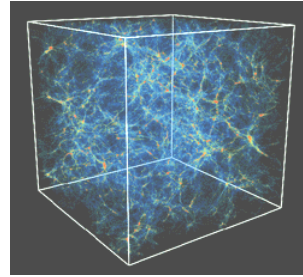
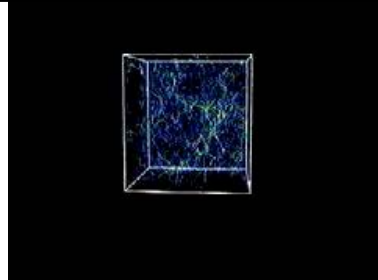
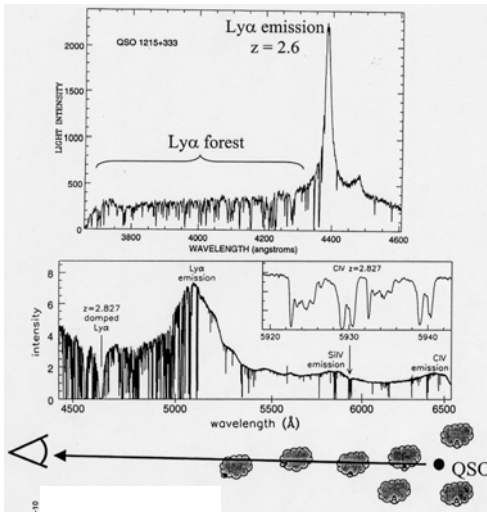


# The Ly $\alpha$ Forest Revisited



- It's the cosmic web.
- Contains most of the baryons at high redshift.
- Contains 30% of baryons at  $z = 0$ .

## 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	$z \gtrsim 10$	$\leq 0.48$
The intergalactic medium	$z \sim 10$	0.48
Dark halos of galaxies	$z \sim 5$	1.20
The first 10% of heavy elements	$z \gtrsim 3$	$\leq 2.19$
Rich clusters of galaxies	$z \sim 2$	$\leq 3.34$
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.)

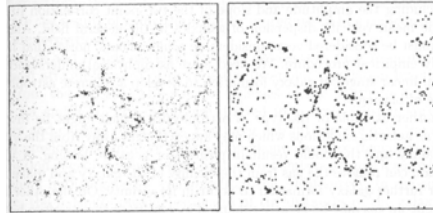
# Bias

- CDM simulations → accurate predictions of CDM structure.
- Problems describing baryon response.
  - Observations → preference for galaxies to form in denser regions.

$$\left(\frac{\delta\rho}{\rho}\right)_B = b \left(\frac{\delta\rho}{\rho}\right)_D \text{ in CDM simulation } \rightarrow$$

$$b^2 = \frac{\sigma_8^2(\text{galaxies})}{\sigma_8^2(\text{mass})} \text{ from observations,}$$

where  $\sigma_8$  = variance of mass distr. in  $8h^{-1}$  Mpc co-moving sphere.



Dark matter

Baryons (for  $b = 2.5$ )

- So arbitrary assumptions are needed to describe the observable galaxies.

## The Hubble Deep Field



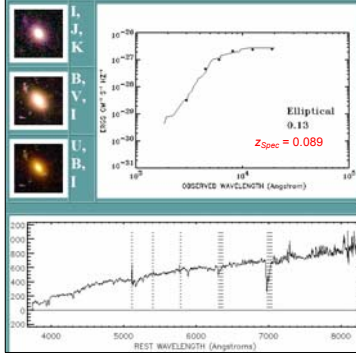
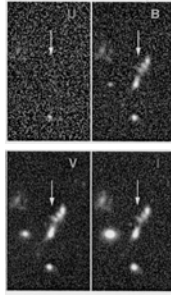
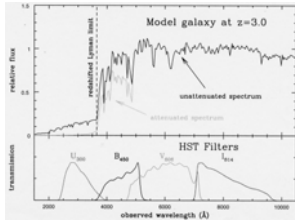
### Northern field:

- 10 days, 150 orbits
  - WFPC2 camera
  - 5.3 arcmin<sup>2</sup>
- 5000 objects
  - 20 stars
  - rest are galaxies

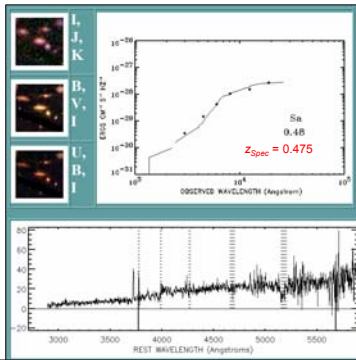
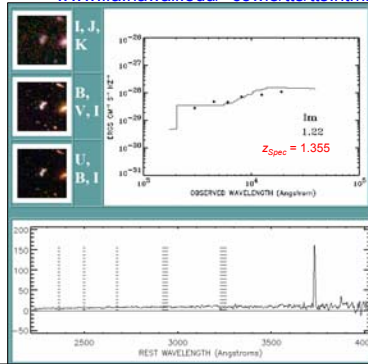
### Southern field:

- 70 hours
- QSO in center

# Photometric Redshifts

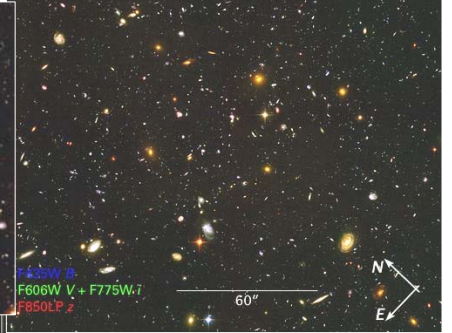
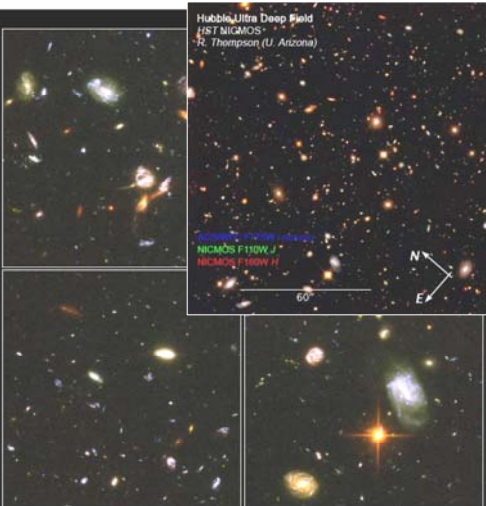


- Pioneered by Loh & Spillar 1986
- Used with HDF and most deep surveys since.
- Reasonable redshift accuracy.
- Reasonable ability to classify galaxies.
- Only need a few broad-band images, not spectra.



# Hubble Ultra Deep Field

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



## Advanced Camera for Surveys

- 3 x 3 arcmin<sup>2</sup>
- 11.3 days exposure.

## NICMOS

- 2.4 x 2.4 arcmin<sup>2</sup>
- 4.5 days exposure

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

## Other deep surveys:

- **Chandra Deep Fields**
  - North (Centered on HDF North)
  - South (New location; no QSO; but HUDF now centered here)
- **GOODS (Great Observatories Origins Deep Survey)**
  - Less deep survey, but over wider area
  - Incorporates HST, Chandra, Spitzer, XMM Newton + ground-based observations.
  - Fields centered at:
    - Hubble Deep Field North (same as CDF North)
    - Chandra Deep Field South (same as HUDF)

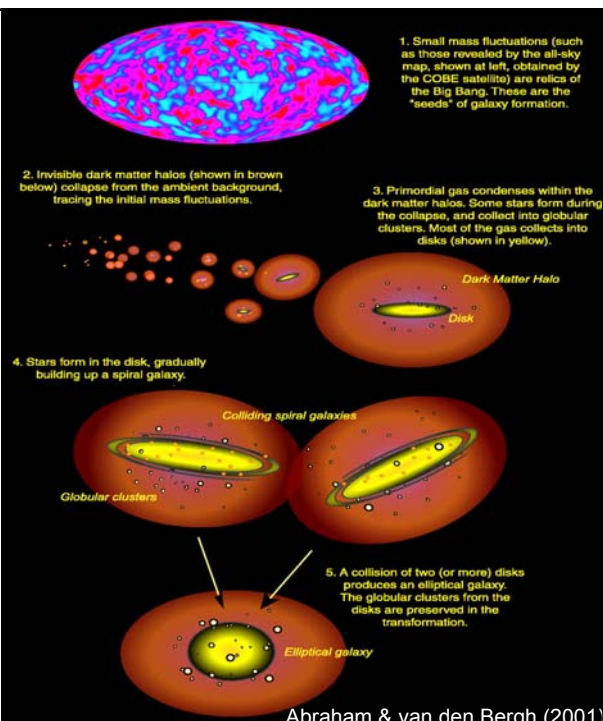
## Basic idea behind galaxy formation - objects start small and grow by merging

Do galaxies form this way?

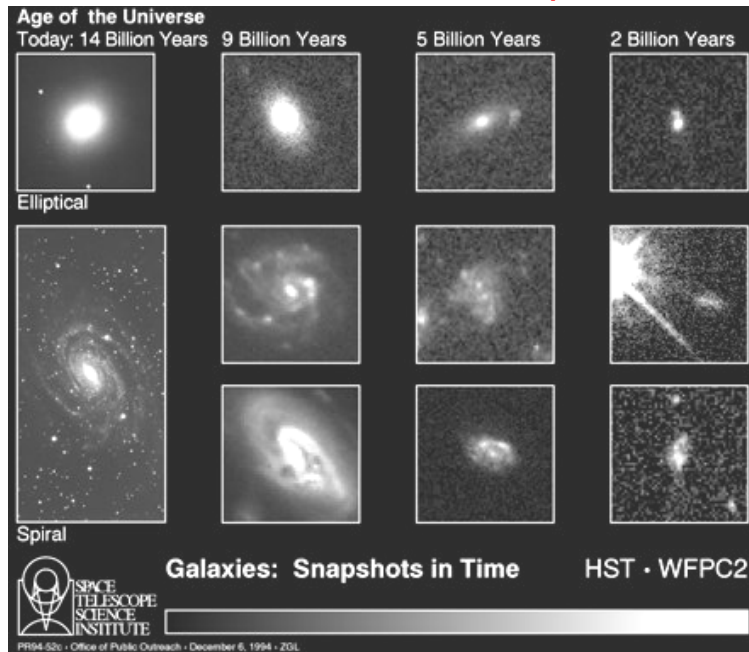
Does star formation occur before, during or after mass assembly?

When and how do Hubble Types form?

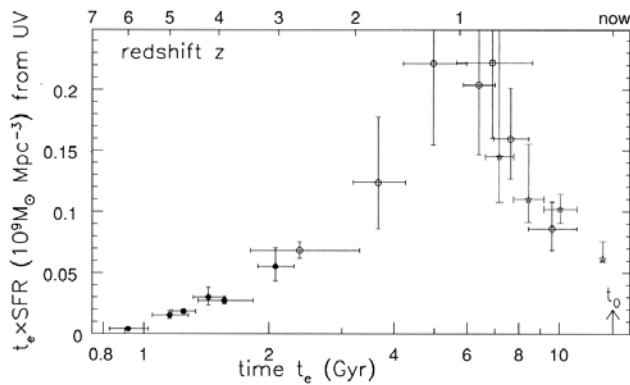
From a talk by Chris Conselice



## From the HST PR dept:



## Star formation rate as a function of time



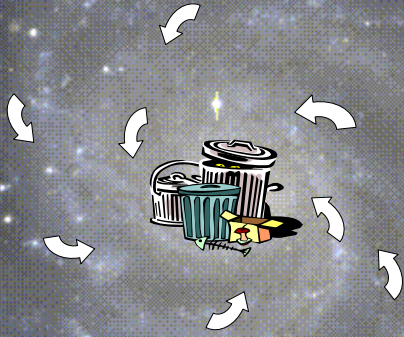
Measured from

- Blue light (O star continuum)
- $H\alpha$  emission (H II regions)

"Madau diagram"

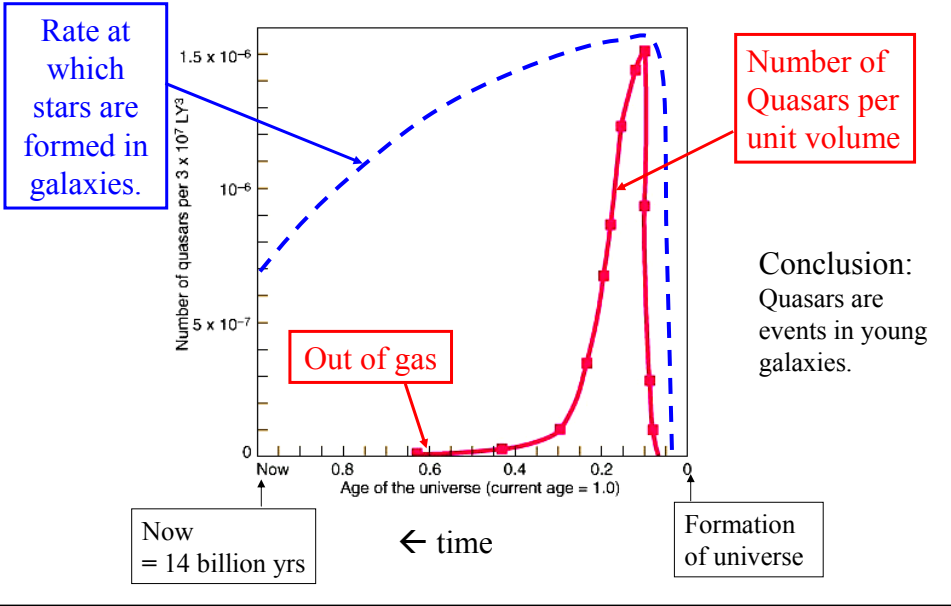
# Galaxy Formation

## Gravity → Material Falls to Center

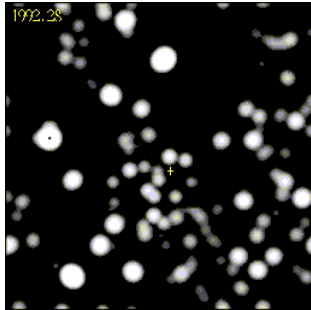


Quasar = gas falling into massive black hole.

## Most Quasars Lived and Died Long Ago

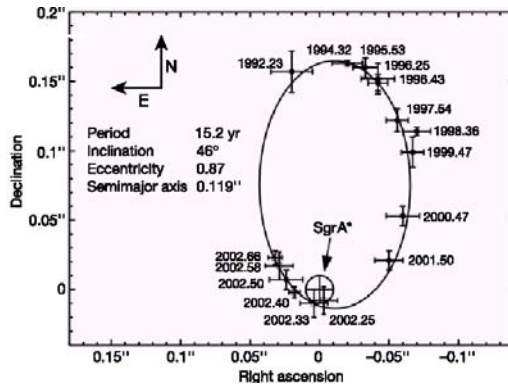


# Sidetrack: The Black Hole at the the Galactic Center



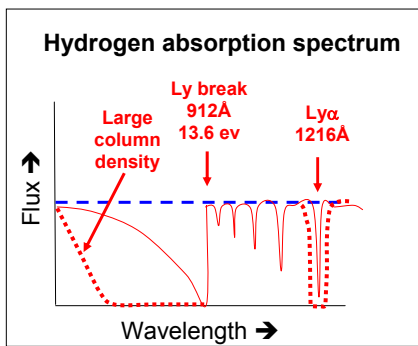
Infrared observations over 6 years.

Velocities of stars in very center  
 → 1 million  $M_{\odot}$  black hole  
 at position of Sagittarius A\*

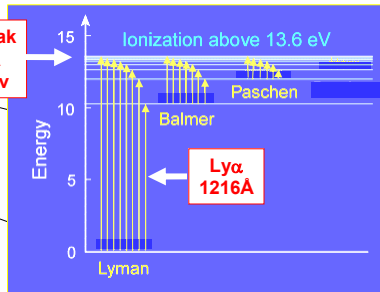


Follows complete orbits to within 60AU from black hole.

# The Gunn – Peterson Effect

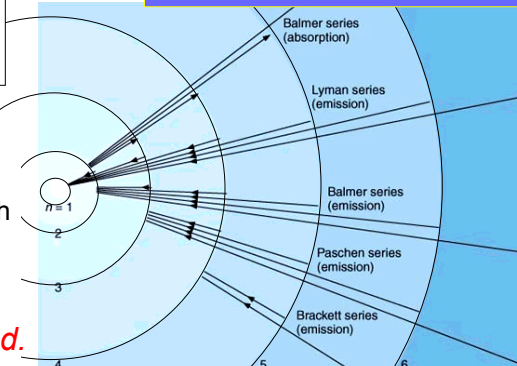


Ly break  
 912Å  
 13.6 eV



- Expect Ly continuum absorption from Inter-Galactic Medium to completely block all radiation with  $\lambda < 912\text{\AA}$
- Why doesn't it?

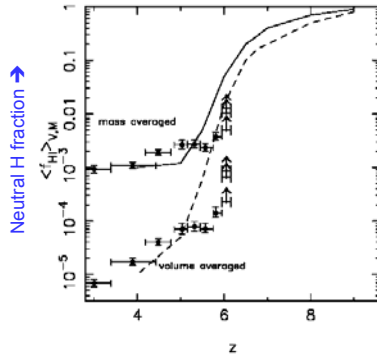
*IGM is ionized. Re-ionized.*



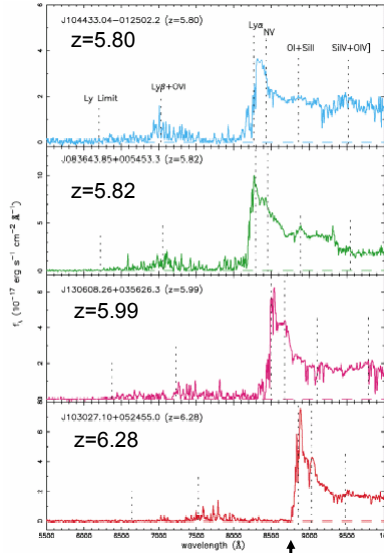
# The dark ages

## When did re-ionization occur?

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

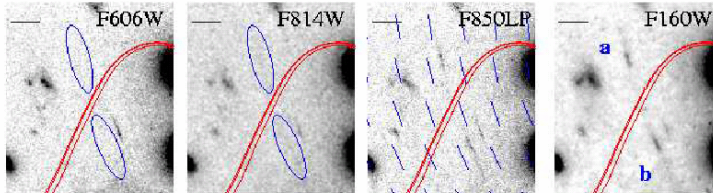


- But WMAP finds  $z = 10.9^{+2.7}_{-2.3}$  (420 Myr) for re-ionization
  - From polarization of CMB.
- patchy re-ionization?



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

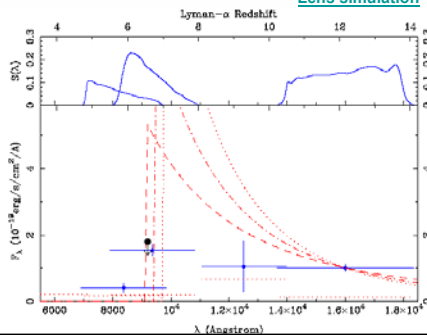
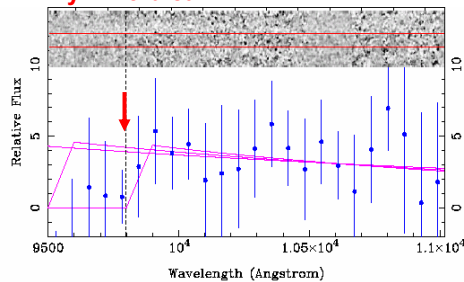
$z = 7$   
galaxy  
?



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  $9600\text{\AA}$ . 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 ~ 10 galaxies?

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

DANIEL P. STARR<sup>1</sup>, RICHARD S. ELLIS<sup>1</sup>, JOHAN RICHARD<sup>1</sup>, JEAN-PAUL KNEIB<sup>1,2</sup>, GRAHAM P. SMITH<sup>1,2</sup>, MICHAEL R. SANTOS<sup>2</sup>

*Draft version January 10, 2007*

