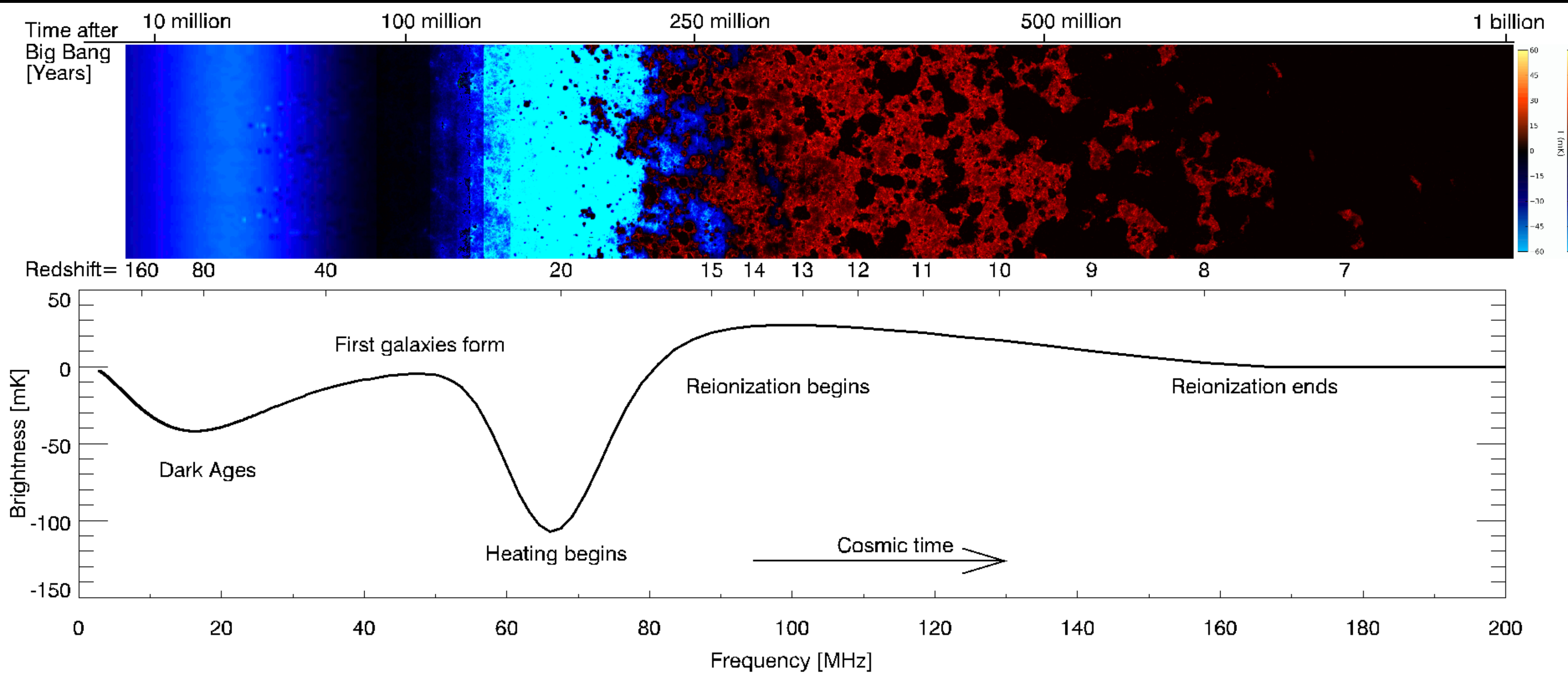
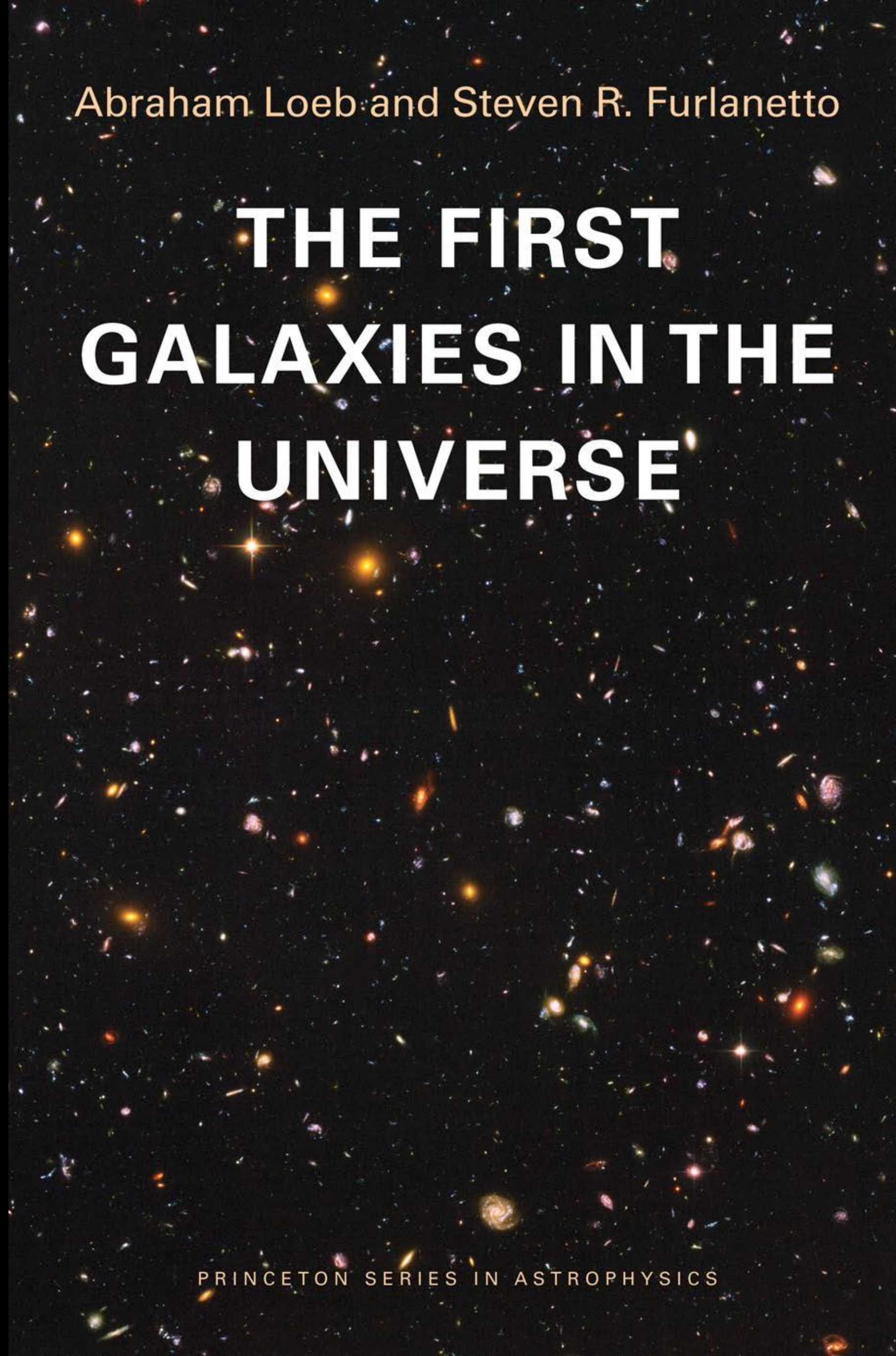
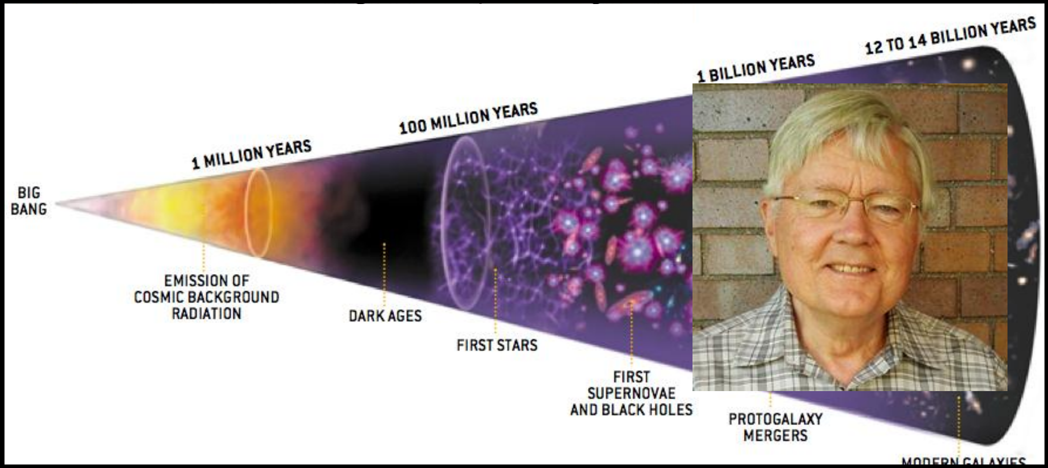
The First Stars and Galaxies: Basic Theoretical Framework



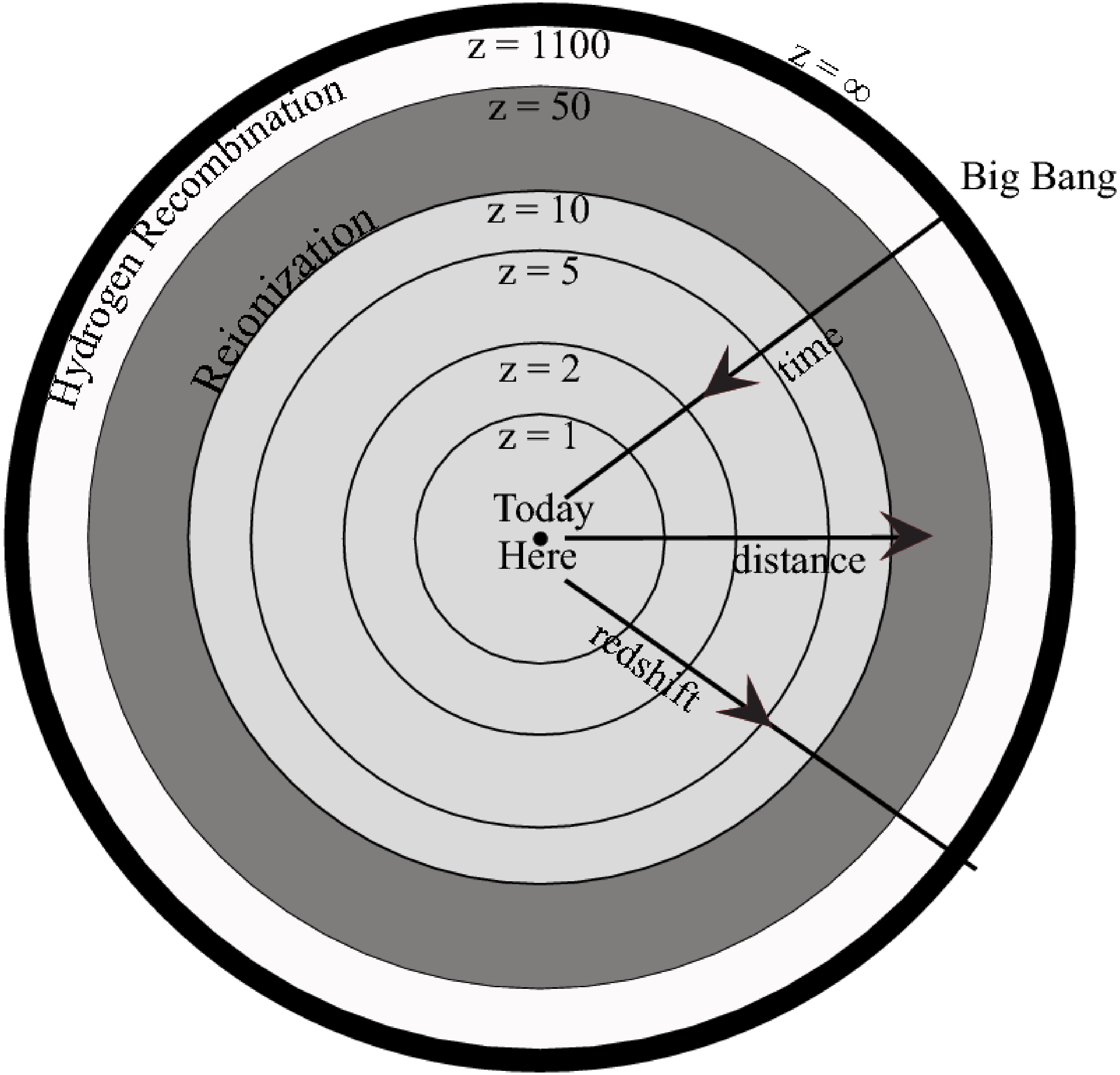

Abraham Loeb and Steven R. Furlanetto
THE FIRST GALAXIES IN THE UNIVERSE
PRINCETON SERIES IN ASTROPHYSICS

Richard Larson: *a brilliant first star who illuminated the physics of galaxy and star formation during the dark ages of astrophysics*

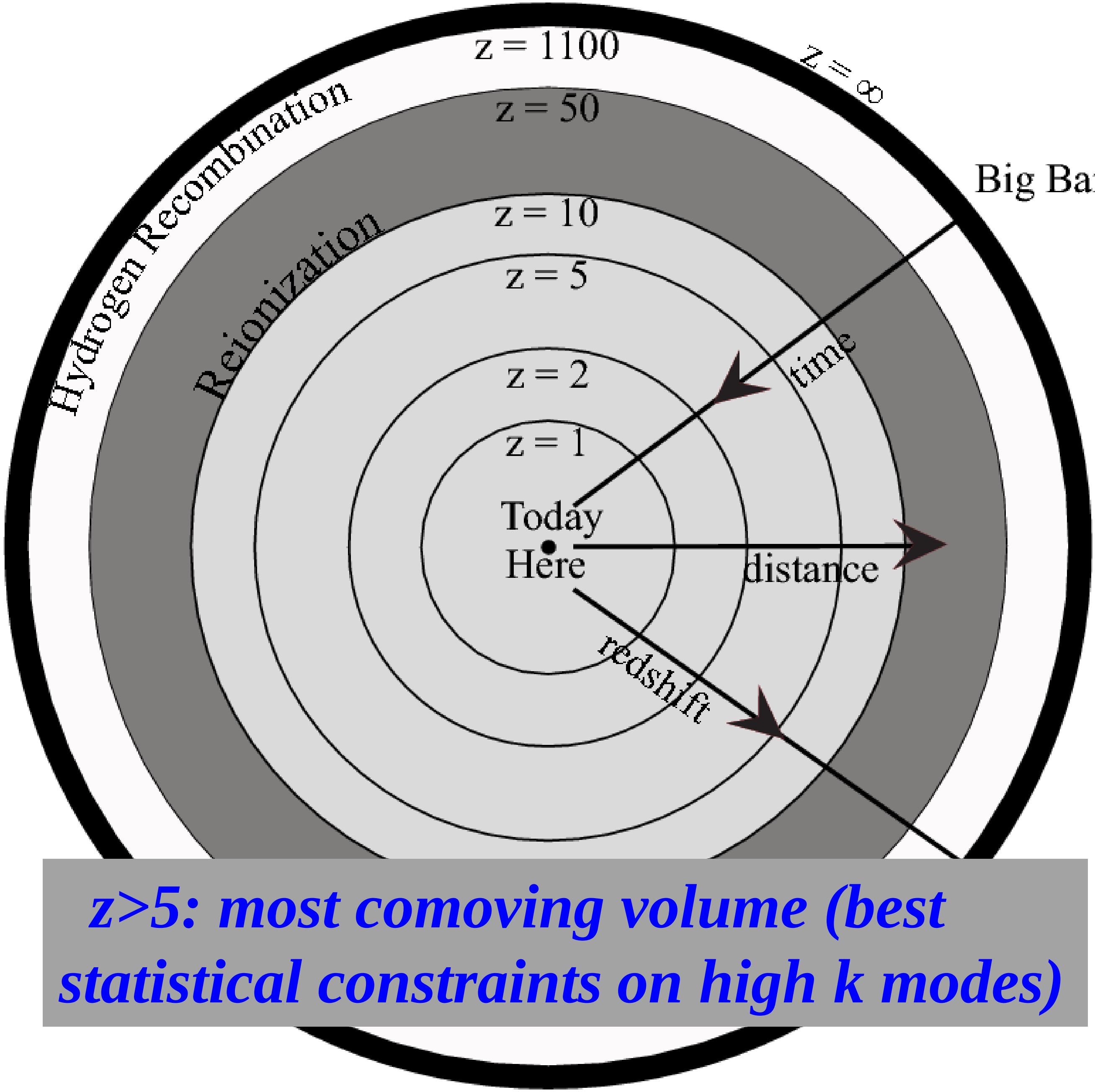


- PhD (1968): “Dynamics of Collapsing Protostar”
- Galaxy formation and evolution: with Tinsley
- Larson Laws : “Turbulence and Star Formation in Molecular Clouds” (1981)
- First stars: with Bromm and Coppi

The Visible Universe

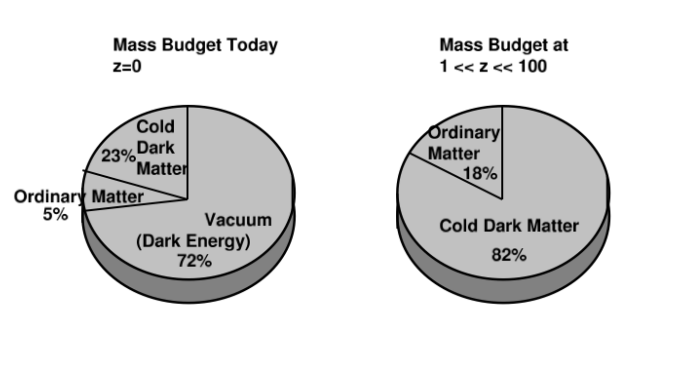


The Visible Universe

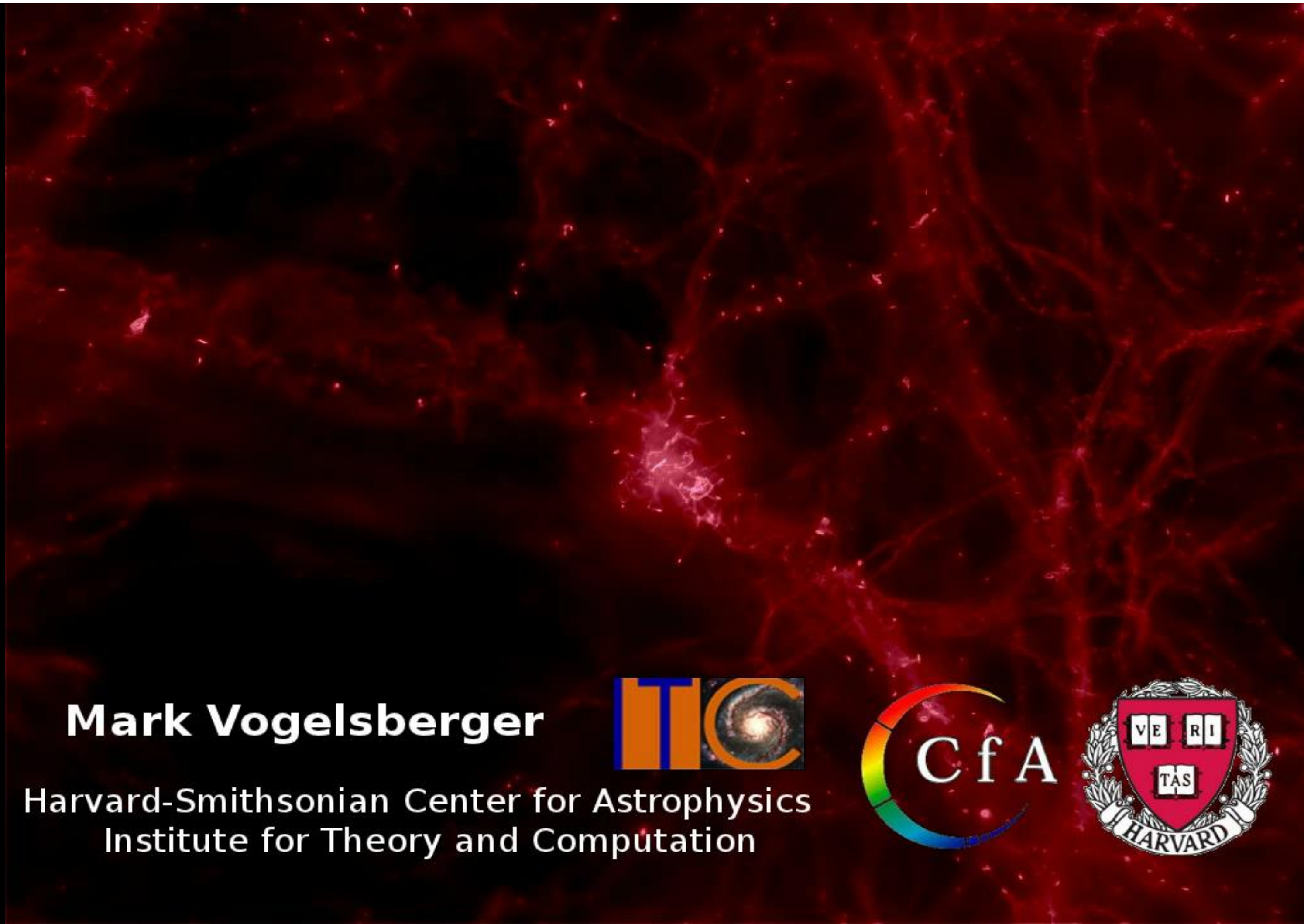


z>5: most comoving volume (best statistical constraints on high k modes)

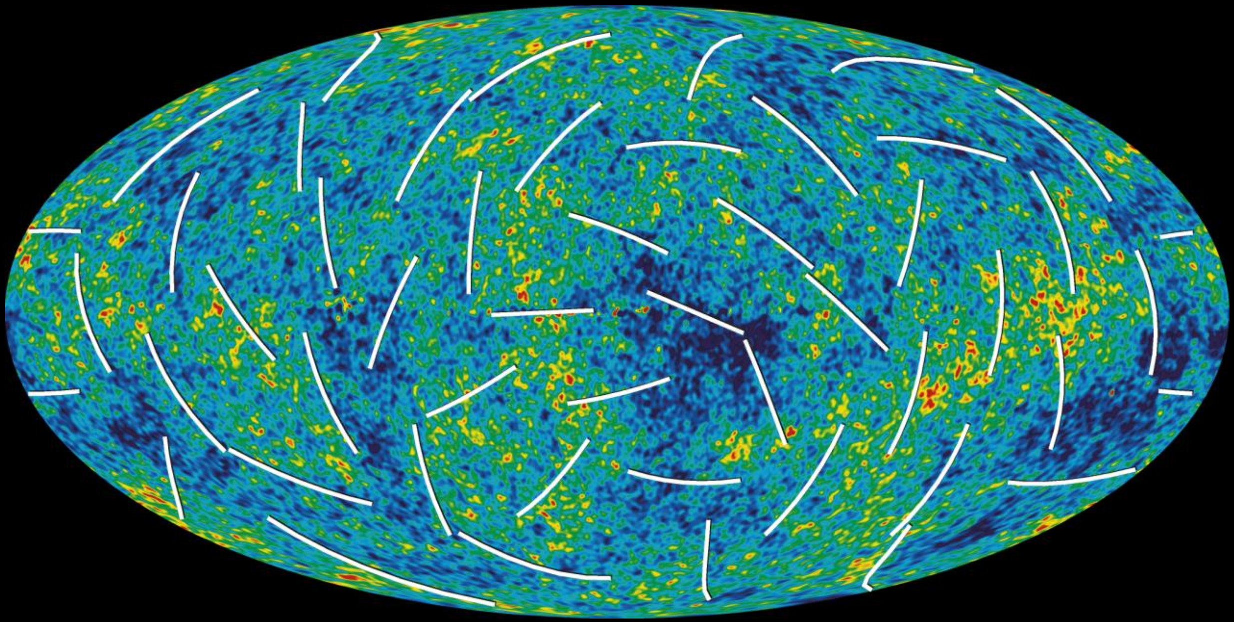
Standard Model



Ω_Λ	Ω_m	Ω_b	h	n_s	σ_8
0.72	0.28	0.05	0.7	1	0.82



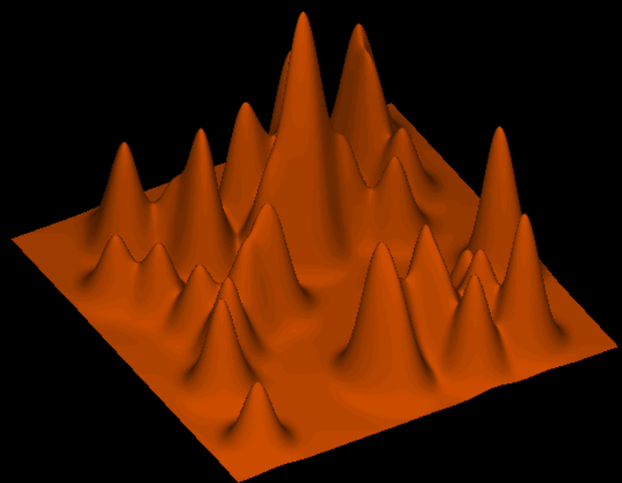
Cosmic Microwave Background *(WMAP7)*



$$\tau_{e-scatt} = 8.8 \pm 1.5\%$$

The polarization data indicates that the first stars must have formed <500 million years after the big bang, when the universe was only a few percent of its current age!

Baryon Streaming Relative to Dark Matter



$$R \sim c_s t \sim (c/\sqrt{3})t$$

$$v_b \sim 30 \text{ km s}^{-1} \text{ relative to dark matter at } z \sim 10^3$$

- Streaming of baryons relative to dark matter potential wells acts as an effective inhomogeneous sound speed
- Coherence scale of ~3 cMpc >> Jeans scale at *z*~50

Tseliakhovich & Hirata (2010)

$v_b \propto (1+z)^{-1}$ is significant only for halos with $T_{\rm vir}$ well below the HI cooling threshold of $\sim 10^4$K

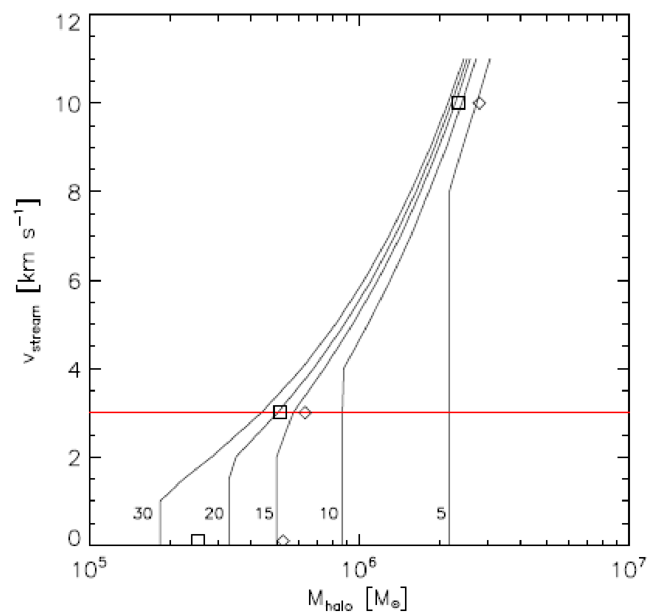
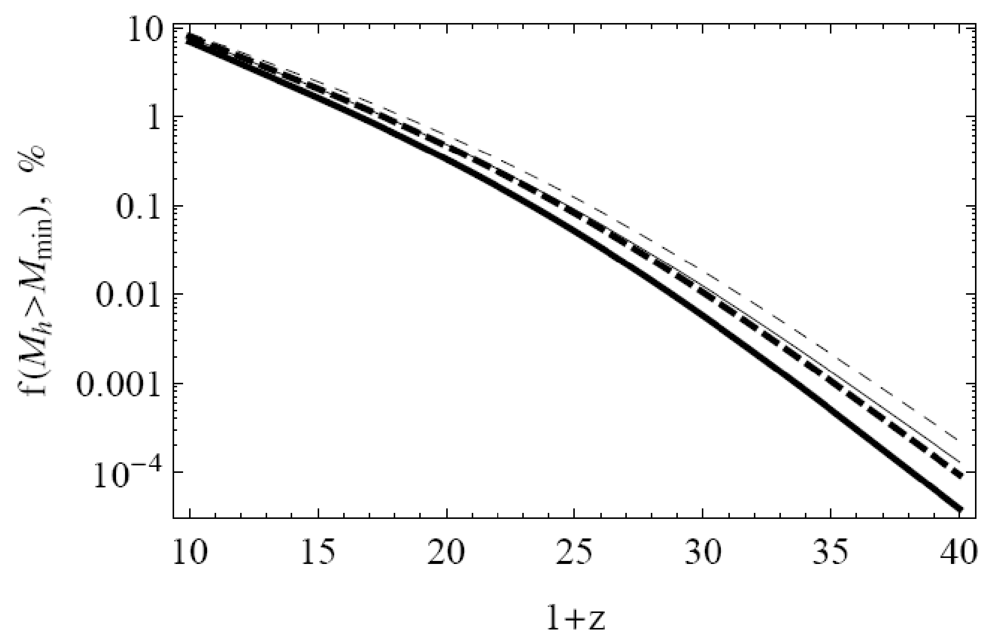


FIG. 2.— Effect of relative streaming on the minimum halo mass into which primordial gas can collapse. Each line represents the necessary halo masses for baryon collapse at a different redshift, marked in the plot. The diamonds represent the final halo masses found in 'standard collapse' simulations ($z_{\rm col}$ = 14 for no streaming), and the squares represent masses from the 'early collapse simulations' ($z_{\rm col}$ = 24 for no streaming). Note that the halo mass does not noticeably increase unless the initial streaming velocites are very high ($\gtrsim$ 3 km s^{-1}). Also note that halos collapsing at high redshift are more affected by relative streaming, as the physical streaming velocities are higher at these early times.

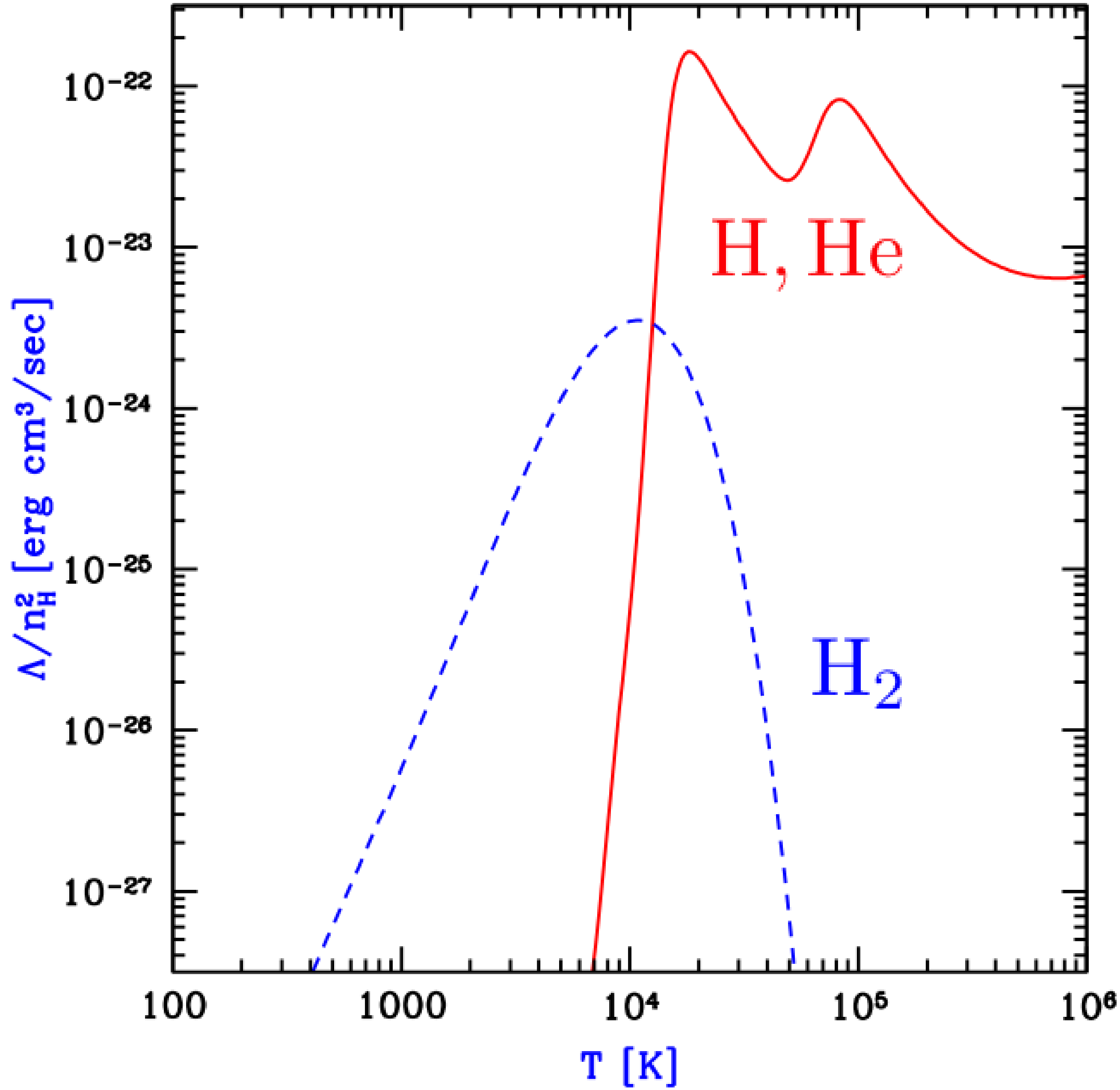


igure 8. In the left panel we plot the total mass fraction in halos a
bove the minimum cooling mass (solid lines). In the right panel we

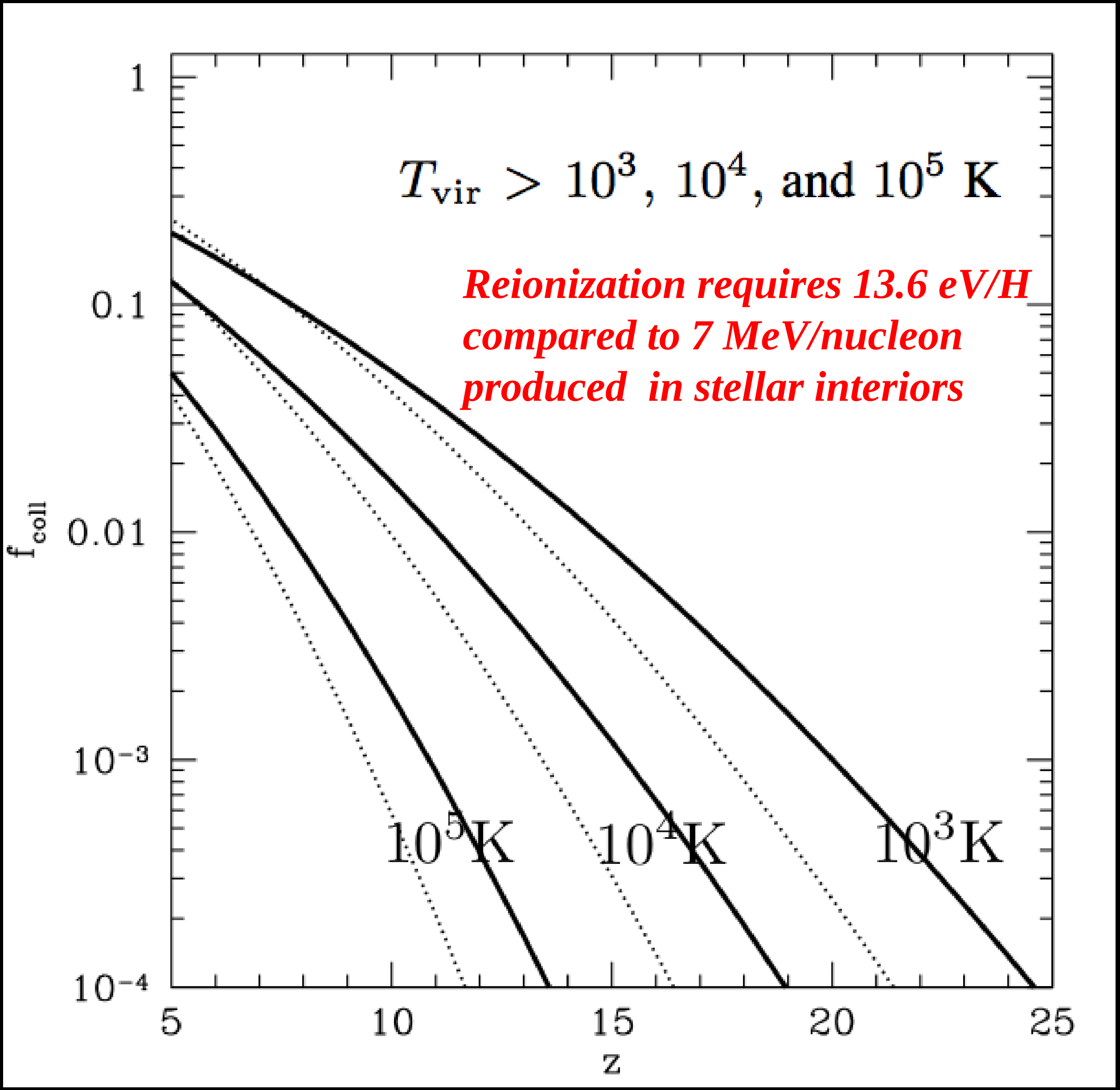
Stacy, Bromm, & Loeb (2011)

Tseliakhovich, Barkana, & Hirata (2011)

Cooling Rate of Primordial Gas

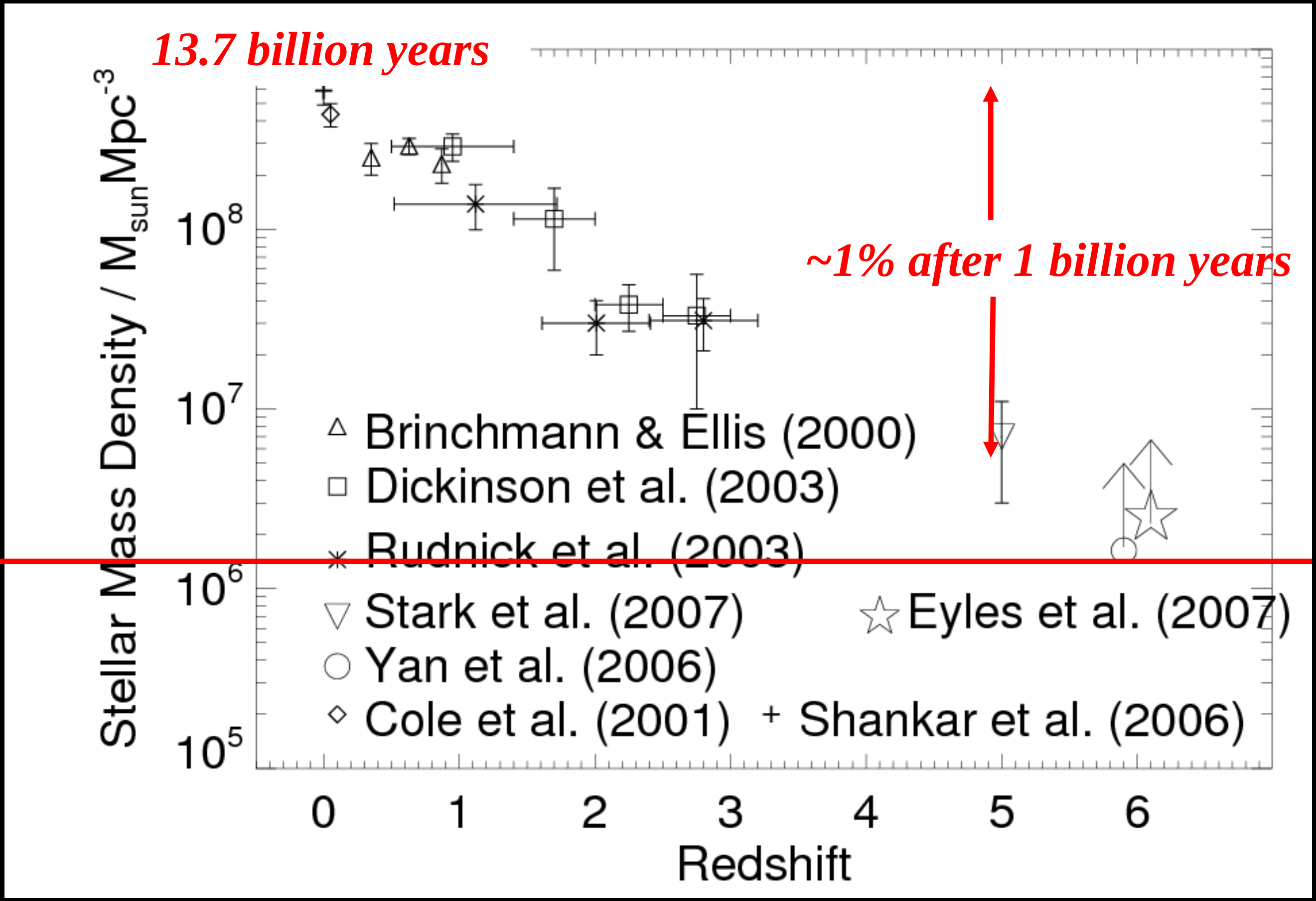


Fraction of collapsed matter



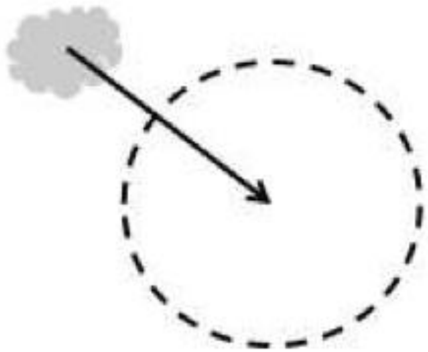
Observed Growth of Mass in Stars

← *Time*

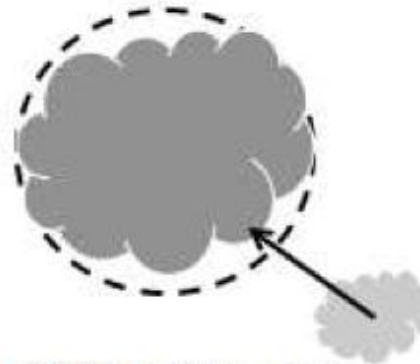


one ionizing photon per atom

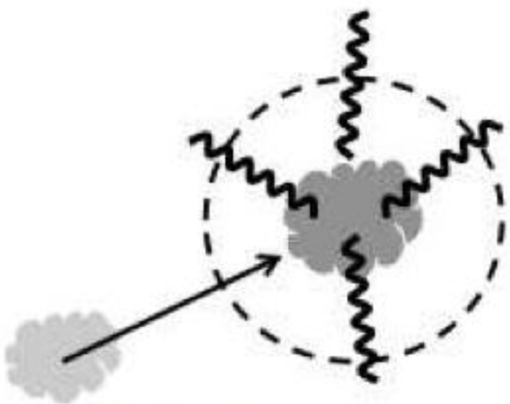
Population III.1



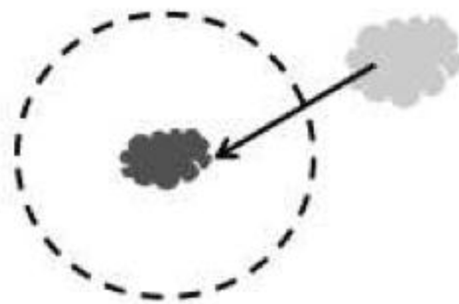
(a) Gas accretion onto dark matter halo; heating to virial temperature



(b) Buildup of H_2 and recombination of H I until saturation



(c) Radiative cooling via H_2 and collapse to “loitering” density



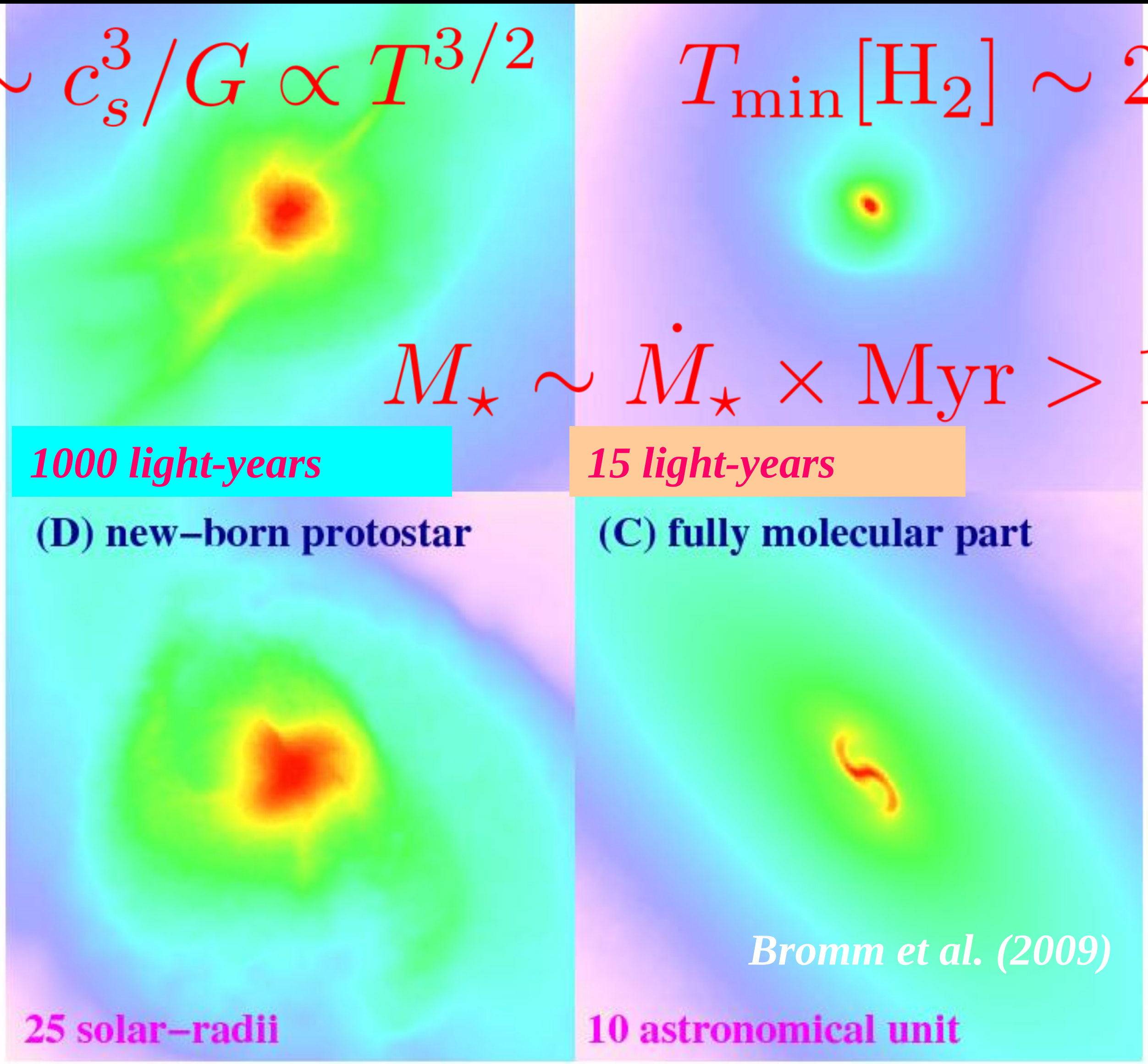
(d) Gravitational collapse once Jeans unstable

The First Stars Are Predicted to Have Formed ~100 Million Years After the Big Bang

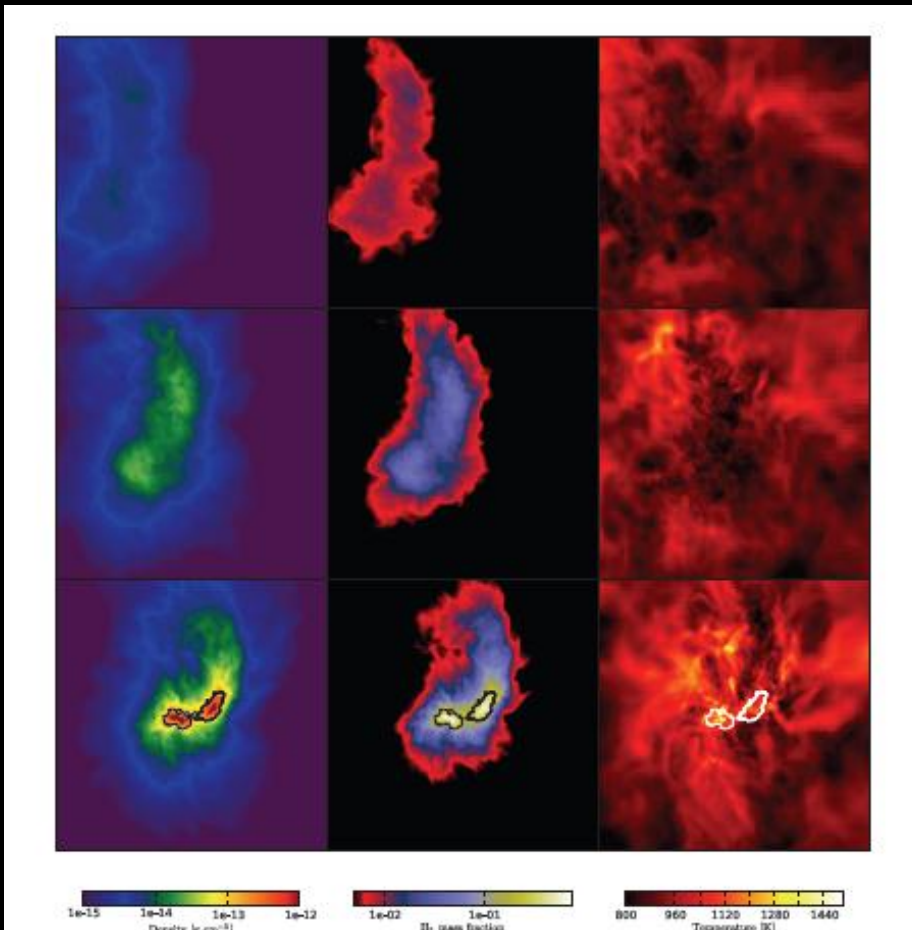
$$\dot{M}_\star \sim c_s^3/G \propto T^{3/2}$$

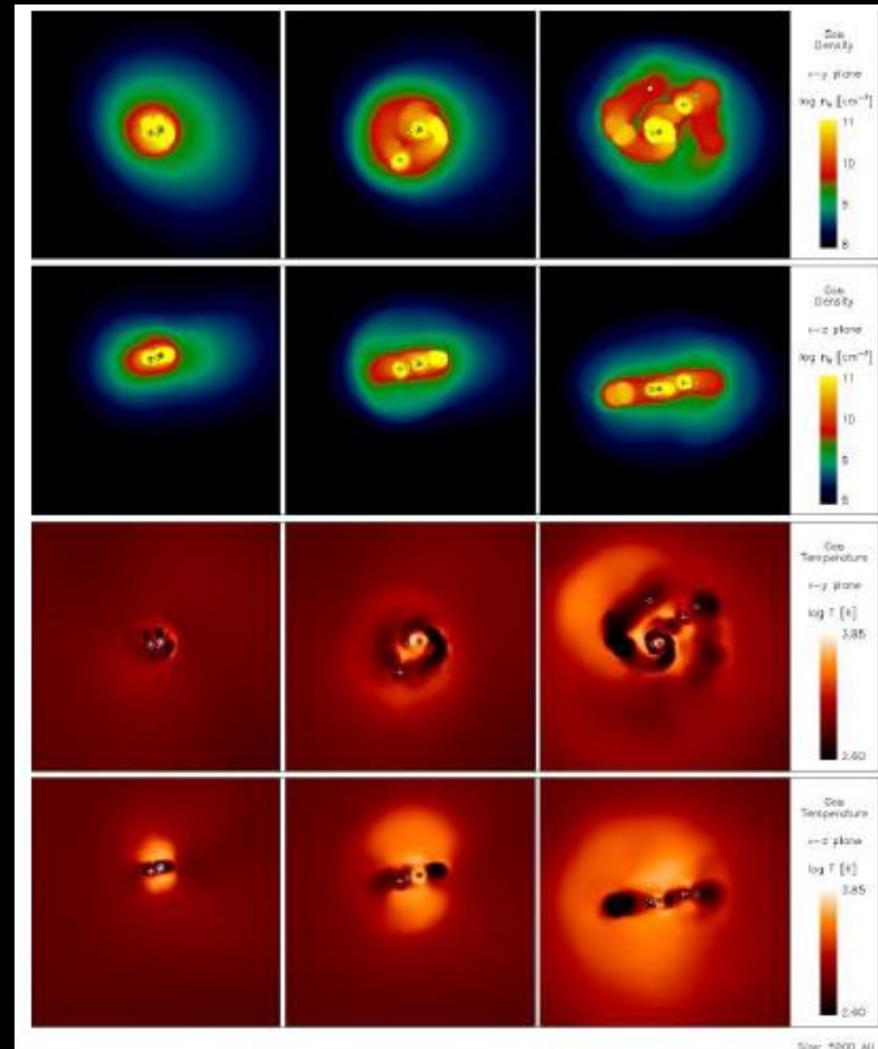
$$T_{\rm min}[{\rm H_2}] \sim 200{\rm K}$$

$$M_\star \sim \dot{M}_\star \times {\rm Myr} > 10 M_\odot$$



Population III Binaries or Multiples

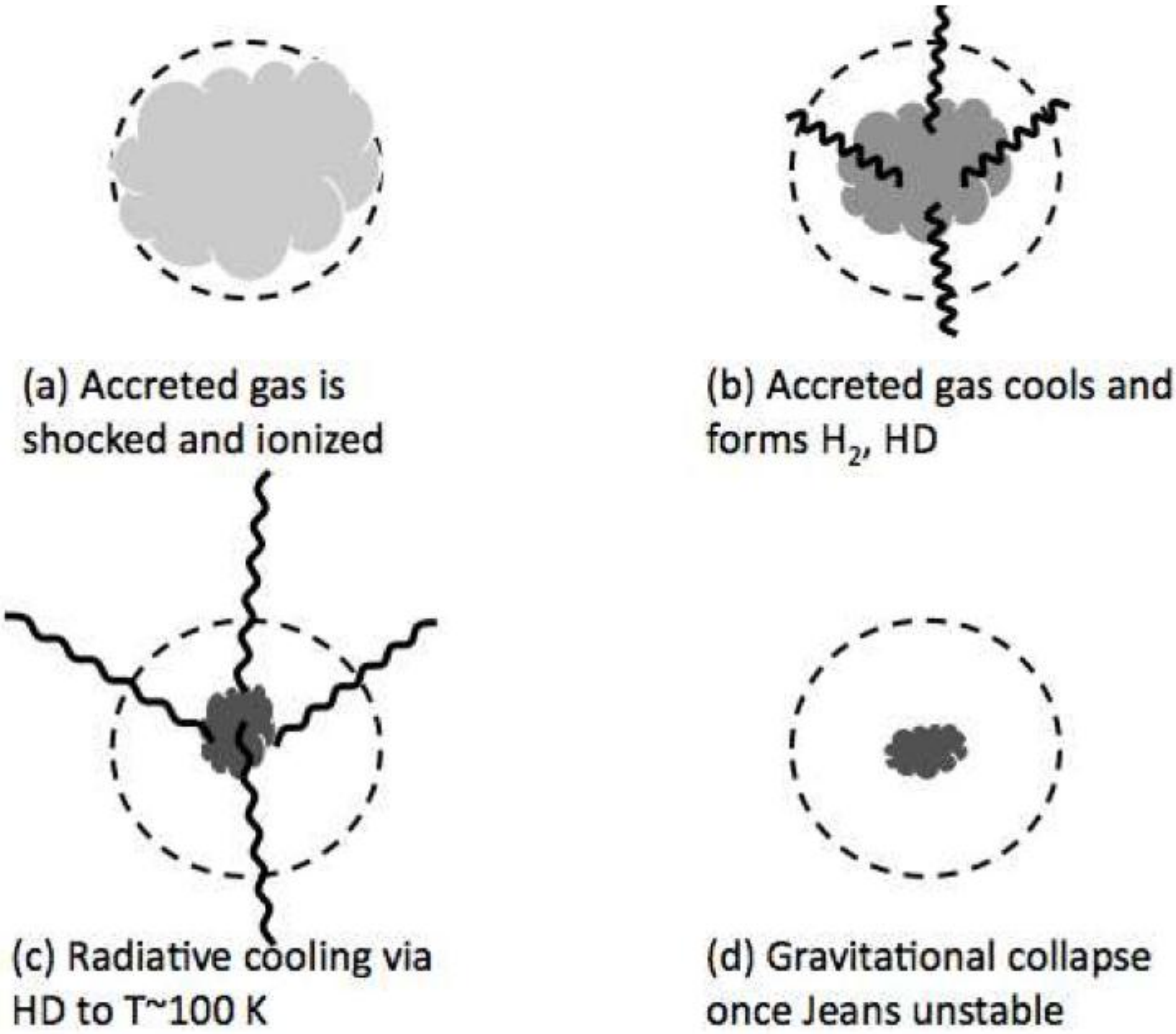


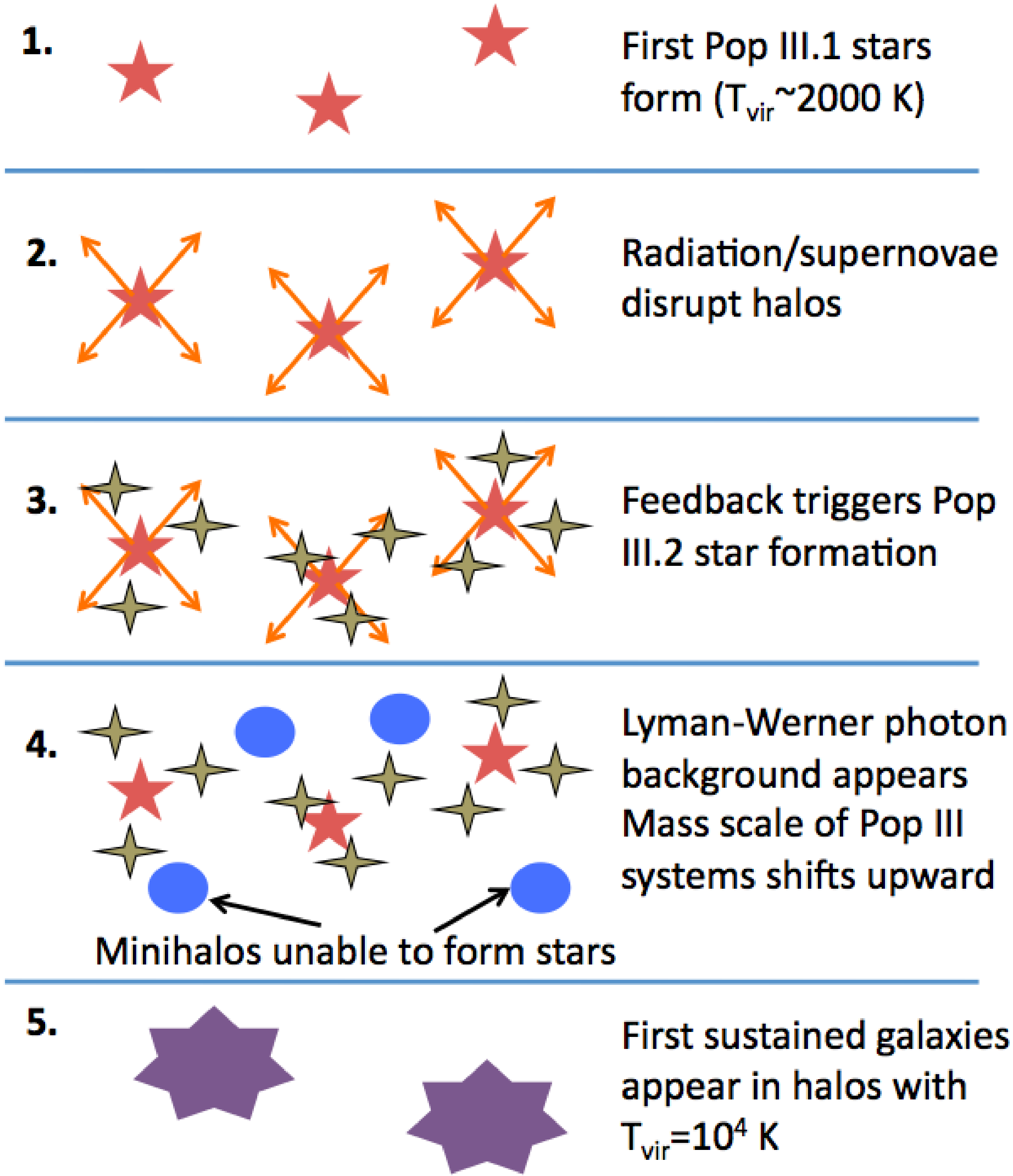


Turk, Abel, & O'Shea 2009

Stacy, Greif, & Bromm 2009

Population III.2




1.
First Pop III.1 stars form (T_{vir}~2000 K)
2.
Radiation/supernovae disrupt halos
3.
Feedback triggers Pop III.2 star formation
4.
Lyman-Werner photon background appears
Mass scale of Pop III systems shifts upward
Minihalos unable to form stars
5.
First sustained galaxies appear in halos with $T_{vir}=10^4$ K

Observing the Stars

James Webb Space Telescope: Searching for the First Light

Mirror diameter: 6.5 meter

Material: beryllium

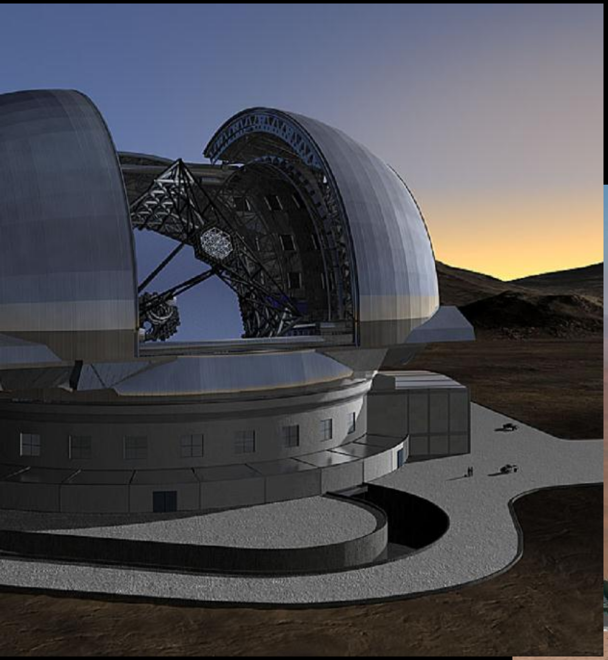
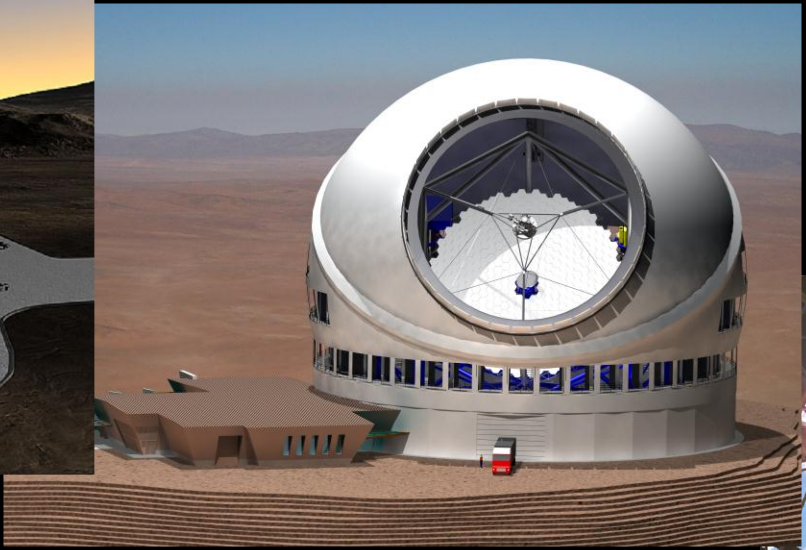
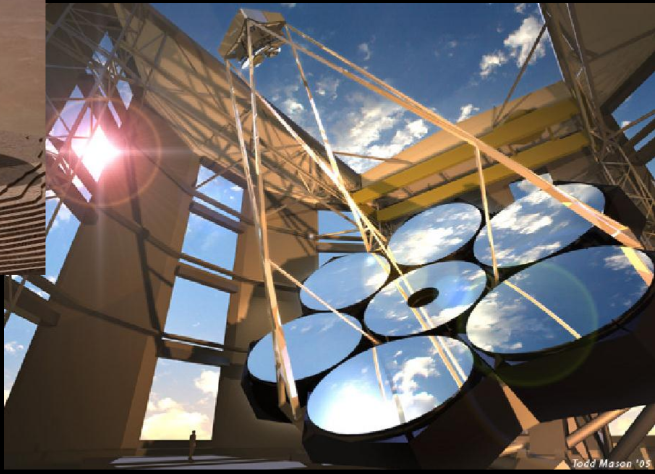
18 segments

Wavelength coverage: 0.6-28 micron

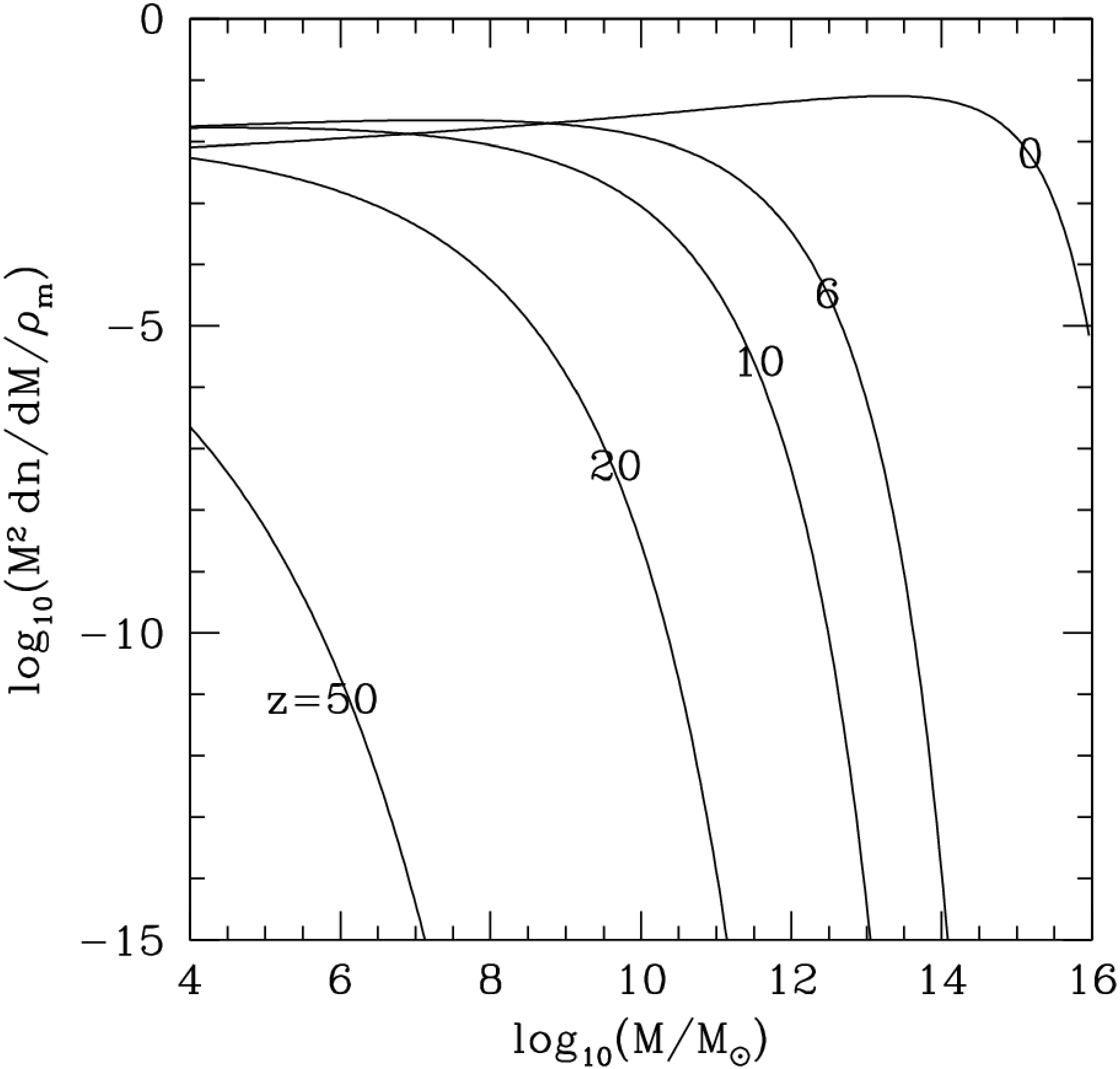
L2 orbit

Launch date: 2018?

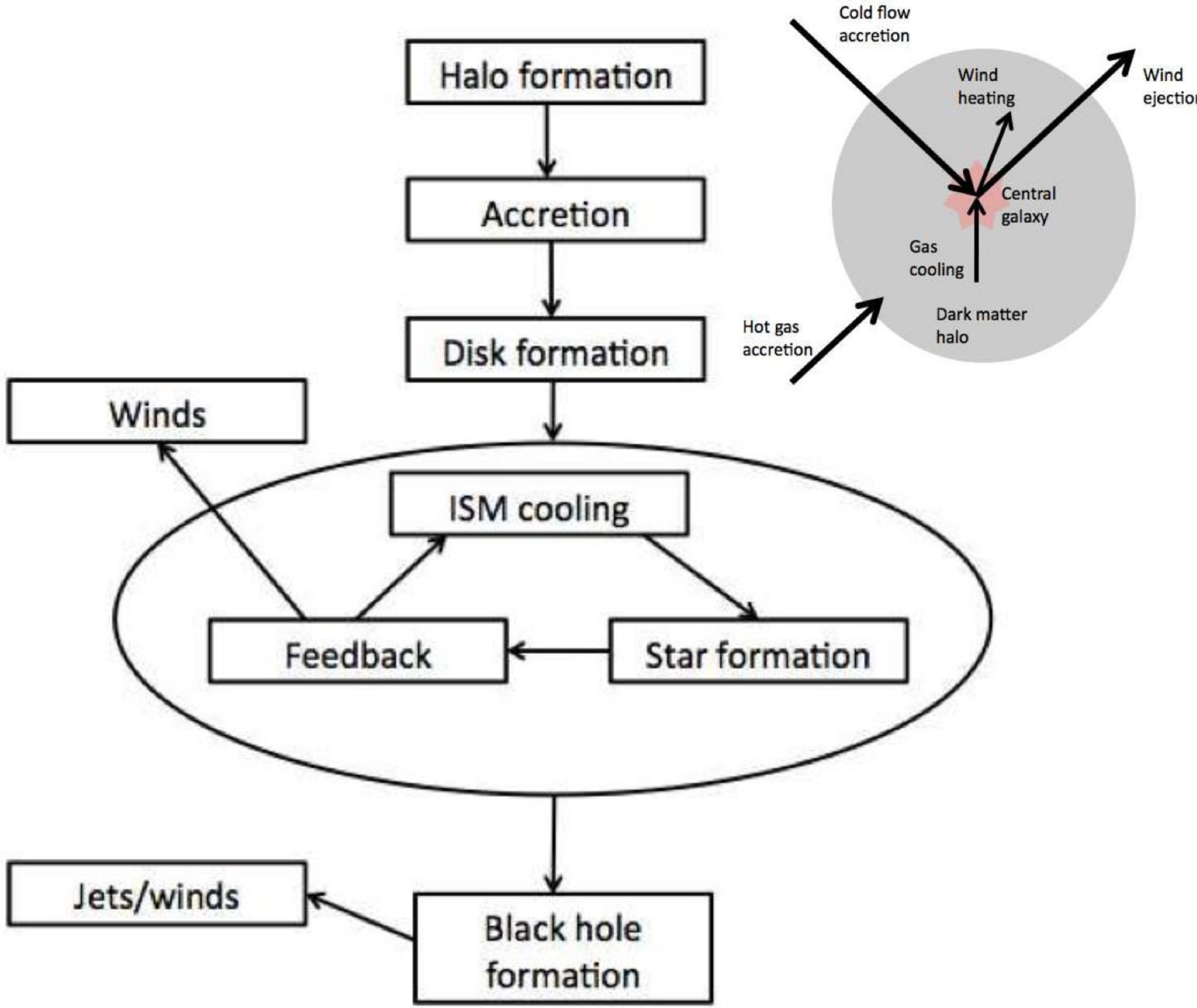
Extremely Large Telescopes (24-42 meters)

- GMT=Seven mirrors, each 8.4m in diameter
- TMT, EELT – segmented 30,42m aperture

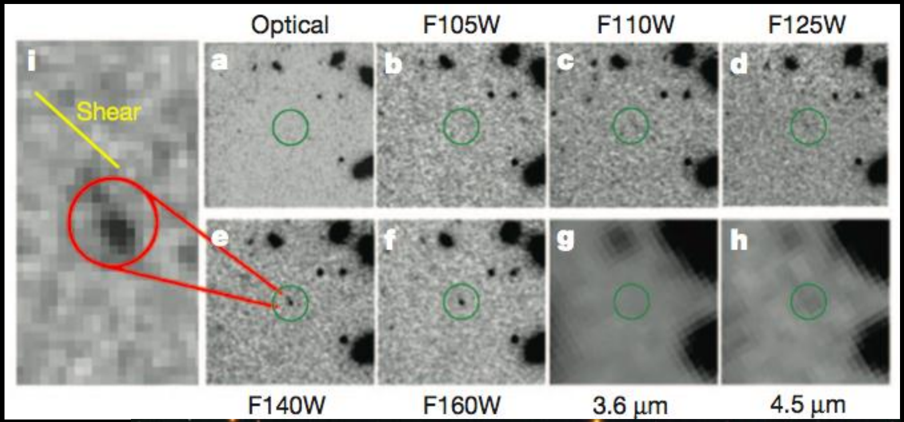


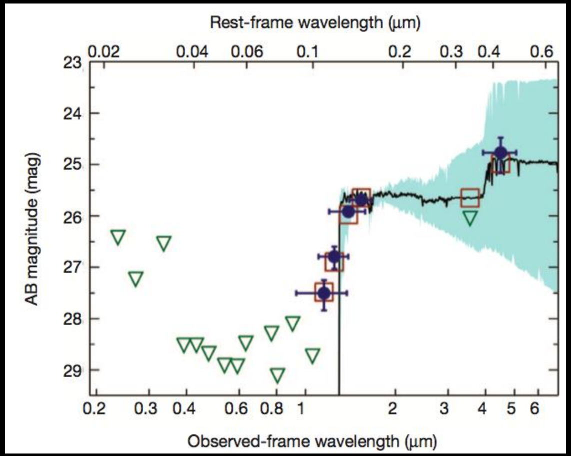
0
−5
−10
−15
4
6
8
10
12
14
16
$\log_{10}(M^2\,dn/dM/\rho_m)$
$\log_{10}(M/M_\odot)$
z=50
20
10
6
0

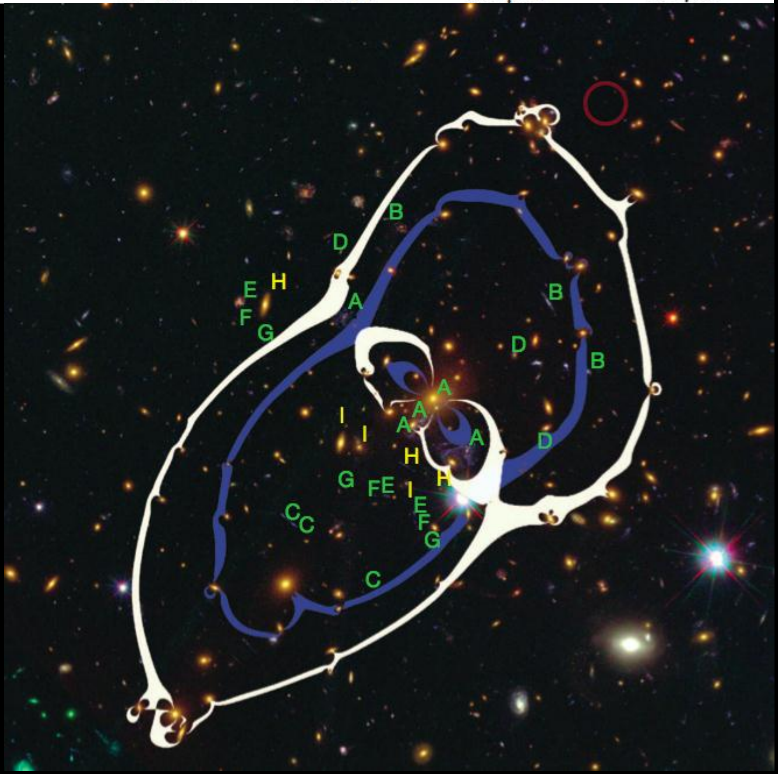


Halo formation
Accretion
Disk formation
Winds
ISM cooling
Feedback
Star formation
Jets/winds
Black hole formation
Cold flow accretion
Wind heating
Wind ejection
Central galaxy
Gas cooling
Hot gas accretion
Dark matter halo

A Magnified Young Galaxy at z~9.6





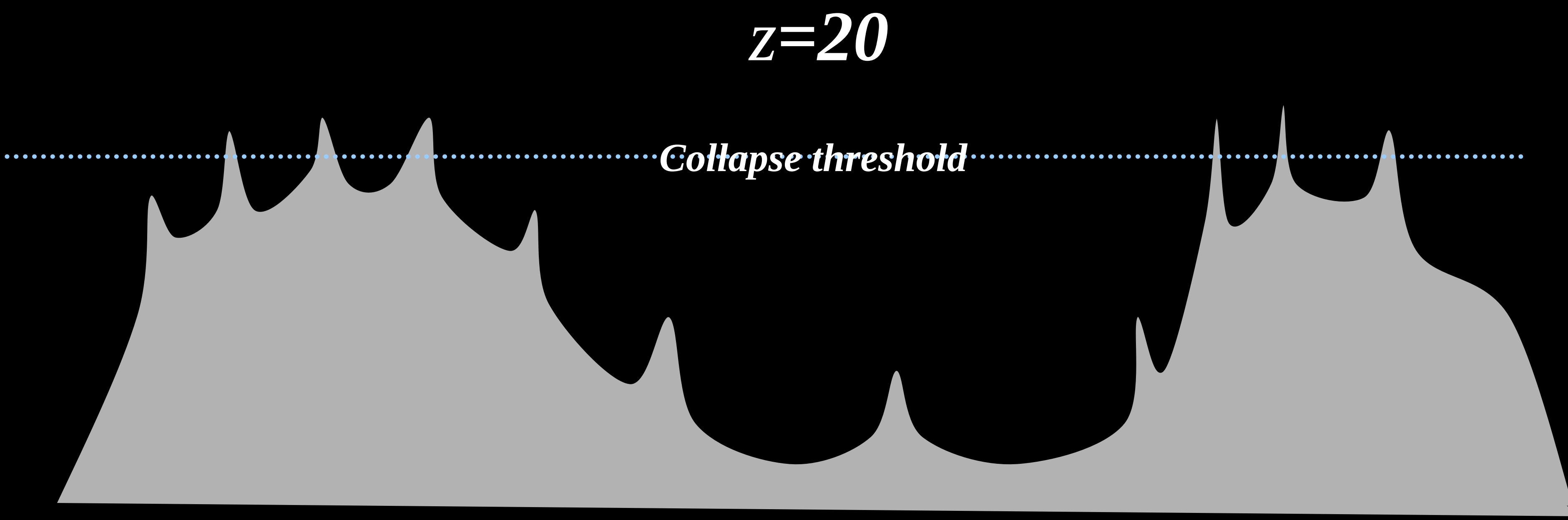


$$M_\star \sim 10^8 M_\odot$$

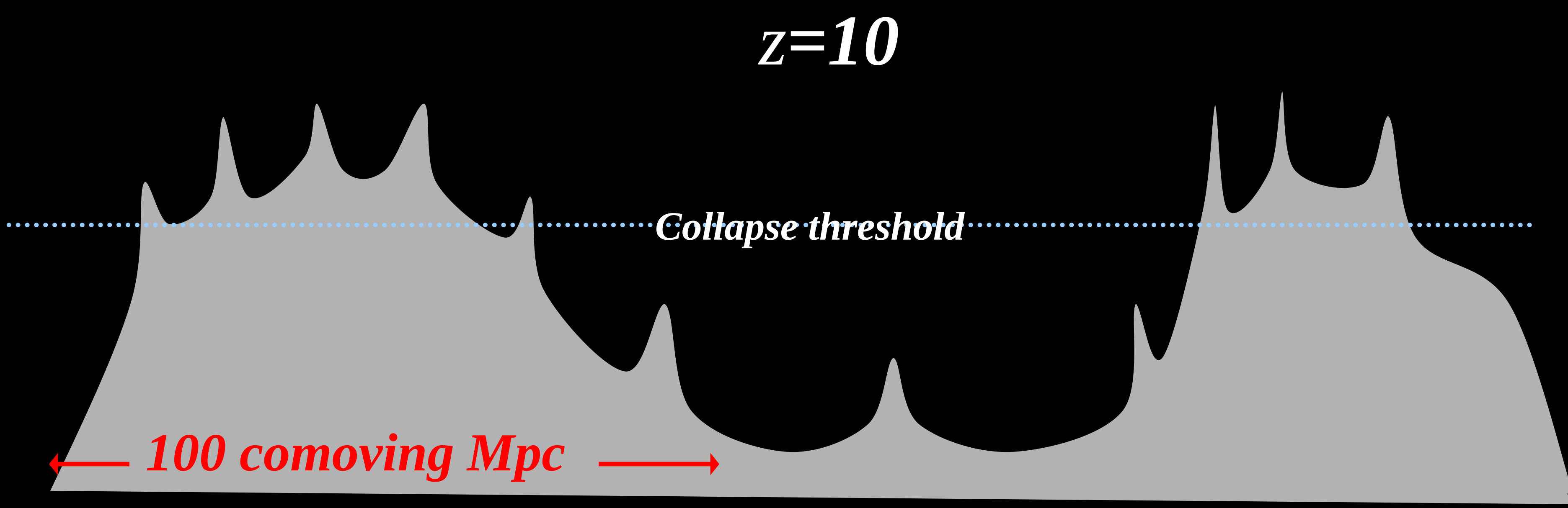
$$\mu \sim 15$$

Zheng et al. (2012)

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



<u>First Galaxies Were Strongly Clustered on Scales of up to ~100 comoving Mpc</u>



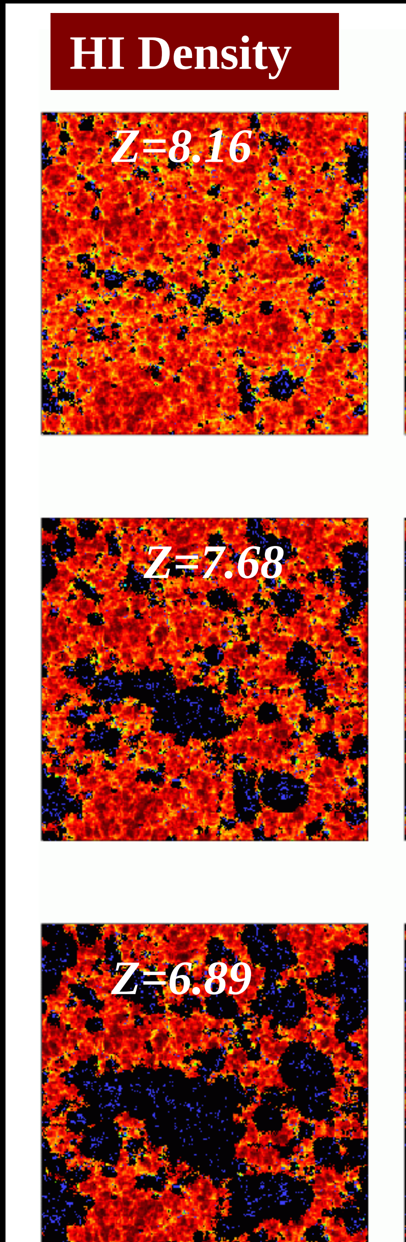
<u>Challenges for numerical simulations of reionization:</u>

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

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

***Following gravity, hydrodynamics, radiative transfer and feedback (dissociation of molecular hydrogen, photo-ionization, heating, metal enrichment)**

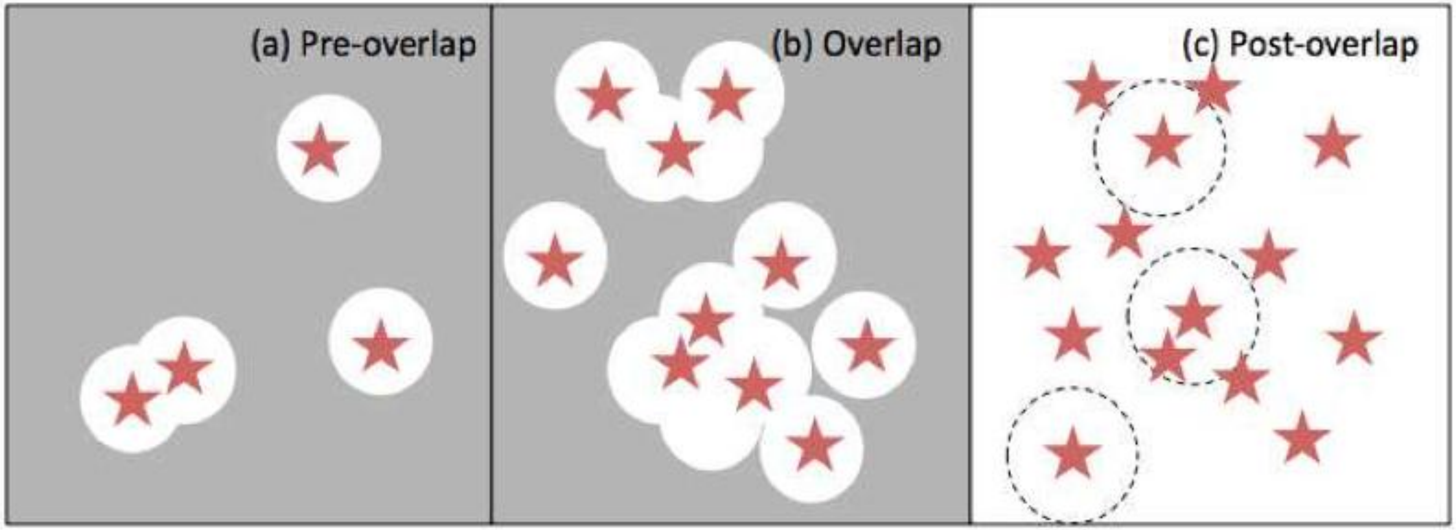
Reionization



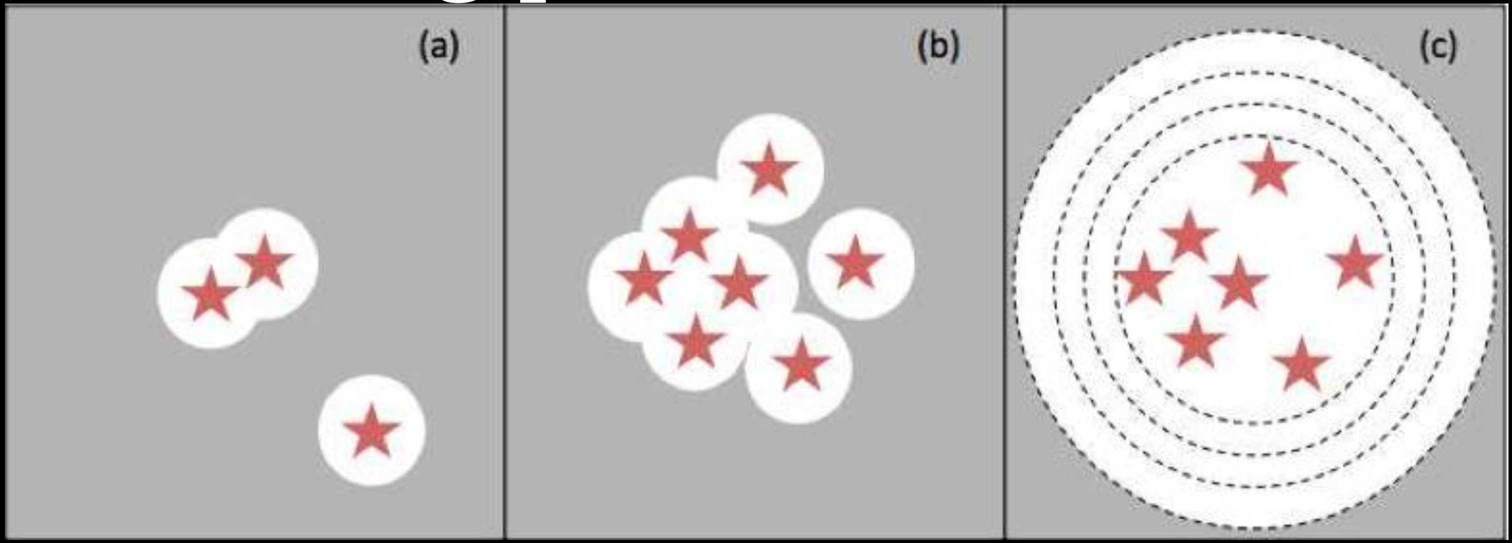
Zahn et al. 2006

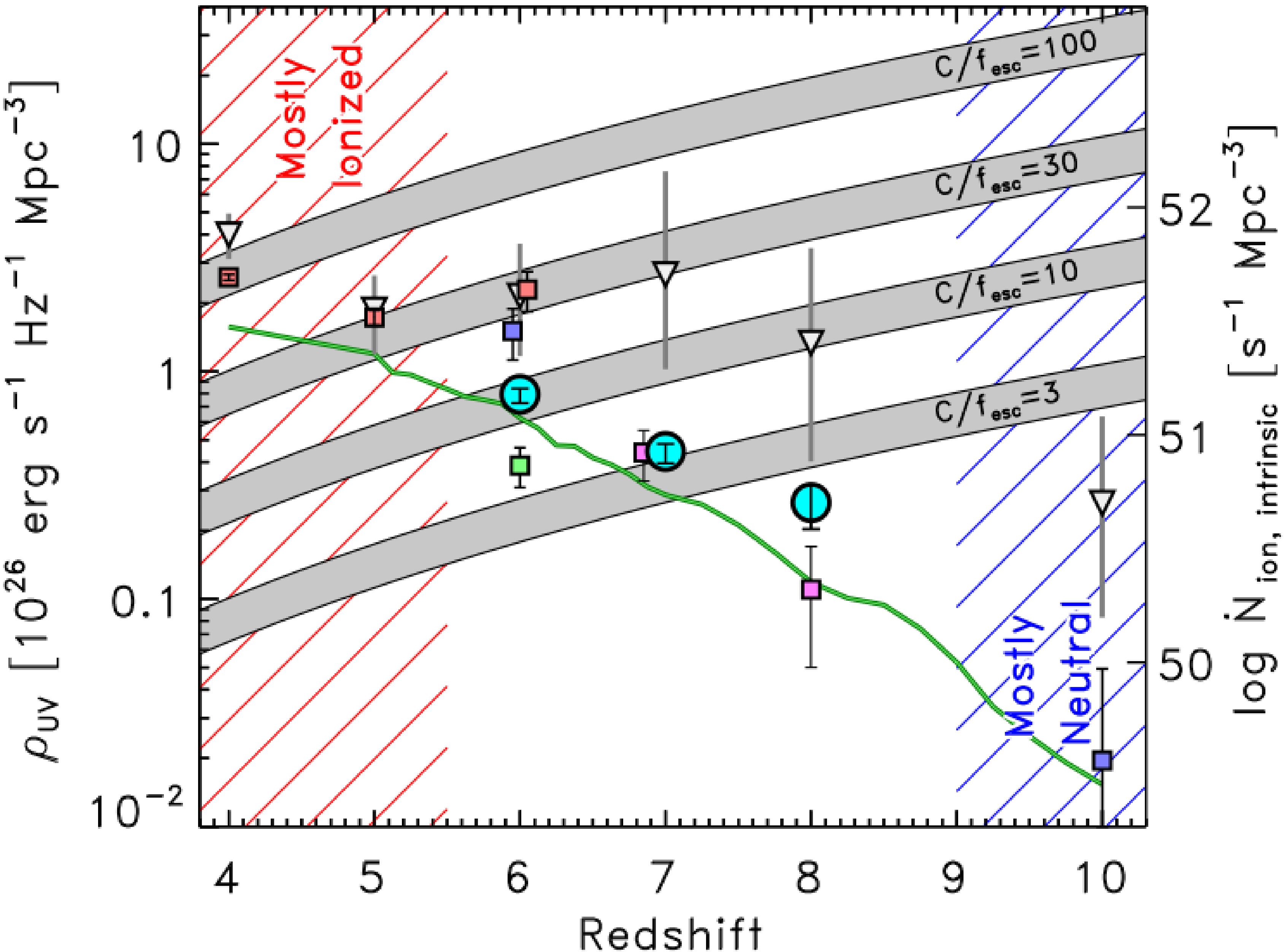
Trac, Cen, & Loeb 2008

THE REIONIZATION OF INTERGALACTIC HYDROGEN



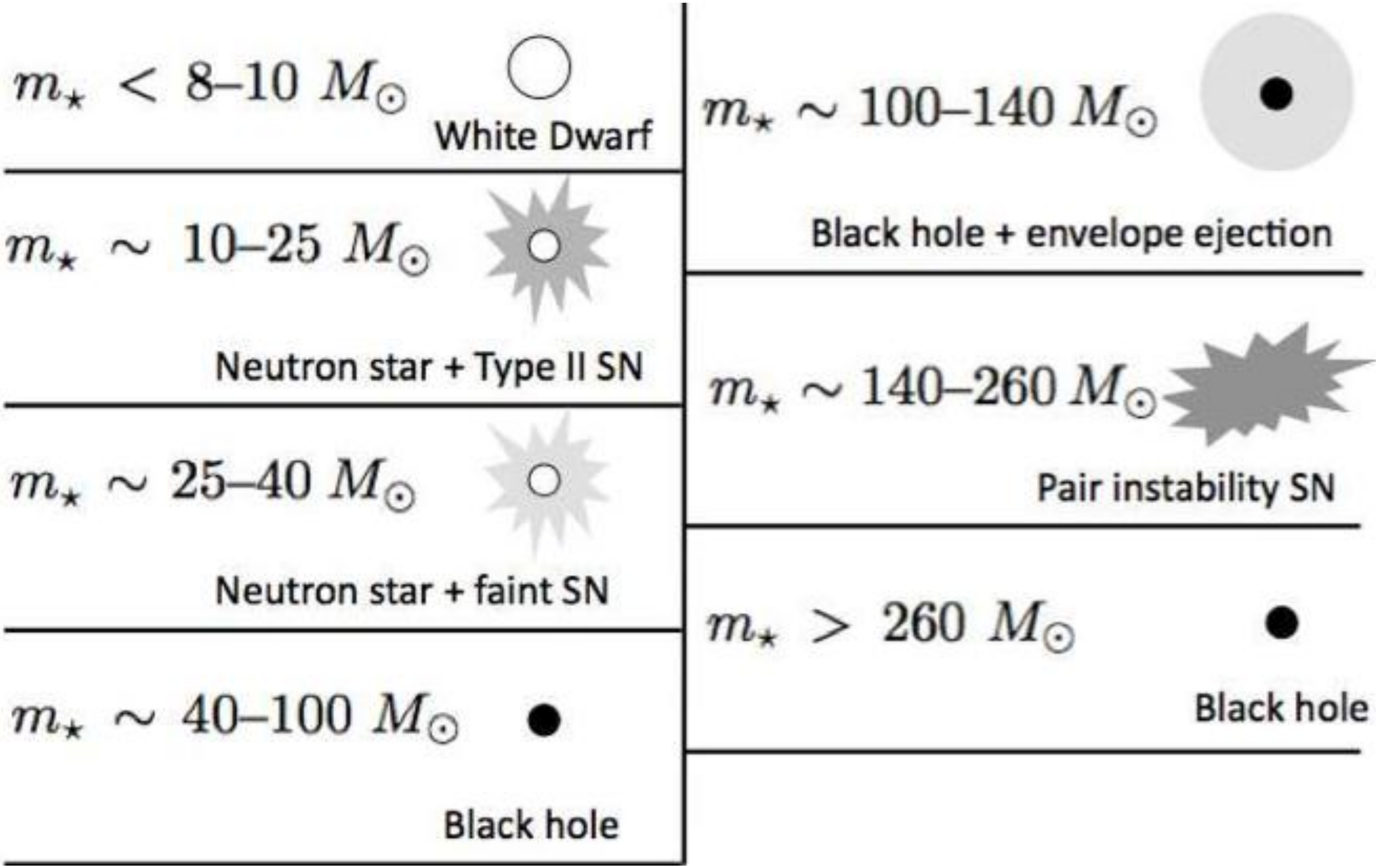
ionizing photons = # H atoms





Finkelstein et al. (2012)

Stellar Remnants



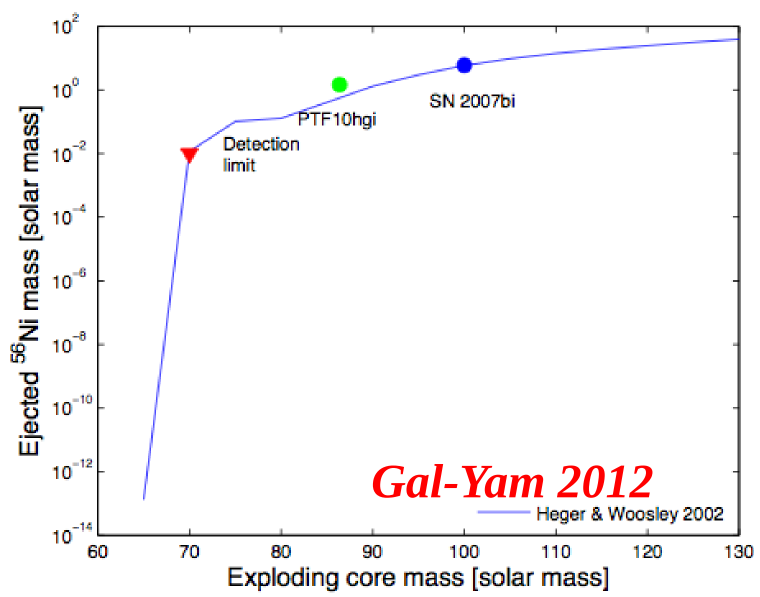
Enrichment by >0.001 of solar metallicity: C+/O cooling is more effective than H_2 cooling: Pop III → Pop II (dust)

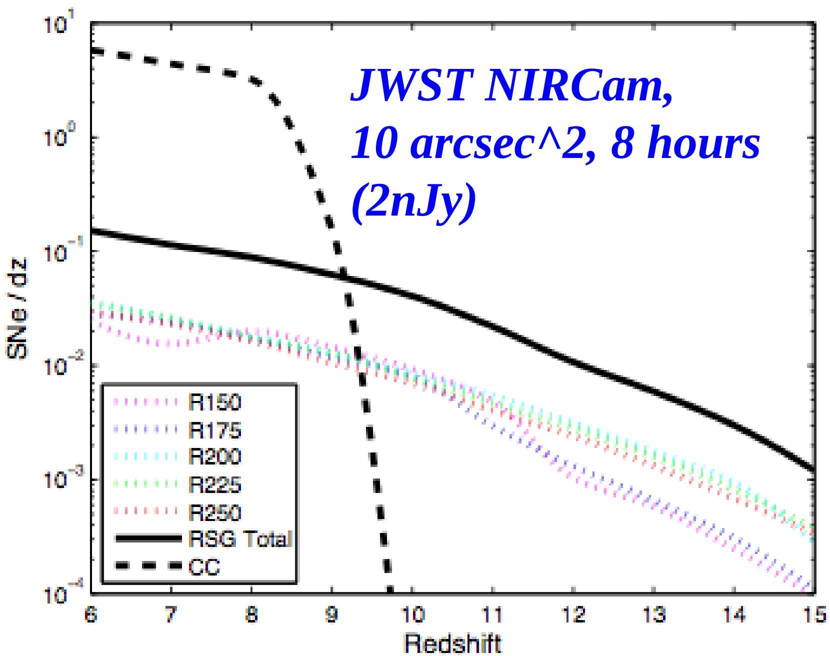
Pair Instability Supernovae

**Best understood SNe*

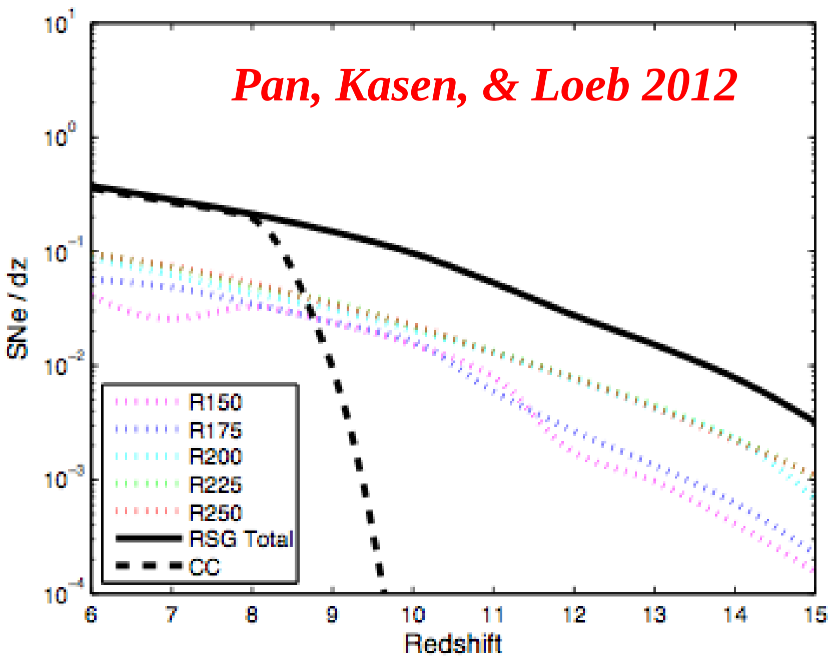
**Examples are known up to z~4 (Cooke et al. 2012)*

$$E \sim 10^{53} \text{ ergs}$$



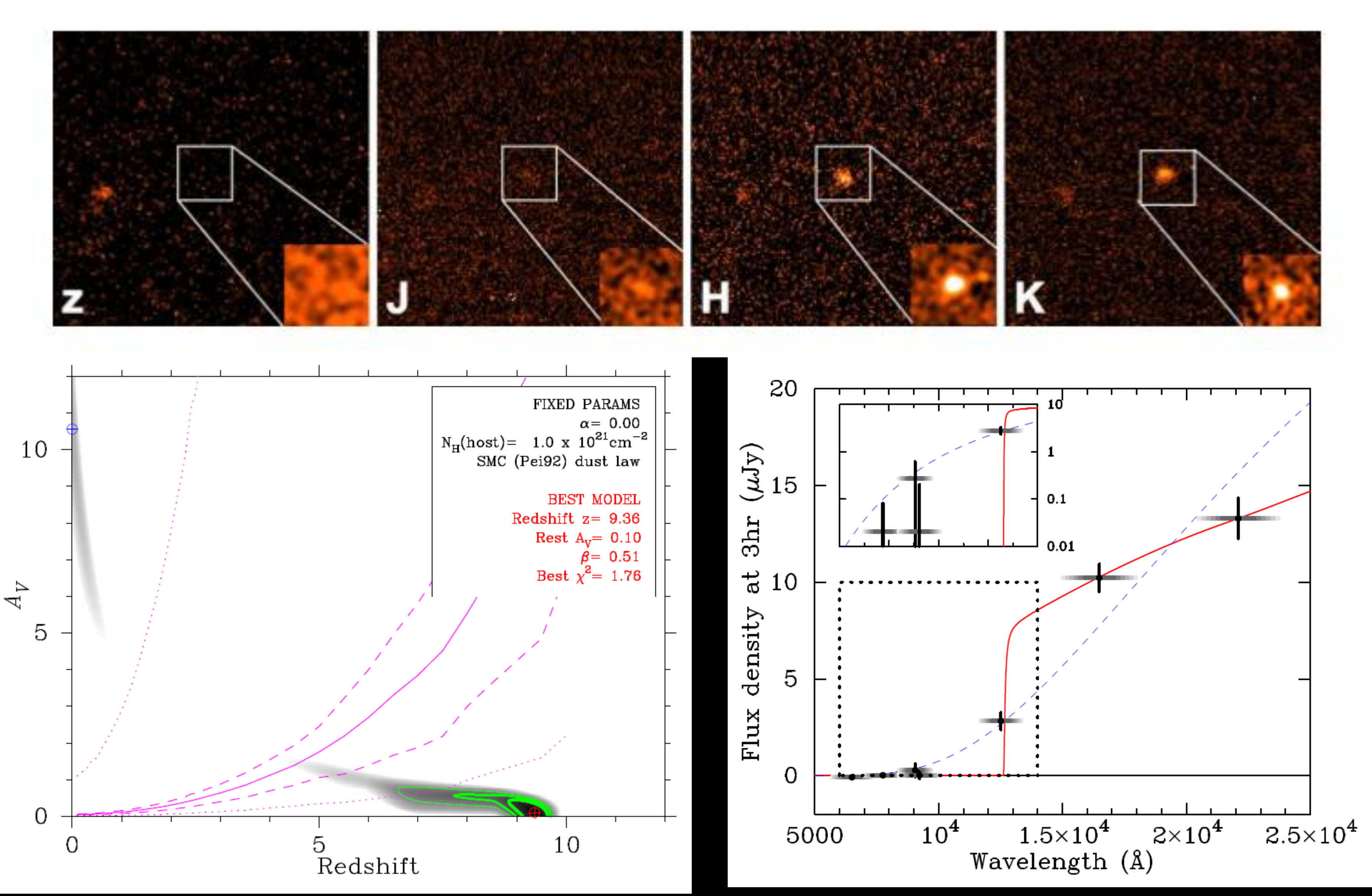


(a) Pop III Salpeter IMF model



(b) Pop III Flat IMF model

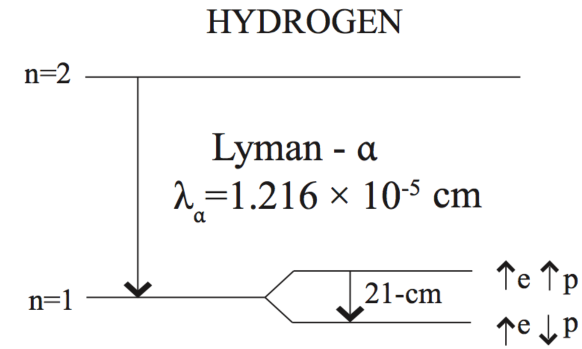
GRB 090429B at *t=520* million years (*z~9.4*)

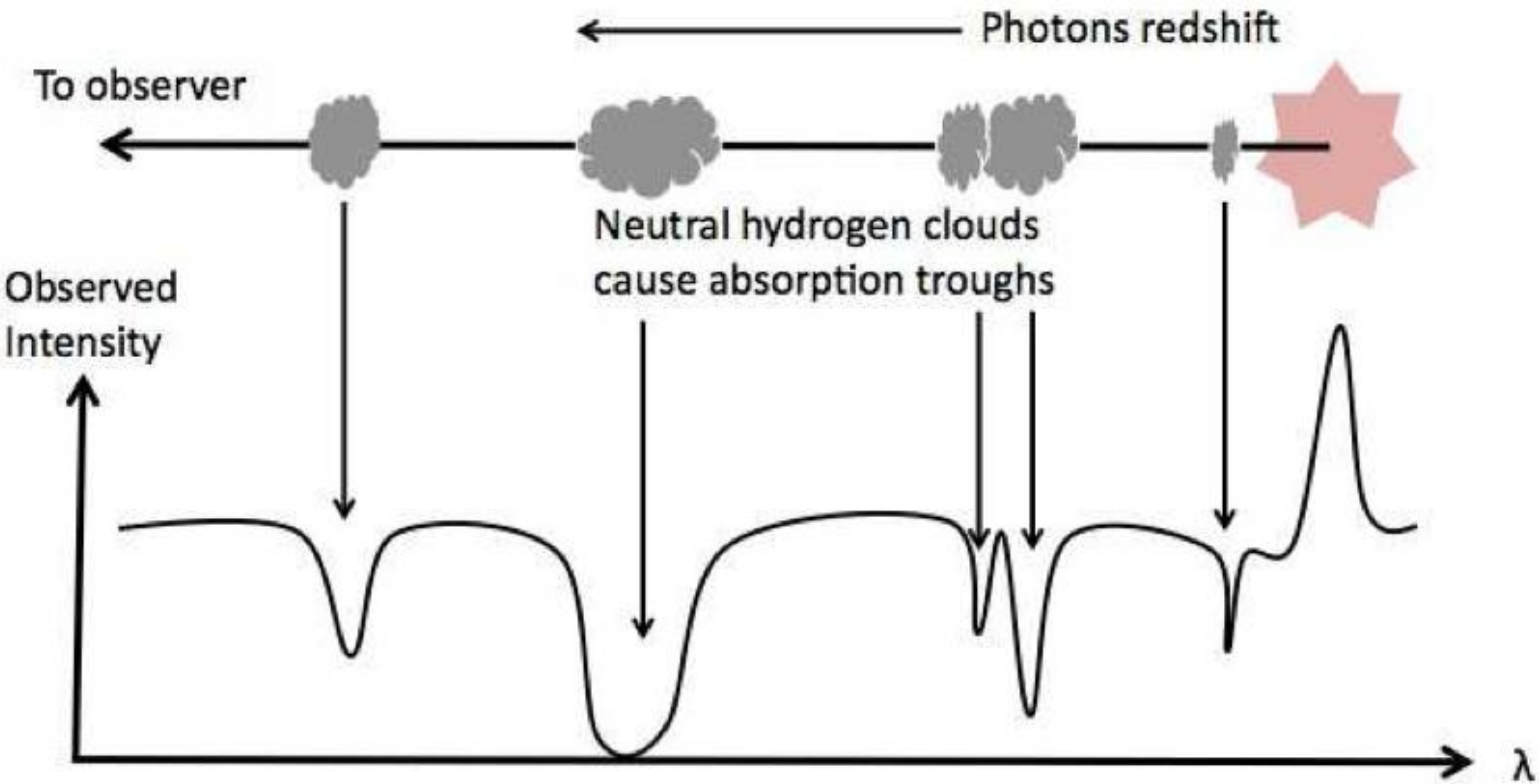


Cucchiara et al. (2011)

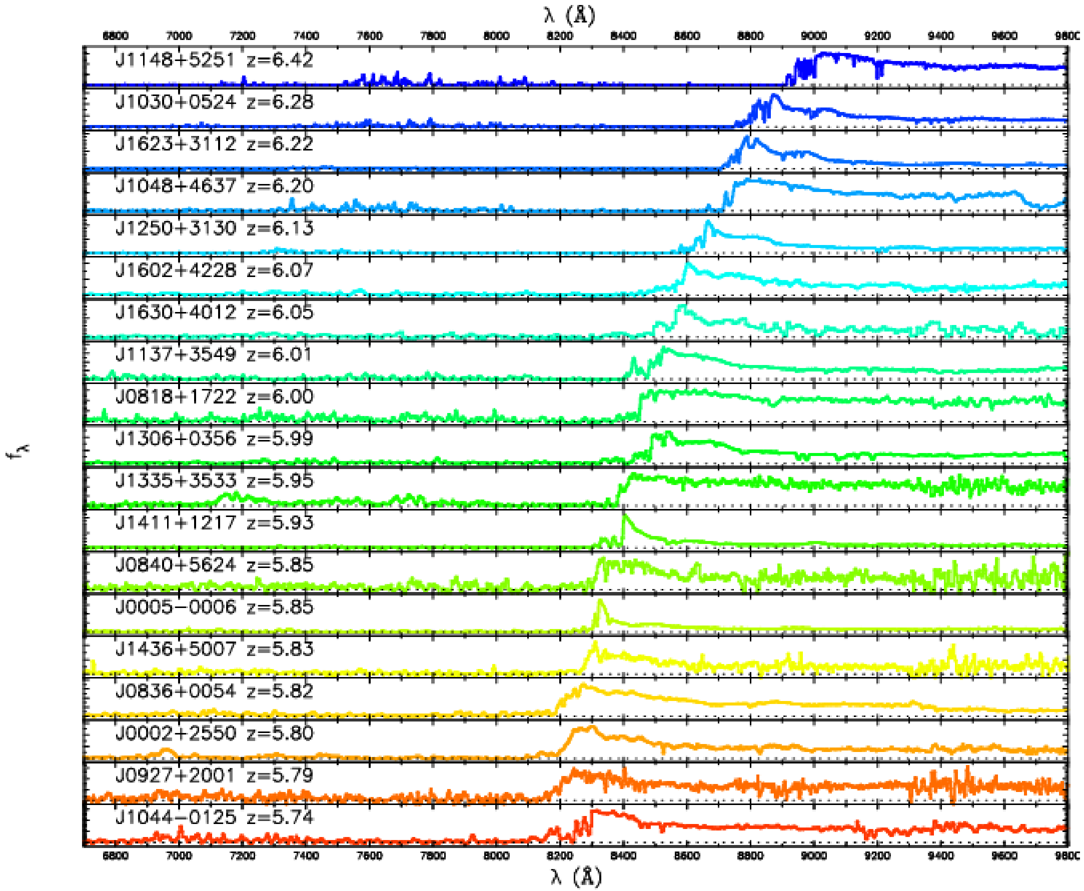
Observing the Diffuse Gas

THE INTERGALACTIC MEDIUM

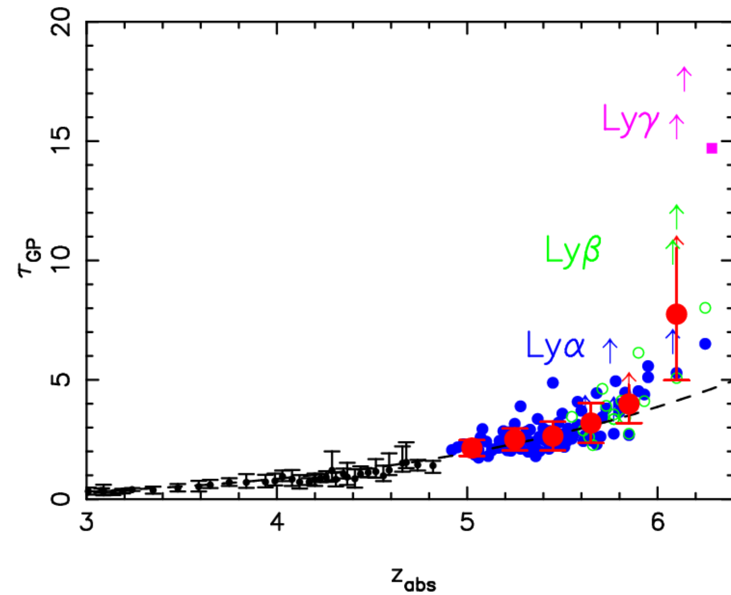


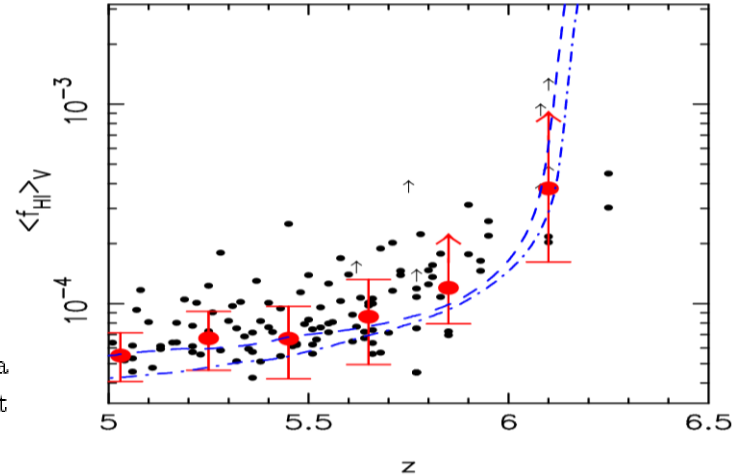


So far, the intergalactic hydrogen was mainly probed by quasar spectra



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.

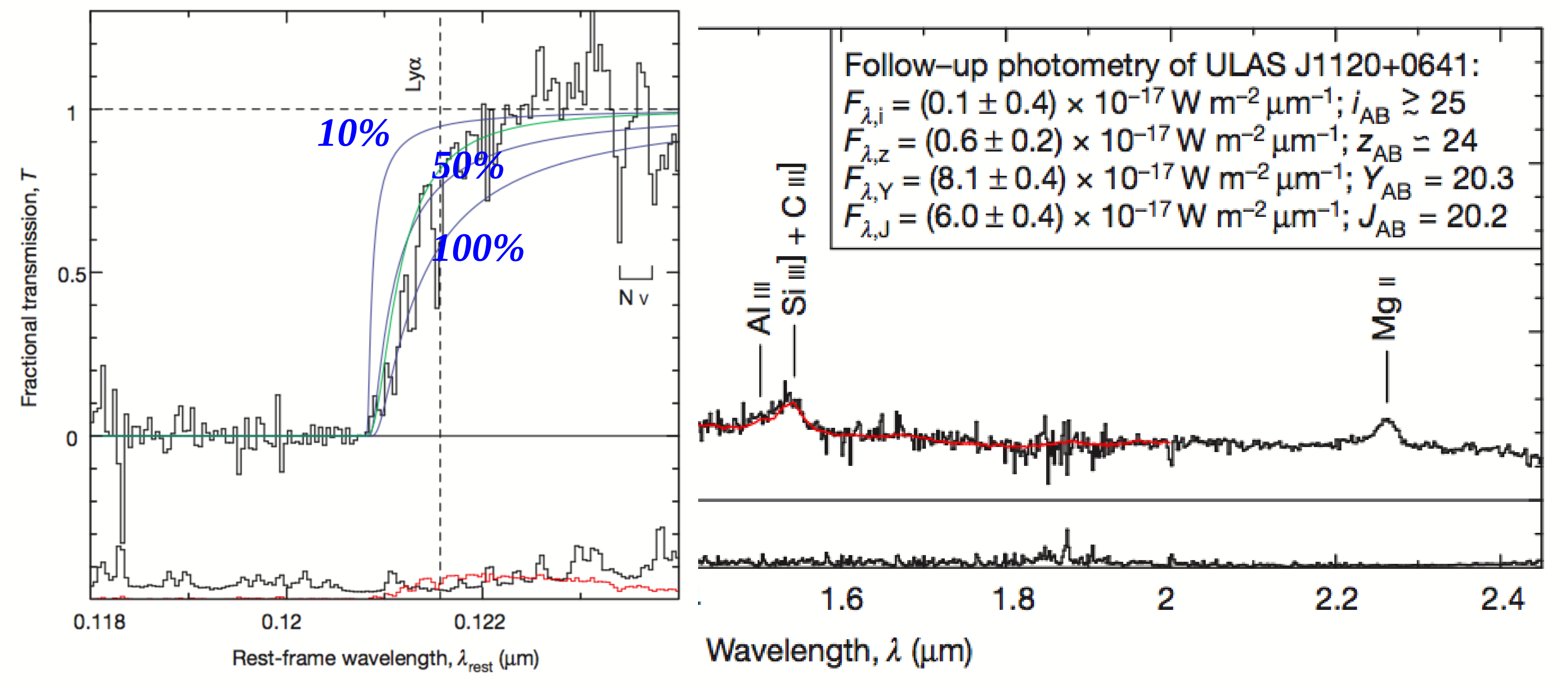




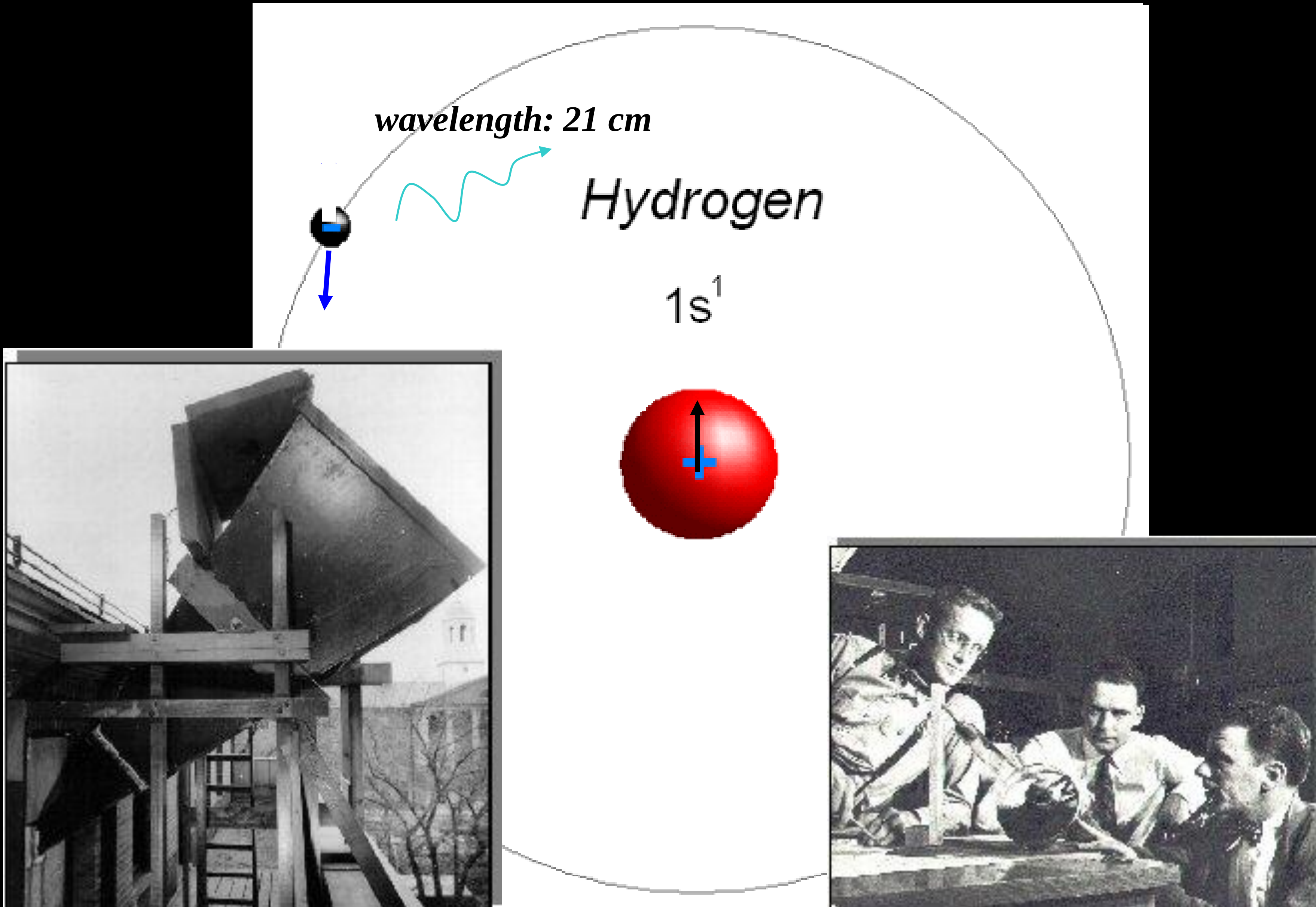
Fan et al. 2005

A luminous quasar at a redshift of $z = 7.085$

Daniel J. Mortlock[1], Stephen J. Warren[1], Bram P. Venemans[2], Mitesh Patel[1], Paul C. Hewett[3], Richard G. McMahon[3], Chris Simpson[4], Tom Theuns[5,6], Eduardo A. Gonzáles-Solares[3], Andy Adamson[7], Simon Dye[8], Nigel C. Hambly[9], Paul Hirst[10], Mike J. Irwin[3], Ernst Kuiper[11], Andy Lawrence[9] & Huub J. A. Röttgering[11]



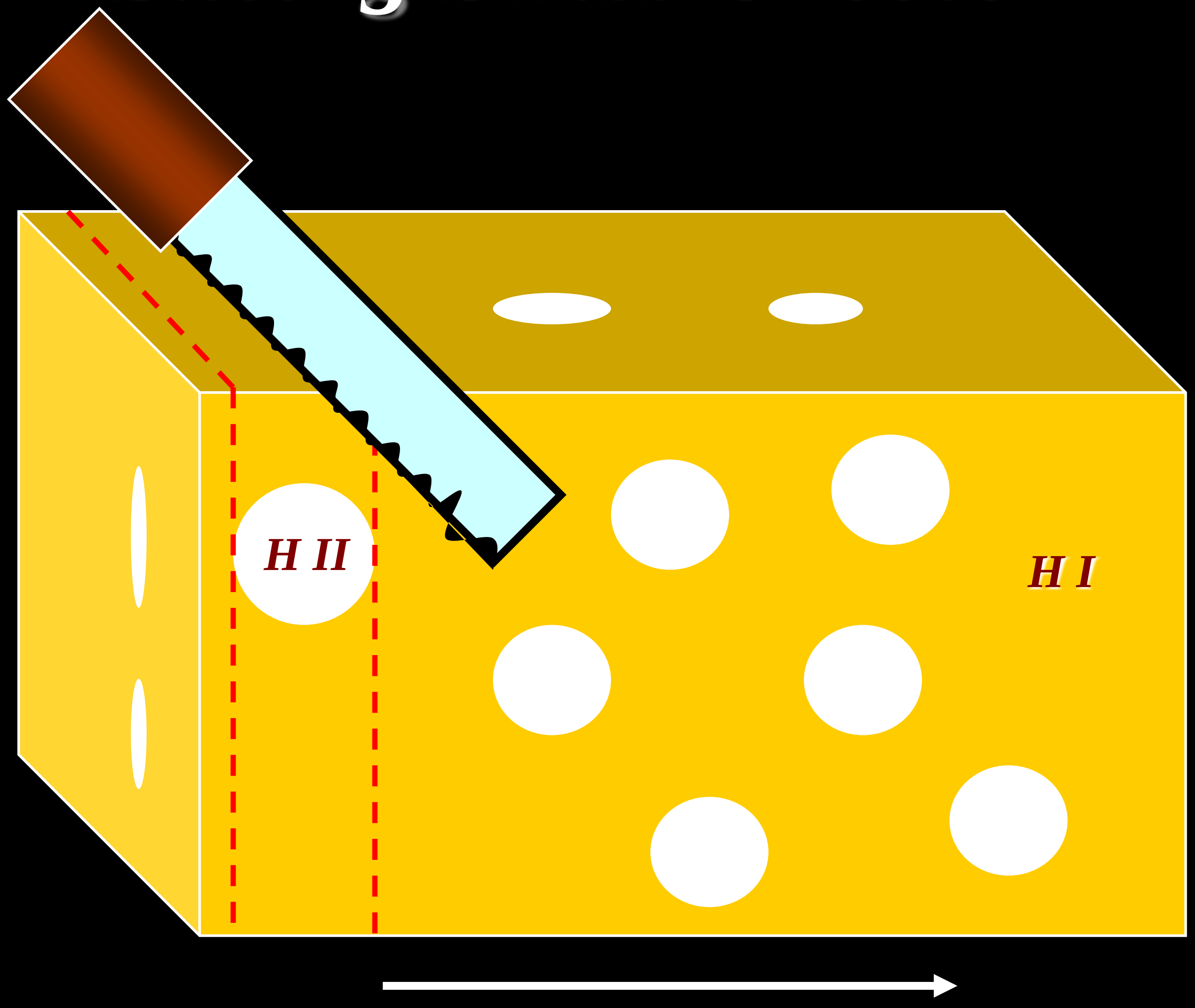
Nature (June 2011)

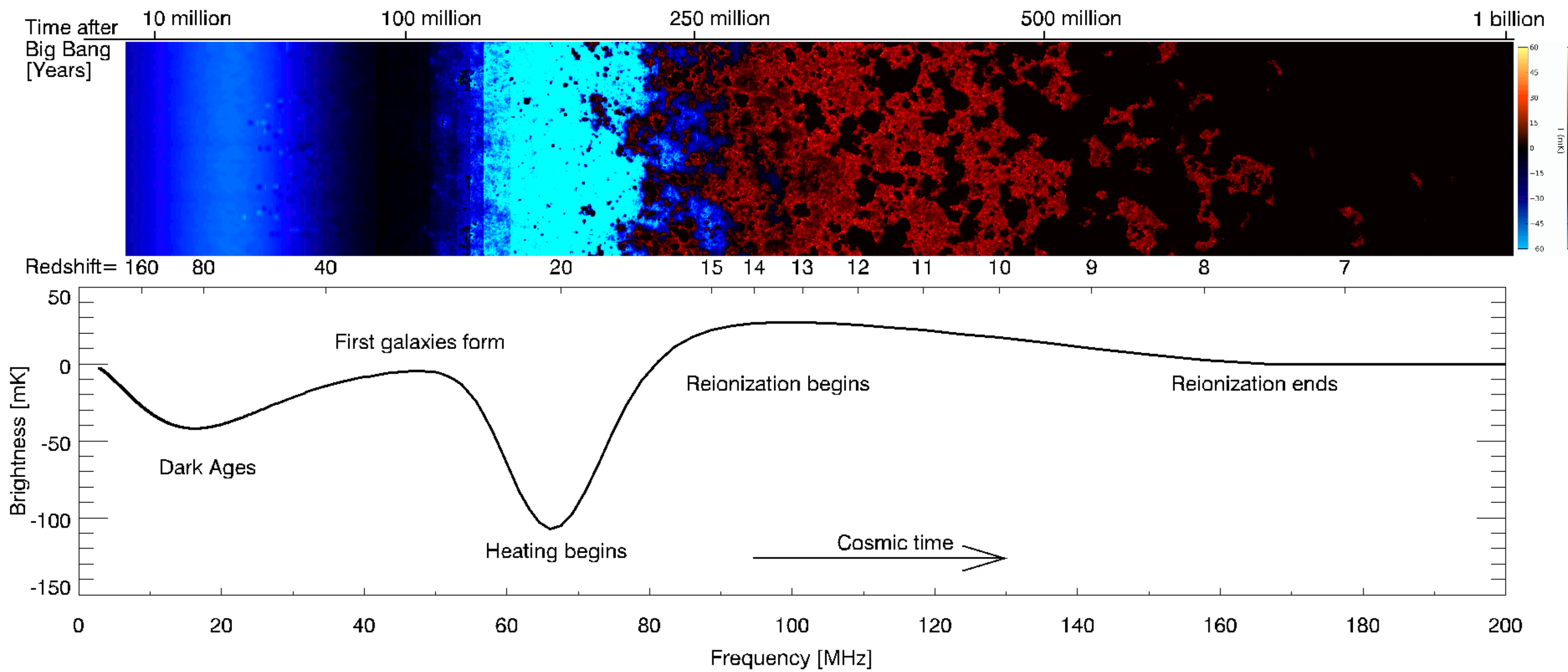


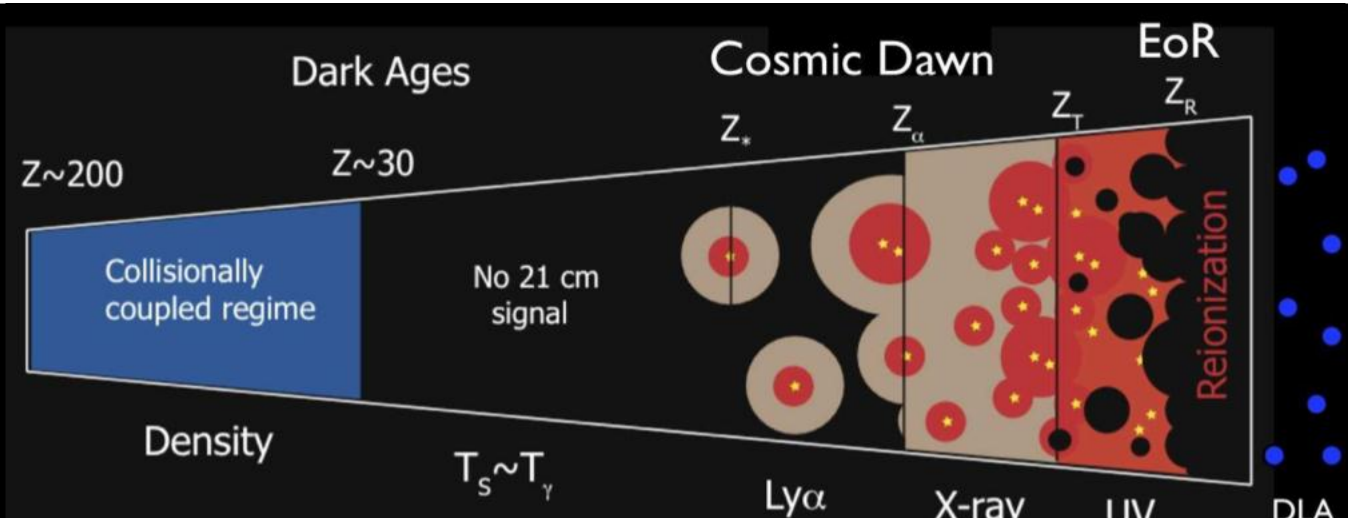
Harvard connection: *Theodore Lyman, Cecilia Payne-Gaposchkin, Edward Purcell , George Field …*

21cm Tomography of Ionized Bubbles During Reionization is like

Slicing Swiss Cheese



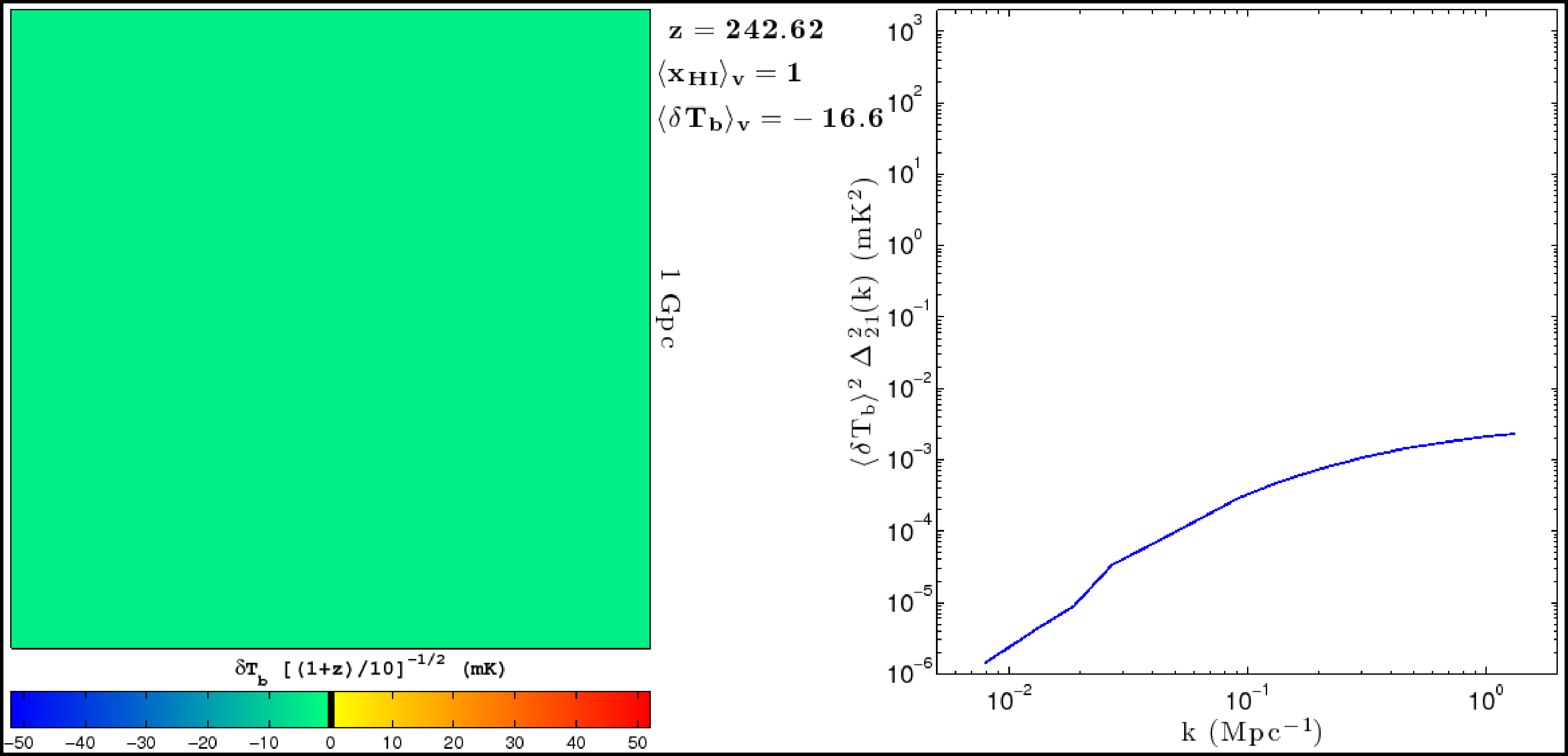




$\lambda_{\rm dB} \sim h/p \propto a \qquad T_k \propto p^2/m_p \propto (1+z)^2$

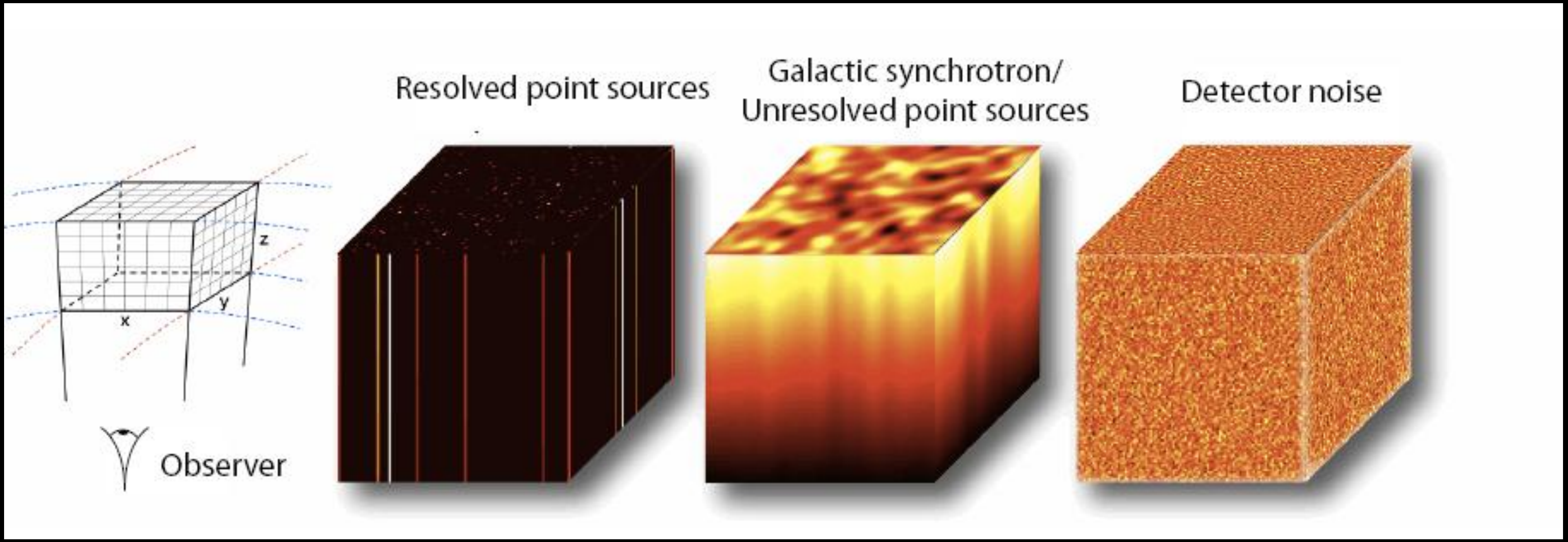
Pritchard & Loeb 2012

Cosmological Evolution of the 21-cm Signal



Mesinger, Furlanetto, & Cen (2011)

Foregrounds



Liu & Tegmark (2011)

Experiments

LOFAR (Low-frequency Array)

Netherlands/Europe

MWA (Murchison Wide-Field Array)

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

PAPER

UCB, South Africa

21CMA (formerly known as PAST)

China

GMRT (Giant Meterwave Radio Telescope)

India/CITA

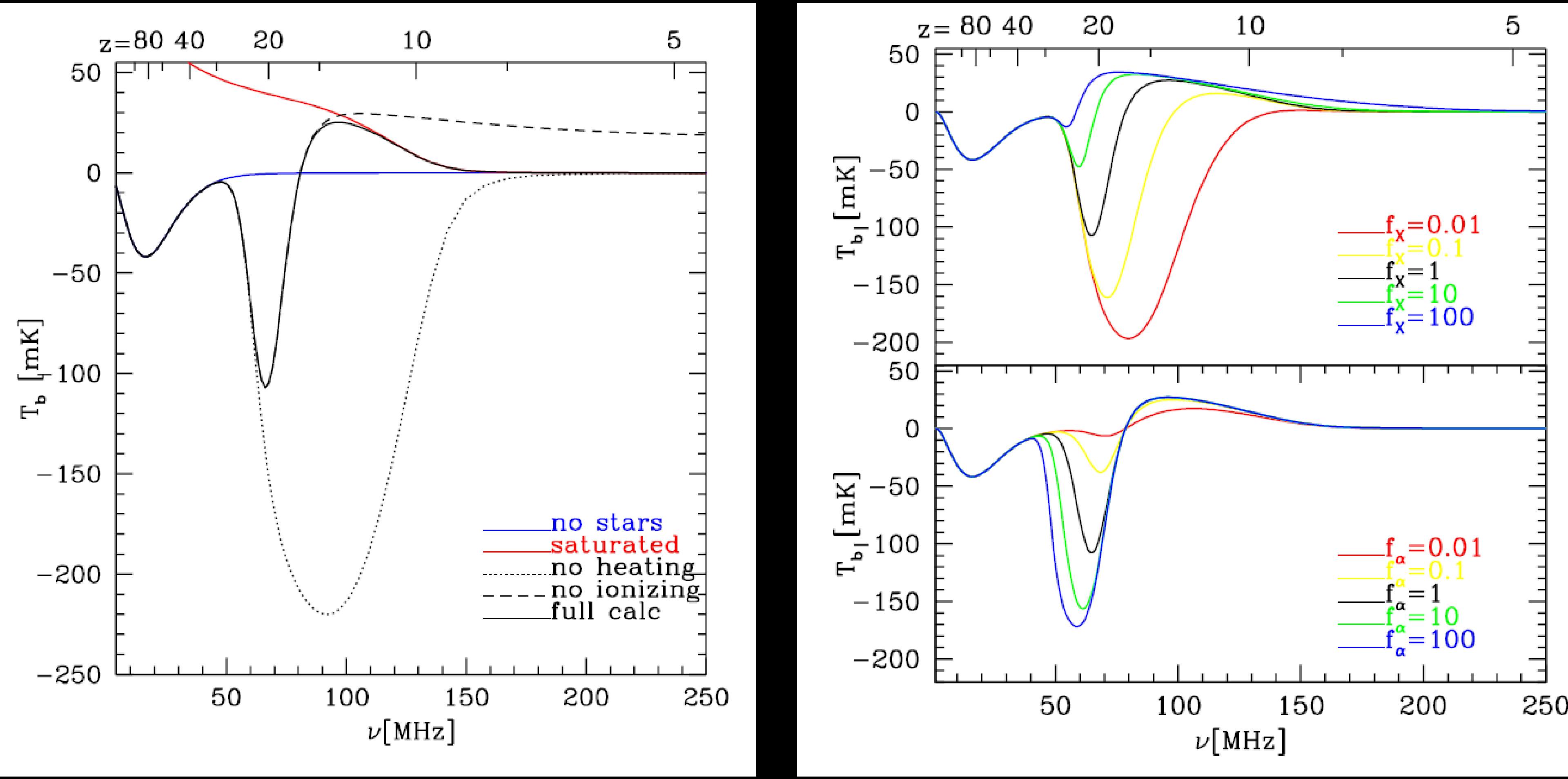
SKA (Square Kilometer Array)

International

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


- 4mx4m tiles of 16 dipole antennae, 80-300MHz
- 128 antenna tiles with total collecting area 2000 sq.m. at 150MHz across a 1.5km radius; few arcmin resolution

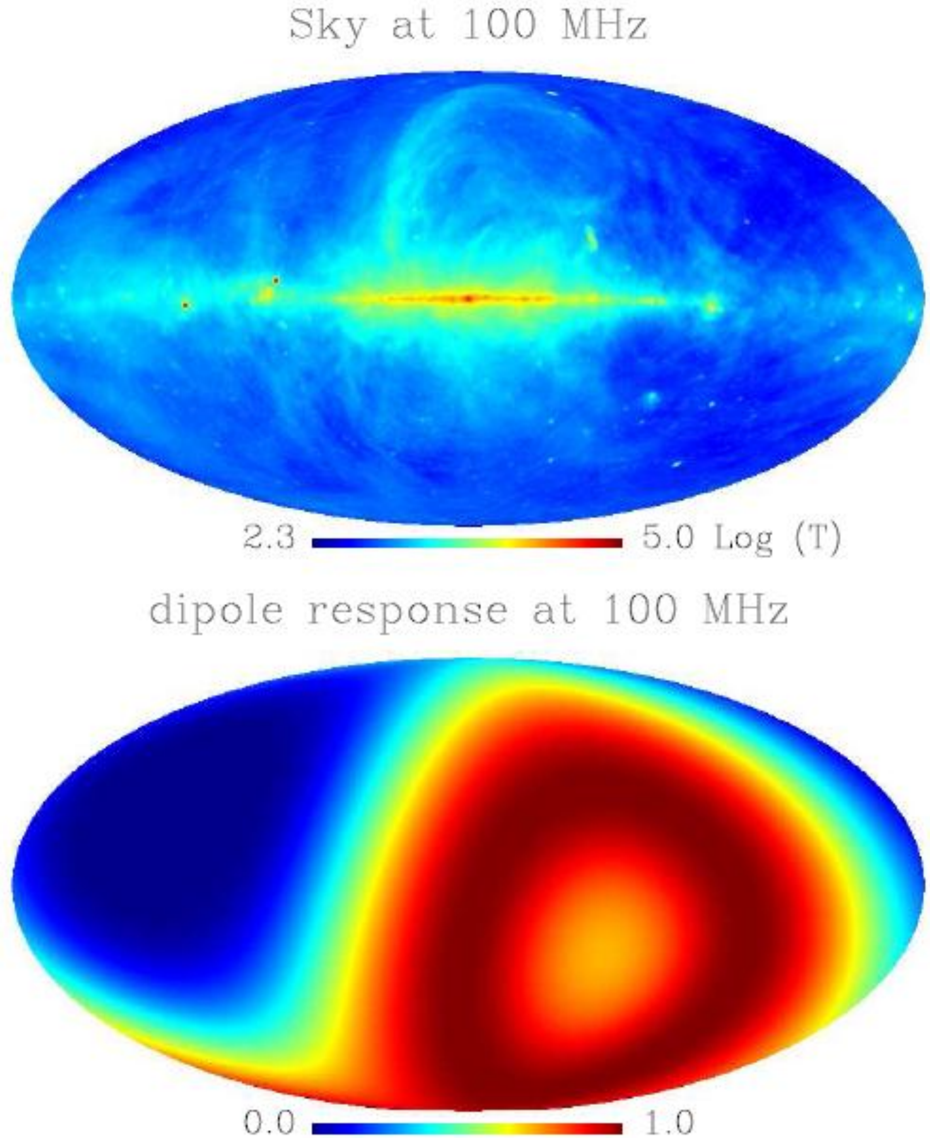
The Global 21-cm Signal



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

The EDGES Experiment

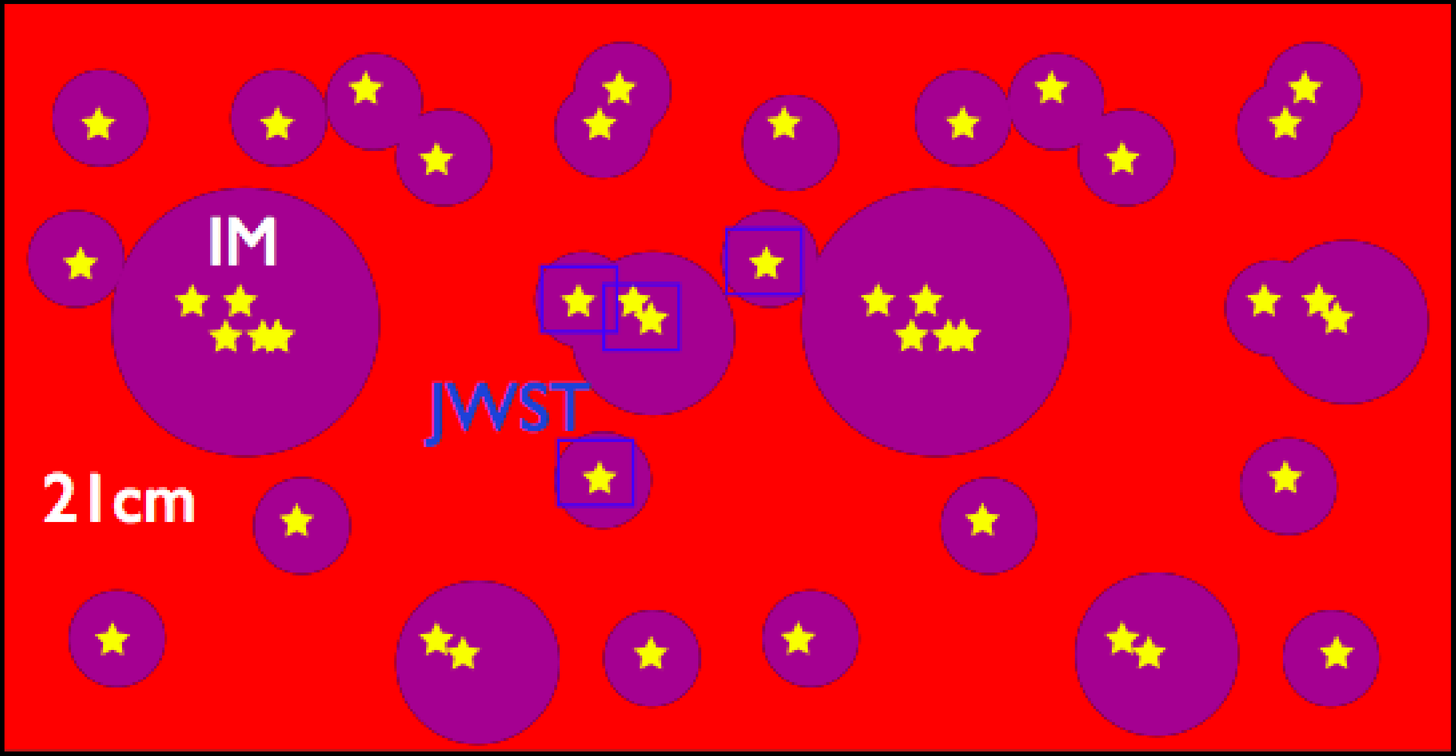
The Experiment to Detect the Global EOR Signature (EDGES)



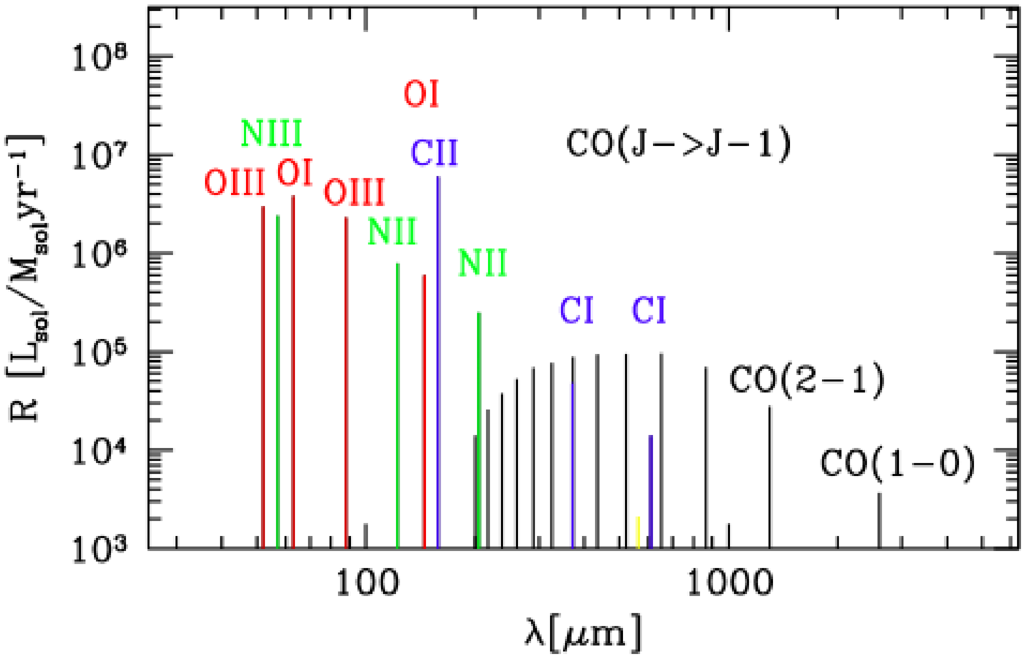
Intensity Mapping of Other Lines

(without resolving individual galaxies)

Galaxy surveys, Intensity Mapping and 21-cm Mapping



Other Emission Lines from Galaxies



Species	Emission Wavelength[μm]	R[$L_\odot/(M_\odot/yr)$]
CII	158	6.0×10^6
OI	145	3.3×10^5
NII	122	7.9×10^5
OIII	88	2.3×10^6
OI	63	3.8×10^6
NIII	57	2.4×10^6
OIII	52	3.0×10^6
^{12}CO(1-0)	2610	3.7×10^3
^{12}CO(2-1)	1300	2.8×10^4
^{12}CO(3-2)	866	7.0×10^4
^{12}CO(4-3)	651	9.7×10^4
^{12}CO(5-4)	521	9.6×10^4
^{12}CO(6-5)	434	9.5×10^4
^{12}CO(7-6)	372	8.9×10^4
^{12}CO(8-7)	325	7.7×10^4
^{12}CO(9-8)	289	6.9×10^4
^{12}CO(10-9)	260	5.3×10^4
^{12}CO(11-10)	237	3.8×10^4
^{12}CO(12-11)	217	2.6×10^4
^{12}CO(13-12)	200	1.4×10^4
CI	610	1.4×10^4
CI	371	4.8×10^4
NII	205	2.5×10^5
^{13}CO(5-4)	544	3900
^{13}CO(7-6)	389	3200
^{13}CO(8-7)	340	2700
HCN(6-5)	564	2100

Cross Correlating CO (galaxies) and 21-cm (HI)

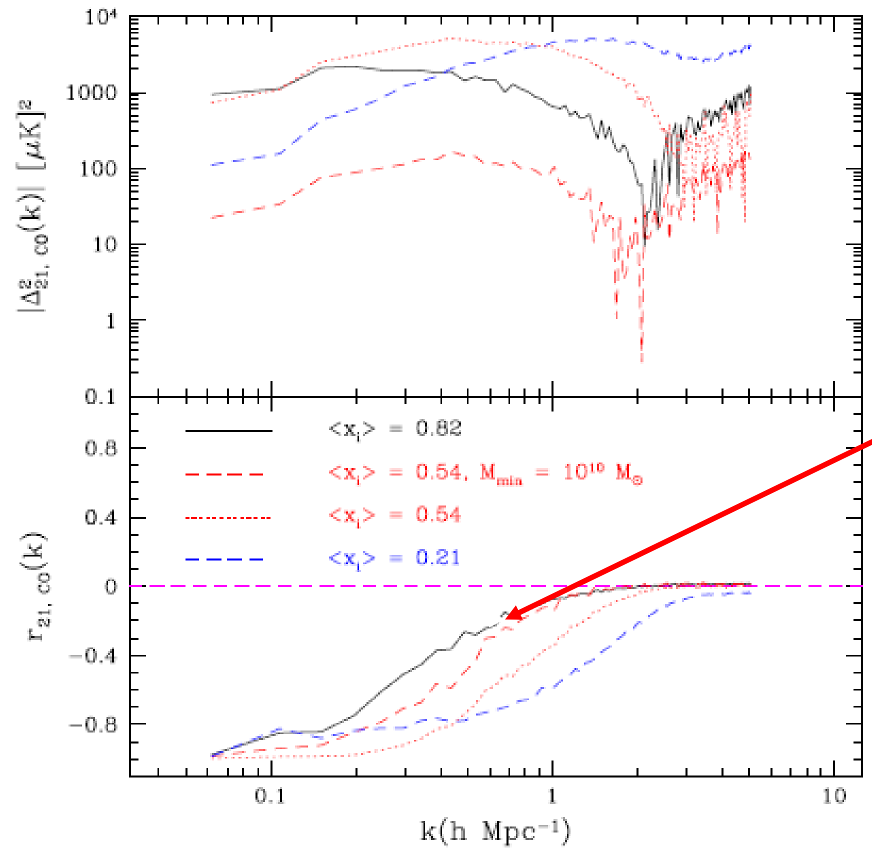


Figure 1.6 Cross-correlation between CO(2-1) emission and the spin-flip background in a numerical simulation of reionization (as in Fig. 1.5). The dot-dashed, dotted, and solid curves take $z = 9.8$, 7.3, and 6.8 (or $Q_{HII} = 0.21$, 0.54, and 0.82 in this model), assuming that all galaxies emit CO(2-1). The long-dashed curve takes $z = 7.3$ but assumes that only massive galaxies emit CO. The top and bottom panels show the absolute value of the cross-power spectrum and the cross-correlation coefficient, respectively. Figure credit: Lidz et al. 2011.

size of ionized bubble

Lidz et al. (2011)

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 the necessary spatial resolution to properly identify the ionizing sources.***

The Optimal Cosmic Time for Constraining the Initial Density Perturbations

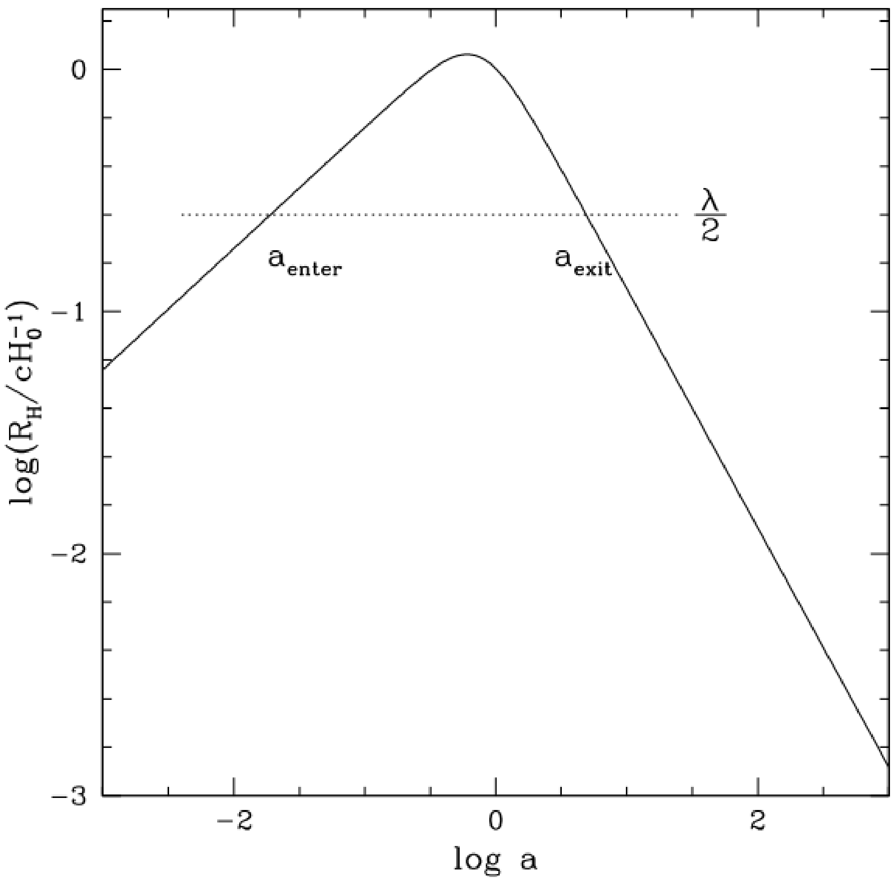


FIG. 1: In the standard (post-inflation) cosmological model, a Fourier mode with a comoving wavelength λ which enters the comoving scale of the Hubble radius $R_{\rm H} = c(aH)^{-1}$ (in units of $cH_0^{-1} = 4.3$ Gpc) at some early time (corresponding to a redshift $z = a_{\rm enter}^{-1} - 1$), would eventually exit the Hubble radius at a later time (corresponding to $a_{\rm exit}$). Hence, there is only a limited period of time when the mode can be observed.

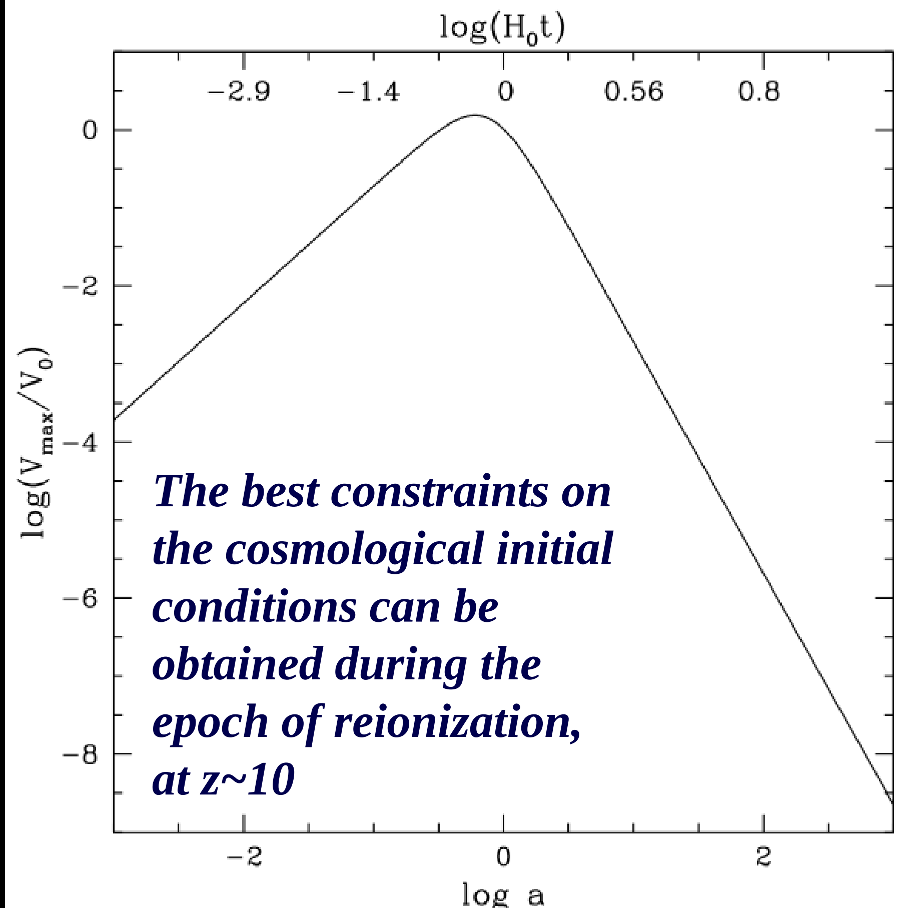
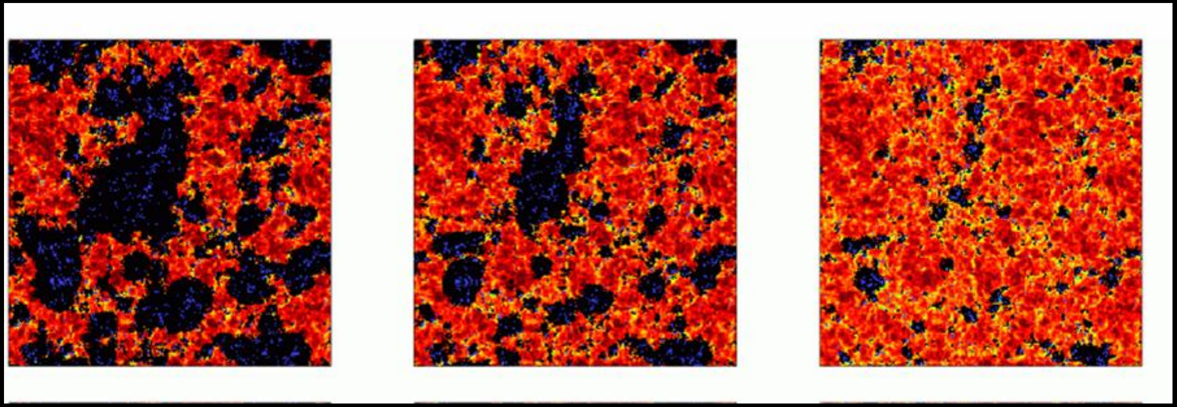


FIG. 2: The Hubble volume $V_{\rm max}$, normalized by its present-day value $V_0 = \frac{4\pi}{3}(c/H_0)^3 = 3.3 \times 10^2$ Gpc^3, as a function of cosmic time t (top axis, in units of the Hubble time $H_0^{-1} = 14$ Gyr) and scale factor $a = (1+z)^{-1}$ (bottom axis).

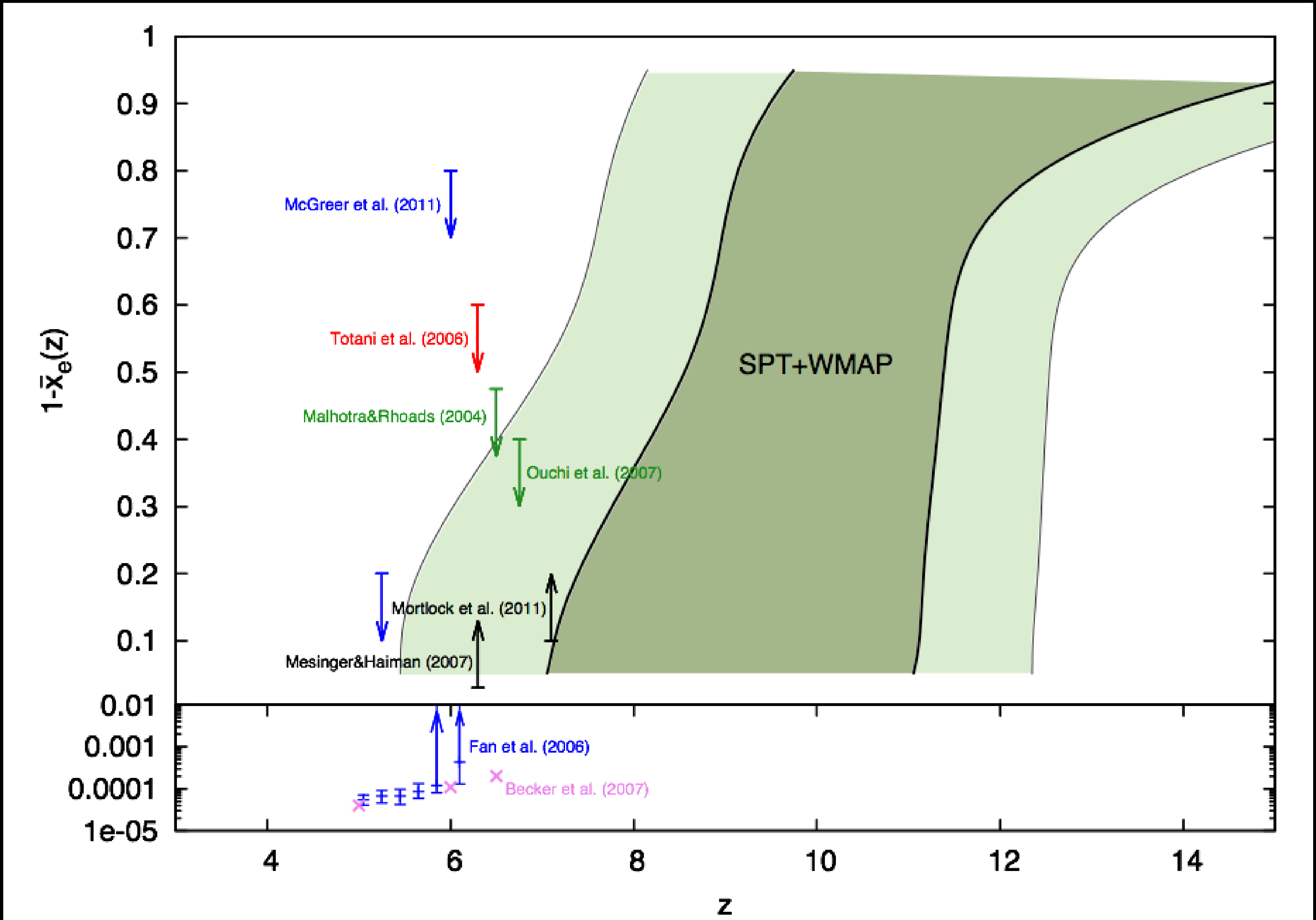
How Did the First Stars and Black Holes Form?

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



Surprises may signal new physics

When Was the Universe Ionized?



Zahn et al. 2012

The Optimal Cosmic Epoch for Precision Cosmology

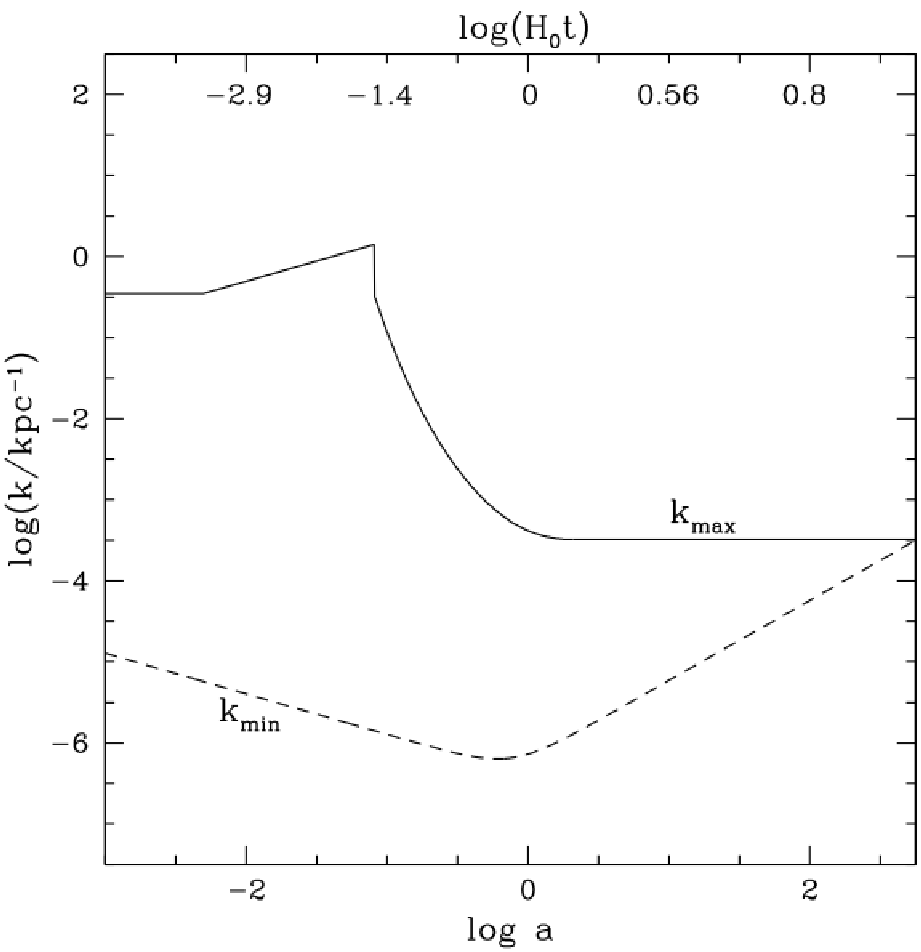


FIG. 3: The range of comoving wavenumbers for which the linear power spectrum can be observed per Hubble volume as a function of cosmic time and scale factor. The minimum wavelength $\lambda_{\min} = 2\pi/k_{\max}$ is taken as the larger among the baryonic Jeans scale and the scale where nonlinear structure forms at any given redshift. The maximum wavelength $\lambda_{\max} = 2\pi/k_{\min}$ is set by the Hubble diameter $2R_{\rm H}$.

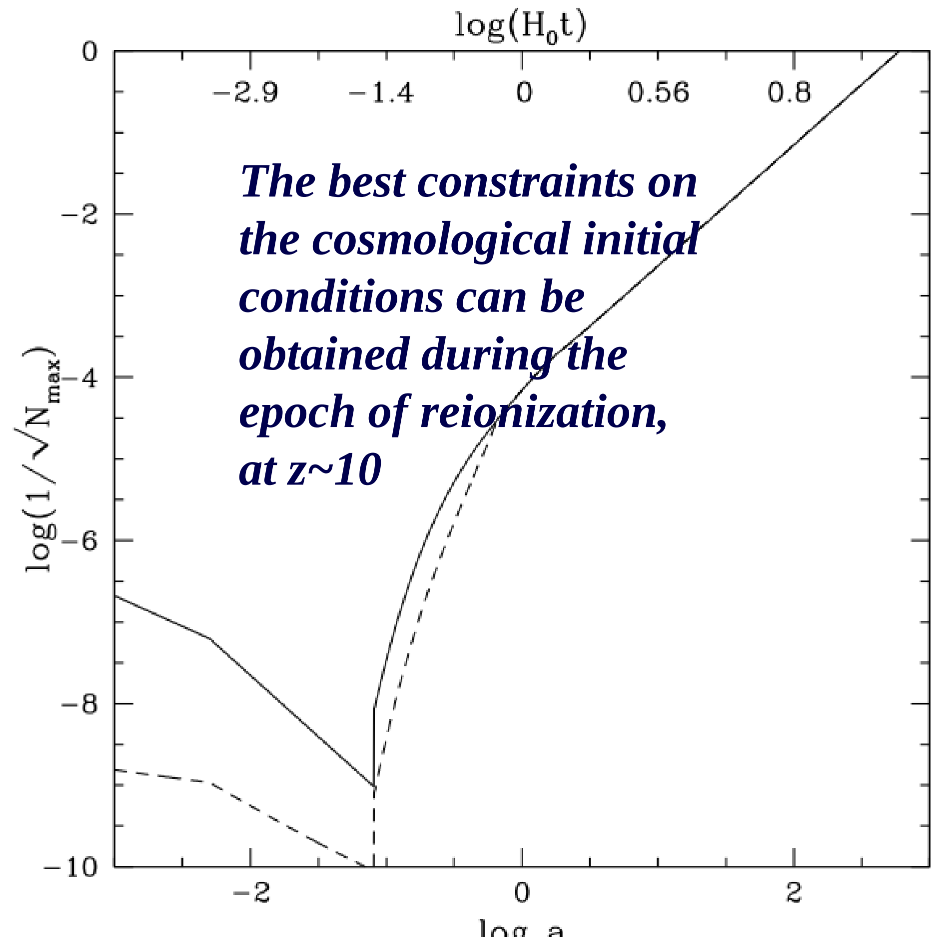
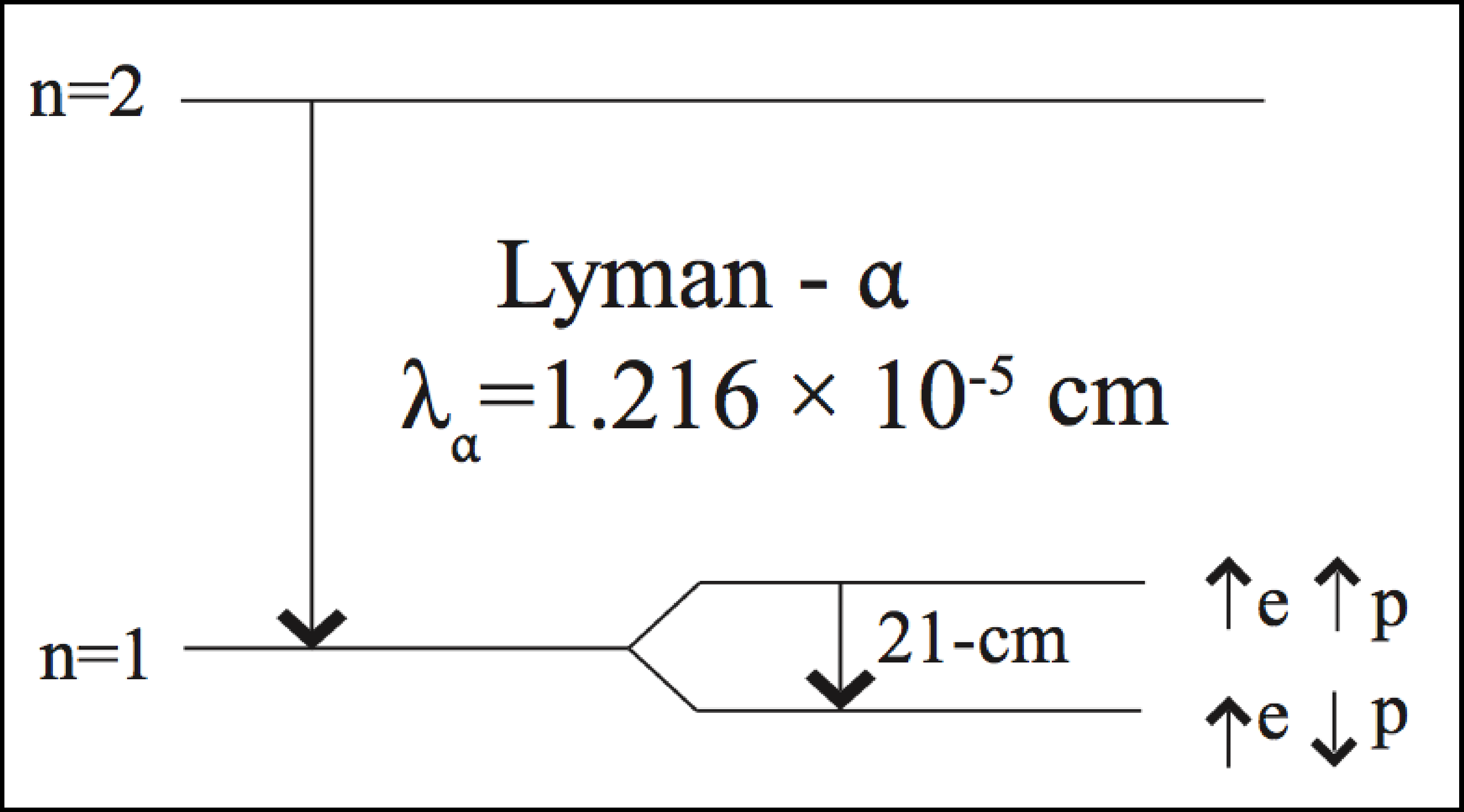


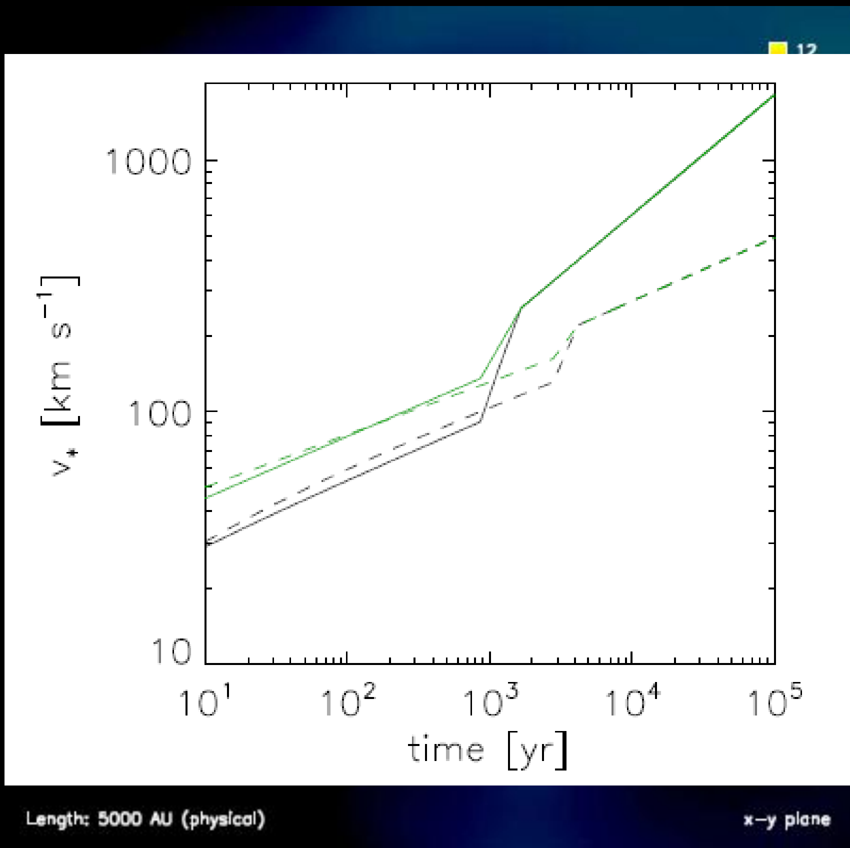
FIG. 4: The minimum fractional error attainable for the power-spectrum amplitude $1/\sqrt{N_{\max}}$ per Hubble volume, as a function of cosmic time and scale factor (solid line). The dashed line includes the reduction in the statistical uncertainty for a present-day observer who surveys a spherical shell of comoving width $2R_H(t)$ centered at the corresponding cosmic times.

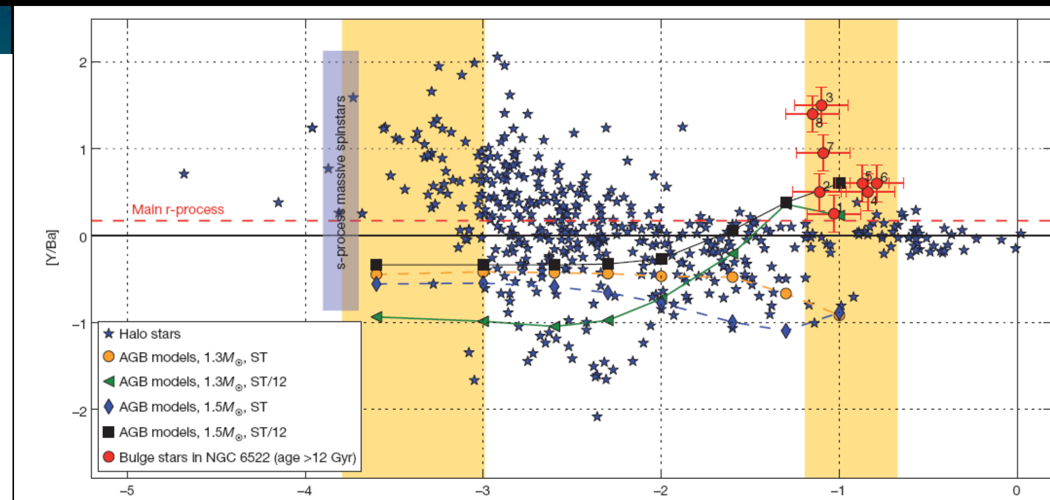
Hydrogen

- Most abundant element produced in the Big Bang



First Stars Had High Spin





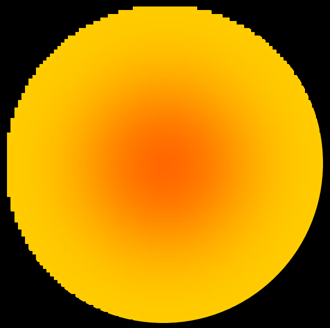
Sr and Y abundance in eight ~12Gyr old stars in NGC 6522 require a rotation speed of ~500 km/s (slow neutron capture is 10,000 more effective than in non-rotating stars).

Implications: *rotational mixing, GRBs*

Stacy, Bromm, & Loeb (2010)

Chiappini et al., Nature (2011)

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



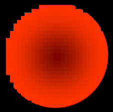
Massive, metal free stars

$M > 300 M_\odot$	$\sim 10^5$
$M > 100 M_\odot$	$\sim 4 \times 10^4$

$$T_{\rm eff} \sim 10^5 \mathrm{K}$$

$$L = L_E \propto M$$

Gain by up to a factor of ~30!



Salpeter mass function

Metal free	$\sim 7 \times 10^3$
$Z = 0.01 Z_\odot$	$\sim 3.5 \times 10^3$

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

Threshold Metallicity

High mass
(Pop-III) stars

Low mass
(Pop-I/II) stars

$Z_{\rm crit}$

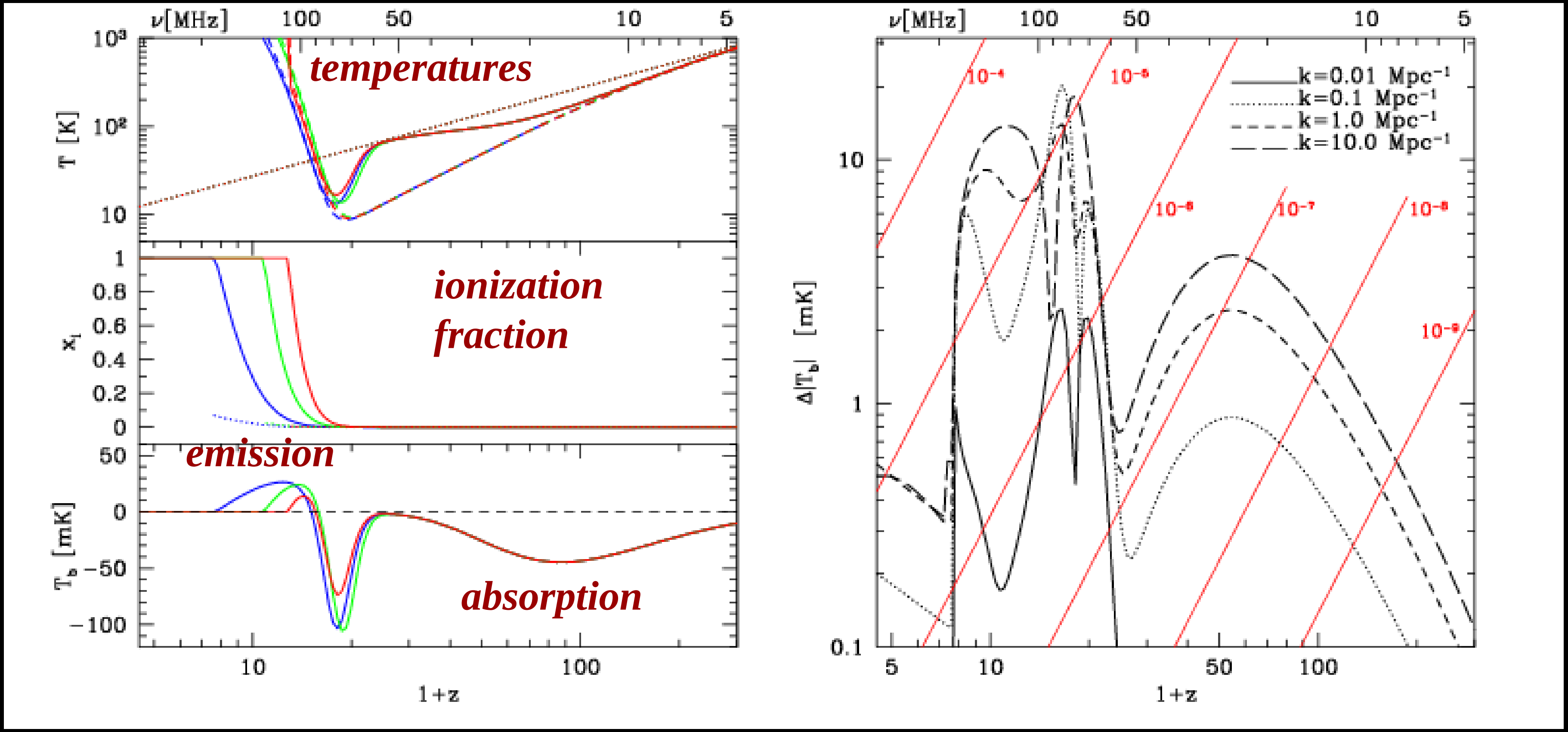
Atomic cooling (CII, OI) → $Z_{\rm crit} \sim 10^{-3} Z_{\odot}$

Dust, molecules (CO) → $Z_{\rm crit} \sim 10^{-5} Z_{\odot}$

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

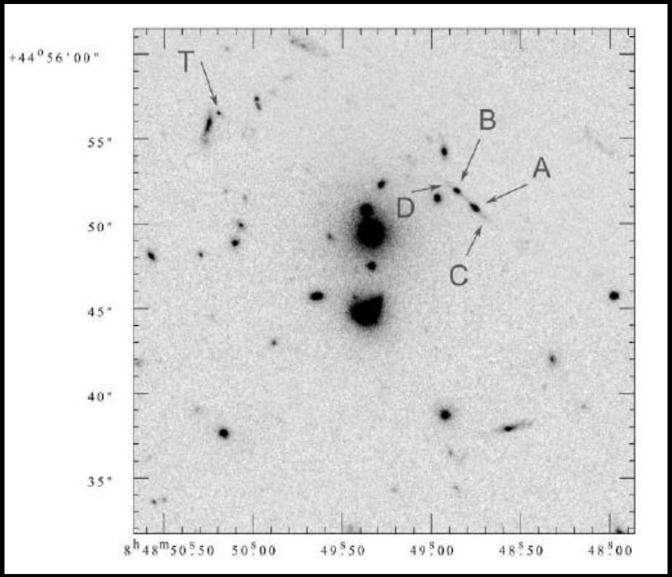
but: $Z_{\rm C,O} > 10^{-3} Z_{\odot}$

21-cm Tomography throughout Cosmic History



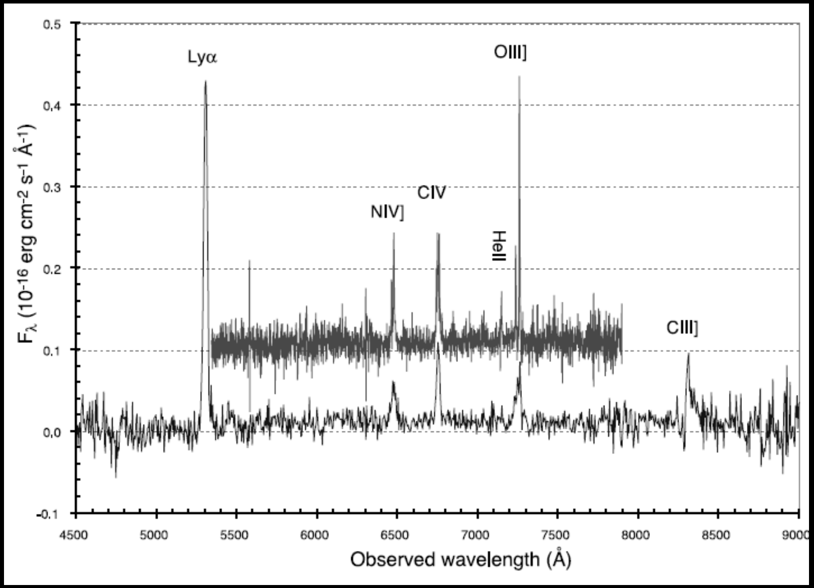
(Pritchard & Loeb, Phys. Rev. D, 2008)

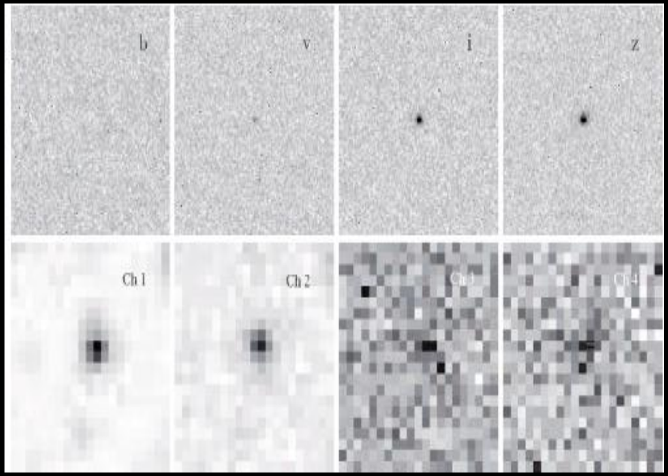
Low-Metallicity H II Regions with a $\sim 10^5$ K Ionizing Continuum



z=3.357

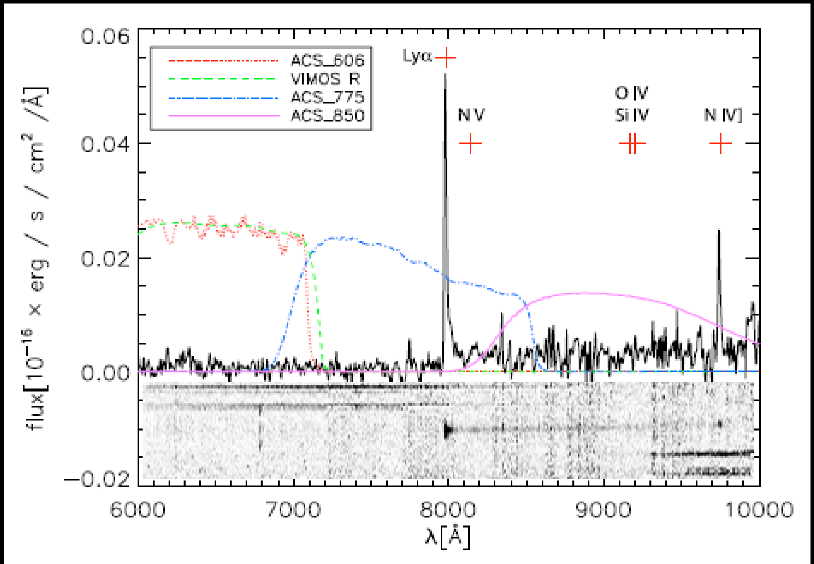
Fosbury et al. (2003)





z=5.563

Raiter et al. (2003)



Requirements for Reionization by Pop II Stars:

- To produce one ionizing photon per baryon:

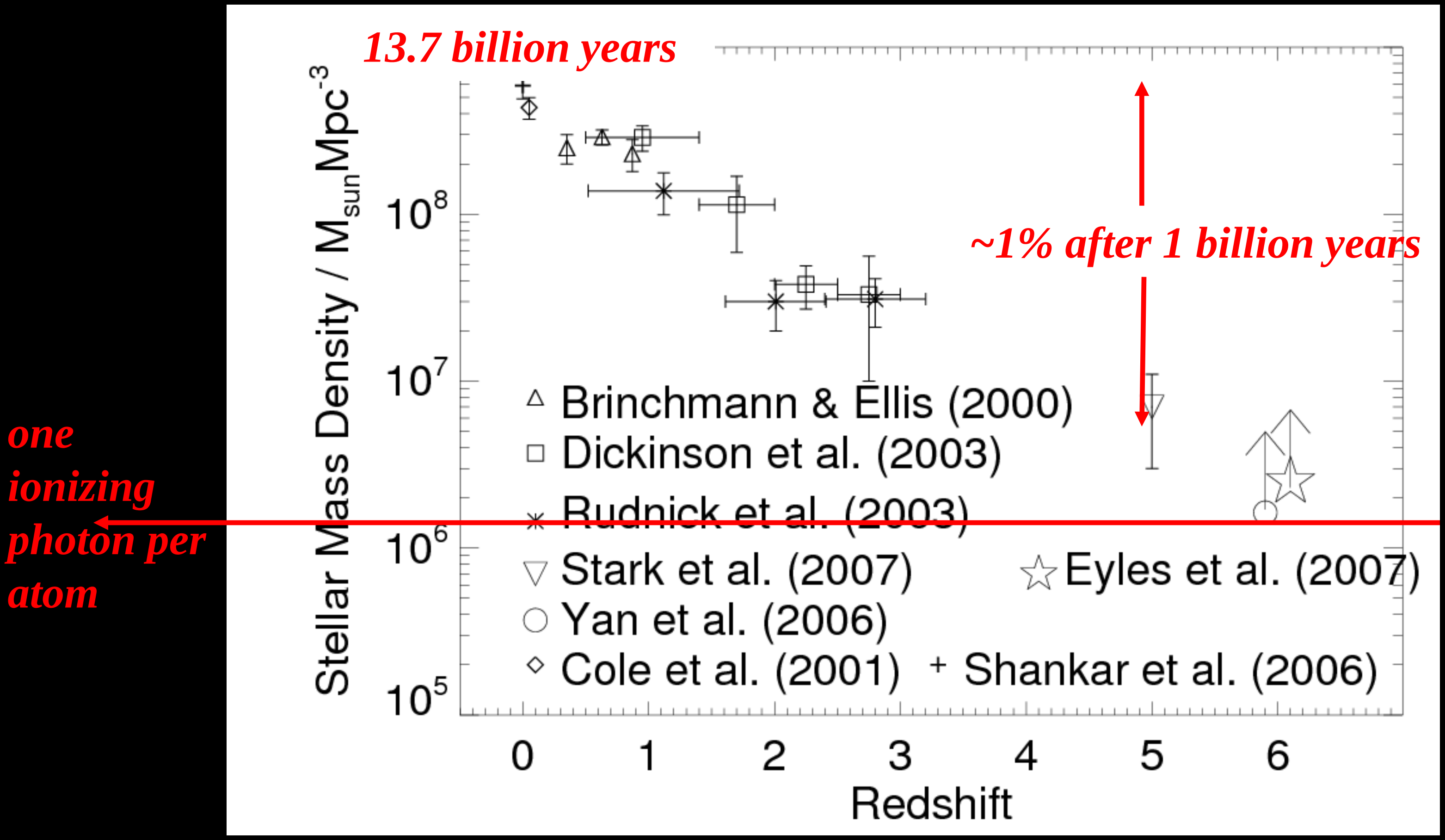
$$\rho_\star \approx 1.7 \times 10^6 f_{\rm esc}^{-1} \ M_\odot {\rm Mpc}^{-3}$$

- To keep the IGM ionized by compensating for recombinations:

$$\dot{\rho}_\star \approx 2 \times 10^{-3} f_{\rm esc}^{-1} C \left(\frac{1+z}{10}\right)^3 \ M_\odot \ {\rm yr}^{-1} \ {\rm Mpc}^{-3}$$

Observed Growth of Mass in Stars

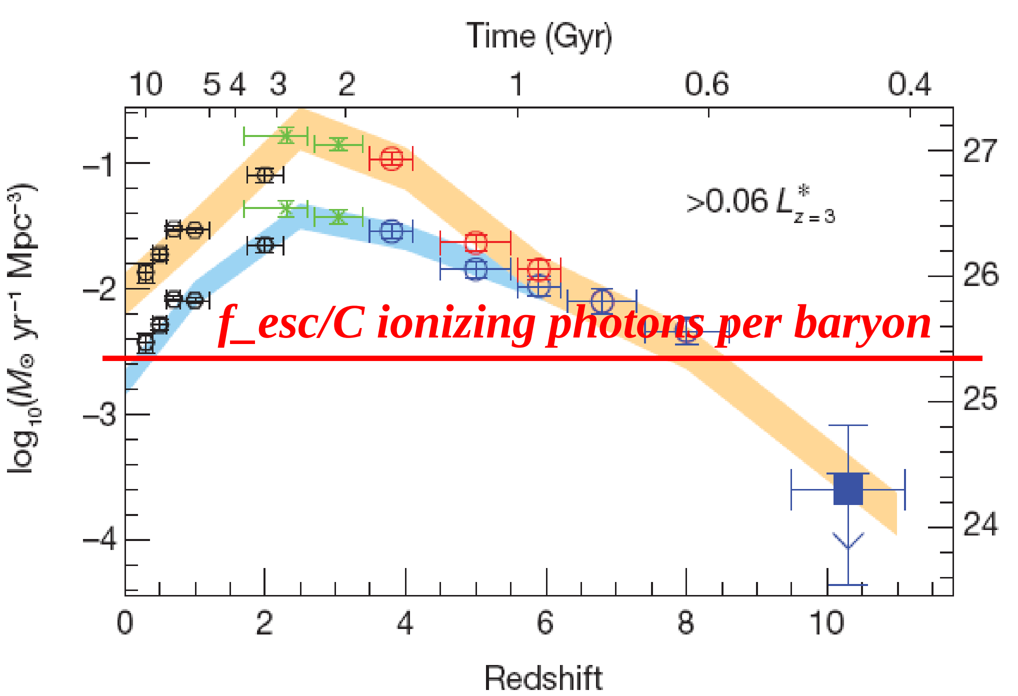
← Time

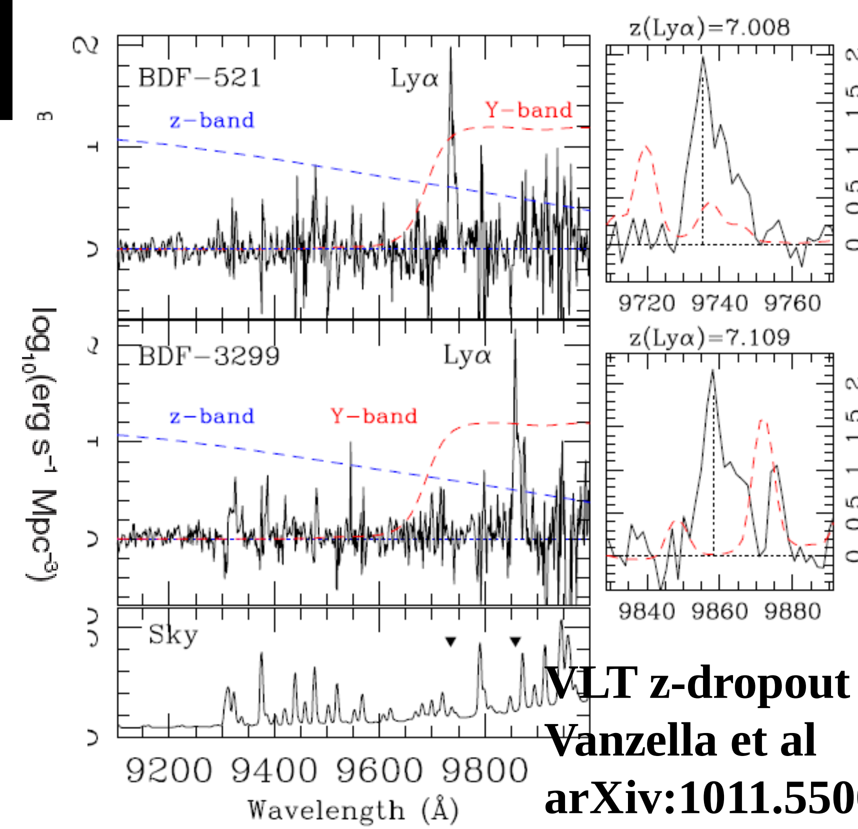


Redshift Record of Observed Galaxies

(one z~10 candidate, Bouwens et al., Nature 2011)

HST WFC3/IR: ***~140 galaxies at z~7-8***





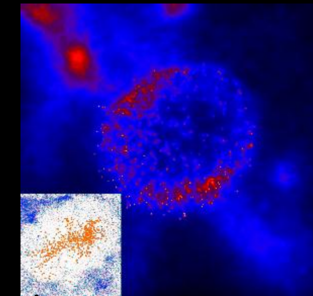
VLT z-dropout
Vanzella et al
arXiv:1011.5500

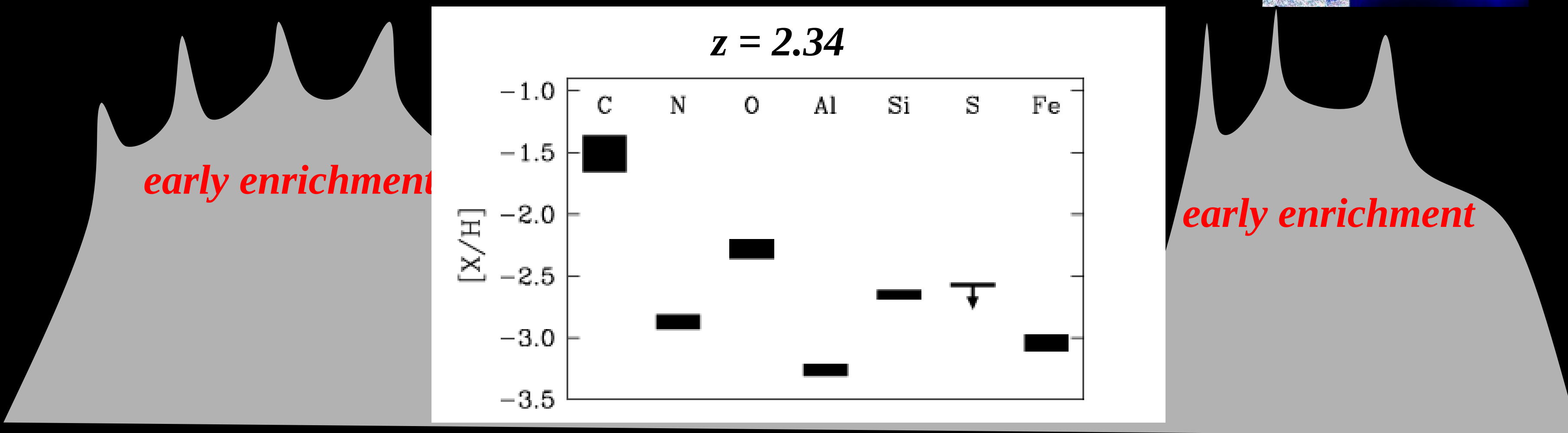
Prediction from Barkana & Loeb (2000):

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)

→Enrichment of Primordial Gas with Heavy Elements was Highly Inhomogeneous





early Pop-III *late Pop-III* *early Pop-III*

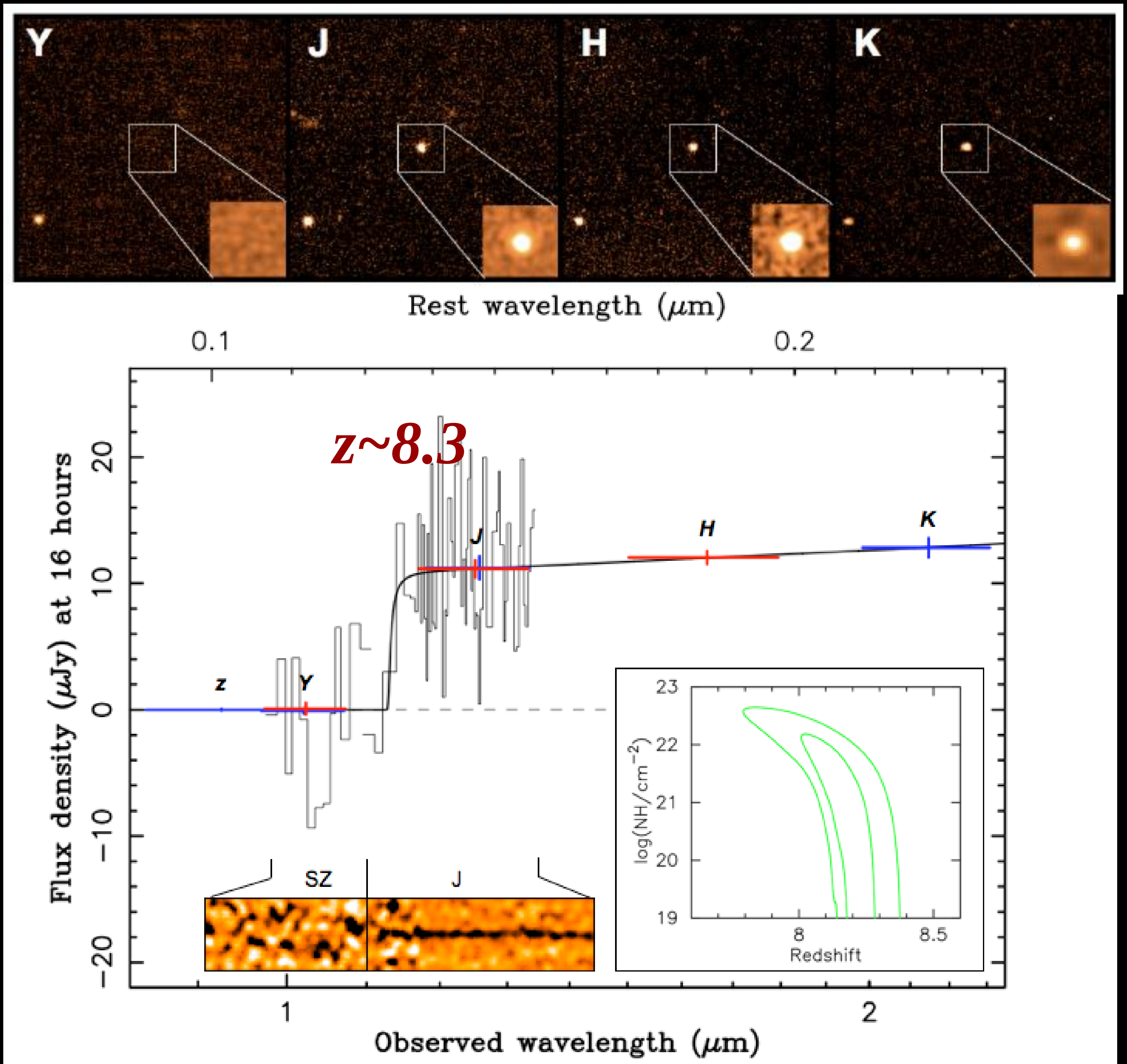
A carbon-enhanced metal-poor damped Lyα system: Probing gas from Population III nucleosynthesis?*

Ryan Cooke[1]†, Max Pettini[1], Charles C. Steidel[2], Gwen C. Rudie[2], and Regina A. Jorgenson[1]

[1] *Institute of Astronomy, Madingley Road, Cambridge, CB3 0HA*

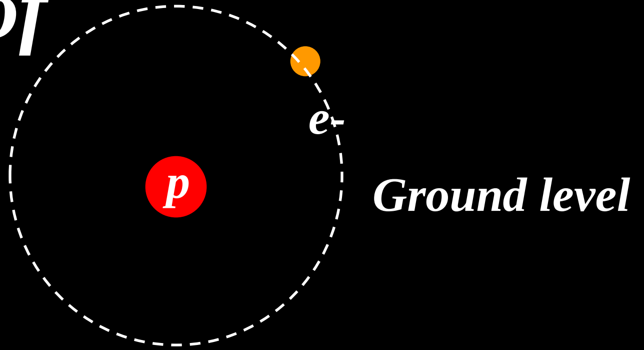
[2] *California Institute of Technology, MS 249-17, Pasadena, CA 91125, USA*

A Bright Explosion 600 Million Years after the Big Bang



Mapping the Cosmic Distribution of

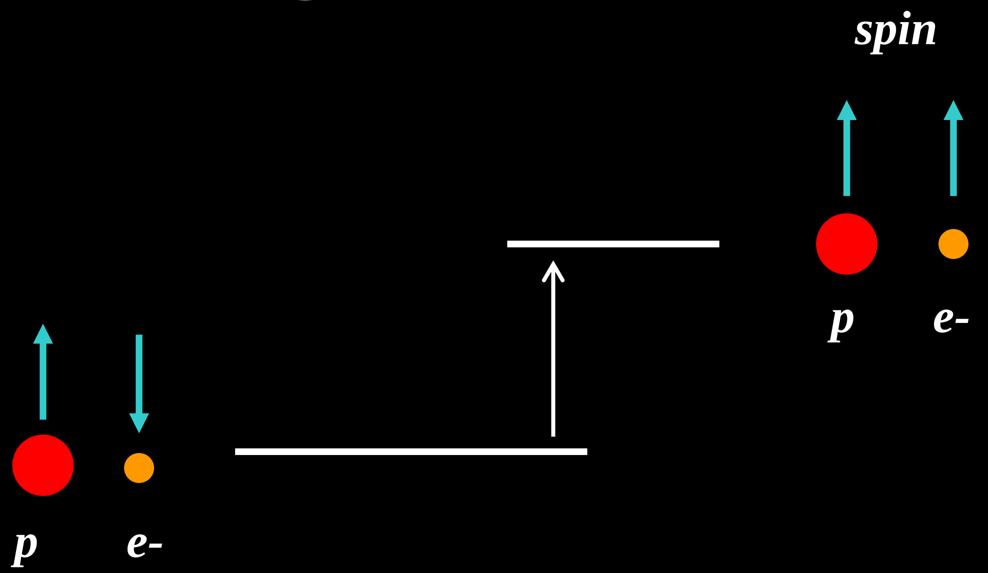
Hydrogen



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

Couple T_s ***to*** T_k

Couples T_s ***to*** T_γ

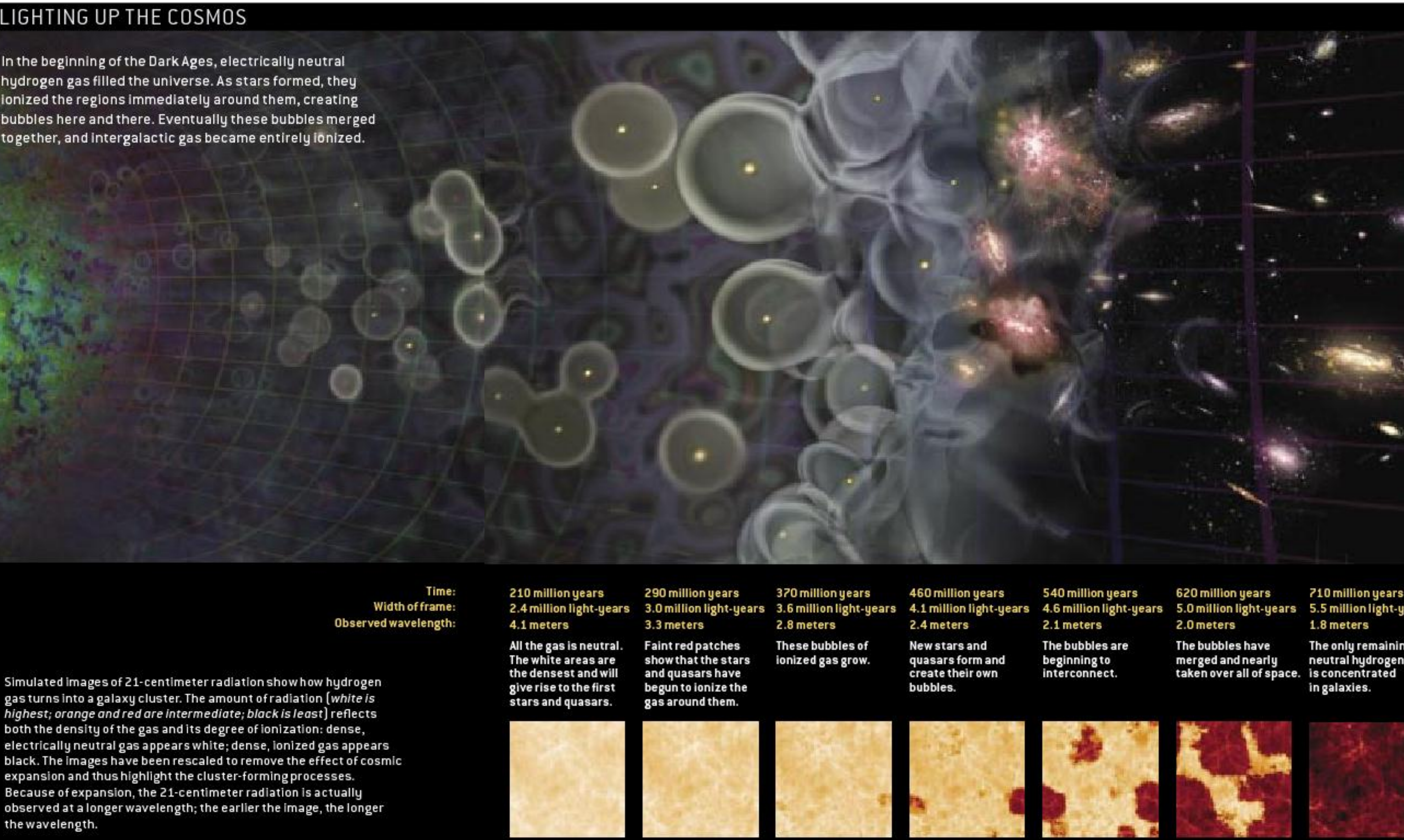


Spin Temperature

$$\frac{n_1}{n_0} = 3\exp(-\frac{0.07\mathrm{K}}{T_s})$$

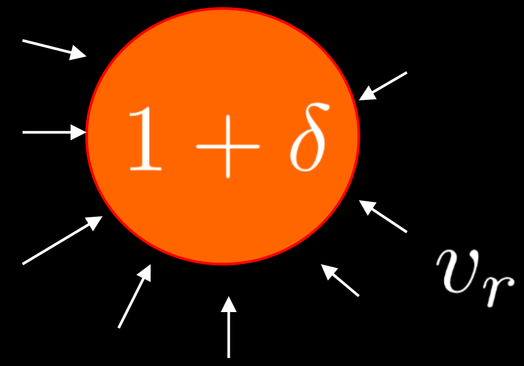
Predicted by Van de Hulst in 1944; Observed by Ewen &Purcell in 1951

21cm Mapping of Cosmic History in the 21st Century



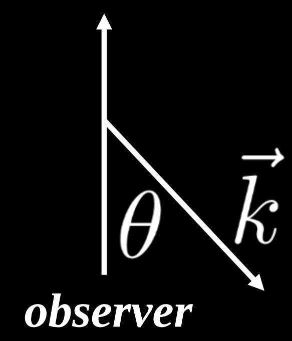
Line-of-Sight Anisotropy of 21cm Flux Fluctuations

$$T_b = \frac{\tau}{(1+z)}(T_s - T_{\mathrm{CMB}})$$



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

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



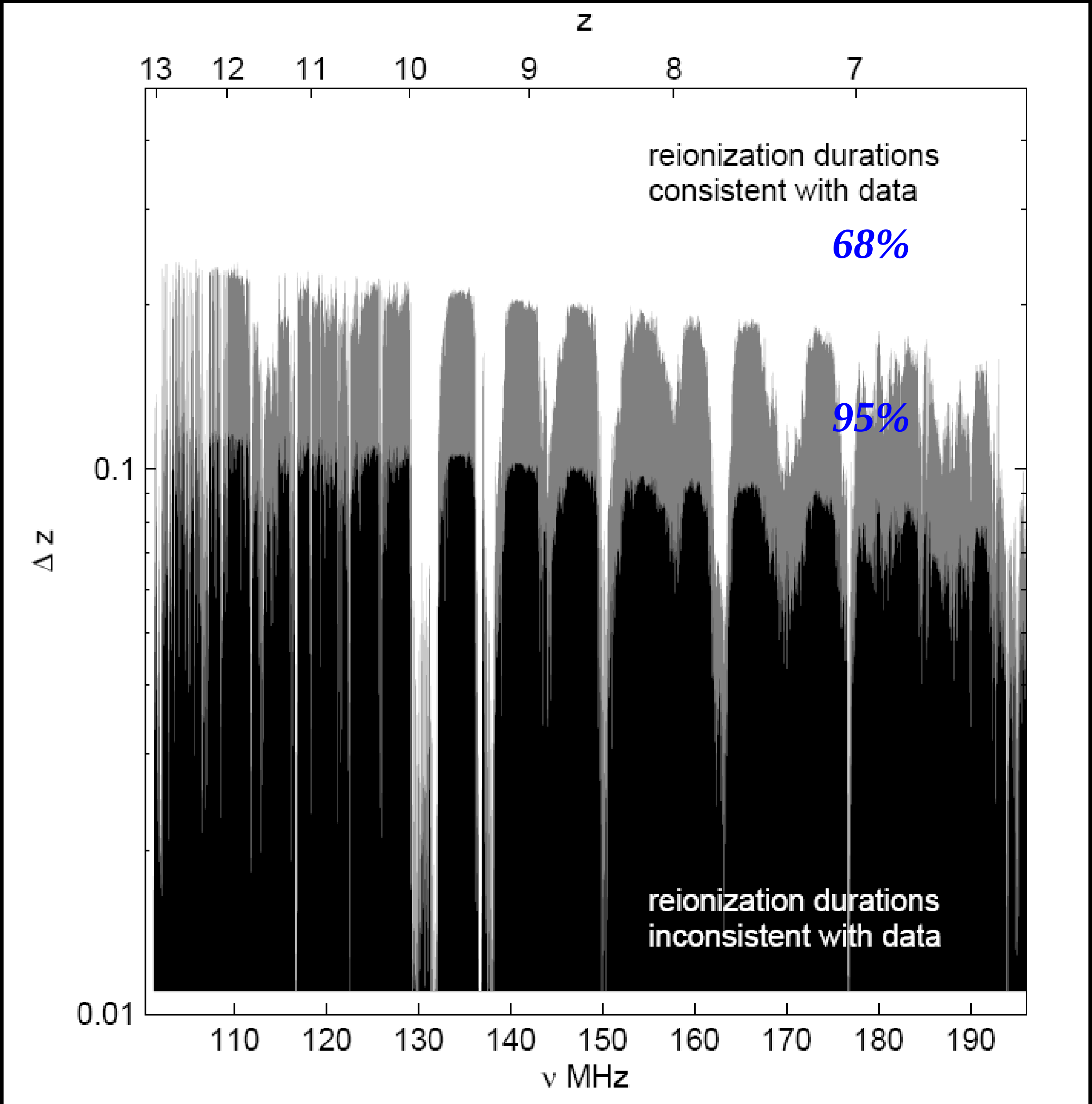
$$\delta_{T_b}(\vec{k}) = -\cos^2\theta \times \delta(\vec{k})$$

$$P(\vec{k}) = [\delta_{\mathrm{iso}}(k) + \delta(k)\cos^2\theta]^2$$

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

Barkana & Loeb 2004; see also Bharadwaj & Ali 2004

Reionization Was Not Abrupt!



Bowman & Rogers 2010

Separating the Physics from the Astrophysics

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

Astrophysics: *consequences of star formation*

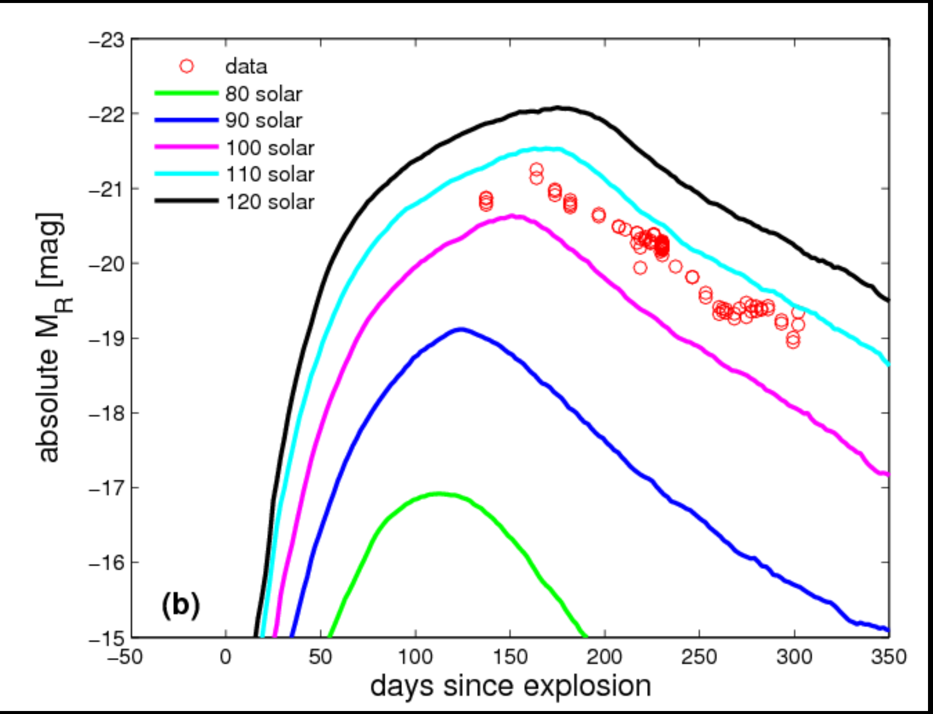
Three epochs:

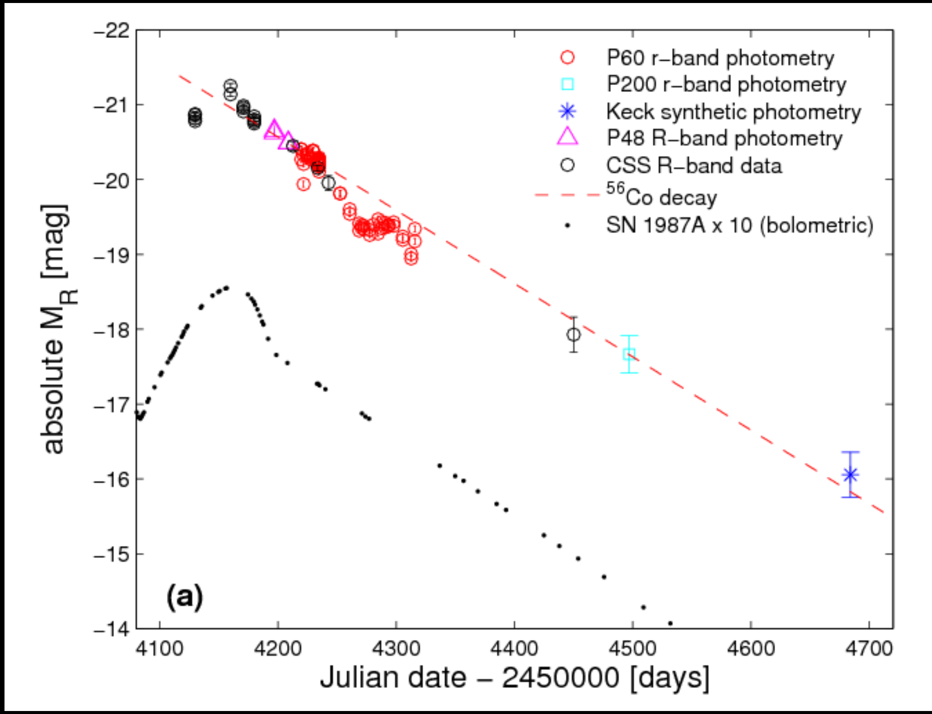
- ***Before the first galaxies (z>25):*** mapping of density fluctuations through 21cm absorption
- ***During reionization:*** anisotropy of the 21cm power spectrum due to peculiar velocities
- ***After reionization (z<6):*** dense pockets of residual hydrogen (DLAs) trace large scale structure

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

Status: **analogous to CMB research prior to COBE**

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

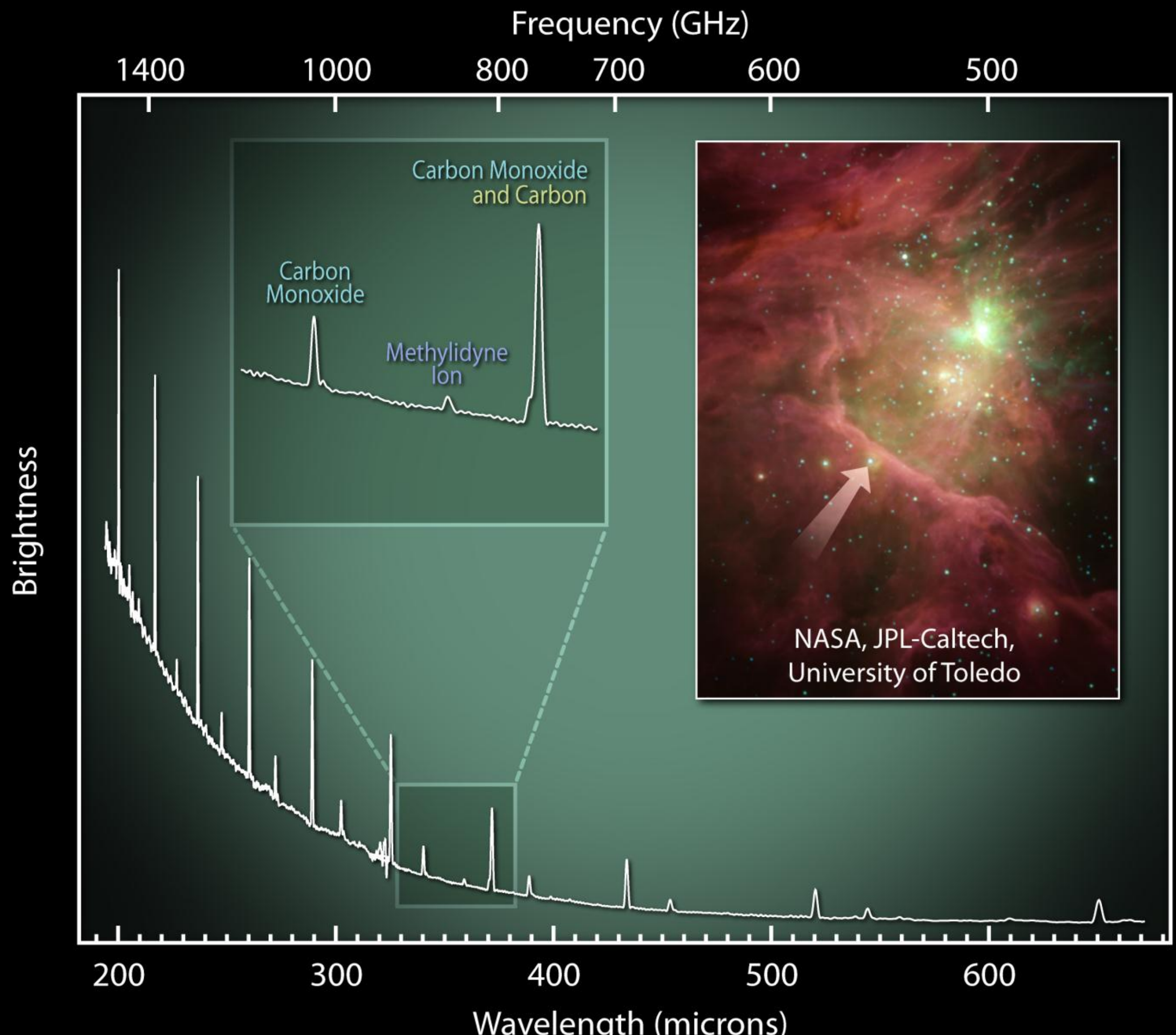




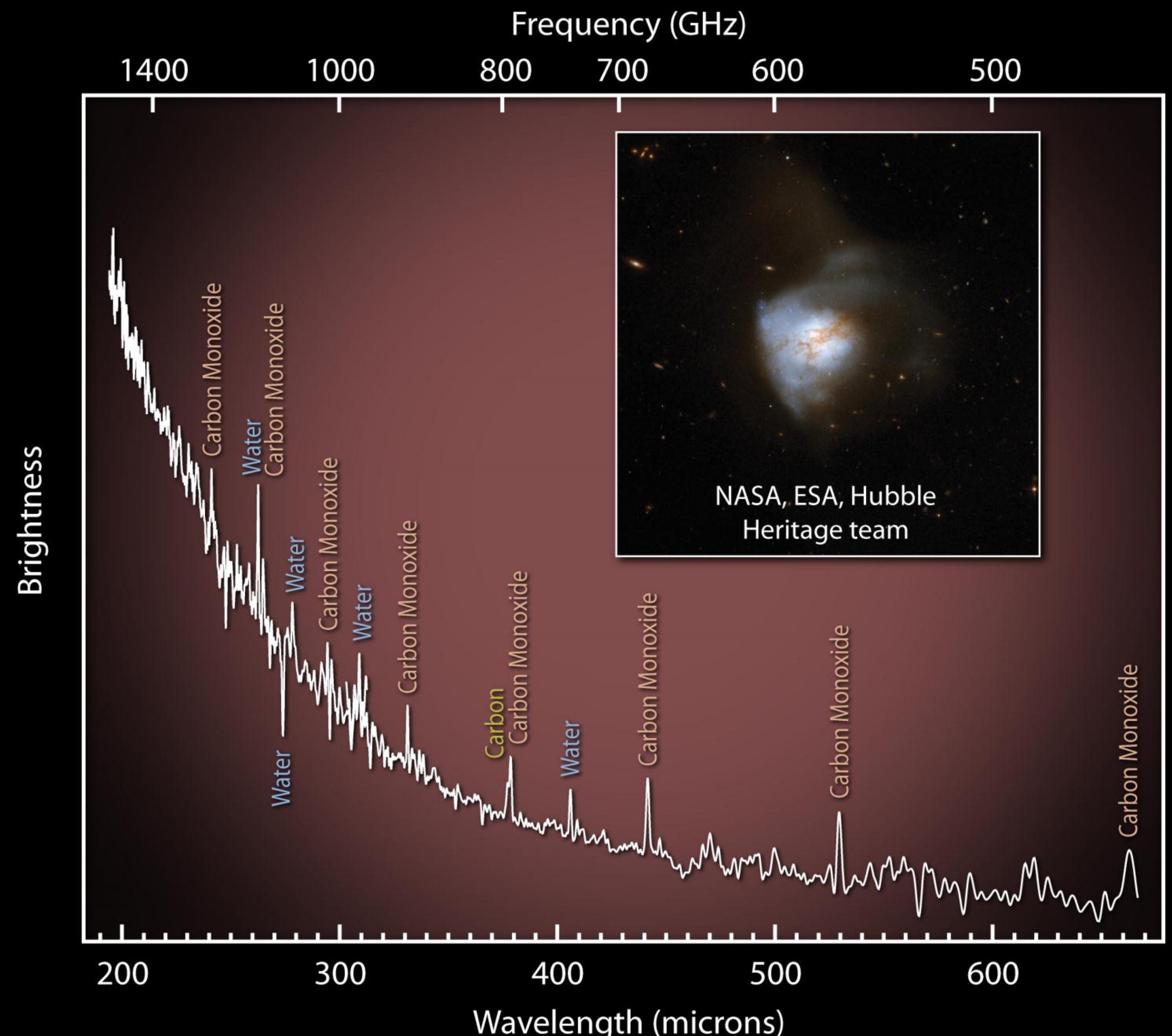
- Nickel mass of ~4-7 (ejecta mass of 100) ; kinetic energy of
- Dwarf galaxy at z=0.128 with M_B=-16.3 mag, and 12+[O/H]=8.25

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

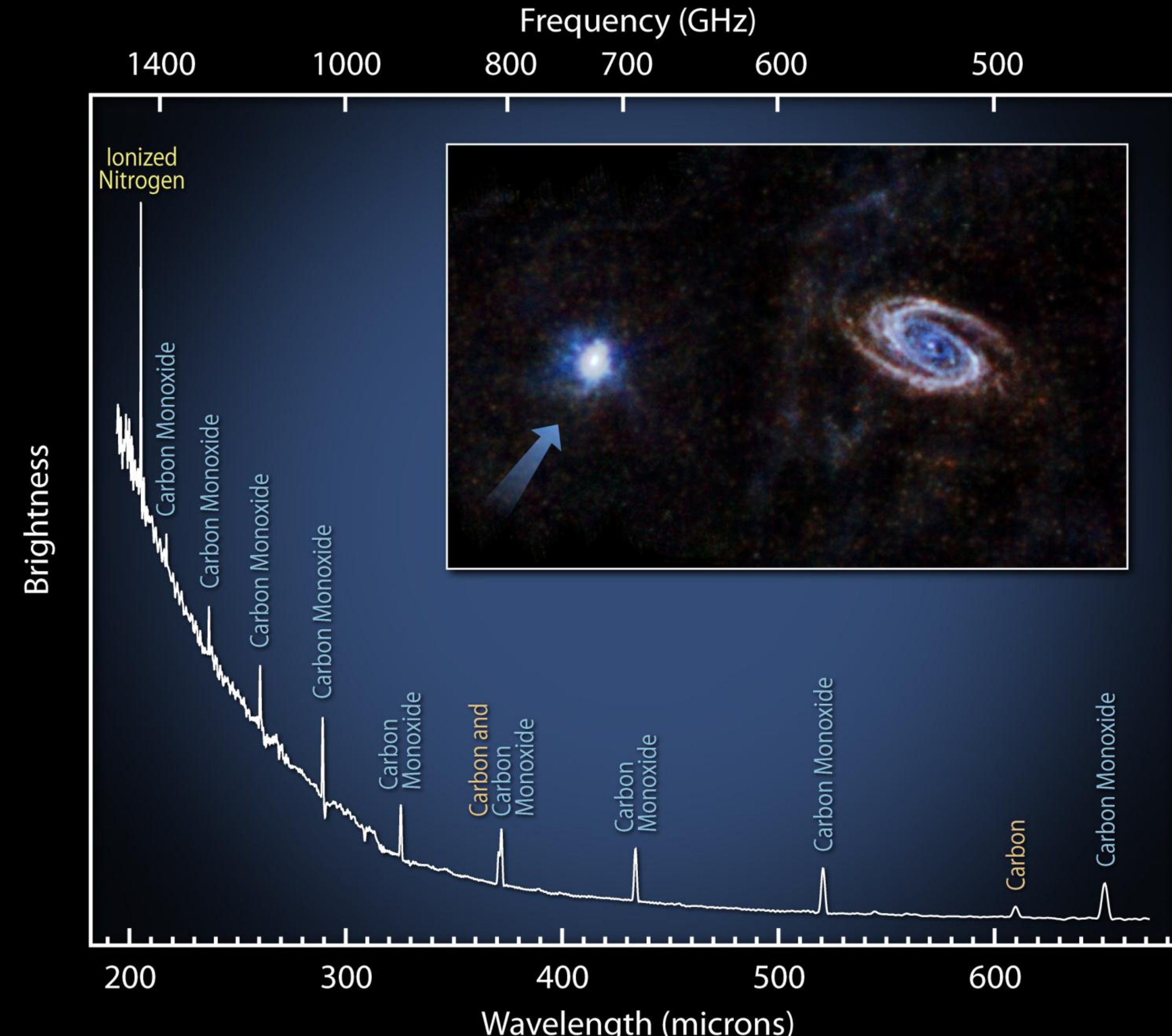
Herschel Spectra



Orion Bar


Frequency (GHz)
1400
1000
800
700
600
500
Brightness
Carbon Monoxide
Water
Carbon Monoxide
Water
Carbon Monoxide
Water
Carbon Monoxide
Water
Carbon
Carbon Monoxide
Water
Carbon Monoxide
Carbon Monoxide
Carbon Monoxide
NASA, ESA, Hubble
Heritage team
200
300
400
500
600
Wavelength (microns)

Arp 220


Frequency (GHz)
1400
1000
800
700
600
500
Ionized Nitrogen
Carbon Monoxide
Carbon Monoxide
Carbon Monoxide
Carbon Monoxide
Carbon Monoxide
Carbon and Carbon Monoxide
Carbon Monoxide
Carbon Monoxide
Carbon
Carbon Monoxide
Brightness
200
300
400
500
600
Wavelength (microns)

Messier 82