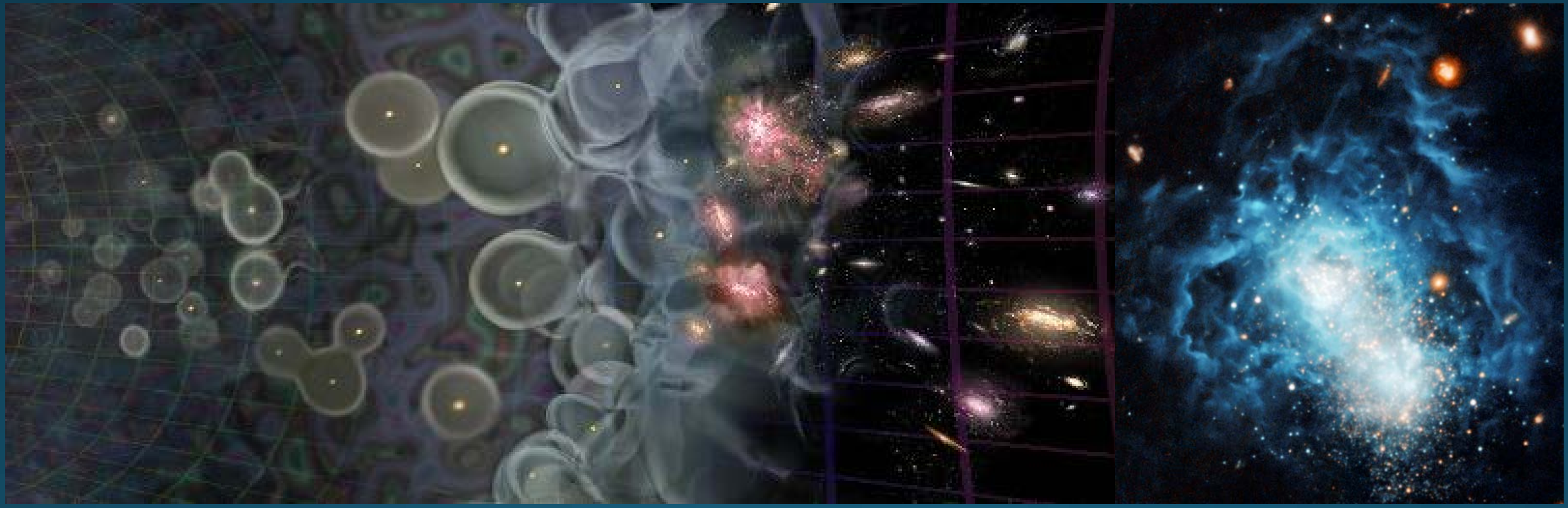
Physics of Galaxies, 2015
10 credits
Lecture 8: The High-Redshift Universe



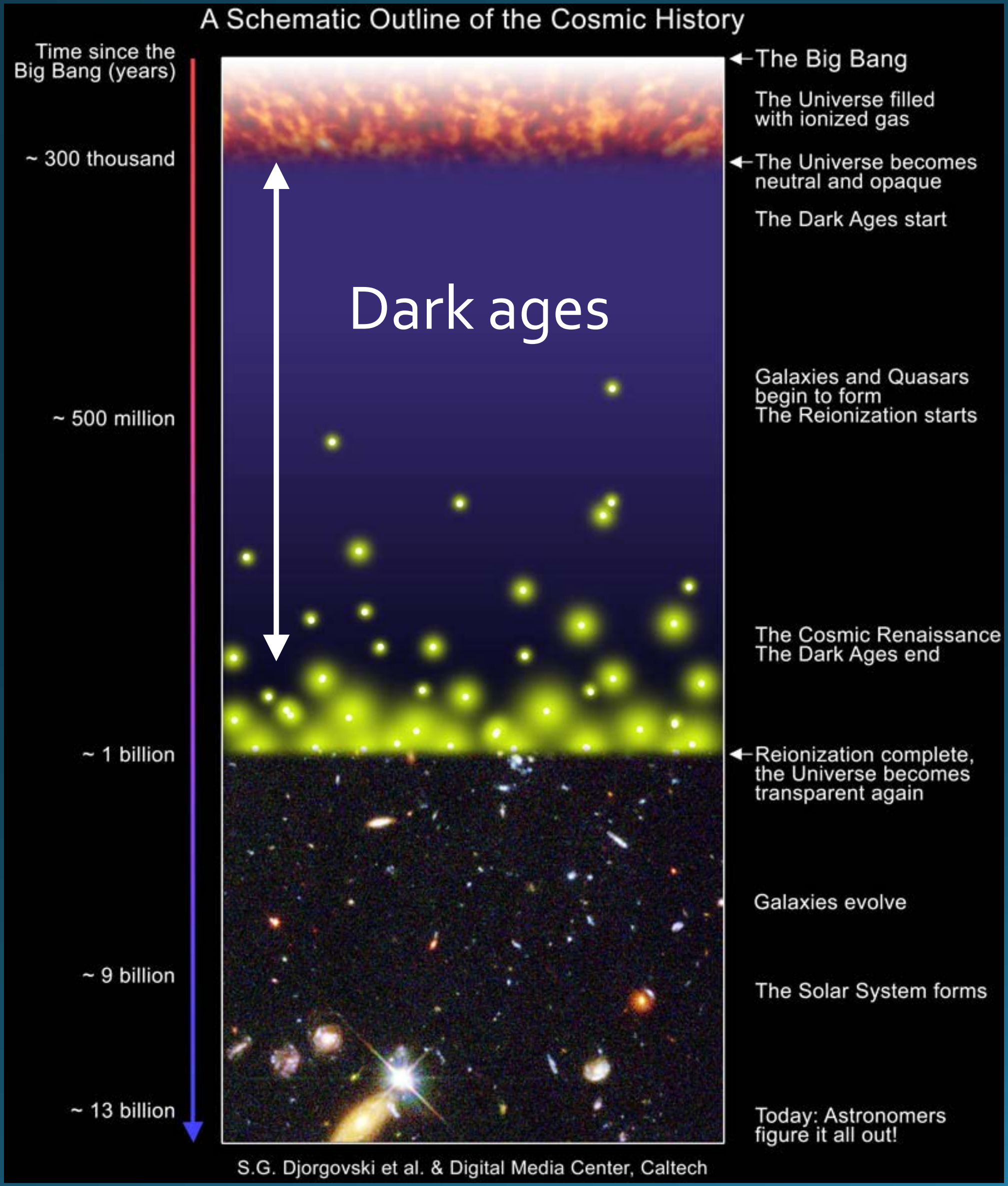
Outline: Part I

- The first stars and galaxies
  - End of the dark ages
  - Pop III stars
  - Dark stars
  - First galaxies

Outline: Part II

- Finding high-redshift objects
  - Deep fields
  - Gravitational lensing
  - Dropout techniques
  - Lyα searches
- Future prospects

The end of the dark ages



First stars

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

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

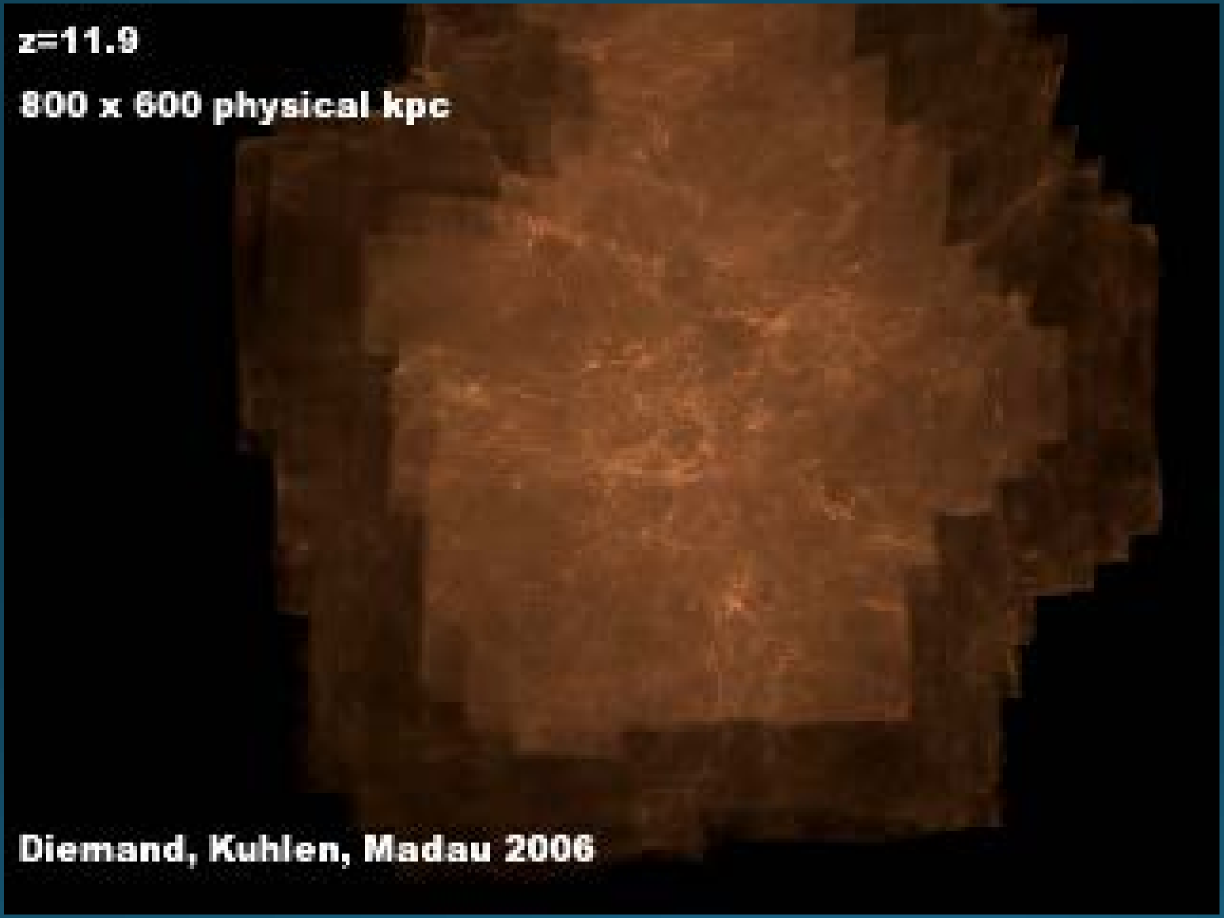
First galaxies

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

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

Current observational limit: HST and 8-10 m telescopes on the ground can detect light sources up to $z \approx 10$

Merging cold dark matter halos



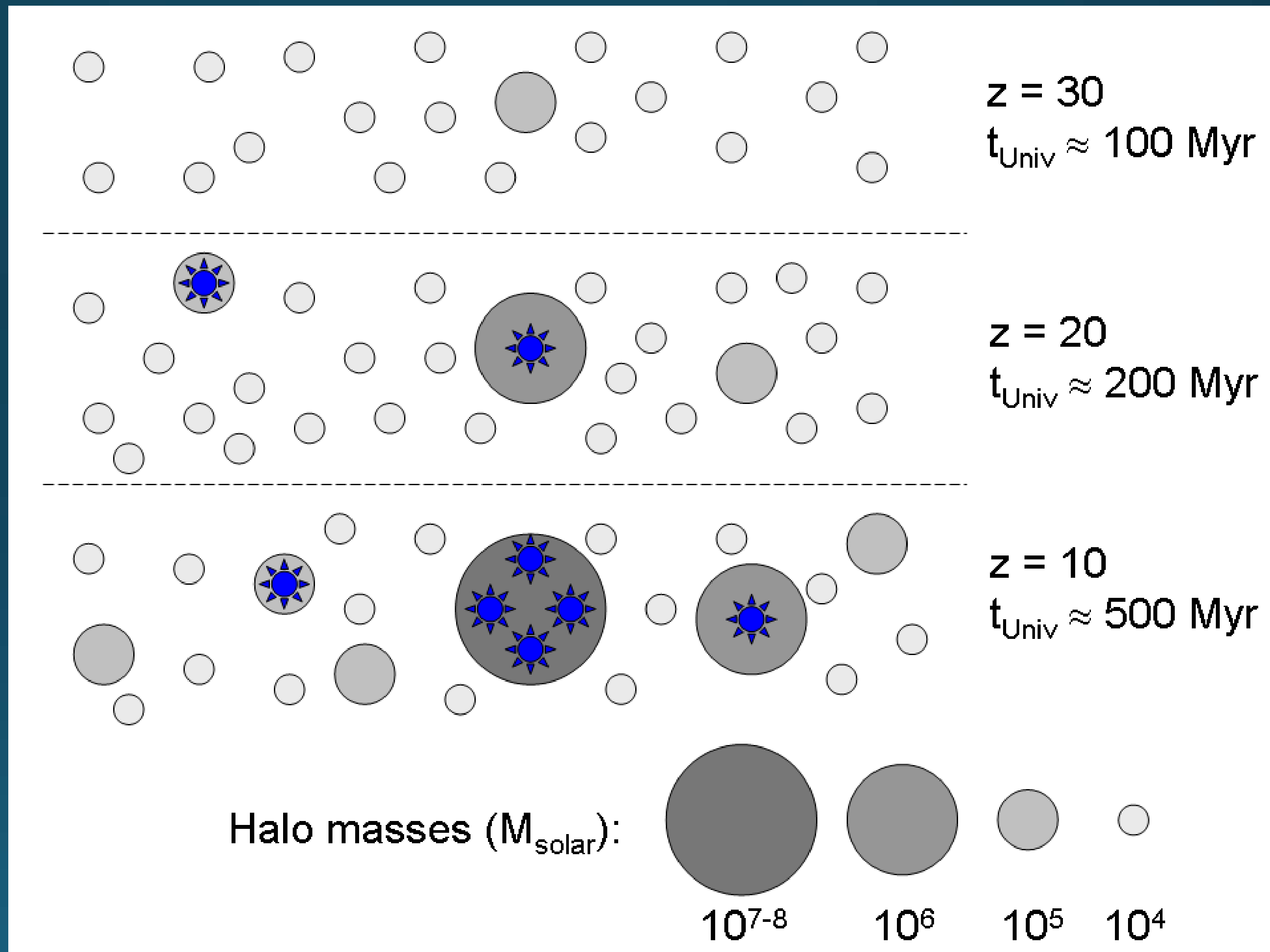
Formation of a ~10^{12} M_{solar} dark matter halo
Simulation runs from $z \approx 12$ to 0 ($t_{Univ} \approx 0.25$ to 13.7 Gyr)

Structure formation

Minihalos

First stars
(in minihalos)

First galaxy



Population I, II and III

- Population I: Metal-rich stars

  Example: Stars in the Milky Way disk

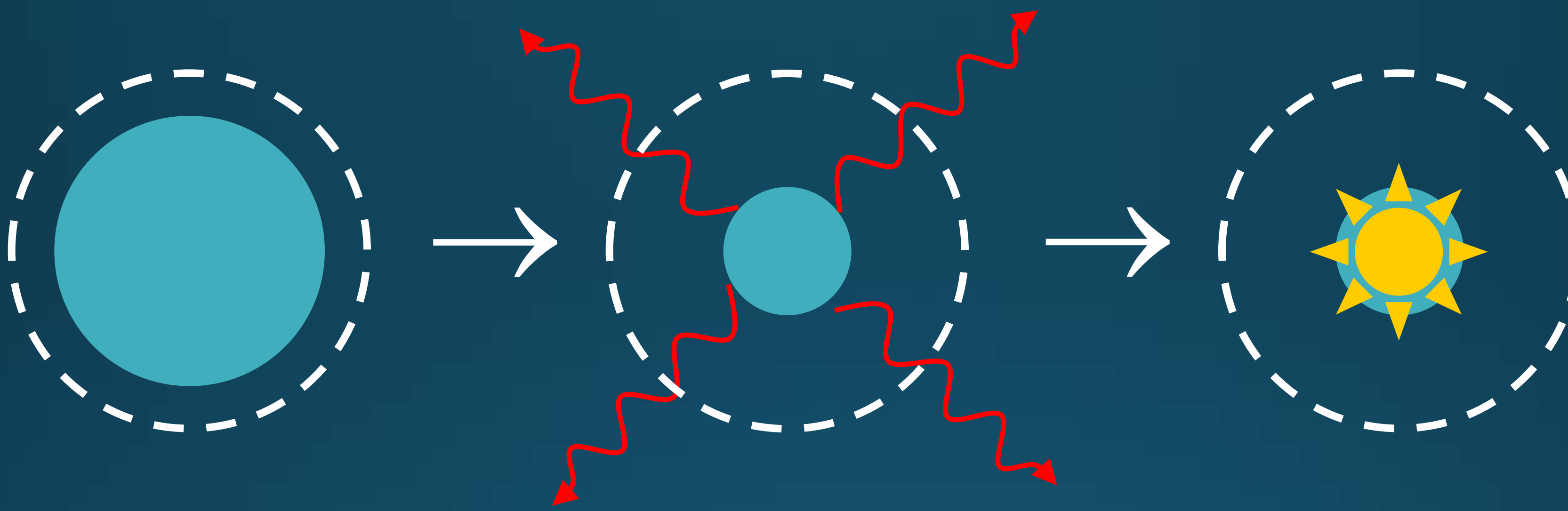
- Population II: Metal-poor stars

  Example: Stars in the Stellar halo of the Milky Way

- Population III: (Almost) Metal-free stars

  Example: Stars forming in minihalos at $z \approx 20$

Star formation in dark matter halos



Dark matter halo
with gas inside

The gas cools by
radiating photons
and contracts

Star formation

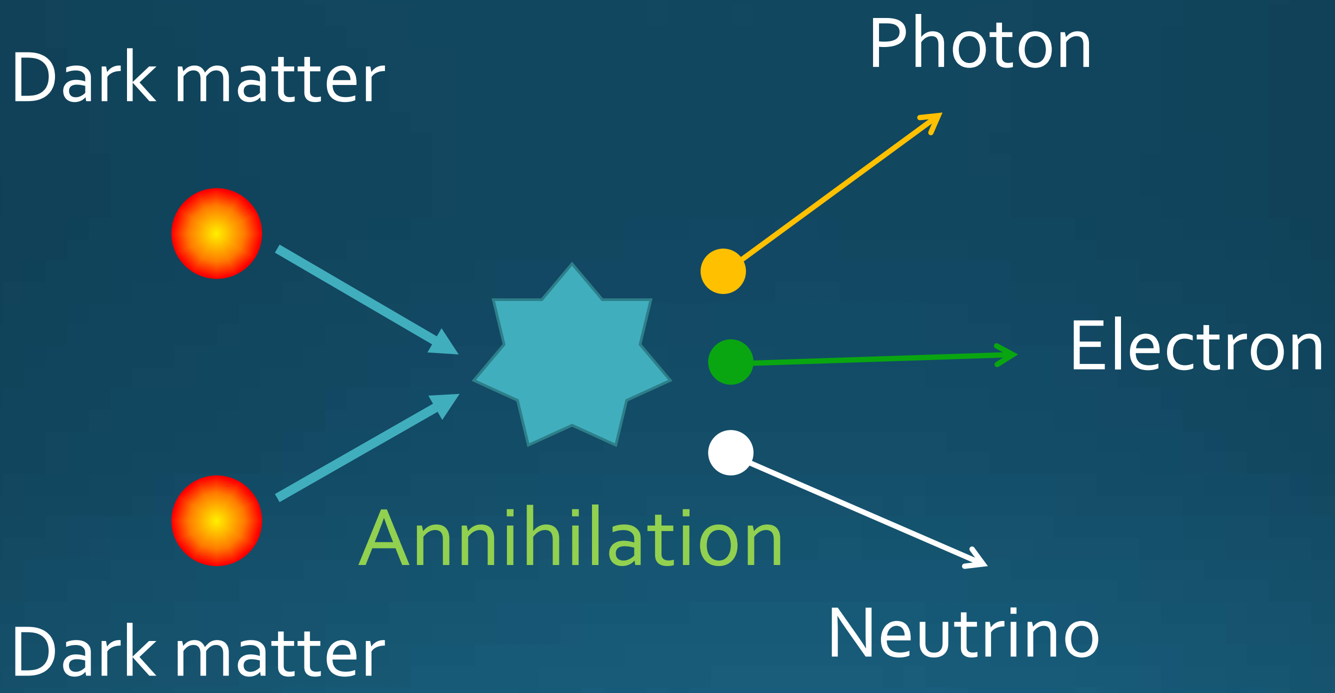
Problem: Low metallicity at high redshifts →
Lack of efficient coolants

Population III stars

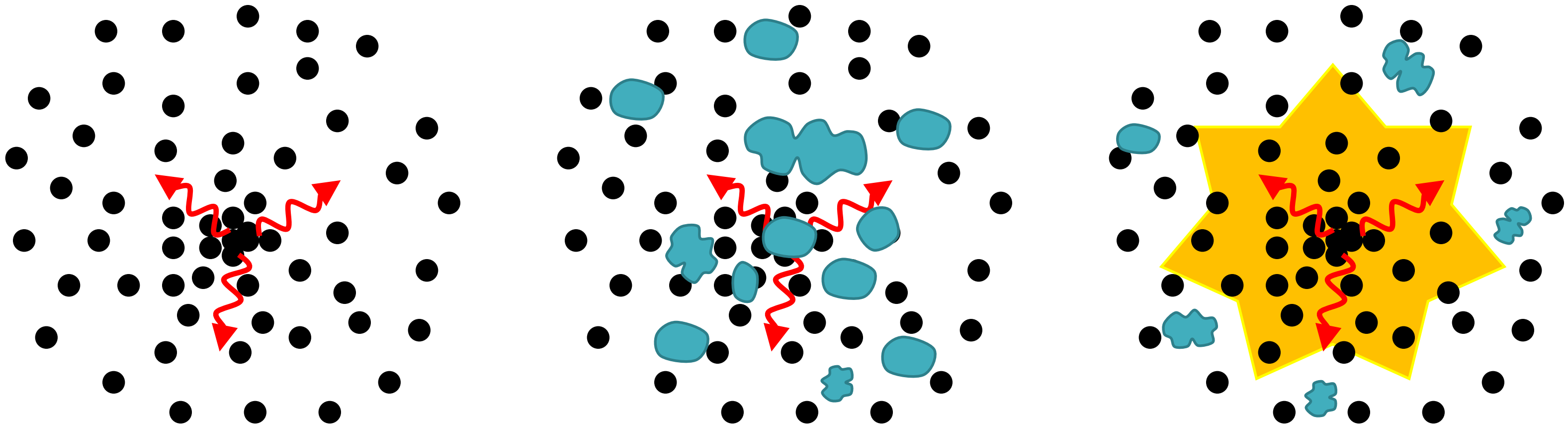
- These stars will be *very massive*, hot and short-lived.
- Mass range 10^1-10^3 Msolar (but predictions still shaky)
- The first ones are expected in minihalos – prior to the formation of the
  first galaxies.
- Feedback $\rightarrow$ *Only a few stars (maybe just one) per minihalo*

Normal star ≈ hydrogen bomb

Dark matter annihilation



Dark stars



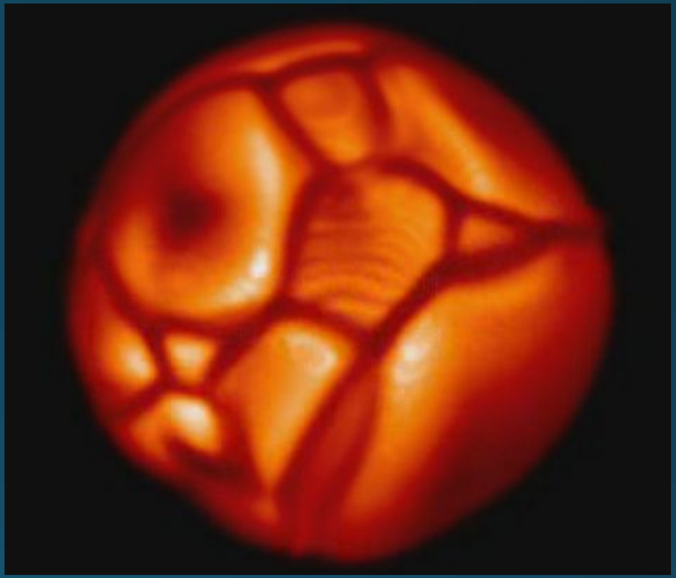
WIMP annihilation in centre of CDM halo

Gas cools and falls into the centre

Star fueled by WIMP annihilation rather than hydrogen fusion

Dark star properties

- Conventional Pop III stars
  - Teff $\sim$ 50 000-100 000 K
  - M $\sim 10^1$-10^3 Msolar
  - Lifetime $\tau \sim 10^6$-10^7 yr
- Pop III dark stars
  - Teff $\approx$ 4000-50000 K Cooler!
  - M $\sim 10^2$-10^7 Msolar More massive???
  - Lifetime $\tau \sim 10^6$-10^{10} yr More long-lived???



Problem: Still no consensus on likely masses or life times of dark stars

The sizes of primordial stars I

The Sun

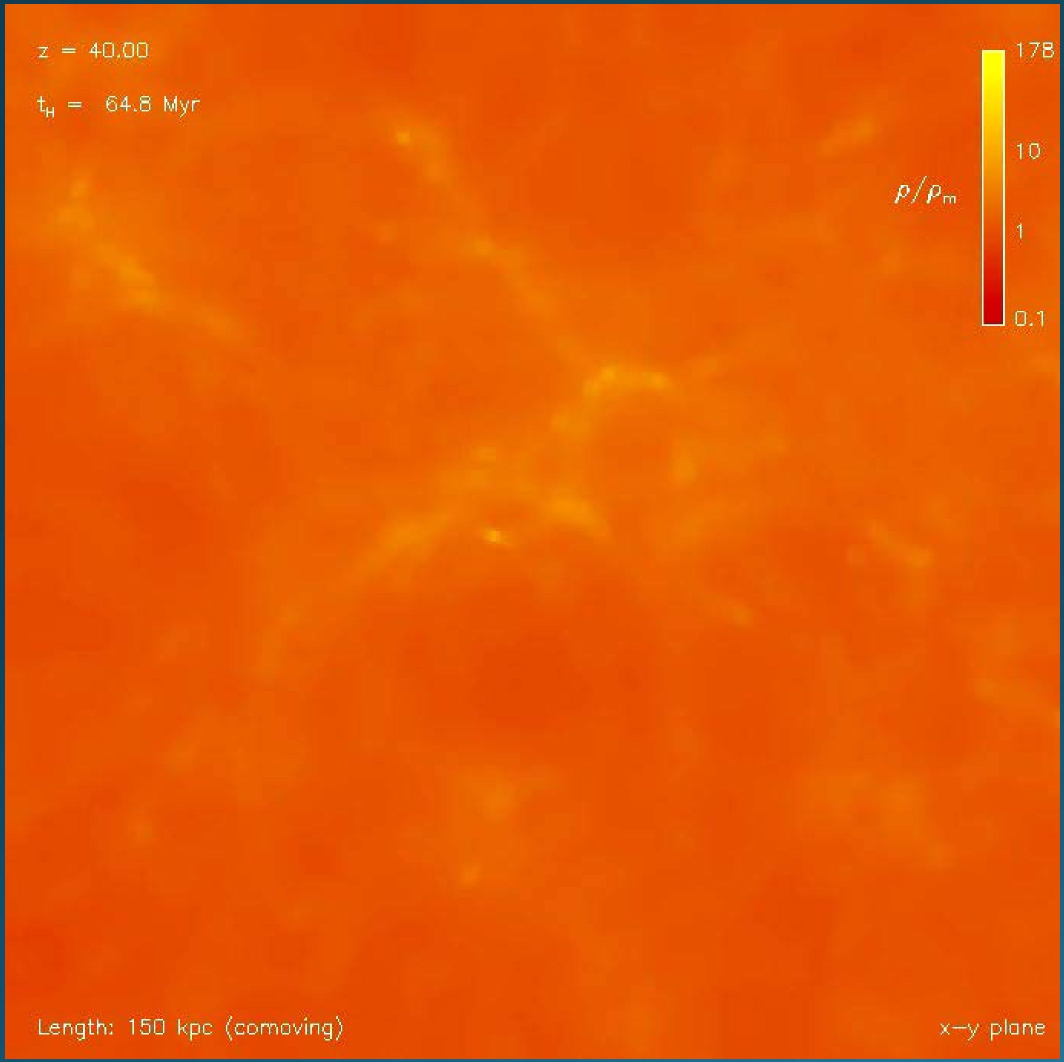
Vanilla population III star

The sizes of primordial stars II

The Sun

Supermassive dark star

Formation of the first galaxies



Greif et al. 08

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

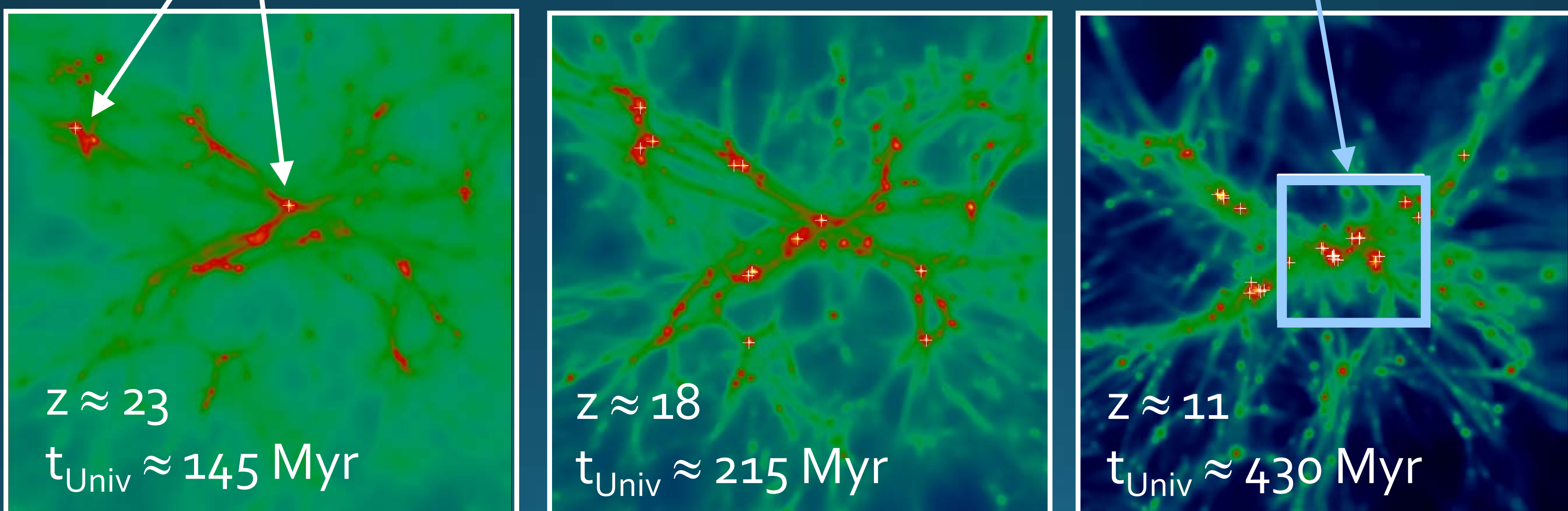
Simulation runs
from $z \approx 40$ to 11
($t_{Univ} \approx 65$ to 430 Myr)

Star formation inside and outside the first galaxies

Star formation in minihalos

Minihalo mergers and further star formation

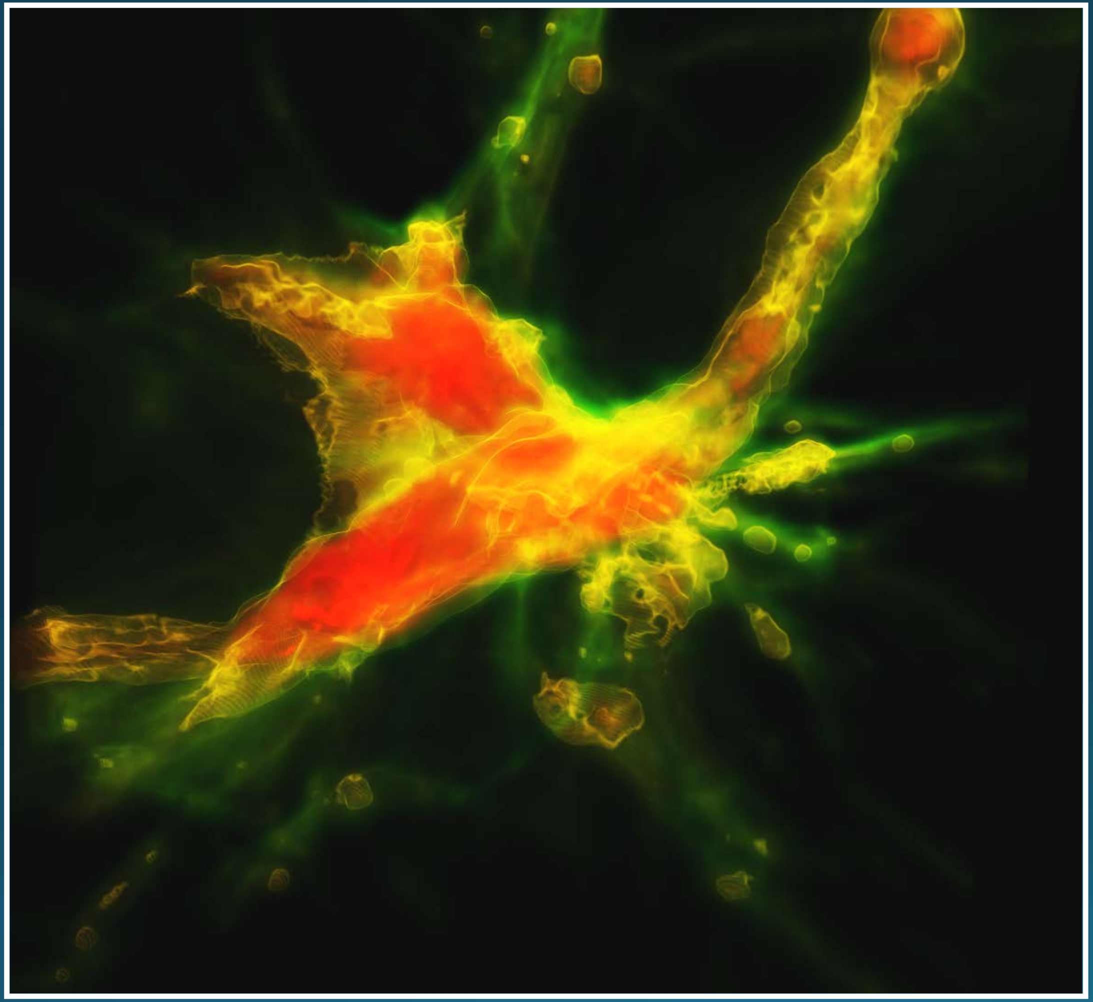
Object qualifies as a *galaxy*



Greif et al. 08

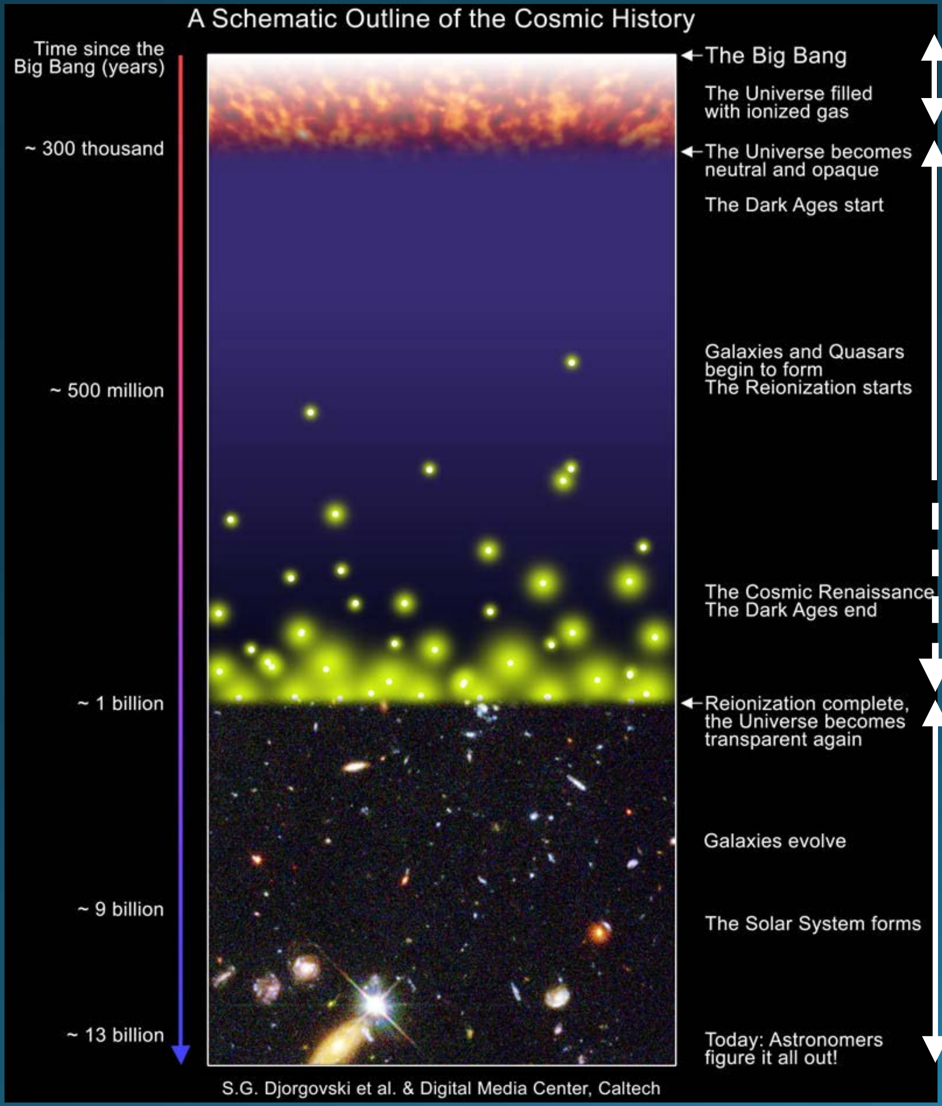
Gas density shapshots

A galaxy is born (at z ≈ 10)



Greif et al. 08

Reionization



<u>Intergalactic medium</u>

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?
- *High-redshift galaxies?* ← Popular scenario
- Accreting black holes?
- Decay of exotic particles?

How to find and study high-redshift galaxies

Imaging strategies

- Deep field-style observations
  - Very long exposures of single patch (devoid of bright foreground objects) in the sky
- Cluster-lensing observations
  - Hunt for gravitationally lensed background objects in relatively short exposures (few hours per filter) of a low-z galaxy cluster

The Hubble Ultra Deep Field

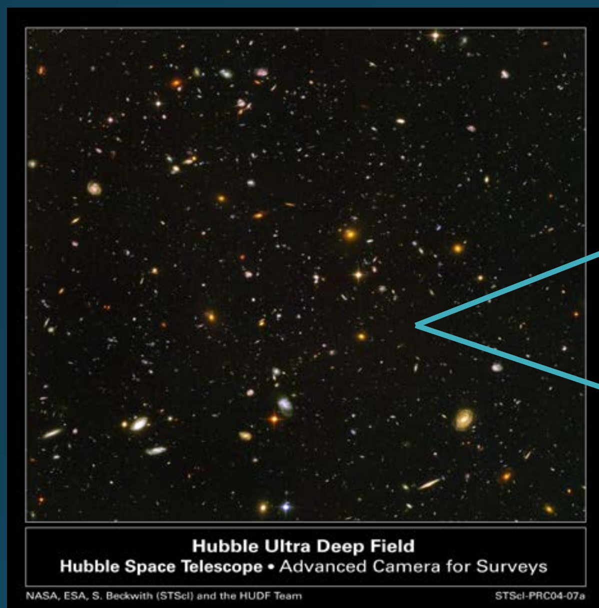
Up to 100 h exposures per filter

Hubble Ultra Deep Field
Hubble Space Telescope • Advanced Camera for Surveys

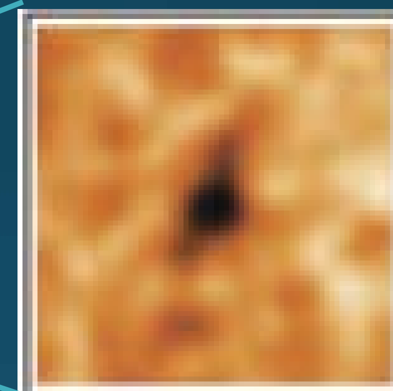
NASA, ESA, S. Beckwith (STScI) and the HUDF Team

STScI-PRC04-07a

Example of one of the most distant galaxy candidates so far



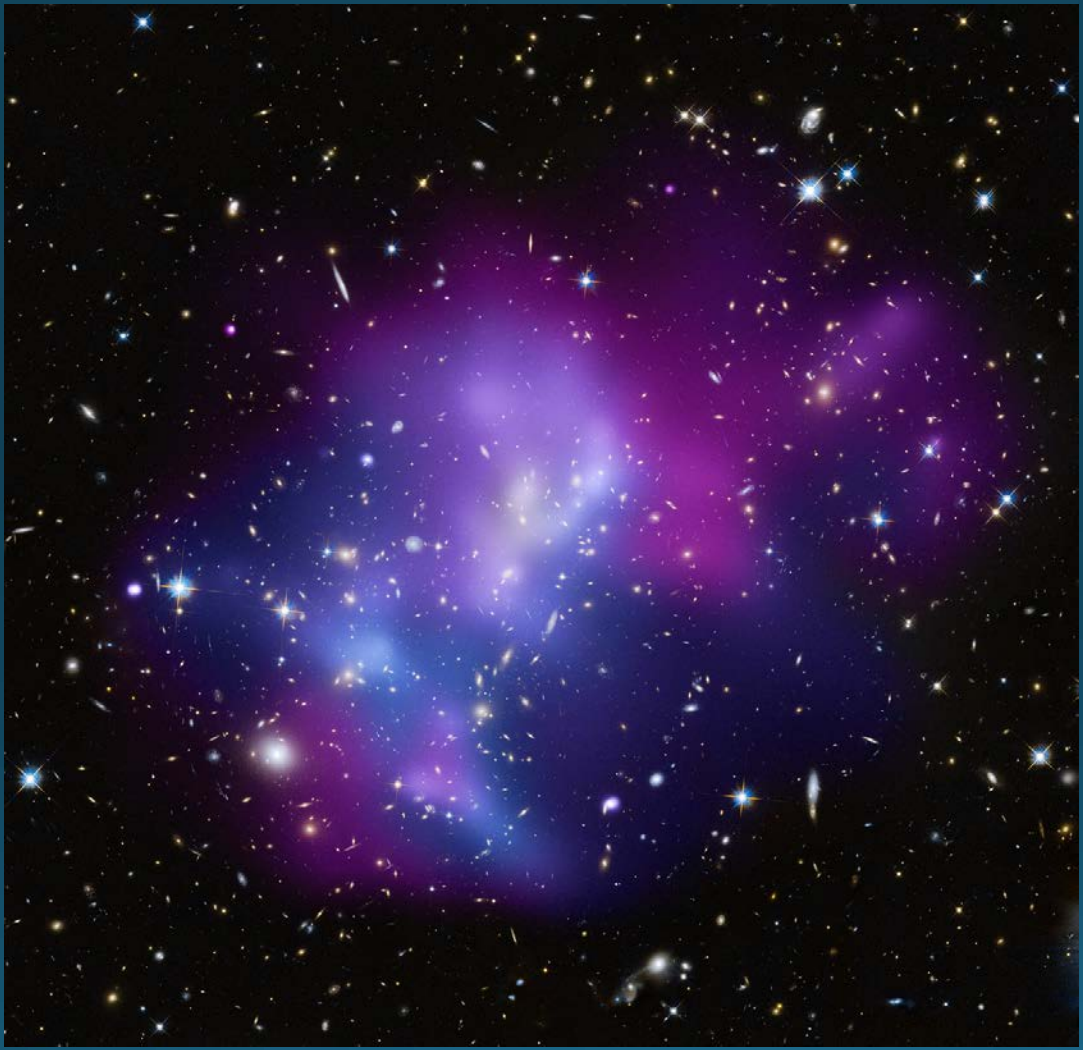
2.4 arcsec x 2.4 arcsec



Bouwens et al. (2010)

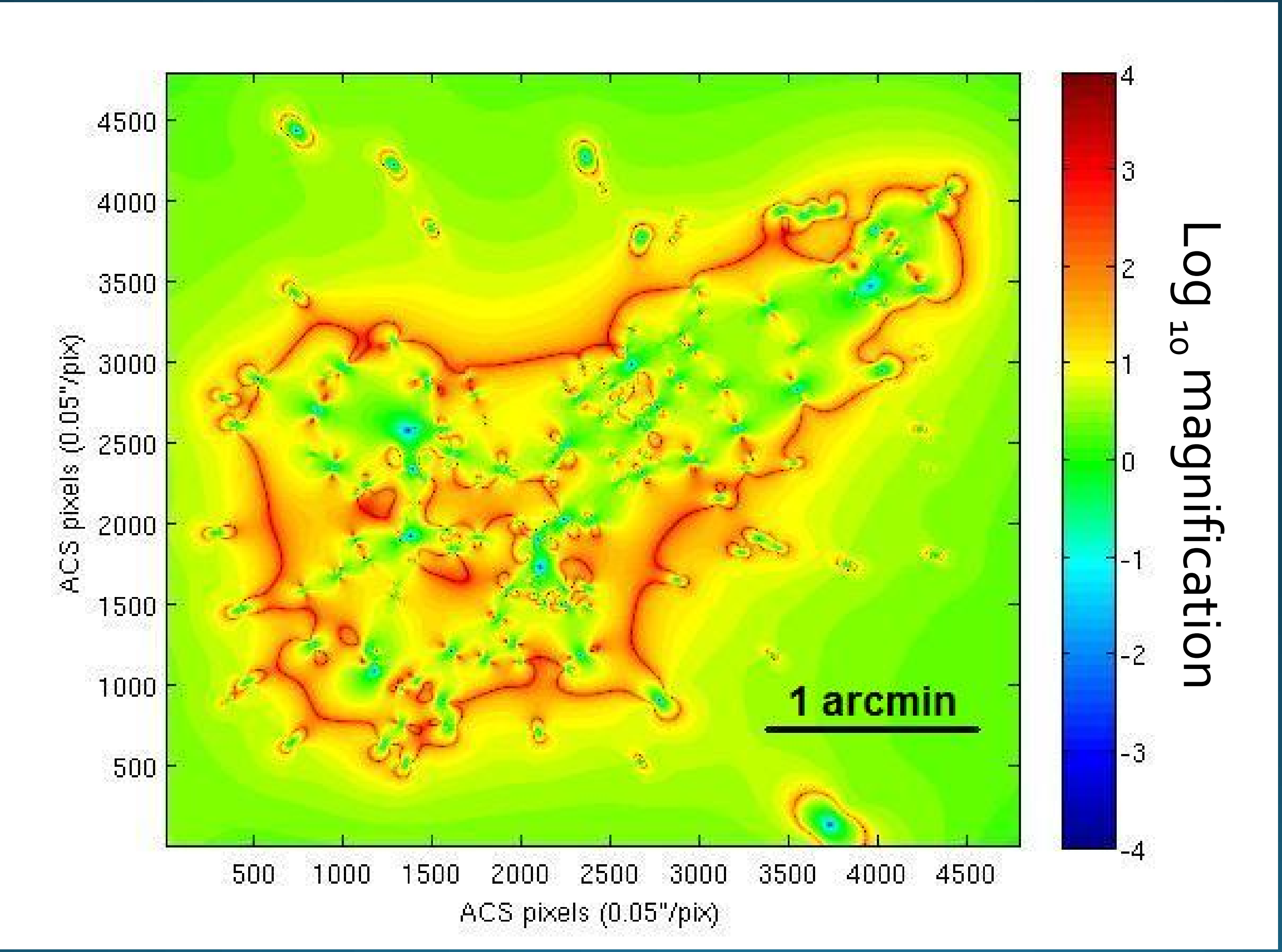
$z \approx 10$ candidate

Cluster lensing I



Galaxy cluster at z≈0.5

Cluster lensing II



Magnification map

Pros and Cons of Cluster Lensing

+ Background sources appear brighter by a factor μ

- The volume probed becomes smaller by a factor μ

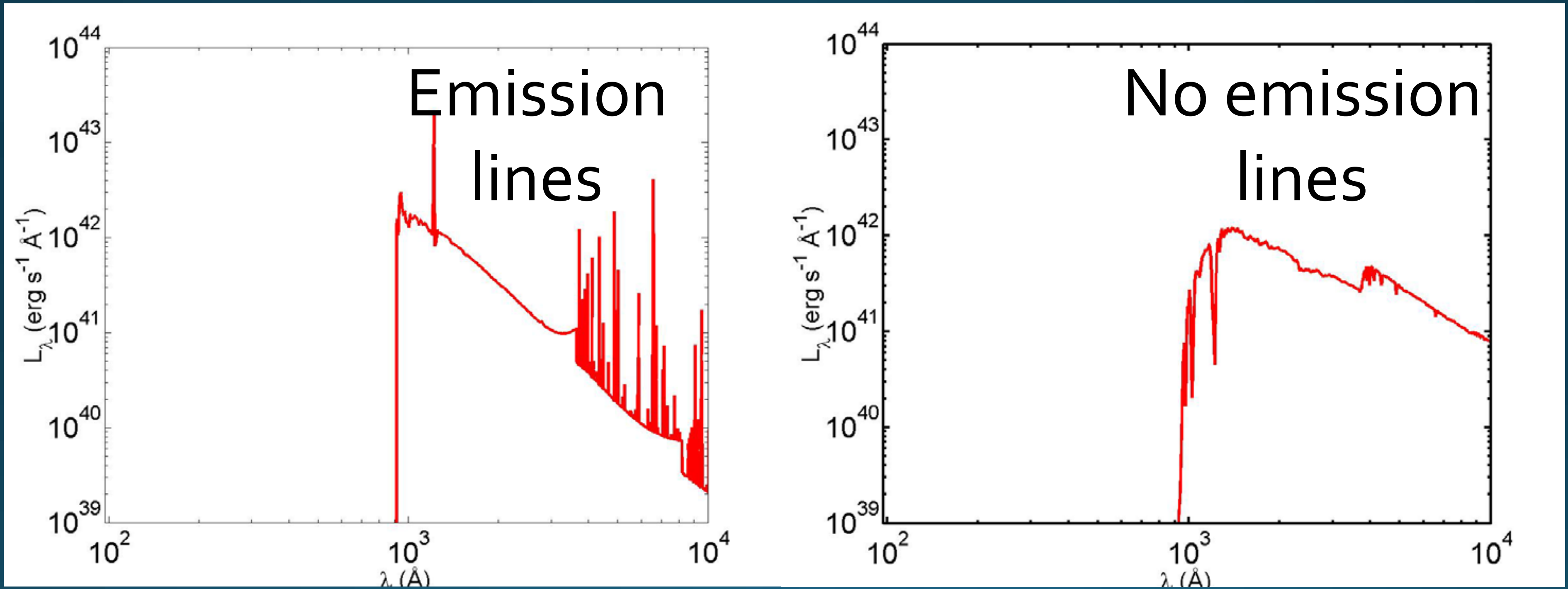
Bottom line: Lensed survey fields can be superior for sources that are *very faint*, *not too rare* and *not too highly clustered*

Selecting high-z galaxy candidates

Two techniques:

- Dropout selection
  - Crude redshift estimator ($\Delta z \approx 1.0$)
  - But works well for all high-z, star-forming galaxies
- Lyman-alpha surveys
  - High-precision redshift estimation ($\Delta z \approx 0.1$)
  - But doesn't work well at $z>6$
  - And not all galaxies are Lyα-emitters

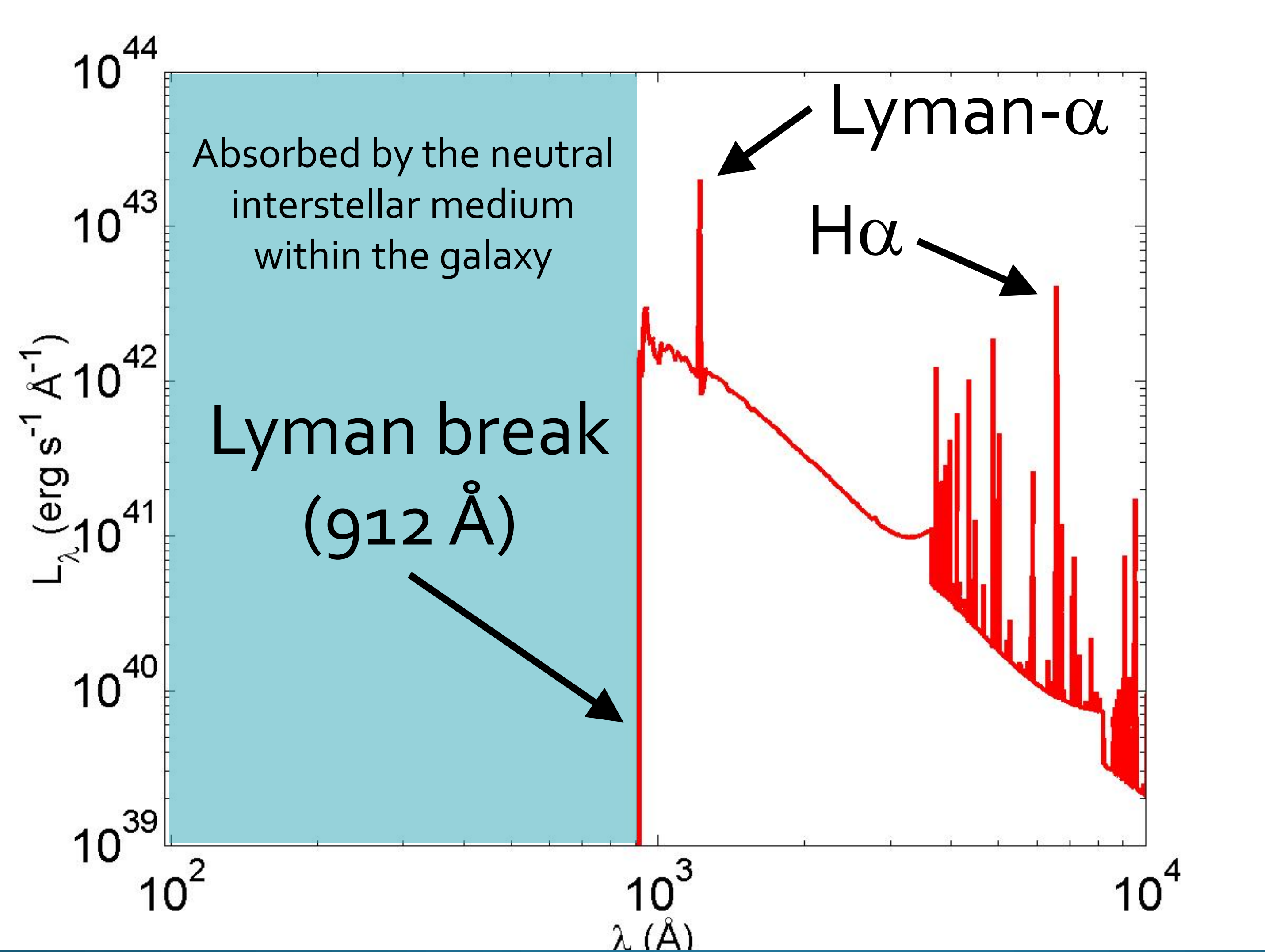
The UV/optical spectra of galaxies I



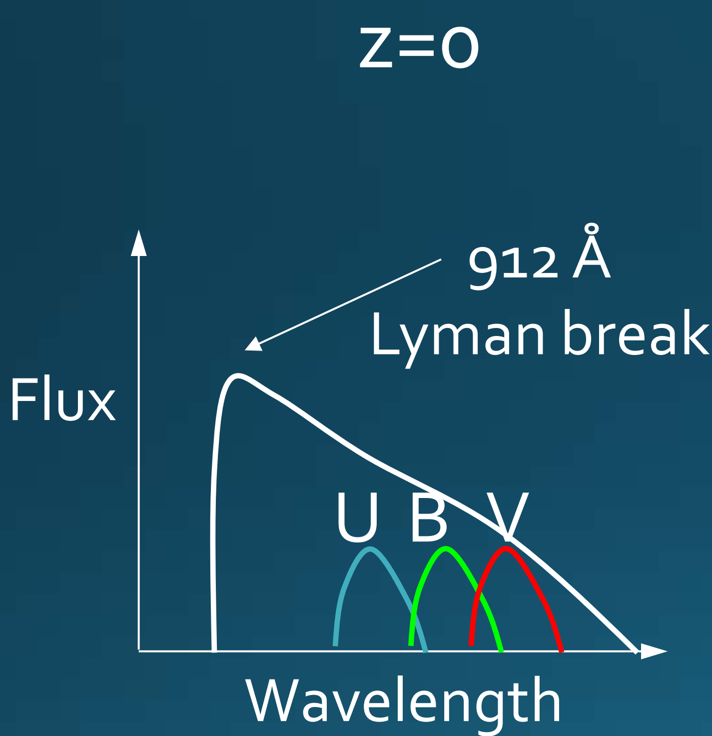
Young galaxy

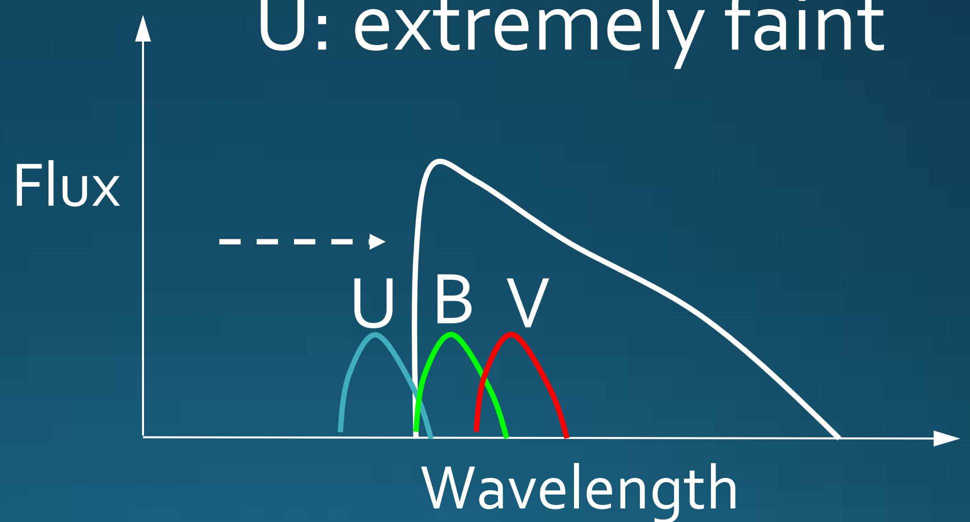
Old galaxy

The UV/optical spectra of galaxies



Drop-out techniques: Lyman-Break Galaxies



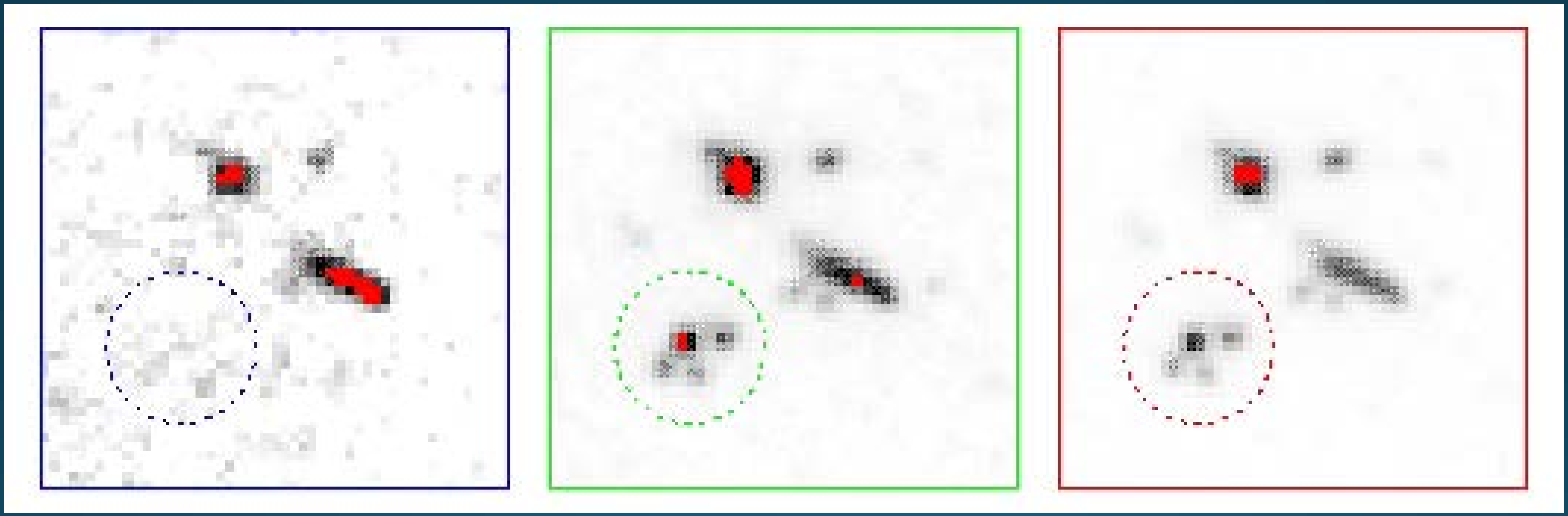


z>2.5

B-V ~ normal

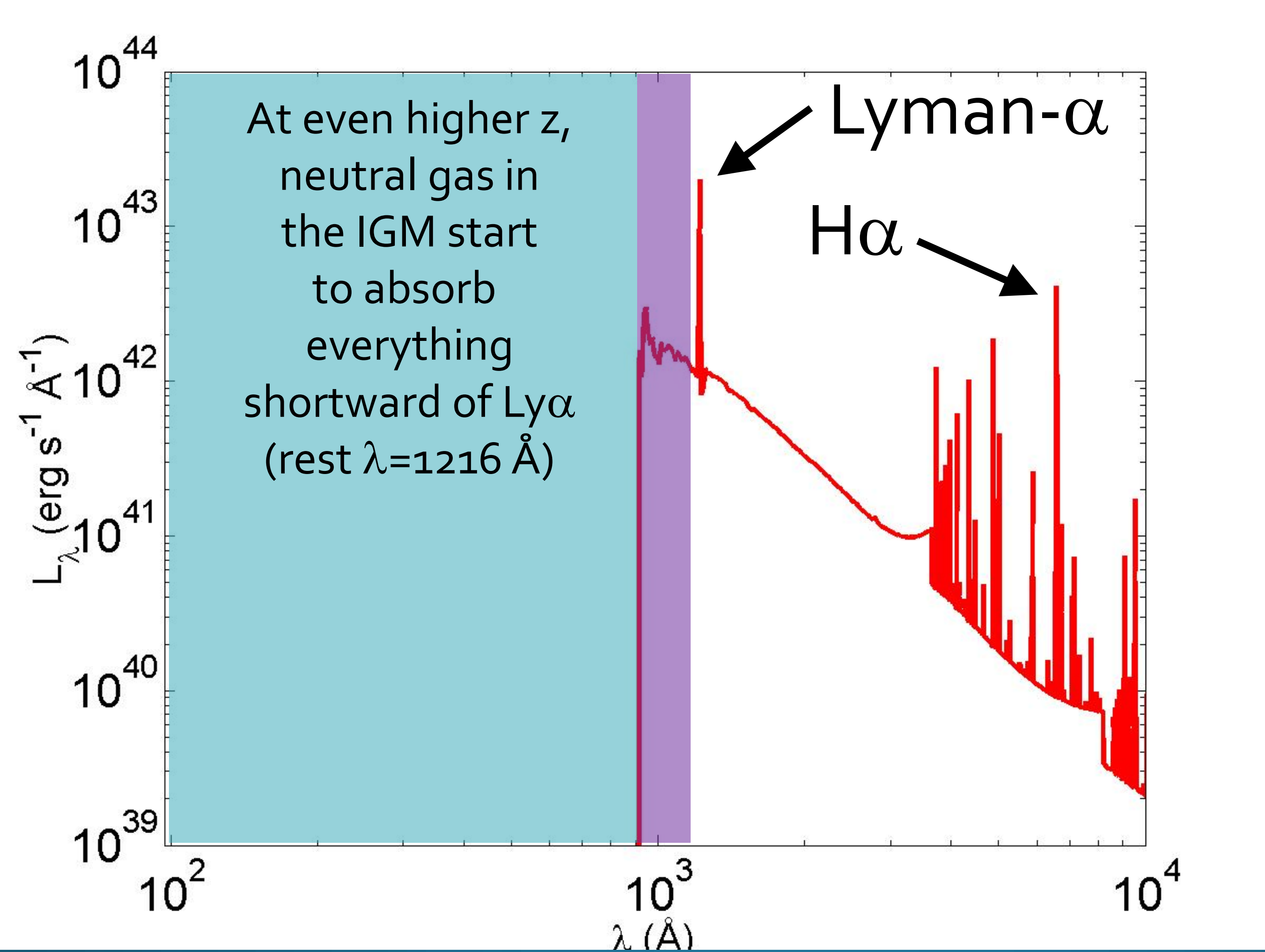
U: extremely faint

Drop-out techniques: Lyman-Break Galaxies



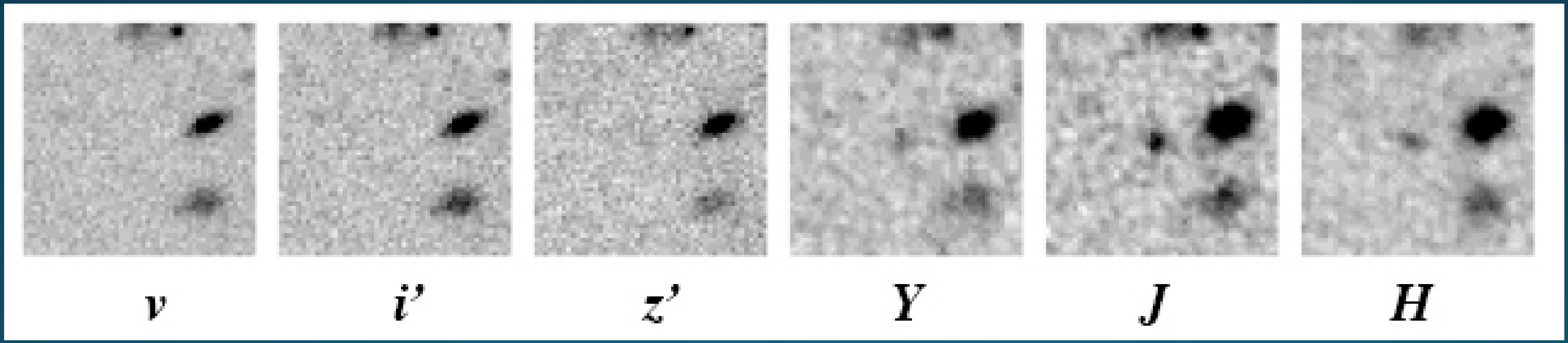
U B V

Reionization-epoch galaxies



Drop-out techniques: z>6 objects

Eventually, the break shifts into the near-IR. Example: z-band dropout (z≈6.5)

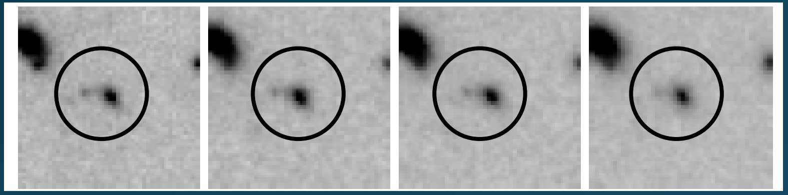


Optical Near-IR

λ

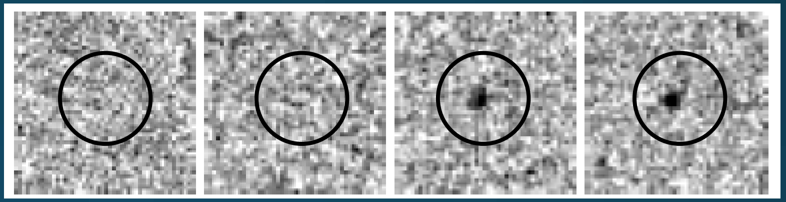
Intermission:
Which of these drop-out candidates is likely to have the highest redshift?

A



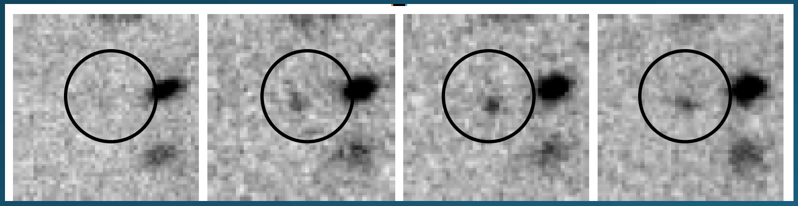
z Y J H

B



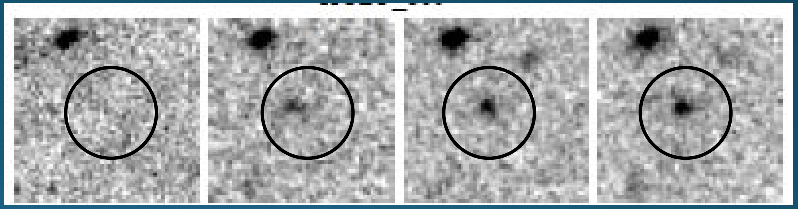
z Y J H

C



z Y J H

D



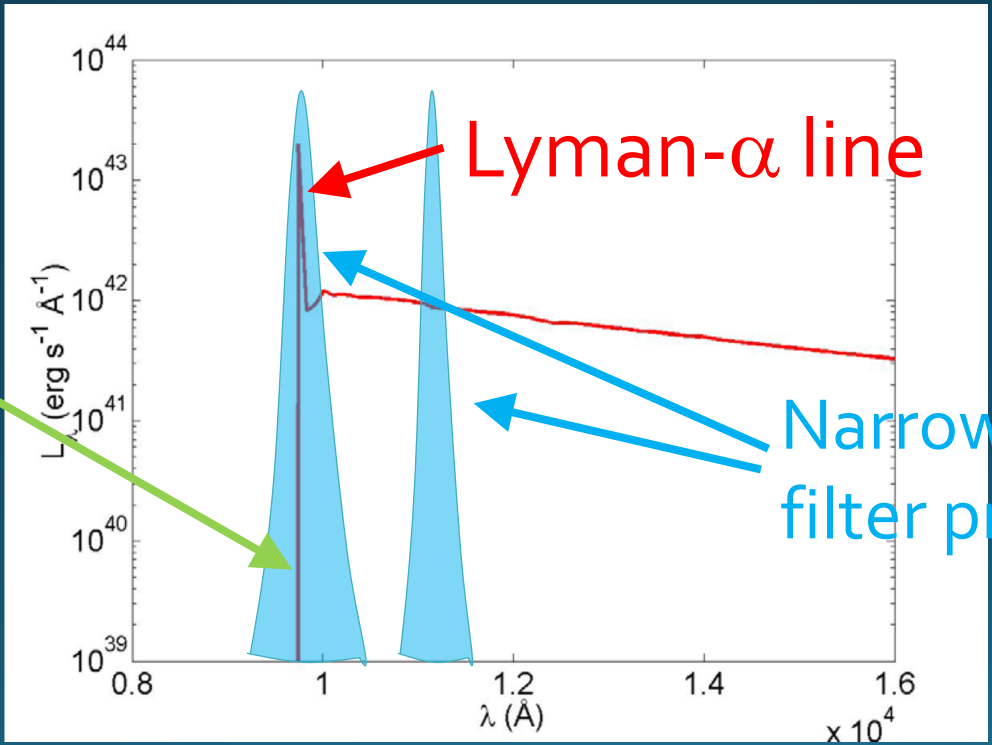
z Y J H

λ λ

Lyman-alpha surveys

- Potentially the brightest line in rest frame UV/optical
- Two narrowband images (covering continuum and line) required for survey of redshift range ($\Delta z \sim 0.1$)

Sharp drop (absorption in neutral IGM)

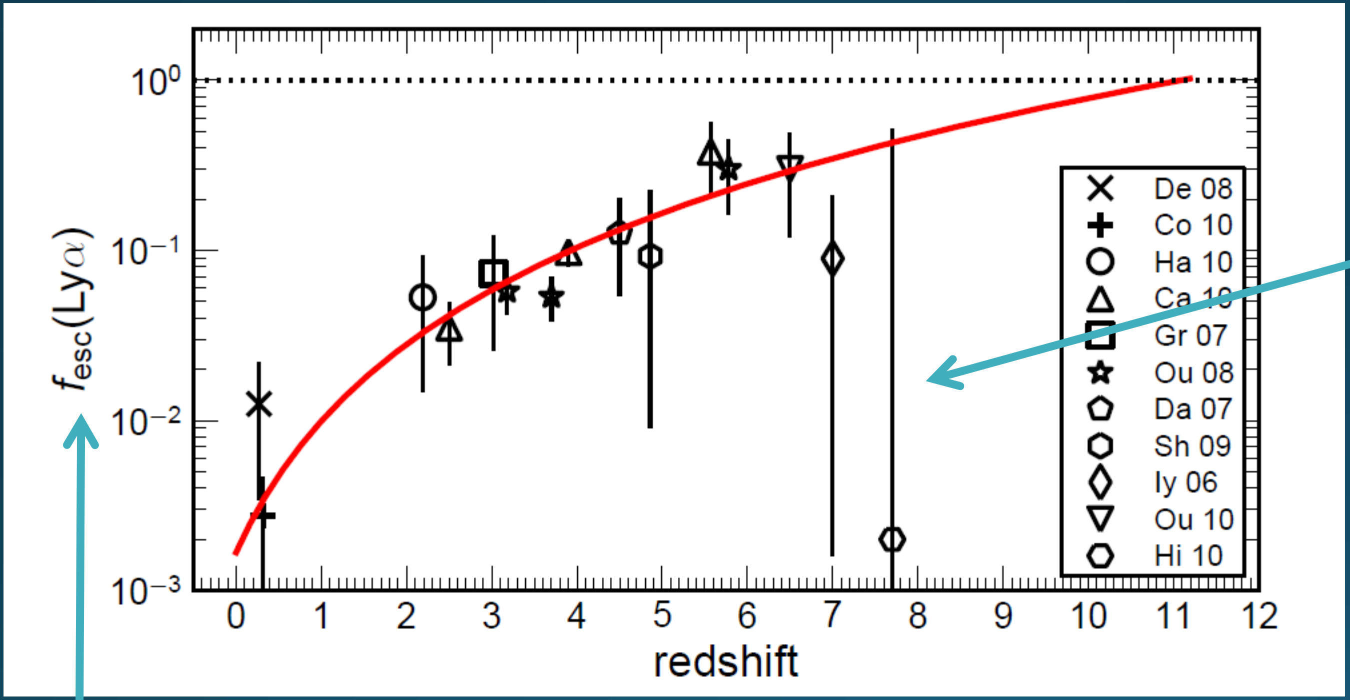


Lyman-α at z=7

Problem I: Lyman-α notoriously difficult to predict

- Lyα resonant line → random walk through neutral interstellar medium
- Many Lyα photons destroyed by dust before emerging
- Lyα flux ranges from low to very high

Problem II: Lyman-α largely absorbed in the neutral intergalactic medium at z>6



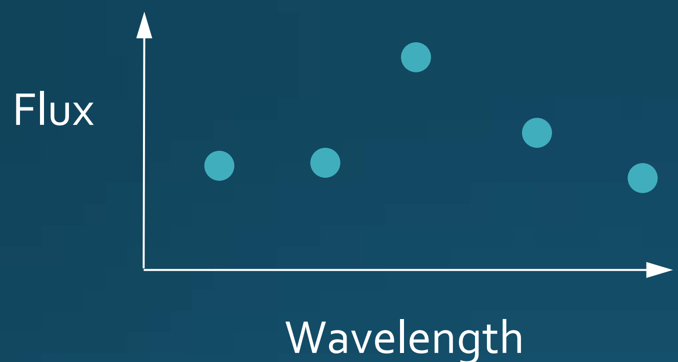
Abrupt drop → Lyα not good way to find z>6 galaxies (but may be good way to probe reionization)

Fraction of Lyα photons reaching the observer

Hayes et al. 11

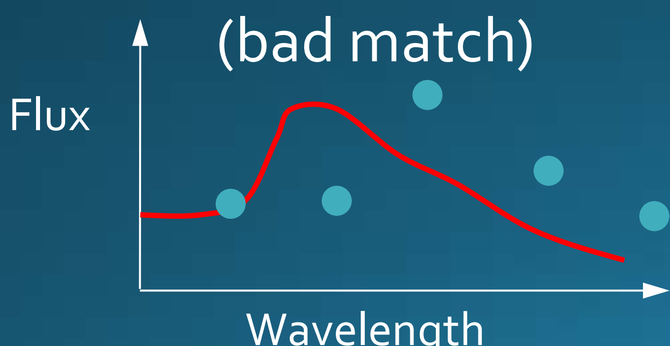
Photometric redshifts

- Estimate the galaxy type (morphological) and assume that the galaxy is identical to some template (often an average over many galaxy spectra of similar type)

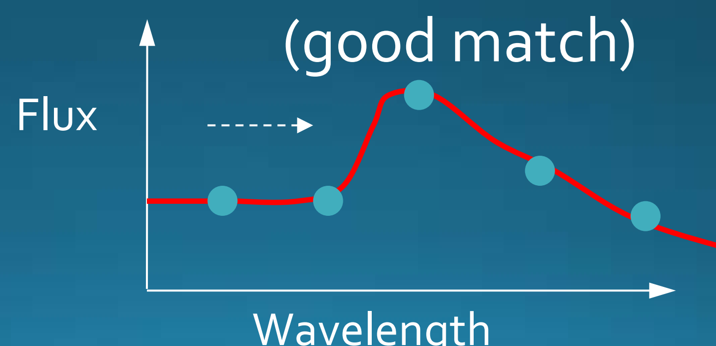


Measured photometrical data points

z=0 template spectrum (bad match)



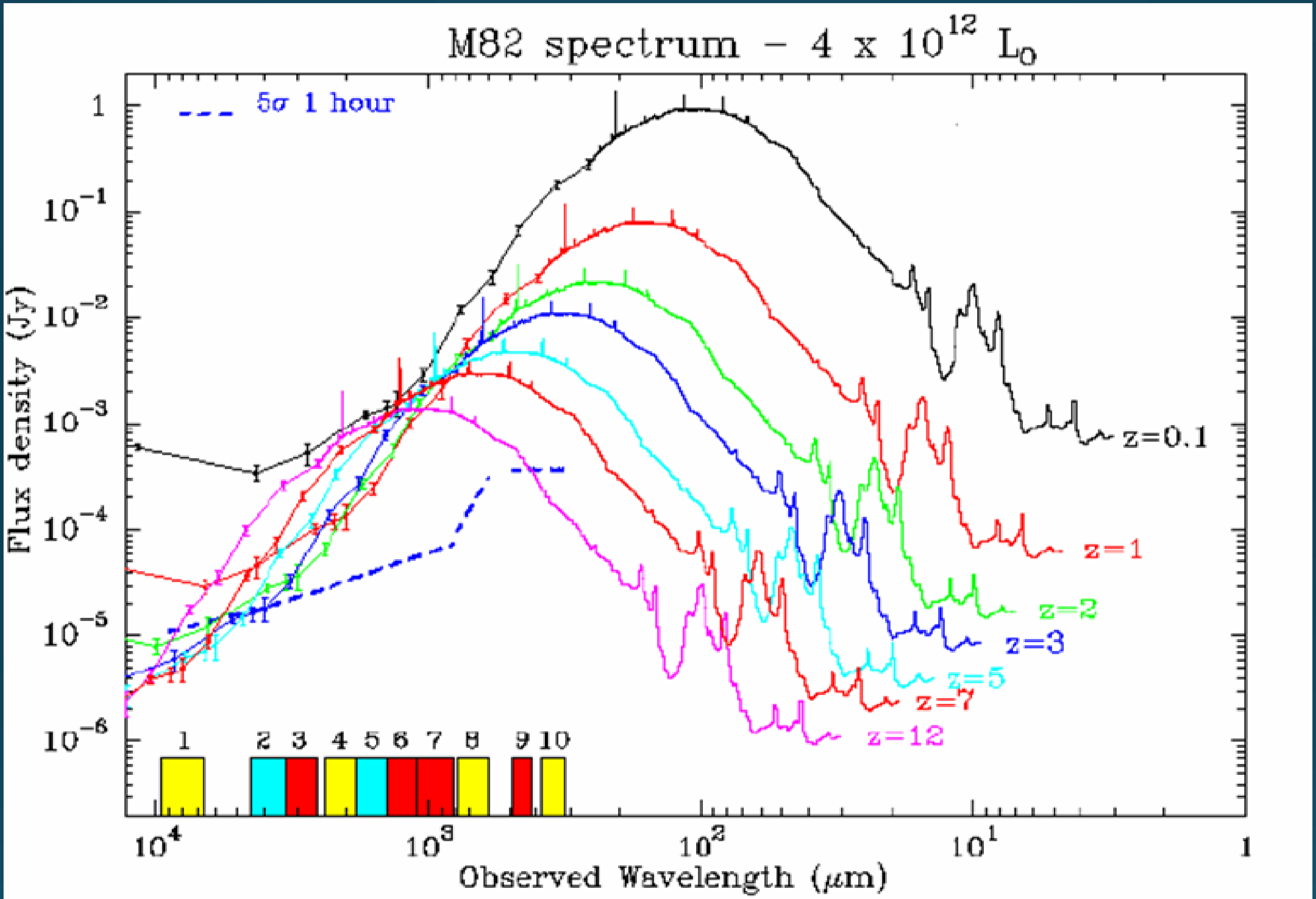
Redshifted template spectrum (good match)



New telescope for high-z studies: ALMA

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

Can be used to search for dust emission and emission lines like [CII] @ 158 μm and [OIII] @88 μm (rest-frame) from z>6 galaxies

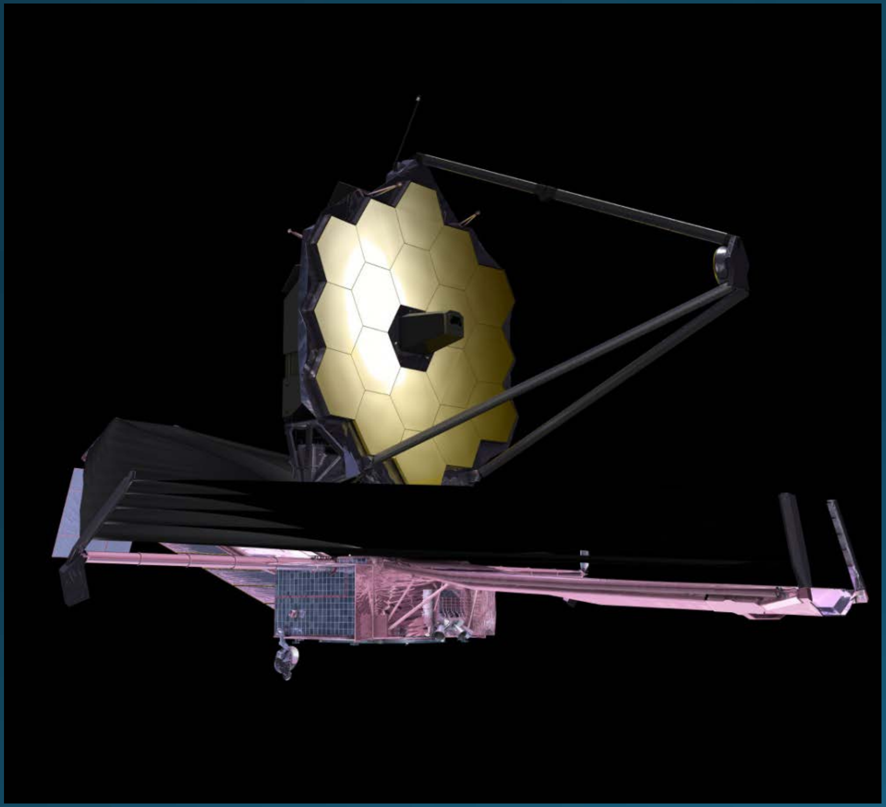


ALMA receivers

De Breuck 05

Dust continuum flux drops slowly with z (if no source evolution).

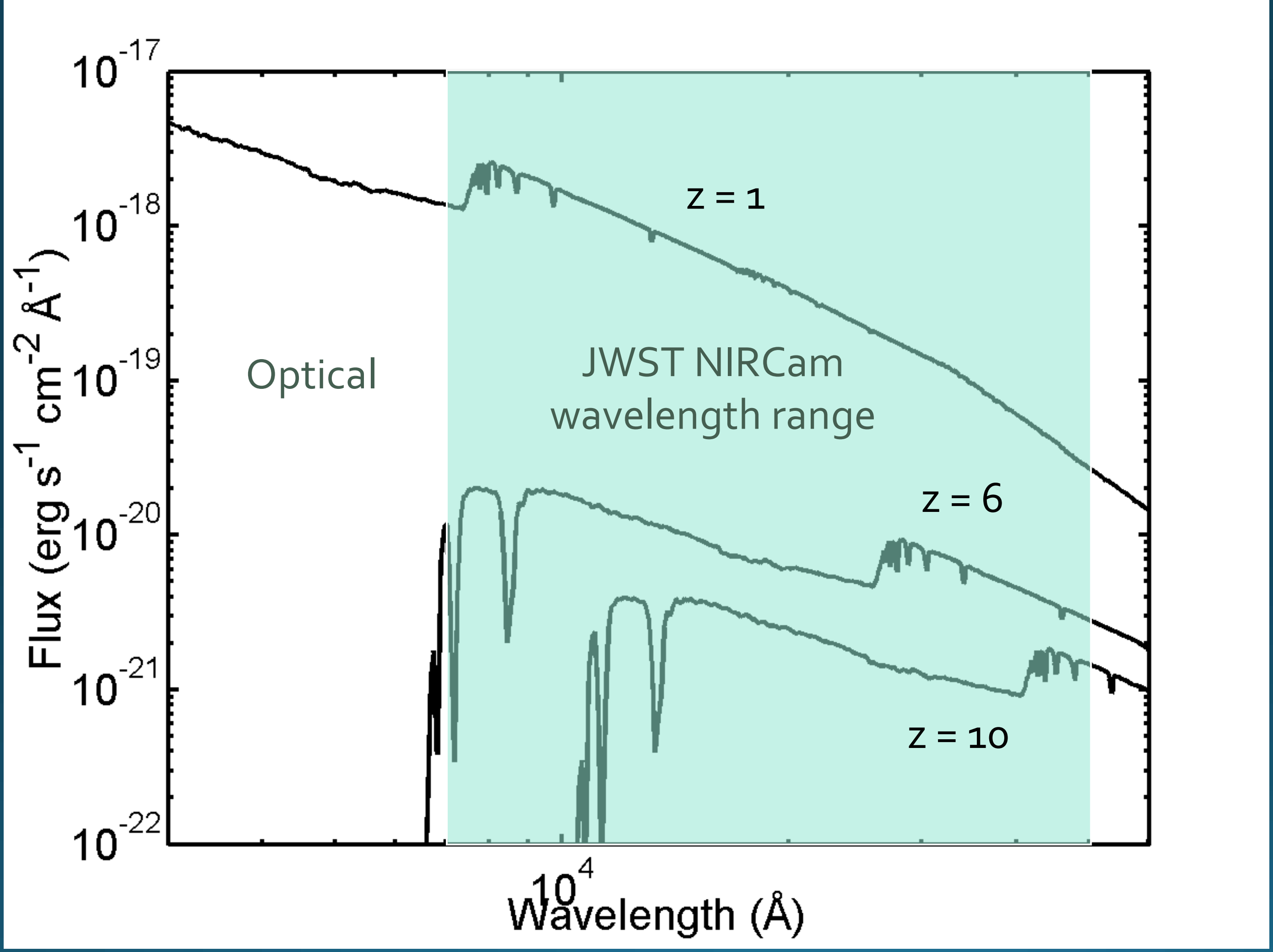
Future prospects: JWST



James Webb Space Telescope
'The first light machine'
To be launched by
NASA / ESA / CSA in 2018

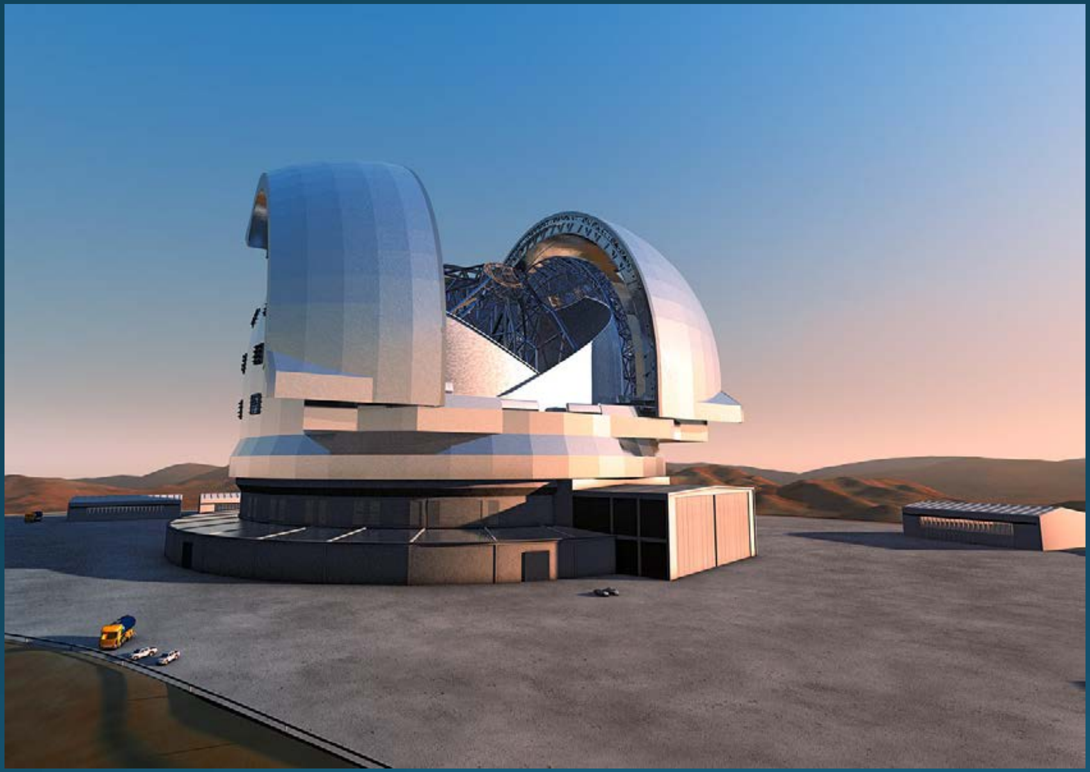
6.5 m mirror
Observations @ 0.6-29 μm
Useful for:
Galaxies up to $z \approx 15$
Pop III supernovae

Why infrared?



Zackrisson et al. (2001) model

Future prospects: E-ELT



39 m European Extremely Large Telescope (E-ELT) estimated to be completed in early 2020s.