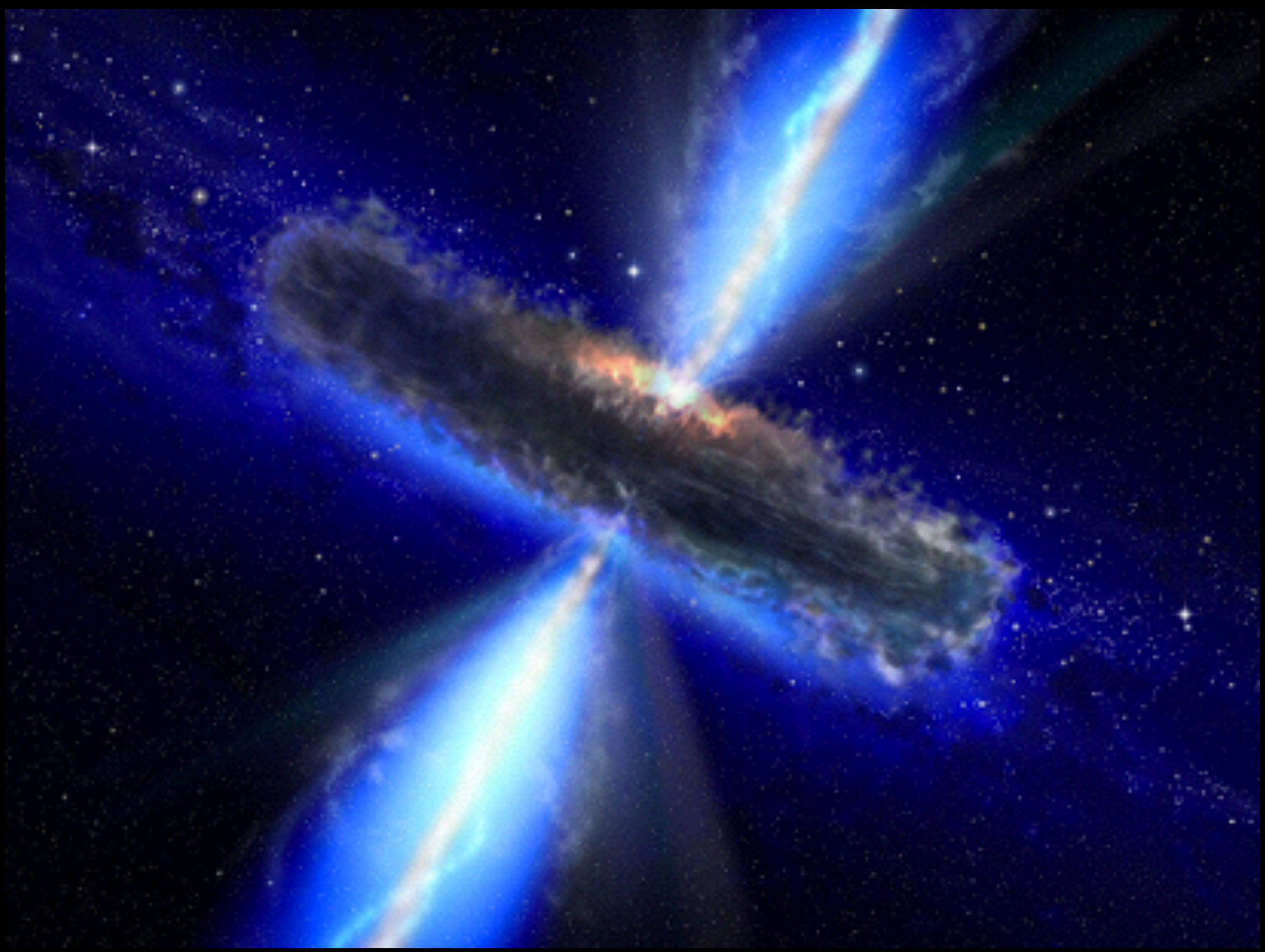
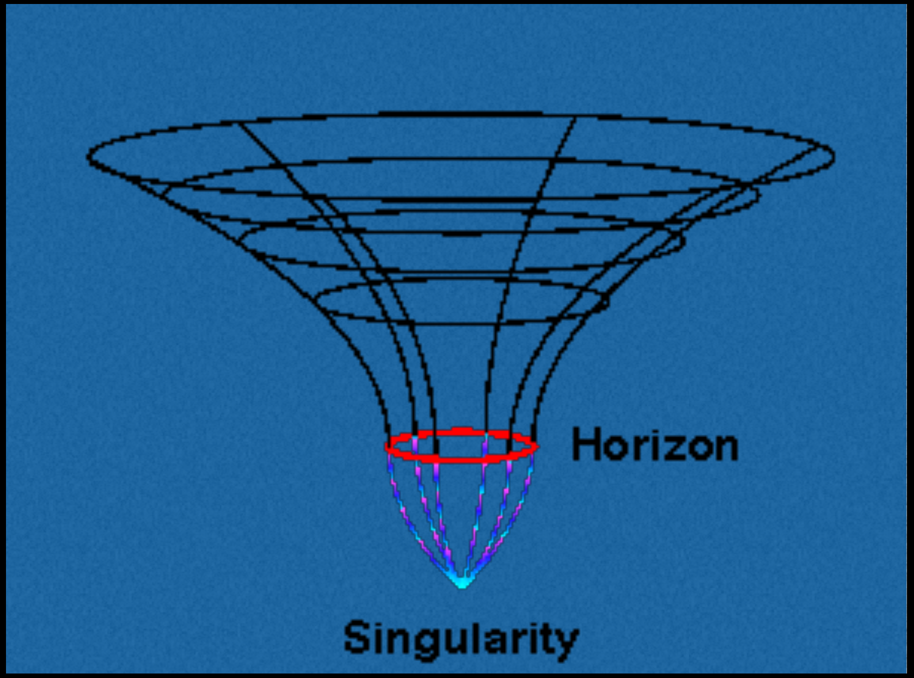
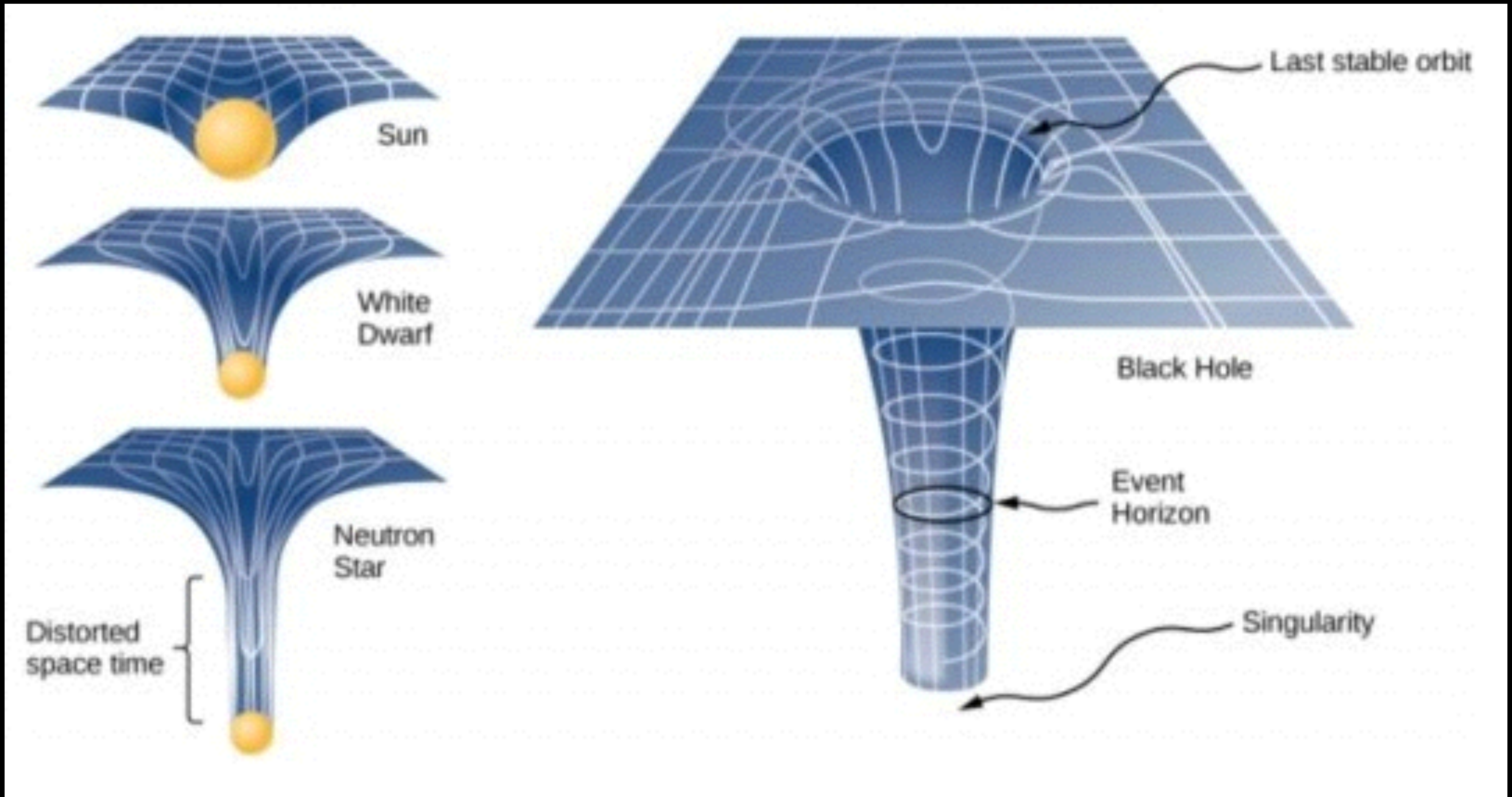
Active Galaxies and Black Holes
7/23/20
Day 9 Astronomy Summer School





Space time is curved by mass



The 'influence' anything has over gravity is <u>directly</u> related to the object's mass

Escape Velocity

What velocity would a chunk of satellite debris need to escape the Earth's gravity?

Initially, it has **Kinetic Energy** ($.5m_e v^2$), but it is also stuck in a **Potential** ($-GMm/r$).

At escape: it loses all its **Kinetic Energy** to overcome the **Potential**, but this leaves the debris with a final velocity of zero

$$(K + U_g)_i = (K + U_g)_f$$

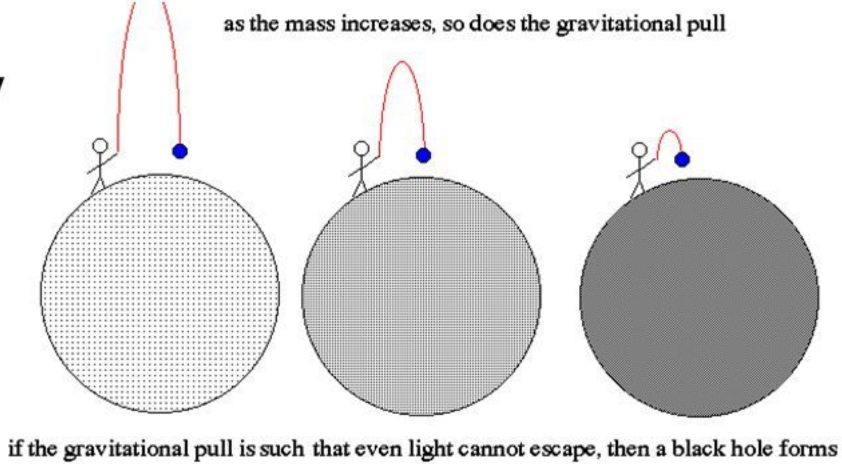
$K_f = 0$ because final velocity is zero, and $U_{gf} = 0$ because its final distance is infinity, so

$$\Rightarrow \frac{1}{2} m v_e^2 + \frac{-GMm}{r} = 0 + 0$$

$$\Rightarrow v_e = \sqrt{\frac{2GM}{r}} = \sqrt{\frac{2\mu}{r}}$$

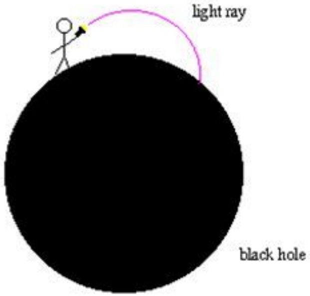
Black holes in Newtonian physics

First suggested by Laplace in 1796



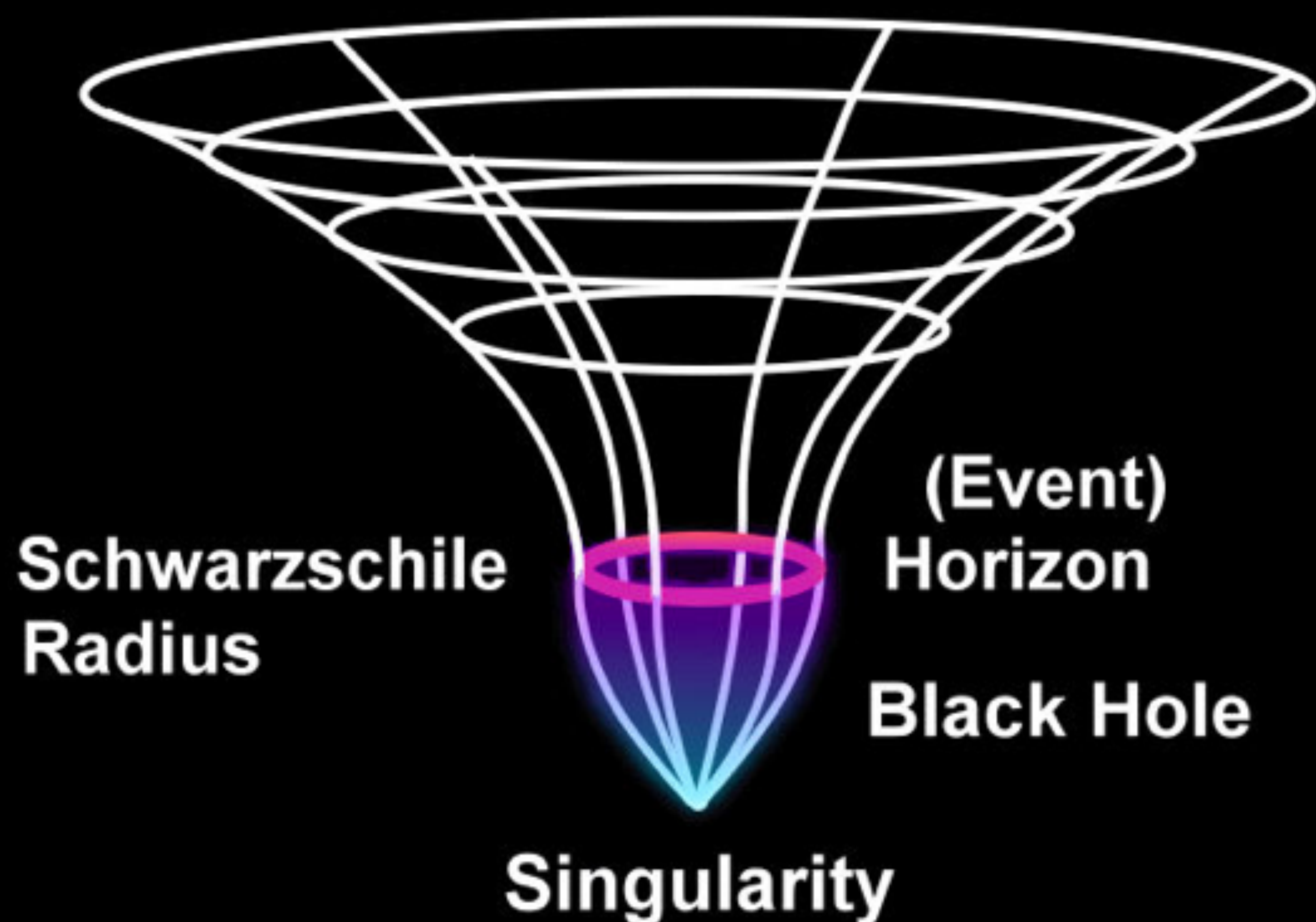
Critical (Schwarzschild) radius

$$V_{esc} = \sqrt{\frac{2GM}{R_s}} = c \Rightarrow R_s = \frac{2GM}{c^2}$$



The result is accidentally correct, but derivation is wrong and picture is wrong. We need general relativity!

Why is this radius so significant??



Black holes are **<u>defined</u>** by the puzzling fact that their escape velocity is the speed of light!

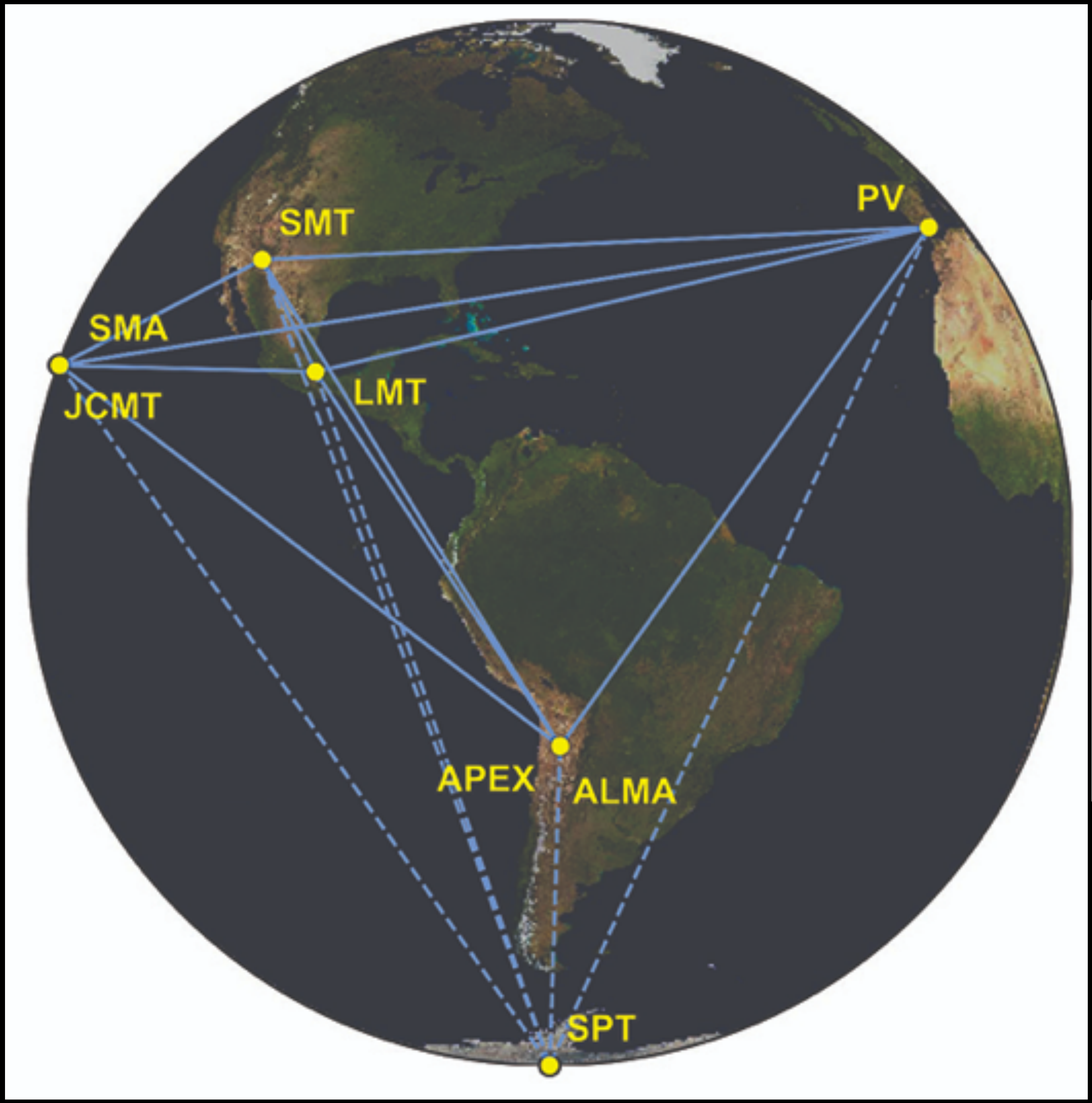
Zoom-in M87

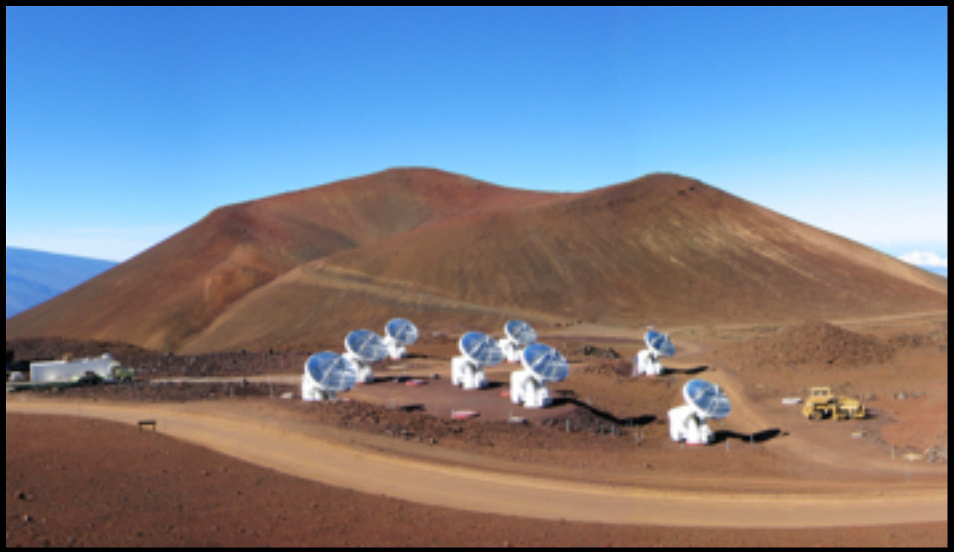
- https://www.youtube.com/watch?v=19to087TYv8 (0:54)

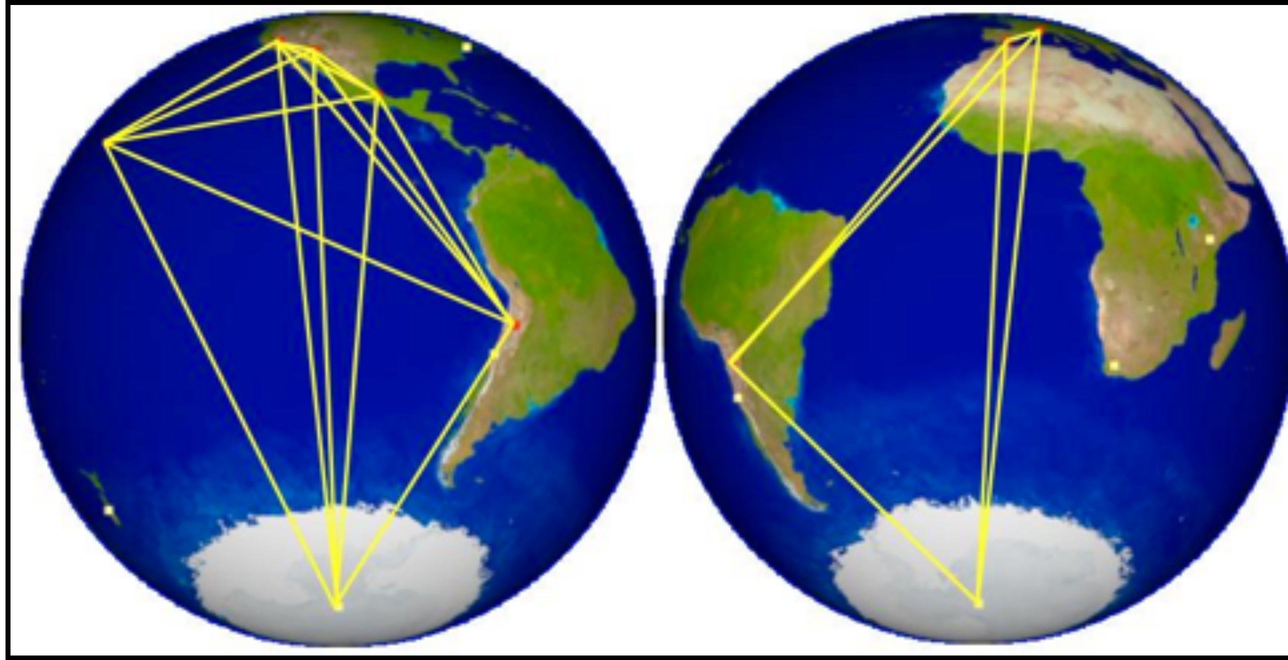
- How big is the black hole on the sky?
    - Around 10 micro-arcseconds

- How big does a telescope need to be to resolve it?
    - Around the size of the Earth

Event Horizon Telescope

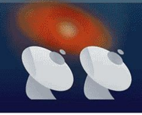






Interferometry

Interferometry is a powerful tool in astronomy that links together one or more pairs of radio antennas, even those thousands of kilometers apart, to create a new and vastly more powerful “virtual” telescope called an interferometer.



Interferometers harness the space between the antennas: the **larger the spacings, the higher the resolving power,** allowing it to see finer and finer details, like the zoom lens of a camera.

How Is This Done?

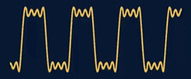
Astronomers reconstruct images of an object in space using interferometers, telescopes that observe the Fourier transform of an object’s brightness pattern on the sky.

Inteference Pattern

Wave patterns from an interferometer are similar to the wave patterns created when light passes through a pair of slits. In radio astronomy, the antenna pair takes the place of the two slits, but the resulting patterns are similar.

Fourier Transform

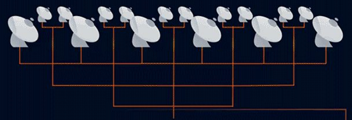
The Fourier transform is a mathematical tool that deconstructs any signal into a sum of sine waves.

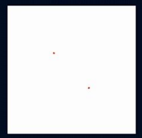


A sine wave in 2 dimentions looks like a set of stripes

More Antennas = Clearer Picture

Turning this pattern into an image takes many hours of observations. Like a time-lapse exposure, this slowly builds up an image of even a very dim source. It also allows Earth’s rotation to, in effect, fill in the empty spaces in the array to produce a more complete picture.

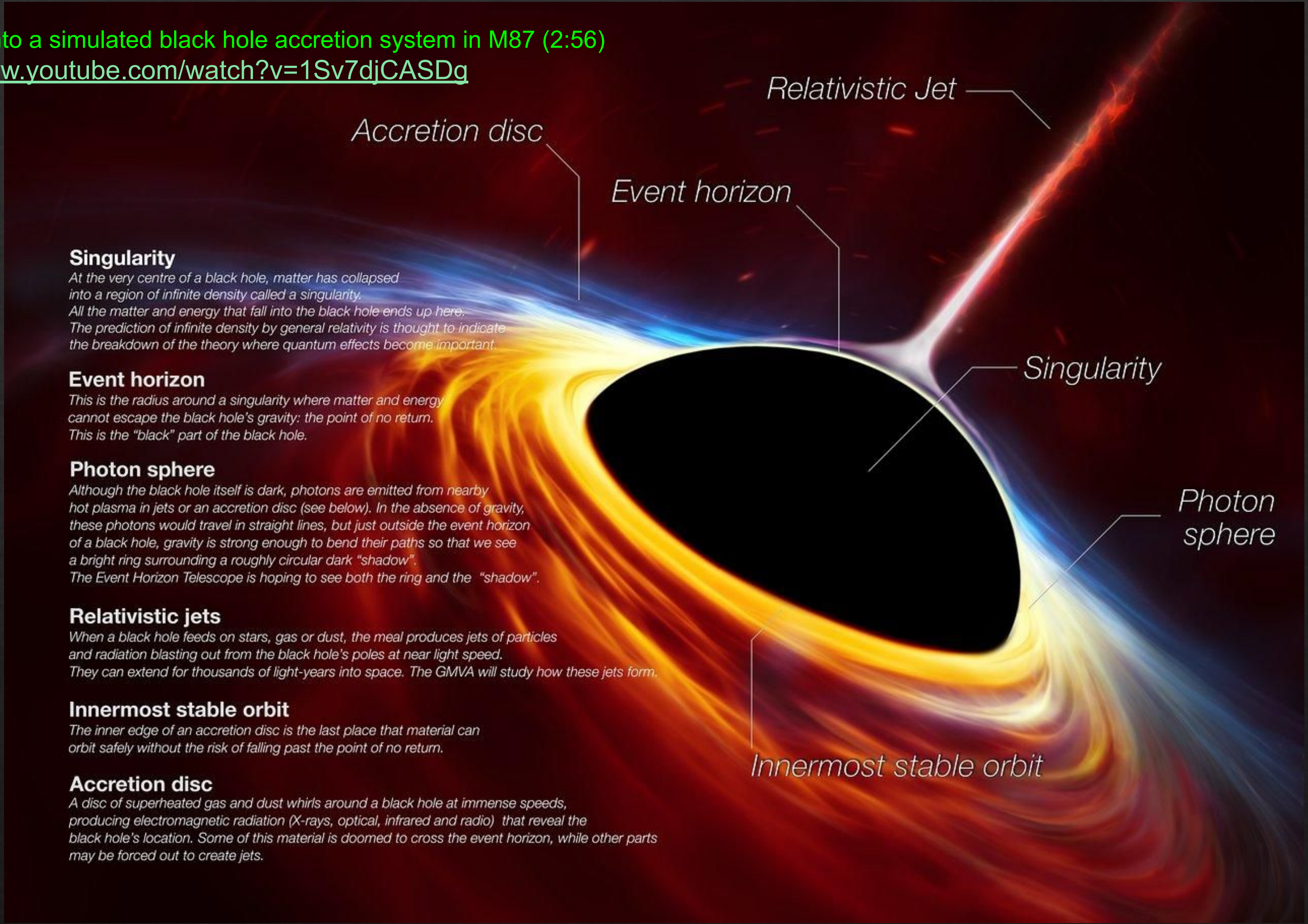




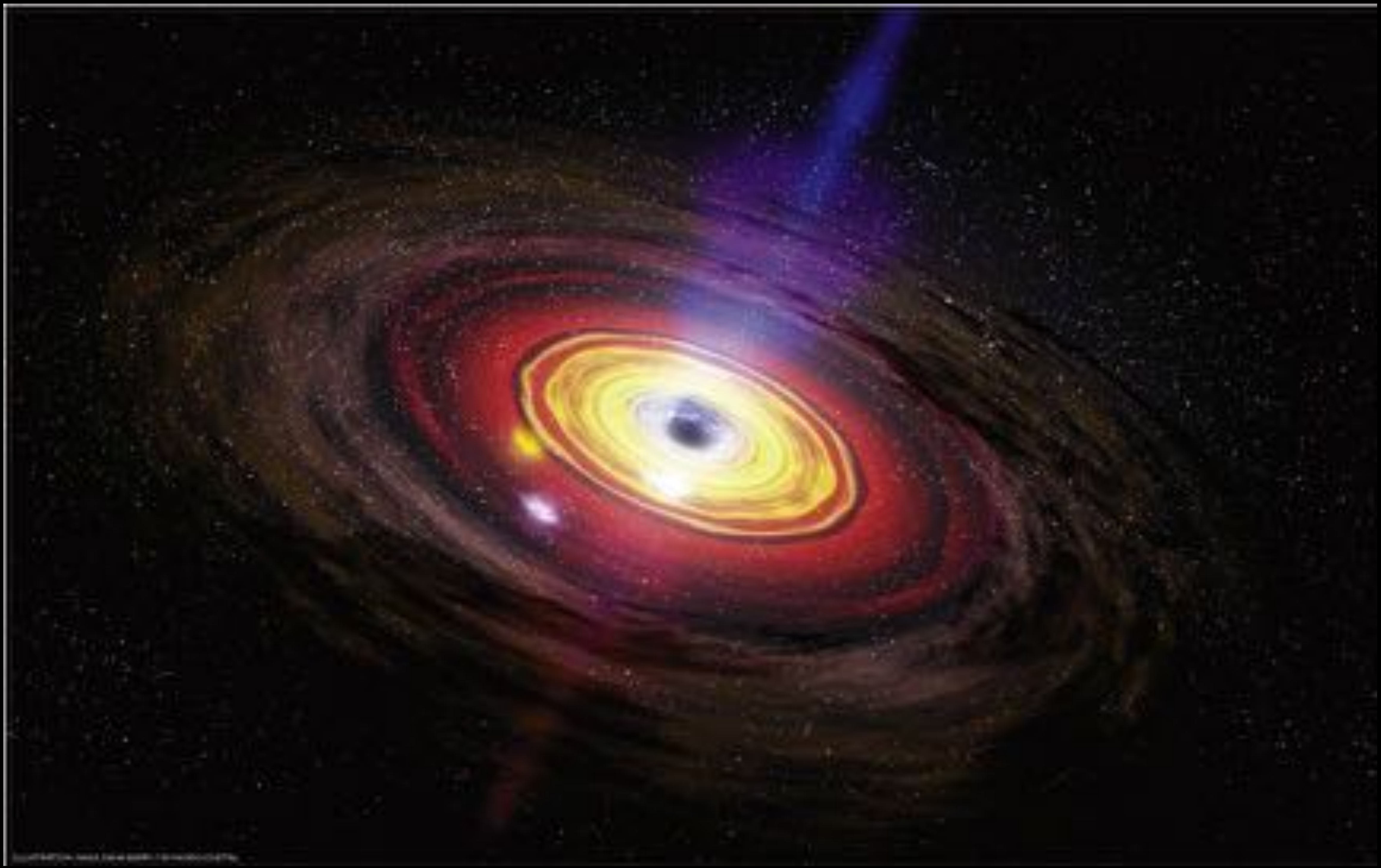
2 Antennas

The signals received at each antenna must be matched wave for wave, even for antennas that are half a world away. Atomic clocks at each site allow for their observations to be mathematically combined using a specialized supercomputer called a **correlator.**

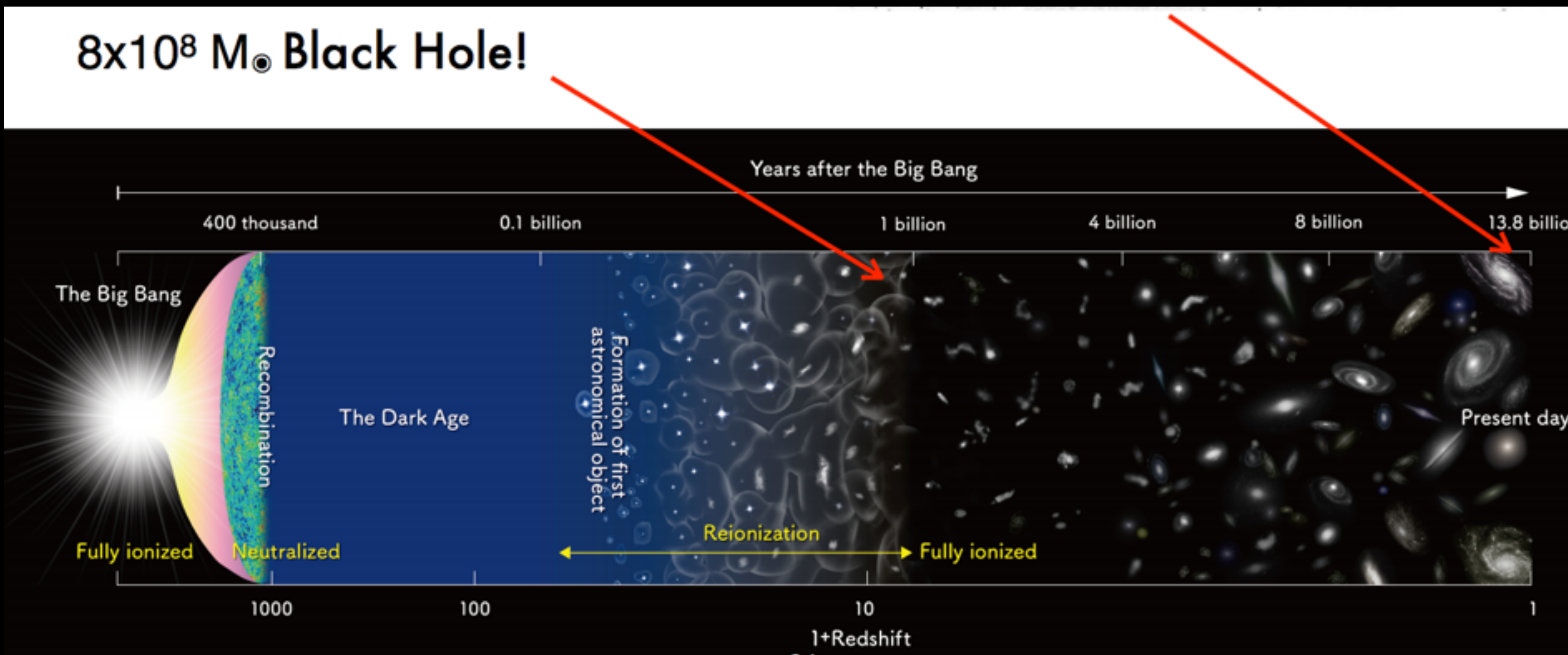
Zooming into a simulated black hole accretion system in M87 (2:56)
https://www.youtube.com/watch?v=1Sv7djCASDg



Active Galaxies



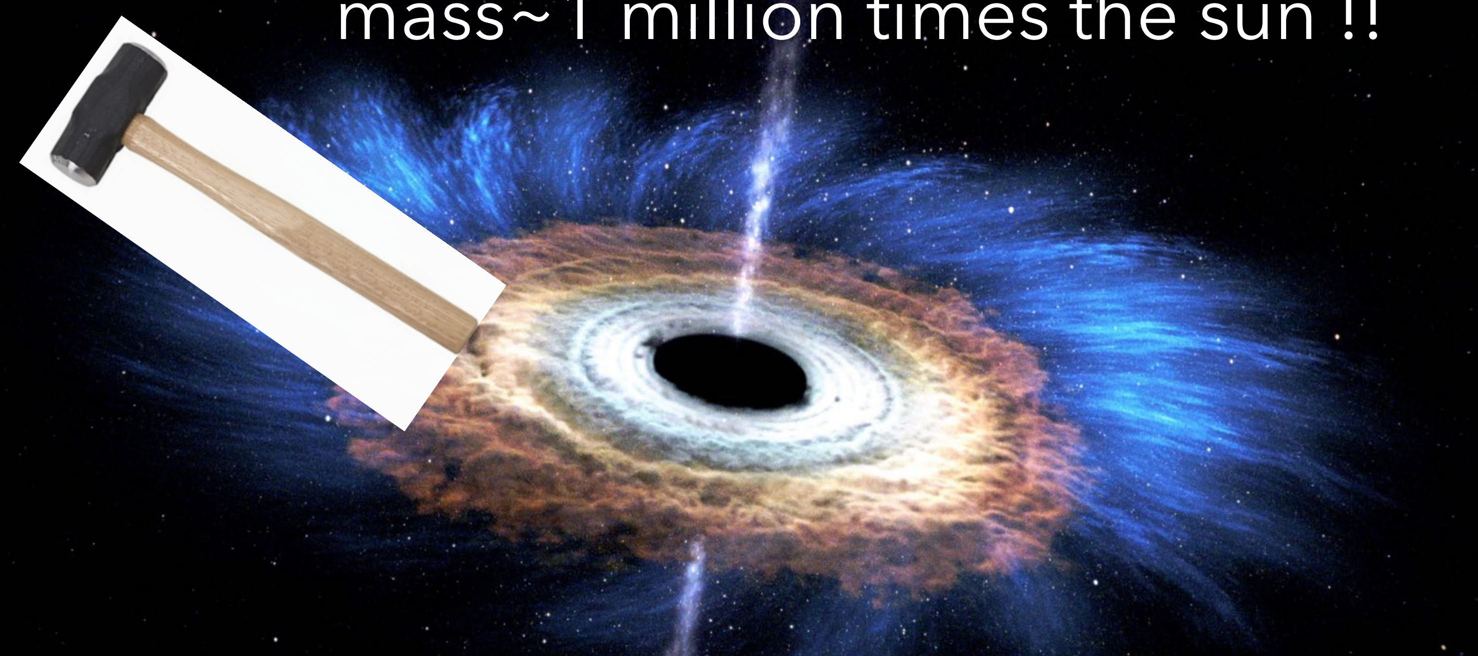
Zoomed out big picture: Where are the black holes?



Active Galaxies

- Most massive galaxies have a supermassive black hole at their center: What are these black holes 'doing'?

mass~1 million times the sun !!

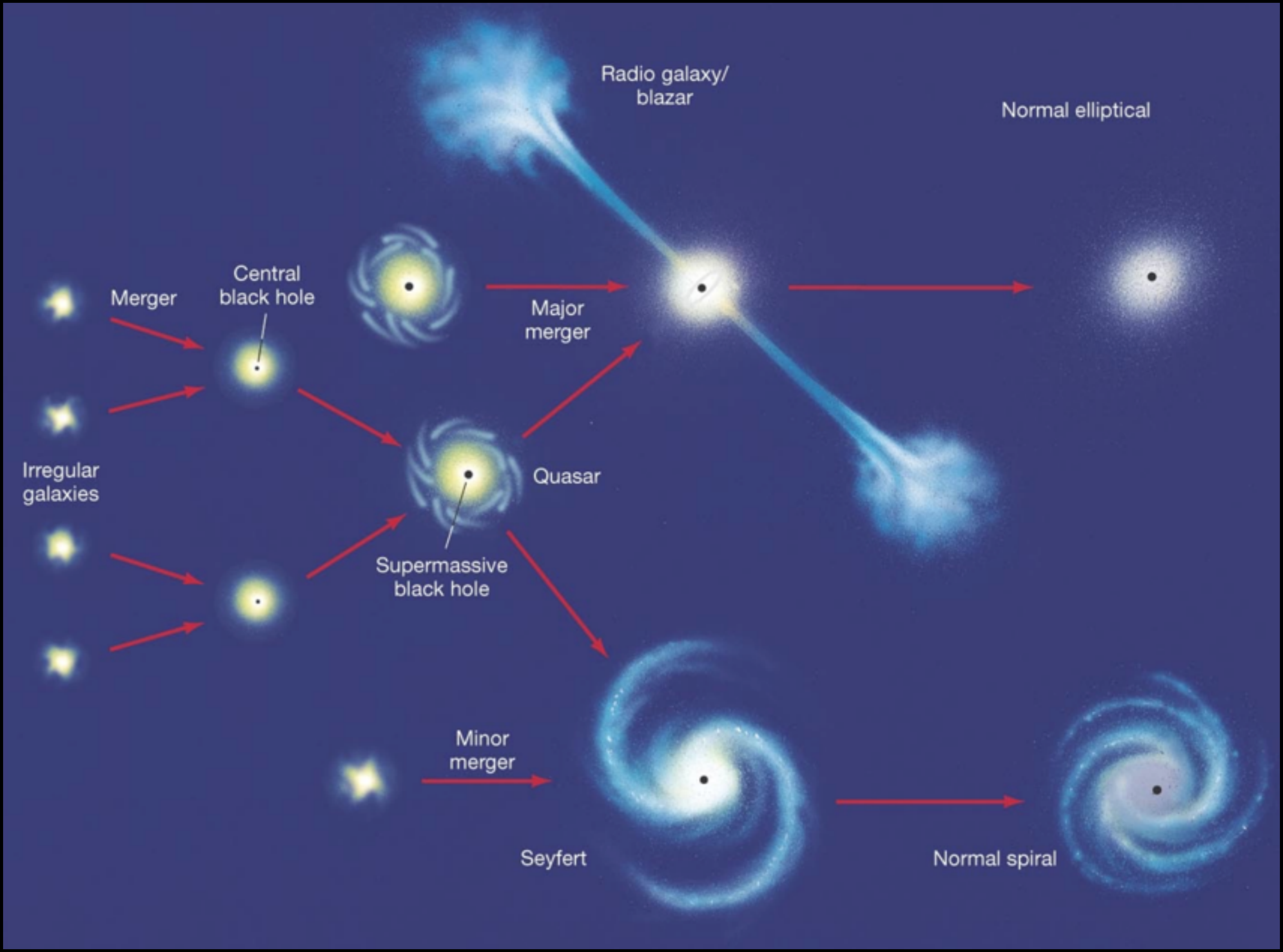


<u>"Nuclear Activity"</u>: When a galaxy's geometric center aka few pc (~200-500,000 AU) exhibits local properties not found elsewhere in the galaxy

This phenomena likely related to:

1. Central black hole
2. Bottom of the potential well (Gravity near the center)

Formation/evolution theories for active galaxies



Brief history

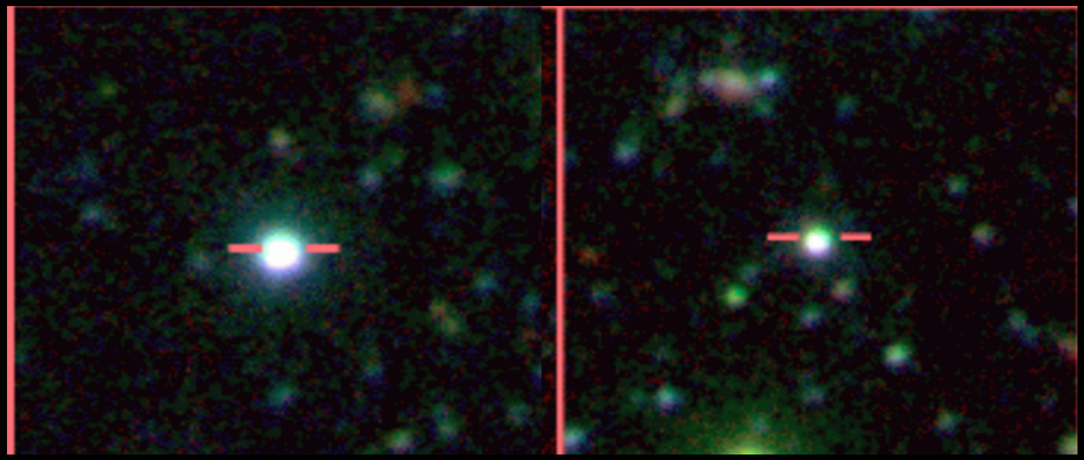
- In 1943, Carl Seyfert identifies class of spiral galaxies with unusually bright central regions

Seyfert Galaxy NGC 7742

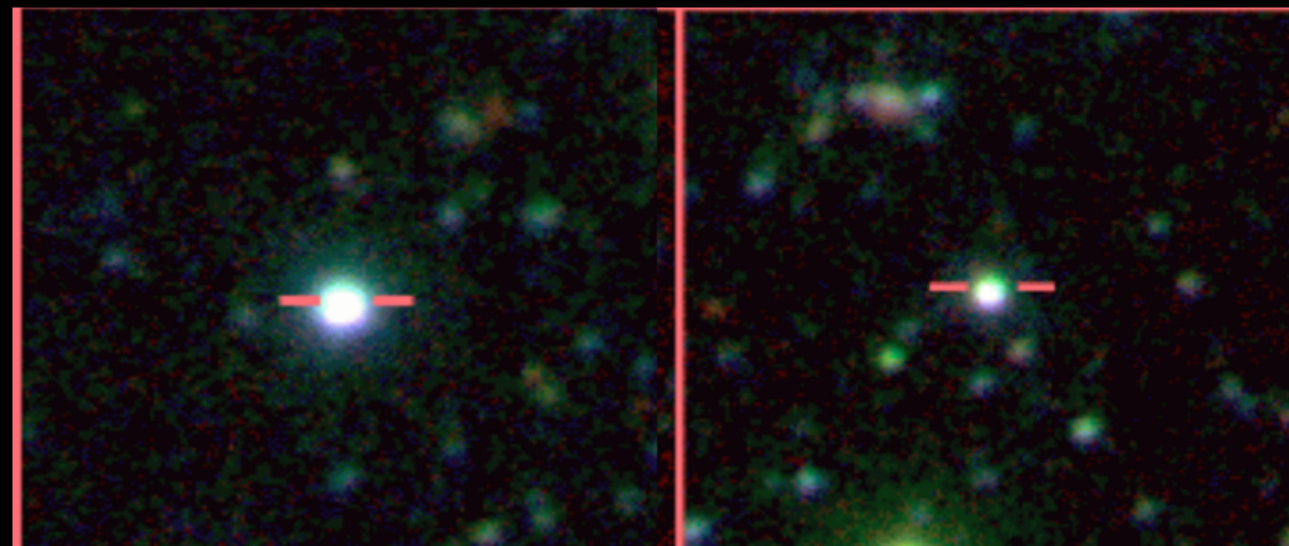
- Central regions appeared to be stellar, but had spectra dominated by high-excitation emission lines (AKA: Something very energetic going on here!)

- In 1950s, with the development of radio telescopes, some objects in sky were found to emit strongly in radio
- Positions of radio sources found to coincide with objects that looked like stars….

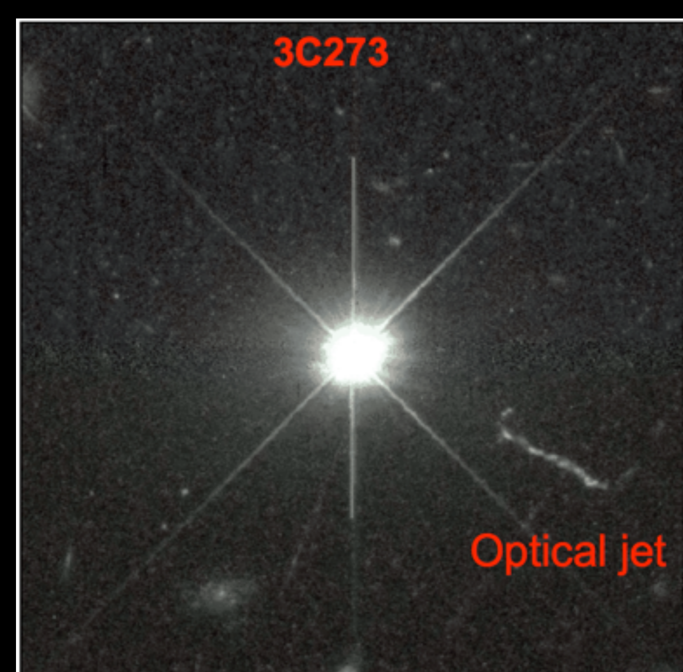
- "Radio stars"… but no known stellar mechanism could produce SO much radio emission



Brief history

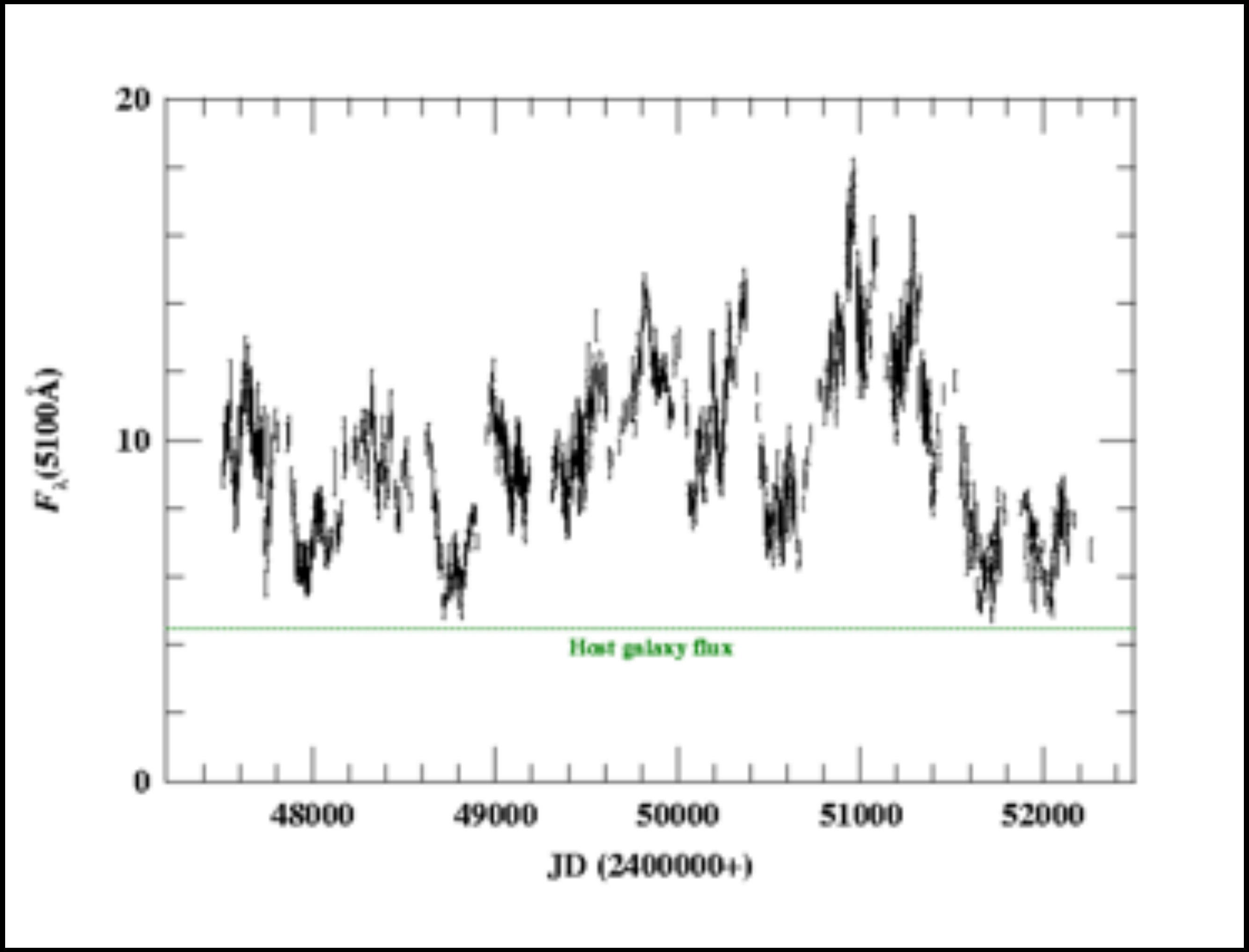


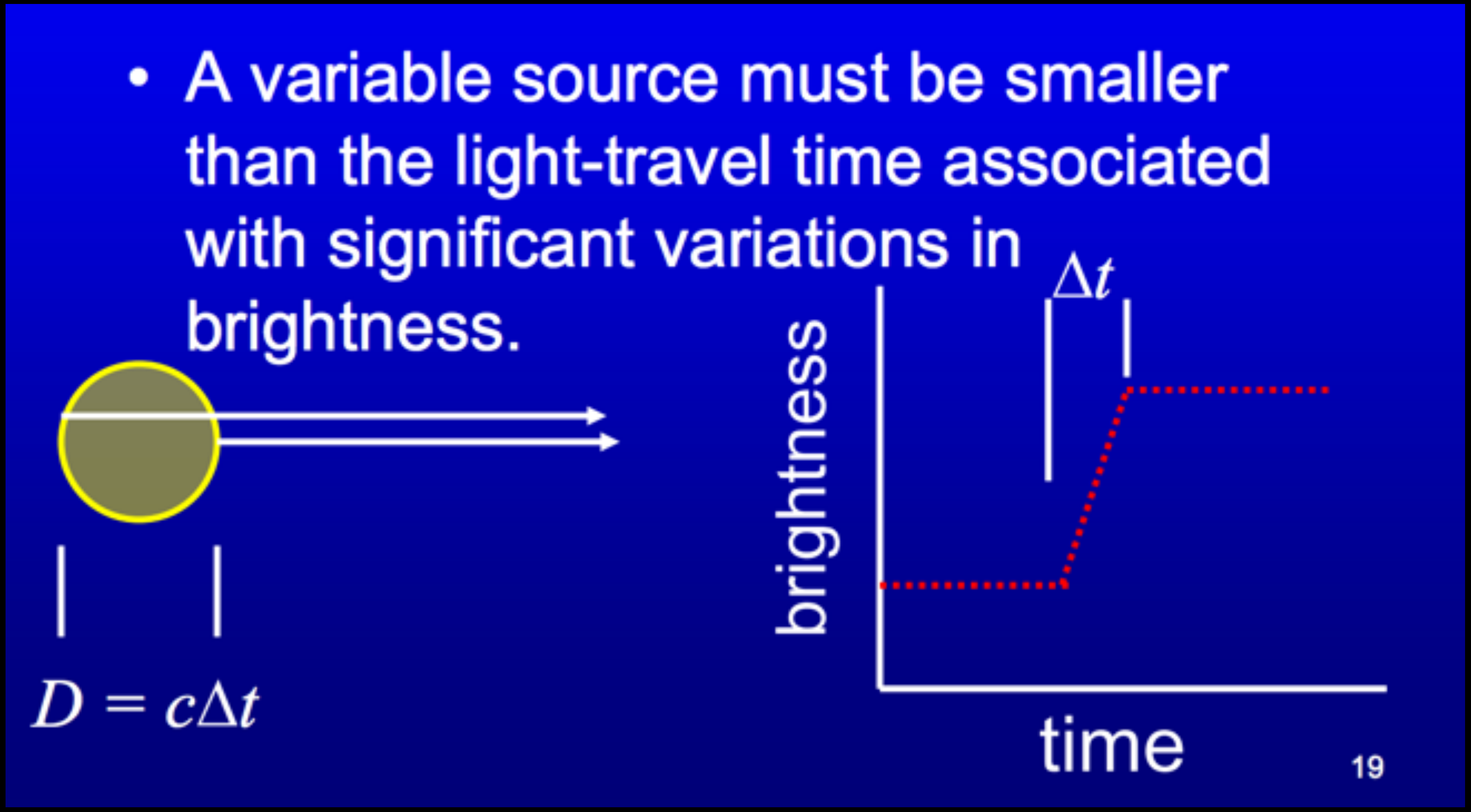
- In 1960s: Realized spectra showed broad emission lines and objects were much further than nearby stars–> ~100x more luminous than galaxies like the Milky Way
- Soon others were discovered even further away (up to redshift 6!)



Variability

The plot thickens when we discover the brightness of quasars is variable; i.e. we see them get brighter and dimmer over a span of **days**



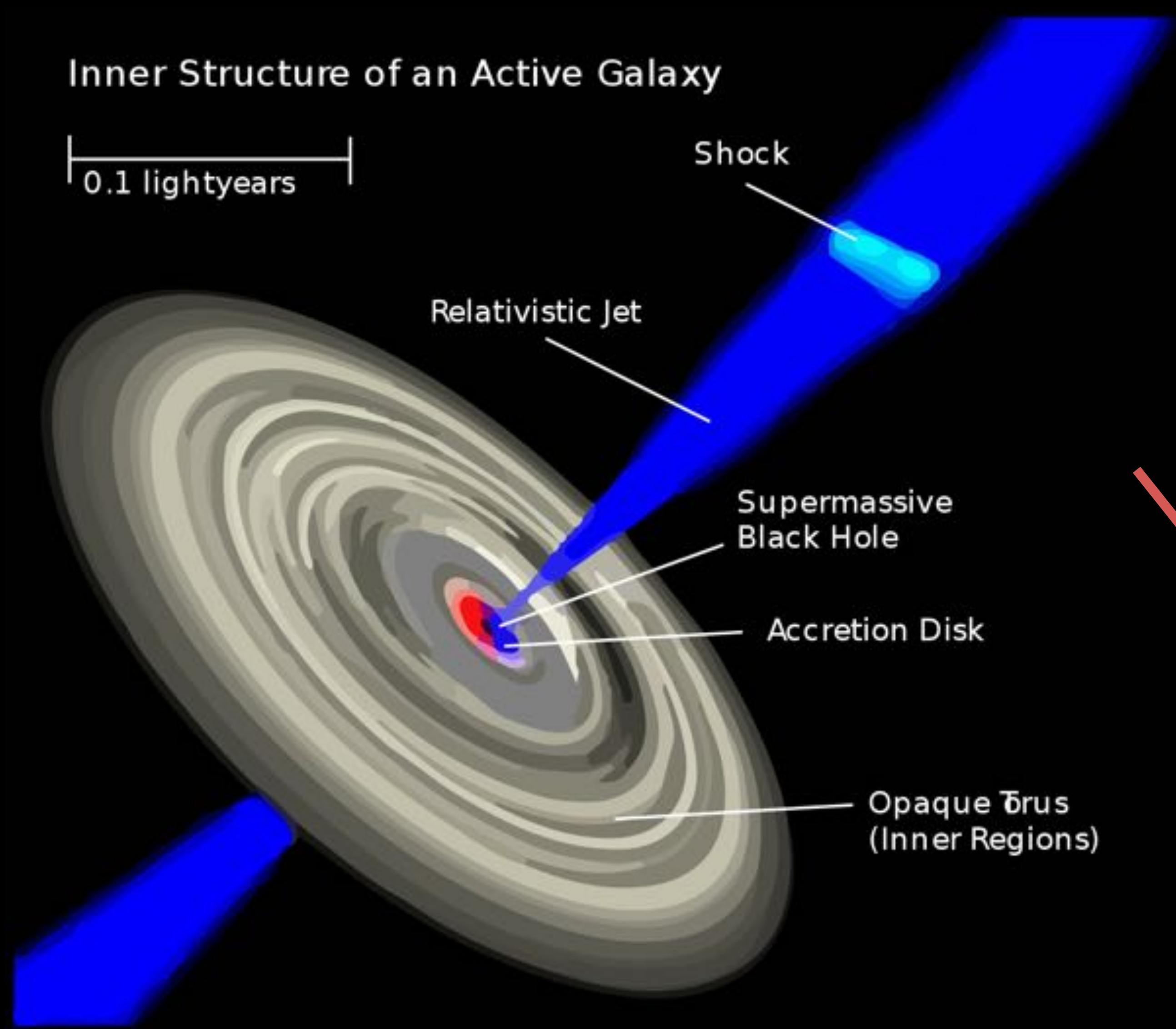


If variability is ~days, size of emitting object must be only a few light-days (size of a couple of our solar systems put together!)

For context:

This is like the volume of something the size of our solar system emitting the power of a trillion (10^{12}) stars!

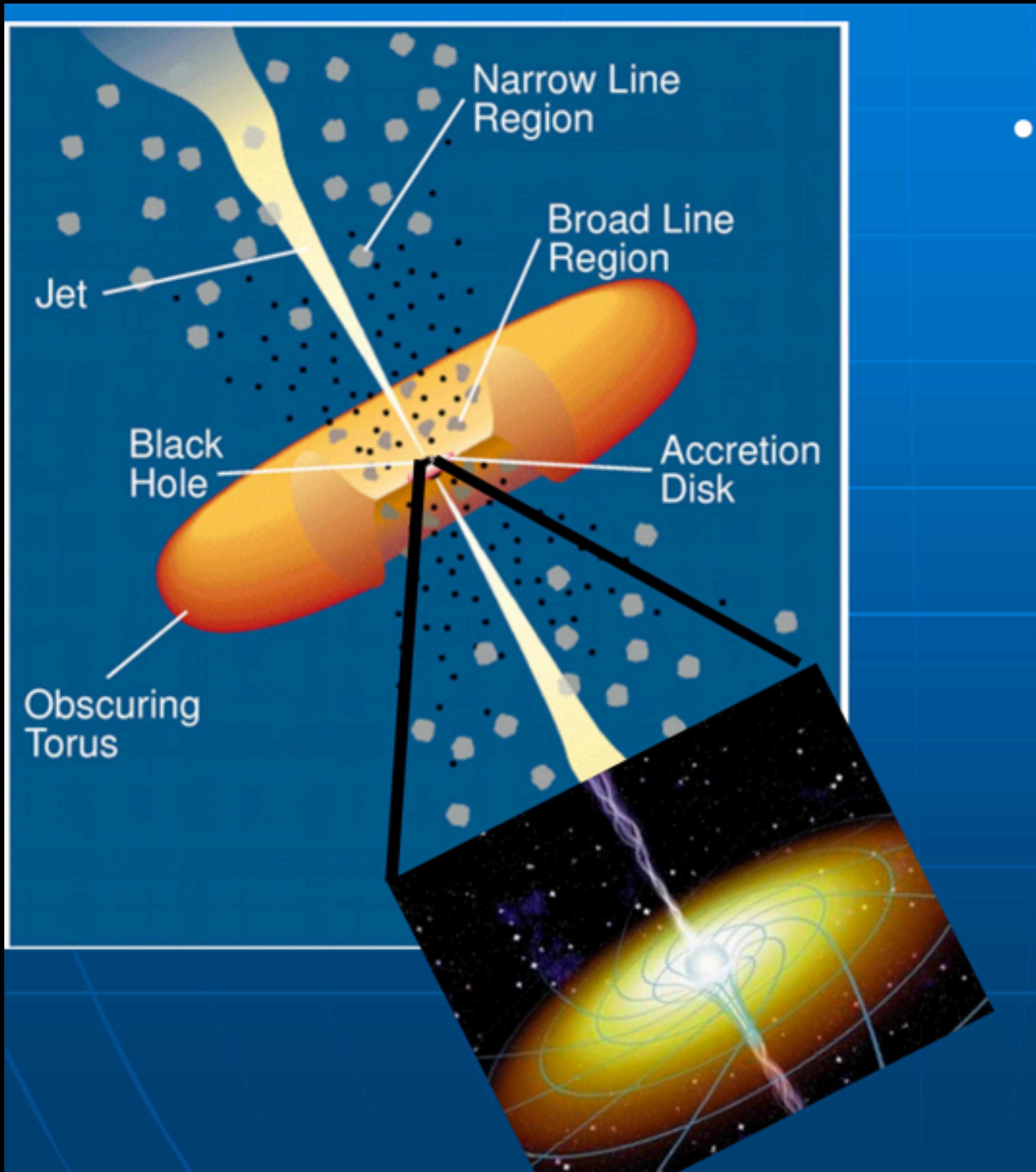
Closer look



0.1 ly= tiny

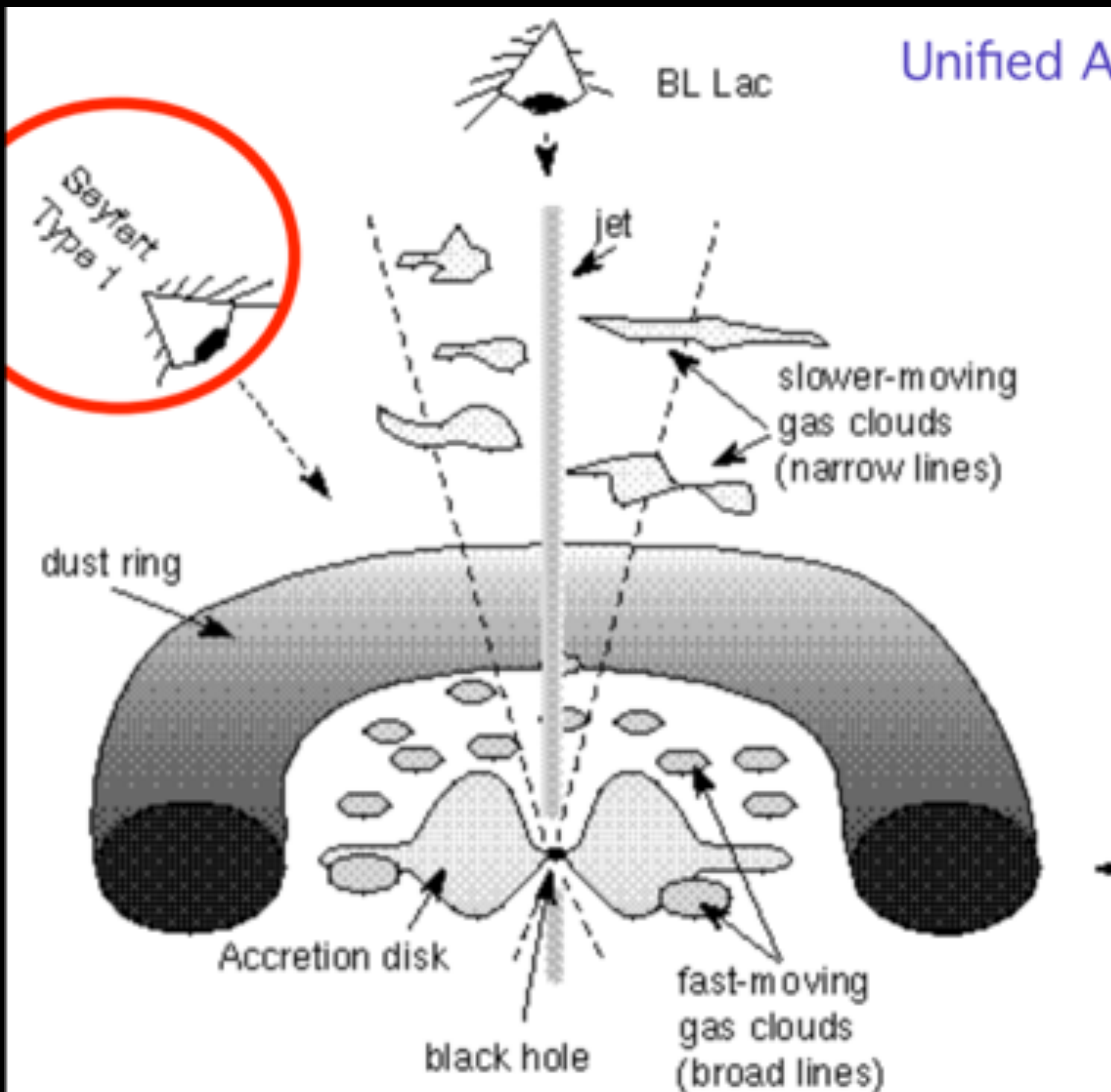
VERY tiny portion of the entire galaxy!

Closer look



- AGN are powered by accretion of matter onto supermassive black holes
- **Potential energy** converts to **kinetic energy** as material moves closer to BH. Some energy can be converted into thermal energy and radiated away
- Disk will also heat material to high temperatures due to friction and form from angular momentum

To fall in or not to fall in?



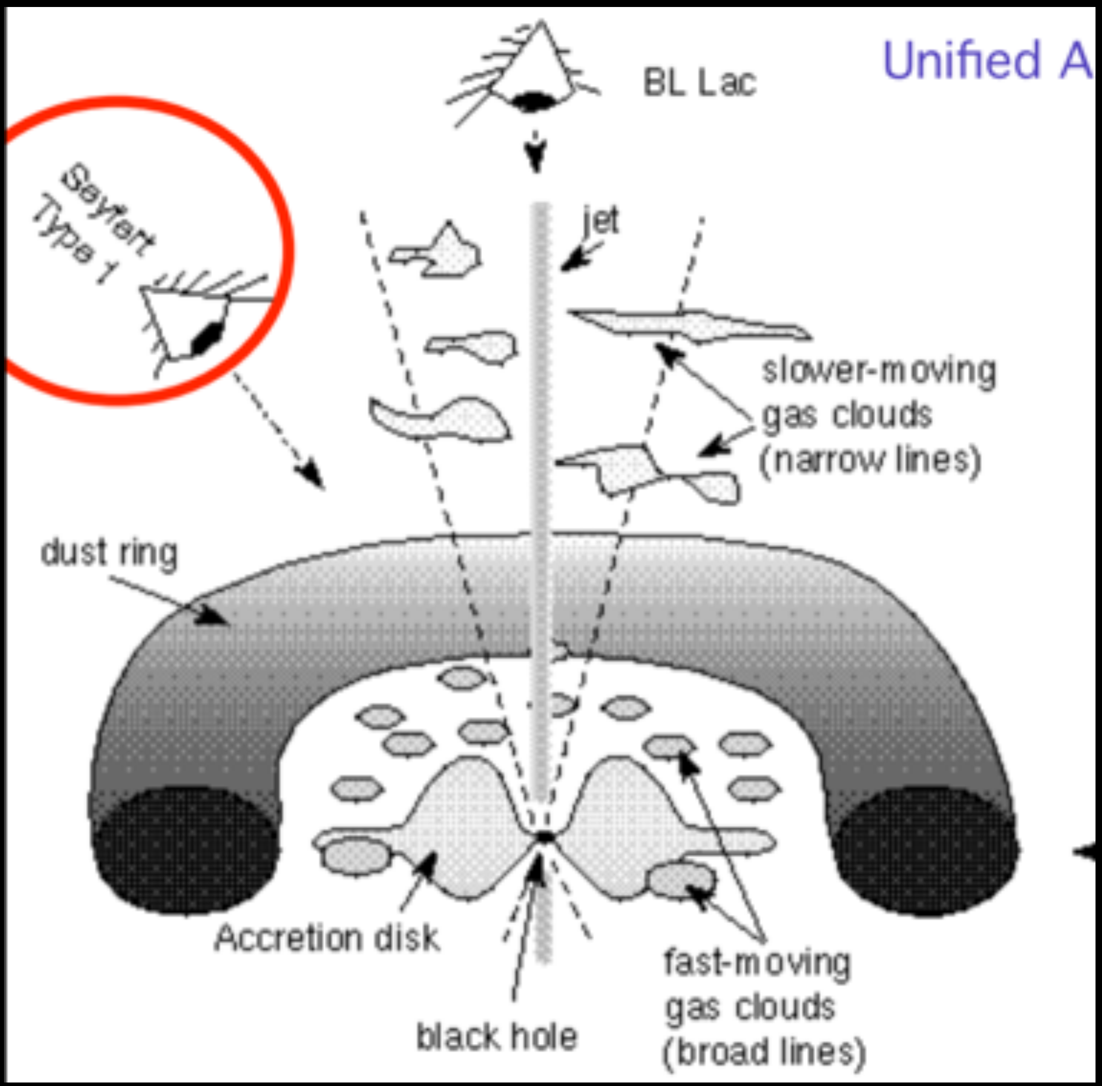
Eddington Luminosity:

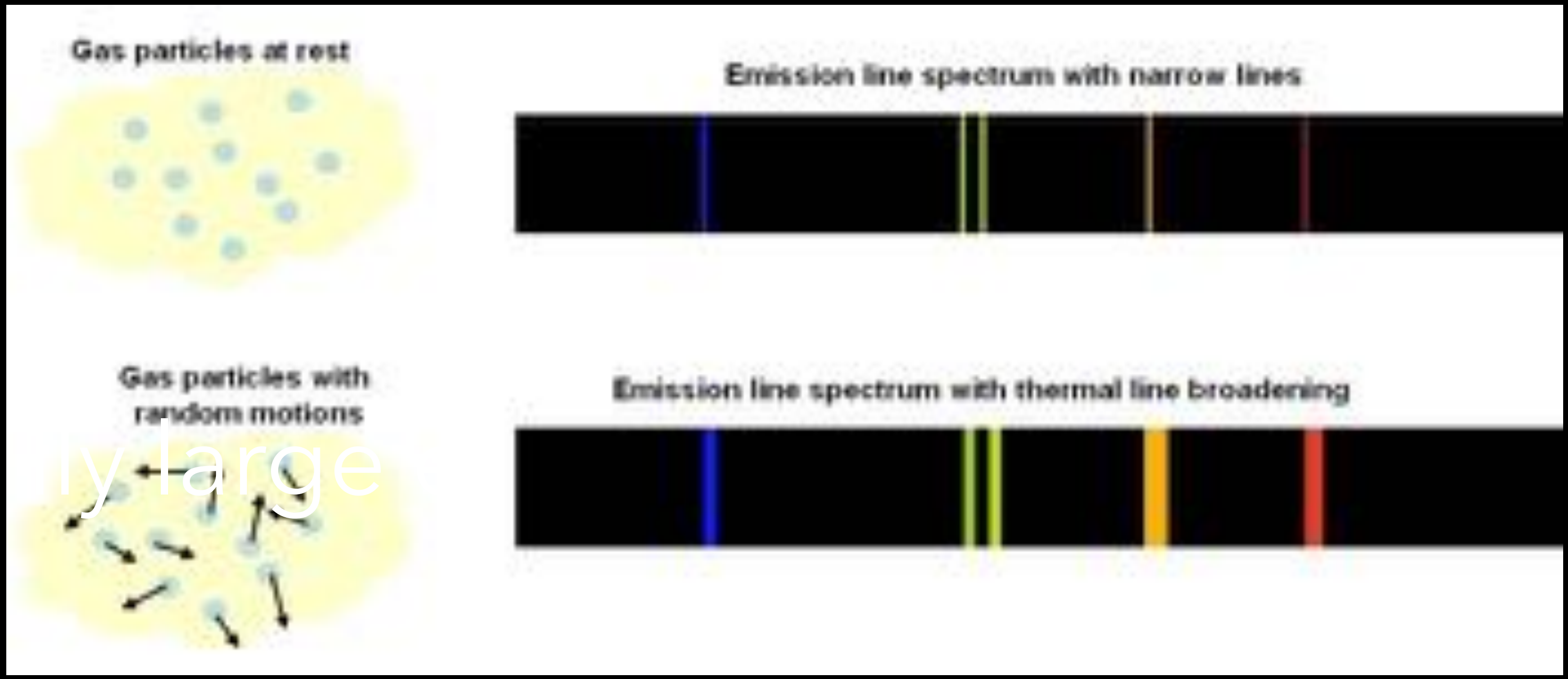
Critical luminosity for balance of **radiation** and **gravity**

For accretion to occur AT ALL: L < Ledd

Typical accretion rate of an AGN:
1 moon per second !!

Emission lines: An important signature!

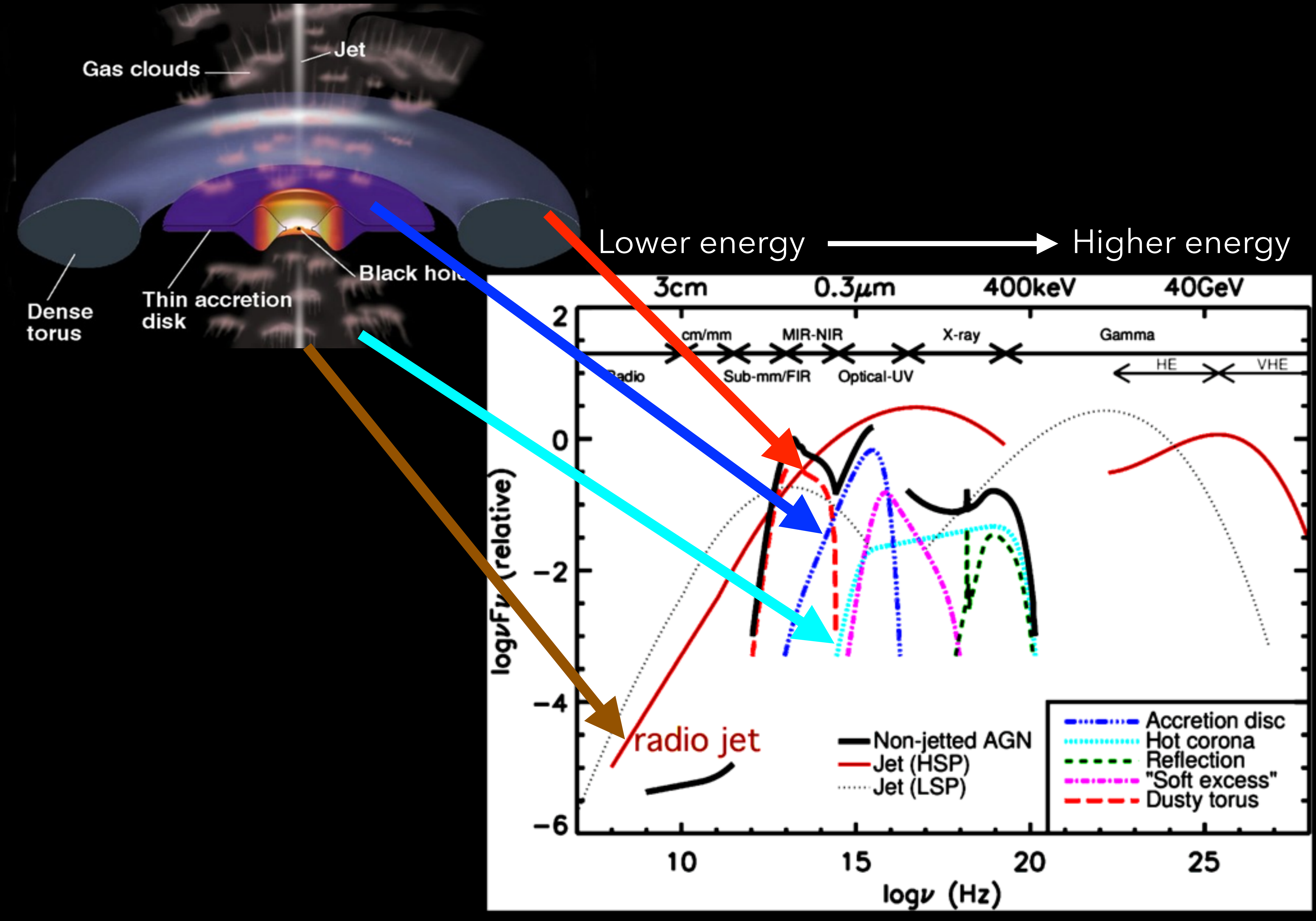




AGN sites produce a lot of energy -> gas is moving rapidly-> creating characteristically large emission lines

Clouds moving at 1,000-5,000 km/s

How do we see them…? At many wavelengths!



Thinking Question ….

We've shown AGN can emit at many parts of the electromagnetic spectrum… Does this make it easier or harder to identify them?

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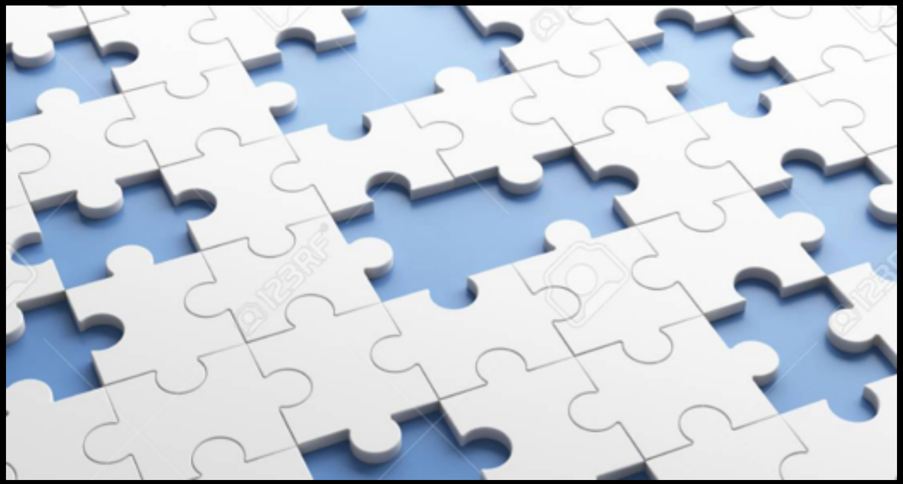
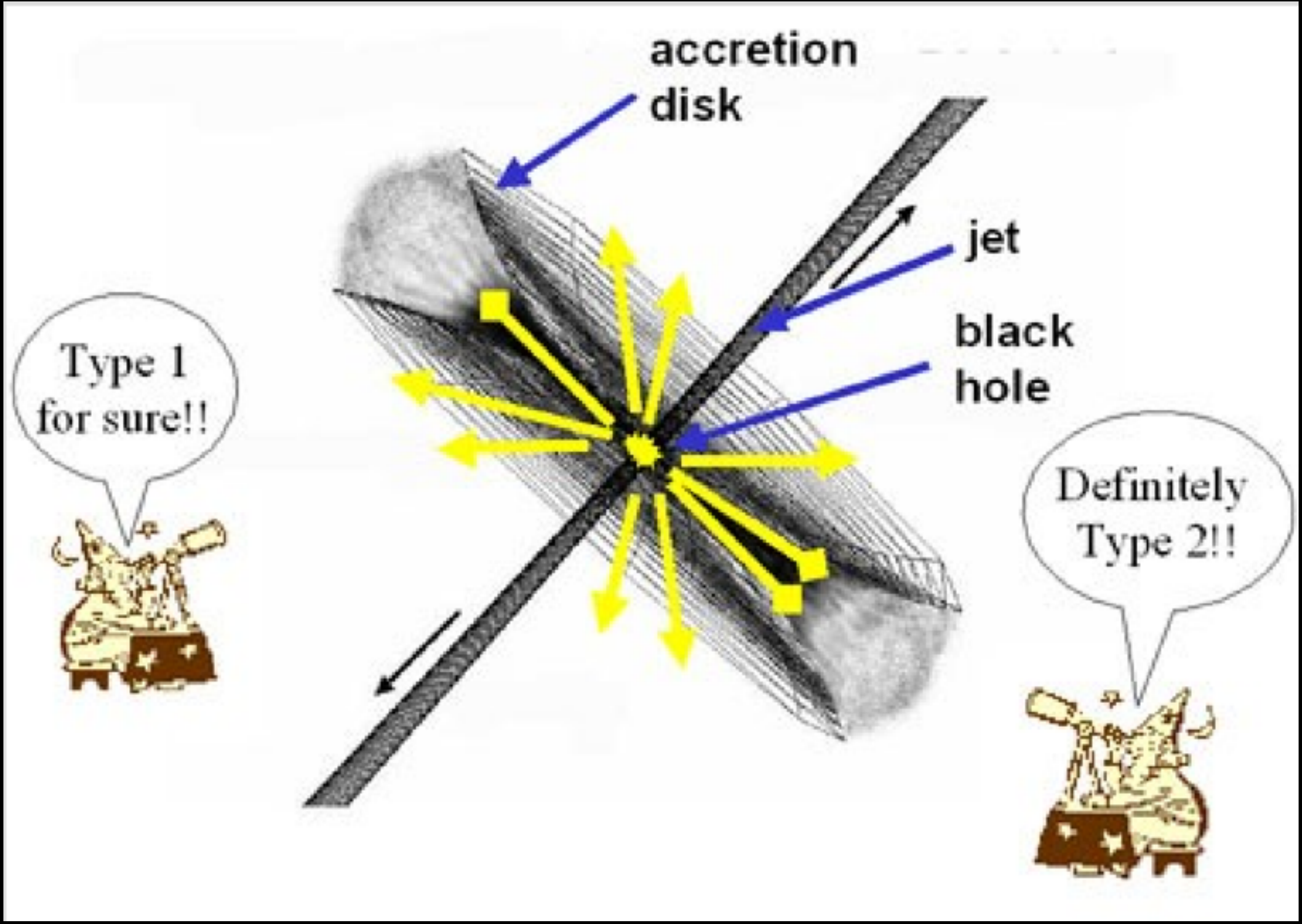
A double-edge sword: The fact that there are quite a few sure-fire signatures of AGN is helpful to identify them. But, because some show one or more of these signs, there isn't ONE way to catch them ALL, so we have bits and pieces of the whole story.



Unification model: Can 'Type' depend on the angle you are looking from?



Classifying Active Galaxies

1. Seyferts
2. Radio AGN
3. Quasars

Lower luminosity AGN

Higher luminosity AGN

Seyfert Galaxies

- Spiral galaxies with high surface brightness cores
- Spectrum of central core will show strong, broad emission lines

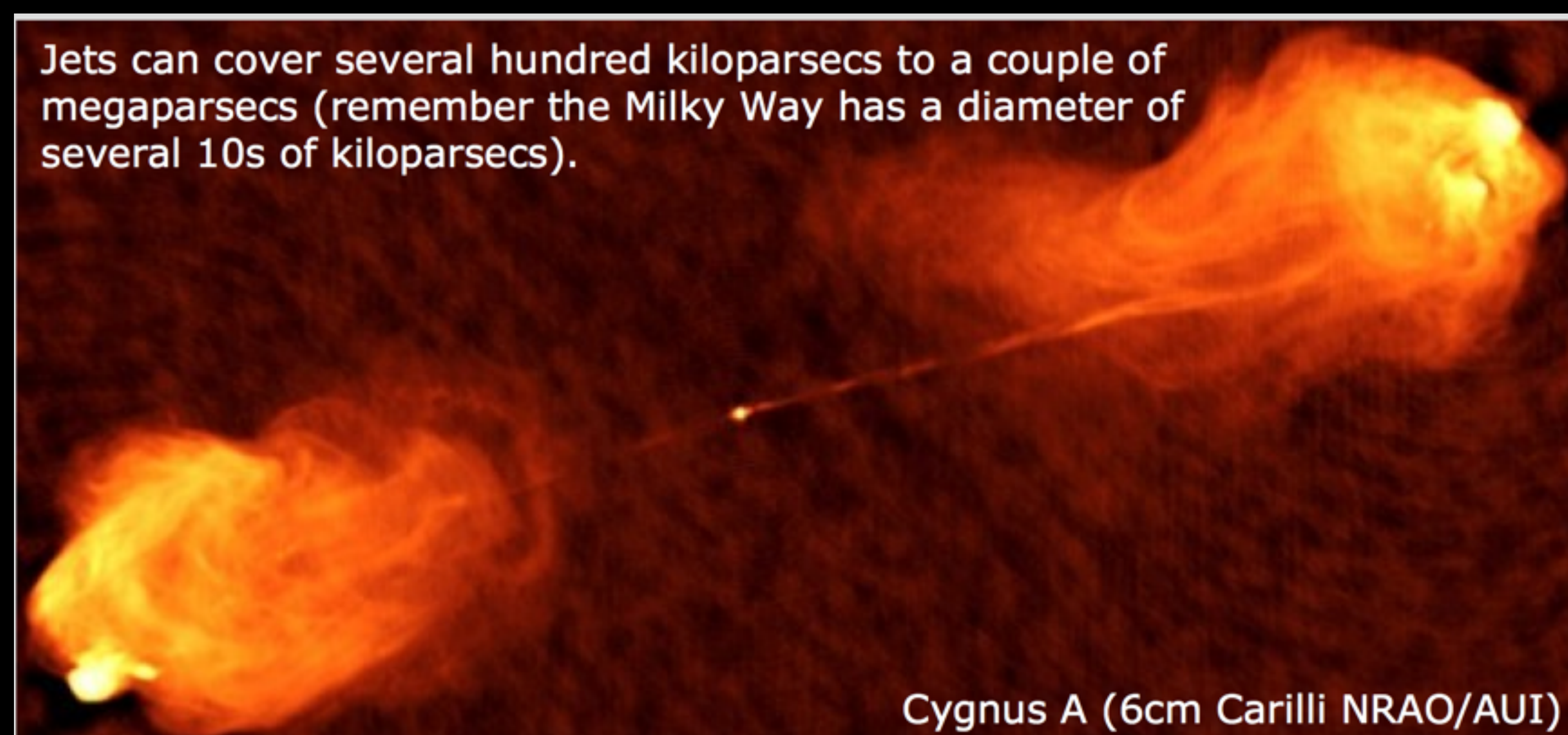
- Some have broad emission lines, some have narrow, we think based on the angle we are viewing them.

Radio AGN

Radio emission in jet-like form from lobes

Compared to other kinds of AGN, AGN that emit in radio are actually not accreting material as rapidly/efficiently

The M87 Jet

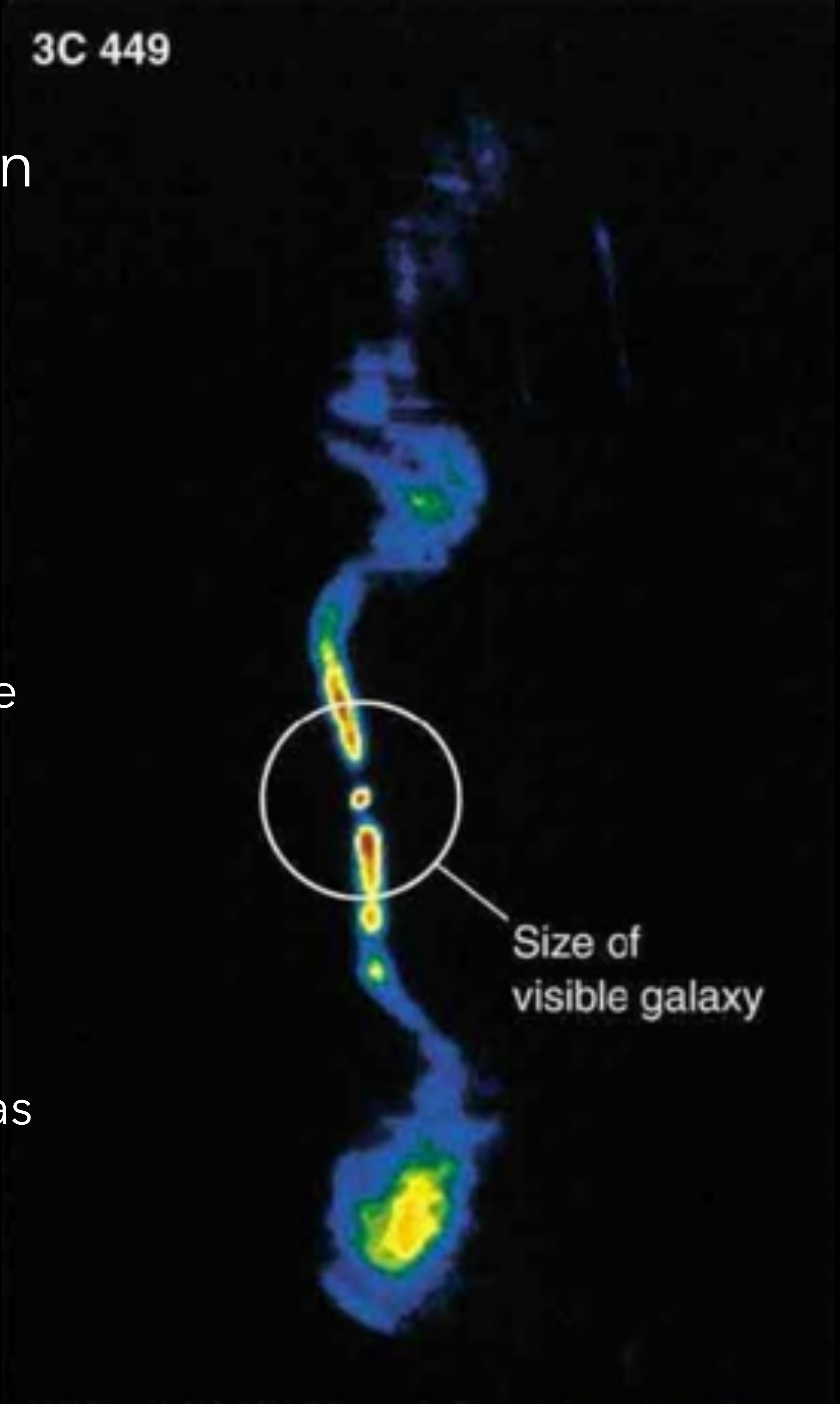


Radio AGN: Extended emission

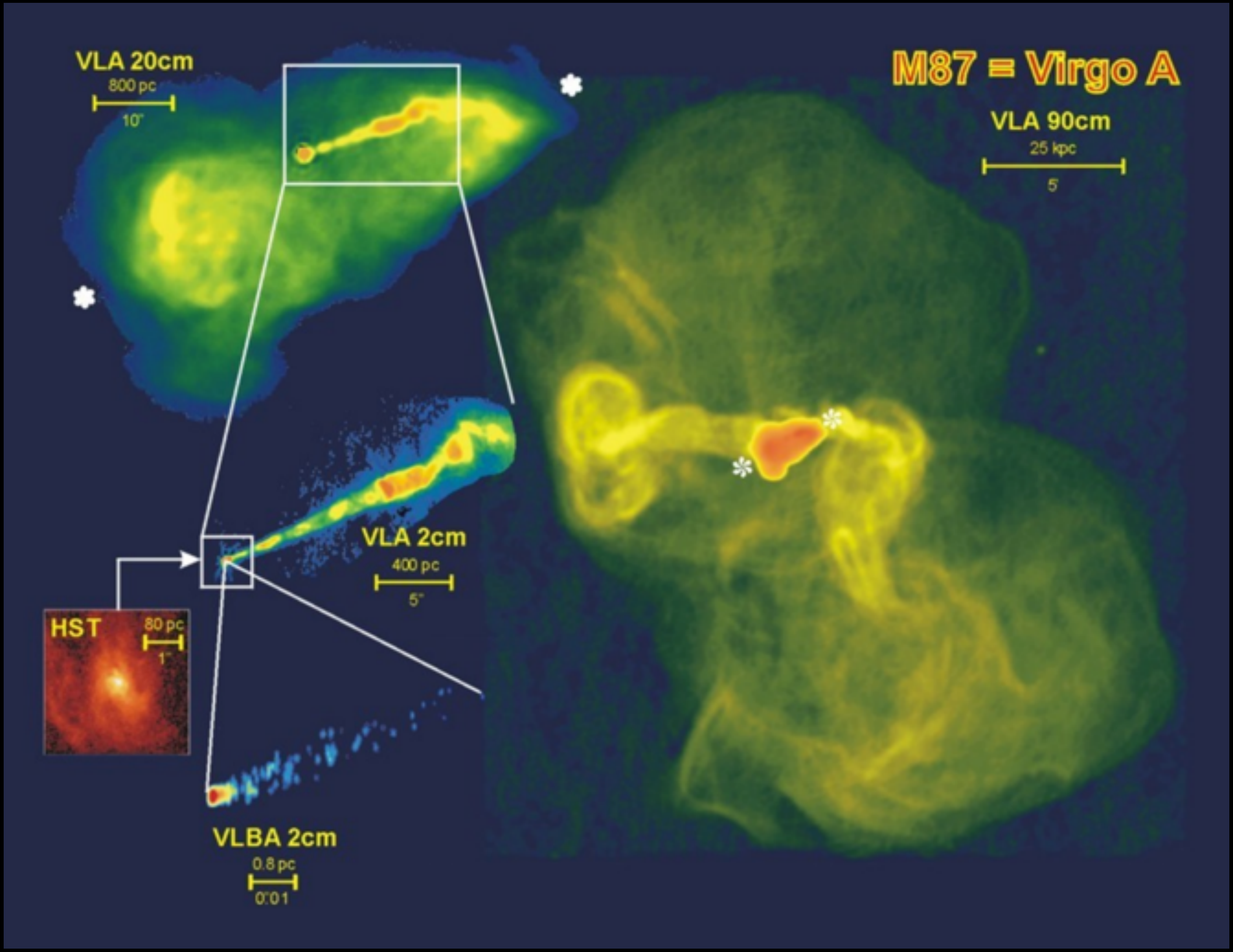
Relativistic jets:
Electrons shot out from the nucleus in narrow beams

Lobes:
When the electrons in the beam hit the gas surrounding the galaxy, the beam spreads out to form lobes

Shock front:
The fast and intense compression of gas near the radio lobes

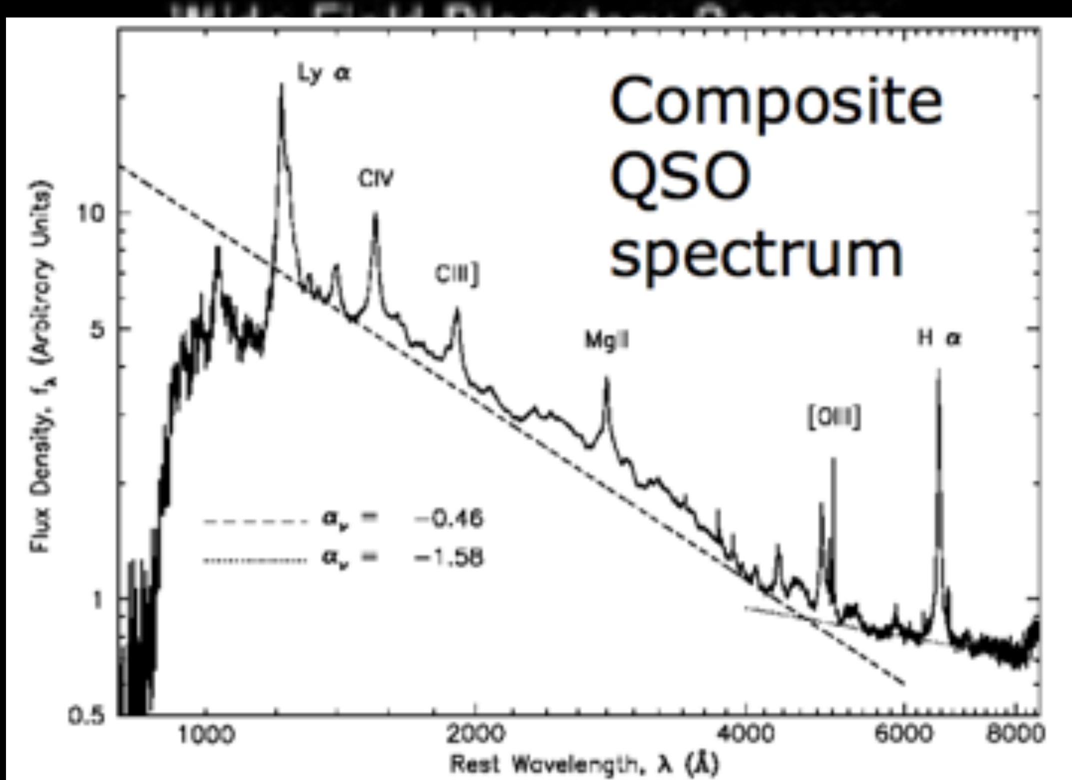


Radio images

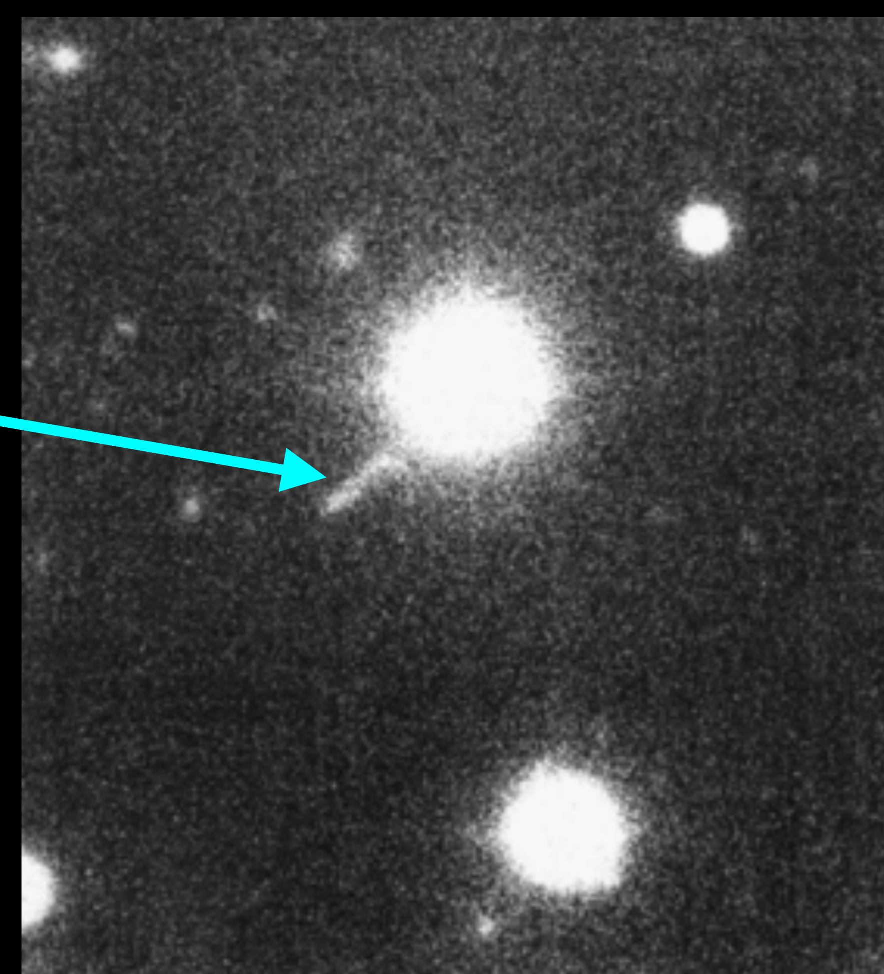


Quasars

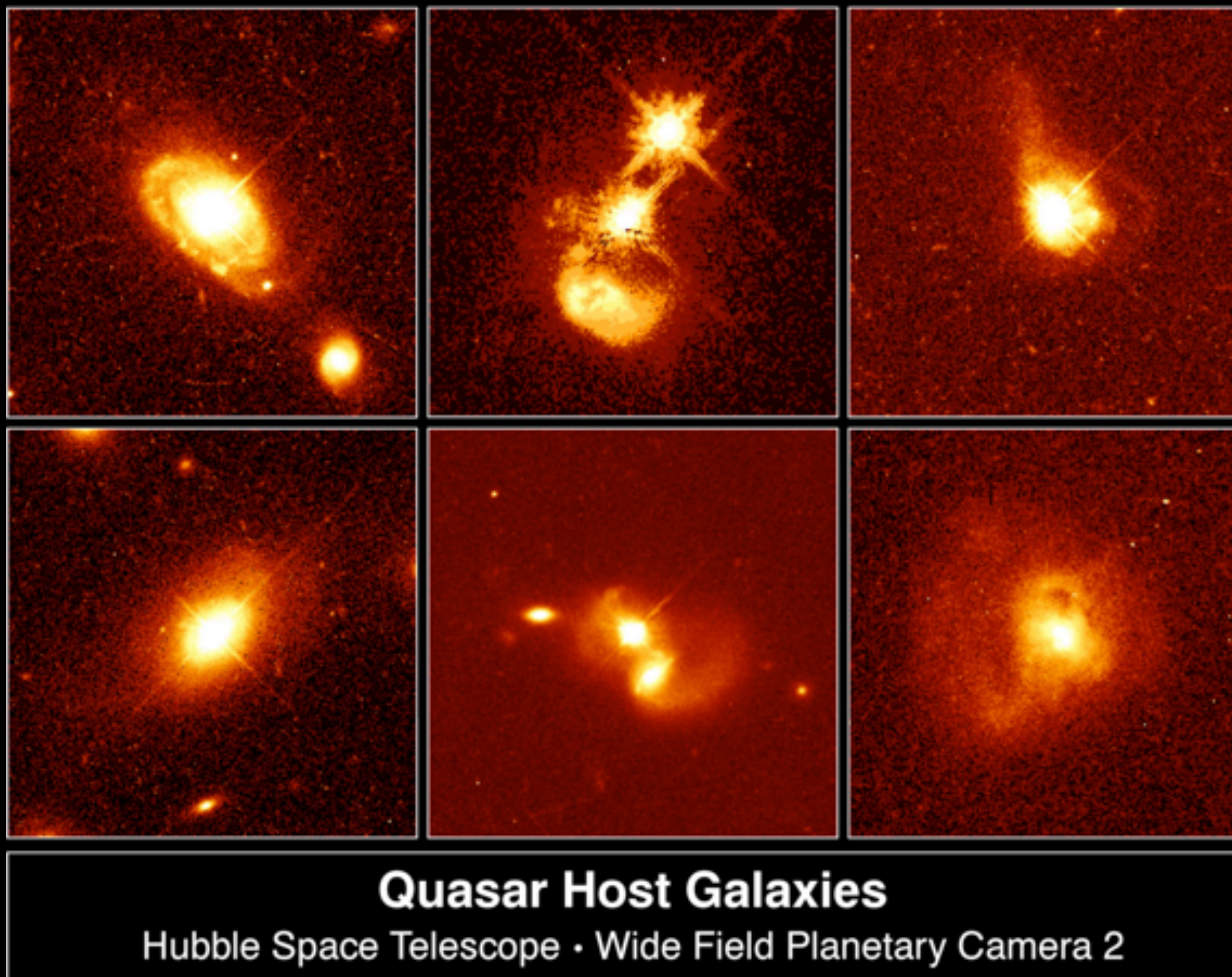
- Short for "Quasi-stellar radio source"
- Also bright unresolved galaxy nucleus, can outshine host galaxy by x100
- Among the most luminous, powerful, energetic objects in the universe



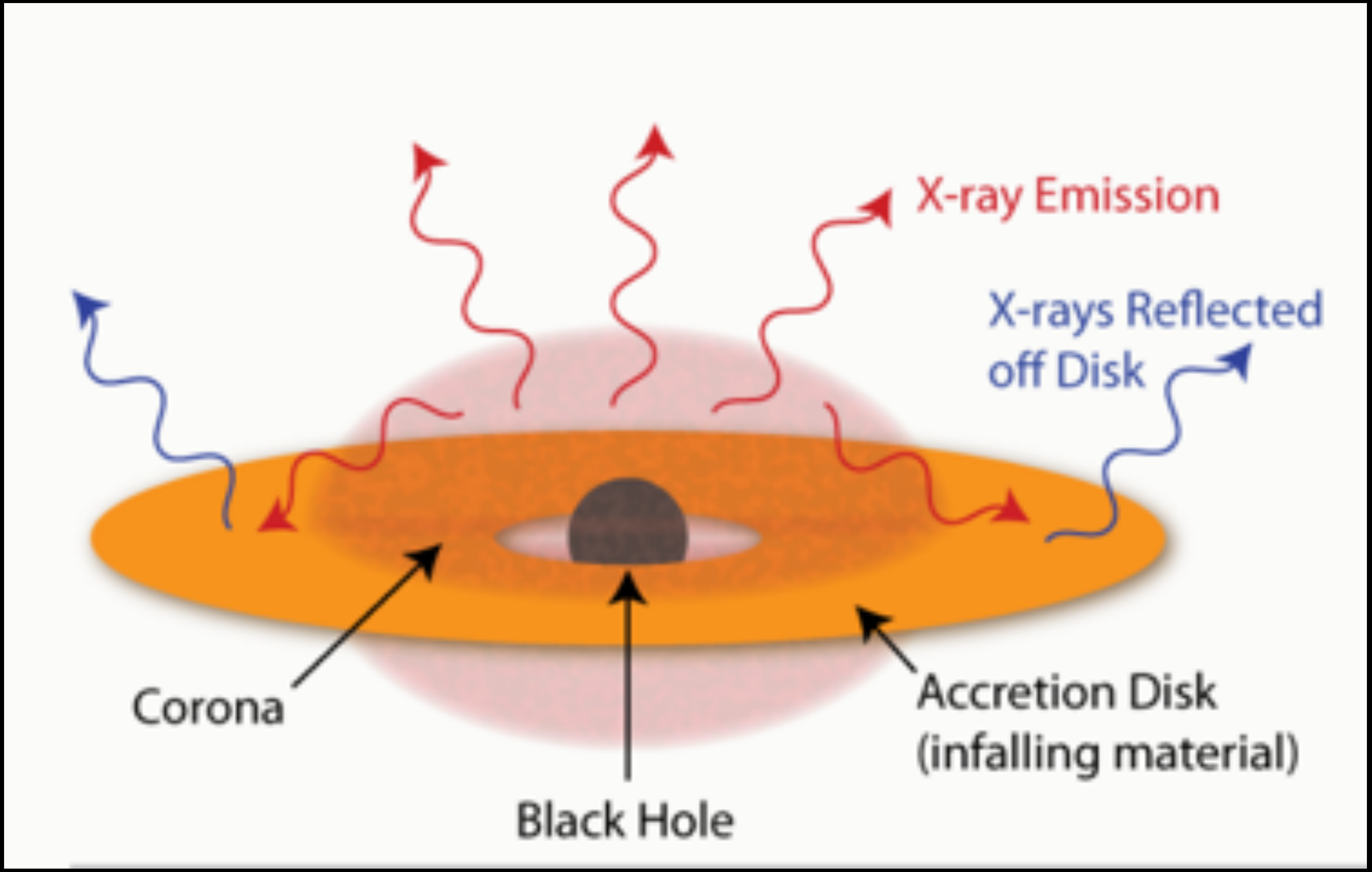
Jet!



Quasars in merging galaxy systems



AGN in X-ray

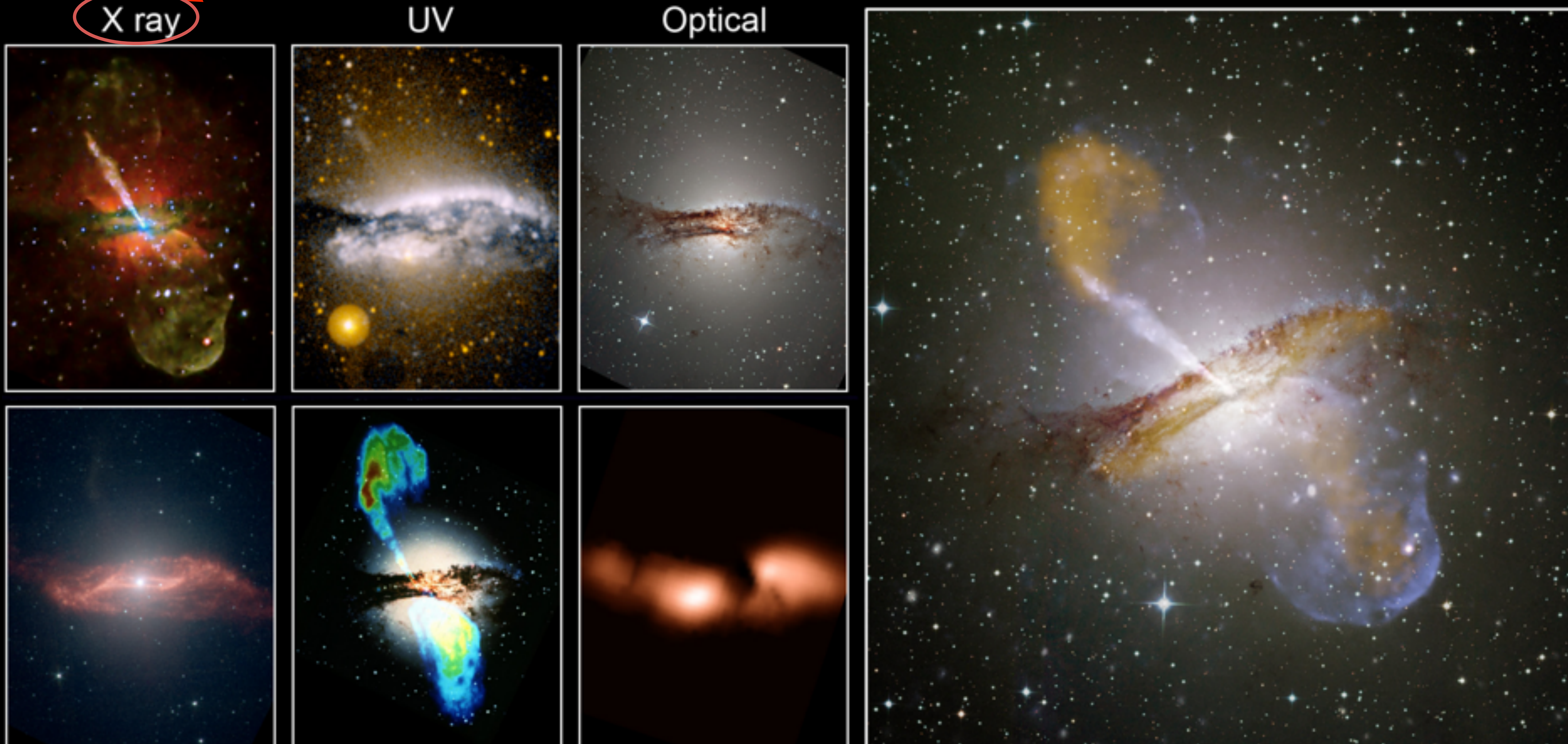

X-ray Emission
X-rays Reflected off Disk
Corona
Black Hole
Accretion Disk (infalling material)

Finding AGN in X-ray surveys

The multi-wavelength view of active galaxies

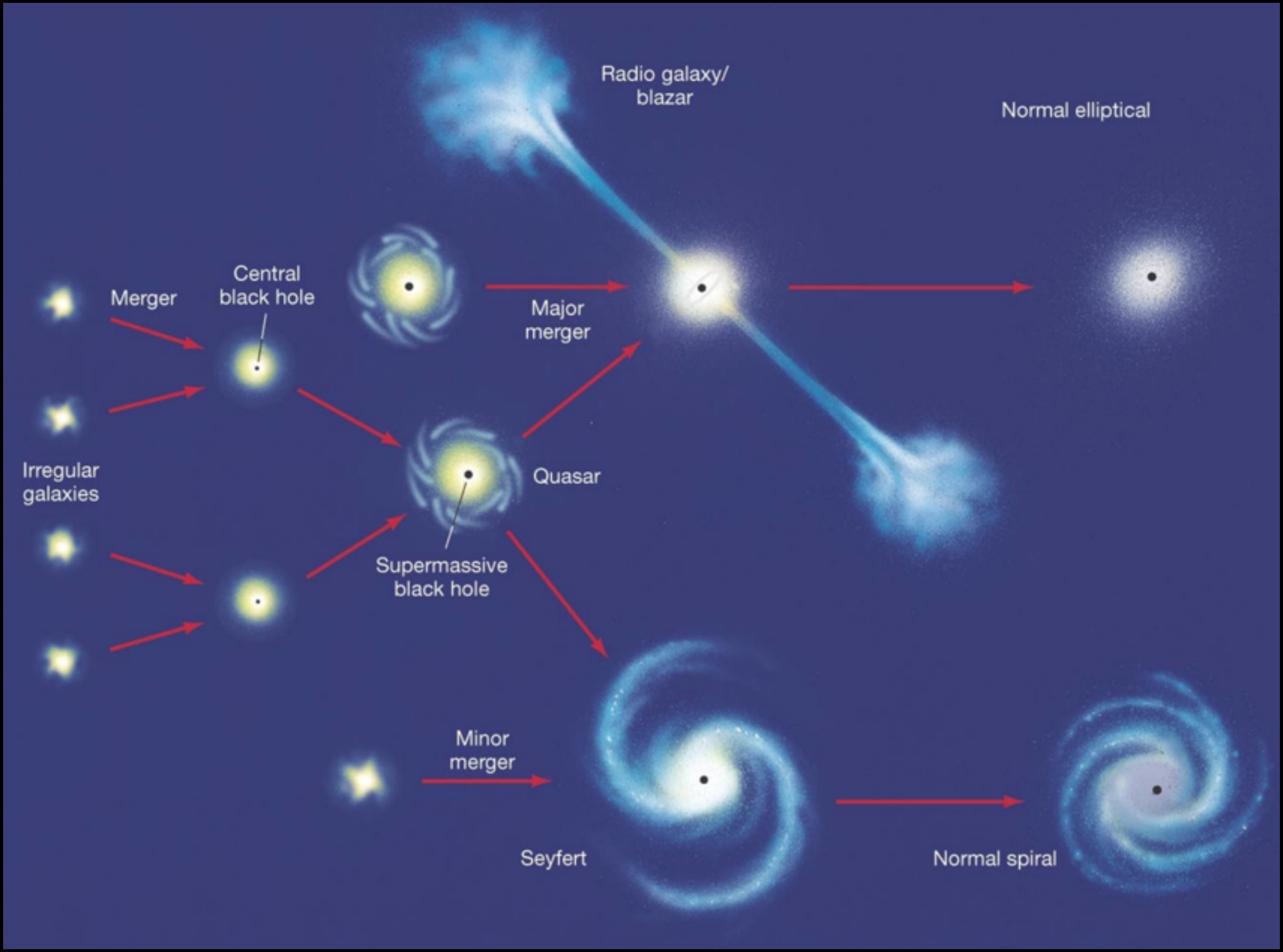
Hot gas with a temperature similar to that of the core of our sun

X ray UV Optical



MIR Radiocontinuum H I X ray + Optical + Submillimetre + Radio Composition

Formation/evolution theories for active galaxies



Galaxy -Supermassive Black Hole Co-evolution