Galaxy Formation and Evolution: Linking the pieces

Disk galaxies can collide and merge
When they do so, gas clouds in the disk are driven into the central regions
This inflow can feed a central black hole, causing it to grow
The inflow can also drive a central starburst and starburst wind

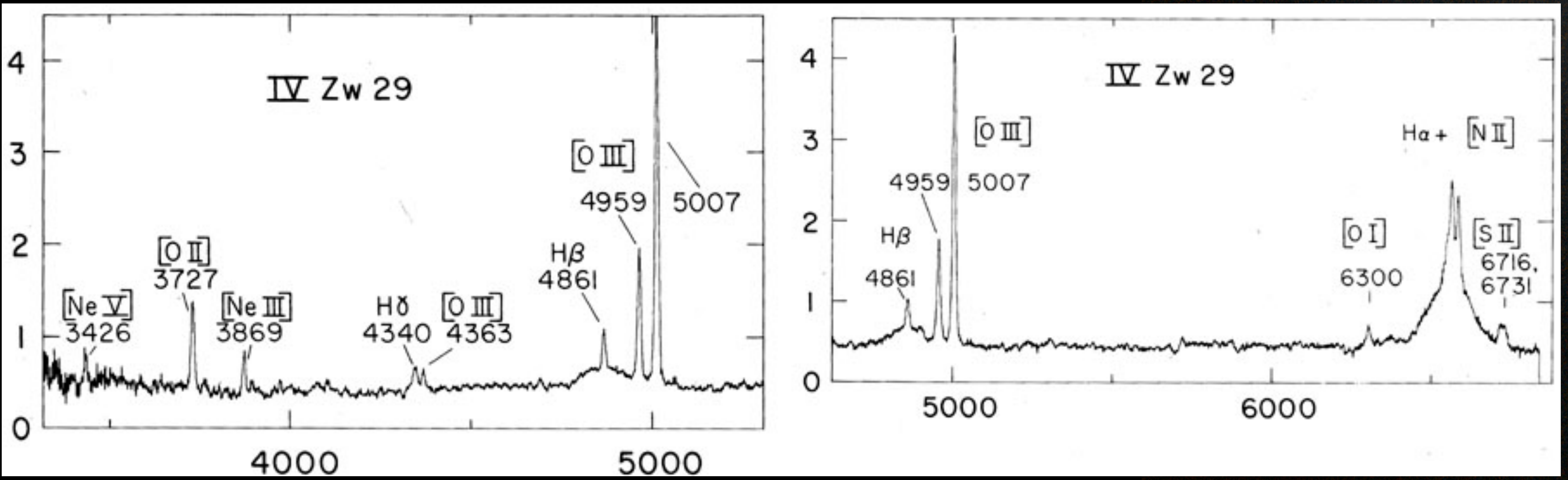
These processes convert cold gas into stars and hot gas
The merging process also scrambles up stars on circular orbits into random orbits

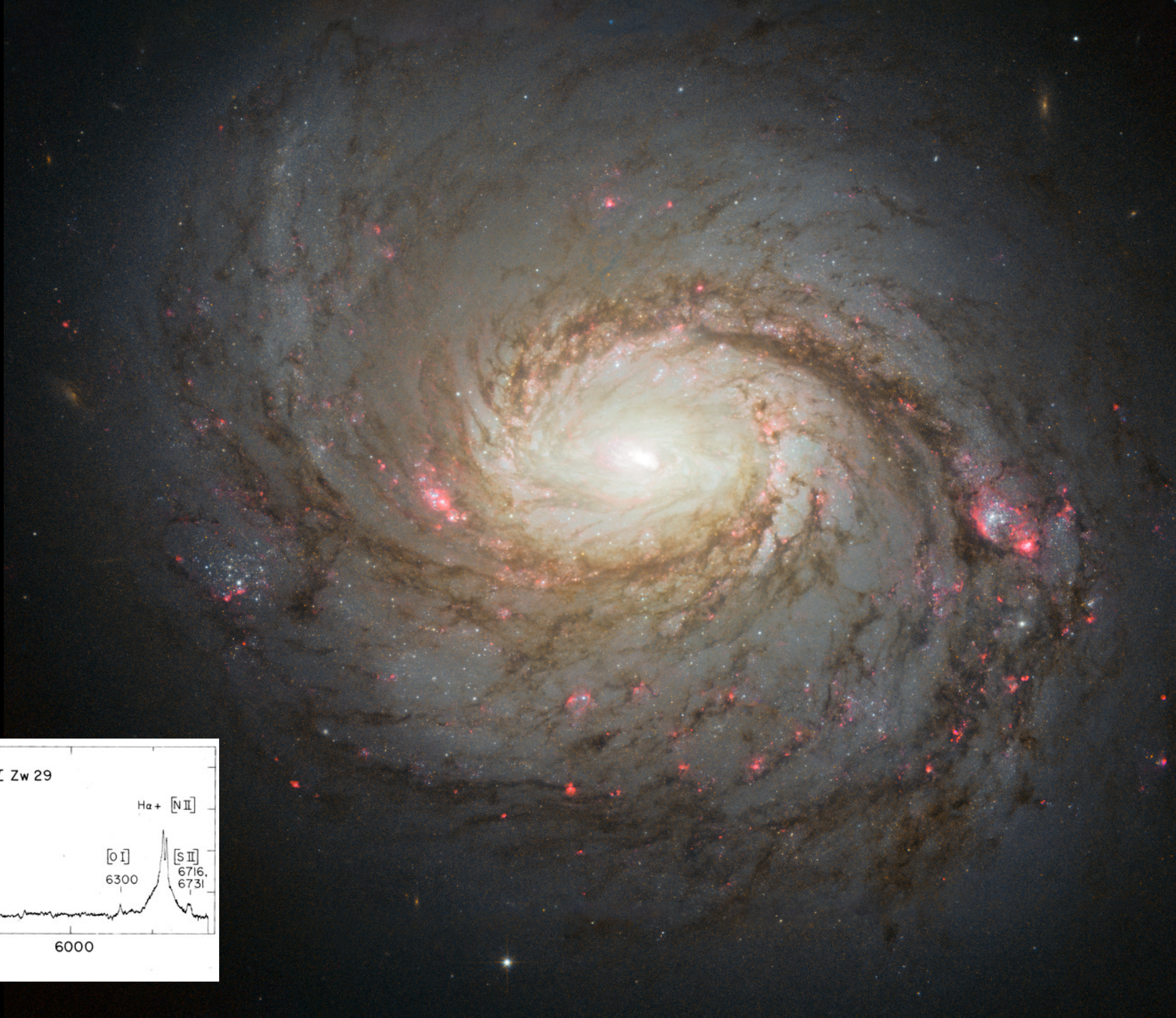
Major mergers are thought to be closely tied to formation of elliptical galaxies. What types of mergers these were is still not clear. An example of a merger-spawned elliptical galaxy in the making:

The first hint of strange activity in otherwise normal galaxies came from the spectrum of NGC 1068. NGC 1068 was found to have broad and narrow emission lines in its nucleus, produced by highly ionized gas

Broad emission lines: fast motions (1000 - 5000 km/s)
Narrow emission lines: slower motions (~500 km/s)
High ionization: strong energy source

NGC 1068 is an example of a Seyfert galaxy. We classify Seyfert galaxies by their emission line shapes.
Seyfert 1: both broad and narrow lines
Seyfert 2: narrow lines only



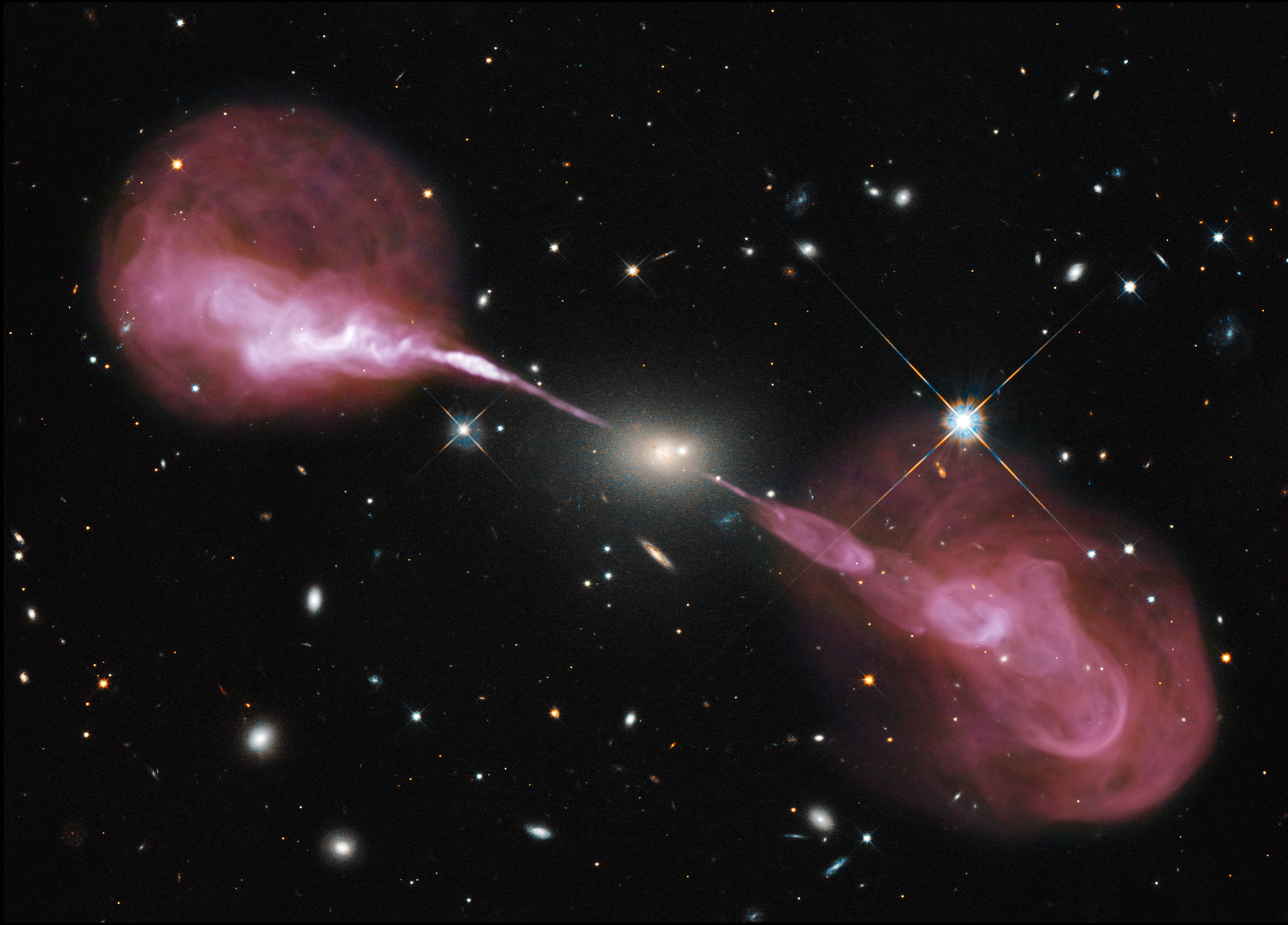


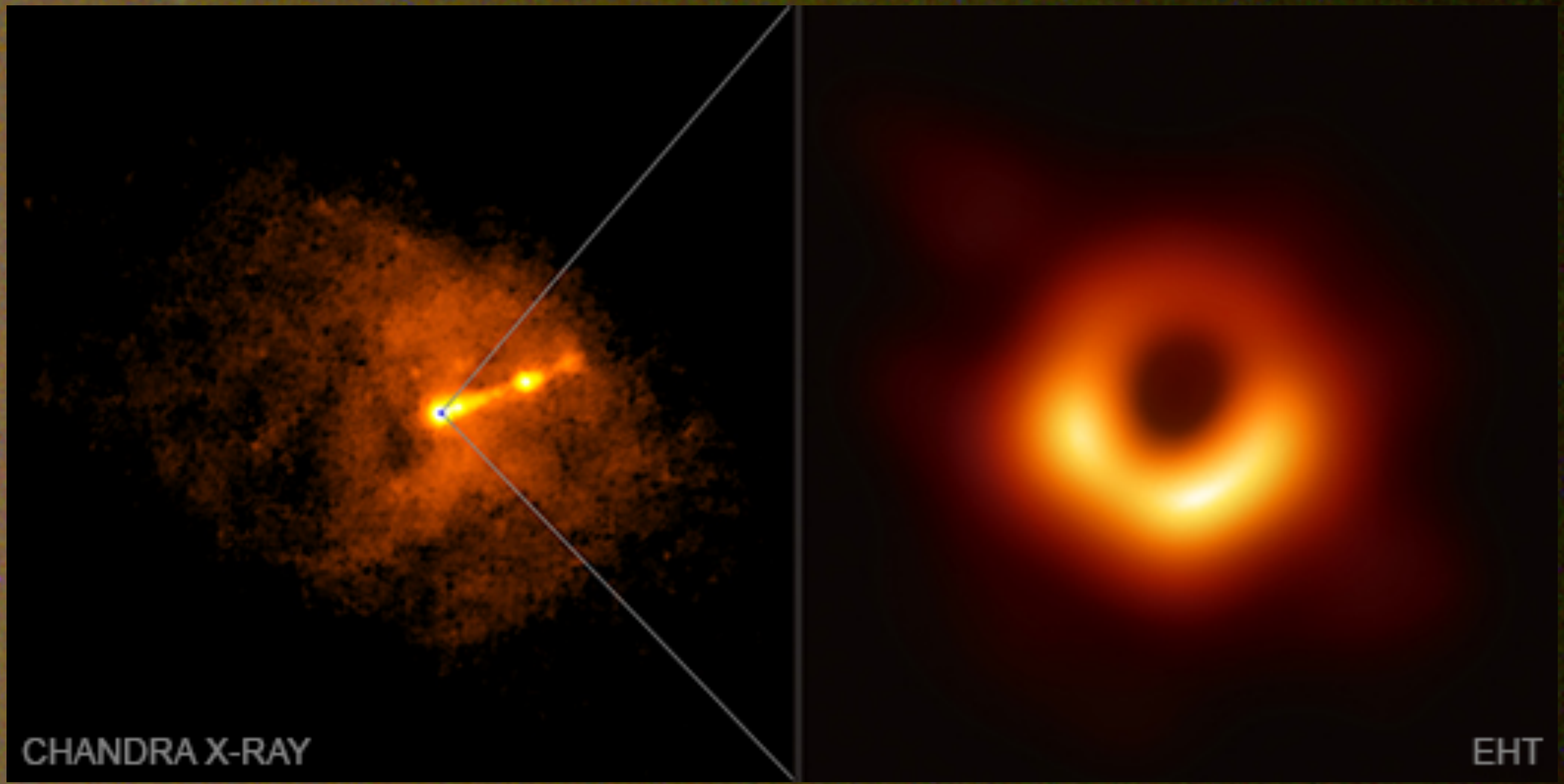
Radio galaxies

As radio astronomers mapped the sky, they found several bright radio sources associated with distant galaxies. One of the brightest was the radio source Hercules A.

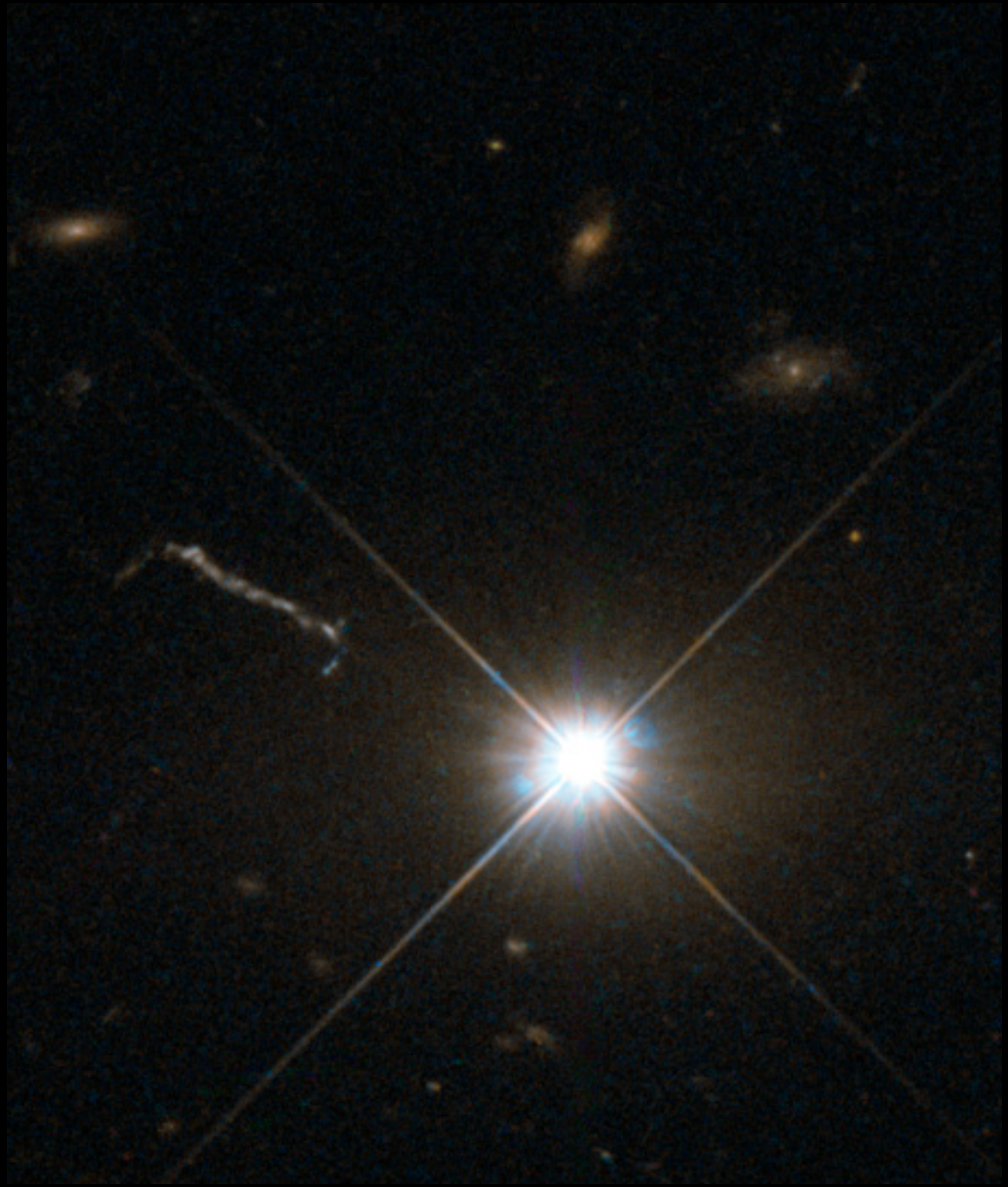
Hercules A is a double-lobed radio source, where the lobes contain hot, ionized gas. Also notice the jets from the center. At the center sits a giant elliptical galaxy, at a distance of ~ 650 Mpc (z=0.155). At this distance, the lobes are separated by more than 250 kpc, and they have a radio luminosity of ~ 10^{45} erg/s, 10^6 times greater than the radio luminosity of normal galaxies.

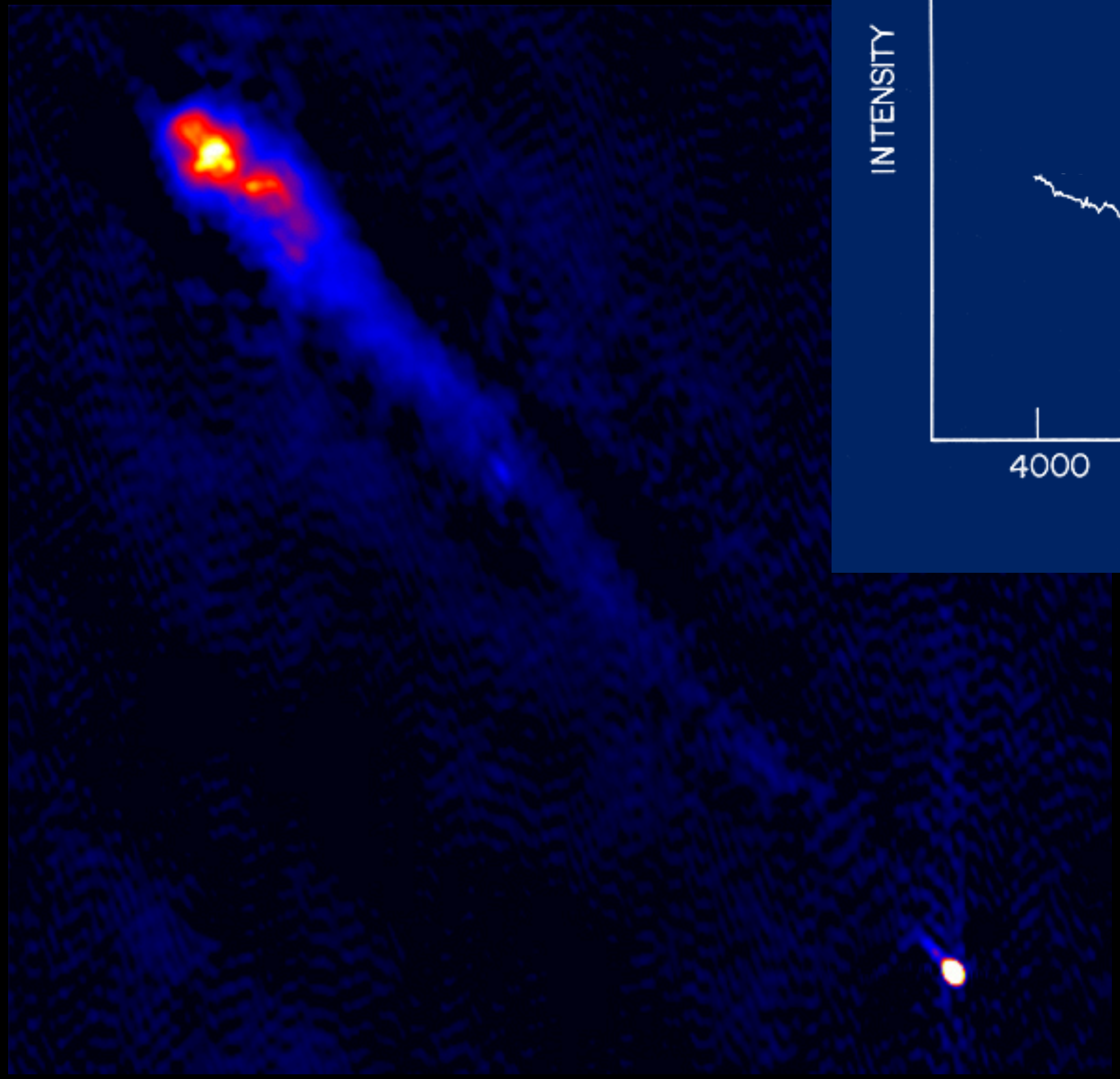
Radio galaxies, unlike Seyferts, are generally hosted by elliptical galaxies, not spirals. Seyferts are also radio quiet.

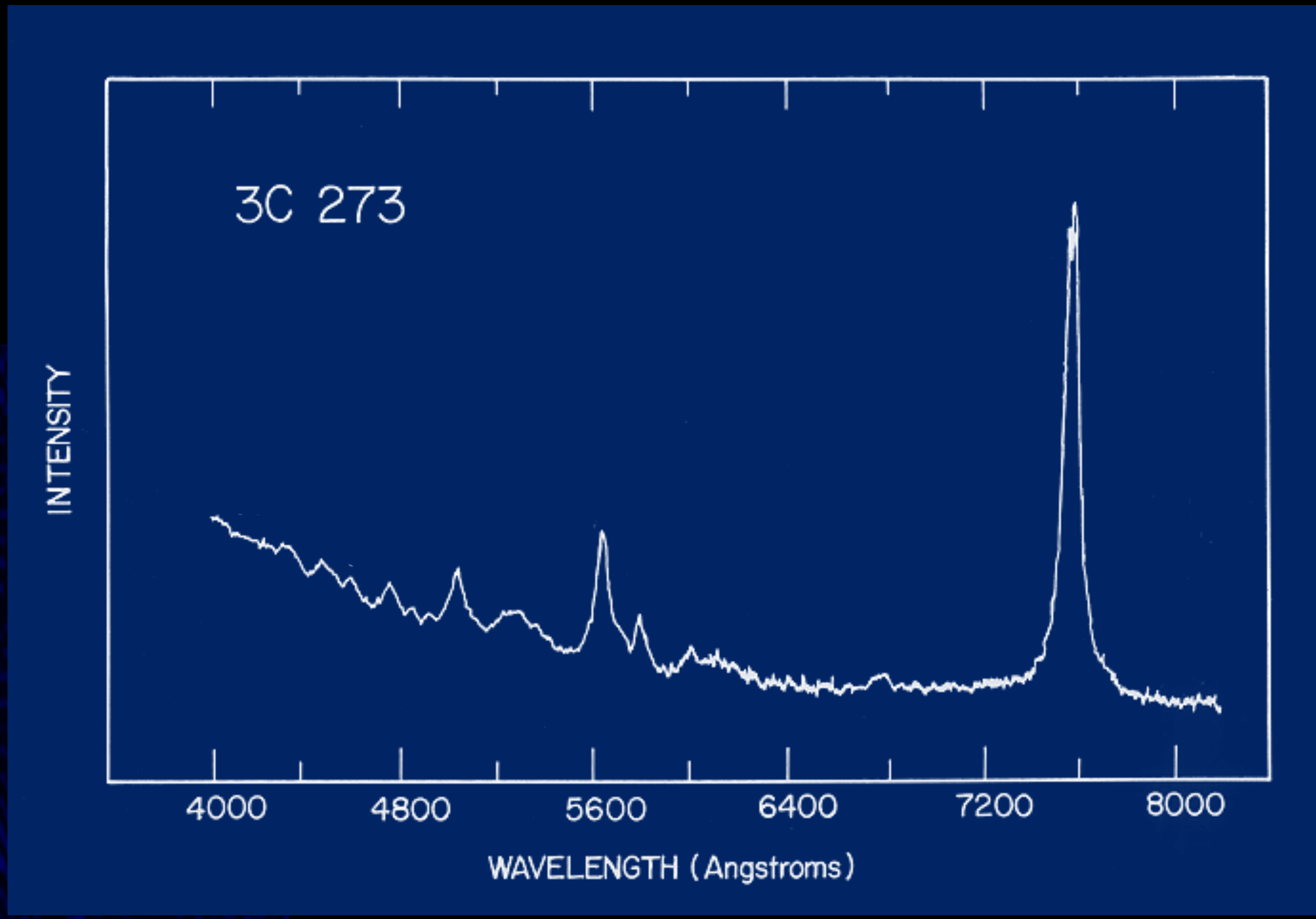




M87, the central elliptical in Virgo, also is a radio galaxy. It is close enough that we can examine its center in detail, where we can actually see the jet in the optical:







Some radio sources were not found to be associated with obvious nearby galaxies. Instead, astronomers only found star-like objects, with very bizarre spectra — they had extremely broad emission lines which could not be associated with any known elements or molecules. The name "quasi-stellar radio source" or quasar was given to these objects.

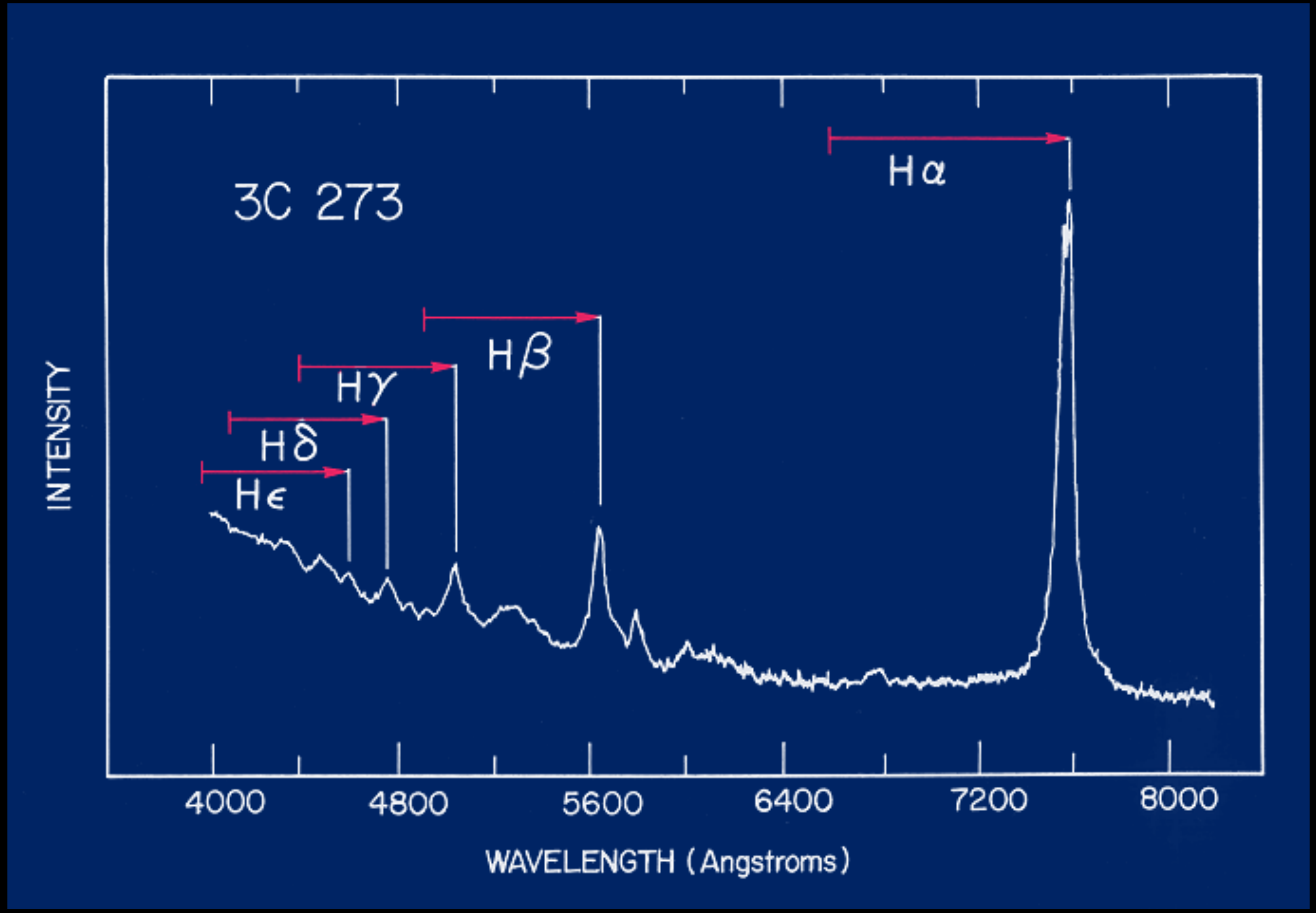
$$z = \frac{\Delta\lambda}{\lambda}$$

In 1963, Maarten Schmidt realized that the emission lines from the quasar 3C 273 were actually from a very well-known element: hydrogen. They were, however, shifted to much redder wavelengths than expected, indicating (by Hubble's law) that the object was very far away.

An aside: redshifts

At large recession velocities, astronomers typically talk about the redshift of a galaxy, given by measuring the wavelengths of their spectral lines. Redshift ("*z*") then measures how far those lines are shifted from their normal wavelength.

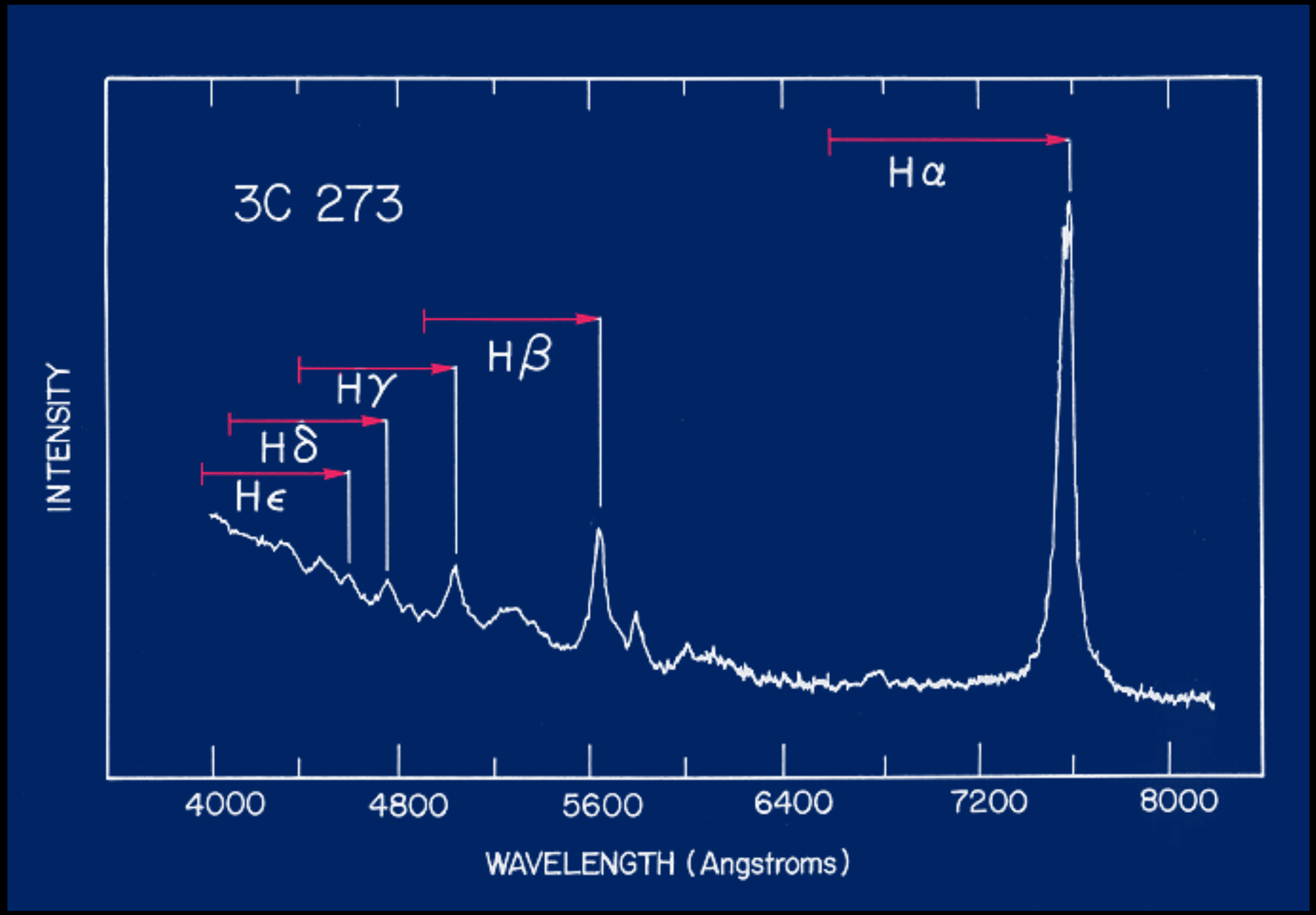
Small *z*: low velocity
Large *z*: high velocity
Most galaxies we see pretty pictures of are nearby with small redshifts of $z<0.05$.



$$z = \frac{\Delta\lambda}{\lambda}$$

3C 273 had a redshift of z=0.158, and has a "recessional velocity" which was ~ 15% of the speed of light! This puts 3C 273 at a distance of ~ 650 Mpc. Nothing had ever been observed this distant.
Shortly thereafter, another quasar, 3C 48 was found to have a redshift z=0.367, putting it ~1500 Mpc away.
(note: at these redshifts, the notion of distance becomes ill-defined, because of the curvature of space. we'll talk about that more when we talk about cosmology!)

Quasars were the most distant objects ever discovered. Yet they are relatively bright. This means the must be extremely luminous: 10^3 - 10^5 times more luminous than the entire Milky Way.



What else can we say about active galaxies?

They vary their light output on very short timescales.

Active galaxies change brightness on the timescale of hours.

This again places an upper limit to the size of the energy source:

They are luminous.

Quasars have luminosities 100-1000 times that of the Milky Way.

Yet it all comes from a region smaller than the Solar System!

They must be massive objects.

Remember that light itself (photons) can impart a force onto a particle (for example, an electron). Balance radiation pressure with gravity:

$$\frac{GMm}{R^2} = \frac{L}{4\pi R^2}\frac{\sigma}{c}$$

And solve for the gravitational mass:

$$M = \frac{L}{4\pi}\frac{\sigma}{cGm}$$

What does this mean? If the mass is at least this much, gravity will hold the system together. If the mass is less than this, radiation pressure wins and the system will be pushed driven apart. *So unless quasars are wildly out of equilibrium, their luminosity places a lower limit on their mass.* This is called the Eddington limit. It actually holds for a wide variety of astrophysical applications.

Using numbers typical for quasars, we get a mass of ~ a few x 10^8 M_{sun}.

So — Very massive. Very luminous. Very small. What does this sound like?

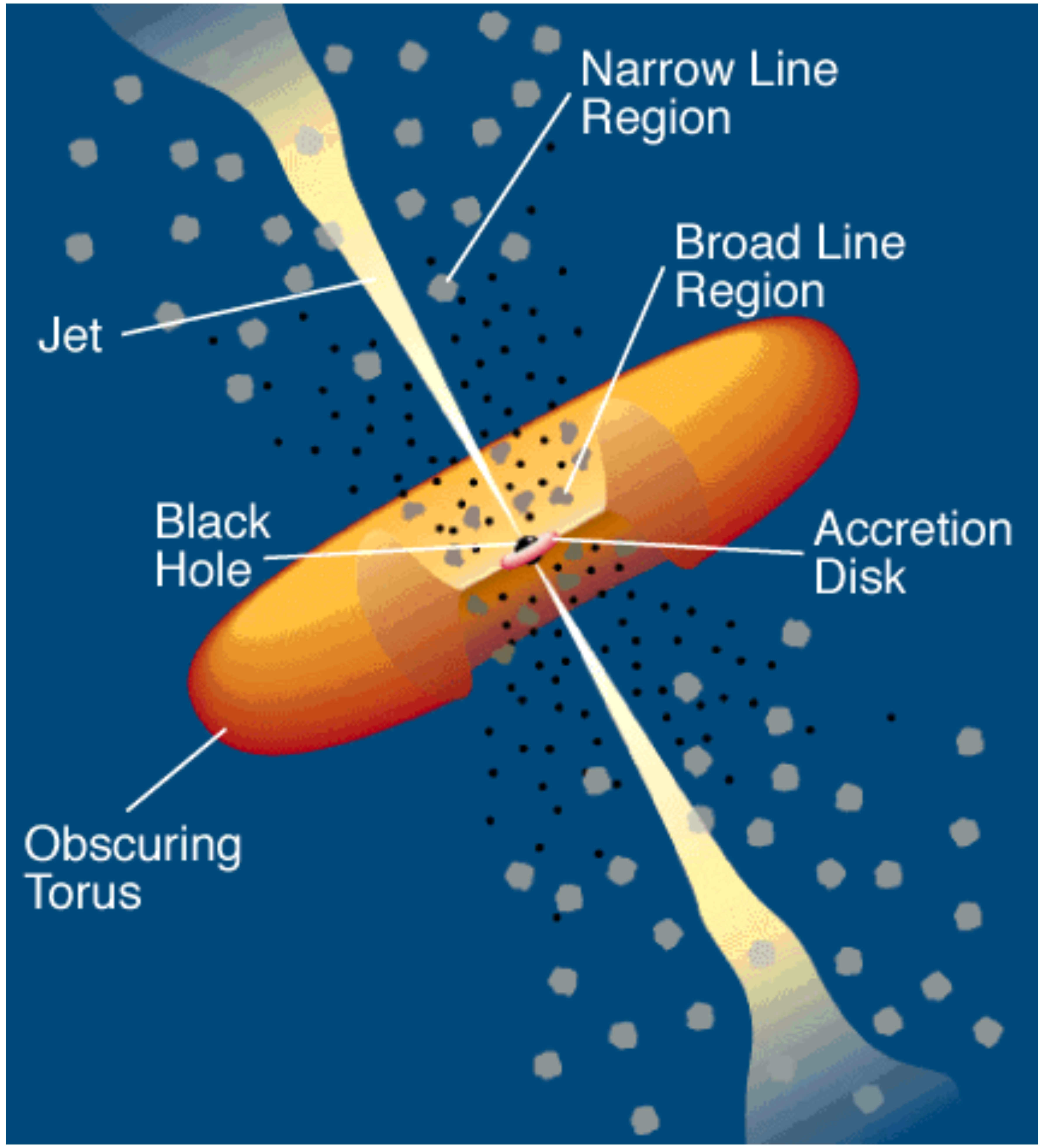
But why are there so many types of active galaxies?

These observations and arguments all suggest that active galaxies are powered by material accreting onto a massive central black hole in the nuclei of galaxies. What does the nucleus look like?

Anatomy of an active galactic nucleus:

Central black hole
Accretion disk: hot, luminous gas accreting onto the black hole.
Jets: charged particles moving at relativistic speeds out of the nucleus
Broad-line region: Gas clouds near the accretion disk, turbulent motions at high speed.
Dusty torus: a ring of denser gas and dust surrounding the nucleus.
Narrow-line clouds: Gas clouds further out, moving more slowly.

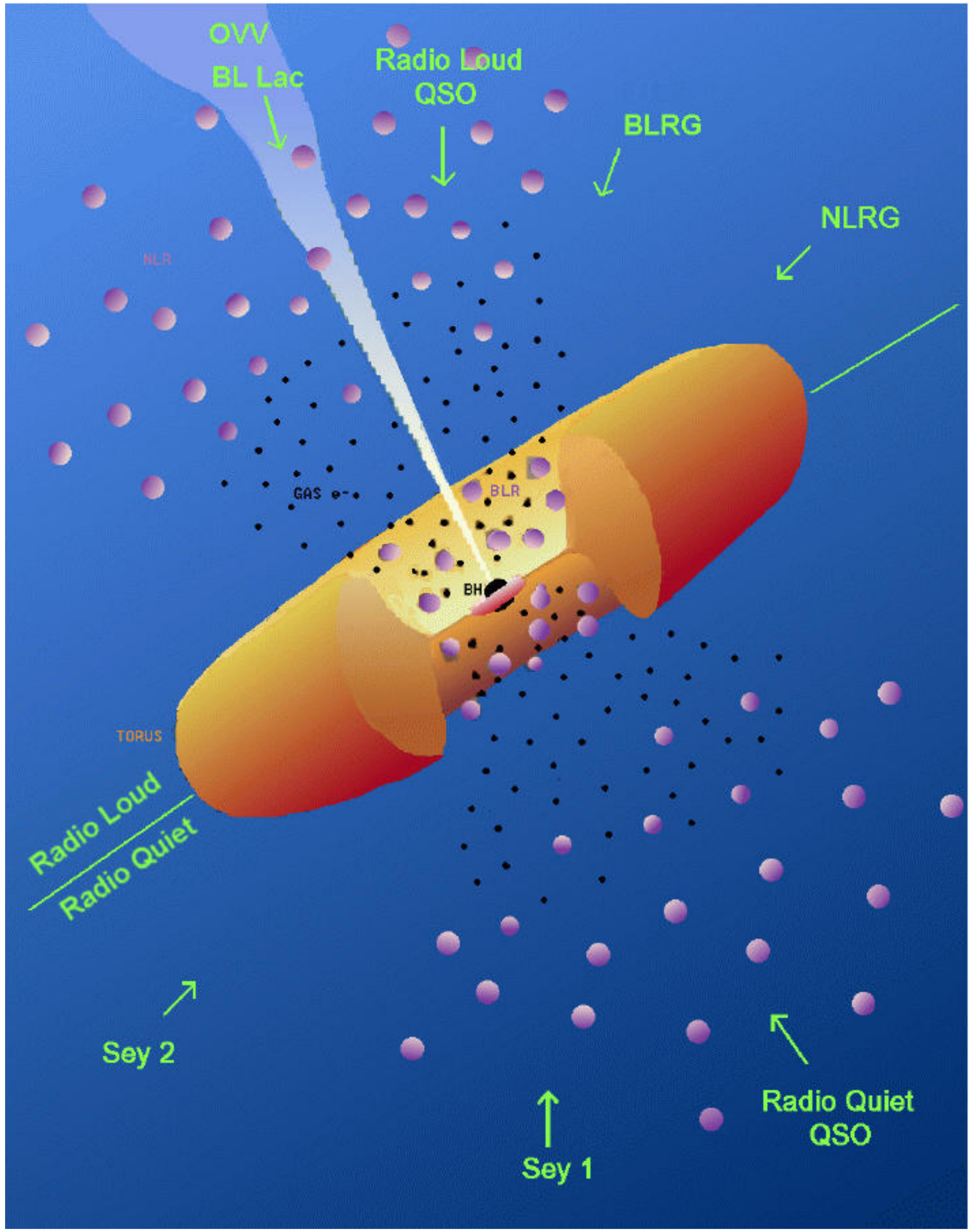
To achieve the necessary luminosity, ~ 1-10 M_{sun}/yr must be accreted onto the black hole.



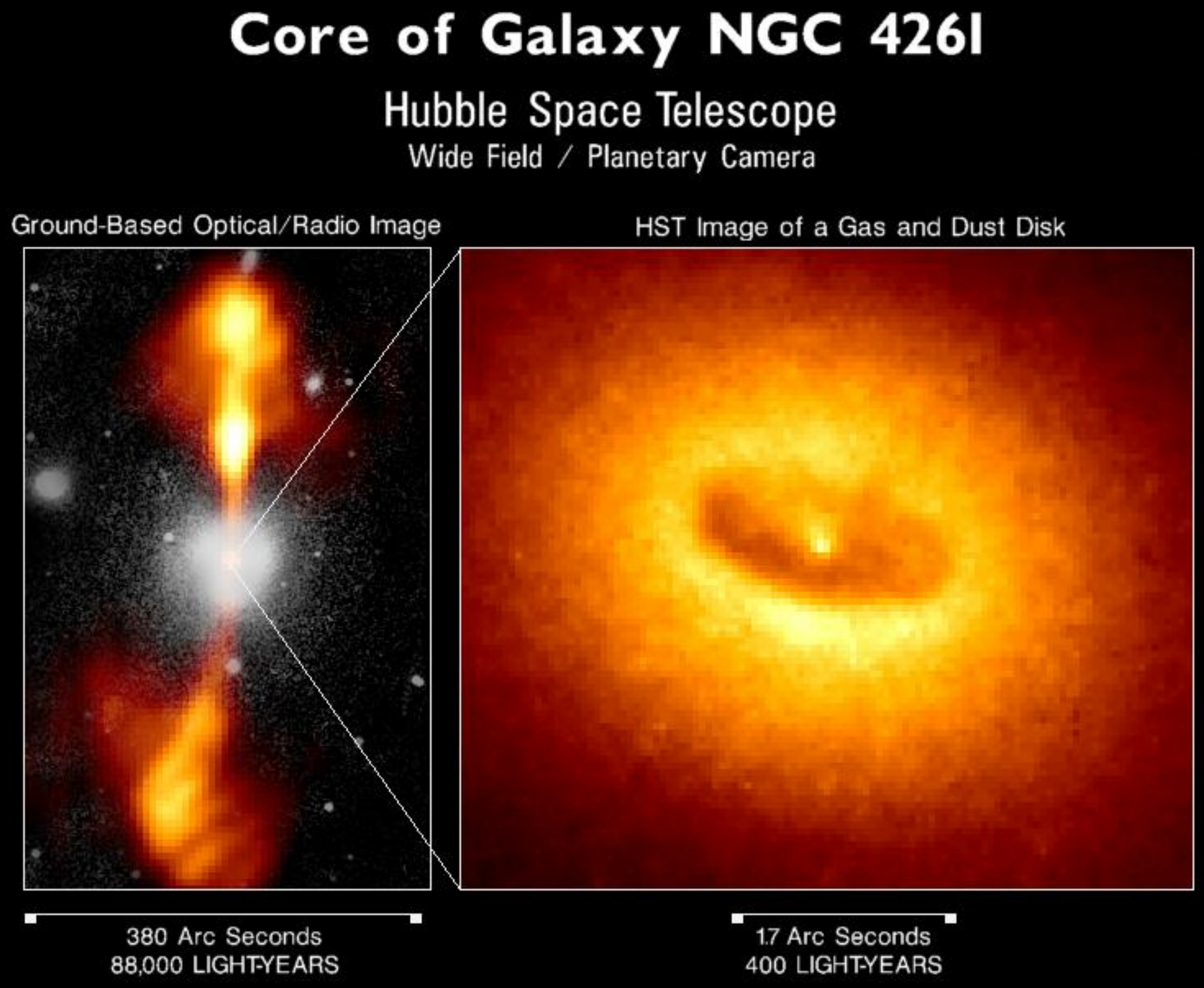
How does this "unify" the different classes of active galaxies?
Largely through viewing angle:

So Seyfert galaxies, radio galaxies, and quasars are similar objects
— accretion powered active nuclei.

Real physical differences exist in things like total luminosity (quasars vs seyferts) or in radio power (seyferts vs quasars/radio galaxies) or in host galaxies (seyferts vs radio galaxies).



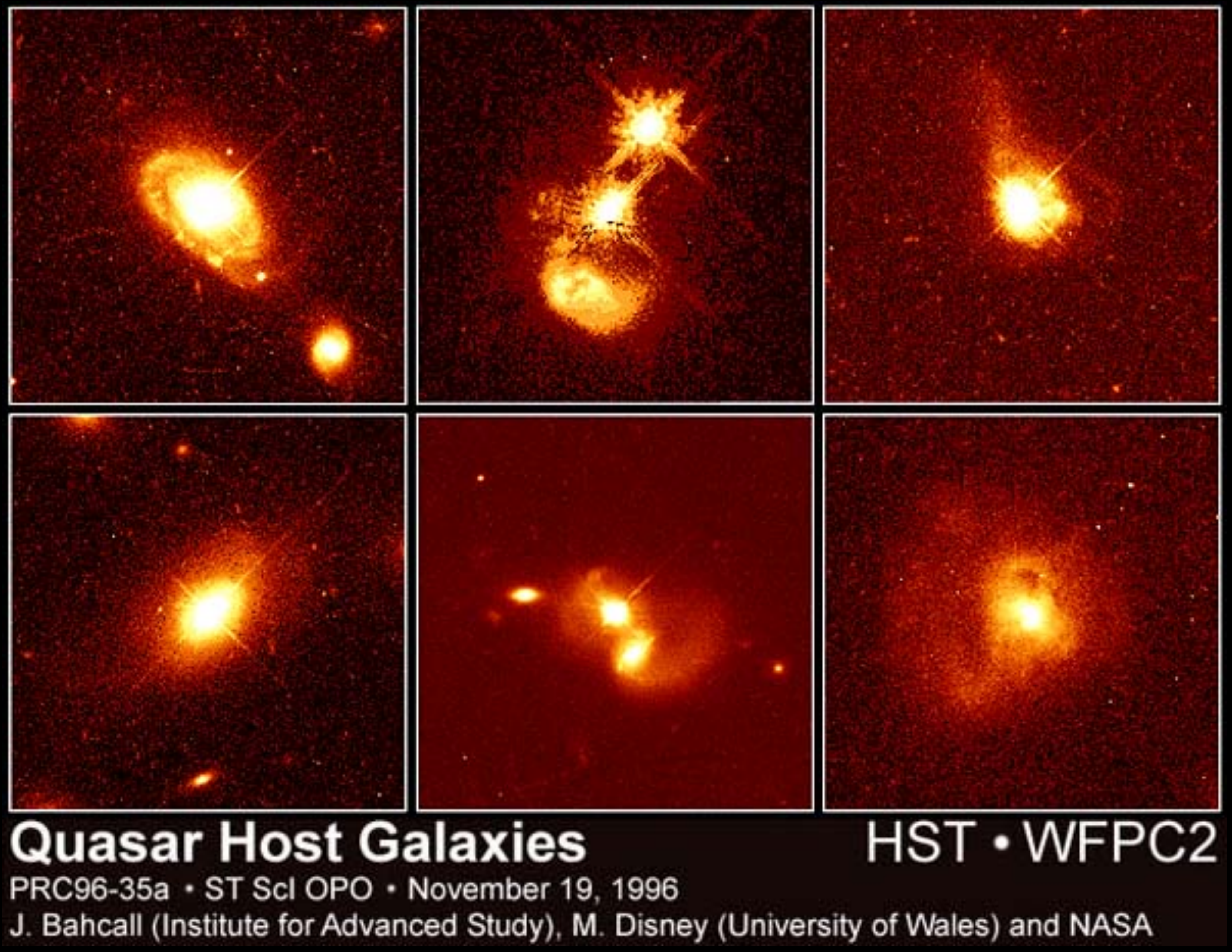
(Note that we are not seeing the accretion disk or the obscuring torus here; this is a disk of gas and dust much further out!)



What triggers this activity?

1. **What do the host galaxies of quasars look like?**

These disturbed hosts suggest that quasars form when galaxies are experiencing interactions or gravitational perturbations.



2. When were quasars most active?

We can look at the distribution in redshift of quasars. They occur much more frequently at high redshift, meaning they are very far away, so we are seeing them as they were long ago. *We are actually looking at the early universe*.

Quasars formed when the universe was young, probably coincident with the violence associated with galaxy formation. They quickly died out after that — only a very few remain.

Question: If quasars are associated with galaxy formation, what should we find in the centers of nearby galaxies?