[20] Active Galaxies 1 (4/17/18)

Upcoming Items

1. Homework #5 due in one week.
2. Read Ch. 21.4 for next class and do the self-study quizzes

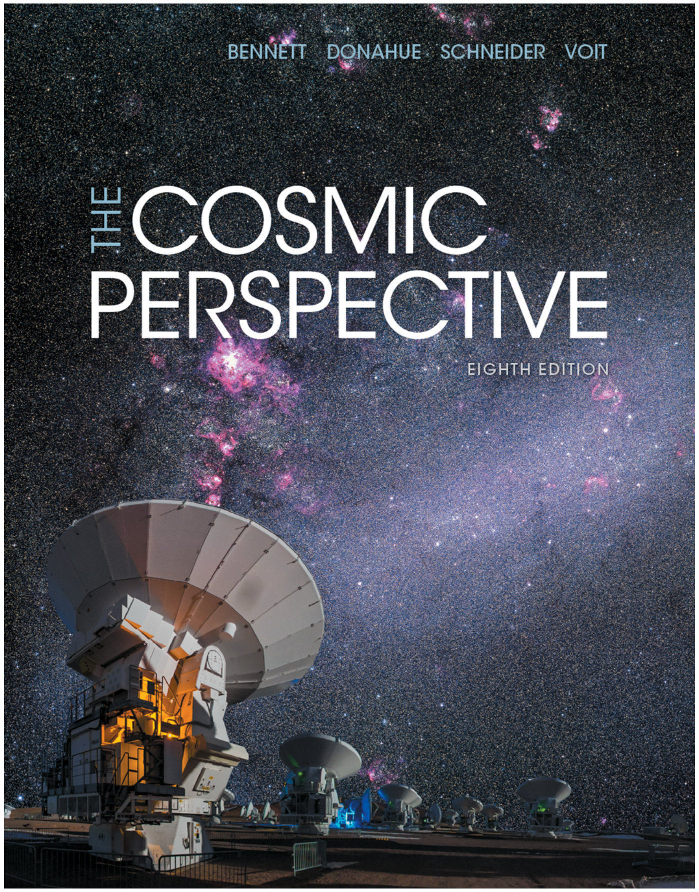
APOD 4/5/17: NGC 1275 Active Galaxy in Perseus

LEARNING GOALS

Ch. 21.3

For this class, you should be able to…

- … *use the minimum timescale of variability of a luminous object to put an upper limit on its physical size;*
- … *put a lower limit on the mass of an accreting object by assuming it is emitting light at the Eddington limit;*
- … *describe the observational evidence and theoretical considerations that imply quasars and active galaxies are powered by supermassive black holes.*



Any astro questions?

Active Galaxies 1

- Some galaxies have very bright centers: active galactic nuclei (AGN). Quasars are the most luminous examples.
- Their luminosities can be enormous (> 10^{12} $L_{\odot}$).
- Their luminosities can vary rapidly (and thus they come from a region smaller than our solar system).
- They emit energy over a wide range of wavelengths (contain matter with a wide temperature range).
- Active galaxies are sometimes associated with collisions.
- Accretion of gas onto a supermassive black hole is likely the only way to explain all the properties of quasars and active galaxies. Consideration of the Eddington limit gives a lower bound on the mass.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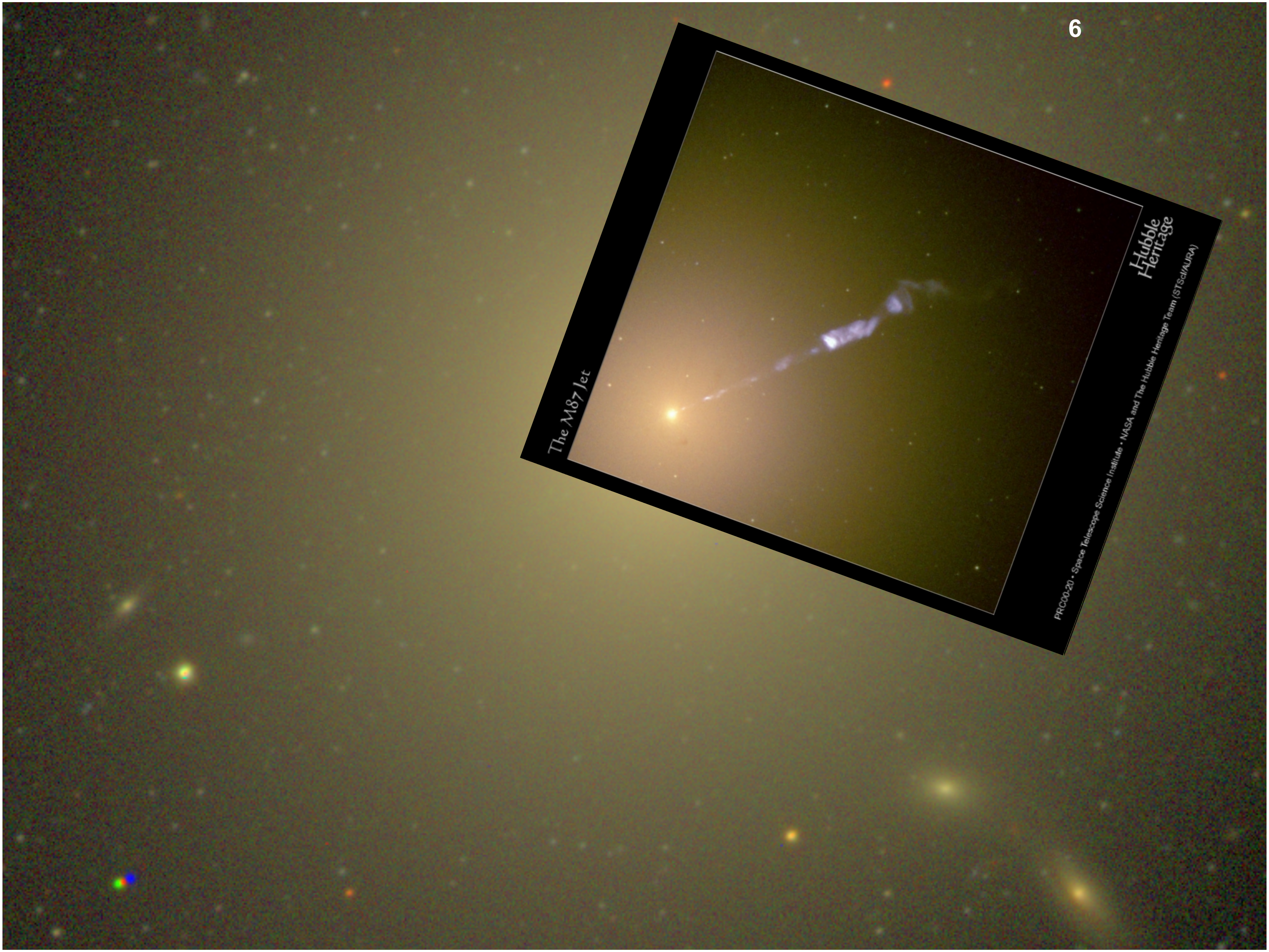
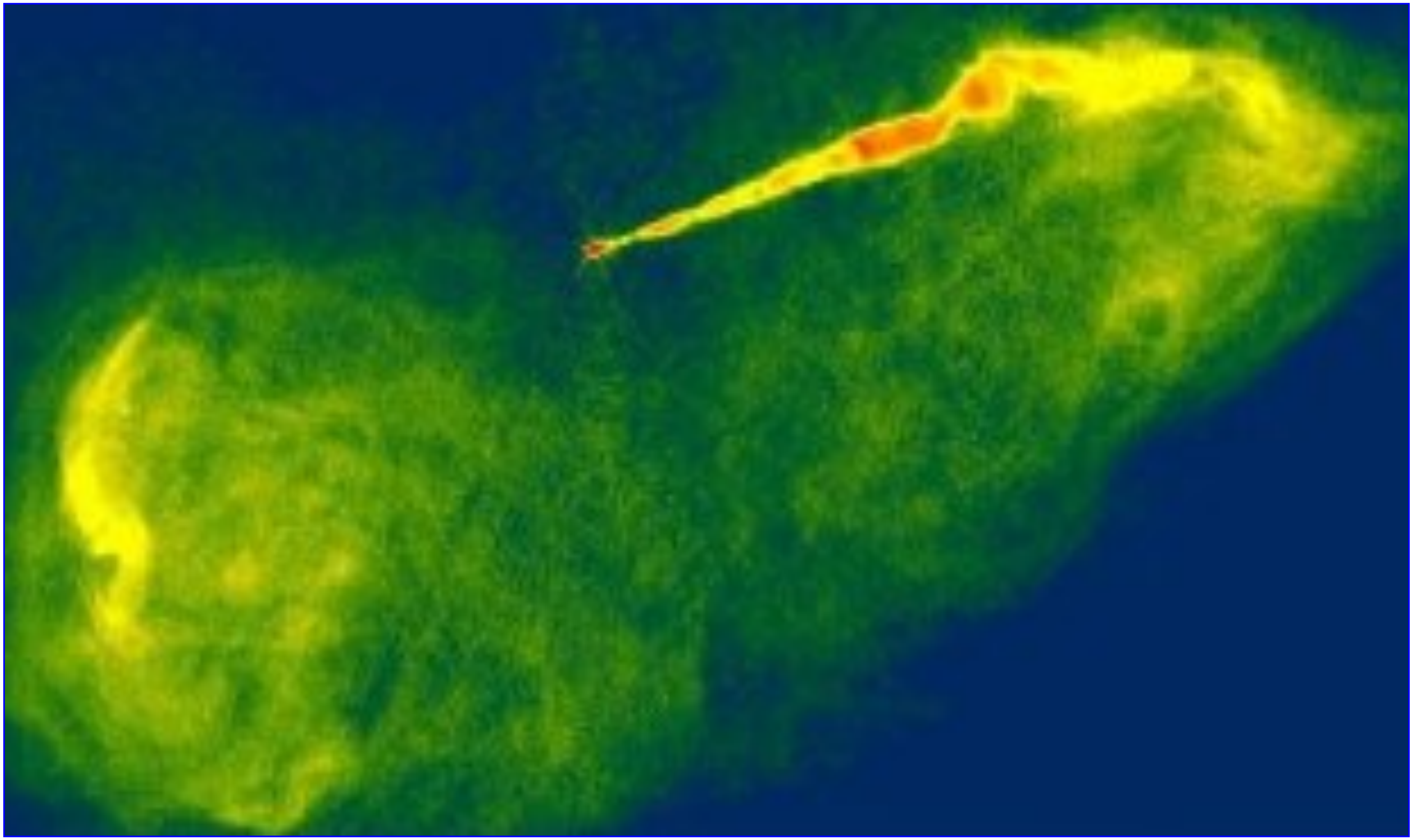
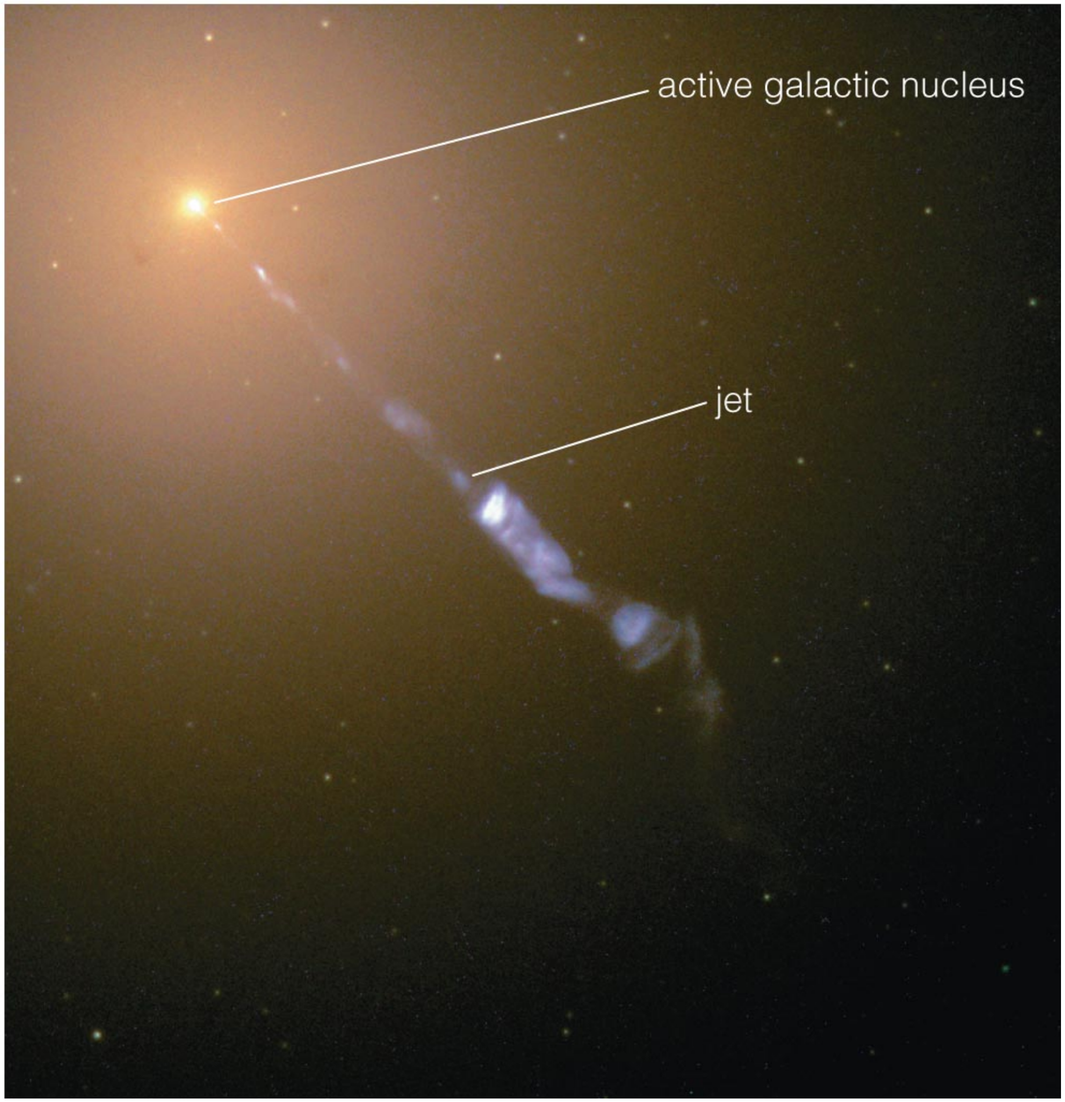

The M87 Jet
Hubble Heritage
PRC00-20 • Space Telescope Science Institute • NASA and The Hubble Heritage Team (STScI/AURA)



- M87 with the VLA (radio).

Active nucleus in M87



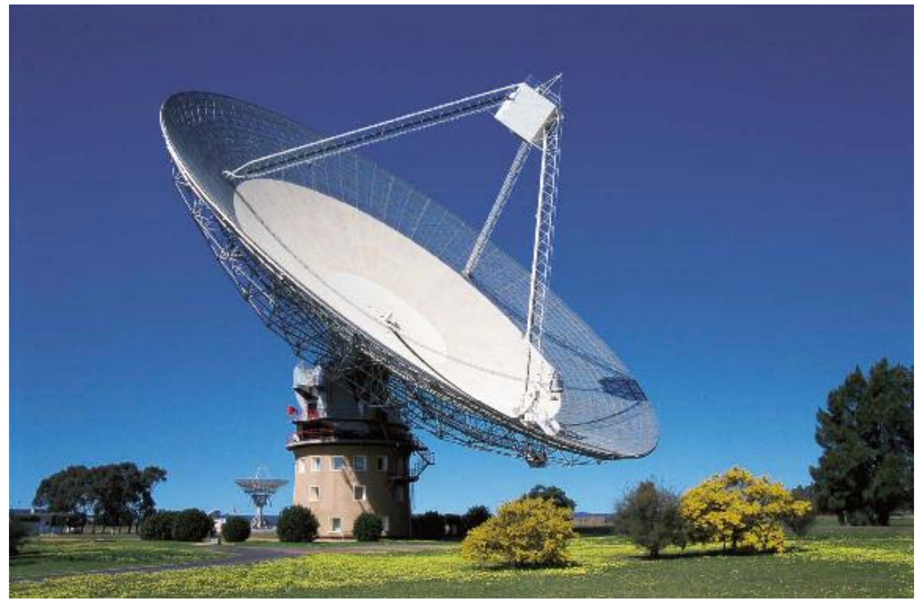
- If the center of a galaxy is unusually bright, we call it an ***active galactic nucleus***.
- ***Quasars*** are the most luminous examples.
- (More about the jet later…)

The Discovery of Quasars

- In the early 1960s, radio astronomers started to survey the sky.
- Found many mysterious radio sources…
- Some looked like stars (point sources): these came to be called quasi-stellar radio sources (***quasars*** for short).
- Very difficult to identify: radio images were too fuzzy to allow quasars to be localized on sky at first.

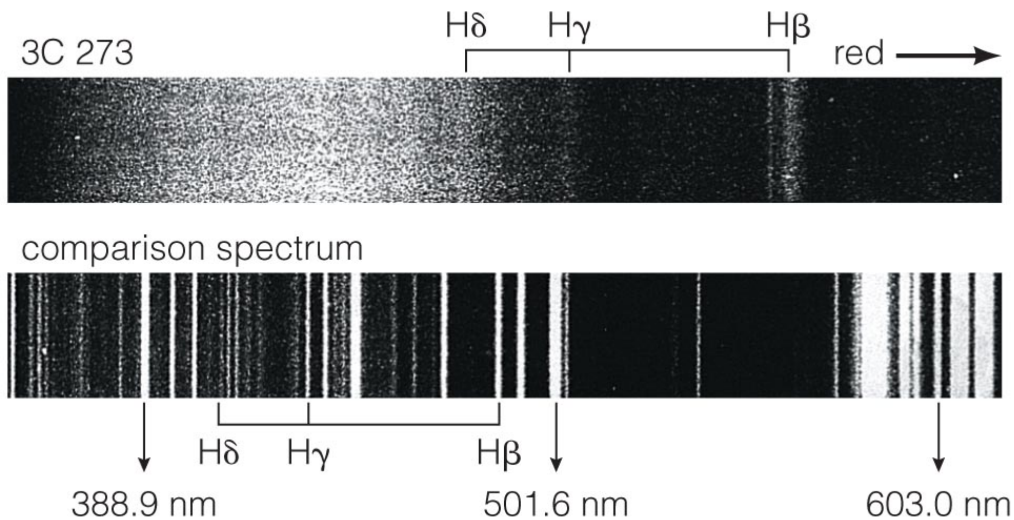
3C 273: The 1st Discovered Quasar

- Cyril Hazard used lunar occultation to localize the quasar 3C 273.
- Found a 13th-magnitude object at that location.
- Maarten Schmidt & Bev Oke took spectra. Found "extreme" redshift—recession speed of ~50,000 km/s.
- (Note: 3C 273 can be seen with a good amateur telescope, but is 2.4 billion light-years away! Impress your friends…)



Parkes radio telescope in Australia.

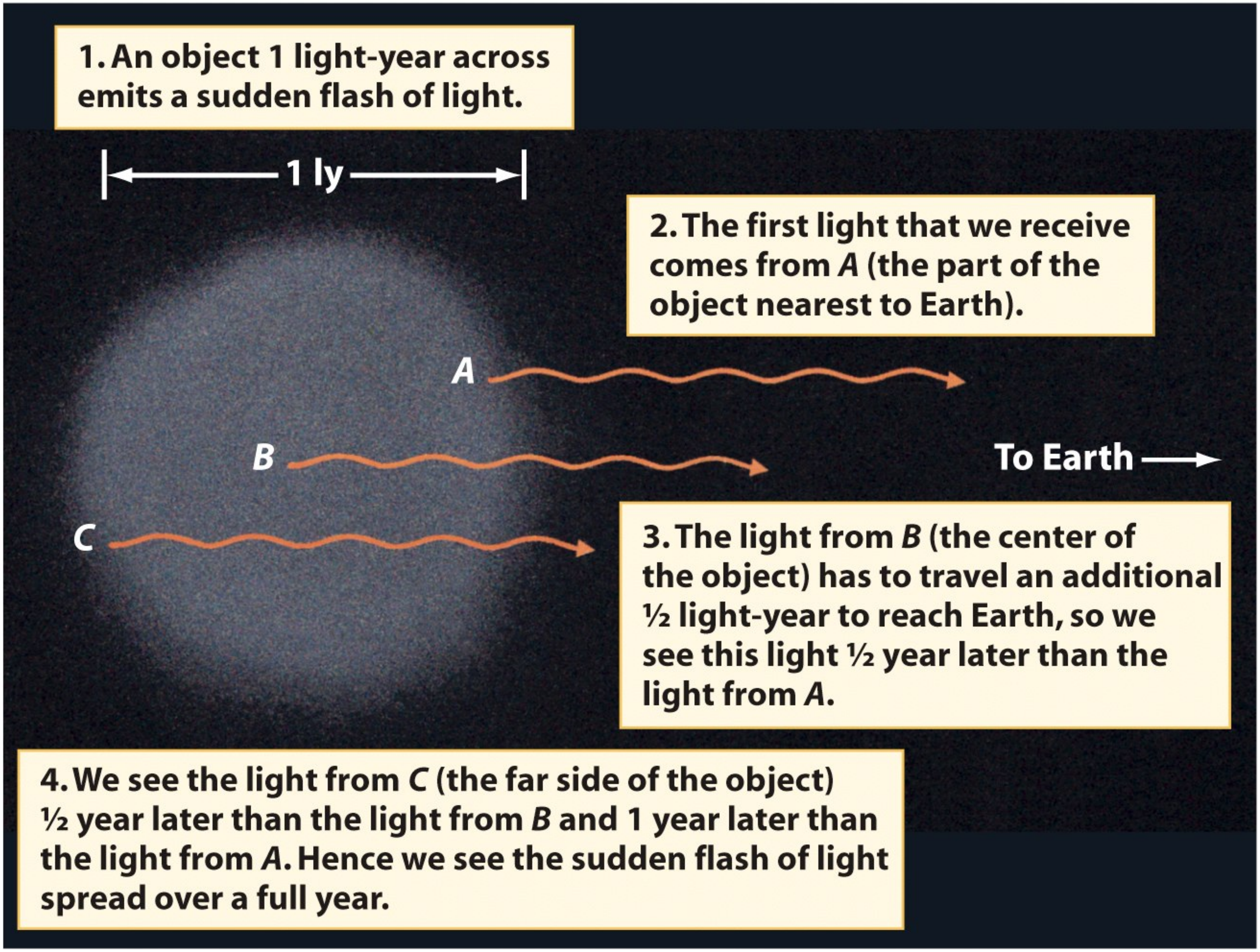
Quasars are Distant and Luminous

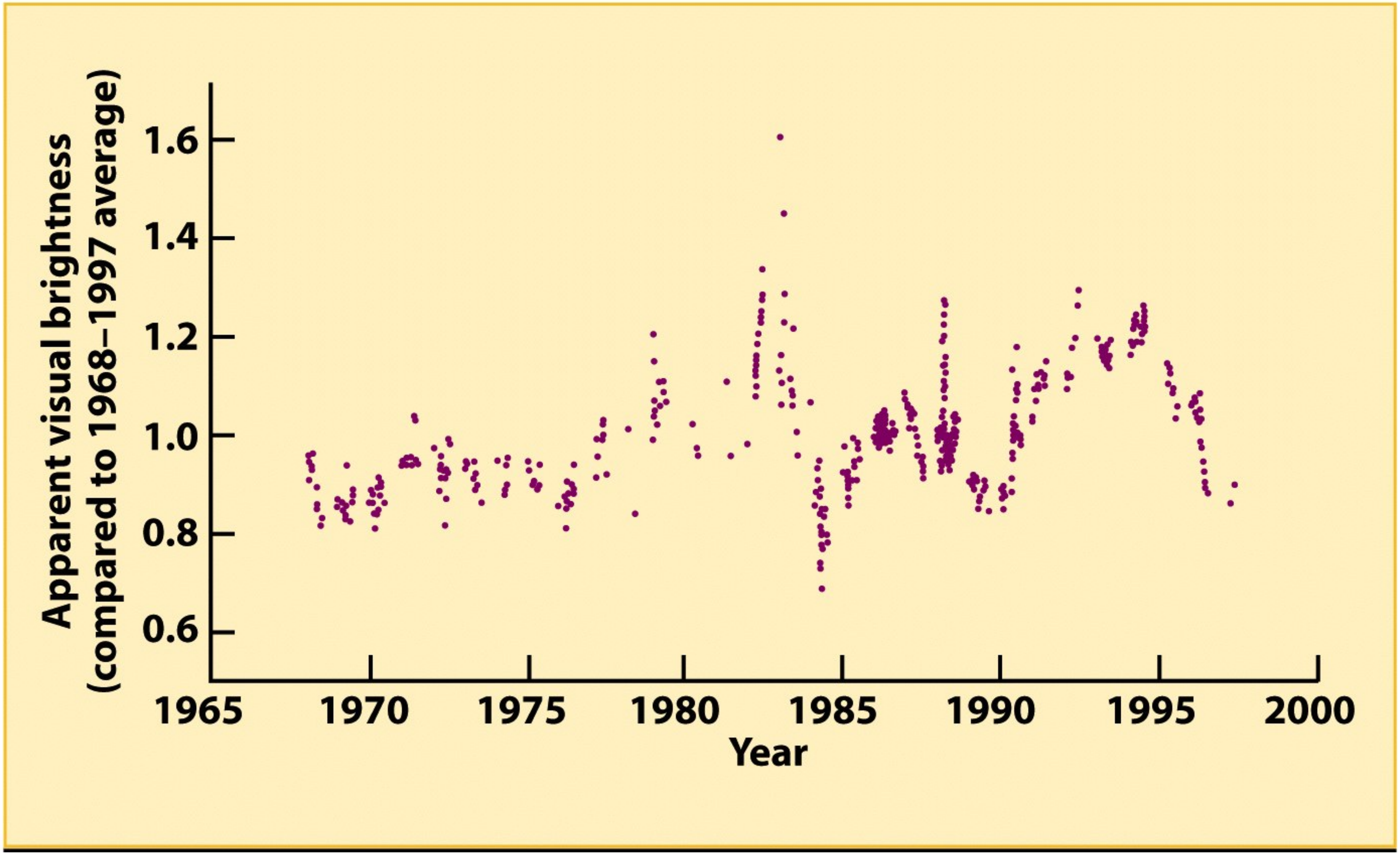


- The highly redshifted spectra of quasars indicate large distances ($z \sim 0.06–7.1$).
- From brightness and distance we find that luminosities of some quasars are greater than $10^{12}\ L_{\odot}$ (> 100× MW!).

Quasars are Extremely Compact

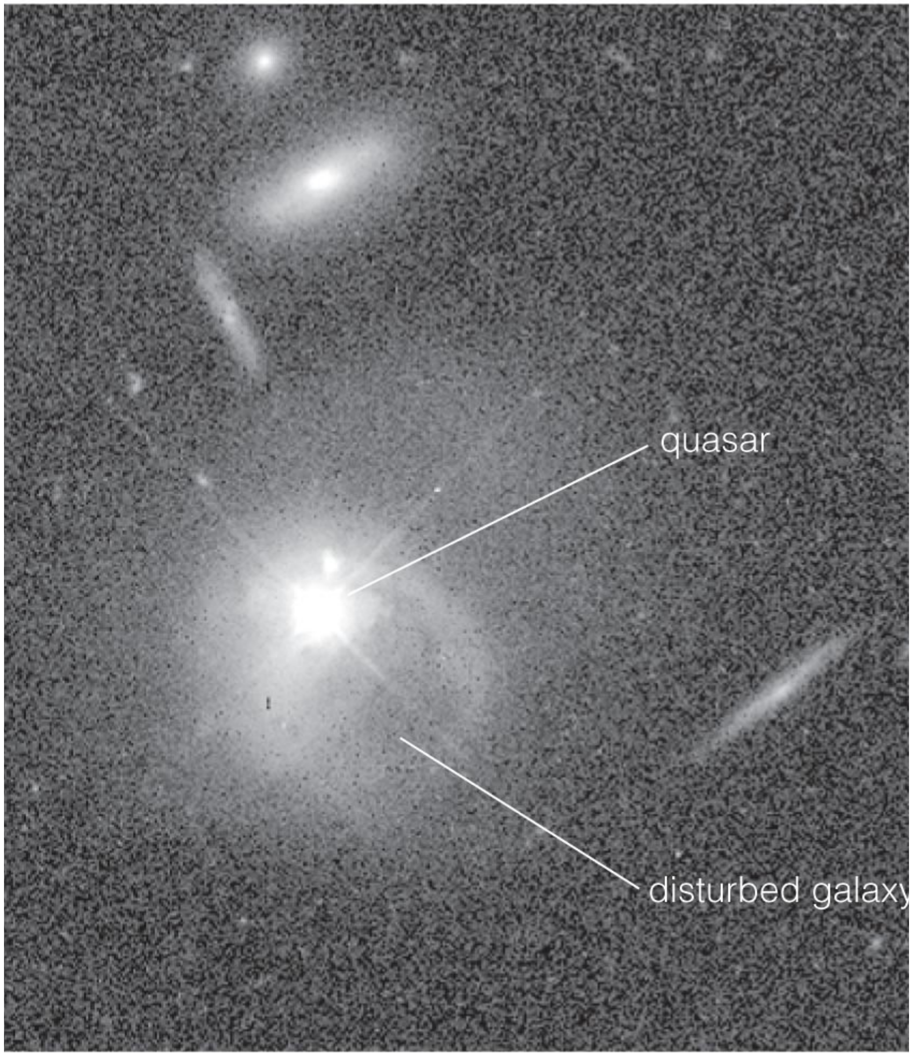
- The prototype quasar 3C 273 shows variability on timescales as short as a day.
- So whatever is powering the quasar can be no bigger than about a light-day across: an object cannot vary in brightness faster than light can travel across that object.
- This means that all of the energy from 3C 273 comes from a region *smaller than our solar system*.


1. An object 1 light-year across emits a sudden flash of light.
1 ly
2. The first light that we receive comes from *A* (the part of the object nearest to Earth).
A
B
C
To Earth
3. The light from *B* (the center of the object) has to travel an additional ½ light-year to reach Earth, so we see this light ½ year later than the light from *A*.
4. We see the light from *C* (the far side of the object) ½ year later than the light from *B* and 1 year later than the light from *A*. Hence we see the sudden flash of light spread over a full year.



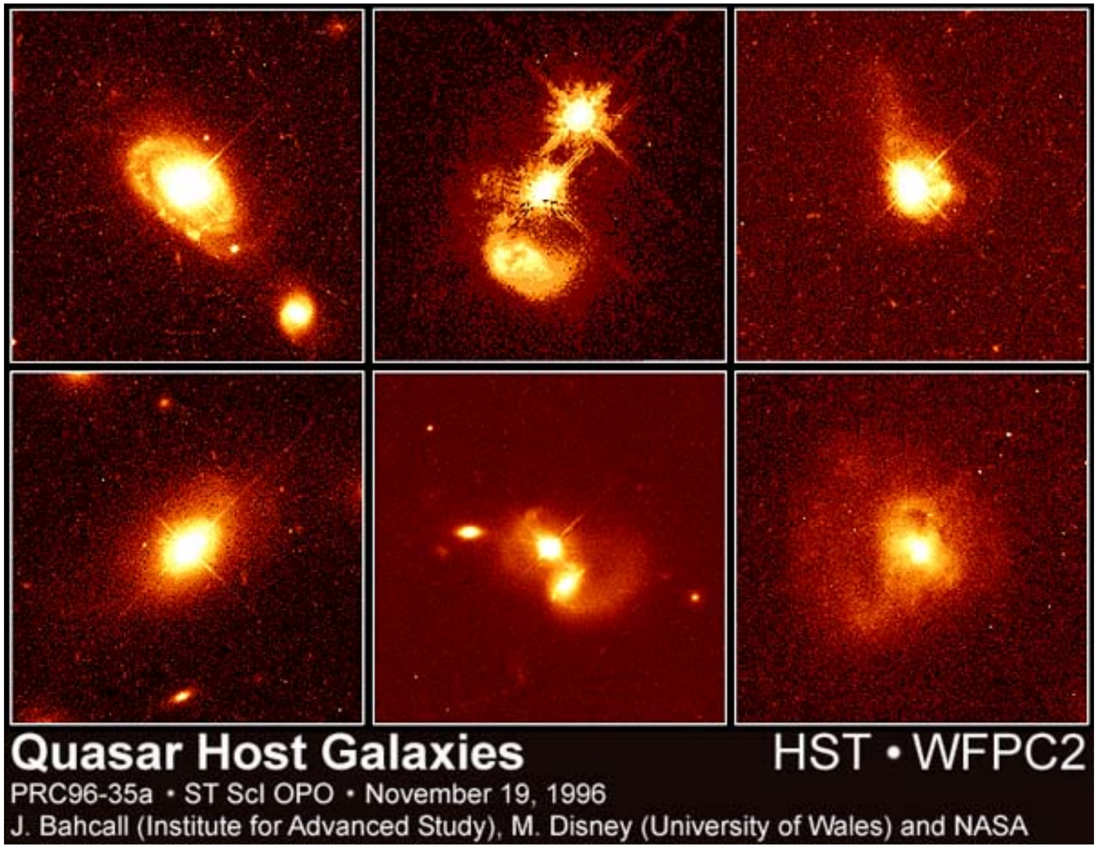
Variations in apparent brightness of 3C 273.

Quasars Live in Galaxies

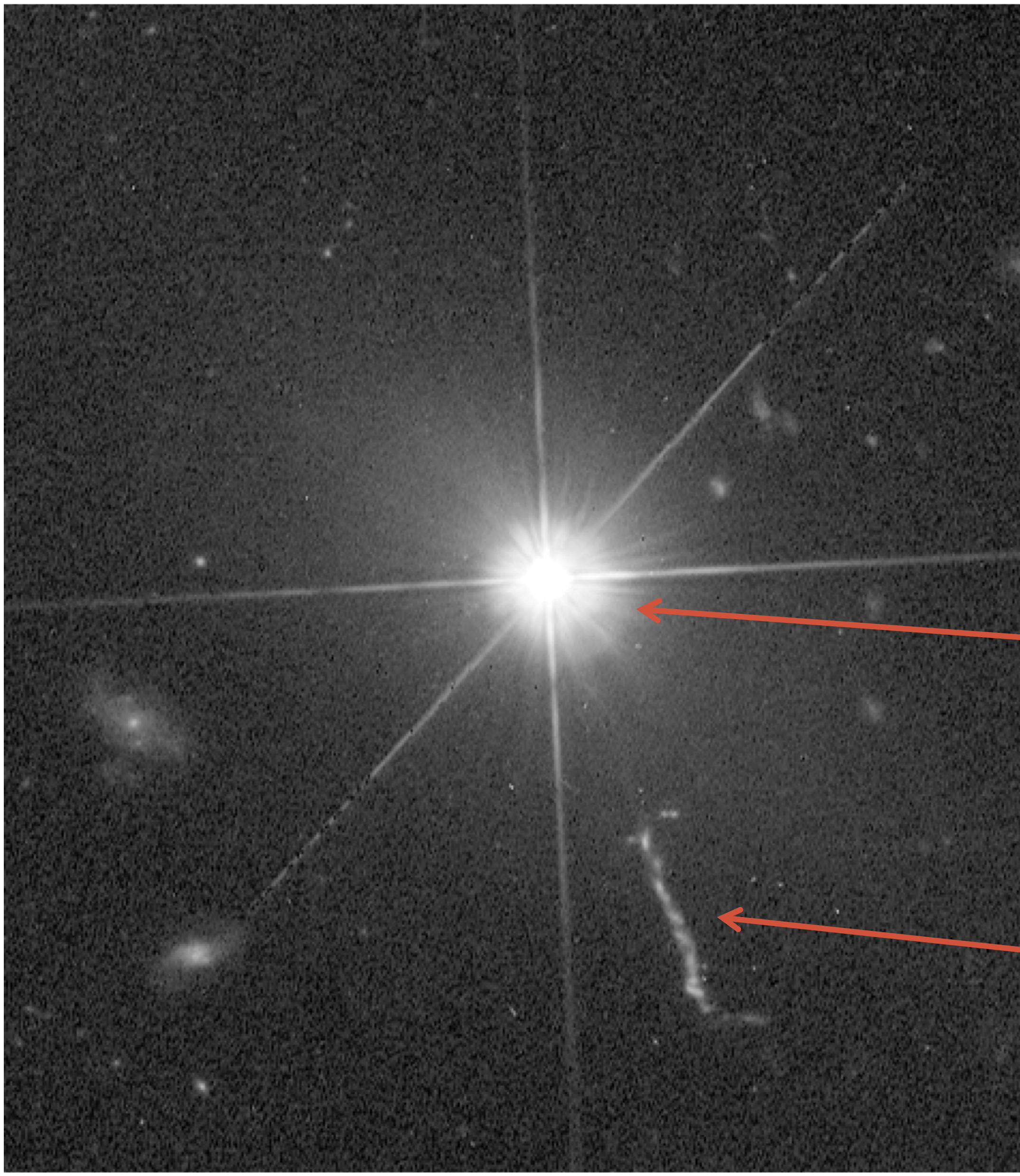


- Quasars are often bright enough to outshine their host galaxies.
- Observations like this one verified that quasars live at the centers of galaxies.
- The redshifts of the quasar and the surrounding galaxy in this image are the same.

Colliding Galaxies Often Host Quasars



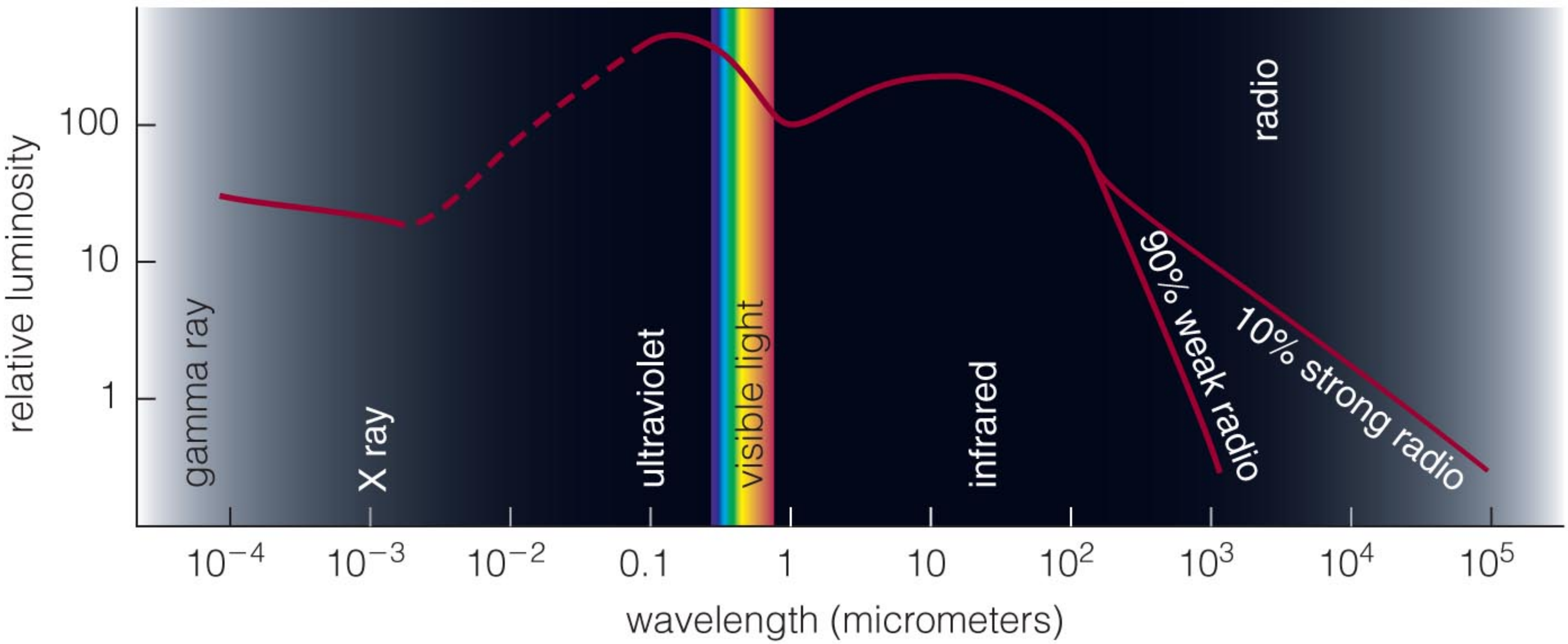
- Galaxies around quasars sometimes appear disturbed by collisions.
- These host galaxies are bright enough that we can see them *and* the quasar.



- 3C 273 appears as a luminous point source plus an extended radio (and optical) jet.

There's a galaxy in there!

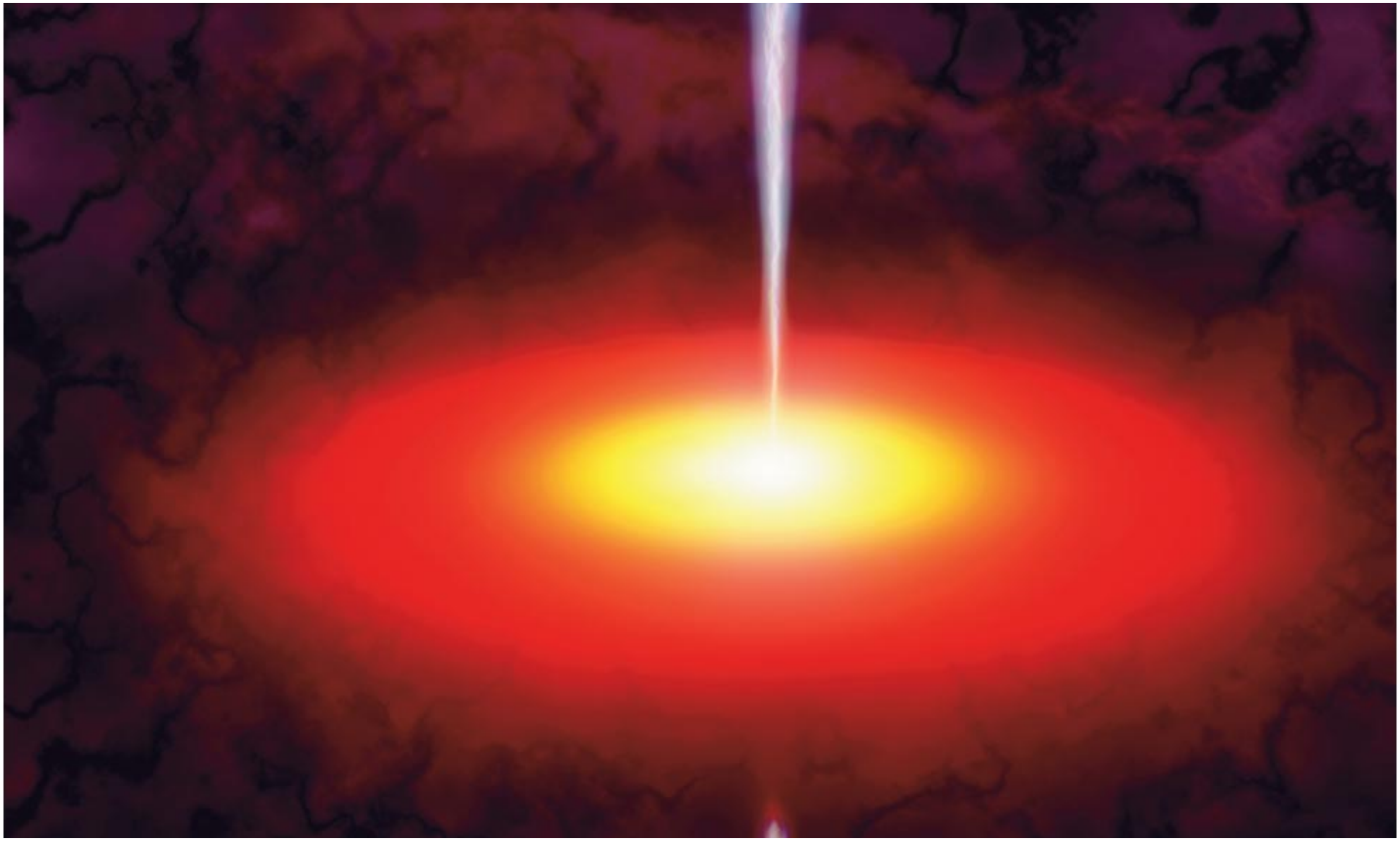
Jet!



- Quasars radiate energy over a wide range of wavelengths, including radio (synchrotron radiation), implying they contain material at many temperatures (and strong magnetic fields).

Characteristics of Active Galaxies

- Their luminosities can be enormous ($> 10^{12}\ L_\odot$). (That's more than 100 Milky Way galaxies!)
- Their luminosities can rapidly vary (come from a space smaller than solar system).
- They emit energy over a wide range of wavelengths (contain matter with a wide temperature range).
- Some galaxies drive jets of plasma at near light speed (next class).



Accretion of gas onto a supermassive black hole appears to be the only way to explain all the properties of quasars.

Powering AGN

- Define efficiency ε by

$$L = \varepsilon \dot{M} c^2 \ \ (\dot{M} = \text{mass accretion rate [kg/s]}).$$

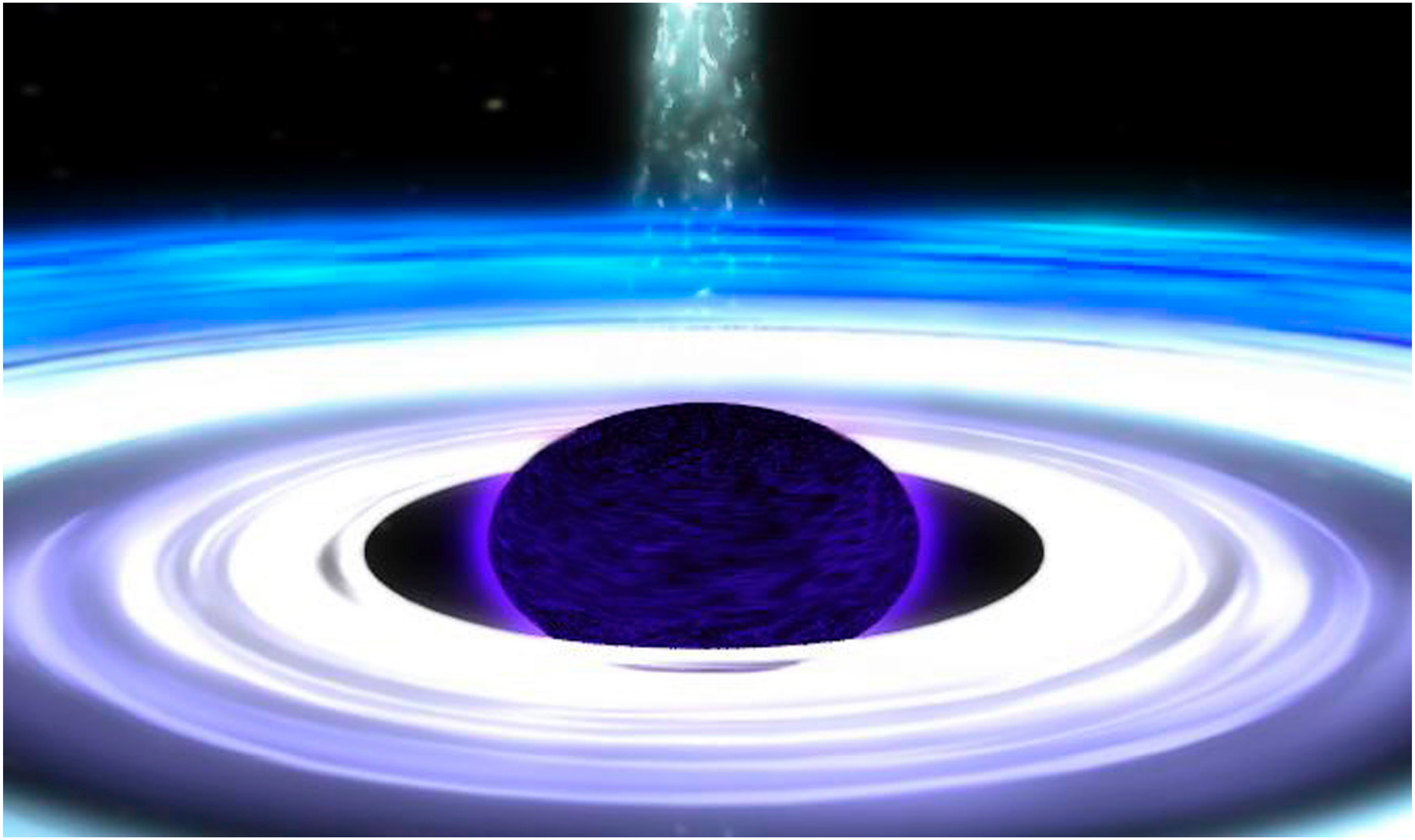
- Remember efficiency of different processes:
  - Chemical burning, $\varepsilon \approx 10^{-9}$.
  - Nuclear fusion, $\varepsilon \approx 0.007$.
  - Accretion onto a black hole, $\varepsilon \approx 0.1$.
  - Matter/anti-matter annihilation, $\varepsilon = 1$.

Powering AGN

- Suppose the AGN has a power of 10^{40} W (quite luminous) and lasts for *at least* 10 Myr.

- Then, what masses are needed to power the AGN?
  - Chemical burning… $2\times10^{12}\ M_{\odot}$.
  - Nuclear burning… $2\times10^{9}\ M_{\odot}$.
  - Accretion… $2\times10^{8}\ M_{\odot}$.
  - Matter/anti-matter… $2\times10^{7}\ M_{\odot}$.

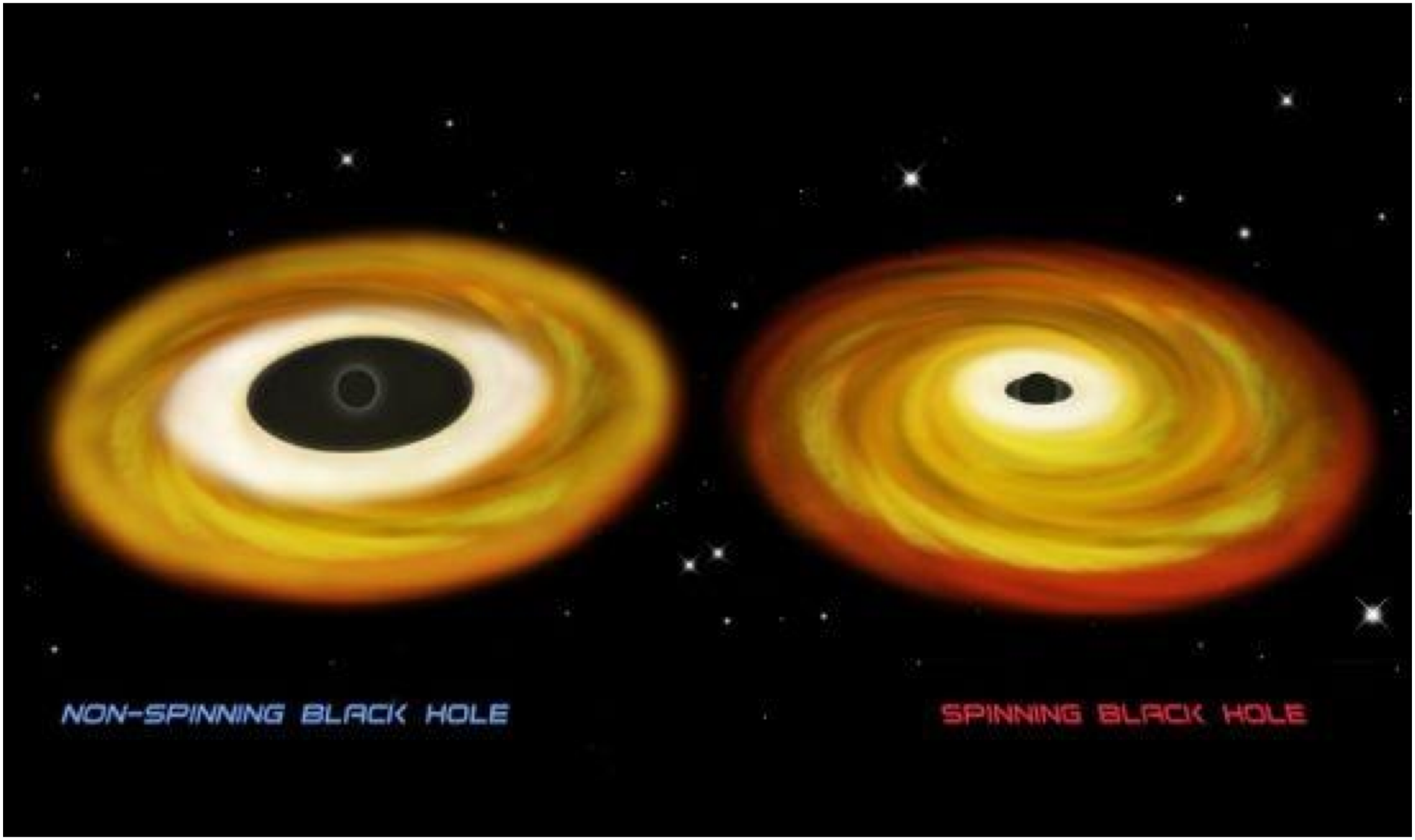
- Masses tend to argue for accretion (there are not large amounts of anti-matter in space!).



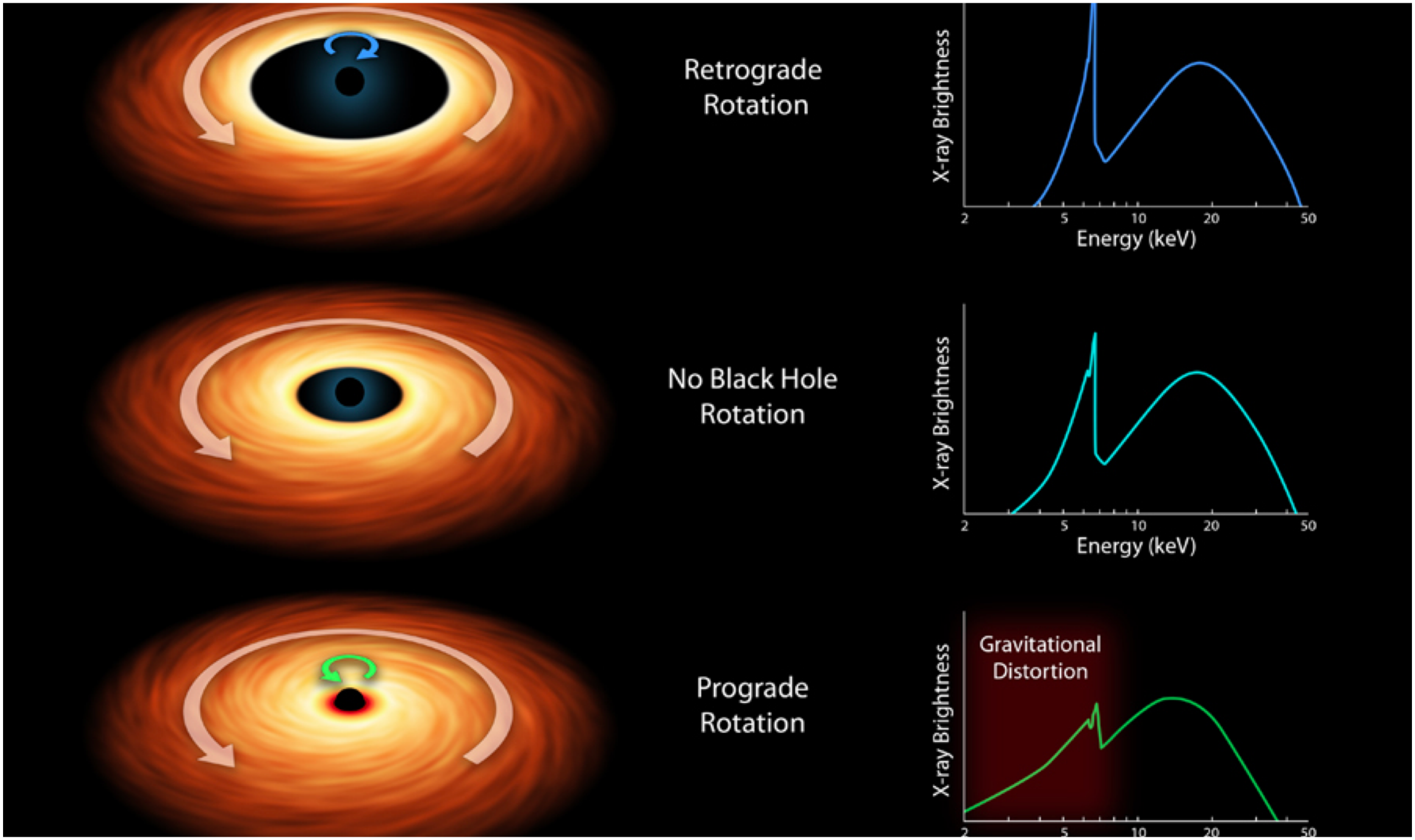
- We now believe that AGN are indeed supermassive black holes growing via disk accretion.

Energy from a Black Hole

- Gravitational potential energy of matter falling into black hole turns into kinetic energy.
- Friction in an accretion disk turns kinetic energy into thermal energy (heat).
- Heat produces thermal radiation (photons):
  - X rays ionize surrounding gas (which then emits visible light) and heat dust grains (which then emit infrared light).
  - Electrons spiraling around jets emit radio light.
- This process can convert 5% to 40% of $E = mc^2$ into radiation.



- The spin (angular momentum) of a black hole changes the efficiency of accretion.



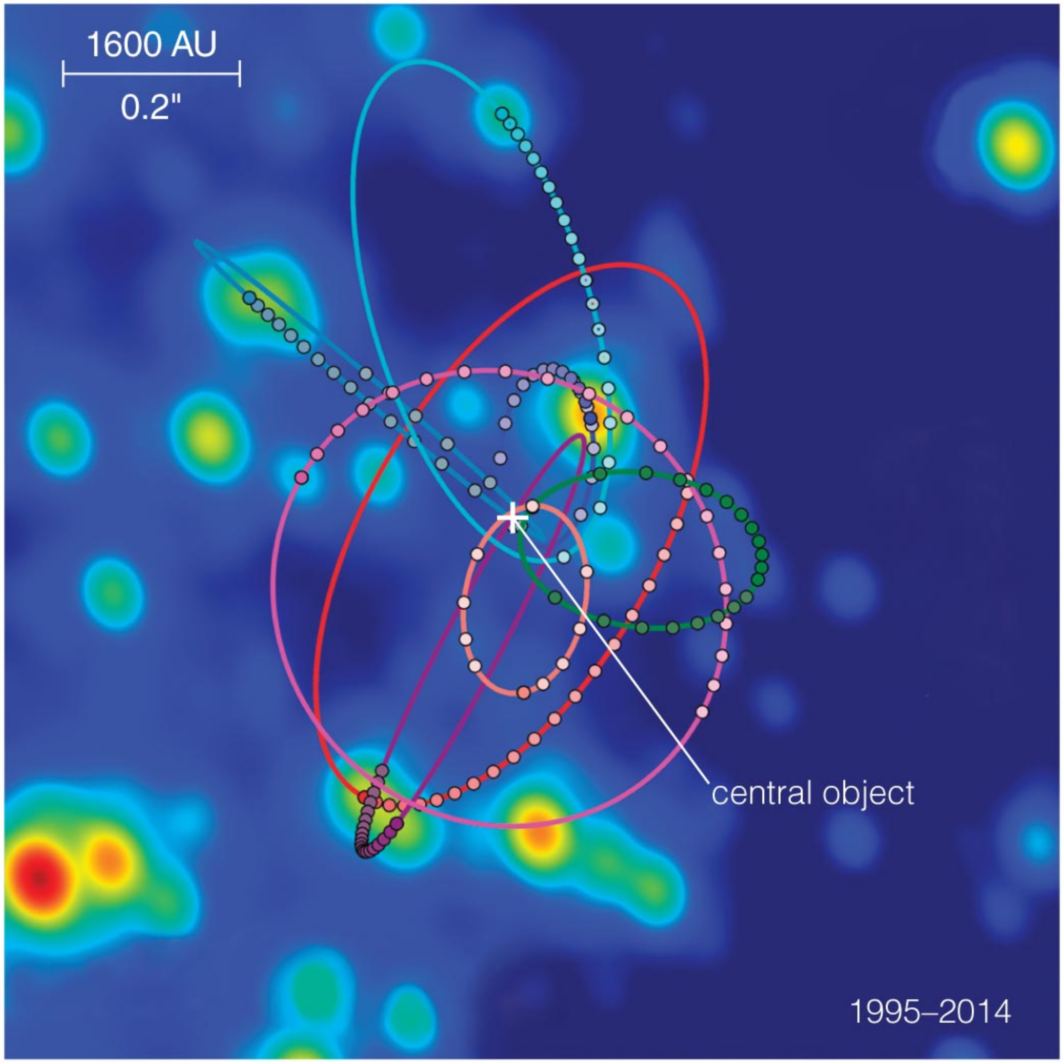
- Iron emission lines can be used to measure black hole spin.
- The closer the material can get to the black hole, the more gravitationally redshifted it is.

The Eddington Limit

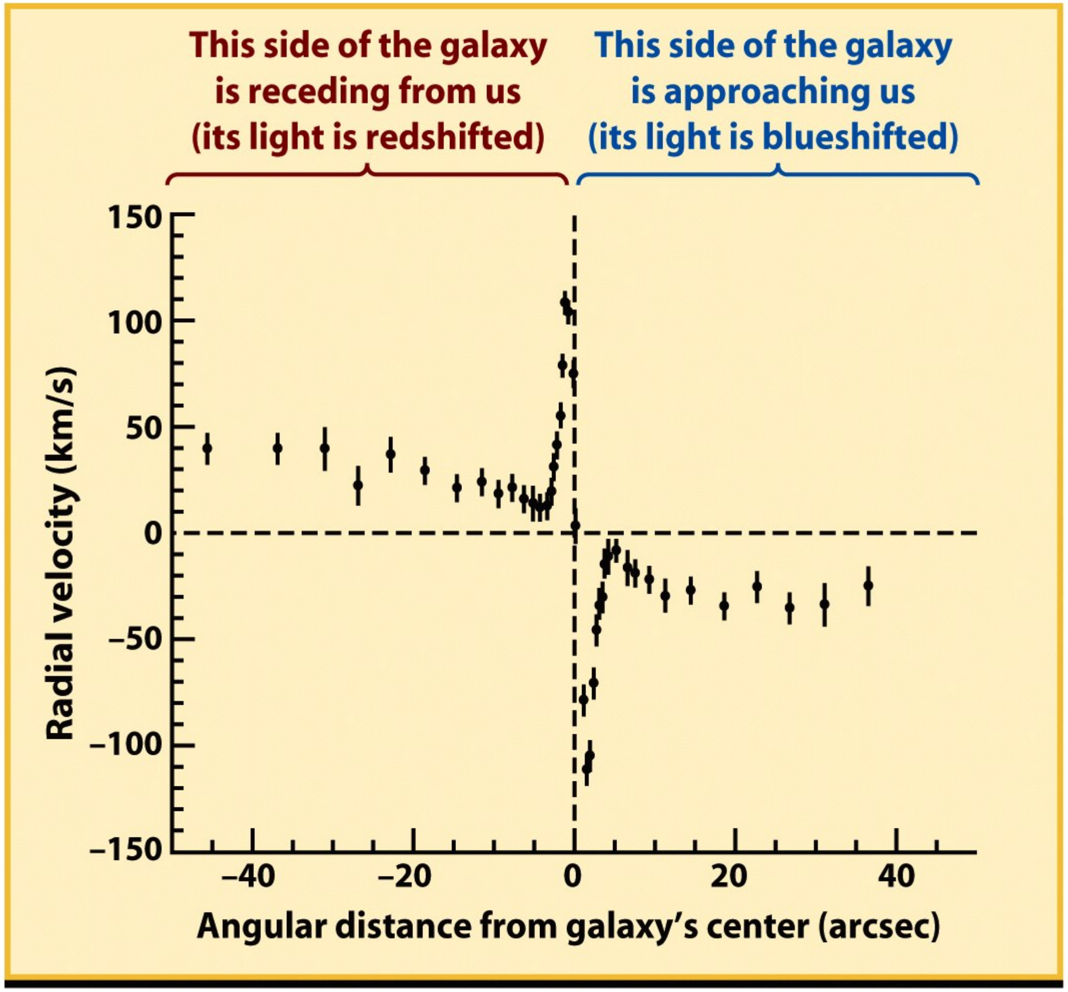
- There is a natural limit to the luminosity that can be radiated by accretion around a black hole.
- If the luminosity exceeds the *Eddington limit*, radiation pressure stops the accretion rate from getting faster.
- Numerically,

$$L_{\mathrm{Edd}} = 30{,}000\left(\frac{M}{\mathrm{M}_{\mathrm{Sun}}}\right)\mathrm{L}_{\mathrm{Sun}}.$$

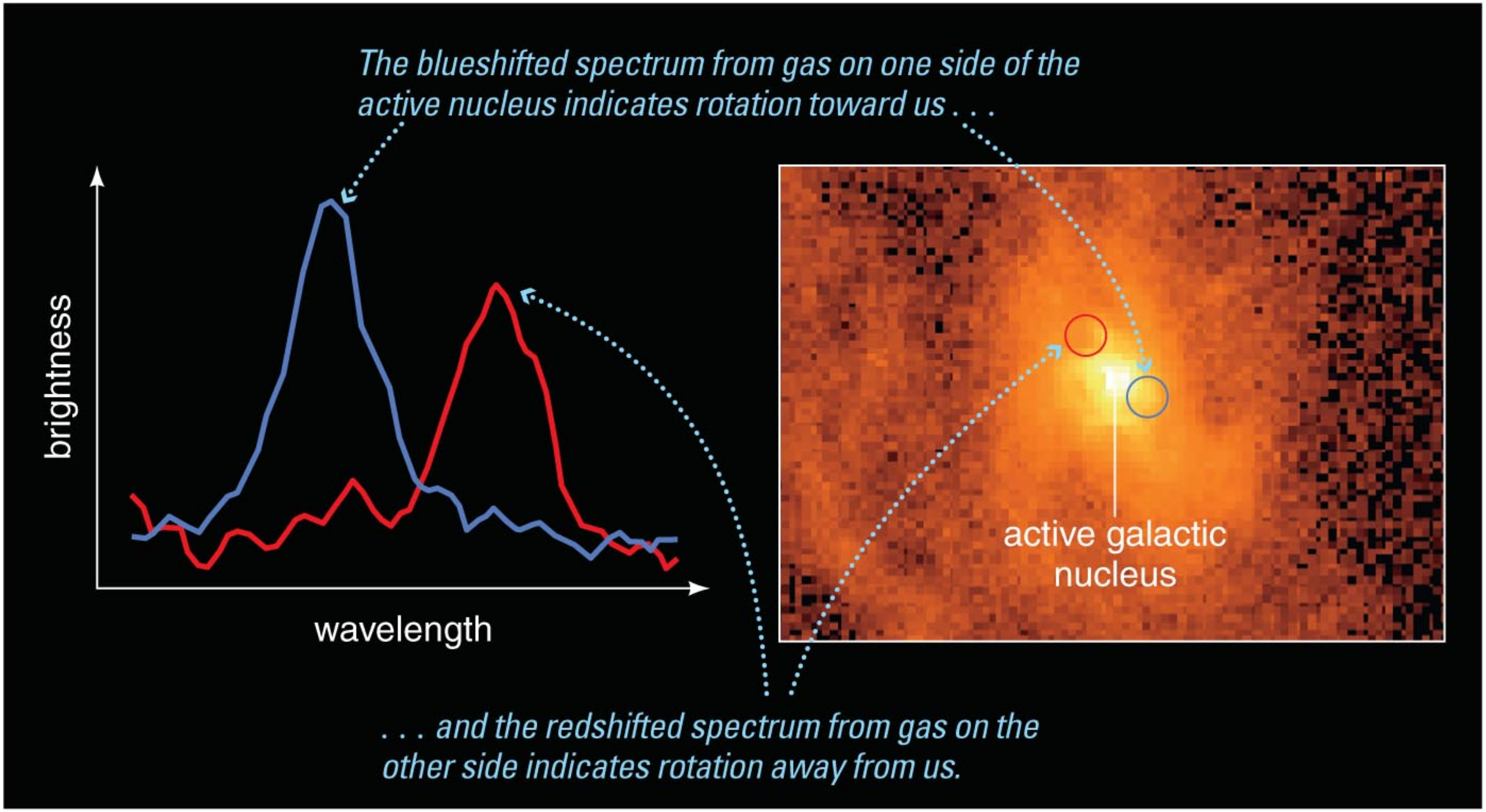
- E.g., 3C 273 has a luminosity of about $3\times10^{13}\ \mathrm{L}_{\odot}$. The minimum-mass black hole that could power the quasar is therefore about $10^{9}\ \mathrm{M}_{\odot}$.



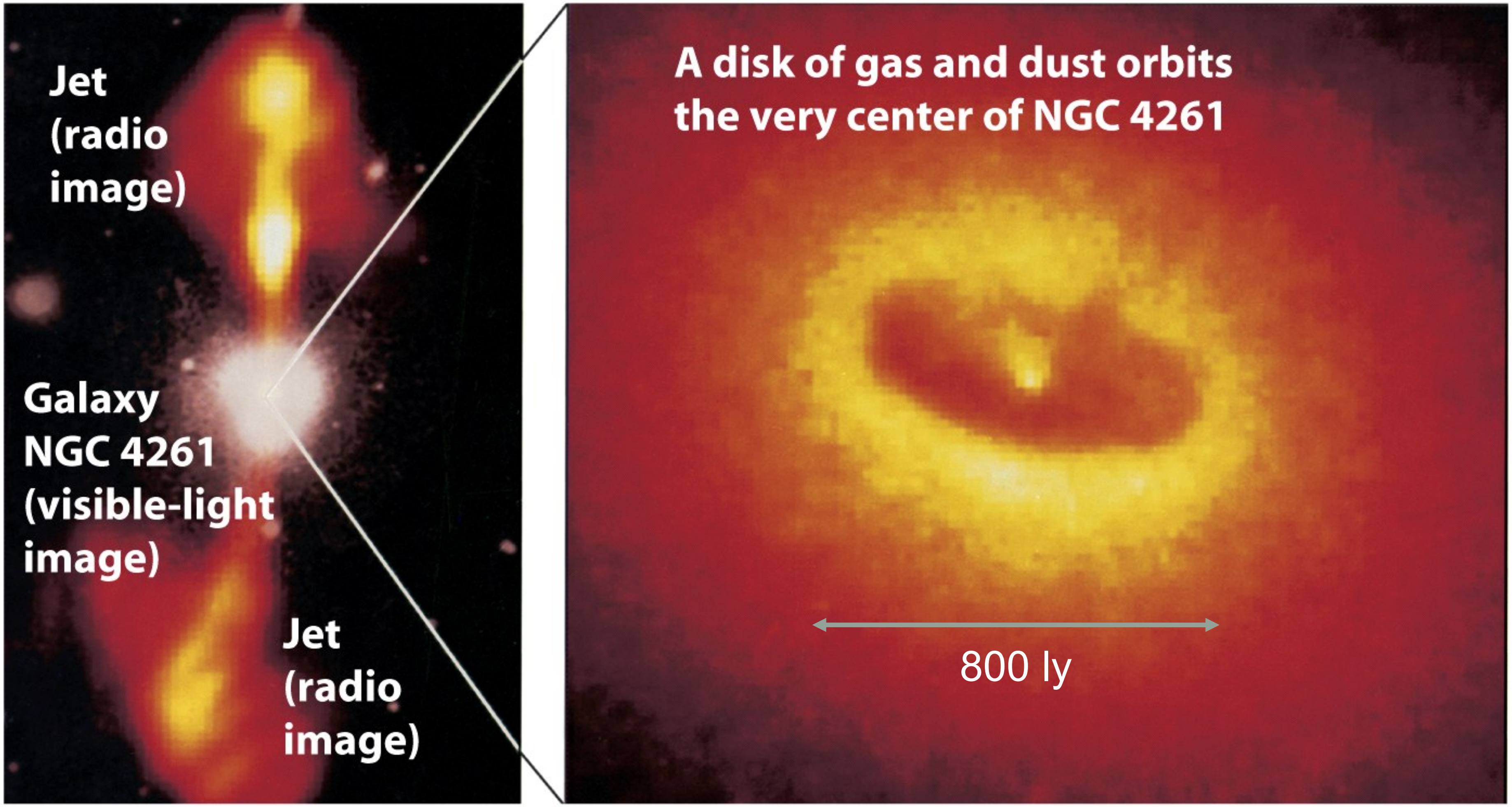
Orbits of stars at the center of the Milky Way indicate a black hole with mass $\sim 4\times10^6\ M_\odot$.



- Rotation curve of the core of M31, indicating central $\sim 4\times10^{7}\ M_{\odot}$ black hole.



The orbital speed and distance of gas orbiting the center of M87 indicate a black hole with mass of $\sim 6\times10^{9}\ M_{\odot}$.



(a) Galaxy NGC 4261

(b) Evidence for a supermassive black hole in NGC 4261