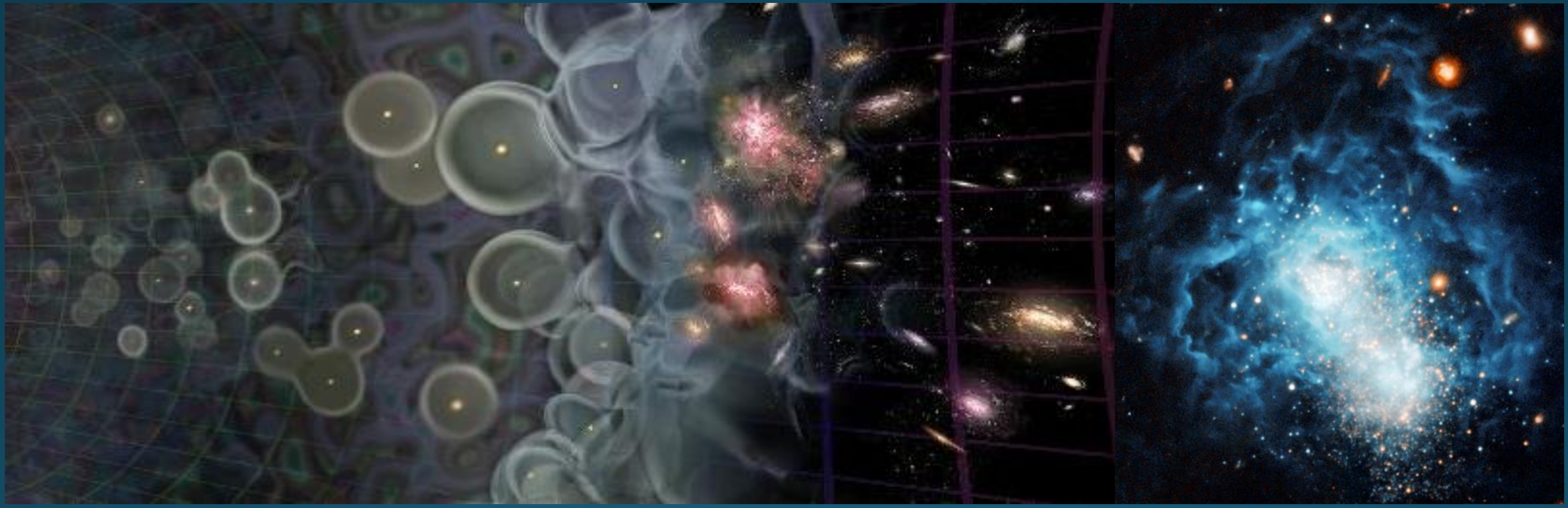
Physics of Galaxies 2019
10 credits
Lecture 8: The High-Redshift Universe



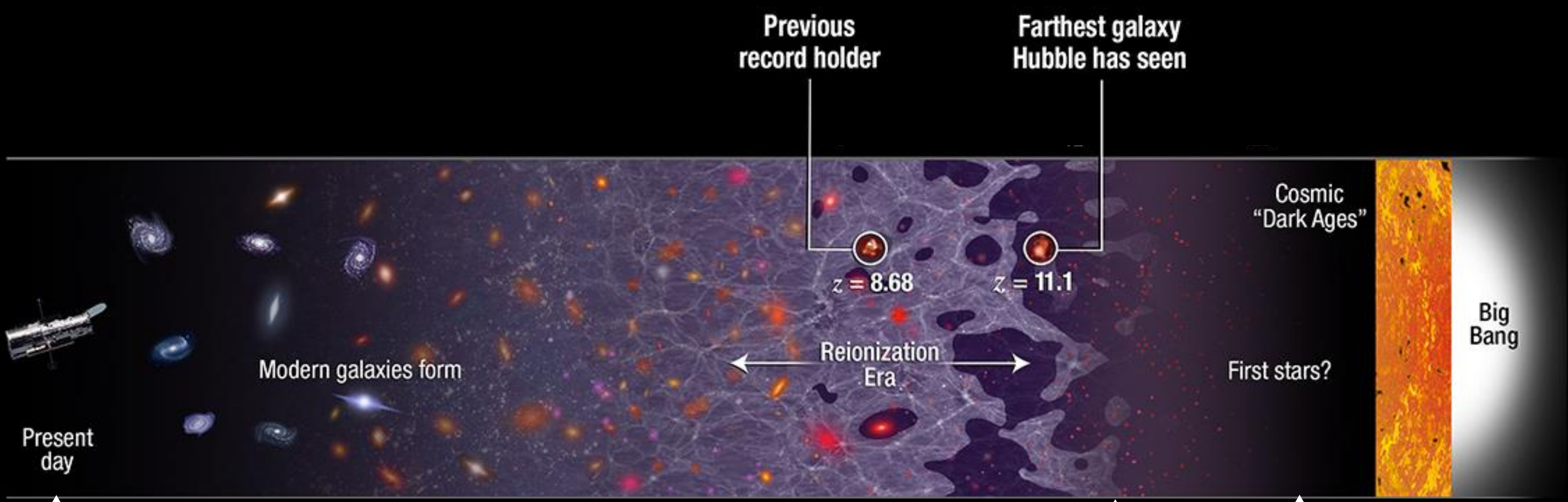
Outline: Part I

- The first stars and galaxies
  - End of the dark ages
  - Pop III stars
  - First galaxies
  - Supermassive black holes

Outline: Part II

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

The first billion years of cosmic history



13.8 Gyr after the Big Bang, redshift z = 0

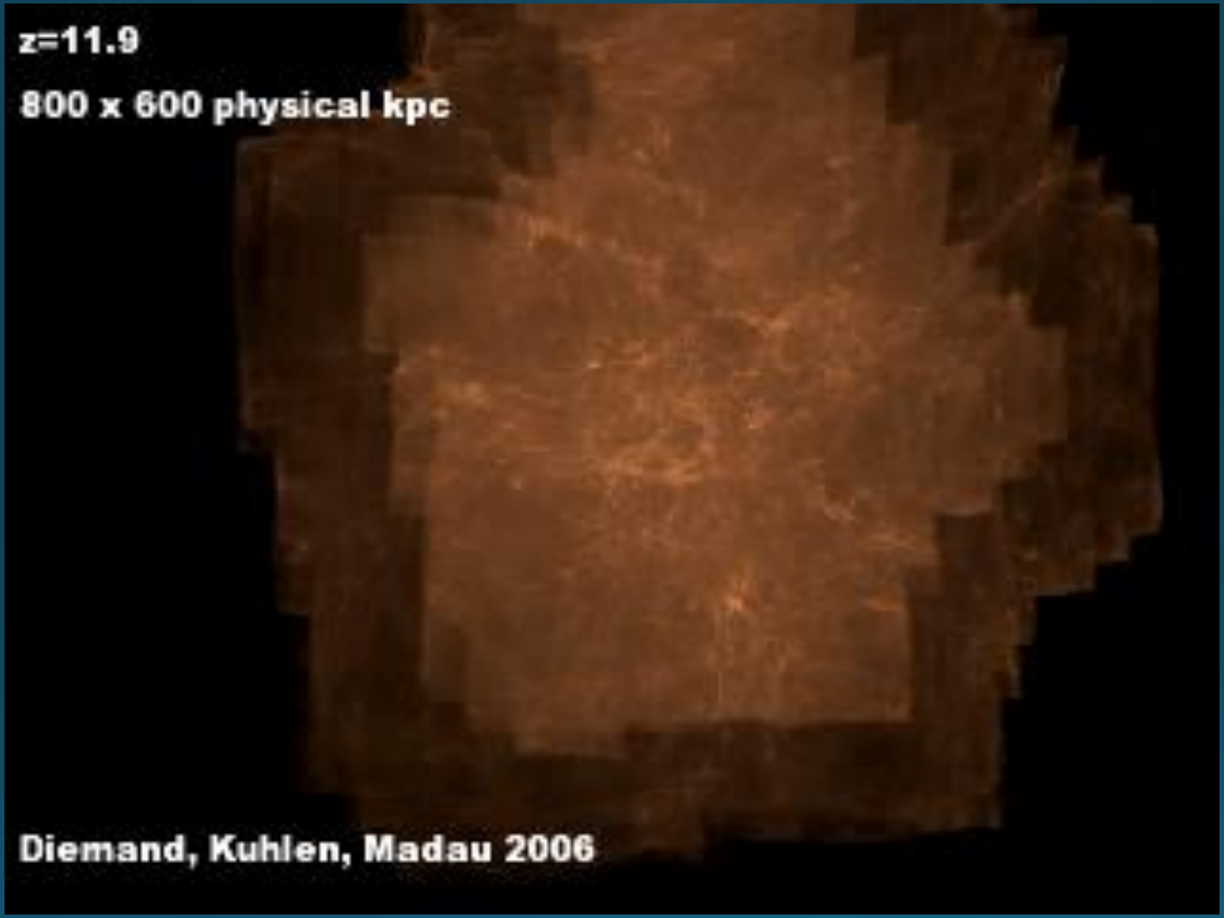
≈1 Gyr, z = 6

0.25 Gyr, z = 15
First galaxies?

0.1 Gyr, z = 30
First stars?

Unsolved puzzles in this era:
Cosmic reionization, origin of supermassive black holes, nature of the first stars

Merging cold dark matter halos



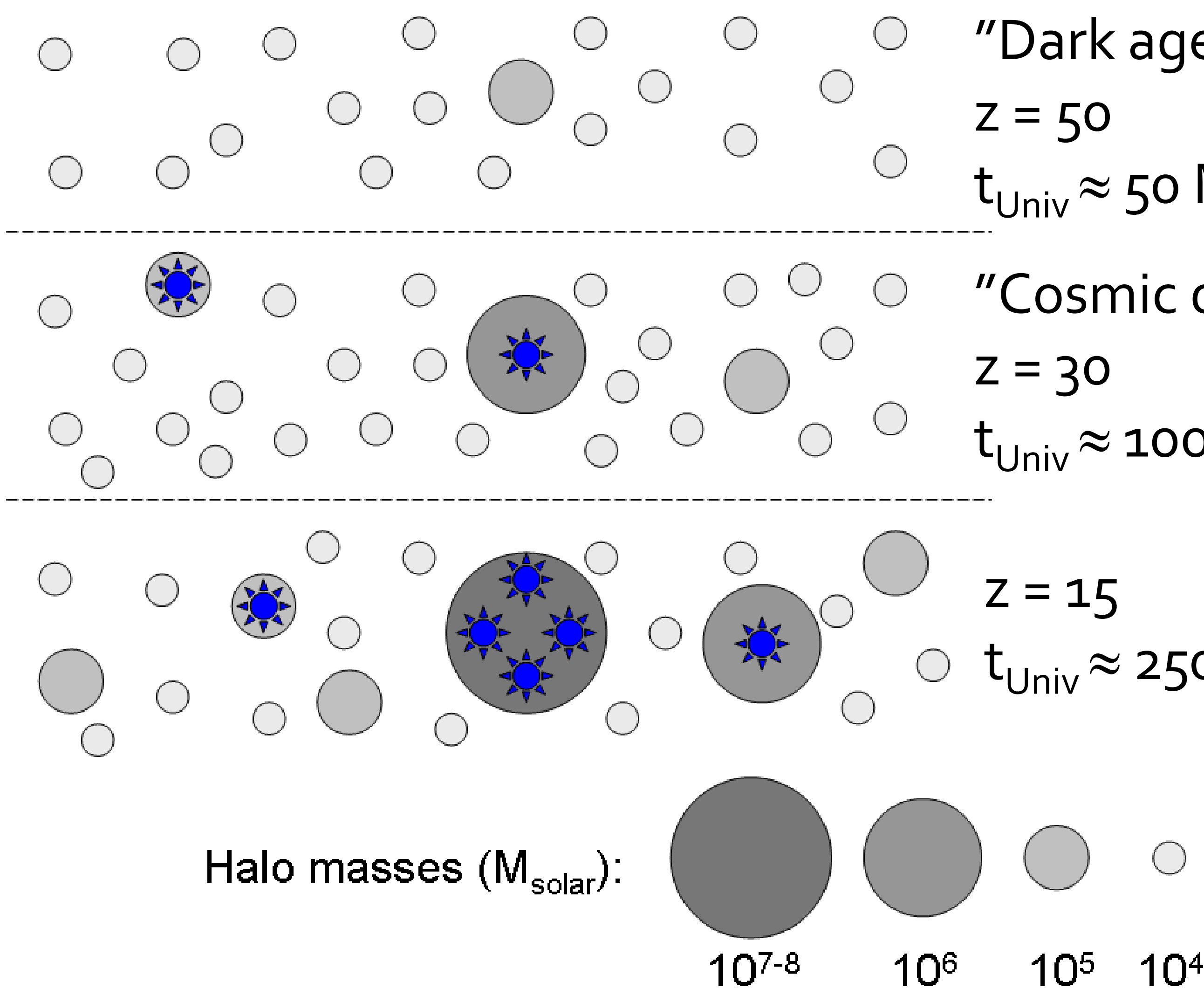
Formation of a ~10^{12} M_{solar} dark matter halo
Simulation runs from $z \approx 12$ to 0 ($t_{Univ} \approx 0.25$ to 13.7 Gyr)

Structure formation

Minihalos

First stars
(in minihalos)

First galaxy



"Dark ages"
$z = 50$
$t_{Univ} \approx 50$ Myr

"Cosmic dawn"
$z = 30$
$t_{Univ} \approx 100$ Myr

$z = 15$
$t_{Univ} \approx 250$ Myr

Population I, II and III

- Population I: Metal-rich stars

  Example: Stars in the Milky Way disk

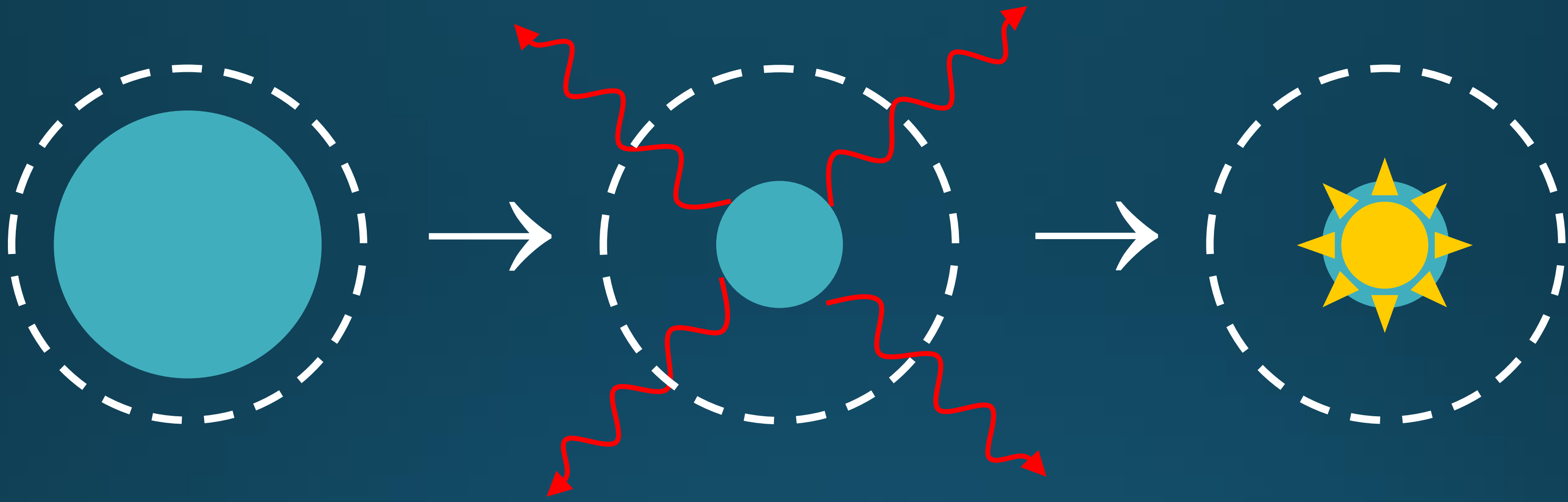
- Population II: Metal-poor stars

  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

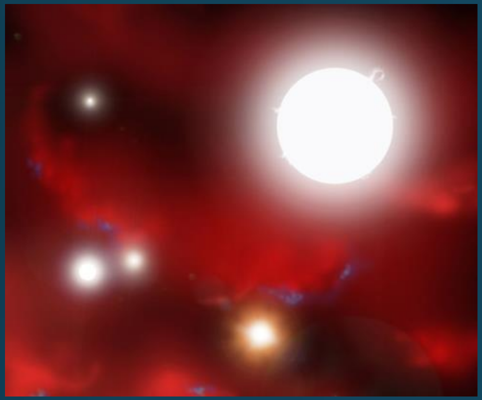
Problem: Low metallicity at high redshifts →

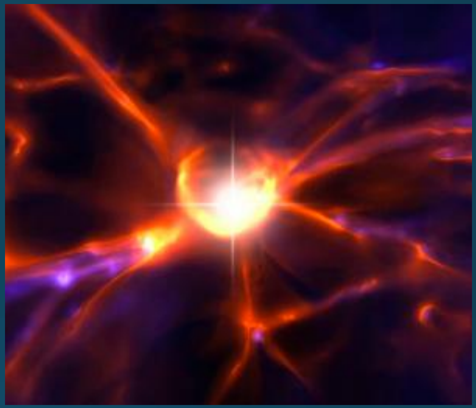
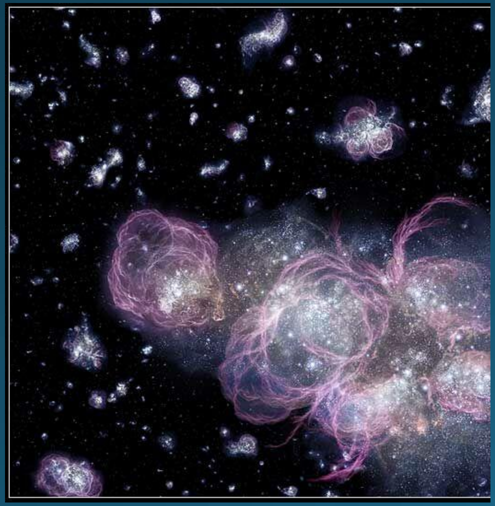
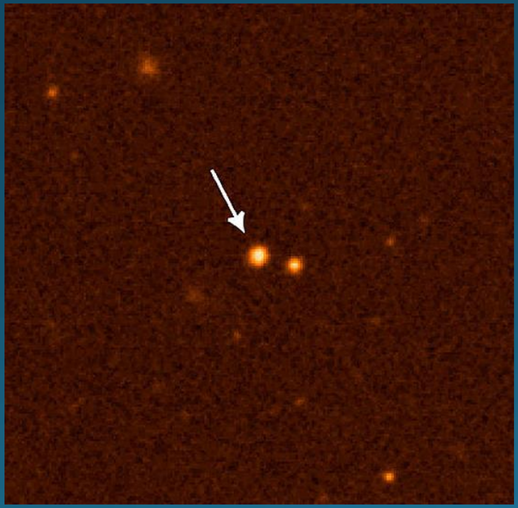
Lack of efficient coolants

Population III stars

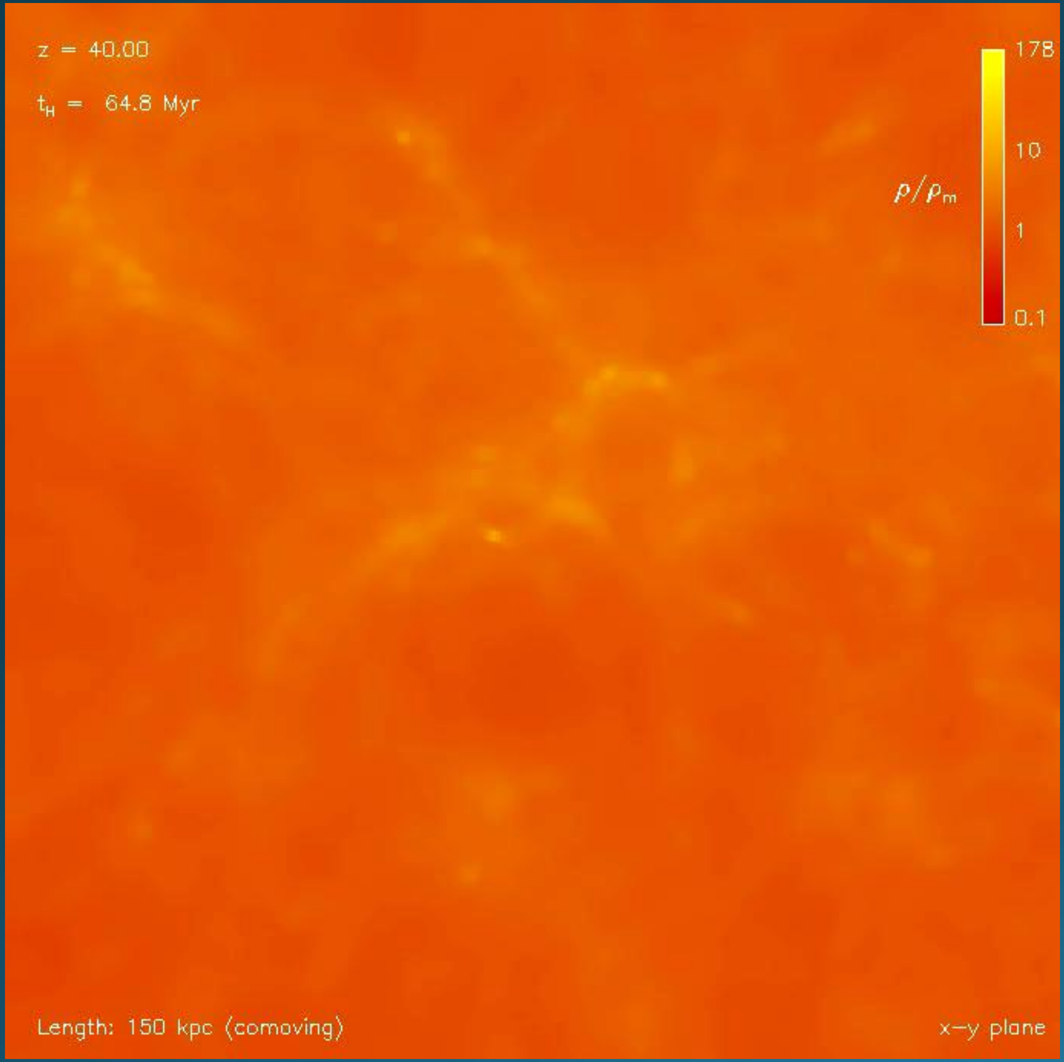
- These stars will be *very massive*, hot and short-lived.
- Mass range 10^1-10^3 Msolar (but predictions still shaky)
- The first ones are expected in minihalos – prior to the formation of the first galaxies.
- Feedback $\rightarrow$ *Only a few stars (maybe just one) per minihalo*

Intermission: The first stars(?)




Formation of the first galaxies



Greif et al. 08

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

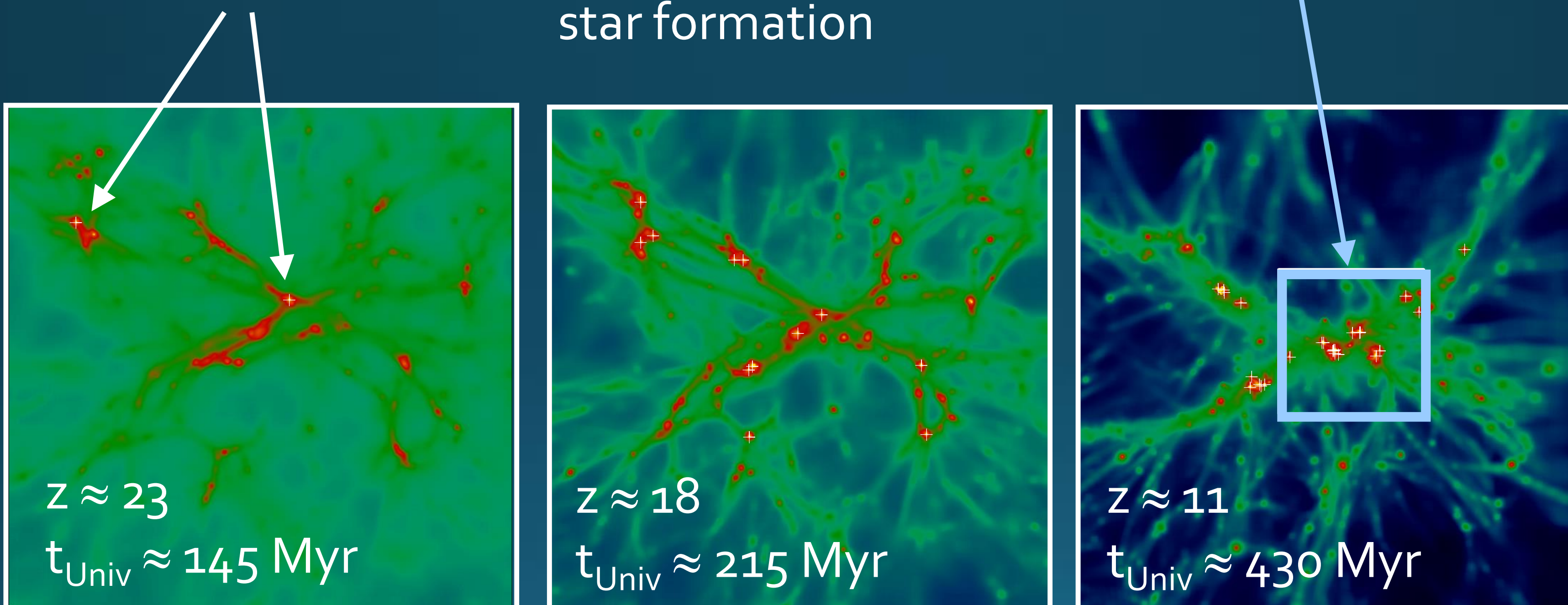
Simulation runs
from $z \approx 40$ to 11
($t_{Univ} \approx 65$ to 430 Myr)

Star formation inside and outside the first galaxies

Star formation in minihalos

Minihalo mergers and further star formation

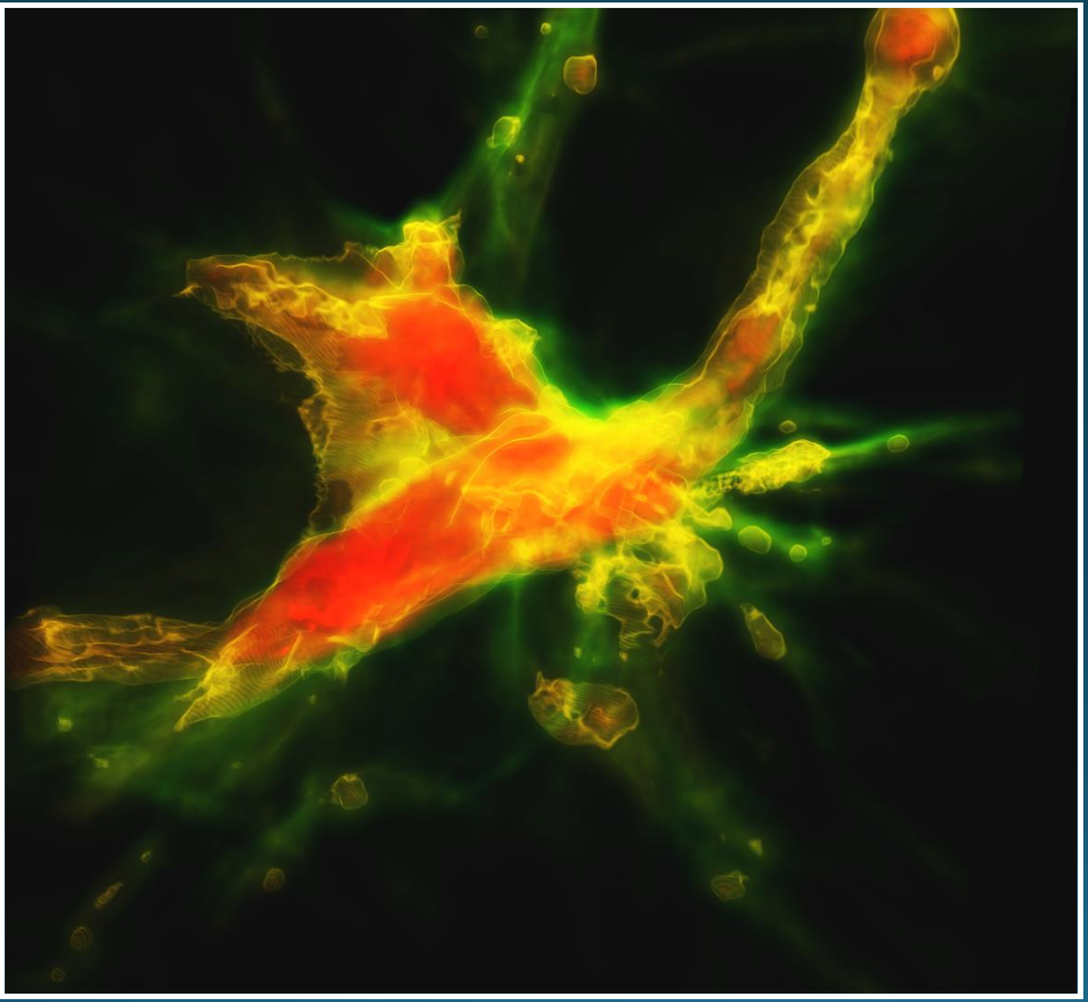
Object qualifies as a *galaxy*



Greif et al. 08

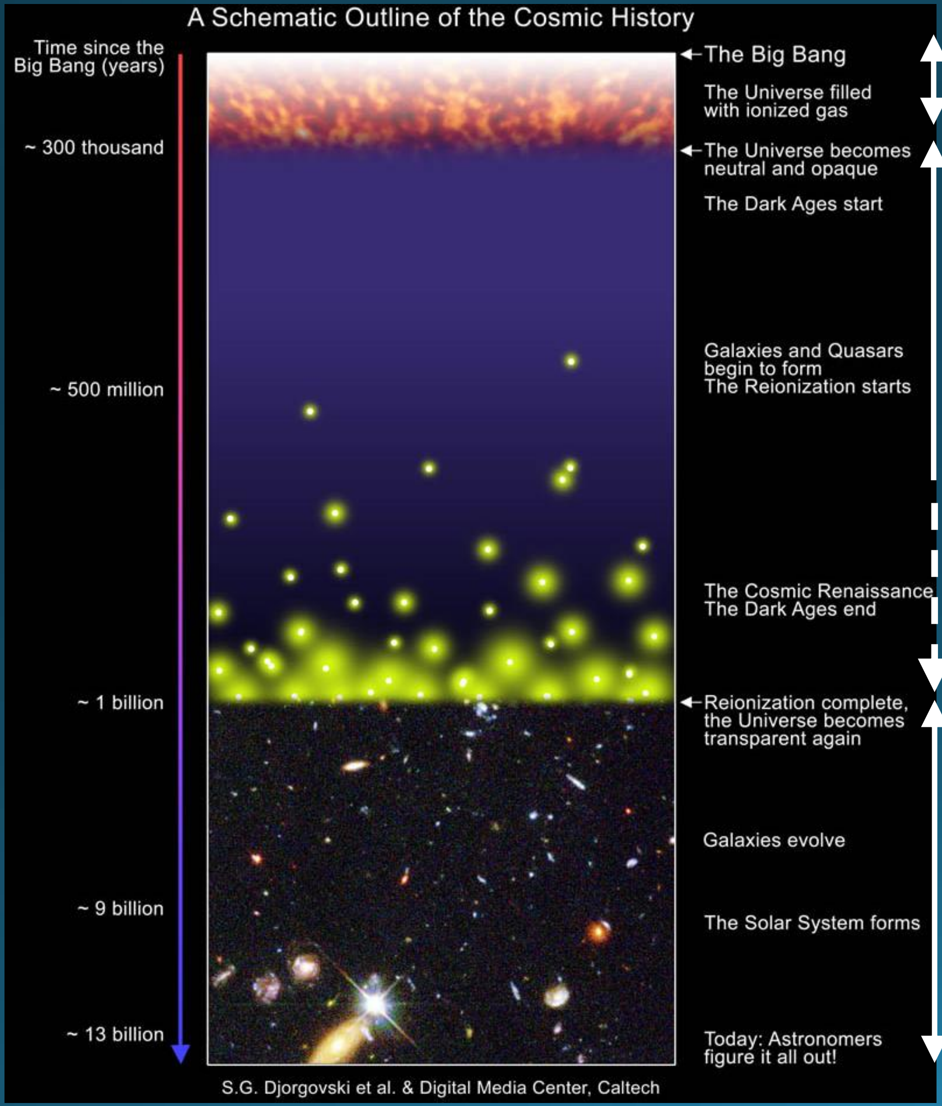
Gas density shapshots

A galaxy is born (at z ≈ 10)



Greif et al. 08

Cosmic Reionization



<u>Intergalactic medium</u>

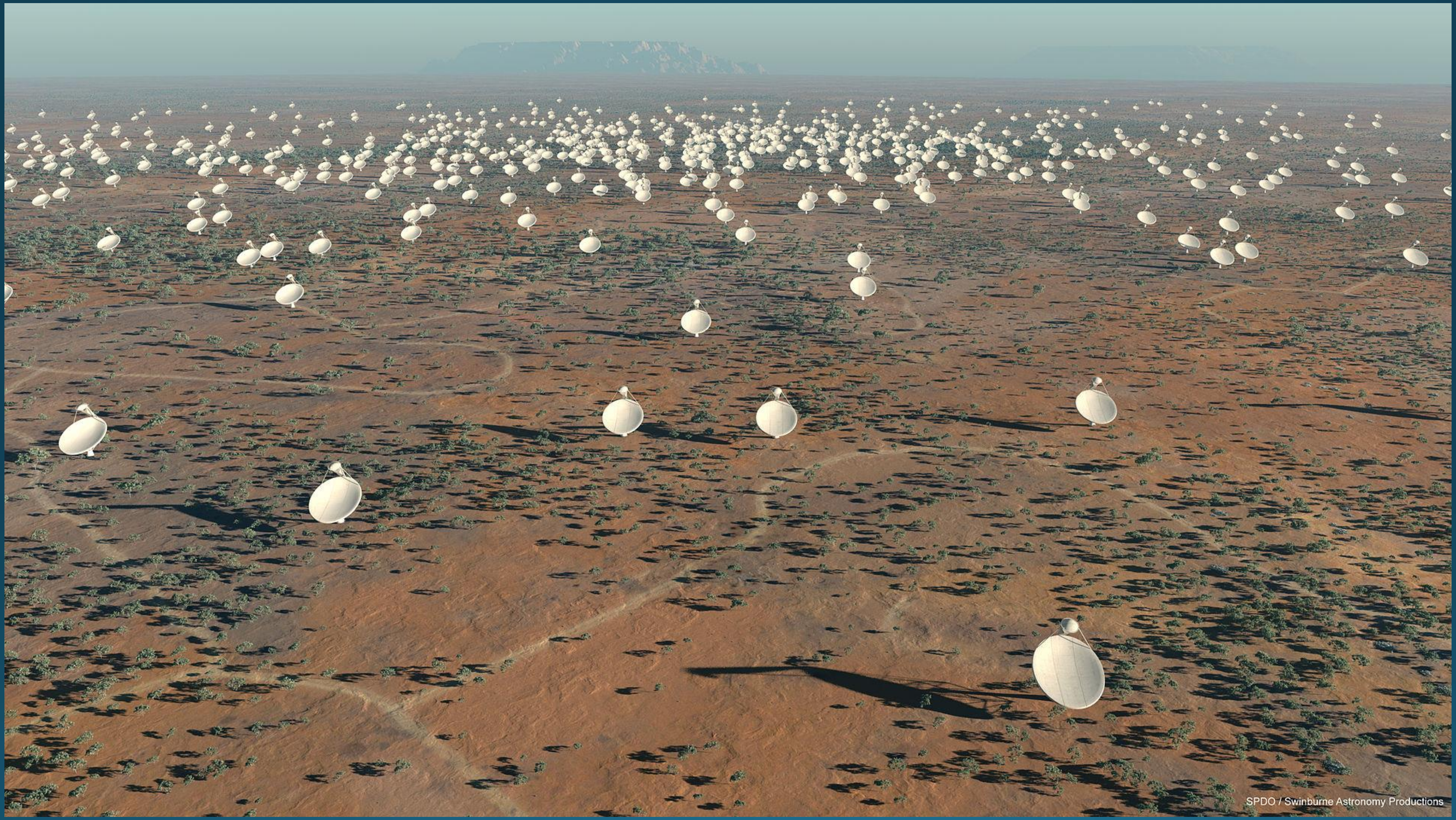
Ionized

Neutral

CMBR (Planck)
$\rightarrow z_{reion} \approx 8$
Lyα absorption in quasars
$\rightarrow z_{reion} > 6$

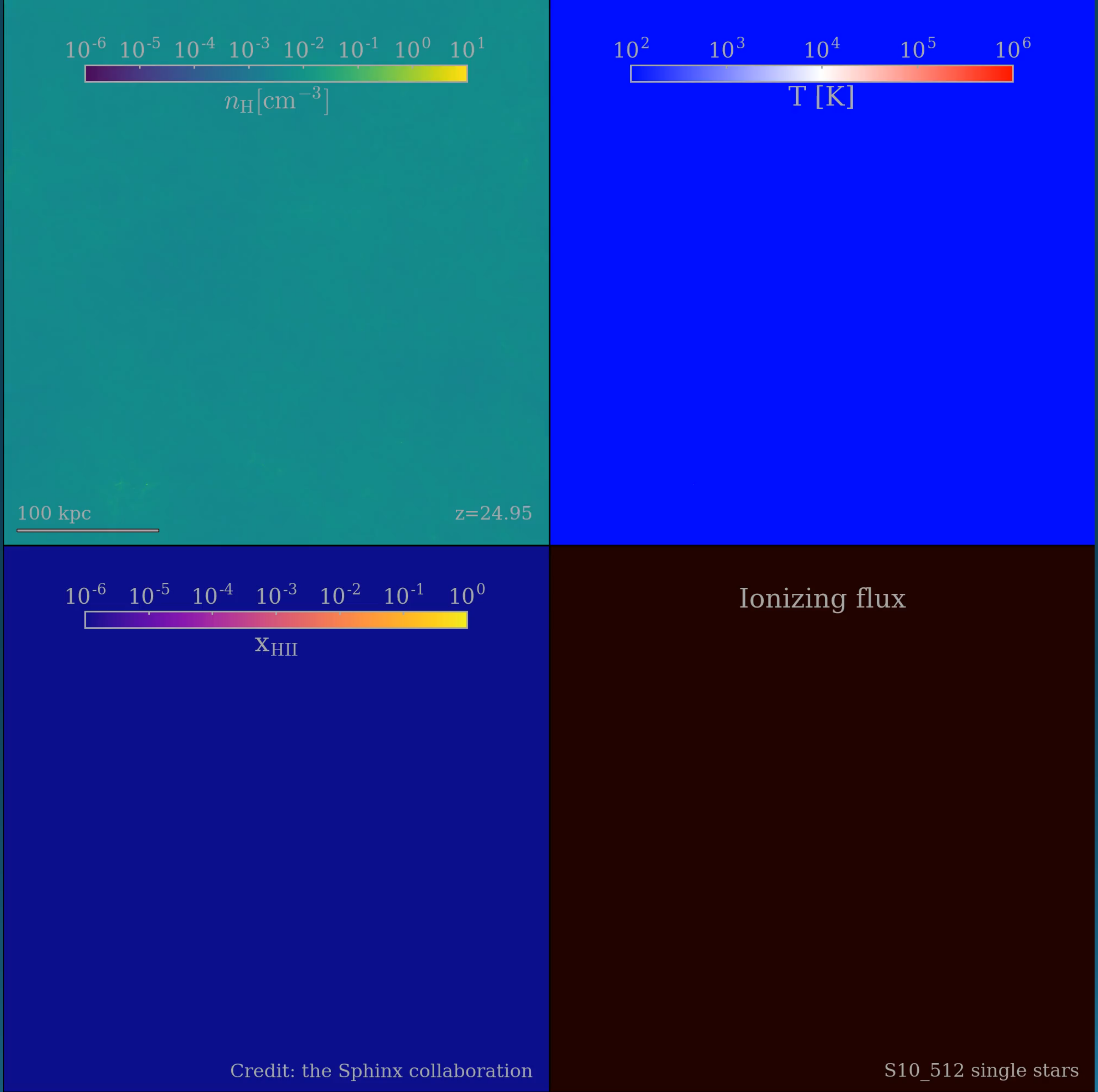
Reionized

Intermission: Name the telescope!



What caused reionization?

- Population III stars in minihalos?
- *High-redshift galaxies?* ← Popular scenario
- Accreting black holes?
- Decay of exotic particles?



10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1}
$n_{\mathrm{H}}[\mathrm{cm}^{-3}]$
100 kpc
z=24.95
10^{2} 10^{3} 10^{4} 10^{5} 10^{6}
T [K]
10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0}
x_{HII}
Credit: the Sphinx collaboration
Ionizing flux
S10_512 single stars

Supermassive black holes in the early Universe

nature
International journal of science

Letter | Published: 06 December 2017

An 800-million-solar-mass black hole in a significantly neutral Universe at a redshift of 7.5

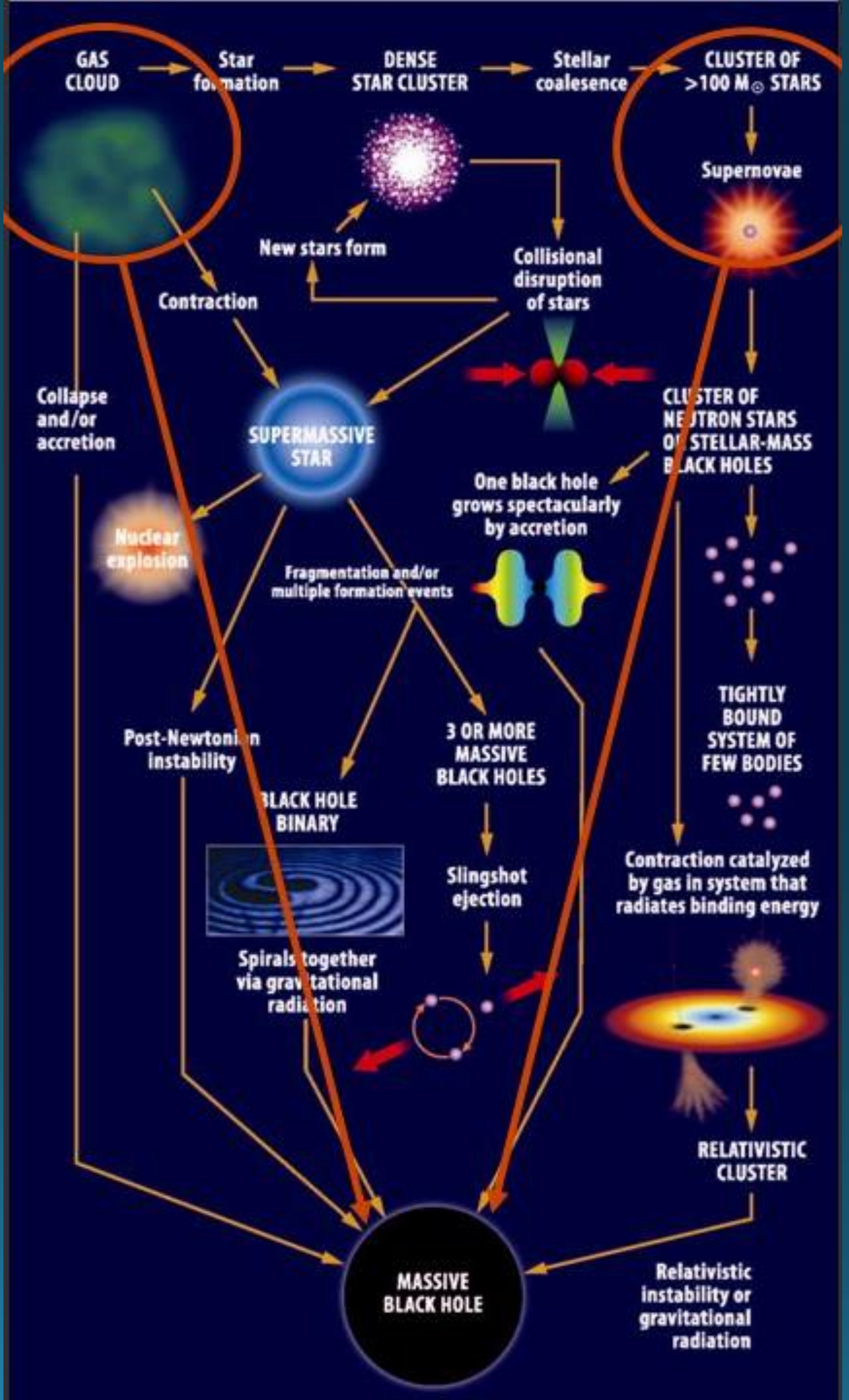
Eduardo Bañados, Bram P. Venemans, Chiara Mazzucchelli, Emanuele P. Farina, Fabian Walter,
Feige Wang, Roberto Decarli, Daniel Stern, Xiaohui Fan, Frederick B. Davies, Joseph F. Hennawi

Previous record holder: Mortlock (2011) quasar,
with a black hole mass of $\approx 2\times10^9$ $M_\odot$ SMBH at $z\approx7.1$
At these redshifts, the Universe is less than 1 Gyr old....
Problem: How do you form a $\sim10^9$ $M_\odot$ SMBH in that time?

How to form a supermassive black hole…

Promising seeds:

- Direct collapse black hole
- Very massive or even supermassive stars



Intermission: Name the telescope!

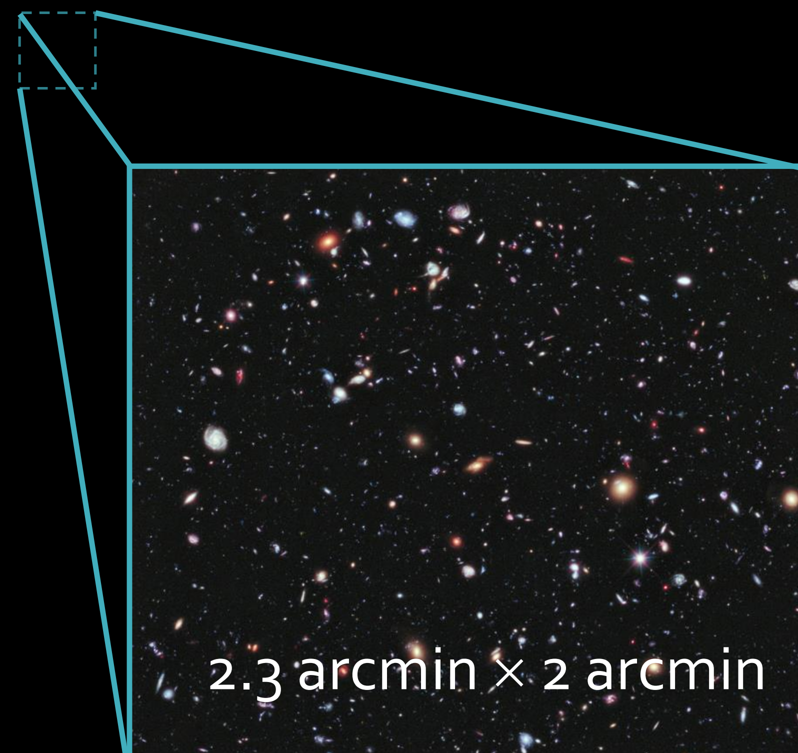
How to find and study high-redshift galaxies

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 Extreme Deep Field

Total exposure time: 23 days
(2 million seconds)

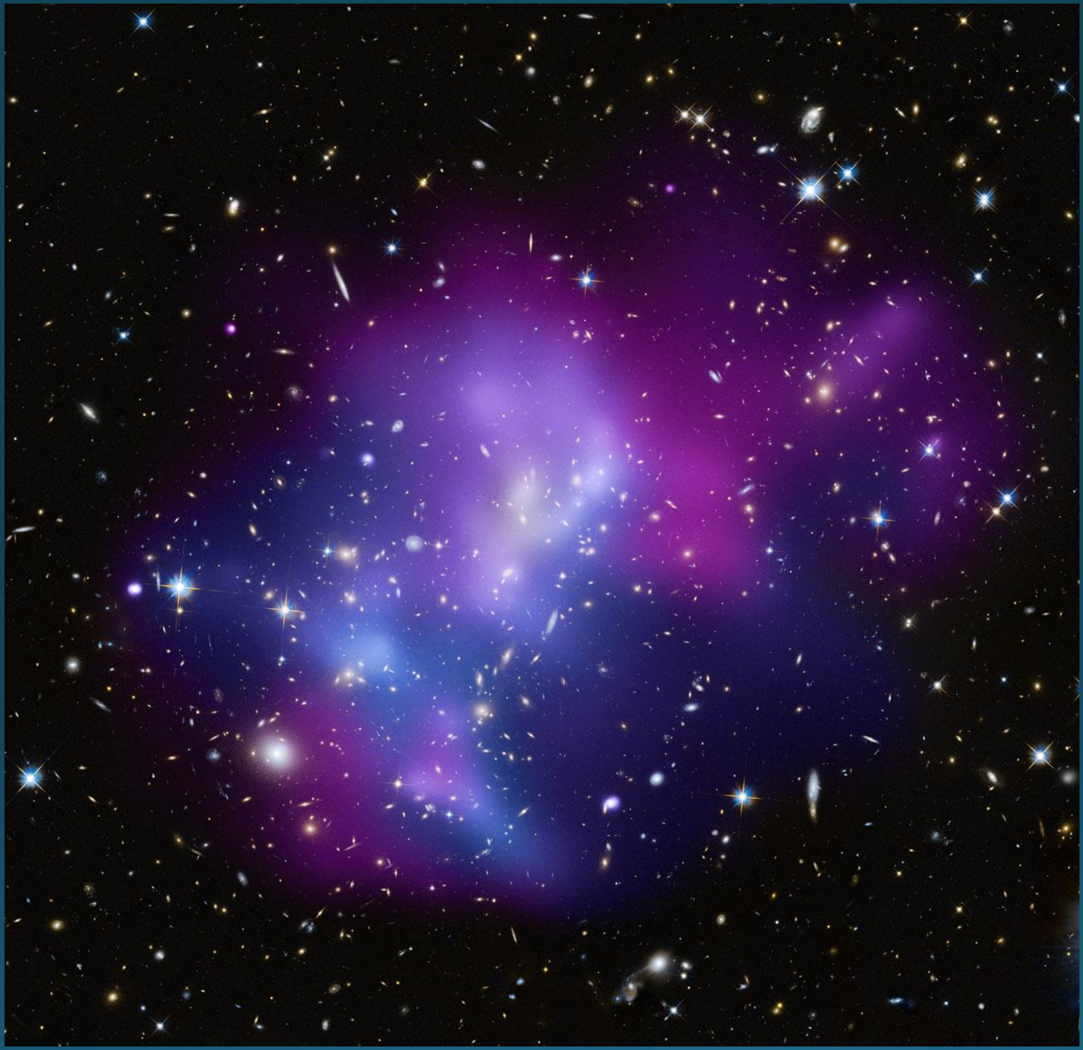


The Hubble Extreme Deep Field

The most distant galaxy so far

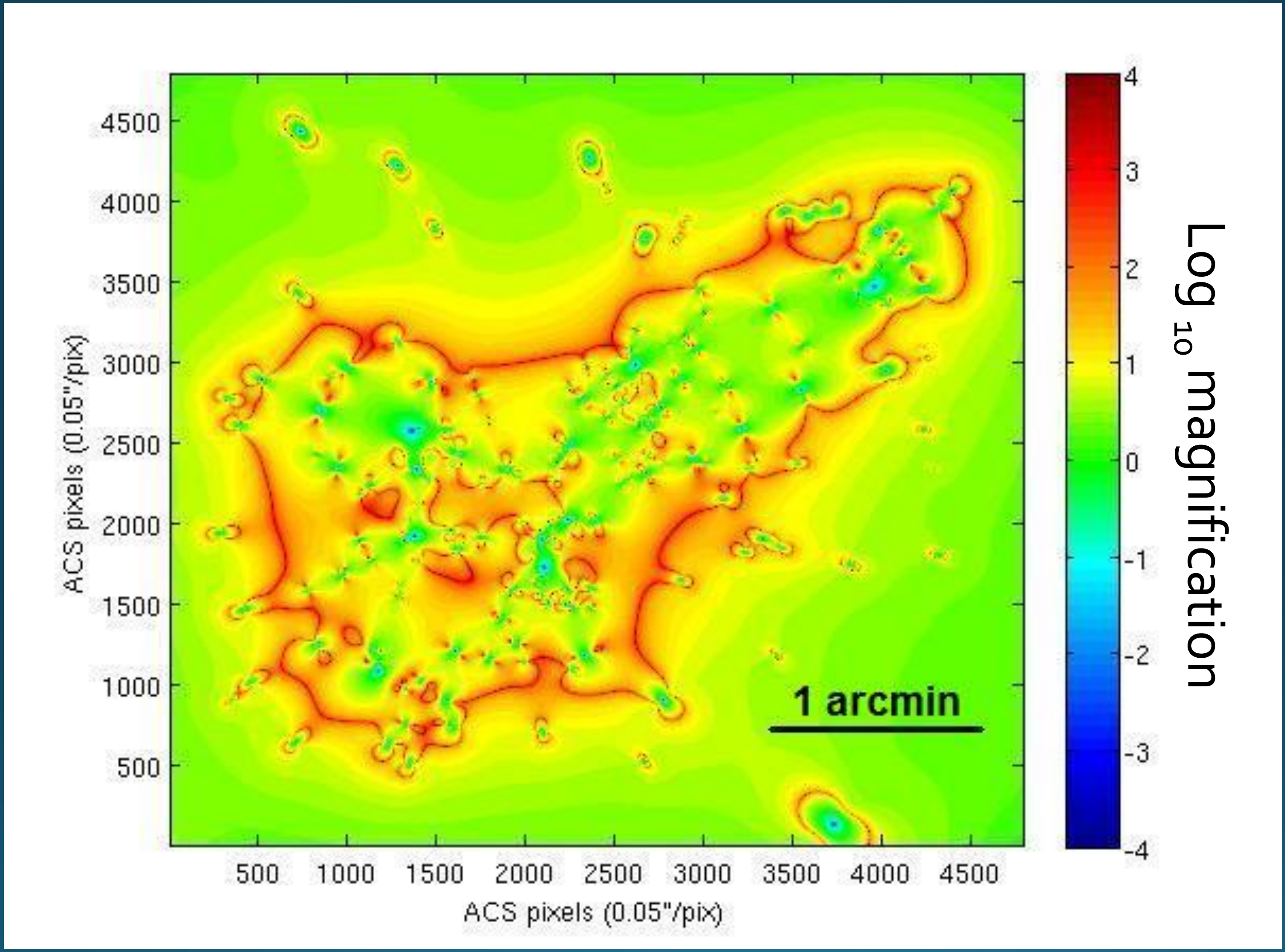
Intermission: Name the telescope!

Cluster lensing I



Galaxy cluster at z≈0.5

Cluster lensing II



Magnification map

Pros and Cons of Cluster Lensing

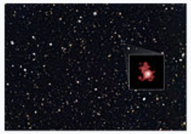
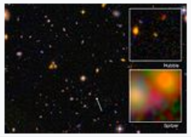
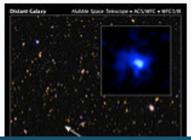
+ Background sources appear brighter by a factor μ

- 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*

Intermission:
Why are redshift records important?

Most distant astronomical objects with spectroscopic redshift determinations

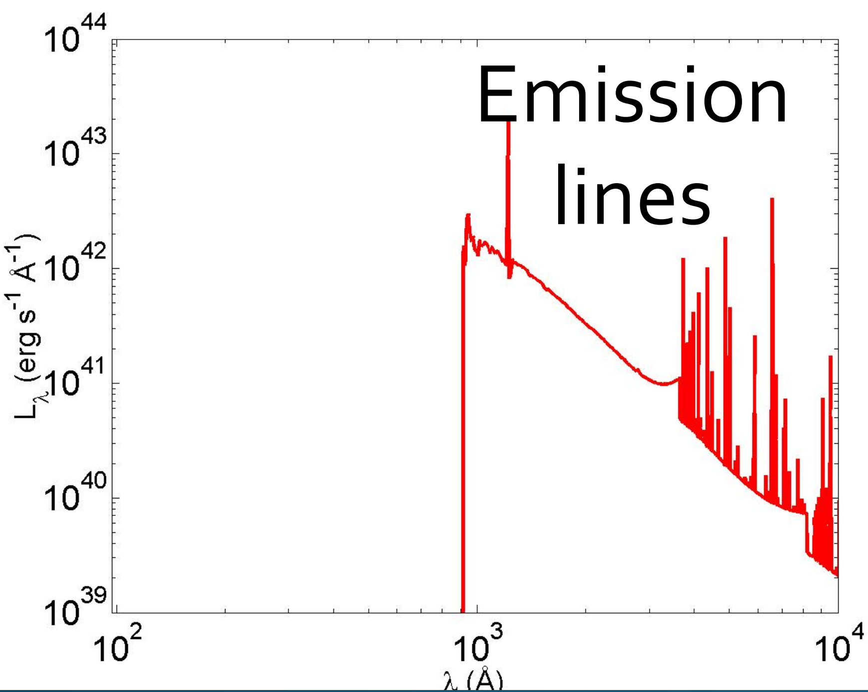
	Name	Redshift (z)	Gigalightyears. Light travel distance§ (Gly)[1]	Type	Notes
	GN-z11	z = 11.09	13.39	Galaxy	Confirmed galaxy[2]
	MACS1149-JD1	z = 9.11	13.26	Galaxy	Confirmed galaxy[3]
	EGSY8p7	z = 8.68	13.23	Galaxy	Confirmed galaxy[4]
	A2744 YD4	z = 8.38	13.20	Galaxy	Confirmed galaxy[5]
	GRB 090423	z = 8.2	13.18	Gamma-ray burst	[6][7]
	EGS-zs8-1	z = 7.73	13.13	Galaxy	Confirmed galaxy[8]

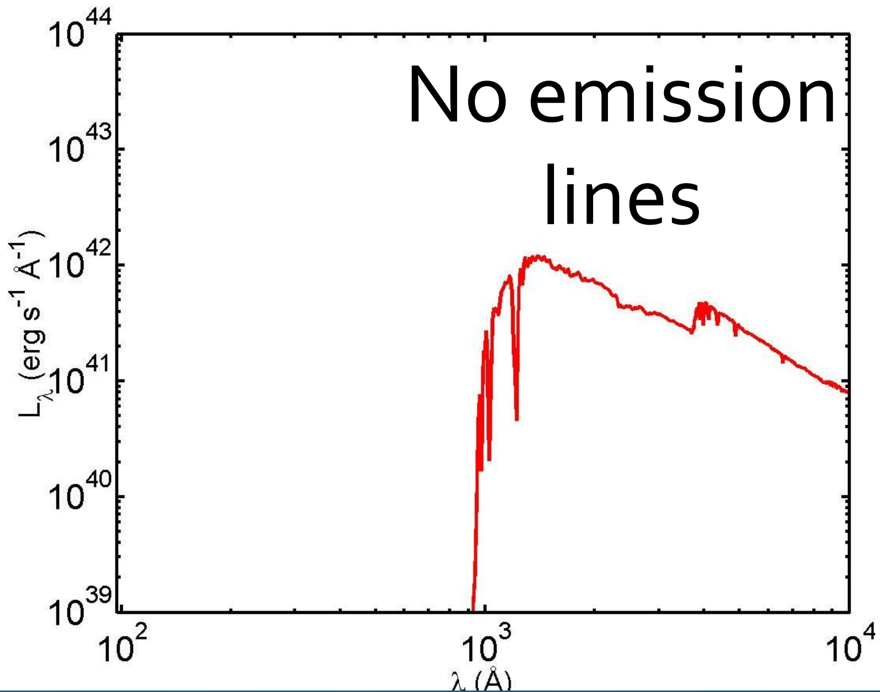
Selecting high-z galaxy candidates

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

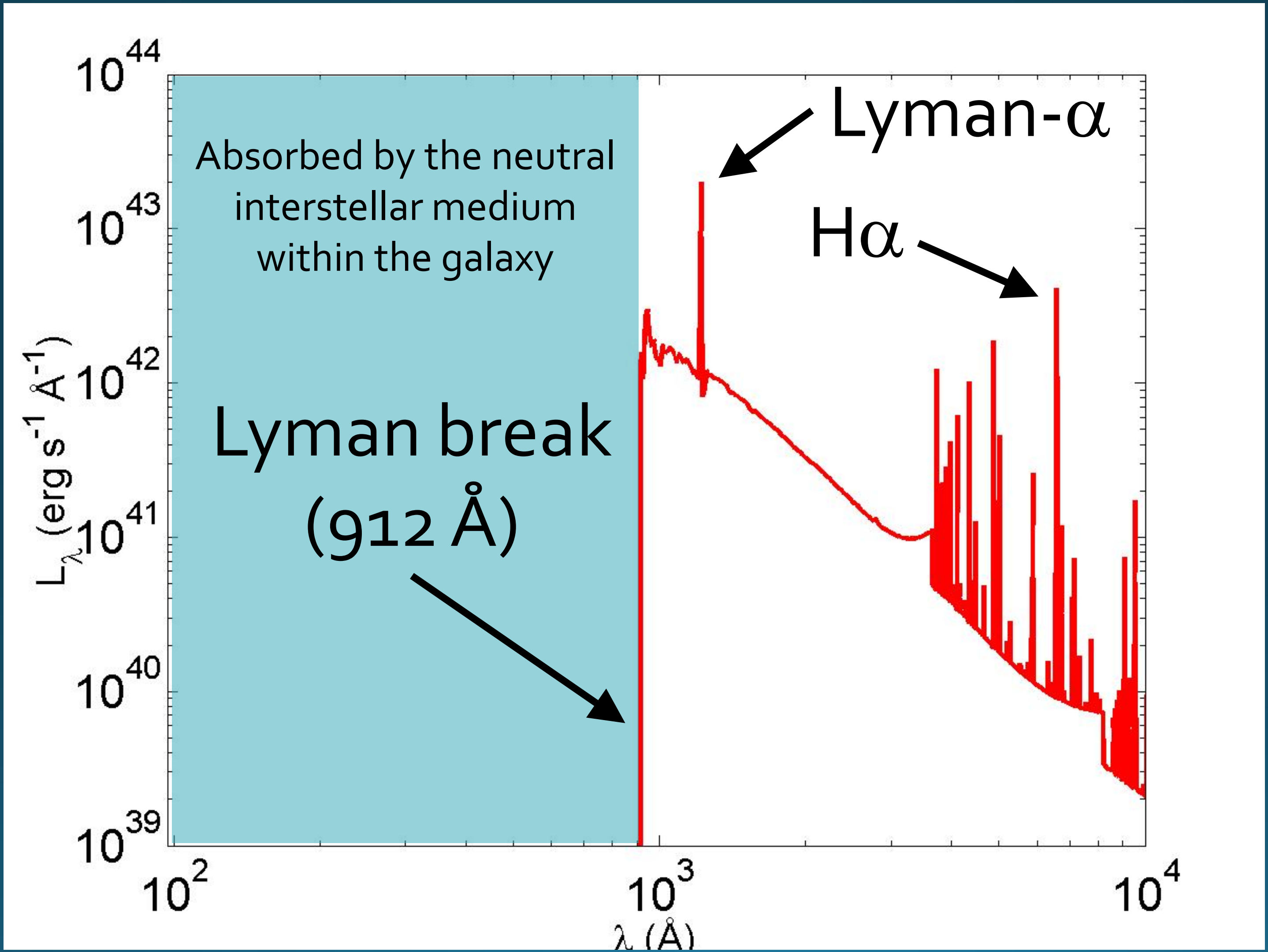




Young galaxy

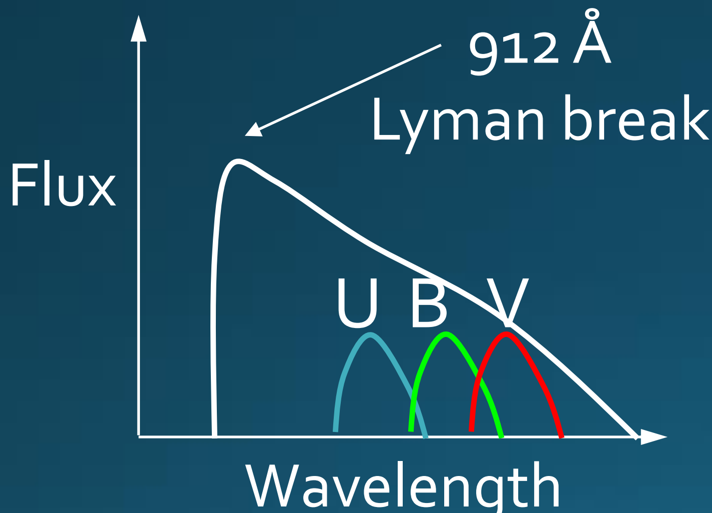
Old galaxy

The UV/optical spectra of galaxies



Drop-out techniques: Lyman-Break Galaxies

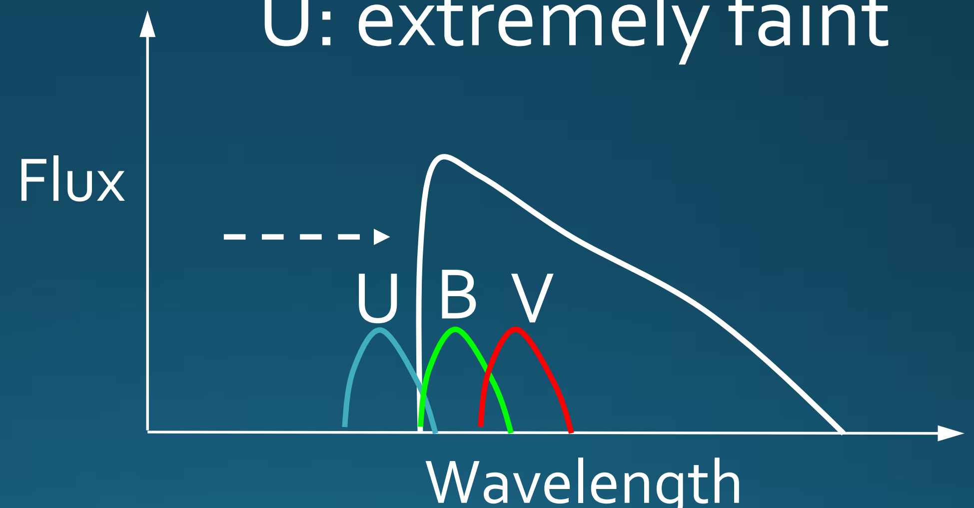
z=0



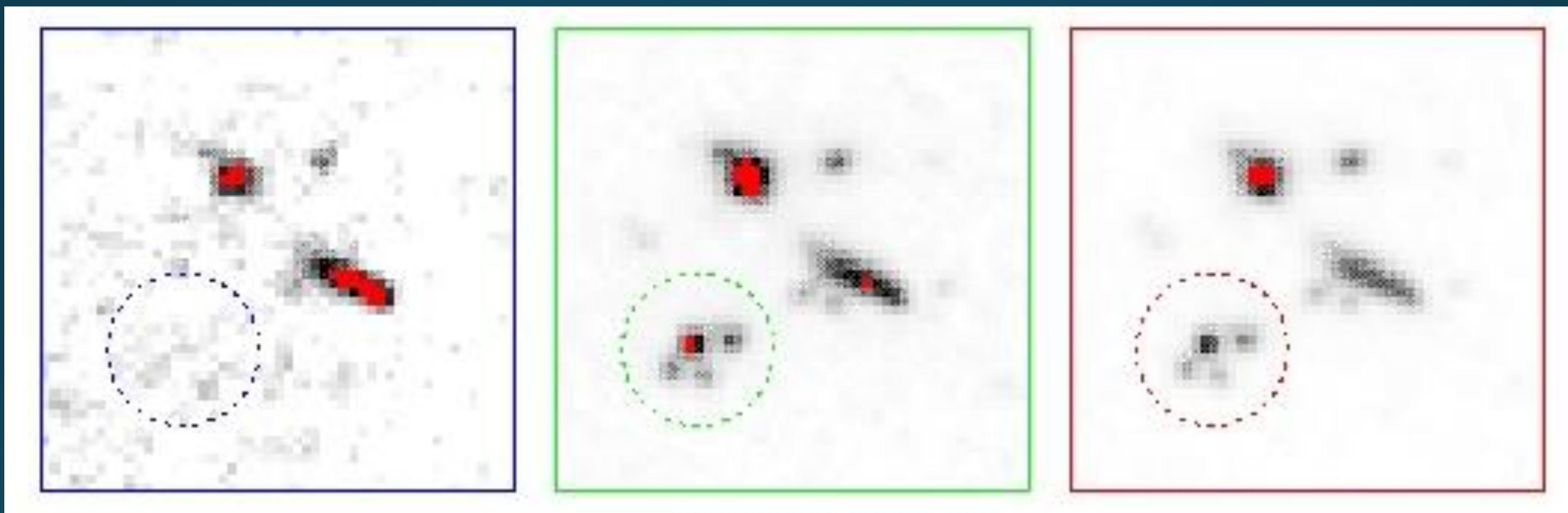
z>2.5

B-V ~ normal

U: extremely faint

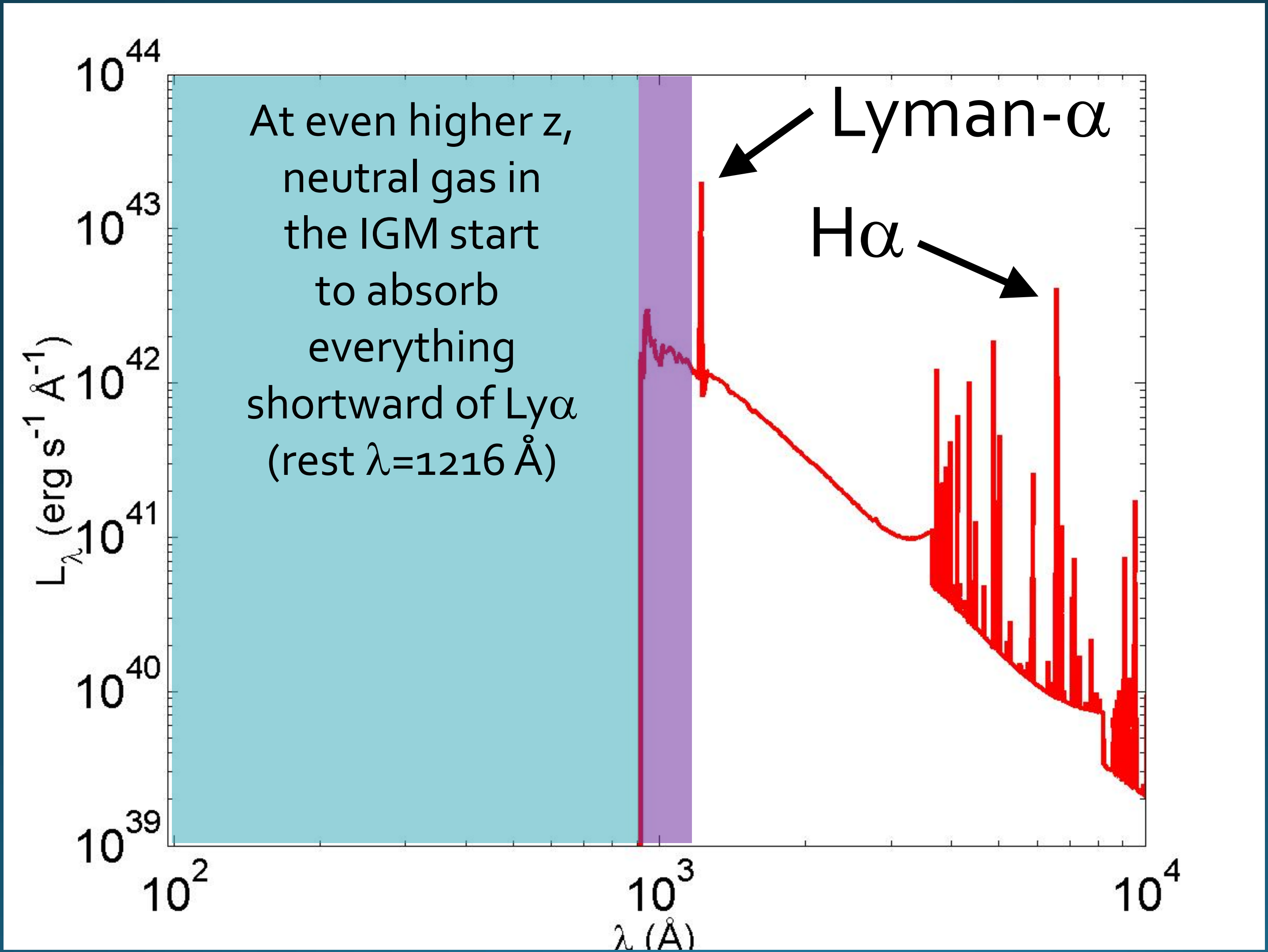


Drop-out techniques: Lyman-Break Galaxies



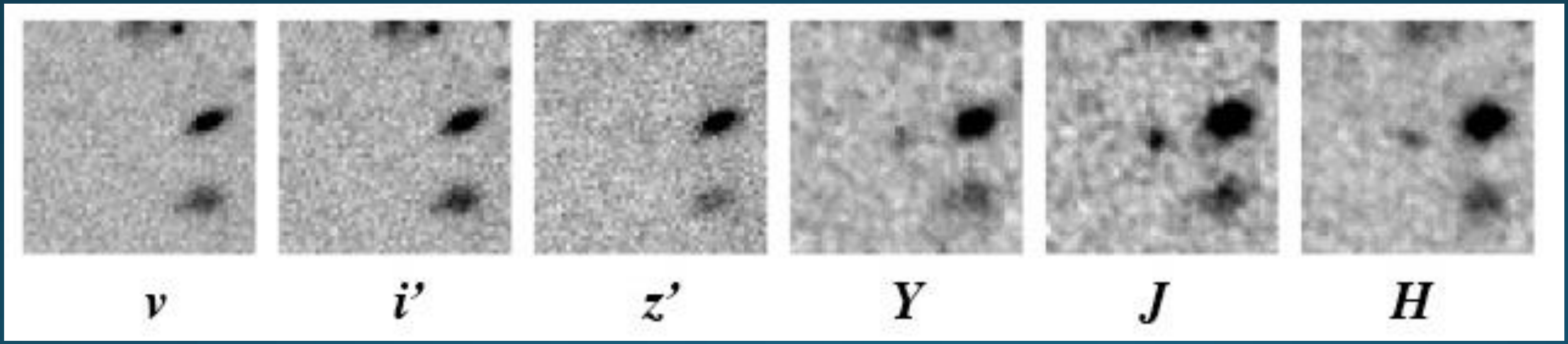
U B V

Reionization-epoch galaxies



Drop-out techniques: z>6 objects

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



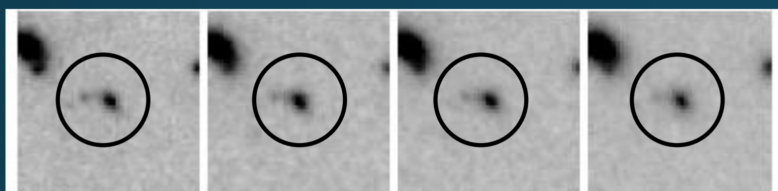
Optical

Near-IR

λ

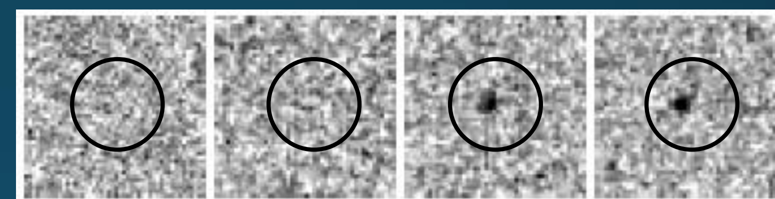
Intermission:
Which of these drop-out candidates is likely to have the highest redshift?

A



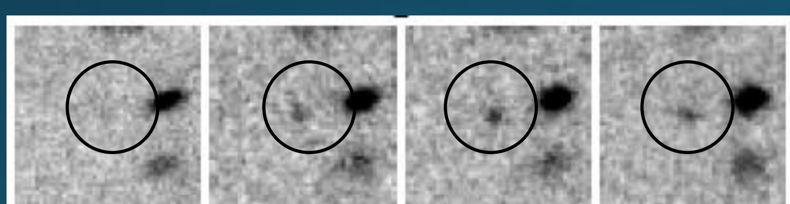
z Y J H

B



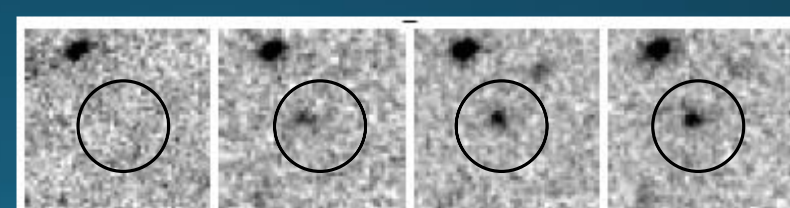
z Y J H

C



z Y J H

D



z Y J H

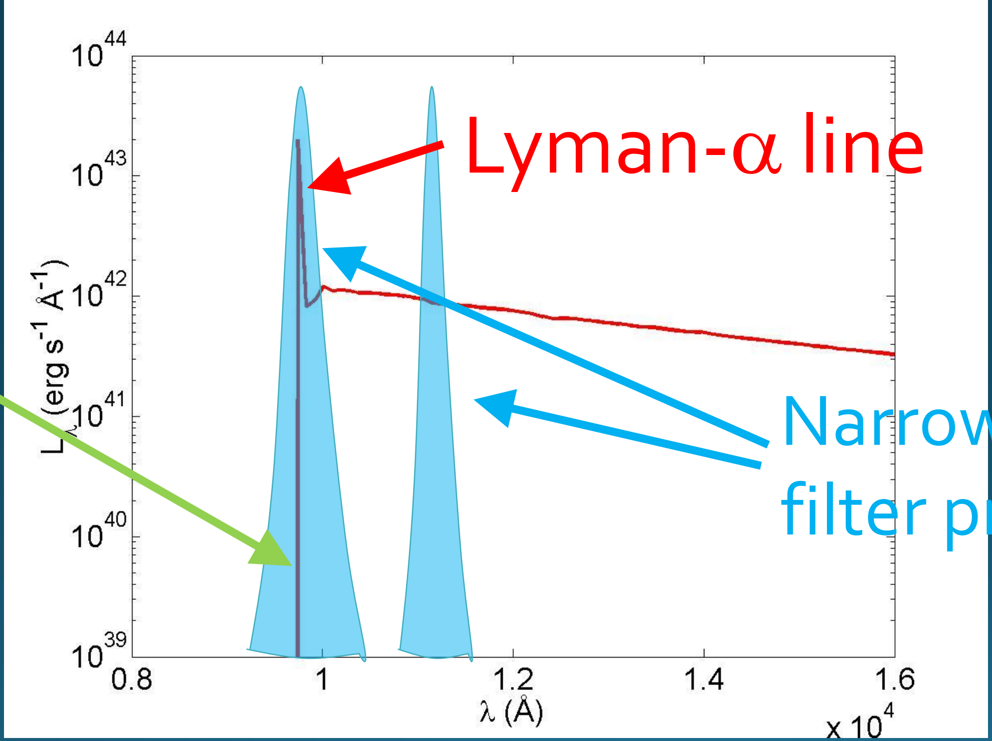
λ

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)



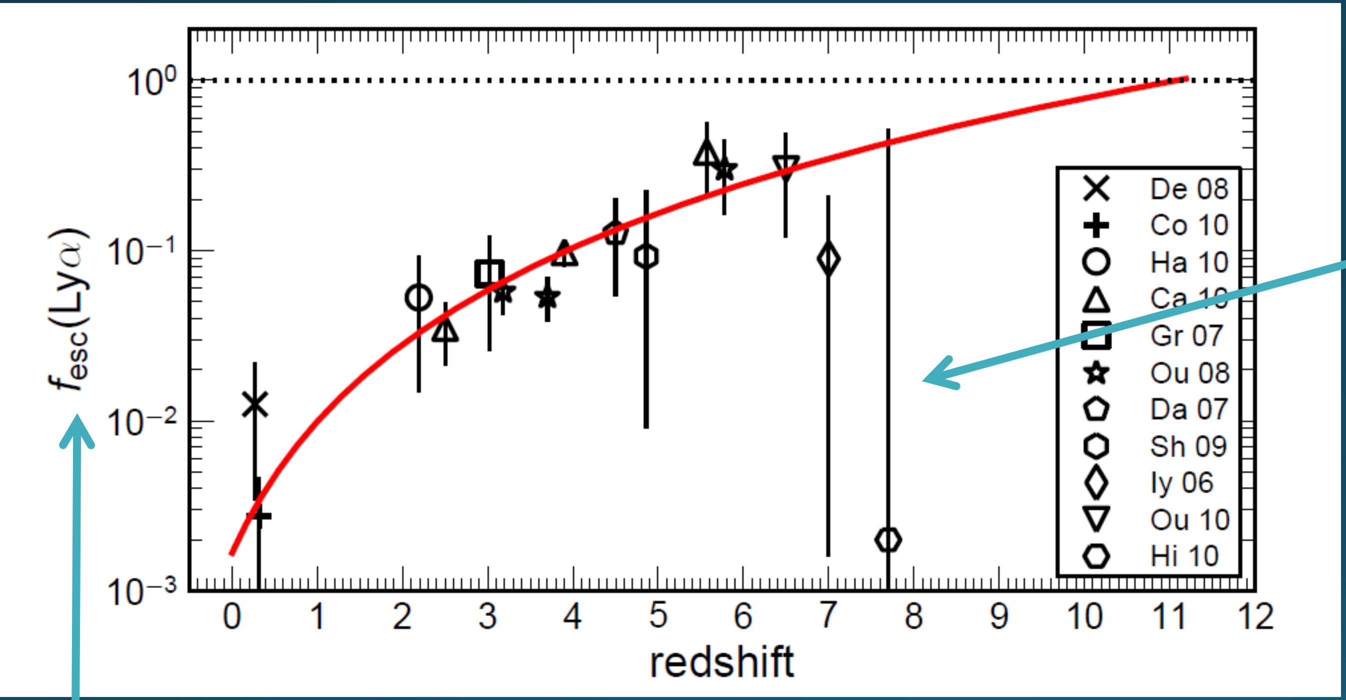
Narrowband filter profiles

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



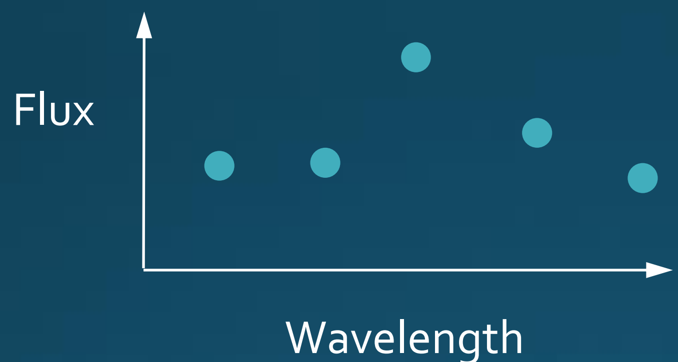
Abrupt drop → Lyα not good way to find z>6 galaxies (but may be good way to probe reionization)

Fraction of Lyα photons reaching the observer

Hayes et al. 11

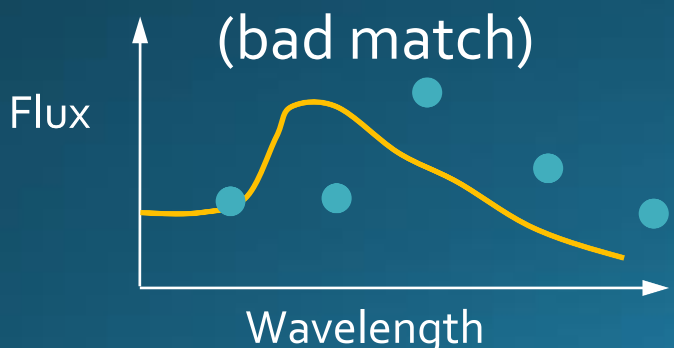
Photometric redshifts

- 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)

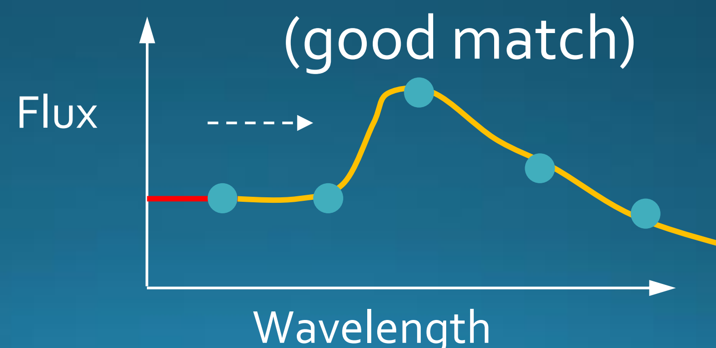


Measured photometrical data points

z=0 template spectrum (bad match)



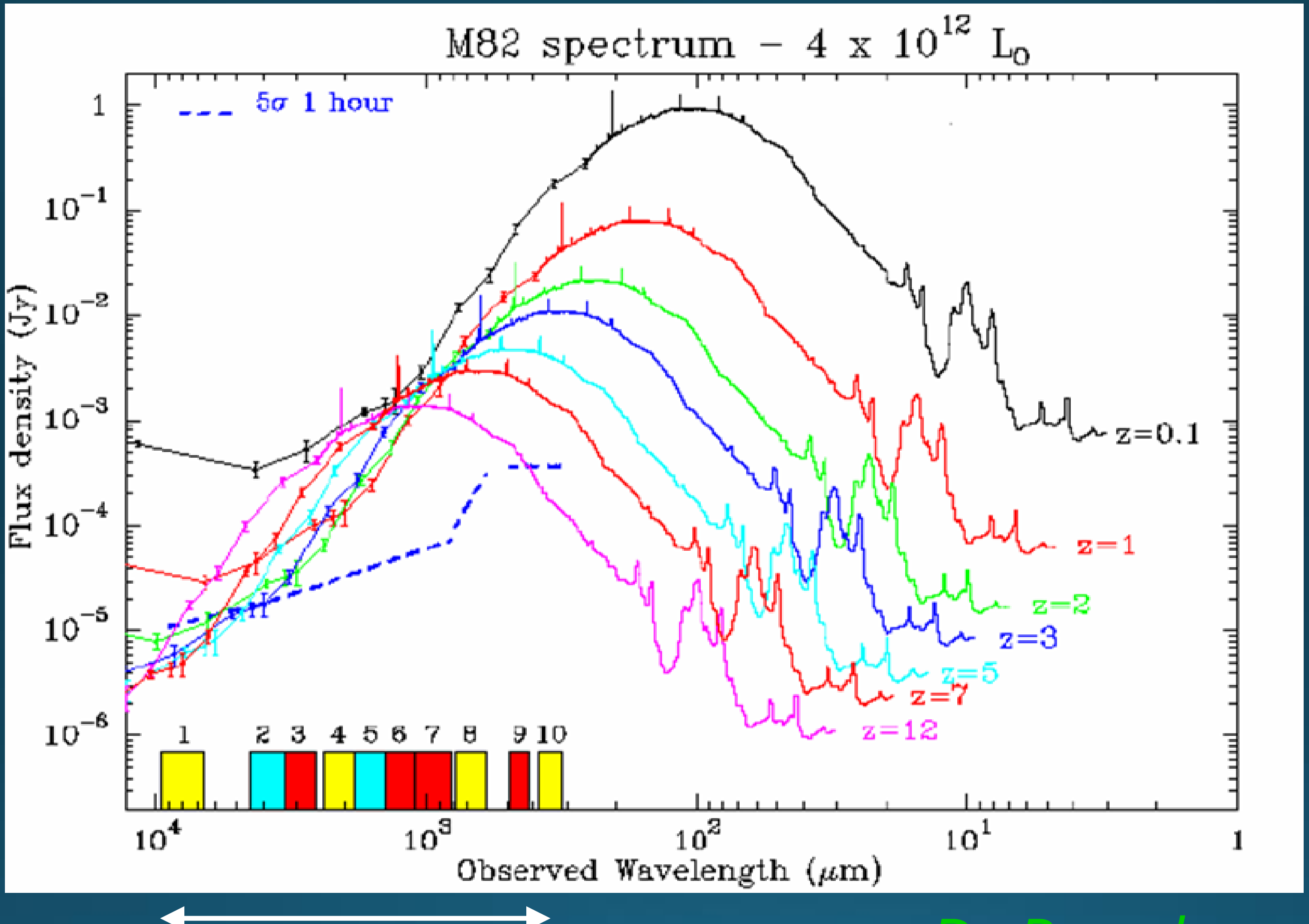
Redshifted template spectrum (good match)



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)

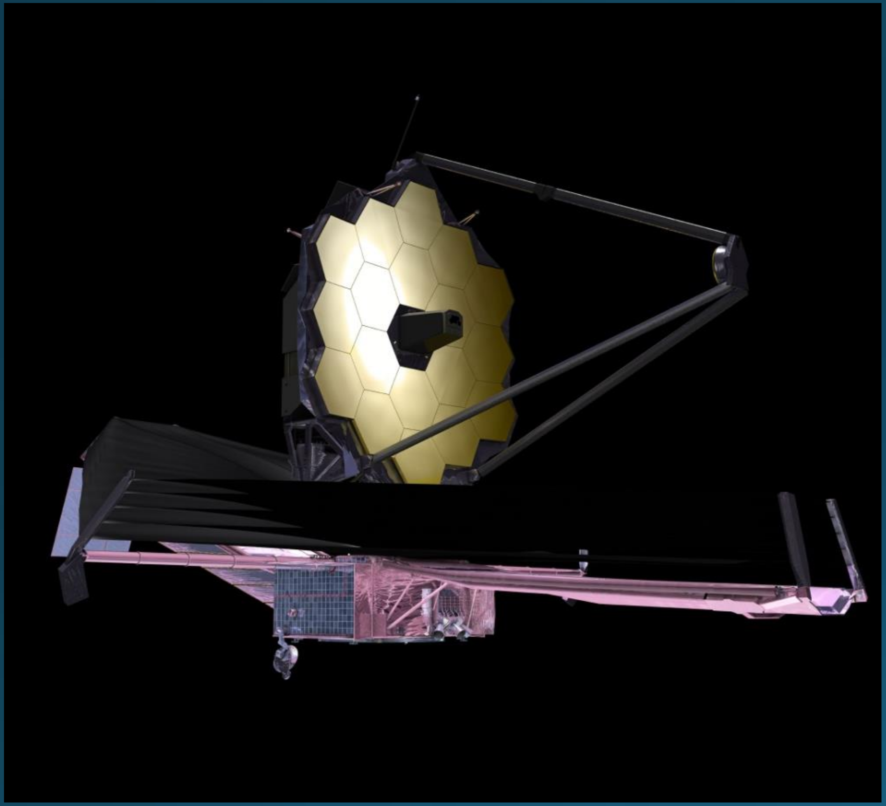
Can be used to search for dust emission and emission lines like [CII] @ 158 μm and [OIII] @88 μm (rest-frame) from $z>6$ galaxies



De Breuck 05

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

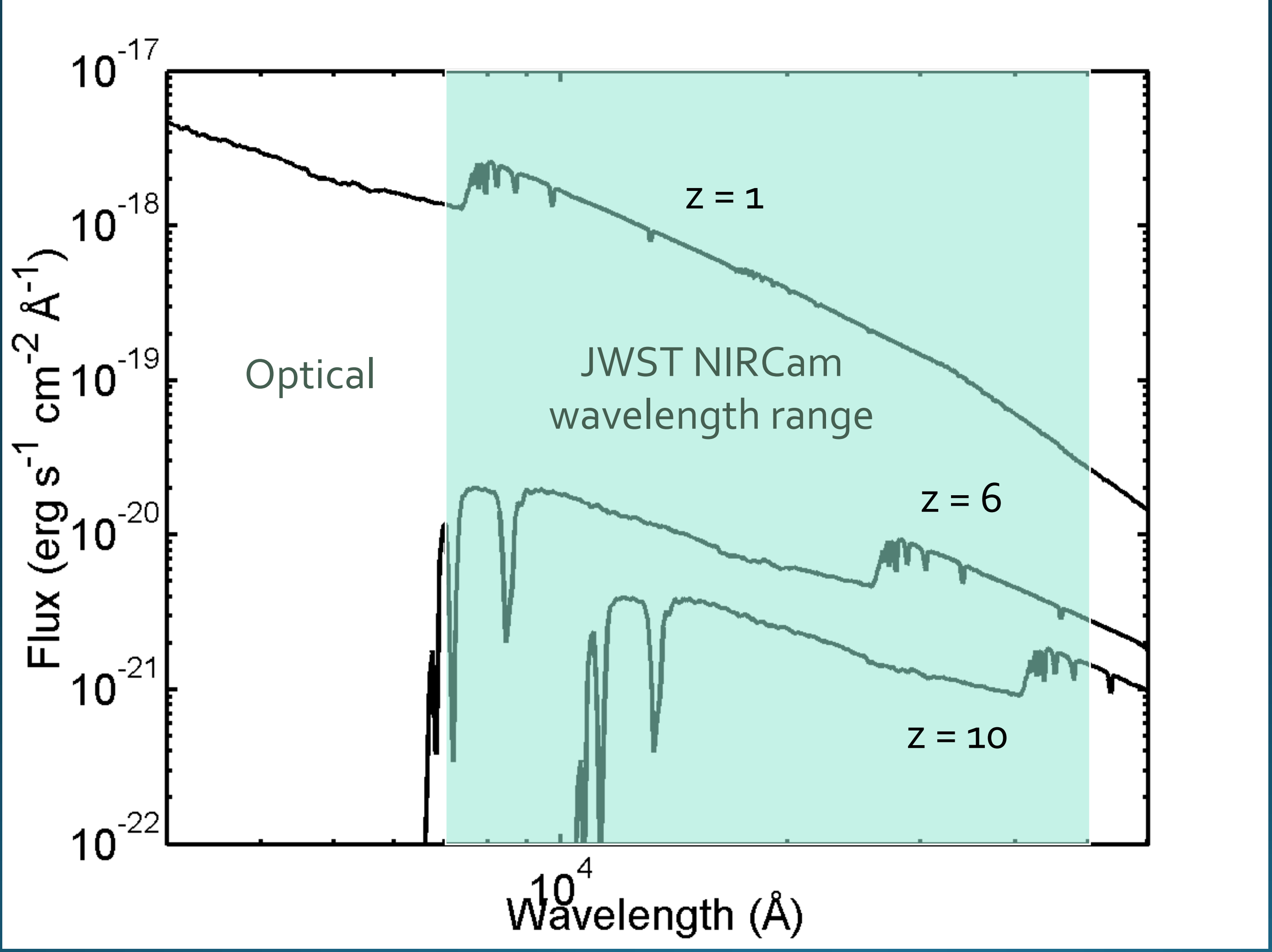
Future prospects: JWST



James Webb Space Telescope
'The first light machine'
To be launched by
NASA / ESA / CSA in 2021

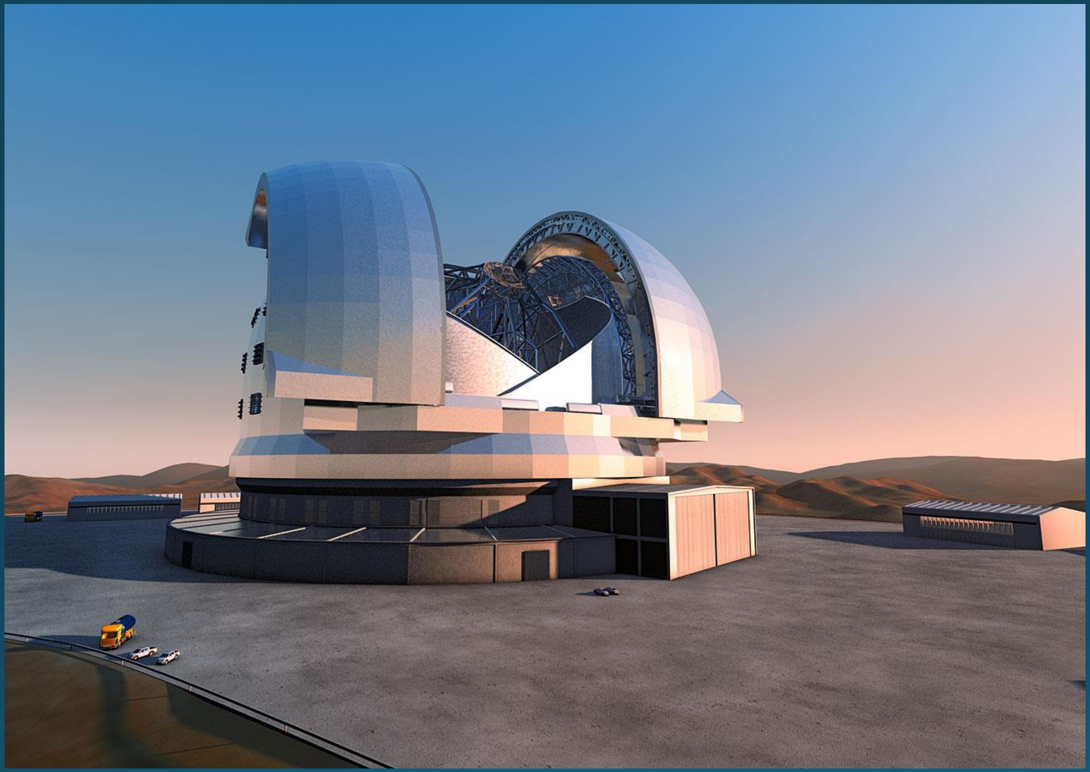
6.5 m mirror
Observations @ 0.6-29 μm
Useful for:
Galaxies up to $z \approx 15$
Pop III supernovae

Why infrared?



Zackrisson et al. (2001) model

Future prospects: ELT



39 m Extremely Large Telescope (ELT) estimated to be completed in 2025