Paris, November 25, 2011

The First Galaxies

Abraham Loeb and Steven R. Furlanetto

(advanced textbook, ~ 500 pages, to appear in 2012)

PRINCETON UNIVERSITY PRESS
PRINCETON AND OXFORD

ASTROPHYSICS | PHYSICS

Though astrophysicists have developed a theoretical framework for understanding how the first stars and galaxies formed, only now are we able to begin testing those theories with actual observations of the very distant, early universe. We are entering a new and exciting era of discovery that will advance the frontiers of knowledge, and this book couldn't be more timely. It covers all the basic concepts in cosmology, drawing on insights from an astronomer who has pioneered much of this research over the past two decades.

Abraham Loeb starts from first principles, tracing the theoretical foundations of cosmology and carefully explaining the physics behind them. Topics include the gravitational growth of perturbations in an expanding universe, the abundance and properties of dark matter halos and galaxies, reionization, the observational methods used to detect the earliest galaxies and probe the diffuse gas between them—and much more.

Cosmology seeks to solve the fundamental mystery of our cosmic origins. This book offers a succinct and accessible primer at a time when breathtaking technological advances promise a wealth of new observational data on the first stars and galaxies.

- Provides a concise introduction to cosmology
- Covers all the basic concepts
- Gives an overview of the gravitational growth of perturbations in an expanding universe
- Explains the process of reionization
- Describes the observational methods used to detect the earliest galaxies

Abraham Loeb is professor of astronomy and director of the Institute for Theory and Computation at Harvard University.

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Princeton Frontiers in Physics is a new series of short introductions to some of today's most exciting and dynamic research areas across the physical sciences. Written by leading specialists, these stimulating books address fundamental questions that are challenging the limits of current knowledge. With forward-looking discussions of core ideas, ongoing debates, and unresolved problems, the books in this series make cutting-edge research in the physical sciences more accessible than ever before—for students, scientists, and scientifically minded general readers.

"Abraham Loeb, a leading figure in exploring the emergence of first galaxies and stars, introduces the astrophysics of the first billion years. With a strong emphasis on the underlying physics, this book will be an essential starting point for both observers and theorists who are interested in this rapidly evolving area of cosmology."
—**David Spergel**, Princeton University

"A lucid, concise account of our current understanding of how light burst from darkness when the first stars and galaxies formed early in the expansion of the universe. Starting from basic physical principles, Loeb describes the physical processes that shaped the evolution of the universe, how they led to the formation of the first black holes, quasars, and gamma-ray bursts, and how upcoming observations will test these ideas."
—**Christopher F. McKee**, University of California, Berkeley

"This is a lively, well-written book. Loeb is an excellent writer and talented instructor who is also internationally recognized in the research community. The topic at hand—the first stars and galaxies—is truly an exciting frontier for which Loeb and his collaborators have developed much of the theoretical framework, and for which the observational possibilities are rapidly developing. The timing of this book couldn't be better."
—**Richard S. Ellis**, California Institute of Technology

"This is an extremely good book. Loeb guides readers through the early, formative history of the universe. He does not shy away from key calculations, but always tries to make things as simple as possible. His style is truly engaging, with a constant eye on the big picture. It makes for a thrilling read. Indeed, I found it difficult to put down."
—**Volker Bromm**, University of Texas, Austin

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ISBN 978-0-691-14516-7
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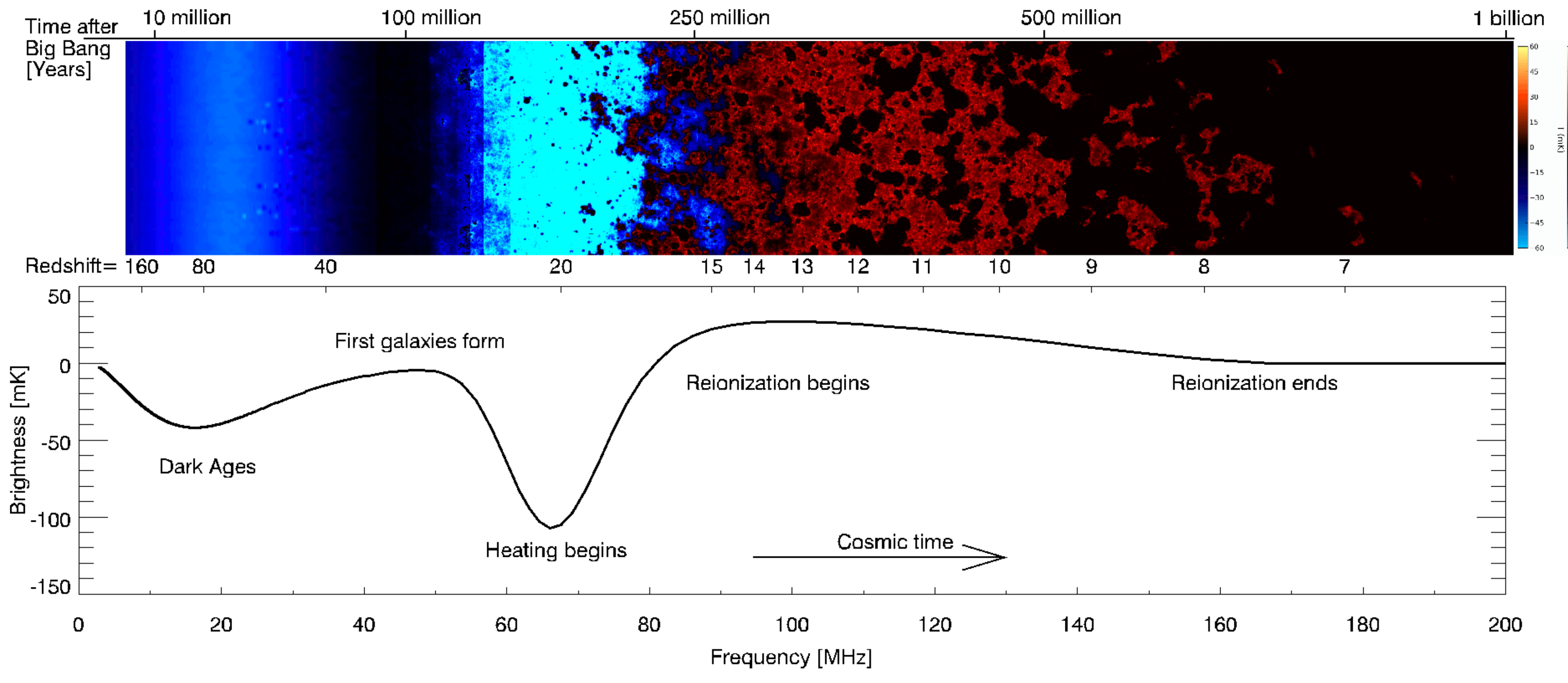
LOEB

How Did the First Stars and Galaxies Form?

ABRAHAM LOEB

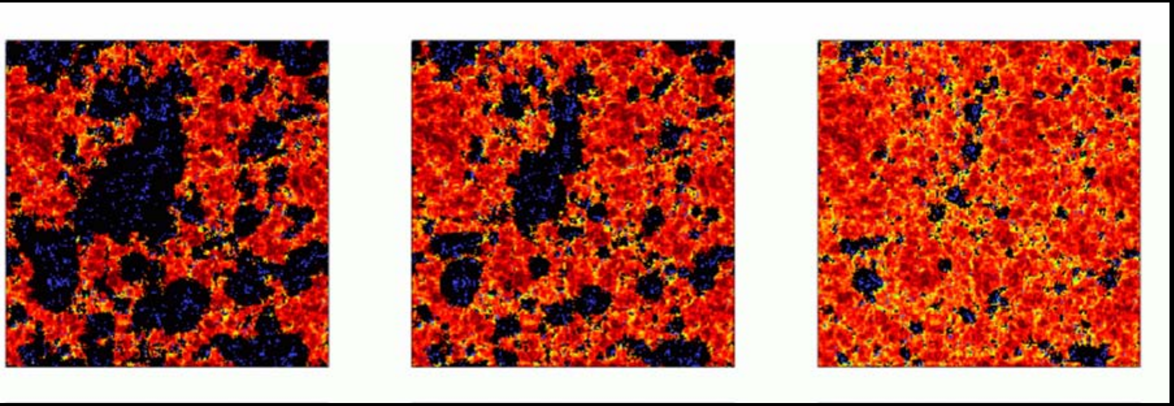
How Did the First Stars and Galaxies Form?



Pritchard & Loeb, Nature (2010)

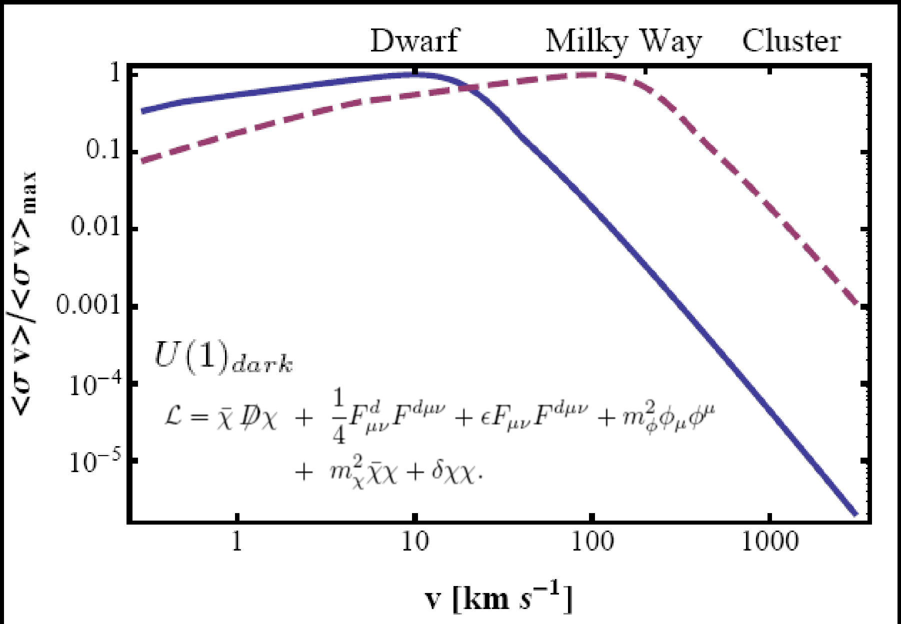
How Did the First Stars and Black Holes Form?

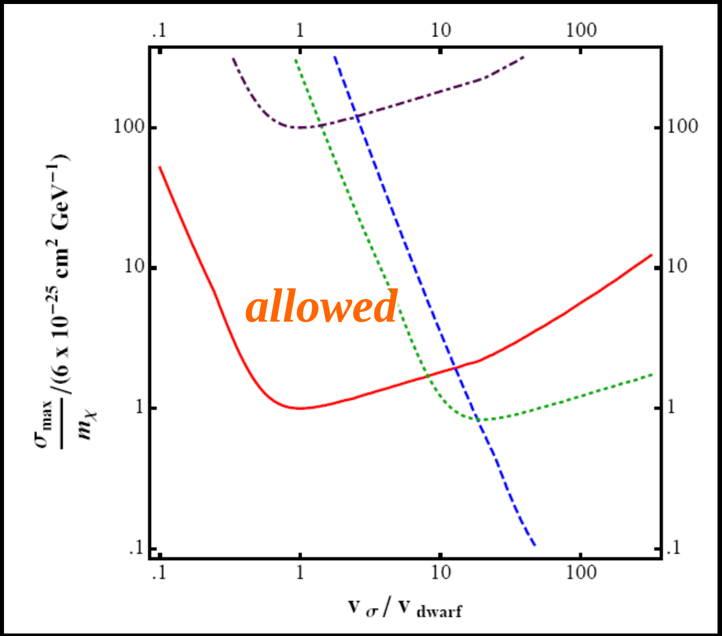
* Standard model of physics and cosmology
* Initial conditions from inflation
* Weakly-interacting Cold Dark Matter



Surprises may signal new physics

Example of New Physics (“venture capital”)

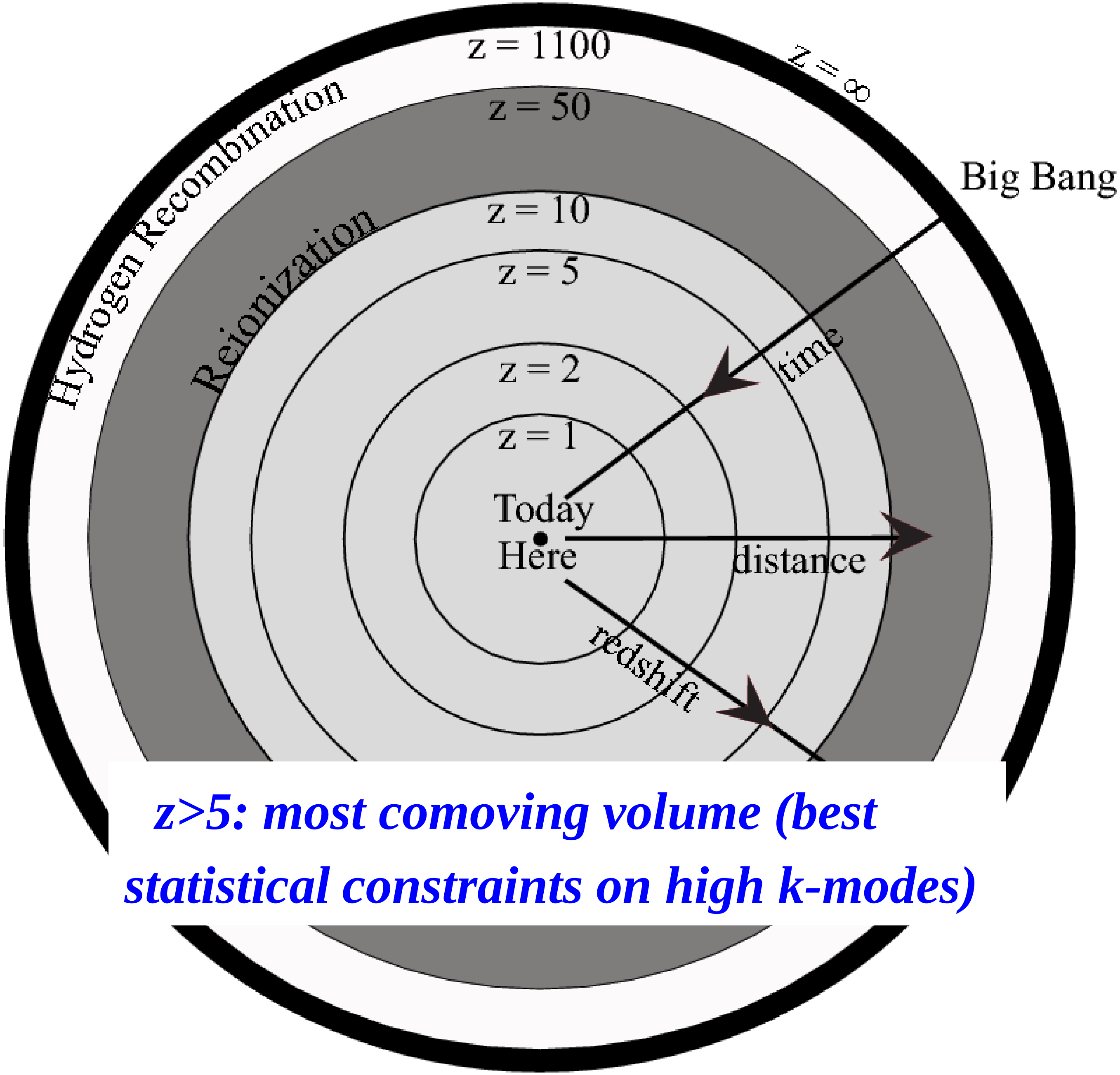




- Strong scattering of dark matter particles (~Thomson cross-section/proton mass) mediated by a massive gauge-boson
- Excited states: exothermic
- Cores in dwarf galaxies; evaporation of low-mass halos (missing satellite problem, old globular clusters).

Loeb & Weiner, Phys. Rev. Lett. (2011)

The Visible Universe



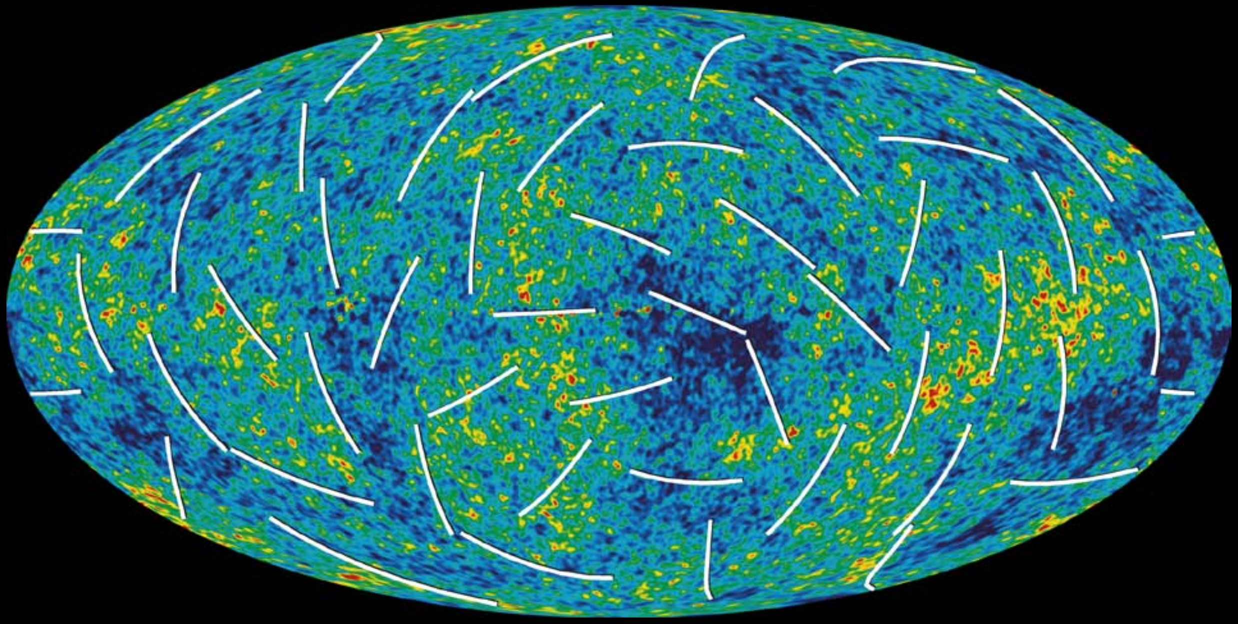
z>5: most comoving volume (best statistical constraints on high k-modes)

Now is the best cosmic time for constraining observationally the initial conditions:

$$N \sim (ct/\lambda)^3 \propto (t/a)^3$$

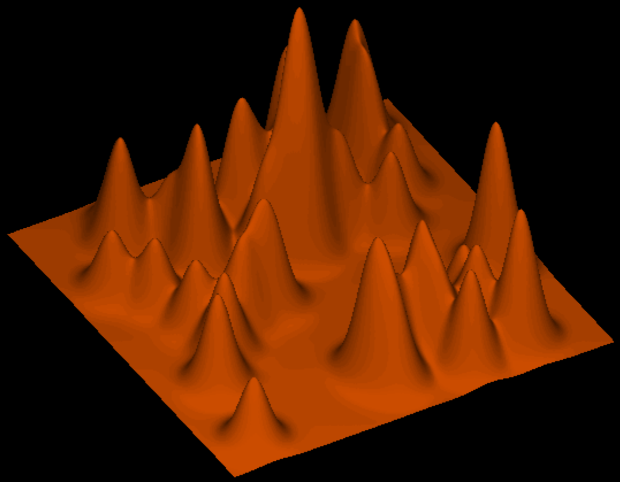
$$dN/dt = 0 \rightarrow t = 1/H \approx 14Gyr$$

Cosmic Microwave Background *(WMAP7)*



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

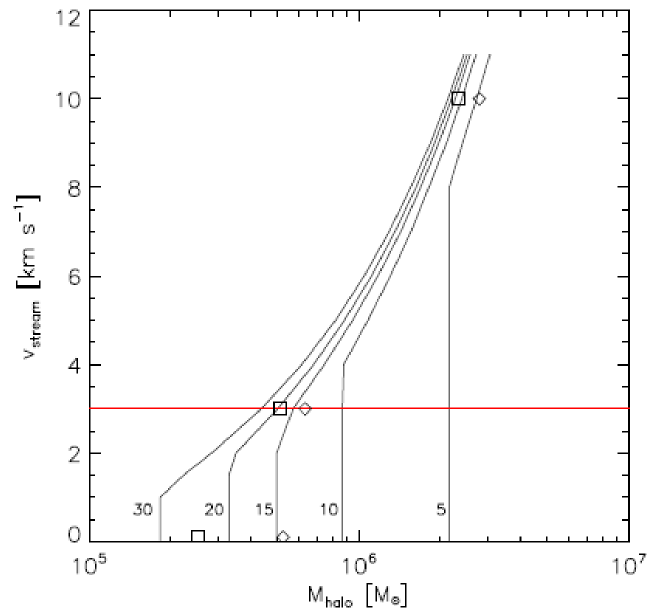
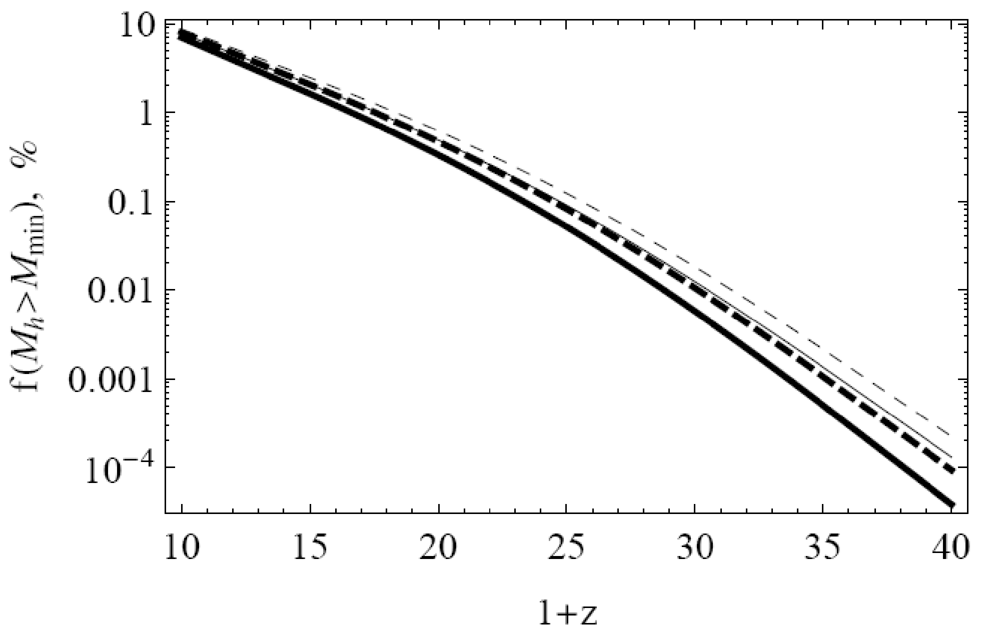


FIG. 2.— Effect of relative streaming on the minimum halo mass into which primordial gas can collapse. Each line represents the necessary halo masses for baryon collapse at a different redshift, marked in the plot. The diamonds represent the final halo masses found in 'standard collapse' simulations ($z_{\rm col}$ = 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
above the minimum cooling mass (solid lines). In the right panel we

Stacy, Bromm, & Loeb (2011)

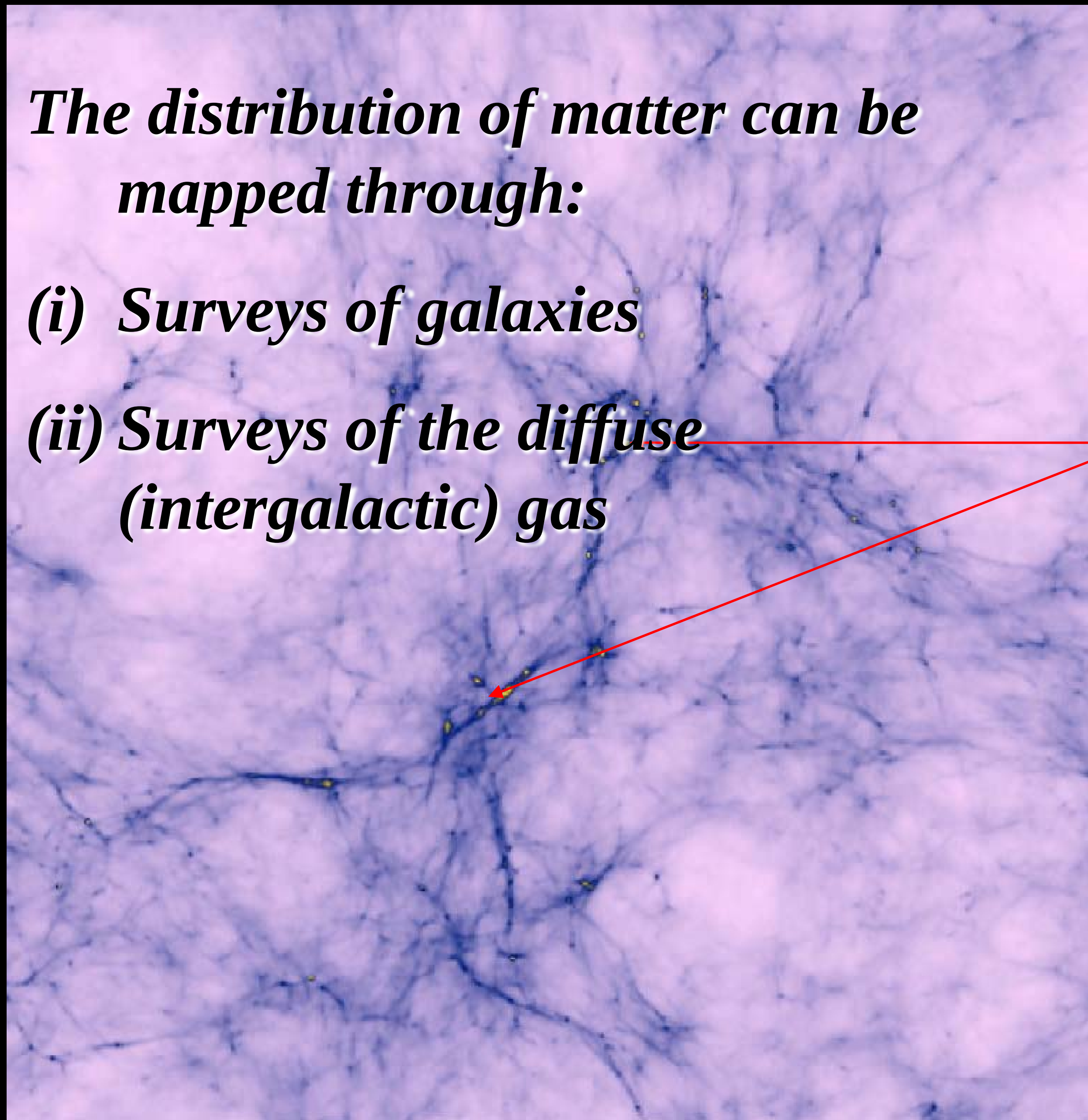
Tseliakhovich, Barkana, & Hirata (2011)

The First Dwarf Galaxies Formed at z~50

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

Yoshida et al. 2003

Observing the Stars

Requirements for Reionization by Pop II Stars:

- To produce one ionizing photon per baryon:

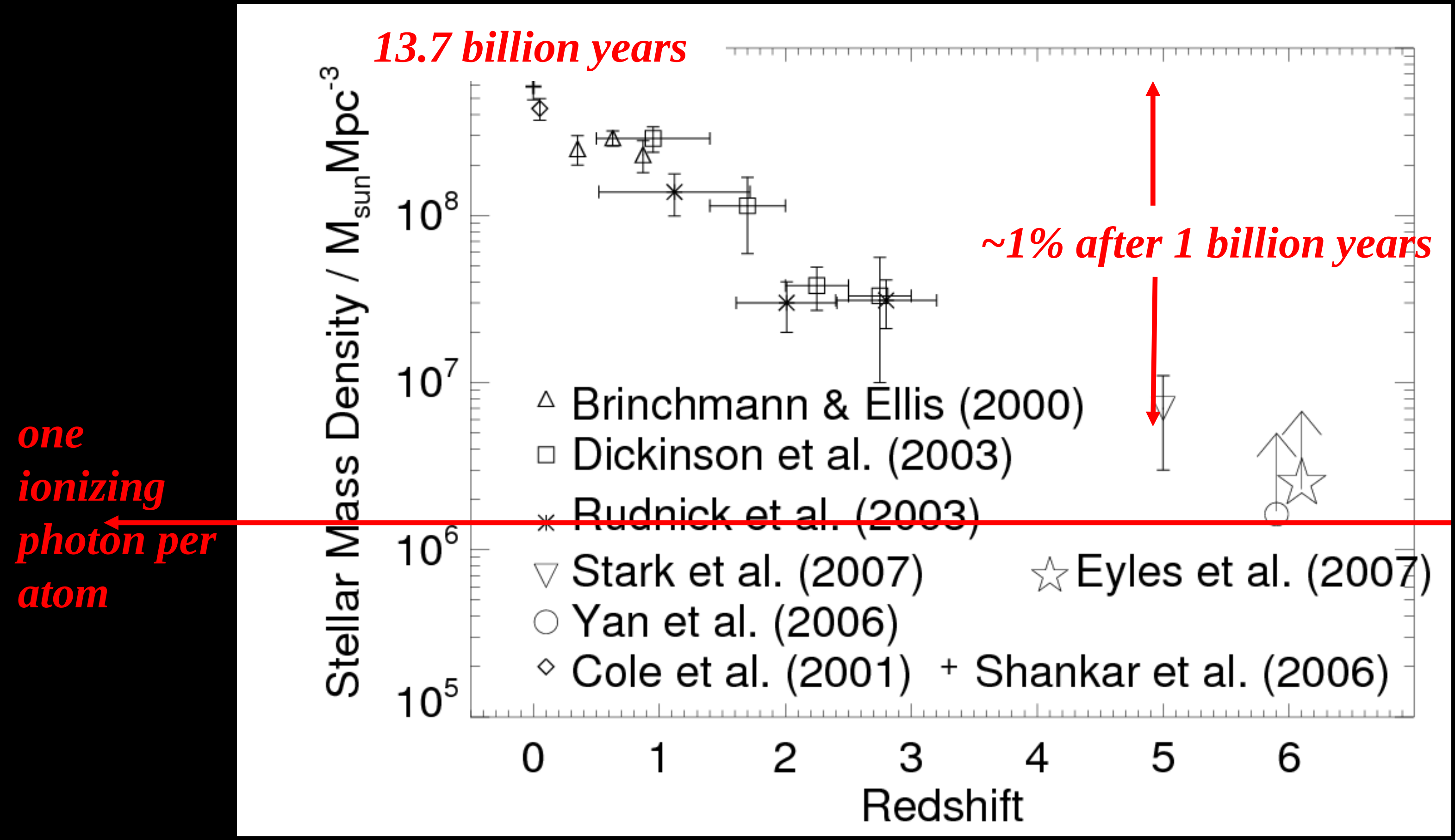
$$\rho_\star \approx 1.7 \times 10^6 f_{\rm esc}^{-1}\ M_\odot {\rm Mpc}^{-3}$$

- 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

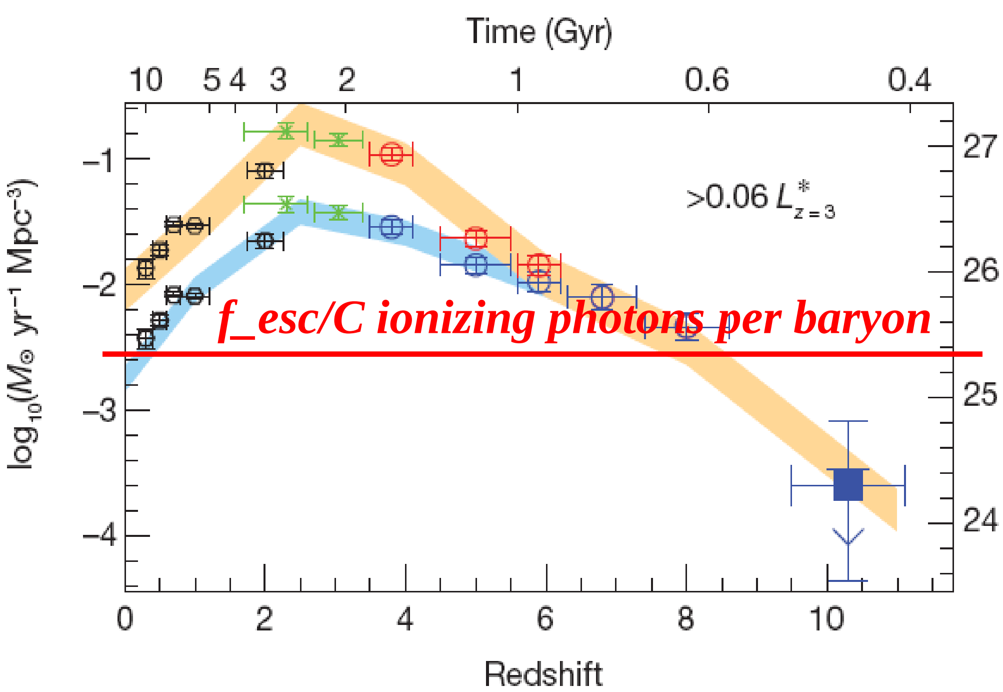
← Time

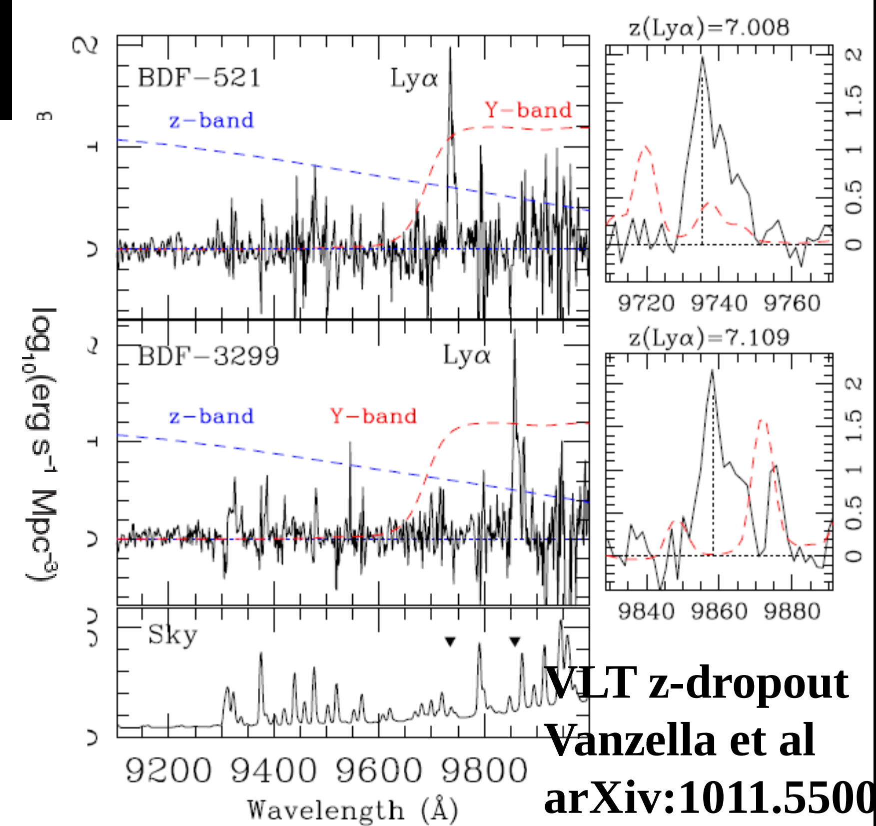


Redshift Record of Observed Galaxies

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

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



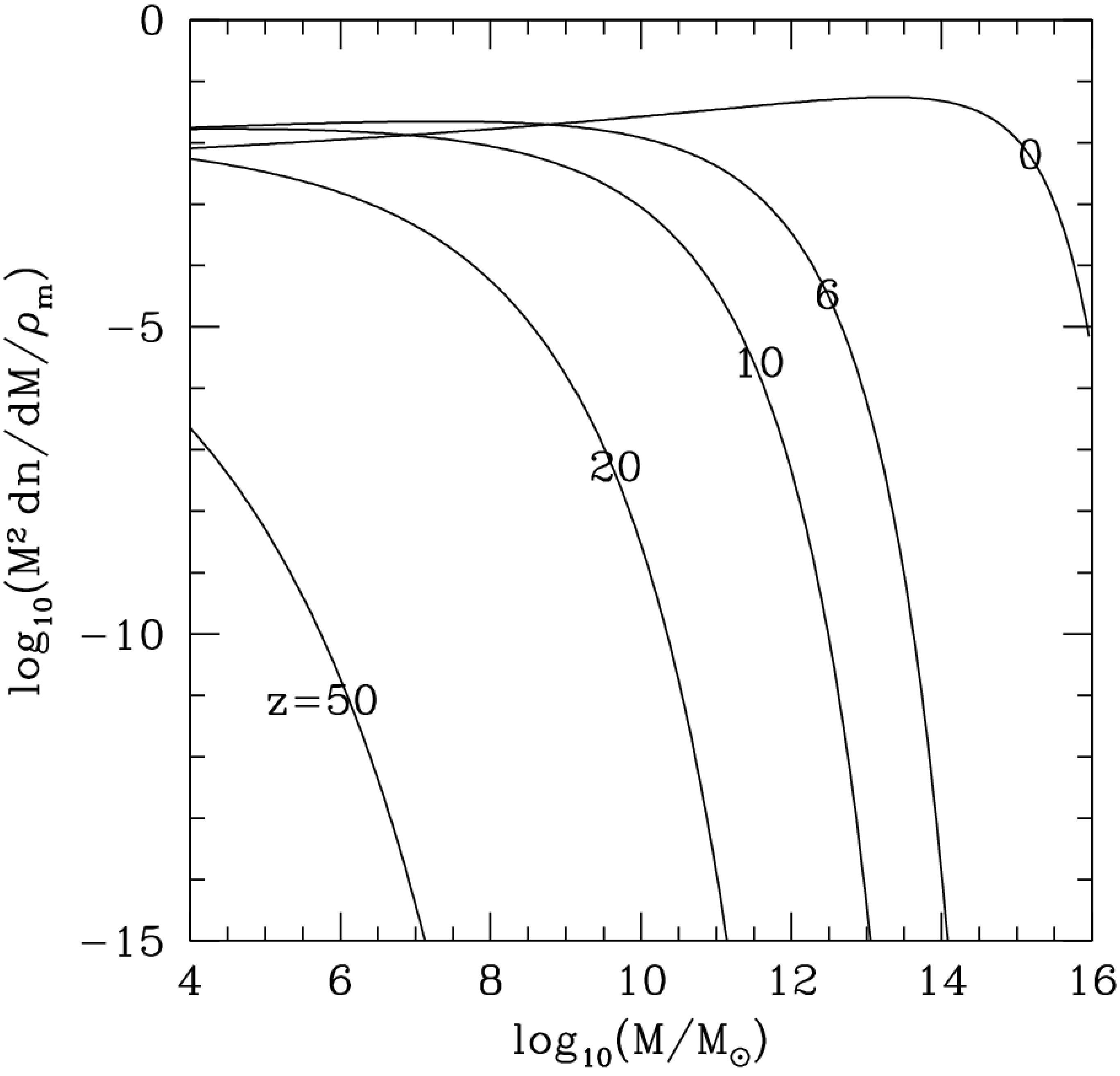


VLT z-dropout
Vanzella et al
arXiv:1011.5500

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)



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

James Webb Space Telescope: Searching for the First Light

Mirror diameter: 6.5 meter

Material: beryllium

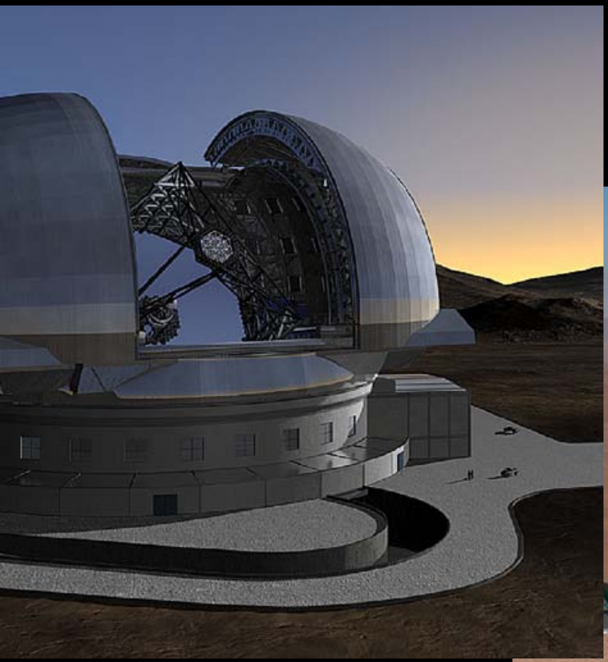
18 segments

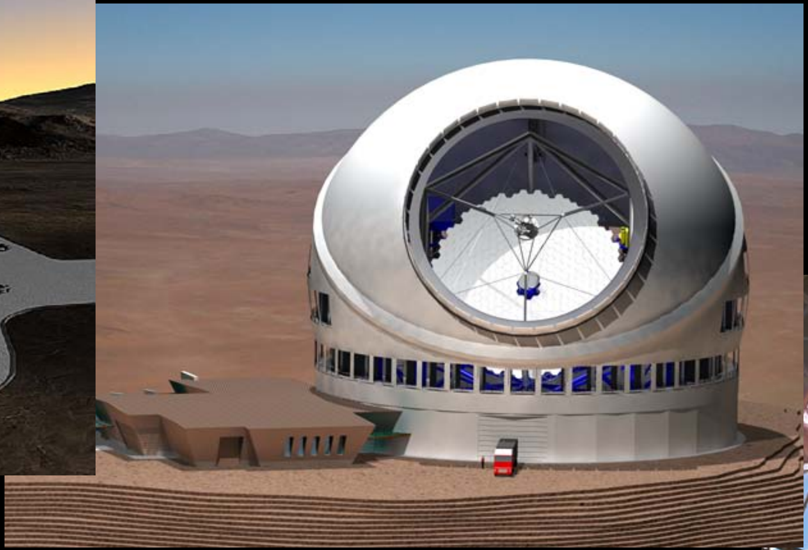
Wavelength coverage: 0.6-28 micron

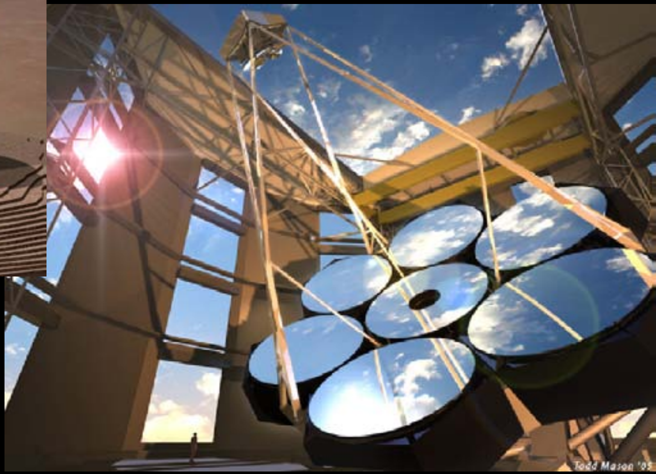
L2 orbit

Launch date: 2018?

Extremely Large Telescopes (24-42 meters)

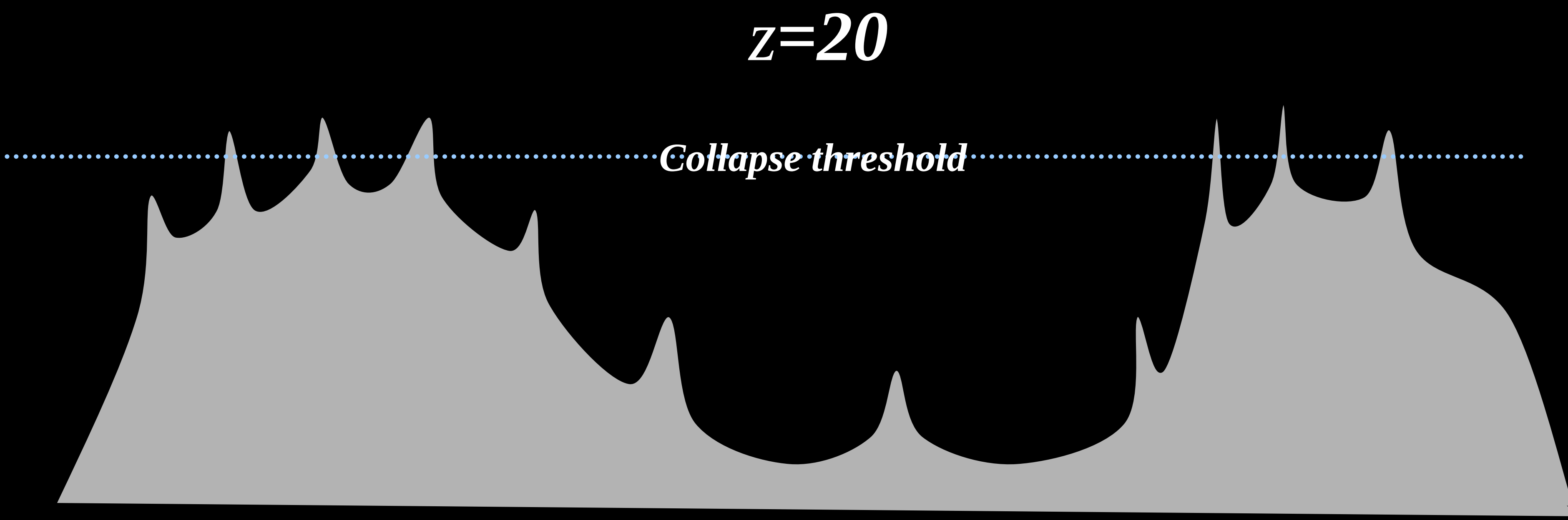




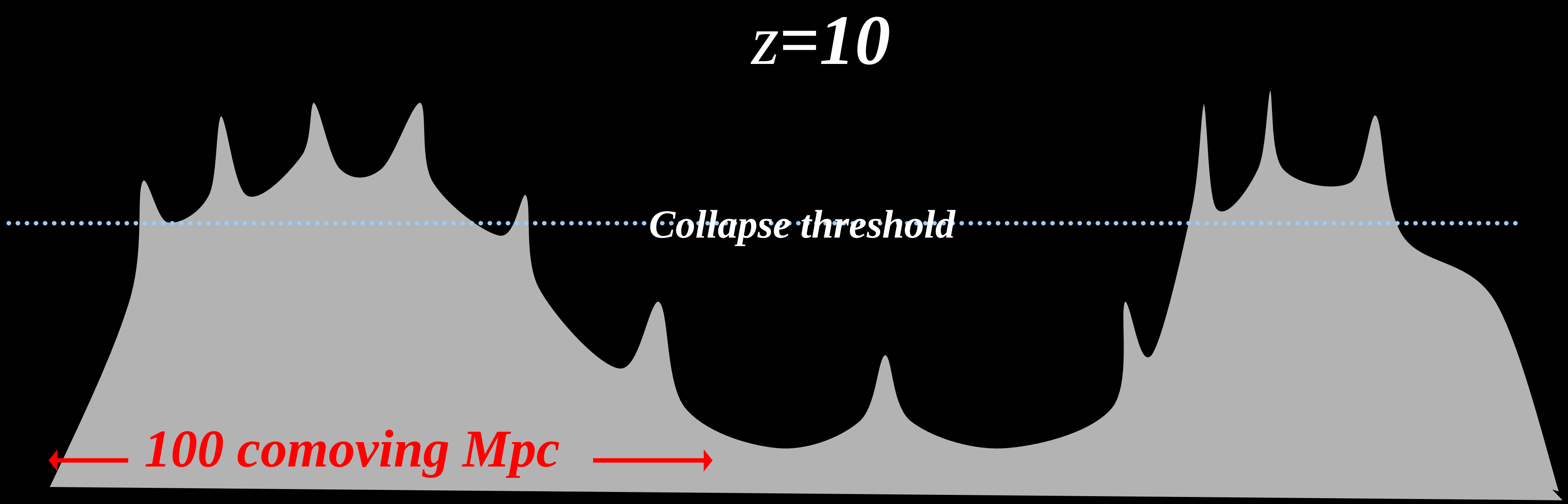


- GMT=Seven mirrors, each 8.4m in diameter
- TMT, EELT – segmented 30,42m aperture

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



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



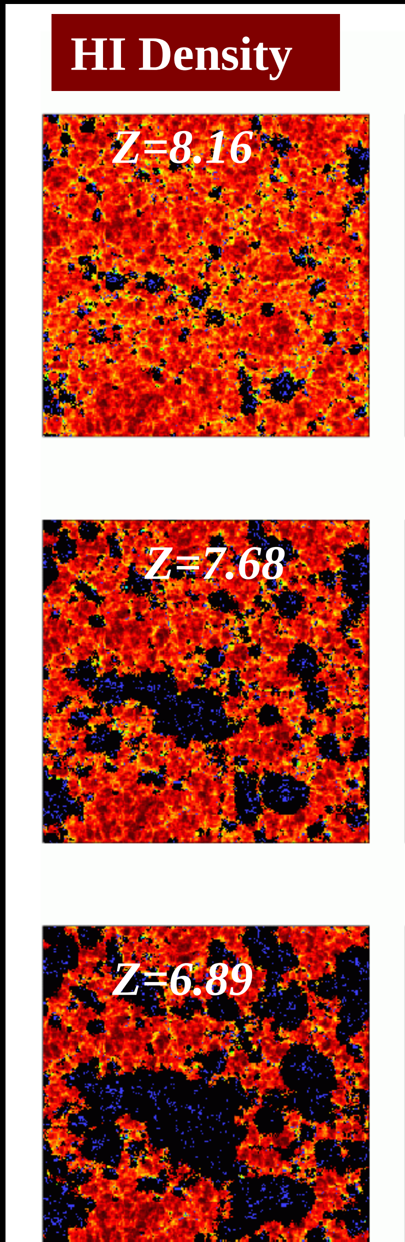
Challenges for numerical simulations of reionization:

**Resolving dwarf galaxies as sources of ionizing photons*

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

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

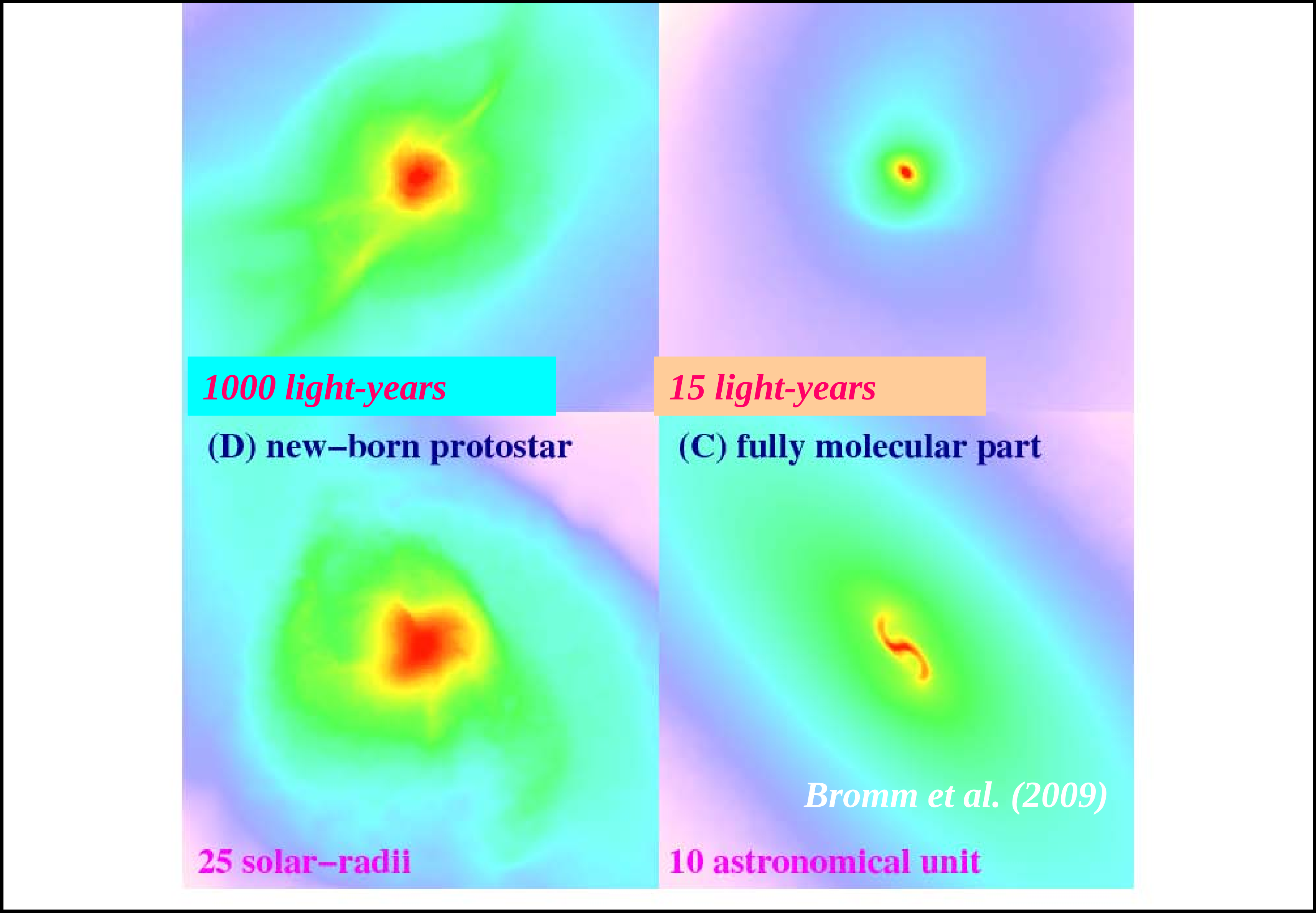
Reionization



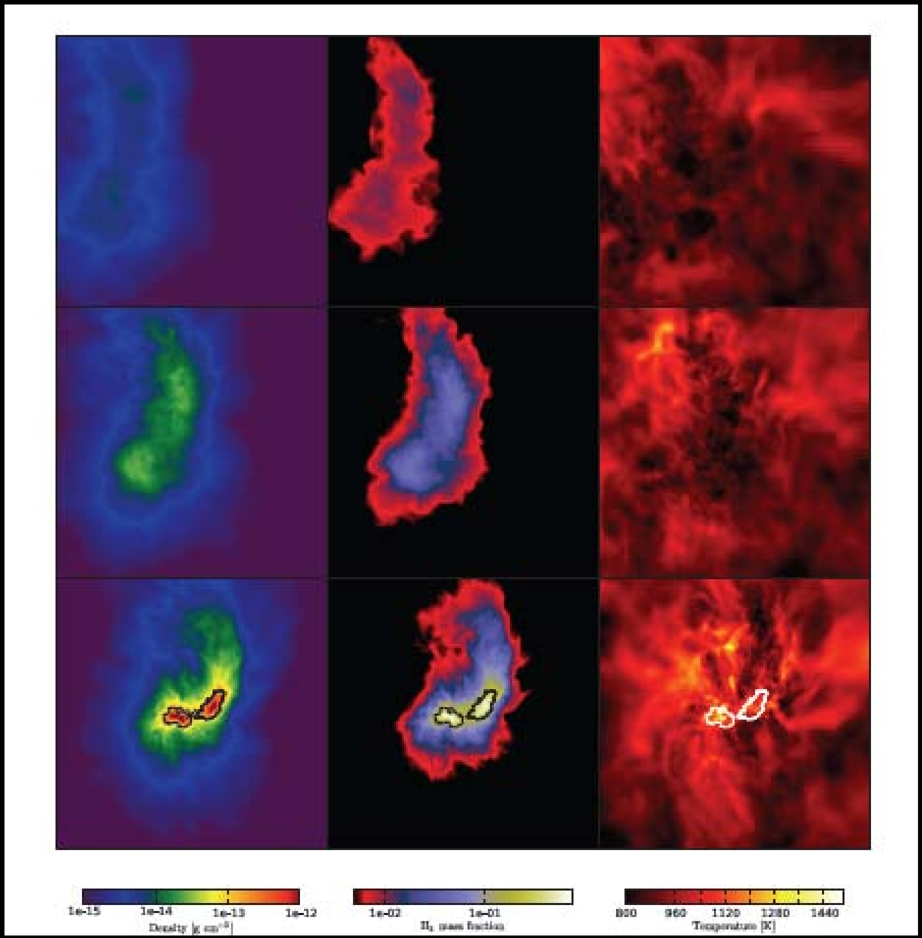
Zahn et al. 2006

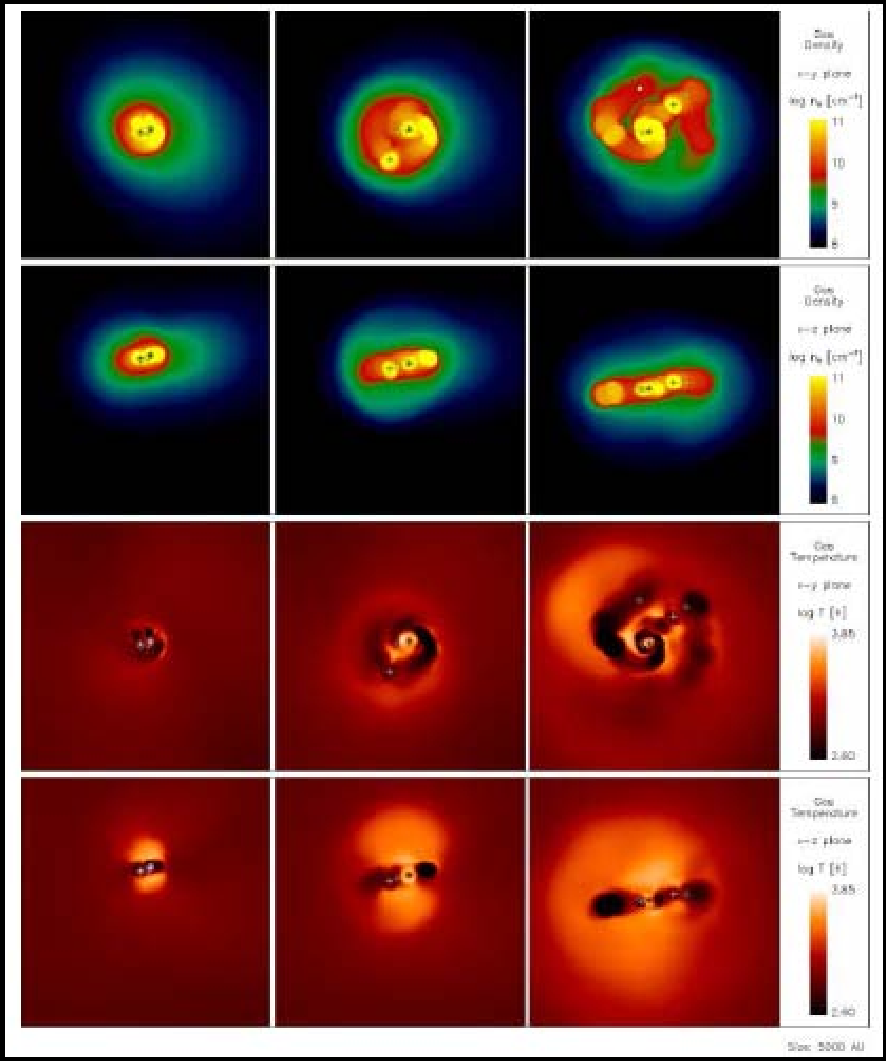
Trac, Cen, & Loeb 2008

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



Population III Binaries

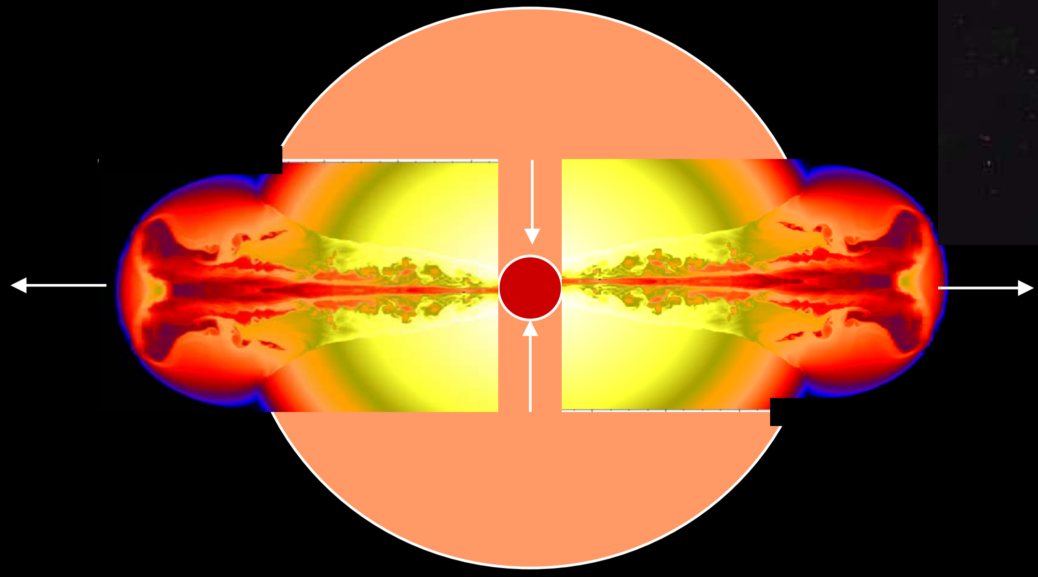




Turk, Abel, & O'Shea 2009

Stacy, Greif, & Bromm 2009

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

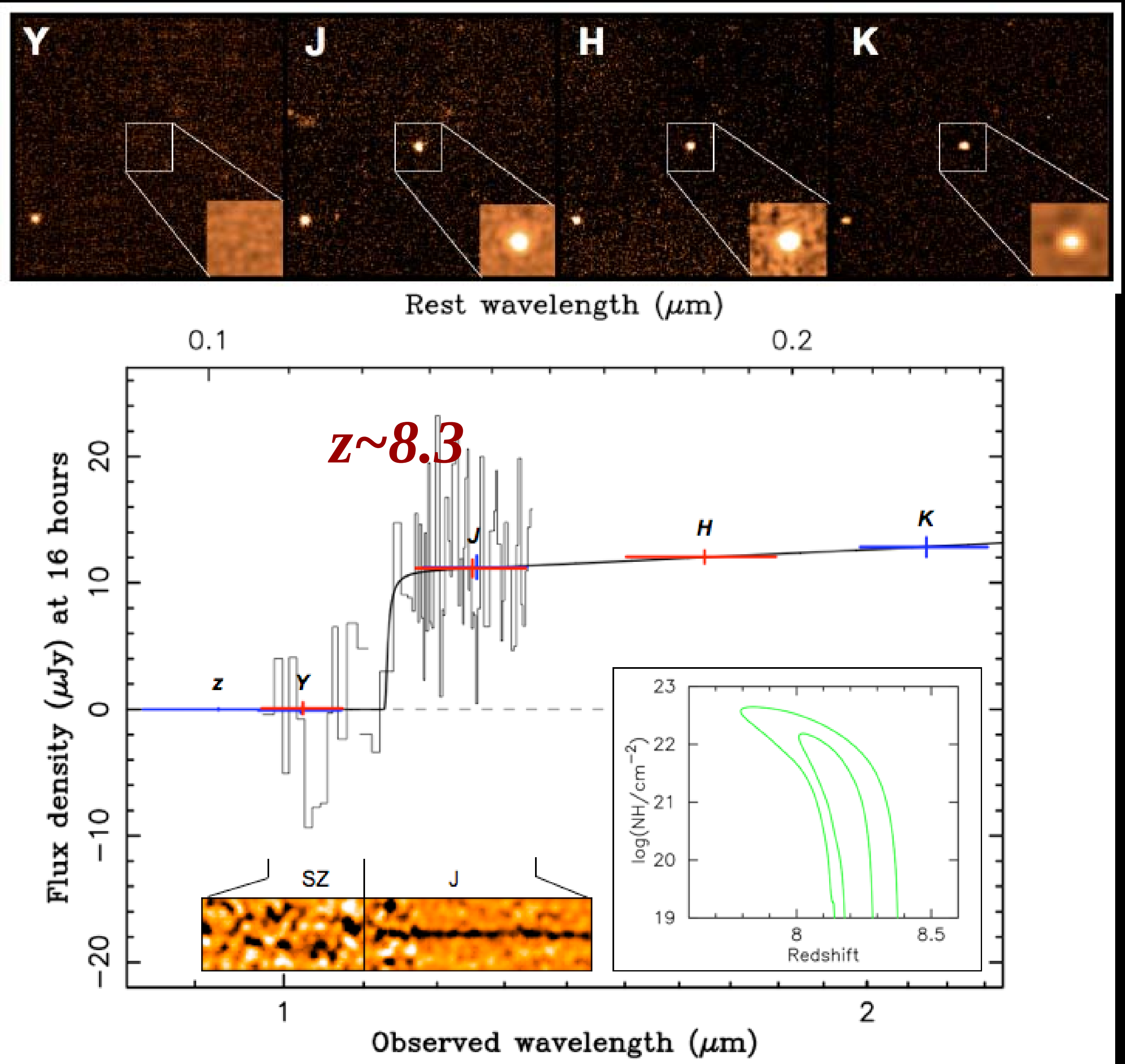


Collapse of a Massive Star

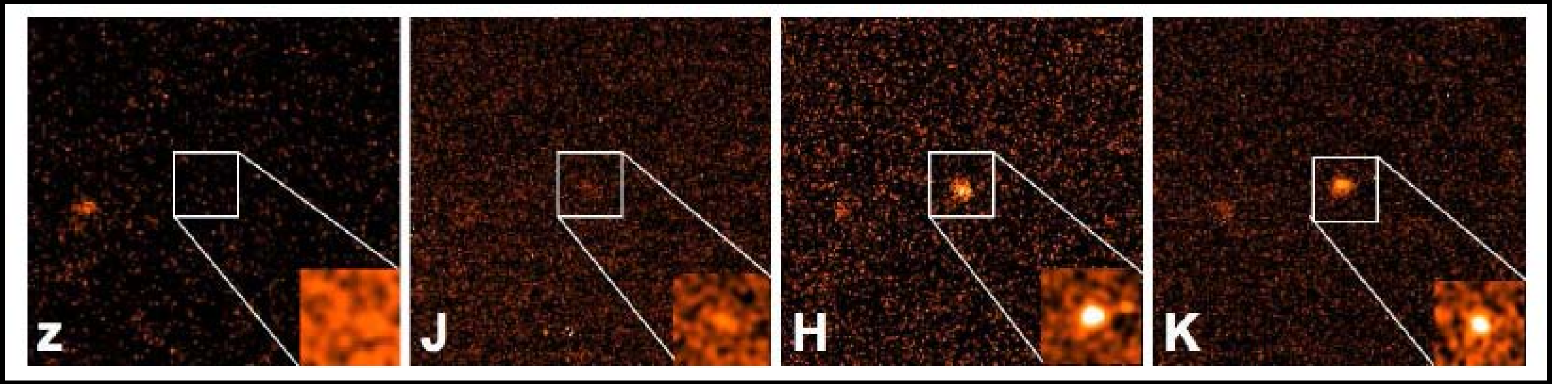
(accompanied by a supernova)

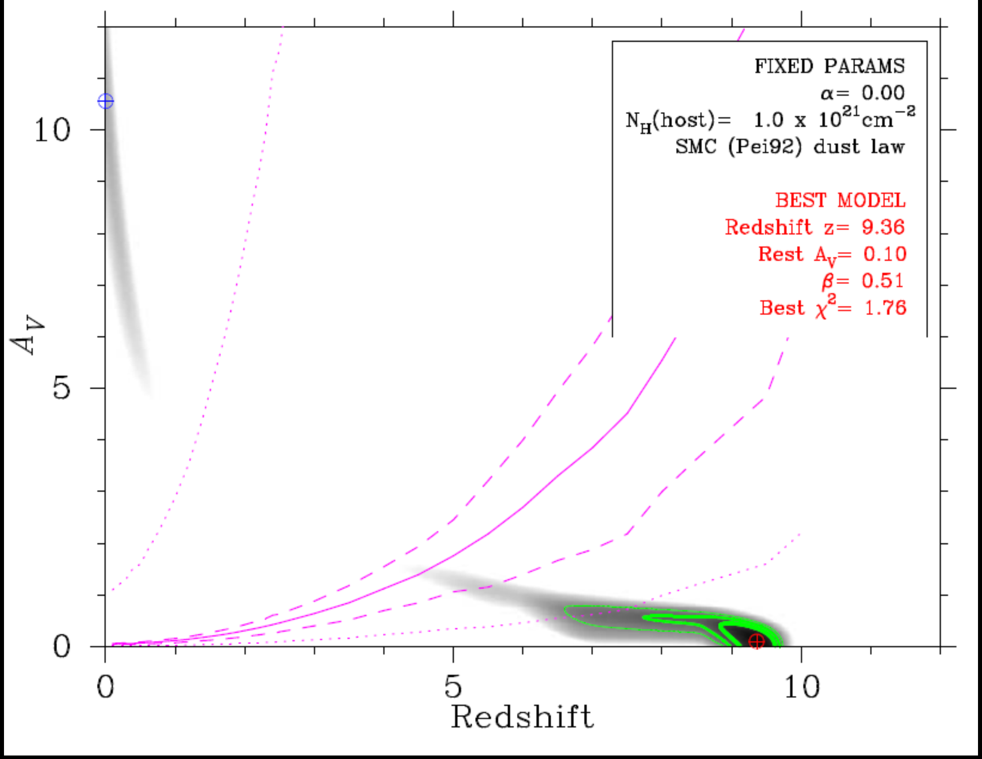
Existing finder: ***Swift;*** **Proposed:** ***JANUS, EXIST (high-z GRBs)***

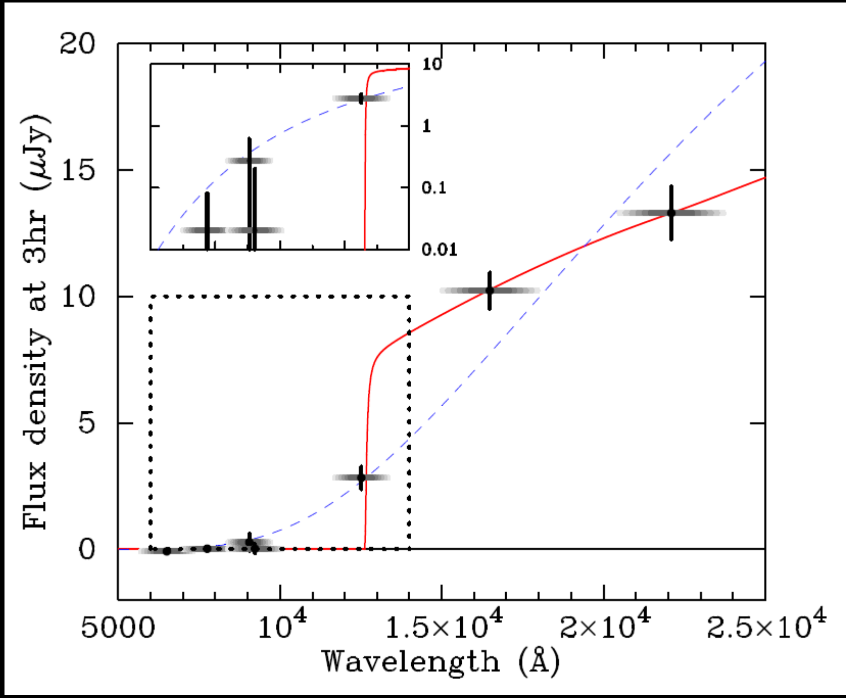
A Bright Explosion 620 Million Years after the Big Bang



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



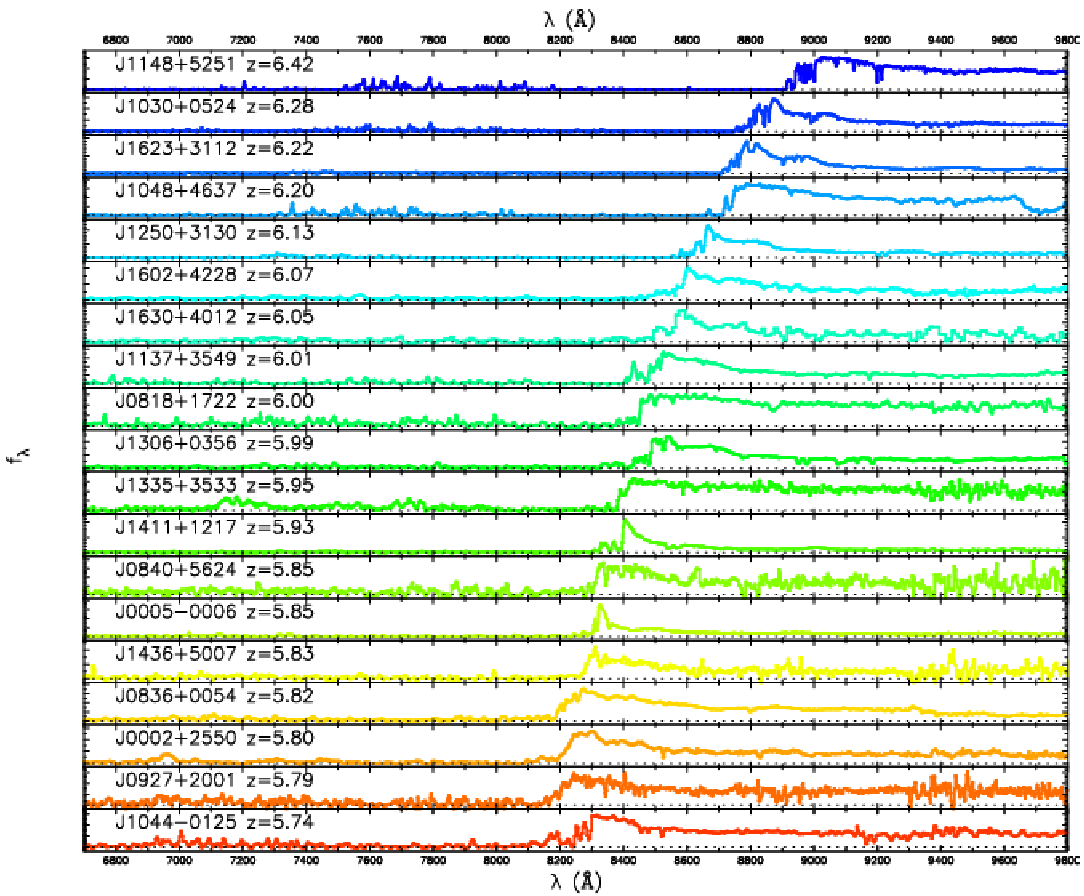




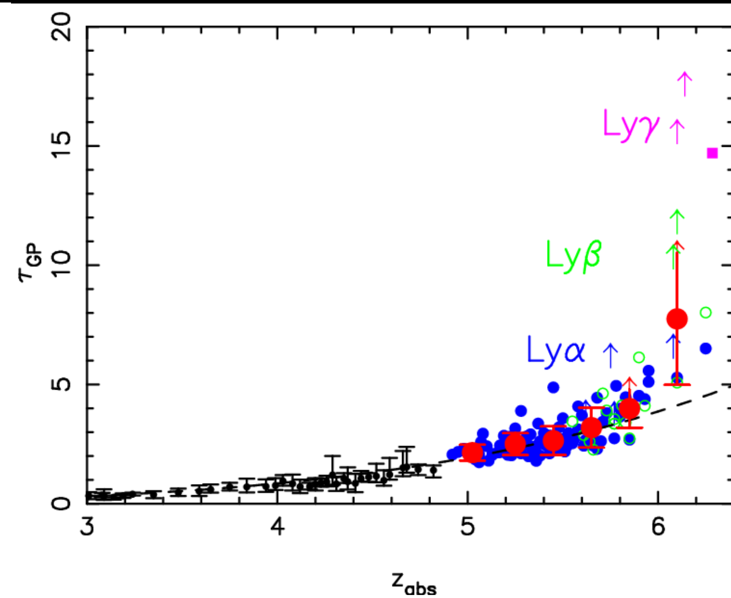
Cucchiara et al. (2011)

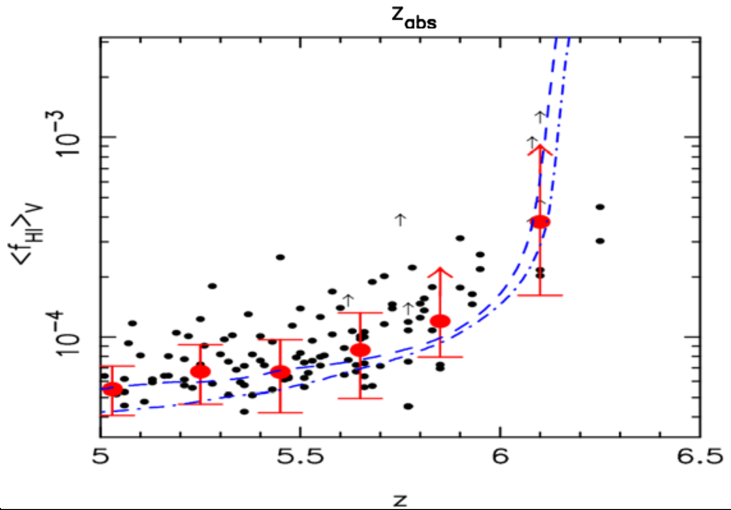
Observing the Diffuse Gas

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.

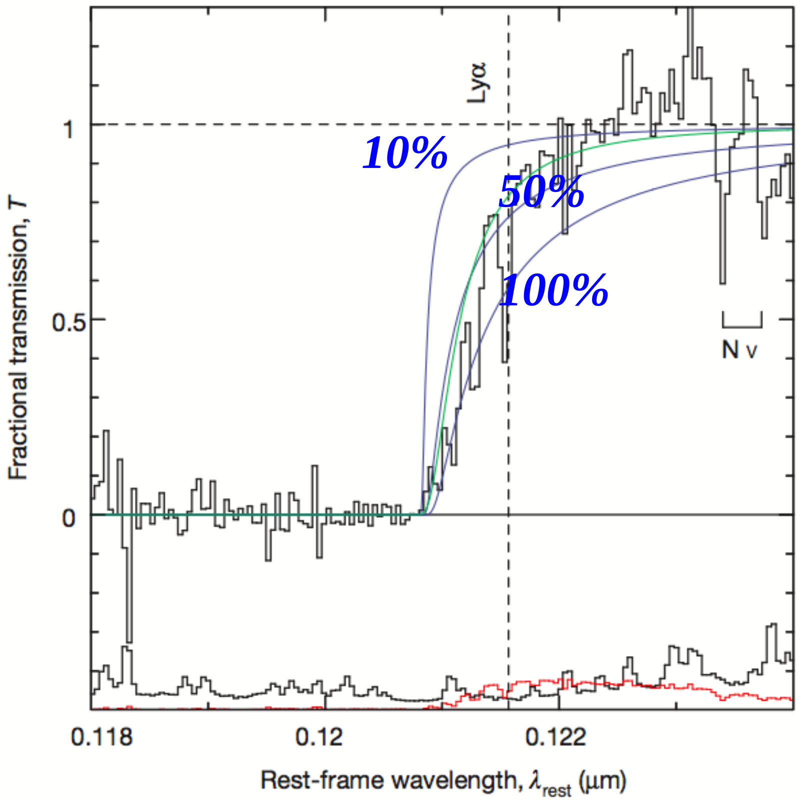


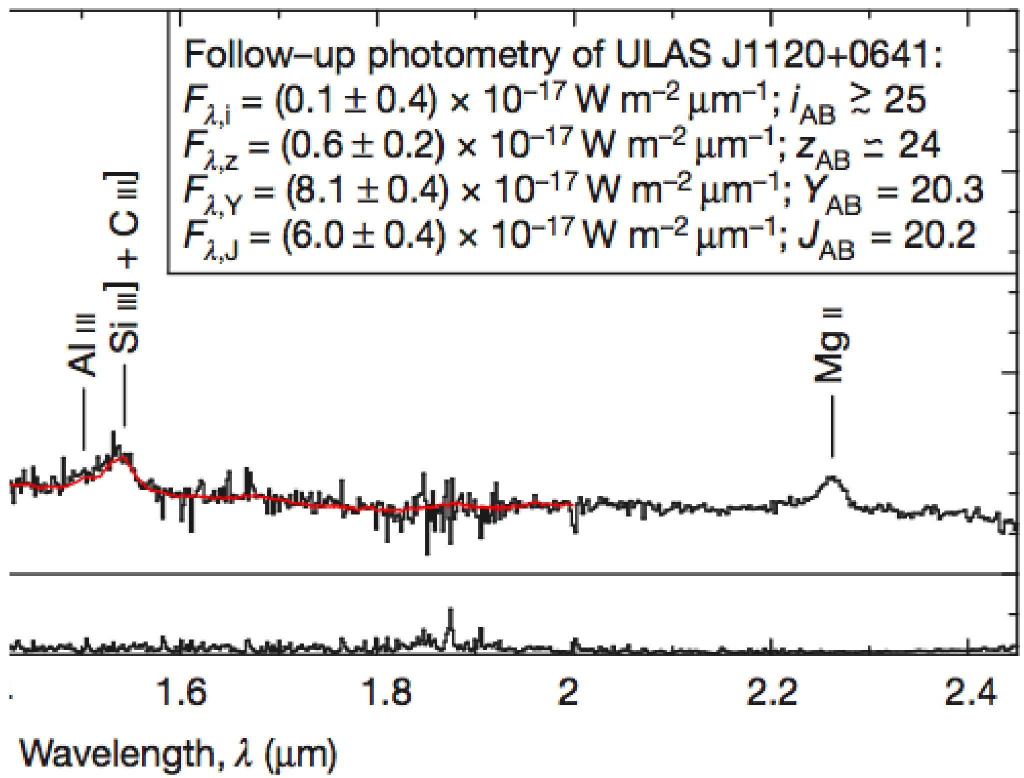


Fan et al. 2005

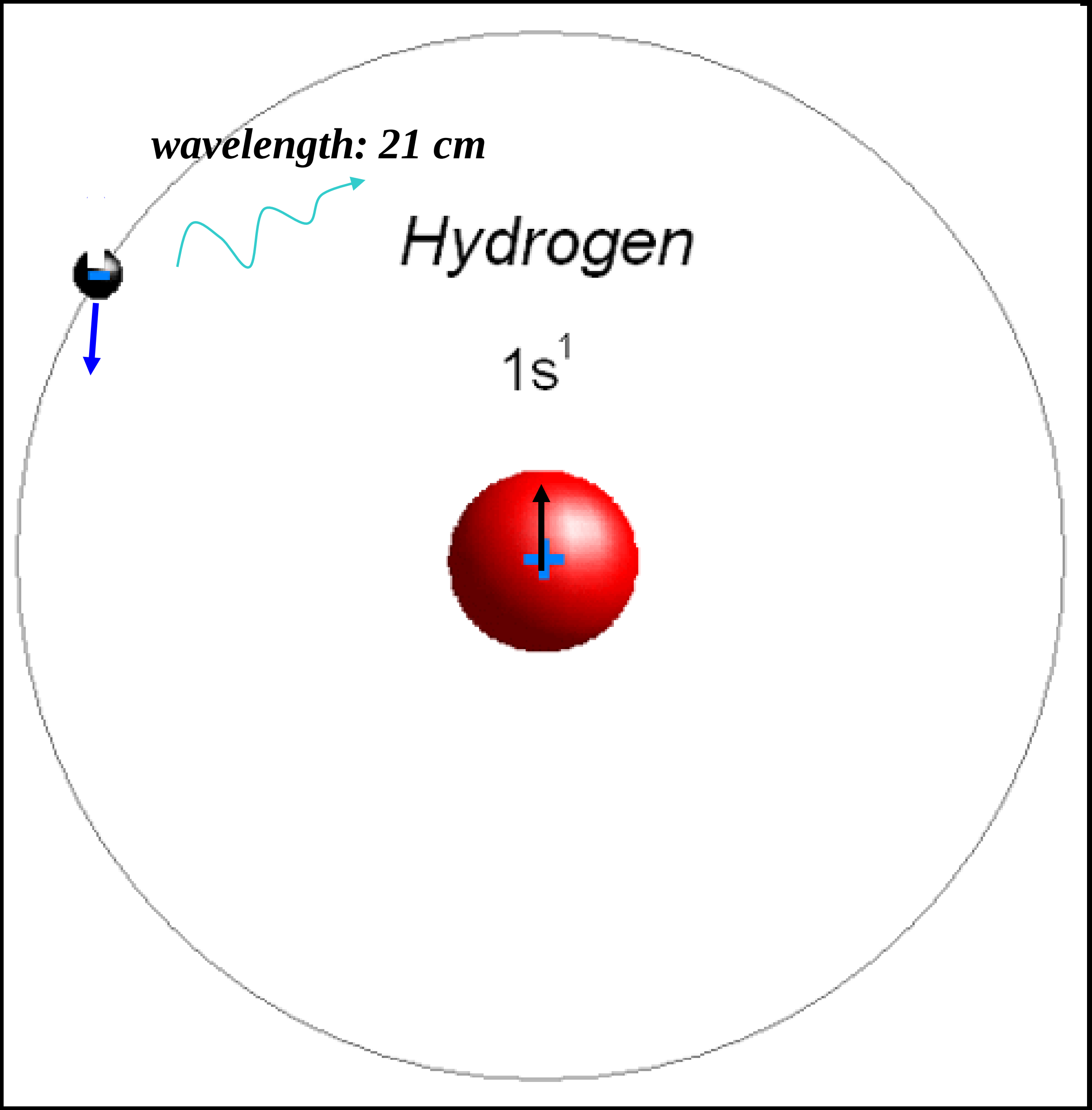
A luminous quasar at a redshift of $z = 7.085$

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]



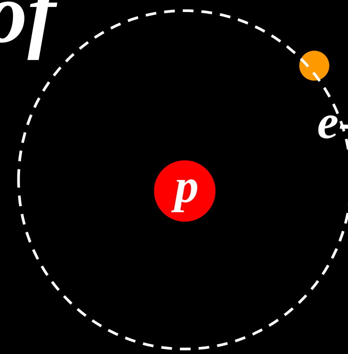


Nature (June 2011)



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

Mapping the Cosmic Distribution of Hydrogen



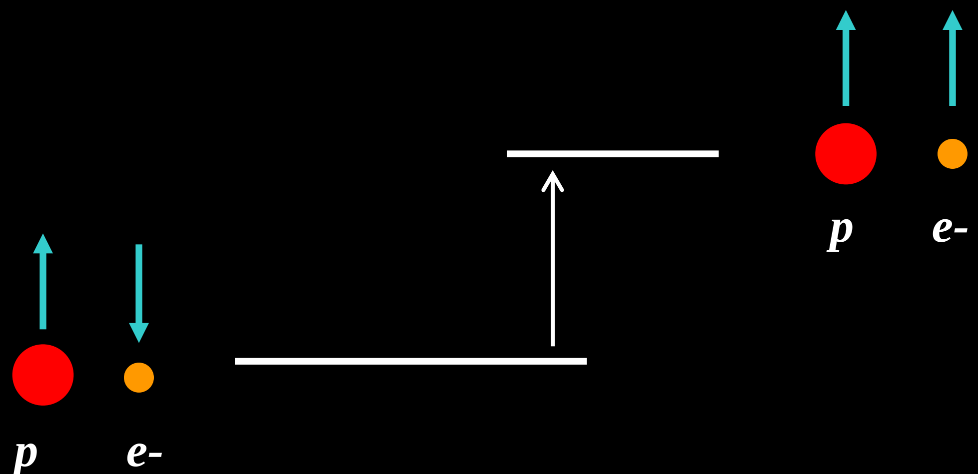
Ground level

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

Couple T_s ***to*** T_k

Couples T_s ***to*** T_γ

spin



$_1S_{1=2}$

$_0S_{1=2}$

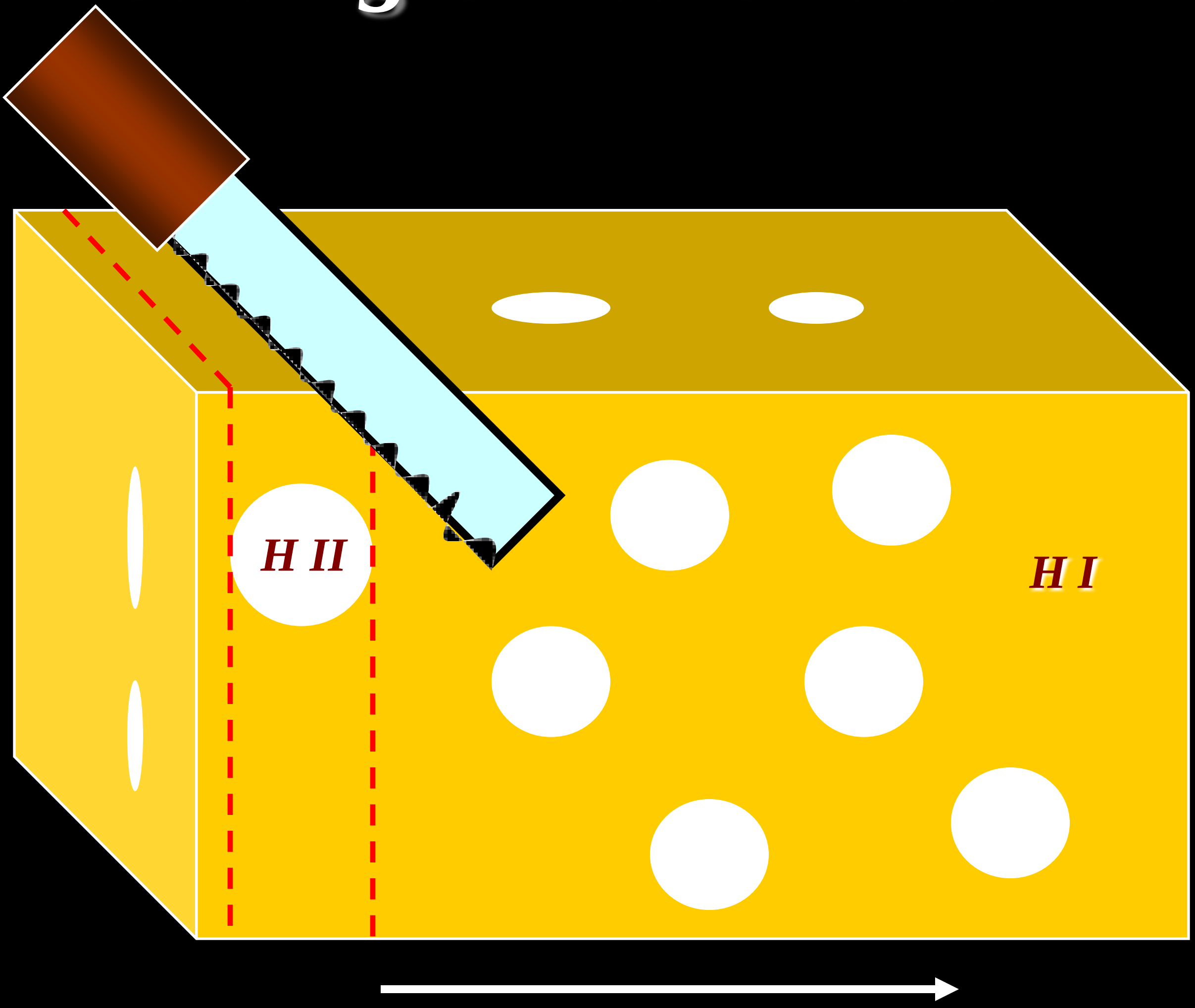
Spin Temperature

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

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

21cm Tomography of Ionized Bubbles During Reionization is like

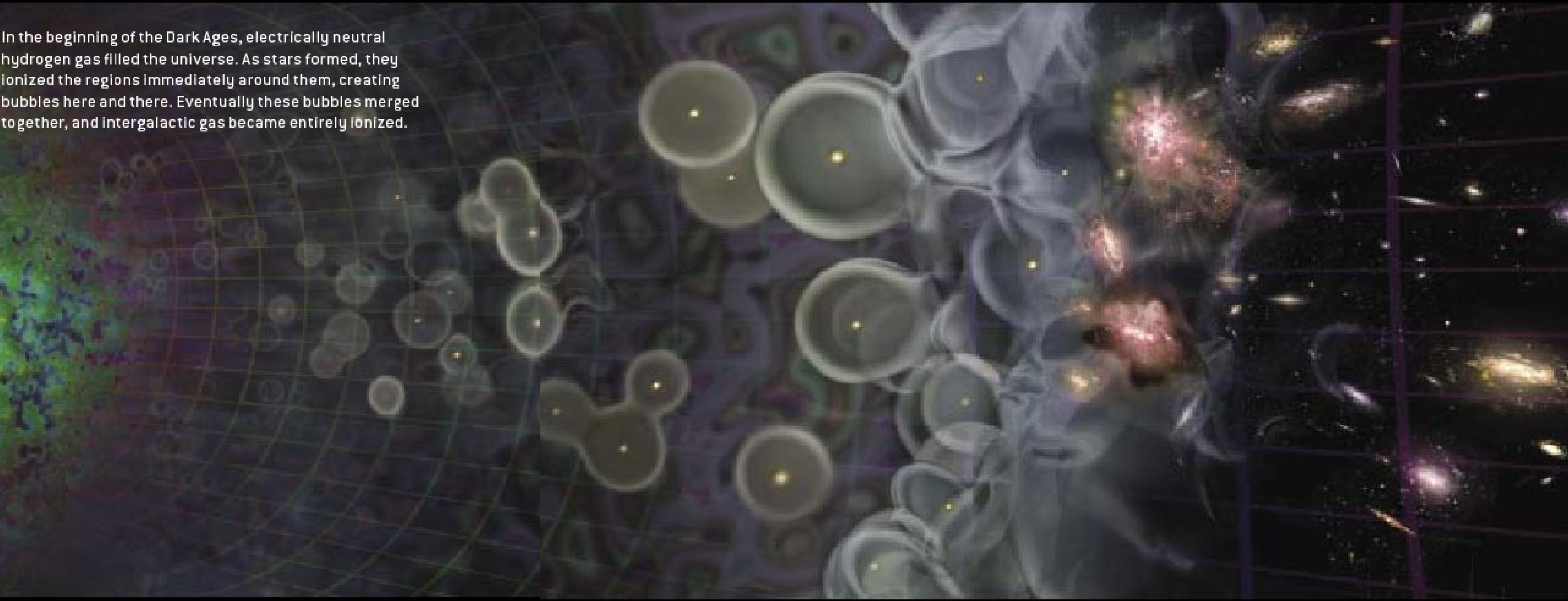
Slicing Swiss Cheese



Observed wavelength ⇔ distance

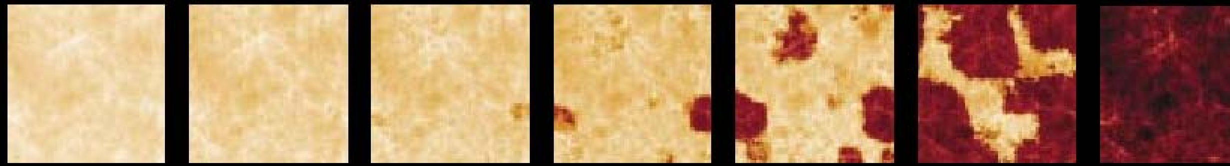
21cm Mapping of Cosmic History in the 21st Century

LIGHTING UP THE COSMOS

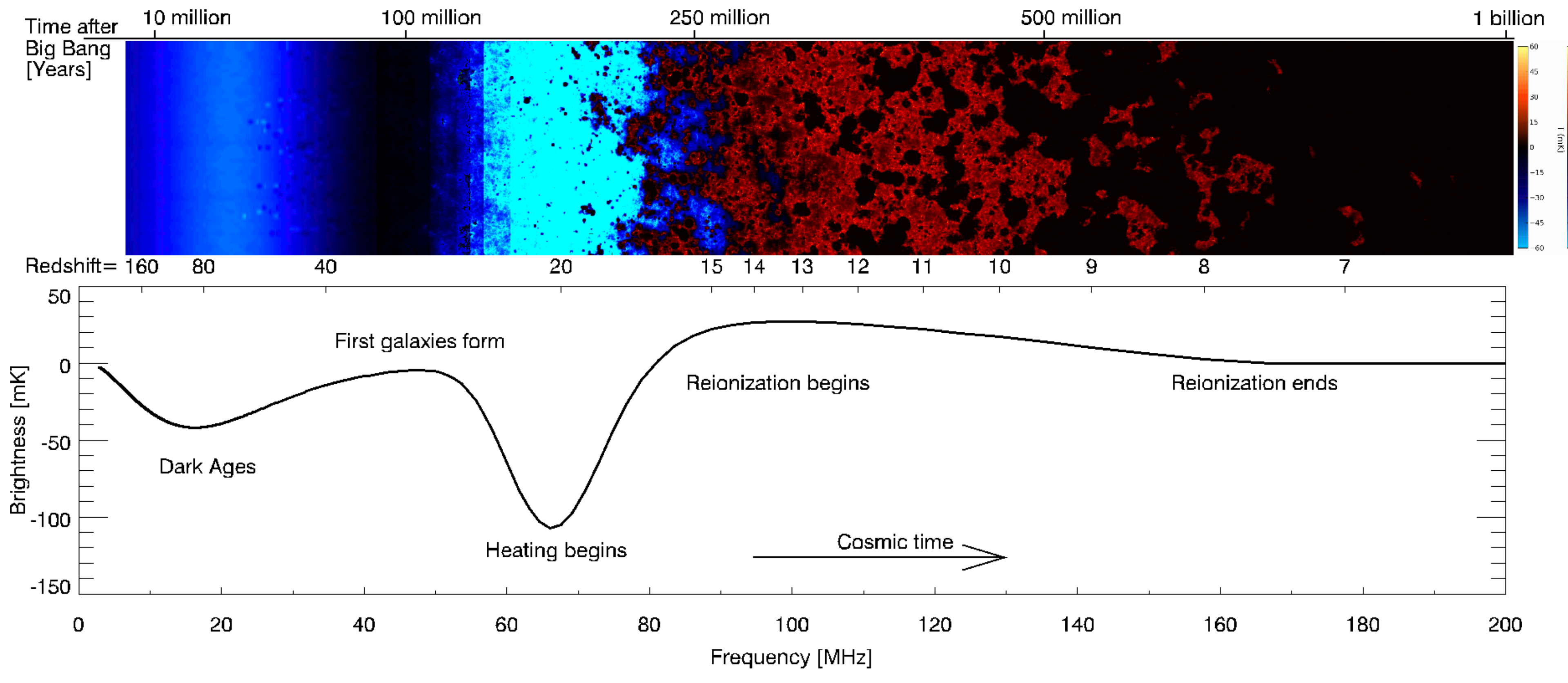


In the beginning of the Dark Ages, electrically neutral hydrogen gas filled the universe. As stars formed, they ionized the regions immediately around them, creating bubbles here and there. Eventually these bubbles merged together, and intergalactic gas became entirely ionized.

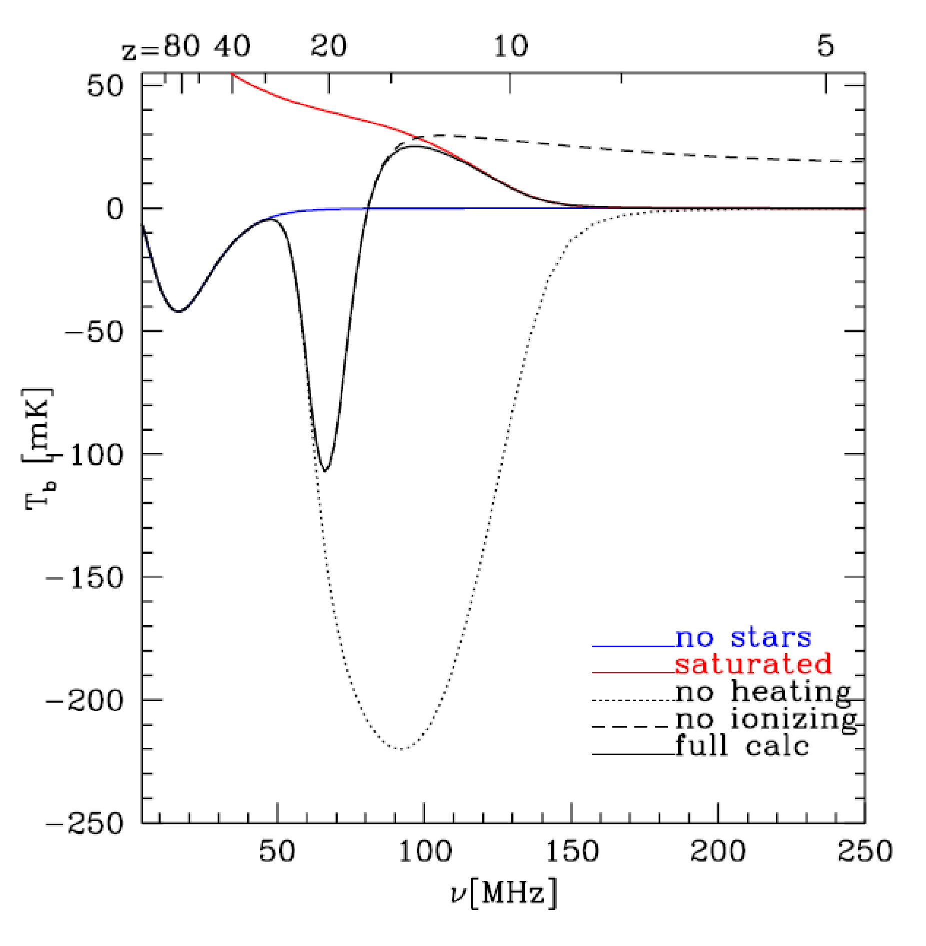
Time:	210 million years	290 million years	370 million years	460 million years	540 million years	620 million years	710 million years
Width of frame:	2.4 million light-years	3.0 million light-years	3.6 million light-years	4.1 million light-years	4.6 million light-years	5.0 million light-years	5.5 million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

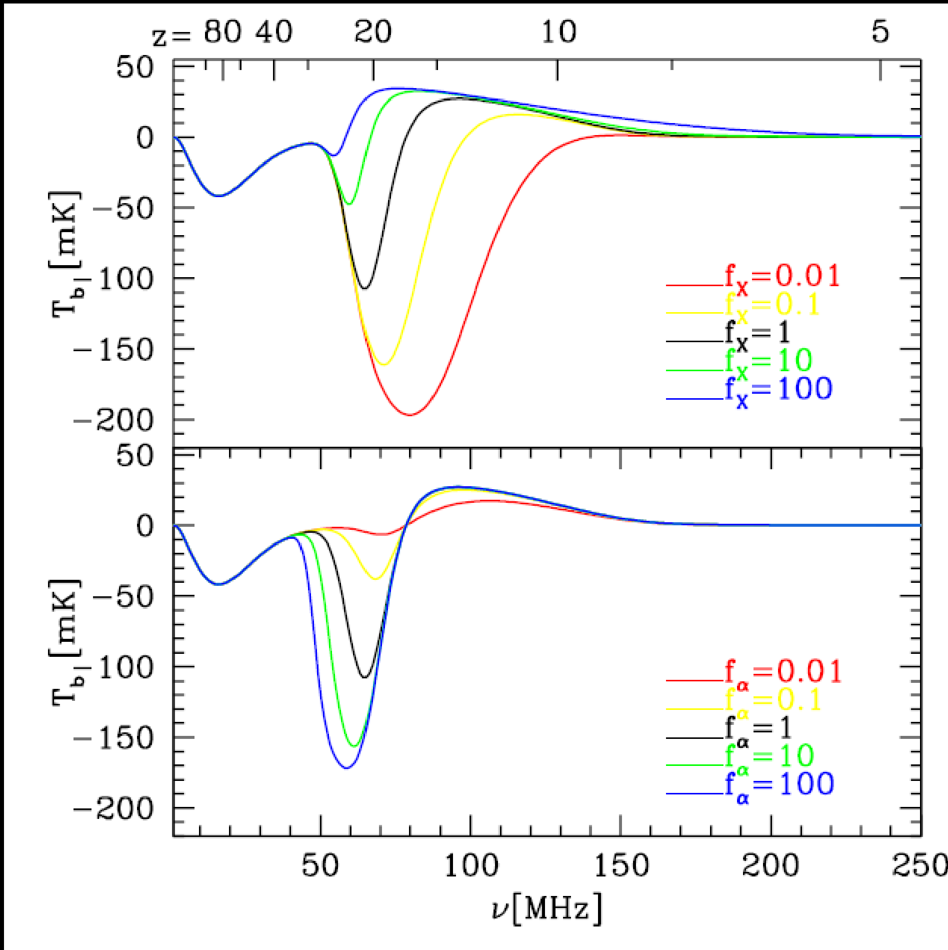


Simulated images of 21-centimeter radiation show how hydrogen gas turns into a galaxy cluster. The amount of radiation (*white is highest; orange and red are intermediate; black is least*) reflects both the density of the gas and its degree of ionization: dense, electrically neutral gas appears white; 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.


Time after
Big Bang
[Years]
10 million
100 million
250 million
500 million
1 billion
Redshift=
160
80
40
20
15
14
13
12
11
10
9
8
7
50
0
-50
-100
-150
Brightness [mK]
First galaxies form
Dark Ages
Heating begins
Reionization begins
Reionization ends
Cosmic time
0
20
40
60
80
100
120
140
160
180
200
Frequency [MHz]

The Global 21-cm Signal

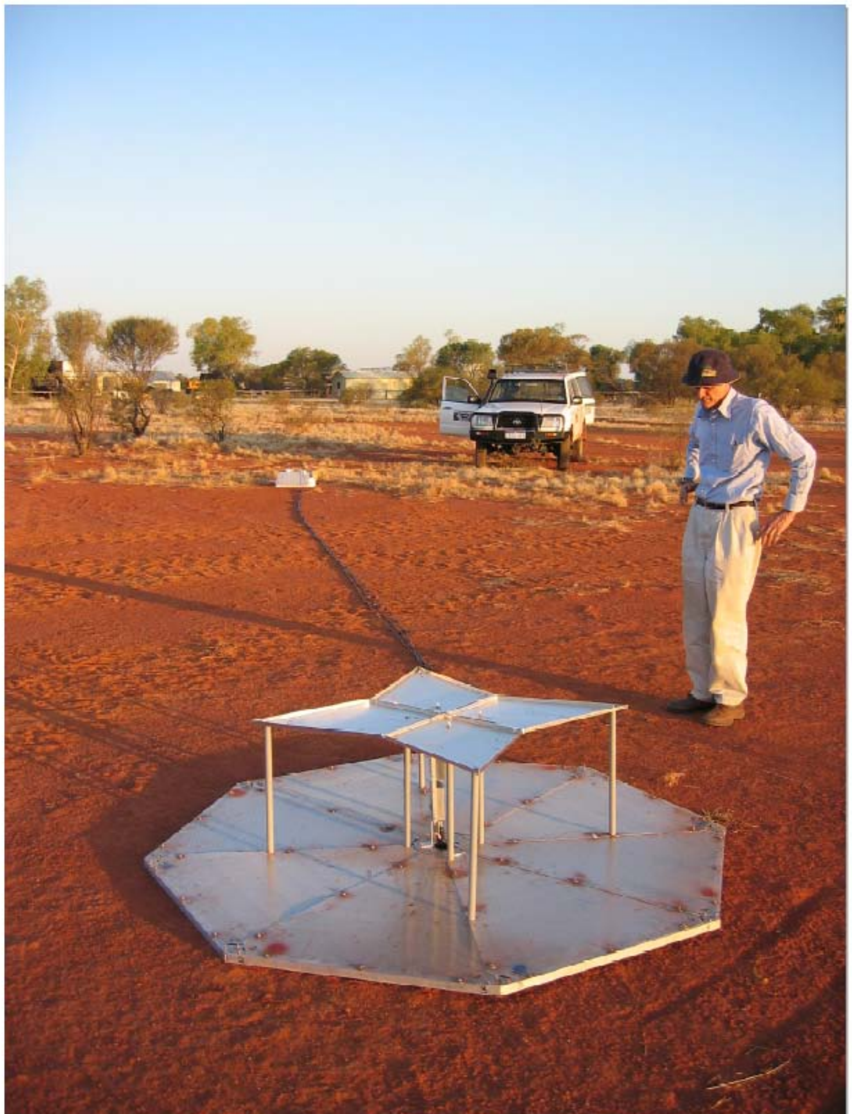


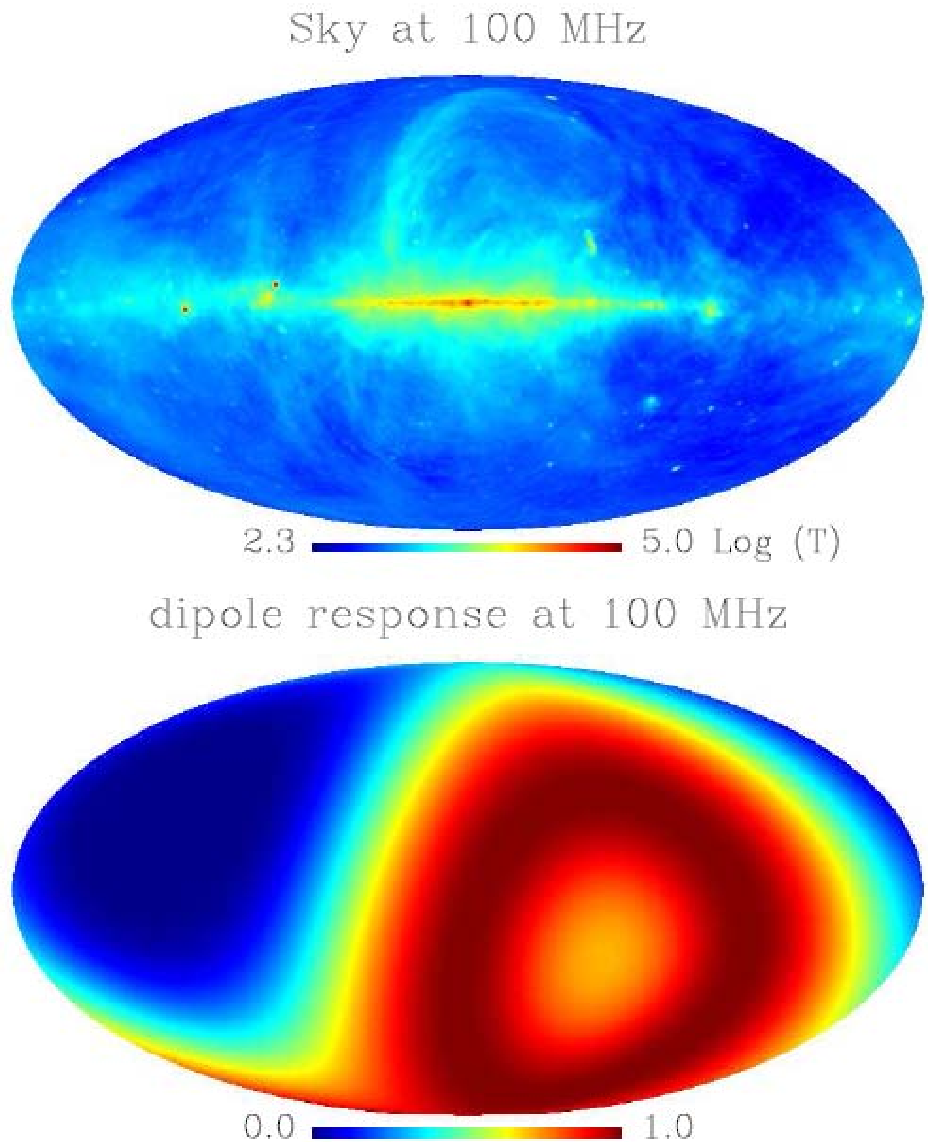


(Pritchard & Loeb, Phys. Rev. D, 2010)

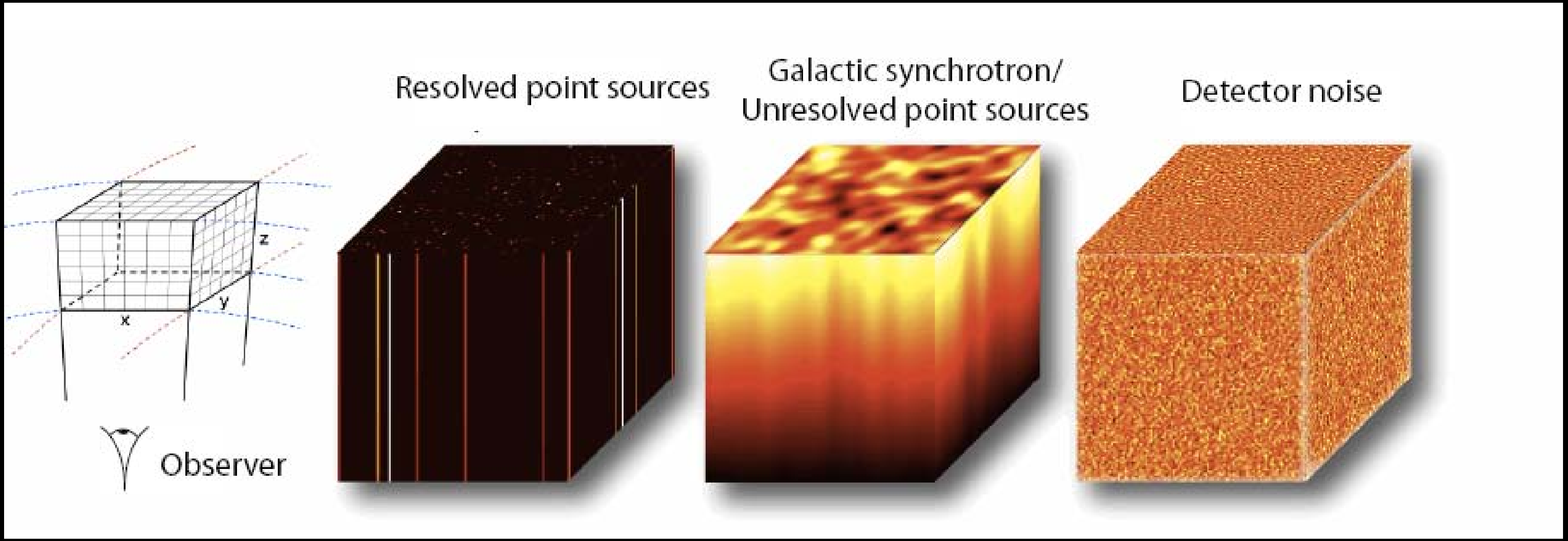
The EDGES Experiment

The Experiment to Detect the Global EOR Signature (EDGES)



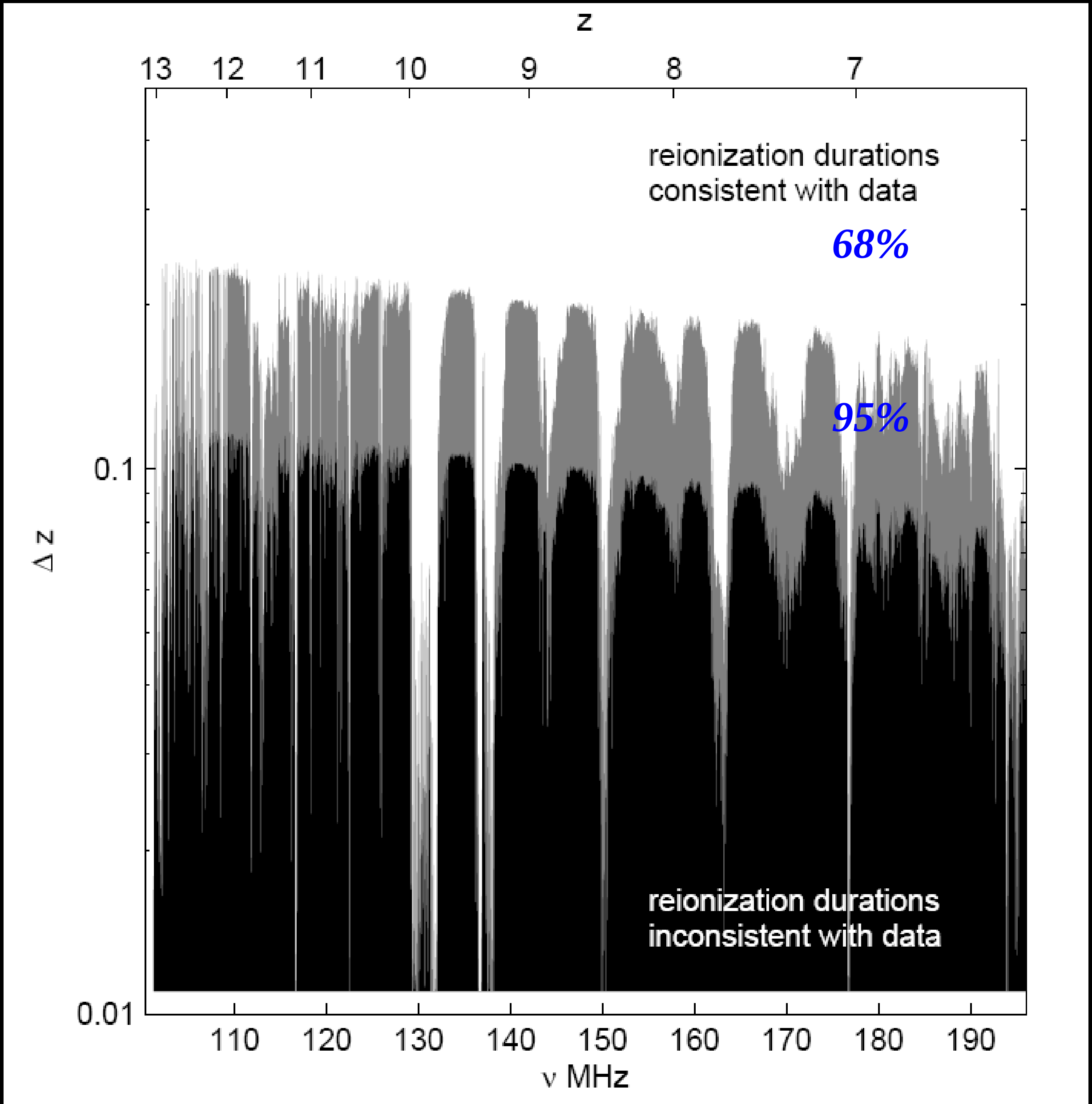


Foregrounds



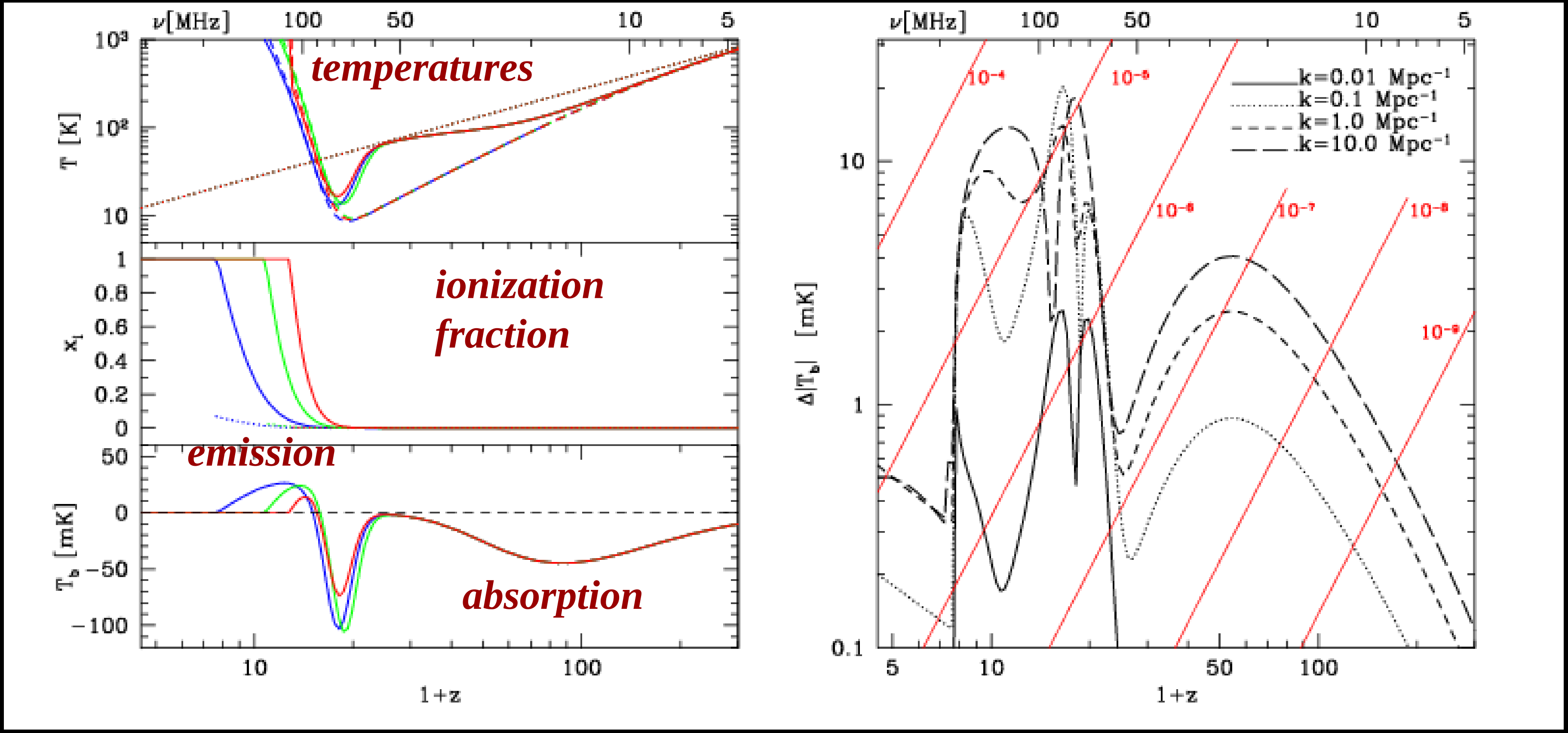
Liu & Tegmark (2011)

Reionization Was Not Abrupt!



Bowman & Rogers 2010

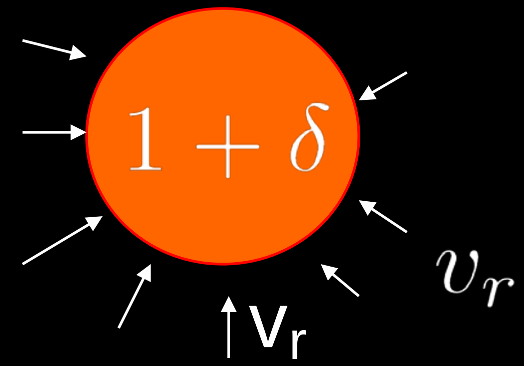
21-cm Tomography throughout Cosmic History



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

Line-of-Sight Anisotropy of 21cm Flux Fluctuations

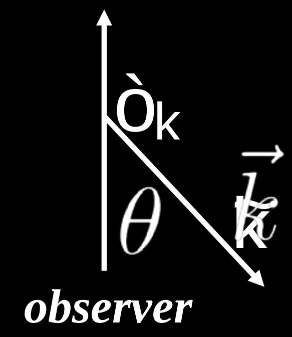
$$T_b = \frac{\tau}{(1+z)}(T_s - T_{\rm CMB})$$



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

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

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



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

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

Barkana & Loeb 2004; see also Bharadwaj & Ali 2004

Experiments

*MWA (Murchison Wide-Field Array)

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

*LOFAR (Low-frequency Array)

Netherlands/Europe

*21CMA (formerly known as PAST)

China

*PAPER

UCB

*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 area; few arcmin resolution

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**

When Was the Universe Ionized?

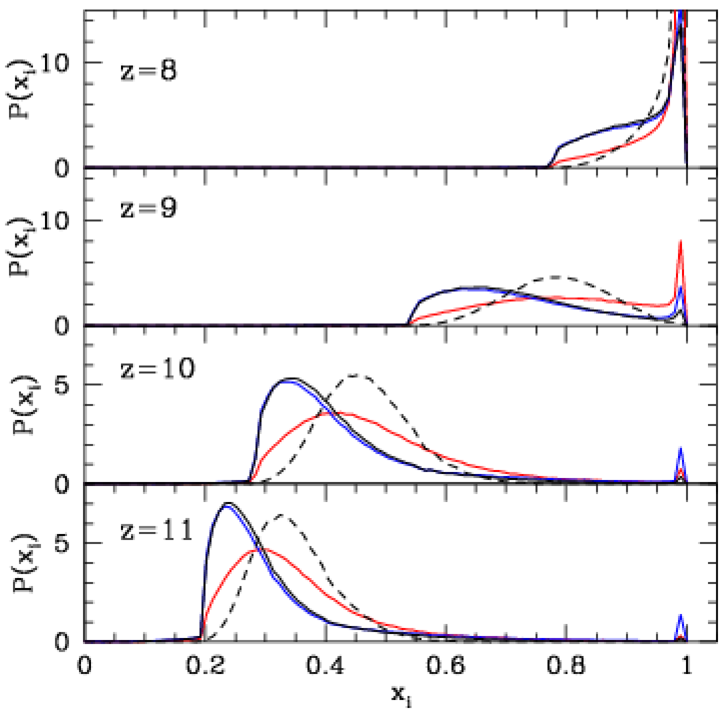


Figure 5. Distribution of x_i at redshifts $z = 8$, 9, 10, and 11 for the ζ parametrization. Same curve styles as for Figure 4.

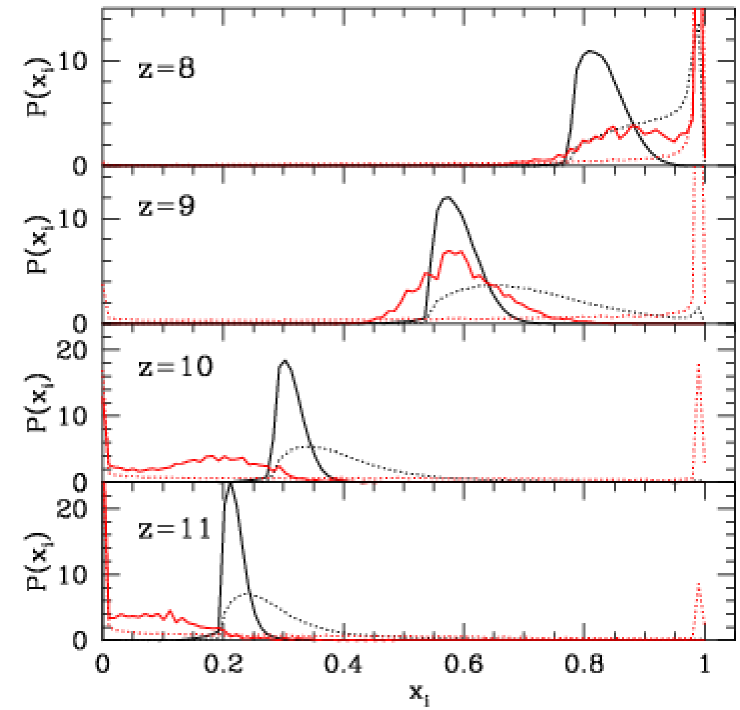


Figure 14. Distribution of x_i at redshifts $z = 8$, 9, 10, and 11 when 21 cm measurements are included. In each panel, we plot the distribution of the ζ (black) and $\dot{N}_{\rm ion}$ (red) parametrizations with (solid curves) and without (dotted curves) a 21 cm measurement of $x_i(z = 9.5) = 0.5 \pm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

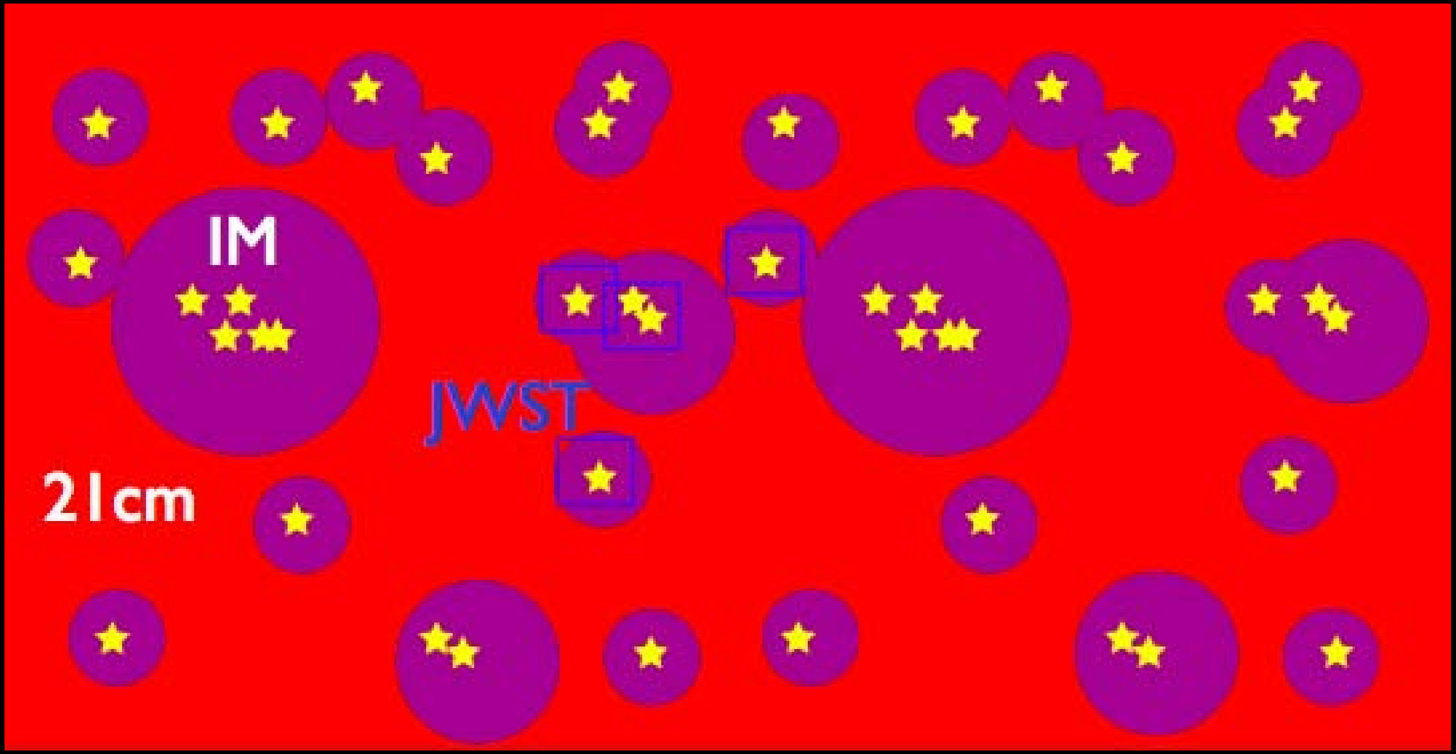
- Based on Lya forest at z<6 and CMB data

Pritchard, Loeb, & Wyithe, arXiv:0908.3891

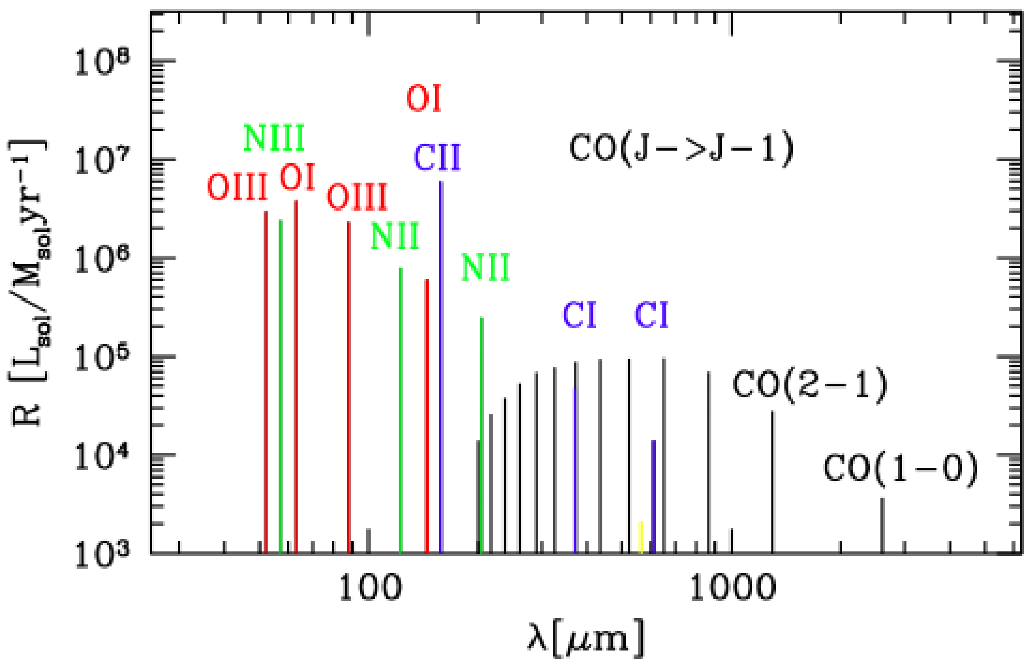
Intensity Mapping of Other Lines

(without resolving individual galaxies)

Galaxy surveys, Intensity Mapping and 21-cm Mapping

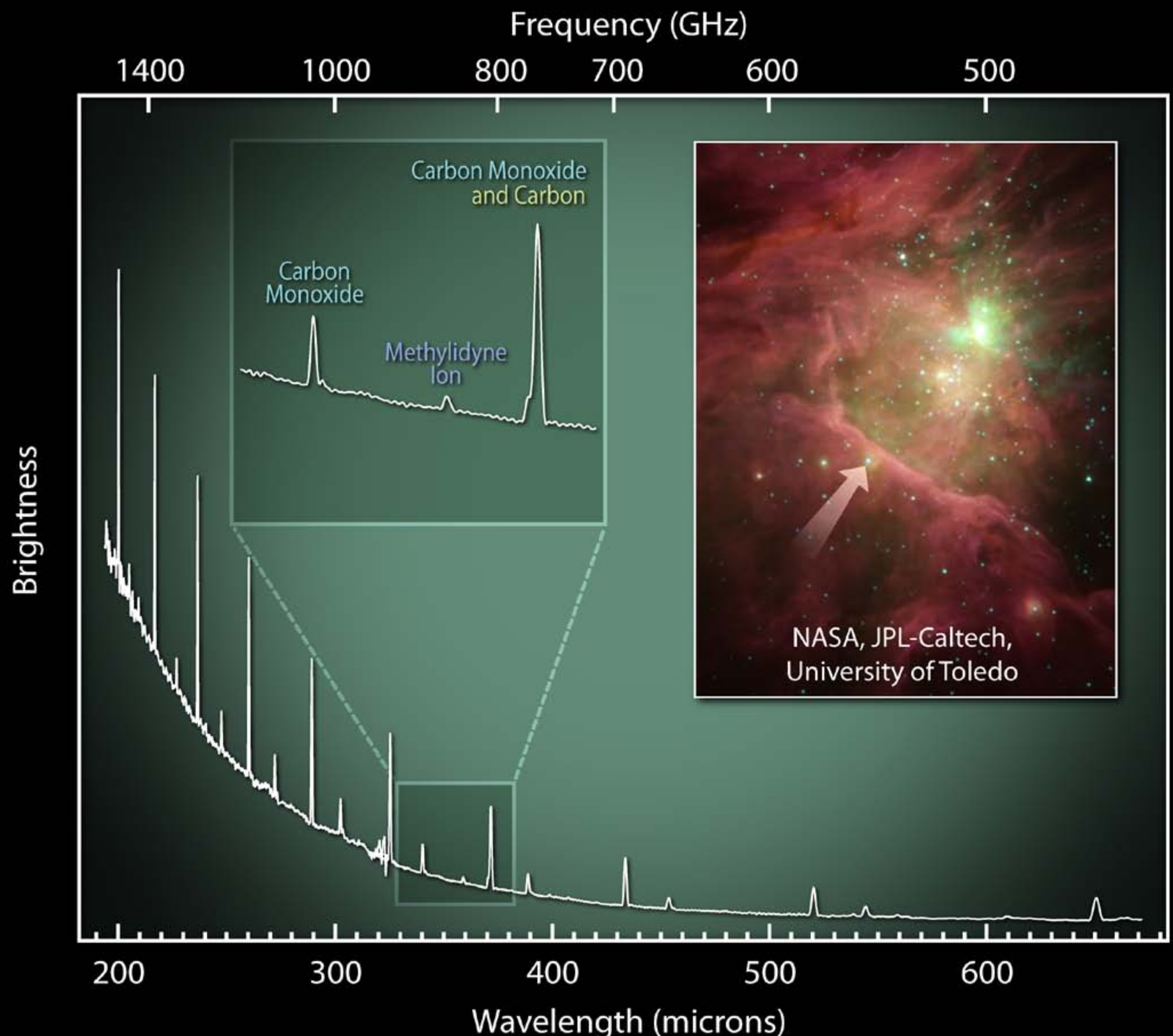


Other Emission Lines from Galaxies

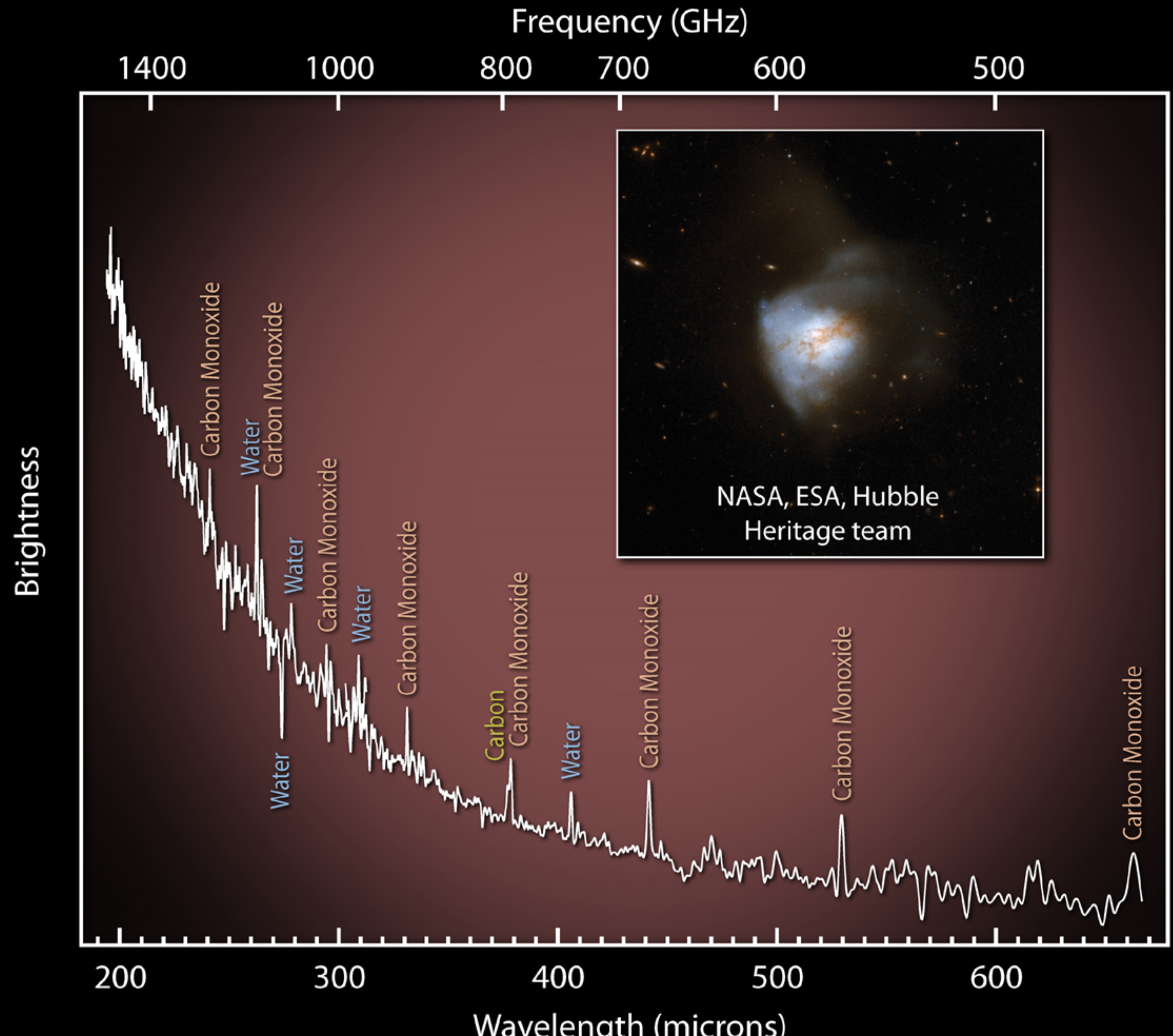


Species	Emission Wavelength[μm]	R[$L_\odot/(M_\odot/yr)$]
CII	158	6.0×10^6
OI	145	3.3×10^5
NII	122	7.9×10^5
OIII	88	2.3×10^6
OI	63	3.8×10^6
NIII	57	2.4×10^6
OIII	52	3.0×10^6
^{12}CO(1-0)	2610	3.7×10^3
^{12}CO(2-1)	1300	2.8×10^4
^{12}CO(3-2)	866	7.0×10^4
^{12}CO(4-3)	651	9.7×10^4
^{12}CO(5-4)	521	9.6×10^4
^{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

Herschel Spectra

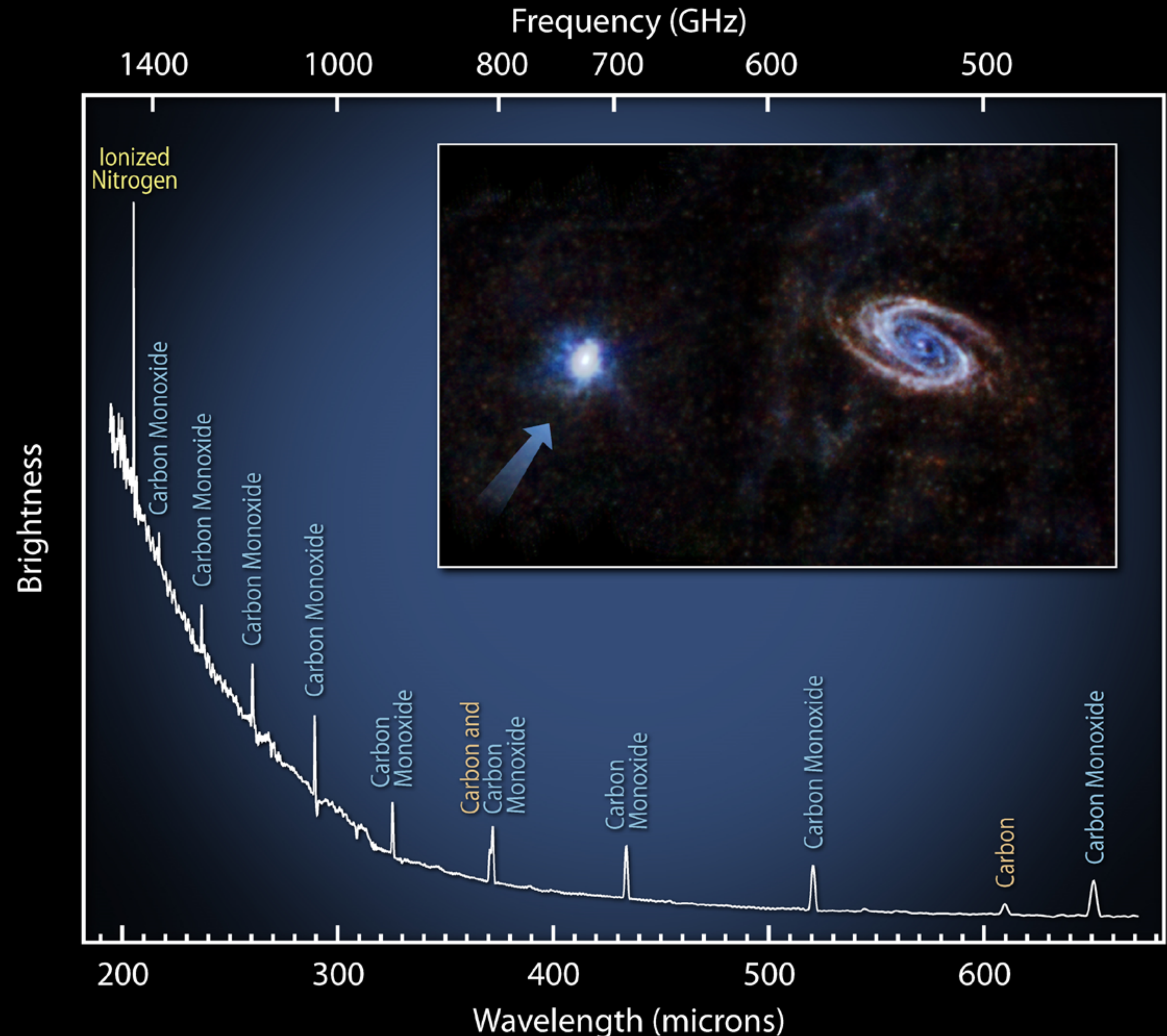


Orion Bar



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

Messier 82

Cross-Correlation of Different Lines Removes Contamination from Other Redshifts

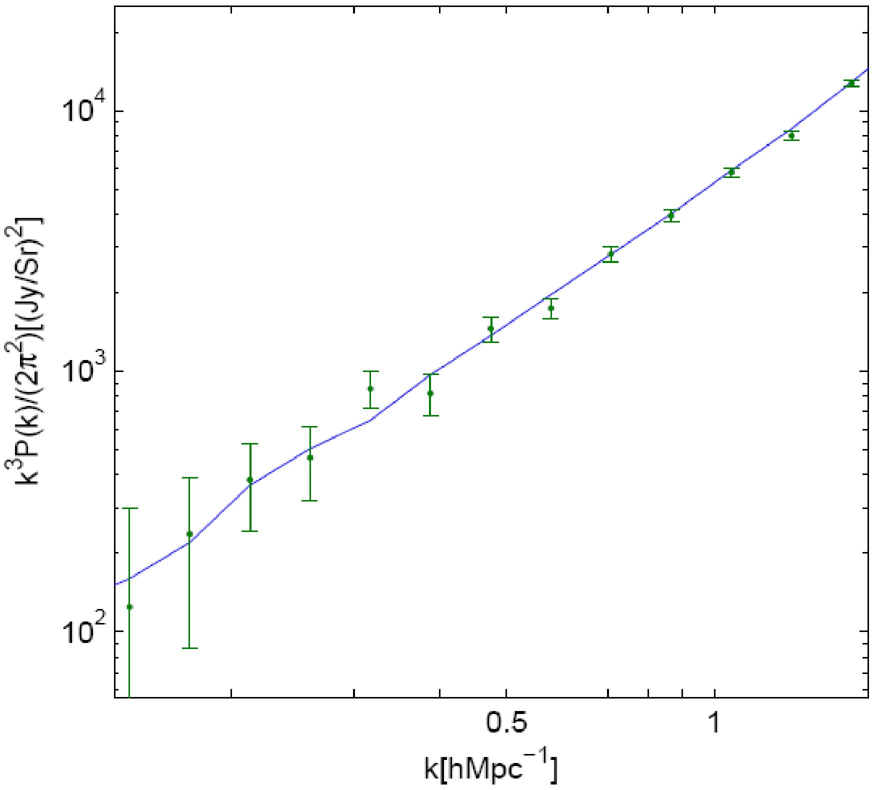


FIG. 4: The cross power spectrum of OI(63 μm) and OIII(52 μm) at $z = 6$ measured from simulated data for our hypothetical instrument modeled after SPICA. The blue curve is the cross power spectrum measured when only line emission from galaxies in the target lines are included. The green points are the recovered power spectrum when detector noise, bad line emission, galaxy continuum emission, and bright astrophysical foreground and background emission (i.e. dust in our galaxy and the CMB) are included. The error bars are the theoretical prediction of the root mean square error derived in [1] and given by Eq. (7). In determining the error bars we have estimated $P_{1\text{total}}$ and $P_{2\text{total}}$ using our simulated data. These errors include detector noise, bad line emission and sample variance.

Visbal & Loeb (JCAP, 11, 1016, 2010); Visbal, Trac, & Loeb (2011)

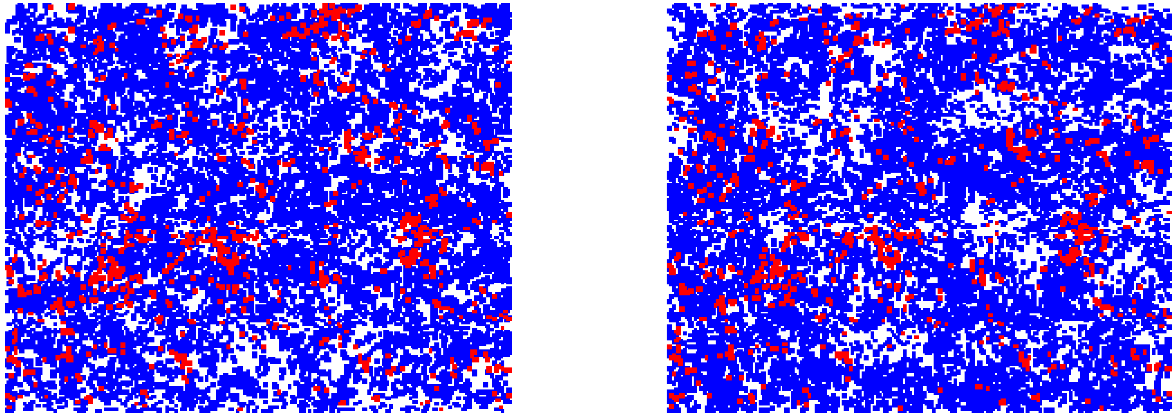


FIG. 1: A slice of our simulated realization of line emission from galaxies at 441μm (left) and 364μm (right). The slice is 250 comoving Mpc across and has a depth of $\Delta\nu/\nu = 0.001$. The colored squares indicate pixels in our SPICA example (presented below) which have line emission greater than $2 \cdot 10^{-21}$erg/s/cm^2/Hz/Sr. The emission from OI(63μm) and OIII(52μm) are shown as red in the left and right plots respectively. These lines come from the same galaxies at $z = 6$. All of the other lines in Table I are included and plotted in blue. If one cross correlates data at these two frequencies the emission in OI and OIII from $z = 6$ will correlate, but the other emission is essentially uncorrelated.

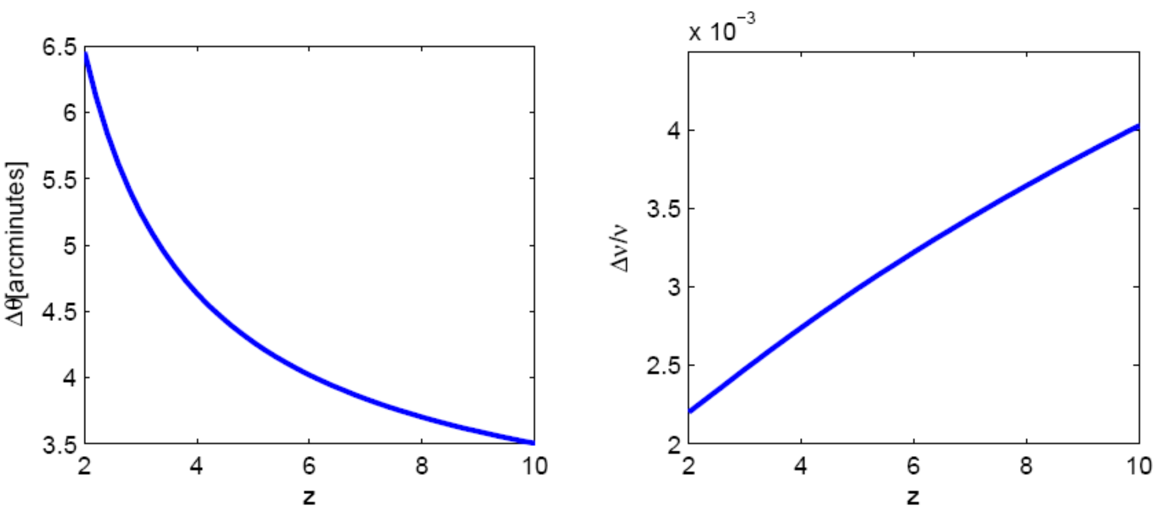
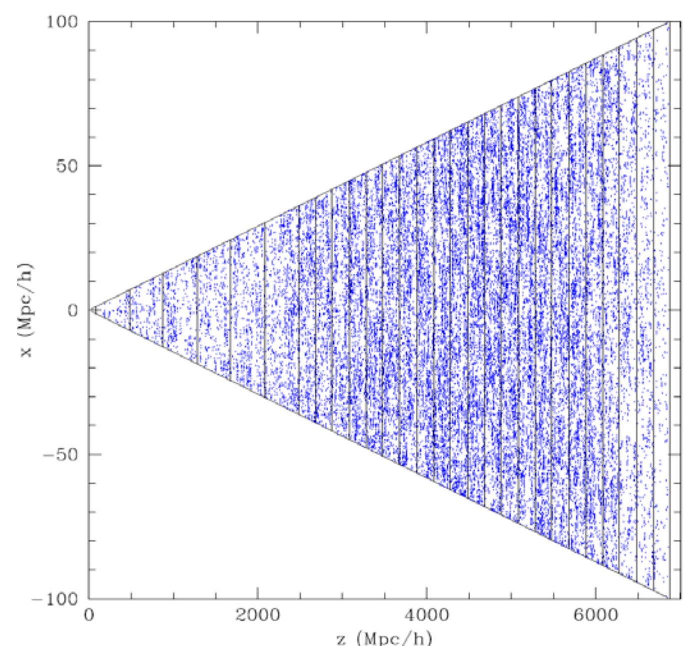


Figure 1. The angle and frequency range corresponding to 10 comoving Mpc.



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

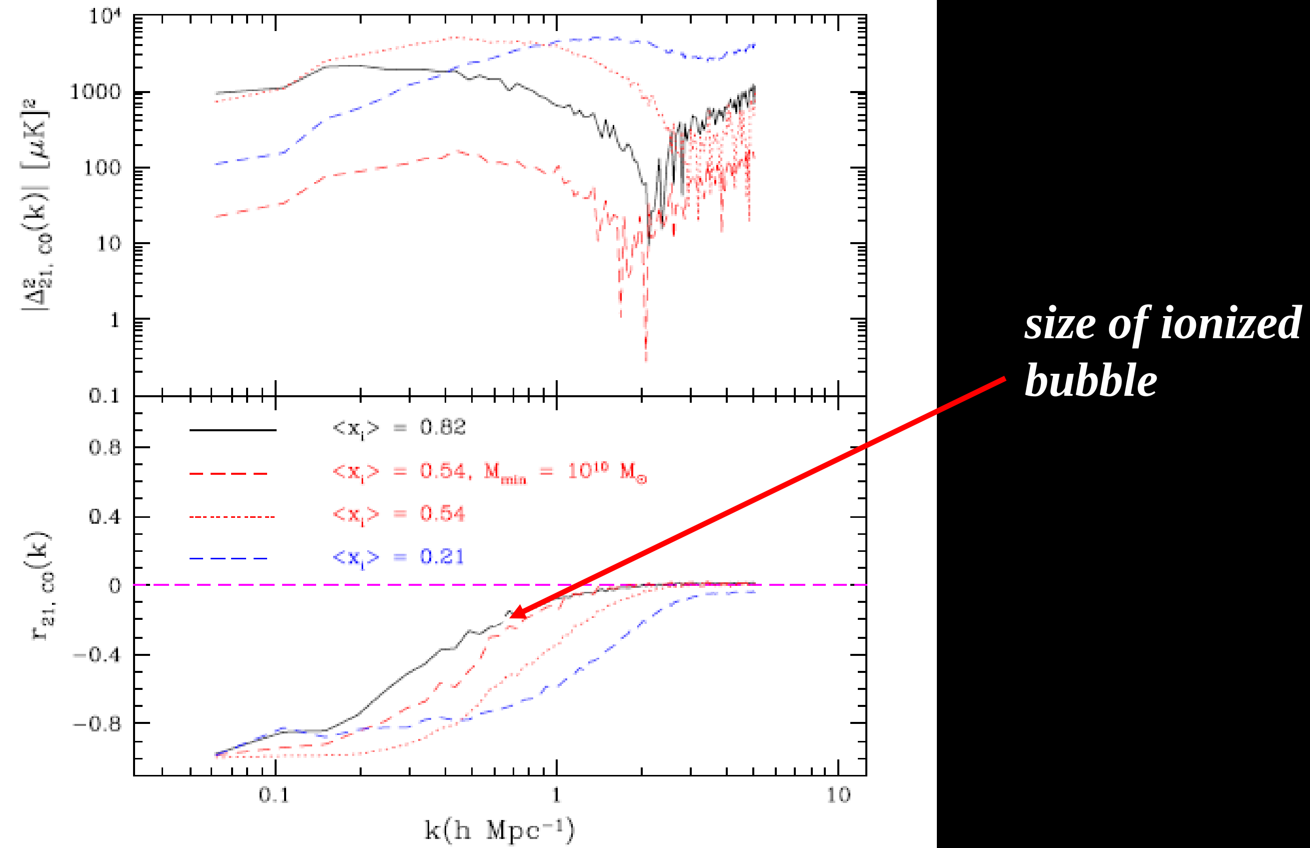
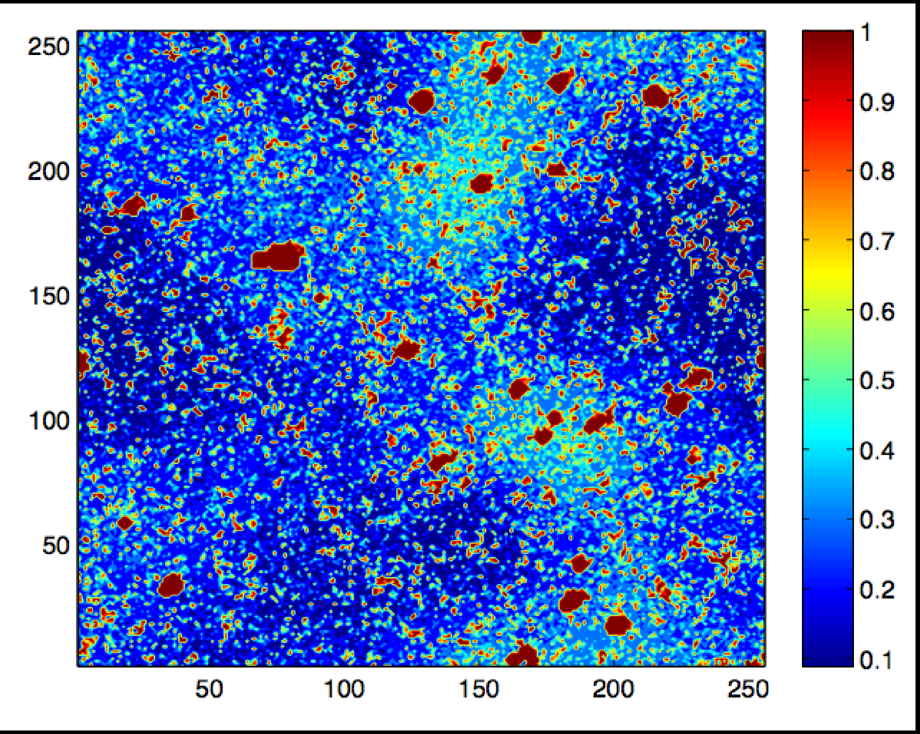
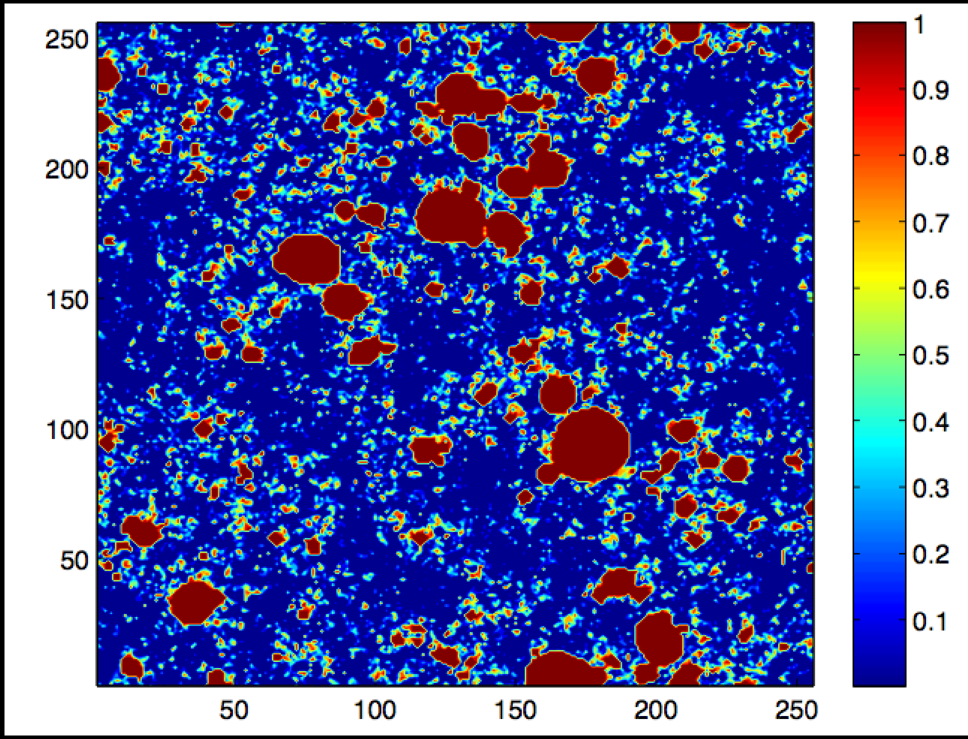


Figure 1.6 Cross-correlation between CO(2-1) emission and the spin-flip background in a numerical simulation of reionization (as in Fig. 1.5). The dot-dashed, dotted, and solid curves take $z = 9.8$, 7.3, and 6.8 (or $Q_{\rm HII} = 0.21$, 0.54, and 0.82 in this model), assuming that all galaxies emit 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.

Lidz et al. (2011)

Gauging the Contribution of X-ray Sources to Reionization from the kSZ Signal





50% X-rays

no X-rays

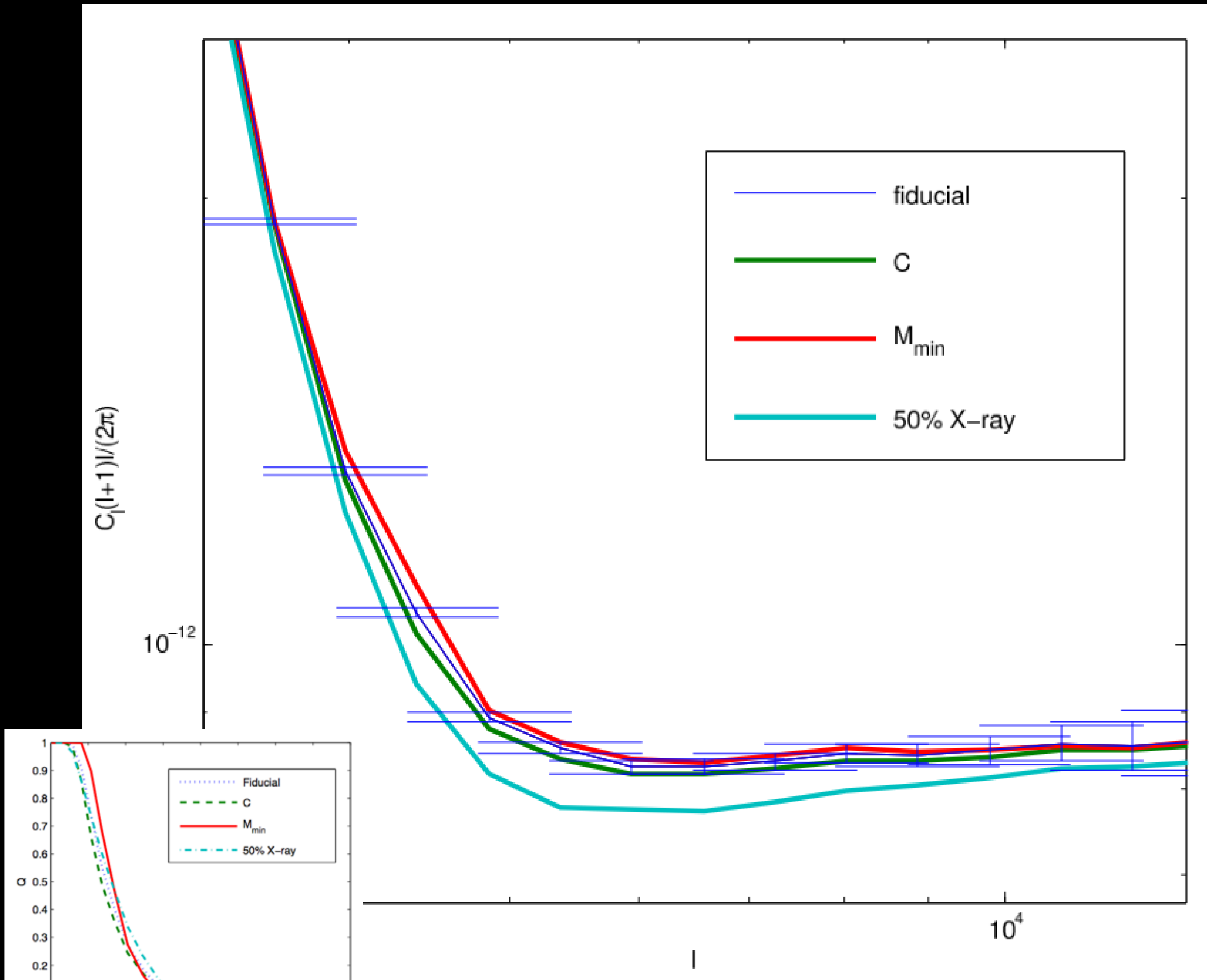
Visbal & Loeb 2011

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.***

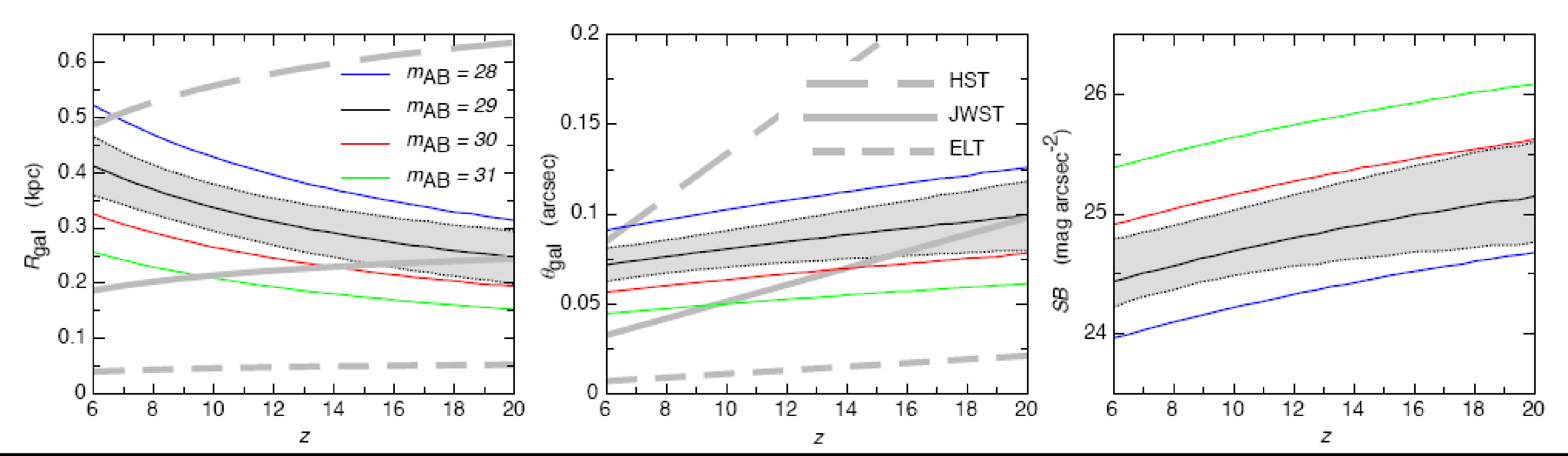
Open Problems

- ***Did massive Pop-III stars contribute significantly to reionization and the 21-cm signal?***
- ***Were the earliest X-ray sources dominated by IC cooling of SNe e- or High-Mass X-ray binaries or massive black holes? Simulations of inhomogeneous X-ray heating are needed.***
- ***How important was the opacity and evaporation of minihalos below the gas cooling threshold? Simulations are needed.***
- ***Are there radio-loud sources for detecting the 21-cm forest in absorption at z~10?***
- ***Is there an efficient algorithm for removing foreground of the global signal (not throwing the baby with the bath-tub water). In particular, taking advance of the foreground dependence on sky coordinates.***
- ***What are the prospects for observatories of the post-reionization signal to constrain w(z)? None funded so far.***
- ***What are the signatures of exotic heating sources: dark matter annihilation, cosmic strings, etc. ?***



Forthcoming data from SPT, ACT

Will JWST Resolve Galaxies at z~10?



(Wyithe & Loeb 2010)

LETTER

doi:10.1038/nature09462

Spectroscopic confirmation of a galaxy at redshift $z = 8.6$

M. D. Lehnert[1], N. P. H. Nesvadba[2], J.-G. Cuby[3], A. M. Swinbank[4], S. Morris[5], B. Clément[3], C. J. Evans[6], M. N. Bremer[7] & S. Basa[3]

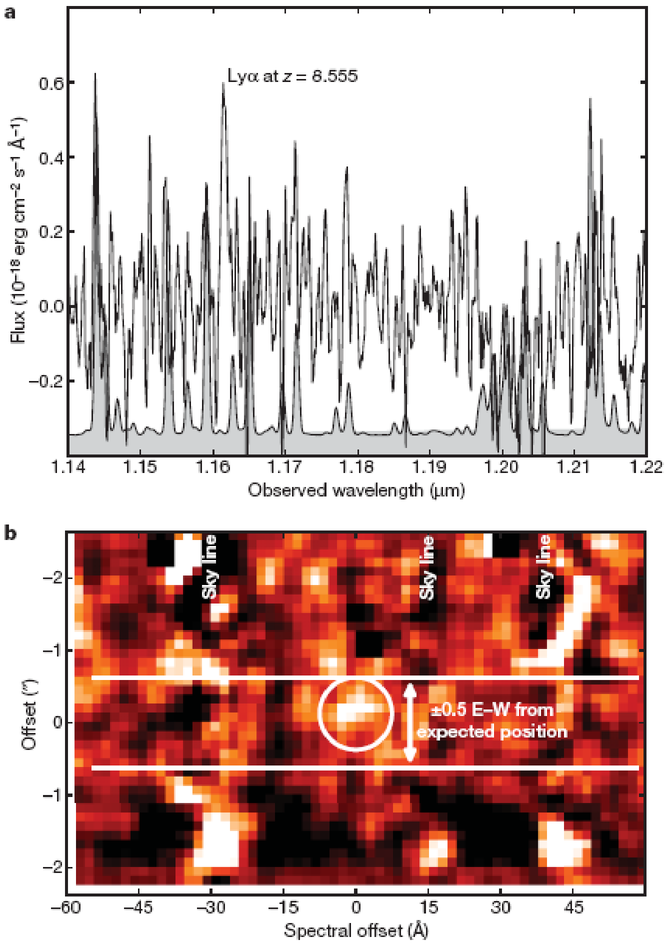


Figure 1 | Two representations of the spectrum of UDFy-38135539 showing

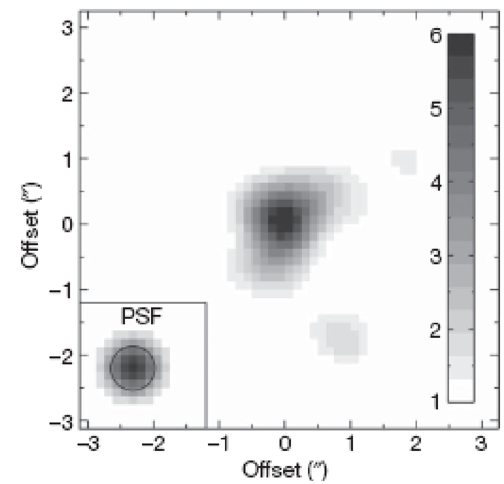
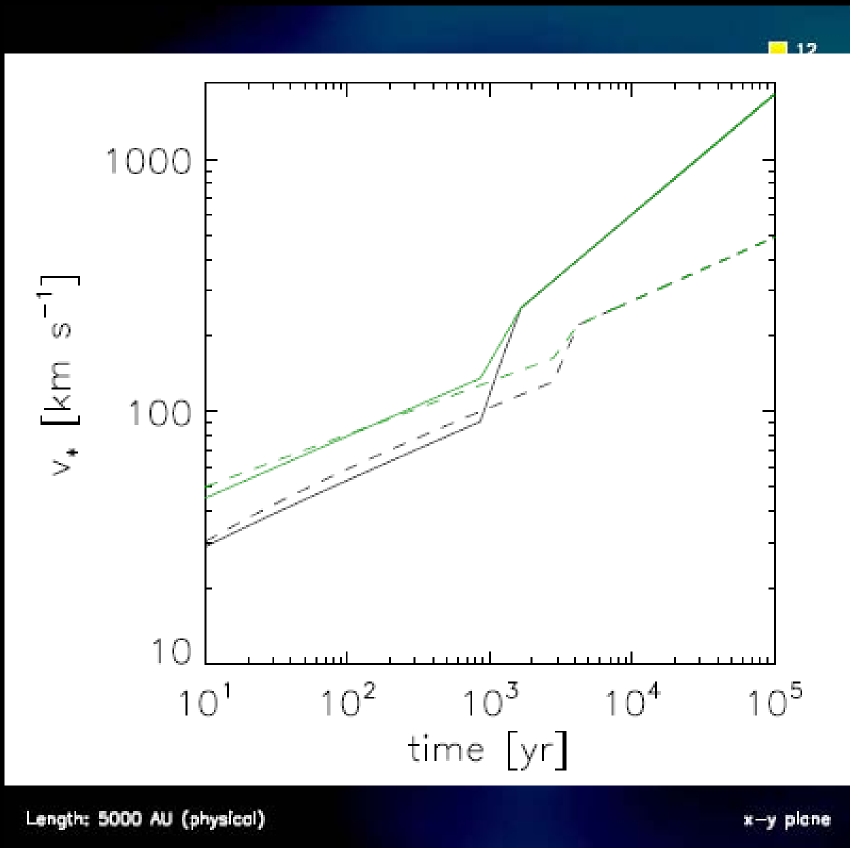
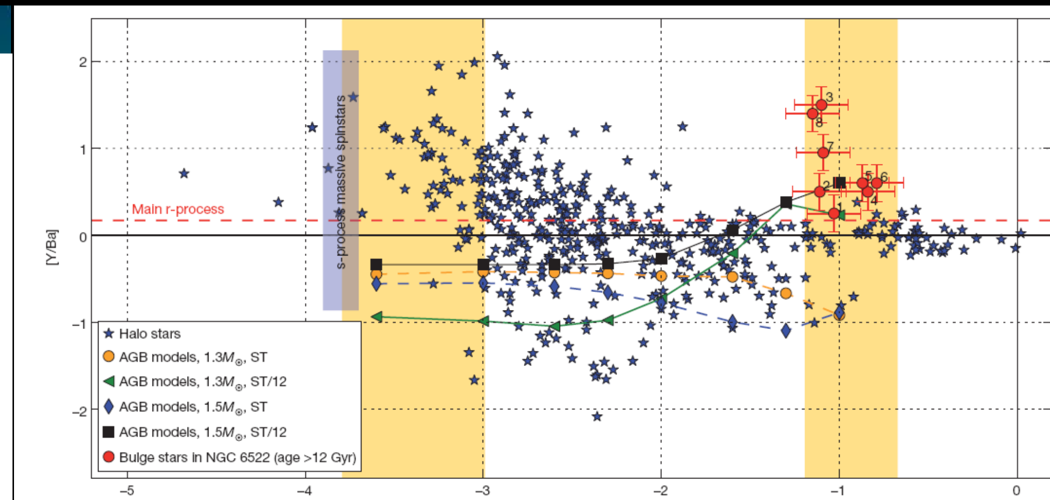


Figure 2 | Lyα line image of UDFy-38135539. The line image

First Stars Had High Spin





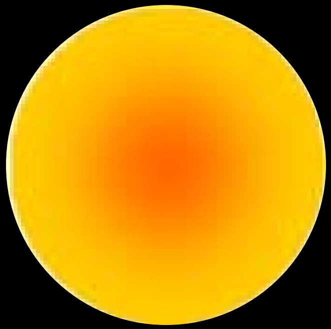
Sr and Y abundance in eight ~12Gyr old stars in NGC 6522 require a rotation speed of ~500 km/s (slow neutron capture is 10,000 more effective than in non-rotating stars).

Implications: *rotational mixing, GRBs*

Stacy, Bromm, & Loeb (2010)

Chiappini et al., Nature (2011)

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



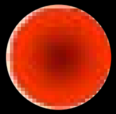
Massive, metal free stars

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

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

$$L = L_E \propto M$$

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

$Z_{\rm th}$ $Z_{\rm crit}$

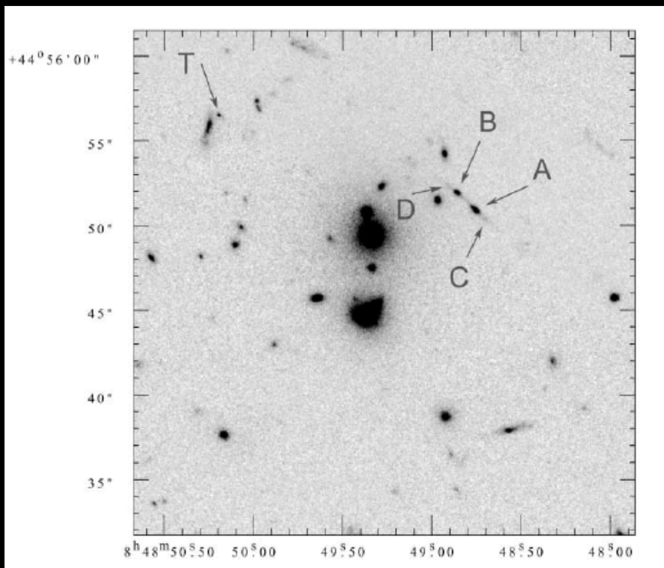
Atomic cooling (CII, OI) → $Z_{\rm crit} \sim 10^{-3} Z_\odot$

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

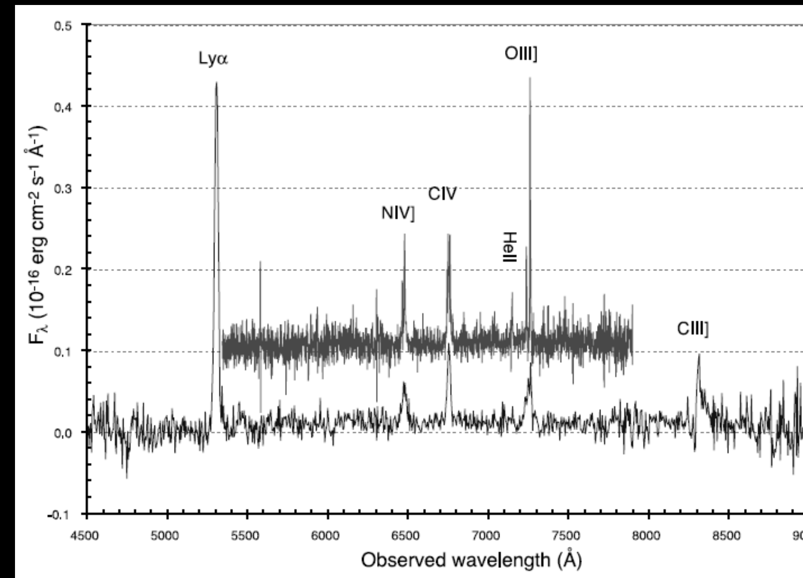
Milky-Way halo anemic stars: $Z_{\rm Fe} \sim 10^{-5} Z_\odot$

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

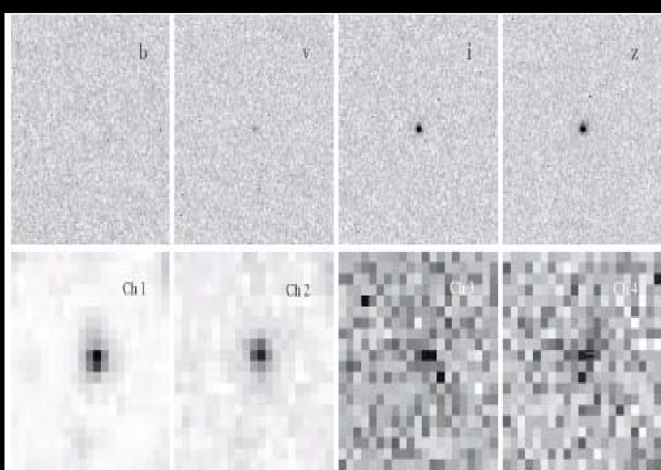
Low-Metallicity H II Regions with a ~10^5 K Ionizing Continuum



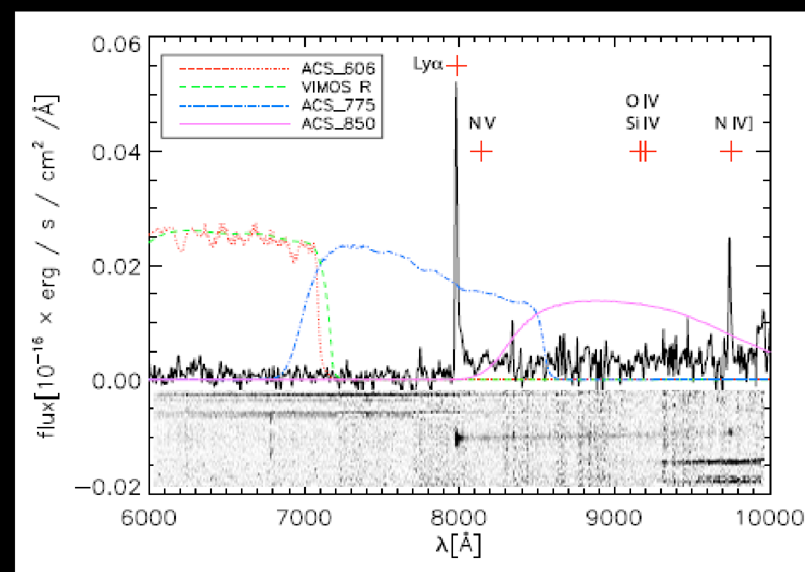
z=3.357



Fosbury et al. (2003)

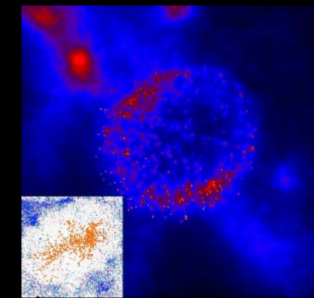


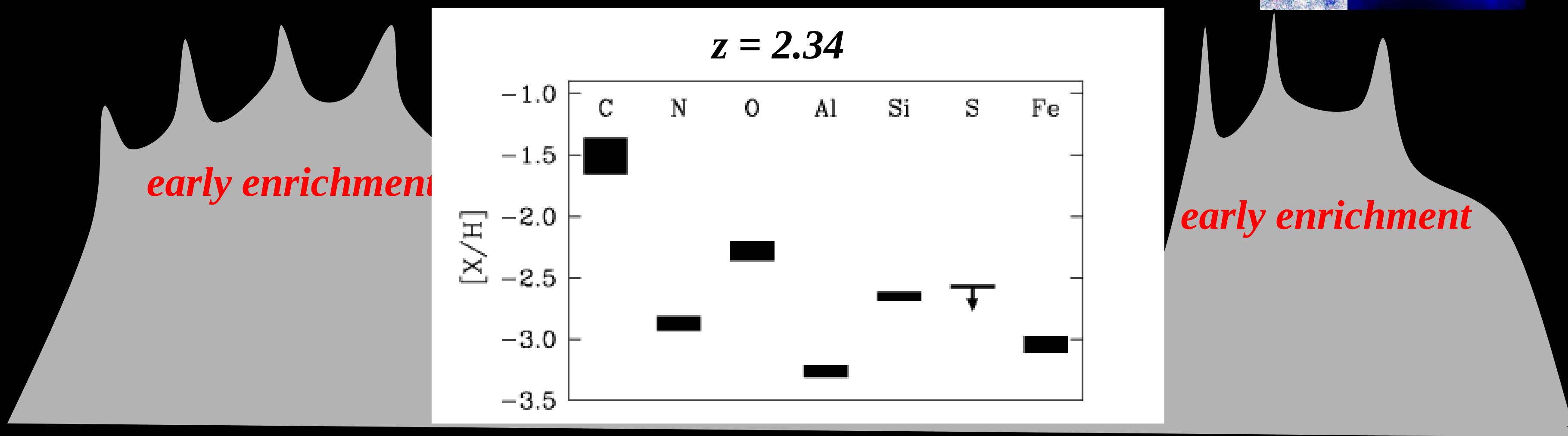
z=5.563



Raiter et al. (2003)

→Enrichment of Primordial Gas with Heavy Elements was Highly Inhomogeneous





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

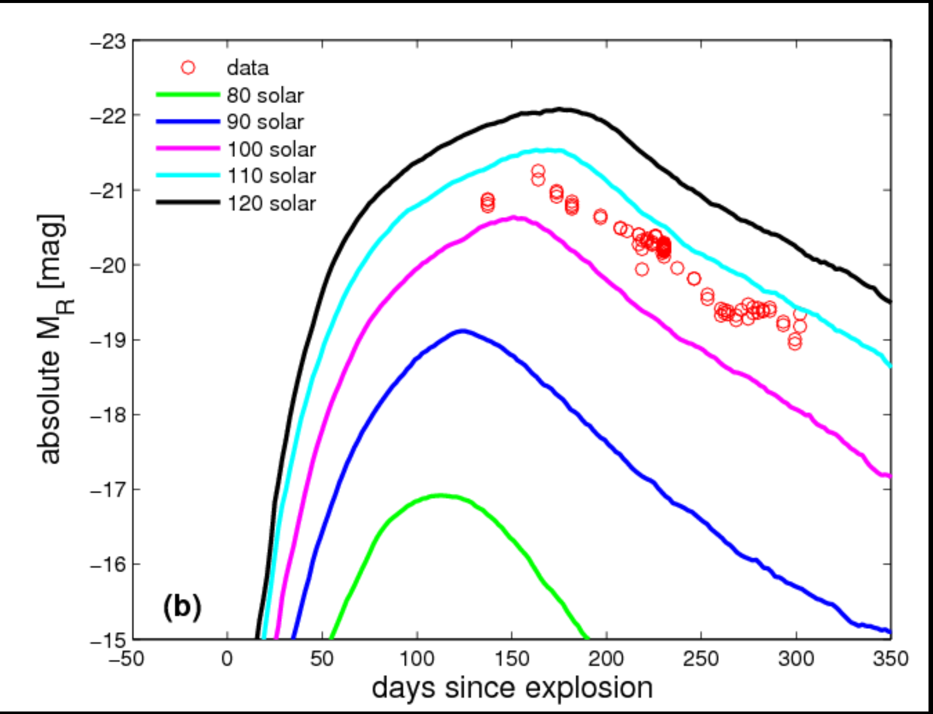
A carbon-enhanced metal-poor damped Lyα system: Probing gas from Population III nucleosynthesis?*

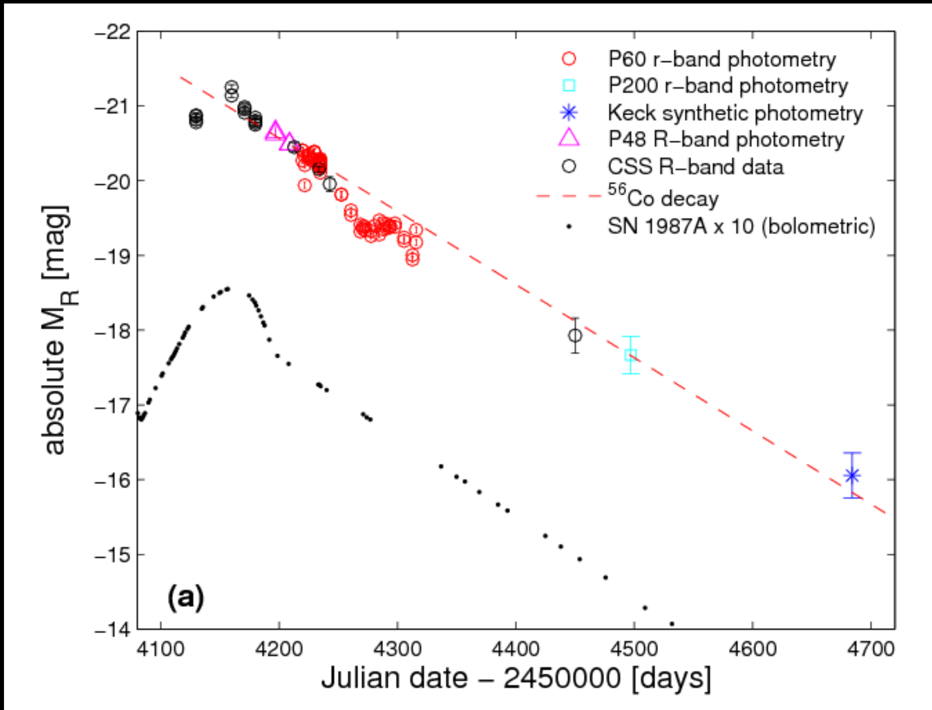
Ryan Cooke[1]†, Max Pettini[1], Charles C. Steidel[2], Gwen C. Rudie[2], and Regina A. Jorgenson[1]

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

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

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

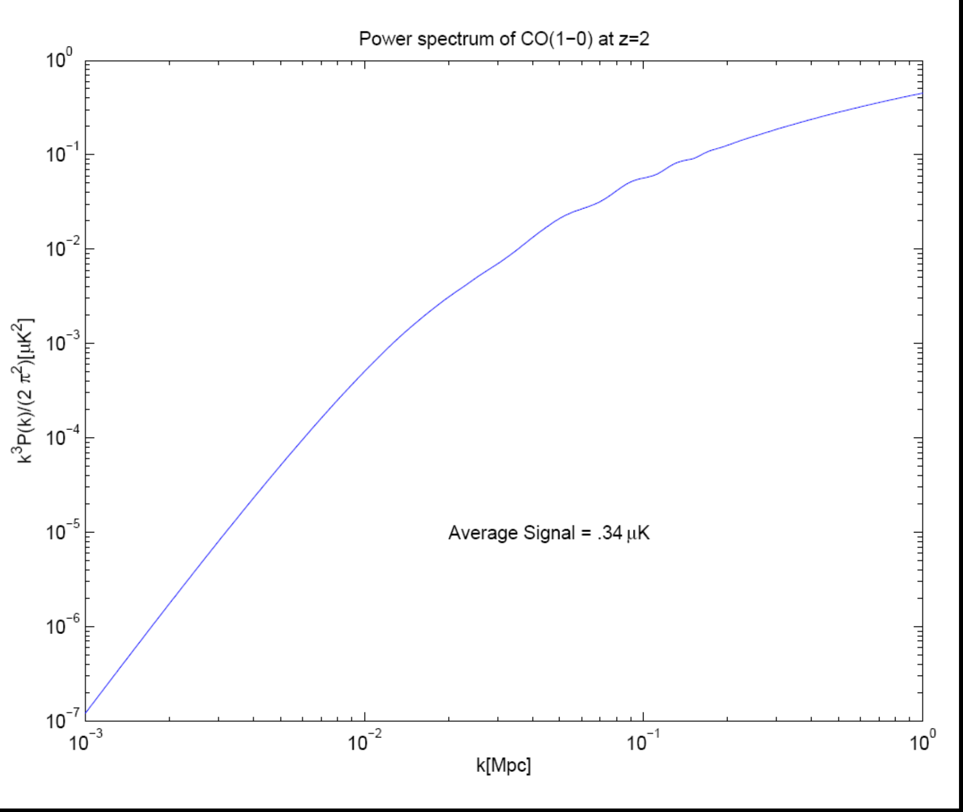


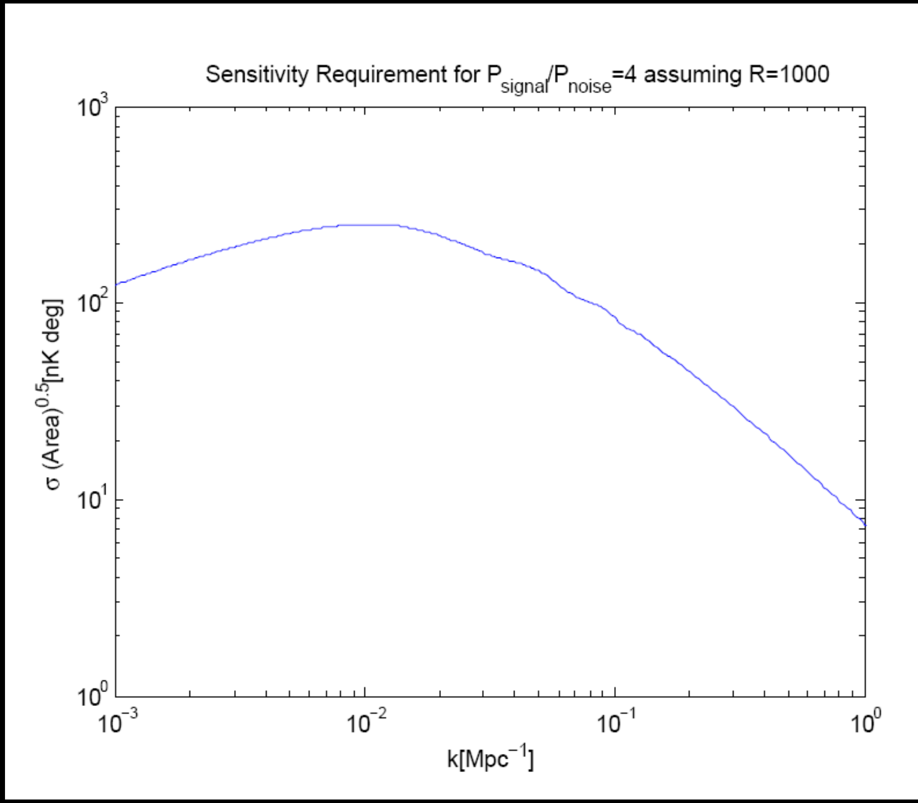


- Nickel mass of ~4-7 (ejecta mass of 100) ; kinetic energy of
- Dwarf galaxy at z=0.128 with M_B=-16.3 mag, and 12+[O/H]=8.25

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

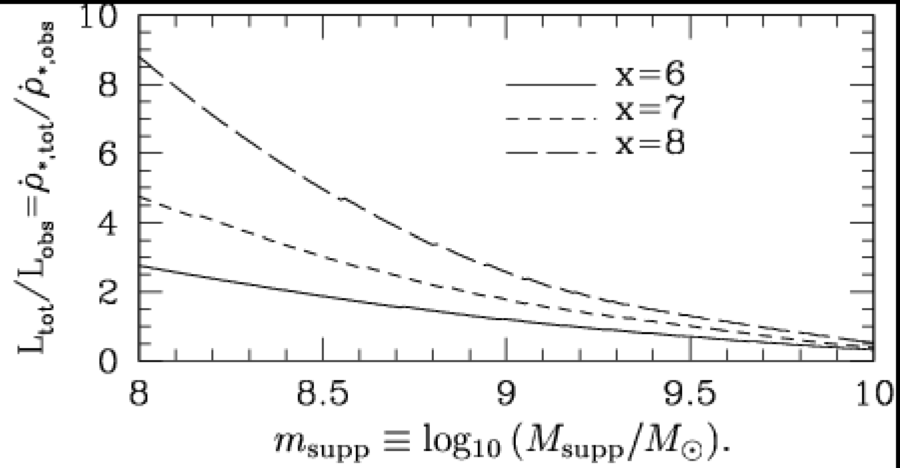
Baryonic Acoustic Oscillations from CO(1-0,2-1) Intensity Mapping at z~2

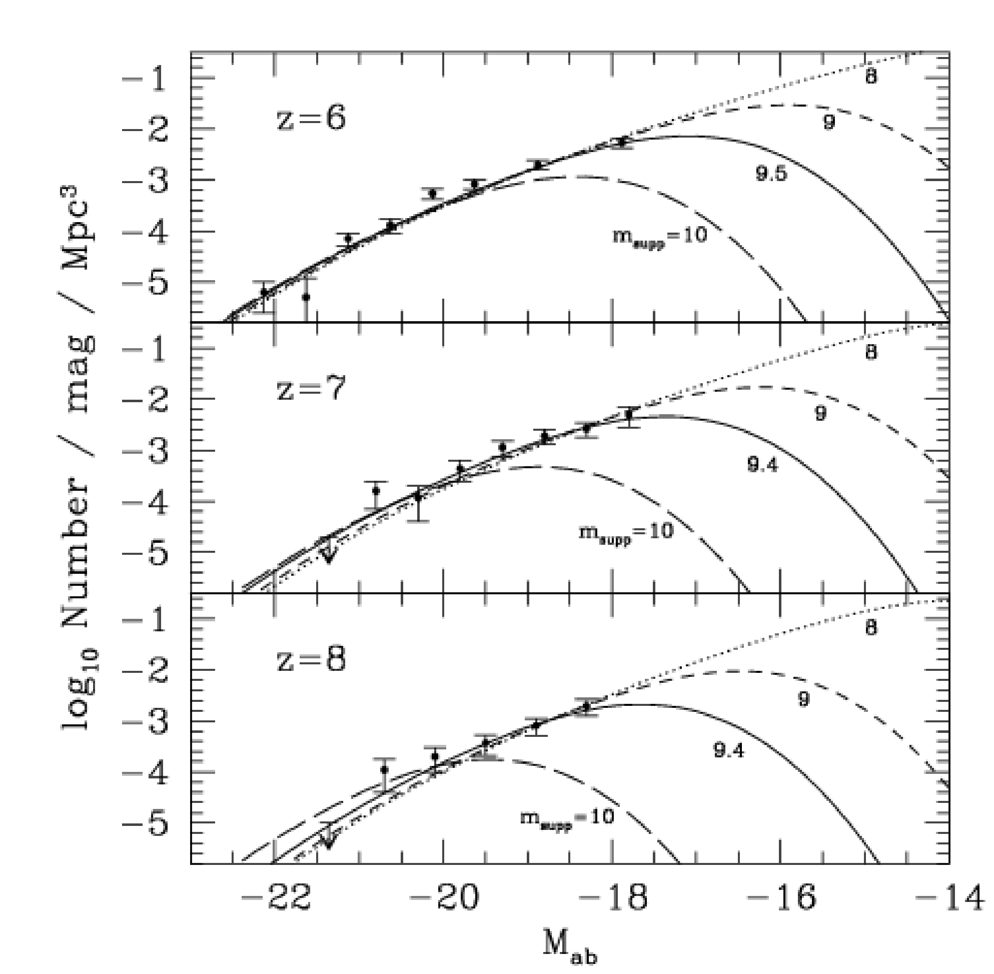




Visbal, Eisenstein, Loeb, & Kovac 2011

Minimum Halo Mass of Galaxies



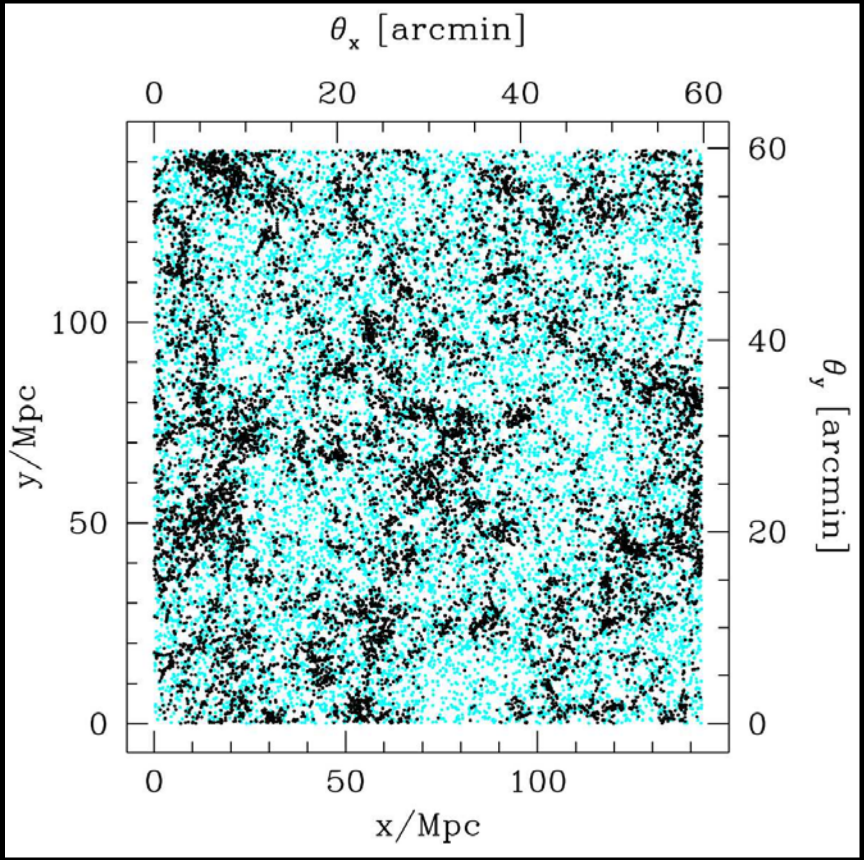


Munoz & Loeb, arXiv:1010.2260

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
$b_{\rm SDSS}$	$=$	$0.95^{+0.05}_{-0.06}$
σ_8	$=$	$0.75^{+0.03}_{-0.04}$
$\sigma_8 \Omega_m^{0.6}$	$=$	$0.34^{+0.02}_{-0.03}$
$A_{\rm SZ}$	$=$	$0.78^{+0.23}_{-0.78}$
t_0	$=$	$13.8^{+0.1}_{-0.2}$ Gyr
τ	$=$	$0.069^{+0.026}_{-0.029}$
θ_A	$=$	$0.594 \pm 0.002\ ^\circ$
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…

100 Mpc *structure in the simulated distribution of galaxies at z=6*

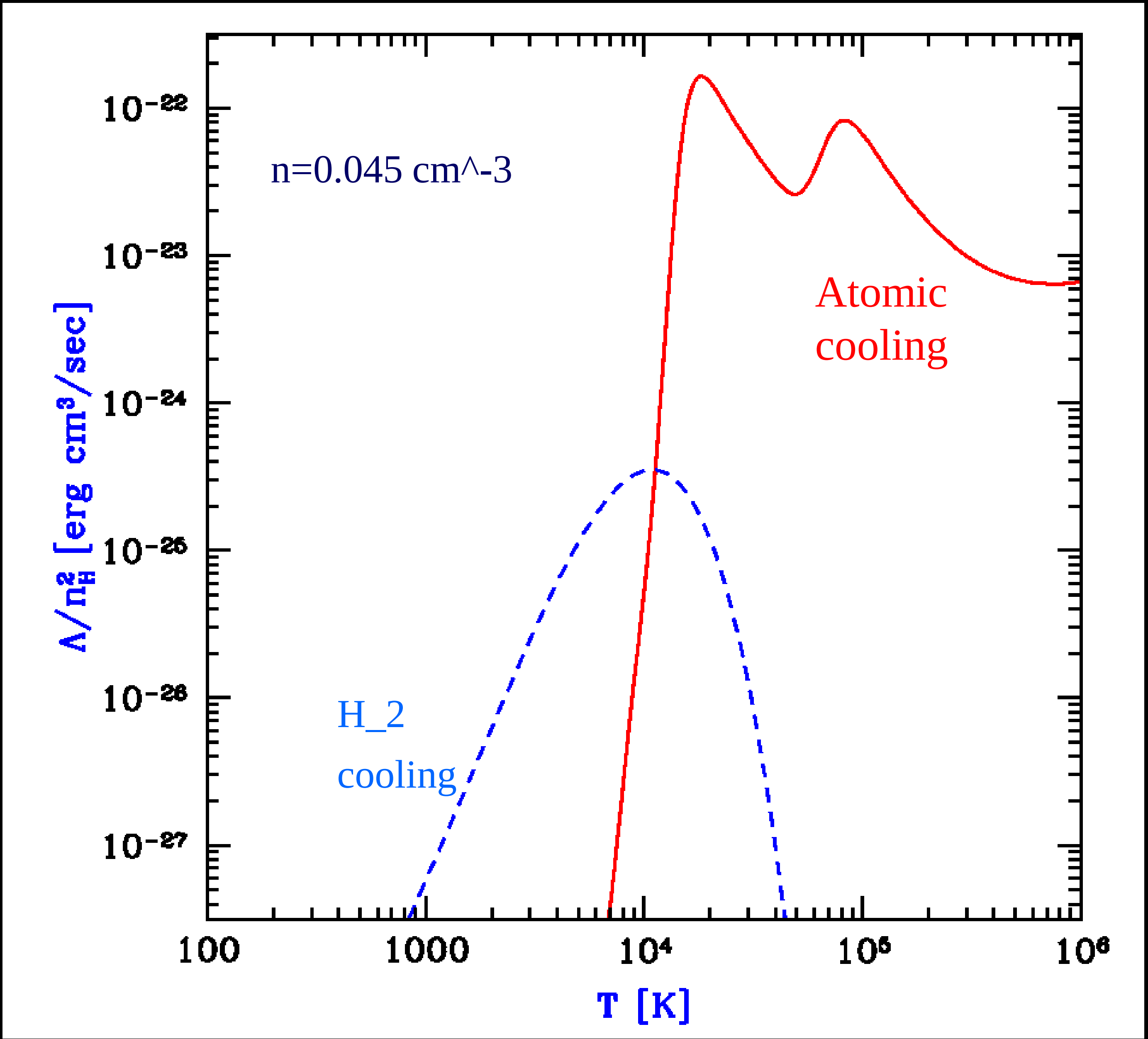


Munoz, Trac, & Loeb 2009

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)

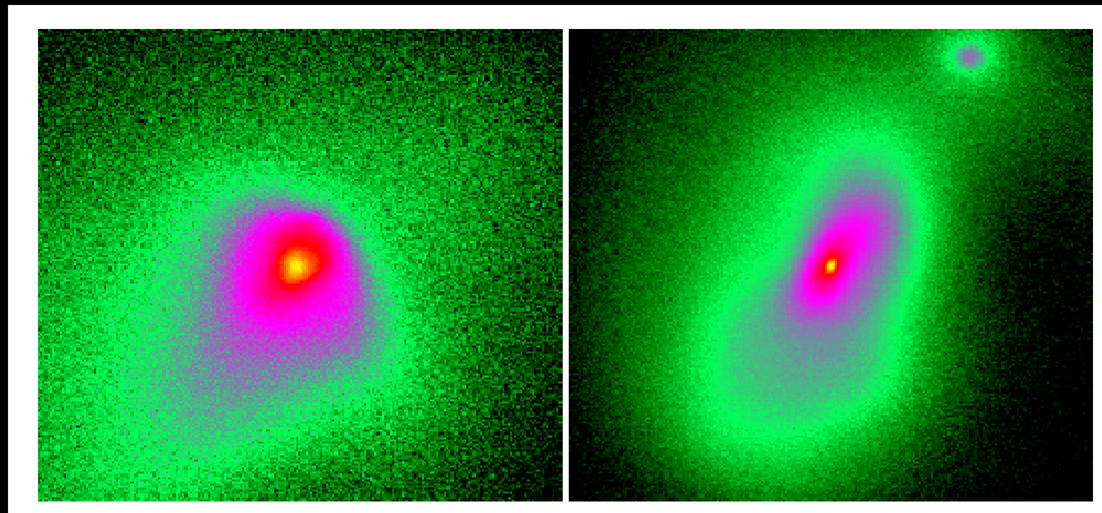
Cooling Rate of Primordial Gas



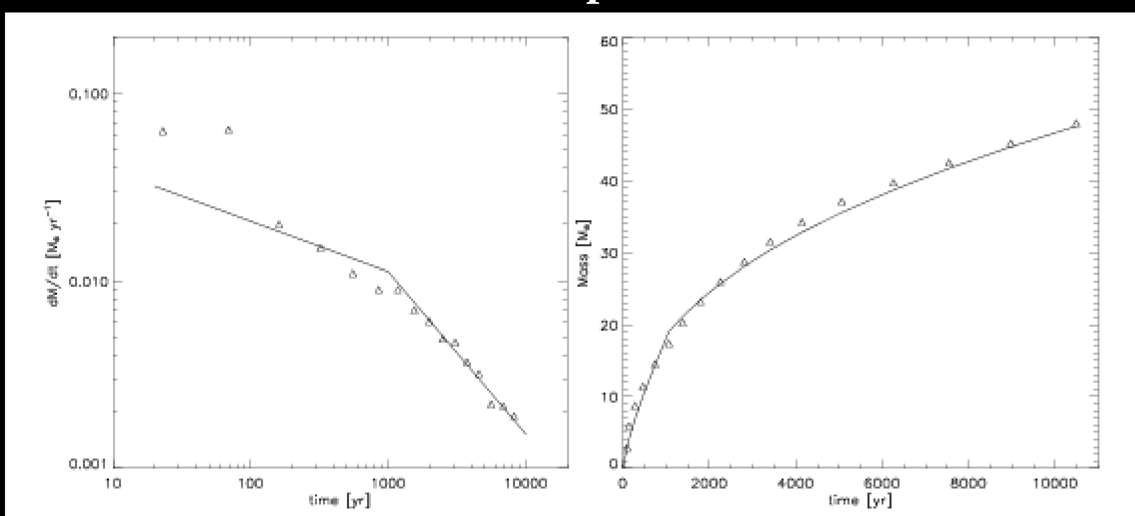
Massive Accretion by Pop-III Proto-Stars

Bromm & Loeb, astro-ph/0312456

Resolving accretion flow down to ~0.03 pc



23.5pc ***0.5pc***



Final stellar mass is feedback limited (radiation, wind)

Probing Reionization with MW Satellites

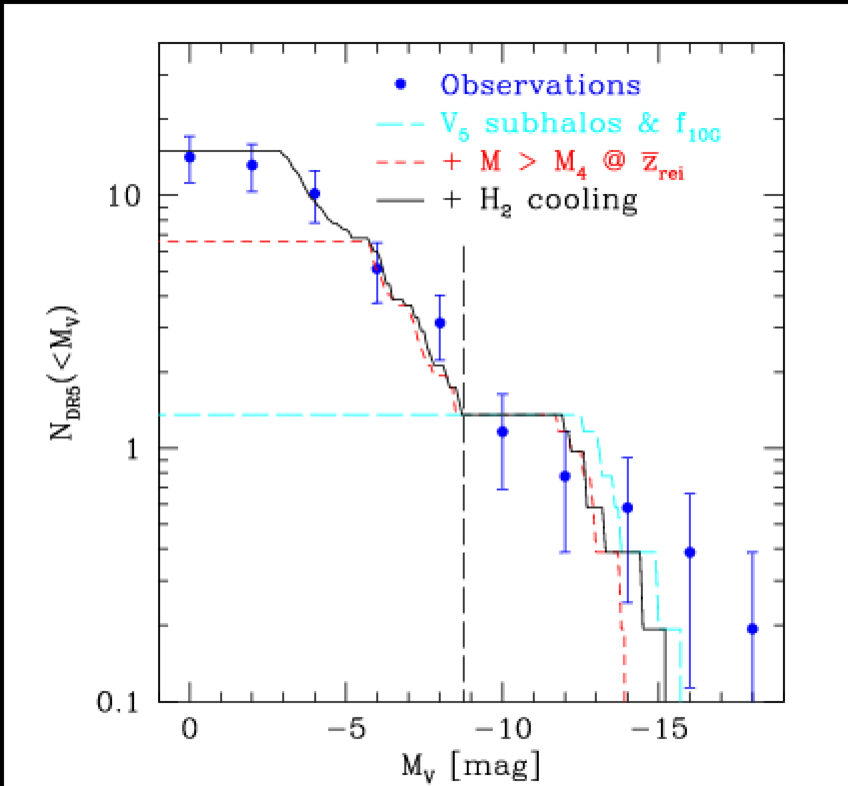


Figure 1. The luminosity function (LF) of MW satellites in the SDSS footprint with the DR5 selection threshold. The observed function is shown by the blue points with the non-SDSS objects each contributing a fractional amount $f_{DR5} = 0.194$ to the total. The curves show the theoretical predictions including successively more elaborate models. The model given by the long-dashed, cyan curve illuminates only those VLII subhalos with maximum circular velocities that exceed V_5 at some point in their histories and continue to form stars after reionization via atomic hydrogen cooling (with an efficiency of $f_5 = 0.02$) and metal cooling in the last 10 Gyr ($f_{10G} \neq 0$). The short-dashed, red curve includes star formation in subhalo progenitors more massive than M_4 at $\bar{z}_{rei} = 11.2$ assuming a single redshift of reionization for the entire MWgfr and $f_{HI,ex} = 0.02$. The solid, black curve fitting the faint end of the observed LF additionally takes into account molecular hydrogen cooling, prior to suppression at $z_{H_2} = 23.1$, in progenitors more massive than $M_{H_2} = 10^5\, M_\odot$ with $f_{H_2} = 0.4$. The long-dashed vertical line demarcates the luminosities at which pre- vs. post-SDSS satellites are observed.

- ***Via-Lactae II:*** dark matter simulation of the MW halo merger tree
- ***Resolution to "missing satellite problem":*** photo-ionization heating and molecular hydrogen suppression

Munoz, Madau, Loeb & Diemand 2009

Primary challenge: foregrounds

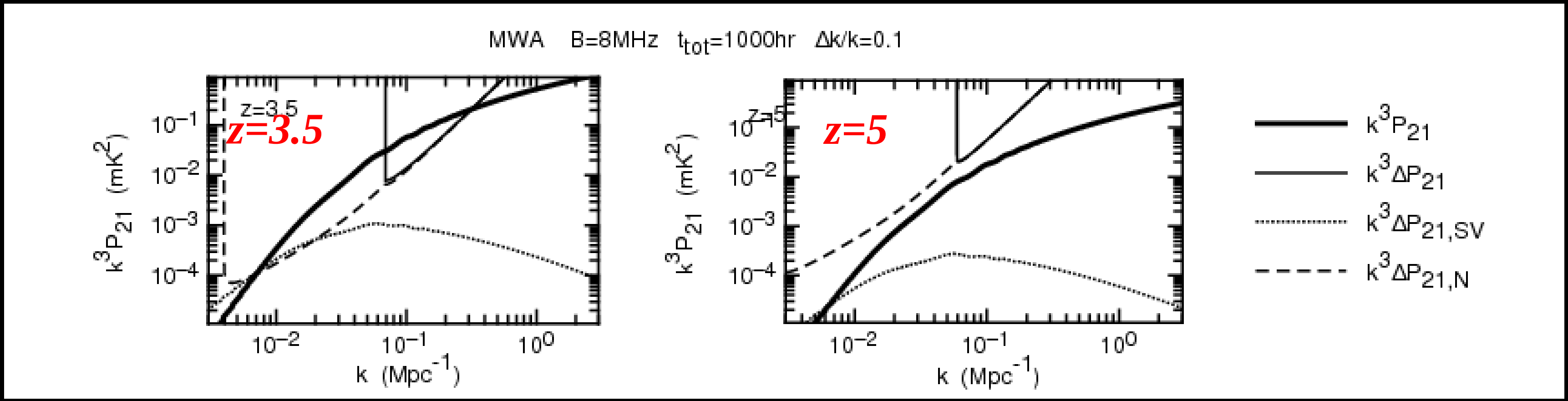
- Terrestrial: radio broadcasting
- Galactic synchrotron emission
- Extragalactic: radio sources

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

21cm Cosmology After Reionization?

Damped Lya absorbers:

→ on 10cMpc

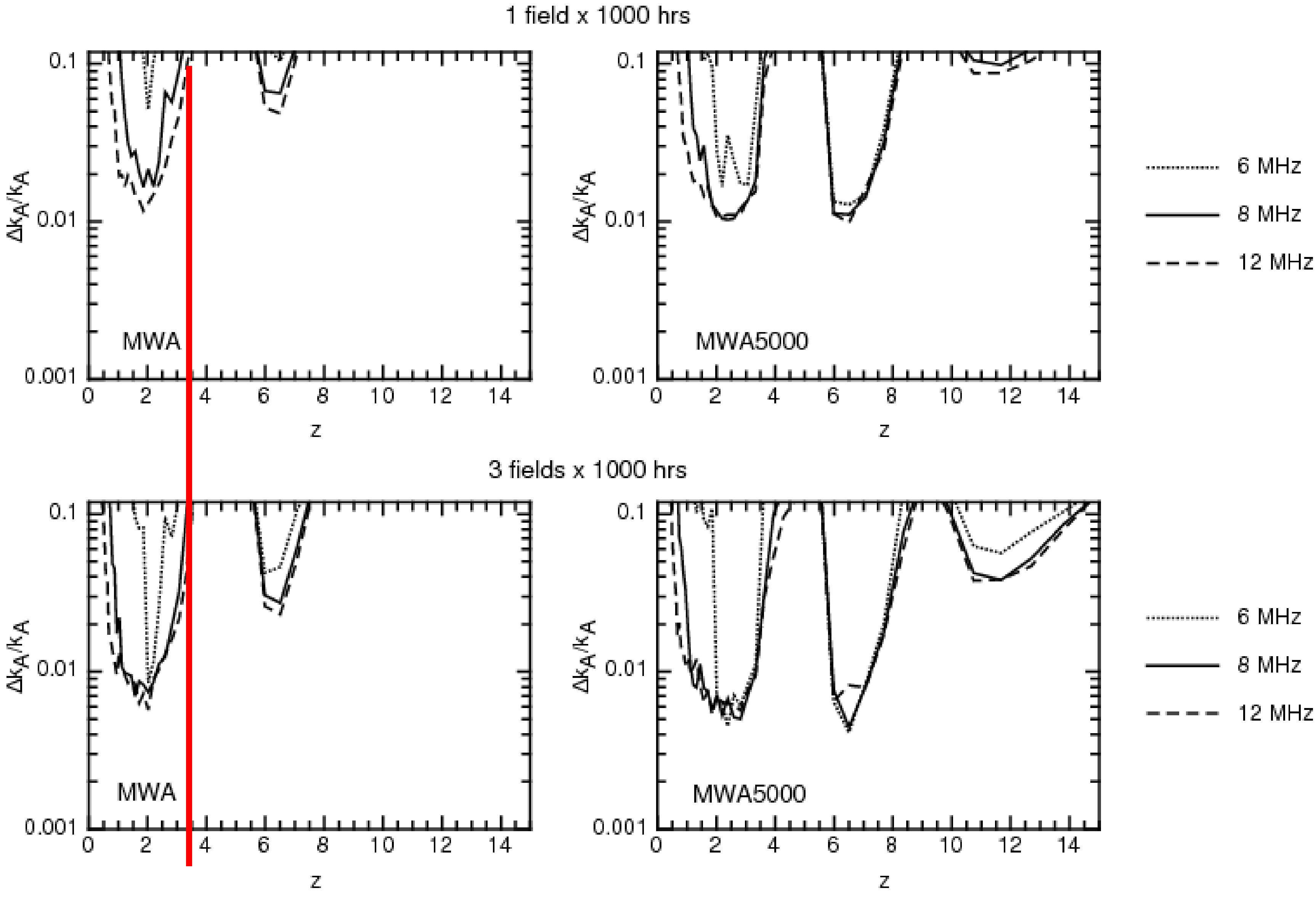


Acoustic peak: constrain dark energy at 0<z<15

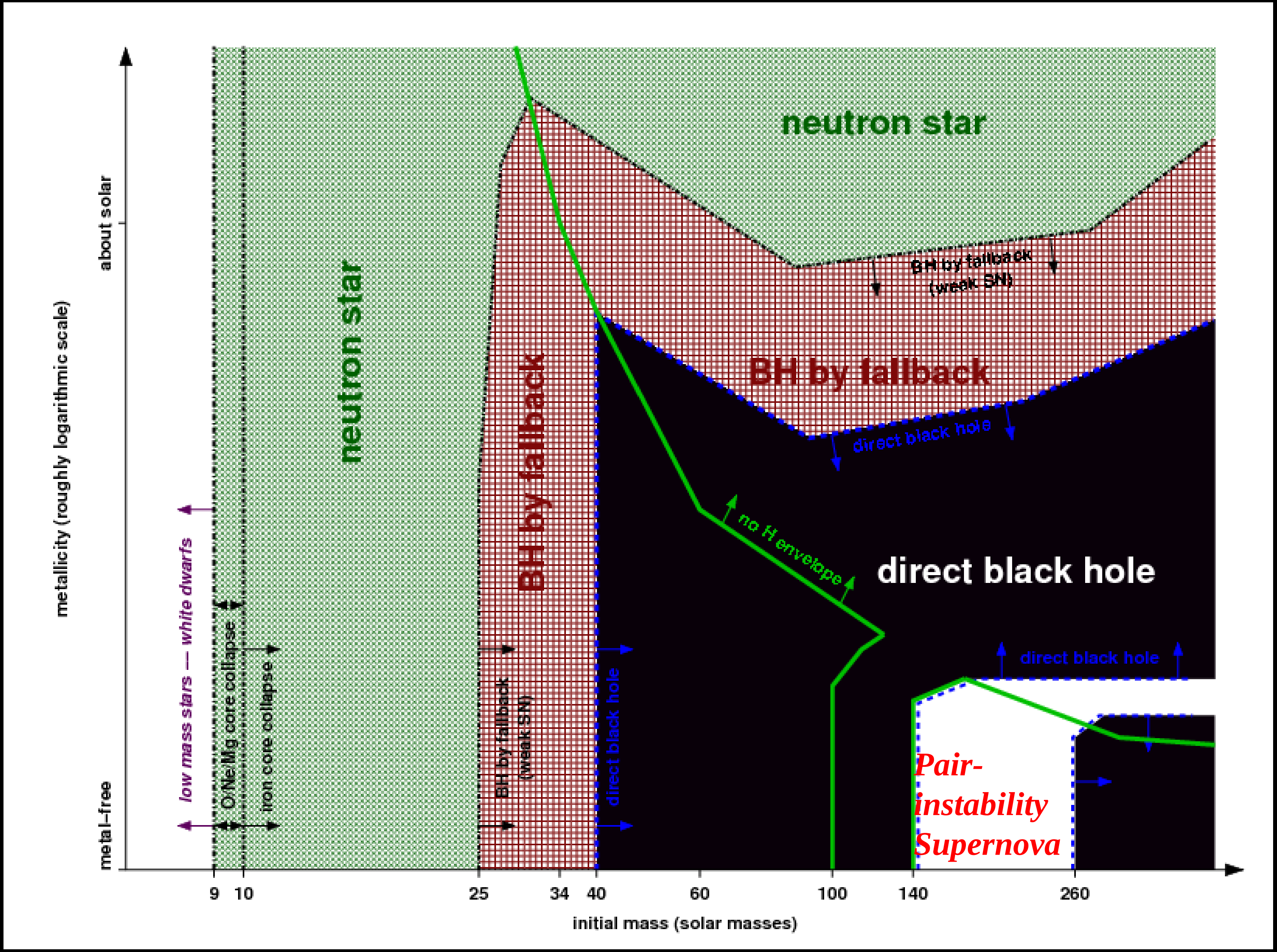
Wyithe & Loeb 2007

Acoustic Oscillations

Wyithe, Loeb & Geil

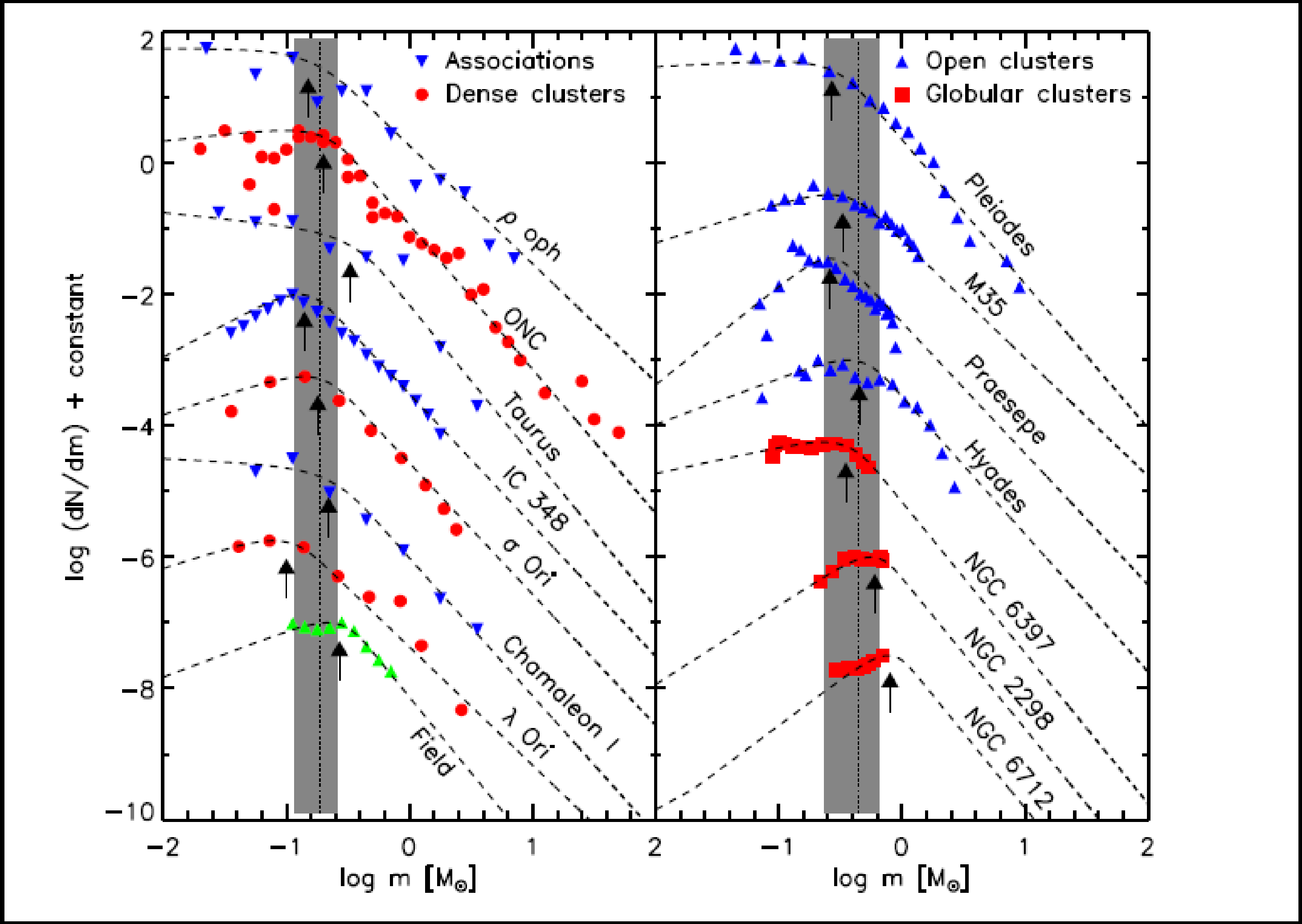


How do massive stars end their life?



Heger et al. 2003

The Initial Mass Function of Stars Populations I/II



Bastian et al. (2010)

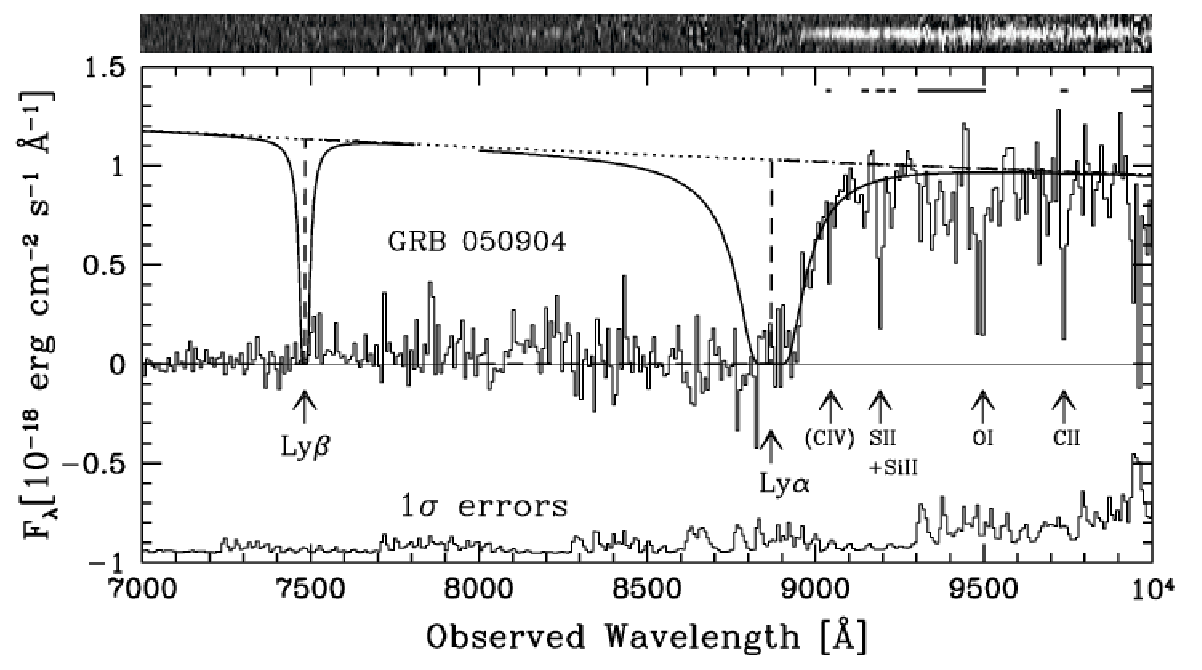
Populations III:

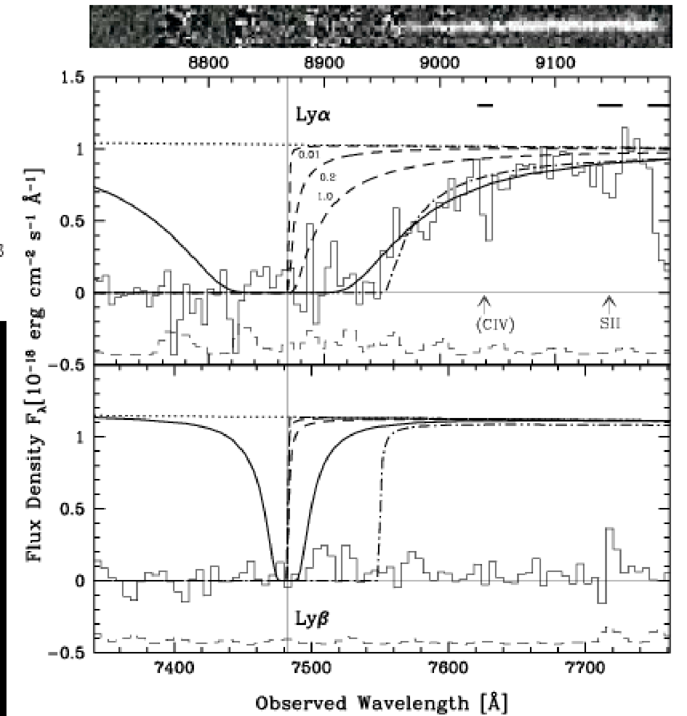
with CMB temperature floor

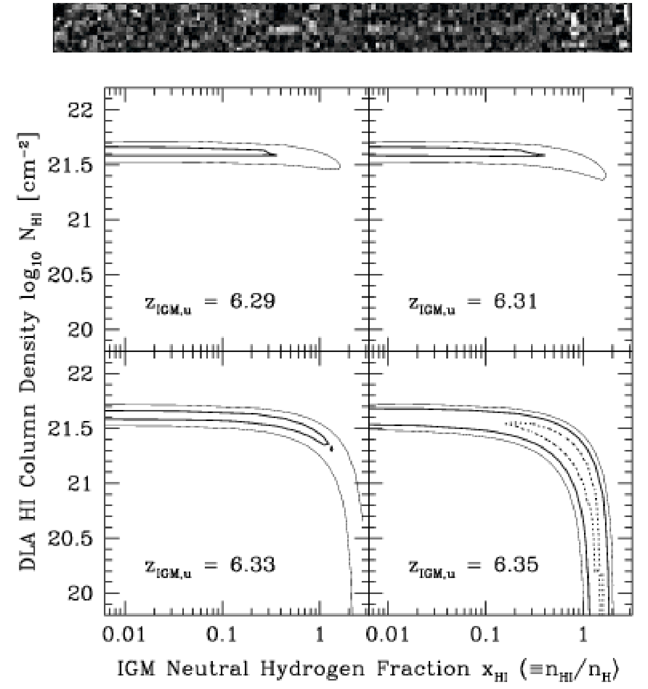
Implications for the Cosmic Reionization from the Optical Afterglow Spectrum of the Gamma-Ray Burst 050904 at $z = 6.3$*

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…

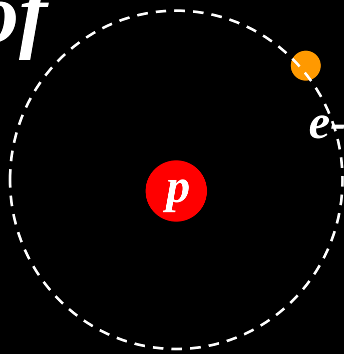






Mapping the Cosmic Distribution of

Hydrogen



Ground level

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

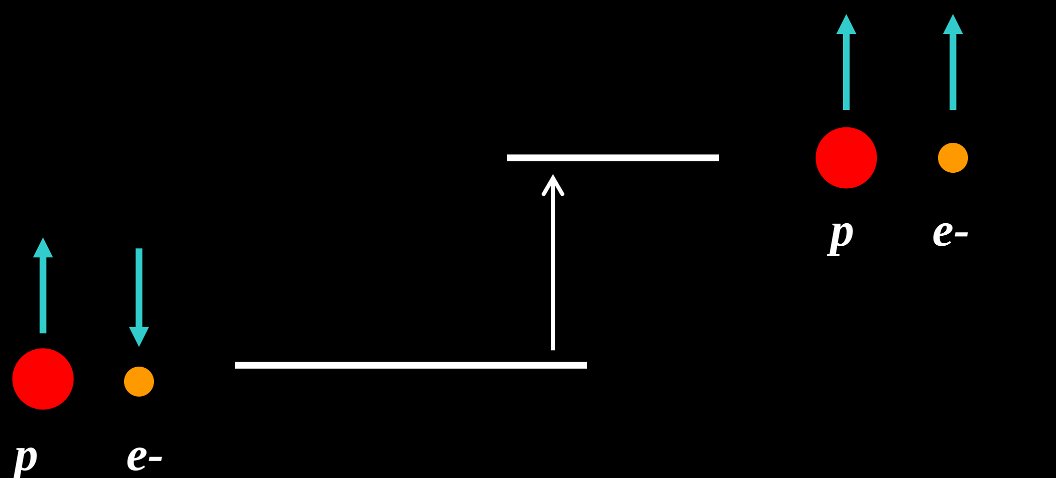
Couple T_s ***to*** T_k

Couples T_s ***to*** $T_í$

spin

$_1S_{1=2}$

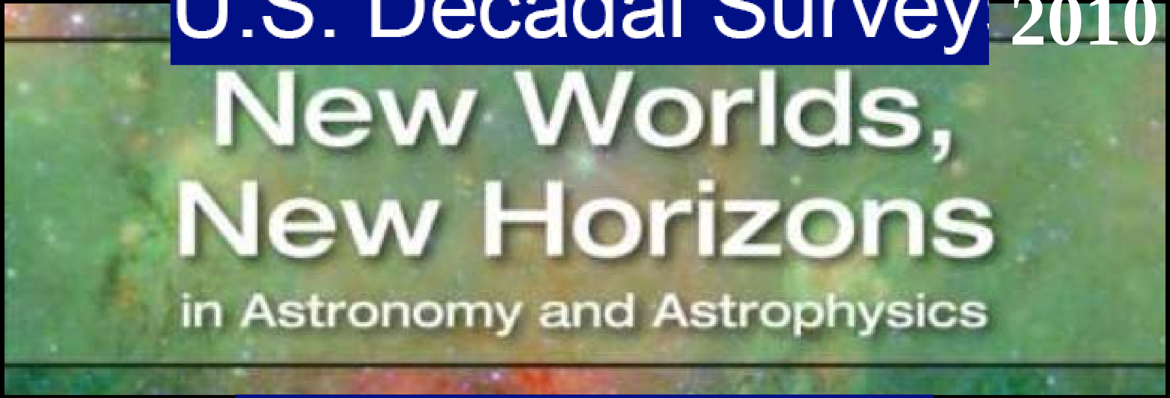
$_0S_{1=2}$



Spin Temperature

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

U.S. Decadal Survey 2010



principal questions

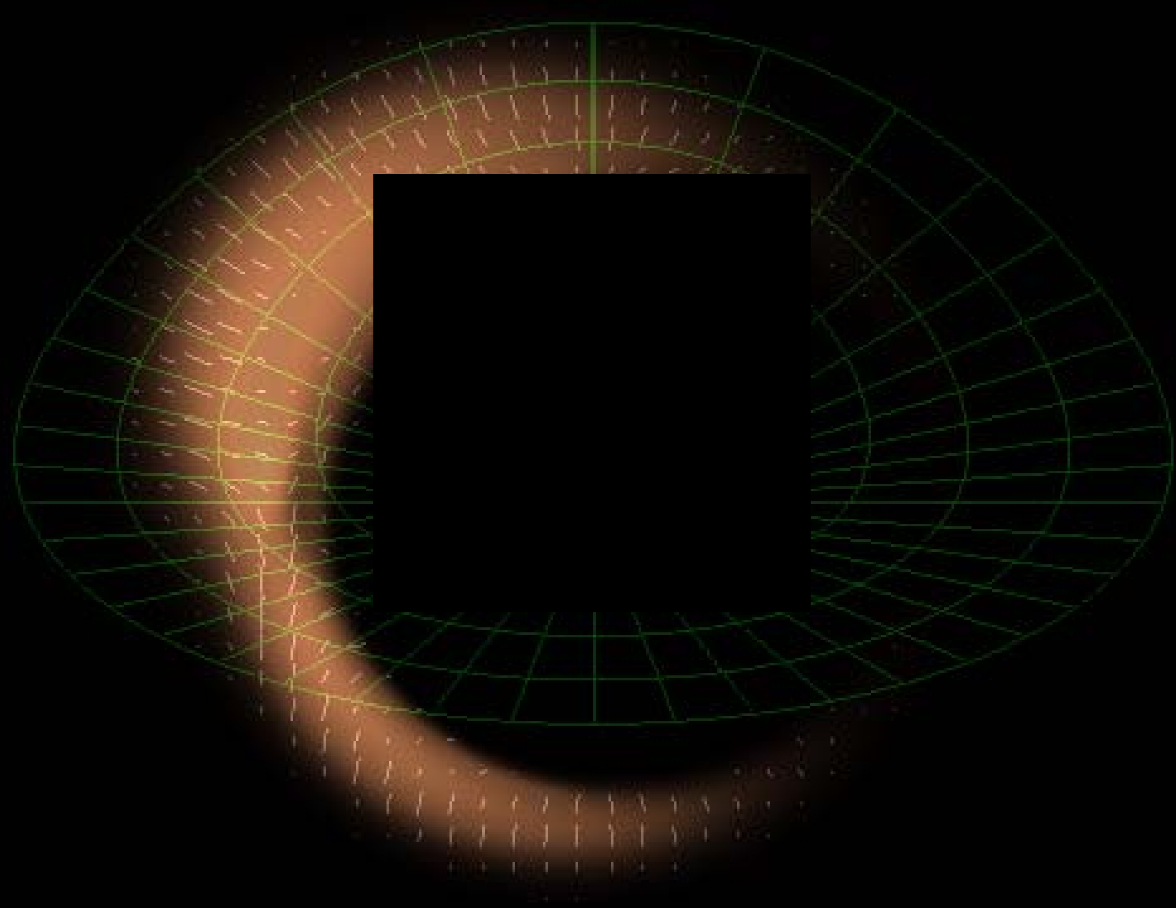
- How did the universe begin?
- What were the first objects to light up the universe and when did they do it?
- How do cosmic structures form and evolve?
- What are the connections between dark and luminous matter?
- What is the fossil record of galaxy assembly and evolution from the first stars to the present?
- How do stars and black holes form?

Cosmic Dawn

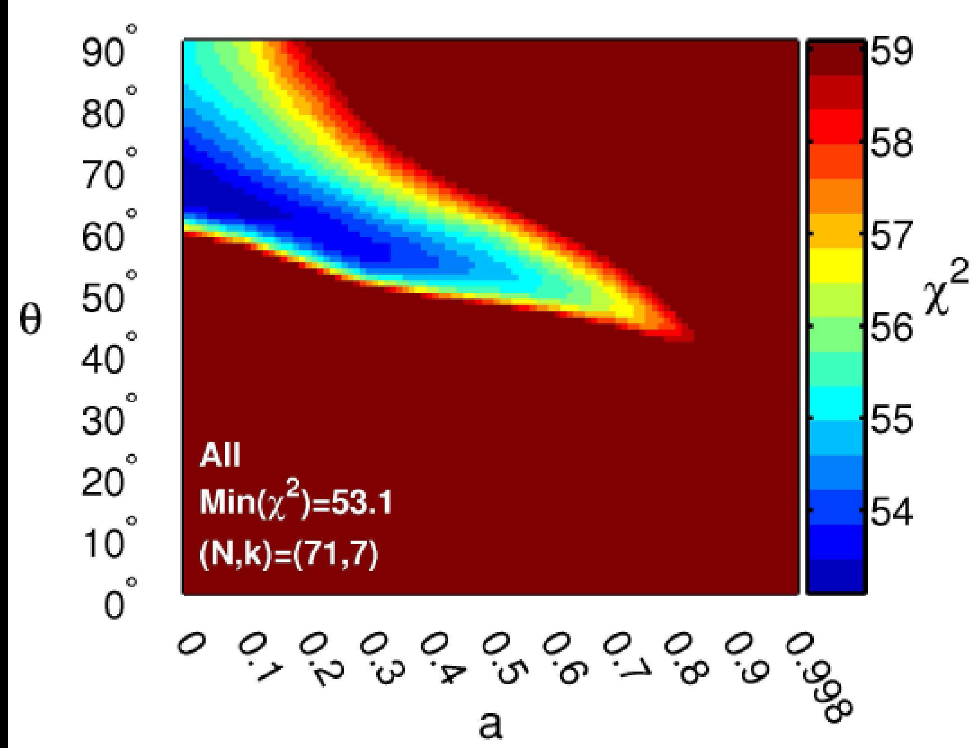
Searching for the first stars, galaxies, and black holes

– Locating “reionization” – finding the epoch ~0.5 billion years, when light from the first stars split interstellar hydrogen atoms into protons and electrons

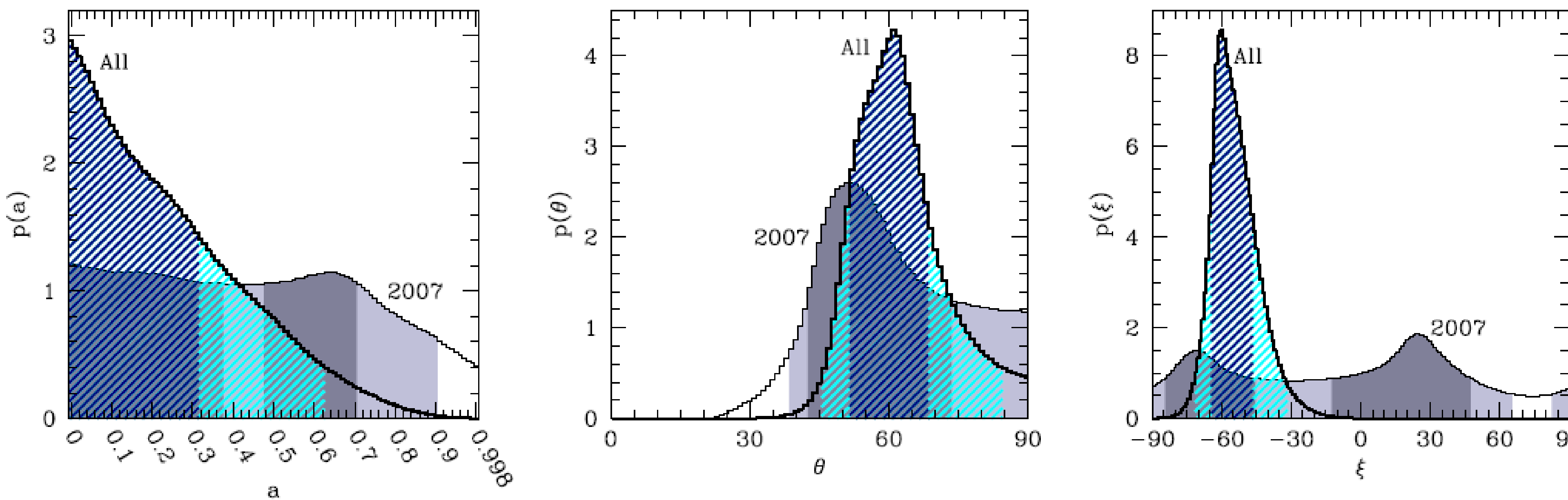
Physics + Astrophysics: Imaging Black Holes



Broderick & Loeb 2005



All
Min(χ^2)=53.1
(N,k)=(71,7)
θ
a
χ^2



All
2007
p(a)
a
p(θ)
θ
p(ξ)
ξ

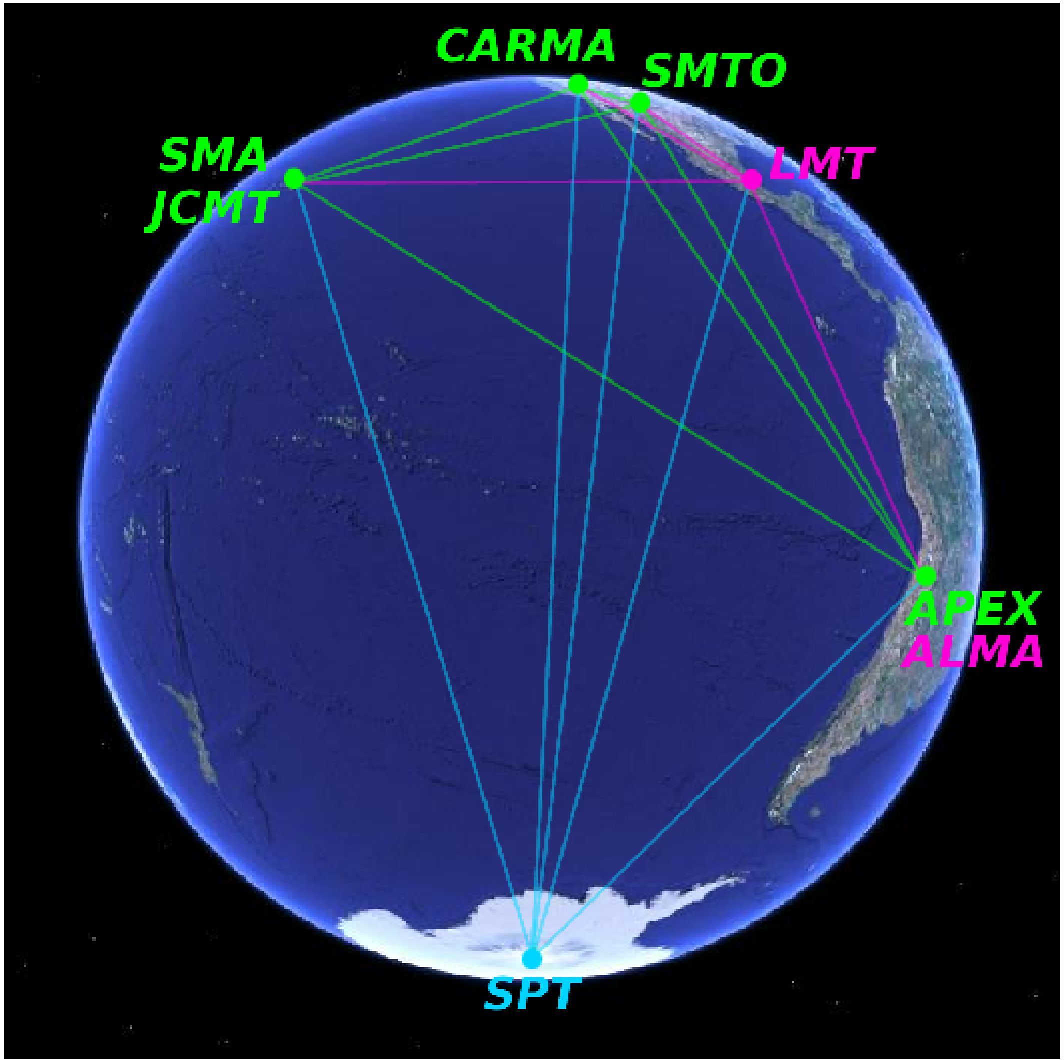
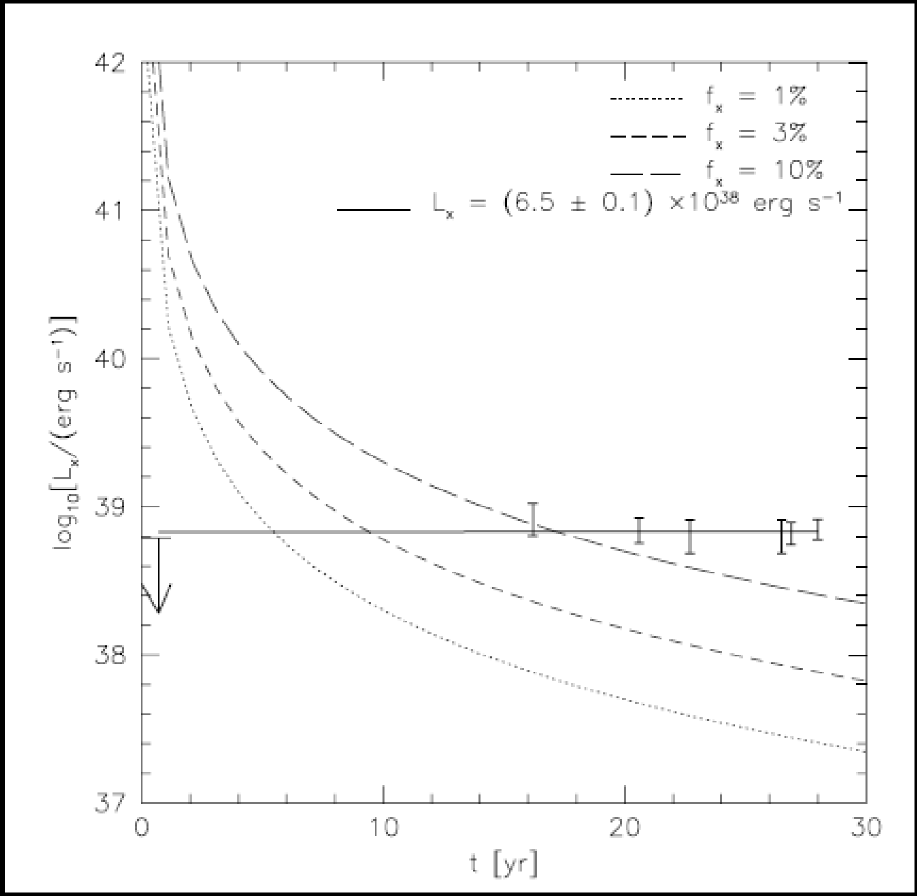


Figure 3: Existing and upcoming sub-millimeter radio telescopes in the Western hemisphere as seen from Sgr A*. Green telescopes already exist and are ready to be phased into a small array. The *Large Millimeter Telescope* (LMT) will begin operations at sub-millimeter wavelengths sometime next year. The *Atacama Large-Millimeter Array* (ALMA) is scheduled to be completed by 2012, though it will begin taking data in 2010. Already at the ALMA site, the *Atacama Pathfinder EXperiment* (APEX) is presently operating. Finally, the *South Pole Telescope* (SPT) needs only a millimeter receiver to be adapted for sub-mm VLBI. The projected baselines associated with these telescopes are shown in green for telescopes

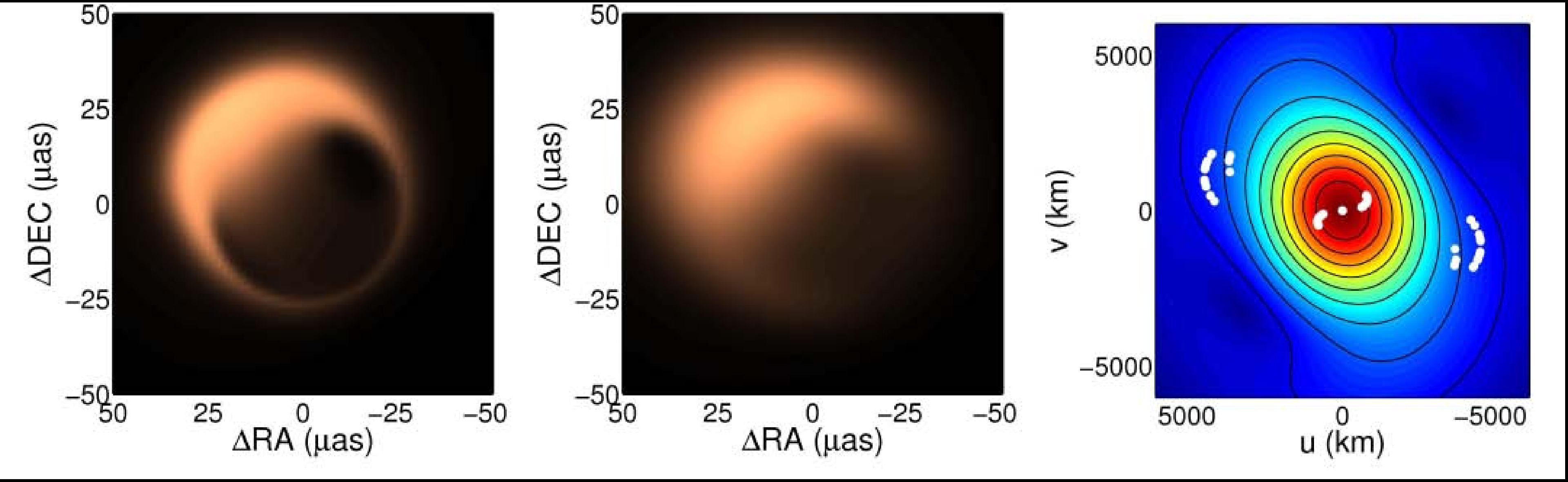
SN1979C: Possible Birth of a Black Hole

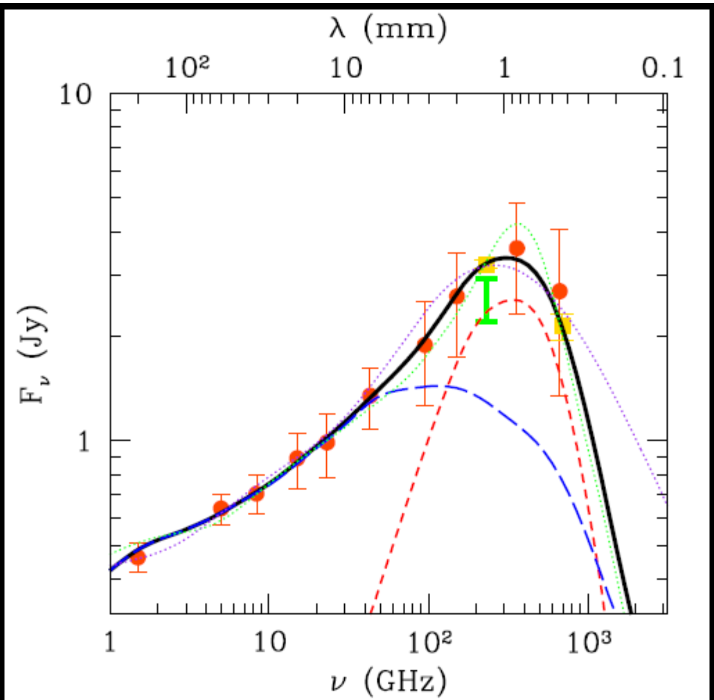


- SN IIL, 20Mì progenitor in M100
- Steady X-ray luminosity near the Eddington limit of a 5-10 Mì black hole

Patnaude, Loeb, & Jones 2010

Evidence for a Low-Spin BH in SgrA*



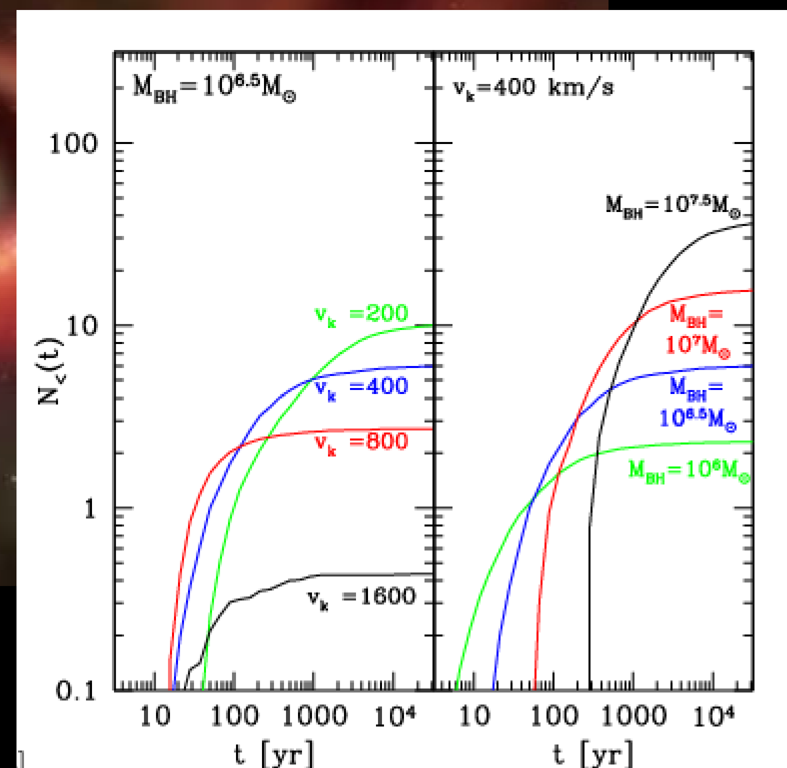


Broderick, Fish, Doeleman & Loeb 2010

EM Counterpart of LISA Sources: Tidal Disruption of Stars

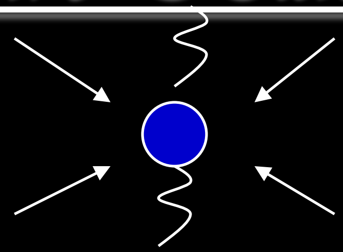
$r_t \propto (M/m_\star)^{1/3} R_\star$

"loss cone" filled by GW recoil



(Stone & Loeb 2010)

Massive Black Holes



Maximum (Eddington) luminosity is proportional to black hole mass M

Stellar mass seed requires ~billion years to grow to an SDSS quasar (   )

…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…

Black Hole Recoil

Physics

Astrophysics

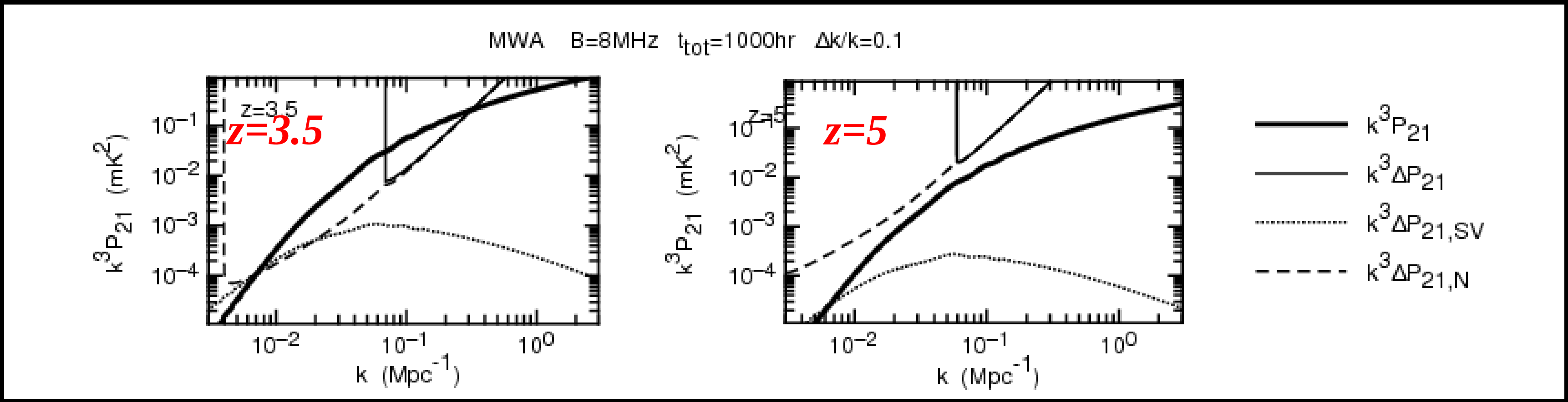
(Centrella et al.   2007)

(Blecha & Loeb 2009)

21cm Cosmology After Reionization?

Damped Lya absorbers:

→ on 10cMpc



Acoustic peak: constrain dark energy at 0<z<15

Wyithe & Loeb 2007