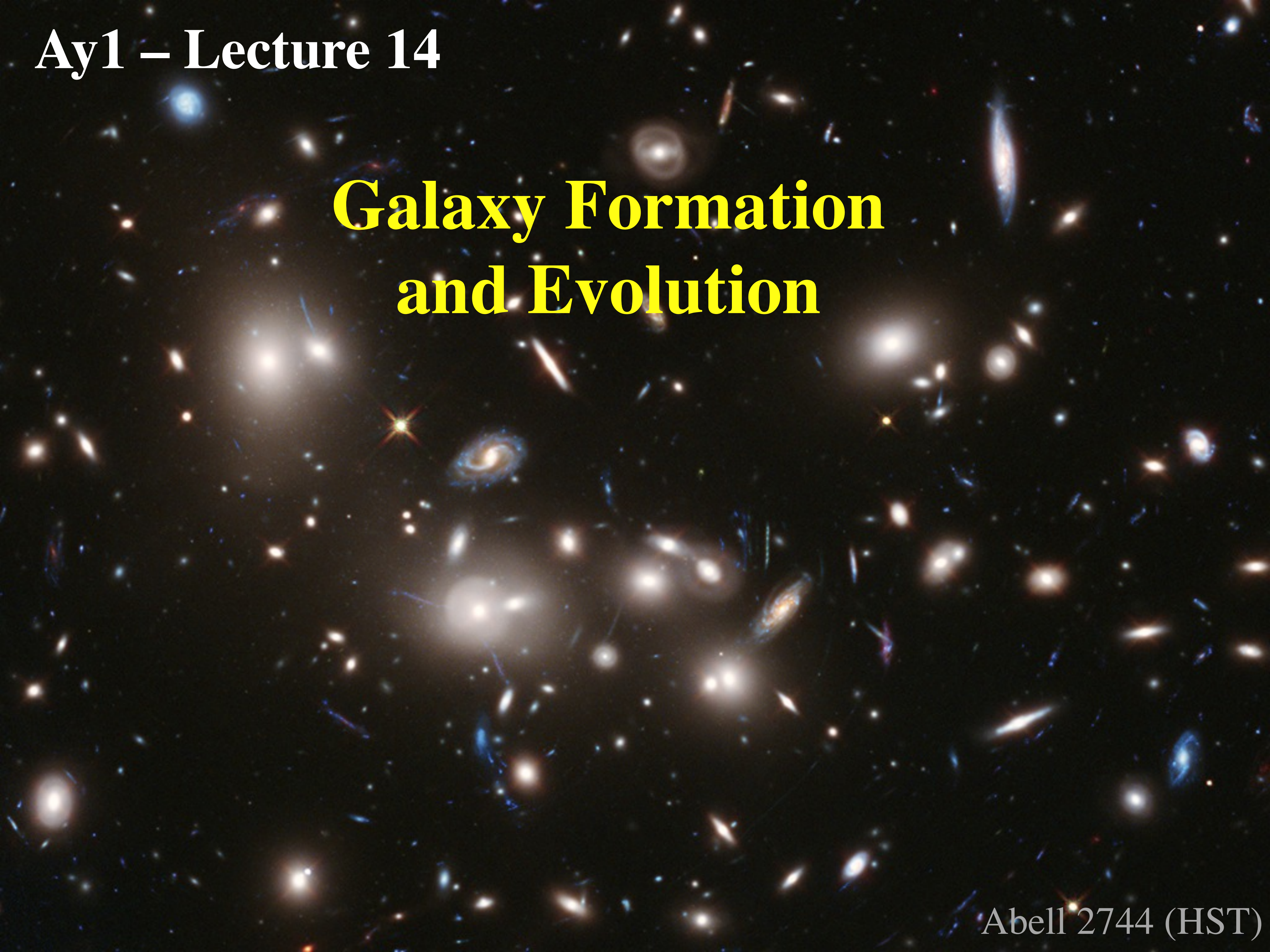
Ay1 – Lecture 14

Galaxy Formation and Evolution



Abell 2744 (HST)

14.1 Galaxy Evolution: the Basics

Galaxies Must Evolve

- Stars evolve: they are born from ISM, evolve, shed envelopes or explode, enriching the ISM, more stars are born…
- Structure evolves: density fluctuations collapse and merge in a hierarchical fashion

Galaxy Evolution

Assembly of the mass → **Conversion of gas into stars and v.v., feedback processes**

DM dominated
Cannot be observed directly, but may be inferred
Easy to model, mainly dissipationless

This is what is observed, and where energy is generated
Dissipative, and very hard to model

Evolution Timescales and Evidence

Timescales for galactic evolution span wide range:

~ 100 Myr - galaxy free-fall and cooling time scales

10 -100 Myr - lifetimes of massive stars

10 -100 Myr - lifetime of the bright phase of a luminous Active Galactic Nucleus (?)

Few × 100 Myr - rotation period of spiral galaxy

~ Gyr - time required for two galaxies to merge

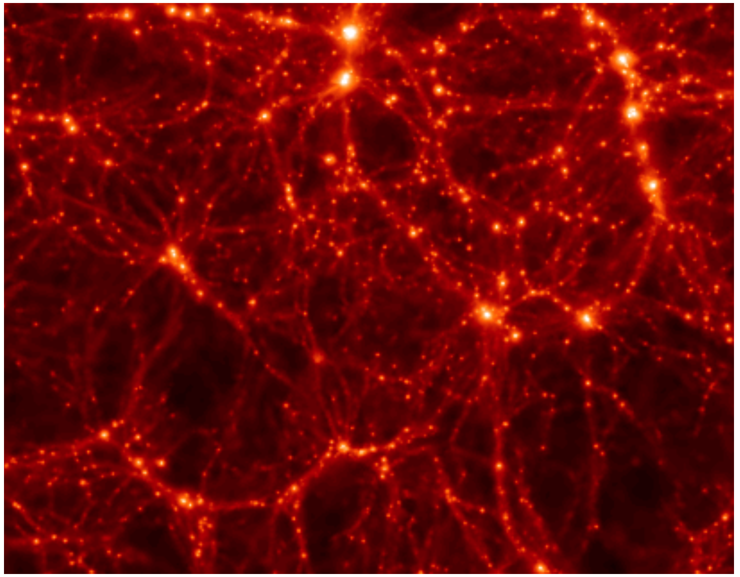
~ 10 Gyr - age of the Universe

Observational evidence for evolution is found in:

- Stellar populations in the Milky Way (e.g., metallicity as a function of stellar age, etc.)
- Systematics of nearby galaxy properties
- **Properties of distant galaxies seen at earlier epoch**

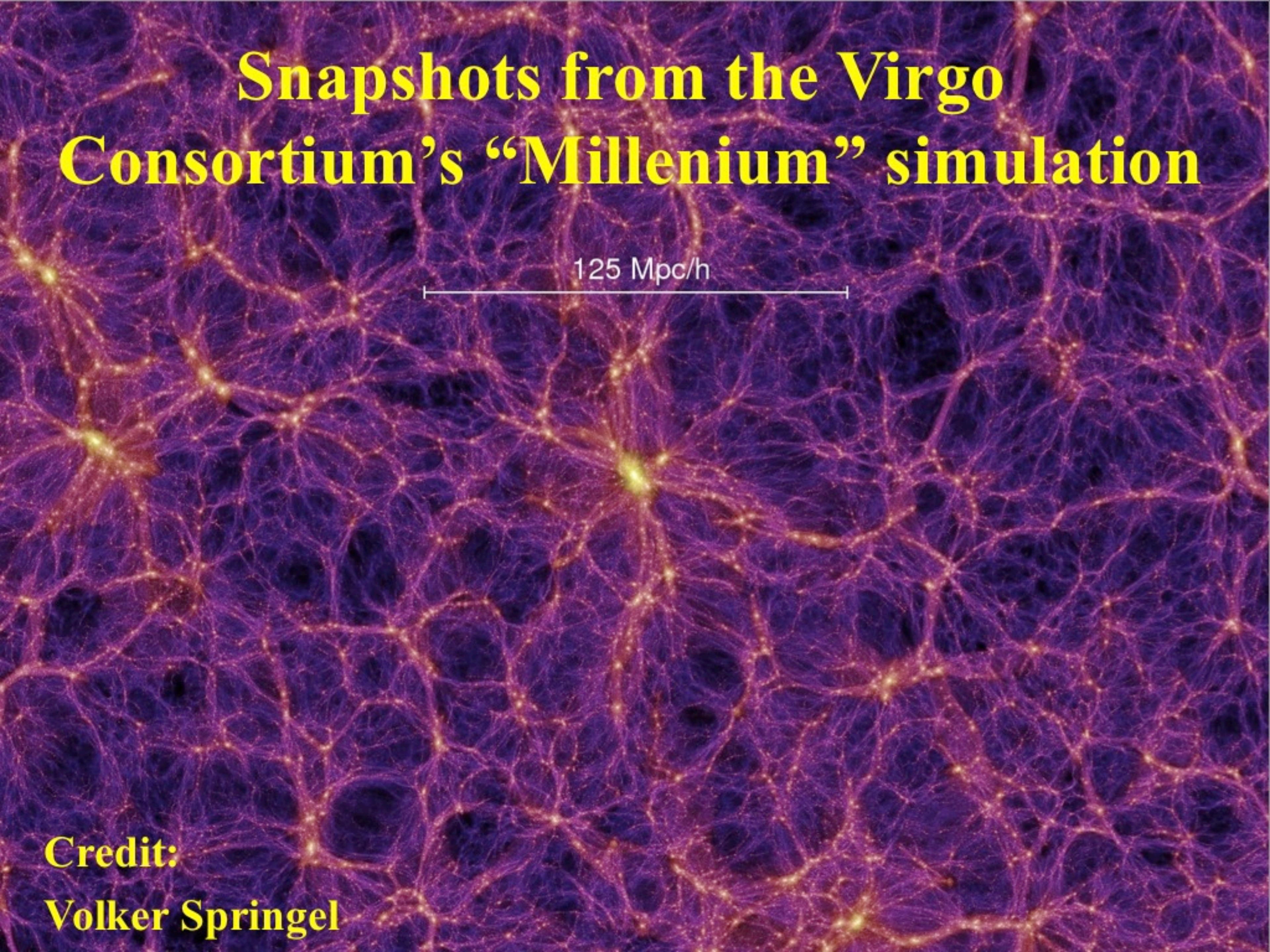
Theoretical Tools and Approaches

1. **Assembly of the mass:** numerical modeling of structure formation. Fairly well advanced, but it is hard to treat any dissipative processes very accurately. Well constrained from large-scale structure formation

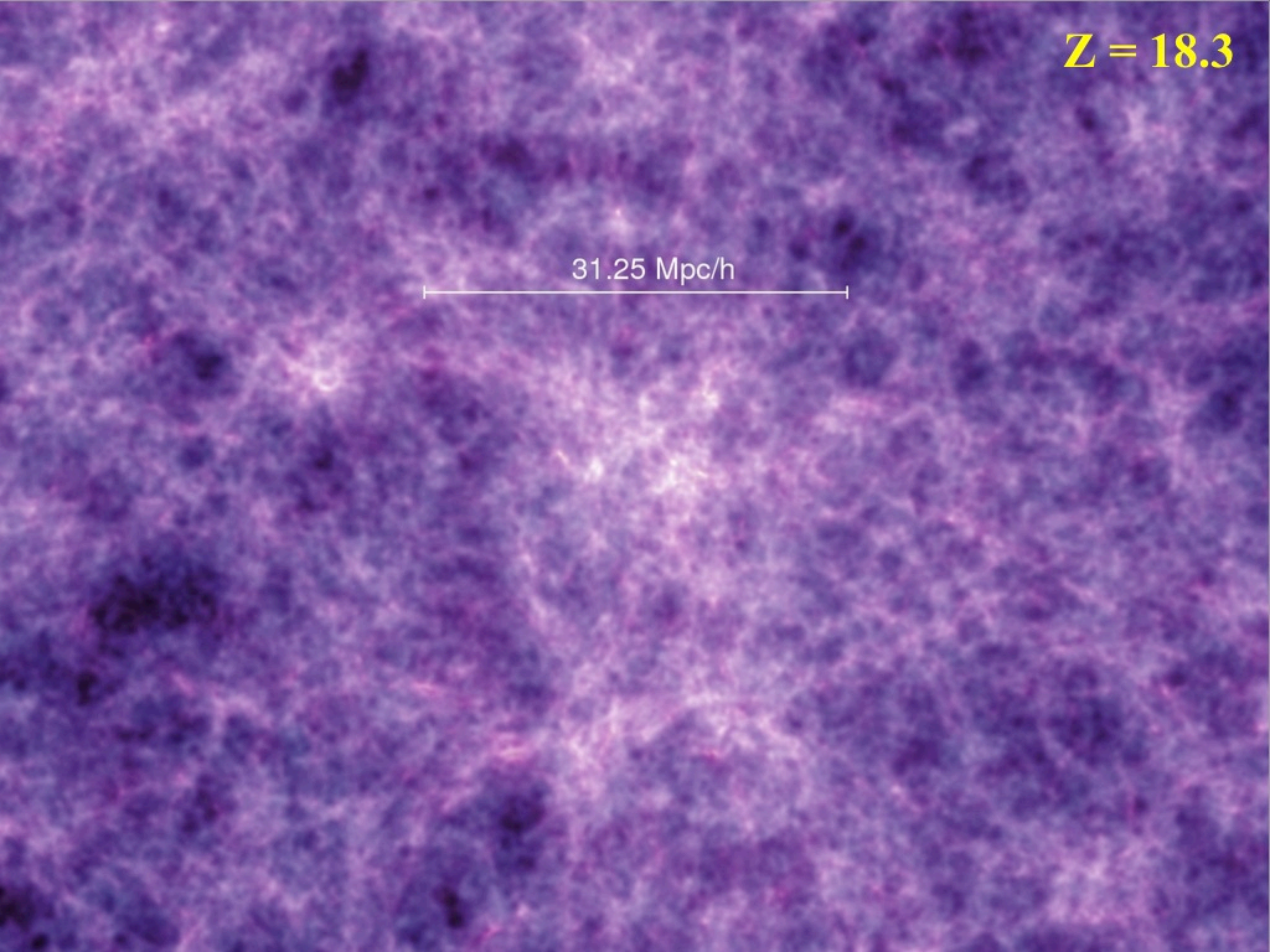


2. **Evolution of stellar populations:** based on stellar evolution models, and fairly well understood. Lots of parameters: the stellar initial mass function, star formation history, stellar evolutionary tracks and spectra as functions of metallicity. Poorly constrained

Snapshots from the Virgo Consortium's "Millenium" simulation



Credit:
Volker Springel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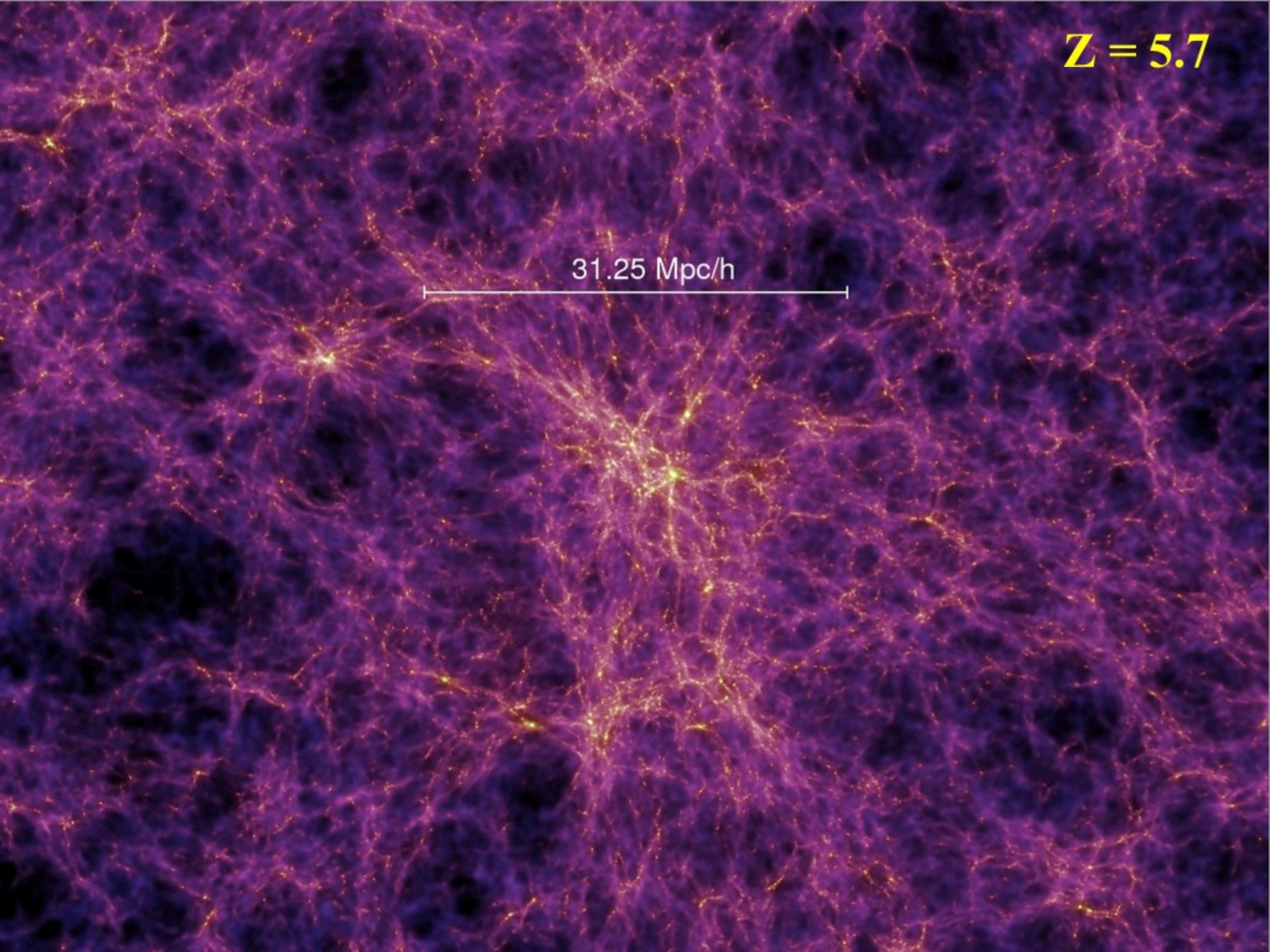
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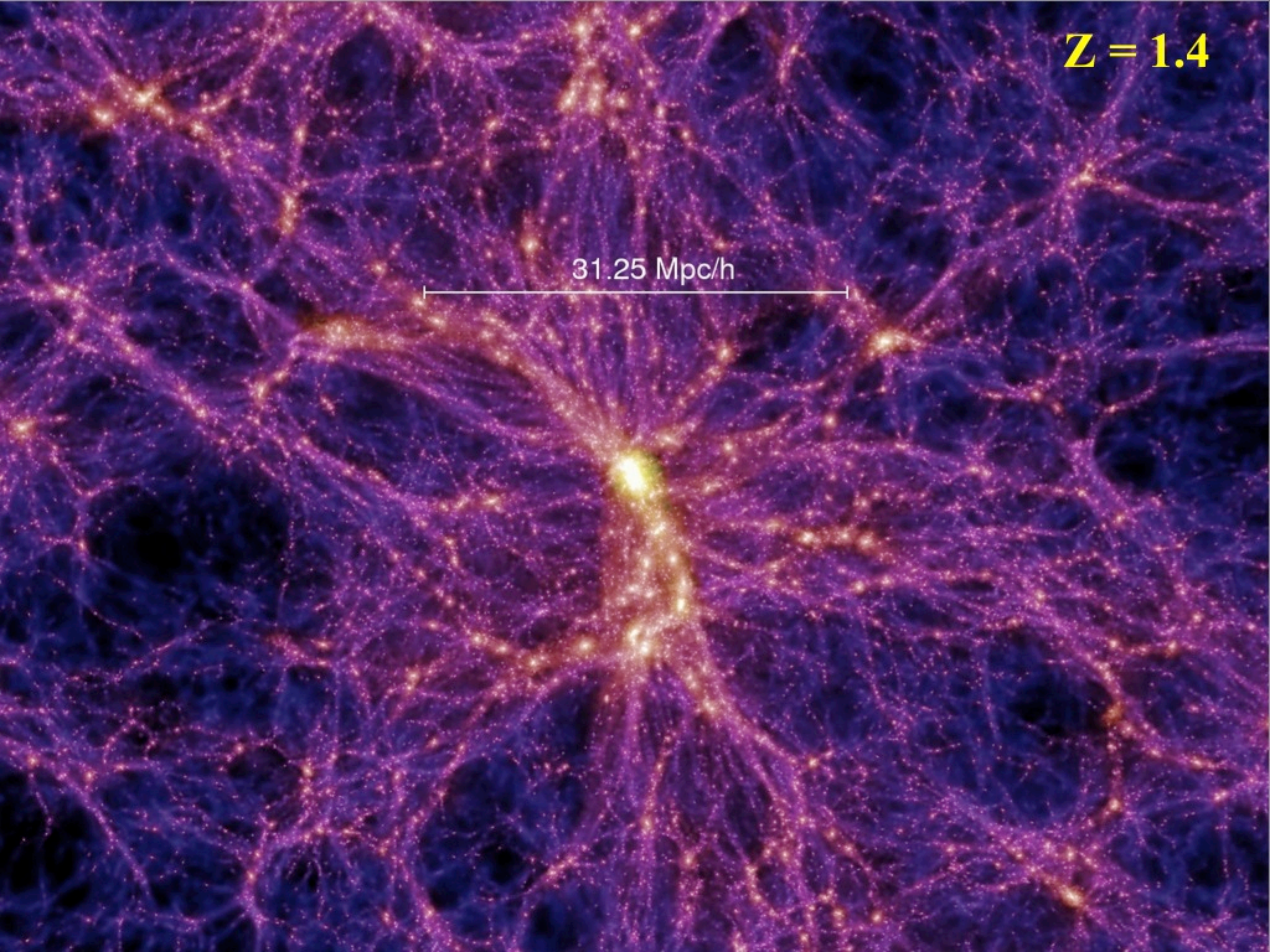
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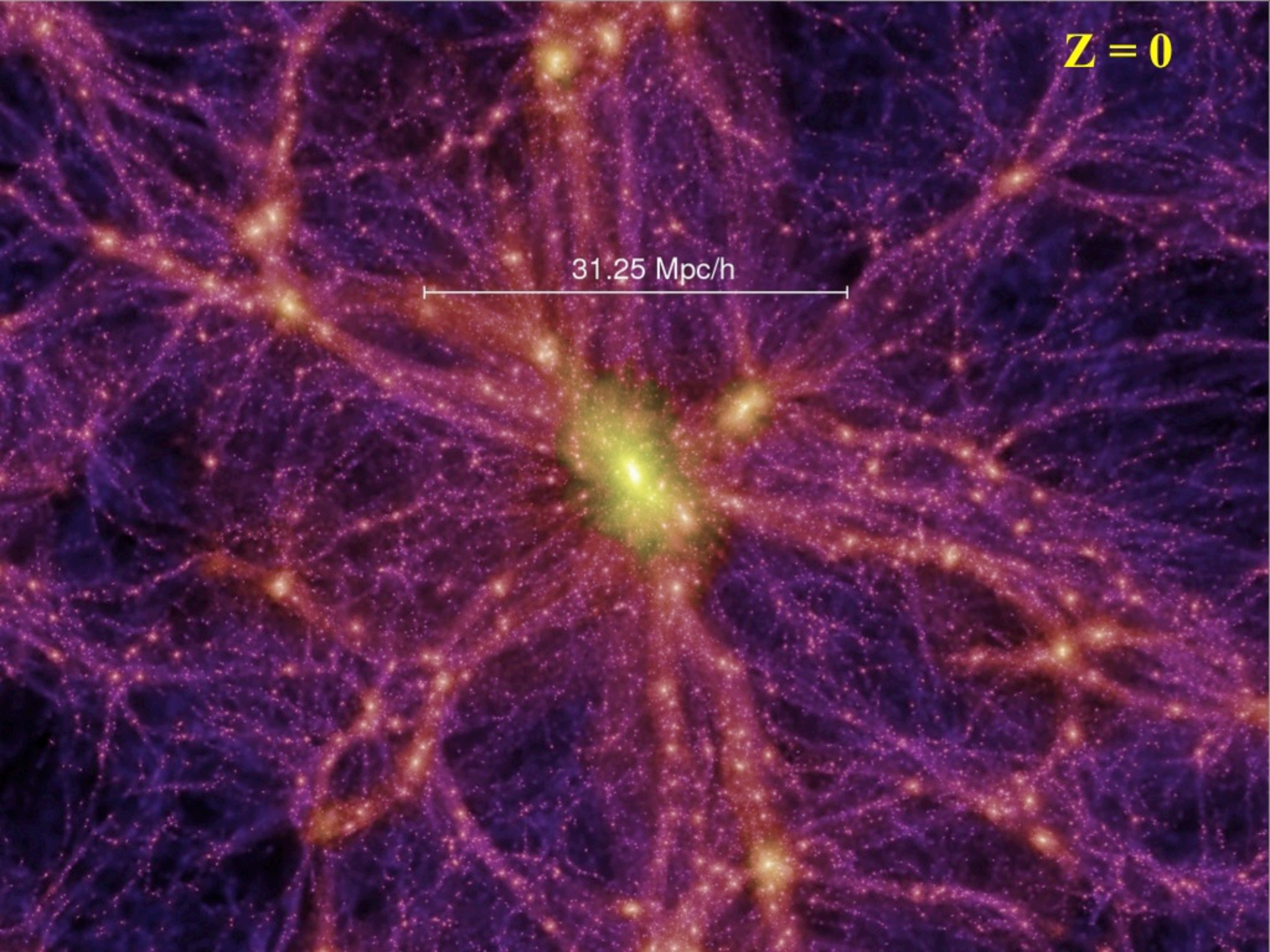
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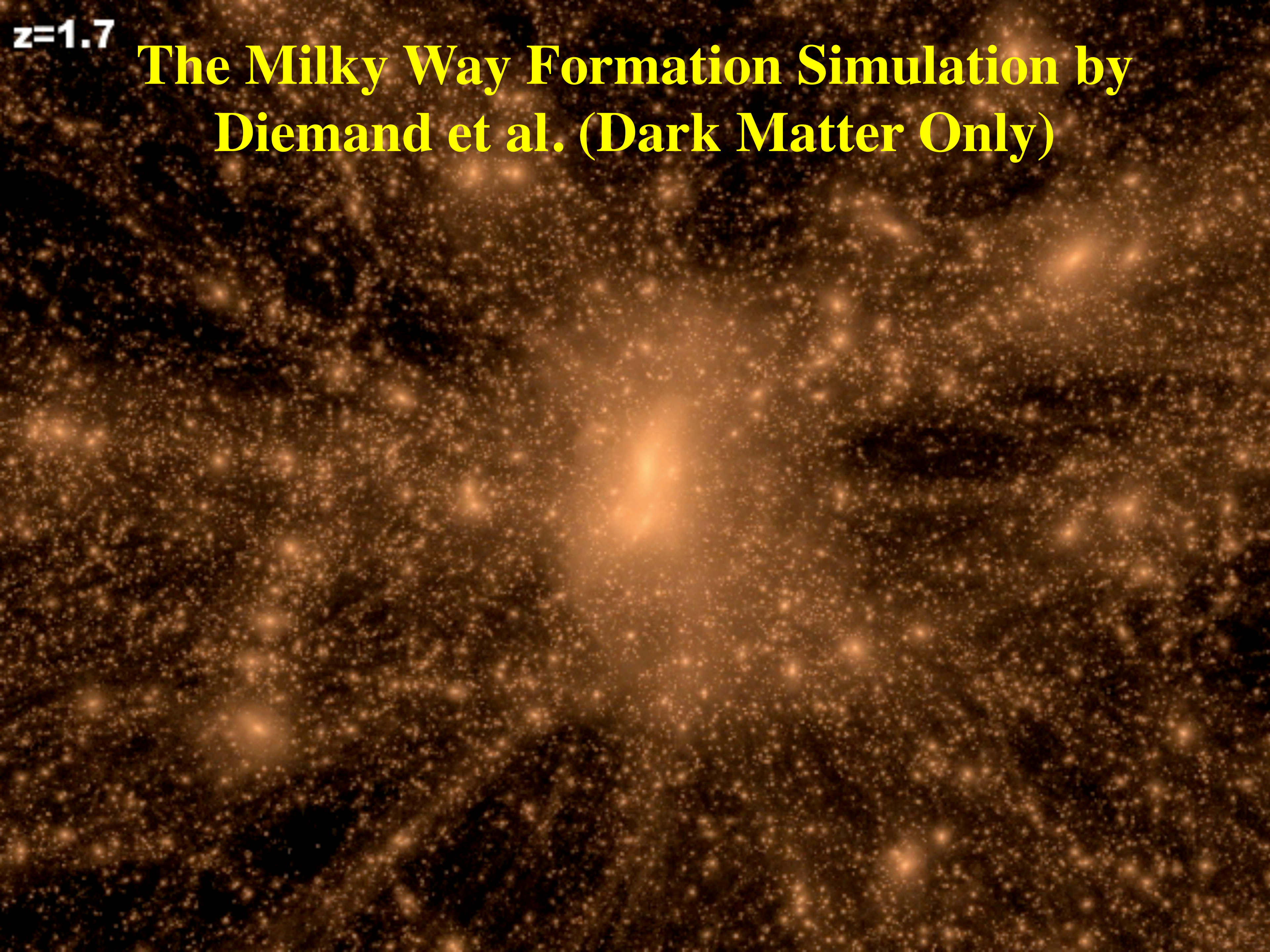
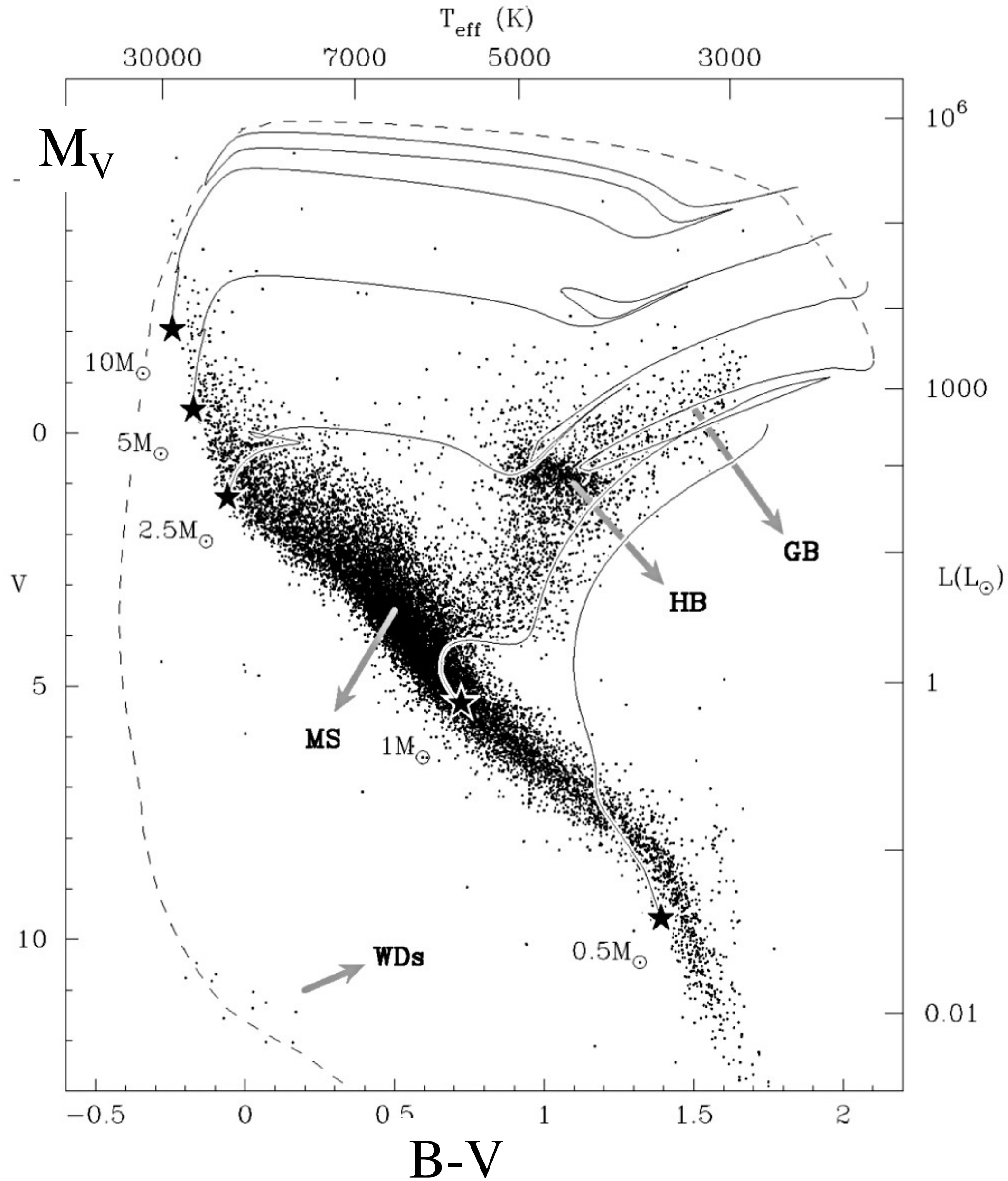
The Milky Way Formation Simulation by Diemand et al. (Dark Matter Only)



Stellar Population Synthesis Models

We can synthesize predicted galaxy spectra as a function of time by assuming the following:

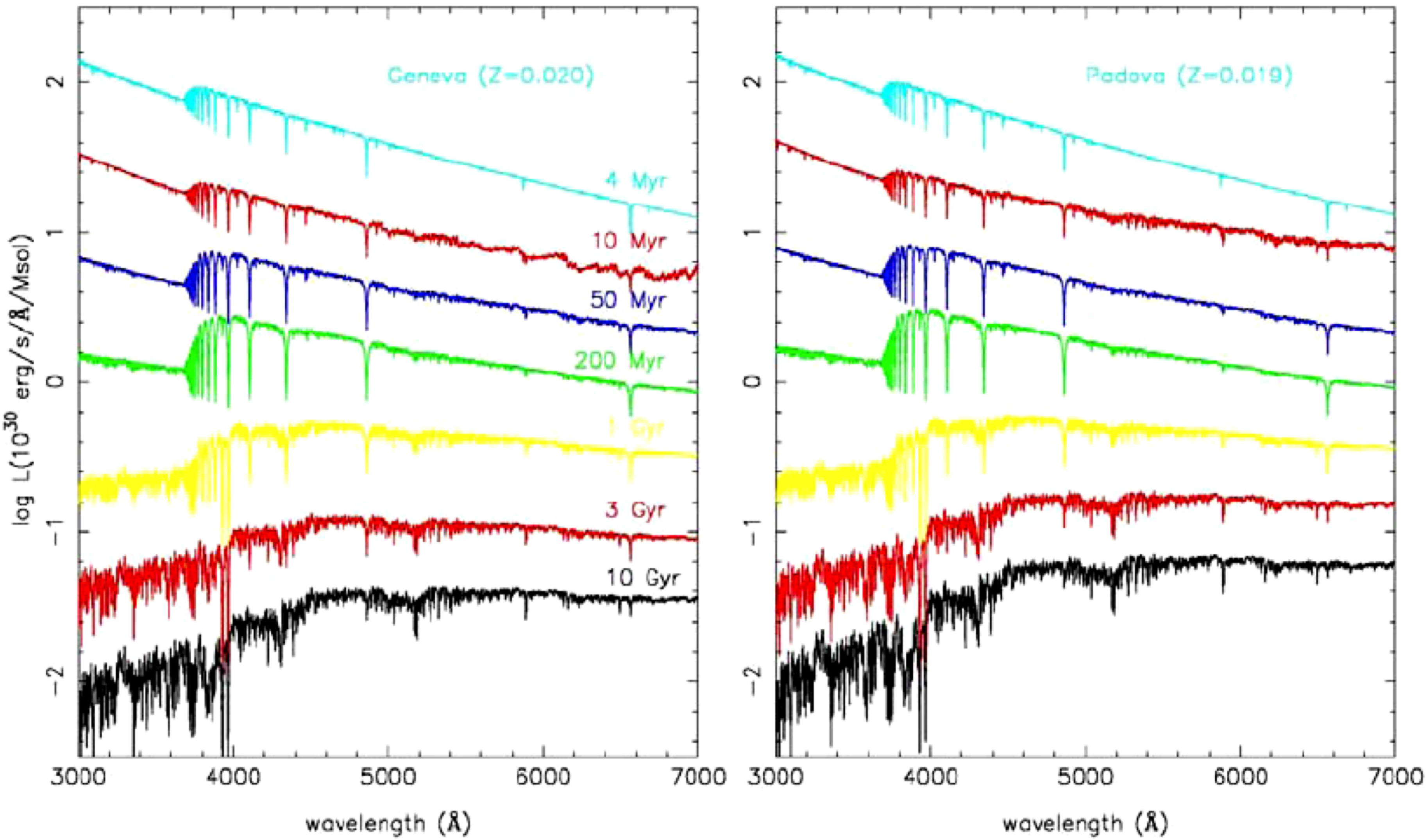
- Star formation rate as a function of time
- Initial mass function of stars
- Libraries of stellar spectra for stars of different masses, metallicities and ages, etc.
- Stellar evolutionary tracks (isochrones)



Modeling Evolution of Stellar Pop's

- Stellar evolution is relatively well understood both observationally and theoretically; the key points:
  - Massive stars are very hot, blue, very luminous, and have very short lives; they dominate the restframe UV light
  - Thus we expect largest effects in the bluer parts of the spectrum
- Star formation histories are a key assumption:
  - Ellipticals are best fit by a burst of early star formation followed by a relatively "passive evolution" where they fade and get redder quickly
  - Spirals are best fit by a slowly declining or nearly constant star formation – they stay bluer and don't fade as much

Predicted Spectral Evolution

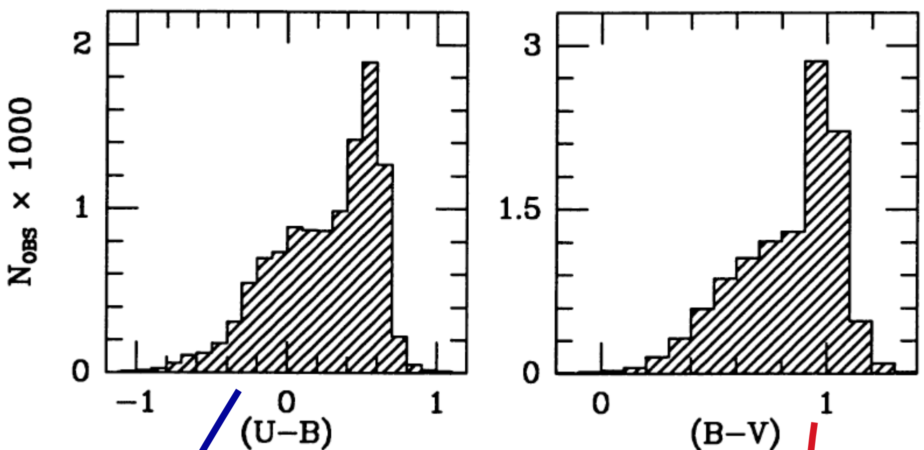


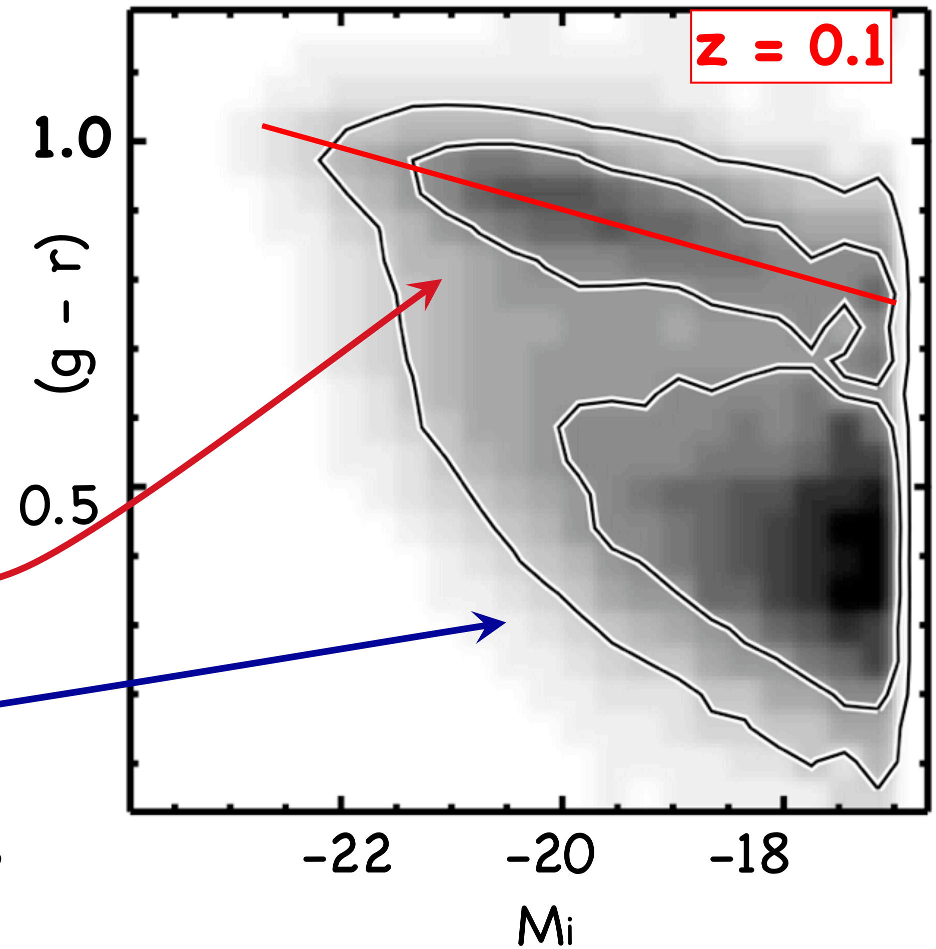
Generally, models fade in time, and faster in the UV than in the IR

Colors of Stellar Populations: Differences in Star Formation Histories

< blue

red >





The red sequence: mostly E's, no active star formation

The blue blob: mostly Spirals, with active star formation

14.2 Observations of Galaxy Evolution

Observational Tools and Approaches

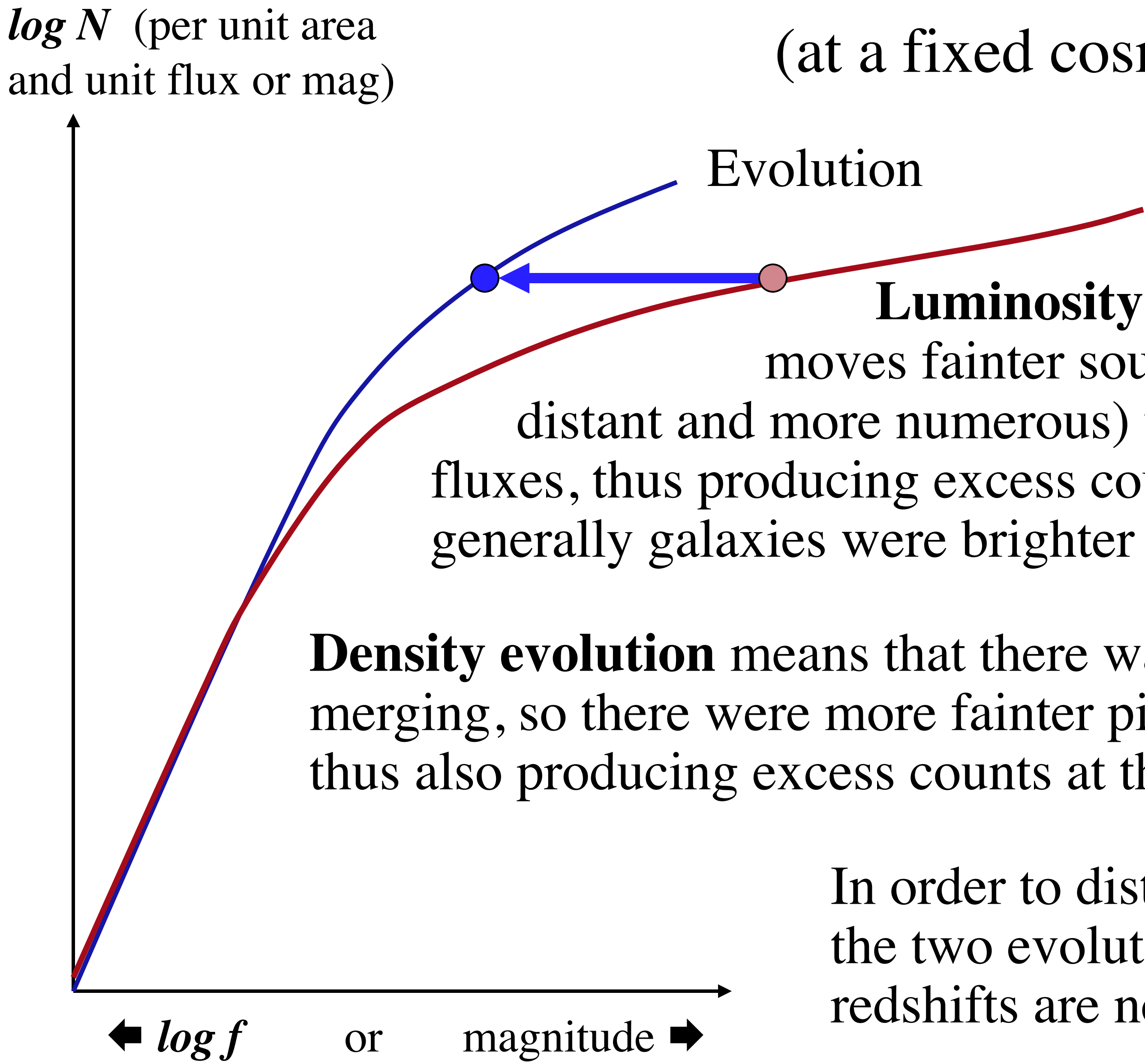
- **Deep imaging surveys** and source counts, at wavelengths from UV to FIR
  - Sources are always selected in emission, and any given band has its own selection effects and other peculiarities
  - With enough bandpasses, one can estimate "photometric redshifts", essentially very low resolution spectroscopy; may be unreliable
  - Measurements of galaxy clustering provide additional information
- **Deep spectroscopic redshift surveys**: redshifts are usually obtained in the visible, regardless of how the sources are selected
  - As a bonus, one can also estimate current star formation rates and rough chemical abundances from the spectra
- **Diffuse extragalactic backgrounds:** an integrated emission from all sources, regardless of the flux or surface brightness limits
  - Extremely hard to do
  - No redshift information

Observing Galaxy Evolution

- If redshifts are not available, we can do source counts as a function of limiting flux or magnitude; and colors as a function of magnitude (acting as a proxy for distance - not a great approximation)
- But you really do need redshifts, to get a true evolution in time, and disentangle the various evolution effects
- The field is split observationally:
  - **Unobscured star formation** evolution: most of the energy emerging in the restframe UV, observed in the visible/NIR
  - **Obscured star formation**: energy from young stars reprocessed by dust to emerge in FIR/sub-mm
  - They have different limitations and selection effects

Source Counts: The Effect of Evolution

(at a fixed cosmology!)



Luminosity evolution moves fainter sources(more distant and more numerous) to brighter fluxes, thus producing excess counts, since generally galaxies were brighter in the past

Density evolution means that there was some galaxy merging, so there were more fainter pieces in the past, thus also producing excess counts at the faint end

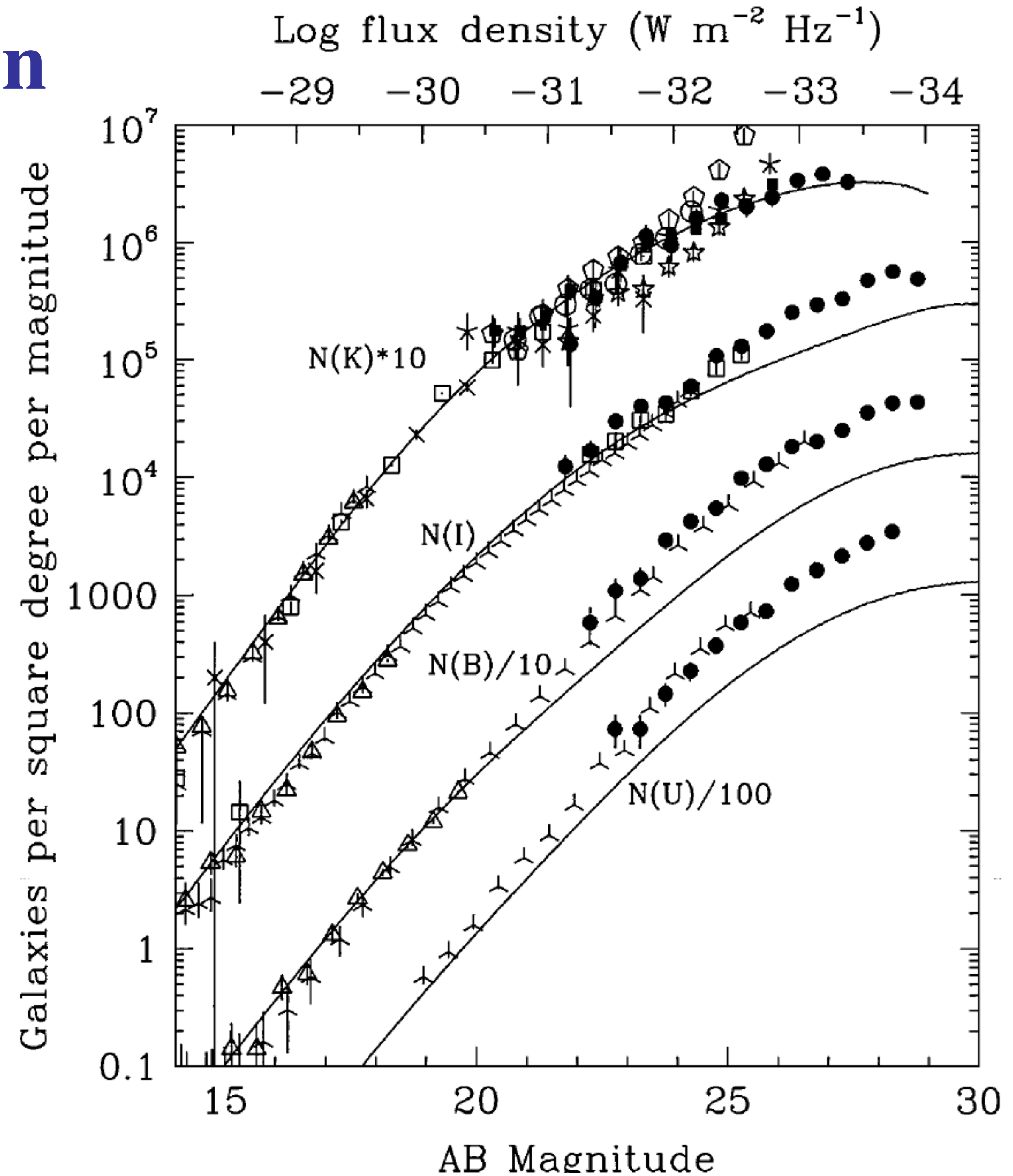
In order to distinguish between the two evolution mechanisms, redshifts are necessary

Galaxy Counts in Practice

The deepest galaxy counts to date come from HST deep and ultra-deep observations, reaching down to ~ 29th mag

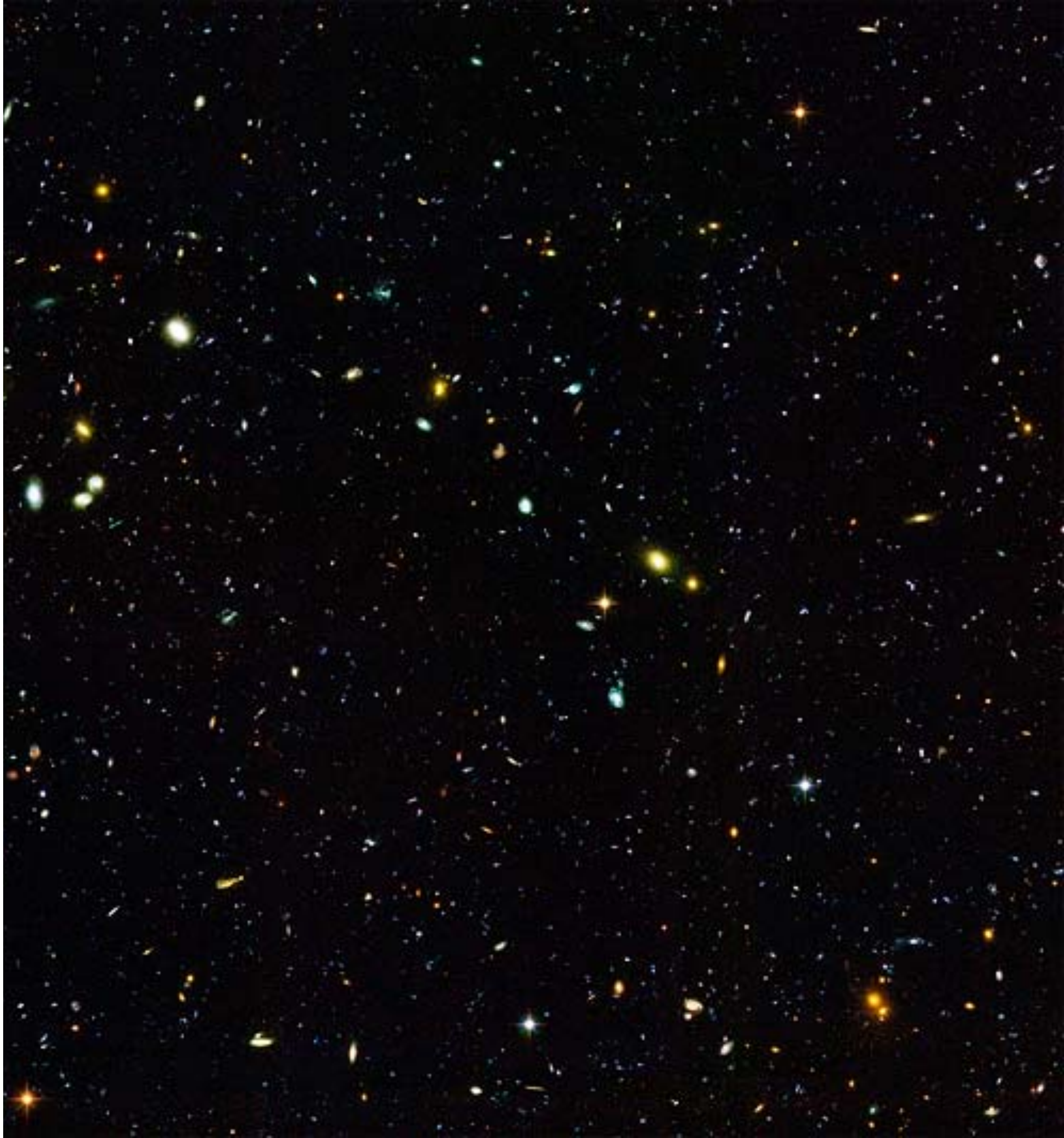
All show excess over the no-evolution models, and more in the bluer bands

The extrapolated total count is ~ 10^{11} galaxies over the entire sky



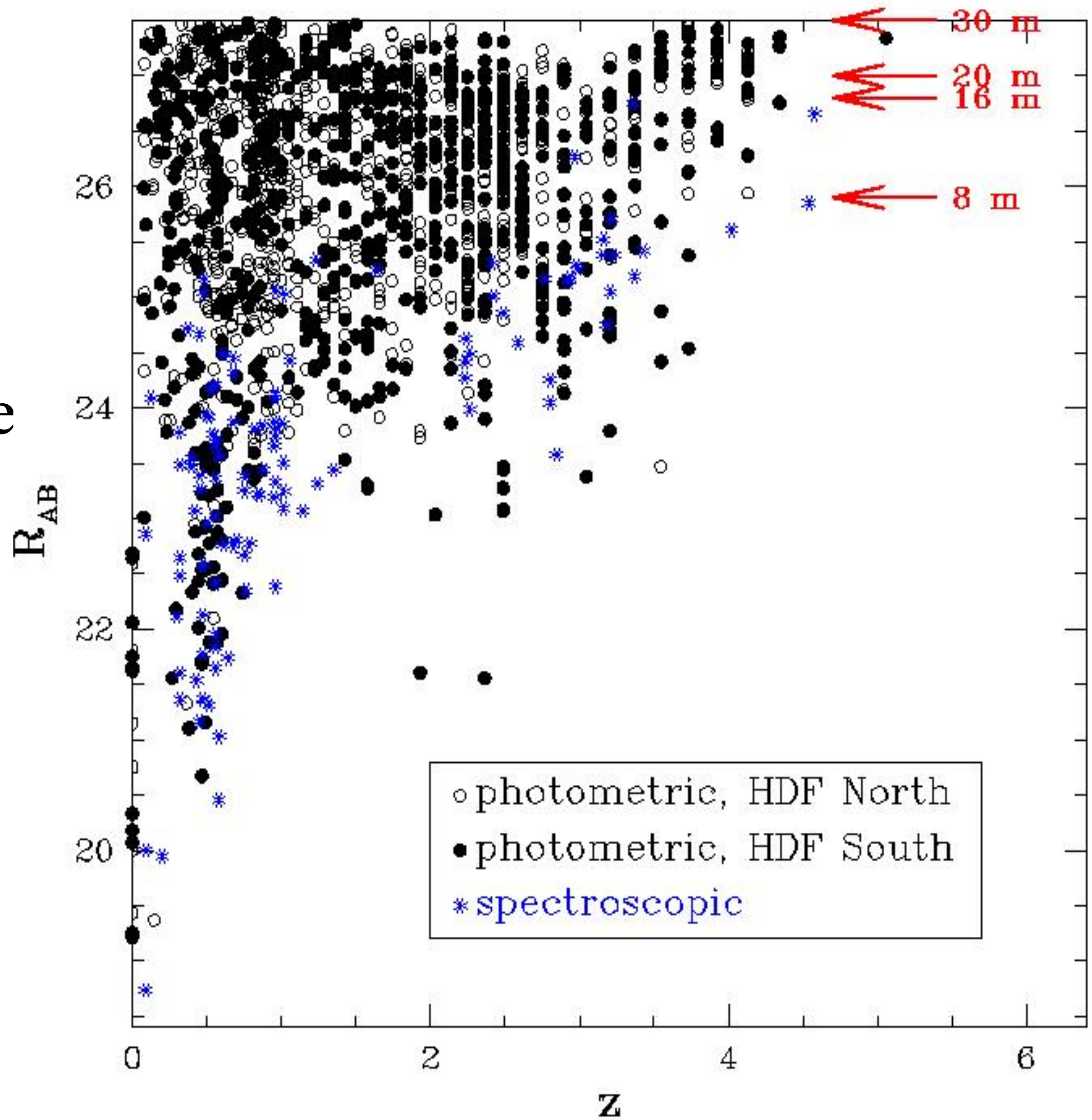
A proven powerful combination is to use deep HST imaging (e.g., HDF N and S, HUDF, GOODS field, etc.) and Keck or other 6 to 10-m class telescope for spectroscopy.

Various deep fields also have multi-wavelength data from Chandra, VLA, Spitzer …



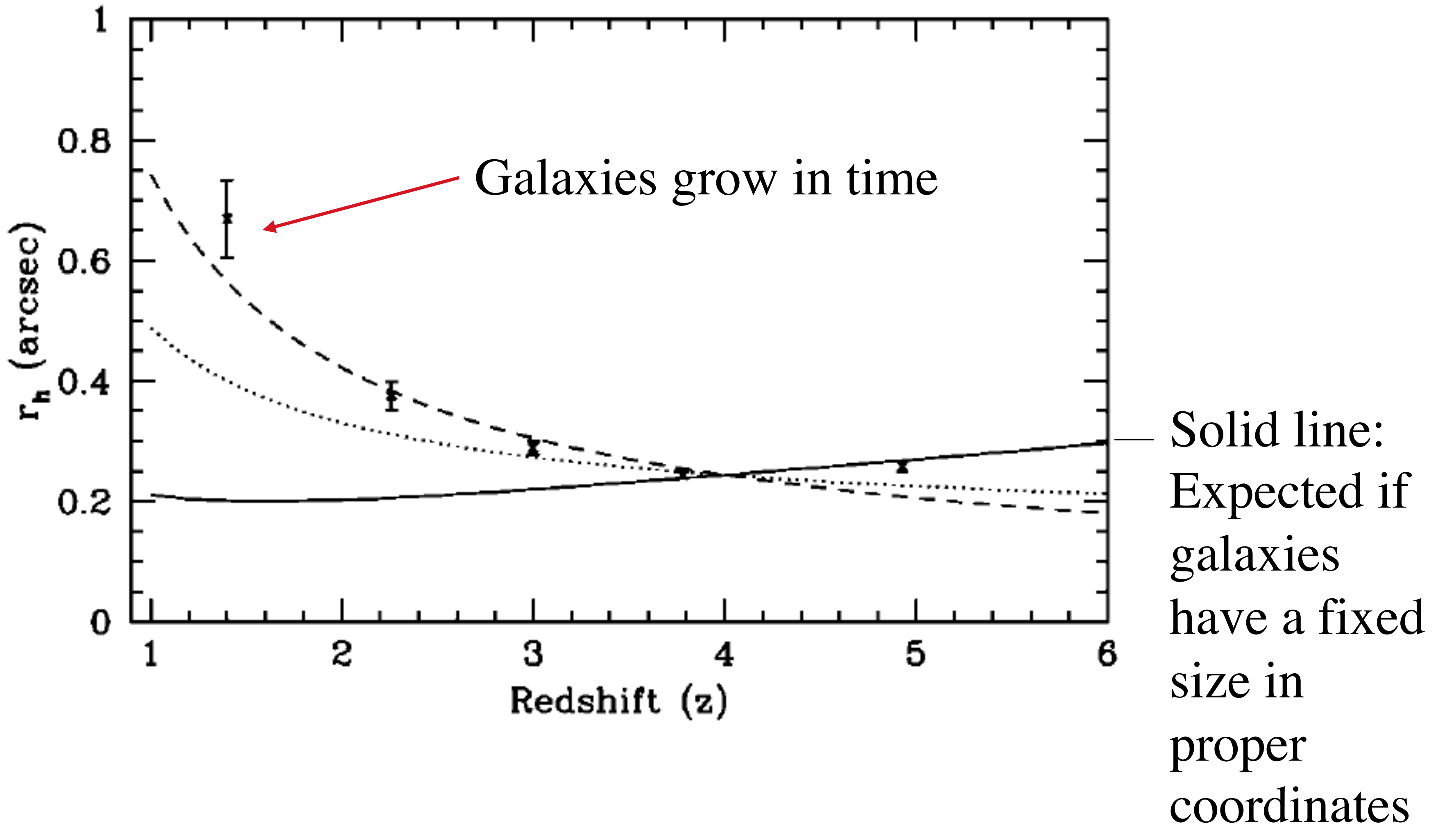
Deep Redshift Surveys

- To really understand what is going on, separate the effects of luminosity and density evolution, and break the degeneracy between distance and intrinsic luminosity at a given flux, we need redshifts
- To go beyond $z > 1$, we have to go faint, e.g. to $R > 23$ - 24 mag



Evolution of Galaxy Sizes

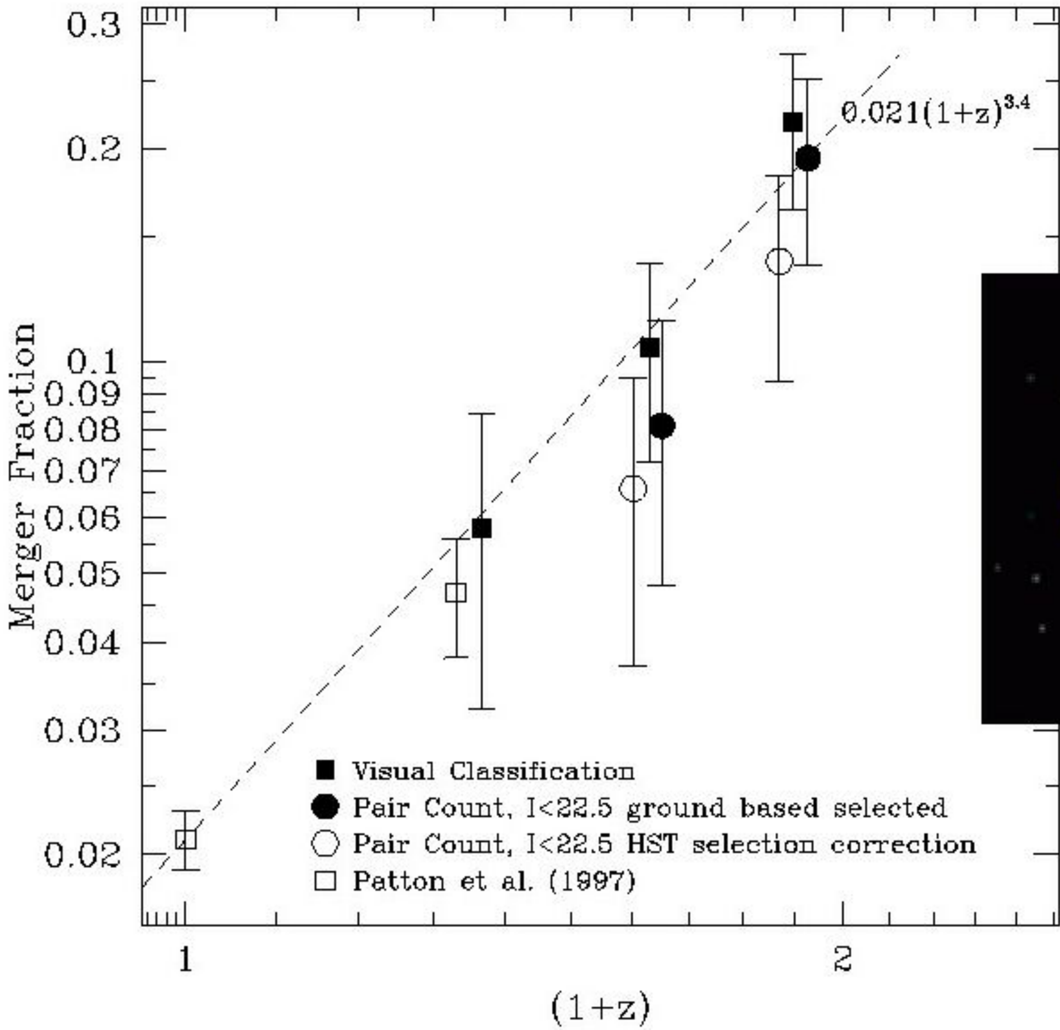
HST imaging suggests that galaxies were smaller in the past

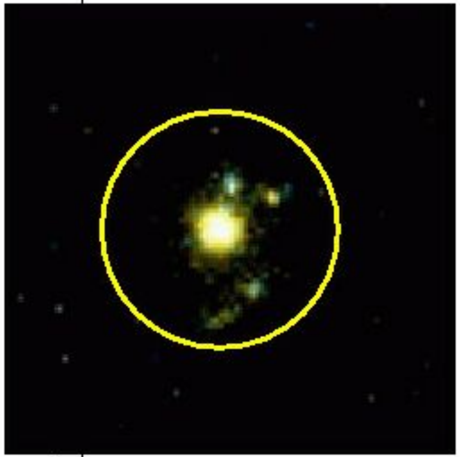


Evolution of the Merger Rate

Merger fraction

~ (1 + z) $^{3.4}$





(LeFevre et al. 2000)

Good evidence for a rapid rise in merging fraction at higher z' s, but conversion to mass assembly rate is not straightforward

Galaxies in the past were…

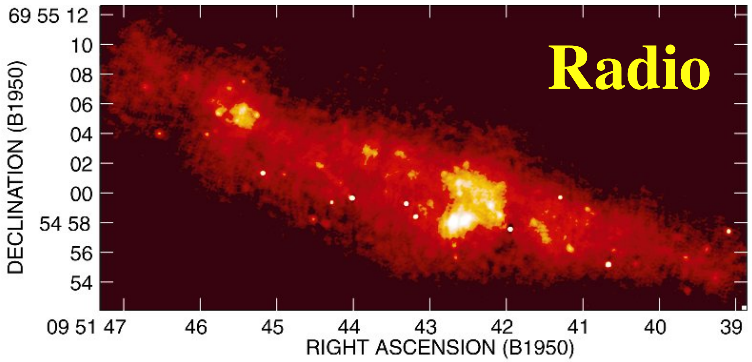
- Bluer
- Brighter at a given mass

but

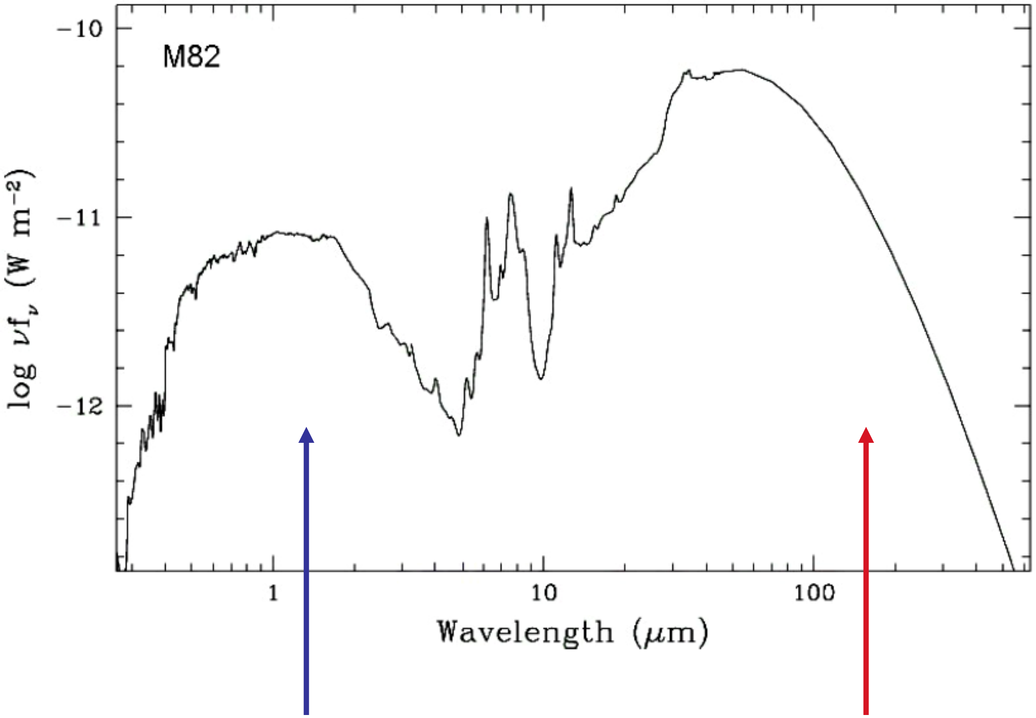
- Smaller mass on the average
- Smaller in size
- More numerous

14.3 The Cosmic Star Formation History

M82, a Prototypical Starburst Galaxy

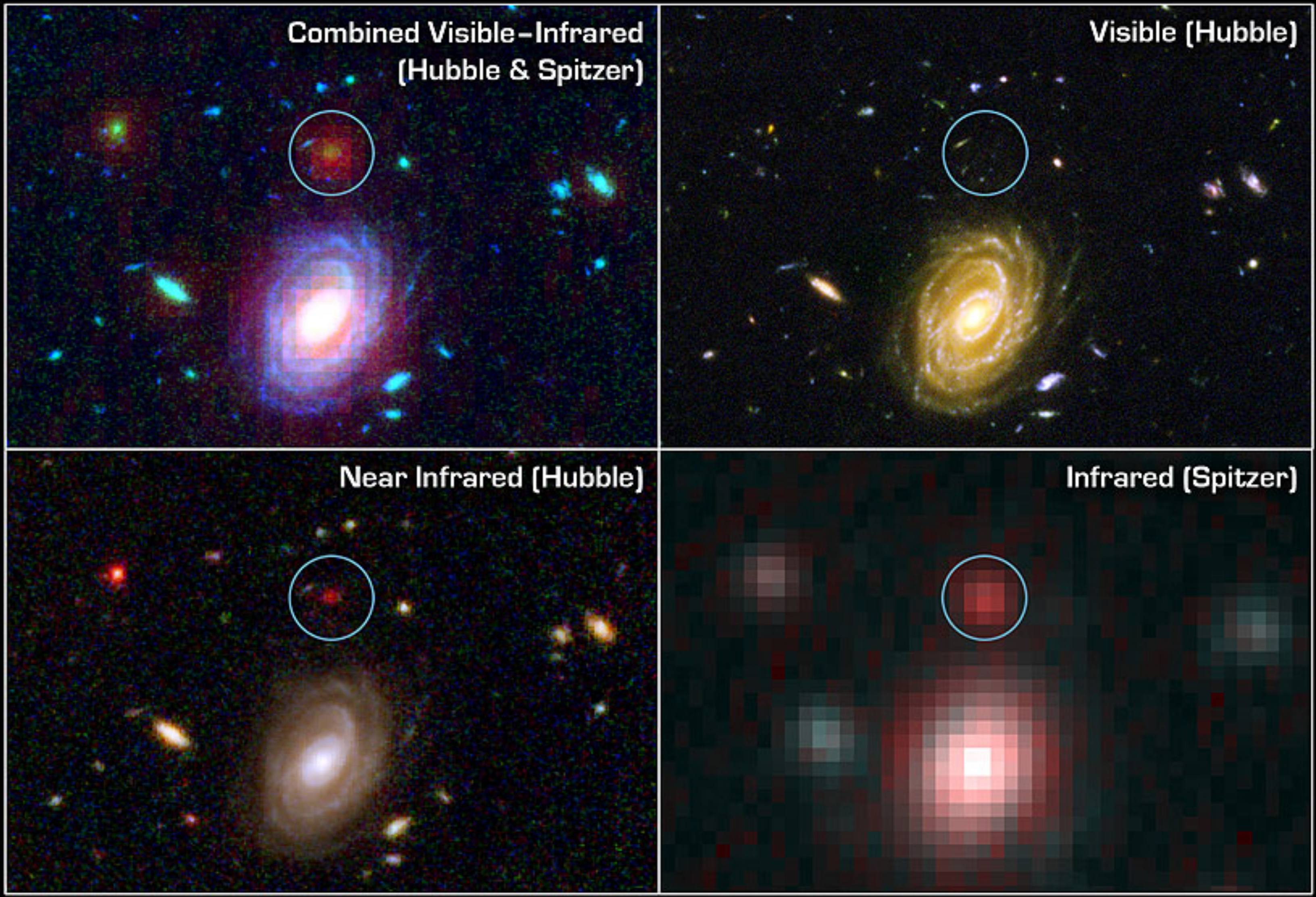


The spectrum of M82, UV to sub-mm



Unobscured starlight

Reprocessed radiation from dust



Distant Galaxy in the Hubble Ultra Deep Field

Spitzer Space Telescope • IRAC
Hubble Space Telescope • ACS • NICMOS

NASA, ESA / JPL-Caltech / B. Mobasher (STScI/ESA)

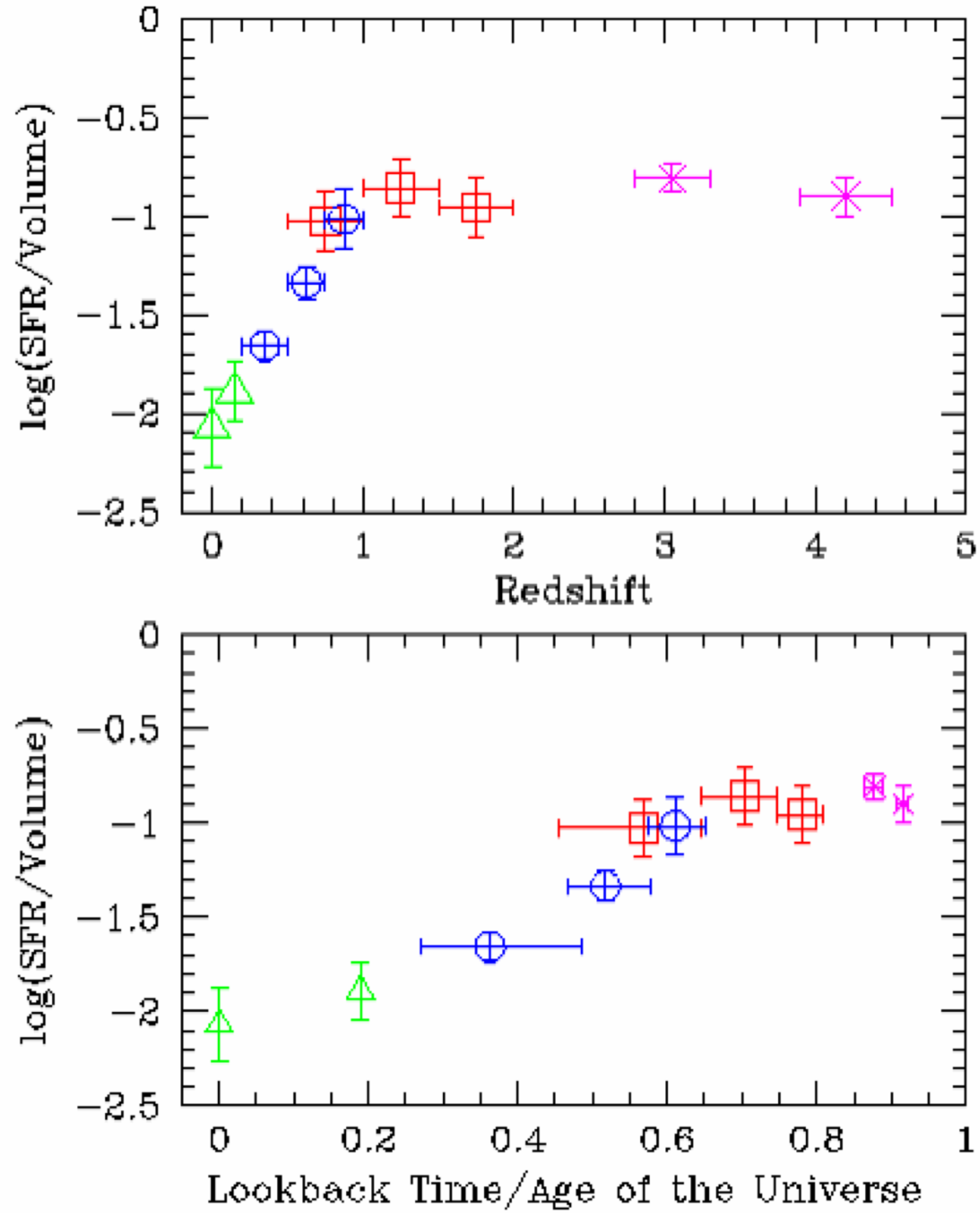
ssc2005-19a

Cosmic Star Formation History

From various luminosity densities converted to star formation rates, we can construct a possible history of the comoving SFR density

At face value it implies the universe was much more active in the past (z ~1 - 2) but what happens earlier is unclear

There are many complications of interpretation, including the reliability of each SFR diagnostic, dust extinction, incompleteness, etc.

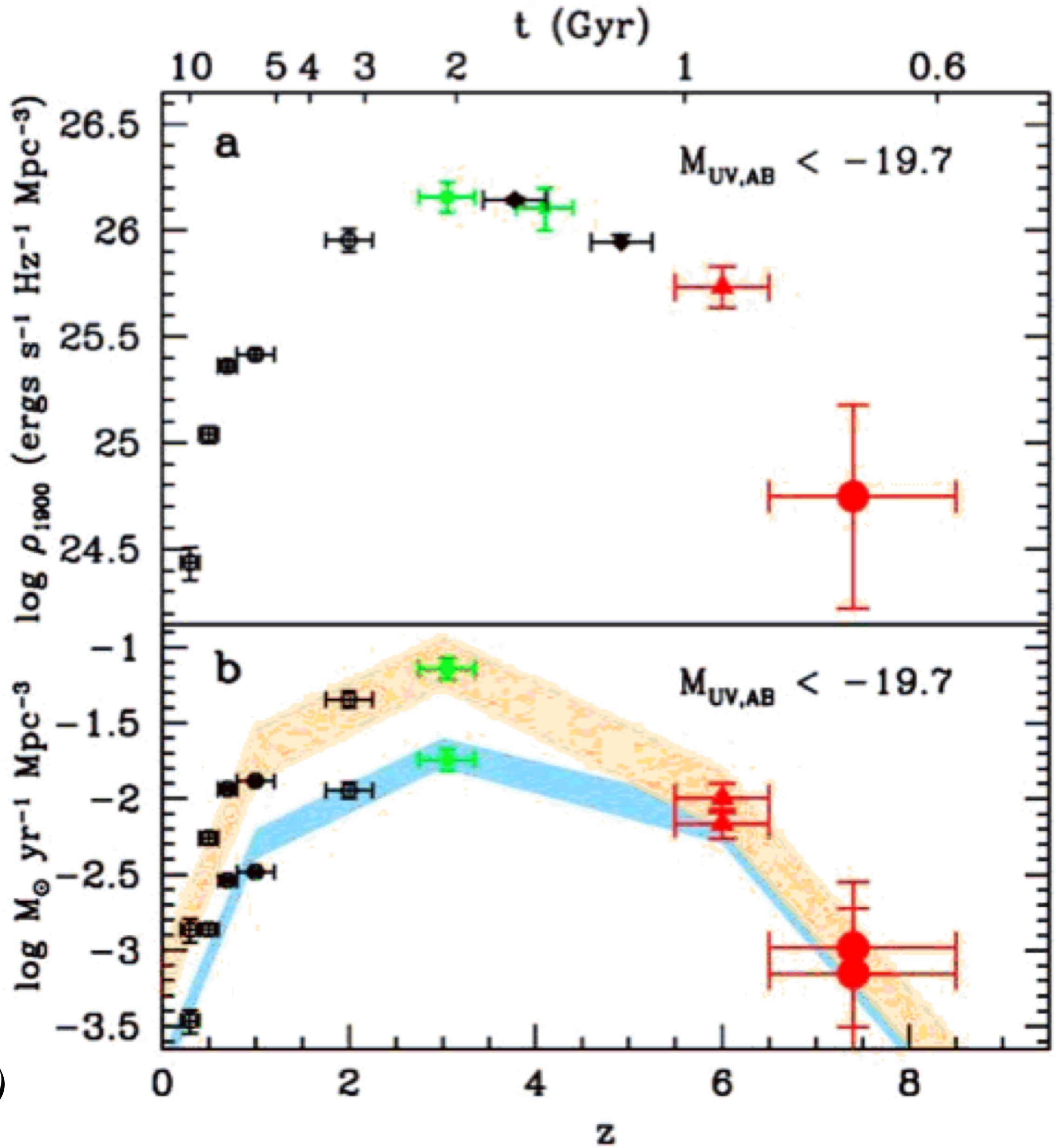


Now pushing to z ~ 8 (and beyond?)

Use the color dropout technique to identify high-z galaxy candidates in deep HST images: different color bins give different redshift shells. Then add up the light.

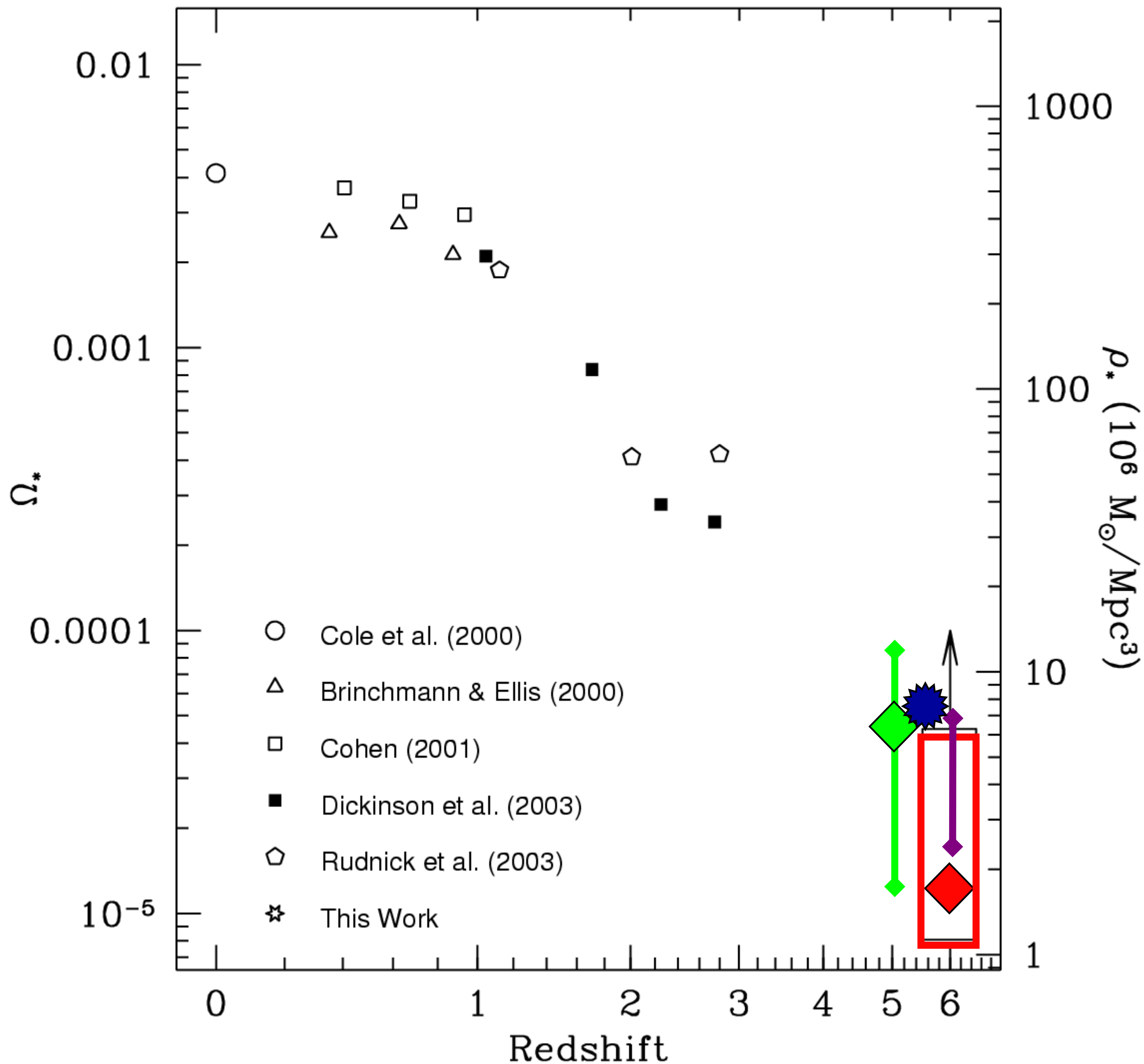
There seems to be a rollover at z > 5 - 6: the epoch of the initial galaxy build-up?

(Bouwens & Illingworth 2006)



Build-up of Stellar Mass Density

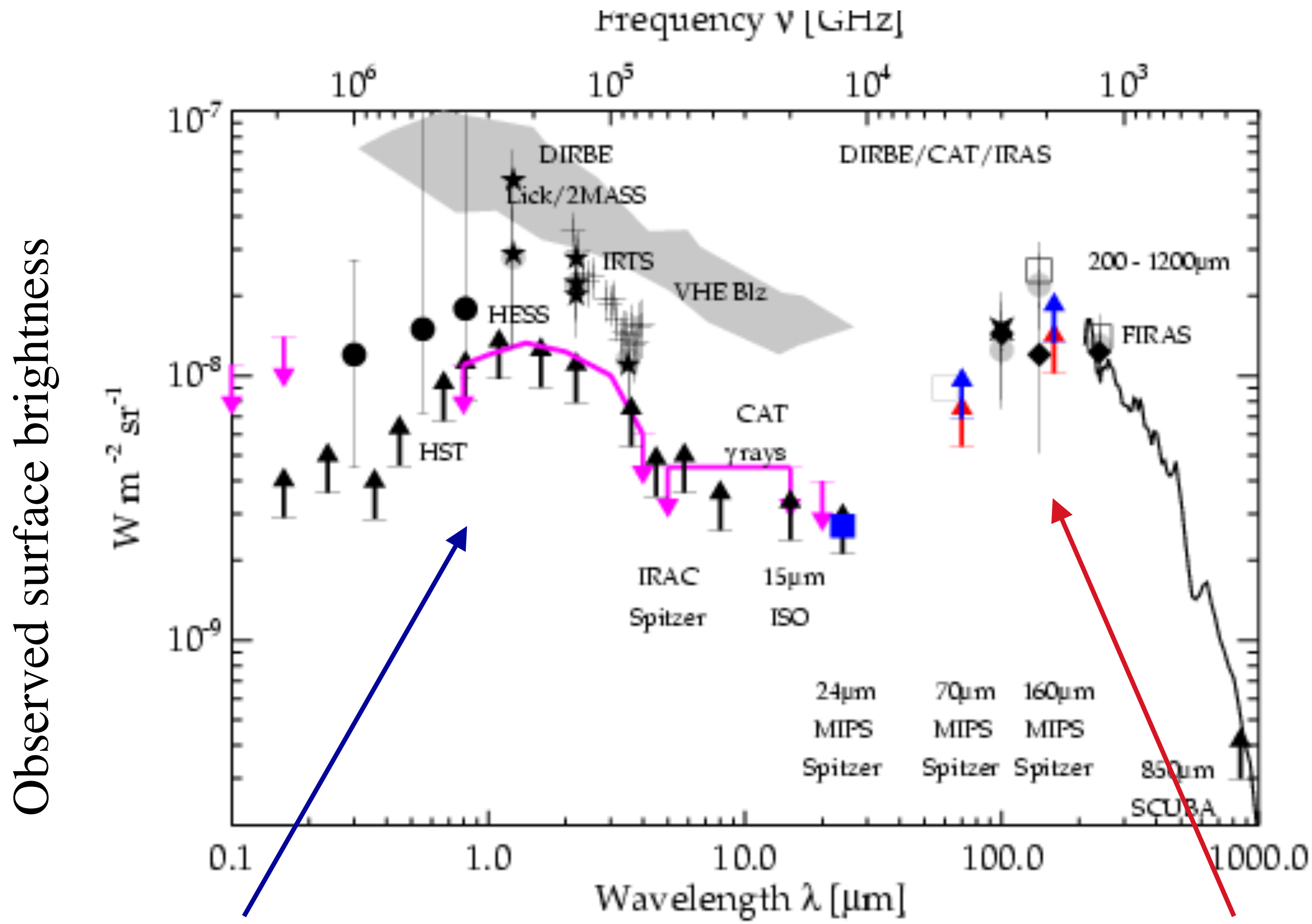
Co-moving stellar mass density grew rapidly from z ~ 6 (or earlier) to z ~ 1, but has not changed much since then



All Starlight in the Universe

- Any deep survey is limited in flux and surface brightness: some fainter and/or more diffuse sources are likely missed; thus, our source counts give us only a lower limit to the total energy emitted by evolving galaxies
- An alternative approach is to measure ***integrated diffuse backgrounds, due to all sources***
  - This is really hard to do, for many reasons
  - Redshifts are lost, but at least the energy census is complete
- The total energy in the diffuse extragalactic backgrounds from UV to sub-mm is ~ 100 nW m^{-2} sr^{-1} ($\pm$50% or so)
  - This is distributed roughly equally between the UV/Opt (unobscured SF) and FIR/sub-mm (obscured SF)
  - A few percent of the total is contributed by AGN
  - This is only a few percent of the CMB

Diffuse Optical and IR Backgrounds



Unobscured component
(restframe UV, obs. Optical/NIR)

Obscured component
(restframe FIR, obs. FIR/sub-mm)

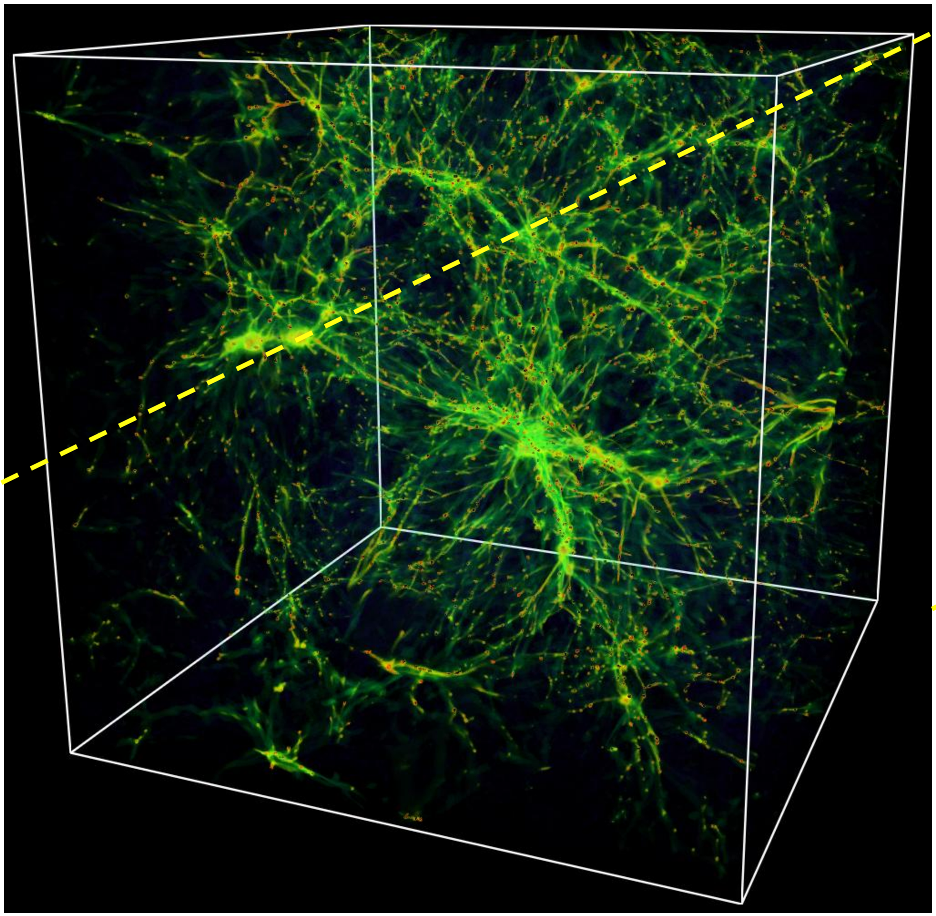
14.4 Cosmic Web: The Intergalactic Medium

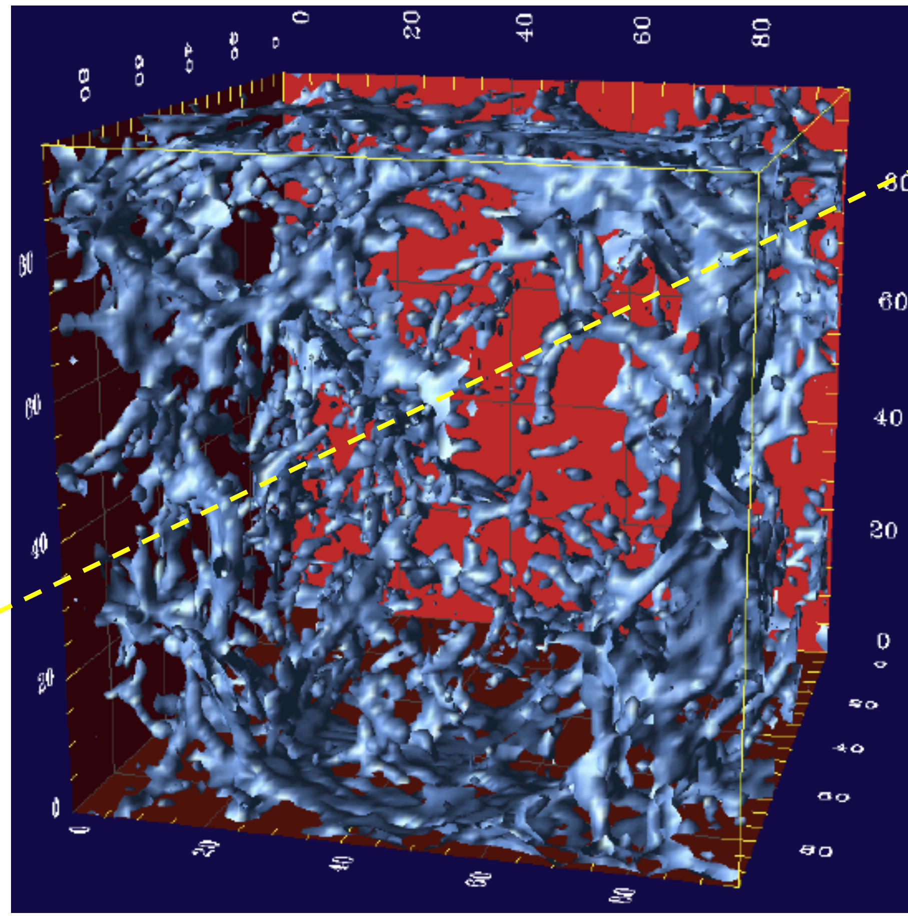
Intergalactic Medium (IGM)

- Essentially, baryons between galaxies
- Its density evolution follows the large scale structure formation, and the potential wells defined by the dark matter, forming a web of filaments, the co-called **"Cosmic Web"**
- Gas falls into galaxies, where it serves as a replenishment fuel for star formation
- Likewise, enriched gas is driven from galaxies through the radiatively and SN powered **galactic winds**, which chemically enriches the IGM
- Chemical evolution of galaxies and IGM thus track each other
- Star formation and active galactic buclei provide the **ionizing flux** for the IGM

Cosmic Web: Numerical Simulations

Our lines of sight towards some luminous background sources intersect a range of gas densities, condensed clouds, galaxies …

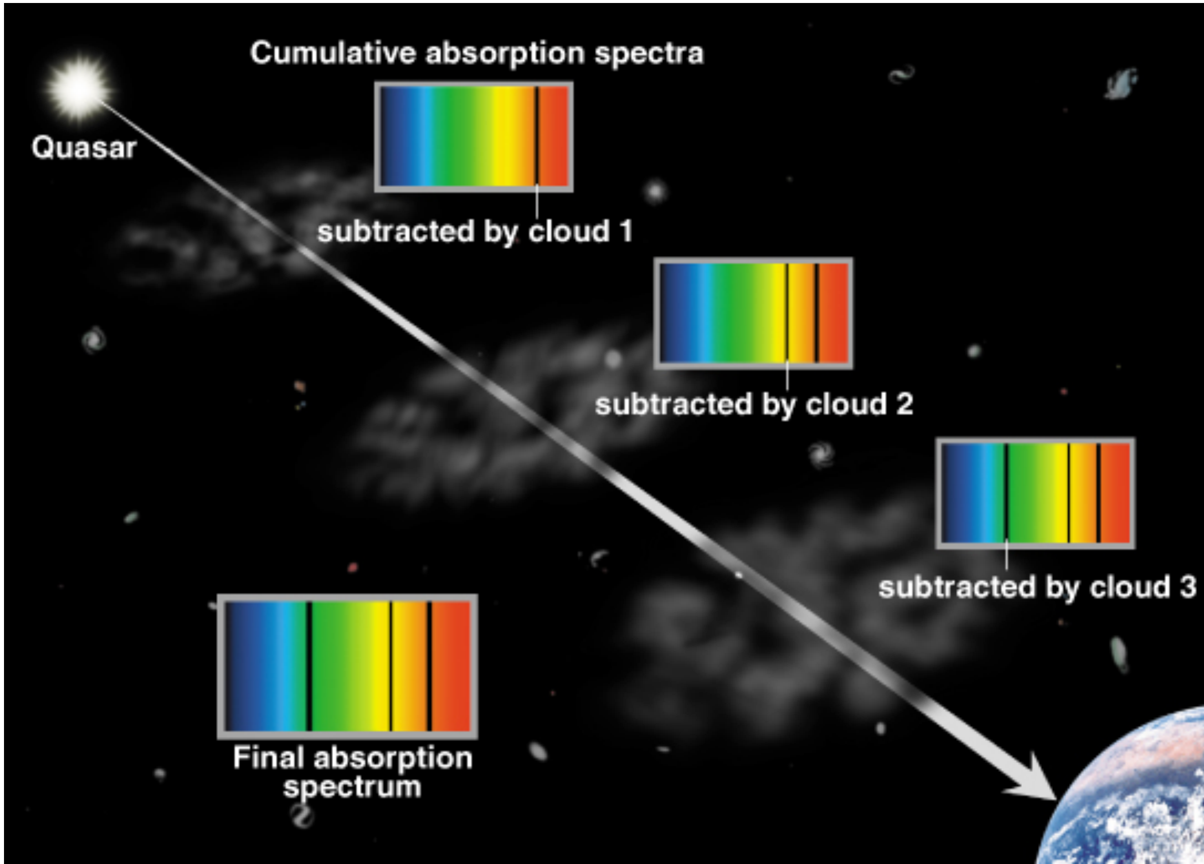




(from R. Cen)

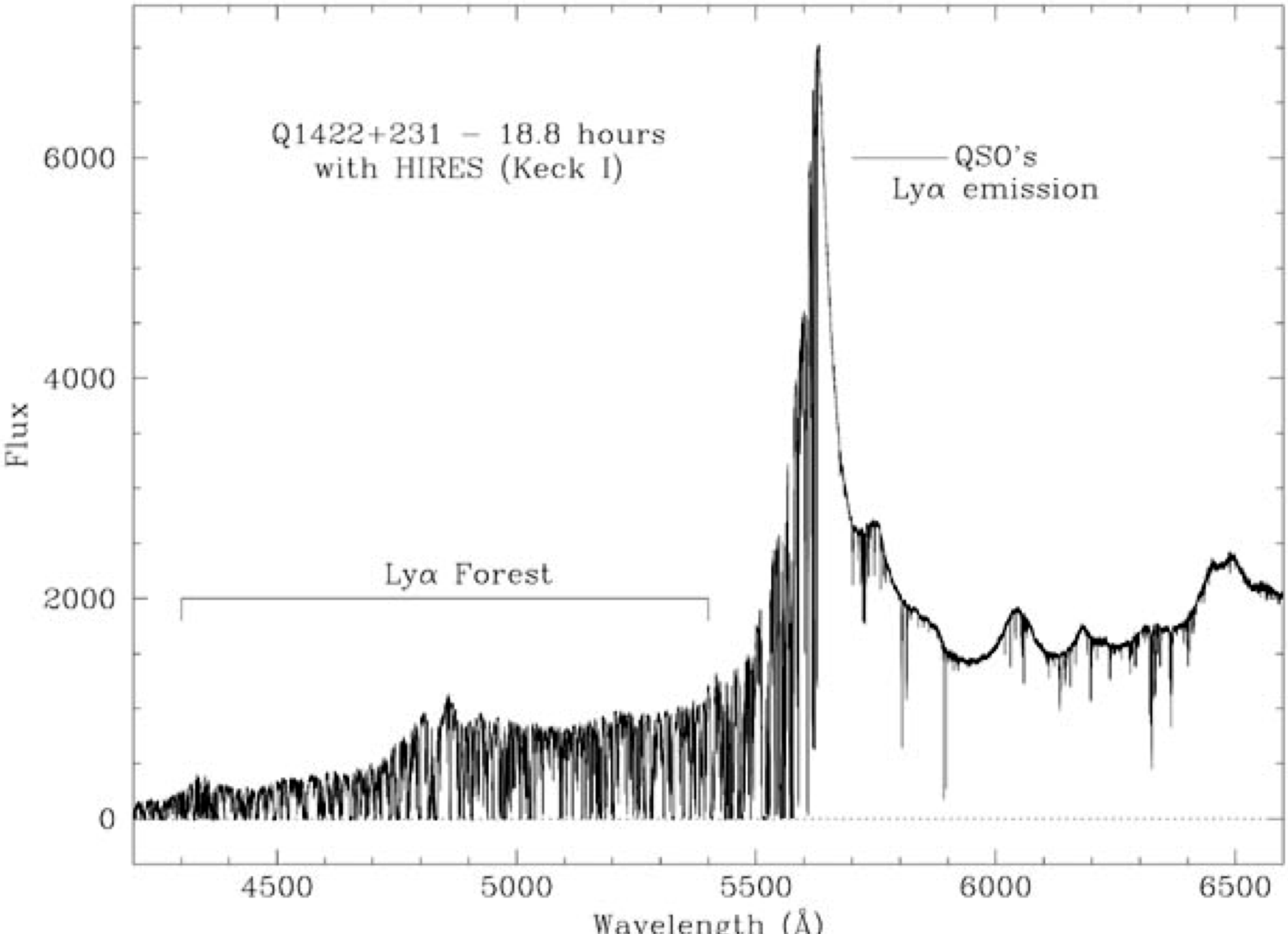
QSO Absorption Line Systems

- An alternative to searching for galaxies by their ***emission*** properties is to search for them by their ***absorption***
- Quasars are very luminous objects and have very blue colours which make them relatively easy to detect at high redshifts
- GRB are also used
- Note that this has ***different selection effects*** than the traditional imaging surveys: not by luminosity or surface brightness, but by the size and column density



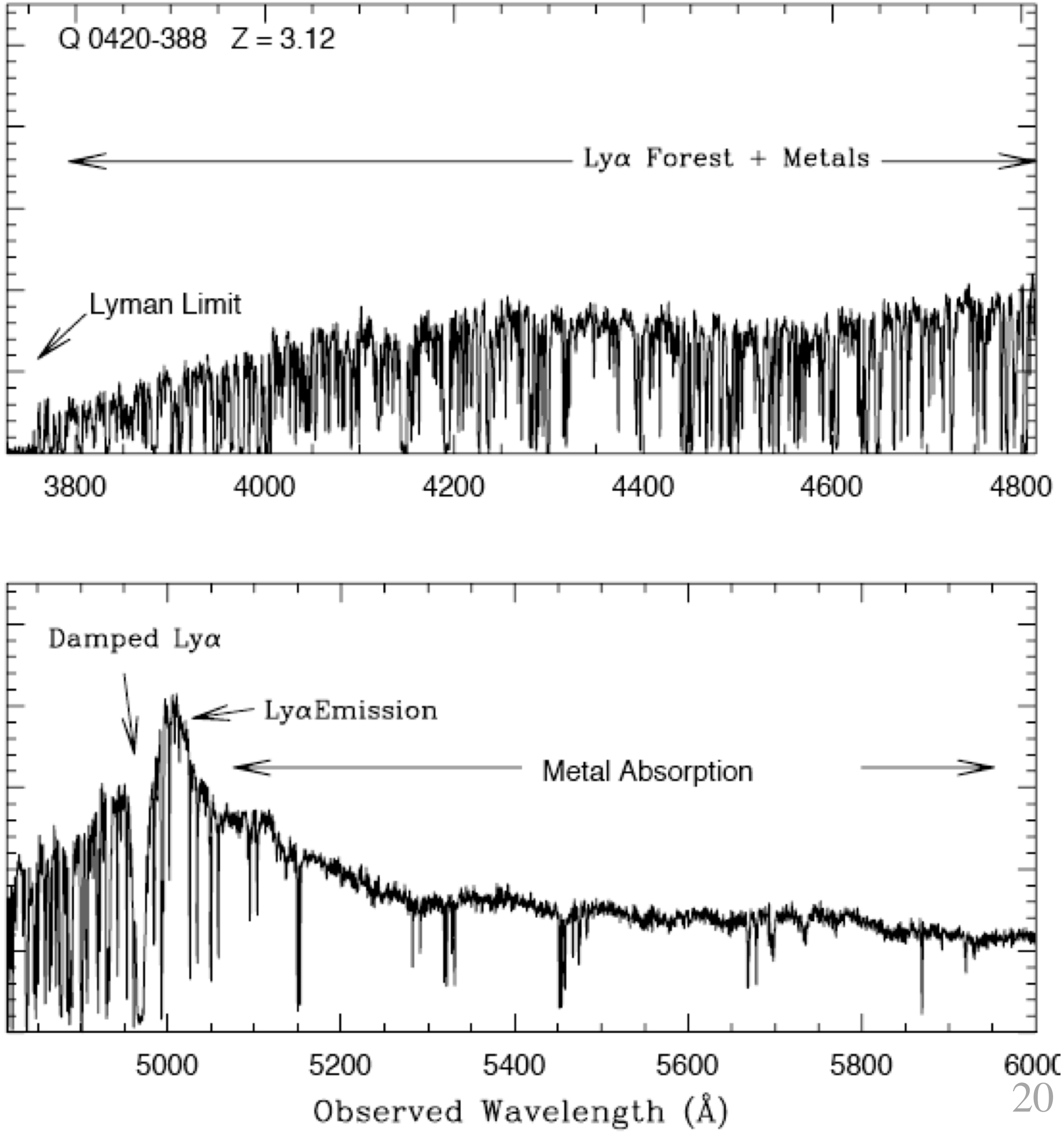
Types of QSO Absorption Lines

- **Lyman alpha forest:**
  - Numerous, weak lines from low-density hydrogen clouds
  - Proto-galactic clouds, with low density, they are not galaxies
- **Lyman Limit Systems** (LLS) **and "Damped" Lyman alpha** (DLA) absorption lines:
  - Rare, strong hydrogen absorption, high column densities
  - Coming from intervening galaxies
  - An intervening galaxies often produce both metal and damped Lyman alpha absorptions
- **Helium** equivalents are seen in the far UV part of the spectrum
- **"Metal" absorption lines**
  - Absorption lines from heavy elements, e.g., C, Si, Mg, Al, Fe
  - Most are from intervening galaxies

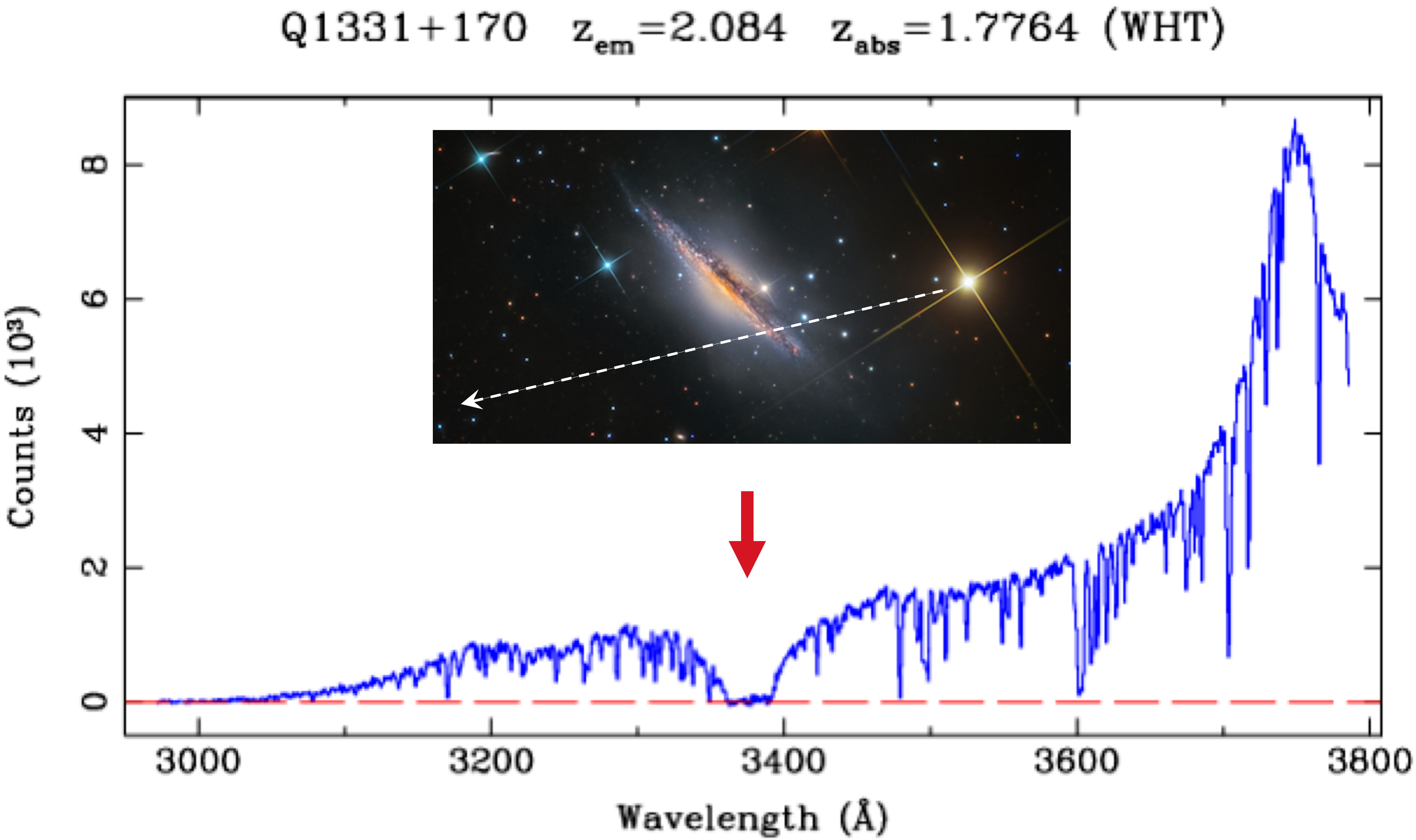


Q1422+231 – 18.8 hours
with HIRES (Keck I)
QSO's
Lyα emission
Lyα Forest
Flux
6000
4000
2000
0
4500
5000
5500
6000
6500
Wavelength (Å)

Types of QSO Absorption Systems

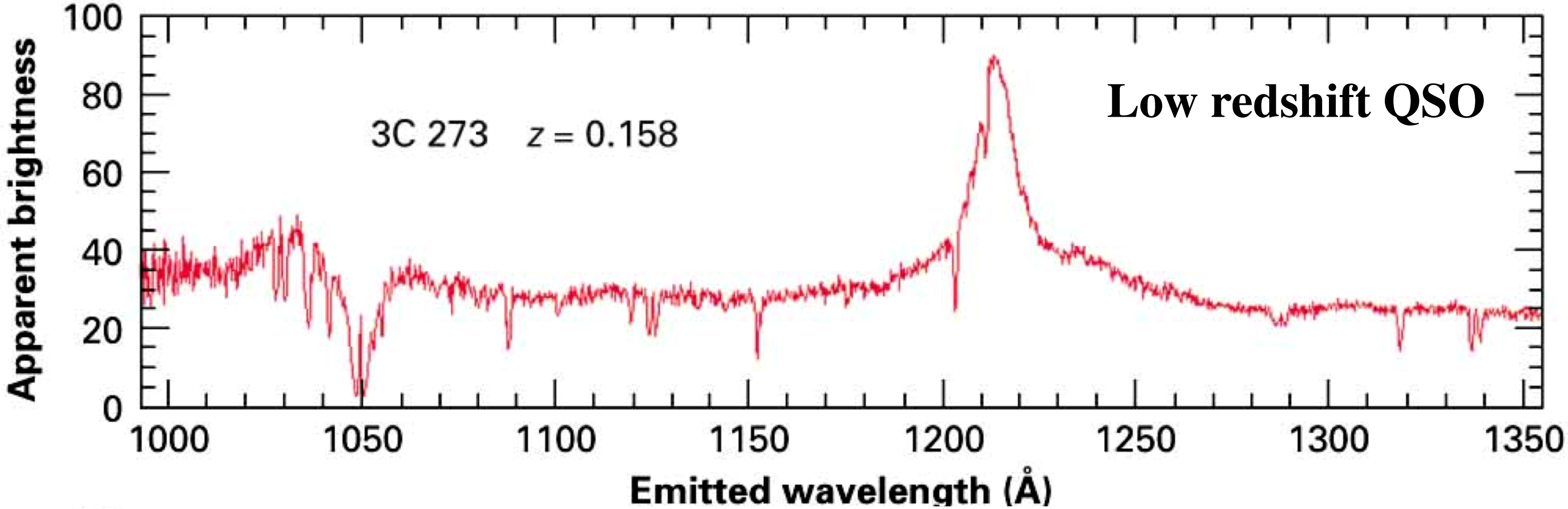


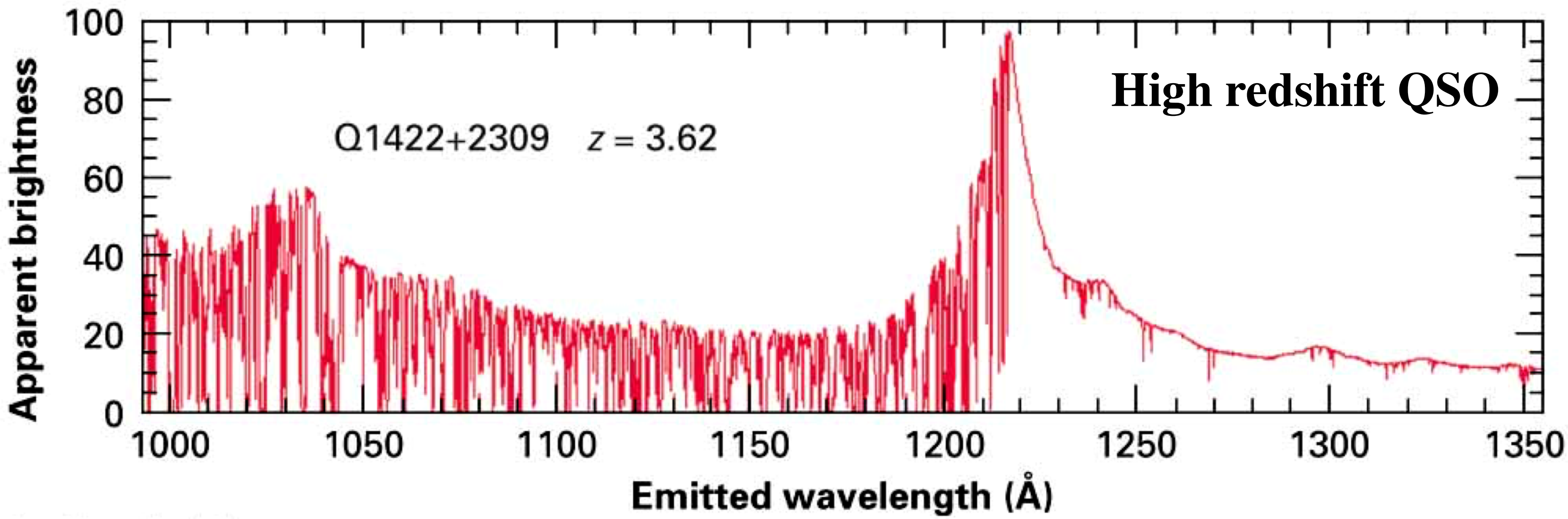
Damped Lyman α Systems
Saturated absorbers from distant galaxy disks



Evolution of the Hydrogen Absorbers

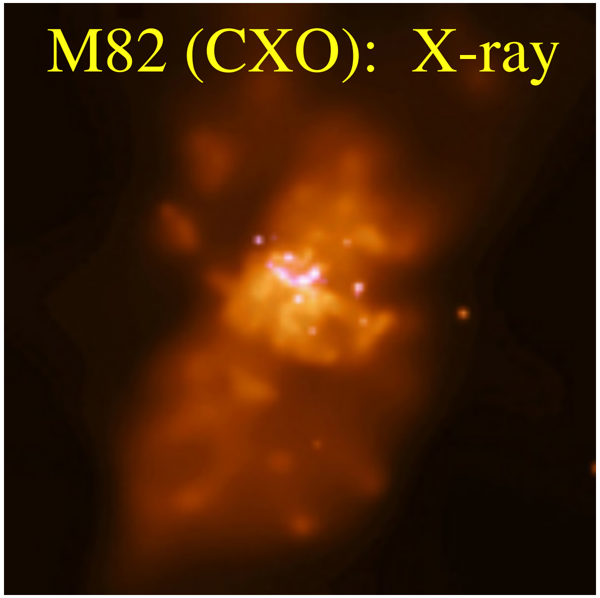
They were much more numerous far away (= early on)

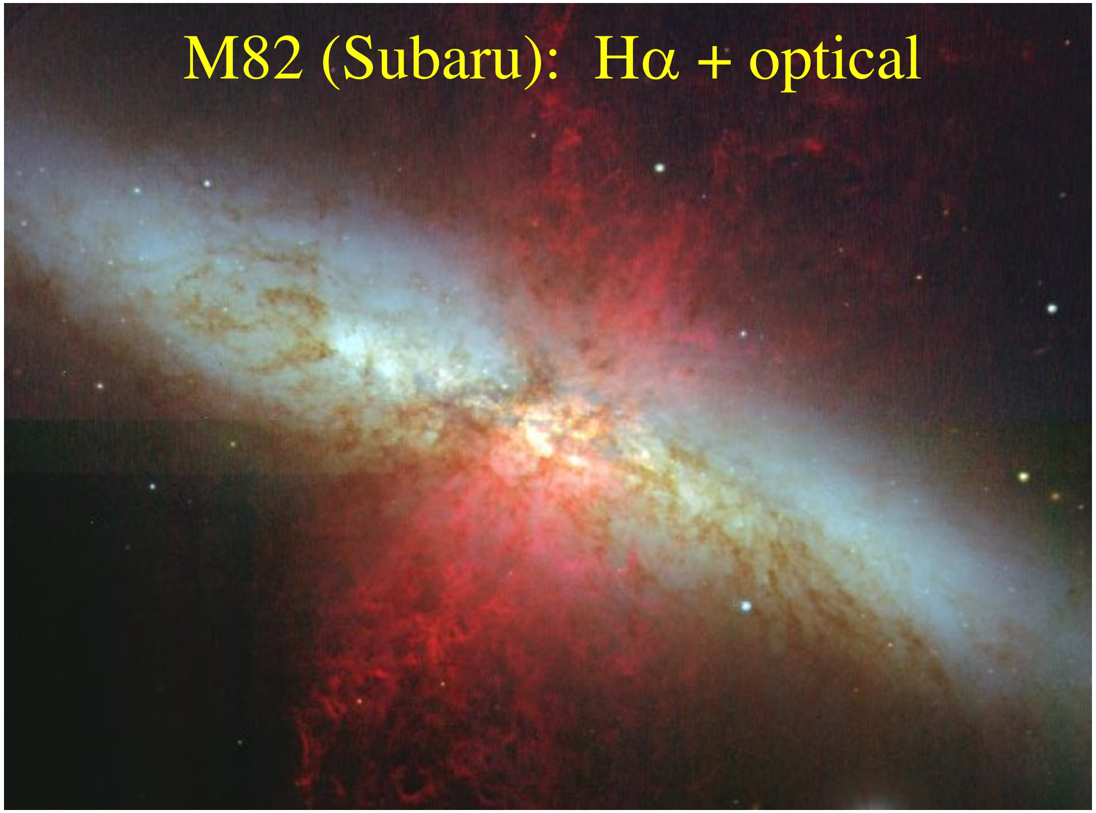


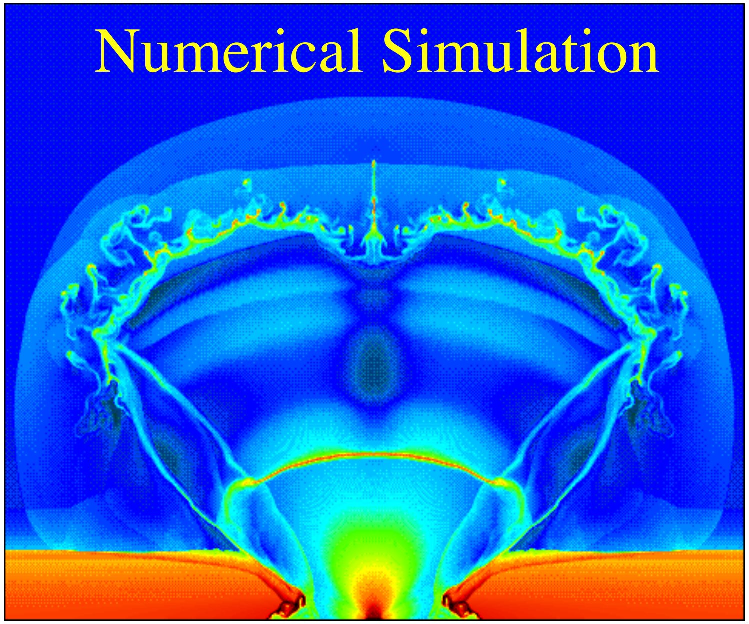


Galactic Winds

Starburst can drive winds of enriched gas (e.g., from supernova ejecta) out to the intergalactic medium. This gas can then be accreted again by galaxies. In a disk galaxy, the winds are generally bipolar outflows







14.5 The Earliest Galaxies

Galaxy Formation

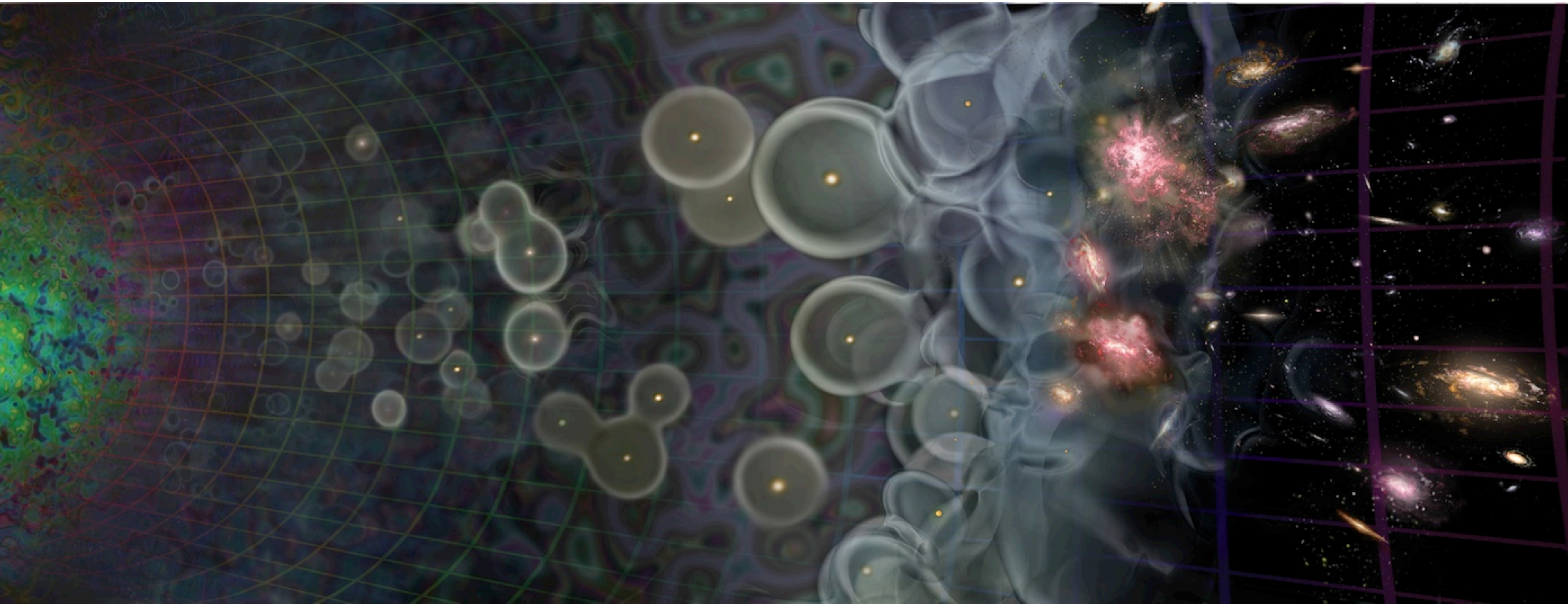
- The early stages of galaxy evolution - but there is no clear-cut boundary, and it also has two principal aspects: assembly of the mass, and conversion of gas into stars
- Must be related to large-scale (hierarchical) structure formation, plus the dissipative processes
- Probably closely related to 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 it 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

Energy Release From Forming Galaxies

- Release of the binding energy from a collapsing protogalaxy

  Typically ~ 10^{59} erg
- Thermonuclear burning in stars

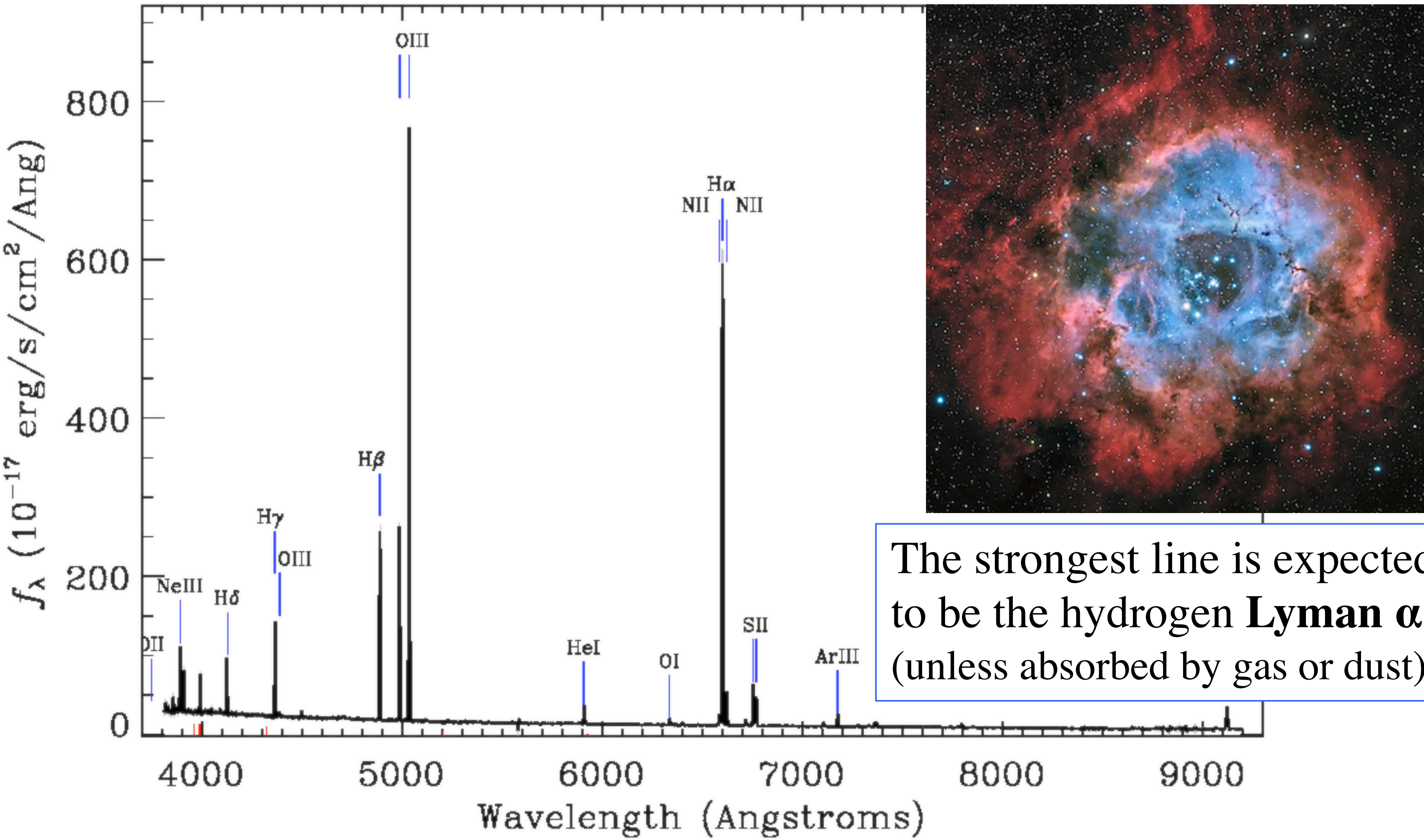
  Typically ~ 10^{60} erg
- Release of the binding energy from the collapsing protostars

  Typically ~ 10^{59} erg
- Energy input from an active nucleus, if present

  Up to ~ 10^{60} erg

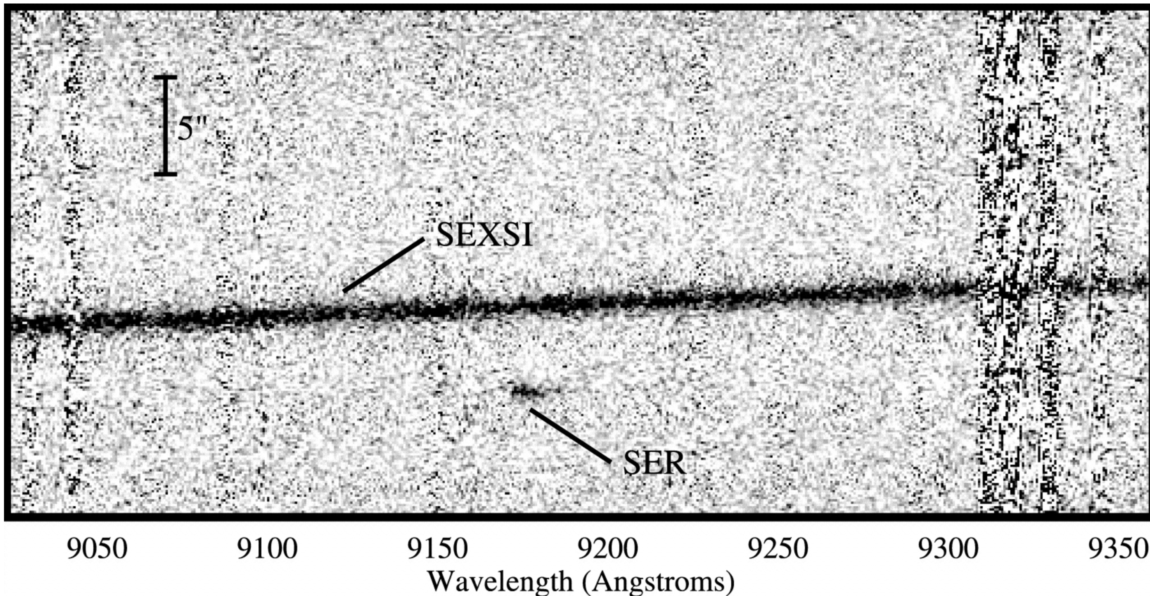
Emission Line Search for Young Galaxies

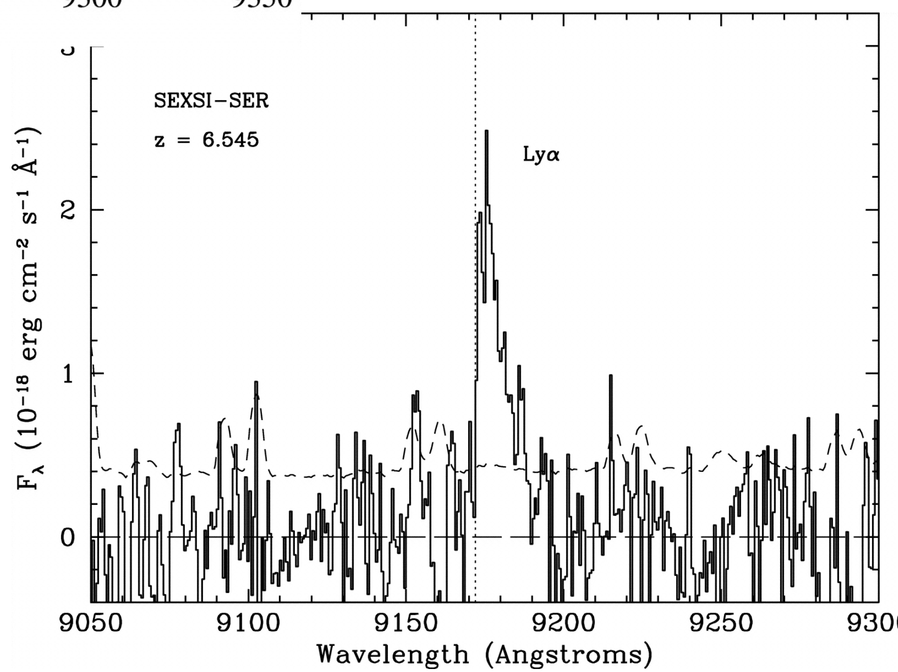
Spectra of star forming regions have strong recombination lines of hydrogen and various ions, e.g., Hα, [O III], etc.



The strongest line is expected to be the hydrogen **Lyman α** (unless absorbed by gas or dust)

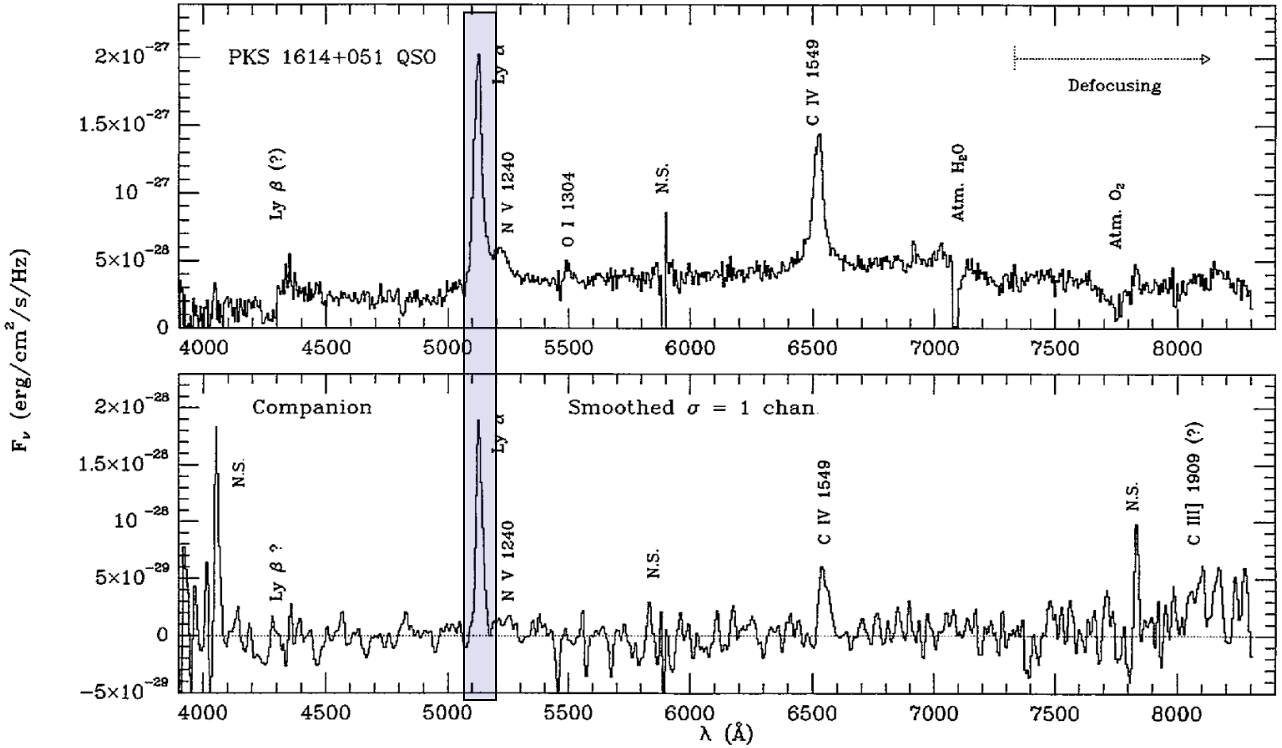
Long-Slit Spectroscopy + Serendipity

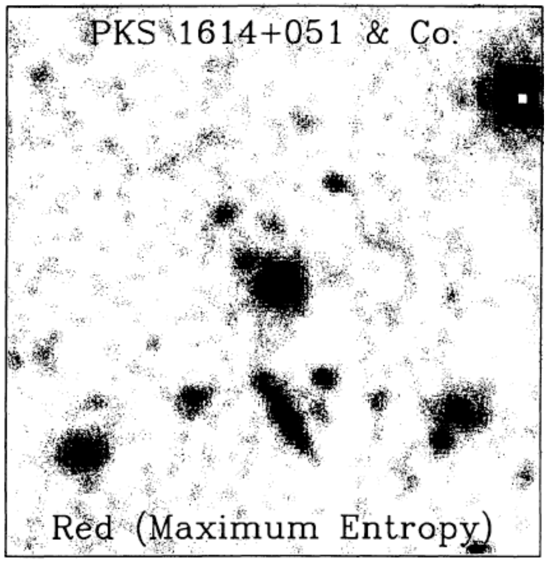


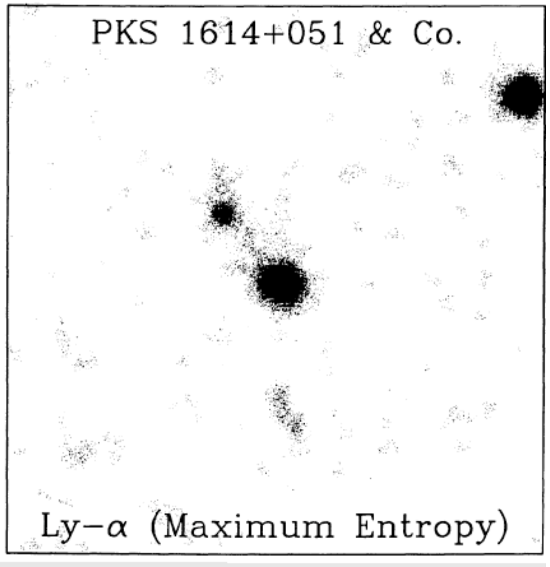


Narrow-Band Imaging

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

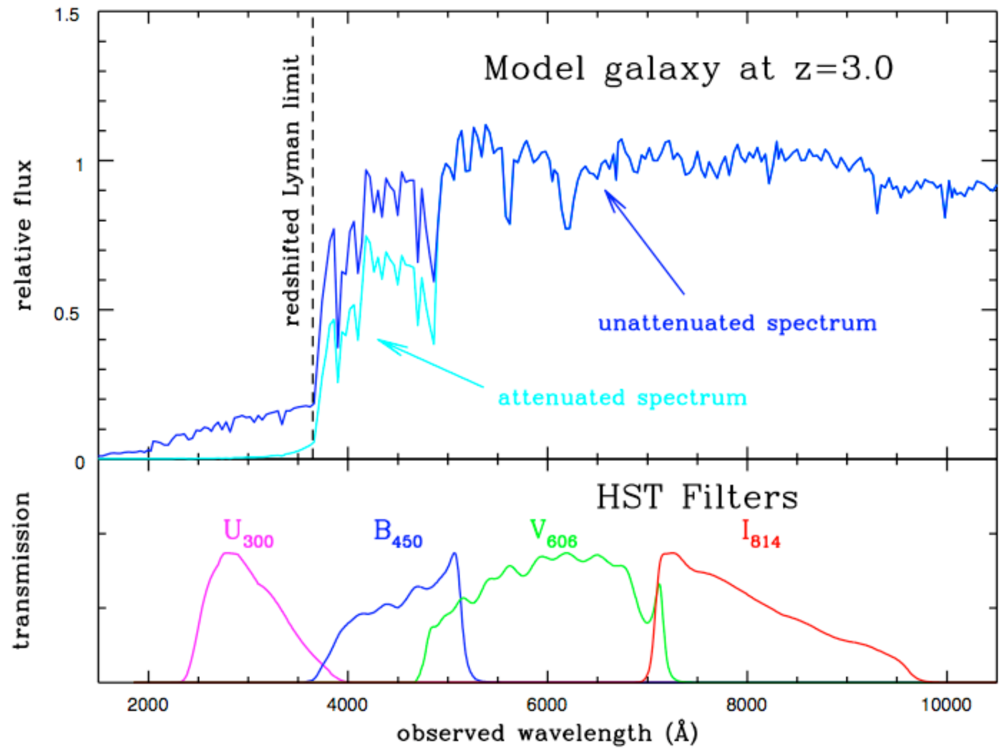


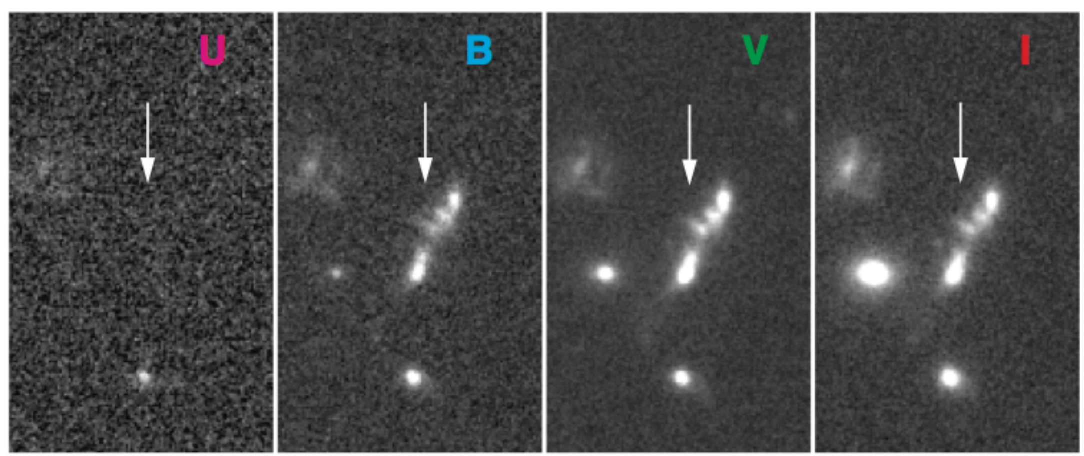




The Lyman-Break Method

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





Color-Selected Candidate High-z Galaxies

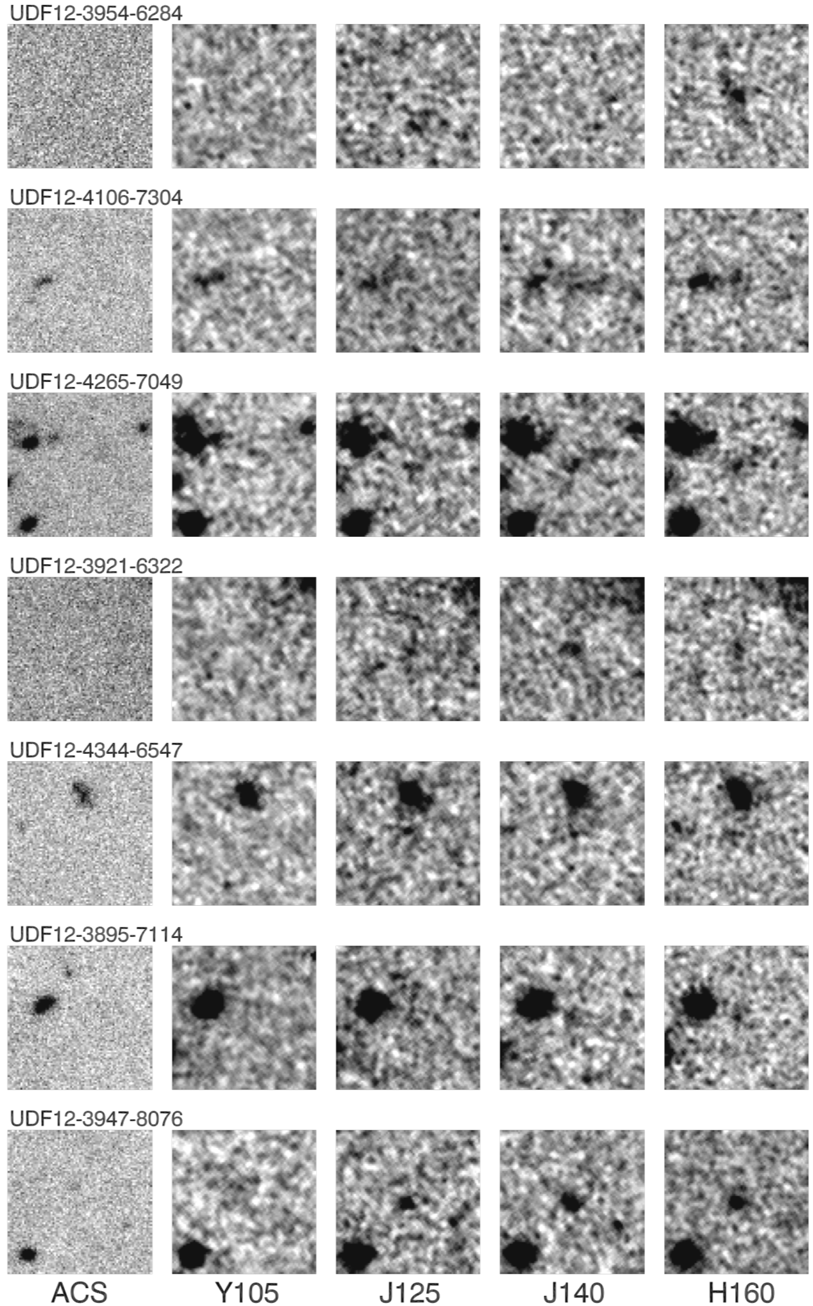
7 star-forming galaxies located $8.5<z<12$

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) ApJ 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

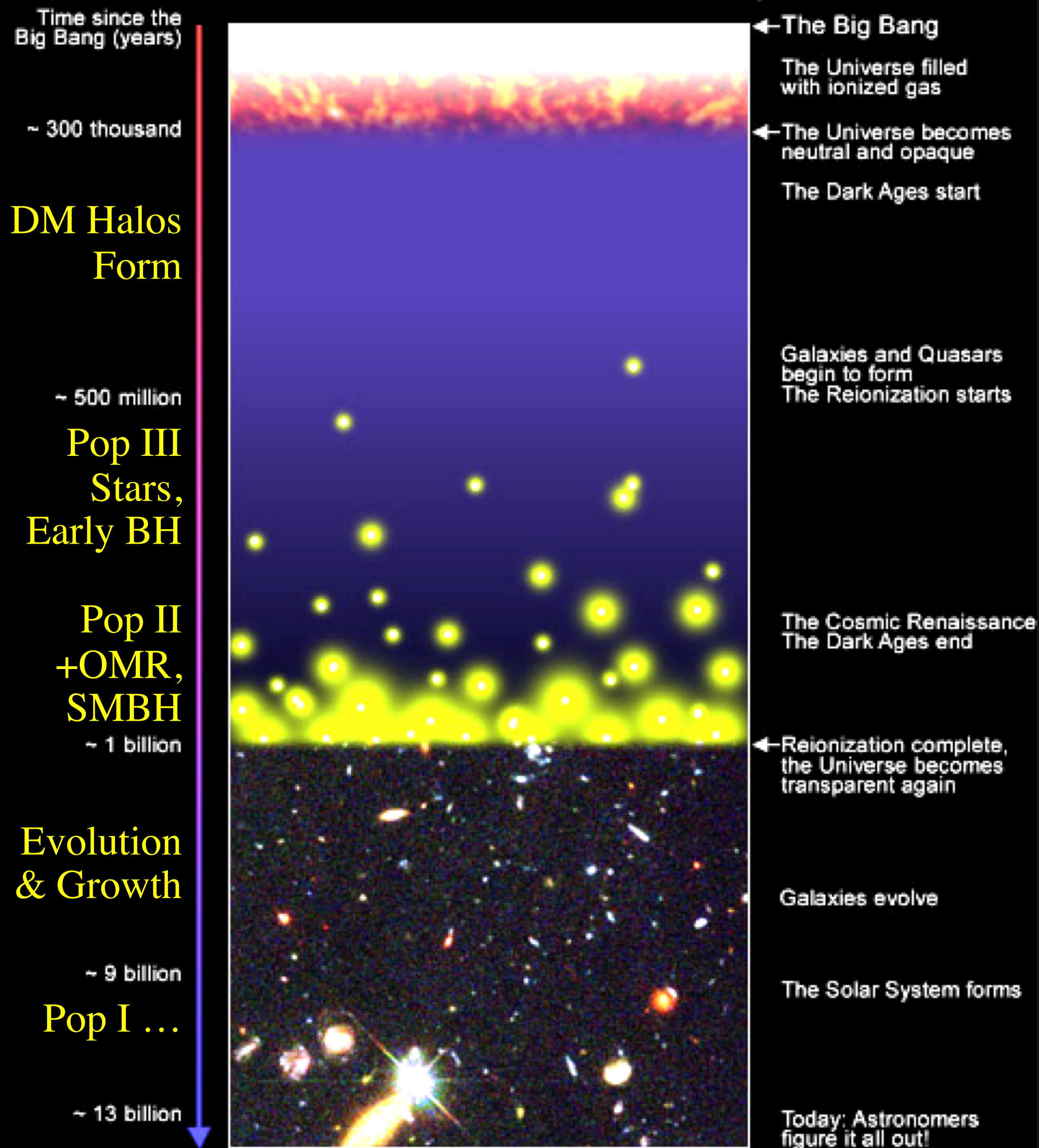
z=8.6 590 Myr

GN-z11: A Galaxy at z = 11.1?

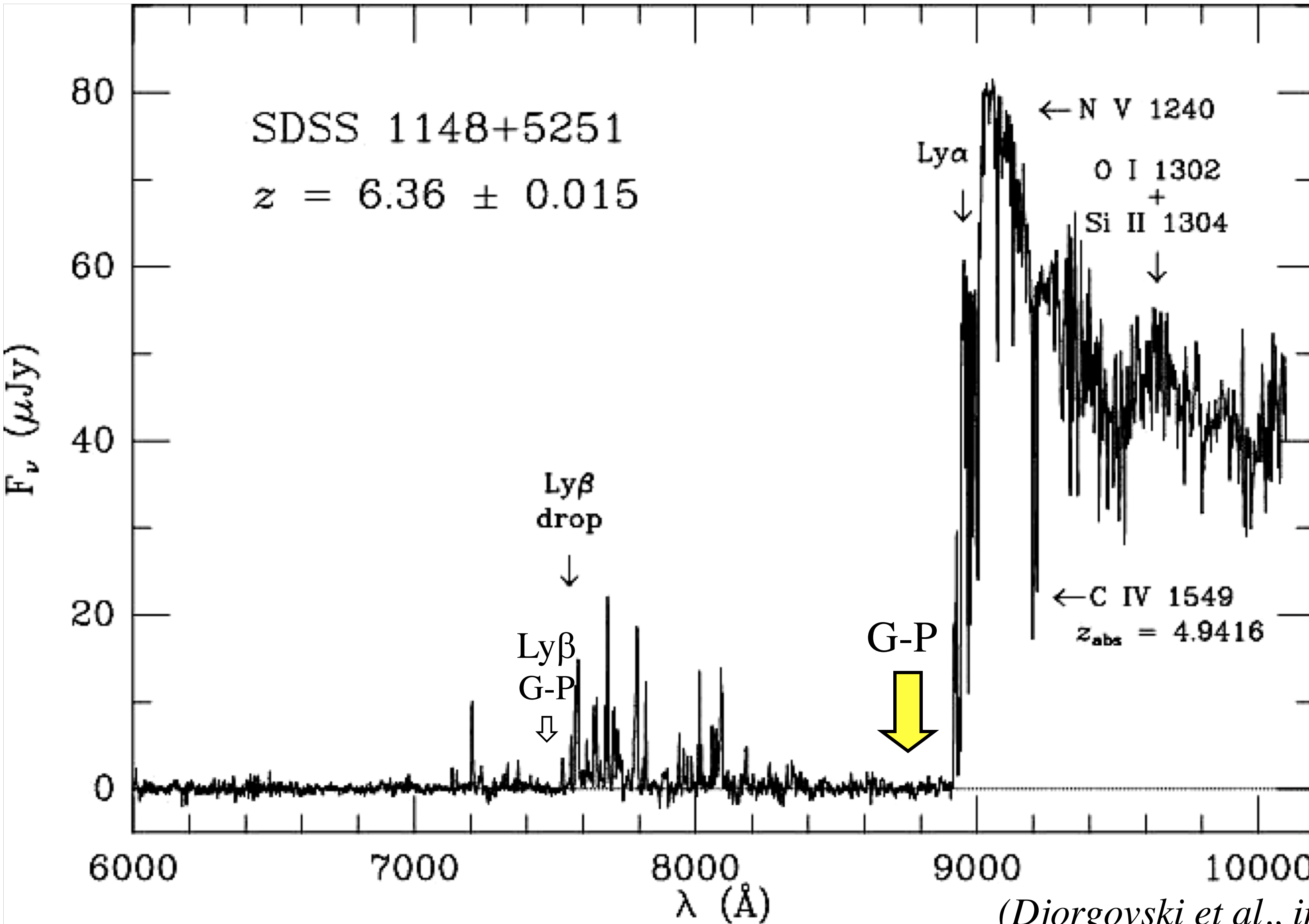

14.6 Reionization Era:
The Cosmic Renaissance

The Cosmic Reionization Era

(The Cosmic Renaissance)



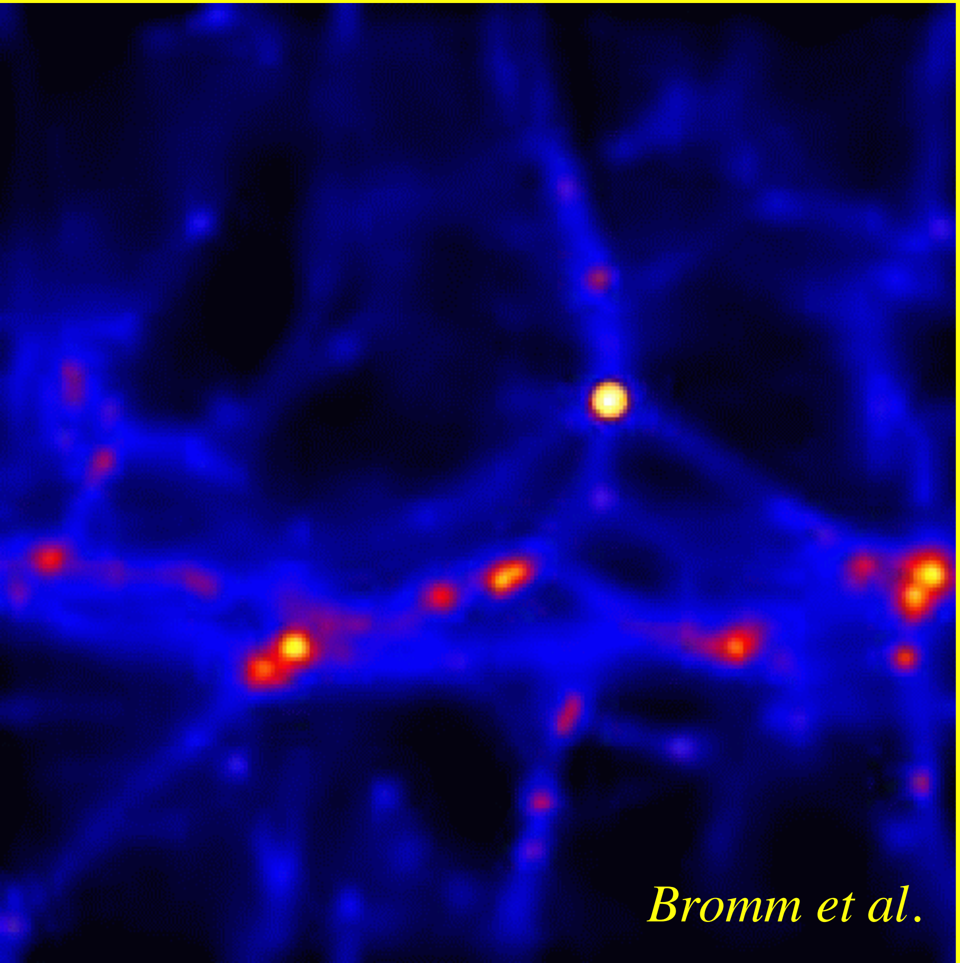
"Gunn-Peterson like" troughs are now observed along all available lines-of-sight at at $z \sim 6$

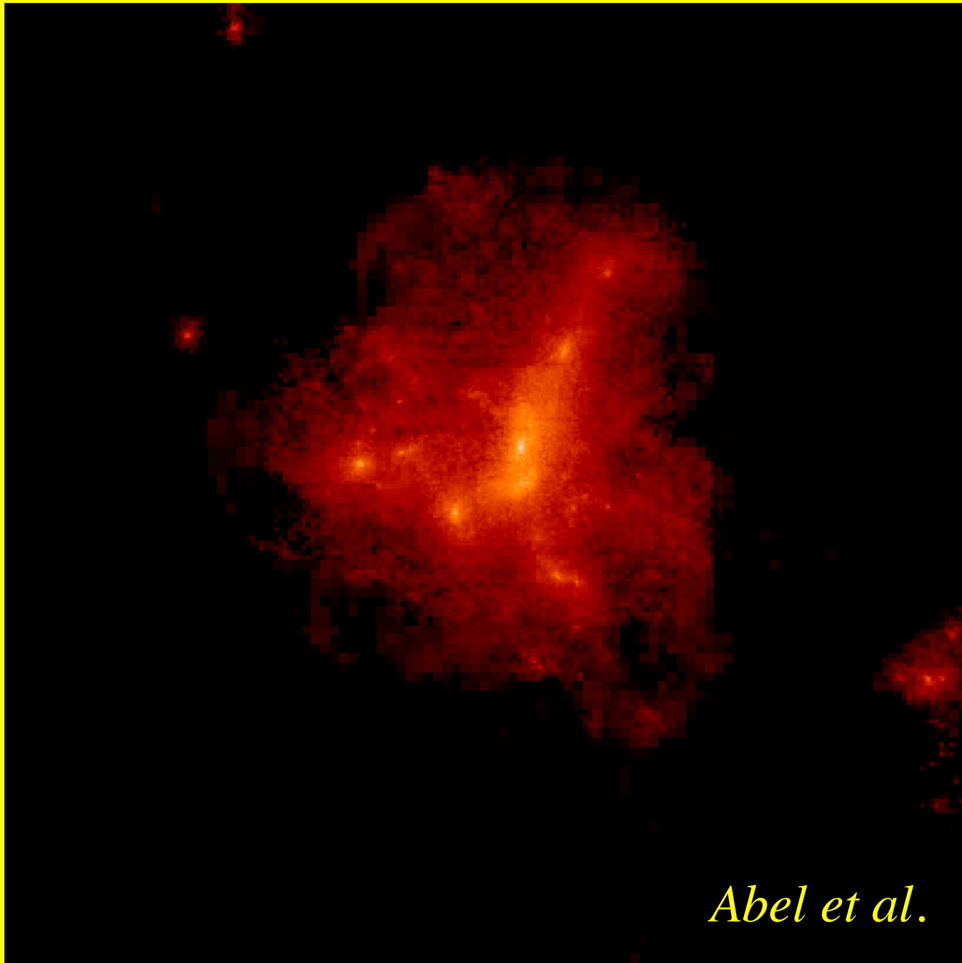


(Djorgovski et al., in prep.)

The First Stars

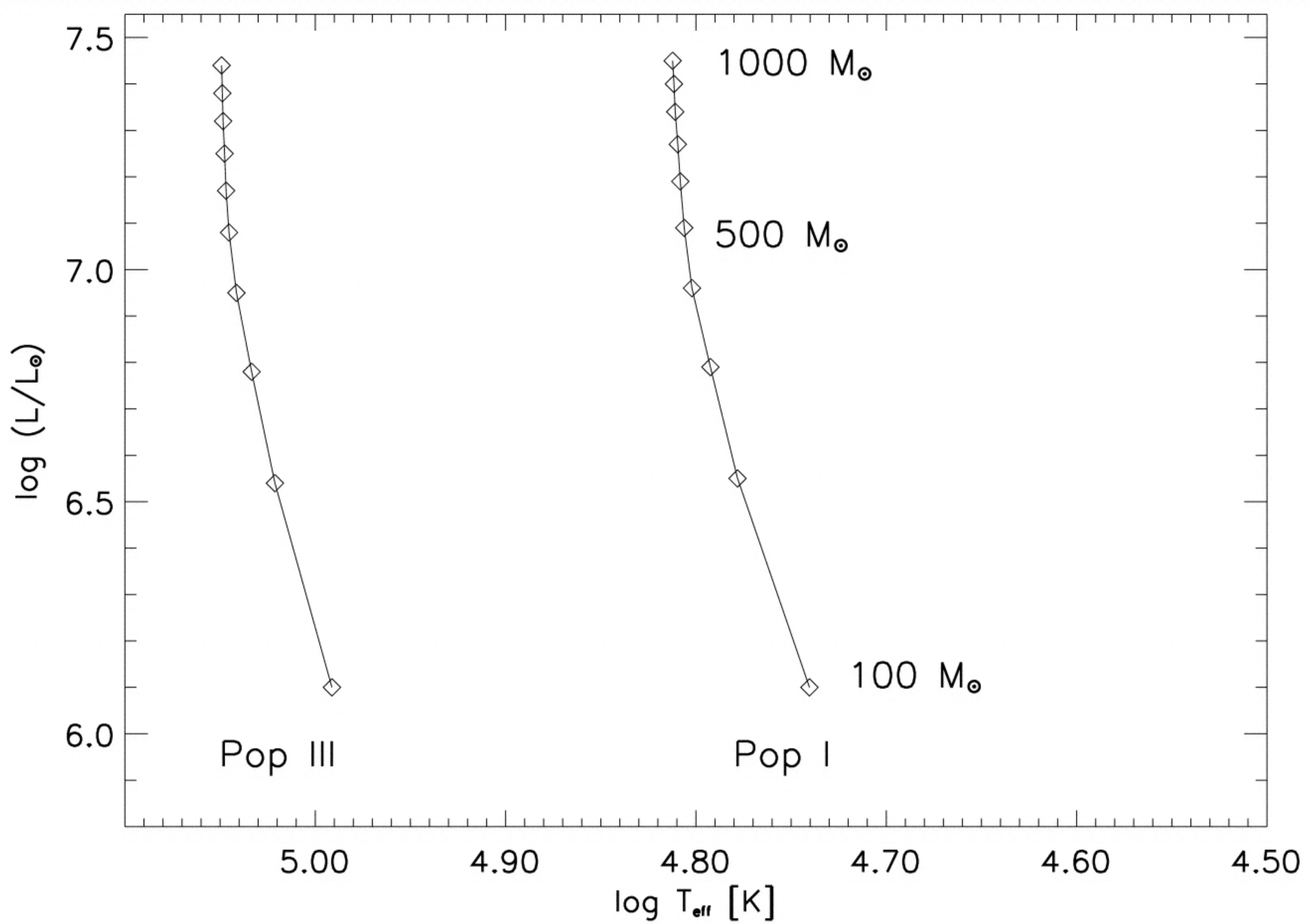
Gas infall into the potential wells of the dark matter fluctuations leads to increased density, formation of H_2, molecular line cooling, further condensation and cloud fragmentation, leading to the formation of the **first stars**





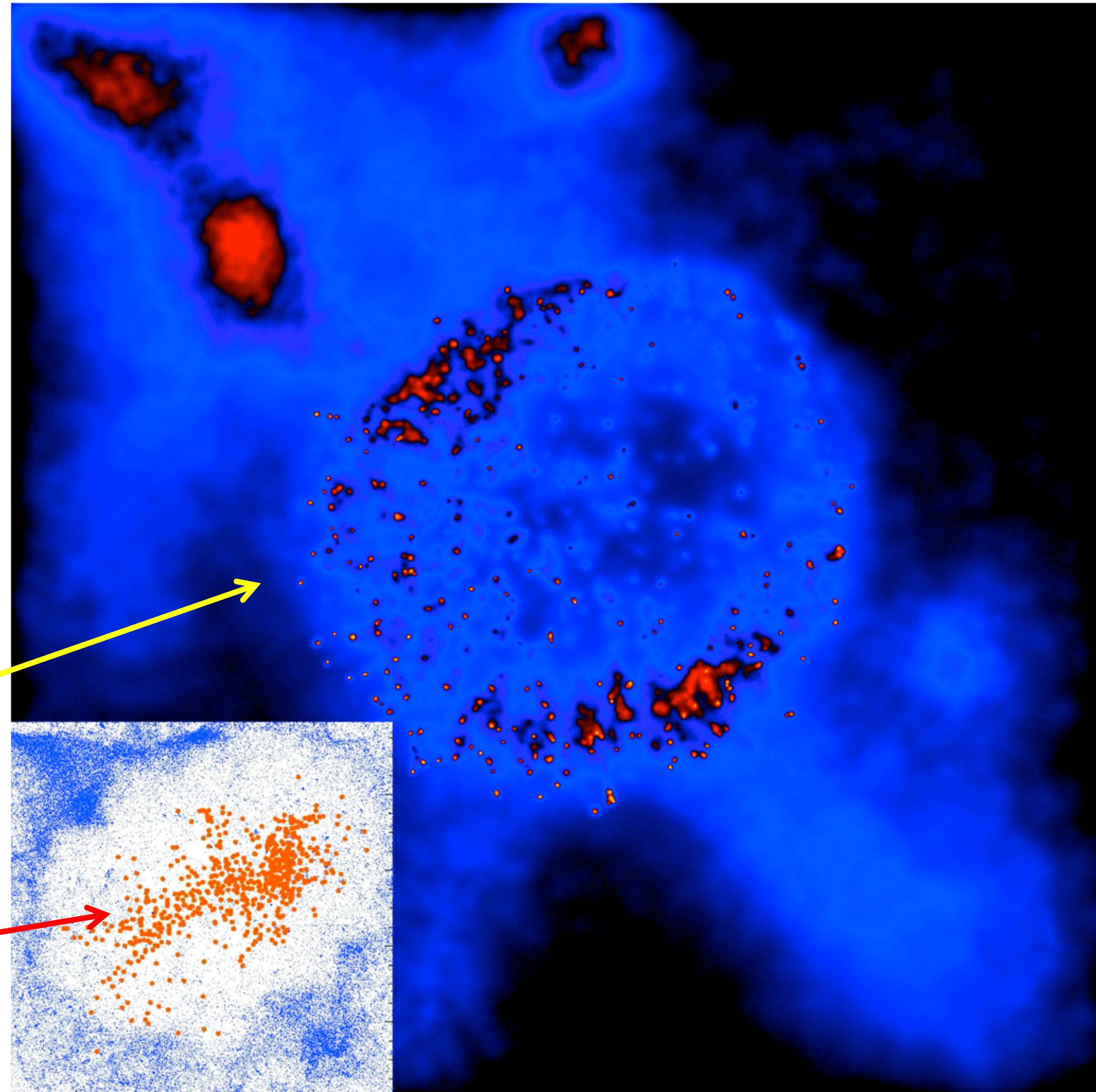
Population III Stars: Hot and Luminous

They can easily reionize the universe by z ~ 6



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 $Z_{crit} \sim 10^{-3.5} Z_{\odot}$



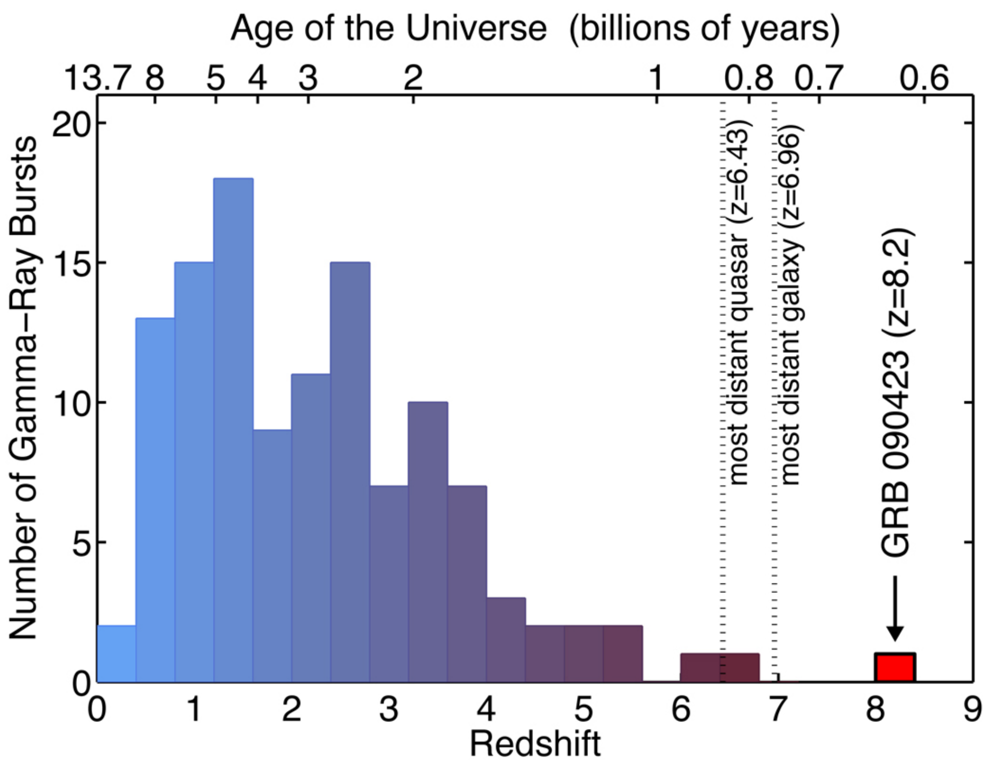
Simulated Pop III SN shell after ~ 10^6 yr

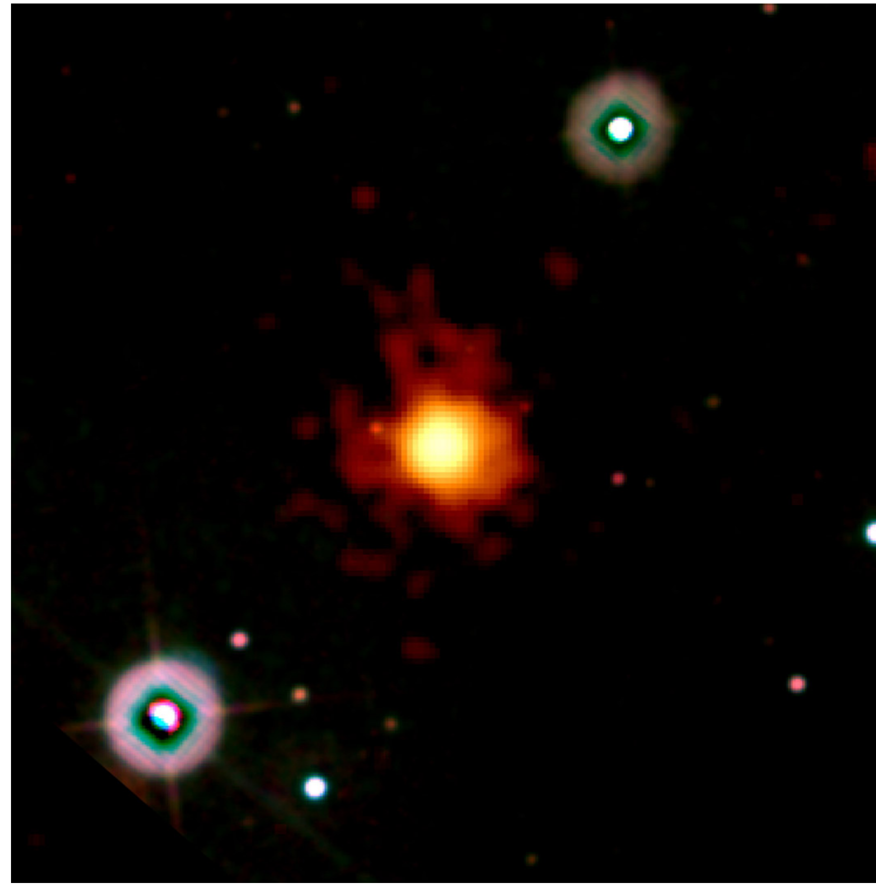
Distrib. of metals (red)

(from Bromm et al. 2003)

GRB 090423 at z ~ 8.2 (?)

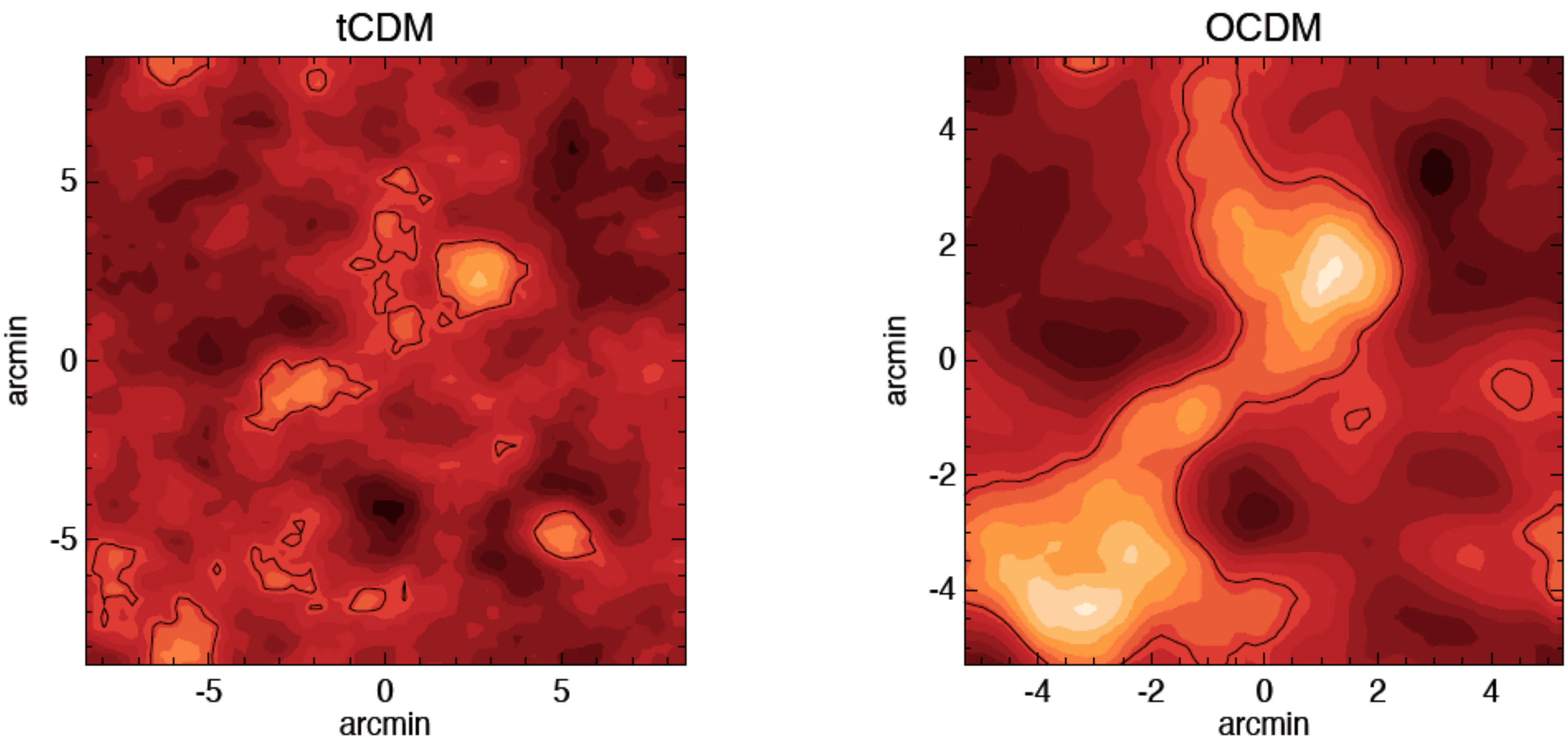
The current record holder – no details available yet





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)