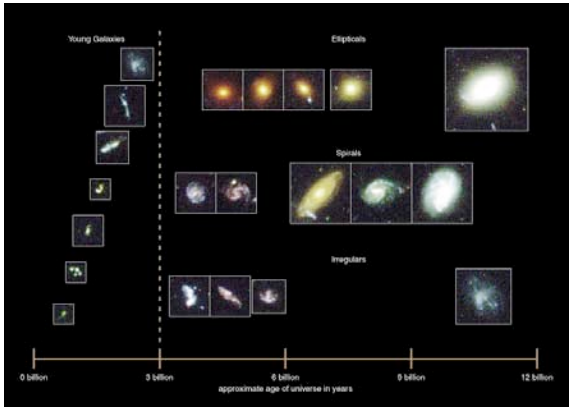
Galaxy Evolution…

- …is the study of how galaxies form and how they change over time.
- As was the case with stars…
  - we can not observe an individual galaxy evolve
  - but we can observe different galaxies at various stages of their life cycles



- This is made easier by virtue of lookback time.
- We can plot a "family album" for each type of galaxy.
- The greater the redshift...
  - the younger the galaxy!

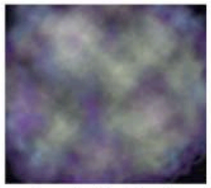
Modeling Galaxy Formation

- With our current telescope technology…
  - we are unable to see back to the time when galaxies first formed
  - we must rely on theoretical (computer) models to describe how galaxies formed
- The following assumptions are made when constructing these models:
  1. the Universe was uniformly filled with Hydrogen & Helium gas for the first million years after the Big Bang (called **Dark Ages**)
  2. this uniformity was not quite perfect; some regions of the Universe were slightly denser than others (called **Primordial Fluctuations**)
- All of the H & He gas expanded with the Universe at first.
  - after about a billion years, the denser regions slowed down and began to collapse under self-gravity (our familiar **gravitational collapse**!)
  - the collapsing gas became **protogalactic clouds**

Modeling Galaxy Formation

- As a protogalactic cloud collapses, its gravitational potential energy heats up gas and then is "radiated away".
  - Gas gets colder as radiation takes energy away with it from the cloud. **Energy Stolen**!
  - stars begin to form in the coldest, molecular cloud cores
  - same physics as when ionized and atomic ISM condenses into molecular clouds and forms star in the star-gas-star cycle of the Milky Way
- Conservation of angular momentum
  - caused remaining gas to rotate faster and flatten…star formation continues in disk
  - with no gas left in the spheroid, no new stars are formed and only old, red stars remain

Modeling Galaxy Formation



(a) A protagalactic cloud contains only hydrogen and helium gas.

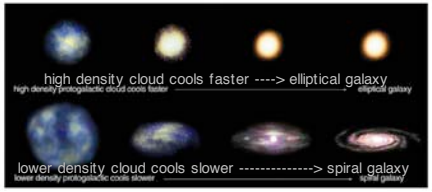
(b) Halo stars begin to form as the protogalactic cloud collapses.

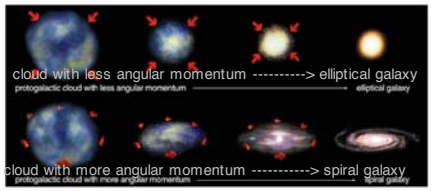
(c) Conservation of angular momentum ensures that the remaining gas flattens into a spinning disk.

(d) Billions of years later, the star–gas–star cycle supports ongoing star formation within the disk. The lack of gas in the halo precludes further star formation outside the disk.

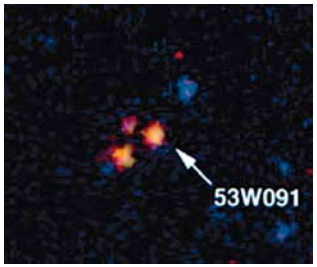
What Determines Galaxy Type?

- *Not Solid Yet*, but we can explore two options:
  - the initial conditions of the protogalactic cloud; i.e. destined from birth
  - later interactions with other galaxies; i.e. a life-altering conversion
- Two plausible explanations regarding the birth properties of the protogalactic cloud:
  - Protogalactic spin…the initial angular momentum determines how fast the cloud will form a disk before it is completely turned into stars
  - Protogalactic cooling…the initial density determines how fast the cloud can form stars before it collapses into a disk





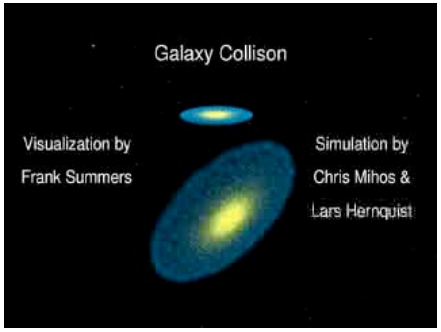
What Determines Galaxy Type?



- This giant elliptical provides evidence for the protogalactic cooling explanation.
  - it is very distant (young) and very red, even accounting for redshift
  - white and blue stars are missing
  - Explosive, instantaneous starformation occurred at very early times
  - star formation has ceased very early in the galaxy's history
  - no gas will be left to form a disk
- Galaxy Interactions
  - when two spiral galaxies collide
  - tidal forces randomize the orbits of stars
  - gas either falls to the center to form stars
  - or it is stripped out of the galaxies
  - the disk is removed
- The galaxy becomes an elliptical.

When Spirals Collide

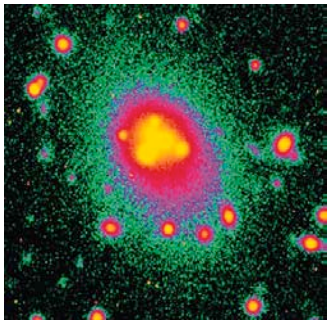
Model of Galaxy Interaction



Movie. Click to play.

The Role of Galaxy Clusters

- Galaxy clusters provide evidence that some galaxies are shaped by interactions:
  - elliptical galaxies are more common in cluster centers
  - collisions will occur more often in crowded cluster centers
  - **central dominant (CD) galaxies** are gigantic ellipticals found in cluster centers
  - they grow large by consuming other galaxies



- These CD galaxies often contain tightly bound clumps of stars.
- They are probably the leftover cores of galaxies which were *cannibalized* by the CD.
- Some CD galaxies are more than 10 times as massive as the Milky Way.
  - making them the largest galaxies in the Universe!