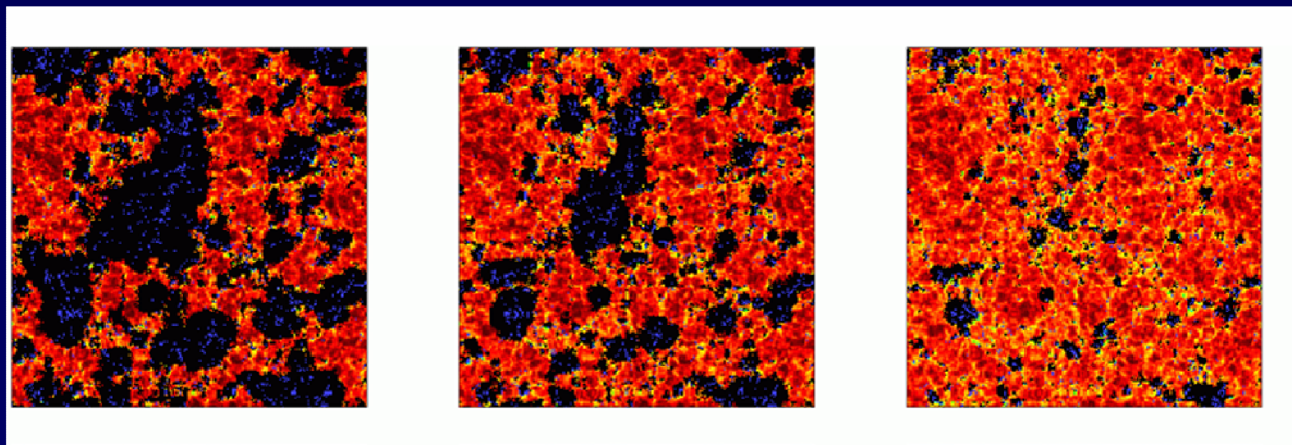
The end of the Cosmic Dark Ages: First Light and Reionization

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



Surprises may signal new physics

How Did the First Stars and Galaxies Form?

Abraham Loeb

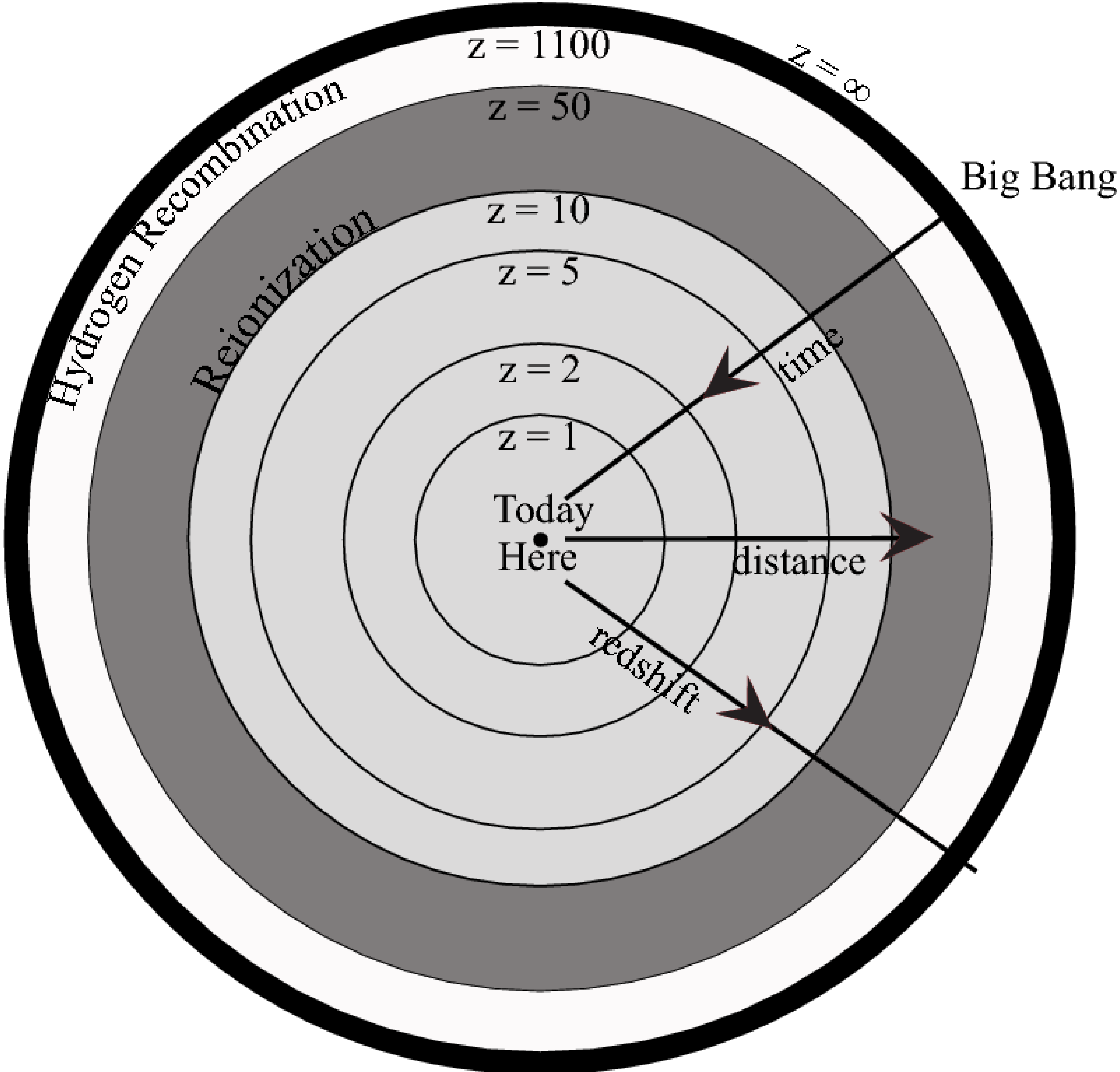
PRINCETON UNIVERSITY PRESS
PRINCETON AND OXFORD

Contents

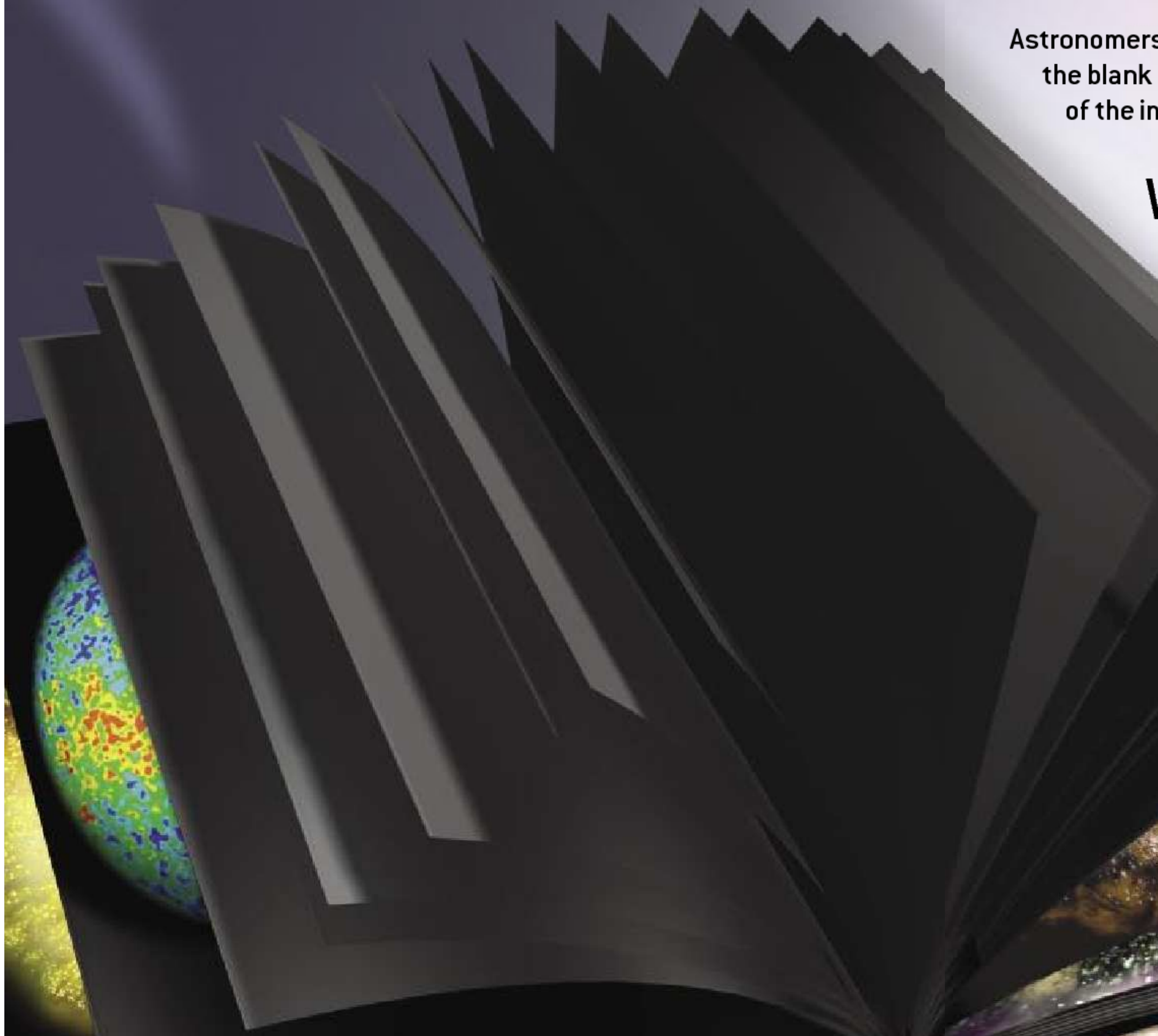
WMAP Cosmological Parameters
Model: lcdm
Data: all

$10^2\Omega_b h^2$	=	$2.19^{+0.06}_{-0.08}$
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…


z = 1100
z = ∞
z = 50
Big Bang
Hydrogen Recombination
z = 10
Reionization
z = 5
time
z = 2
z = 1
Today
Here
distance
redshift

THE DARK AGES of the Universe



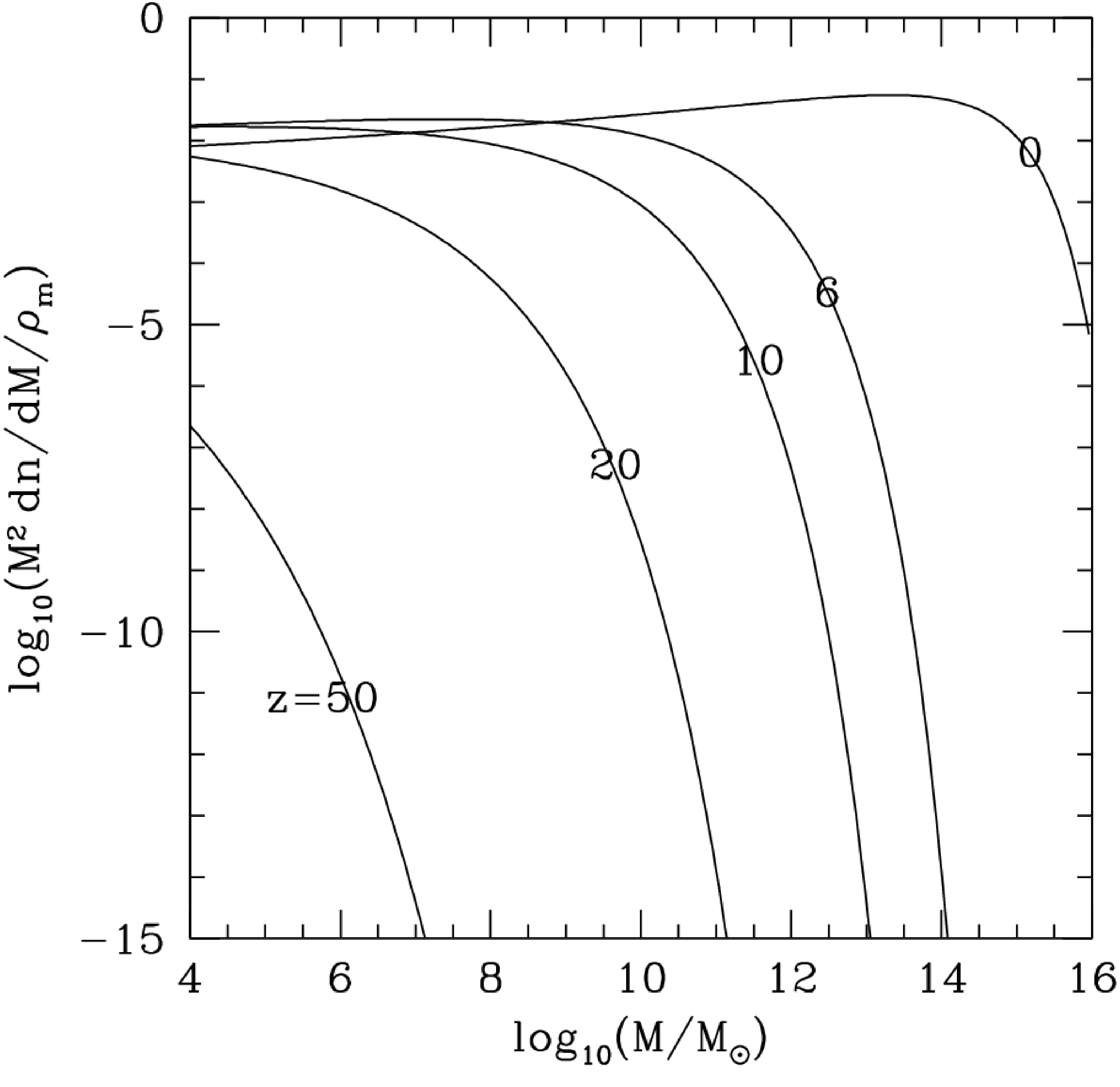
Astronomers are trying to fill in the blank pages in our photo album of the infant universe

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.

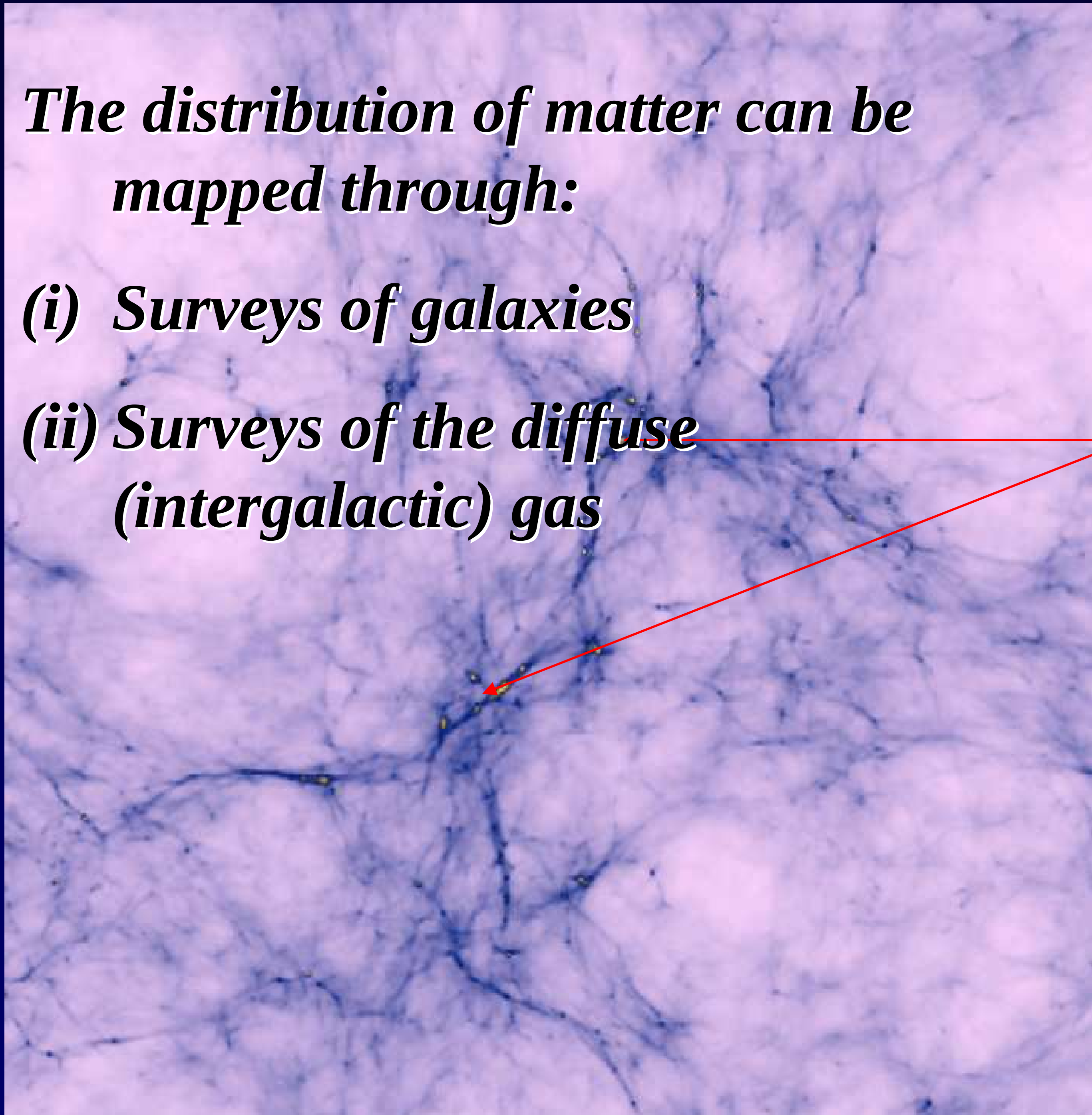
Cosmologists are addressing some of the fundamental questions that people attempted to resolve over the centuries through philosophical thinking, but we are doing so based on systematic observation and a quantitative methodology. Perhaps the greatest triumph of the past century has been a model of the 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



0
−5
−10
−15
4
6
8
10
12
14
16
$\log_{10}(M^2\, dn/dM/\rho_m)$
$\log_{10}(M/M_\odot)$
0
6
10
20
z=50

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***

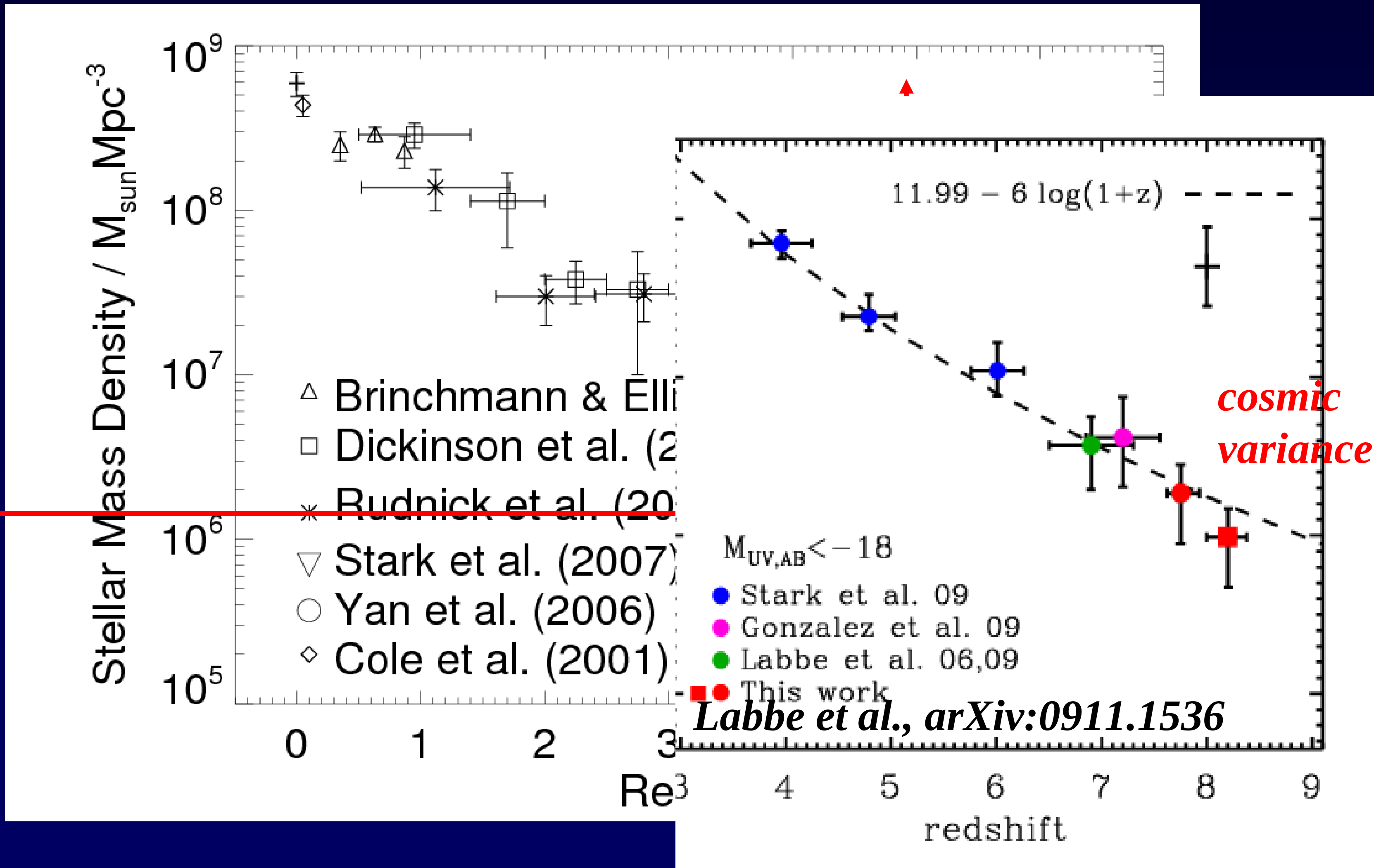
molecular hydrogen in Jeans mass objects

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

Yoshida et al. 2003

Observing the Stars

Observed Growth of Stellar Mass Budget

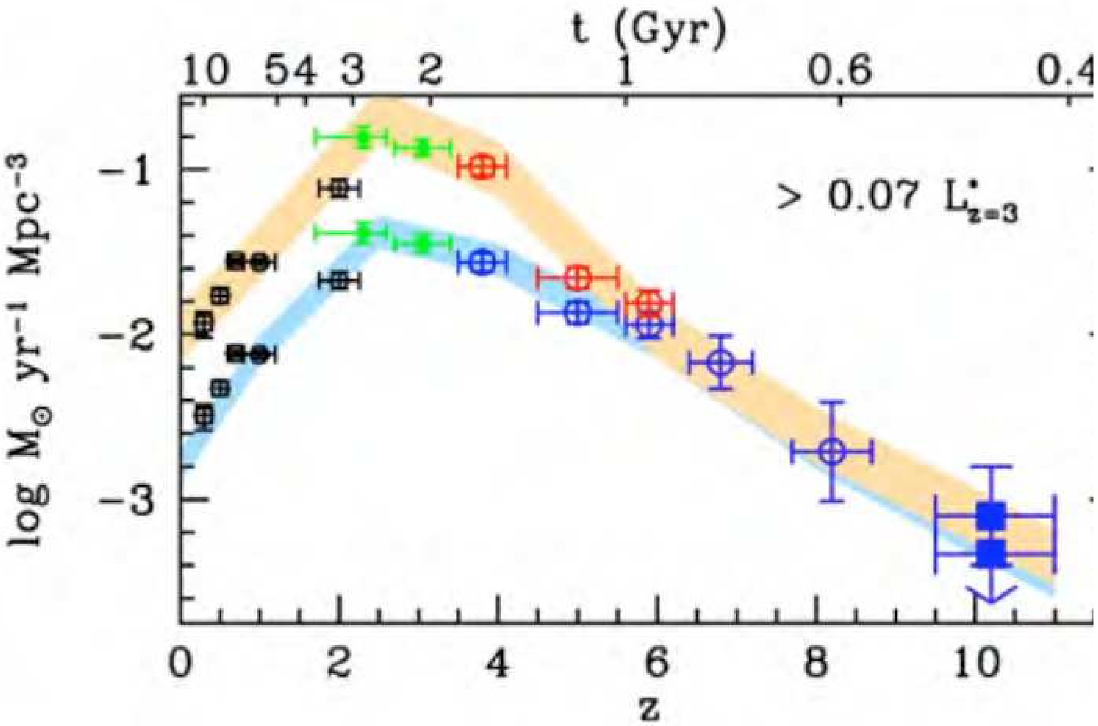


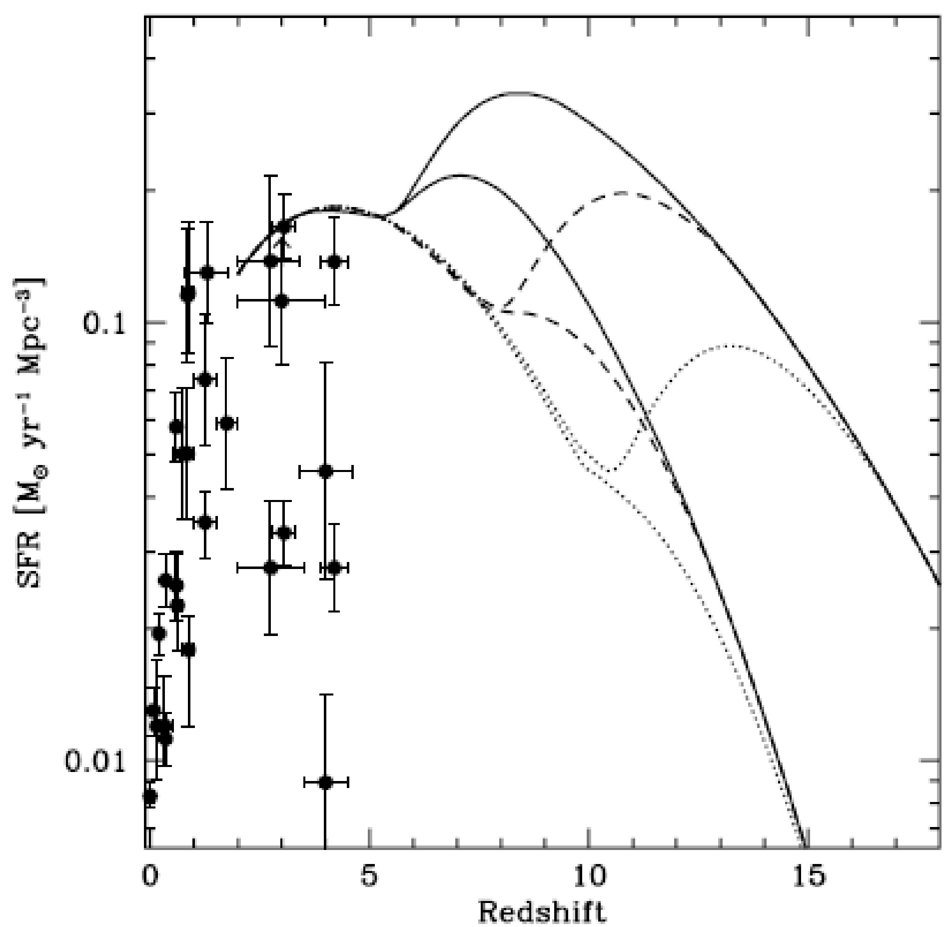
f_esc
ionizing
photons
per baryon

cosmic
variance

Redshift Record of Observed Galaxies

(Bouwens et al., arXiv:0912.4263)





Prediction from Barkana & Loeb (2000):

Most SFR at z>10 is in galaxies fainter than 1nJy!

(AB>32.9 at 0.6-3.5 micron, ~10 x fainter than WFC3/IR sensitivity)

James Webb Space Telescope: Searching for the First Light

Mirror diameter: 6.5 meter

Material: beryllium

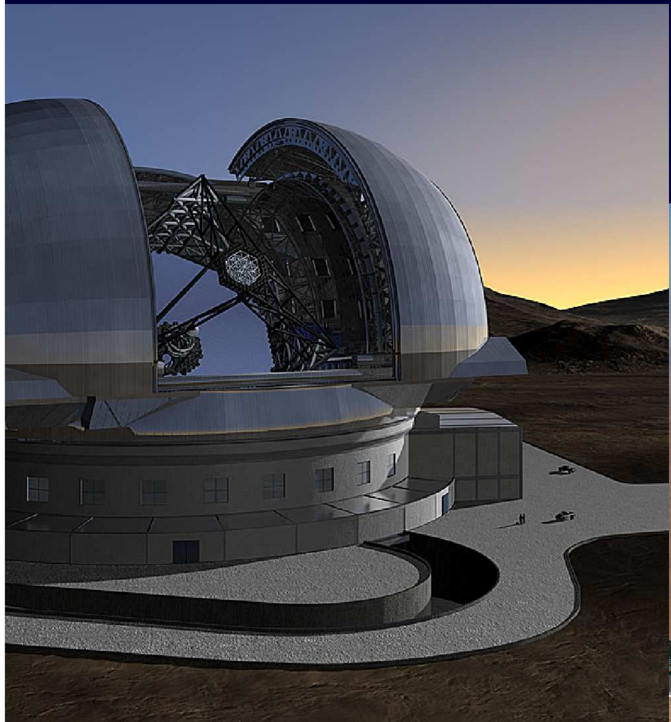
18 segments

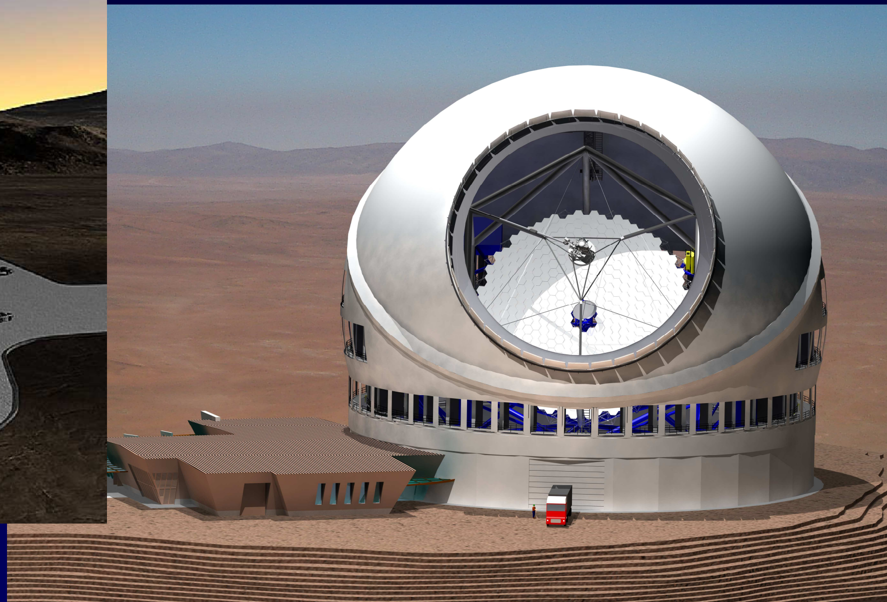
Wavelength coverage: 0.6-28 micron

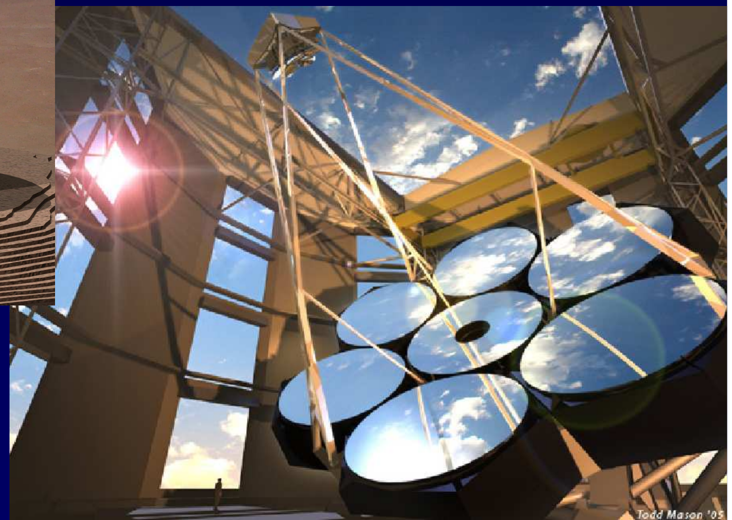
L2 orbit

Launch date: 2014

Extremely Large Telescopes (24-42 meters)

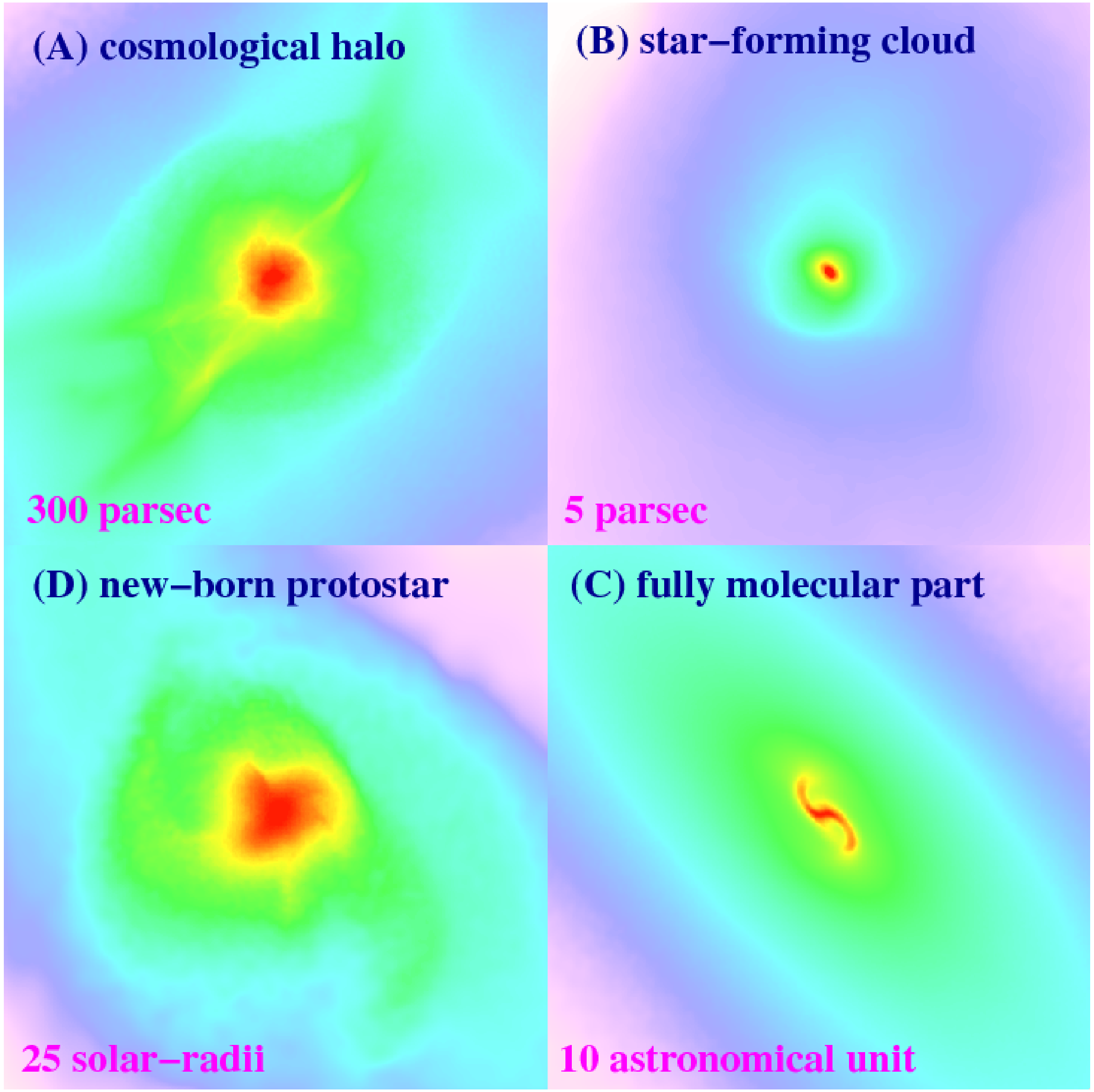






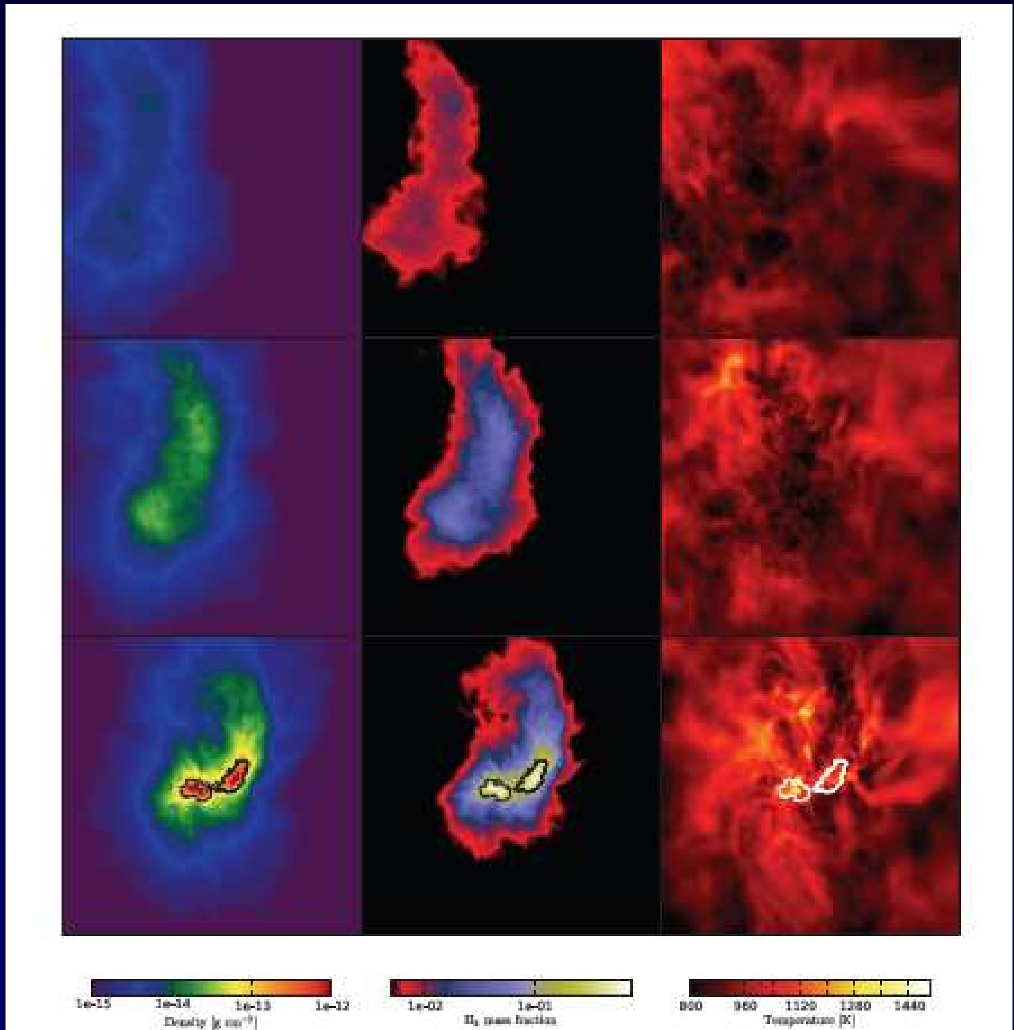
- GMT=Seven mirrors, each 8.4m in diameter
- TMT, EELT – segmented 20-40m aperture

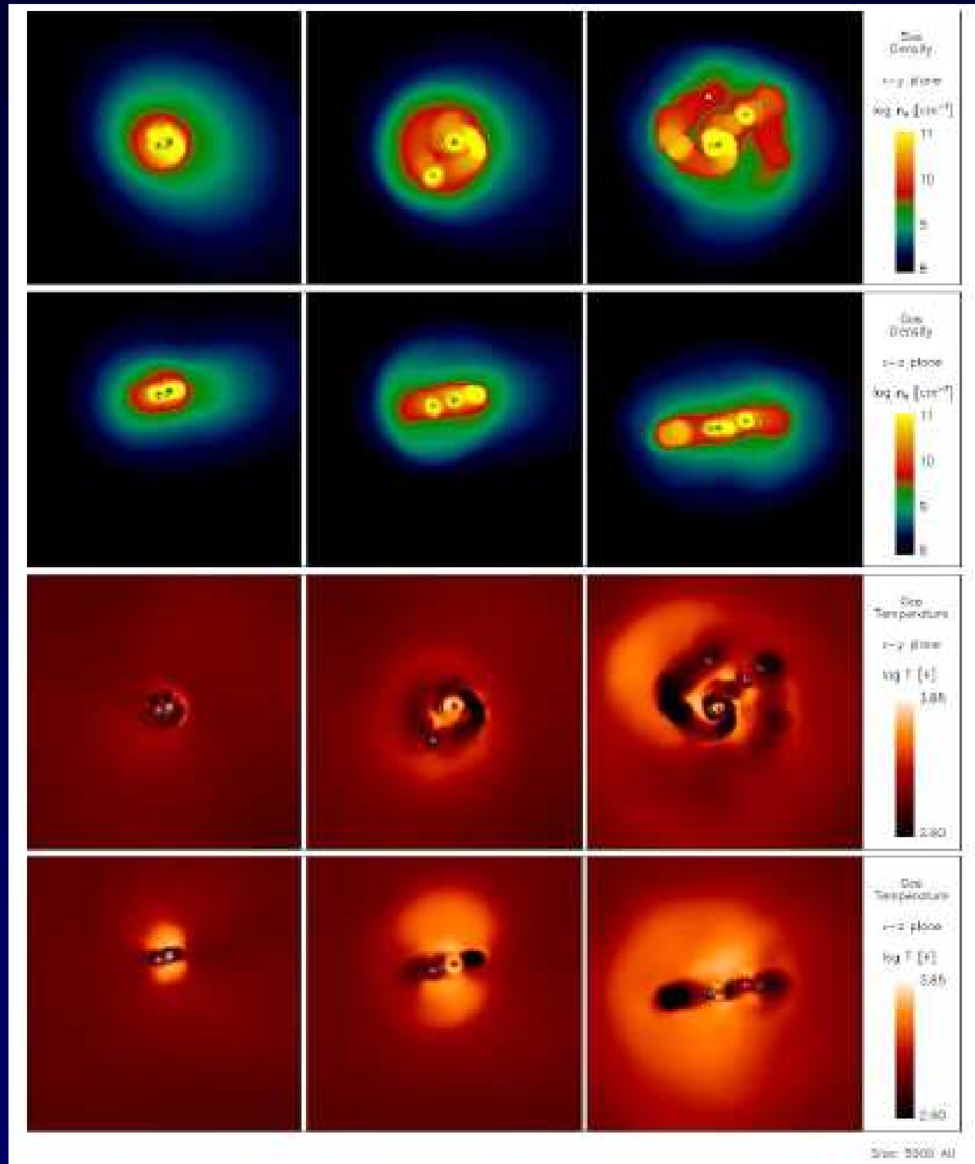
Theoretical Simulations of the First Stars



Bromm, Yoshida, Hernquist, & McKee (2009)

Population III Binaries

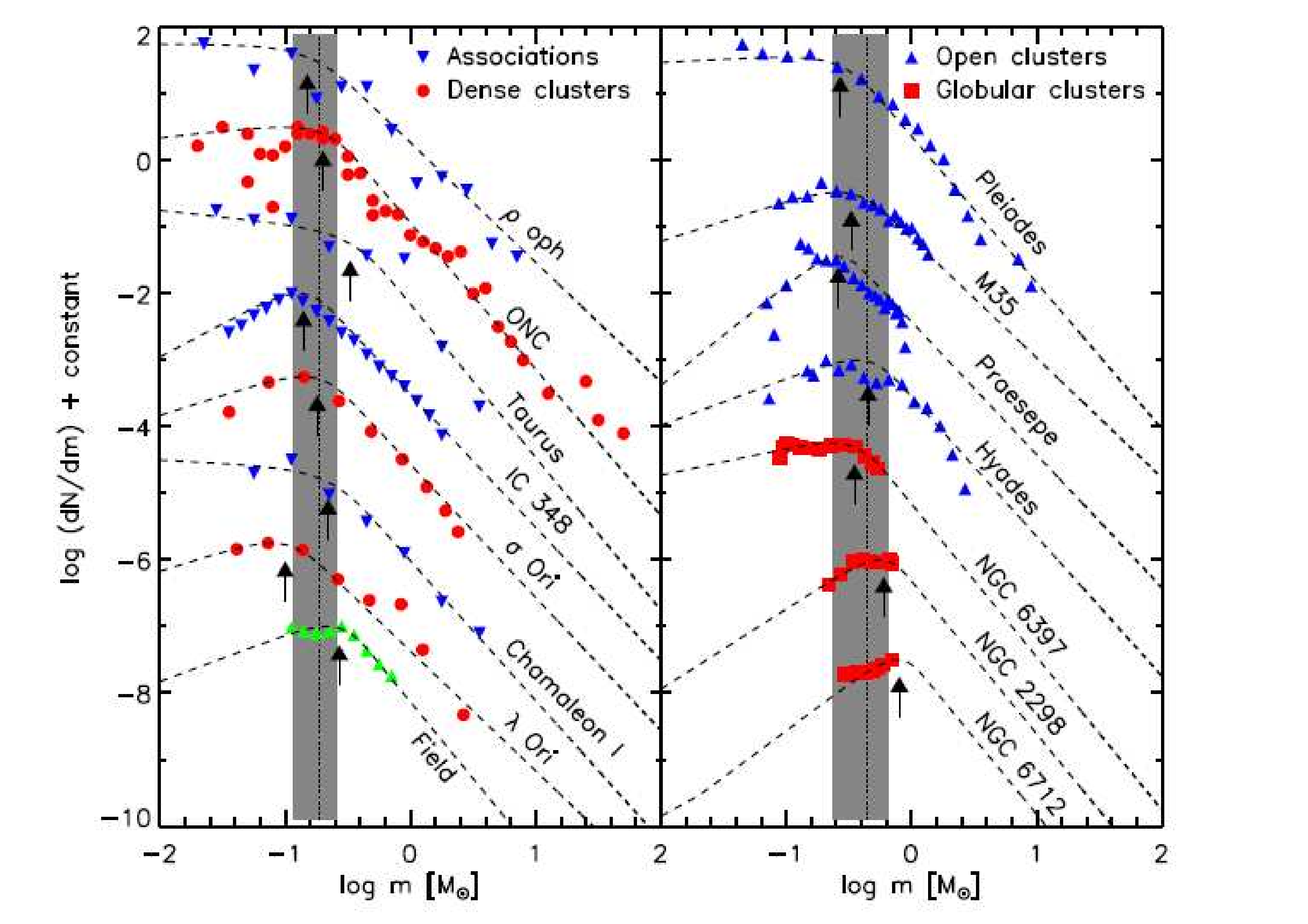




Turk, Abel, & O'Shea 2009

Stacy, Greif, & Bromm 2009

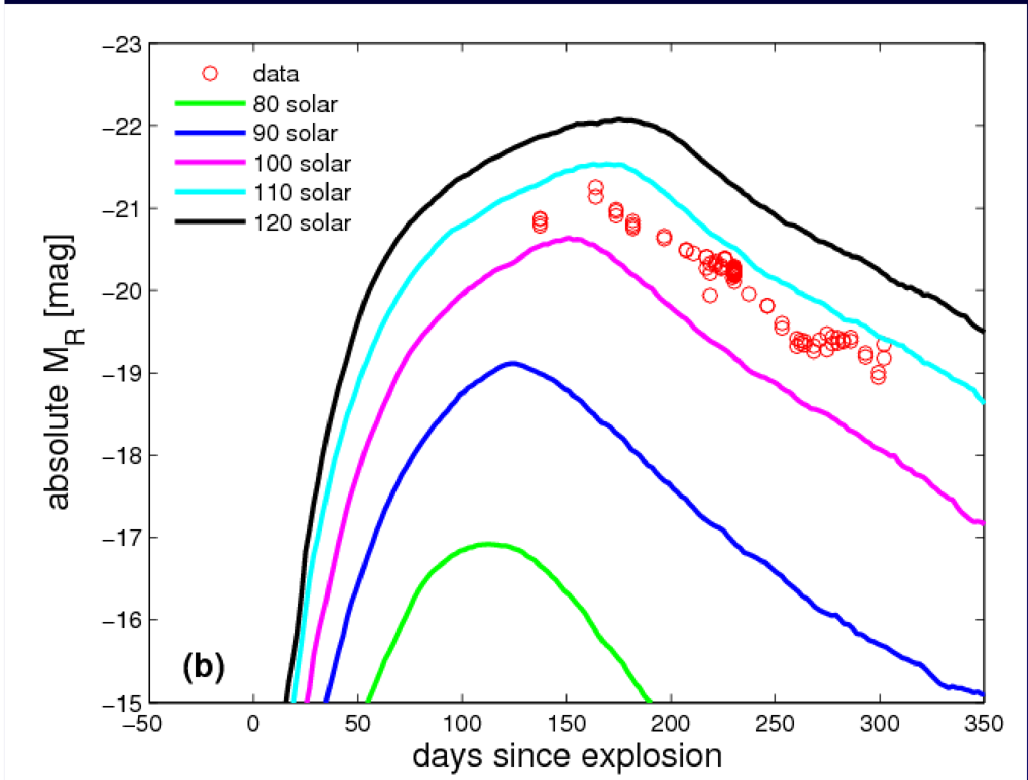
The Initial Mass Function of Stars Populations I/II

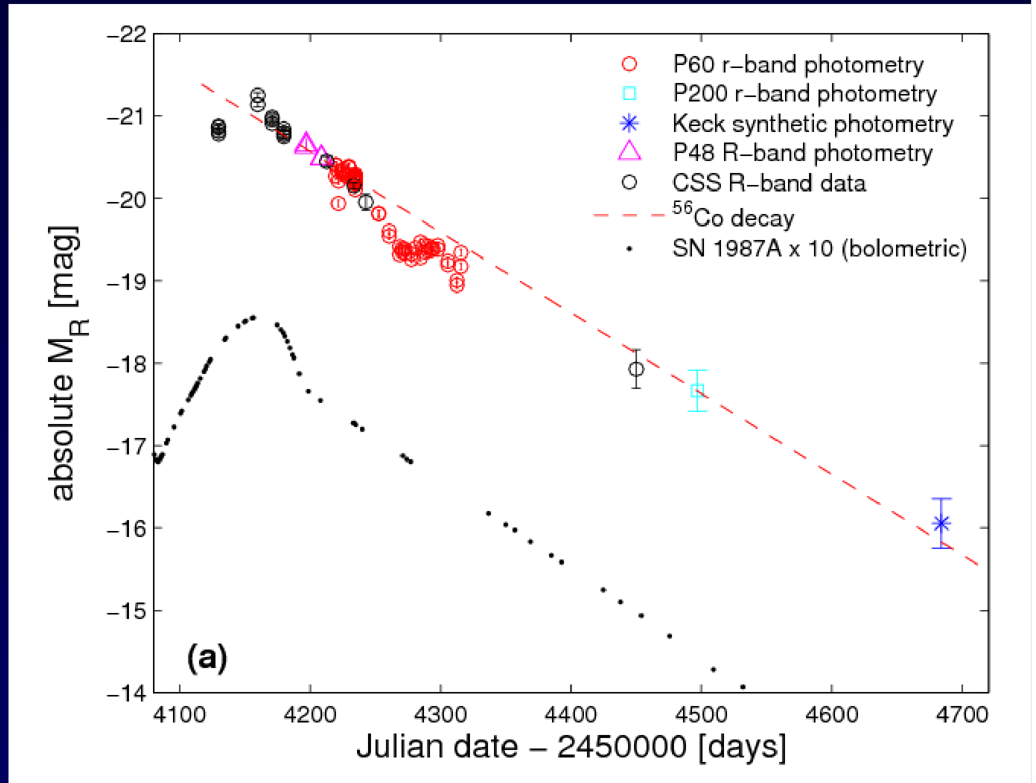


Bastian et al. (2010)

Populations III: $\dot{M} \sim c_s^3/G$ ***with CMB temperature floor***

SN 2007bi – *a Pair Instability Supernova in a Nearby Metal-Poor Dwarf Galaxy*





- Nickel mass of ~4-7$M_\odot$ (ejecta mass of 100 $M_\odot$) ; kinetic energy of $\sim 10^{53}$ergs
- Dwarf galaxy at z=0.128 with M_B=-16.3 mag, and 12+[O/H]=8.25

Gal-Yam et al., Nature (arXiv:1001.1156)

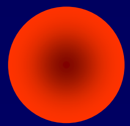
Number of ionizing photons (>13.6eV) per baryon incorporated into stars:

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!



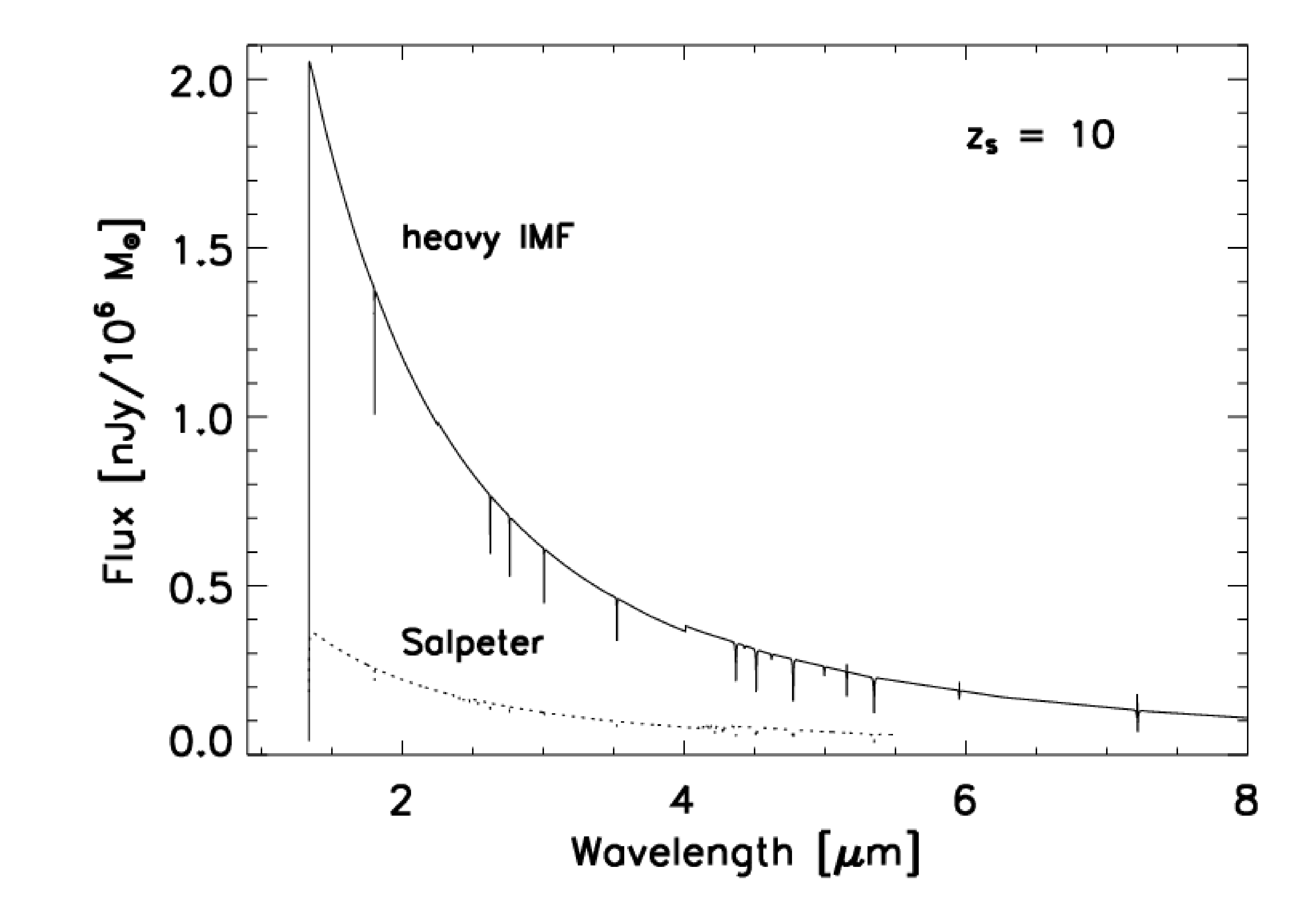
Salpeter mass function

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

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

Spectral signature of Pop-III stars:

strong UV continuum, helium recombination lines – such as 1640A*(1+z), low metal abundance



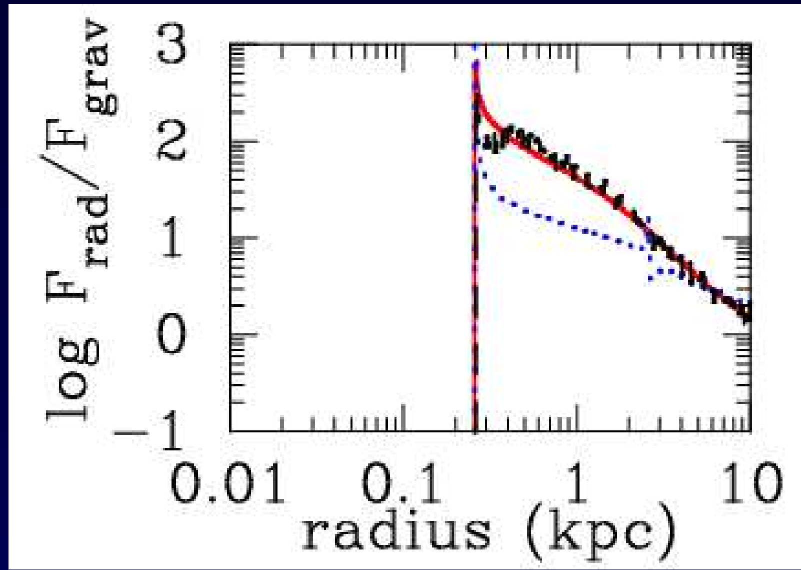
Bromm, Kudritzki, & Loeb (2001)

Outflows Driven by Lya Radiation Pressure

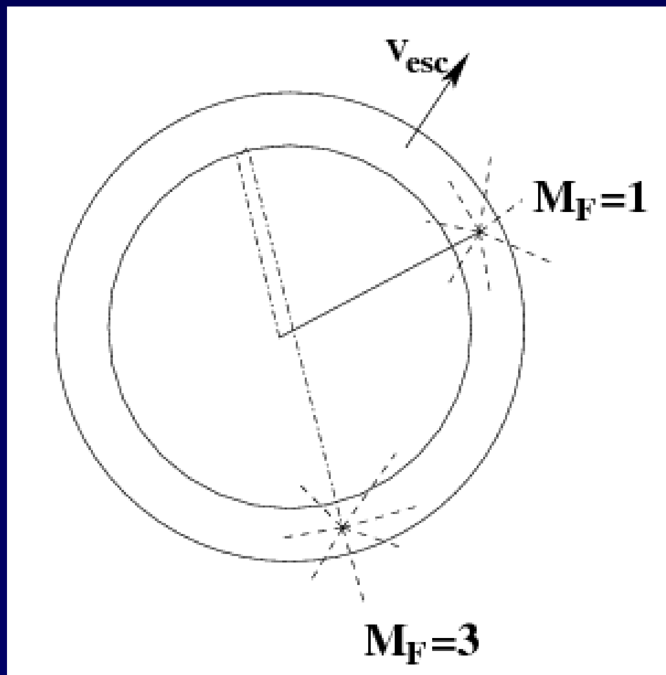
- IGM around the mini-halos hosting the first stars

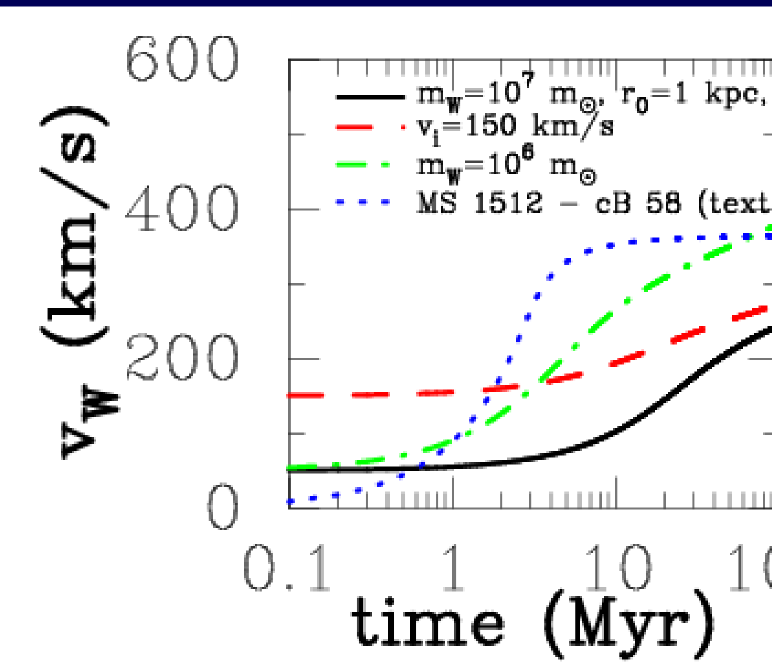
$$M_\star = 100 M_\odot$$

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



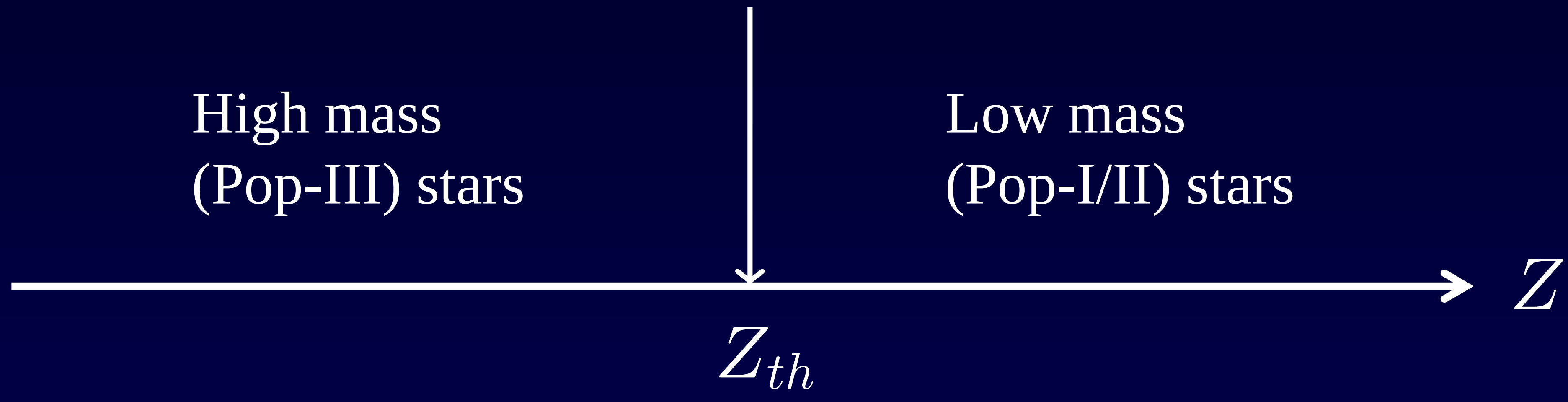
- Supershells around starburst galaxies





Dijkstra & Loeb 2008

Threshold Metallicity



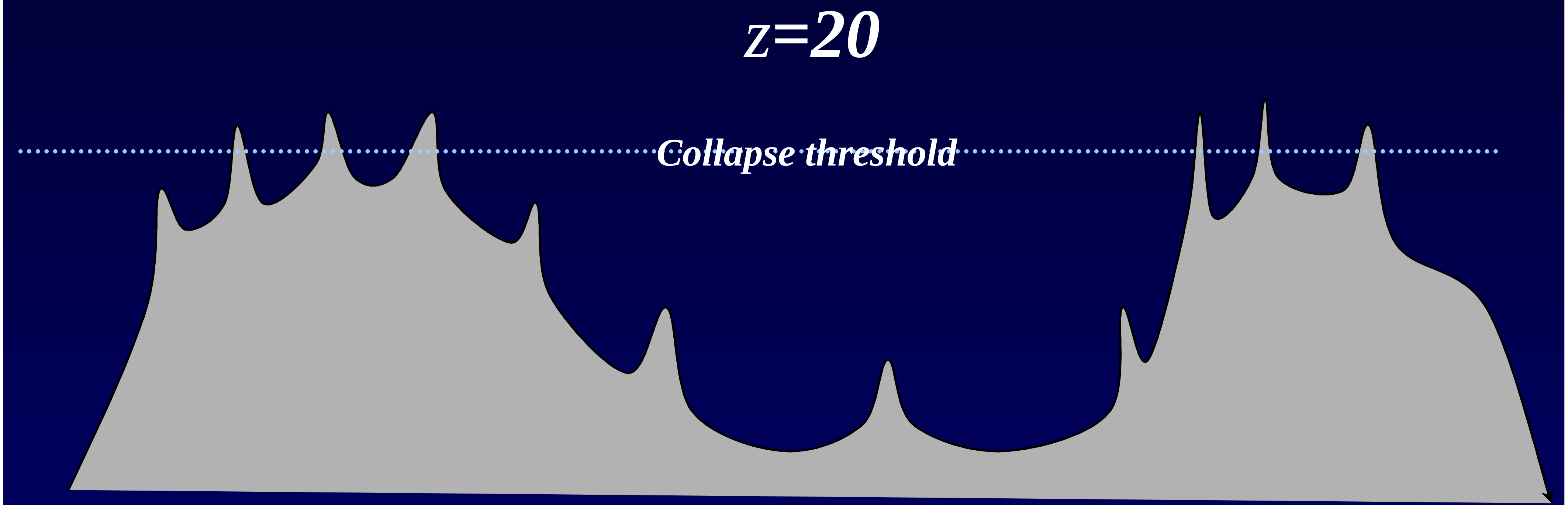
Atomic cooling (CII, OI) → $Z_{th} \sim 10^{-3} Z_{\odot}$

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

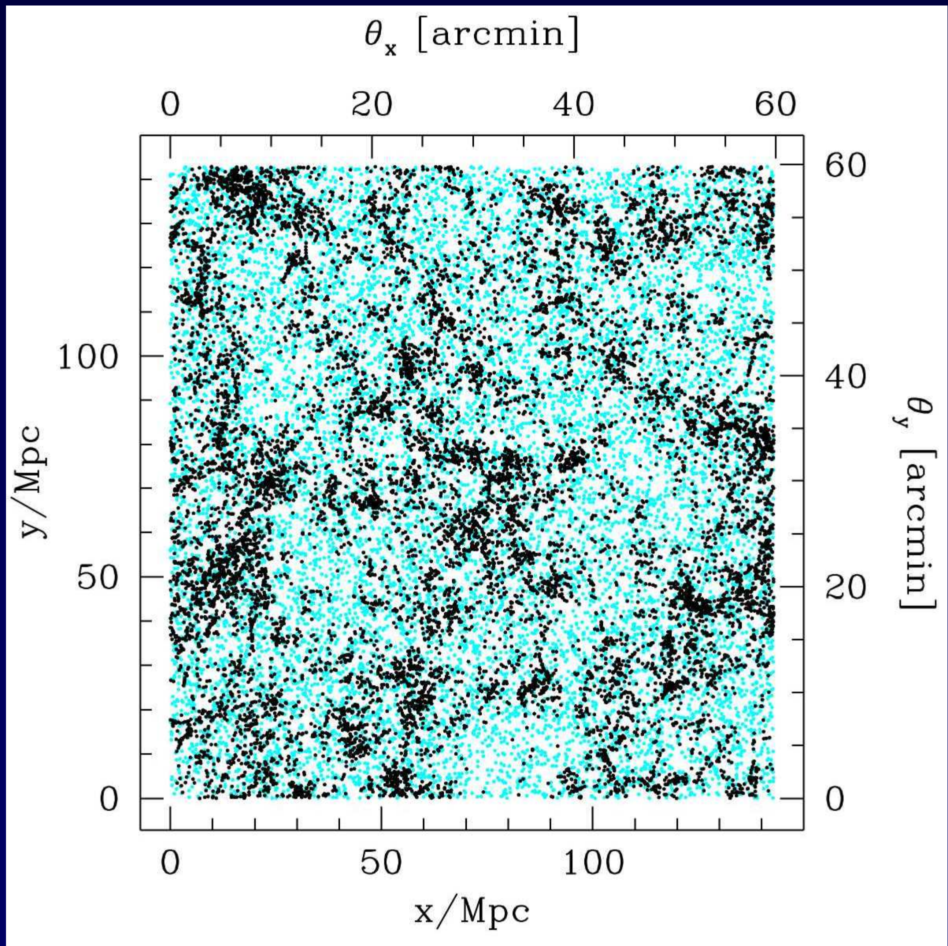
Milky-Way halo metal-poor stars: $Z_{Fe} \sim 10^{-5} Z_{\odot}$

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

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

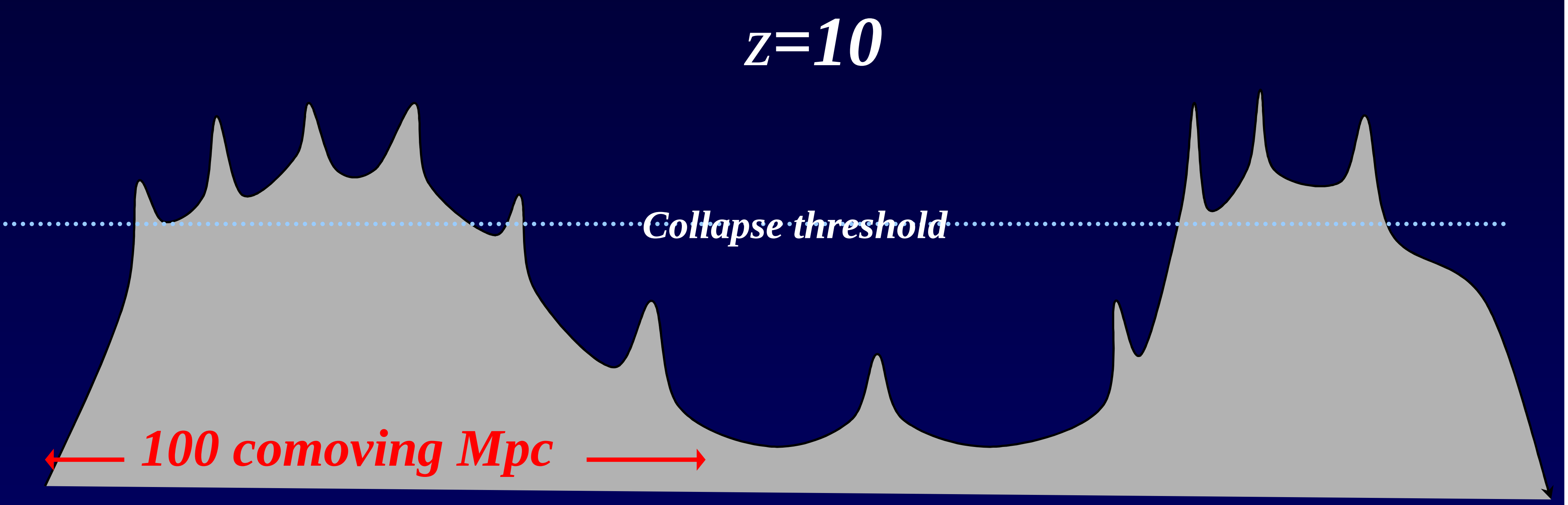


100 Mpc *structure in the simulated distribution of* $10^{10} M_{\odot}$ *galaxies at z=6*



Munoz, Trac, & Loeb 2009

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



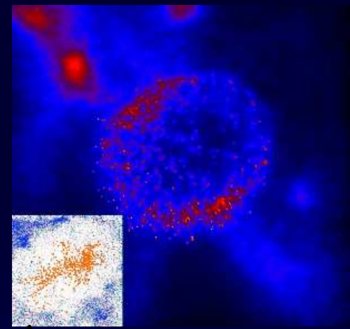
Challenges for numerical simulations of reionization:

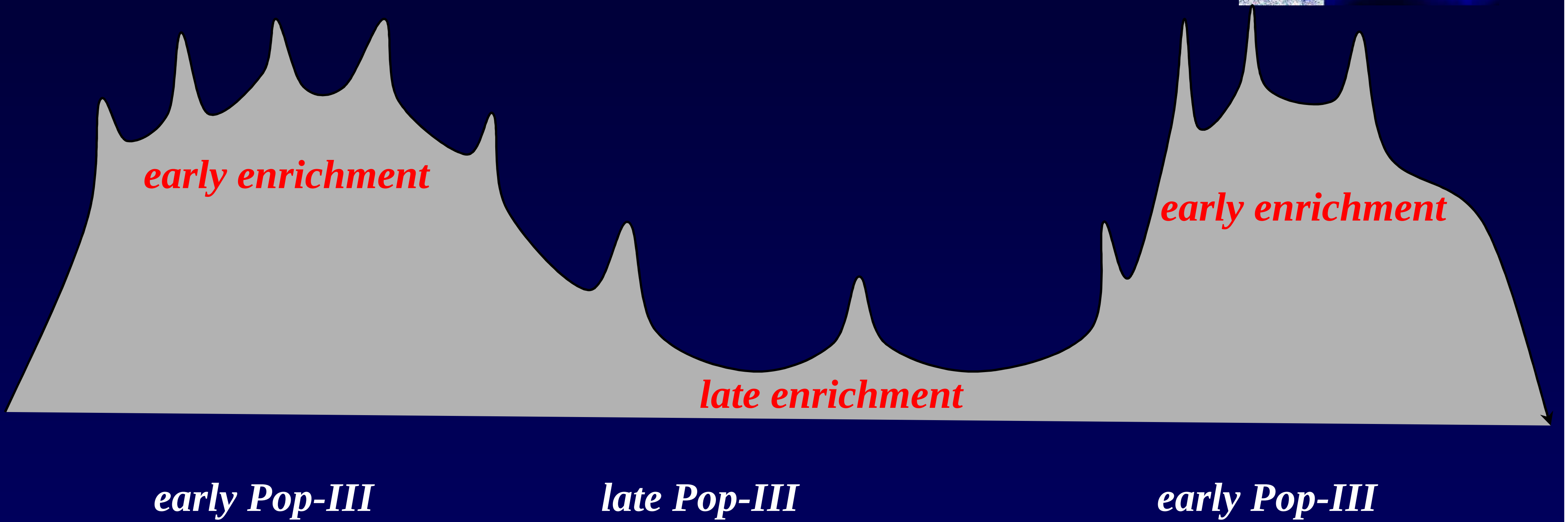
**Resolving dwarf galaxies as sources of ionizing photons*

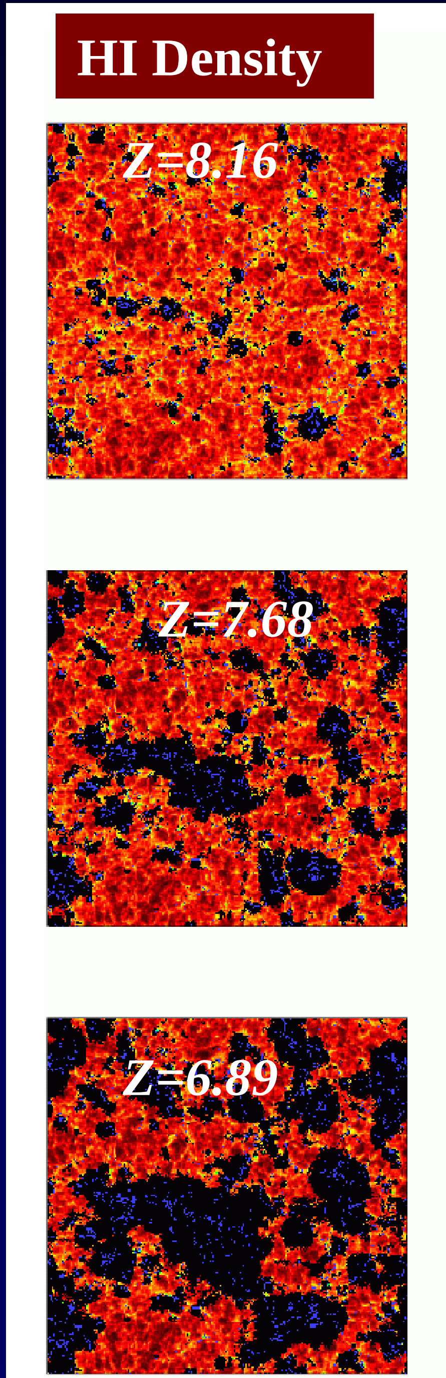
**Simulation box >100 comoving Mpc on a side*

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

→*Enrichment of Primordial Gas with Heavy Elements was Highly Inhomogeneous*







Zahn et al. 2006

Reionization

x_HI(z)

T(z)

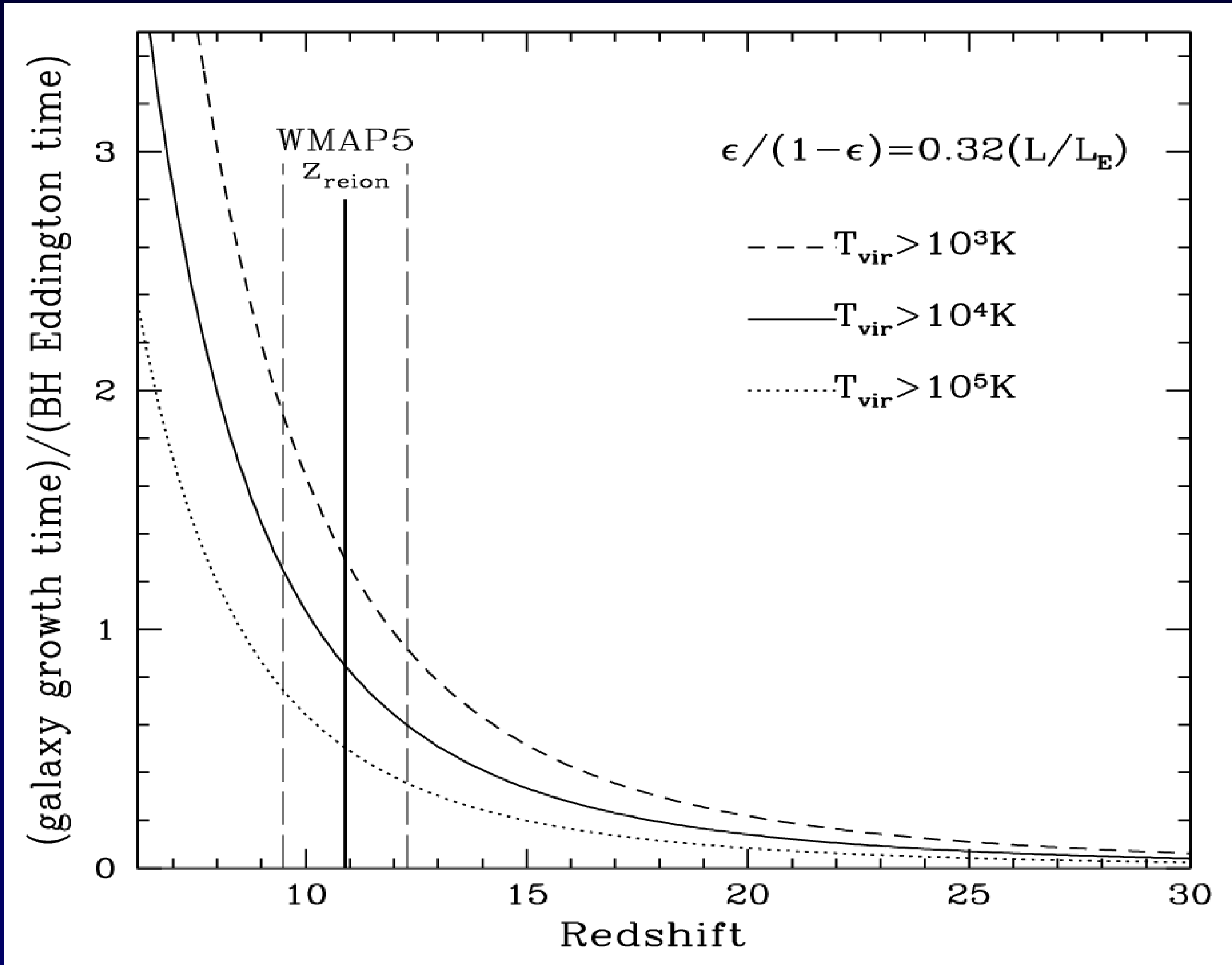
PopII/Pop III

Trac, Cen, & Loeb 2008

Imprints of inhomogeneous reionization:

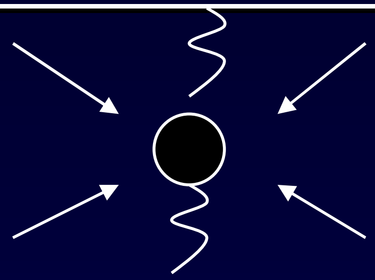
- The minimum virial temperature of galaxies was increased up to ~100,000K inside ionized regions
- Change in the clustering of galaxies (Babich & Loeb 2006; Wyithe & Loeb 2007) and the star formation rate density (Barkana & Loeb 2000)

The Race Between Stars and Quasars in Reionizing Cosmic Hydrogen



Loeb, arXiv:0811.2222, 2008

Nuclear Black Holes



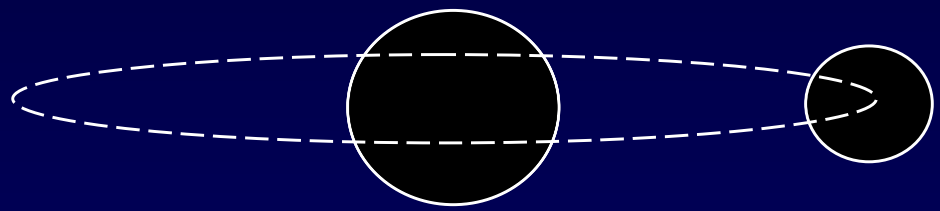
$$L = \epsilon \dot{M} c^2 \qquad t_E = M/\dot{M} = 4 \times 10^7 \frac{(\epsilon/10\%)}{(L/L_E)} \text{years}$$

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

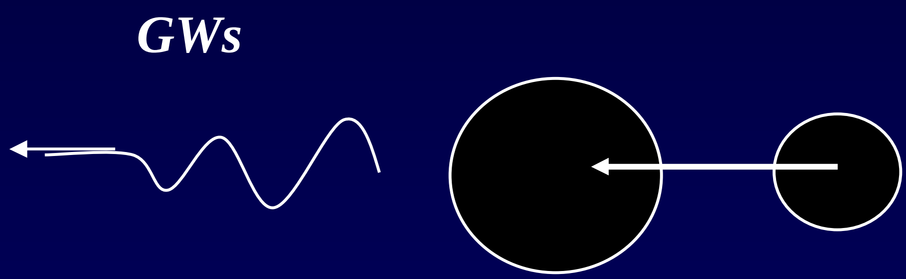
Stellar mass seed requires ~billion years to grow to an SDSS quasar ($10^9 M_\odot$ **)**

….But a billion year is the Hubble time at z~6, and feedback from star formation and quasar activity as well as BH kicks are likely to suppress continuous accretion…

Gravitational Wave Recoil

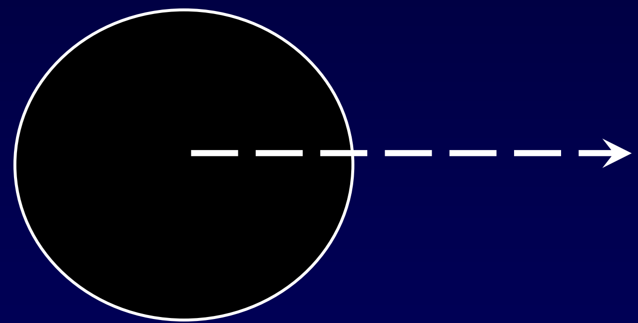


Gravitational Wave Recoil

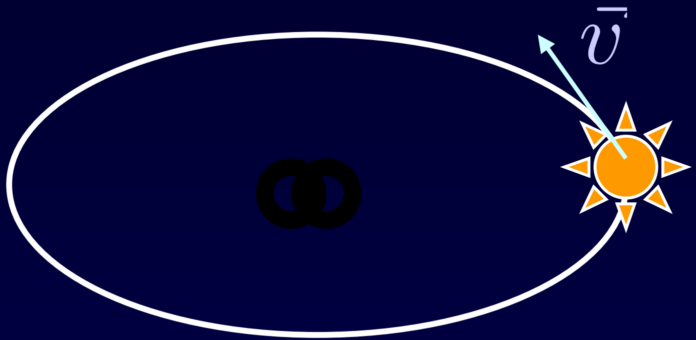


Anisotropic emission of gravitational waves → momentum recoil

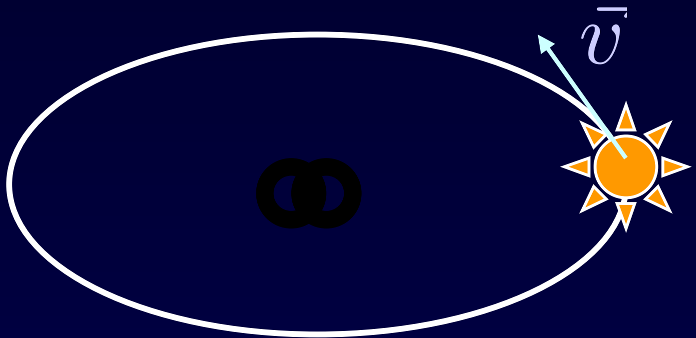
Gravitational Wave Recoil



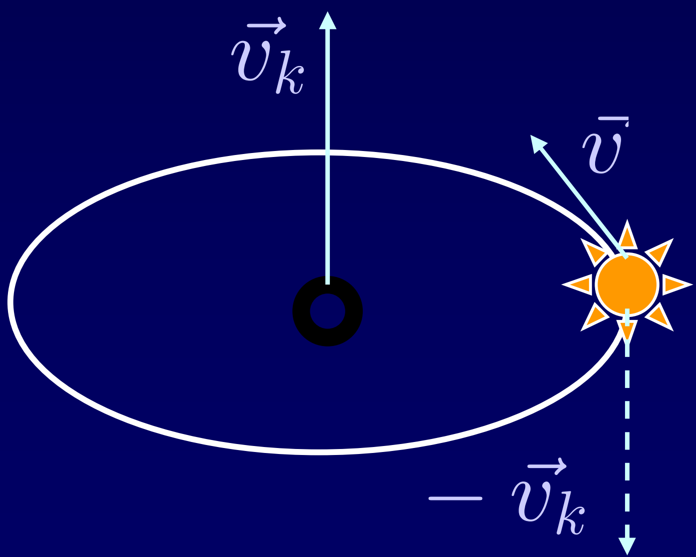
Recoil speed (~tens-4000 km/s) is independent of remnant black hole mass → *low-mass halos may easily lose their low-mass seeds after several mergers*



$$E = \frac{1}{2}v^2 - \frac{GM}{r} = -\frac{1}{2}v^2$$

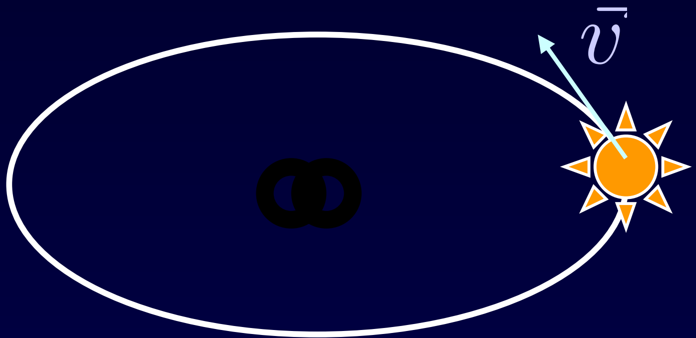


$$E = \frac{1}{2}v^2 - \frac{GM}{r} = -\frac{1}{2}v^2$$

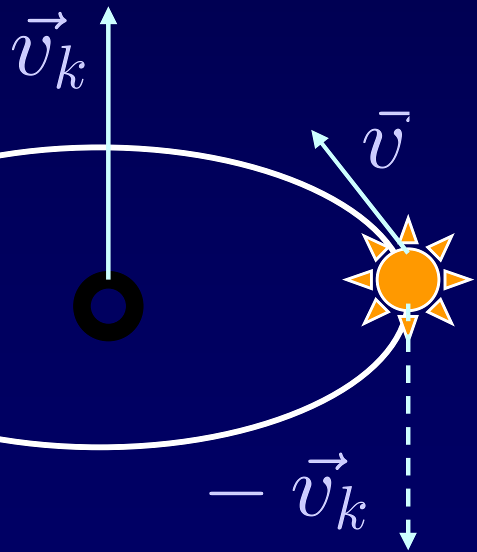


$$E = \frac{1}{2}(\vec{v} - \vec{v}_k)^2 - \frac{GM}{r}$$

$$= \vec{v} \cdot \vec{v}_k + \frac{1}{2}(v_k^2 - v^2)$$



$$E = \frac{1}{2}v^2 - \frac{GM}{r} = -\frac{1}{2}v^2$$



$$E = \frac{1}{2}(\vec{v} - \vec{v}_k)^2 - \frac{GM}{r}$$

$$= \vec{v} \cdot \vec{v}_k + \frac{1}{2}(v_k^2 - v^2)$$

→ *test particles with* $v \gg v_k$ ***remain bound***

Star Clusters Around Recoiled Black Holes in the Milky Way Halo

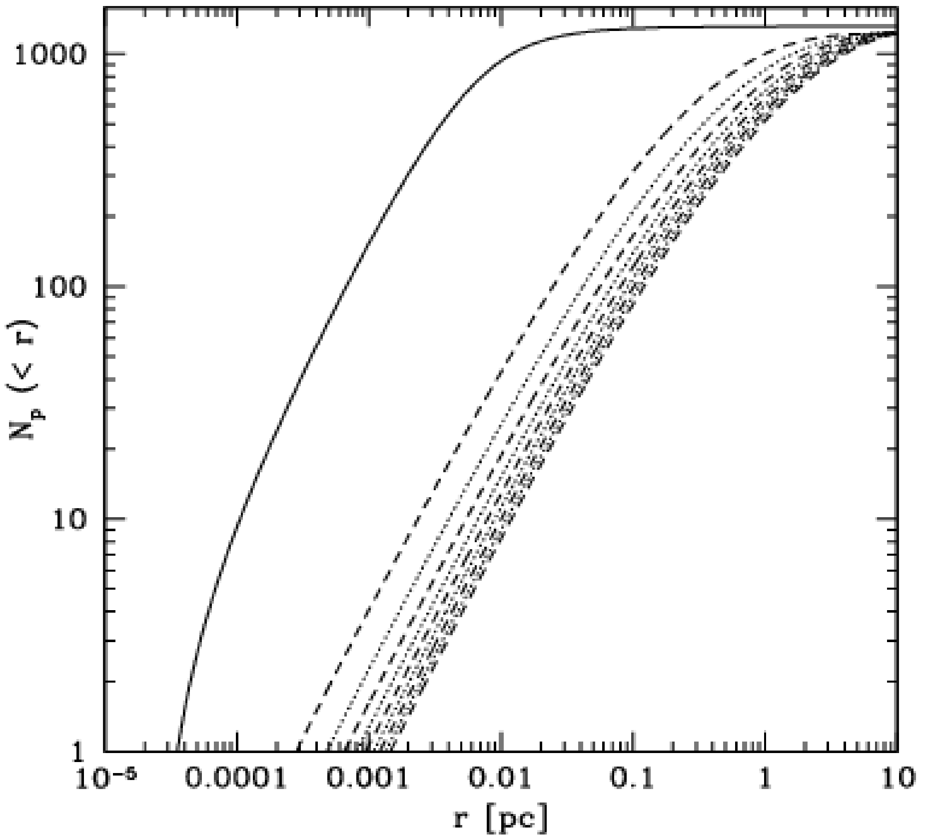


Figure 2. The total number of projected stars interior to r, $N_p(<r)$, for $M_\bullet = 10^5 \mathrm{M}_\odot$ and $\alpha = 1.75$. The solid line corresponds to the cluster immediately after being ejected from its parent galaxy with $v_k = 5.8\sigma_*$. The alternating dashed and dotted lines correspond to the projected number of stars after every $10 t_r \approx 650$ Myr. Immediately after ejection, the cluster rapidly expands until its relaxation time becomes comparable to the age of the Universe, with very little mass loss. In the case of $\alpha = 1$, the cluster evolves similarly, but only with ~ 100 stars in the cluster. For a $10^5 \mathrm{M}_\odot$ BH, the circular velocity of the stars is $\approx 66\,\mathrm{km\,s^{-1}}(r/0.1\,\mathrm{pc})^{-1/2}$.

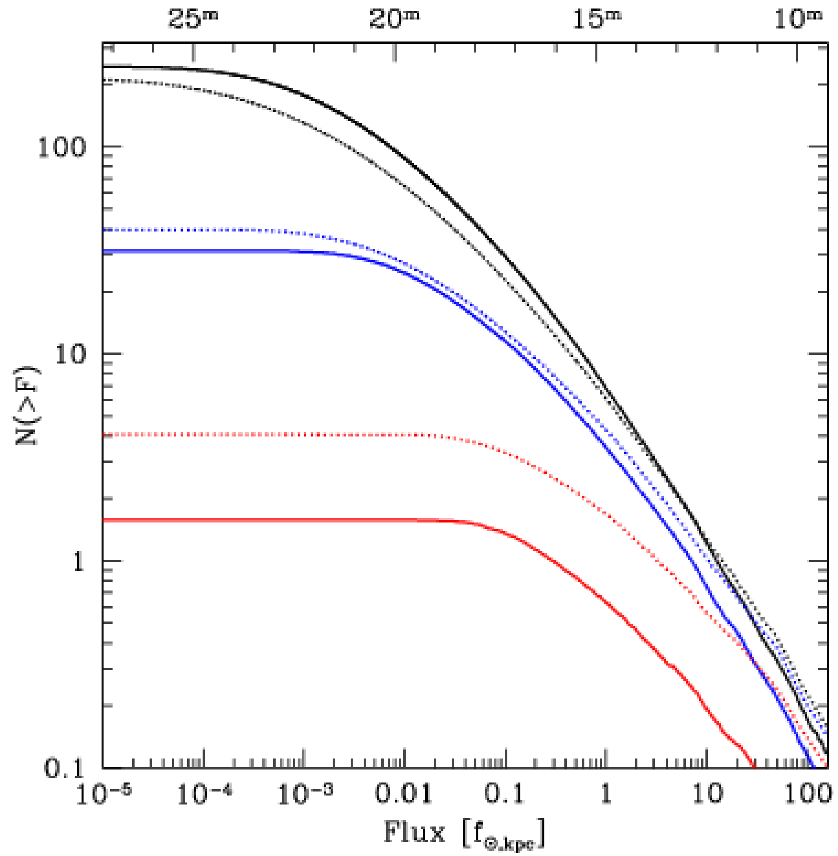
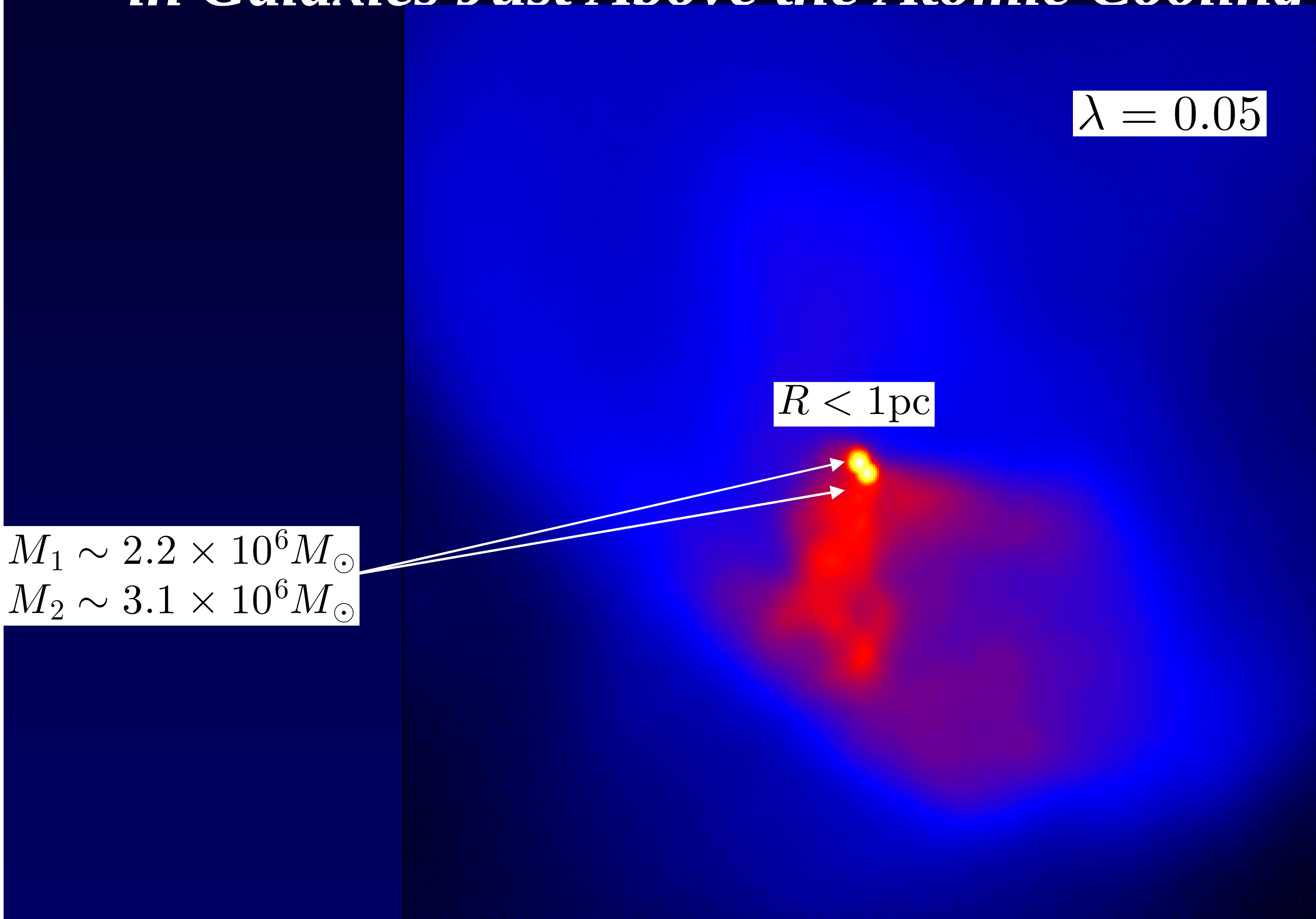


Figure 1. The cumulative distribution of ejected star clusters in the MW Halo. Plotted is the flux distribution associated with BHs masses greater than $10^3 \mathrm{M}_\odot$ (black), $10^4 \mathrm{M}_\odot$ (blue), and $10^5 \mathrm{M}_\odot$ (red), in our models with BH spin $a = 0.9$ (solid) and $a = 0.1$ (dashed) lines, plotted in units of the flux of the Sun at a distance of 1 kpc ($f_{\odot,\mathrm{kpc}}$). The top axis is labeled with the apparent bolometric magnitude of the clusters. Nearly all BHs with $M_\bullet \gtrsim 2\times10^3 \mathrm{M}_\odot$ have apparent magnitudes greater than 21, the rough magnitude limit of SDSS. The mass distribution of the ejected BHs has approximately equal mass per log $M_\bullet$ interval, with $\mathrm{d}N_{\mathrm{BH}}/\mathrm{d}M_\bullet \propto M_\bullet^{-1}$.

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

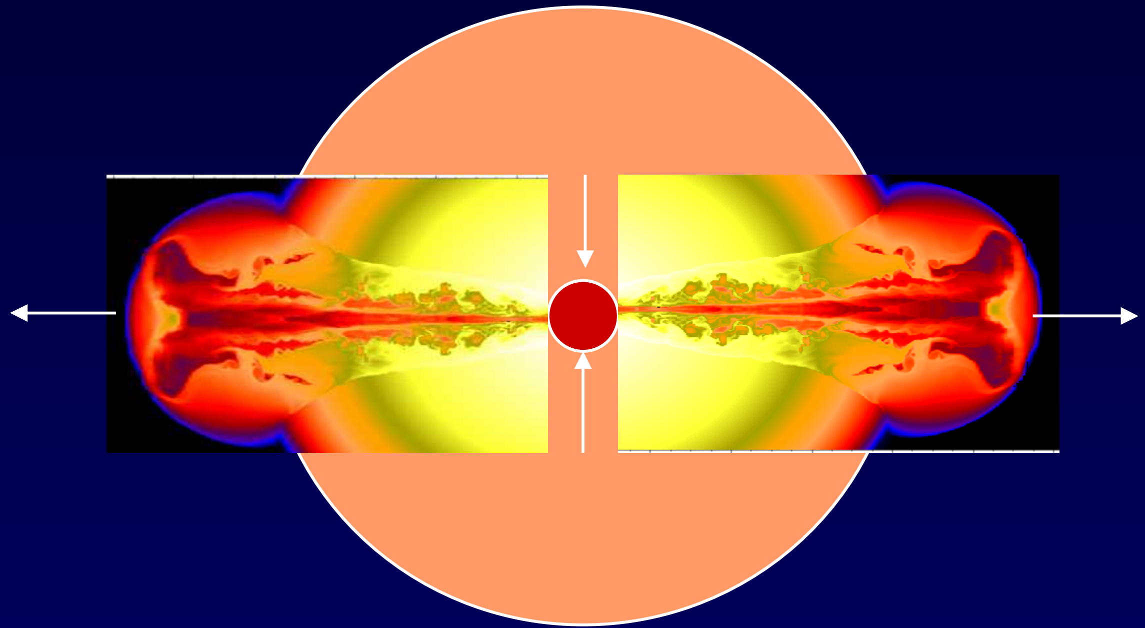


Unusual environments: H_2 suppressed ***; binary black holes may form –LISA sources***

***Numerical simulations:* Bromm & Loeb 2003**

Recent work: Dijkstra et al. 2008; Regan & Haehnelt 2009

Long Gamma-Ray Bursts: Observing One Star at a Time



Collapse of a Massive Star

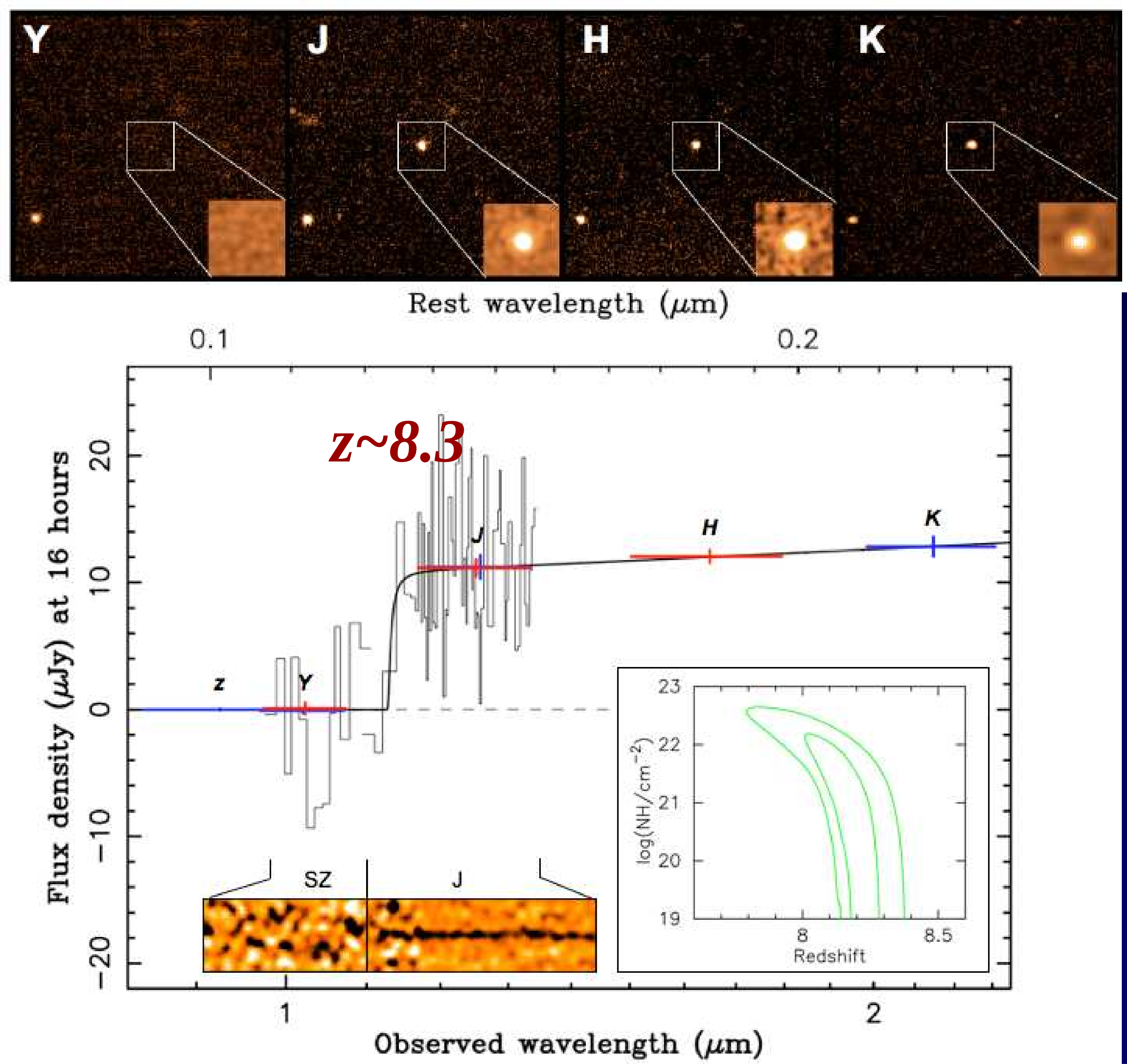
(accompanied by a supernova)

High-Redshift Gamma-Ray Bursts

Existing finder: ***Swift;*** **Proposed:** ***EXIST***

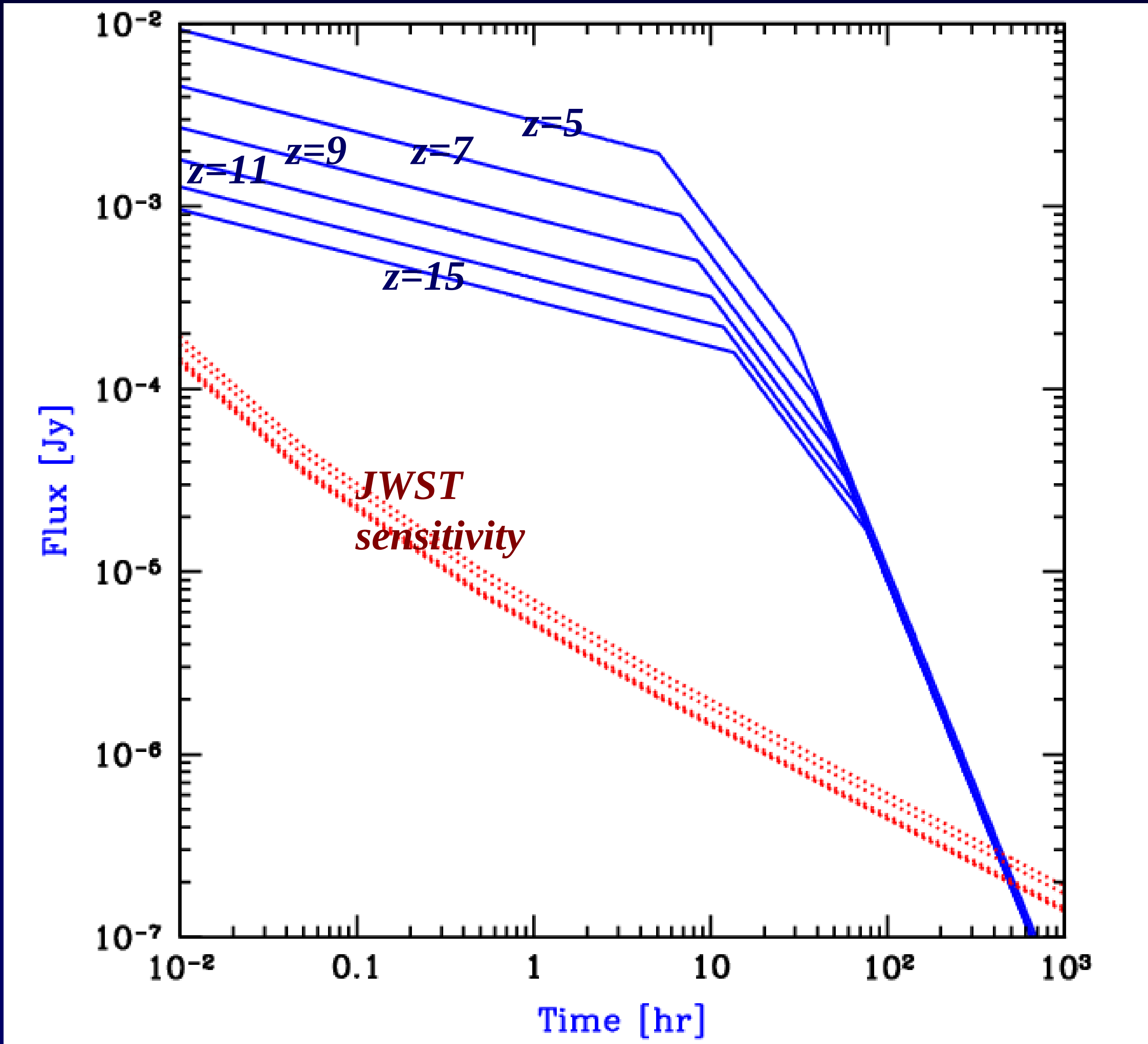
- **Key observational question:** ***how to efficiently identify high-z GRBs ?***
- **Key theoretical question:** ***Pop-III progenitors?***
- **Requirements:** ***sufficient angular momentum to make a disk around the central black hole & loss of progenitor's envelope, so that central engine would still be active upon jet exit. Related issues: binarity, winds.***

A Bright Explosion 620 Million Years after the Big Bang



Detectability of Afterglow Emission Near the Lya Wavelength

Photometric redshift identification: based on the Lya trough



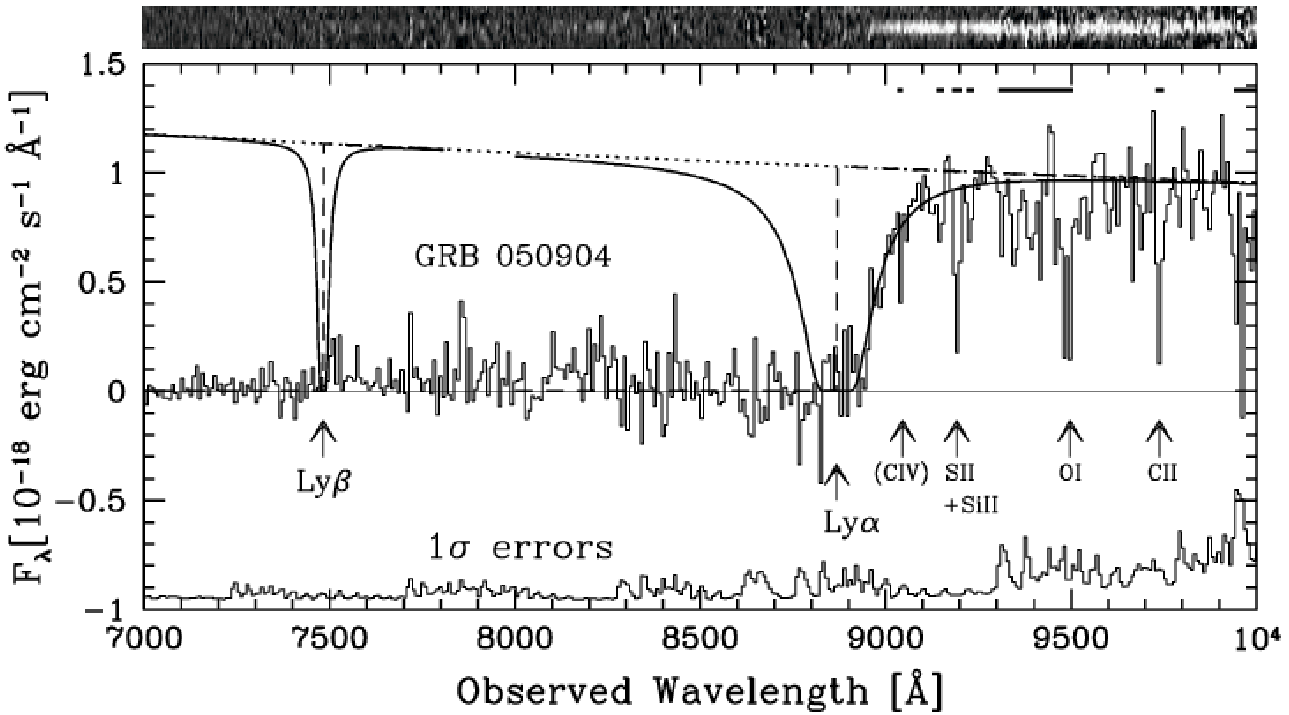
Barkana & Loeb 2003

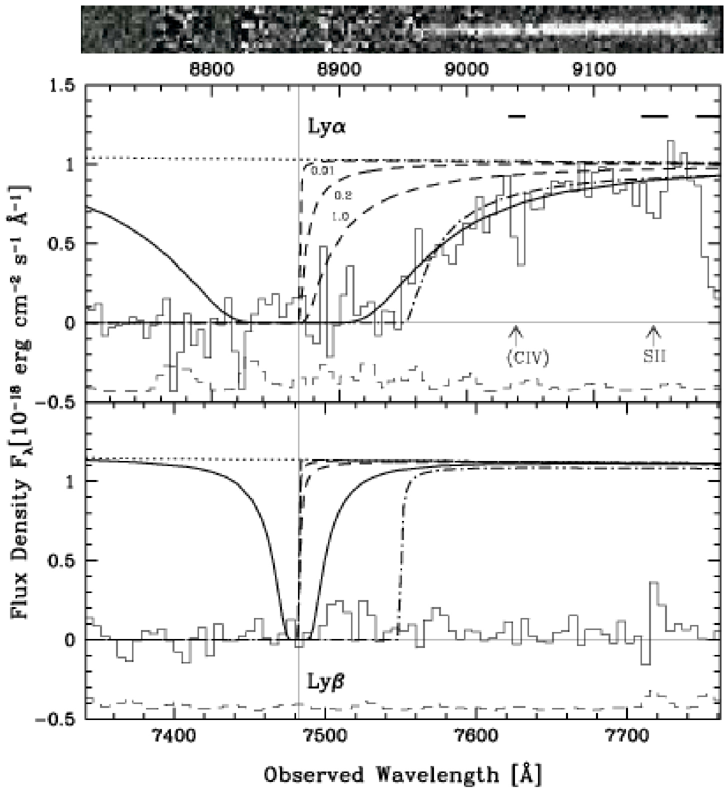
astro-ph/0305470

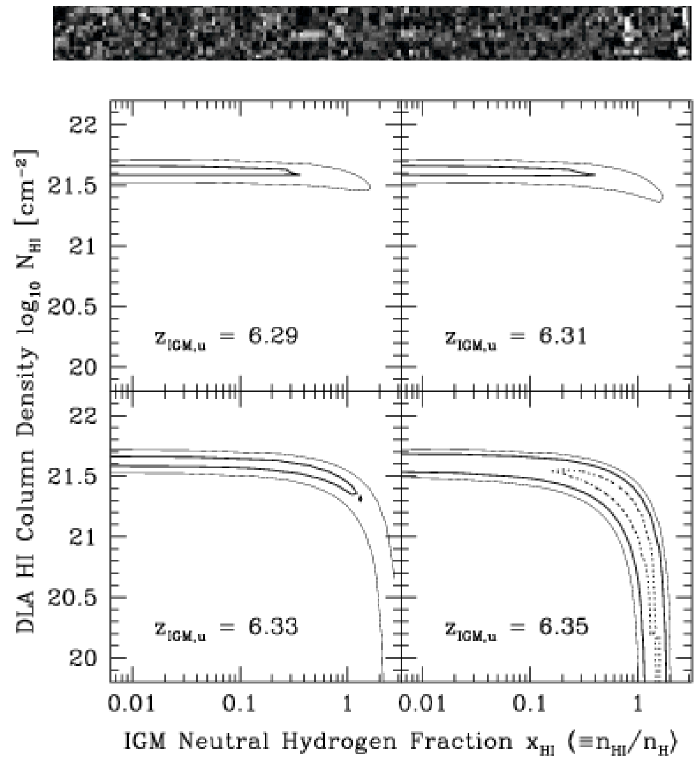
Implications for the Cosmic Reionization from the Optical Afterglow Spectrum of the Gamma-Ray Burst 050904 at $z = 6.3$*

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]

But associated DLAs hide Lya absorption from the IGM…





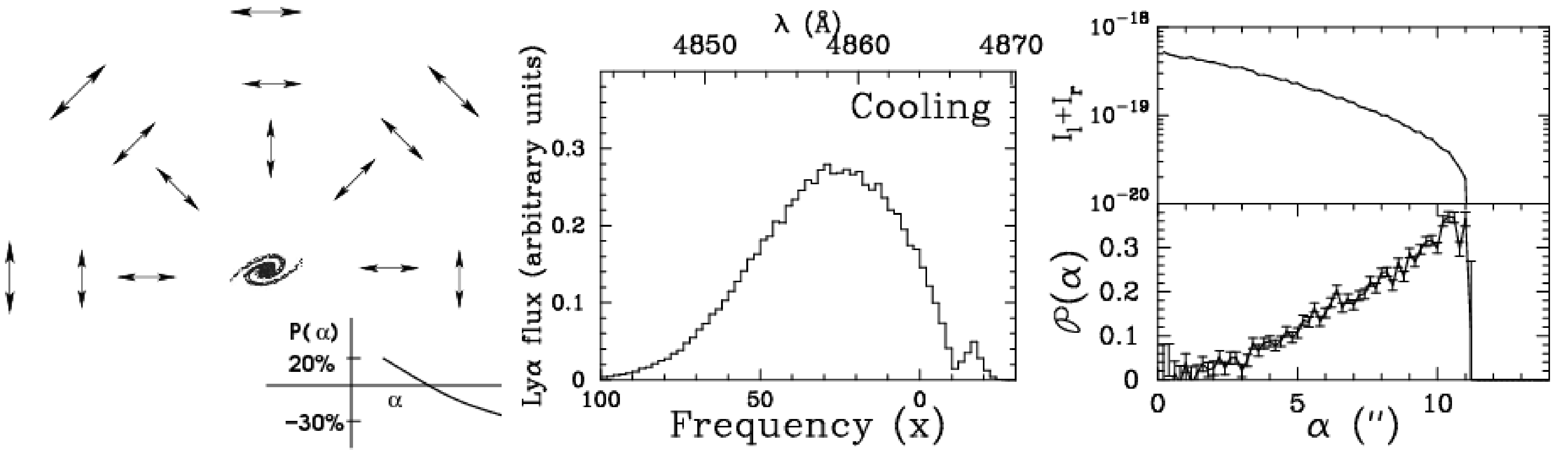


Searches for high-z Galaxies:

- Lyman-break
- $\mathrm{Ly}\alpha$
- Other lines (H_{α} , CO, CII, OI, He)

A future frontier*: polarized** $\mathrm{Ly}\alpha$ ***halos

Collapsing gas cloud



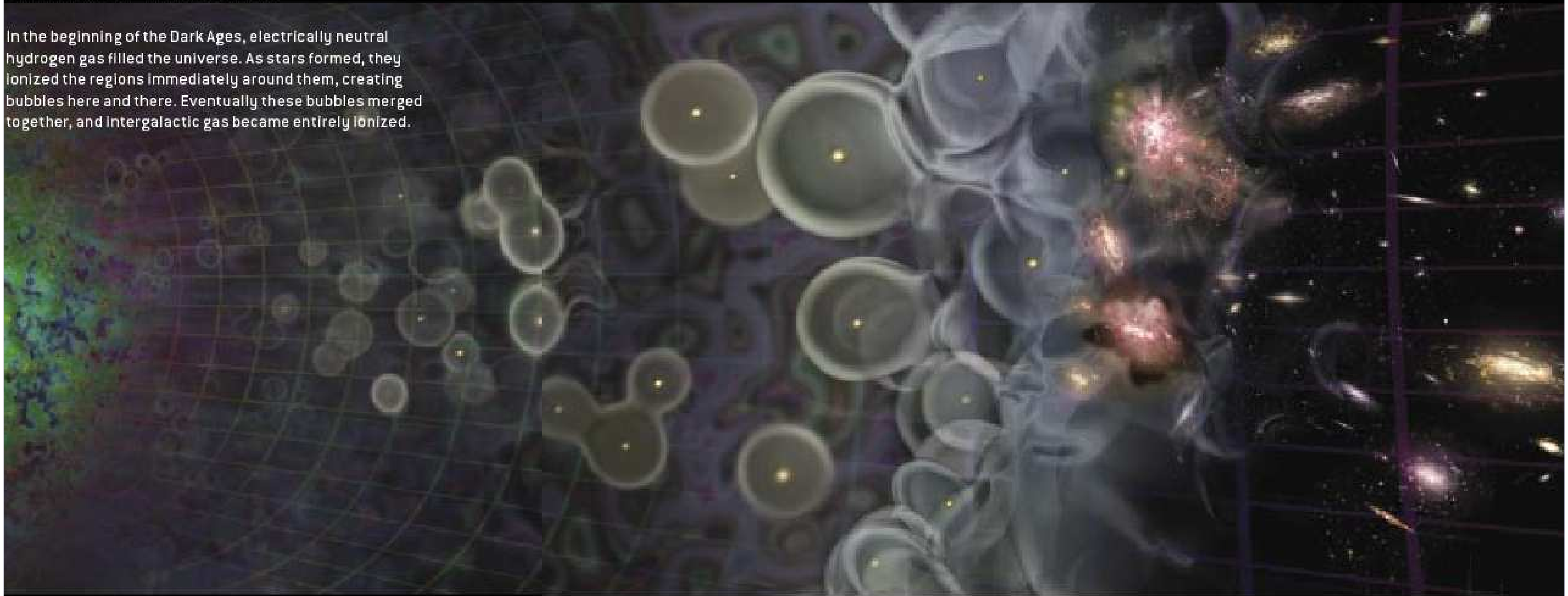
Rybicki & Loeb 1999; Dijkstra & Loeb arxiv:0711.2312

Observing the Diffuse Gas

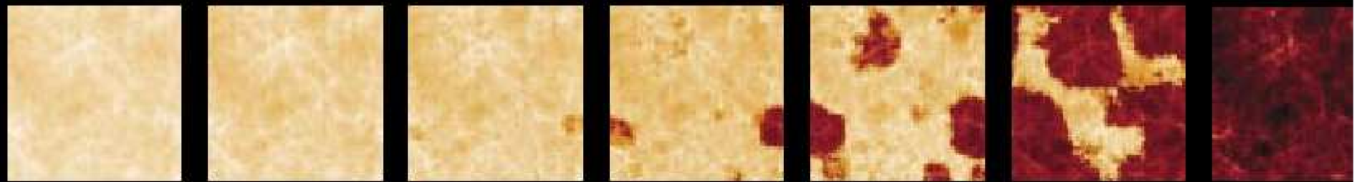
21cm Mapping of Cosmic History

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.



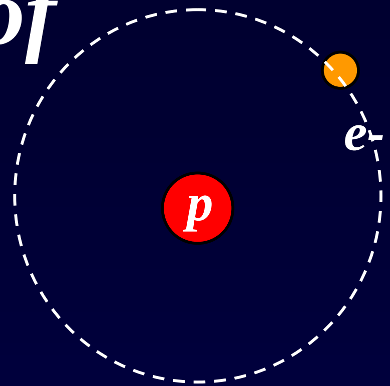
Time:	210 million years	290 million years	370 million years	460 million years	540 million years	620 million years	710 million years
Width of frame:	2.4 million light-years	3.0 million light-years	3.6 million light-years	4.1 million light-years	4.6 million light-years	5.0 million light-years	5.5 million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

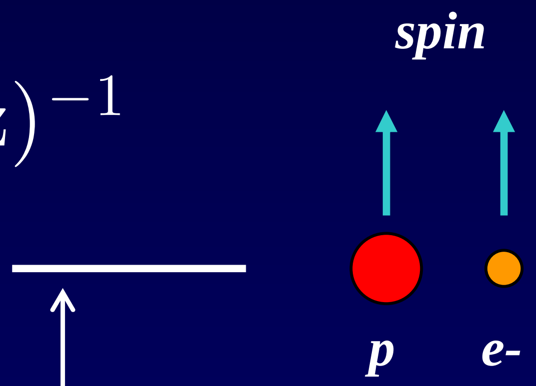


Ground level

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

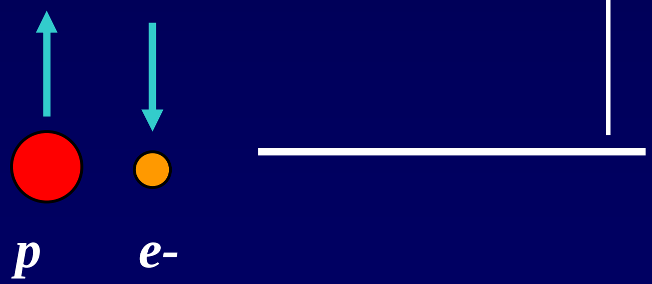
Couple T_s ***to*** T_k ***Couples*** T_s ***to*** T_γ

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



$_1S_{1/2}$

$_0S_{1/2}$



Spin Temperature

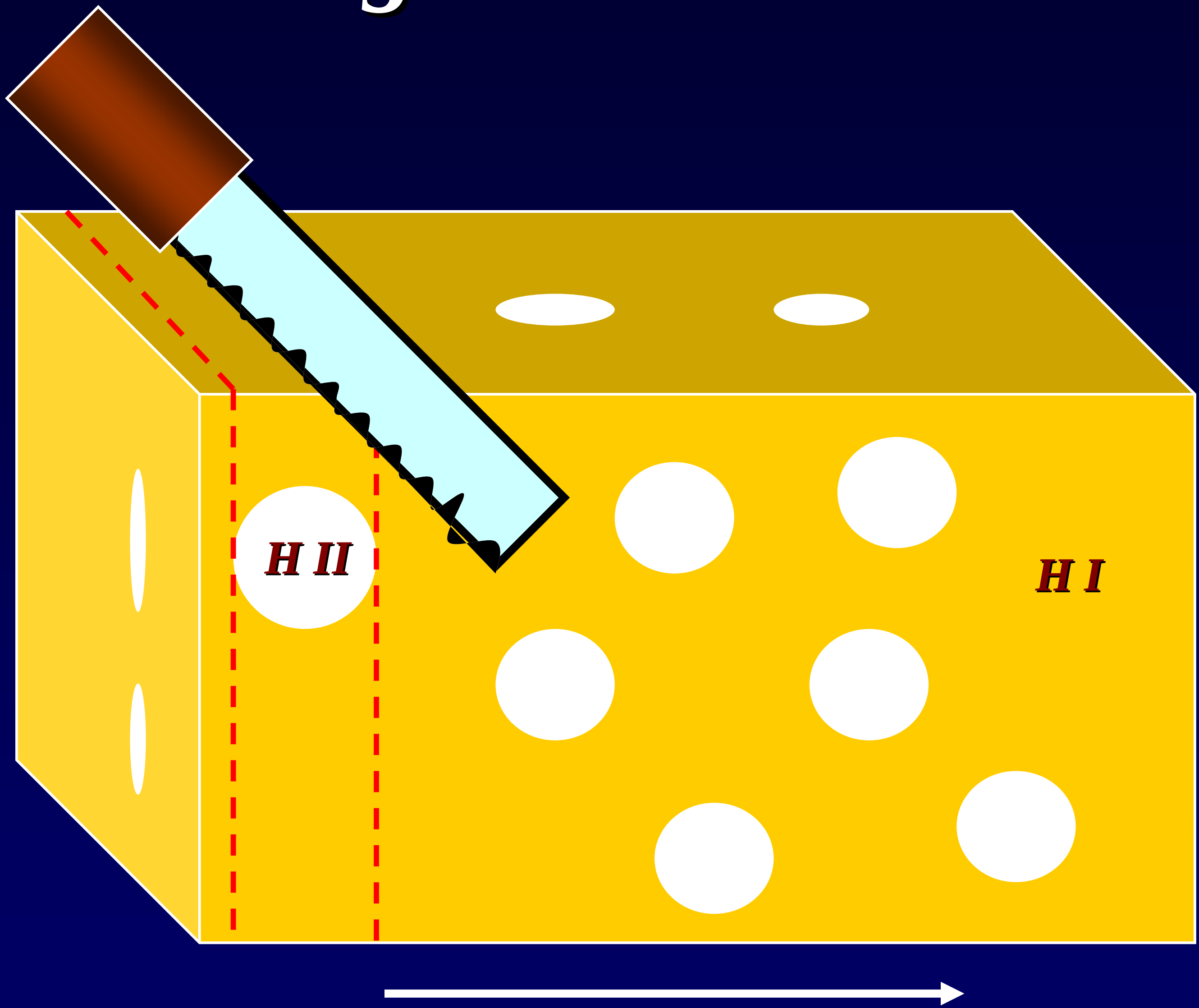
$$\frac{n_1}{n_0} = \frac{g_1}{g_0}\exp\{-\frac{0.068\text{K}}{T_s}\}$$

$$(g_1/g_0) = 3$$

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

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

Separating the Physics from the Astrophysics

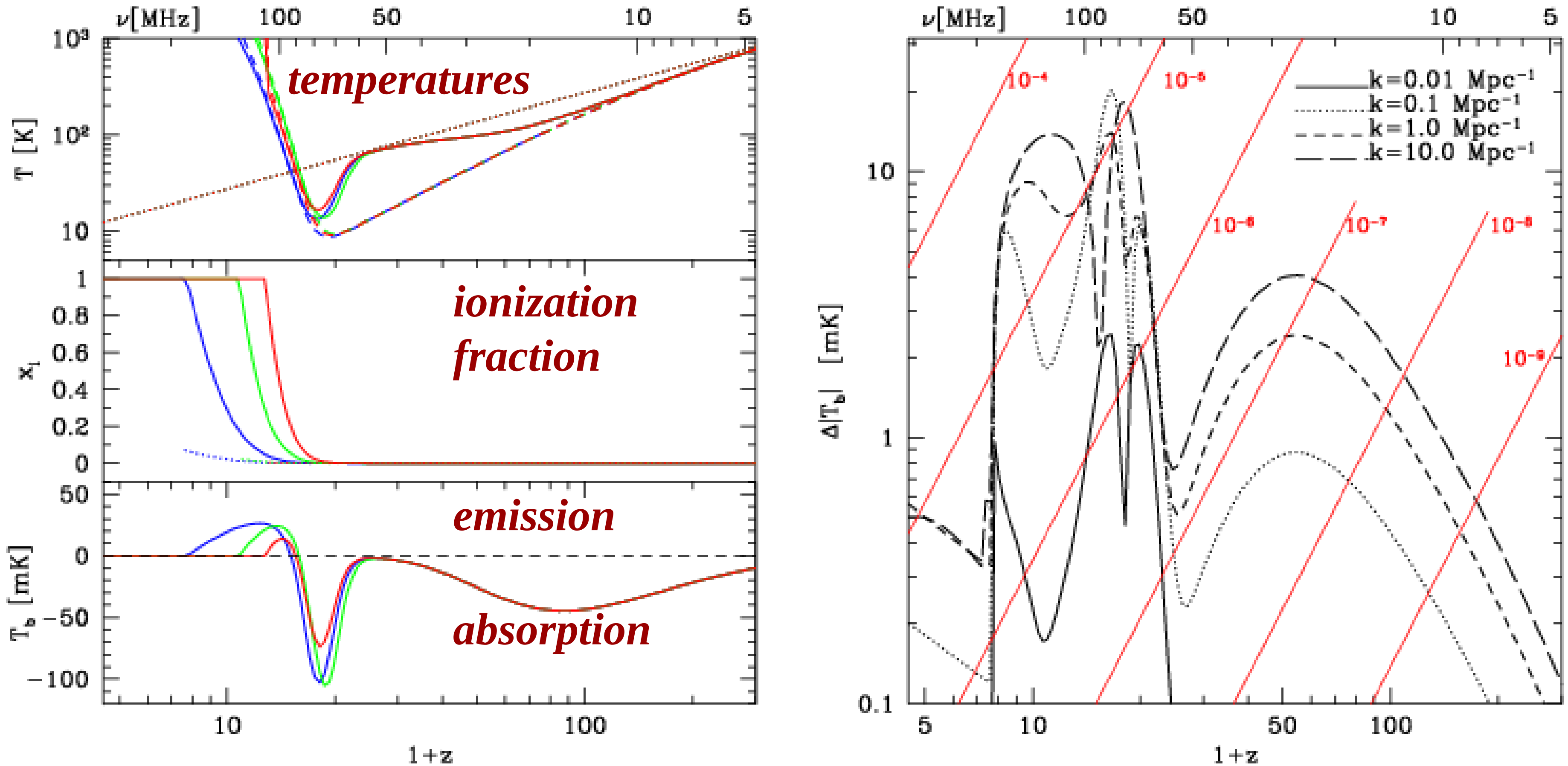
Physics: *initial conditions from inflation; nature of dark matter and dark energy*

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

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



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 requirec .

(Pritchard & 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)***

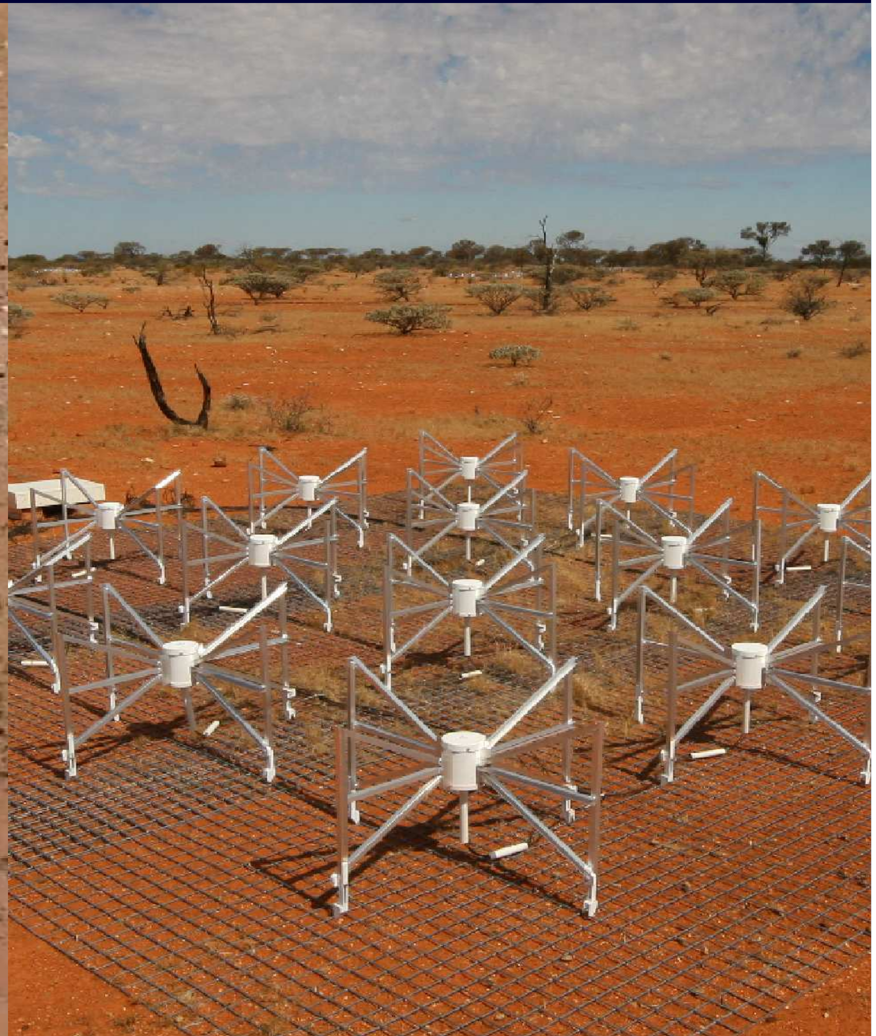
International

Observatory Parameters

experiment	site	type	ν range MHz	Area m^2	date	goal
Mark I[a]	Australia	spiral	100-200	few	2007	All Sky
EDGES[b]	Australia	four-point	100-200	few	2007	All Sky
GMRT[c]	India	parabola array	150-165	4e4	2007	CSS[d]
PAPER[e]	Australia	dipole array	110-190	1e3	2007	PS/CSS/Abs
21CMA[f]	China	dipole array	70-200	1e4	2007	PS
MWAd[g]	Australia	aperture array	80-300	1e4	2008	PS/CSS/Abs
LOFAR[h]	Netherlands	aperture array	115-240	1e5	2008	PS/CSS/Abs
SKA[i]	TBD	aperture array	100-200	1e6	2015	Imaging

Status: analogous to CMB research prior to COBE

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

When Was the Universe Ionized?

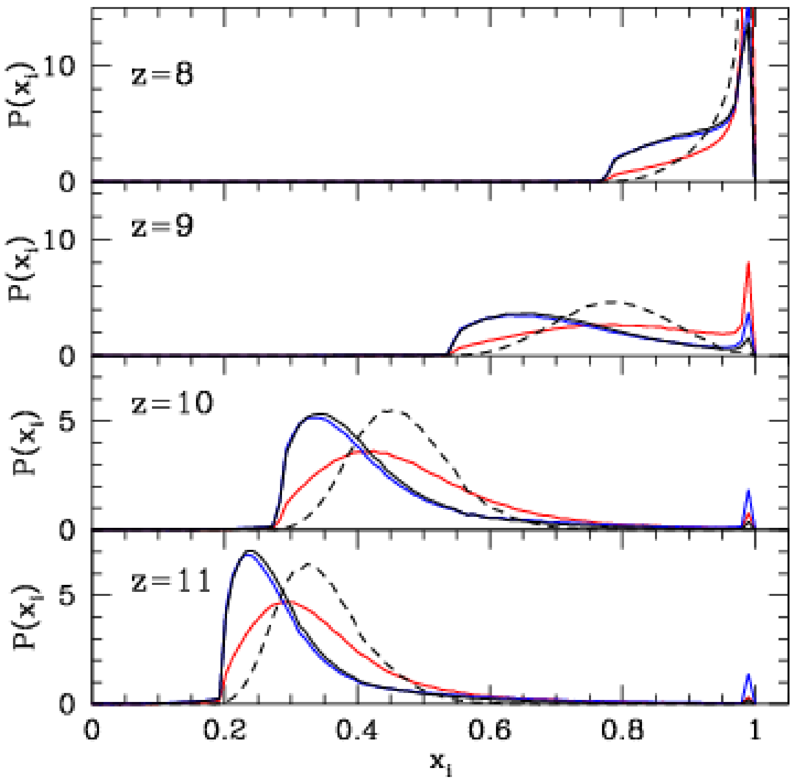


Figure 5. Distribution of x_i at redshifts $z = 8$, 9, 10, and 11 for the ζ parametrization. Same curve styles as for Figure 4.

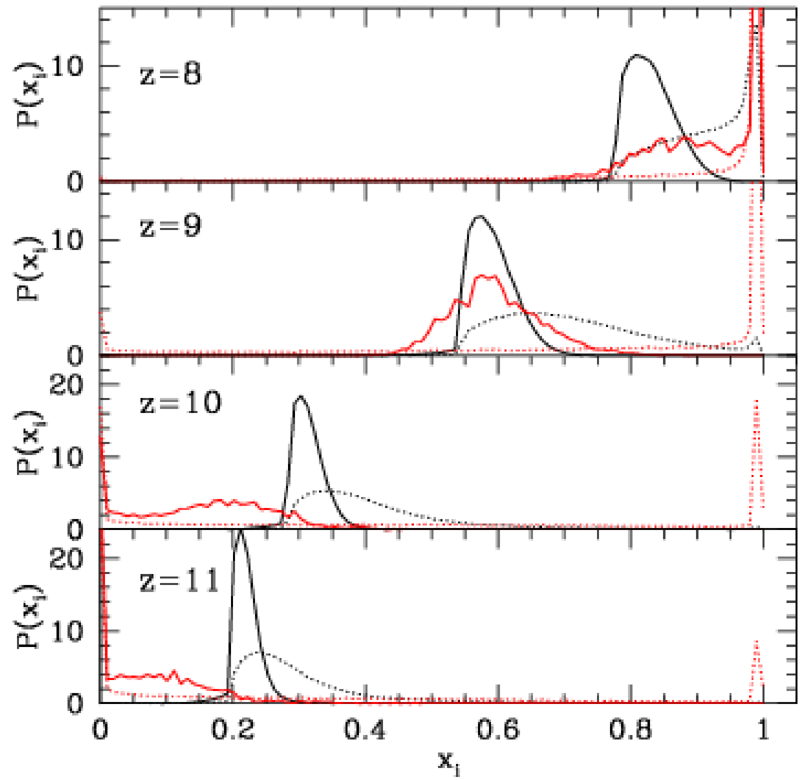


Figure 14. Distribution of x_i at redshifts $z = 8$, 9, 10, and 11 when 21 cm measurements are included. In each panel, we plot the distribution of the ζ (black) and $\dot{N}_{\rm ion}$ (red) parametrizations with (solid curves) and without (dotted curves) a 21 cm measurement of $x_i(z = 9.5) = 0.5 \pm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

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

Pritchard, Loeb, & Wyithe, arXiv:0908.3891

The Next Decade Promises to be Exciting!

- ***Large-aperture infrared telescopes and radio arrays will image galaxies and the diffuse cosmic gas during the epoch of reionization. 21-cm brightness fluctuations are expected to be anti-correlated with infrared galaxies during reionization and correlated after reionization.***
- ***Adequate simulations of reionization are starting to employ sufficiently large (>100Mpc) boxes with sufficient spatial resolution to properly identify the ionizing sources.***