

**Physics 343 Lecture # 12:
active galactic nuclei, etc.**

Schedule for this week and thereafter

Monday 4/21: Lab # 5 due

Tuesday-Wednesday 4/22-23: Lab # 6 observations for those not going to WV (only Sections B/E/G/H will meet) – check your email for lab instructions

Friday-Sunday 4/25-27: WV trip

Monday 5/5: Lab # 6 due; student choice lecture

May 5th student choice topic(s)!

Suggestions received so far:

(1) inflation and the BICEP2 results

(2) [was there another?]

21? people + 6 cars to Green Bank

<u>Departs</u>	<u>Driver</u>	<u>Passengers</u>
12:30pm	Baker	Dobaria, Fekete, Wasserman
1:30pm	TBD	Belfer, Kaufman
2:00pm	Leung	Trinker
3:00pm	Yolleck	Kammerer, King, Pinheiro
3:00pm	Singh	Leong, Patel, Rice
4:00pm	Rivera	Fahy, Parikh, Porter

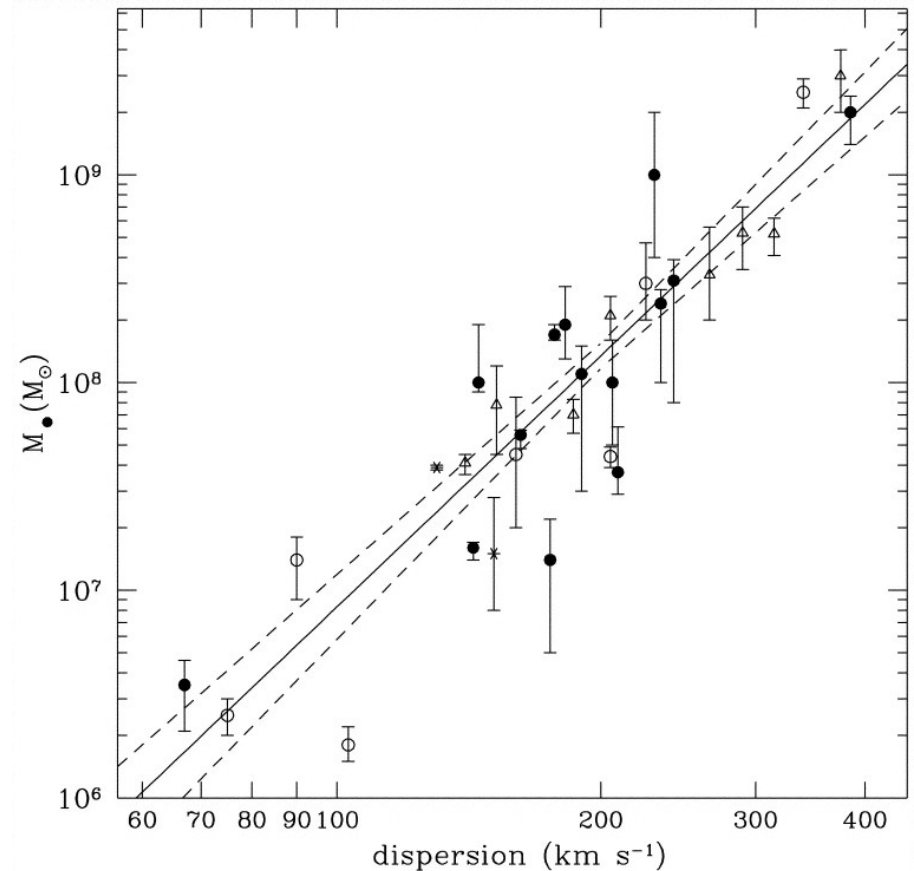
Return trip: passengers can be reshuffled if needed.
One passenger cell phone number per car. Do NOT trust GPS once in West Virginia! If your name is in red I need to see you after class.

Today: black holes are (nearly) ubiquitous

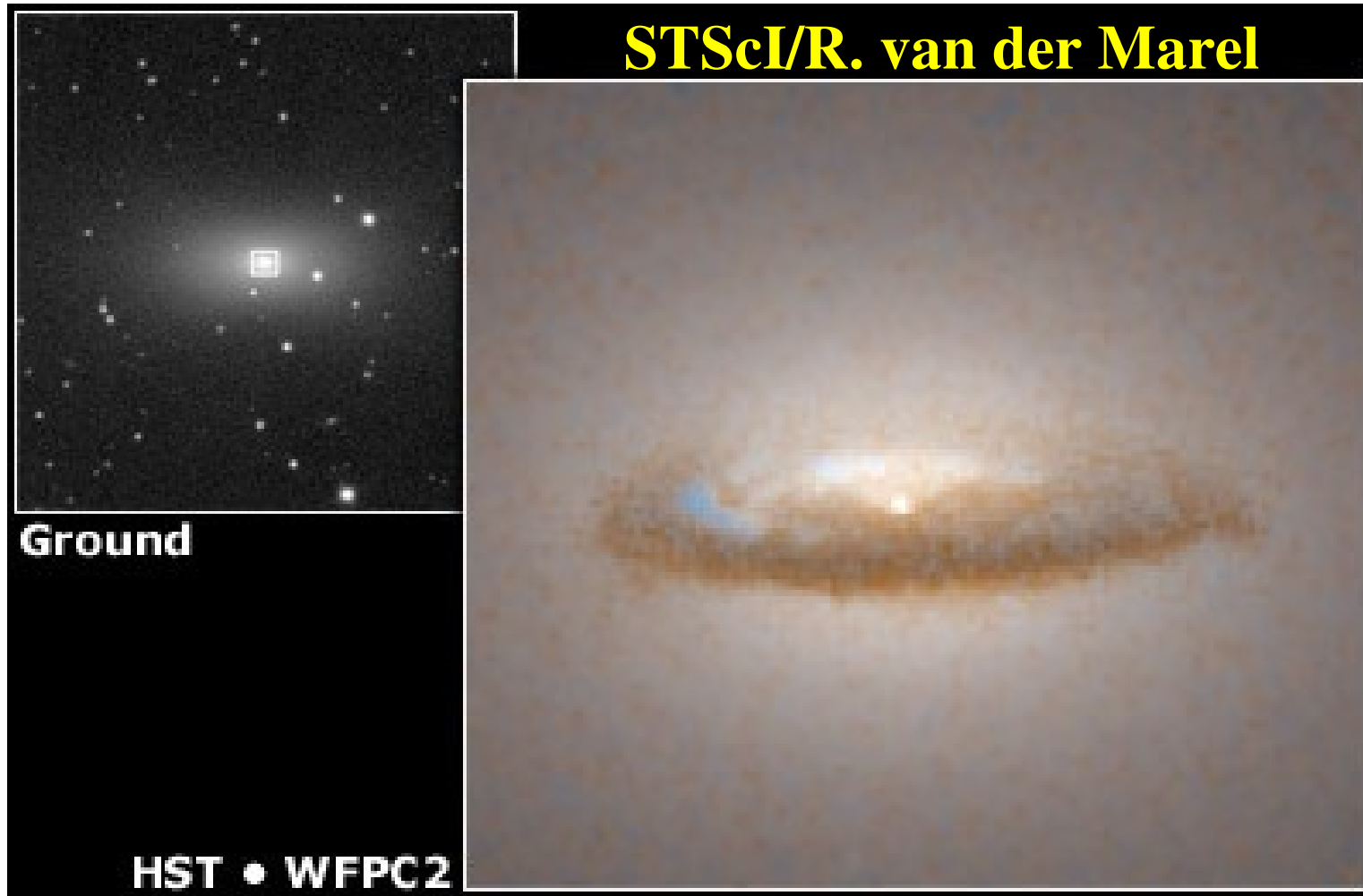
Elliptical galaxies and spiral galaxies with massive bulges **all** seem to have massive central black holes, whose masses follow a tight proportionality with **velocity dispersion**.

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

Tremaine et al. (2002)

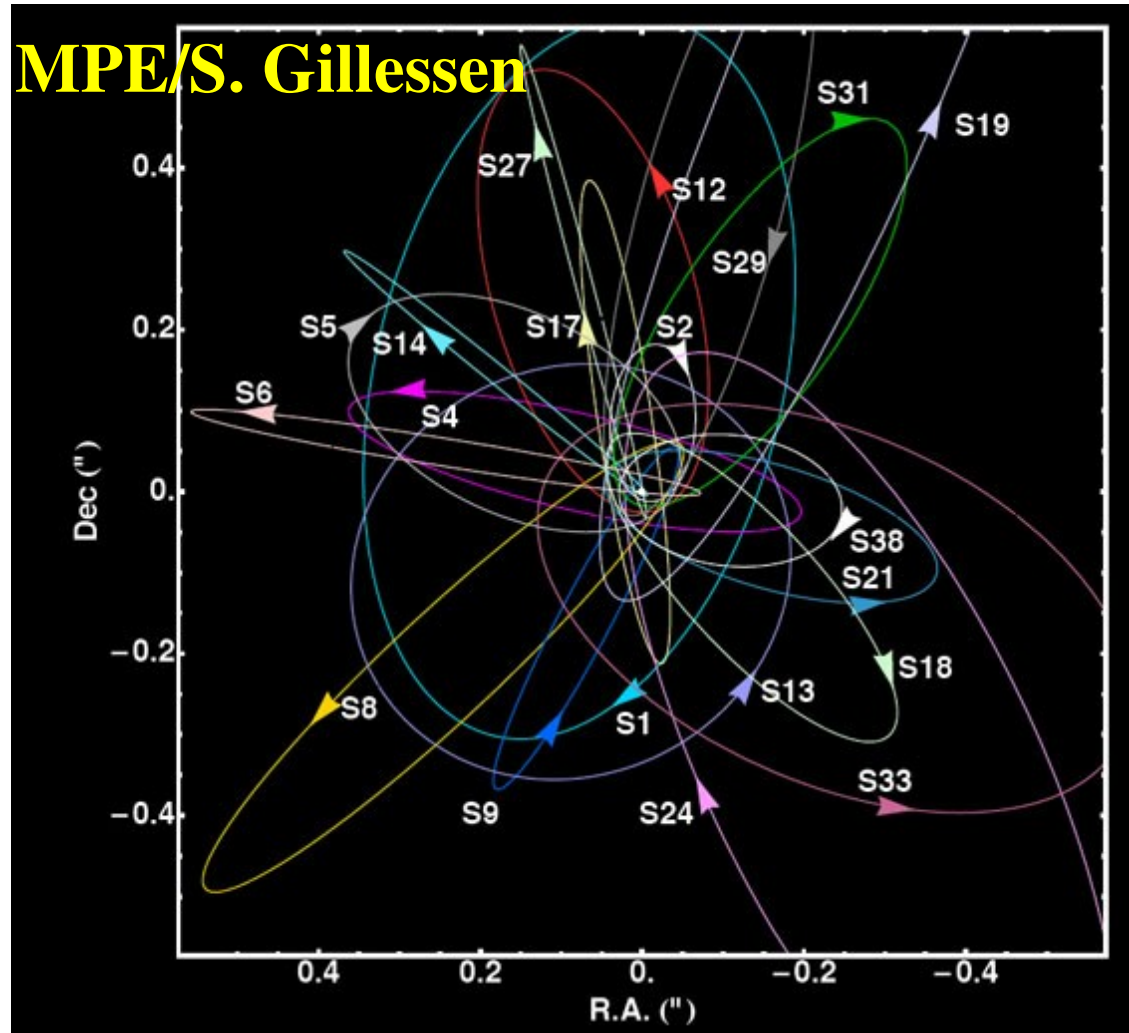


Measuring black hole masses



Some black hole masses are measured via gas dynamics, using the same equations you used in labs 4 and 5.

Measuring black hole masses



Milky Way's black hole mass has been measured by the proper motions of individual stars.

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

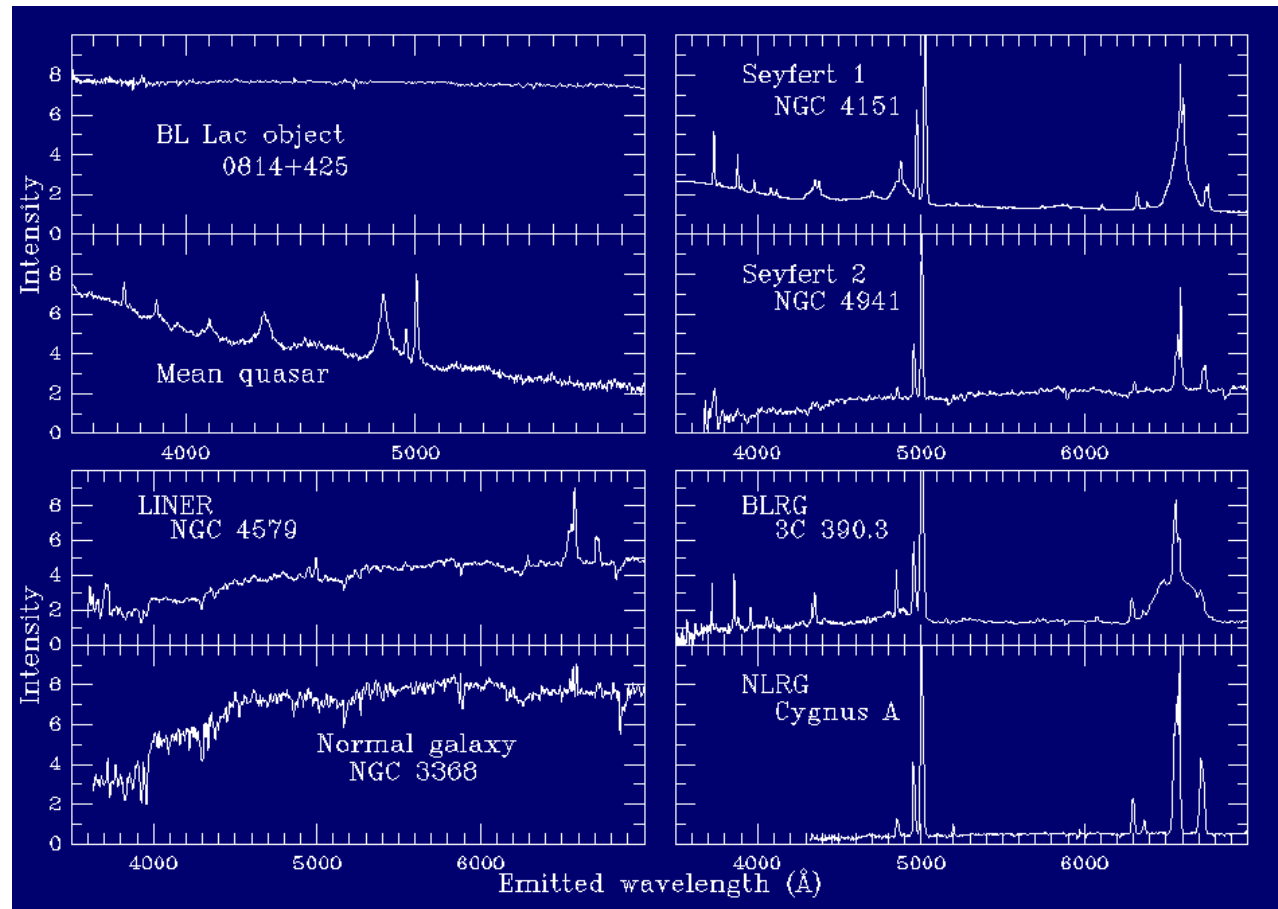
The alternative scenario is that a large fraction of the thermal energy is converted to **radiation**. In this case, we have a radiatively efficient accretion flow, and can observe one or more consequences that mark the center of a galaxy as an active galactic nucleus (**AGN**; plural = “AGN” or [ugh...] “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 **quasars** (quasi-stellar objects) depending on L .

Courtesy W. Keel.

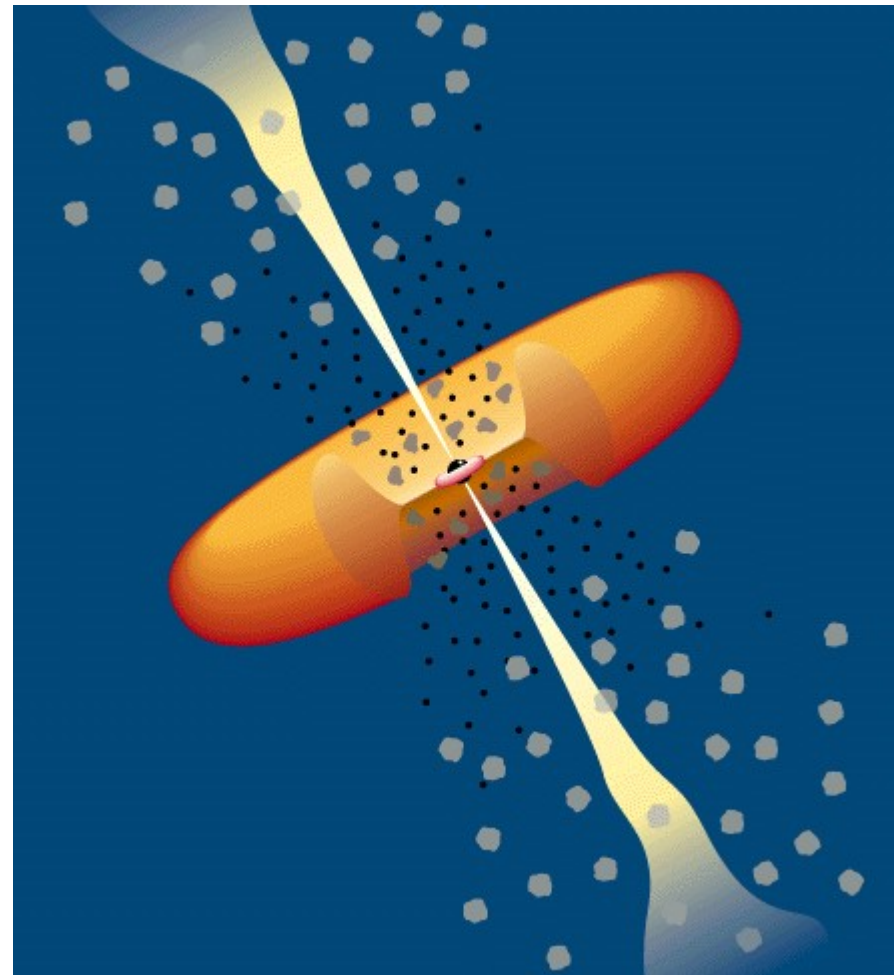


AGN in the optical: type 1 vs. type 2

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

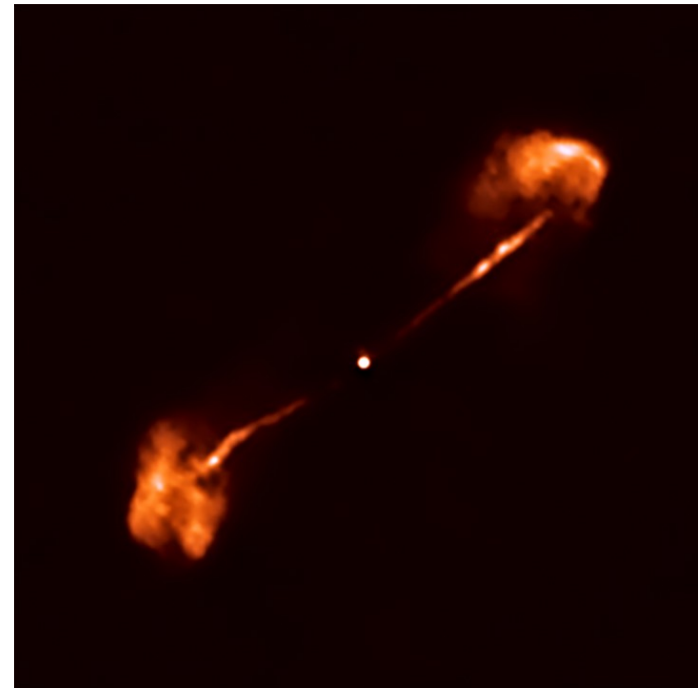
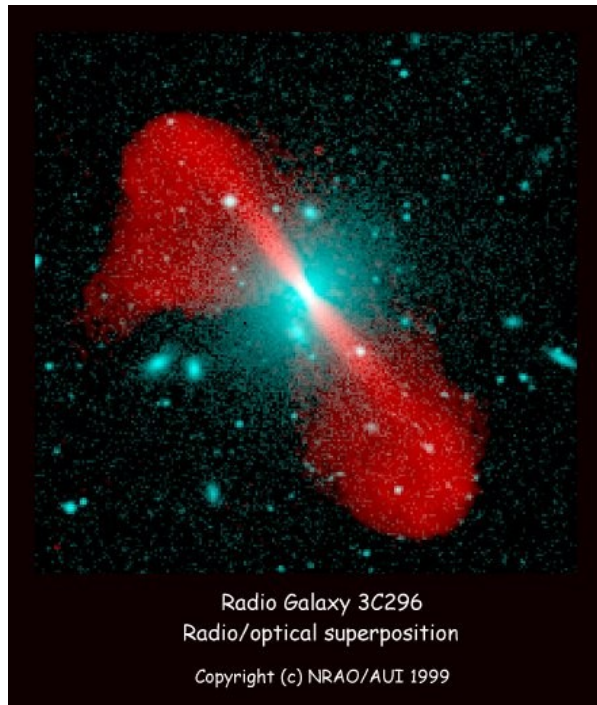
Independent of whether an AGN is type 1 or type 2 in the optical, or whether it shows X-ray emission or not, it may be either **radio-loud** or **radio-quiet**.

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

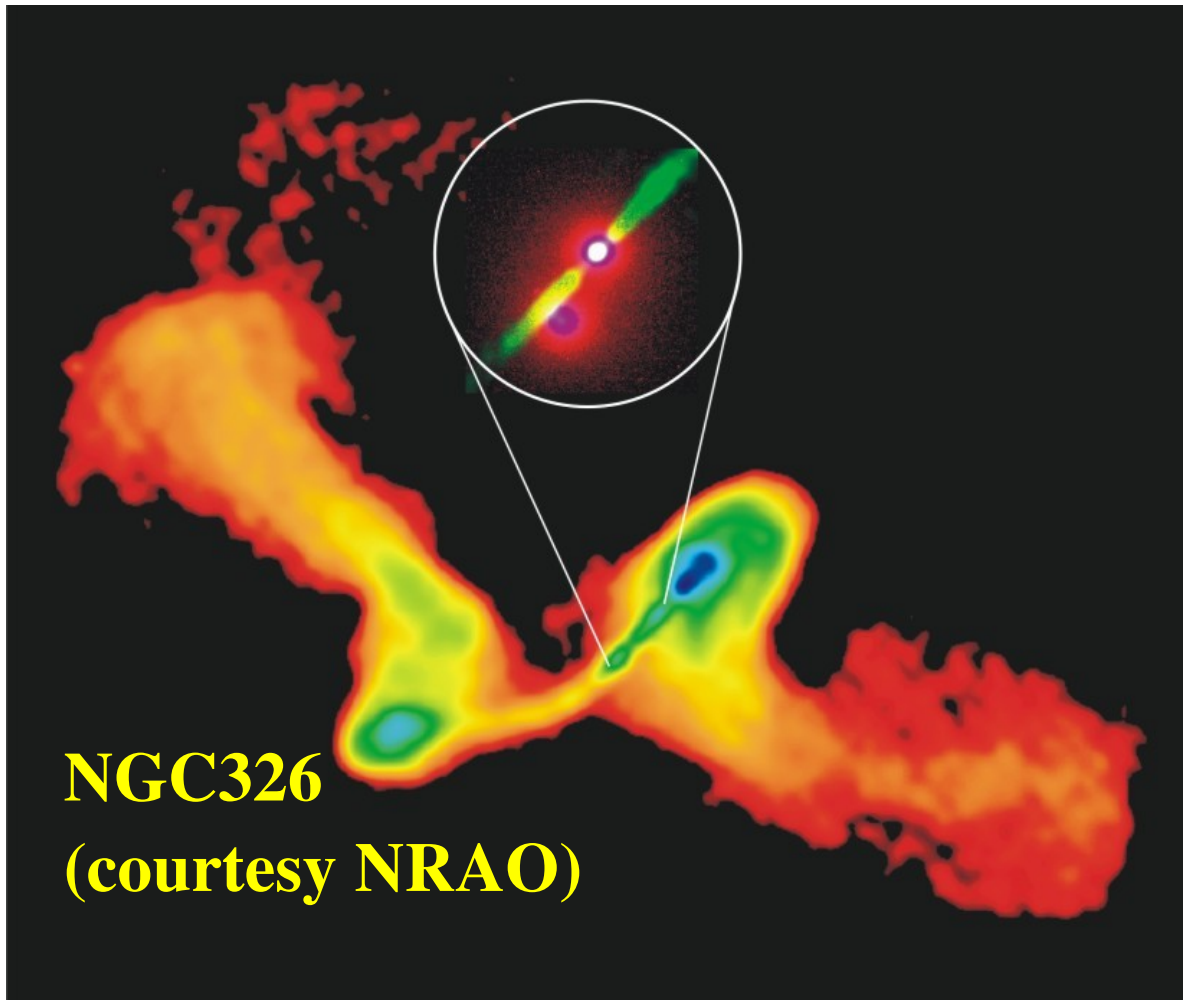
Two categories of radio galaxies

Among radio-loud objects, we have

- (1) Fanaroff-Riley type I (“FRI”) objects that are core-dominated**
- (2) Fanaroff-Riley type II (“FR II”) objects that are lobe-dominated**



Some FR II 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!

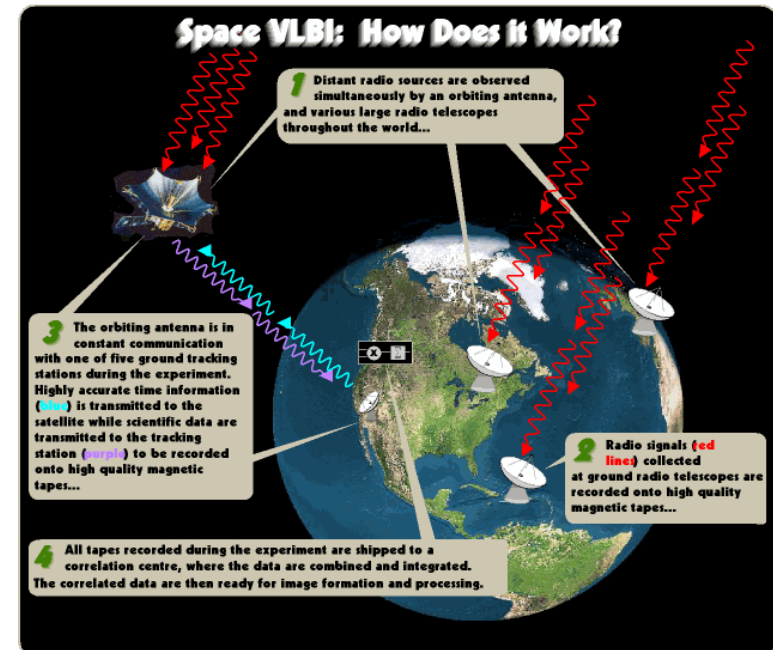
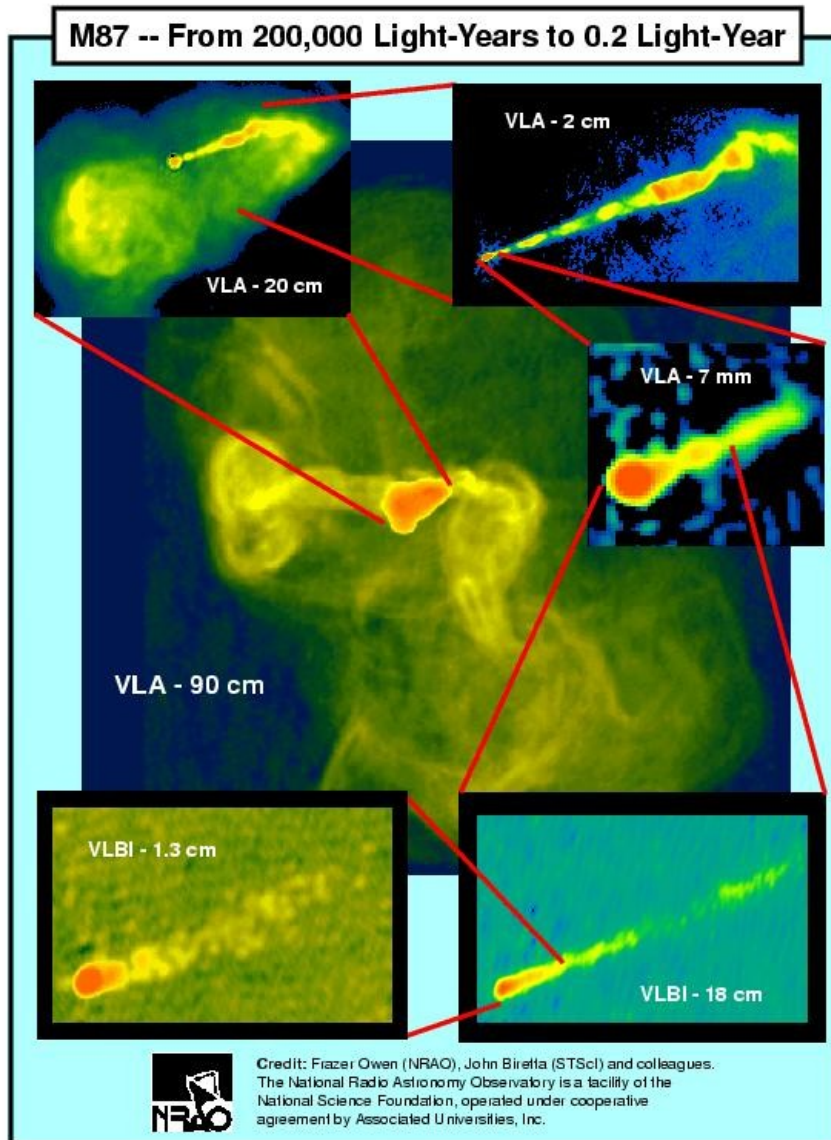


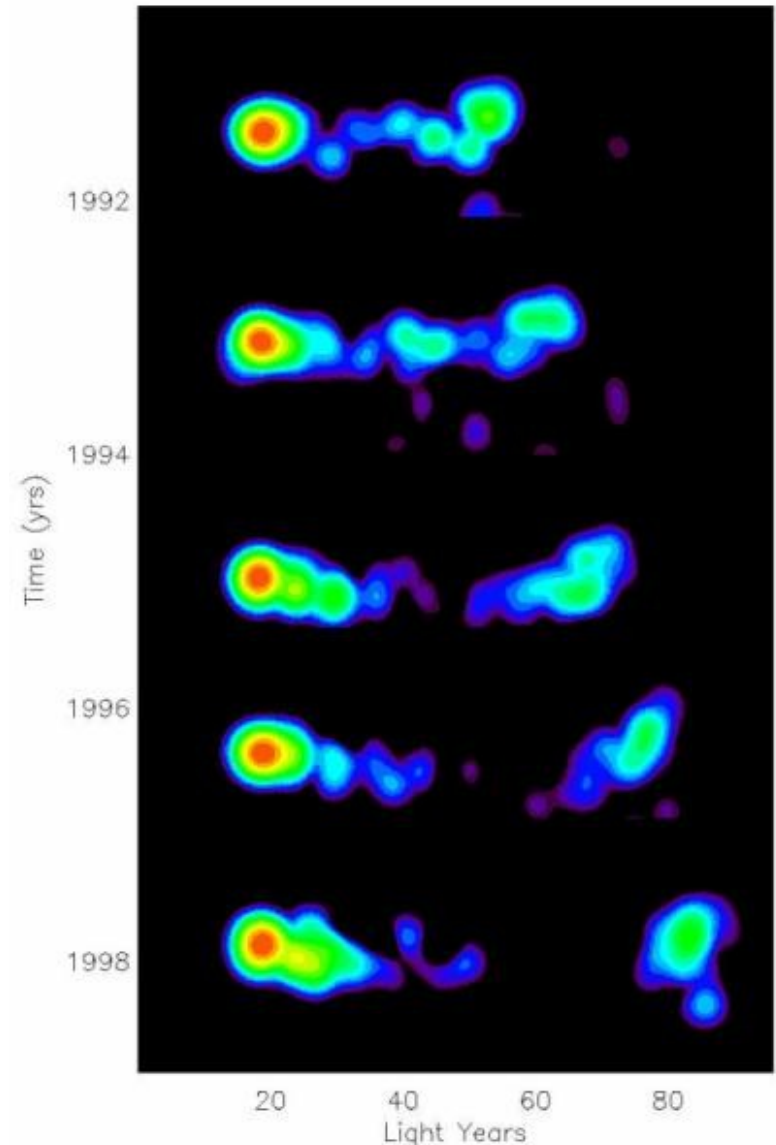
Exhibit A: M87 in the Virgo Cluster



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

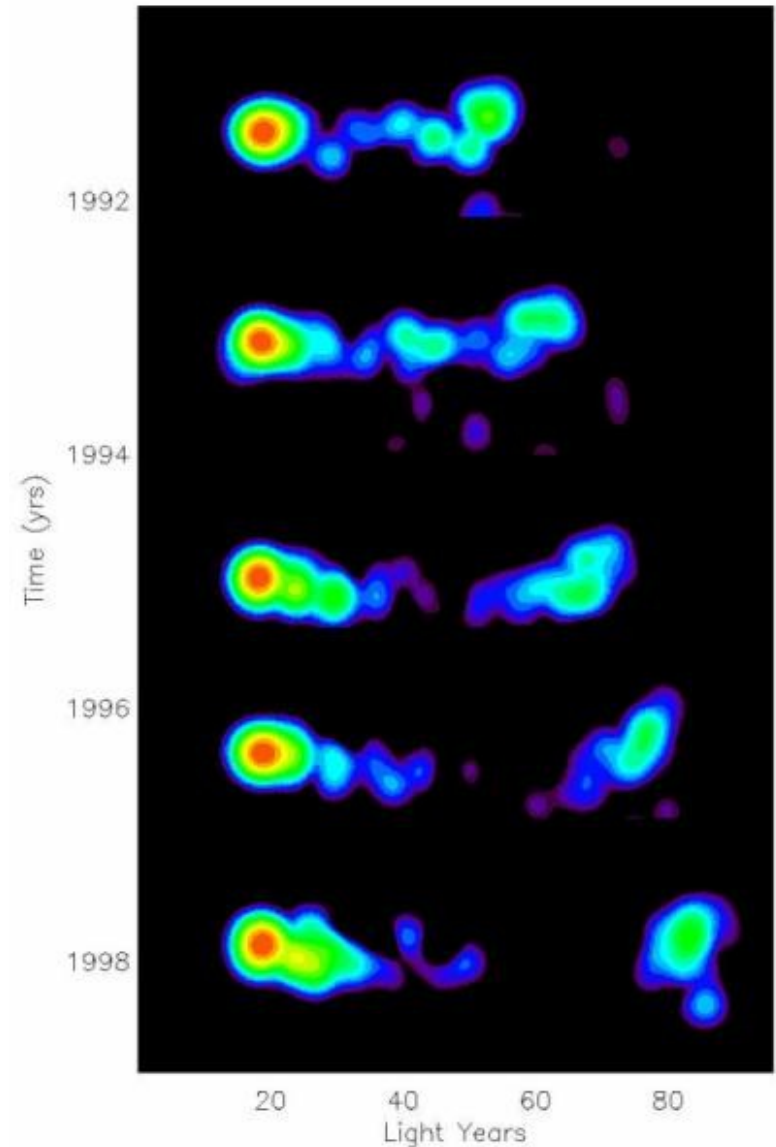
We can watch jets evolve in real time!

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.

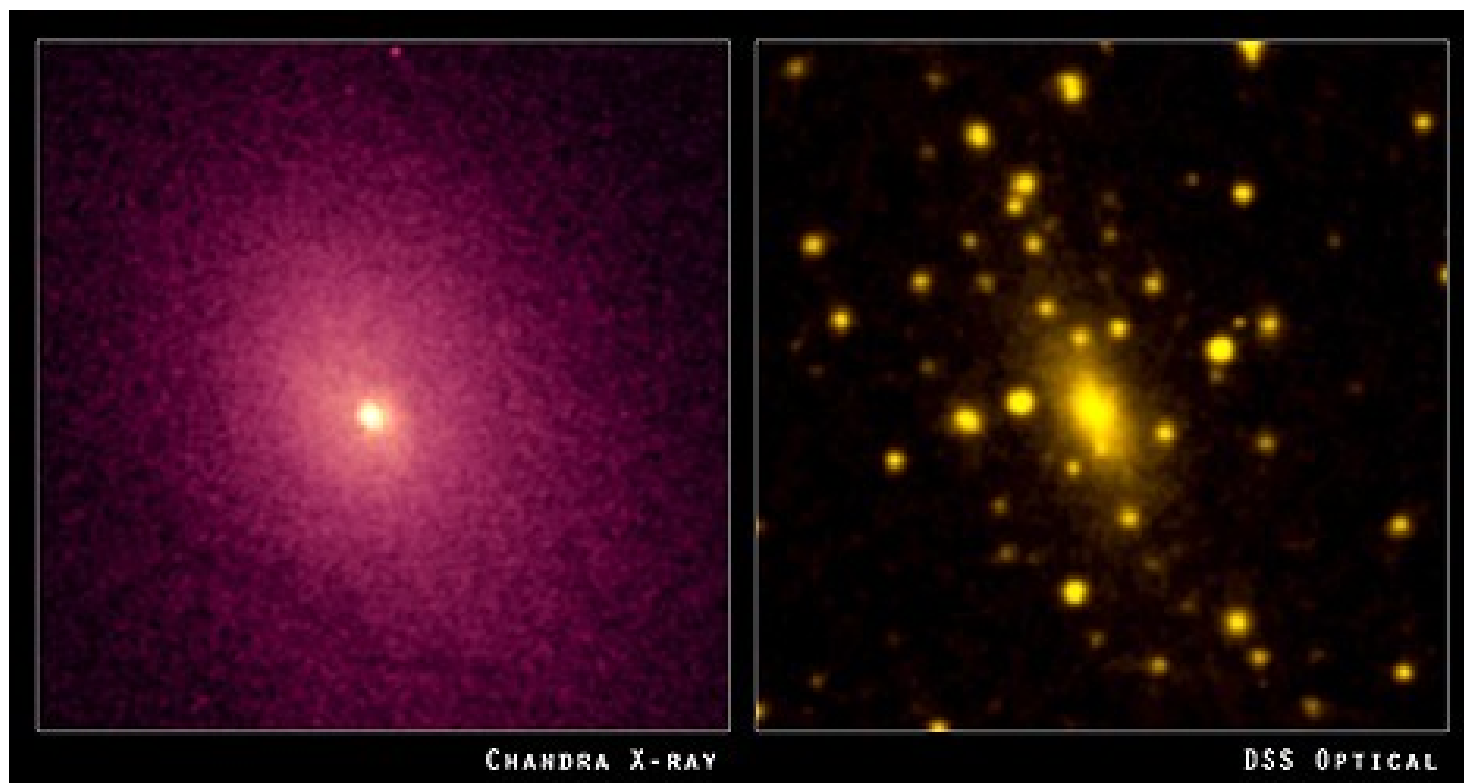


“Superluminal” motion: an optical illusion

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



Galaxy clusters

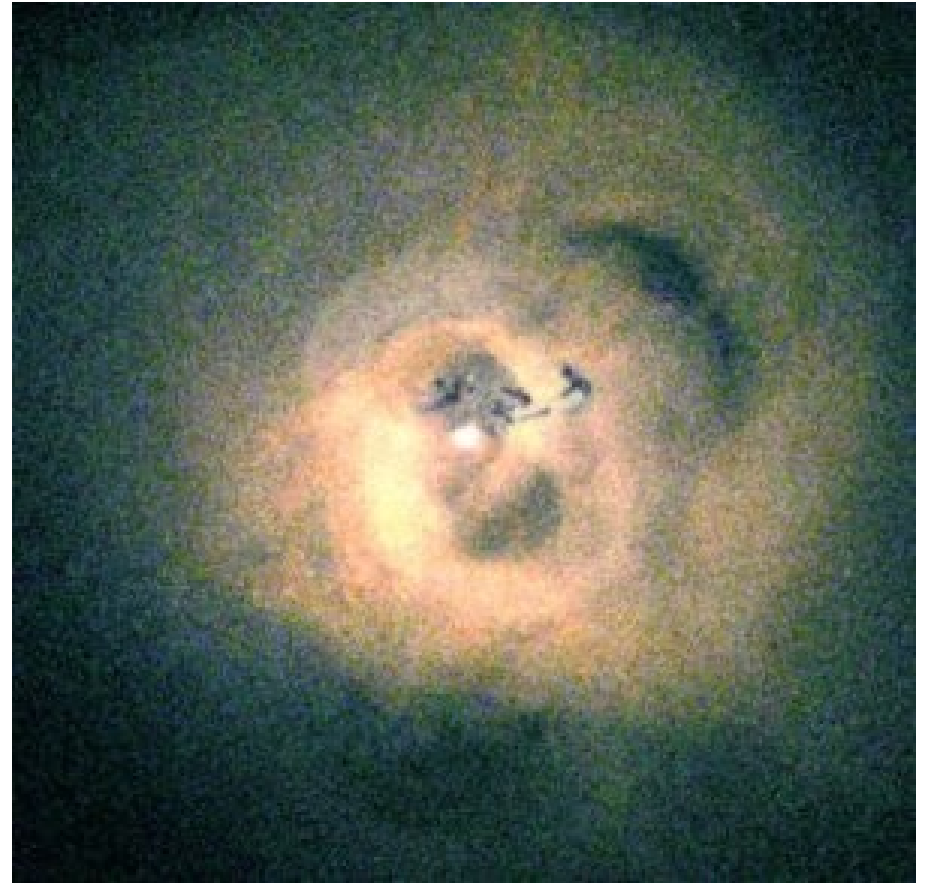


Galaxy clusters have most of their (ordinary, baryonic) mass in the form of hot intracluster gas. Why doesn't this cool, flow to the center, and form stars in the central elliptical?

AGN feedback

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

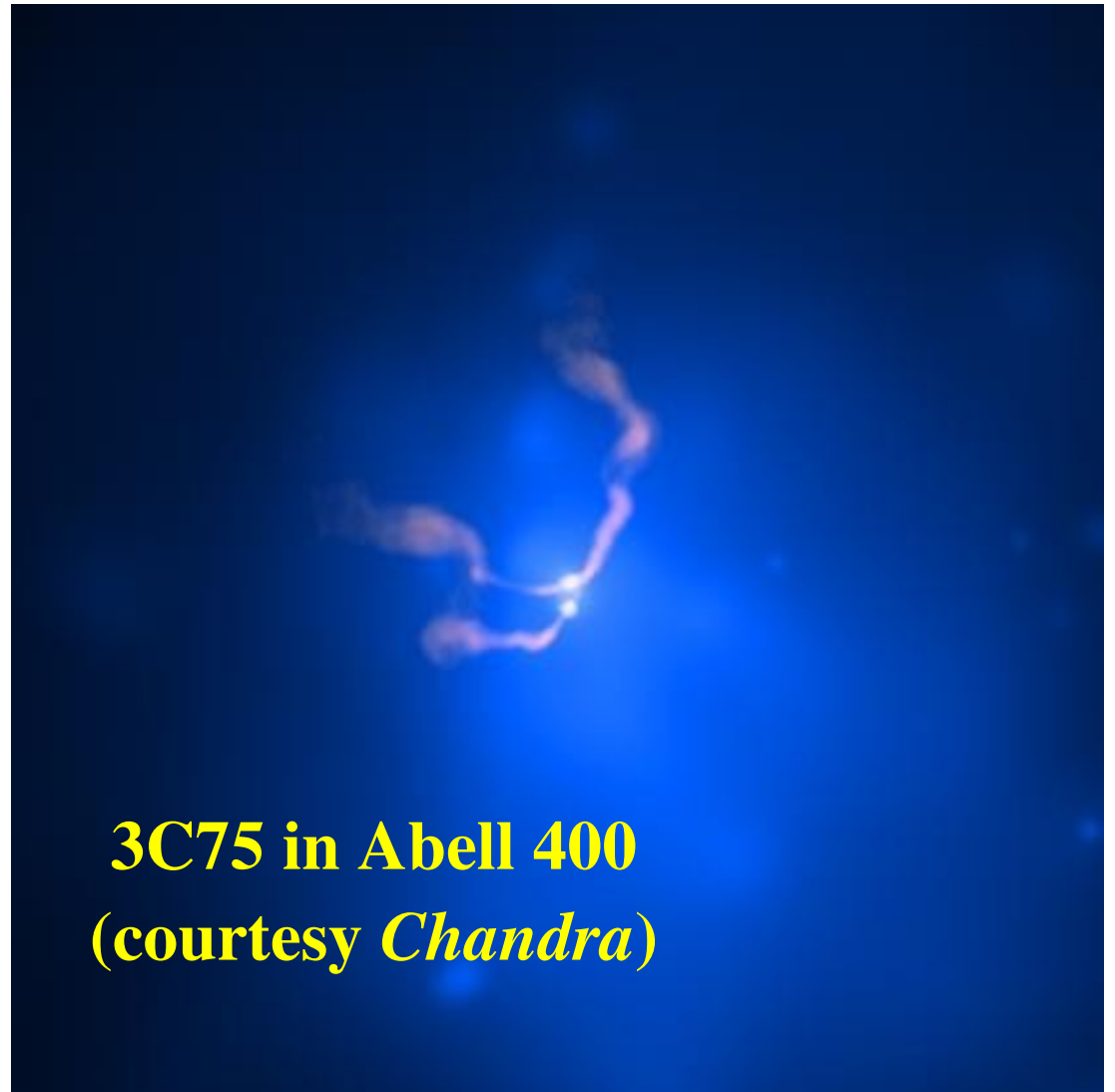
We think these were produced in past radio-loud events: a jet in the central elliptical turns on when the black hole is fed, driving away further fuel until it shuts itself off.



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