Active Galactic Nuclei & Groups of Galaxies

Radio galaxies, QSOs, Blazars, Seyferts
Accretion disks and jets
Groups, Clusters, and Superclusters
Cluster Dynamics
Dark Matter
Interacting Galaxies

April 11, 2024

University of Rochester

AGN & Groups of galaxies

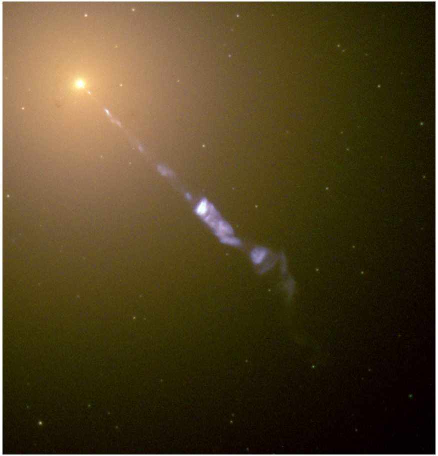
- Radio galaxies, quasars, and blazars
- Relativistic and superluminal motion in quasar jets
- Seyferts: active spiral galaxies
- AGN accretion disks
- Groups, clusters, and superclusters
- Galaxy cluster dynamics
- Dark matter in clusters of galaxies
- Interacting galaxies: starbursts, the origin of AGN

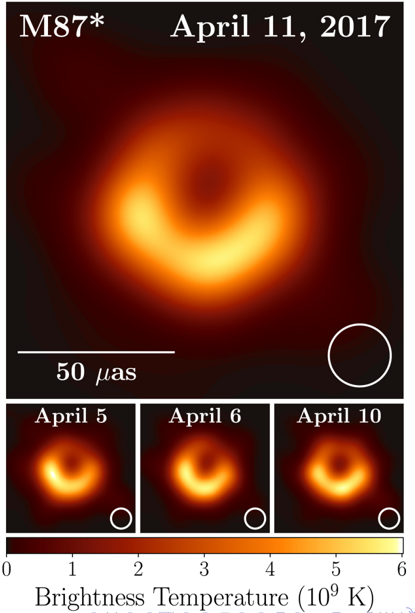
Reading: Kutner Sec. 18.4 & 19.1, Ryden Ch. 21.4–21.5 & Ch. 22

Detail of Markarian's Chain, L. Orazi, StarKeeper.

The “shadow” of a quasar’s black hole

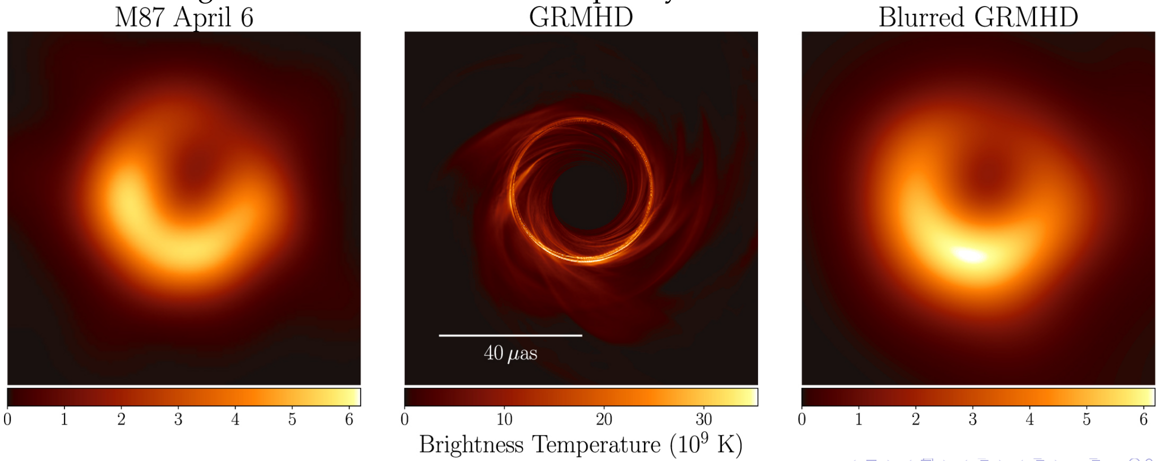
In 2019, the EHT collaboration took the world’s first image of the light in orbit around a supermassive black hole.





Reality v. simulation

The image on the left is of M87's supermassive black hole. The center image is the result of a simulation (with "infinite" resolution), and the image on the right is the center simulation image blurred to match the telescope's systematics.



Apparent superluminal motion in quasar jets

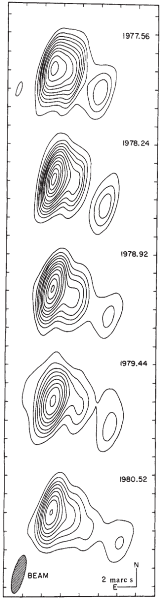
The innermost parts of the radio jet in 3C 273 consist mainly of small “knots” with separations that change measureably with time.

Right: Radio images taken over three years (1977-1980), plotted as temperature contours (Pearson et al. 1981). The dense region of lines on the left is the center of the quasar.

One tick on the map corresponds to 20.2 ly at the distance of 3C 273, so the knot on the right moved 21 ly in 3 yr.

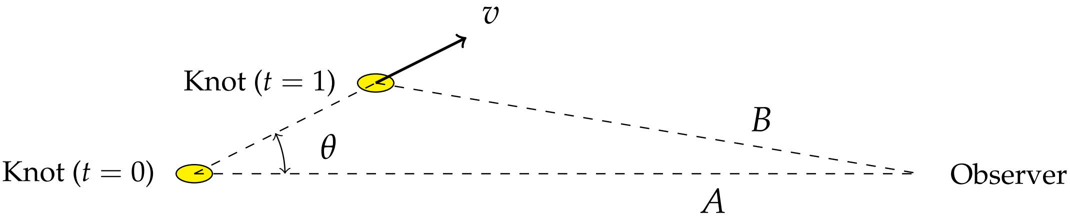
I.e., $v = 7c$; the knot appears to be moving superluminally (faster than the speed of light), and not by a little bit.

How is this possible?



Apparent superluminal motion: An optical illusion

The apparent superluminal motion of the knot is a trick of perspective that occurs when the knot's true speed is relativistic ($v \approx c$).



Light path B is shorter than light path A and, if $\theta \ll 45^\circ$ and $v \approx c$, B is almost 1 ly shorter than A. This "head start" makes the light arrive sooner than expected, giving the **appearance** that the knot is moving faster than c.

Apparent superluminal motion

The apparent speed perpendicular to the line of sight is

$$v_{\perp,\text{apparent}} = \frac{v \sin\theta}{1 - \frac{v}{c}\cos\theta} = \frac{v \sin\theta}{1 - \beta\cos\theta}$$

$$\left(v_{\perp,\text{apparent}}\right)_{\text{max}} = v\frac{1}{\sqrt{1-\beta^2}} = \gamma v$$

(See this week's recitation for the derivation.) Thus apparent speeds in excess of the speed of light can be obtained.

However, the apparent speeds only turn out to be much in excess of the speed of light if the actual speed of the radio-emitting knots is close to the speed of light. Superluminal motion indicates that the real motion is relativistic.

Radio Galaxies

Radio galaxies were discovered in the 1950s at about the same time as quasars.

However, they are quite distinct from quasars. QSOs in the 1950s looked pointlike and were associated only with pointlike optical objects.

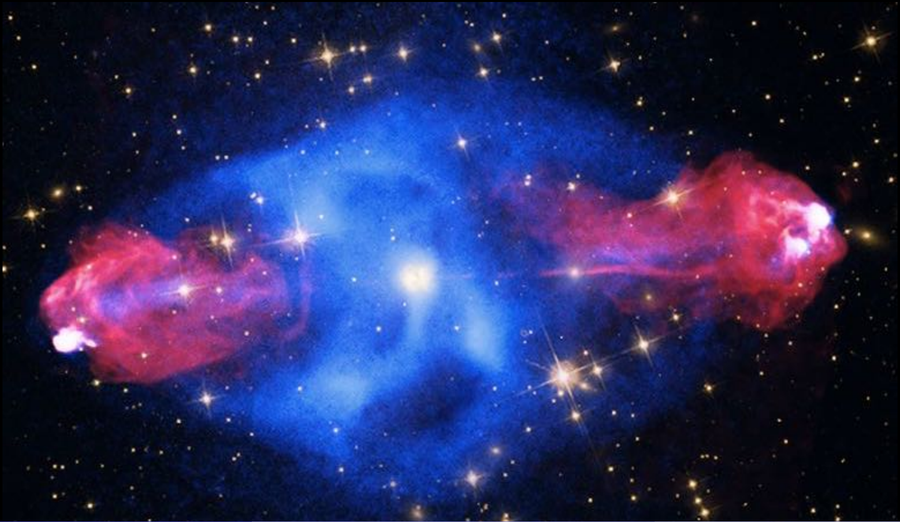
In contrast, radio galaxies appear to consist of a pair of extended radio lobes on either side of a visible, elliptical galaxy.

As radio interferometric measurements improved, radio galaxies were shown to also possess compact and pointlike central objects coincident with the galactic nuclei and connected to the lobes by narrow, usually straight jets.

The lobes themselves have fine filamentary structure. Many have hot spots as the ends of the jets.

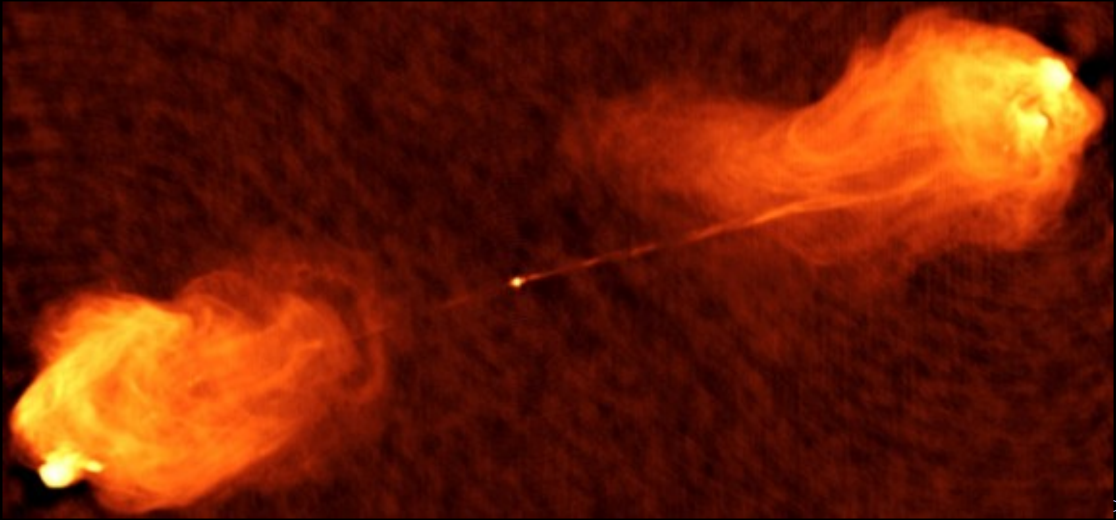
The archetypal radio galaxy: 3C 405 (Cygnus A)

X-ray/optical/radio overlay of Cygnus A, the first known radio galaxy (Baade & Minkowski 1954). Visible image from HST-WFPC2; X-ray from NASA/CXC (Wilson 2000); radio from NRAO/AUI (Perley 1984).



The archetypical radio galaxy: 3C 405 (Cygnus A)

X-ray/optical/radio overlay of Cygnus A, the first known radio galaxy (Baade & Minkowski 1954). Visible image from HST-WFPC2; X-ray from NASA/CXC (Wilson 2000); radio from NRAO/AUI (Perley 1984).



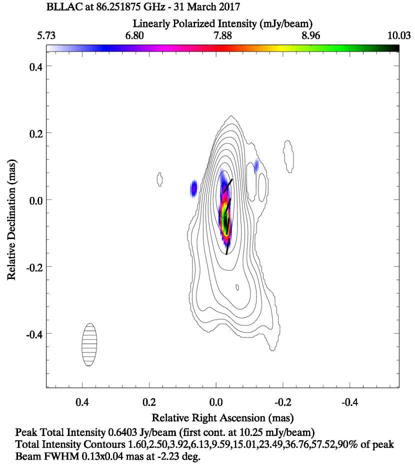
Blazars

Blazars are bright and starlike. Only a very faint luminosity has been detected around them to indicate that they are the nuclei of galaxies (e.g., Oke & Gunn 1974).

The spectra from blazars are smooth, making it hard to measure Doppler shifts.

Most blazars are strong pointlike radio sources with significant variability. Stars are not. This was the first real indication that blazars are distant galaxies.

In fact, the variability implies a huge luminosity produced in a very small volume, implying the presence of a supermassive black hole. Only very short (< mas) jets have been observed, as seen in BL Lac on the right.



Archetypical blazar BL Lacertae in polarized 86 GHz radio emission, from the GMVA (BU/MPIfR).

Seyfert galaxies

Discovered in the 1940s by Carl Seyfert, these are **spiral galaxies** with starlike nuclei, often brighter than the rest of the galaxy, with ionized gas associated with these centers.

Type 1 Seyferts: Some Seyferts are found with very broad recombination lines ($\sim 10^3$ km/s in width) associated with the nuclei. Example: NGC 4151.

Type 2 Seyferts: Other Seyferts have only narrow-line spectra ($\lesssim 10^2$ km/s) at the nucleus. Example: NGC 1068.

There are intermediate types of Seyferts as well.

The rotational and random speeds inferred from spectral lines near the galactic centers indicate supermassive black holes are present in these galaxies, like the blazars and quasars (QSOs).

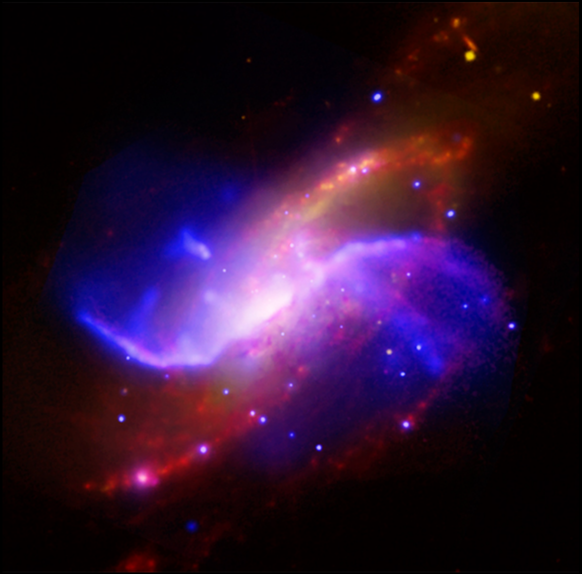
Seyfert galaxies

Since spirals have a lot more interstellar gas and dust than elliptical radio galaxies and QSOs, the jets do not make it out of the galaxy.

Example: M106 (NGC 4258)

- Very short jet, oriented roughly along the galaxy's axis, seen in nucleus.
- The rest of the jet is apparently entrained in the disk of the galaxy.

M106 in X-rays from jet-driven shocks (blue) and visible light from normal galactic processes (red). Second visible image from R. Gendler.



Seyfert galaxies

Since spirals have a lot more interstellar gas and dust than elliptical radio galaxies and QSOs, the jets do not make it out of the galaxy.

Example: M106 (NGC 4258)

- Very short jet, oriented roughly along the galaxy's axis, seen in nucleus.
- The rest of the jet is apparently entrained in the disk of the galaxy.

M106 in X-rays from jet-driven shocks (blue) and visible light from normal galactic processes (red). Second visible image from R. Gendler.

The unified AGN model

Quasars, radio galaxies, and blazars are all powered by black holes but present different observational characteristics. It turns out that they are **the same thing** but viewed from different angles.

Relativistic accelerating electric charges **beam** the light they emit in the direction that they are going (topic covered in PHYS 218).

Thus, the approaching jet along our line of sight at an angle θ should be much brighter than the receding one (counterjet). Under simple assumptions for steady jets, (Blandford & Königl 1979),

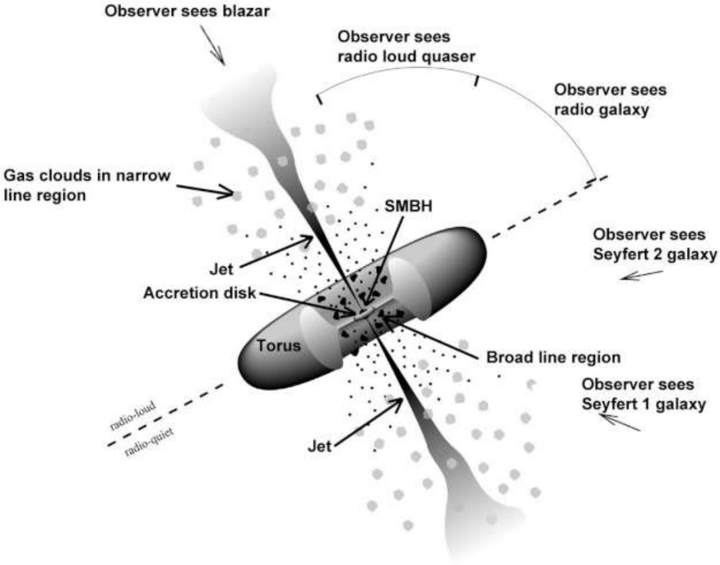
$$\frac{f_{\rm jet}}{f_{\rm counterjet}} = \left(\frac{1+\beta\cos\theta}{1-\beta\cos\theta}\right)^3 \gg 1 \text{ if } \theta \to 0, \beta \to 1$$

- Radio galaxy jets appear bipolar $\leftrightarrow$ θ closer to 90°
- Quasar jets appear one-sided $\leftrightarrow$ jet viewed closer to $\theta = 0$, consistent with the observation of superluminal motion
- Blazars show no jets, or an extremely short one-sided jet $\leftrightarrow$ viewed at $\theta \approx 0$

The unified AGN model

Schematic of the unified model of AGN. See also Beckmann & Shrader (2012) and Netzer (2015). The model indicates that observations depend only on:

1. Orientation w.r.t. the jet
2. Coverage of the nucleus by a torus of dust in the galactic plane
3. Luminosity of the central black hole



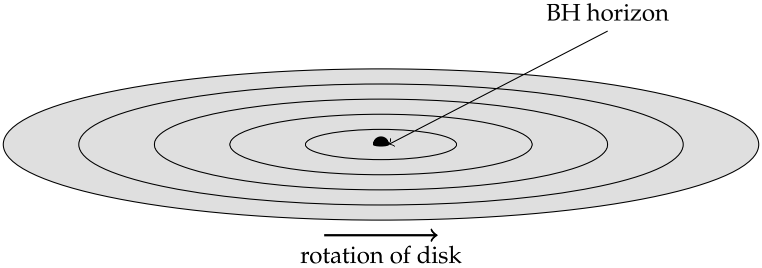
AGN accretion disks

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 $\mathcal{O}(100\ \mathrm{pc})$ from the central black hole.

Operation of AGN accretion disks

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

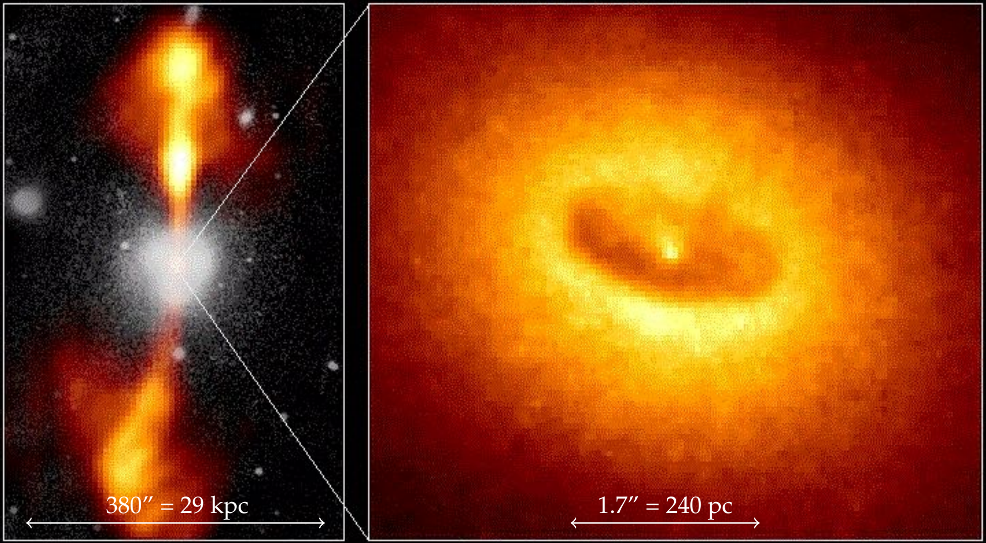
A large amount of power, mostly in the form of X-rays and γ rays, is emitted by the infalling material. The pressure exerted by this radiation slows down the rate at which accretion takes place.

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

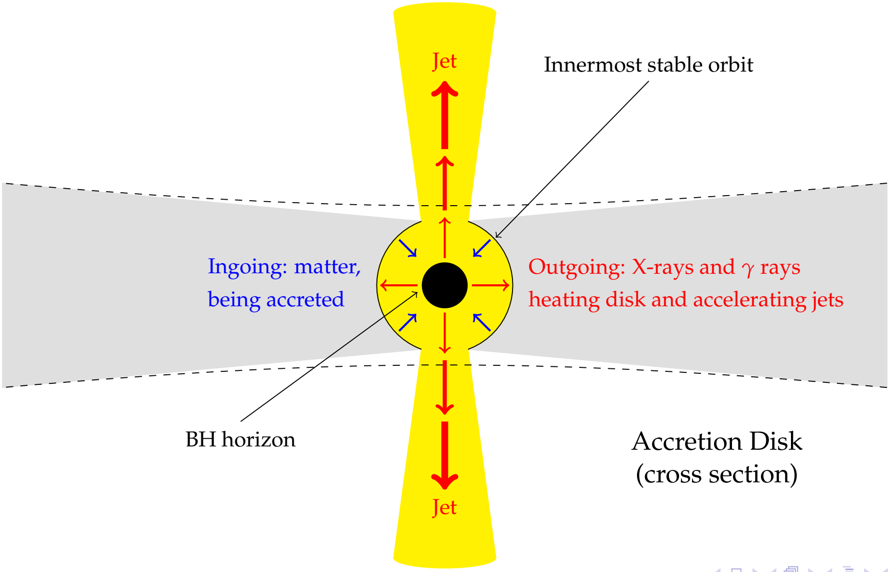
Some of the particles absorbing the highest-energy light are accelerated to speeds approaching c.

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.

NGC 7731

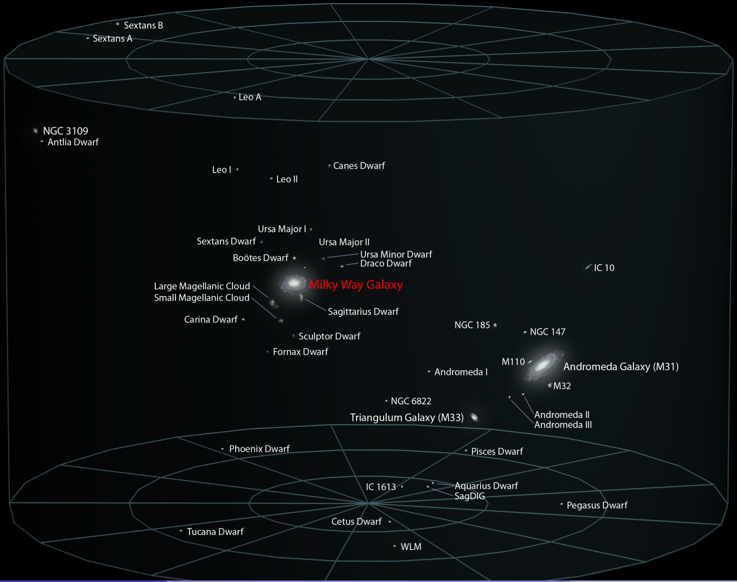
- Clusters themselves are parts of larger structures called **superclusters**. The Virgo Cluster is near the center of the Virgo (a.k.a. Local) Supercluster.
- Superclusters are connected by thin filaments of galaxies (often composed of galaxy groups) which outline **voids**.

Stephan's Quintet

Image from Dietmar Hager, Stargazer Observatory.

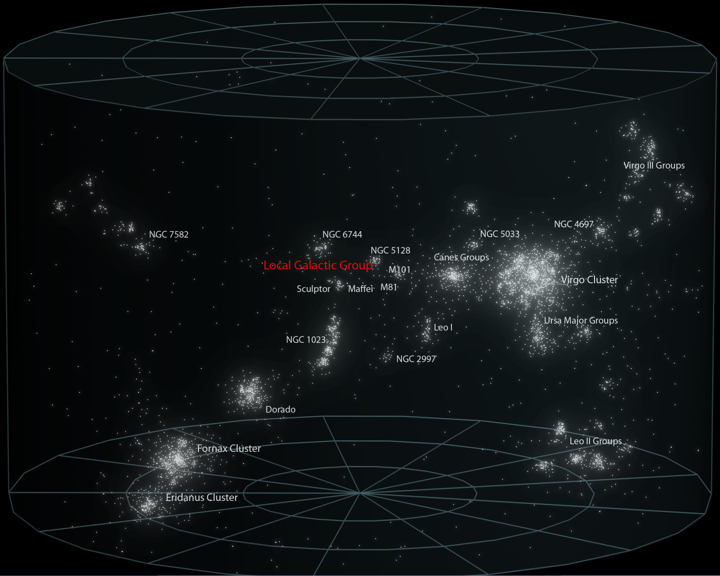
The Local Group

Andrew Z. Colvin



The Virgo Supercluster

Andrew Z. Colvin



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.

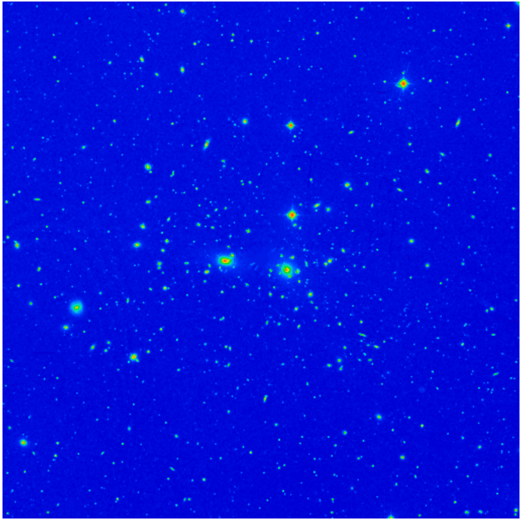
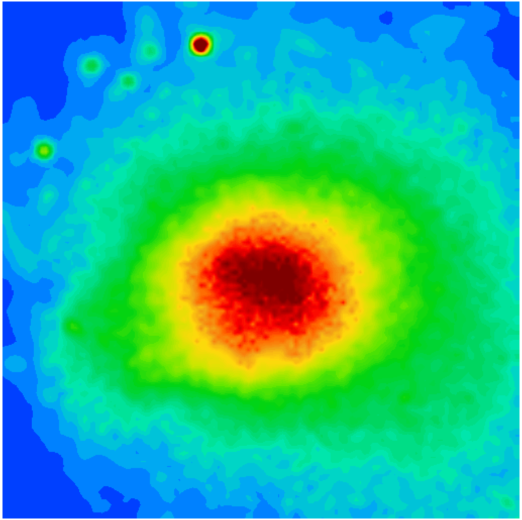
Clusters come in a variety of "richness" (degree of central concentration).

- **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 insterstellar matter is visible at X-ray energies as a hot intrucluster medium (ICM).

The Coma Cluster ($d = 99$ Mpc)

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