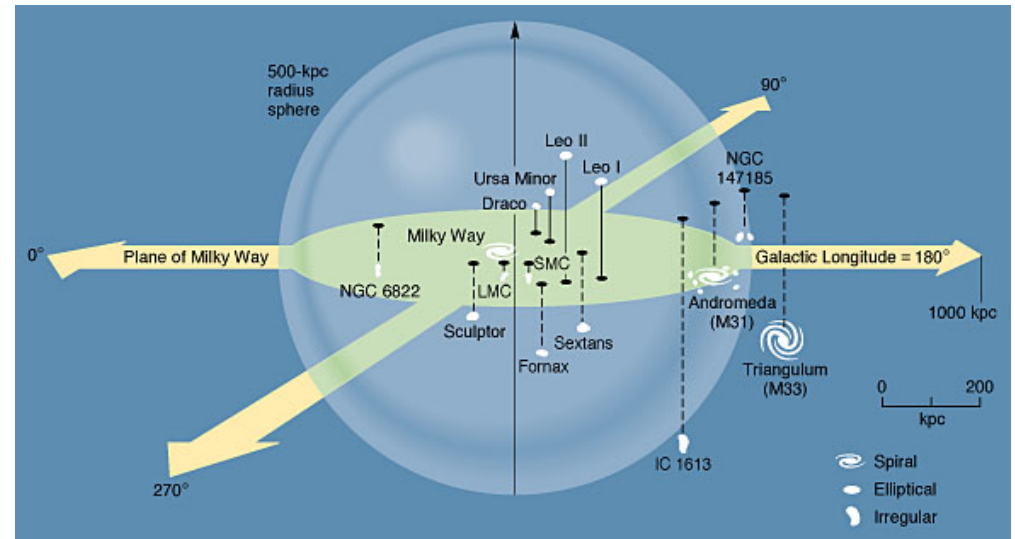


Set 3:

# Galaxy Evolution

# Environment

- Galaxies are clustered, found in groups like the local group up to large clusters of galaxies like the Coma cluster
- Small satellite galaxies like the LMC and SMC are merging into the Milky way. Recent discovery of other satellites like the Sagittarius dwarf and tidal streams



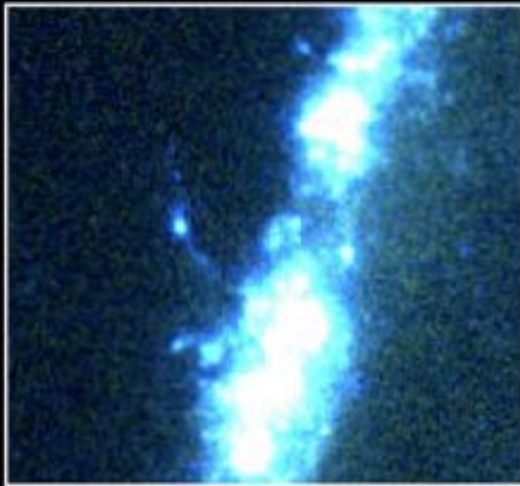
# Environment

- cD galaxies in centers of rich galaxy clusters are the products of frequent mergers in the cluster environment.
- HST images of galaxies in the process of merging
- Theoretically, structure in the universe is thought to form bottom up from the merger of small objects into large objects
- Over the lifetime of the universe, galaxy evolution is a violent process

# Antennae Galaxies



# Cartwheel Galaxy



**Cartwheel Galaxy**

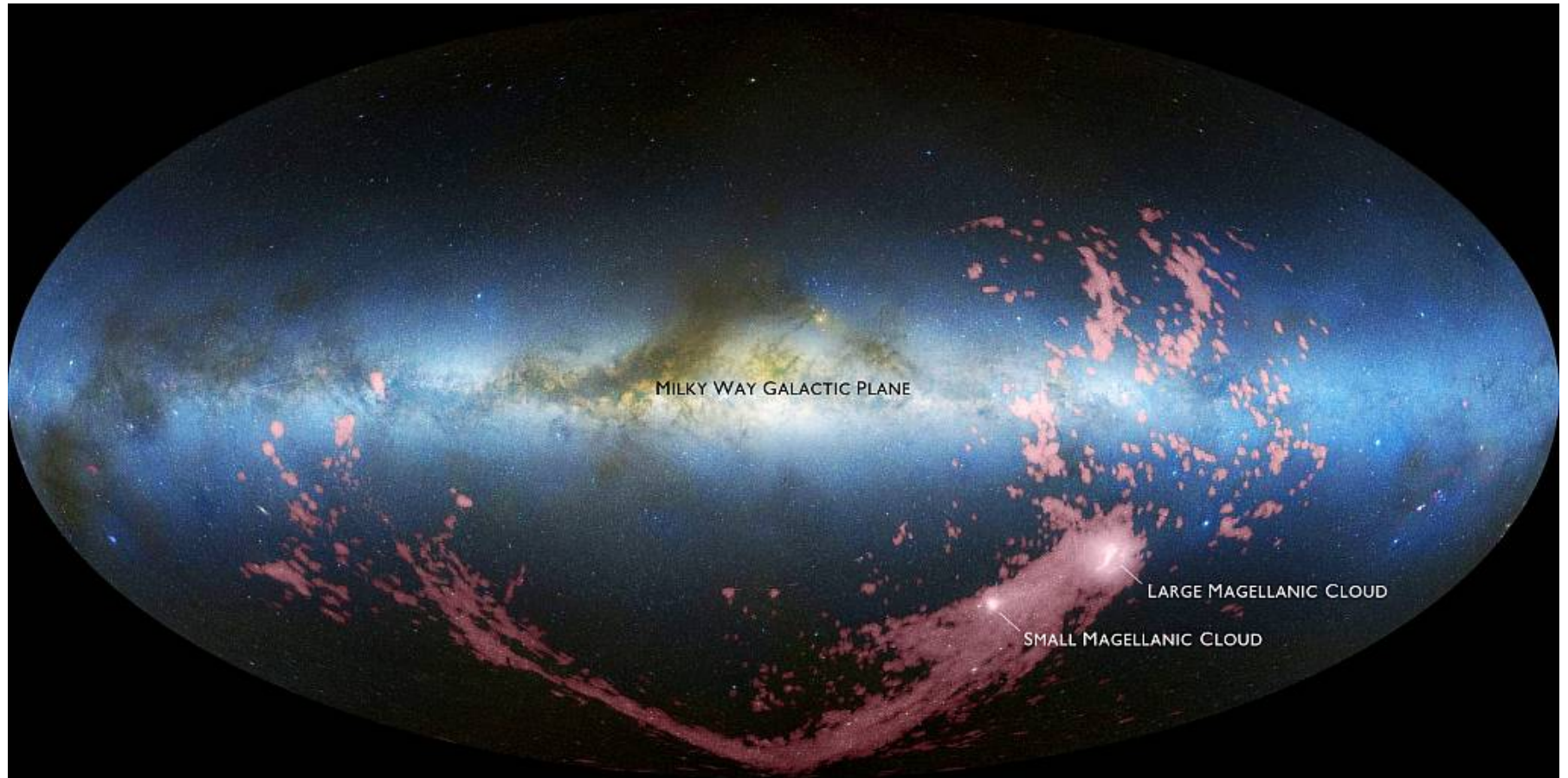
PR95-02 • ST ScI OPO • January 1995 • K. Borne (ST ScI), NASA

HST • WFPC2

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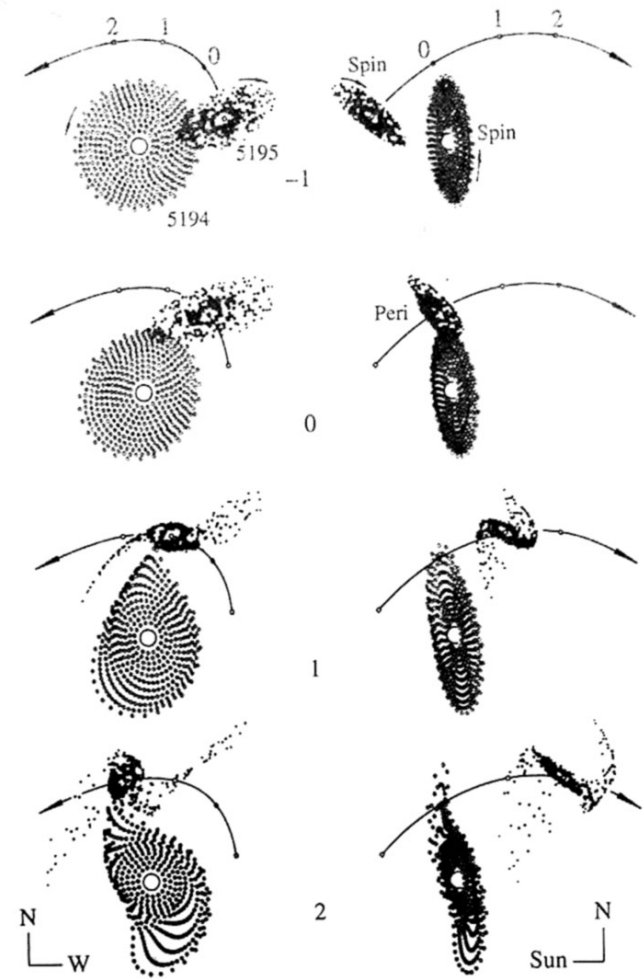


# Gas in Magellanic Stream



# N-body and Hydro Simulations

- To understand the physical processes behind the observations,  $N$ -body and hydrodynamic simulations are used
- In an interaction between galaxies, stars and dark matter essentially never physically collide - act as collisionless point particles or “ $N$ -bodies” that interact gravitationally
- Gas is more complicated and can shock, etc - use hydrodynamic techniques + cooling and star formation



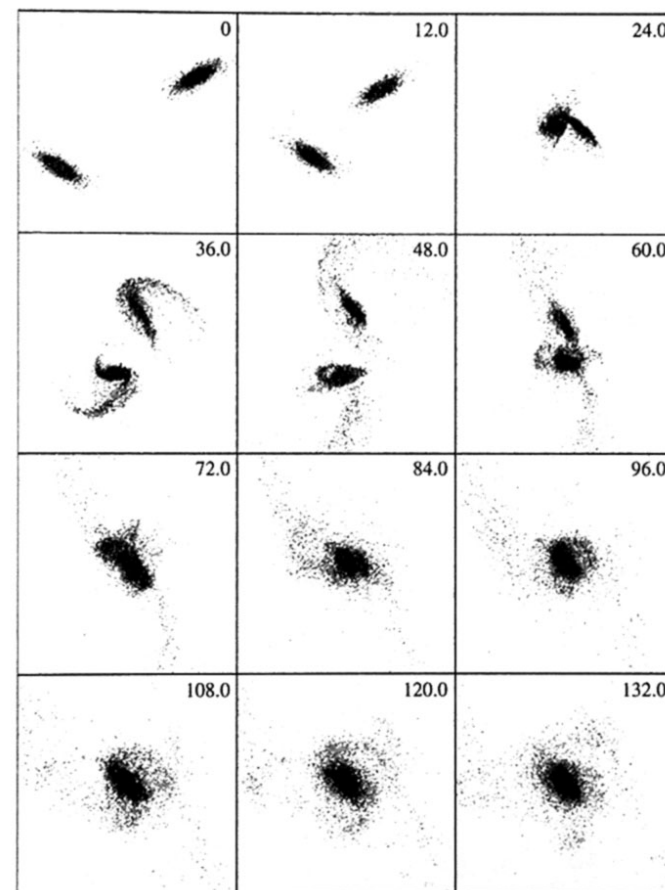
# Interactions and Mergers

- $N$ -body simulations reproduce the main features of mergers in terms of stars
- As galaxies approach, tidal forces pull stars out into tidal streams much like tides on the Earth - features like the Antennae galaxies or the Magellenic stream
- Similar to the spiral arm considerations, conservation of angular momentum says that bodies that are pulled inwards advance in their orbits, outwards trail



# Interactions and Mergers

- In a minor merger, a satellite galaxy can warp the disk of a larger galaxy in a major merger two spirals may have their disks disrupted and become an elliptical
- Eventually the merger completes
  - though collisionless the stars interact gravitationally and their motion dissipates through dynamical friction



# Dynamical Friction

- Consider a single encounter of an object of mass  $M$  with a (smaller) mass  $m$
- Two body encounter can be re-expressed as a single particle of the reduced mass in the potential of the combined mass: Newton's third law

$$M\ddot{\mathbf{x}}_M = \mathbf{F}_{Mm} = -\mathbf{F}_{mM} = -m\ddot{\mathbf{x}}_m$$

- Center of mass  $\mathbf{x}_{cm} = (M\mathbf{x}_M + m\mathbf{x}_m)/(M + m)$  has zero acceleration (uniform velocity)

$$\ddot{\mathbf{x}}_{cm} = 0 = \frac{M}{M + m}\ddot{\mathbf{x}}_M + \frac{m}{M + m}\ddot{\mathbf{x}}_m$$

- Separation  $\mathbf{R} = \mathbf{x}_m - \mathbf{x}_M$  obeys

$$\ddot{\mathbf{R}} = \ddot{\mathbf{x}}_m - \ddot{\mathbf{x}}_M$$

# Dynamical Friction

- Eliminate  $\mathbf{x}_M$

$$\ddot{\mathbf{x}}_M = -\frac{m}{M}\ddot{\mathbf{x}}_m$$

$$\ddot{\mathbf{R}} = \left(1 + \frac{m}{M}\right)\ddot{\mathbf{x}}_m$$

- Gravitational acceleration

$$\ddot{\mathbf{x}}_m = -\frac{GM}{R^2}\hat{\mathbf{r}}$$

$$\ddot{\mathbf{R}} = -\frac{G(M + m)}{R^2}\hat{\mathbf{r}}$$

- Test particle moving in gravitational potential of combined mass (equivalently particle with reduced mass  $\mu = mM/(m + M)$  with the force  $GMm/R^2$ ) if  $M \gg m$  then  $m$  is essentially the test mass and center of mass frame is rest frame of  $M$

# Dynamical Friction

- Want to find the change in velocity of  $M$  due to interactions with  $m$  given kinematics of the reduced mass  $\mathbf{V} = \dot{\mathbf{R}}$

$$\Delta \mathbf{v}_m - \Delta \mathbf{v}_M = \Delta \mathbf{V}$$

$$m \Delta \mathbf{v}_m + M \Delta \mathbf{v}_M = 0$$

$$\Delta \mathbf{v}_M = - \left( \frac{m}{m + M} \right) \Delta \mathbf{V}$$

- Now determine  $\Delta \mathbf{V}$  from single particle kinematics. Consider an initial relative velocity  $\mathbf{V}$  and an impact parameter  $b$ , the initial separation transverse to  $\mathbf{V}$
- If the impact parameter is sufficiently large then the encounter is weak and the trajectory of the test particle is only slightly deflected

# Dynamical Friction

- The test particle then experiences the potential on the unperturbed trajectory: “Born approximation”. The force perpendicular to the velocity

$$\dot{V}_{\perp} = -\frac{G(M+m)}{b^2 + x^2(t)} \frac{b}{\sqrt{b^2 + x^2}}$$

where  $x(t) = V_0 t$  if  $t = 0$  and  $x = 0$  is set to be at the closest approach

$$|\Delta V_{\perp}| = \int_{-\infty}^{\infty} dt \frac{G(M+m)b}{(b^2 + V_0^2 t^2)^{3/2}} = \frac{2G(M+m)}{bV_0}$$

- Change in  $V_{\perp}$  has no net effect since there is an equal probability of an impact with  $-b$ .



# Dynamical Friction

- There is a coherent effect on  $V_{\parallel}$ . Energy conservation says that the speed  $V_0$  is conserved so that  $V_{\parallel}$  is reduced

$$\theta_{\text{def}} \approx \sin \theta_{\text{defl}} = \frac{|\Delta V_{\perp}|}{V_0} = \frac{2G(M + m)}{bV_0^2}$$

$$|\Delta V_{\parallel}| = V_0(1 - \cos \theta_{\text{defl}}) \approx \frac{1}{2}V_0\theta_{\text{defl}}^2 \approx \frac{2G^2(m + M)^2}{b^2V_0^3}$$

with a direction opposite to  $V_0$

- Back to the change in the velocity of the real mass  $M$

$$|\Delta v_{M\parallel}| = \frac{2G^2m(m + M)}{b^2V_0^3}$$

with the same direction as  $V_0$  - i.e.  $M$  will get a kick in the direction of oncoming  $m$  particles

# Dynamical Friction

- Now consider the mass  $M$  to be moving through a sea of particles  $m$  with number density  $n$  and mass density  $\rho = mn$
- Rate of encounters at an impact parameter  $db$  around  $b$  will be  $nV_0\sigma$  where  $\sigma$  is the cross sectional area

$$nV_0 \times 2\pi b db$$

- Total rate of change of velocity is the integral over all allowed impact parameters

$$\left| \frac{dv_{M\parallel}}{dt} \right| = \int_{b_{min}}^{b_{max}} V_0 n |\Delta v_{M\parallel}| 2\pi b db$$

$$\left| \frac{dv_{M\parallel}}{dt} \right| = \frac{4\pi G^2 m n (m + M)}{V_0^2} \ln \frac{b_{max}}{b_{min}} = \frac{4\pi G^2 \rho (m + M)}{V_0^2} \ln \frac{b_{max}}{b_{min}}$$

# Dynamical Friction

- Rate depends weakly (logarithmically) on the limits for the impact parameter.  $b_{max}$  is size of  $m$  system.  $b_{min}$  is set by the validity of the “Born approximation”

$$\Delta V_{\perp} = \frac{2G(M + m)}{b_{min} V_0} \approx V_0$$

$$b_{min} \approx \frac{2G(M + m)}{V_0^2}$$

- For  $b_{max} < b_{min}$  this term must go to zero and a better calculation from Chandrasekar (see Binney & Tremaine) replaces the log “Gaunt” factor with

$$\ln \frac{b_{max}}{b_{min}} \rightarrow \ln \left[ 1 + \left( \frac{b_{max} V_0^2}{G(M + m)} \right)^2 \right]^{1/2} \equiv \ln \Lambda$$

# Dynamical Friction

- Considering  $M$  to be falling into a body of density  $\rho$  whose particles  $m \ll M$  have no net velocity  $V_0 = -v_M$  there is a frictional force that will stop the body

$$M \frac{d\mathbf{v}_M}{dt} \approx - \left[ \frac{4\pi G^2 \rho M^2}{v_M^2} \ln \Lambda \right] \hat{\mathbf{v}}_M$$

# Galaxy Formation

- The same process of merging but with smaller proto-Galactic objects of  $10^6 - 10^8 M_\odot$  can eventually assemble the galaxies of  $10^{12} M_\odot$  we see today. Both lower and upper range determined by cooling.
- Proto-galactic objects can form if cooling is sufficiently rapid that the heating of the gas during collapse (which would prevent collapse due to pressure, internal motions) can be overcome
- Recall virial theorem supplies estimate of thermal kinetic energy

$$-2\langle K \rangle = \langle U \rangle$$

$$-2N \frac{1}{2} \mu m_H \sigma^2 = -\frac{3}{5} \frac{GMN \mu m_H}{R}$$

where  $\mu m_H$  is the average mass of particles in the gas,  $M$  is the total mass and  $\sigma$  is the rms velocity



# Galaxy Formation

- Solve for velocity dispersion for a self gravitating system

$$\sigma = \left( \frac{3}{5} \frac{GM}{R} \right)^{1/2}$$

- Associate the average kinetic energy with a temperature, called the virial temperature

$$\frac{1}{2} \mu m_H \sigma^2 = \frac{3}{2} k T_{\text{virial}}$$

where  $\mu$  is the mean molecular weight. Solve for virial temperature

$$T_{\text{virial}} = \frac{\mu m_H \sigma^2}{3k} = \frac{\mu m_H}{5k} \frac{GM}{R} \approx \frac{\mu m_H}{5k} G M^{2/3} \left( \frac{4\pi\rho}{3} \right)^{1/3}$$

- Cooling is a function of the gas temperature through the cooling function.

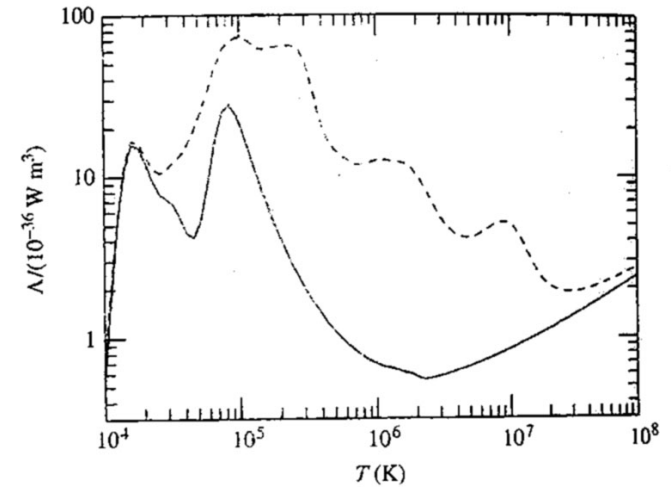
# Galaxy Formation

- Cooling rate (luminosity) per volume

$$r_{\text{cool}} = n^2 \Lambda(T)$$

$n^2$  (number density squared) comes from the fact that cooling is usually a 2 body process - for  $T > 10^6$  K thermal bremsstrahlung and Compton scattering, for  $T \sim 10^4 - 10^5$  K from the collisional excitation of atomic lines of hydrogen and helium

- Galaxy formation only starts when dark matter mass makes the virial temperature exceed  $T \sim 10^4$  K when cooling becomes efficient  $M \sim 10^8 M_{\odot}$  -first objects and current dwarf ellipticals



# Galaxy Formation

- Cooling time is the time required to radiate away all of the thermal energy of the gas

$$r_{\text{cool}} V t_{\text{cool}} = \frac{3}{2} N k T_{\text{virial}}$$

$$t_{\text{cool}} = \frac{3}{2} \frac{k T_{\text{virial}}}{n \Lambda}$$

- Compared with the free fall time - from our dimensional relation

$$G \rho R^3 \propto G M \sim R v^2 \sim R (R^2 / t_{\text{ff}}^2)$$

we get  $t_{\text{ff}} \propto (G \rho)^{-1/2}$  with the proportionality given for the time of collapse for a homogeneous sphere of initial density  $\rho$

$$t_{\text{ff}} = \left( \frac{3\pi}{32} \frac{1}{G \rho} \right)^{1/2}$$

# Galaxy Formation

- If  $t_{\text{cool}} < t_{\text{ff}}$  then the object will collapse essentially in free fall - fragment and form stars. If opposite, then gravitational potential energy heats the gas making it stabilized by pressure establishing virial equilibrium

$$\left( \frac{t_{\text{ff}}}{t_{\text{cool}}} \right) > \left( \frac{3\pi}{32} \frac{1}{G\rho} \right)^{1/2} \frac{2}{3} \frac{n\Lambda}{kT_{\text{virial}}}$$

- Taking typical numbers  $T \sim 10^6 \text{K}$  and  $n \sim 5 \times 10^4 \text{m}^{-3}$  and with the density of the collapsing medium being associated with the gas  $\rho = \mu m_H n$  gives an upper limit on the gas mass that can cool of  $10^{12} M_{\odot}$  comparable to a large galaxy.

# Disk Formation

- Proto-galactic gas fragment and collide retaining initial angular momentum provided from torques from other proto-galactic systems
- Rotationally supported gas disk, cooling in dense regions until HI clouds form from which star formation occurs - thick disk
- Cool molecular gas settles to midplane of thick disk efficiently forming stars - thinness is self regulating - if disk continued to get thinner then density and star formation goes up heating the material and re-puffing out the disk