Physics 343 Lecture # 11:
active galactic nuclei, etc.

Schedule for this week and next

Monday-Thursday 4/9-12: "on call" office hours for Lab # 5, in my office (Section A/B/E/F) or in the computer lab (Section C/D), which you are strongly encouraged to attend...

Monday 4/16: Lab # 5 due

Monday-Tuesday 4/16-17: Lab # 6 observations for those not going to WV (only Sections A/C/D will meet); details pending

Friday 4/20: drive NJ → WV

A useful tip for Lab # 5

If you are cleaning a pseudo-continuum map in Difmap and would like to restart the cleaning process from scratch (e.g., with a different set of clean boxes or number of iterations), type clrmod true, true, true.

April 30 student choice topics!

Suggestions received so far:

(1) the search for extraterrestrial life (SETI)

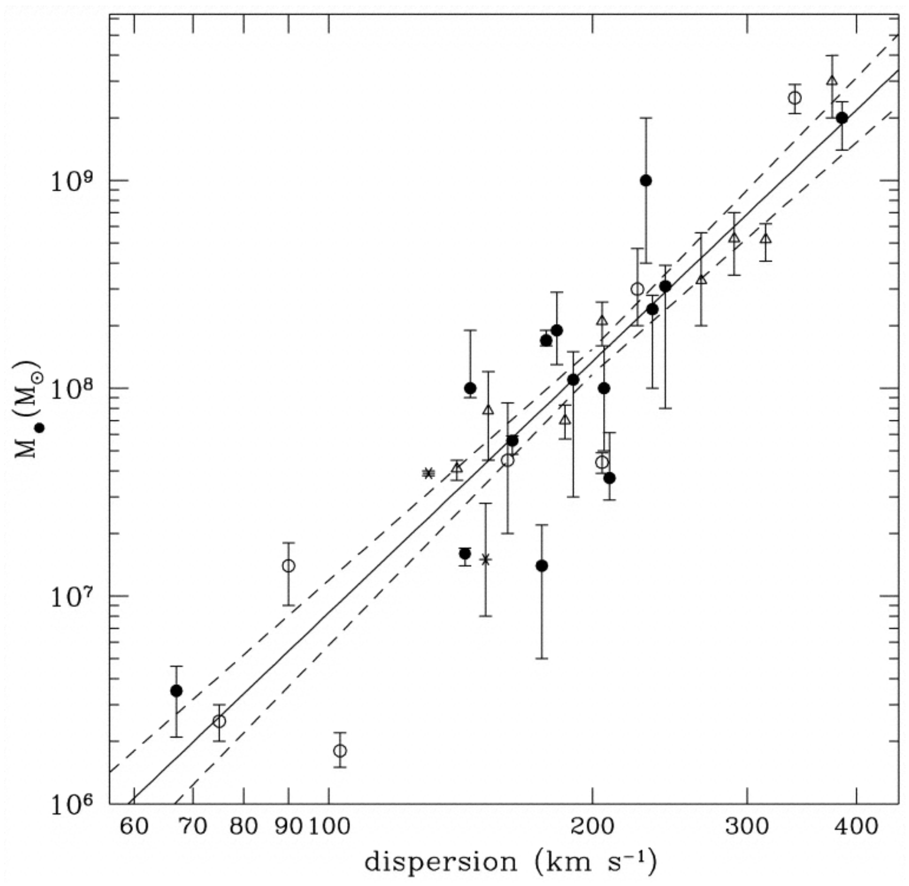
(2) [something else that must have been suggested orally]

Today: black holes are (nearly) ubiquitous

Elliptical galaxies and spiral galaxies with massive bulges all seem to have massive central black holes, whose masses follow a tight proportionality with velocity dispersion.

(Bulgeless disk galaxies do not follow the same relation.)

Tremaine et al. (2002)



The Schwarzschild radius

As a reminder: a black hole is an object so massive that there is a Schwarzschild radius R_S from within with not even light can escape. (This is an example of an "event horizon", although not the only example.)

R_S can be derived by setting the escape velocity equal to c:

$$R_S = 2GM/c^2$$

(This is not a valid relativistic derivation, but it happens to yield the right answer!)

What happens to gas near a black hole?

Conservation of angular momentum means gas doesn't fall straight into the Schwarzschild radius.

Instead, potential energy (-*GMm/r* for a particle with mass *m* and distance *r* from the black hole) is slowly converted into thermal energy (i.e., heat) due to particle collisions. This is a process known as accretion.

What happens next?

Broadly speaking, there are two options...

Option # 1: radiatively inefficient accretion

The thermal energy can remain in the form of thermal energy (i.e., the accreting gas remains hot), or be converted into kinetic energy (i.e., turbulence/outflow).

In either case, little radiation emerges; astronomers refer to these situations as RIAFs (radiatively inefficient accretion flows).

The black hole at the center of the Milky Way drives a RIAF!

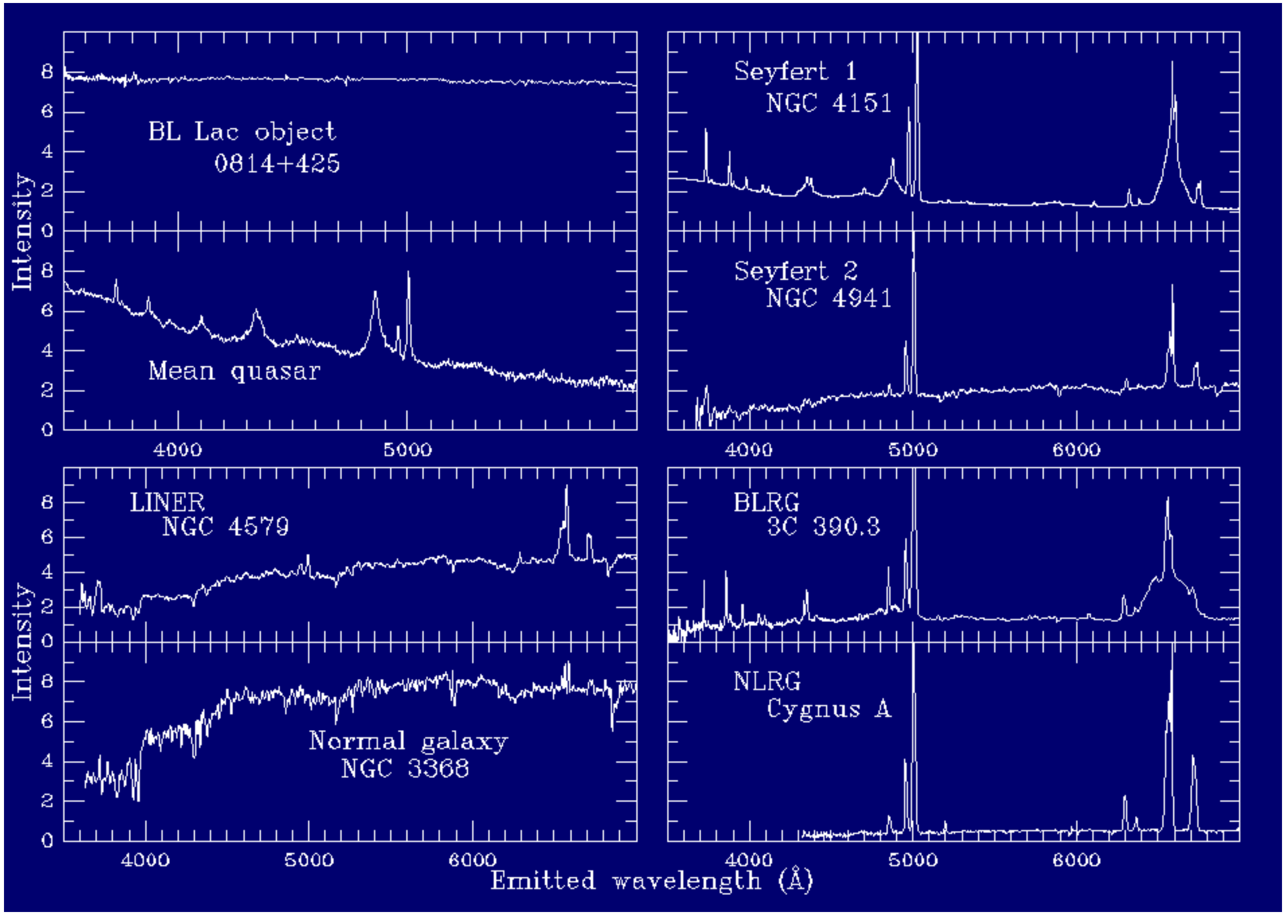
Option # 1: radiatively efficient accretion

The alternative scenario is that a large fraction of the thermal energy is converted to radiation. In this case, we have a radiatively efficient accretion flow, and can observe one or more consequences that mark the center of a galaxy as an active galactic nucleus (AGN; plural = "AGN" or [ugh...] "AGNs").

AGN in the optical

High-energy photons emerging from an AGN accretion flow (typically, an accretion disk) can ionize atoms in the surrounding gas.

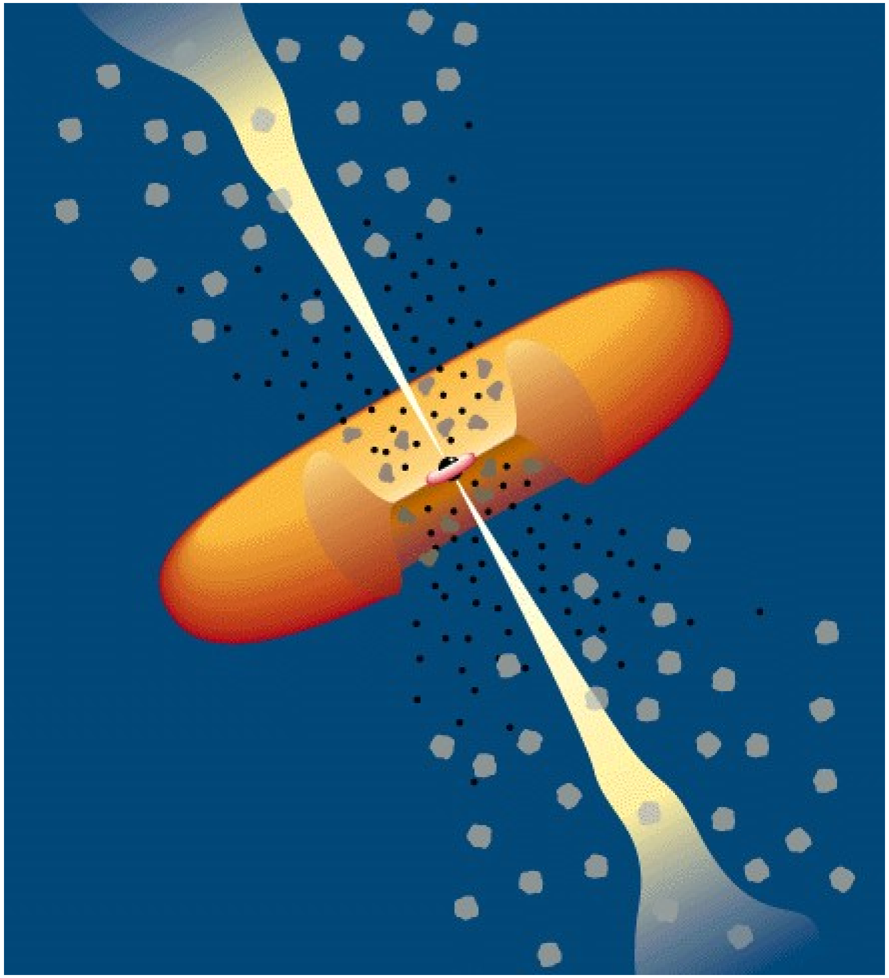
Optically bright AGN are identified as Seyfert nuclei or QSOs (quasi-stellar objects) depending on *L*.



Courtesy W. Keel.

AGN in the optical: type 1 vs. type 2

Some optically bright AGN show broad lines (> 1000 km/s in width) from ionized gas; others do not. Astronomers refer to these as "type 1" and "type 2" AGN.



Which we see depends on our viewing angle relative to a torus (i.e., doughnut) of cold, dusty molecular gas that can hide a broad-line region.

Courtesy M. Urry.

AGN in the X-ray

Sometimes the optical emission from ionized gas is so deeply enshrouded by dust (along all sightlines) that we can't detect an AGN in the optical at all!

In such cases, detecting high-energy photons directly in the X-ray may work better.

AGN in the radio

Independent of whether an AGN is type 1 or type 2 in the optical, or whether it shows X-ray emission or not, it may be either radio-loud or radio-quiet.

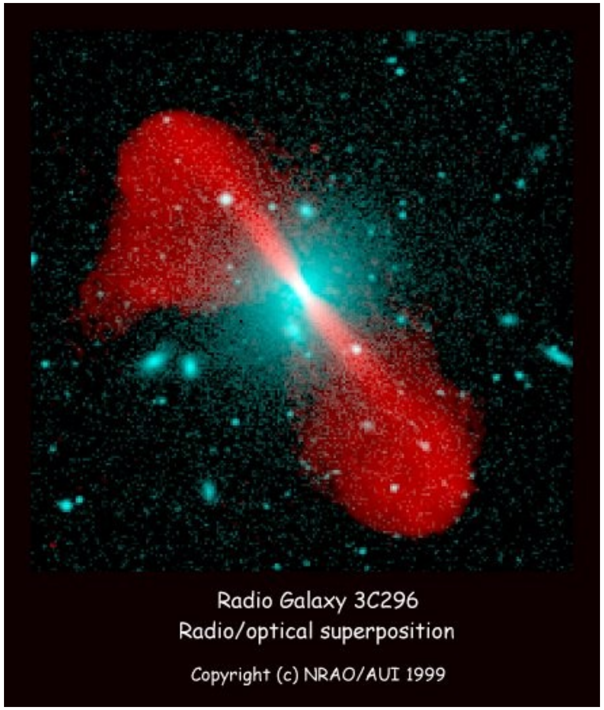
Radio emission is continuum emission due to synchrotron radiation (particles spiralling in a strong magnetic field... although precisely which particles is not always clear!).

Two categories of radio galaxies

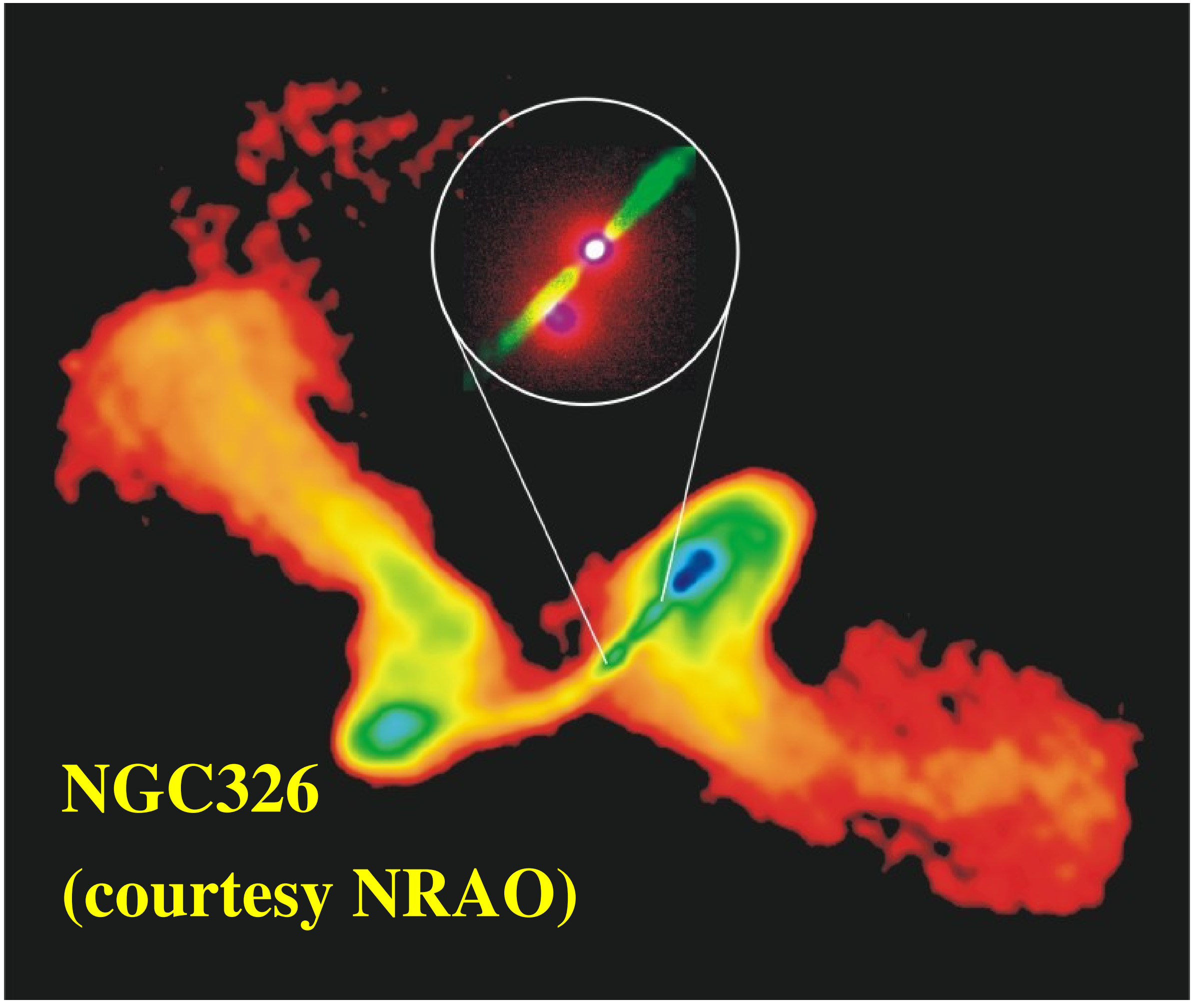
Among radio-loud objects, we have

(1) Fanaroff-Riley type I (“FRI”) objects that are core-dominated

(2) Fanaroff-Riley type II (“FRII”) objects that are lobe-dominated



Some FRII sources are "X-shaped"

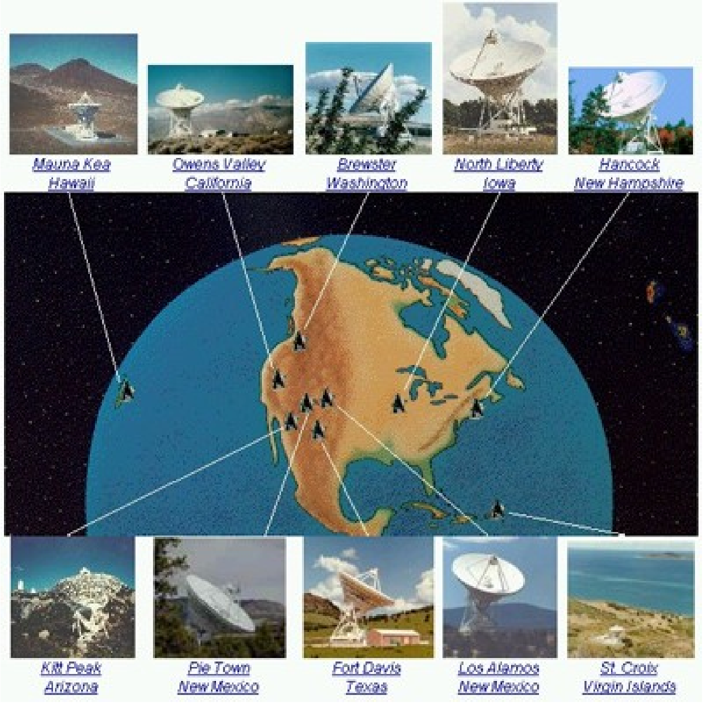


Main map = radio from Very Large Array; inset = optical from *Hubble Space Telescope*.

Are we seeing evidence of post-merger black hole spin flip?

VLBI mapping of radio galaxies

Very long baseline interferometry (VLBI) can be used to study the central parts of AGN: the emission is so strong on small scales that even intercontinental baselines can detect it!



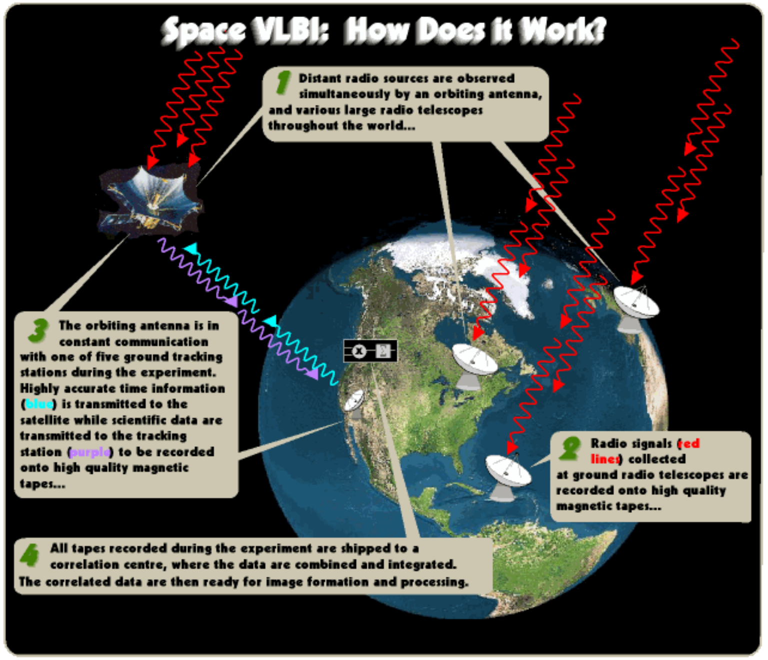
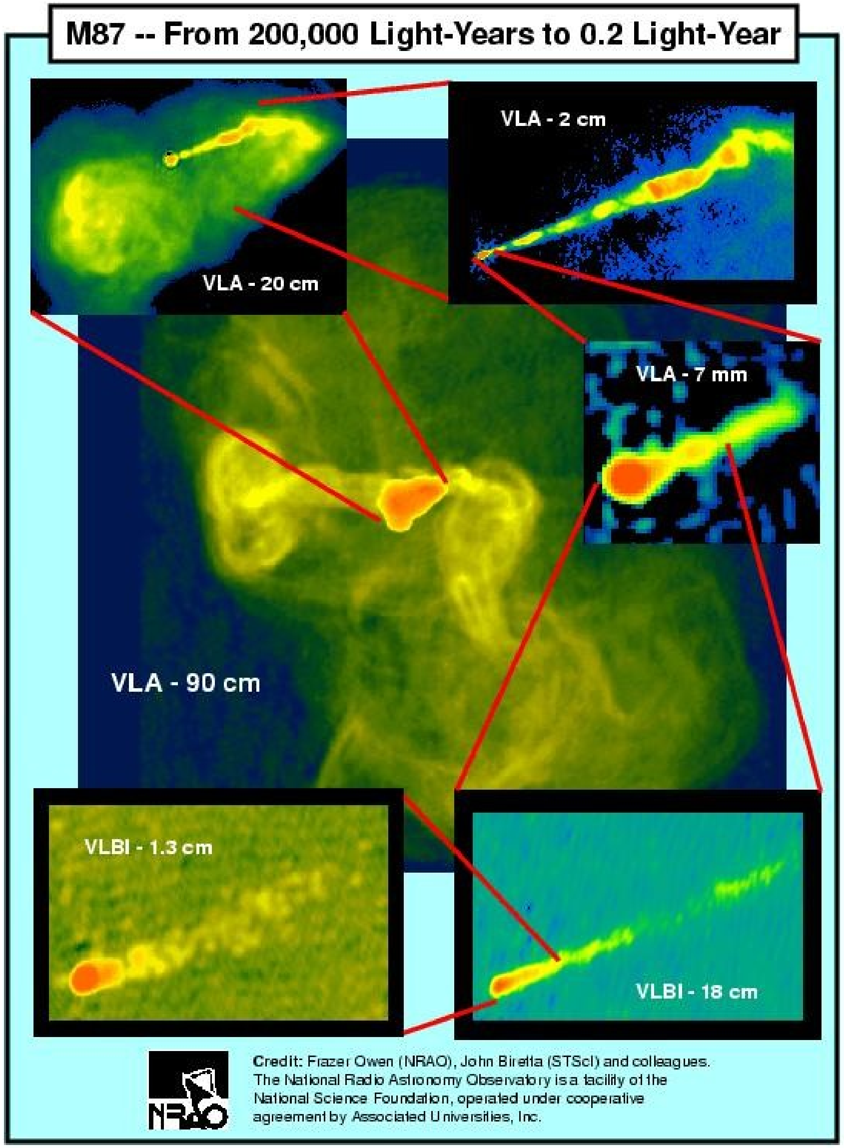


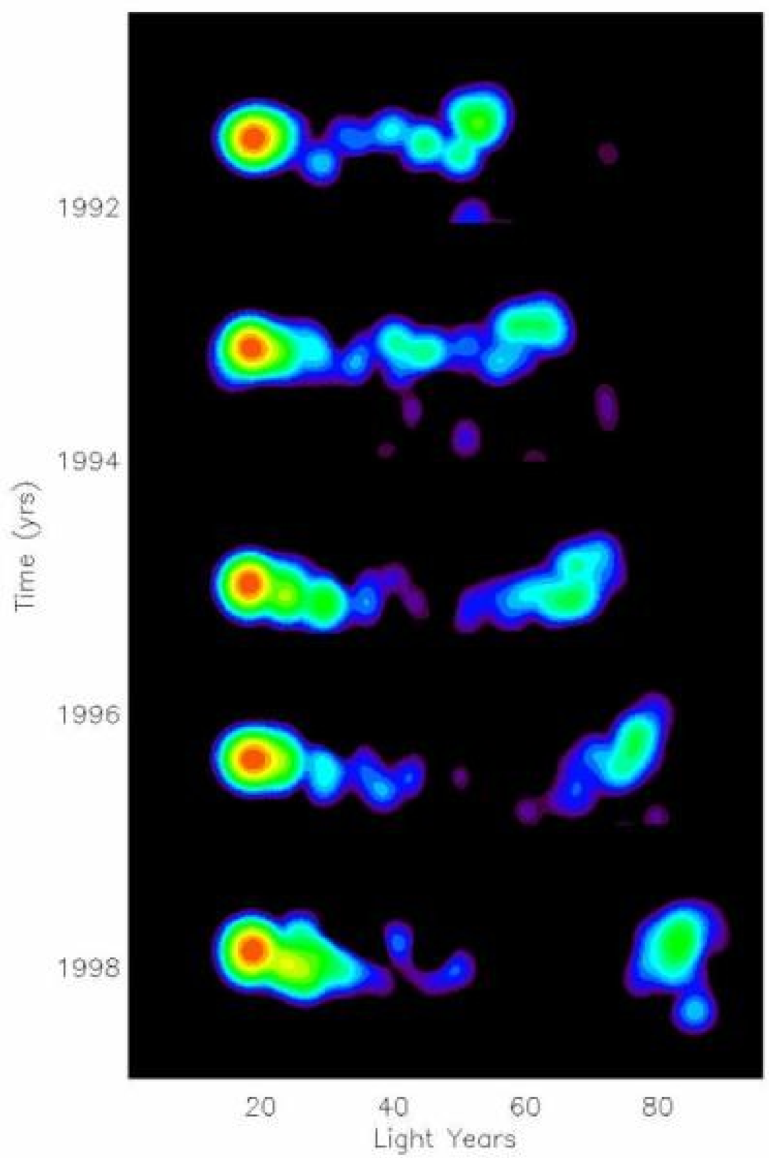
Exhibit A: M87 in the Virgo Cluster



Mapped with the VLA and the VLBA: note λ/B trends!

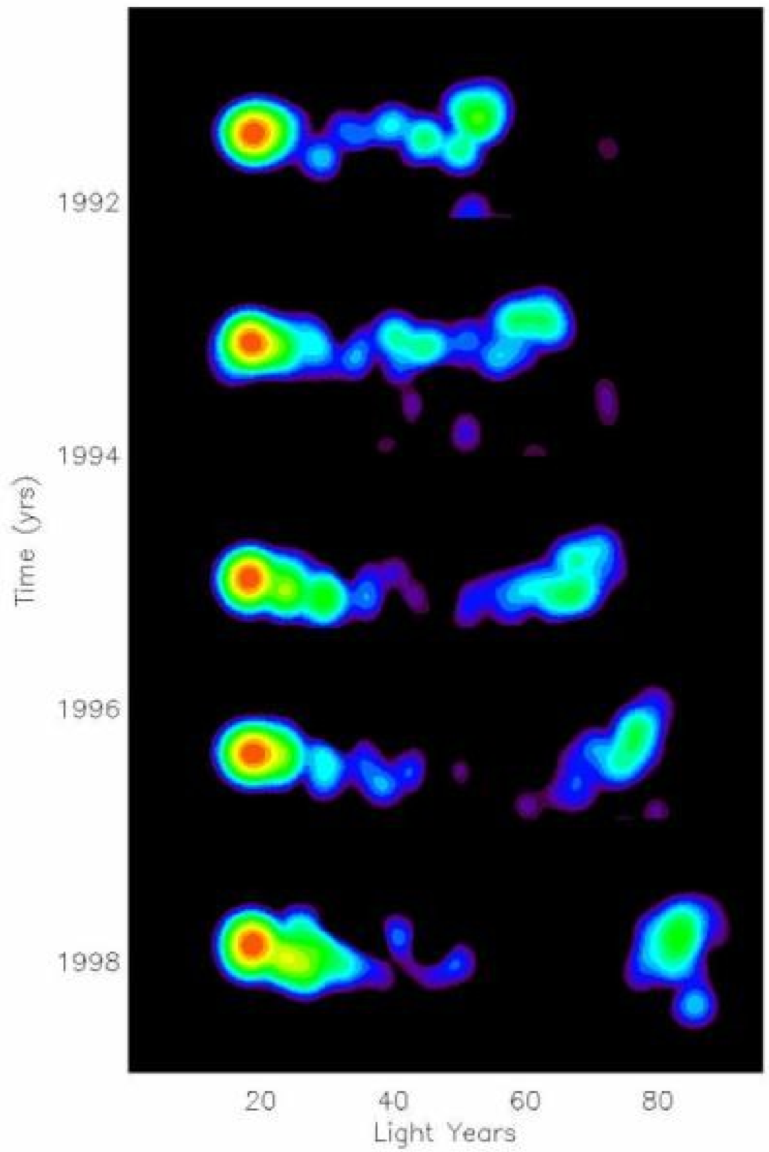
We can watch jets evolve in real time!

Example: VLBI observations of 3C279 reveal that blobs of radio-emitting plasma move 25 light-years in projection on the sky over the course of seven years of observations.

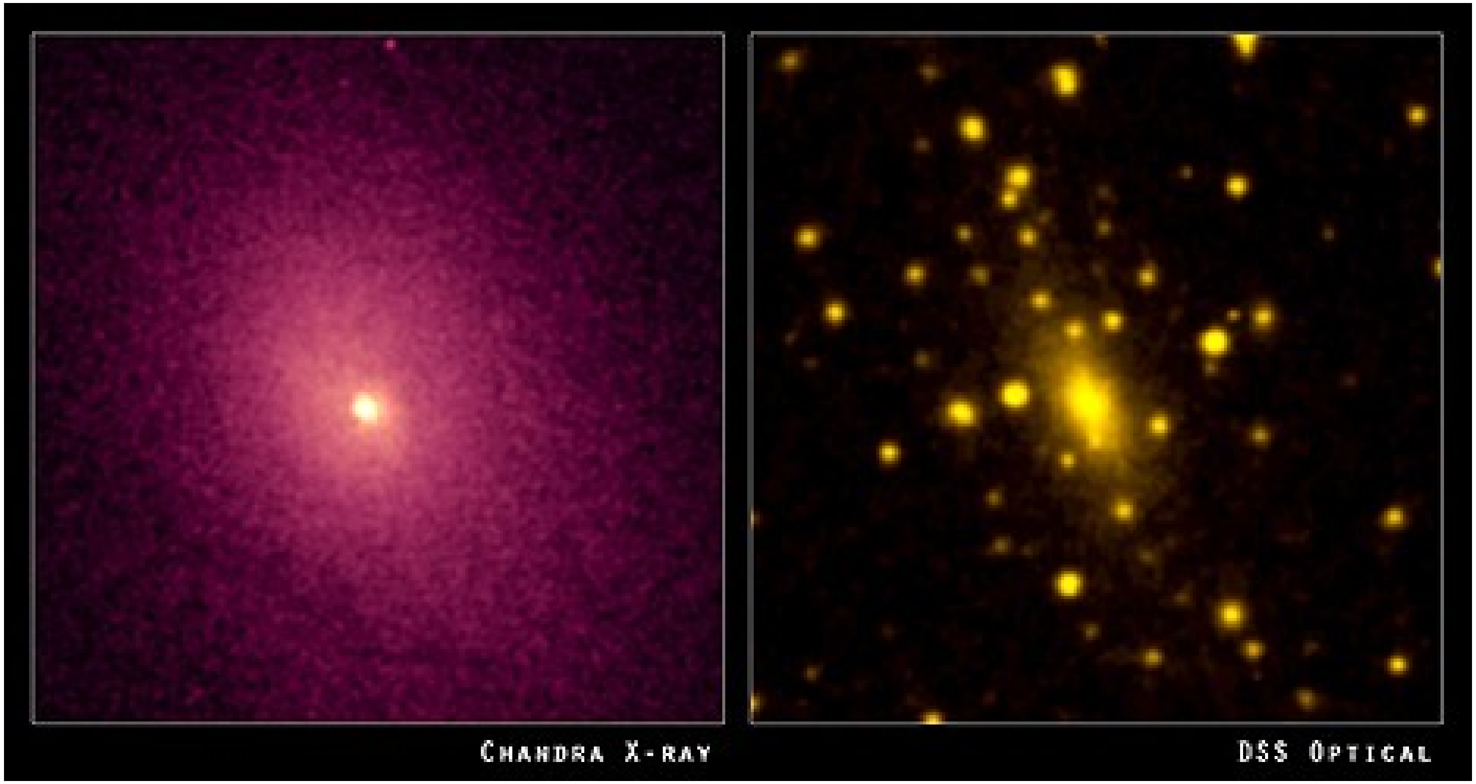


“Superluminal” motion: an optical illusion

Motion along the line of sight accounts for the apparent velocity > *c*.

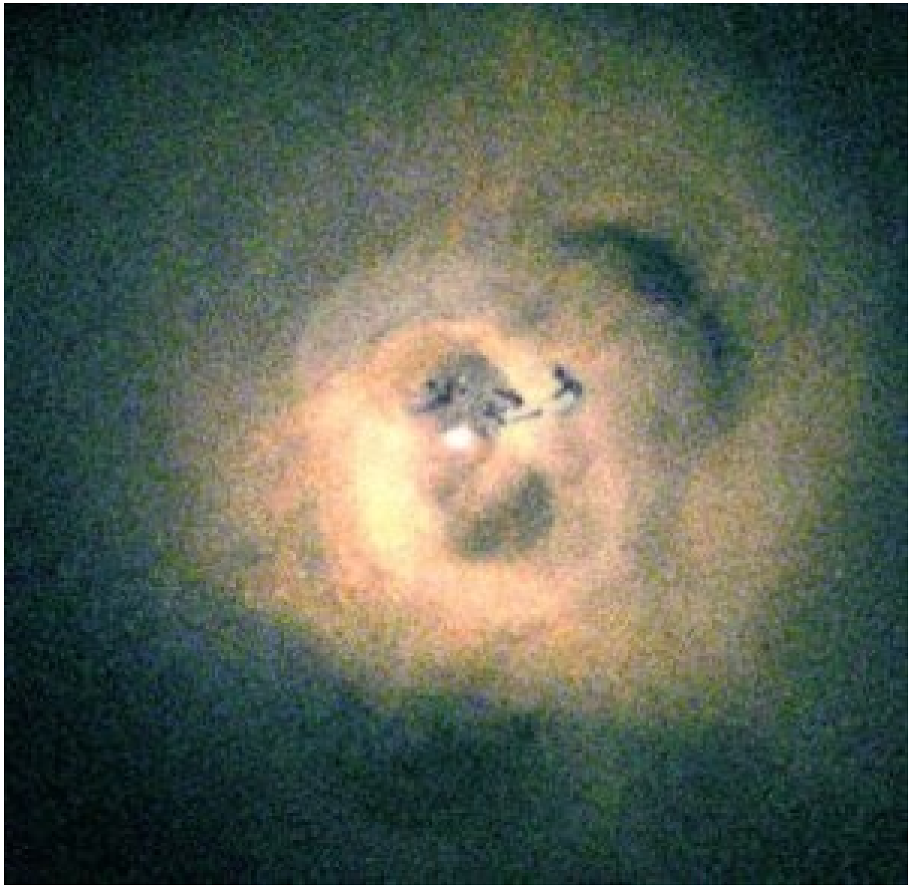


Galaxy clusters



Galaxy clusters have most of their (ordinary, baryonic) mass in the form of hot intracluster gas. Why doesn't this cool, flow to the center, and form stars in the central elliptical?

AGN feedback



Deep X-ray imaging of many clusters (here, the Perseus Cluster) shows shells and bubbles.

We think these were produced in past radio-loud events: a jet in the central elliptical turns on when the black hole is fed, driving away further fuel until it shuts itself off.

Use bent jets to find new clusters?

Radio jets + X-ray emission from hot intracluster gas: jets are bent as galaxies fall into clusters.

Horseshoe-shaped jets may mark the locations of undiscovered clusters!

Quiz