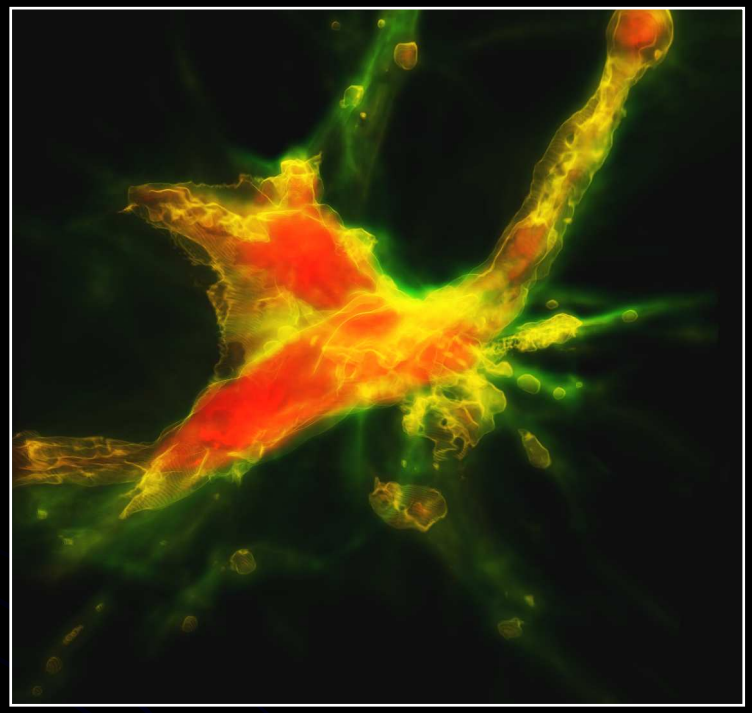
The First Galaxies



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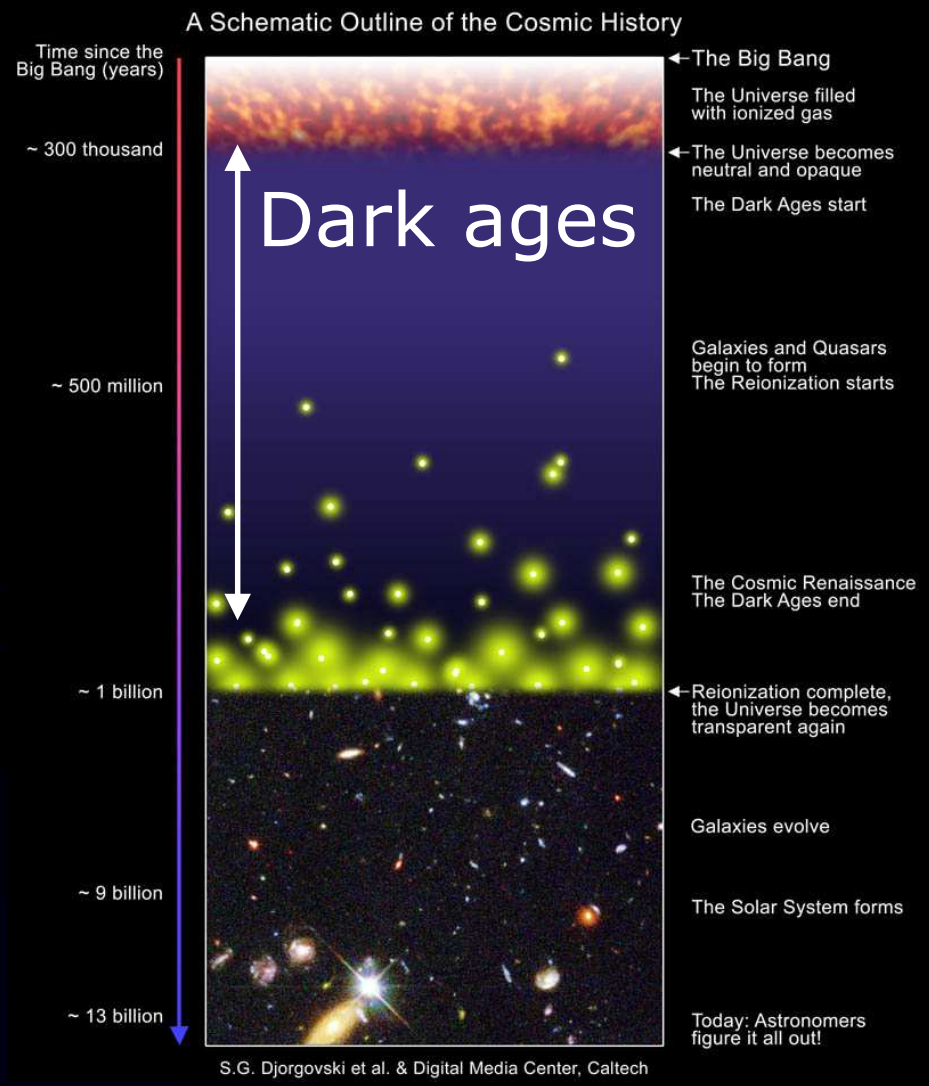
Outline

- The first galaxies – what, when, why?
- What's so special about them?
- Why are they important for cosmology?
- How can we detect them?

First galaxies – when?



First stars

$z \approx 20$

$t_{Univ} \approx 200$ Myr

First galaxies

$z \approx 10$

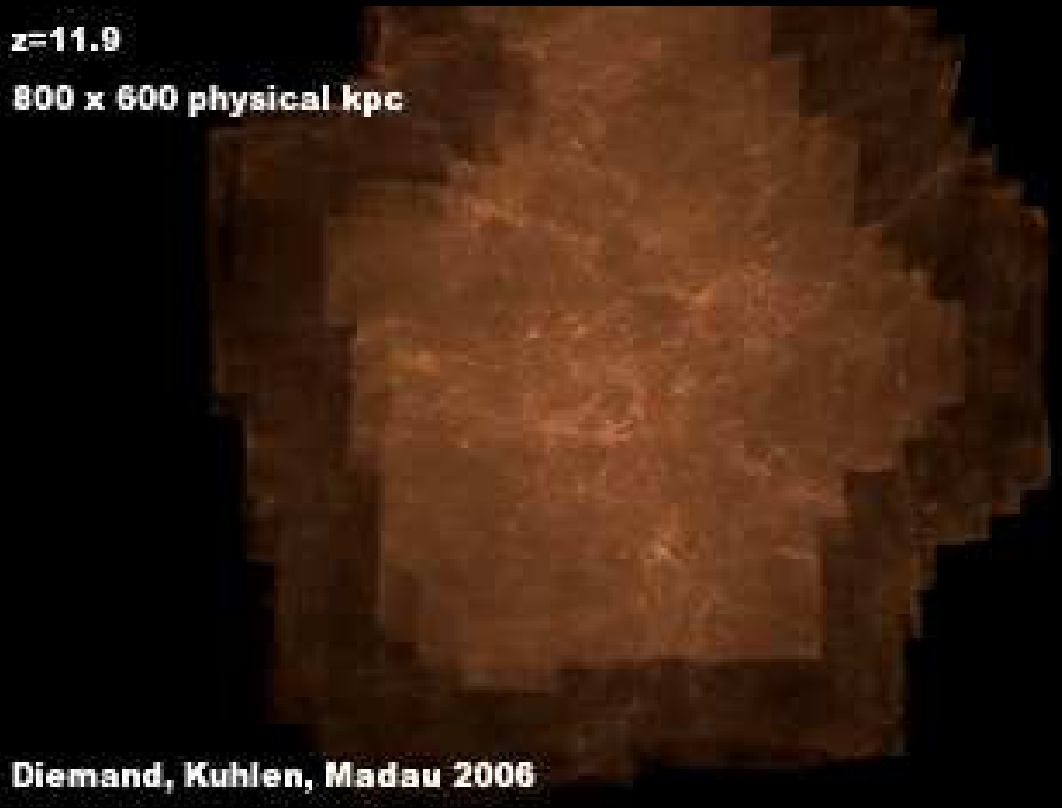
$t_{Univ} \approx 500$ Myr

HST and Keck have already started to detect *candidates* up to $z \approx 10$

The epoch of first galaxy formation

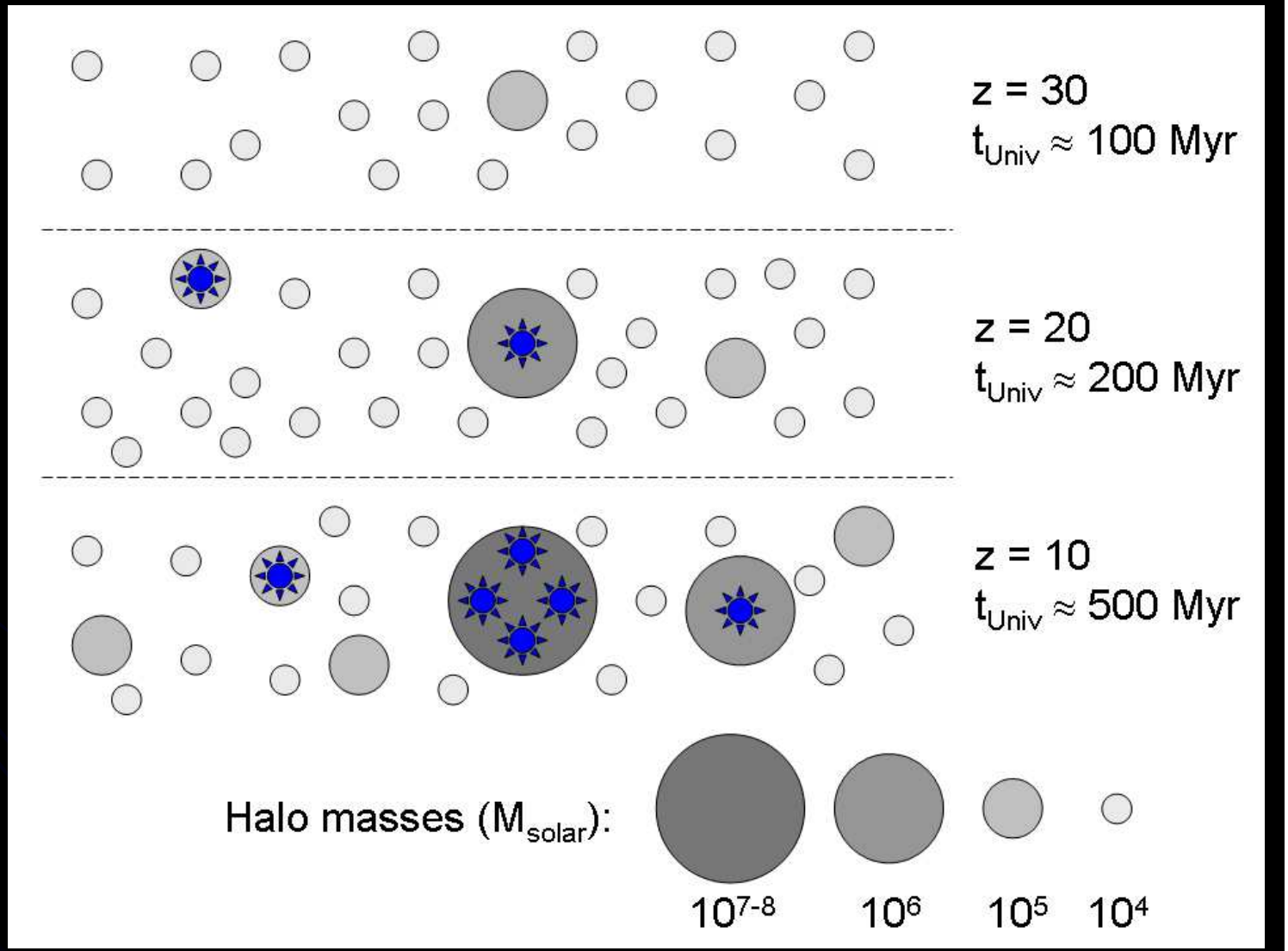
- The Universe is young (< 500 Myr)
- The metallicity is very low
- The matter is densely packed
  (more than 1000 times denser than today)
- Only low-mass dark matter halos around
  ($M < 10^8 M_{solar}$)

Merging cold dark matter halos



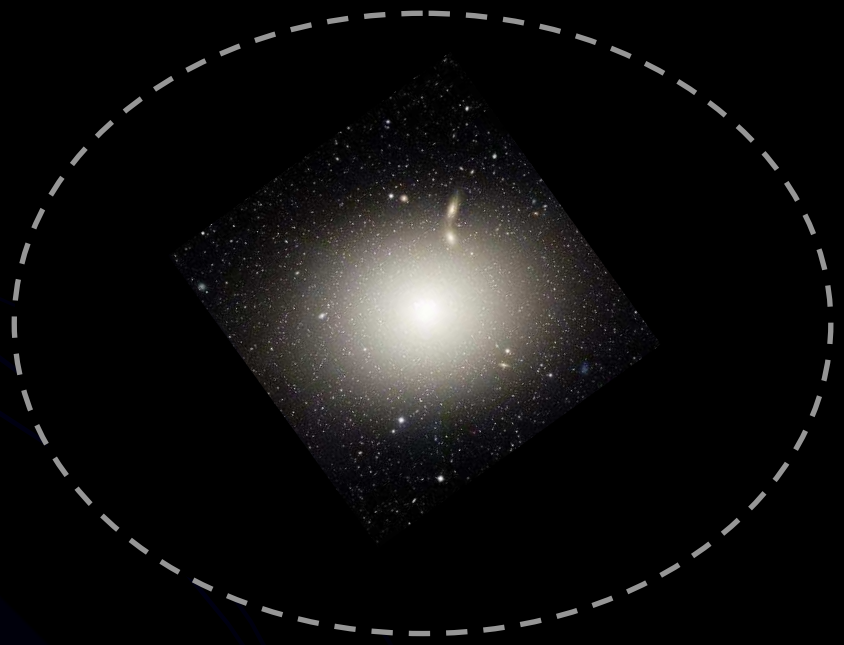
Formation of a ~10^{12} M_{solar} dark matter halo
Simulation runs from z ≈ 12 to 0 (t_{Univ} ≈ 0.25 to 13.7 Gyr)

Early times


Minihalos
First stars
(in minihalos)
First galaxy
z = 30
$t_{Univ} \approx 100$ Myr
z = 20
$t_{Univ} \approx 200$ Myr
z = 10
$t_{Univ} \approx 500$ Myr
Halo masses (M_{solar}):
10^{7-8}
10^{6}
10^{5}
10^{4}

What passes for a galaxy these days?

In the local Universe, galaxies are considered different from from star clusters because they have dark matter. But at high redshifts, even star clusters may be sitting inside dark matter halos…



Elliptical galaxy
(with dark halo)

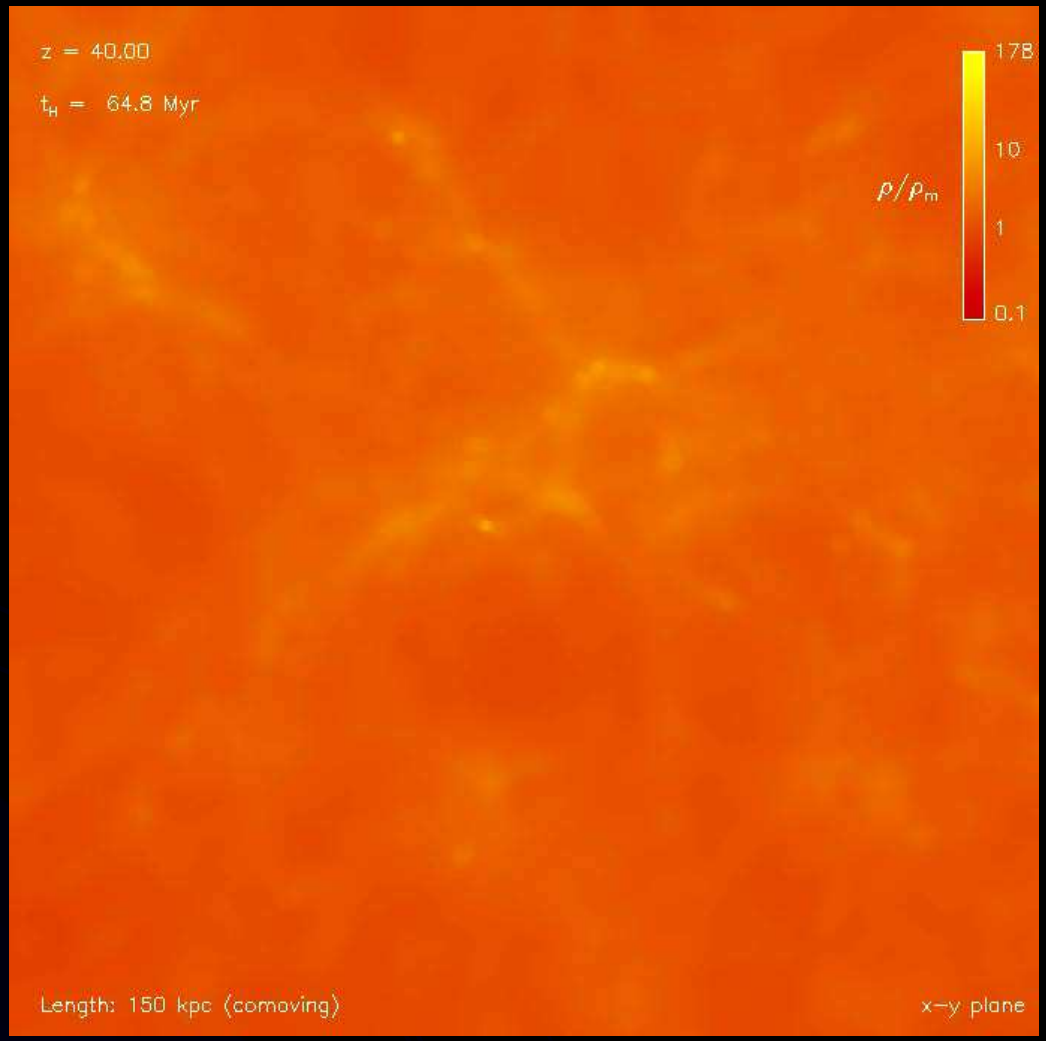
Globular cluster
(without dark halo)

Working definitions

- Galaxy at low redshift:
  Stellar system with *dark matter*
  $\rightarrow$ $M_{tot} > 10^{7} M_{solar}$
- Galaxy at high redshift:
  Object able to *retain photoheated gas* and *sustain continuous star formation*
  $\rightarrow$ $M_{tot} > 10^{7\text{-}8} M_{solar}$

To make things simple: Stellar system with dark matter and $M_{tot} > 10^{7\text{-}8} M_{solar}$

Formation of the first galaxies

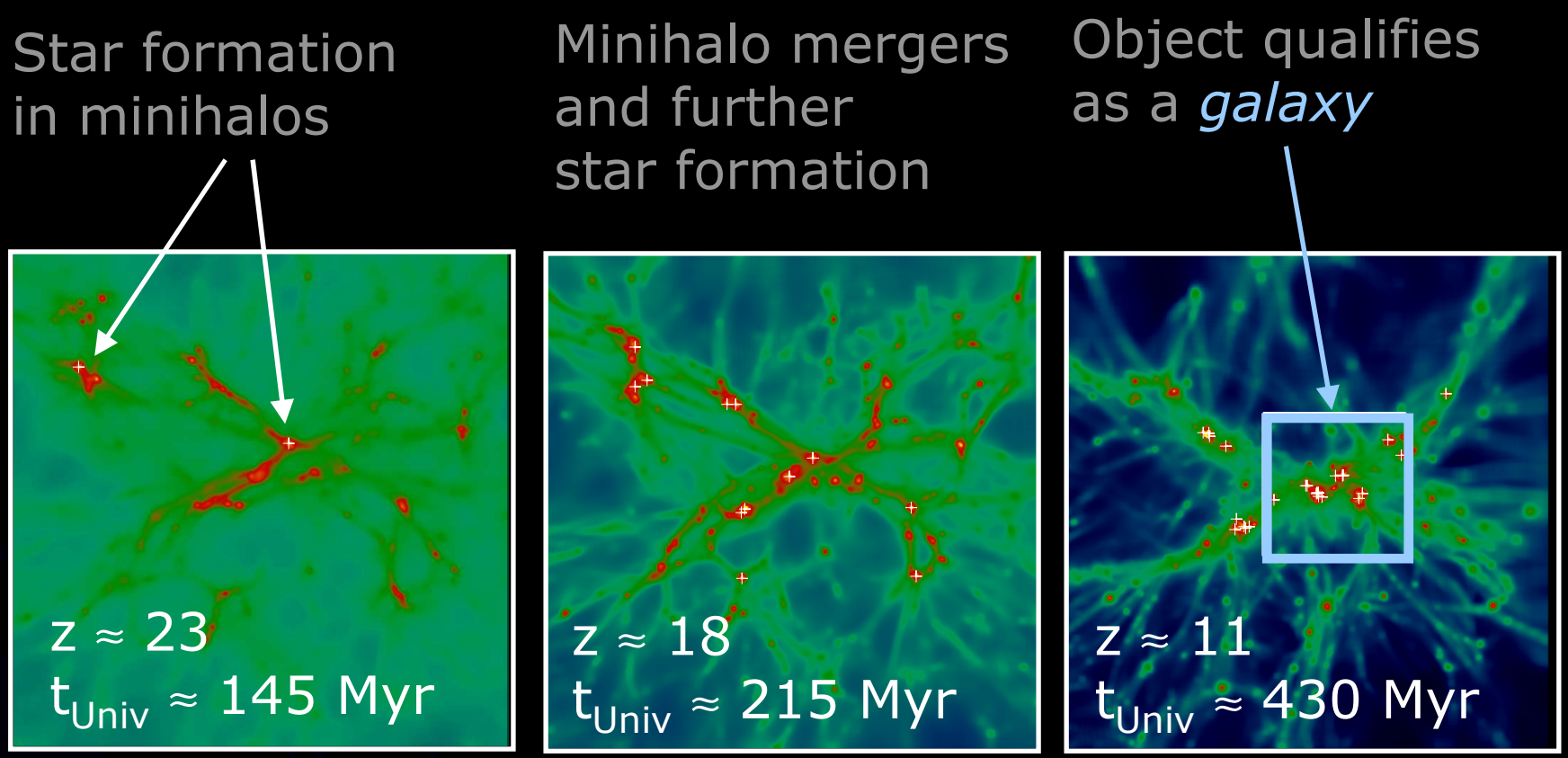


Formation of a
$\sim 10^7$ M_{solar}
dark matter halo

Simulation runs
from $z \approx 40$ to 11
($t_{Univ} \approx 65$ to 430 Myr)

Greif et al. 08

Star formation inside and outside the first galaxies

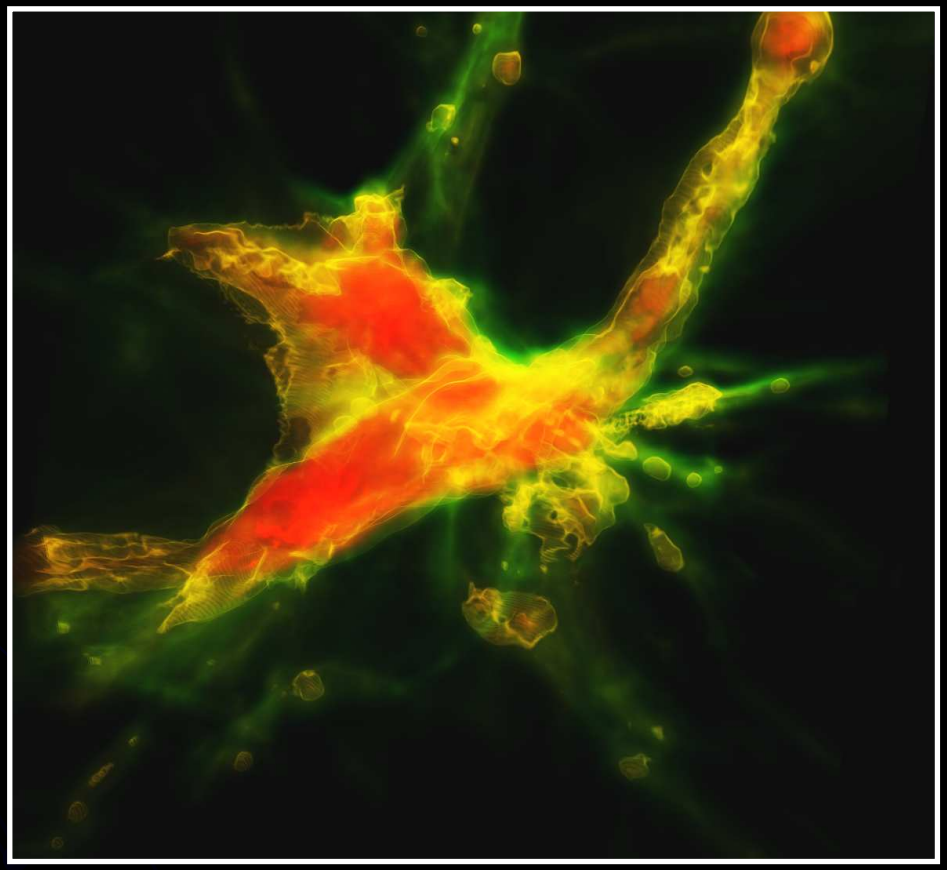


Greif et al. 08

Gas density shapshots

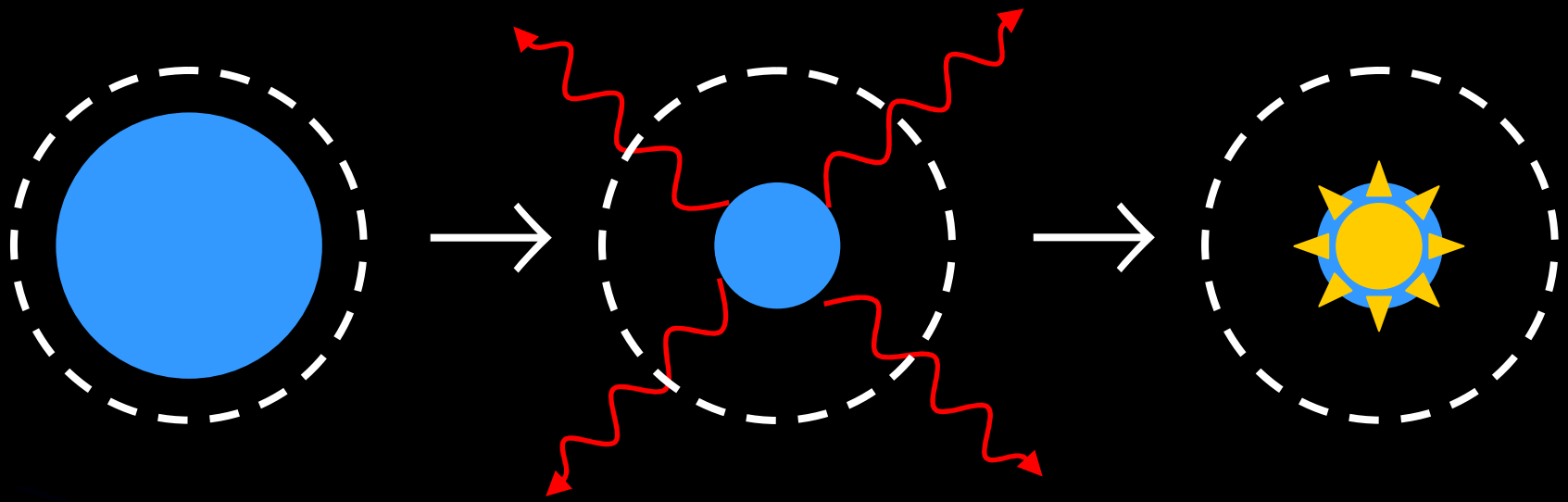
A galaxy is born (at z ≈ 10)

Highly irregular object at, but quite likely curious in other ways as well…



Greif et al. 08

Star formation in dark matter halos



Dark matter halo with gas inside

The gas cools by radiating photons and contracts

Star formation

Problem: Low metallicity at high redshifts $\rightarrow$
Lack of efficient coolants

Population I, II and III

- Population I: Metal-rich stars
  Example: Stars in the Milky Way disk
- Population II: Metal-poor stars
  Example: Stars in the Stellar halo of the Milky Way
- Population III: (Almost) Metal-free stars
  Example: Stars forming in minihalos at z~20

Population III stars

	Coolant	Type	Mass (M_{solar})	T_{eff} (K)	Lifetime (Myr)
Stage 1: $M_{halo}>10^5$ M_{solar}	H_2	III.1	100-300	~10^5	2-3
Stage 2: $M_{halo}>10^5$ M_{solar} + UV flux	HD	III.2	10-100	3×10^4 - 10^5	2-20

These stars will be *very massive*, hot and short-lived. The first ones are expected in minihalos – prior to the formation of the first galaxies. Feedback $\rightarrow$ *Only a few stars (maybe just one) per minihalo*.

Transition to population II

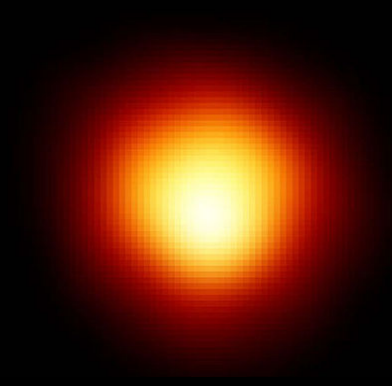
- Step 3: HI cooling in $M_{DM} > 10^7 M_{solar}$ halos Self-regulated star formation $\rightarrow$ *First galaxies!*
- Some population III stars may explode as supernovae $\rightarrow$ *Metal enrichment*
- $Z > 10^{-5}$-$10^{-3.5} \rightarrow$ Metal cooling efficient $\rightarrow$ Population II stars (typical mass $<1 M_{solar}$)

The first galaxies are likely to contain *both pop III and pop II stars*

Dark stars

WIMP annihilations may affect the formation of pop III stars in the centres of minihalos $\rightarrow$ Pop III star fueled by WIMP annihilation alongside fusion

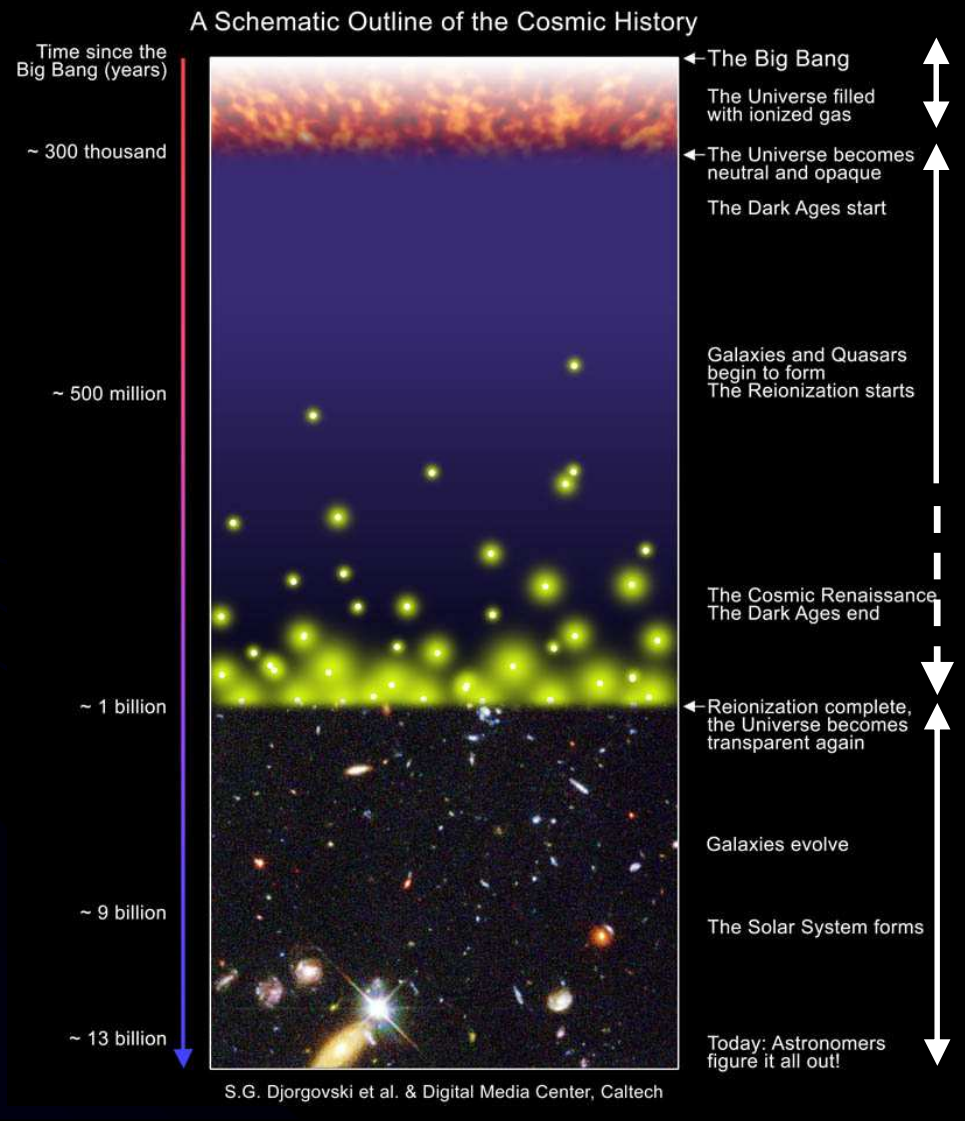
	Pop III.1 star	Dark star
T_{eff}(K):	100 000	5 000-30 000
Mass (M_{solar}):	100-300	100-1000
Luminosity (L_{solar}):	10^6-10^7	10^6-10^7
Lifetime (Myr):	2-3	Longer?



Recap

- Properties of the first galaxies:
  - Redshift $z \approx 10$
  - Low masses
  - Low metallicities
  - Irregular
  - May contain very massive stars

Reionization



Intergalactic medium

Ionized

Neutral

CMBR (WMAP)
$\rightarrow z_{reion} \approx 11$

Lyα absorption in quasars
$\rightarrow z_{reion} \approx 6$

Reionized

What caused reionization?

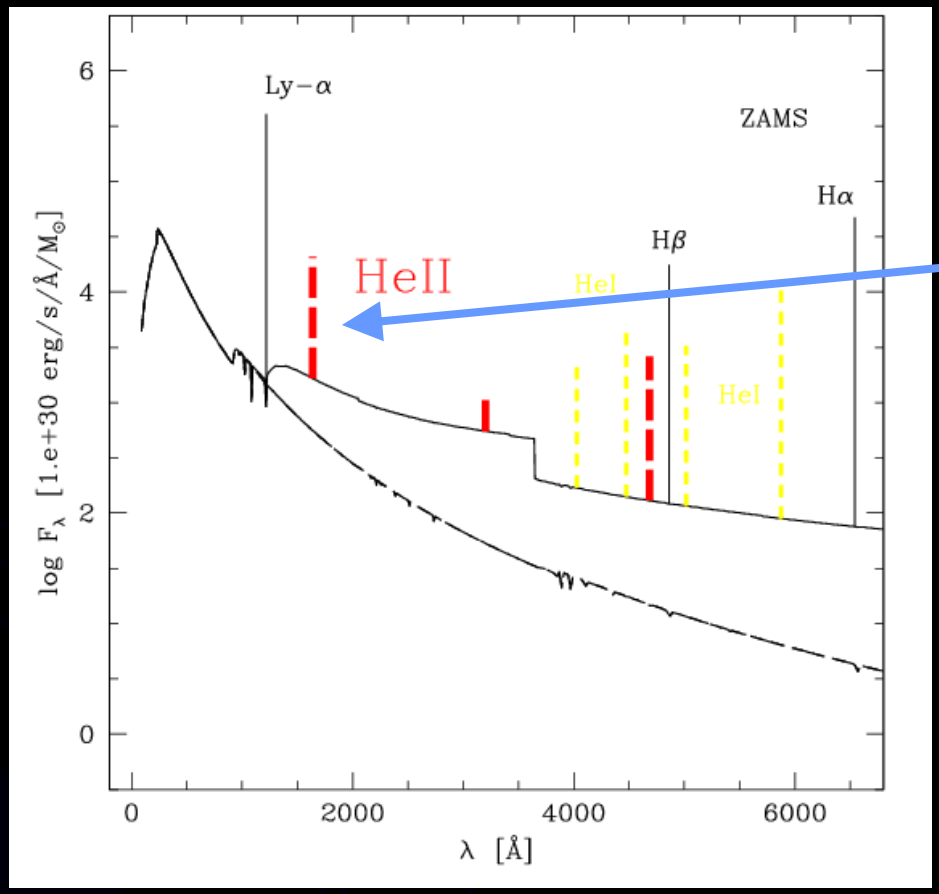
- Population III stars in minihalos?
- *First galaxies?*
- Miniquasars?
- Decay of exotic particles?
- Evaporating primordial black holes?

How much did the first galaxies contribute to reionization?

This depends on:

- The number density of galaxies at high z
  Observable!
- The Lyman continuum flux per galaxy
  Depends on age, Z, IMF, star formation history – *very tricky*
- The Lyman continuum escape fraction
  Can be probed observationally at z<6
  and by simulations at higher z

First galaxies as probes of pop III



Schaerer (2003)

Strong HeII @ 1640 Å means very hot ionizing continuum

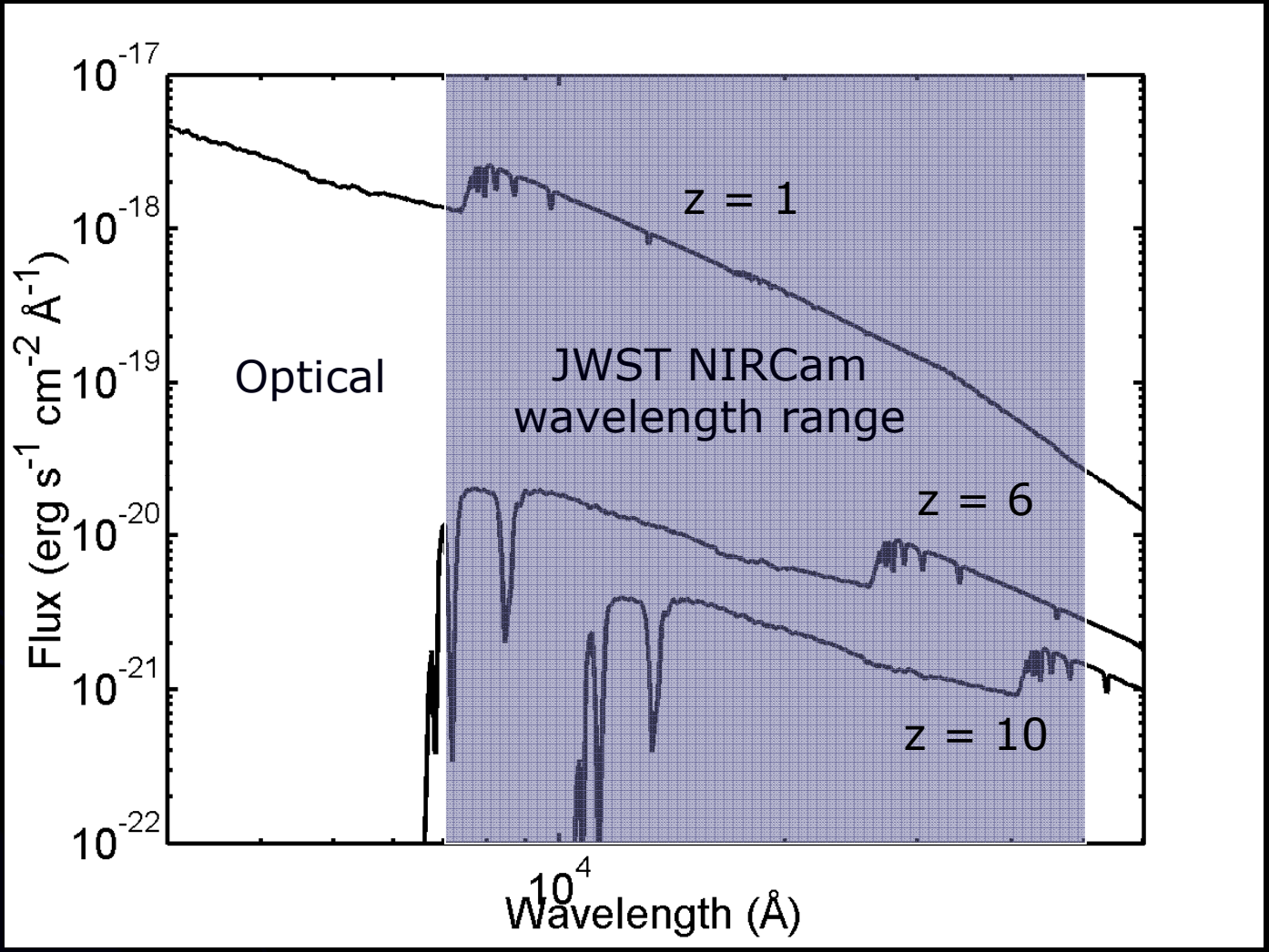
Pop III stars are difficult to detect one by one, but can alter emission-line ratios in the spectra of high-redshift galaxies

Detection prospects: JWST

James Webb Space Telescope
'The first light machine'
To be launched by
NASA / ESA / CSA in 2014

6.5 m mirror
Observations @ 0.6-29 μm

Why infrared?



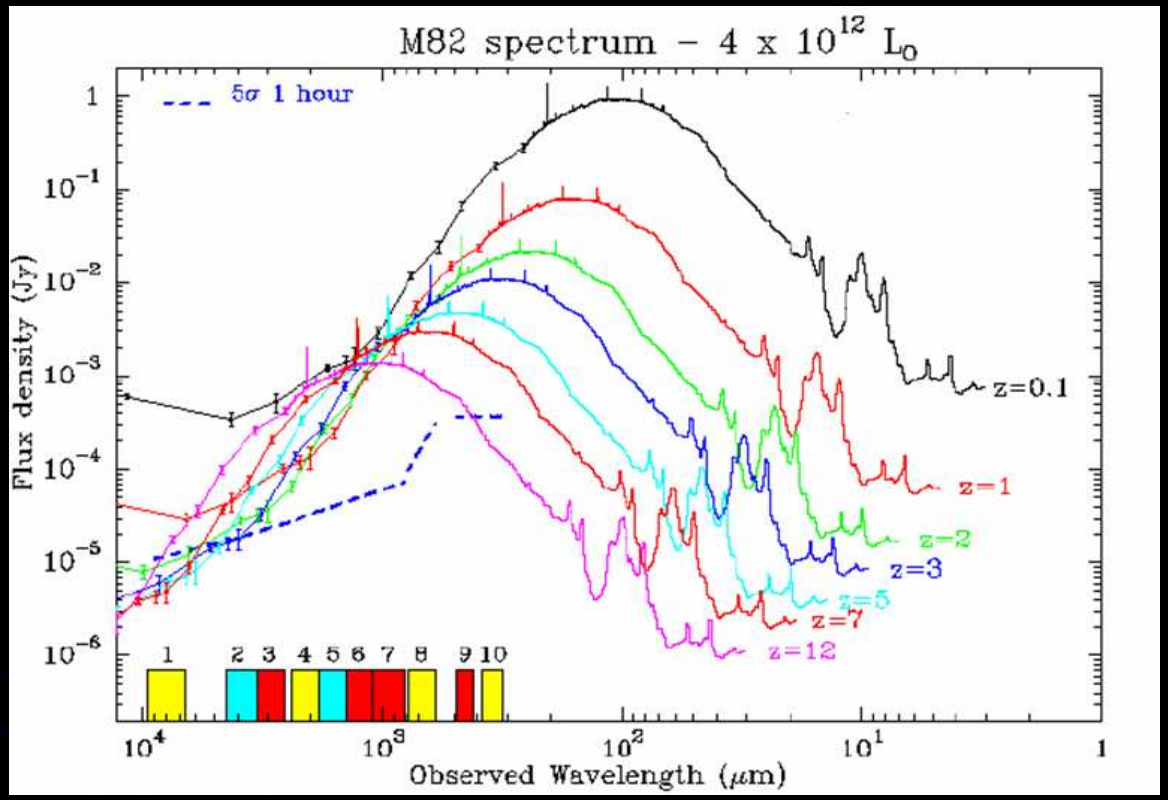
Zackrisson et al. (2001) model

Detection prospects: ALMA

Atacama Large Millimeter/ submillimeter Array
An array of seventy 12-m antennas operating @ 200-10000 μm (sub-mm)

To be completed by by ESO / NRAO / NAOJ in 2012

Dust continuum and the [CII] line



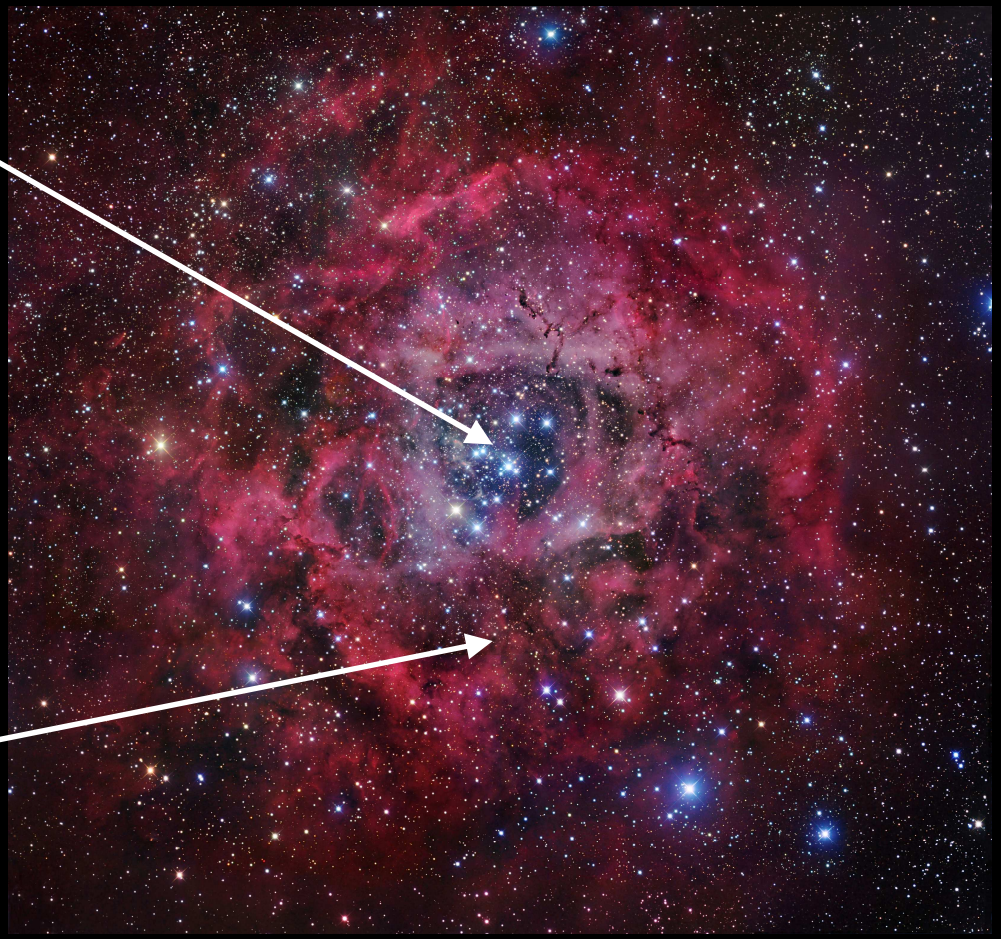
ALMA receivers

De Breuck 05

Dust continuum flux drops slowly with z
(if no source evolution)
Also useful up to z~8: [CII]158 μm line

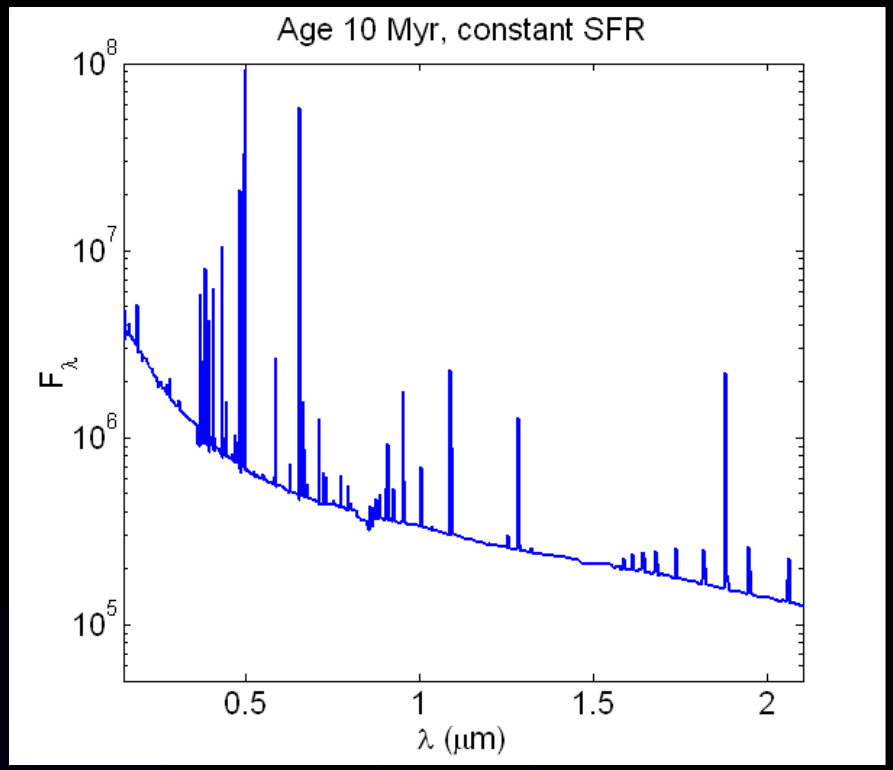
Nebular Emission from high-z galaxies

Young stars

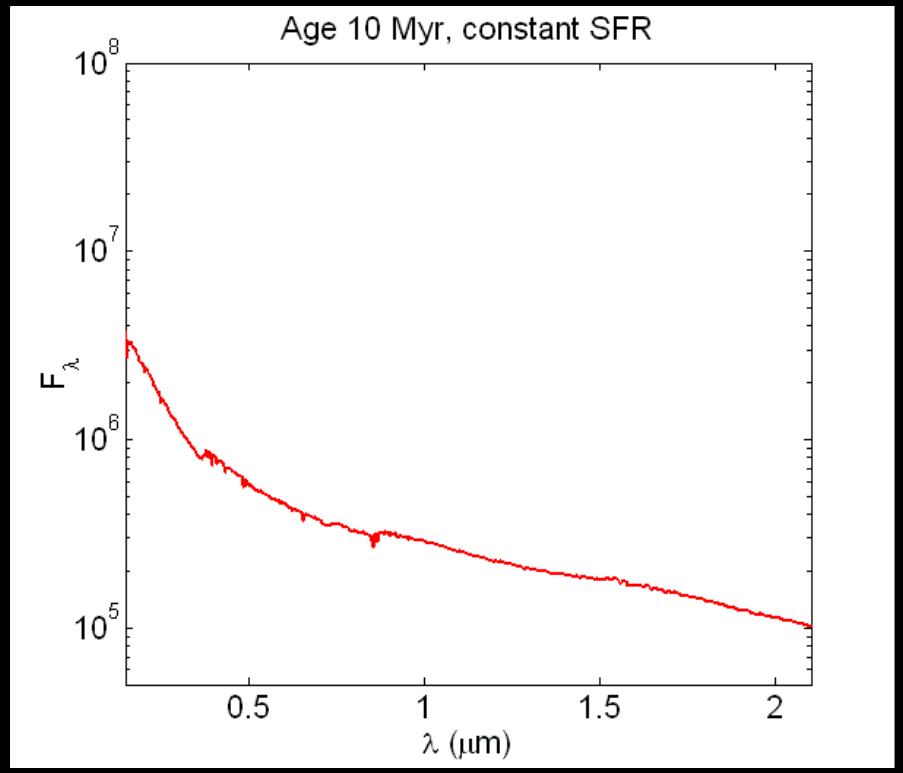


Photoionized gas

Nebular Emission from high-z galaxies II



Stars + nebula



Stars only

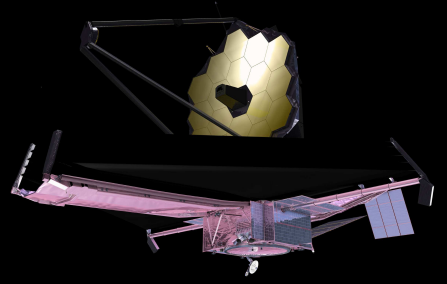
Summary

First galaxies – expected properties:

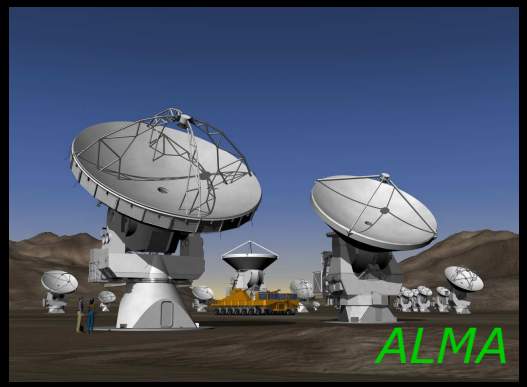
- Low-mass, low-metallicity objects at $z \approx 10$
- Likely to contain population III stars

First galaxies as probes of cosmology:

- Were the first stars very massive?
- Did the Universe form dark stars at high z?
- What caused the reionization of the Universe?



JWST



ALMA