Lecture 23 : Structure Formation II

- Large scale structure in the Universe
- Origins of structure

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This week: read Chapter 15

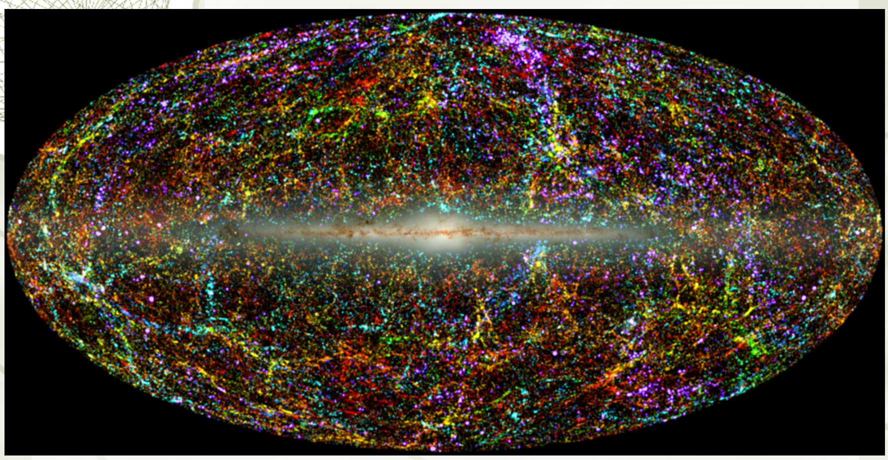
RECAP: Homogeneity

- The universe started from a near-perfectly smooth state: peaks and valleys in the CMB are at the level of about 1 part in 10^5

RECAP: Homogeneity

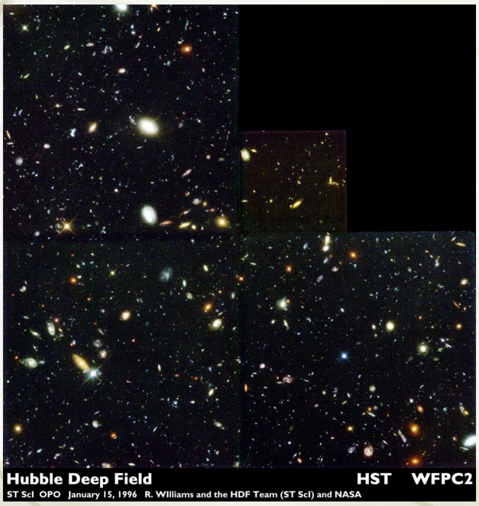
- The universe started from a near-perfectly smooth state: peaks and valleys in the CMB are at the level of about 1 part in 10^5
- Today, the universe is smooth (homogeneous) averaged over large scales… (what's the name of this principle?)

2MASS view of infrared galaxies



Blue: near; red: far
Credit: T. Jarrett, IPAC

But, on smaller scales, the present Universe is not homogeneous!!



The big question…

- How did we get from the almost perfect homogeneity just after the big bang to the "lumpy" situation in the Universe now?

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- How did we get from the almost perfect homogeneity just after the big bang to the “lumpy” situation in the Universe now?
- Basic answer: gravitational collapse.

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- Expect:
  - Top-down if dark matter is hot
  - Bottom-up if dark matter is cold
- Why?
  - Because hot dark matter particles would have large random motions that would tend to smooth out smaller-scale perturbations

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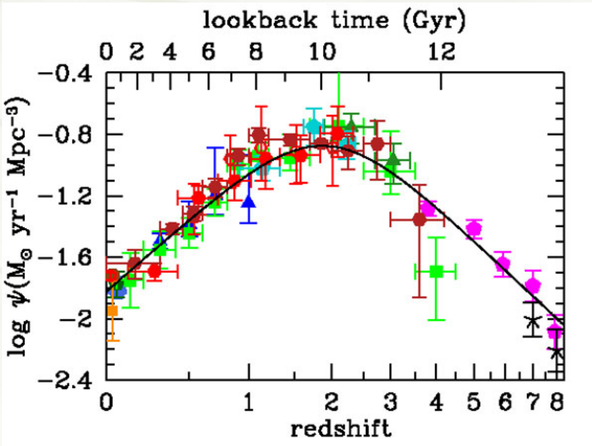
Cosmic history of star formation

Star formation activity per Mpc^3



Madau & Dickinson (2014), ARAA 52

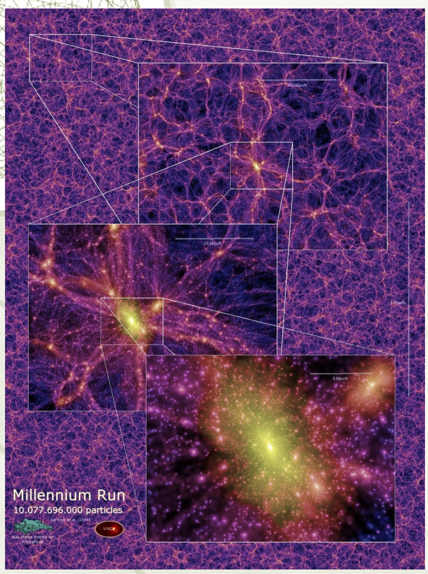
III : THE FORMATION OF STRUCTURE

- 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 CBR observations and correlation functions 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
    - EG z=30 corresponds to ≈80Myr after Big Bang, but <1% of present age of Universe

- 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 "Millenium simulation"

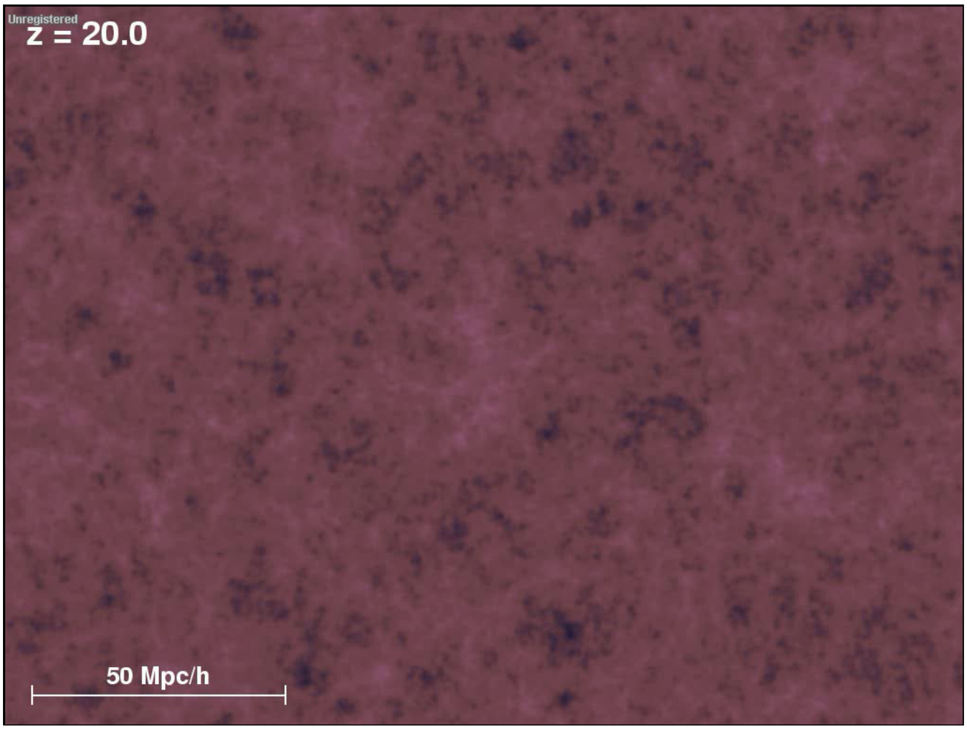


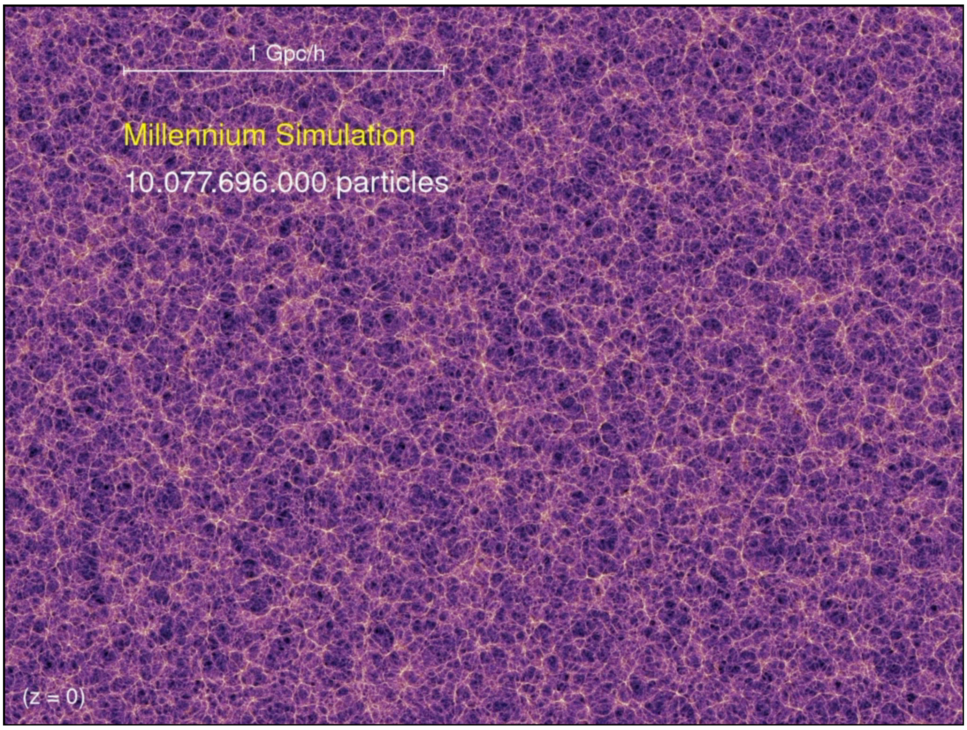
The largest N-body simulation carried out until a few years ago:

- Follows what becomes 20 million galaxies over 2 billion years
- Volume (2 Glyr)^3
- More than 10^{10} particles
- 25 Terabytes of data produced

Image (credit: *V.Springel*):

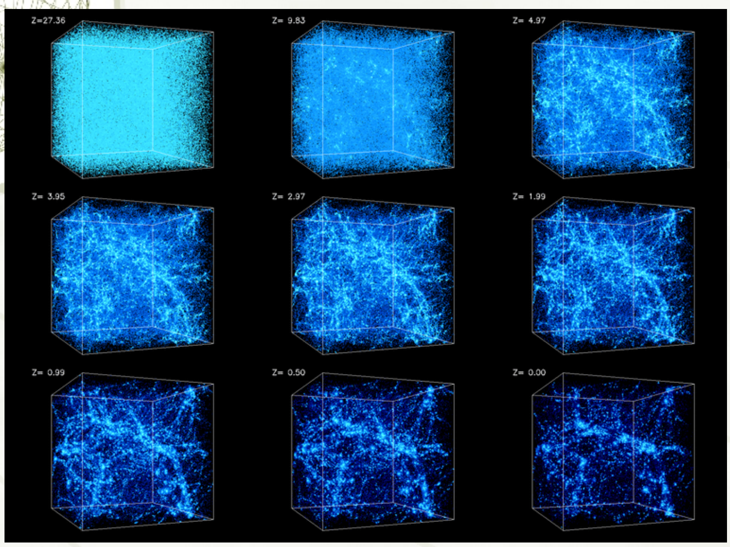
20Mpc thick slice at z=0 with 4x zoomed regions


Unregistered
z = 20.0
50 Mpc/h


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

- 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

Formation of large-scale structure: snapshots



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

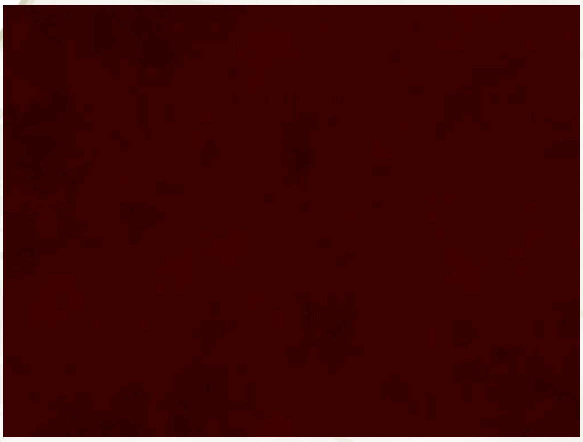
Features to notice…

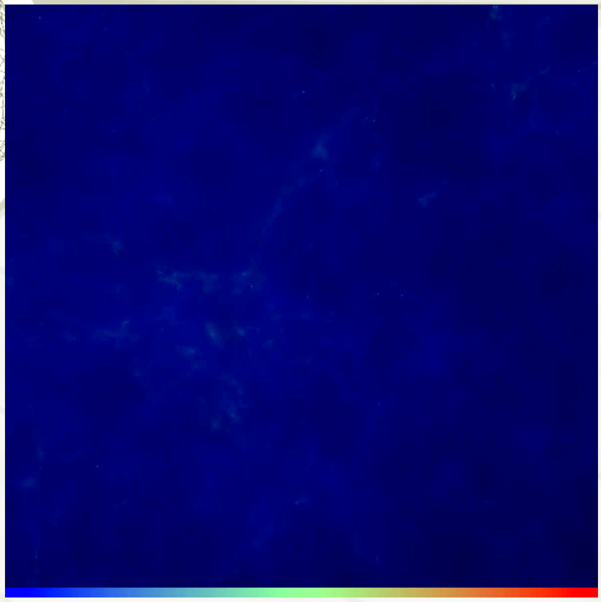
- Filaments become more prominent over time
- Clusters form at intersections of filaments
- Little changes from $z = 0.5$ to $z = 0$ (present), because Universe becomes dominated by dark energy!
- On large scales at late times, gravity cannot compete with the dark energy-driven acceleration and the growth of structures ceases 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 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.)





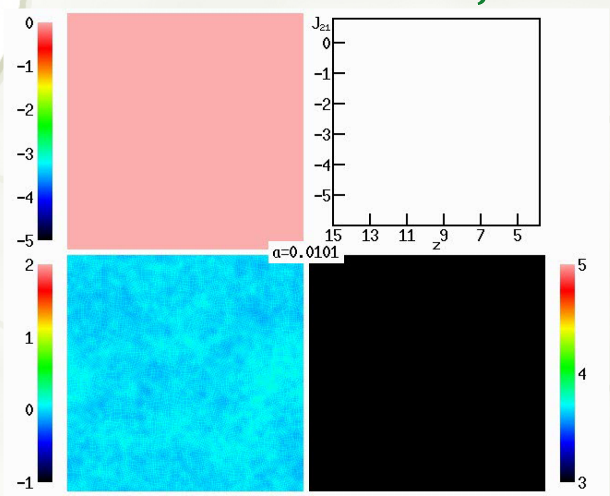
Things to notice…

- 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.

Aquarius simulation: making something like the Milky Way

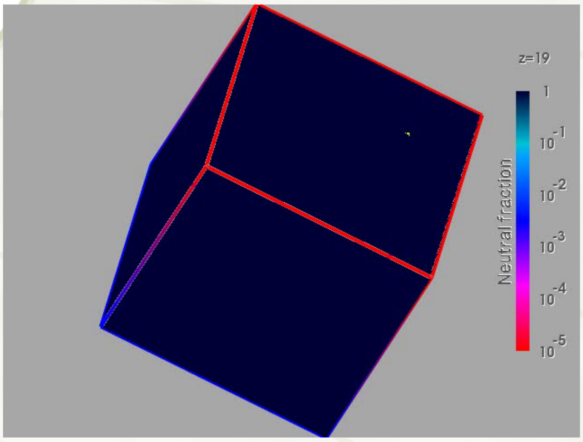
- Can also follow more complex processes within galaxies as they form…
  - Star formation will occur
  - Massive stars produce ultraviolet radiation
  - Radiation will escape from galaxies and reionize the gas in the Universe
    - Gas was previously neutral (atoms) starting at z=1100

Reionization due to star formation



Nick Gnedin (U.Chicago)

Reionization due to star formation



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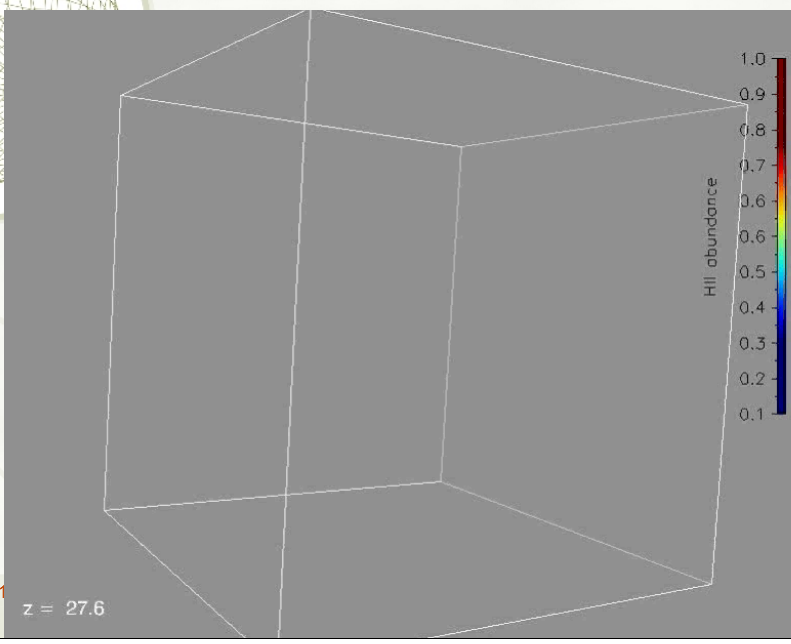
Nick Gnedin (U.Chicago)

Formation of the First Galaxies (Ricotti et al 2002)



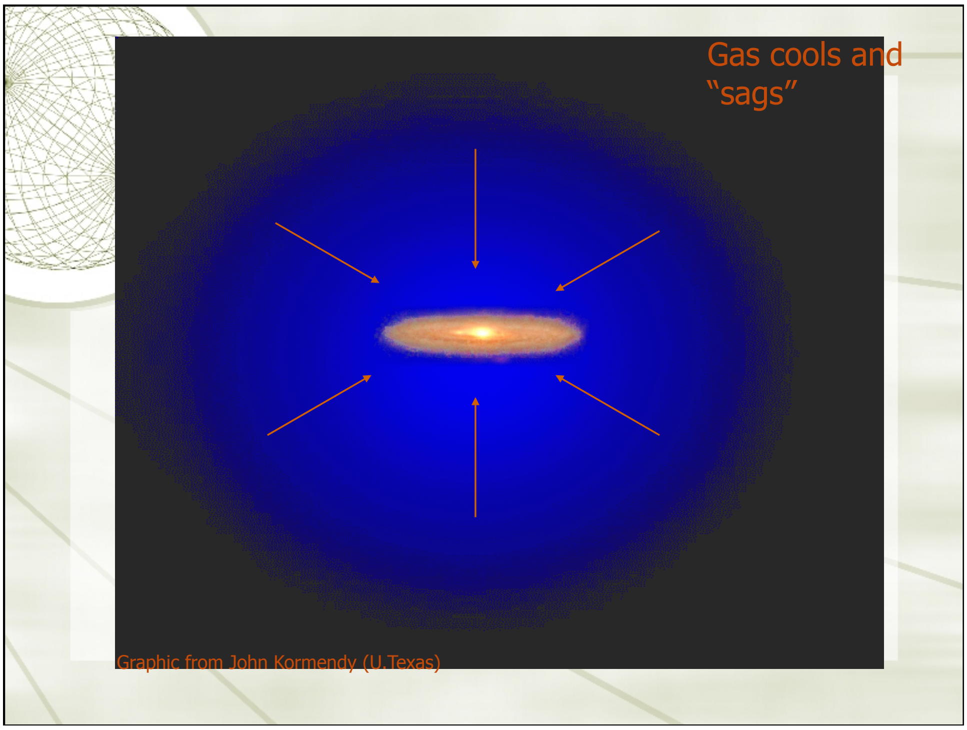
Reionization due to star formation

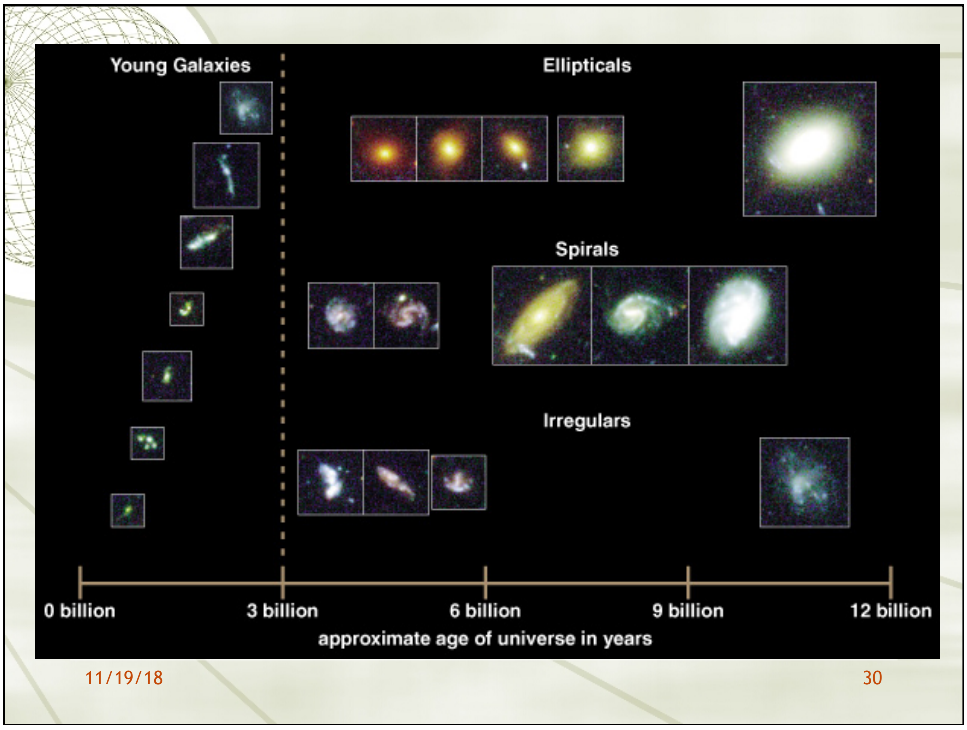
Continuous

Bursty

Structure formation: summary

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


Gas cools and "sags"
Graphic from John Kormendy (U.Texas)


Young Galaxies
Ellipticals
Spirals
Irregulars
0 billion
3 billion
6 billion
9 billion
12 billion
approximate age of universe in years
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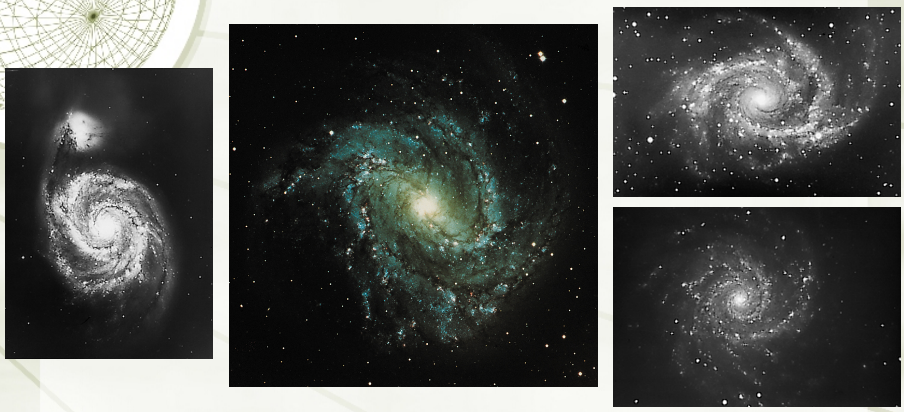
30

Typical spiral galaxies



"Disk" orbits, young stars (Pop I)

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

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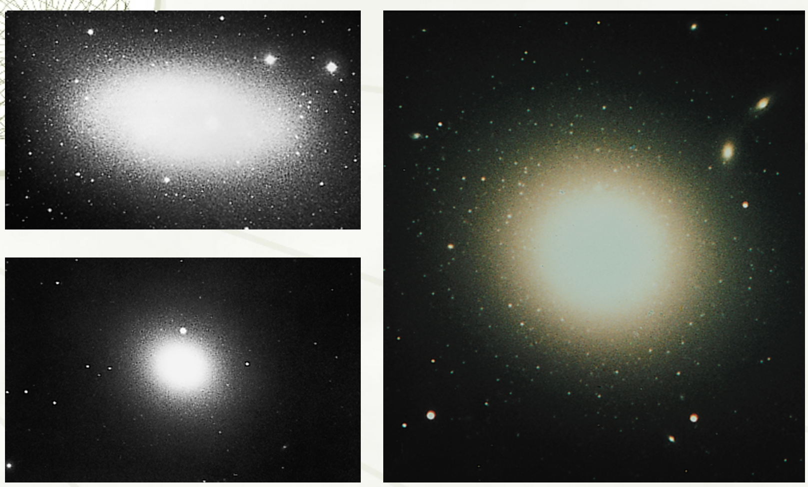
Typical elliptical galaxies



"Bulge" orbits, old stars (Pop II)

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

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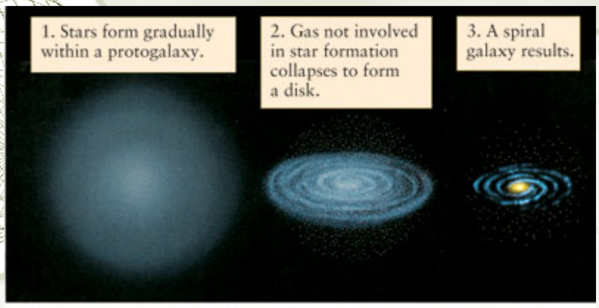
Irregular galaxies

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

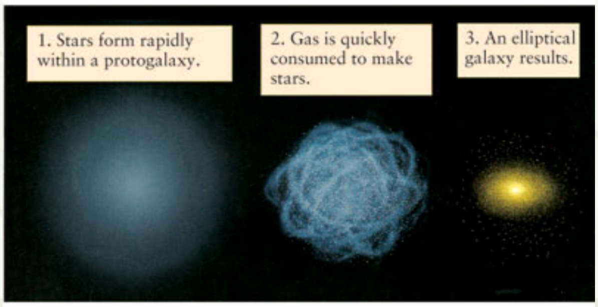
Figure 16.5, Arny, *Explorations,* McGraw-Hill

Feedback processes are very important



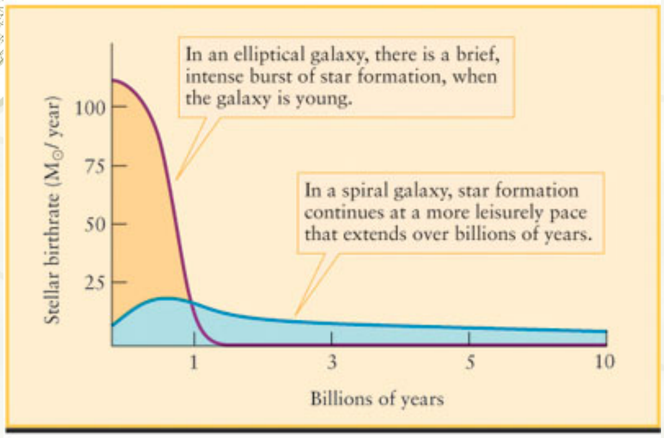
(a) Formation of a spiral galaxy

High angular momentum halo

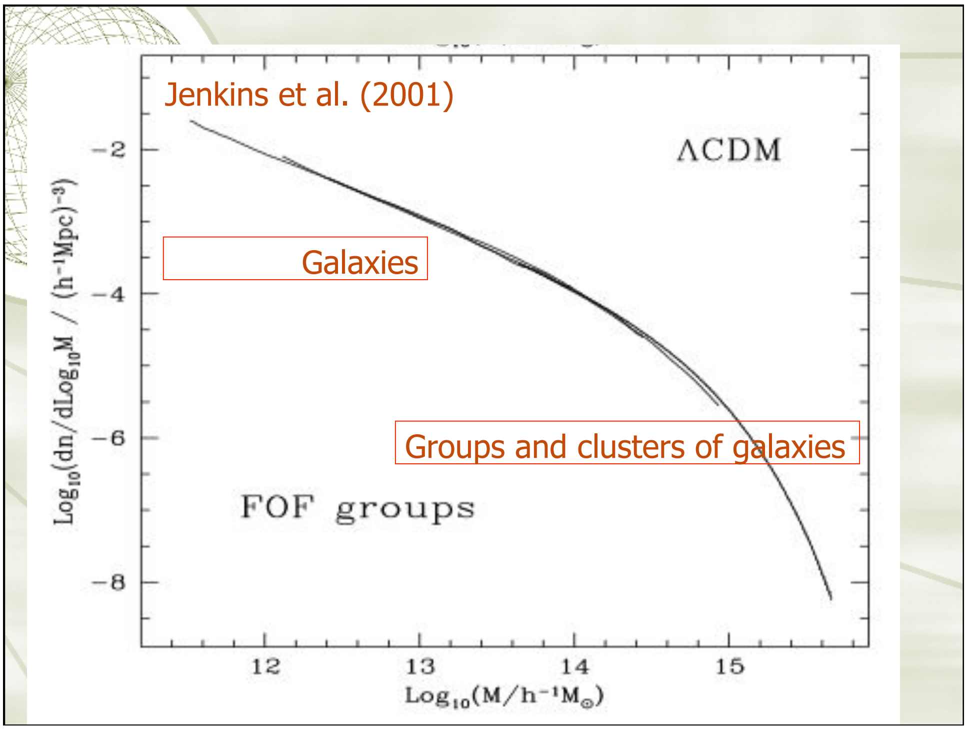


(b) Formation of an elliptical galaxy

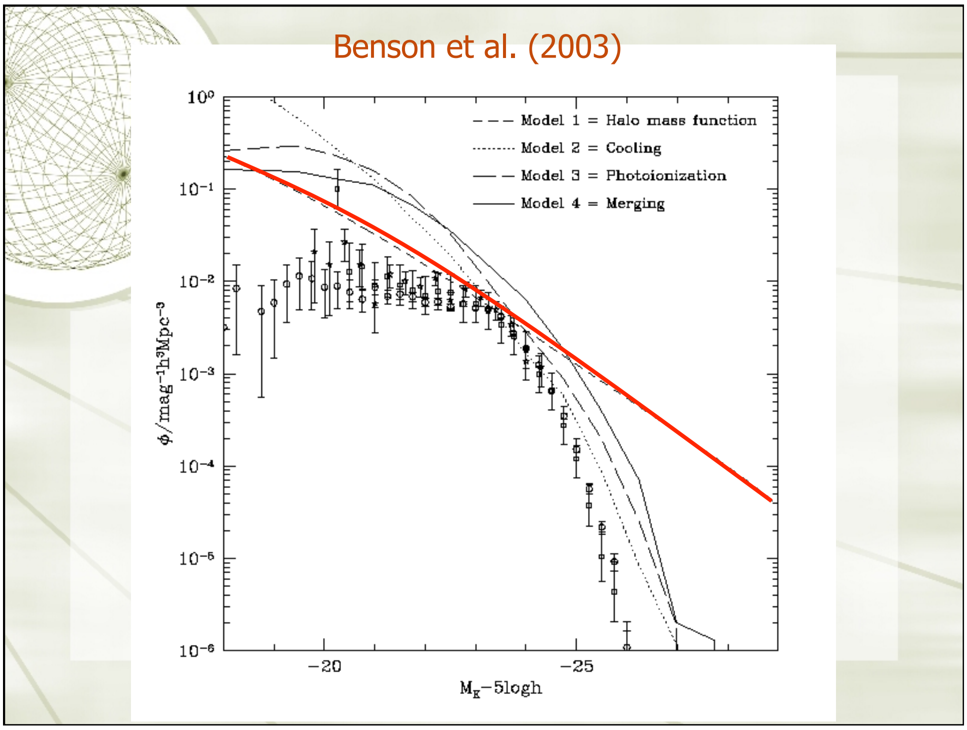
Low angular momentum halo



(c) The stellar birthrate in galaxies



Jenkins et al. (2001)
ΛCDM
Galaxies
Groups and clusters of galaxies
FOF groups
Log10(dn/dLog10M / (h⁻¹Mpc)⁻³)
-2
-4
-6
-8
12
13
14
15
Log10(M/h⁻¹M⊙)



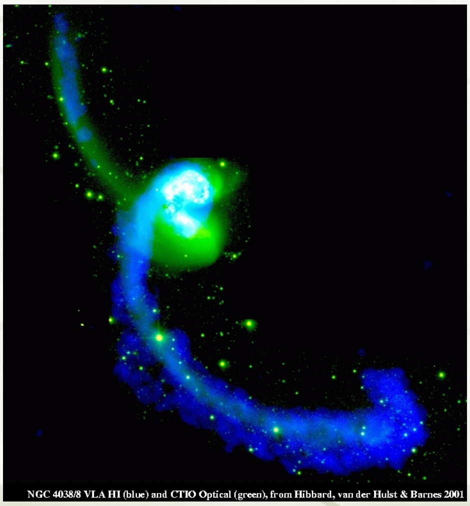
Benson et al. (2003)
Model 1 = Halo mass function
Model 2 = Cooling
Model 3 = Photoionization
Model 4 = Merging
φ/mag⁻¹h³Mpc⁻³
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
−20
−25
M_K−5logh

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.

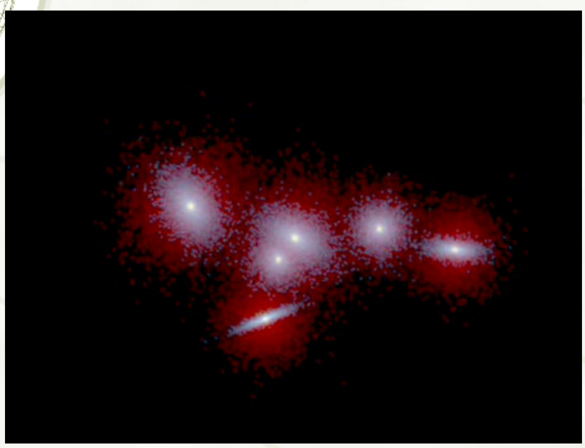
The Antennae Galaxy



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

Close Up with HST

Computer simulation of galaxy collisions that make a big elliptical



J. Barnes, UH

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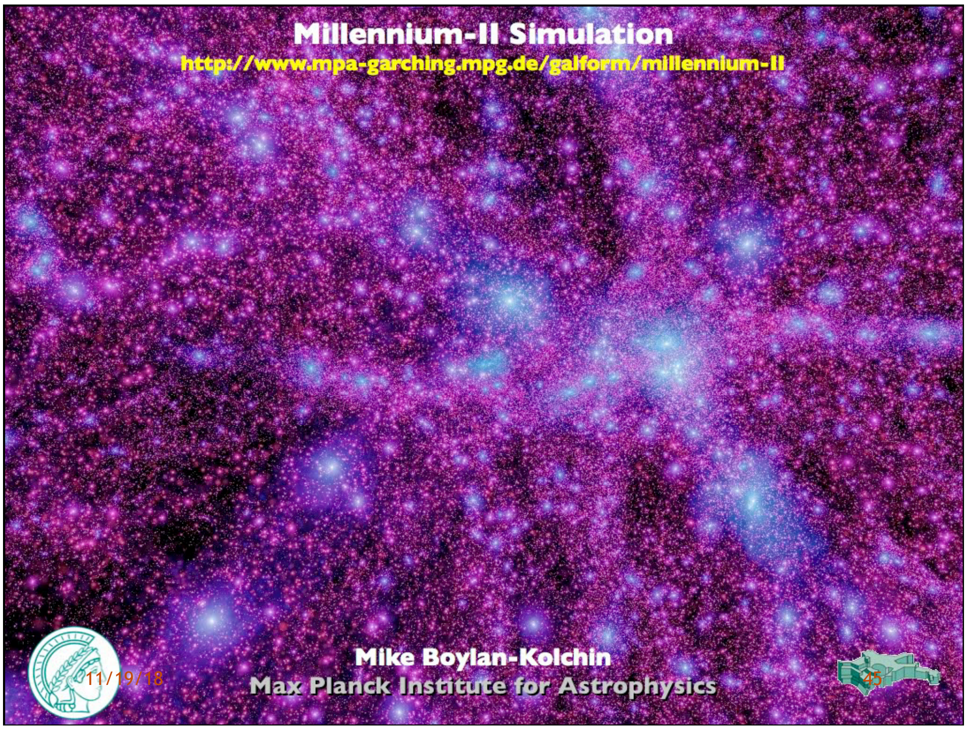

Universe starts simple but becomes very complex!

- Form order to disorder, but in special places in the universe order wins
- Life and intelligent life around stars is possible because of the sun: we create a lot of entropy but locally entropy can decrease!

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Next time…

- Cosmological puzzles…
- …and how "inflation" solves them

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