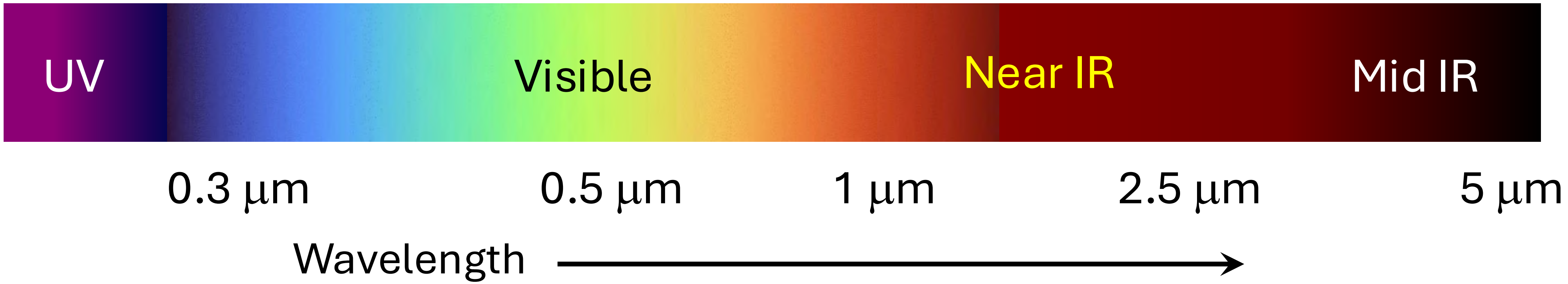
Ay 1 – Lecture 13

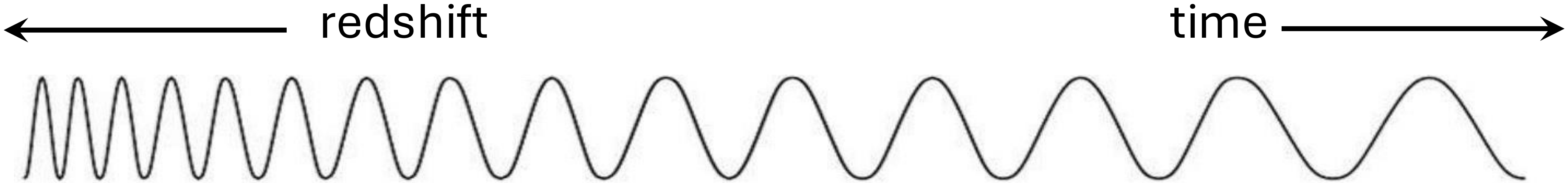
Galaxy Formation and Evolution

Redshift is a Measure of Distance and the Lookback Time

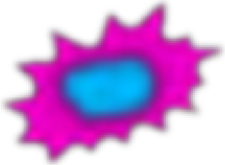
Electromagnetic Spectrum:



Expansion of the universe stretches the wavelengths of light as it travels

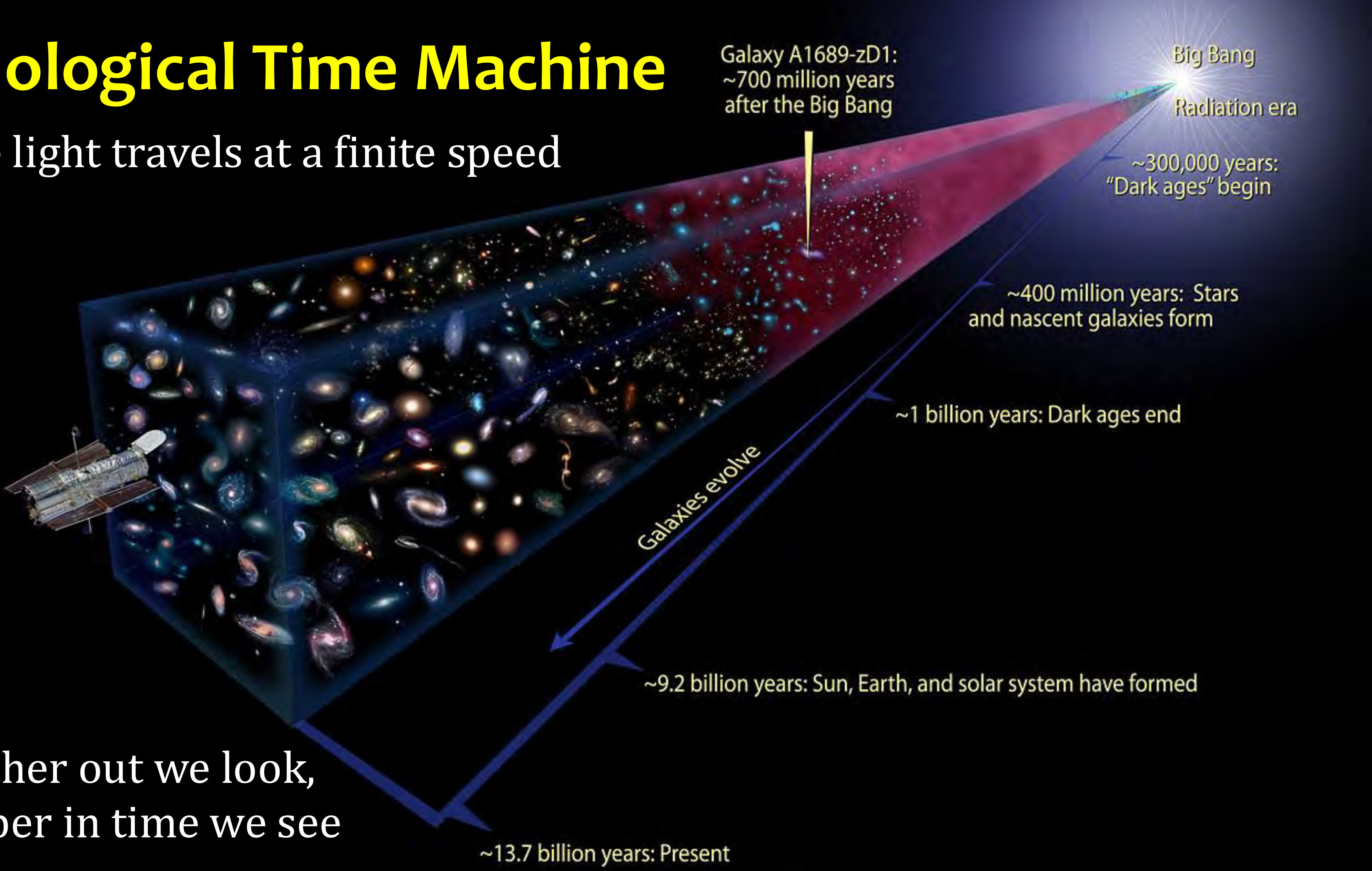


Light that started at the redshift $\boldsymbol{z} = 10$ now has the wavelengths 11 times larger

 Light emitted in UV/blue . . . . Is now observed in Infrared 

Cosmological Time Machine

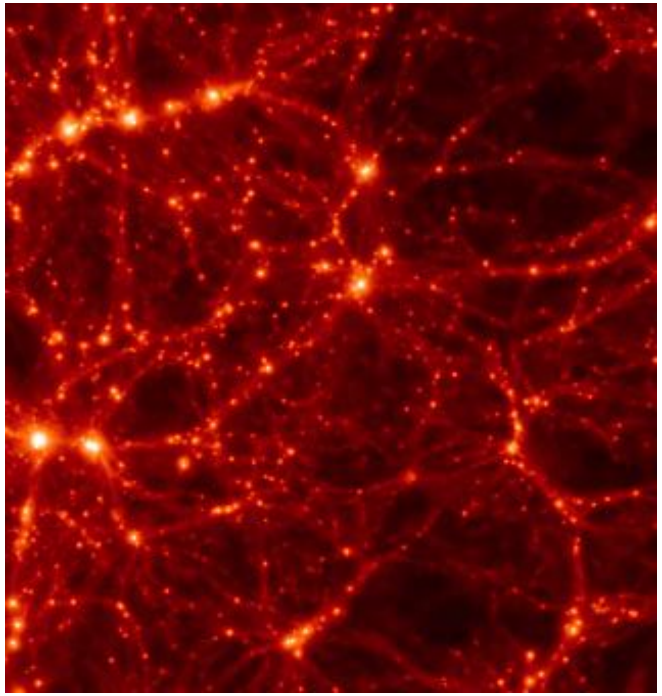
Because light travels at a finite speed



The further out we look,
the deeper in time we see

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 into ever larger structures



Galaxy Evolution

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

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

Visible matter. 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 a wide range:

~ 100 Myr - galaxy collapse 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 $\times$ 100 Myr - rotation period of spiral galaxy

~ 1 Gyr - time required for two galaxies to merge

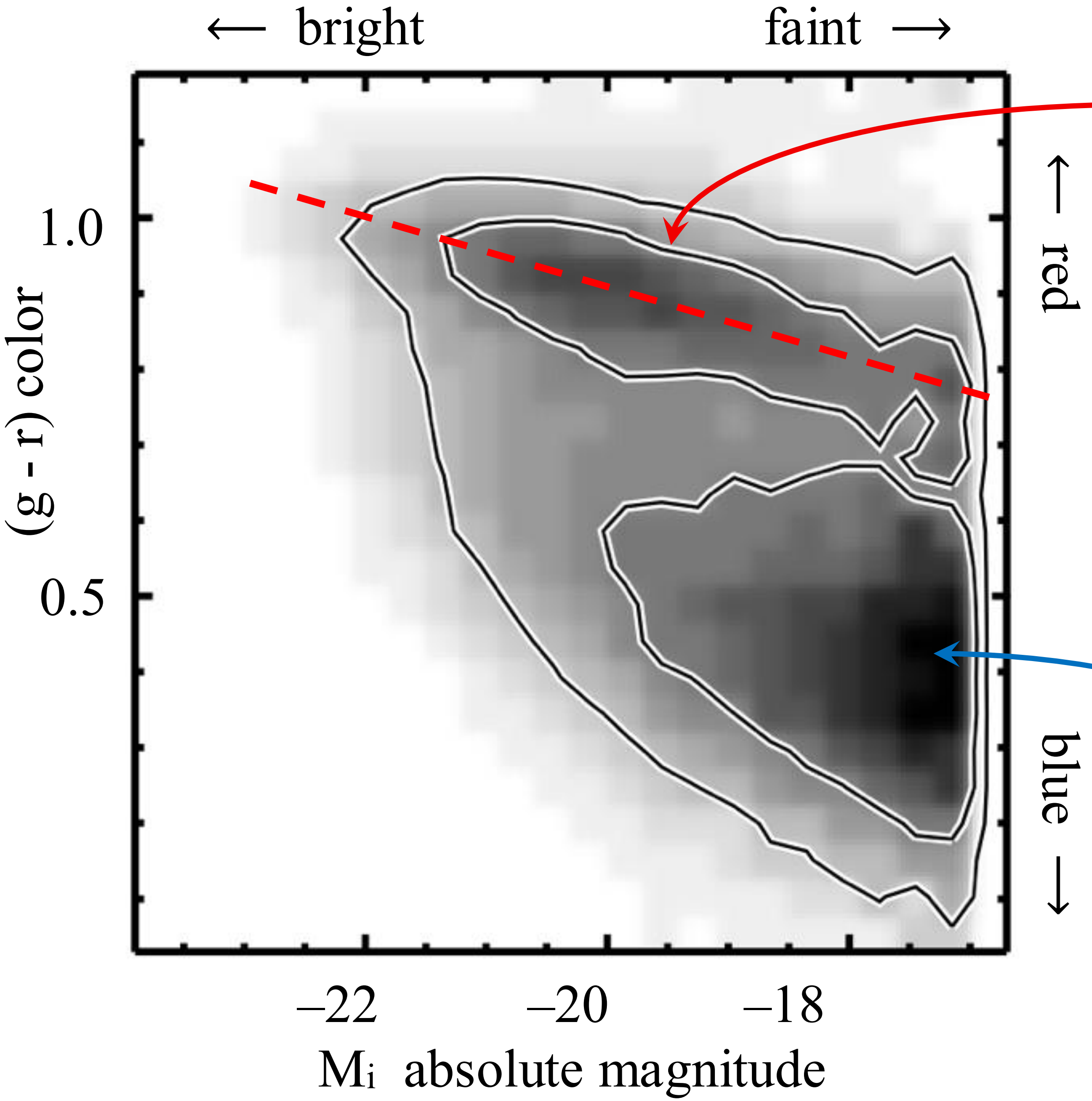
~ 10 Gyr - age of the Universe

Observational evidence for evolution is found in:

- Stellar populations in the Milky Way (metallicities, ages, dynamics…)
- Systematics of nearby galaxy properties (correlations, scaling laws)
- **Properties of distant galaxies seen directly at earlier epochs:**

The deeper in space we look, the deeper in time we see

Galaxy Colors Reflect Their Star Formation Histories



The **red sequence**: mostly ellipticals, no active star formation (thus the red colors)

The correlation (more luminous ellipticals are redder) is due to their larger metallicities. More massive ones retain more of their stellar evolution products, and have stronger absorption lines in the blue

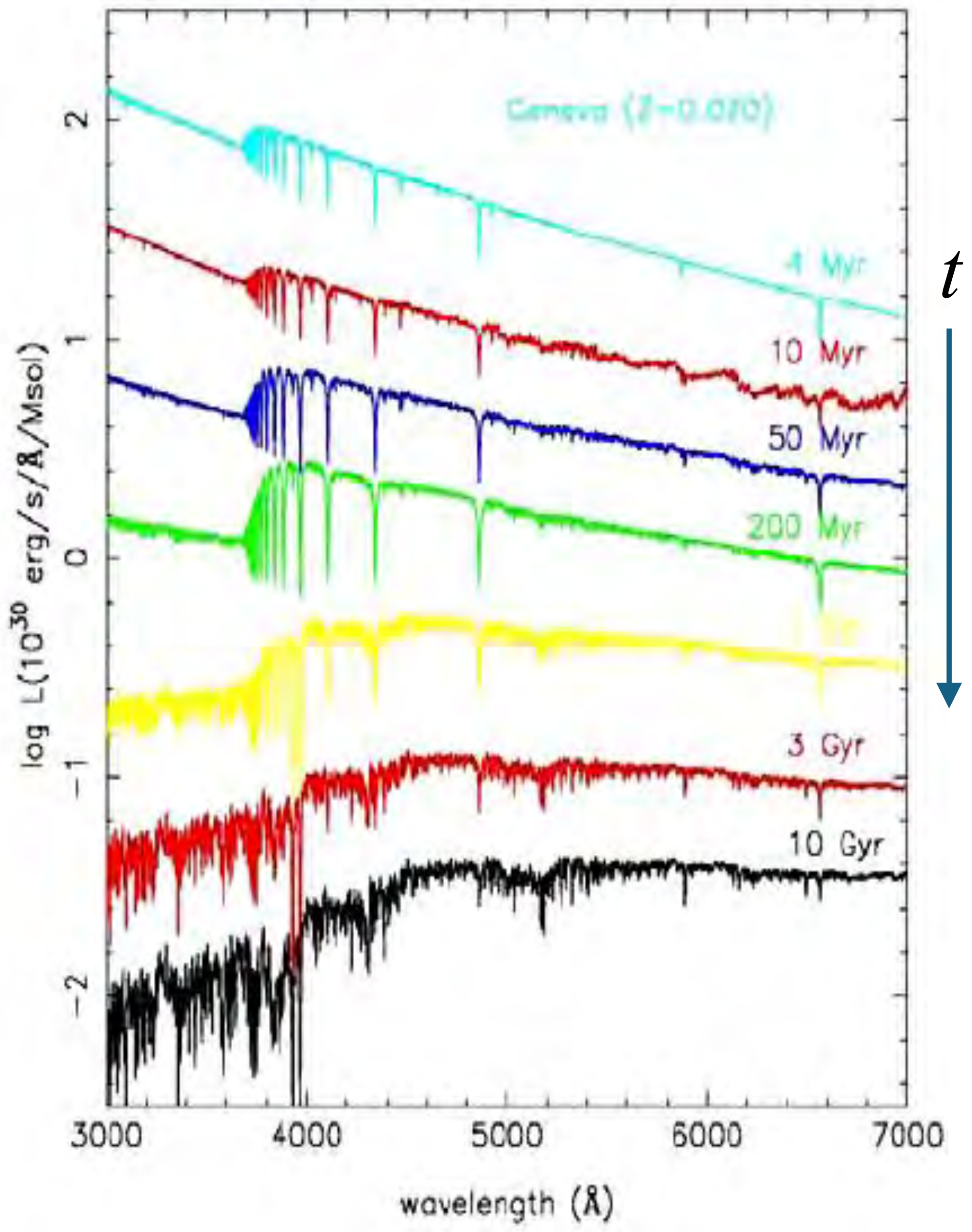
The blue sequence: mostly spirals, with active star formation

Broader distribution due to a range of star formation rates and dust reddening

Modeling the Evolution of Stellar Populations

Stellar evolution is relatively well understood both observationally and theoretically:

- ✷ Massive stars are very hot, blue, very luminous, and have very short lives; they dominate the blue/UV ligh
  - → Thus we expect ***largest and fastest effects in the bluer parts of the spectrum***
- ✷ We need to *assume* ***the stellar initial mass function***
- ✷ We need ***libraries of stellar spectra*** for stars of different masses, metallicities, ages, etc.
- ✷ We need ***stellar evolutionary tracks*** (isochrones)
- ✷ ***Star formation histories*** are a key assumption:
  - → Ellipticals are best fit by a burst of early star formation and then 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



Observational Tools and Approaches

- **Deep imaging surveys** at wavelengths from UV to FIR
  - Sources are usually selected in emission, and any given band has its own selection effects and other peculiarities
  - With enough filter bandpasses, we can estimate photometric redshifts, essentially a very low resolution spectroscopy
  - Sometimes the sources are selected from absorption
  - Galaxy clustering provide additional information
- **Deep spectroscopic redshift surveys**: redshifts measure the distance, and are usually obtained in the visible
  - 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

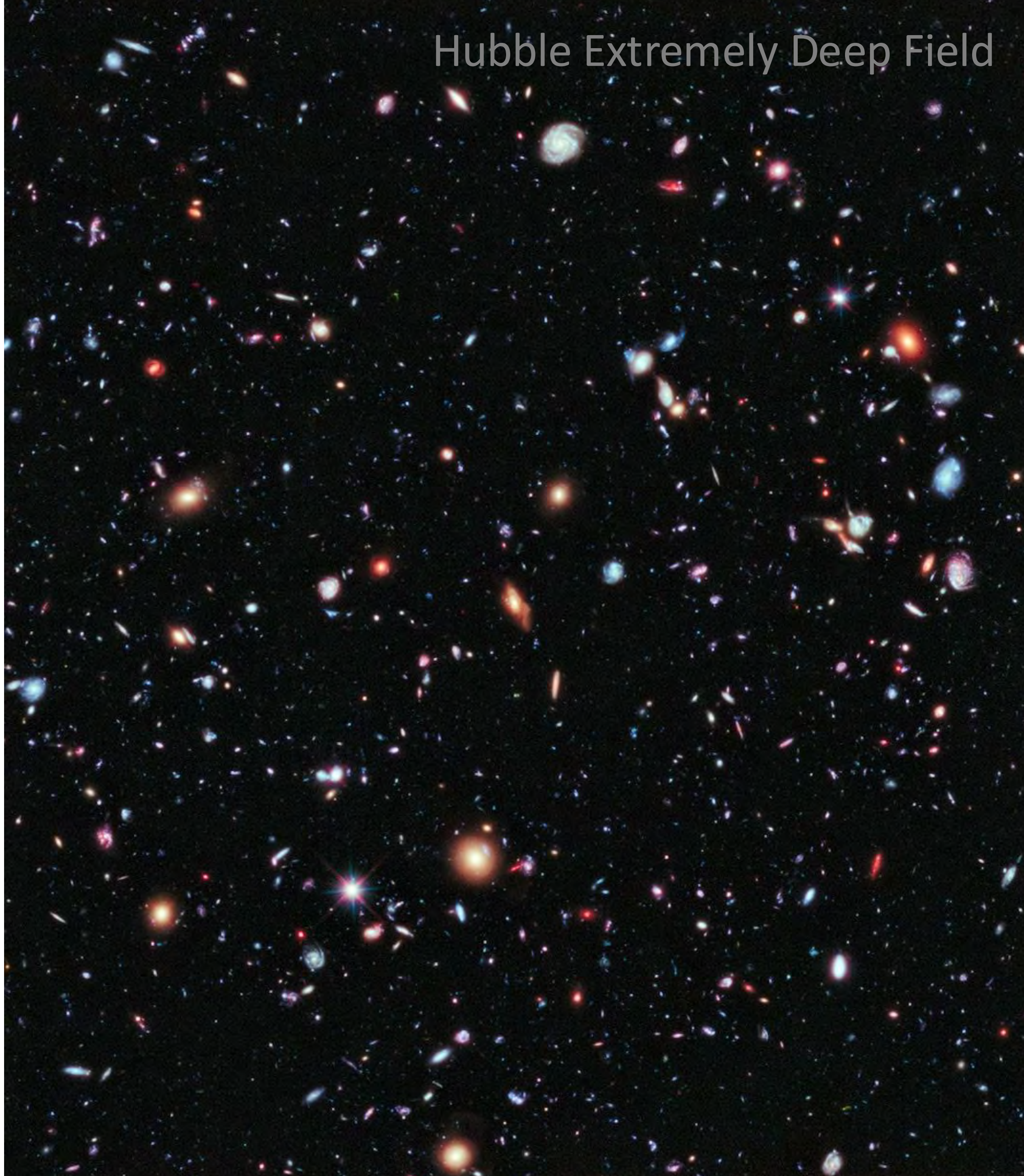
Ultra Deep Fields

Selected deep imaging fields, using stacked imaging from space (HST, JWST, etc.) and ground, over a range of wavelengths (X-ray, UV, Vis, IR, Radio…)

Typically a few arcmin across, reaching ~ 30 mag, high redshifts, lookback times > 13 Gyr

Usually followed by deep redshift surveys to get the distances and various physical properties of sources, using large ground-based telescopes (Keck, VLT, …)

Provide the best constraints on galaxy evolution and formation



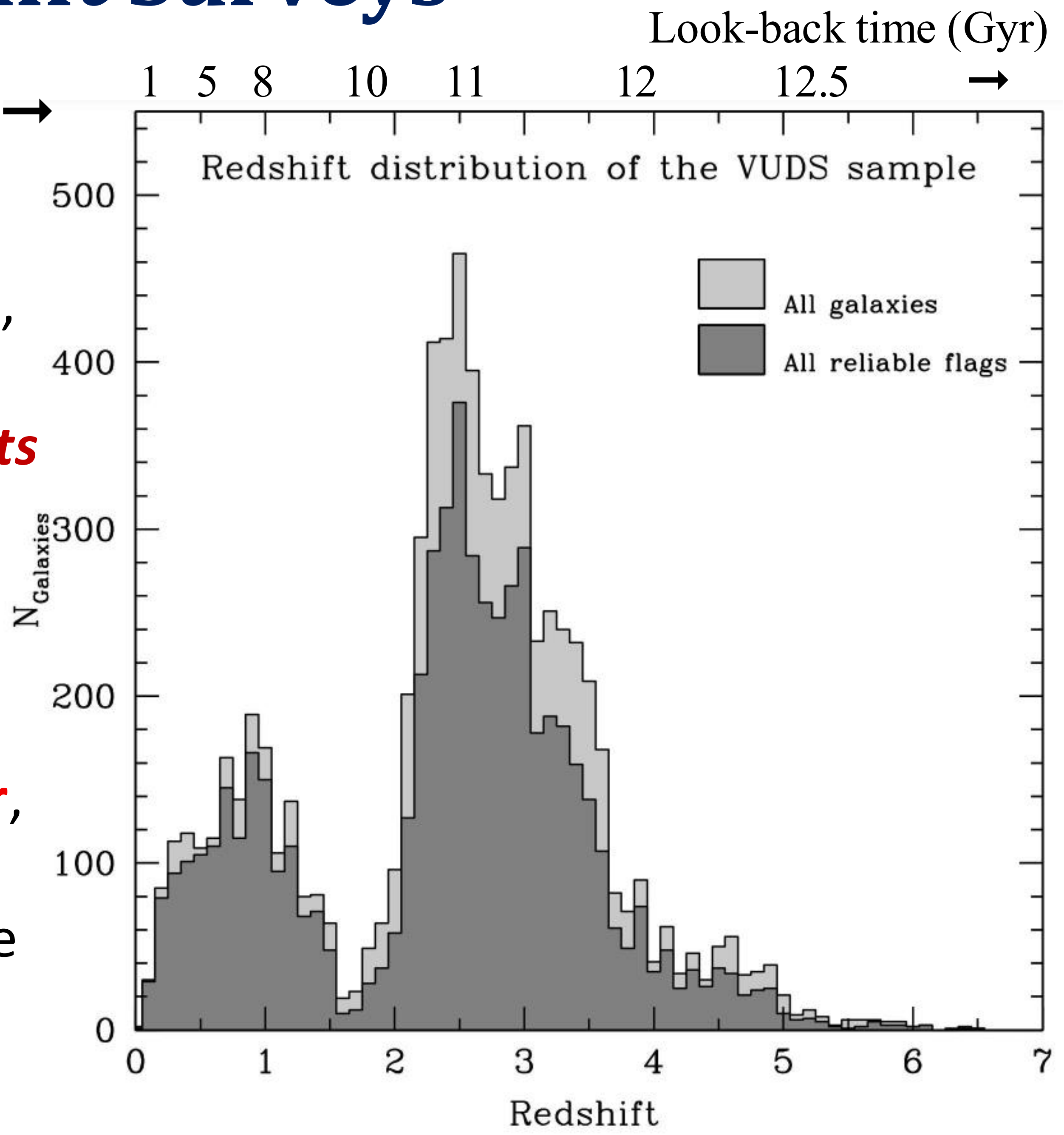
Deep Redshift Surveys

Example: the VLT Ultra-Deep Survey (VUDS) ➞

To really understand things, separate the effects of luminosity and density evolution, and between the distance and intrinsic luminosity at a given flux, we need ***redshifts***

The targets are selected from ultra-deep imaging surveys

The results imply that galaxies in the past were **bluer** (more star formation), **brighter**, **smaller mass** on the average, **smaller size**, and **more numerous** (they gradually merge into more massive galaxies)



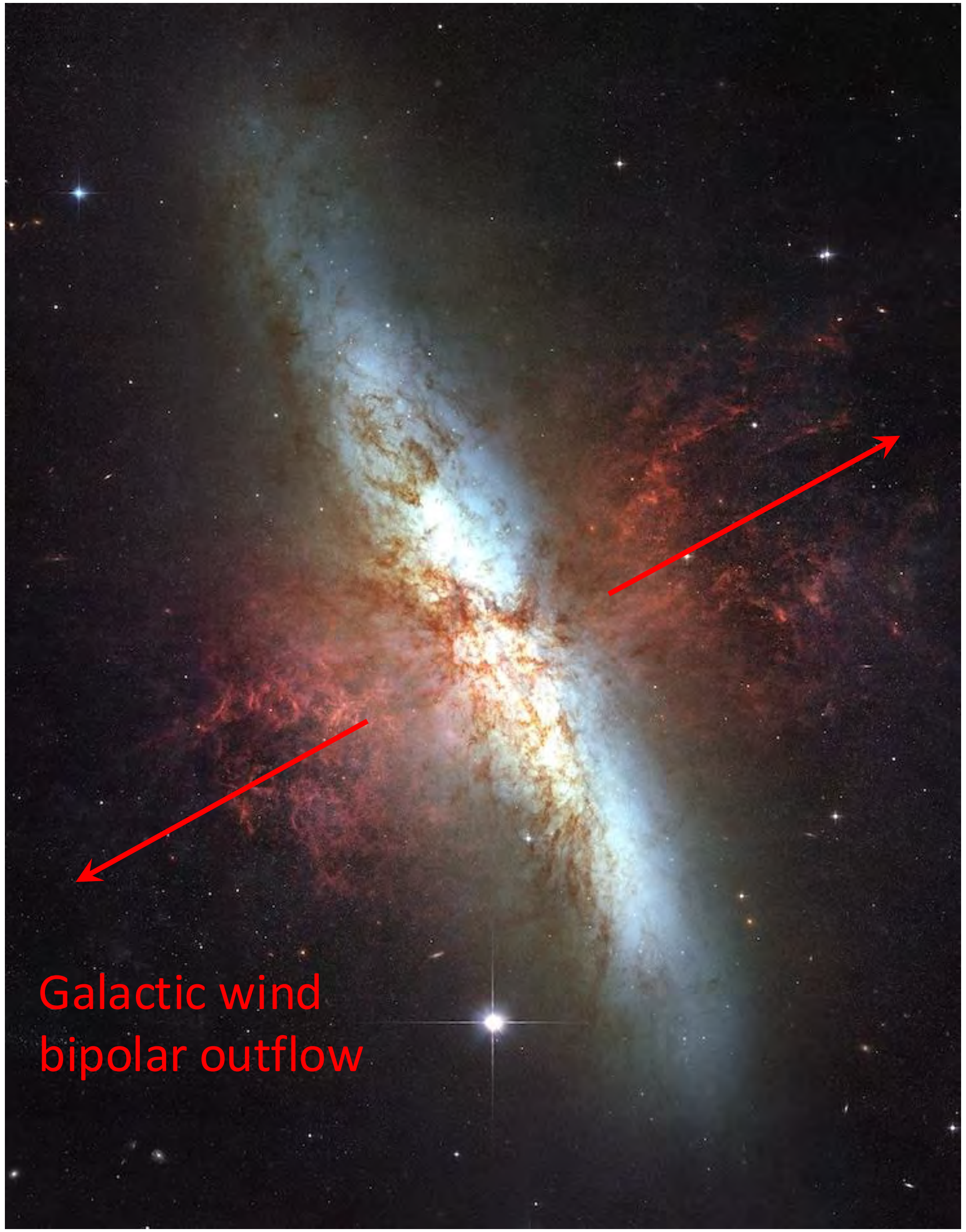
The Two Modes of Star Formation

All star formation (except for the very first generation of Population III stars) happens in the dense molecular gas and dust clouds. The **dust absorbs the light from young stellar photospheres and re-emits it in mid/far infrared**

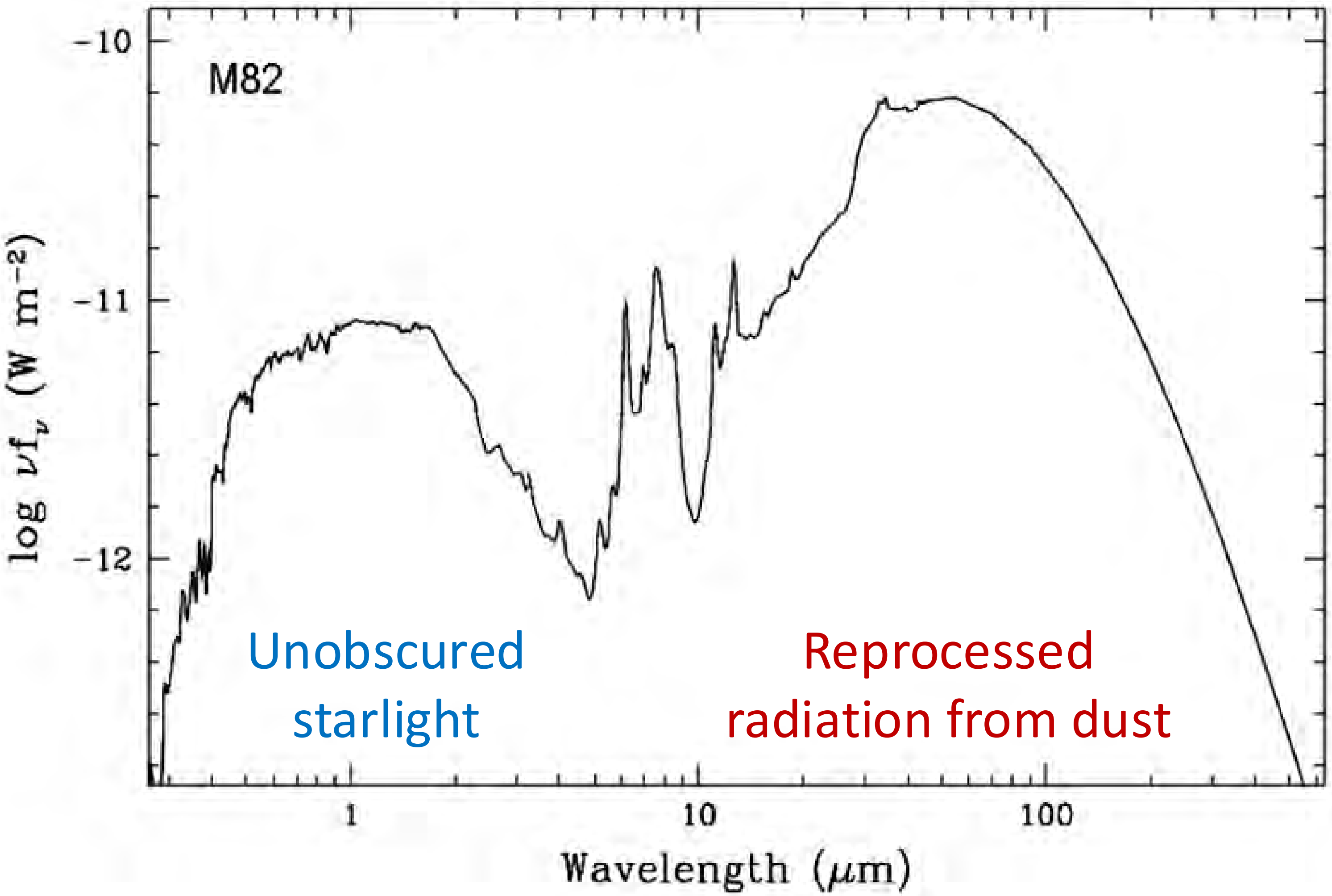
The field of galaxy evolution is thus split observationally:

- **Unobscured star formation** evolution: most of the energy emerging in the restframe UV, observed in the visible/NIR at large redshifts
- **Obscured star formation**: energy from young stars is reprocessed by dust to emerge in FIR/sub-mm
- They have different limitations and selection effects
- We now know that ***roughly a half of the star formation in the universe was obscured by dust***

M82, a Prototypical Dusty Starburst Galaxy

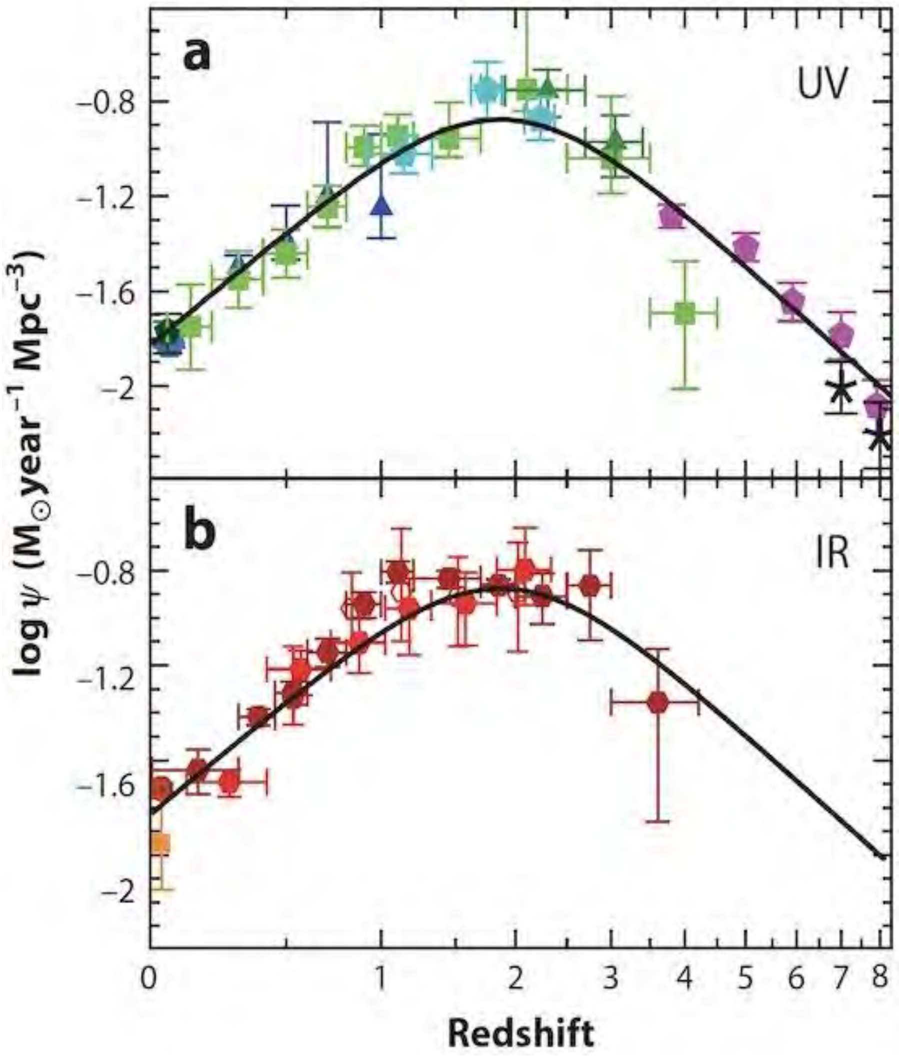


The spectrum of M82, UV to sub-mm

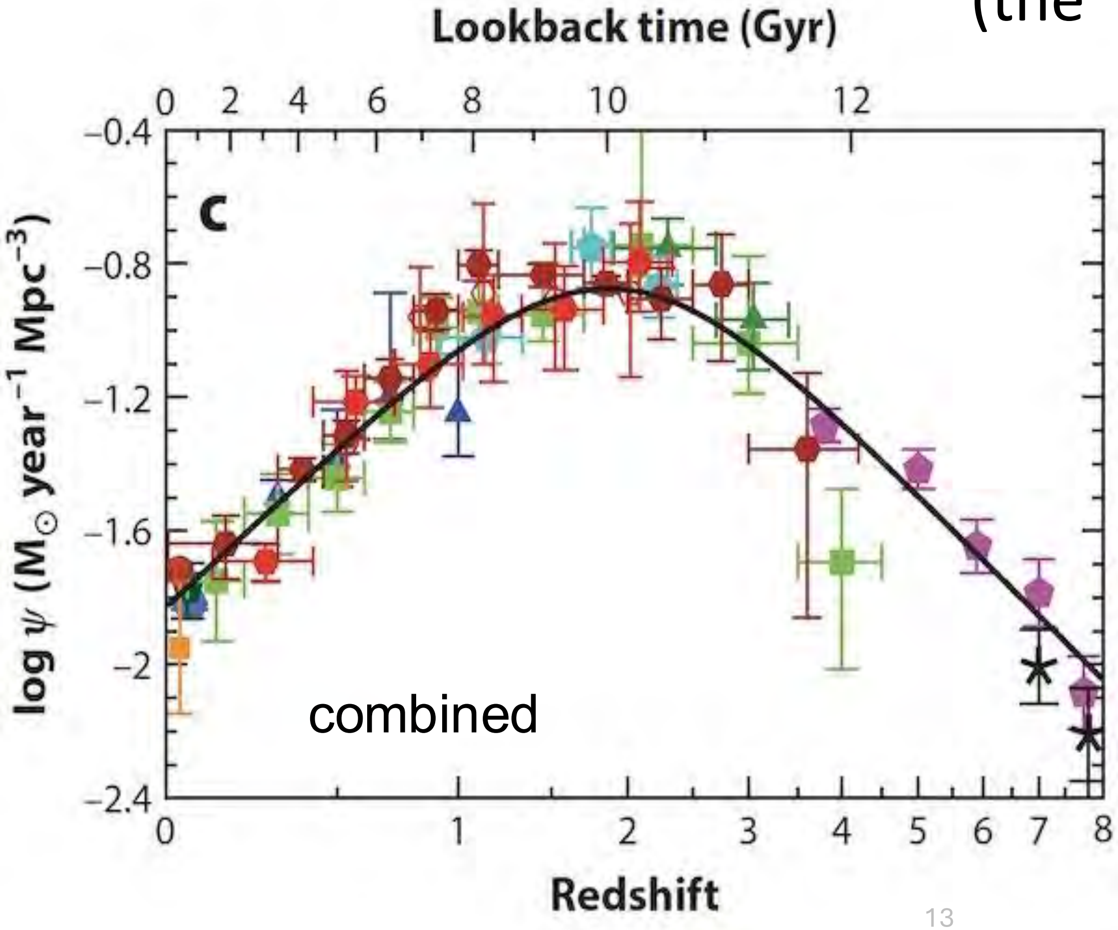


Cosmic Star Formation History

Combining data from many surveys, observations in UV/optical give us the unobscured star formation rate, and in Far-IR/sub-mm the obscured component

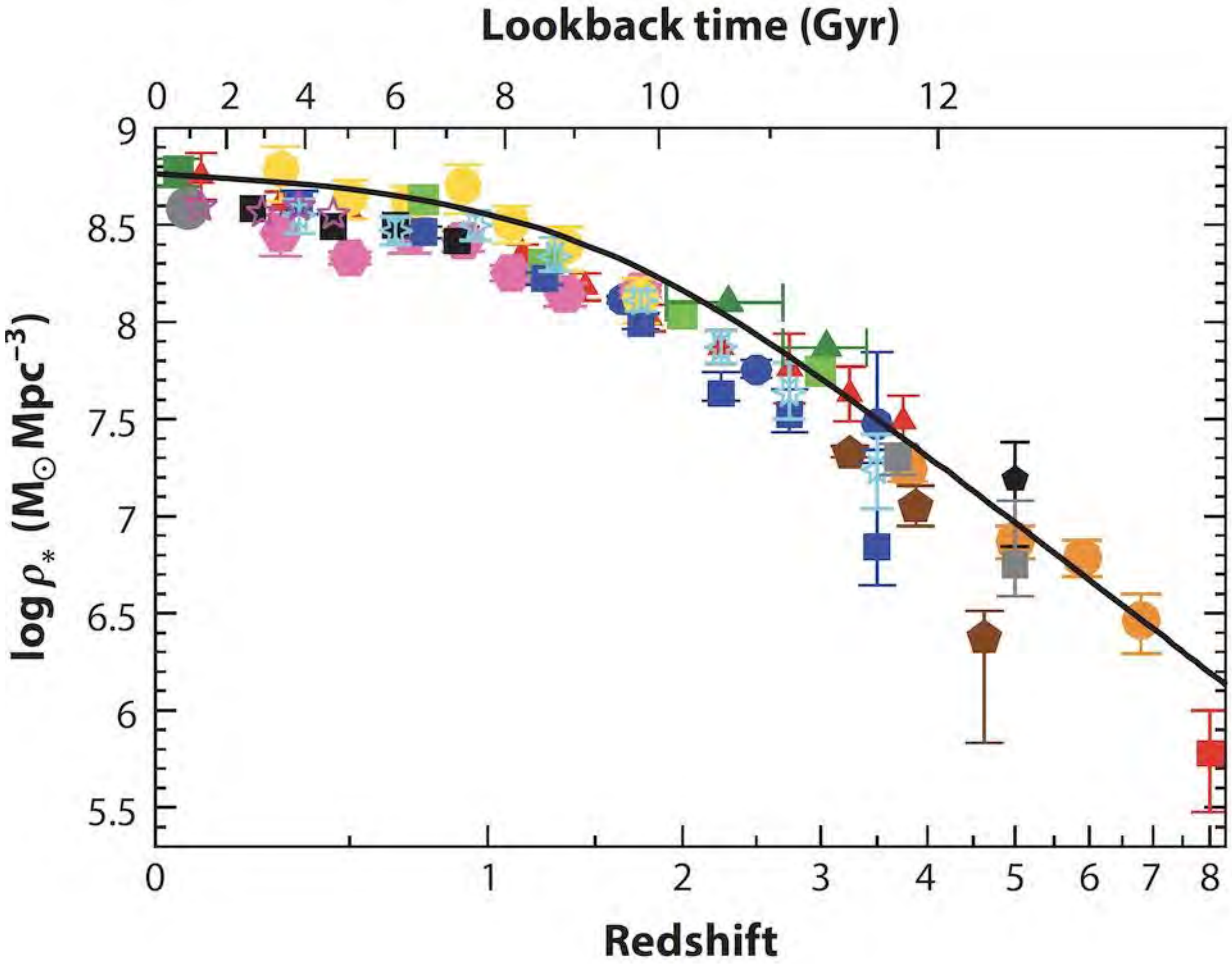


The average star formation peaks around z ~ 2 (the "cosmic noon")



Note that they track each other

Build-up of the Stellar Mass Density

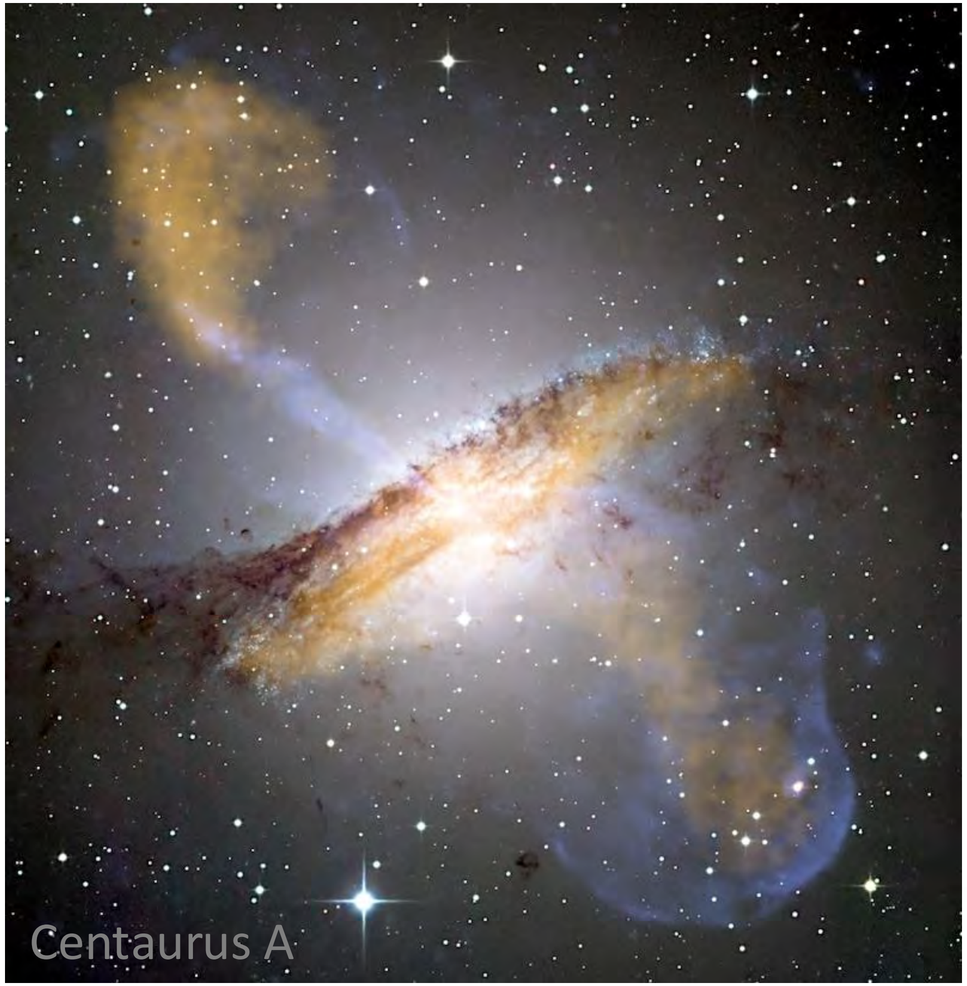


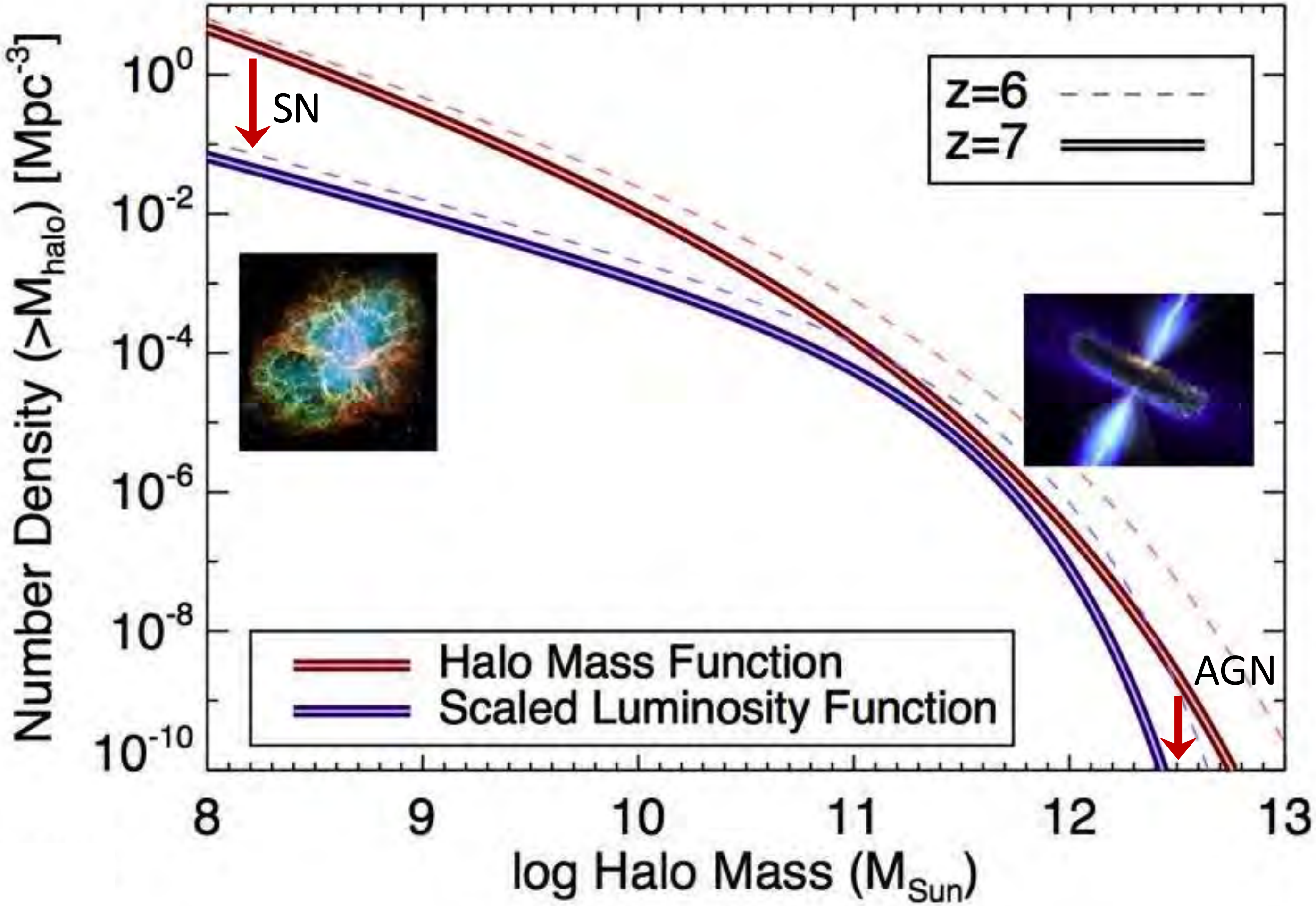
Integrating the star formation history gives us the cumulative growth of the *stellar* mass in galaxies

About 2/3 of all stars were produced by the redshift of 1, in the first ~40% of the age of the universe

Galactic Winds and AGN Feedback on Galaxy Formation

Stellar and Supernova driven galactic winds, and energy input from active galactic nuclei (AGN) can expel and ionize gas, this suppressing star formation. This feedback modifies the galaxy luminosity and mass function on both ends

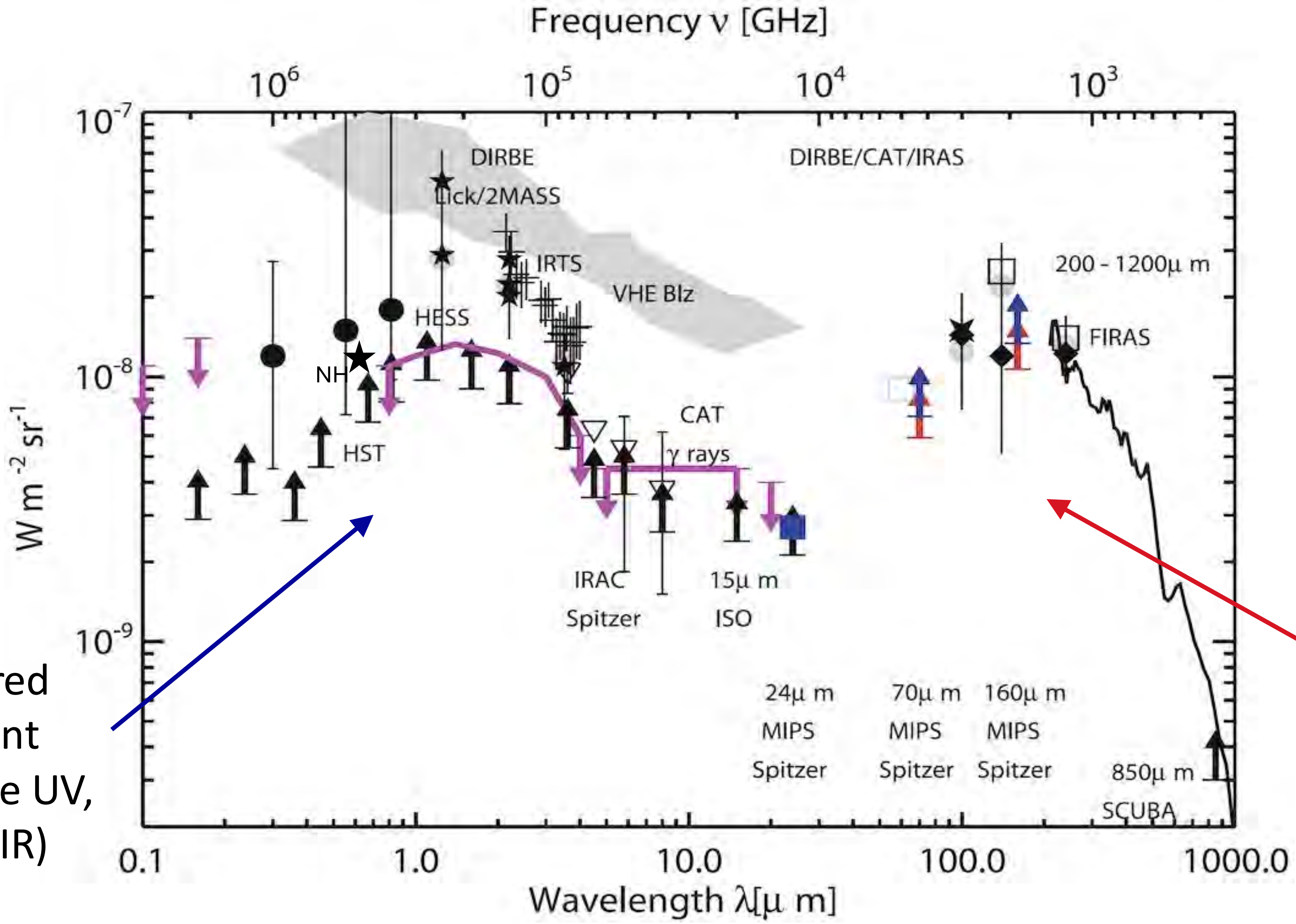




All Starlight in the Universe

- 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}** (±50% or so)
  - This is distributed roughly equally between the UV/Visible (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 ebergy density

Diffuse Optical and IR Backgrounds



"Spectrum of the Universe"

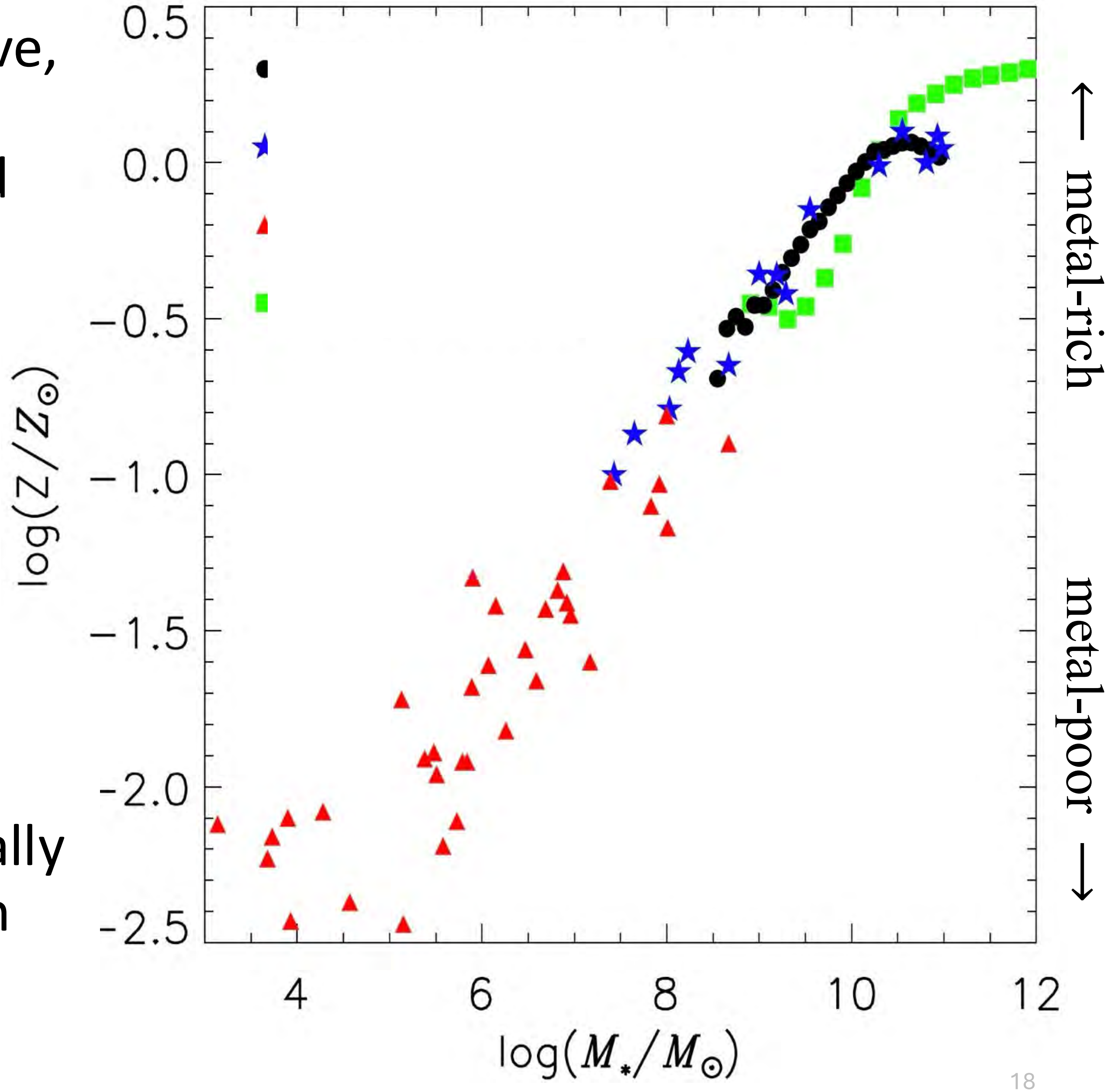
Unobscured component (restframe UV, Visible, NIR)

Obscured component (restframe FIR)

Galaxy Mass and Chemical Evolution

As stars form and evolve, they create heavier chemical elements and return them to the interstellar medium, so the following generations of stars are ever more metal-rich

More massive galaxies can retain more effectively the chemically enriched material from the supernova ejecta

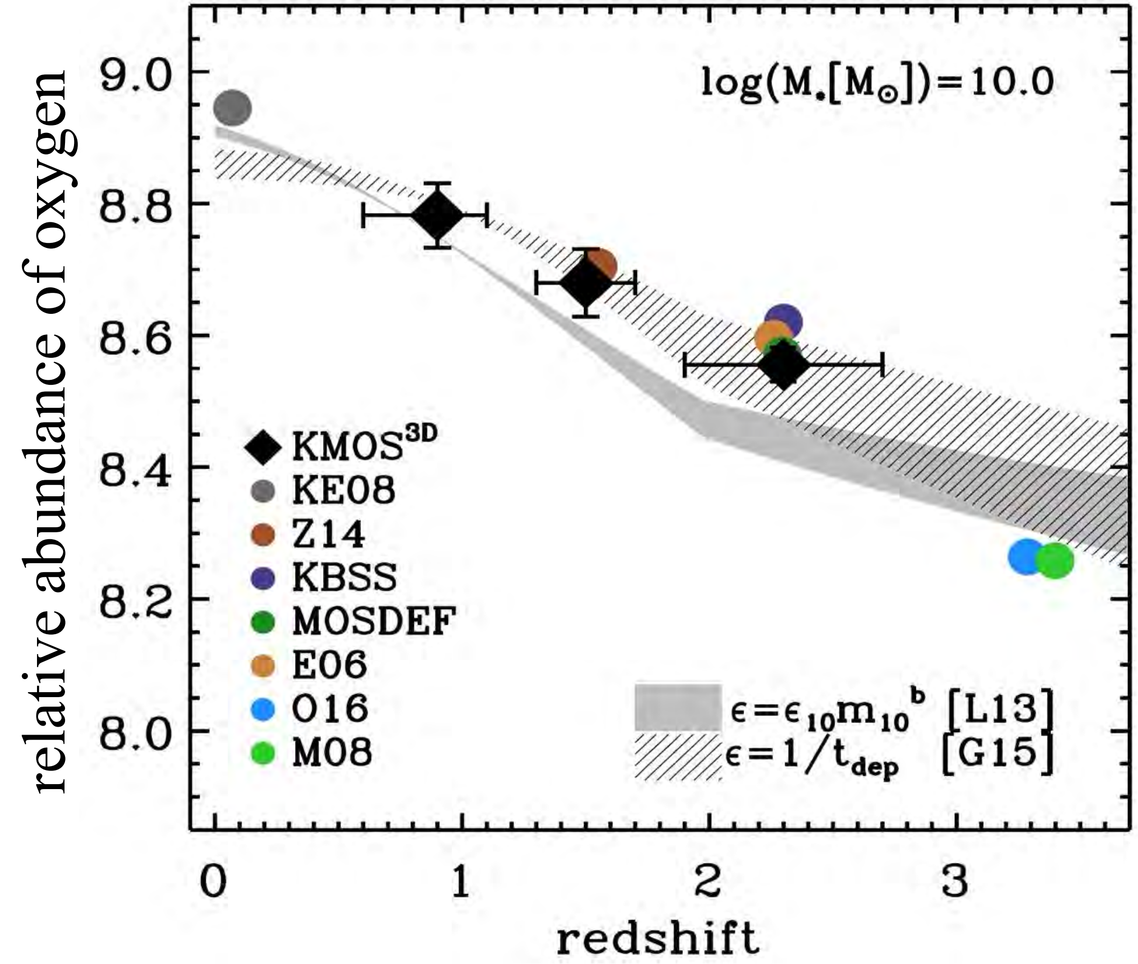


More massive galaxies in the nearby universe are thus more metal-rich

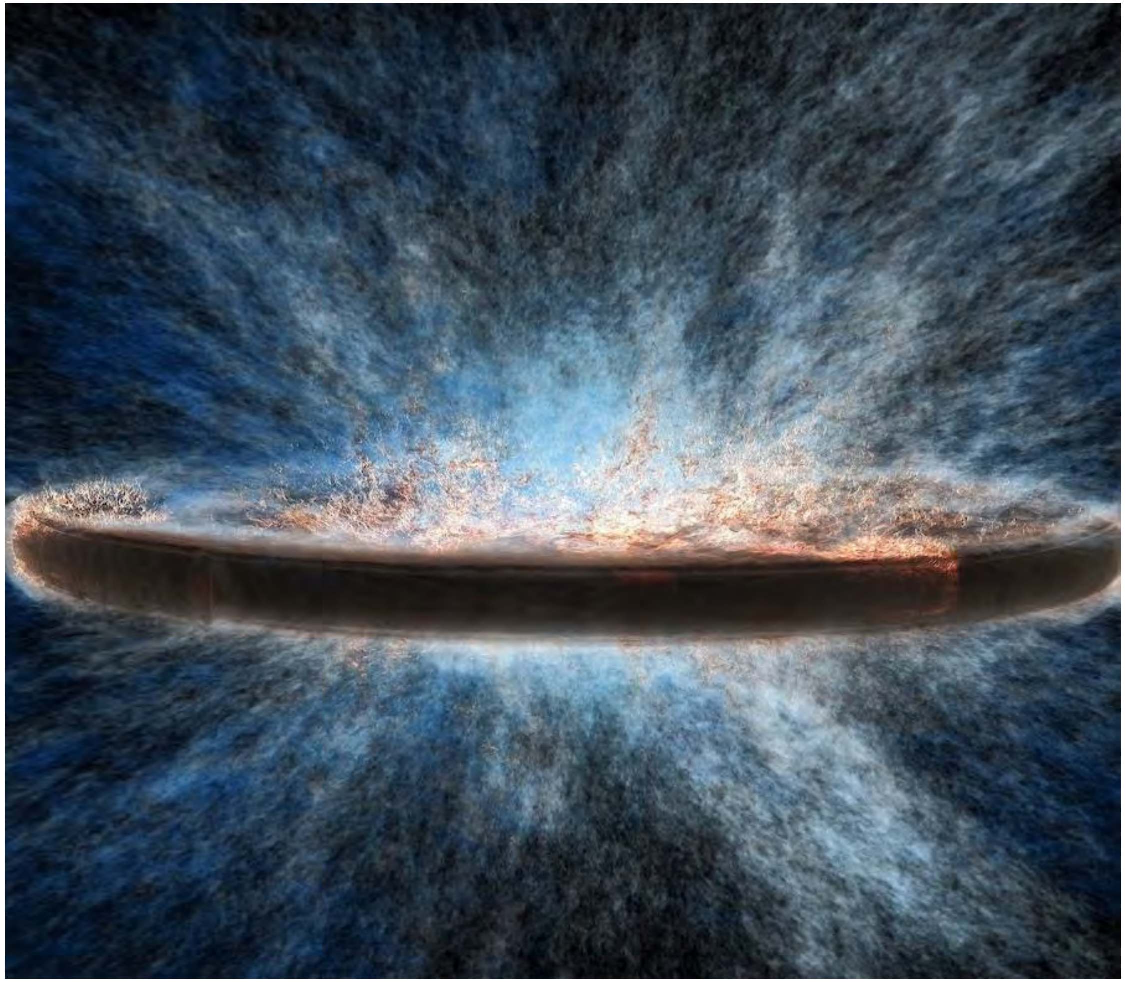
The same trend exists at all redshifts

Chemical Evolution of Galaxies

The overall metallicity of galaxies increases in time



Some of the enriched gas is expelled by the galactic winds, where it mixes with the intergalactic medium

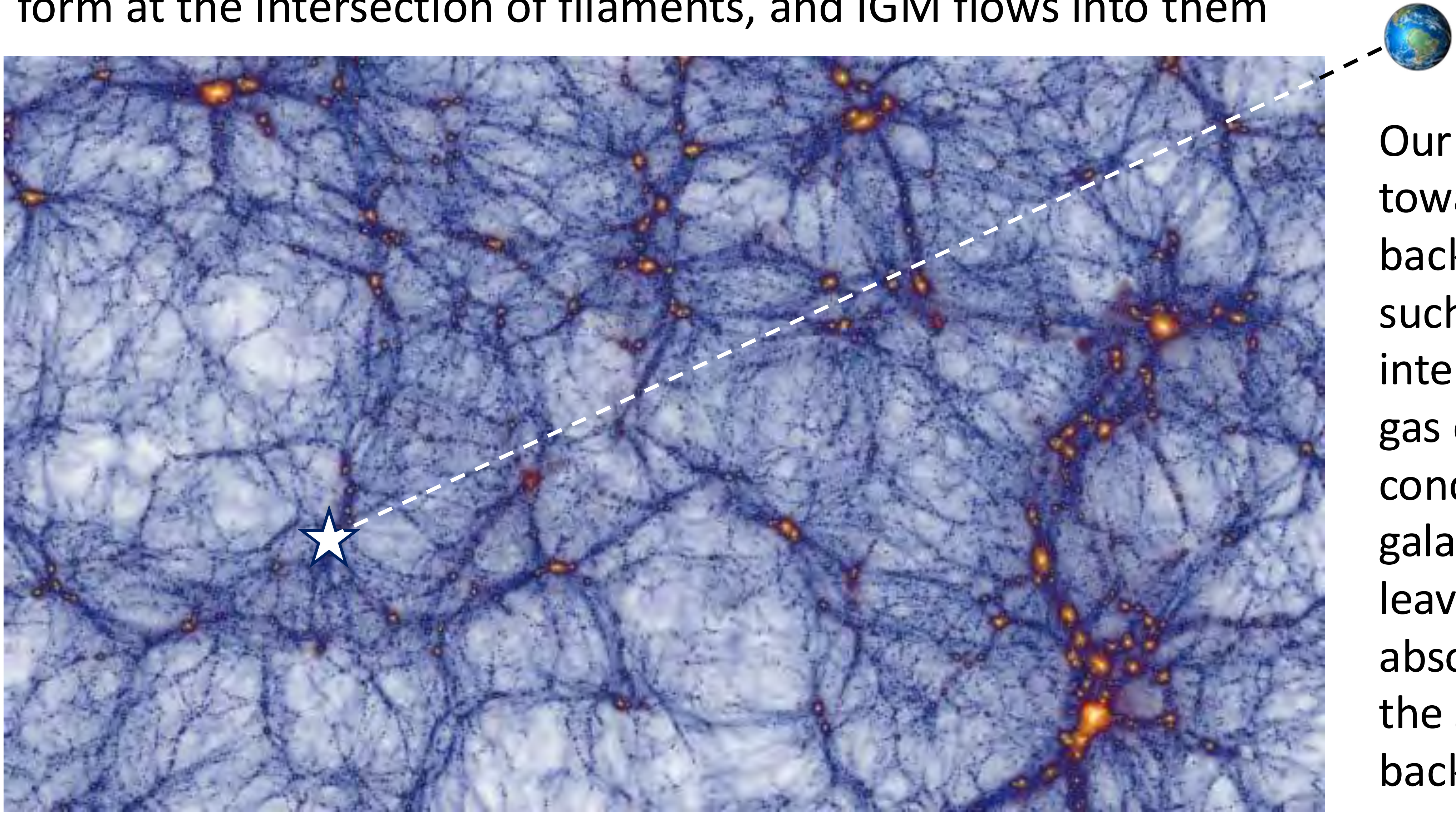


Intergalactic Medium (IGM)

- Essentially, baryons (normal matter) between galaxies. Most baryons in the universe are in the IGM
- 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 nuclei provide the **ionizing flux** for the IGM, which has been fully ionized for the last ~ 12 Gyr

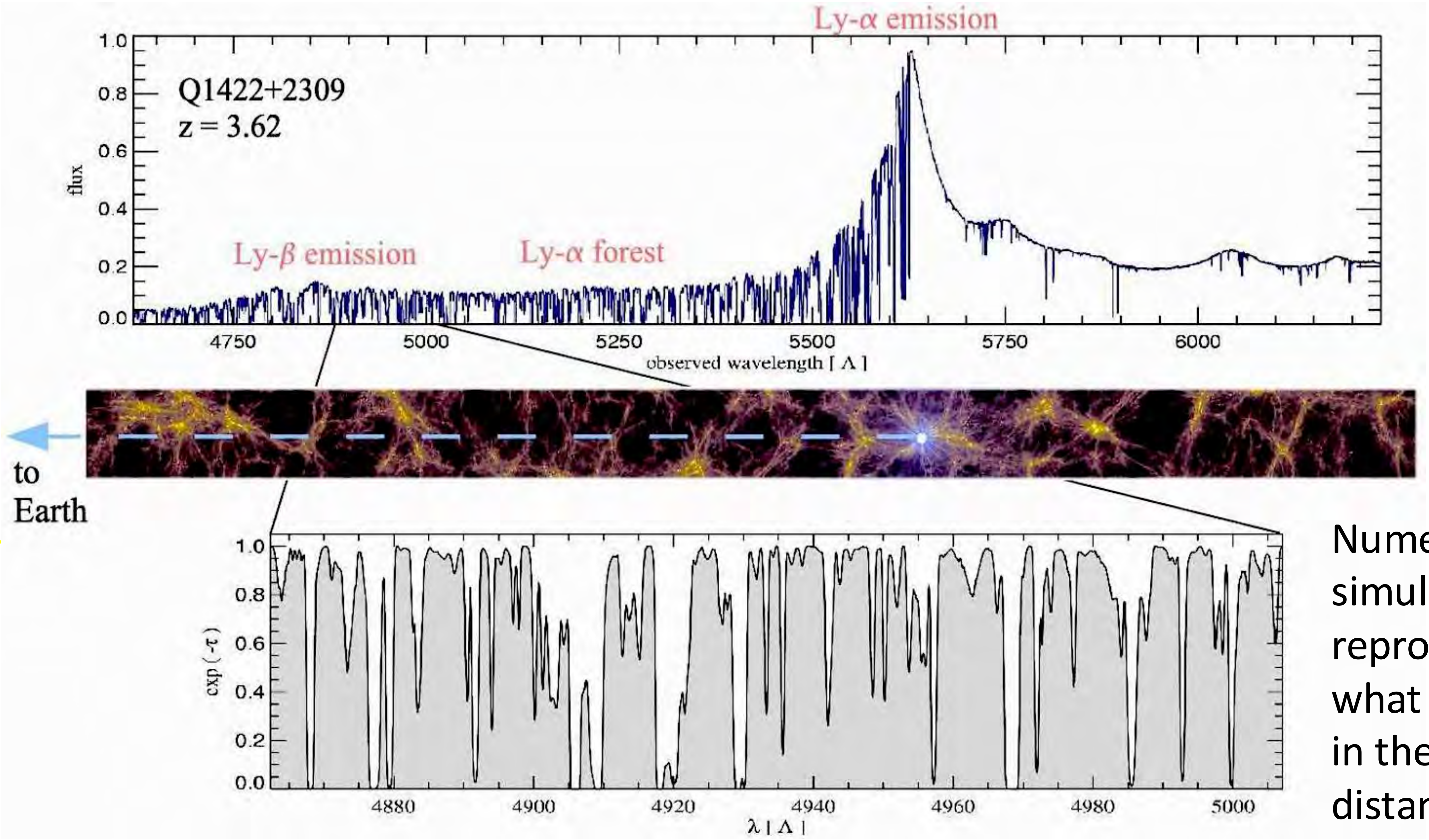
Cosmic Web Numerical Simulations

Hydrogen follows the evolving dark matter structure of filaments and voids. Galaxies form at the intersection of filaments, and IGM flows into them

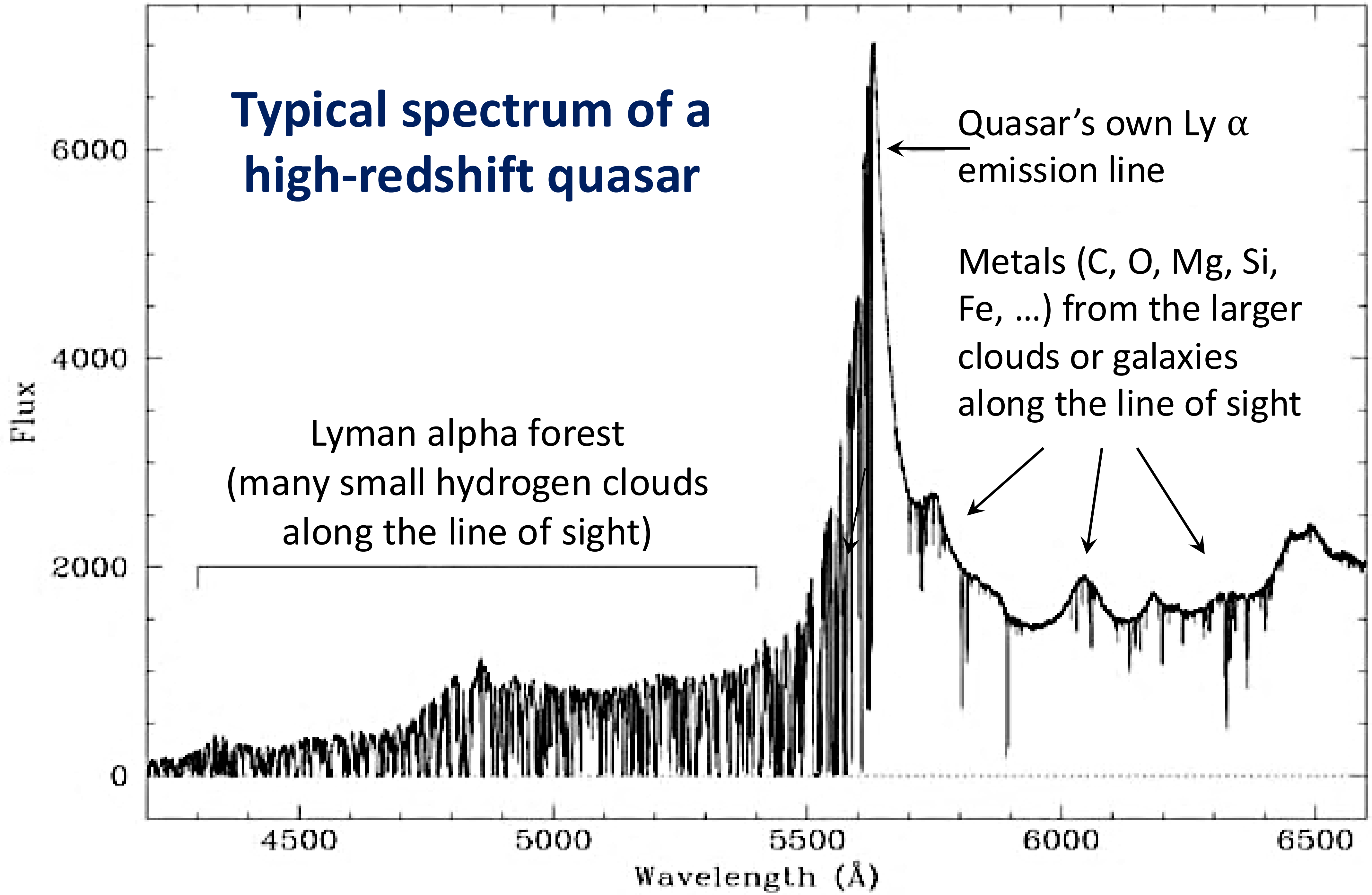


Our lines of sight towards luminous background sources such as quasars intersect a range of gas densities, condensed clouds, galaxies, etc. They leave an imprint of absorption lines in the spectrum of the background source

Cosmic Web and the Quasar Absorption Spectra



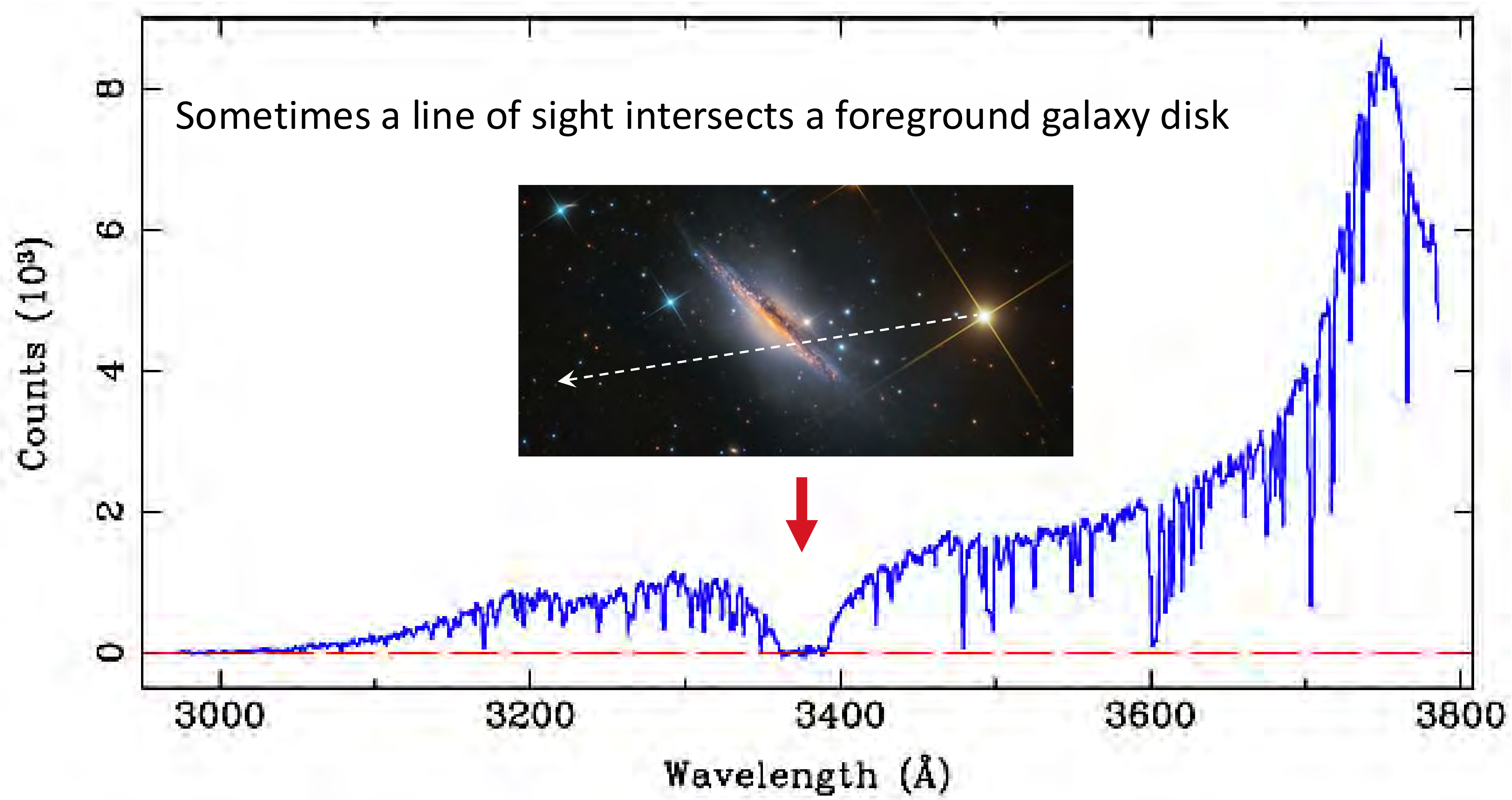
Numerical simulations reproduce well what is observed in the spectra of distant quasars



Typical spectrum of a high-redshift quasar
Quasar's own Ly α emission line
Metals (C, O, Mg, Si, Fe, …) from the larger clouds or galaxies along the line of sight
Lyman alpha forest (many small hydrogen clouds along the line of sight)
Flux
0
2000
4000
6000
4500
5000
5500
6000
6500
Wavelength (Å)

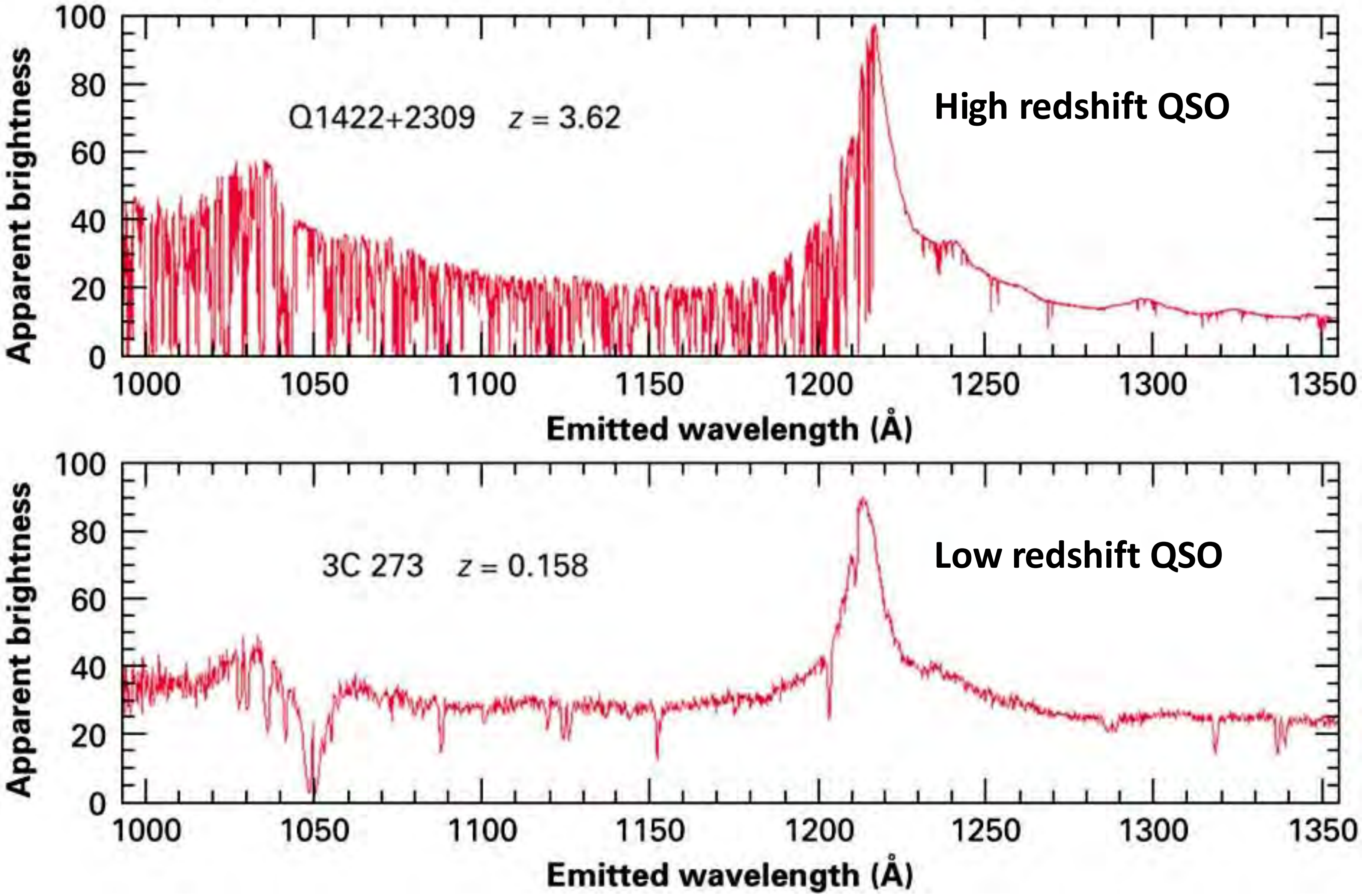
Damped Lyman α Systems

Saturated absorbers from distant galaxy disks



Evolution of the Hydrogen Absorbers

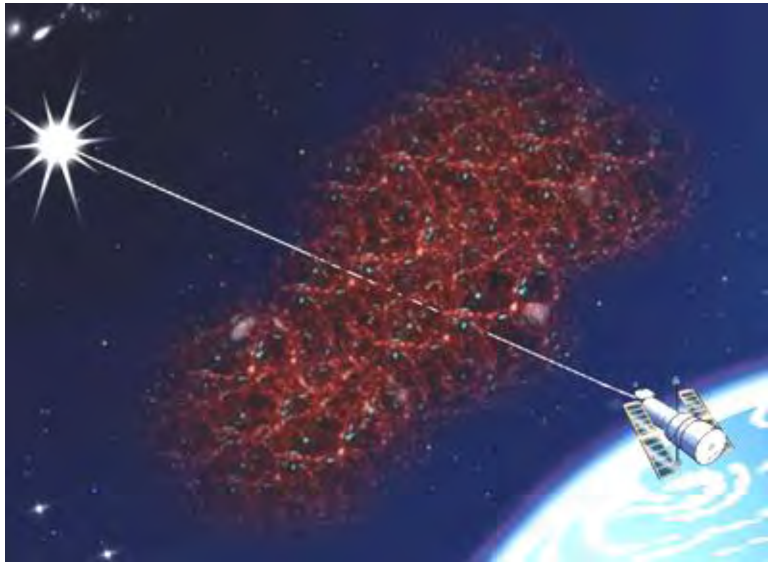
They were much more numerous far away (= early on)

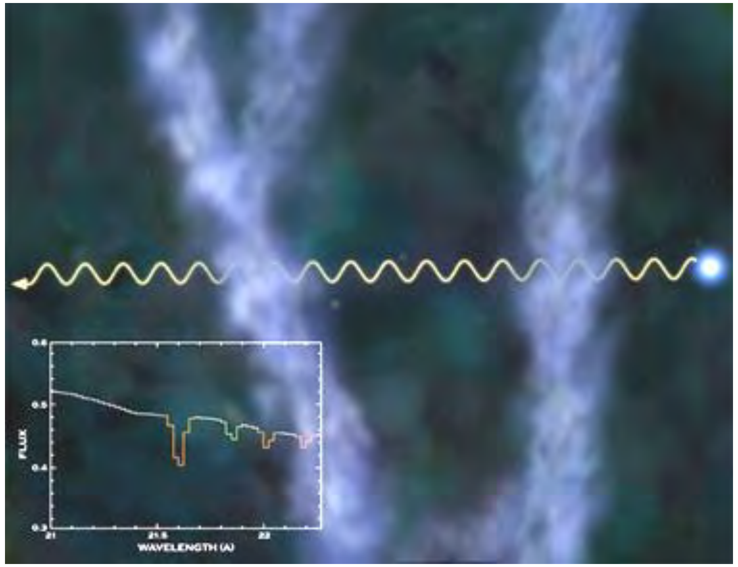


The disappearance of Ly α clouds is mostly due to them falling into galaxies

“Missing” Baryons in the IGM

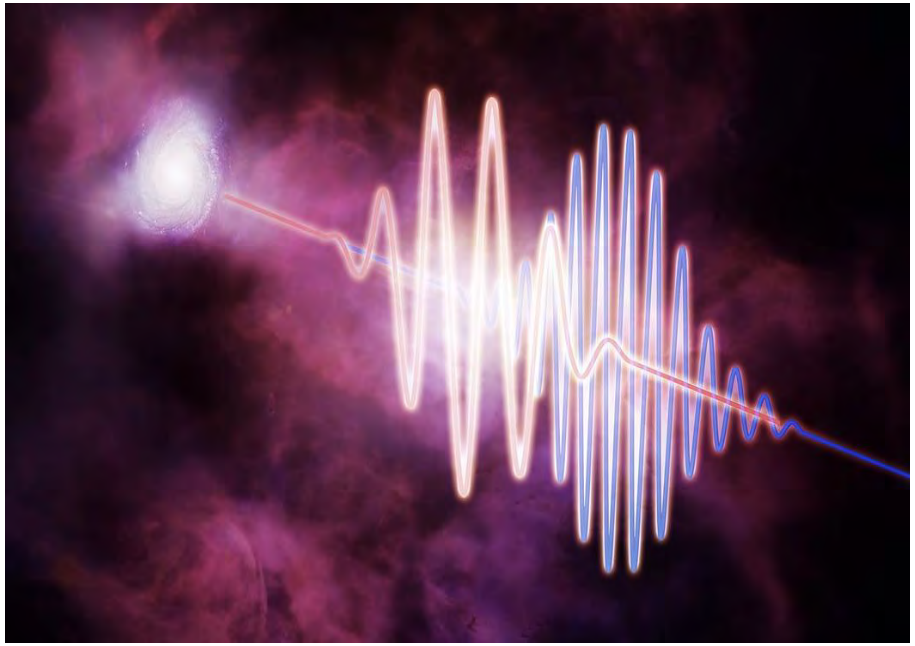
About 90% of all baryons (normal matter) in the universe is in the form of a ~ 10^5 - 10^6 K gas, which emits mostly in FUV/soft-Xray, which is absorbed by the neutral hydrogen in our Galaxy, and is thus essentially impossible to detect in emission





However, it was ***detected in absorption*** in the UV spectra of quasars ⟵

Another method is from the **Fast Radio Bursts** (FRBs): IGM plasma delays the radios signals at different frequencies, from which we can deduce the amount of the IGM between us and the source ⟶



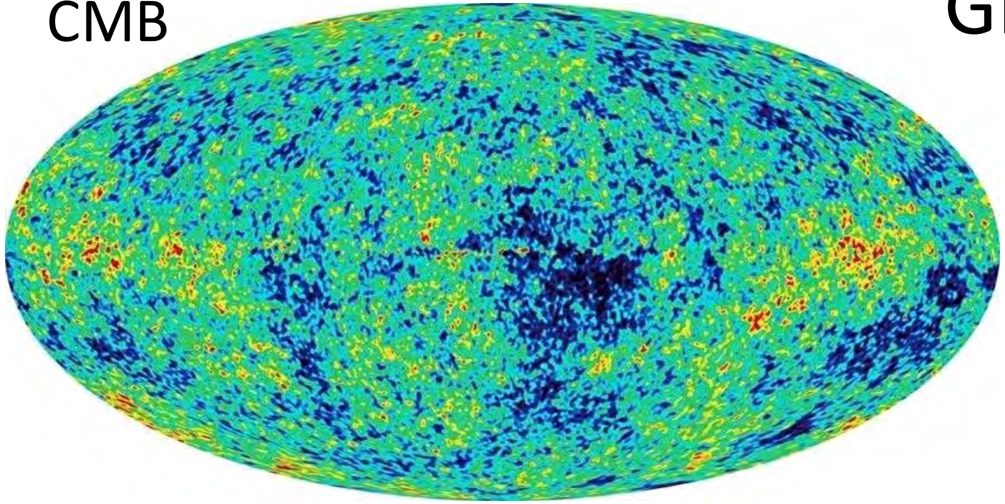
IGM Summary

- Intergalactic medium (IGM) is the gas associated with the large scale structure, rather than galaxies themselves; e.g., along the still collapsing filaments, thus the "cosmic web"
  - However, large column density hydrogen systems, and strong metallic absorbers are always associated with galaxies
- It is condensed into clouds, the smallest of which form the "Ly α forest"
- It is ionized by the UV radiation from star forming galaxies and quasars
- It is metal-enriched by the galactic winds, which expel the gas already processed through stars; thus, it tracks the chemical evolution of galaxies
- Studied through absorption spectra against background continuum sources, e.g., quasars or GRB afterglows

Cosmic Structure Formation and Evolution

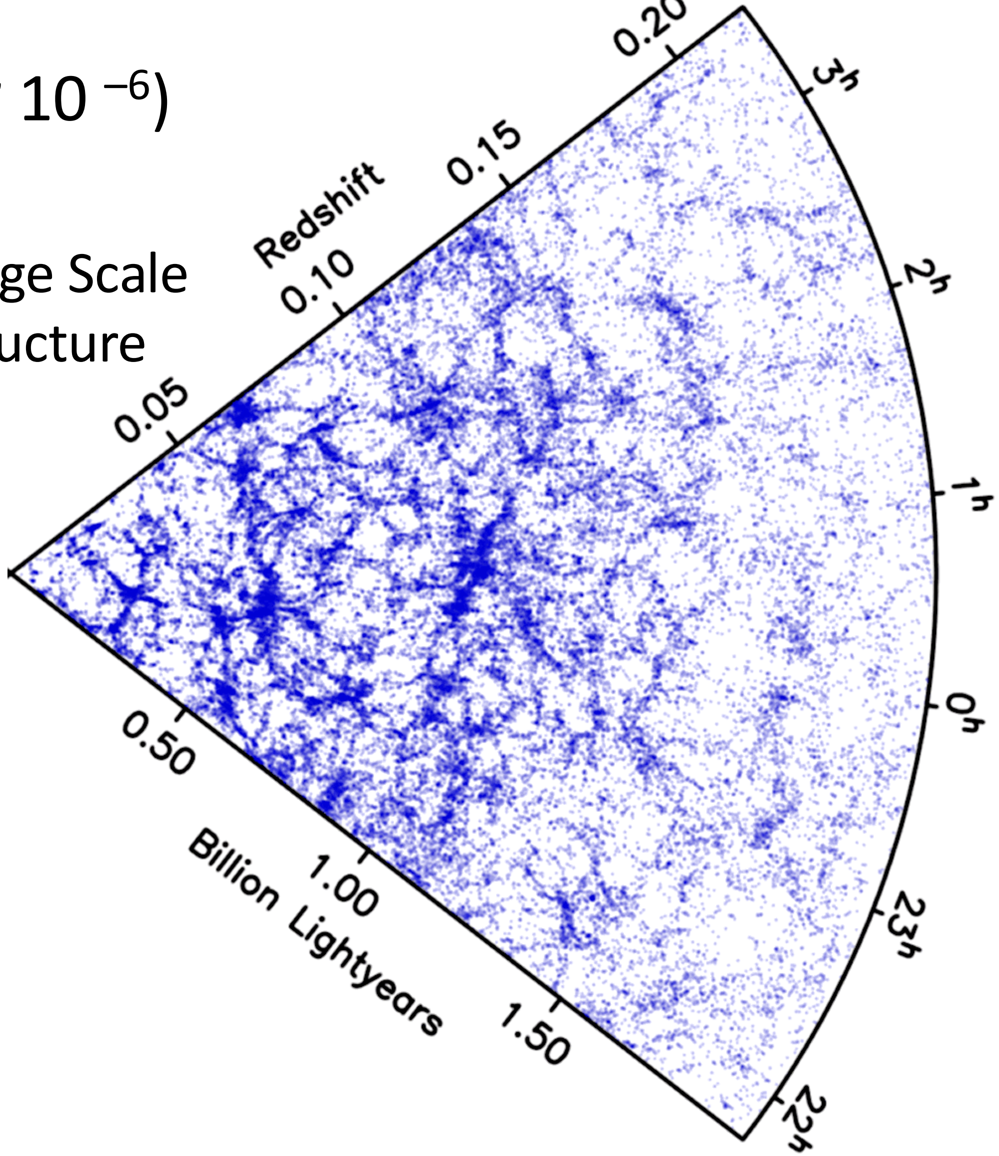
Growing density contrast ($\Delta\rho/\rho$)

CMB



From this ($\Delta\rho/\rho \sim 10^{-6}$)

Large Scale Structure



to this ($\Delta\rho/\rho \sim 10^{+2}$)

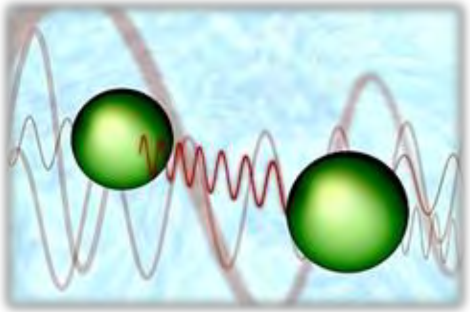
to this ($\Delta\rho/\rho \sim 10^{+6}$)

Galaxy Formation

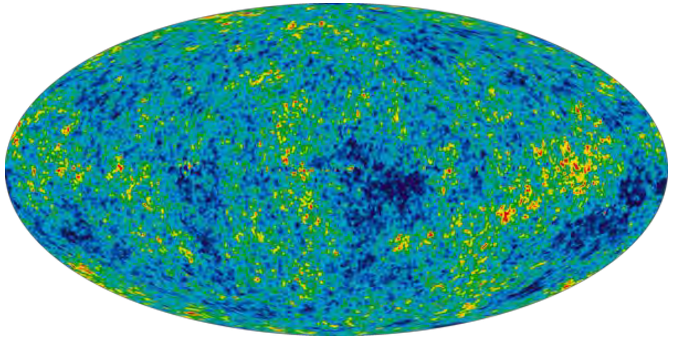
- The **earliest stages of galaxy evolution** - but there is no clear-cut boundary. It also has two principal aspects: **assembly of the mass**, and **conversion of gas into stars**
  - Generally, we think of massive galaxy formation at high redshifts ($z \sim 5 - 15$, say); dwarfs may be still forming now
- Must be related to **large-scale (hierarchical) structure formation**, plus the dissipative processes due to star formation
- Probably also closely related to the **formation of the massive central black holes** as well; they form and grow through mergers and gas accretion
- ***JWST observations have found populations of what must be young galaxies*** (ages < 1 Gyr), ostensibly progenitors of large galaxies today, at $z \sim 7 - 15$ or so
- The frontier is now at $z \sim 6 - 15$, the so-called **Reionization Era,** when the first stars and galaxies reionize the universe

How Galaxies Form

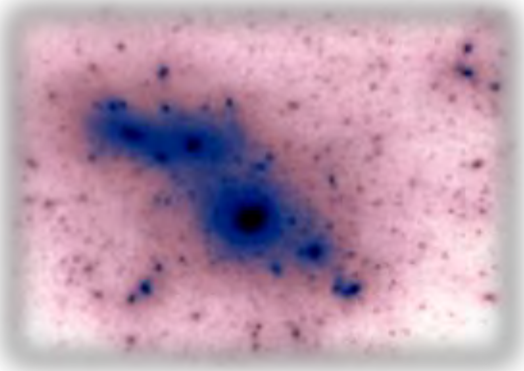
From density fluctuations in the early universe that collapse under their own gravity and merge into ever larger structures



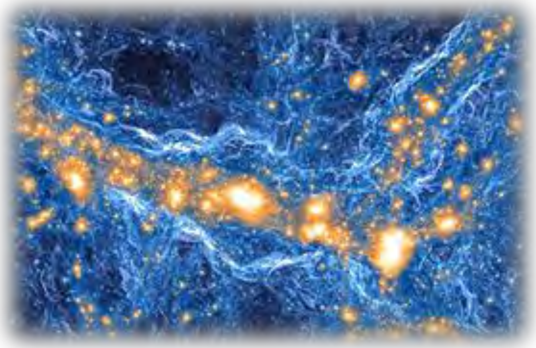
Their seeds are ***quantum fluctuations*** in the very early universe (age << 1 sec) , which get inflated by many orders of magnitude



We observe them as the fluctuations in the ***Cosmic Microwave Background,*** when the universe transitions from ionized plasma to neutral gas (age = 380,000 years)



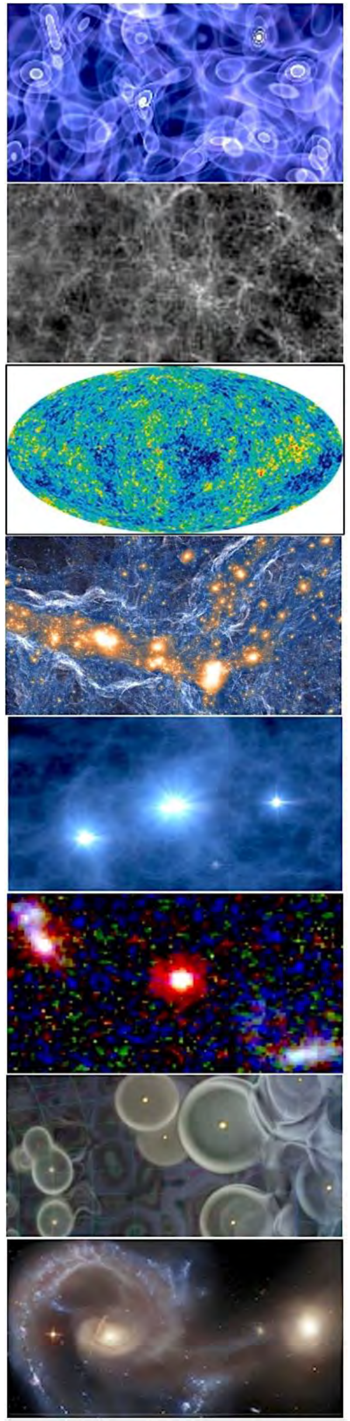
Dark matter halos form first, and baryons (gas) pour into them and ***make stars*** (age up to 100 million years)



Newly made galaxies ***reionize the universe*** and ***keep merging*** into larger galaxies (age ½ to 1 billion years and later)

A Timeline of Galaxy Formation

z	age	
?	?	Quantum fluctuations in the early universe become the seeds of density fluctuations
10^4	10^4	Radiation → matter dominance; DM fluctuations begin to grow
	10^5	
10^3		Recombination; universe becomes neutral and opaque to UV light; CMB released
	10^6	Baryons start falling into DM halos, cooling makes them more concentrated than DM
	10^7	
10^2	10^8	The first (Pop. III) stars; reionization starts
		The earliest observed galaxies (JWST)
10^1		Universe reionized by young stars and AGN
6	10^9	Reionization ends; galaxy evolution begins

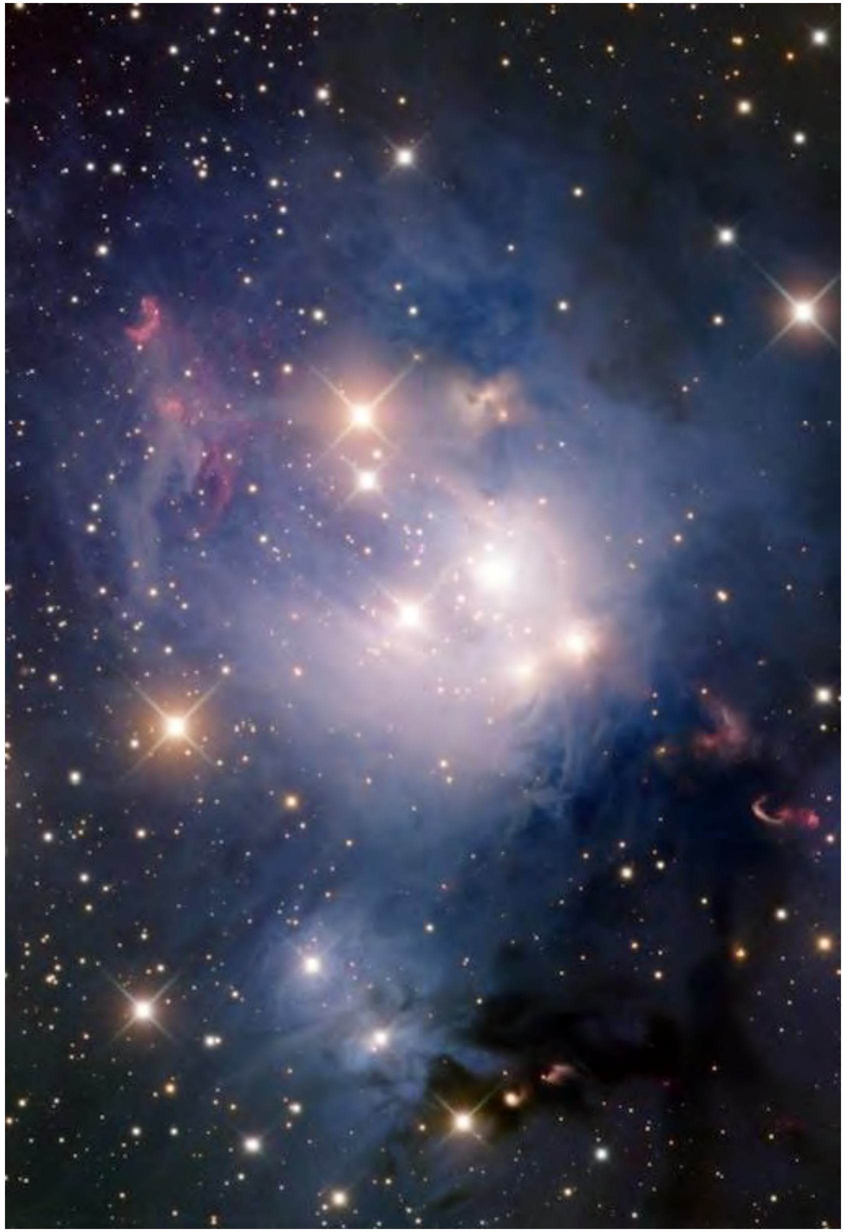


Dark Matter vs. Gas and Radiation from Young Stars

The “Illustris” Simulation:
gas velocities overlaid on
dark matter density

Energy Release From Forming Galaxies

- **Release of the binding energy** from a collapsing protogalaxy, ~ $10^{58} – 10^{59}$ erg (and comparable for the collapsing protostars)
- **Thermonuclear burning in stars** in the initial starbursts and Supernovae, ~ $10^{59} – 10^{60}$ erg
- Energy input from **an active nucleus**, if one is present, up to ~ $10^{58} – 10^{60}$ erg
- A few percent of the total energy emerges in the form of **emission lines**, as young stars (and AGN if present) ionize the gas
- But what is observed is not ***energy***, but ***luminosity***, energy/timescale. Assuming $\Delta E \sim 4 \times 10^{59}$ erg and $\Delta t \sim 3 \times 10^{8}$ yrs ~ 10^{16} s, then $\boldsymbol{\langle L \rangle \sim 10^{10} L_\odot}$, but that can be off by a couple orders of magnitude



The First Stars (Population III)

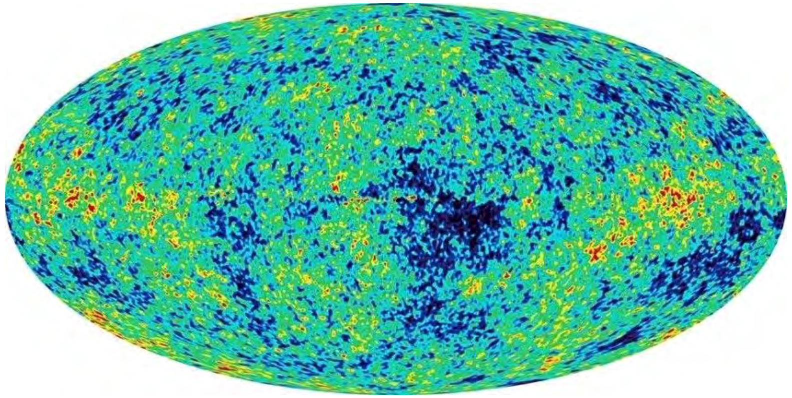
They **form from H and He only**, as the gas falls into the potential wells of dark matter halos. Protostars cool inefficiently just through the H_2 molecular line emission, which allows **these stars to reach high masses, 100s to 1000s of $M_\odot$**

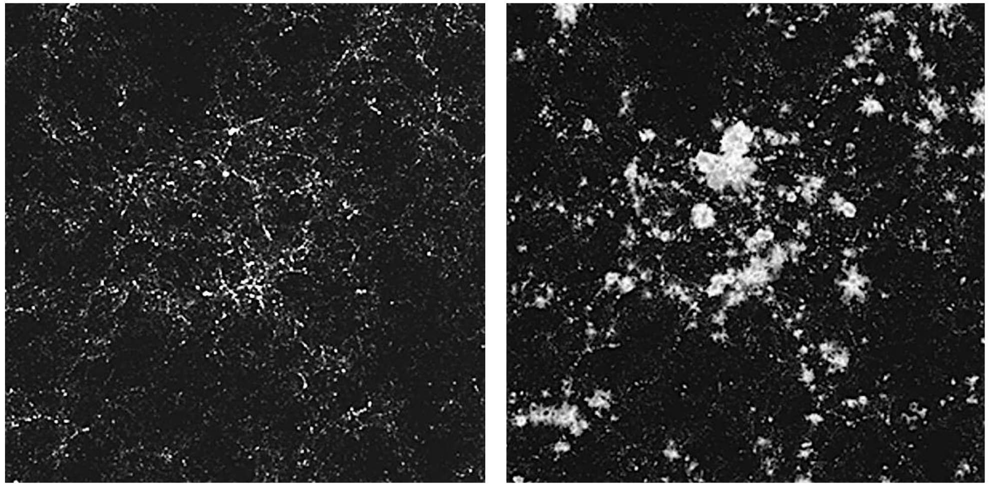
They are thus very hot and very luminous, and can ionize all hydrogen in their vicinity, starting the reionization era

… And then they would explode, ejecting the newly formed elements into the IGM, from which the Population II stars can form

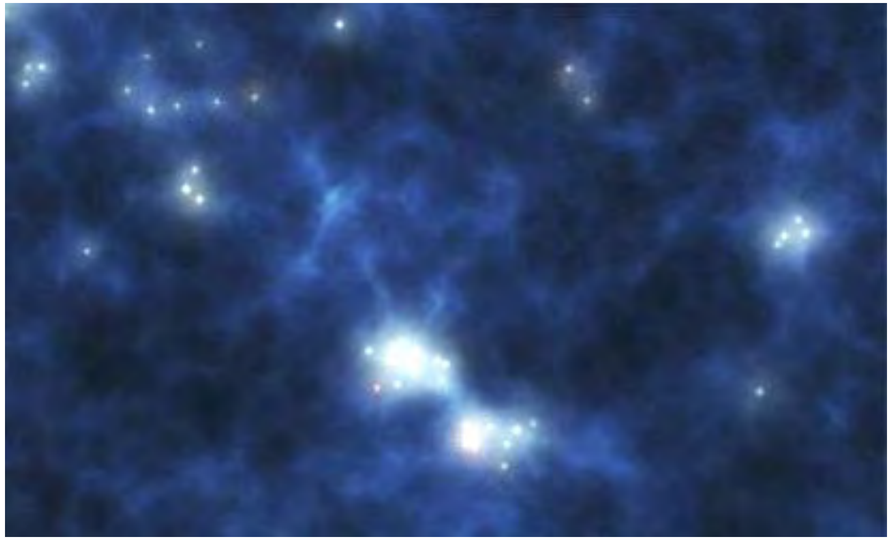
Reionization: the Cosmic Renaissance

After the recombination, when the universe is 380,000 years old, the CMB is released, the *universe is filled with neutral gas*, and it is opaque to UV radiation





Dark halos continue to grow, but there are *no sources of light* – the universe enters the **dark ages** that last ~ 100 Myr

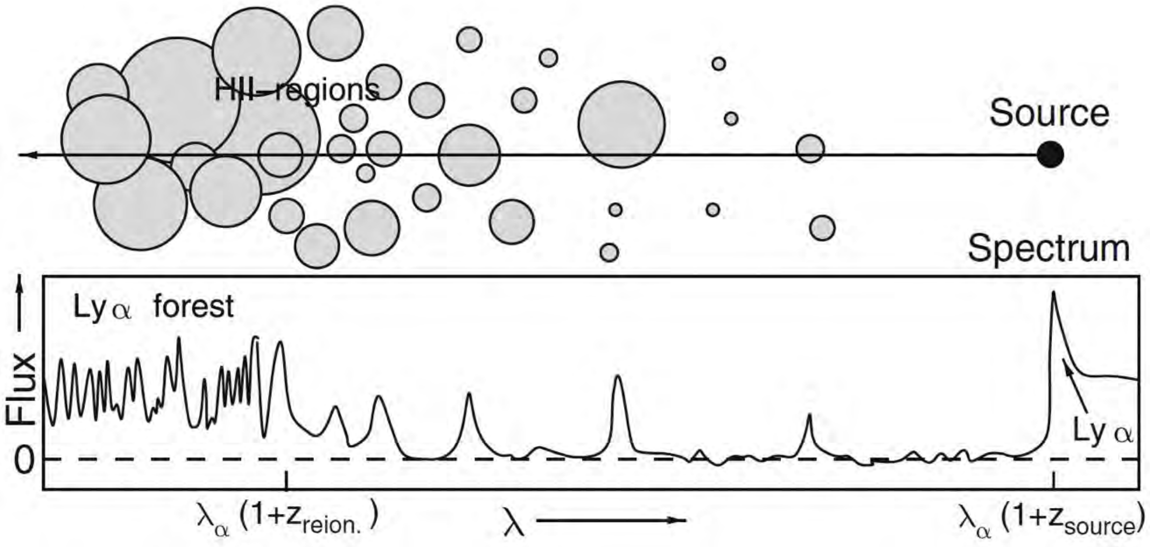


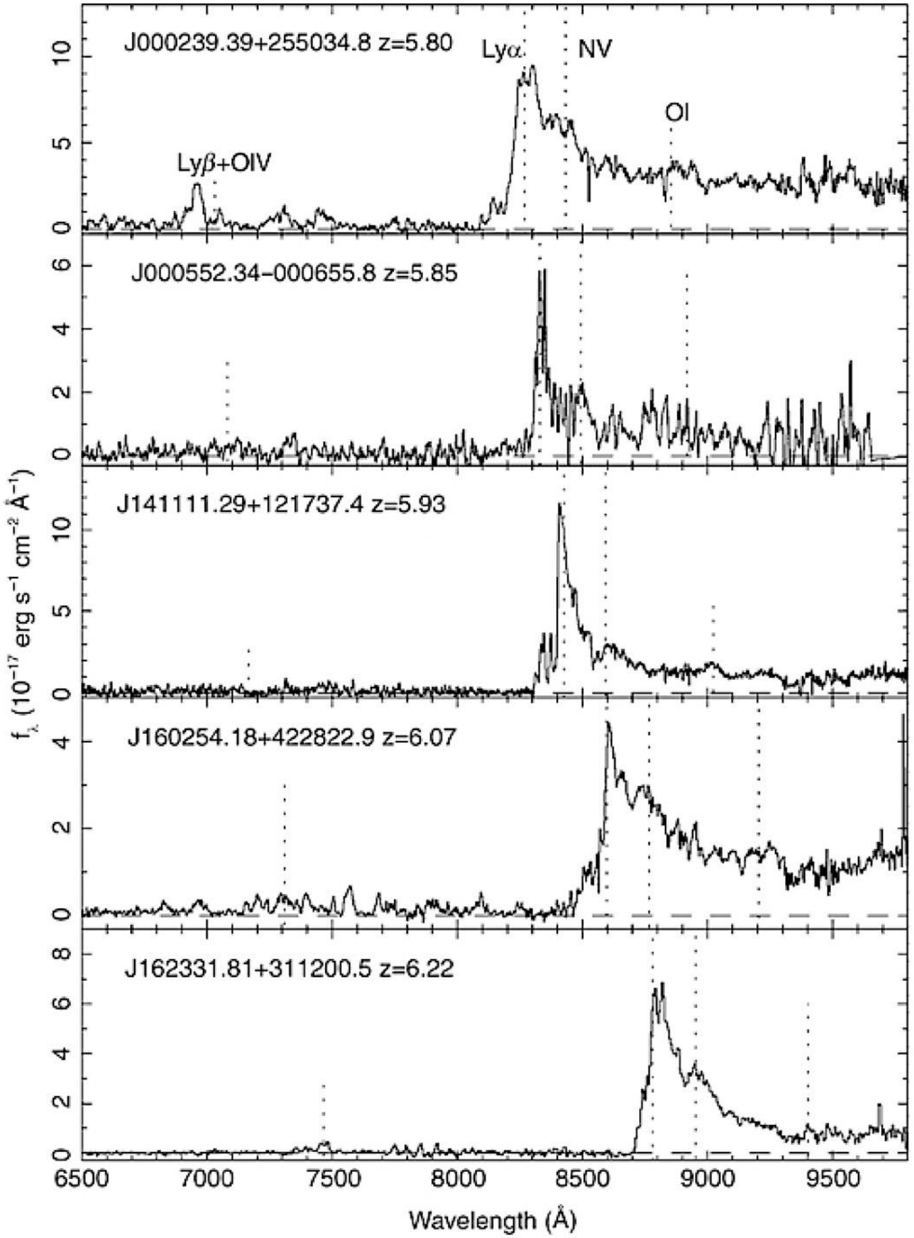
Once the young, massive stars form, their ***UV radiation reionizes the universe***. Each young galaxy creates *a bubble of ionized gas* around it. These bubbles grow, and *when they overlap, the **reionization** is complete*

The Approach to the Reionization Era

Near the end of the reionization era, the remaining pockets of neutral hydrogen will absorb the UV light at any wavelengths bluer than the Lyman α line, leaving a deep, extended absorption (the Gunn-Peterson effect)

Towards the observer

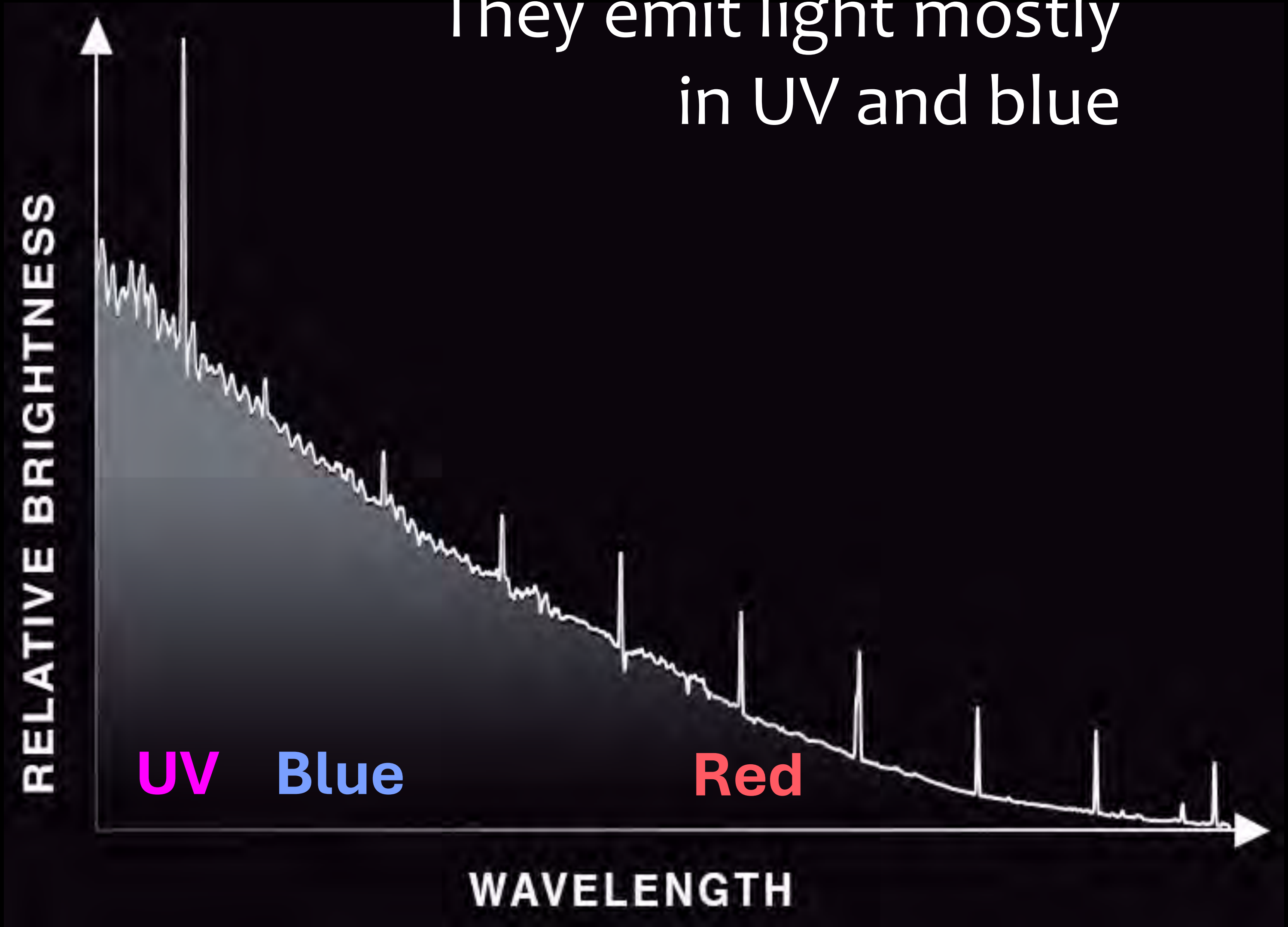




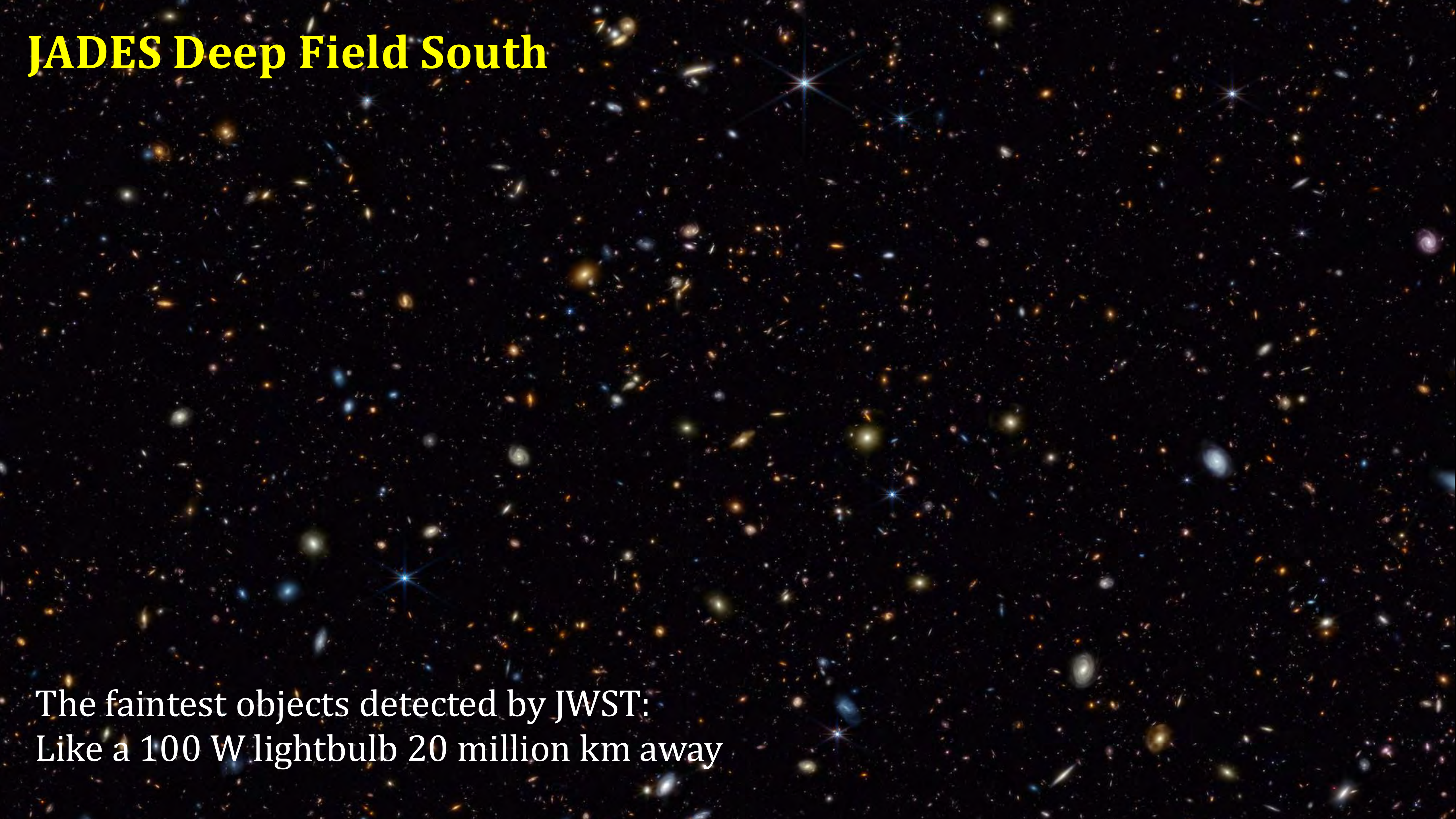
This is as observed along all quasar or galaxy lines of sight at $z \gtrsim 6$ (the end of the reionization era), and galaxies that ionize the IGM are detected by the JWST

Spectra of Young Galaxies

Dominated by hot, luminous stars



JADES Deep Field South



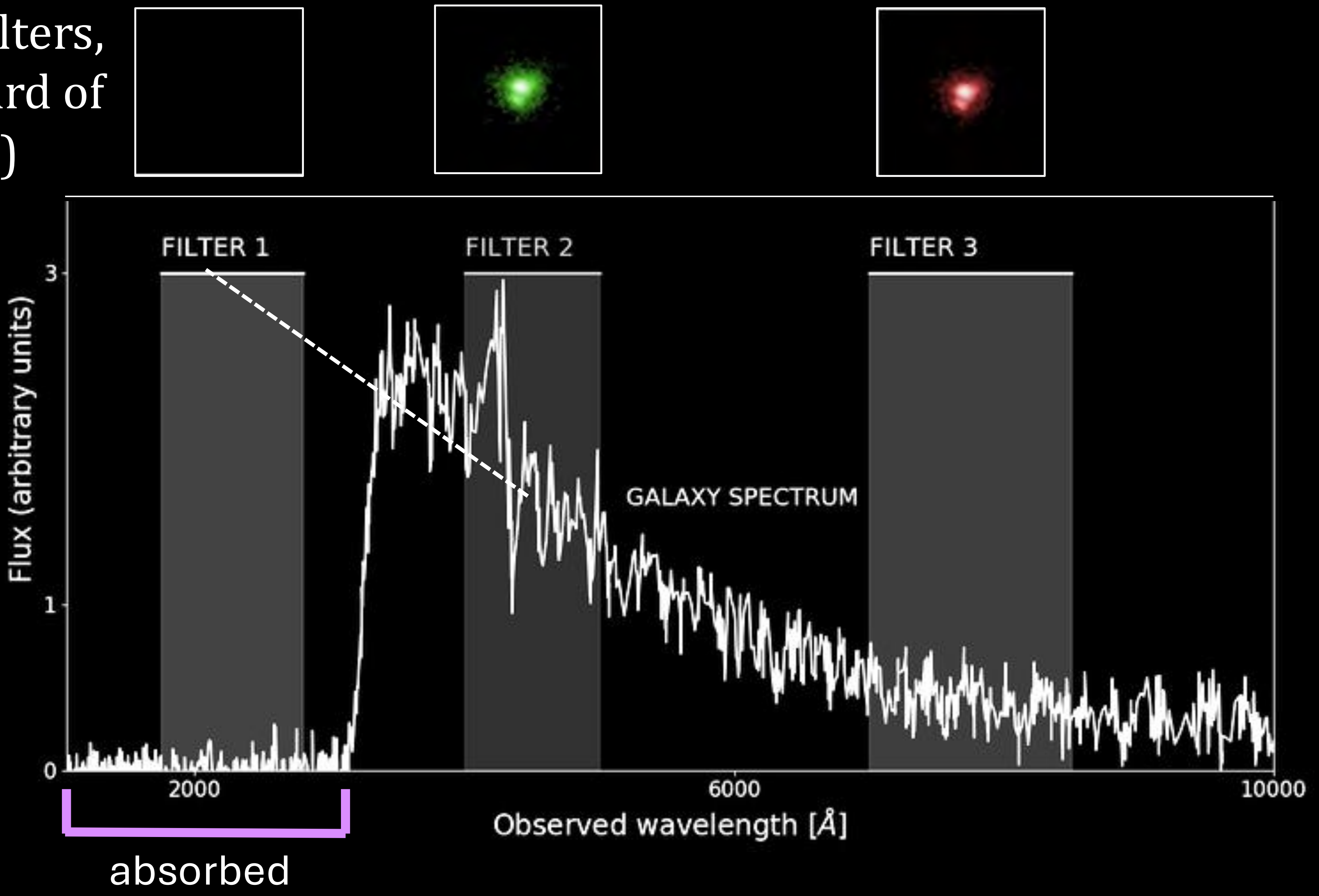
The faintest objects detected by JWST:
Like a 100 W lightbulb 20 million km away

How to Find the Most Distant Galaxies

Take images in three filters, one of which is blueward of 121.6 nm (the Lyα line)

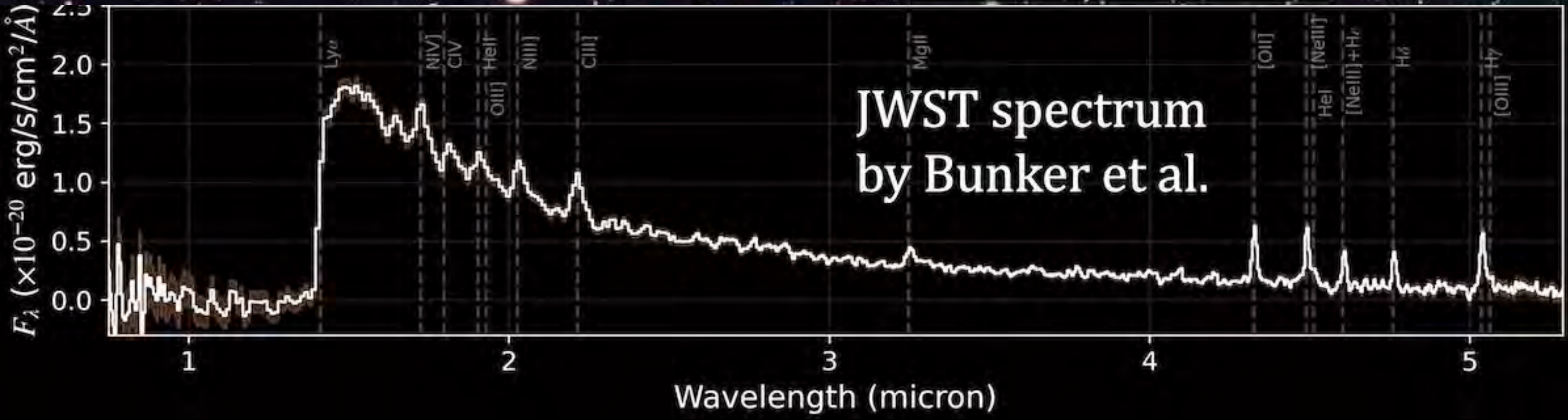
Intergalactic hydrogen between us and that galaxy absorbs all light shortward of that wavelength

That creates a break in the spectrum – the galaxy "disappears"



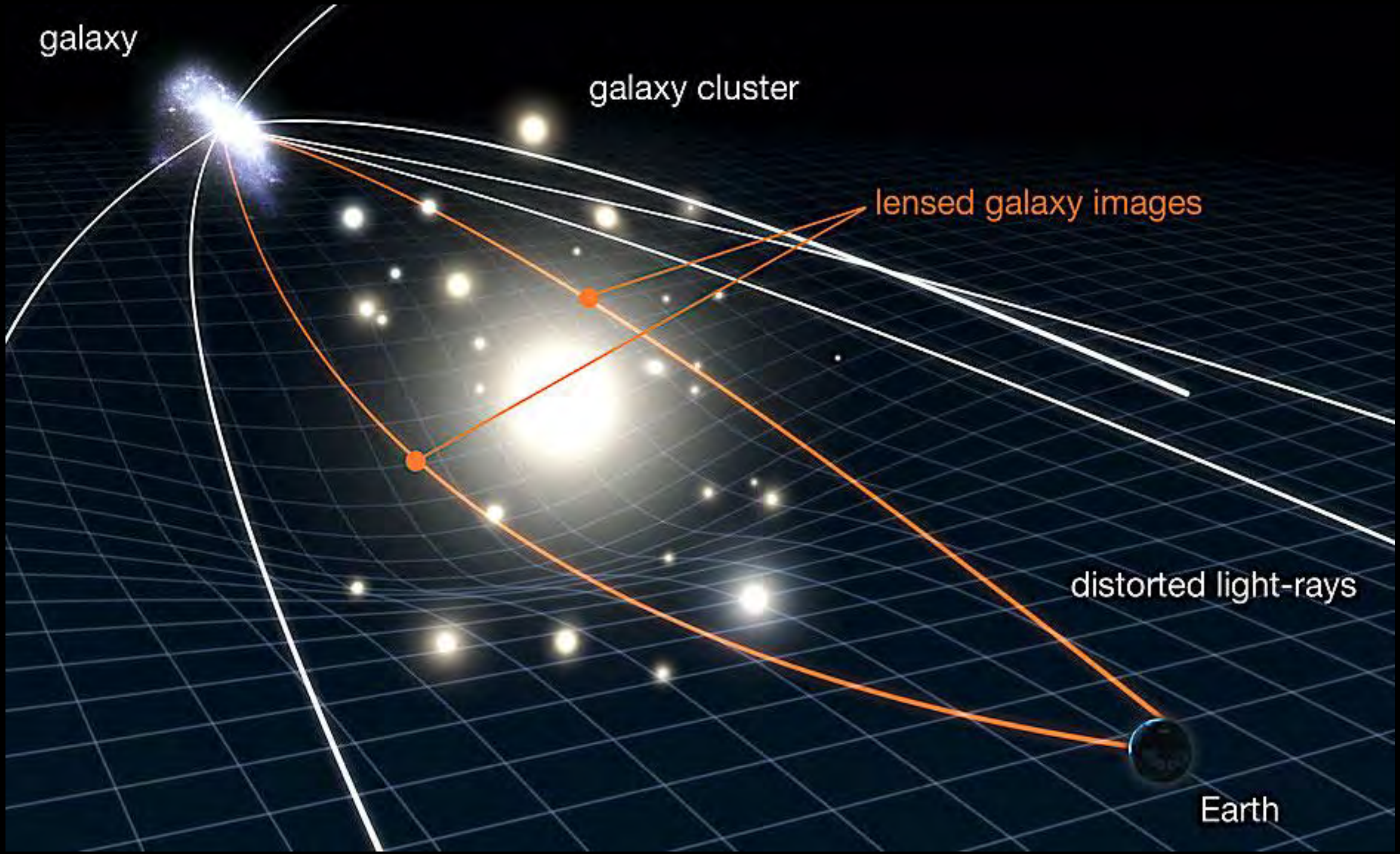
GN-z11: A Galaxy at z ~ 11

Originally found in deep HST images by Oesch et al.



See Deeper With Gravitational Lenses

Massive objects like galaxy clusters magnify the images of more distant objects behind them



The images of faint background galaxies appear as arclets. The magnification could be by a factor of several tens, thus making it as if we are using a telescope that is larger by the corresponding factor

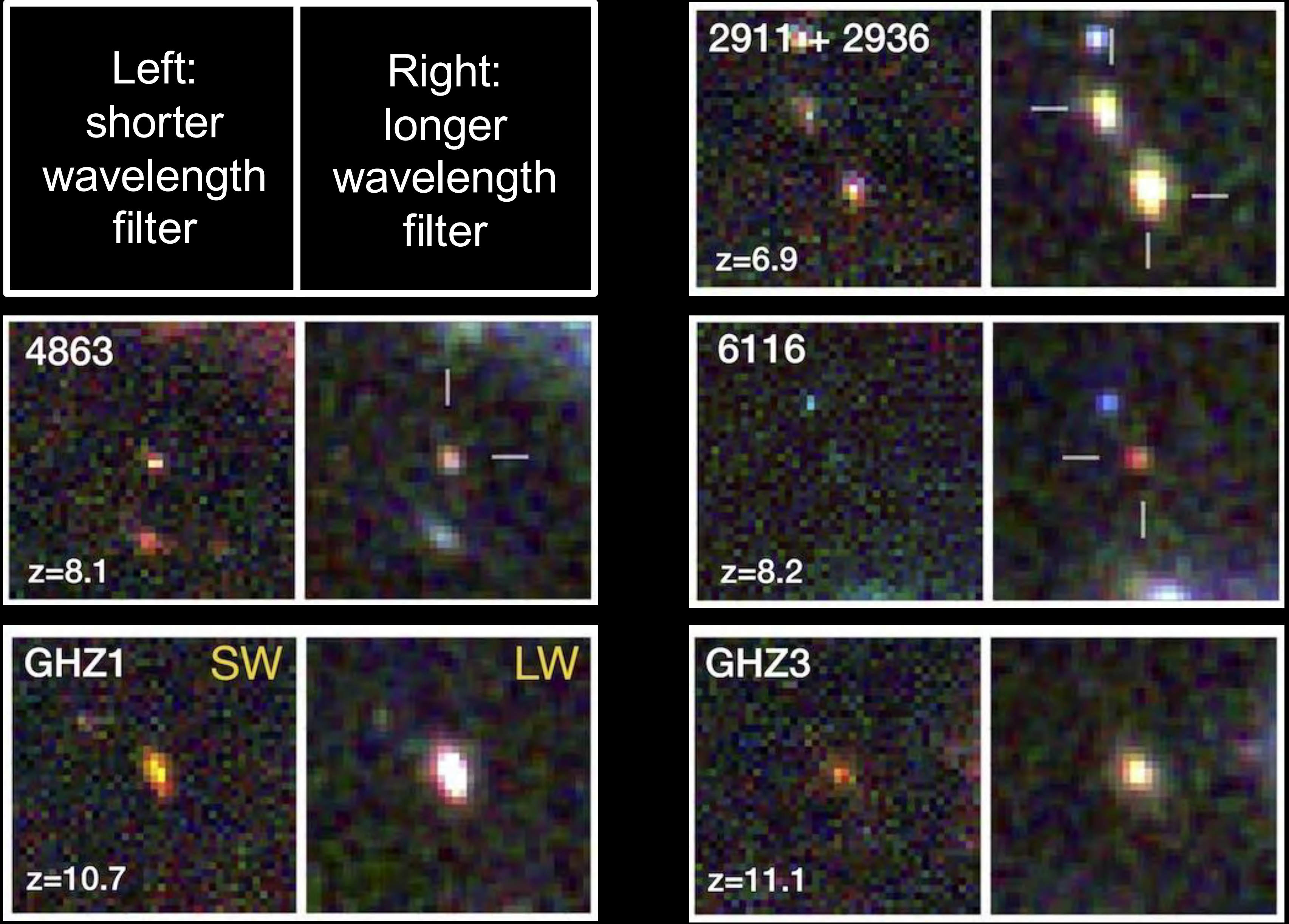
This was first suggested by Fritz Zwicky in 1937

JWST First Light Image

Examples of JWST Galaxies at z ~ 7 – 12

Left: shorter wavelength filter

Right: longer wavelength filter



JWST At the Galaxy Formation Frontier

JWST is now finding young and still forming galaxies when the universe was only 300 – 500 million years old

Their unexpectedly large luminosities are telling us something about their star formation rate history and the masses of the first stars

We are also starting to see evidence for the first supermassive black holes – the birth of quasars

This is transforming our knowledge of galaxy formation and early evolution

Key Concepts in This Lecture

- **Galaxy formation and evolution** processes consist of the **mass assembly** through mergers (dissipationless) and **evolution of stellar populations and gas** (dissipative)
- Observations are usually based on **deep imaging surveys** over many wavelengths, followed by **deep redshift surveys**
- The **history of star formation** starts low and grows in time, peaks around the redshifts 2 to 3, and then declines, driven by dissipative merging and infall
- A **half** of all star formation was **obscured by dust**, and observable in FIR/sub-mm
- **Intergalactic medium (IGM)** consists mainly of primordial H+He clouds (seen as the Lyman-α forest), but some metallic line absorbers as well
- **Chemical evolution** of galaxies and IGM is coupled: gas flows into galaxies, and enriched gas is expelled to IGM due to stellar and SN winds
- Mechanical winds and ionizing radiation from young stars and AGN constitutes **feedback**, that limits the growth of galaxies
- Energy output from galaxies is due to the release of binding energy, stellar nuclear burning, and formation of supermassive black holes by accretion
- We now observe **young and forming galaxies** at large redshifts with JWST

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