Galaxy Groups & The Big Bang

Cluster dynamics
Dark matter
Interacting galaxies
Homogeneity and Isotropy of the Universe
Big-Bang and Steady State Cosmology
Detection of the Big Bang

April 18, 2024

University of Rochester

Galaxy Groups & Cosmology: The Big Bang

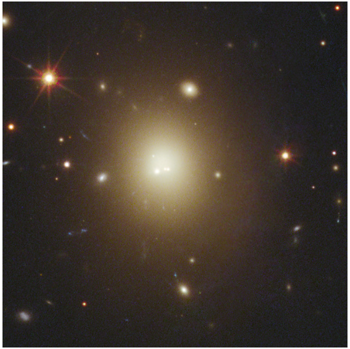
- Galaxy cluster dynamics
- Dark matter in clusters of galaxies
- Interacting galaxies: starbursts, the origin of AGN
- The expanding, isotropic, and homogeneous Universe
- Big-Bang and steady-state cosmology
- Alpher, Herman, and decoupling
- Penzias and Wilson's detection of the Big Bang's blast
- Big Bang nucleosynthesis

Reading: Kutner Ch. 20.1–20.2, & 21.2, Ryden Ch. 23.1, and Ned Wright's cosmology tutorial

cD galaxies

cD galaxies are giant ellipticals with a few other differences from normal besides the total mass:

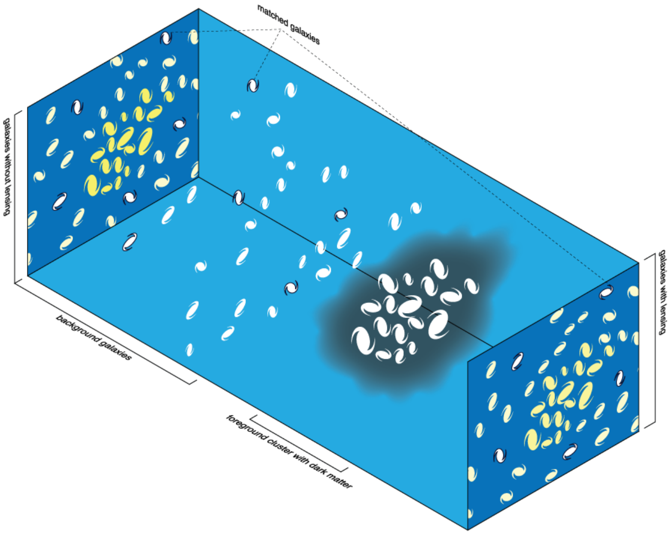
- More extended relative to their core radii and the normal elliptical galaxy luminosity profile.
- Often exhibit multiple nuclei, either because they are assimilating other cluster members ("galactic cannibalism") or because these nuclei are cluster galaxies on linear (highly eccentric) orbits.
- Often surrounded with shells of infalling intergalactic gas that compress and cool as they fall ("cooling flows").
- Often associated with bright, strong gravitational lensing of more distant galaxies, clusters, or quasars.



Abell 2261 BCG

Dark matter gravitational lenses

Weak lensing of background galaxies by a foreground cluster. Image from Wikimedia Commons.



Abell 2218 and Gravitational Lensing

Galaxy Cluster Abell 2218 HST • WFPC2

NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

Masses of galaxy clusters

The masses of clusters can be measured by adding up the masses of the contents. There are a few ways to do this.

1. Count the galaxies and add up their masses, including dark-matter halos.
2. Measure the X-ray spectrum and image.
   - The X-ray emission is due to radiation by electrons scattering from nuclei, a process called thermal bremsstrahlung or free-free emission.
   - The X-ray brightness at any energy is proportional to the square of the electron density. The X-ray “color” gives the temperature.
   - Usually, the X-ray distribution appears spherically symmetric and fairly smooth.

Masses of galaxy clusters

Results for typical galaxy clusters like Coma and Virgo:

- Galaxies and X-rays distributed similarly, with a core radius around 1 Mpc — looks like **hydrostatic equilibrium**.
- The radial dependence of the number per unit projected area is like the radial dependence of surface brightness in ellipticals:

$$\mathcal{N}(r) = \mathcal{N}(0) \exp\left[-\left(\frac{r}{r_0}\right)^{-1/4}\right] \qquad r_0 = \textbf{core radius}$$

- Galaxies, including their dark halos, typically amount to 1–3$\times 10^{13} M_\odot$.
- X-ray-emitting gas has a density, temperature, and mass around

$$n_e \sim 10^{-4}\ \mathrm{cm}^{-3} \qquad T \sim 10^8\ \mathrm{K} \qquad M \sim 1-3\times 10^{14} M_\odot$$

ten times as much as the galaxies.

Masses of galaxy clusters

This reveals two odd dynamical features of galaxy clusters:

1. The relaxation times for galaxy clusters,

$$t_c \approx \left(\frac{2r_0}{v}\right)\frac{N}{24\ln\left(N/2\right)}$$

tend to be larger than the age of the Universe (1.4×10^{10} yr), but in principle need to be much smaller in order to treat the galaxies in a cluster as a gas. E.g., for the Coma cluster,

$$N = 10^4 \qquad r_0 = 3\text{ Mpc} \qquad v = 1700\text{ km/s} \qquad \Longrightarrow\ t_c = 1.7 \times 10^{11}\text{ yr}$$

However, $\mathcal{N}(r)$ looks just like that for thermalized galaxy bulges and star clusters, and the distribution of their random velocities looks like a Maxwell-Boltzmann distribution.

Masses of galaxy clusters

2. The thermal velocity for intracluster gas,

$$v_{\mathrm{th}} = \sqrt{\frac{3kT}{m_{\mathrm{H}}}}$$

is typically about the same as the escape speed from the observed mass,

$$v_{\mathrm{esc}} = \sqrt{\frac{2GM}{r_0}}$$

Thus, all of the hot gas originally in the typical galaxy cluster should have escaped by now. The Jeans escape timescale (ASTR 111) is

$$\tau_{\mathrm{Jeans}} = \frac{\sqrt{\pi}}{8}\left(\frac{2k_B T}{m_{\mathrm{H}}}\right)^{3/2}\frac{r_0^3}{(GM)^2}e^{GMm_{\mathrm{H}}/k_B T r_0} \approx 10^9\ \mathrm{yr}$$

for typical galaxy clusters.

Masses of galaxy clusters

If the equilibrium-like appearance of the distribution of galaxies in clusters is taken to indicate equilibrium despite the inferred relaxation time, we can apply the **virial theorem** to estimate masses:

$$M = \frac{2r_0\overline{v^2}}{G} = \frac{6r_0\overline{v_r^2}}{G}$$

where $\overline{v_r^2}$ is the random component of the radial velocity relative to the cluster average.

This typically gives a result ten times higher than the mass of visible galaxies and X-ray gas. For example, in the Coma cluster,

$$M_{\text{X-ray}} = 3 \times 10^{14} M_\odot \qquad M = \frac{2r_0\overline{v^2}}{G} = 4 \times 10^{15} M_\odot$$

Dark matter revisited

The discrepancy between visible-galaxy mass and virial mass was first noticed by Fritz Zwicky (Zwicky 1933) for the Coma cluster. He suggested an invisible form of matter to make up the difference — the original suggestion for the existence of dark matter.

Right: image of Zwicky from the Swiss Fritz Zwicky Society.

So, what if the galaxy clusters are 90% dark matter?

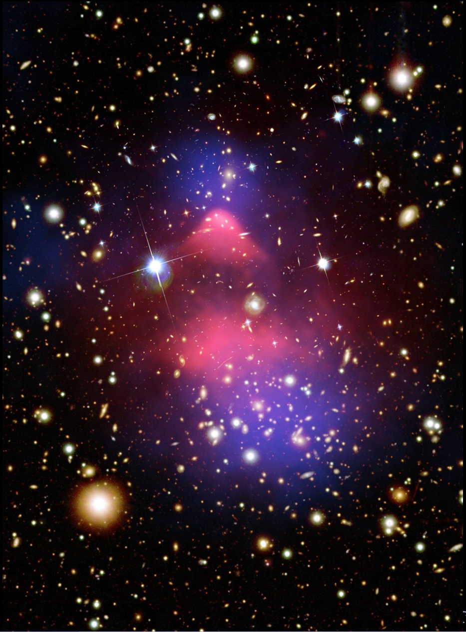
- Then the clusters *could* be in equilibrium. The dark matter "nucleus" of each cluster could have thermalized early in the life of the Universe, and the visible galaxies formed after their dark halos were already in equilibrium.
- This is enough mass to keep the X-ray gas from getting away: with the mass above, the Jeans escape time for the hot ICM in Coma is 2×10^{15} yr, much longer than the age of the Universe.

Dark matter revisited

In the case of the Bullet Cluster, 1E 0657-558, dark matter appears more directly.

The Bullet Cluster consists of two merging galaxy clusters. In the interaction, the hot gas from the clusters, visible in X-rays (red), has suffered inelastic collisions and is now separate from the dark matter (blue).

The dark matter is detected via weak gravitational lensing (Clowe et al. 2006).



Interacting galaxies

Galaxies have extents (tens of kpc) that are a significant fraction of the typical separations of galaxies in groups or clusters (hundreds of kpc). Thus, collisions between galaxies are not all that rare.

The stellar disks can be relatively unaffected by galaxy-galaxy encounters because the stars themselves do not collide.

However, the interstellar clouds are big and they suffer inelastic collisions and tidal "stripping" that can result in the transfer of ISM from one galaxy to another. We will consider two possibilities:

1. Transfer with large angular momentum: ISM settles into the disk and/or **polar rings**.
2. Transfer with small angular momentum: ISM falls into the galactic nucleus, leading to **starbursts**.

Interacting galaxies: Polar ring galaxies

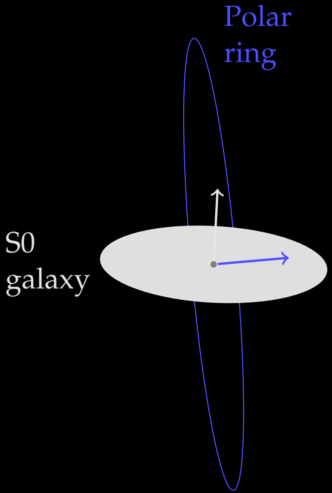
Transferred material which has substantial angular momentum in the frame of its new host galaxy quickly adopts appropriate orbits.

If the orbital plane is not coaxial with one of the host galaxy's principal axes, or if the host has substantial ISM, the transferred material settles into the host's disk plane relatively quickly ($\sim$Gyr).

But material which winds up in a polar orbit in a galaxy without much ISM can be stable for very long periods of time.

Thus polar ring galaxies, which look like spiral galaxies in one plane and elliptical or lenticular galaxies in a perpendicular plane, can form and be readily observed.

Polar Ring Galaxy NGC 4650A



Rotation axes of galaxy and ring are almost ⊥.

Interacting galaxies: Starbursts

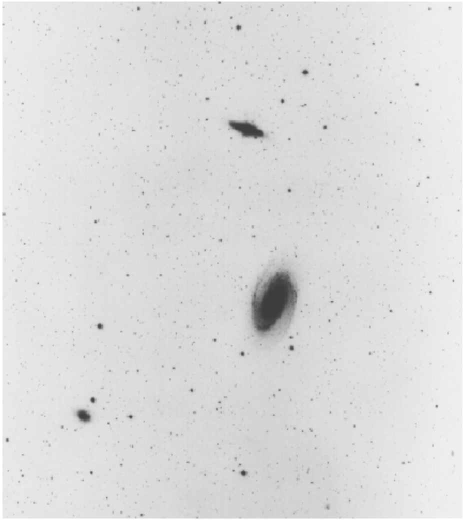
A starburst is a brief but dramatic increase in the rate of production of stars by a factor of 100 to 1000 more than the normal rate in the disks of spiral galaxies.

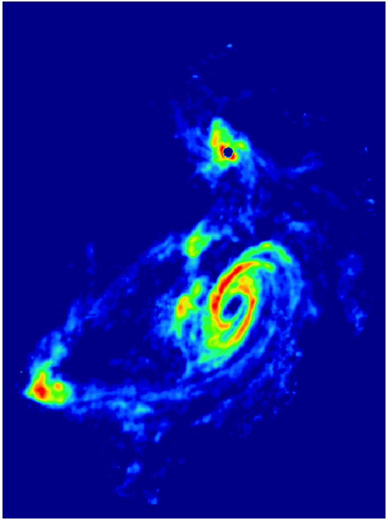
Starbursts are identifiable from their large numbers of OB stars and supernovae.

Starbursts are associated with either interacting galaxies in which ISM has been transferred (e.g., M82 interacting with M81) or the merger of two galaxies (e.g., NGC 4038/4039).

Very close encounters can result in galaxy mergers. If such galaxies are gas-rich, then collisions among their interstellar clouds can result in compression or loss of angular momentum (with subsequent infall to one of the galactic nuclei), again resulting in a starburst.

Galaxy mass transfer: M81, M82, and NGC 3077





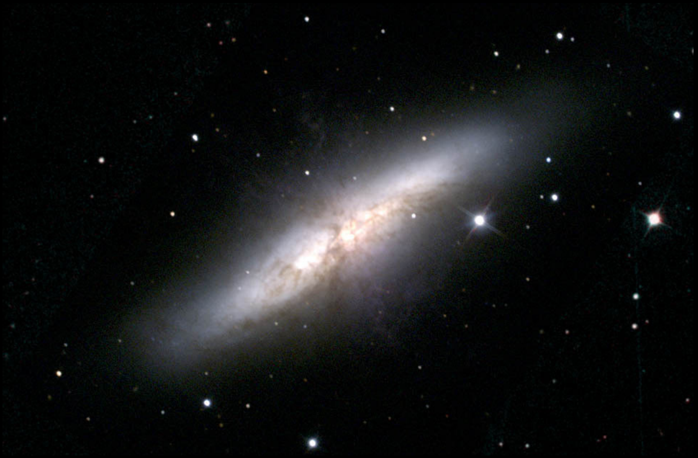
Left: visible light from M81-M82 system (Palomar). *Right:* HI 21 cm observations (VLA) (Yun et al. 1994).

Archetypical starburst galaxy M82 (NGC 3034)

BVR image of the "Cigar" Galaxy M82 (NOAO).

The star formation rate in the nucleus of M82 is a factor of 10 to 100 larger than in a spiral disk.

Star formation is enhanced due to the infall of interstellar material "stolen" from M81.



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Spitzer IRAC mid-IR image by C. Engelbracht and the SINGS team (NASA/JPL/UAz).

Galaxy interactions & active galaxies

AGN activity is very frequently detected among interacting galaxies.

This suggests that active-galaxy accretion disks form in galaxy interactions, presumably from the lowest angular-momentum material transferred.

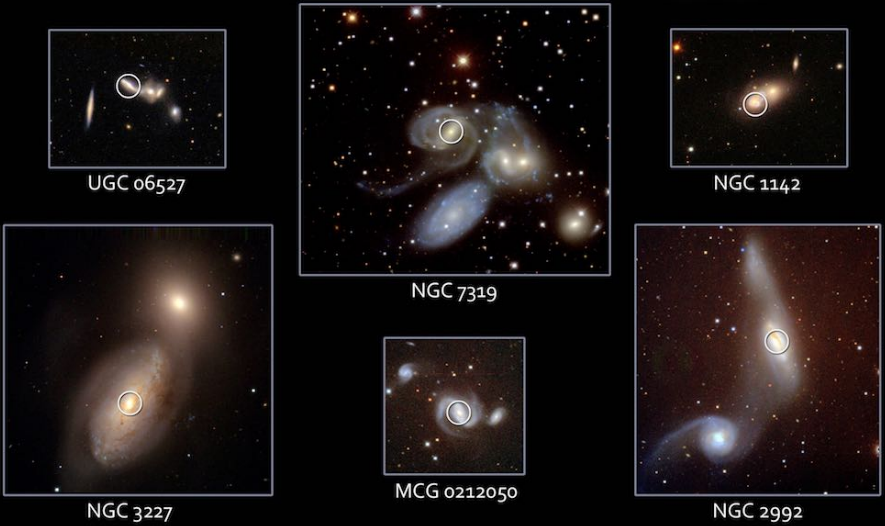
This also suggests that the formation of the central black holes themselves is related to galaxy interaction.

On the other hand, as previously discussed, *currently* inactive galaxies have central supermassive black holes with masses that scale with global properties of their host galaxies (Gultekin et al. 2009). So:

- Big galaxies $\Longrightarrow$ big black holes. . .
- or lots of mass capture $\Longrightarrow$ big black holes. . .
- or both?

AGN in merging galaxies

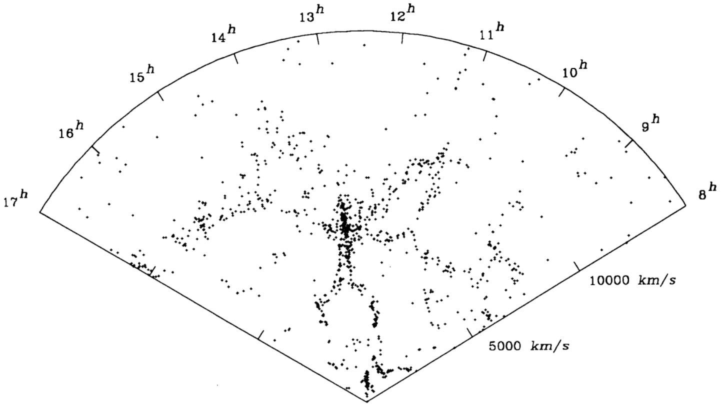
Visible images (NOAO) and X-ray detections (NASA/Swift)



The distribution of galaxies in the universe

Superclusters are more easily seen in 3D maps of the Universe; they appear as elongated highly dense clusters of galaxies (the "Finger of God" effect).

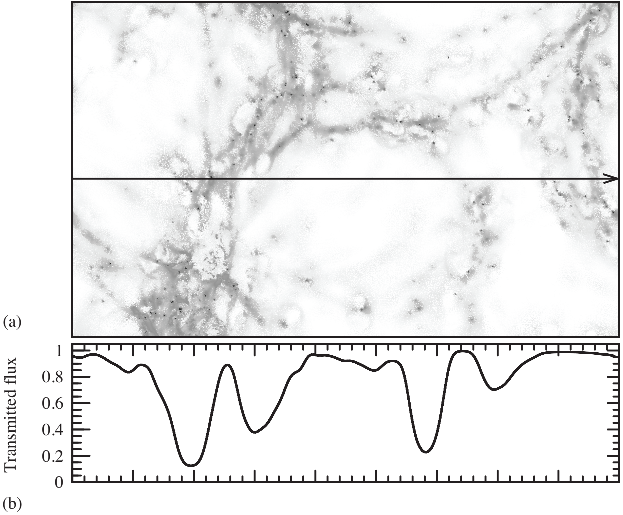
Clusters (and superclusters) are connected by thin filaments of galaxies. The extremely underdense, spherical regions of the galaxy distribution outlined by these clusters and filaments are voids.



A slice of the sky from the CfA Redshift Survey. Each dot represents a galaxy.

Probing the IGM & ICM

Because quasars are so distant, their light must pass through hundreds of megaparsecs of intergalactic gas before it reaches us. This gas will absorb photons at wavelengths corresponding to its chemical composition, so a quasar's spectrum will exhibit absorption lines from the interstellar gas.



Probing the IGM & ICM

The absorption features will be redshifted to correspond to the distance between us and the gas. We will often see a "forest" of absorption features, such as the Lyman alpha forest shown in the quasar spectrum below.