What to Expect at H^0 and He^+ Reionization?

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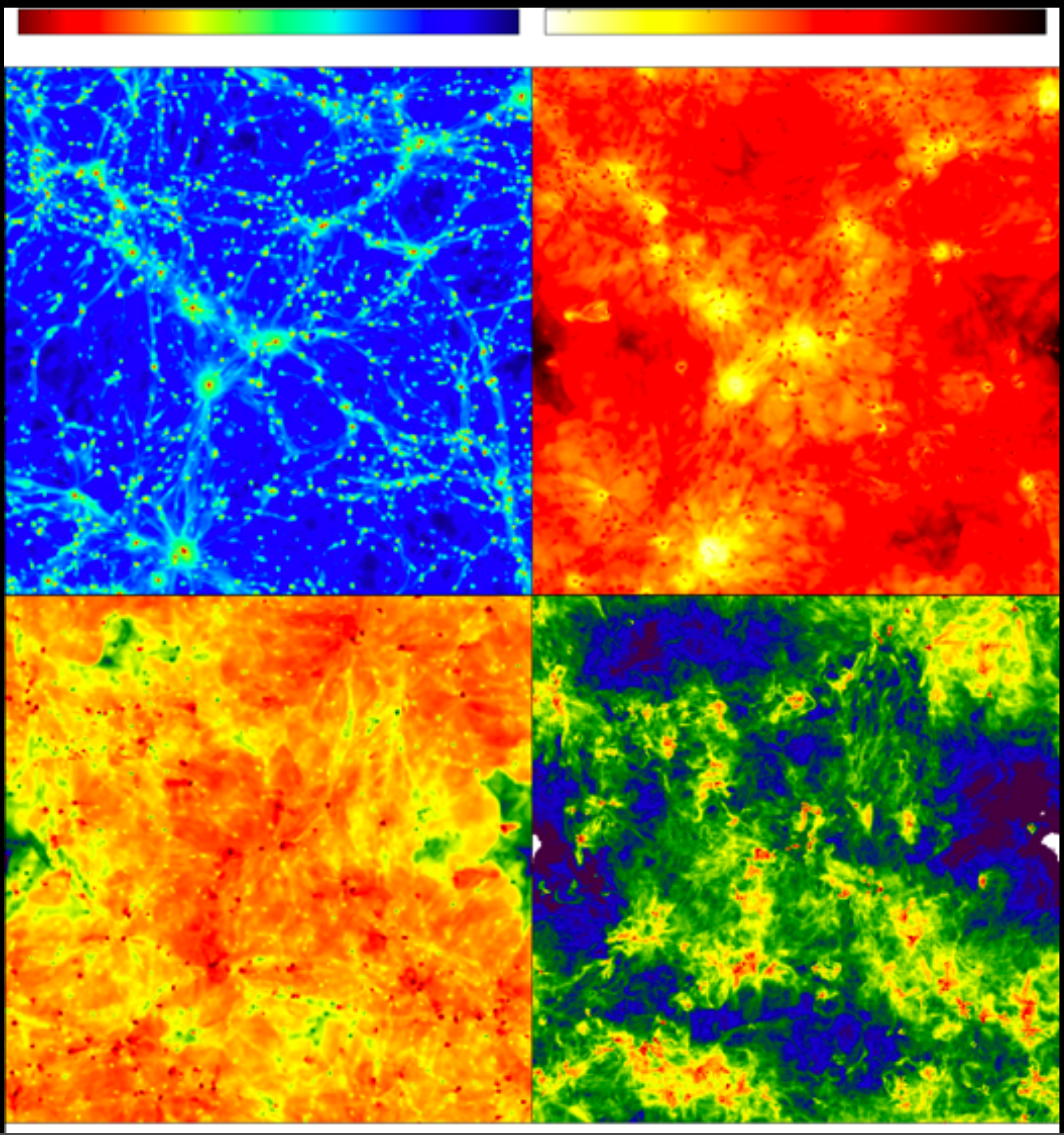
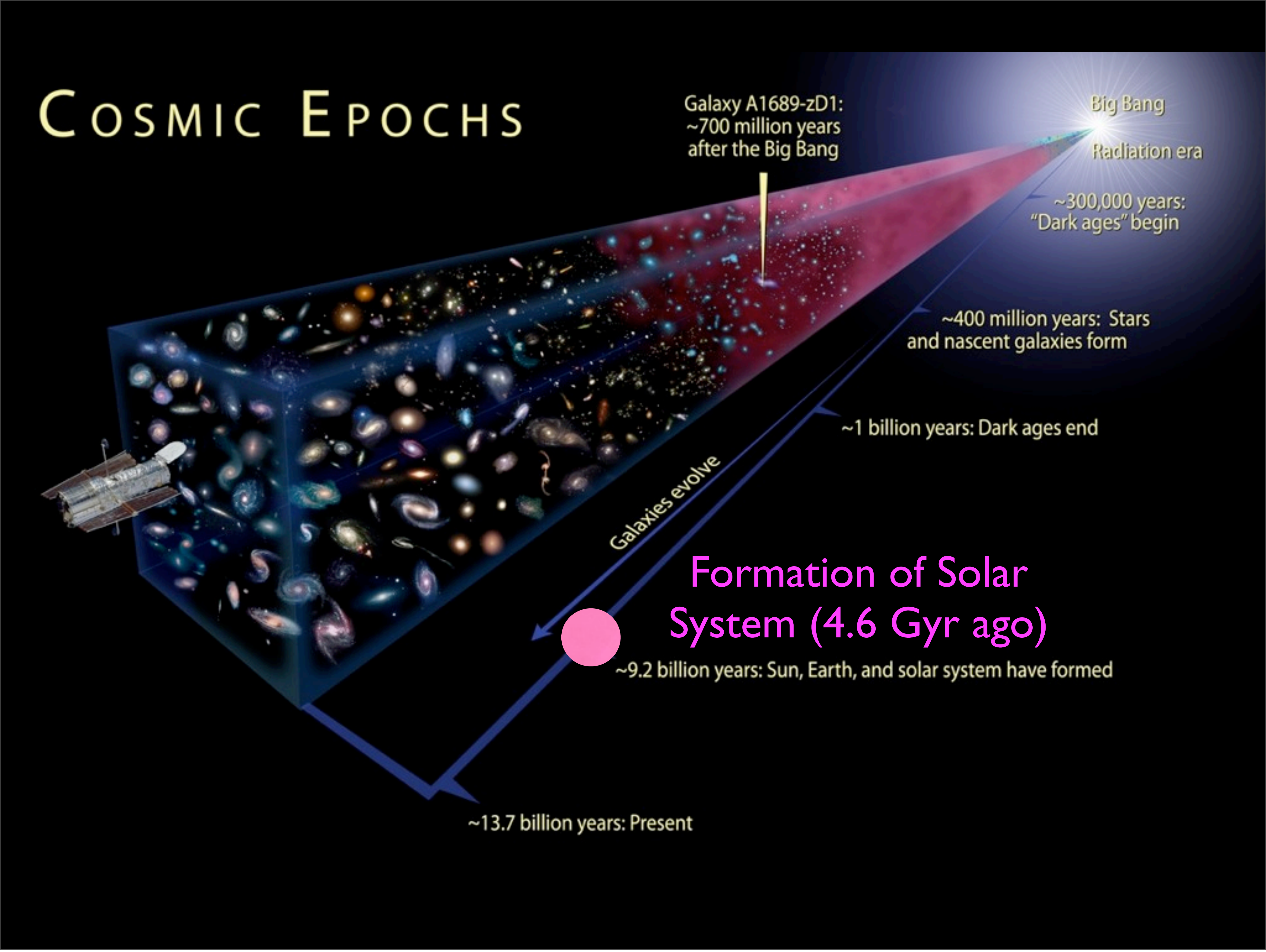


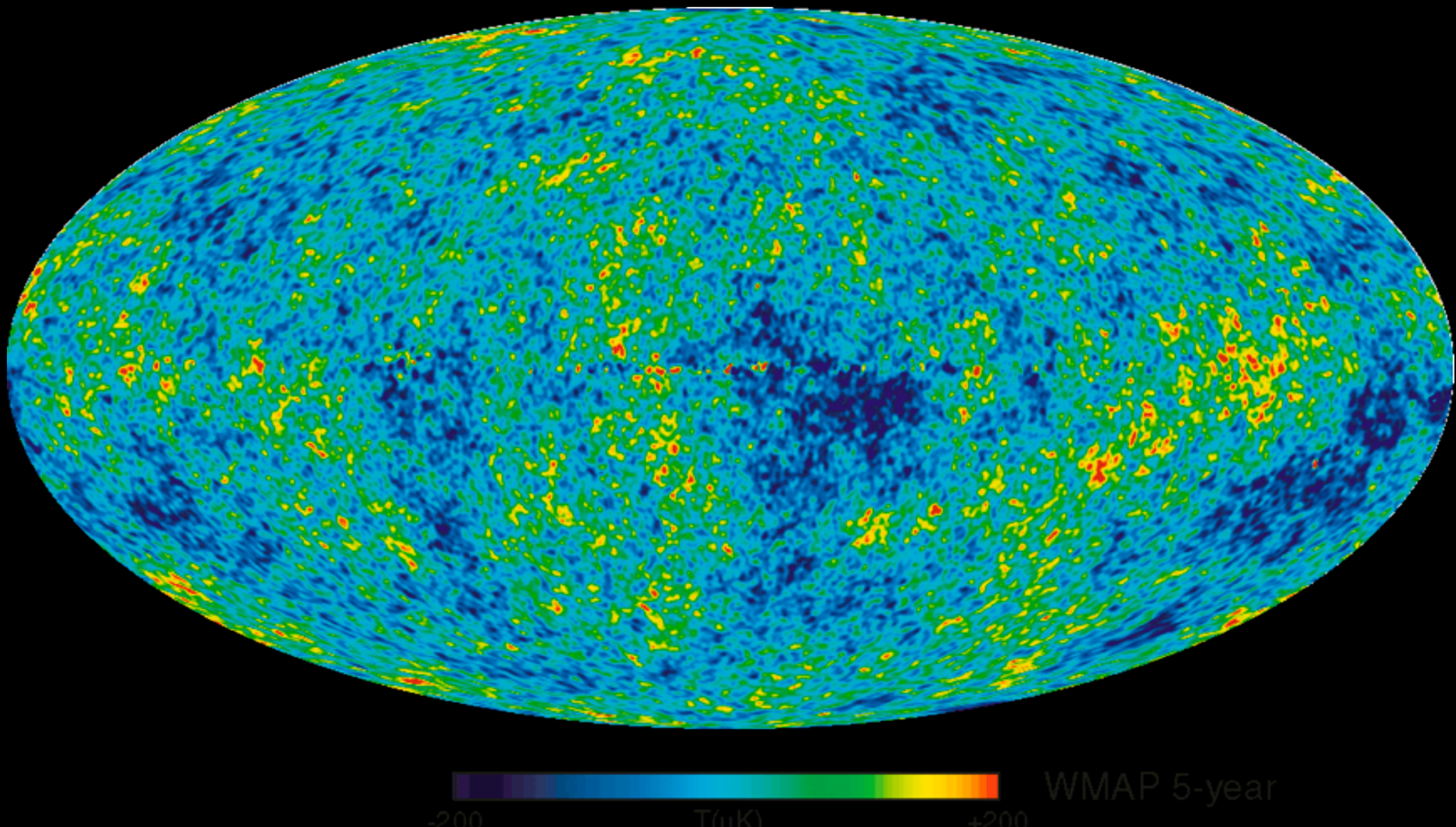
Lunar Astrophysics Conf.
(Boulder, CO Oct 5, 2010)


Cosmic Epochs
Galaxy A1689-zD1:
~700 million years
after the Big Bang
Big Bang
Radiation era
~300,000 years:
"Dark ages" begin
~400 million years: Stars
and nascent galaxies form
~1 billion years: Dark ages end
Galaxies evolve
Formation of Solar
System (4.6 Gyr ago)
~9.2 billion years: Sun, Earth, and solar system have formed
~13.7 billion years: Present

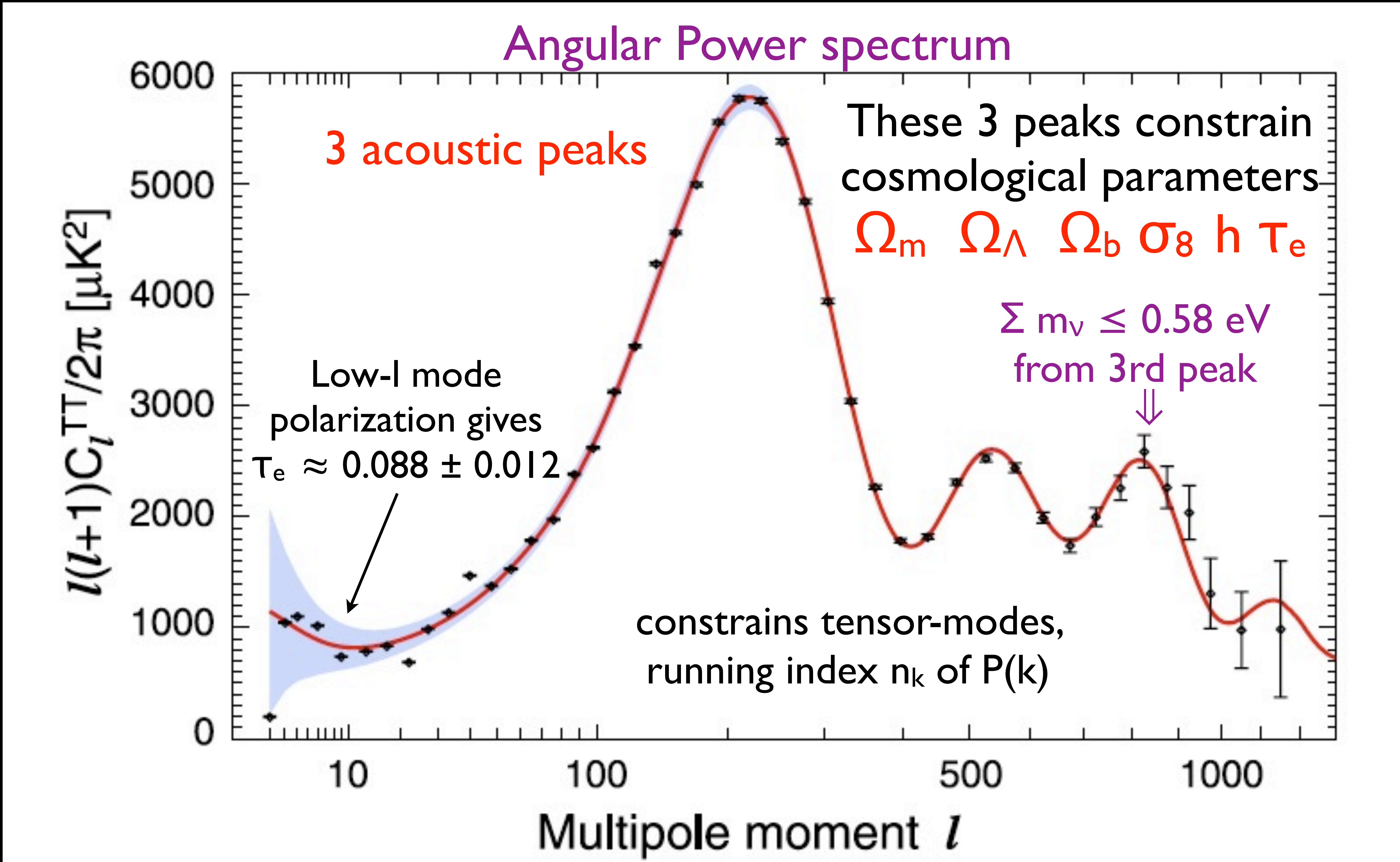
Cosmic Microwave Background

Seeds for the the first structures (t = 380,000 yr)

(These temperature fluctuations are only 1 part in 10^5)



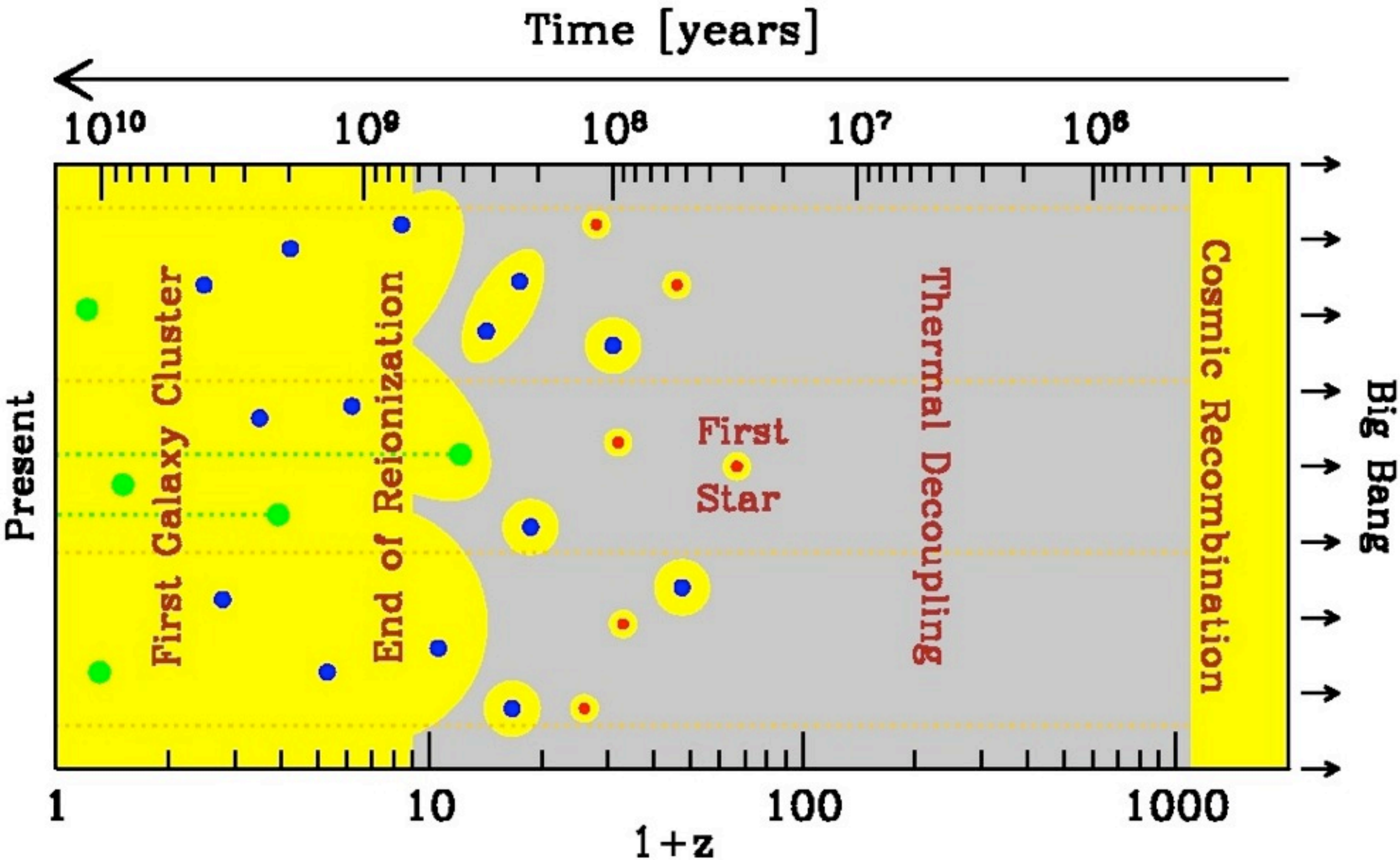
WMAP-7 (7-year CMB data)



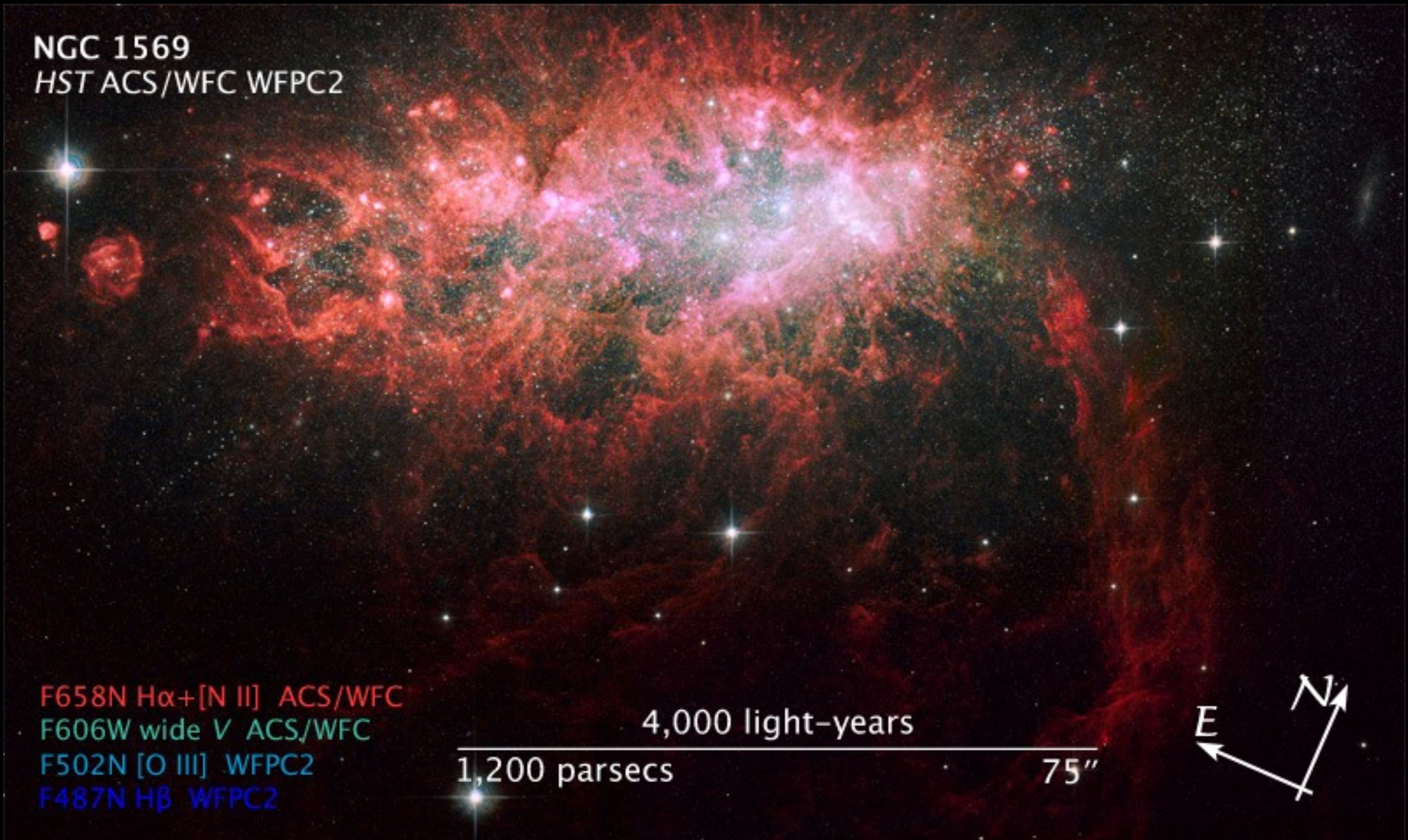
Komatsu et al. (2010)

Schematic: Great Moments after the Big Bang

$z_{rec} \approx 1090$; $z_{rei}(H) \approx 7\text{-}10$; $z_{rei}(He^{+}) \approx 2.7$

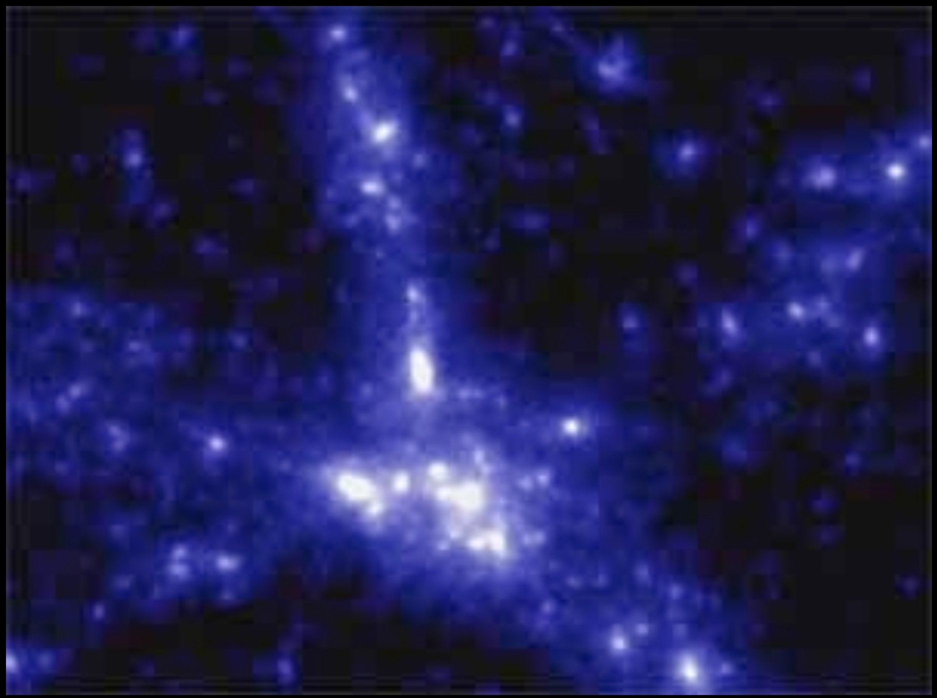


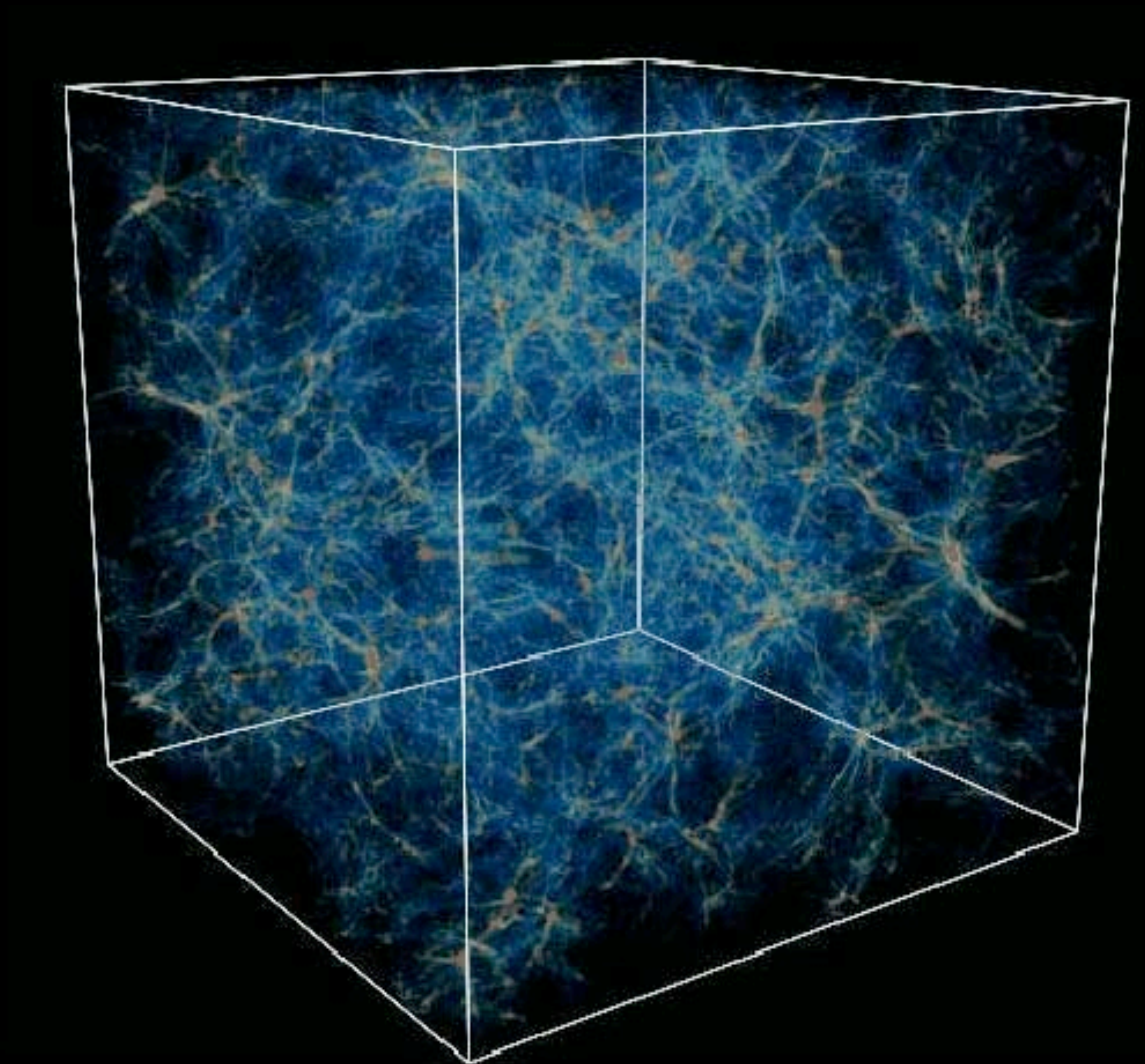
Star Formation in nearby galaxy
"only" 11 Million light years away

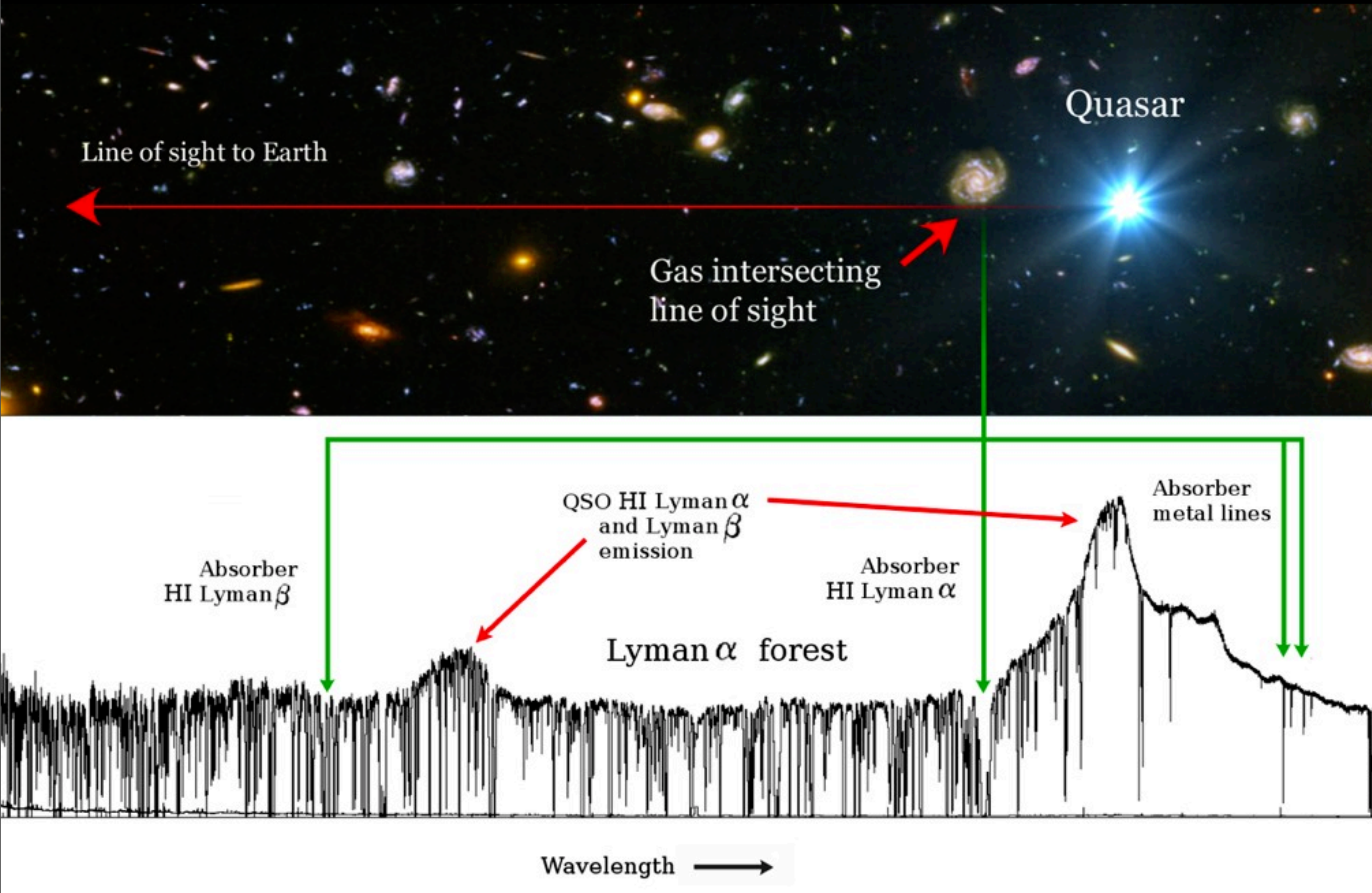


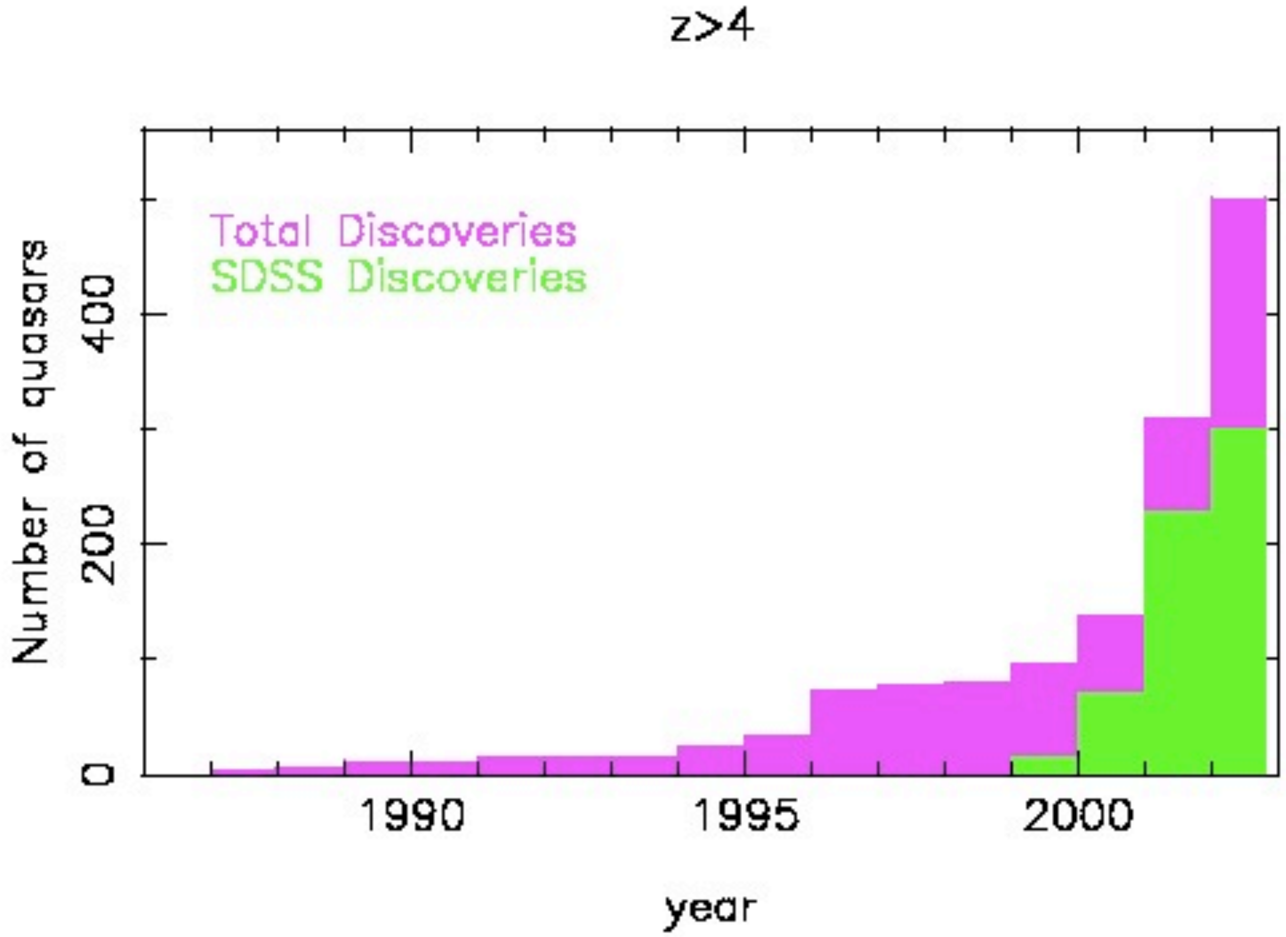
The "Cosmic Web" of Intergalactic Matter

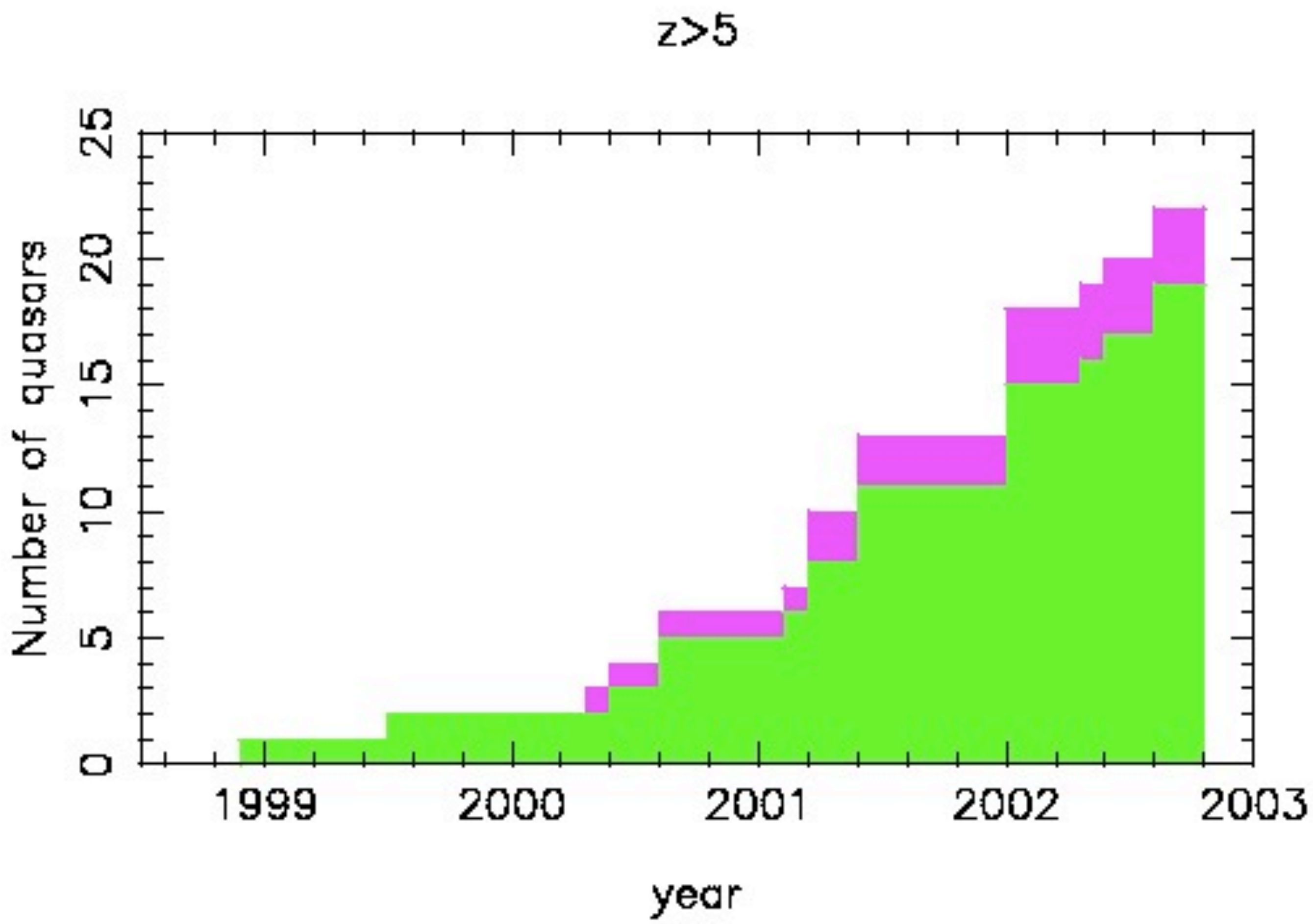
12-13 Billion Yrs Ago -- First Galaxies and New Stars






Quasar
Line of sight to Earth
Gas intersecting line of sight
QSO HI Lyman α and Lyman β emission
Absorber metal lines
Absorber HI Lyman β
Absorber HI Lyman α
Lyman α forest
Wavelength



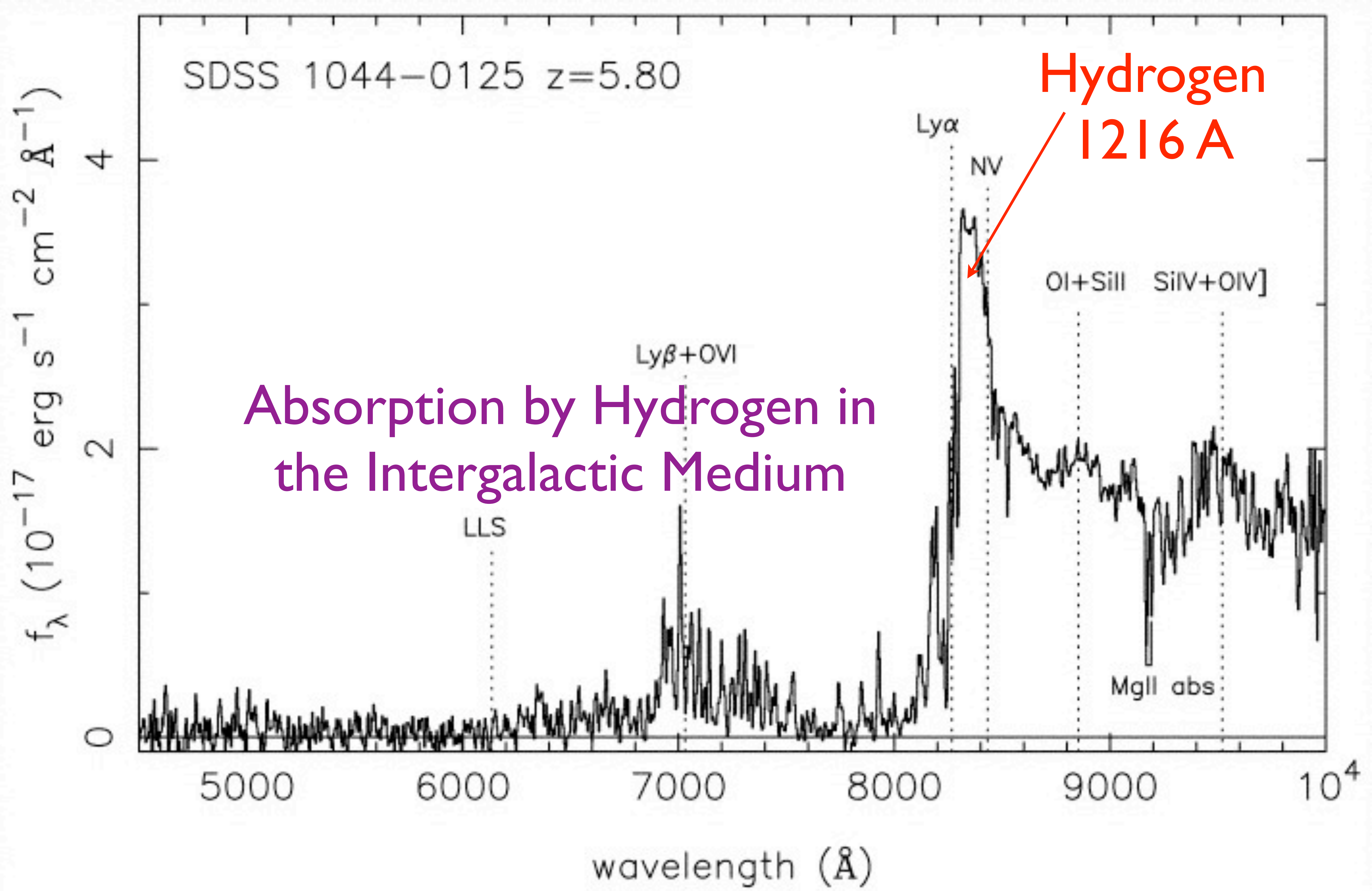


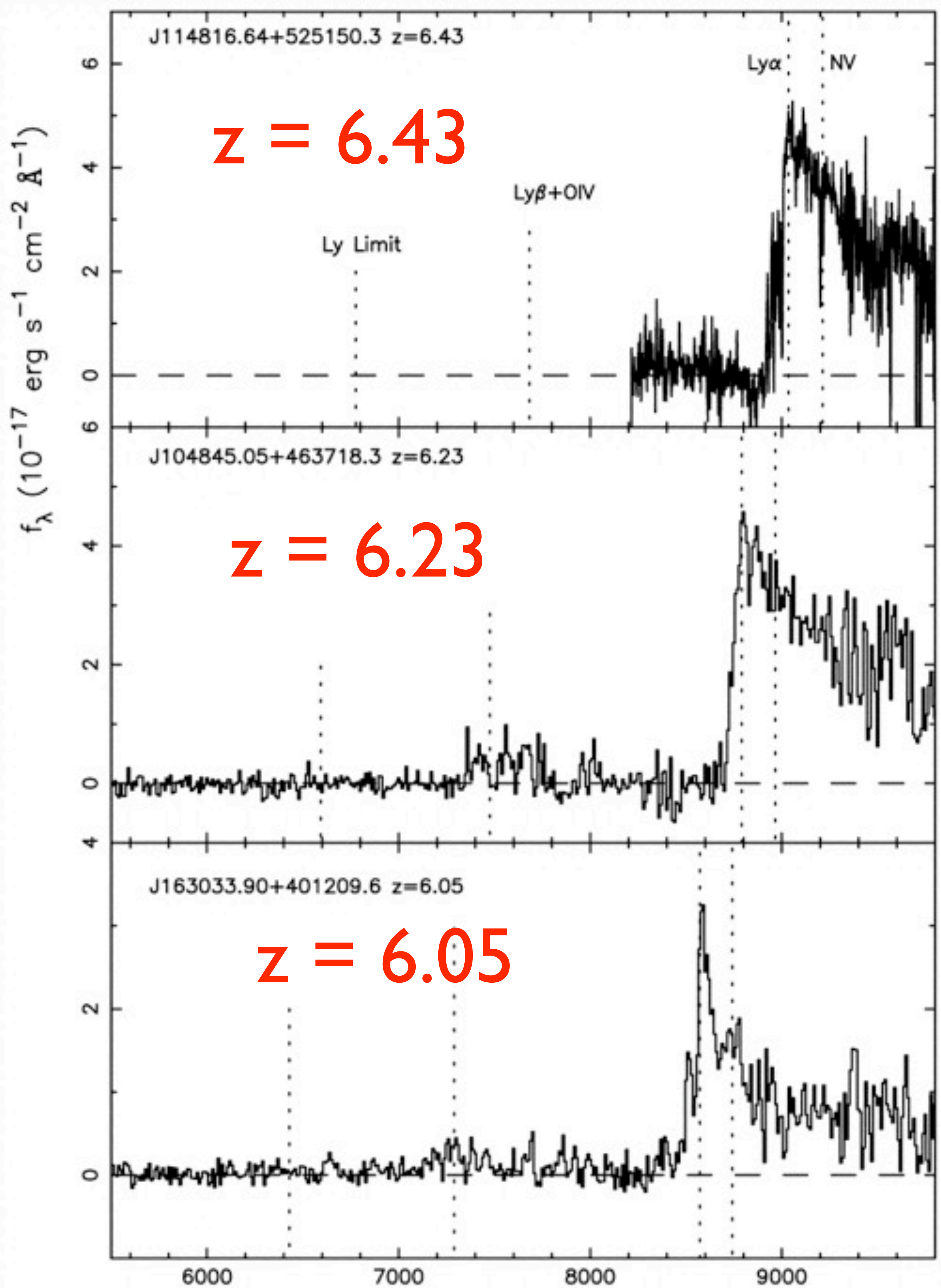
Increase in numbers of high-z Quasars

Xiaohui Fan 2006

Large-Scale Surveys (Sloan 2.5m telescope)

Quasar at redshift z = 5.80





Spectra of 3 quasars at redshifts z > 6

"Lookback times":

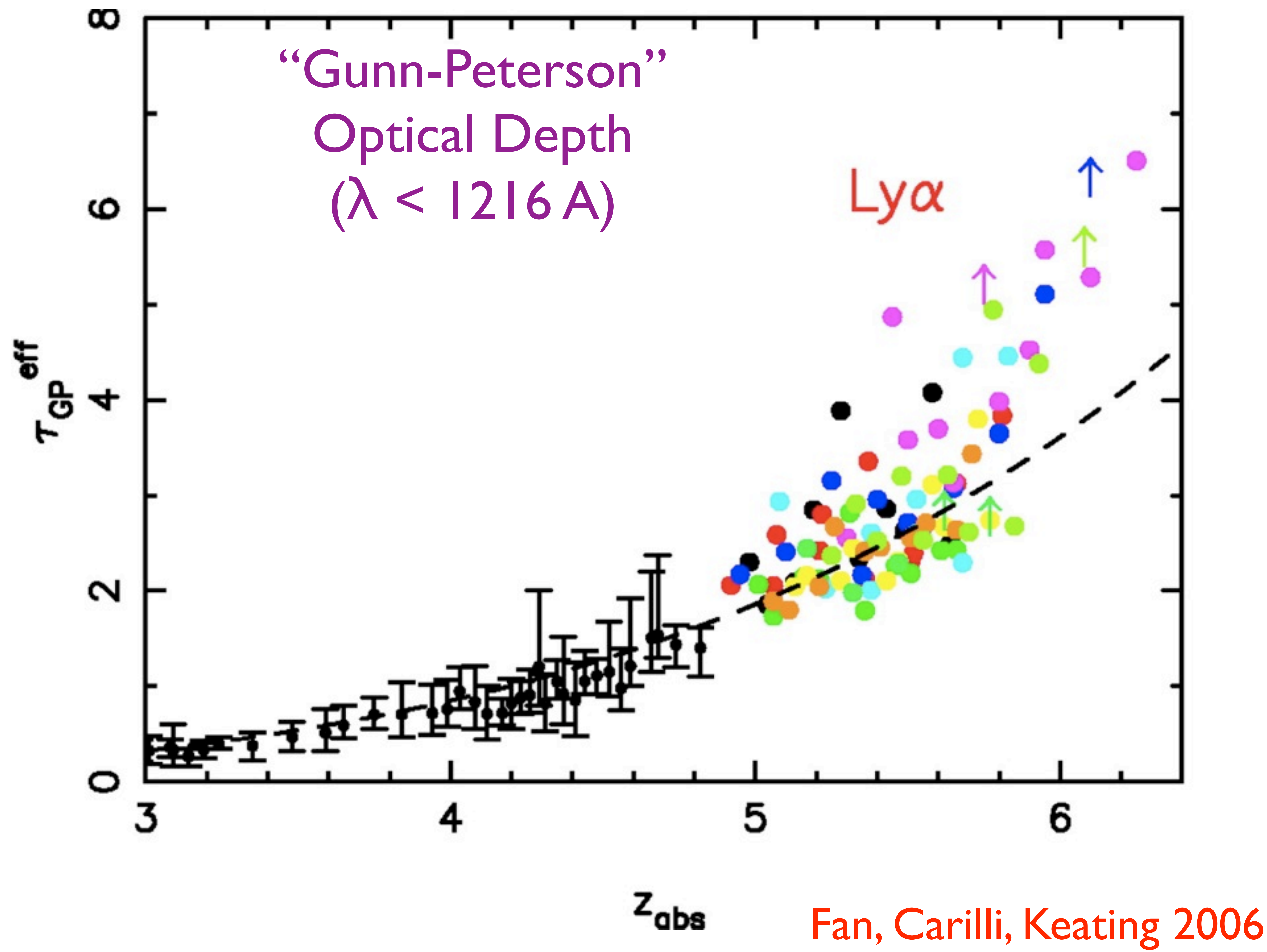
z	Age (Gyr)
6.43	12.676 Gyr
6.23	12.640 Gyr
6.05	12.606 Gyr

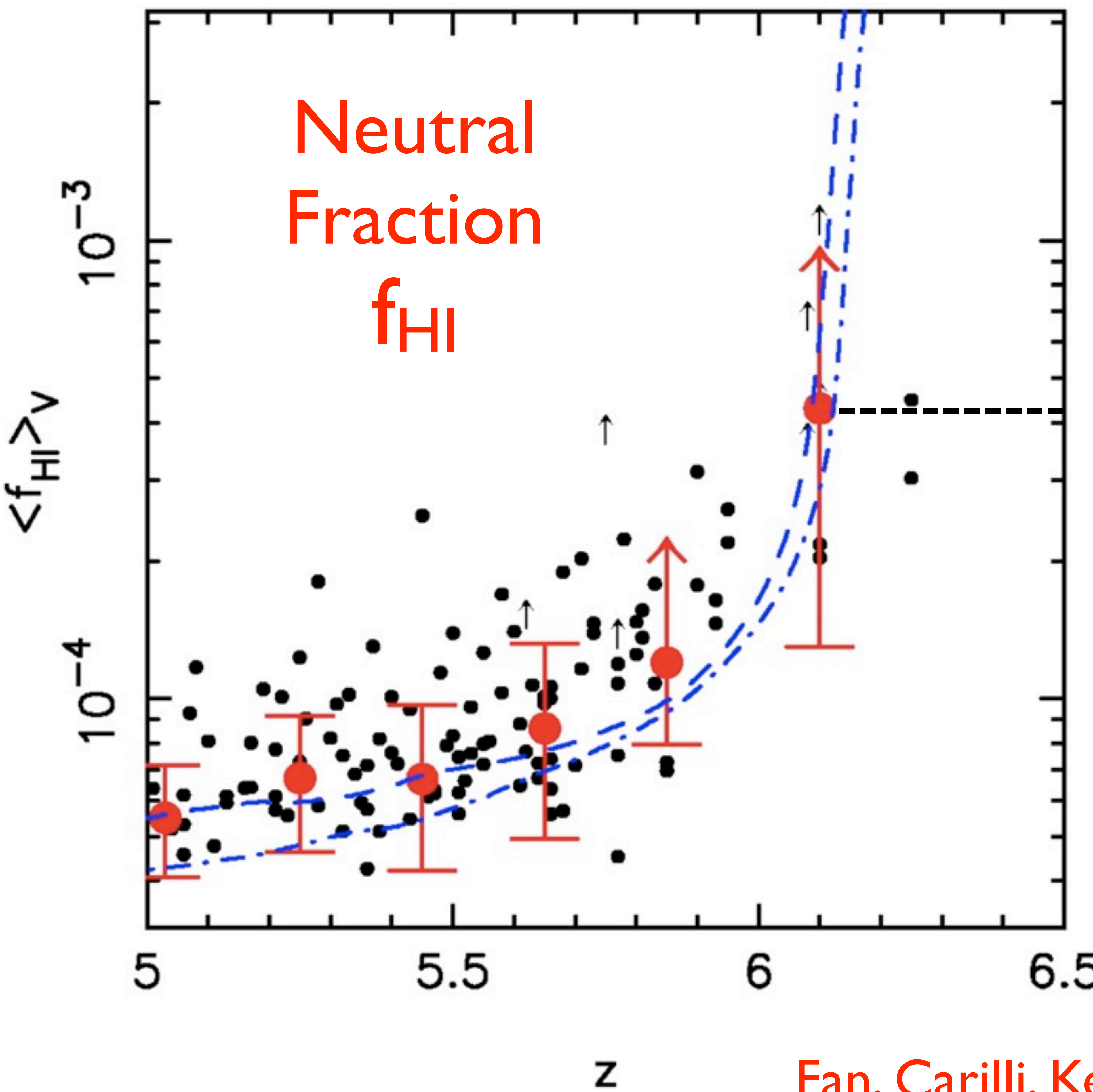
Gunn-Peterson Optical Depth

$$\tau_{GP} = (\pi e^2/m_e c)[\lambda_{Ly\alpha}\, f_{Ly\alpha} / H(z)]\, n_{HI}$$
$$\approx (4\times 10^5)\, [(1+z)/7]^{3/2}\, \underbrace{f_{HI}}_{\text{neutral fraction}}\, \underbrace{\delta_H}_{\text{over-density}}$$

At z = 6, even a neutral fraction of 10^{-4} will produce $\tau_{GP} = 40$

(the current limit is $\tau_{GP} \approx 6$ (at z = 6.1)


"Gunn-Peterson"
Optical Depth
(λ < 1216 A)
Lyα
τ_{GP}^{eff}
z_{abs}
0
2
4
6
8
3
4
5
6
Fan, Carilli, Keating 2006

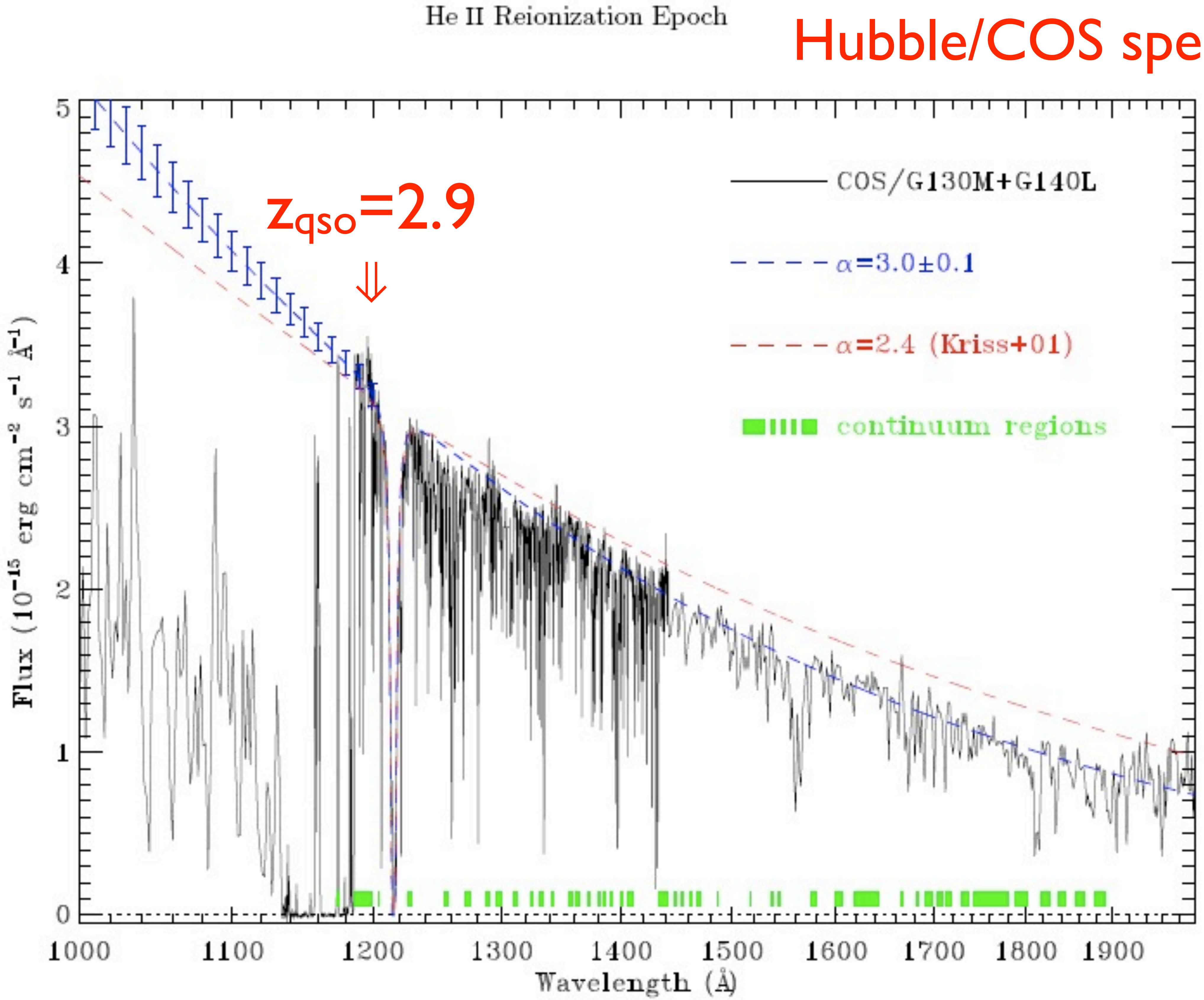


4×10^{-4}
($z = 6.1$)

Fan, Carilli, Keating 2006

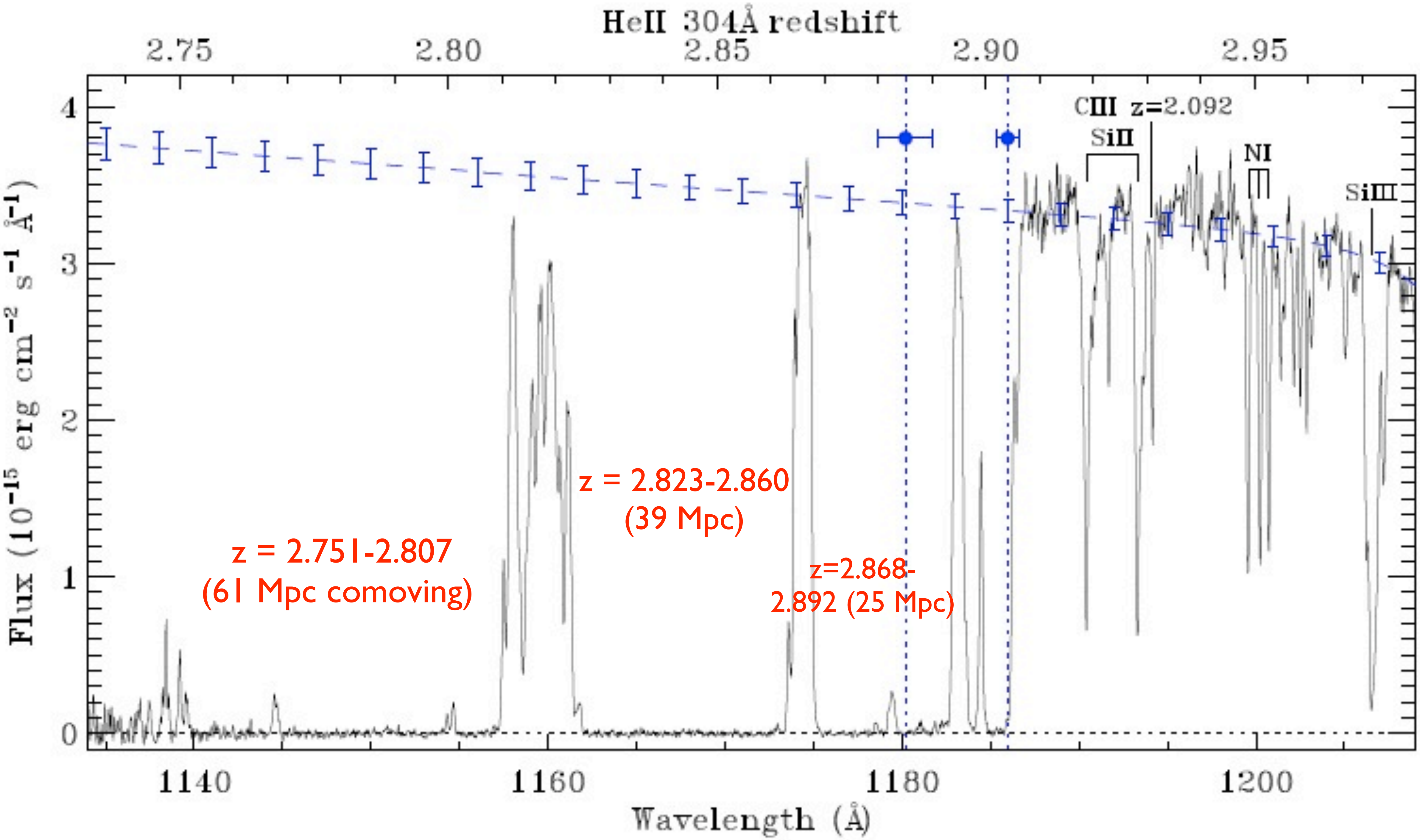
He II Gunn-Peterson Absorption

Hubble/COS spectra



Shull, et al. 2010 (ApJ, 722, 1312)

Patchy He II Reionization (z ≈ 2.7-2.9)
(Note long troughs of strong absorption)



Shull et al. 2010

Summary of what's known about z_{rei}

(1) Gunn-Peterson (H I Lyα absorption)

τ_{GP} is rising fast: $\tau = 6$ at $z = 6$

$\langle f_{HI} \rangle = 4\times10^{-4}$ at this epoch ($t = 1$ Gyr)

Some simulations suggest that $z_r \approx 6.3 \pm 0.2$

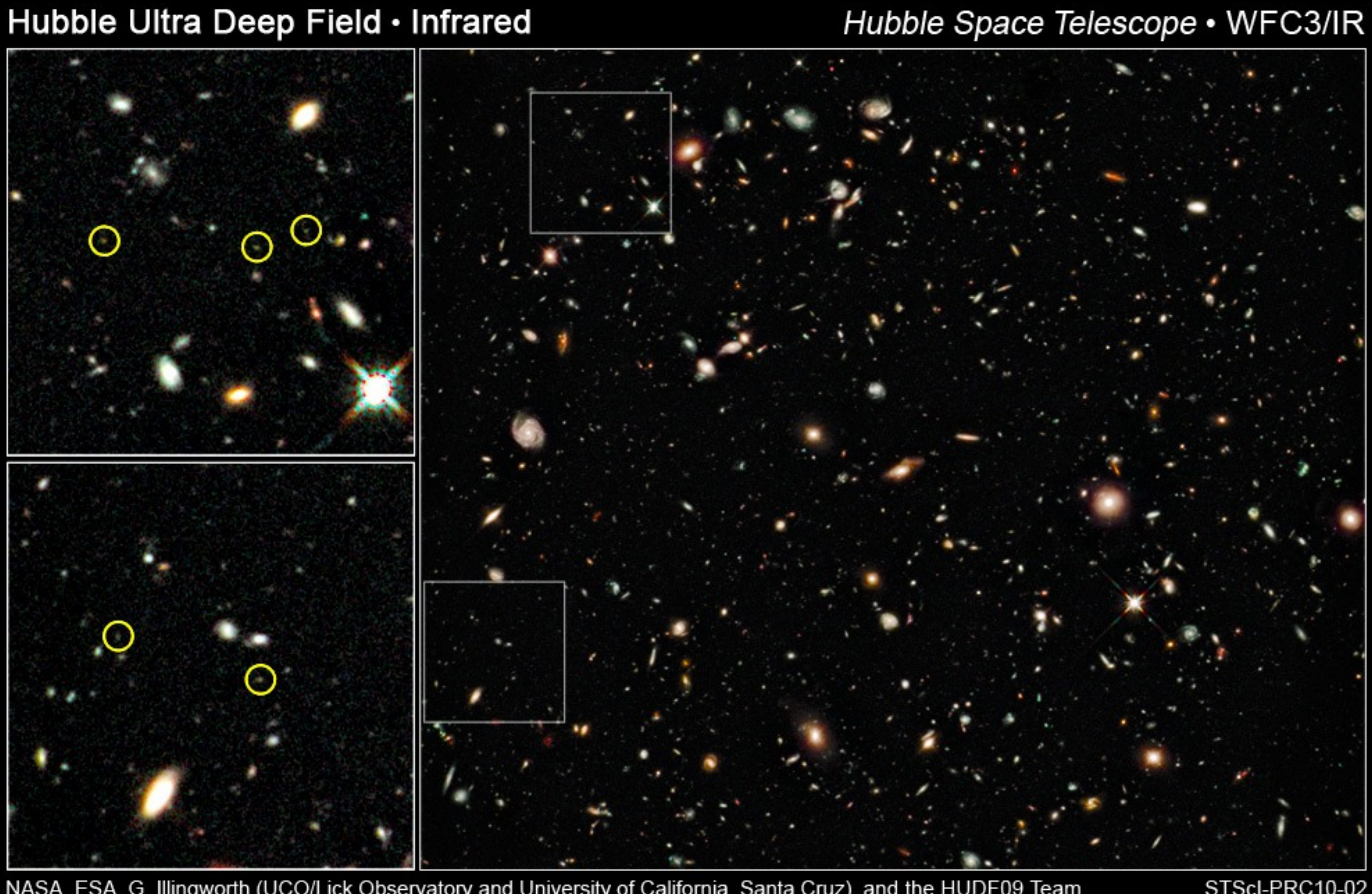
A partially ionized IGM ($z = 7$-15)?

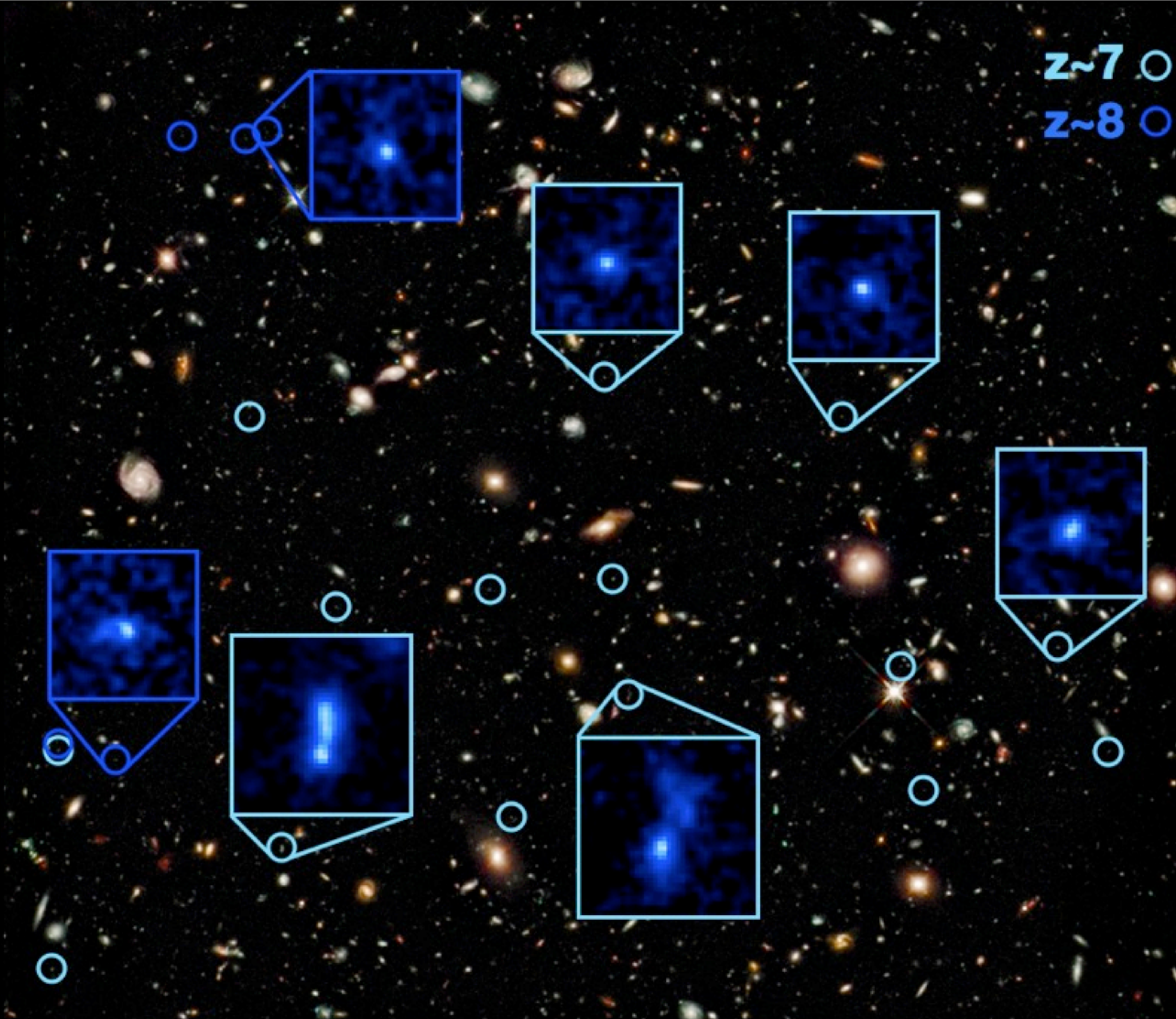
(2) CMB optical depth ($\tau_e = 0.088 \pm 0.015$)

WMAP-7: $z_{rei} \approx 10.5 \pm 1.4$ (1σ)

Half this value ($\tau_e = 0.05$) could be produced by ionized IGM back to $z = 7$

News Release (Jan 2010) - Early Galaxies





HUDF09 WFC3/IR Image with z~7 and z~8 Galaxies

Credit: NASA, ESA, G. Illingworth, R. Bouwens (University of California, Santa Cruz), and the HUDF09 Team.

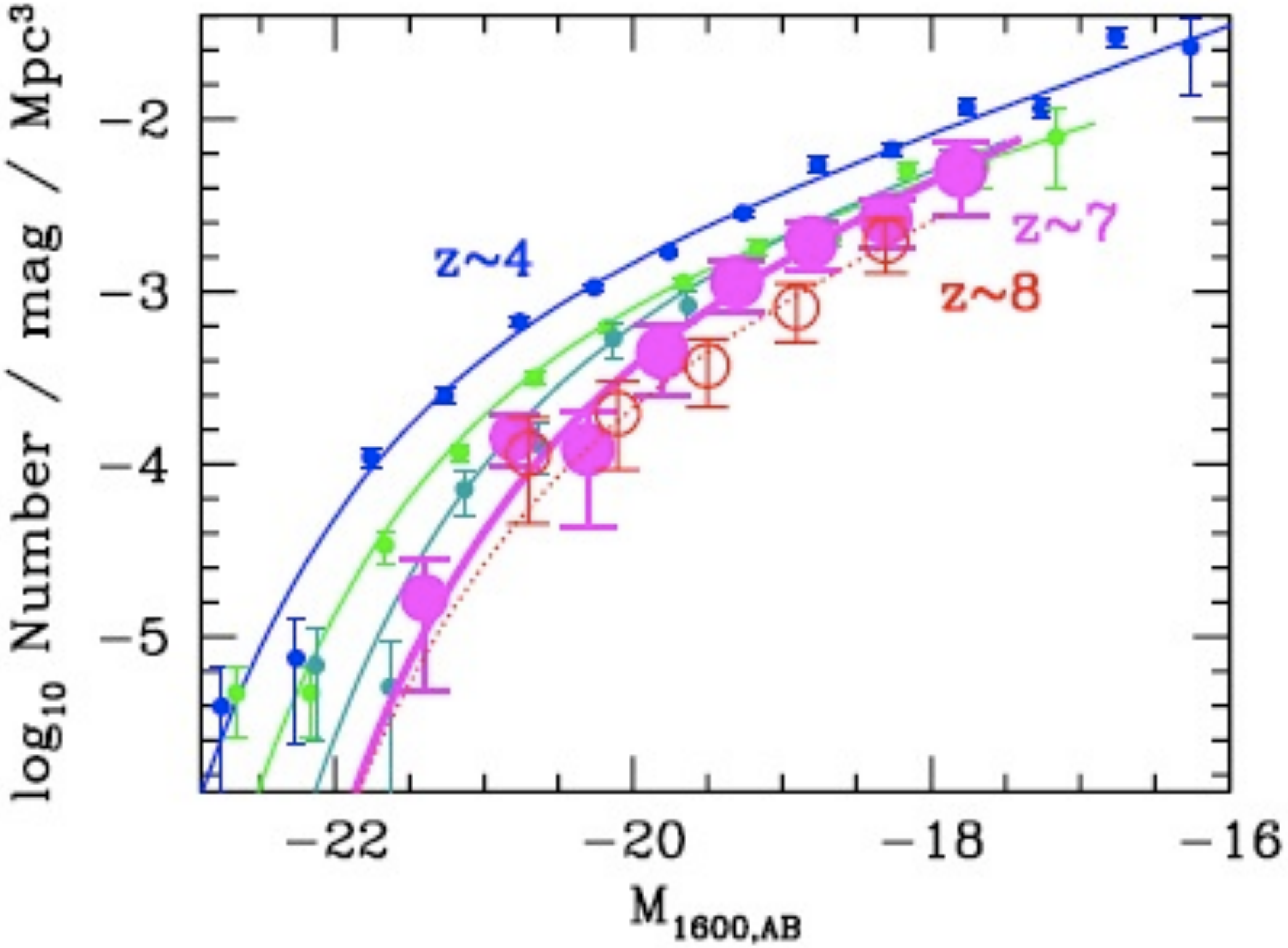


FIG. 12.— Rest-frame *UV* LFs derived for galaxies at $z \sim 7$ (*magenta circles with* 1σ *errors*) at $z \sim 8$ (*open red circles*), compared against similar LF determinations at $z \sim 4$ (*blue*), $z \sim 5$ (*green*), and $z \sim 6$ (*cyan*) from Bouwens et al. (2007). The $z \sim 7$ LF results incorporate the Bouwens et al. (2010d) NICMOS + ISAAC + MOIRCS search results (see Figure 10). The upper limits are 1σ. The magenta and red lines show the best-fit Schechter functions at $z \sim 7$ and $z \sim 8$. The uniformly steep faint-end slopes α of the *UV* LF are quite apparent. Most of the evolution in the *UV* LF from $z \sim 8$ to $z \sim 4$ appears to be in the characteristic luminosity (by $\sim$1 mag).

Galaxy Luminosity Function

evolving rapidly from z = 8⇒4

Faint-end slope steeper at z = 7-8

$\Phi(L) = \Phi^*(L/L^*)^\alpha \exp(-L/L^*)$

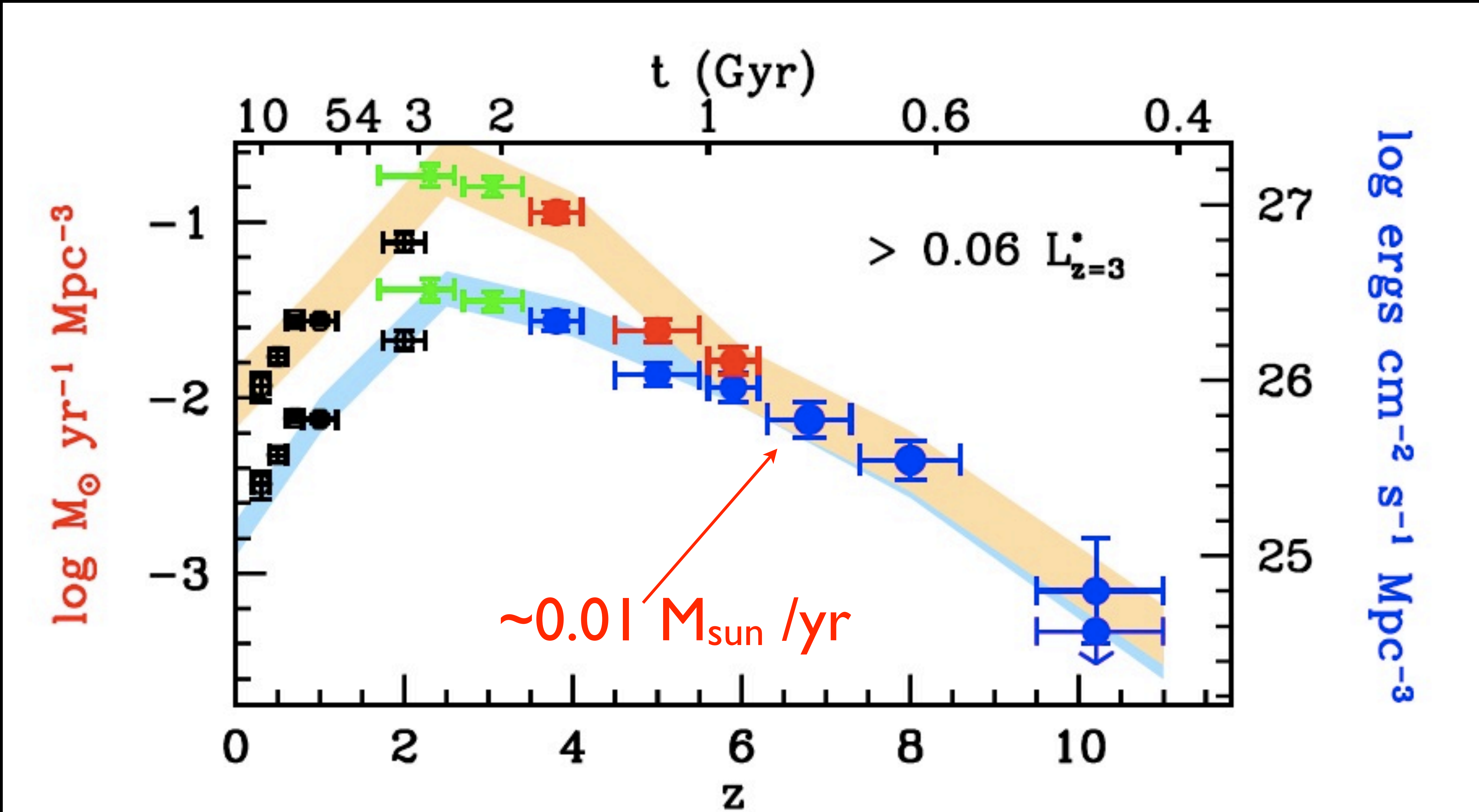
$\alpha \approx -1.2$ ($z < 1$)

$\alpha \approx -1.9$ ($z > 7$)

Oesch et al.
Bouwens et al.
2010, ApJ

Global Star-Formation Rate (density)

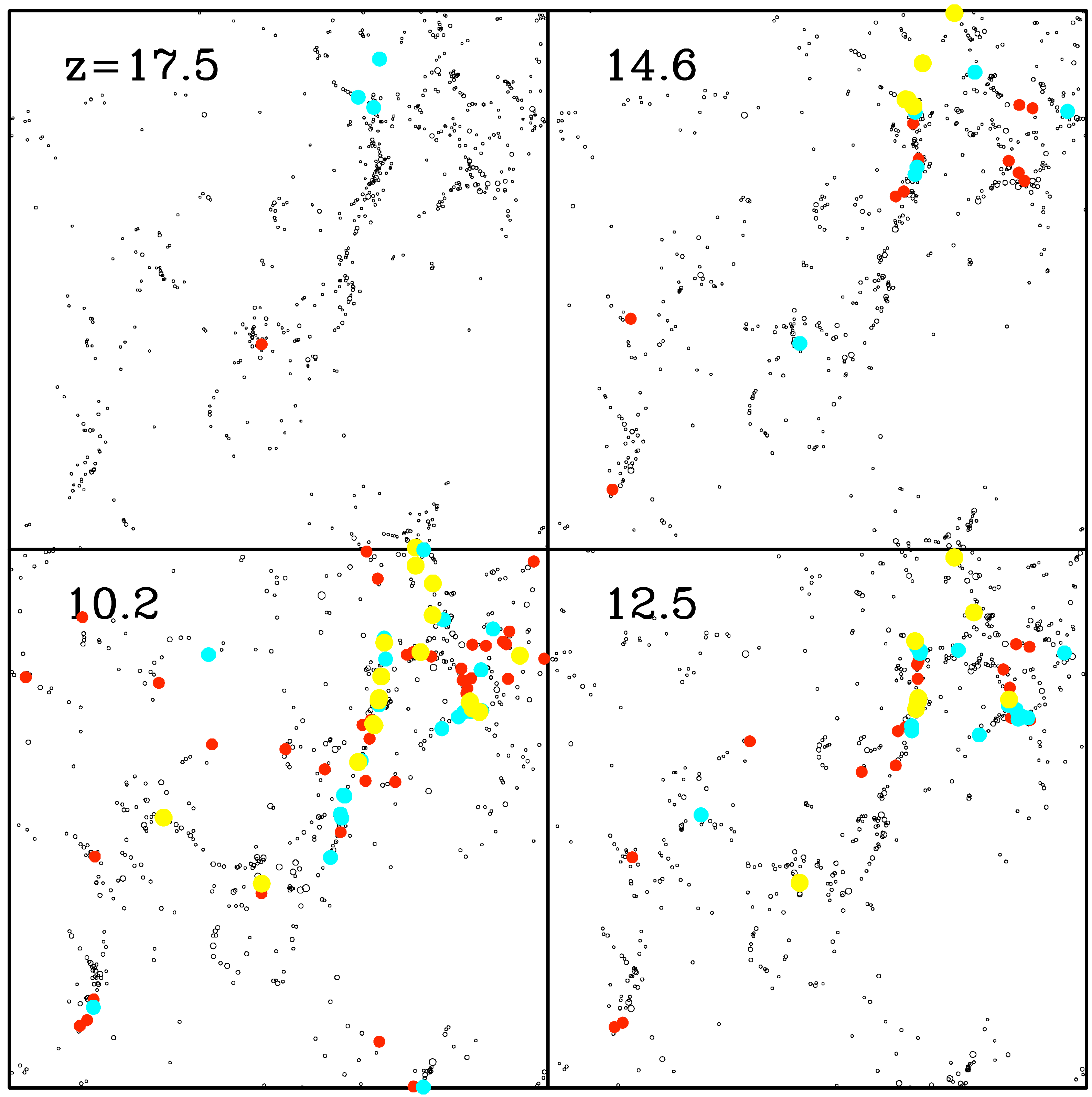
Bouwens et al. (2010)



This SFR density is insufficient for $z_{rei} > 7$

Computer Simulations: First Galaxies

(Ricotti, Gnedin & Shull 2008 -- dwarf galaxy chains)



What are the main uncertainties in determining the Epoch of Reionization (for hydrogen)?

Major concern:

* Reconcile GP ($z = 6.5$) and CMB ($z = 10$)

**Planck mission may help here*

(1) Faint-end of luminosity function (α, L_{min})

(2) IGM topology (filaments, voids, clumping)

(3) Escape fraction (f_{esc}) of ionizing photons

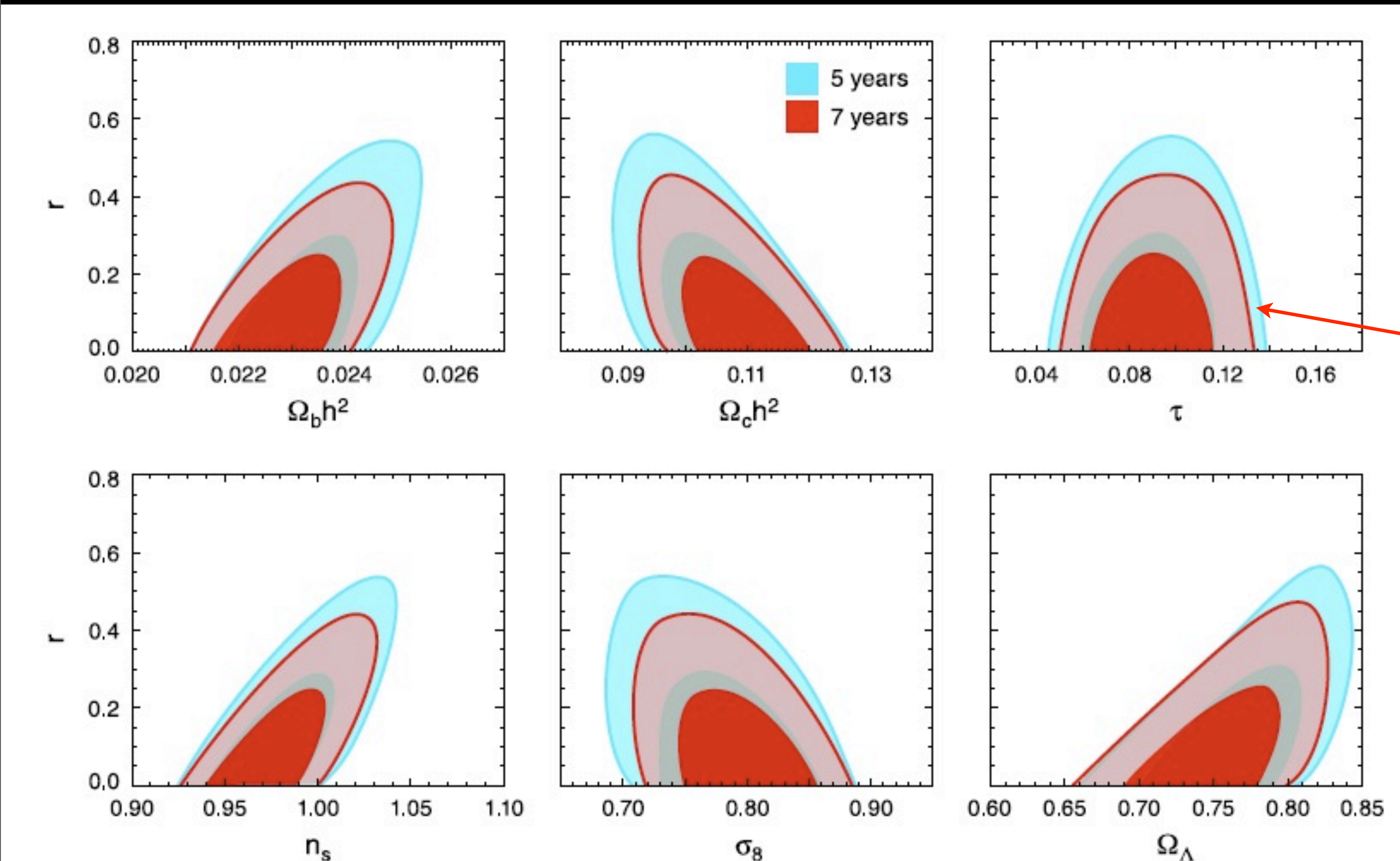
(4) X-ray emissivity (black holes, XRBs)

Derived parameters	
t_0	13.75 ± 0.13 Gyr
H_0	71.0 ± 2.5 km/s/Mpc
σ_8	0.801 ± 0.030
Ω_b	0.0449 ± 0.0028
Ω_c	0.222 ± 0.026
$z_{\rm eq}$	3196^{+134}_{-133}
$z_{\rm reion}$	10.5 ± 1.2

WMAP-7 (CMB fits)

Larson et al. (2010)

95% CL shown in red



$\tau = 0.088 \pm 0.015$

(at 68% CL)

Balance photoionizations with recombinations

(Scaled to z = 7 and parameters C, f_{esc} , Q_{LyC})

Similarly, the f_{esc} needed to reionize the universe can then be related to the critical star formation rate, $\dot{\rho}_{crit}$, needed to keep the universe ionized:

$$\dot{\rho}_{crit}(z) = (0.012\, M_\odot\, \mathrm{yr}^{-1}\, \mathrm{Mpc}^{-3})\left[\frac{1+z}{8}\right]^3 \left[\frac{C_H/5}{f_{esc}/0.5}\right]\left[\frac{0.004}{Q_{LyC}}\right] T_4^{-0.845} \quad (21)$$

Gas density

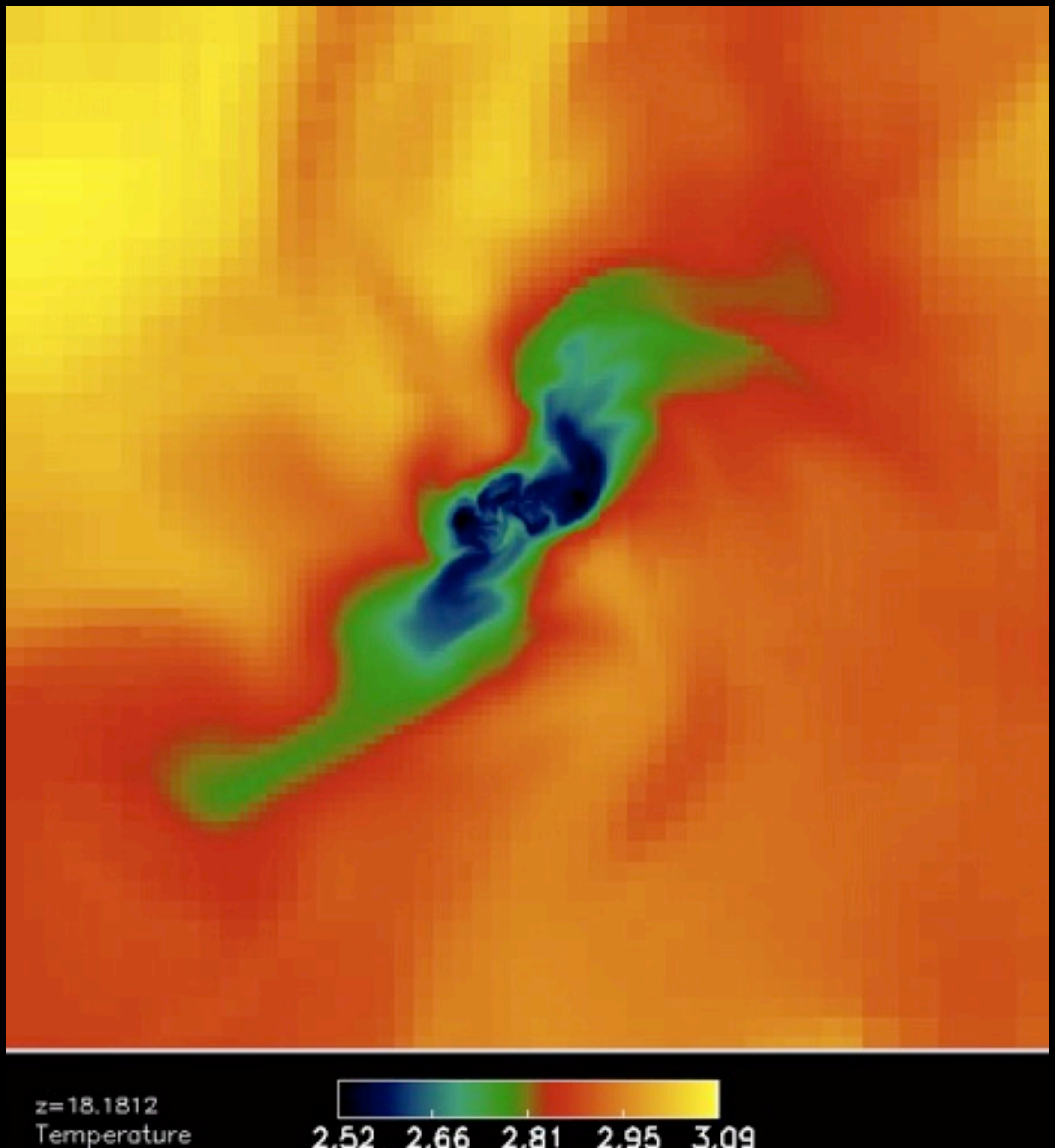
clumping & LyC escape factors

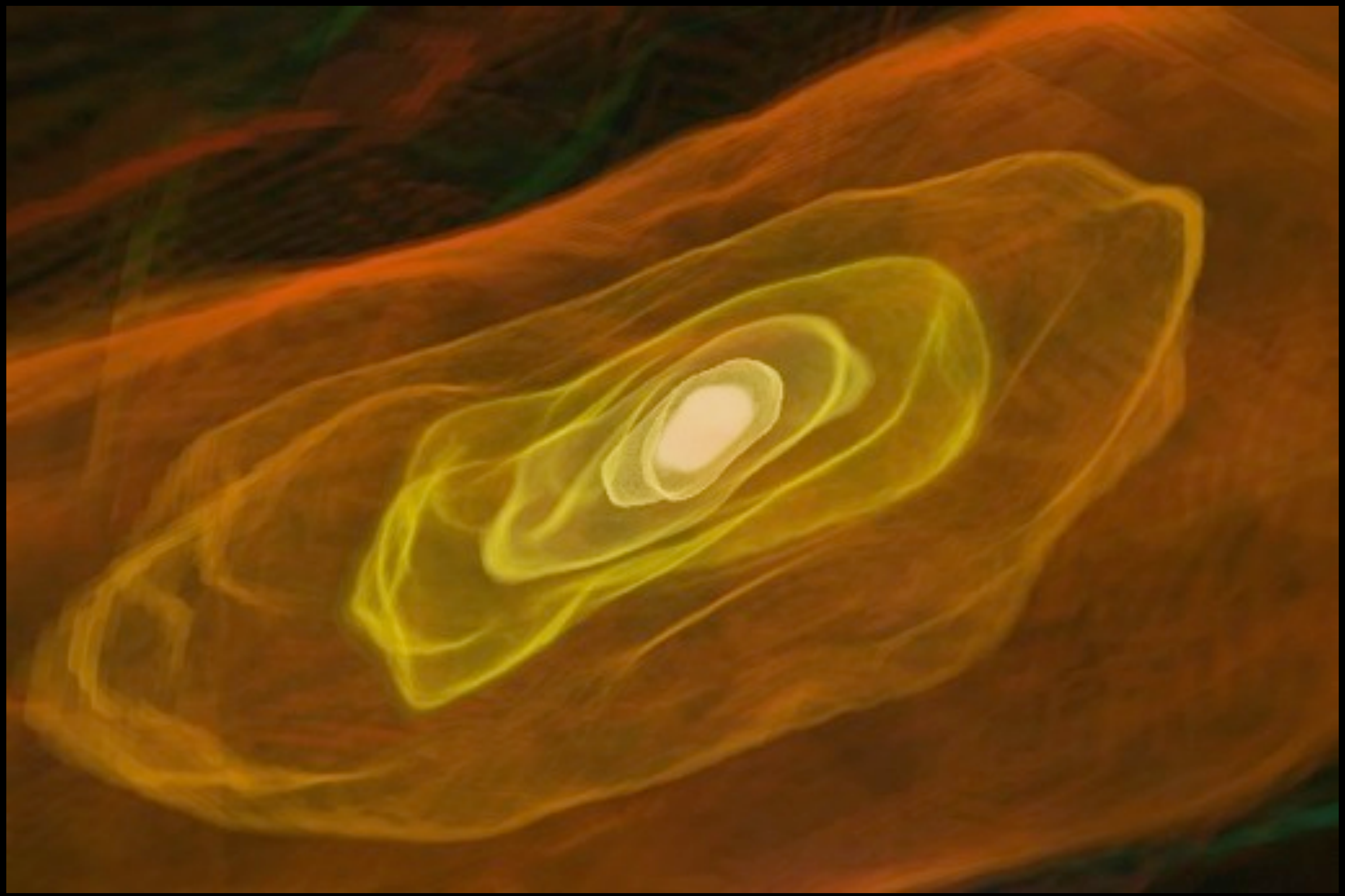
LyC production (IMF, Z-atmosphere

Shull & Trenti 2010

What might the First Stars look like?

Slow cooling and gravitational collapse of proto-galactic clouds

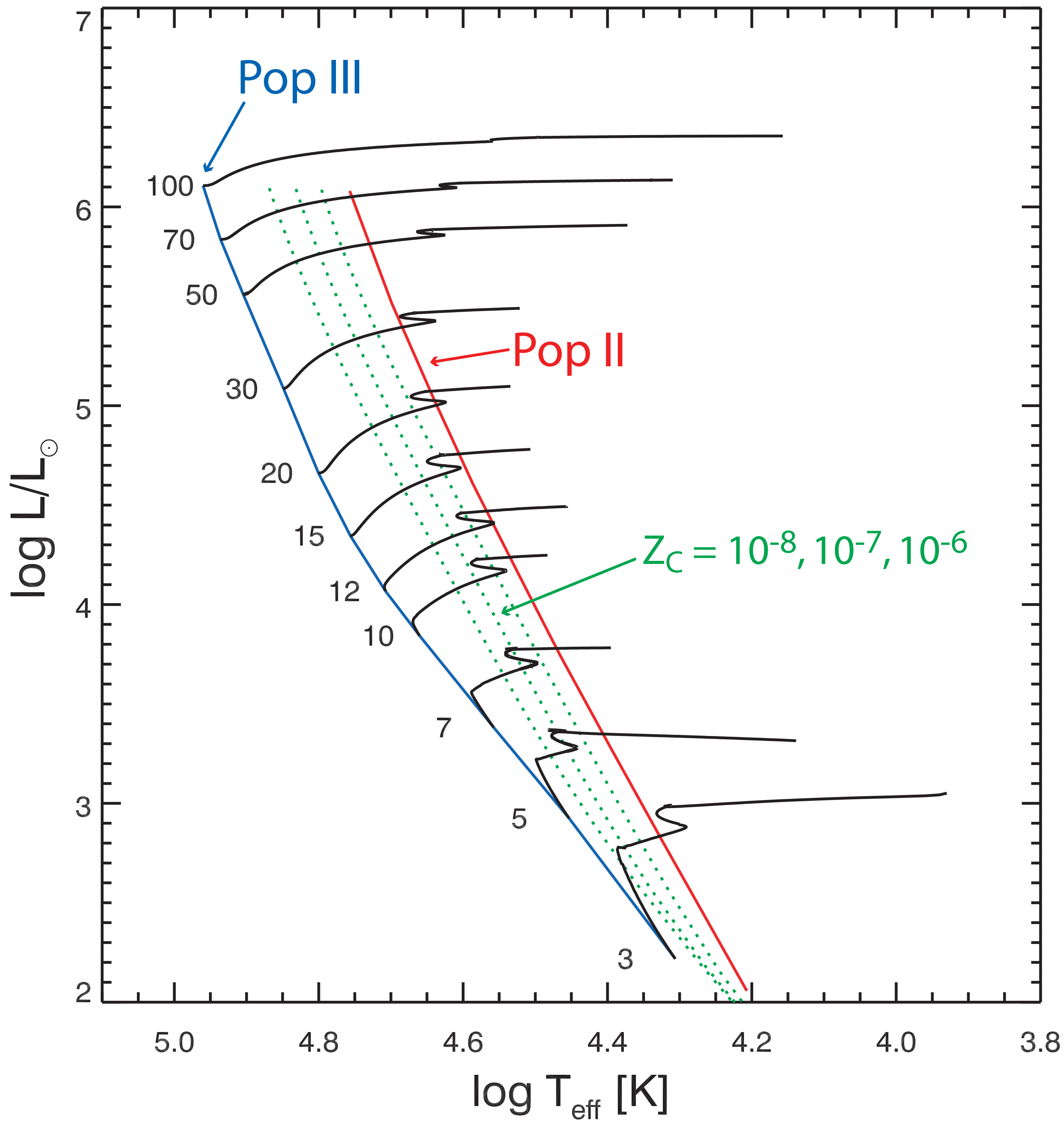




Wise, Abel, Turk et al.

Evolution of Low-Metal Stars

Tumlinson, Shull, & Venkatesan (2003, ApJ, 584, 608)



Why important?

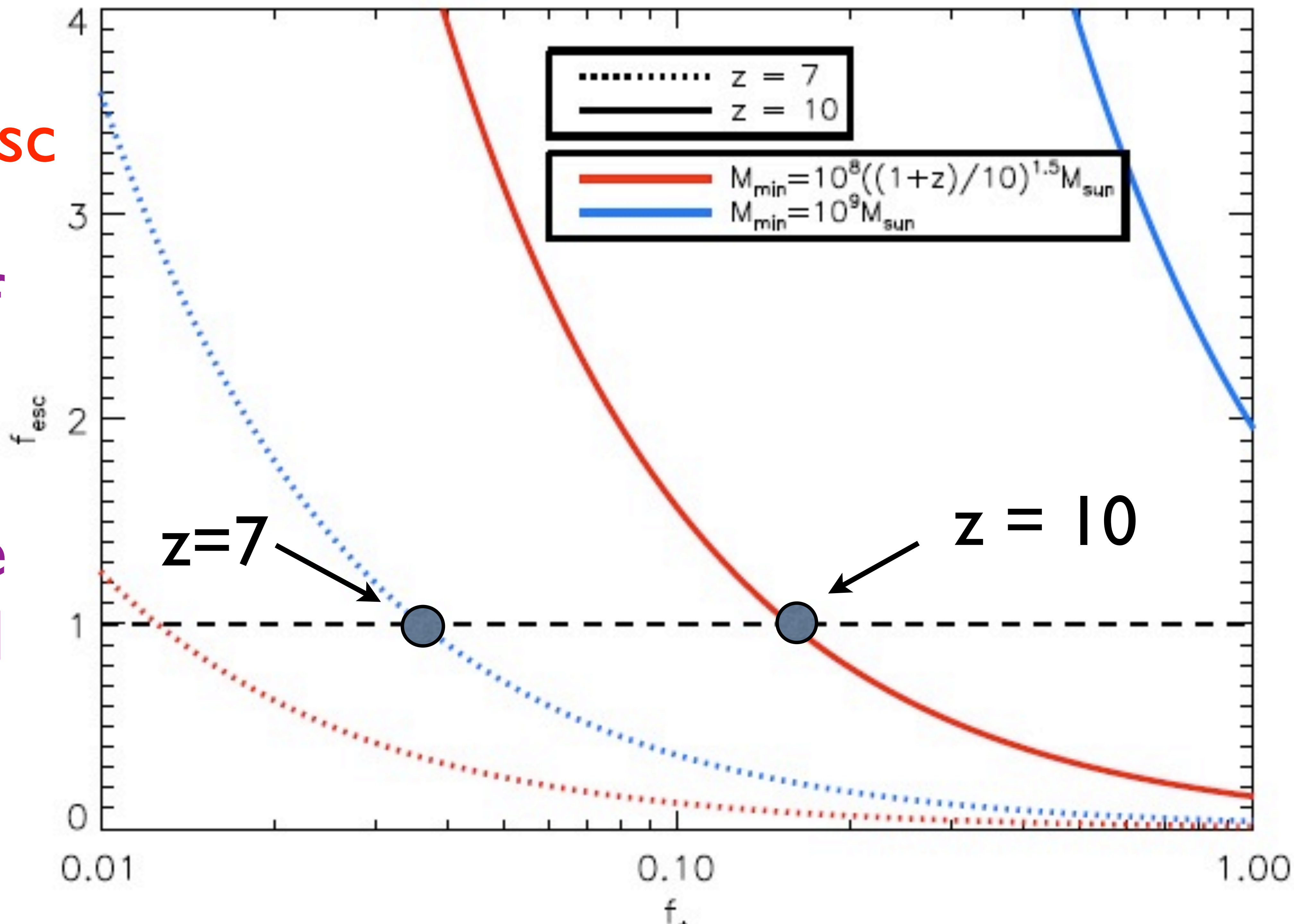
Increased T_{eff} for Pop III stars at low metallicity

10-100 M_{sun} dominate the IGM ionization (Increase Q_{LyC})

but for how long?

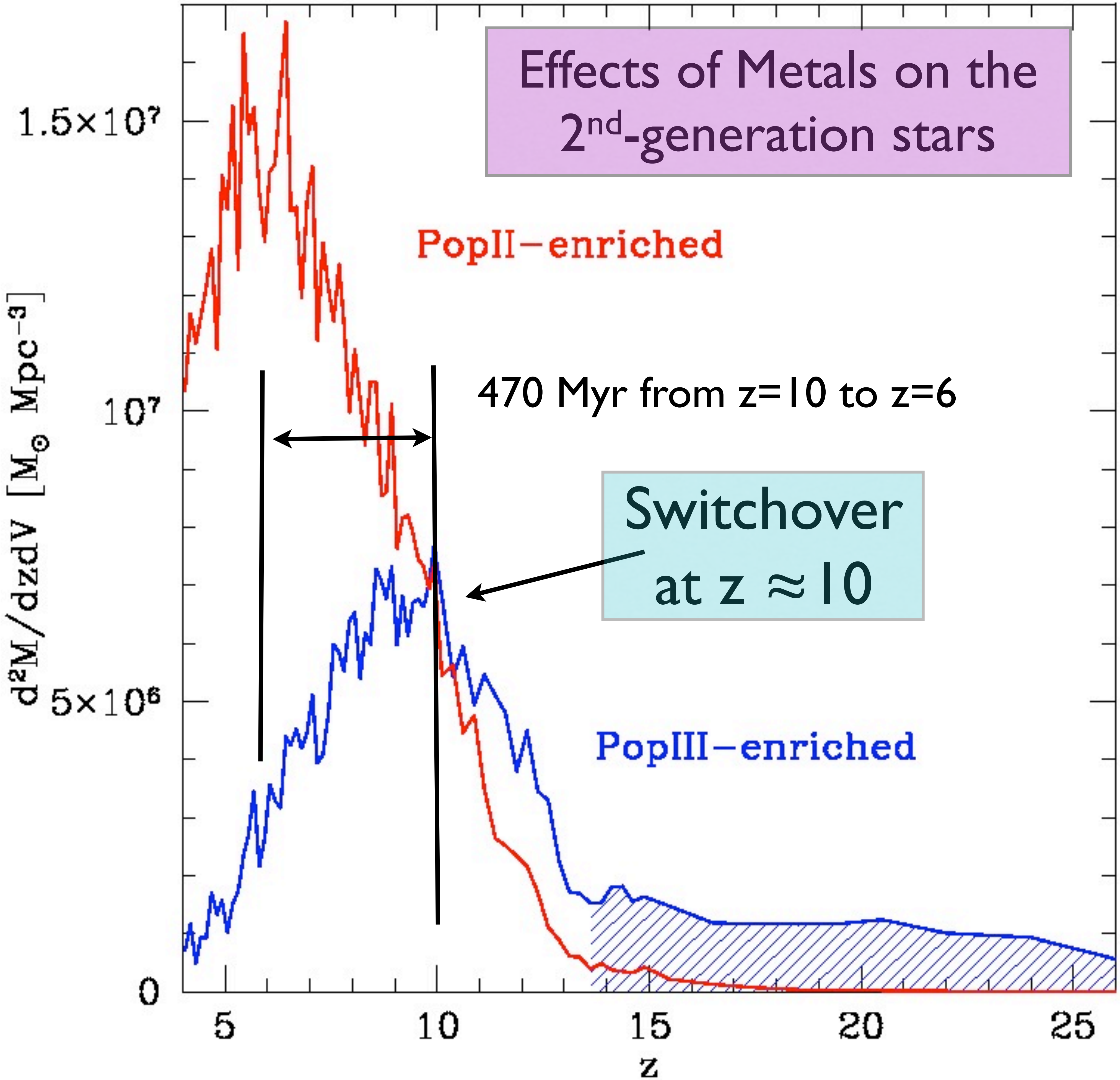
f_{esc}

Fraction of ionizing photons that escape to the IGM



Star-formation fraction

Fig. 5.— The f_{esc} needed from a population of galaxies with various values of f_* to reionize the universe at $z = 7$ or 10. If the required f_{esc} lies above 1 (the dashed line), the population cannot reionize the universe.



Trenti & Shull 2009

Cosmological simulations (halo dynamics metal transport, star formation)

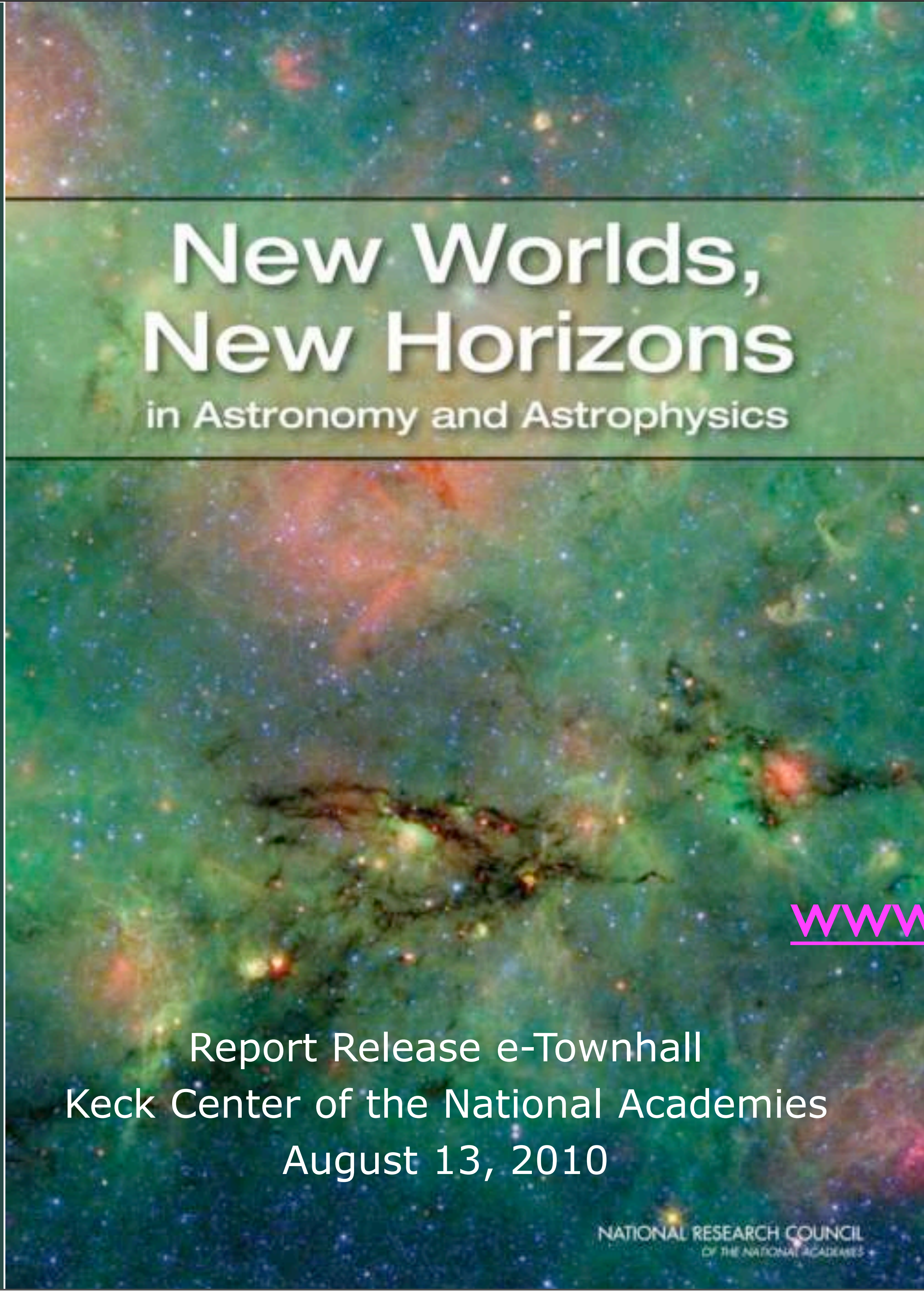
Ages:

946 Myr (z=6)

480 Myr (z=10)

273 Myr (z=15)

($h = 0.7$, $\Omega_m = 0.28$, $\Omega_\Lambda = 0.72$ flat)



Go to NRC website for Astro2010

www.nationalacademies.org/astro2010

Science Frontier Panels:

Discovery areas:

- Identification and characterization of nearby habitable exoplanets
- Gravitational wave astronomy
- Time-domain astronomy
- Astrometry
- The epoch of reionization

These were used to recommend:

LSST -- time-domain astronomy

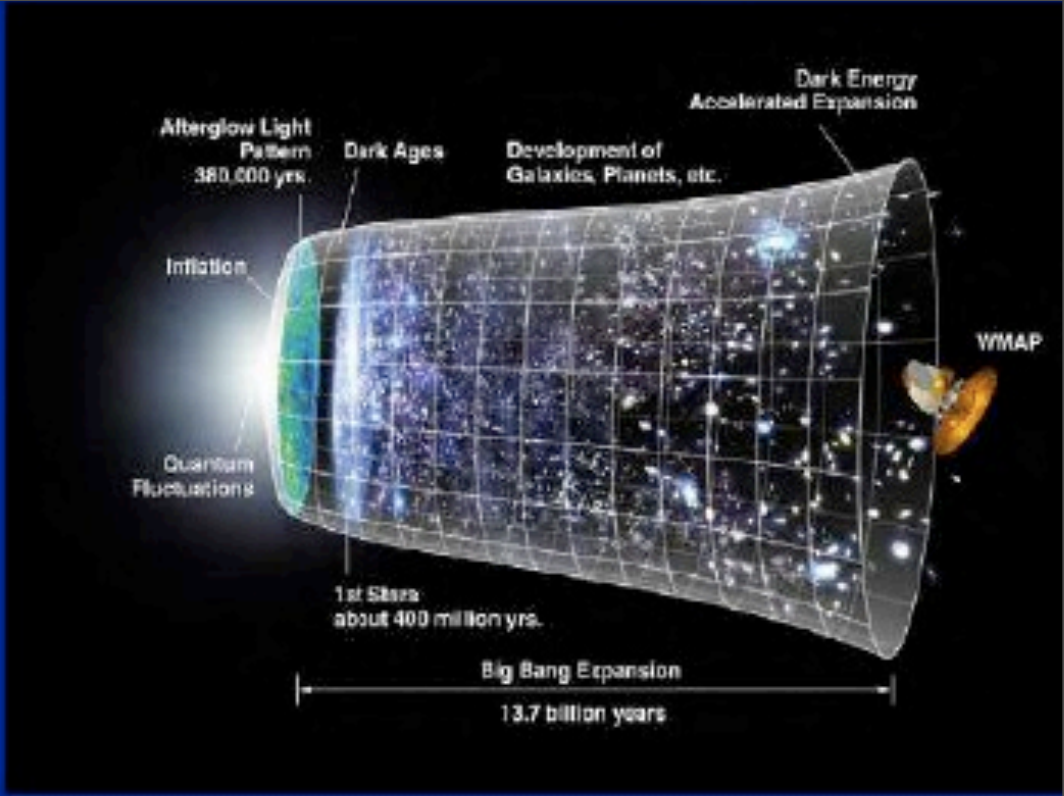
LISA -- gravitational waves

New Worlds Technology Pgm

Reionization Epoch studies ⇐

Cosmic Dawn

Searching for the first stars, galaxies, and black holes



- We have learned much about the history of the universe, from the Big Bang to today
- A great mystery now confronts us: when and how the first galaxies formed and the earliest stars started to shine - our cosmic dawn
- JWST, ALMA and radio telescopes already under construction will help point the way
- Approaches: *Direct searches for first galaxies and BH mergers*
  - Locating “reionization” – finding the epoch ~0.5 billion years, when light from the first stars split interstellar hydrogen atoms into protons and electrons
  - “Cosmic paleontology” – finding the rare stars with the lowest concentrations of heavy elements

Mid-Scale Innovations Program - Details

- **RECOMMEND annual proposals for:**
  - **Conceptual and preliminary design activities**
  - **Detailed design and construction**
- ~7 projects funded over decade
  - Possible exemplars include: BigBOSS, CMB, ExoPlanet initiatives, FASR, HAWC, HERA, Adaptive Optics, NanoGRAV
- Funding increase from ~$18M currently to competed $40M per year

Epoch of Reionization

Explorer Program - Science

- Rapid, targeted, competed investigations
- Versatile program delivers high scientific return
- WMAP, Swift, GALEX, WISE… are extraordinarily successful past examples
- NuSTAR, GEMS, Astro-H very promising

These are all X-ray missions;
is there room for others?