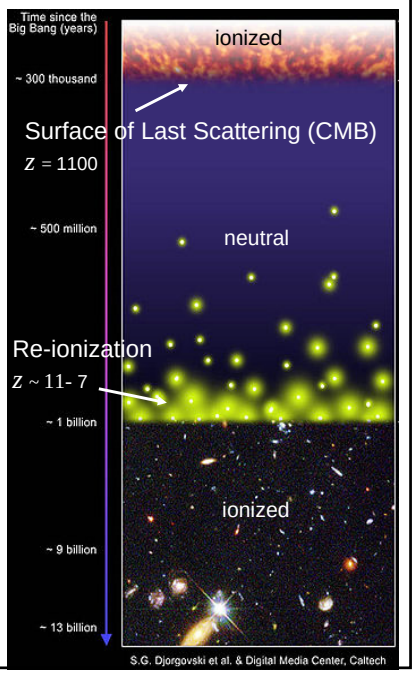
When did galaxy formation occur?

[CO Table 30.3]

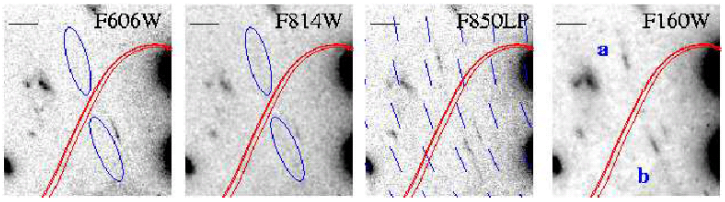
Structure	Age of U. (Gyr)	Redshift
Density fluctuations in CMB	0.00018	$z = 1089$
Spheroids of galaxies	0.18	$z \sim 20$
The first engines of active galactic nuclei		$z \geq 10$
The intergalactic medium	0.48	$z \sim 10$
Dark halos of galaxies	1.20	$z \sim 5$
The first 10% of heavy elements	≤ 2.19	$z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



How did galaxy formation occur?

ΛCDM ➔ bottom up
smaller ➔ larger

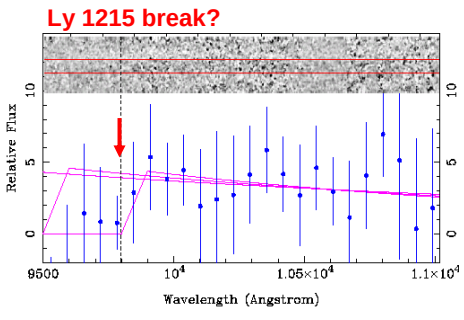
z = 7 galaxy ?

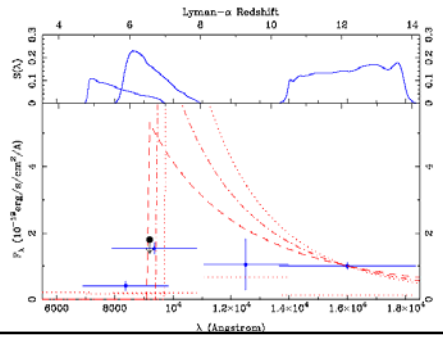


Gravitationally lensed galaxy observed at Keck by Ellis et al.

Figure 1: *WFPC2*-F606W, *WFPC2*-F814W, *ACS*-F850LP and NICMOS-F160W images of Abell 2218 of the new faint pair in the lensing cluster Abell 2218 (z=0.175). The signals redward of the *WFPC2*-F814W observation suggests a marked break occurs in the continuum signal at around 9600Å . Red lines correspond to the predicted location of the critical lines at z_s=5,6.5 and 7 (from bottom to top, the latter two being almost coincident). The scale bar at the top left of each image represents 2″. The predicted shear direction (thin blue lines) closely matches the orientation of the lensed images.

Ly 1215 break?





Z ~ 10 galaxies?

A KECK SURVEY FOR GRAVITATIONALLY-LENSED LYMAN α EMITTERS IN THE REDSHIFT RANGE 8.5<Z<10.4: NEW CONSTRAINTS ON THE CONTRIBUTION OF LOW LUMINOSITY SOURCES TO COSMIC REIONIZATION

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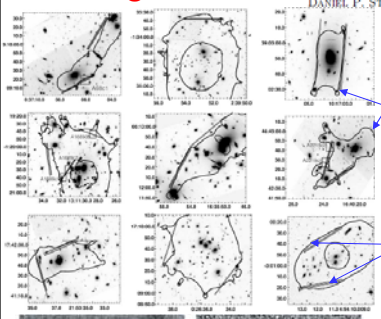
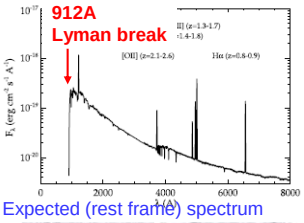
Draft version Ja

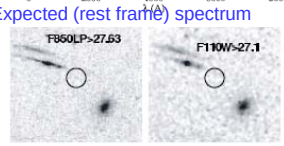


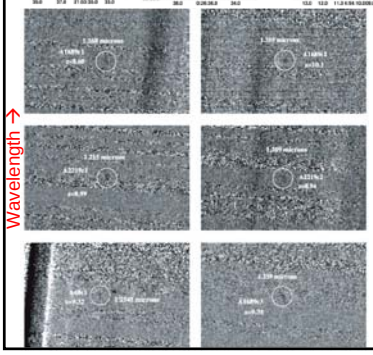
Grav. lensing critical curves

Keck NIRSPEC slit positions



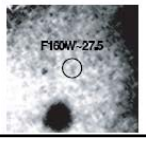
Expected (rest frame) spectrum





INFRARED SPECTA
6 possible Lyα emission lines (circled)
z ~ 8.5 – 10.4

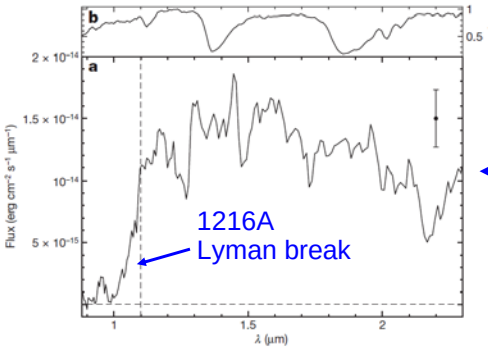
2 best bets are *z* ~ 10



HST broadband images show no continuum emission.

z = 8.1 Gamma Ray Burst

- Detected with Swift satellite.
- Core collapse supernova (massive star) – beamed jet.
- Follow up infrared spectrum with 3.6m telescope shows underlying galaxy.
- Universe 640 million yrs old.



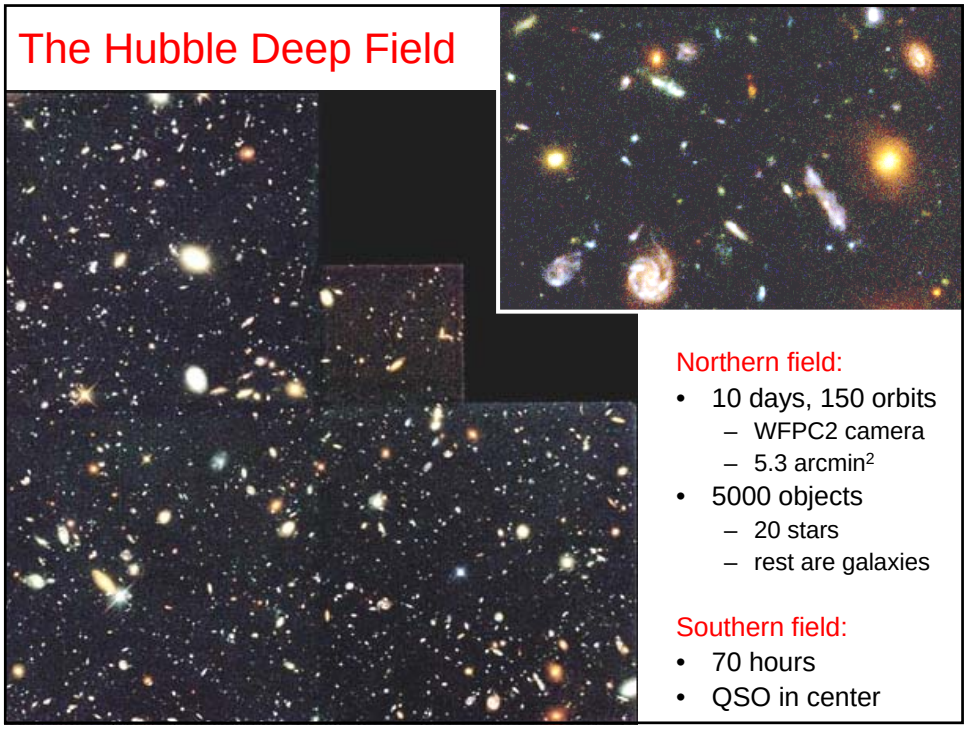
Atmospheric transmission

Near-IR spectrum

1216A
Lyman break

Salvaterra et al. 2009, Nature, 461, 1258

The Hubble Deep Field



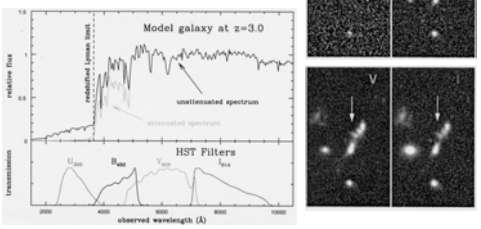
Northern field:

- 10 days, 150 orbits
  - WFPC2 camera
  - 5.3 arcmin^2
- 5000 objects
  - 20 stars
  - rest are galaxies

Southern field:

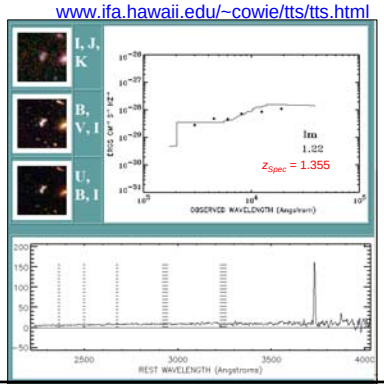
- 70 hours
- QSO in center

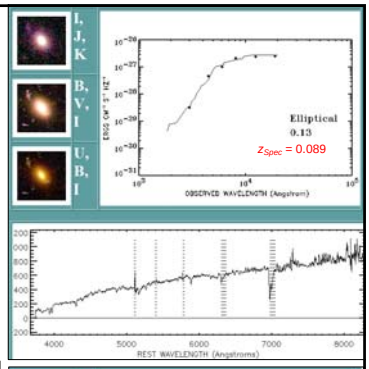
Photometric Redshifts

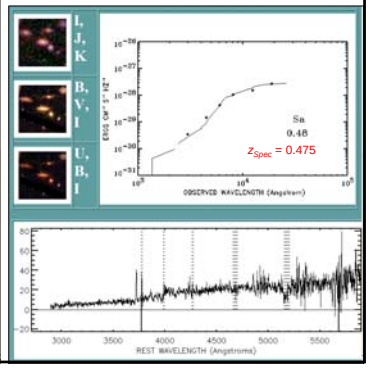


www.ifa.hawaii.edu/~cowie/tts/tts.html

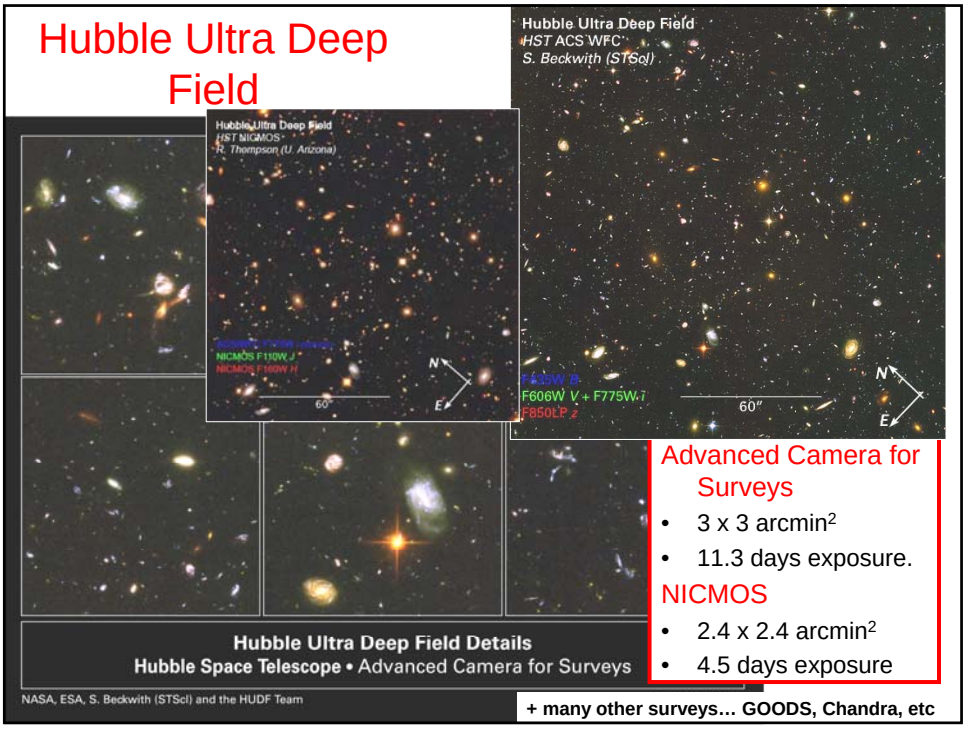
- Pioneered by Loh & Spillar 1986
- Used with HDF and most deep surveys since.
- Reasonable redshift accuracy.
- Reasonable ability to classify galaxies.
- Only need a few broad-band images, not spectra.







Hubble Ultra Deep Field



Advanced Camera for Surveys

- 3 x 3 arcmin^2
- 11.3 days exposure.

NICMOS

- 2.4 x 2.4 arcmin^2
- 4.5 days exposure

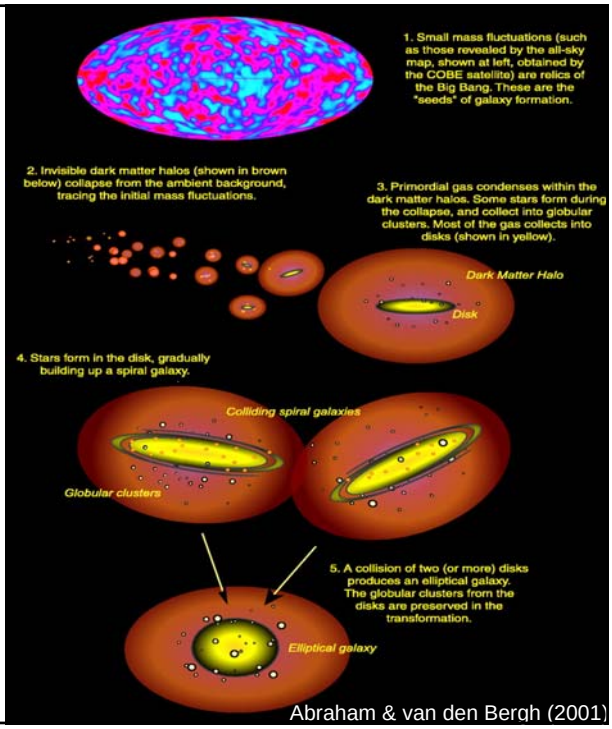
+ many other surveys… GOODS, Chandra, etc

Basic idea behind galaxy formation - objects start small and grow by merging

Do galaxies form this way?

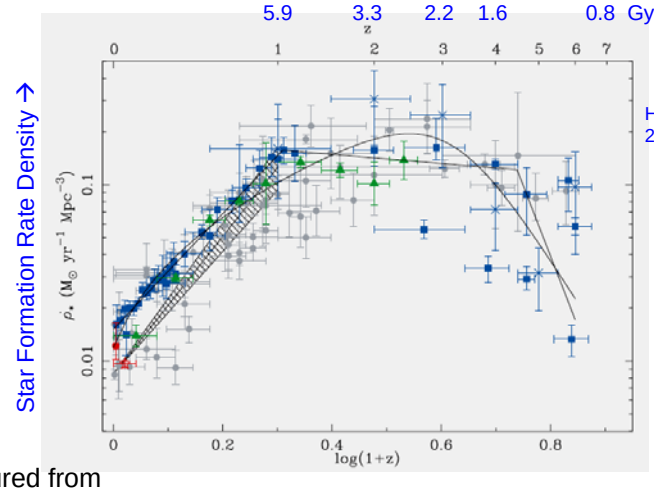
Does star formation occur before, during or after mass assembly?

When and how do Hubble Types form?



Abraham & van den Bergh (2001)

Star formation rate as a function of time



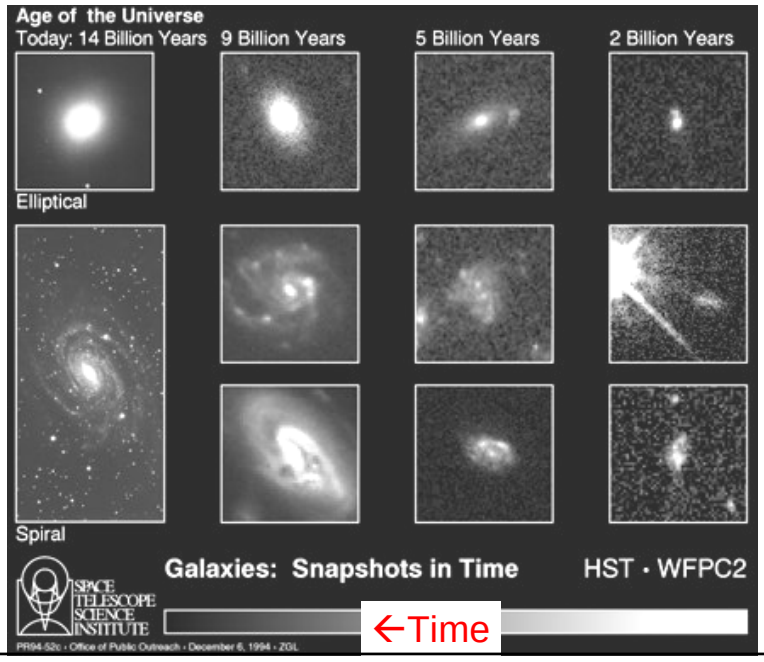
Hopkins & Beacom 2006, ApJ, 651, 142

Measured from

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

"Madau diagram"

From the HST PR dept:



Each box is same size in proper distance units