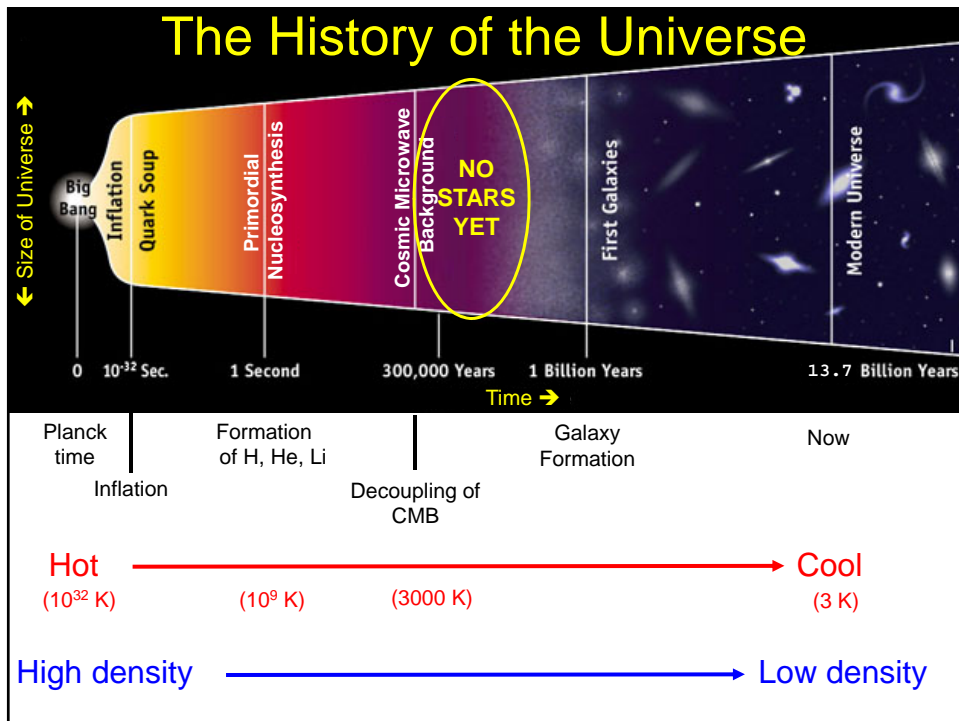


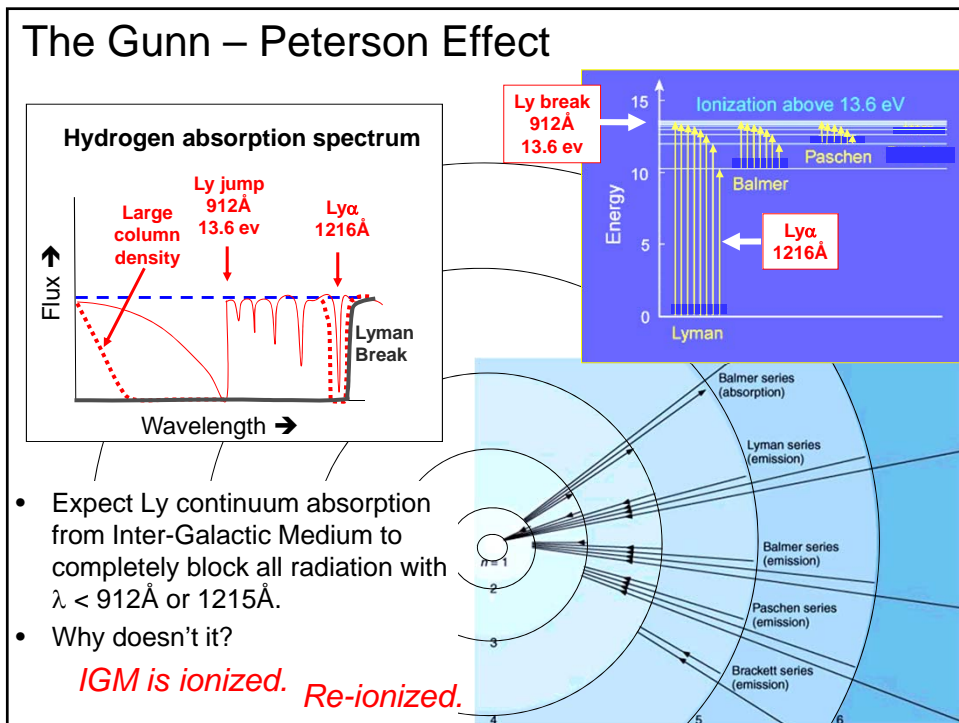
When did galaxy formation occur?

Ned Wright's
Cosmology
Calculator

Structure	Redshift	Age of U. (Gyr)
Density fluctuations in CMB	$[z_{\text{dec}}]_{\text{WMAP}} = 1089$	0.00018
Spheroids of galaxies	$z \sim 20$	0.18
The first engines of active galactic nuclei	$z \gtrsim 10$	≤ 0.48
The intergalactic medium	$z \sim 10$	0.48
Dark halos of galaxies	$z \sim 5$	1.20
The first 10% of heavy elements	$z \gtrsim 3$	≤ 2.19
Rich clusters of galaxies	$z \sim 2$	≤ 3.34
Thin disks of spiral galaxies	$z \sim 1$	5.93
Superclusters, walls, and voids	$z \sim 1$	5.93

TABLE 30.3 Redshifts for Structure Formation. Approximate redshifts at the time of the formation of various structures. (Adapted from Peebles, *Principles of Physical Cosmology*, Princeton University Press, Princeton, NJ, 1993.)

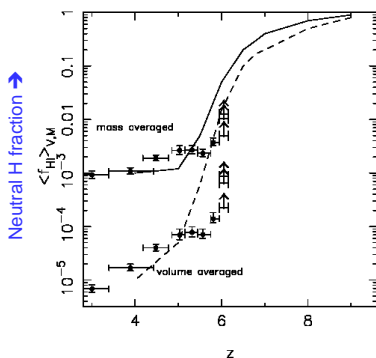




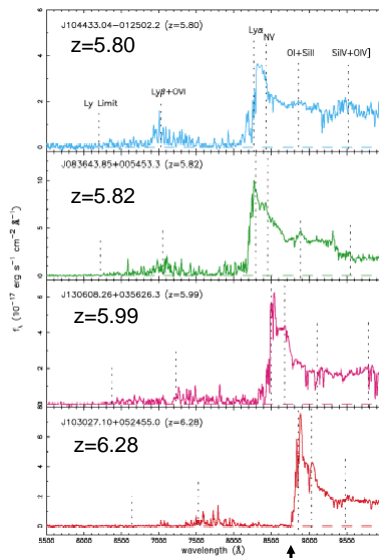
Re-ionization = end of Dark Ages

When did re-ionization occur?

- We see QSOs at $z \sim 6$ with Gunn-Peterson absorption.

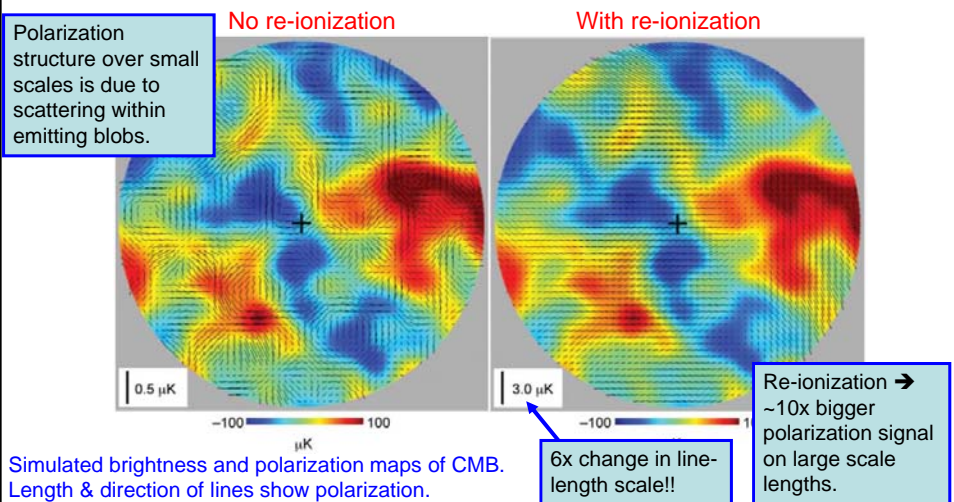
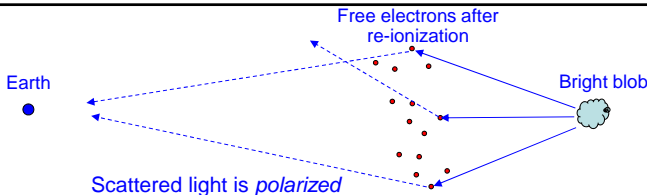


- But WMAP finds $z = 10.5 \pm 1.2$ (450 Myr) for re-ionization
 - From polarization of CMB.
- patchy re-ionization?



Continuum disappears at $\text{Ly}\alpha$ (1215Å)

CMB Polarization due to electron scattering by re-ionized gas.



Simulated brightness and polarization maps of CMB. Length & direction of lines show polarization.

Searching directly for patchy reionization:

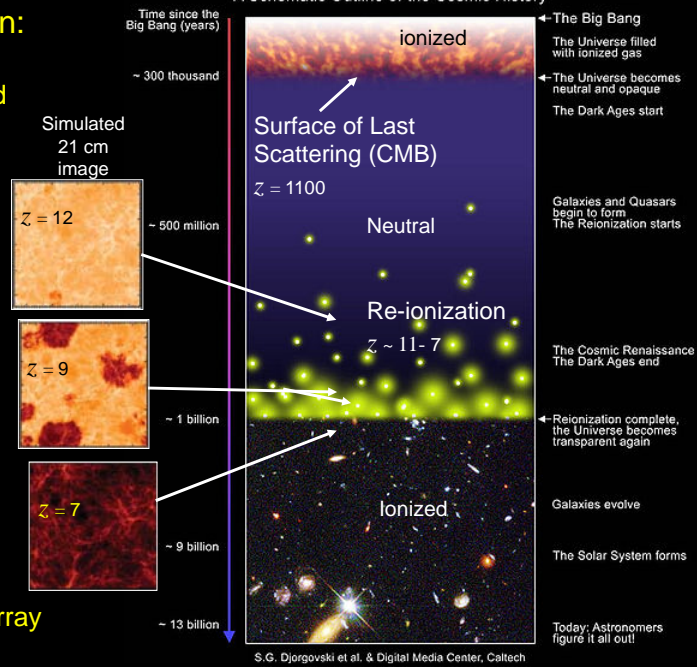
- 21 cm line produced in H I regions
- not absorbed

Low Frequency Radio Telescopes:

- $\lambda \sim 2\text{m}$
- LOFAR
 - Netherlands
 - $6 < z < 11$
- Murchison Widefield Array
 - Australia
- Square Kilometer Array

What is the Reionization Era?

A Schematic Outline of the Cosmic History

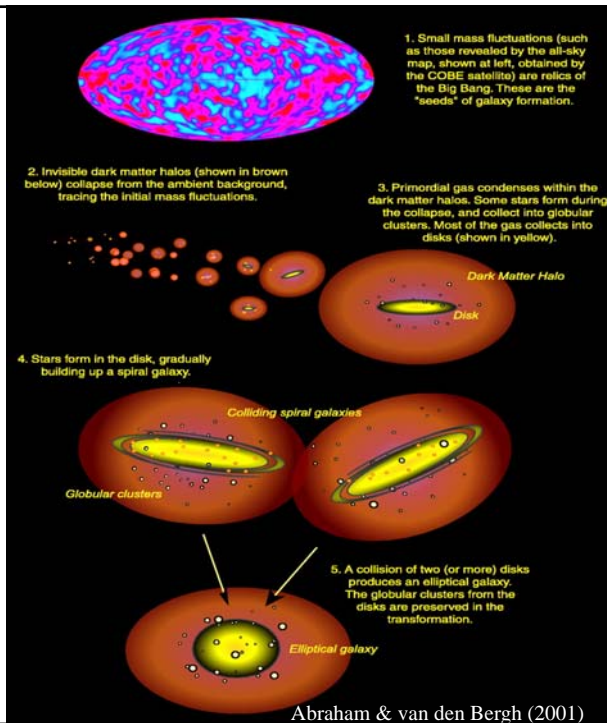


How did galaxy formation occur?

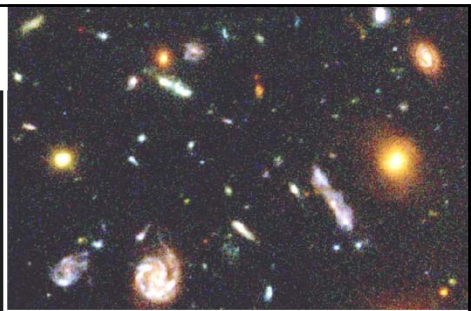
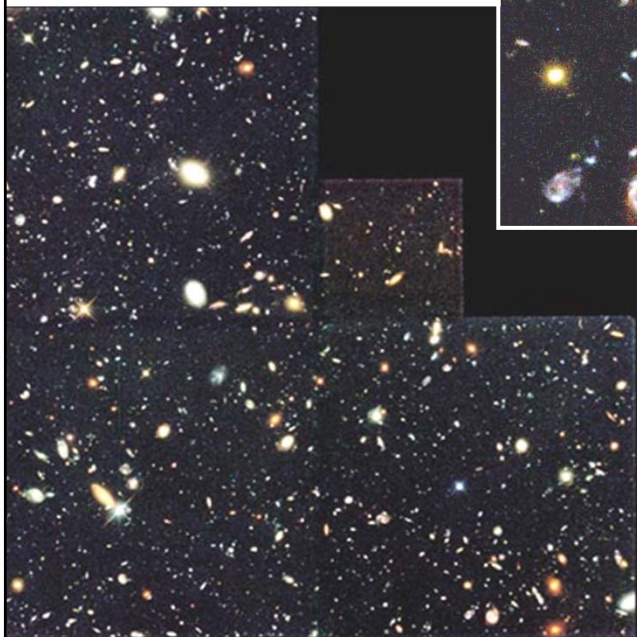
Prediction is:

Λ CDM \rightarrow bottom up
smaller \rightarrow larger

Need to test this!



The Hubble Deep Field



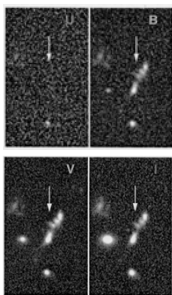
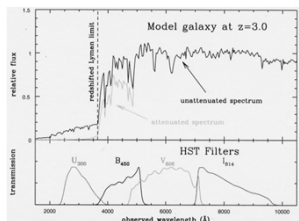
Northern field:

- 10 days, 150 orbits
 - WFC2 camera
 - 5.3 arcmin²
- 5000 objects
 - 20 stars
 - rest are galaxies

Southern field:

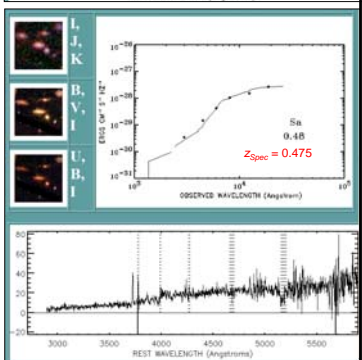
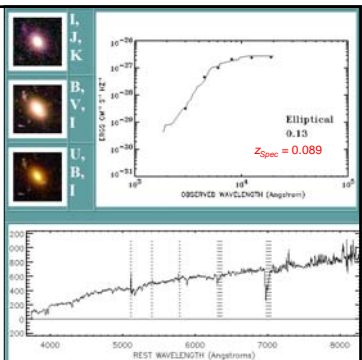
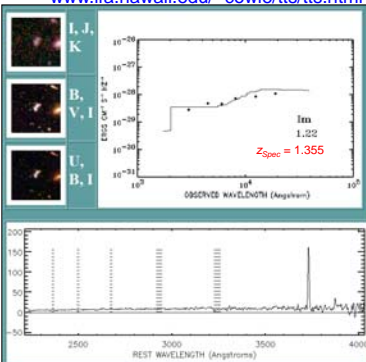
- 70 hours
- QSO in center

Photometric Redshifts



www.ifa.hawaii.edu/~cowie/ts/ts.html

- Pioneered by Loh & Spillar 1986
- Used with HDF and most deep surveys since.
- Reasonable redshift accuracy.
- Reasonable ability to classify galaxies.
- Only need a few broad-band images, not spectra.



Hubble Ultra Deep Field

Hubble Ultra Deep Field
HST ACS WFC
S. Beckwith (STScI)

Hubble Ultra Deep Field
HST NICMOS
R. Thompson (U. Arizona)

Advanced Camera for Surveys

- 3 x 3 arcmin²
- 11.3 days exposure.

NICMOS

- 2.4 x 2.4 arcmin²
- 4.5 days exposure

Hubble Ultra Deep Field Details
Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, S. Beckwith (STScI) and the HUDF Team

+ many other surveys... GOODS, Chandra, etc

From the HST PR dept:

Age of the Universe	Today: 14 Billion Years	9 Billion Years	5 Billion Years	2 Billion Years
Elliptical				
Spiral				

Each box is same size in proper distance units

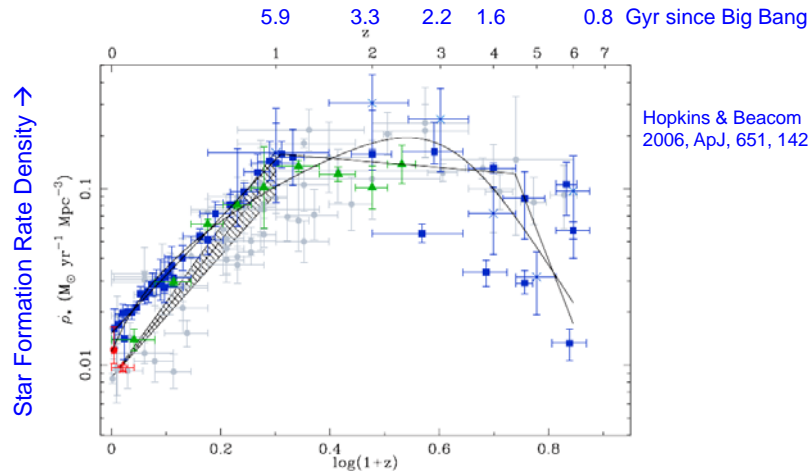
Galaxies: Snapshots in Time HST · WFC2

←Time

SPACETELESCOPE
SCIENCE
INSTITUTE

PR94-52c - Office of Public Outreach - December 6, 1994 - ZGL

Star formation rate as a function of time



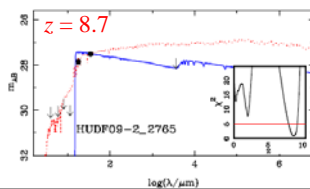
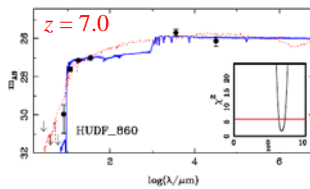
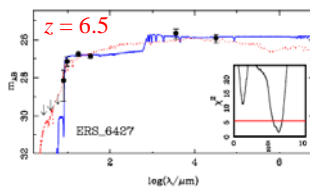
Measured from

- Blue light (O star continuum)
- H α emission (H II regions)

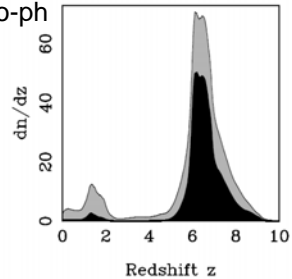
“Madau diagram”

A current example:

70 Ly-break galaxies with $6.0 < z < 8.7$



McLure et al. 2011 astro-ph arXiv:1102-4881



- Hubble Ultra Deep Field and ERS optical/IR imaging.
- Median stellar mass $\sim 2 \times 10^9 M_{\text{Sun}}$.
- looking for a connection between star-formation rate and total mass of stars in these galaxies.
 - None found.