Probing the first stars and their effects on the universe

Other Conference Item

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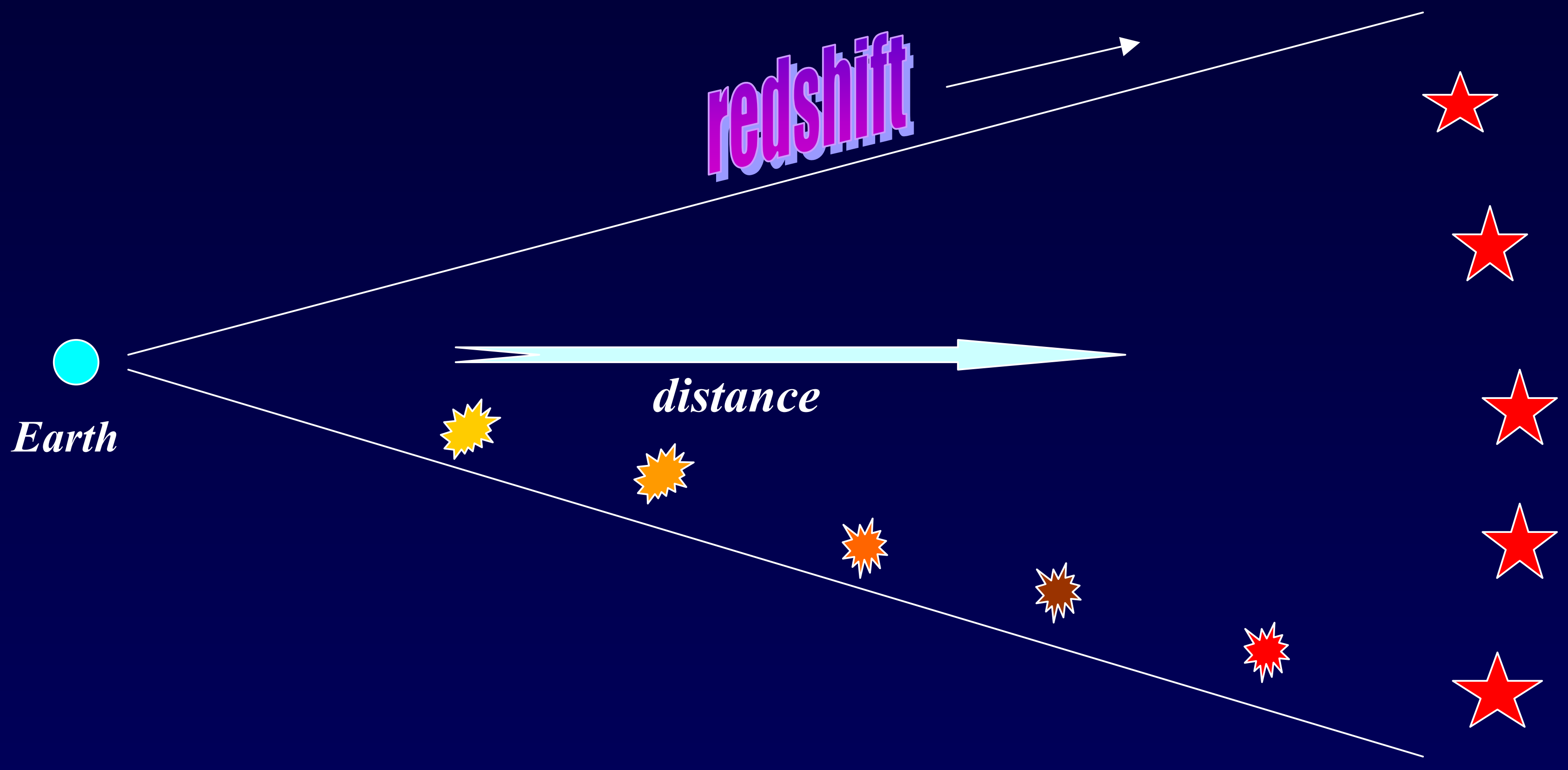
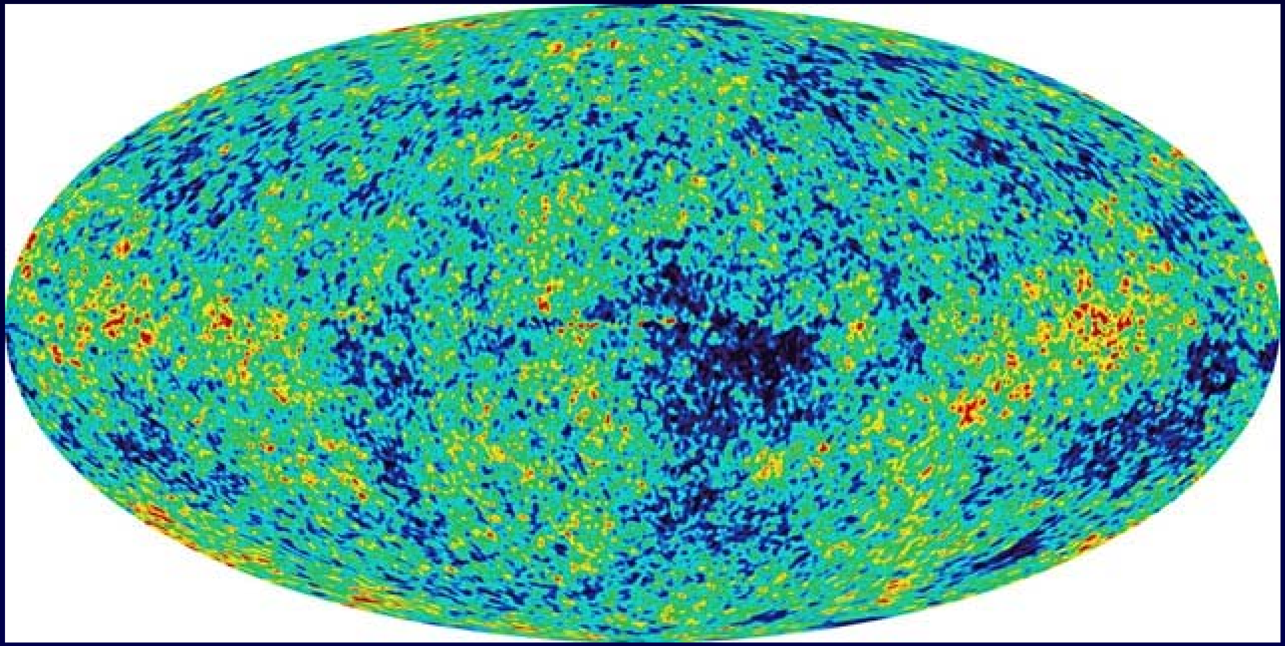
Cosmic-Archeology : the First Stars and Their Effects on the Universe



The more distant a source is, the more time it takes for its light to reach us. Hence the light must have been emitted when the universe was younger. By looking at distant sources we can trace the history of the universe.

First Year Data from *WMAP*



Polarization/temperature correlation implies an electron-scattering optical depth after cosmological recombination at z=1088 of:

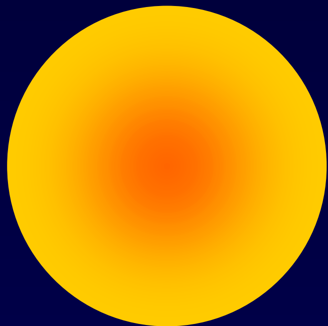
$$= 0{:}17 \quad 0{:}04$$

Implying that the universe was reionized at $z = 17 \quad 5$

Only 200 million years after the big bang

Kogut et al. 2003

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

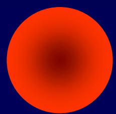


T_{eff} ø 10^5K
$L = L_E$ / M

Massive, metal free stars

M > 300M ì	100; 000
M > 100M ì	40; 000

Gain by up to a factor of ~30!

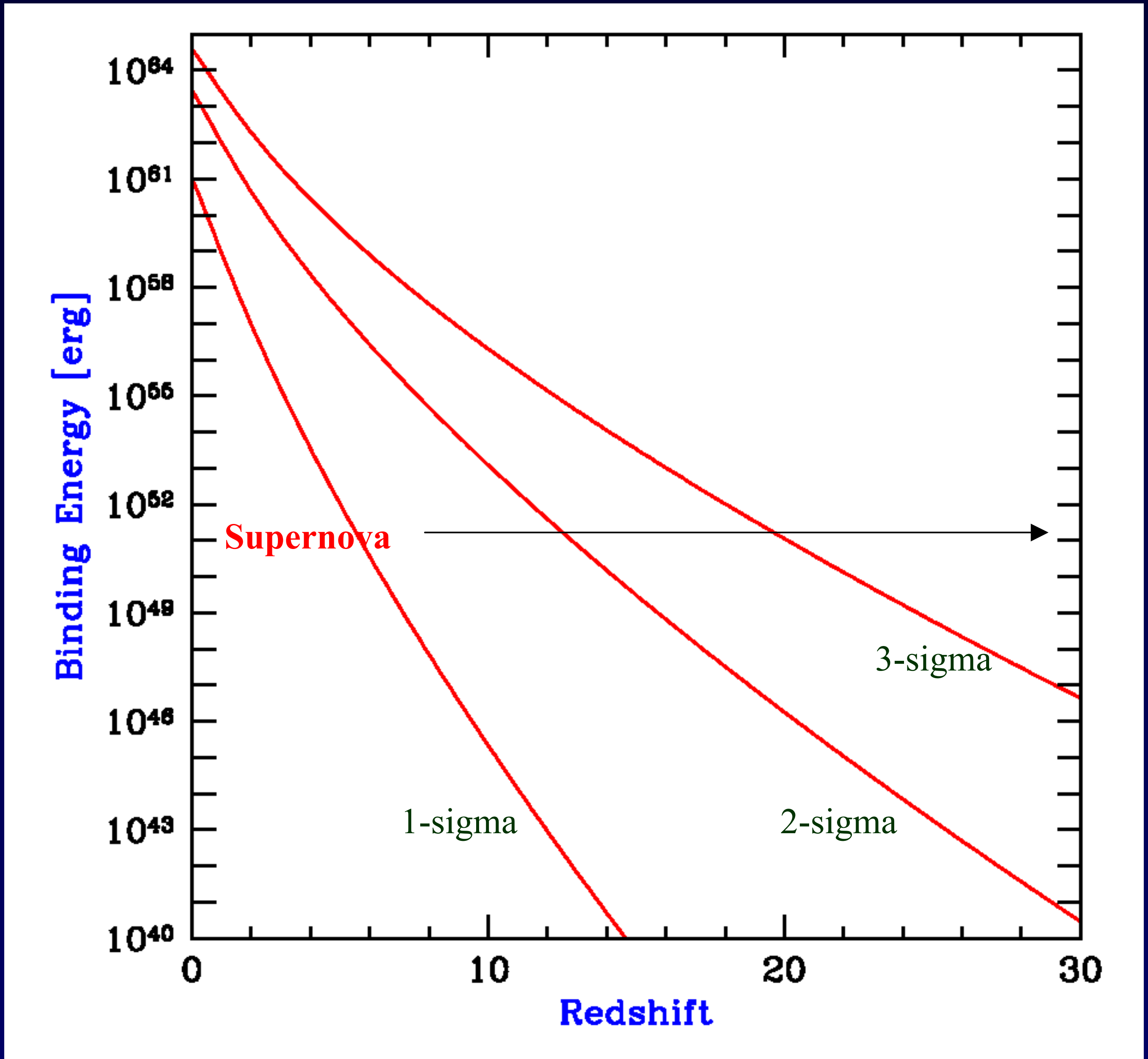


Salpeter mass function

Metal free	7; 000
Z = 0:01Z ì	3; 500

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

Binding Energy of Dark Matter Halos



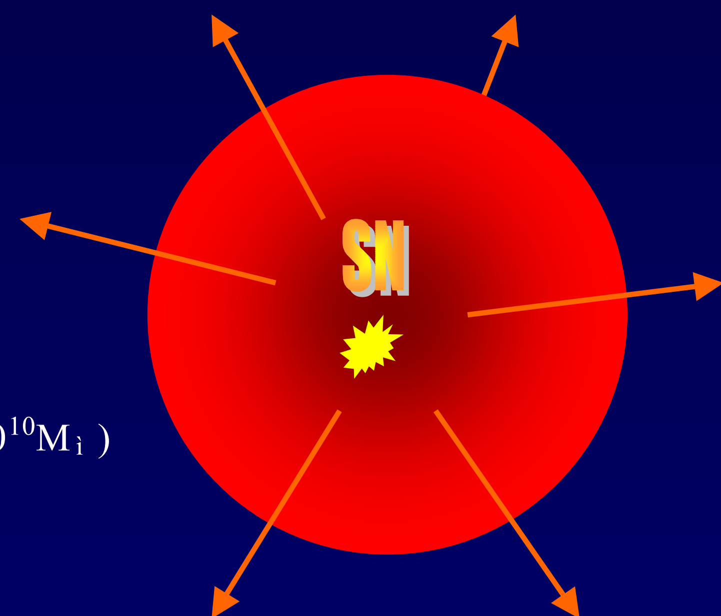
Self-Regulated Star Formation

<u>Virial temperature < 10,000K</u>

H_2 ***destruction by starlight (10.2<E<13.6 eV)***

Evaporation of gas cloud by photo-ionization heating to >10,000K

<u>Virial temperature > 10,000K</u>



$$M_{?} \,/\, E_{SN}\ ø\ \tfrac{3}{2} M_{gas} û^{2}$$

$$f_{?} = \frac{M_{?}}{M_{gas}} \,/\, û^{2} \,/\, M_{halo}^{2=3}$$

As observed for local dwarf galaxies $(M_{?} < 3\ â\ 10^{10} M_{ì})$

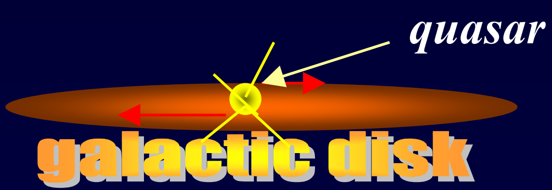
in SDSS (Kaufmann et al. 2002)

Self-regulation of Supermassive Black Hole Growth

$L t_{dyn}$ ø $\frac{3}{2} M_{gas} \hat{u}^{2}$

halo velocity dispersion

dynamical time of galactic disk



$\max f L g = L_{E} / M_{bh}$

$$! \quad \frac{M_{bh}}{10^{8} M_{ì}} = 1{:}5 \quad \frac{\hat{u}}{200\mathrm{km{=}s}}^{5}$$

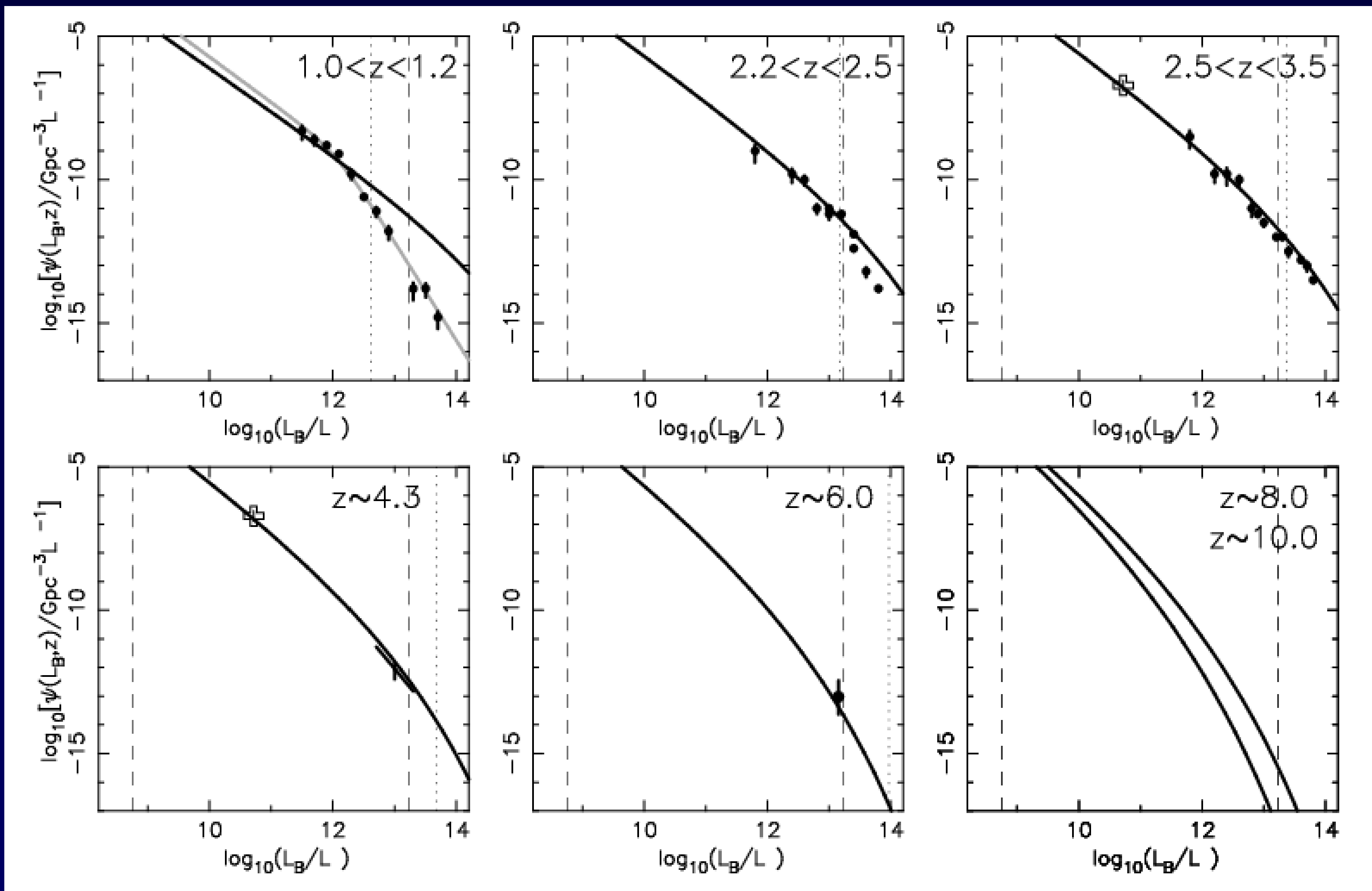
After translating ! ? ***this relation matches the observed*** M $\hat{u}_{ã}$ ***correlation in nearby galaxies (Tremaine et al. 2002; Ferarrese & Merritt 2002)***

Silk &Rees 1998; Wyithe & Loeb 2003

Quasar Luminosity Function

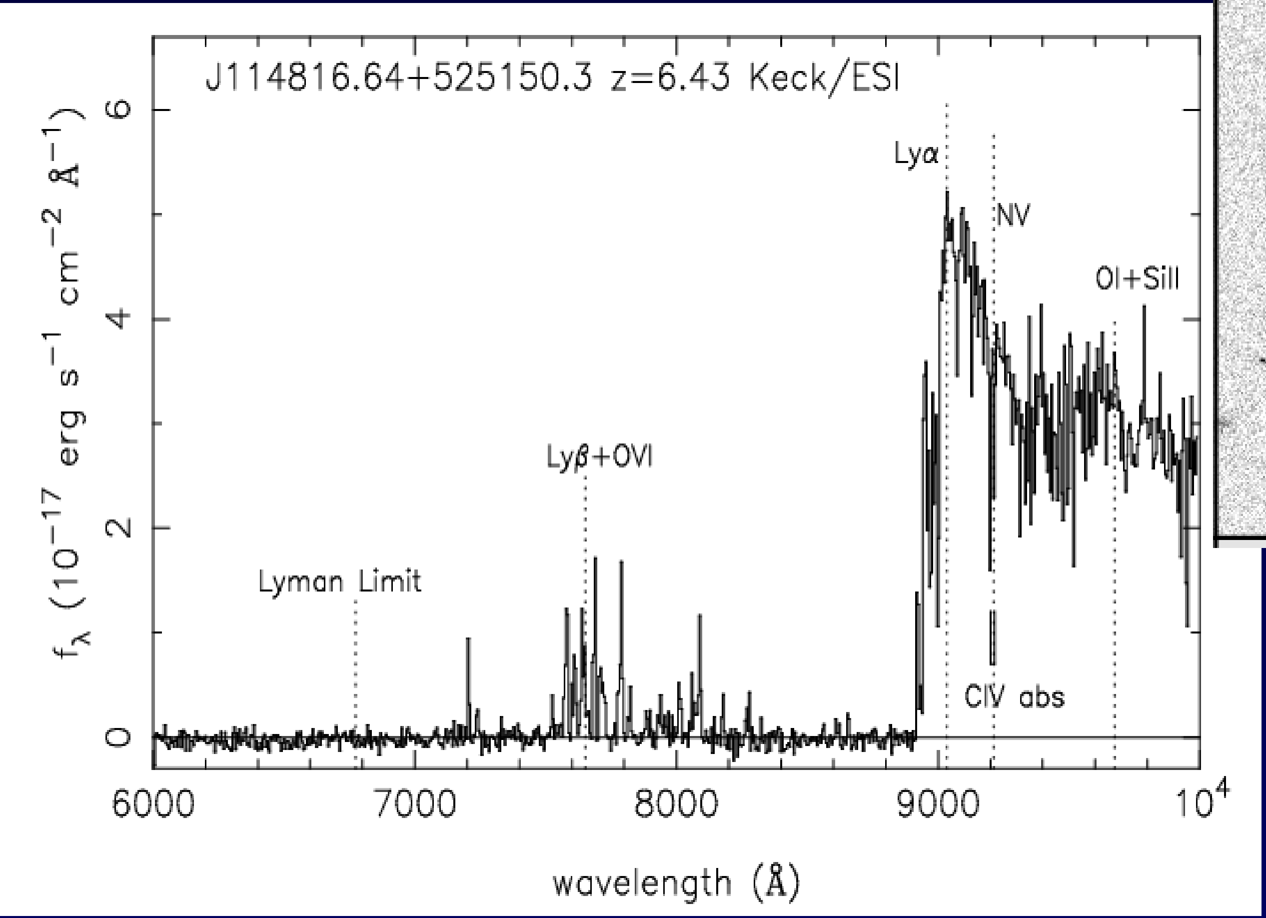
**Each galaxy merger leads to a bright quasar phase during which the black hole grows to a mass* $M_{bh} / \hat{u}^5$ *and shines at the Eddington limit.*

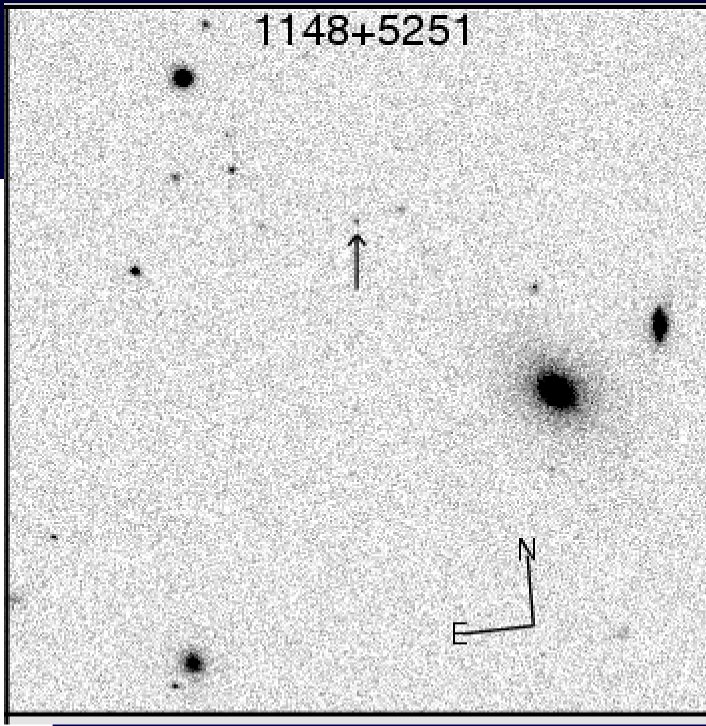
**Merger rate: based on the extended Press-Schechter model in a LCDM cosmology.*



Wyithe & Loeb 2003

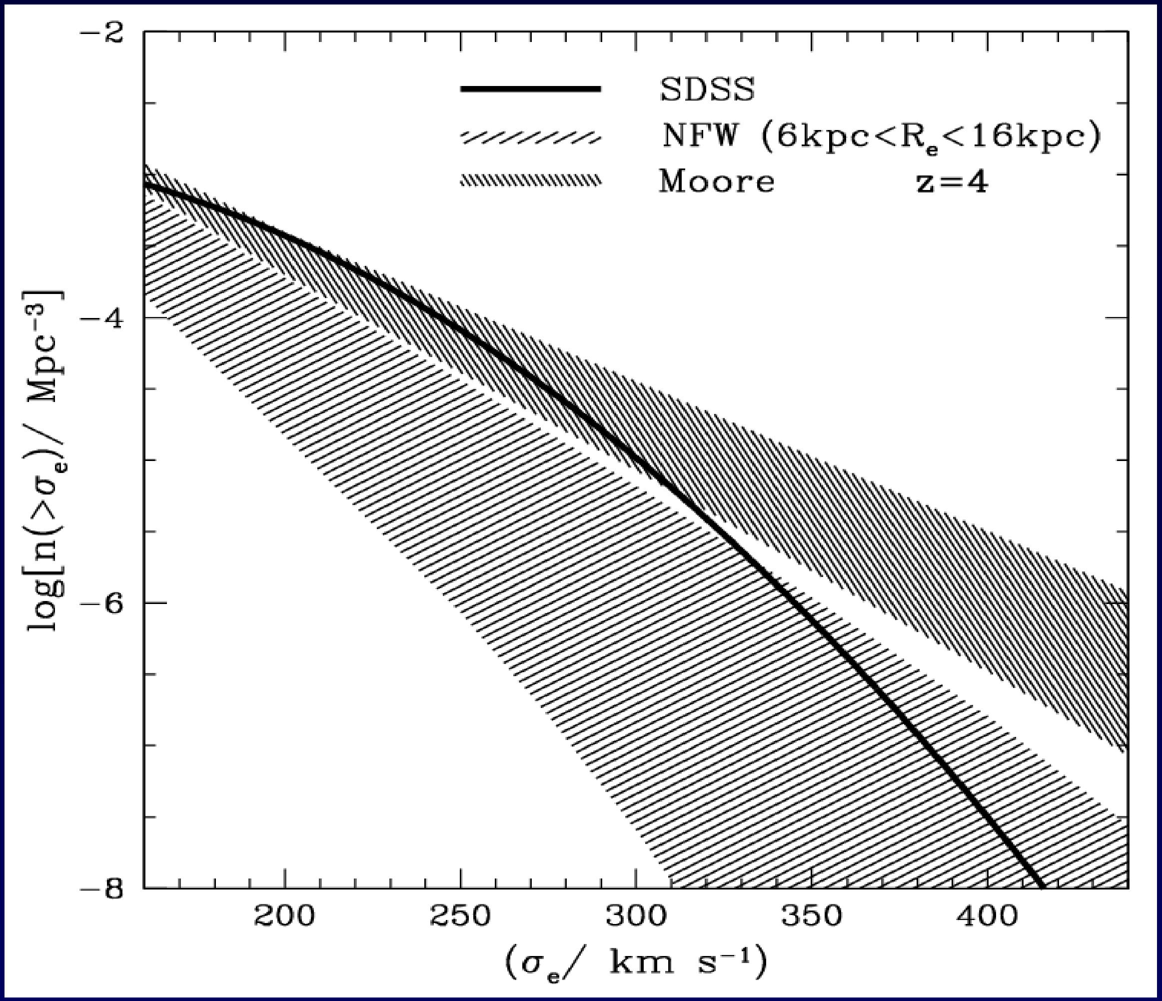
The Earliest Quasar Detected: z=6.43



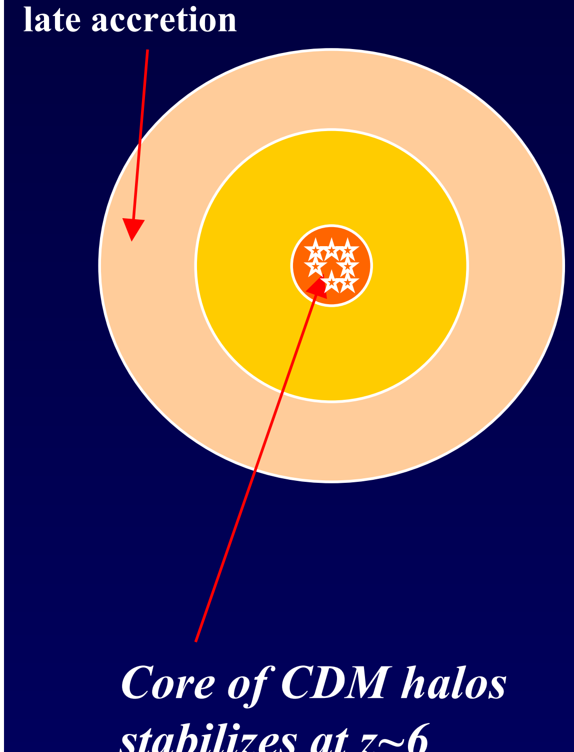


Fan et al. 2002

Did the most massive galaxies form at z>6, only a billion years after the Big-Bang?

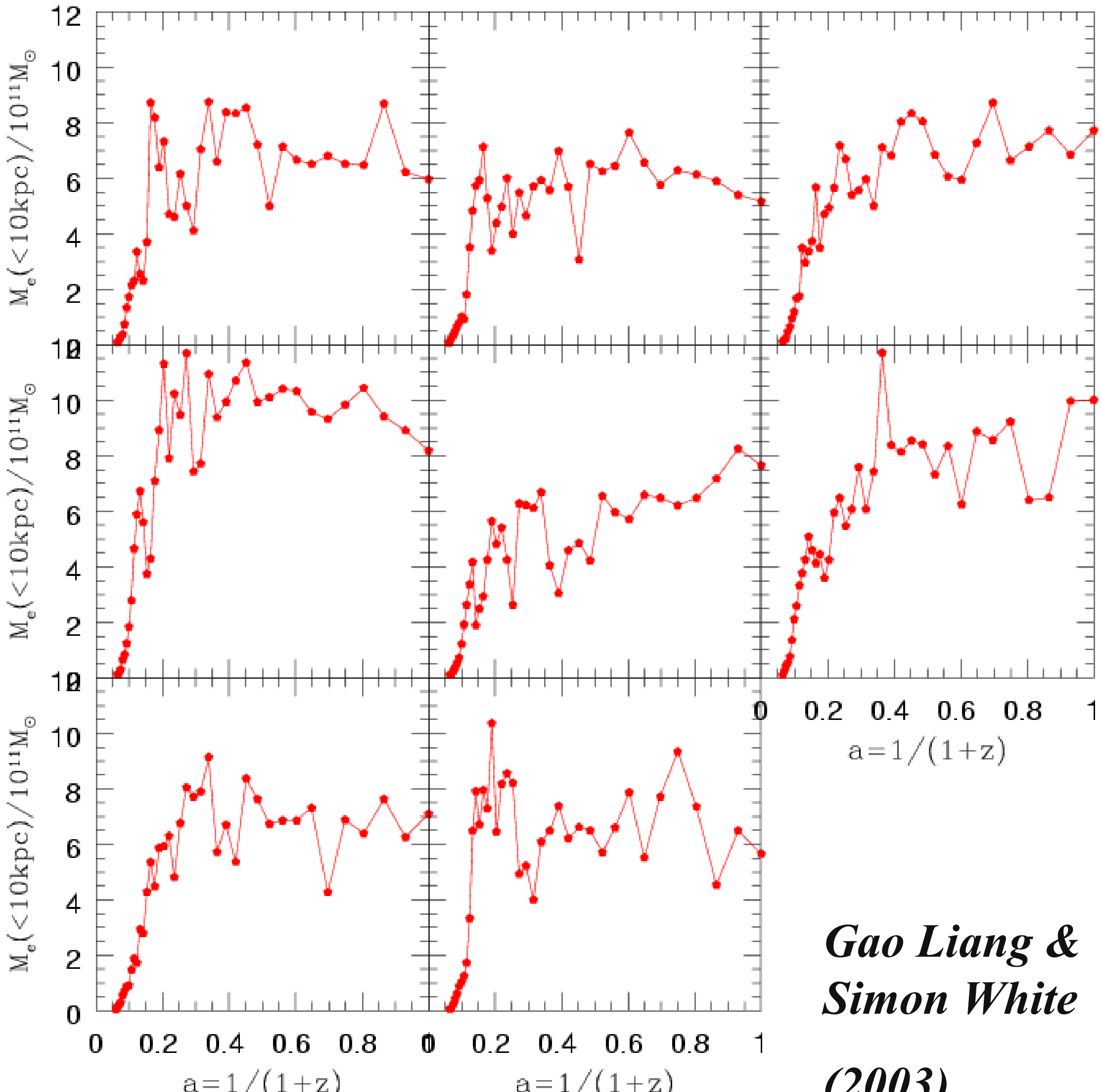


Stars=collisionless fluid

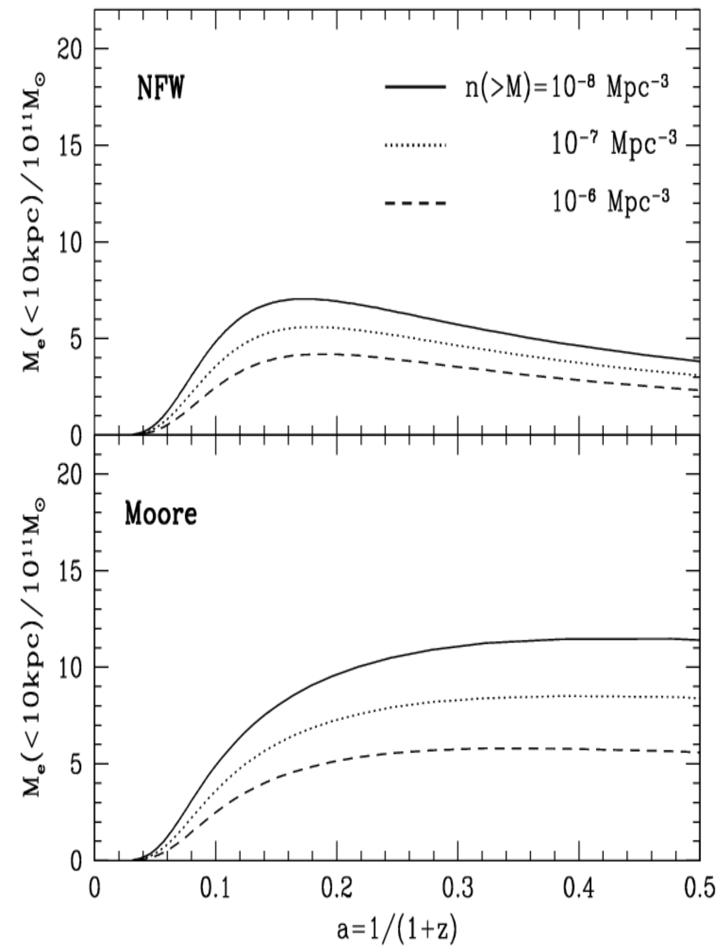


Loeb & Peebles 2002

Proposal confirmed by N-body simulations



Gao Liang & Simon White (2003)

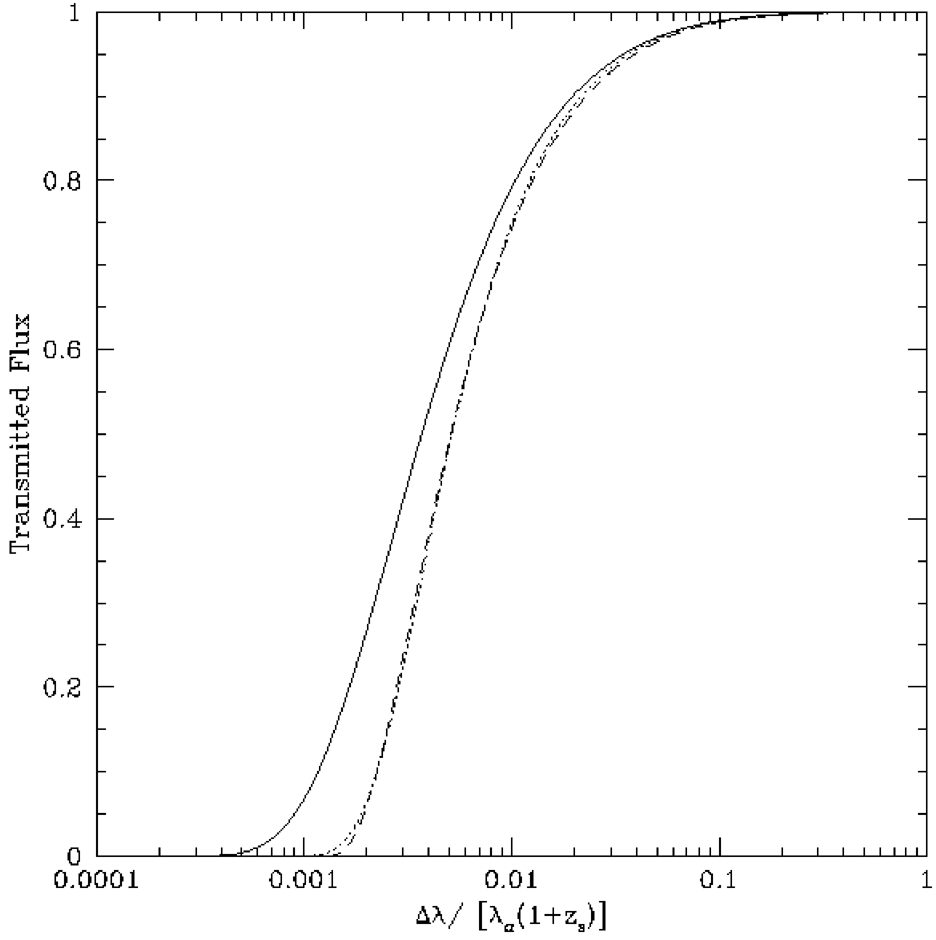


Loeb & Peebles 2002

The Gunn-Peterson Effect

$$\tau_s = \frac{\pi e^2 f_\alpha \lambda_\alpha n_{\rm H\,I}(z_s)}{m_e c H(z_s)} \approx 6.45 \times 10^5 x_{\rm H\,I} \left(\frac{\Omega_b h}{0.03}\right) \left(\frac{\Omega_m}{0.3}\right)^{-1/2} \left(\frac{1+z_s}{10}\right)^{3/2}$$

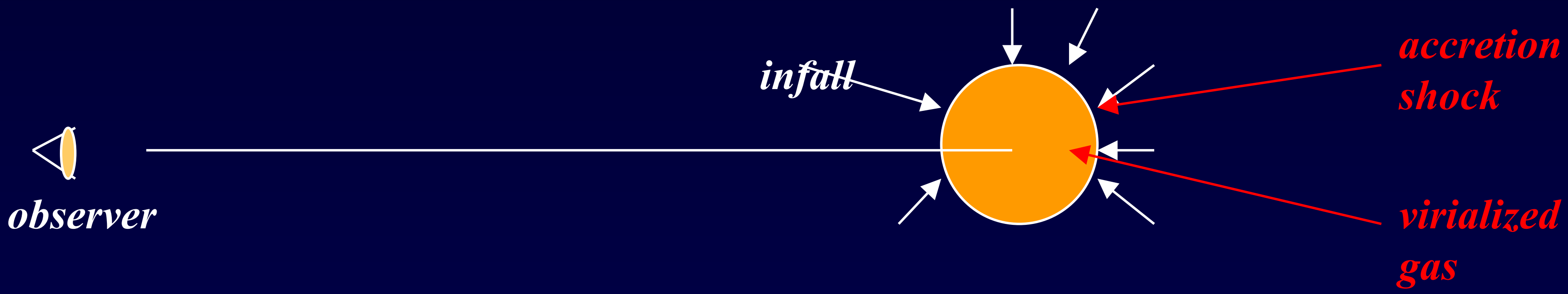
The damping wing of the Lyman-alpha transition of neutral hydrogen:

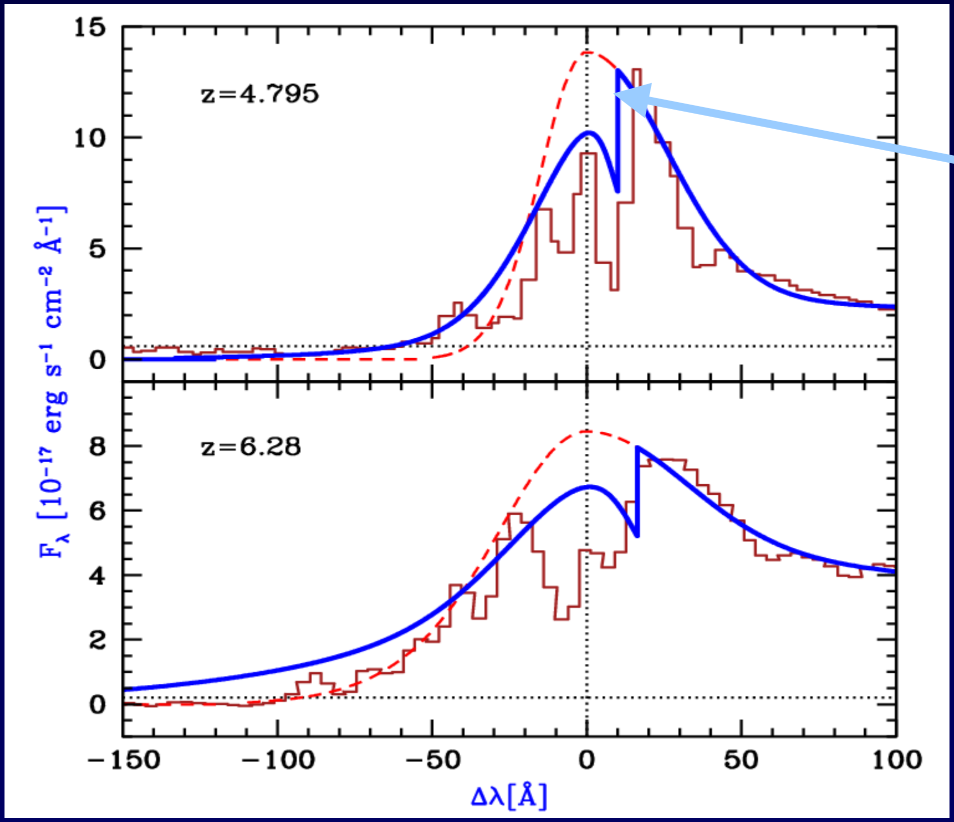


Miralda-Escude
1998

Limitations of Quasars as Probes of the Lyα Damping Wing:

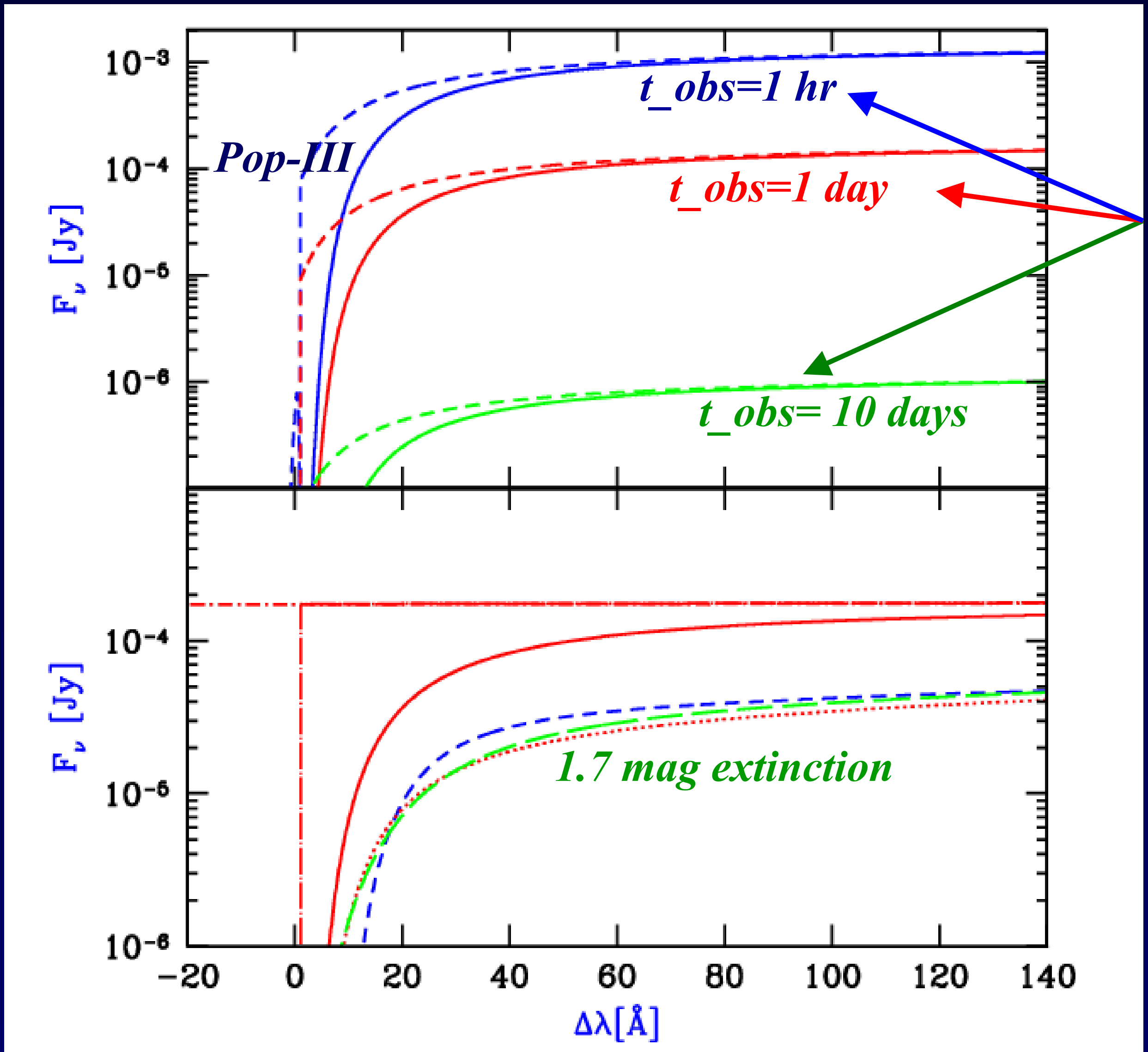
Proximity effect (ionization sphere)+Cosmological Infall





Barkana & Loeb, Nature, 2003

However most stars form in much smaller dwarf galaxies, which perturb only weakly the ionization state and Hubble flow of the surrounding gas...

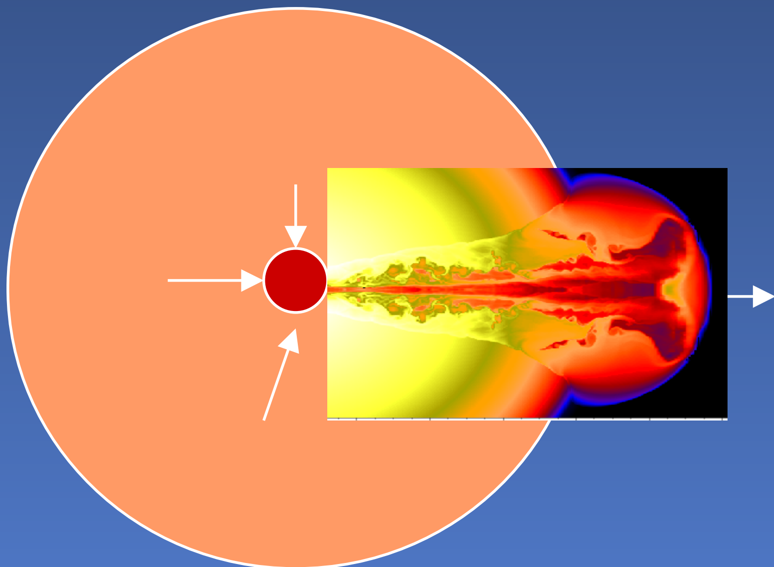


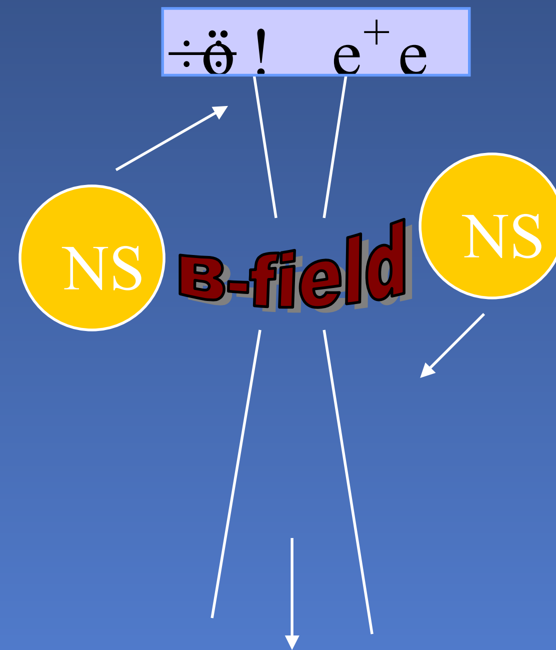
GRB afterglow flux at different observed times after the GRB trigger

Barkana & Loeb 2003 astro-ph/0305470

Gamma-Ray Bursts:

Probing the First Stars, One Star at a Time





Collapse of a Massive Star
(possibly leading to a supernova)

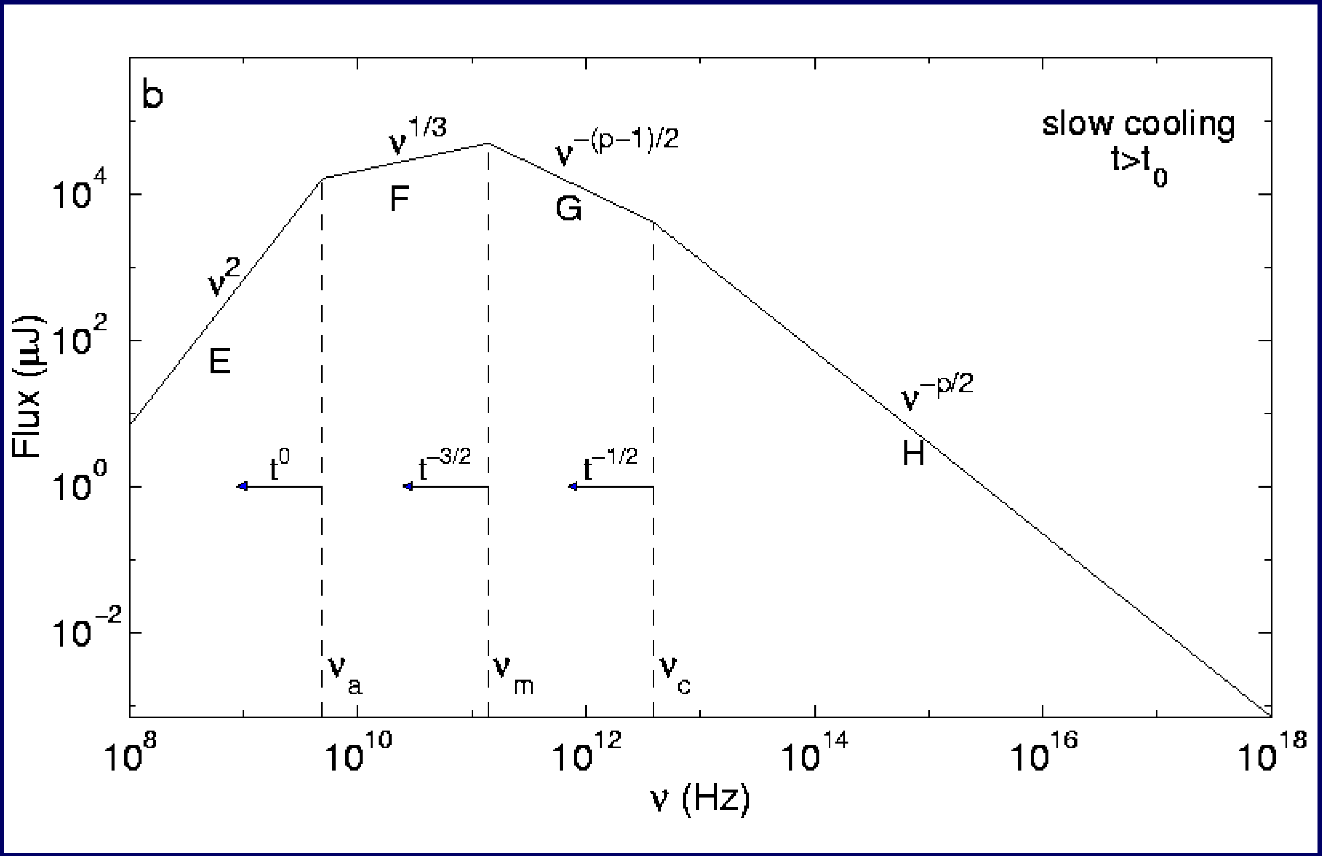
Coalescence of NS/NS
or NS/BH Binaries

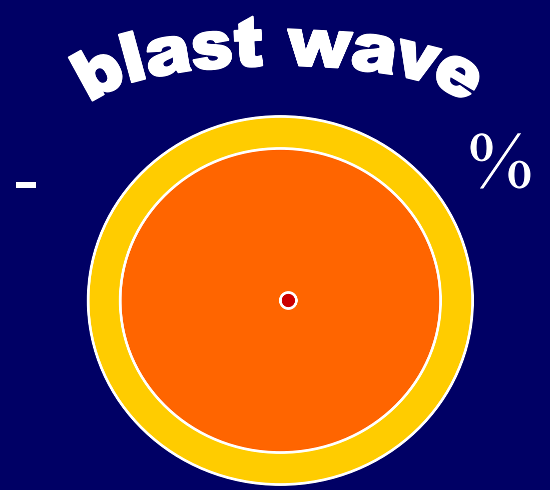
$$\frac{10^{51}\text{ergs}}{4\text{ù}} = 2\ \text{â}\ \frac{10^{54}\text{ergs}}{\text{ù}(\text{ò}{=}5^{\text{î}})^{2}}$$

In both cases the original progenitors are massive stars
(which should exist at high redshifts)

Gamma-Ray Burst Afterglows

Optical-UV broad-band emission allows detection of Lya trough and metal line absorption in the intergalactic medium



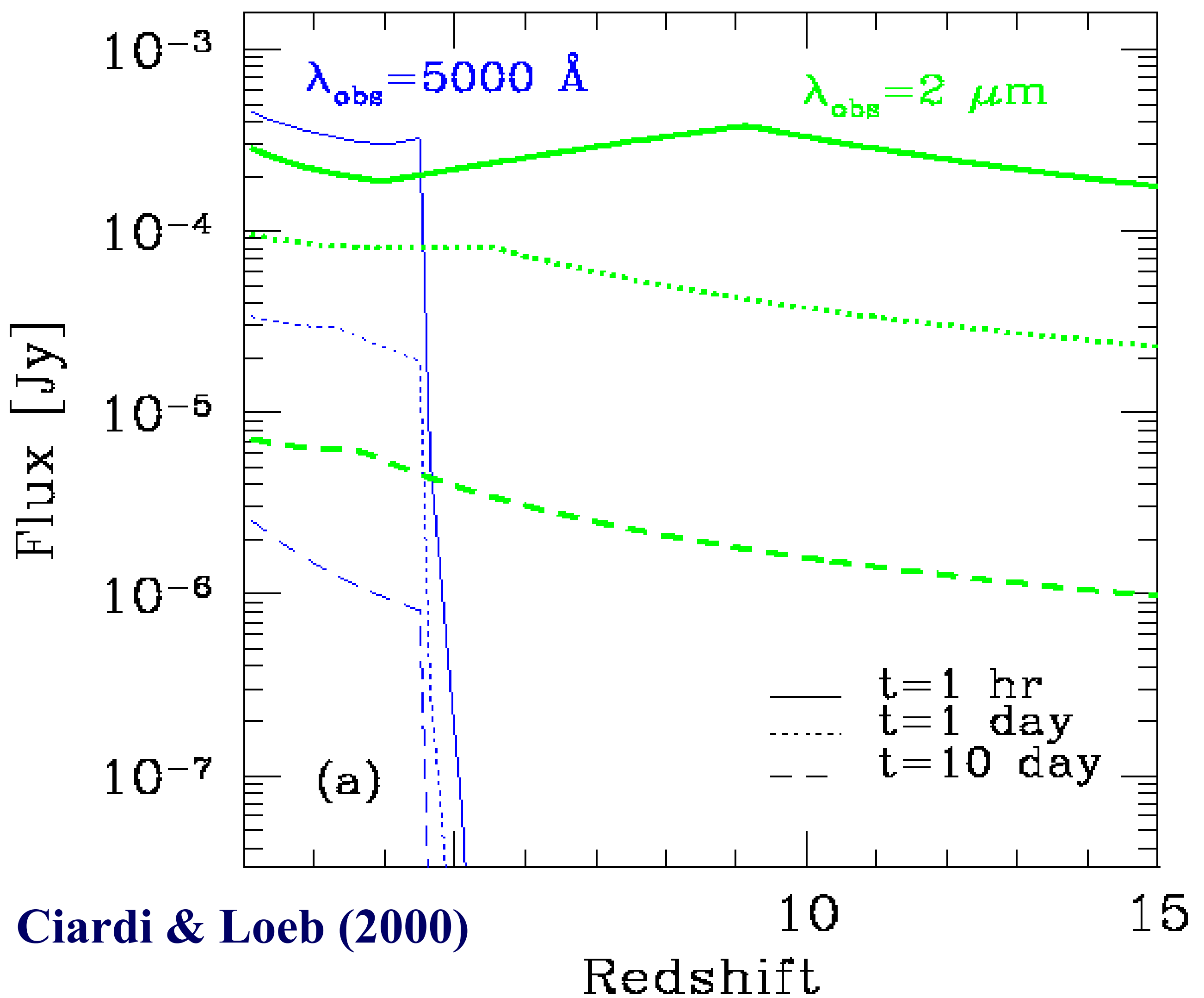


$\acute{\imath}_{\,shock}$ ù $6{:}4\ E_{52}^{1=8}\, n_0^{à\,1=8}\ \ t_{day}^{à\,3=8}$

R_{shock} ù $10^{17}\ E_{52}^{1=4}\, n_0^{à\,1=4}\, t_{day}^{1=4}$ cm

Synchrotron emission by a power-law population of relativistic e-

Optical-IR Flux vs Redshift: *Cosmological Time Stretching Compensates for Increase in Luminosity Distance*

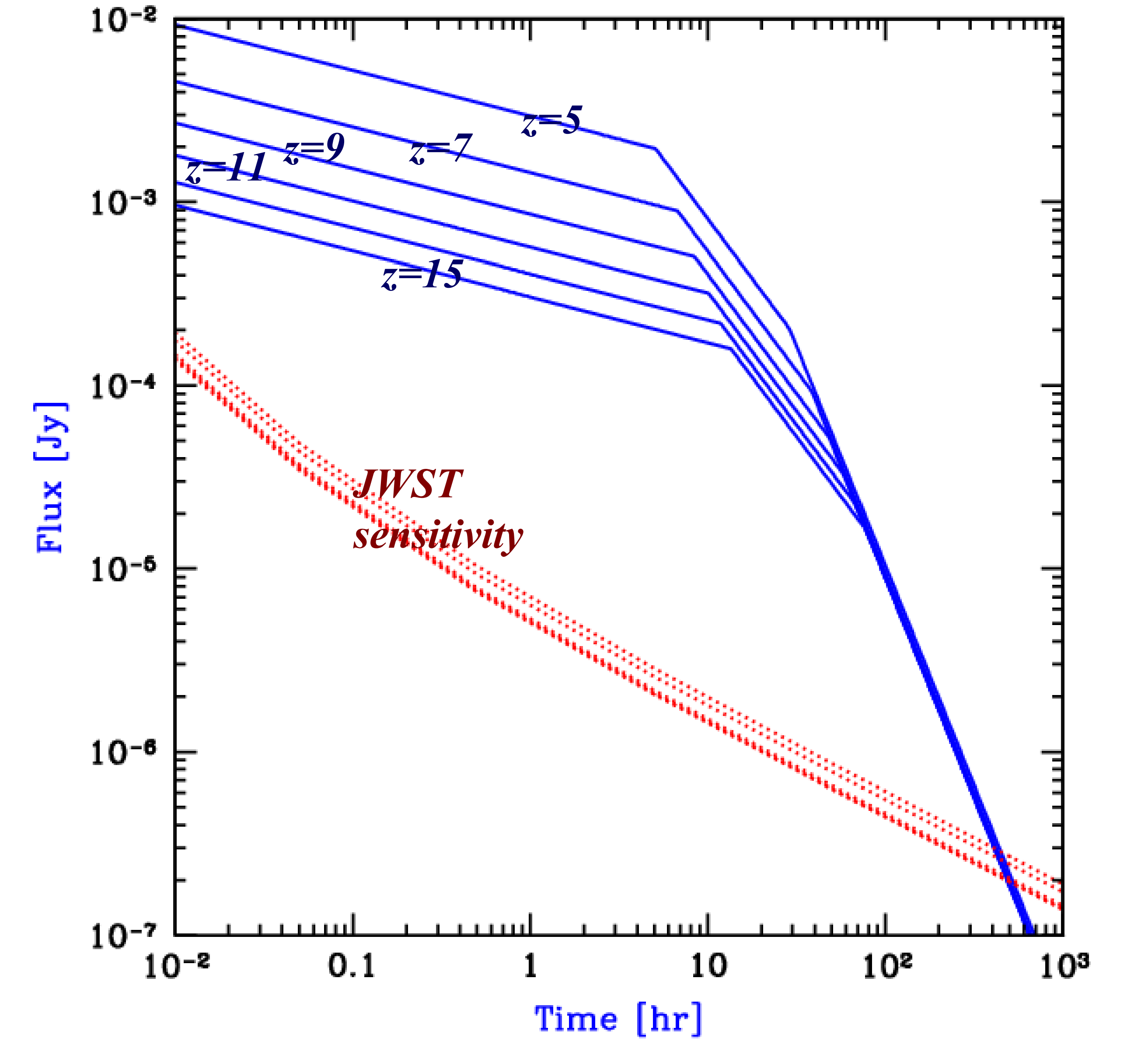


Ciardi & Loeb (2000)

•*GRBs are powerful probes of the IGM at high-redshifts !*

Detectability of Afterglow Emission Near the Lya Wavelength

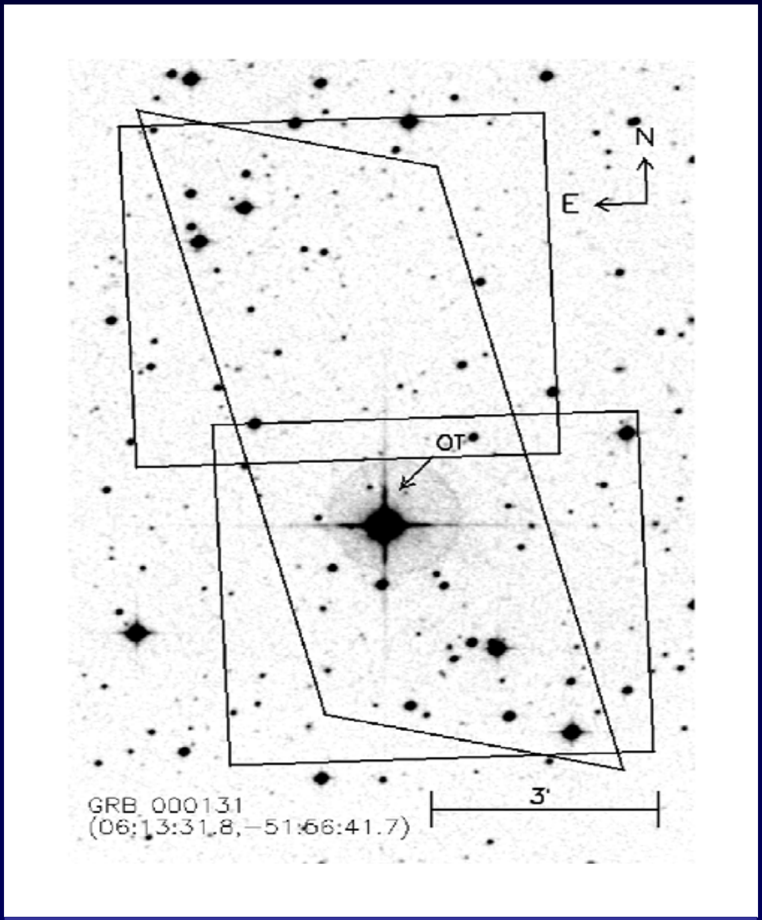
Photometric redshift identification: based on the Lya trough



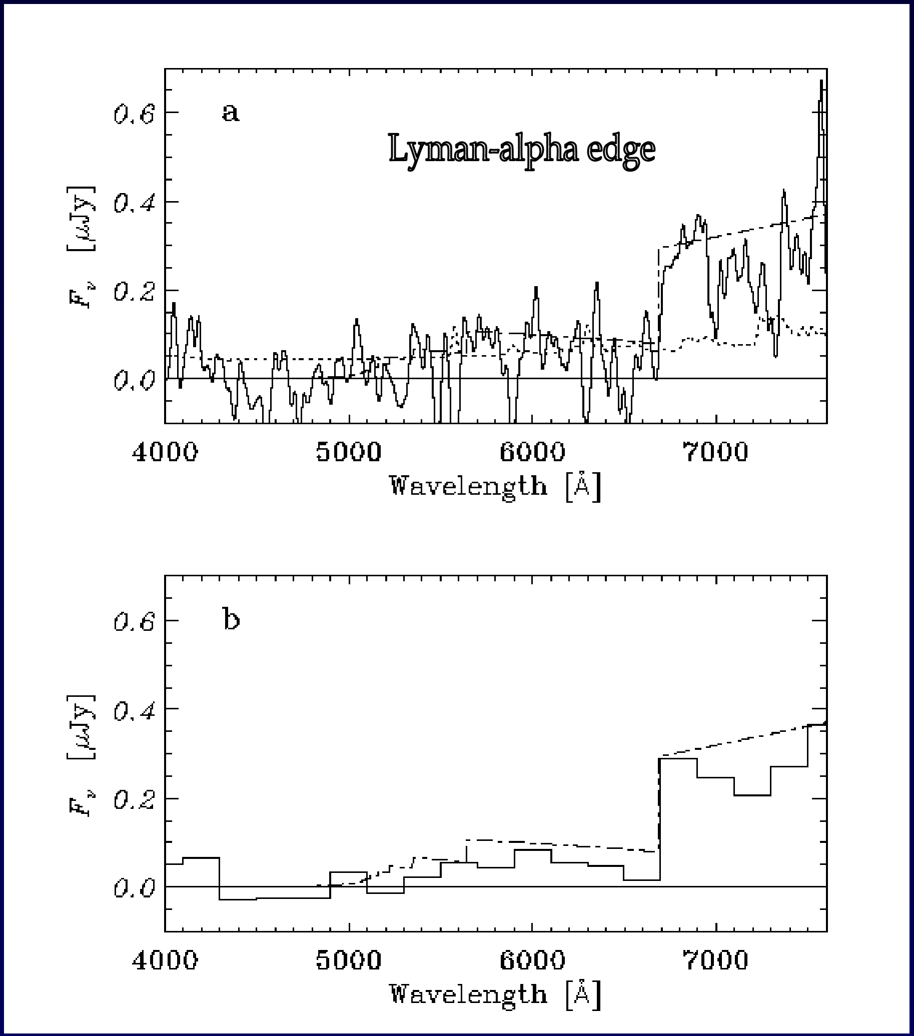
Barkana & Loeb 2003

astro-ph/0305470

Gamma-Ray Bursts: The Brightest Explosions in the Universe



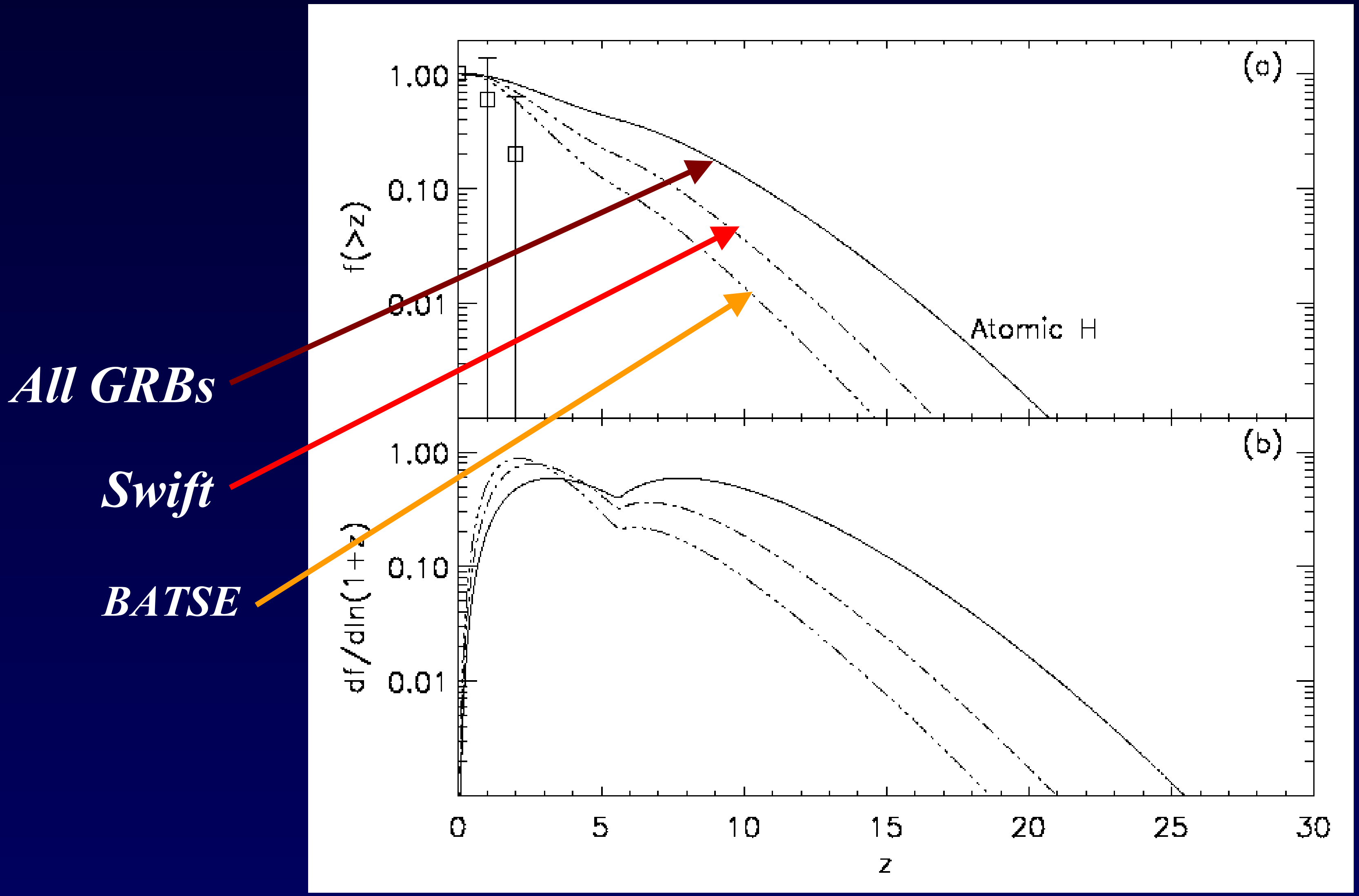
VLT Image



GRB 000131 at z=4.5

Anderson et al. 2000

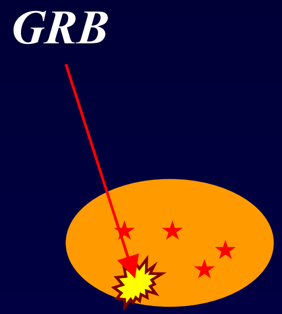
Fraction of GRBs Above a Given Redshift



Bromm & Loeb 2002

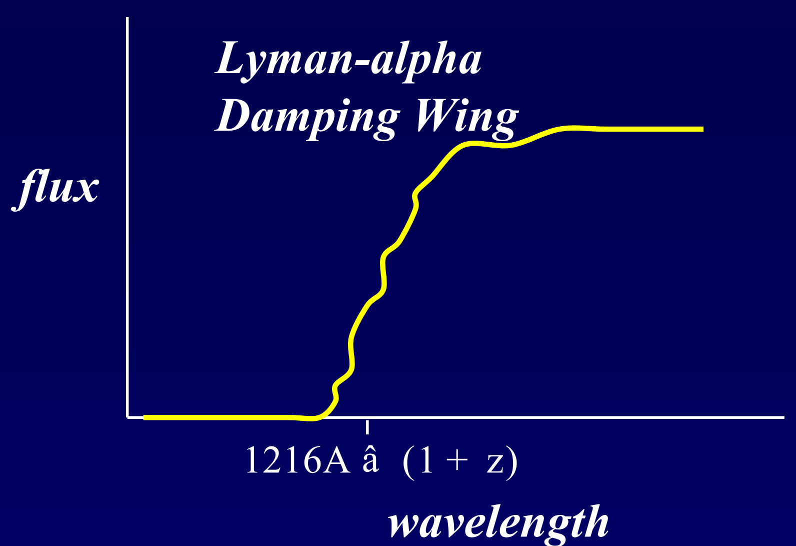
Results are sensitive to the uncertain GRB luminosity function.

Gamma-Ray Burst Afterglows

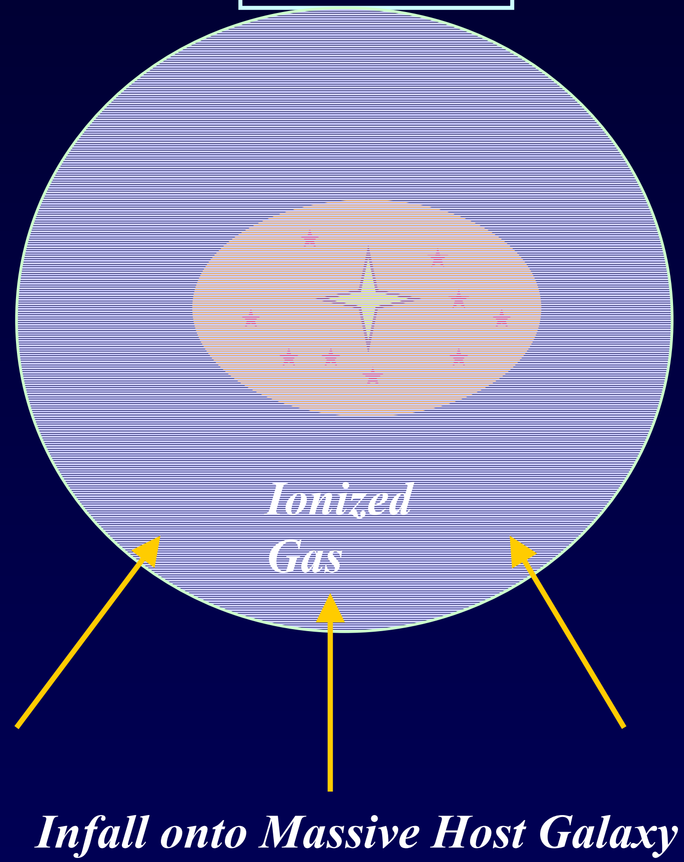


$$M_{ionized} \approx 4 \times 10^4 M_\odot \times \frac{E}{10^{51} ergs}$$

Weak contamination by Lya emission line



Quasars



Quasars get fainter with increasing redshift because galaxies are less massive and the luminosity distance increases at higher redshifts!

Advantages of GRB Afterglows Relative to Quasars
(see details in astro-ph/0307231)

- *Luminous stellar sources) high redshifts*
  - outshine galaxies and quasars, as they become less luminous at increasingly higher redshifts
  - -ray trigger allows all-sky monitoring
- *Featureless broad-band spectra extending into the rest-frame UV*
  - absorption features can be used to probe the ionization and metallicity states of the IGM
- *Observed flux at a fixed observed age does not fade significantly with increasing GRB redshift* (cosmological time stretching counteracts increase in luminosity distance)
- *Weak Feedback on Surrounding IGM*
  - *Short-lived event:* negligible ionizing effect of a GRB on the IGM
  - *Low mass host galaxies:* weak IGM infall & *Lya* line emission

Swift Overview
Catching Gamma Ray Bursts on the Fly

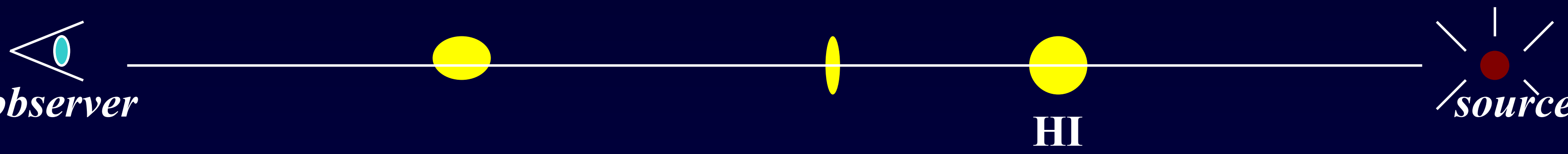
Capabilities

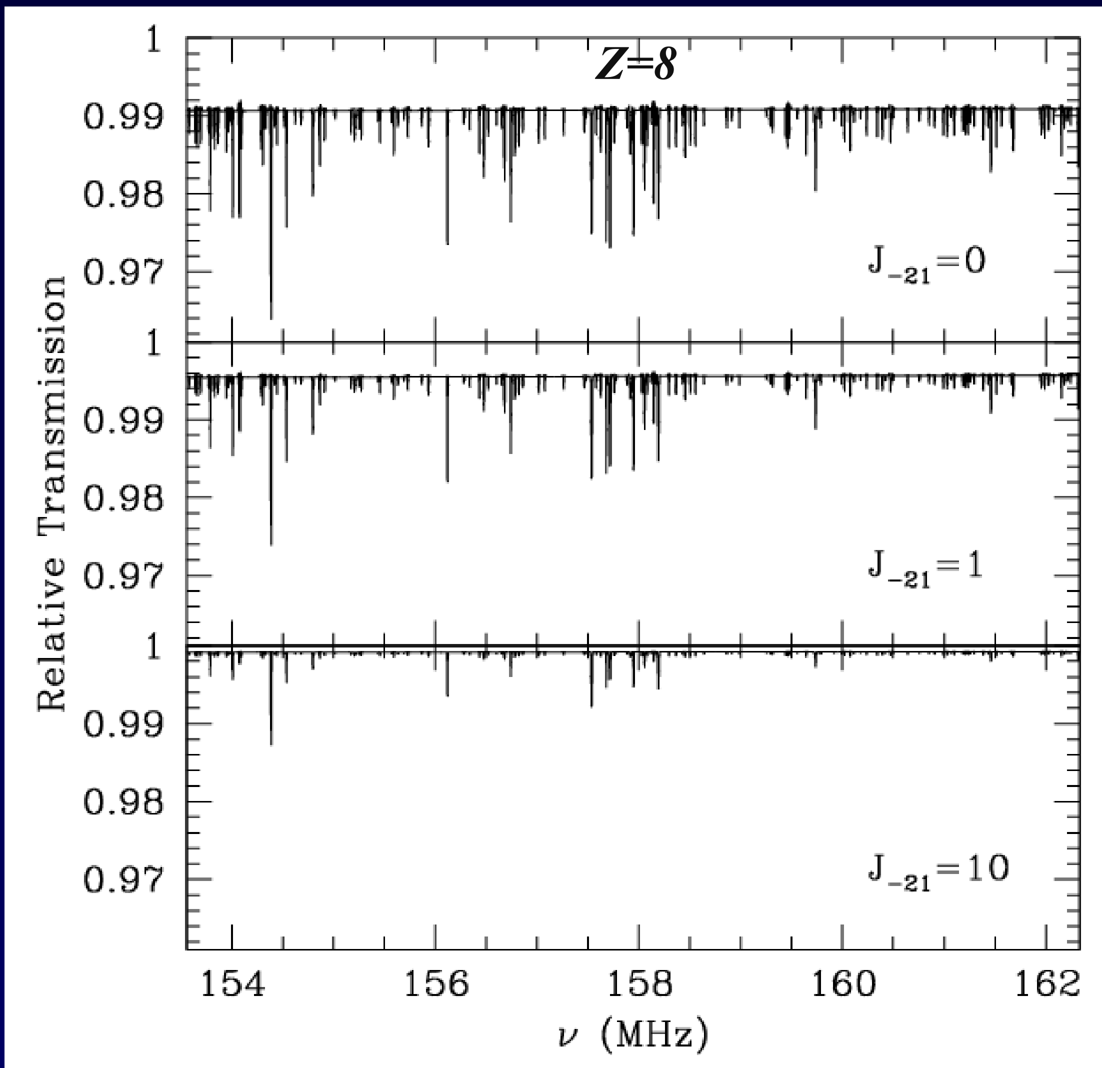
- ~1000 GRBs studied over a three-year period
- 0.3–2.5 arc-second positions for each GRB
- Multiwavelength observatory (gamma, X-ray, UV, and Optical) to monitor afterglows
- 20–70 s reaction time
- Five times more sensitive than BATSE
- Spectroscopy from 0.2 to 150 keV
- Six colors covering 170–650 nm
- UV and optical spectroscopy with R ~ 300–600 for $M_b < 17$
- Capability to directly measure redshift
- Results publicly distributed with seconds

Planned for launch in 2003

Challenge: select photometrically all high-redshift GRBs (using the Lya break) and follow-up on them spectroscopically

Probes of Neutral Hydrogen: 21 cm Absorption





Contributions:

**Gaseous mini-halos and disks*

(Furlanetto & Loeb 2002)

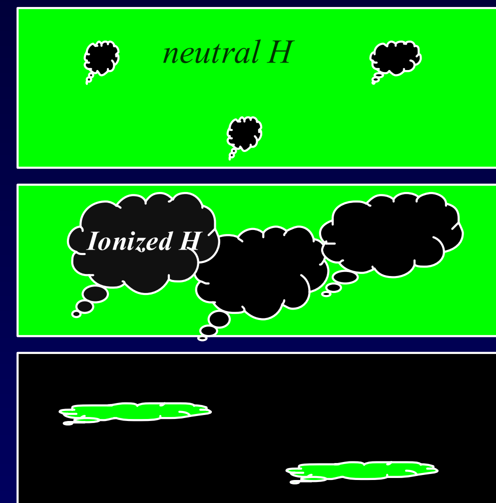
**Sheets and filaments in the intergalactic medium*

(Carrili, Gnedin, & Owen 2002)

Detection with the planned Low Frequency Array (LOFAR) and Square Kilometre Array (SKA) is feasible for sources brighter than 10 mJy at z~10.

Evolutionary Stages of Reionization

- ***Pre-overlap***
- ***Overlap***
- ***Post-overlap***



SDSS quasars at z>6.3 & IGM thermal history based on the Lya forest .

(Theuns et al. 2001;Hui & Haiman 2003)

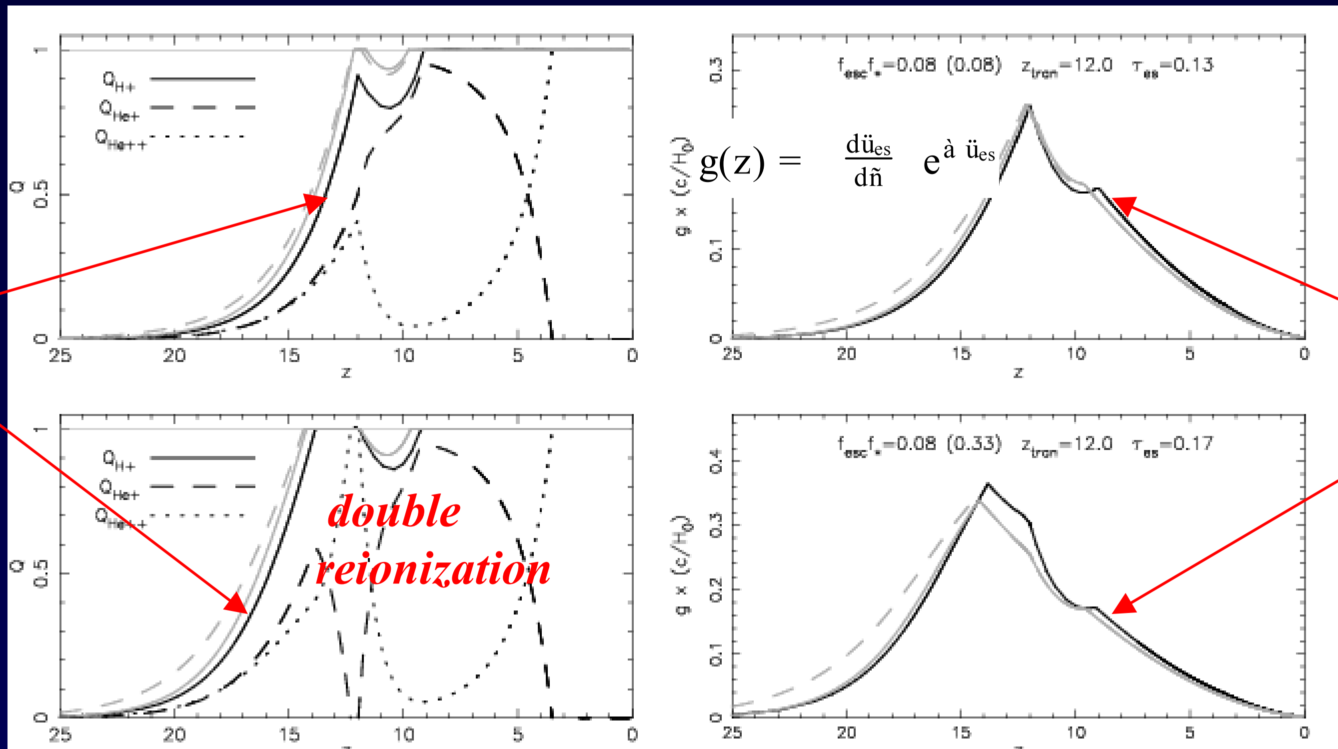
→ ***Overlap of HII regions completed at 6.3<z<9***

Sudden reionization at z<9 would imply $_{es} < 0{:}09$

But from WMAP: $_{es} = 0{:}17 \quad 0{:}04$???

Solution: IGM was partially ionized over an extended period at z>10

volume filling fraction



visibility function

redshift *redshift*

Such reionization histories were discussed prior to WMAP

see: Wyithe & Loeb, astro-ph/0209056; Cen, astro-ph/0210473

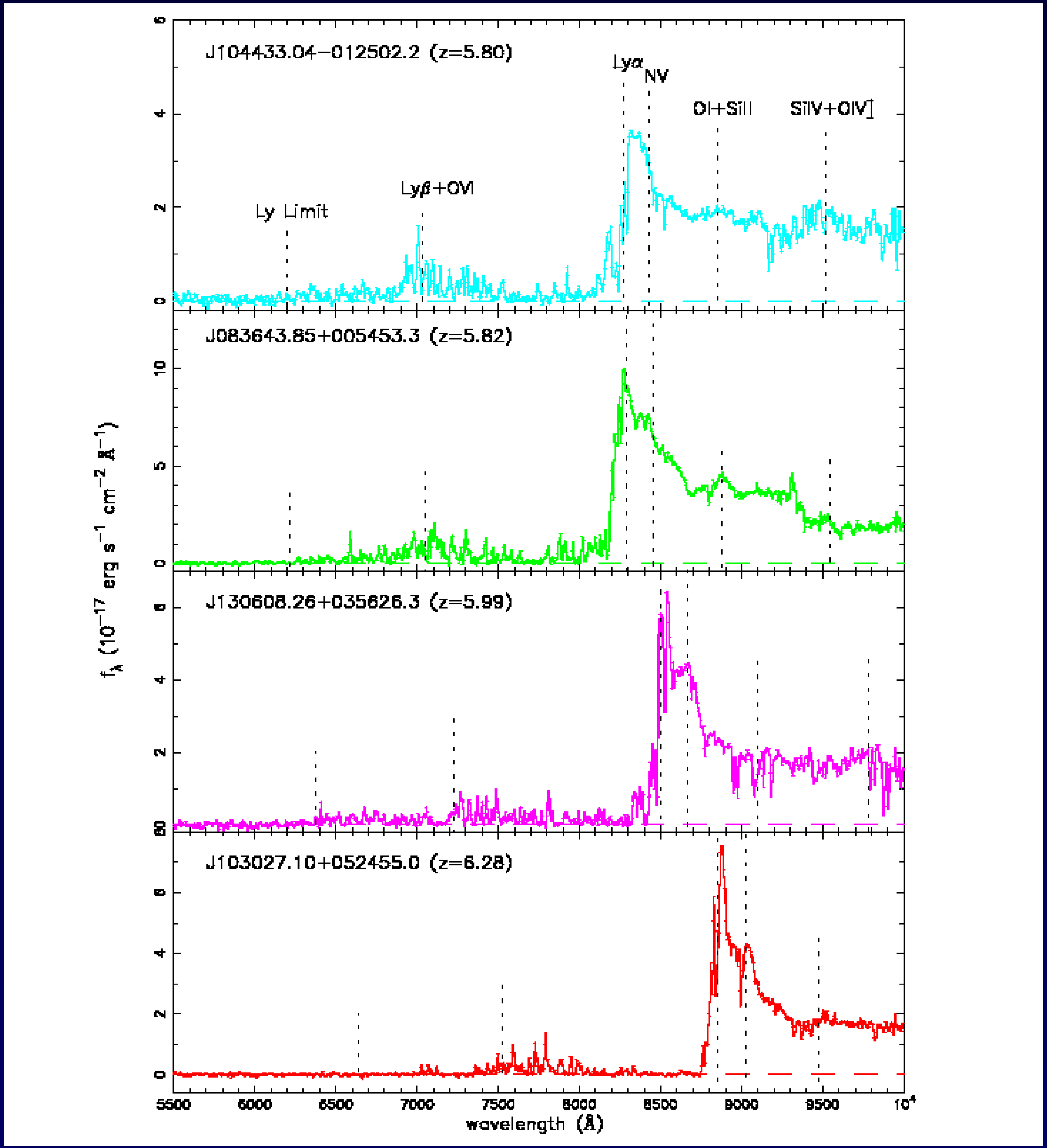
Results

•*Pop-II stars yield* $_{es} < 0:09$ *if HII overlap is at z<9 and require* $f_{?} f_{esc} > 1$ *if* $_{es} = 0:17$

•*Massive, metal free stars are required at z>10 if feedback regulates star formation in early dwarf galaxies as it does in local dwarfs.*

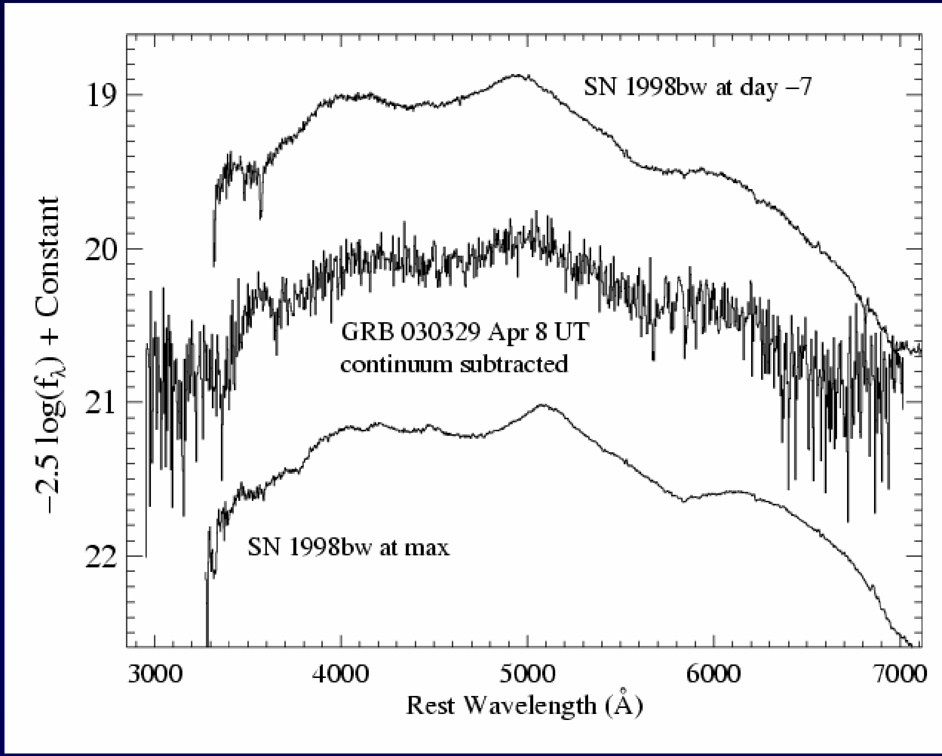
Wyithe & Loeb, astro-ph/0302297

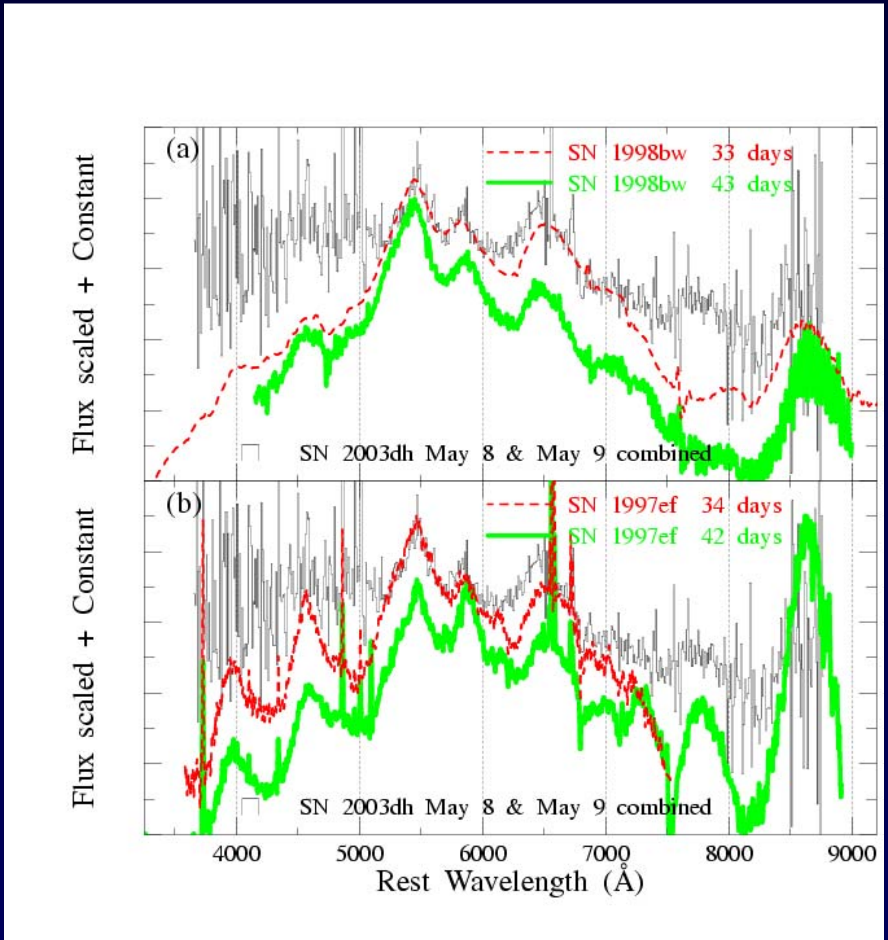
Have we observed the Gunn-Peterson Trough?



Becker et al. 2001

Association of Long-Duration GRBs with SNe Ib,c





Stanek et al. 2003

Kawabata et al. 2003

Astronomy of the Early Universe

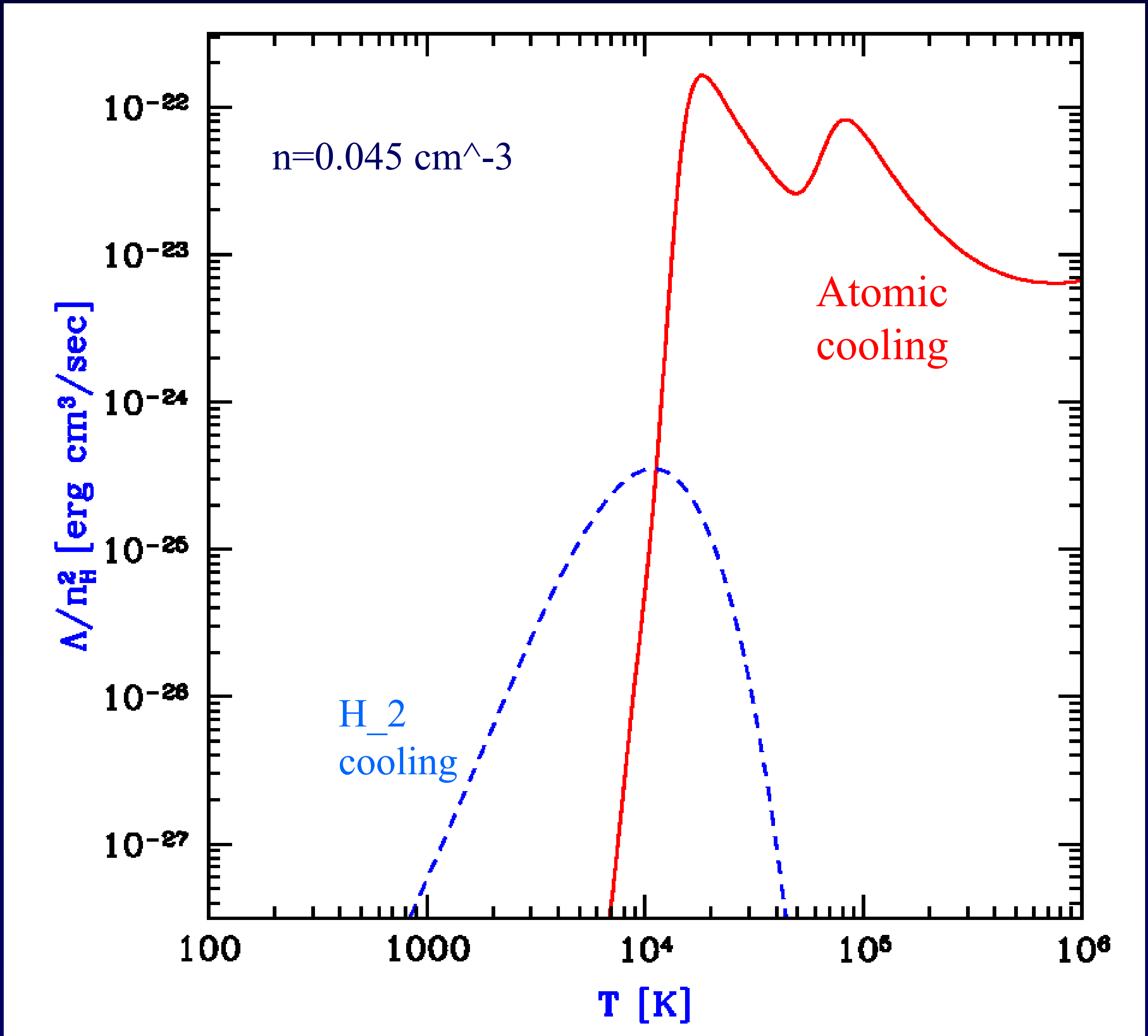
Most pressing questions:

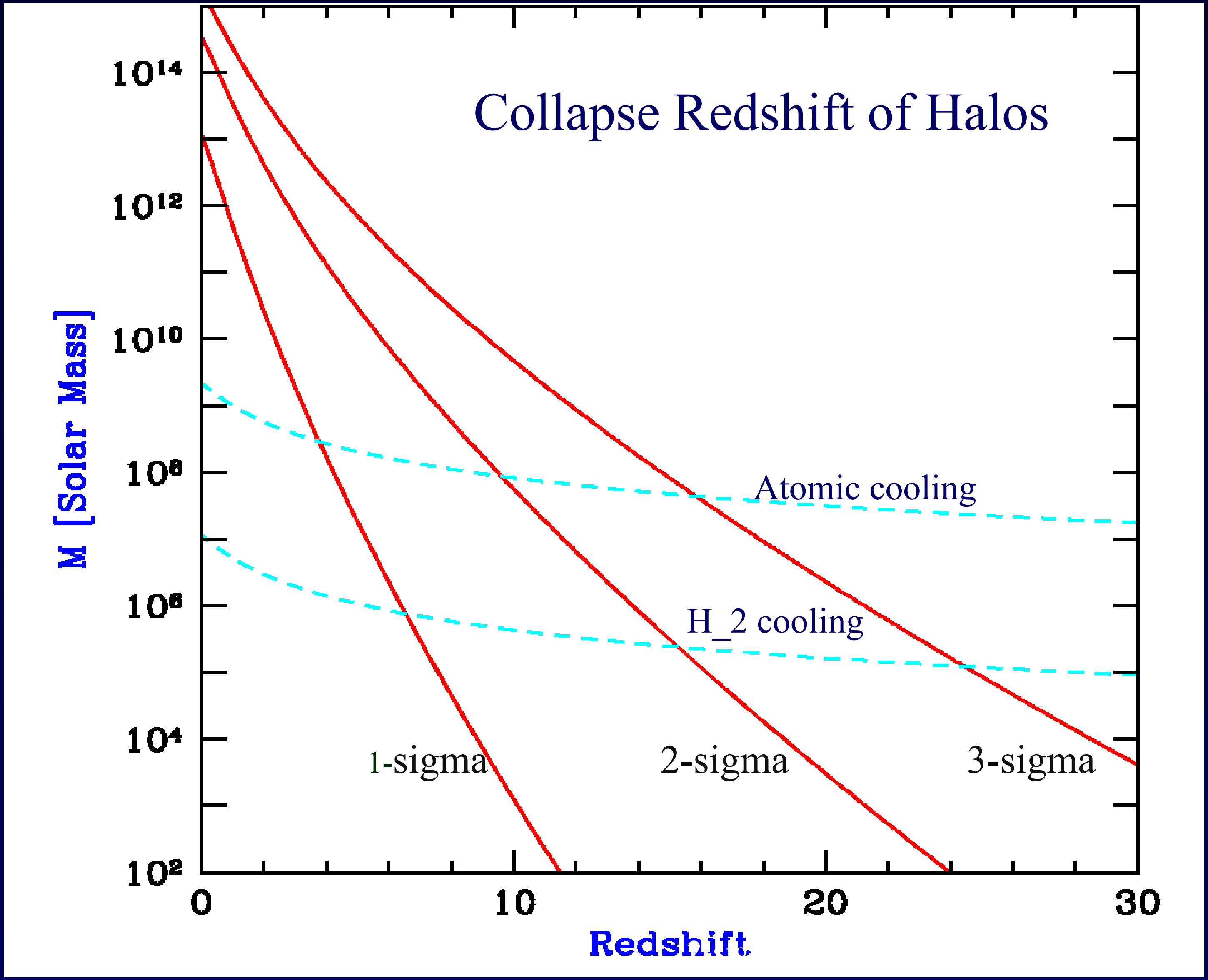
- ***When did the first stars form?***
- ***When was the universe re-ionized?***
- ***How quickly was the intergalactic medium enriched with metals from the first stars?***

Methodology:

- ***How should we search for the first luminous objects?***

Cooling Rate of Primordial Gas





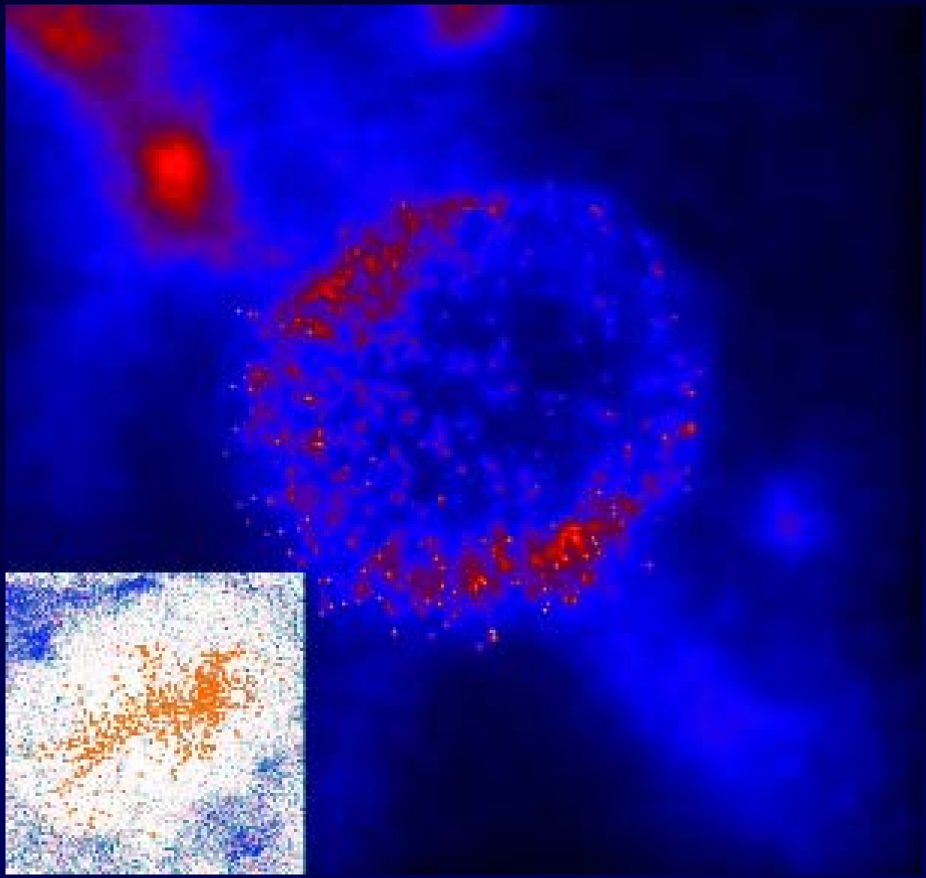
Reviews on the physics of reionization:

*Barkana & Loeb 2001, *Physics Reports* 349, 125

*Loeb & Barkana 2001, *Ann.Rev.Ast.&Ap*, 39, 19

SPH Simulation of a Hypernova Explosion

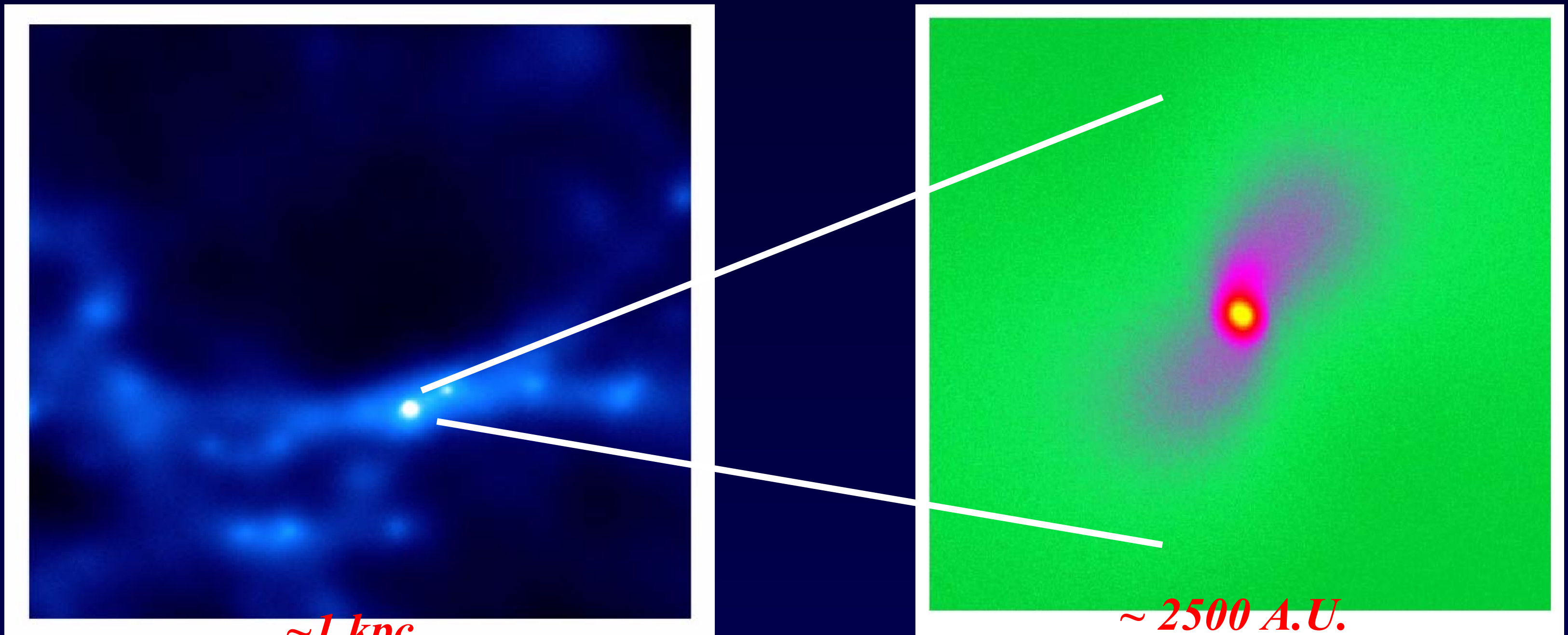
$$E_{SN} = 10^{53} ergs; E_{vir} = 10^{51} ergs$$

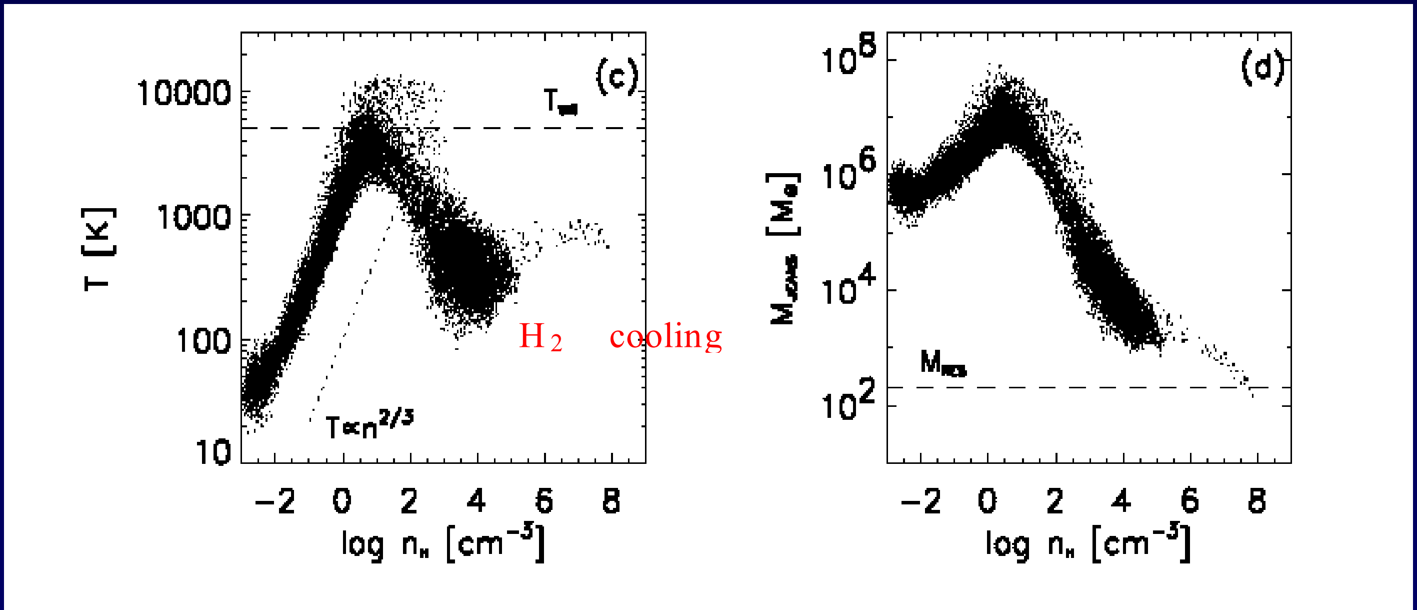


1kpc

Bromm, Yoshida, & Hernquist 2003

Metal-Free Stars were massive: Simulations



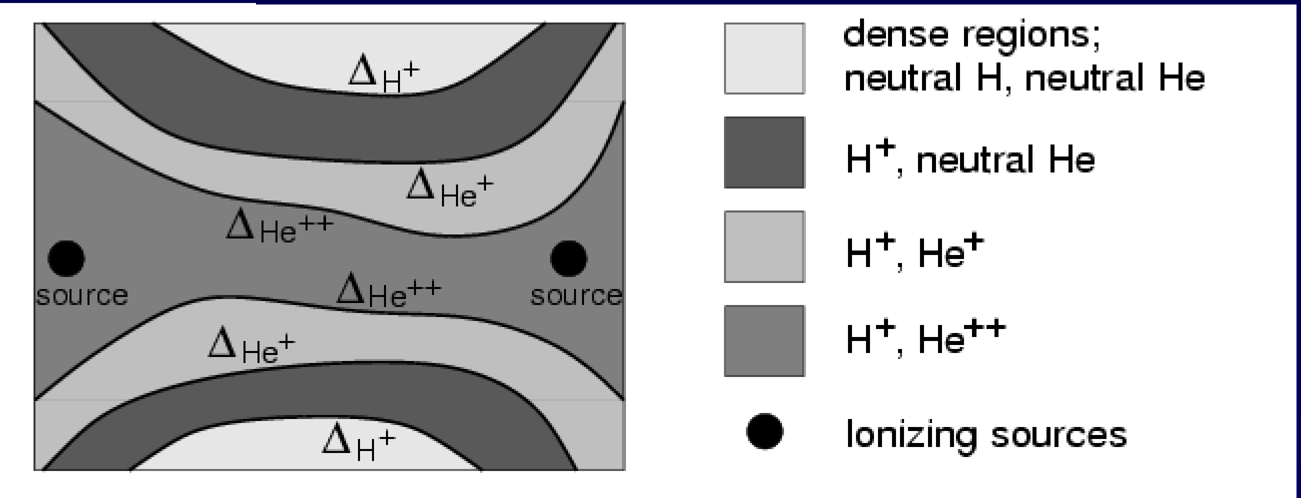


Abel, Bryan, & Norman 2000

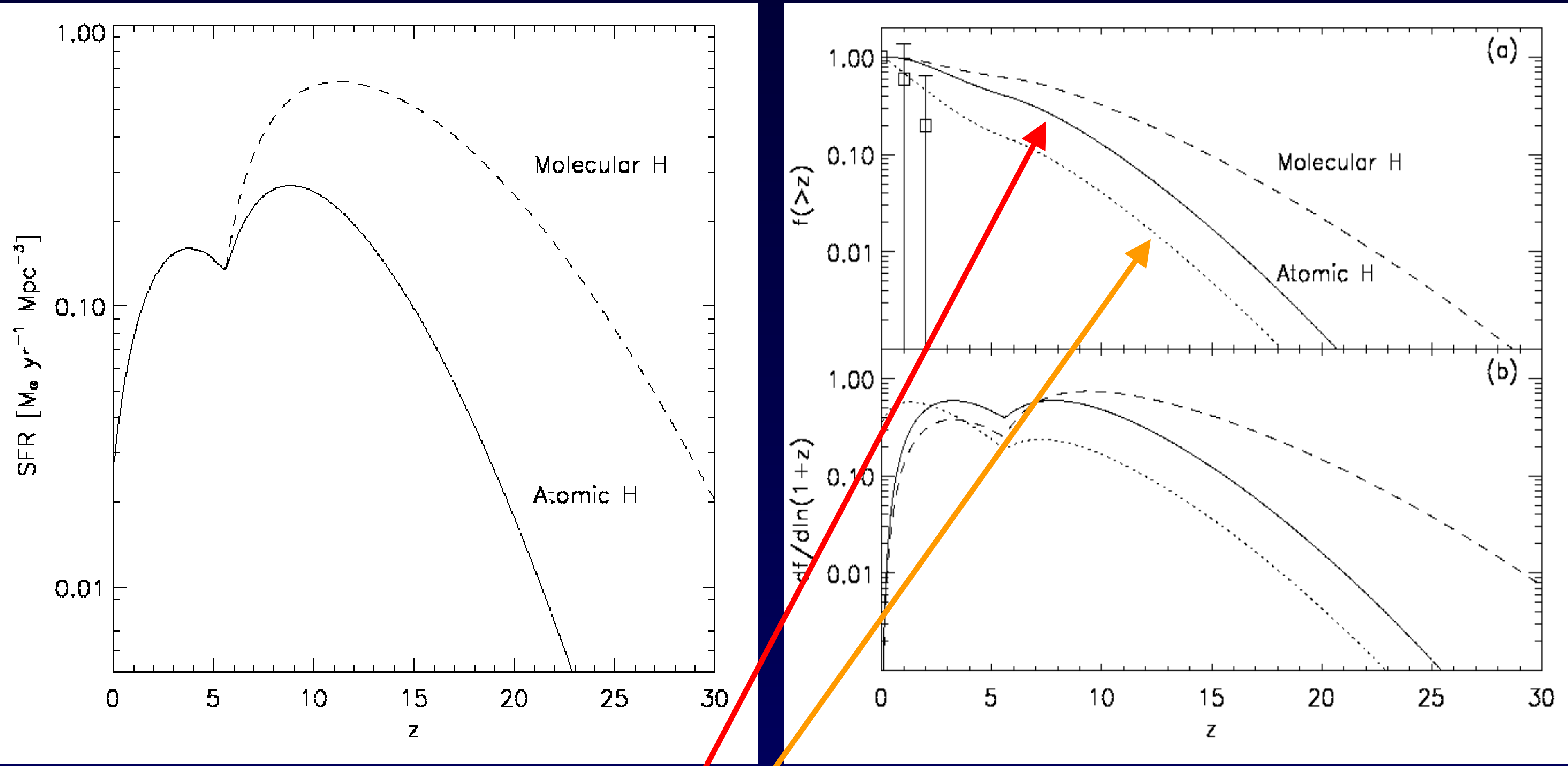
Bromm, Coppi, & Larson 2000

Model Ingredients

- *Transition redshift at which Pop-II stars start to dominate the ionizing background relative to metal free stars,* z_{tr}
- *Ionization starts in low-density regions and then progresses into high overdensities, with distribution of overdensities derived from hydrodynamic IGM simulations (Miralda-Escude et al. 2000)*
- *Escape fraction of ionizing radiation from galaxies:* f_{esc}
- *Collapsed fraction of baryons calculated for the standard LCDM parameters (with no tilt)*
- *Helium and hydrogen are treated self-consistently*



Predicted Redshift Distribution of GRBs



GRB fraction with redshift >z on the sky

Fraction of stellar mass formed by redshift z

Bromm & Loeb 2002

Ionization History of Hydrogen

REDSHIFT →

6

1000

Now

Big Bang

← *TIME*

Billion years

Million years

Ionized

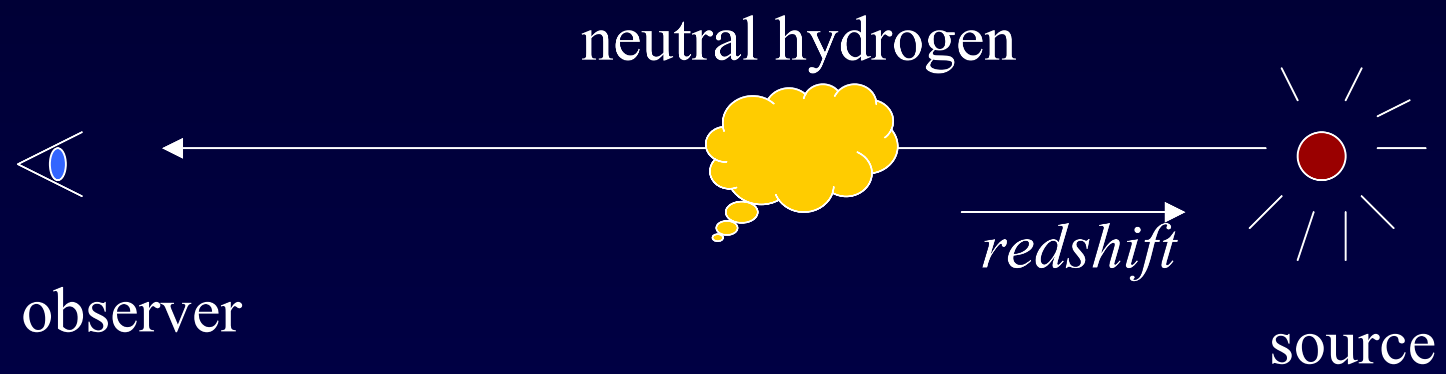
Neutral Hydrogen (HI)

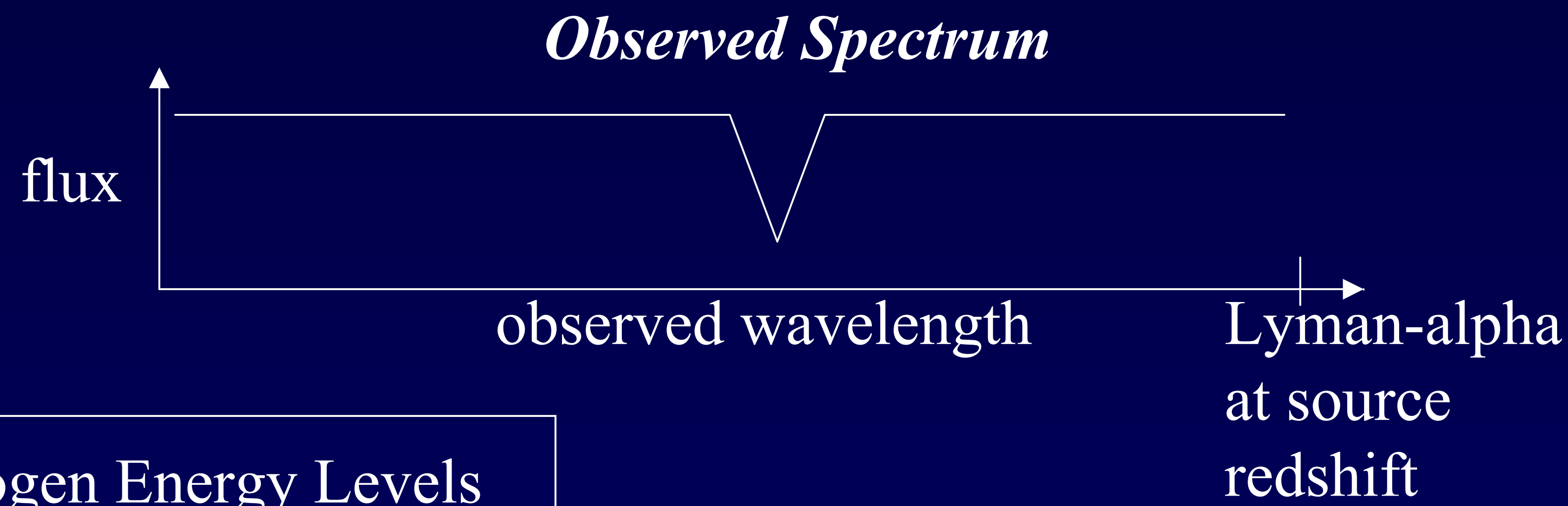
Ionized

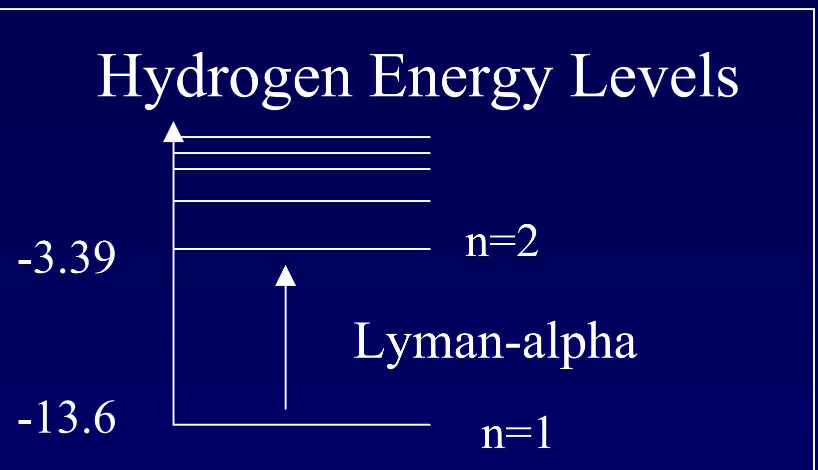
by the first stars and quasars

T>3000 K

Absorption by Diffuse Neutral Hydrogen



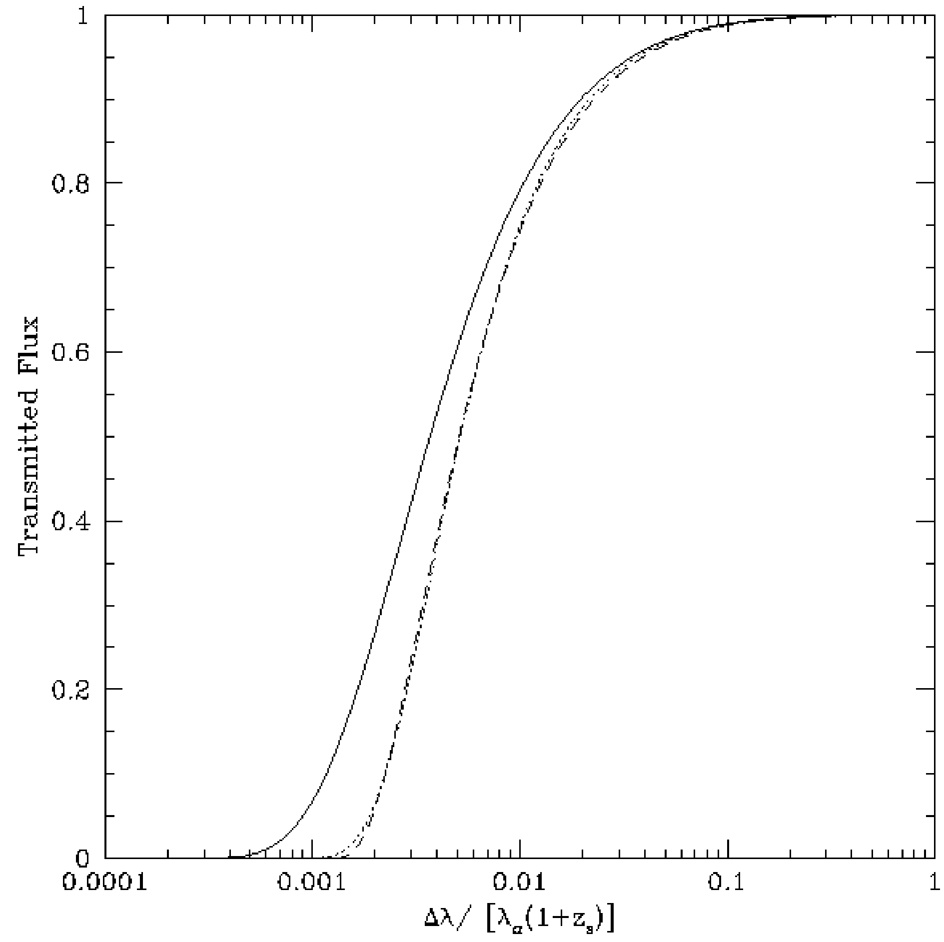




The Gunn-Peterson Effect

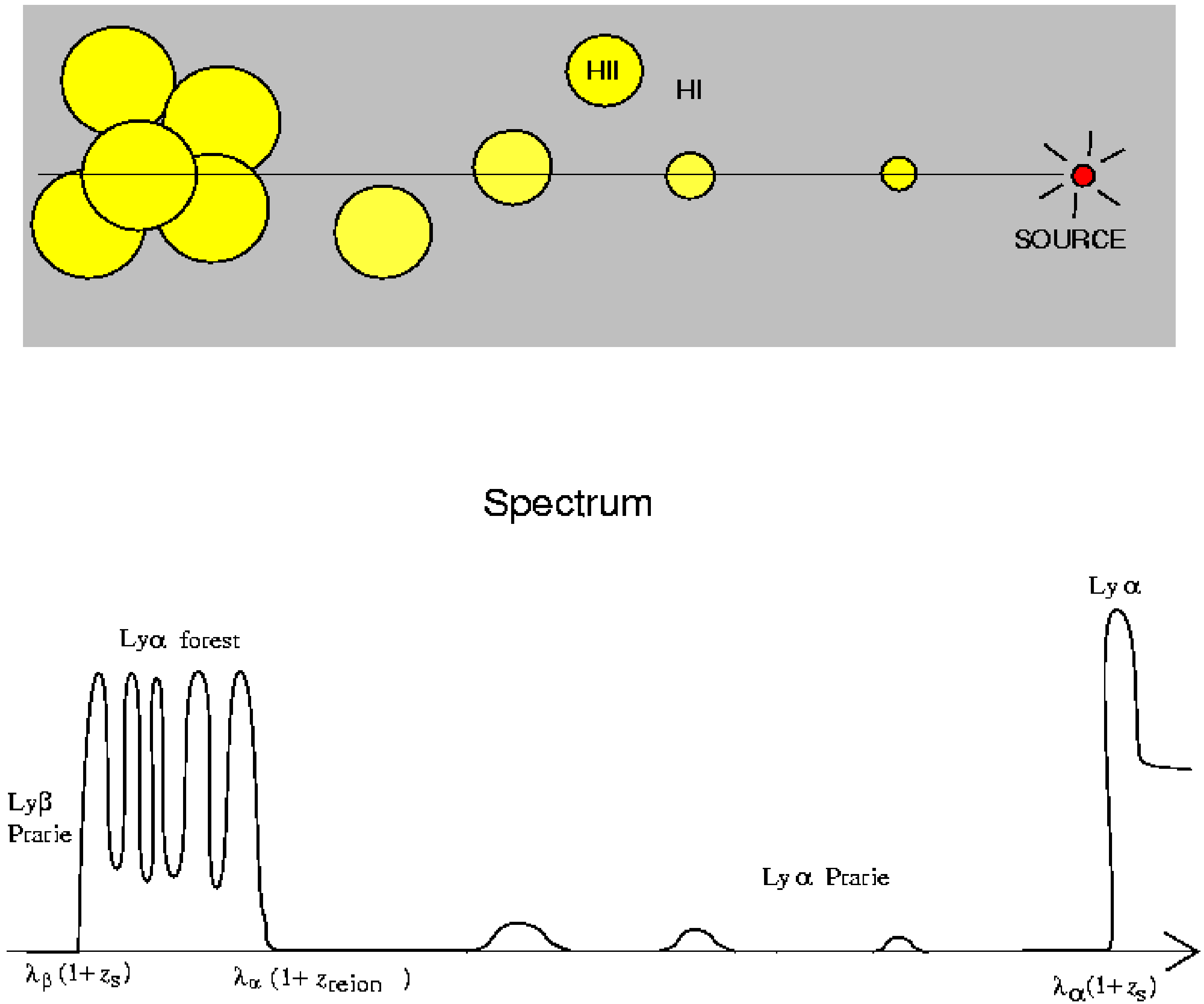
$$\tau_s = \frac{\pi e^2 f_\alpha \lambda_\alpha n_{\mathrm{HI}}(z_s)}{m_e c H(z_s)} \approx 6.45 \times 10^5 x_{\mathrm{HI}} \left(\frac{\Omega_b h}{0.03}\right) \left(\frac{\Omega_m}{0.3}\right)^{-1/2} \left(\frac{1+z_s}{10}\right)^{3/2}$$

The damping wing of the Lyman-alpha transition of neutral hydrogen:



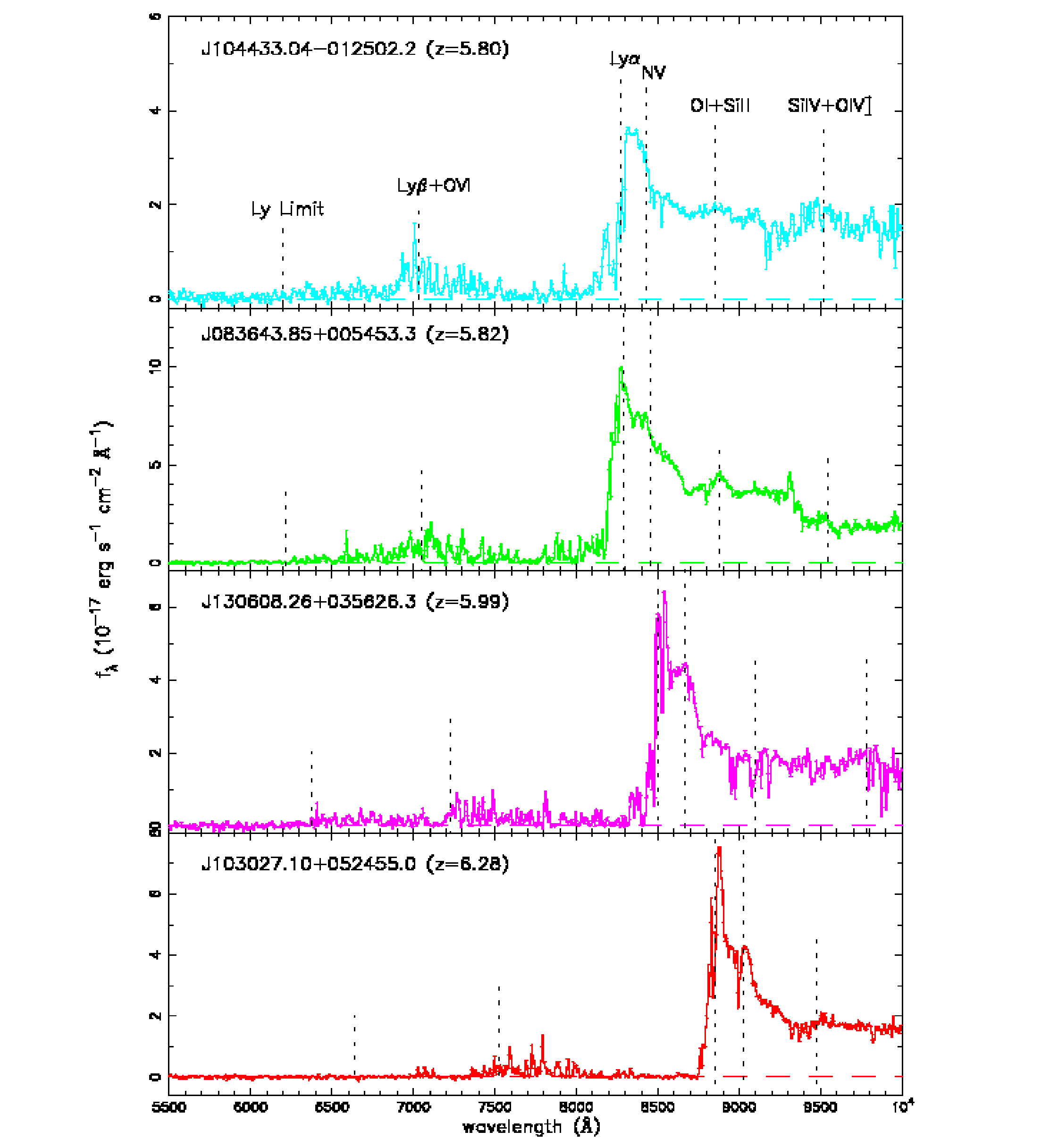
Miralda-Escude 1998

Spectrum of a Lighthouse Just Beyond the Reionization Redshift



$$1 < \frac{1+z_s}{1+z_{reion}} < \frac{\lambda_\alpha}{\lambda_\beta} = 1.18$$

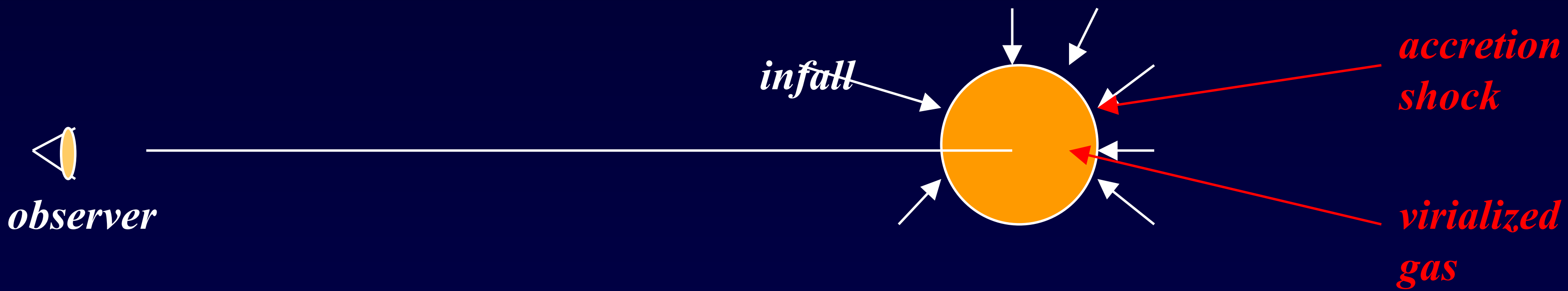
Have we observed the Gunn-Peterson Trough?

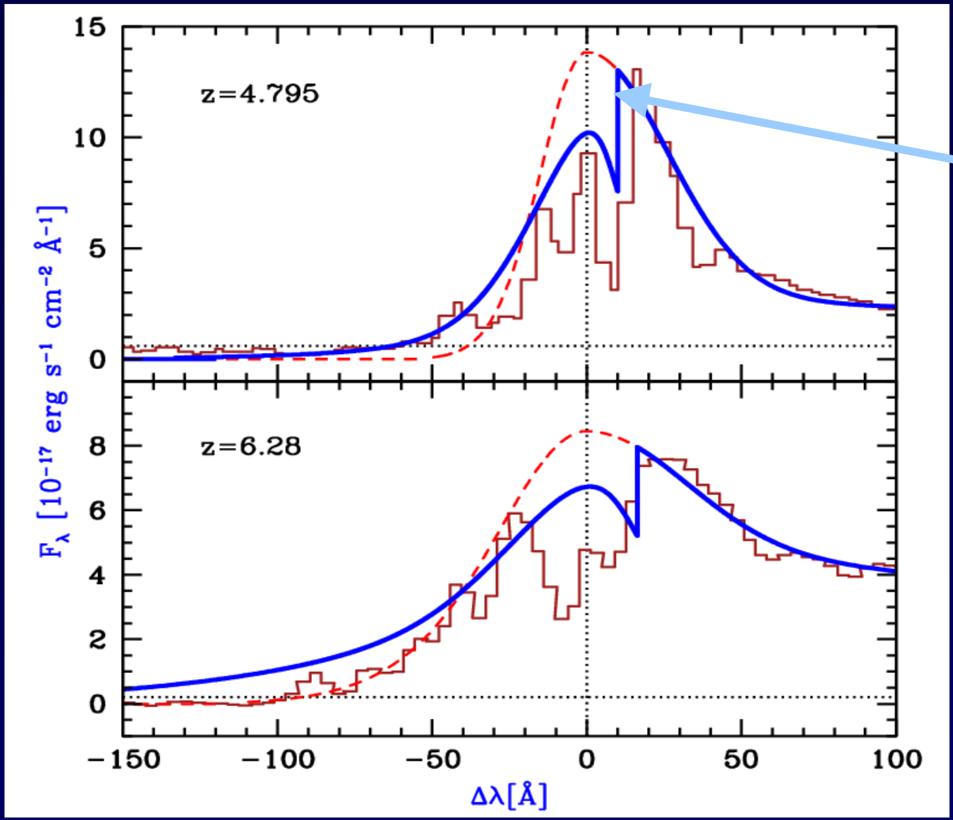


Becker et al. 2001

Limitations of Quasars as Probes of the Lya Damping Wing:

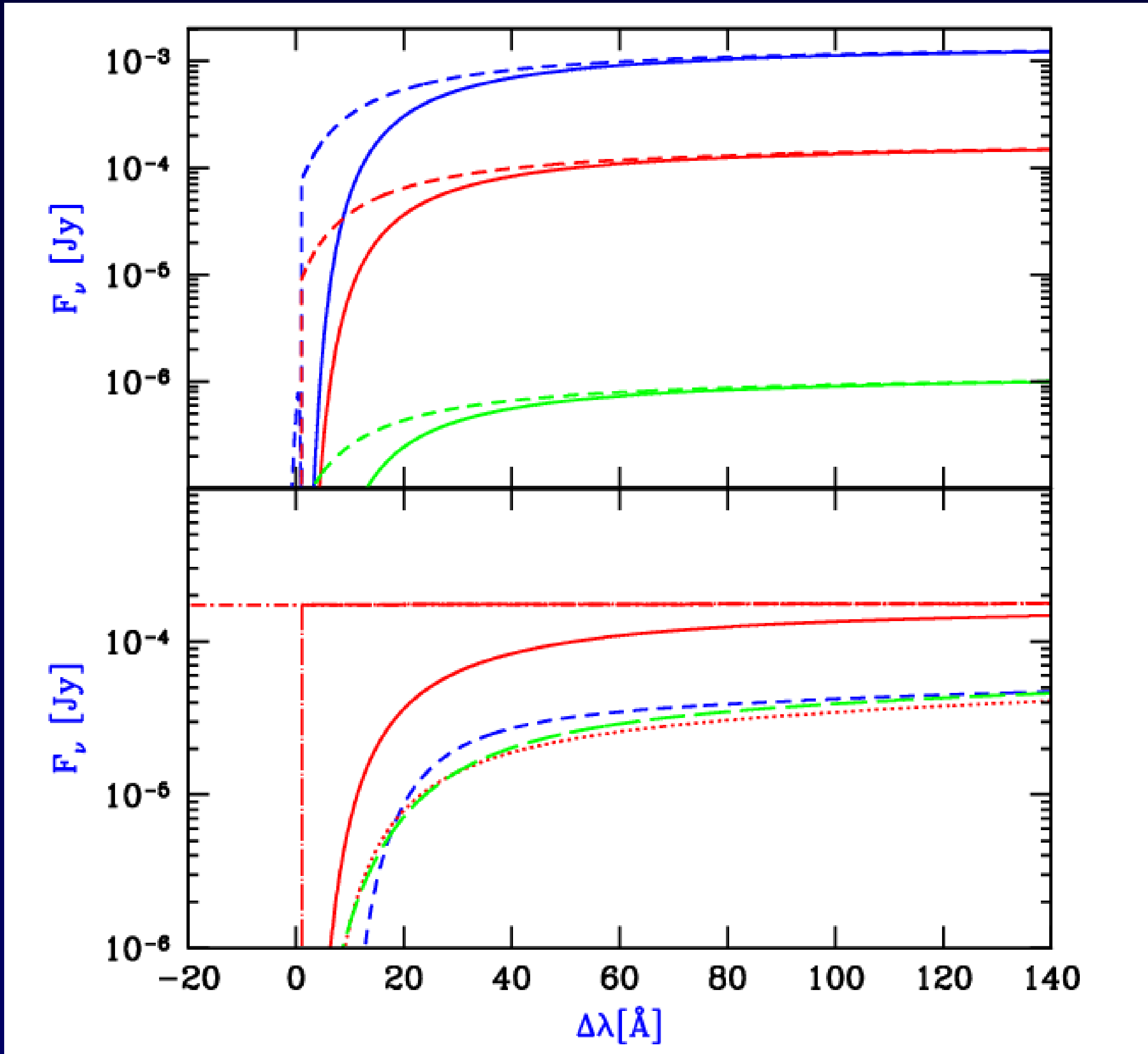
Proximity effect (ionization sphere)+Cosmological Infall





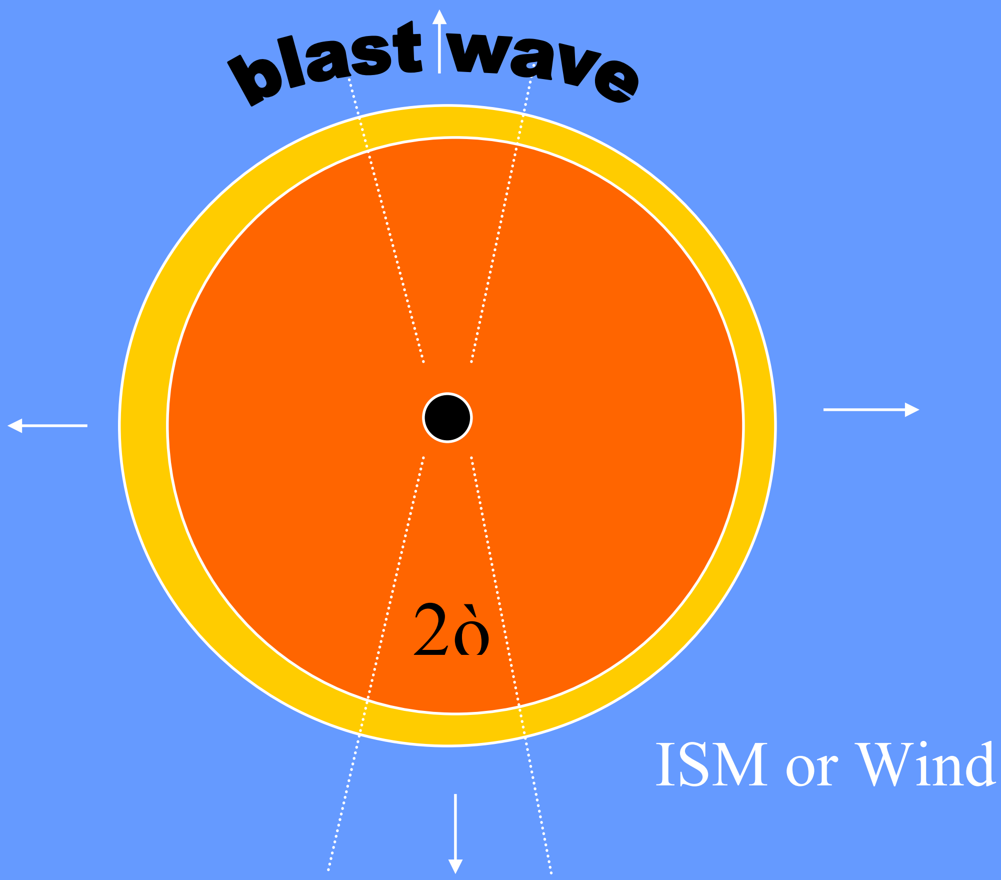
Barkana & Loeb, Nature, 2003

However most stars form in much smaller dwarf galaxies, which perturb only wealy the ionization state and Hubble flow of the surrounding gas...



Barkana & Loeb 2003

Gamma-Ray Bursts (GRBs)



$_0$ 100

$_e$ 0:2

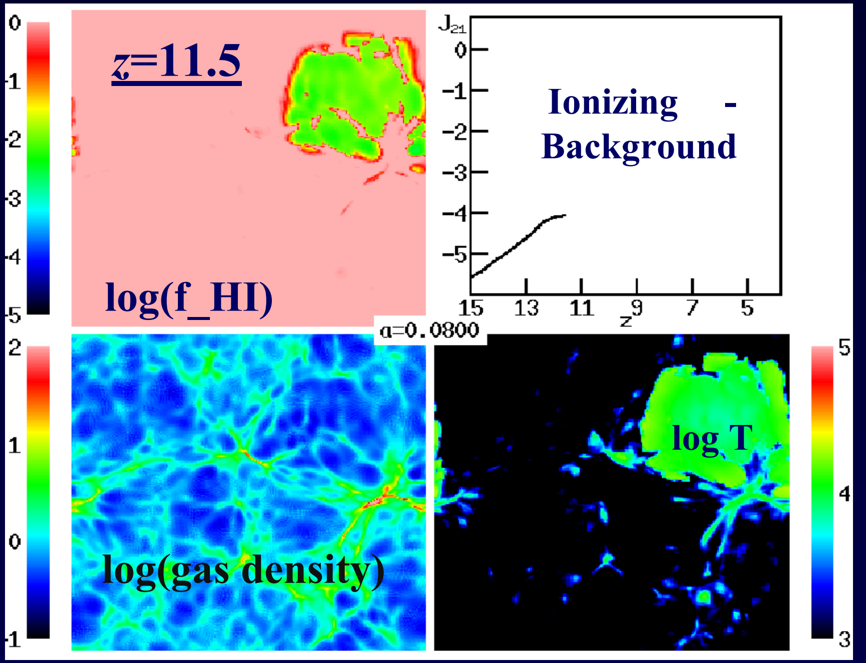
$_B$ 0:1

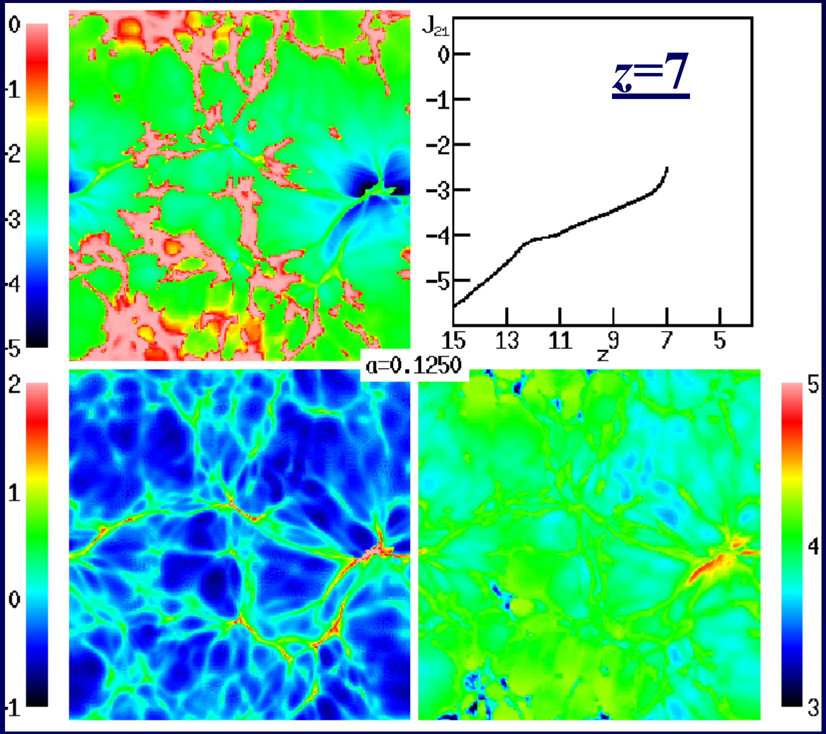
n_0 ø 1cm ^{3}

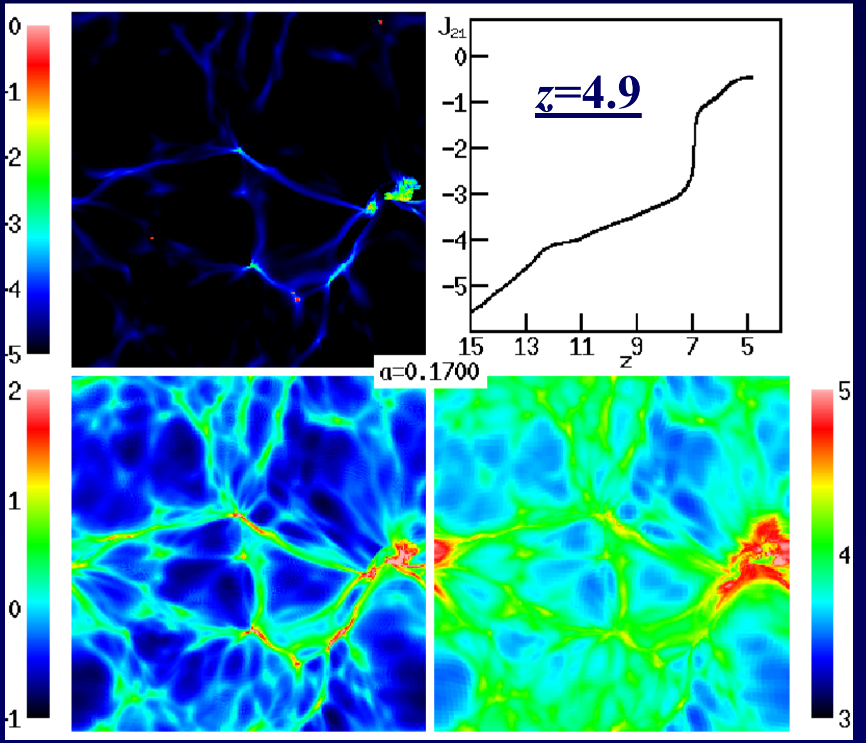
ò > í ^{1} ! as spherical

Simulation of Reionization

Gnedin (2000)

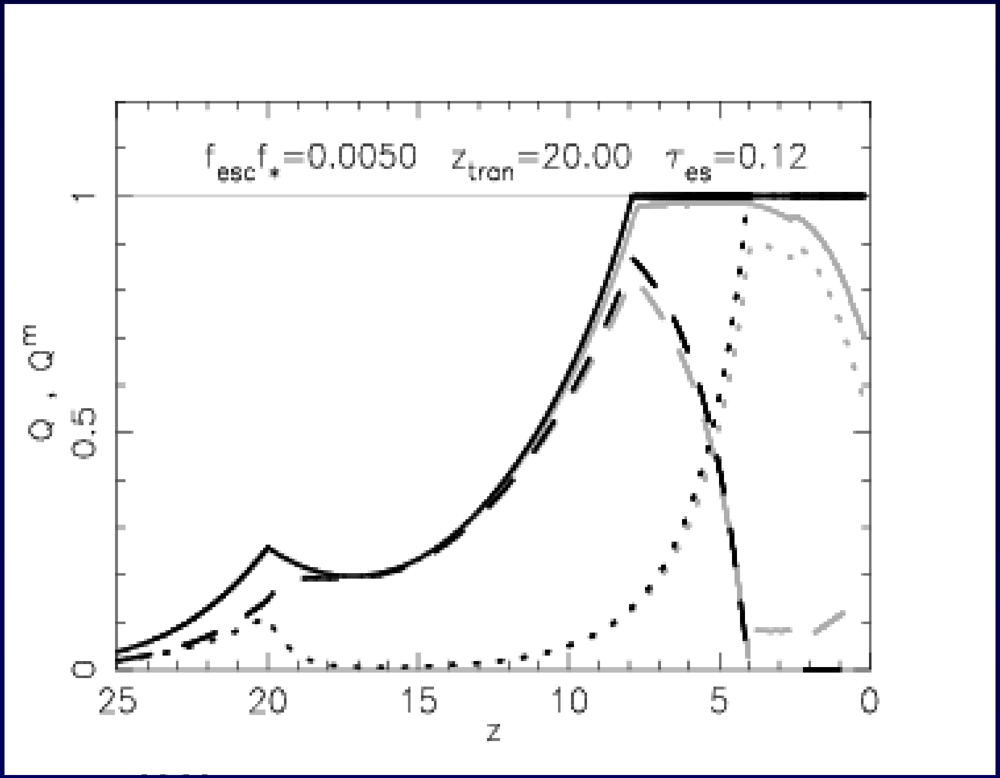






Reionization Histories of H, He

Free Parameters: *(i) transition redshift,* z_{tran}*, above which the stellar IMF is dominated by massive, zero-metallicity stars; (ii) the product of the star formation efficiency and the escape fraction of ionizing photons in galaxies,* $f_{esc}f_{?}$.



H+

He+

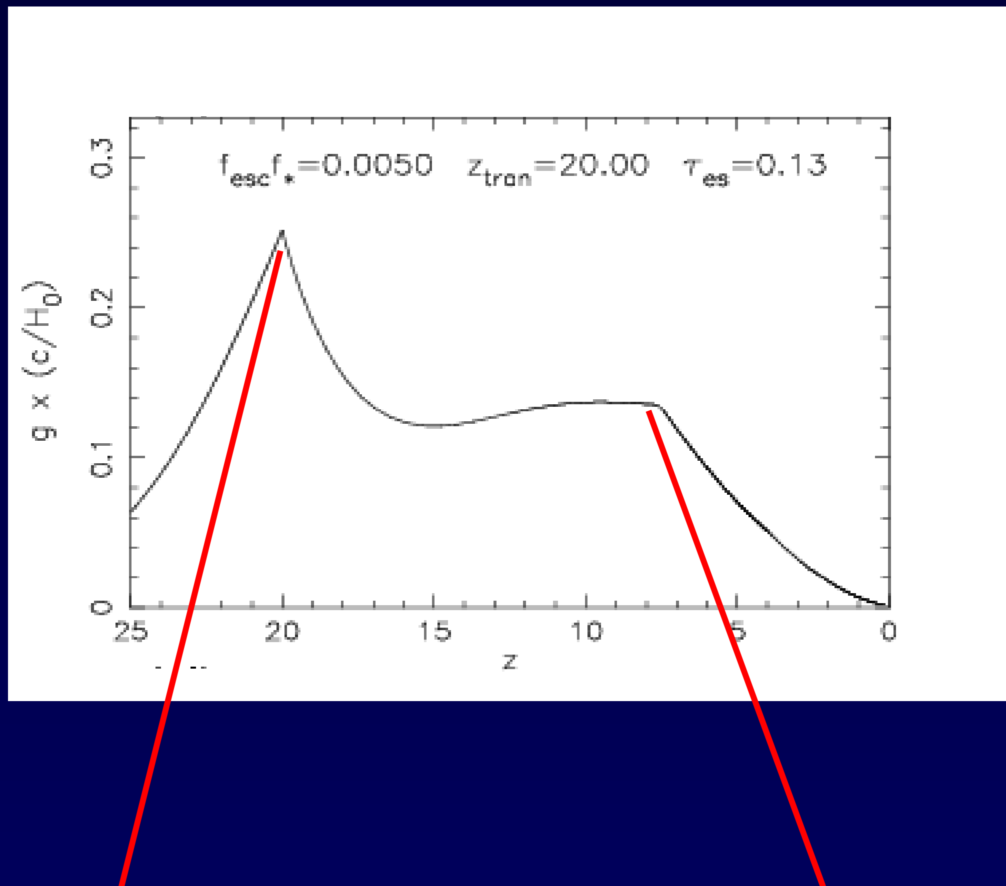
He++

Quasar model fits luminosity function data up to z=6

Wyithe & Loeb 2002

Visibility Function due to Electron Scattering

Scattering probability per conformal time: $g=$ ïœe



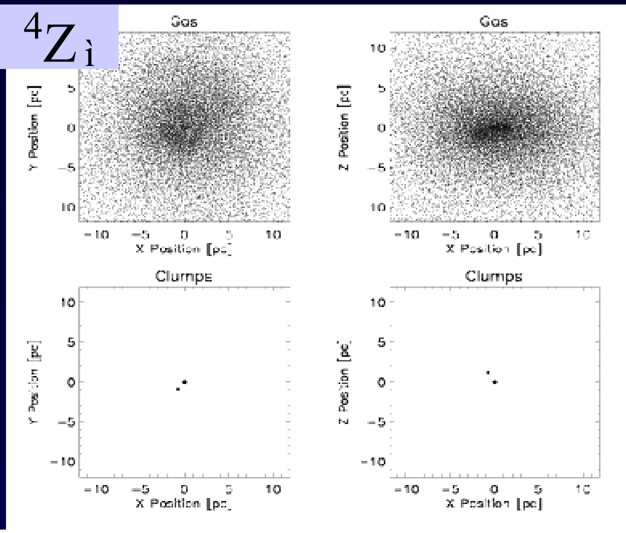
failed overlap

successful overlap

Wyithe & Loeb 2002

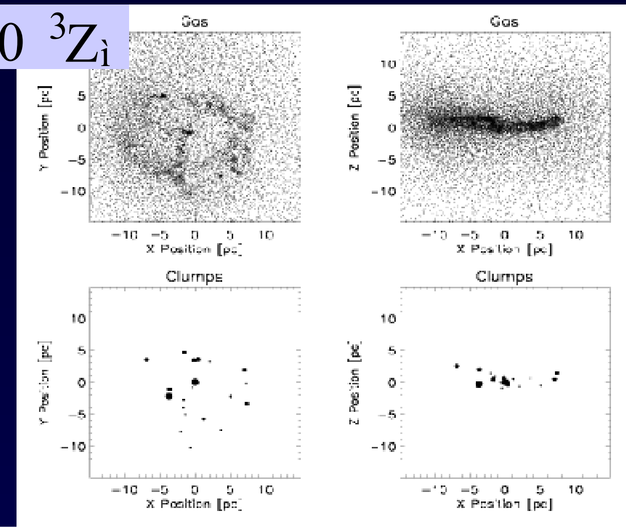
Dependence of Fragmentation on Metallicity

$Z = 10^{-4} Z_\odot$



Bromm et al. 2001

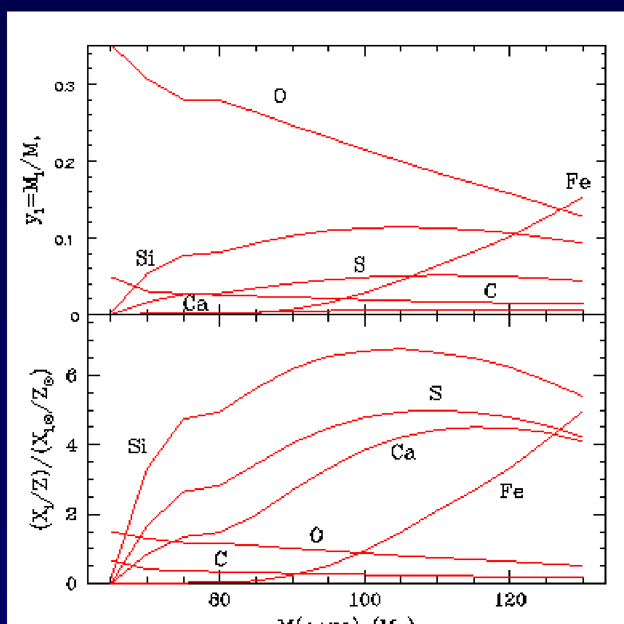
$Z = 10^{-3} Z_\odot$



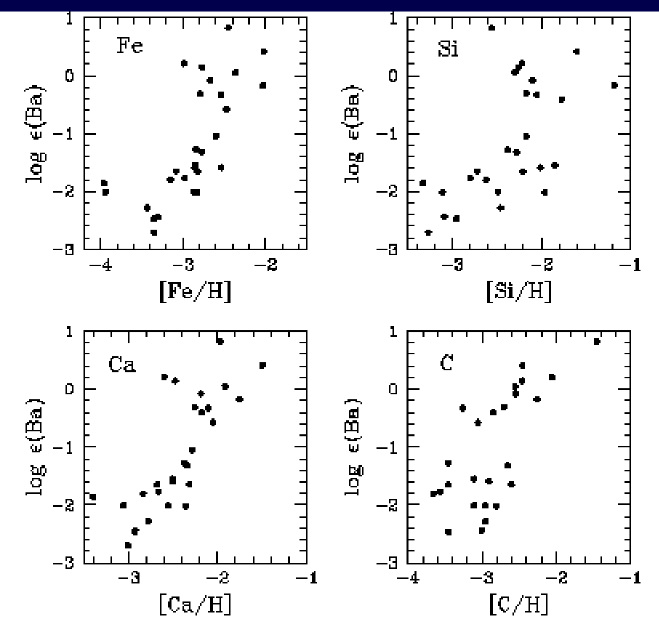
Radiative cooling=adiabatic heating at virialization

$\rightarrow \quad Z_{crit} = 10^{-3}(M/10^6 M_\odot)^{1/3}$

Metal Yield of Massive Early Stars



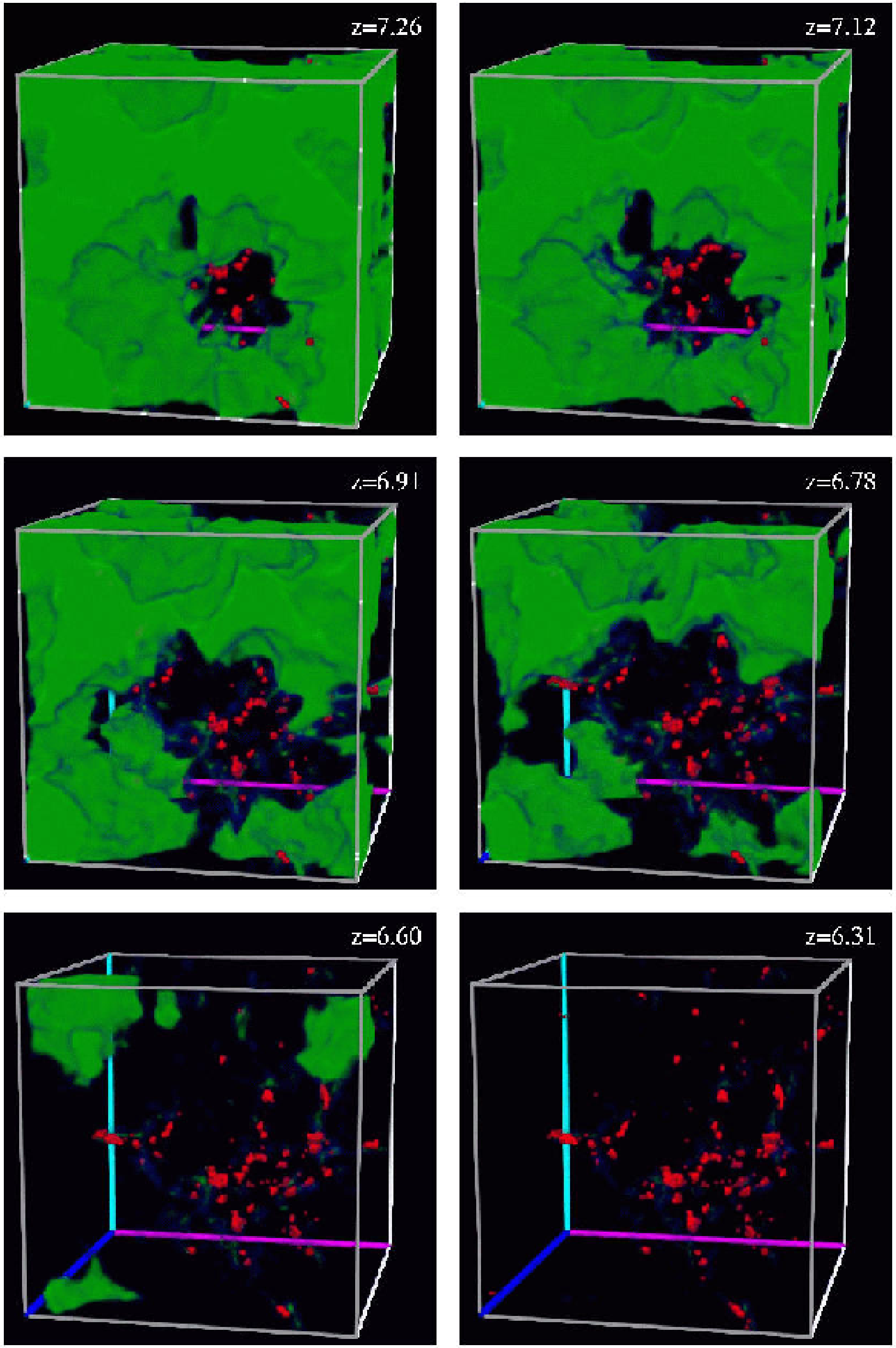
Heger & Woosley 2001

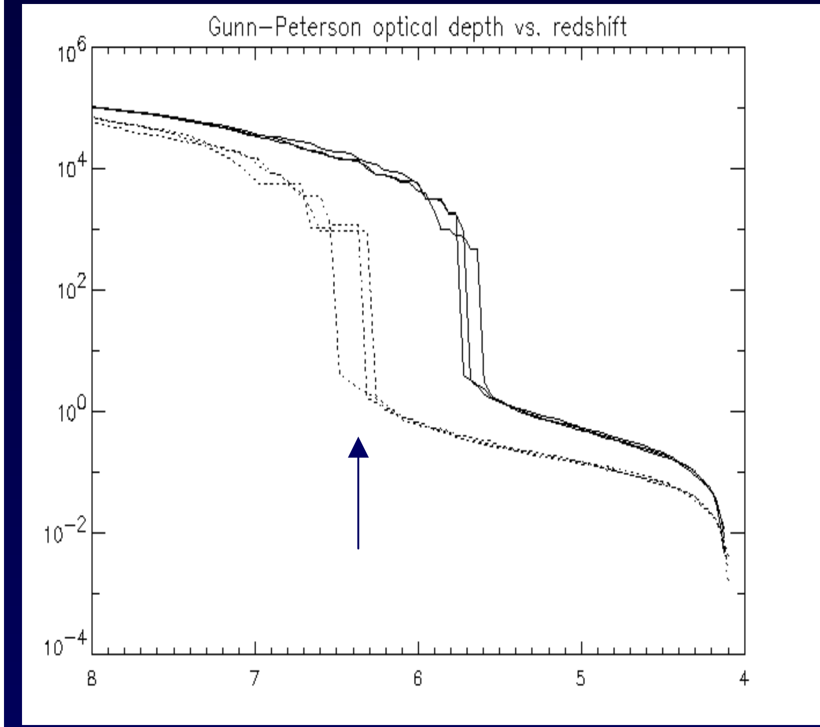


Data for Halo Stars

Wasserburg & Qian 2001

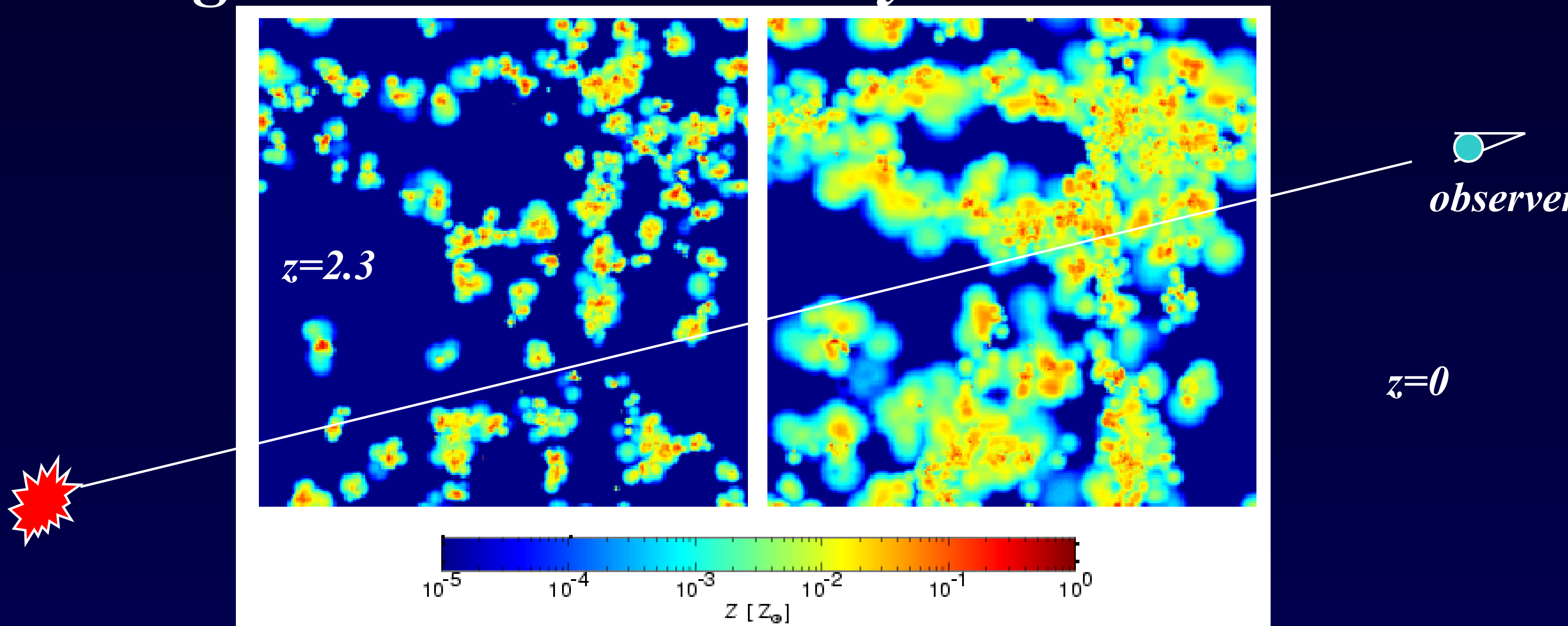
Simulation of Reionization

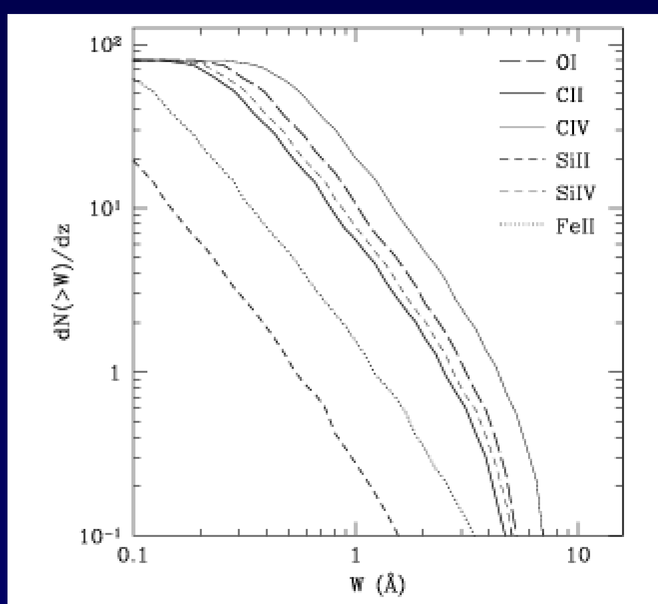




Razoumov, Norman, Abel, & Scott 2001

Probing Metal Enrichment by the First Galaxies





Number of intersections with equivalent width >W per unit redshift at a redshift z=8

Furlanetto & Loeb 2003