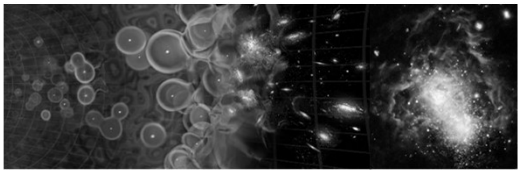
Physics of Galaxies 2018
10 credits
Lecture 8: The High-Redshift Universe



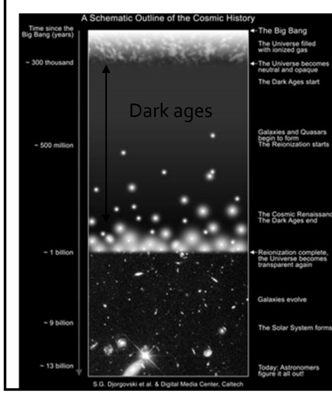
Outline: Part I

- 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

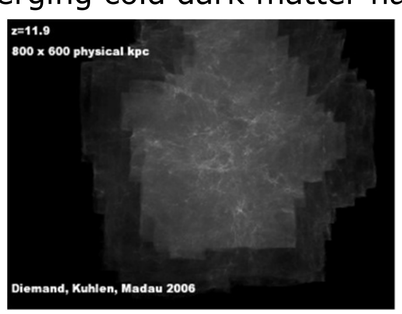


First stars
$z \approx 20\text{-}30$
$t_{Univ} \approx 100\text{-}200$ Myr

First galaxies
$z \approx 10\text{-}15$
$t_{Univ} \approx 300\text{-}500$ Myr

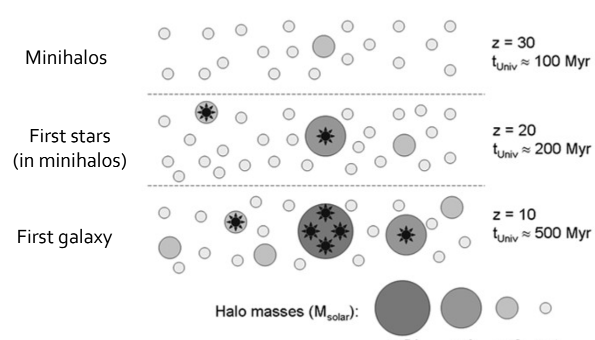
Current observational limit: HST and 8-10 m telescopes on the ground can detect light sources up to $z \approx 11$

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)

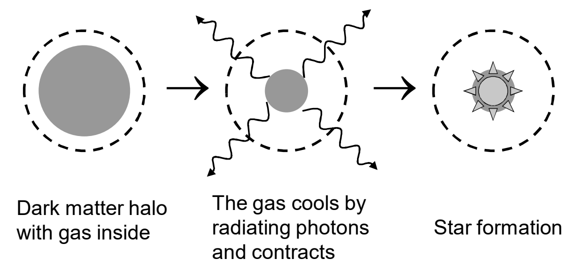
Structure formation



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≈20

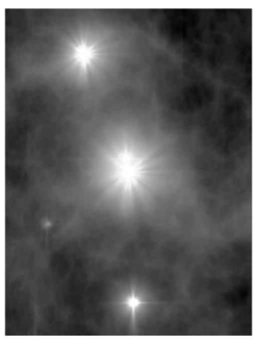
Star formation in dark matter halos



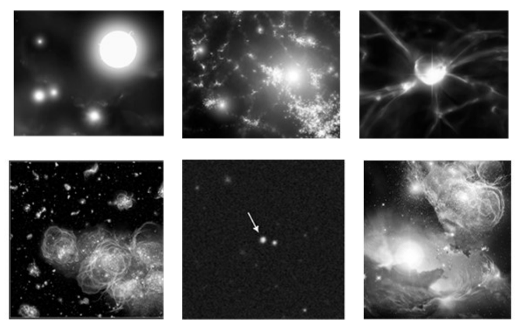
Problem: Low metallicity at high redshifts →
Lack of efficient coolants

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*

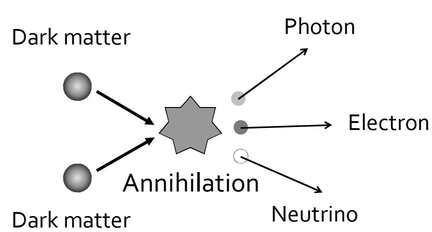


Intermission: The first stars(?)

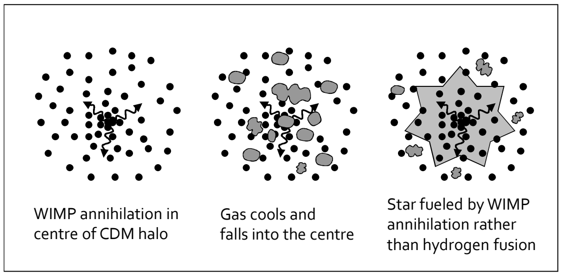


Normal star ≈ hydrogen bomb

Dark matter annihilation

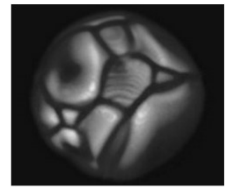


Dark stars



Dark star properties

- Conventional Pop III stars
  - Teff ~ 50 000-100 000 K
  - M ~ 10^1-10^3 Msolar
  - Lifetime $\tau \sim 10^6$-10^7 yr
- Pop III dark stars
  - Teff ≈ 4000-50000 K Cooler!
  - M ~ 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

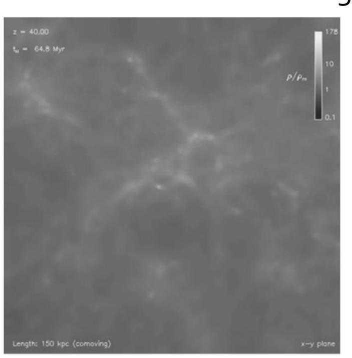
Vanilla population III star

The sizes of primordial stars II

The Sun

Supermassive dark star

Formation of the first galaxies

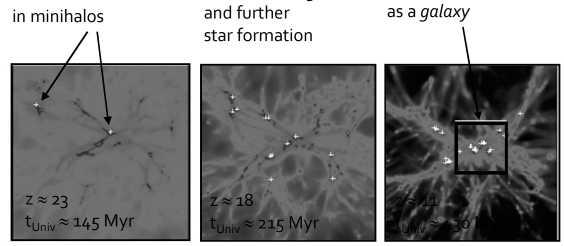


Formation of a ~ 10^7 M_{solar} dark matter halo

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

Greif et al. 08

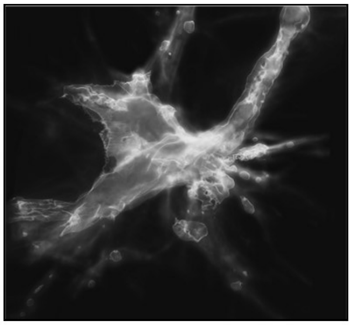
Star formation inside and outside the first galaxies



Greif et al. 08

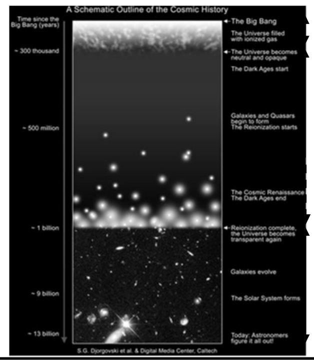
Gas density shapshots

A galaxy is born (at z ≈ 10)



Greif et al. 08

Reionization



<u>Intergalactic medium</u>

Ionized

Neutral

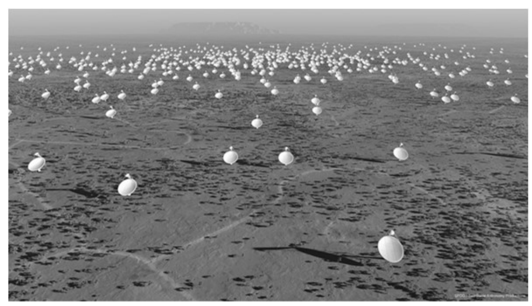
CMBR (Planck) → $z_{reion} \approx 8$
Lyα absorption in quasars → $z_{reion} > 6$

Reionized

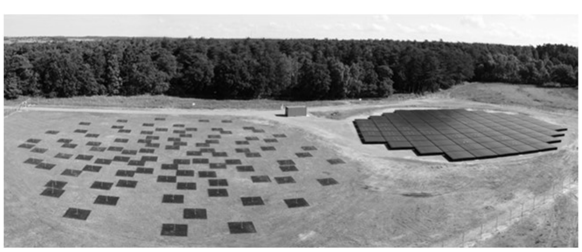
What caused reionization?

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

Intermission: Name the telescope!



Intermission: Name the telescope!



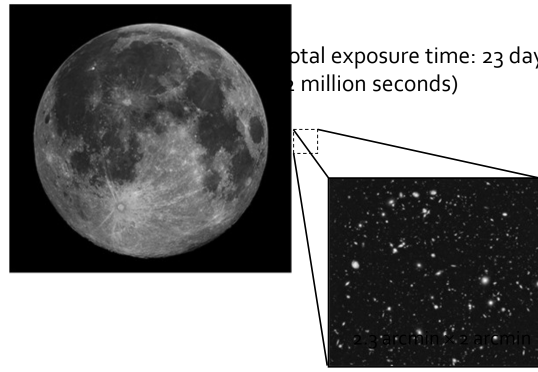
Intermission: Name the telescope!

How to find and study high-redshift galaxies

<u>Imaging strategies</u>

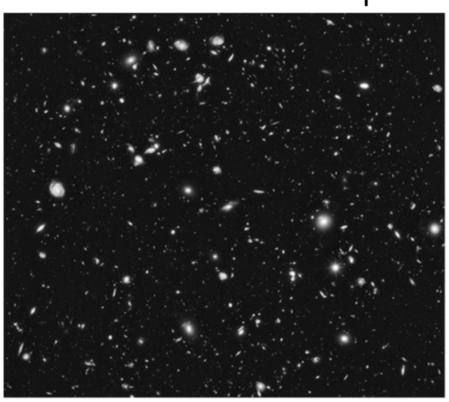
- Deep field-style observations
  - Very long exposures of single patch (devoid of bright foreground objects) in the sky
- Cluster-lensing observations
  - Hunt for gravitationally lensed background objects in relatively short exposures (few hours per filter) of a low-z galaxy cluster

The Hubble Extreme Deep Field

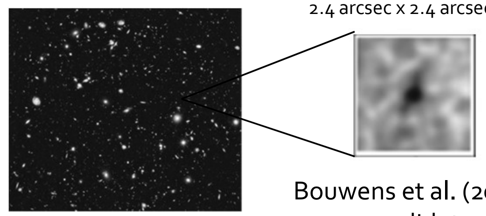


otal exposure time: 23 days
million seconds)

The Hubble Extreme Deep Field



Example of one of the most distant galaxy candidates so far

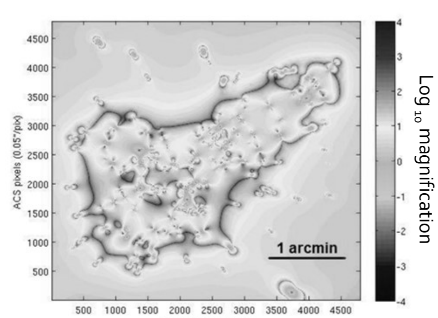


Bouwens et al. (2010)
z ≈ 10 candidate

Cluster lensing I

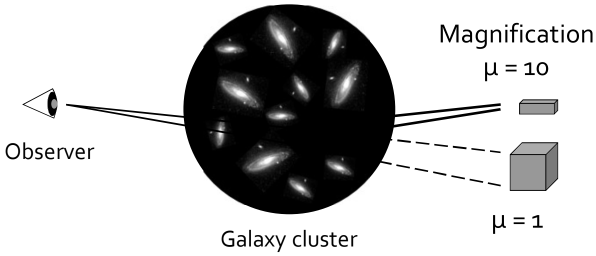
Galaxy cluster at z≈0.5

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 <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

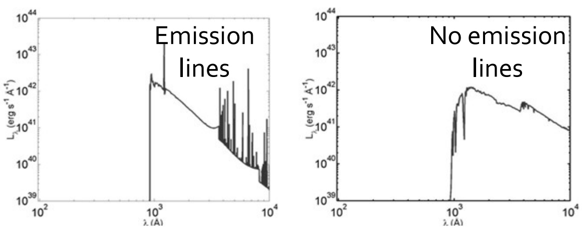
Name	Redshift (z)	Gigalightyears. Light travel distance§ (Gly)[1]	Type	Notes
GN-z11	z = 11.09	13.39	Galaxy	Confirmed galaxy[2]
EGSY8p7	z = 8.68	13.23	Galaxy	Confirmed galaxy[3]
GRB 090423	z = 8.2	13.18	Gamma-ray burst	[4][5]
EGS-zs8-1	z = 7.73	13.13	Galaxy	Confirmed galaxy[6]
z7 GSD 3811	z = 7.66	13.11	Galaxy	galaxy[7]
z8 GND 5296	z = 7.51	13.10	Galaxy	Confirmed galaxy[8][9]

Selecting high-z galaxy candidates

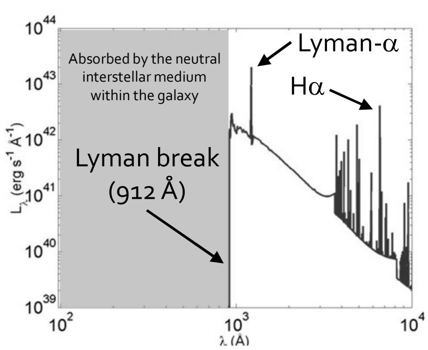
<u>Two techniques:</u>

- 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

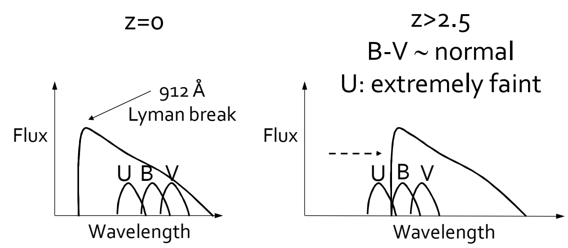
The UV/optical spectra of galaxies I



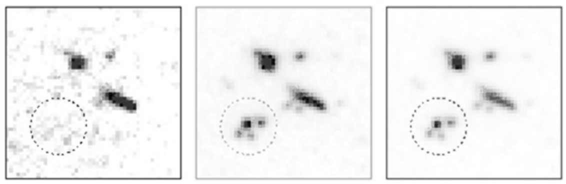
The UV/optical spectra of galaxies



Drop-out techniques: Lyman-Break Galaxies

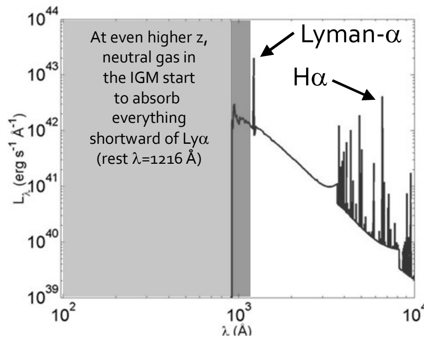


Drop-out techniques: Lyman-Break Galaxies



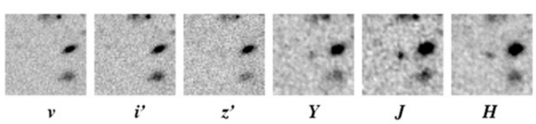
U B V

Reionization-epoch galaxies

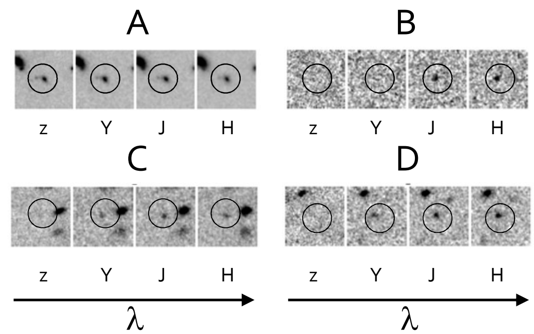


Drop-out techniques: z>6 objects

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

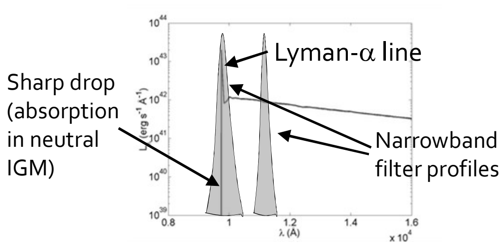


Intermission:
Which of these drop-out candidates is likely to have the highest redshift?



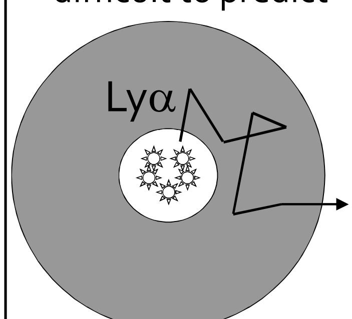
Lyman-alpha surveys

- Potentially the brightest line in rest frame UV/optical
- Two narrowband images (covering continuum and line) required for survey of redshift range (Δz~0.1)



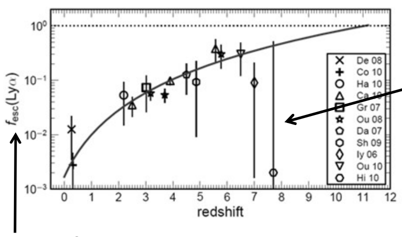
Lyman-α at z=7

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



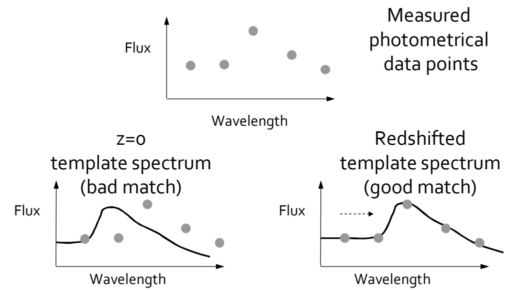
Abrupt drop → Lyα not good way to find z>6 galaxies (but may be good way to probe reionization)

Fraction of Lyα photons reaching the observer

Hayes et al. 11

Photometric redshifts

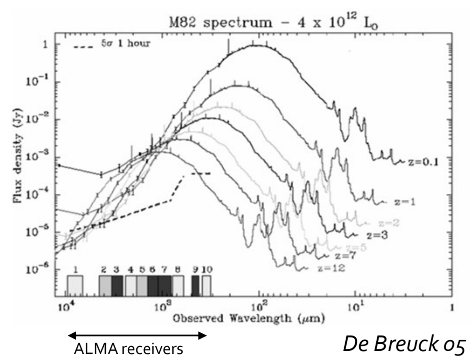
- Estimate the galaxy type (morphological) and assume that the galaxy is identical to some template (often an average over many galaxy spectra of similar type)



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)

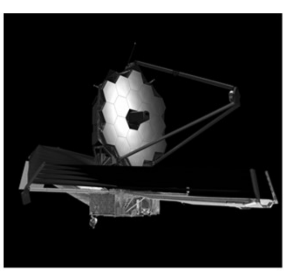
Can be used to search for dust emission and emission lines like [CII] @ 158 μm and [OIII] @88 μm (rest-frame) from z>6 galaxies



De Breuck 05

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

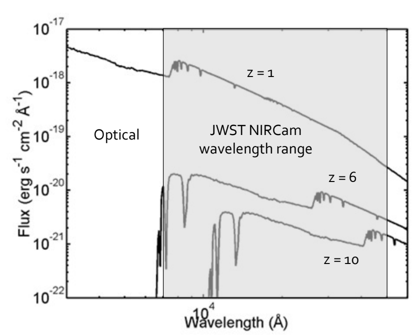
Future prospects: JWST



James Webb Space Telescope
'The first light machine'
To be launched by NASA / ESA / CSA in 2020

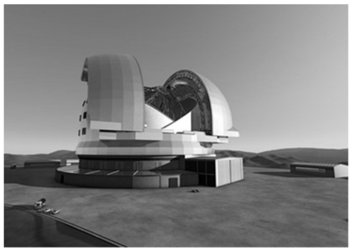
6.5 m mirror
Observations @ 0.6-29 μm
Useful for:
Galaxies up to z $\approx$ 15
Pop III supernovae

Why infrared?



Zackrisson et al. (2001) model

Future prospects: ELT



39 m Extremely Large Telescope (ELT) estimated to be completed in 2024.