Galaxy Clusters

Definition and Phenomenology

Gravitationally bound galaxy associations:

- Groups: < 50 members, $\sigma \approx 150$ km/s, $M \approx 2 \cdot 10^{13}\ M_S$
- Clusters: > 50 members, $\sigma \approx 800$ km/s, $M \approx 1 \cdot 10^{15}\ M_S$

(velocity dispersion $\sigma \propto \langle v^2 \rangle^{1/2}$)

Classification as regular or irregular; more detailed scheme:

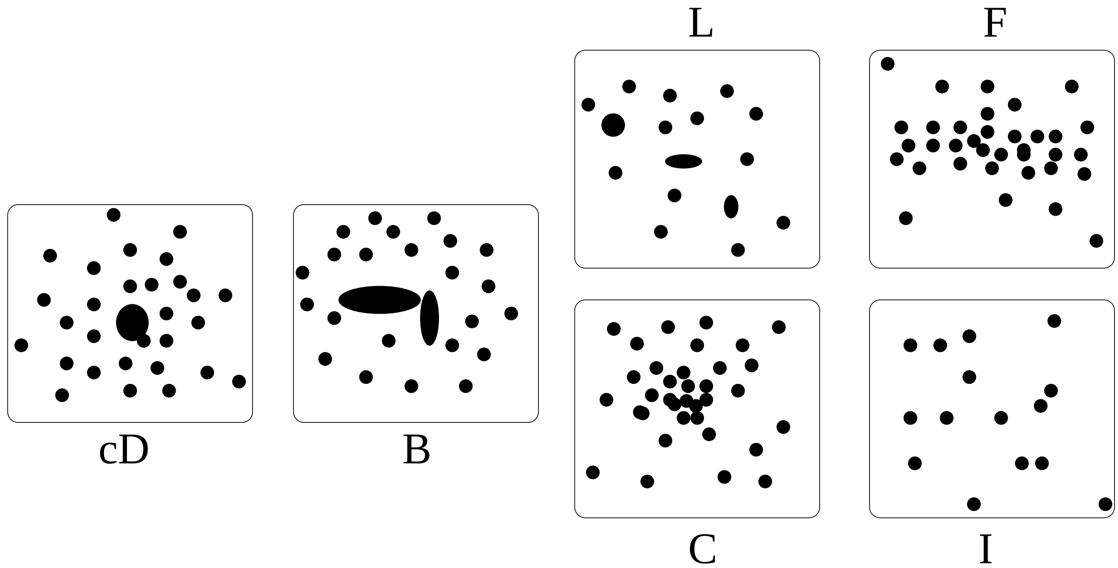

Figure 1: Cluster classification scheme

- regular clusters often dominated by cD-galaxy, high richness, few structure
- irreg. clusters show strong structure, lower richness, less pronounced core

cD-Galaxies

- Giant, bright ellipticals; $M \approx 10^{13} - 10^{14}\ M_S$;
  some measure ≈ 1 Mpc across; mass-to-light-ratio $\approx 750\ \frac{M_S}{L_S}$
- much larger stellar halo than normal E's
- often multiple cores
- are only found in centers of clusters

Dynamical Friction

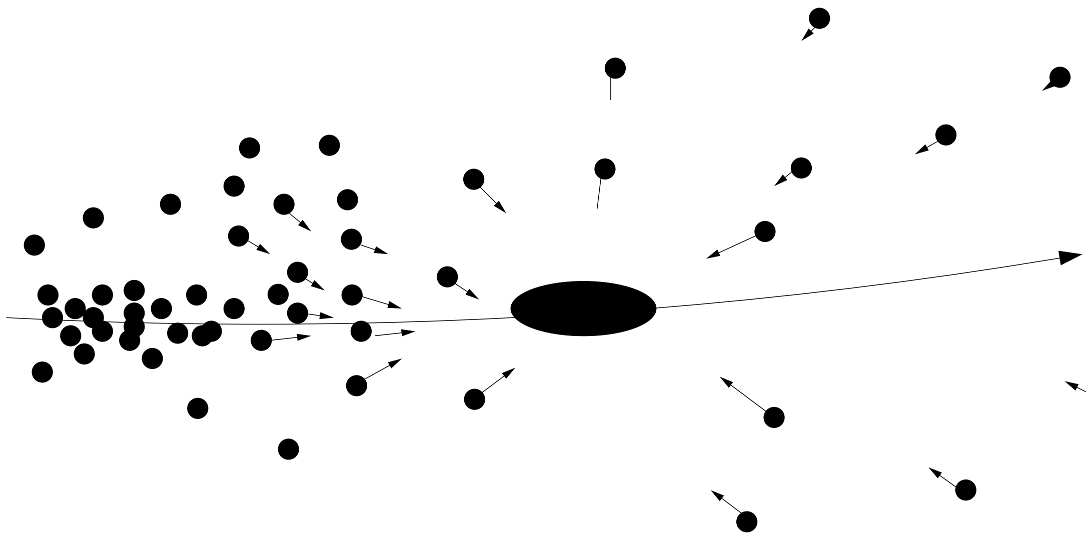

Figure 2: Dynamical friction

Galaxy moving through cluster creates overdensity behind it, galaxy is slowed down:

$$\frac{d\vec{v}}{dt} \propto -\frac{m\rho\vec{v}}{v^3}$$

$\Rightarrow$ Dyn. friction most important for massive galaxies, which therefore concentrate around the cluster's center.

Cluster Dynamics

Two-body-encounters dynamically unimportant, relaxation time scale for this process ("thermalization") $\gg$ age of universe.

Vel.-dispersion for diff. galaxy types approx. equal, thermalization by collisions would yield $\sigma_v \approx m^{-1/2}$.

$\Rightarrow$ Velocity distribution determined by large-scale processes during cluster formation.

Conclusion: Regular clusters are relaxed,
irreg. clusters possibly still forming / developing

X-Ray-Emission

GCs brightest X-Ray-sources besides AGNs; diffuse, non-variable radiation.
Spectrum points to bremsstrahlung (free-free-emission),
gas temperature $T \approx 5 \cdot 10^7$ K.

Common model: gas in hydrostatic equilibrium and isothermal;
fit of model to observed X-Ray-intensity
$\rightarrow$ estimation of cluster mass.

Resulting mass fractions:

- 3% galaxies;
- 15% intergalactic gas;
- 80% unknown

Other Methods of Mass Determination

- *Dynamical mass:* assumption that cluster is virialized ($2E_{\text{kin}} + E_{\text{pot}} = 0$);
  measurement of σ_v and cluster radius

$$\rightarrow \quad \frac{M}{L_{\text{tot}}} \approx 300\ h^{-1}\ \frac{M_S}{L_S}$$

- *Gravitational lensing:* light is deflected in grav. fields; cluster may function as "lens" ($\rightarrow$ arcs). Model mass distribution is fitted to match obs. shape of arcs.

All three methods: clusters dominated by dark matter

Scaling Relations

Expectation:

$$T_X \propto \frac{M}{r};$$

Since $M = \frac{4\pi}{3}\rho r^3$

$$\Rightarrow T_X \propto r^2 \propto M^{2/3}.$$

For a virialized cluster $M \propto r\sigma_v^2$.
Thus

$$M \propto \sigma_v^3$$

$$T_X \propto \sigma_v^2$$

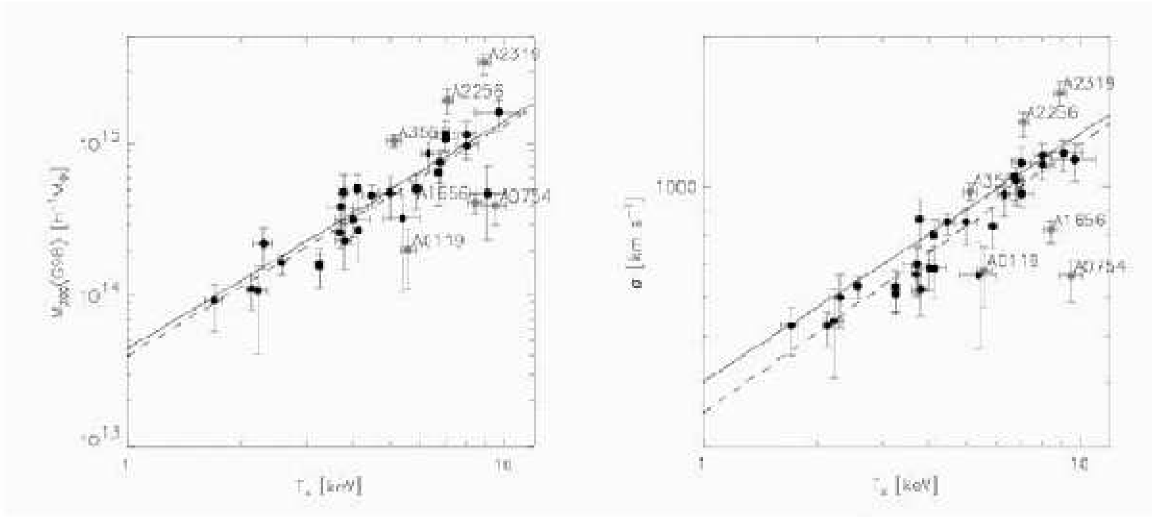

Figure 3: (a) $T_X \propto M^{2/3}$; (b) $\sigma_v \propto T^{1/2}$

Cluster Development

- Luminosity function: no clear evolution of cluster population in luminosity.
- Butcher-Oemler-effect: at high z clusters become bluer (more spirals).
- Color-Magnitude-diagram: well defined sequence of early type galaxies.
  Same sequence for different clusters at comparable z
  ($\rightarrow$ redshift determination).
  For higher z the sequence is bluer.

  Explanation:
  Age of stellar populations in cluster galaxies at same z essentially the same;
  populations continuously become redder as their age increases.
  Color of early-type galaxies consistent with age of universe.

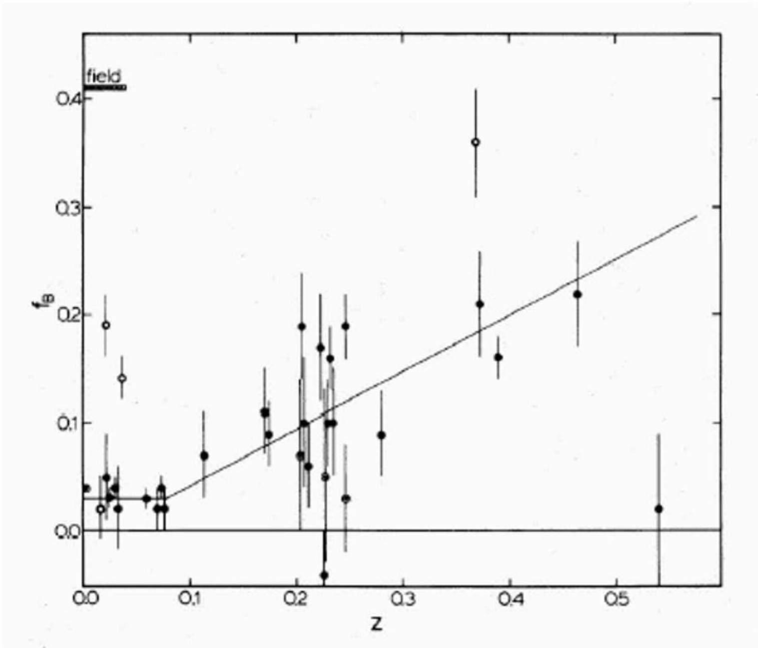

Figure 4: Butcher-Oemler-effect: fraction of blue galaxies vs. redshift

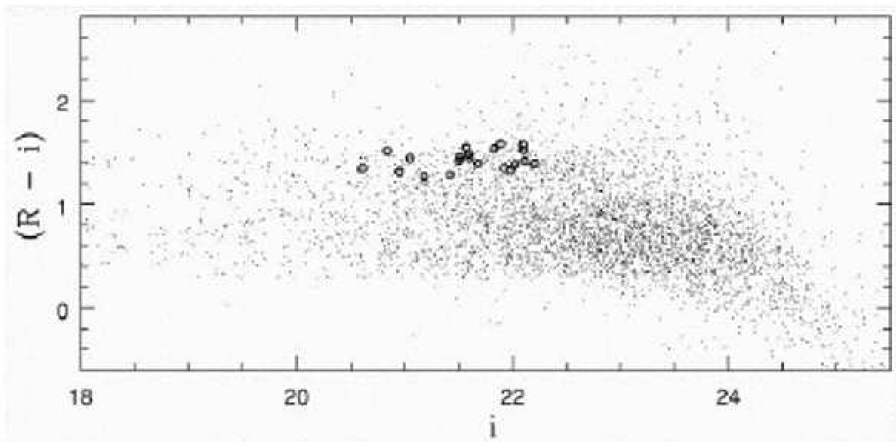

Figure 5: Color-magnitude diagram for a cluster at $z = 0.9$