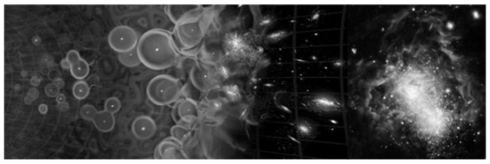
Physics of Galaxies 2020
10 credits
Lecture 8: The High-Redshift Universe

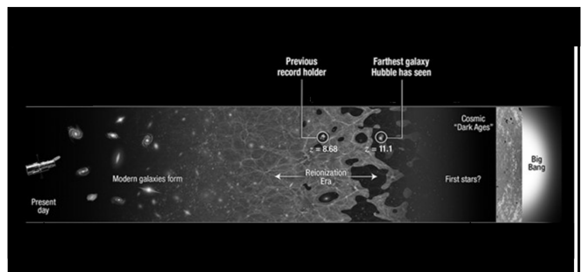


Outline: Part I

- 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 Big Bang,
redshift z = 0

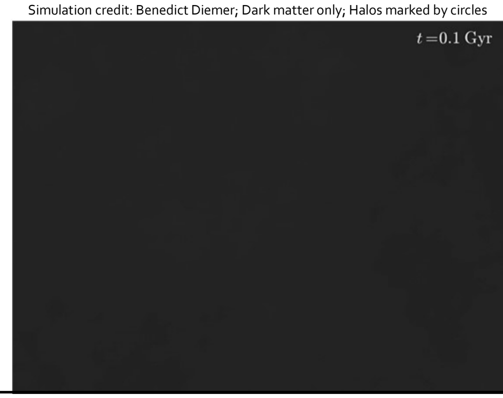
z = 6 z = 15 z = 30
First galaxies? First stars?

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

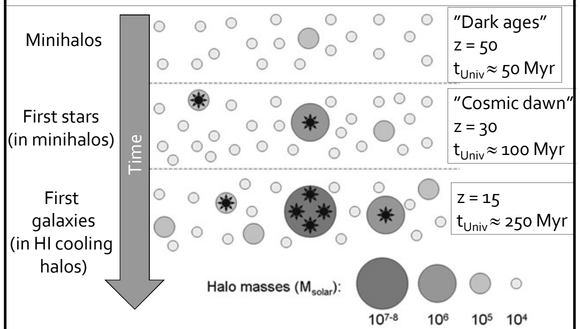
Mysteries in the first billion years

- **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



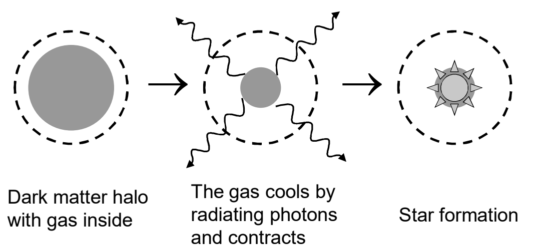
Dark ages, first stars, first galaxies



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≈30

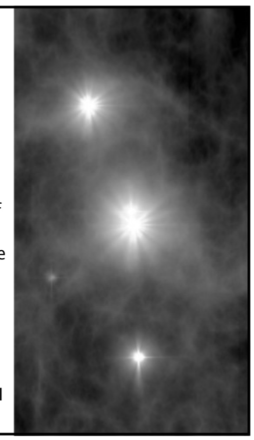
Star formation in dark matter halos



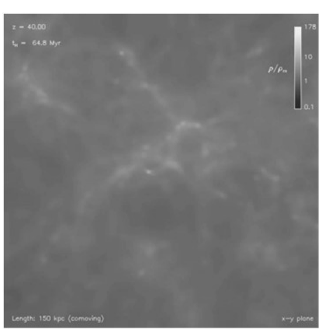
Problem: Low metallicity at high redshifts →
Lack of efficient coolants

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 (~10⁵ 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

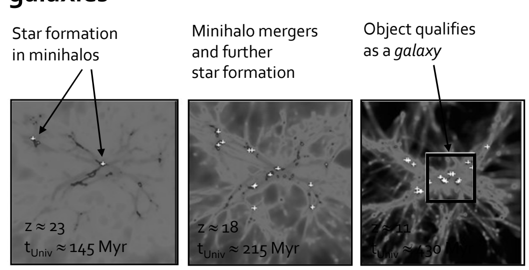


Greif et al. 08

Formation of a ~ 10^7 M_{solar} dark matter halo

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

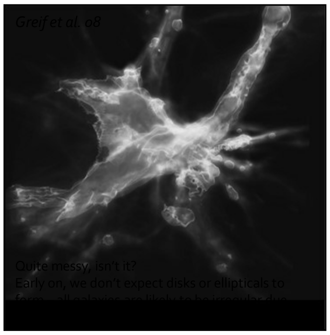
Star formation inside and outside the first galaxies



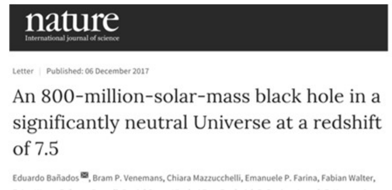
Greif et al. 08

Gas density shapshots

A galaxy is born (at $z \approx 10$)



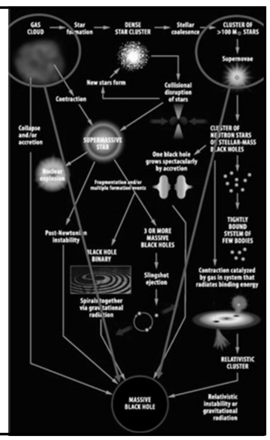
Supermassive black holes in the early Universe



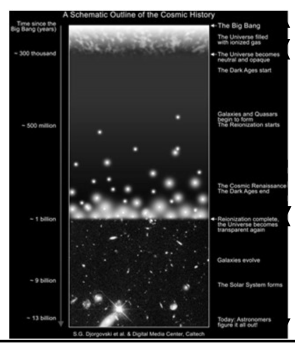
Previous record holder: Mortlock (2011) quasar,
with a black hole mass of $\approx 2\times10^9$ $M_\odot$ SMBH at $z\approx7.1$
At these redshifts, the Universe is less than 1 Gyr old….
Problem: How do you form a $\sim10^9$ $M_\odot$ SMBH in that time?

How to form a supermassive black hole…

Promising seeds:
- **Direct collapse black hole**
- **Very massive or even supermassive stars**



Cosmic Reionization



Intergalactic medium

Ionized

Neutral

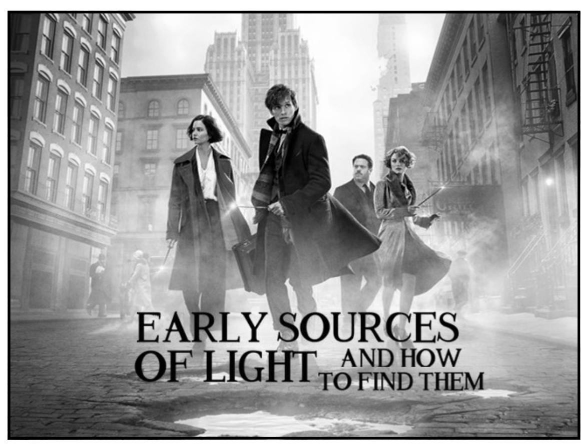
CMBR (Planck)
$\rightarrow z_{reion} \approx 8$
Lyα absorption in quasars
$\rightarrow z_{reion} > 6$

Reionized

Cosmic reionization

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

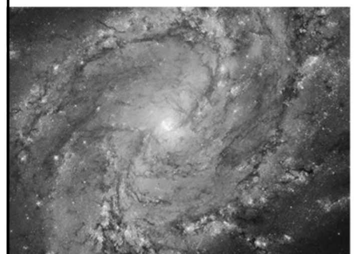
Simulation credit: Marcelo Alvarez (CITA), Tom Abel (Stanford)
Visualization credit: Marcelo Alvarez, Ralf Kaehler (Stanford), Tom Abel



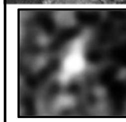
PART II: HOW TO FIND THEM

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

Imaging at high redshift

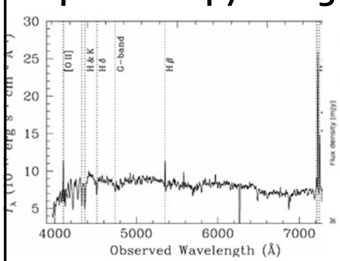


This is what a galaxy may look like to a low-redshift astronomer….

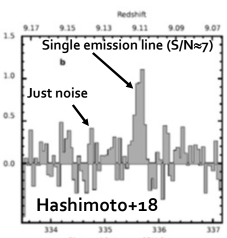


This is what a good(!) image of a galaxy at the highest redshifts typically looks like…
Note: Not to scale (would be about the size of one othe smallest dots in the upper image)

Spectroscopy at high redshift



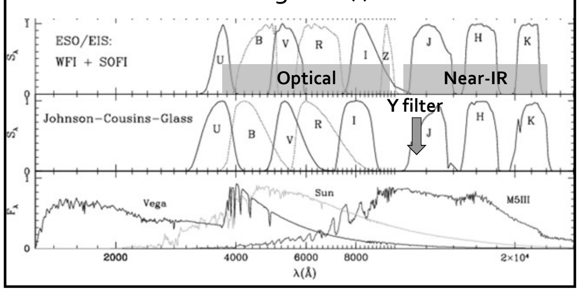
This is what the spectrum of a low-redshift galaxy typically looks like (S/N>30)



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)

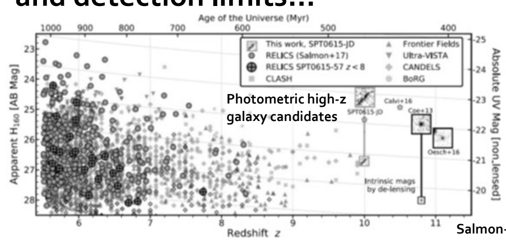
$$m_{\rm AB} \approx -2.5\log_{10}\left(\frac{f_\nu}{\rm Jy}\right) + 8.90.$$

Difference between apparent and absolute magnitude:

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

D_L: Luminosity distance (depends on z and cosmological parameters)
Can be calculated by many on-line cosmology calculators!

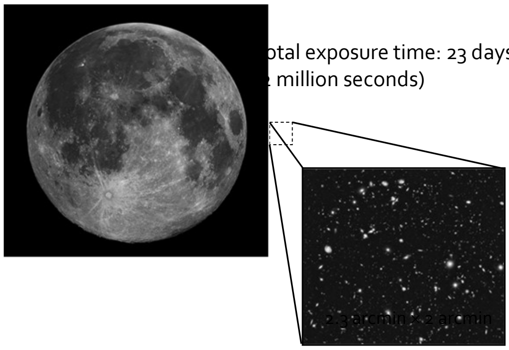
Some rough brightness estimates and detection limits…



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

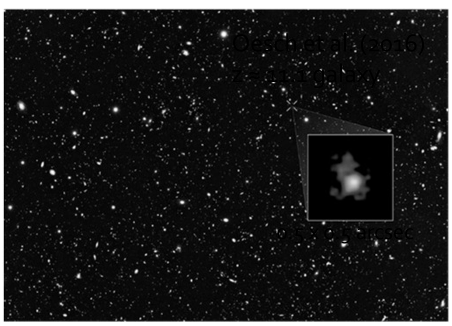
The Hubble Extreme Deep Field

otal exposure time: 23 days
million seconds)

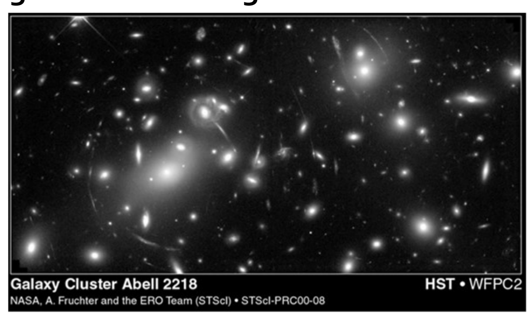


Hubble Extreme Deep Field

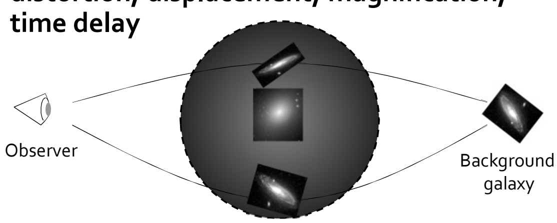
The most distant galaxy so far



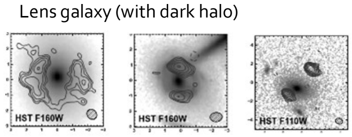
Gravitational Lensing: A great tool for hunting-down galaxies at the high-redshift frontier!



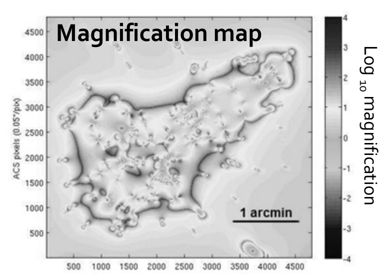
Strong lensing → Multiple images, distortion, displacement, magnification, time delay



Sub-mm maps (contours) of lensed systems overlaid on HST images
If the lens is a single galaxy, the image separation is ~1″

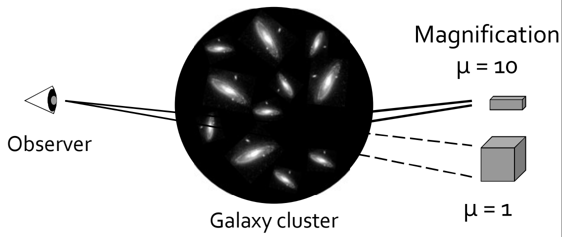


Cluster lensing – very important for high-z studies!



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



Good: Background sources appear brighter by a factor μ
A magnification of μ=10 makes the object 2.5 mag brighter!
Bad: The background 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

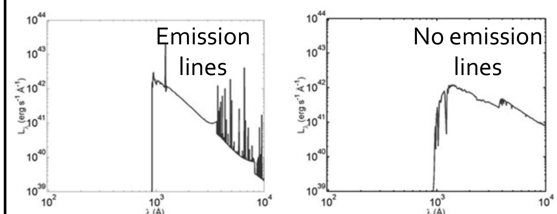
	Name	Redshift (z)	Gigalightyears. Light travel distance§ (Gly)[1]	Type	Notes
	GN-z11	z = 11.09	13.39	Galaxy	Confirmed galaxy[2]
	MACS1149-JD1	z = 9.11	13.26	Galaxy	Confirmed galaxy[3]
	EGSY8p7	z = 8.68	13.23	Galaxy	Confirmed galaxy[4]
	A2744 YD4	z = 8.38	13.20	Galaxy	Confirmed galaxy[5]
	GRB 090423	z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

UV/optical spectra of high-z galaxies

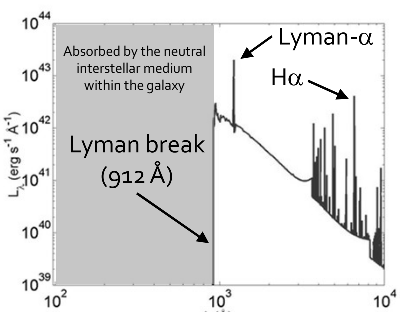


High-z galaxy with active star formation

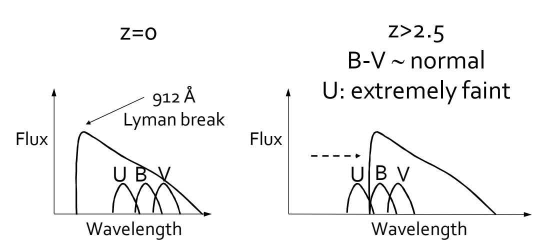
High-z galaxy with no star formation

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

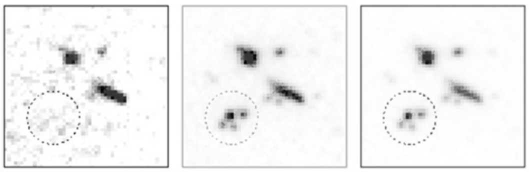
The UV/optical spectra of high-z galaxies



Drop-out techniques: Lyman-Break Galaxies

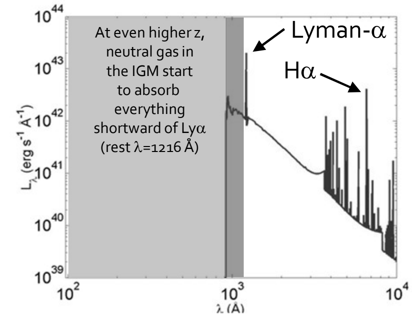


Drop-out techniques: Lyman-Break Galaxies



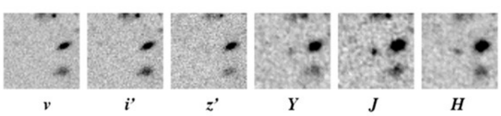
U B V

Reionization-epoch galaxies



Drop-out techniques: z>6 objects

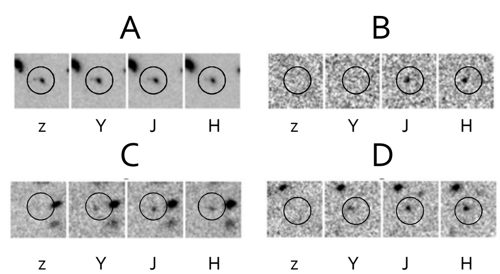
Eventually, the break shifts into the near-IR. Example: z-band dropout (z≈6.5)



Optical Near-IR

λ

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

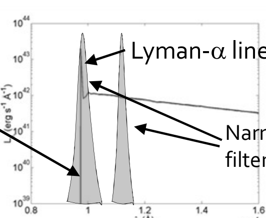


λ λ

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 (Δz~0.1)

Sharp drop (absorption in neutral IGM)

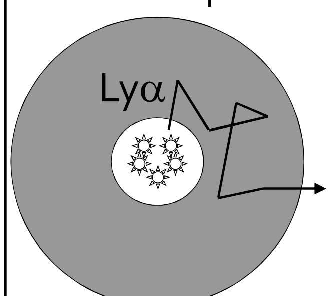


Lyman-α line

Narrowband filter profiles

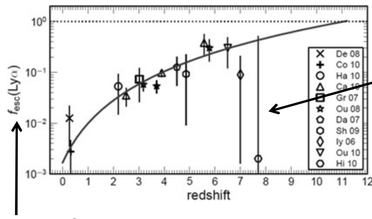
Lyman-α at z=7

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



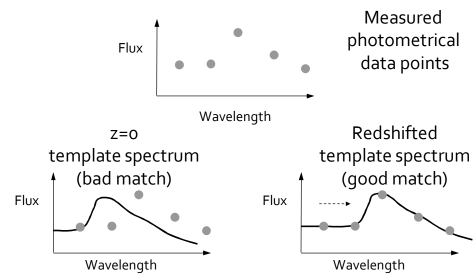
Abrupt drop → Lyα not good way to find z>6 galaxies (but may be good way to probe reionization)

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)



Telescopes: Today

Commonly used in high-z studies:

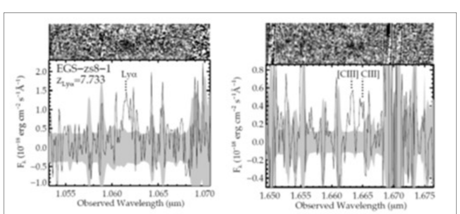
- **Near-IR:** 8-10 m telescopes on the ground
  Hubble space telescope
- **Mid-IR:** Spitzer space telescope (retired)
- **mm/sub-mm:** ALMA, NOEMA
- **X-rays:** Chandra X-ray observatory

8-10m groundbased telescopes

Suitable for high-z studies:

- 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



Stark+17

Main use at z>6:

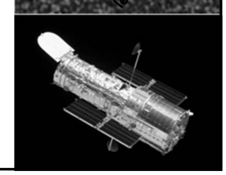
- Spectroscopy to detect rest-frame UV emission lines (Lyα @ 1216 Å, HeII @ 1640 Å, OIII] @ 1606 Å, CIII] @ 1907, 1909 Å , CIV @ 1548 Å) → Redshift + diagnostics on interstellar medium and ionizing flux
- Photometry → Photometric redshift, strength/slope of UV continuum

Hubble Space Telescope

2.4 m UV/optical/near-IR telescope
Resolution ≈ 0.05 arcec
Field of view ≈ 2 arcmin

Main use at the highest redshifts:

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

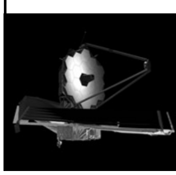
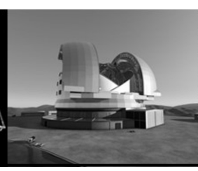
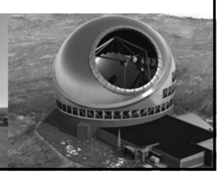
Main use at high z:
Searching for dust continuum emission and emission lines like: [CII]@158 μm, [OIII] @88 μm.
Resolution: ~0.1 arcsec
Field of view: ~ 10 arcsec

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)

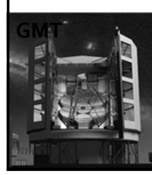
Telescopes: Tomorrow

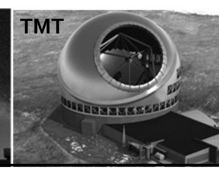
- **Near-IR from the ground:** GMT, TMT, ELT
- **Near/mid-IR from space:** J WST, Euclid, WFIRST
- **X-rays:** Athena, Lynx

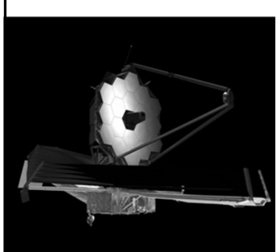
GMT, TMT, ELT

- **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)





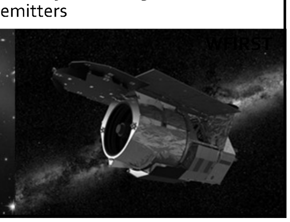
James Webb Space Telescope



'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
<u>Main use at high z:</u>
Deep photometry (down to 31 AB mag) and spectroscopy for galaxies up to z ≈ 15; searching for extreme-z exotica

Euclid & WFIRST: Near-IR survey telescopes

- **Euclid (ESA, 1.2m, 2022):** Near-IR, field of view 0.53 deg^2, 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 deg^2, 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, 1.4m^2, 2031):** 5-10 arcsec resolution, 0.44deg^2 field of view
  Use at high z: Finding quasars up to z≈10
- **Lynx X-ray Observatory (NASA, 2m^2, 2036?):** 0.5 arcsec resolution, 0.13 deg^2 field of view
  Use at high z: mini-quasars (black hole mass down to ~10^4 $M_{\odot}$) at z≈7-10