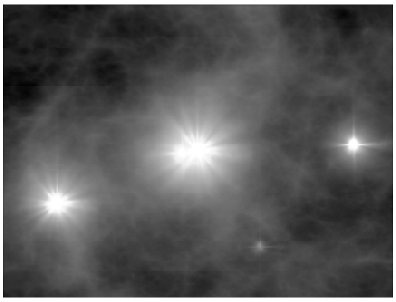
Galaxies AS7007, 2012
Lecture 8: The High-Redshift Universe



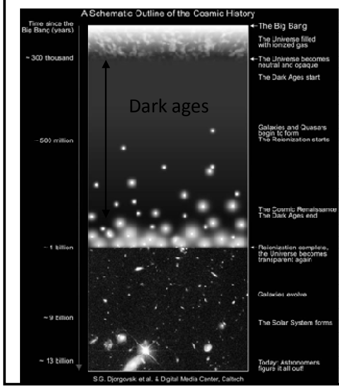
Outline: Part I

- 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

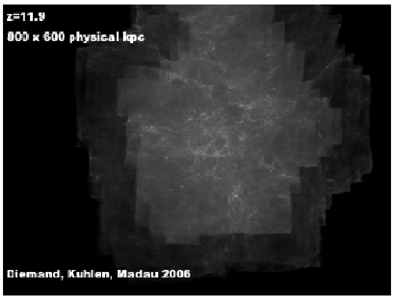


First stars
$z \approx$ 20-30
$t_{Univ} \approx$ 100-200 Myr

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

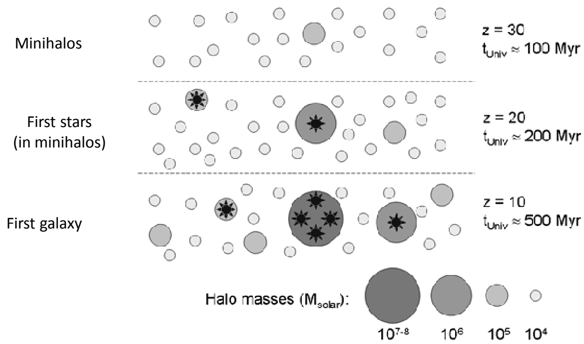
Current observational limit: HST and 8-10 m telescopes on the ground can detect light sources up to $z \approx 10$

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)

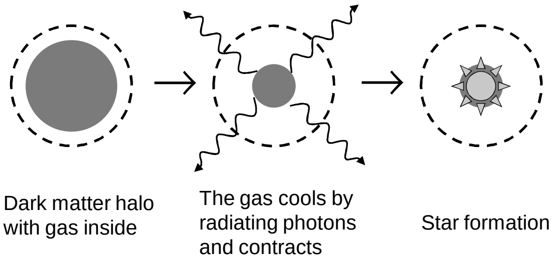
Structure formation



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 $z \approx 20$

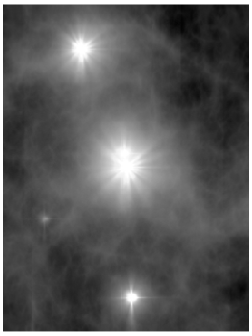
Star formation in dark matter halos



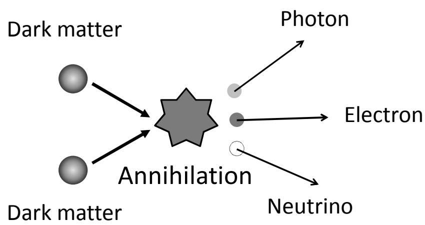
Problem: Low metallicity at high redshifts →
Lack of efficient coolants

Population III stars

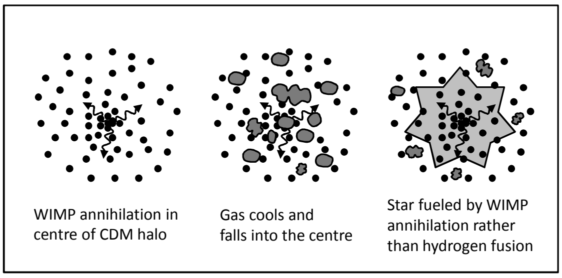
- These stars will be *very massive*, hot and short-lived.
- Mass range 10^1-10^2 Msolar (but predictions still shaky)
- The first ones are expected in minihalos – prior to the formation of the first galaxies.
- Feedback → *Only a few stars (maybe just one) per minihalo*



Recap: Dark matter annihilation

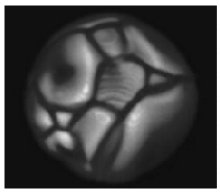


Dark stars



Dark star properties

- Conventional Pop III stars
  - Teff ~ 50 000-100 000 K
  - M ~ 10^1-10^2 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

Sizes I

The Sun

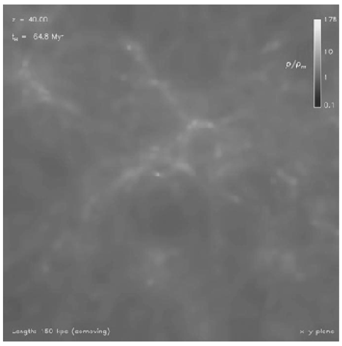
Vanilla population III star

Sizes 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)

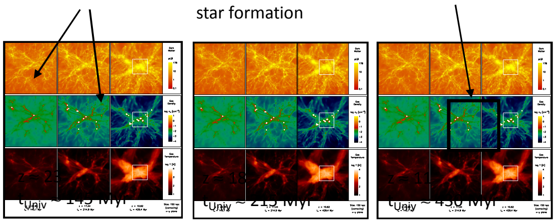
Greif et al. 08

Star formation inside and outside the first galaxies

Star formation in minihalos

Minihalo mergers and further star formation

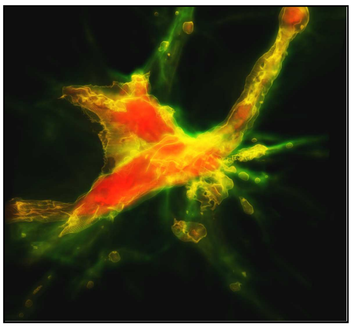
Object qualifies as a *galaxy*



Greif et al. 08

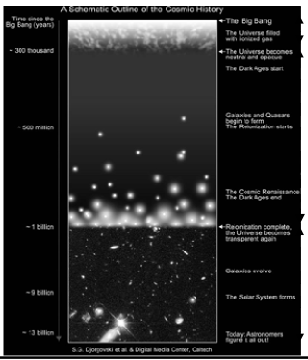
Gas density shapshots

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



Greif et al. 08

Reionization



<u>Intergalactic medium</u>

Ionized

Neutral

CMBR (WMAP) $\rightarrow z_{reion} \approx 11$
Lyα absorption in quasars $\rightarrow z_{reion} \approx 6$

Reionized

What caused reionization?

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

The current observational frontier

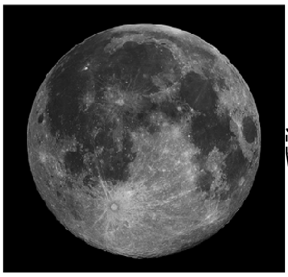
- Spectroscopic record:
  – Lyman-α detected from a galaxy at $z \approx 8.6$ (Lehnert et al. 2010) using the ESO Very Large Tele
- Photometric record:
  – A galaxy at $z \approx 10$ (Bouwens et al. 2011) detected in ultra deep Hubble Space Telescope imaging data

Part II: How to find and study high-redshift galaxies

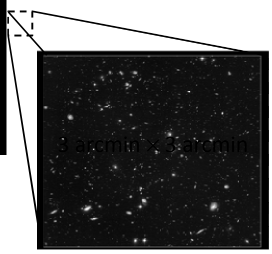
<u>Imaging strategies</u>

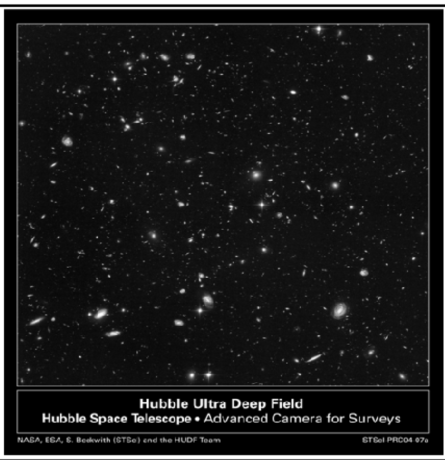
- Deep field-style observations
  - Very long exposures of single patch (devoid of bright foreground objects) in the sky
- Cluster-lensing observations
  - Hunt for gravitationally lensed background objects in relatively short exposures (few hours per filter) of a low-z galaxy cluster

The Hubble Ultra Deep Field



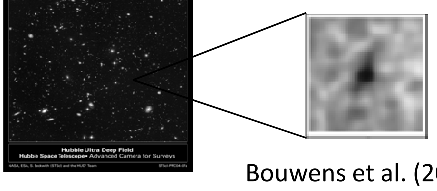
to 100 h exposures per filter





The most distant galaxy so far

2.4 arcsec x 2.4 arcsec

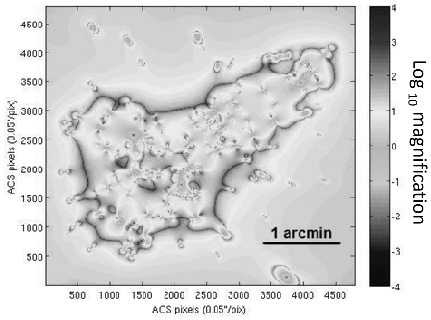


Bouwens et al. (2010)
$z \approx 10$ candidate

Cluster lensing I

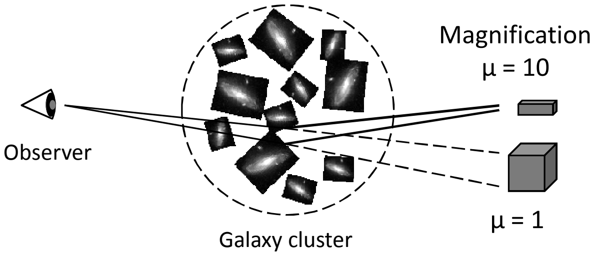
Galaxy cluster at z≈0.5

Cluster lensing II



Magnification map

Pros and Cons of Cluster Lensing



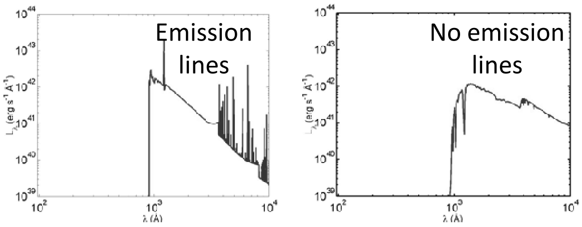
+ Background sources appear brighter by a factor μ
 - The volume probed becomes smaller by a factor μ
Bottom line: Lensed survey fields can be superior for sources that are *very faint*, *not too rare* and *not too highly clustered*

Selecting high-z galaxy candidates

Two techniques:

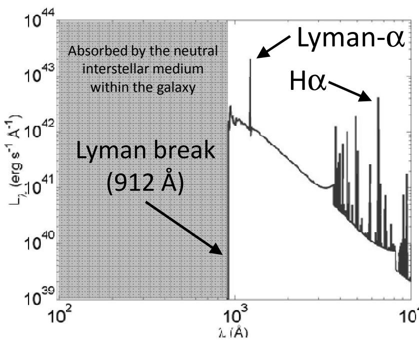
- Dropout selection
  - Crude redshift estimator (Δz≈1.0)
  - But works well for all high-z, star-forming galaxies
- Lyman-alpha surveys
  - High-precision redshift estimation (Δz≈0.1)
  - But doesn't work well at z>6
  - And not all galaxies are Lyα-emitters

The UV/optical spectra of galaxies I

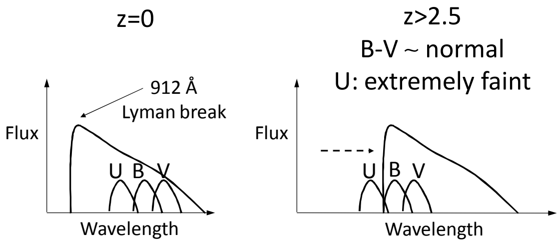


Young galaxy   Old galaxy

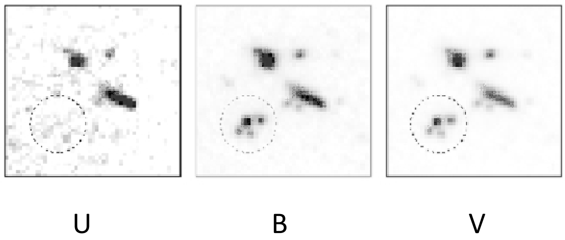
The UV/optical spectra of galaxies



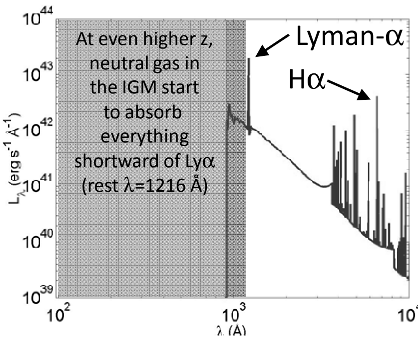
Drop-out techniques: Lyman-Break Galaxies



Drop-out techniques: Lyman-Break Galaxies

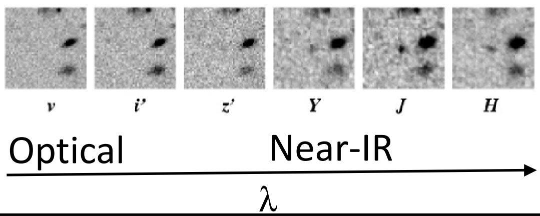


Reionization-epoch galaxies

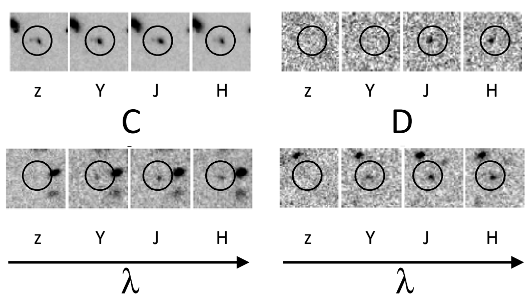


Drop-out techniques: z>6 objects

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

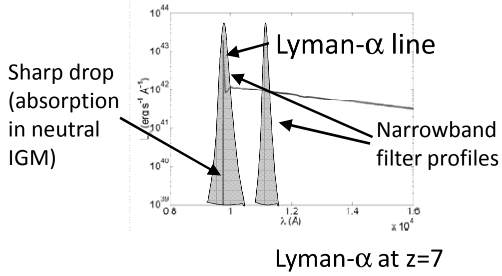


Intermission: Which of these drop-out candidates is likely to have the highest redshift?



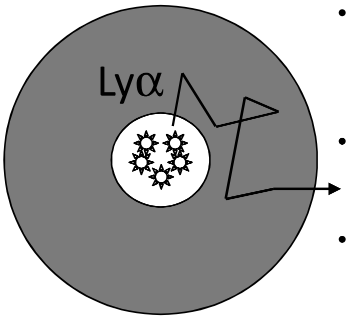
Lyman-alpha surveys

- 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)



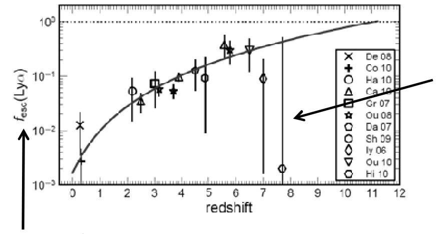
Lyman-α at z=7

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



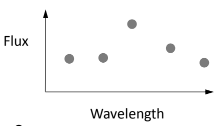
Abrupt drop → Lyα not good way to find z>6 galaxies (but may be good way to probe reionization)

Fraction of Lyα photons reaching the observer

Hayes et al. 11

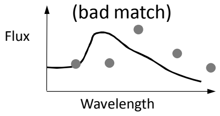
Photometric redshifts

- 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)

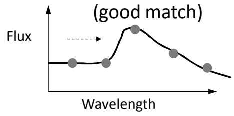


Measured photometrical data points

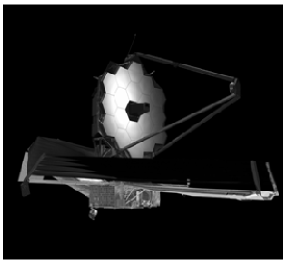
z=0 template spectrum (bad match)



Redshifted template spectrum (good match)



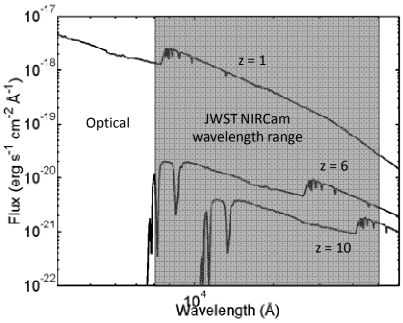
Future prospects: JWST



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

Why infrared?

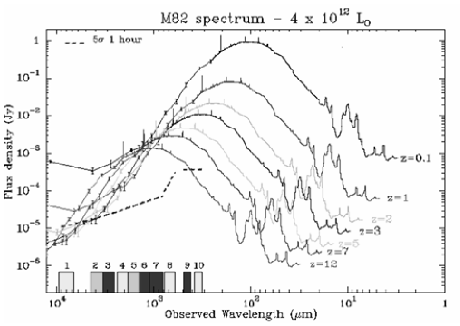


Zackrisson et al. (2001) model

Future prospects: ALMA

Atacama Large Millimeter/ submillimeter Array (ALMA): An array of seventy 12-m antennas operating @ 200-10000 μm (sub-mm)

To be completed by by ESO / NRAO / NAOJ in 2012

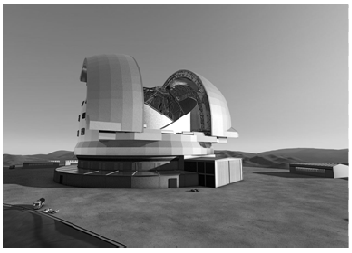


ALMA receivers

De Breuck 05

Dust continuum flux drops slowly with z (if no source evolution). Also useful up to z≈8: [CII]158 μm line

Future prospects: E-ELT



39 m European Extremely Large Telescope (E-ELT) estimated to be completetd in early 2020s.