# Clusters of galaxies

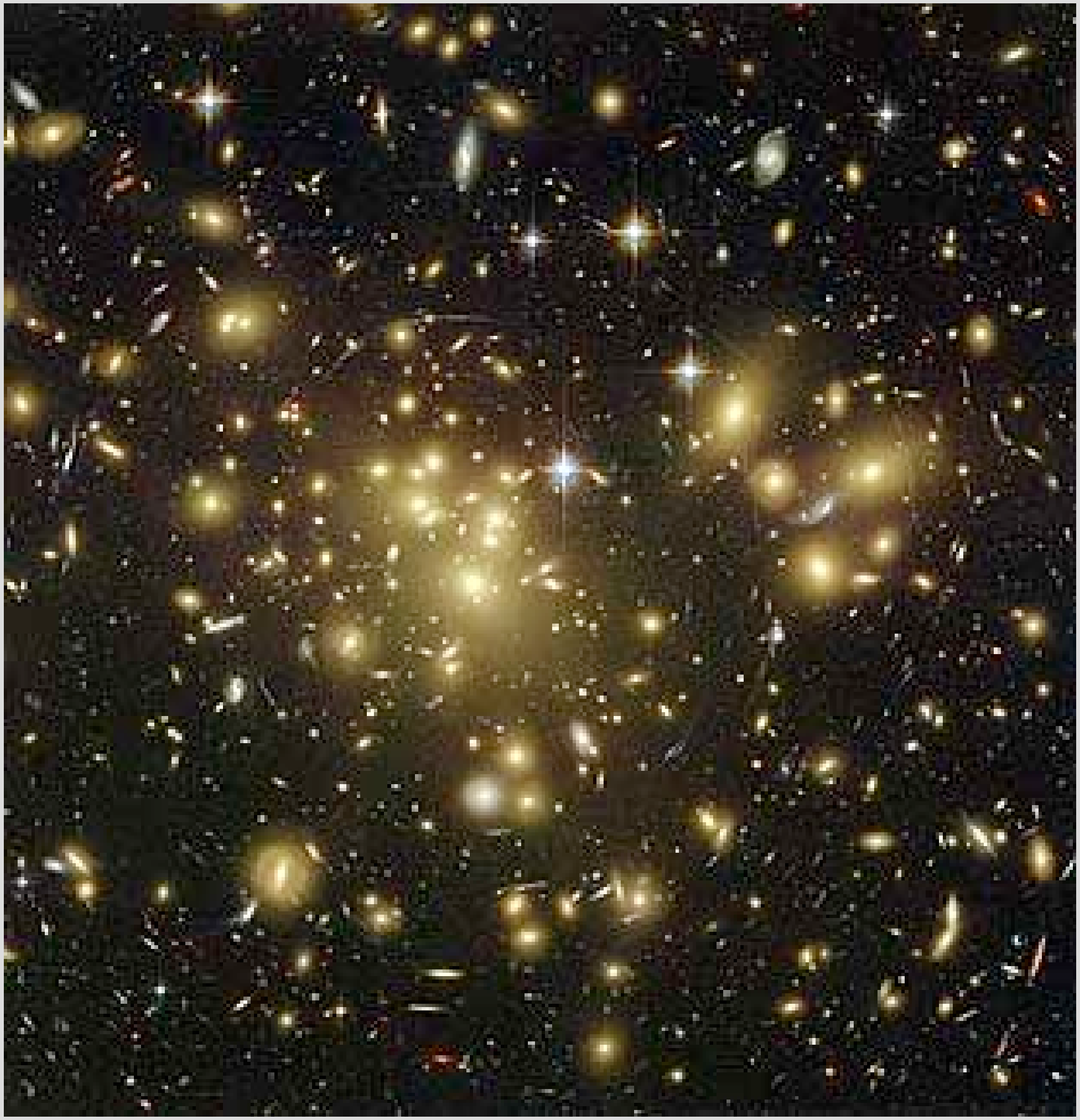
Most galaxies belong to some larger bound structure. Conventionally consider **groups** and **clusters**, with characteristic properties:

| | **Groups** | **Clusters** |
|---|---|---|
| Core radius | 250 $h^{-1}$ kpc | 250 $h^{-1}$ kpc |
| Median radius | 0.7 $h^{-1}$ Mpc | 3 $h^{-1}$ Mpc |
| Velocity dispersion (line of sight) | 150 km $s^{-1}$ | 800 km $s^{-1}$ |

(h is Hubble's constant in units of 100 km $s^{-1}$ $Mpc^{-1}$)

Roughly, consider a group to possess a handful to tens of bright galaxies, while a cluster may have several hundred galaxies.

# A1689 imaged with ACS on HST



## Why are clusters interesting?

Observationally:

- Large number of galaxies at the same distance
- Most dramatic place to look for environmental effects on galaxy formation and evolution

Theoretically:

- `Largest bound structures in the Universe'. Time for a galaxy to cross a cluster is:

$$t_{cross} \approx 10^{10} \left( \frac{d}{10 \text{ Mpc}} \right) \left( \frac{v}{1000 \text{ km s}^{-1}} \right)^{-1} \text{ yr}$$

…galaxies on the outskirts of a cluster have only made ~ a few orbits of the cluster.

- `Fair sample of the Universe'. Deep potential well of a rich cluster retains gas at T ~ $10^8$ K. Expect that the ratio:

$$f = \frac{M_{baryons}}{M_{total}}$$

$M_{baryons}$ ← Stars + gas

$M_{total}$ ← Stars, gas, dark matter

roughly represents global value.

- Rare objects, formed from the most overdense peaks in the initial density field. Implies that their number density (number per $Mpc^3$) is a sensitive function of the **amplitude** of the initial fluctuations.

## Surveys for galaxy clusters

Galaxy clusters contain galaxies, hot gas, and dark matter.
Can survey for each of these components using observations in different wavebands:

Optical

Look for an overdensity of galaxies in patches on the sky

Can use color information (clusters contain many elliptical galaxies, which are red) to help

Disadvantages: vulnerable to projection effects, rich cluster in the optical may not have especially high mass

# Abell clusters

Catalog of galaxy clusters compiled by George Abell from visual inspection of sky survey plates.

Selection criteria:

- **Richness**. Let $m_3$ be the magnitude of the third brightest galaxy in a group or cluster. Require at least 50 galaxies with magnitudes between $m_3$ and $m_3 + 2$.
- **Compactness**. The > 50 members must be enclosed within a circle of radius 1.5 $h^{-1}$ Mpc.

Original catalog contained ~ 2700 clusters.
Error rate was around 10%.

## X-ray

Galaxy clusters contain hot gas, which radiates X-ray radiation due to bremsstrahlung.

Advantage: bremsstrahlung scales with density and temperature as $n^2T^{1/2}$ - i.e. *quadratically* in the density. **Much less** vulnerable to accidental line-of-sight projection effects.

Disadvantage: still not detecting clusters based on mass.

## Sunyaev-Zeldovich effect

Distortion of the microwave background due to photons scattering off electrons in the cluster. Measures:

$$\int n_e dl$$

Mass weighted measure, though of gas not dark matter.

## Gravitational lensing

Detect clusters from the distortion of background galaxy images as light passes through the cluster.

Measures the total mass

**But** very difficult - not yet used as a survey technique

## Mass estimates

Simplest mass estimate for clusters uses the observed properties + the Virial Theorem. For a system in equilibrium with kinetic energy K and potential energy W:

$$2K + W = 0$$

$$K = \frac{1}{2} M v^2 \qquad W = \frac{GM^2}{R}$$

This gives: $$M \sim \frac{\sigma^2 R}{G} \sim 2 \times 10^{14} \left( \frac{\sigma}{10^3\ \mathrm{kms}^{-1}} \right)^2 \left( \frac{R}{1\ \mathrm{Mpc}} \right) \mathrm{M}_{\mathrm{sun}}$$

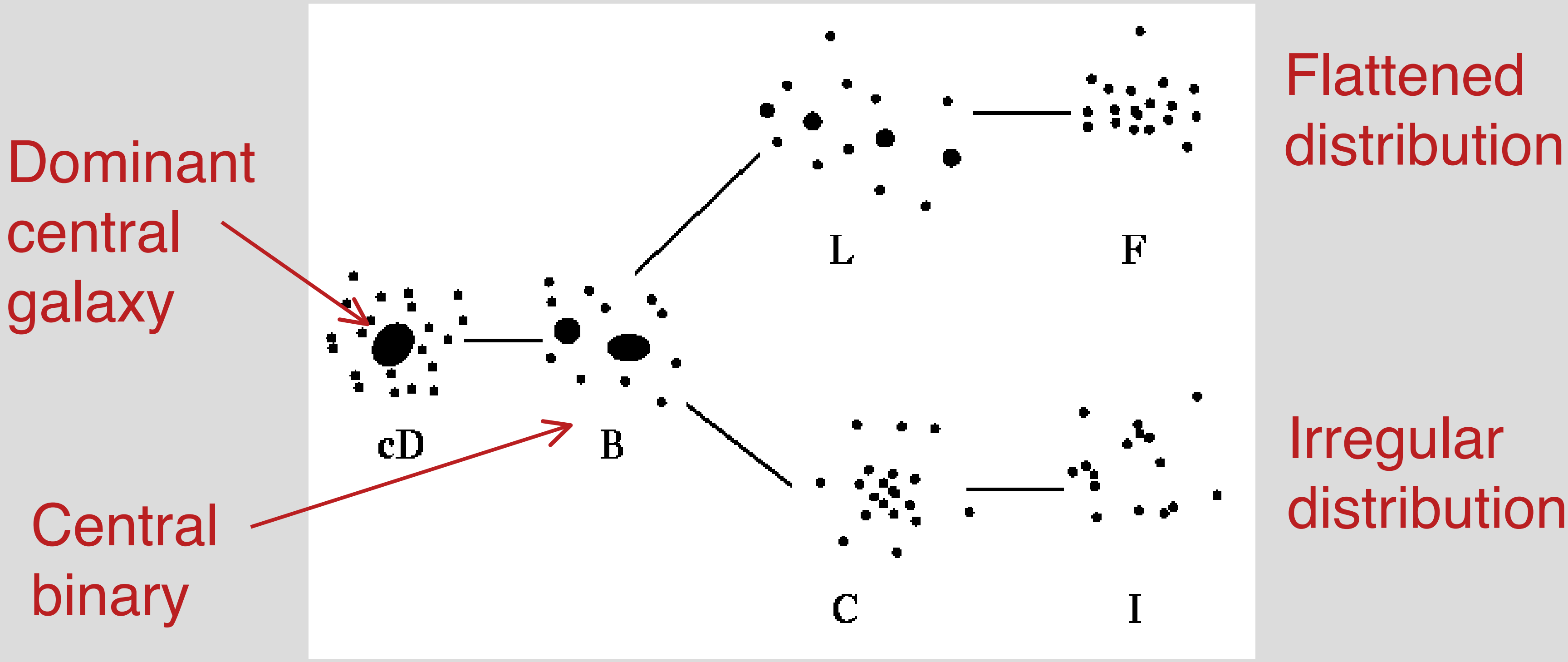
Very approximate - but right order of magnitude.
Rich cluster has a mass of ~$10^{15}$ Solar masses

Can also measure mass using X-ray observations and gravitational lensing.

## Classification of clusters

Can classify clusters of galaxies according to (i) **richness**, and (ii) **morphology**. No morphological scheme enjoys same support as Hubble's tuning fork diagram for galaxies. Example:

Rood and Sastry scheme




Importance: some clusters have cD galaxies. Expect a range of morphologies because clusters are young, merging systems…