Galaxy Groups and Clusters

- Half of galaxies are in groups or clusters
- Half of members in a volume less than 1 Mpc$^3$
- Gravitationally isolated from Hubble flow
- Clusters contain $\sim 50$ luminous members in inner Mpc
- Being a member alters evolution of a galaxy: they fall in through hot gas and pressure strips away cool gas in outer parts
- Groups are dominately formed of spirals
- Clusters are dominately formed of ellipticals and S0’s, predominately giant or dwarfs.
- Groups and clusters are younger than the oldest stars
- Motions are too slow for more than 1 or 2 transit times so far
- Much baryonic mass is hot gas, emitting X-rays, but most might be intercluster cool gas
- Most mass is dark
Nearby Galaxy Groups
Stephan’s Quintet

A rare compact group, galaxies almost touch, 85 Mpc distant and 80 kpc across.

Long tails of stars have been pulled from the disks.

About $10^9 M_\odot$ in hot gas with $T_X \sim 10^7$ K, consistent with the velocity dispersion of the galaxies of 300 km/s.

About $10^{10} M_\odot$ in cool gas, mostly outside the galaxies, apparently stripped out.

NGC 7318b, recently arrived, tore out the tail from NGC 7319.

A smaller spiral, NGC 7320c, passed through 500 Myr ago and will return.
M81 Group

Sparse group (> 34 members), connections of long HI streamers torn from galactic disks. Distance is 3.6 Mpc, total mass $10^{12} M_\odot$. 
NGC 1550 Group

Has about 15 members within 1 Mpc of the S0 galaxy NGC 1550, including two ellipticals.

Radiates $4 \times 10^9 \, L_\odot$ in X-rays (10 times that of Stephan’s Quintet).

Metallicity about 0.1 solar.

Galaxy velocity dispersion $\sigma_r = 310$ km/s, approximate distribution with a Plummer model with $a = 100$ kpc.

$$\frac{3\sigma_r^2}{2} = \frac{\text{KE}}{\mathcal{M}} = -\frac{\text{PE}}{2\mathcal{M}} = \frac{3\pi}{64} \frac{G\mathcal{M}}{a}$$

$$L_X = n^2 \Lambda(T_X), \quad \Lambda \sim 3 \times 10^{-27} T_X^{1/2} \, \text{erg/s}$$

$$n \propto r^{-\beta}, \quad I_X \propto L_X R \propto r^{1-2\beta}$$

Hydrostatic equilibrium:

$$\mathcal{M}(< r) = -\frac{kN_o}{\mu} \frac{r^2}{Gn} \frac{d(nT)}{dr}$$
Assume a Plummer model for groups with the same $a$ and mass for each galaxy. The Virial Theorem predicts

$$\sigma_r^2 \propto M_{\text{tot}}/a \propto N/a$$

where $N$ is the number of galaxies in a group. The speeds of group galaxies $100 \text{ km/s} < \sigma_r < 500 \text{ km/s}$, about the same as the stellar velocities within galaxies. Dynamical friction is therefore important.
A galaxy of mass $M$ moves past a star of mass $m$ at velocity $V$. $M$ acquires a speed $\Delta V_\perp = \frac{2Gm}{bV}$ perpendicular to $V$. We require $b >> \frac{2GM}{V^2}$.

The star acquires an equal and opposite momentum. The total KE in perpendicular motions is

$$\Delta KE_\perp = \frac{M}{2} \left( \frac{2Gm}{bV} \right)^2 + \frac{m}{2} \left( \frac{2GM}{bV} \right)^2 = \frac{2G^2mM(M + m)}{b^2V^2}.$$ 

This energy comes from the forward motion of the galaxy, which changes by $\Delta V_\parallel$. To lowest order

$$-\Delta V_\parallel = \frac{\Delta KE_\perp}{MV} = \frac{2G^2mM}{b^2V^3}.$$ 

The average rate at which it slows is

$$-\frac{dV}{dt} = \int_{b_{\text{min}}}^{b_{\text{max}}} nV \frac{2G^2mM}{b^2V^3} = \frac{4\pi G^2Mnm}{V^2} \ln \Lambda$$

$n$ is the stellar density. Can also be applied to a small galaxy orbiting within a dark halo of density $nm$.

Using the dark halo potential

$$nm = \rho_H \simeq \frac{V^2}{(4\pi Gr^2)},$$

$$F_\parallel = -\frac{G\mathcal{M}^2}{r^2} \ln \Lambda = \mathcal{M} \frac{dr}{dt}$$

Integrating:

$$t_{\text{sink}} = \frac{r^2V}{2G\mathcal{M} \ln \Lambda}.$$
Mergers and Simulations

NGC 4676 "the Mice"

R band, HI contours

Fig 7.5 (J. Hibbard, J. Barnes) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007
Starbursts

Mergers often have $10^9 - 10^{10} \, M_\odot$ of dense molecular gas brought inward to center which is gravitationally compressed and leads to violent star formation.

If dust is present, it intercepts the stellar light and re-radiates it in the infrared.
M82 – A Starburst Galaxy

Makes $2 - 4 \mathcal{M}_\odot/yr$ of new stars, same as Milky Way, in 600 pc region.

Radio-bright knots where stars ionize the gas, produce free-free radiation.

Supply of $2 \times 10^8 \mathcal{M}_\odot$ will be exhausted in $\tau_{ff} = 100$ Myr
Luminous and ultraluminous infrared galaxies (ULIRG) form stars at rate
\[ \dot{M}_* \sim \frac{L_{FIR}}{6 \times 10^9 L_\odot} \dot{M}_\odot \text{ yr}^{-1}. \]

Most powerful ULIRG have 1000\(\dot{M}_\odot/\text{yr}\) rate.

Half of ULIRG also have active galactic nuclei.

Arp 220 is a close-by merging pair 75 Mpc distant, with 
\[ \dot{M} \sim 200 \dot{M}_\odot/\text{yr}. \]

Has \(10^9 \dot{M}_\odot\) H\(_2\) in a 20 pc gas disk.

Can’t sustain activity for more than 1 Gyr.

Rounder cores, more random motions, less rotation: form ellipticals?
Nearby Galaxy Clusters
Properties of Clusters

5-10% of luminous galaxies live in clusters.

Most members are dwarfs.

Virgo central regions have $0.5 \text{ L}_{\odot}/\text{pc}^2$

Virgo core radius is about 0.5 Mpc

Fornax cluster has 1/5 as many members, but is more compact, with twice the luminosity density, but less hot gas, relatively.

The core of a galaxy like NGC 1399 is $10^7$ times as dense as the center of the Fornax cluster.
Rich Clusters

Examples are Coma, Perseus Clusters. As clusters become more massive, they become denser; radii hardly change. Infalling clumps add 10% every few Gyr, but will cease in 2-3 Hubble times as the expansion of the universe will overwhelm a cluster’s gravity.

Spirals excluded from the centers. Galaxies fall supersonically into clusters; shocks leave gas behind. By observing novae and planetary nebulae, it is estimated $\sim 10 - 20\%$ of stars are intercluster, probably torn out of infalling galaxies.

Virial estimates of masses $\sim 2 - 7 \times 10^{14} M_\odot$ for Virgo–Coma. Hot gas indicates masses 50% larger.
Hot Cluster Gas

Mass in hot gas equals stars in poor clusters, but 10 times stars in a rich cluster. It can be traced to larger radii than stellar light.

Temperature of gas increases with cluster luminosity, consistent with galaxy velocity dispersion. As new clumps added, $T_X$ grows.

Models suggest $T_X$ increases faster than $L$, so high $z$ clusters should be cooler for a given $L$; not observed, indicating early energy sources (starbursts and active nuclei).

Cooling time is $\propto n_X T_X / L_X$, or

$$t_{\text{cool}} = \frac{3nkT}{3 \times 10^{-27} n^2 \sqrt{T}}$$

$$\approx 14 \left( \frac{10^{-3} \text{cm}^{-3}}{n} \right) \sqrt{\frac{10^7 K}{T}} \text{ Gyr}$$

Since cool gas and star formation not observed in central galaxy, gas must be reheated by supernovae or radio sources. Gas in outer regions doesn't cool quickly and does not form stars.
Cosmic Baryonic Budget

Hot gas accounts for 0.1 of the mass of a luminous cluster, but much less in smaller systems. Together with stars, accounts for about 1/6 of total mass.

But baryons are more concentrated in galaxies (less than half of mass inside solar circle is dark).

Dense gas in the damped Lyman-$\alpha$ clouds (neutral and atomic) is half the mass of hot gas.

A large amount of ionized gas could be hidden; it’s low density prevents it from cooling. This diffuse gas is in the Lyman-$\alpha$ forest.

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**Fukigita & Peebles 2004**

<table>
<thead>
<tr>
<th>Where it is</th>
<th>Density ($10^{-3} \rho_{\text{crit}}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total (benchmark cosmology)</td>
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<tr>
<td>Intergalactic gas</td>
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<tr>
<td>Diffuse and ionized</td>
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<td>Damped Lyman-$\alpha$ clouds</td>
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<td>Hot gas in clusters and Es</td>
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<tr>
<td>Stars and stellar remnants</td>
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<tr>
<td>Stars in Es and bulges</td>
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<td>Stars in disks</td>
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<td>Dead stars</td>
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<tr>
<td>Brown dwarfs</td>
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<tr>
<td>Cool gas in galaxies</td>
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</table>
Did Galaxies Grow By Mergers?

- Largest red galaxies (cD and ellipticals) live in dense regions while star-forming spirals and irregulars fill less dense regions.

- At $z = 1$, about 5-10% of galaxies are in major mergers, so that within last 5 Gyr, 2/3 of luminous galaxies have had a merger.

- If ellipticals formed from mergers their stars are older. Clumps are ideal sites for mergers because of low random velocities, and so dense with ellipticals.

- In a major merger of two equal masses, disks are destroyed and cool gas is lost; star-formation terminates. Remnant will have only middle-aged and old stars.

- A merged system will become less dense. A system of size $R$ with $N$ galaxies of mass $M$ has energy $PE/2 = -GNM^2/(2R)$. After merger, and virialized, the energy is $PE/2 = -G(NM)^2/(2R_g)$ so $R_g = NR$. Merged systems are less dense by $1/N^2$. 

![Graph showing central V-brightness and measured core radius vs. luminosity (10^8 L_\odot) with absolute B-magnitude M_B.](image-url)

Fig 6.6 (Kormendy, Philipps) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007
Did Galaxies Grow By Mergers?

▶ If merged systems still contained some cool gas, it would settle to center and trigger star formation.
▶ Merged galaxies therefore develop metal-rich centers.
▶ With a small, dense, inner disk, these galaxies would rapidly rotate, and resemble "disky" ellipticals.
▶ When these merged systems merge again, more luminous systems are formed, and tend to be triaxial, so resemble "boxy" ellipticals.
▶ Problems:

- Where does "fundamental plane" relationship come from?
- Why are luminous red galaxies not rare at high redshifts? More efficient star forming?
Gravitational Lensing

▶ Microlensing by a compact (point) source

\[ \alpha \approx \frac{4GM}{bc^2} \]

▶ Lensing by extended objects
Sources near the Einstein radius

\[ \alpha(b) = \nabla \psi_L(b) \]
\[ \psi_L(b) = \frac{4G}{c^2} \int \Sigma(b') \ln |b - b'| dS \]

▶ Weak lensing
Sources are well outside the Einstein radius

Fig 7.13 (G. Smith) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007
Gravitational Microlensing

Use small angle approximations:

\[ \beta = \frac{y}{d_S} \]
\[ \theta = \frac{x}{d_S} = \frac{b}{d_{\text{Lens}}} \]
\[ \alpha = \frac{(x - y)}{d_{LS}} \]
\[ \theta - \beta = \frac{\alpha d_{LS}}{d_S} \]
\[ \theta = \frac{4G\mathcal{M}}{\theta c^2} \frac{d_{LS}}{d_{\text{Lens}} d_s} \equiv \frac{\theta_E^2}{\theta} \]

If \( d_s = N d_{\text{Lens}} \)

\[ \theta_E = 0.002 \sqrt{\frac{1 \text{ kpc}}{d_{\text{Lens}}} \frac{N - 1}{N} \frac{\mathcal{M}}{\mathcal{M}_\odot}} \]

Solving \( \theta^2 - \beta \theta - \theta_E^2 = 0 \):

\[ \theta_\pm = \frac{\beta \pm \sqrt{\beta^2 + 4\theta_E^2}}{2} \]

When \( d_{\text{Lens}} << d_S \), \( \alpha \approx \theta - \beta = \frac{\theta_E^2}{\theta} \).

Images are magnified and brightened (\( I(x) \) is unchanged):

\[ \frac{F_{\text{image,}}}{F_{\text{source}}} = \frac{A_{\text{image,}}}{A_{\text{source}}} = \frac{xdx}{ydy} = \left| \frac{\theta}{\beta} d\theta \right| = \frac{1}{4} \left( \frac{\beta}{\sqrt{\beta^2 + 4\theta_E^2}} + \sqrt{\beta^2 + 4\theta_E^2} \beta \pm 2 \right) \]
Gravitational Lensing by a Collection of Point Masses

For one point source, we can write

$$\alpha(b) = \frac{d\psi_L}{db}, \quad \psi_L = \frac{4GM}{c^2} \ln b.$$  

Summing the effect from a collection of point masses:

$$\alpha(b) = \nabla \psi_L(b)$$

$$\psi_L(b) = \frac{4G}{c^2} \int \Sigma(b') \ln |b - b'| dS'$$

If axisymmetric, one finds

$$\alpha(b) = \frac{4G}{bc^2} \int_0^b \Sigma(R) 2\pi R dR$$

$$= \frac{4G}{c^2} \frac{M(< b)}{b}$$

This is proven by noting that a ray passing through a uniform circular ring is not bent, and a ray passing outside is bent the same as from a point mass at the center.
Extension to Asymmetric Galaxy Clusters

\[ \theta - \beta = \alpha(\theta) \frac{d_{LS}}{d_S} = \frac{4GM(<b)}{\theta c^2} \frac{d_{LS}}{d_{Lens}d_S} \]

Since \( b = \theta d_{Lens} \),

\[ \beta = \theta \left[ 1 - \frac{M(<b)}{\pi b^2 \Sigma_{crit}} \right] \]

\[ \Sigma_{crit} = \frac{c^2}{4\pi G} \frac{d_S}{d_{Lens}d_{LS}} \]

If \( \Sigma(0) > \Sigma_{crit} \), an image at \( \beta = 0 \) will be an Einstein ring of angular size

\[ \theta_E = \frac{b_E}{d_{Lens}} \]

where \( M(<b_E) = \pi b_E^2 \Sigma_{crit} \).

If \( d_S, d_{LS} >> d_{Lens} \)

\[ \Sigma_{crit} \approx 2 \times 10^{14} \left( \frac{100 \text{ Mpc}}{d_{Lens}} \right) M_\odot \text{ pc}^{-2} \]

\[ M(<\theta_E) \approx \left( \frac{d_{Lens}}{100 \text{ Mpc}} \right) \left( \frac{\theta_E}{1''} \right)^2 10^{10} M_\odot. \]
Weak Lensing

Galaxies behind a cluster but well outside of its Einstein radius have weakly magnified tangential images. The radial axes are in the ratio

\[
\frac{x}{y} : \frac{dx}{dy}, \quad \left| \frac{d\beta}{d\theta} \right| : \left| \frac{\beta}{\theta} \right|
\]

Shear $\gamma$ measures compression. Assuming $b >> \theta_E d_{\text{Lens}}$,

\[
\gamma = \frac{1}{2} \left( \frac{d\beta}{d\theta} - \frac{\beta}{\theta} \right)
\]

\[
= \frac{\mathcal{M}(b)/(\pi b^2) - \Sigma(b)}{\Sigma_{\text{crit}}}.
\]

In the event that $\Sigma(R)$ is constant, $\theta \propto \beta$.

Measuring average shapes of many galaxies in the background allows an estimate of shear and distribution of mass.

Studies of halos of bright galaxies show they are larger and more massive than rotation measures imply.

Trying to determine how dark matter is distributed between clusters is a complex calculation because the light is bent by many clusters along the line of sight.