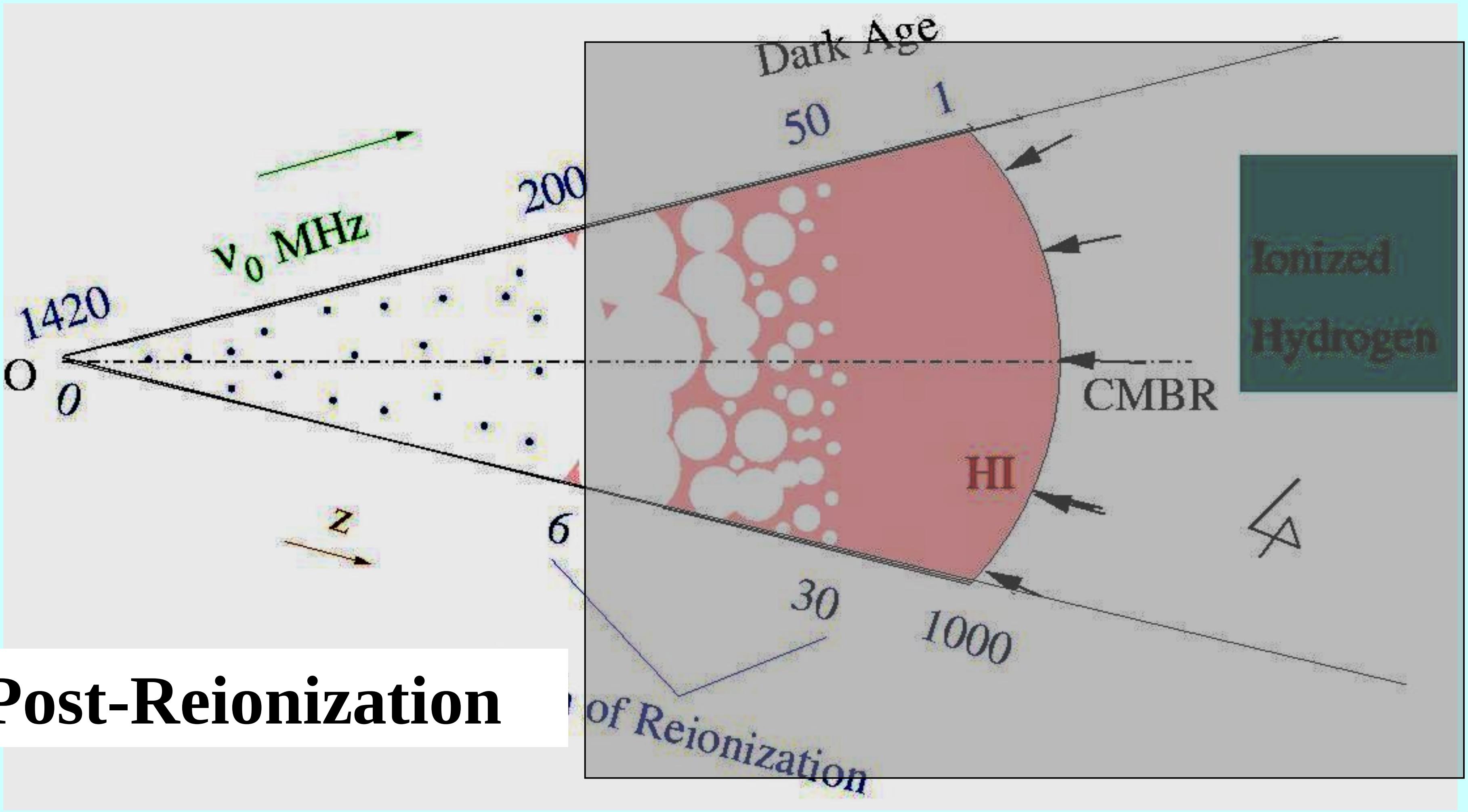
Majumdar, et al., 2014

HI Evolution



HI seen in emission

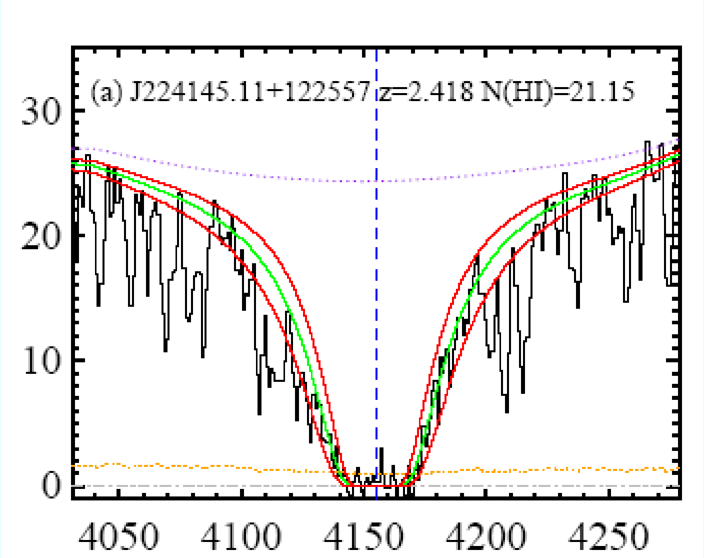
HI Evolution

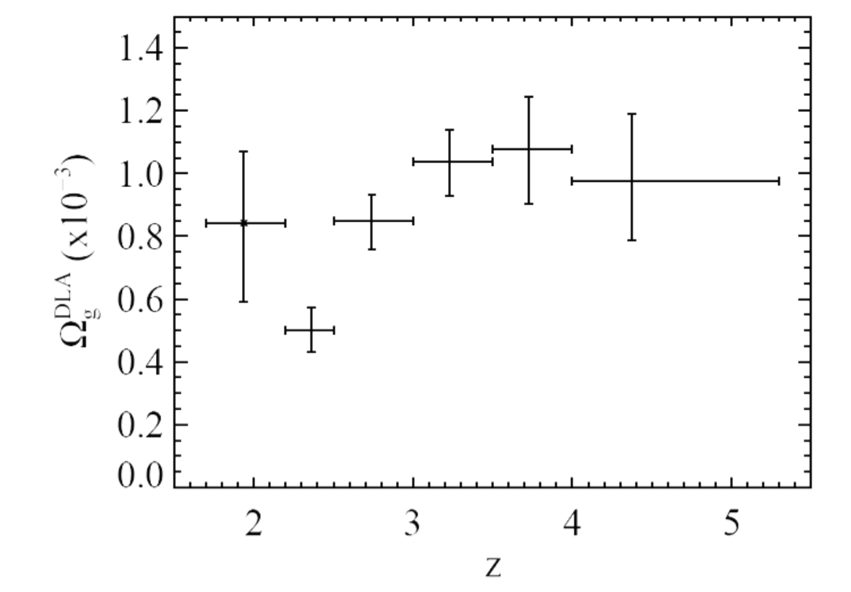


Post-Reionization

HI seen in emision

Damped Ly-α Clouds (DLA)

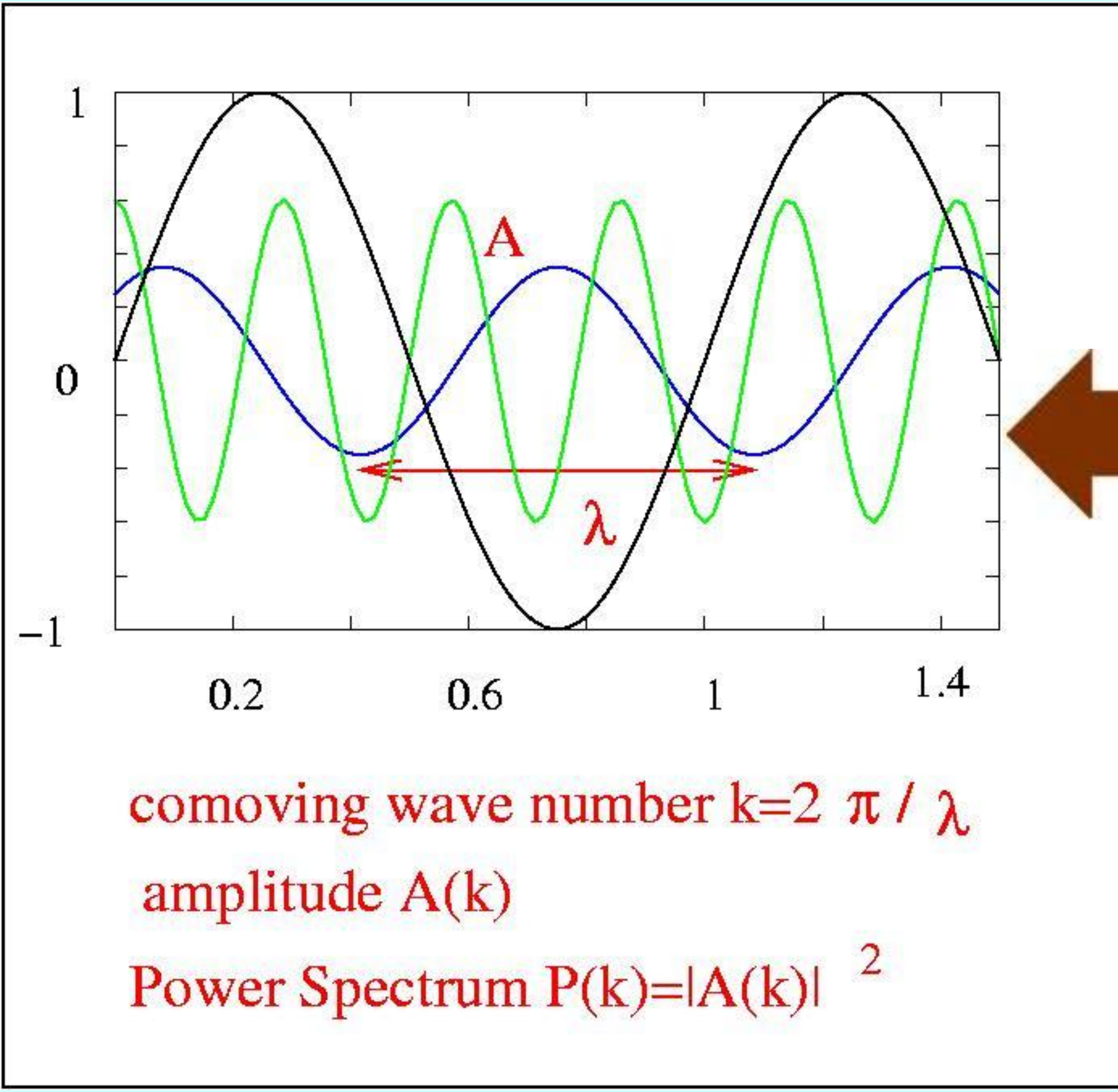


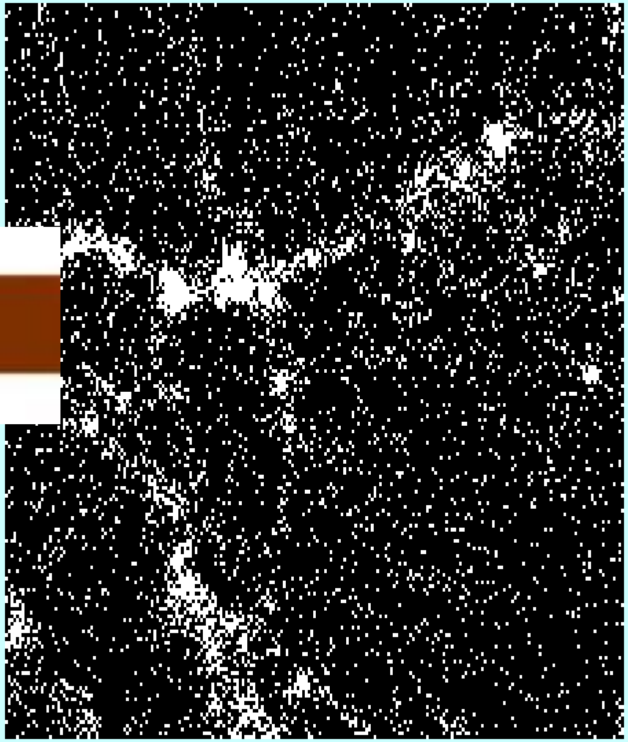


Bulk of neutral gas in DLAs

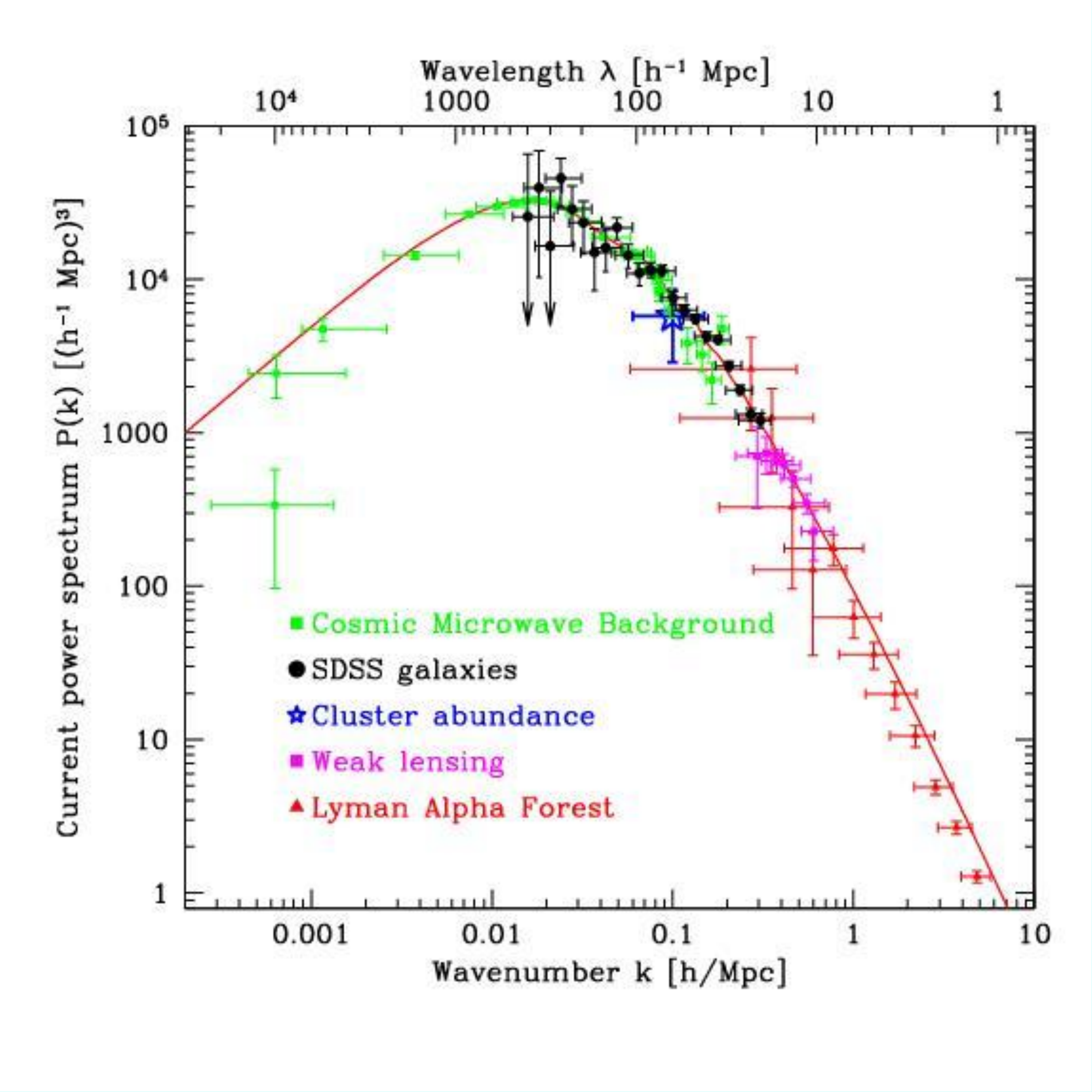
$\Omega_{GAS} \sim 10^{-3}$ $1 < z < 6$

erve?


1
0
−1
0.2
0.6
1
1.4
A
λ
comoving wave number k=2 π / λ
amplitude A(k)
Power Spectrum P(k)=|A(k)| 2



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

Our Efforts Started With

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

Using HI to Probe Large Scale Structures at z ∼ 3

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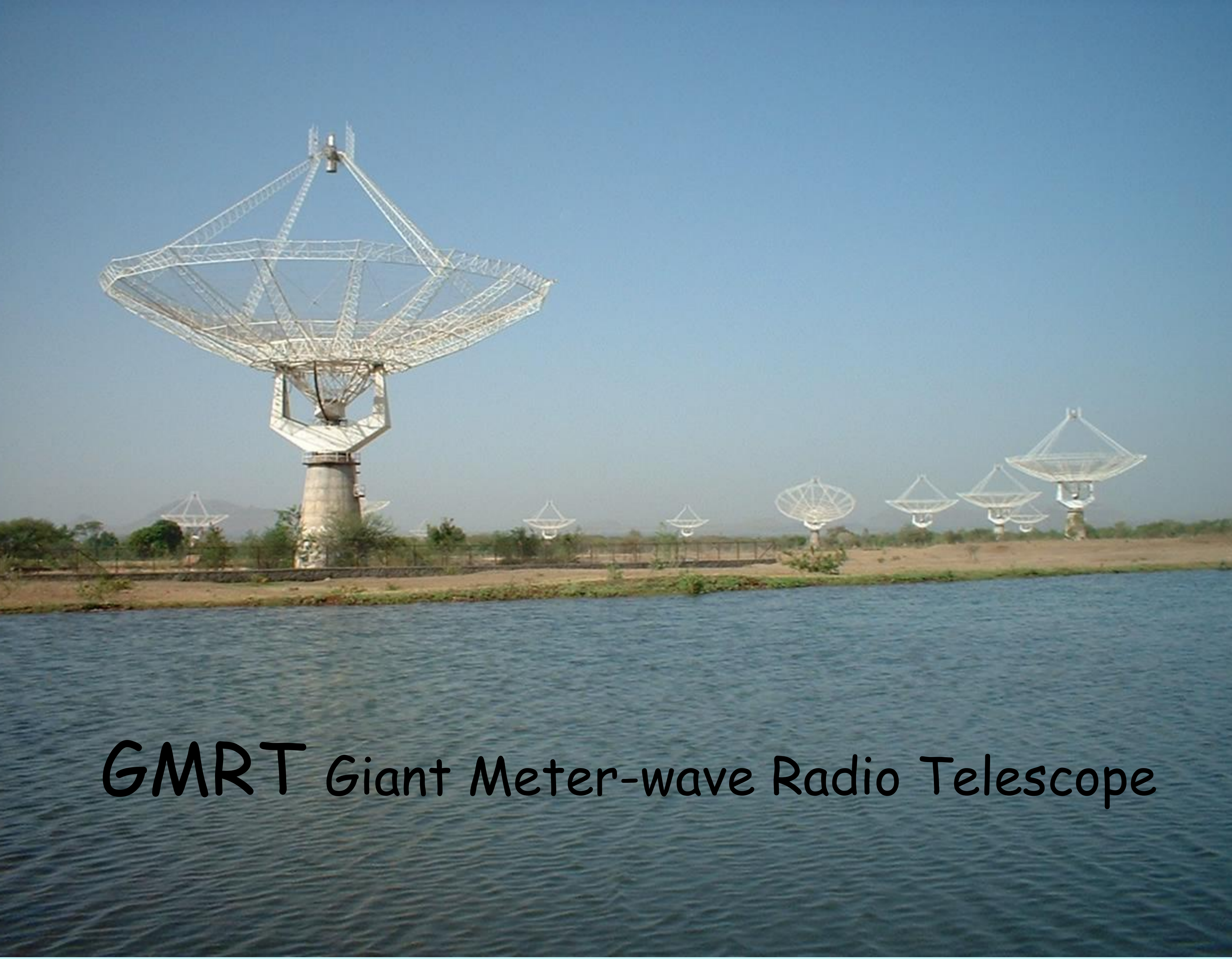
[3] *Harish-Chandra Research Institute, Chhatnag Road, Jhusi, Allahabad 211 019, India*

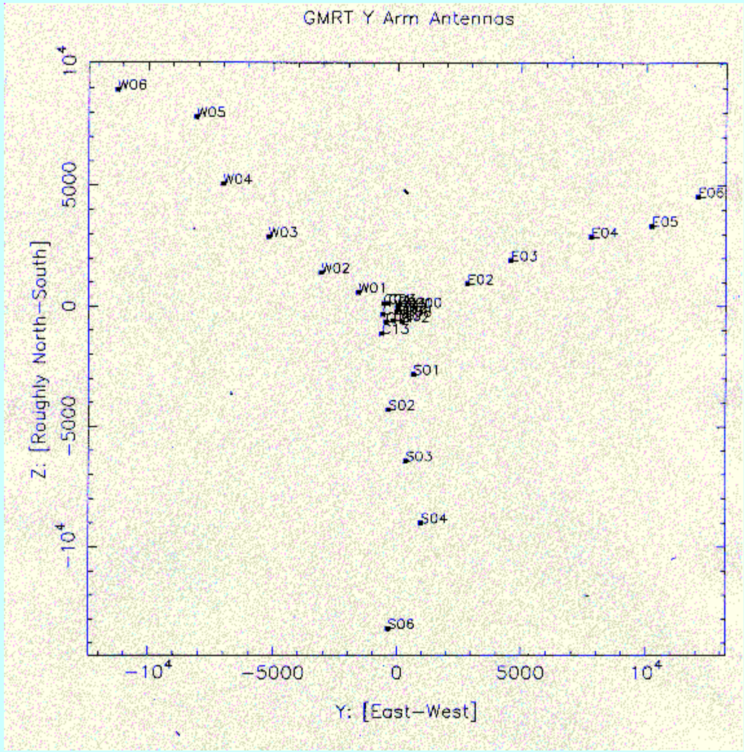
Received 2000 March 14; accepted 2000 October 21.

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 ∼ 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

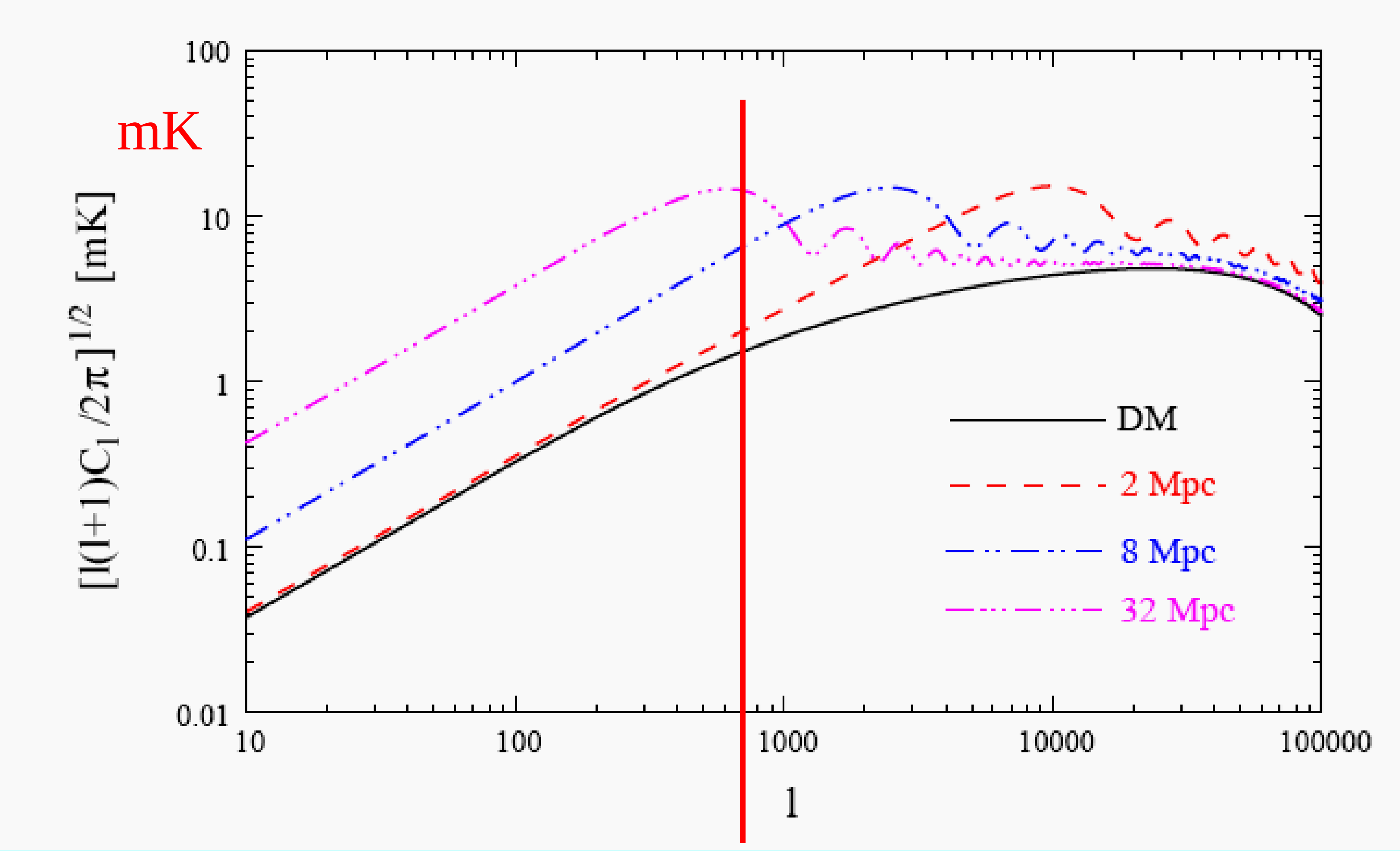
32 MHz bands with 128 separate channels

Have we observed the cosmological 21-cm radiation?

No!

Predicted Signal

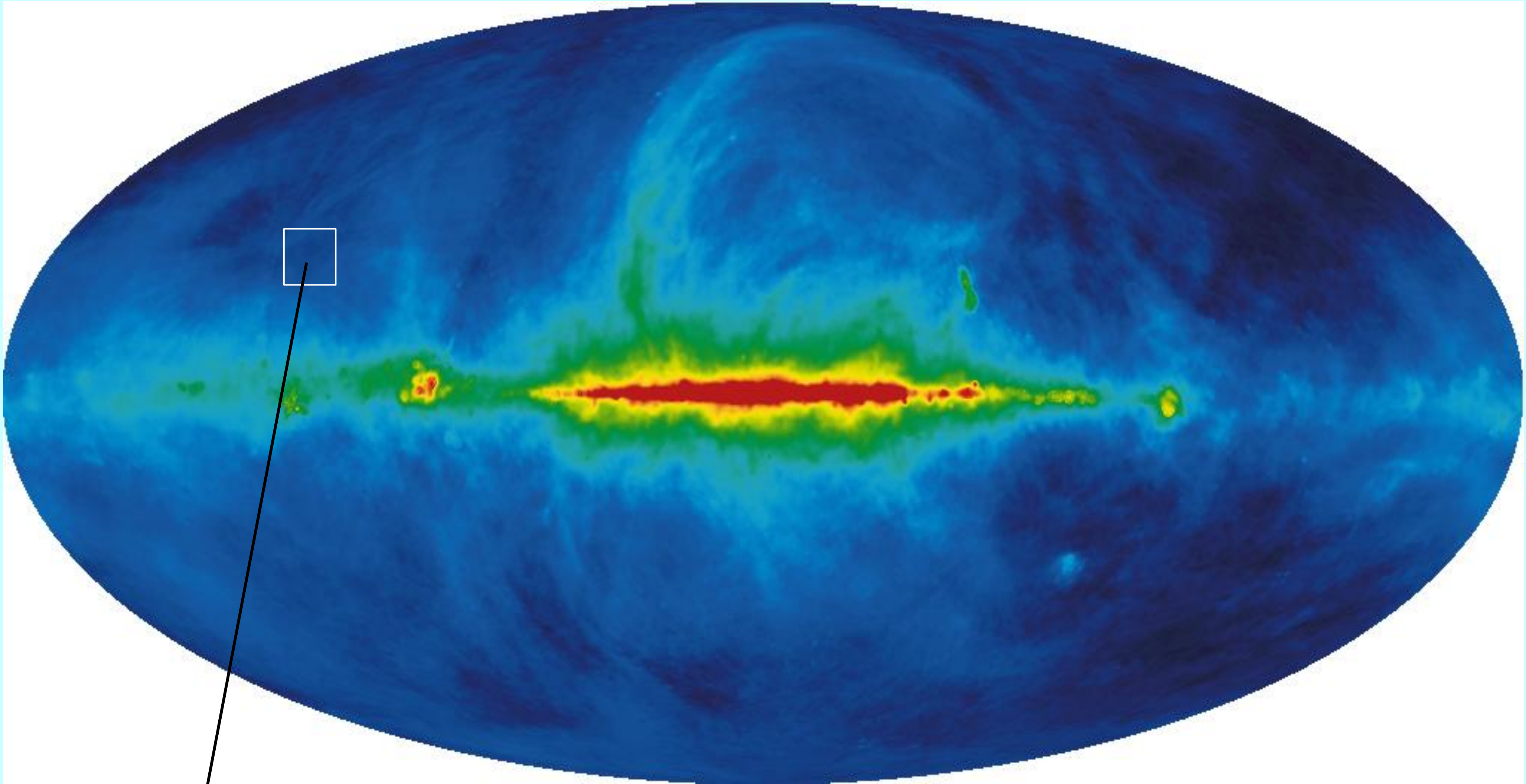
z=10, x=0.5



10 arc-minutes

Datta, Roy Choudhury & Bharadwaj 2007, 387,767

Haslam Map - 408 MHz All-Sky Survey)



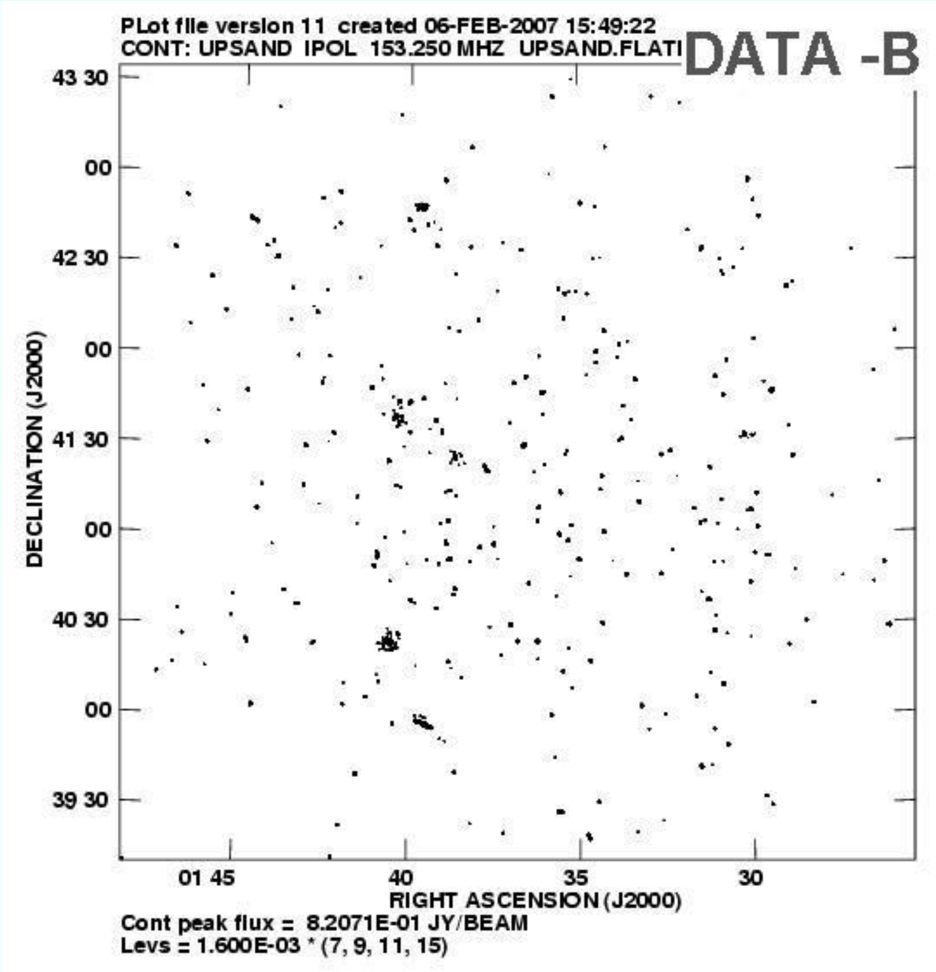
≈ 4^0 Angular scales (off-galactic)

Galactic coordinates (l, b) $151.80^\circ, 13.89^\circ$

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

14 hrs GMRT Observations

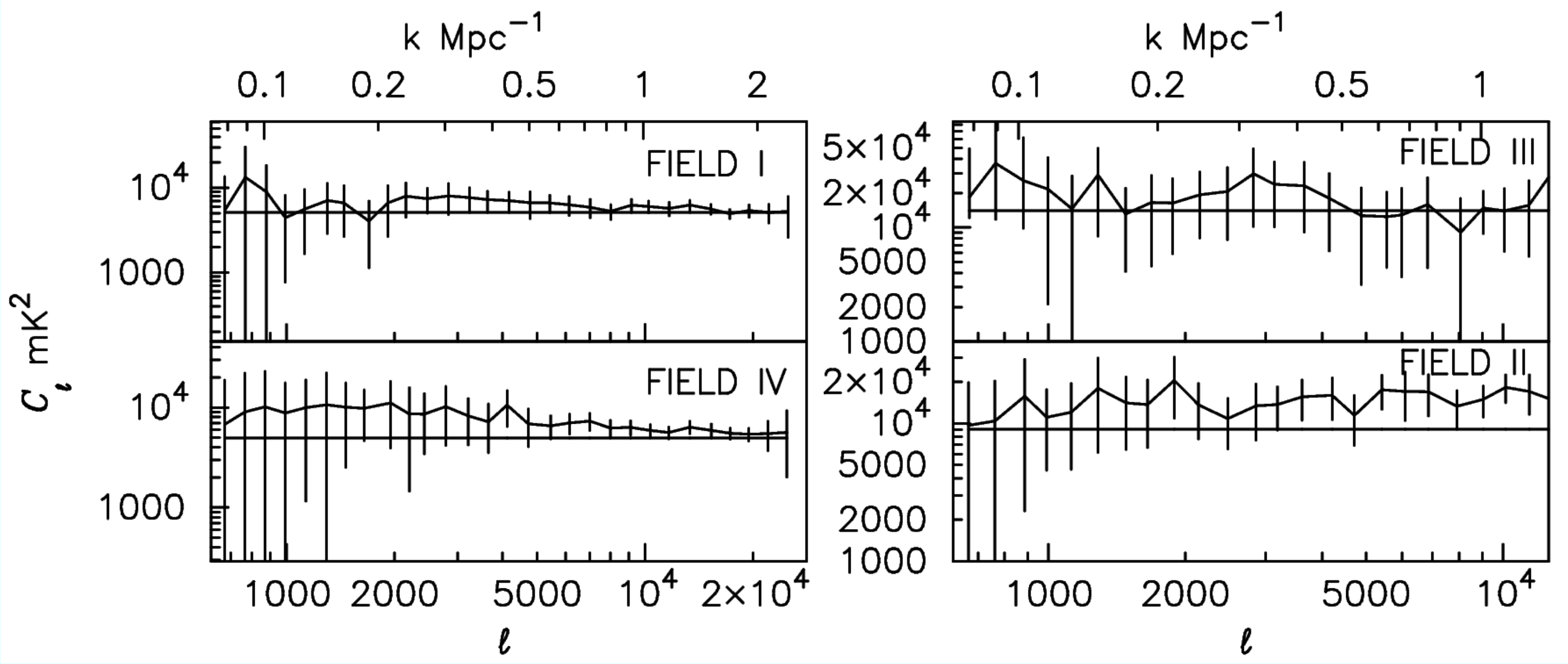
RA 01 36 46 DEC 41 24 23



FIELD IV

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

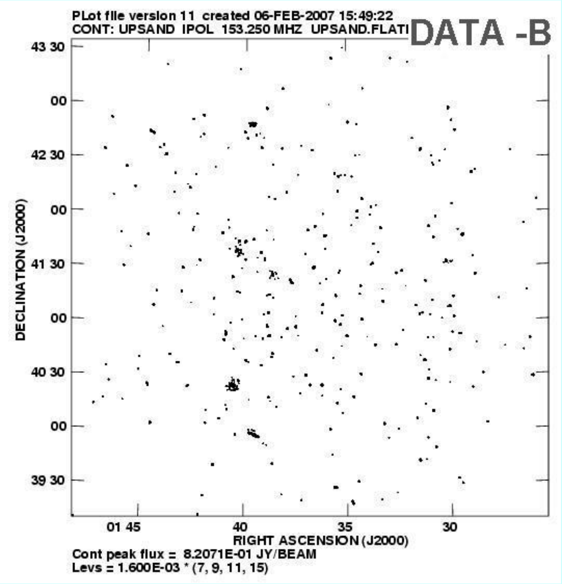
Measured C_ℓ

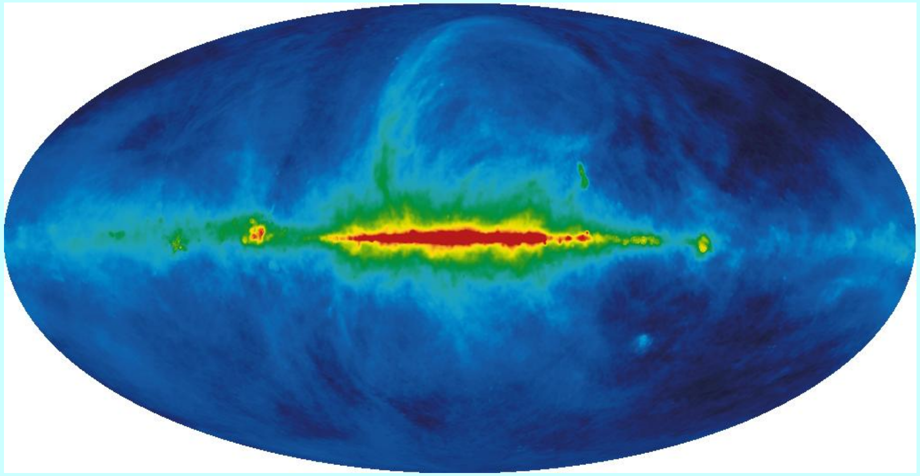


Expected 21-cm Signal $C_\ell \sim 10^{-3} - 10^{-4}$ mK^2

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

Foregrounds



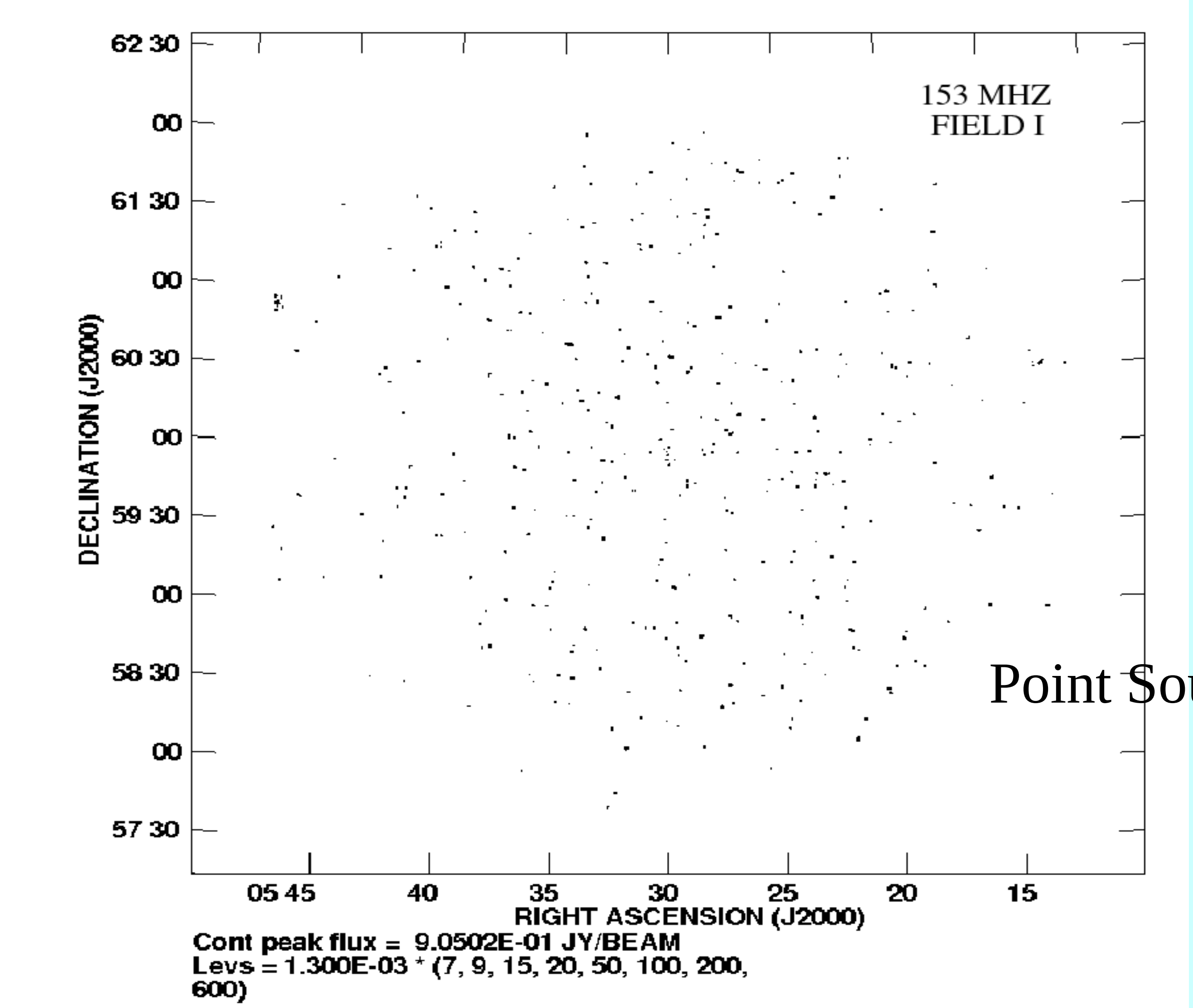


Point Sources

Diffuse

Removal is Biggest Challenge

GMRT Observations



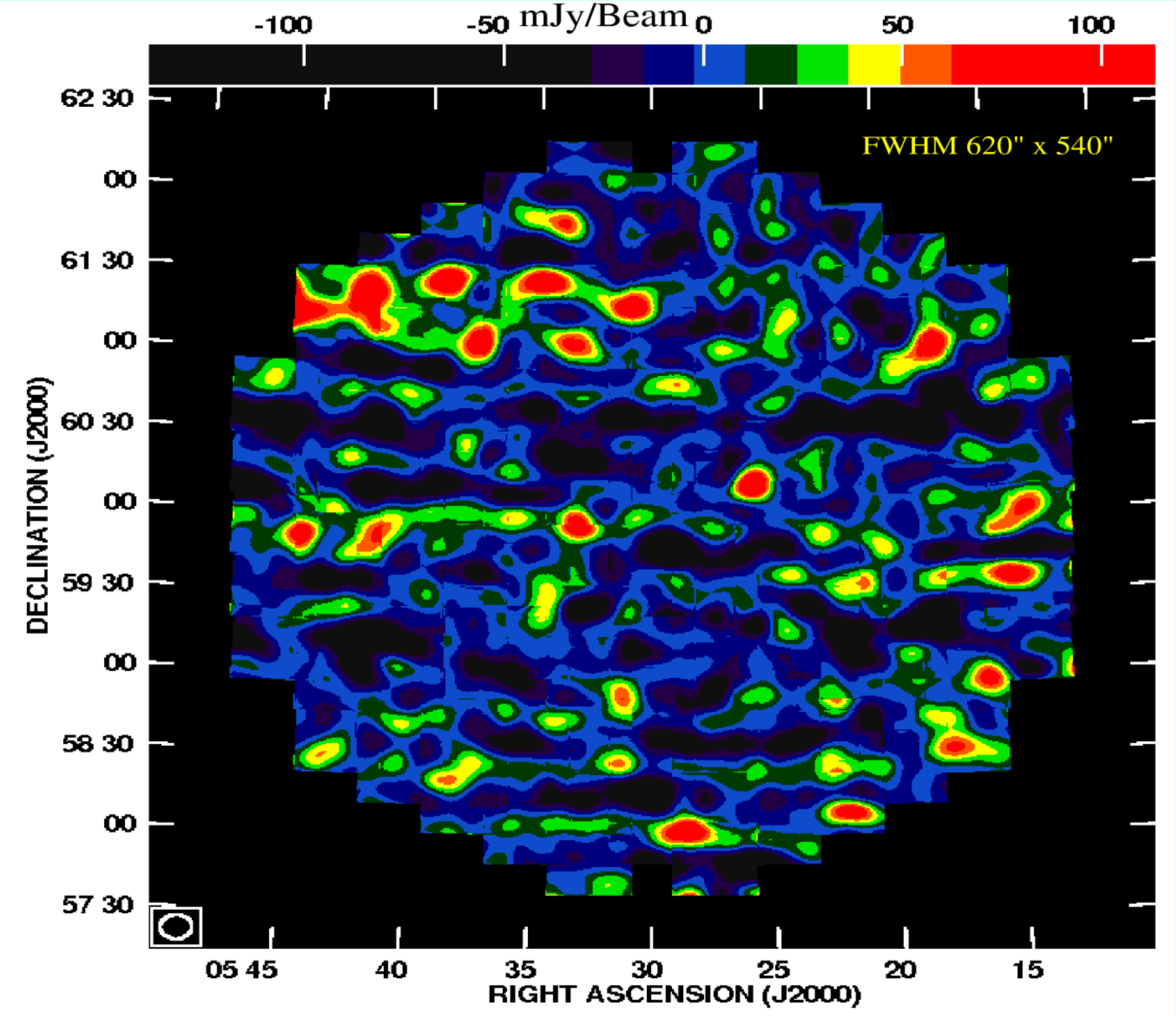
FIELD I

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.

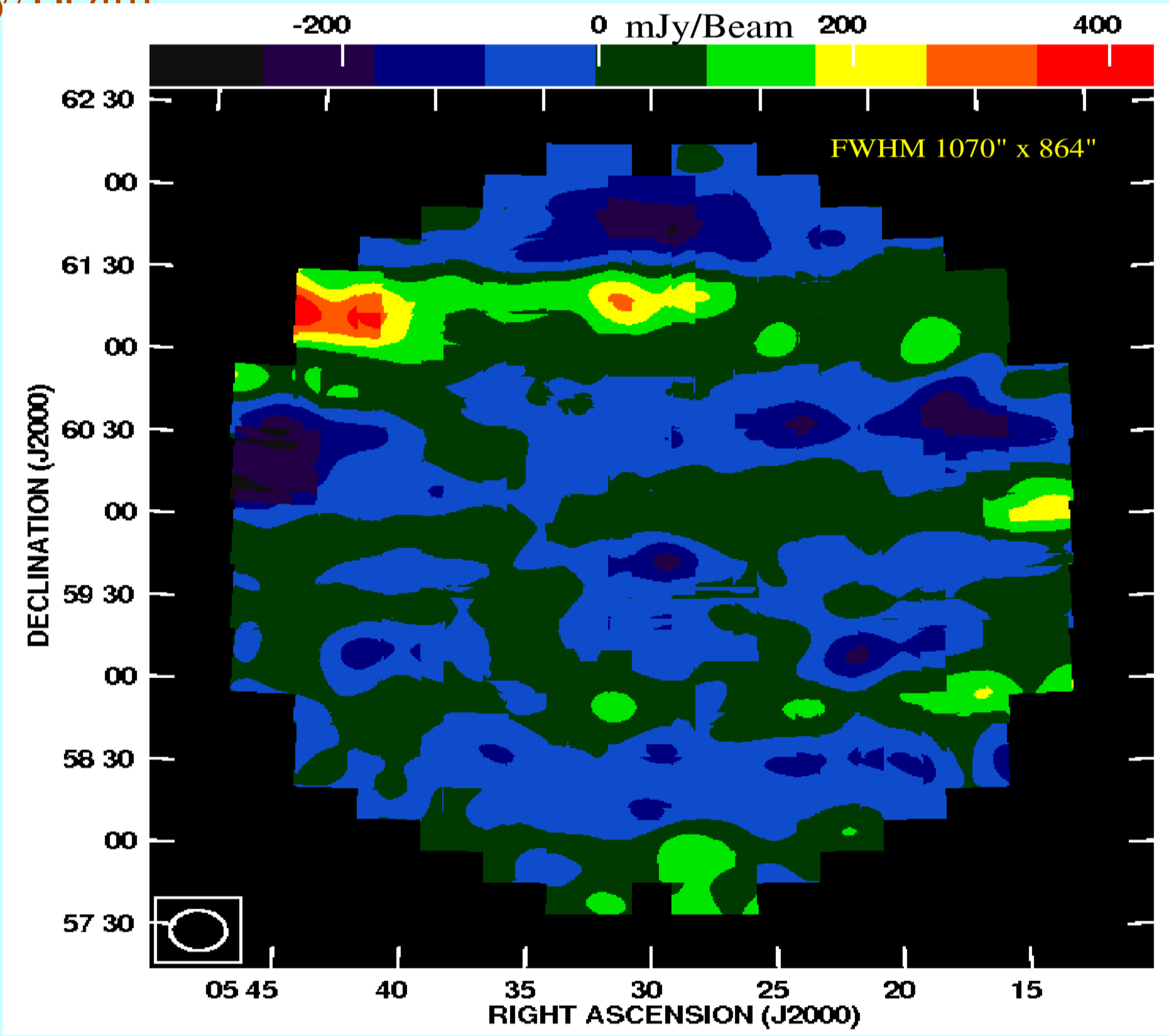


Diffuse Structure Appearing On the Map on Scales > 10 arcmin

Angular resolution	rms (mJy/Beam)	Conversion factor (mJy/Beam) to (K)	rms (K)
620″ × 540″	23.50	0.17	4.00

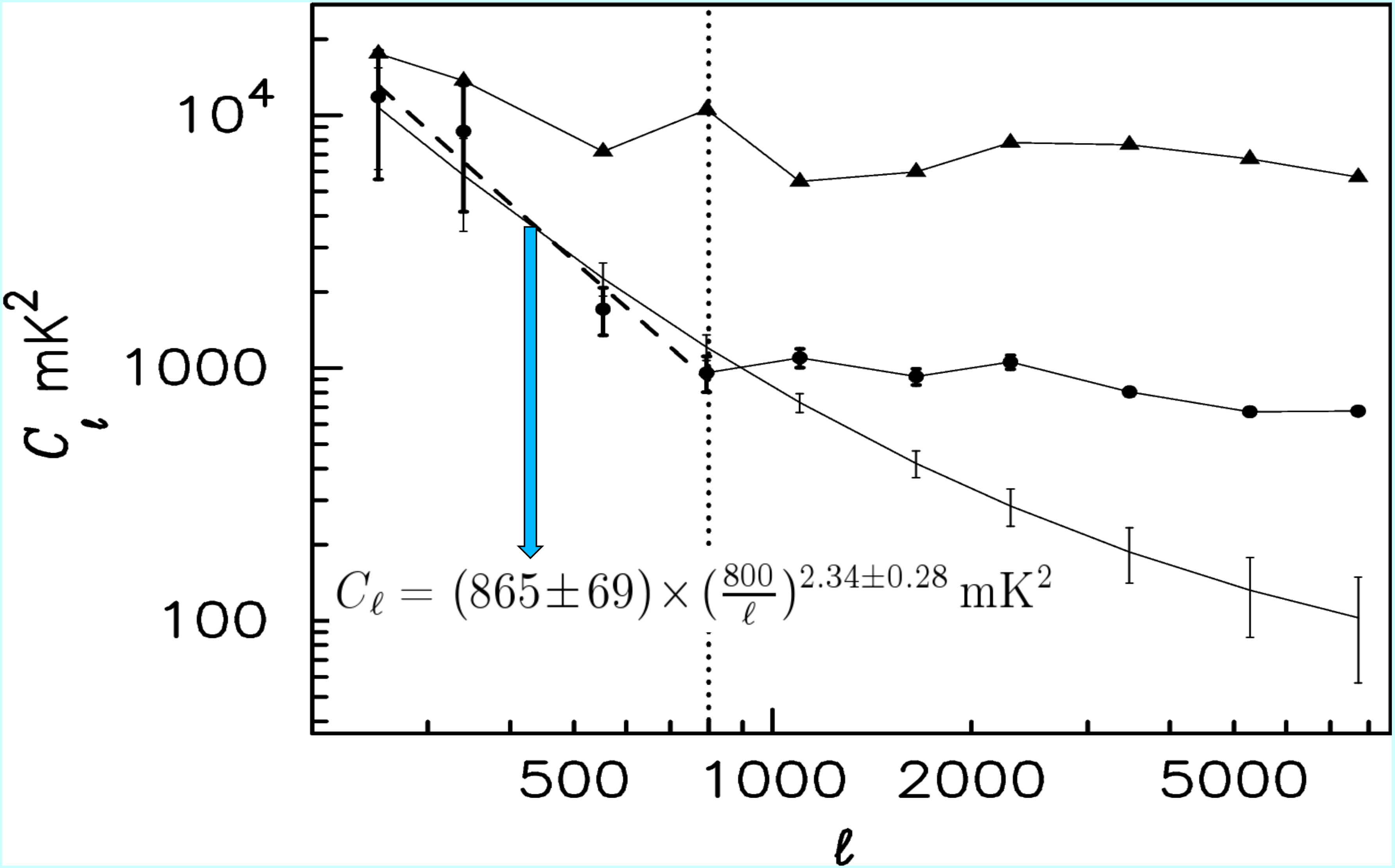
The brightest structures in this map are at 10σ level compared to the local rms value ~ 35 mJy/Beam

Taper @ |U|=100



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

Angular Power spectrum :

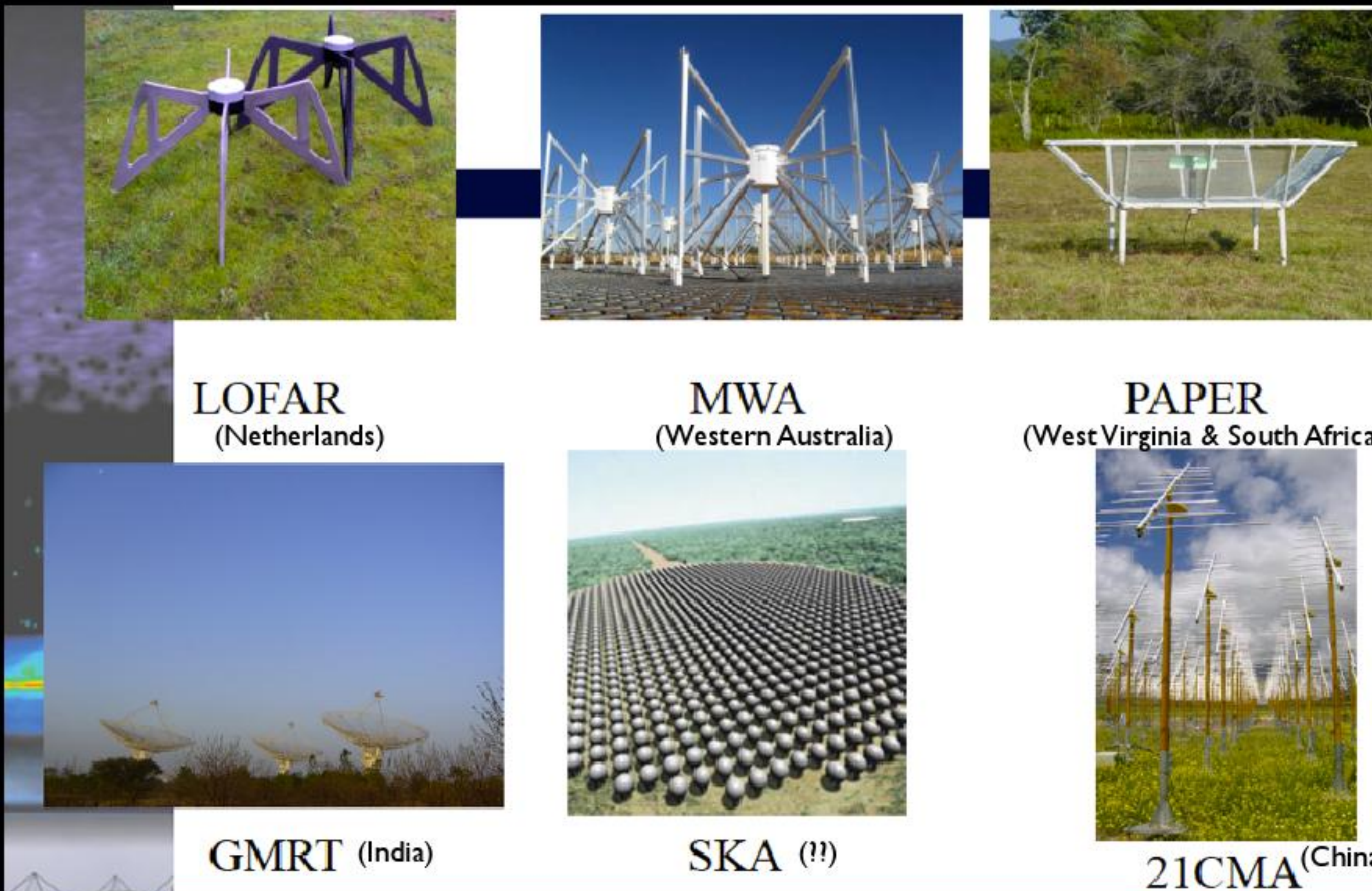


- The power spectrum of the Diffuse emission was fitted by a power-law down to $\ell = 800$ ($\theta \approx 10'$):

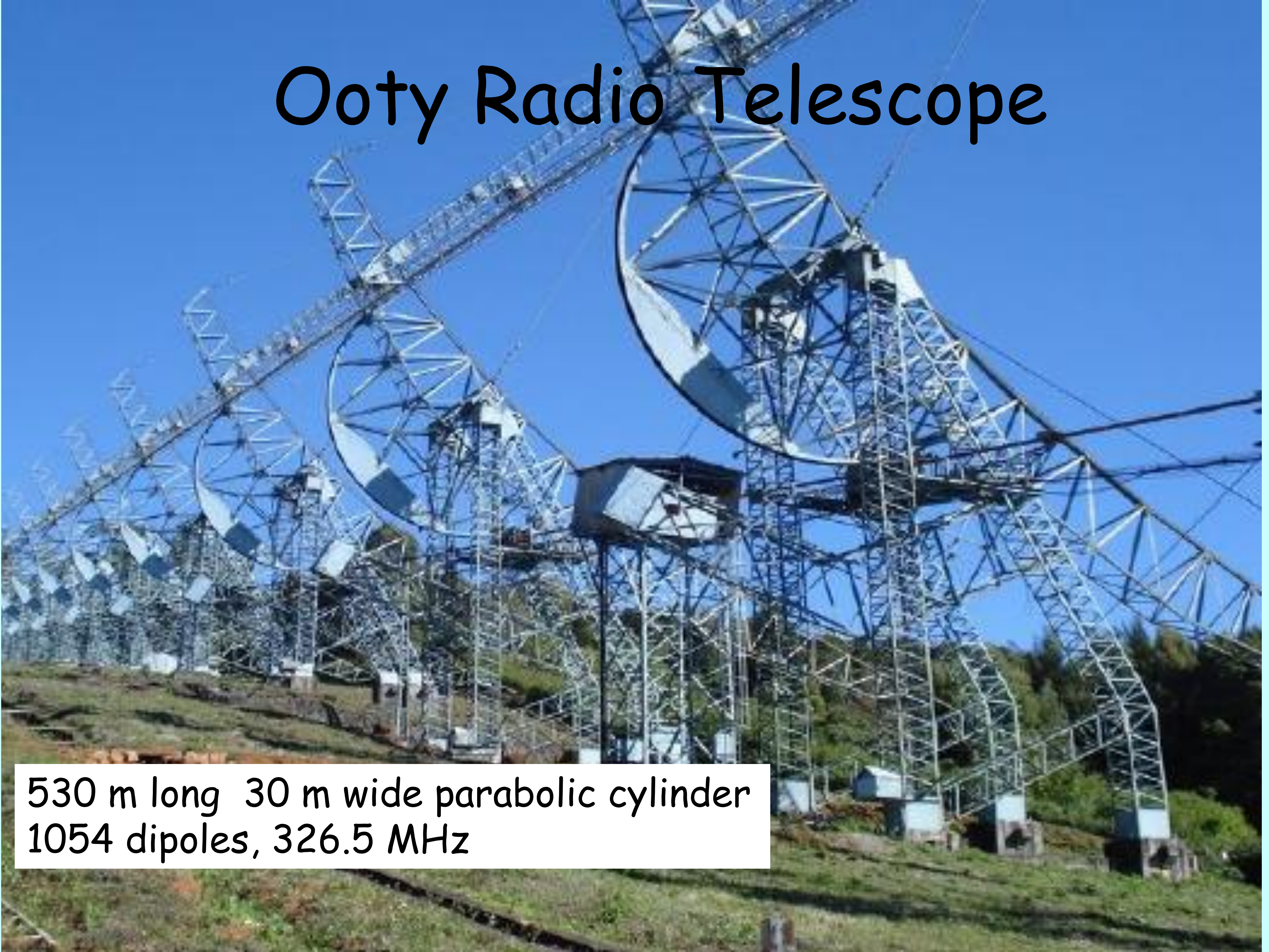
Currently working on

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

Efforts to Detect the Spatially Fluctuating 21cm Signal from Reionization

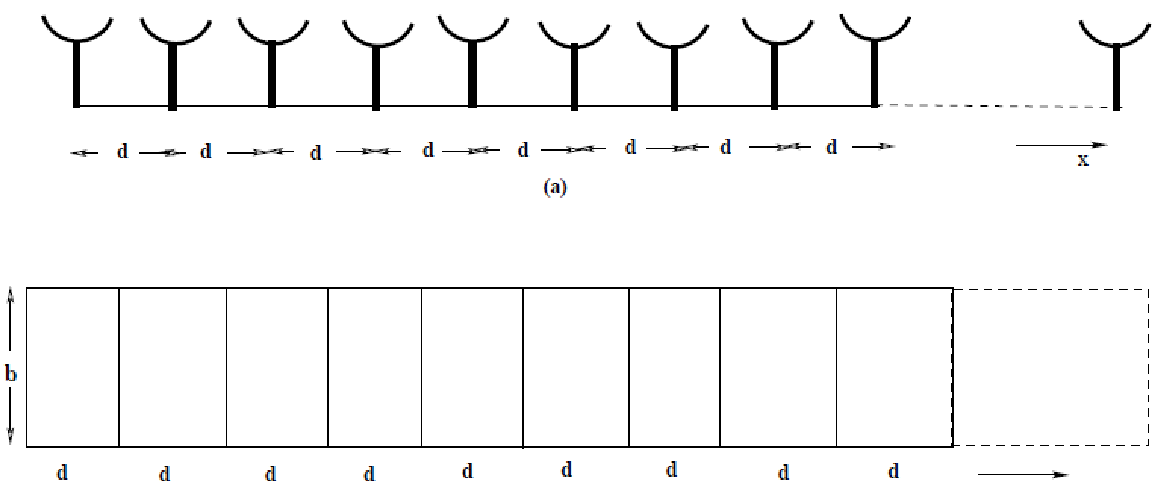


Ooty Radio Telescope



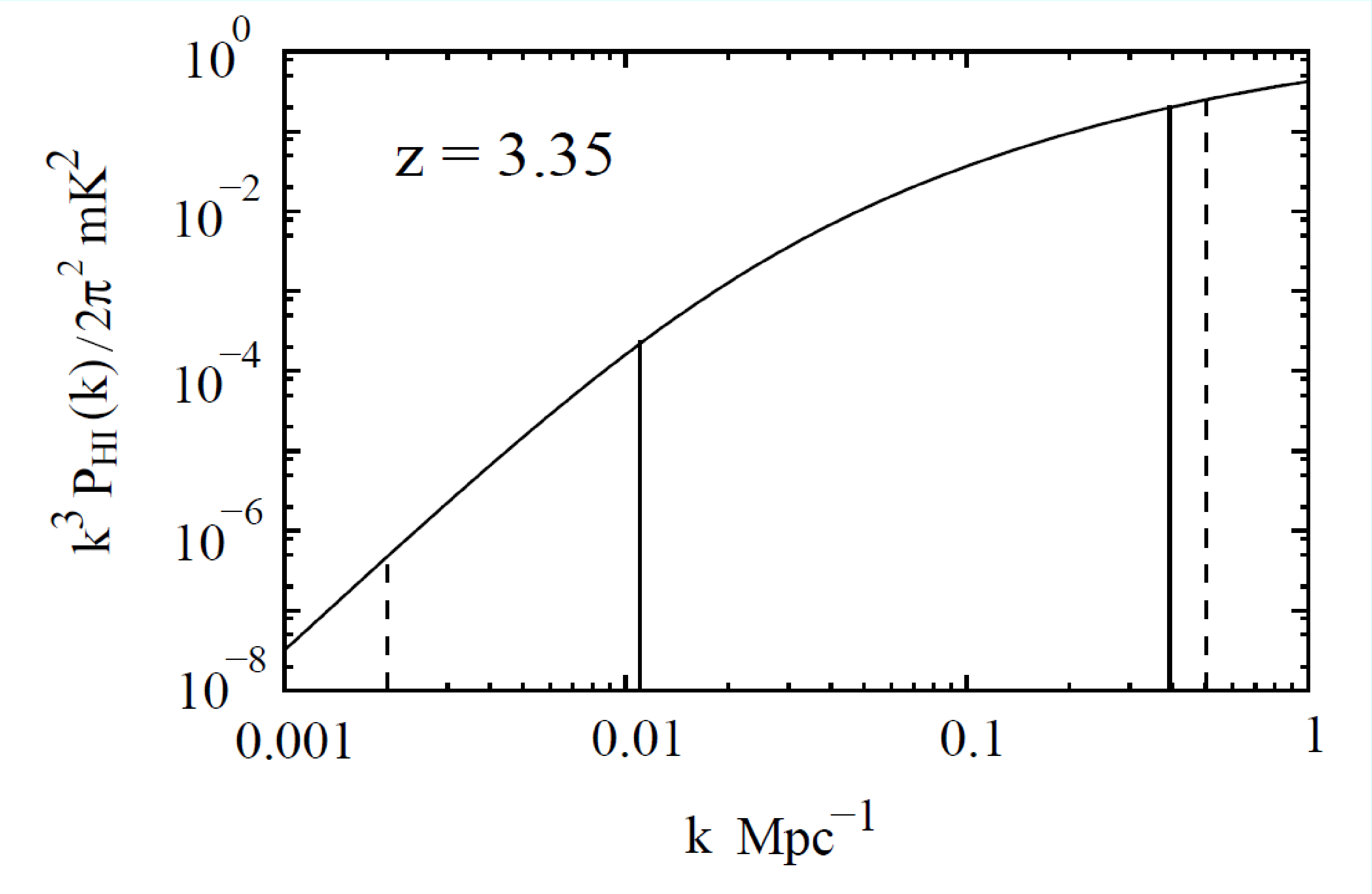
530 m long 30 m wide parabolic cylinder
1054 dipoles, 326.5 MHz

Ooty Wide Field Array - OWFA



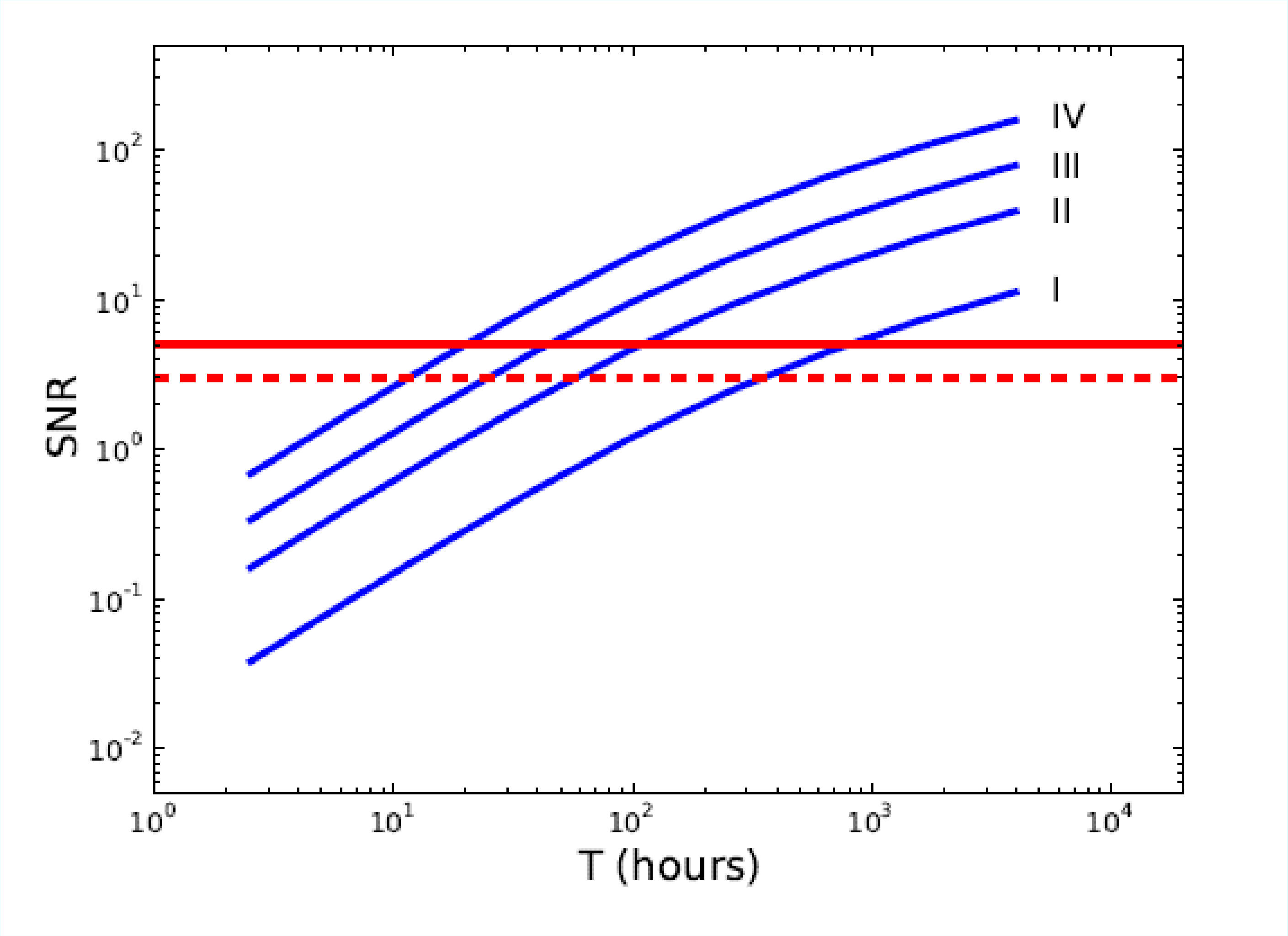
Parameter	Phase I	Phase II
No. of antennas (N_A)	40	264
Aperture dimensions ($b \times d$)	$30\,\mathrm{m} \times 11.5\,\mathrm{m}$	$30\,\mathrm{m} \times 1.92\,\mathrm{m}$
Field of View(FoV)	$1.75^\circ \times 4.6^\circ$	$1.75^\circ \times 27.4^\circ$
Smallest baseline (d_{min})	11.5 m	1.9 m
Largest baseline (d_{max})	448.5 m	505.0 m
Angular resolution	$7'$	$6.3'$
Total bandwidth (B)	18 MHz	30 MHz
Single Visibility rms. noise (σ) assuming $T_{sys} = 150\,\mathrm{K}, \eta = 0.6$, $\Delta\nu_c = 0.1\,\mathrm{MHz}, \Delta t = 16\,\mathrm{s}$	1.12 Jy	6.69 Jy

HI SIgnal



Ali & Bharadwaj, 2014

Predictions for OWFA



5 σ detection possible in ~ 100 hors of observation

Bharadwaj, Ali and Sarkar, 2014, in Preparation


Thank You

Concluding Remarks

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

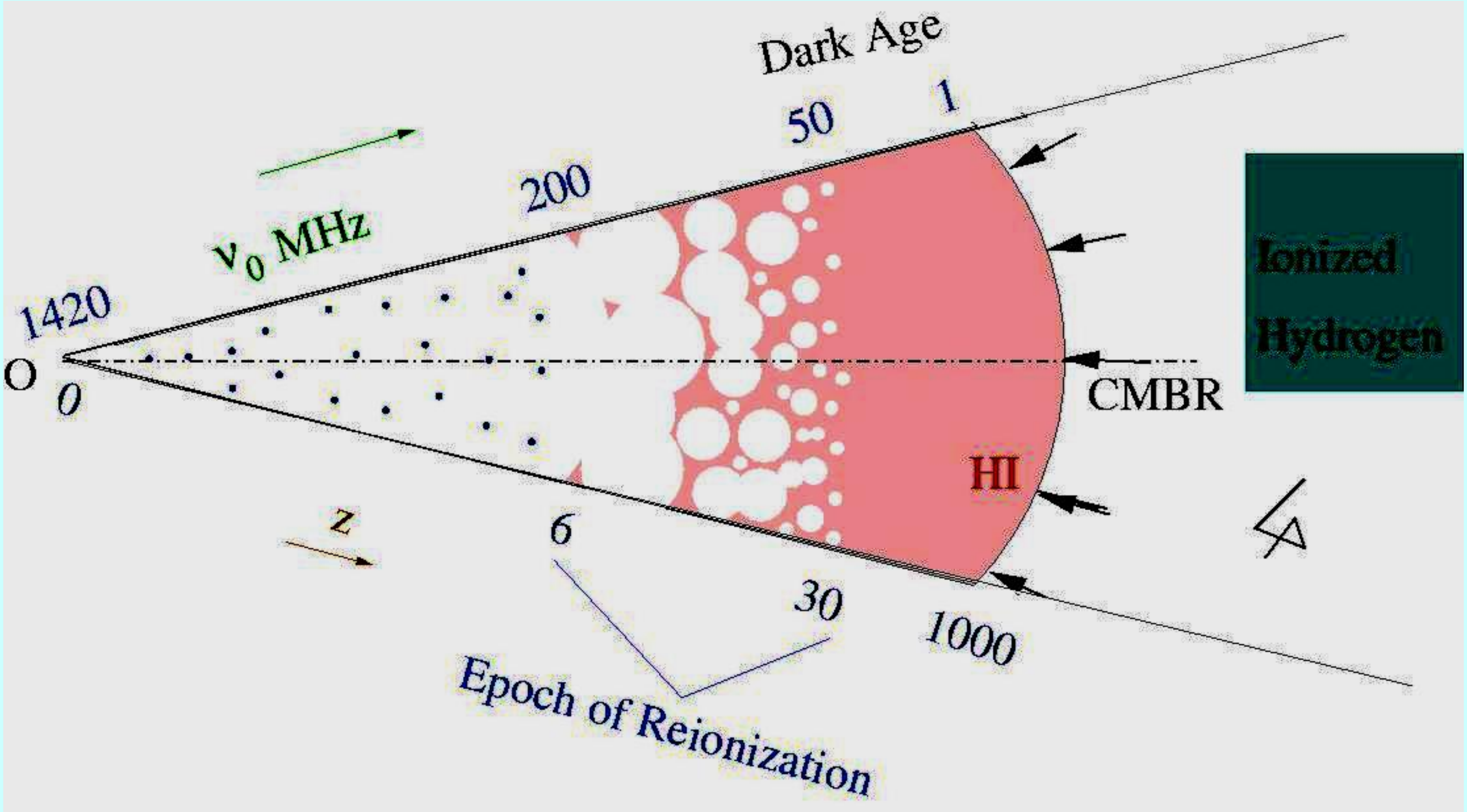
21-cm signal

$$\tau = \frac{3\bar{n}_{\rm H} h_{\rm p} c^3 A_{10}}{32\pi k_{\rm B} T_{\rm s} \nu_{\rm e}^2 H(z)} \left[1 + \Delta_{\rm H} - \frac{1}{H(z)a(z)} \frac{\partial v}{\partial r} \right]$$

$$\delta T_{\rm b}(\boldsymbol{n}, \nu) = \bar{T} \left[\left(1 - \frac{T_\gamma}{T_{\rm s}} \right) \left(\Delta_{\rm H} - \frac{1}{Ha} \frac{\partial v}{\partial r} \right) + \frac{T_\gamma}{T_{\rm s}} s \Delta_{\rm H} \right]$$

$$\bar{T} = 2.67 \times 10^{-3}{\rm K} \quad \frac{\Omega_{\rm b} h^2}{0.02} \frac{(1+z)^{1/2}}{\Omega_{\rm m0}^{1/2} h}$$

HI Evolution



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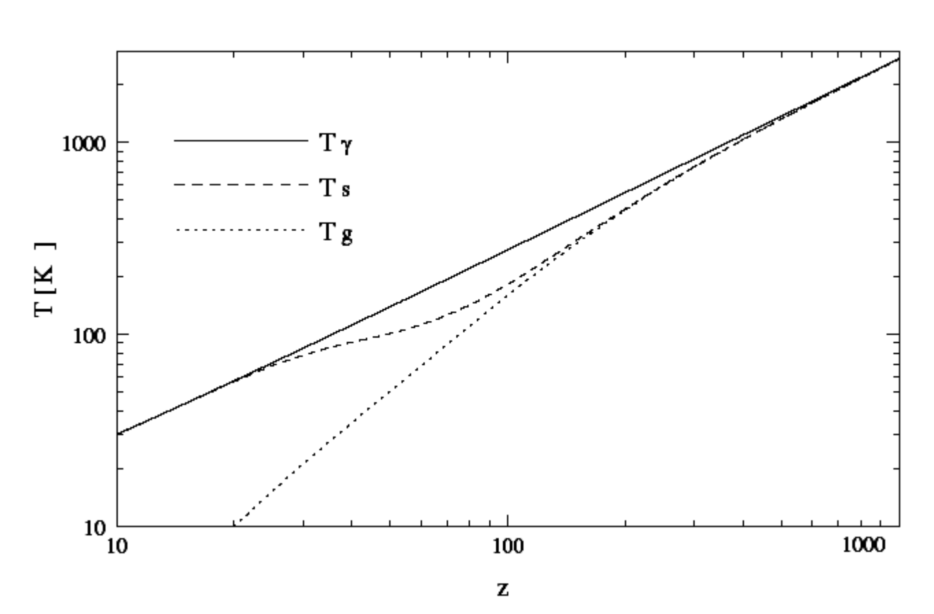
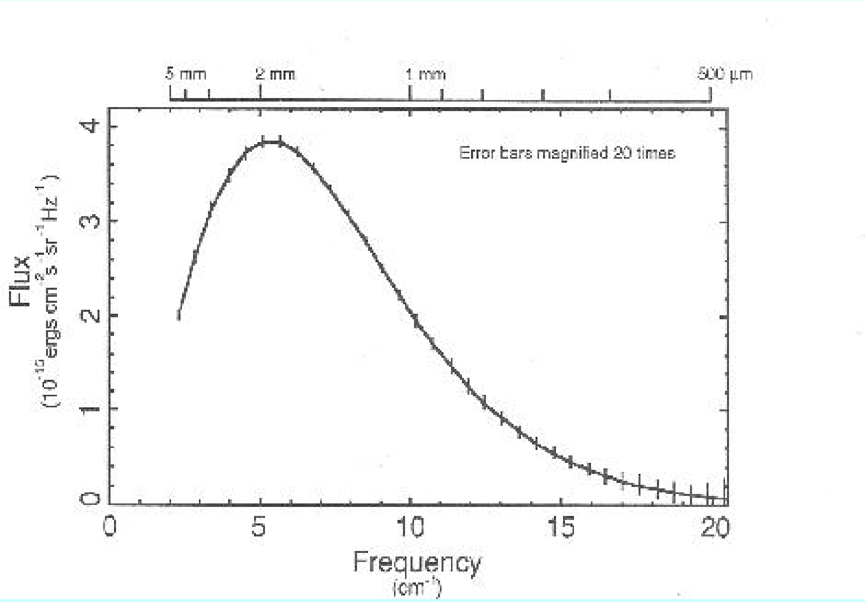
Will be seen in absorption against CMBR 200 > z > 30





Ts < Tγ

Statistical Signal

$$a_{lm}(\nu) = \int \mathrm{d}\Omega\, Y^*_{lm}(\hat{\mathbf{n}})\, T(\nu, \hat{\mathbf{n}})$$

$$C_l(\nu_1, \nu_2) \equiv \langle a_{lm}(\nu_1)\, a^*_{lm}(\nu_2) \rangle$$

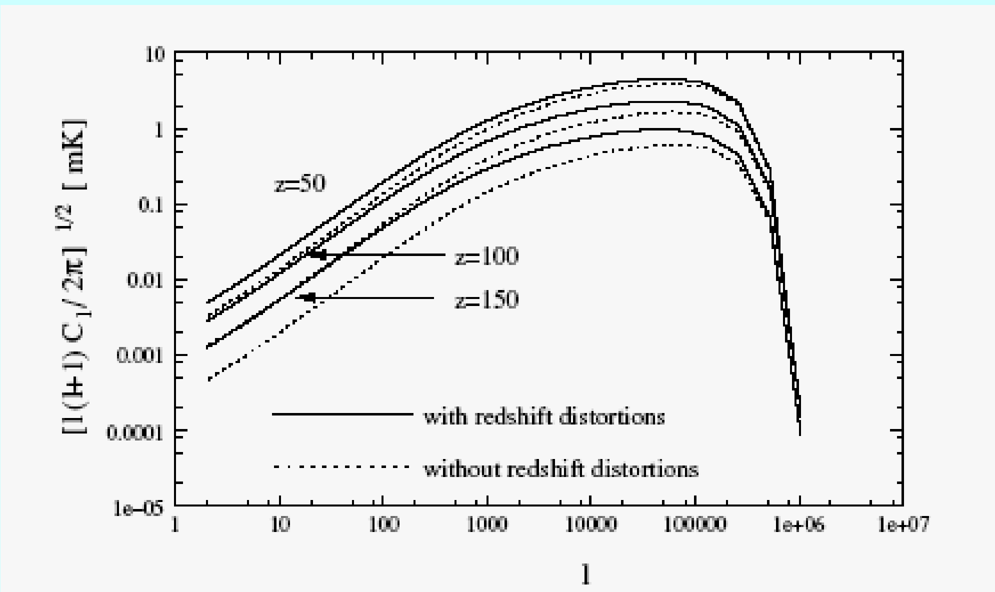
MAPS

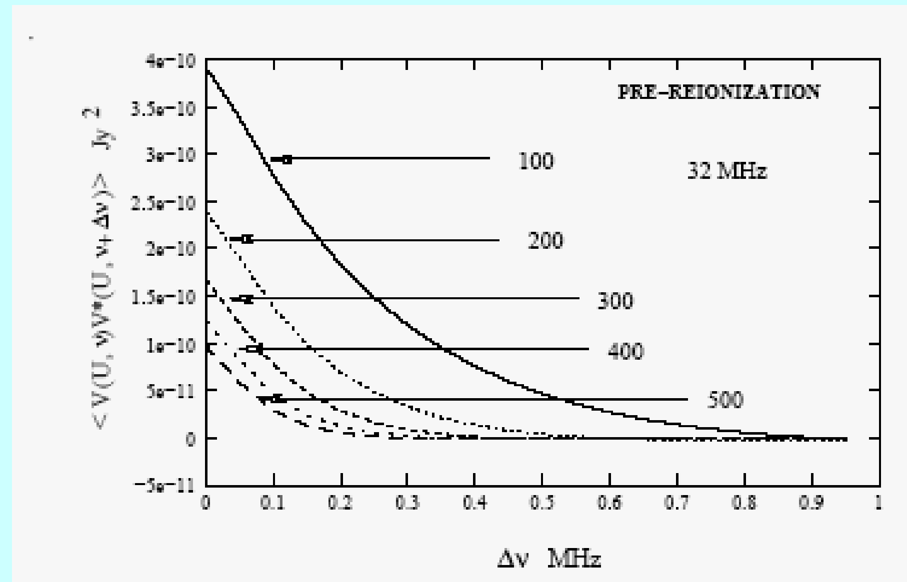
$$C_l(\Delta\nu) \equiv C_l(\nu, \nu + \Delta\nu)$$

$$\kappa_l(\Delta\nu) \equiv \frac{C_l(\Delta\nu)}{C_l(0)}$$

$$C_l^{\rm flat}(\Delta\nu) = \frac{\bar{T}^2}{\pi r_\nu^2} \int_0^\infty \mathrm{d}k_\parallel\, \cos(k_\parallel r'_\nu \Delta\nu)\, P_{\rm HI}(\mathbf{k})$$

Prereionization Signal





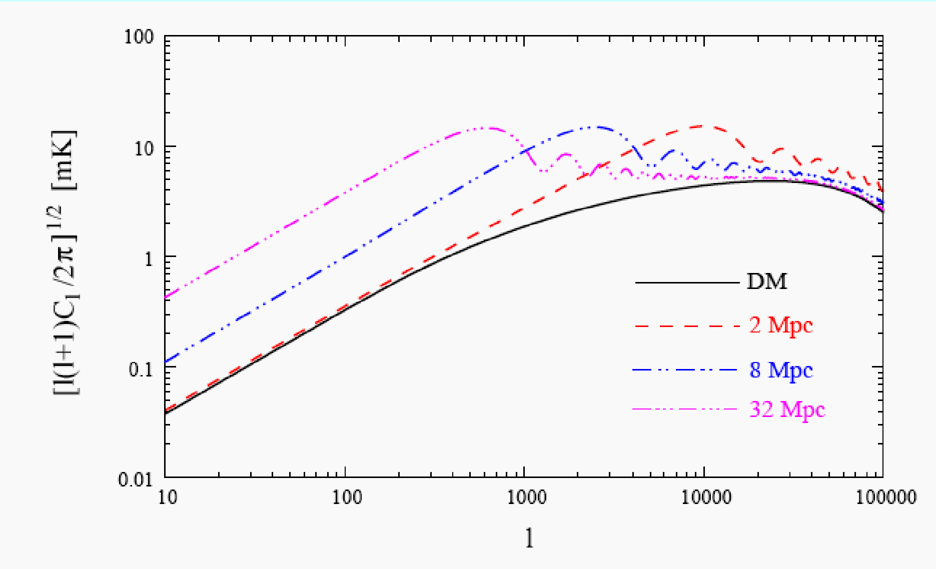
Very sensitive probe of the dark matter power spectrum

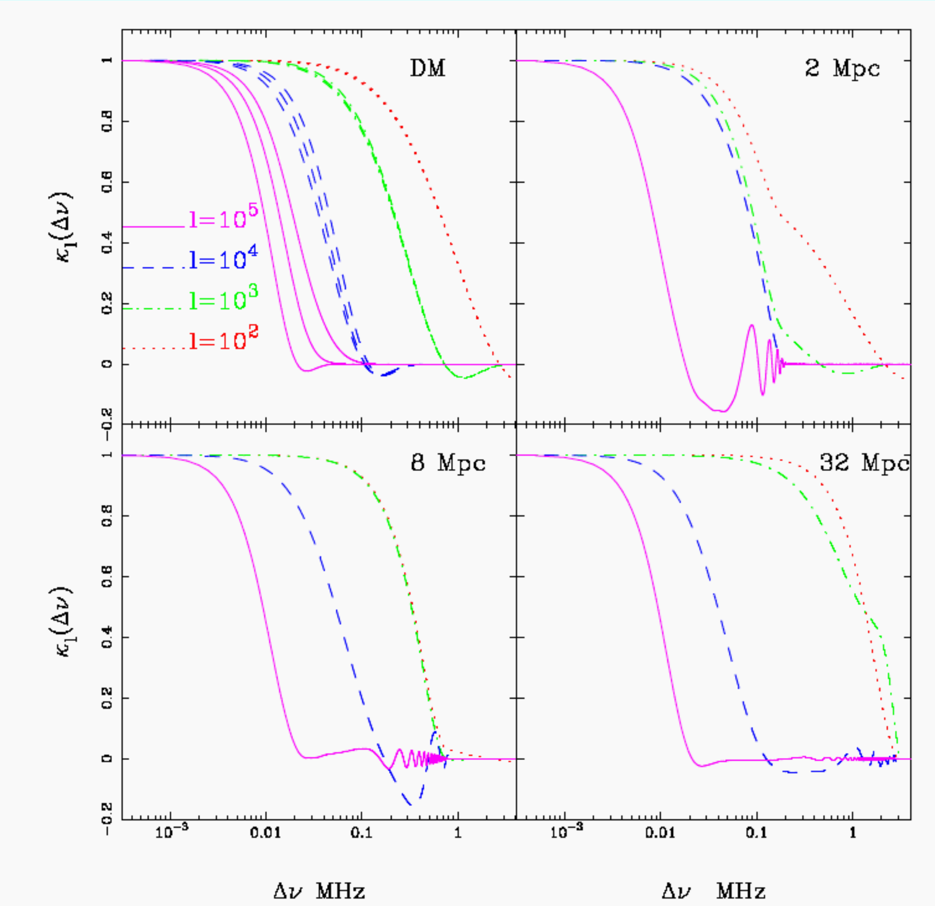
Epoch of reionization

- Luminous sources produce UV/X-ray
- Ionize and heat IGM
- $T_s > T_\gamma$
- 21-cm signal is in emission
- HI distribution is patchy
- ionized bubbles around luminous sources

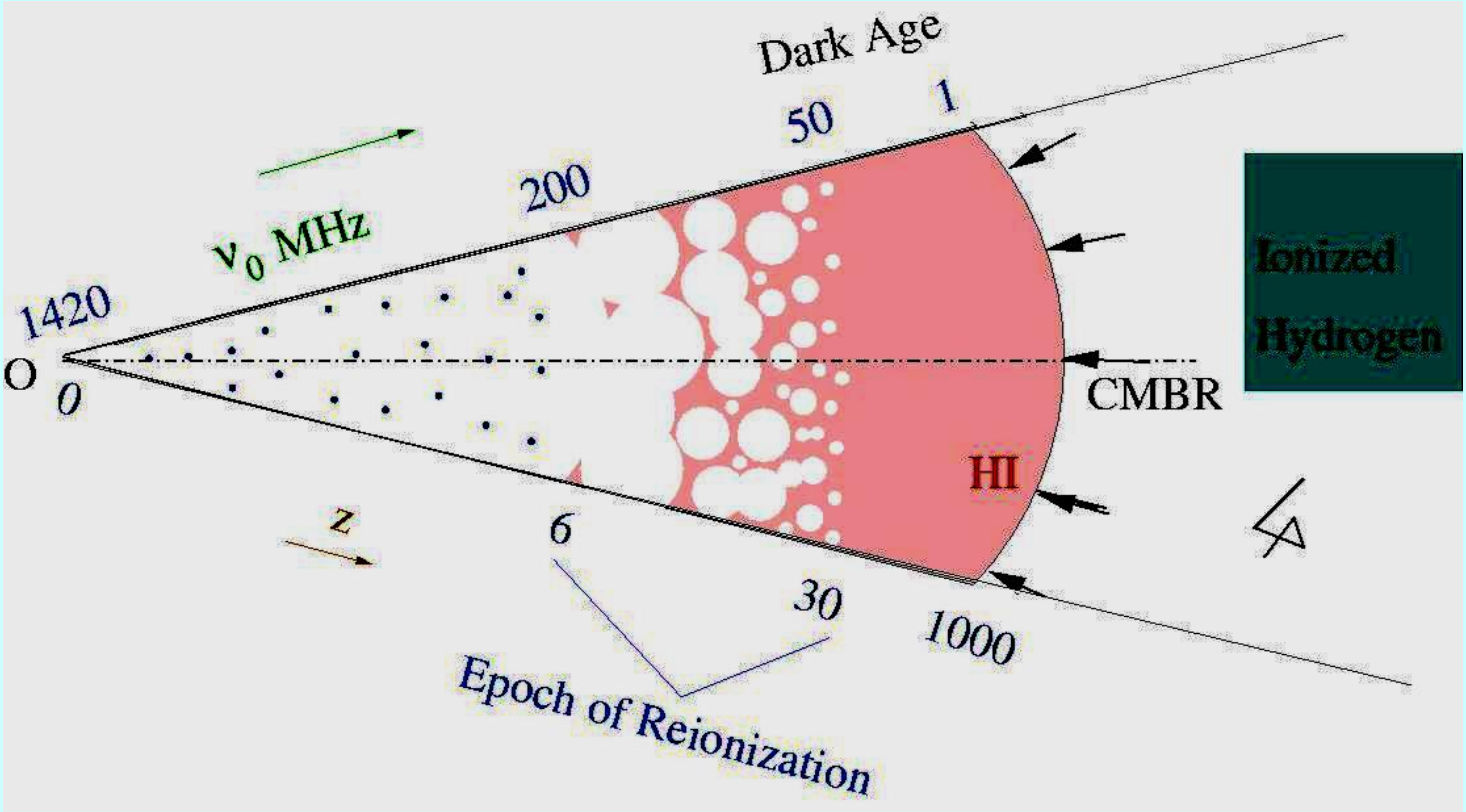
Reionization Signal

X=0.5, z=10





HI Evolution



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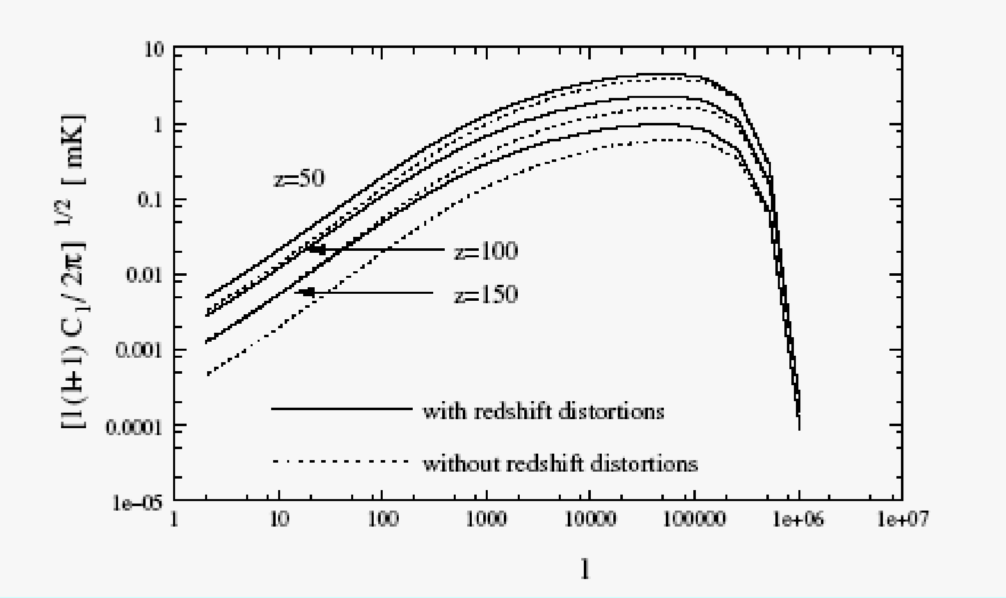
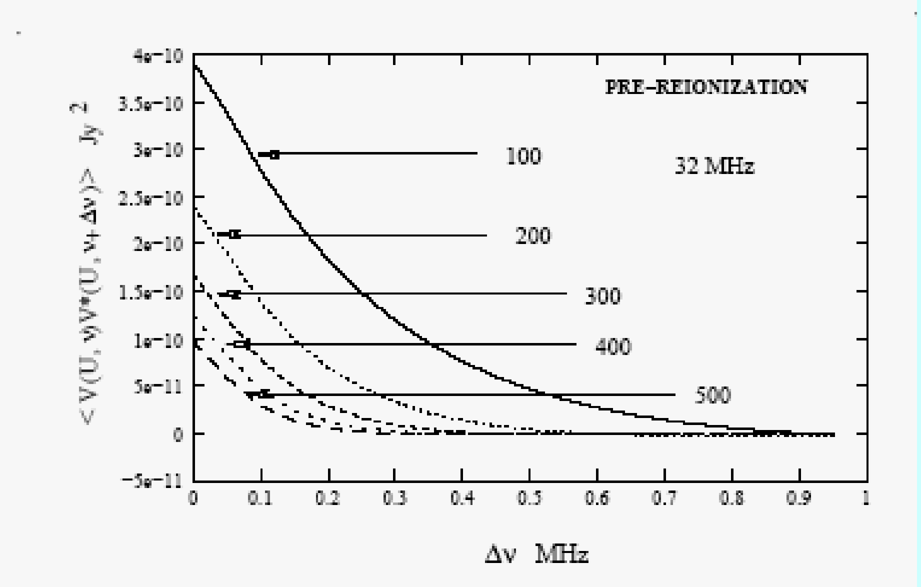
Prereionization Signal





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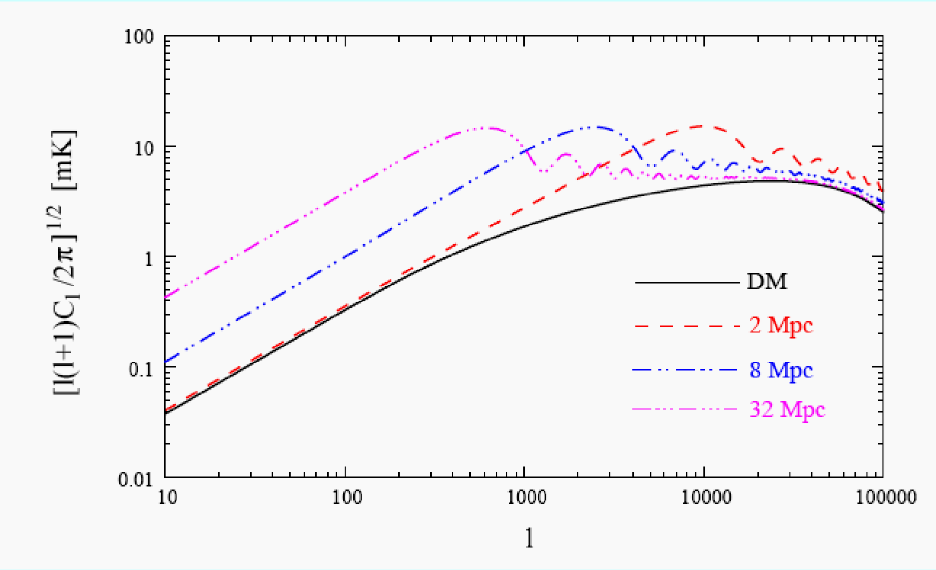
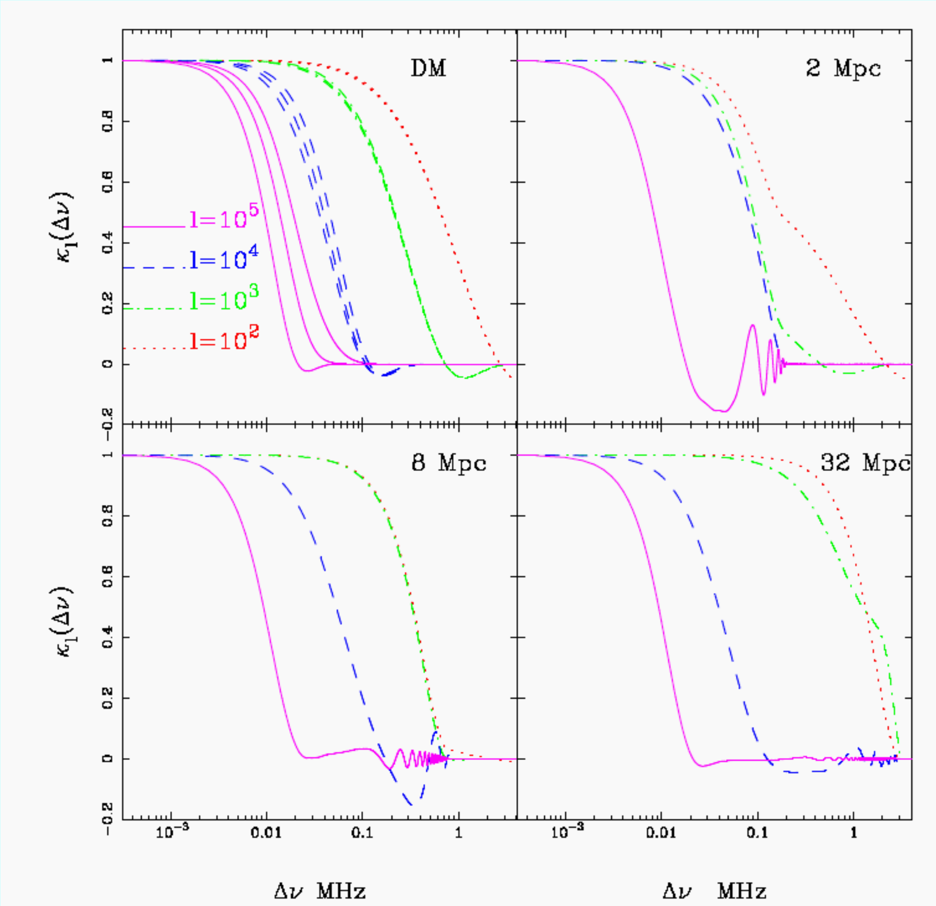
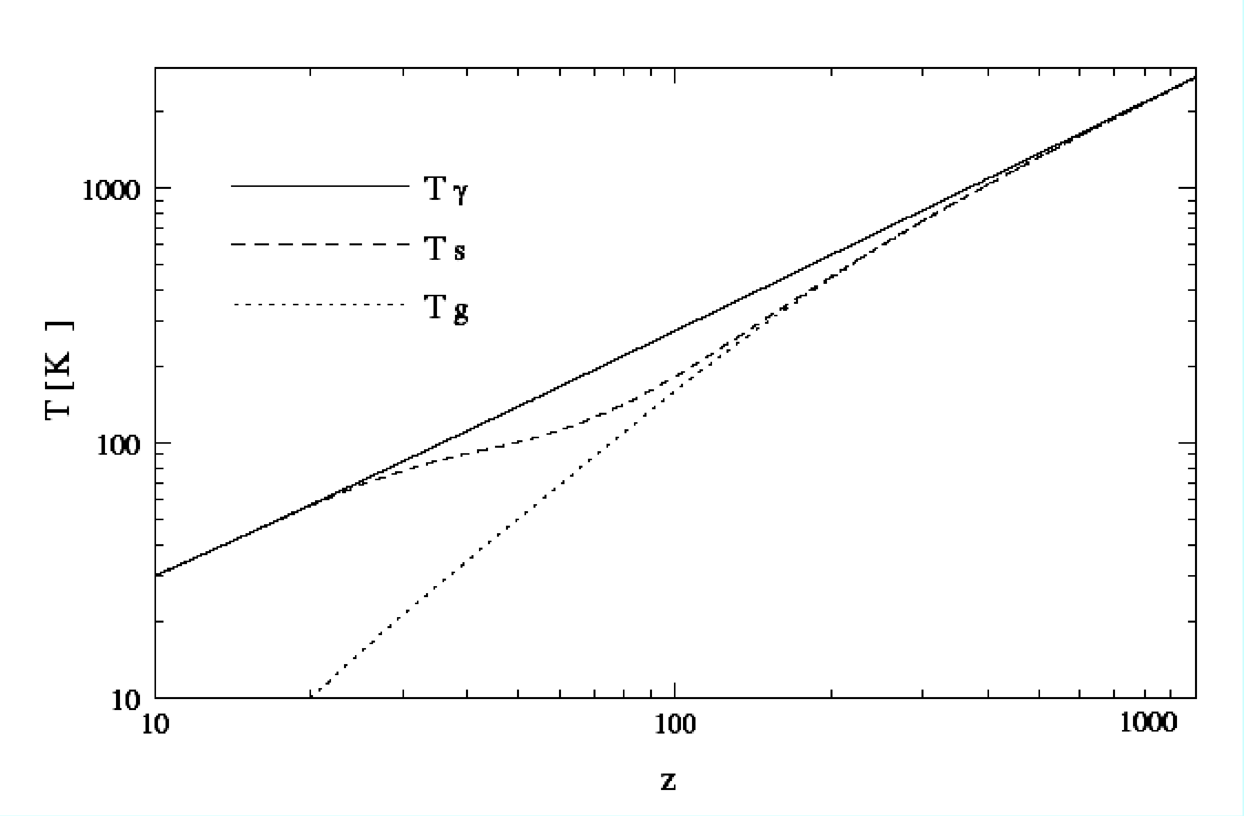




z > 1000



T_{γ} =2.725 K (1+z)

Hydrogen is ionized at z>1,000

Recombination – HI formed for first time at z=1,000