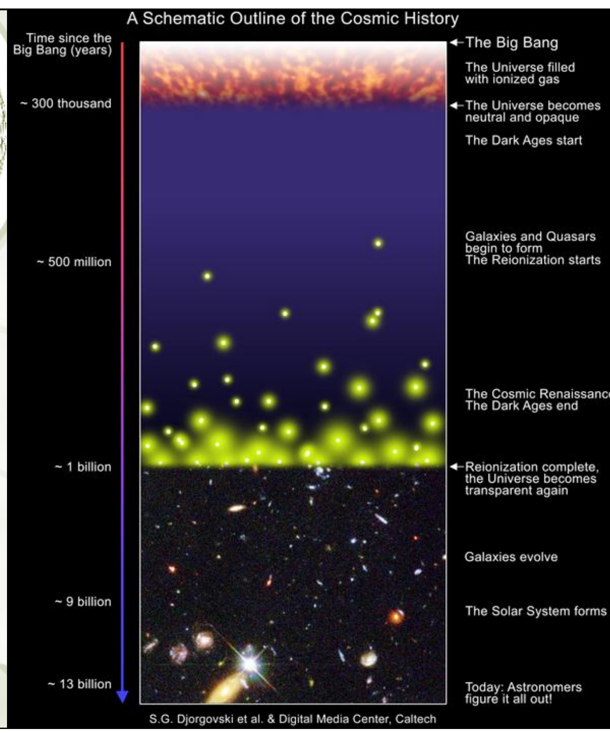
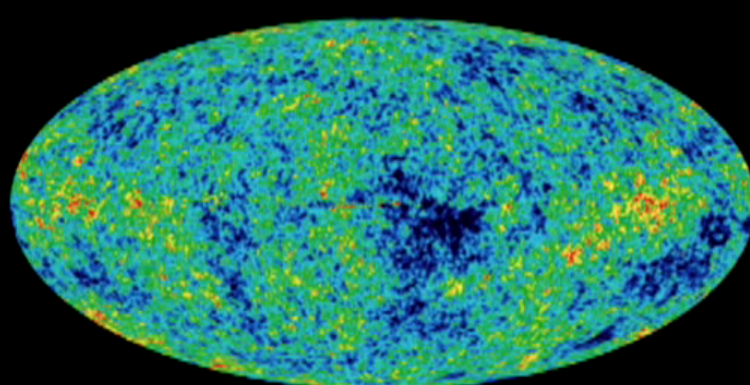
Lecture 21 : Where did the galaxies come from?

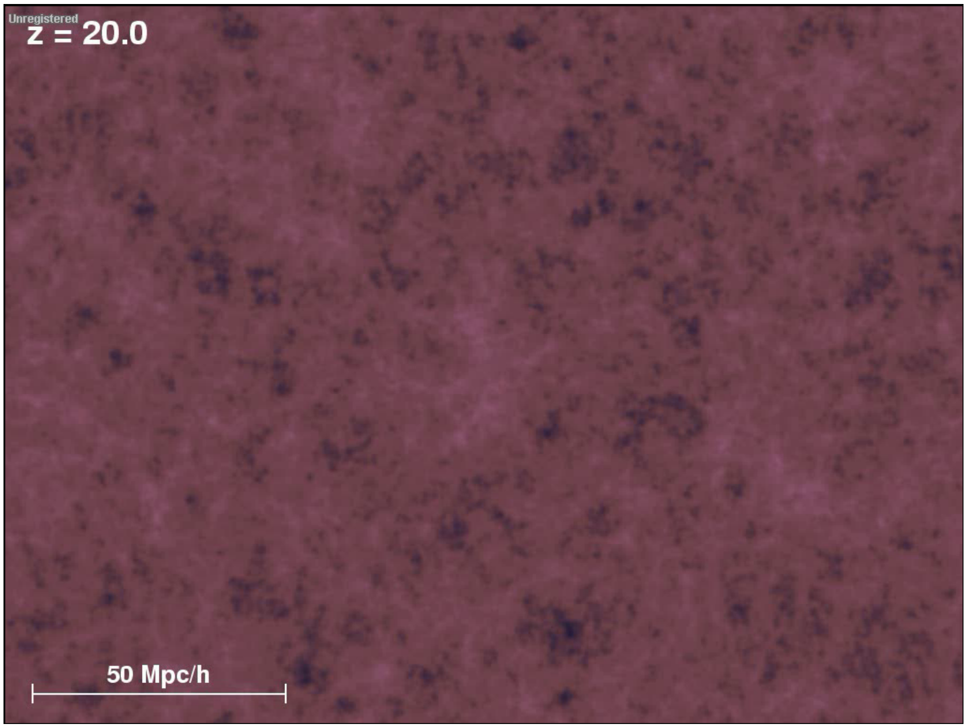
- From homogeneity to structure…
  - Gravitational evolution of dark matter
  - Formation of dark matter halos
- Galaxy formation

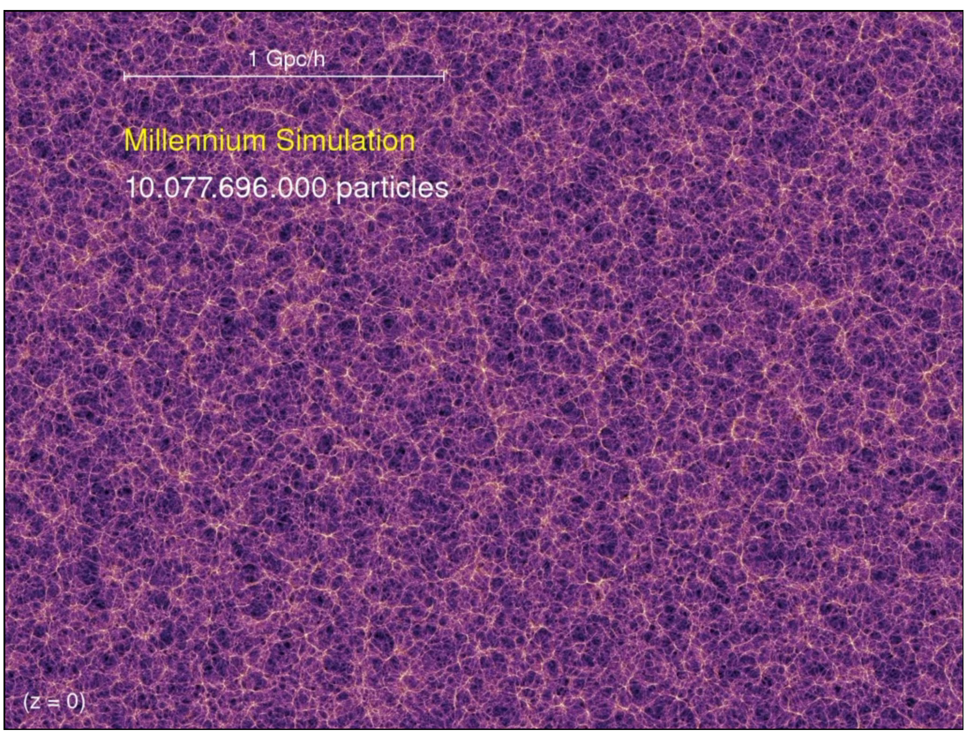


I : Formation of structure

- **Question** : how does the Universe go from being homogeneous to being full of structure?
- **Basic idea** : Something introduced very small disturbances into the Universe at very early time. Those small disturbances then grew due to the action of gravity (close analogy with the Jean's instability)
- Slightly more detail of the standard model:
  - Initial disturbance ("seed perturbations") were quantum fluctuations introduced during the "epoch of inflation" ($t \sim 10^{-35}$s)
  - The perturbations grow very slowly due to action of gravity until matter starts to dominate the energy density of the Universe (t~70,000ys)… they then start to grow faster
  - Perturbations are at level of 1 part in 10^5 at epoch of recombination… this produces observed anisotropies in CMB.
  - They continue to grow after that… eventually forming a filamentary structure of Dark Matter. This is the "skeleton" for galaxy formation!

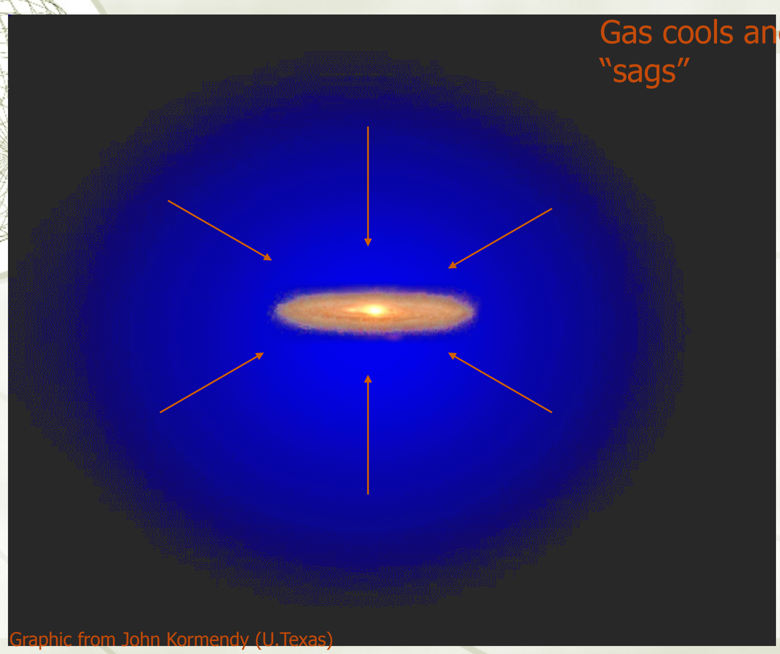


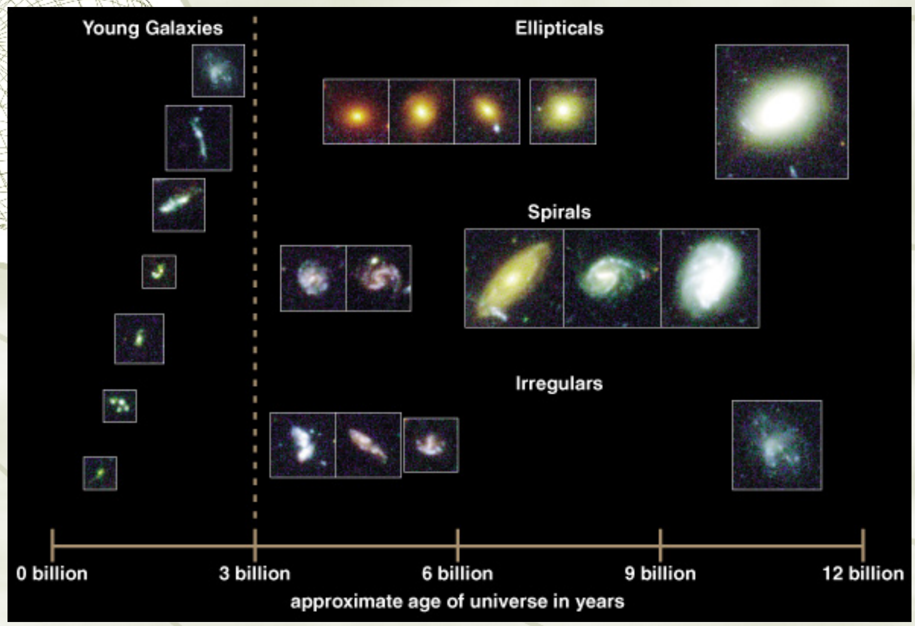

Unregistered
z = 20.0
50 Mpc/h


1 Gpc/h
Millennium Simulation
10.077.696.000 particles
(z = 0)

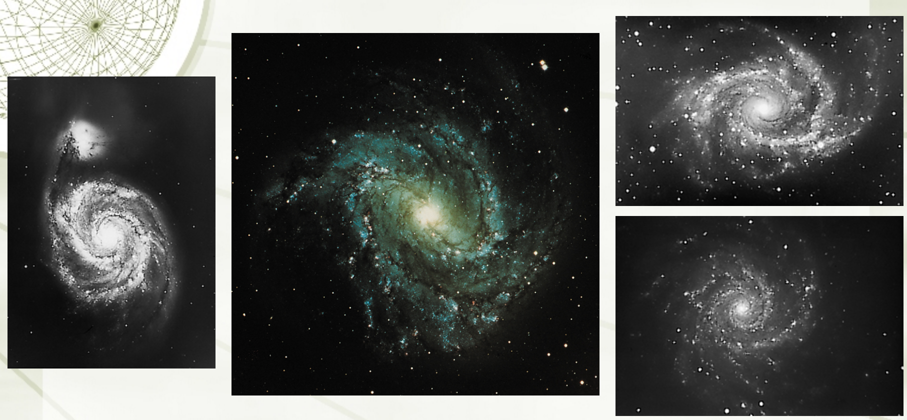
II : Galaxy formation

- Gravitational collapse forms “dark matter halos”
- Dark matter halos have range of
  - Masses (range from <$10^8 M_{sun}$ to $10^{15} M_{sun}$)
  - Angular momenta (barely spinning to rapidly spinning halos)
- Unlike dark matter, normal (“baryonic”) matter can emit radiation and cool down
  - Normal matter falls into halo, cools, settles to center
  - Once cool dense clouds form, can get star formation
  - Through this process, a galaxy is build up
  - What determines whether a galaxy is a disk/spiral or an elliptical?





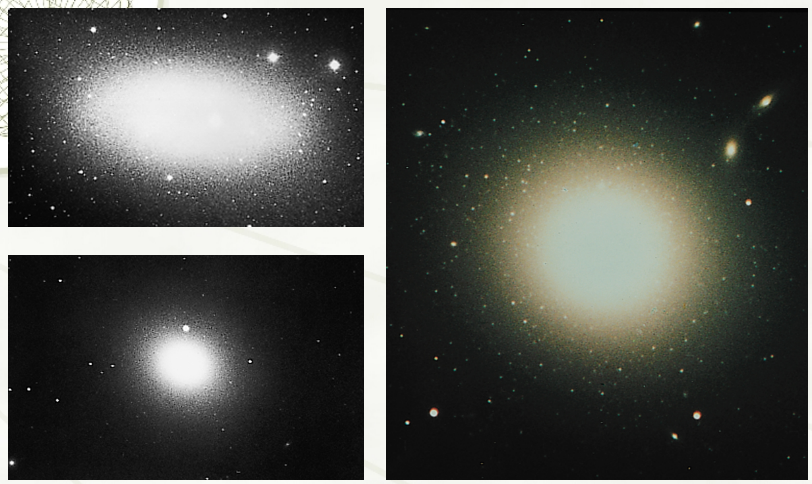
Typical spiral galaxies



"Disk" orbits, young stars (Pop I)

Figure 16.3, Arny, *Explorations,* McGraw-Hill

Typical elliptical galaxies



“Bulge” orbits, old stars (Pop II)

Figure 16.4, Arny, *Explorations,* McGraw-Hill

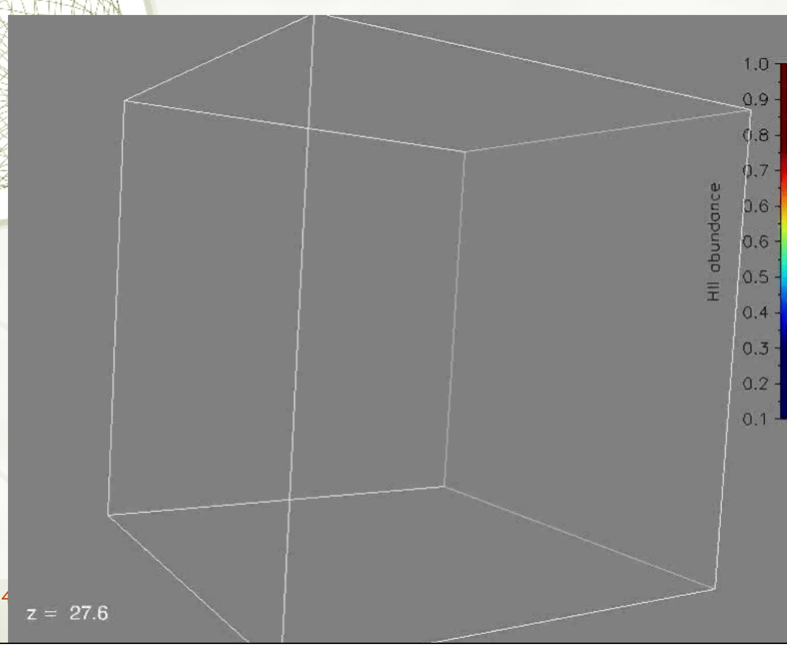
Irregular galaxies

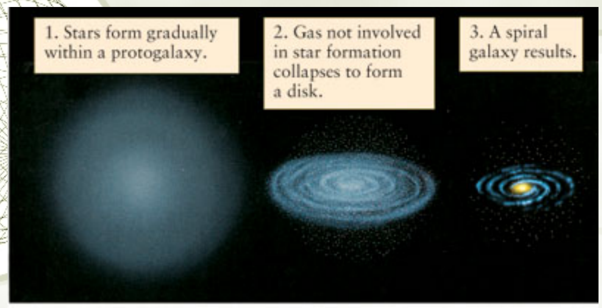
Lots of gas, dust, star formation; young galaxies?

Figure 16.5, Arny, *Explorations,* McGraw-Hill

Feedback processes are very important

Formation of the First Galaxies (Ricotti et al 2002)



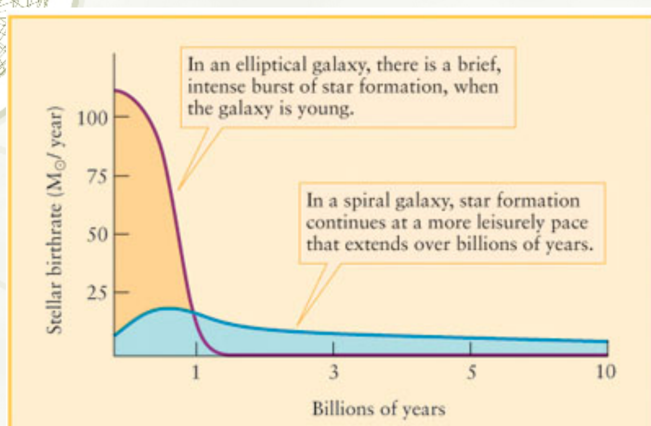


(a) Formation of a spiral galaxy

(b) Formation of an elliptical galaxy

High angular momentum halo

Low angular momentum halo



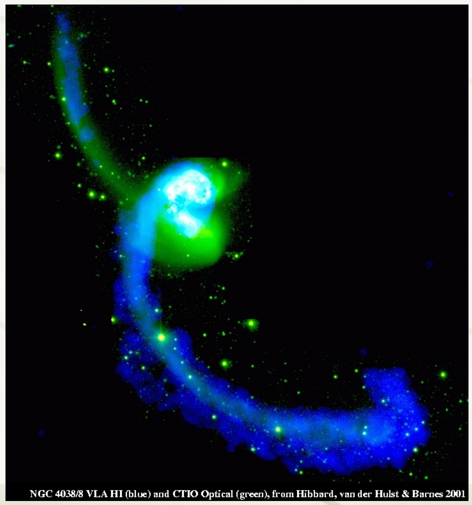
(c) The stellar birthrate in galaxies

III : THE SUBSEQUENT EVOLUTION OF GALAXIES

- Even once galaxies forms, they undergo interesting evolutionary processes.
- Internal evolution:
  - Starbursts – periods of intense star formation. Just after a starburst a galaxy looks very blue (lots of young stars).
  - Quasar activity – events where there is heavy accretion onto a central massive black hole. Produces a powerful object known as a **quasar**.

- External evolution:
  - Galaxies can collide and, sometimes, merge.
  - This can make galaxies change their type… two big spiral galaxies can merge together to form a big elliptical galaxy.
  - Particularly famous examples of colliding galaxies are the Antennae galaxy, and the Cartwheel Galaxy.
  - In both cases, significant internal evolution (star formation) is driven by the collision.

The Antennae Galaxy



Close Up with HST

The Cartwheel Galaxy