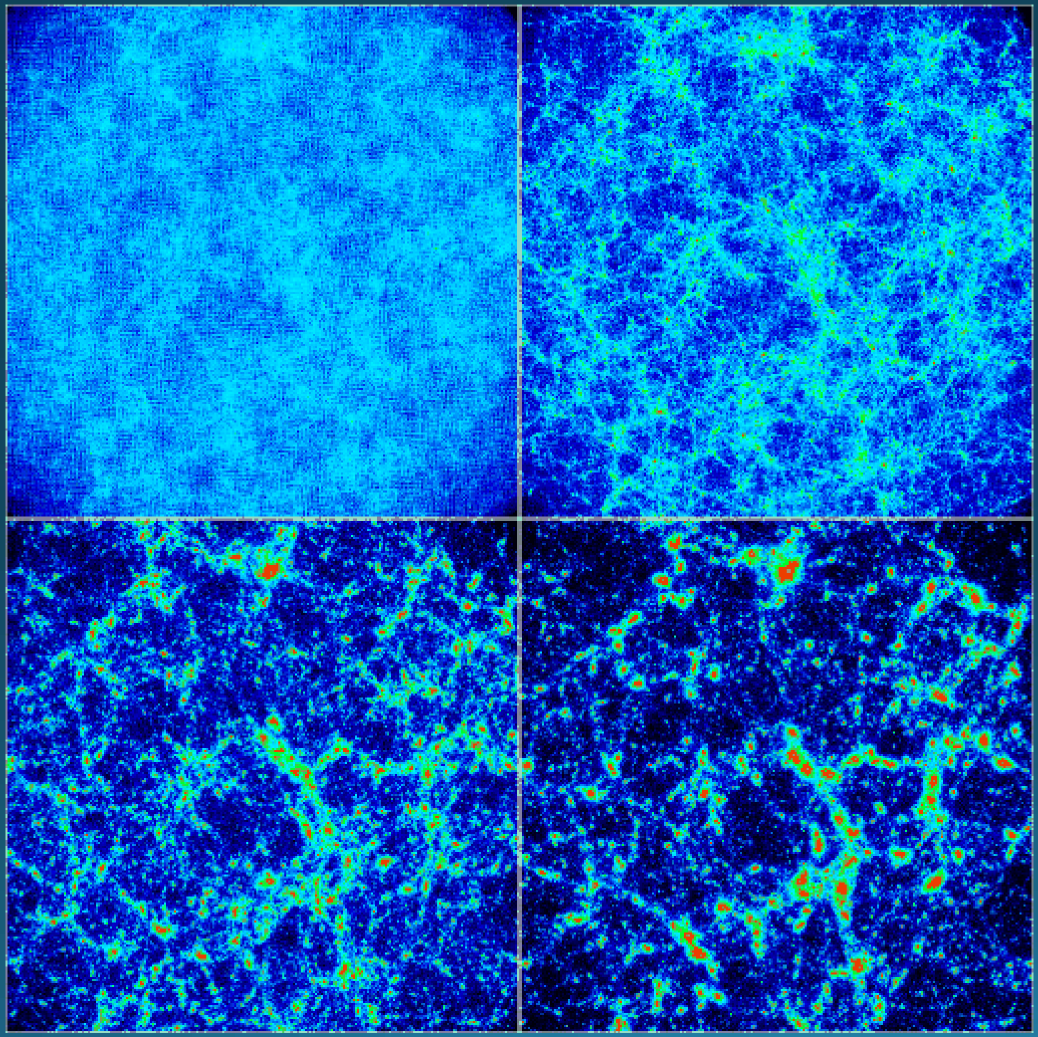
Cosmology 1FA209, 2017
Lecture 9: Structure formation



Note: Slight change in hand-in problem

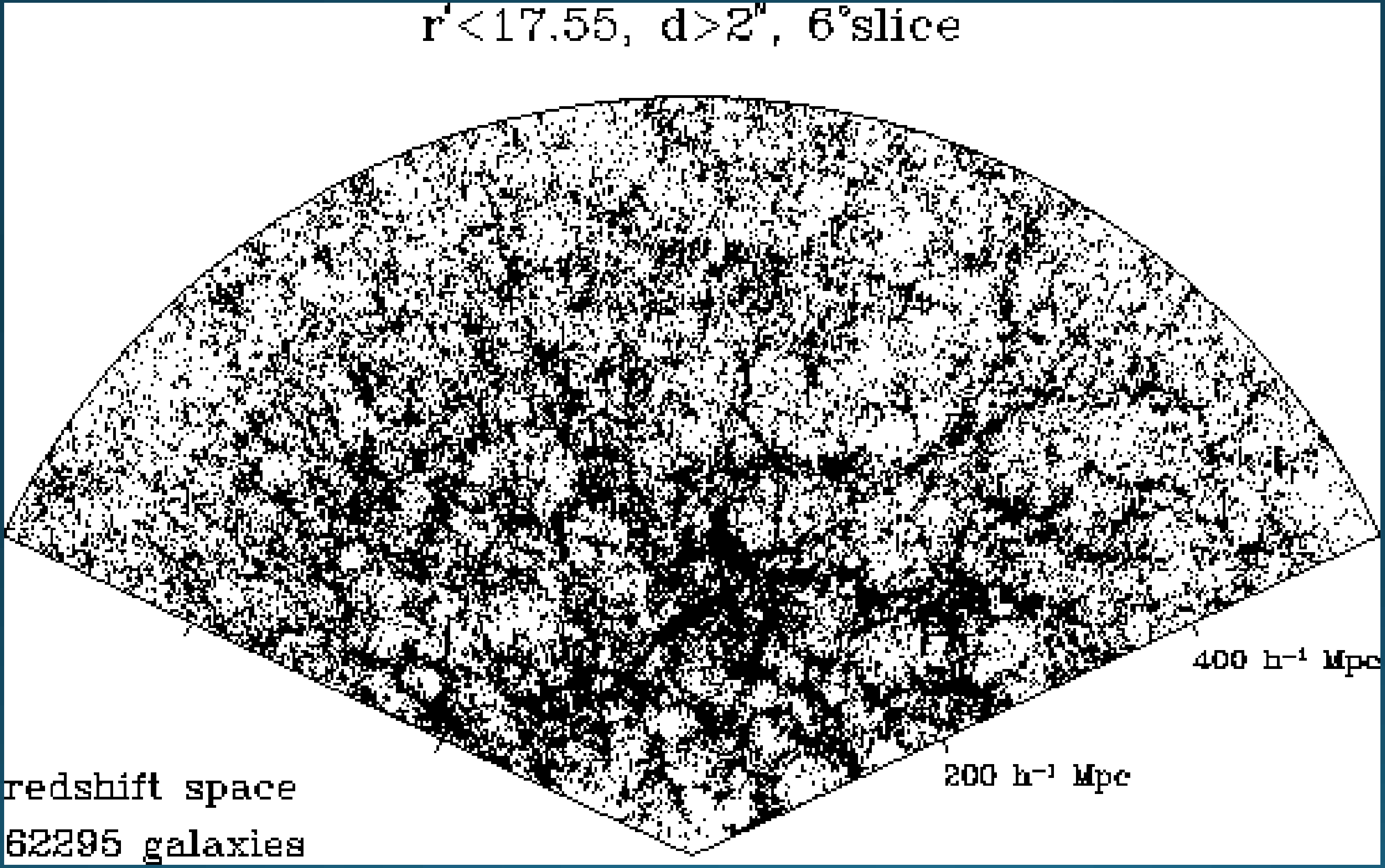
5. *Fermi problem: Dark matter*
Let's assume that 10% of the dark matter consists of Earth-mass primordial black holes. If you were to set a Death star-sized space station on autopilot along a straight path at near-light speed (and turning off all automatic evasive-maneuver capabilities) in intergalactic space for $\sim 10^8$ yrs, how many such black holes do you expect to collide with? Make an order-of-magnitude estimate of this, quantify the uncertainty and make a top-3 list of the most important shortcomings/simplications that are likely to affect your estimate (and clearly explain why this is so).

Outline

- Structure formation
  - Jeans length, Jeans mass
  - Structure formation with and without dark matter
  - Cold versus hot dark matter
  - Dissipation
  - The matter power spectrum
  - Baryon acoustic oscillations
- Reionization and high-z objects
  - What caused reionization?
  - The first stars and galaxies

Covers chapter 11 & 12 in Ryden + extra stuff

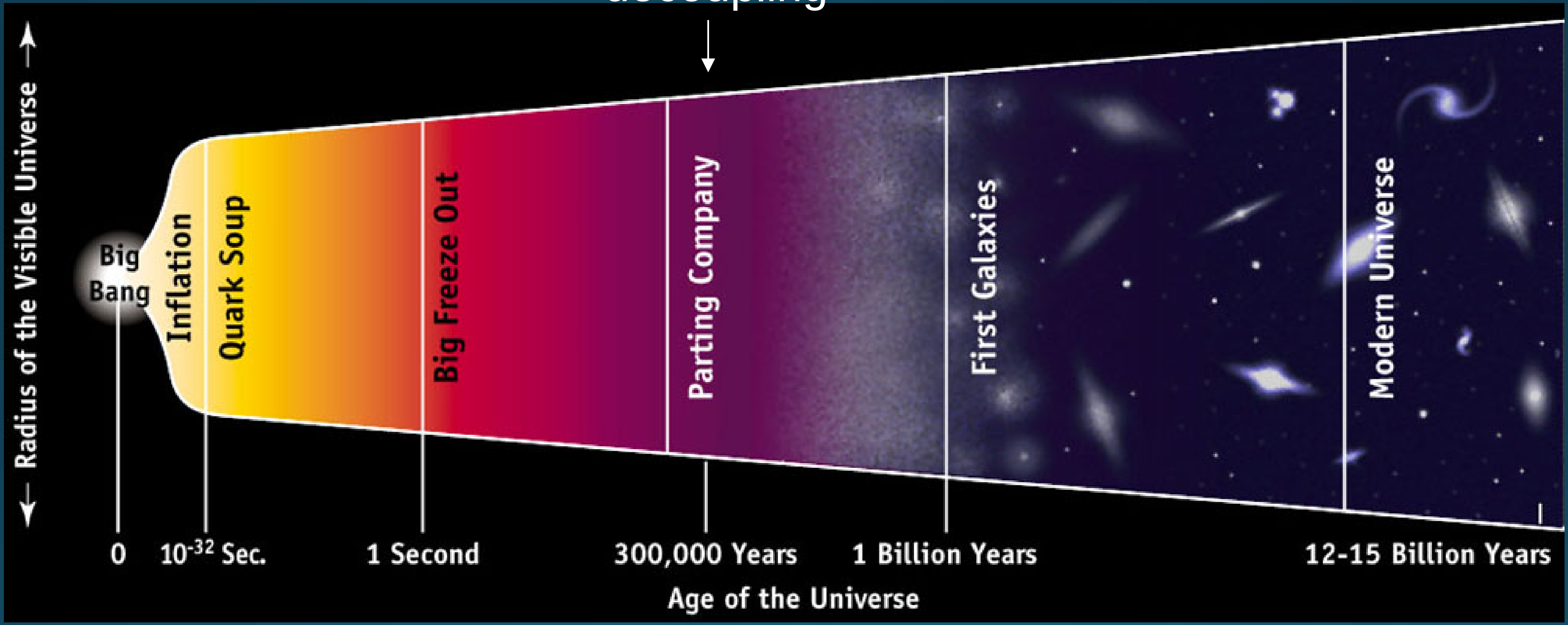
Walls, Filaments, Voids



Voids ~ 70 Mpc

Cosmic epochs

Matter-radiation decoupling



Likely seeds of galaxy formation: Quantum fluctuations expanded to macroscopic scales by inflation

Jeans length I

Which baryonic objects will collapse under the force of gravity?

- Two time scales:
  - Dynamical collapse time, t_{dyn}
  - Characteristic time scale for pressure build-up, t_{pre}
- $t_{pre} > t_{dyn} \rightarrow$ Object collapses
- $t_{pre} < t_{dyn} \rightarrow$ Hydrostatic equilibrium attained; collapse prevented

Jeans length II

Jeans length λ_J: Size of overdense regions for which $t_{pre} = t_{dyn} \rightarrow$

Regions of size > λ_J will collapse

Regions of size < λ_J will not

$$\lambda_J = \sqrt{\frac{\pi c^2}{G\bar{\varepsilon}}} c_s$$

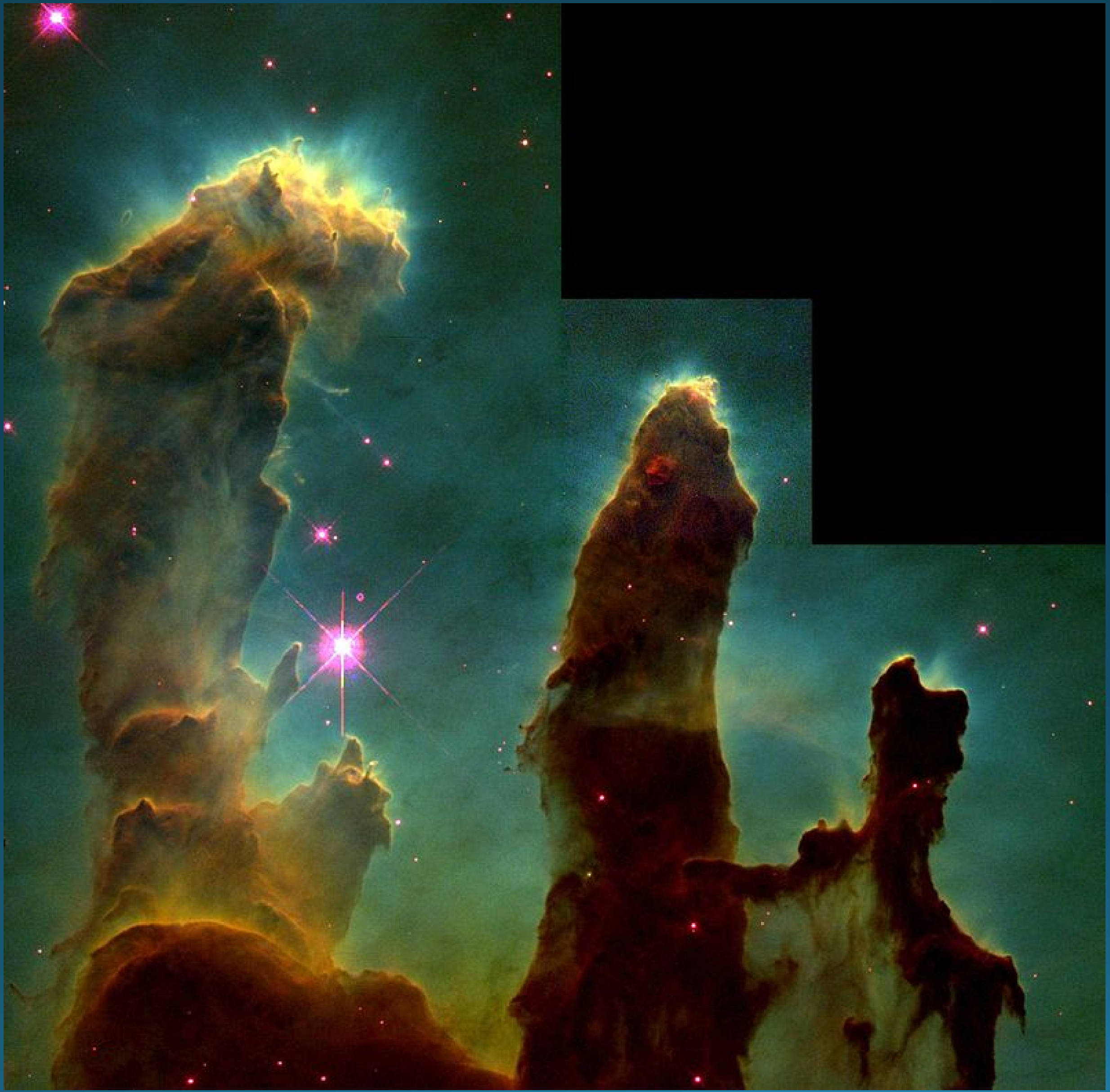
Sound speed in overdense region

Mean density of overdense region

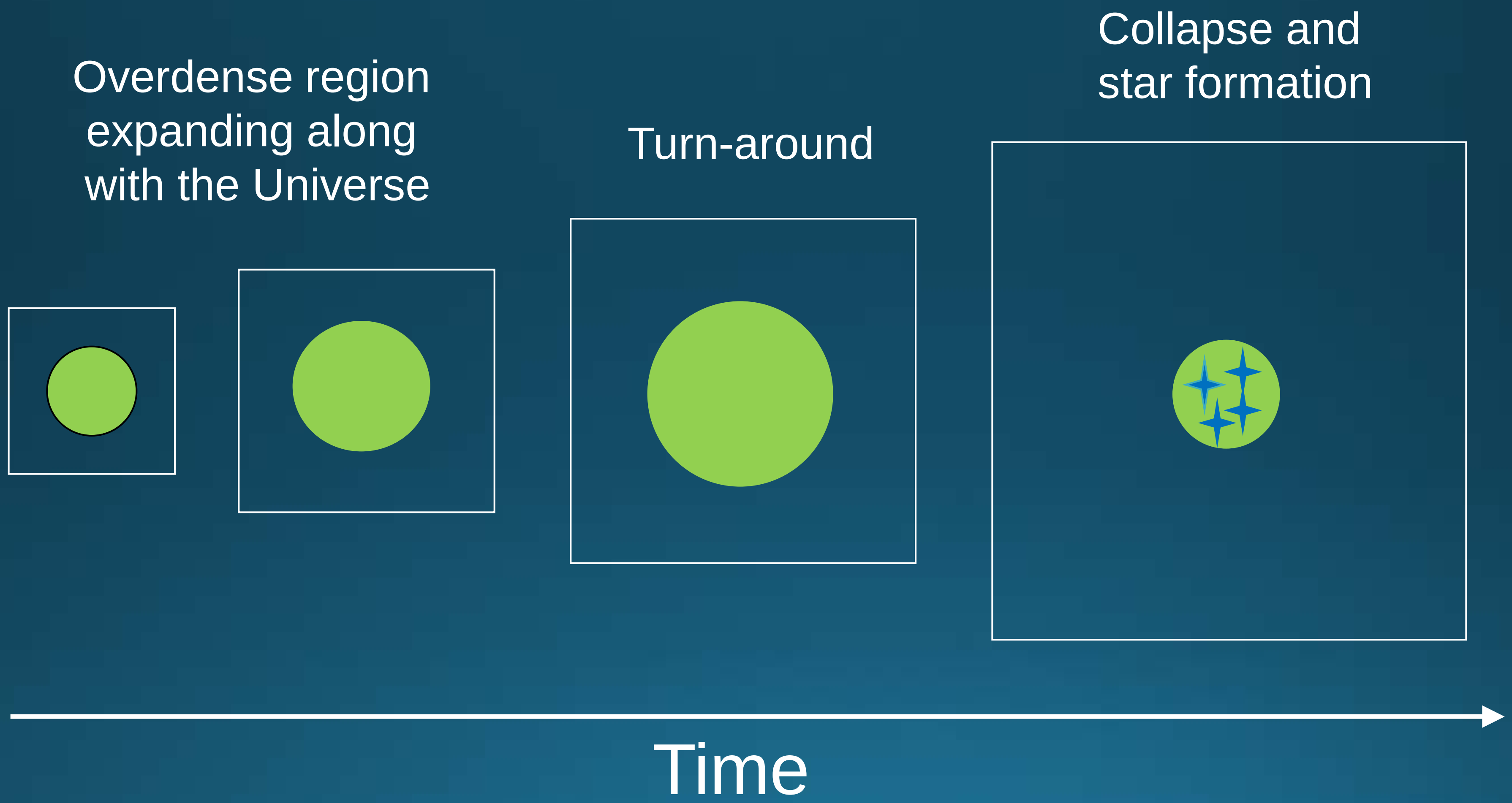
Jeans mass

- Jeans mass M_J: Mass of baryons inside sphere of radius λ_J
  - $M > M_J \rightarrow$ Collapse
- Before decoupling: photon-baryon fluid with very high M_J (~ 10^{19} M_{solar})
- After decoupling: M_J drops to (~10^4-10^5 M_{solar}) in baryon fluid $\rightarrow$ Baryons lose pressure support

Intermission: What is this?



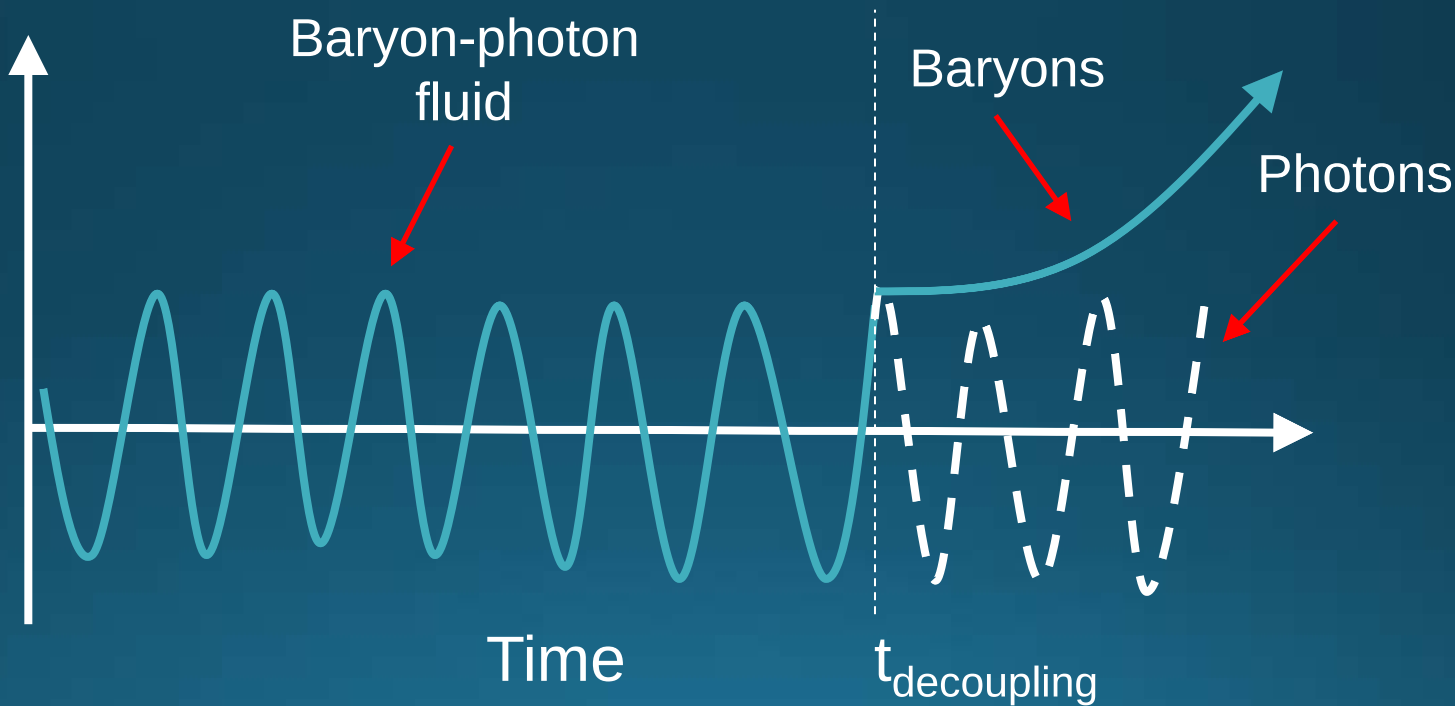
Collapse in an expanding Universe



Structure Formation *Without* Non-Baryonic Dark Matter

- Density perturbations that will eventually form galaxies and galaxy clusters cannot start to grow until after decoupling (t ≈ 0.35 Myr)

$$\delta = \frac{\varepsilon - \bar{\varepsilon}}{\varepsilon}$$

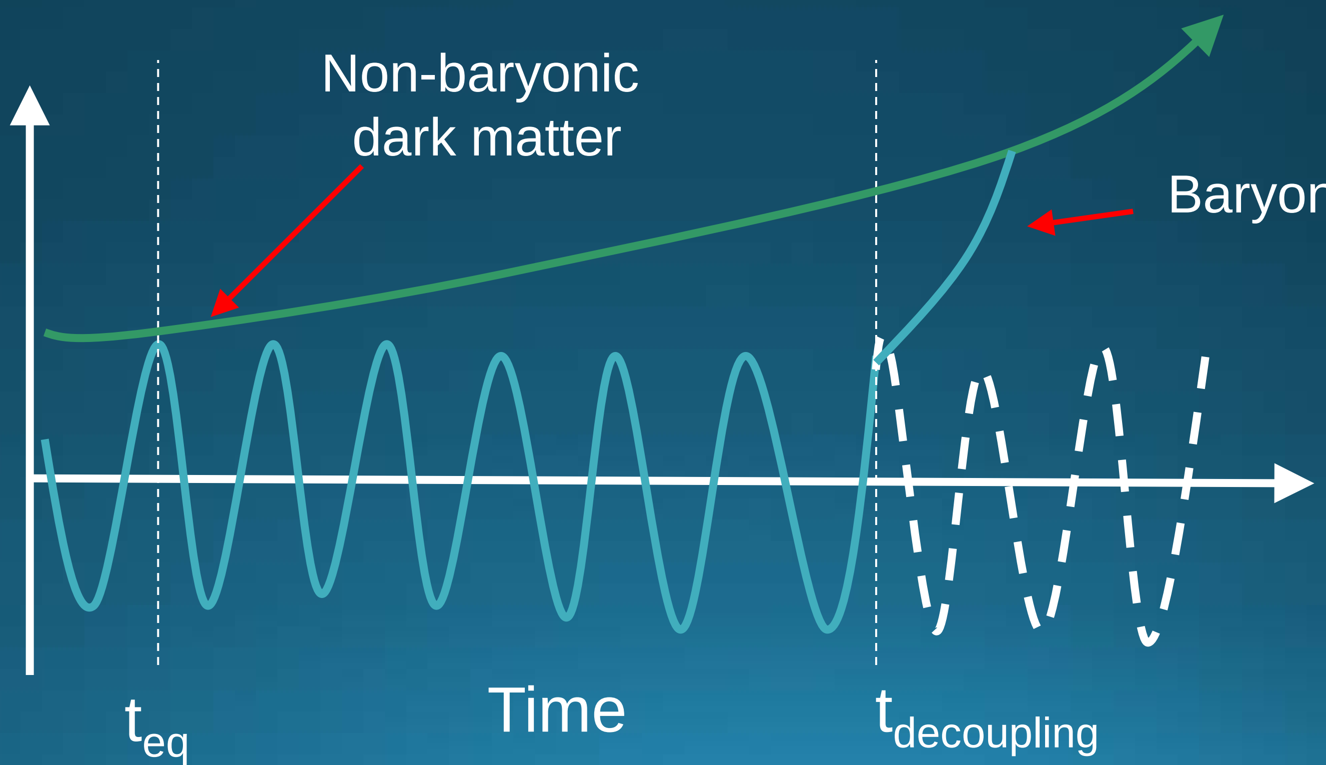


Problem: Too slow structure formation – fails to explain the observed structures at high and low redshift

Structure Formation *With* Non-Baryonic Dark Matter

- Density perturbations will start to grow at the epoch of matter-radiation equality (t ≈ 0.047 Myr)
- Baryons will fall into the potential wells already produced by the dark matter

$$\delta = \frac{\varepsilon - \bar{\varepsilon}}{\varepsilon}$$

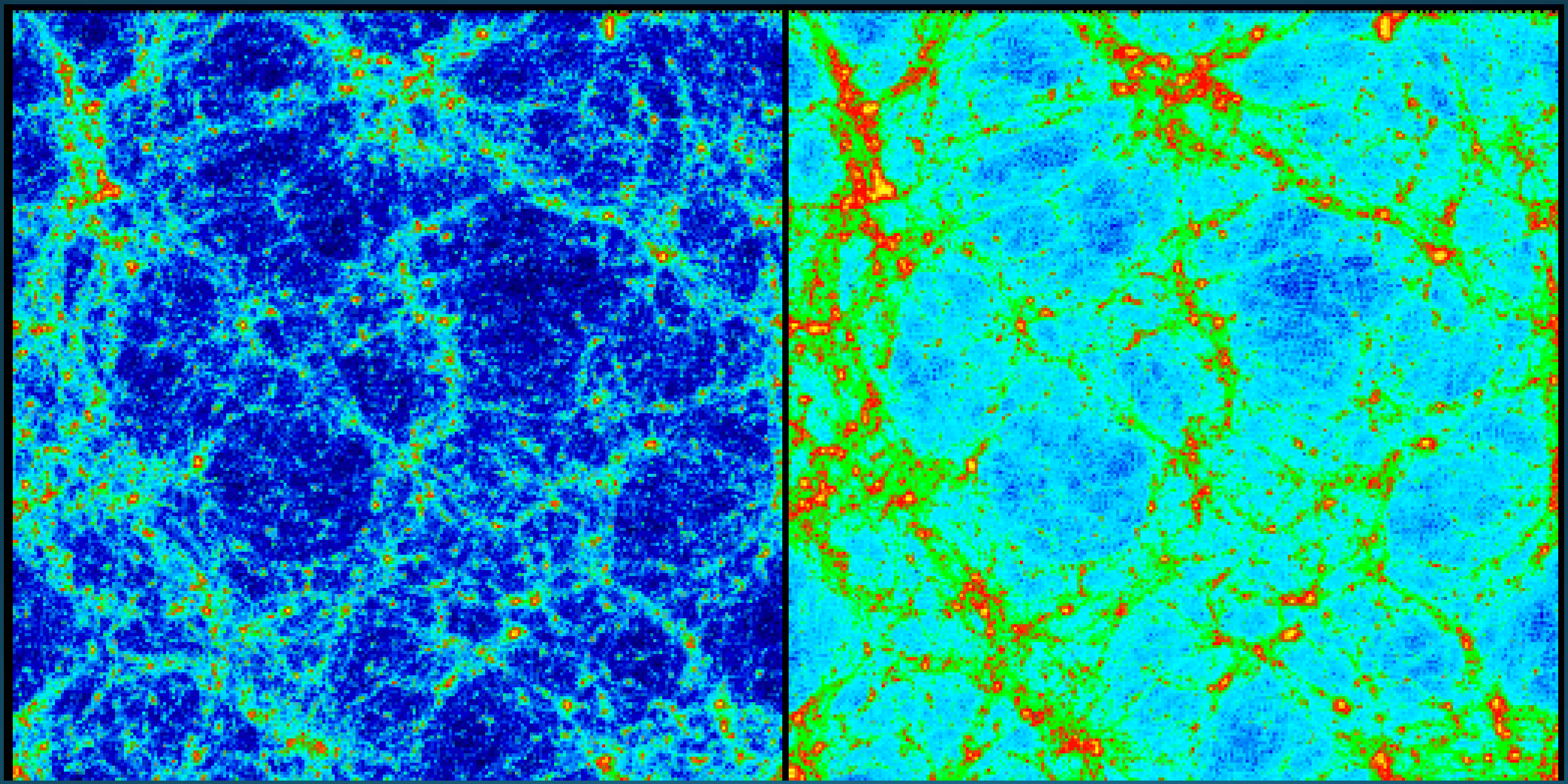


Hot & cold dark matter I

- Hot dark matter (HDM): Relativistic velocities at decoupling
- Cold dark matter (CDM): Non-relativistic velocities at decoupling
- Warm dark matter (WDM): Intermediate velocities at decoupling

Velocities of the dark matter particles regulate how massive the first collapsing objects are

Hot & cold dark matter II



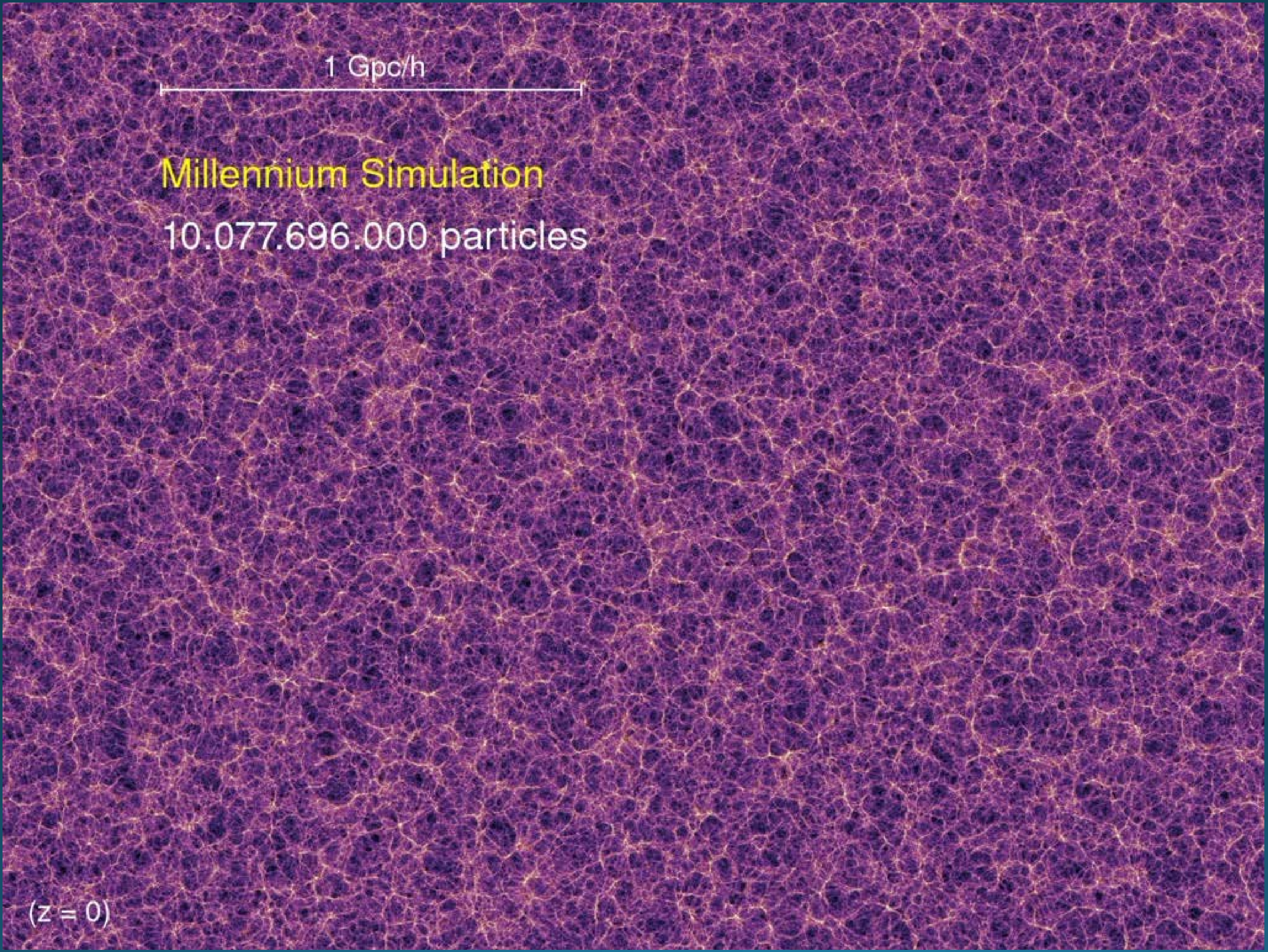
Cold dark matter | Cold + hot dark matter

HDM $\rightarrow$ Top-down structure formation

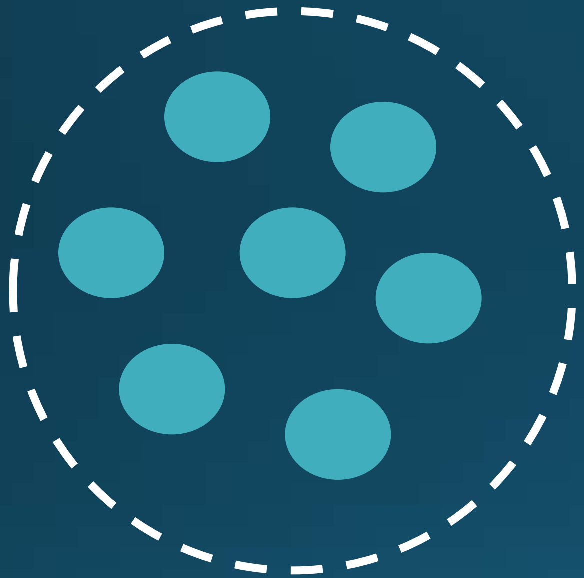
- Free-streaming wipes prevents growth of density perturbations on small scales
- Top-down: Big structures form first, small ones later
- Overdensitities of galaxy cluster mass collpase before the galaxies inside are formed
- Massive galaxies form before dwarf galaxies

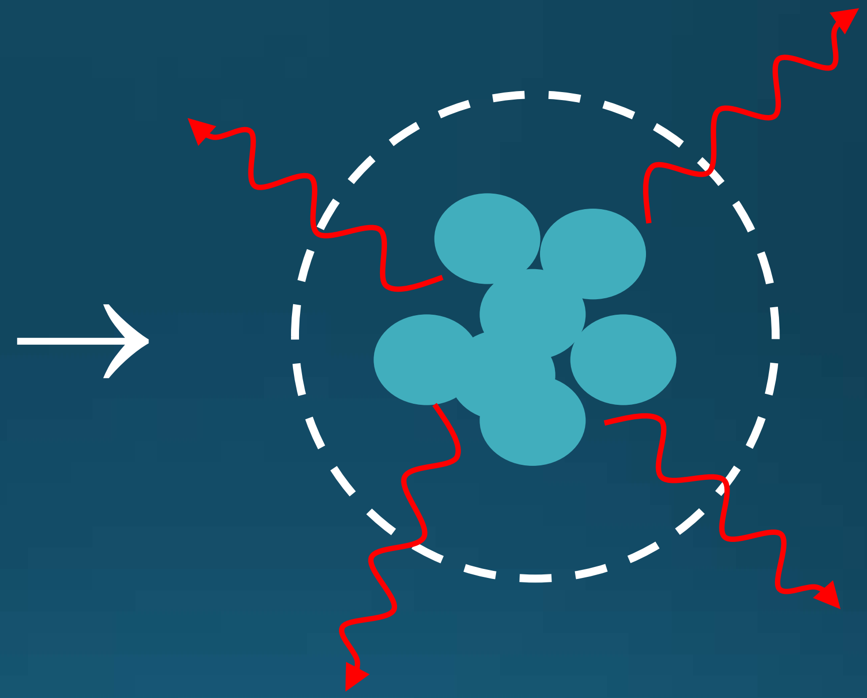
CDM $\rightarrow$ Bottom-up structure formation

- Bottom-up = Small structures form first, big ones later
- Potential wells in non-baryonic CDM form before decoupling, into which baryons may fall after decoupling
- Small objects form first, galaxy clusters last (some are still collapsing)


1 Gpc/h
Millennium Simulation
10.077.696.000 particles
(z = 0)

Dissipation inside dark matter halos





Isolated dark matter halo with baryons (gas) inside

The baryons cool (dissipate) by radiating photons and sink towards the centre. The dark matter halo contracts slightly due to the changes in the gravitational field

Intermission: What is this?

The Matter Power Spectrum

Most inflation models predict an adiabatic, power-law spectrum of Gaussian perturbations

Amplitude

Wave number

$$P \propto k^n$$

Corresponding potential fluctuations:

$$\delta\Phi \propto M^{(1-n)/6}$$

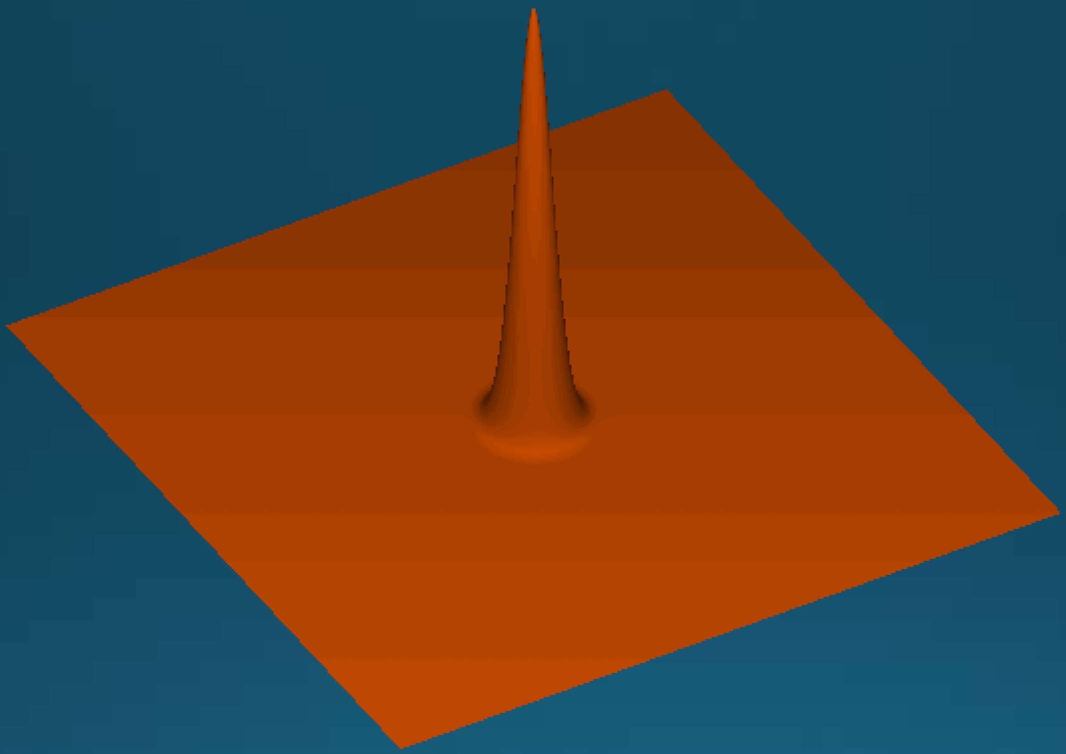
$$n = 1 \Rightarrow \text{Harrison - Zeldovich spectrum}$$

$$\text{(scale - free)}$$

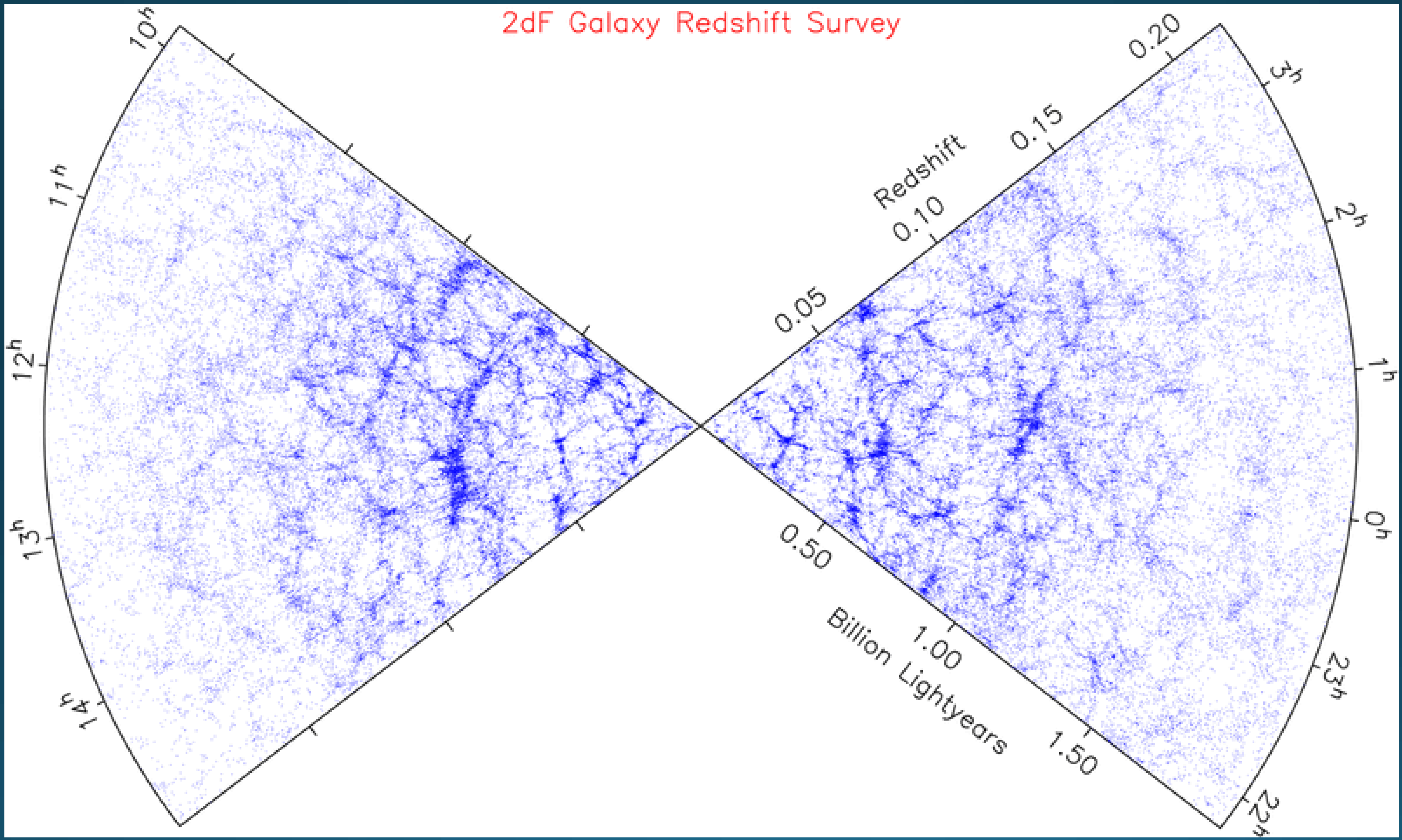
Baryon Acoustic Oscillations

- Overdensities (in baryons and dark matter), eject spherical sound waves
- Sound speed ~0.5 c
- Photons decouple $\rightarrow$ Sound speed drops
- Wave stalls at $R_{comoving}$~160 Mpc
- This overdensity of gas acts as seed for galaxy formation and can be detected in large galaxy surveys
- The 160 Mpc radius serves as a standard ruler

Baryon Acoustic Oscillations II

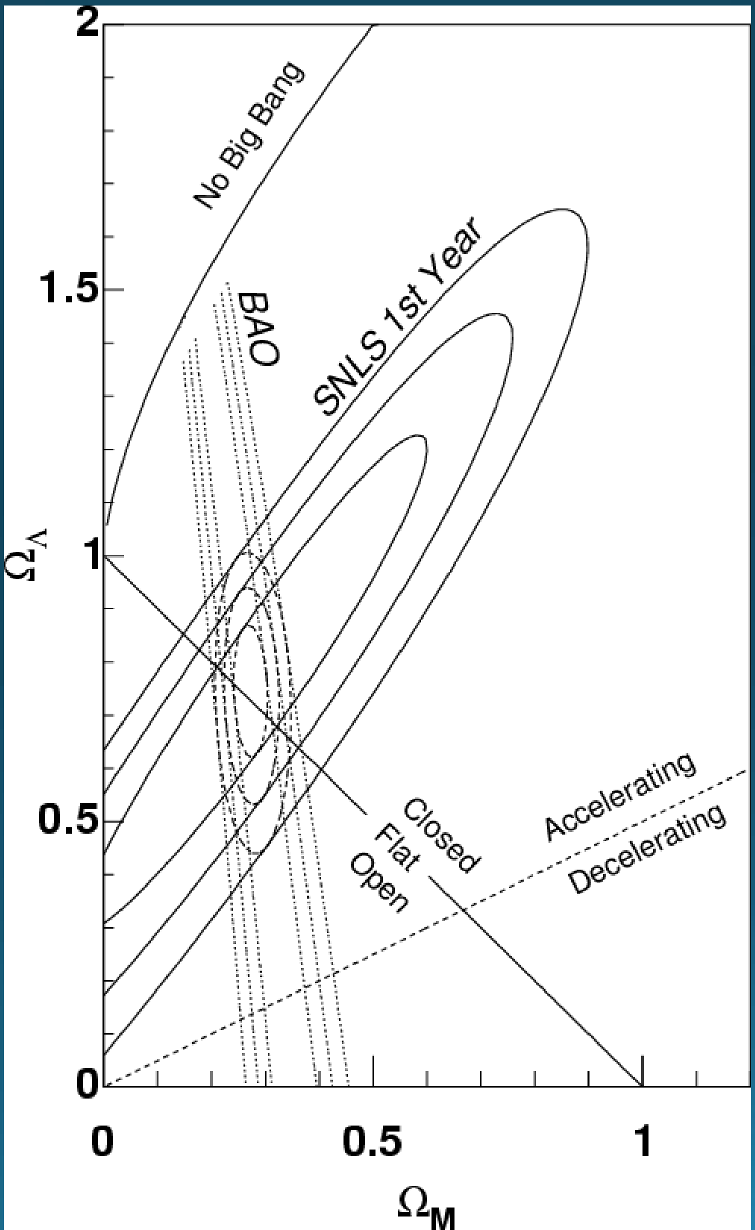


Baryon Acoustic Oscillations III



The 160 Mpc galaxy overdensity cannot be seen with the naked eye, but can be extracted using statistical analysis methods → Cosmological parameters can be derived

Baryon Acoustic Oscillations IV



Star Formation and Feedback

Stars form
in the cooled gas

Feedback from star formation kicks in. Young, hot stars ionize part of the gas. Stellar winds and supernovae blow the gas outwards – some of it may leave the halo

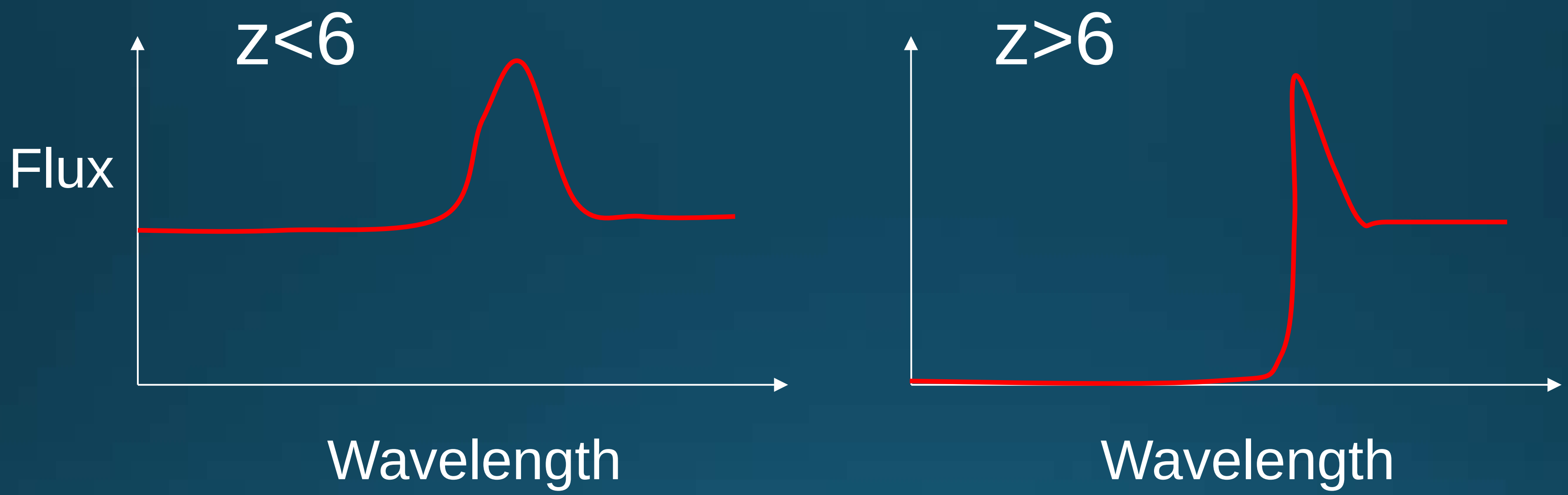
Intermission: What is this?

Reionization

- The Universe cooleds and becomes neutral at the epoch of recombination
- But most of the gas in the local Universe is ionized $\rightarrow$ Somewhere along the way the Universe must have experienced reionization
- Conjecture: Reionization is caused by the formation of astronomical objects (sources of Lyman continuum photons)
- The first astronomical light sources are expected to light up at around z = 30—15 (100—300 Myr after the Big Bang)

When did reionization take place?

Quasar Lyα spectra (The Gunn—Peterson test)

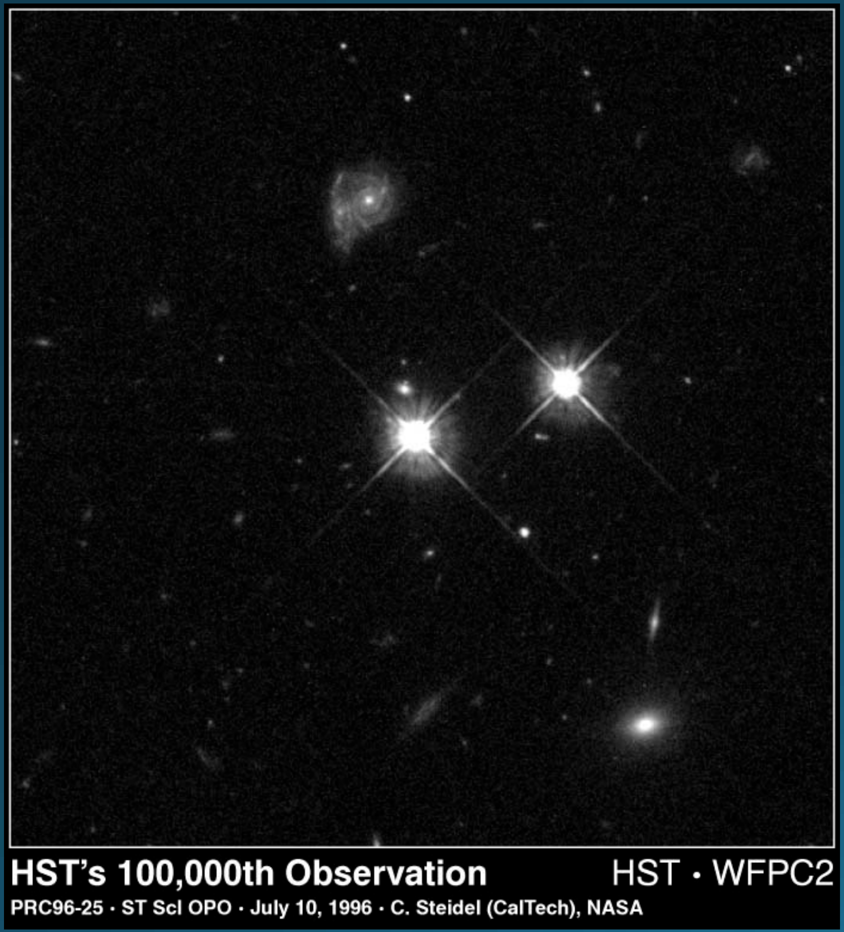


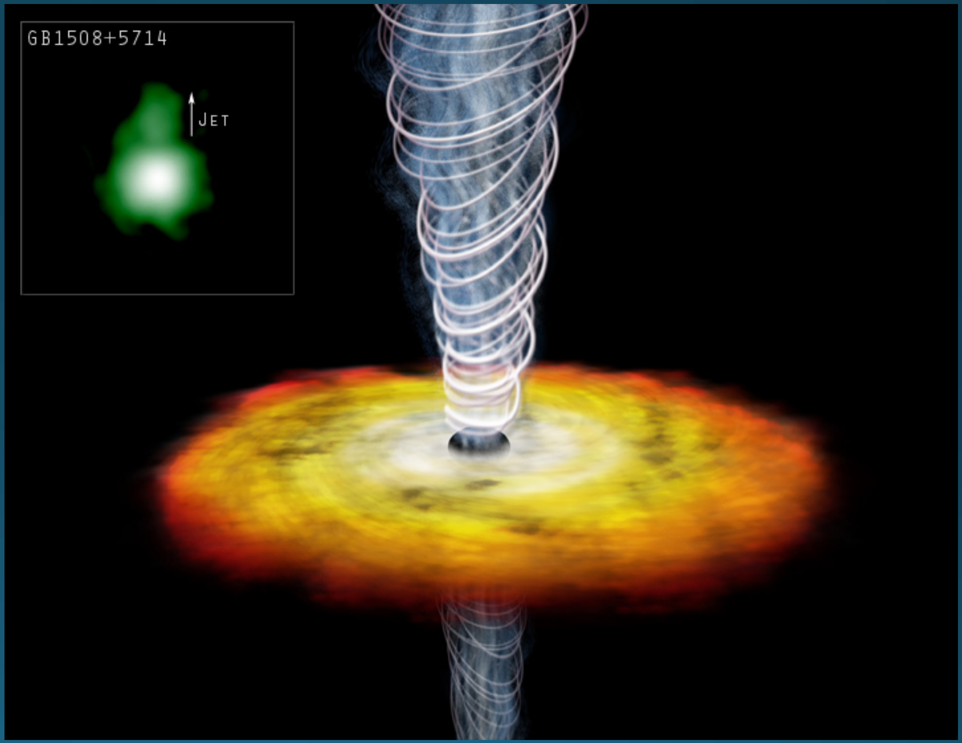
- Gunn-Peterson test $\rightarrow$ Reionization ended at z≈6
- CMBR analysis measures electron scattering optical depth τ $\rightarrow$ Reionization started at z≈12

What caused reionization?

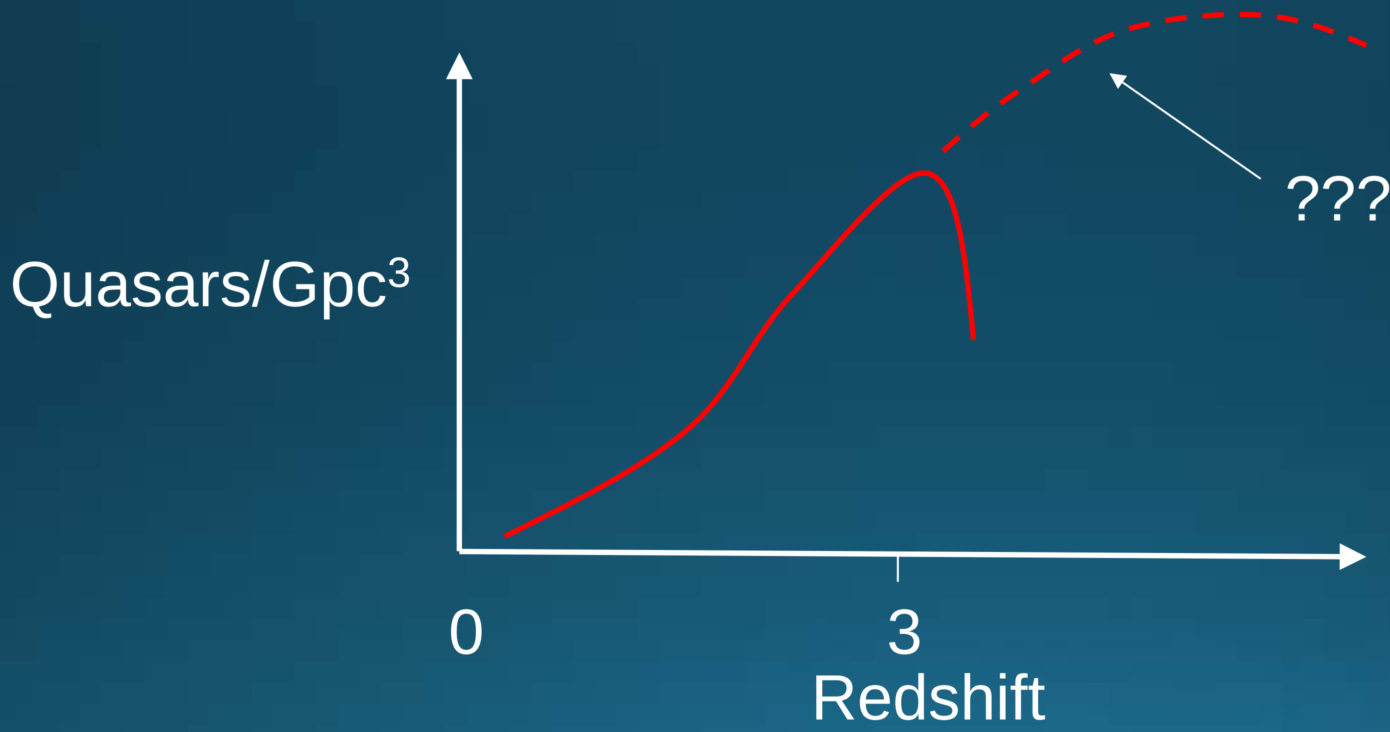
- Quasars?
- Starburst galaxies?
- Population III stars?
- Evaporating primordial black holes?
- Decaying dark matter?

Quasars


HST's 100,000th Observation
HST • WFPC2
PRC96-25 • ST ScI OPO • July 10, 1996 • C. Steidel (CalTech), NASA

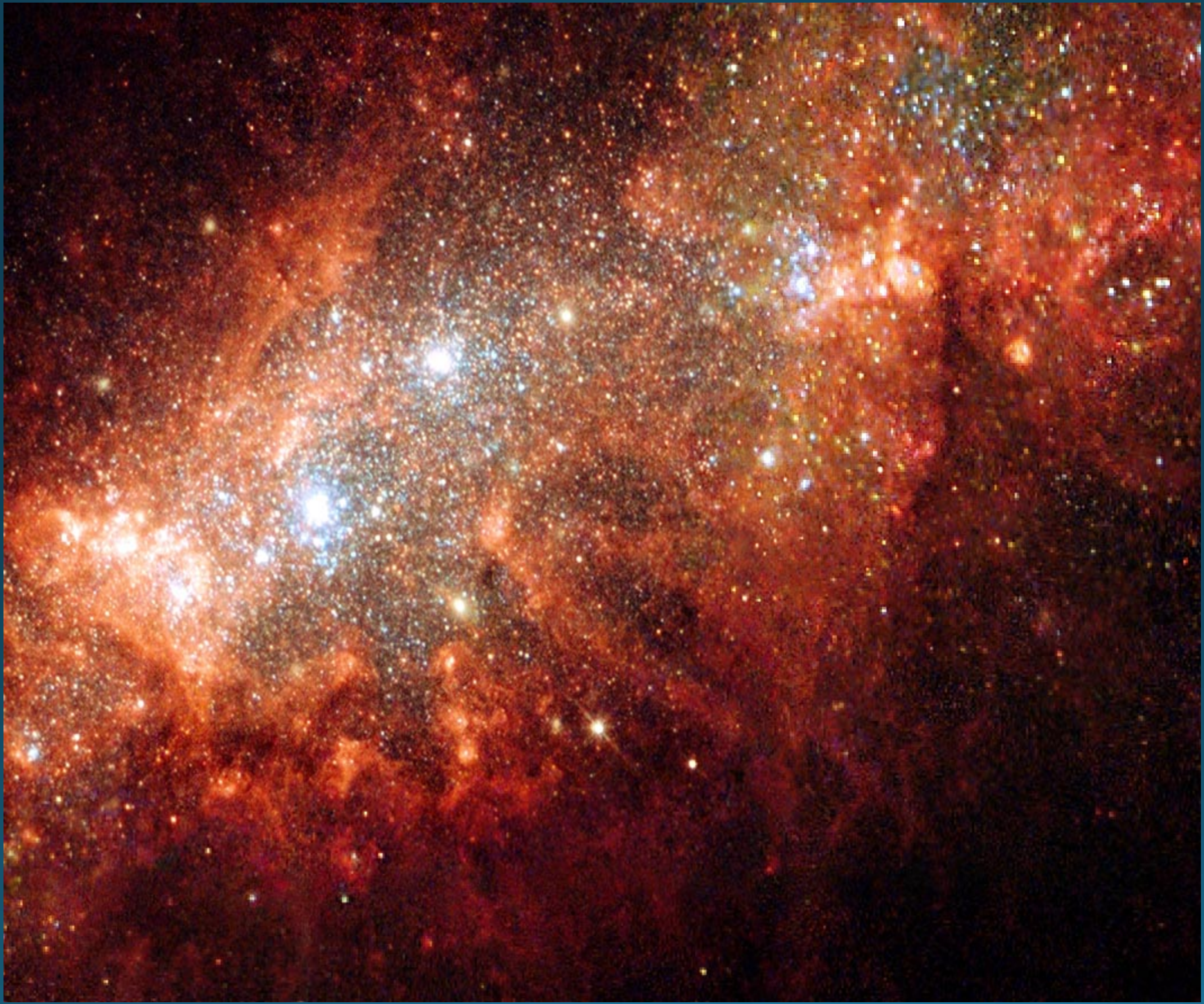

GB1508+5714
JET

Quasars as Sources of Lyman Continuum Radiation at High Redshift



Probably too few…

Starburst Galaxies



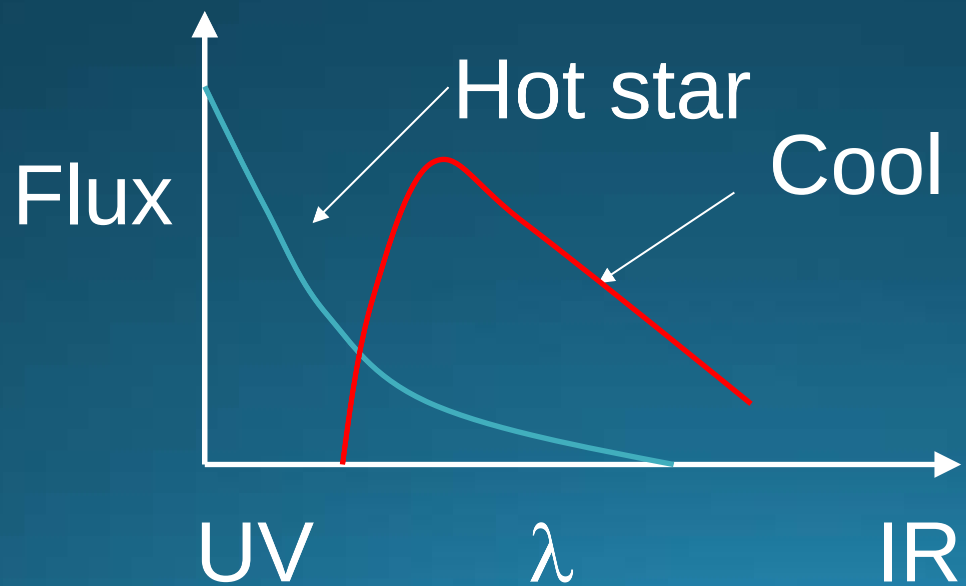
Why Do Starburst Galaxies Produce Lots of Lyman Continuum Photons?

- Stars are born in the mass range ~ 0.08—120 solar masses
- The highest-mass stars have the shortest lifetimes (a few Myr)

→ Large numbers of high-mass stars are only found in galaxies that actively form stars

- High-mass stars are typically hotter than low-mass stars
- Hot stars emit more UV radiation (stars are almost black bodies)

→Starbursts emit more Lyman continuum radiation than galaxies with low star formation rates

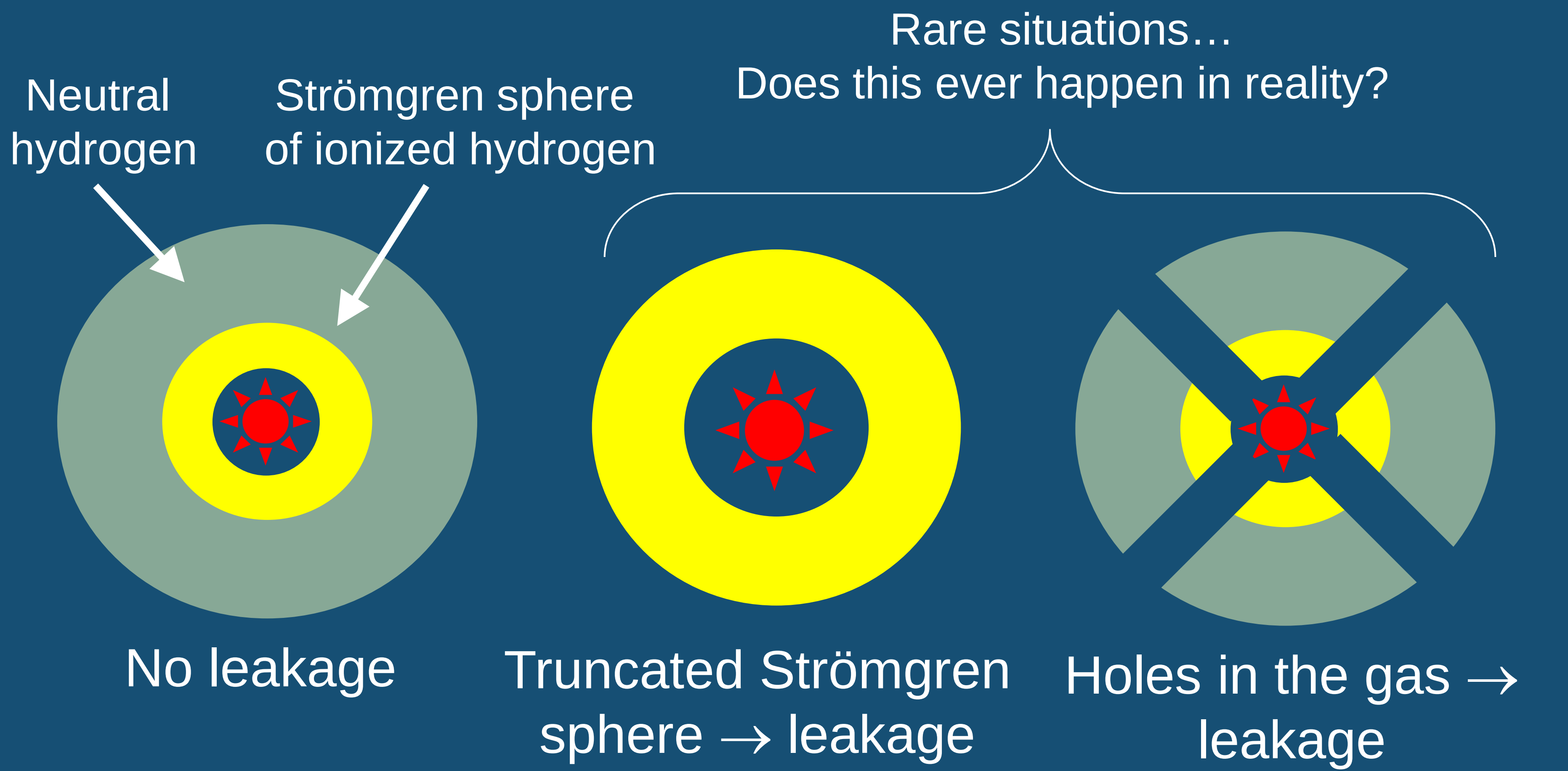


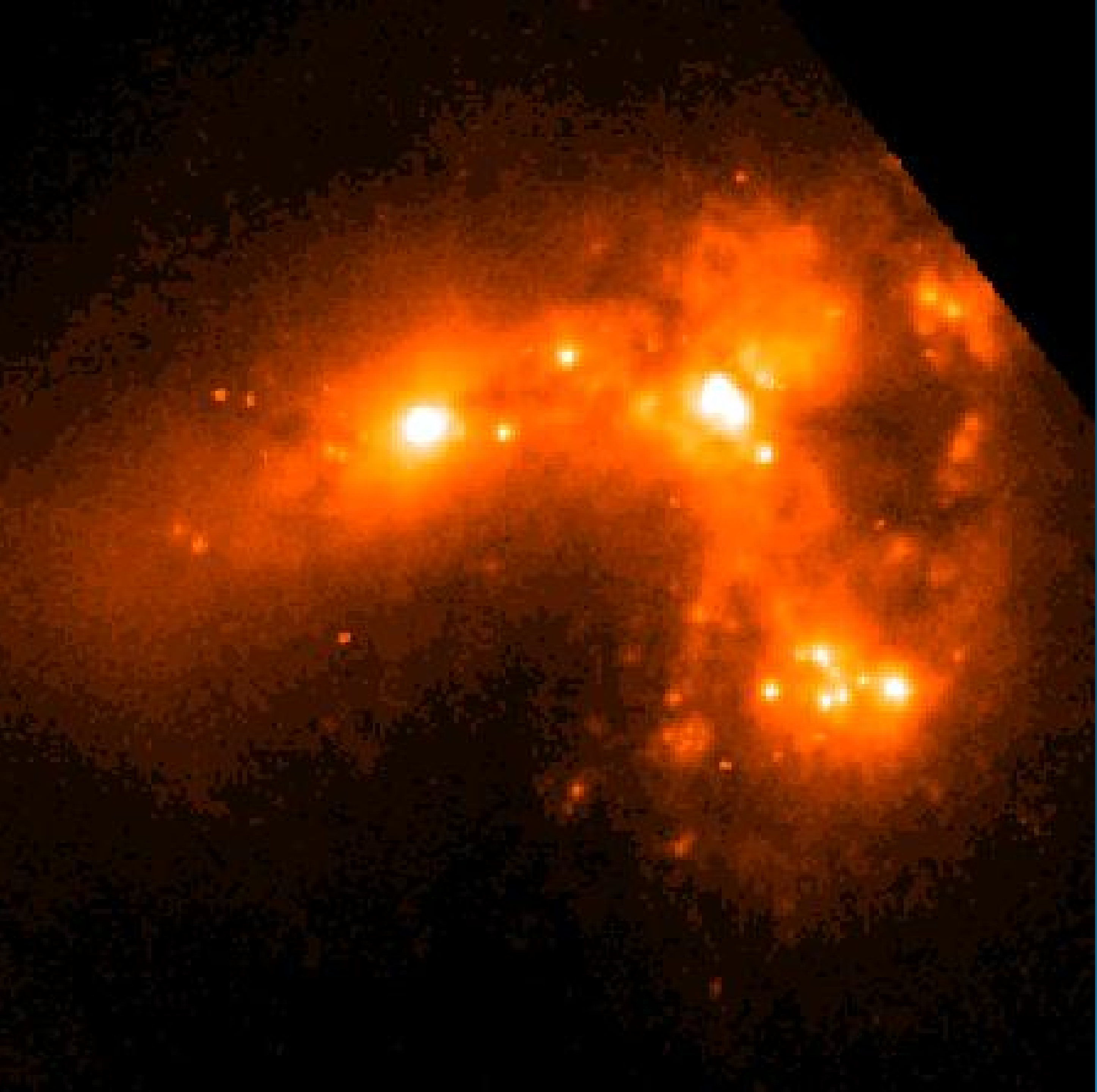
Black: Neutral hydrogen
Blue: Ionized hydrogen
Red/White: Partially ionized hydrogen
Yellow: Galaxies

What is this?

Starburst galaxies

Additional caveat: Starburst galaxies must have significant Lyman continuum escape fractions to contribute to reionization





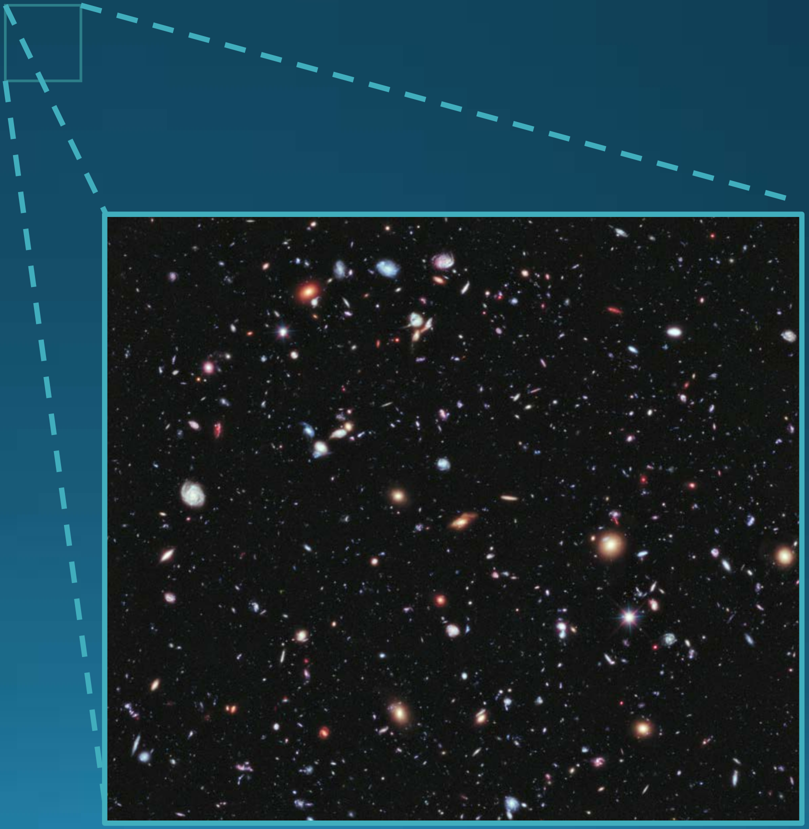
Haro 11 – The first detection of Lyman continuum leakage in the local Universe

Population III stars

- Population I stars (young, metal-rich, disk)
- Population II stars (old, metal-poor, stellar halo)
- Population III stars (the oldest stars, metal-free)

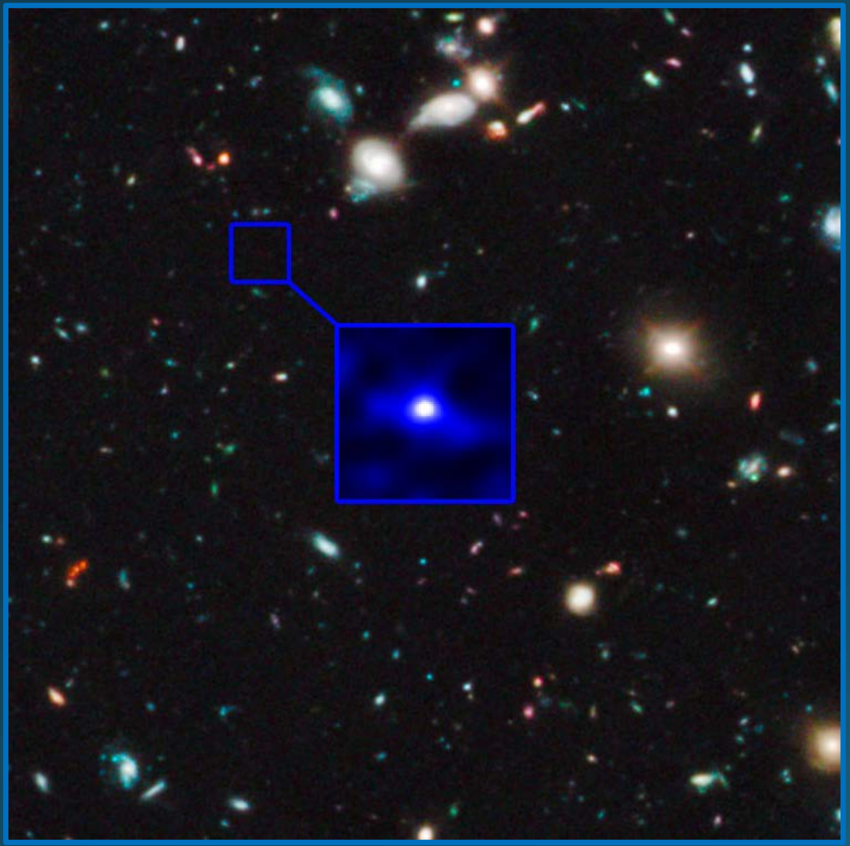
Population III stars may have been very massive (~10 — 1000 solar masses)
$\rightarrow$ Short-lived, but produce a lot of Lyman continuum emission during their lifetimes

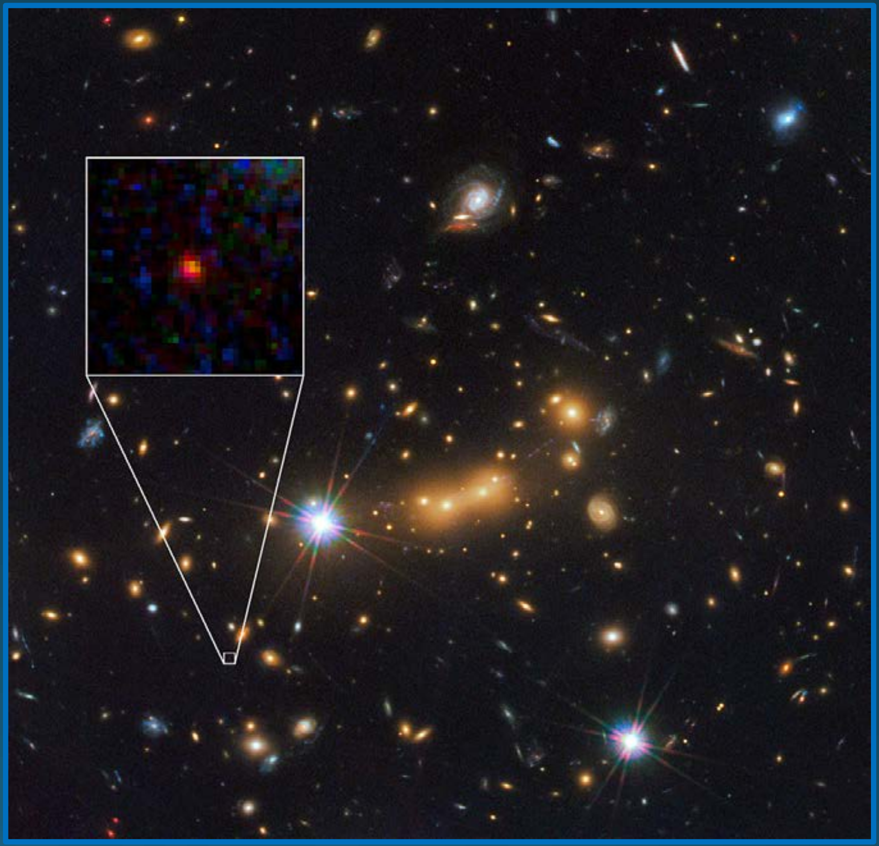
Intermission: What is this?




Hubble Extreme Deep Field

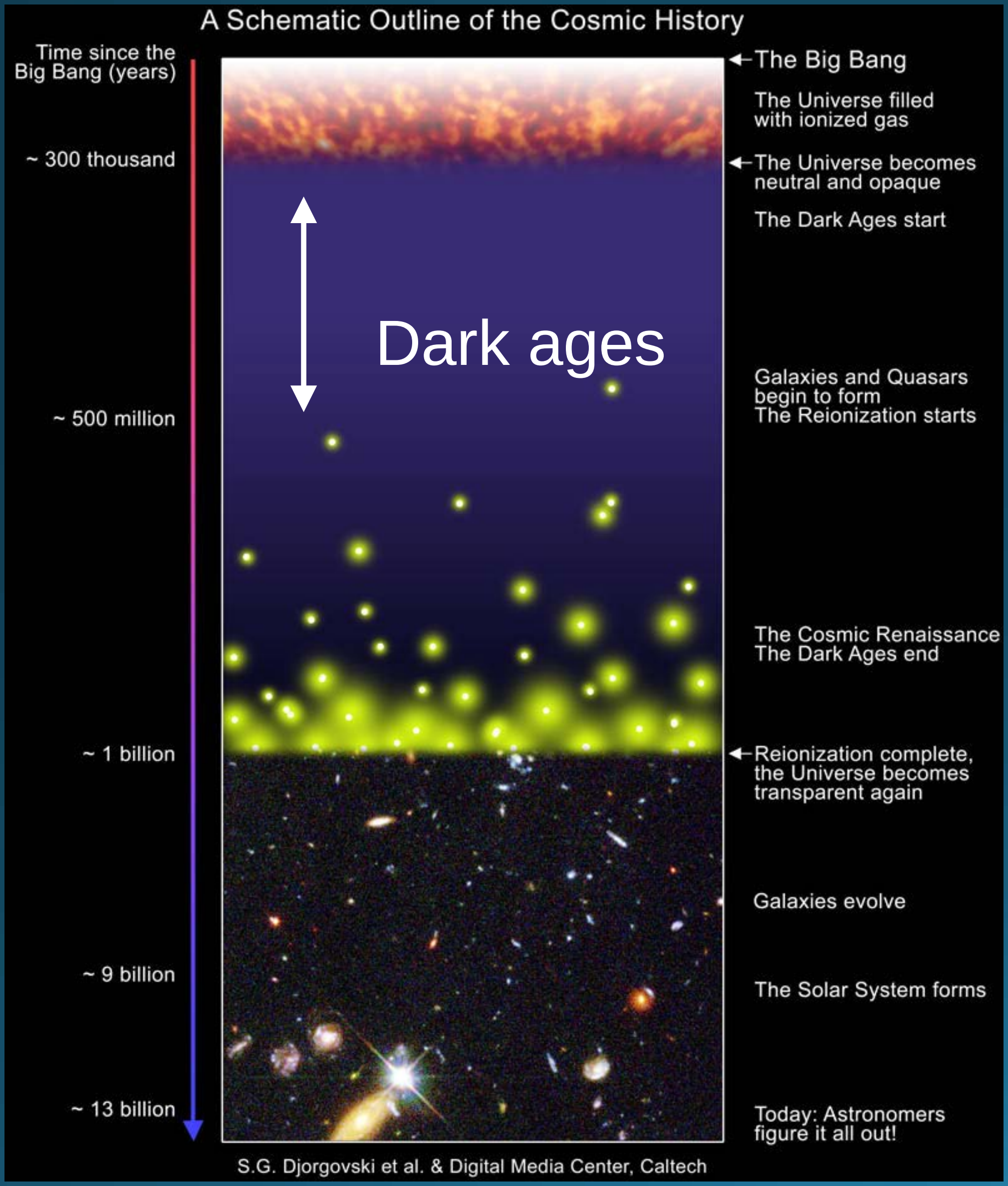
The most distant galaxies – so far





Snapshots of galaxies as they were about 500 million years after the Big Bang

The end of the Dark Ages



First stars

$z \approx 20\text{-}30$

$t_{Univ} \approx 100\text{-}200$ Myr

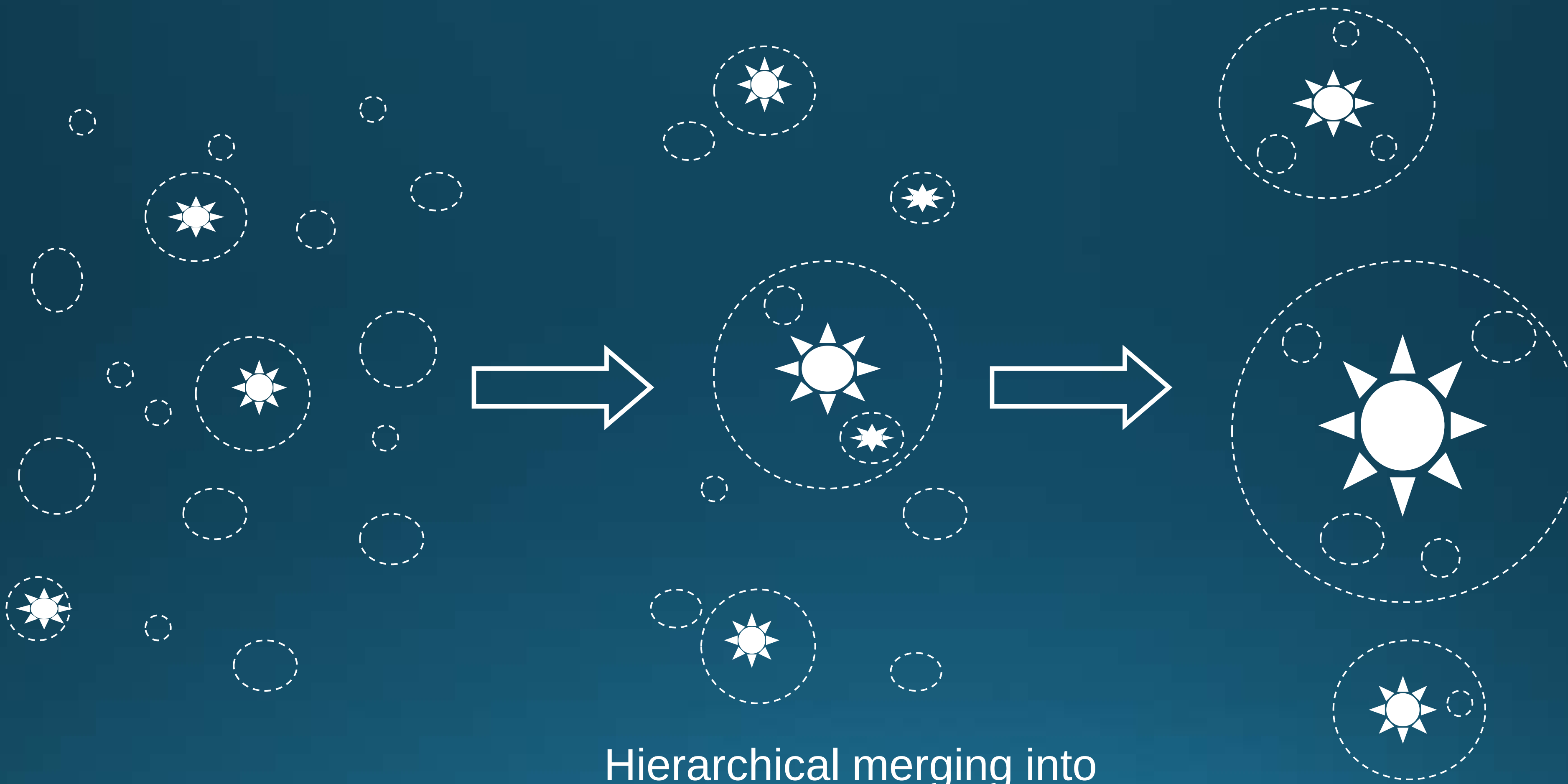
First galaxies

$z \approx 10\text{-}15$

$t_{Univ} \approx 300\text{-}500$ Myr

Intermission: What is this?

Cold Dark Matter →
Hierarchical galaxy formation



Dark matter halos
with some star formation

Hierarchical merging into
bigger and bigger halos
and galaxies. Mergers
induce new star formation.

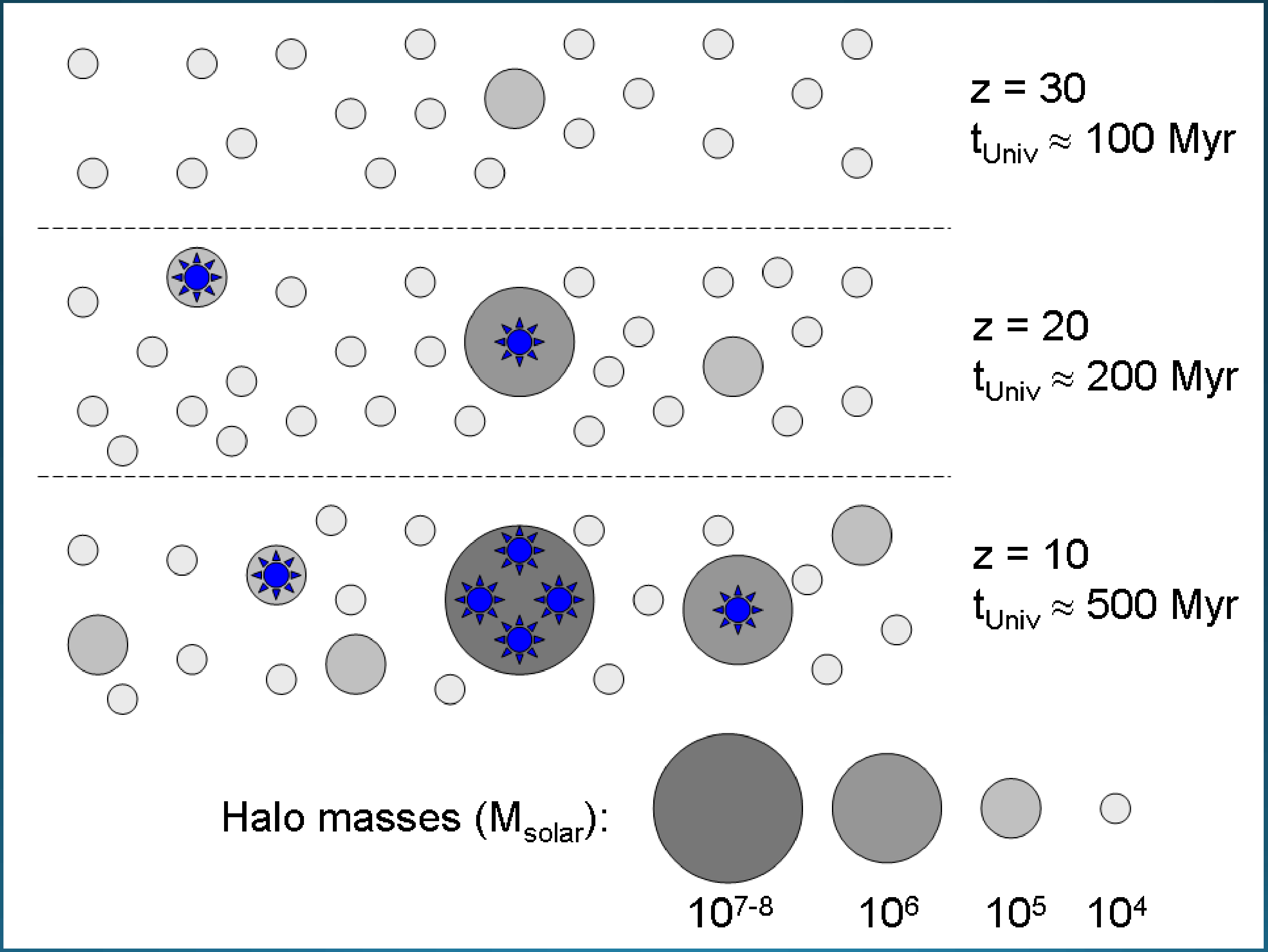
Today

The first stars and galaxies

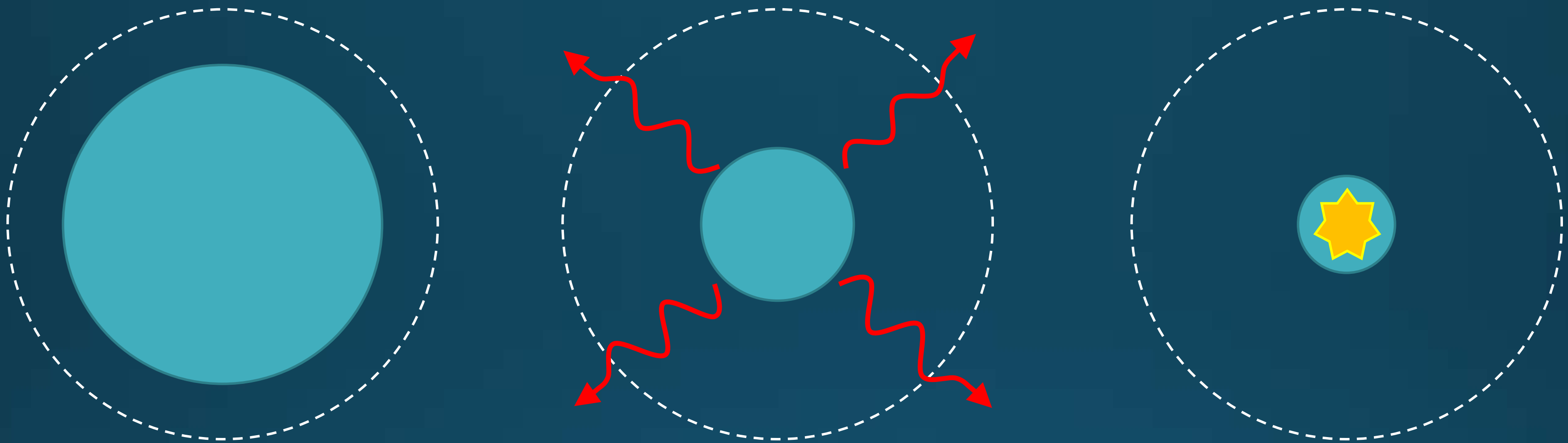
Minihalos

First stars (in minihalos)

First galaxy



Pop III stars forming in minihalos



Metal-free gas in a 10^5-10^6 Msolar halo (“minihalo”) at z=20-30

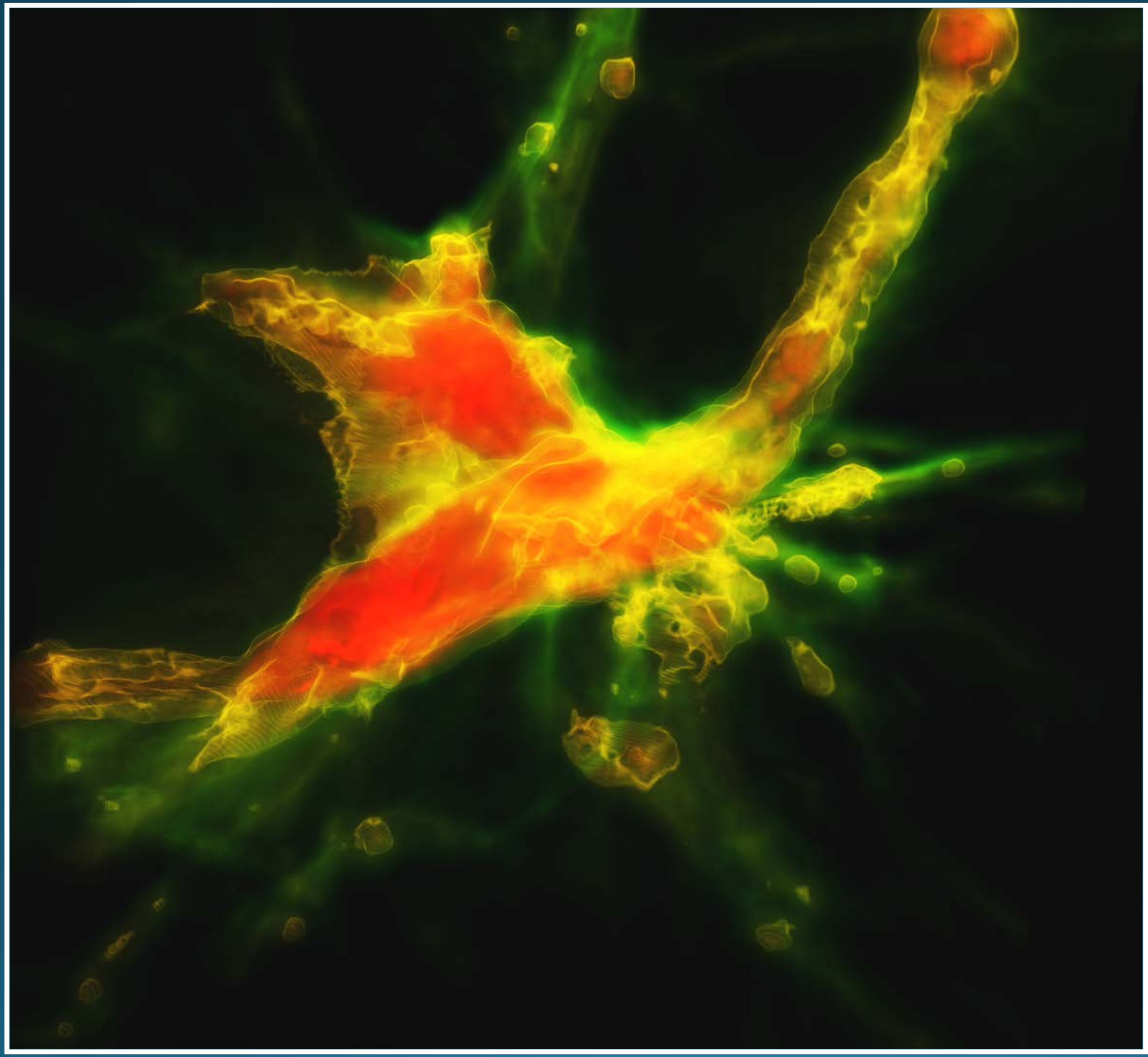
Radiative cooling → gas collapses towards the center

Small number of pop III stars formed (possibly just one)

Lack of metals at high z → Star formation relies on molecular cooling

Limited fragmentation → Pop III stars very massive (~10-100 Msolar)

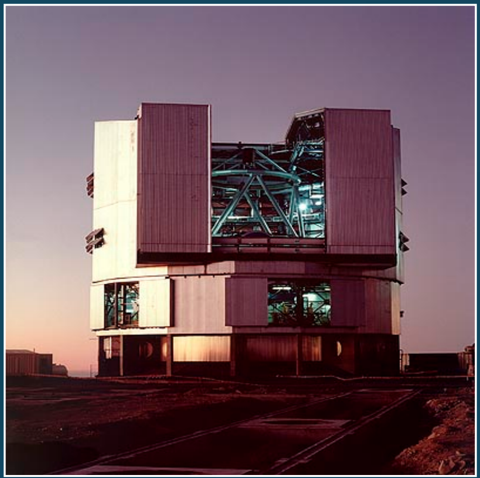
Intermission: What is this?



Hunting for the first stars and galaxies

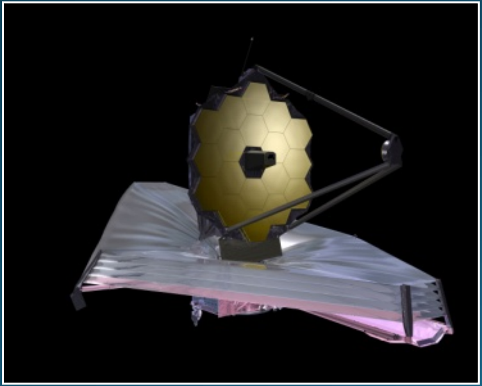
Now

HST

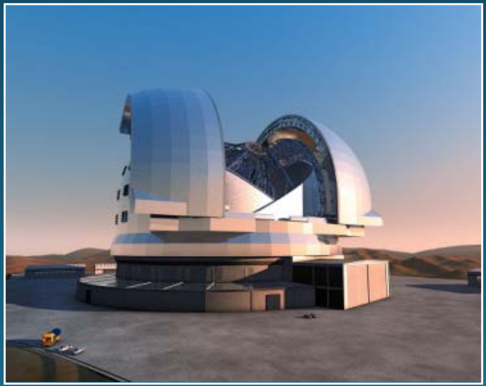


VLT

Future

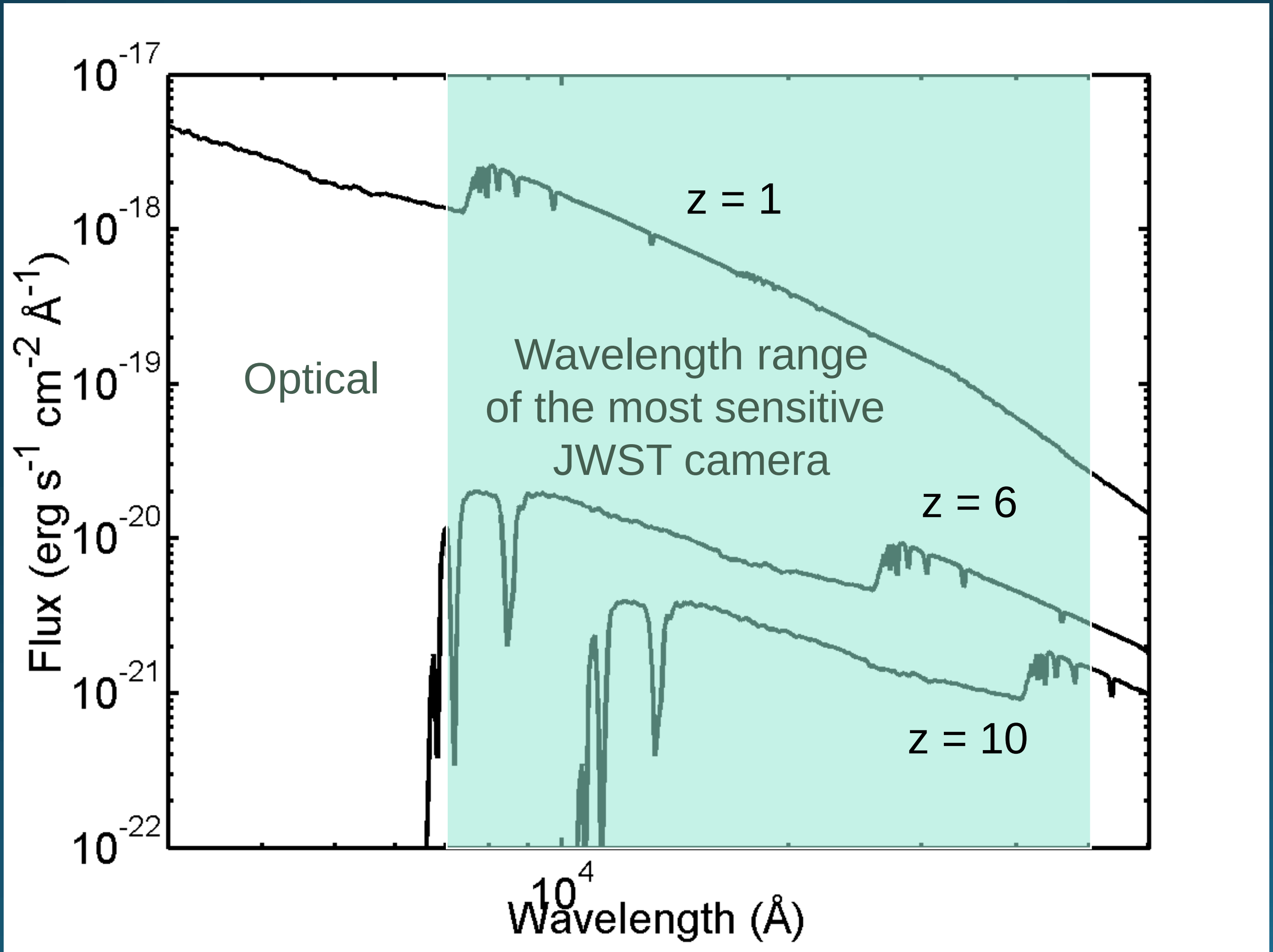


JWST (2019)

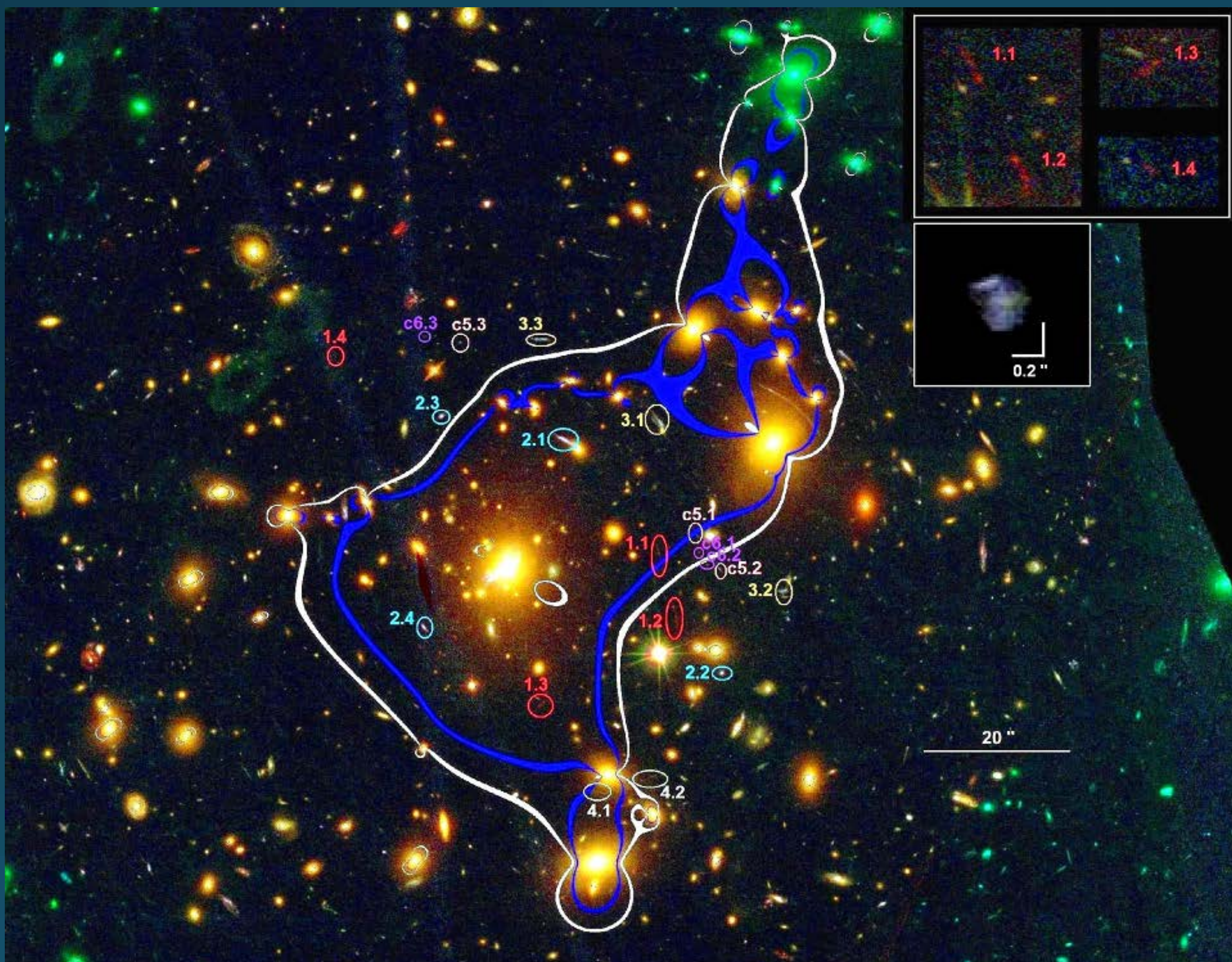


ELT (2024)

Infrared – the prime wavelength range for studying the first galaxies

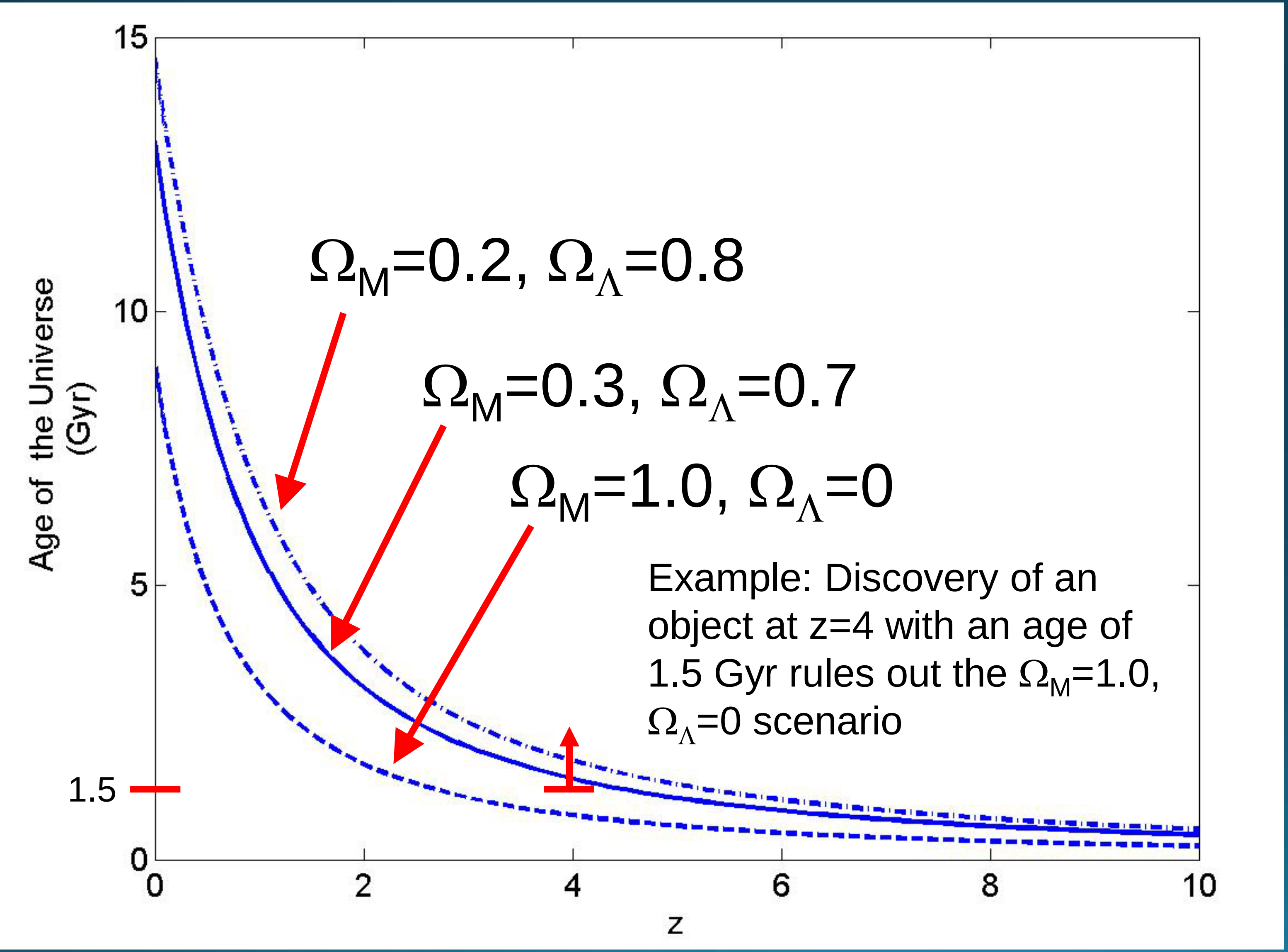


Gravitational telescopes



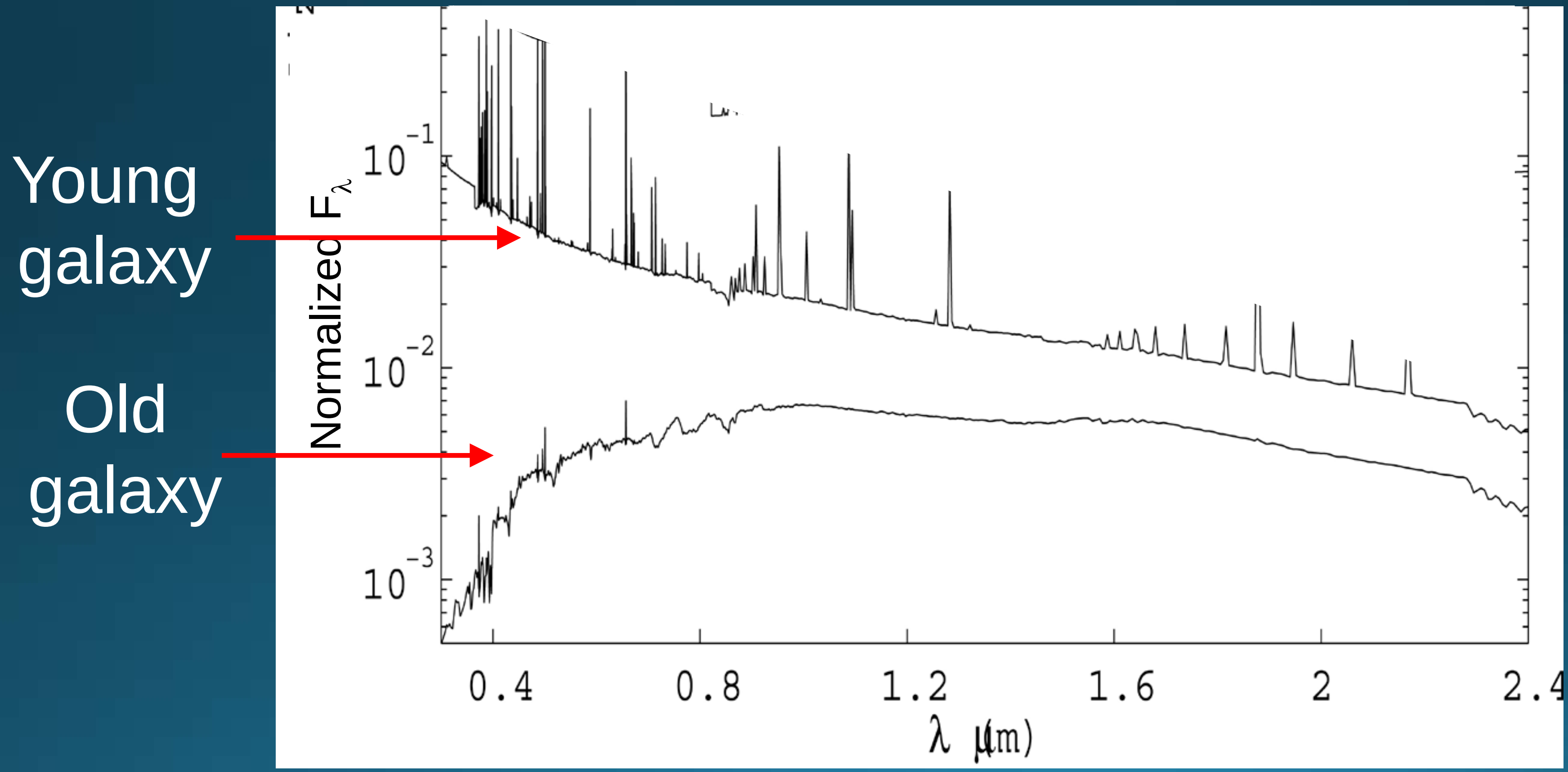
Foreground galaxy cluster magnifies background objects → Objects otherwise too faint to be detected can be seen

High-Redshift Objects as Probes of Cosmology: Ages



Spectroscopic age determinations of galaxies

Stars typically become redder when they grow older → The shape of the spectrum of a galaxy (containing billions of stars) is indicative of the age



Recap: Unsolved problems

- What drove inflation?
- What is the dark matter?
- What is the dark energy?
  - How will the Universe end?
- What were the initial conditions?
  - Why is the Universe expanding?
  - Why is there something instead of nothing?
- Why is there more matter than antimatter?
- Is the Universe spatially infinite?
- What caused reionization?
- What came before the Big Bang?
- Are there parallel Universes?