Ay 127

Galaxy Formation,

Reionization,

the First Stars and Quasars

Galaxy Formation

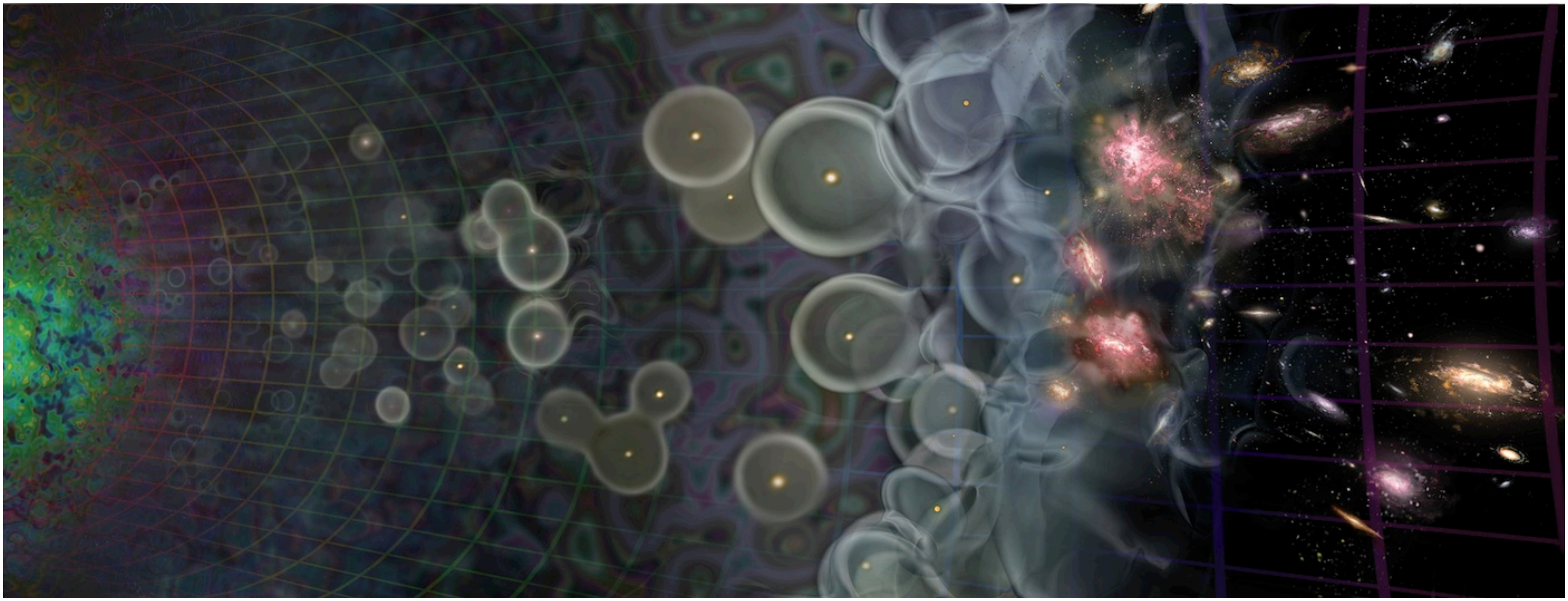
- The early stages of galaxy evolution - but there is no clear-cut boundary, and it also has two principal aspects: assembly of the mass, and conversion of gas into stars
- Must be related to large-scale (hierarchical) structure formation, plus the dissipative processes - it is a very messy process, much more complicated than LSS formation and growth
- Probably closely related to the formation of the massive central black holes as well
- Generally, we think of massive galaxy formation at high redshifts ($z \sim 3$ - 10, say); dwarfs may be still forming now
- Observations have found populations of what must be young galaxies (ages < 1 Gyr), ostensibly progenitors of large galaxies today, at $z \sim 5$ - 7
- The frontier is now at $z \sim 7$ - 20, the so-called Reionization Era

A General Outline

- The smallest scale density fluctuations keep collapsing, with baryons falling into the potential wells dominated by the dark matter, achieving high densties through cooling
  - This process starts right after the recombination at $z \sim 1100$
- Once the gas densities are high enough, star formation ignites
  - This probably happens around $z \sim 20$ - 30
  - By $z \sim 6$, UV radiation from young galaxies reionizes the unverse
- These protogalactic fragments keep merging, forming larger objects in a hierarchical fashion ever since then
- Star formation enriches the gas, and some of it is expelled in the intergalactic medium, while more gas keeps falling in
- If a central massive black hole forms, the energy release from accretion can also create a considerable feedback on the young host galaxy

An Outline of the Early Cosmic History

(illustration from Avi Loeb)



Recombination: Release of the CMBR

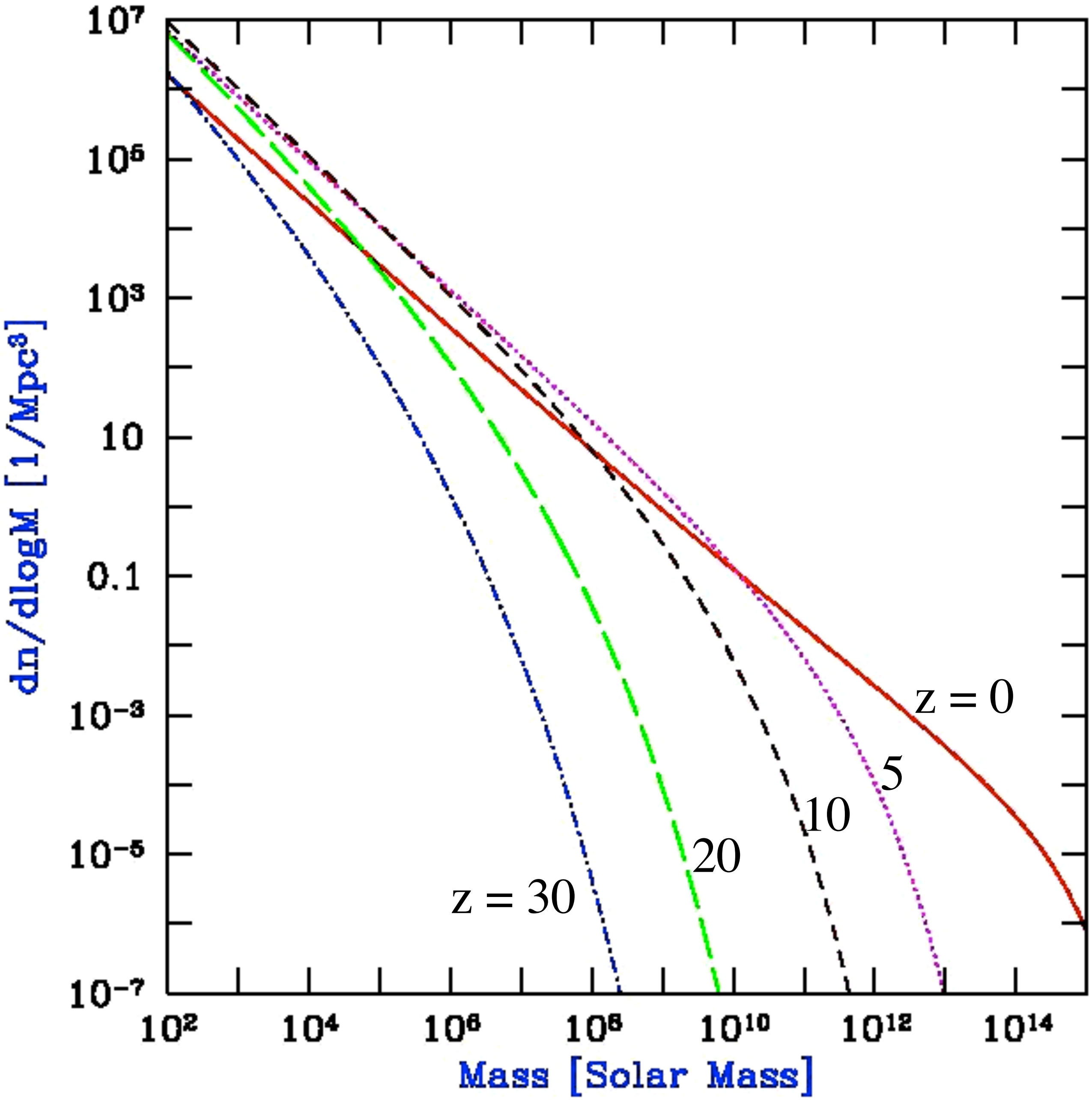
Dark Ages: Collapse of Density Fluctuations

Reionization Era: The Cosmic Renaissance

Galaxy evolution begins

The Evolving Dark Halo Mass Function

(Press-Schechter)



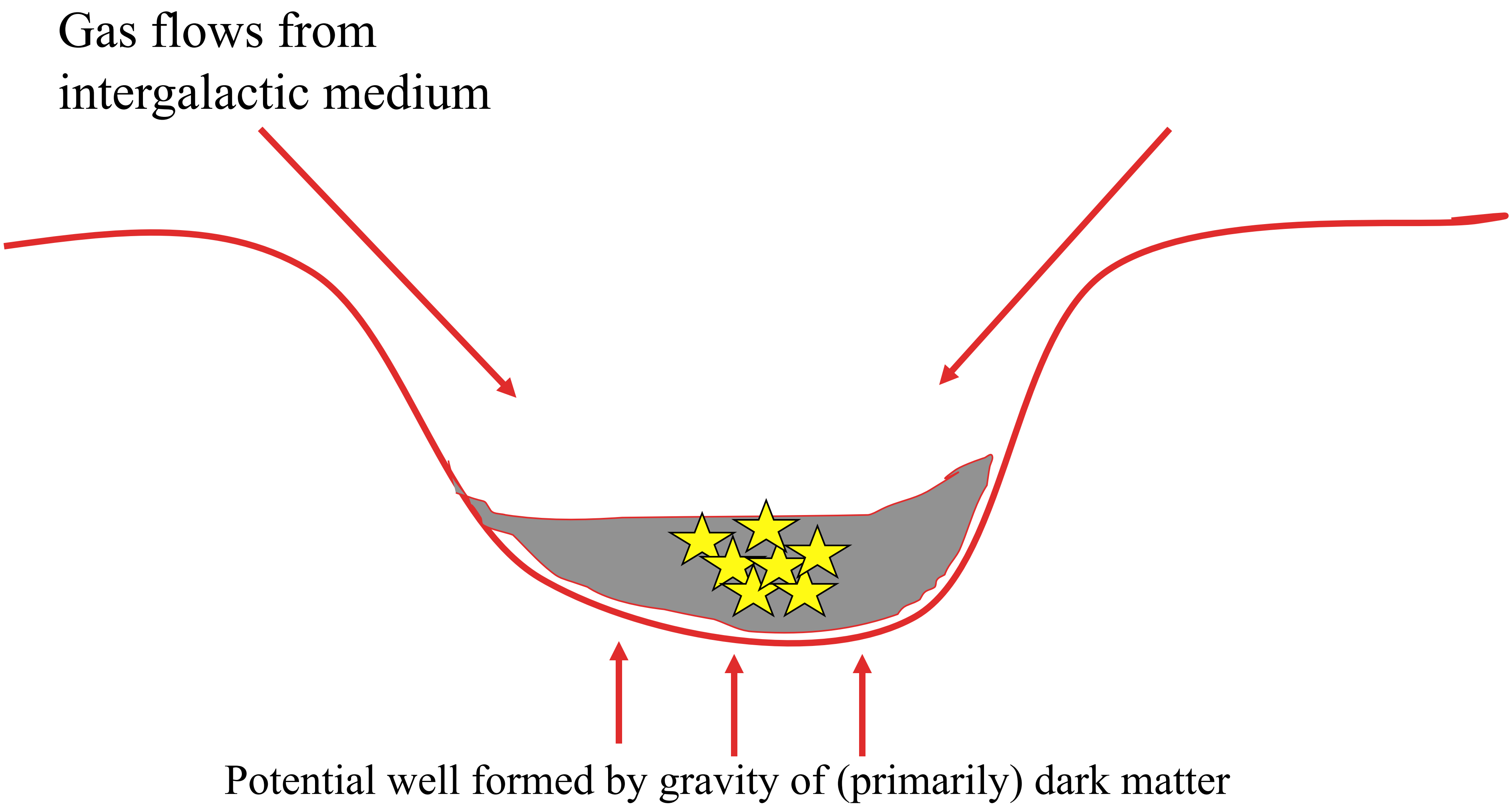
Barkana & Loeb

Physical Processes of Galaxy Formation

- Galaxy formation is actually ***a much messier problem than structure formation.*** In addition to gravity and build-up of host dark halos (fairly well understood) we need to add:
  - Shock heating of gas
  - Cooling of gas into dark halos
  - Formation of stars (also not a well understood process!) from the cold gas
  - The evolution of the resulting stellar population
  - Feedback processes generated by the ejection of mass and energy from evolving stars
  - Production and mixing of heavy elements (chemical evolution)
  - Effects of dust obscuration
  - Formation of black holes at galaxy centers and effects of AGN emission, jets, etc.

  … etc., etc., etc.

Recipe for Galaxy Formation



What is a Protogalaxy?

Not a very well defined answer; some possibilities:

- Galaxy in the first X % or Y yrs of its life (X=?, Y=?)
- Galaxy which has formed X % of its stars (X=?)
- Galaxy which has assembled X% of its final mass (X=?)
- Initial density fluctuation which has not formed any stars yet
- Galaxy at a very high redshift $z > Z$ (Z=?)

… etc., etc.

- Generally we think of the progenitors of massive galaxies today, roughly in the first Gigayear of their life, i.e., at $z > 5$ish
- We certainly expect vigorous star formation to be occuring, and therefore a luminous object

Energy Release From Forming Galaxies

Galaxies collapse and cool. The release of the binding energy is:

$$|E_{bind,gal}| \simeq M_{cool} \langle V_{3d}^2 \rangle \simeq$$

$$\simeq 1.2 \times 10^{59} \mathrm{erg} \times (M_{cool}/10^{11} M_\odot)\ (V_{3d}/250 \mathrm{km\ s}^{-1})^2$$

where M_{cool} is the total mass which can cool radiatively

Binding energy was also released by collapsing protostars, and is of a comparable magnitude:

$$|E_{bind,\star}| \simeq G\ M_{\Sigma\star}\ \langle M_\star \rangle / \langle R_\star \rangle \simeq$$

$$\simeq 4 \times 10^{58} \mathrm{erg} \times (M_{\Sigma\star}/10^{10} M_\odot)\ (\langle M_\star \rangle / M_\odot)\ (R_\odot / \langle R_\star \rangle)$$

where $M_{\Sigma\star}$ is the total mass converted to stars in the PG phase, $\langle M_\star \rangle$ is the average star mass, and $\langle R_\star \rangle$ is the average star radius.

Energy Release From Forming Galaxies

Probably the most important energy source in PGs was the nuclear burning in initial starbursts:

$$E_{nuc} \simeq \epsilon \, M_{\Sigma\star} \, c^2 \, \Delta X \simeq 10^{60}\mathrm{erg} \, (\epsilon/0.001) \, (M_{\Sigma\star}/10^{10} M_\odot) \, (\Delta X/0.05)$$

where $M_{\Sigma\star}$ is the total mass burned in stars in the PG phase, $\epsilon \simeq 1$ Mev$/m_p c^2 \simeq 0.001$ is the average net efficiency of nuclear reactions in stars, and $\Delta X \simeq \Delta Z + \Delta Y \simeq 0.05$ is the fraction of the hydrogen converted to helium and metals.

Note: the mean metallicity of old stellar populations is ~ Solar, i.e., about 1.7% by mass; and you get ~ 3-5 g of He (ΔY) for each 1 g of metals (ΔZ) produced in stellar burning

Finally, early active galactic nuclei may have been important contributors to the energy budget in at least some, and possibly all PGs. Their energy release could have rivaled other mechanisms. Taking a rough guess for the average luminosity $\langle L_{bol} \rangle$ and the duration of the active episode Δt:

$$E_{AGN} \sim \langle L_{bol} \rangle \, \Delta t \simeq 1.2 \times 10^{60}\mathrm{erg} \, (\langle L_{bol} \rangle / 10^{10} L_\odot) \, (\Delta t / 10^8 \mathrm{yr})$$

Expected Observable Properties of PGs

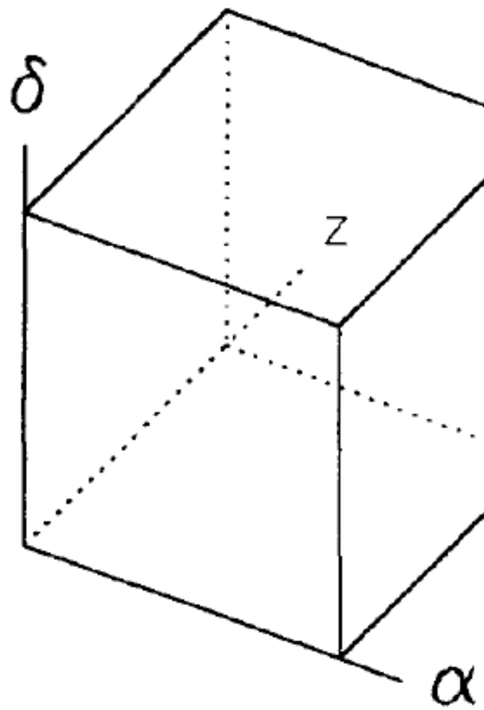
- We expect a release of $\Delta E \sim 10^{60}$ ergs from a typical proto-elliptical (or a large bulge); but over what time scale?
  - The starburst time scale of ~ 10^7 - 10^8 yrs
  - The free-fall time scale of ~ 10^8 yrs
  - The merging time scale of ~ 10^9 yrs
- Since luminosity is $L \sim \Delta E / \Delta t$, we estimate typical

$$L_{PG} \sim 10^{11} - 10^{12}\ L_{\odot},$$

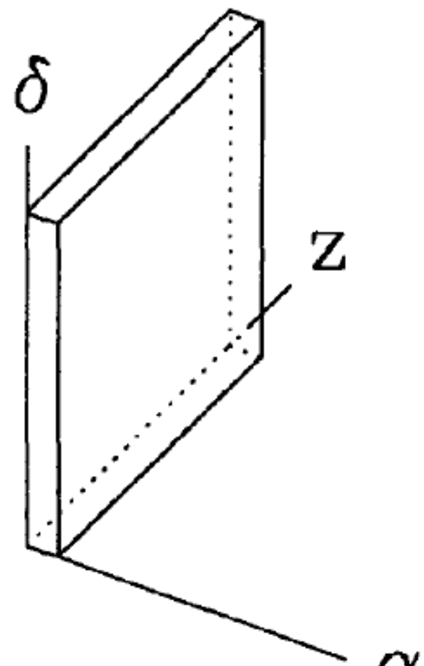
or absolute magnitudes $M \sim -22$ to -25 mag

- Given the luminosity distances to z ~ 6 - 8, the expected apparent magnitudes are in the range ~ 26 to 30 mag
- A few % of the total energy is in recombination lines, e.g., Lyα
- But the **Big Question** is: ***is this luminosity obscured by dust?***
  - No: optical surveys
  - Yes: sumb-mm/FIR surveys

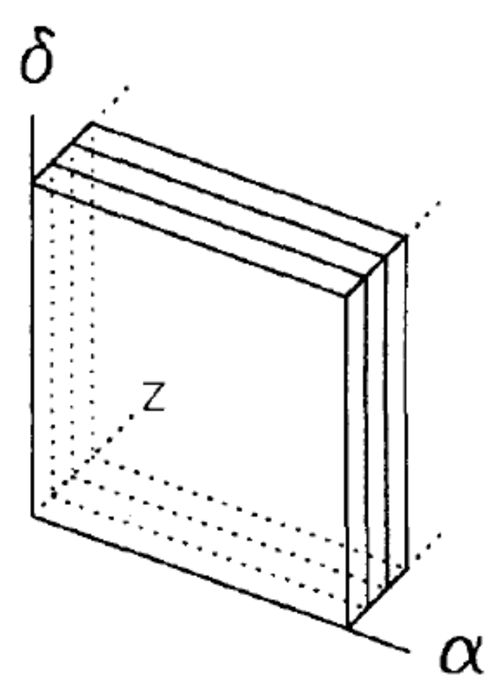
Emission Line Search Methodologies



Slitless spectroscopy:
Large volume, but low S/N (~ depth)



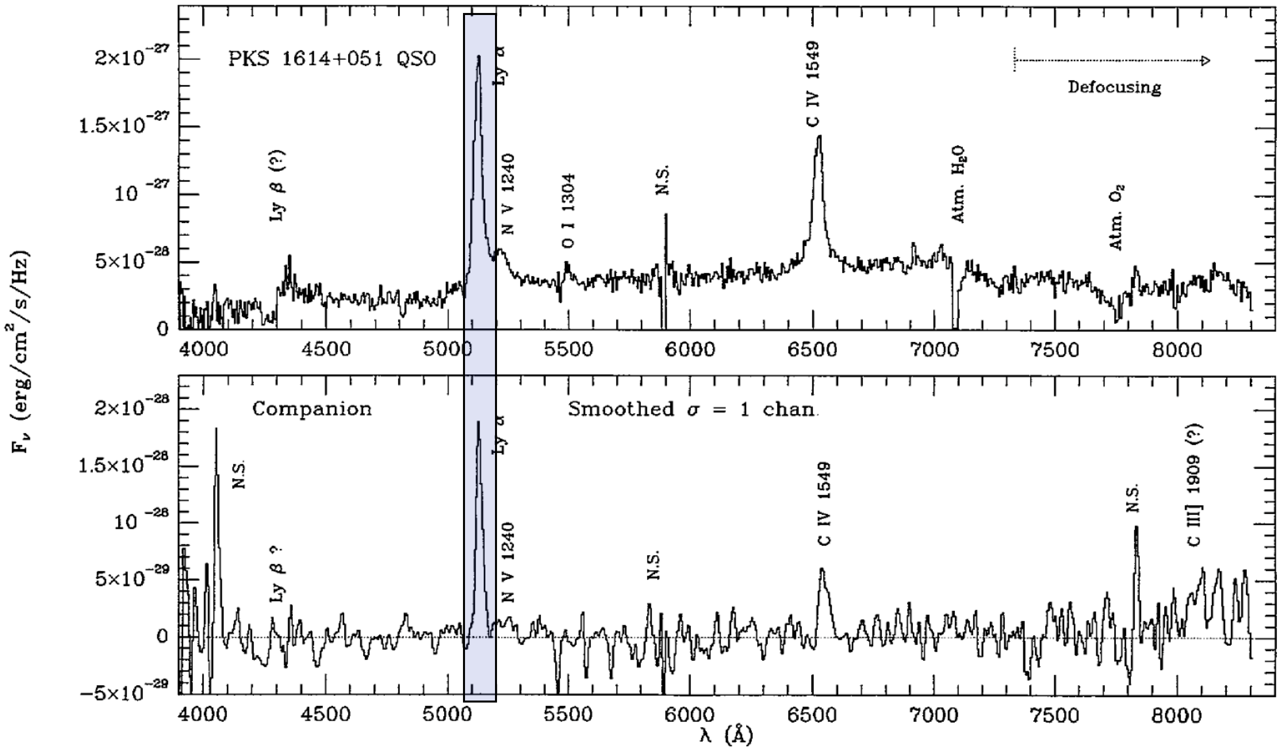
Long-slit spectroscopy:
Small volume,
large redshift range,
good depth

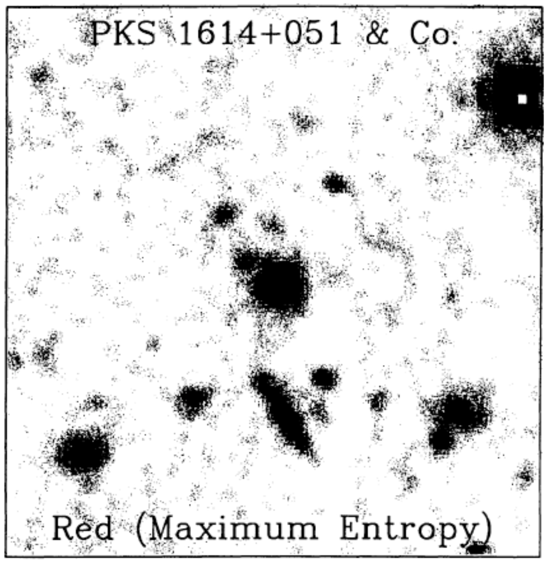


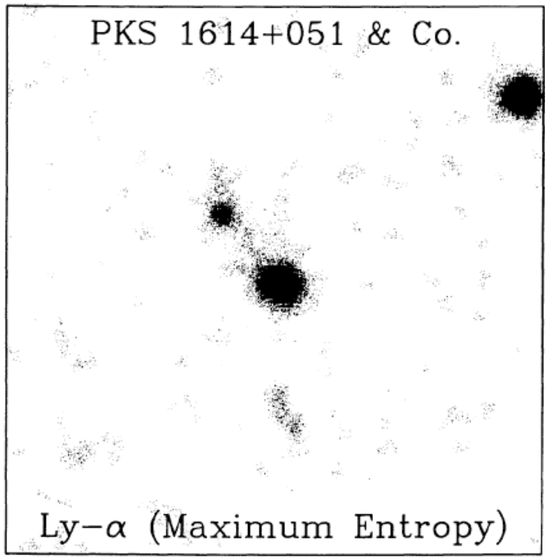
Narrow band imaging:
Moderate volume,
small redshift range,
good depth

Narrow-Band Imaging

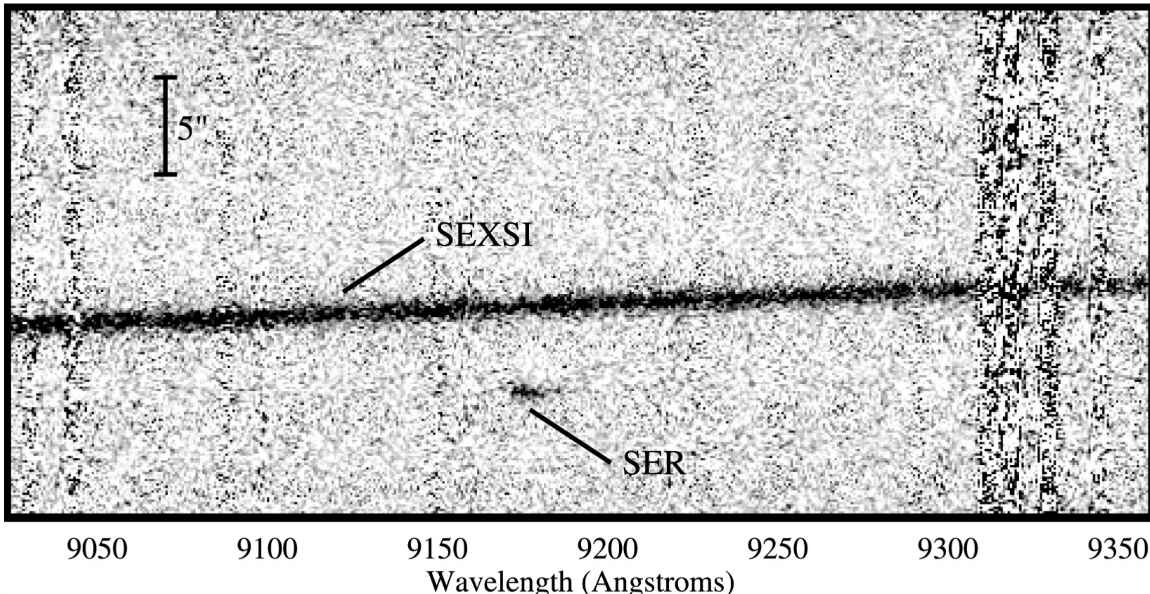
A greatly increased contrast for an object with a strong line emission

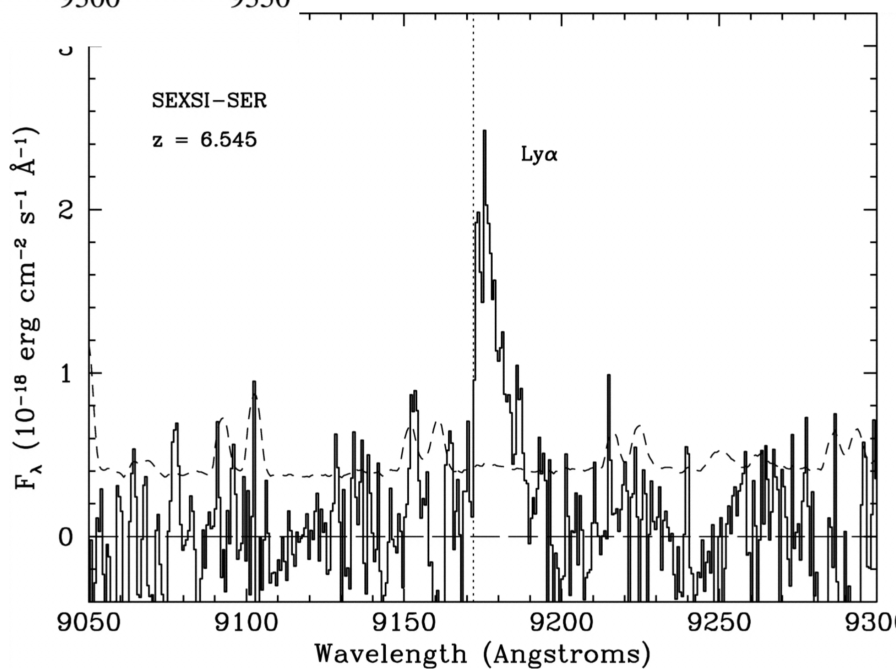






Long-Slit Spectroscopy + Serendipity



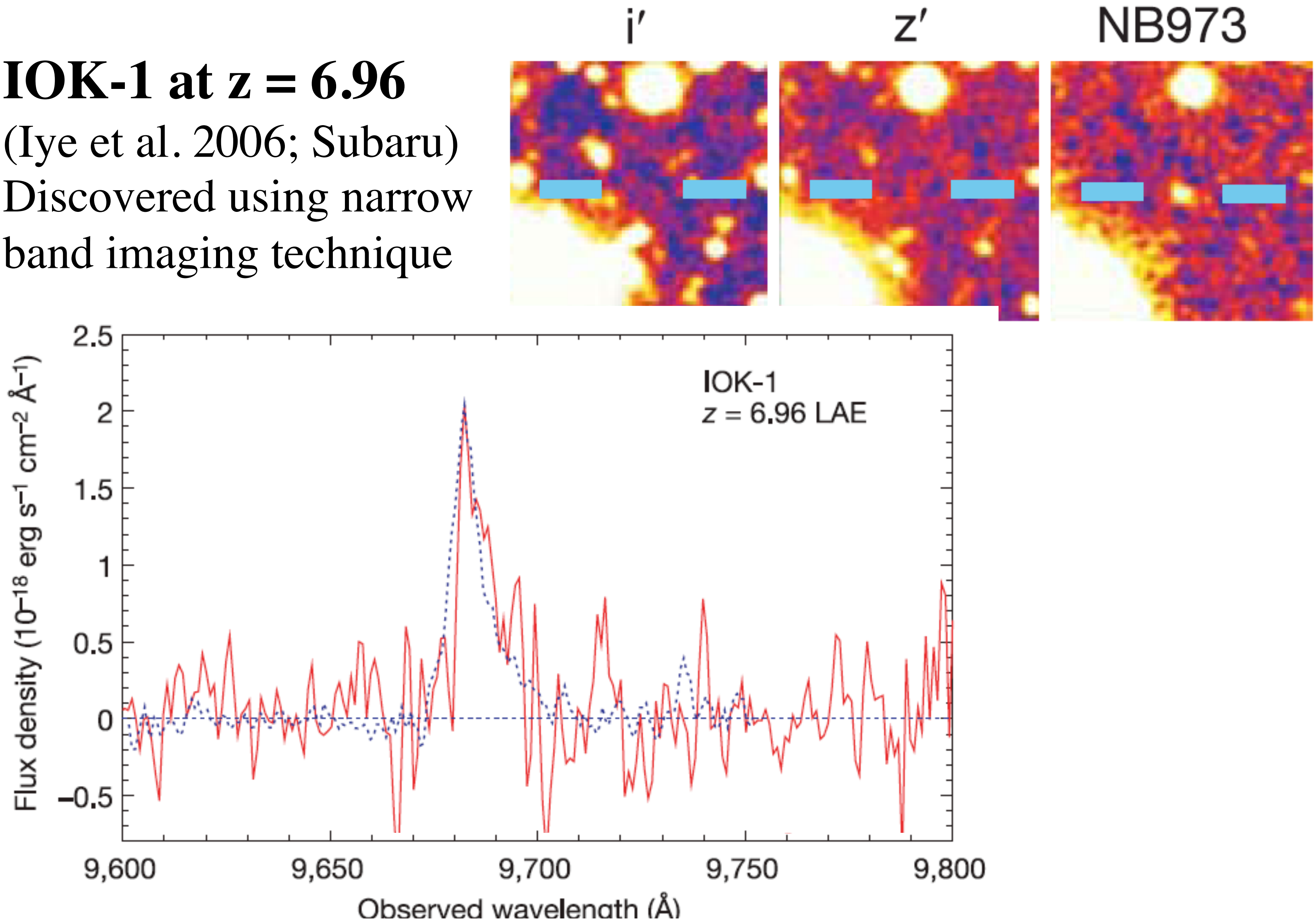


A Galaxy at z ~ 7

IOK-1 at z = 6.96

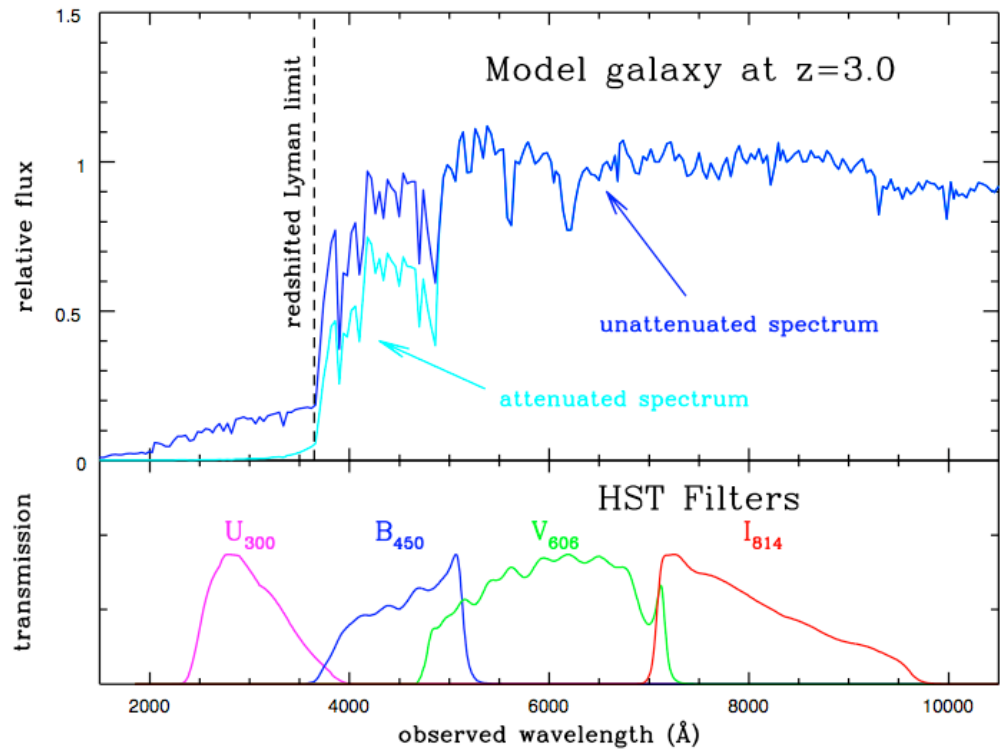
(Iye et al. 2006; Subaru)

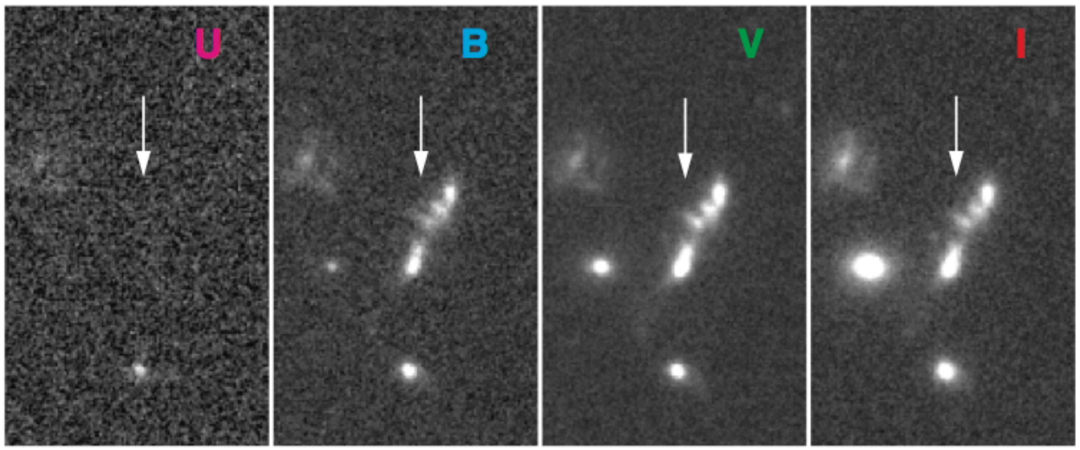
Discovered using narrow band imaging technique



The Lyman-Break Method

Absorption by the interstellar and intergalactic hydrogen of the UV flux blueward of the Ly alpha line, and especially the Lyman limit, creates a continuum break which is easily detectable by multicolor imaging

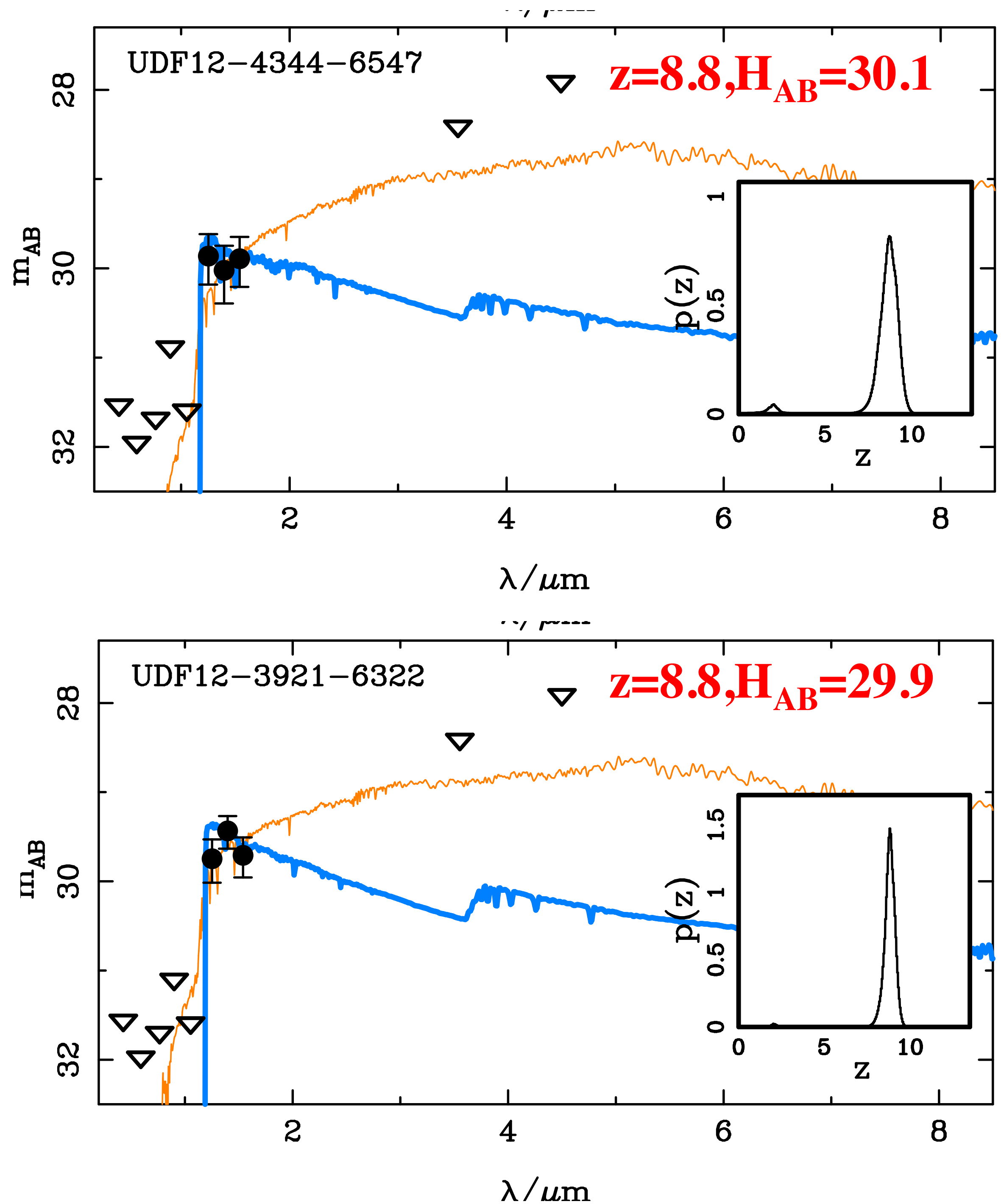




Photometric Redshifts

Using the combination of 4 optical and 4 infrared filters, the redshifts of individual galaxies can be estimated for systems well beyond current spectroscopic reach

(from R. Ellis)



Color-Selected Candidate High-z Galaxies

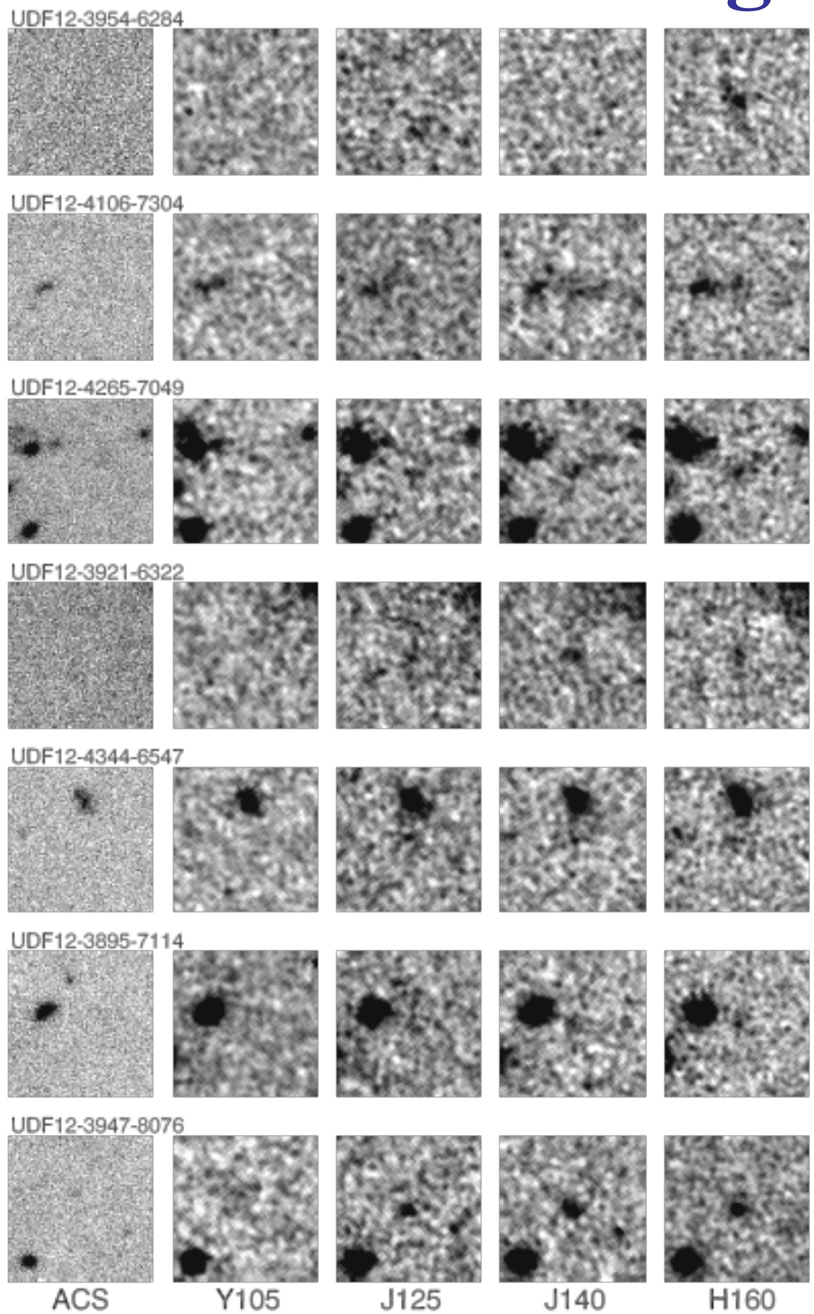
7 star-forming galaxies located 8.5<z<12

5σ detections in (160W+140W +125W) stack (m_{AB} < 30.1)

2σ rejection in ultradeep F105W (m_{AB} > 31.0)

2σ rejection in ACS BViz (m_{AB} > 31.3)

Ellis et al (2013) Ap J Lett 763, L7



z=11.9? 380 Myr

z=9.5 520 Myr

z=9.5 520 Myr

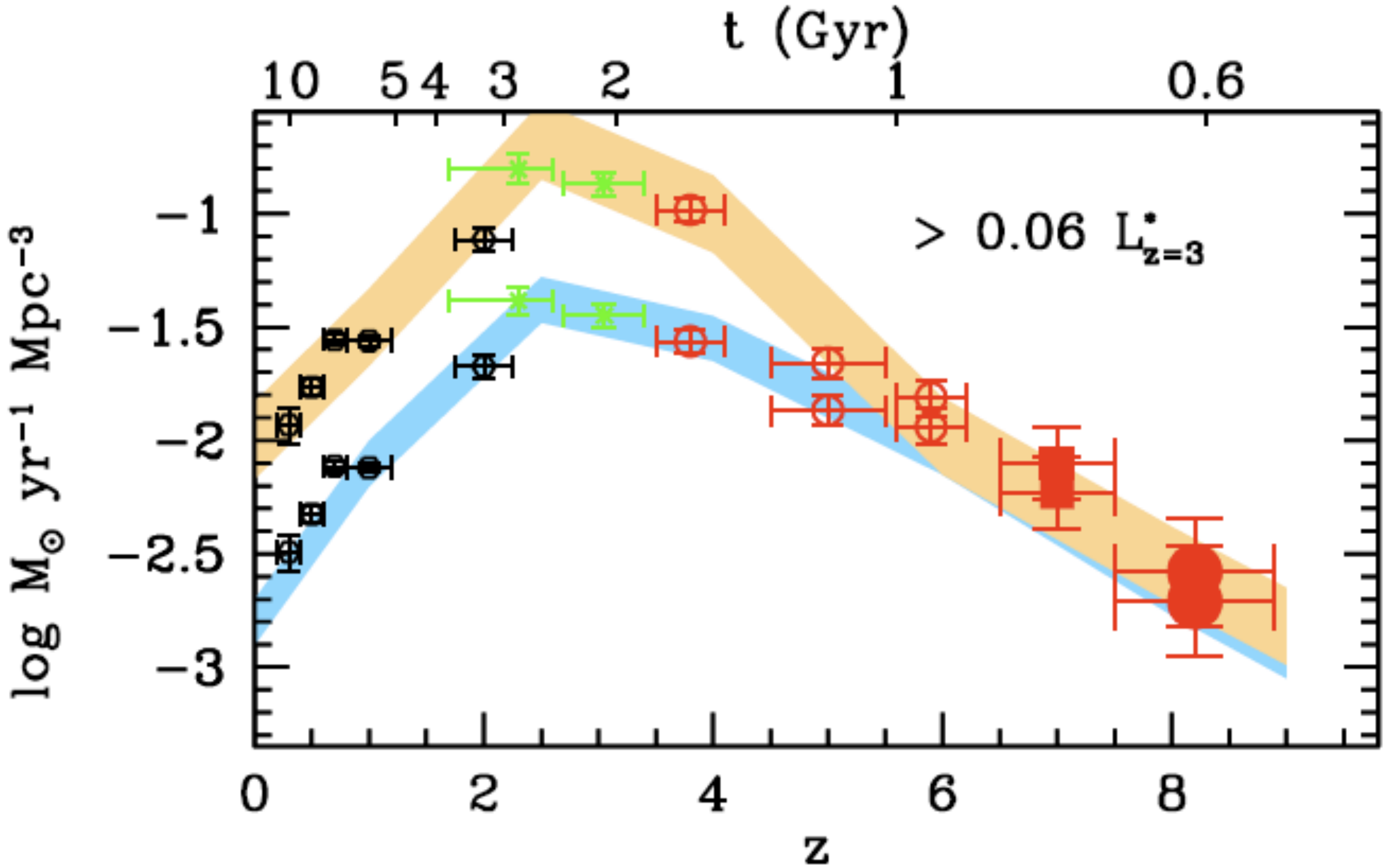
z=8.8 570 Myr

z=8.8 570 Myr

z=8.6 590 Myr

z=8.6 590 Myr

Star formation density of LBGs

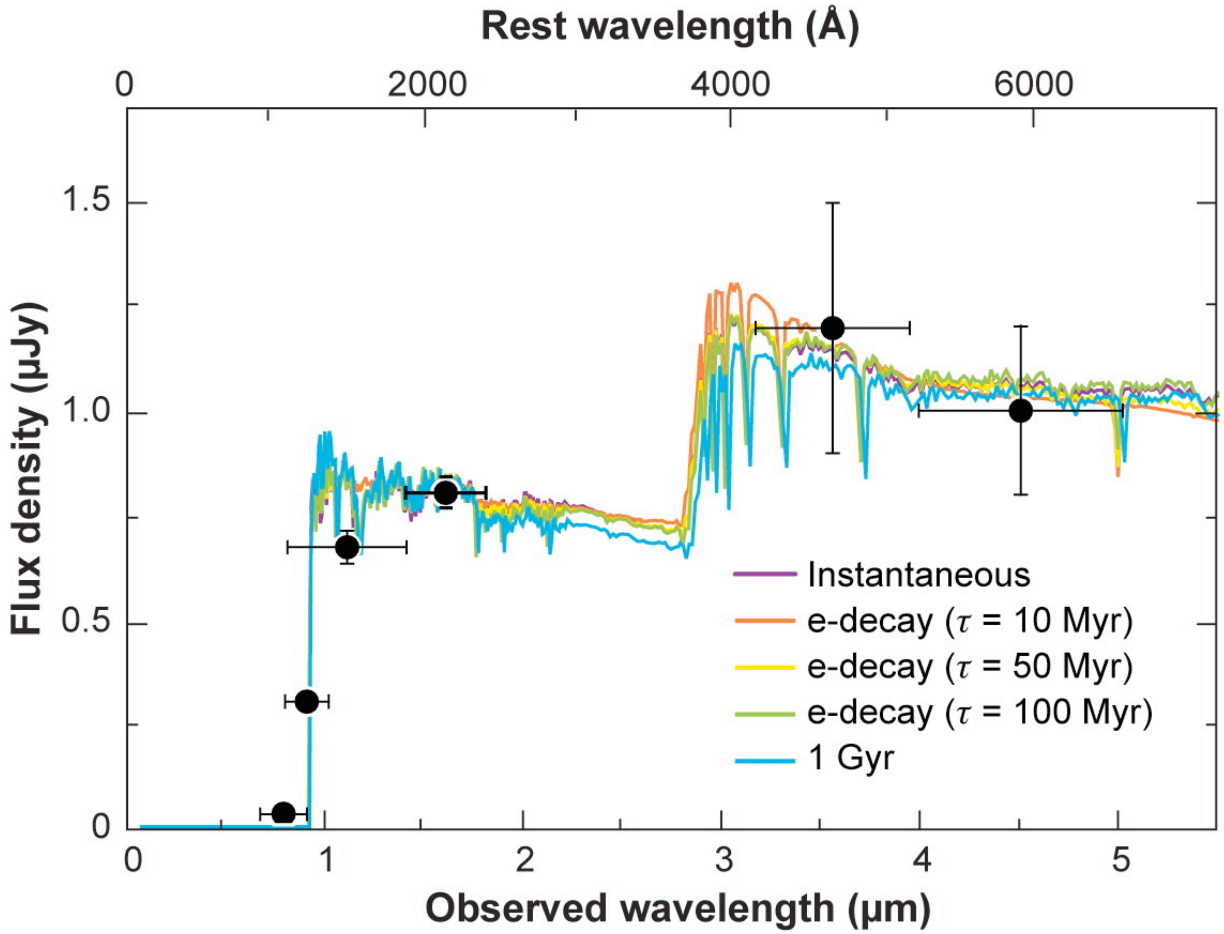


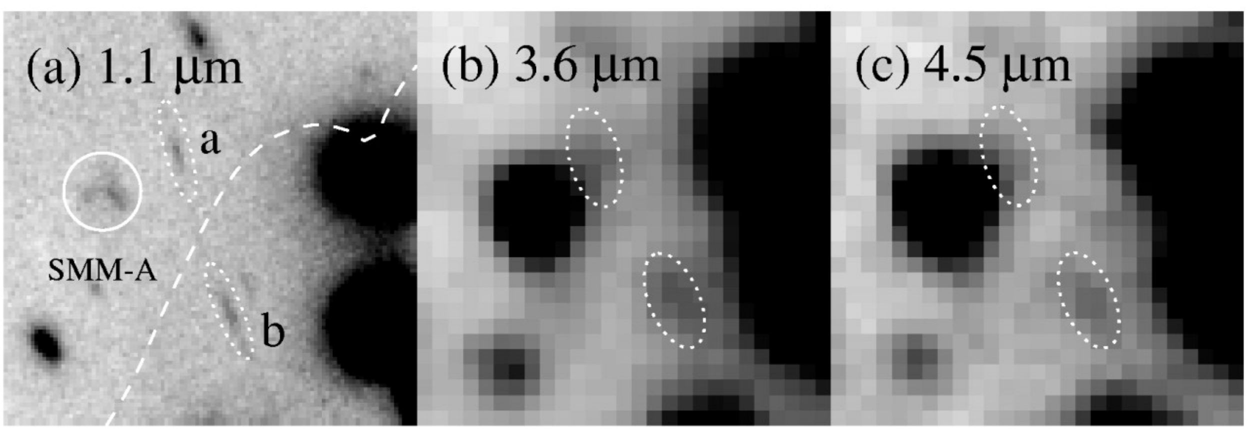
Monotonically declining population to z ~ 6 and beyond

Drop of ×8 in UV luminosity density over 2 < z < 6

Bouwens et al (2009, 2011)

However, even some galaxies at $z > 6$ seem to have been forming stars for a while, indicating a very early onset of galaxy formation





Lensed arc galaxy at $z \sim 6.7$ (?) behind A2218

(Egami et al. 2005)

Biasing and Early Structure Formation

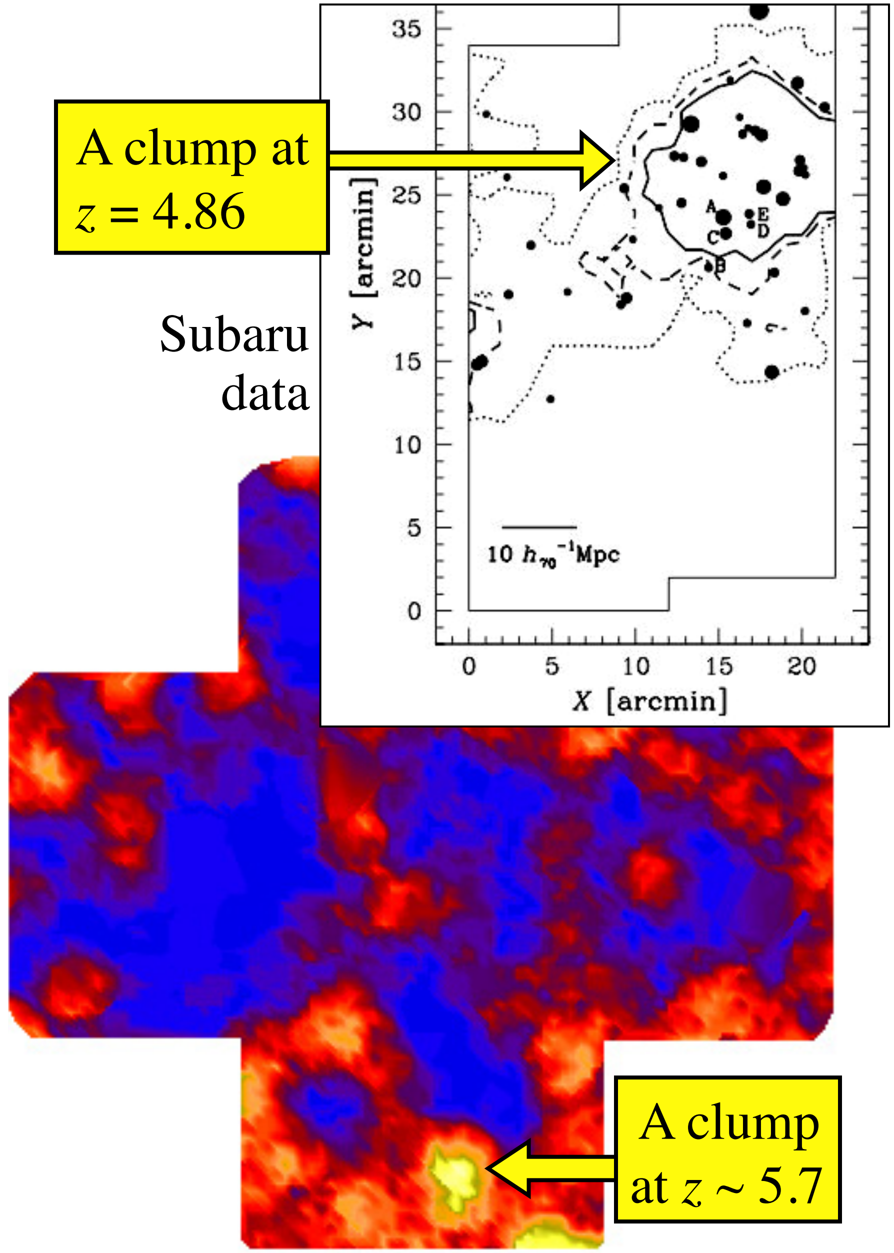
- ***Strong, bias-driven clustering*** of the first luminous sources is generally expected in most models
- There is a lot of evidence that this does occur at $z \sim 4 - 6$, from clustering of Lyα galaxies, to clustering of Ly-break galaxies around high-z QSOs
- This may lead to a ***clumpy reionization***, which among other things would produce a rise in the cosmic variance of the IGM transmission in the approach to reionization
- There is some evidence that this indeed does occur, from the spectra of z ~ 6 QSOs - and this may help improve our understanding of the final phases of reionization

Evidence for a Strong Biasing at High *z*'s

- LBGs at $z \geq 3$, ~ Mpc scales *(Steidel, Adelberger, et al.)*
- Clustered QSO companions at $z \sim 4 - 6$, scales ~ 0.1 - 1 Mpc *(Djorgovski et al., Stiavelli et al., etc.)* ; and also radio galaxies at similar z's *(Venemans et al.)*
- Clustered Lyα and LB galaxies at z ~ 4.9 - 5.7, scales ~ a few Mpc *(Shimasaku et al., Ouchi et al., Hu et al., etc.)*
- Estimated **bias factors $b \sim 3 - 6$**, but could be as high as ~ 10 - 30!

A clump at $z = 4.86$

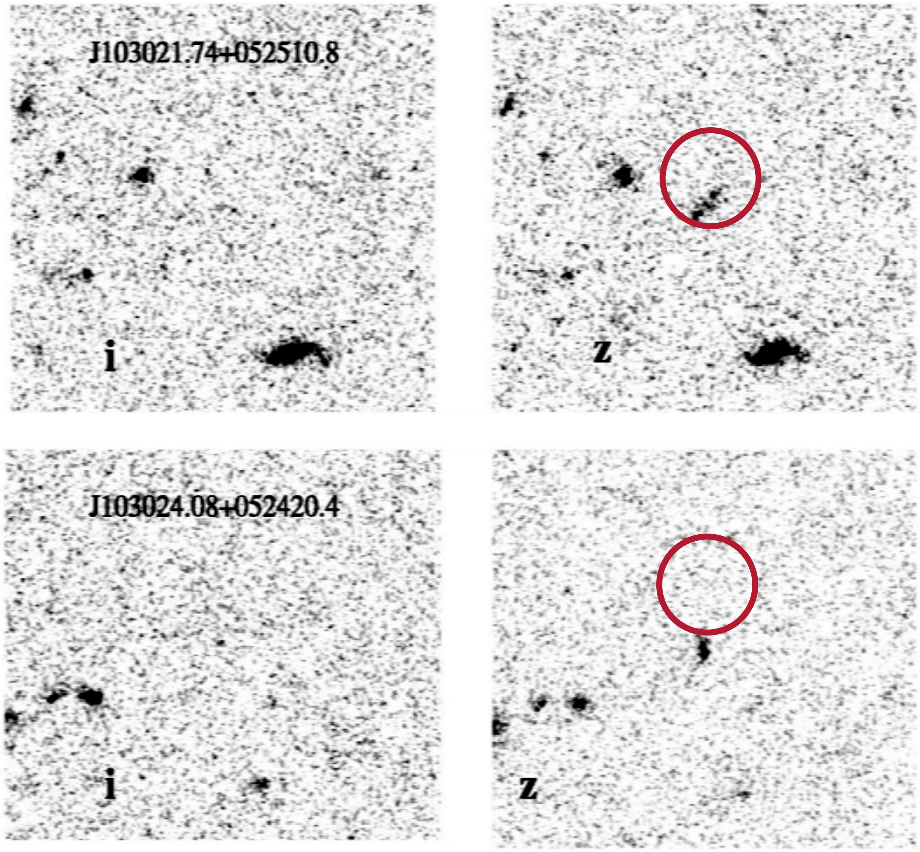
Subaru data

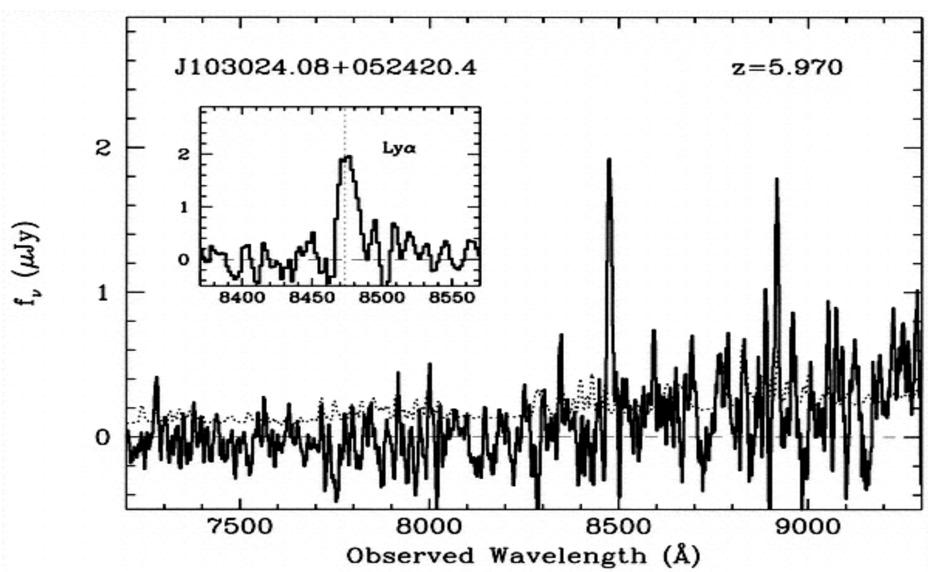


Protoclusters Around z ~ 6 QSOs?

Evidence for an excess of color-selected galaxies in the fields of $z \sim 6$ QSOs

Examples of color-selected candidates ➡



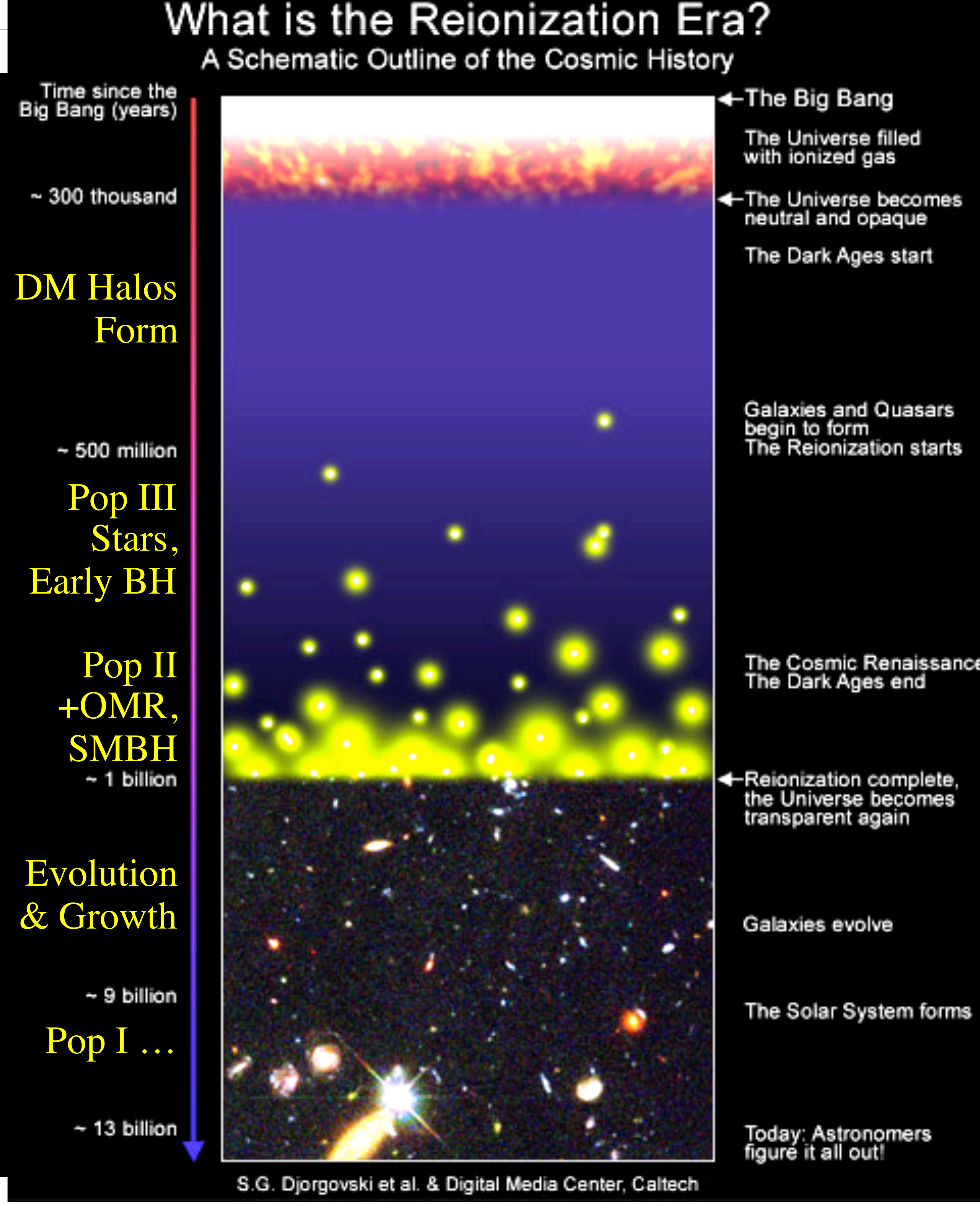


⬅ Spectroscopic confirmations

(Stiavelli et al. 2005, Bouwens et al. 2005, Kim et al. 2009)

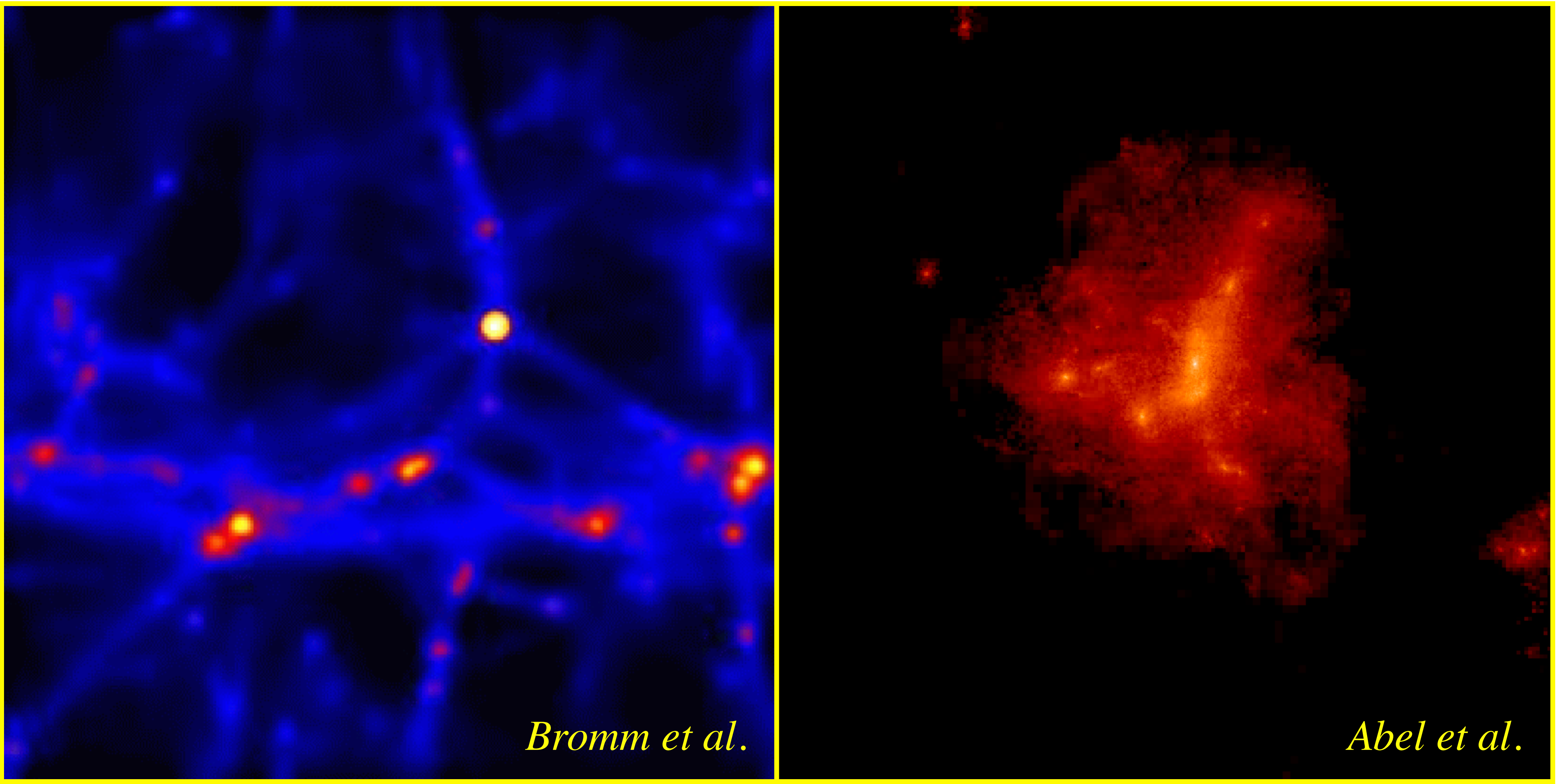
The Cosmic Reionization Era

(The Cosmic Renaissance)



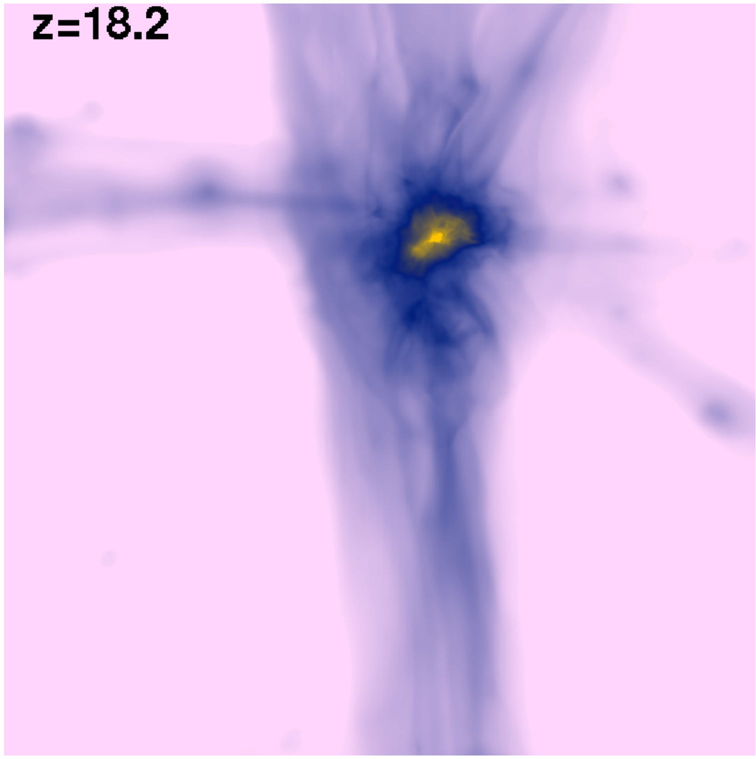
The First Stars

Gas infall into the potential wells of the dark matter fluctuations leads to increased density, formation of H_2, molecular line cooling, further condensation and cloud fragmentation, leading to the formation of the **first stars**

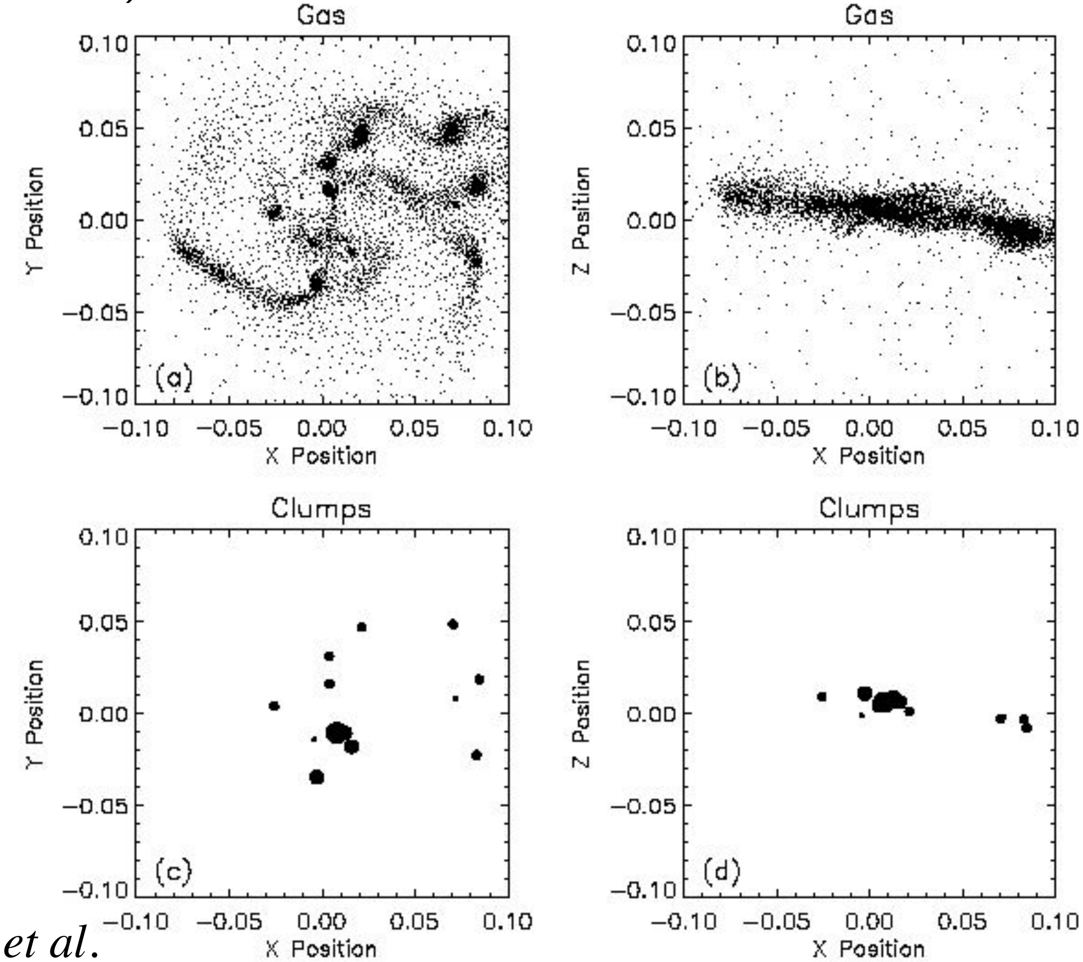


Primordial Star Formation: a Top-Heavy IMF?

Expected in all modern models of Pop III star formation, characteristic $M \sim 10^2$ - 10^4 $M_\odot$ (due to a less efficient cooling of protostellar clouds)

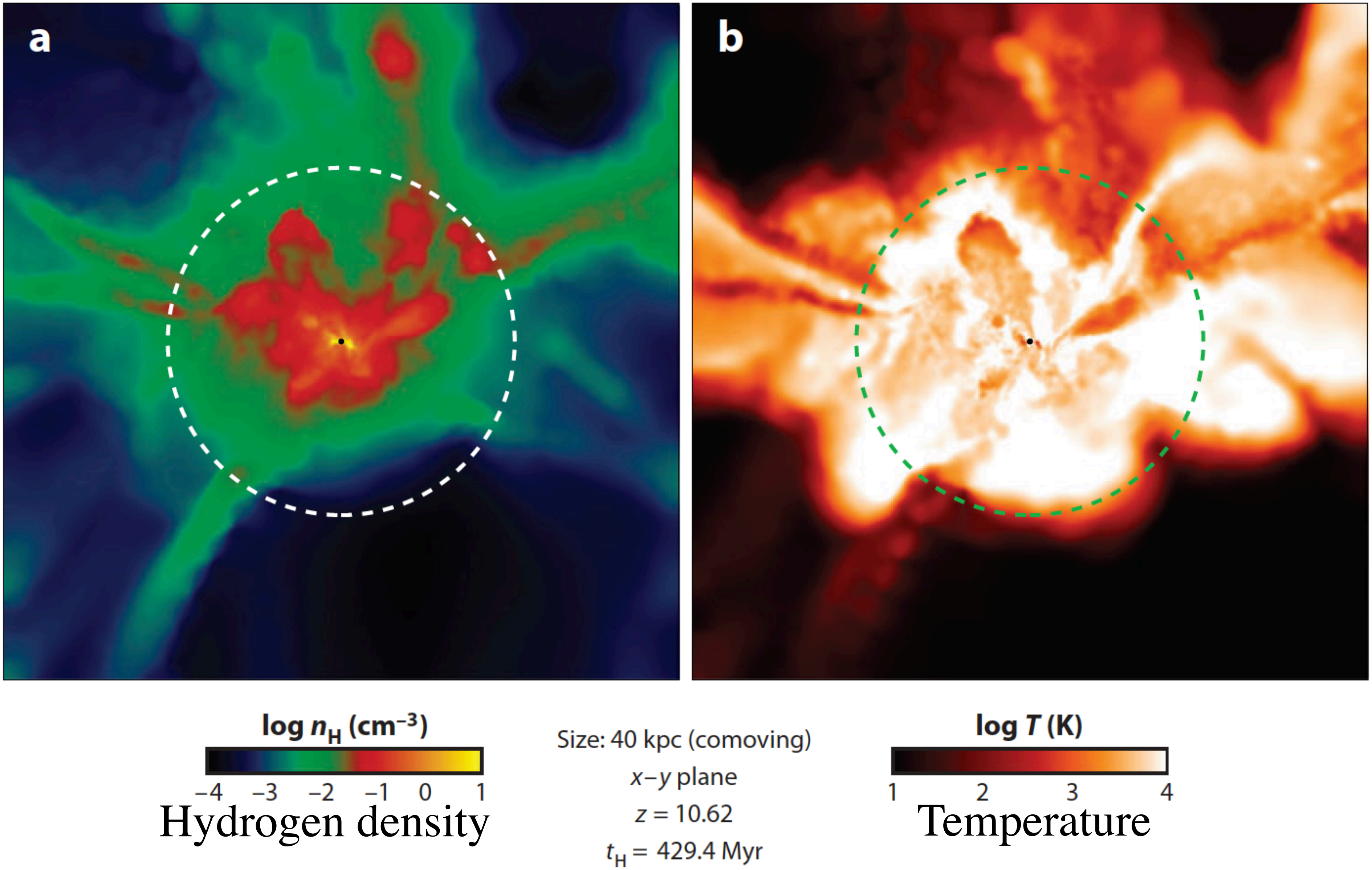


Abel et al.



Bromm et al.

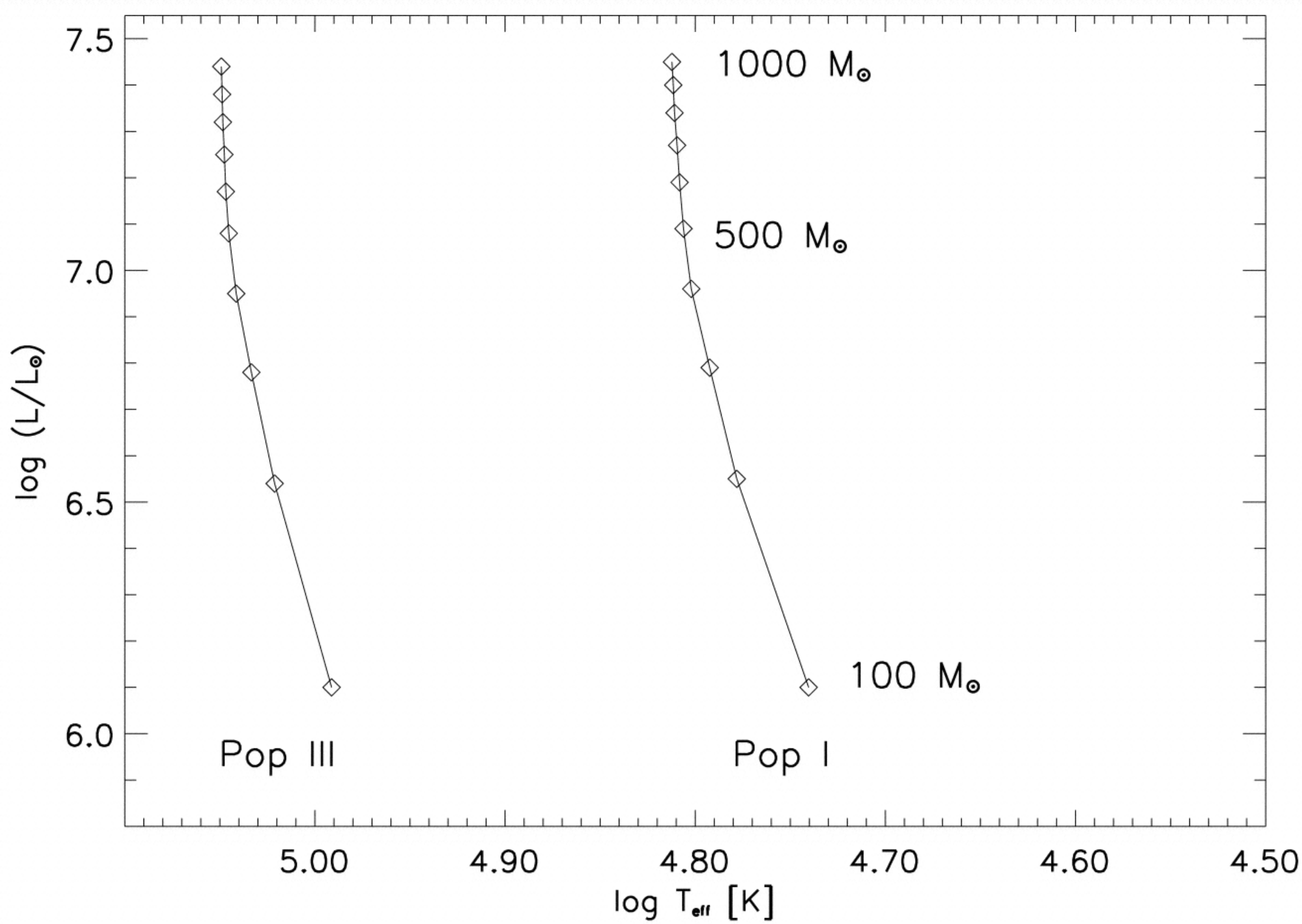
Turbulent Inafall into the First Galaxies



(from Bromm & Yoshida)

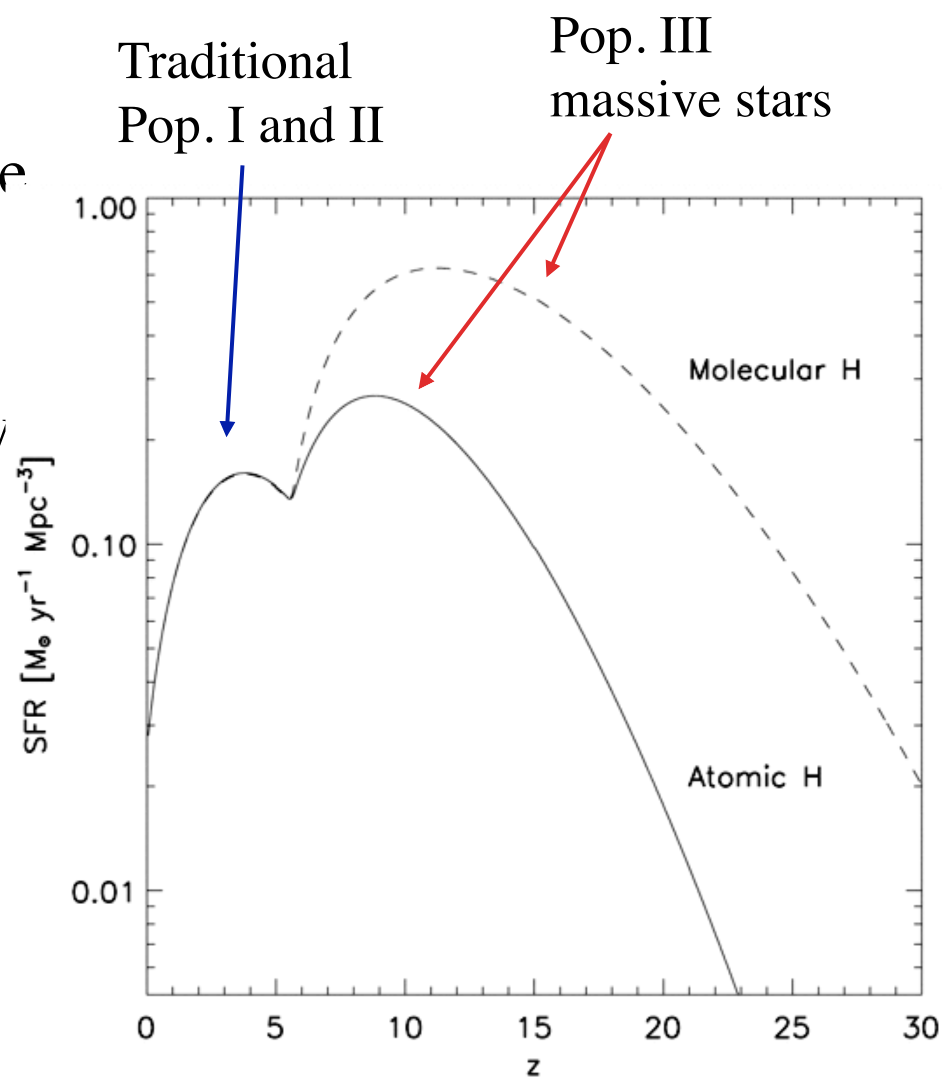
Population III Stars: Hot and Luminous

They can easily reionize the universe by z ~ 6



Population III Stars

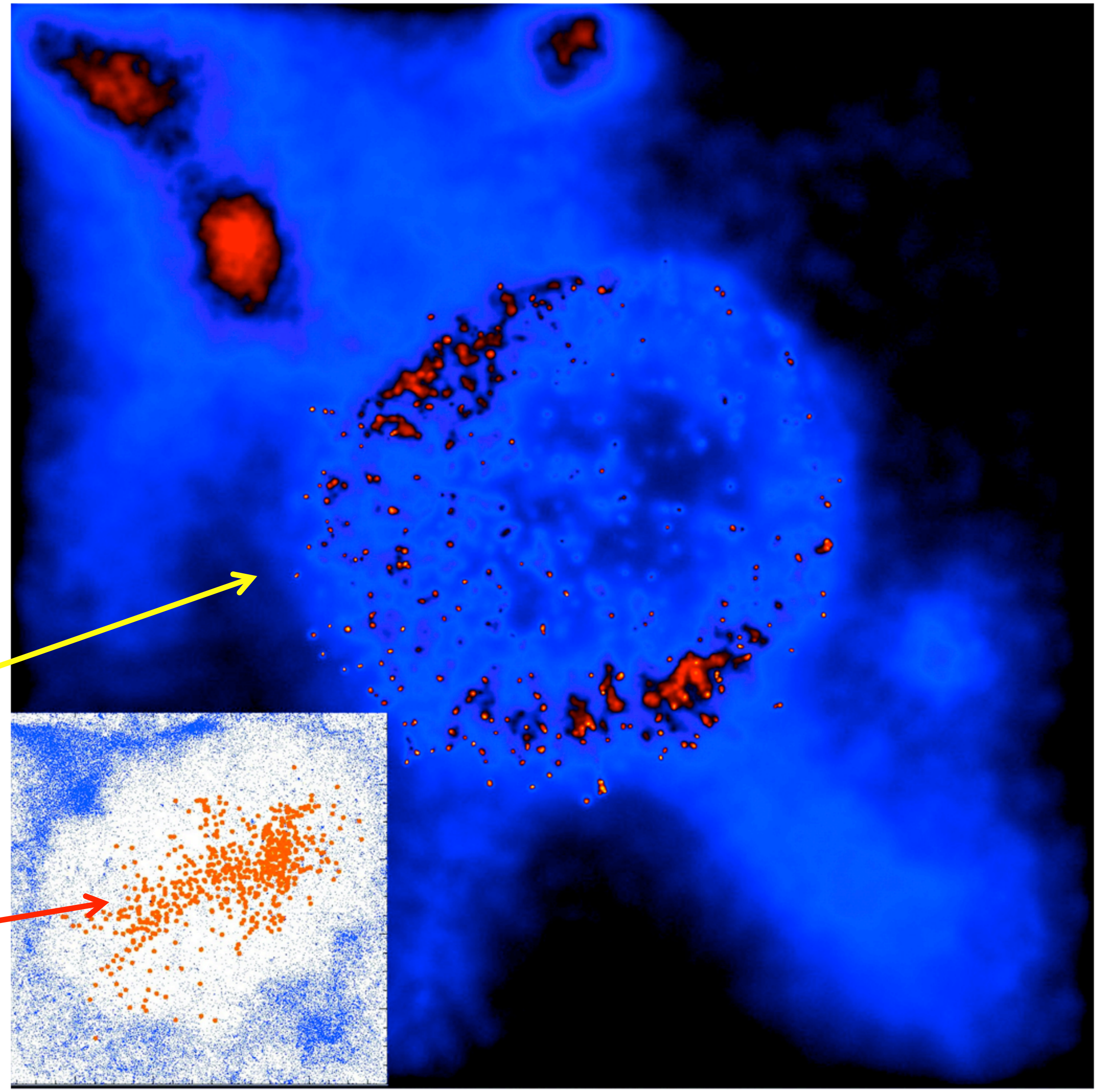
- They may have formed in large numbers as early as z ~ 20 - 30, and (partly?) reionized the universe, as WMAP data indicate
- However, their feedback may have extinguished the star formation in their hosts, possibly leading to a (partial?) recombination
- Then the formation of Pop. II stars may have reionized the universe again, ending the process at z ~ 6, as QSO data indicate



(Bromm & Loeb)

Population III Supernovae

- Early enrichment of the protogalactic gas
- Transition to the "normal" Pop II star formation and IMF when the metallicity reaches a critical value $Z_{crit} \sim 10^{-3.5}\, Z_{\odot}$

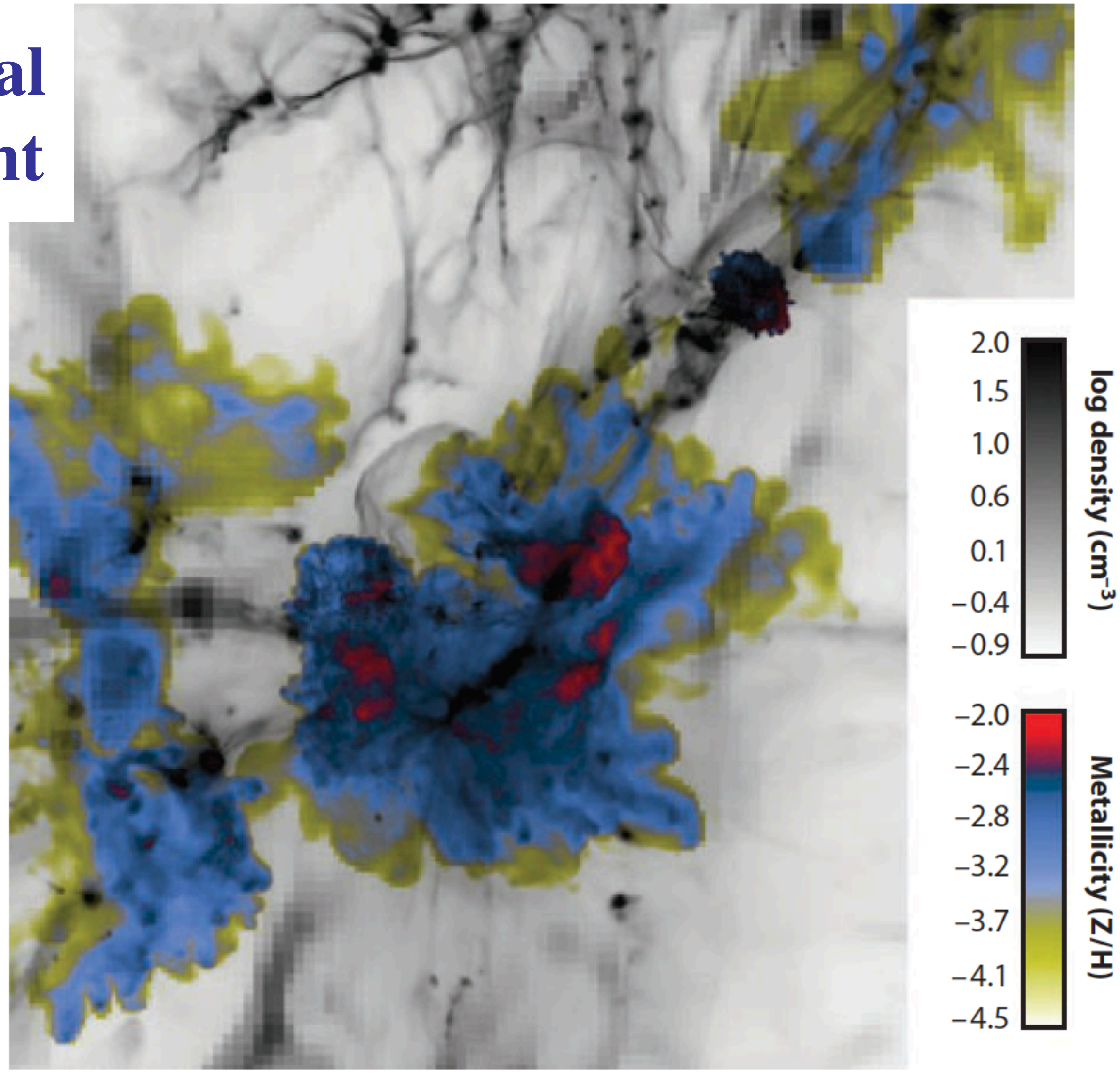


Simulated Pop III SN shell after $\sim 10^6$ yr

Distrib. of metals (red)

(from Bromm et al. 2003)

Early Metal Enrichment

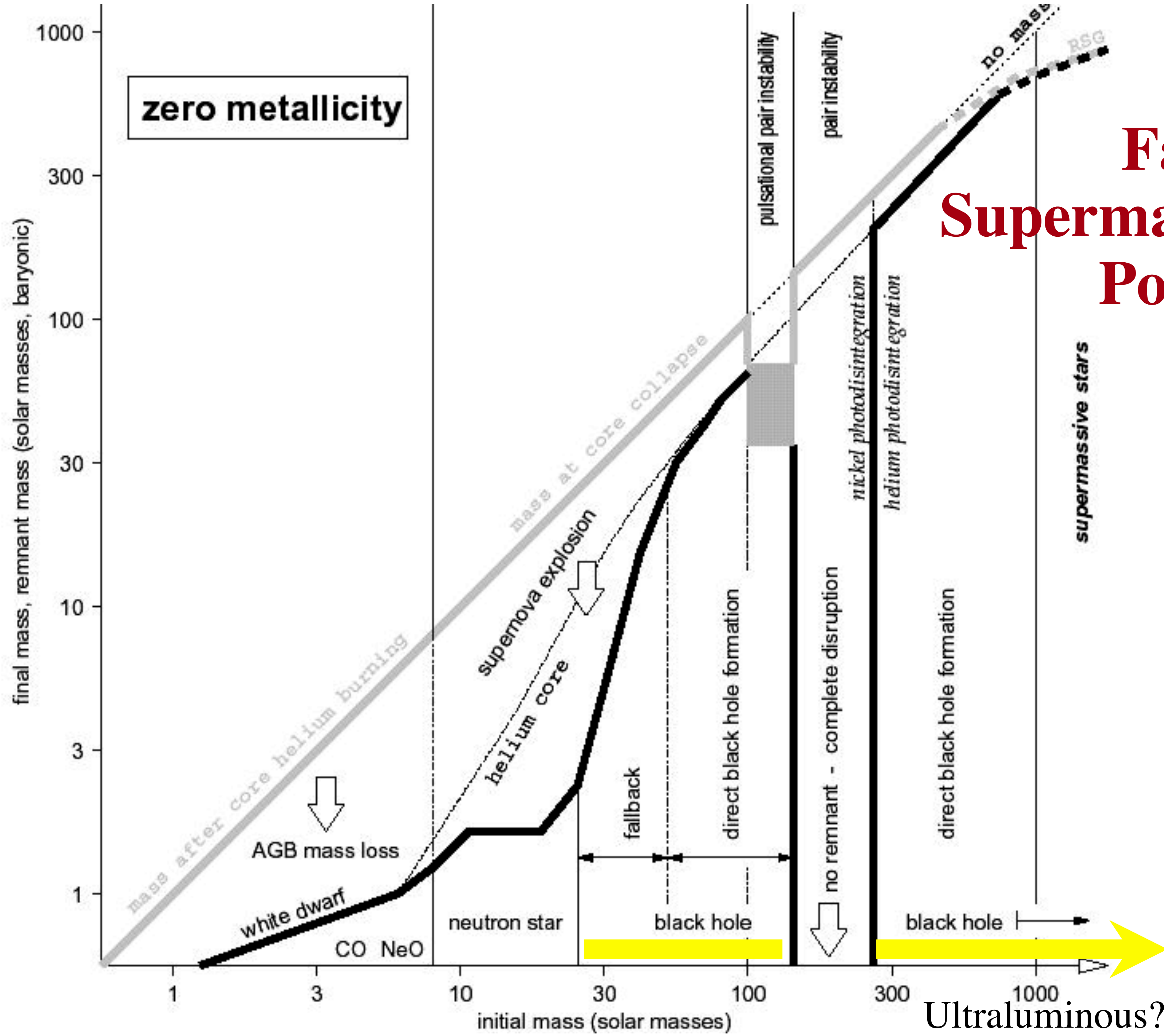


(from Bromm & Yoshida)

Figure 7

Metal enrichment in the first galaxy. Shown is the aftermath of tens of pair-instability supernovae (PISNe) that exploded inside the progenitor minihalos. The situation here corresponds to $z \simeq 17$. The projection of metallicity is shown in color, whereas that of gas density is shown in shades of gray; values are indicated by the insets. The box has a proper size of 8.6 kpc. Adapted from Wise & Abel (2008).

The Fate of Supermassive Pop. III Stars



GRB!

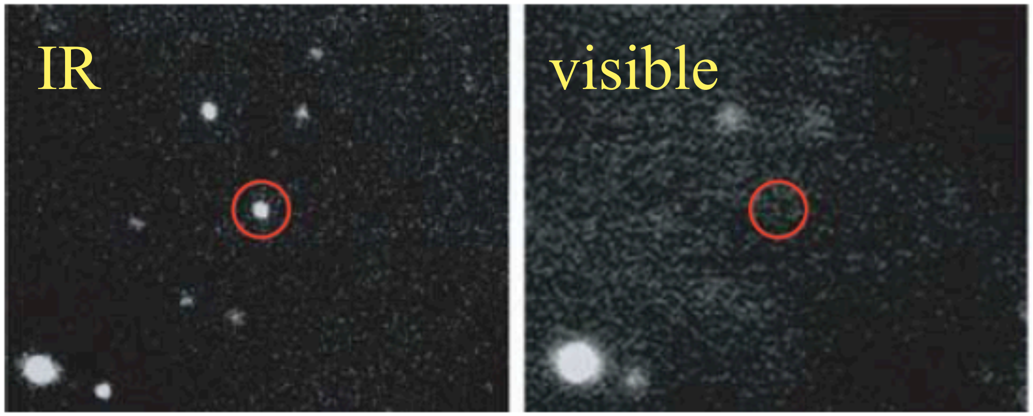
Ultraluminous?

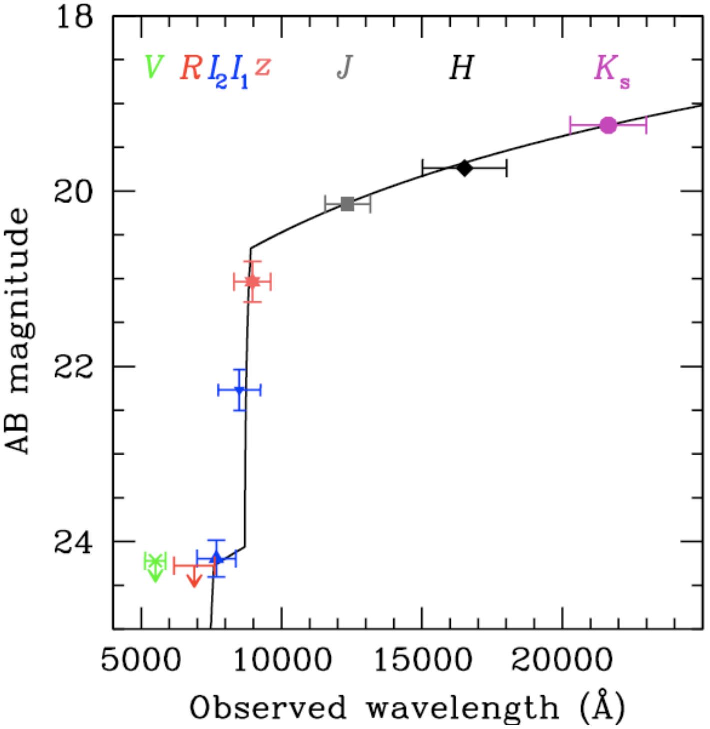
(Heger, Woosley, et al.)

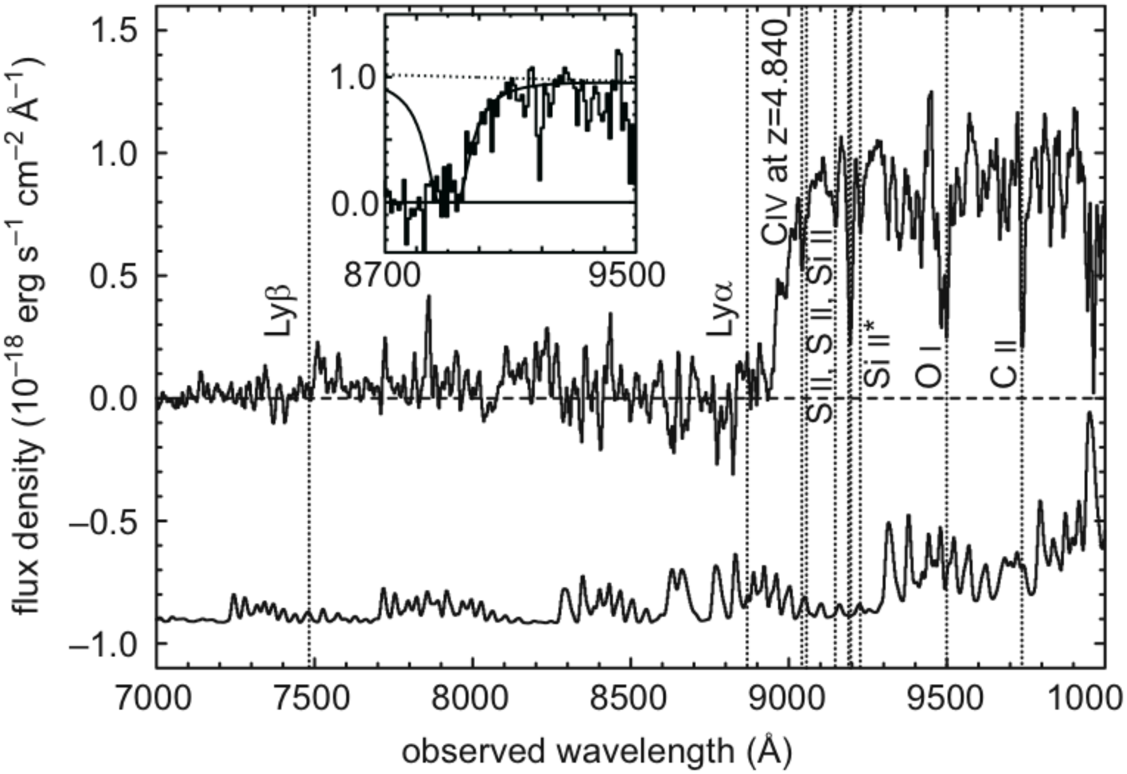
GRB 050904 at z = 6.295

A preview of the more distant, Pop. II flashes to come!

(Kawai et al. 2006, Haislip et al. 2006, Tagliaferri et al. 2006, etc.)

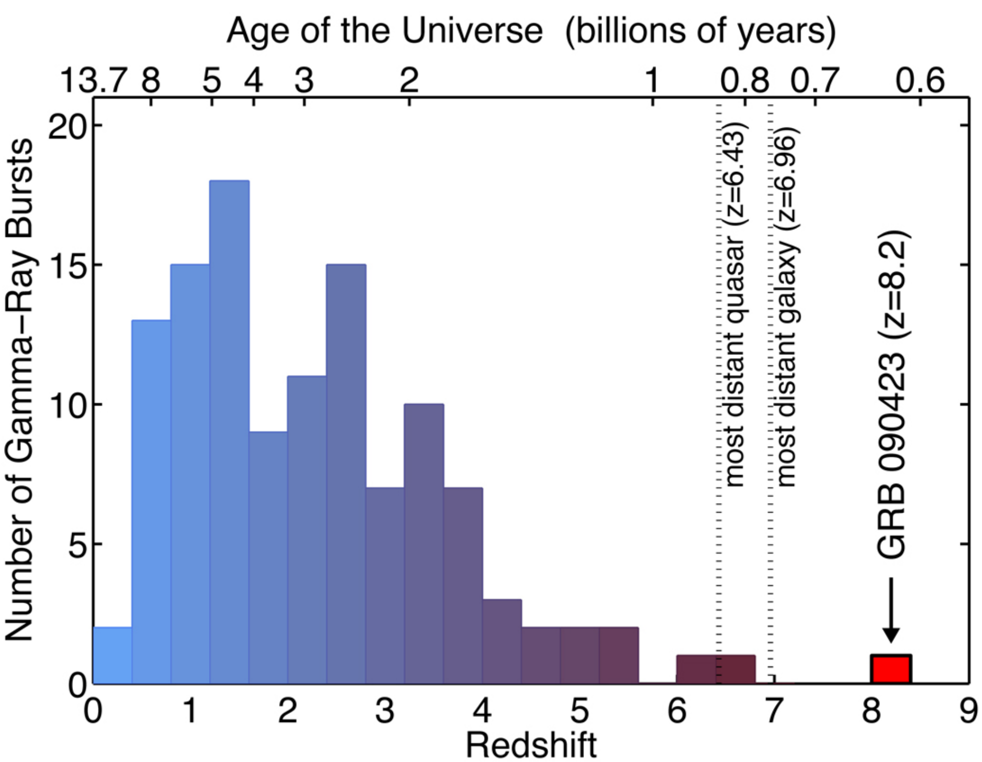


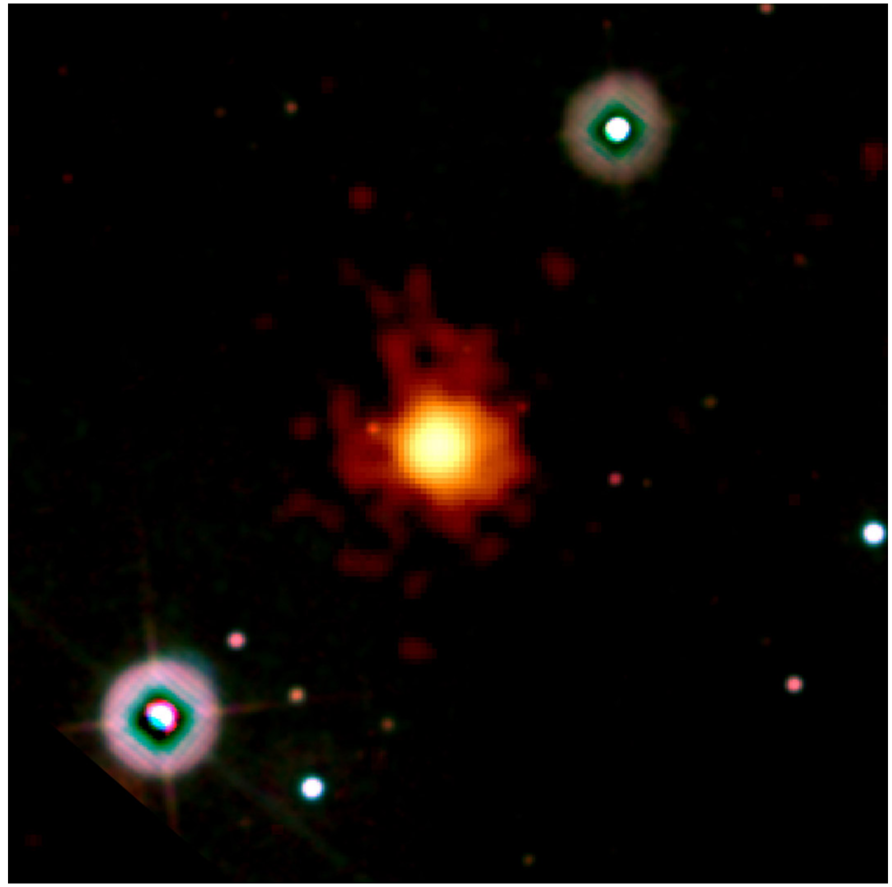




GRB 090423 at z ~ 8.2 (?)

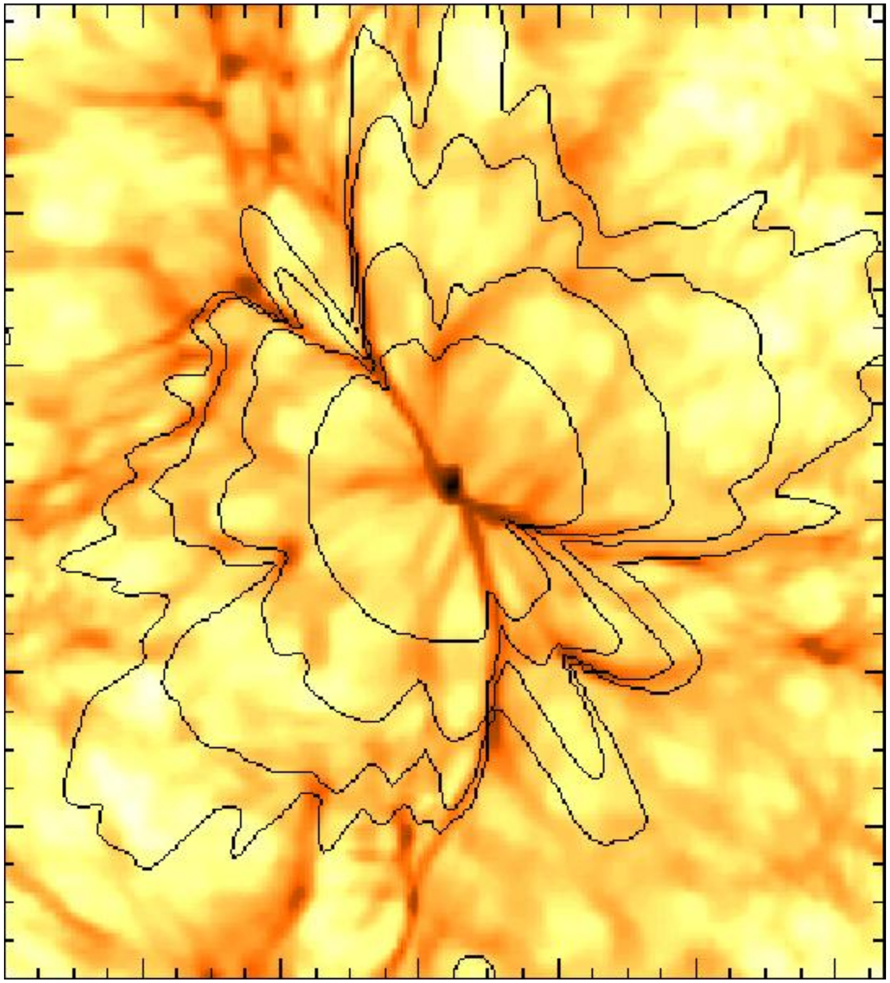
The current record holder – no details available yet

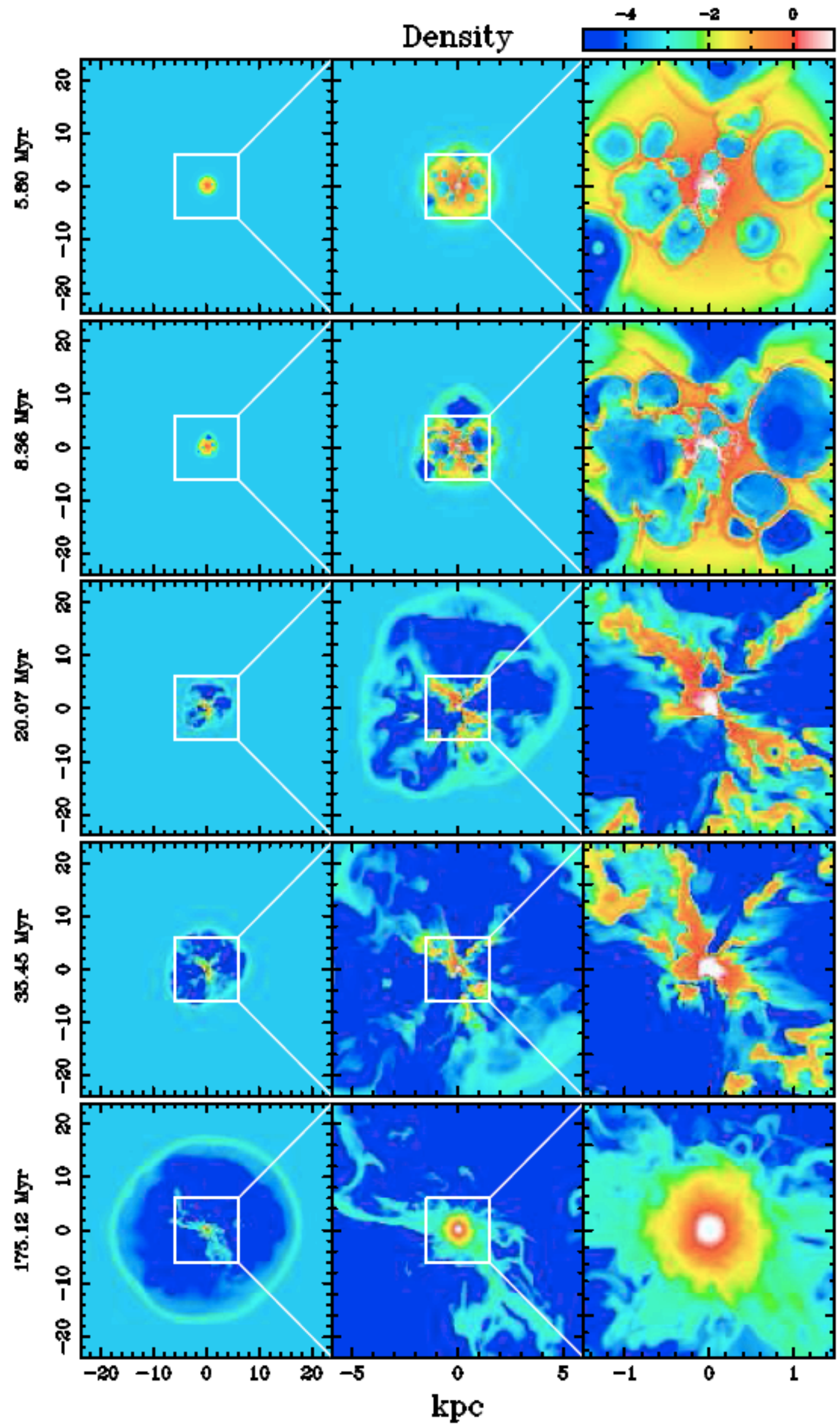




Simulations of the Cosmic Reionization

(from P. Madau et al.)

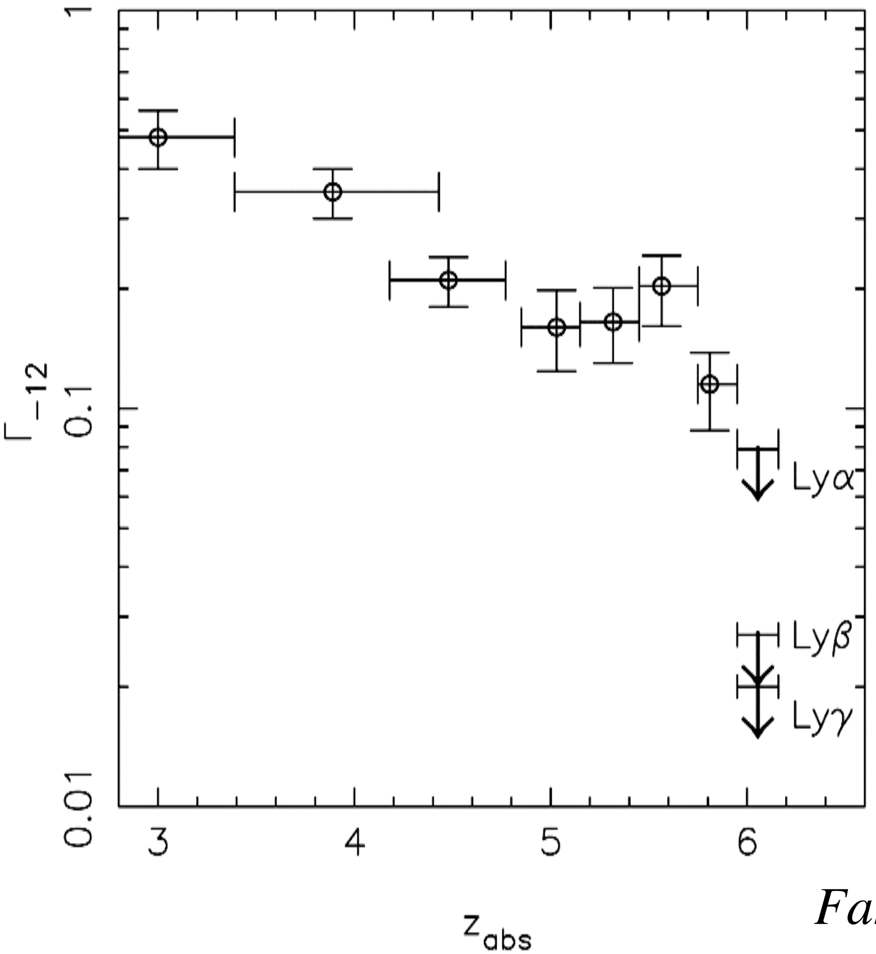




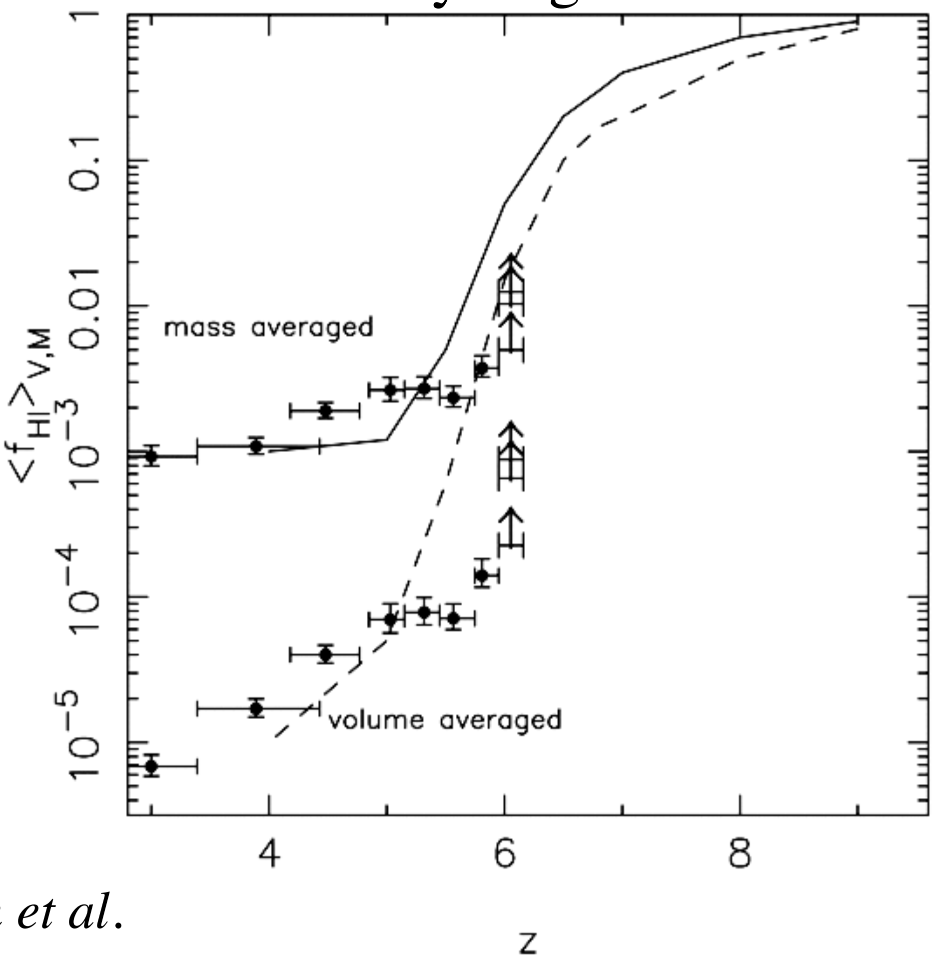
QSO Observations Suggest the End of the Reionization at z ~ 6

A sudden change in the UV opacity of the intergalactic medium

Photoionization Rate



Neutral Hydrogen Fraction

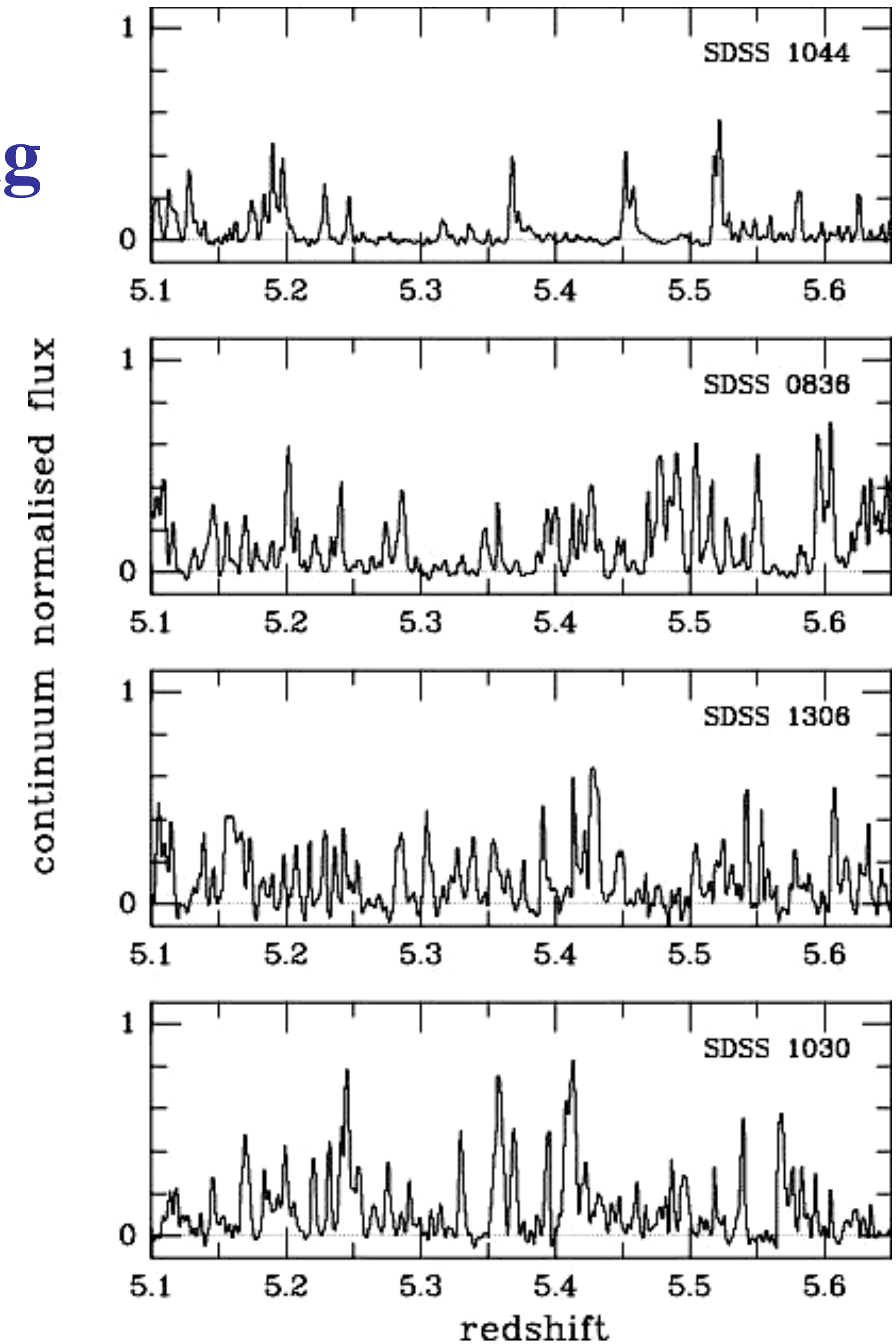


Fan et al.

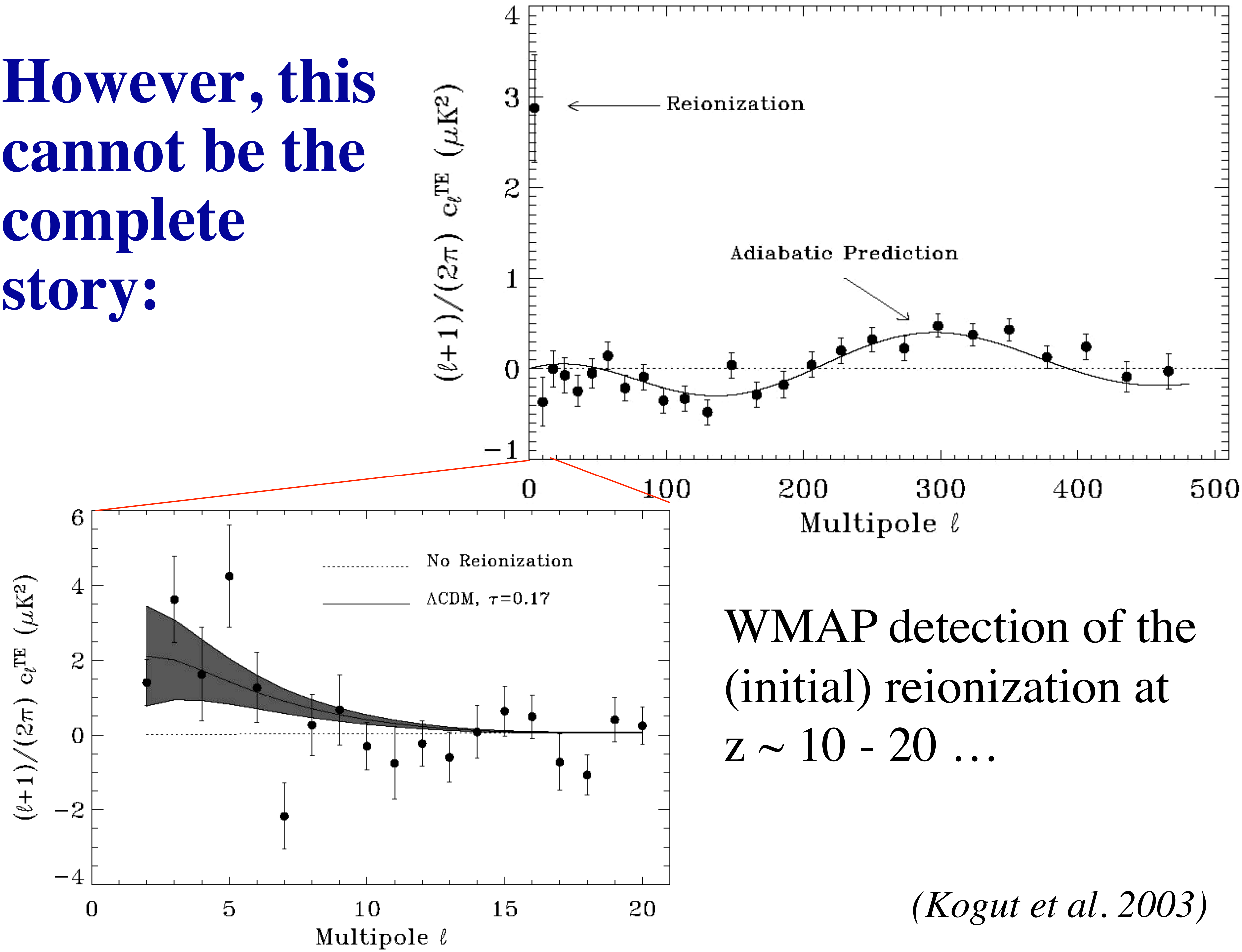
Substantial Diversity of IGM Absorption Seen Along Diffferent Lines of Sight

Shown here is the IGM transmission over the same redshift window, but along 4 different QSO lines of sight

A Considerable Cosmic Variance Exists in the transmission of the Lyα forest at $z > 5$



However, this cannot be the complete story:

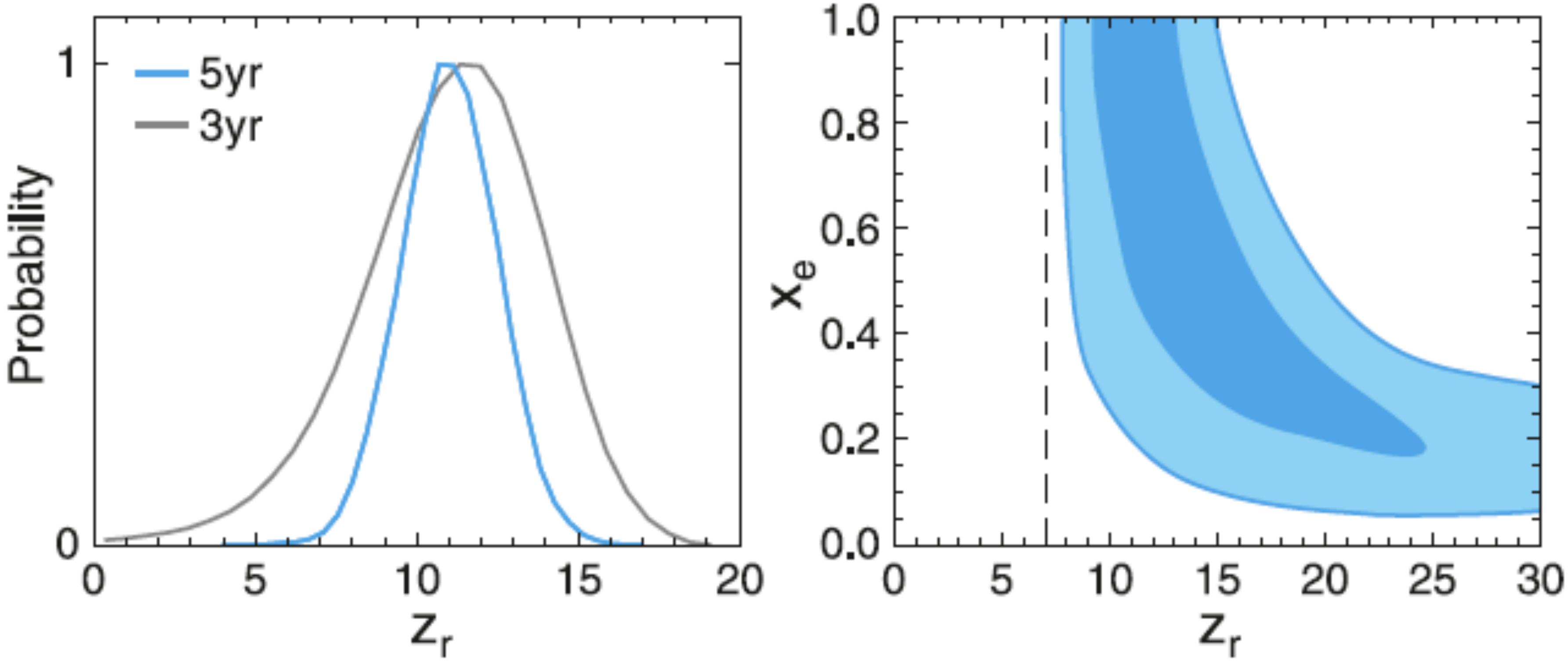


WMAP detection of the (initial) reionization at z ~ 10 - 20 …

(Kogut et al. 2003)

CMB Constraints on Reionization

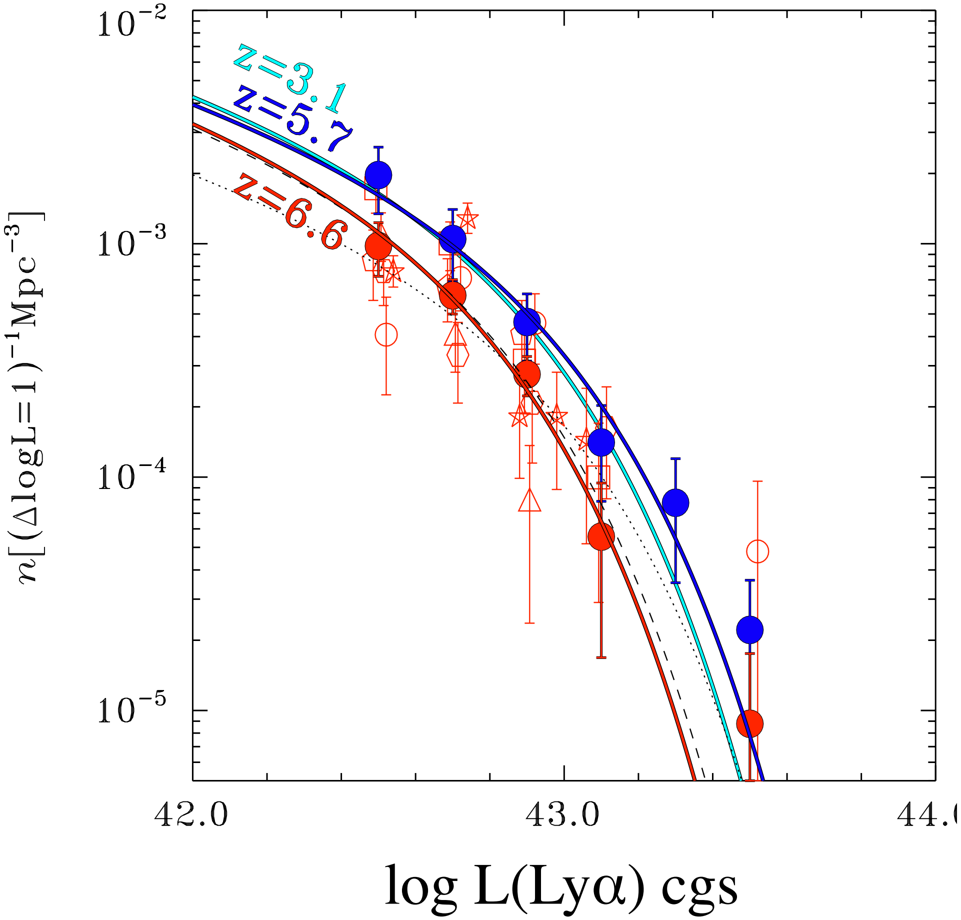
WMAP+eCMB, Hinshaw et al (2012): $\tau = 0.084 \pm 0.013$
consistent with an instantaneous reionization at $z = 10.3 \pm 1.1$
But also consistent with an extended reionization from
$z \sim 20 - 25$ to $z \sim 6$ (more realistic)

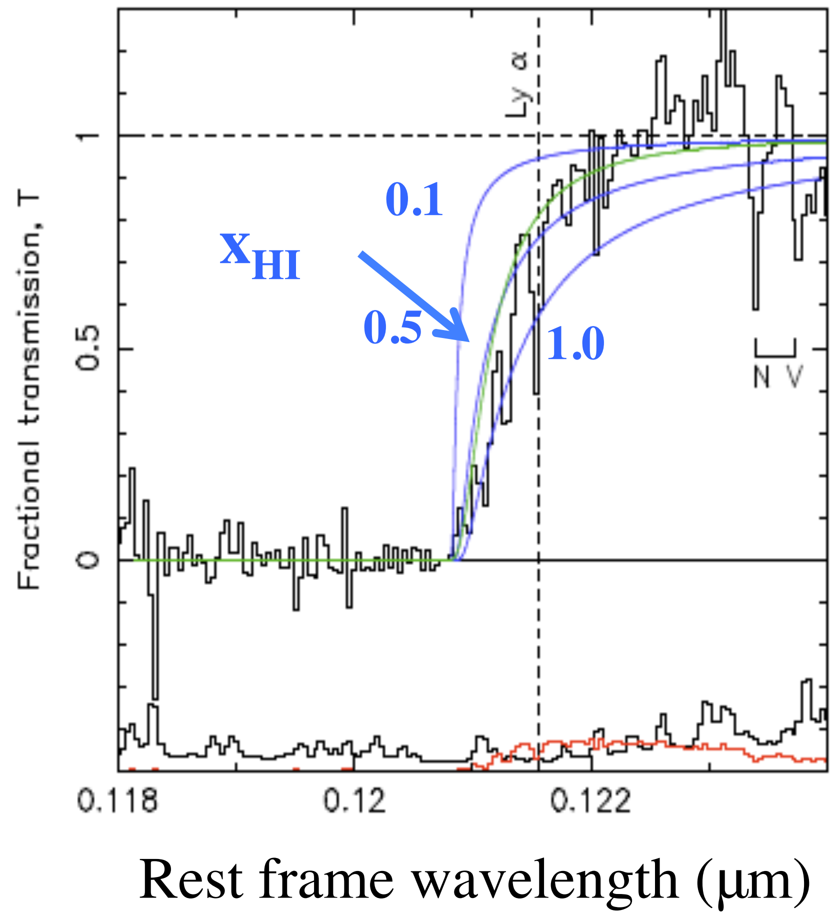


Further Evidence for Late Reionization

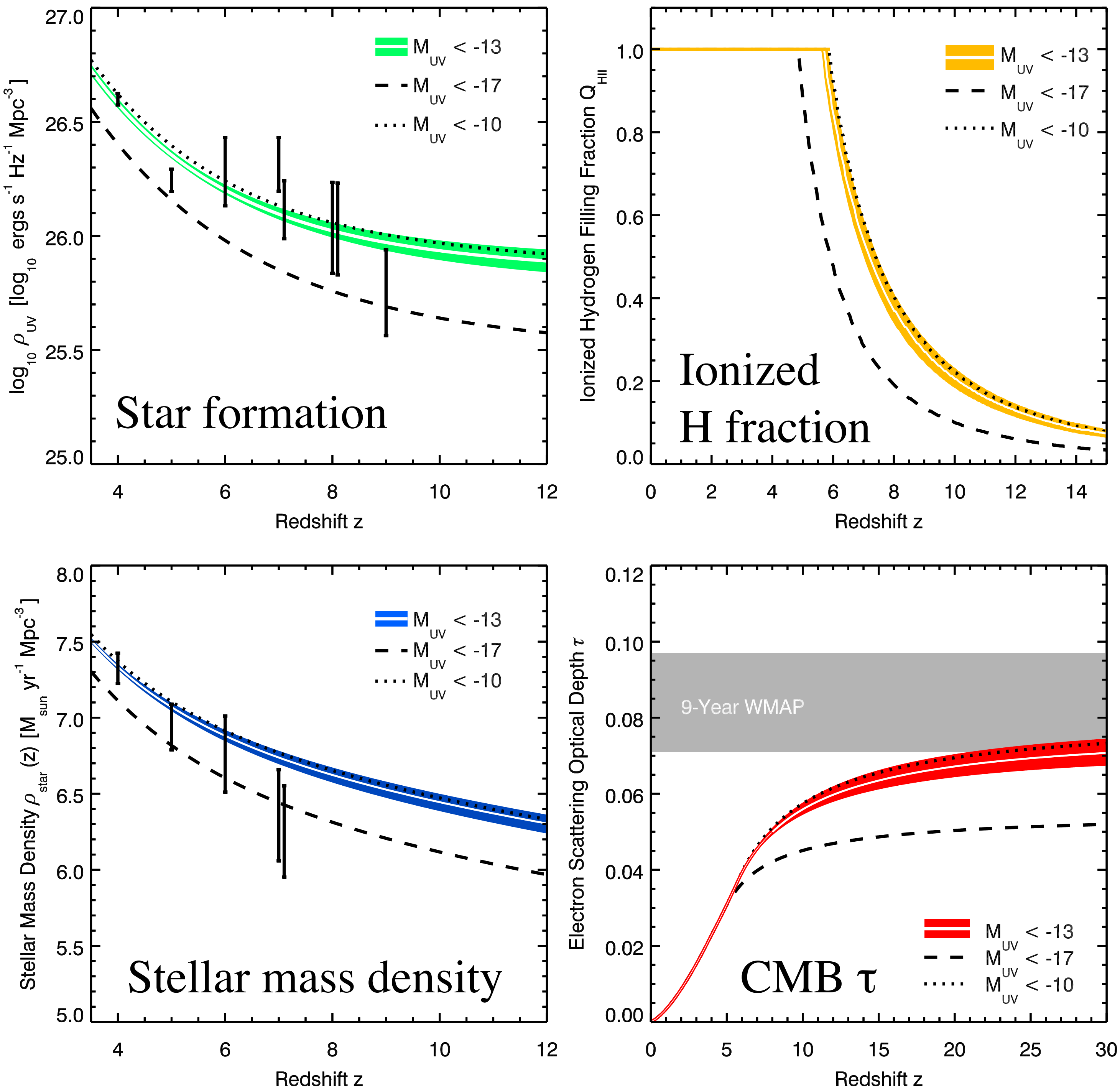
Rapid decline in abundance of Lyα emitters from 5.7 < z < 6.6 (Ouchi et al 2010): $x_{HI} \sim 0.1$ at z = 6.6?

Damping wing of Lyα in z=7.085 QSO: $x_{HI} > 0.1$ at z~7? (Mortlock et al. 2011, Bolton et al. 2011)





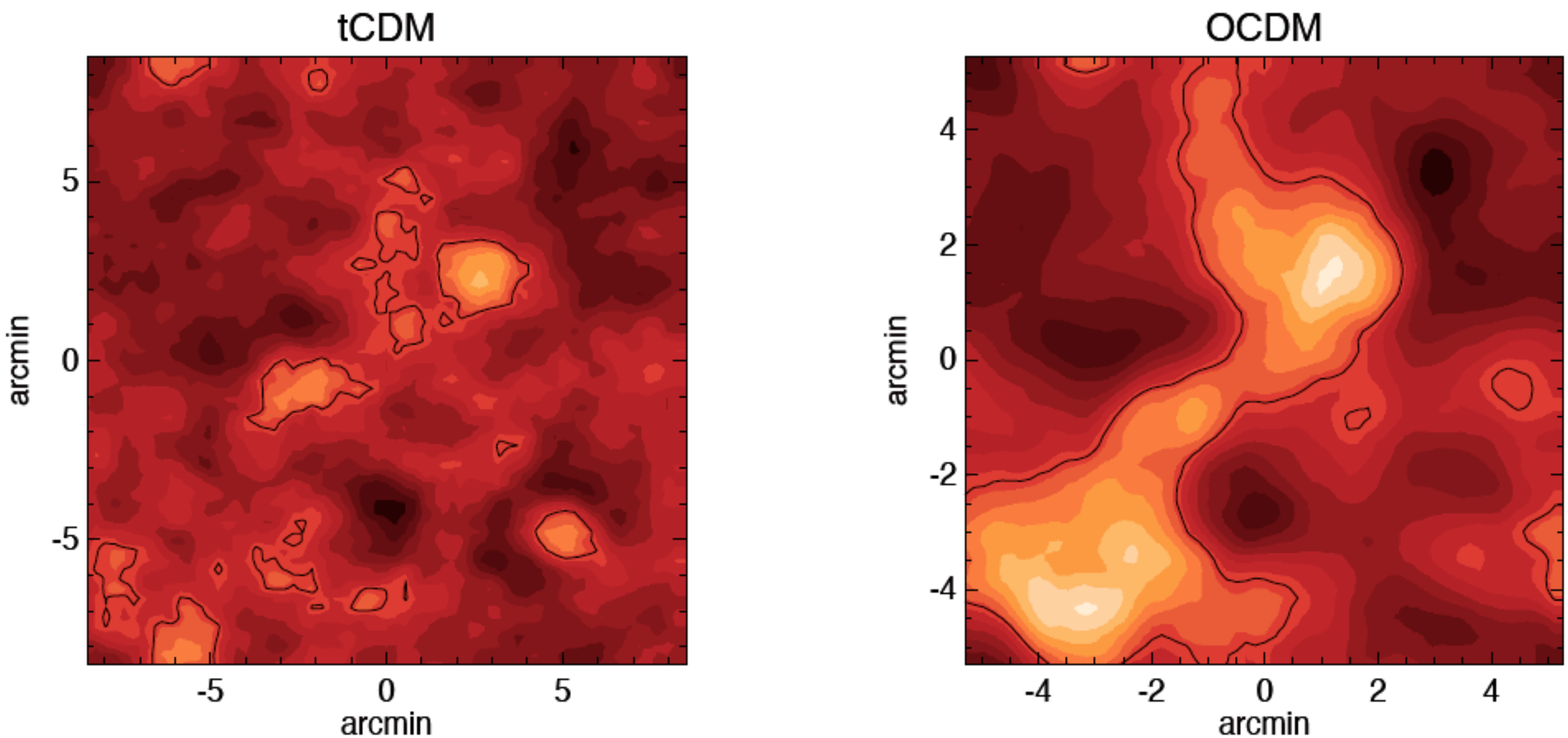
Putting It All Together



Based on the Hubble Ultra Deep Field analysis (Robertson et al. 2013)

Looking Even Deeper: The 21cm Line

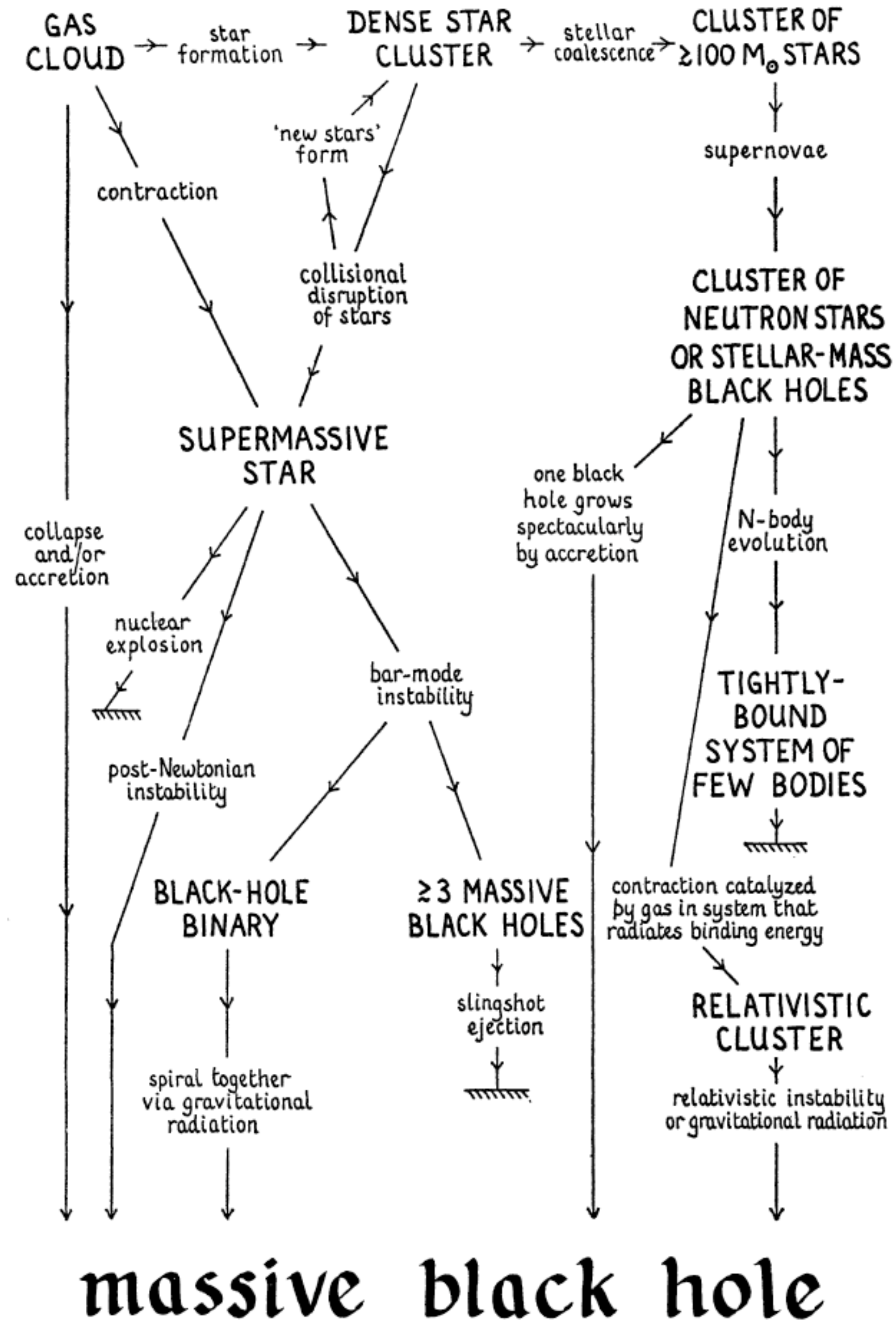
We can in principle image H I condensations in the still neutral, pre-reionization universe using the 21cm line. Several experiments are now being constructed or planned to do this, e.g., the Mileura Wide-Field Array in Australia, or the Square Kilometer Array (SKA)



(Simulations of $z = 8.5$ H I, from P. Madau)

The Origins of QSOs and SMBHs

(picture from Rees 1978) ➙



The key questions:

1. What are the relevant astrophysical origins of the seed BHs?
2. What are the relevant growth processes into SMBHs?
3. What can we observe at high redshifts?
4. How does it all relate to galaxy formation and growth?

First black holes in pregalactic halos $z \approx 10\text{-}30$

$M_{BH} \sim 100\text{-}600\ M_{sun}$

PopIII stars remnants
(Madau & Rees 2001,
Volonteri, Haardt & Madau 2003)

✓ Simulations suggest that the first stars are massive $M \sim 100\text{-}600\ M_{sun}$
(Abel et al., Bromm et al.)

✓ Metal free dying stars with $M > 260 M_{sun}$ leave remnant BHs with $M_{seed} \geq 100 M_{sun}$ (Fryer, Woosley & Heger)

(from M. Volonteri)

$M_{BH} \sim 10^3\text{-}10^6\ M_{sun}$

Viscous transport + supermassive star (e.g. Haehnelt & Rees 1993, Eisenstein & Loeb 1995, Bromm & Loeb 2003, Koushiappas et al. 2004)

✓ Efficient viscous angular momentum transport + efficient gas confinement

Bar-unstable self-gravitating gas + large "quasistar" (Begelman, Volonteri & Rees 2006)

✓ Transport angular momentum on the dynamical timescale, process cascades

✓ Formation of a BH in the core of a low entropy quasistar $\sim 10^4\text{-}10^6$ Msun

✓ The BH can swallow the quasistar

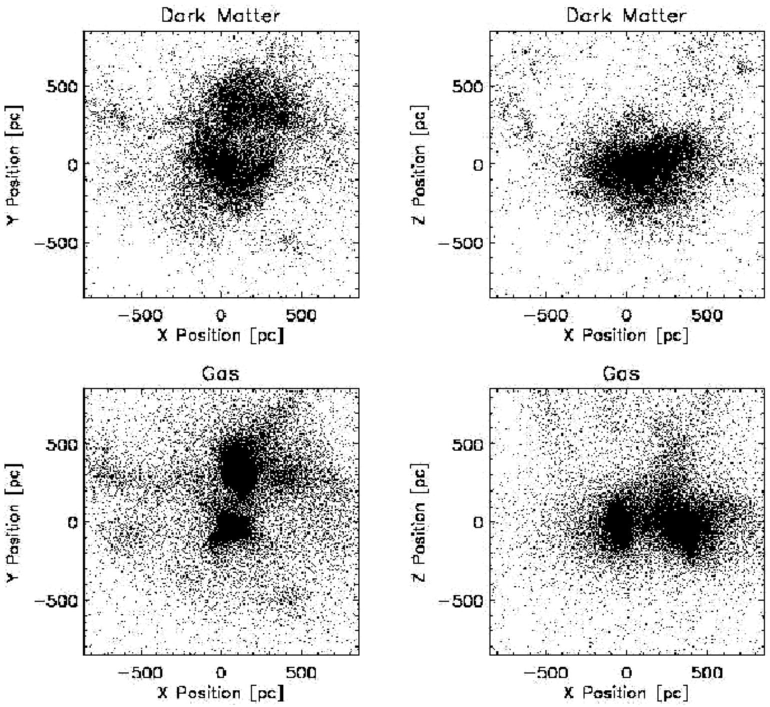
The Nature of the BH "Seeds"

Some plausible choices include:

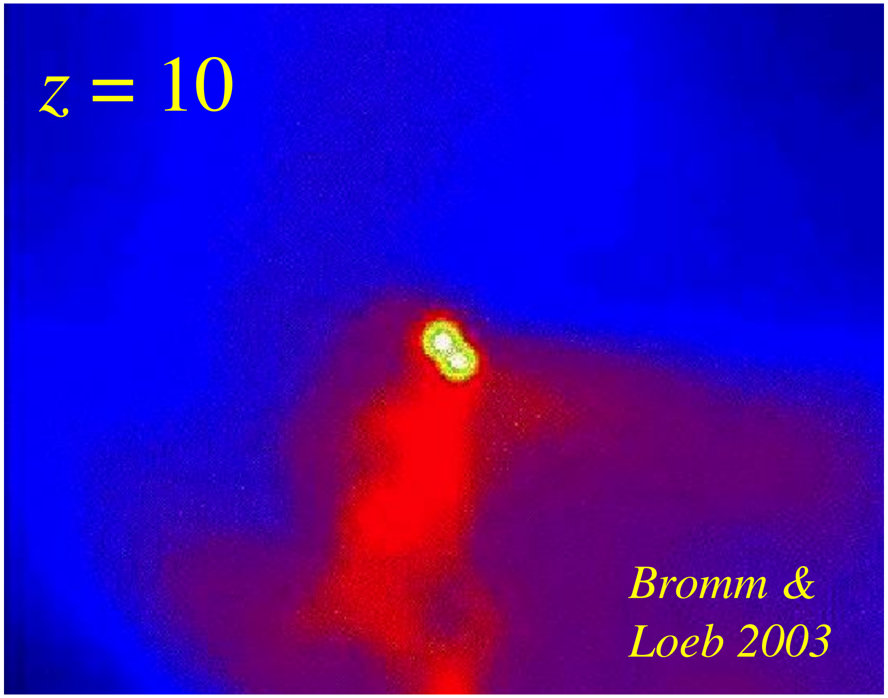
- Primordial, i.e., created by localized gravitational collapses in the early universe, e.g., during phase transitions
  - No evidence and no compelling reasons for them, but would be very interesting if they did exist; could have "any" mass…
  - See many good reviews by B. Carr
- Remnants of Pop. III massive stars: $M_{seed} \sim 10 - 100\ M_\odot$
  - Could be detectable as high-z GRBs
- Gravitational collapse of dense star clusters, or runaway mergers of stars: $M_{seed} \sim 10^2 - 10^4\ M_\odot$
- Direct gravitational collapse of dense protogalactic cores: continues directly as a SMBH growth

More than one of these processes may be operating …

Pop III Black Holes and the Origin of AGN

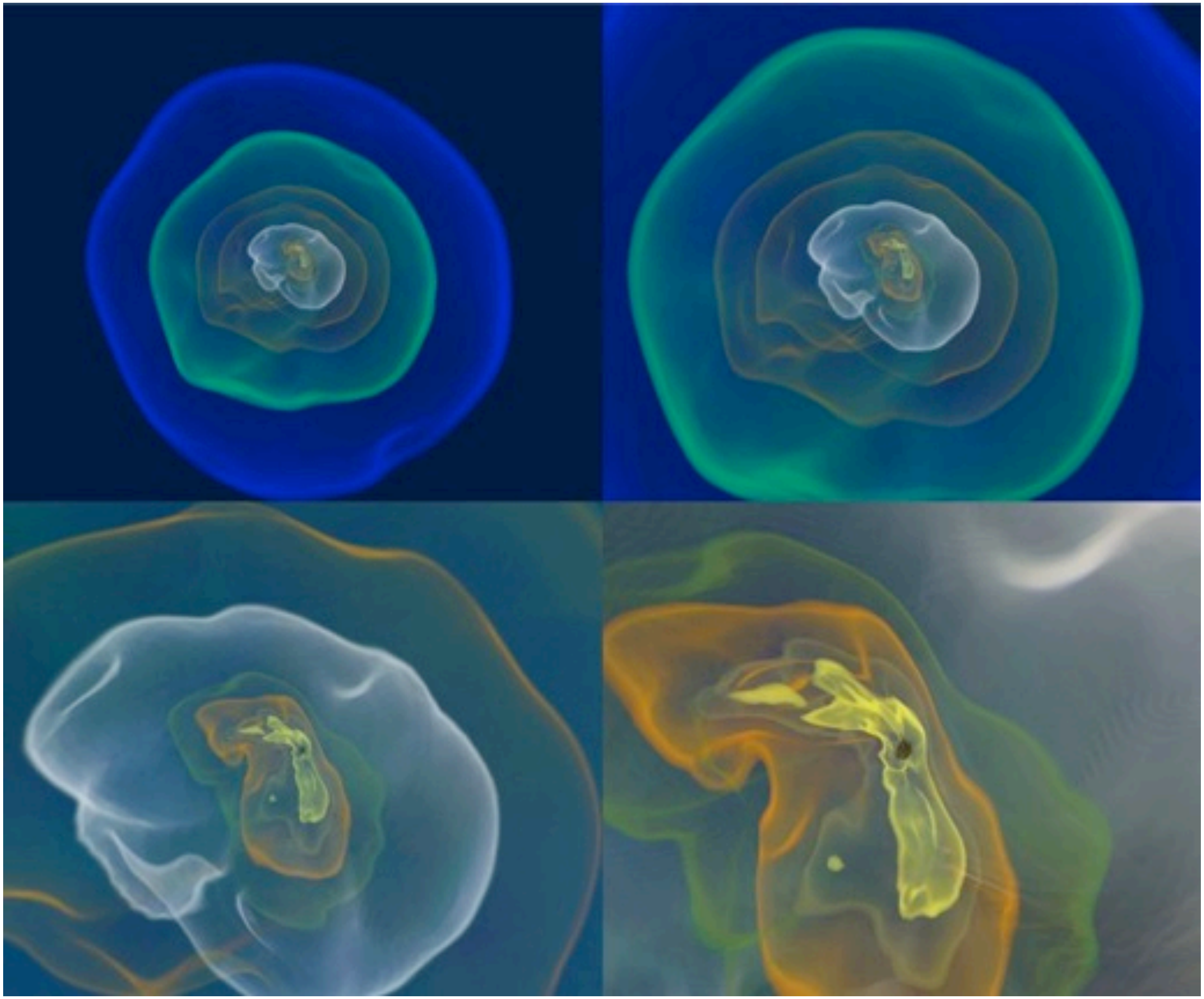


- Explosions of massive Pop III stars can produce relict BHs with $M_\bullet \sim$ few - $10^2\ M_\odot$
- Direct collapse of zero-spin mini-halos may lead to BHs with $M_\bullet \sim 10^4$ - $10^6\ M_\odot$



- They can grow through rapid accretion and merging to become central engines of AGN (SMBH)
- Mergers of these early BHs may generate gravitational waves detectable by LISA

Formation of a SMBH by Direct Collapse

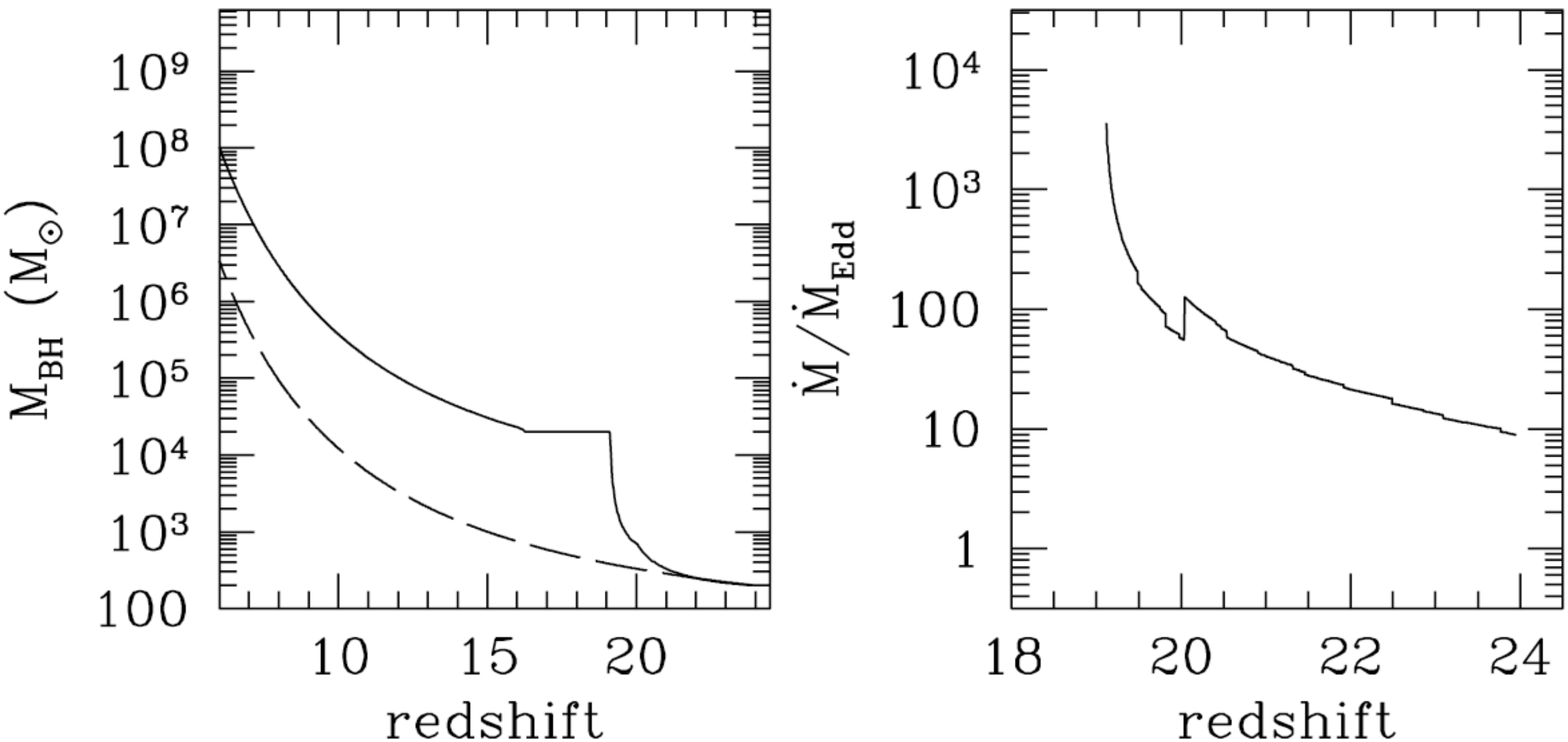


Numerical simulation by Wise, Turk, Abel (KIPAC)

Possible Rapid Early Accretion Growth

Once the BH seeds form, e.g., from Pop. III stellar remnants in densest young halos, a SMBH may grow rapidly via supercritical accretion, reaching $M_\bullet \sim 10^9\,M_\odot$ by $z \sim 6$

e.g., Volonteri & Rees 2005:



Energetics of the Early QSO Growth

Since the baryonic material used to build SMBHs comes from initial radii $R_{init} \sim 10^2$ - 10^4 pc, and ends at $R_{final} \sim R_\bullet \sim 10^{-7}$ - 10^{-4} pc, substantial fraction of the rest mass must be dissipated.

For a Schwarzschild BH, max. efficiency is $\varepsilon_{max} \approx 0.06$; for a Kerr BH, $\varepsilon_{max} \approx 0.42$; typically assumed $\varepsilon \sim 0.1$.

Thus, a total dissipated energy is:

$$E_{SMBH} \sim 2 \times 10^{62} \, (M_\bullet/10^9 M_\odot) \, (\varepsilon/0.1) \text{ erg}$$

Released over $\Delta t \sim 700$ Myr $\sim 2 \times 10^{16}$ s, it implies

average luminosity $L \sim 10^{46}$ erg/s $\sim 2 \times 10^{12} \, L_\odot$

(summed over all progenitor pieces)

Depending on the relative rates of BH and star formation, this may provide a significant fraction of the early reionization photons

The Rapid SMBH Growth Challenge

In the standard $\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$, $h = 0.7$ cosmology:

Redshift	Age/Myr
30	103
20	185
6.5	869
6	963

➡ **Available time to grow a SMBH ~ 700 - 800 Myr**

For a final SMBH mass $M_\bullet \sim 10^9\ M_\odot$:

For the seed BHs mass $M_{seed} \sim 10\ M_\odot$, need ~ 18 *e*-foldings

For the $M_{seed} \sim 100\ M_\odot$, need ~ 16 *e*-foldings

➡ Barely OK for the Salpeter time ~ 45 (ε/0.1) Myr

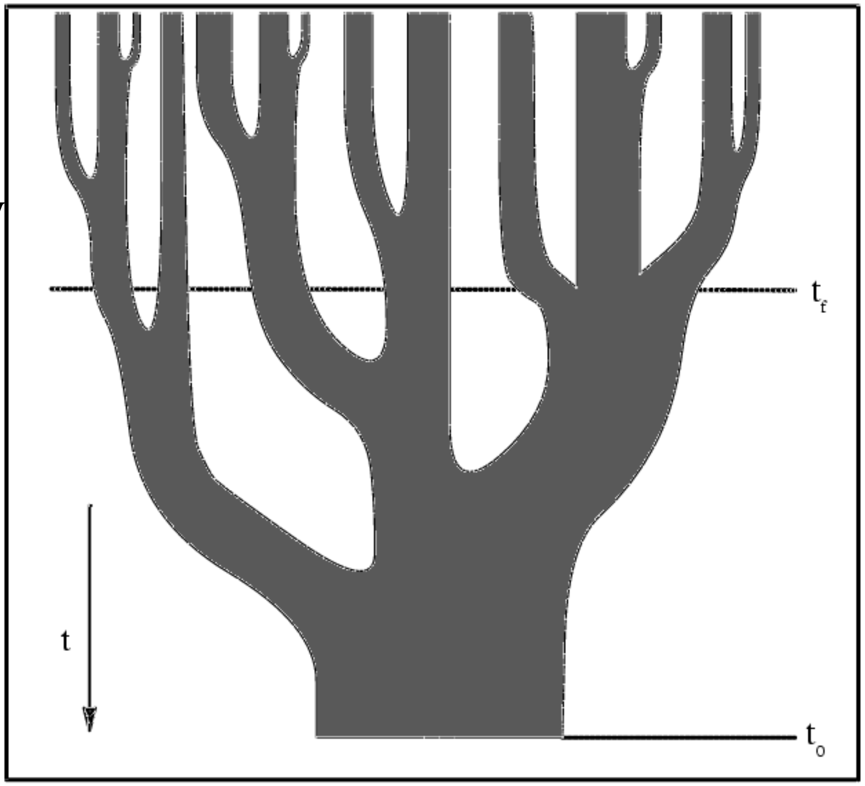
➡ SMBH growth has to be ~ Eddington limited

➡ **Very luminous sources!**

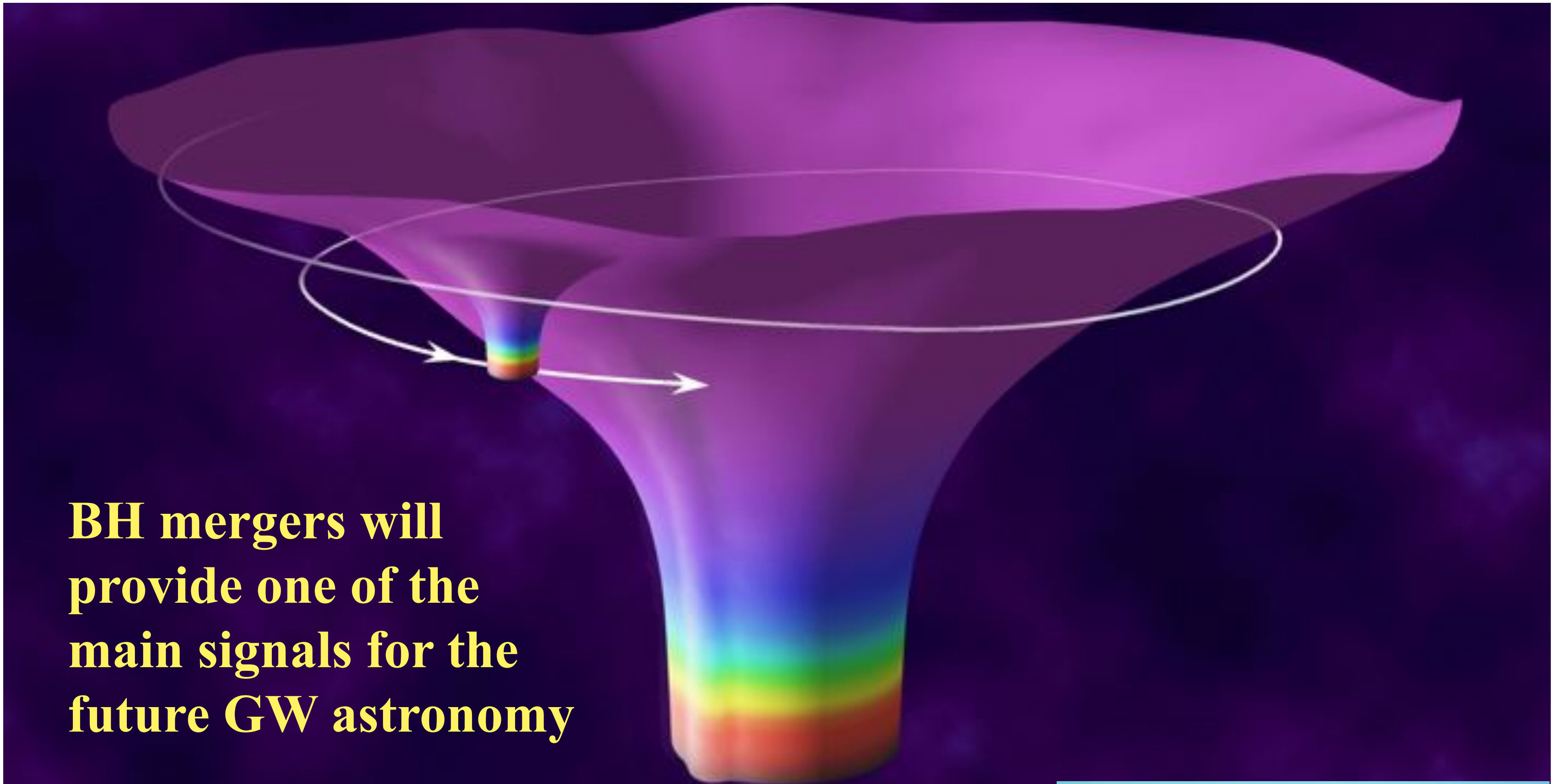
… But the limiting factor may be getting rid of the angular momentum …

SMBH Growth Mechanisms

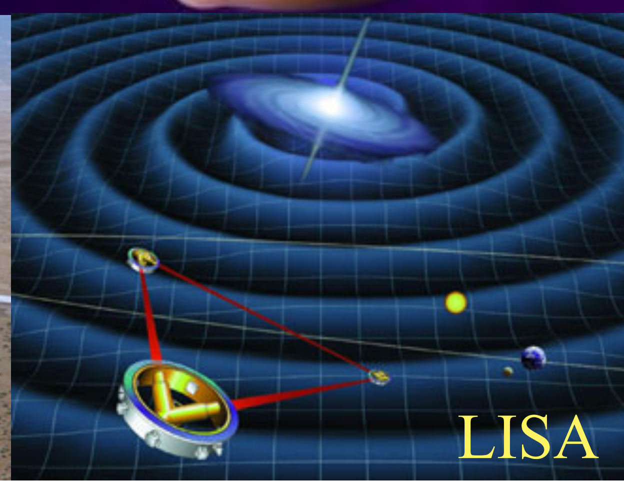
- In a hierarchical picture, as galaxies merge so will their BH's
  - Some may get ejected in 3-body interactions; their subsequent fate may be interesting
- This can naturally lead to the establishment of the SMBH - host galaxy correlations, which may be also sharpened by the AGN feedback



- Note that BH merging simply *re-arranges* the distribution of the collapsed mass; *collapsed mass grows by accretion*, following the BH seed collapse
- This fueling/build-up may be especially effective in mergers

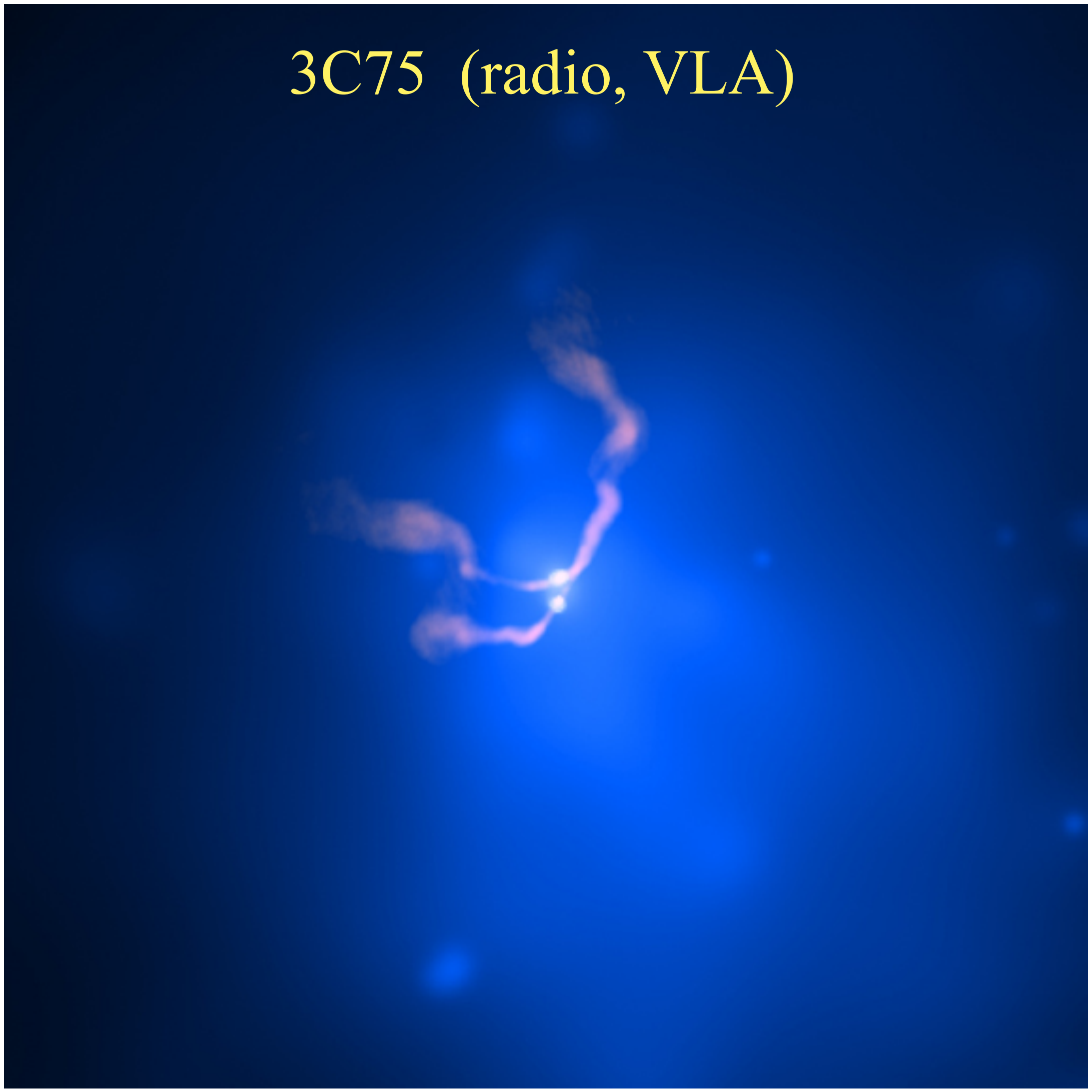

BH mergers will
provide one of the
main signals for the
future GW astronomy

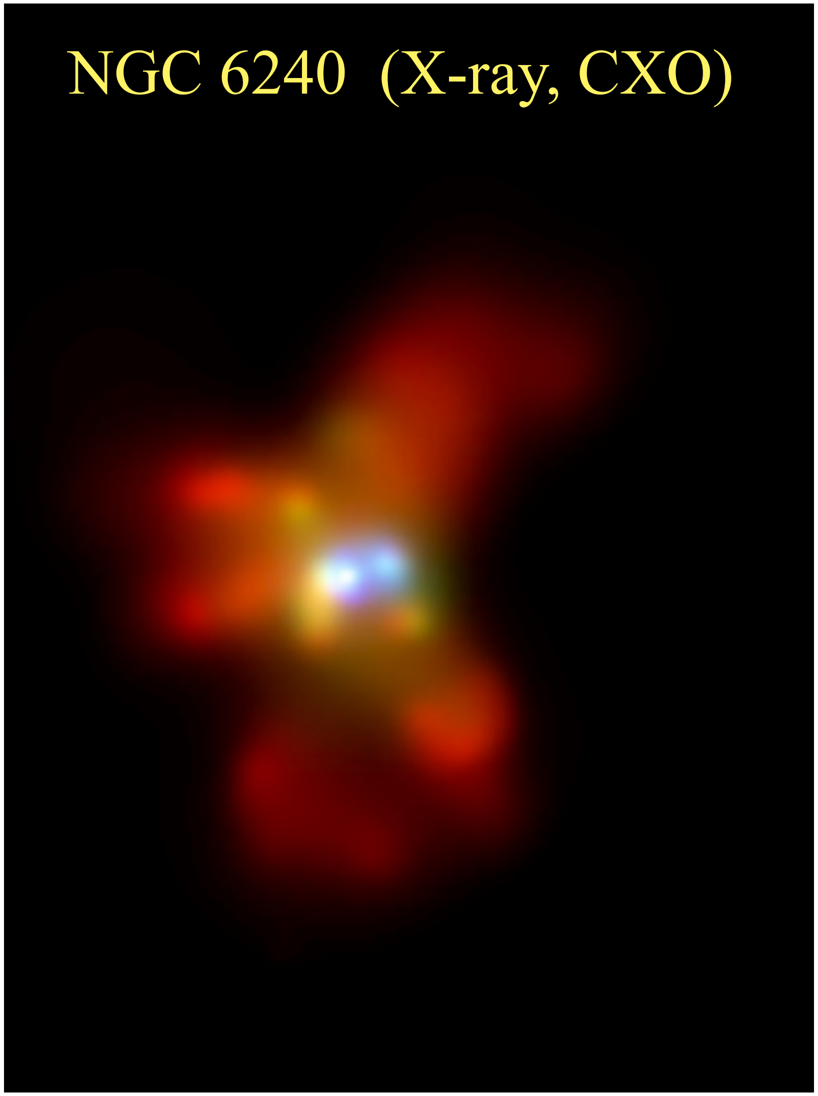

LIGO


LISA


VIRGO

Pre-Merger SMBH Binaries Are Observed at Low Redshifts





Possible Electromagnetic Signatures of BH Mergers

- Merging BHs are expected to be GW sources, but should there be also some observable EM signatures?
- Binary BHs can effectively clear out their influence region, but in reality, things may be more messy
- Accretion disk(s) may be present before, or after the merger