Looking back in time over the last 13 Gyr
How did galaxies form and evolve?
Studying the Formation and Evolution of Galaxies

* Today the Universe is 13.7 Gyr old and many massive mature galaxies (e.g., ellipticals, spirals) with well-defined components (e.g., disks, bars, bulges) are already in place.

* One of the main goals of astronomy is to answer questions such as:
  - When and how did proto-galaxies – the precursors of galaxies-- first form?
  - How did these proto-galaxies evolve and assemble over the last 13 Gyr into the mature galaxies that we see today?
  - When and how did most of the stars that we see today in galaxies form?
  - When did barred spiral galaxies like our own Milky Way come into existence?
  - What was the role played by dark matter?

To answer these questions, need to 

**observe galaxies at different cosmic epochs or lookback times**

Lookback time \( T_{\text{back}} \) at epoch when Universe had age \( t \)

\[ = \text{Age of Universe today (13.7 Gyr)} - t \]
Galaxy surveys use Hubble to get high resolution images of galaxies to separate galaxies from each other to resolve components (bulge, disks, bars, spirals, tidal tails) of each galaxy.

The thousands of galaxies surveyed have different lookback times $T_{\text{back}}$ because light reaching us now was emitted

-- by distant galaxies a long time ago, when Univ was much younger
-- by nearby galaxies only recently

Use ground telescopes to get redshift $z$ of each galaxy. See in-class equations

- Cosmological vs Doppler Redshift
- Friedmann equation of motion to derive age $t(z)$ of Universe at
- Angular diameter distance

**Key Ingredients of Galaxy Surveys: HST Images and Redshifts**
Age as a function of cosmological redshift $z$

Age in Gyr vs cosmological redshift $z$ in a cosmological model with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $\Omega_k = 0$, $H_0 = 70$.

See in-class equations:
- Cosmological versus Doppler redshift
- Friedmann equation of motion to derive age of Universe as a function of redshift $z$. 

Lookback Time

Age of Universe
Angular Diameter Distance as a function of cosmological redshift $z$

See in-class equations
- Angular Diameter Distance and the conversion from arcsecond to kpc at different redshifts

Angular Diameter Distance in Mpc vs cosmological redshift $z$ in a cosmological model with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $\Omega_k = 0$, $H_0 = 70$
Important criteria for a powerful galaxy survey

What are the 4 criteria that a galaxy survey should satisfy in order to be effective, and why? See in-class notes
Latest Galaxy Surveys: GEMS, GOODS, HUDF

Early galaxy surveys, including the famous Hubble Deep Field (HDF) in 1996 used the old WFPC2 camera aboard HST. WFPC2 had a very small field of view.

The Advanced Camera for Surveys (ACS) installed in 2002 is 10 times more powerful than WFPC2:
- has a larger field of view (60 times larger)
- more sensitive
- higher angular resolution

It has allowed several state-of-the art surveys of galaxy evolution in 2004:
- the GEMS survey
- the GOODS survey
- the HST Ultra Deep Field (HUDF)

-- See in-class notes for comparison of GEMS vs HUDF: area, depth, lookback times
GEMS surveys galaxies out to lookback times of 9 Gyr, when Univ was 4.7 Gyr old. HUDF surveys galaxies out to lookback times of 13 Gyr, when Univ was 0.7 Gyr old.