6. Spatial distribution of galaxies.

→ not even distributed.

→ most are in groups up to ~50 galaxies,

or in clusters ~ 50 – 1000 giant galaxies.

Groups:

→ Milky Way is in the local group, 4 Sp, dw Ir & many dE/dSph.

→ typically $R \sim 1.5$ Mpc $\sigma \sim 150$ km s^{-1}

↖ velocity dispersion of the galaxies.

applying virial theorem
(applies to all grav. bound systems in eqm)

$\Rightarrow M \sim 10^{13} M_\odot$

$\Rightarrow \frac{M}{L} \sim 250$ ⇒ groups are v. dark matter dominated (more so than the individual galaxies).

→ 7 groups within ~~kkpc~~ 10 Mpc
closest is Sculptor group at 1.8 Mpc

→ 80% of giant galaxies are in groups of which ~70% are spirals.

Clusters

→ closest is the Virgo cluster at 16 Mpc

An irregular (asymmetrical) cluster
with ~ 250 giant gals.
~ 2000 dwarf galaxies

4 gEs at centre, but most giants are still
Ss ~ 68%.

⇒ dynamically young cluster

⇒ still assembling, not enough time for galaxies to collide.

→ nearest regular cluster is the coma cluster at 90 Mpc

A rich cluster with ~ 1000 giant gals
~ 10,000 dwarf galaxies

2 cD galaxies at centre,

Most giants are Es, Spirals only ~15%.

→ dynamically evolved.

→ typically $R \sim 6$ Mpc $\sigma \sim 800\ \mathrm{km\,s^{-1}}$

$\Rightarrow M \sim 10^{15} M_\odot \quad \frac{M}{L} \sim 400$

even more dark matter dominated than groups.

Groups and clusters are filled with hot gas, imaged in X-rays.

Example: Coma cluster

$R \simeq 3\,Mpc \quad v_r = 977\,km\,s^{-1}$

recall, $\sigma = \sqrt{3}\, v_r = 1700\,km\,s^{-1}$

use virial theorem

$\Rightarrow M_{tot} = 3 \times 10^{15} M_\odot$

recall, virial temperature

$$\tfrac{3}{2} k T_{virial} \simeq \tfrac{1}{2} \mu m_p \sigma^2$$

μ ← mean molecular weight ~ ½ for ionised hydrogen (one e^-, one p^+)

$$\Rightarrow T_{viral} \simeq \frac{1}{6} \frac{m_p}{k} \sigma^2 = \underline{6 \times 10^7 K}$$

($\simeq$ measured X-ray temperature is $9 \times 10^7 K$)

Recall, bremsstrahlung cooling

$$L_x = \underbrace{1.42 \times 10^{-40} n_e^2 T^{1/2}}_{\text{emissivity}} \underbrace{\frac{4}{3}\pi R^3}_{\text{volume}}$$

L_x: X-ray luminosity

X-ray observations $\Rightarrow L_X = 5\times10^{37}$ W.

$\Rightarrow n_e \simeq 100\,m^{-3}$ very low density.

recall, cooling timescale by equating total thermal energy in gas with cooling rate,

$$\underbrace{\tfrac{3}{2}NkT = \tfrac{3}{2}V(n_e+n_i)kT = 3Vn_ekT}_{\text{thermal energy}} = \underbrace{\mathcal{L}_V V t_{cool}}_{\text{cooling}}$$

$$\Rightarrow t_{cool} \simeq \frac{3Vn_ekT}{1.42\times10^{-40}T^{1/2}n_e^2} = \frac{3kT^{1/2}}{1.42\times10^{-40}n_e}$$

$\simeq \underline{\underline{7\times10^{11}\,yr}}$ ~ 50 Hubble times!

So no significant cooling can have occurred to date.

$$M_{gas} \simeq \tfrac{4}{3}\pi R^3 n_e m_p \simeq \underline{\underline{3\times10^{14} M_\odot}}$$

huge! 10% of total mass of cluster.

$\Rightarrow$ 90% is dark matter.

10% is hot gas — accreting into the cluster, not via galaxies.

~1% is stars.

For clusters, gravitational lensing provides an independent method for measuring mass, and the mass distribution.

Observations of the Bullet cluster show two colliding clusters, with the non-interacting dark matter components separated from the collisional hot gas. V. strong evidence that dark matter cannot be explained by modified gravity.

→ on larger scales clusters & groups are not evenly distributed. There are distinct voids with no groups or clusters, and filaments in which groups are found. cluster located at intersections of filaments.

→ numerical simulations suggest such structure is natural consequence of gravitational collapse of cold dark matter in an expanding universe.

→ observed distn. of galaxies requires a bias to high density regions.

→ These simulations point to small structures forming first (dwarf galaxies) and giant galaxies gradually assembling from fragments.

→ observation of structure ~~#~~ vs redshift can test models of cosmology & dark matter.

⟶ 3rd yr cosmology.