

Active Galactic Nuclei & Groups of Galaxies

Accretion disks and jets
Groups, Clusters, and Superclusters
Cluster Dynamics
Dark Matter
Interacting Galaxies

April 15, 2025

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AGN accretion disks

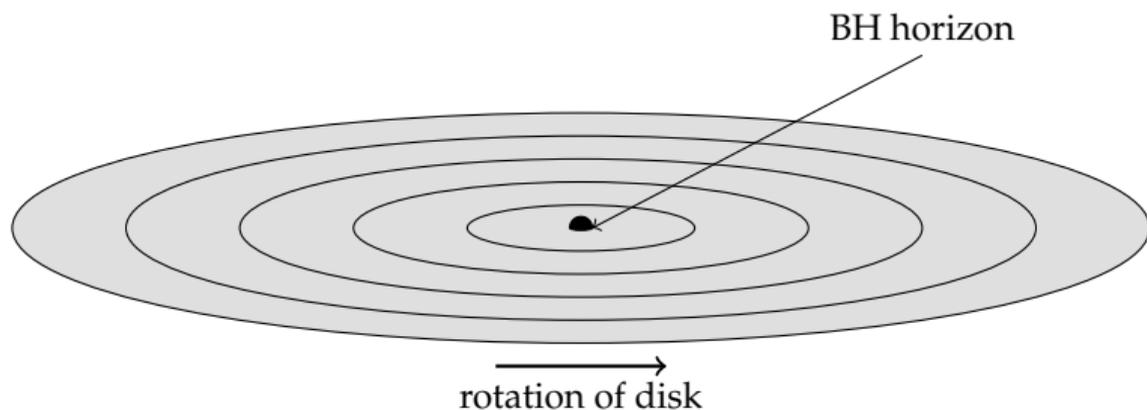
A disk-shaped collection of matter surrounding the black hole in an AGN arises rather naturally, just as it does in galactic black holes and young stellar objects.

- ▶ Stars in a galaxy perpetually collide elastically, exchanging energy, momentum, and angular momentum.
- ▶ Two stars originally in similar orbits and undergoing such a collision will usually find themselves pushed to different orbits, one going to a smaller-circumference orbit and one going to a larger orbit.
- ▶ Thus some stars and gas clouds are pushed to the very center of the galaxy after a number of these encounters.
- ▶ There they are tidally sheared in the strong gravity near the black hole.



AGN accretion disks

Eventually the tidally-disrupted material from many stellar encounters settles down into a flared disk. Collisions among particles in the disk cause material to lose spin and become accreted by the black hole. In a perspective view:



The disk can contain $10^3 - 10^6 M_{\odot}$ and extend $\mathcal{O}(100 \text{ pc})$ from the central black hole.

Operation of AGN accretion disks

For non-spinning black holes, the innermost stable circular orbit (ISCO) is $3R_{\text{Sch}}$ and no orbits exist within $1.5R_{\text{Sch}}$. Within this volume the disk structure breaks down and material tends to stream towards the horizon.

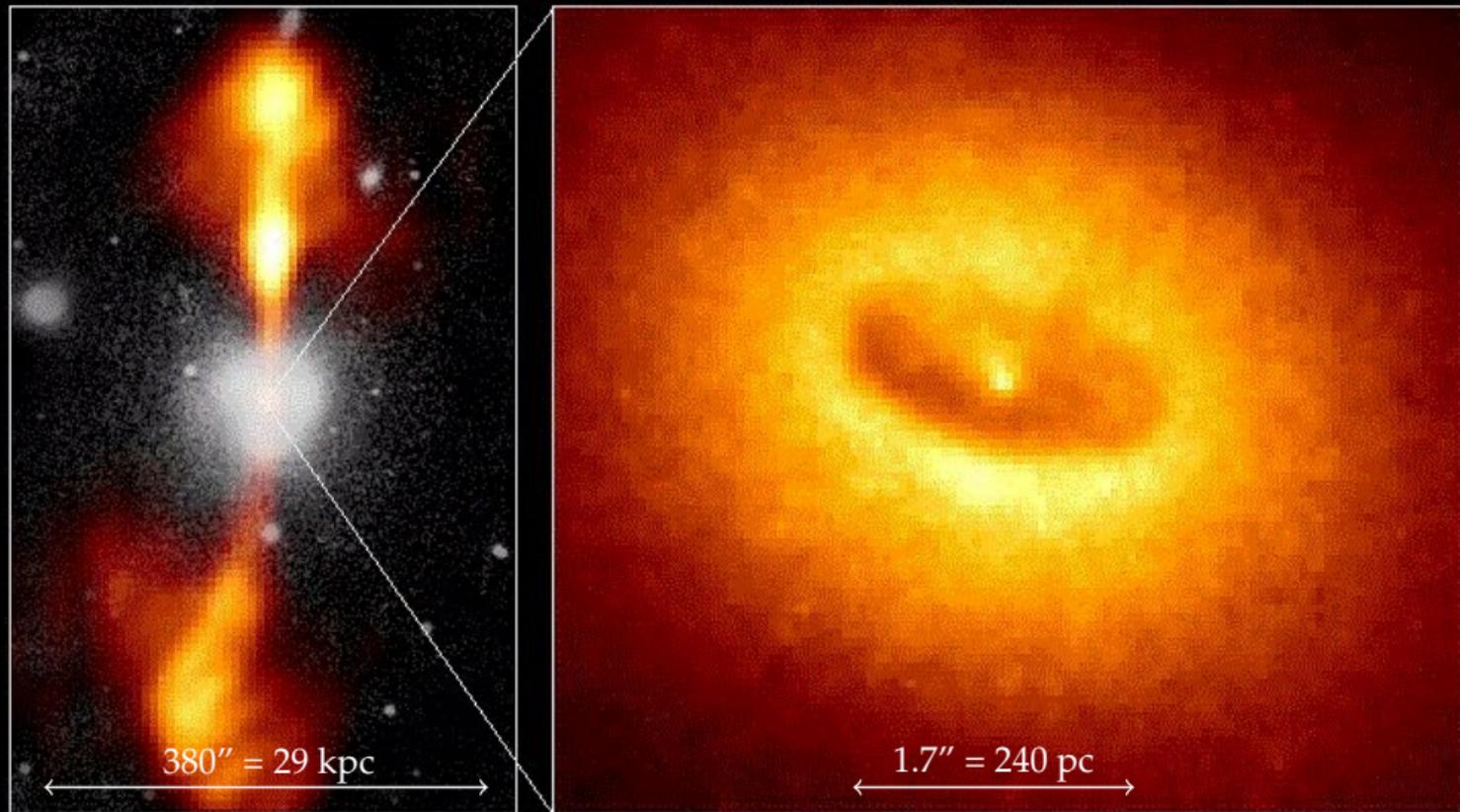
A large amount of power, mostly in the form of X-rays and γ rays, is emitted by the infalling material. The pressure exerted by this radiation slows down the rate at which accretion takes place.

Much of this high-energy light is absorbed by the disk, which heats up and re-radiates the energy as longer wavelength light.

The heated disk is observed as a **compact central object** seen in radio images of radio galaxies and QSOs.

Accretion disk in NGC 4261

Giant elliptical galaxy NGC 4261. Left: optical/radio overlay. Right: HST image of core. From NASA/STScI.



Operation of AGN accretion disks

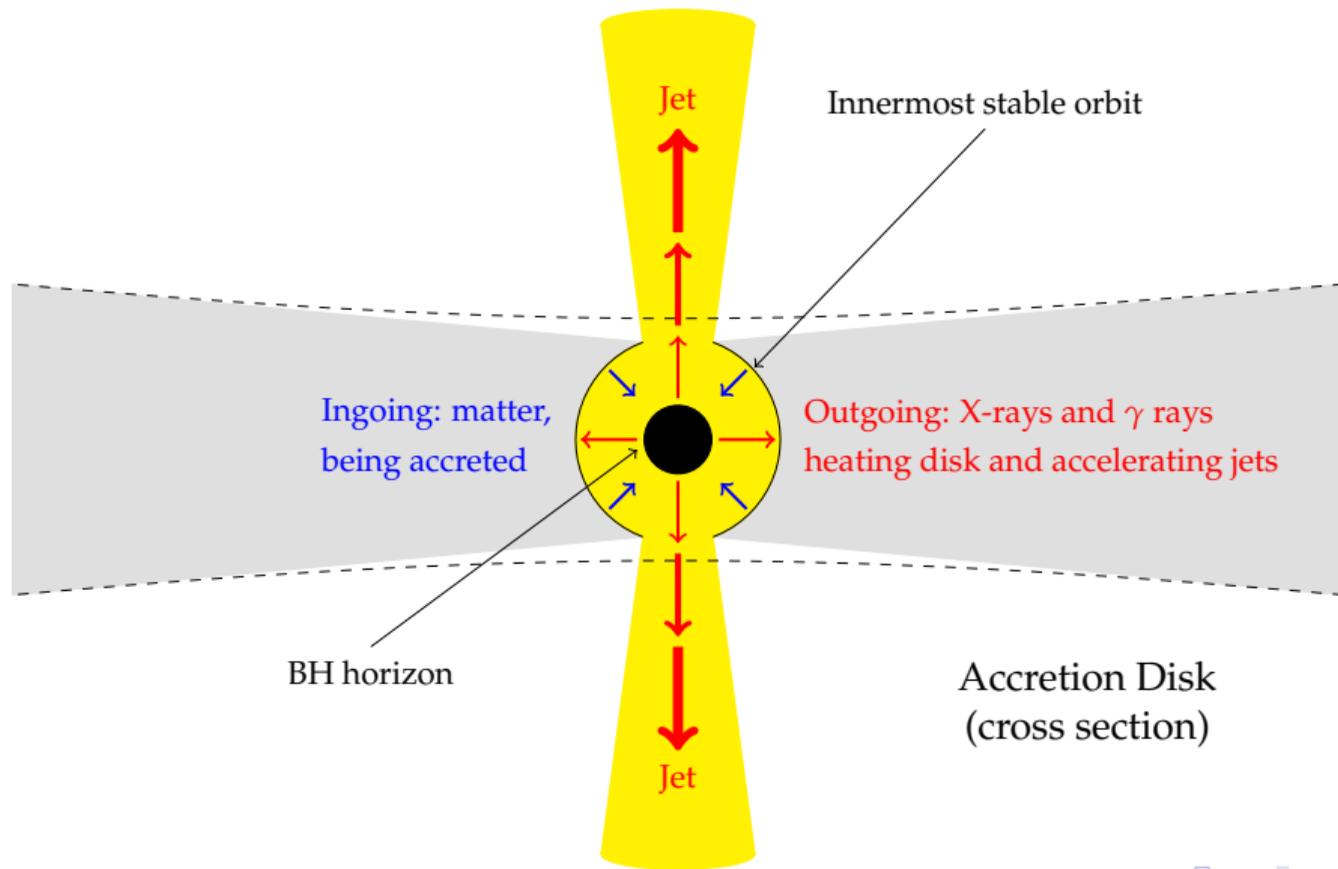
Some of the particles absorbing the highest-energy light are accelerated to speeds approaching c .

If their velocity takes them into the disk then they just collide with disk material and lose their energy to heat. If their velocity takes them perpendicular to the disk, they may escape ([Blandford & Rees 1975](#)).

Jets: high-speed particles escaping perpendicular to the disk, observed in radio and visible images of radio galaxies and quasars.

Accelerated by gravity, radiation pressure, and magnetic effects, the escaping material is expected to be relativistic, just as we observe in jets.

Structure of an AGN accretion disk (not to scale!)



Galaxy groups and clusters

Much of the Universe' mass exists in the form of a hierarchy of gravitationally bound groups or clusters of galaxies.

- ▶ The Local Group includes the Milky Way, M31, M33, and a bunch of dwarf ellipticals and irregulars.
- ▶ Groups are usually part of **clusters**. The local group belongs to the Virgo Cluster.
- ▶ Clusters themselves are parts of larger structures called **superclusters**. The Virgo Cluster is near the center of the Virgo (a.k.a. Local) Supercluster.
- ▶ Superclusters are connected by thin filaments of galaxies (often composed of galaxy groups) which outline **voids**.



NGC 7731

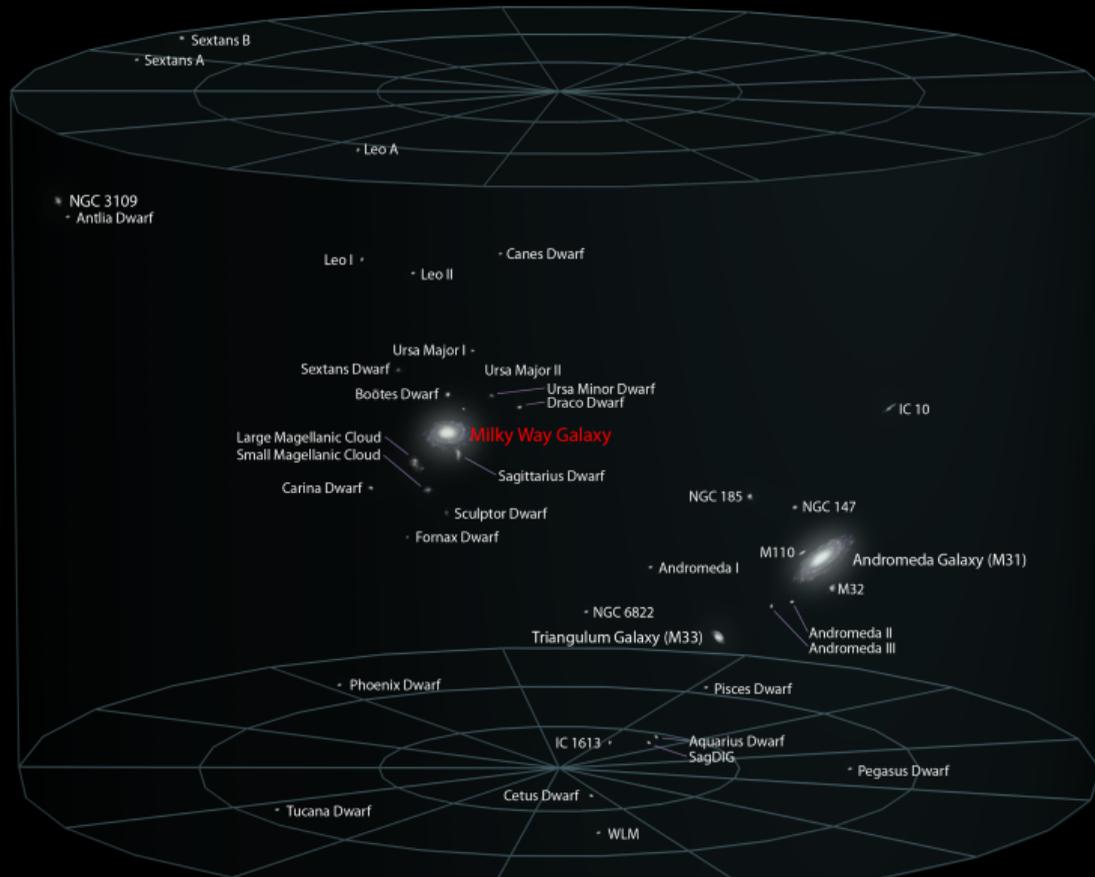
Stephan's Quintet



Image from Dietmar Hager, Stargazer Observatory.

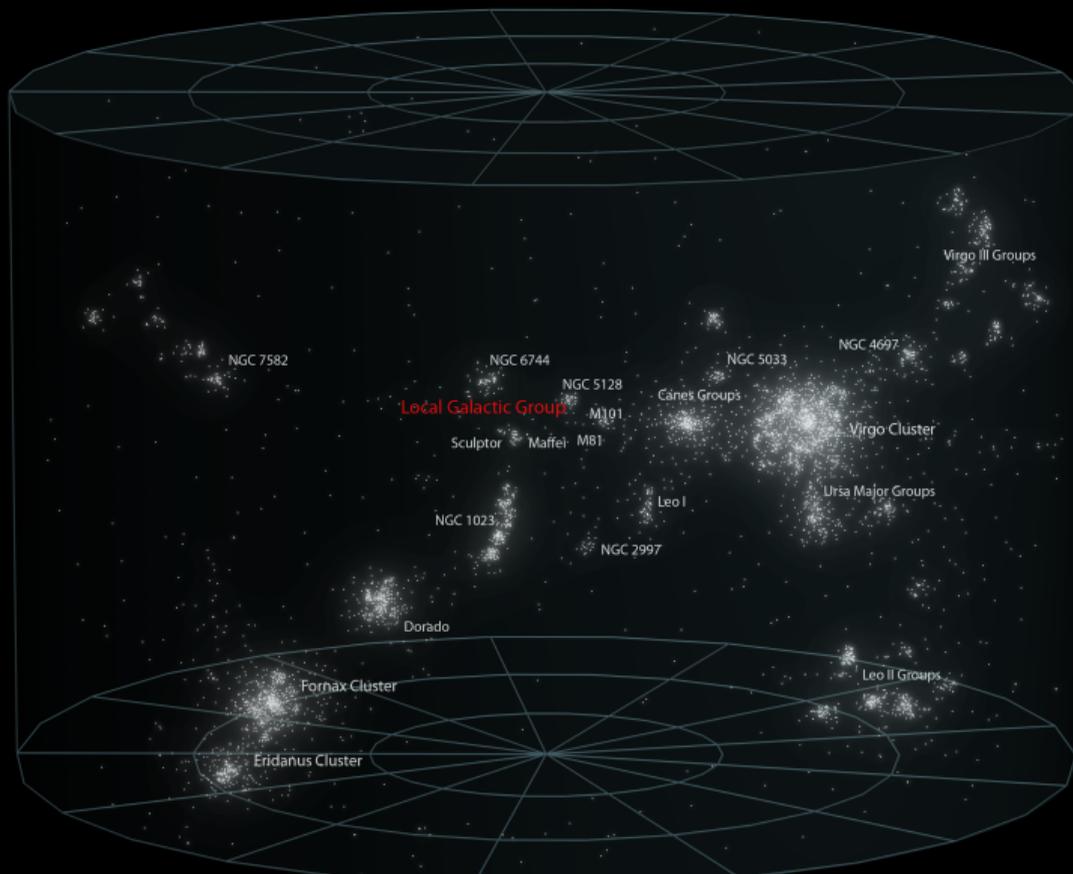
The Local Group

Andrew Z. Colvin



The Virgo Supercluster

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Typical galaxy clusters

Galaxy clusters usually contain between several hundred and several thousand galaxies, spread over tens of Mpc but with cores 1–3 Mpc in radius.

Clusters come in a variety of “richness” (degree of central concentration).

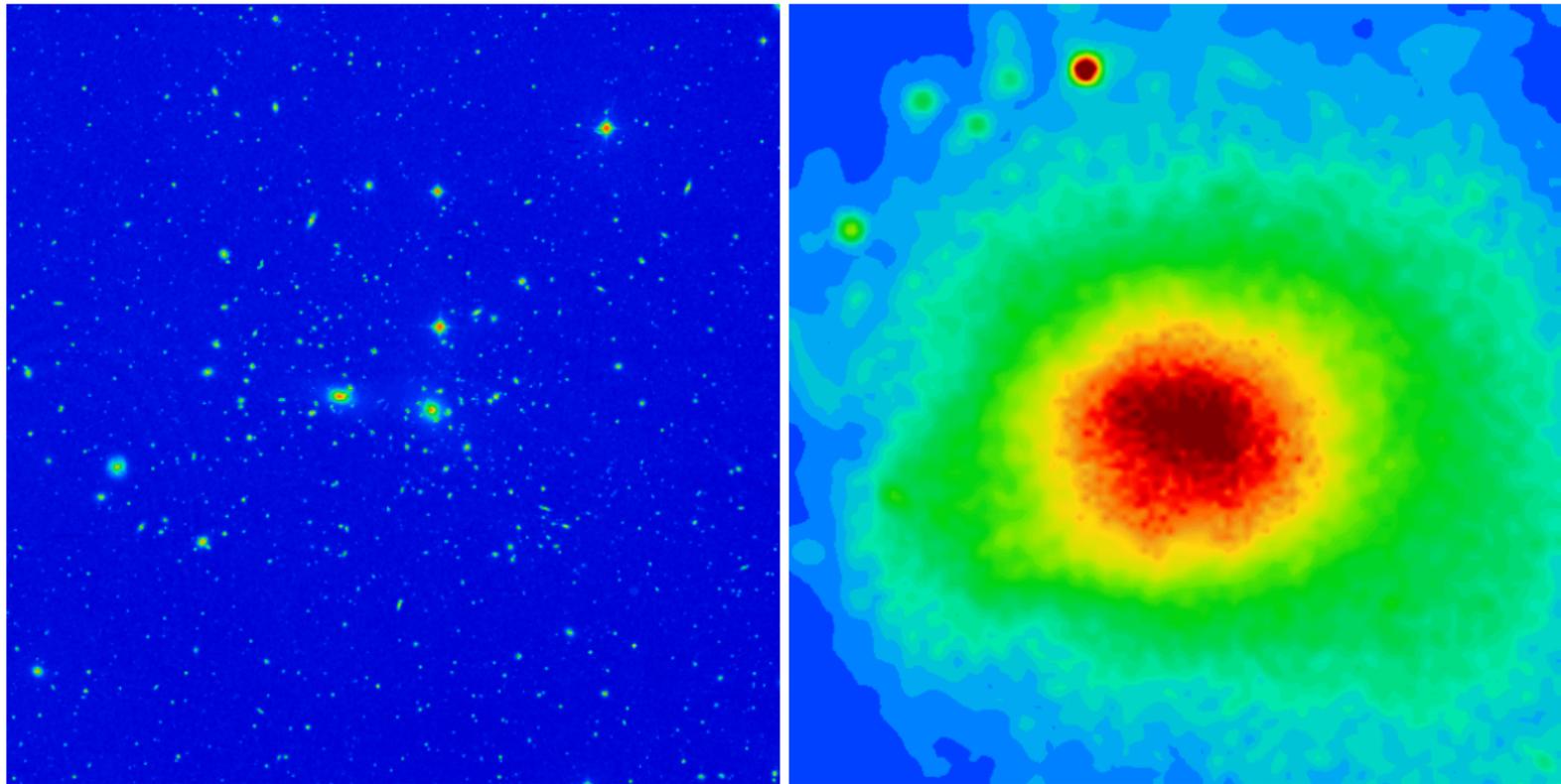
Rich clusters are dominated at their centers by one or more **cD galaxies** (supergiant ellipticals) and include mostly ellipticals.

Poor clusters are often dominated by spirals.

Spiral galaxies within rich clusters tend to have **less diffuse interstellar matter** than field galaxies; **S0 galaxies are much more abundant** in clusters than in the field. Both tendencies are probably due to galaxy collisions.

The stripped-off interstellar matter is visible at X-ray energies as a hot intracluster medium (ICM).

The Coma Cluster ($d = 99$ Mpc)



Left: visible light (UK Schmidt) — galaxies. *Right:* X-rays (ROSAT) — hot intracluster gas.

cD galaxies

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

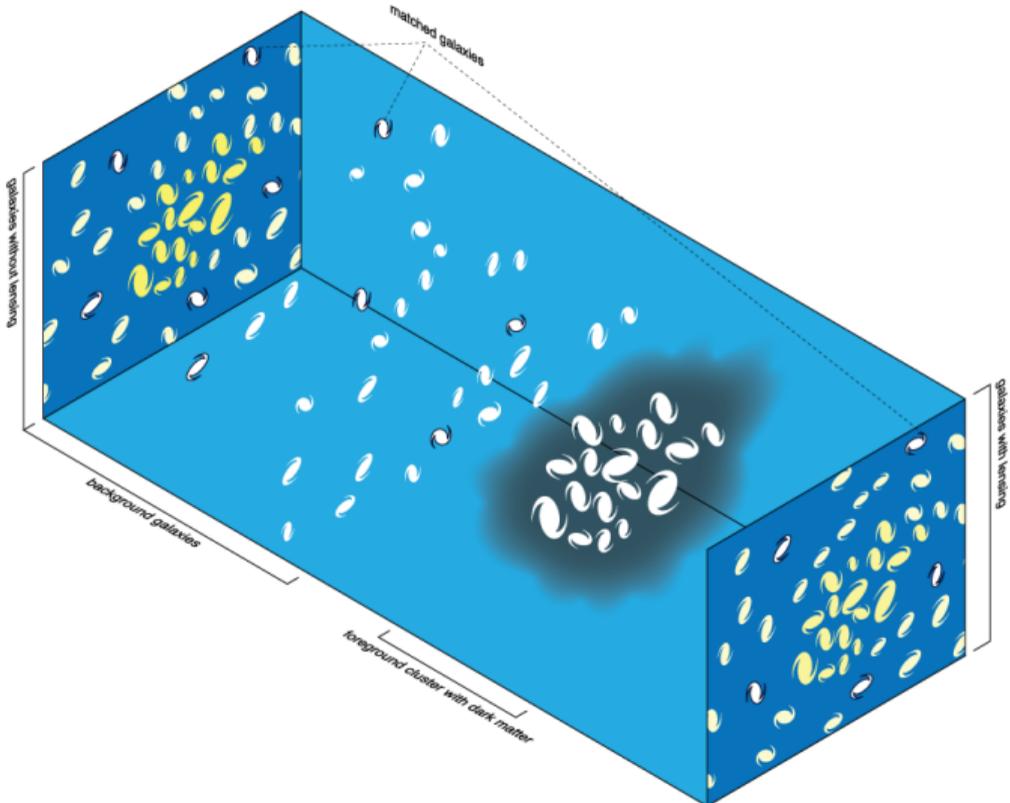
- ▶ More extended relative to their core radii and the normal elliptical galaxy luminosity profile.
- ▶ Often exhibit multiple nuclei, either because they are assimilating other cluster members (“galactic cannibalism”) or because these nuclei are cluster galaxies on linear (highly eccentric) orbits.
- ▶ 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.



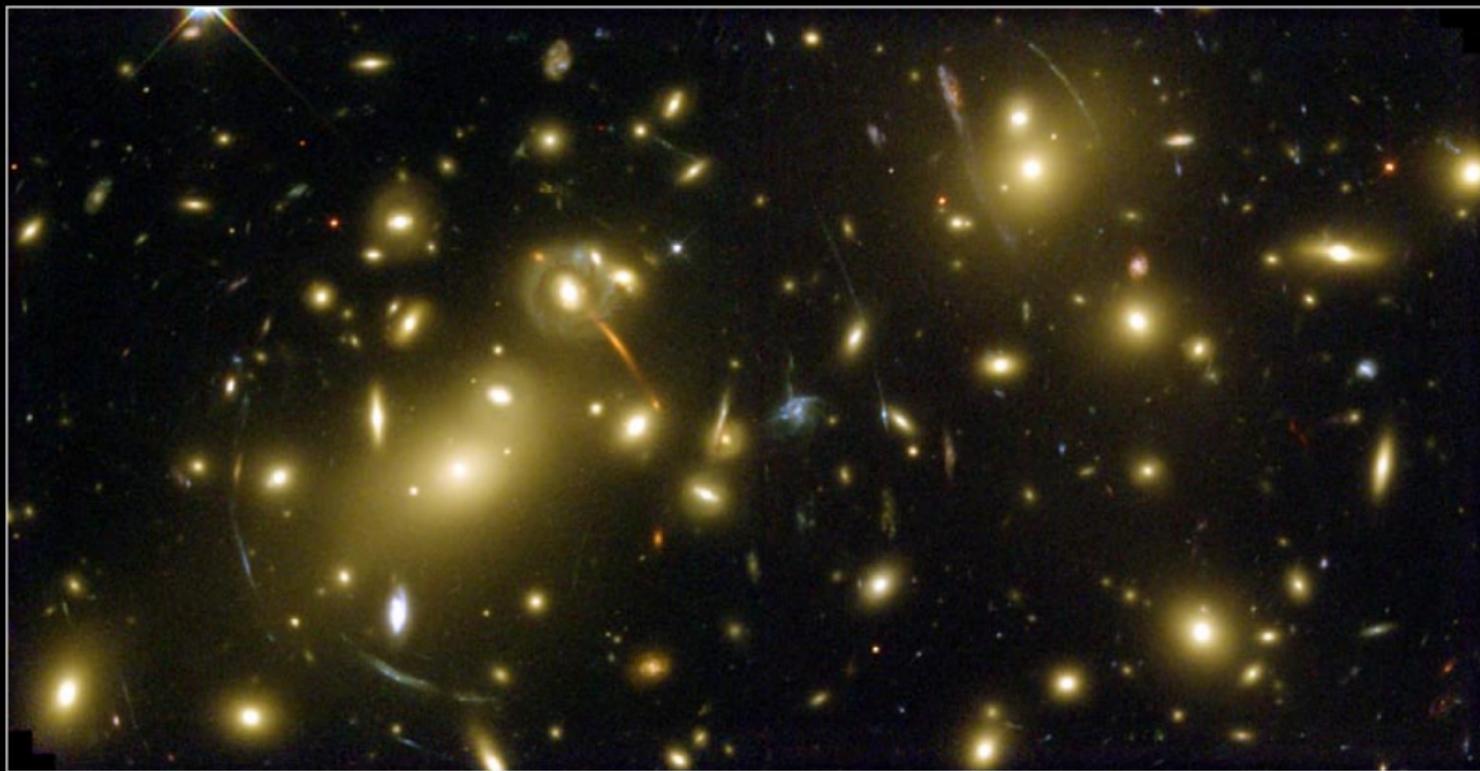
Abell 2261 BCG

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:

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

- ▶ 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

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

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,

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

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,

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

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,

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

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

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

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

$$\tau_{\text{Jeans}} = \frac{\sqrt{\pi}}{8} \left(\frac{2k_{\text{B}}T}{m_{\text{H}}} \right)^{3/2} \frac{r_0^3}{(GM)^2} e^{GMm_{\text{H}}/k_{\text{B}}Tr_0} \approx 10^9 \text{ yr}$$

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,

$$M_{\text{X-ray}} = 3 \times 10^{14} M_{\odot}$$

$$M = \frac{2r_0\overline{v^2}}{G} = 4 \times 10^{15} M_{\odot}$$

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?

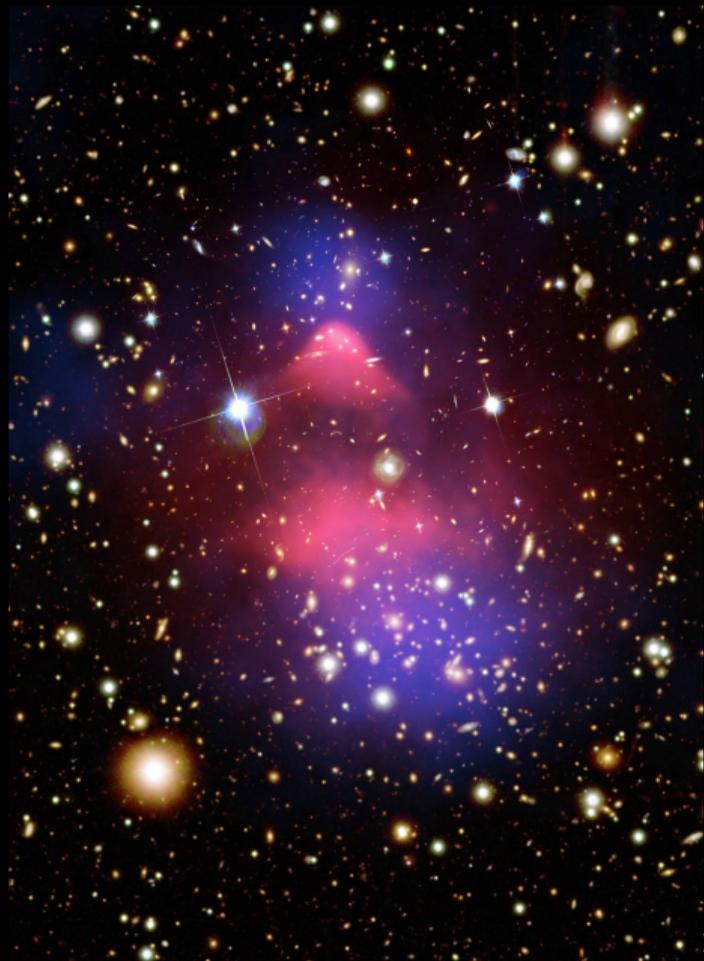
- ▶ Then the clusters *could* be in equilibrium. The dark matter “nucleus” of each cluster could have thermalized early in the life of the Universe, and the visible galaxies formed after their dark halos were already in equilibrium.
- ▶ This is enough mass to keep the X-ray gas from getting away: with 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

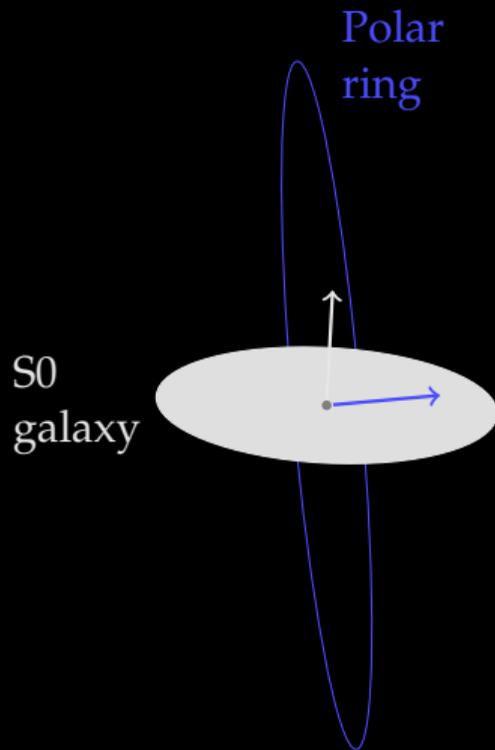
Transferred material which has substantial angular momentum in the frame of its new host galaxy quickly adopts appropriate orbits.

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 \perp .

Polar-Ring
Galaxy
NGC 4650A



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Science Institute
Hubble Heritage Team
(AURA/STScI/NASA)

Hubble
Heritage

Interacting galaxies: Starbursts

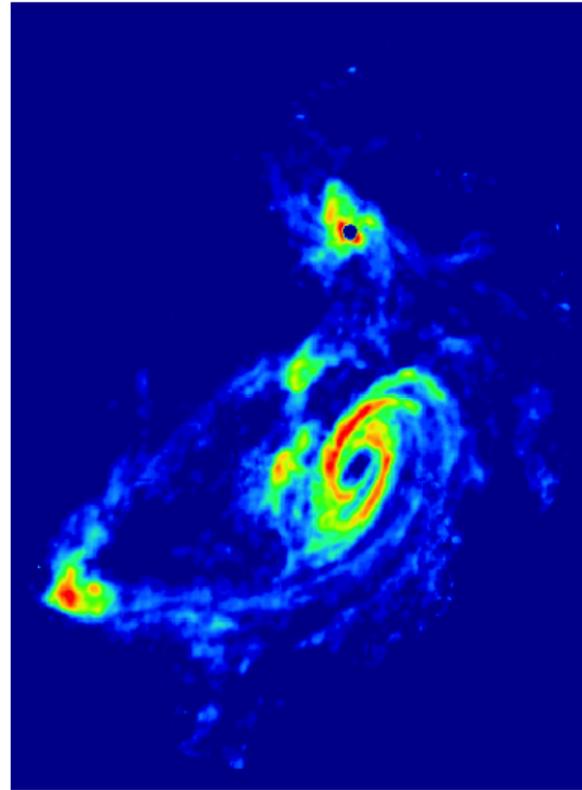
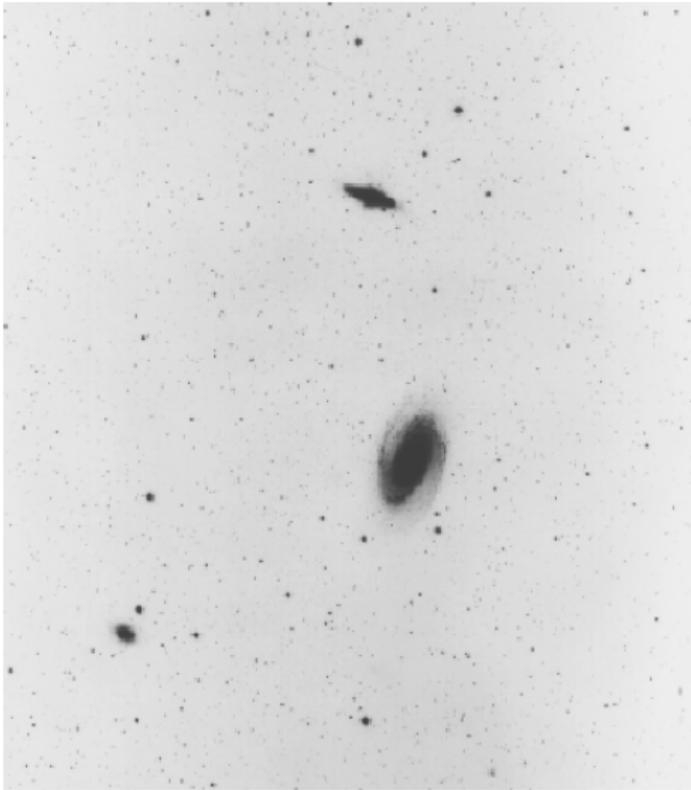
A starburst is a brief but dramatic increase in the rate of production of stars by a factor of 100 to 1000 more than the normal rate in the disks of spiral galaxies.

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).

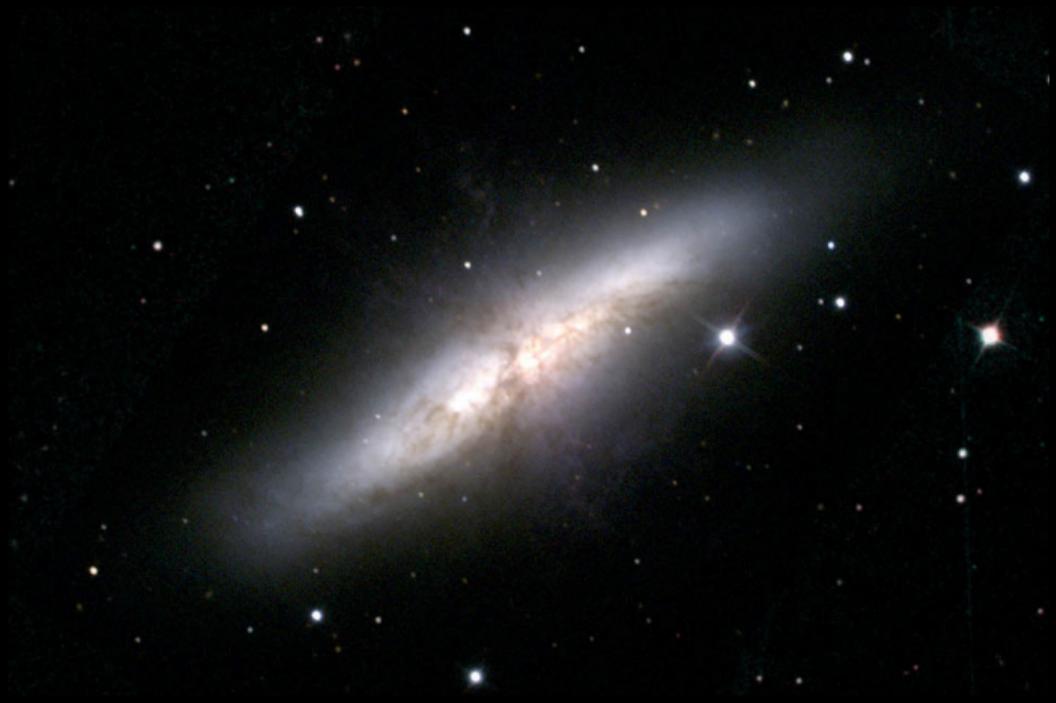
Right: HI 21 cm observations (VLA) (Yun et al. 1994).

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.



Archetypical starburst galaxy M82 (NGC 3034)

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

