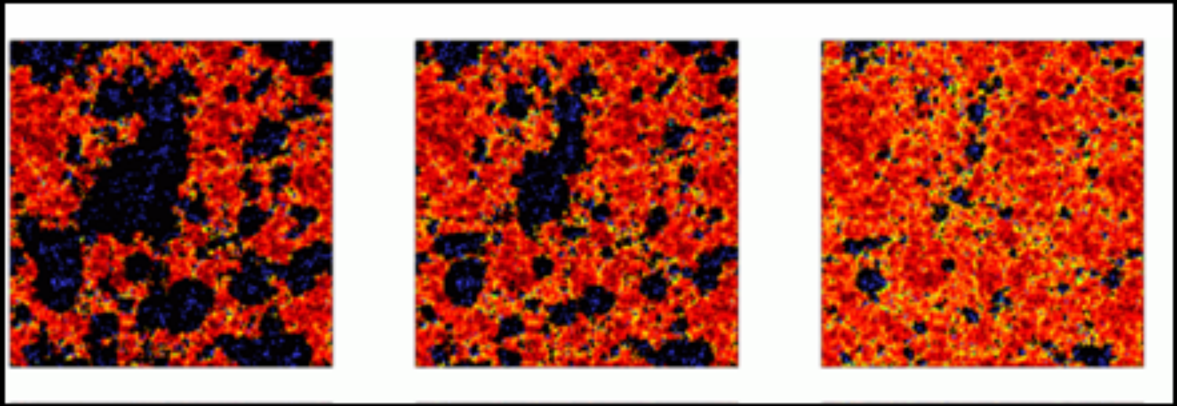
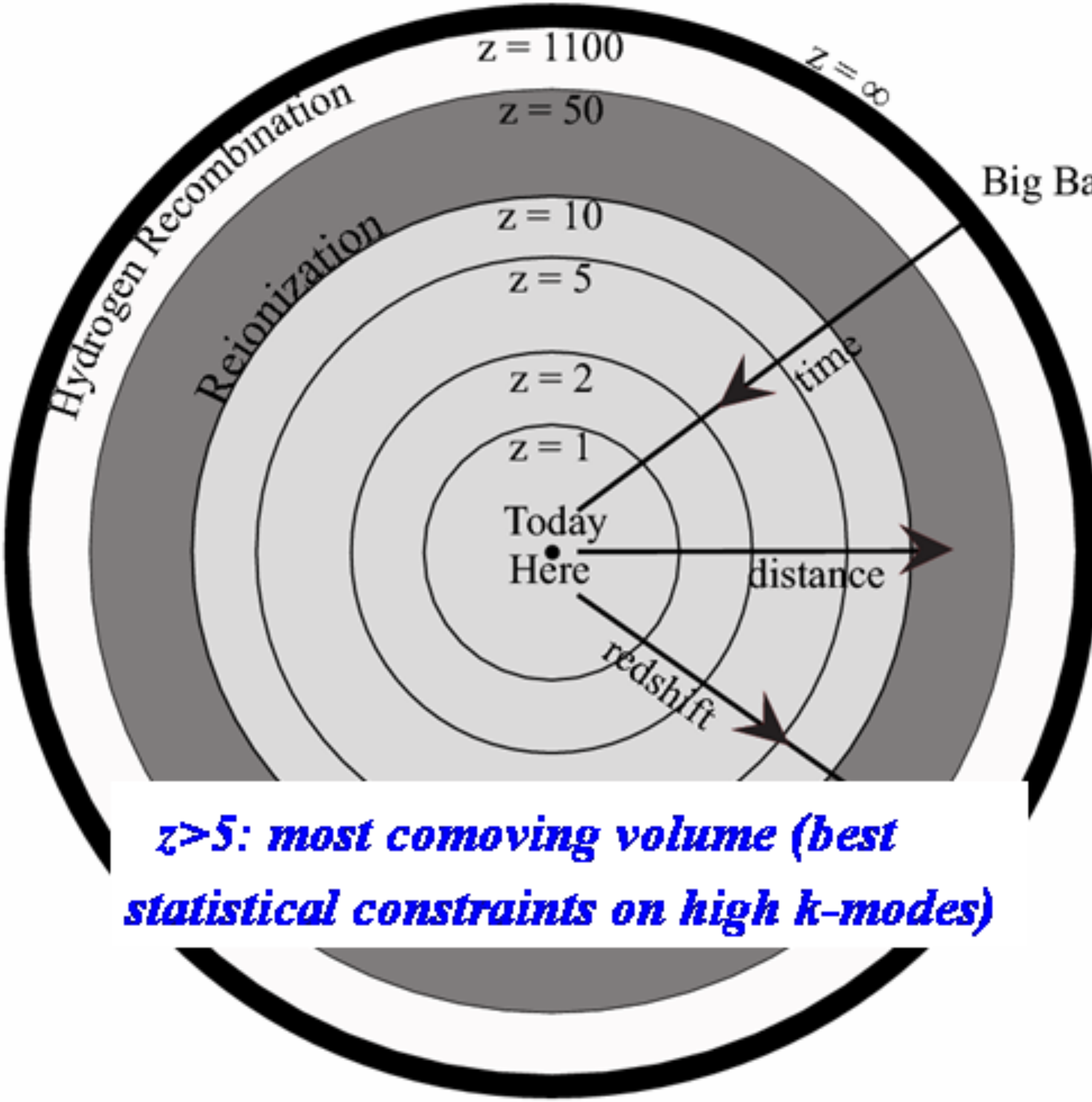
21 cm Cosmology in the 21st Century

- *Standard model of physics and cosmology*
- *Initial conditions from inflation*
- *Weakly-interacting Cold Dark Matter*



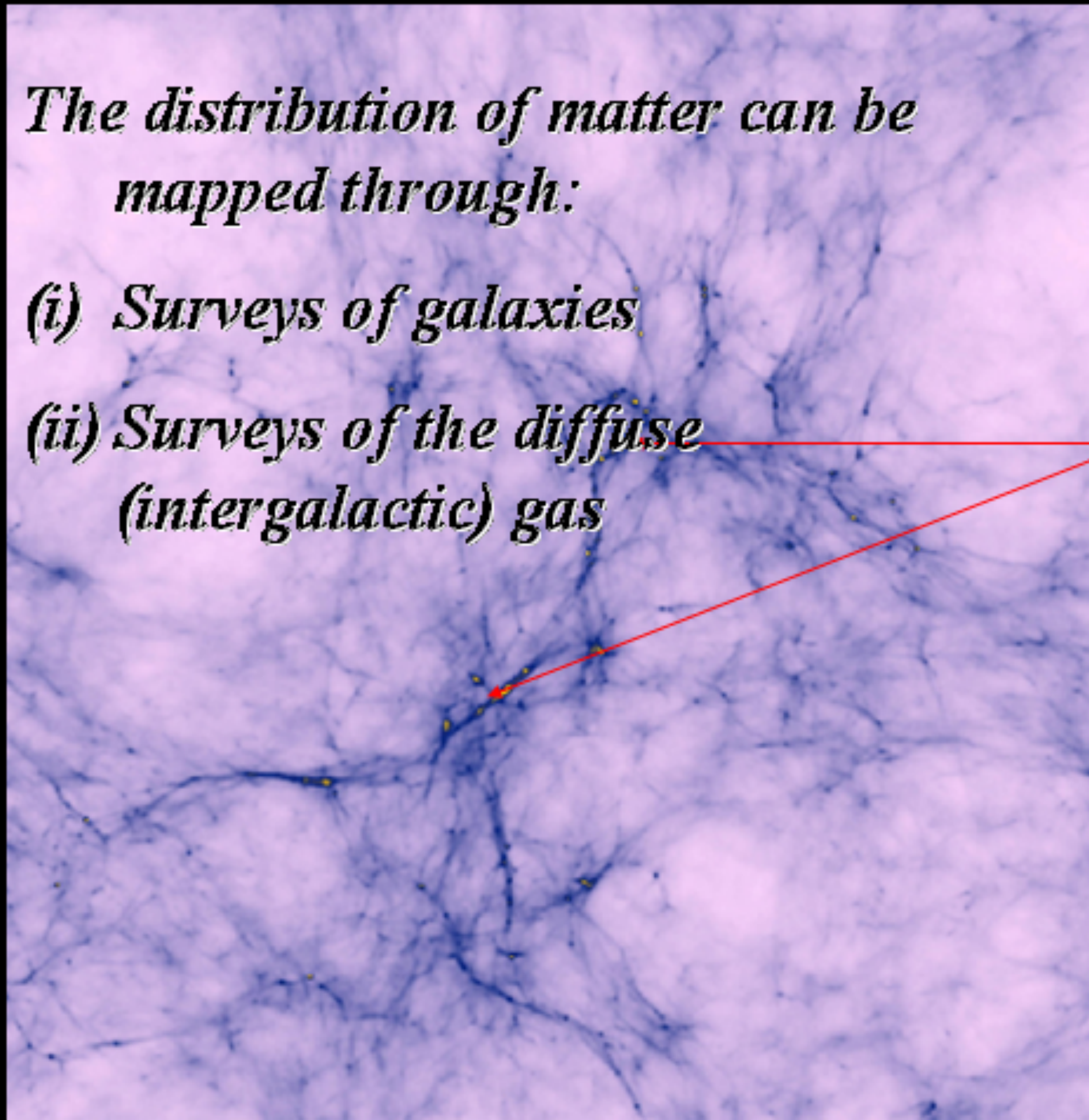
Surprises may signal new physics

The Visible Universe



z>5: most comoving volume (best statistical constraints on high k-modes)

The First Dwarf Galaxies Formed at z~50

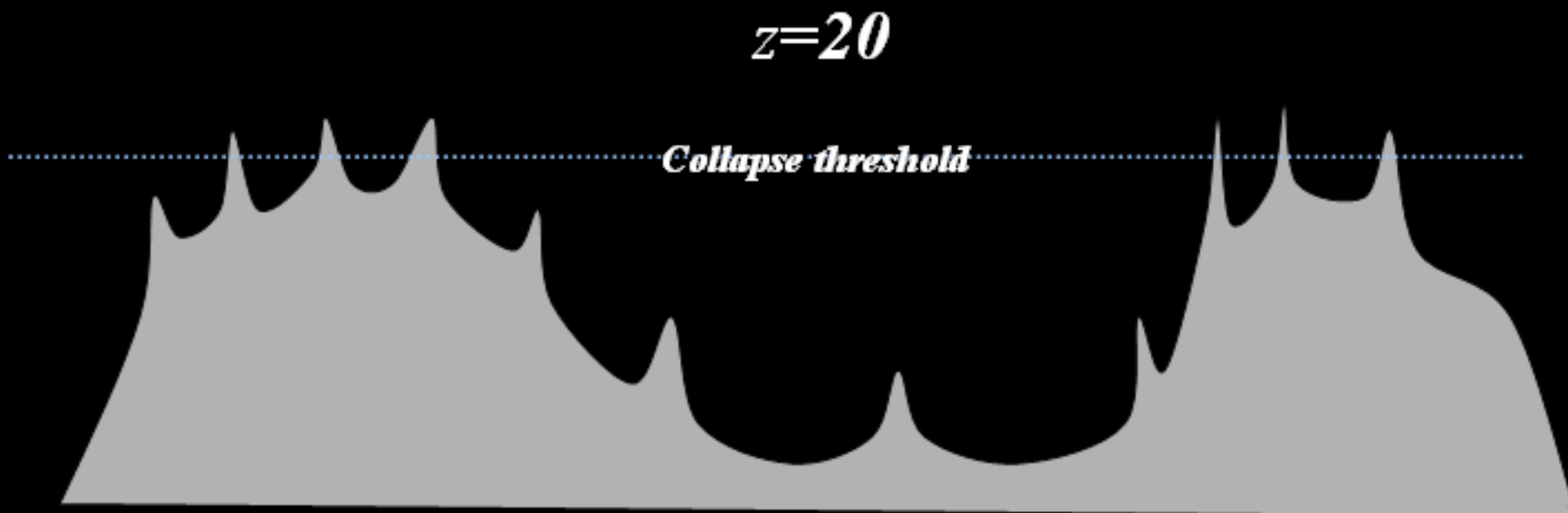


molecular hydrogen in Jeans mass objects

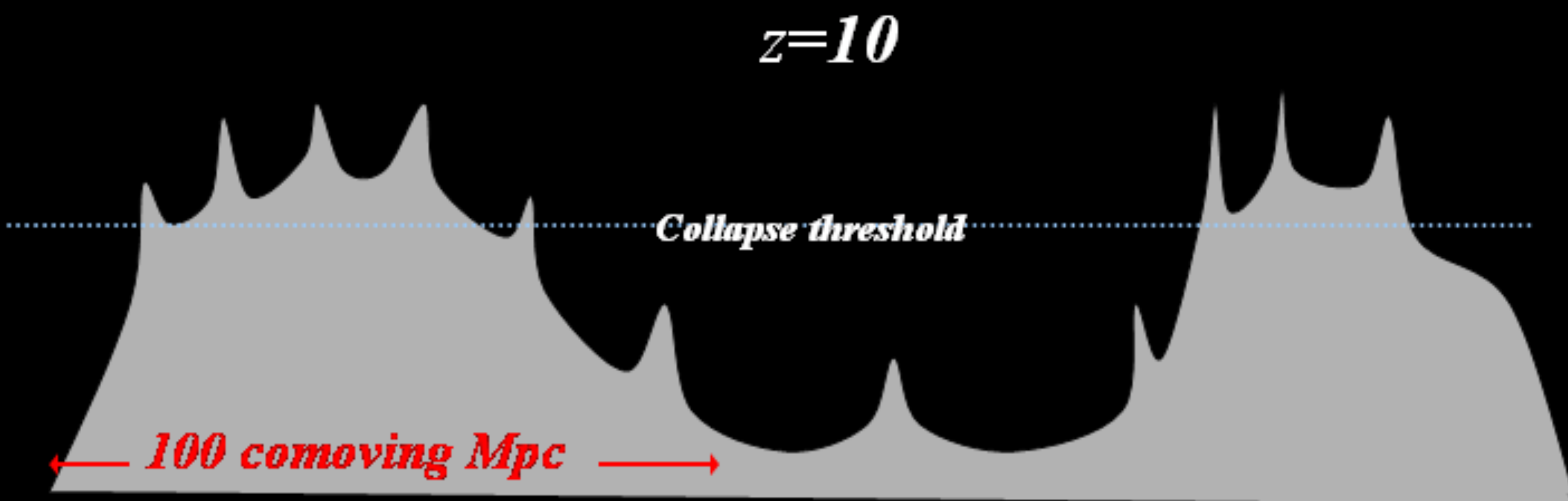
$(\sim 10^5 M_\odot)$

Yoshida et al. 2003

First Galaxies Were Strongly Clustered on Scales of up to ~100 comoving Mpc



First Galaxies Were Strongly Clustered on Scales of up to ~100 comoving Mpc



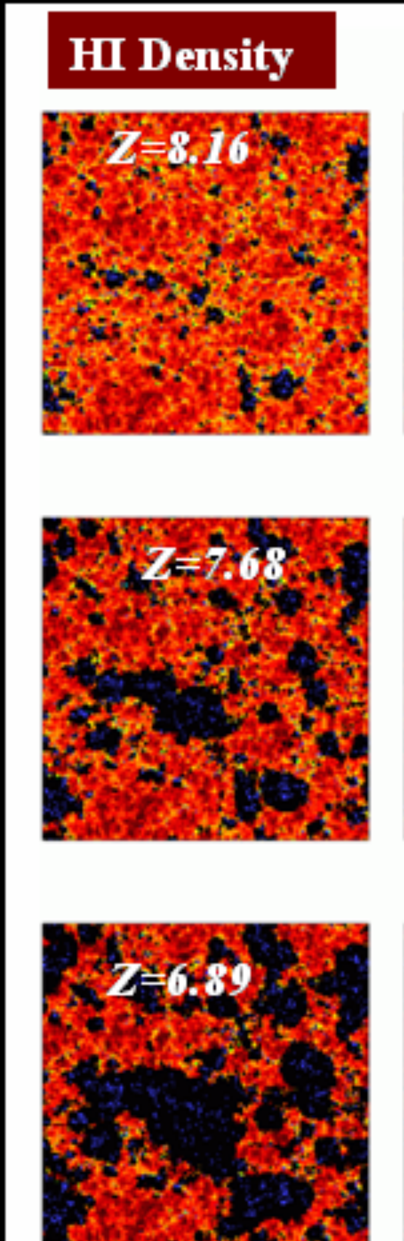
Challenges for numerical simulations of reionization:

**Resolving dwarf galaxies as sources of ionizing photons*

**Simulation box >100 comoving Mpc on a side*

**Following gravity, hydrodynamics, radiative transfer and their interaction*

Reionization



Zahn et al. 2006

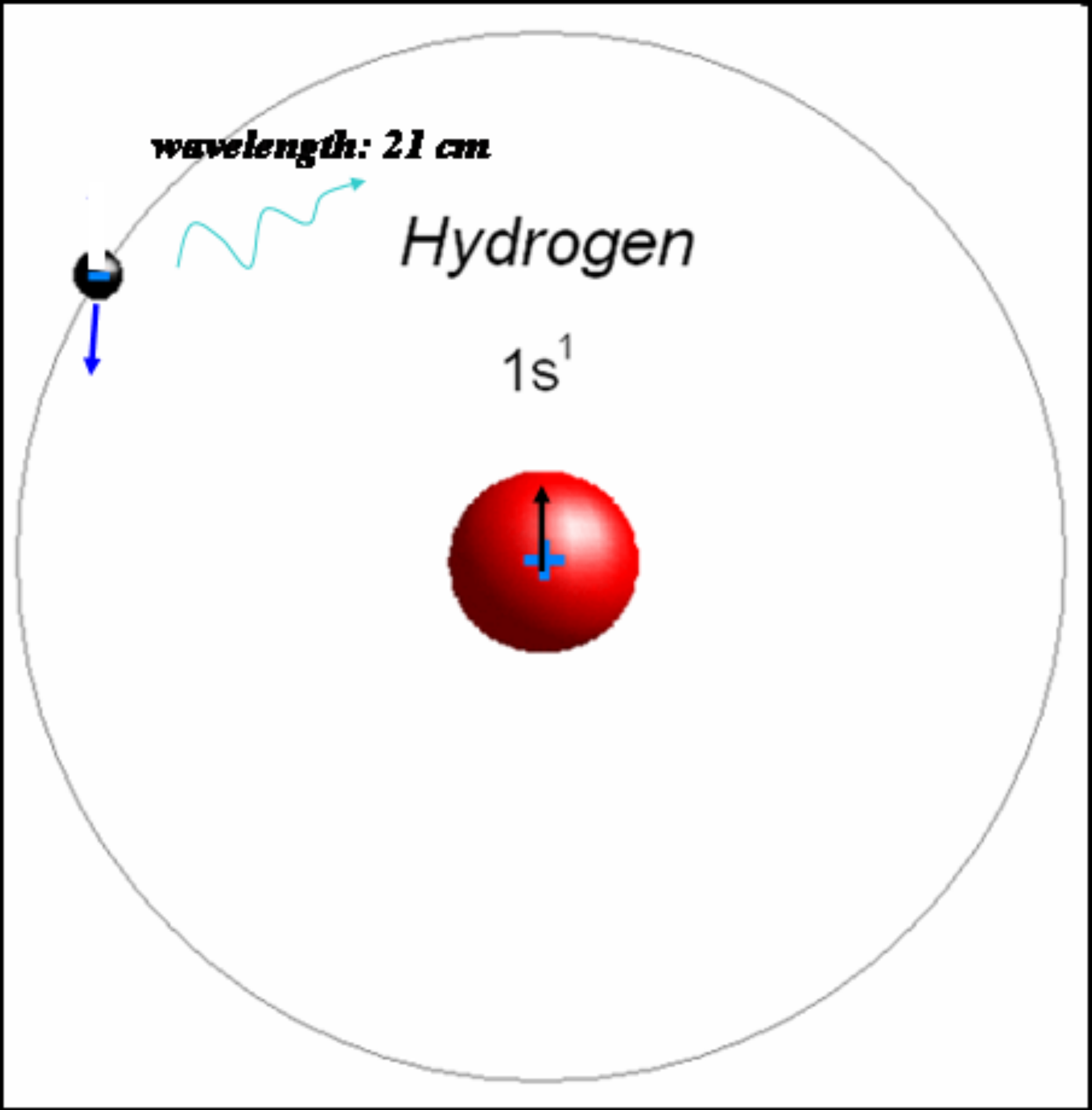
x_HI(z)

PopII/Pop III

T(z)

Trac, Cen, & Loeb 2008

Observing the Diffuse Gas



<u>Harvard connection:</u> ***Theodore Lyman, Cecilia Payne-Gaposchkin, Edward Purcell , George Field …***

Mapping the Cosmic Distribution of

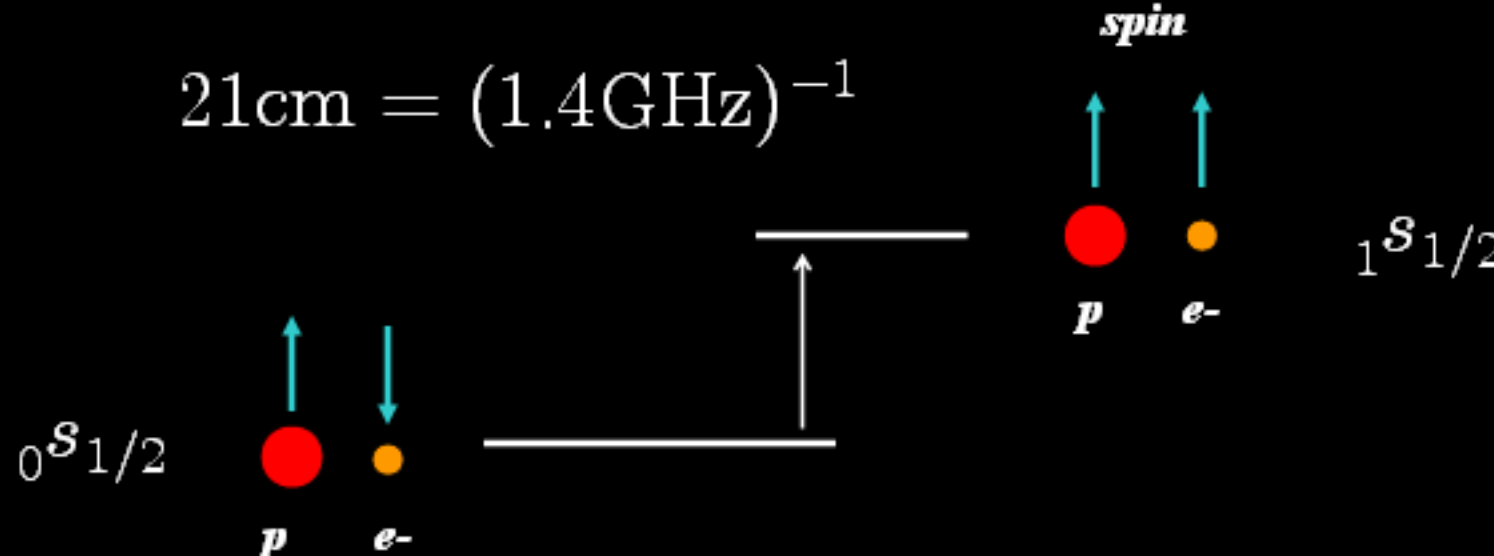
Hydrogen

Ground level

excitation rate= (Lya & atomic collisions)+(radiative coupling to CMB)

Couple T_s ***to*** T_k ***Couples*** T_s ***to*** T_γ

$$21\text{cm} = (1.4\text{GHz})^{-1}$$

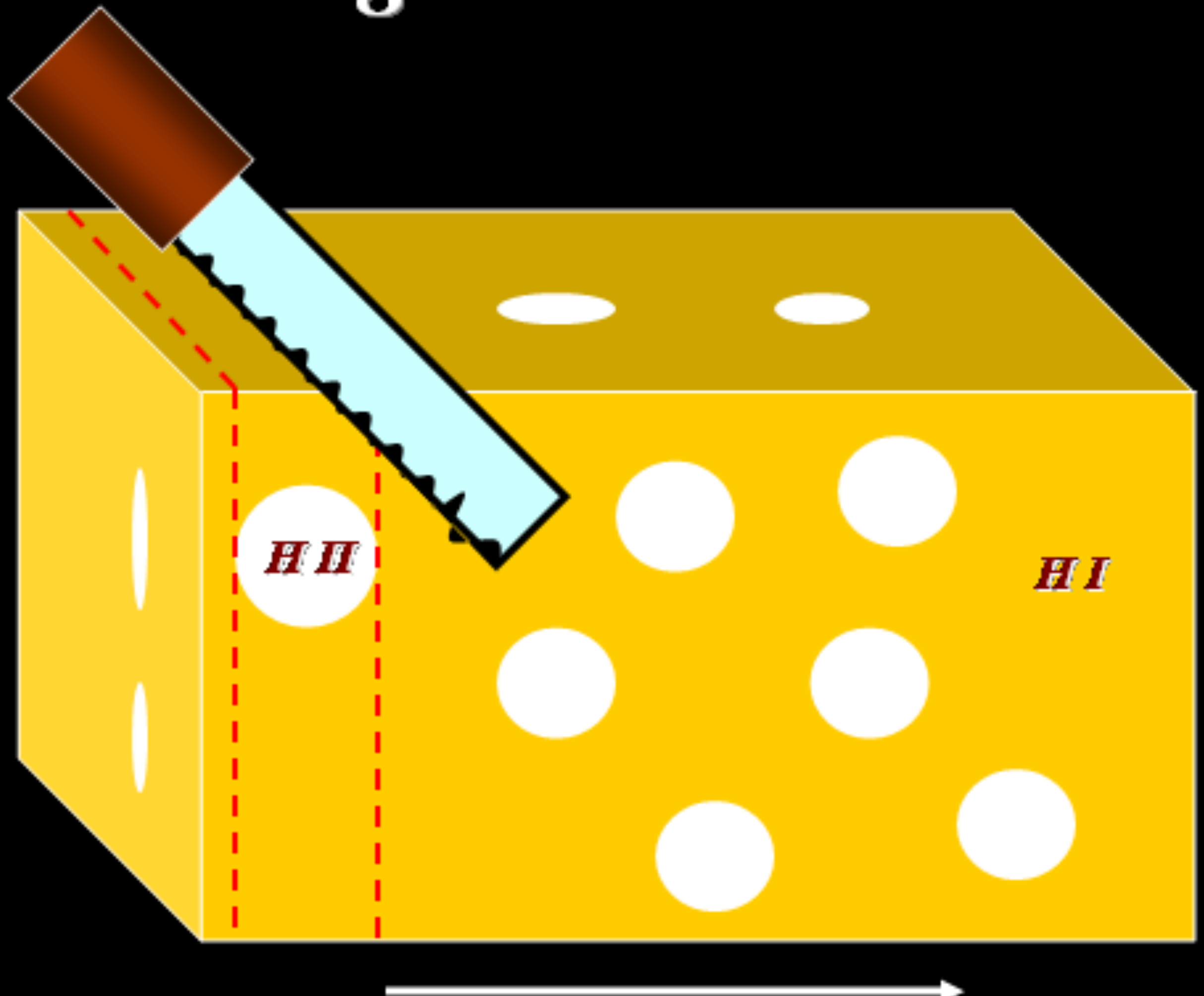


Spin Temperature $$\frac{n_1}{n_0} = \frac{g_1}{g_0}\exp\{-\frac{0.068\text{K}}{T_s}\}$$ $$(g_1/g_0) = 3$$

Predicted by Van de Hulst in 1944; Observed by Ewen &Purcell in 1951 at Harvard

21cm Tomography of Ionized Bubbles During Reionization is like

Slicing Swiss Cheese

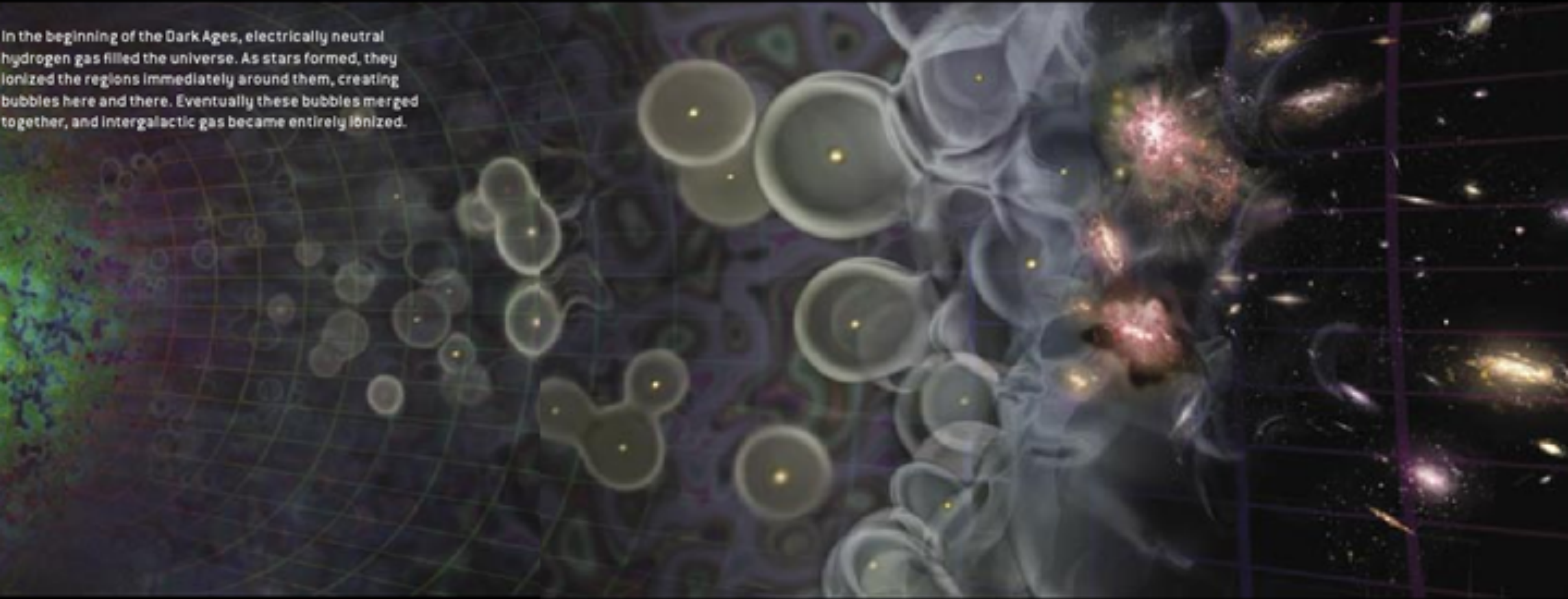


Observed wavelength ⇔ distance

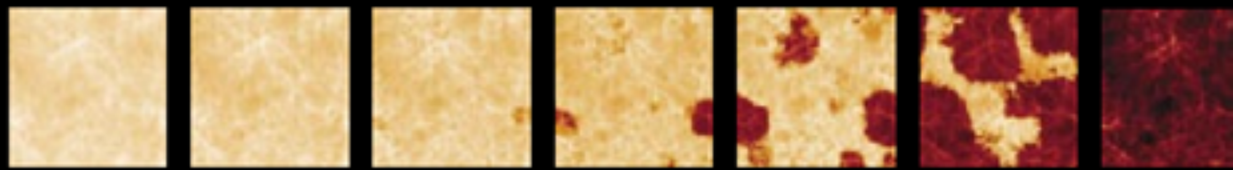
$$21\text{cm} \times (1+z)$$

21cm Mapping of Cosmic History in the 21st Century

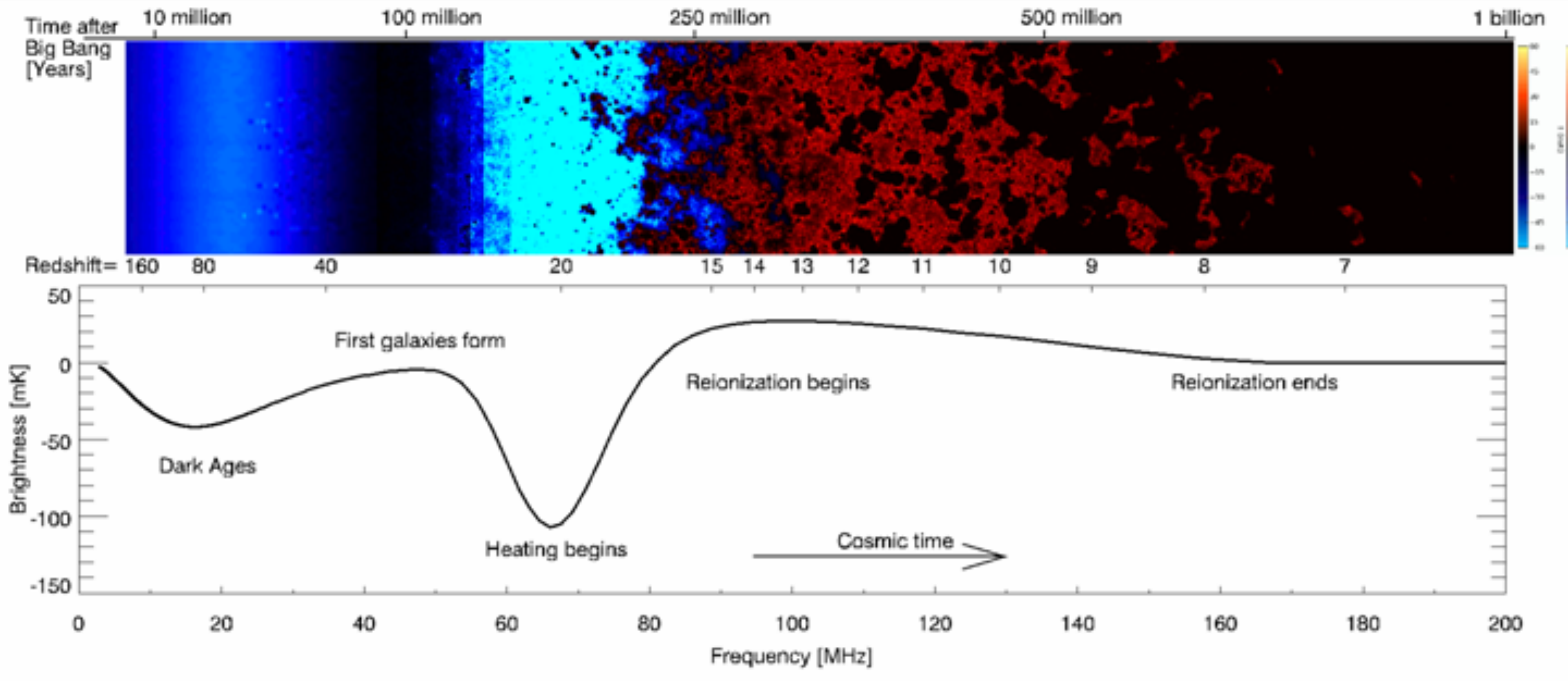
LIGHTING UP THE COSMOS



Time:	210 million years	290 million years	370 million years	460 million years	540 million years	620 million years	710 million years
Width of frame:	2.4 million light-years	3.0 million light-years	3.6 million light-years	4.1 million light-years	4.6 million light-years	5.0 million light-years	5.5 million light-y
Observed wavelength:	4.1 meters	3.3 meters	2.8 meters	2.4 meters	2.1 meters	2.0 meters	1.8 meters
	All the gas is neutral. The white areas are the densest and will give rise to the first stars and quasars.	Faint red patches show that the stars and quasars have begun to ionize the gas around them.	These bubbles of ionized gas grow.	New stars and quasars form and create their own bubbles.	The bubbles are beginning to interconnect.	The bubbles have merged and nearly taken over all of space.	The only remainin neutral hydrogen is concentrated in galaxies.

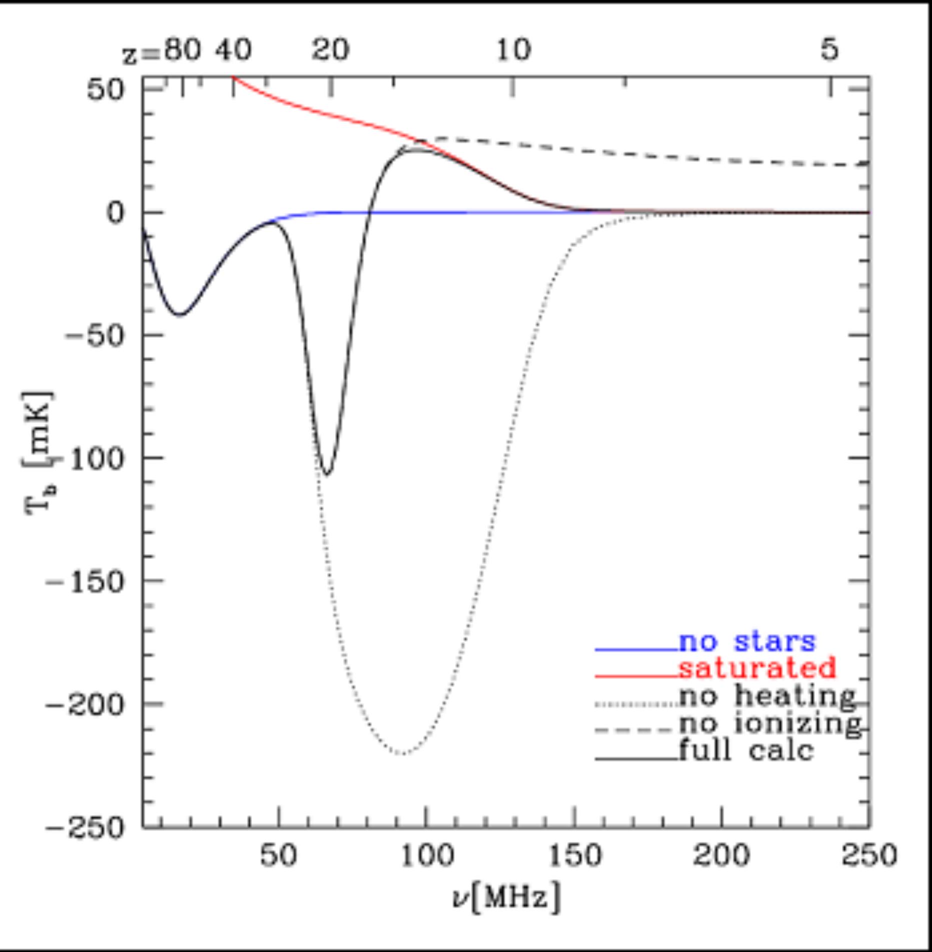


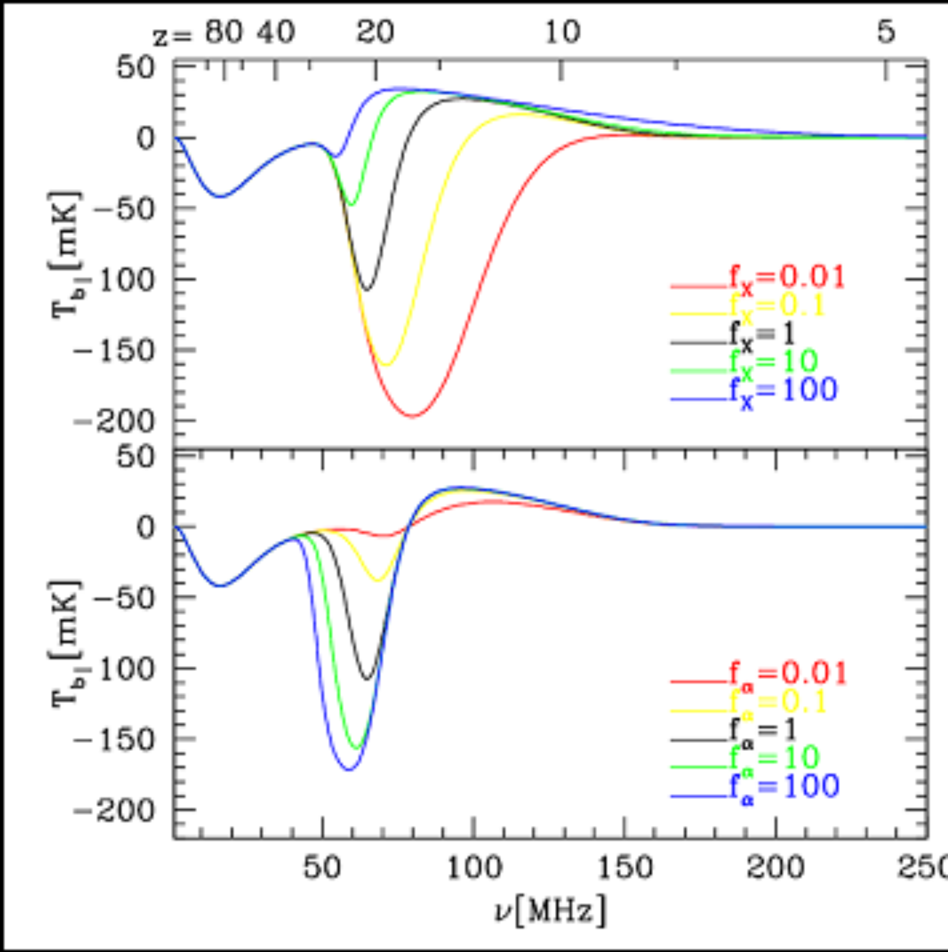
Simulated images of 21-centimeter radiation show how hydrogen gas turns into a galaxy cluster. The amount of radiation [*white is highest; orange and red are intermediate; black is least*] reflects both the density of the gas and its degree of ionization: dense, electrically neutral gas appears white; dense, ionized gas appears black. The images have been rescaled to remove the effect of cosmic expansion and thus highlight the cluster-forming processes. Because of expansion, the 21-centimeter radiation is actually observed at a longer wavelength; the earlier the image, the longer the wavelength.



Time after Big Bang [Years]
10 million
100 million
250 million
500 million
1 billion
Redshift= 160 80 40 20 15 14 13 12 11 10 9 8 7
Brightness [mK]
First galaxies form
Dark Ages
Heating begins
Reionization begins
Reionization ends
Cosmic time
Frequency [MHz]

The Global 21-cm Signal

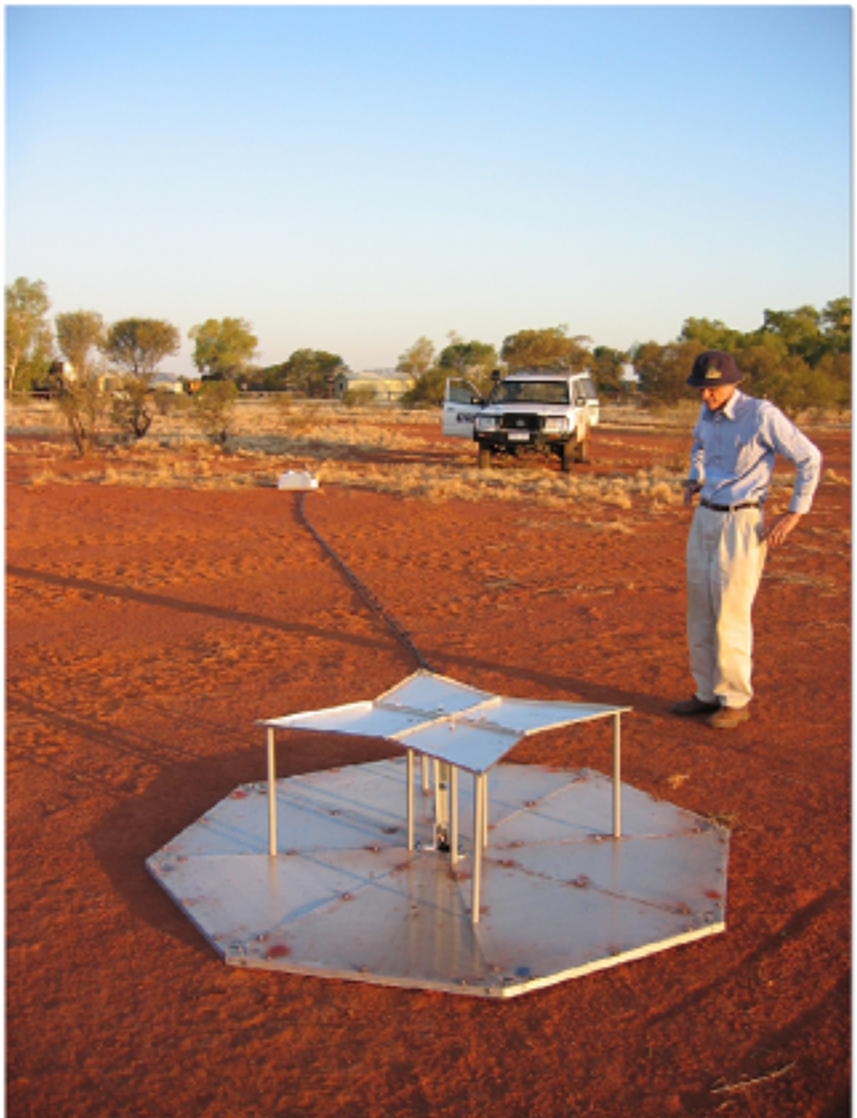


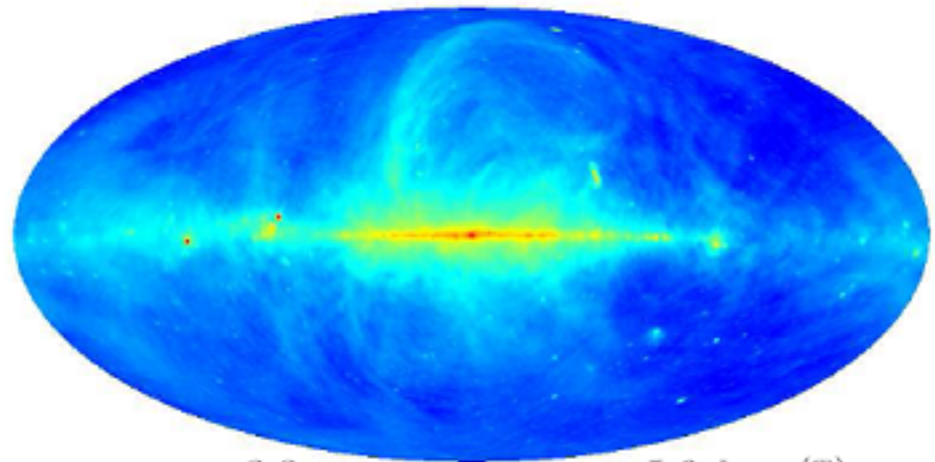


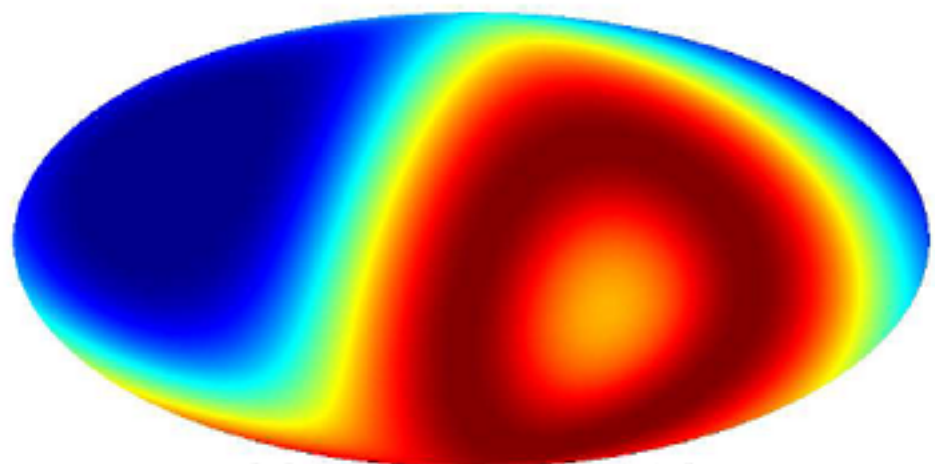
(Pritchard & Loeb, Phys. Rev. D, 2010)

The EDGES Experiment

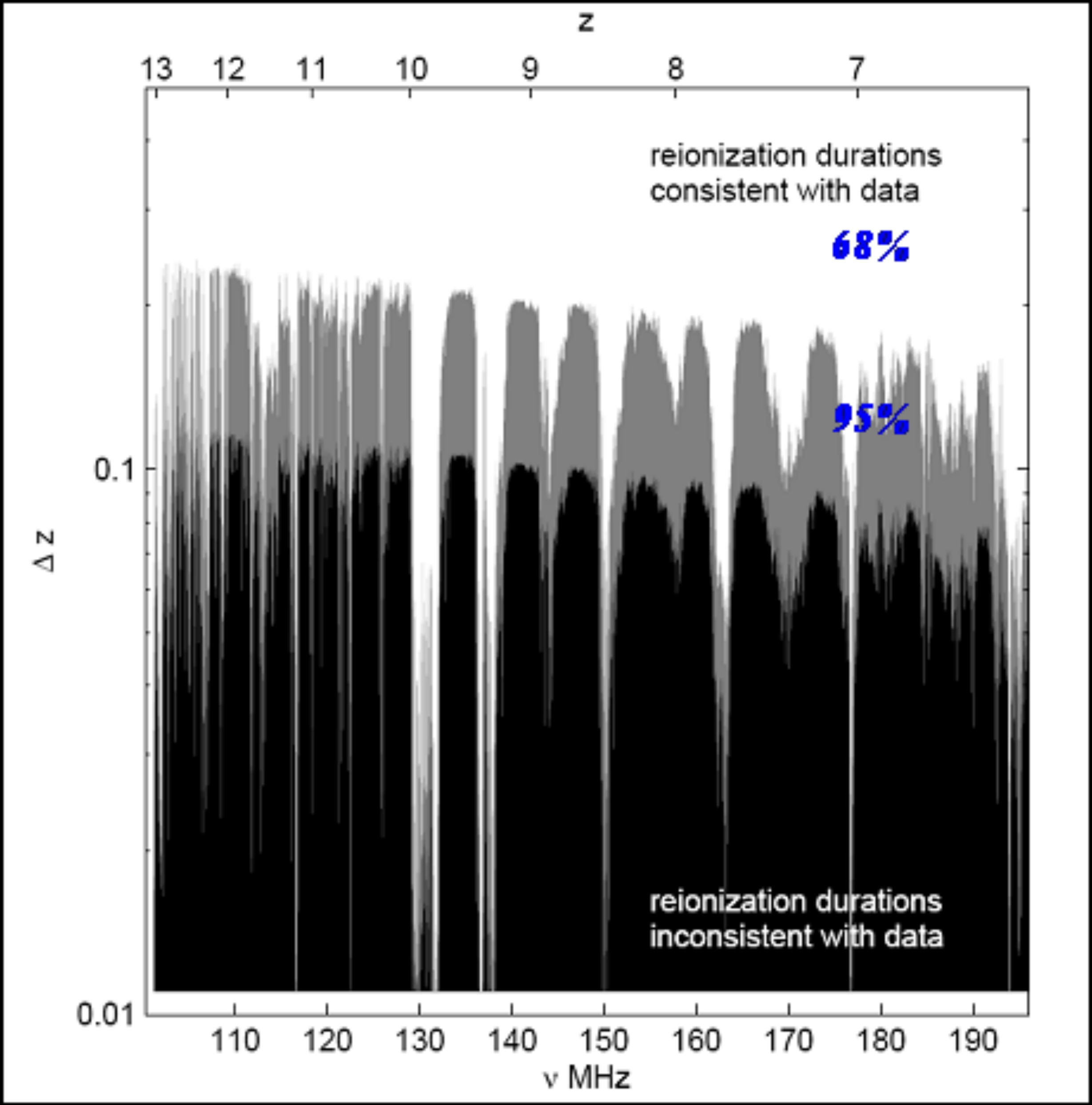
The Experiment to Detect the
Global EOR Signature (EDGES)





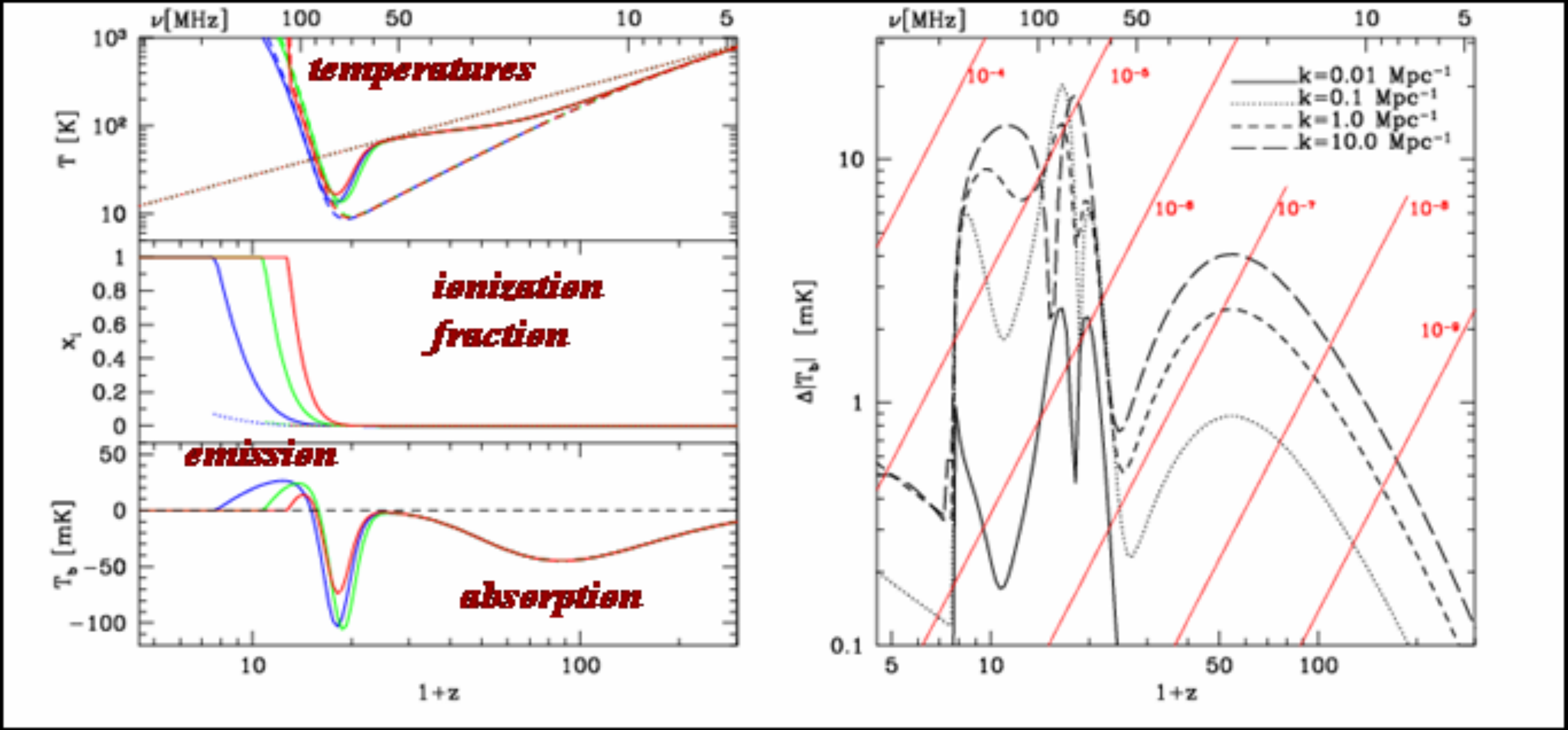


Reionization Was Not Abrupt!



Bowman & Rogers 2010

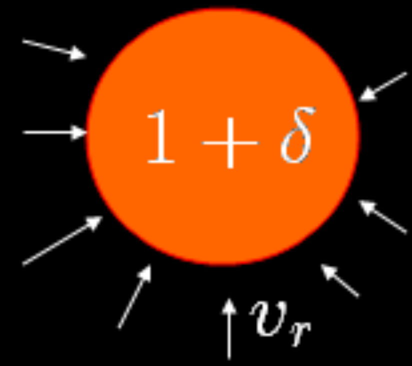
21-cm Tomography throughout Cosmic History



(Pritchard & Loeb, Phys. Rev. D, 2008)

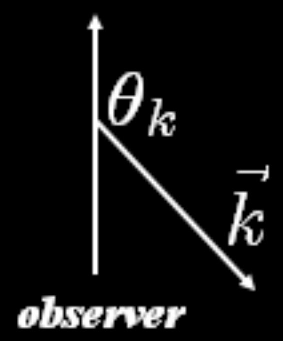
Line-of-Sight Anisotropy of 21cm Flux Fluctuations

$$T_b = \tau \left(\frac{T_s - T_\gamma}{1+z}\right)$$



Peculiar velocity changes $\tau \propto \frac{n_{\rm HI}}{dv_r/dr} = \bar{n}(1+\delta) \sim \bar{H}(1-\frac{1}{3}\delta)$

→ ***Power spectrum is not isotropic*** ***("Kaiser effect")***



$$\frac{dv_r}{dr} \longrightarrow \quad \delta_v(\vec{k}) = -\cos^2\theta_k \times \delta(\vec{k})$$

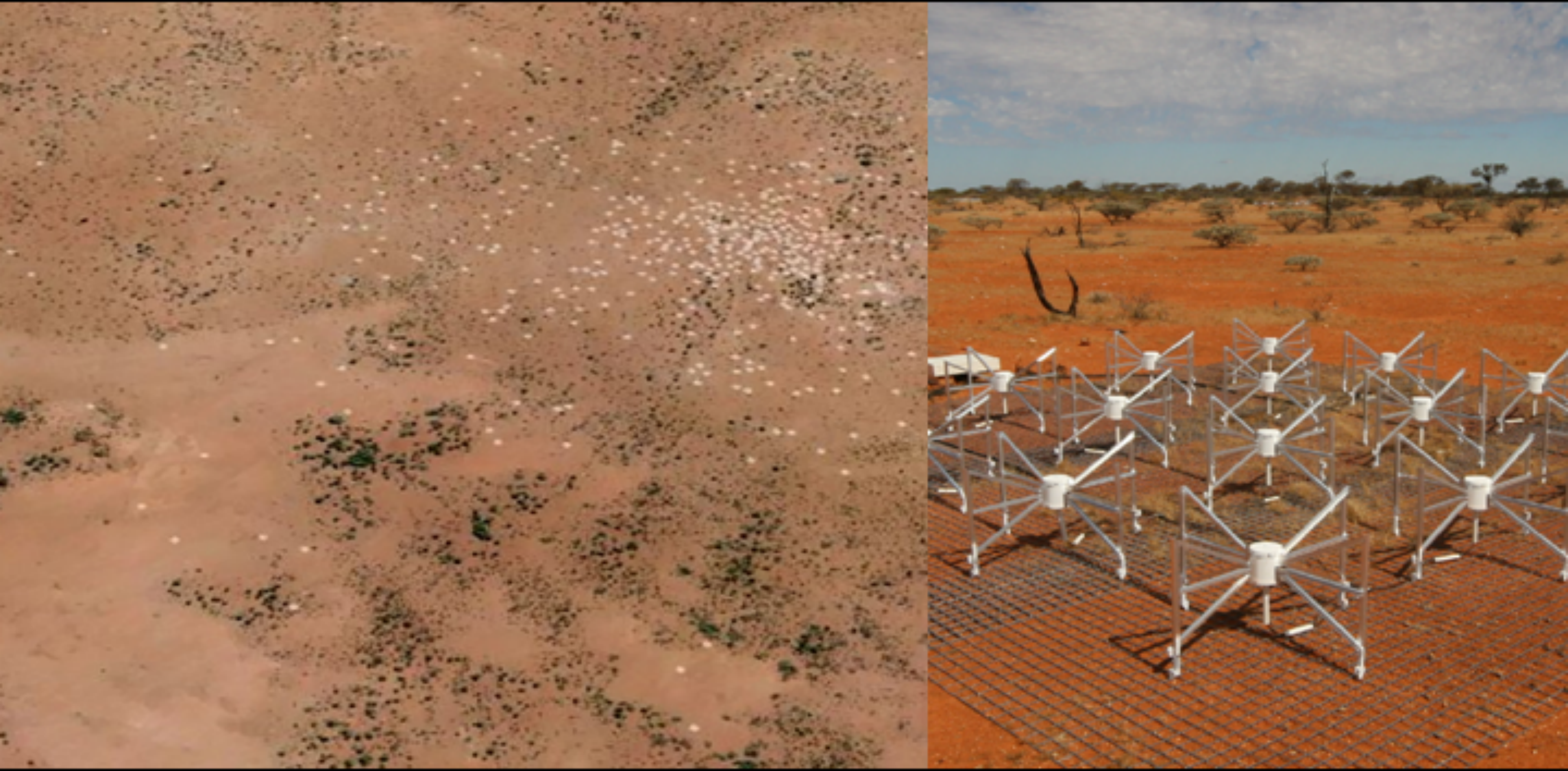
$$P_{T_b} = [\cos^2\theta_k \delta(\vec{k}) + \delta_{\rm iso}(\vec{k})]^2$$

$$\delta_{\rm iso} = \beta\delta + \delta_{x_{\rm HI}} + \delta_T + \ldots$$

$\cos^4\theta_k, \cos^2\theta_k, \cos^0\theta_k$ ***terms allow separation of powers***

Barkana & Loeb 2004; see also Bharadwaj & Ali 2004

Murchison Wide-Field Array: 21cm emission from diffuse hydrogen at z=6.5-15



- 4mx4m tiles of 16 dipole antennae, 80-300MHz
- 500 antenna tiles with total collecting area 8000 sq.m. at 150MHz across a 1.5km area; few arcmin resolution

Experiments

*MWA (Murchison Wide-Field Array)

MIT/U.Melbourne,ATNF,ANU/CfA/Raman I.

*LOFAR (Low-frequency Array)

Netherlands/Europe

*21CMA (formerly known as PAST)

China

*PAPER

UCB/NRAO

*GMRT (Giant Meterwave Radio Telescope)

India/CITA/Pittsburg

*SKA (Square Kilometer Array)

International

Separating the Physics from the Astrophysics

Physics: *initial conditions from inflation; nature of dark matter and dark energy*

Astrophysics: *consequences of star formation*

Three epochs:

- ***Before the first galaxies (z>25):*** mapping of density fluctuations through 21cm absorption
- ***During reionization:*** anisotropy of the 21cm power spectrum due to peculiar velocities
- ***After reionization (z<6):*** dense pockets of residual hydrogen (DLAs) trace large scale structure

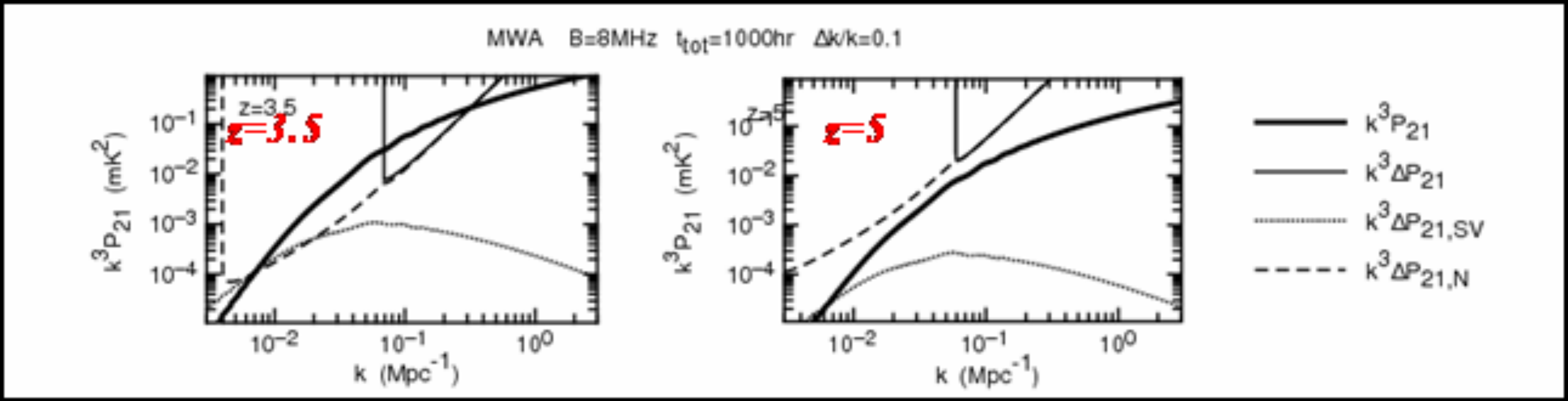
21cm Cosmology After Reionization?

Damped Lya absorbers: $\Omega_{\rm DLA} \sim 10^{-3}$

$$f_{\rm HI} = (\Omega_{\rm DLA}/\Omega_b) \approx 3\%, \text{ at} : z < 6$$

$\sigma_8 \sim 0.2$, at : $z \sim 4$ → $(\delta T)_{\rm signal} \sim 0.1{\rm mK}$ on 10cMpc

$$(\delta T)_{\rm noise} \propto (1+z)^{2.6}$$



Acoustic peak: constrain dark energy at 0<z<15

Wyithe & Loeb 2007

Testing gravity: measuring the gravitational growth of perturbations on small scales (not probed so far) which are still in the linear regime at high redshifts ($1<z<15$)

Status: analogous to CMB research prior to COBE

When Was the Universe Ionized?

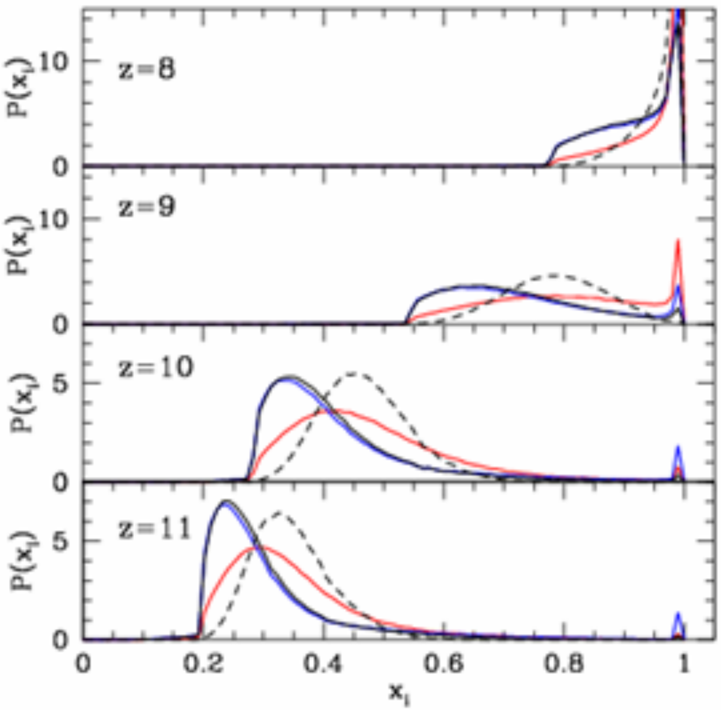


Figure 5. Distribution of x_i at redshifts $z = 8$, 9, 10, and 11 for the ζ parametrization. Same curve styles as for Figure 4.

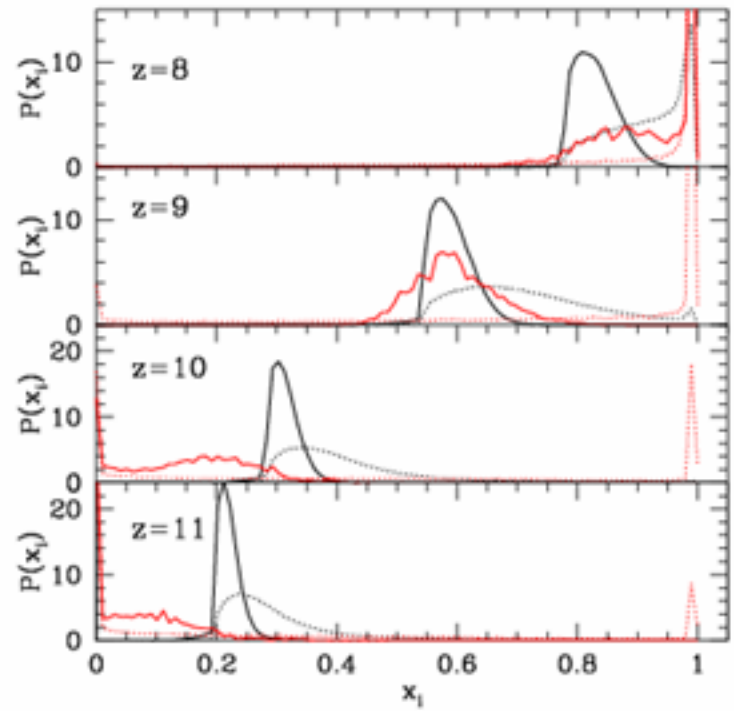


Figure 14. Distribution of x_i at redshifts $z = 8$, 9, 10, and 11 when 21 cm measurements are included. In each panel, we plot the distribution of the ζ (black) and $\dot{N}_{\rm ion}$ (red) parametrizations with (solid curves) and without (dotted curves) a 21 cm measurement of $x_i(z = 9.5) = 0.5 \pm 0.05$.

- Based on Lya forest at z<6 and CMB data

Pritchard, Loeb, & Wyithe, arXiv:0908.3891

Open Problems

- *Did massive Pop-III stars contribute significantly to reionization and the 21-cm signal?*
- *Were the earliest X-ray sources dominated by IC cooling of SNe e- or X-ray binaries or massive black holes? Simulations of inhomogeneous X-ray heatig are needed.*
- *How important was the opacity and evaporation of minihalos below the gas cooling threshold? Simulations are needed.*
- *Are there radio-loud sources for detecting the 21-cm forest in absorption at z~10?*
- *Is there an efficient algorithm for removing foreground of the global signal (not throwing the baby with the bath-tub water). In particular, taking advance of the foreground dependence on sky coordinates.*
- *What are the prospects for observatories of the post-reionization signal to constrain w(z)? None funded so far.*
- *What are the signatures of exotic heating sources: dark matter annihilation, cosmic strings, etc. ?*