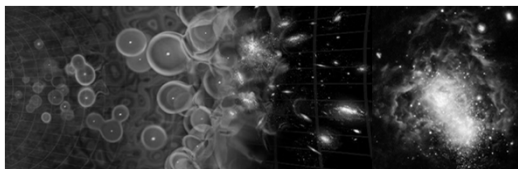# Physics of Galaxies, 2015
10 credits
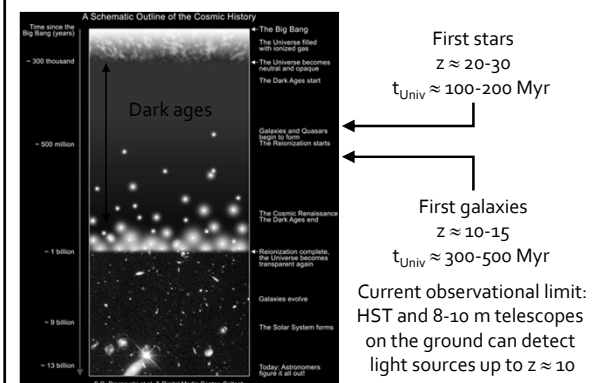### Lecture 8: The High-Redshift Universe

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Outline: Part I

- **The first stars and galaxies**
  - End of the dark ages
  - Pop III stars
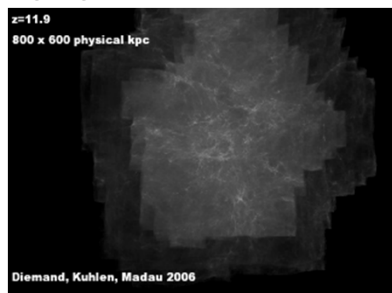 - Dark stars
  - First galaxies

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 ≈ 20-30
t_{Univ} ≈ 100-200 Myr

First galaxies
z ≈ 10-15
t_{Univ} ≈ 300-500 Myr

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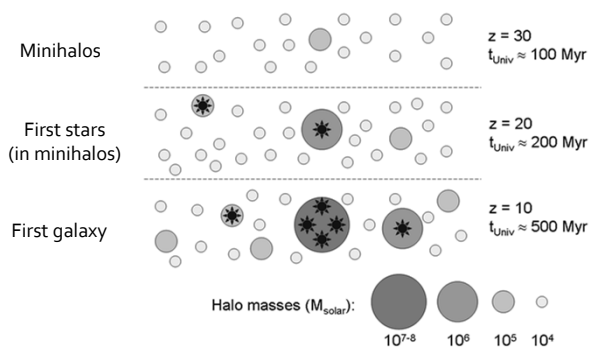HST and 8-10 m telescopes
on the ground can detect
light sources up to z ≈ 10

Merging cold dark matter halos

Formation of a ~10^{12} M_{solar} dark matter halo
Simulation runs from z ≈ 12 to 0 (t_{Univ} ≈ 0.25 to 13.7 Gyr)

Structure formation

Minihalos — z = 30, t_{Univ} ≈ 100 Myr

First stars (in minihalos) — z = 20, t_{Univ} ≈ 200 Myr

First galaxy — z = 10, t_{Univ} ≈ 500 Myr

Halo masses (M_{solar}): 10^{7-8} 10^6 10^5 10^4

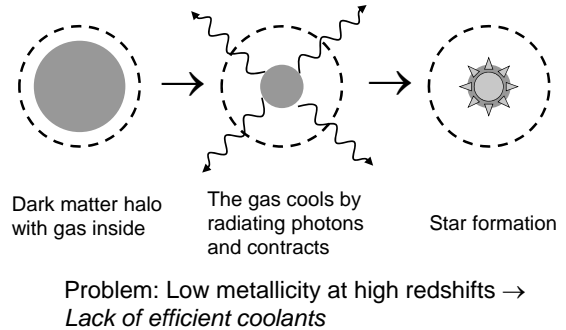## Population I, II and III

- 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

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
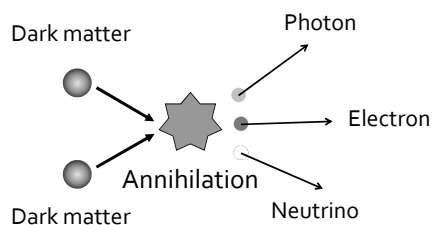
Population III stars

- 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.
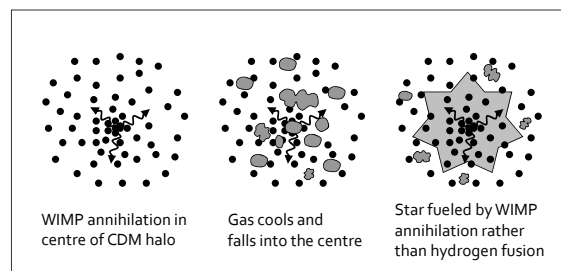- Feedback → *Only a few stars (maybe just one) per minihalo*

## Normal star ≈ hydrogen bomb

Dark matter annihilation

Dark matter

Photon

Electron

Annihilation

Dark matter

Neutrino

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 ~ 50 000-100 000 K
  - M ~ 10^1-10^3 Msolar
  - Lifetime τ ~ 10^6-10^7 yr
- Pop III dark stars
  - Teff ≈ 4000-50000 K   Cooler!
  - M ~ 10^2-10^7 Msolar   More massive???
  - Lifetime τ ~ 10^6-10^{10} yr More long-lived???
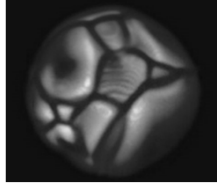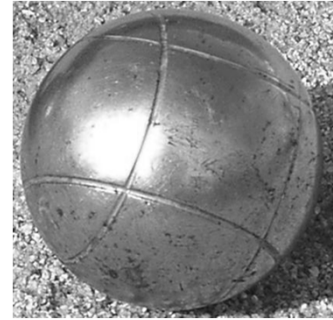
Problem: Still no consensus on likely masses or life times of dark stars

The sizes of primordial stars I

The Sun

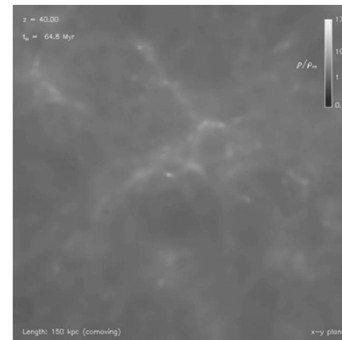Vanilla population III star

The sizes of primordial stars II

The Sun

Supermassive dark star
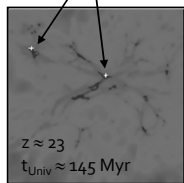
Formation of the first galaxies

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

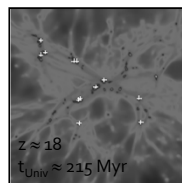Simulation runs from z ≈ 40 to 11 (t_{Univ} ≈ 65 to 430 Myr)

Greif et al. 08

Star formation inside and outside the first galaxies

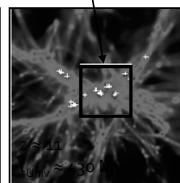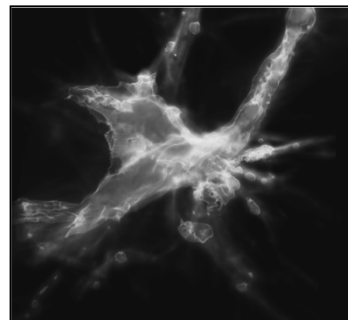Star formation in minihalos

Minihalo mergers and further star formation
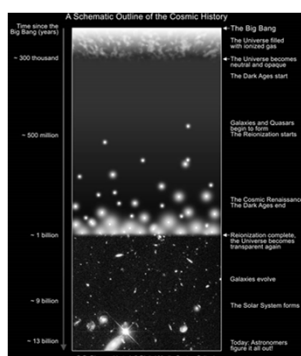
Object qualifies as a *galaxy*

z ≈ 23
t_{Univ} ≈ 145 Myr

z ≈ 18
t_{Univ} ≈ 215 Myr

Greif et al. 08

Gas density shapshots

A galaxy is born (at z ≈ 10)

Greif et al. 08

Reionization

A Schematic Outline of the Cosmic History

Time since the Big Bang (years)

~ 300 thousand

~ 500 million

~ 1 billion

~ 9 billion

~ 13 billion

The Big Bang
The Universe filled with ionized gas
The Universe becomes neutral and opaque
The Dark Ages start

Galaxies and Quasars begin to form
The Reionization starts

The Cosmic Renaissance
The Dark Ages end

Reionization complete, the Universe becomes transparent again

Galaxies evolve

The Solar System forms

Today. Astronomers figure it all out!

S.G. Djorgovski et al. & Digital Media Center, Caltech

Intergalactic medium

Ionized

Neutral

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

Reionized
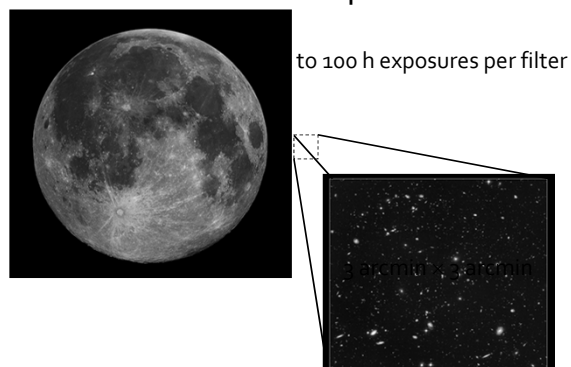
What caused reionization?

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

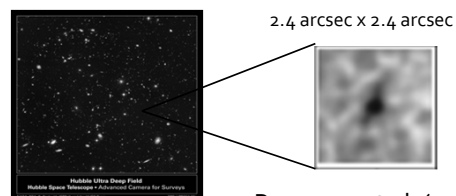## How to find and study high-redshift galaxies

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
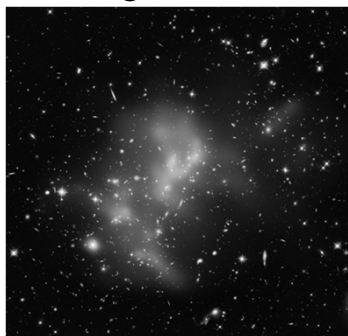
The Hubble Ultra Deep Field

to 100 h exposures per filter

3 arcmin x 3 arcmin

Hubble Ultra Deep Field
Hubble Space Telescope • Advanced Camera for Surveys
NASA, ESA, S. Beckwith (STScI) and the HUDF Team
STScI-PRC04-07a

Example of one of the most distant galaxy candidates so far

2.4 arcsec x 2.4 arcsec

Hubble Ultra Deep Field
Hubble Space Telescope • Advanced Camera for Surveys
NASA, ESA, S. Beckwith (STScI) and the HUDF Team
STScI-PRC04-07a
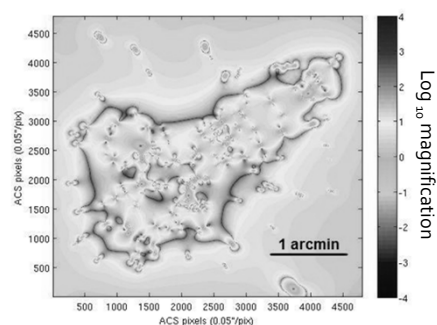
Bouwens et al. (2010)
z ≈ 10 candidate

Cluster lensing I

Galaxy cluster at z≈0.5

Cluster lensing II

Magnification map

Pros and Cons of Cluster Lensing

Magnification
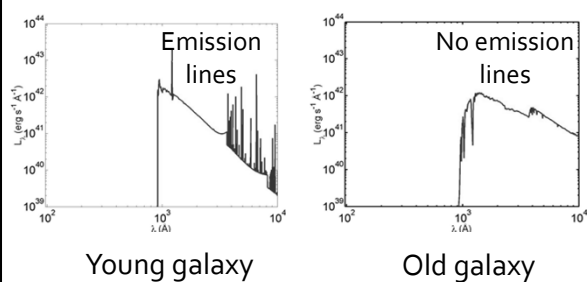
μ = 10

Observer

Galaxy cluster

μ = 1
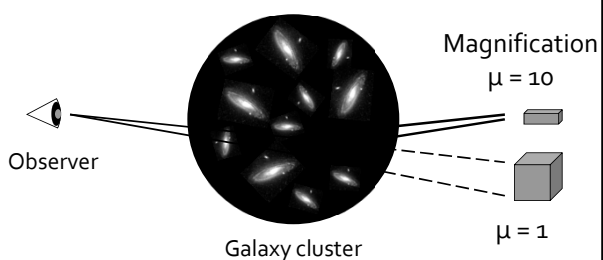
+ Background sources appear brighter by a factor μ

- 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*
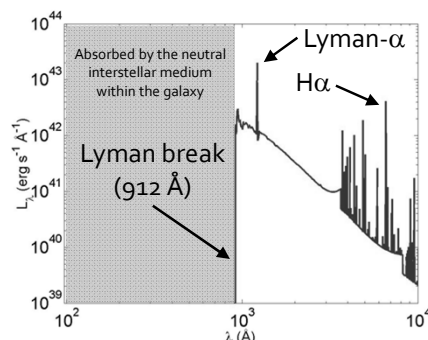
Selecting high-z galaxy candidates

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
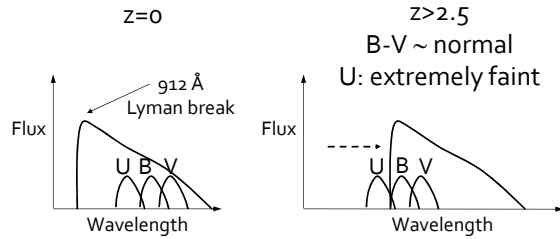 - And not all galaxies are Lyα-emitters

The UV/optical spectra of galaxies I

Emission lines
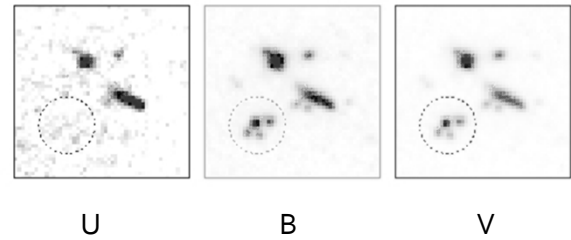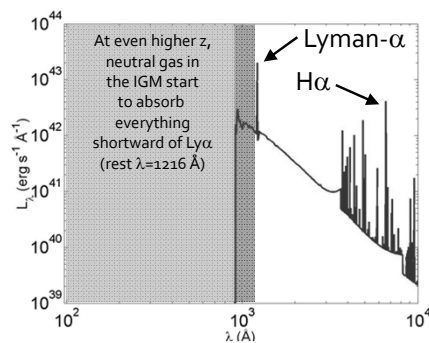
No emission lines

Young galaxy   Old galaxy

The UV/optical spectra of galaxies

Absorbed by the neutral interstellar medium within the galaxy

Lyman-α

Hα

Lyman break (912 Å)

Drop-out techniques: Lyman-Break Galaxies

z=0

z>2.5
B-V ~ normal
U: extremely faint

912 Å
Lyman break

Flux

U B V

Wavelength

Flux

U B V

Wavelength

Drop-out techniques: Lyman-Break Galaxies

U   B   V

Reionization-epoch galaxies

At even higher z, neutral gas in the IGM start to absorb everything shortward of Lyα (rest λ=1216 Å)
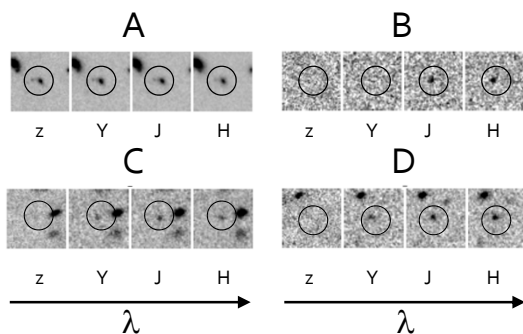
Lyman-α

Hα

L_λ (erg s^{-1} Å^{-1})

λ (Å)

Drop-out techniques: z>6 objects

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

v   i'   z'   Y   J   H

Optical   Near-IR

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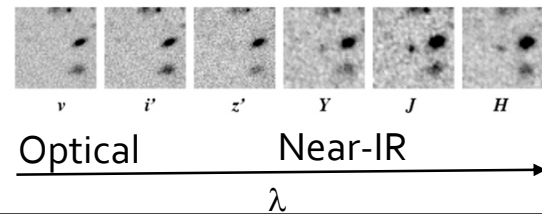
Intermission:
Which of these drop-out candidates is likely to have the highest redshift?

A

z   Y   J   H

B

z   Y   J   H

C

z   Y   J   H
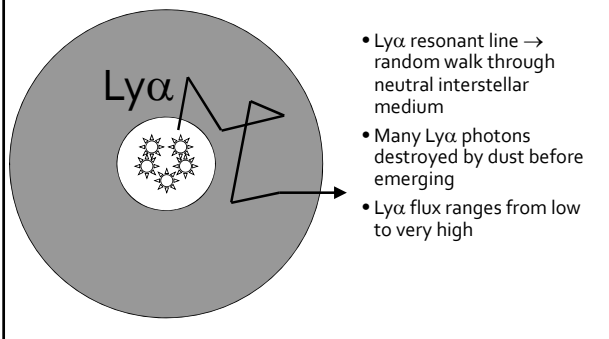
D
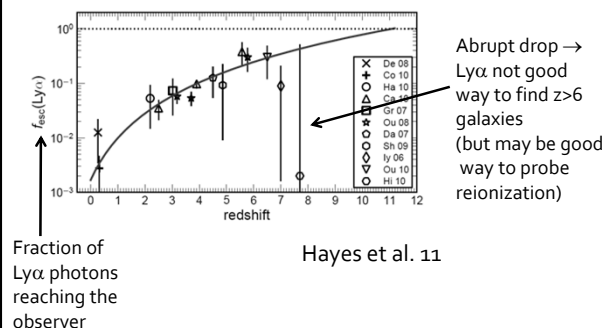

z   Y   J   H

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

L_λ (erg s^{-1} Å^{-1})

λ (Å)   x 10^4

Lyman-α at z=7
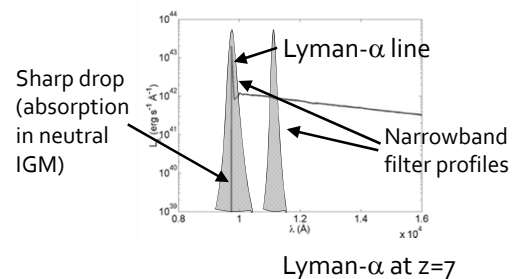
Problem I: Lyman-α notoriously difficult to predict

Lyα

- 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

Flux

Wavelength

z=0 template spectrum (bad match)

Flux

Wavelength

Redshifted template spectrum (good match)

Flux

Wavelength
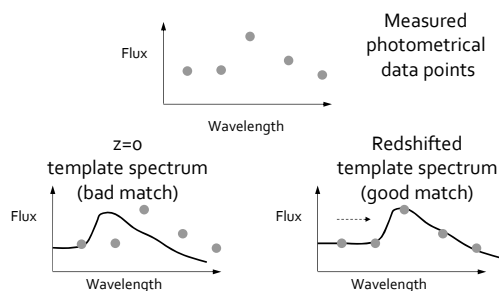
## New telescope for high-z studies: ALMA

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

M82 spectrum – 4 x 10^{12} L$_\odot$

ALMA receivers

De Breuck 05
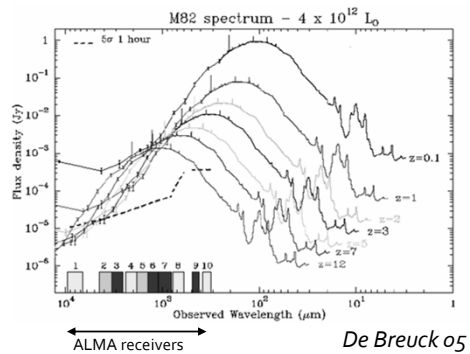
Dust continuum flux drops slowly with z (if no source evolution).
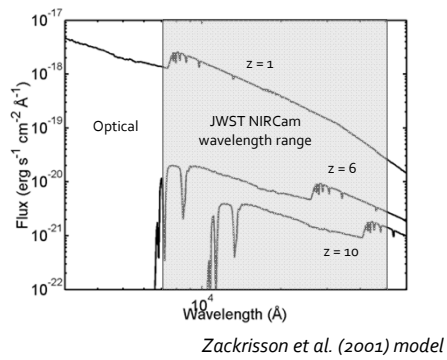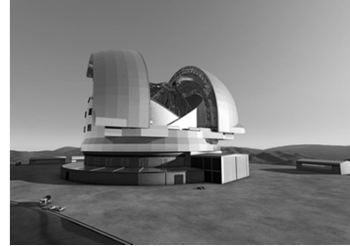
Future prospects: JWST
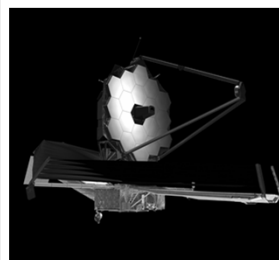
James Webb Space Telescope *'The first light machine'* To be launched by NASA / ESA / CSA in 2018

6.5 m mirror
Observations @ 0.6-29 µm
Useful for:
Galaxies up to z ≈ 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.