

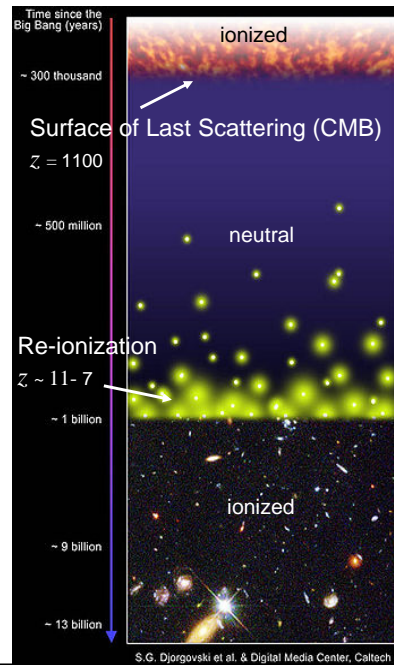
When did galaxy formation occur?

[CO Table 30.3]

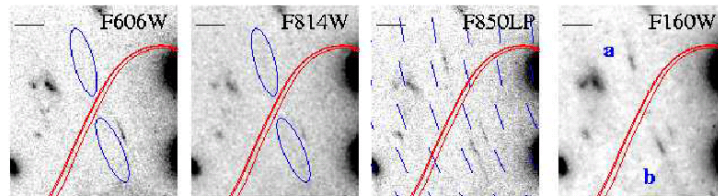
Structure	Age of U. (Gyr)	Redshift
Density fluctuations in CMB	0.00018	$z = 1089$
Spheroids of galaxies	0.18	$z \sim 20$
The first engines of active galactic nuclei		$z \geq 10$
The intergalactic medium	0.48	$z \sim 10$
Dark halos of galaxies	1.20	$z \sim 5$
The first 10% of heavy elements	≤ 2.19	$z \geq 3$
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?

Λ CDM \rightarrow bottom up
smaller \rightarrow larger



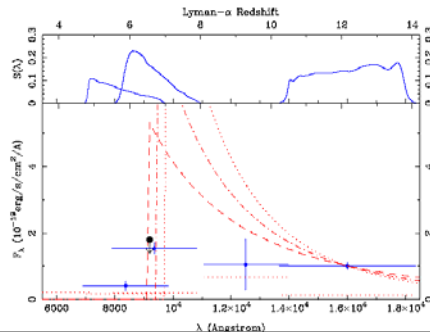
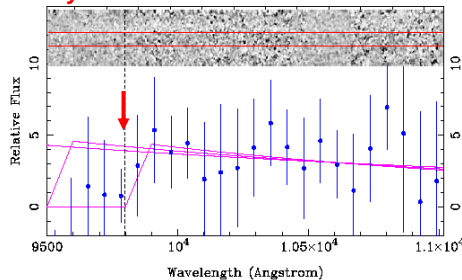
$z = 7$
galaxy
?

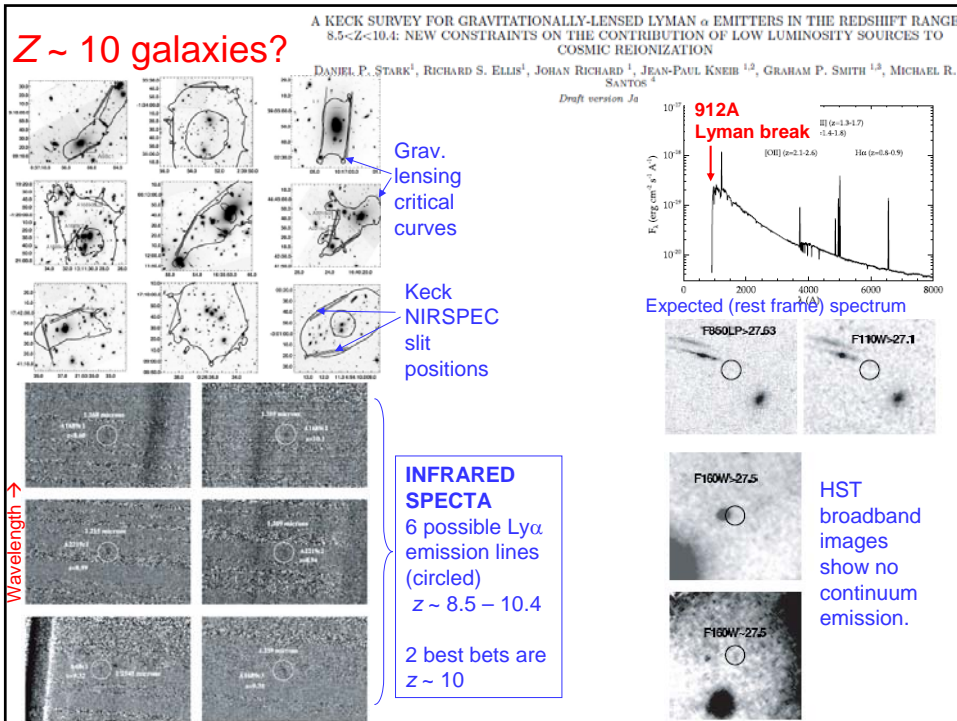


Gravitationally lensed galaxy observed at Keck by Ellis et al.

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 9600\AA . 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.

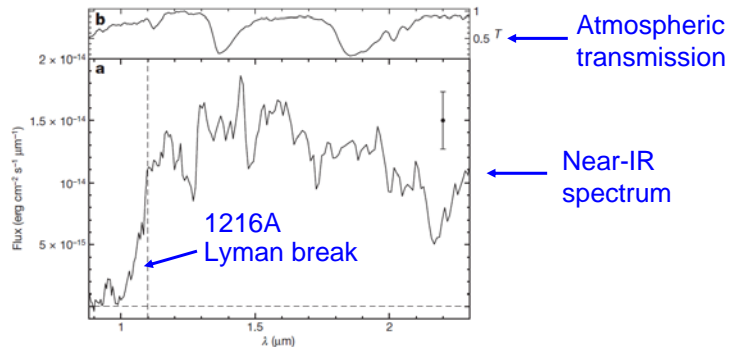
Ly 1215 break?





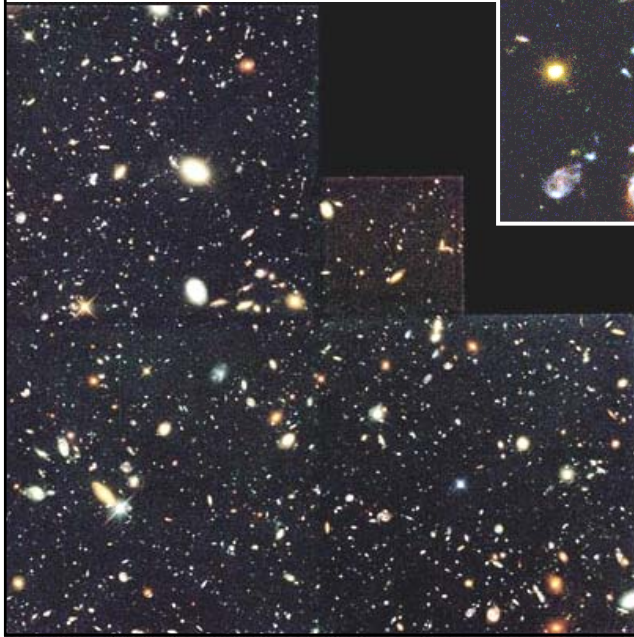
z = 8.1 Gamma Ray Burst

- 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.



Salvaterra et al. 2009, Nature, 461, 1258

The Hubble Deep Field



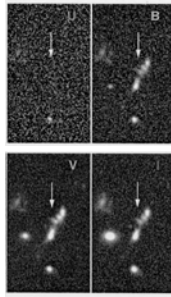
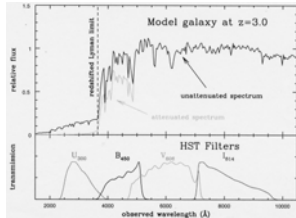
Northern field:

- 10 days, 150 orbits
 - WFPC2 camera
 - 5.3 arcmin²
- 5000 objects
 - 20 stars
 - rest are galaxies

Southern field:

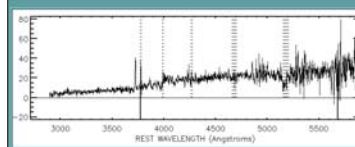
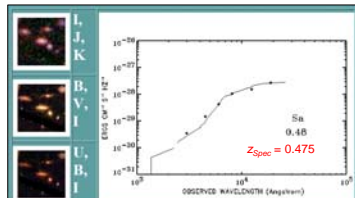
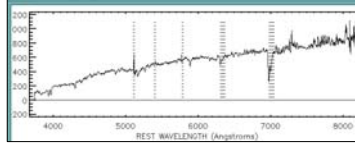
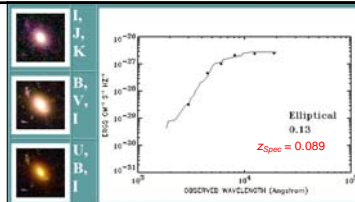
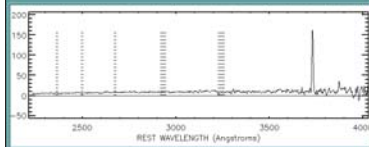
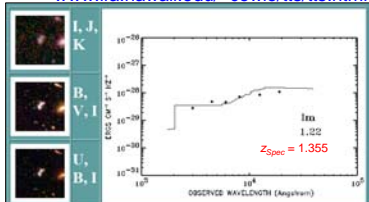
- 70 hours
- QSO in center

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 NICMOS
R. Thompson (U. Arizona)

Filters: F435W, F606W, F850LP, F814W, F555W, F775W, F731M, F732M, F733M, F734M, F735M, F736M, F737M, F738M, F739M, F740M, F741M, F742M, F743M, F744M, F745M, F746M, F747M, F748M, F749M, F750M, F751M, F752M, F753M, F754M, F755M, F756M, F757M, F758M, F759M, F760M, F761M, F762M, F763M, F764M, F765M, F766M, F767M, F768M, F769M, F770M, F771M, F772M, F773M, F774M, F775M, F776M, F777M, F778M, F779M, F780M, F781M, F782M, F783M, F784M, F785M, F786M, F787M, F788M, F789M, F790M, F791M, F792M, F793M, F794M, F795M, F796M, F797M, F798M, F799M, F800M, F801M, F802M, F803M, F804M, F805M, F806M, F807M, F808M, F809M, F810M, F811M, F812M, F813M, F814M, F815M, F816M, F817M, F818M, F819M, F820M, F821M, F822M, F823M, F824M, F825M, F826M, F827M, F828M, F829M, F830M, F831M, F832M, F833M, F834M, F835M, F836M, F837M, F838M, F839M, F840M, F841M, F842M, F843M, F844M, F845M, F846M, F847M, F848M, F849M, F850M, F851M, F852M, F853M, F854M, F855M, F856M, F857M, F858M, F859M, F860M, F861M, F862M, F863M, F864M, F865M, F866M, F867M, F868M, F869M, F870M, F871M, F872M, F873M, F874M, F875M, F876M, F877M, F878M, F879M, F880M, F881M, F882M, F883M, F884M, F885M, F886M, F887M, F888M, F889M, F890M, F891M, F892M, F893M, F894M, F895M, F896M, F897M, F898M, F899M, F900M, F901M, F902M, F903M, F904M, F905M, F906M, F907M, F908M, F909M, F910M, F911M, F912M, F913M, F914M, F915M, F916M, F917M, F918M, F919M, F920M, F921M, F922M, F923M, F924M, F925M, F926M, F927M, F928M, F929M, F930M, F931M, F932M, F933M, F934M, F935M, F936M, F937M, F938M, F939M, F940M, F941M, F942M, F943M, F944M, F945M, F946M, F947M, F948M, F949M, F950M, F951M, F952M, F953M, F954M, F955M, F956M, F957M, F958M, F959M, F960M, F961M, F962M, F963M, F964M, F965M, F966M, F967M, F968M, F969M, F970M, F971M, F972M, F973M, F974M, F975M, F976M, F977M, F978M, F979M, F980M, F981M, F982M, F983M, F984M, F985M, F986M, F987M, F988M, F989M, F990M, F991M, F992M, F993M, F994M, F995M, F996M, F997M, F998M, F999M, F1000M

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

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

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

Do galaxies form this way?

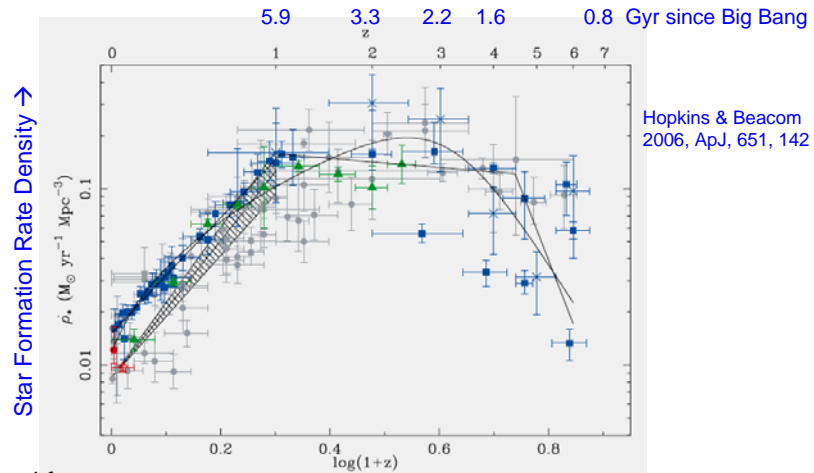
Does star formation occur before, during or after mass assembly?

When and how do Hubble Types form?

1. Small mass fluctuations (such as those revealed by the all-sky map, shown at left, obtained by the COBE satellite) are relics of the Big Bang. These are the "seeds" of galaxy formation.
2. Invisible dark matter halos (shown in brown below) collapse from the ambient background, tracing the initial mass fluctuations.
3. Primordial gas condenses within the dark matter halos. Some stars form during the collapse, and collect into globular clusters. Most of the gas collects into disks (shown in yellow).
4. Stars form in the disk, gradually building up a spiral galaxy.
5. A collision of two (or more) disks produces an elliptical galaxy. The globular clusters from the disks are preserved in the transformation.

Abraham & van den Bergh (2001)

Star formation rate as a function of time

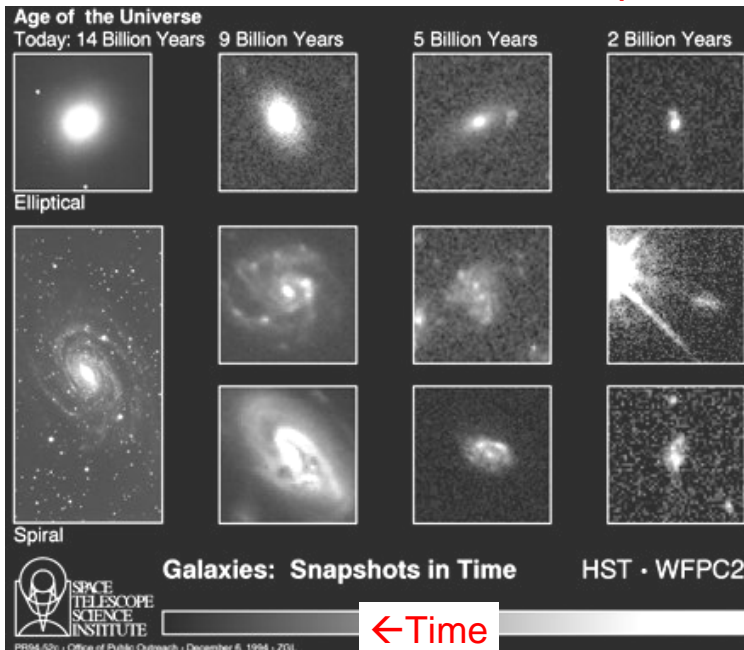


Measured from

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

“Madau diagram”

From the HST PR dept:



Each box is same size in proper distance units