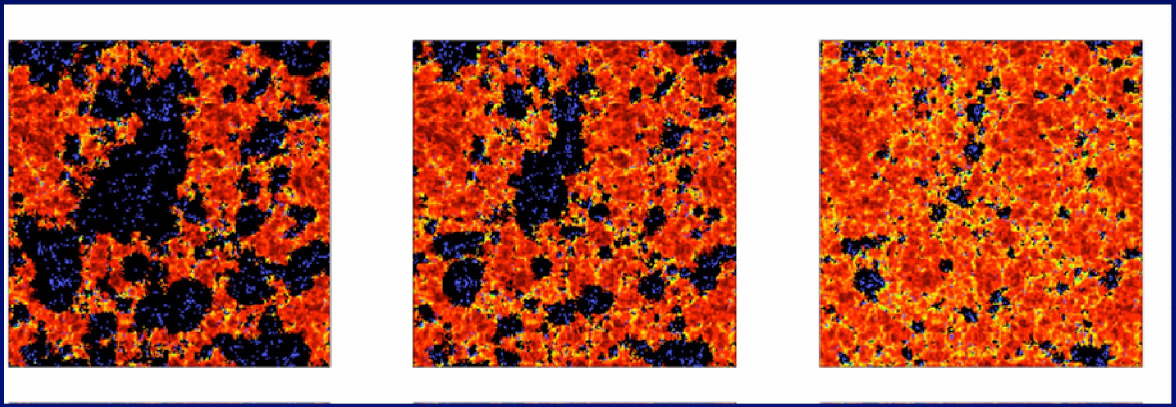
IAP Colloquium, Paris

July 7, 2008

The Physics of Reionization: Common Assumptions

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



Surprises could signal unexpected new physics

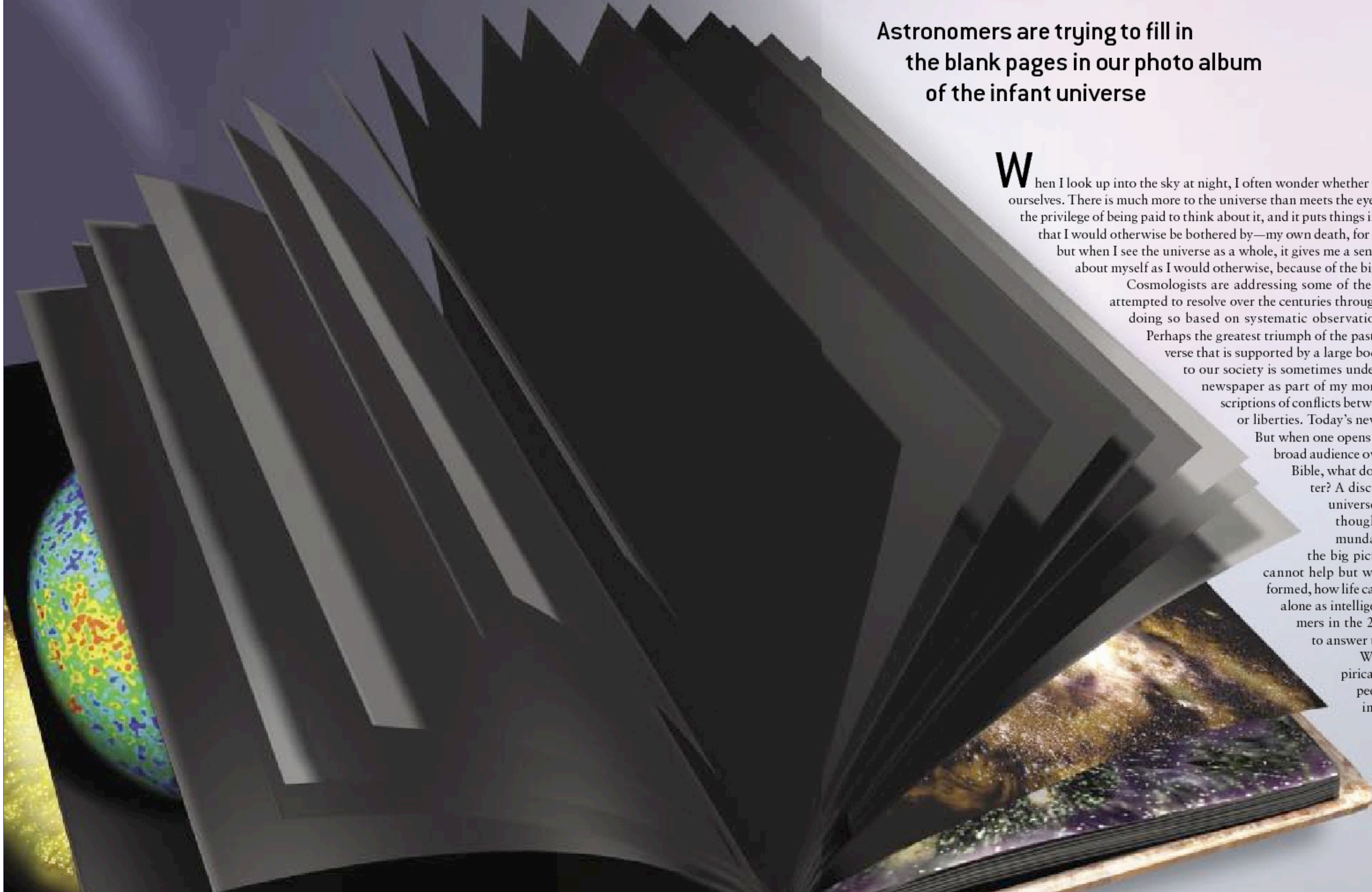
WMAP Cosmological Parameters Model: lcdm Data: all		
$10^2\Omega_b h^2$	=	$2.19^{+0.06}_{-0.08}$
A	=	$0.67^{+0.04}_{-0.05}$
$A_{0.002}$	=	$0.81^{+0.04}_{-0.05}$
$\Delta^2_{\mathcal{R}}$	=	$(20 \times 10^{-10} \pm 1 \times 10^{-10}) \times 10^{-10}$
$\Delta^2_{\mathcal{R}}(k = 0.002/Mpc)$	=	$(24 \times 10^{-10}{}^{+1\times10^{-10}}_{-2\times10^{-10}}) \times 10^{-10}$
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	=	$0.75^{+0.03}_{-0.04}$
$\sigma_8 \Omega_m^{0.6}$	=	$0.34^{+0.02}_{-0.03}$
A_{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_r	=	$9.3^{+2.8}_{-2.0}$

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

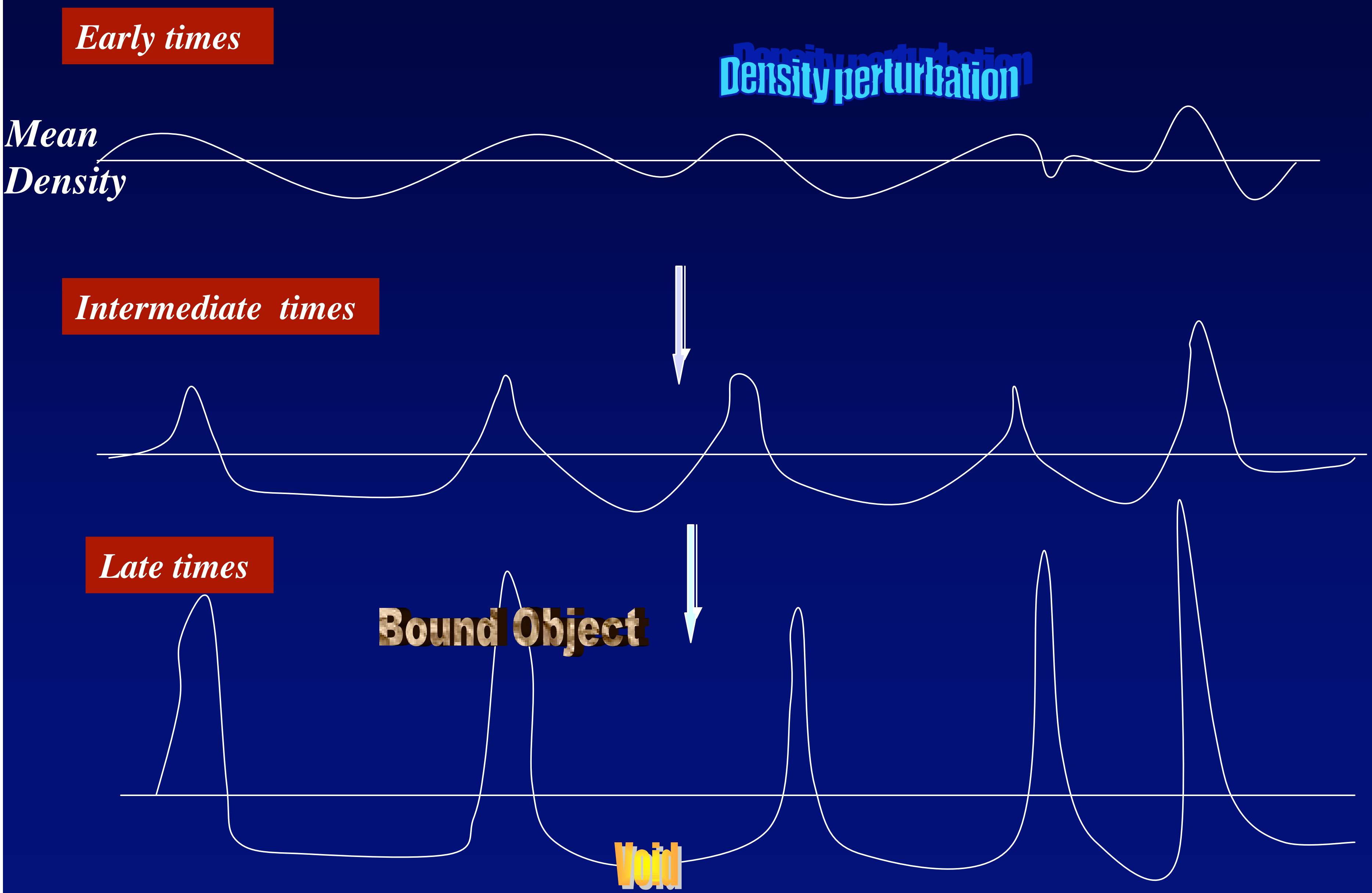


When I look up into the sky at night, I often wonder whether we humans are too preoccupied with ourselves. There is much more to the universe than meets the eye on earth. As an astrophysicist I have the privilege of being paid to think about it, and it puts things in perspective for me. There are things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

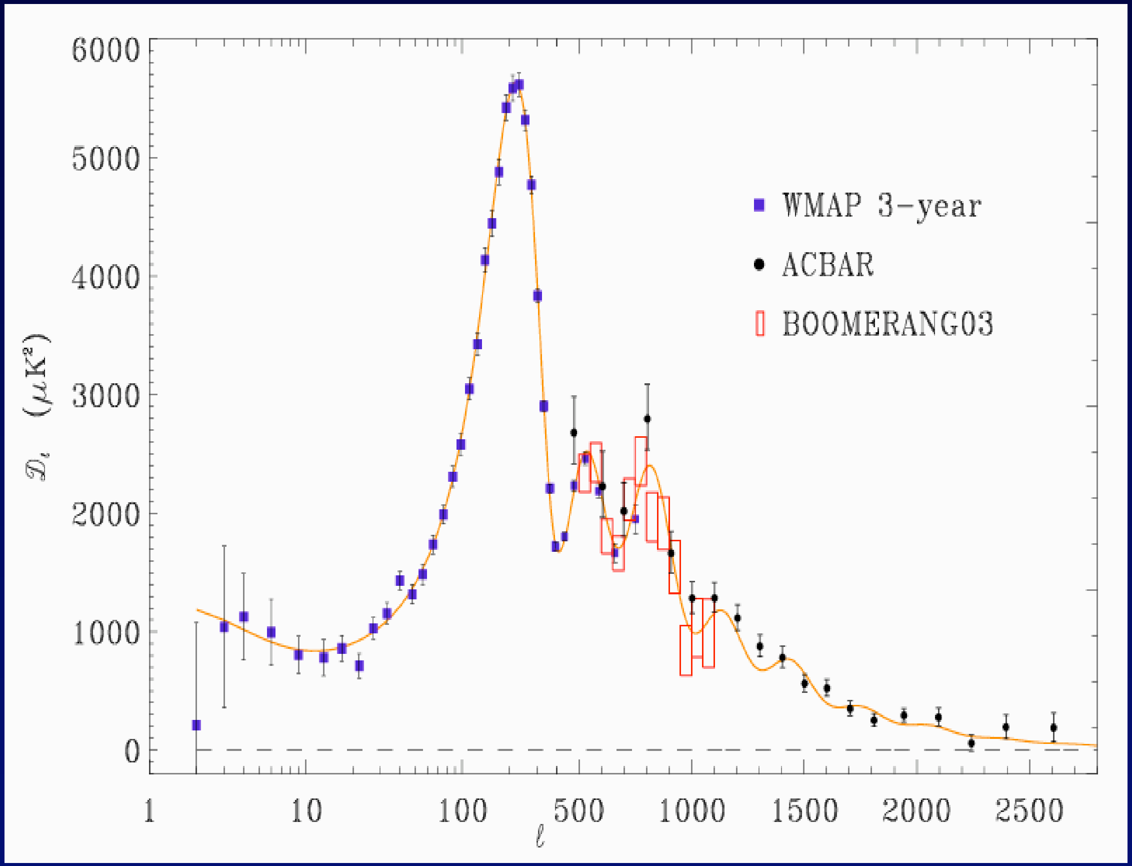
Cosmologists are addressing some of the fundamental questions that people attempted to resolve over the centuries through philosophical thinking, but we are doing so based on systematic observation and a quantitative methodology. Perhaps the greatest triumph of the past century has been a model of the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

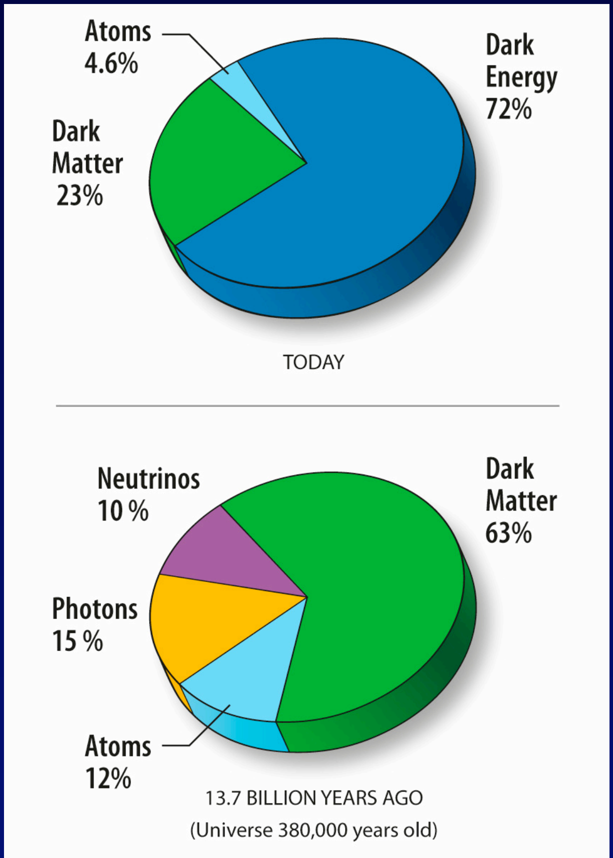
What makes modern cosmology an empirical science is that we are literally able to peer into the past. When you look at your image reflected off a mirror one meter

On small scales the universe is clumpy



Evidence that Most Matter is EM Dark





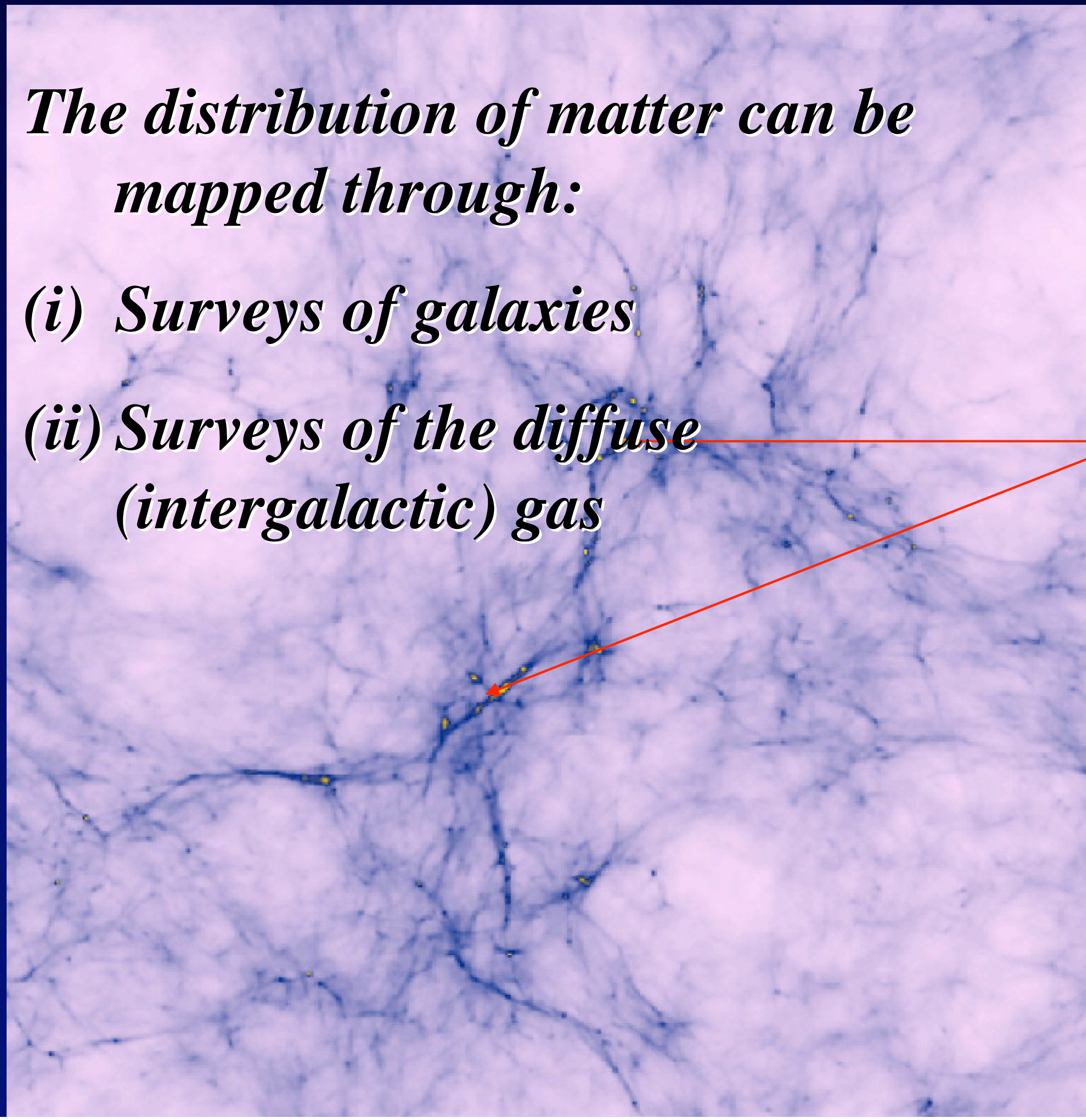
Diffusion damping of small-scale fluctuatons in the baryon-photon fluid prior to cosmic recombination implies that galaxies could not have formed in our Universe without dark matter!

The First Dwarf Galaxies Form at z~30

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

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

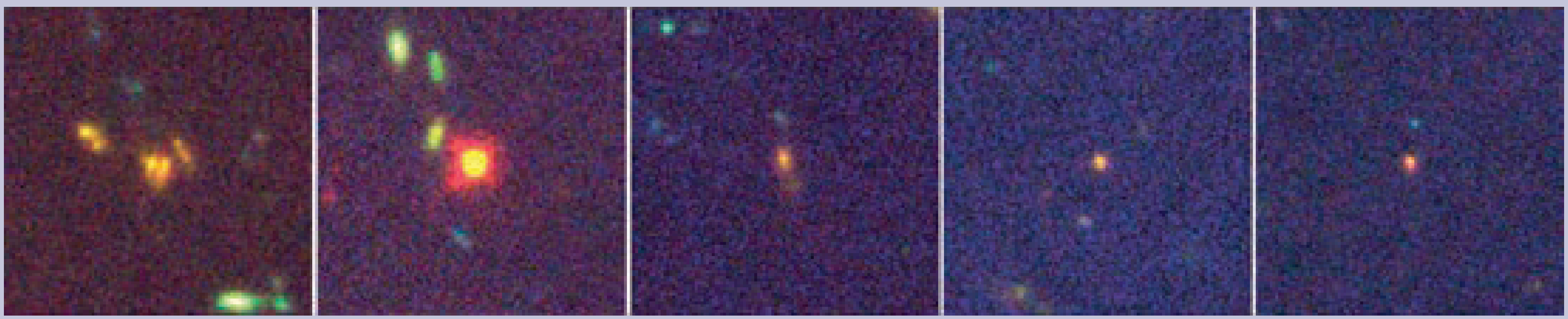
Yoshida et al. 2003

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.

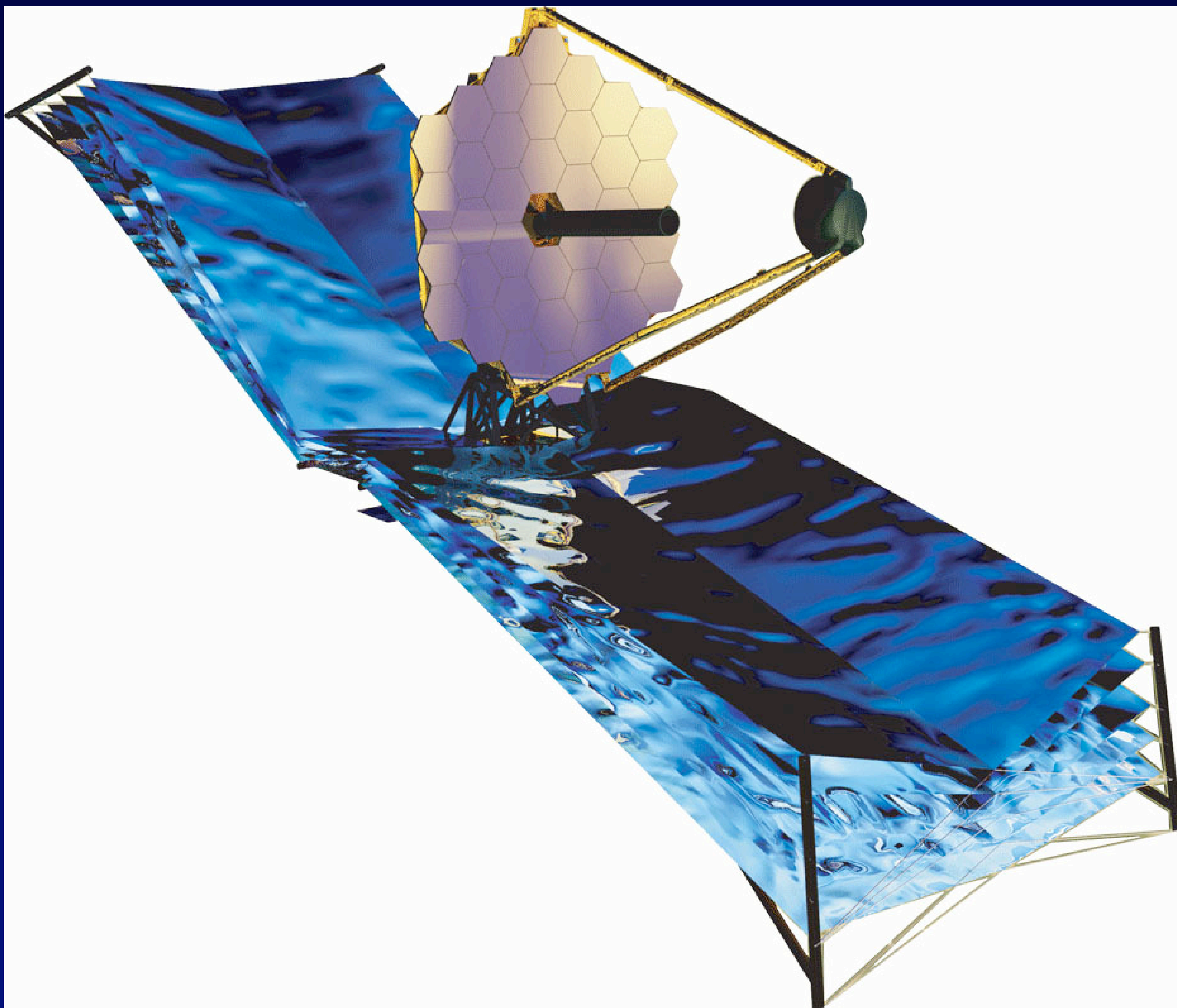
galaxies *z* ~ 3–4 Lookback time 11.4–12 billion years (312 objects)

galaxies *z* ~ 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

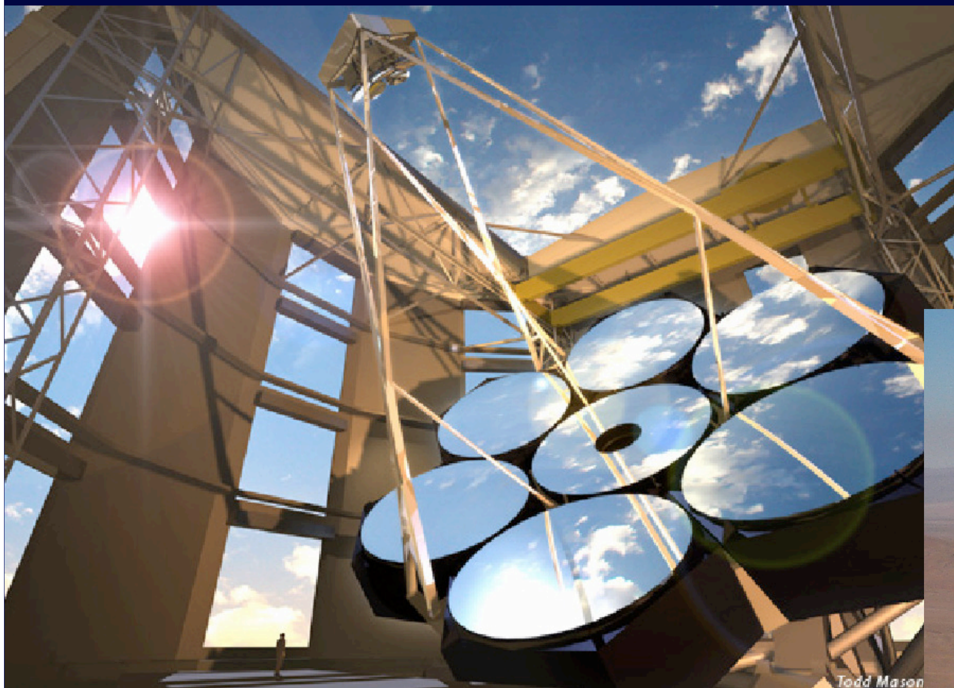
18 segments

Wavelength coverage: 0.6-28 micron

L2 orbit

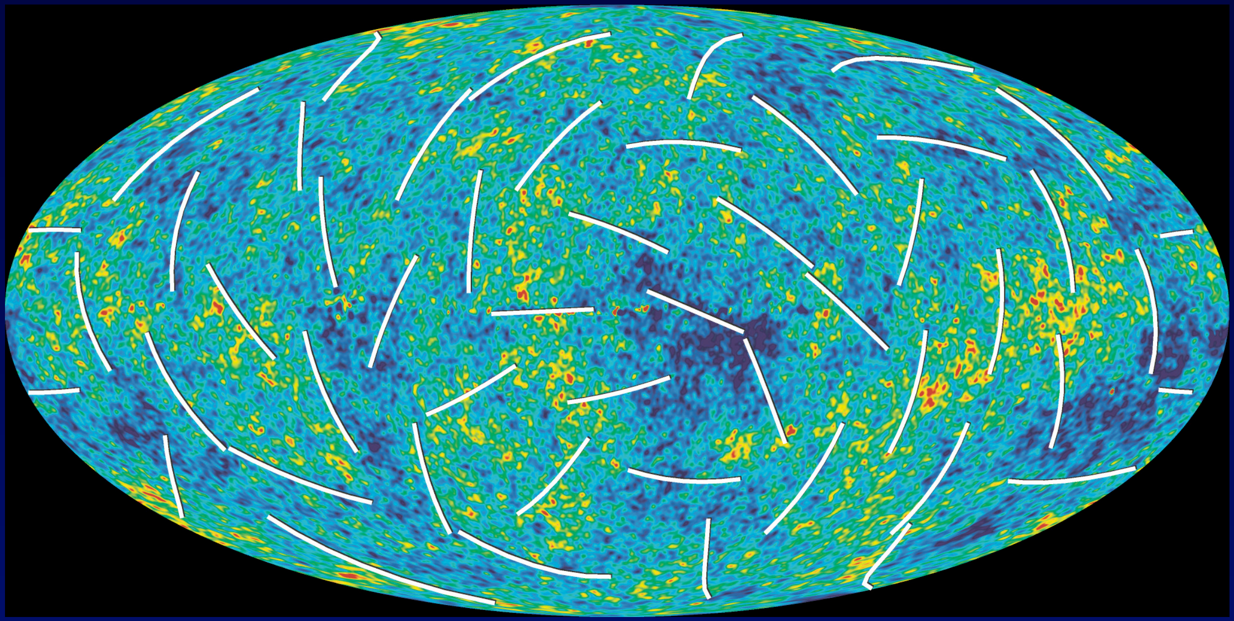
Launch date: 2013

Extremely Large Telescopes (20-40 meters)



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

Cosmic Microwave Background (*WMAP5*)

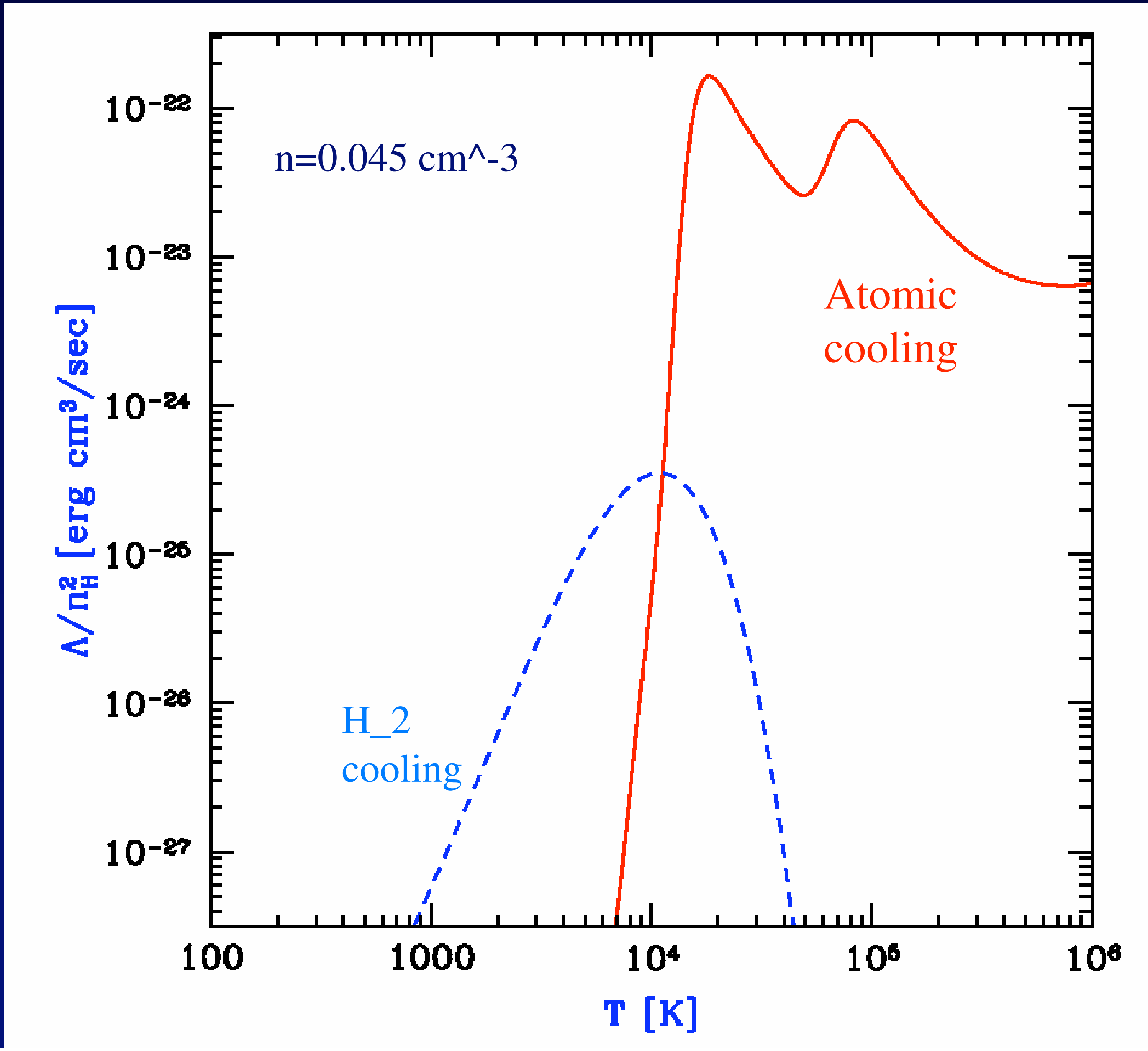


$$\tau = 0.09 \pm 0.02$$

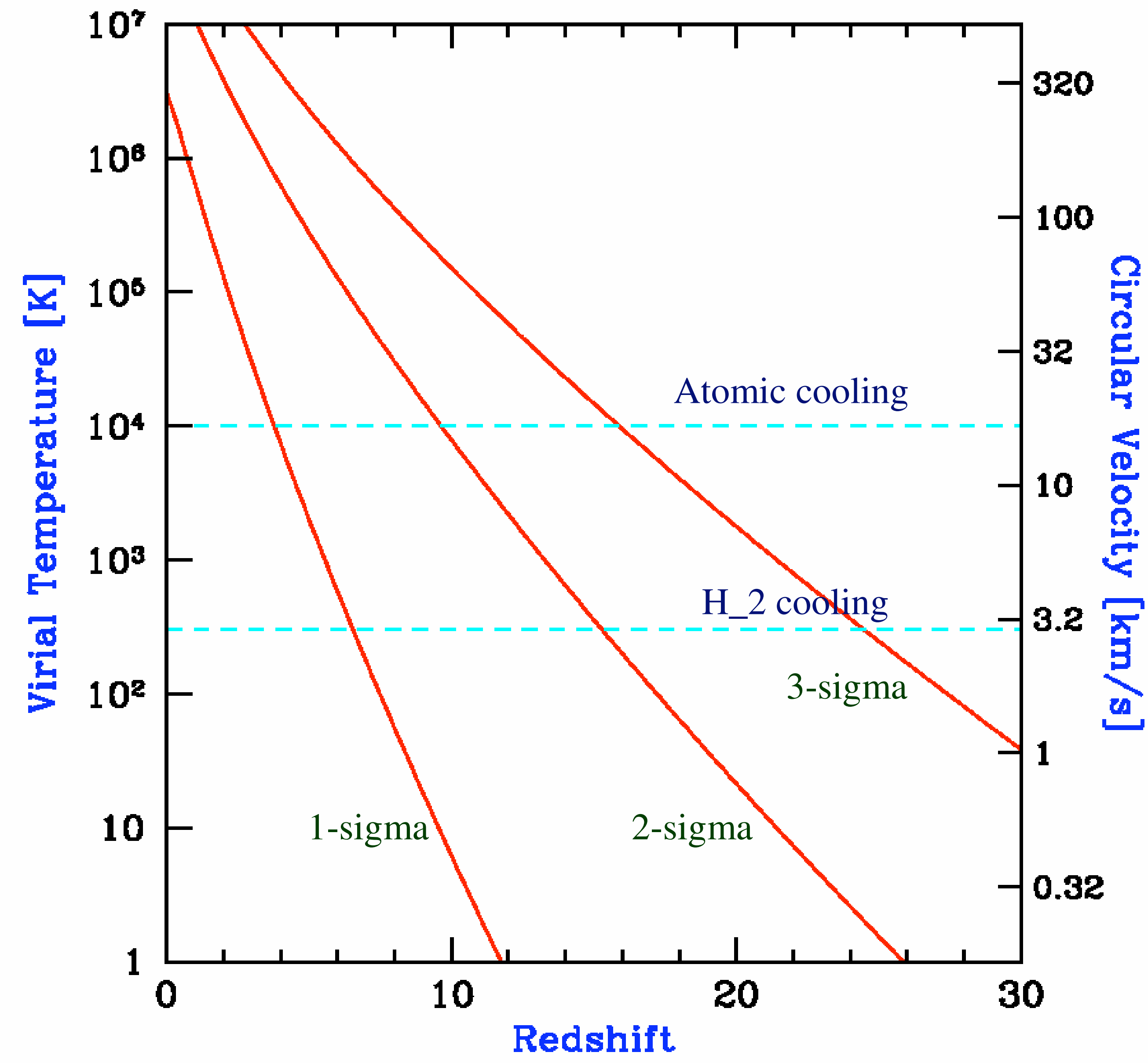
The polarization data indicates that the first stars must have formed 400 million years after the big bang, when the universe was only a few percent of its current age!

Dunkley et al. 2008

Cooling Rate of Primordial Gas

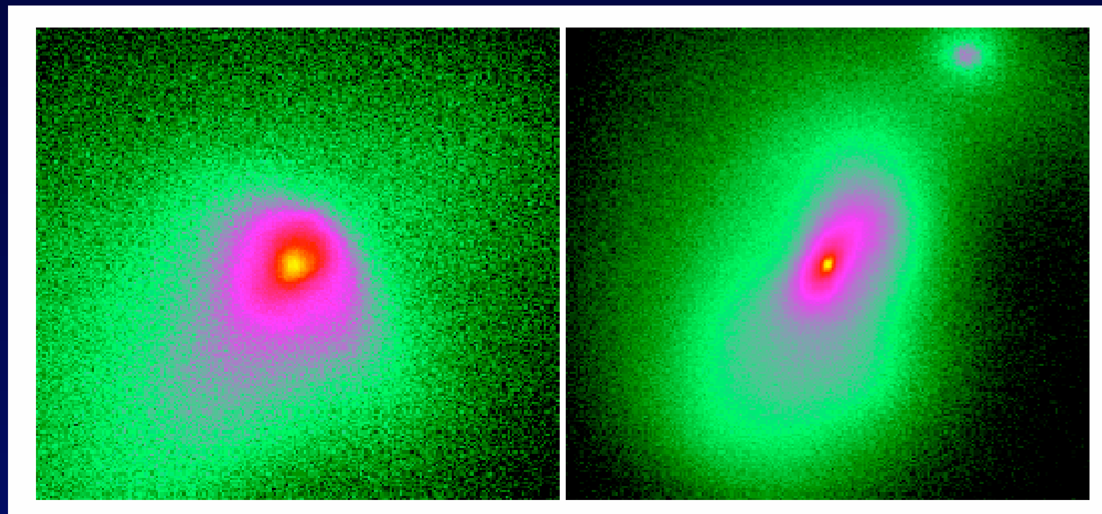


Virial Temperature of Halos



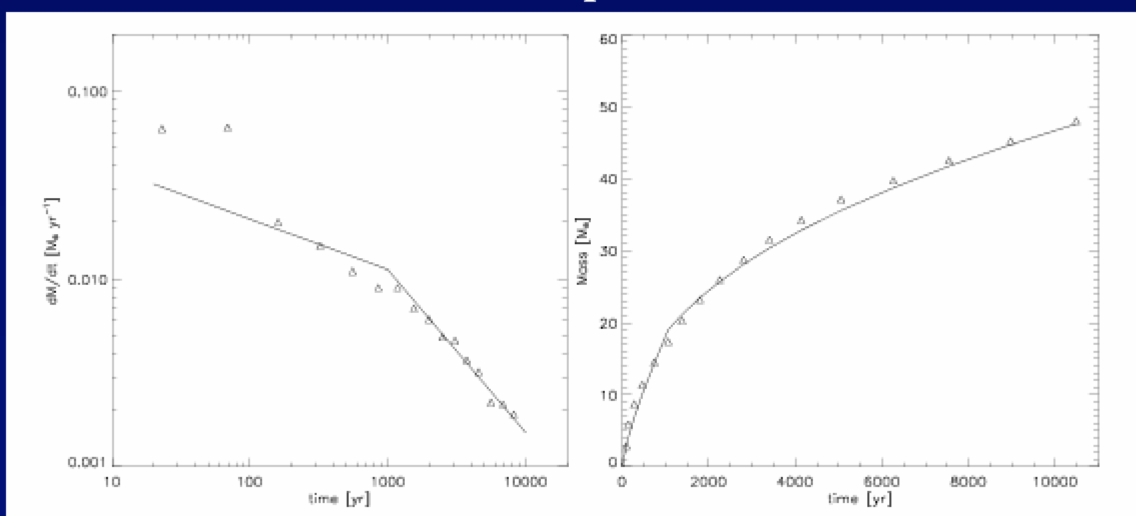
Massive Accretion by Pop-III Proto-Stars

Resolving accretion flow down to ~0.03 pc



Bromm & Loeb, astro-ph/0312456

23.5pc ***0.5pc***



$$\dot{M} \sim c_s^3/G$$

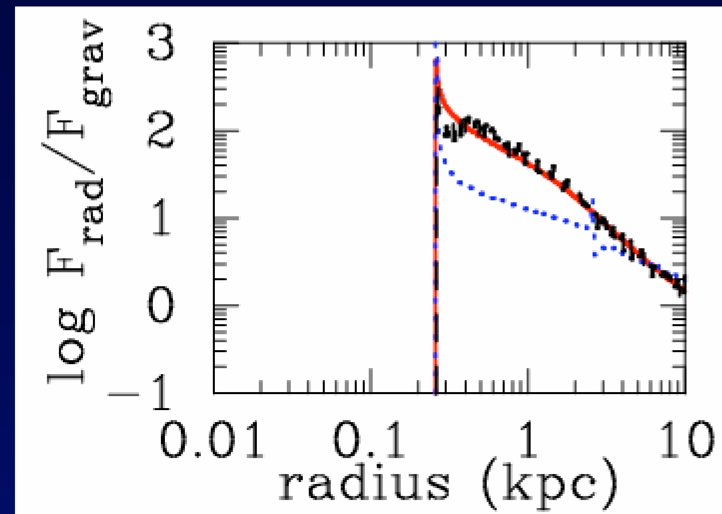
$$T_{\rm min} \sim 200\mathrm{K}$$

$$\mathrm{for} : \mathrm{H_2} - \mathrm{cooling}$$

Final stellar mass is feedback limited (radiation, wind)

Outflows Driven by Lya Radiation Pressure

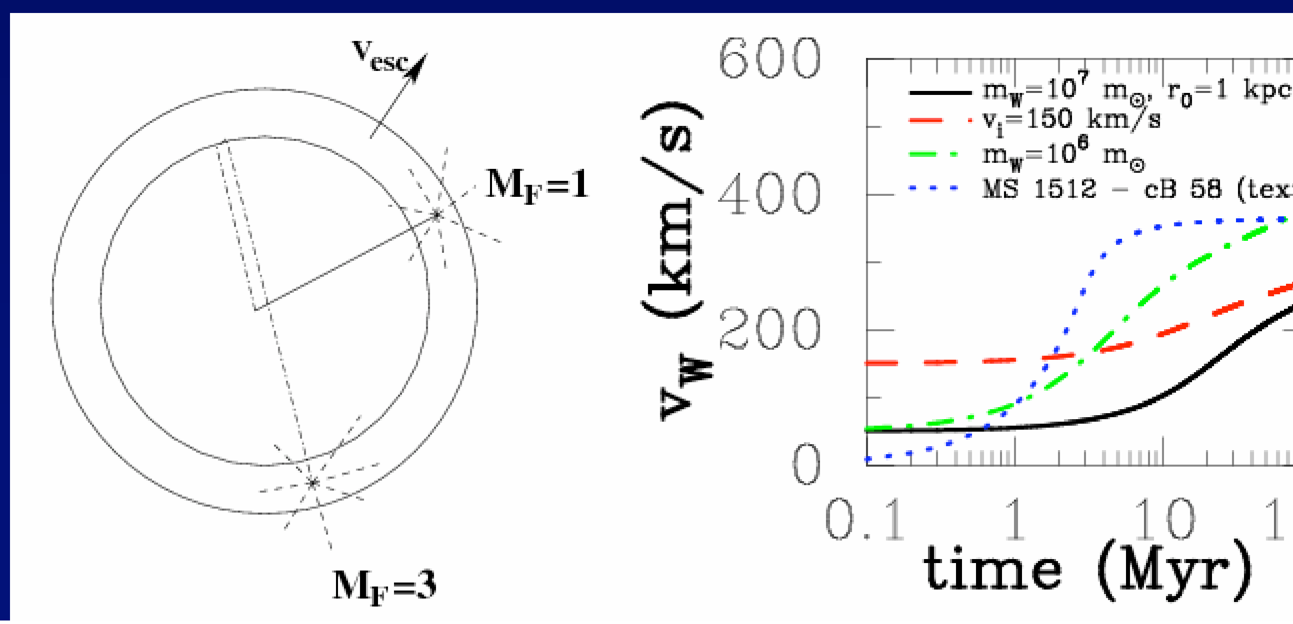
- IGM around the mini-halos hosting the first stars



$$M_\star = 100 M_\odot$$

$$M_{\rm halo} = 10^6 M_\odot$$

- Supershells around starburst galaxies



Dijkstra & Loeb 2008

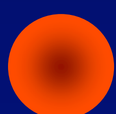
Number of ionizing photons (>13.6eV) per baryon incorporated into stars:

Massive, metal free stars

$M > 300 M_\odot$	$\sim 100,000$
$M > 100 M_\odot$	$\sim 40,000$

$T_{\rm eff} \sim 10^5 {\rm K}$
$L = L_E \propto M$

Gain by up to a factor of ~30!

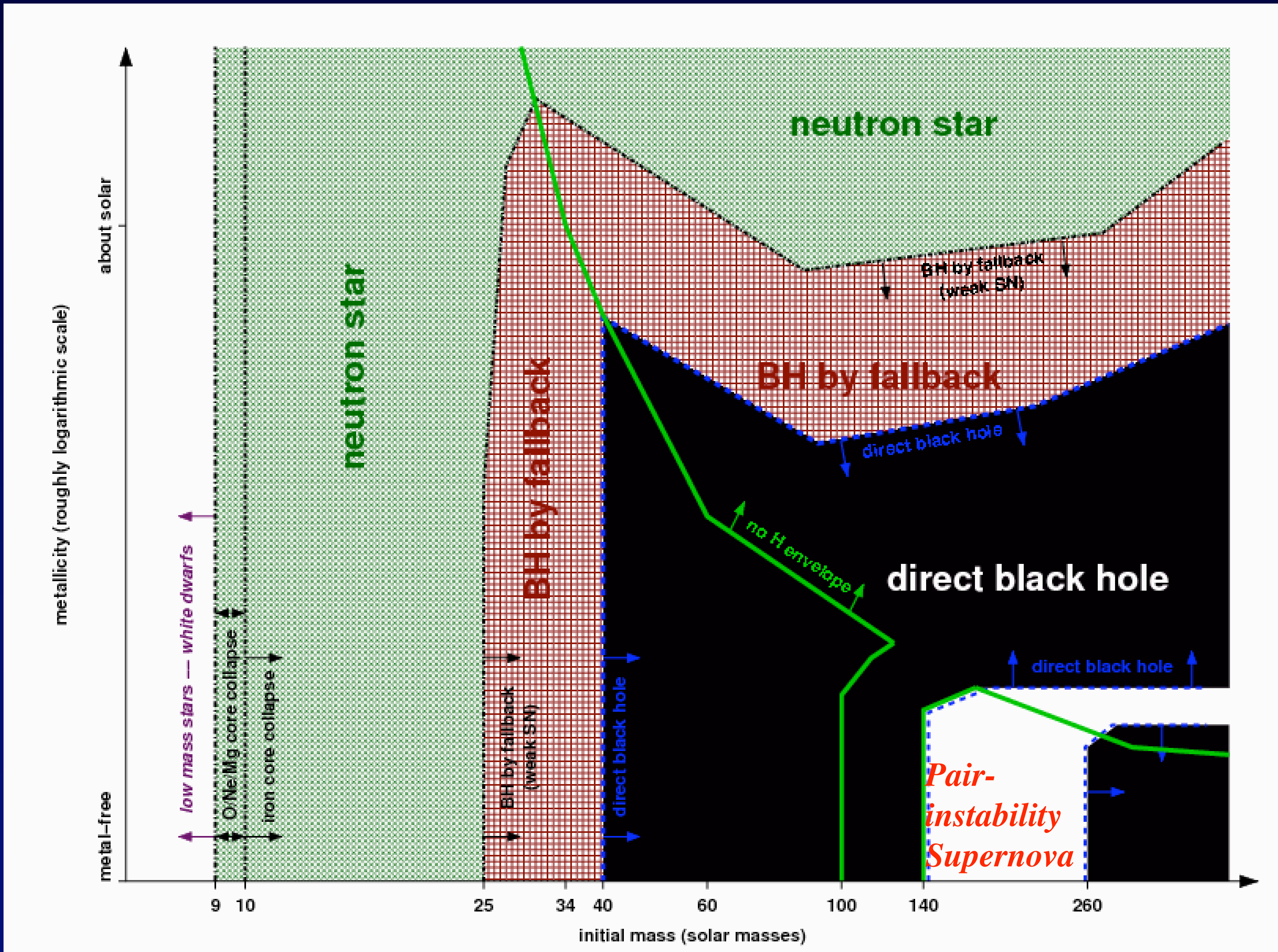


Salpeter mass function

Metal free	$\sim 7,000$
$Z = 0.01 Z_\odot$	$\sim 3,500$

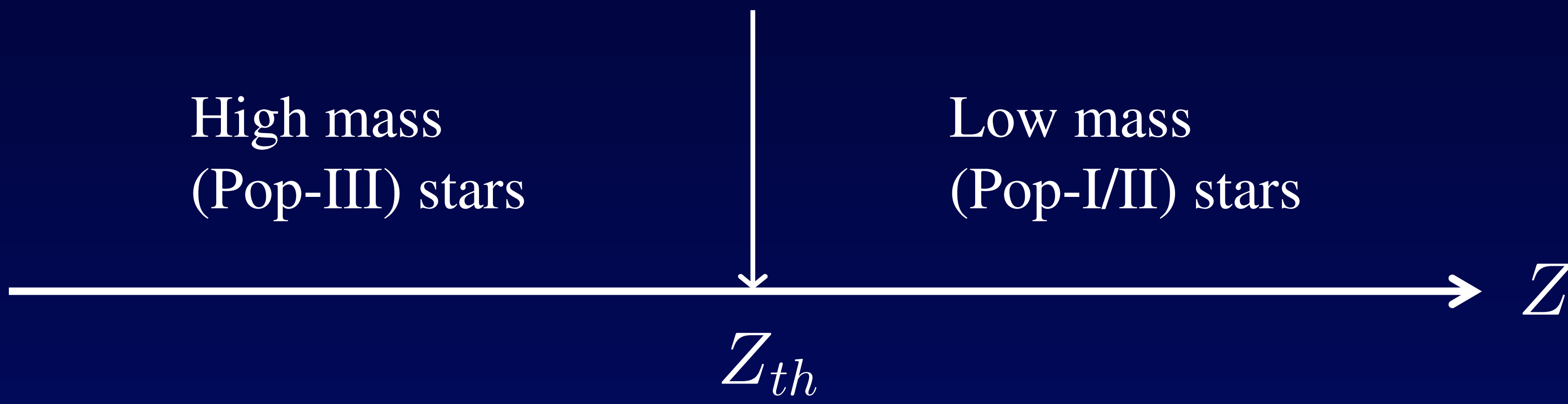
Bromm, Kudritzki, & Loeb 2001, ApJ, 552, 464

How do massive stars end their life?



Heger et al. 2003

Threshold Metallicity



Atomic cooling (CII, OI) → $Z_{th} \sim 10^{-3} Z_{\odot}$

Dust, molecules (CO) → $Z_{th} < 10^{-5} Z_{\odot}$

Milky-Way halo metal-poor stars: $Z_{Fe} \sim 10^{-5} Z_{\odot}$

but: $Z_{C,O} > 10^{-3} Z_{\odot}$

Early Galaxies: *Parametrizing Our Ignorance*

Star Formation

- Mass function of dark matter halos: *N-body simulations*.
- Minimum halo mass for star formation:

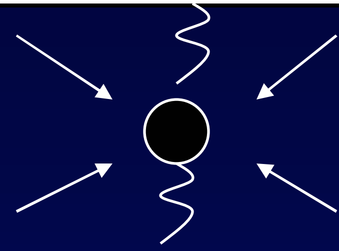
  200K – H_2 cooling

  10^4 K -- atomic H cooling

  10^5 K -- assembly of gas from a photo-ionized IGM
- Star formation efficiency: $f_\star \sim 10\%$
- # of ionizing photons/baryon in stars:

  ~4000 – Pop I/II; ~ 10^5 -- Pop III (metal free)

Nuclear Black Holes



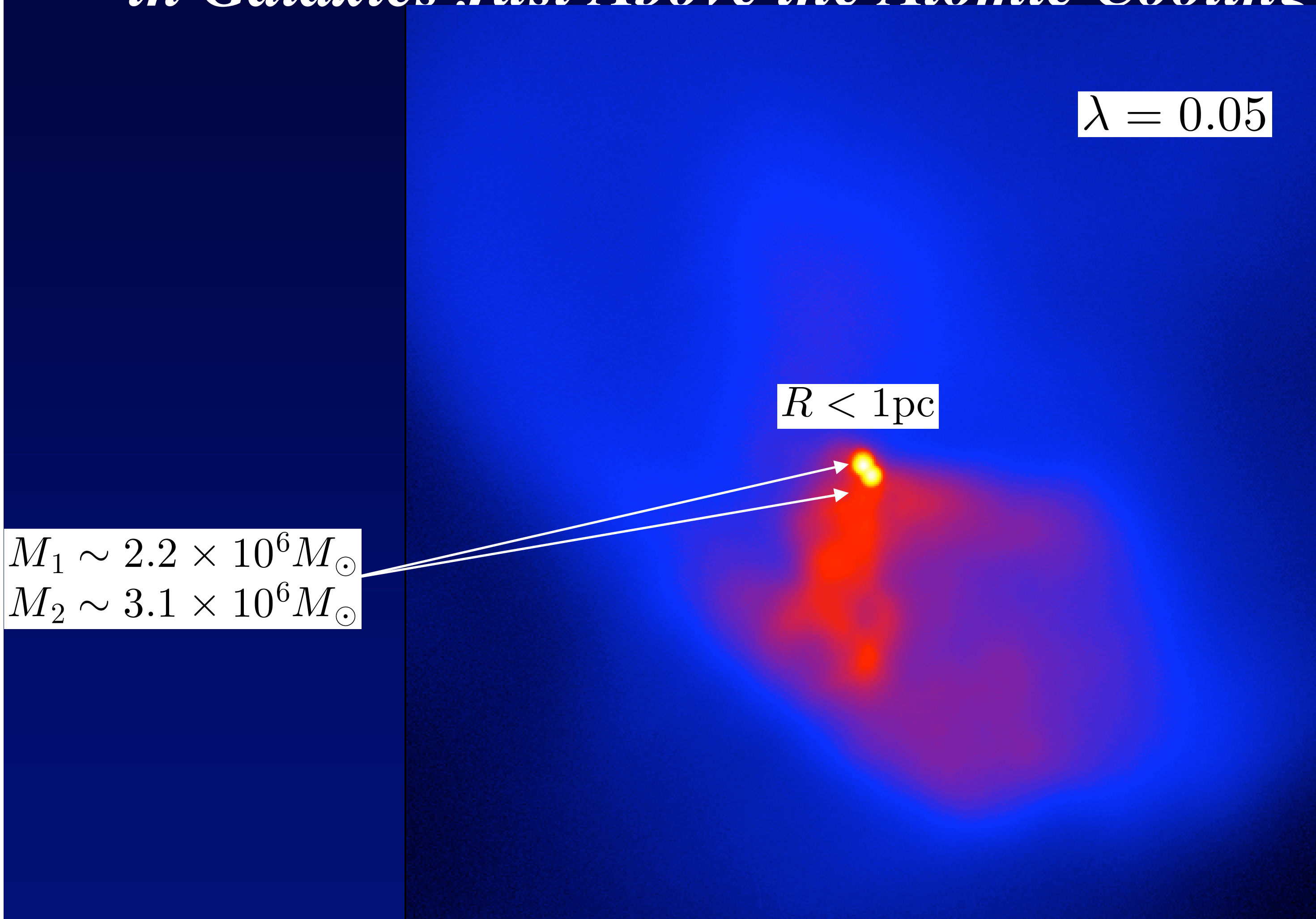
$$L = \epsilon \dot{M} c^2 \qquad t_E = M/\dot{M} = 4 \times 10^7 \frac{(\epsilon/10\%)}{(L/L_E)} \text{years}$$

$$M \propto \exp\{t/t_E\}$$

Stellar mass seed requires ~billion years to grow to an SDSS quasar ($10^9 M_\odot$ **)**

…But a billion year is the Hubble time at z~6, and feedback from star formation and quasar activity is likely to suppress continuous accretion, and also…

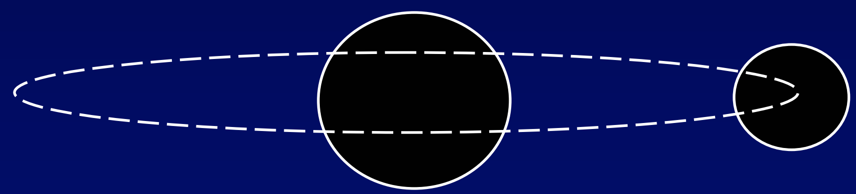
<u>Massive Black Hole Seeds:</u> *Suppressed Fragmentation in Galaxies Just Above the Atomic Cooling Threshold*



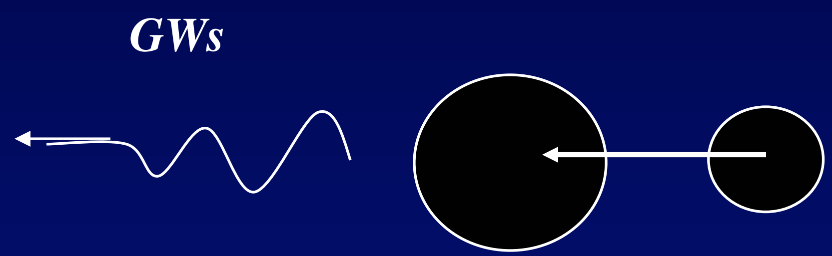
<u>Unusual environments</u>: H_2 suppressed ***; binary black holes may form –LISA sources***

Low-spin systems: Eisenstein & Loeb 1995; <u>Numerical simulations:</u> Bromm & Loeb 2002

Gravitational Wave Recoil

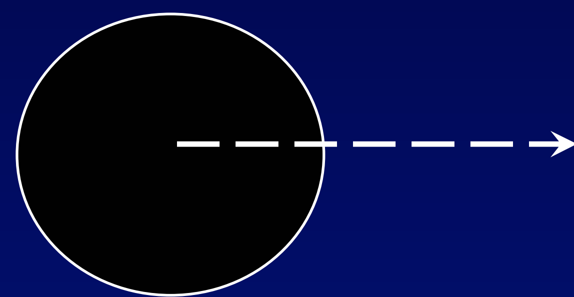


Gravitational Wave Recoil



Anisotropic emission of gravitational waves → momentum recoil

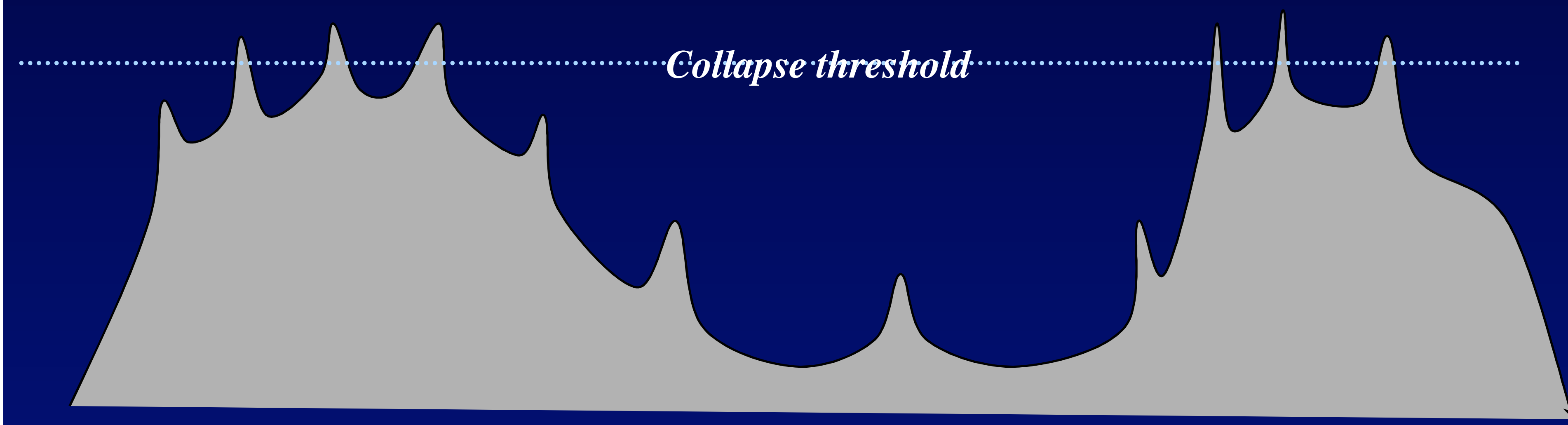
Gravitational Wave Recoil



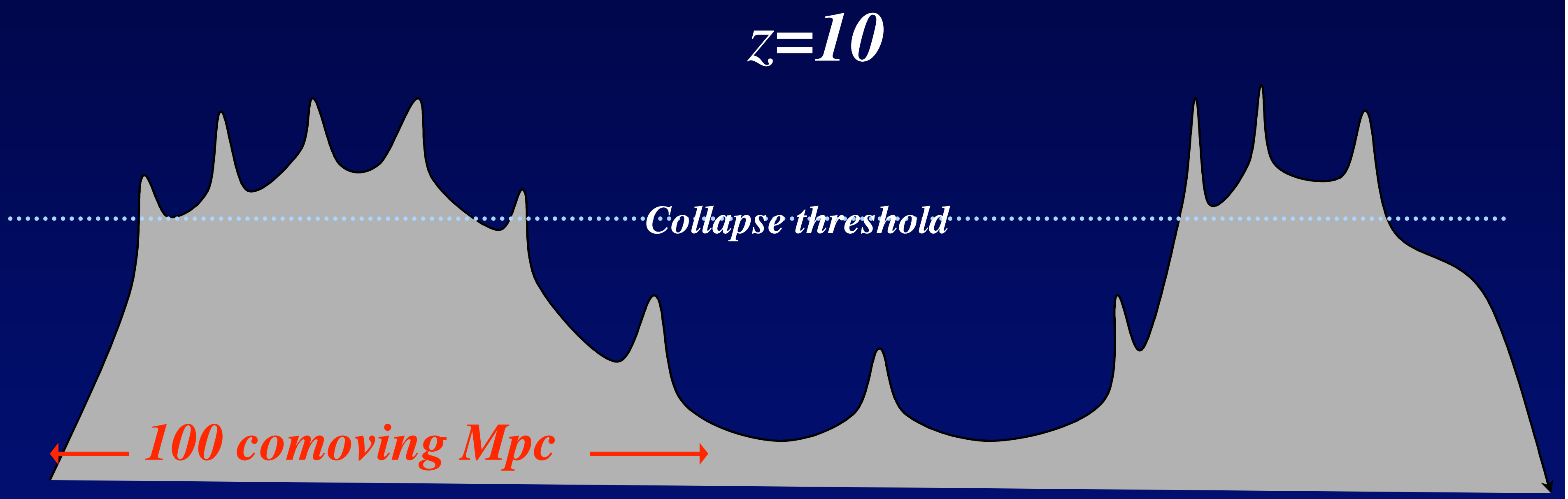
Recoil speed (~tens-4000 km/s) is independent of remnant black hole mass → ***low-mass halos may easily lose their low-mass seeds after several mergers***

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

z=20



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



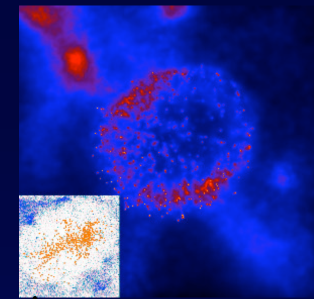
Challenges for numerical simulations of reionization:

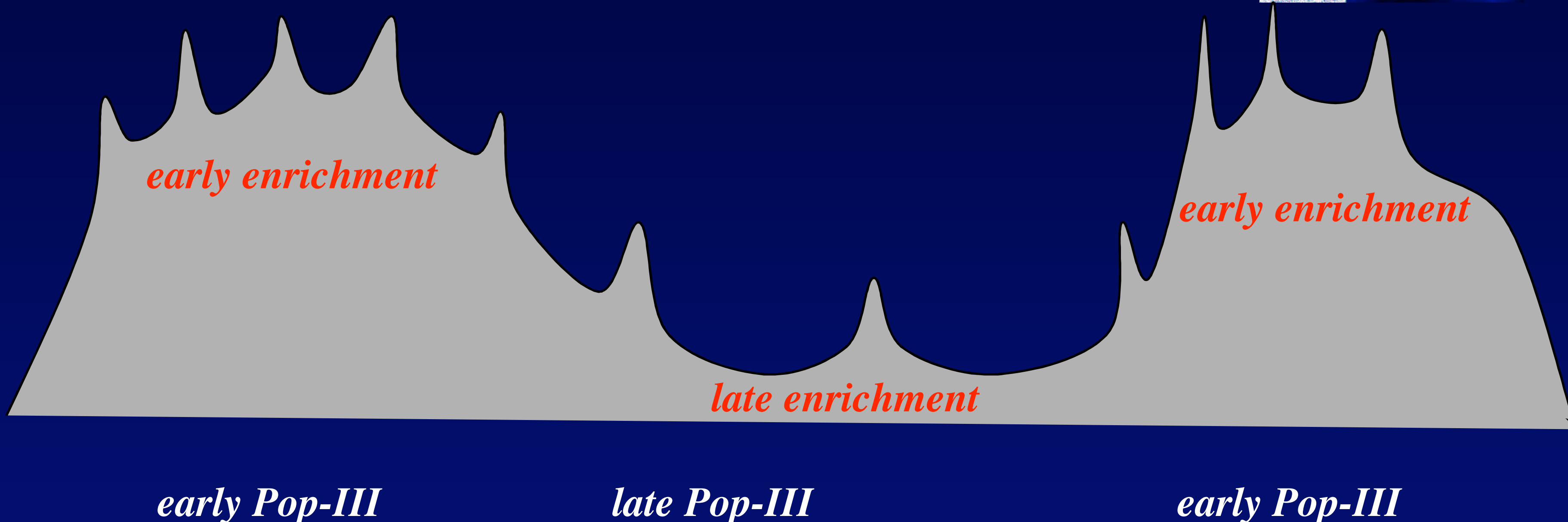
****Resolving dwarf galaxies as sources of ionizing photons***

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

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

→Enrichment of Primordial Gas with Heavy Elements was Highly Inhomogeneous



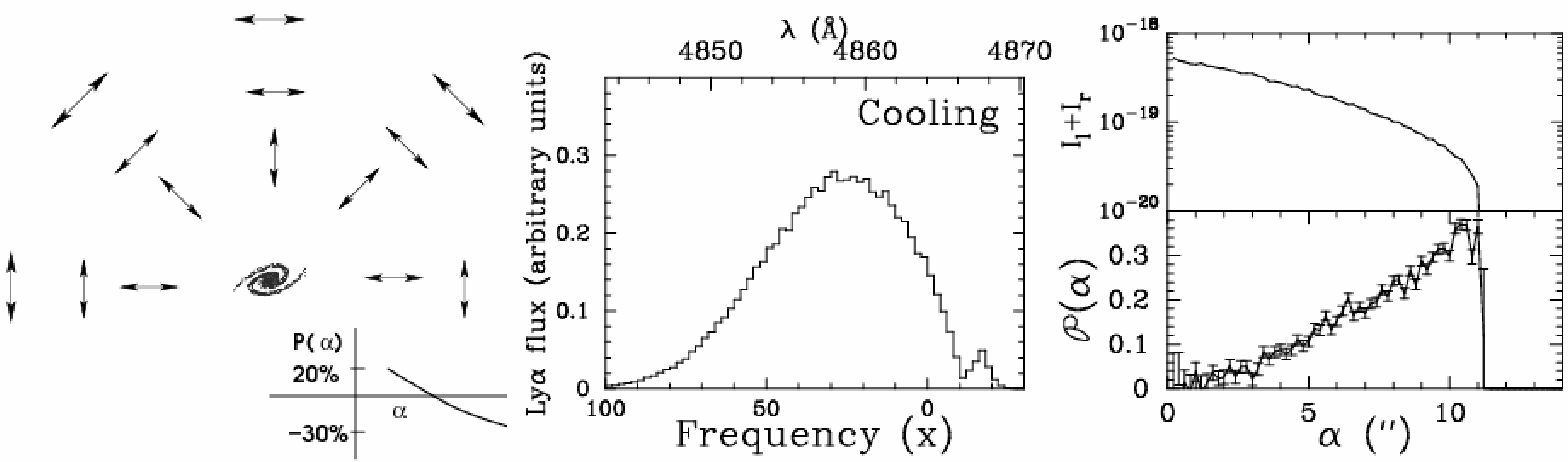


Searches for high-z Galaxies:

- Lyman-break
- Lyα
- Other lines (H_α , CO, CII, OI, He)

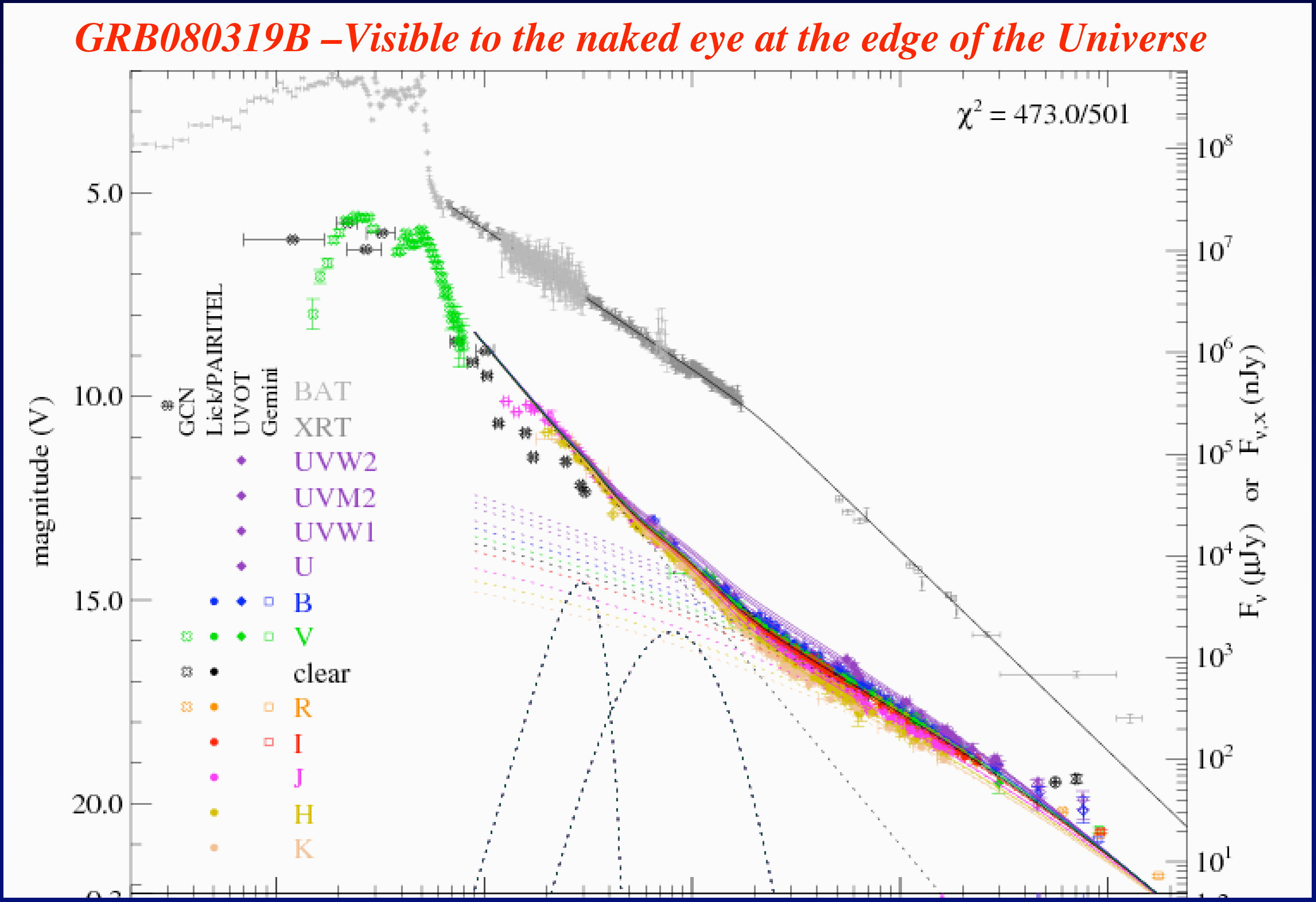
<u>A future frontier</u>: polarized Lyα ***halos***

Collapsing gas cloud



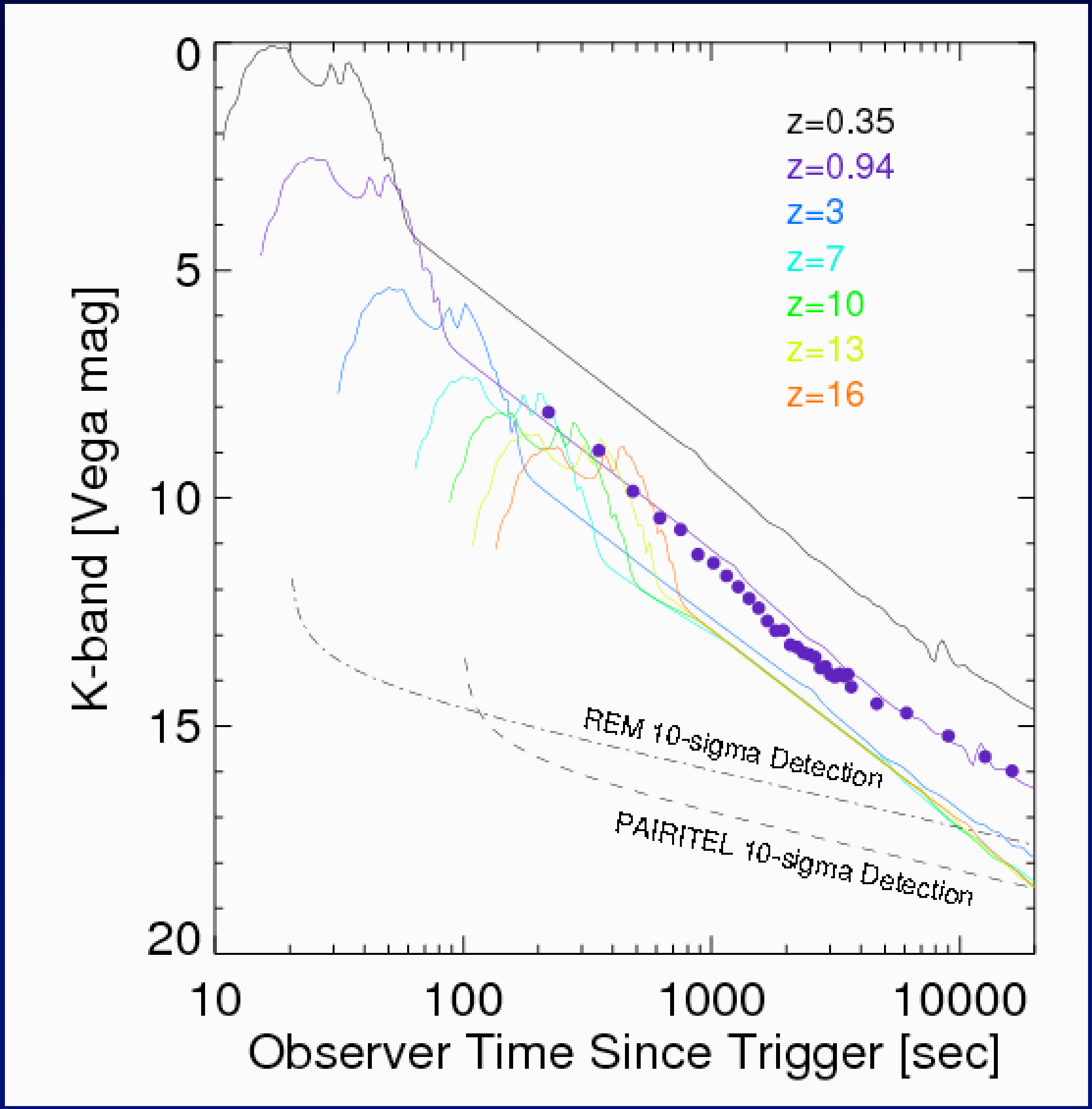
Rybicki & Loeb 1999; Dijkstra & Loeb arxiv:0711.2312

<u>*Long Gamma-Ray Bursts:* *Observing One Star at a Time*</u>



<u>Existing finder:</u> ***Swift;*** **<u>Proposed:</u>** ***JANUS, EXIST (high-z GRBs)***

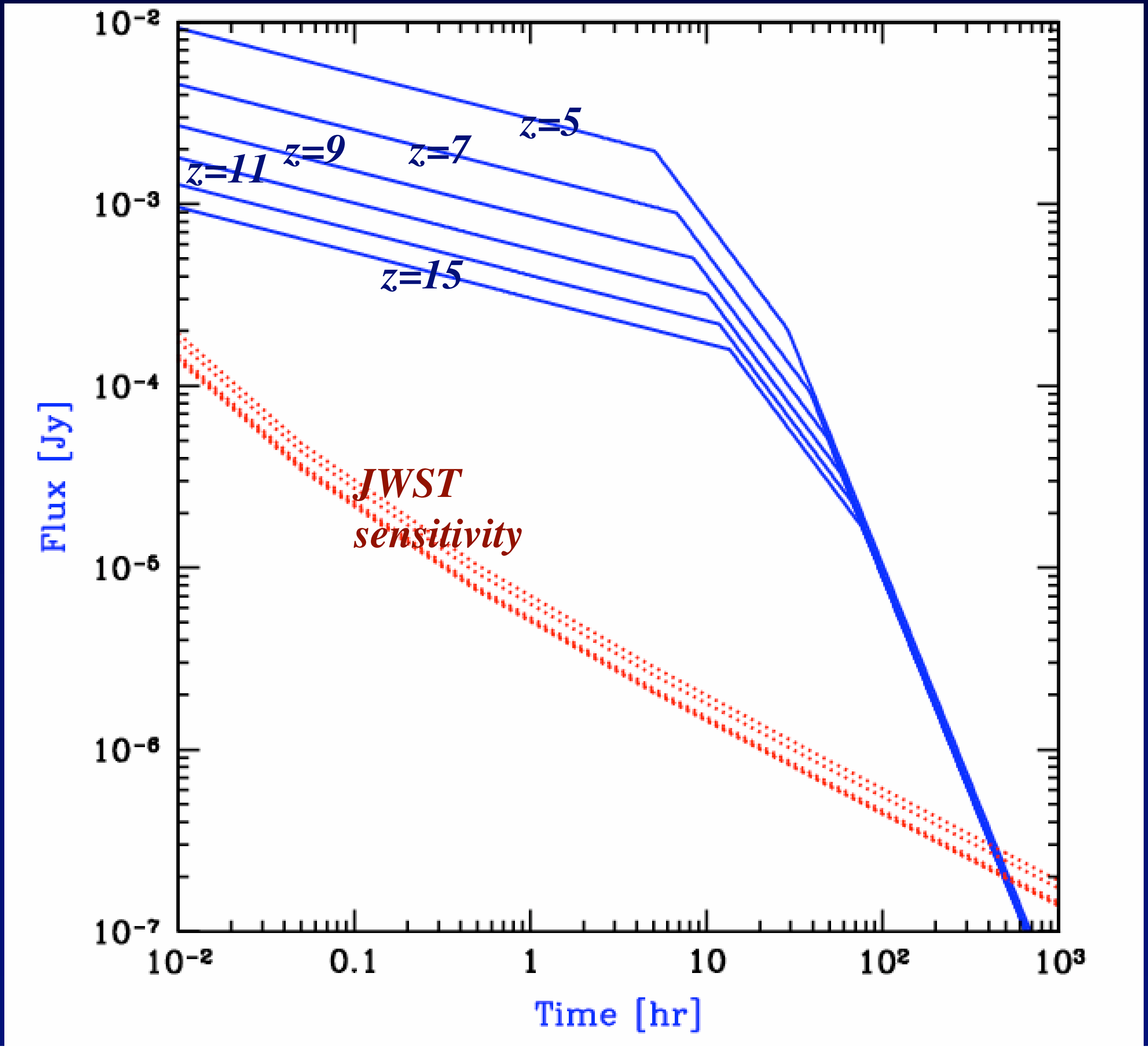
GRB080319B at higher redshifts



Bloom et al.
arXiv:0803.3215

Detectability of Afterglow Emission Near the Lya Wavelength

Photometric redshift identification: based on the Lya trough

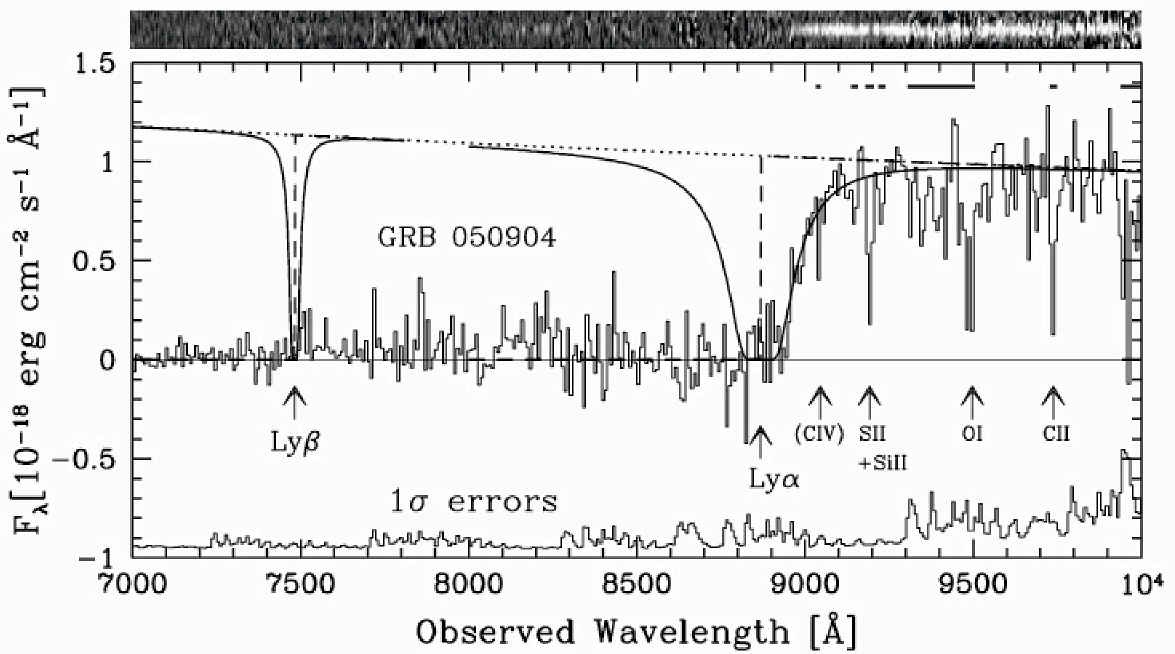


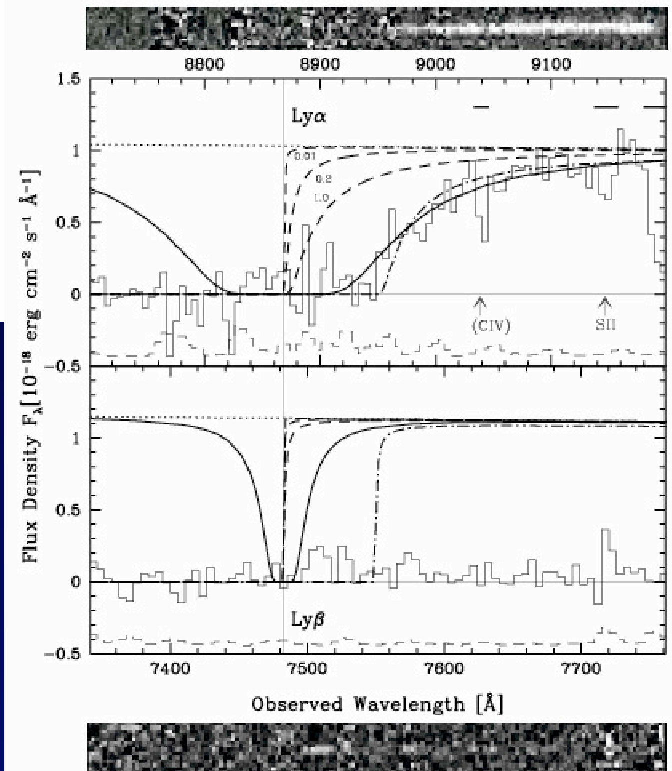
Barkana & Loeb 2003

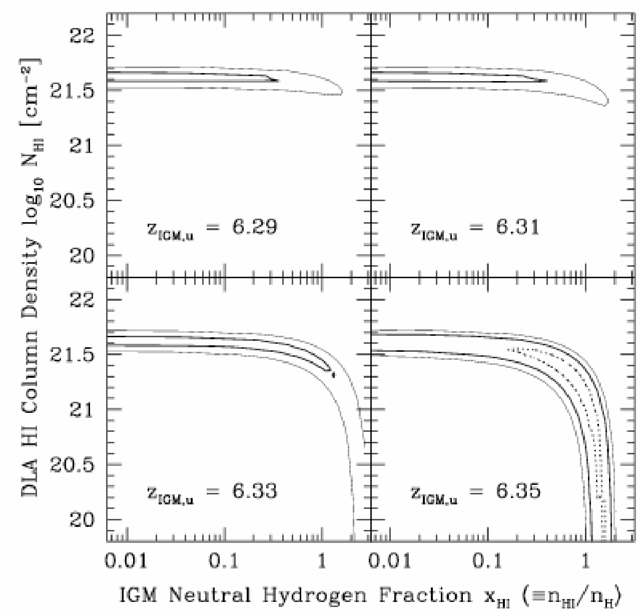
astro-ph/0305470

Implications for the Cosmic Reionization from the Optical Afterglow Spectrum of the Gamma-Ray Burst 050904 at $z = 6.3^*$

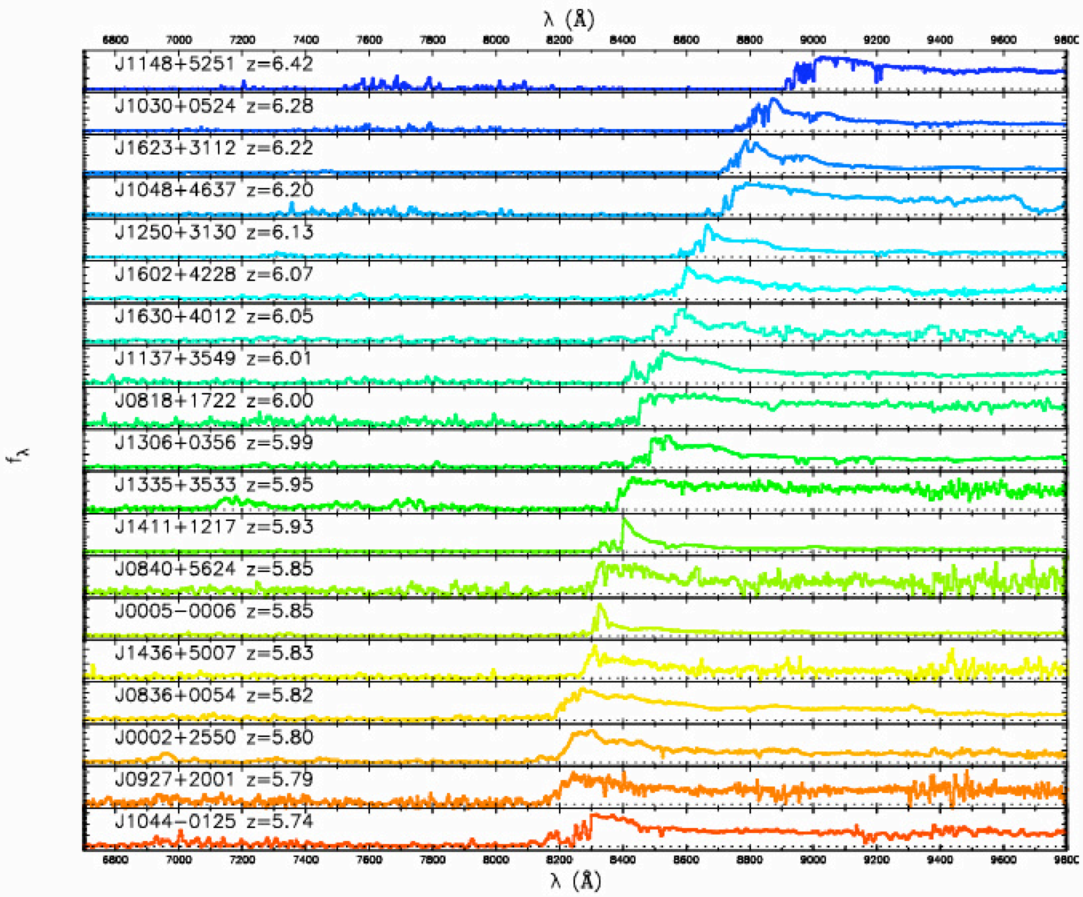
Tomonori TOTANI[1], Nobuyuki KAWAI[2], George KOSUGI[3], Kentaro AOKI[4], Toru YAMADA[3]
Masanori IYE[3], Kouji OHTA[1], and Takashi HATTORI[4]



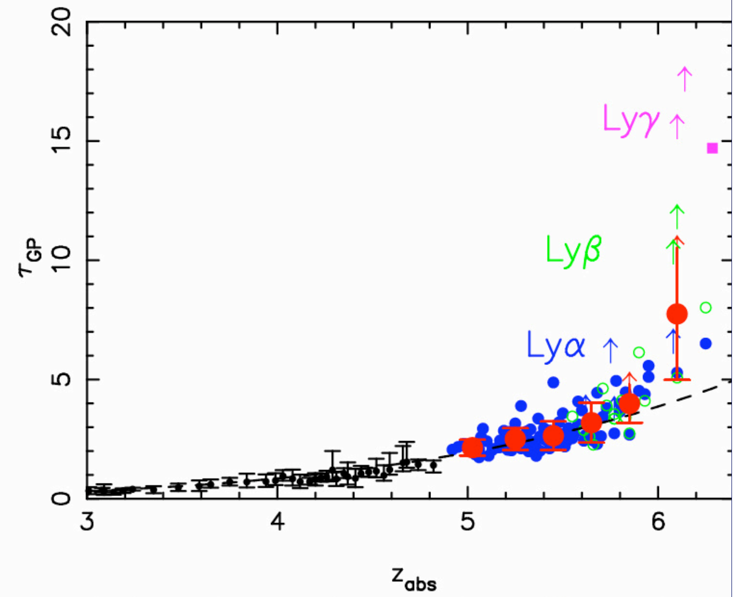


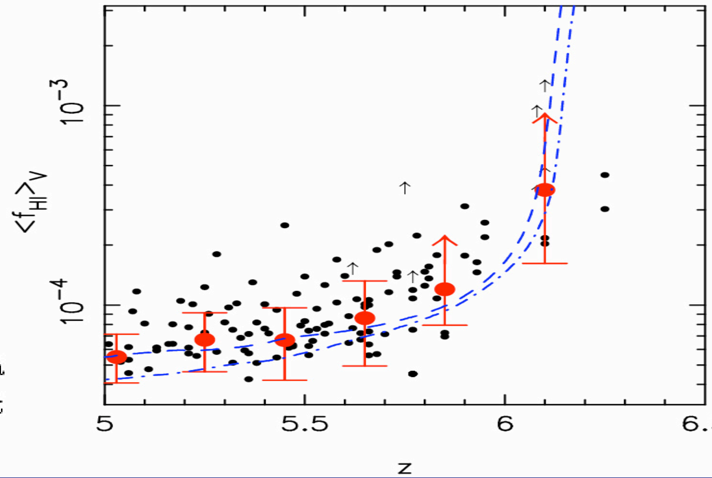


So far, the hydrogen was only probed by quasars



Spectra of our sample of nineteen SDSS quasars at $5.74 < z < 6.42$. Twelve of the spectra were taken with Keck/ESI, while the others were observed with the MMT/Red Channel and Kitt Peak 4-meter/MARS spectrographs. See Table 1 for detailed information.





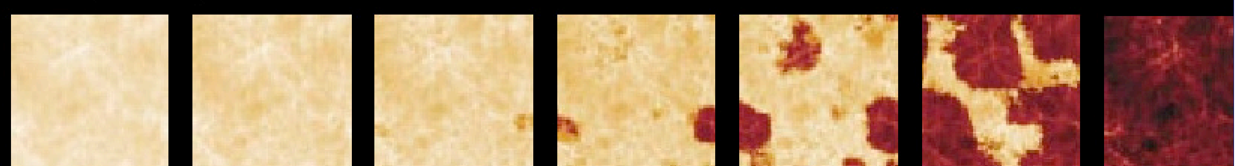
Fan et al. 2005

21cm Mapping of Cosmic History

LIGHTING UP THE COSMOS

In the beginning of the Dark Ages, electrically neutral hydrogen gas filled the universe. As stars formed, they ionized the regions immediately around them, creating bubbles here and there. Eventually these bubbles merged together, and intergalactic gas became entirely ionized.

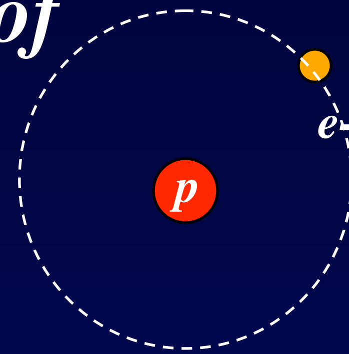
Time:	210 million years	290 million years	370 million years	460 million years	540 million years	620 million years	710 million years
Width of frame:	2.4 million light-years	3.0 million light-years	3.6 million light-years	4.1 million light-years	4.6 million light-years	5.0 million light-years	5.5 million 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.

Mapping the Cosmic Distribution of

Hydrogen

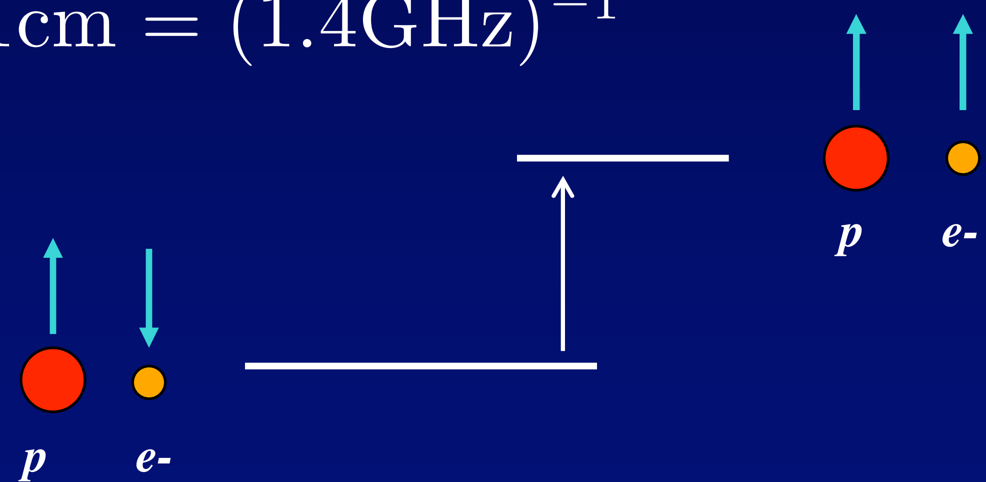


Ground level

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

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

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



$${}_1S_{1/2}$$

$${}_0S_{1/2}$$

Spin Temperature

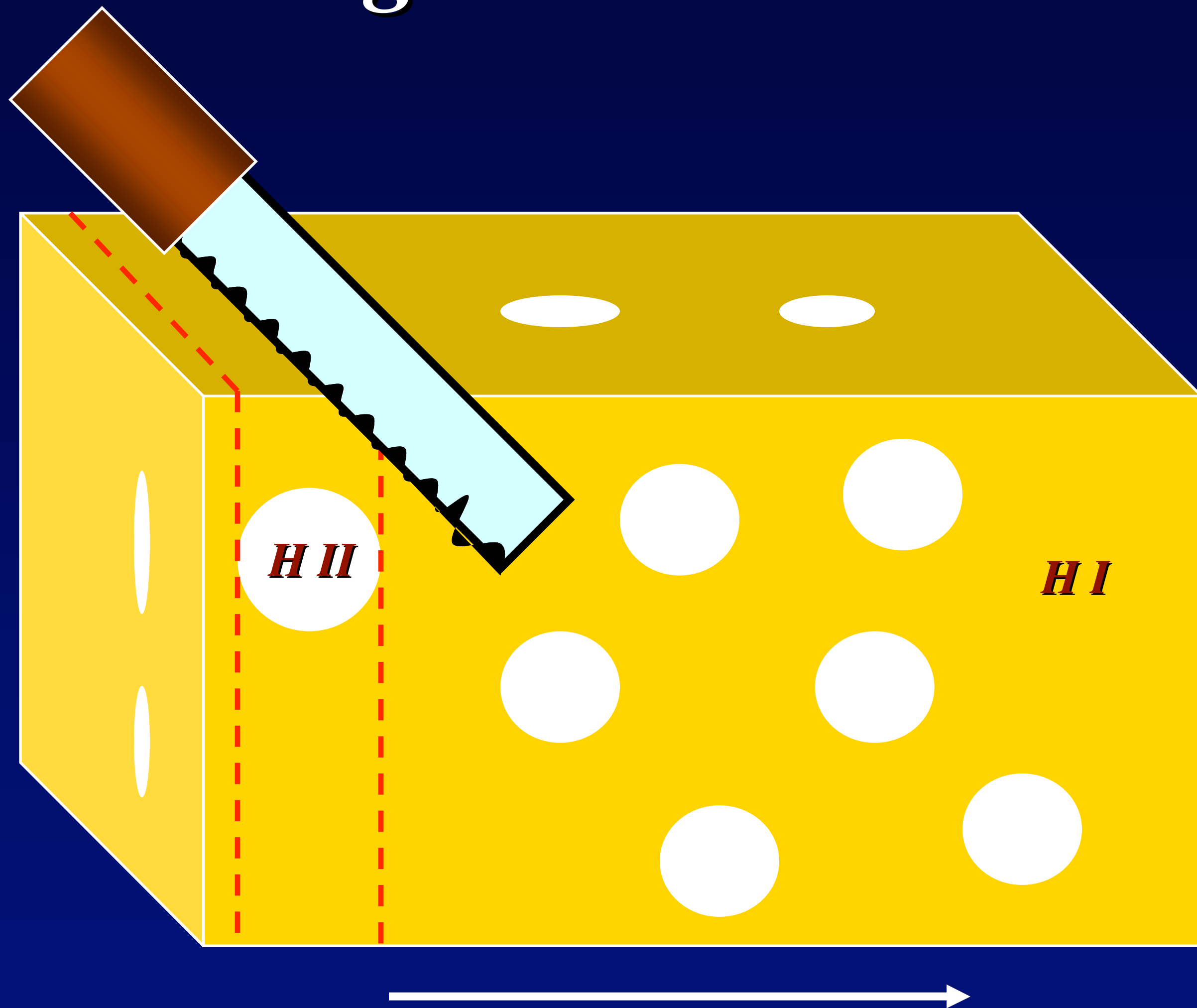
$$\frac{n_1}{n_0} = \frac{g_1}{g_0} \exp\{-\frac{0.068\mathrm{K}}{T_s}\}$$

$$(g_1/g_0) = 3$$

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

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

Separating the Physics from the Astrophysics

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

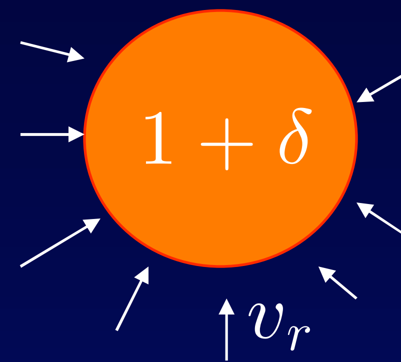
Astrophysics: *consequences of star formation*

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

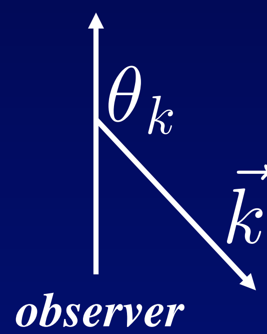
Line-of-Sight Anisotropy of 21cm Flux Fluctuations

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



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

→ Power spectrum is not isotropic (“Kaiser effect”)



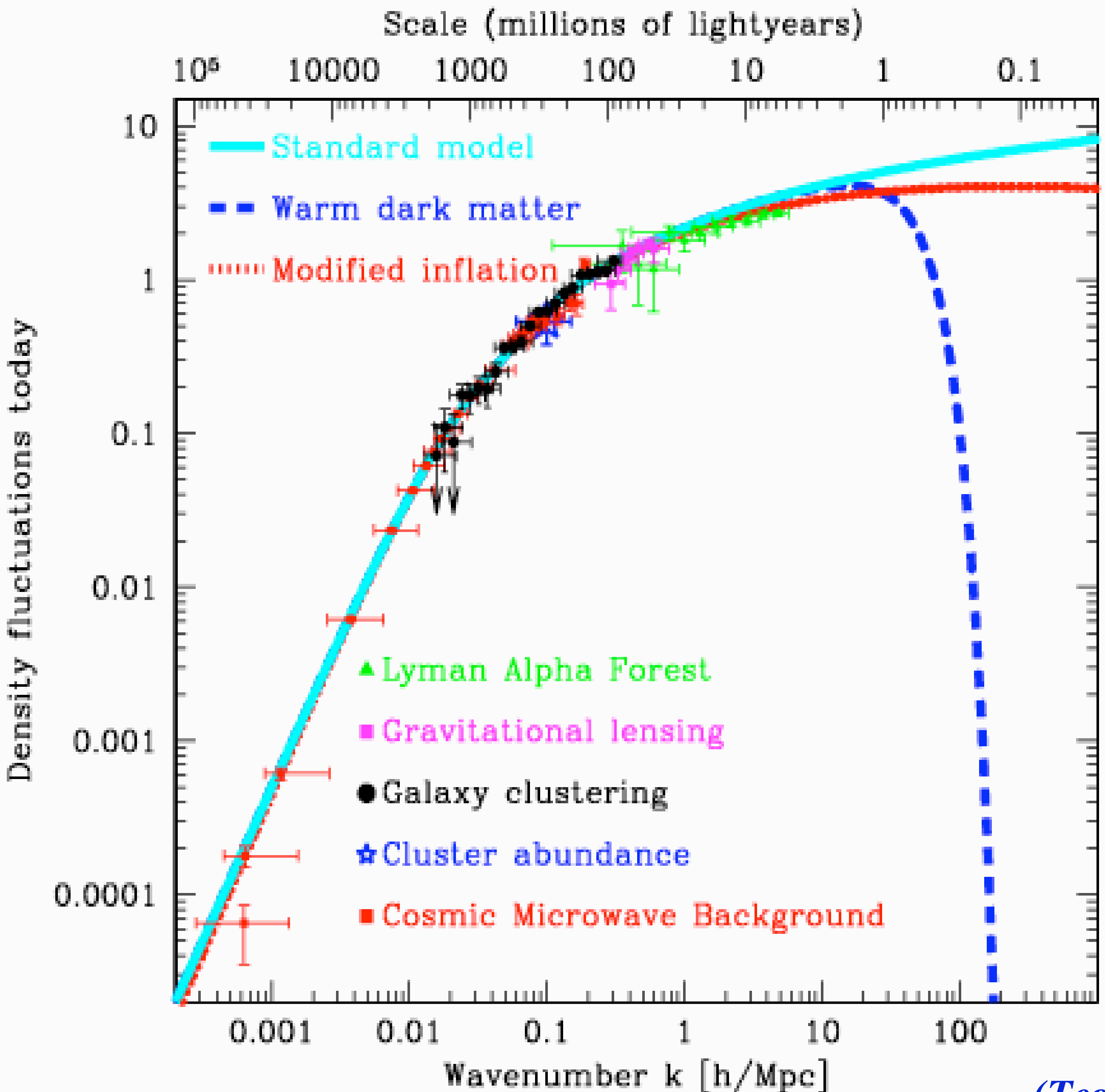
$$\frac{dv_r}{dr} \longrightarrow \qquad \delta_v(\vec{k}) = -\cos^2\theta_k \times \delta(\vec{k})$$

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

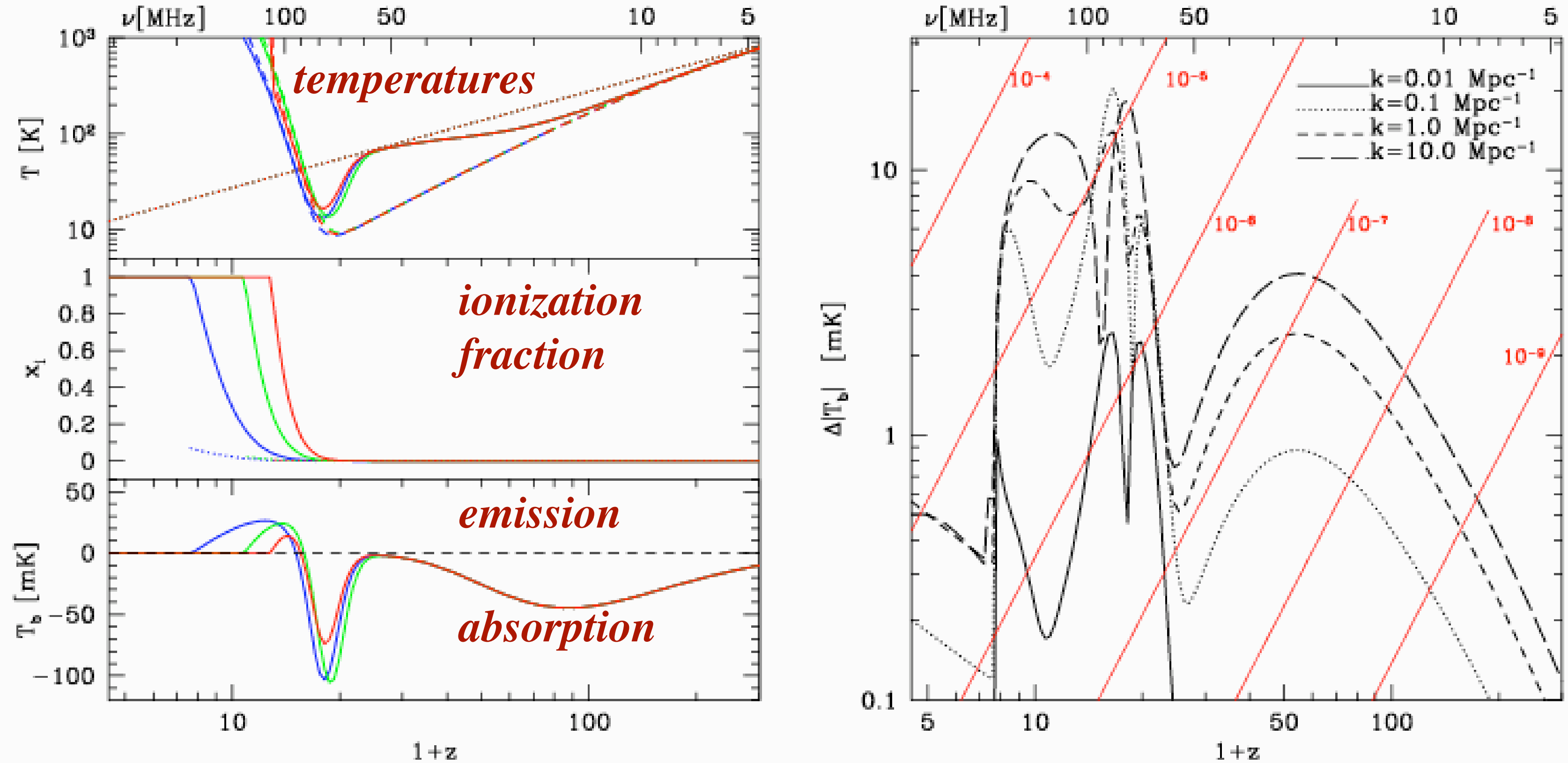
$$\delta_{\rm iso} = \beta\delta + \delta_{x_{\rm HI}} + \delta_T + \ldots$$

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

Barkana & Loeb, astro-ph/0409572; see also Bharadwaj & Ali, astro-ph/0401206



(Tegmark 2008)

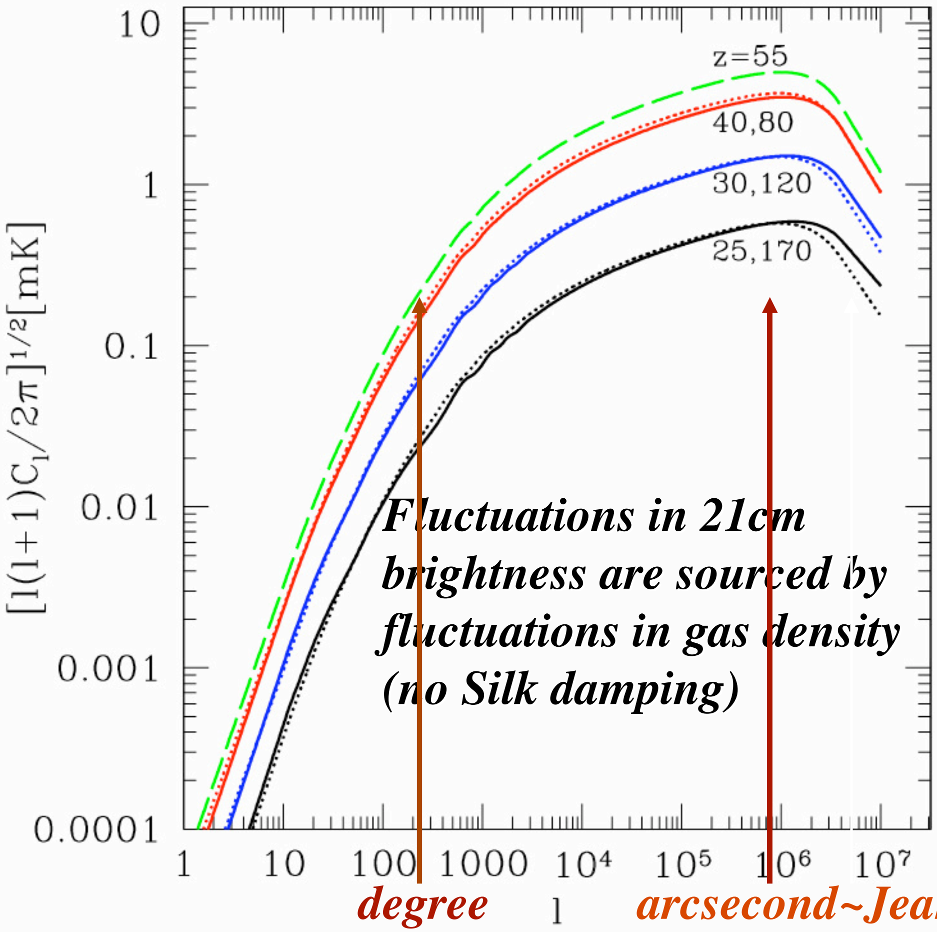


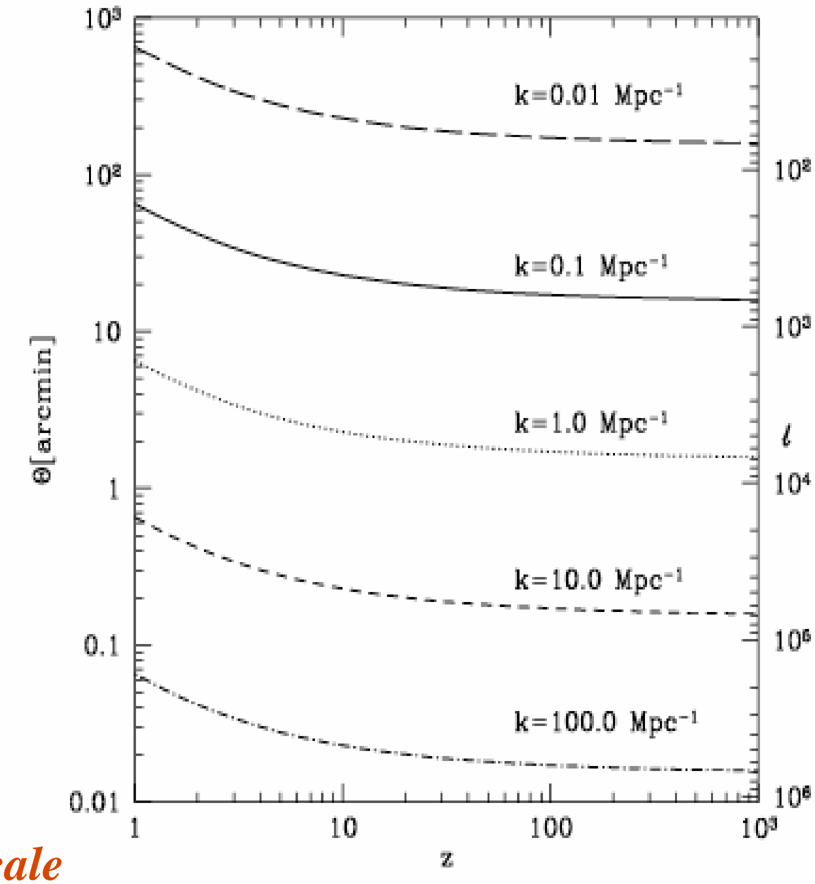
Left: Top panel: Evolution of the mean CMB (dotted curve), intergalactic medium (IGM, dashed curve), and spin (solid curve) temperatures. *Middle panel:* Evolution of the filling fraction of ionized bubbles (solid curve) and electron fraction outside the bubbles (dotted curve). *Bottom panel:* Evolution 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 $T_{\rm sky}(\nu)$ times a factor r ranging from 10^{-4} to 10^{-9}, indicative of the level of foreground subtraction required .

(Pritchard & Loeb 2008)

21 cm Absorption During the Dark Ages

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

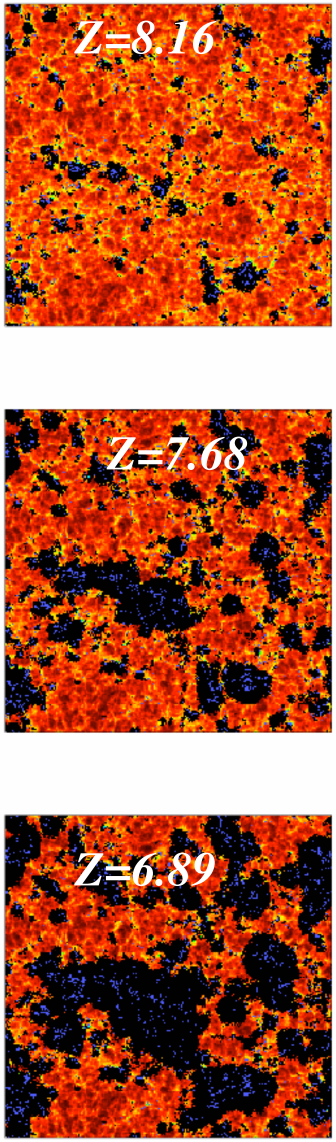




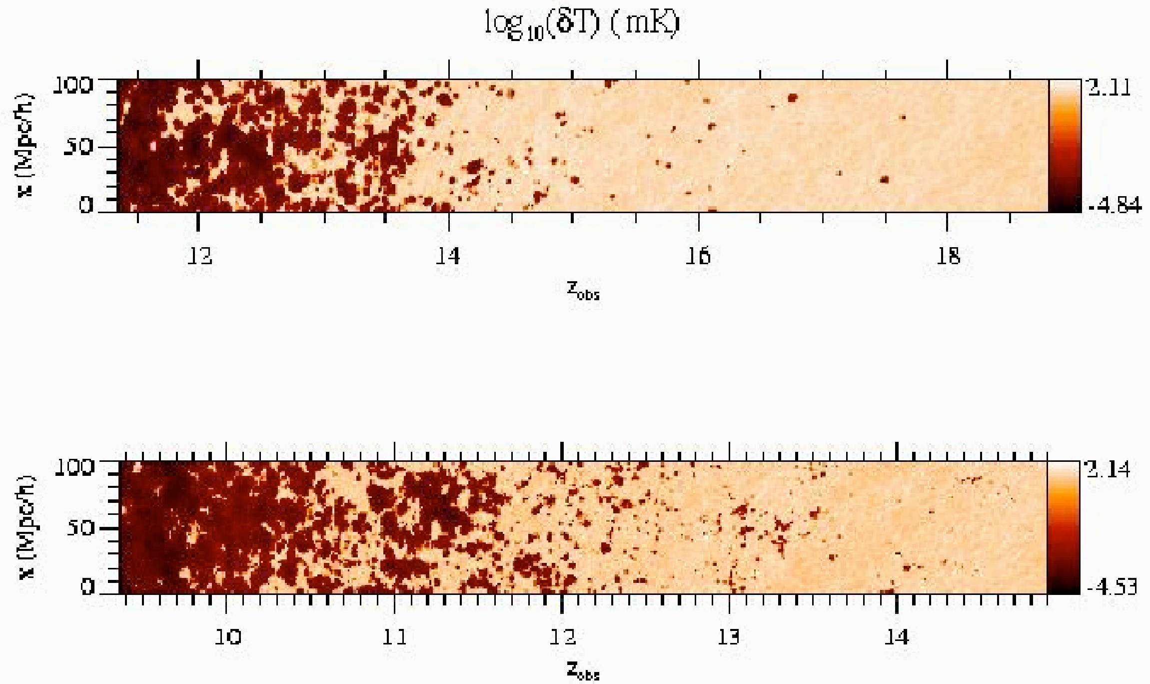
Loeb & Zaldarriaga, Phys. Rev. Lett., 2004

21cm Mapping of Epoch of Reionization

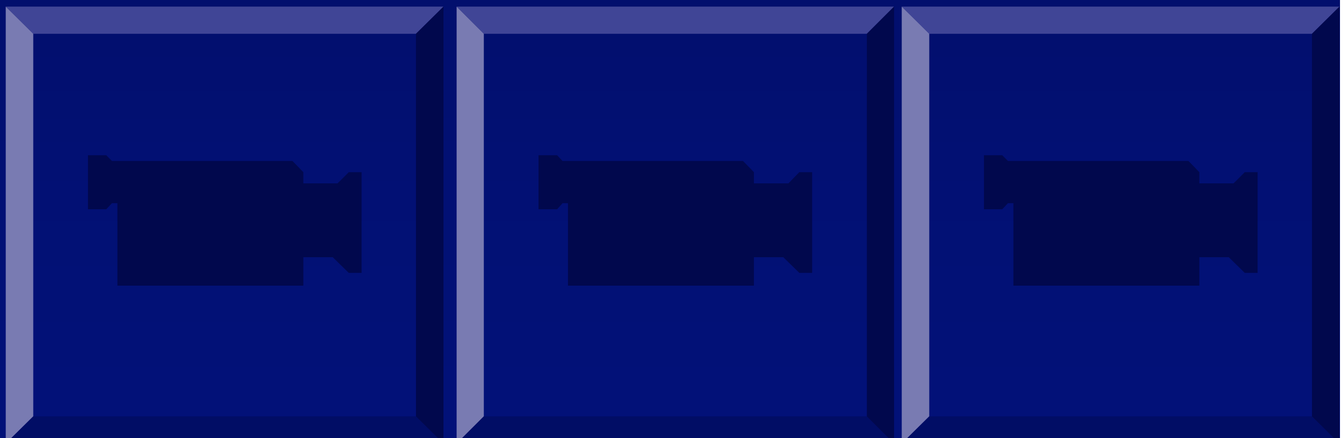
HI Density



Zahn et al. 2006



Mellema et al. 2006



Trac, Cen, & Loeb 2008

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

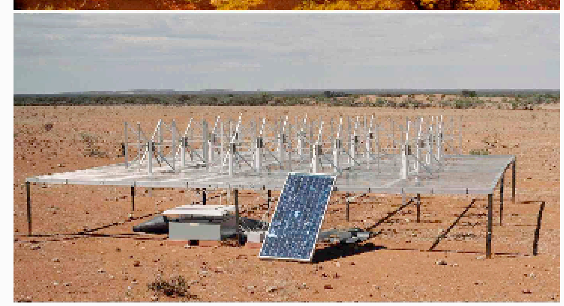
GMRT (Giant Meterwave Radio Telescope)

India/CITA/Pittsburg

SKA (Square Kilometer Array)

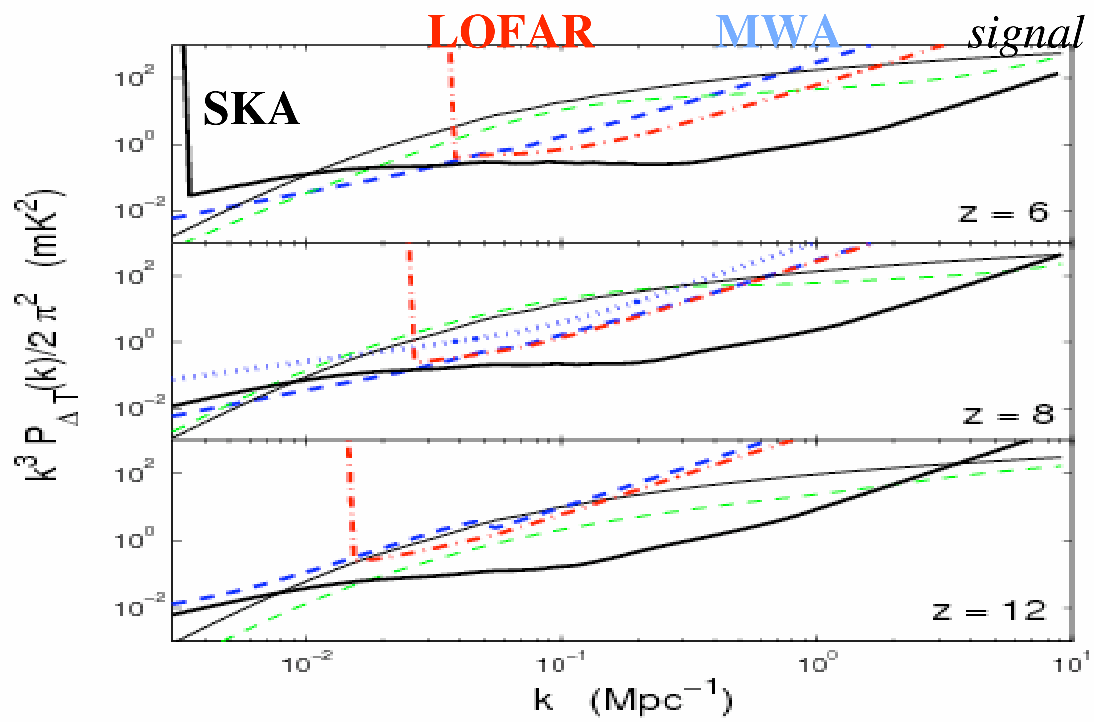
International

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

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***

$$T_{\rm sky} \sim 180 \left(\frac{\nu}{180\ {\rm MHz}}\right)^{-2.6} {\rm K}$$

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

Cross-correlation between 21cm brightness and galaxy density

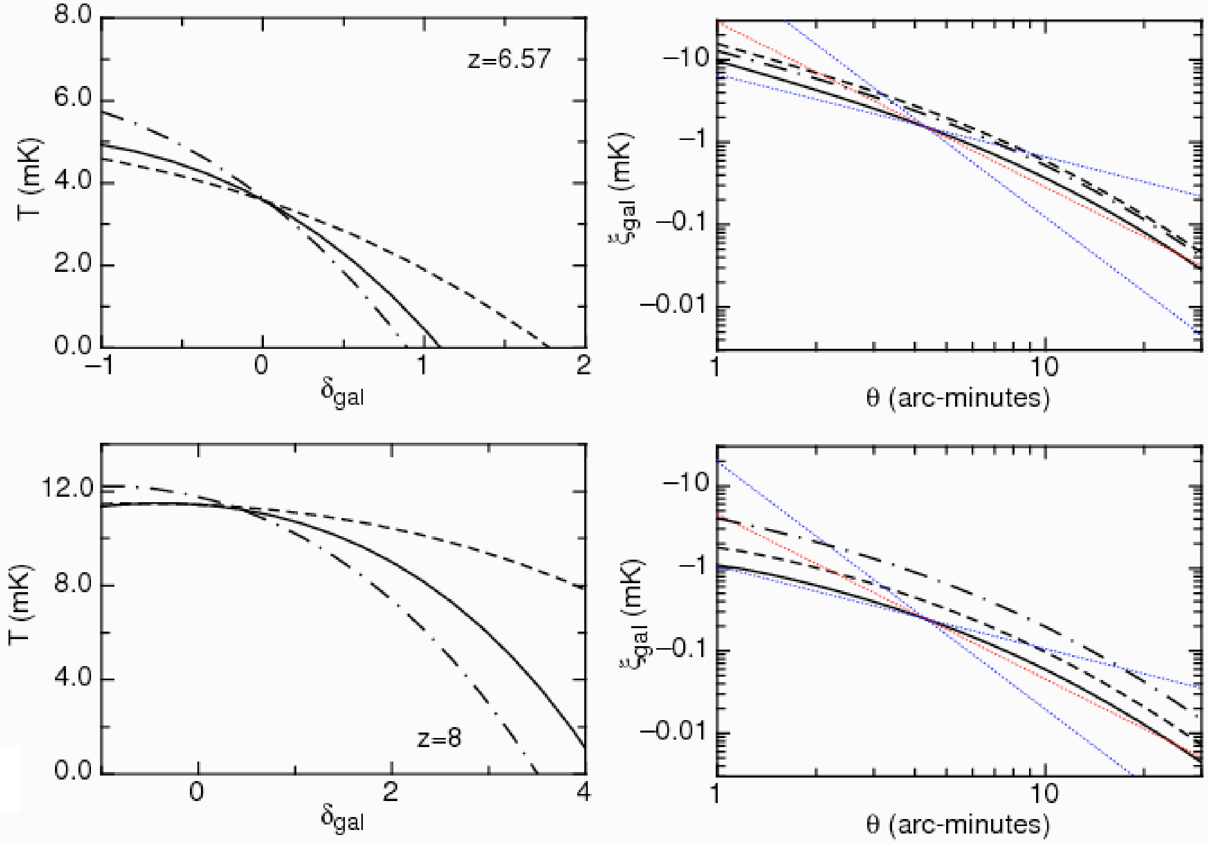


Figure 4. *Left*: 21cm brightness temperature as a function of $\delta_{\rm gal}$. Two values of galaxy mass are assumed for a clumping of $C = 10$, $M = 10^{10}M_{\odot}$ (solid line) and $M = 10^{11}M_{\odot}$ (dashed line). The dot-dashed line shows $C = 2$ with $M = 10^{10}M_{\odot}$. *Right*: The cross-correlation function $\xi_{\rm gal} = \langle \delta_{\rm gal}(T - \langle T \rangle) \rangle$ for the IGM smoothed on various angular scales (θ). The function is presented assuming $C = 10$ for masses of $M = 10^{10}M_{\odot}$ (solid line) and $M = 10^{11}M_{\odot}$ (dashed line). The dot-dashed line represents $C = 2$ with $M = 10^{10}M_{\odot}$. The lines show power-laws of slope $d(\log \xi_{\rm gal})/d(\log \theta) = -1$, -2 and -3. The upper and lower rows correspond to observations at $z = 6.57$ and $z = 8$ respectively.

Wyithe & Loeb (2006)

Clustering of Lya Emitters

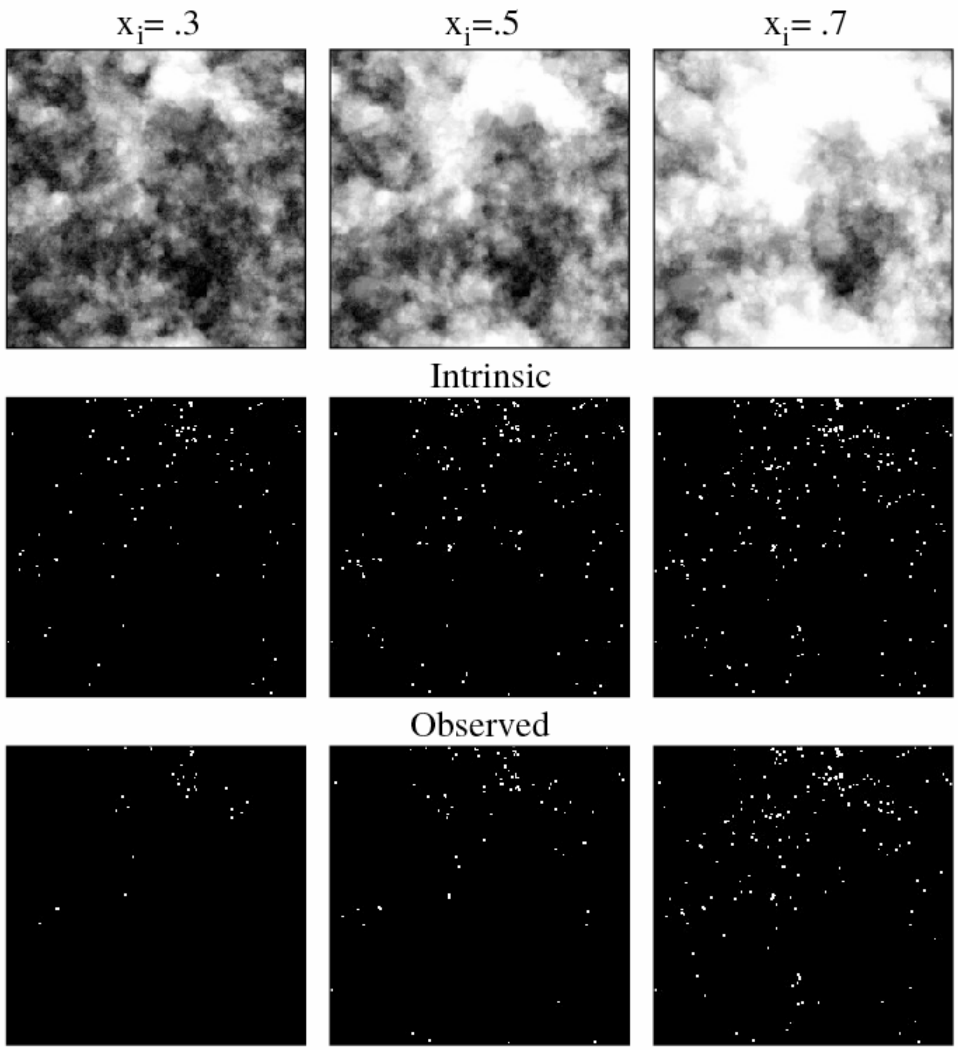


Figure 2. Top panels show the projection of $\bar{x}_i$ in the survey volume. In the white regions the projection is fully ionized and in black it is neutral. The left, middle, and right panels are for $z = 8.2$ ($\bar{x}_i = 0.3$), $z = 7.7$ ($\bar{x}_i = 0.5$), and $z = 7.3$ ($\bar{x}_i = 0.7$). The middle and bottom rows are the intrinsic and observed Lyα emitters maps, respectively, for $f_{\rm E} = 0.25$ and assuming that we can observe unobscured emitters with $m \exp(-\tau_\alpha(\nu_0)) > 7 \times 10^{10} M_\odot$. (Note that $L_{\rm int,E} \propto m$.) The observed distribution of emitters is modulated by the location of the HII regions (compare bottom panels with corresponding top panels). Each panel is 94 Mpc across (or 0.6 degrees on the sky), roughly the area of the current Subaru Deep Field (SDF) at $z = 6.6$ (Kashikawa et al. 2006). The depth of each panel is $\Delta\lambda = 130$ Å, which matches the FWHM of the Subaru 9210 Å narrow band filter. The number densities of Lyα emitters for the panels in the middle row are few times larger than the number density in the SDF photometric sample of $z = 6.6$ LAEs.

McQuinn et al.
arXiv:0704.2239

The Imprint of Reionization on Galaxy Clustering

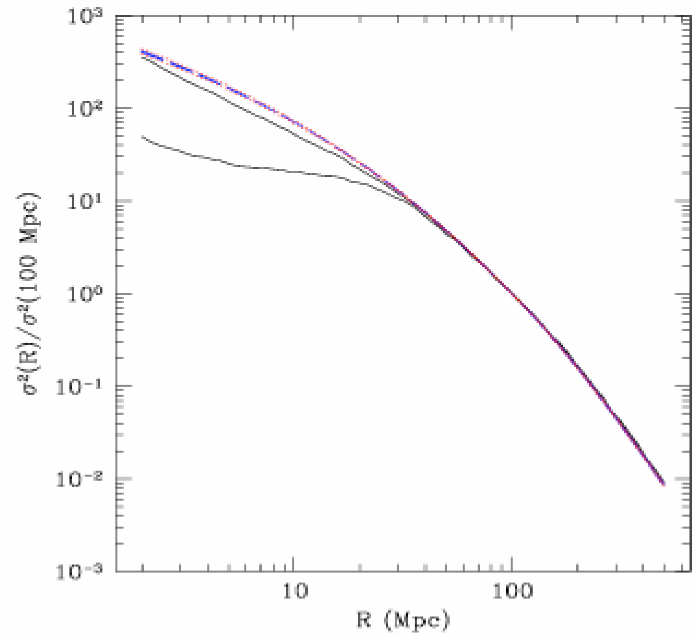


FIG. 5.— The normalized $\sigma^2(R)$ for $z_R = 15$ and $z_R = 6$ (upper and lower solid black curves, respectively); the limiting cases of the best current constraints of n (red, dotted curves) and α (blue, dashed curves).

Inhomogeneous photo-ionization heating to $\sim 10^4\mathrm{K}$ modulates the minimum mass of galaxies on scales of tens of comoving Mpc

Babich & Loeb 2006, ApJ, 640, 1

Highlights

- ***Large-aperture infrared telescopes and radio arrays will probe reionization over the coming decade.***
- ***Simulations of reionization require large (>100Mpc) boxes and high resolution for source identification.***
- ***21cm brightness fluctuations are expected to be anti-correlated with infrared galaxies during reionization***
- ***Reionization leaves an imprint on the clustering of star-forming galaxies at intermediate redshifts. This might compromise the use of these galaxies for precision cosmology (e.g. acoustic oscillations/dark energy).***