Lecture 22: Where did the galaxies come from: continued

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

Hierarchical Formation of Structure

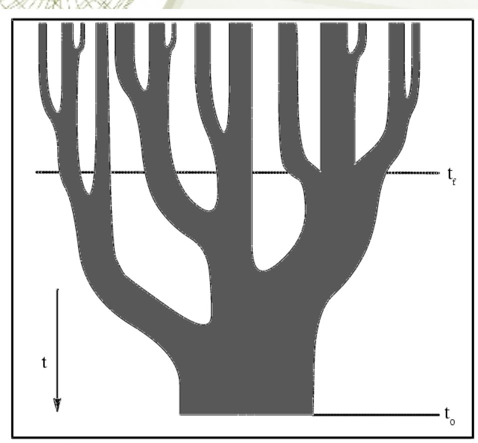
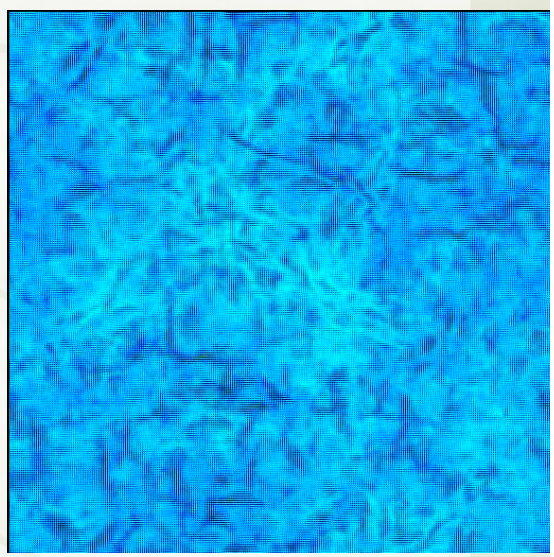
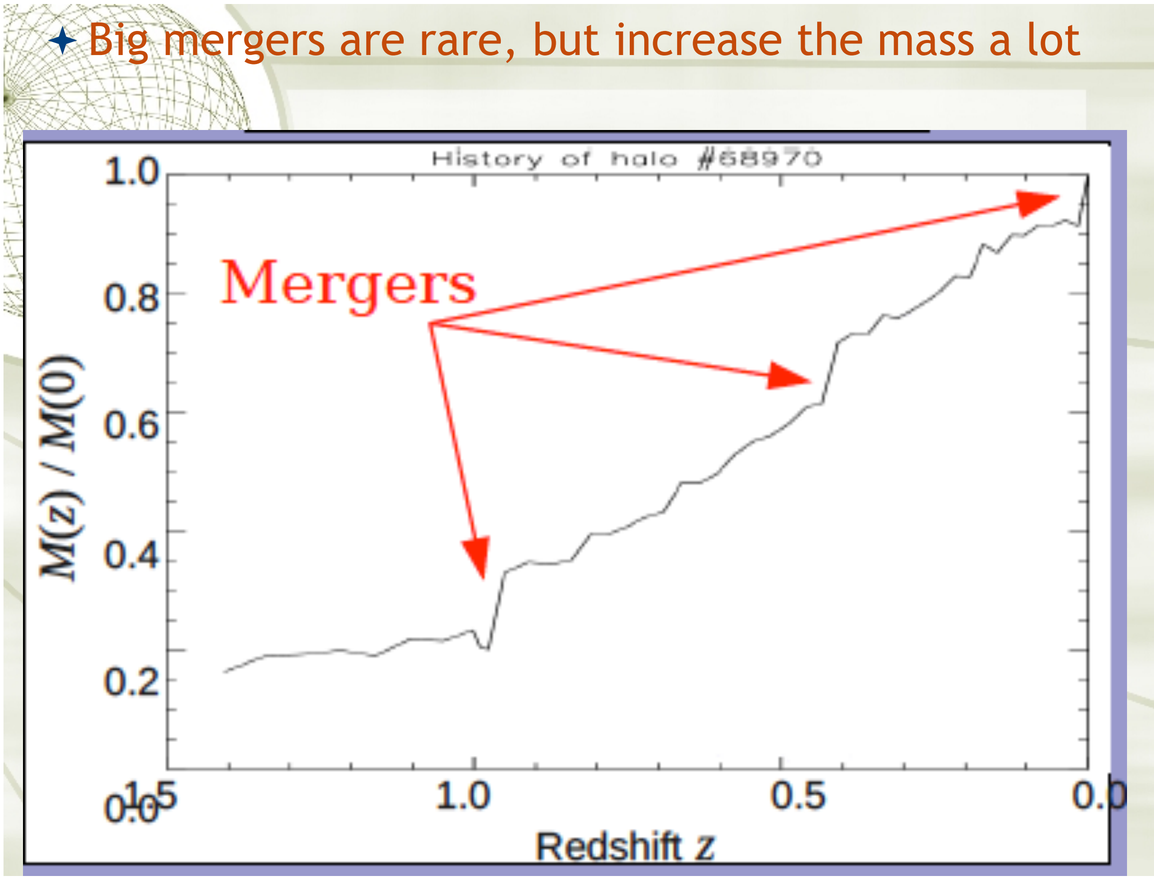
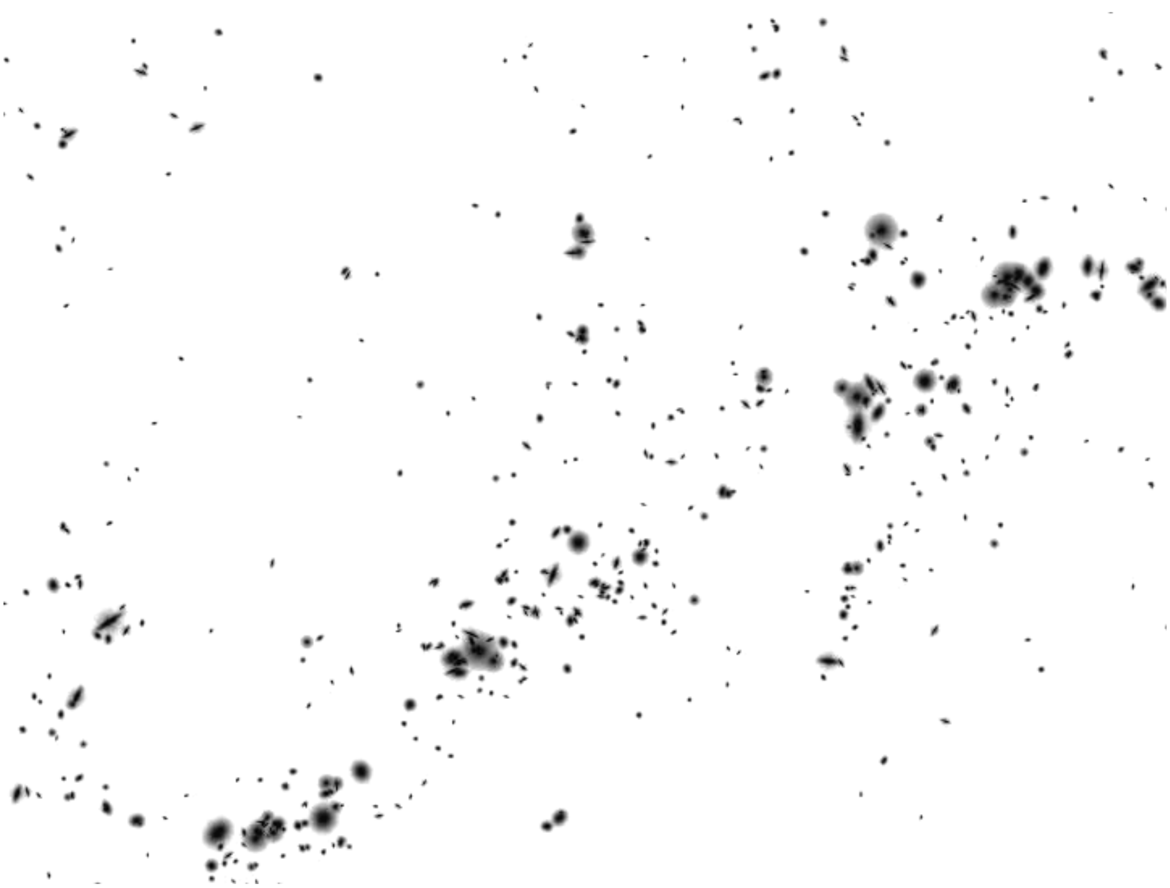


Figure 6. A schematic representation of a "merger tree" depicting the growth of a halo as the result of a series of mergers. Time increases from top to bottom in this figure and the widths of the branches of the tree represent the masses of the individual parent halos. Slicing through the tree horizontally gives the distribution of masses in the parent halos at a given time. The present time t_0 and the formation time t_f are marked by horizontal lines, where the formation time is defined as the time at which a parent halo containing in excess of half of the mass of the final halo was first created.



Bode


Big mergers are rare, but increase the mass a lot
History of halo #68970
Mergers
M(z) / M(0)
1.0
0.8
0.6
0.4
0.2
0.0
1.5
1.0
0.5
0.0
Redshift z



III : THE FORMATION OF STRUCTURE

- Astrophysicists use computer models to follow the growth, then collapse, of inhomogeneities
  - Result is a "numerical simulation" of evolution in the Universe
- Simulations:
  - Simulate the evolution of the Universe in a large "box" of space.
  - "Box" is typically large (10s to 100s of Mpc) compared to clusters but small compared to observable Universe (8 Gpc)
  - Start off with "initial conditions" of nearly uniform distribution of matter, with small inhomogeneities
    - Use "spectrum of perturbations" consistent with CMB observations data from redshift surveys
    - Start at time long after matter/radiation decoupling ($z \approx 1000$, 400,000 yrs after Big Bang)…

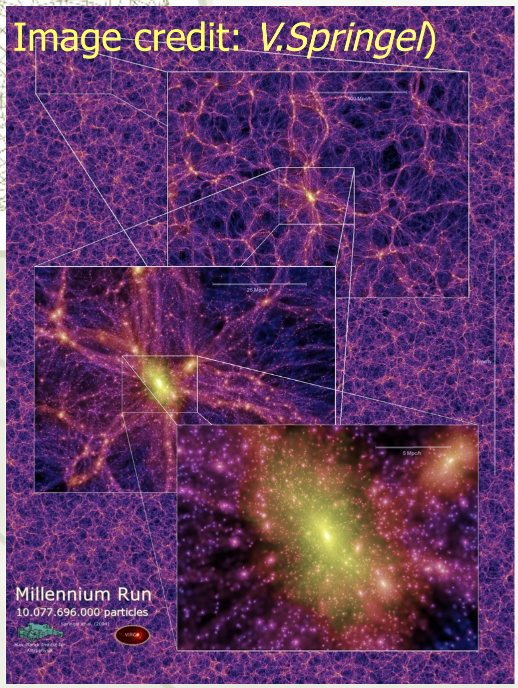
    …but still early enough that inhomogeneities are small

- Numerical programs on supercomputers are used to evolve the governing equations
- Typically need 100,000 or more equivalent CPU hours on supercomputer with 100 or more processors (would take >10 years to run model on a desktop!)
- Follow motions of 100s of millions of particles, each representing mass up to 10^{10} stars (10% of MW mass)
- Physics in equations includes:
  - Expansion of Universe ("box" shown in images is in comoving coordinates; i.e. continuously rescaled to fit screen)
  - gravity of dark matter and baryons
  - Gas pressure forces (only on baryons), if included
  - Dark energy (cosmological constant), if included
- Gravity causes fluctuations to grow: mass condenses into regions that initially had highest density

The complexity of the systems and the physics involved requires numerical simulation !

See http://hipacc.ucsc.edu/Bolshoi/IEEEFeature2012.html

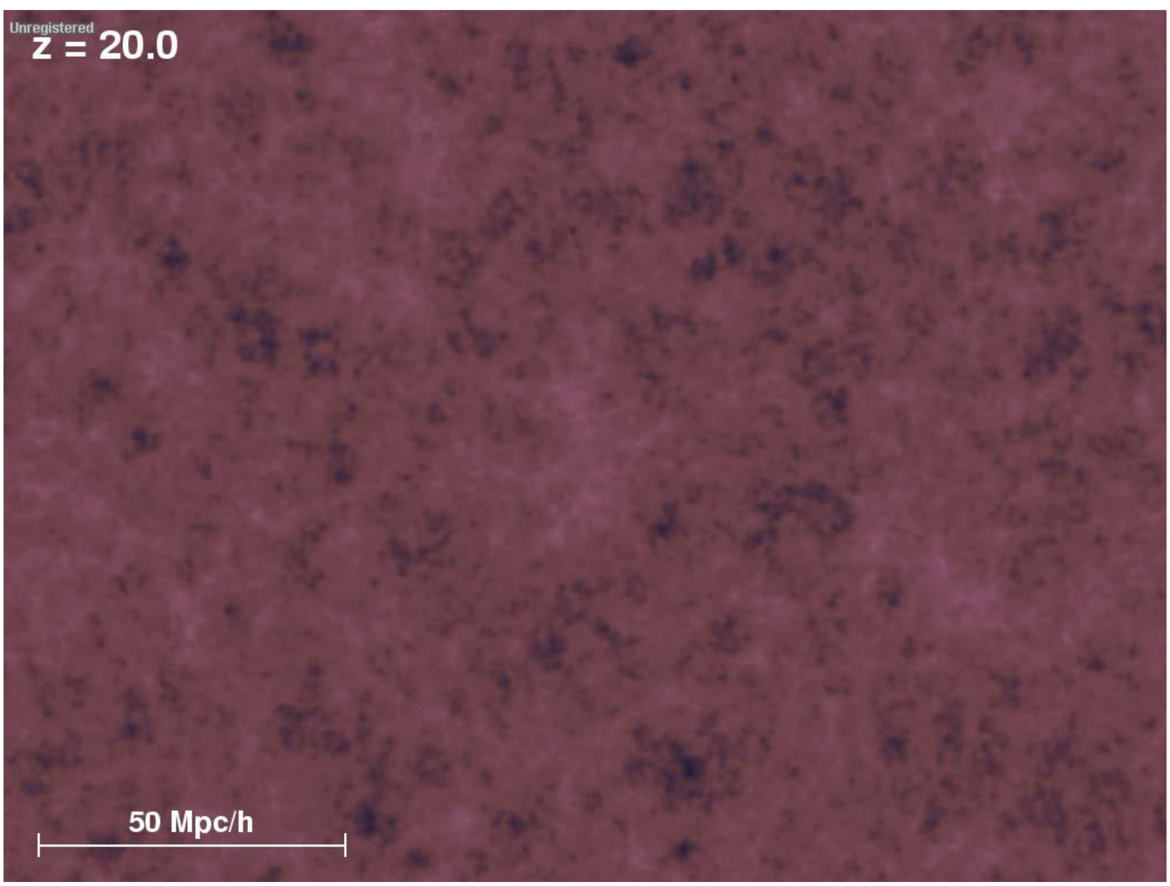
The "Millenium simulation"

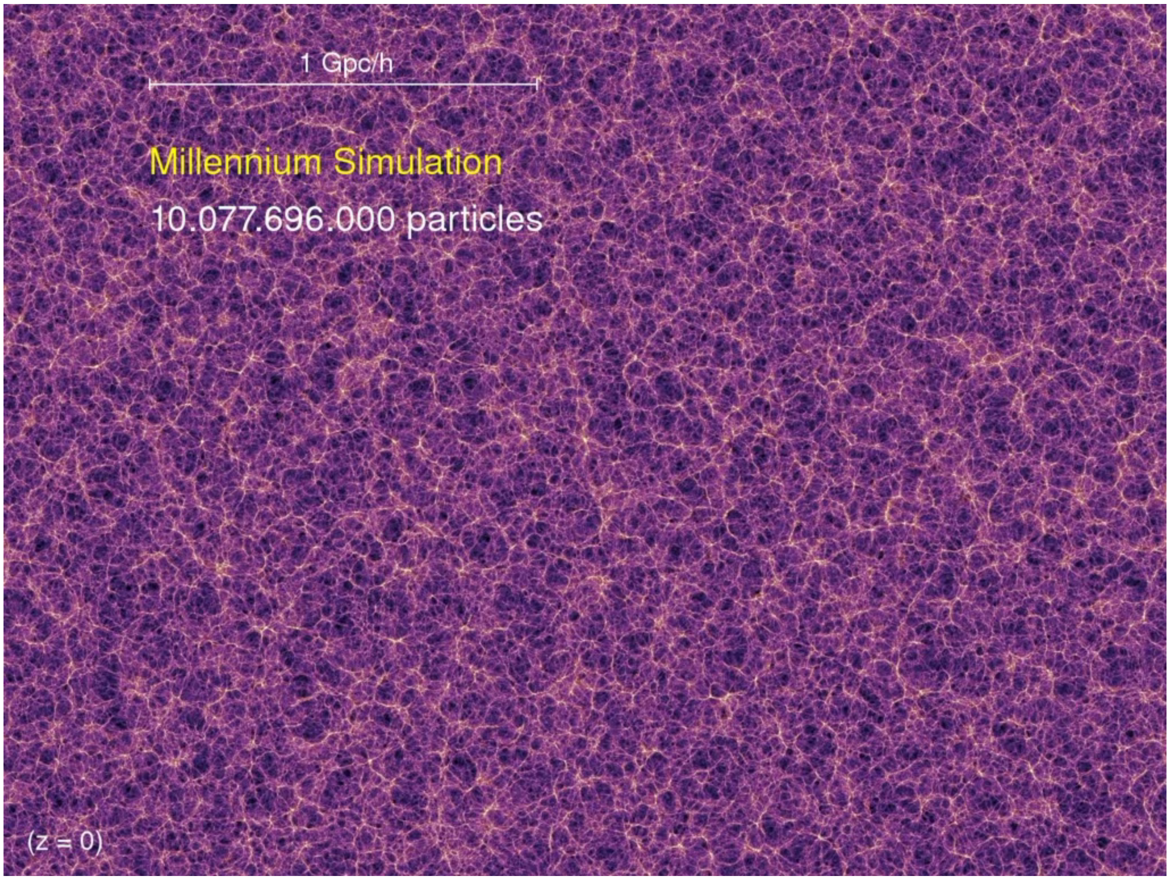


The largest N-body simulation carried out to prior to 2011

- Follows what becomes 20 million galaxies over 2 billion years
- Volume (2 Glyr)^3
- More than 10^{10} particles
- 25 Terabytes of data produced
- In this picture color corresponds to the logarithm of the density (dark purple low, yellow high)

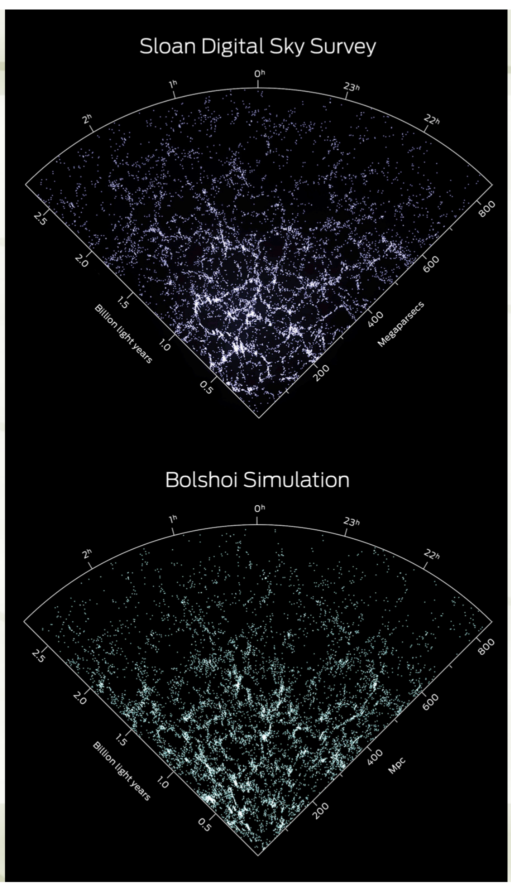
20Mpc thick slice at z=0 with 4x zoomed regions





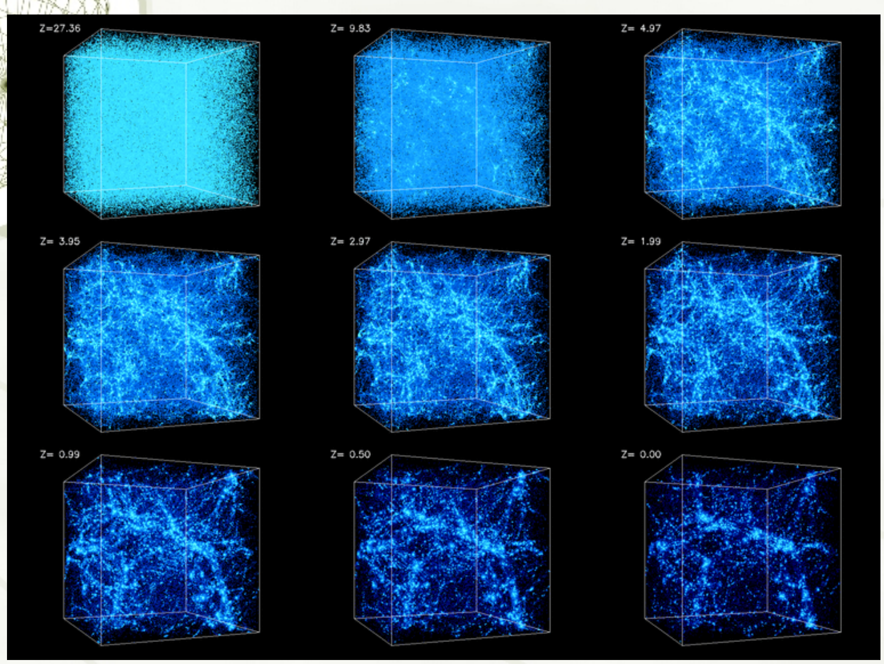
Compare Simulations with the data

The Universe in a Supercomputer- Joel Primack



- Can perform simulations with somewhat smaller box to focus on details, e.g.:
  - Large scale structure
    - this should be similar to that seen in redshift surveys
  - Dynamics within clusters and groups of galaxies
    - up to half of all galaxies in the Universe are thought to be part of groups or clusters
  - Galaxy formation

Formation of large-scale structure: snapshots



Credit: Andrey Kravtsov (U. Chicago) and Anatoly Klypin (New Mexico State U.)

Features to notice…

- Filaments become more prominent over time
- Clusters form at intersections of filaments
- Little changes from $z = 0.5$ to $z = 0$ (present), because Universe becomes dominated by dark energy!- can measure this ; a strong signature of the 'reality' of dark energy
- On large scales at late times, gravity cannot compete with the dark energy-driven acceleration and the growth of structures slows down after $z \sim 1$
- As the contraction of large-scale structures is halted, they expand with the universe and appear "frozen" in co-moving coordinates (box is 43 Mpc=140M lyr on a side)

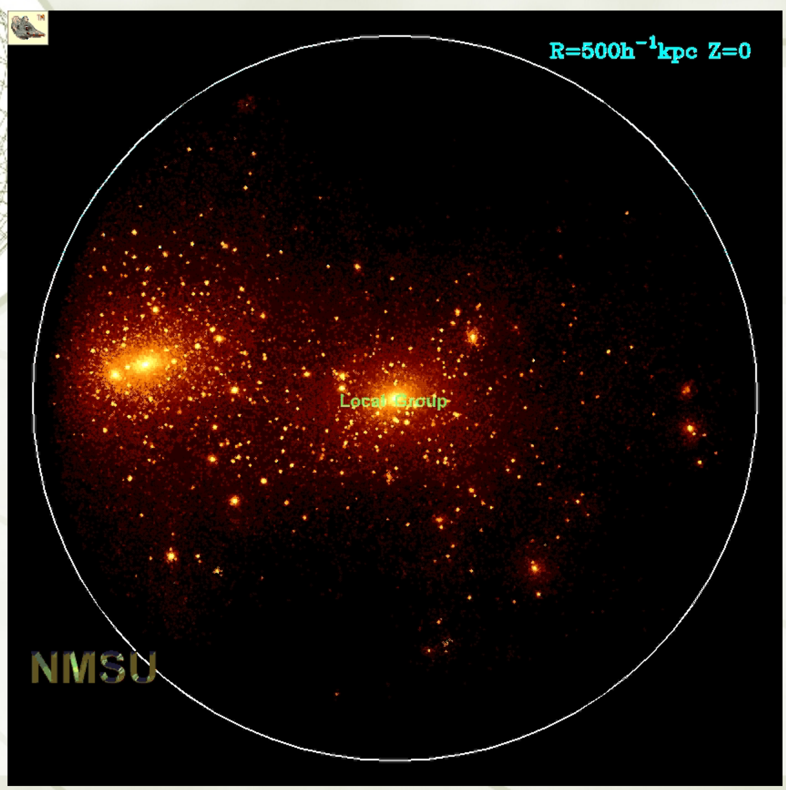
Formation of large-scale structure: the movie

Credit: Andrey Kravtsov (U. Chicago) and Anatoly Klypin (New Mexico State U.)

Formation of a group of galaxies

- Movie is zoom on 1/10th of previous volume
- Box is 4.3 megaparsec or 14 million light years.
- Our "camera" tracks the progenitor of the group; this galaxy remains near the center of the field of view.
- This group is similar to the Local Group, including Milky Way and Andromeda plus many smaller galaxies

Credit: Andrey Kravtsov (U. Chicago) and Anatoly Klypin (New Mexico State U.)

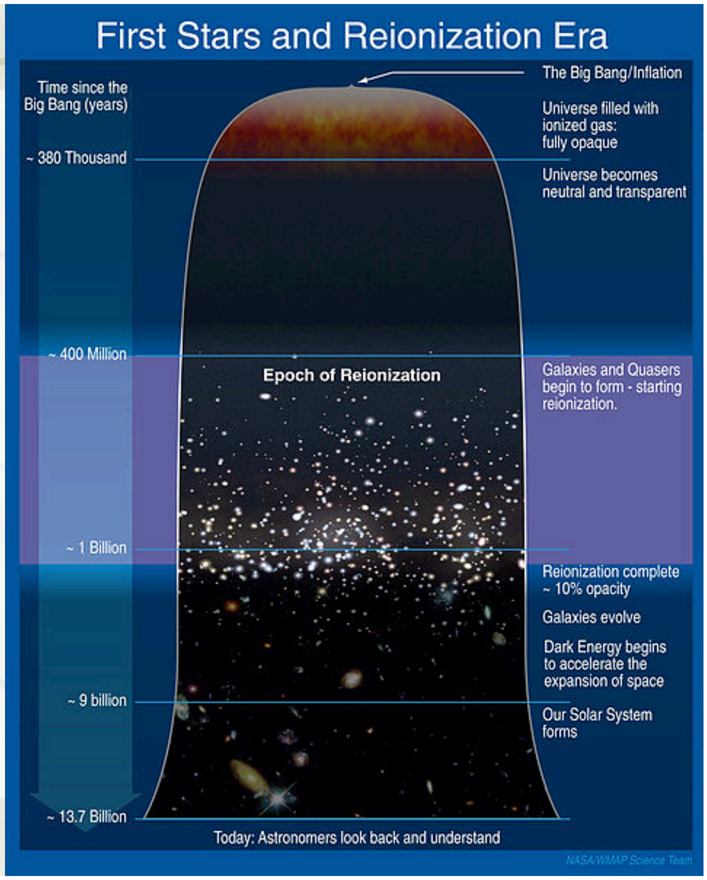


Things to notice…

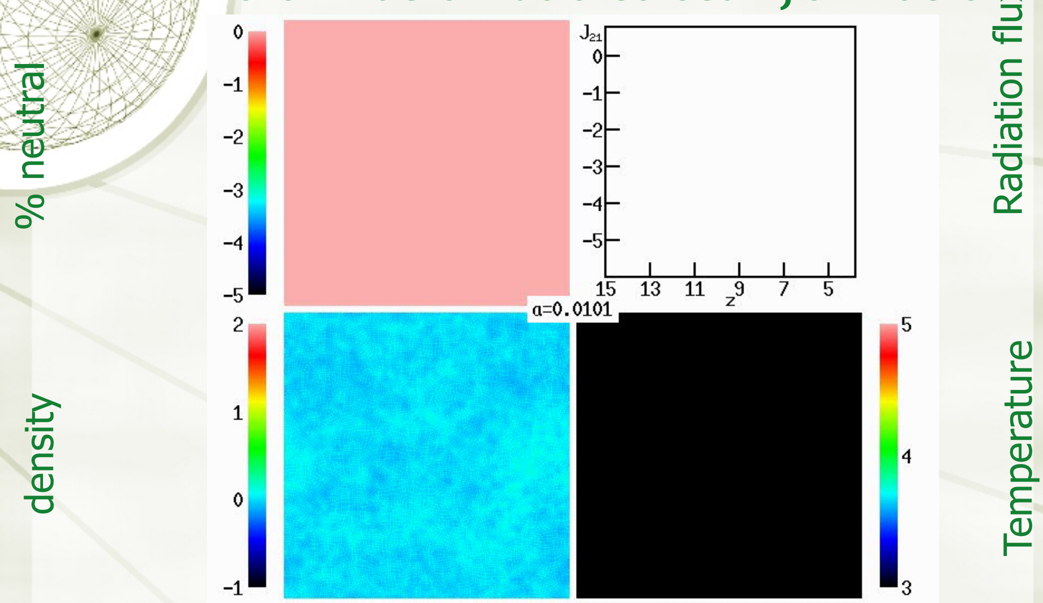
- Low-mass objects form first ($z > 5$),
- Objects grow in size by merging with similar-mass systems or "cannibalism" of lower-mass objects
- Merging continues even to the present day epoch ($z=0$)
  - Note that MW and Andromeda are predicted to merge in the future
- Many of the "cannibalized" systems do not loose their identity and become satellites orbiting in the gravitational pull of larger systems.

- Can also follow more complex processes within galaxies as they form…changes the appearance of galaxies greatly
  - Star formation will occur
  - Massive stars produce ultraviolet radiation
  - Radiation will escape from galaxies and reionize the gas in the Universe
    - Gas was previously neutral (atoms) starting at $z=1100$

- Objects started to form in the early universe energetic enough to ionize neutral hydrogen.
- As these objects formed and radiated energy, the universe went from being neutral back to being an ionized plasma, between 150 million and one billion years after the Big Bang (at a redshift 6 < z < 20).
- However, matter has been diluted by the expansion of the universe, and scattering interactions were much less frequent than before recombination.
- Thus a universe full of low density ionized hydrogen will remain transparent, as is the case today.

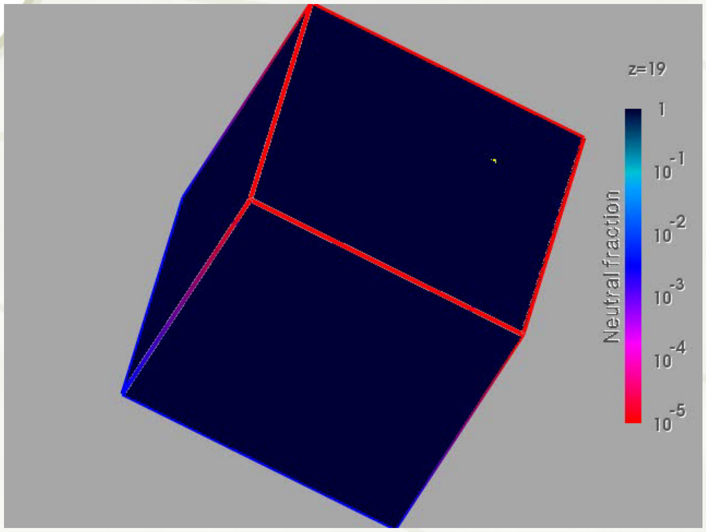


Reionization due to star formation



Nick Gnedin (Colorado)

Reionization due to star formation



Nick Gnedin (Colorado)

Structure formation: summary

- Cosmic structure forms due to growth of small initial "seeds"
- With "cold" dark matter, small things form first ; these then collect into bigger things "bottom up" formation
- Small galaxies formed earlier than large galaxies
- Even after galaxies forms, they undergo interesting evolutionary processes…

EVOLUTION OF GALAXIES

- Internal evolution:
  - "Fresh" gas falls into galaxies from surroundings
  - Gas within galaxy accretes and is compressed
  - 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**.

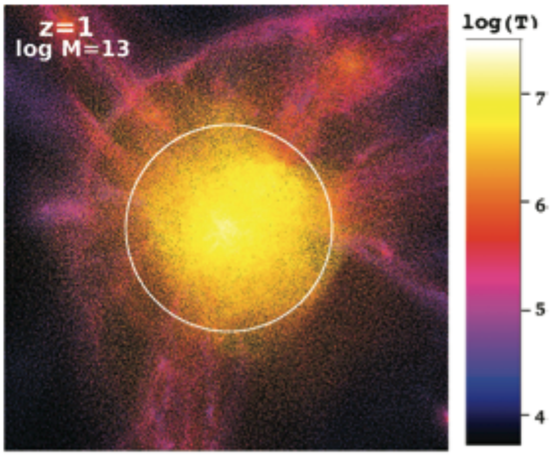
- External evolution:
  - Galaxies can collide and, sometimes, merge.
  - large galaxies "eat" smaller ones
  - This can make galaxies change their type… two big spiral galaxies can merge together to form a big elliptical galaxy.

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.

- Galaxies are complex systems. They are formed by the superposition of different stellar components: bulge, disk, spiral arms, plus a gaseous and a dark matter component.
- Any successful galaxy formation model, should be able to explain the formation mechanism behind each of these.

Formation of Milky Way

How Does Gas Get Into Galaxies

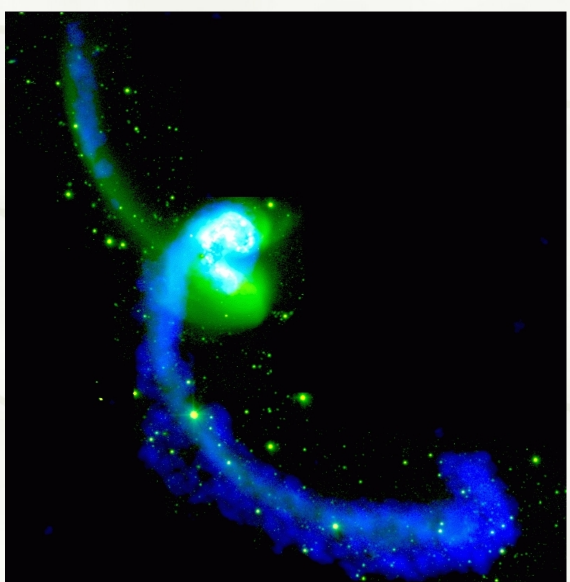


Keres et al. 2009, MNRAS 395, 160-179

Keres et al 2009

- IGM initially diffuse, cool gas
- Overdense regions form
- Majority of gas shock-heated as it falls into dark matter halo
- Cooling
- Star formation

The Antennae Galaxy- a galaxy in collision



NGC 4038/8 VLA HI (blue) and CTIO Optical (green), from Hibbard, van der Hulst & Barnes 2001

What happens when two galaxies collide?

- On the largest scales, the changing gravitational fields cause the galaxies to distort their shapes tremendously to produce great streams of stars and gas that are often ripped from each of the galaxies and hurled into intergalactic space.
- Eventually (~500Myr) most of the matter, settles back into a new system which often looks very different than either of the galaxies before the event.
- When the interstellar clouds in each of the galaxies collide, they can trigger bursts of star formation resulting in very massive, luminous, short lived, stars being formed. These stars can form in large numbers and over small enough regions to produce a 'star-burst' system. If the cores have massive black holes, the systems can flare-up into quasar for millions of years. Sometimes, the luminosity from the central 1000 pcs is as much as the entire Milky Way produces.
- individual stars, they are so small compared to their average distances that they rarely if ever interact

Starbursts- What triggers a starburst?

- Interactions and mergers: When galaxies collide, the resulting compression of the interstellar medium and the changing gravitational field can induce large amounts of star formation.
- Collisions also set in motion a chain of events that cause a lot of the gas from the two galaxies to fall down the gravitational well into the nuclear region of the merged galaxy, where the high gas density enhances the processes triggering star formation and provides a lot of fuel to make many stars.
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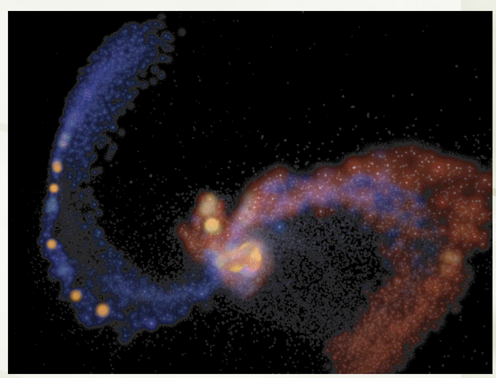
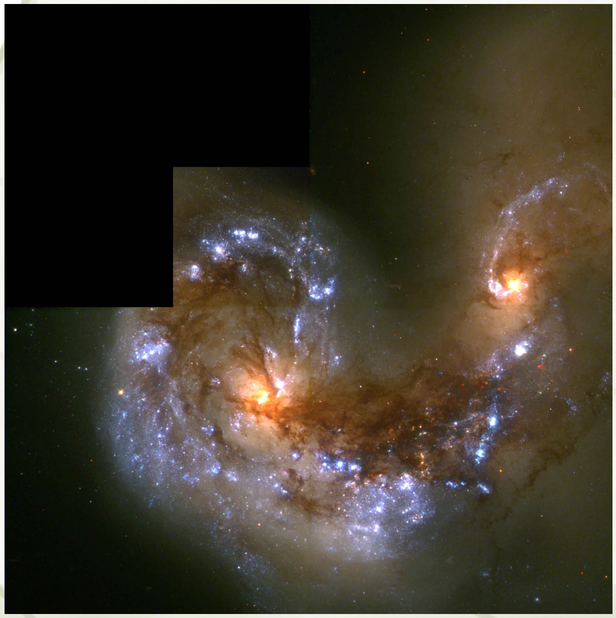
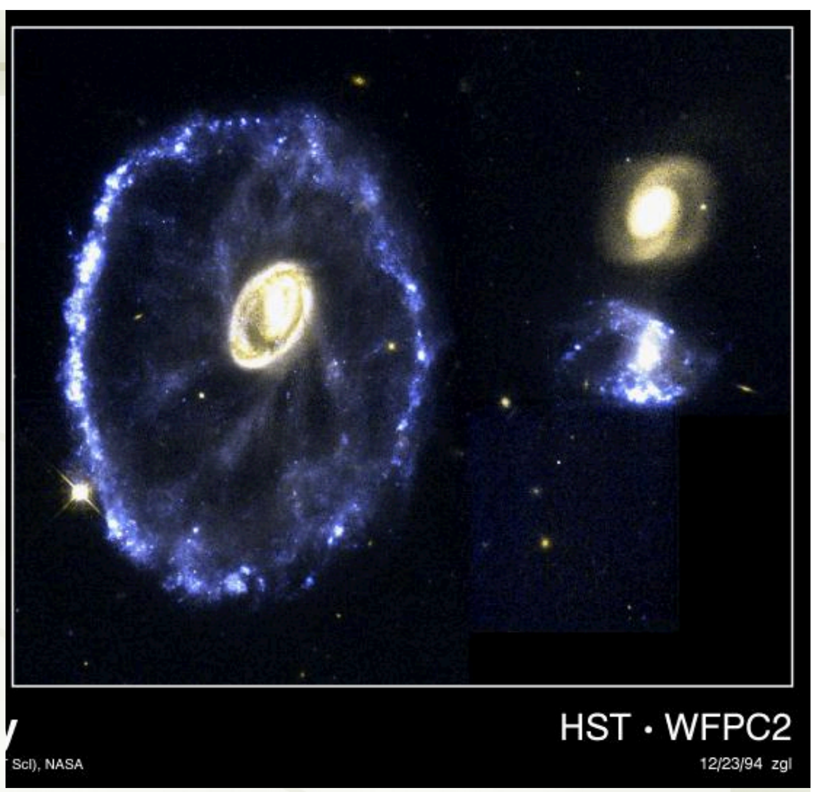


Theoretical merging disk galaxies. The gas is colored red and the stars blue.
The stars are distributed roughly as in the Antennae galaxy, and the gas has been collected into dense concentrations that become the sites for vigorous star formation

Close Up with HST



- A bulls-eye collision- the Cartwheel galaxy
- ring-like structure ~150,000 ly across (larger than the Milky Way)
- The ring is a wave of star formation traveling outwards at about ~10^2 km/sec
- As the wave passes outward it compresses and heats the matter that it passes through, triggering the star formation.



- spiral galaxies NGC 2207 and IC 2163 will slowly pull each other apart, creating tides of matter, sheets of shocked gas, lanes of dark dust, bursts of star formation, and streams of cast-away stars.

Starburst

- Sometimes the energy deposited in the interstellar medium of the starburst galaxy is so large that a 'galactic wind' occurs- ejecting heavy elements formed in the massive stars and other material into the intergalactic medium

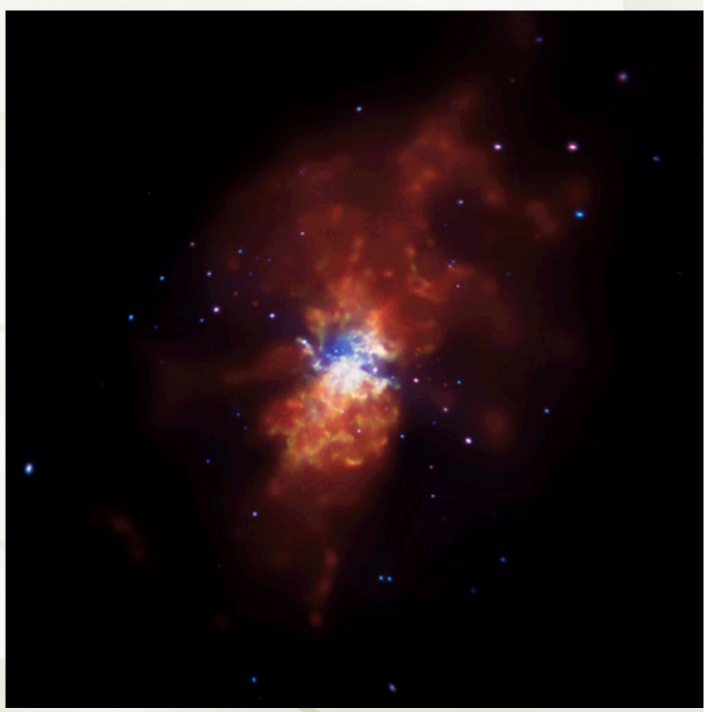
M82- grey/blue is starlight; red is ejected gas (dark lanes are due to dust
M. Westmoquette, L. Smith (UCL), J. Gallagher (Wisconsin), WIYN//NSF, NASA/ESA

Physics Beyond Gravity

- Starburst-driven galactic winds can transport mass, in particular metal enriched gas, and energy out of galaxies and into the intergalactic medium.
- These outflows directly affect the chemical evolution of galaxies, and heat and enrich the intergalactic and intracluster medium
- Similar phenomena can occur due to quasars

The Galactic Wind Can be Very Hot

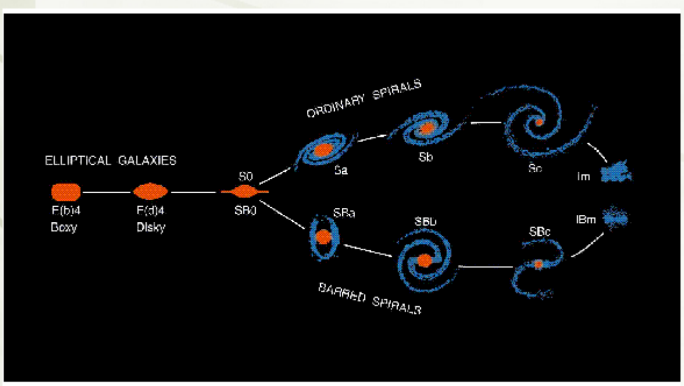
- X-ray Image of M82 - only very hot ($T>2x10^6k$) gas emits in the x-rays



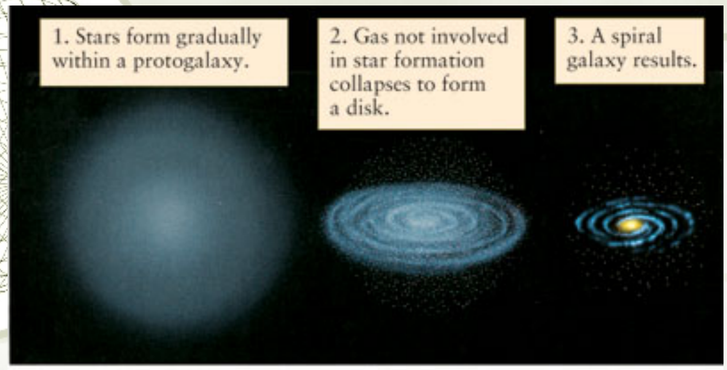
The Two Big Types of Galaxies and their Origins

- The properties of galaxies form a distinct pattern:
- Ellipticals tend to be massive, red and old
- Spirals less massive blue and 'younger'
  - Colors are related to the amount of star formation at present

"You've seen spiral galaxies, you've seen elliptical galaxies..."

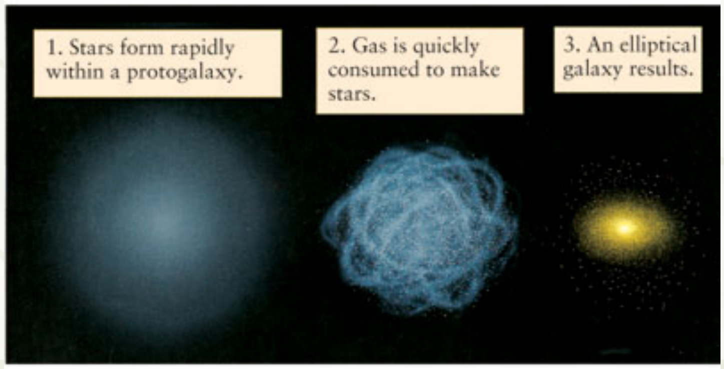


see: Kormendy J., Bender R. (1996) *ApJ*, **464**, L119



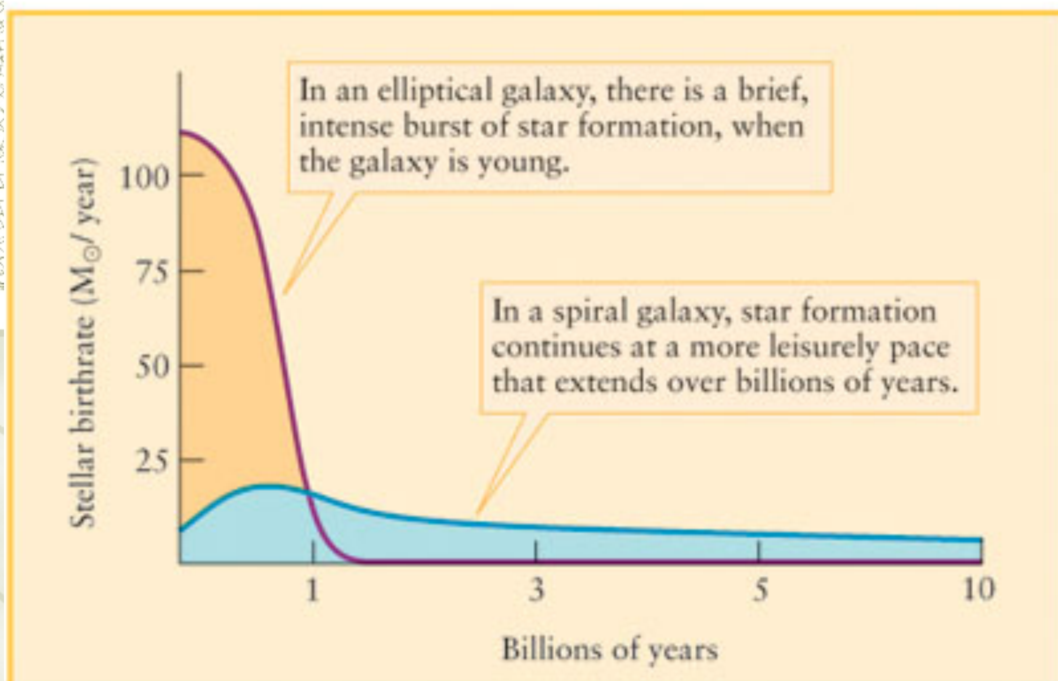
(a) Formation of a spiral galaxy

High angular momentum halo



(b) Formation of an elliptical galaxy

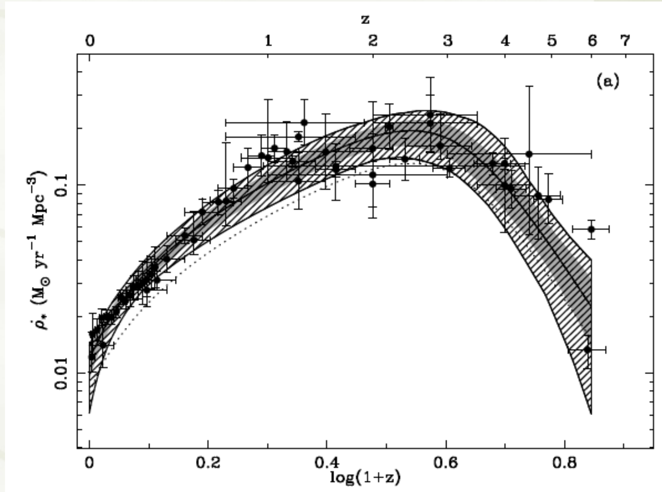
Low angular momentum halo



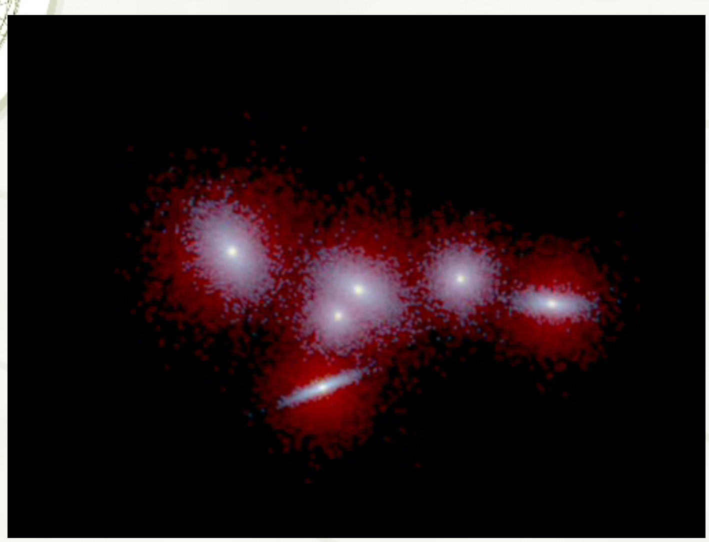
(c) The stellar birthrate in galaxies

Star Formation History of the Universe

- The rate of star formation peaked at z~2 when the universe was 3.3 Gyrs old- 10Gyrs ago
- Peak of elliptical galaxy star formation was at 2-4Gyrs after the Big Bang and stopped rapidly thereafter
- Spirals keep on going



Computer simulation of galaxy collisions that make a big elliptical



J. Barnes, UH

See

A telescope designed to look back in time (http://www.cnn.com/videos/us/2015/04/23/orig-webb-telescope.cnn?iid=ob_homepage_tech_pool&iref=obnetwork)