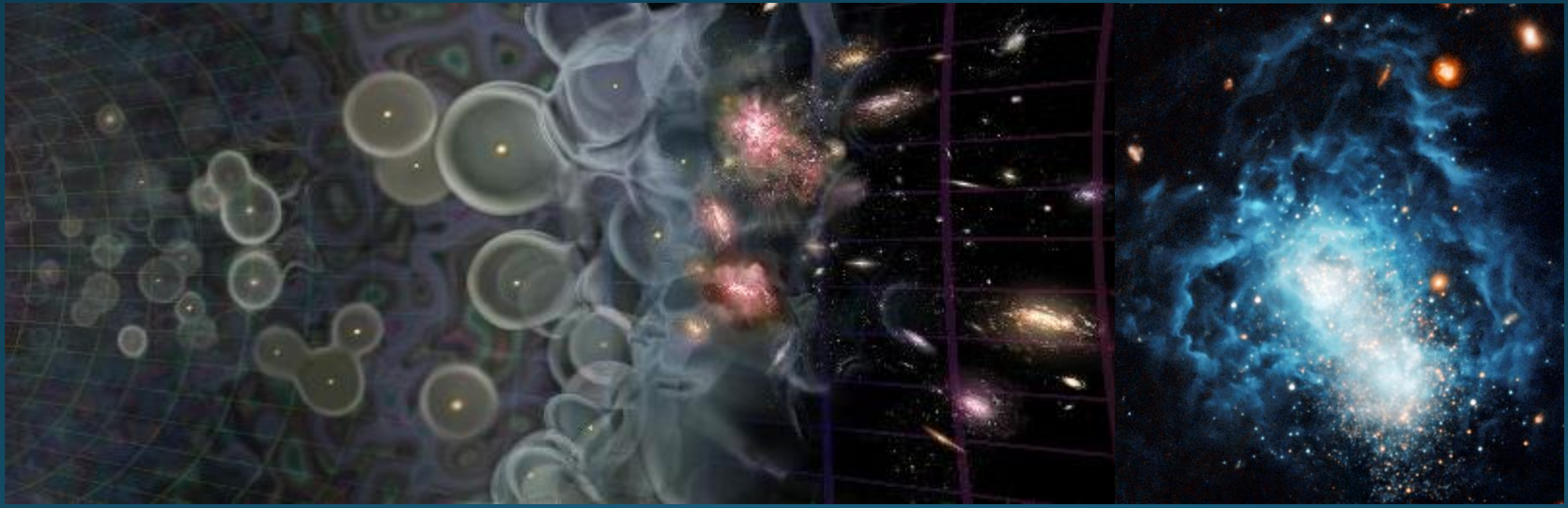
Physics of Galaxies 2020
10 credits
Lecture 8: The High-Redshift Universe



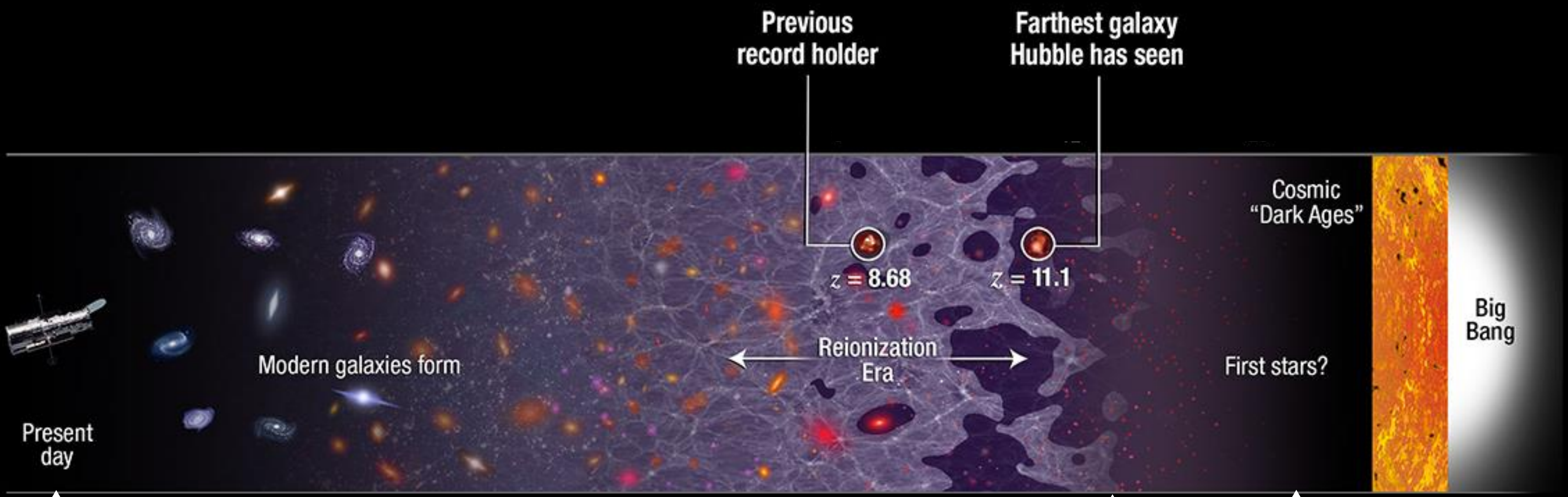
Outline: Part I

- Mysteries in the first billion years
- The first stars and galaxies
  - Dark ages, cosmic dawn
  - Pop III stars
  - First galaxies
  - Supermassive black holes
  - Cosmic reionization

Outline: Part II

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

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

Mysteries in the first billion years

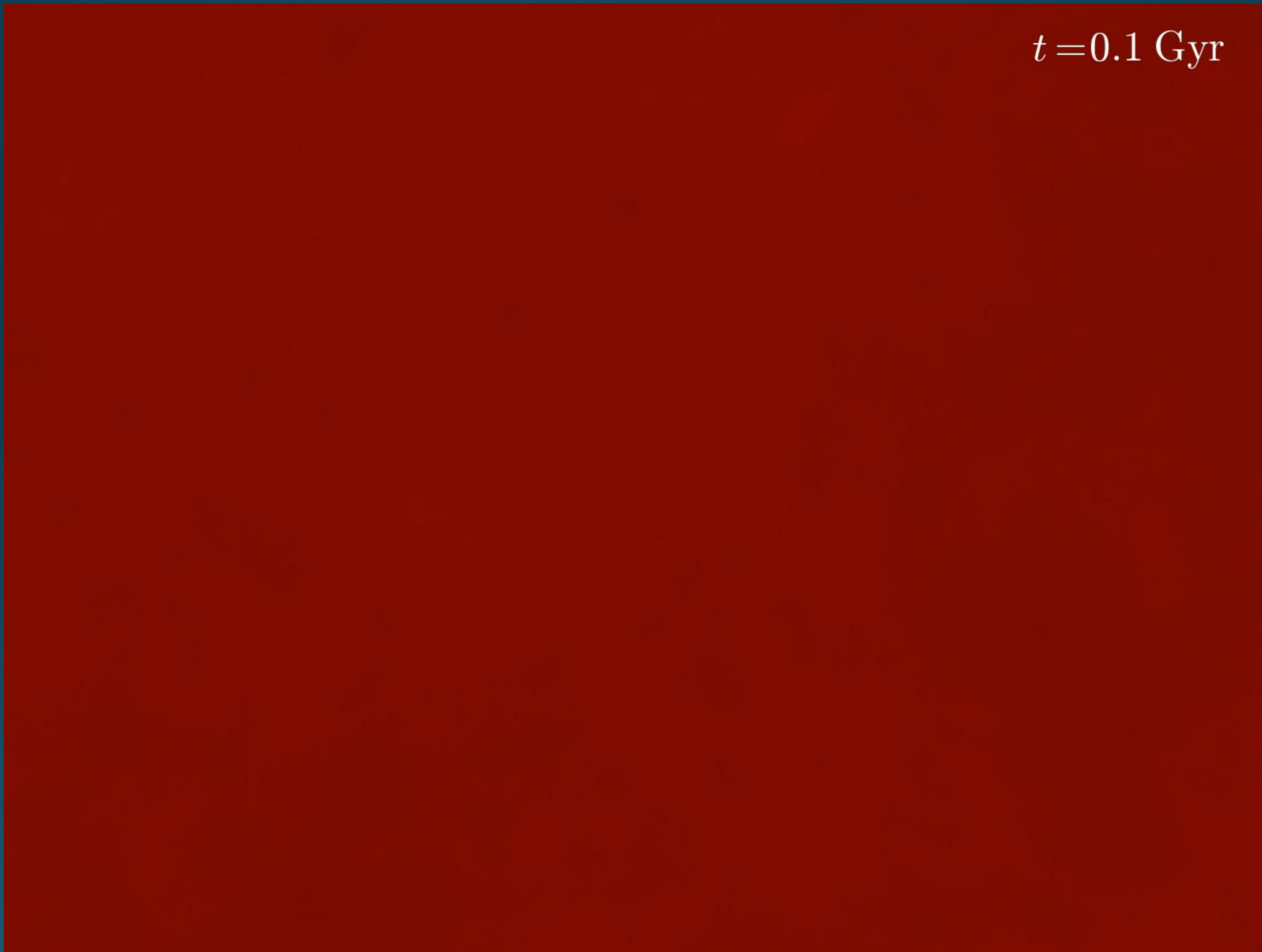
- **What were the first stars (Population III) like?**
  Very massive? Some even supermassive?

- **Where did the first supermassive black holes come from?**
  High-z quasars → Black hole mass ~$10^9\ M_\odot$ at $z \approx 7$
  How do they reach this mass in less than 1 Gyr?
  What were the black hole seeds?

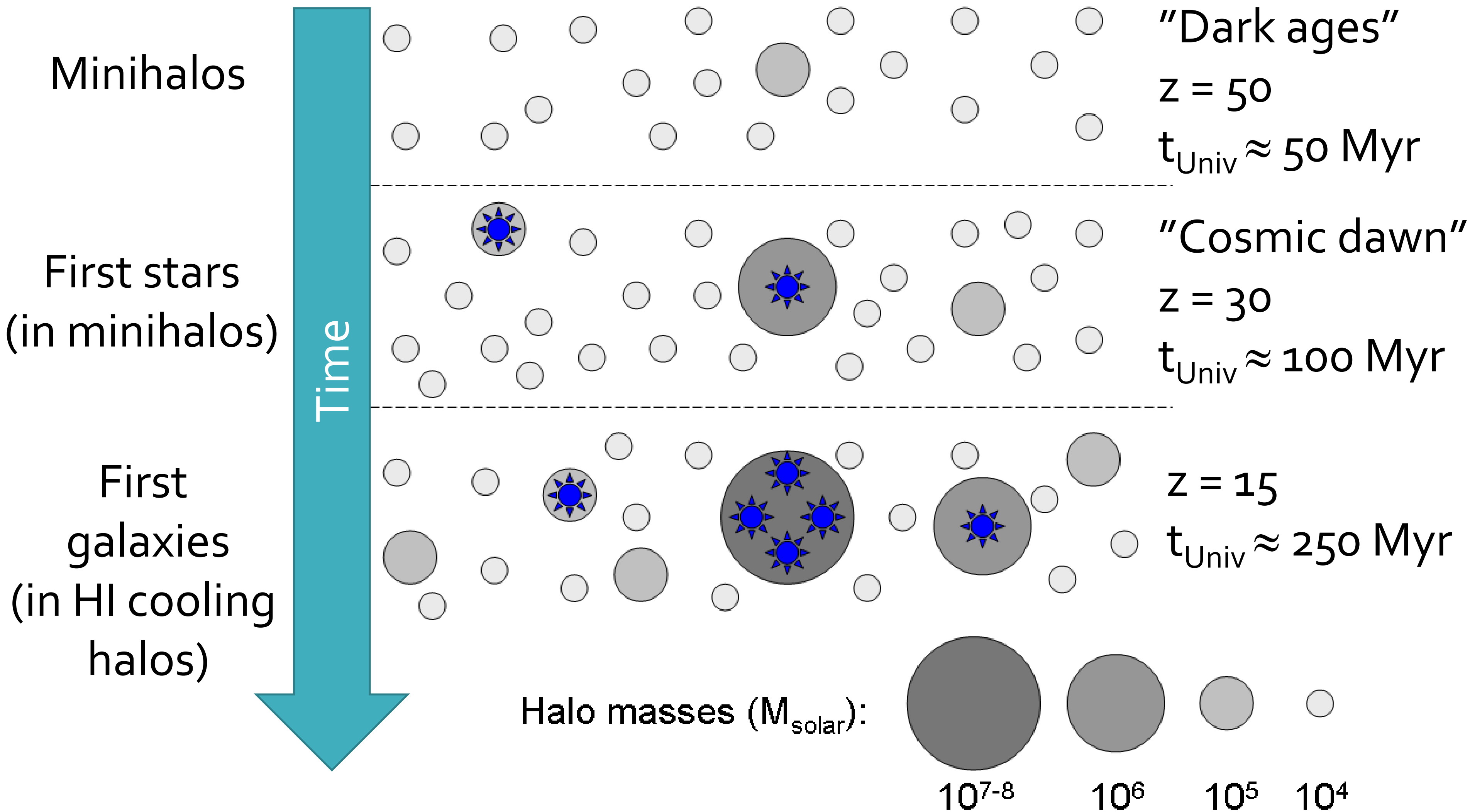
- **How did reionization progress?**
  How did the neutral fraction evolve with redshift?
  Did galaxies do all of the work? Did early AGN contribute?

Structure formation in a dark matter Universe

Simulation credit: Benedict Diemer; Dark matter only; Halos marked by circles



Dark ages, first stars, first galaxies



Stars: Population I, II and III

- Population I: Metal-rich stars

  Example: Stars in the Milky Way disk

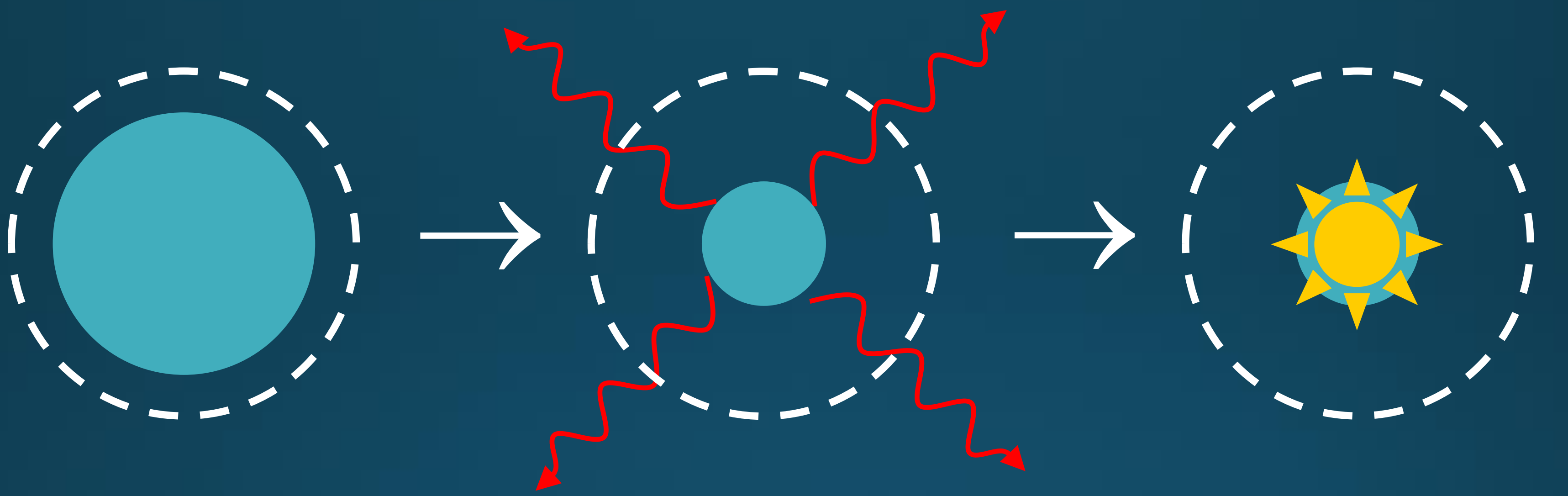
- Population II: Metal-poor stars

  Example: Stars in the Stellar halo of the Milky Way

- Population III: (Almost) Metal-free stars

  Example: Stars forming in minihalos at $z \approx 30$

Star formation in dark matter halos



Dark matter halo with gas inside

The gas cools by radiating photons and contracts

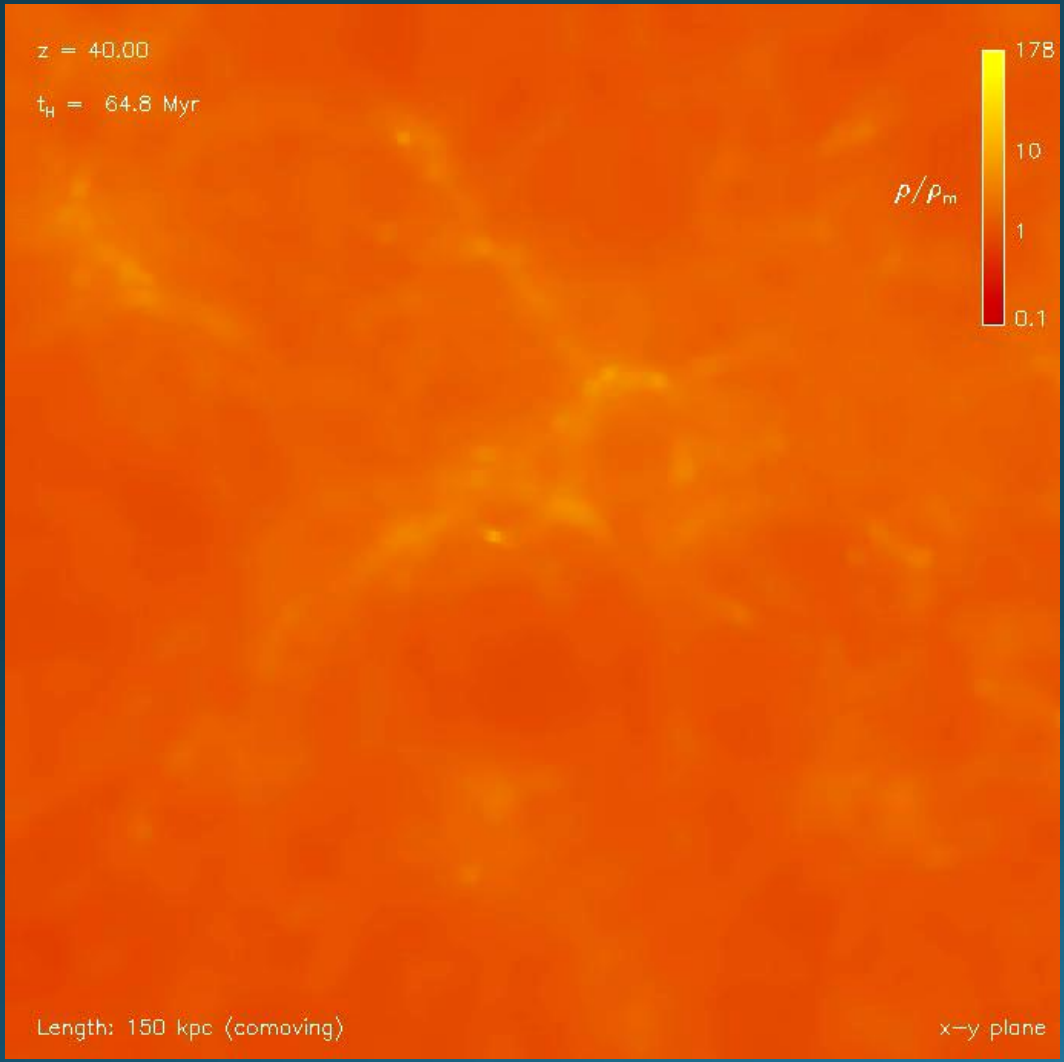
Star formation

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

Population III stars

- The very first generation of stars – started forming in minihalos, before the first galaxies
- Formed from gas of primordial composition (H,He + trace amounts of Li; metallicity Z≈0)
- Cooling properties of Z≈0 gas → These stars should be ***very massive***, ***hot (~10^5 K)*** and ***short-lived***.
- Characteristic mass expected to be ~10^1-10^3 $M_\odot$ (but predictions are shaky)
- Produces the metals required for the metal-enriched stars seen today (Pop I & II) and lots of ionizing UV radiation

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)

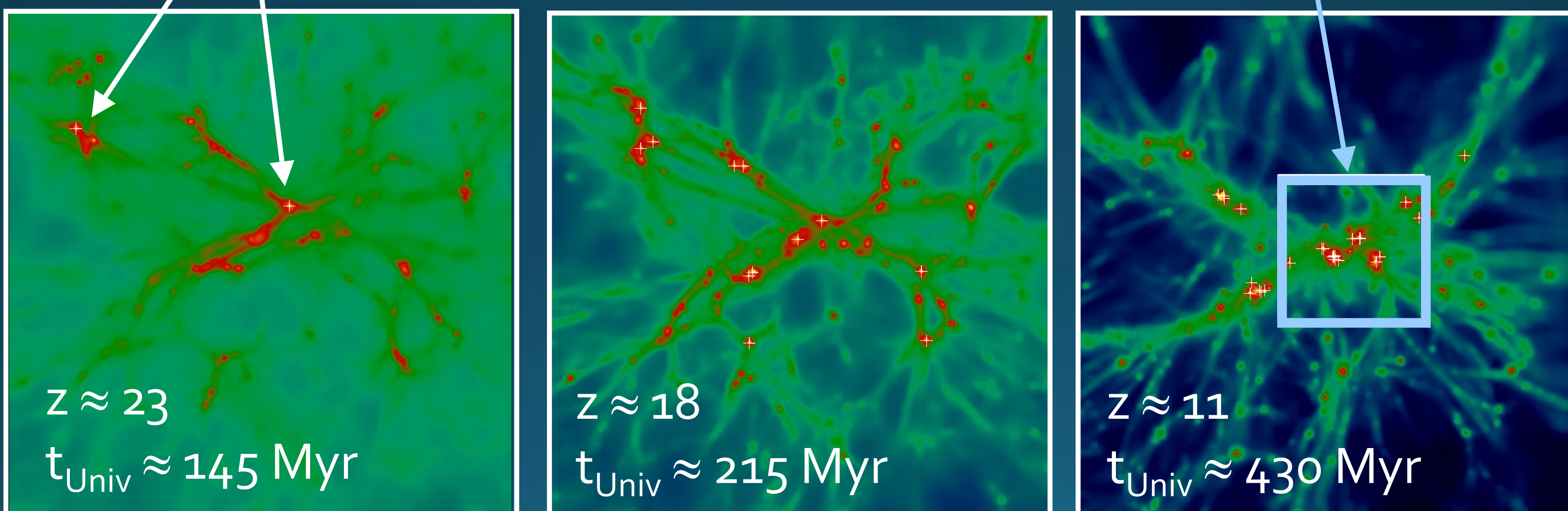
Greif et al. 08

Star formation inside and outside the first galaxies

Star formation in minihalos

Minihalo mergers and further star formation

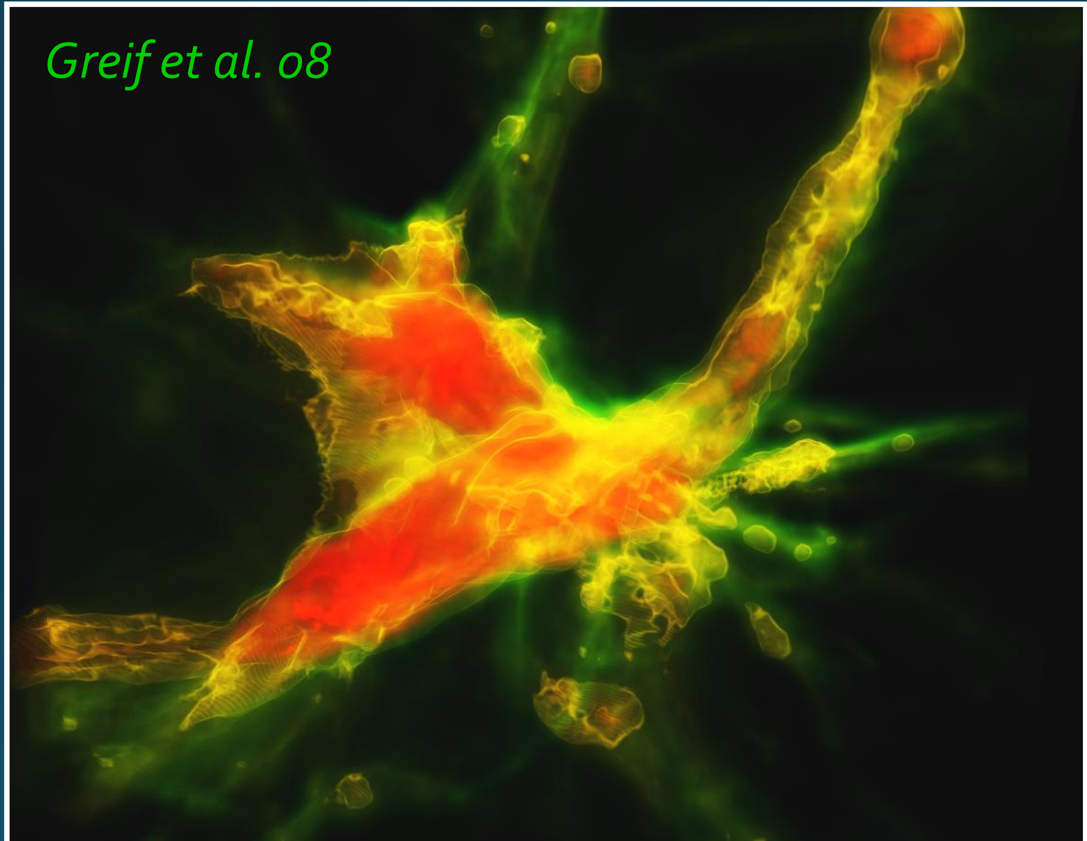
Object qualifies as a *galaxy*



Greif et al. 08

Gas density shapshots

A galaxy is born (at z ≈ 10)



Quite messy, isn't it?
Early on, we don't expect disks or ellipticals to form – all galaxies are likely to be irregular due to high merger rates

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

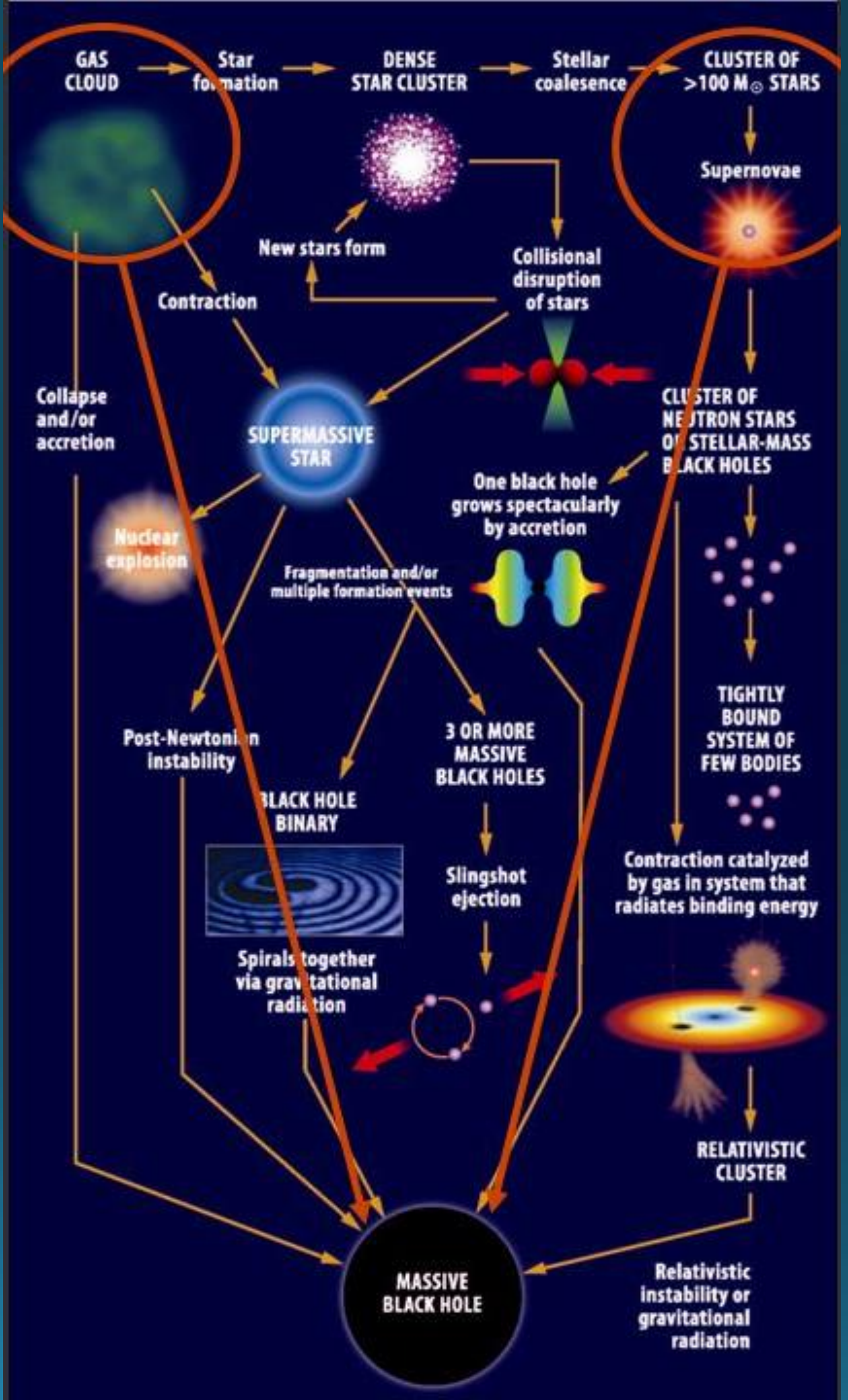
Eduardo Bañados, Bram P. Venemans, Chiara Mazzucchelli, Emanuele P. Farina, Fabian Walter,
Feige Wang, Roberto Decarli, Daniel Stern, Xiaohui Fan, Frederick B. Davies, Joseph F. Hennawi

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?

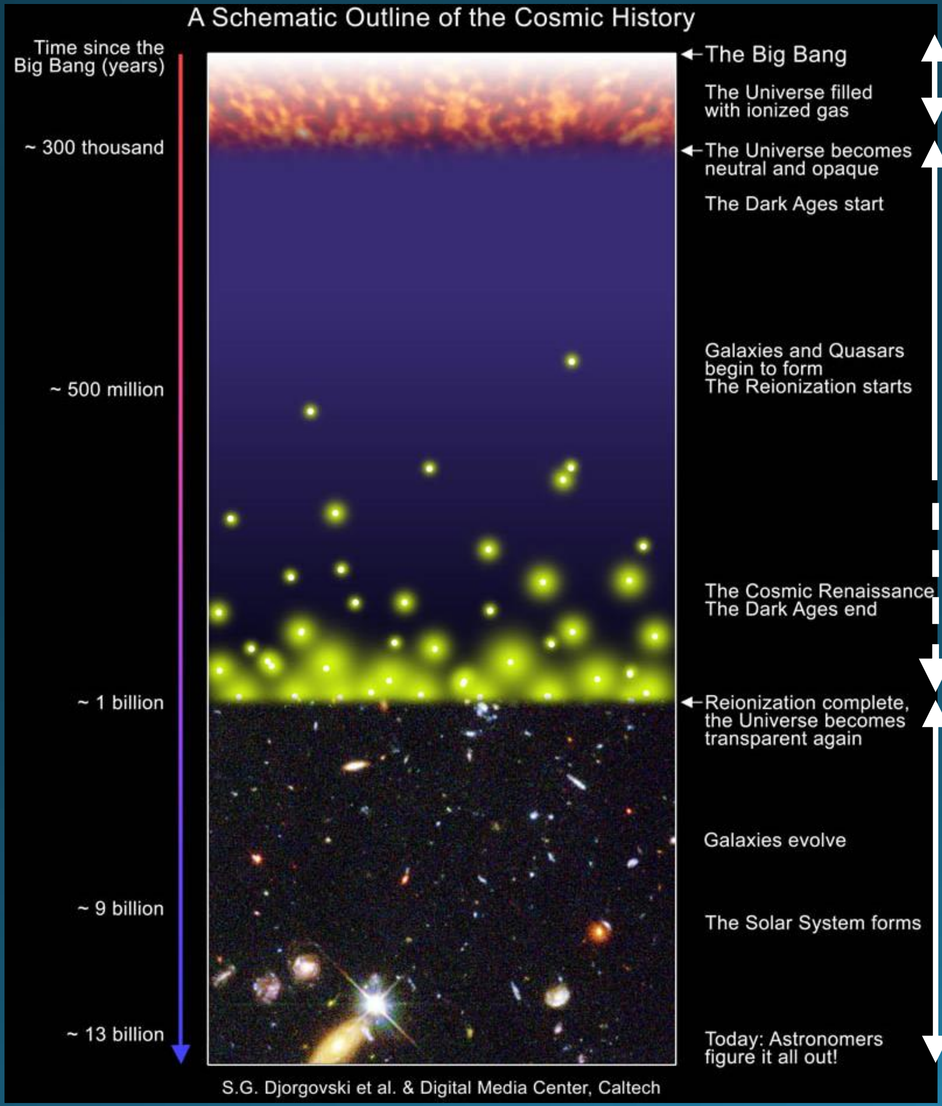
How to form a supermassive black hole…

Promising seeds:

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



Cosmic Reionization



<u>Intergalactic medium</u>

Ionized

Neutral

CMBR (Planck)

$\rightarrow z_{reion} \approx 8$

Lyα absorption in quasars

$\rightarrow z_{reion} > 6$

Reionized

Cosmic reionization

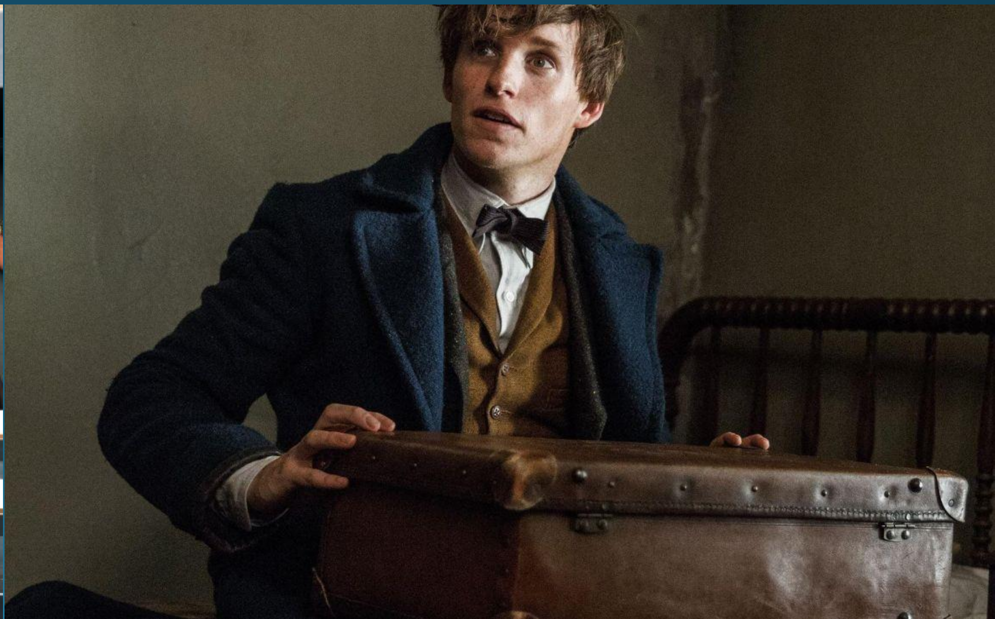
Black: Neutral hydrogen
Blue: Ionized hydrogen
Red/White: Partially ionized hydrogen
Yellow: Galaxies

Simulation credit: Marcelo Alvarez (CITA), Tom Abel (Stanford)
Visualization credit: Marcelo Alvarez, Ralf Kaehler (Stanford), Tom Abel


EARLY SOURCES
OF LIGHT
AND HOW
TO FIND THEM

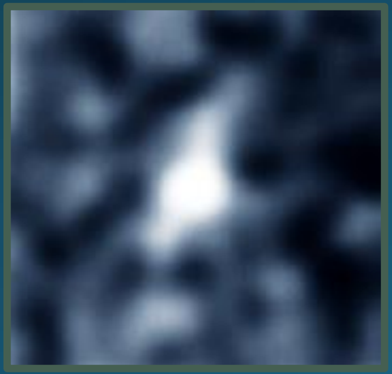
PART II: HOW TO FIND THEM

- Photometry vs spectroscopy
- Selection techniques: Dropouts, Lyα
- Surveys: Deep fields and gravitational lensing
- Telescopes: Today and tomorrrow



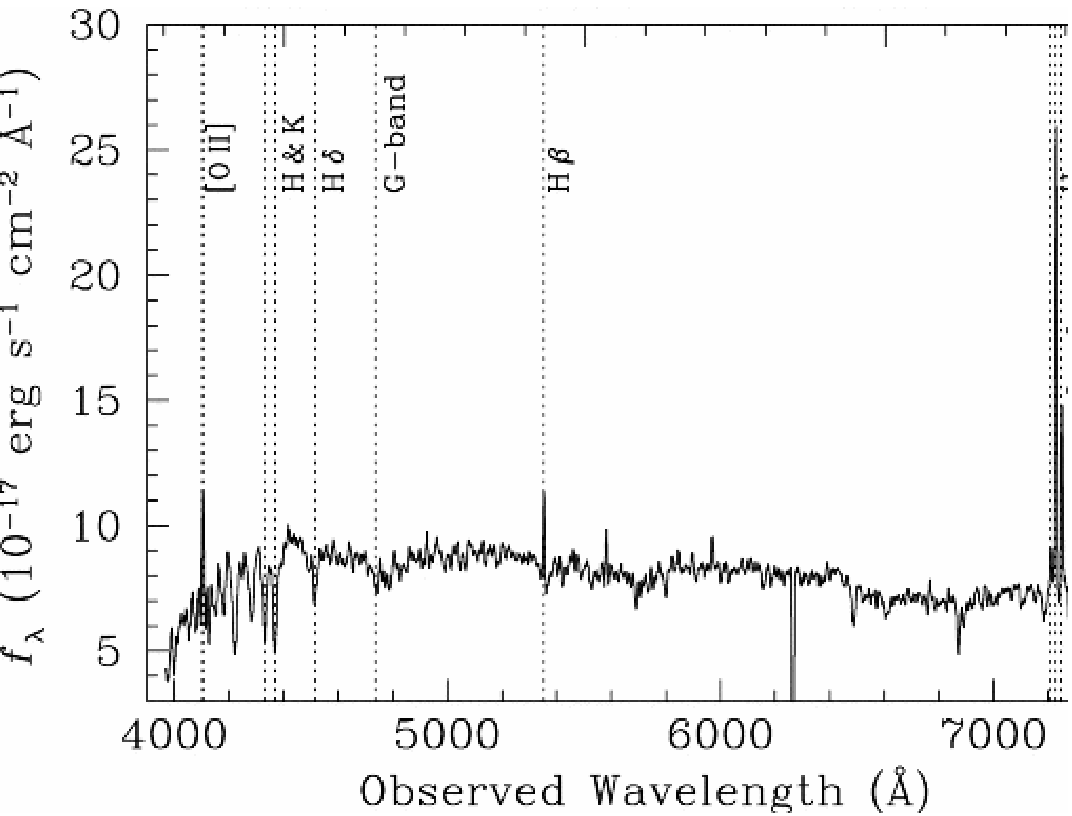
Imaging at high redshift

This is what a galaxy may look like to a low-redshift astronomer….

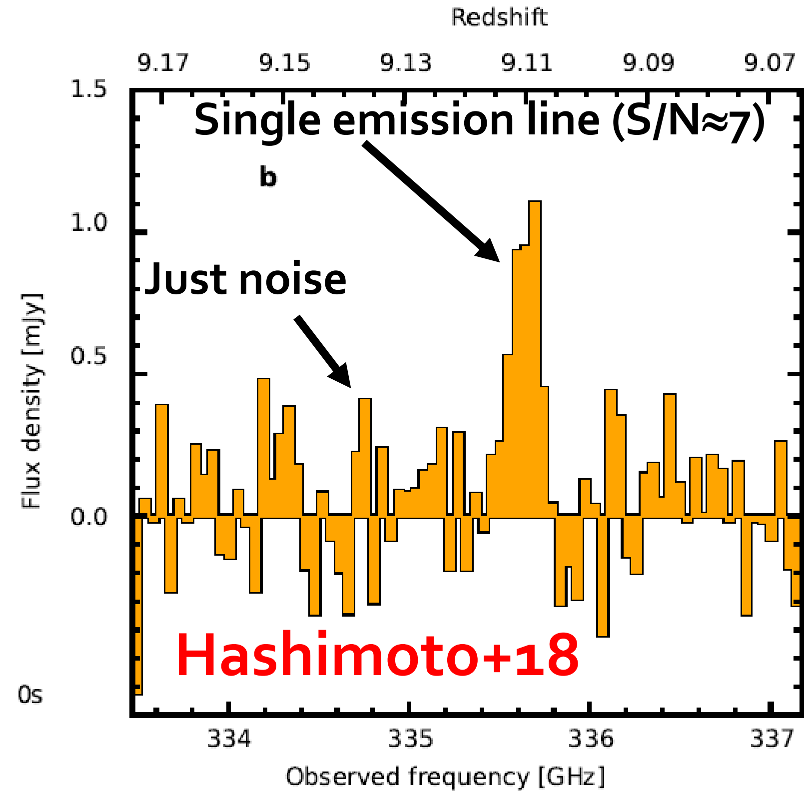


This is what a good(!) image of a galaxy at the highest redshifts typically looks like…
Note: Not to scale (would be about the size of one othe smallest dots in the upper image)

Spectroscopy at high redshift



This is what the spectrum of a low-redshift galaxy typically looks like (S/N>30)

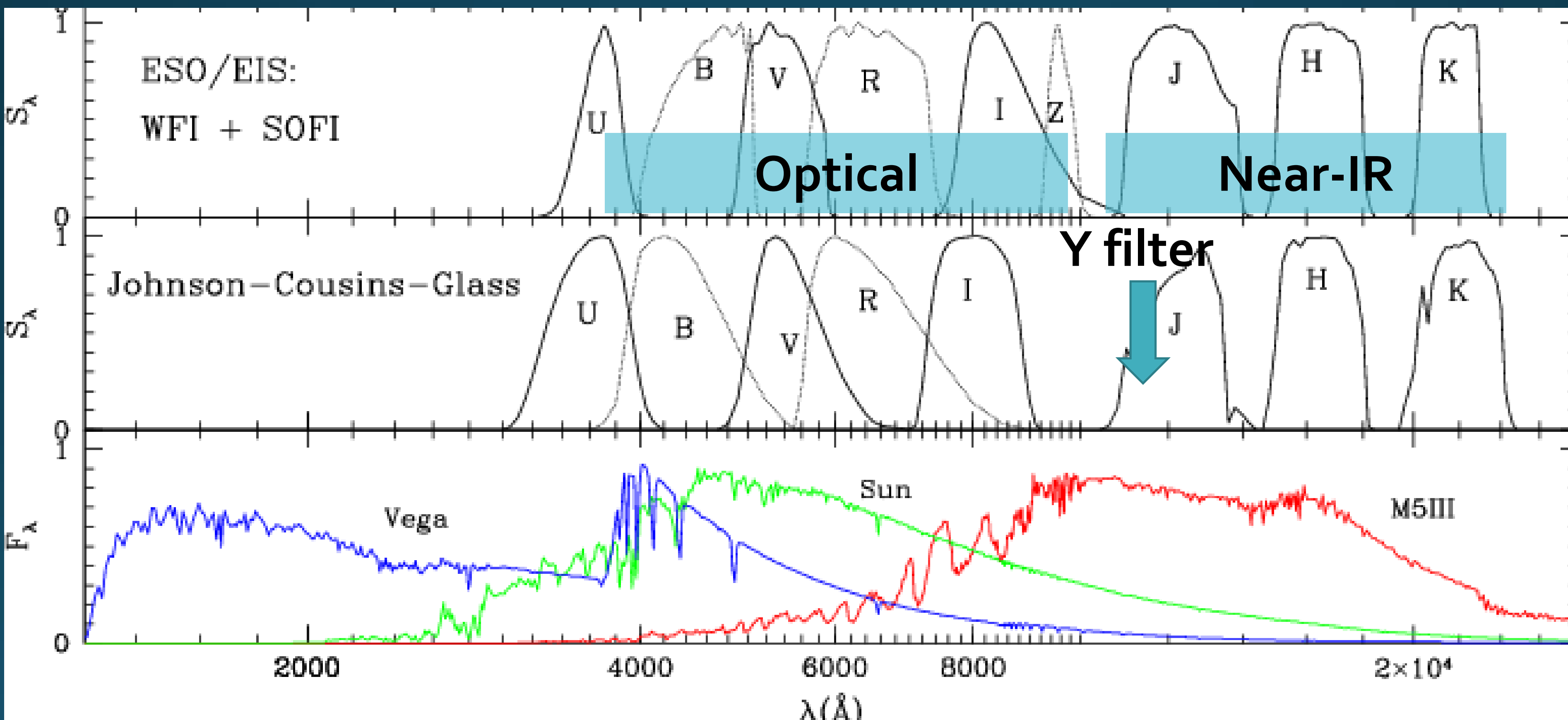


This is what a superb(!) spectrum of a high-redshift looks like (good enough for publication in Nature!)

Photometry ≈ Measuring flux in an image obtained with a well-defined filter

Some common optical & near-IR filters…

Most relevant for high-z: I(i)zYJHK



Brightness: Jansky and AB magnitudes

Very common units in high-redshift astronomy:

1 Jy = Jy = 10^{-26} W Hz^{-1} m^{-2} = 10^{-23} erg s^{-1} Hz^{-1} cm^{-2}

Apparent AB magnitude at frequency ν (a.k.a. monochromatic AB magnitude)

$$m_{\mathrm{AB}} \approx -2.5 \log_{10}\left(\frac{f_\nu}{\mathrm{Jy}}\right) + 8.90.$$

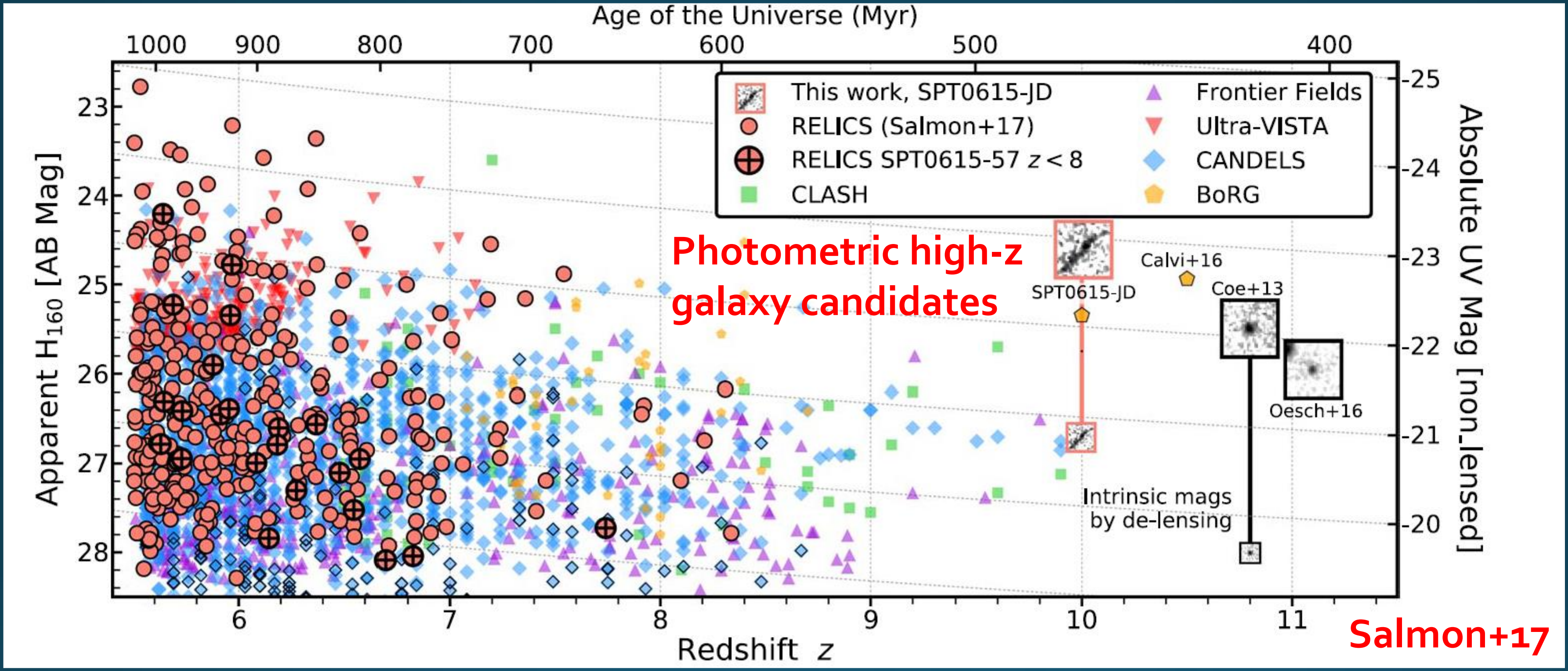
Difference between apparent and absolute magnitude:

$$m_{\mathrm{AB}} - M_{\mathrm{AB}} = 5\log_{10}\left[\frac{D_L}{10\mathrm{pc}}\right] - 2.5\log_{10}(1+z)$$

D_L: Luminosity distance (depends on z and cosmological parameters)

Can be calculated by many on-line cosmology calculators!

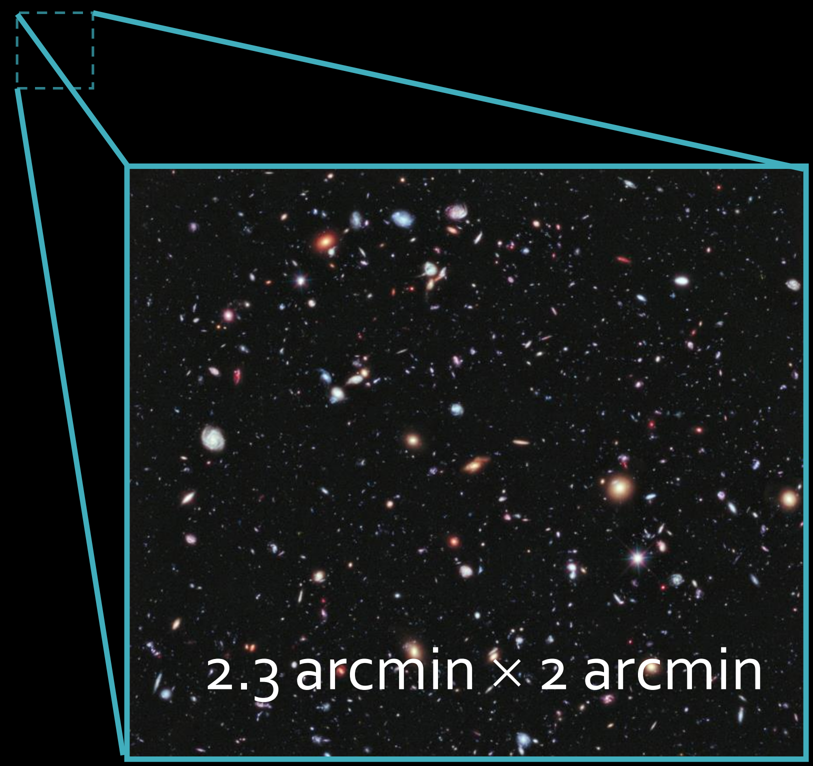
Some rough brightness estimates and detection limits…



- Emission-line spectroscopy at 8-10 m telescopes possible for $m_{AB} \leq 27$ mag
- The upcoming JWST can do imaging/photometry at $m_{AB} \leq 31$ mag and spectroscopy at $m_{AB} \leq 28$ mag
- Currently known quasars at $z \approx 7$ are at $m_{AB} \approx 20\text{-}21$ mag

The Hubble Extreme Deep Field

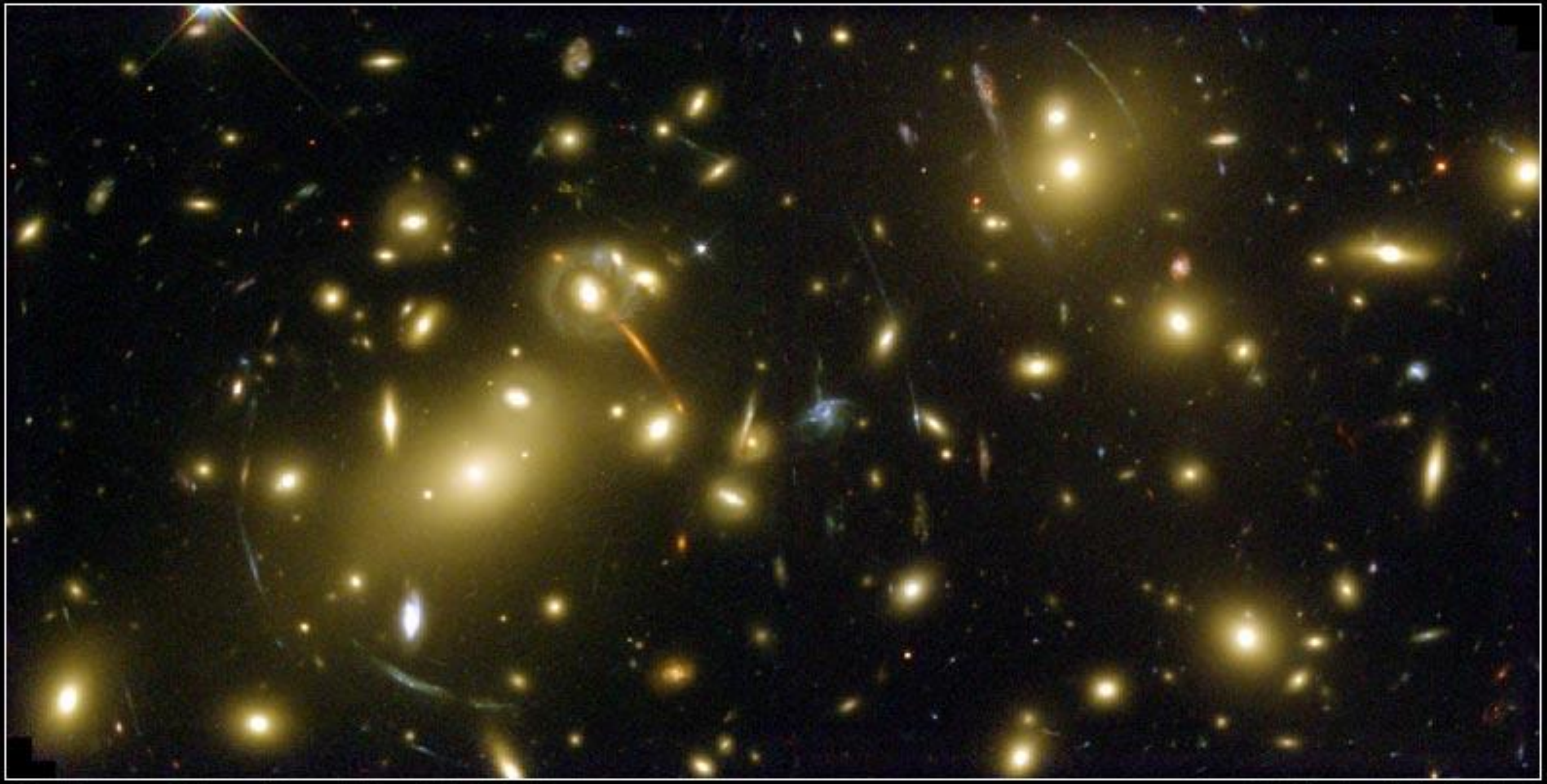
Total exposure time: 23 days
(2 million seconds)



Hubble Extreme Deep Field

The most distant galaxy so far

Gravitational Lensing: A great tool for hunting-down galaxies at the high-redshift frontier!



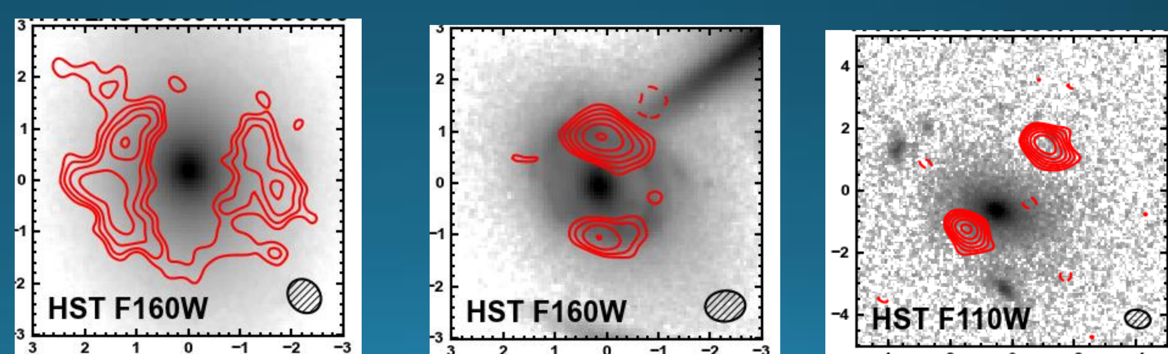
Galaxy Cluster Abell 2218 **HST • WFPC2**

NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

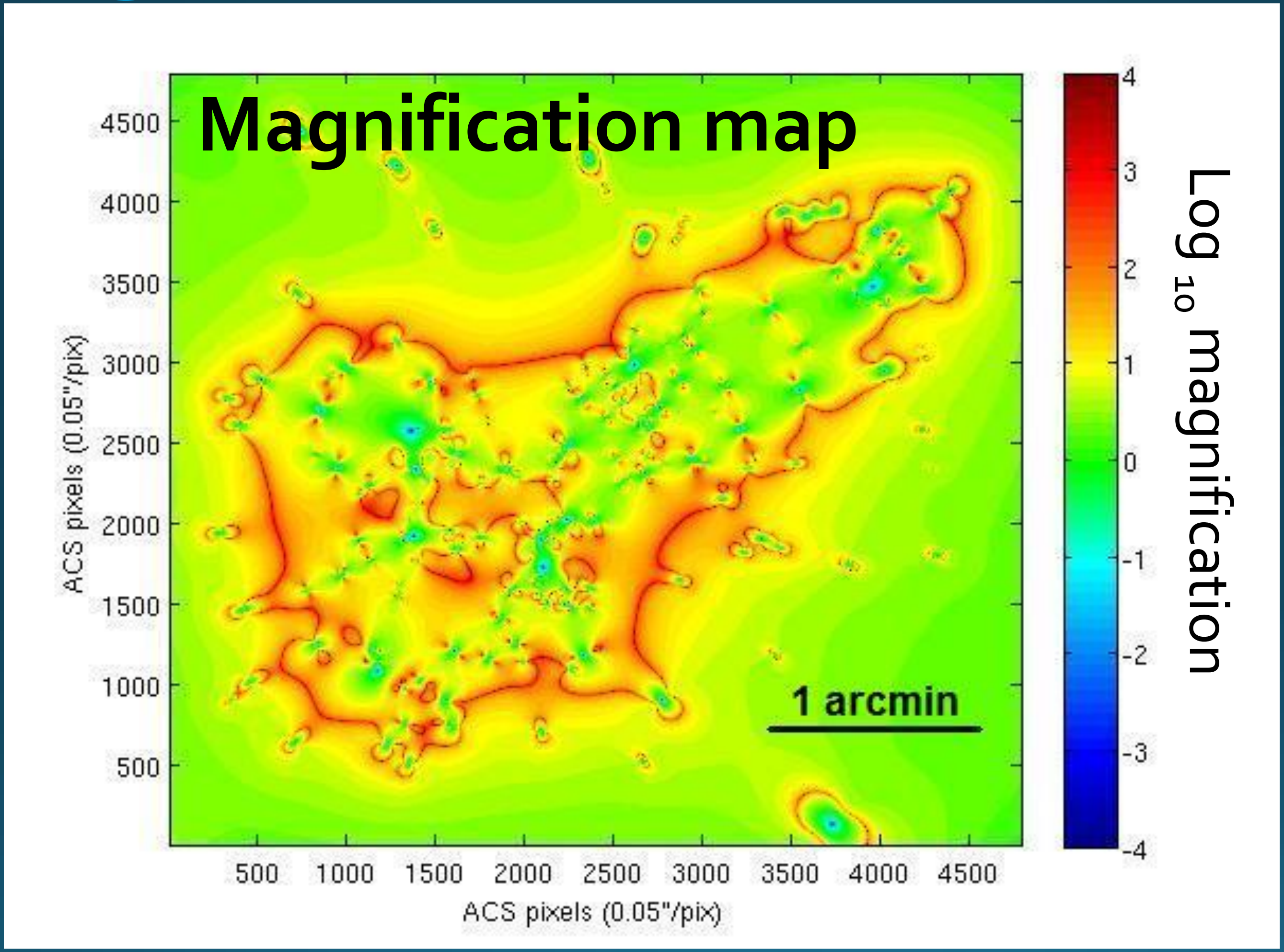
Strong lensing → Multiple images, distortion, displacement, magnification, time delay

Sub-mm maps (contours) of lensed systems overlaid on HST images

If the lens is a single galaxy, the image separation is ~1″



Cluster lensing – very important for high-z studies!



Galaxies can attain magnification of up to ≈100 – smaller objects (e.g. Population III star clusters) can in principle reach even higher μ!

Pros and Cons of Lensing

<u>Good:</u> Background sources appear brighter by a factor μ

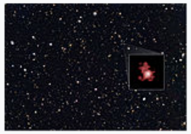
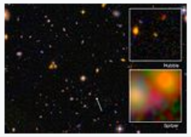
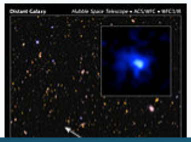
A magnification of μ=10 makes the object 2.5 mag brighter!

<u>Bad:</u> The background volume probed becomes smaller by a factor μ

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

Intermission:
Why are redshift records important?

Most distant astronomical objects with spectroscopic redshift determinations

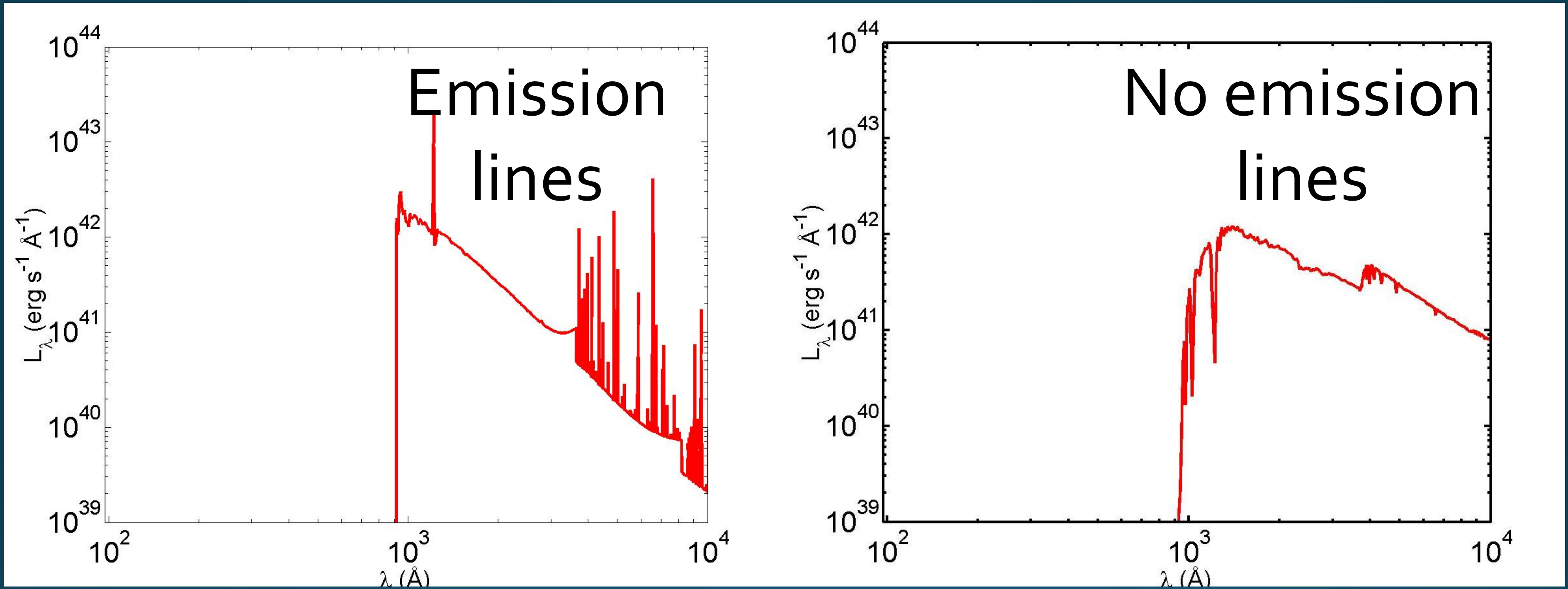
	Name	Redshift (z)	Gigalightyears. Light travel distance§ (Gly)[1]	Type	Notes
	GN-z11	z = 11.09	13.39	Galaxy	Confirmed galaxy[2]
	MACS1149-JD1	z = 9.11	13.26	Galaxy	Confirmed galaxy[3]
	EGSY8p7	z = 8.68	13.23	Galaxy	Confirmed galaxy[4]
	A2744 YD4	z = 8.38	13.20	Galaxy	Confirmed galaxy[5]
	GRB 090423	z = 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

<u>Two techniques:</u>

- 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

UV/optical spectra of high-z galaxies

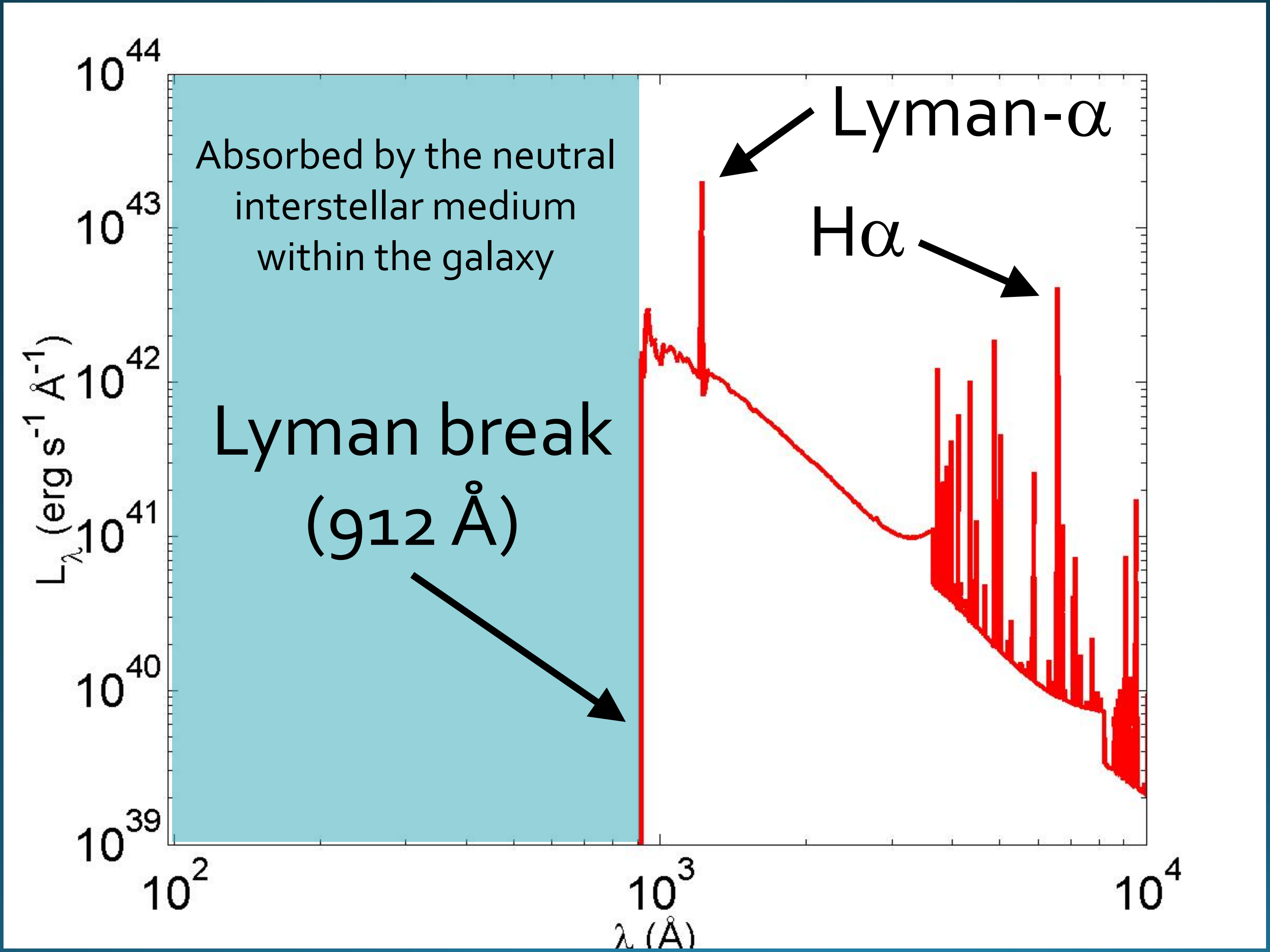


High-z galaxy with active star formation

High-z galaxy with no star formation

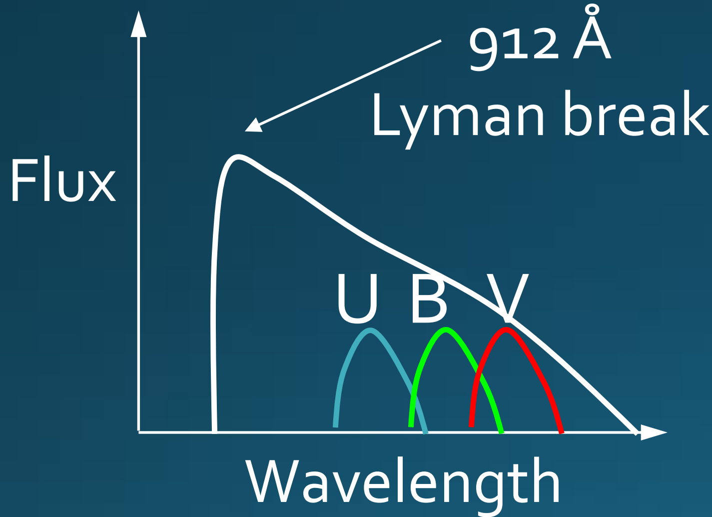
Note: All high-z galaxies are quite young – you can't have old galaxies in an young Universe

The UV/optical spectra of high-z galaxies



Drop-out techniques: Lyman-Break Galaxies

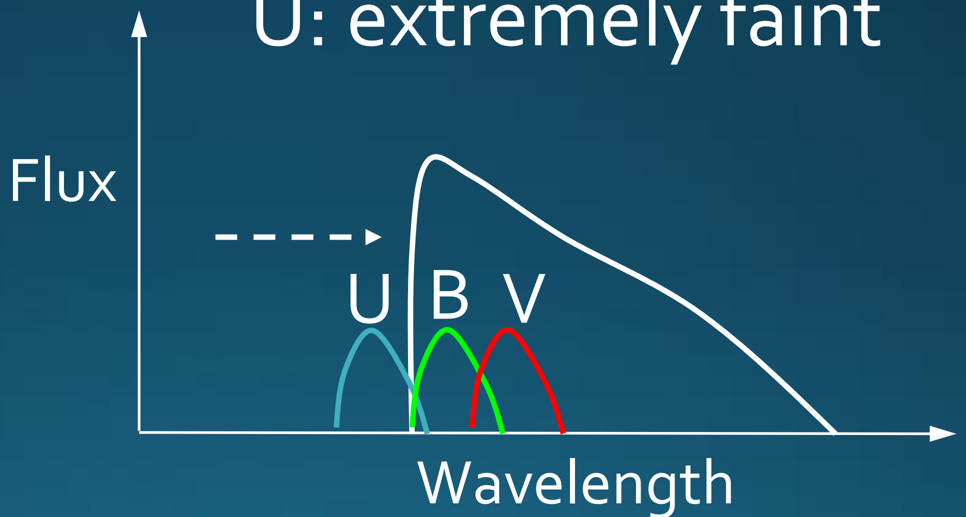
z=0



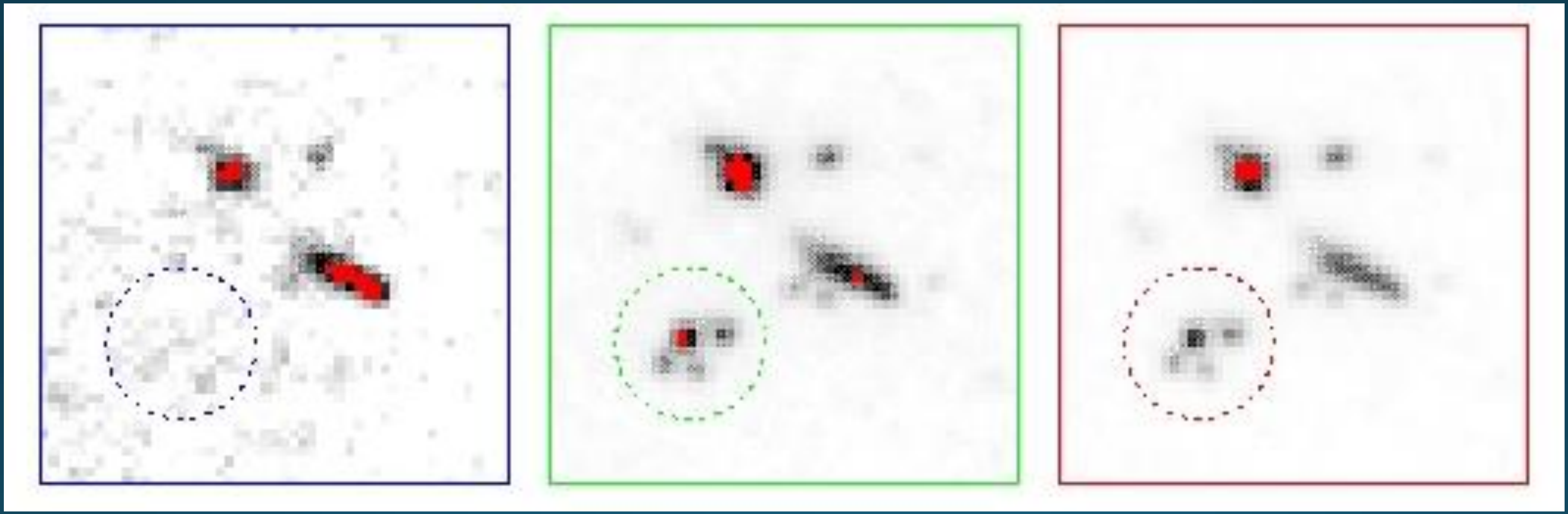
z>2.5

B-V ~ normal

U: extremely faint

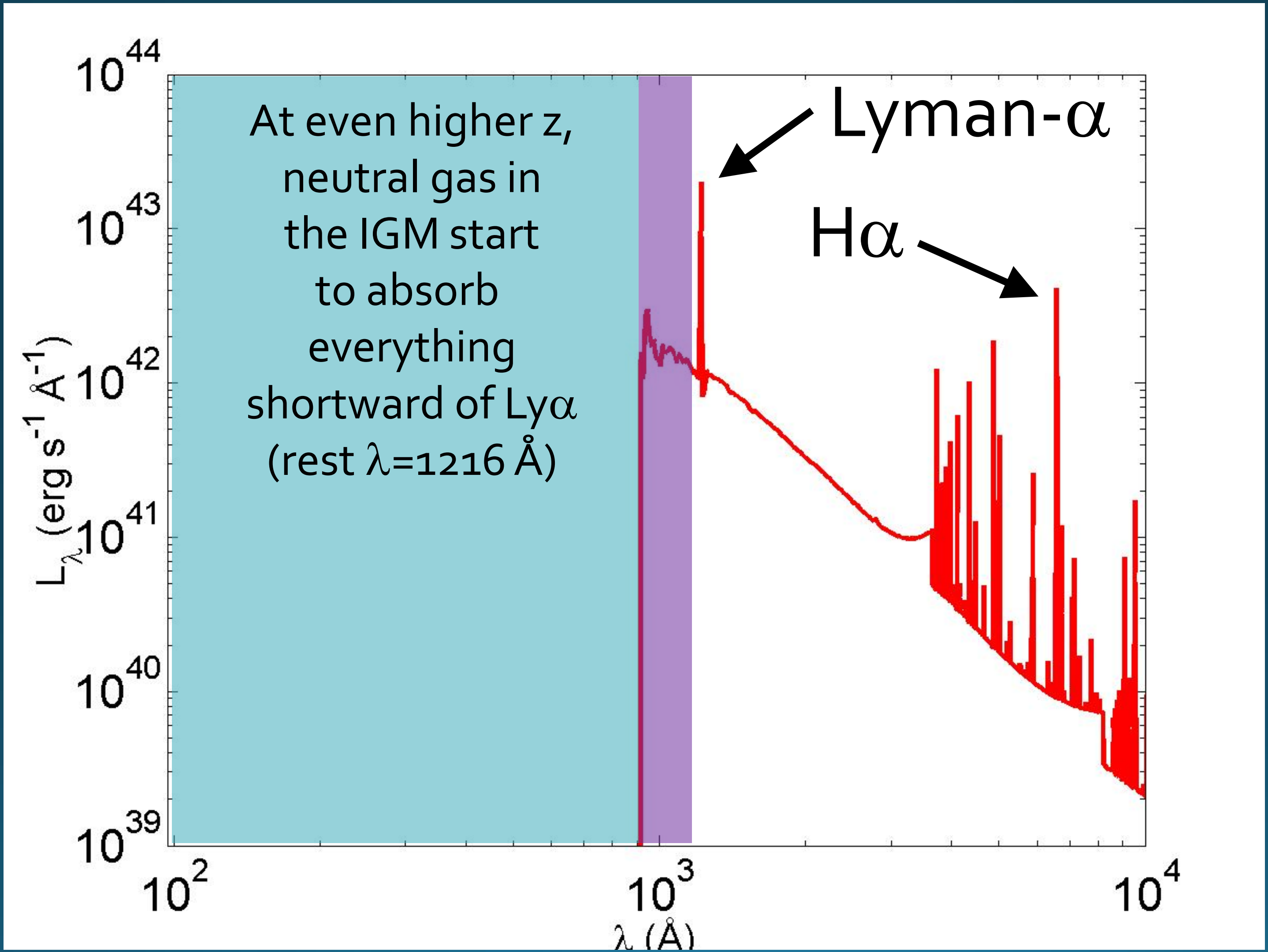


Drop-out techniques: Lyman-Break Galaxies



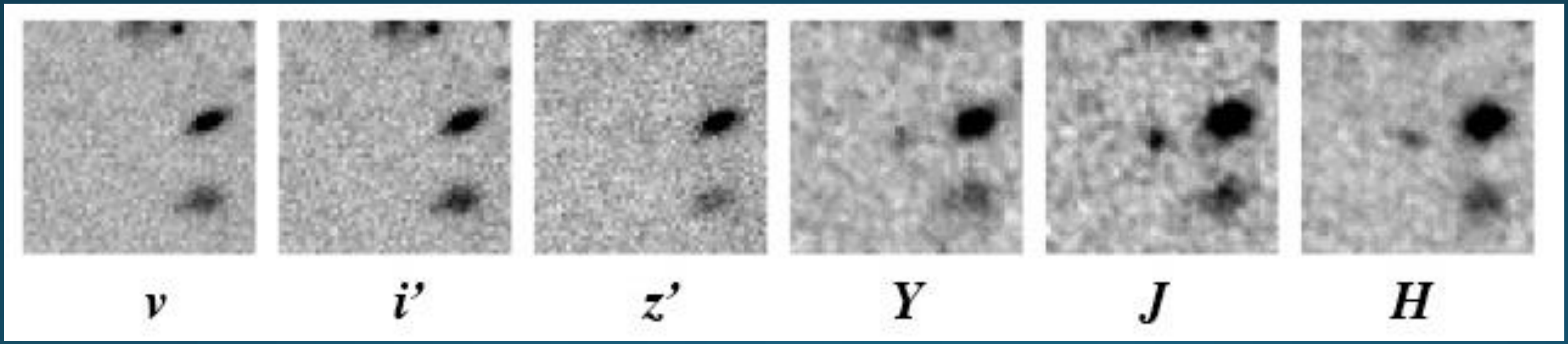
U B V

Reionization-epoch galaxies



Drop-out techniques: z>6 objects

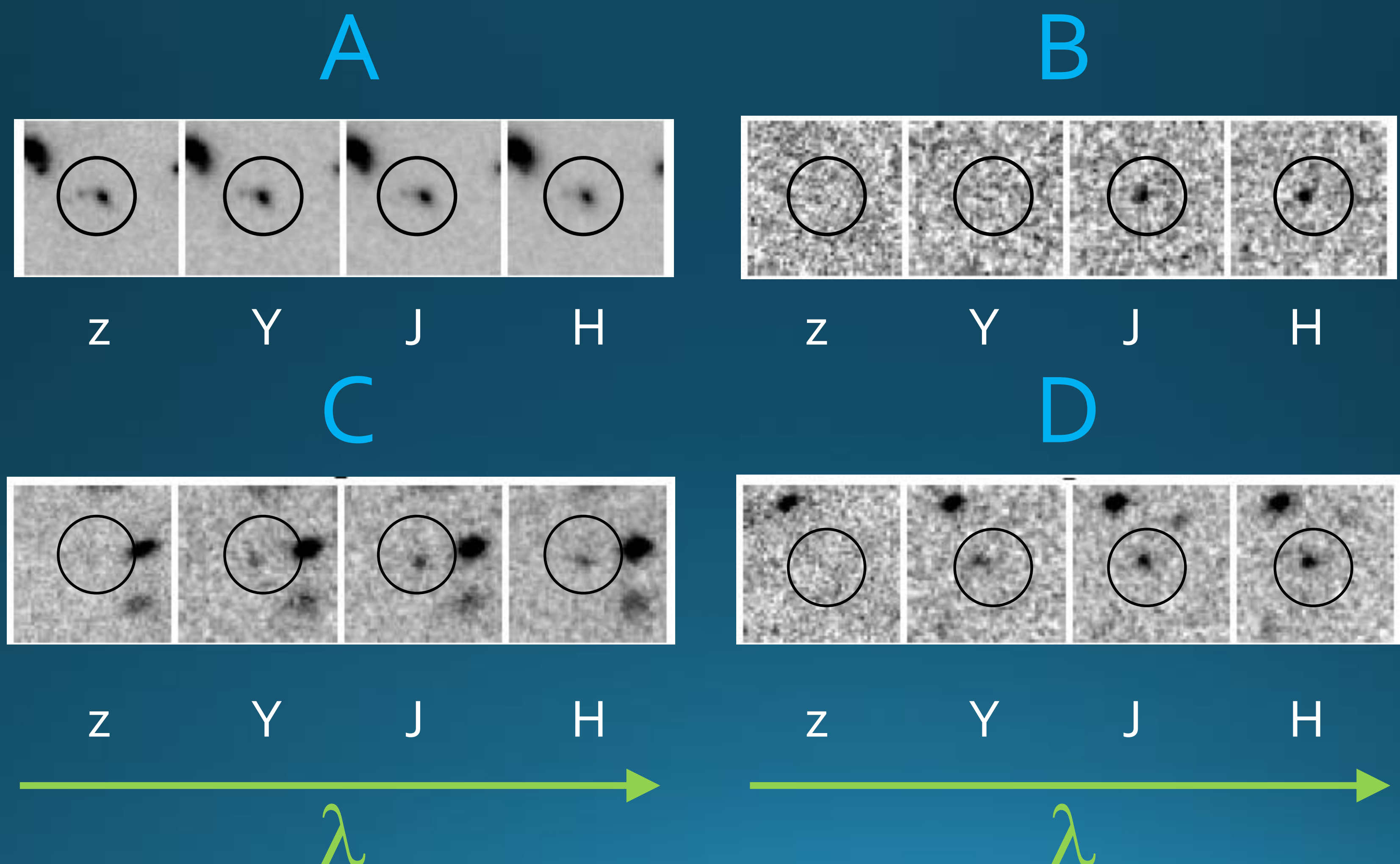
Eventually, the break shifts into the near-IR. Example: z-band dropout (z≈6.5)



Optical Near-IR

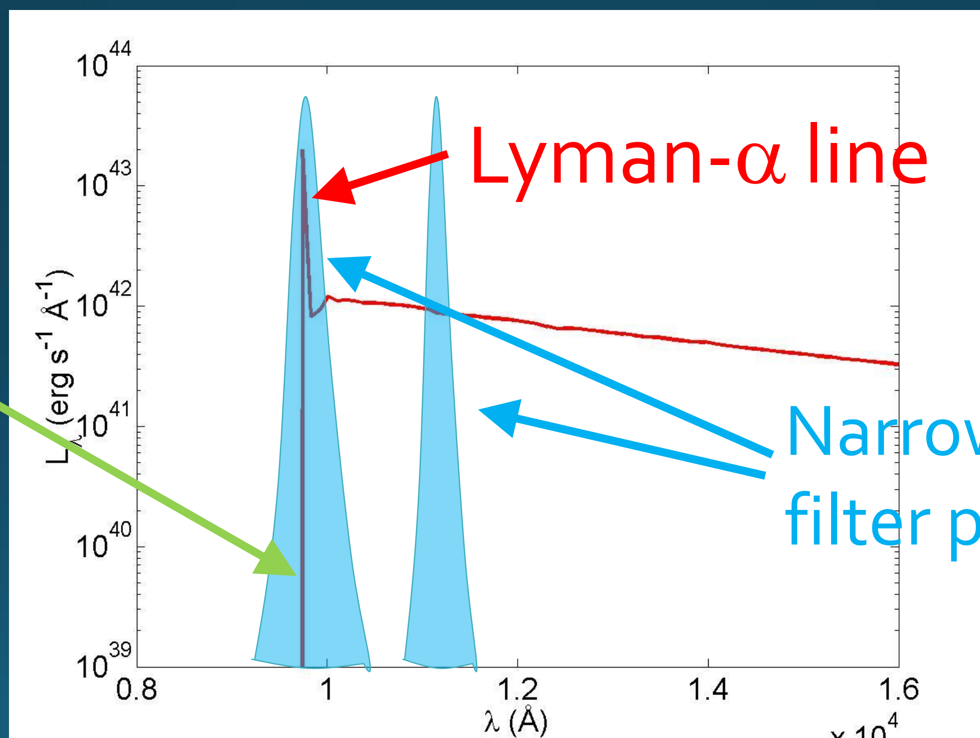
λ

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



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 ($\Delta z \sim 0.1$)

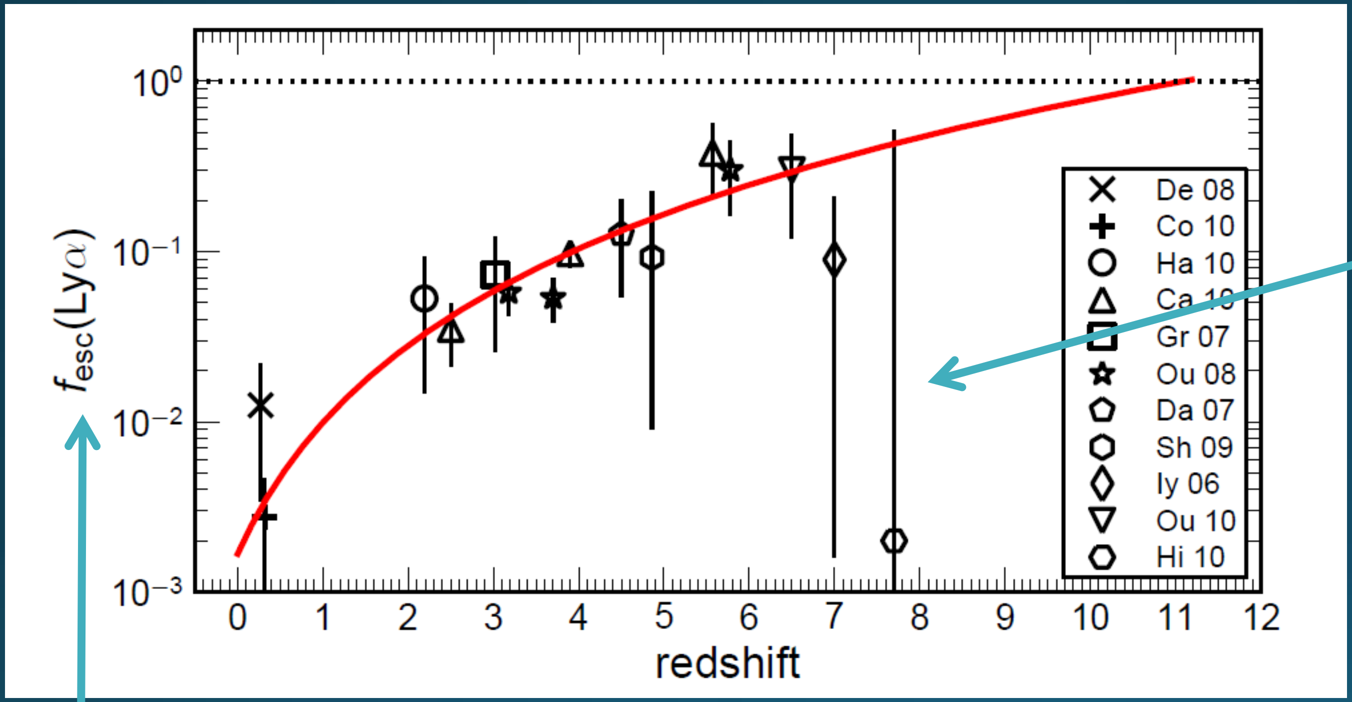


Lyman-α at z=7

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



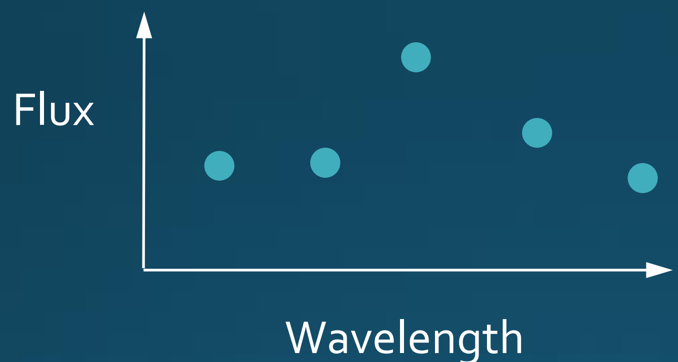
Abrupt drop → Lyα not good way to find z>6 galaxies (but may be good way to probe reionization)

Fraction of Lyα photons reaching the observer

Hayes et al. 11

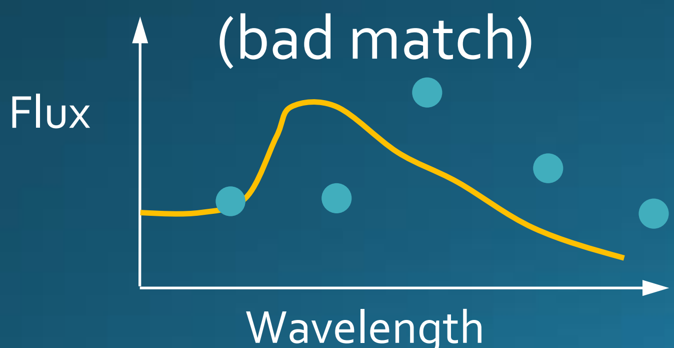
Photometric redshifts

- 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)

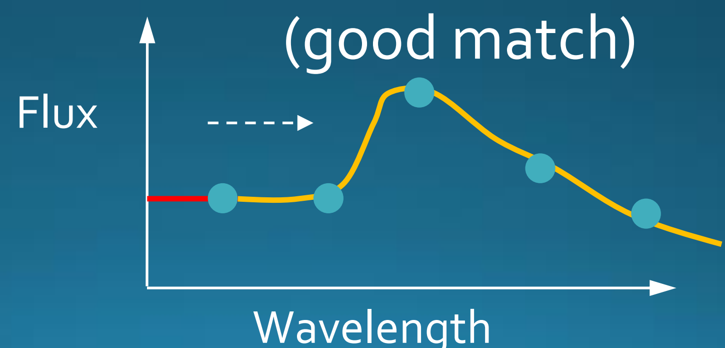


Measured photometrical data points

z=0 template spectrum (bad match)



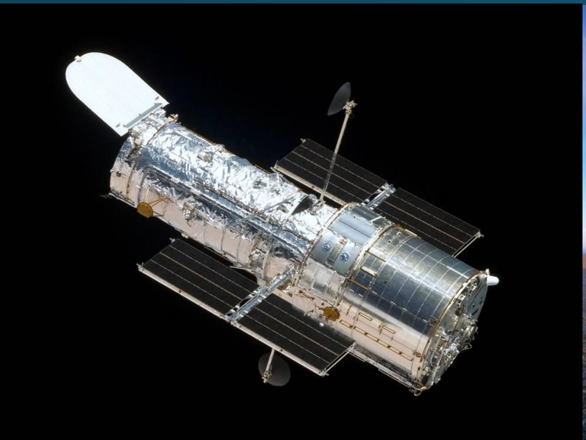
Redshifted template spectrum (good match)



Telescopes: Today

<u>**Commonly used in high-z studies:**</u>

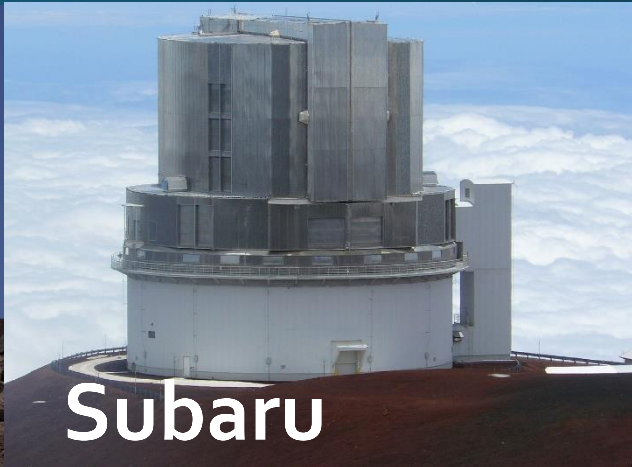
- **Near-IR:** 8-10 m telescopes on the ground
  Hubble space telescope
- **Mid-IR:** Spitzer space telescope (retired)
- **mm/sub-mm:** ALMA, NOEMA
- **X-rays:** Chandra X-ray observatory



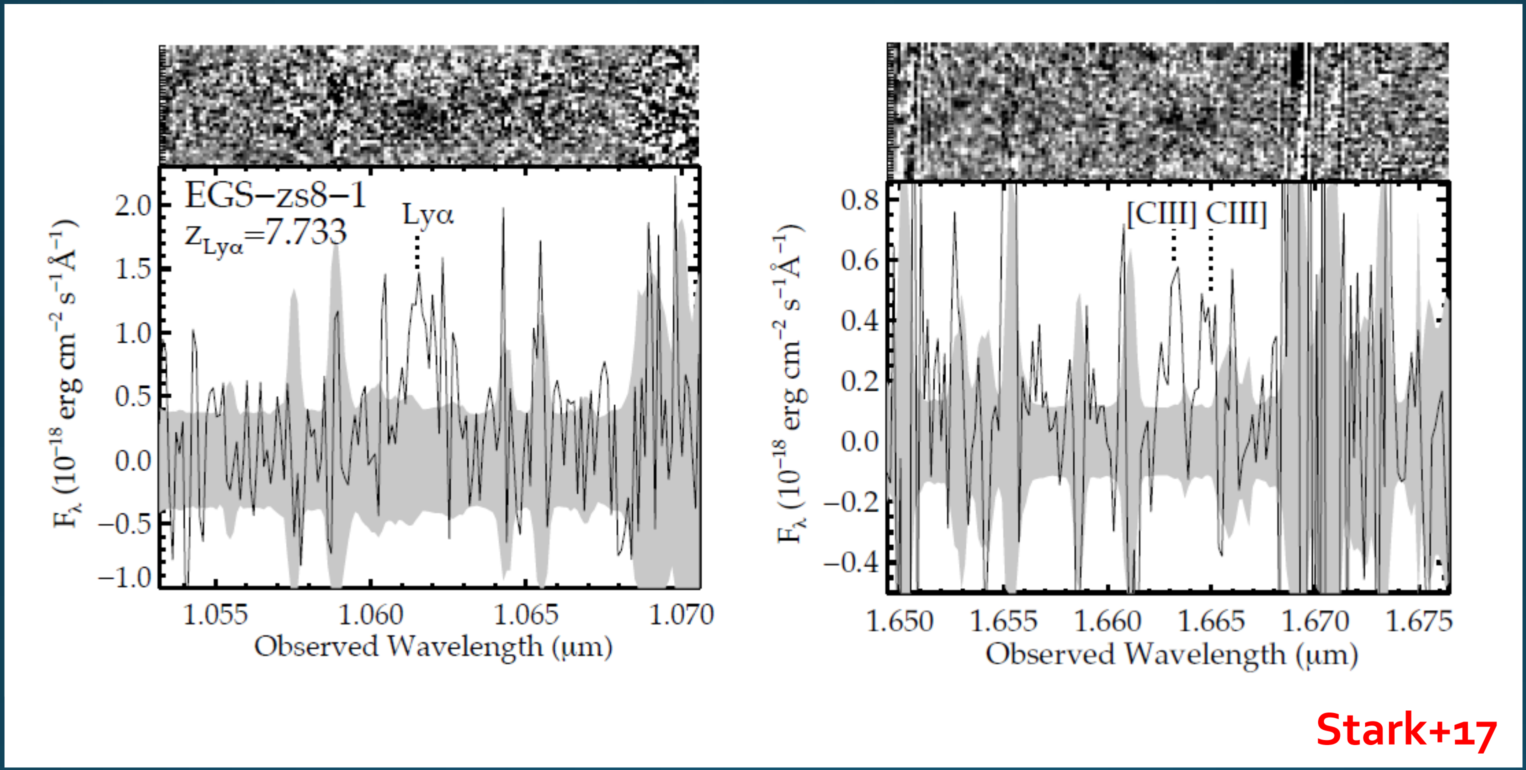
8-10m groundbased telescopes

<u>Suitable for high-z studies:</u>

- Large Binocular Telescope, 8.4m × 2 (Arizona)
- Hobby-Eberly Telescope, 10m (Texas)
- Keck, 10m (Hawaii)
- Subaru, 8.2m (Hawaii)
- Very Large Telescope, 8.2m (Chile)
- Gemini, 8.1m (Hawaii)



8-10m groundbased telescopes II



Main use at z>6:

- Spectroscopy to detect rest-frame UV emission lines (Lyα @ 1216 Å, HeII @ 1640 Å, OIII] @ 1606 Å, CIII] @ 1907, 1909 Å , CIV @ 1548 Å) → Redshift + diagnostics on interstellar medium and ionizing flux
- Photometry → Photometric redshift, strength/slope of UV continuum

Hubble Space Telescope

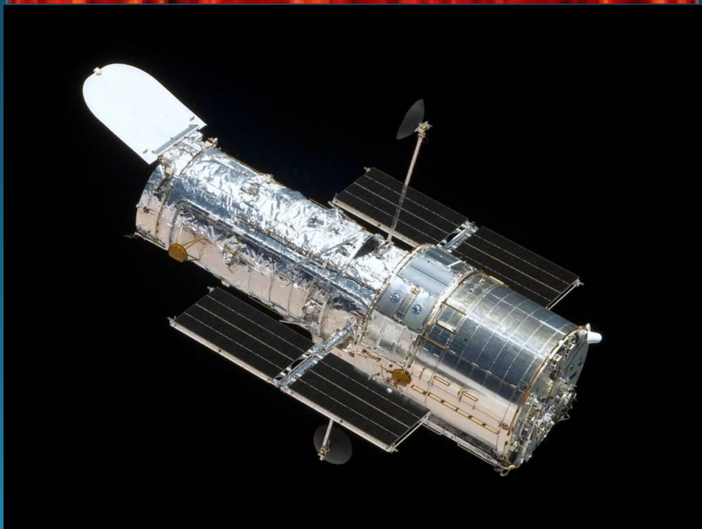
2.4 m UV/optical/near-IR telescope

Resolution ≈ 0.05 arcec

Field of view ≈ 2 arcmin

<u>**Main use at the highest redshifts:**</u>

Extremely deep near-IR images at excellent resolution (0.05 arcsec) → Detecting very faint sources, finding dropouts, studying object morphology



ALMA

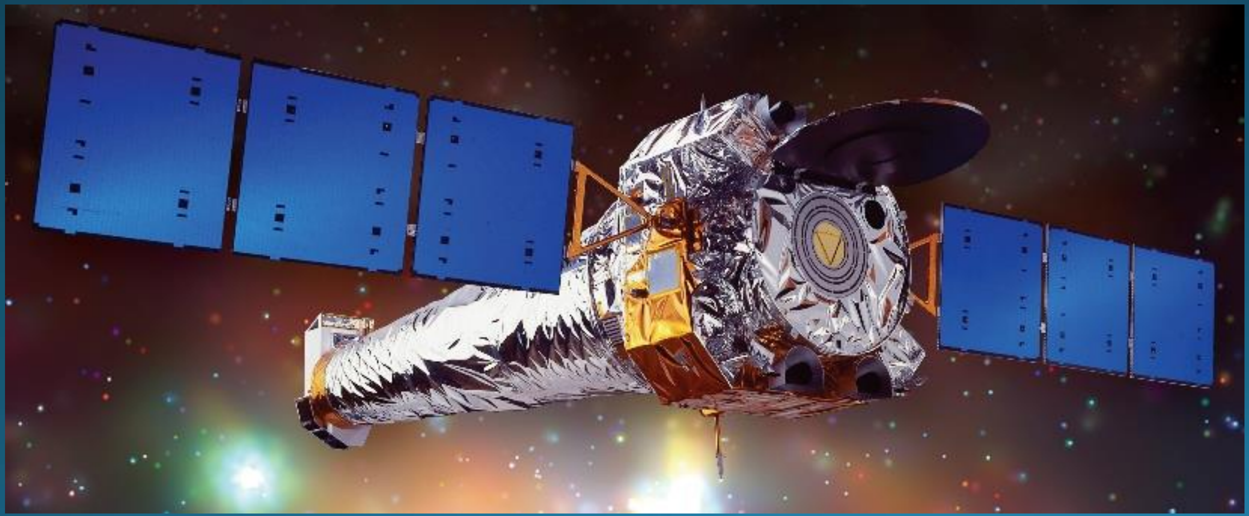
Atacama Large Millimeter/submillimeter Array: An array of seventy 12-m antennas operating @ 200-10000 μm in Chile

NOEMA: Somewhat similar array in the northern hemisphere

Main use at high z:
Searching for dust continuum emission and emission lines like: [CII]@158 μm, [OIII] @88 μm.
Resolution: ~0.1 arcsec
Field of view: ~ 10 arcsec

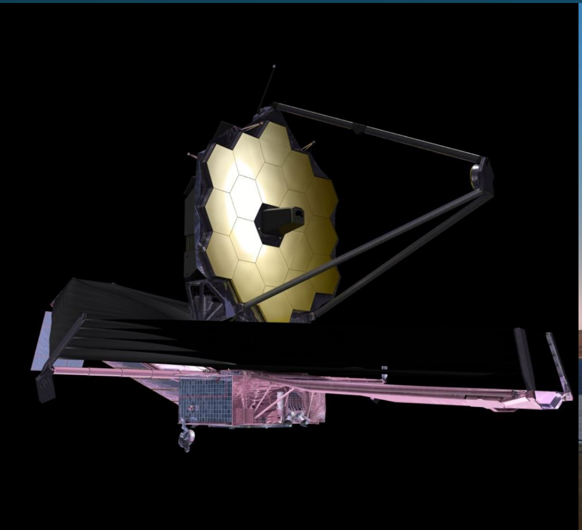
Chandra X-ray observatory

- Detects x-rays (1-100 Å; 10^{-4}-10^{-2} micron)
- Resolution: ≈0.5 arcsec
- Field of view: ≈30 arcmin
- Main use at high z: Finding signatures of black hole accretion (e.g. high-z quasars - but note that all quasars are not detectable in x-rays)



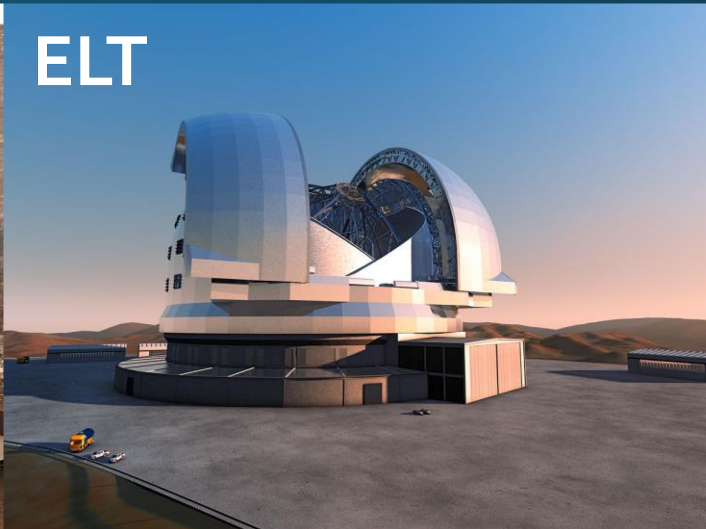
Telescopes: Tomorrow

- **Near-IR from the ground:** GMT, TMT, ELT
- **Near/mid-IR from space:** JWST, Euclid, WFIRST
- **X-rays:** Athena, Lynx

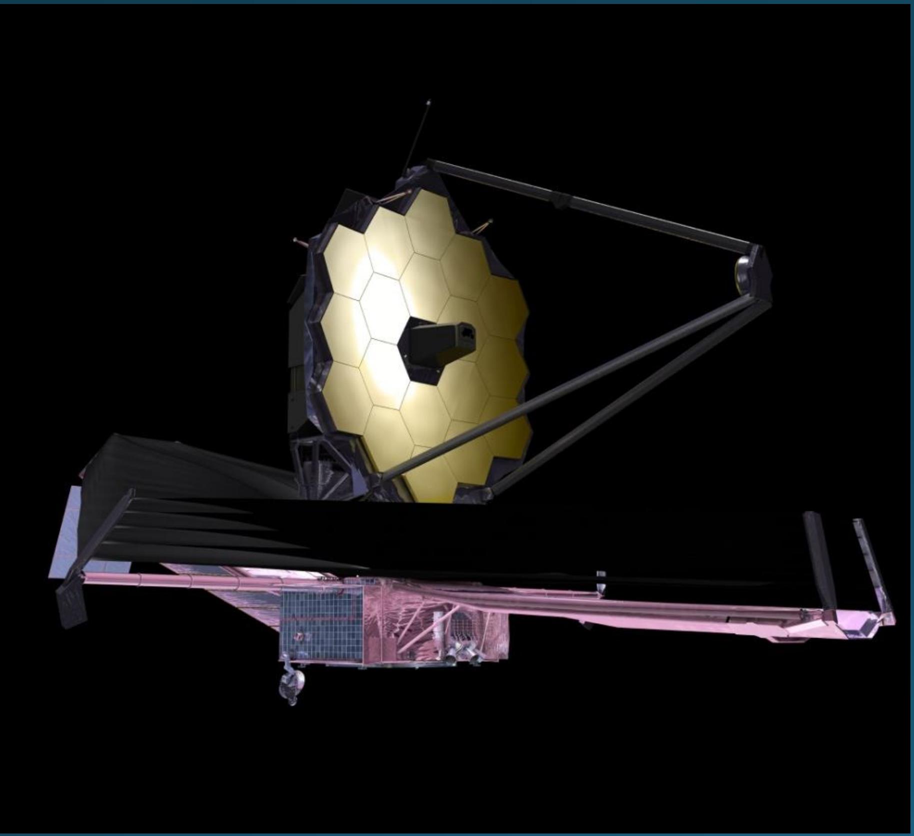


GMT, TMT, ELT

- **Giant Magellan Telescope (Chile, 25m, 2029)**
- **Thirty-Meter Telescope (Hawaii, 30m, 2027?)**
- **Extremely Large Telescope (Chile, 39m, 2025)**
- **Main use at high redshift:** Spectroscopy of high-z objects in the near-IR, at very high angular resolution (~0.01 arcsec)



James Webb Space Telescope



'The first light machine'

6.5 m mirror, near/mid-IR

Launch: 2021

Unprecedented IR sensitivity and the only upcoming telescope to allow deep observations at 3-8 micron

Main use at high z:

Deep photometry (down to 31 AB mag) and spectroscopy for galaxies up to $z \approx 15$; searching for extreme-z exotica

Euclid & WFIRST: Near-IR survey telescopes

- **Euclid (ESA, 1.2m, 2022):** Near-IR, field of view 0.53 deg², photometric limit m_{AB}≈26 AB mag
  Use at high z: Finding bright quasars at z≤9
- **WFIRST (NASA, 2.4m, 2025?):** Near-IR, field of view 0.28 deg², photometric limit m_{AB}≈28 AB mag
  Use at high z: Finding rare types of objects as targets for GMT/TMT/ELT, surveying Lyα-emitters

Athena & Lynx: X-ray telescopes

- **Athena (ESA, 1.4m², 2031):** 5-10 arcsec resolution, 0.44deg² field of view
  Use at high z: Finding quasars up to z≈10
- **Lynx X-ray Observatory (NASA, 2m², 2036?):** 0.5 arcsec resolution, 0.13 deg² field of view
  Use at high z: mini-quasars (black hole mass down to ~$10^4\ M_\odot$) at z≈7-10