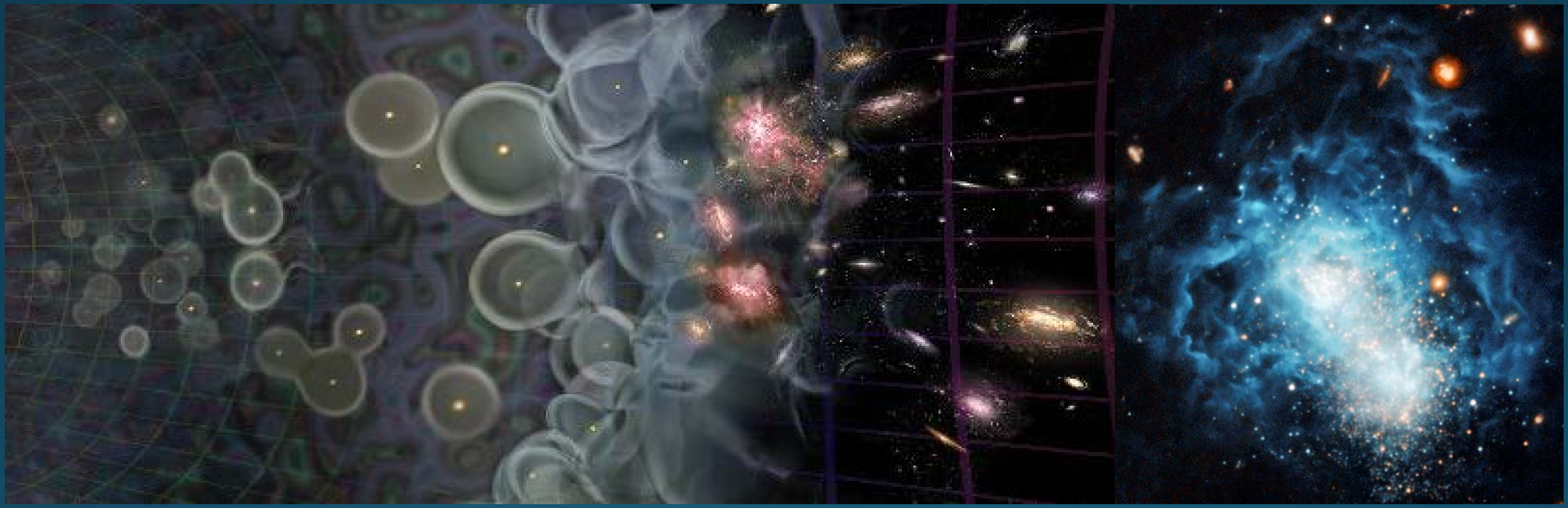
# Physics of Galaxies 2016
# 10 credits
# Lecture 8: The High-Redshift Universe



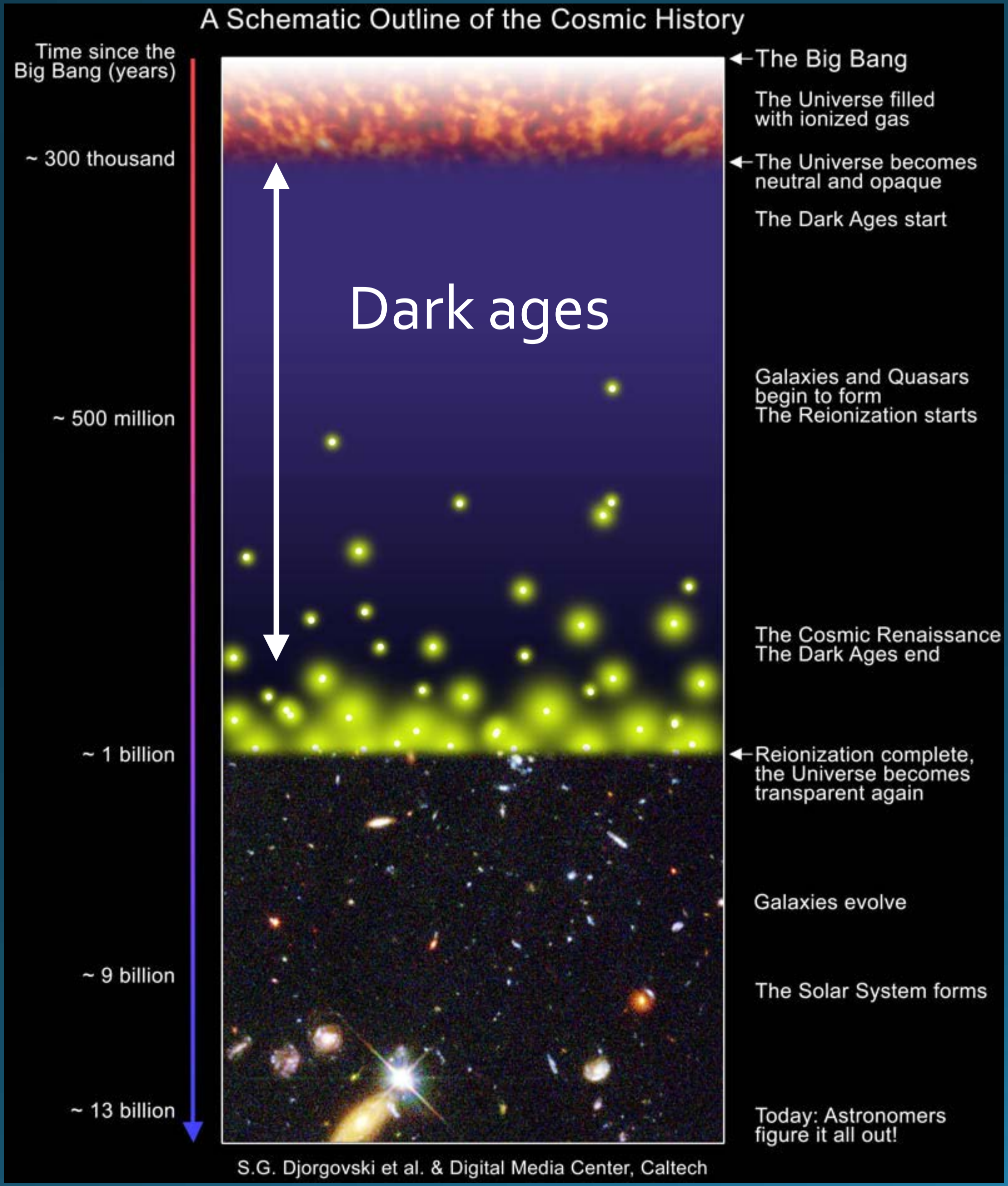
# Outline: Part I

- 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

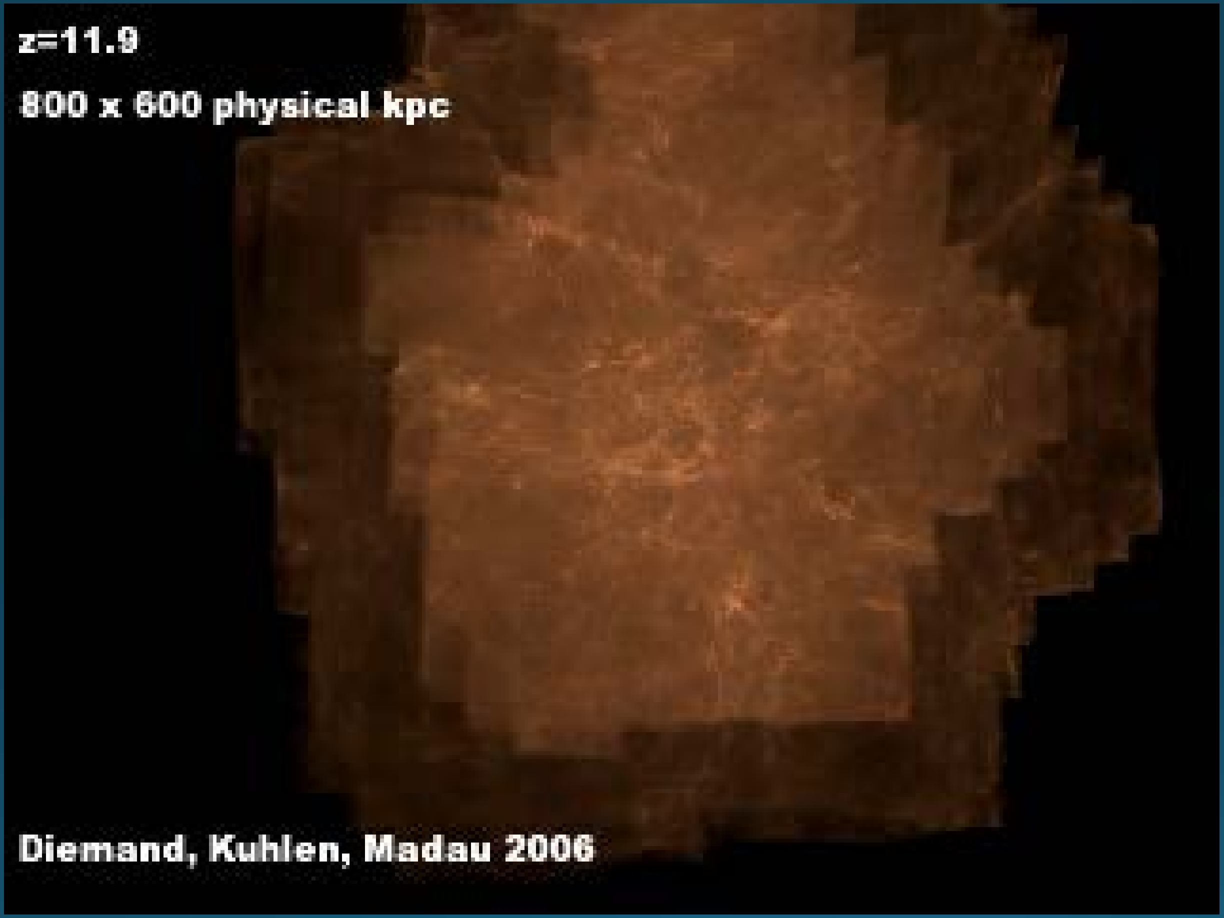
First galaxies

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

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

Current observational limit: HST and 8-10 m telescopes on the ground can detect light sources up to $z \approx 11$

# Merging cold dark matter halos




Formation of a ~$10^{12}$ $M_{solar}$ dark matter halo

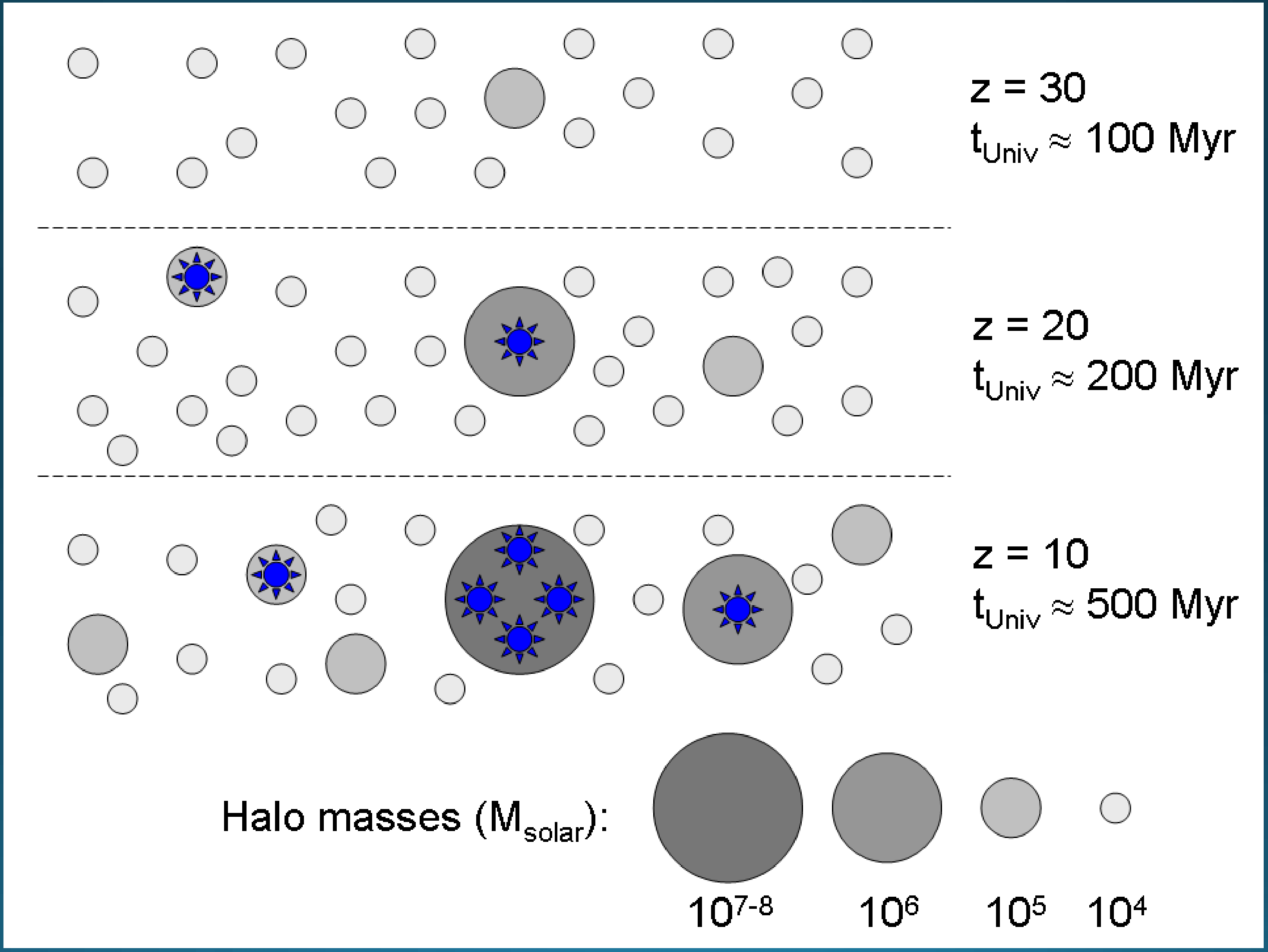
Simulation runs from $z \approx 12$ to 0 ($t_{Univ} \approx 0.25$ to 13.7 Gyr)

# 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

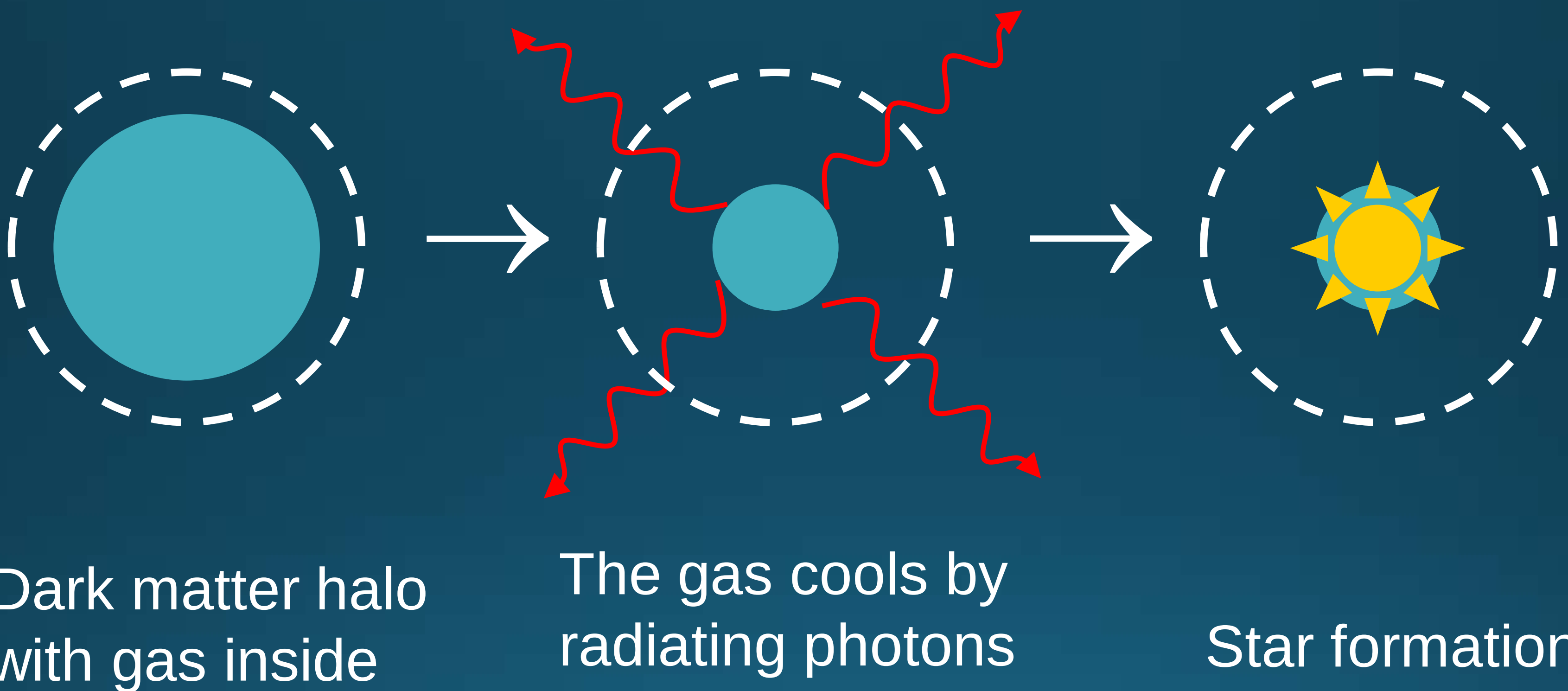
- Population II: Metal-poor stars

  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

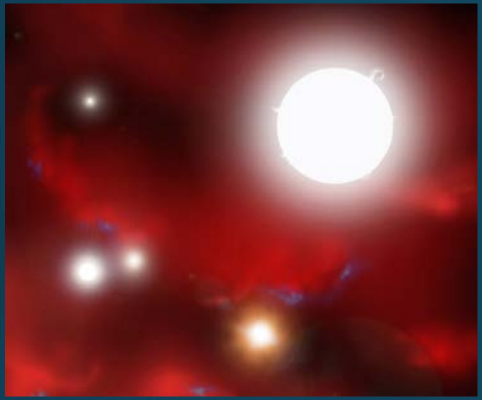


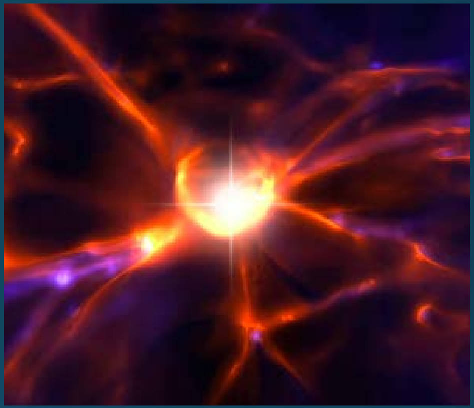
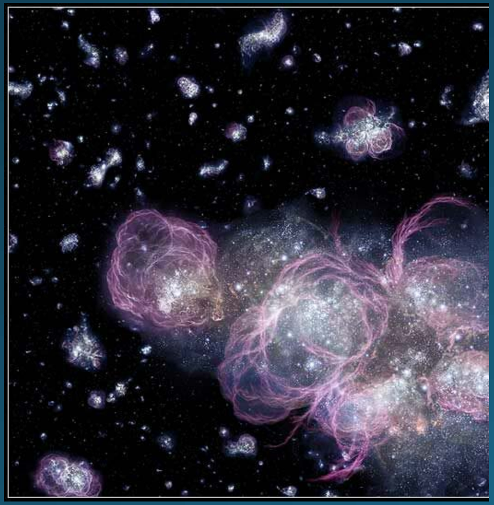
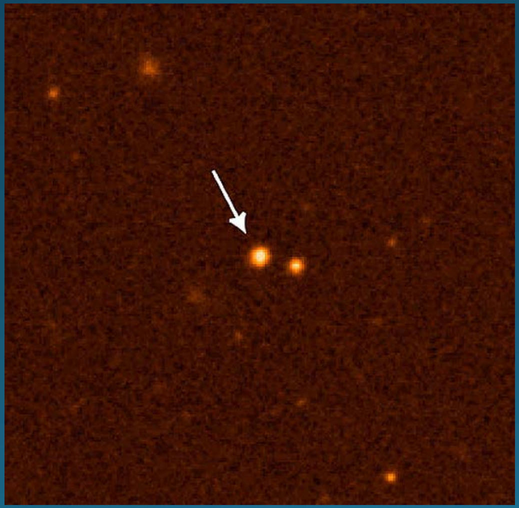

Problem: Low metallicity at high redshifts →
*Lack of efficient coolants*

# 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 → *Only a few stars (maybe just one) per minihalo*

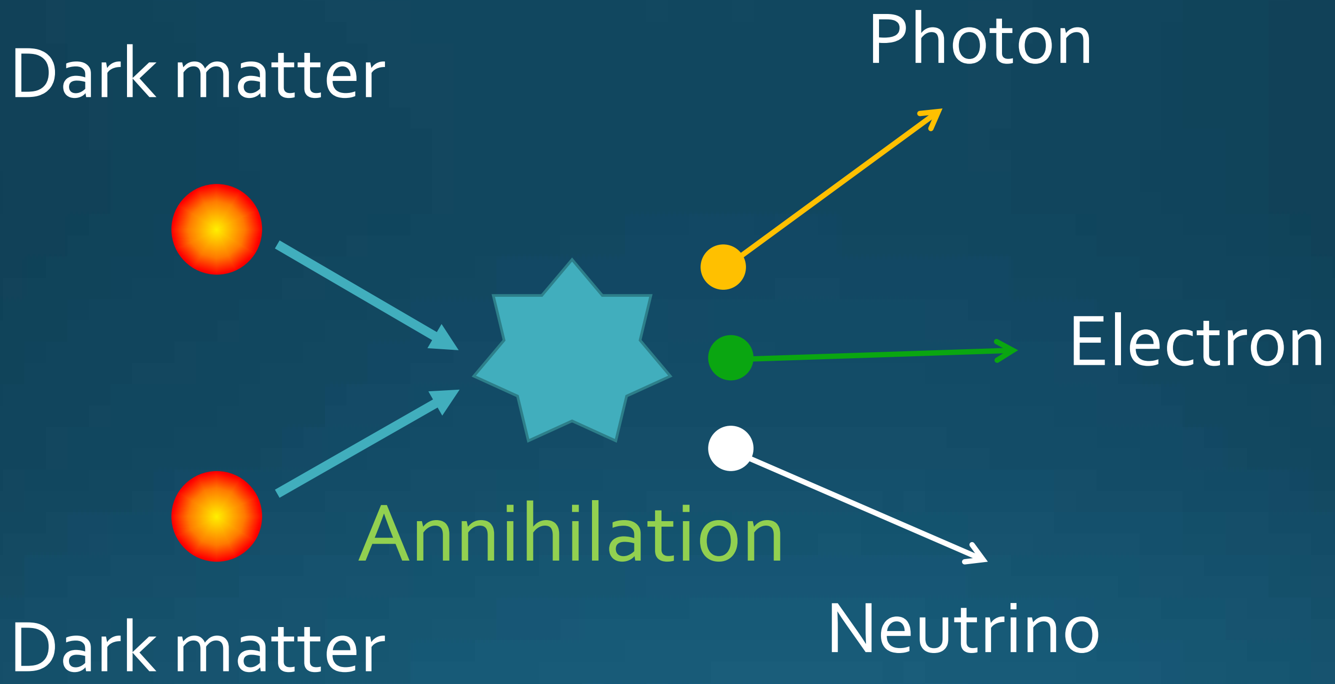
# Intermission: The first stars(?)



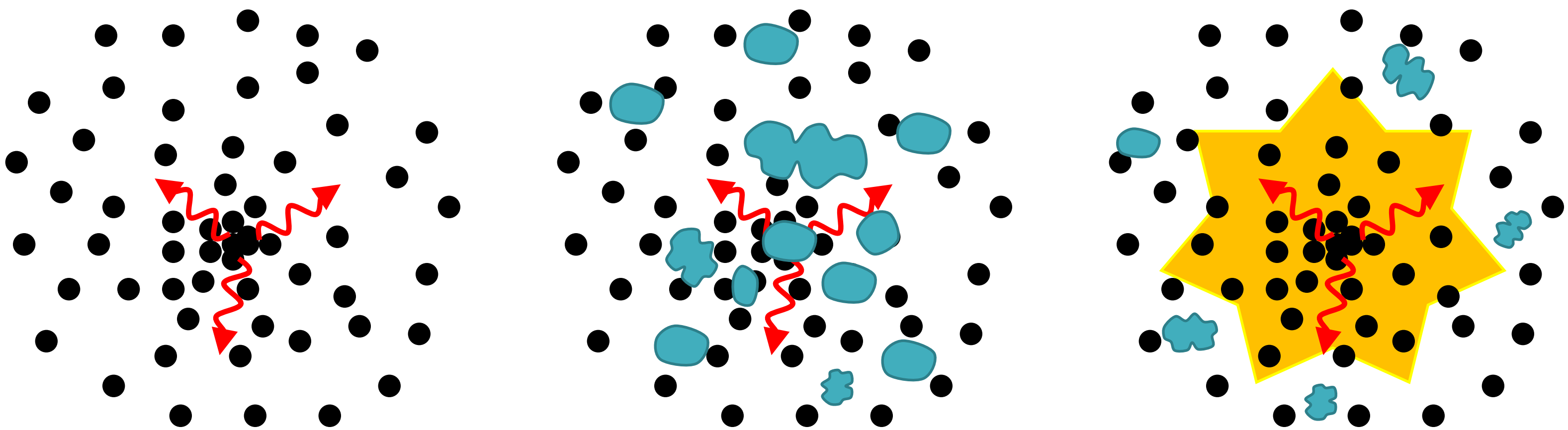





# Normal star ≈ hydrogen bomb

# Dark matter annihilation



# Dark stars

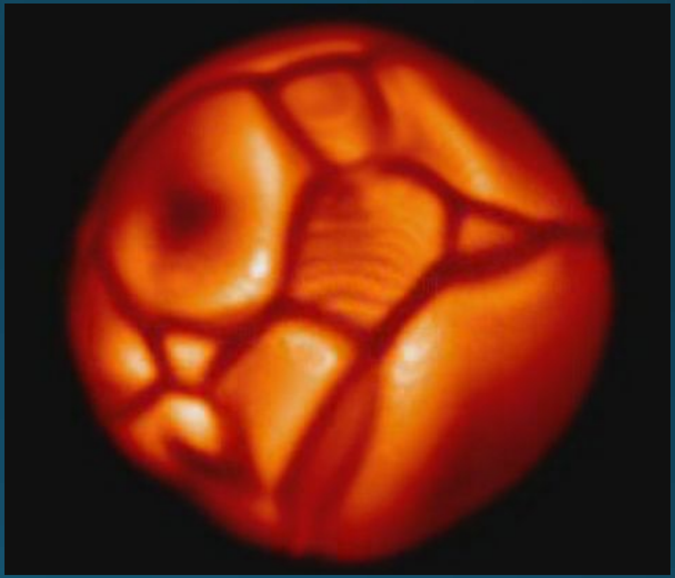


WIMP annihilation in centre of CDM halo

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

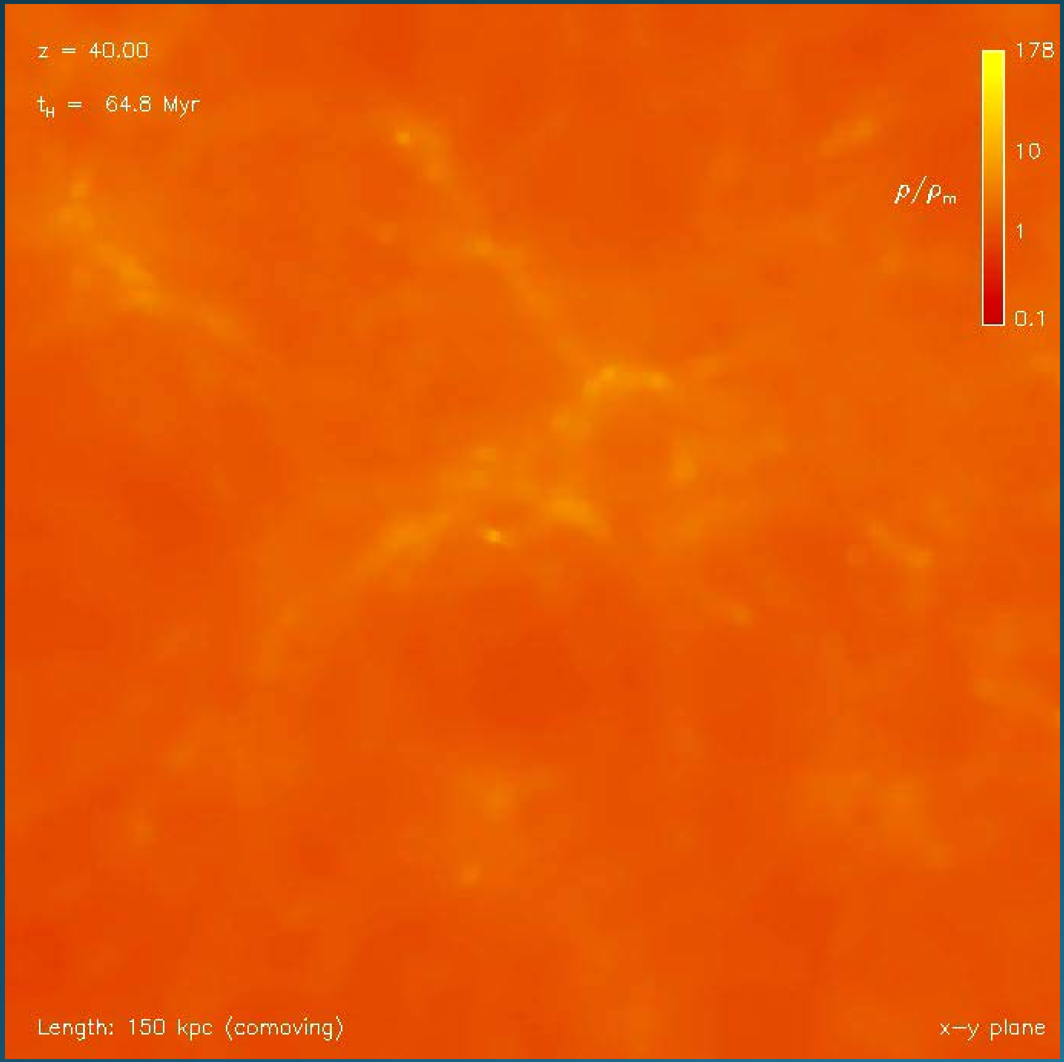
Vanilla population III star

# The sizes of primordial stars II

The Sun

Supermassive dark star

# Formation of the first galaxies




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)

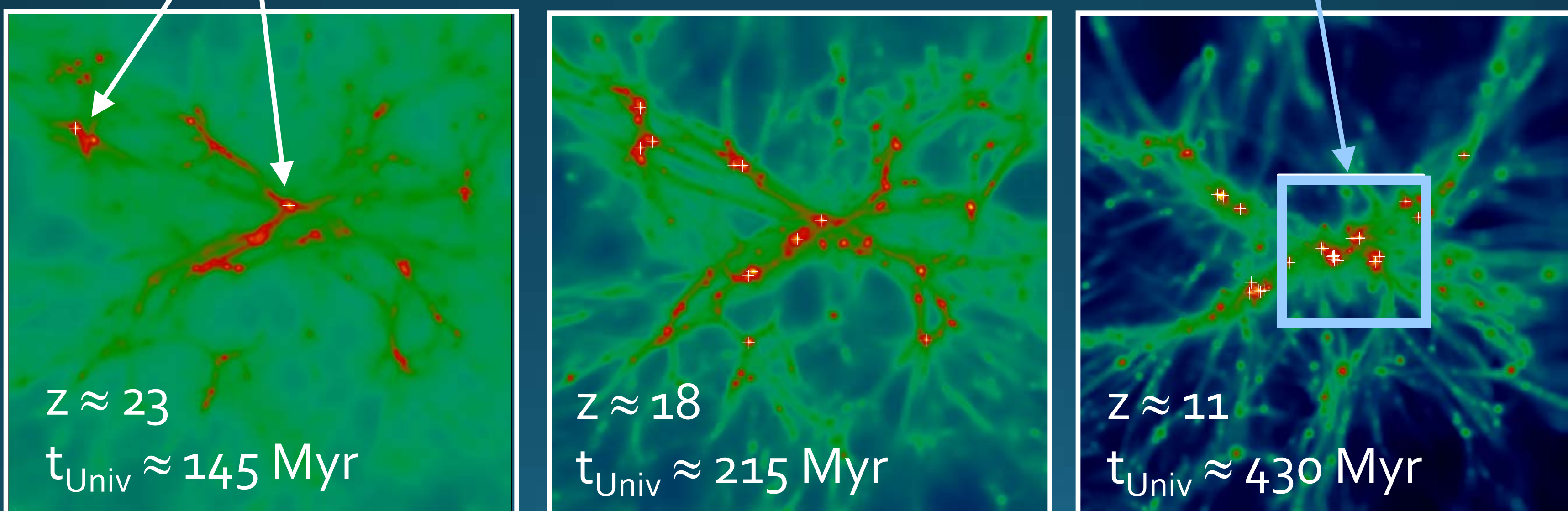
*Greif et al. 08*

# Star formation inside and outside the first galaxies

Star formation in minihalos

Minihalo mergers and further star formation

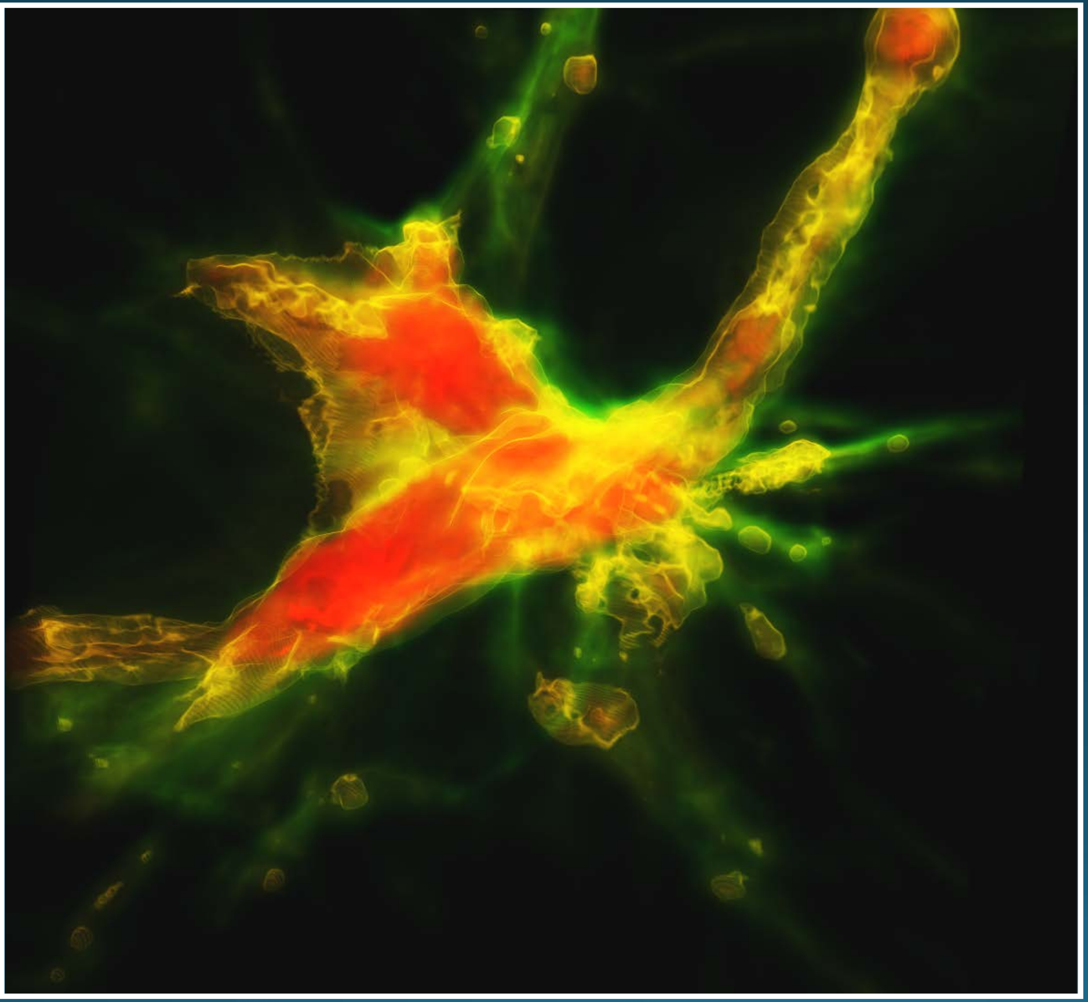
Object qualifies as a *galaxy*




*Greif et al. 08*

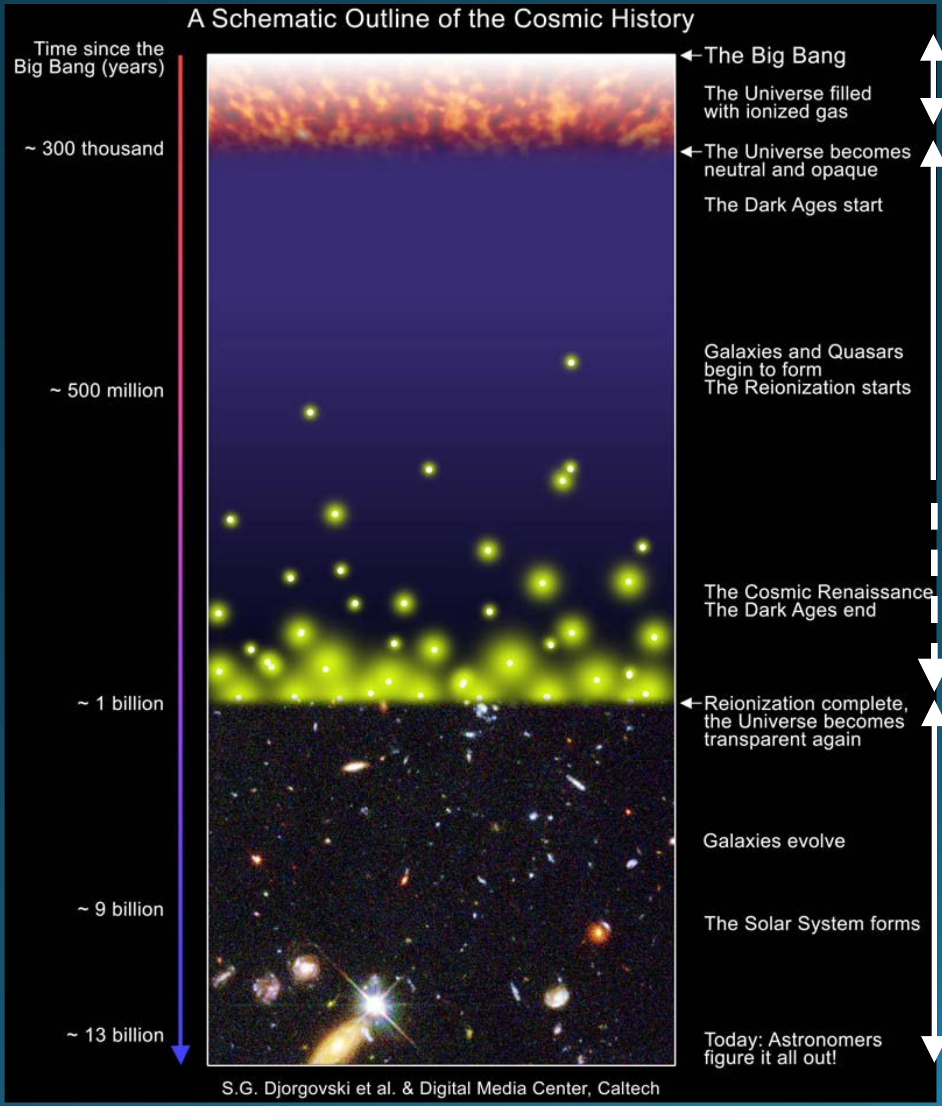
Gas density shapshots

# A galaxy is born (at z ≈ 10)



*Greif et al. 08*

# Reionization




<u>Intergalactic medium</u>

Ionized

Neutral

CMBR (Planck) $\rightarrow z_{reion} \approx 8$

Ly$\alpha$ absorption in quasars $\rightarrow z_{reion} > 6$

Reionized

# What caused reionization?

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

# Intermission: Name the telescope!

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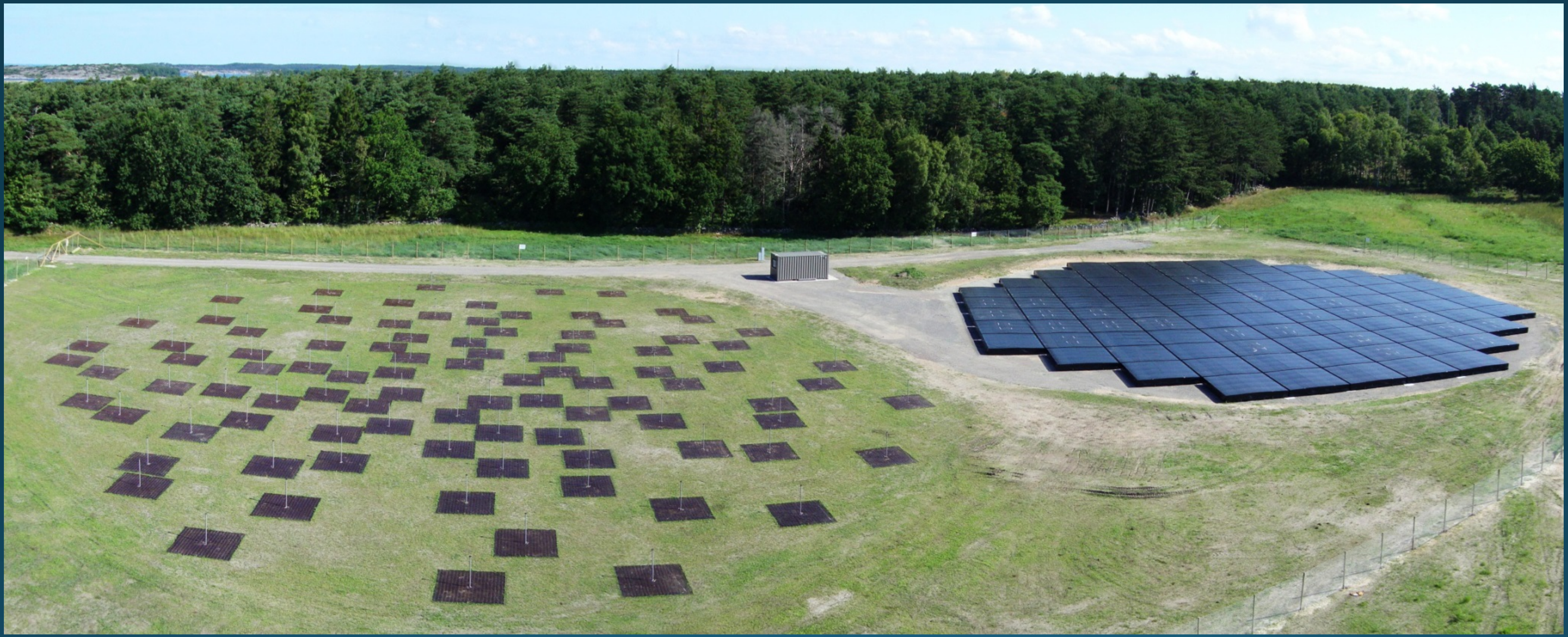


# Intermission: Name the telescope!

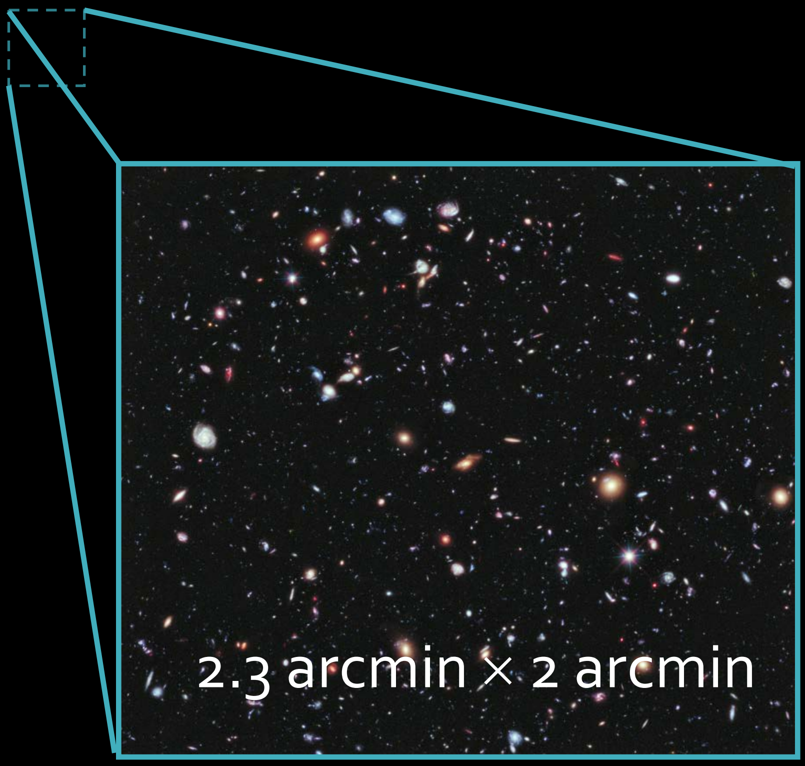
# How to find and study high-redshift galaxies

Imaging strategies

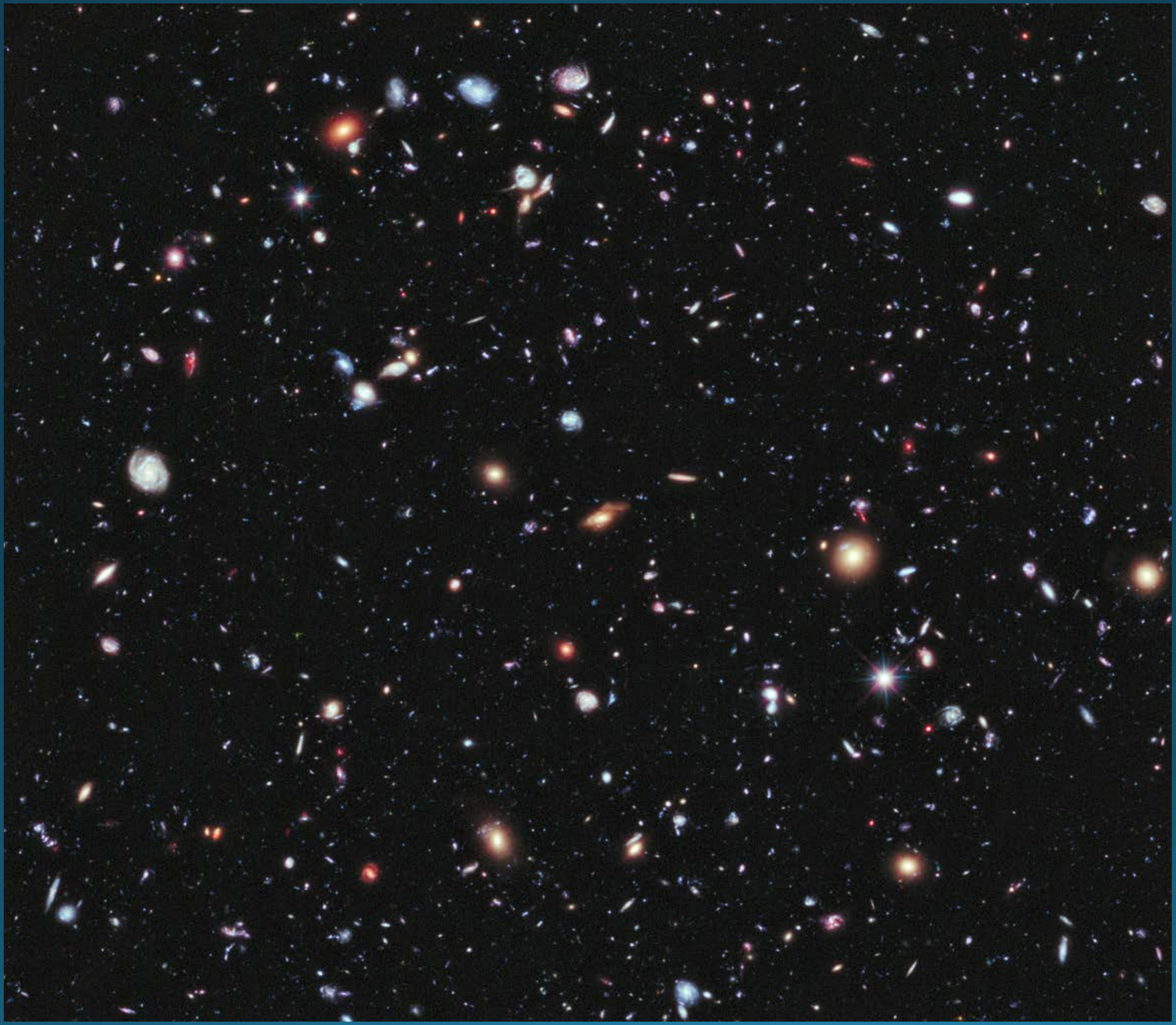
- Deep field-style observations
  - Very long exposures of single patch (devoid of bright foreground objects) in the sky
- Cluster-lensing observations
  - Hunt for gravitationally lensed background objects in relatively short exposures (few hours per filter) of a low-z galaxy cluster

# The Hubble Extreme Deep Field

Total exposure time: 23 days (2 million seconds)

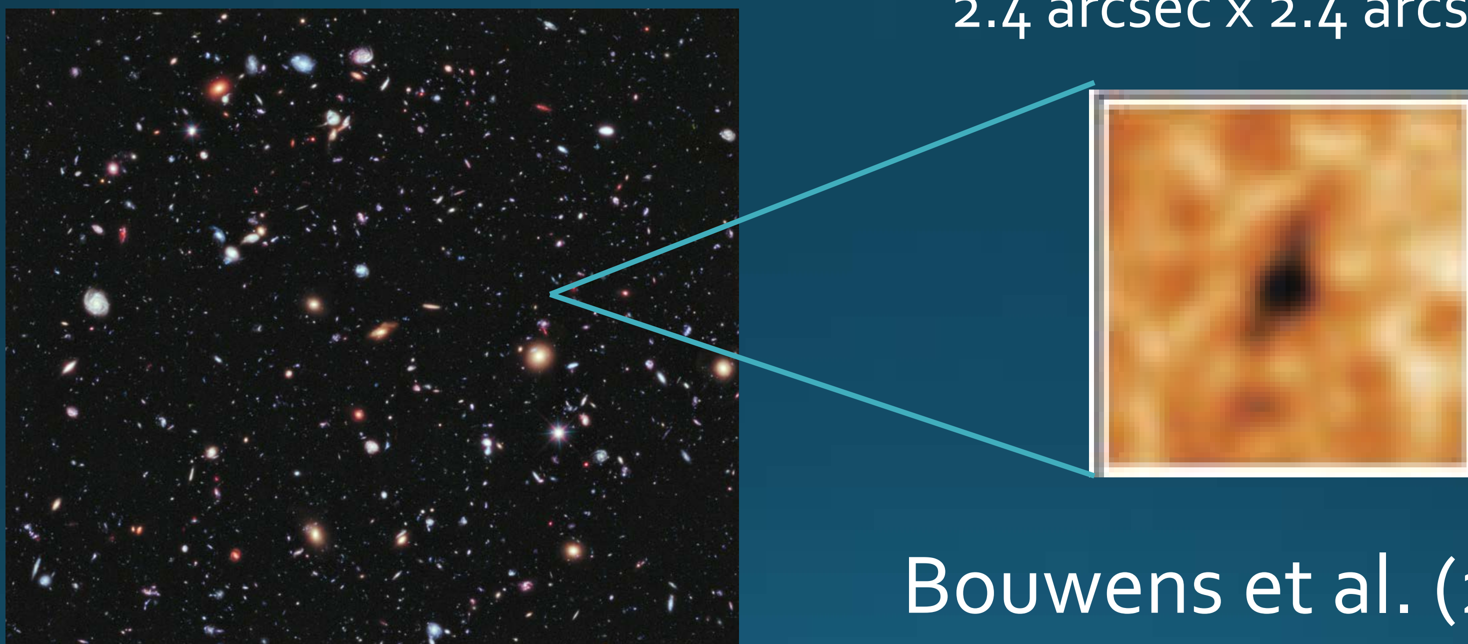


# The Hubble Extreme Deep Field



# Example of one of the most distant galaxy candidates so far

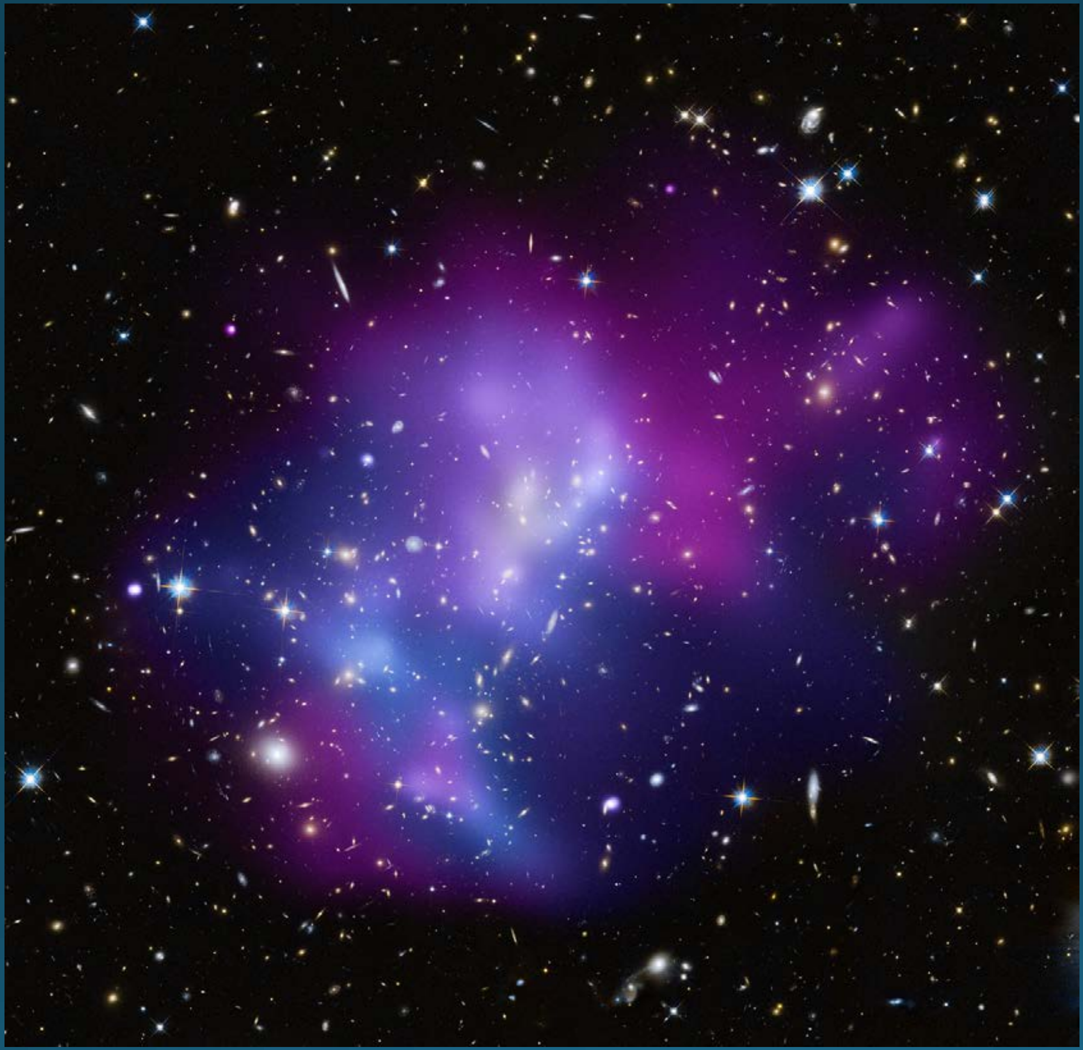
2.4 arcsec x 2.4 arcsec



Bouwens et al. (2010)

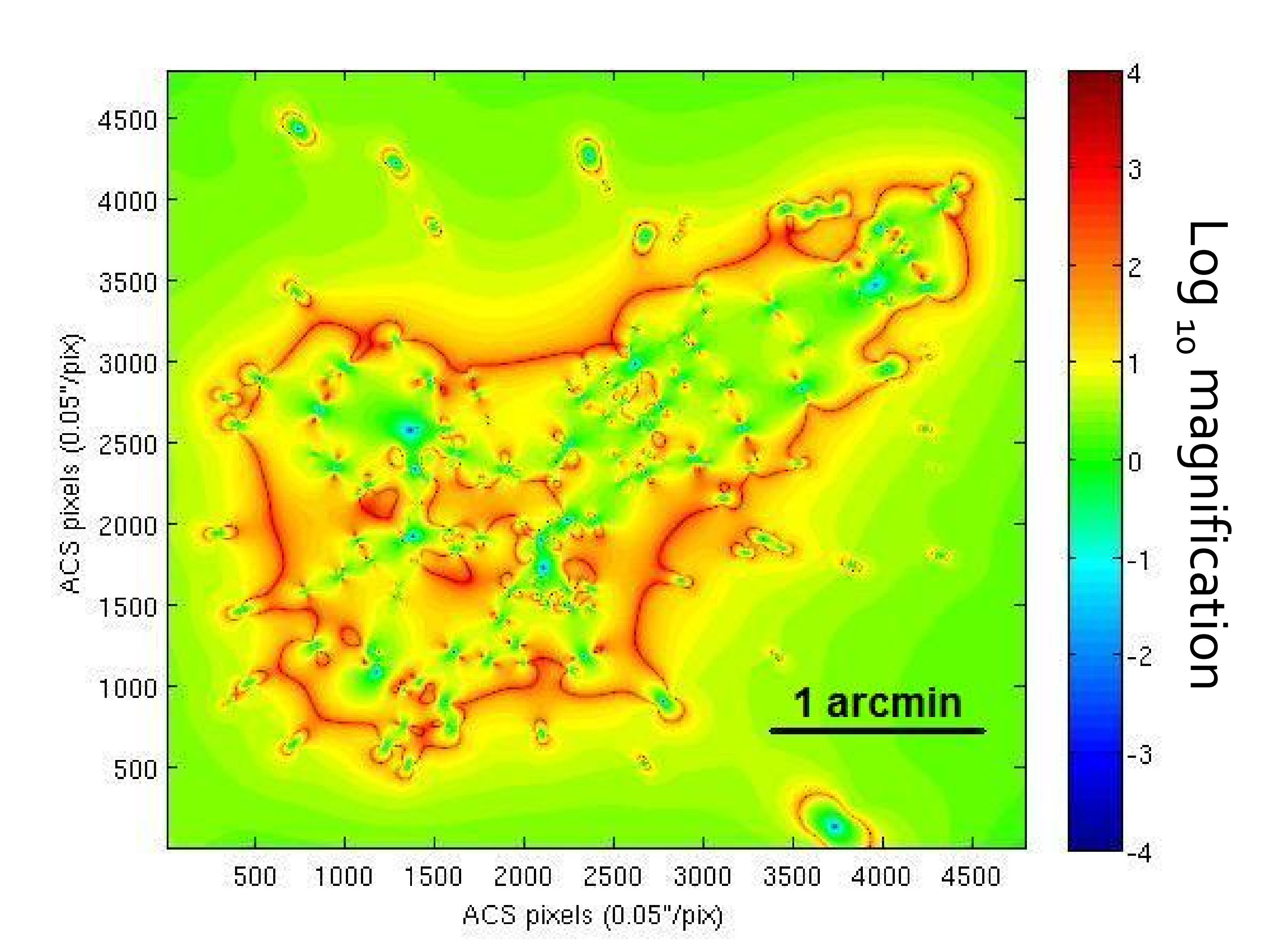
z ≈ 10 candidate

# 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*

# Intermission:
# Why are redshift records important?

## Notably distant objects [ edit ]

1 Gly = 1 billion light-years.

**Most distant astronomical objects with spectroscopic redshift determinations**

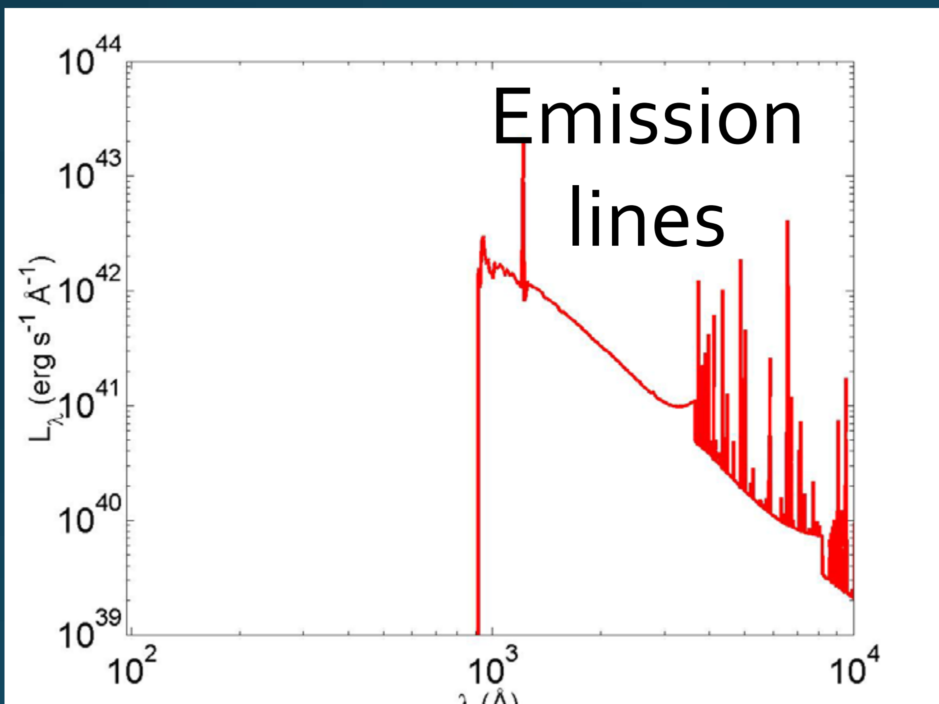
| Name | Redshift (z) | Light travel distance§ (Gly)[1] | Type | Notes |
|---|---|---|---|---|
| GN-z11 | z=11.09 | 13.39 | Galaxy | Confirmed galaxy[2] |
| EGSY8p7 | z=8.68 | 13.23 | Galaxy | Confirmed galaxy[3] |
| GRB 090423 | z=8.2 | 13.18 | Gamma-ray burst | [4][5] |
| EGS-zs8-1 | z=7.73 | 13.13 | Galaxy | Confirmed galaxy[6] |
| z8 GND 5296 | z=7.51 | 13.10 | Galaxy | Confirmed galaxy[7][8] |
| A1689-zD1 | z=7.5 | 13.10 | Galaxy | Galaxy[9] |
| SXDF-NB1006-2 | z=7.215 | 13.07 | Galaxy | Galaxy[10][11] |
| GN-108036 | z=7.213 | 13.07 | Galaxy | Galaxy[11][12] |
| BDF-3299 | z=7.109 | 13.05 | Galaxy | [13] |
| ULAS J1120+0641 | z=7.085 | 13.05 | Quasar | [14] |
| A1703 zD6 | z=7.045 | 13.04 | Galaxy | [11] |

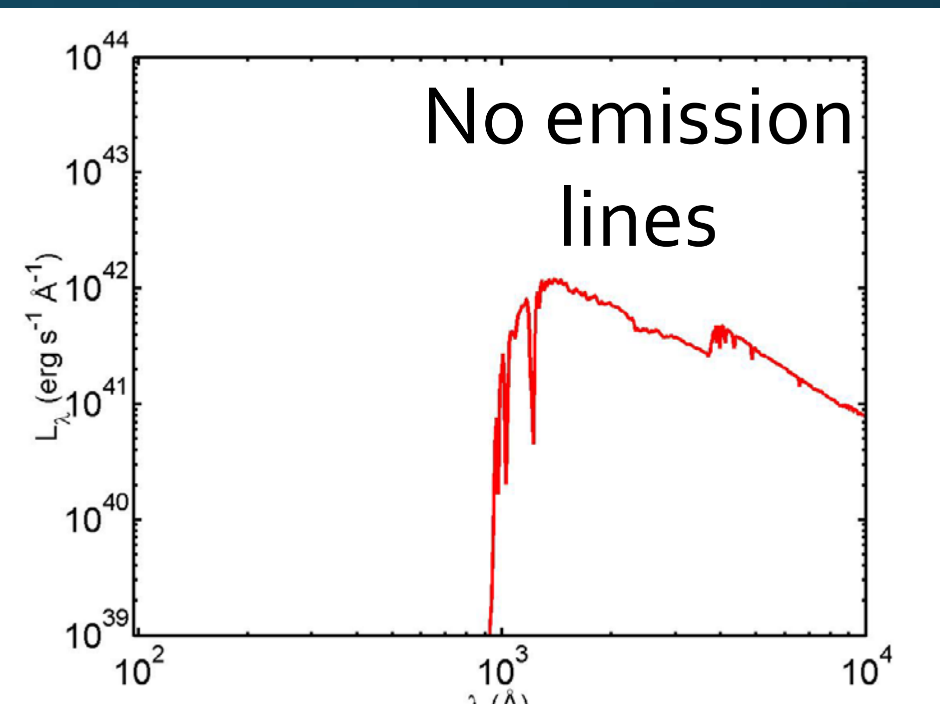
# Selecting high-z galaxy candidates

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 Ly$\alpha$-emitters

# The UV/optical spectra of galaxies I

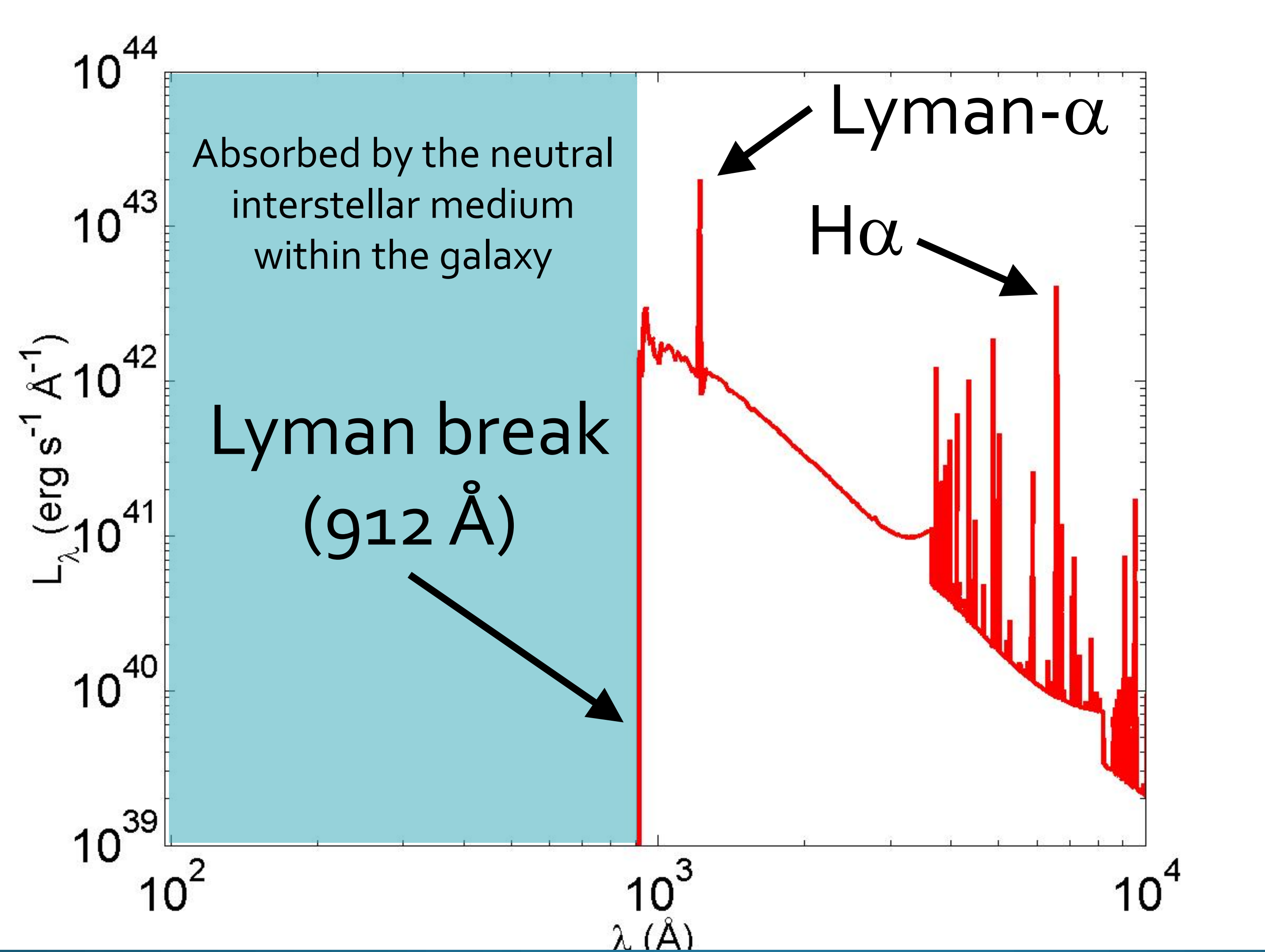



Young galaxy

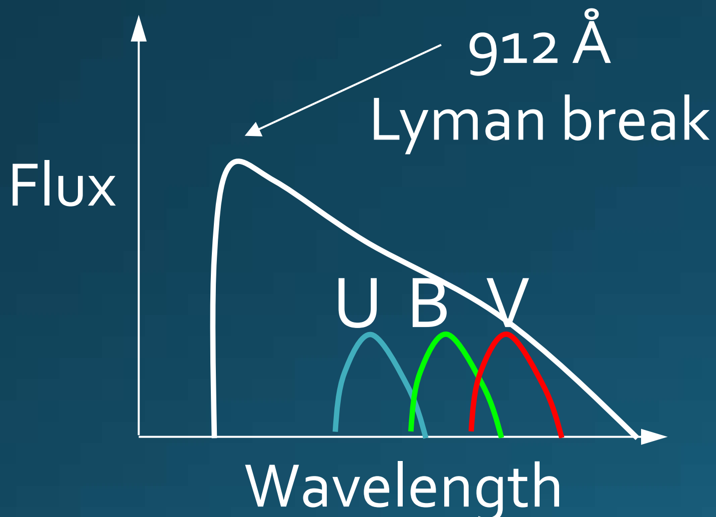
Old galaxy

# The UV/optical spectra of galaxies



# Drop-out techniques: Lyman-Break Galaxies

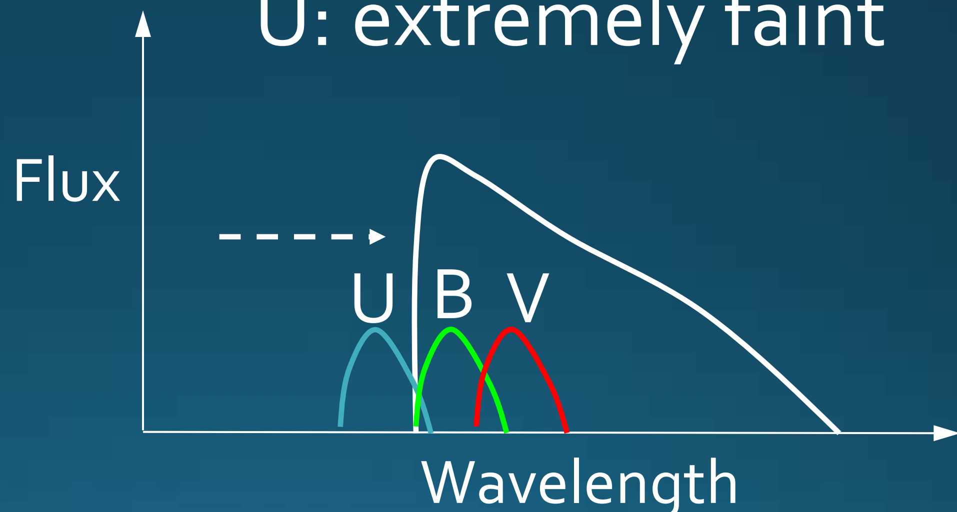
z=0



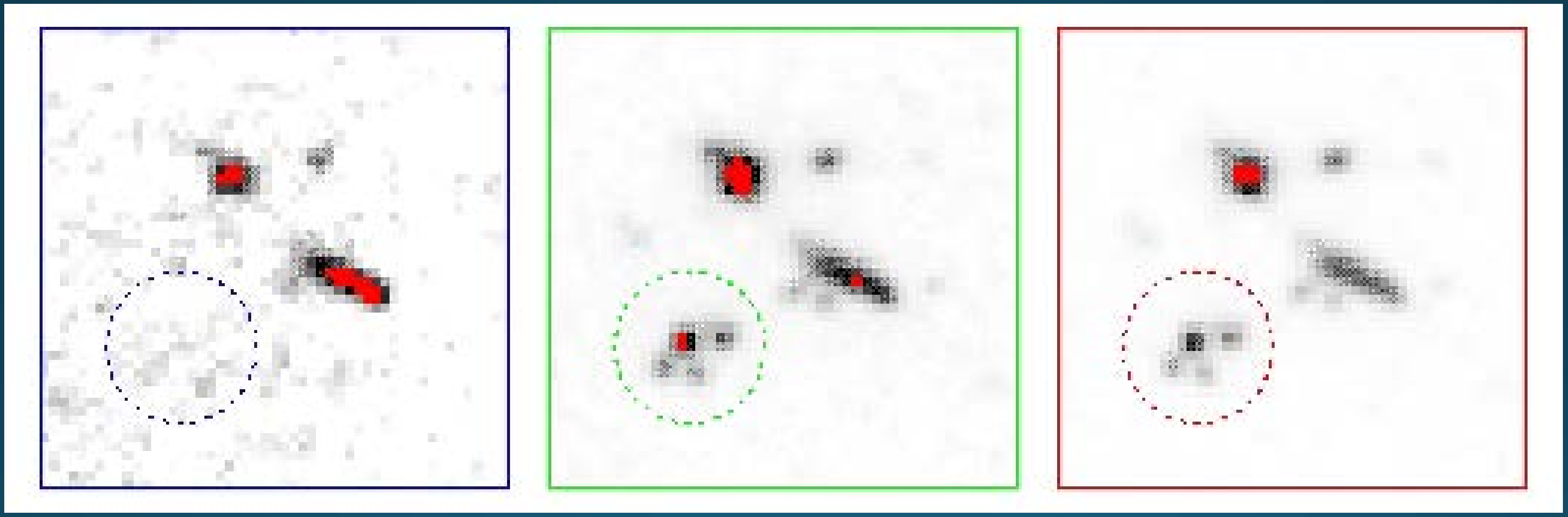

z>2.5

B-V ~ normal

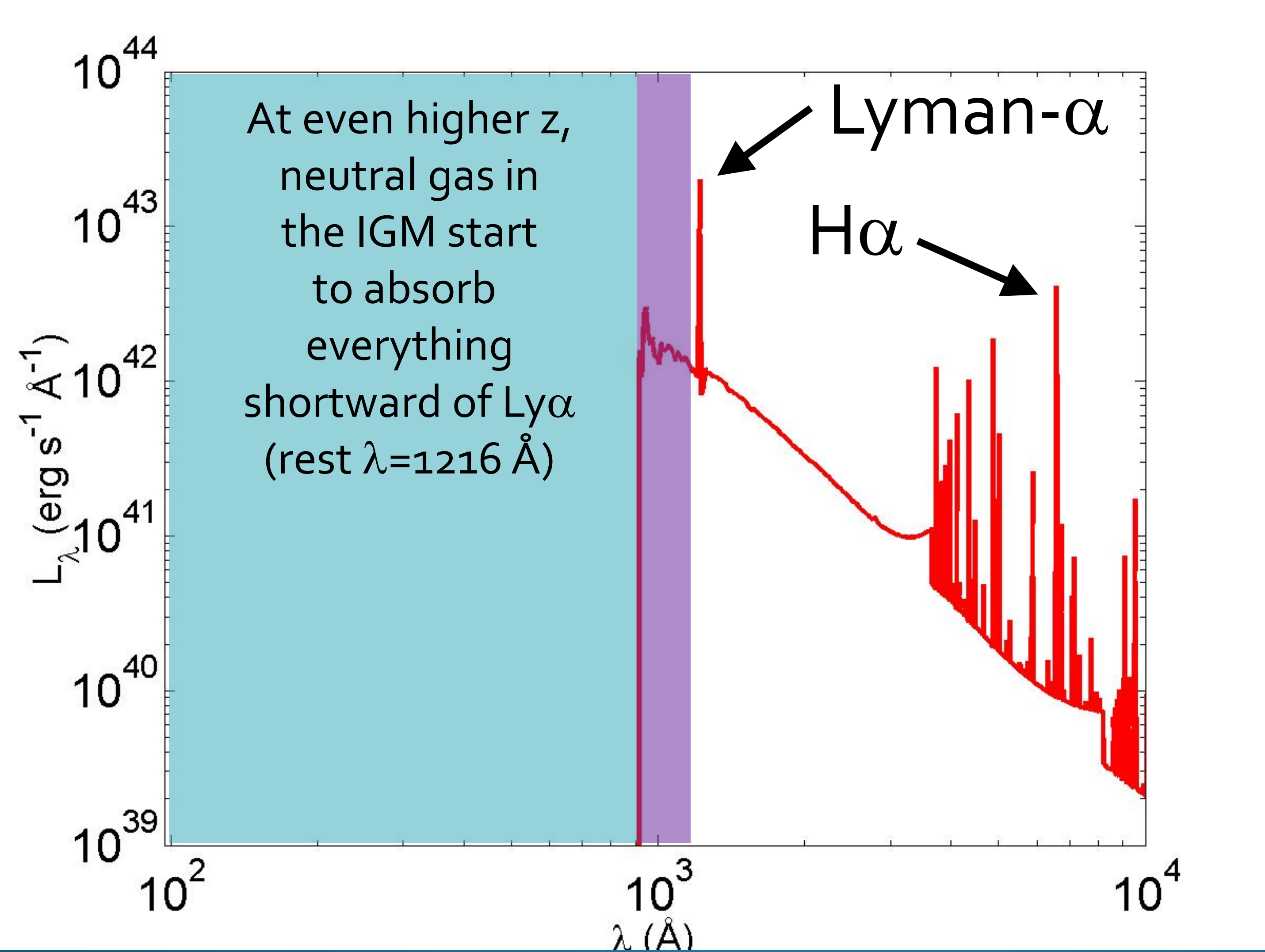
U: extremely faint



# Drop-out techniques: Lyman-Break Galaxies

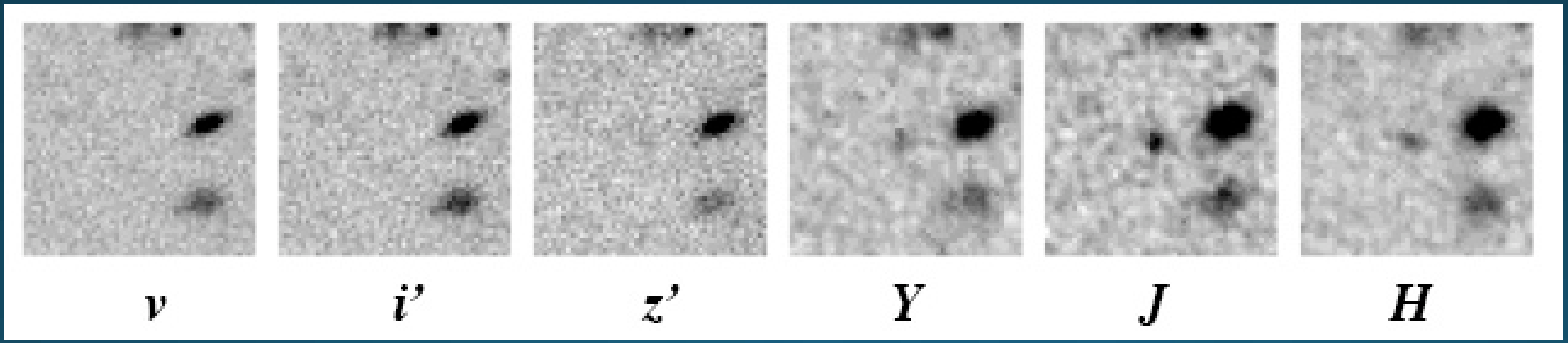


# Reionization-epoch galaxies



# Drop-out techniques: z>6 objects

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



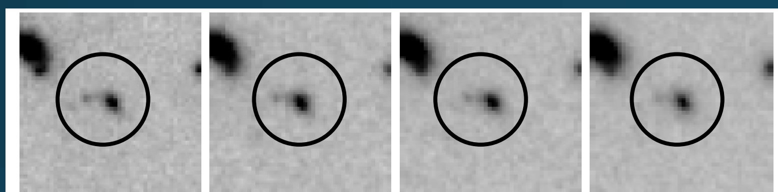

Optical

Near-IR

λ

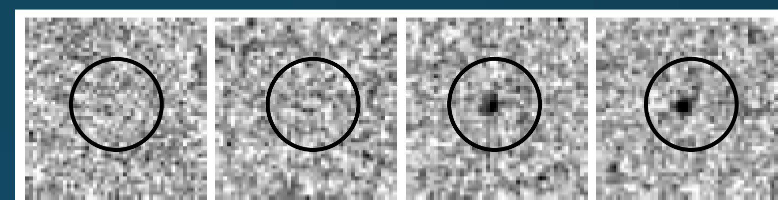
# Intermission:
# Which of these drop-out candidates is likely to have the highest redshift?

A



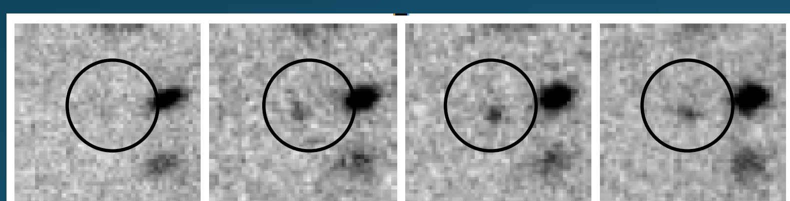
z Y J H

B



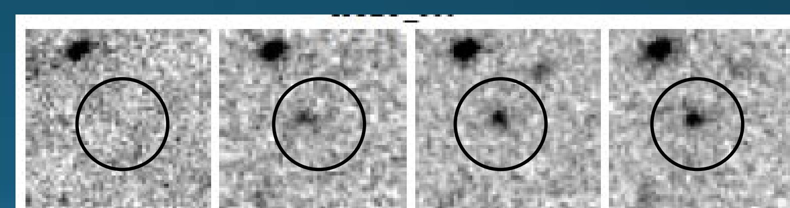
z Y J H

C



z Y J H

D



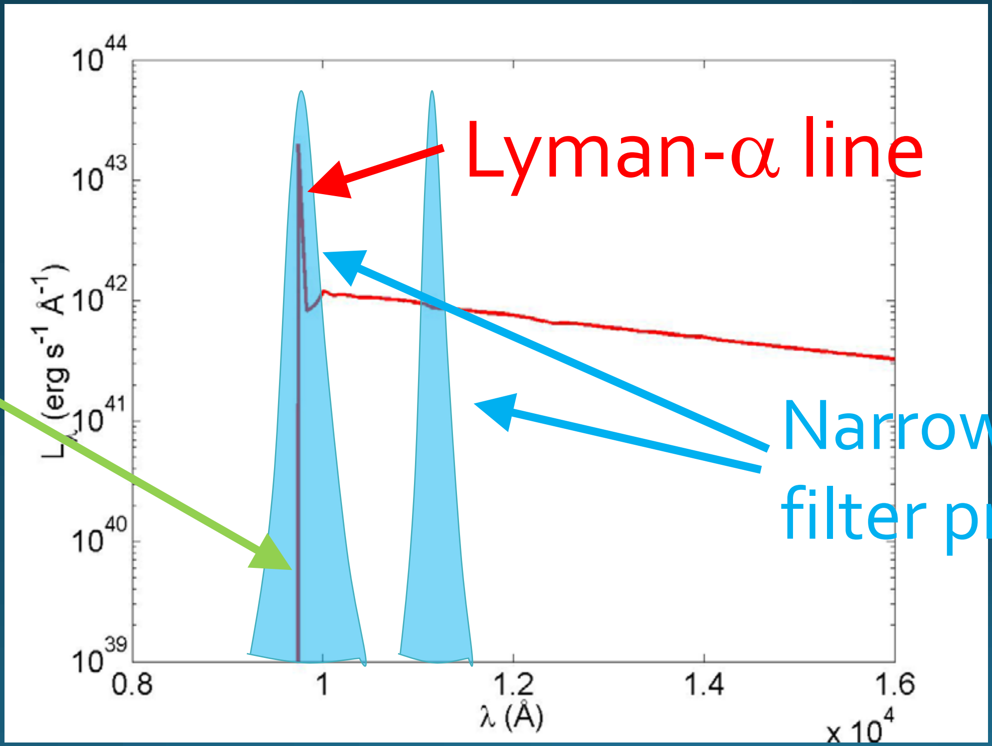
z Y J H

$\lambda$ $\lambda$

# 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 line

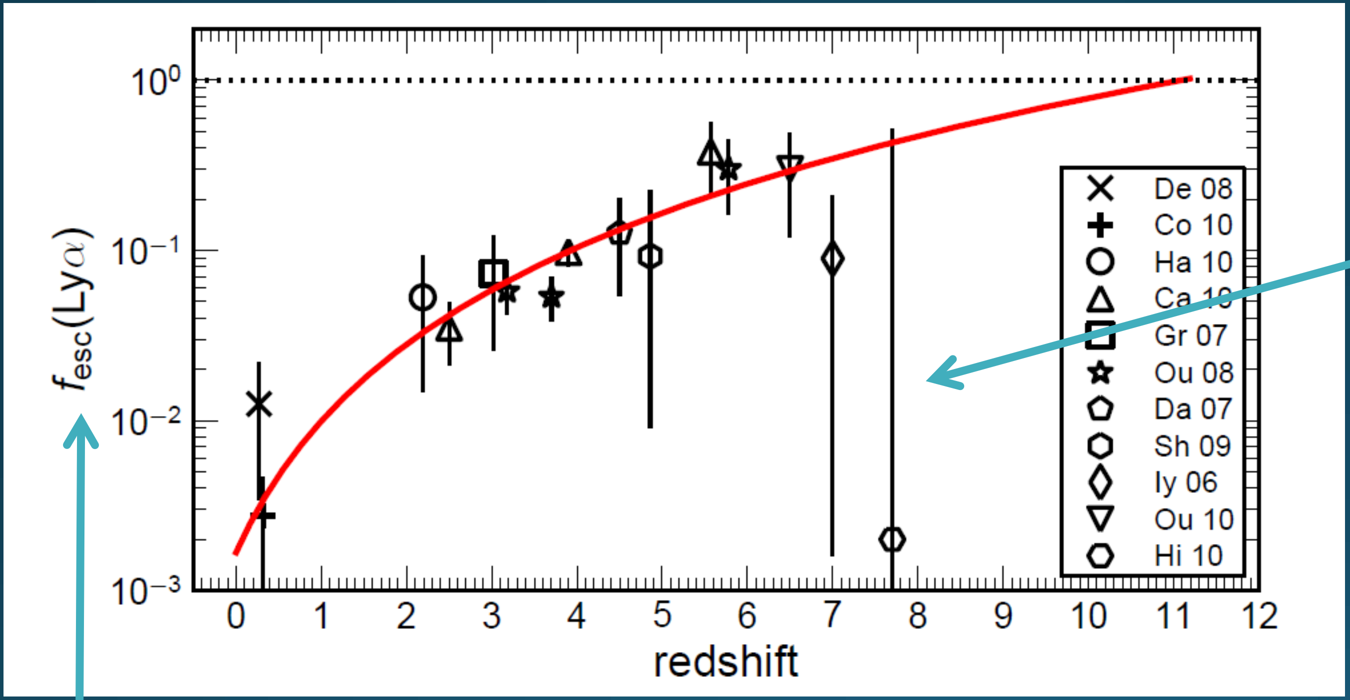
Narrowband filter profiles

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



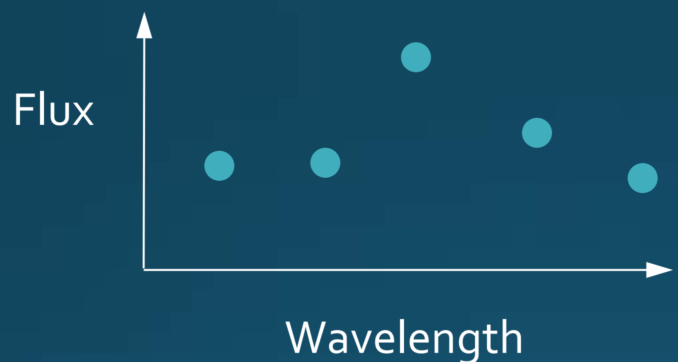

Abrupt drop → Lyα not good way to find z>6 galaxies (but may be good way to probe reionization)

Fraction of Lyα photons reaching the observer

Hayes et al. 11

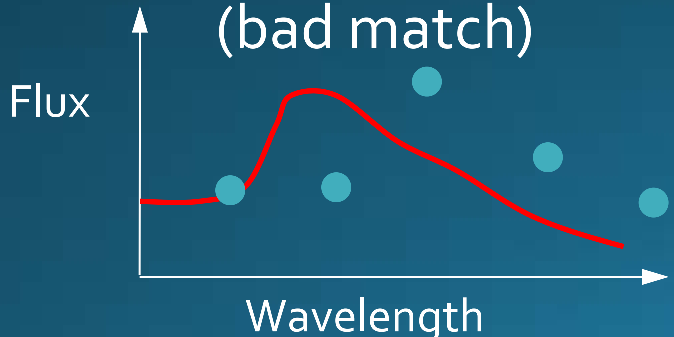
# Photometric redshifts

- 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)

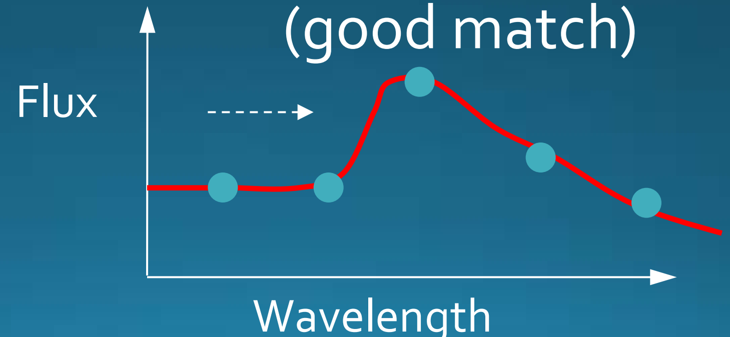



Measured photometrical data points

z=0 template spectrum (bad match)



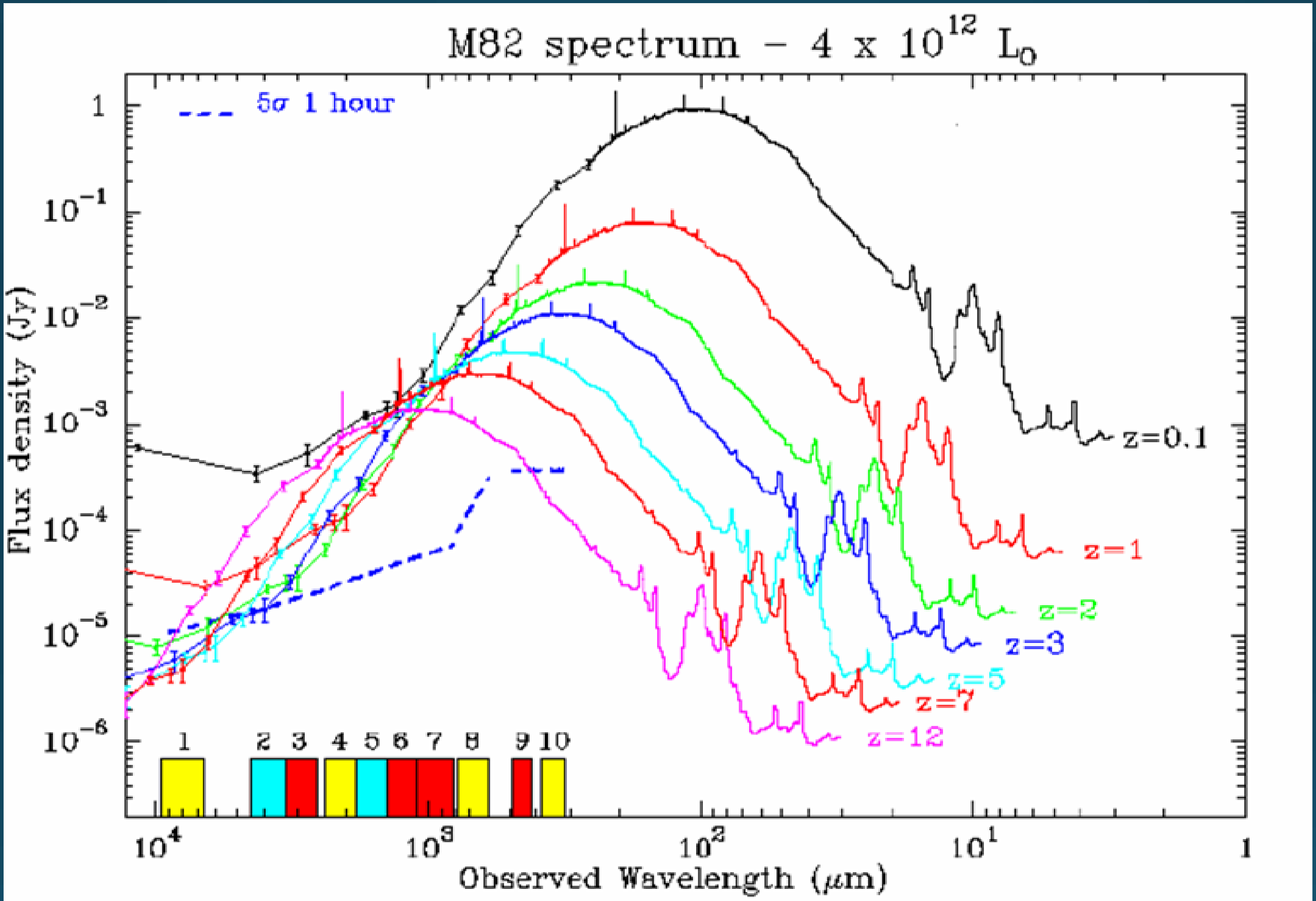

Redshifted template spectrum (good match)



# 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

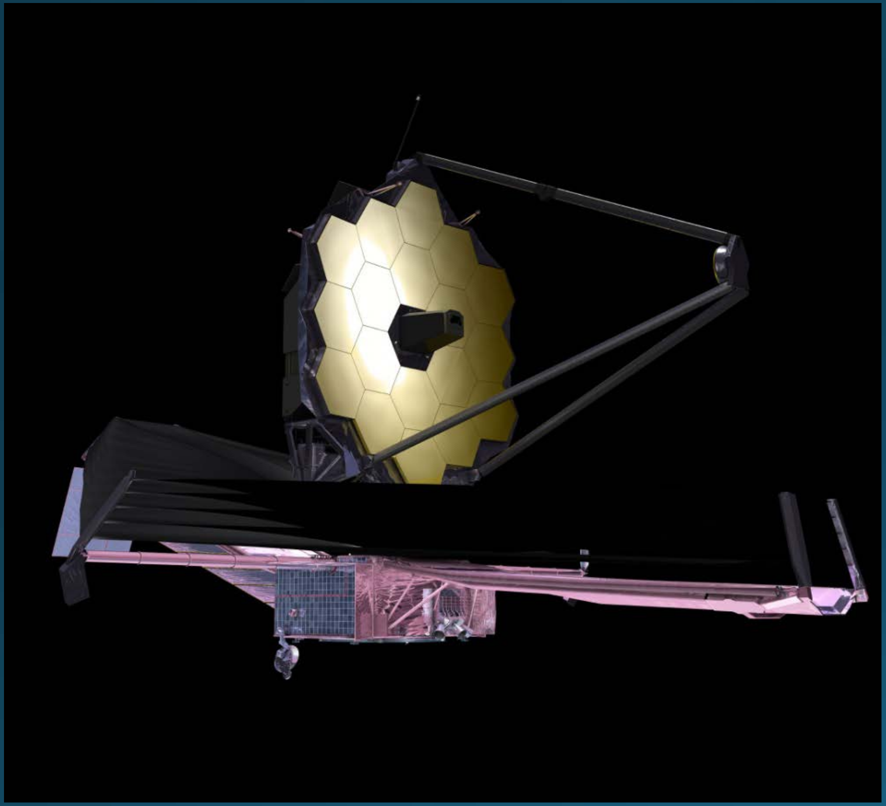



ALMA receivers

*De Breuck 05*

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

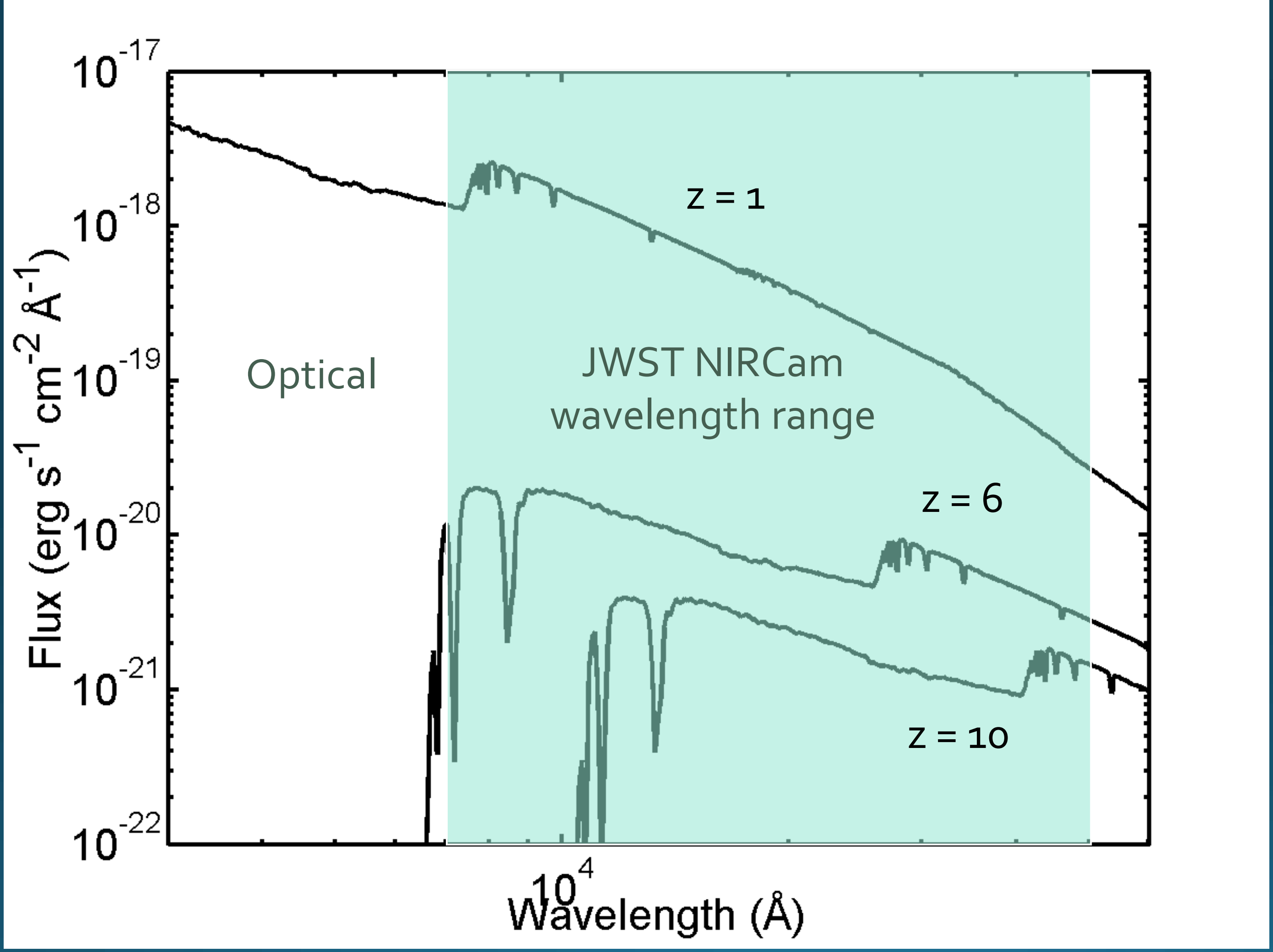
# Future prospects: JWST



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

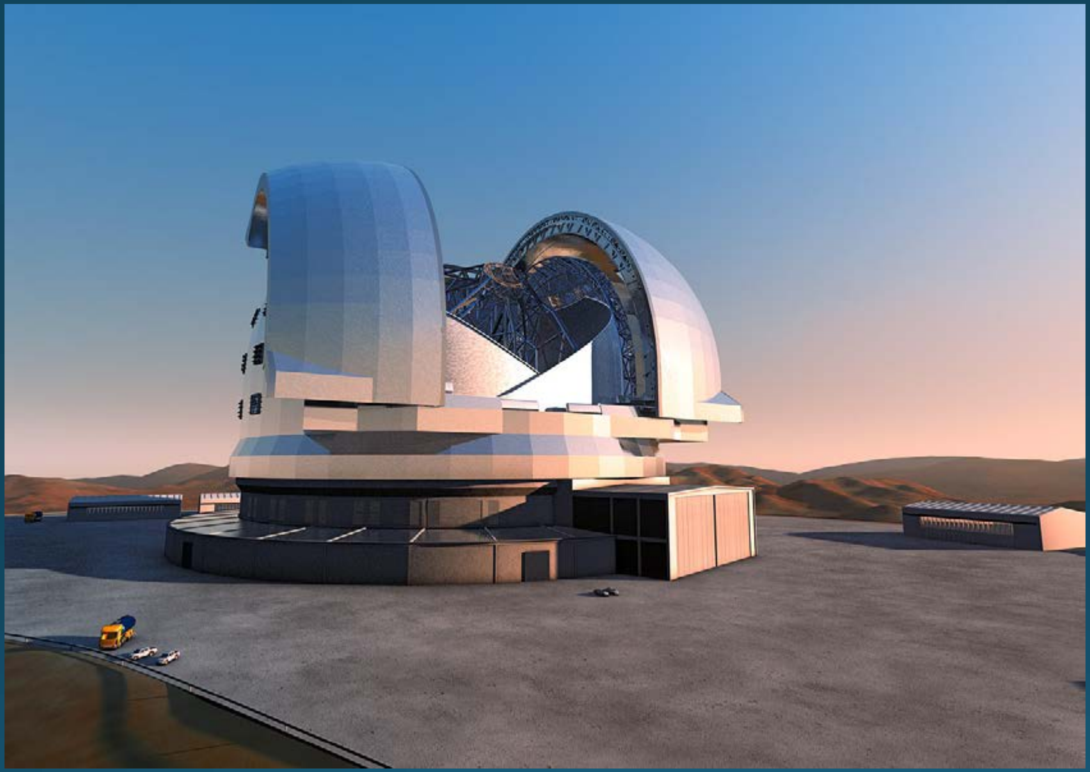
6.5 m mirror
Observations @ 0.6-29 μm
Useful for:
Galaxies up to $z \approx 15$
Pop III supernovae

# 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.