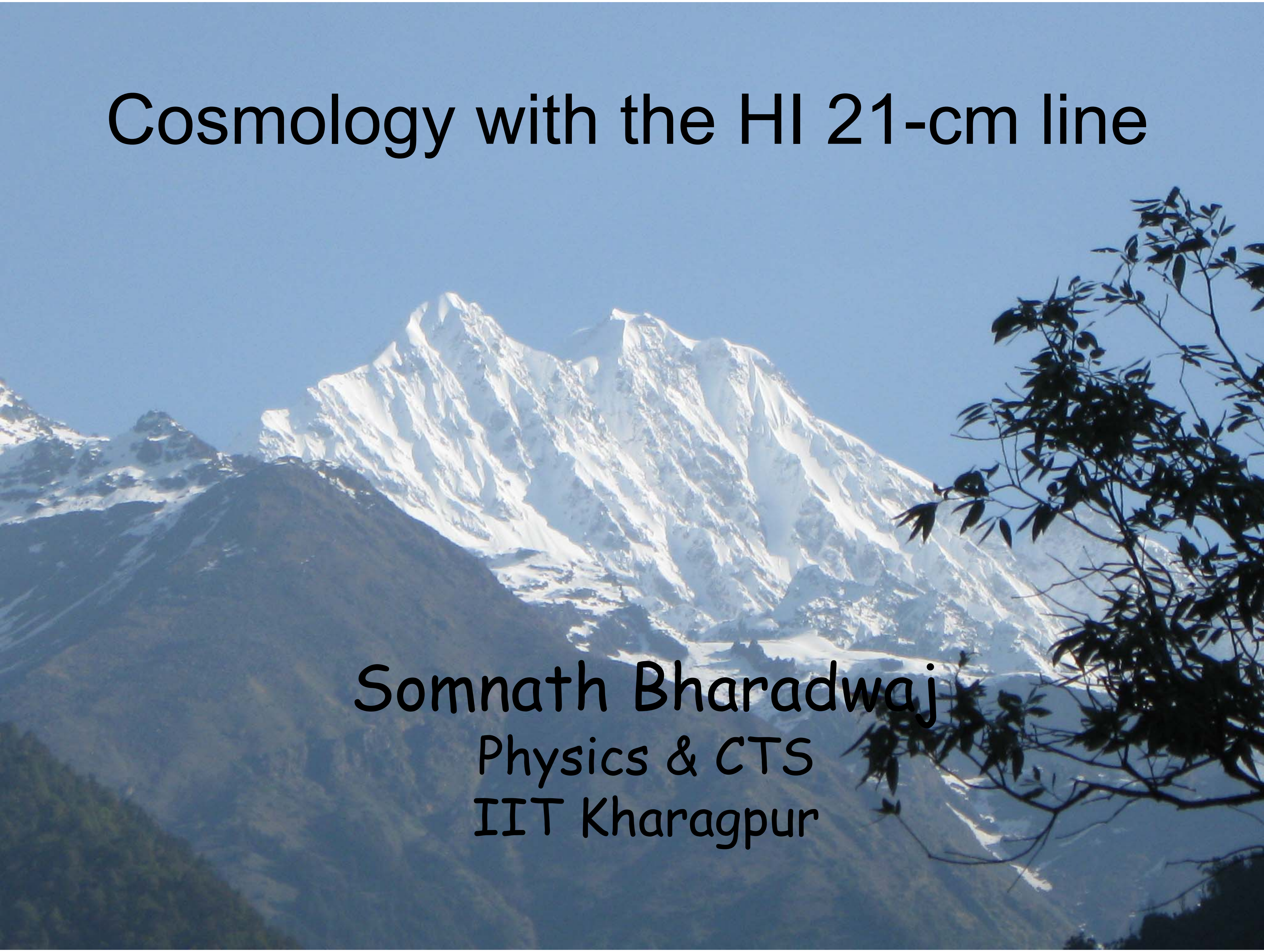

Cosmology with the HI 21-cm line

Somnath Bharadwaj
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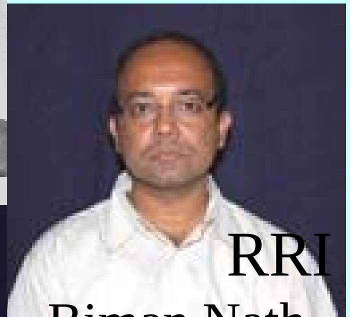
Collaborators

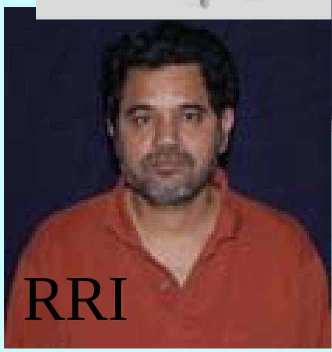
Tarun D Saini

IISc



RRI

Biman Nath



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Shiv K Sethi

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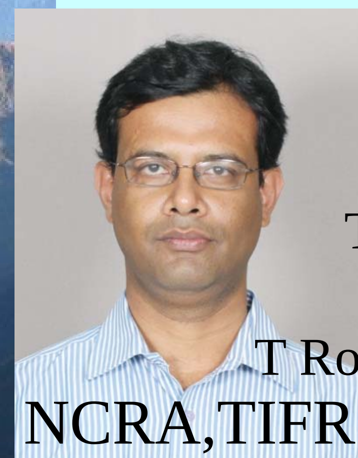

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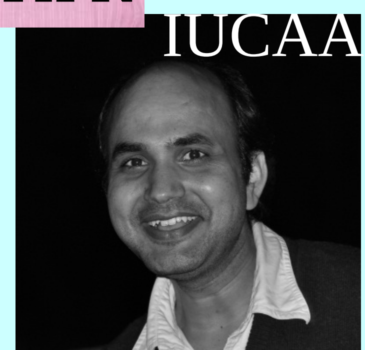


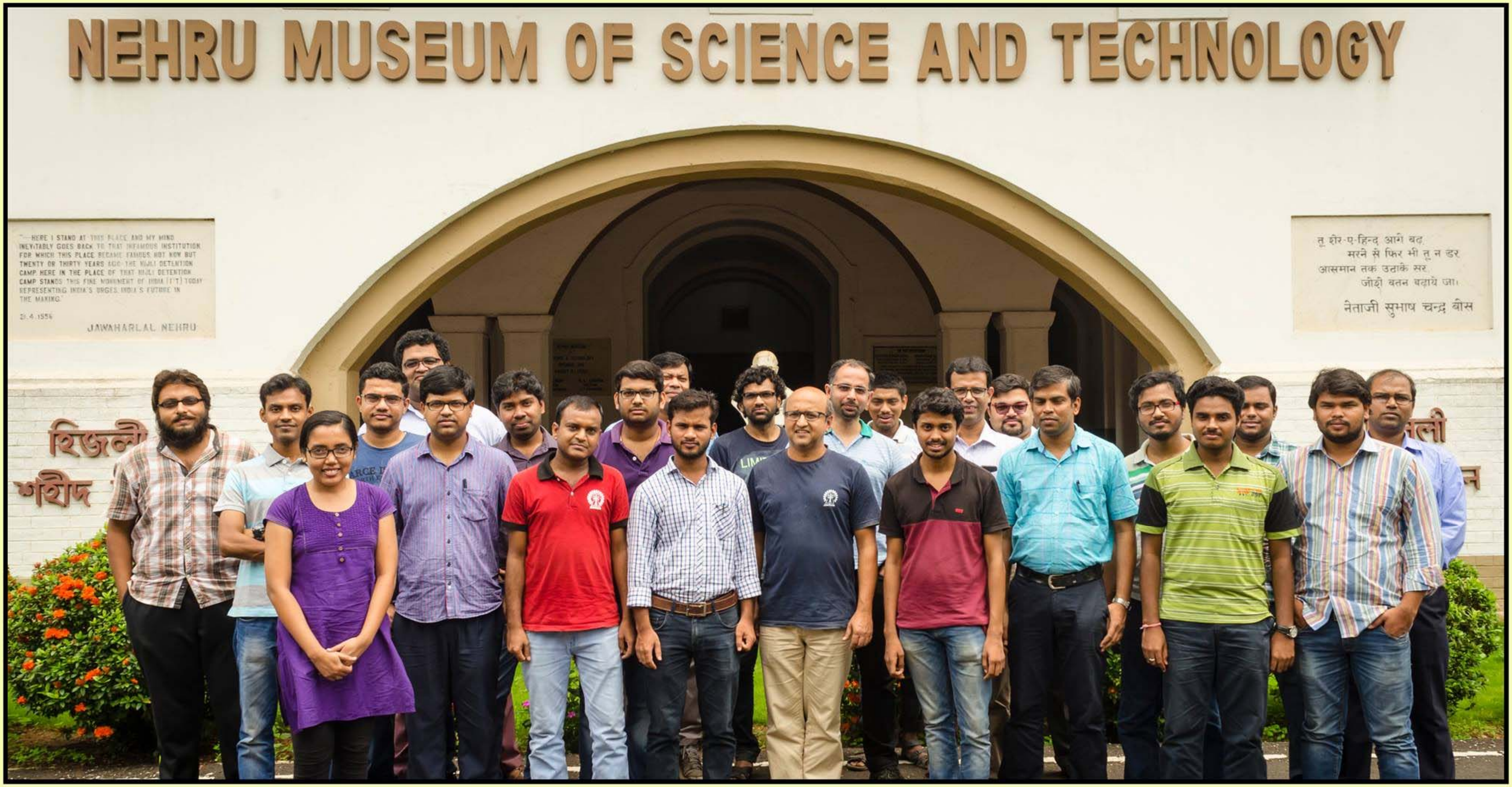
IUCAA

Jayanti Prasad

Suman Majumdar

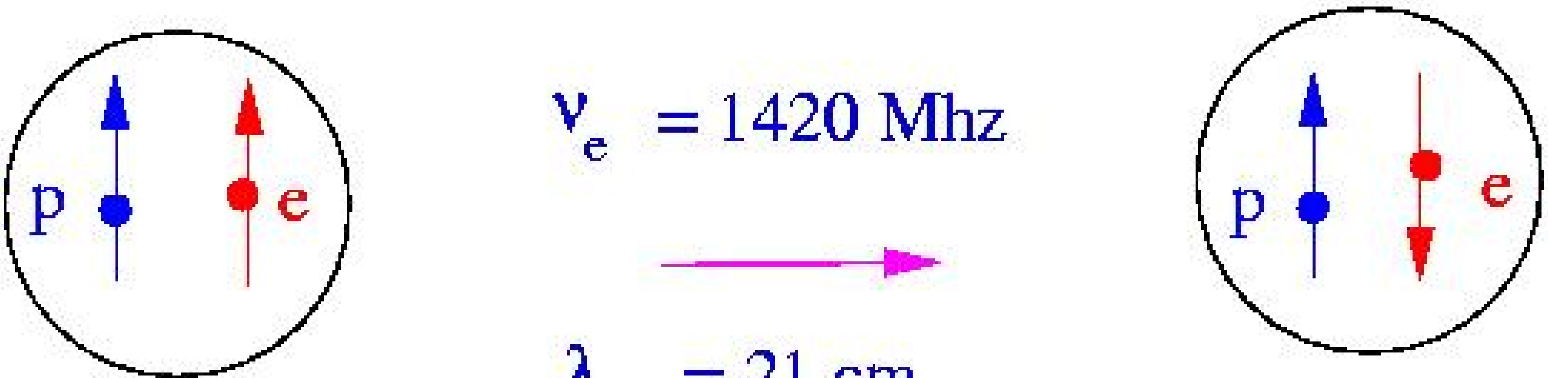
Stockholm

Kanan Datta


NEHRU MUSEUM OF SCIENCE AND TECHNOLOGY
"—HERE I STAND AT THIS PLACE AND MY MIND INEVITABLY GOES BACK TO THAT INFAMOUS INSTITUTION FOR WHICH THIS PLACE BECAME FAMOUS NOT NOW BUT TWENTY OR THIRTY YEARS AGO THE HIJLI DETENTION CAMP HERE IN THE PLACE OF THAT HIJLI DETENTION CAMP STANDS THIS FINE MONUMENT OF INDIA (I.I.T.) TODAY REPRESENTING INDIA'S URGES, INDIA'S FUTURE IN THE MAKING."
21.4.1956
JAWAHARLAL NEHRU
तू शेर-ए-हिन्द आगे बढ़
मरने से फिर भी तू न डर
आसमान तक उठाके सर
जोशे वतन बढ़ाये जा।
नेताजी सुभाष चन्द्र बोस

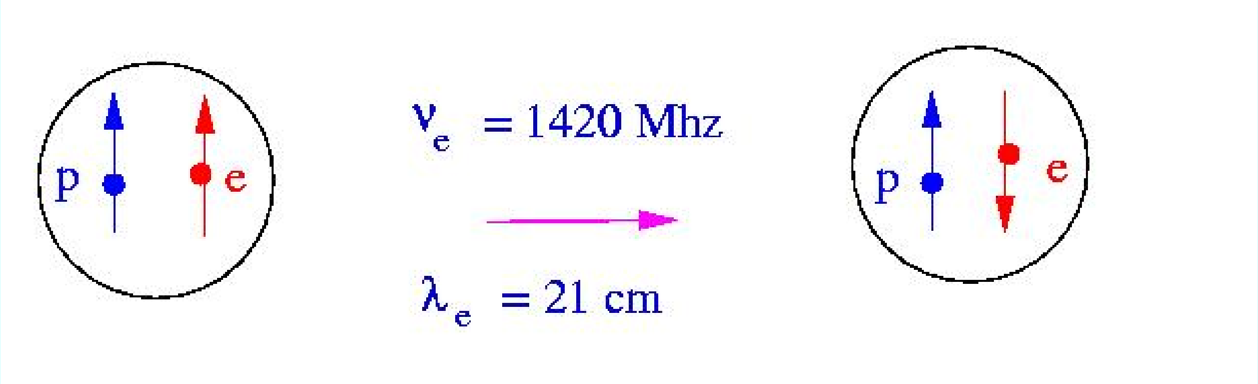
21-cm radiation

Neutral Hydrogen - HI
Ground state



$\nu_o = 1420$ Mhz $/ (1+z)$ $\lambda_o = 21$ cm $(1+z)$

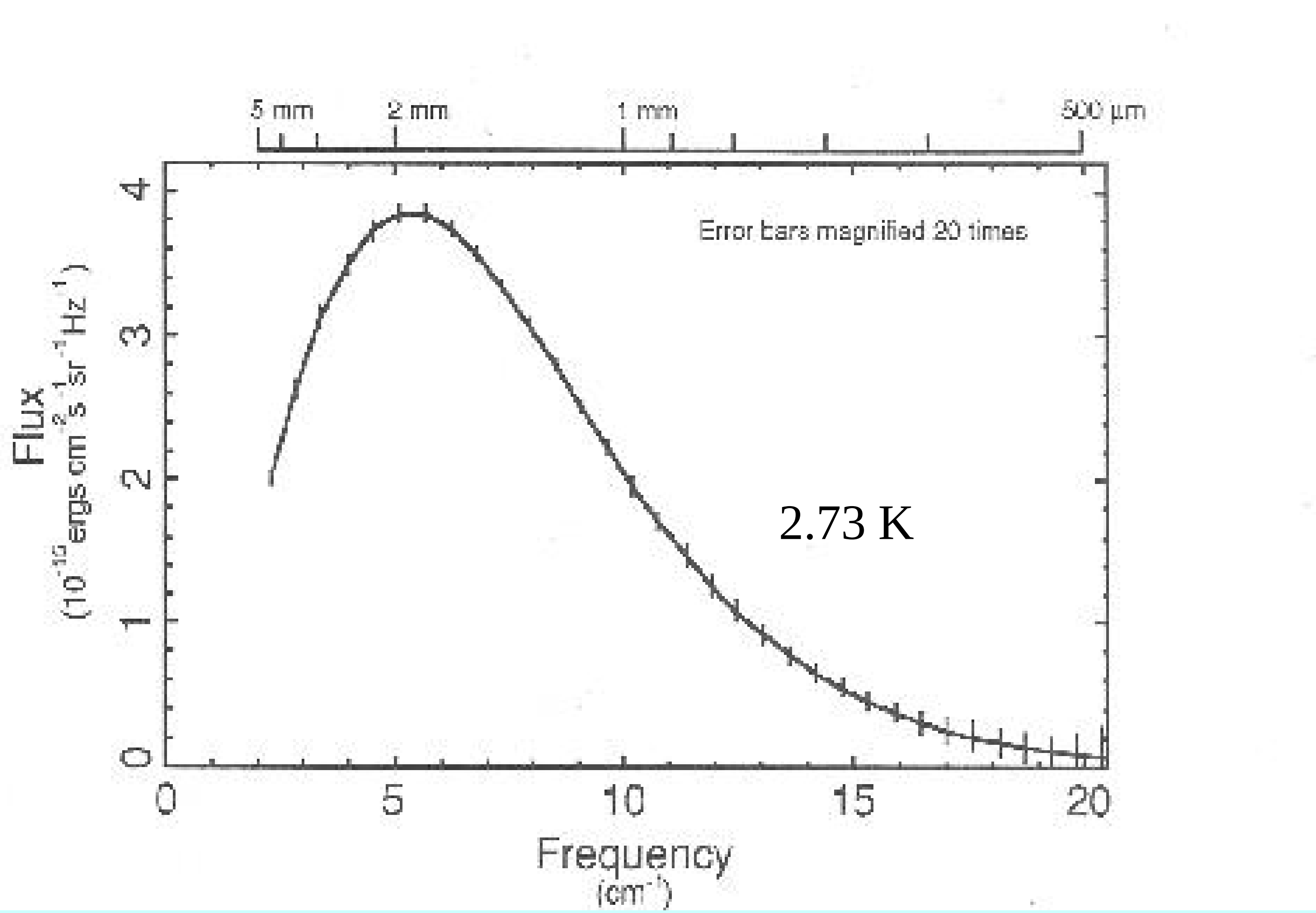
Spin Temperature T_s



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

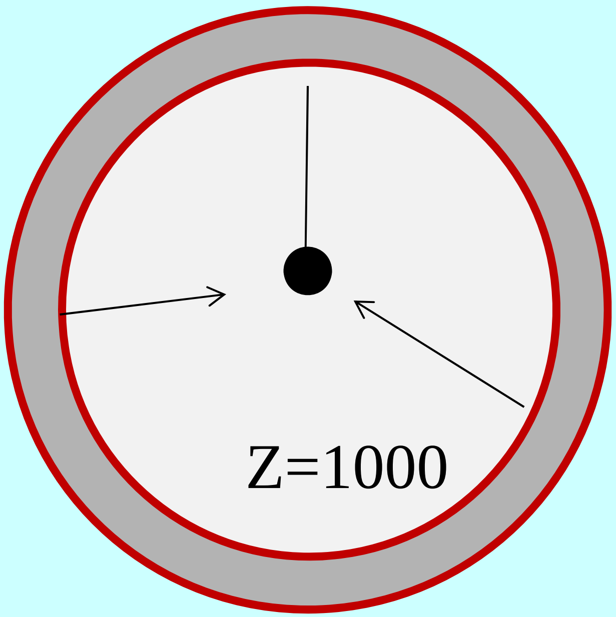
$$T_\star = h_p \nu_e / k_B = 0.068 \text{ K}$$

Cosmic Microwave Background Radiation (CMBR)



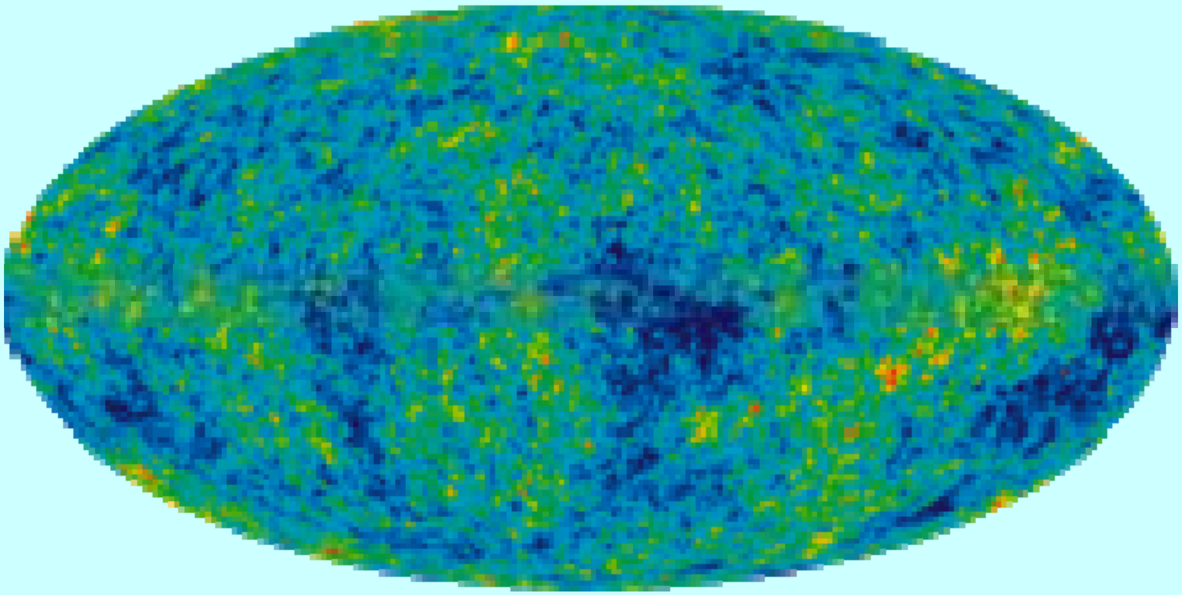
CMBR anisotropies

Universe ionized and opaque at z >1000



Z=1000

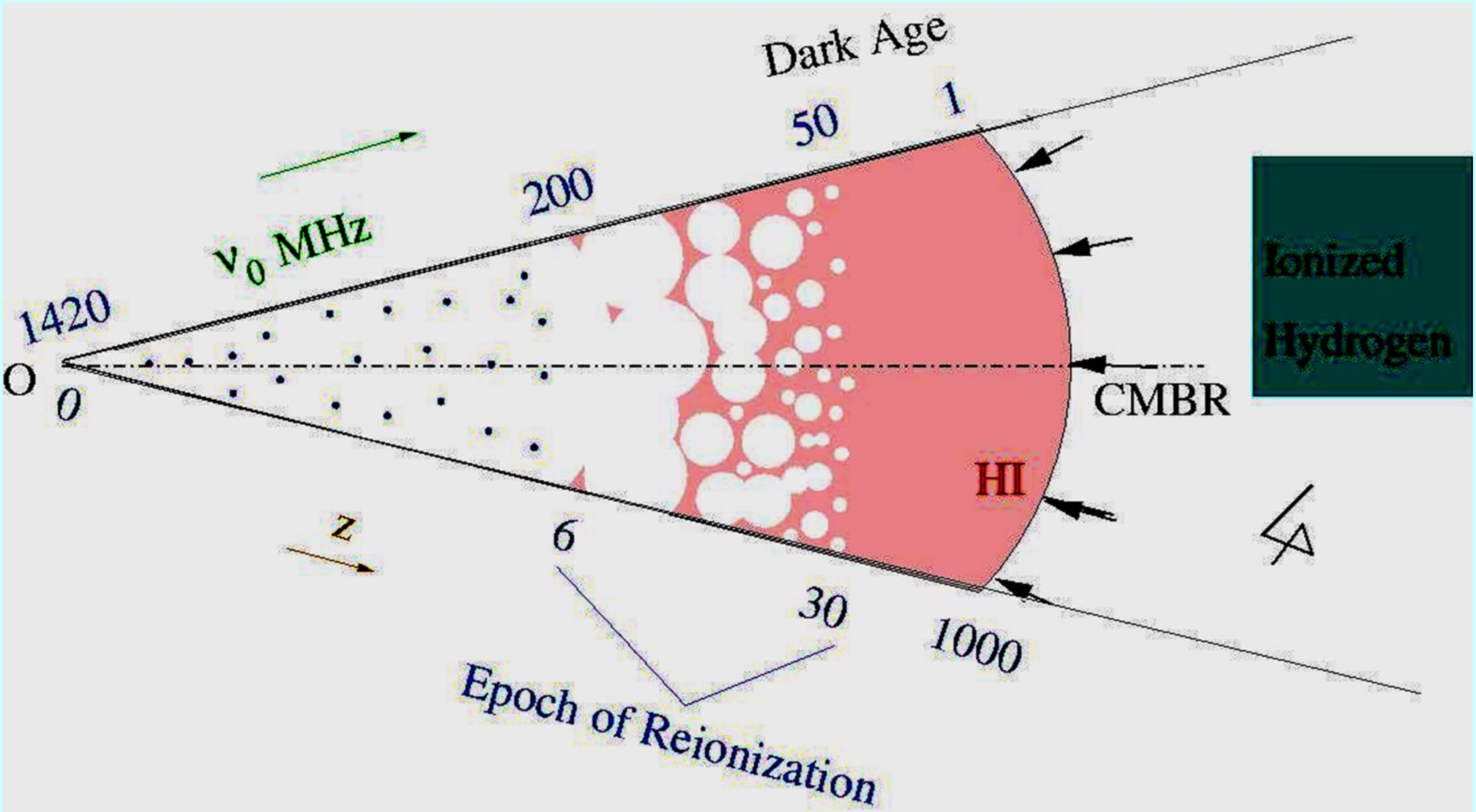
WMAP NASA



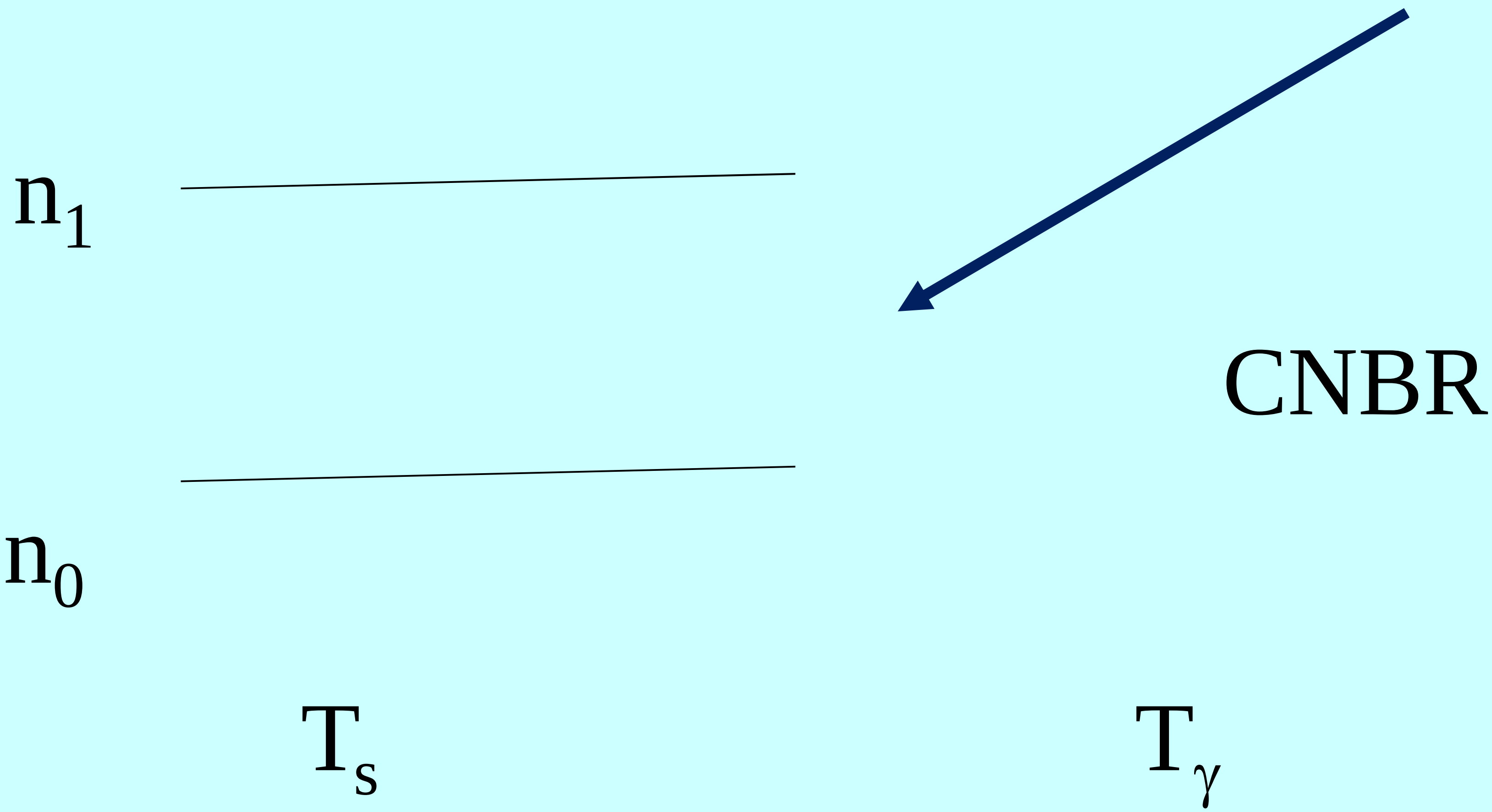
$T_\gamma = (1+z)\ 2.73\ K$

Nearly isotropic $\Delta T \sim 10$ micro K

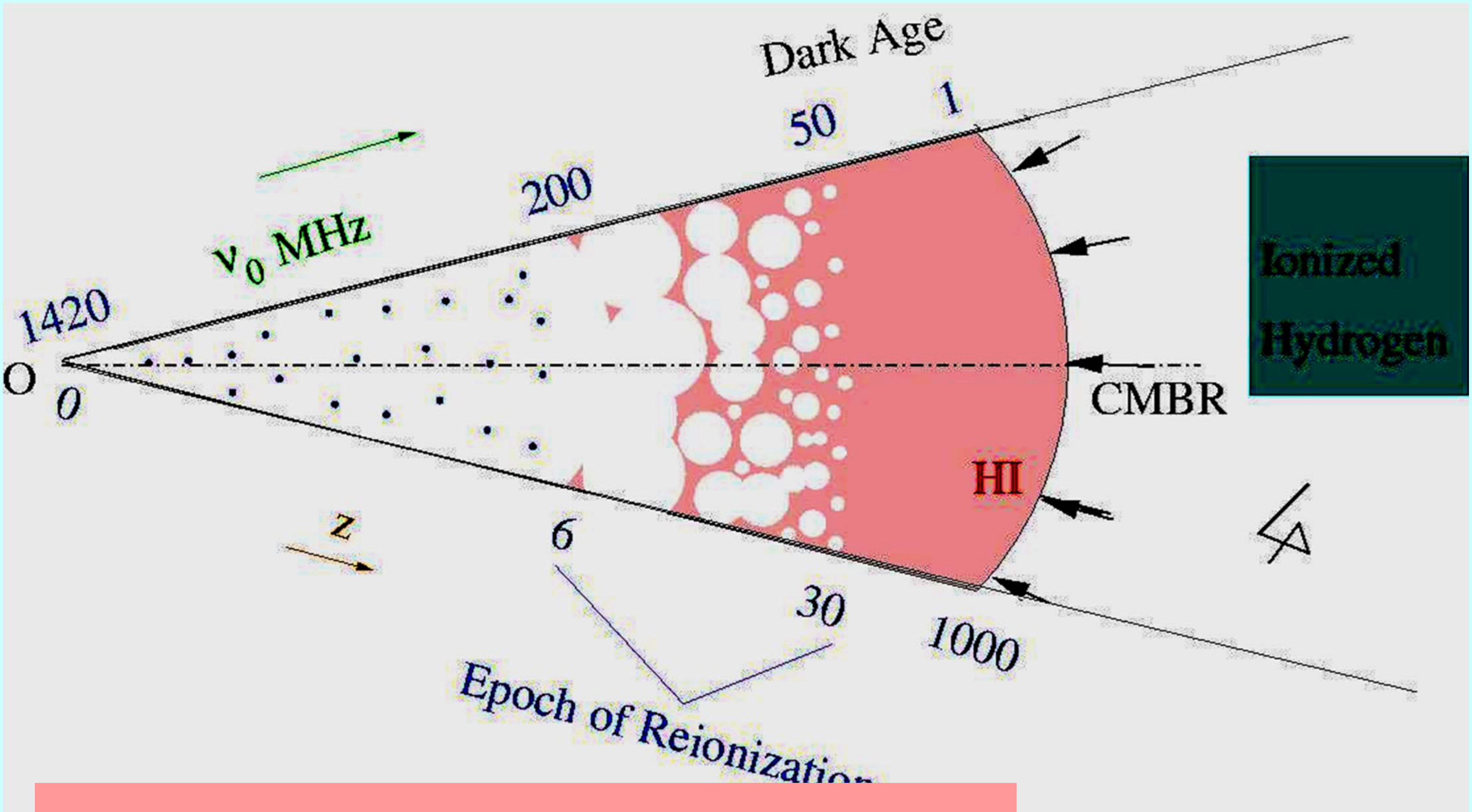
CMBR propagates through HI



21-signal

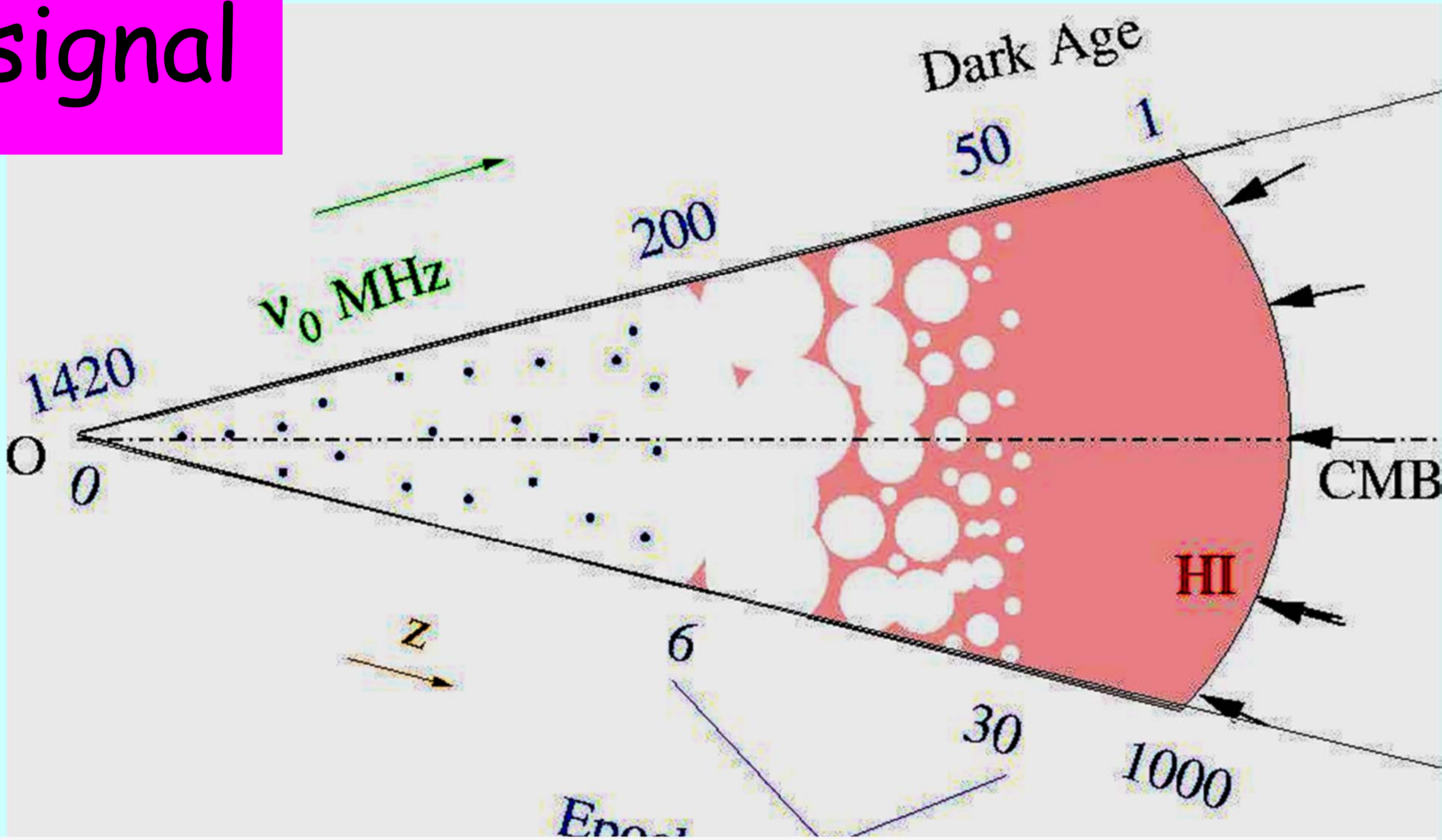


The 21-cm Signal



$$\delta T_b(\mathbf{n},\nu) = T_b(n,\nu) - T_\gamma$$

21-cm signal

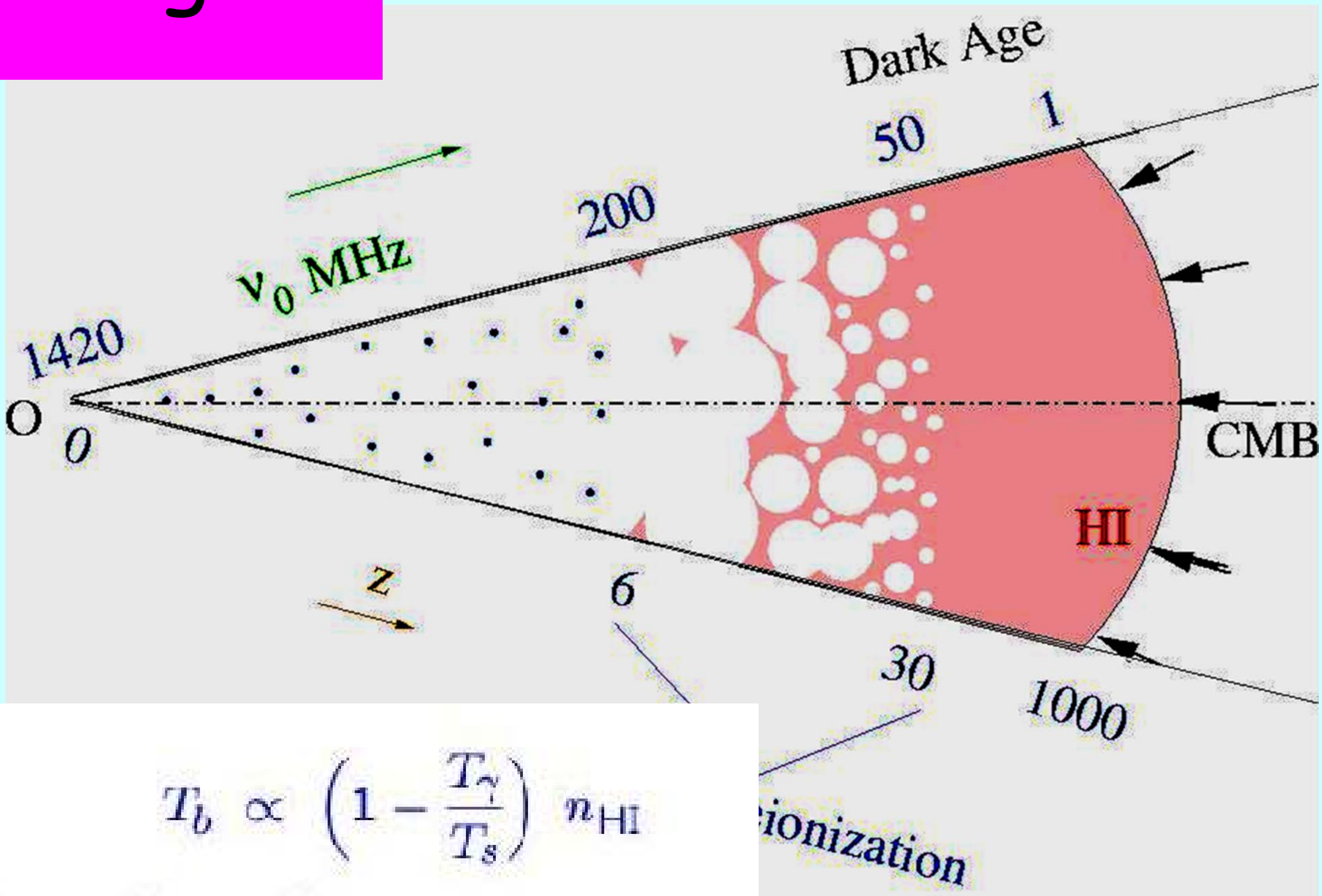


$$\delta T_b(\boldsymbol{n}, \nu) = \bar{T}\left[\left(1 - \frac{T_\gamma}{T_s}\right)\left(\Delta_H - \frac{1}{Ha}\frac{\partial v}{\partial r}\right) + \frac{T_\gamma}{T_s} s \Delta_H\right]$$

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

Bharadwaj & Ali, 2004

21-cm signal

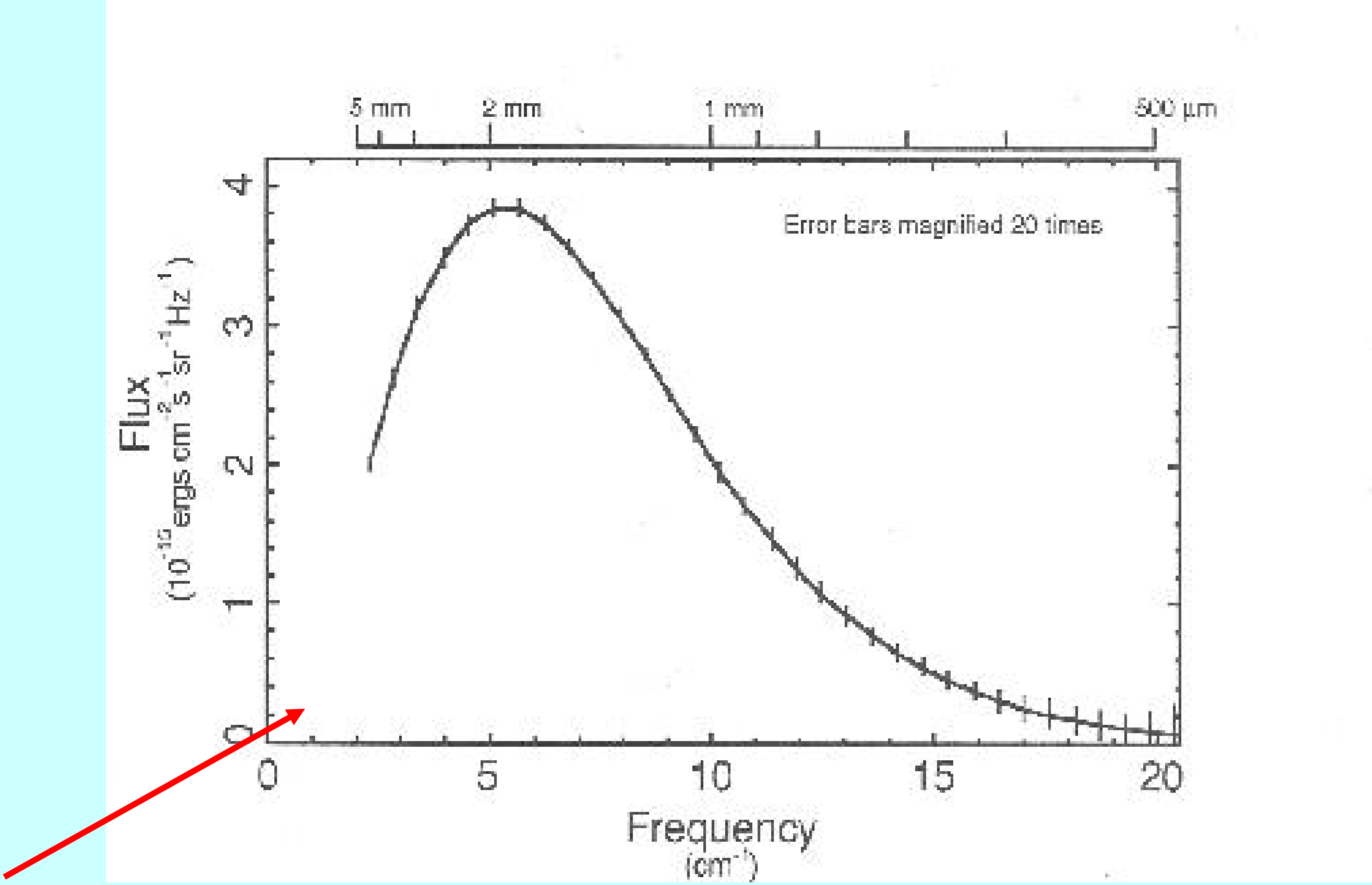


$$T_b \propto \left(1 - \frac{T_\gamma}{T_s}\right) n_{\rm HI}$$

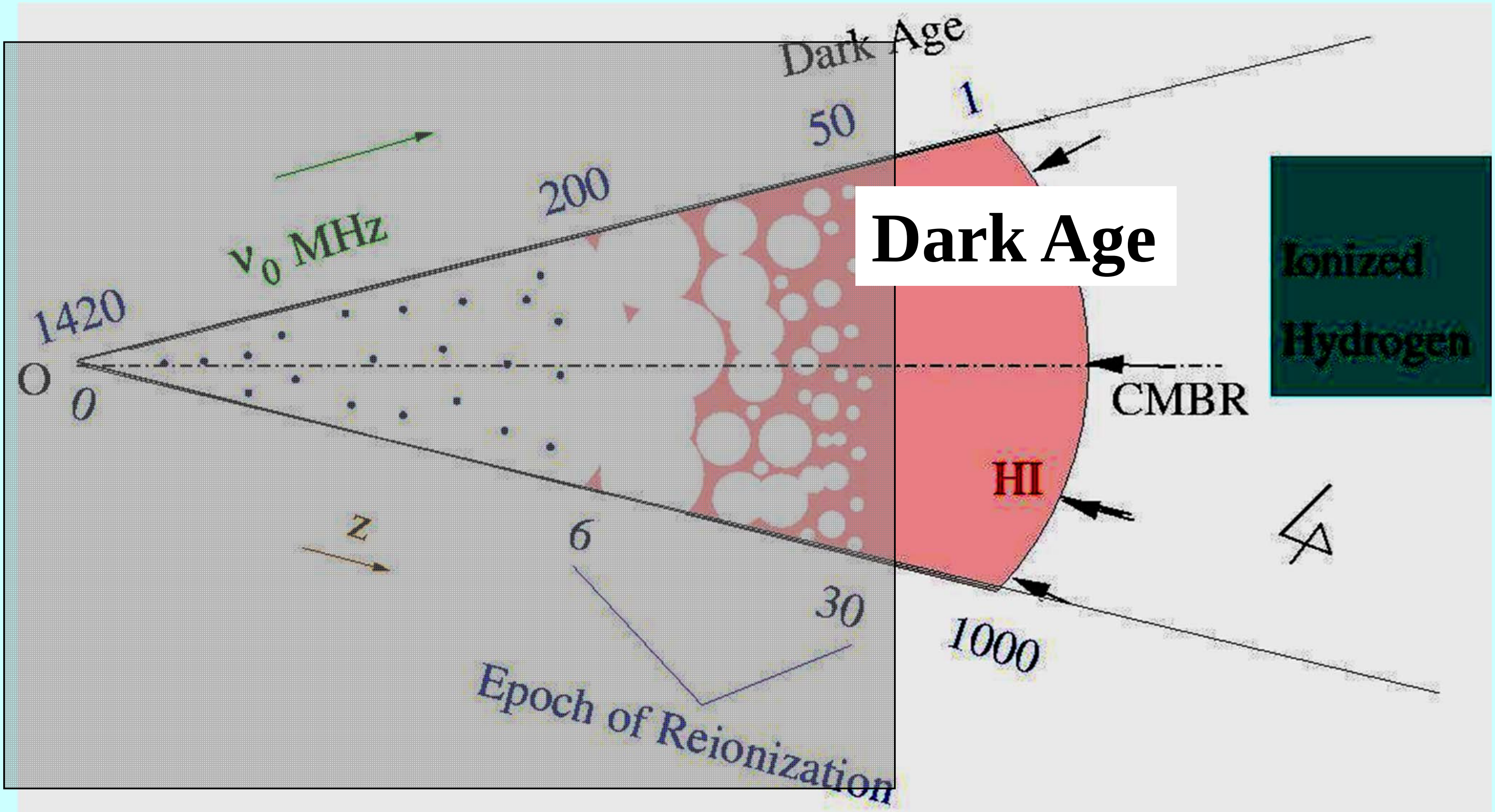
$T_s < T_\gamma$ Absorption

$T_s > T_\gamma$ Emission

Cosmic Microwave Background Radiation (CMBR)



HI Evolution

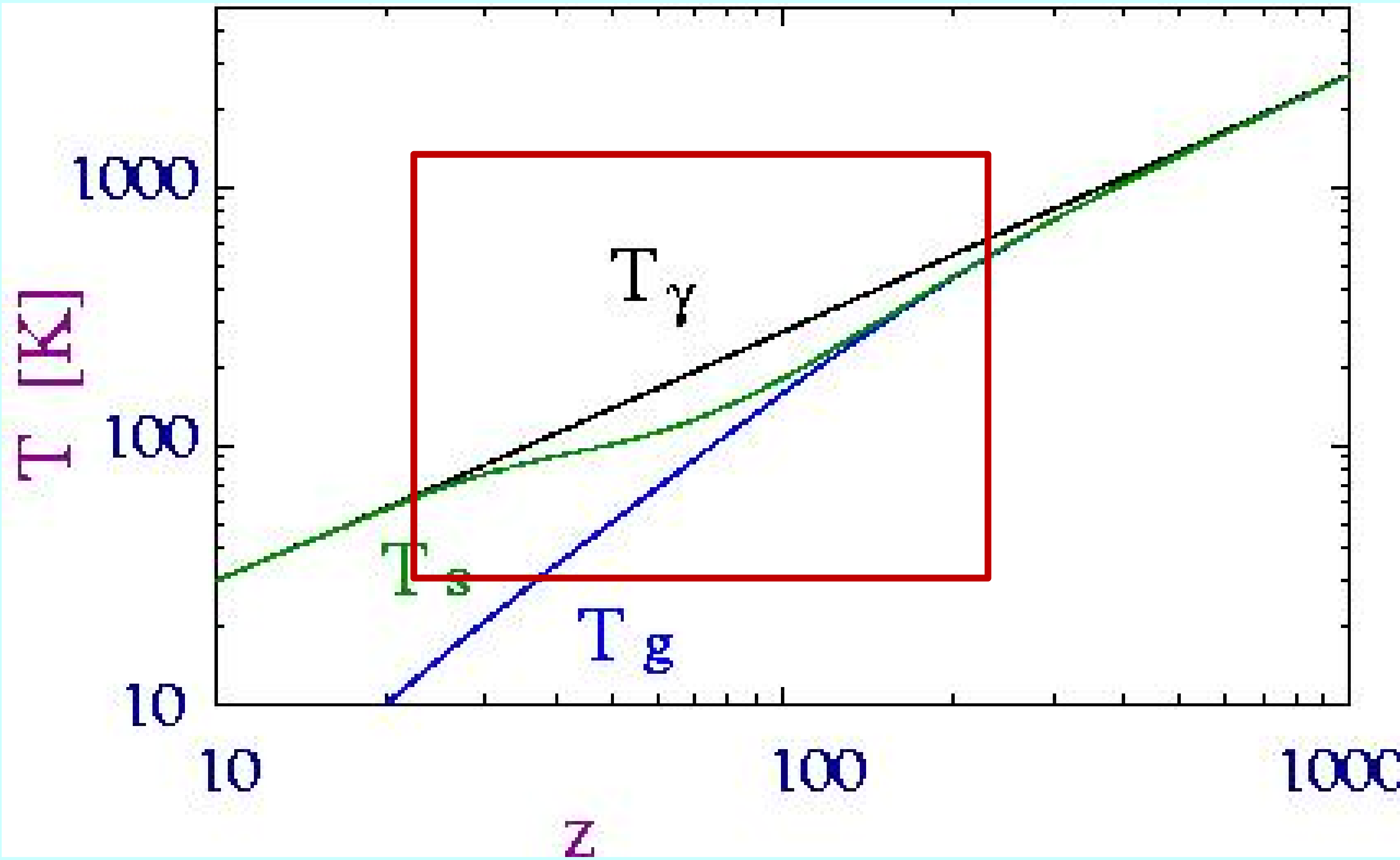


HI seen in absorption against CMBR

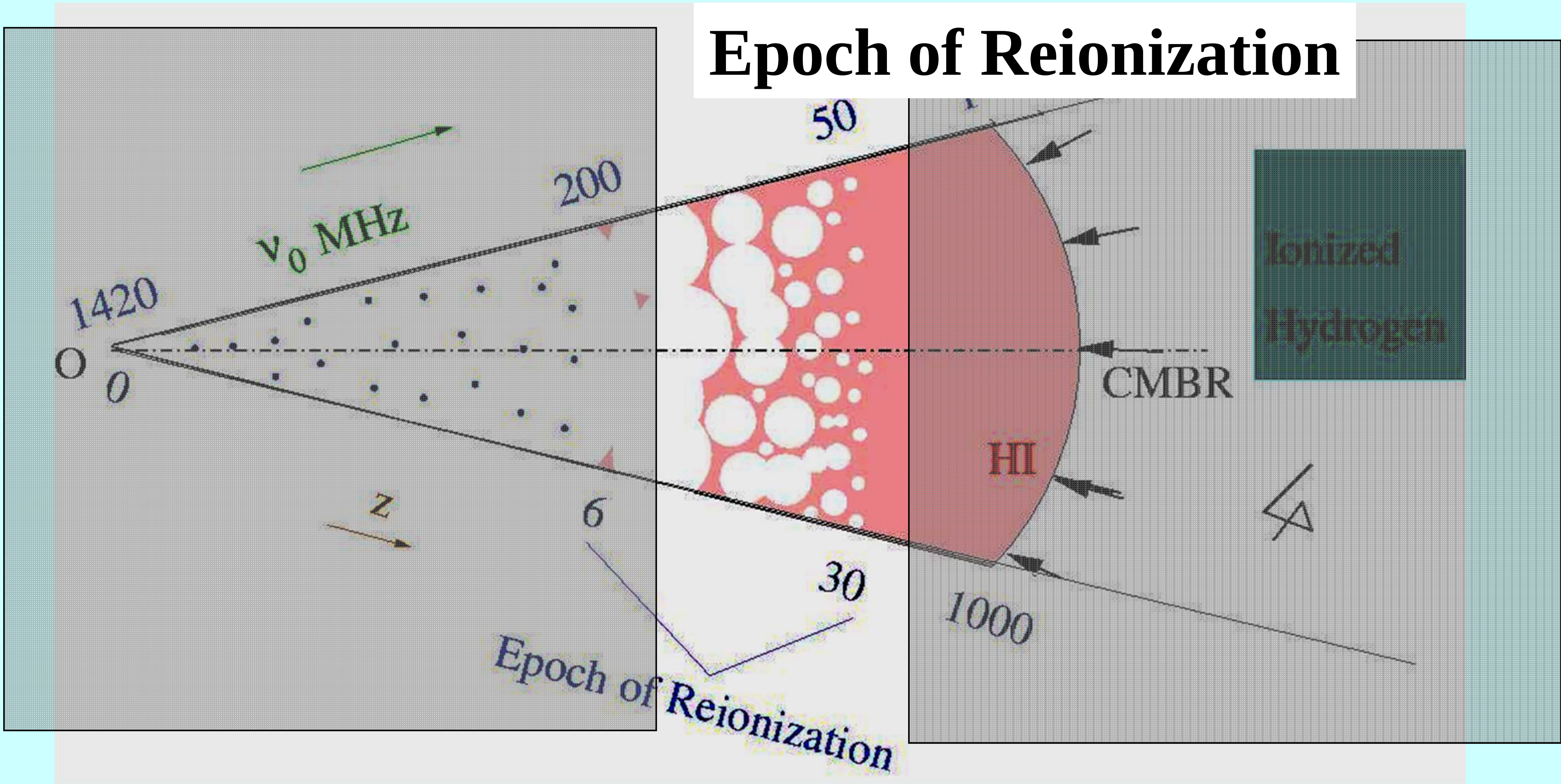
The Dark Ages

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

$T_s < T_\gamma$



HI Evolution

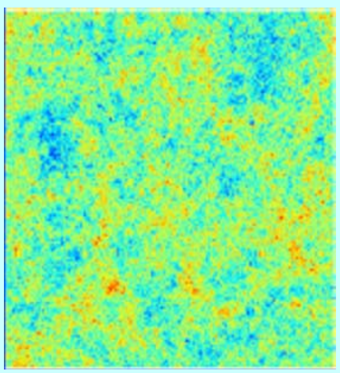


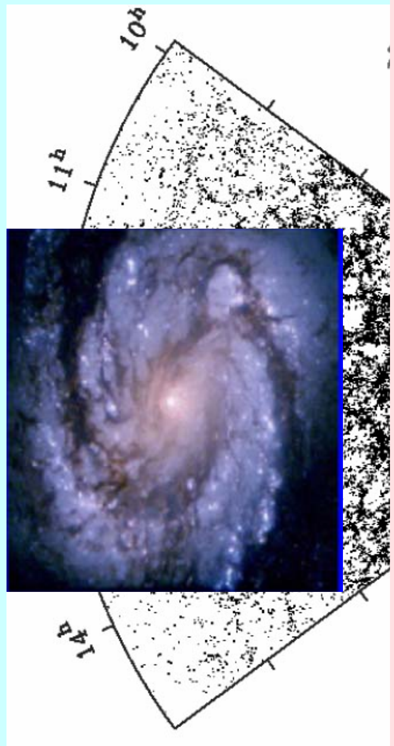
HI seen in emission

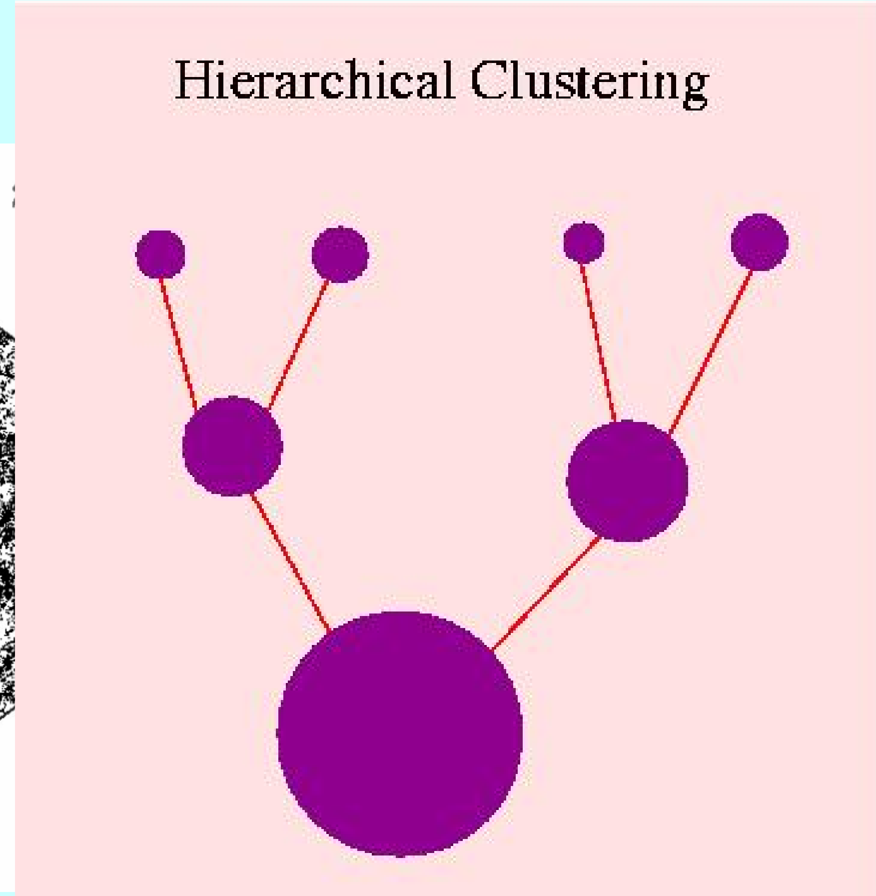
Structure Formation

Z=1000

Z=0





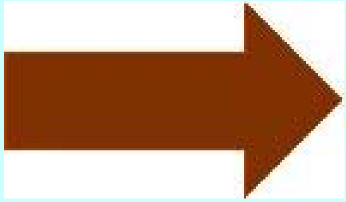


Gravitational Instability

Dark matter dominates the dynamics

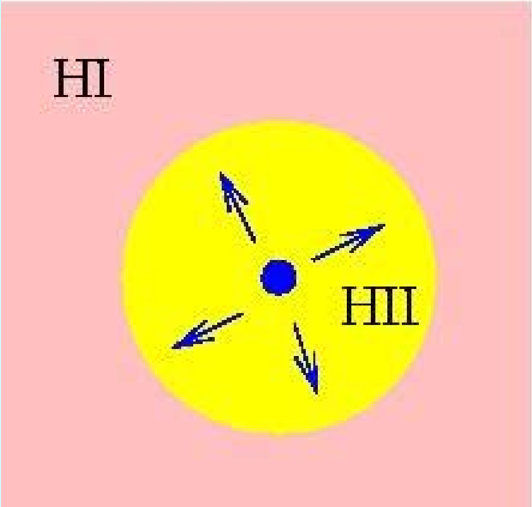
Rionization

Dark Matter Halos
Baryons Condense Within Halos



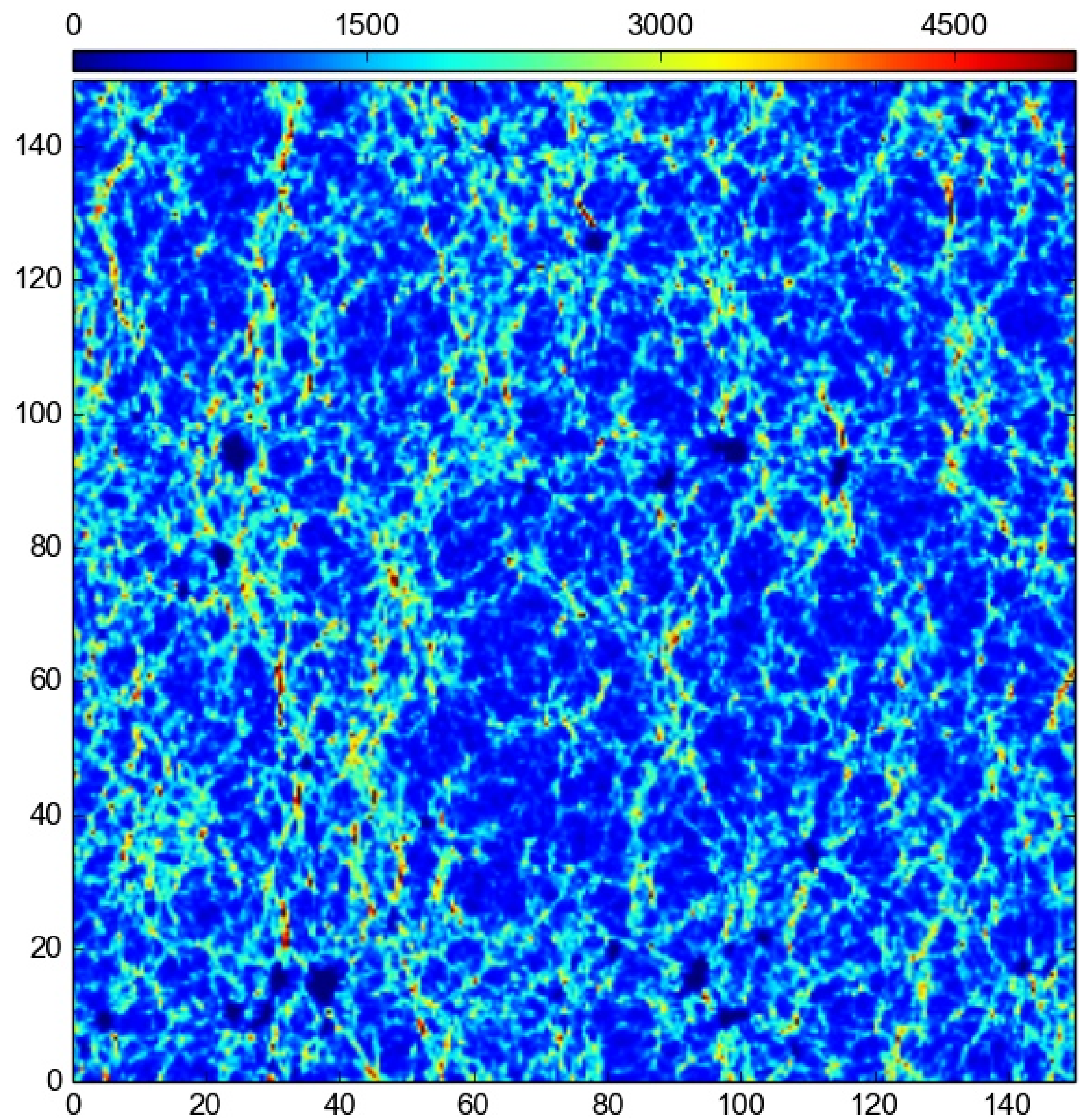
Galaxies

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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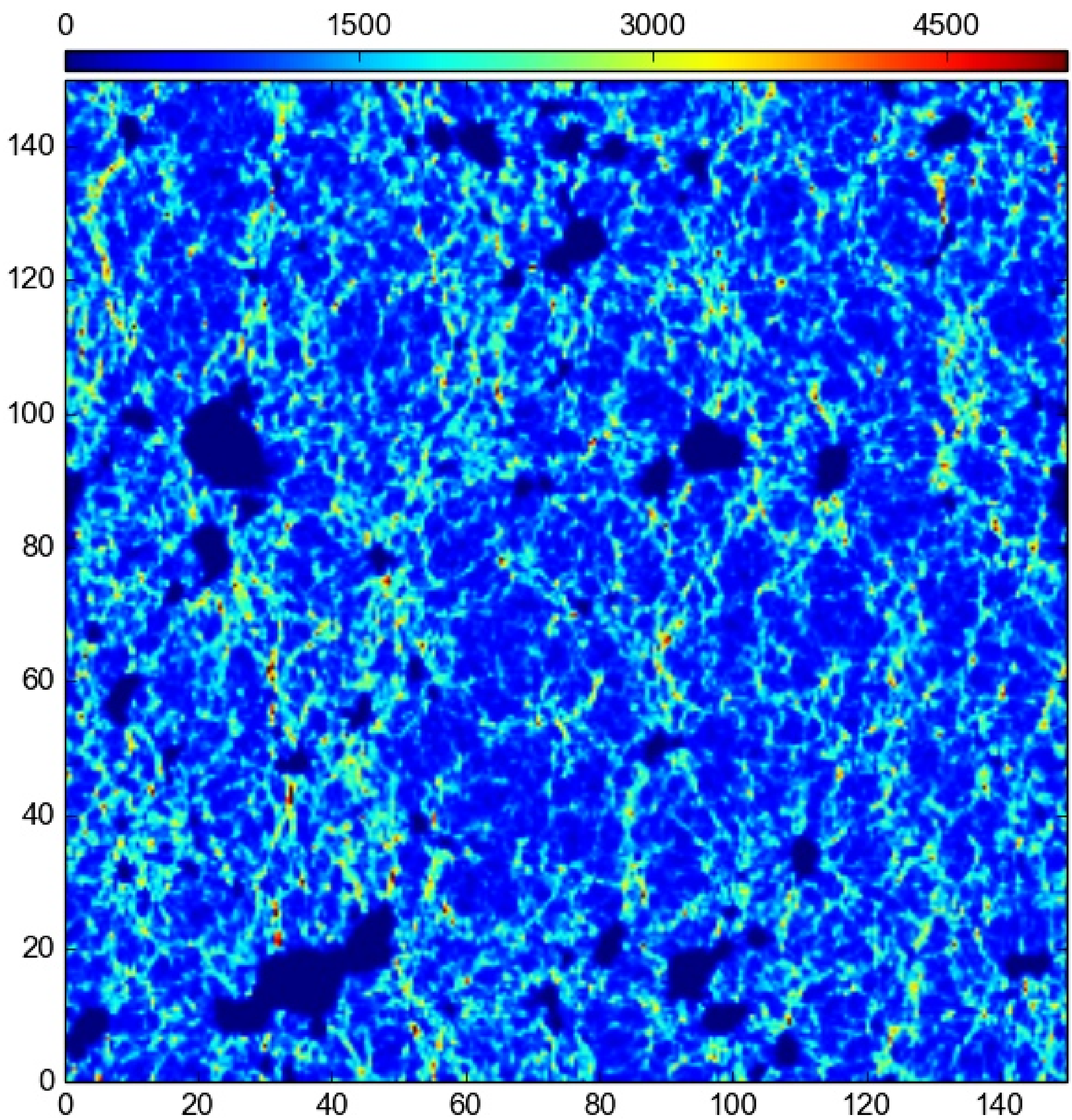
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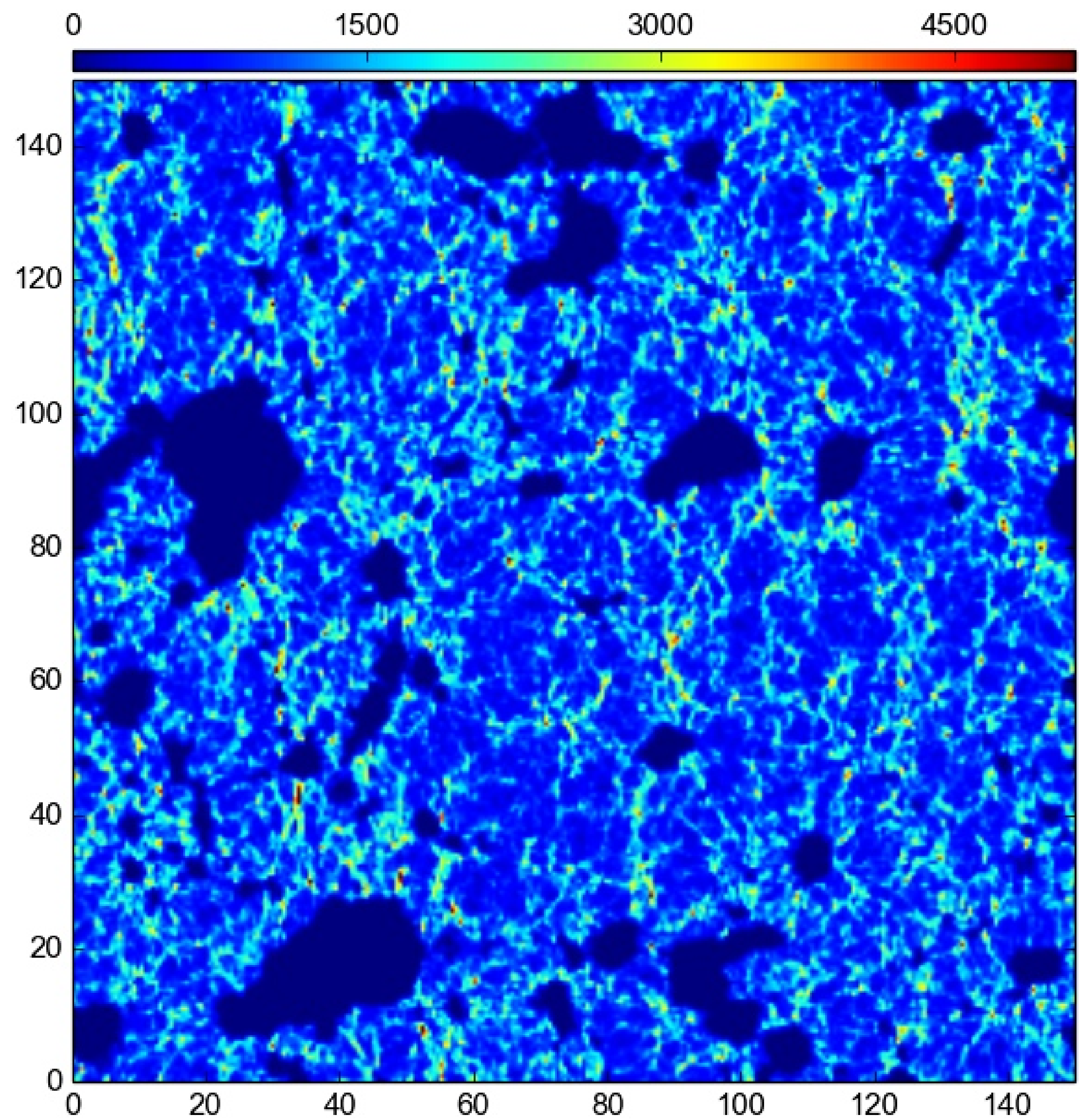
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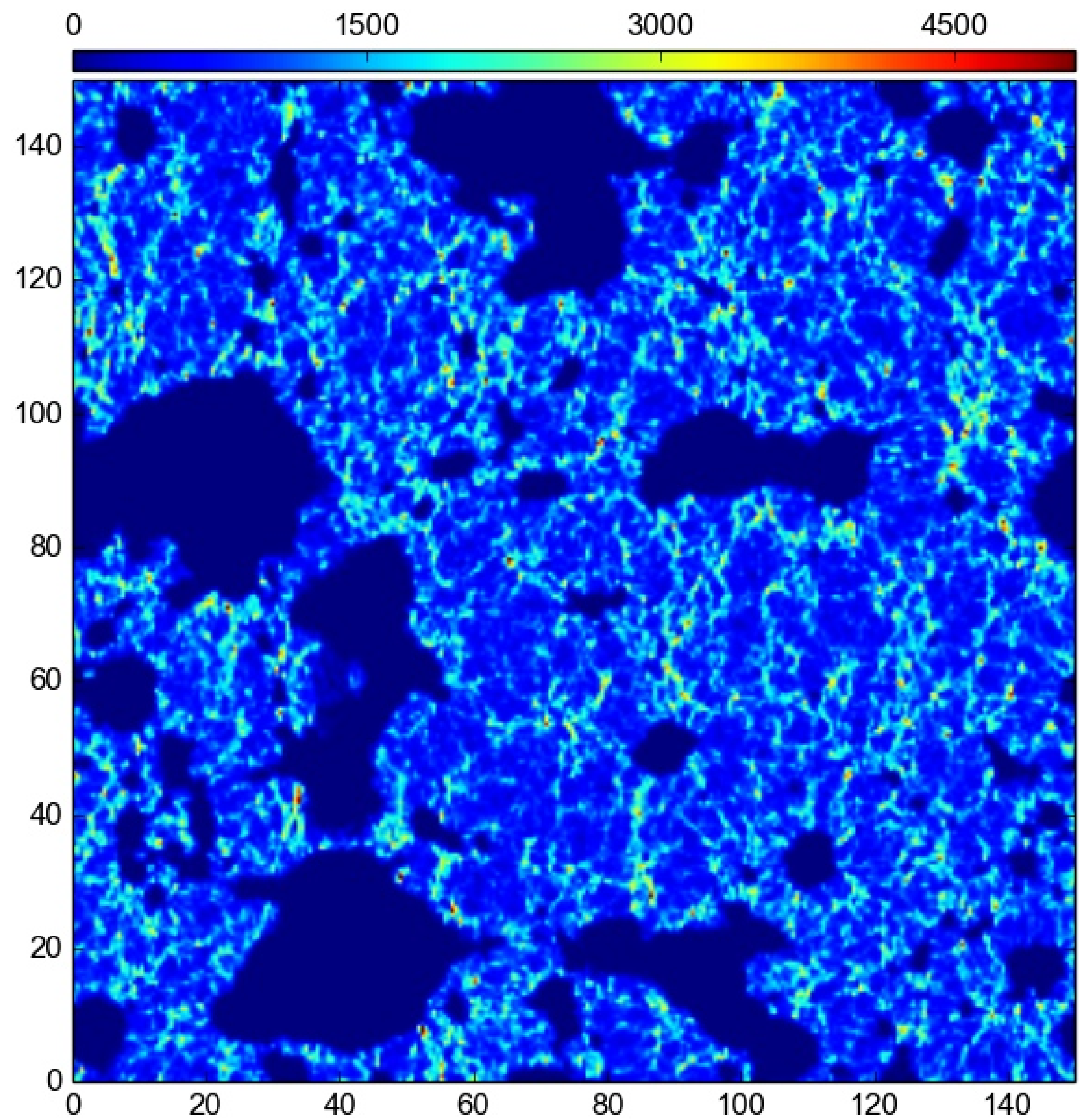
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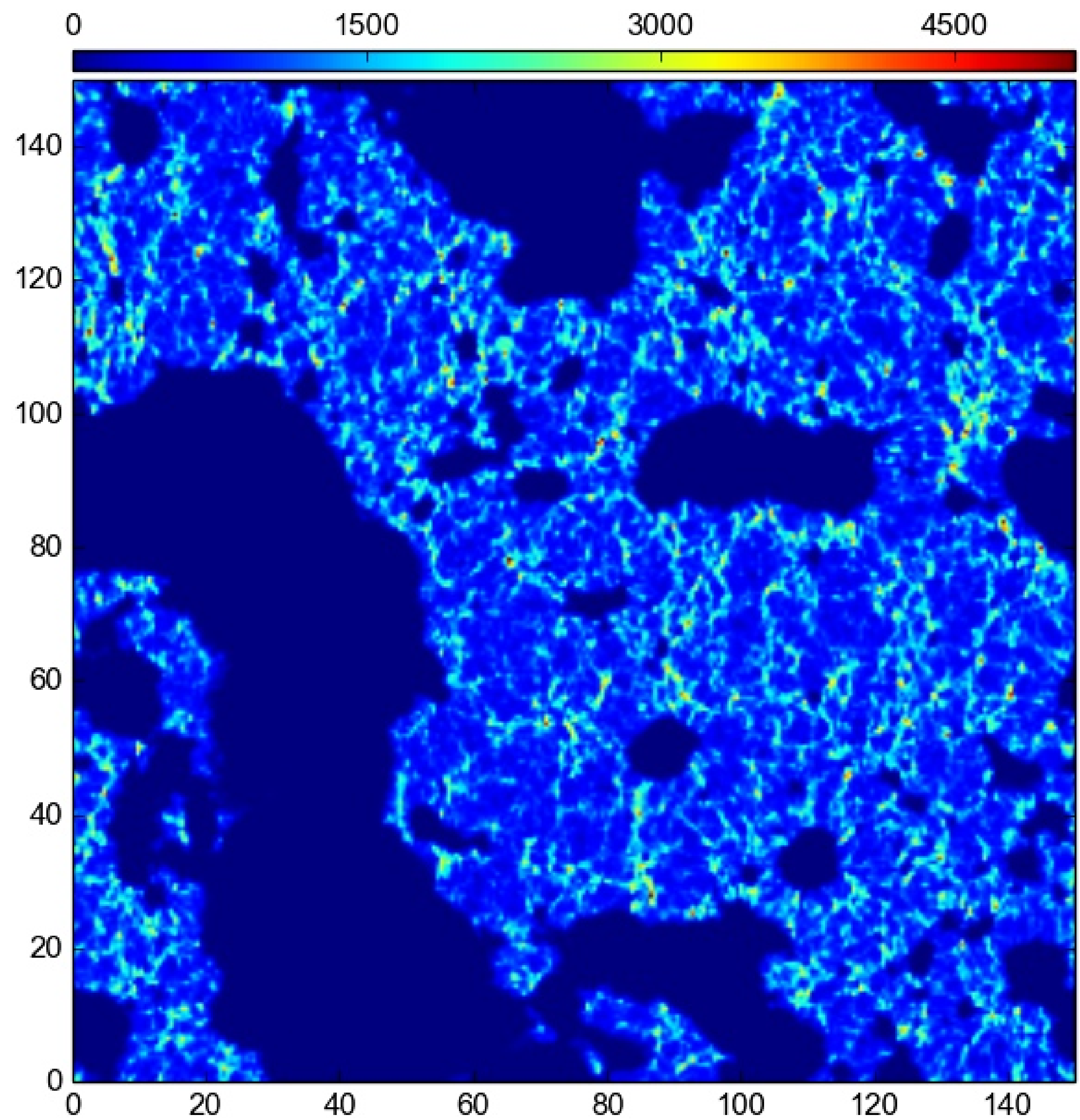
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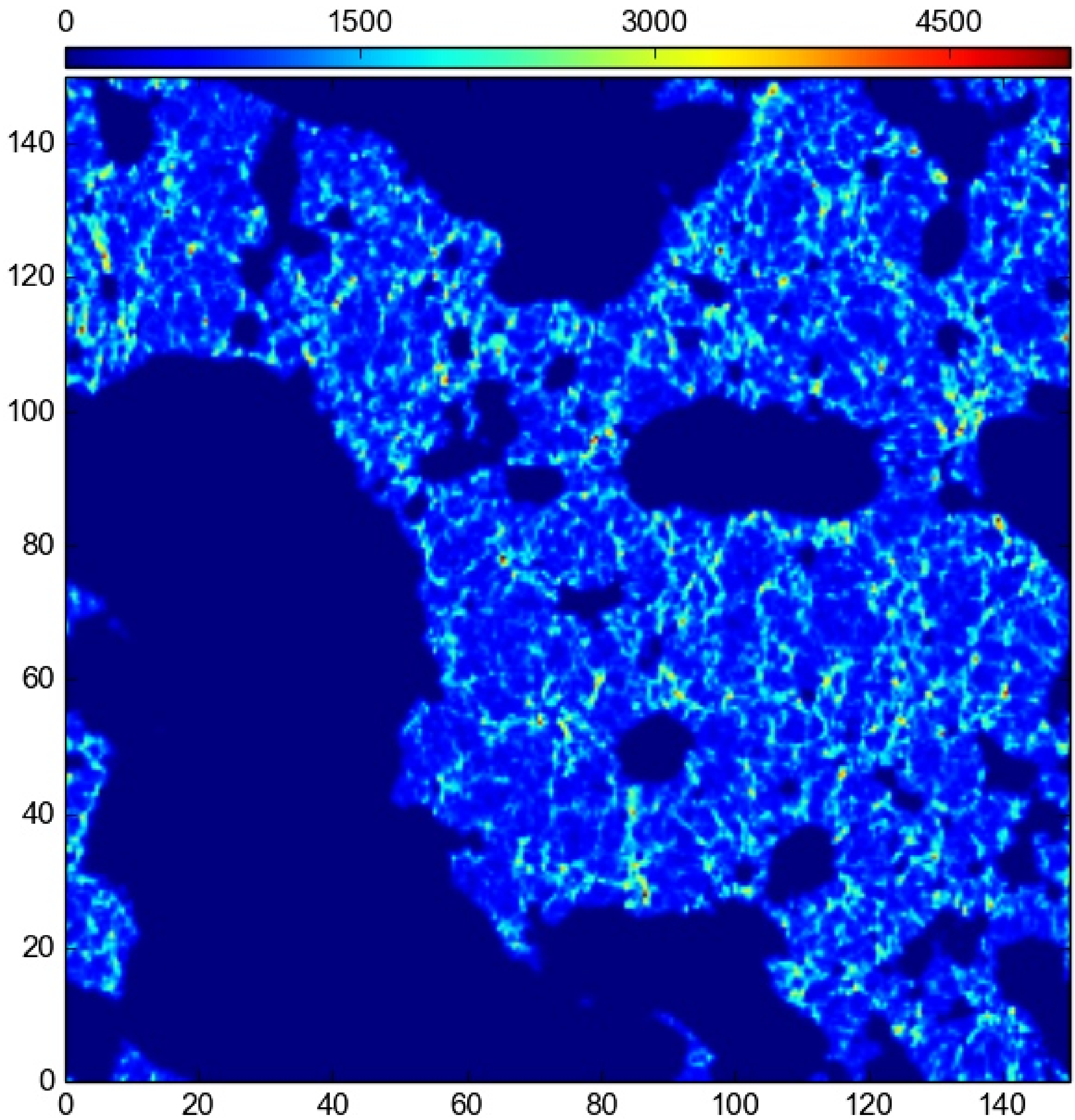
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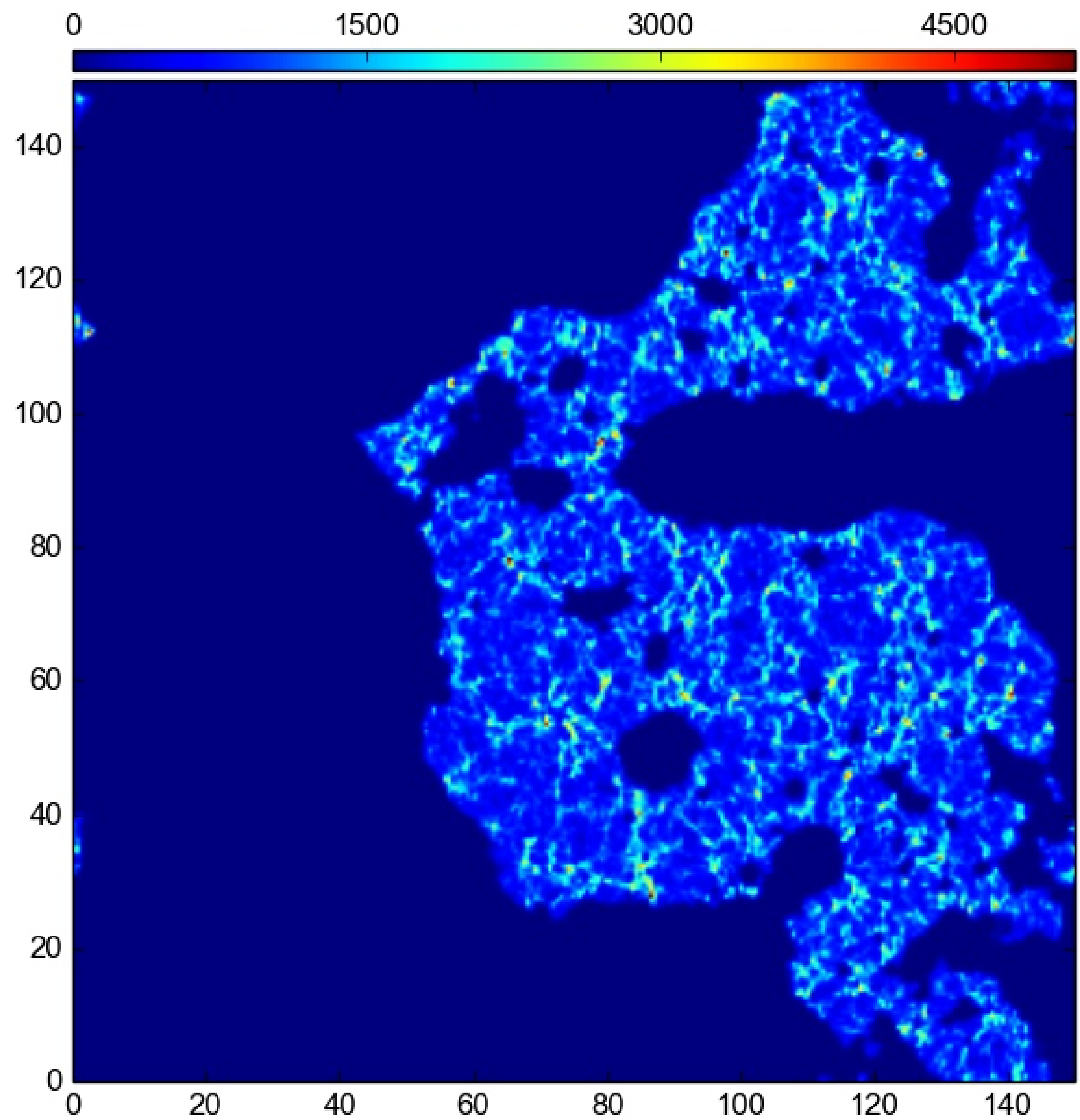
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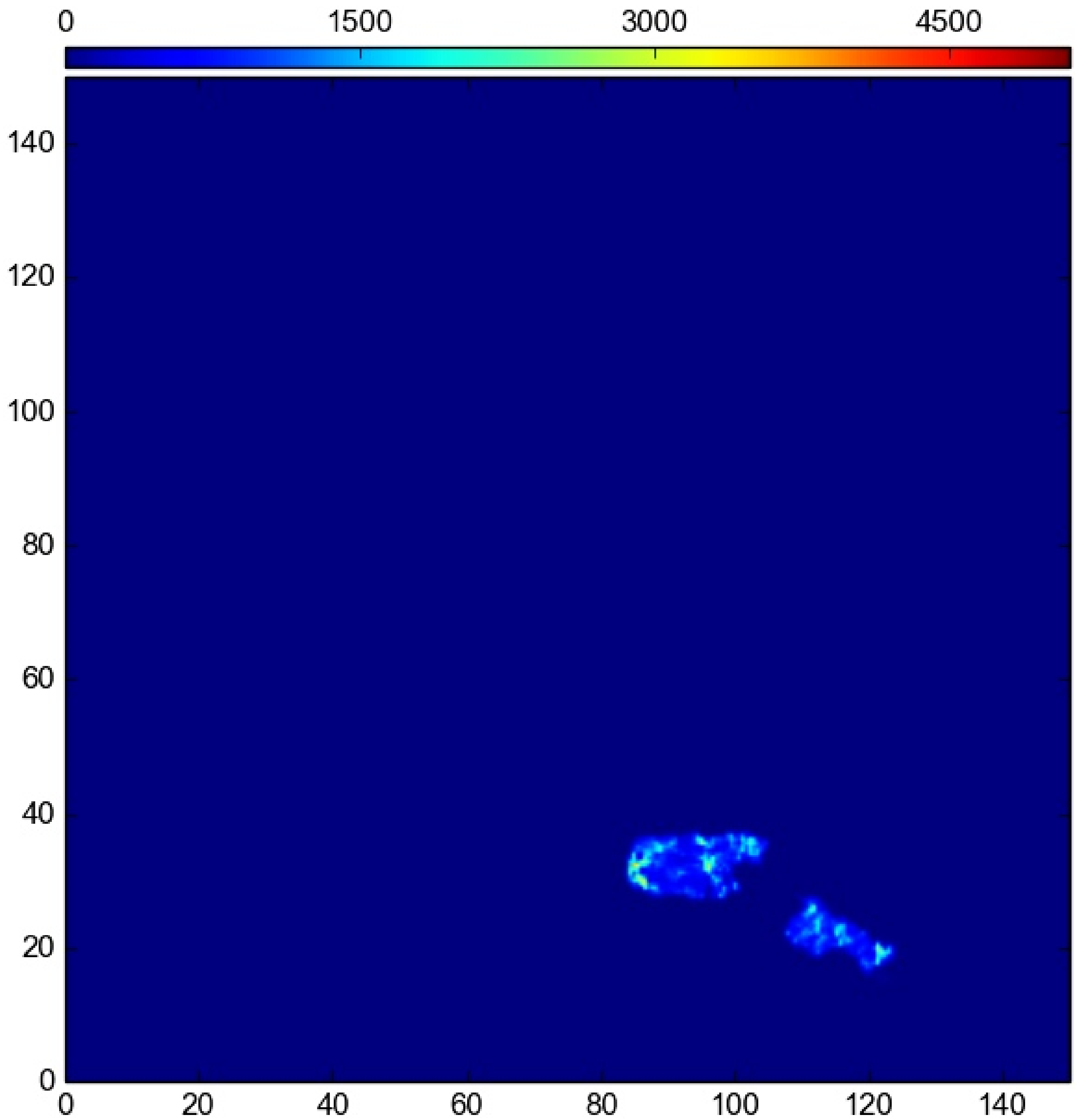
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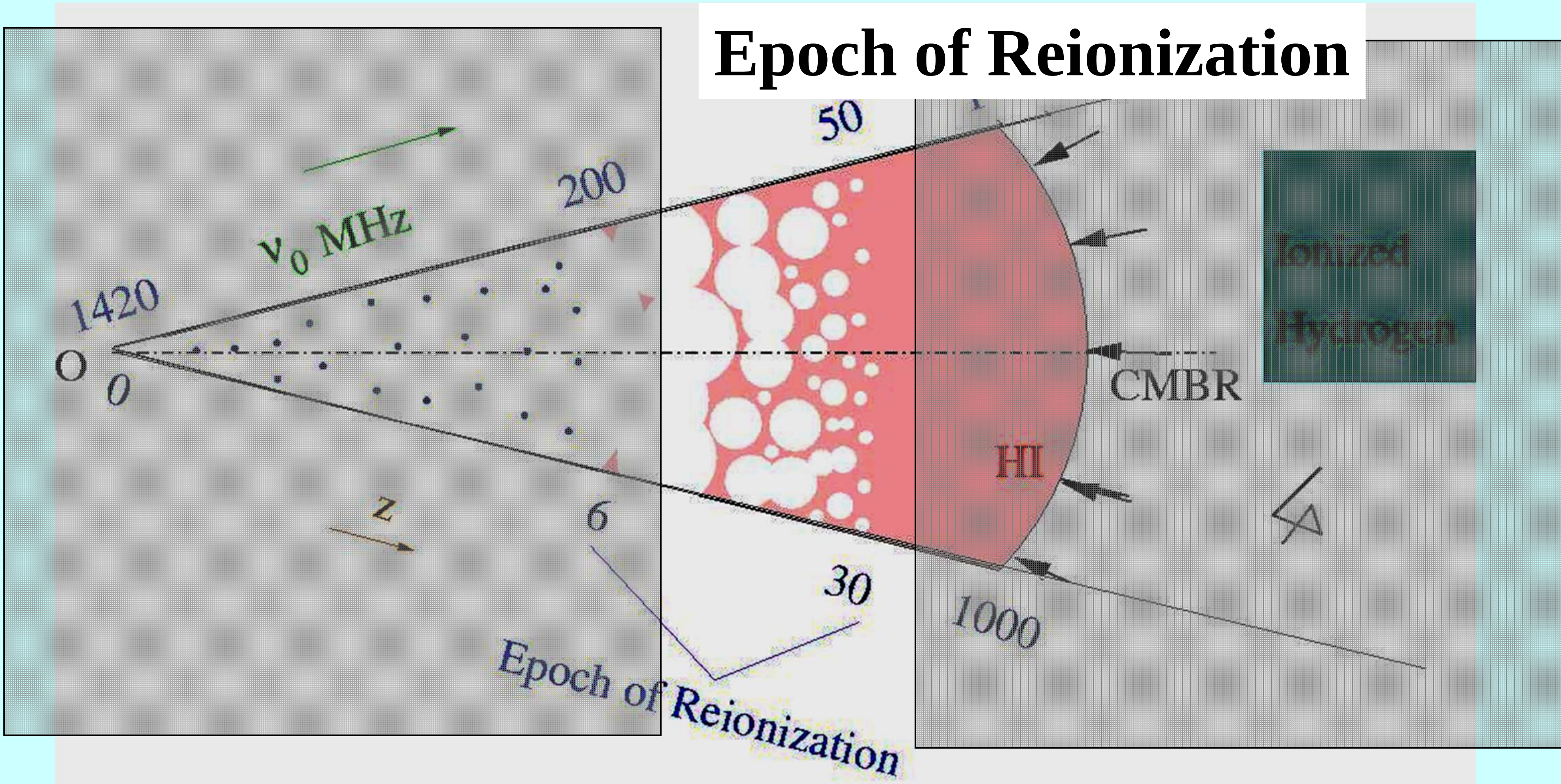
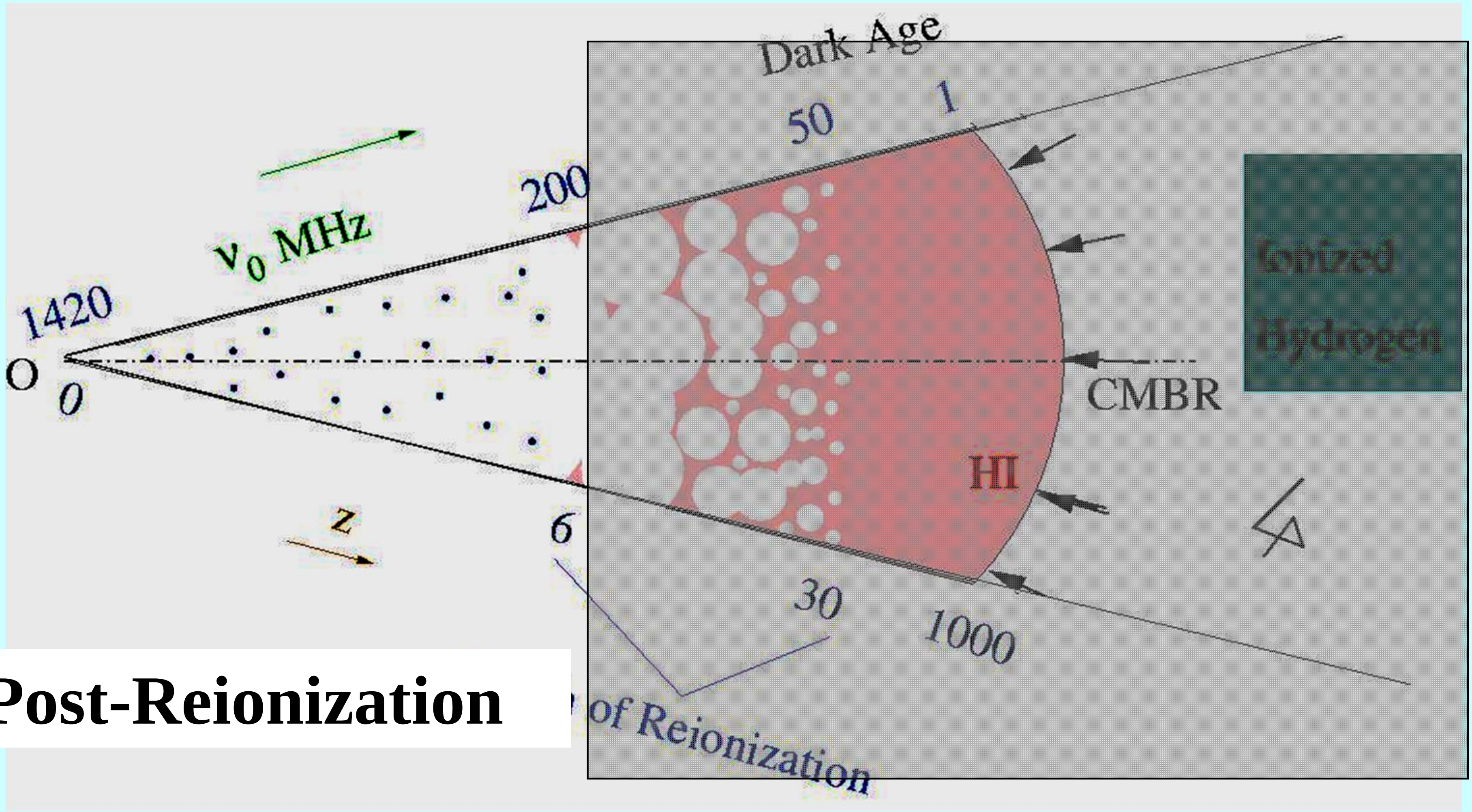
HI Evolution



HI seen in emission

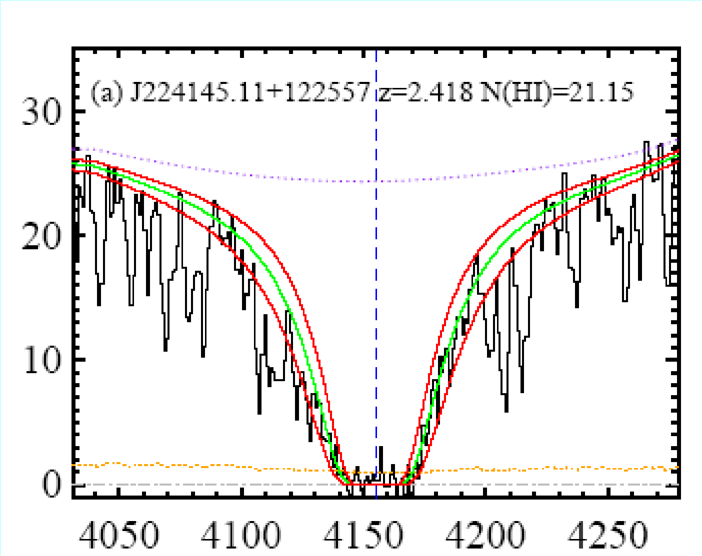
HI Evolution

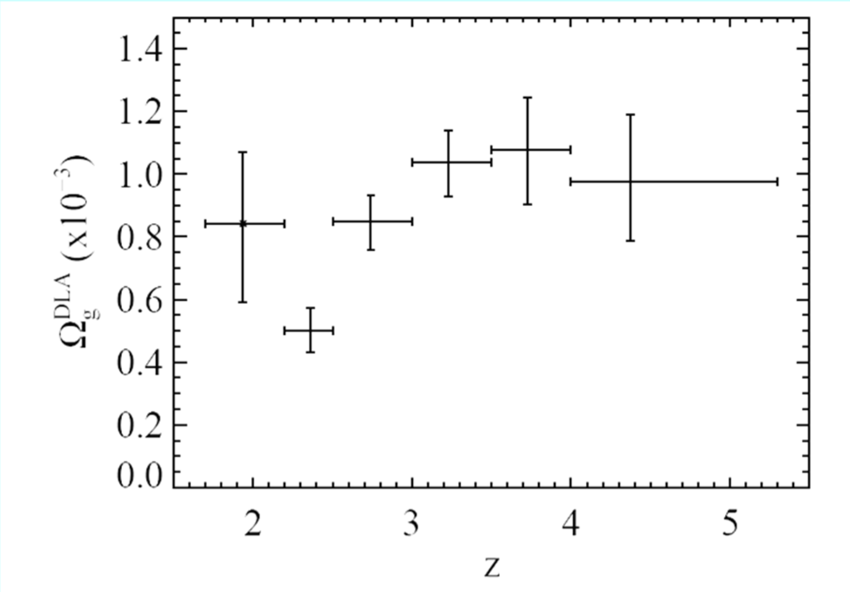


Post-Reionization

HI seen in emision

Damped Ly-α Clouds (DLA)



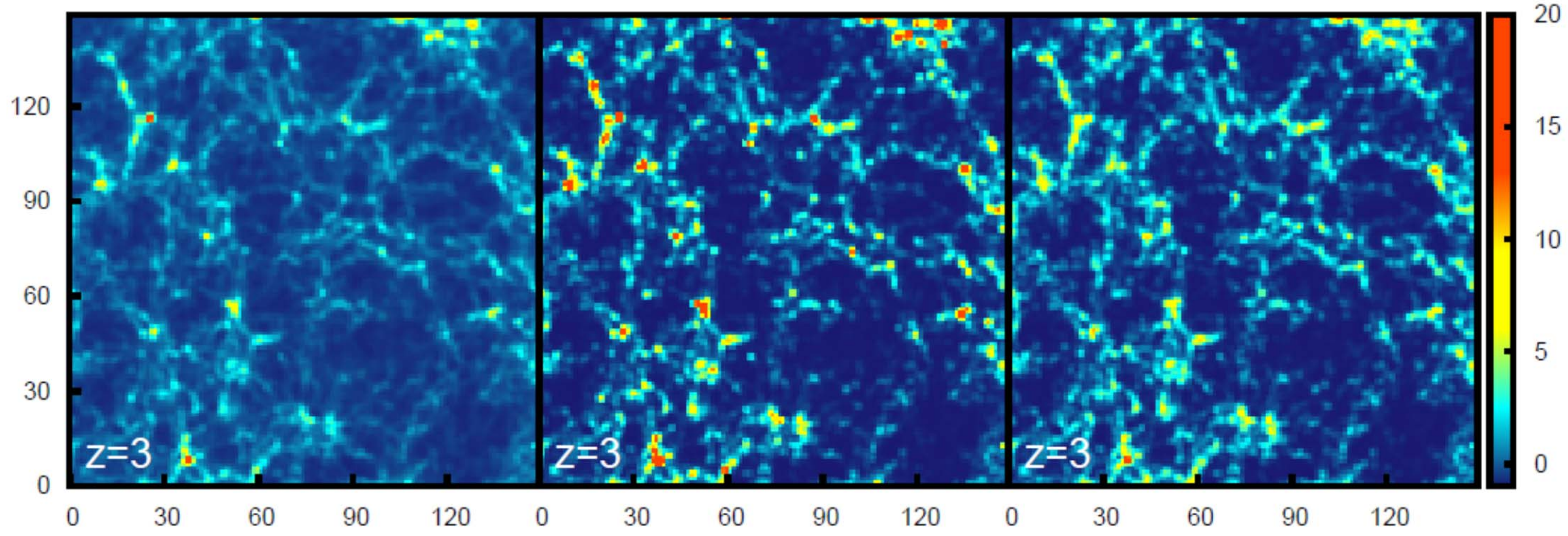


Bulk of neutral gas in DLAs

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

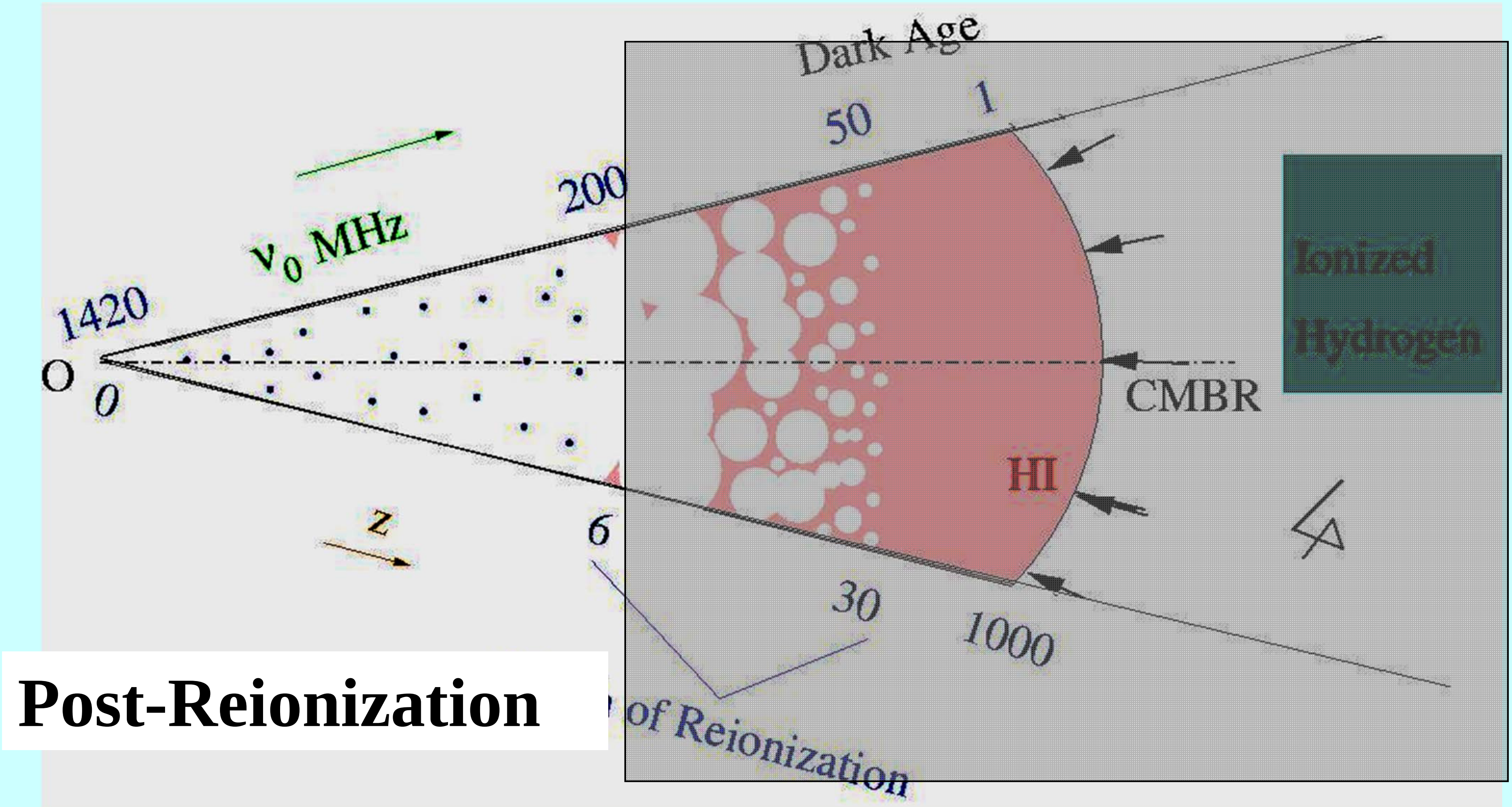
Simulation z=3

Dark Matter Halos HI



Sarkar, D. et al., 2016, MNRAS

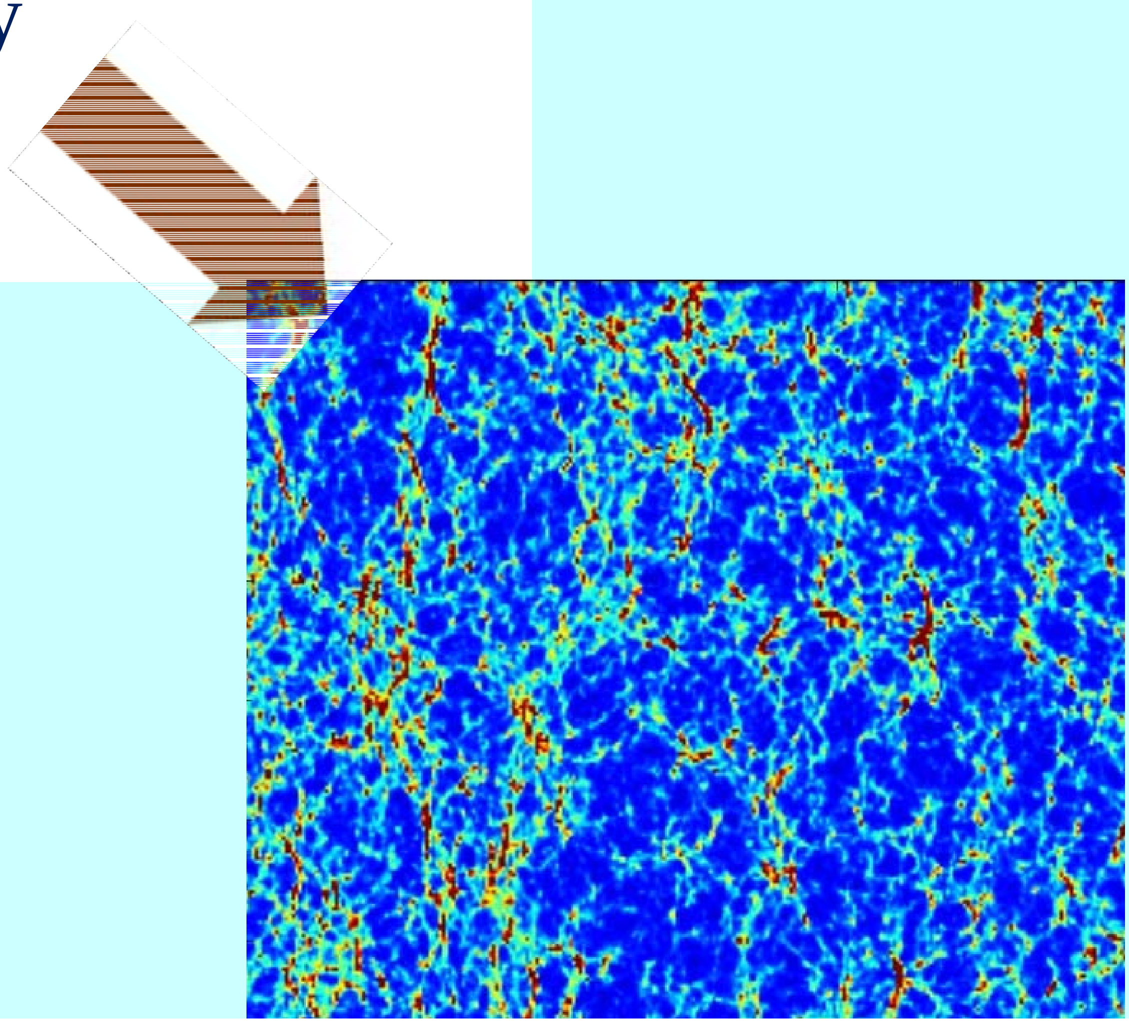
HI Evolution



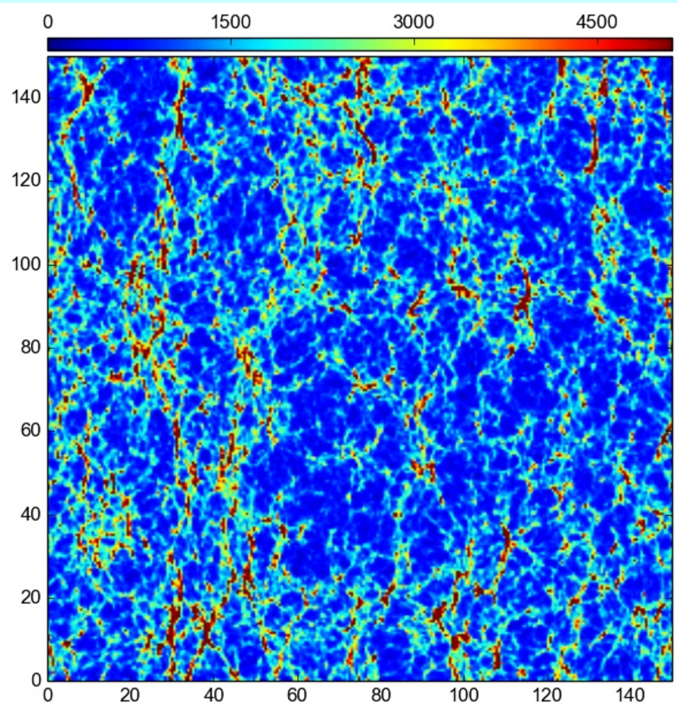
HI seen in emision

What can we observe?

The redshifted 21-cm brightness temperature fluctuates with frequency and angle on sky

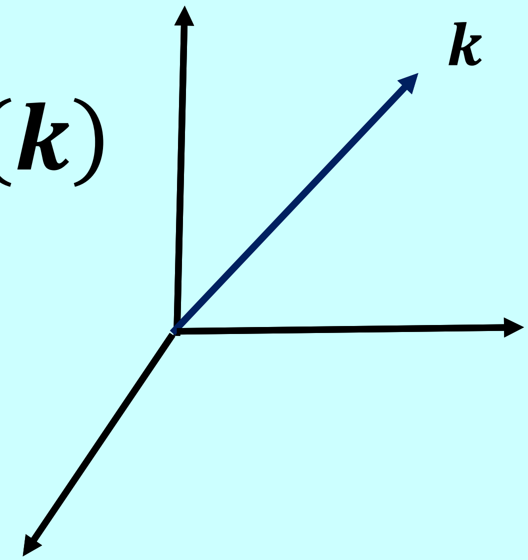


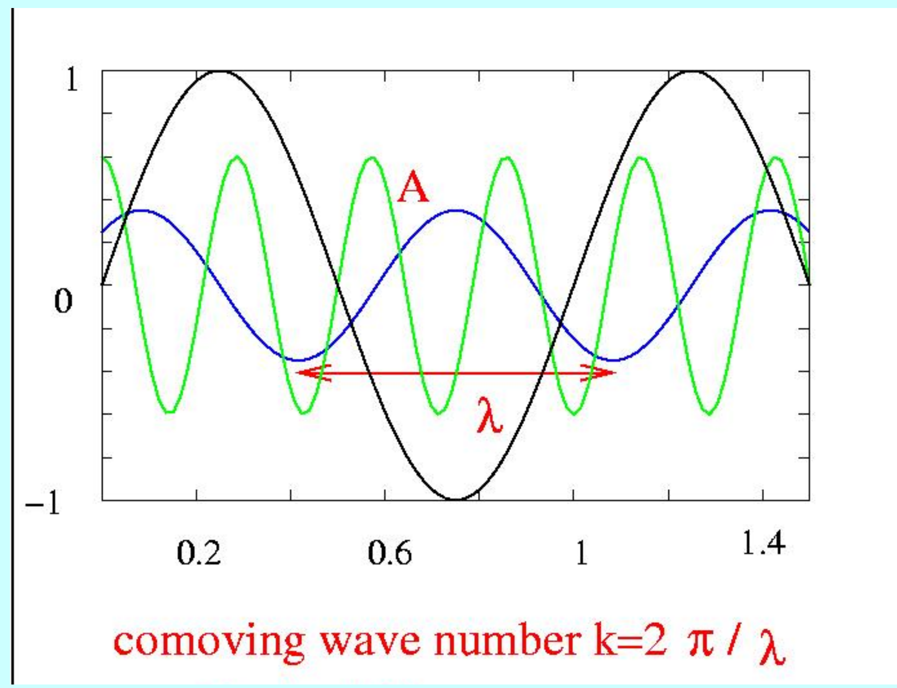
21-cm Power Spectrum



Fourier Transform

$\Delta(\boldsymbol{k})$

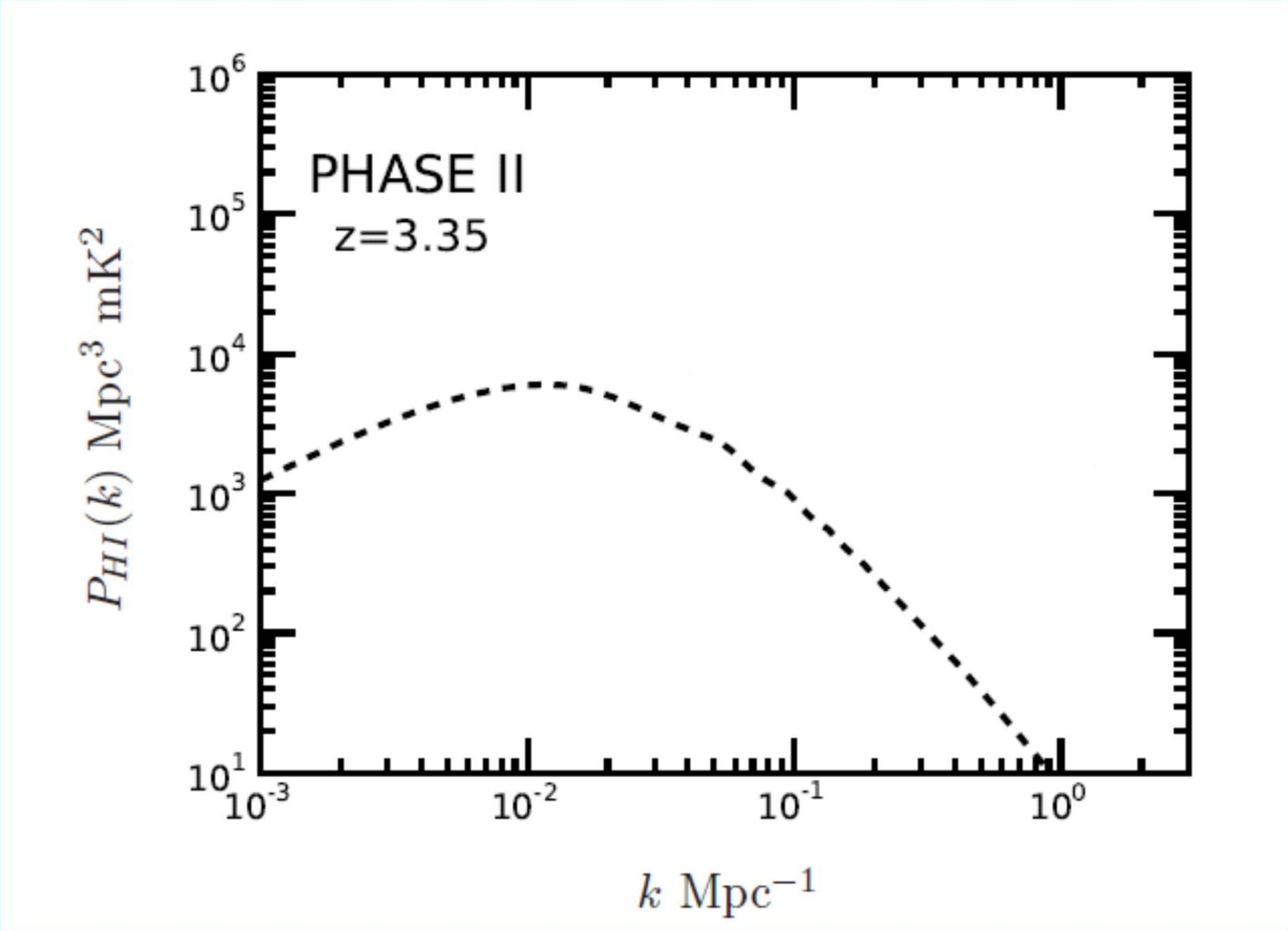




Power Spectrum

$$\hat{P}(k) = \frac{\Delta(\boldsymbol{k})\Delta(-\boldsymbol{k})}{V}$$

21-cm Power Spectrum



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

Our Efforts Started With

Using HI to Probe Large Scale Structures at z ∼ 3

JApA, 2001

Somnath Bharadwaj [1*], Biman B. Nath [2†] & Shiv K. Sethi [3‡]
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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 $10^{-7}\,\mathrm{K}^2$ to $10^{-8}\,\mathrm{K}^2$ 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.

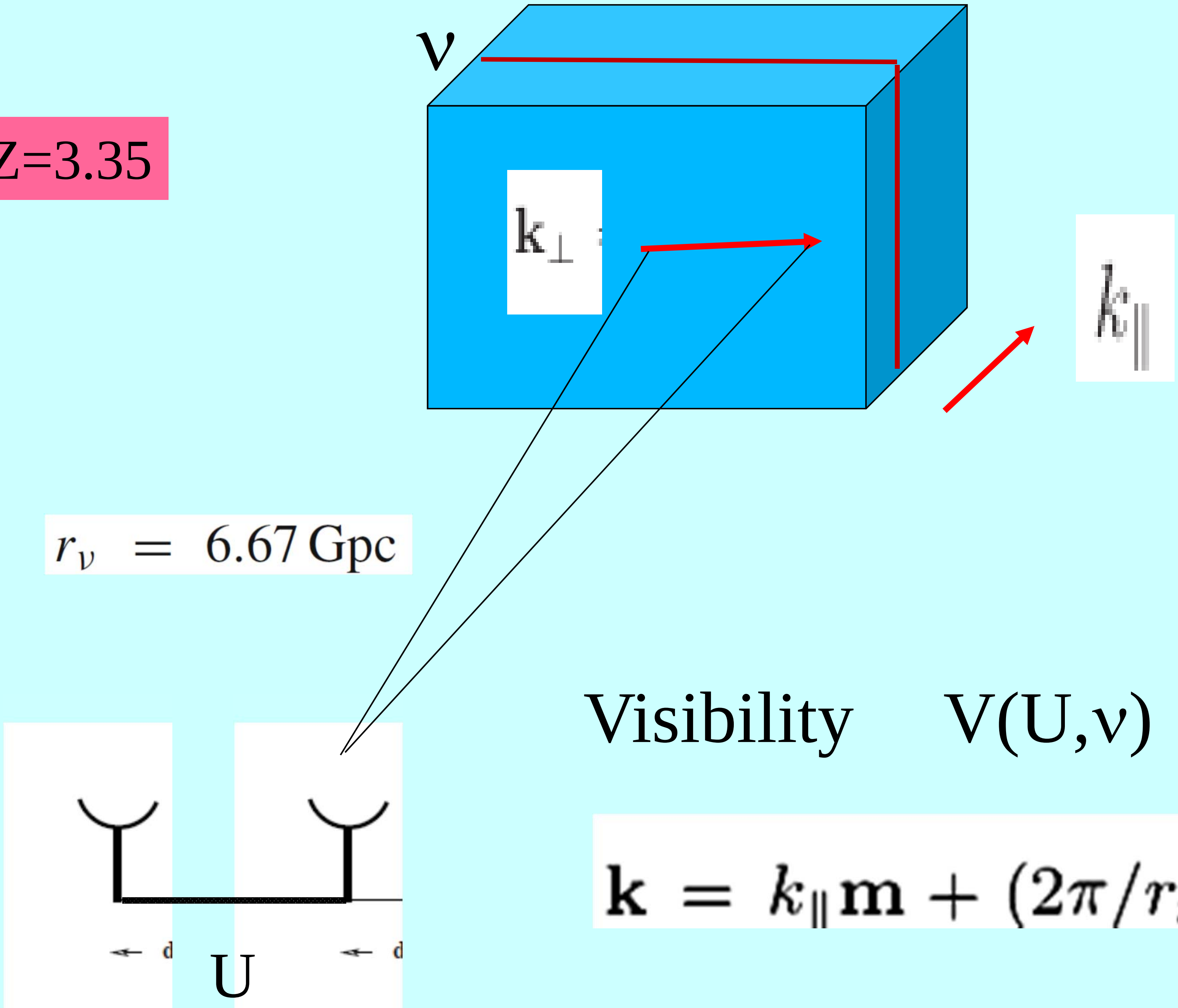

GMRT Giant Meter-wave Radio Telescope

21-cm Visibility Signal

$r'_\nu = 11.33\,\mathrm{Mpc}\,MHz^{-1}$

Z=3.35

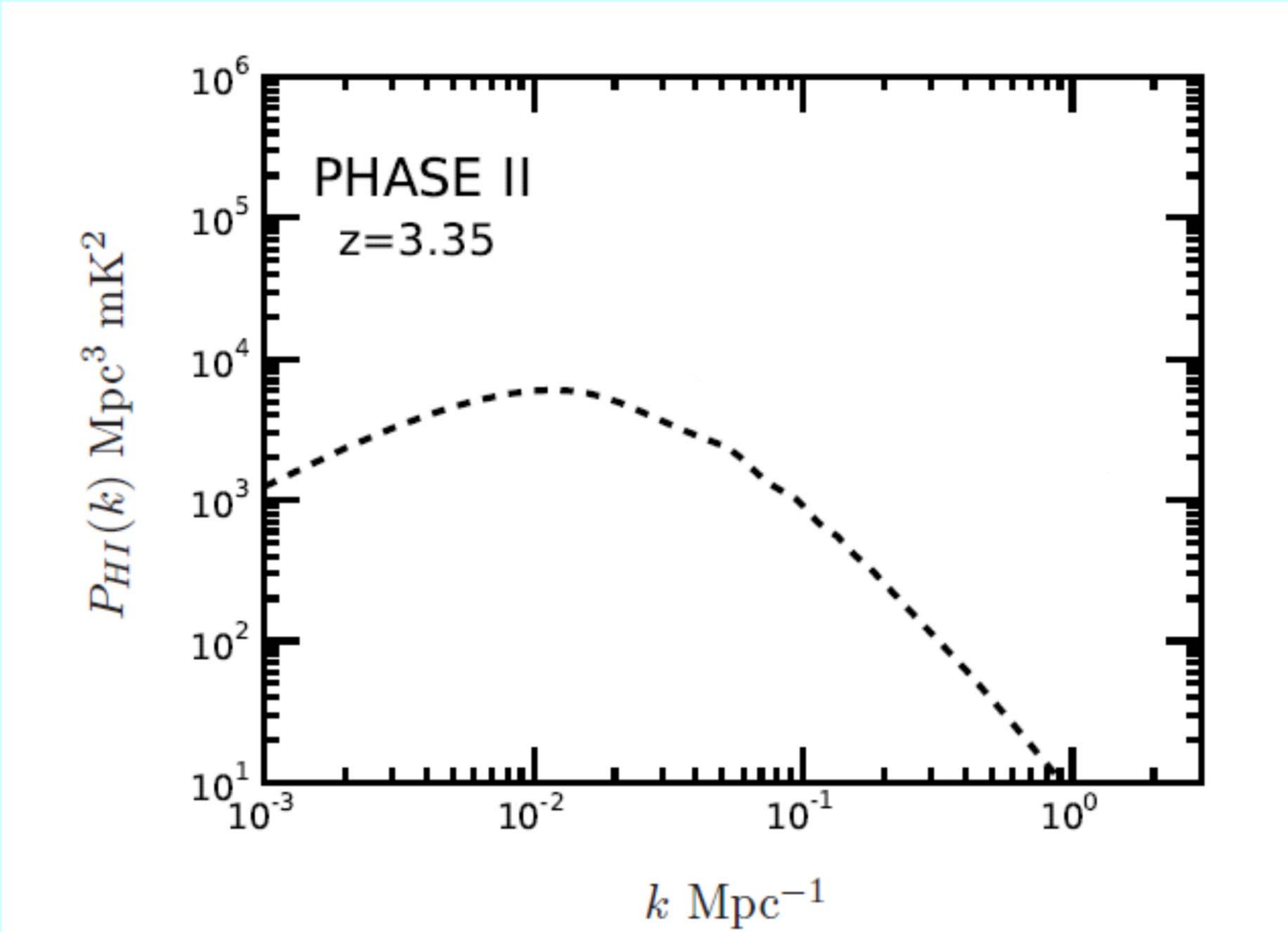
$r_\nu = 6.67\,\mathrm{Gpc}$



Visibility V(U,ν) ↔ Δ(**k**)

$$\mathbf{k} = k_\parallel \mathbf{m} + (2\pi/r_\nu)\mathbf{U}.$$

21-cm Power Spectrum



Efforts to Detect the Spatially Fluctuating 21cm Signal from Reionization

LOFAR
(Netherlands)

MWA
(Western Australia)

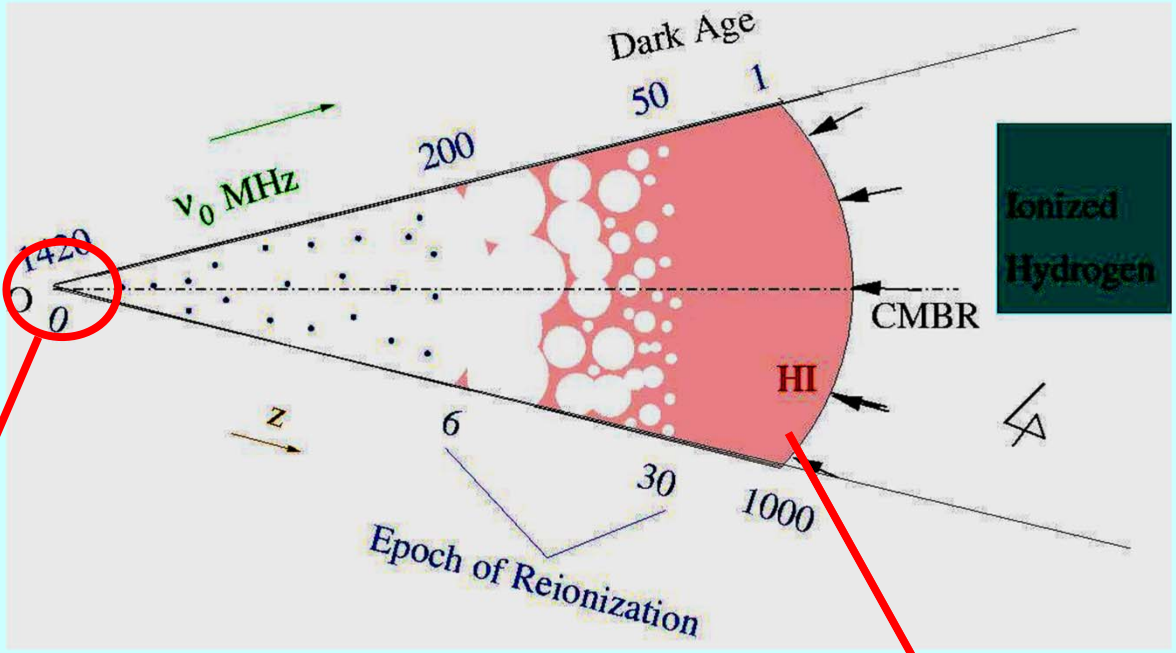
PAPER
(West Virginia & South Africa)

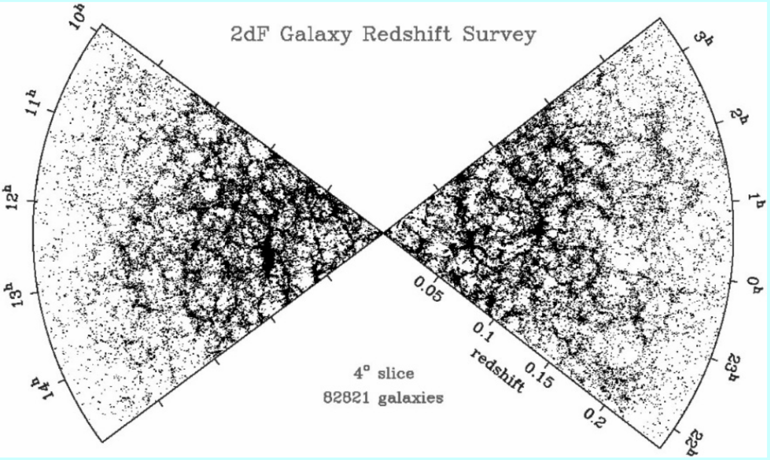
GMRT (India)

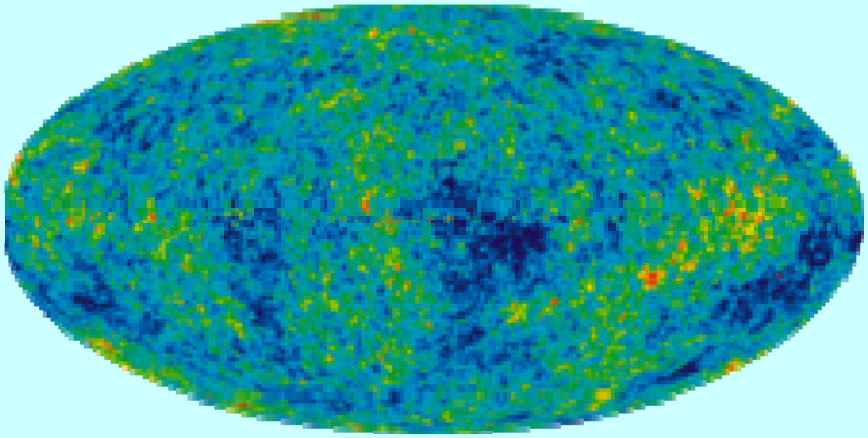
SKA (??)

21CMA (China)

Evolution of the Universe



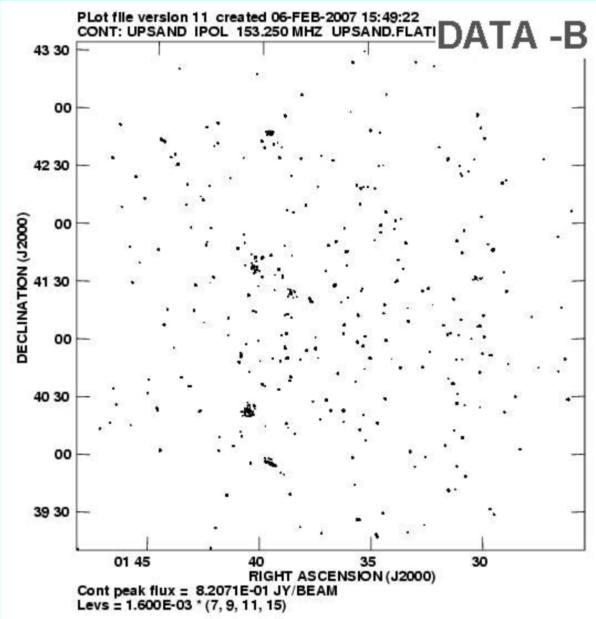


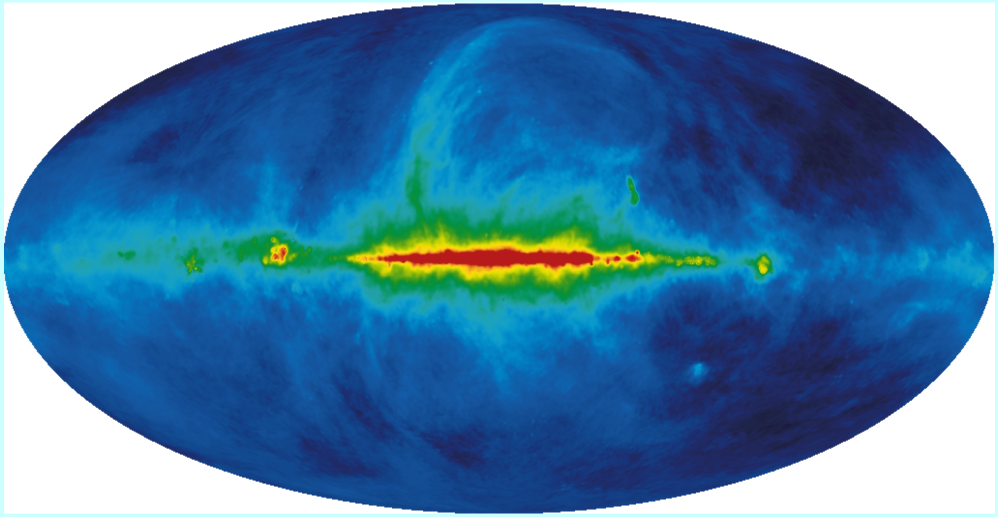


Summary

- 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

Foregrounds





Point Sources

Diffuse

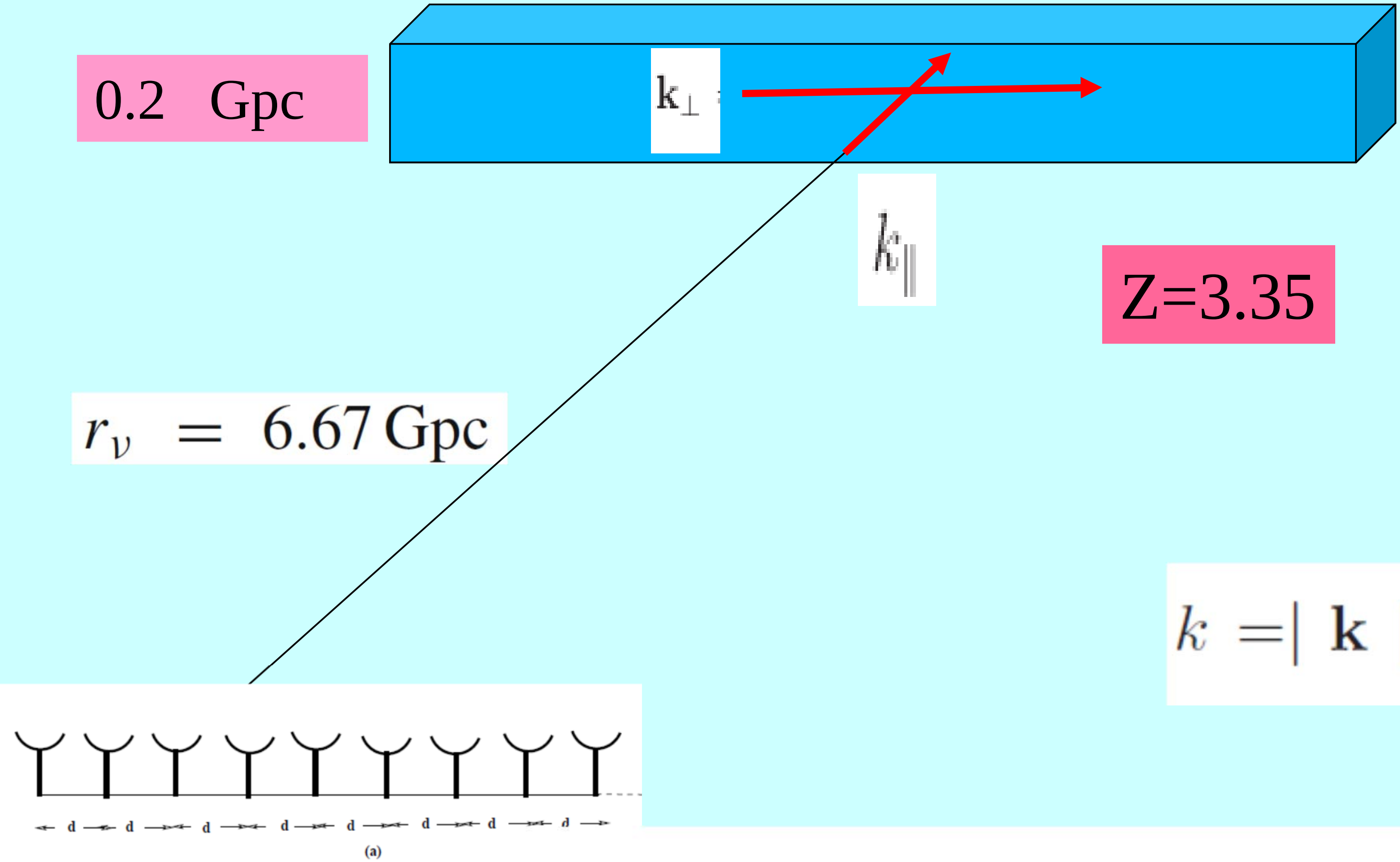
Removal is Biggest Challenge


Thank You

OWFA II

$r\vec{\theta}$ 3.2 Gpc

$r'_{\nu} = 11.33\,\mathrm{Mpc}\,MHz^{-1}$



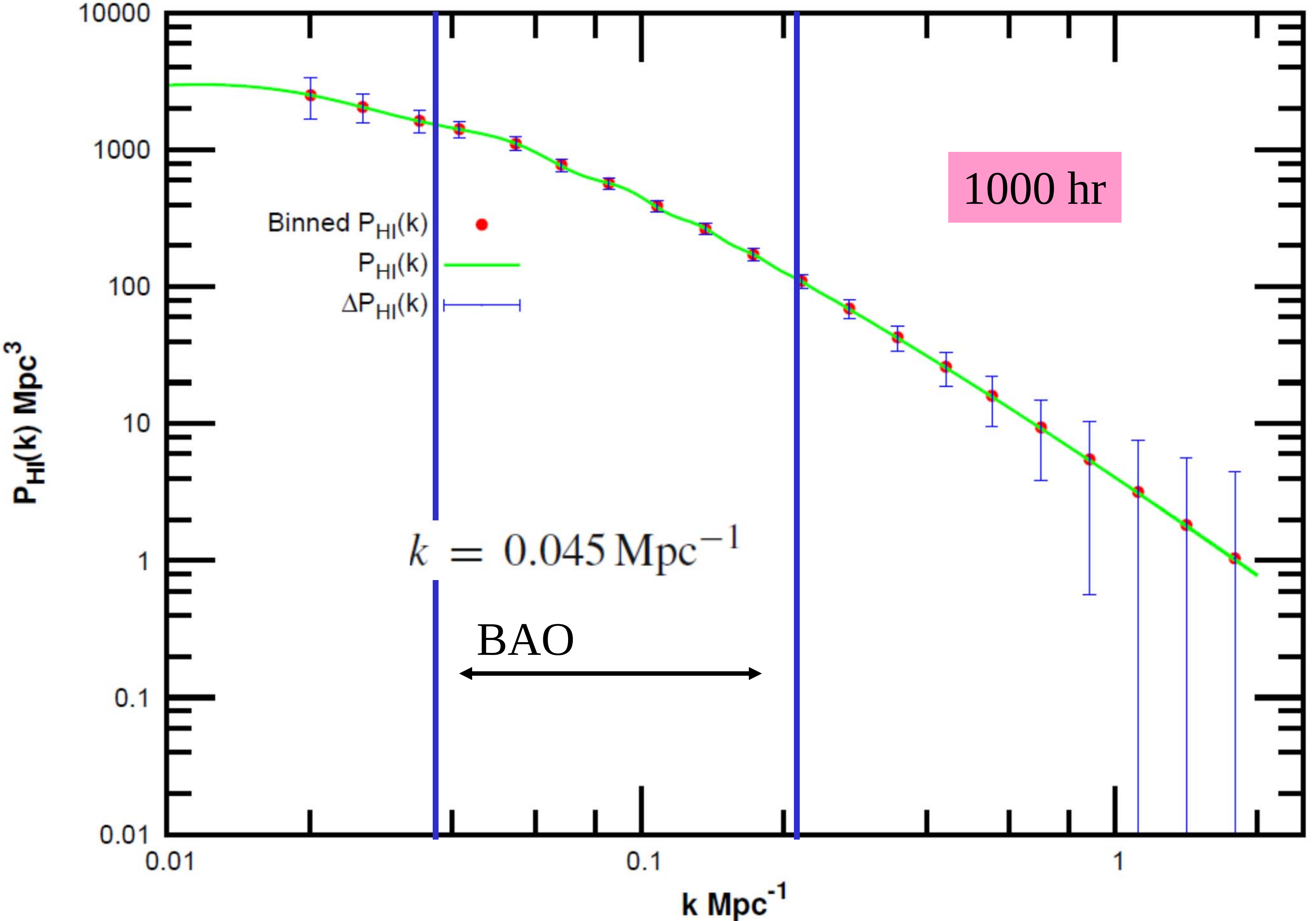
Z=3.35

$$k = |\mathbf{k}| = \sqrt{k_{\parallel}^2 + k_{\perp}^2}$$

Table 2. The $k_{\perp}$ and $k_{\parallel}$ range that will be probed by the different Phases of OWFA.

Mpc^{-1}	Phase I	Phase II	Phase III	Phase IV
$k_{\perp}[min]$	1.1×10^{-2}	1.9×10^{-3}	9.5×10^{-4}	4.8×10^{-4}
$k_{\perp}[max]$	4.8×10^{-1}	5.0×10^{-1}	5.1×10^{-1}	5.1×10^{-1}
$k_{\parallel}[min]$	3.0×10^{-2}	1.8×10^{-2}	9.1×10^{-3}	4.6×10^{-3}
$k_{\parallel}[max]$	2.73	2.73	2.73	2.73

Binned Power Spectrum



Sarkar, A. et al., 2017