Title: Fundamental Physics from 21cm Cosmology

Date: Jun 02, 2008 03:40 PM

URL: http://pirsa.org/08060032

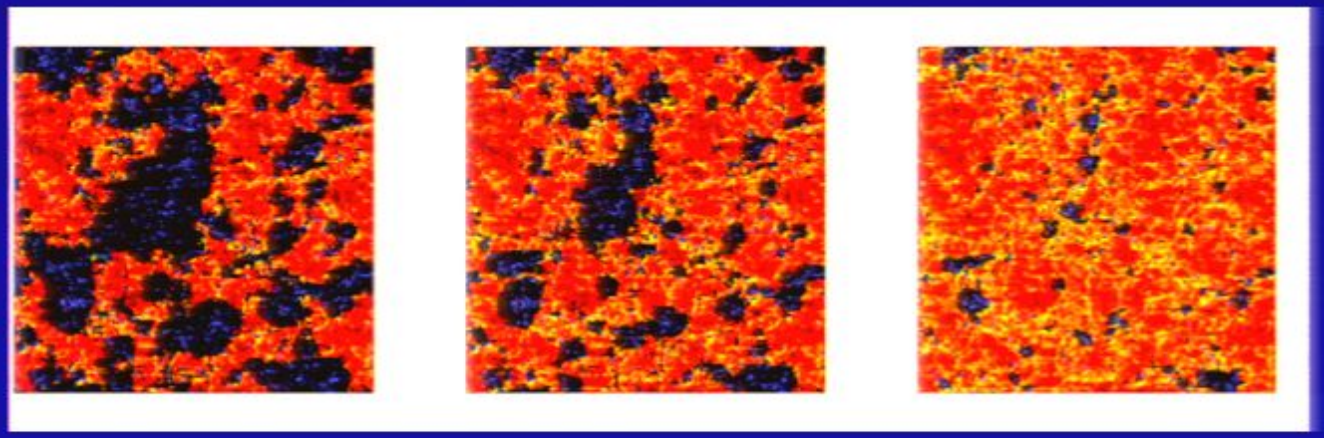
Abstract: The atomic hydrogen gas left over from the Big Bang was affected by processes ranging from quantum fluctuations during the early epoch of inflation to irradiation by the first galaxies at late times. Mapping this gas through its resonant 21cm line serves a dual role as a powerful probe of both fundamental physics and astrophysics. Current cosmological data sets (such as galaxy surveys or the microwave background) cover only 0.1% of the comoving volume of the observable Universe. 21cm observations hold the potential of mapping matter through most of the remaining volume. Radio observatories are currently being designed and constructed with this goal in mind. The three-dimensional 21cm maps could potentially set unprecedented statistical constraints on the power spectrum of cosmic density fluctuations and its gravitational growth with cosmic time. The reduced uncertainties could allow for precise measurements of fundamental parameters, such as the mass of the neutrino or the equation of state of the dark energy (from acoustic oscillations in the 21cm power spectrum), and will test generic predictions of cosmic inflation for deviations of the density fluctuations from scale invariance and gaussianity. The measured gravitational growth of the fluctuations with cosmic time would constrain the nature of the dark matter or alternative theories of gravity.

Fundamental Physics with 21cm Cosmology

Initial conditions from flation

Nature of the dark matter and dark energy

Constrain alternative models of gravity



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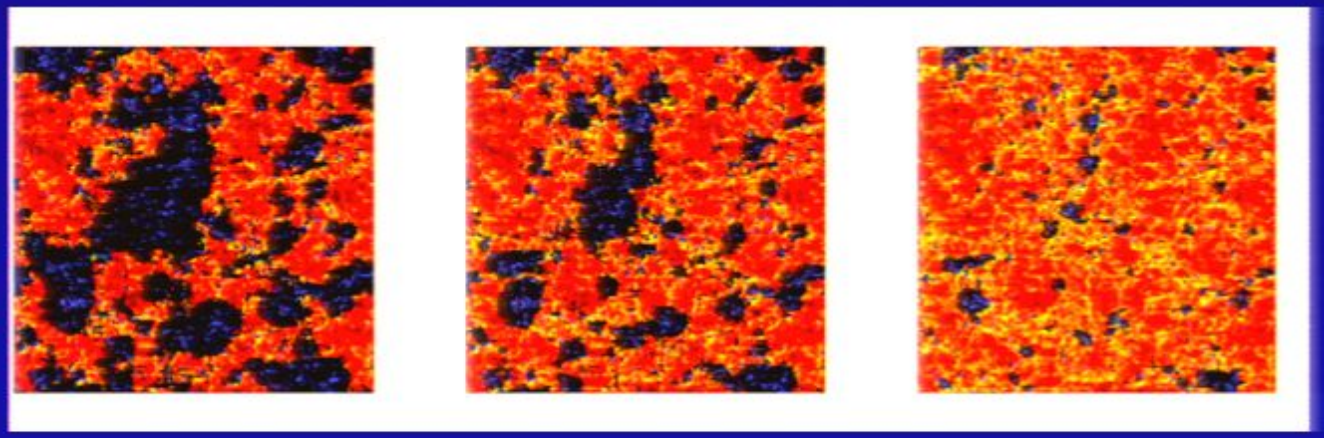


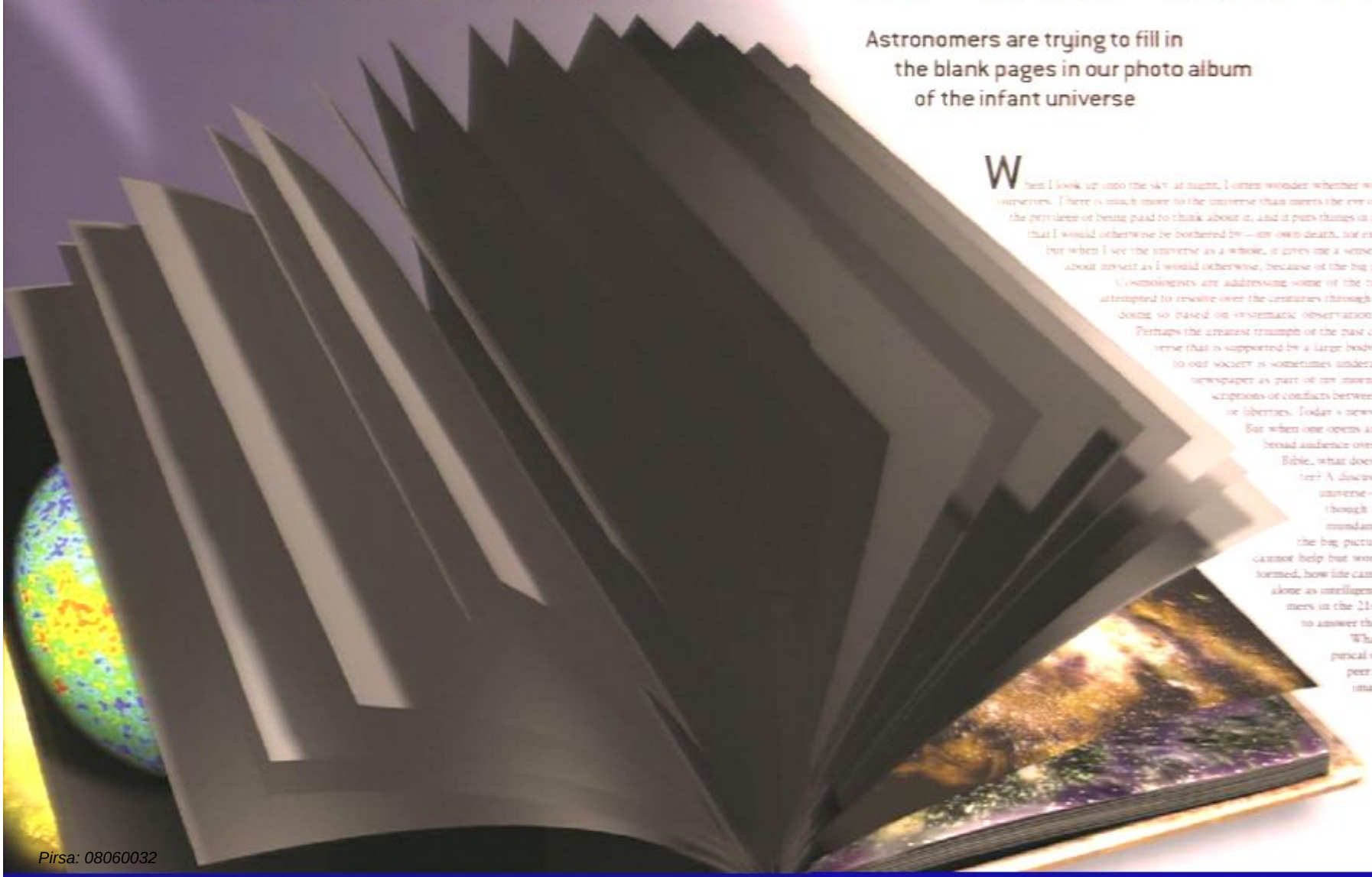
WMAP Cosmological Parameters Model: lcdm Data: all		
$10^2\Omega_b h^2$	=	$2.19^{+0.06}_{-0.08}$
Λ	=	$0.67^{+0.04}_{-0.05}$
$\Lambda_{0.002}$	=	$0.81^{+0.04}_{-0.05}$
$\Delta^2_{\mathcal{R}}$	=	$(20 \times 10^{-10} \pm 1 \times 10^{-10}) \times 10^{-10}$
$\Delta^2_{\mathcal{R}}(k = 0.002\ Mpc)$	=	$(24 \times 10^{-10}{}^{+1 \times 10^{-10}}_{-2 \times 10^{-10}}) \times 10^{-10}$
h	=	$0.71^{+0.01}_{-0.02}$
H_0	=	71^{+1}_{-2} km/s/Mpc
ℓ_A	=	$303.0^{+0.9}_{-1.3}$
n_s	=	$0.938^{+0.013}_{-0.018}$
$n_s(0.002)$	=	$0.938^{+0.012}_{-0.023}$
Ω_b	=	$0.044^{+0.002}_{-0.003}$
$\Omega_b h^2$	=	$0.0220^{+0.0006}_{-0.0008}$
Ω_c	=	$0.22^{+0.01}_{-0.02}$
Ω_Λ	=	0.74 ± 0.02
Ω_m	=	$0.26^{+0.01}_{-0.03}$
$\Omega_m h^2$	=	$0.131^{+0.004}_{-0.010}$
r_s	=	148^{+1}_{-2} Mpc
b_{SDSS}	=	$0.95^{+0.05}_{-0.06}$
σ_8	=	$0.75^{+0.03}_{-0.04}$
$\sigma_8\Omega_m^{0.6}$	=	$0.34^{+0.02}_{-0.03}$
Λ_{SZ}	=	$0.78^{+0.23}_{-0.78}$
t_0	=	$13.8^{+0.1}_{-0.2}$ Gyr
τ	=	$0.069^{+0.026}_{-0.029}$
θ_A	=	0.594 ± 0.002 °
z_{eq}	=	3135^{+85}_{-159}
z_*	=	$9.3^{+2.8}_{-2.0}$

The initial conditions of the Universe can be summarized on a single sheet of paper, yet thousands of books cannot fully describe the complex structures we see today…

THE DARK AGES of the Universe

Astronomers are trying to fill in the blank pages in our photo album of the infant universe

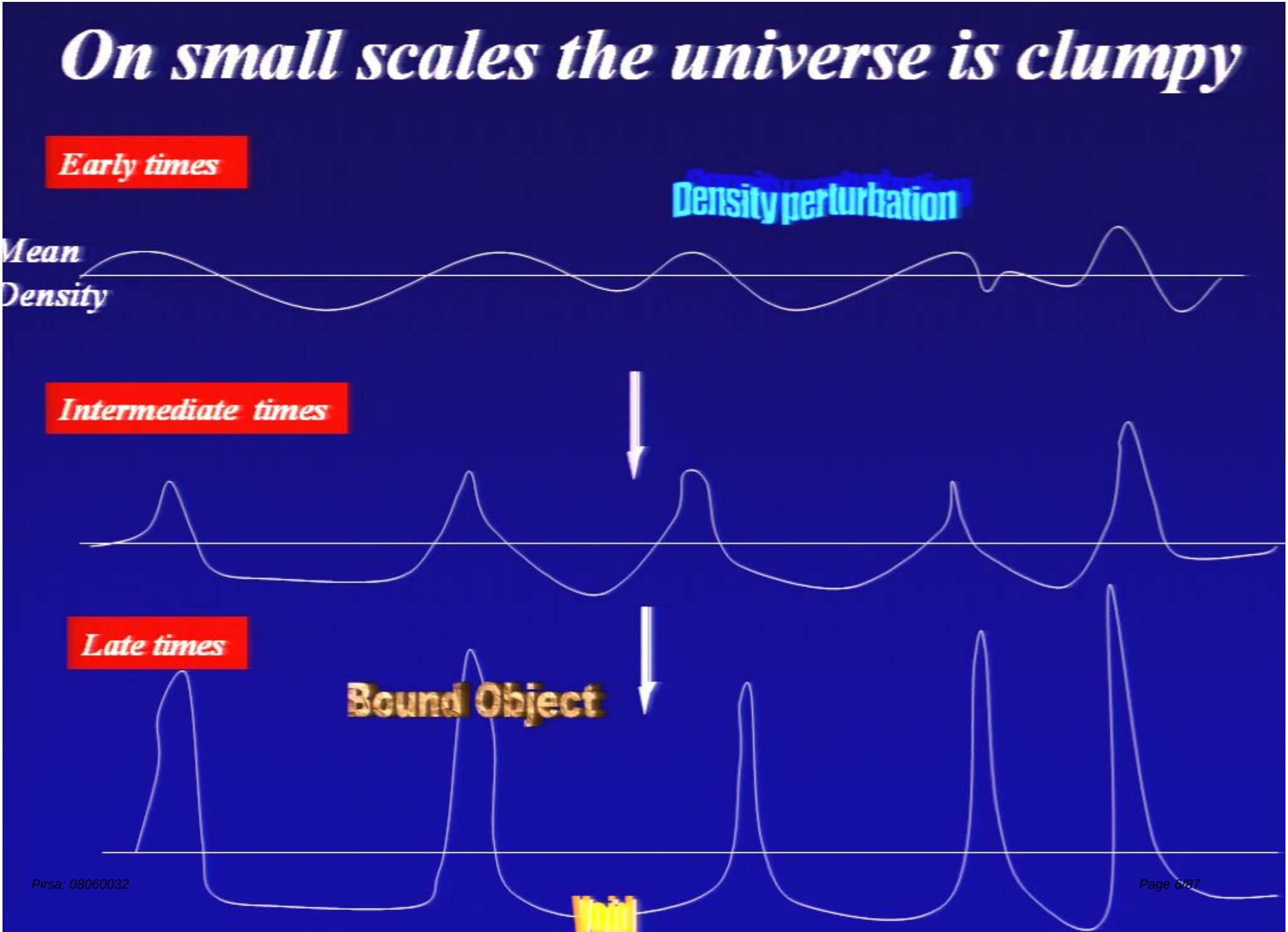
By Abraham Loeb



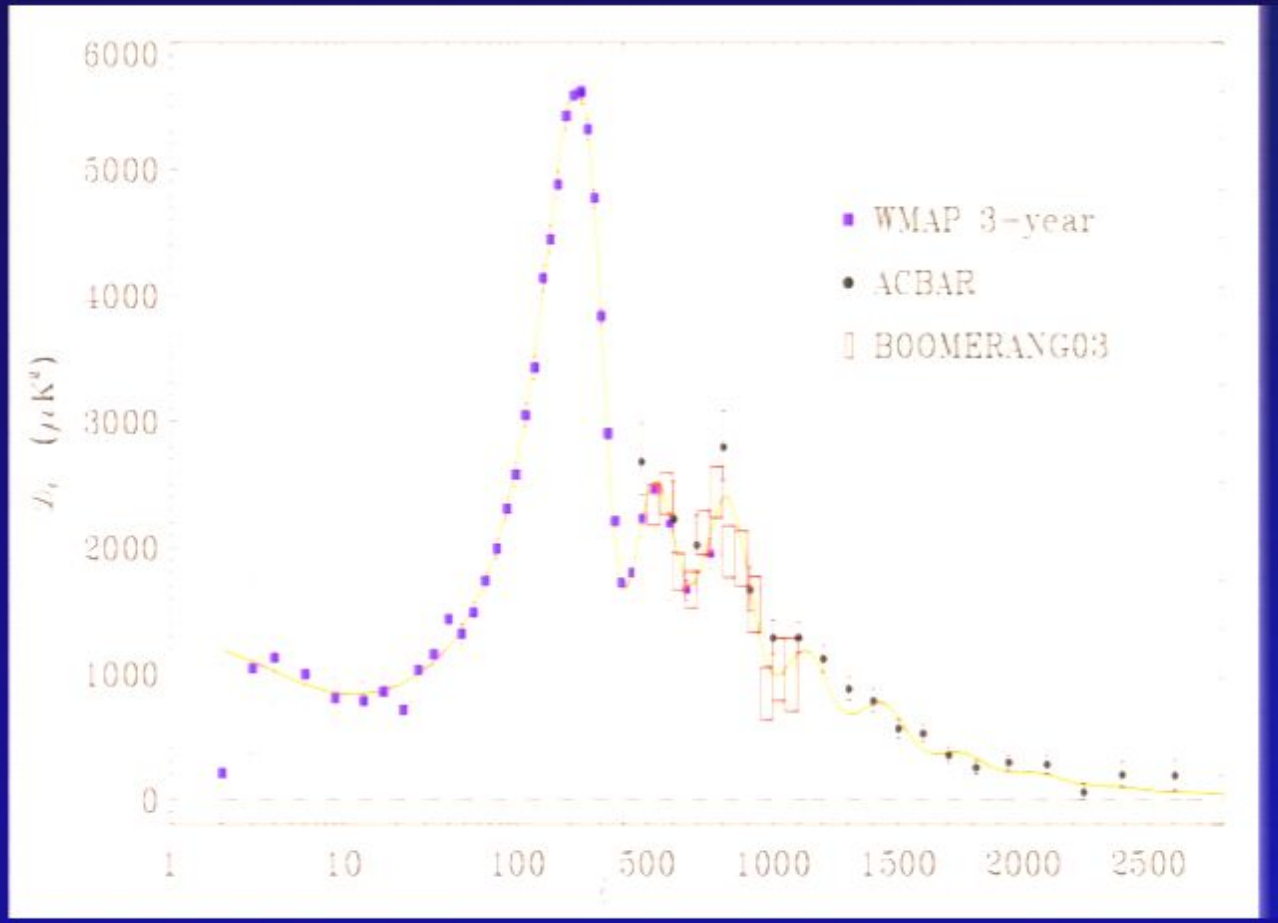
When I look up into the sky at night, I often wonder whether we humans are too preoccupied wi
ourselves. There is much more to the universe than meets the eye on earth. As an astrophysicist I ha
the privilege of being paid to think about it, and it puts things in perspective for me. There are thin
that I would otherwise be bothered by—my own death, for example. Everyone will die sometim
but when I see the universe as a whole, it gives me a sense of longevity. I do not care so muc
about myself as I would otherwise, because of the big picture.

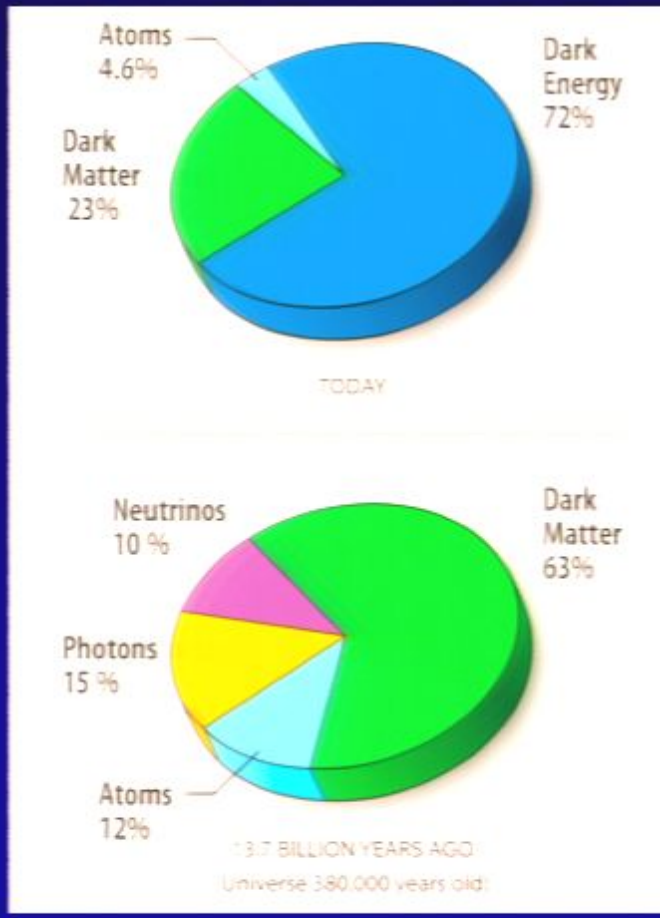
Cosmologists are addressing some of the fundamental questions that peop
attempted to resolve over the centuries through philosophical thinking, but we a
doing so based on systematic observation and a quantitative methodology
Perhaps the greatest triumph of the past century has been a model of the u
verse that is supported by a large body of data. The value of such a mod
to our society is sometimes underappreciated. When I open the dai
newspaper as part of my morning routine, I often see negative d
scriptions of conflicts between people about borders, possession
or liberties. Today's news is often forgotten a few days lat
But when one opens ancient texts that have appealed to
broad audience over a longer period of time, such as t
Bible, what does one often find in the opening cha
ter? A discussion of how the constituents of t
universe—light, stars, life—were created. A
though humans are often caught up wi
mundane problems, they are curious abo
the big picture. As citizens of the universe w
cannot help but wonder how the first sources of lig
formed, how life came into existence and whether we a
alone as intelligent beings in this vast space. Astron
mers in the 21st century are uniquely position
to answer these big questions.

What makes modern cosmology an e
pirical science is that we are literally able t
peer into the past. When you look at yo
image reflected off a mirror one met

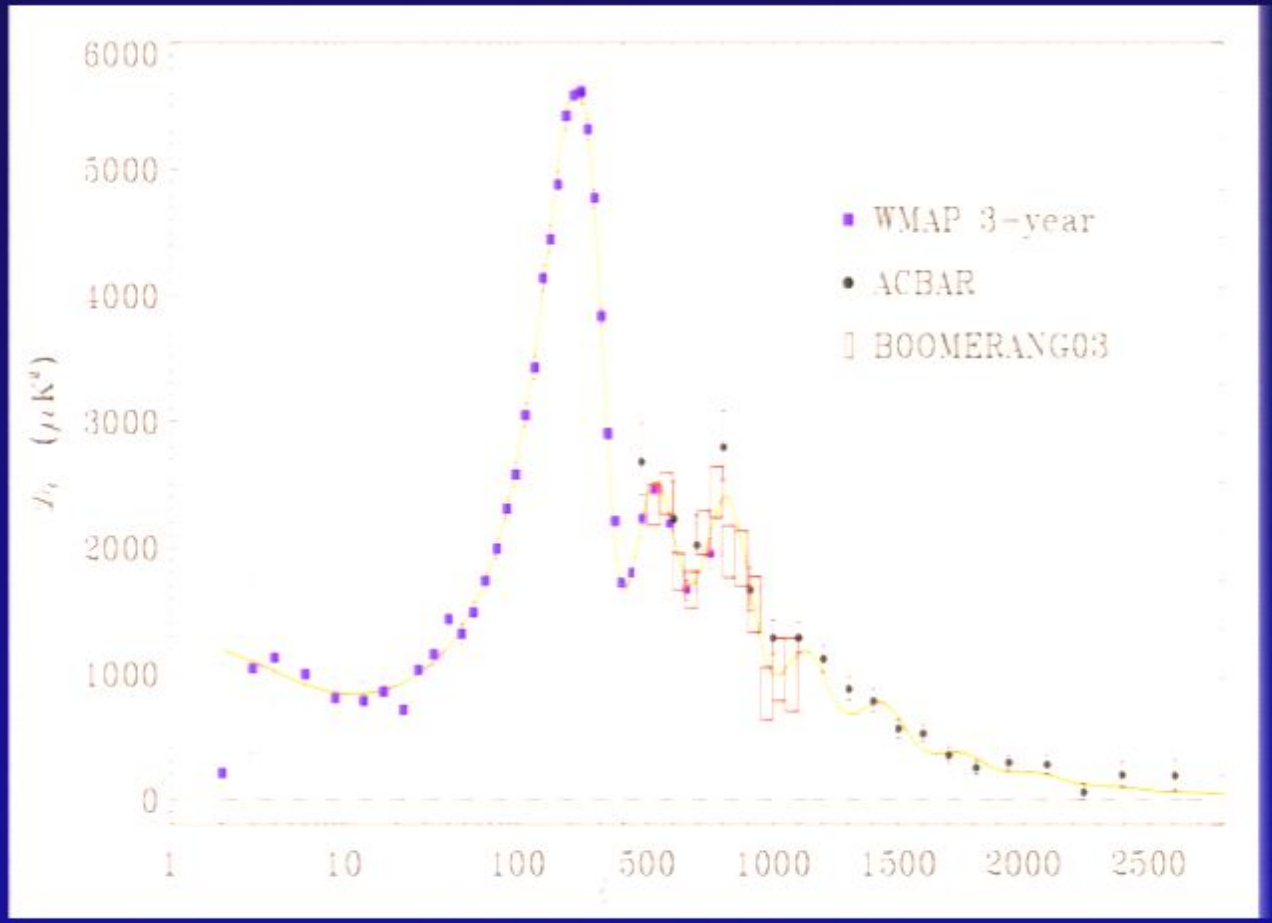

On small scales the universe is clumpy
Early times
Density perturbation
Mean
Density
Intermediate times
Late times
Bound Object

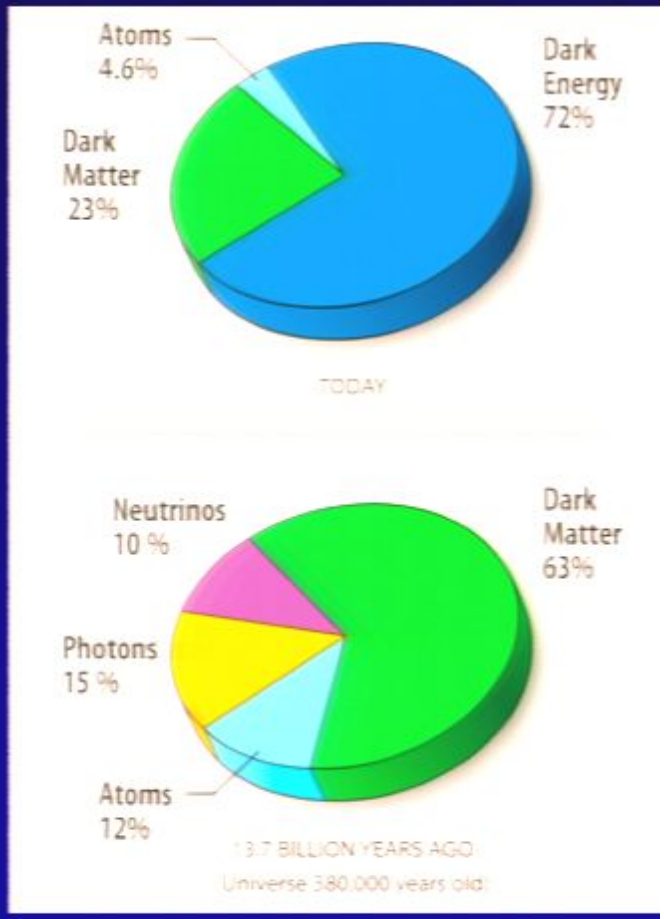
Evidence that Most Matter is EM Dark





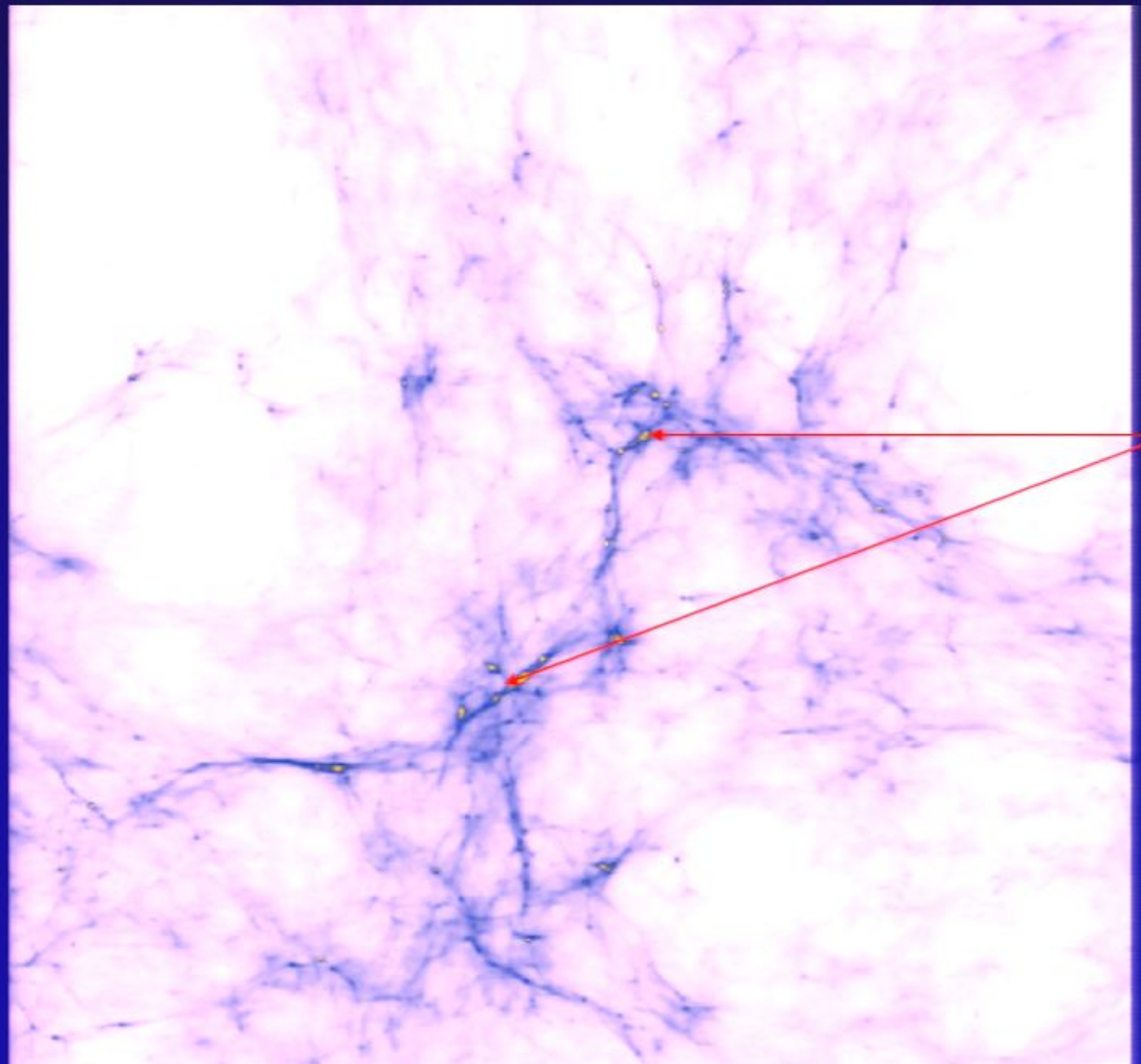
Evidence that Most Matter is EM Dark





Diffusion damping of small-scale fluctuations in the baryon-photon fluid prior to cosmic recombination implies that galaxies could not have formed in our Universe without dark matter!

The First Dwarf Galaxies Form at z~30

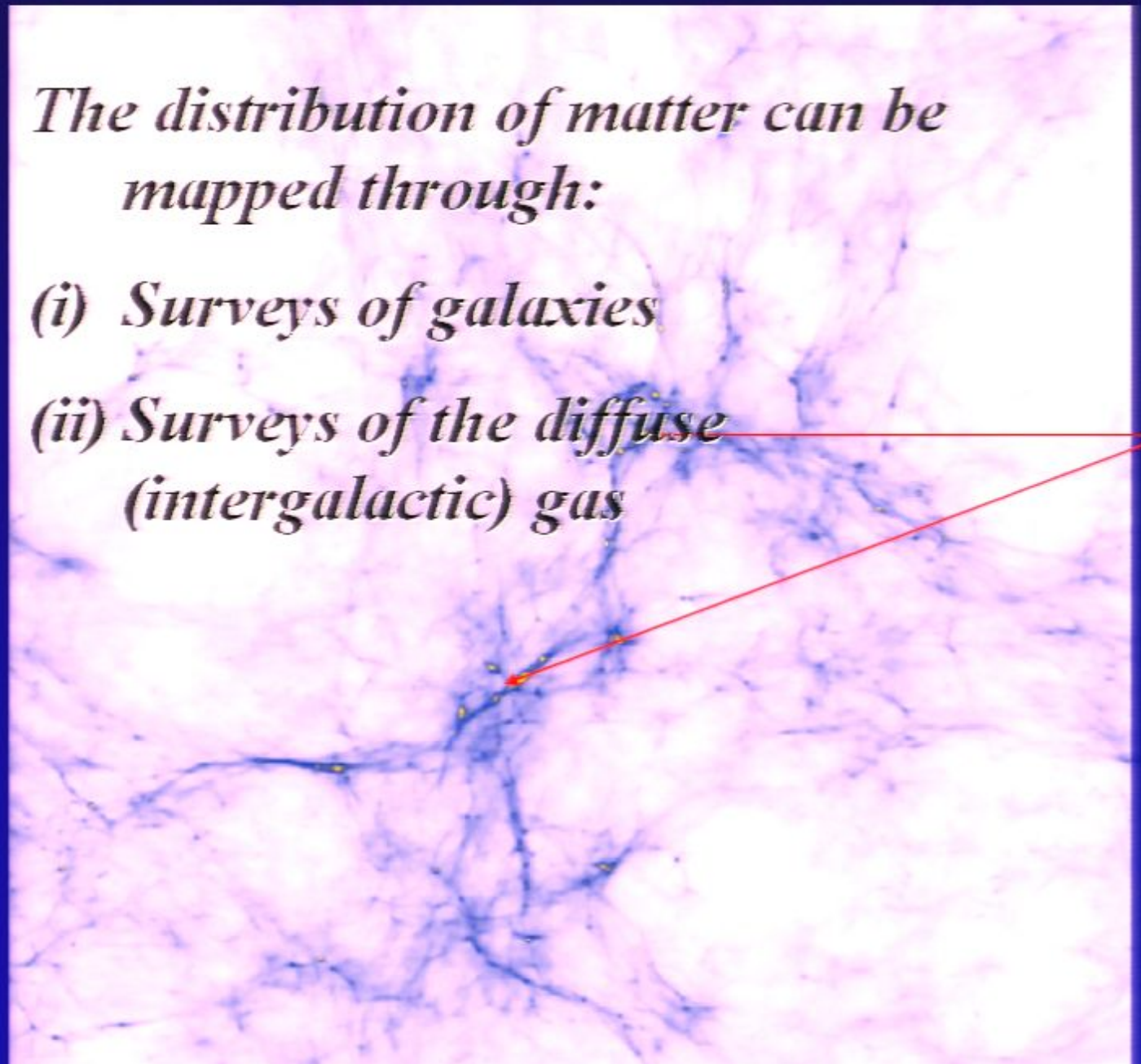


molecular hydrogen in Jeans mass objects

$(\sim 10^5 M_\odot$

Yoshida et al. 2003

The First Dwarf Galaxies Form at z~30



The distribution of matter can be mapped through:

(i) Surveys of galaxies

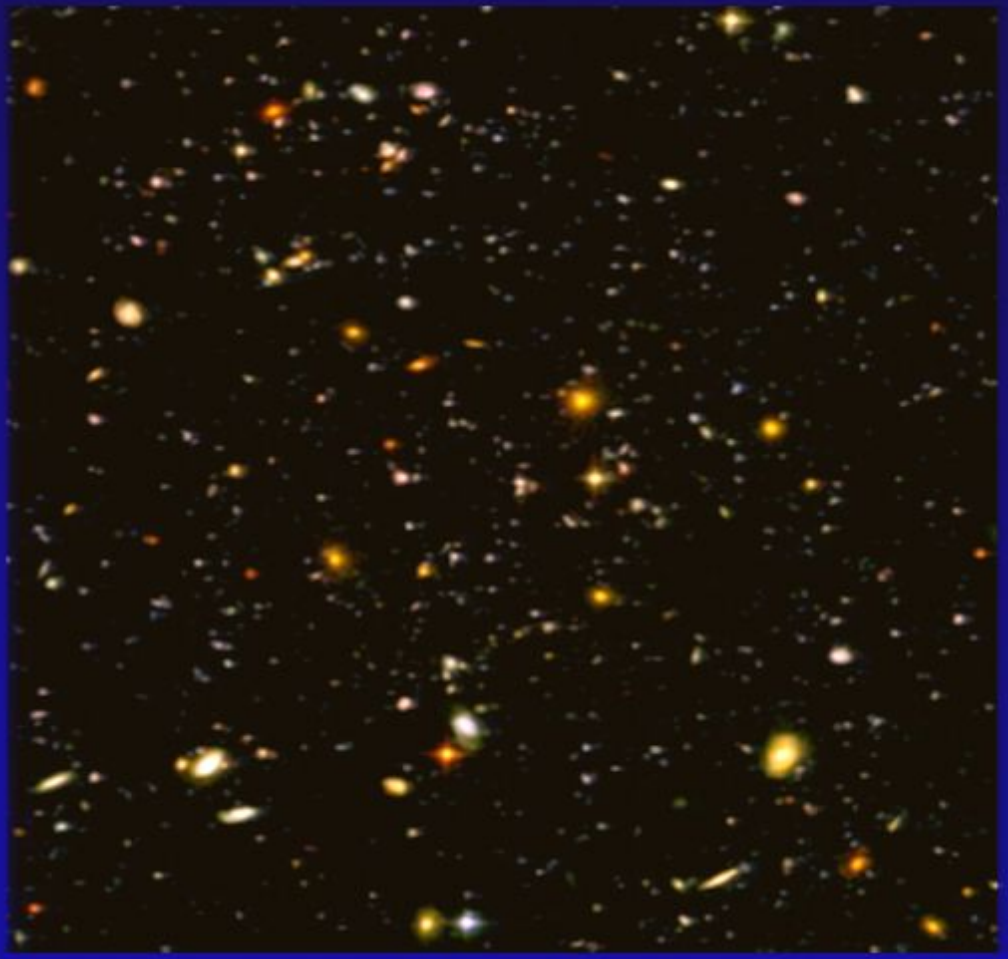
(ii) Surveys of the diffuse (intergalactic) gas

molecular hydrogen in Jeans mass objects

$(\sim 10^5 M_\odot$

Yoshida et al. 2003

Hubble Ultra Deep Field (HUDF)



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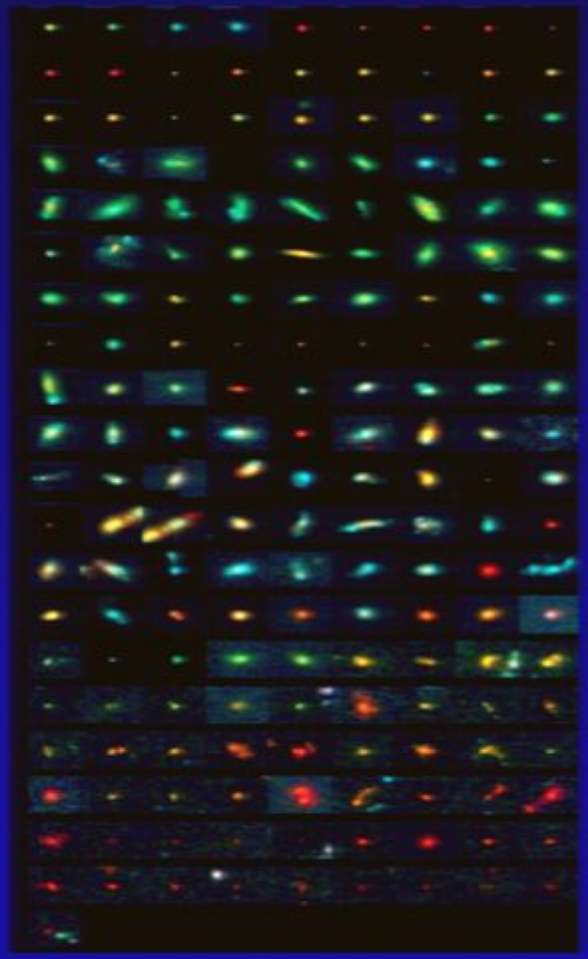

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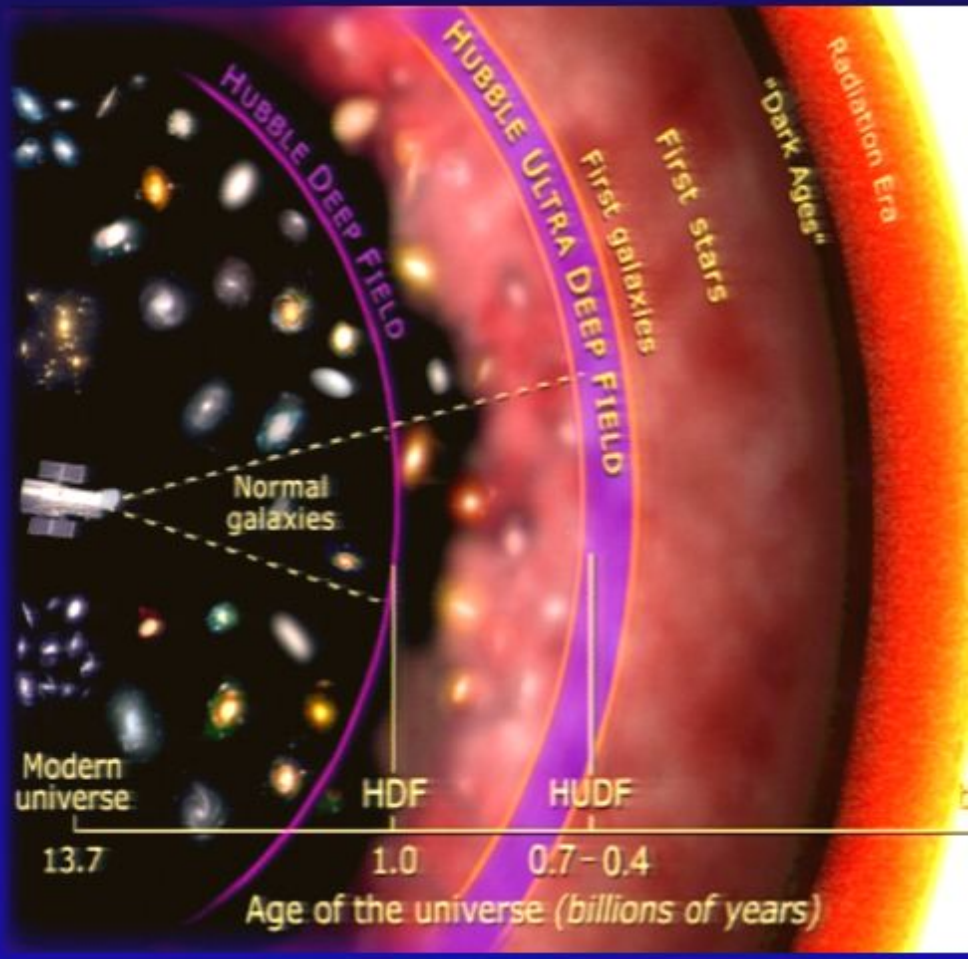
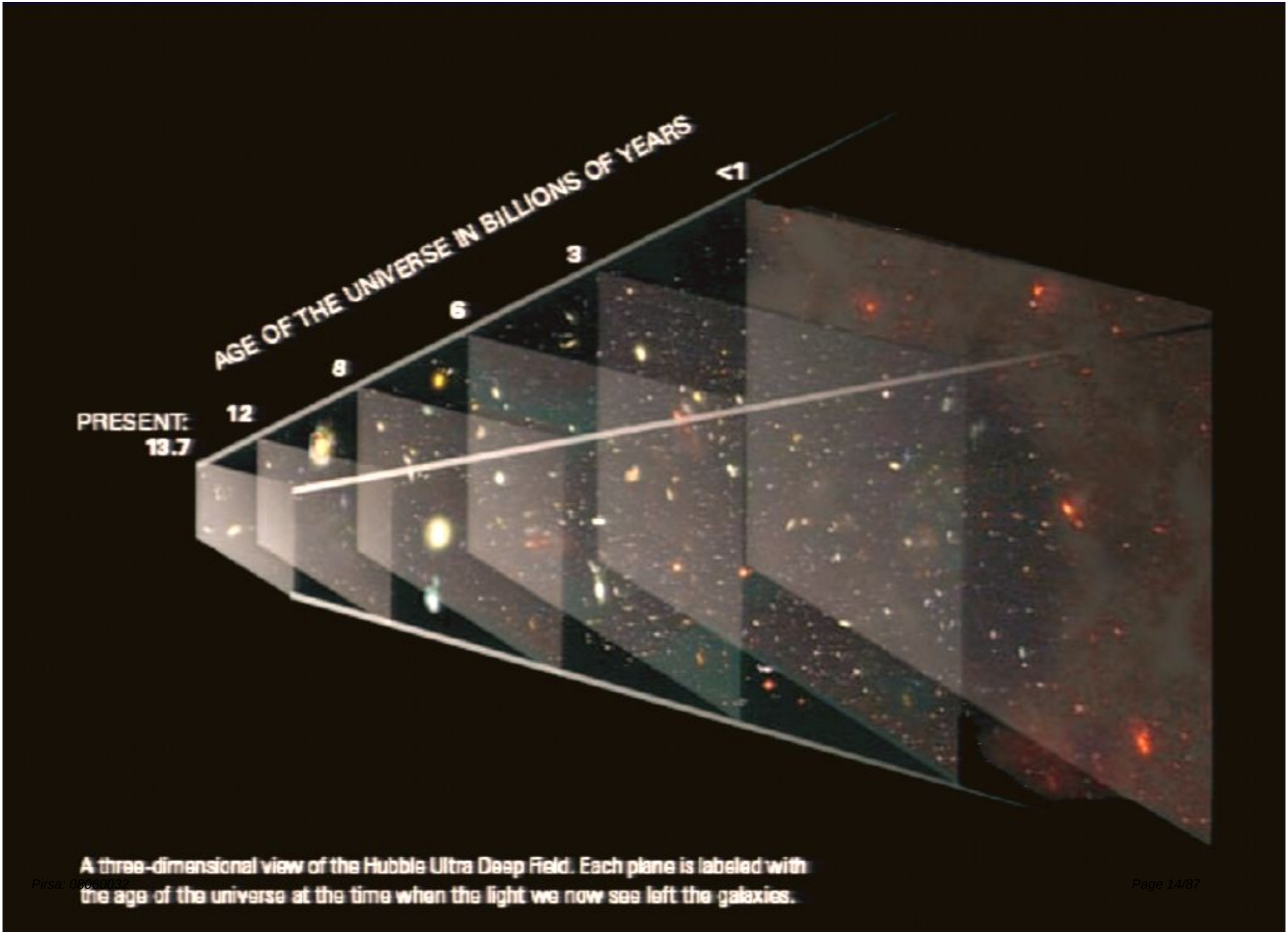


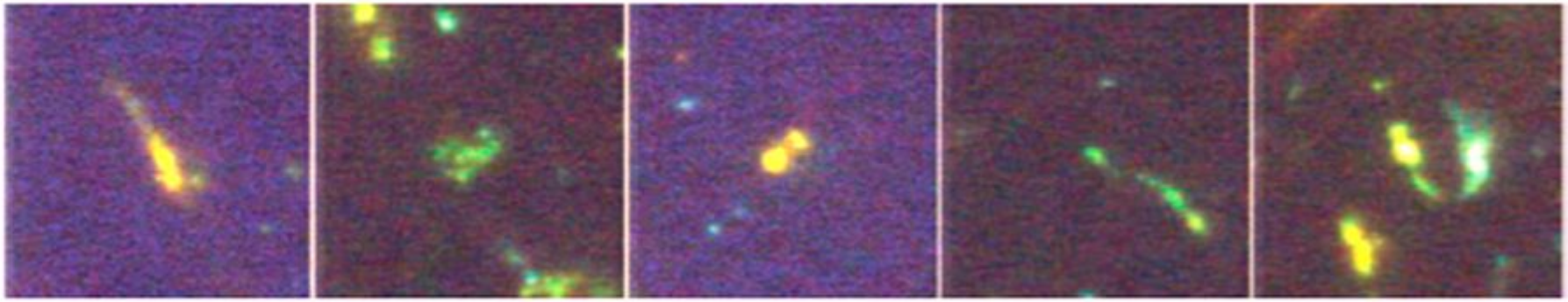


A three-dimensional view of the Hubble Ultra Deep Field. Each plane is labeled with the age of the universe at the time when the light we now see left the galaxies.

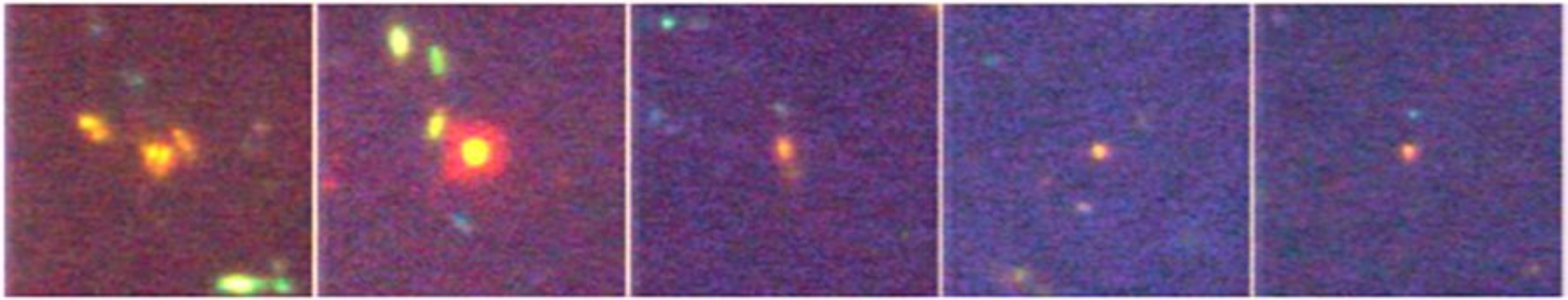
Close-up images of some of the most distant galaxies in the Hubble Ultra Deep Field

Galaxies at very early times tend to be very small and often show signs of interactions. The HUDF contains nearly 50 galaxies at redshifts 5–6, compared to a few tentative identifications in earlier, shallower observations.

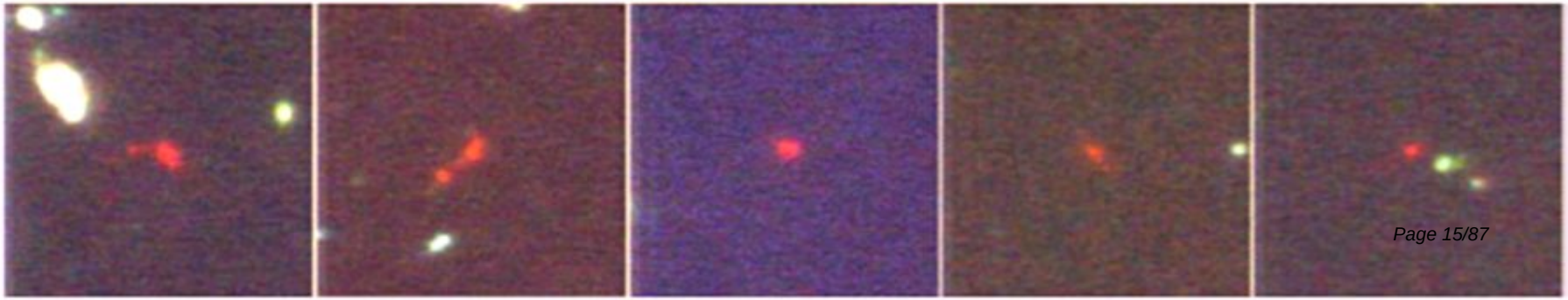
galaxies $z \sim 3$–4 Lookback time 11.4–12 billion years (312 objects)



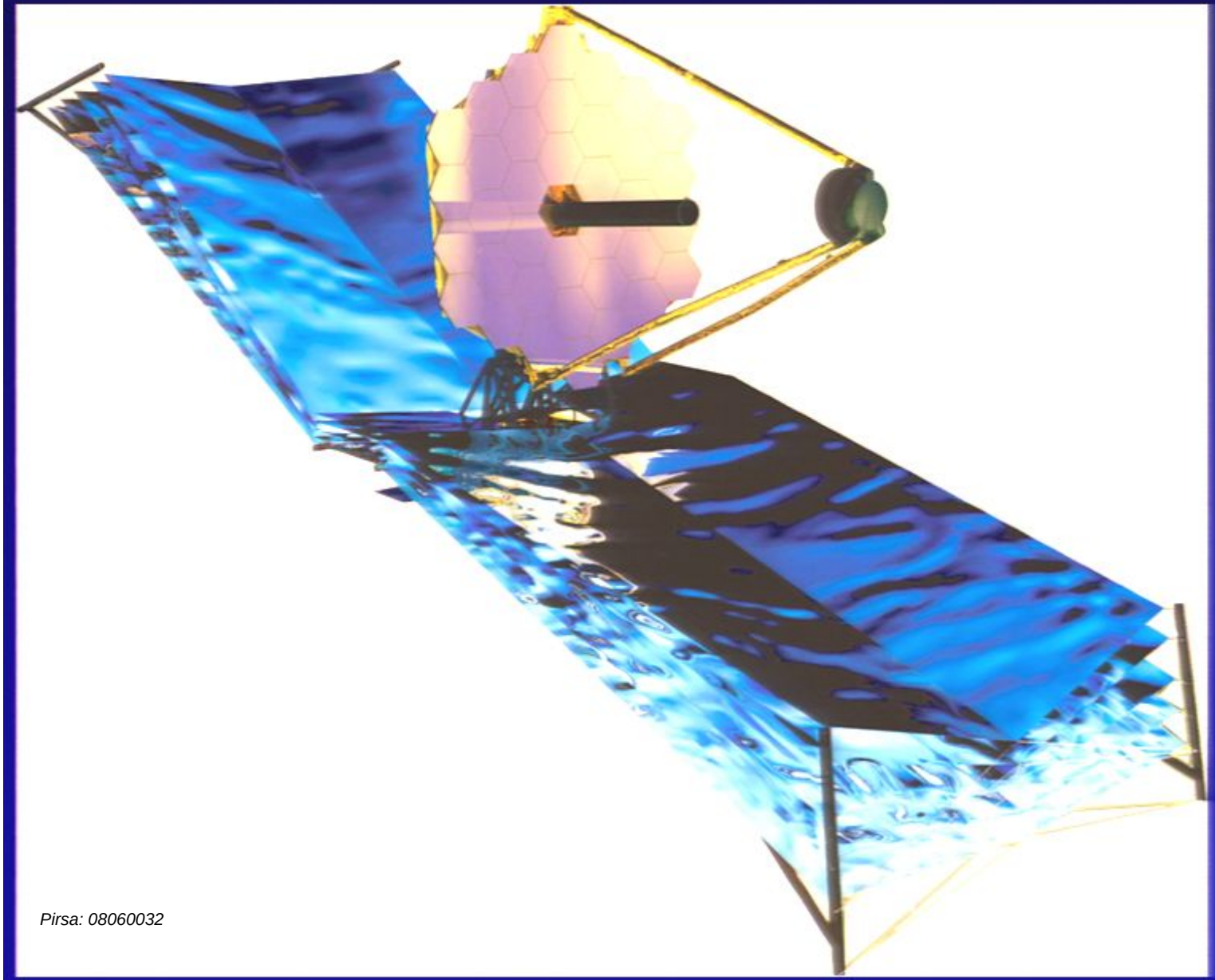
galaxies $z \sim 4$–5 Lookback time 12–12.3 billion years (79 objects)



galaxies $z > 5$ Lookback time 12.3–12.6 billion years (45 objects)



Searching for the First Galaxies:
James Webb Space Telescope



Mirror diameter: 6.5 meter

Material: beryllium

18 segments

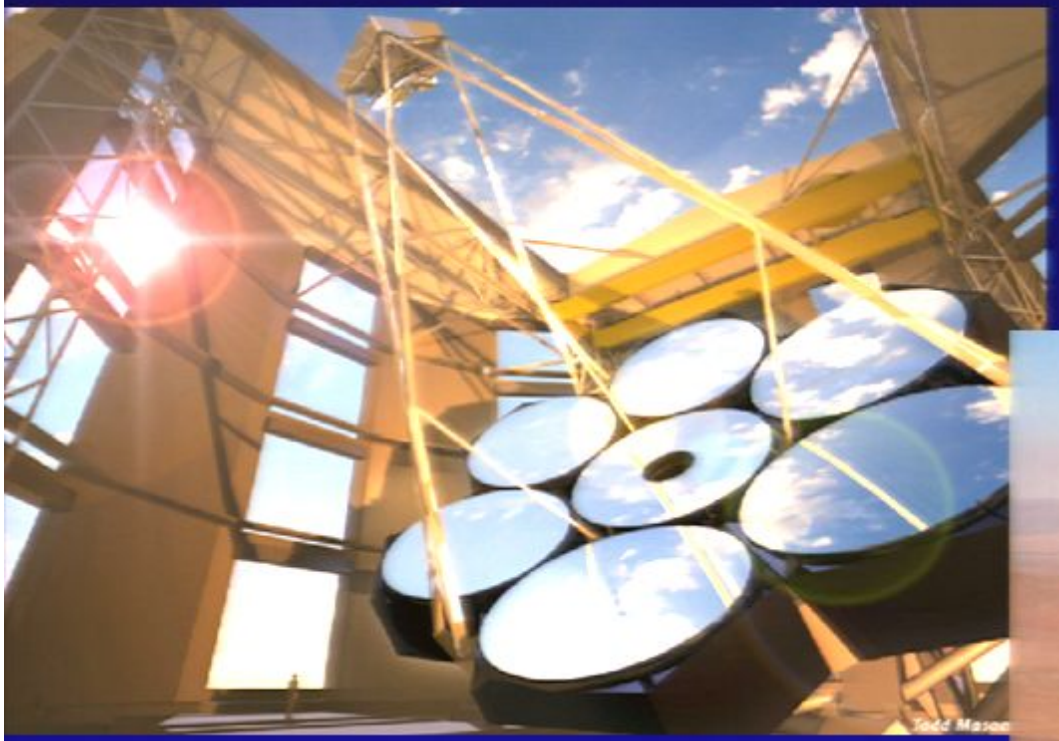
Wavelength coverage 0.6-28 micron

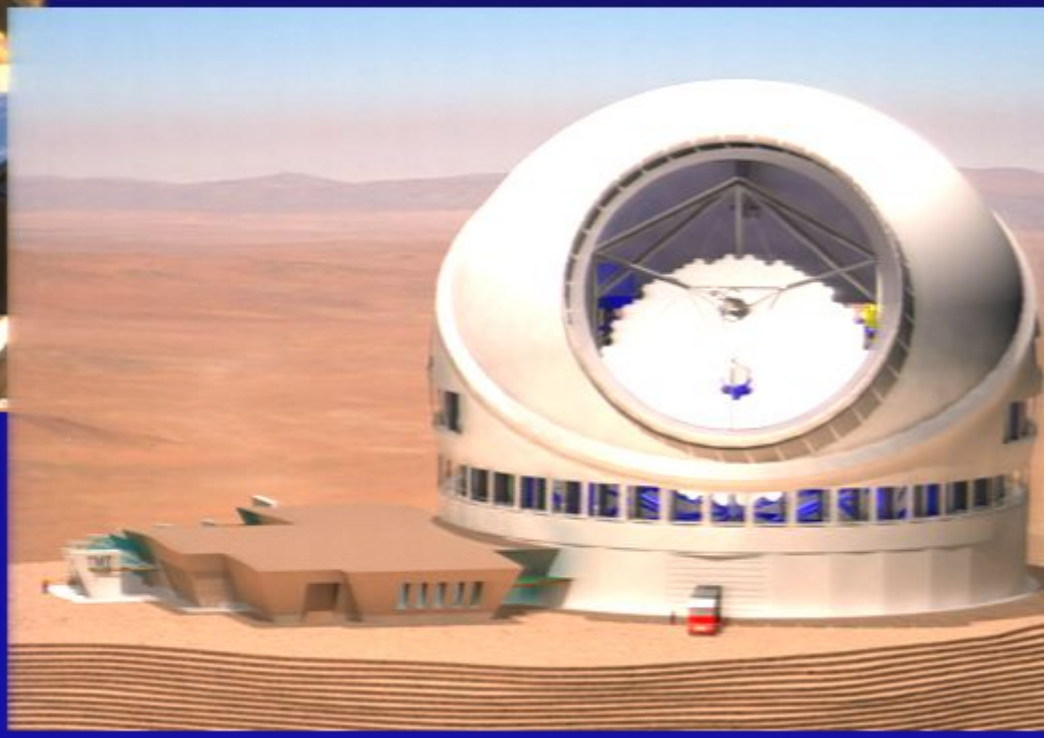
L2 orbit

~$1 billion

Launch date: 2013

Extremely Large Telescopes (20-40 meters





- GMT=Seven mirrors, each 8.4m in diameter
- TMT, EELT – segmented 20-40m aperture

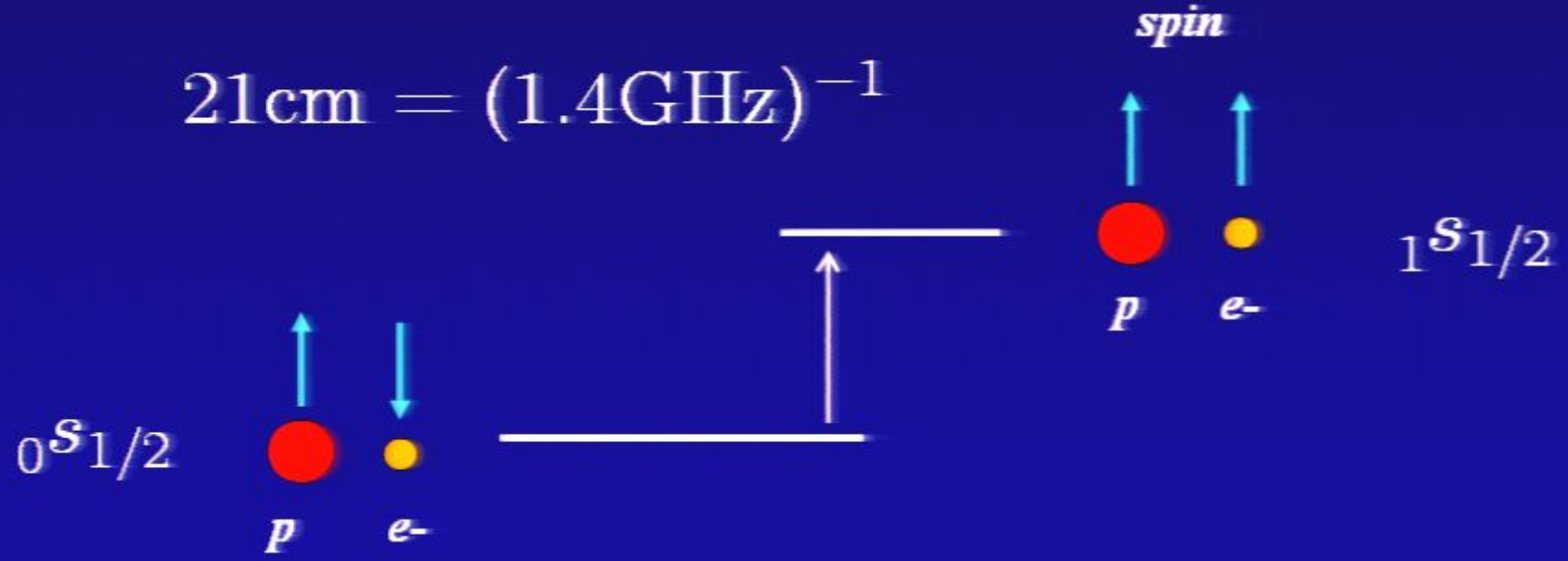
Mapping the Cosmic Distribution of

Hydrogen

Mapping the Cosmic Distribution of

Hydrogen

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



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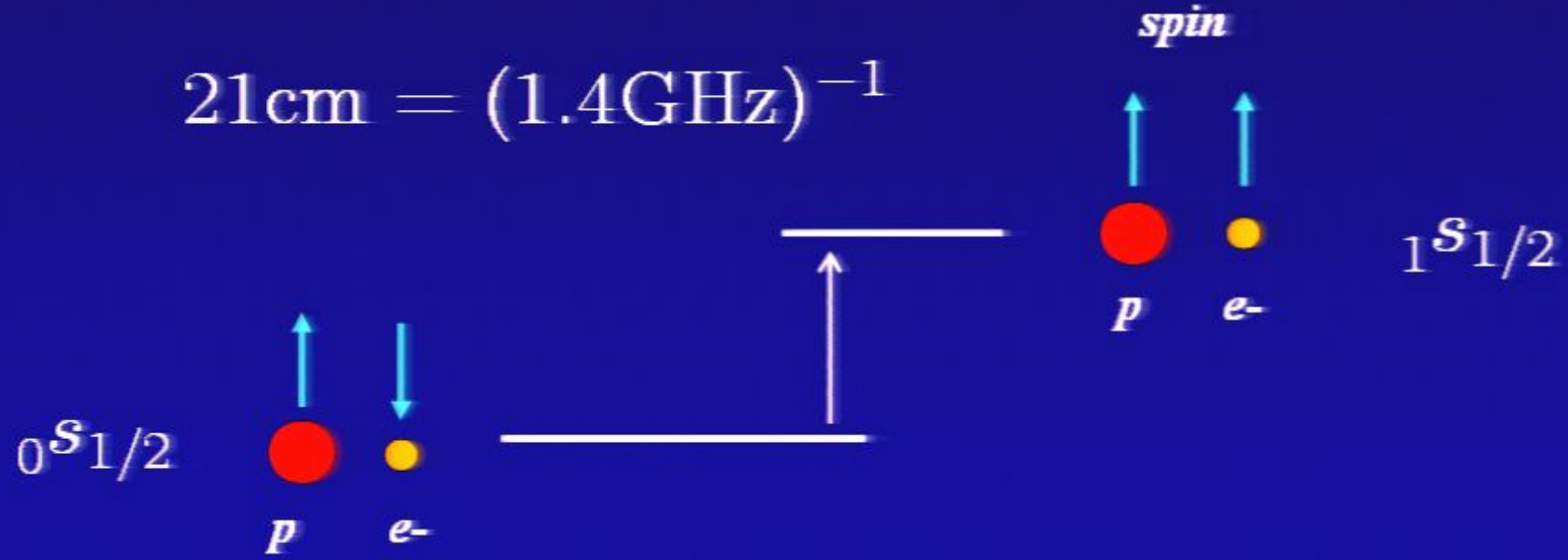
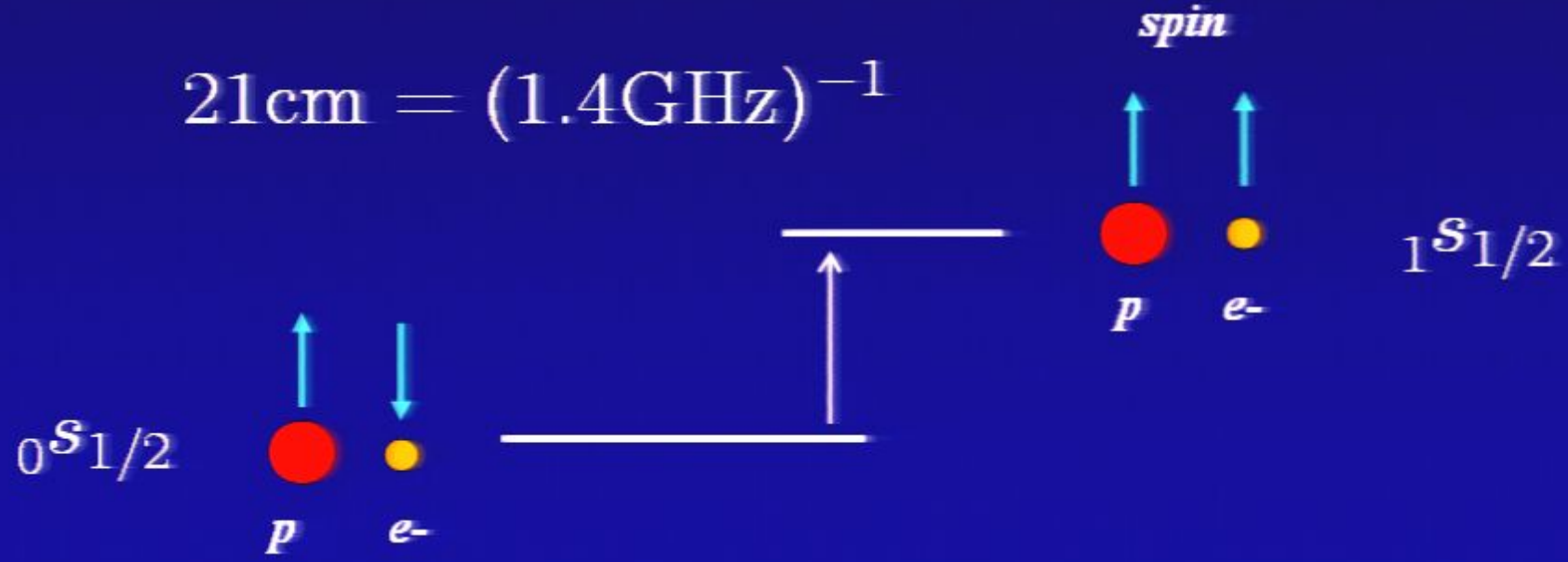


Spin Temperature

Mapping the Cosmic Distribution of

Hydrogen

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



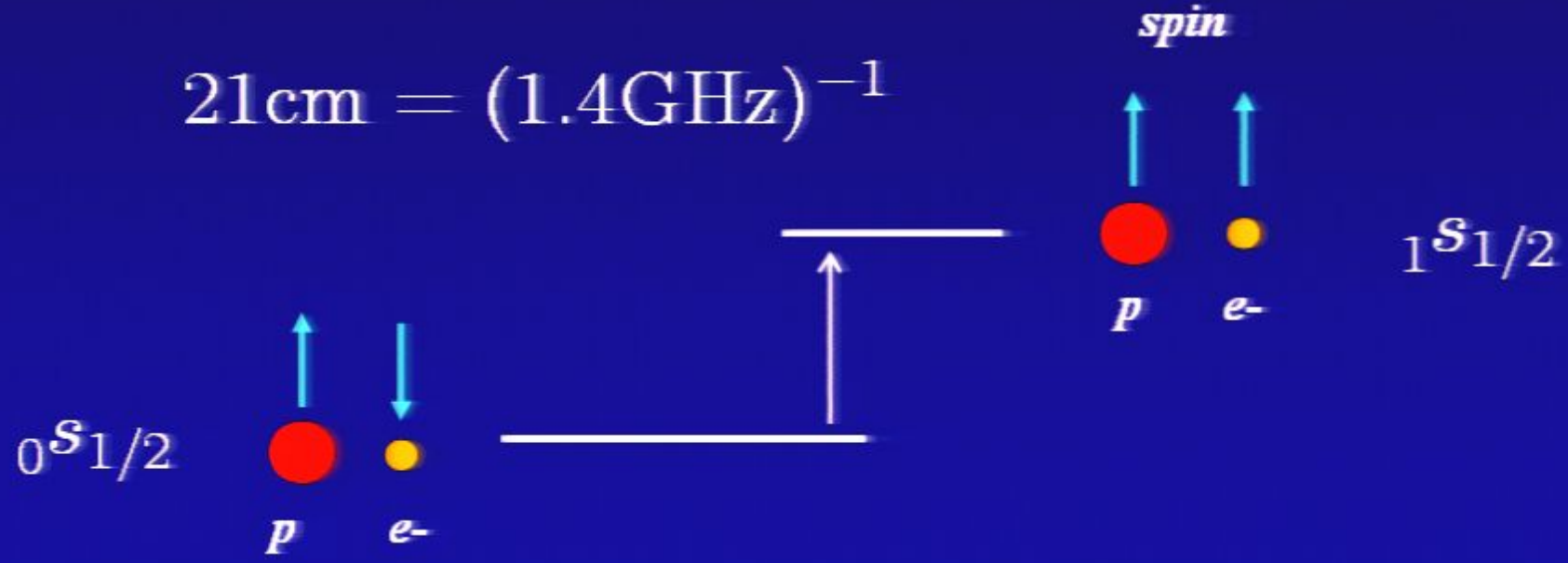
Spin Temperature

$$\frac{n_1}{n_0} = \frac{g_1}{g_0}\exp\{-\frac{0.068\text{K}}{T_s}\}$$

Mapping the Cosmic Distribution of

Hydrogen

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



Spin Temperature

$$\frac{n_1}{n_0} = \frac{g_1}{g_0}\exp\{-\frac{0.068\mathrm{K}}{T_s}\} \qquad (g_1/g_0) = 3$$

Mapping the Cosmic Distribution of

Hydrogen

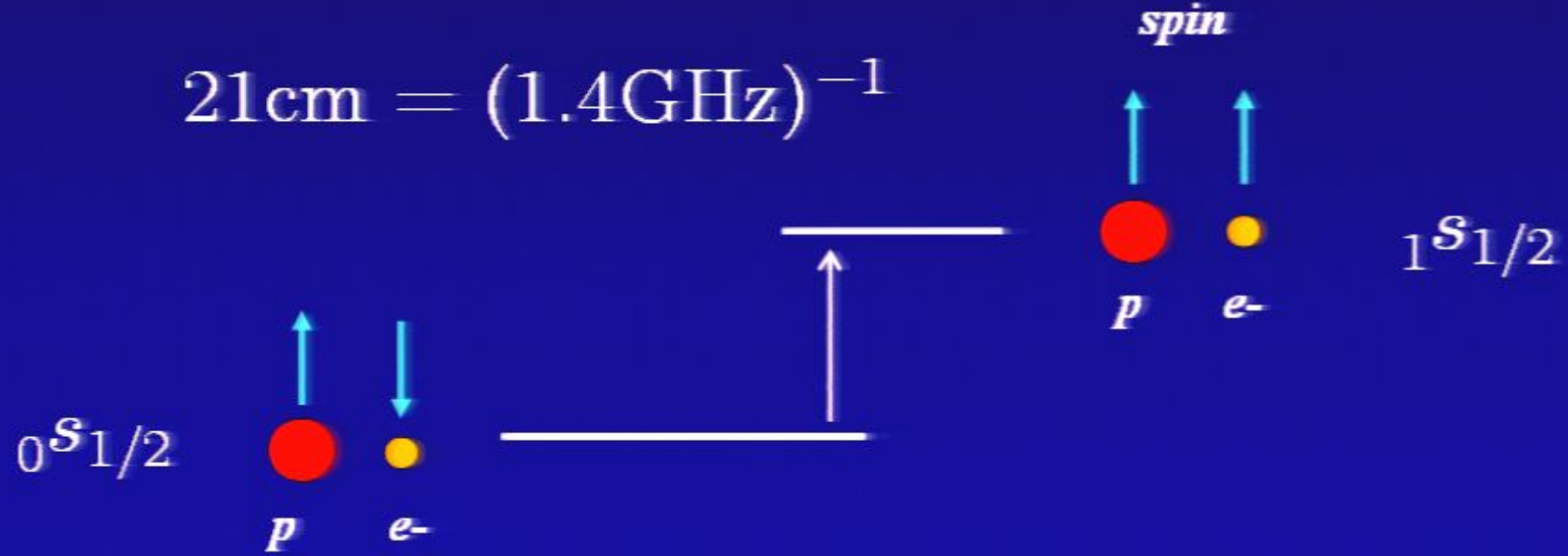
Ground level

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

Couple T_s *to*

spin

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



Spin Temperature

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

Mapping the Cosmic Distribution of

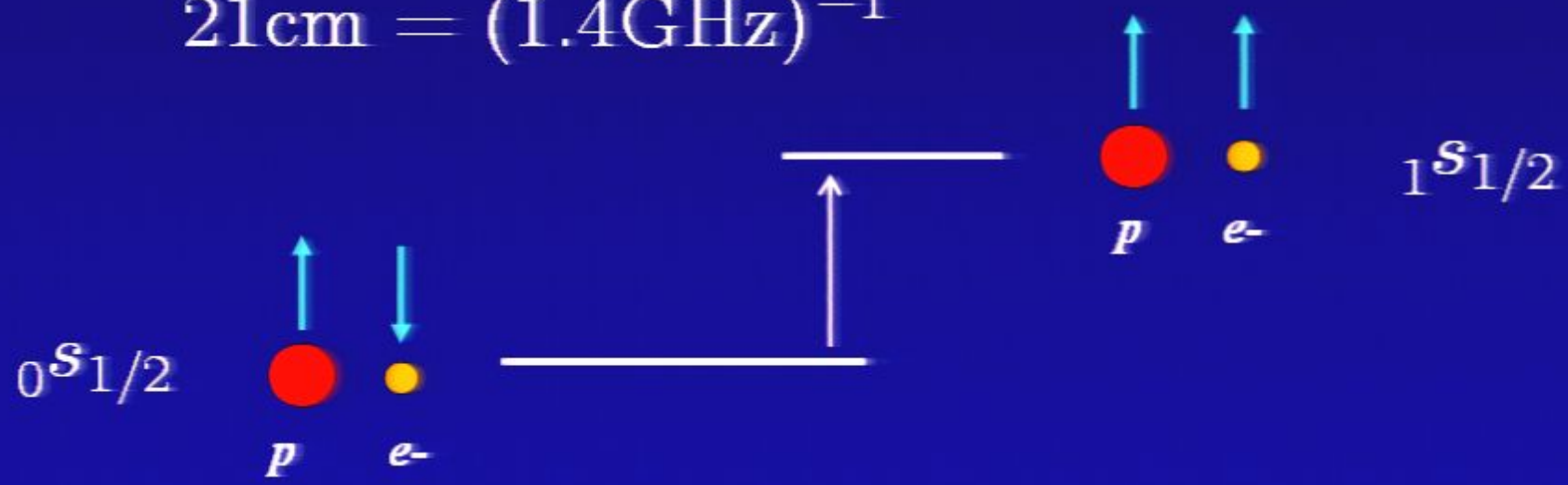
Hydrogen

Ground level

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

Couple T_s *to* T_k *Couples to spin*

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



Spin Temperature

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Mapping the Cosmic Distribution of

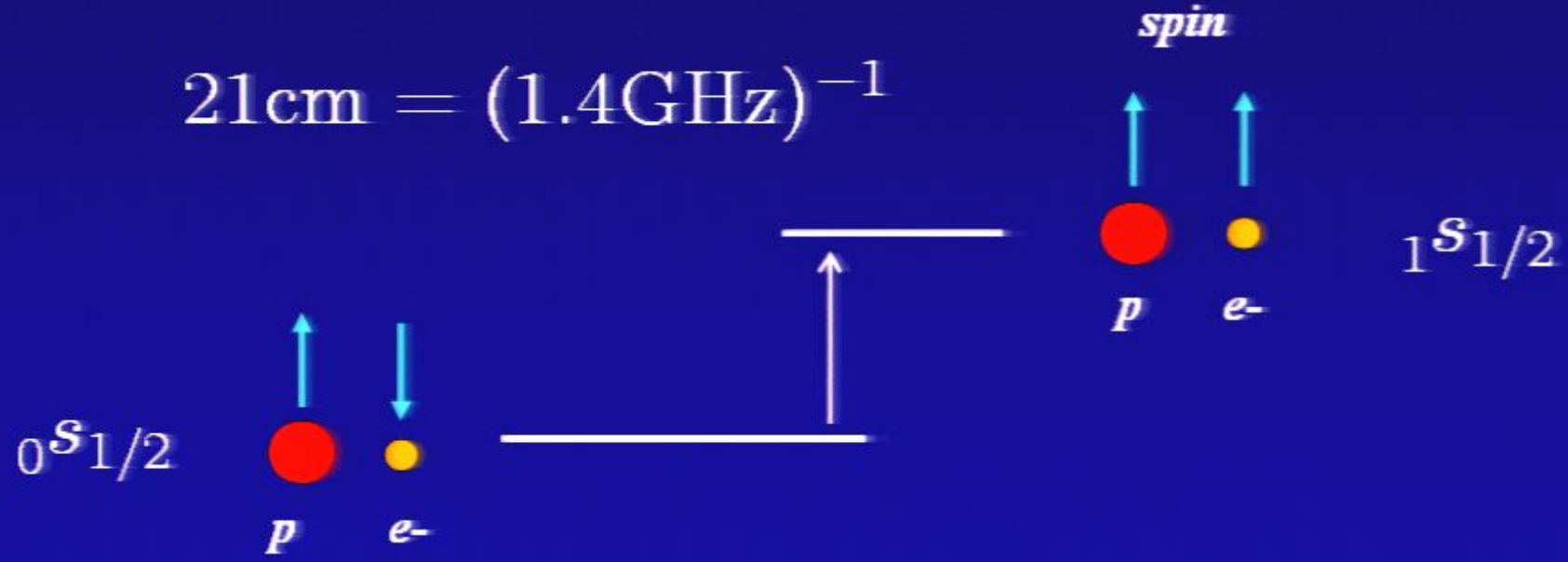
Hydrogen

Ground level

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

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

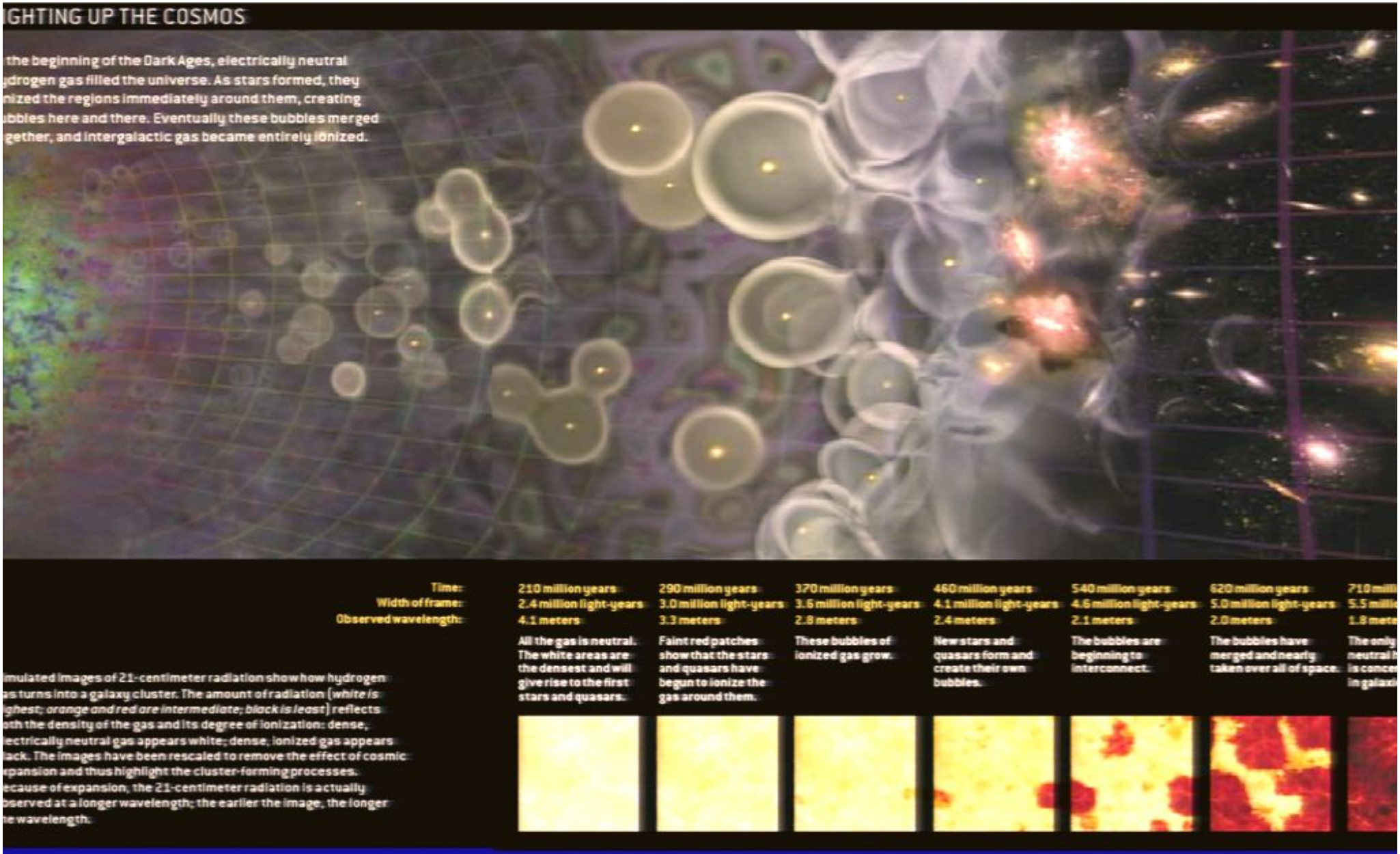
$$21\text{cm} = (1.4\text{GHz})^{-1}$$



Spin Temperature

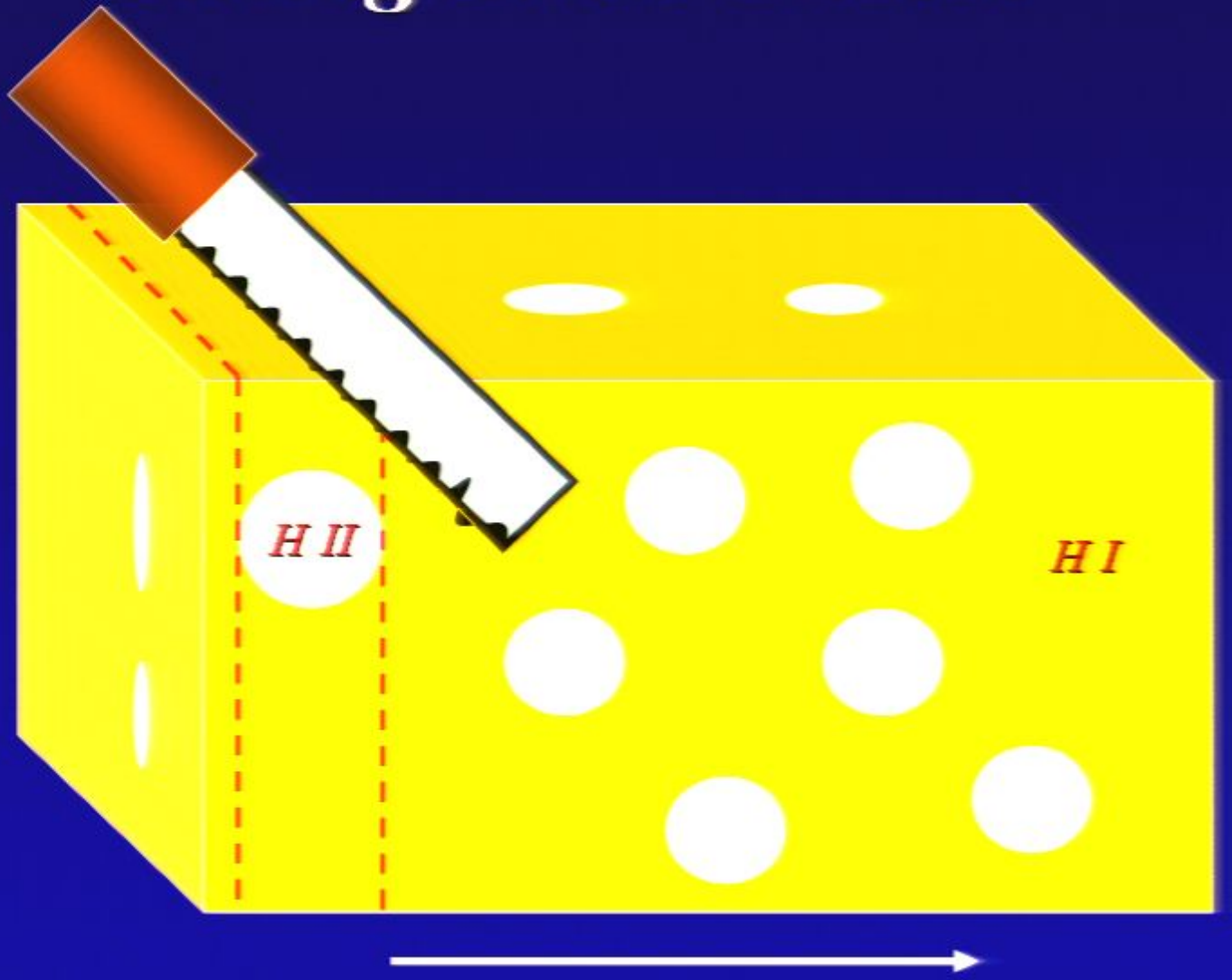
$$\frac{n_1}{n_0} = \frac{g_1}{g_0}\exp\{-\frac{0.068\text{K}}{T_s}\} \qquad (g_1/g_0) = 3$$

21cm Mapping of Cosmic History



21cm Tomography of Ionized Bubbles During Reionization is like

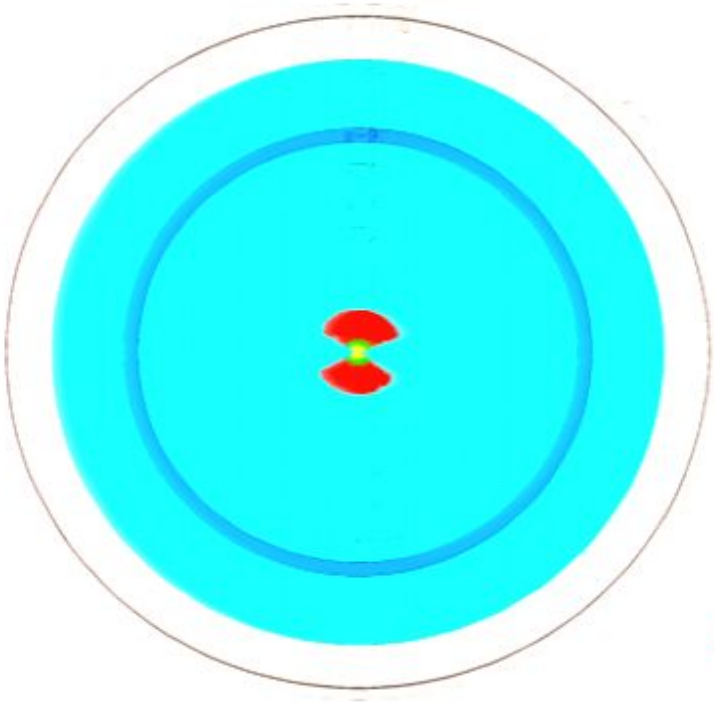
Slicing Swiss Cheese



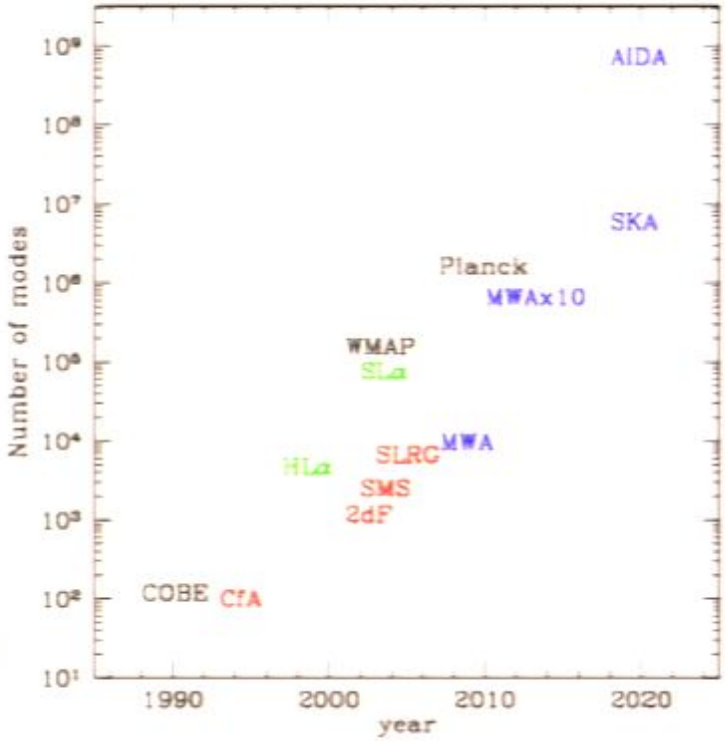
Observed wavelength ⇔ distance

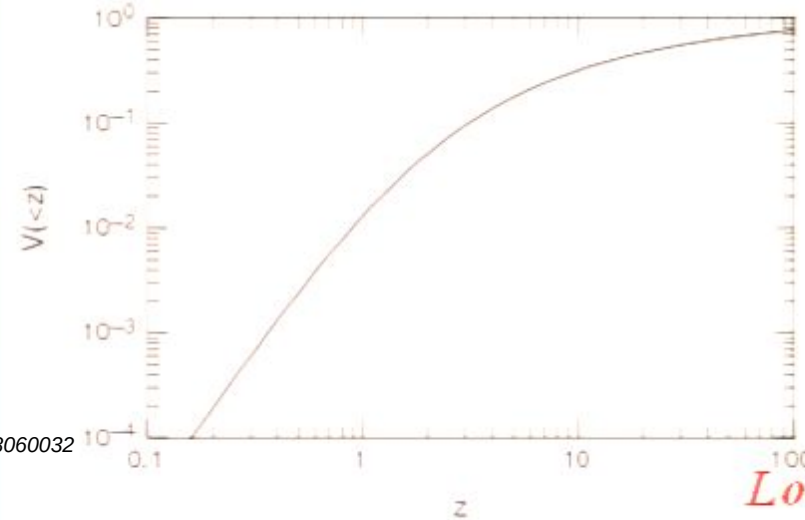
$21\text{cm} \times (1+z)$

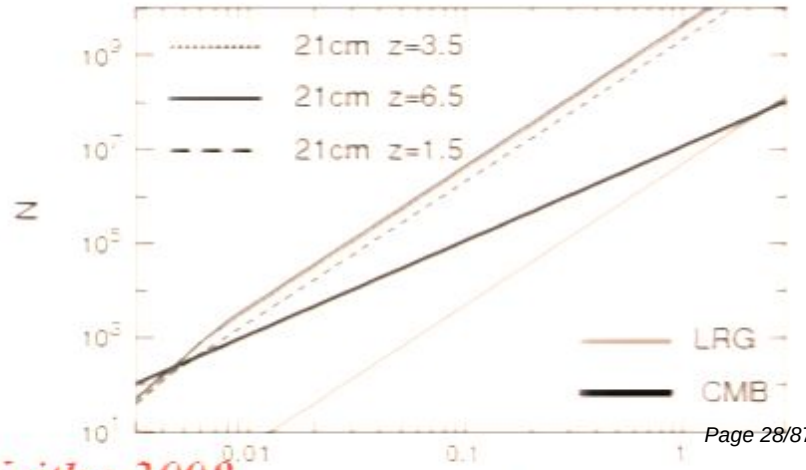
Counting Modes in Cosmological Surveys



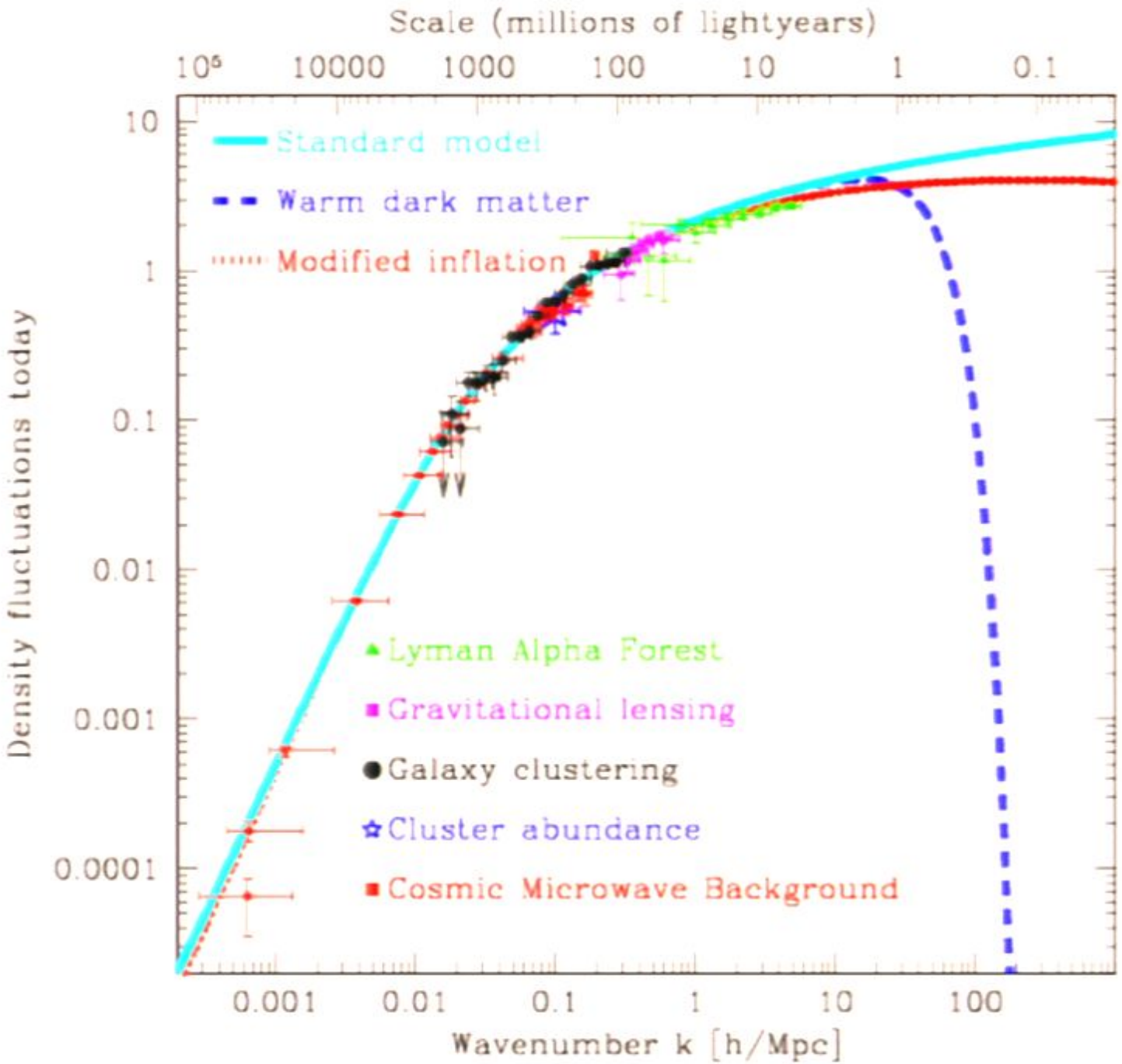
Mao et al. 2008







Loeb & Wyithe 2008


Scale (millions of lightyears)
10⁵
10000
1000
100
10
1
0.1
Standard model
Warm dark matter
Modified inflation
Density fluctuations today
10
1
0.1
0.01
0.001
0.0001
Lyman Alpha Forest
Gravitational lensing
Galaxy clustering
Cluster abundance
Cosmic Microwave Background
0.001
0.01
0.1
1
10
100
Wavenumber k [h/Mpc]

Separating the Physics from the Astrophysics

Separating the Physics from the Astrophysics

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

Astrophysics: *consequences of star formation*

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:

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

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

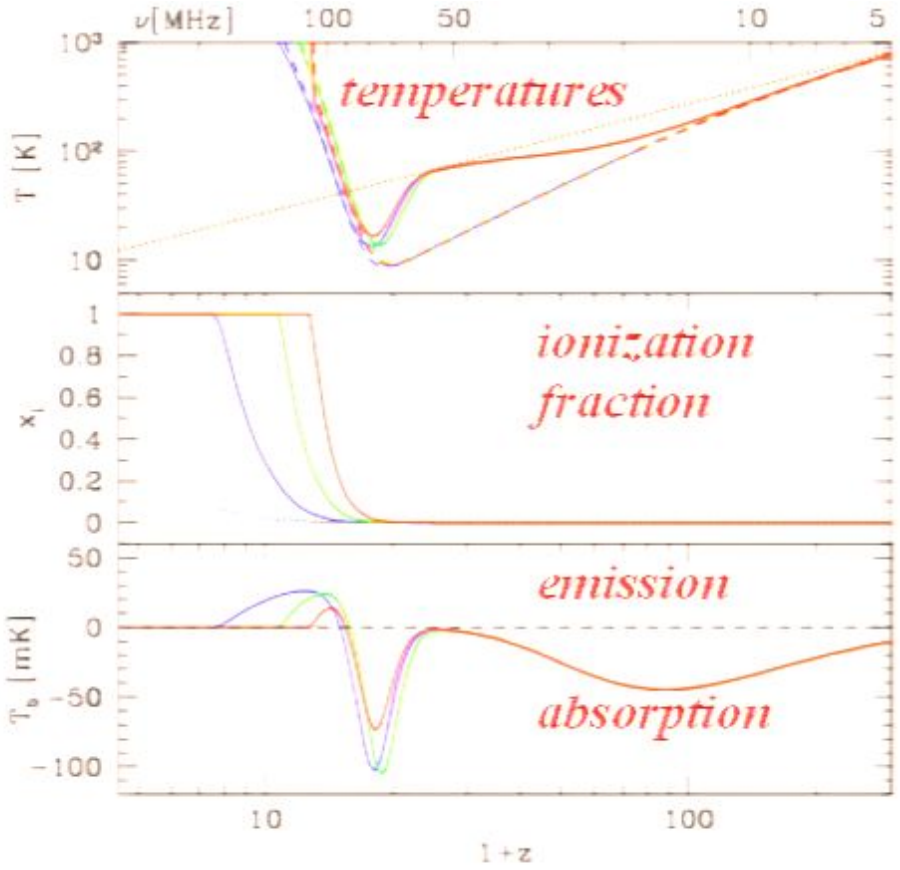
Separating the Physics from the Astrophysics

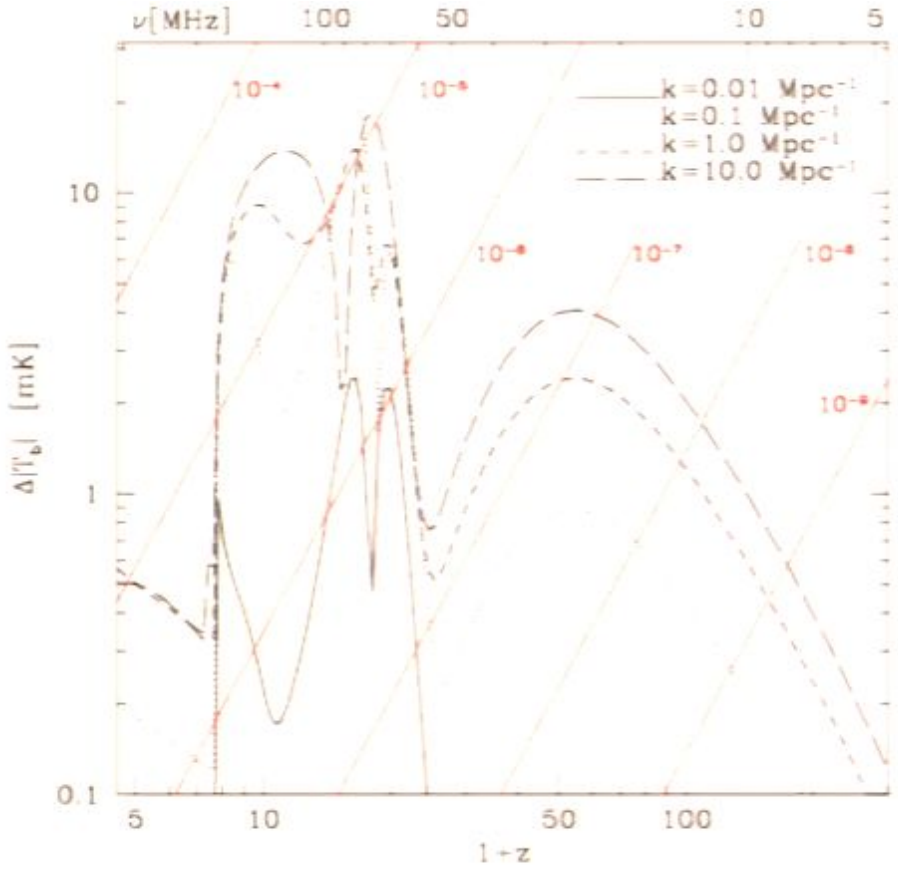
Physics: *initial conditions from inflation; nature of dark matter and dark energy*

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

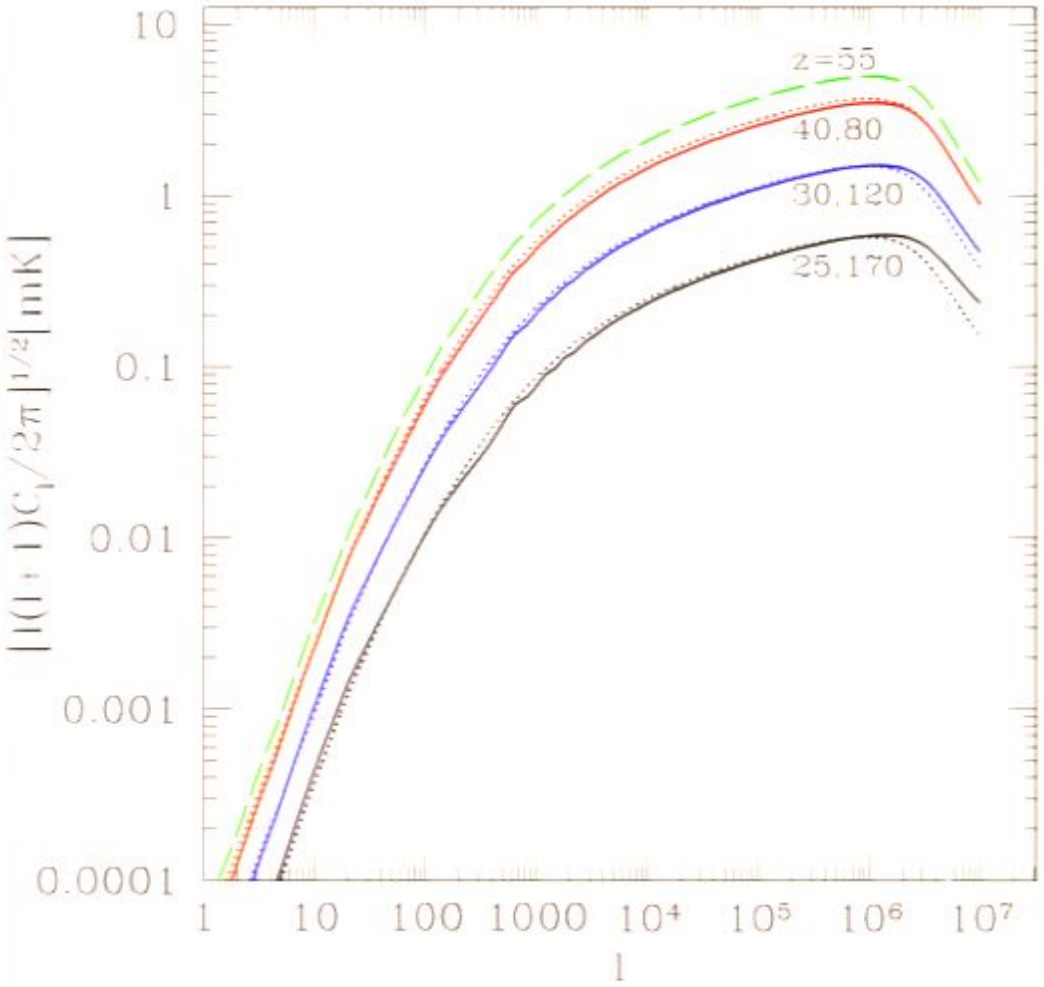


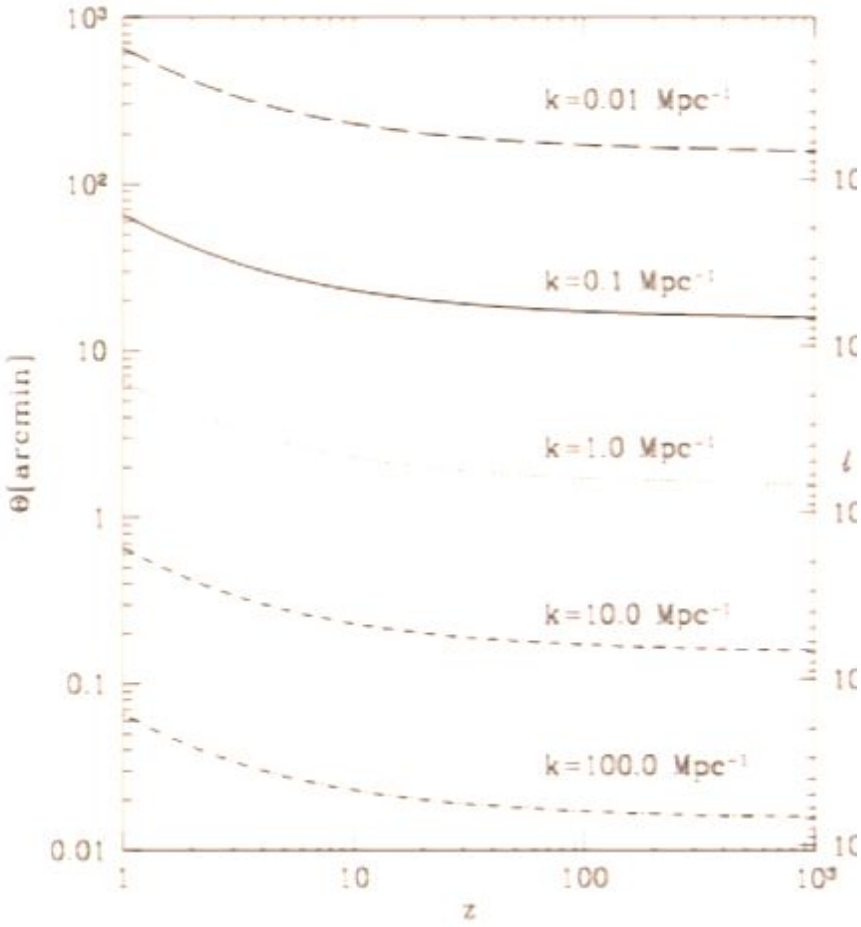


Left: Top panel: Evolution of the mean CMB (dotted curve). intergalactic medium (IGM. dashed curve). and spin (solid curve) temperatures. *Middle panel:* Evolution of the filling fraction of ionized bubbles (solid curve) and electron fraction outside the bubbles (dotted curve). *Bottom panel:* Evolution of mean 21cm brightness temperature. Three different astrophysical models are plotted. corresponding to the -1σ (red curve). best-fit (green curve). and $+1\sigma$ (blue curve) optical depth values derived from WMAP [. *Right:* Redshift evolution of the angle-averaged 21cm power spectrum $\bar{\Delta}_{T_b}$ in the -1σ model for wave-numbers $k = 0.01$ (solid curve). 0.1 (dotted curve). 1.0 (short dashed curve). and 10.0 Mpc^{-1} (long dashed curve). Diagonal lines indicate the foreground brightness of the sky $T_{\mathrm{sky}}(\nu)$ times a factor r ranging from 10^{-4} to 10^{-9}. indicative of the level of foreground subtraction requires. *(Pritchard & Loeb 2008)*

21 cm Absorption During the Dark Ages

$$T_b = \tau \left(\frac{T_s - T_\gamma}{1+z} \right) \qquad T_b = 28\text{mK} \left(\frac{1+z}{10} \right)^{1/2} \left(\frac{T_s - T_\gamma}{T_s} \right)$$





Loeb & Zaldarriaga, Phys. Rev. Lett., 2004

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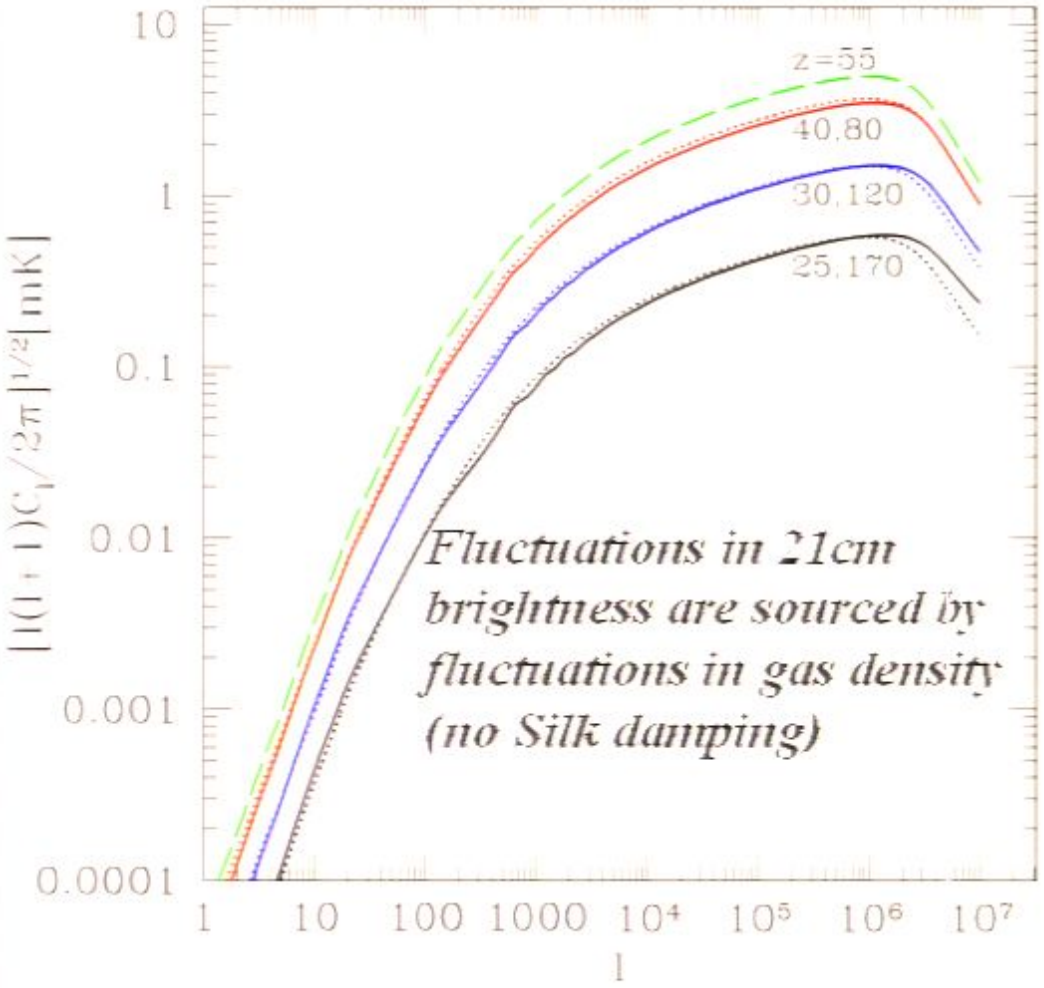

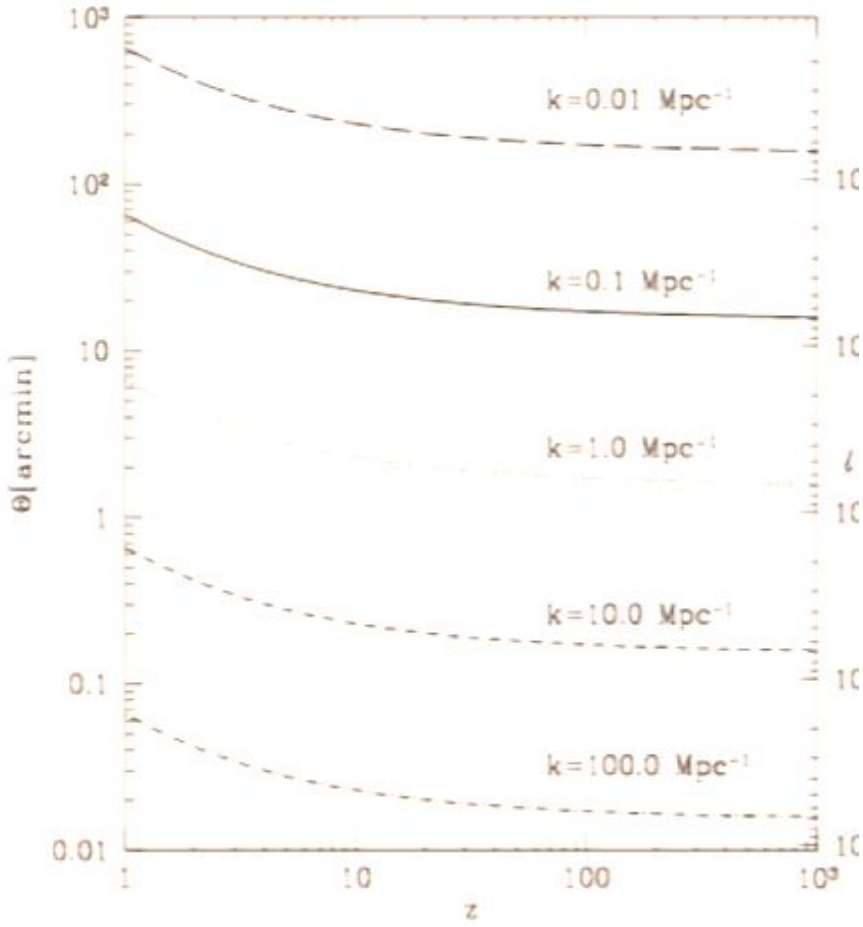

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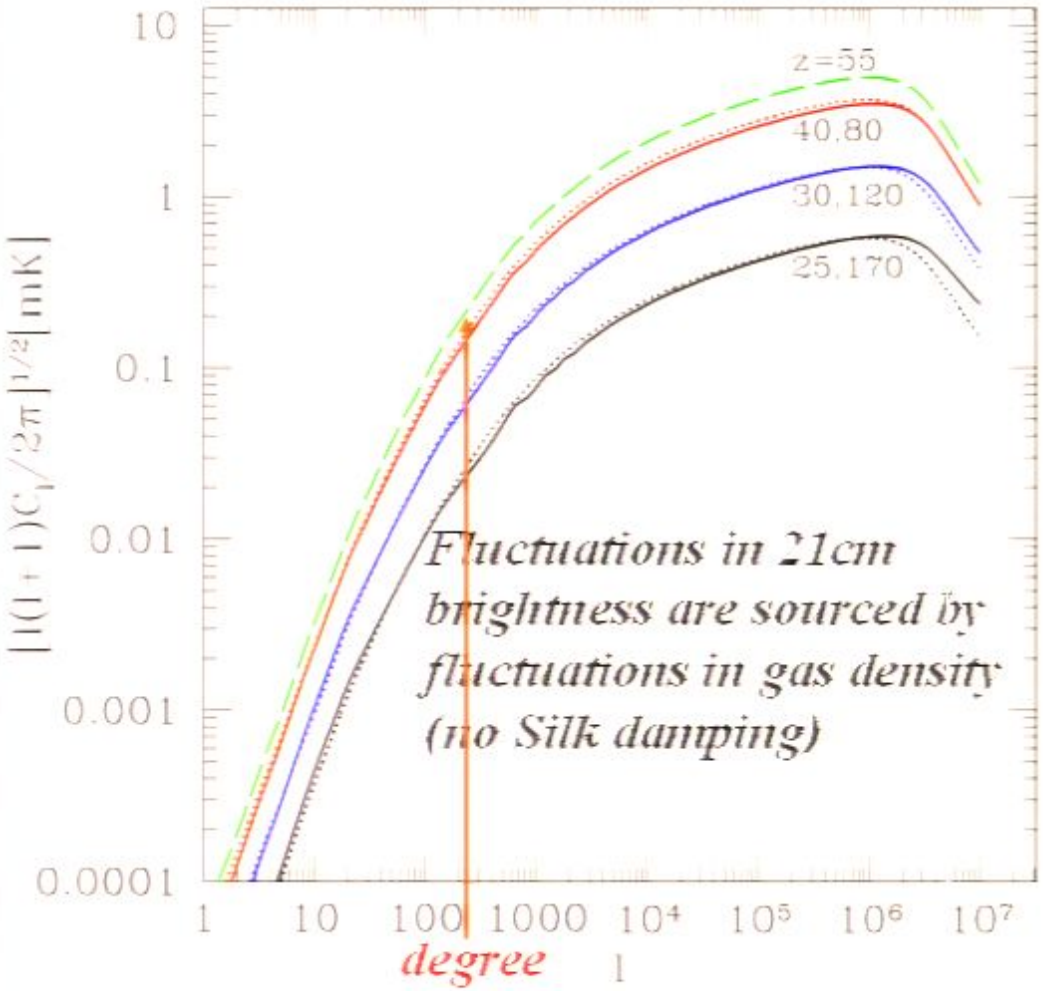
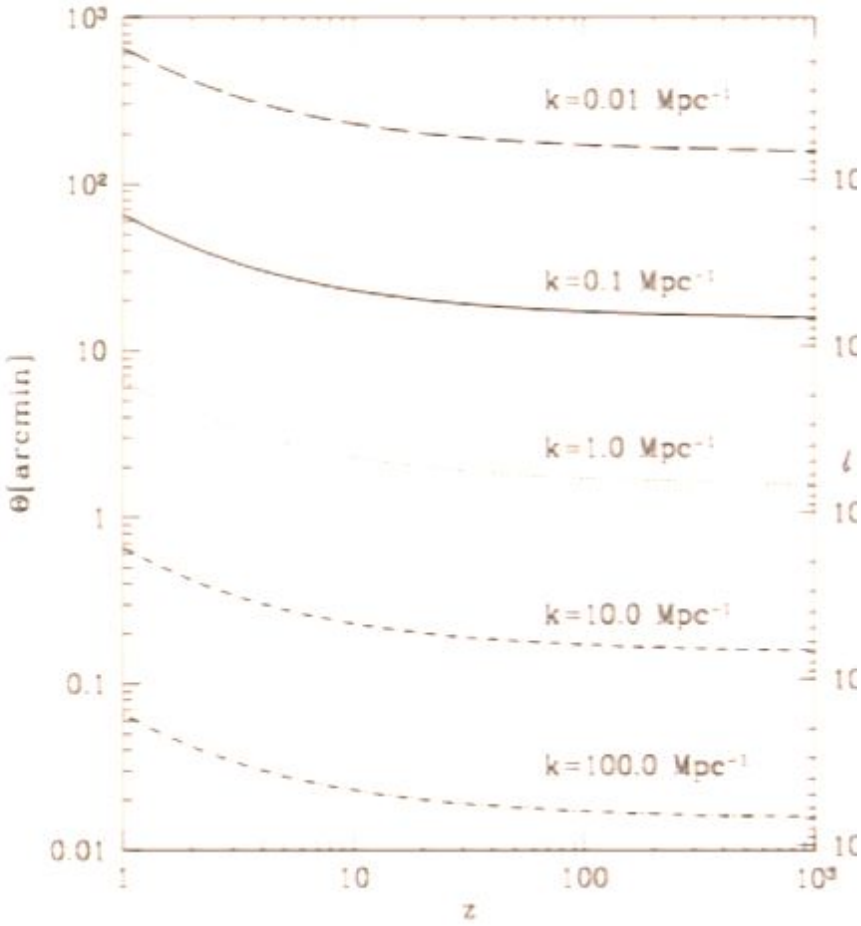
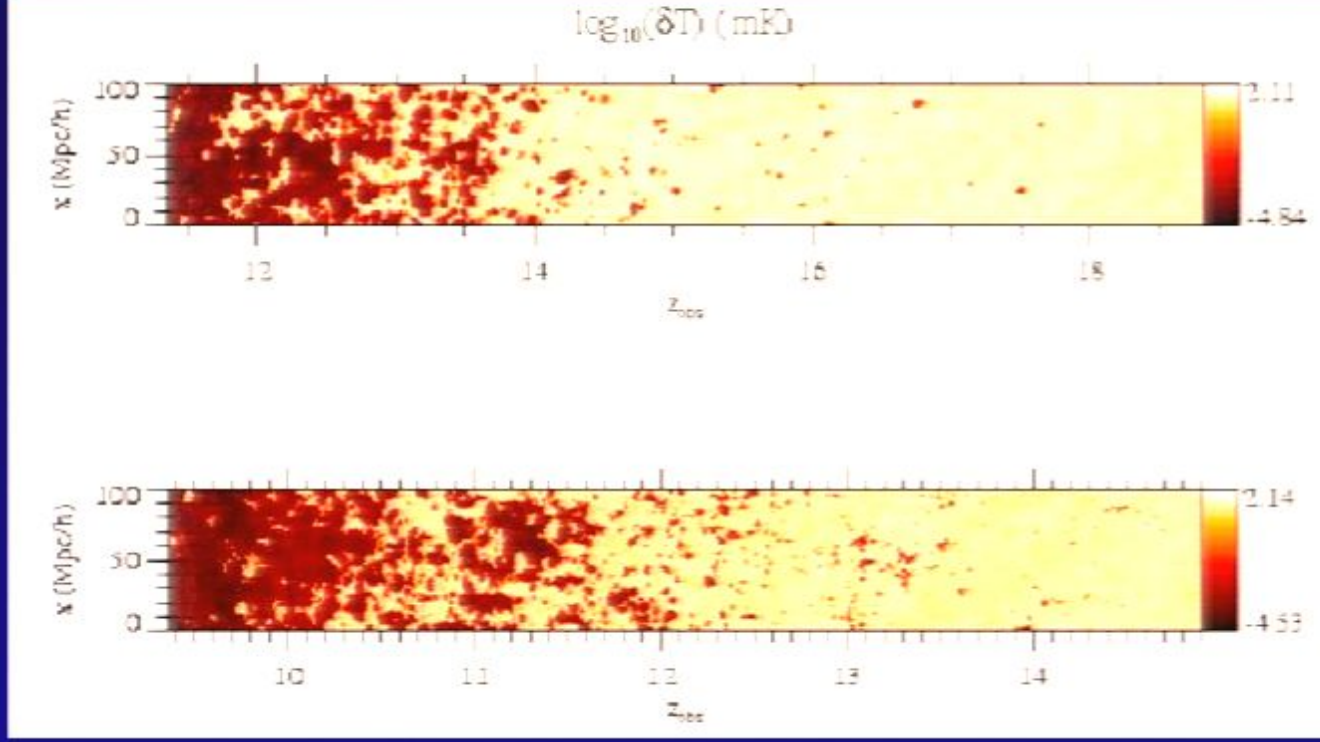




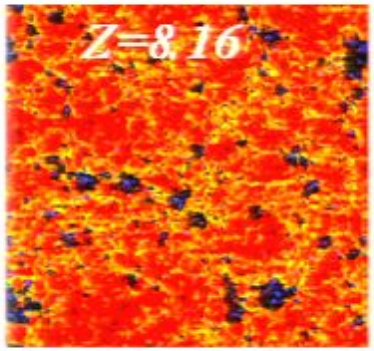
Loeb & Zaldarriaga, Phys. Rev. Lett., 2004

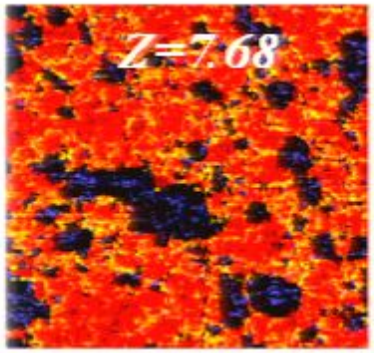
21cm Mapping of Epoch of Reionization

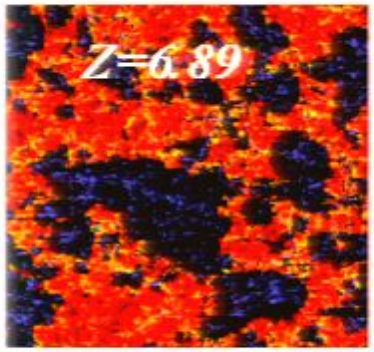


Mellema et al. 2006

HI Density

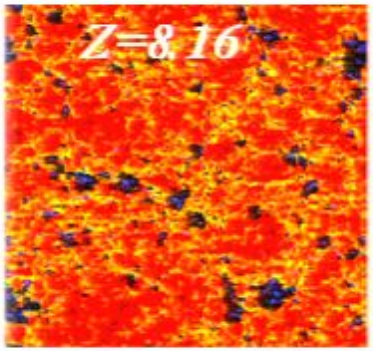


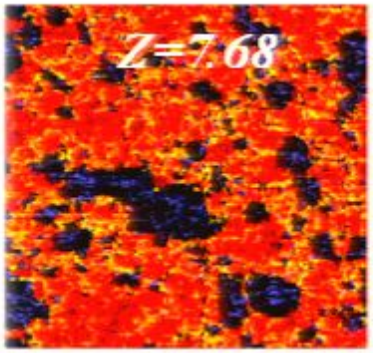


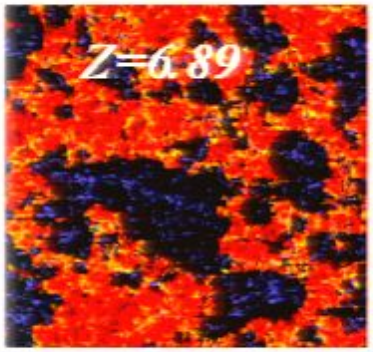


Zahn et al. 2006

HI Density

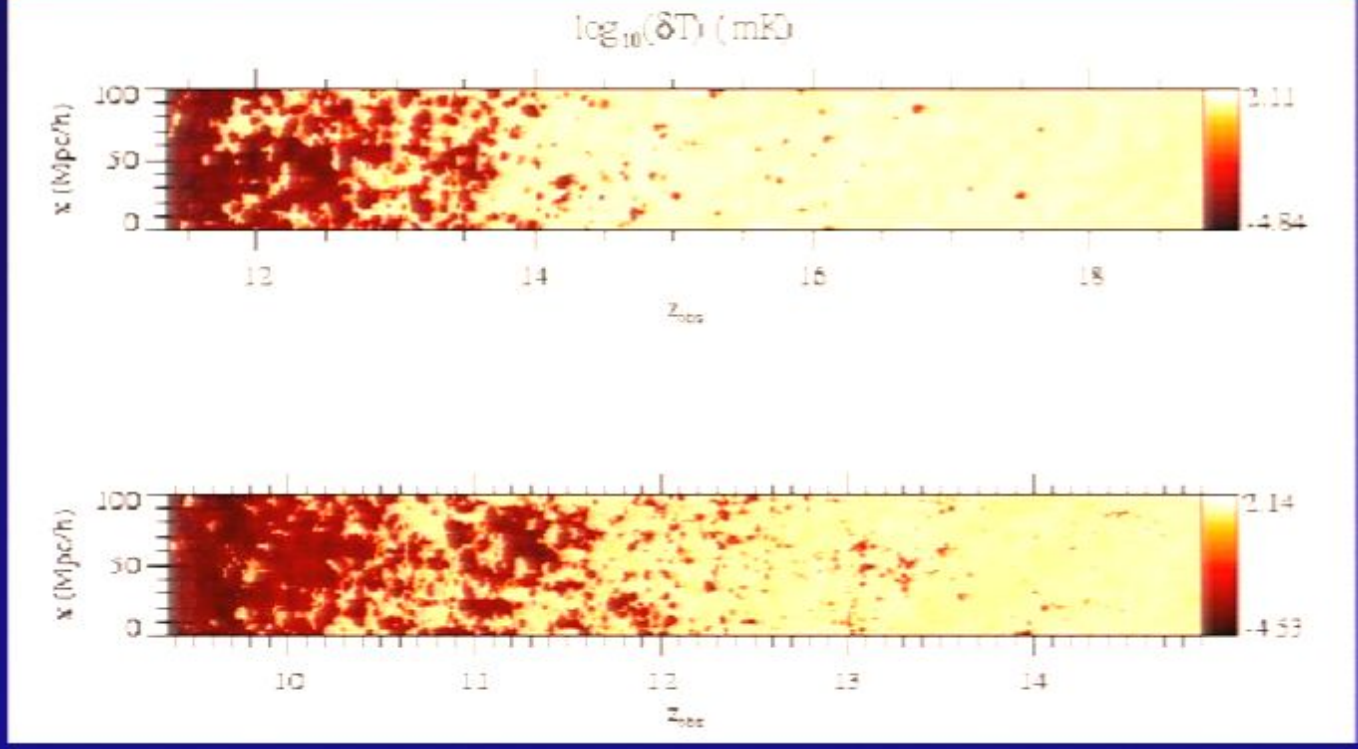






Zahn et al. 2006

21cm Mapping of Epoch of Reionization



Mellema et al. 2006

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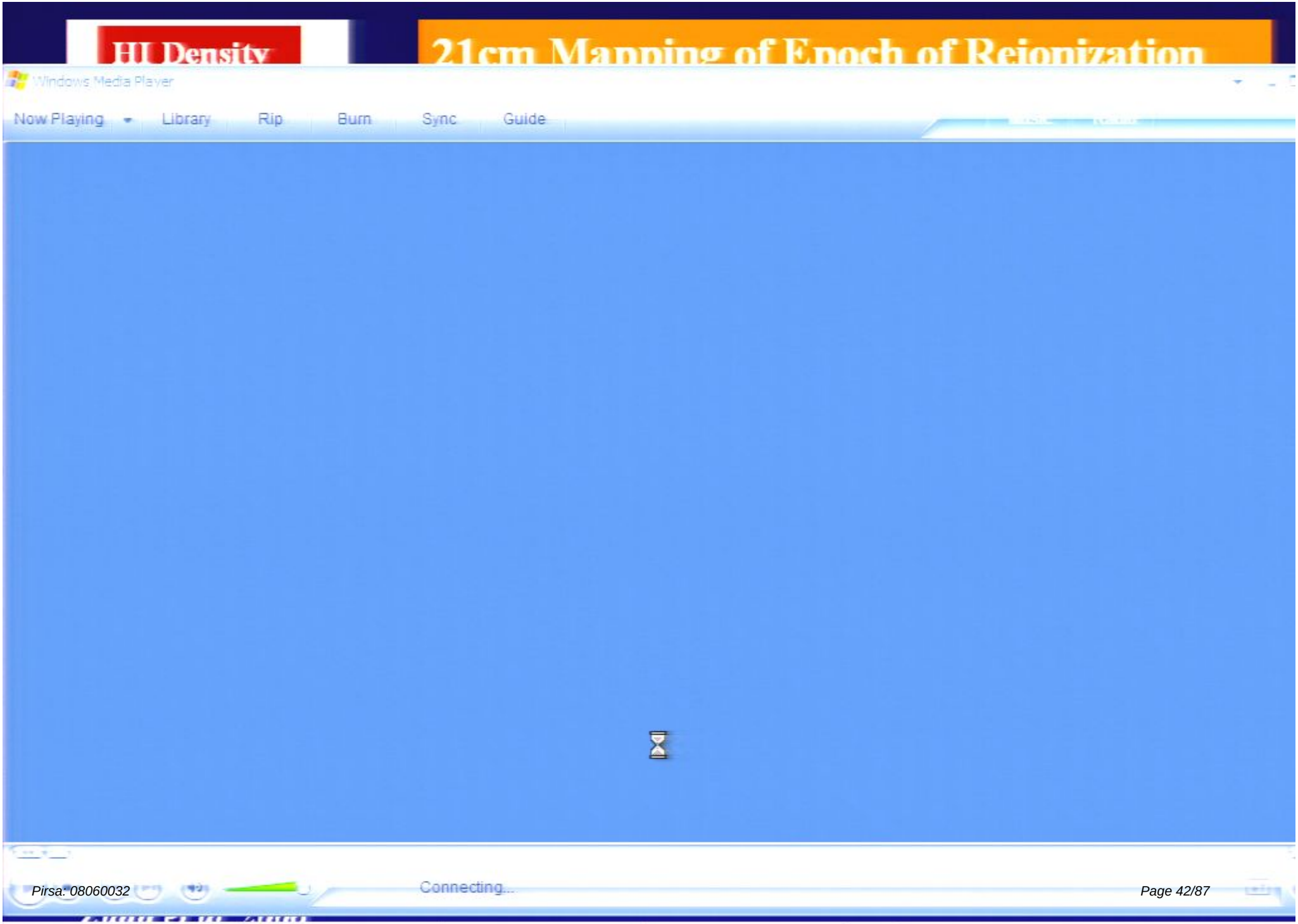
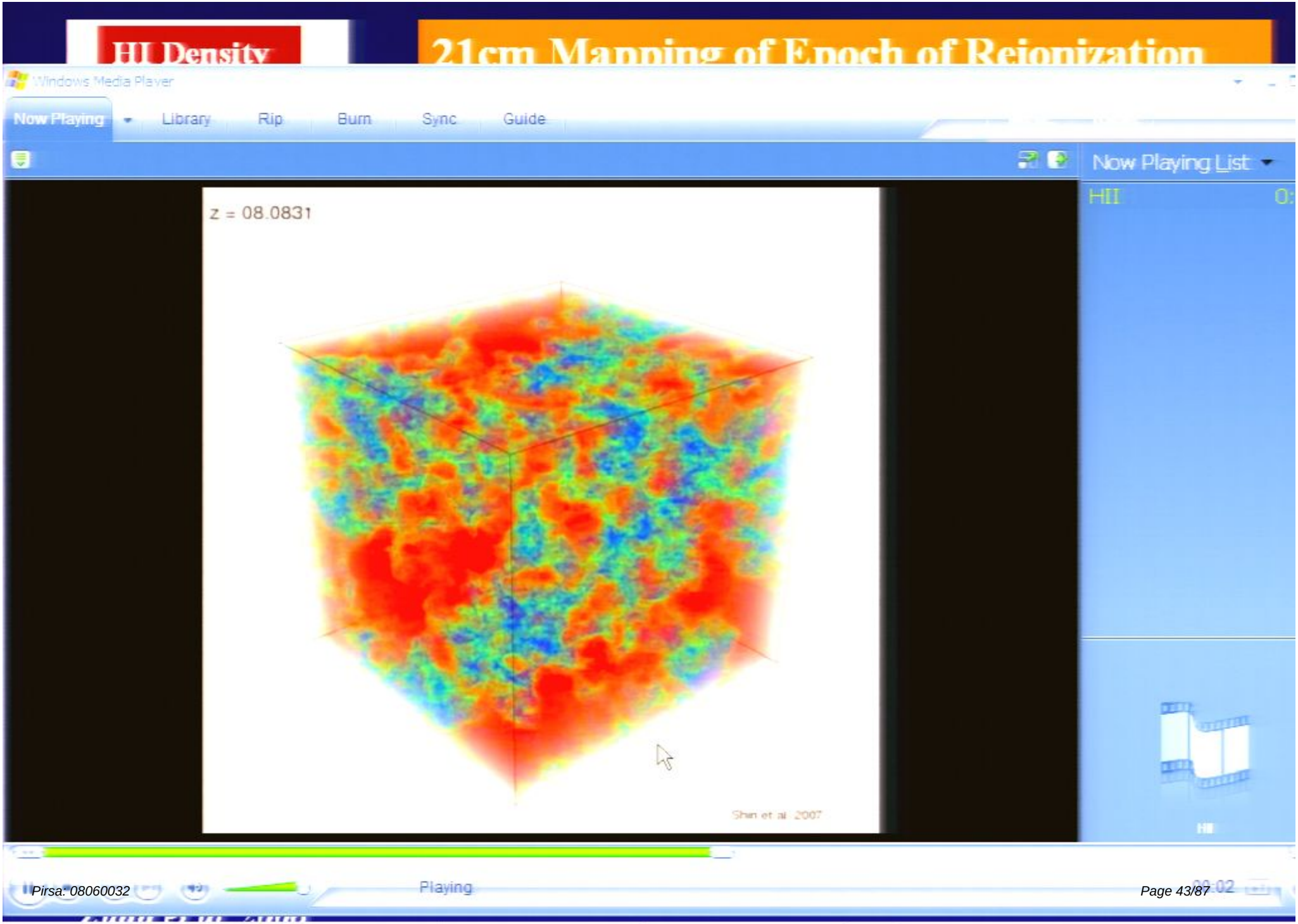
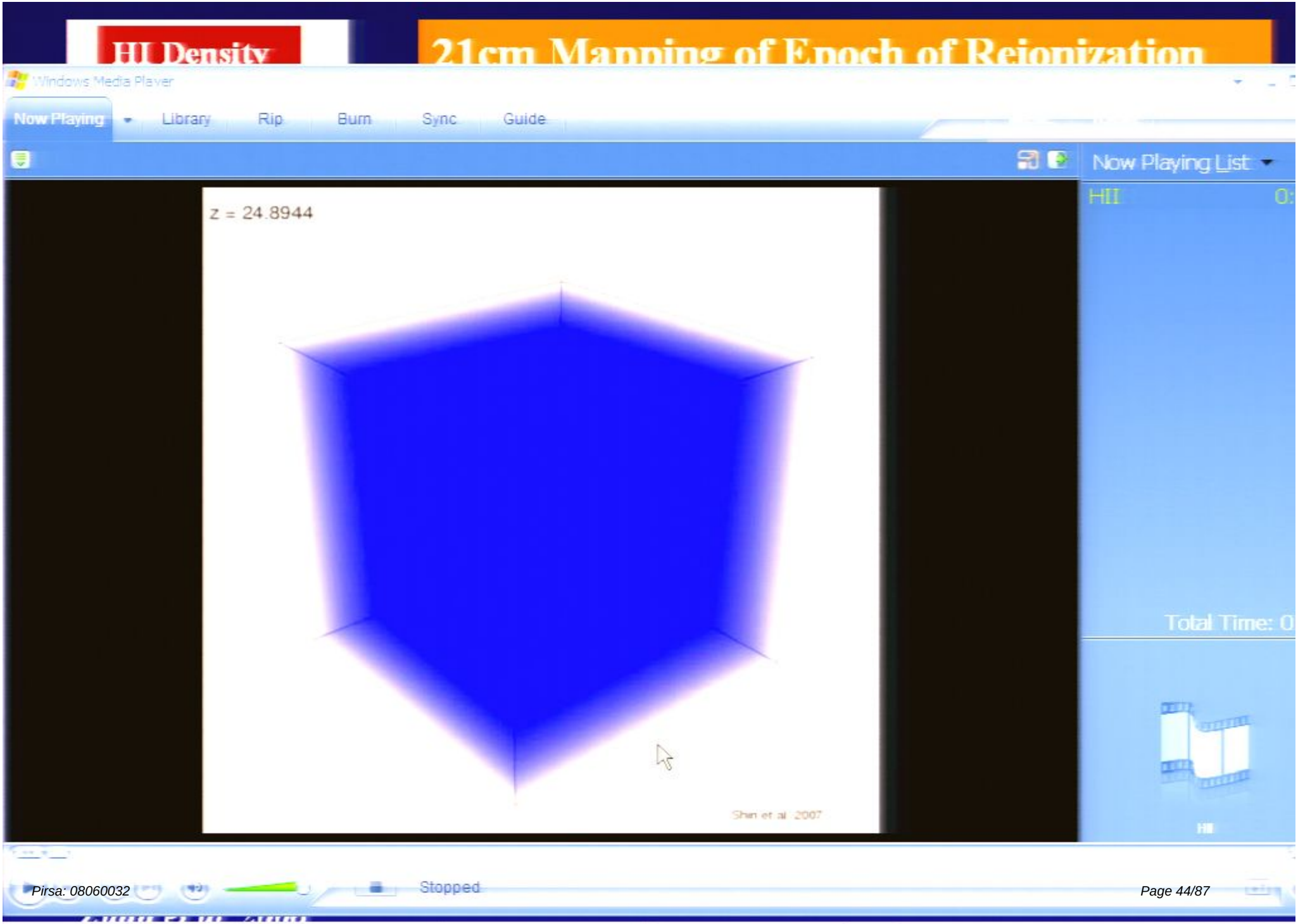
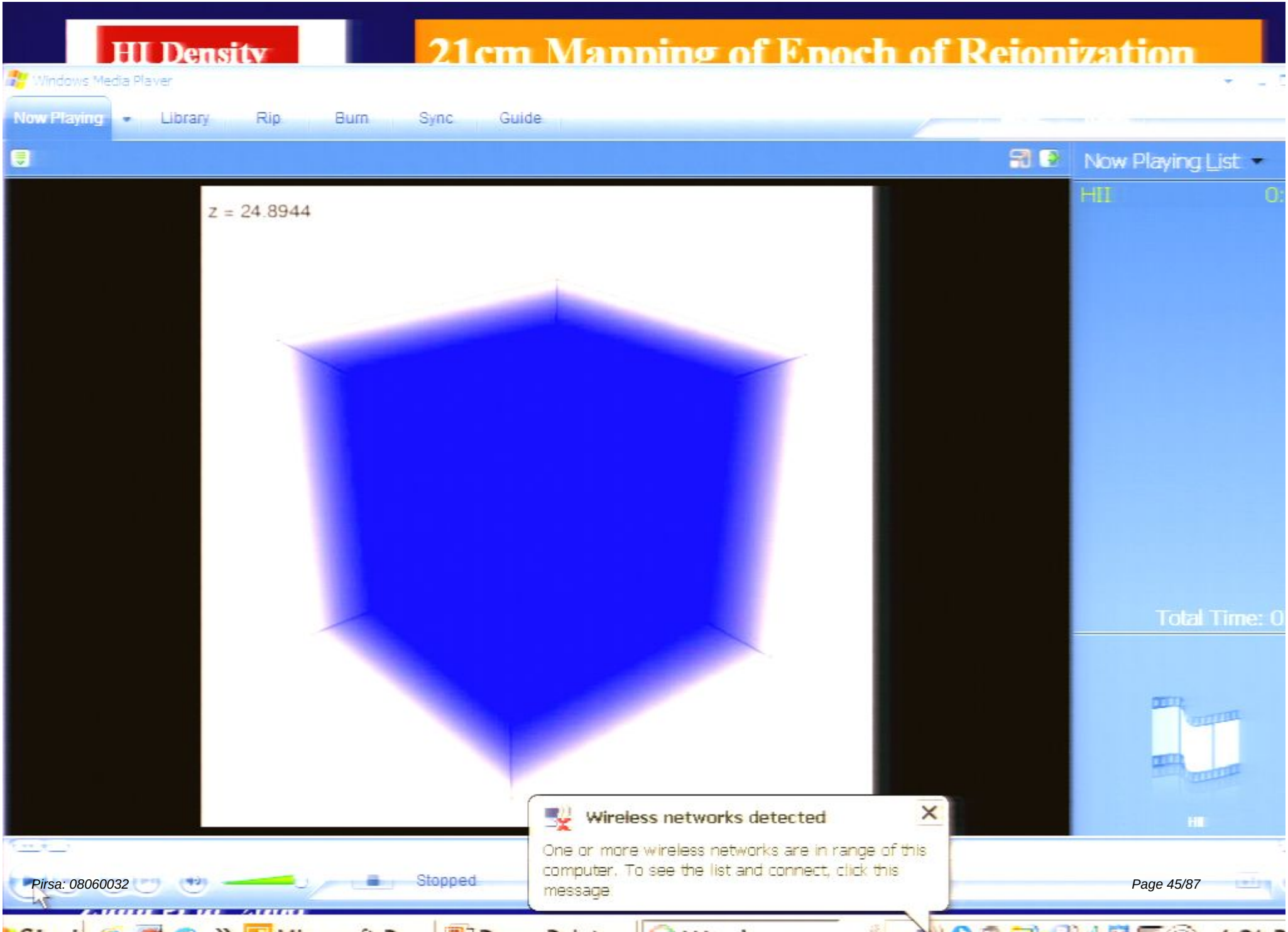
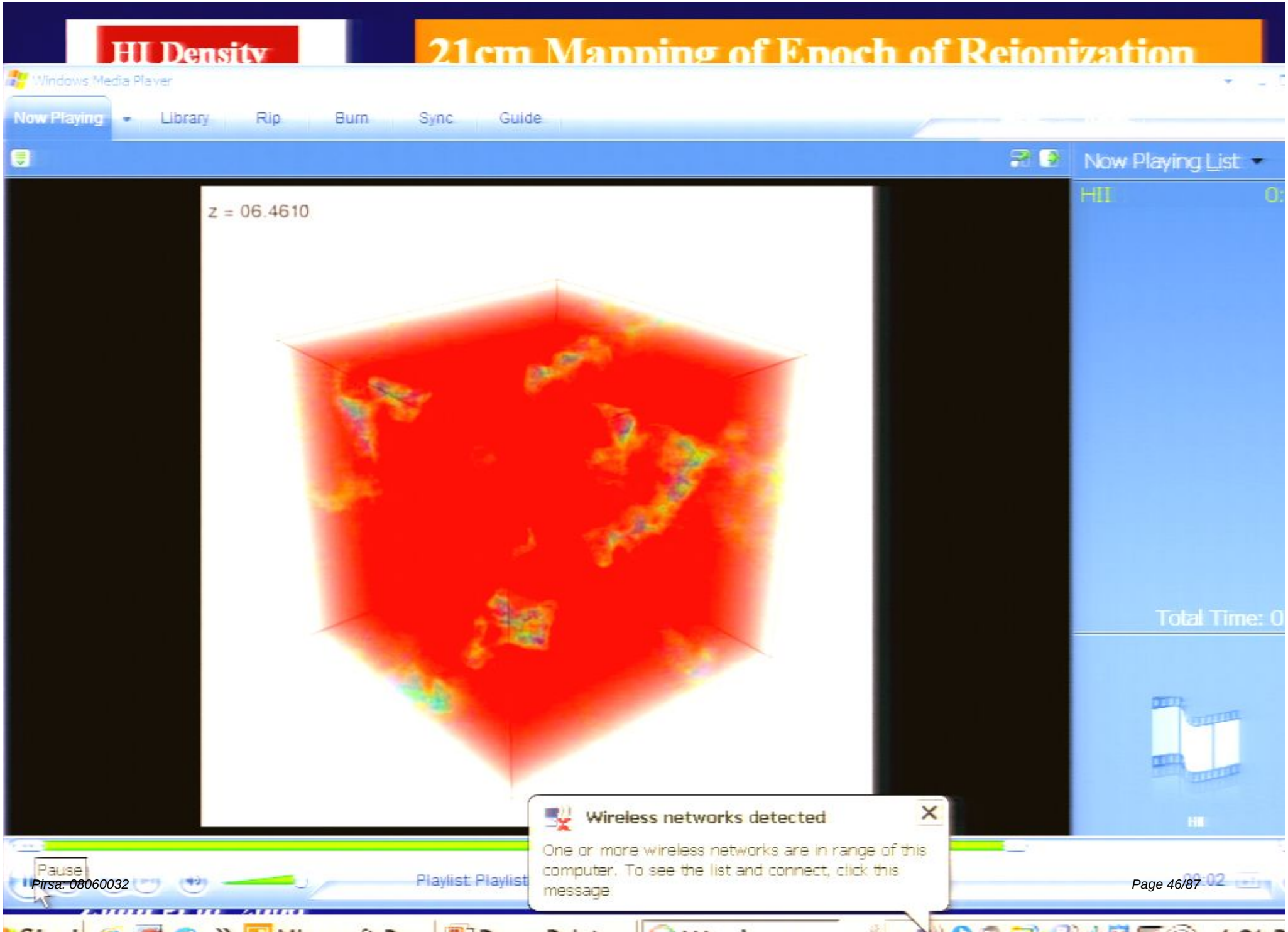
Trac, Cen, & Loeb 2008


HI Density
21cm Mapping of Epoch of Reionization
Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Guide
Connecting...


HI Density
21cm Mapping of Epoch of Reionization
Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Guide
Now Playing List
HII
z = 08.0831
Shin et al. 2007
Playing


HI Density
21cm Mapping of Epoch of Reionization
Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Guide
Now Playing List
HII
Total Time: 0
z = 24.8944
Shin et al. 2007
Stopped


HI Density
21cm Mapping of Epoch of Reionization
Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Guide
Now Playing List
HII
z = 24.8944
Total Time: 0
Wireless networks detected
One or more wireless networks are in range of this computer. To see the list and connect, click this message
Stopped


HI Density
21cm Mapping of Epoch of Reionization
Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Guide
Now Playing List
HII
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Total Time: 0
Wireless networks detected
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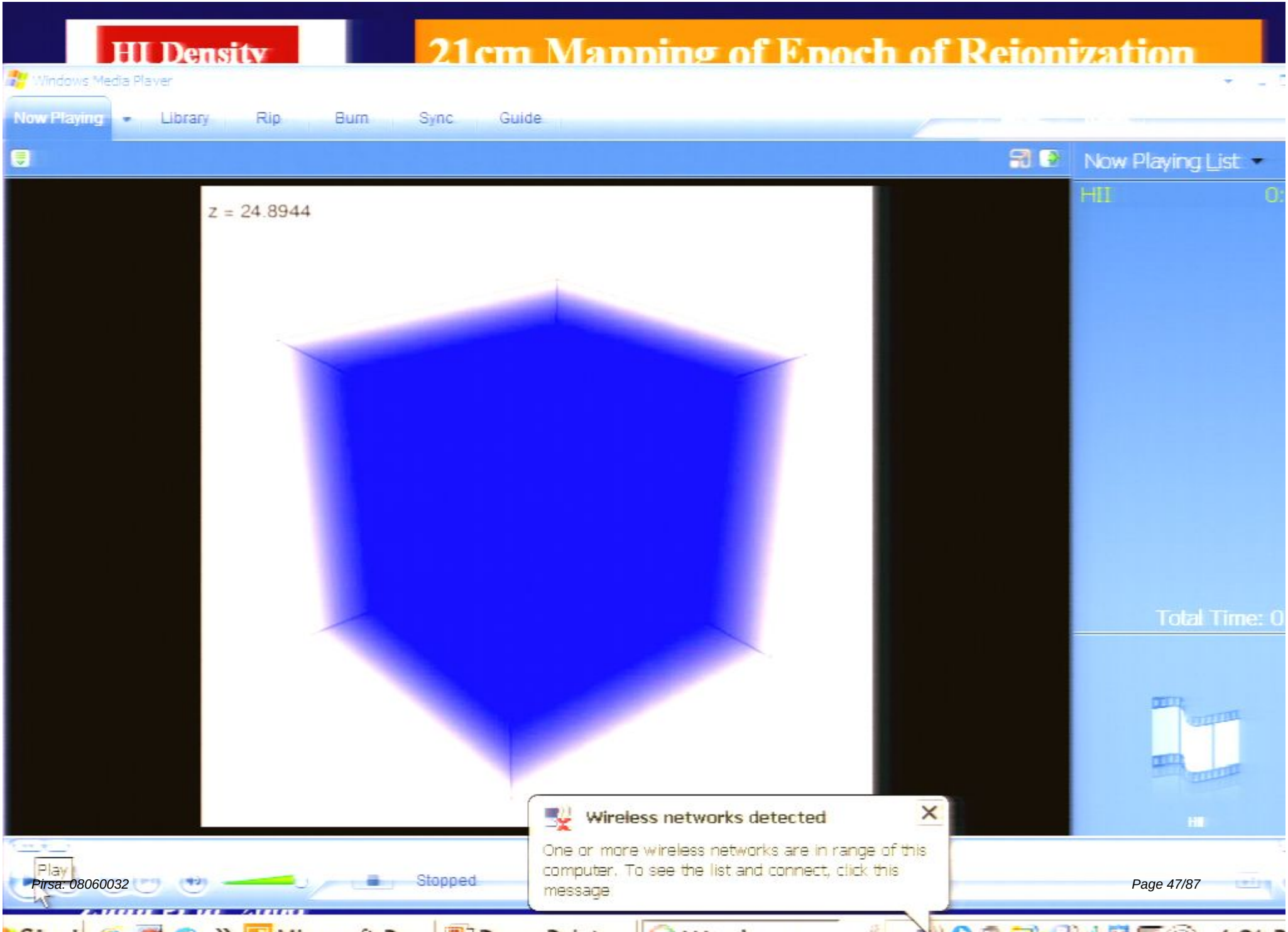
Pause
Playlist: Playlist


HI Density
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Windows Media Player
Now Playing
Library
Rip
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Now Playing List
HII
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Total Time: 0
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Play
Stopped

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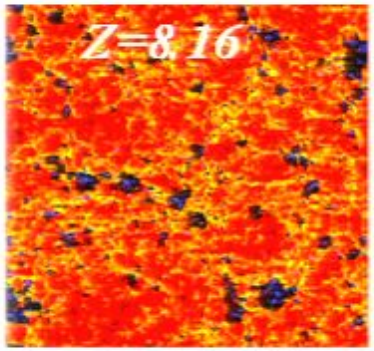

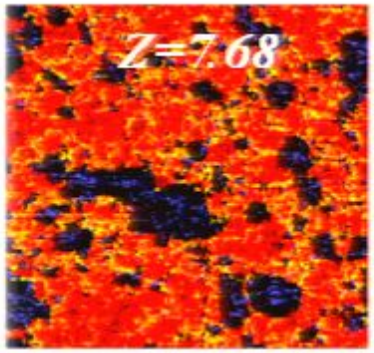

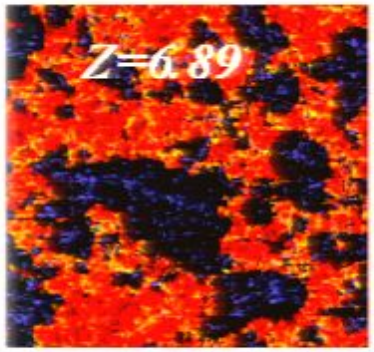

Zahn et al. 2006

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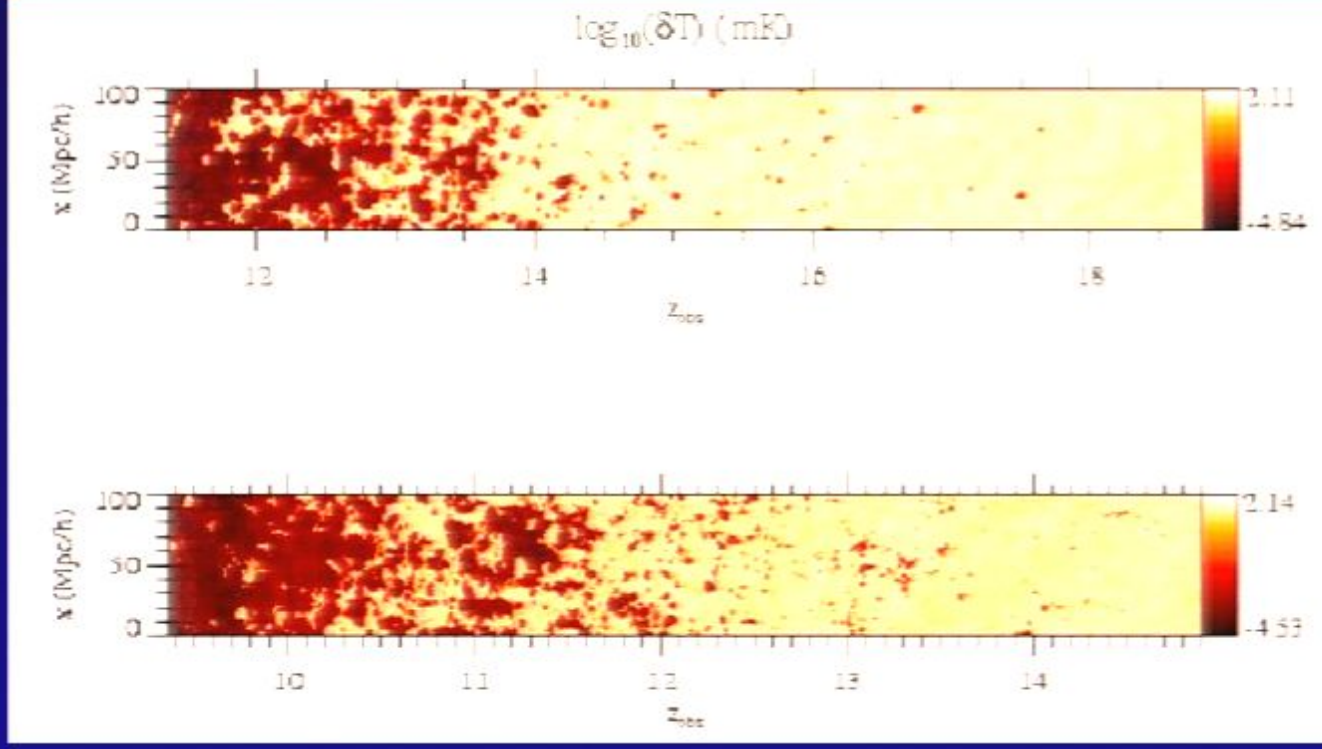


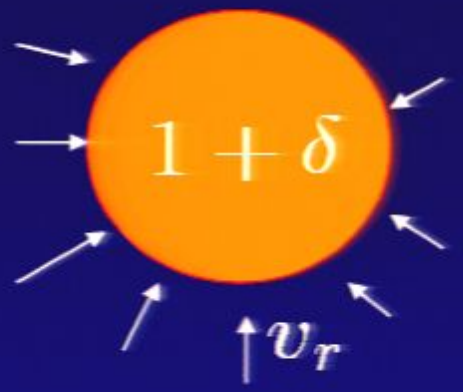
Mellema et al. 2006

Pirsa: 08060032

Trac, Cen, & Loeb 2008

Line-of-Sight Anisotropy of 21cm Flux Fluctuations

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



Barkana & Loeb 2004; see also Bharadwaj & Ali 2004

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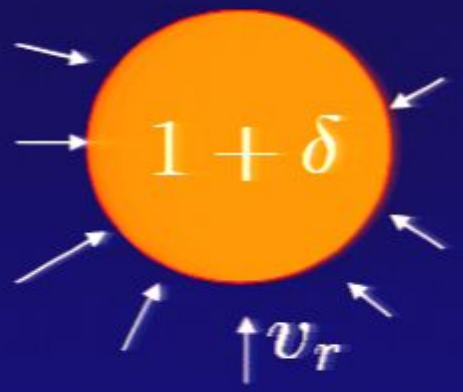

Peculiar velocity changes $\tau \propto \frac{n_{\rm HI}}{dv_r/dr}$

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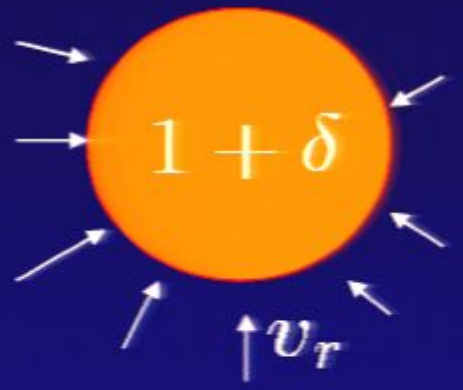

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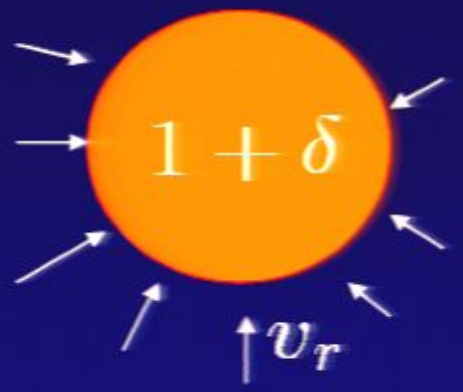

Peculiar velocity changes

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

Barkana & Loeb 2004; see also Bharadwaj & Ali 2004

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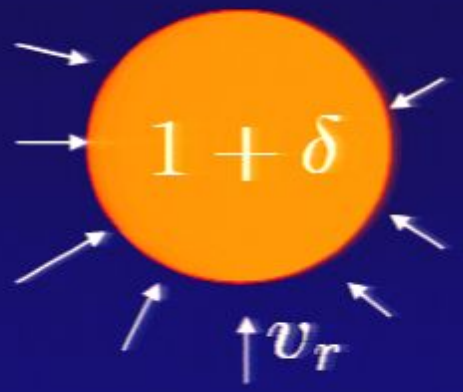

Peculiar velocity changes $\tau \propto \frac{n_{\rm HI}}{dv_r/dr} = \bar{n}(1+\delta) \sim \bar{H}(1-\frac{1}{3}\delta)$

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

Barkana & Loeb 2004; see also Bharadwaj & Ali 2004

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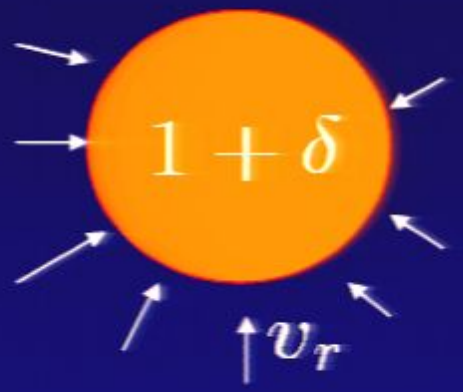

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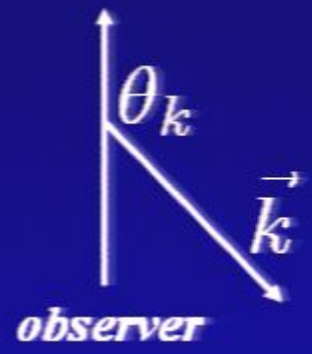

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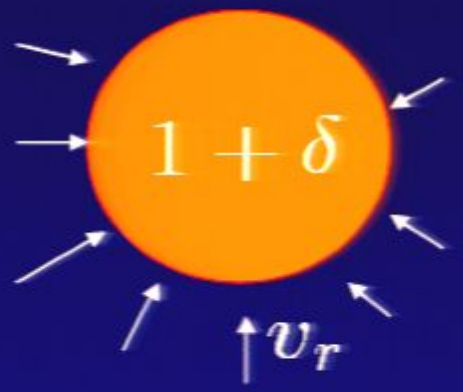

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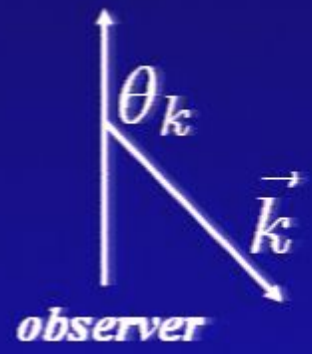
$$\frac{dv_r}{dr} \longrightarrow \quad \delta_v(\vec{k}) = -\cos^2\theta_k \times \delta(\vec{k})$$



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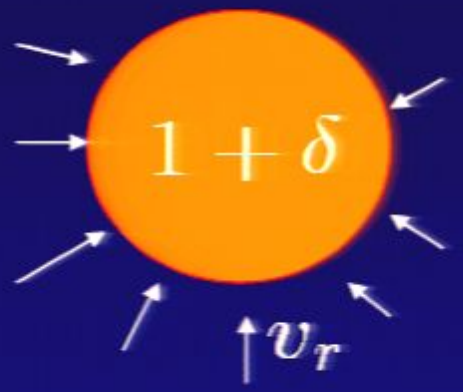

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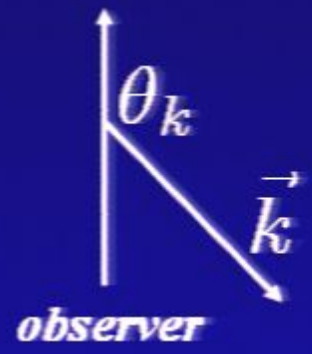

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$$P_{T_b} = [\cos^2\theta_k \delta(\vec{k}) + \delta_{\rm iso}(\vec{k})]^2$$

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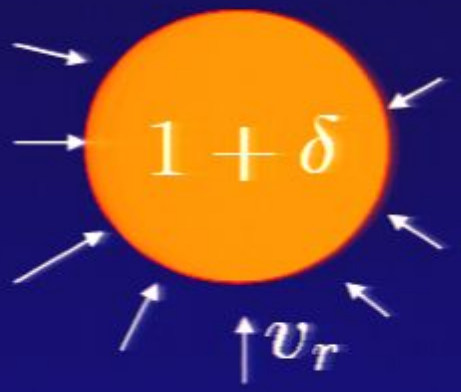

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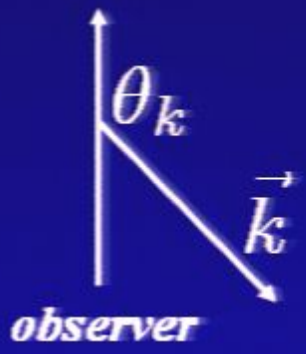

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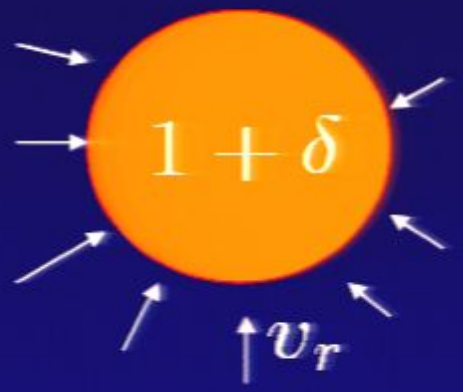
$$\delta_{\rm iso} = \beta\delta + \delta_{x_{\rm HI}} + \delta_T + \ldots$$

Barkana & Loeb 2004; see also Bharadwaj & Ali 2004

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")*

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

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

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

$$\cos^4\theta_k, \cos^2\theta_k, \cos^0\theta_k$$

Barkana & Loeb 2004; see also Bharadwaj & Ali 2004

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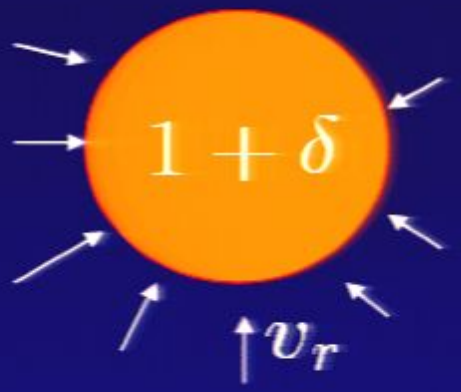

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Barkana & Loeb 2004; see also Bharadwaj & Ali 2004

Experiments

*MWA (Murchison Wide-Field Array)

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

*LOFAR (Low-frequency Array)

Netherlands

*21CMA (formerly known as PAST)

China

*PAPER

UCB/NRAO

*GMRT (Giant Meterwave Radio Telescope)

India/CITA/Pittsburg

*SKA (Square Kilometer Array)

International

Murchison Wide-Field Array: mapping cosmic hydrogen through its 21cm emission

- 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

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- Galactic synchrotron emission

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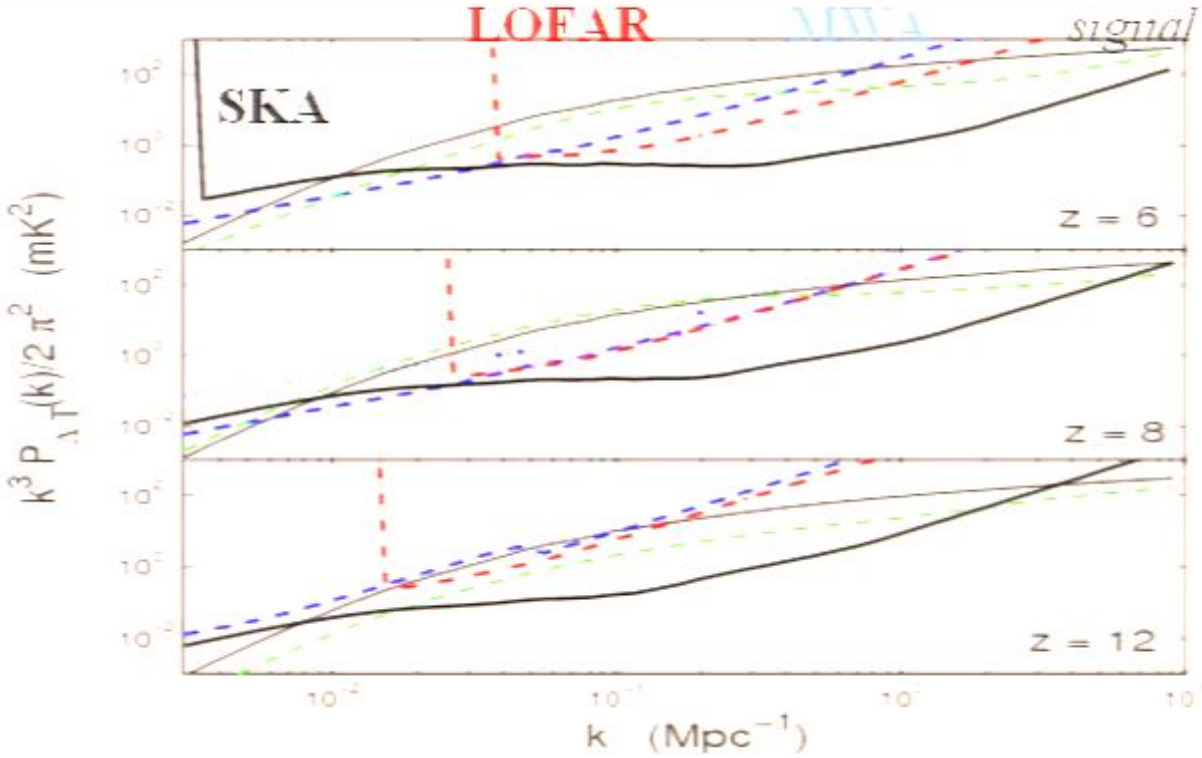
- Extragalactic: radio sources

Although the sky brightness (>10K) is much larger than the 21cm signal (<10mK), the foregrounds have a smooth frequency dependenc while the signal fluctuates rapidly across small shifts in frequency (=redshift). Theoretical estimates indicate that the 21cm signal is detectable with the forthcoming generation of low-frequency arrays (Zaldarriaga et al. astro-ph/0311514; Morales & Hewitt astro-ph/0312437)

Power-Spectrum Sensitivity



Isotropic power spectrum sensitivity, in logarithmic bins with $\Delta k = k/2$, for several experimental configurations. In each panel, the thin solid and dashed curves show estimates of the signal with and without reionization. The thick solid, dashed, and dot-dashed curves show error estimates for 1000 hour observations over 6 MHz with the SKA, MWA, and LOFAR, respectively. Each assumes perfect foreground removal. The dotted curve in the middle panel assumes a flat antenna distribution for the MWA. From *McQuinn et al. 2006*

-1

$$T_{\rm sky} \sim 180 \left(\frac{\nu}{180\ {\rm MHz}}\right)^{-2.6}\ {\rm K} \qquad \Delta T^N|_{\rm int} \sim 2\ {\rm mK} \left(\frac{A_{\rm tot}}{10^5\ {\rm m}^2}\right) \left(\frac{10'}{\Delta\theta}\right)^2 \left(\frac{1+z}{10}\right)^{4.6} \left(\frac{{\rm MHz}}{\Delta\nu}\frac{100\ {\rm hr}}{t_{\rm int}}\right)^{1/2}$$

21cm Cosmology After Reionization?

Wyithe & Loeb 2007

21cm Cosmology After Reionization?

Damped Lya absorbers:

Wyithe & Loeb 2007

21cm Cosmology After Reionization?

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

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Wyithe & Loeb 2007

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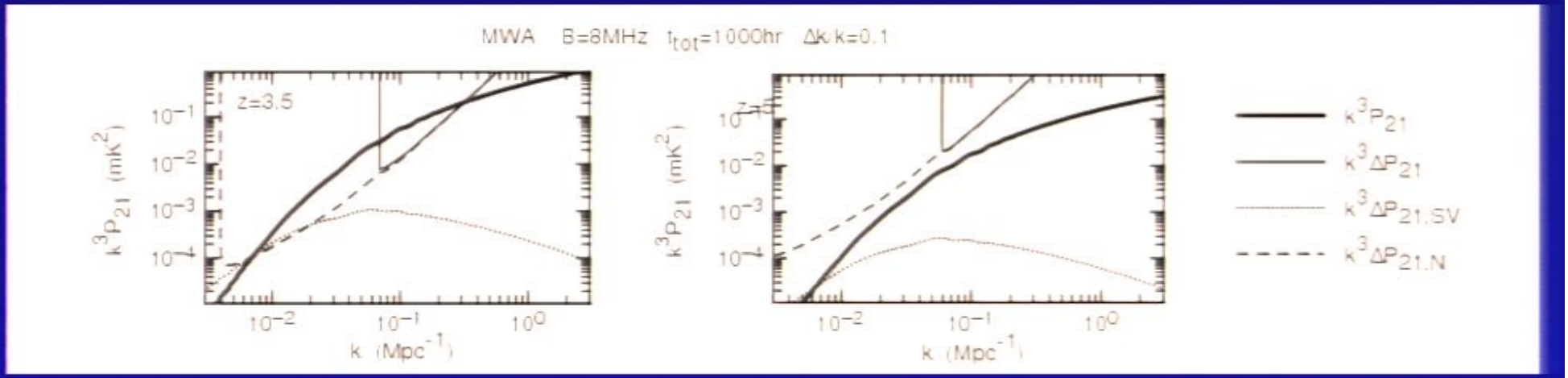
$$(\delta T)_{\rm noise} \propto (1+z)^{2.6}$$



Wyithe & Loeb 2007

Acoustic Oscillations

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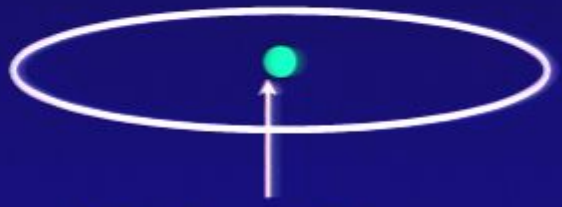
Inflation: t=0

Acoustic Oscillations



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Gas is freed to fall into dark matter potential fluctuations at z~1000

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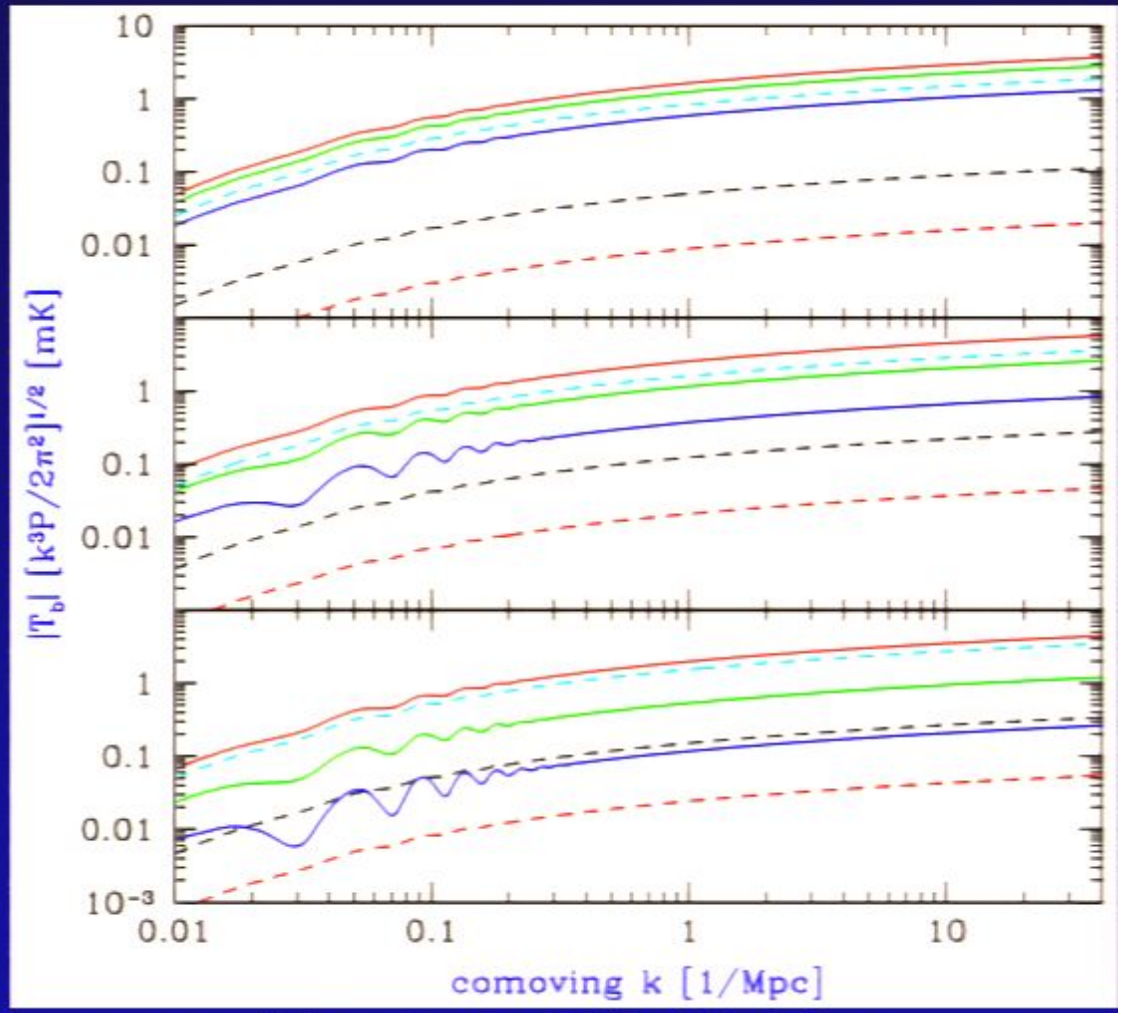

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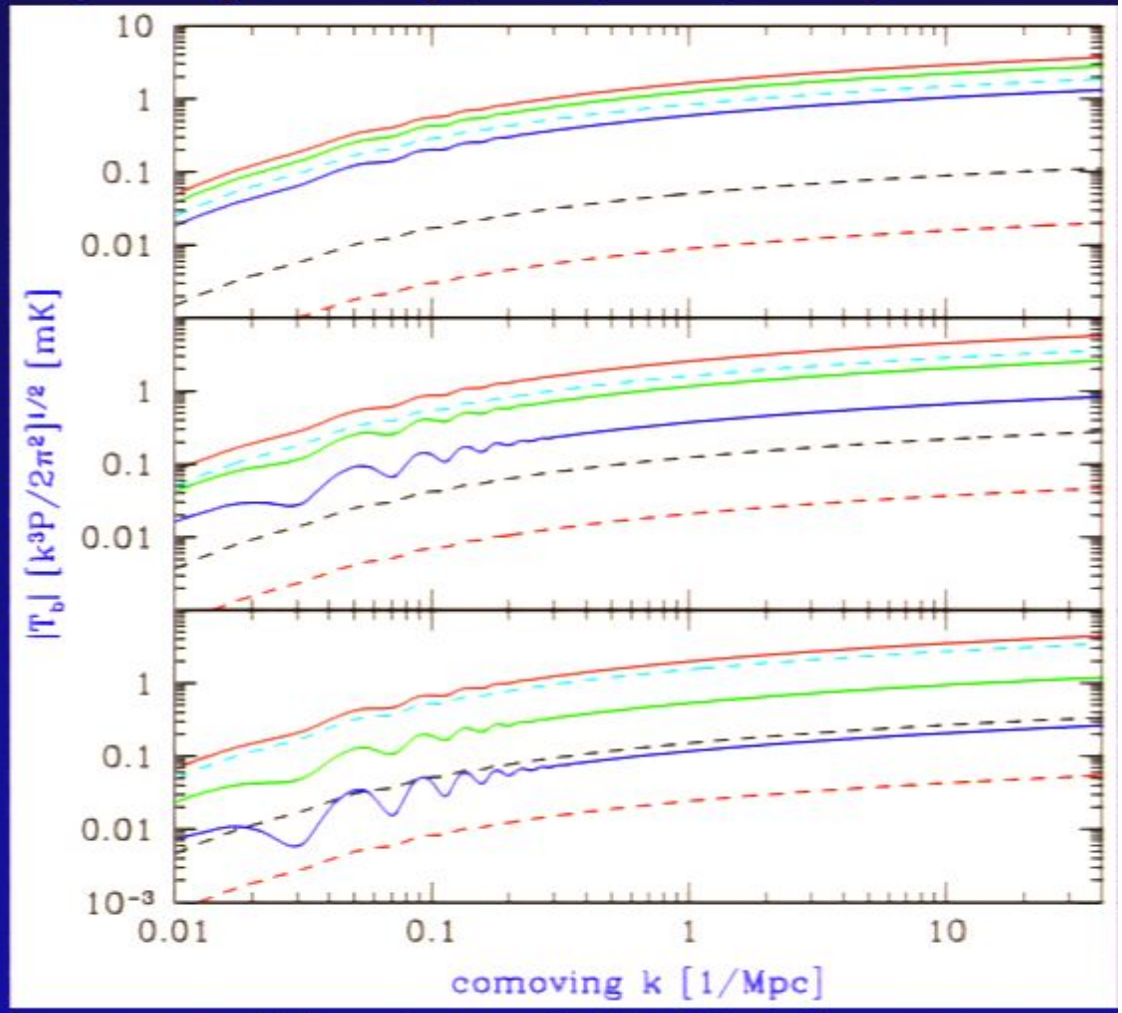

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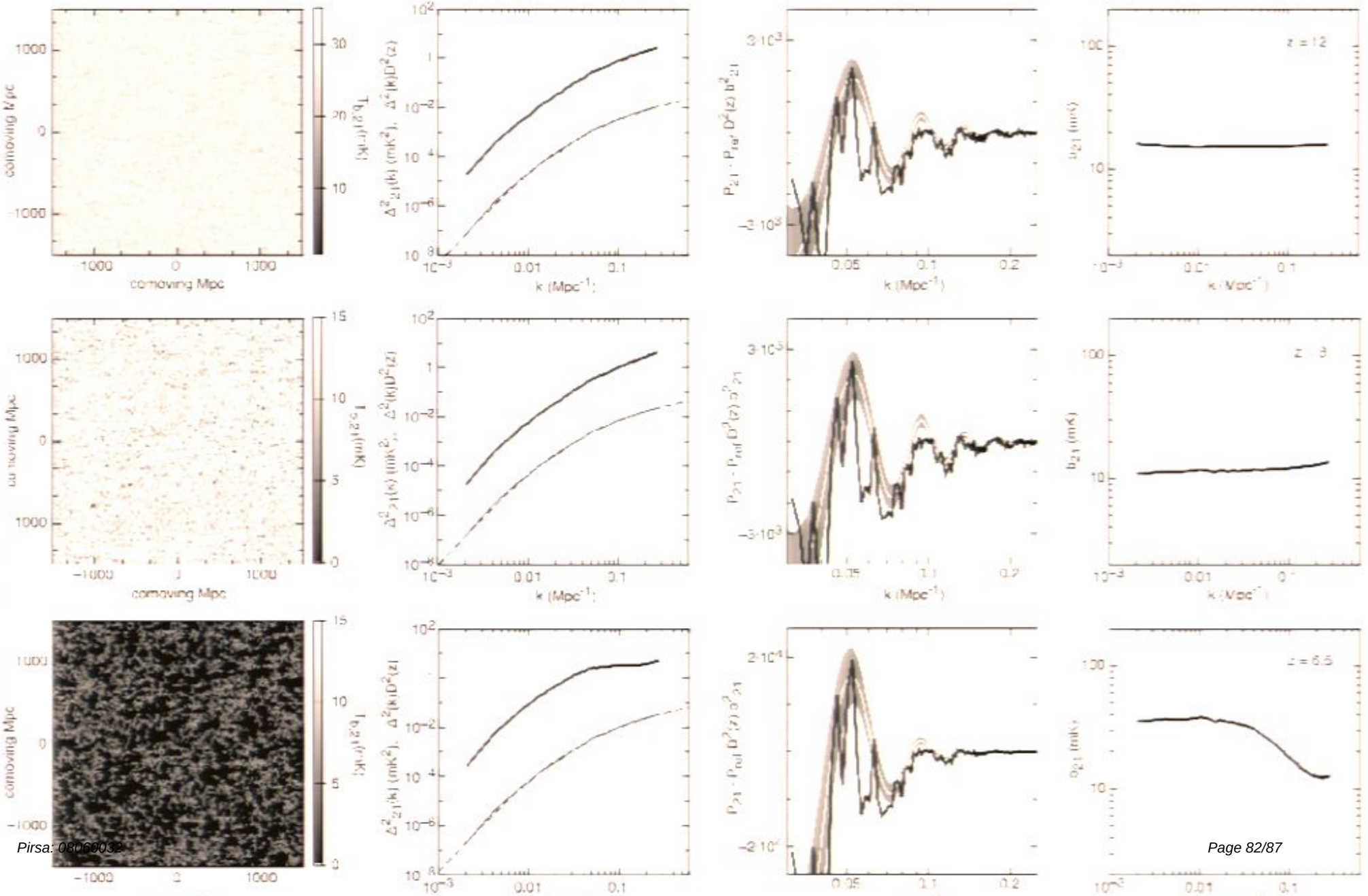

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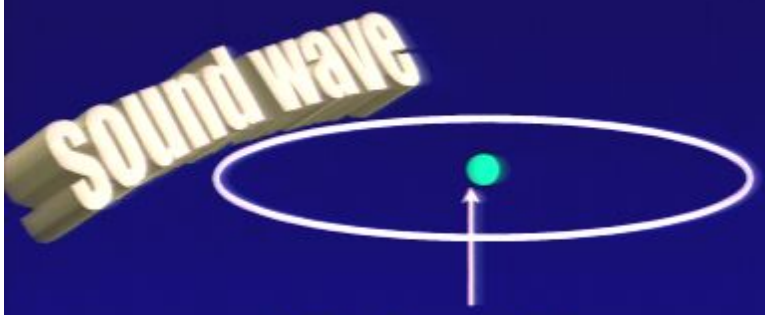

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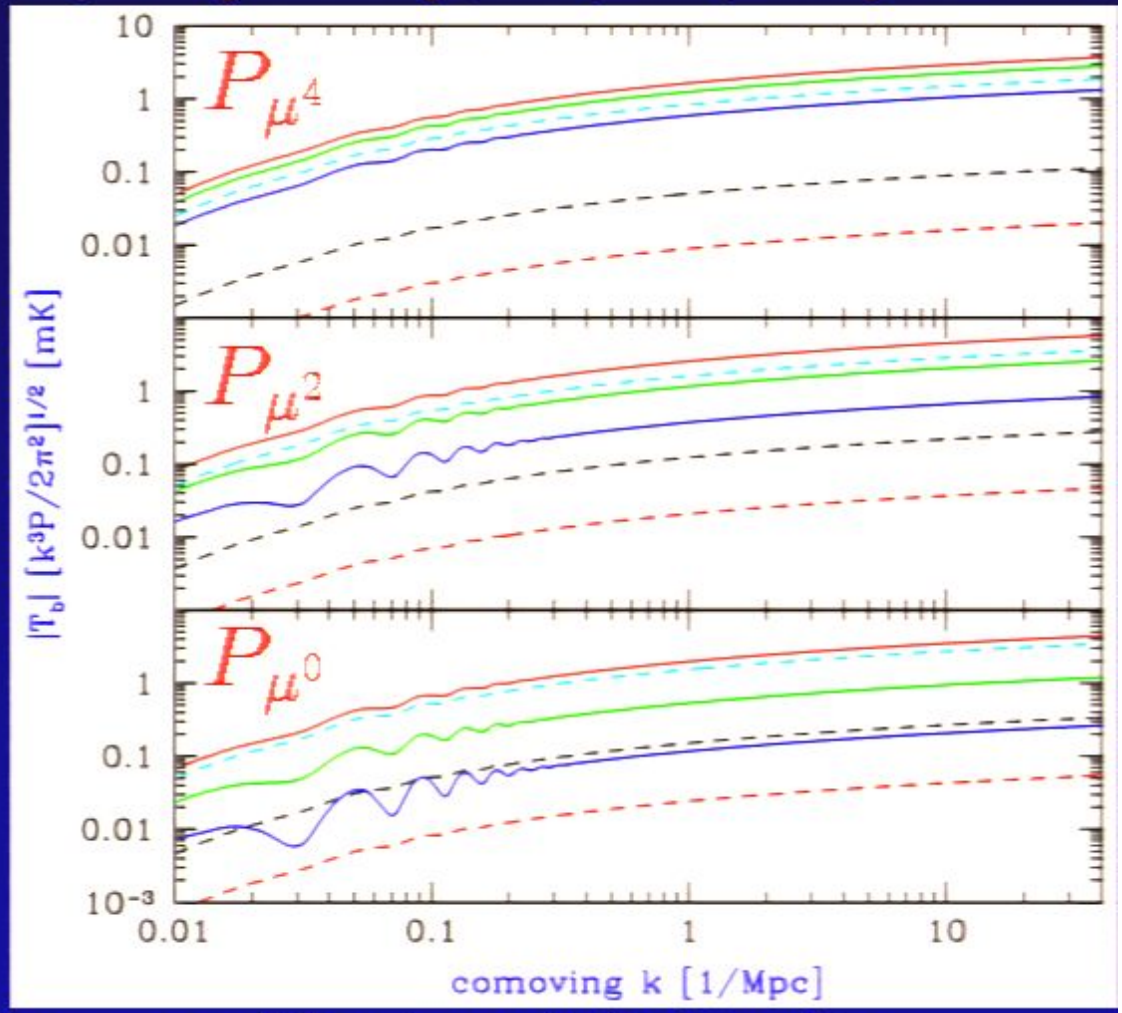

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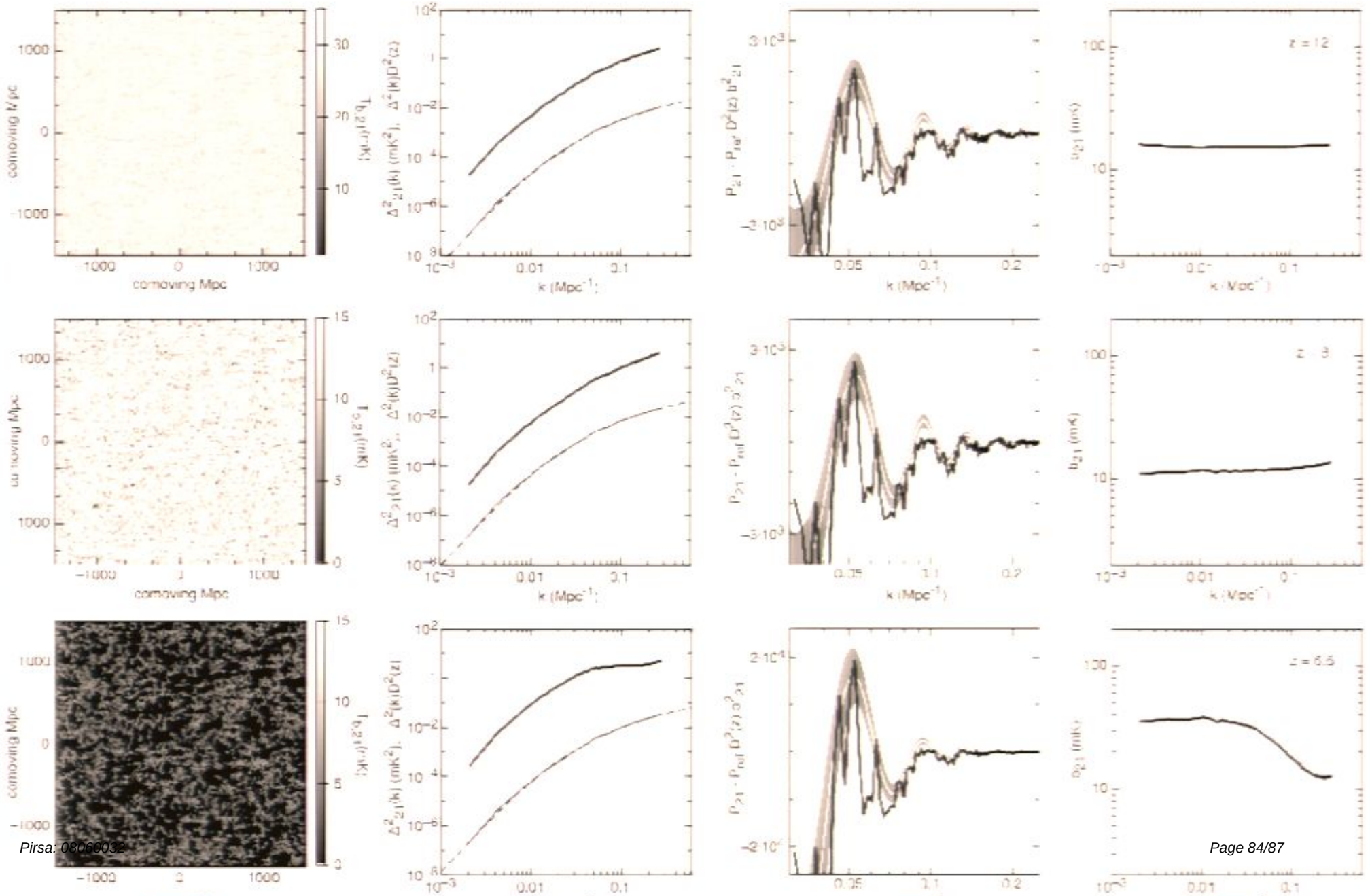
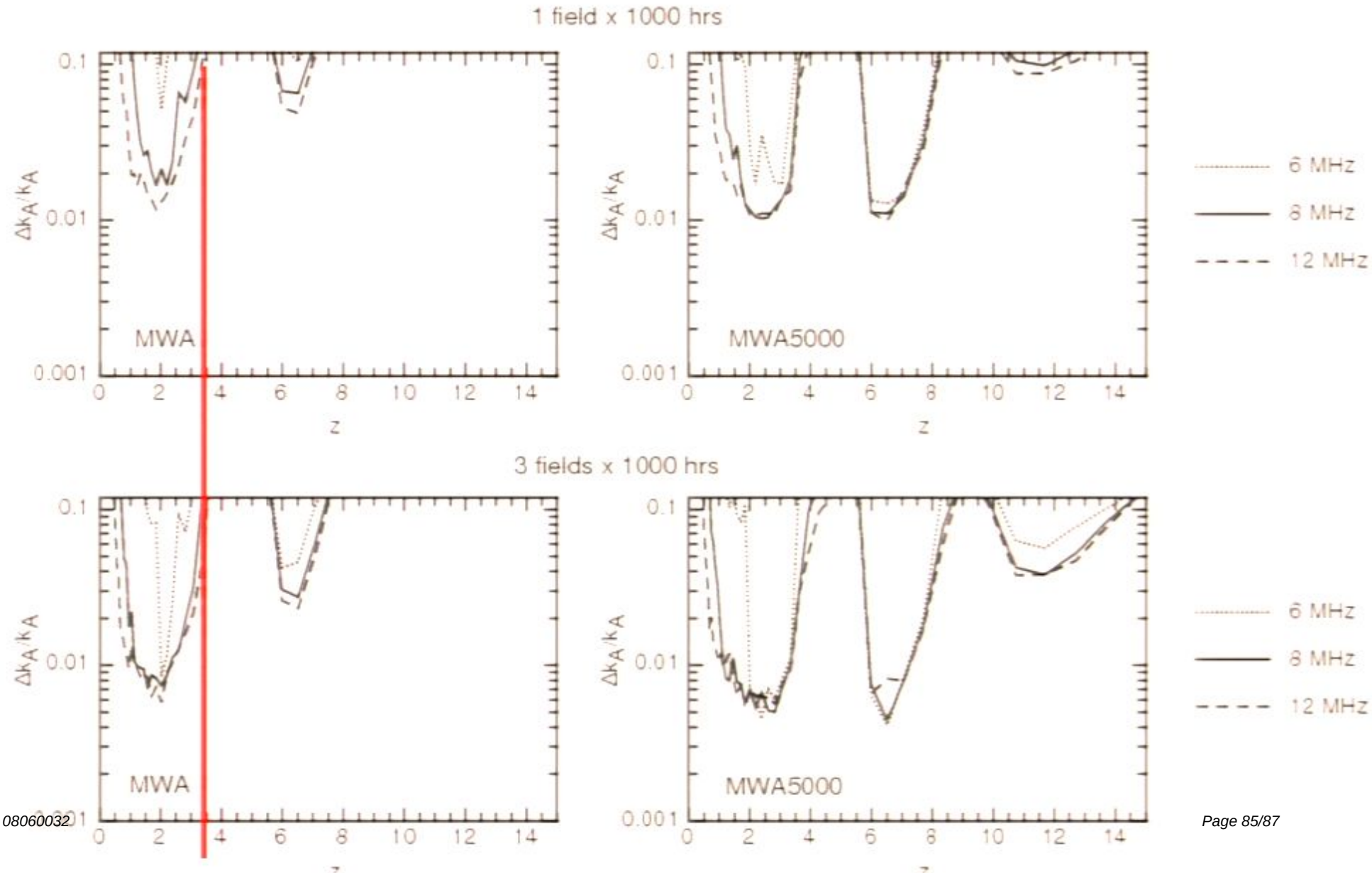
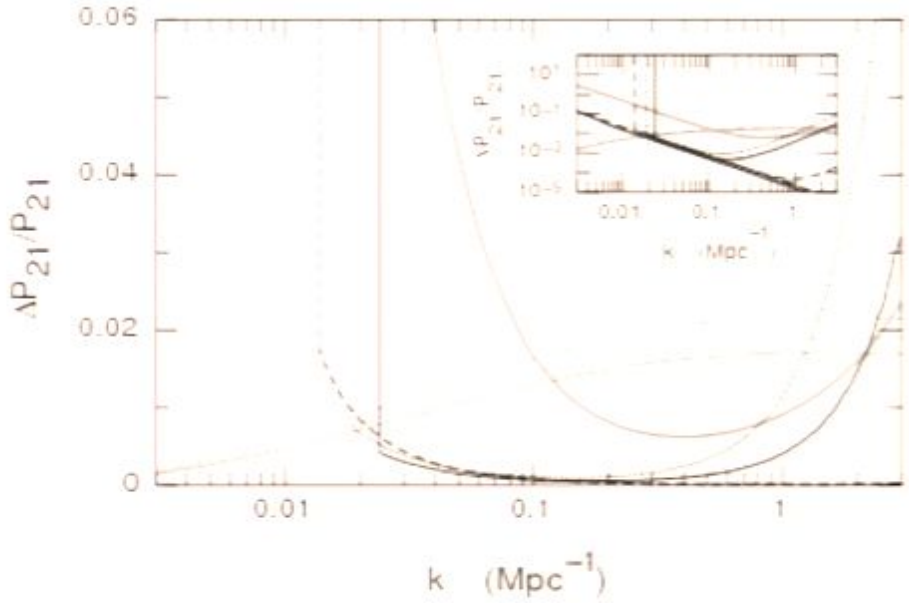


Acoustic Oscillations

Vyithe, Loeb & Geil



Weighting Neutrinos with a 21cm Survey at z<6



The fractional change in the amplitude of the power-spectrum owing to the presence of a massive neutrino (horizontal grey lines, asymptoting towards a constant at high k values). The case shown, $f_\nu = 0.004$, corresponds to $m_\nu = 0.05$eV. For comparison, the limits imposed by cosmic variance on the *SDSS*-LRG measurements of the power-spectrum are marked by the thick grey line. The U-shaped error curves correspond to an all-sky 21cm survey [$f_{\rm sky} = 0.65$ over a redshift range spanning a factor of 3 in $(1+z)$] with MWA5000 and a 10^3 hour integration per field (line styles for $z = 1.5, 3.5, 6.5$ as in Figure 2). The inset shows these results on logarithmic axes that span a larger dynamic range of achievable precision. The straight thin lines in the inset show the cosmic-variance uncertainty in the power-spectrum

Loeb & Wyithe, PRL, in press

Highlights

- *Redshifted 21cm from 0<z<200 can be used to map the matter distribution throughout most of the comoving volume of the observable universe*
- *Dark energy can be constrained through baryonic acoustic oscillations in the 21cm power-spectrum*
- *Neutrino mass can be detected at the level expected from atmospheric neutrino data (0.05eV).*
- *Alternative models of gravity can be constrained by measuring the growth of structure at moderate redshifts that cannot be accessed by other means*