How Do Galaxies Form?

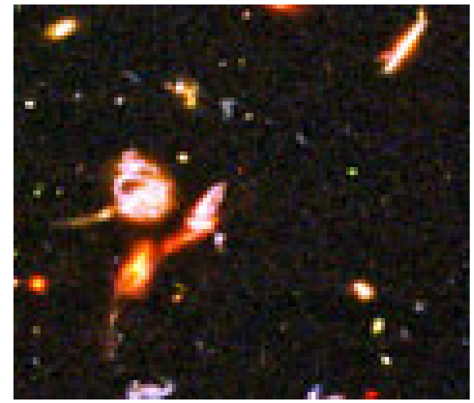
- More difficult to understand than star formation. All happened long ago.

- Recall that the further we look, the further back we look in time: e.g. 1000 Mpc => 3 Gyr

- Hence push to identify the faintest, furthest galaxies in order to understand formation and evolution. Because of the distance, angular sizes are small. Emission greatly redshifted. Can't watch galaxies evolve but must infer evolution from snapshots of different times. All this makes it difficult!
- Old idea: a galaxy forms from a single large collapsing cloud of gas, like Solar Nebula.
- New idea: observations and theory indicate that "sub-galactic" fragments of size several hundred parsecs were the first things to form. Hundreds might merge to form a galaxy.

The Hubble Ultra Deep Field

- Only about 200" across.
- Distant (i.e. younger) galaxies are much smaller and disorganized vs. today's galaxies: consist of "building blocks". Looking back as far as only 0.8 Gyr after Big Bang, or $z \approx 6$.

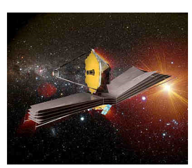


Redshifts determined for many galaxies in this field. Can relate redshift to distance, and thus get, e.g., true sizes of galaxies. Can also relate redshift to age of Universe when light was emitted, and thus study how sizes changed with time.

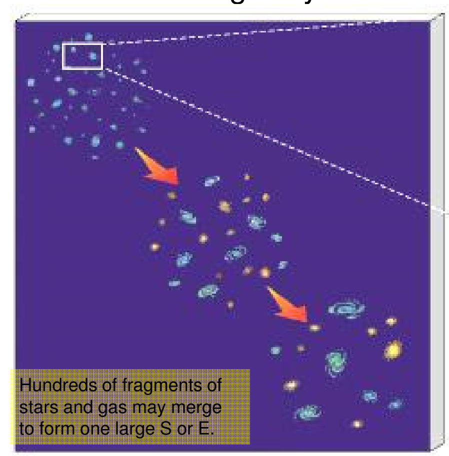
Result: galaxies grew with time. Galaxies with z=6 about 10 times smaller in diameter than today.

What kind of light do we see with optical filters from a galaxy with z=6?

James Webb Space Telescope will do much better, being much more sensitive and optimized for IR observations, with higher resolution.

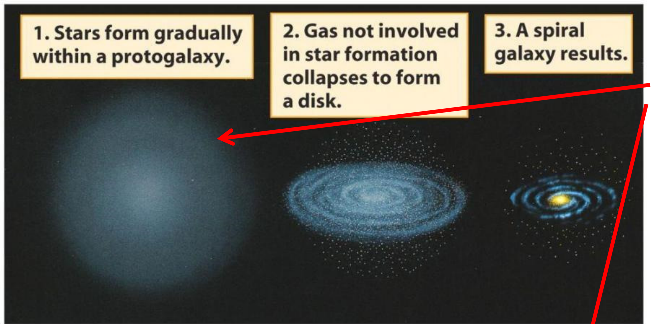


Schematic of galaxy formation



Today's dwarfs: leftover fragments presumably

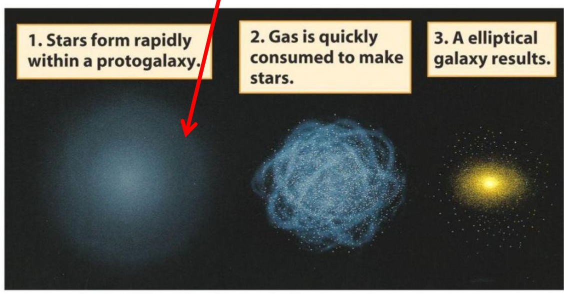
Don't forget: most of the mass is dark matter and this must govern the way in which galaxies form. Computer simulations of galaxy formation and evolution, incorporating as much physics at as high a resolution as is feasible, are a great help.



Formation of a spiral galaxy

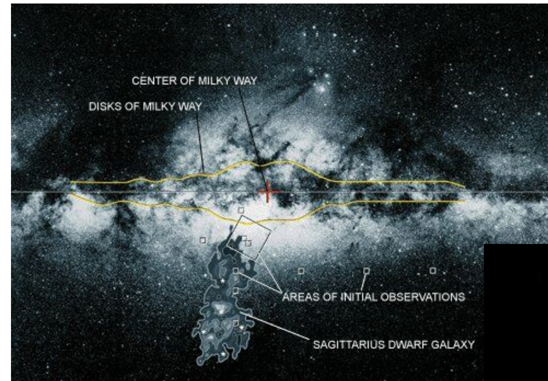
Should show star/gas fragments – not uniform looking cloud!

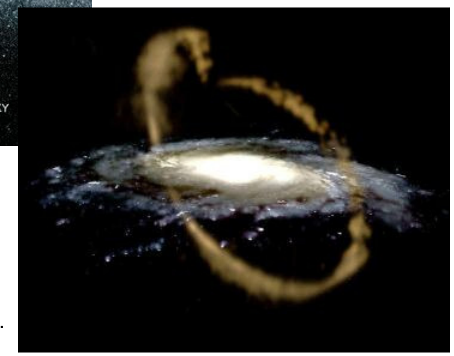
Also, spirals and ellipticals have properties so different that they cannot have been formed out of gas clouds with similar initial conditions, e.g. angular momentum. And it has become clear that not all galaxy properties are dictated at formation...



Formation of an elliptical galaxy

The Milky Way is still accreting dwarf galaxies ("minor mergers")

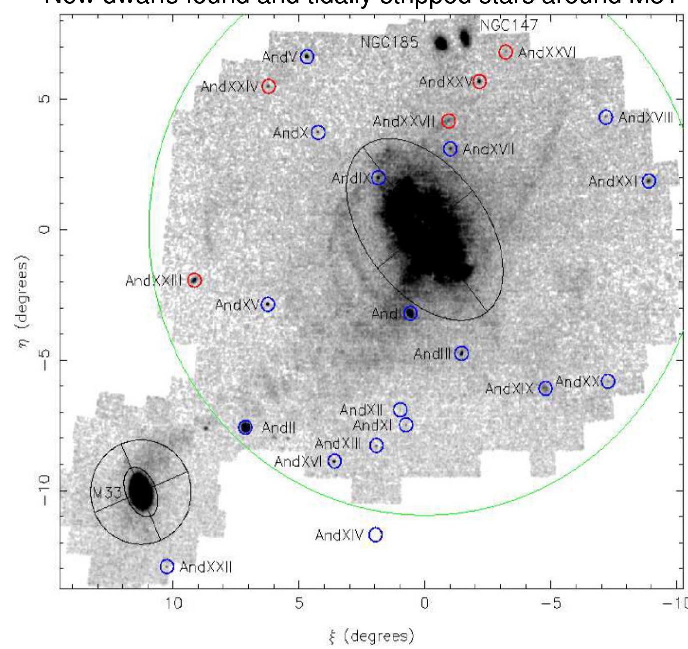




Tidal force stretches dwarfs out when they approach MW, removing many stars from dwarf. Artist's impression of tidally stripped stream of stars from Sag. dwarf. Predicted in simulations. Later found observationally.

Tidally stripped stars from a small galaxy orbiting NGC 5907

New dwarfs found and tidally stripped stars around M31



Large Galaxy Interactions and “Major” Mergers

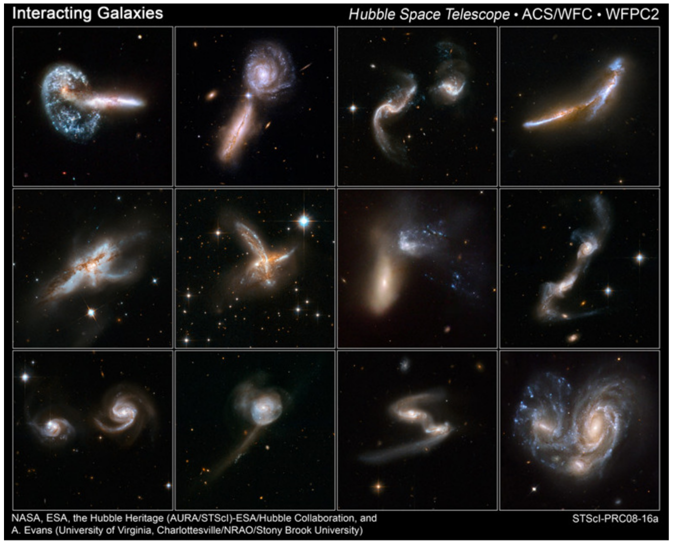
• Large galaxies sometimes come near each other, especially in groups and clusters.

• Tidal force can draw stars and gas out of them => tidal tails in spirals.

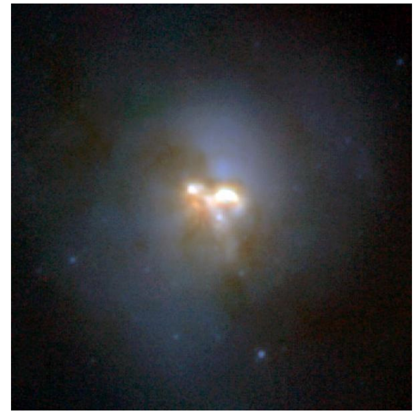
• Galaxy shapes can become badly distorted.

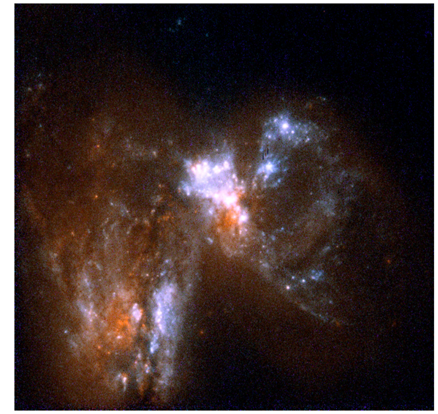
• “Major mergers”: two large galaxies

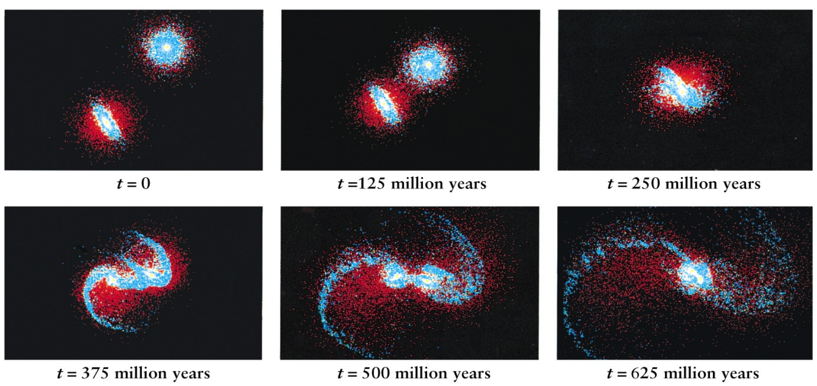
• Simulation



Interactions and mergers also lead to "starbursts": unusually high rates of star formation at centers of merging pairs, lasting probably only 10^8-10^9 years but forming stars at rates 10’s to 1000’s times that of the Milky Way.







Simulations show giant ellipticals may be mergers of two or more spirals. Rotational motion of spirals disrupted, orbits randomized. Gas rapidly consumed into stars in a starburst – little left over. Since ellipticals have old stars, such mergers must have peaked long ago.

It now seems galaxy properties are determined by formation, evolution in isolation and subsequent mergers (major and minor).