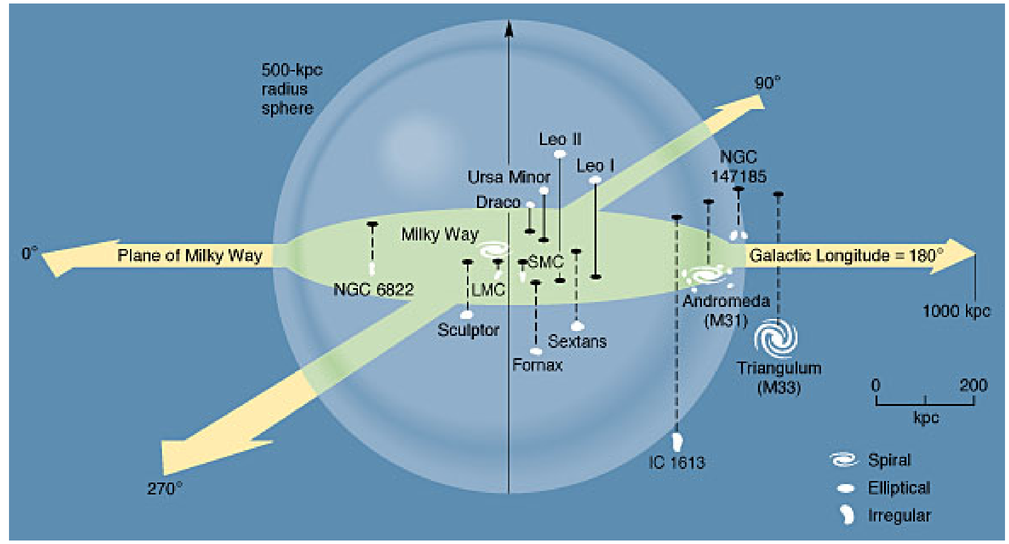
Set 3:

Galaxy Evolution

Environment

- Galaxies are clustered, found in groups like the local group up to large clusters of galaxies like the Coma cluster

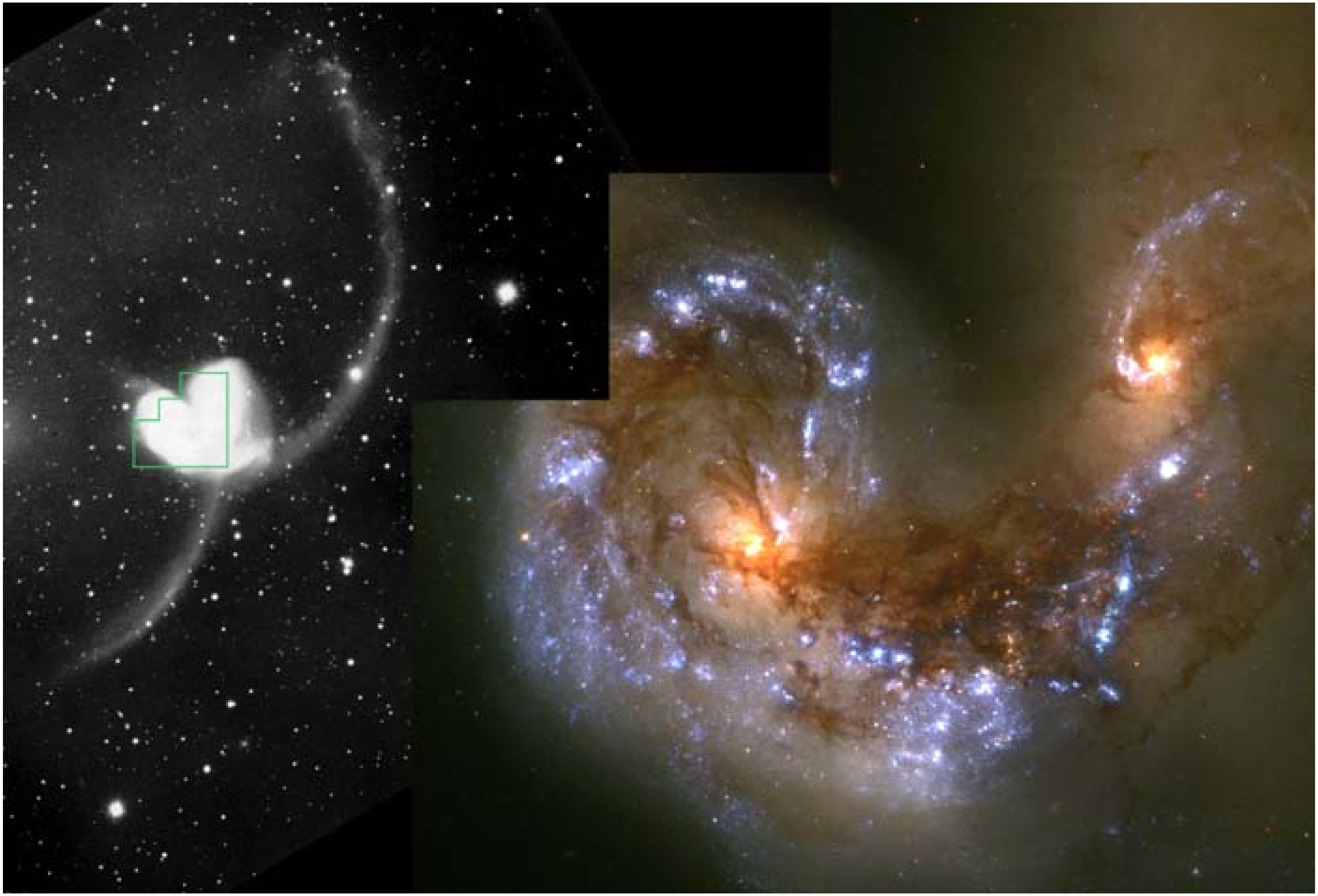


- Small satellite galaxies like the LMC and SMC are merging into the Milky way. Recent discovery of other satellites like the Sagitarius dwarf and tidal streams

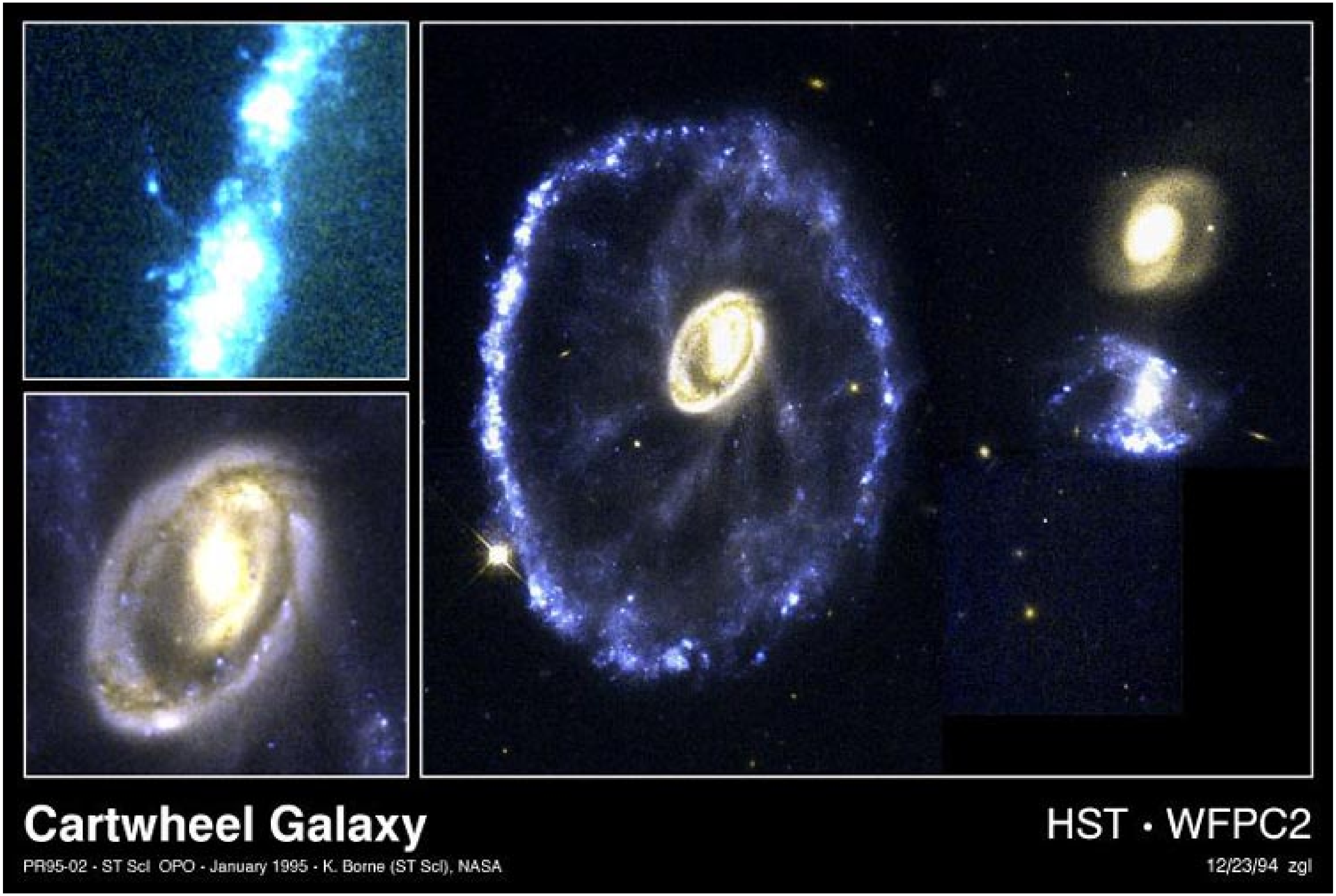
Environment

- 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

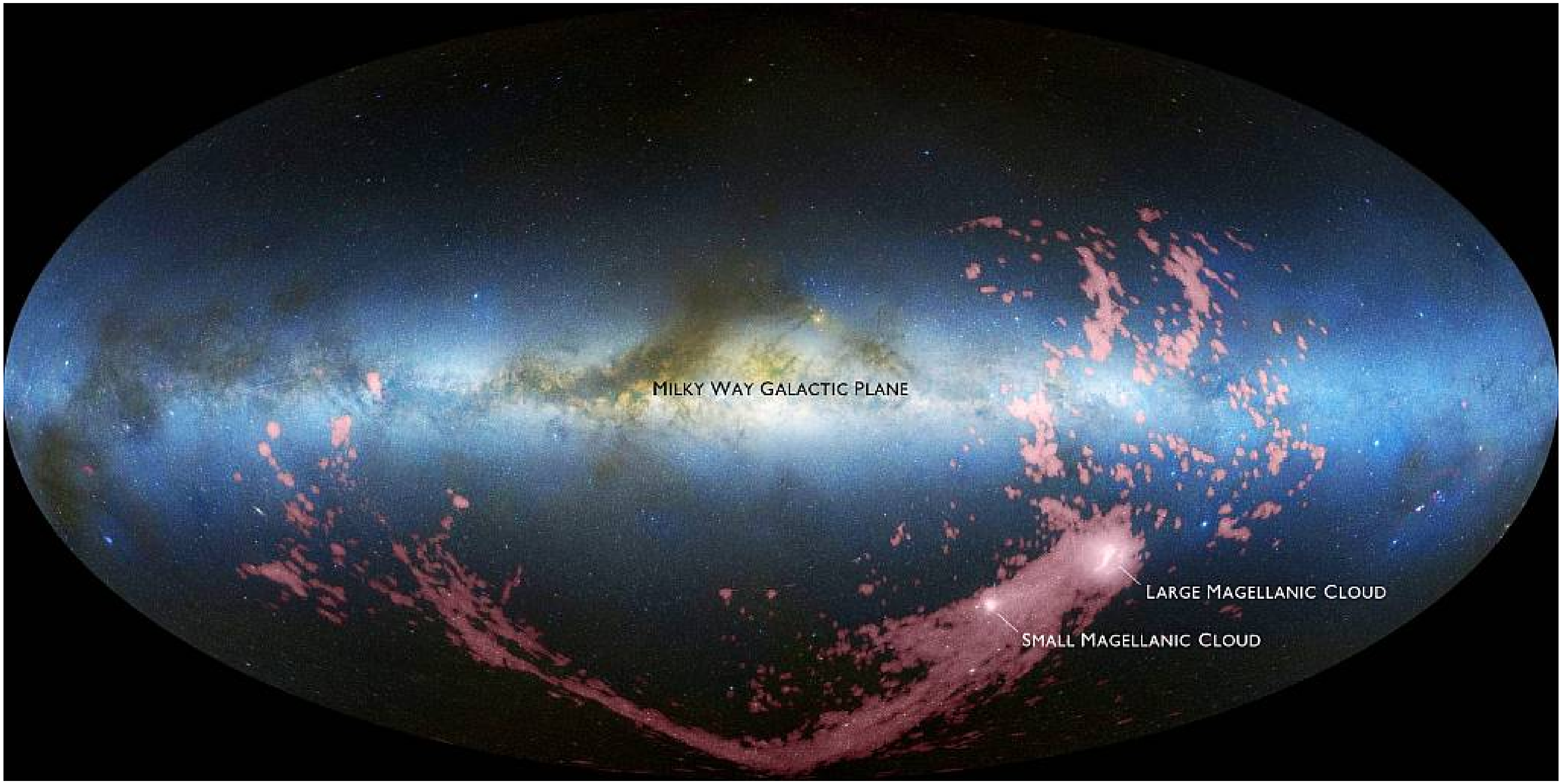
Antennae Galaxies



Cartwheel Galaxy

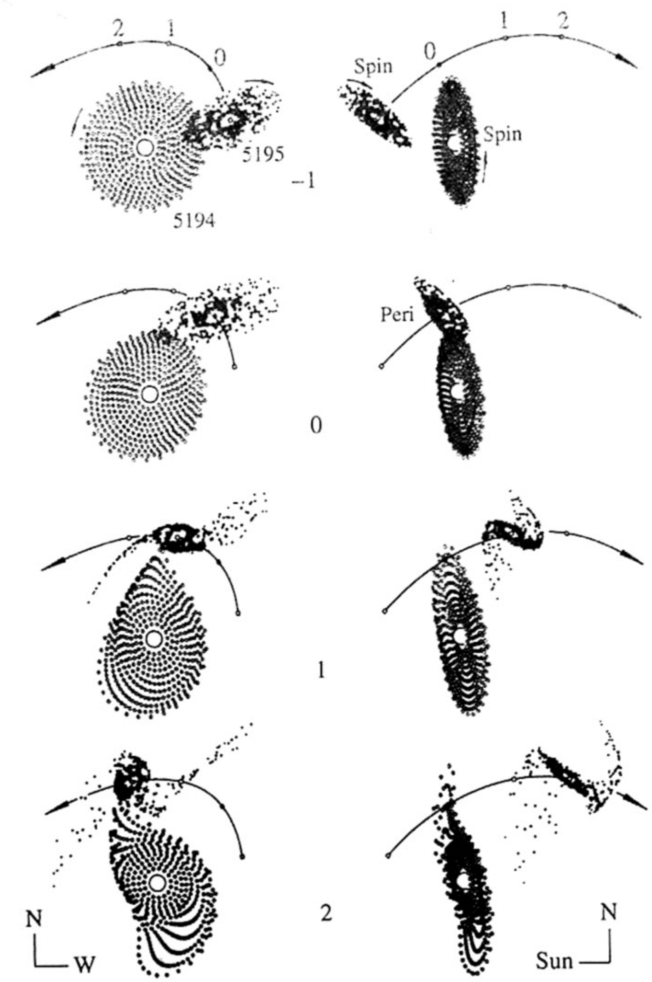


Gas in Magellanic Stream



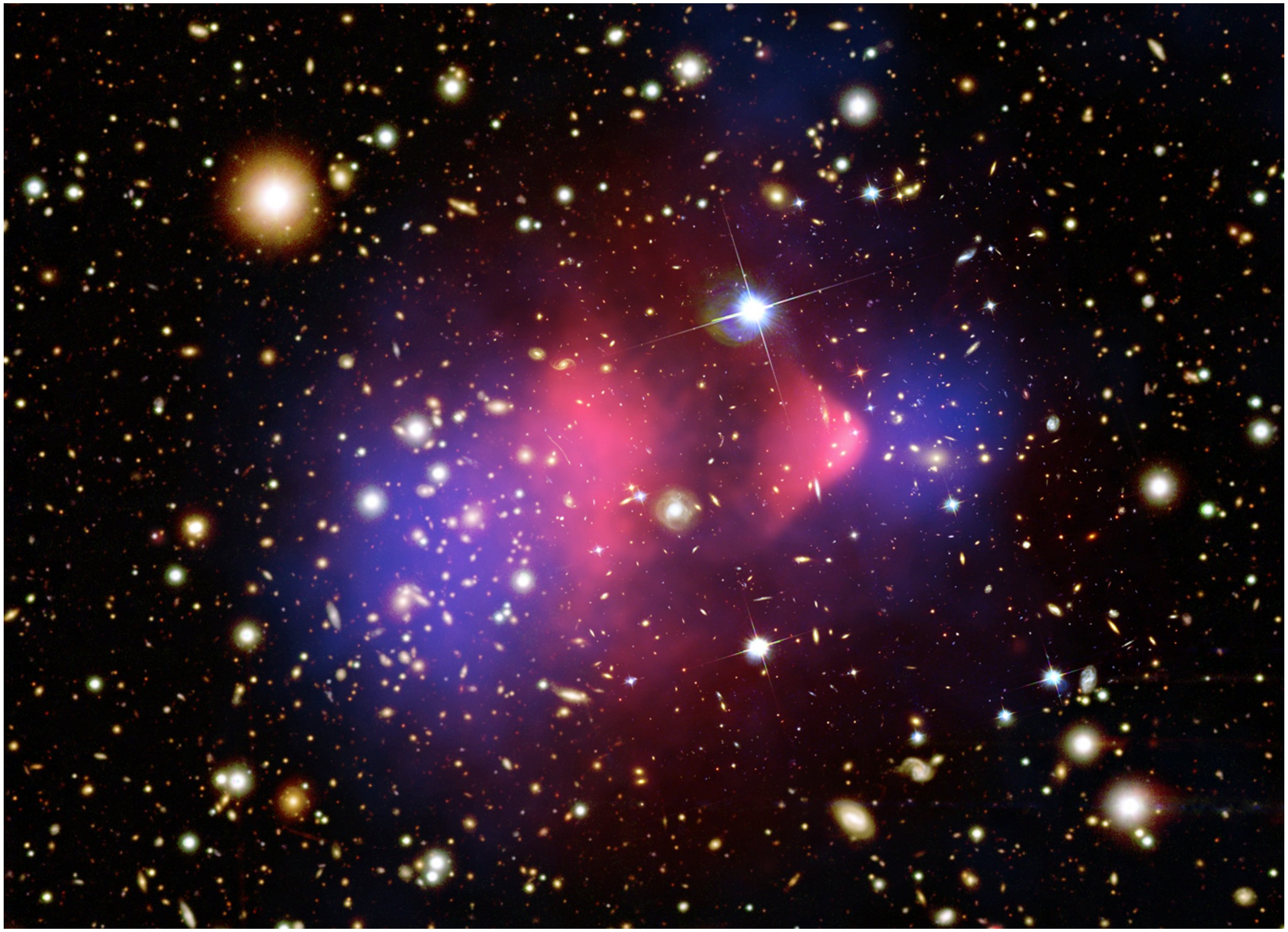
N-body and Hydro Simulations

- 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



Collisionless vs Collisional

- Merging clusters: gas (visible matter) collides and shocks (X-rays), dark matter measured by gravitational lensing passes through

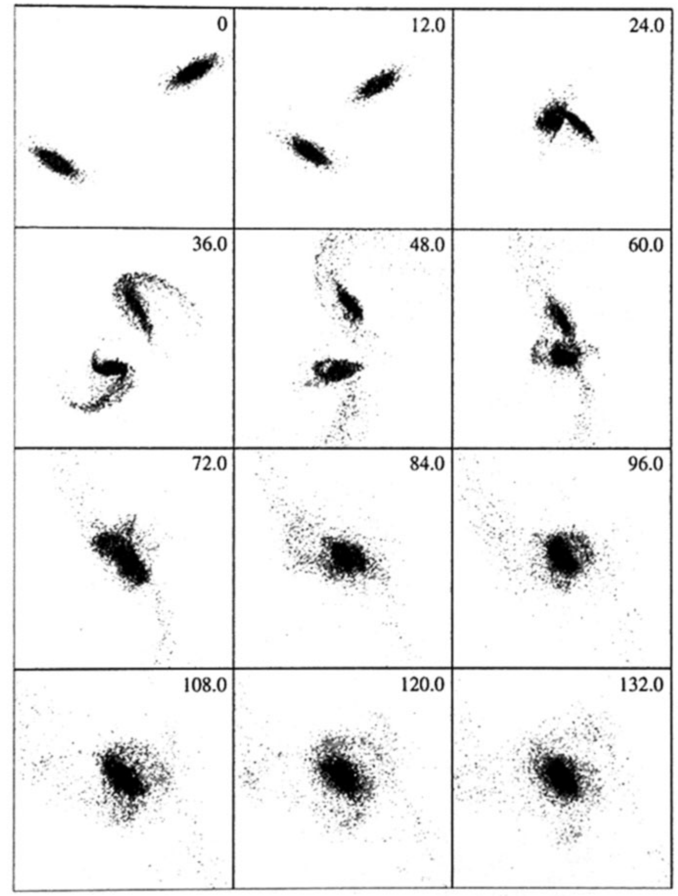


Interactions and Mergers

- 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

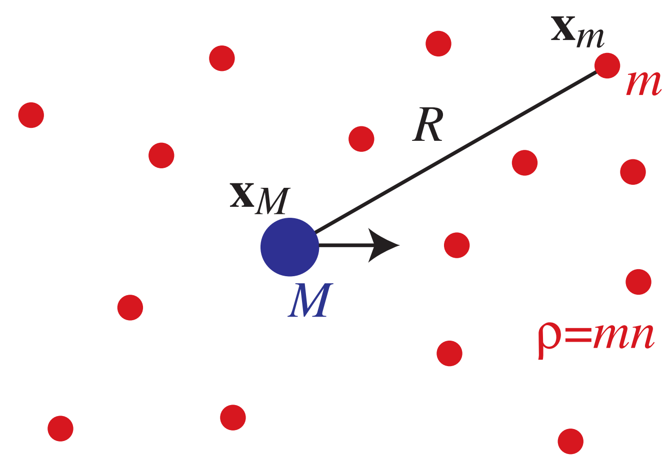
Interactions and Mergers

- 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 large mass M moving through a medium of mass density ρ, which can be thought of as consisting of smaller masses m



- Want to calculate the change in velocity of M after many gravitational encounters with multiple masses m
- Isolate each encounter of M with m as a two body encounter
- Separation $\mathbf{R} = \mathbf{x}_m - \mathbf{x}_\mathrm{M}$ obeys

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

Dynamical Friction

- Eliminate using Newton's third law

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

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

- 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
- 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 $\mathbf{V} = \dot{\mathbf{R}}$

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

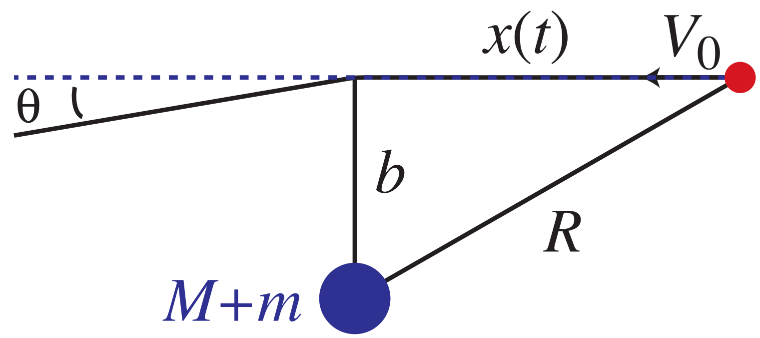
$$m \Delta \mathbf{v}_m + M \Delta \mathbf{v}_M = 0$$

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

- 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

- Test particle then experiences the potential on the unperturbed trajectory: "Born approximation"
- Force perpendicular to the velocity



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

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

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

Dynamical Friction

- Change in $V_\perp$ represents a small deflection in the trajectory

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

- Also a change in $V_\parallel$ since the energy is conserved and kinetic well before and well after the encounter is conserved

$$V_0^2 = V_\perp^2 + V_\parallel^2\Big|_{\mathrm{after}} = V_0^2 \sin^2\theta + V_\parallel^2 \approx V_0^2\theta^2 + V_\parallel^2$$

- For a small change

$$V_0^2 - V_\parallel^2 \approx V_0^2\theta^2 \approx V_0^2 - (V_0 + \Delta V_\parallel)^2 \approx 2|\Delta V_\parallel| V_0$$

$$|\Delta V_\parallel| \approx \frac{1}{2} V_0 \theta^2 \approx \frac{2G^2(m+M)^2}{b^2 V_0^3}$$

with a sign that is opposite to V_0

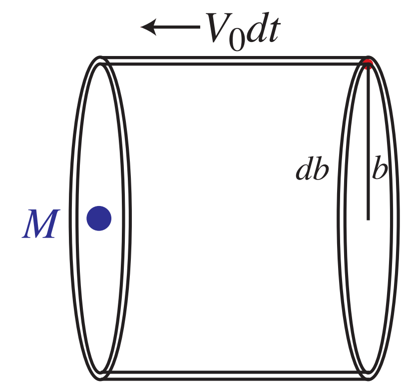
Dynamical Friction

- Calculate backreaction on the velocity of M
- After many encounters, change in $V_\perp$ has no net effect since there is an equal probability of an impact with $-b$.
- There is a coherent effect on $V_\|$
- Change in the velocity of the real mass M reduced by $m/(M+m)$

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

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 is $nd(\text{volume})/dt = nV_0\sigma$ where σ is the cross sectional area

$$\text{encounter rate} = nV_0 \times 2\pi b db$$

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

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

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

Dynamical Friction

- Rate depends weakly (logarithmically) on the limits for the impact parameter. b_{max} is size of m system. $b_{\rm min}$ 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 $b_{\rm max} < 2G(M+m)/V_0^2$ better calculation from Chandrashekar replaces this "Gaunt" factor with

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

so that $\lim_{V_0 \rightarrow 0} b_{min} = b_{max}$

Dynamical Friction

- Considering M to be falling into a body of density ρ 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 μm_H is the average mass of particles in the gas, M is the total mass and σ 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

$$\frac{1}{2}\mu m_H \sigma^2 = \frac{3}{2}kT_{\mathrm{virial}}$$

where μ is the mean molecular weight. Solve for virial temperature

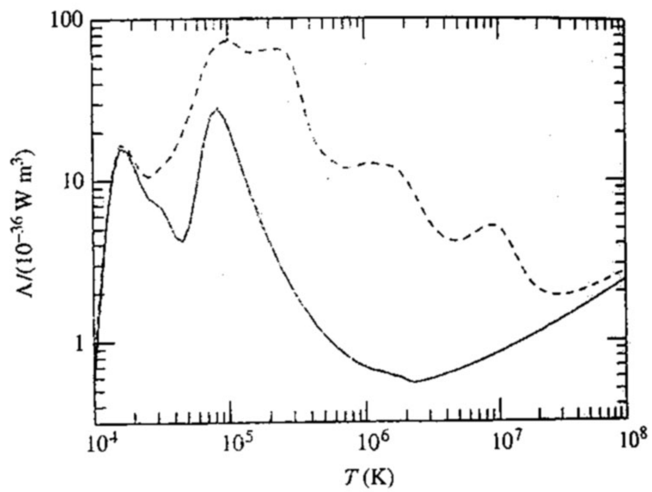
$$T_{\mathrm{virial}} = \frac{\mu m_H \sigma^2}{3k} = \frac{\mu m_H}{5k}\frac{GM}{R} \approx \frac{\mu m_H}{5k} GM^{2/3}\left(\frac{4\pi\rho}{3}\right)^{1/3}$$

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

Galaxy Formation

- Cooling rate (luminosity) per volume

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



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 temperture 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

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

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

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

$$GM \sim Rv^2 \sim R(R^2/t_{\rm ff}^2), \quad M \propto \rho R^3$$

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

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

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 $T \sim 10^6$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