Einführung in die Astronomie II
Teil 15

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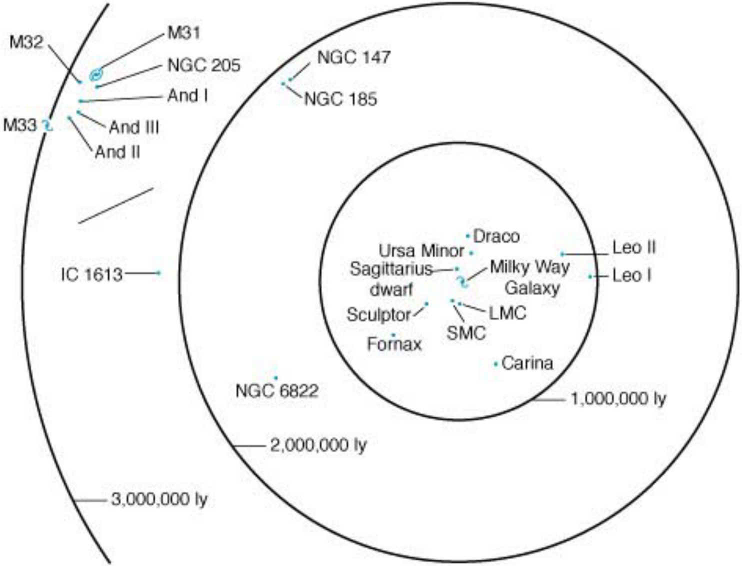
Overview part 15

- clusters of galaxies
- formation and evolution
- gravitational lensing

Clusters and Superclusters !!

- galaxies not randomly scattered in space
- form *clusters* of galaxies
- clusters can be *poor* to *rich*
- poor clusters $\rightarrow$ *groups*
- Example: the *Local Group*

Local Group



M32
M31
NGC 205
And I
M33
And III
And II
NGC 147
NGC 185
IC 1613
Draco
Ursa Minor
Sagittarius dwarf
Milky Way Galaxy
Leo II
Leo I
Sculptor
LMC
SMC
Fornax
Carina
NGC 6822
1,000,000 ly
2,000,000 ly
3,000,000 ly

Local Group

- about 30 galaxies, including ours
- most are dwarf ellipticals
- we still find smaller galaxies as members of the local group

Clusters and Superclusters

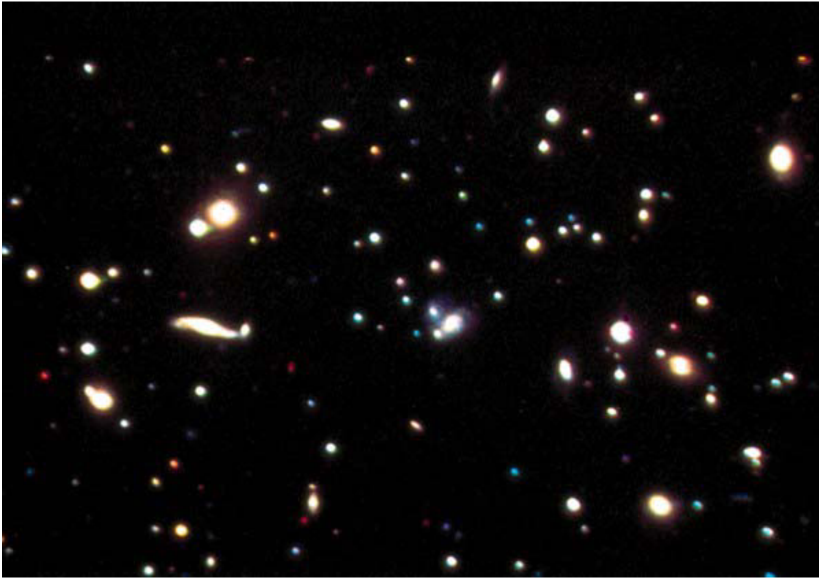
- closest rich cluster: *Virgo cluster*
  - about 2000 galaxies
  - $10^\circ \times 12^\circ$ area in the sky
  - 15 Mpc distance
  - 3 Mpc diameter
  - center of Virgo cluster: 3 giant ellipticals
  - one of those about the size of the local group ...

Virgo cluster (center)

Clusters and Superclusters

- clusters are also classified by their overall shape
- *irregular cluster*: scattered distribution (Virgo)
- *regular cluster*: nearly spherical distribution (local group)
- nearest regular rich cluster: Coma cluster
- shape of a cluster is related to dominant type of galaxies
- rich regular clusters $\rightarrow$ mostly elliptical and S0
- irregular $\rightarrow$ even mix

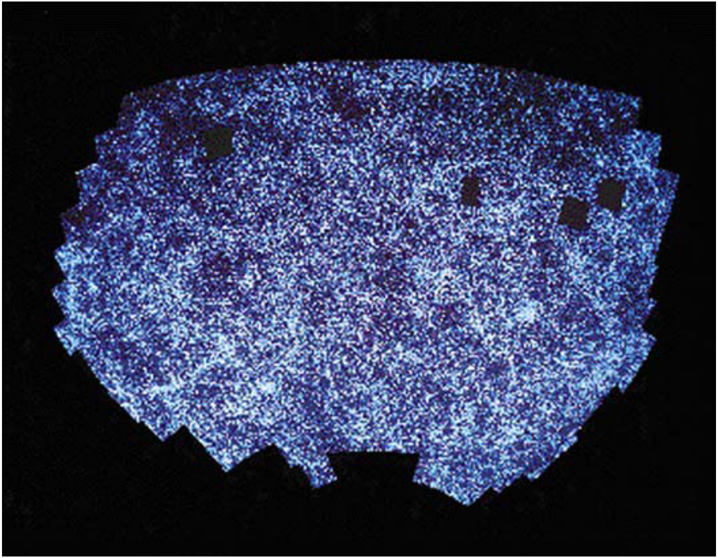
Hercules cluster



Clusters and Superclusters !!

- galaxy clusters group in huge *superclusters*
- dozens of clusters in a 30 Mpc diameter region
- form complex lacy patterns in the sky!
- maps of millions of galaxies (1980's): out to 160 Mpc
- *voids*: regions with few galaxies
  - seem to be elongated or tube-shaped
  - 30 to 120 Mpc across
  - clusters of galaxies concentrate on the surfaces of voids
  - give clues about the early universe

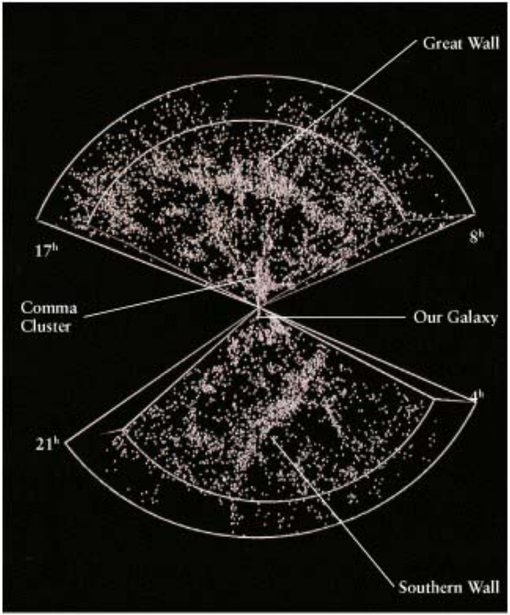
supercluster !!



Clusters and Superclusters !!

- maps also show large structures
  - *Great Wall*: 80 by 230 Mpc region
  - similar: *Southern Wall*: 100 Mpc region
  - sizes of structures seem to be limited by available observations!

large scale structure !!



Collisions: Overview !!

- galaxies move around and collide!
- Milky Way will collide with M31 in a few billion years
- collision compresses gas and dust clouds as they collide with each other
- note: stars don't collide, too much space between them!
- clouds can be "stopped" by a collision and heated to high temperatures
- $\rightarrow$ hot *intracluster gas* at $10^{7 \dots 8}$ K

Collisions: Overview !!

- compressed gas clouds start a burst of star formation!
- $\rightarrow$ *starburst galaxies*
- bright centers with warm dust, very active star formation

Starburst galaxy

Collisions: Overview

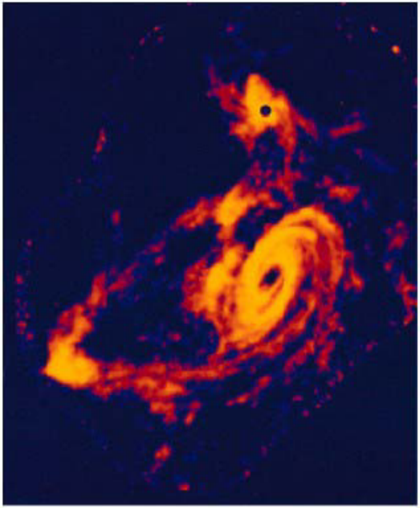
- shows streams of H gas with loops and twists
- $\rightarrow$ several close encounters!
- similar stream connects Milky Way to LMC
- tidal forces deform galaxies and can eject stars into intergalactic space
- stars can also slow down and galaxies can merge
- when the Galaxy collides with M31 a huge number of new stars will form, SNe will explode in large numbers
- $\rightarrow$ sky will be more dramatic than today ...

Collisions: Overview

- *galactic cannibalism*: massive galaxies absorb smaller ones
- maybe the reason for giant ellipticals!
- close encounters between galaxies can also form spiral arms

Interacting galaxies

Interacting galaxies



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Collisions: Overview

- Interactions between galaxies are common:
  - spacing in clusters $\approx$ 100 times size
  - more early type galaxies in the center of clusters
  - more pronounced for denser clusters
  - interactions increase velocity dispersions
    $\rightarrow$ destroy disk structures and create $r^{1/4}$ profiles
  - $\geq$ 50% of H I disks are warped
  - $\geq$ 50% of E's show *concentric rings of stars*
  - intergalactic hot gas in rich clusters with mass $\approx$ mass of stars in cluster

Collisions !!

- chance of star-star collisions extremely low
- $\rightarrow$ interaction is gravitational
- simple model:
  mass M (globular cluster, small galaxy) moves through a "sea" of stars, gas, clouds & dark matter of constant density ρ (the "target galaxy")
- $\rightarrow$ it will move in (nearly) a straight line if $M \gg m$ (m: typical mass of an object in the target)
- if M moves *slowly* through the target:
- M pulls material closer to it while moving through the target

Collisions !!

- → creates a *high-density wake* trailing M

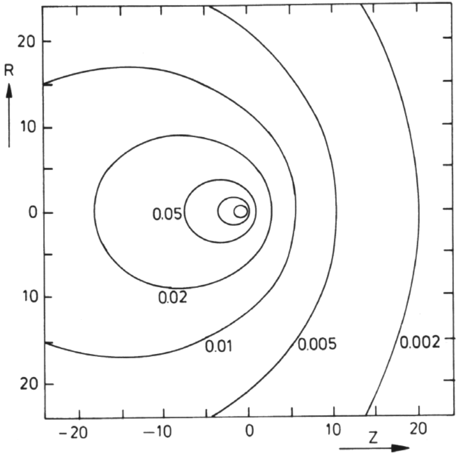


Figure 24.5 The fractional enhancement in the density of stars caused by the motion of a mass M in the positive z-direction. (Figure from Mulder, *Astron. Astrophys.*, *117*, 9, 1983.)

Collisions !!

- the wake creates a gravitational force on M slowing in down
- $\rightarrow$ *dynamical friction*
- dependencies of dynamical friction force f_d:
    1. proportional to ρ
    2. proportional to M^2:
        - 2.1 M creates the wake by pulling material in
        - 2.2 M interacts with wake itself

Collisions !!

- inversely proportional to v_M^2:
  1. v_M increases $\rightarrow$ M has less time to affect any object in the target
  2. v_M increases $\rightarrow$ M is farther away when wake forms

Rapid encounters !!

- v_M so large that stars of target cannot react
- $\rightarrow$ dynamical friction unimportant
- *impulse approximation*
- positions of stars do not change
  $\rightarrow$ potential energy U of galaxies does not change
- velocities of stars *do* change "randomly"
- $\rightarrow$ kinetic energy of the relative motions of the 2 galaxies is transferred into internal kinetic energy

Rapid encounters !!

- Suppose one galaxy gains internal kinetic energy
- before collision: virial equilibrium (i for "initial")

$$2K_i = -U_i = -2E_i$$

- during encounter:

$$K_i \rightarrow K_i + \Delta K$$

- total energy has increased ($U = \mathrm{const.}$)

$$E_f = E_i + \Delta K$$

- $\rightarrow$ galaxy no longer in virial equilibrium

Rapid encounters !!

- after virial equilibrium is reestablished (few orbital periods):

$$K_f = -E_f = -(E_i + \Delta K) = K_i - \Delta K$$

- internal kinetic energy is *reduced* after encounter
- $\rightarrow$ increased U

Rapid encounters !!

- galaxy can do this by *expansion* or *evaporation*
- evaporation could be in the form of *streams* of stars and gas
- cools the galaxy and reestablishes virial equilibrium
- combination of both can occur (more likely in head-on collisions)

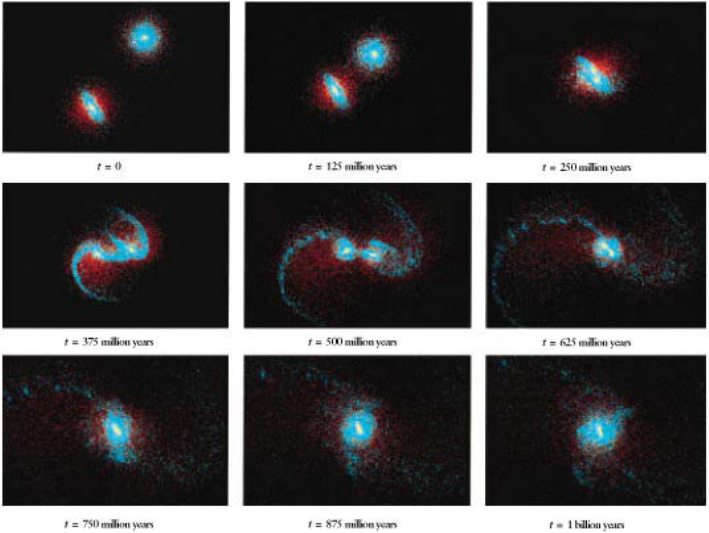
Mergers

- pair of galaxies that is gravitationally bound
- $\rightarrow$ lose orbital energy during encounters
- $\rightarrow$ will *merge* after enough encounters
- tidal forces will also remove orbital kinetic energy $\rightarrow$ leads to streams of stars and gas (Magellanic Stream??)
- $\rightarrow$ *tidal stripping*
- Magellanic Clouds will merge with the Galaxy in ≈ 10 Gyrs
- every giant galaxy will "devour" a few satellites
- gravitational torques $\rightarrow$ counter-rotating cores (some E's)

Collisions

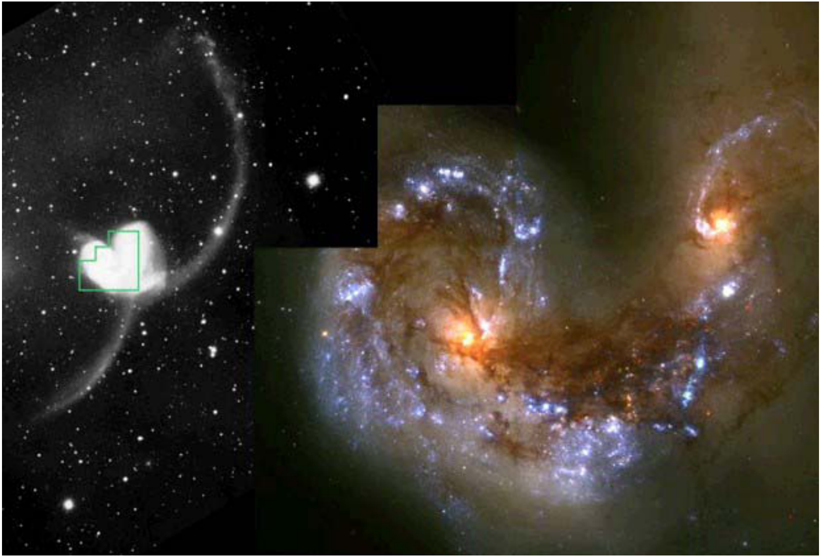
- actual encounter or merger is complex
- followed by numerical simulation, N-body codes
- produce many observed features (*tidal-tail galaxies*)
- close slow encounters deliver bridges and tails

Merger



t = 0
t = 125 million years
t = 250 million years
t = 375 million years
t = 500 million years
t = 625 million years
t = 750 million years
t = 875 million years
t = 1 billion years

Interacting galaxies



Collisions

- “best” effect if orbital angular speed $\approx$ angular speed of some disk stars
- tidal bulges develop on both sides
- dark matter halo decreases time scale for merger
- if satellite moves with an inclination to the disk
  $\rightarrow$ disk warps
- warp can survive for up to 5 Gyr
- $>$ 50% of galactic disks are warped

Collisions

- interaction causes gas compression and cloud collisions
- star forming regions develop
- interacting galaxies *bluer* than field galaxies
- *starburst galaxies*: 98% of L in the IR, extremely bright in IR
- not all of them are interacting galaxies ...

Collisions

- interactions very important for E's:
- cD's are found *only* in the company of other galaxies
- $>$ 50% have multiple nuclei
- have lots of GC's
- $>$ 50% of E's have concentric shells of stars

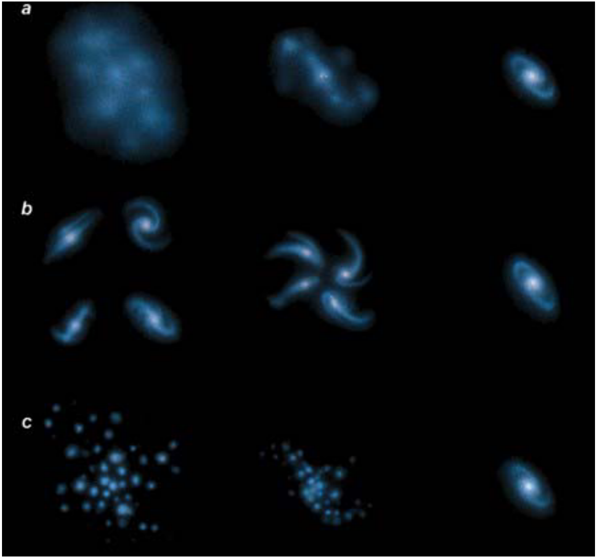
Formation of Galaxies

- same problems as with stars: too slow to observe directly
- look at distant galaxies: they are also *younger*!
- galaxies were bluer in the past than today
- $\rightarrow$ vigorous star formation
- appears to take place in bursts
- HST images show many more spirals among younger galaxies
- today: 5%, early on: 30%

Formation of Galaxies

- many of those young spirals show signs of collisions/mergers
- collisions seem to be responsible for their demise by removing gas due to star formation bursts
- ellipticals were already developed 4 billion years ago!
- appear to have formed in burst of star formation 10-15 billion years ago

Formation of Galaxies



Formation of Galaxies !!

- how do galaxies form?
- 1960's: contraction of huge clouds of gas
- 1970's: merging of several clouds
- or many really small clouds
- merging of gas clouds seems to be the correct idea
- HST images of 11 billion year old galaxy like objects with irregular shapes
- seem to be the merging clouds that make galaxies
- still unresolved question!

Formation: Details

- Eggen–Lynden-Bell–Sandage or *top-down* model:
- rapid collapse of pre-galactic nebula
- oldest halo stars formed early on while on nearly spherical orbits
- explains why halo stars are metal-poor
- first generation of stars $\rightarrow$ SNe $\rightarrow$ slow enrichment of metals in the ISM
- rapid collapse slowed when collisions became more frequent
  $\rightarrow$ galaxy heats up
- angular momentum conserved $\rightarrow$ flattening
- $\rightarrow$ disk develops

Formation: Details

- time scale estimate:

$$t_{\mathrm{ff}} = \left(\frac{3\pi}{32} \frac{1}{G\rho_0} \right)^{1/2} \approx 6.8 \times 10^8 \,\mathrm{yr}$$

- oldest bulge stars formed during initial density increase in the central regions
- bulge stars with large Z formed subsequently

Formation: Details

- problems:
  1. halo objects should orbit mostly in the same direction as the disk
     but net rotation of halo essentially zero!
  2. age spread of GCs $\approx 3\,\text{Gyr}$
     $\rightarrow$ collapse nearly a factor of 5 slower than estimated
  3. multi-component disk??
  4. systematic composition variation in GCs:
     GCs close to disk are more metal-rich than GCs farther out

Formation: Details

- model of galaxy evolution should explain *chemical evolution* of the galaxy
  $\rightarrow$ model the stellar birthrate $B(M, t)$ by

$$B(M, t)dMdt = \psi(t)\xi(M)dMdt$$

  - $B(M, t)$ stars of mass $[M, M + dM]$ born per unit volume at time $[t, t + dt]$
  - $\psi(t)$ star-formation rate (SFR) at t
  - $\xi(M)$ initial mass function (IMF)

Formation: Details

- IMF fit by power-law

$$\xi(M) = CM^{-(1+x)}$$

- Salpeter (1955): $x \approx 1.35$ (*Salpeter law*)
- modern: $x \approx 0.8$ for $M > 1.6\,\mathrm{M}_\odot$ and more complex below $1.6\,\mathrm{M}_\odot$

Formation: Details

- *closed box* model: starting with $Z = 0$ and no influx
- produces too *many* stars with low metallicity
  1/2 of stars in solar neighborhood should have $Z < 1/4$
- observed: only 2% of the F+G stars have low Z
  $\rightarrow$ *G-star problem*
- several mechanisms to help: disk started with $Z > 0$ or continuous infall of metal-poor material onto metal-rich disk or IMF change over time
- *slow* collapse: if cooling time is $> t_{\rm ff}$ (optically thick collapse)

$t_{\mathrm{cool}} > t_{\mathrm{ff}}$

- nebula cannot radiate energy away as fast as it is delivered by the collapse
- temperature rises
  $\rightarrow$ pressure rises
  $\rightarrow$ collapse halts
- for $T \approx 10^6\,\mathrm{K}$ and $n \approx 0.05\,\mathrm{cm}^{-3}$
  $\rightarrow$ mass of $M \approx 10^{12}\,\mathrm{M}_\odot$ is an upper limit for a collapsing cloud
- for $T \approx 10^4\,\mathrm{K}$ the limit changes to $10^8\,\mathrm{M}_\odot$
- galaxies should form in this mass range $\rightarrow$ compares OK to observations

$t_{\mathrm{cool}} > t_{\mathrm{ff}}$

- *however*: during the collapse, other energy sources become available
- first generation SNe send shock waves through the galaxy at 0.1 c
- shocks heat the gas to $\sim 10^6$ K and dissipate energy $\rightarrow$ collapse could slow a little
- doesn't work well enough to explain the age & metallicity problems

Bottom-up process

- density fluctuations in the early universe
- "blobs" with $M \approx 10^6 \ldots 10^8\,\mathrm{M}_\odot$ much more frequent than with $10^{12}\,\mathrm{M}_\odot$
- fragments initially evolved isolated
- formed stars, and maybe GCs in their centers
- $\rightarrow$ individual chemical evolution and history
- fragments gravitation pulled them together
- formed a spheroid of micro-galaxies
- merging of fragments begins

Bottom-up process

- near center of spheroid $\rightarrow$ density larger
  $\rightarrow$ more rapid evolution
  $\rightarrow$ old stars form and chemical enrichment is faster
  $\rightarrow$ old, metal-rich bulge!
- outer regions evolve slower (lower density)
- collisions disrupts majority of fragments
  $\rightarrow$ GCs at the cores of some of the fragments are "liberated"
- collisions raise T_{virial}
  $\rightarrow$ delays collapse by $2 \ldots 3$ Gyr

Bottom-up process

- disrupted systems lead to halo field stars and GCs
- can produce retrograde halo objects from retrograde fragments
- outer fragments evolves like individual dwarf galaxies for a while according to the top-down model
- only about 10% of the original GCs would survive
- low mass GCs disrupted (lower binding energy)
- high mass GCs spiraled in quickly (dynamic friction)

Bottom-up process

- gas clouds collide and dissipated energy
- some initial global angular momentum
  $\rightarrow$ disk of gas forms
- halo stars are not affected by the gas!

Bottom-up process

- computer simulation results:
- thick disk forms with $T \approx 10^6\,\mathrm{K}$
- denser material cools faster ($t_{\mathrm{cool}} \propto 1/n$)
  $\rightarrow$ once $T < 10^4\,\mathrm{K}$, H recombines, H I clouds form
  $\rightarrow$ star formation begins
- early SNe II keep much of the gas at $10^6\,\mathrm{K}$
- SNe increase $[\mathrm{Fe}/\mathrm{H}]$ from -1.5 to -0.5
- molecular gas settles closer to the mid-plane $\rightarrow$ thin disk

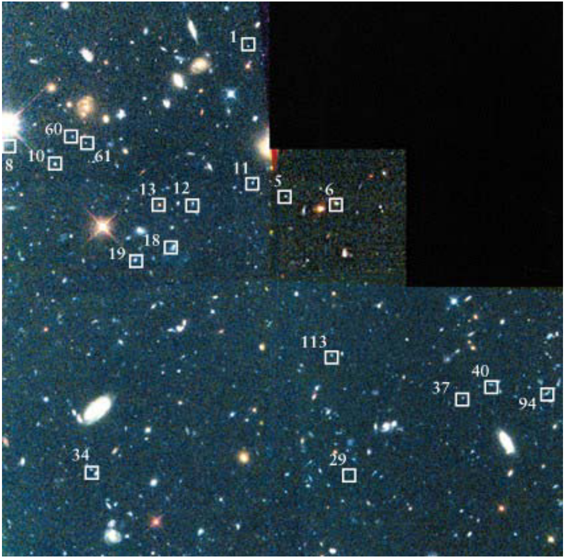
Bottom-up process

- after about 400 Myr $\rightarrow$ star formation in thick disk stops
- for $\approx 5\,\text{Gyr}$ star formation continues in thick disk
  $\rightarrow$ consumes about 80% of the gas
- today star formation continues mostly in the young thin disk
- young stars in the bulge from recent mergers with gas rich small satellites

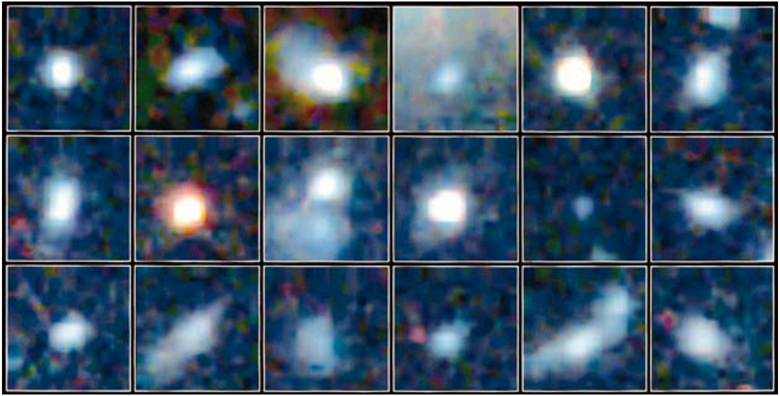
Bottom-up process

- SFR time dependent and depends on Hubble type
- ellipticals can be made by mergers of spirals
- observations of distant galaxies
  $\rightarrow$ allows observation of earlier stages in galactic evolution
- indicates that spirals were more frequent!
- more small, blue galaxies!

galaxy Legos



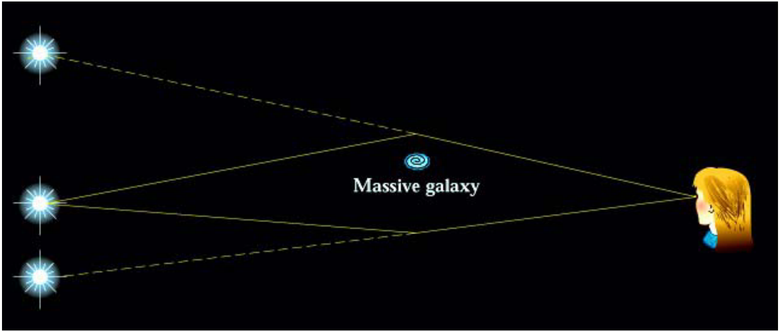
galaxy Legos



gravitational lensing !!

- bending of light by masses
- can produce multiple images of a distant object if a large mass is close to the line of sight
- a number of them has been discovered

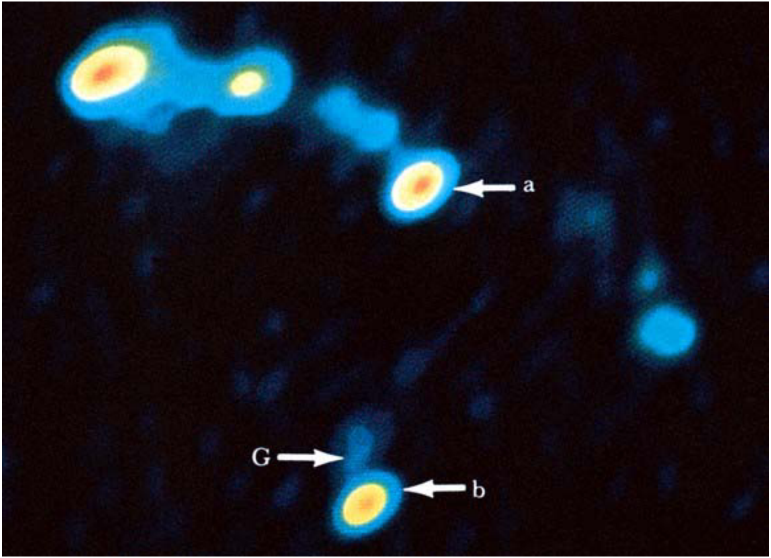
gravitational lensing !!



gravitational lensing

- example: 2 images of a distant quasar produced by a galaxy appearing in the middle of the two
- HST images show blue arcs within clusters
- $\rightarrow$ distorted images of a galaxy behind the cluster!
- use this to determine that 90% of the cluster mass is concentrated on its galaxies
- $\rightarrow$ dark matter appears to be within and close to galaxies

gravitational lensing



gravitational lensing !!