Annoucements

- Homework #8 is available and is due **Monday, October 24.**
- The second exam will be during class on Wednesday, October 26
- E-mail questions before review on Monday, October 24
- Astronomy tutorial: Tuesday 3-5, 7-9 pm in 310 VAN
- Office hours: Tuesday 1–3 pm, Wednesday 10-11 am, or by appointment in 702 VAN

Grading

- 80 points for clicker questions = 80×(% on Icon)
- 80 points for homework = 80×(% on Icon)
- 80 points for each of 3 exams
- Will drop lowest of the 5 scores above
- 160 points for final exam

Do not stop with homework or clicker when you reach 80 points!

More black holes, jets

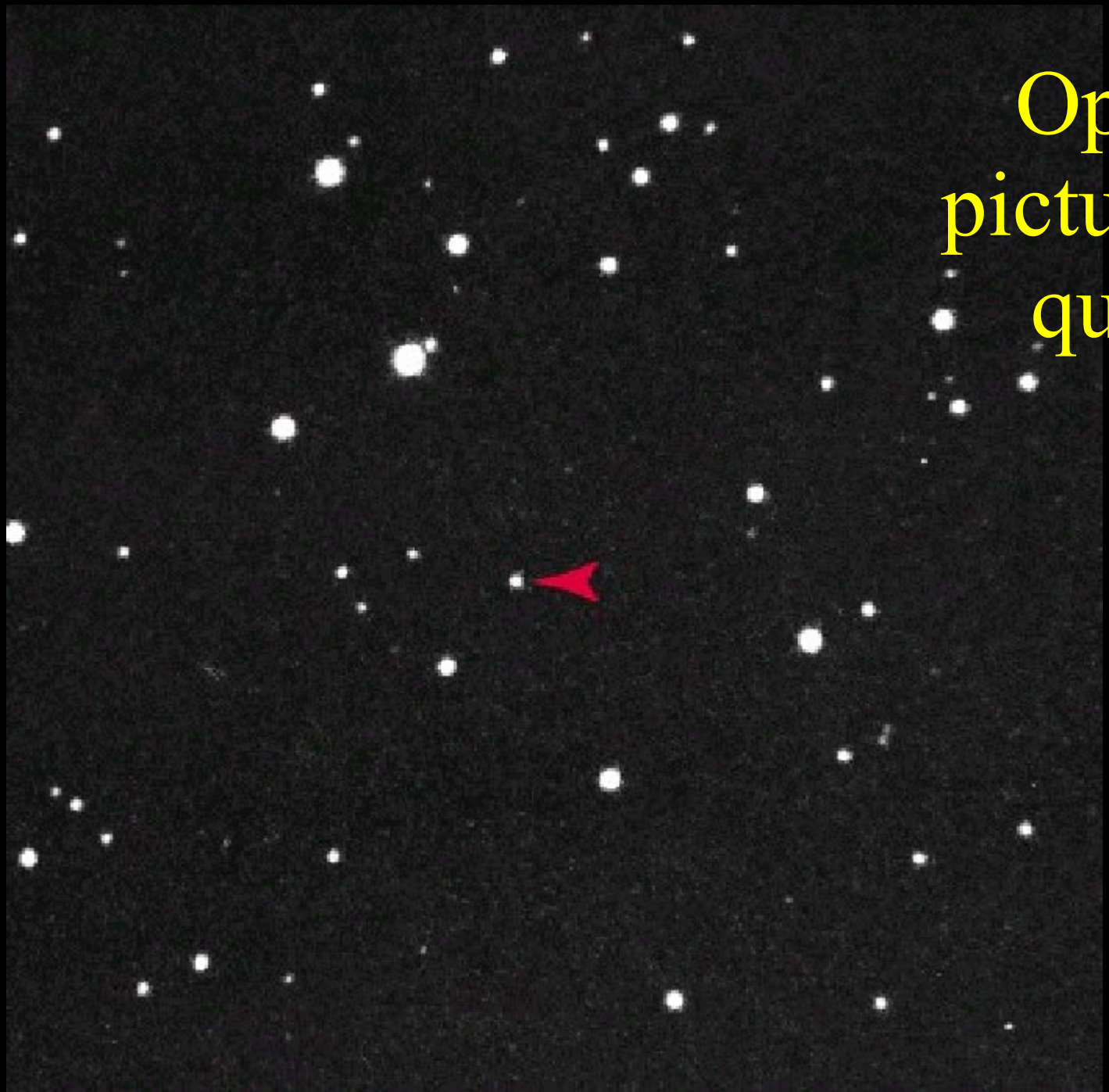
- Quasi-stellar objects
  - Redshifts
  - Variability
  - Supermassive black holes
- Black hole jets
  - Acceleration and Collimation
  - Superluminal motion
  - Evolution of jets
- Medium-sized black holes?

The maximum luminosity for an accreting black hole is the luminosity

A) of a main sequence star of the same mass
B) at which radiation pressure equals gravitation force for infalling matter
C) at which magnetic pressure equals gravitation force for infalling matter
D) produced when Sir Arthur Eddington is dropped into the hole

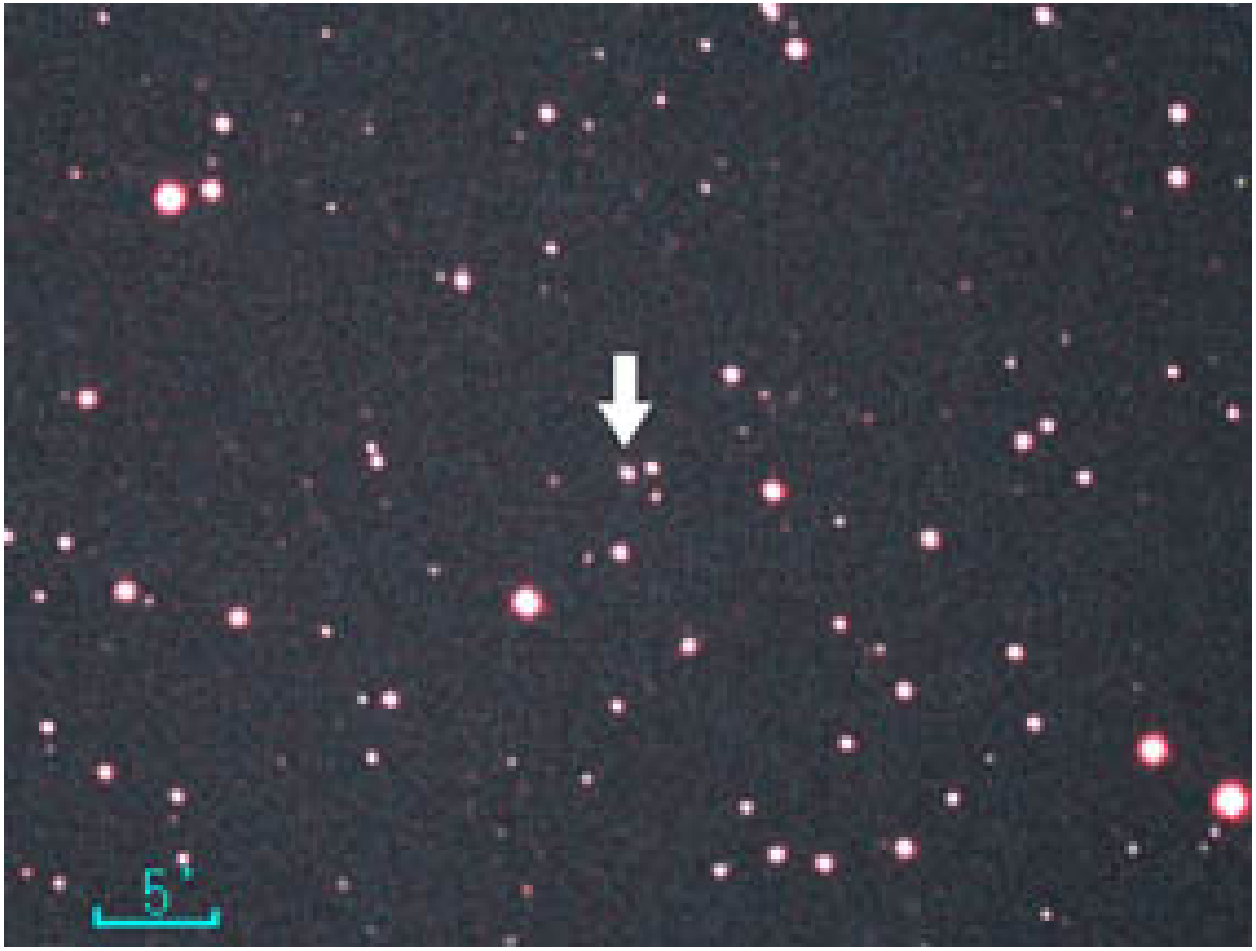
Quasars

- Early radio telescopes found radio emission from stars, nebulae, and some galaxies.
- There were also point-like, or star-like, radio sources which varied rapidly these are the `quasi-stellar' radio sources or quasars.
- In visible light quasars appear as points, like stars.



Optical picture of a quasar

3C273

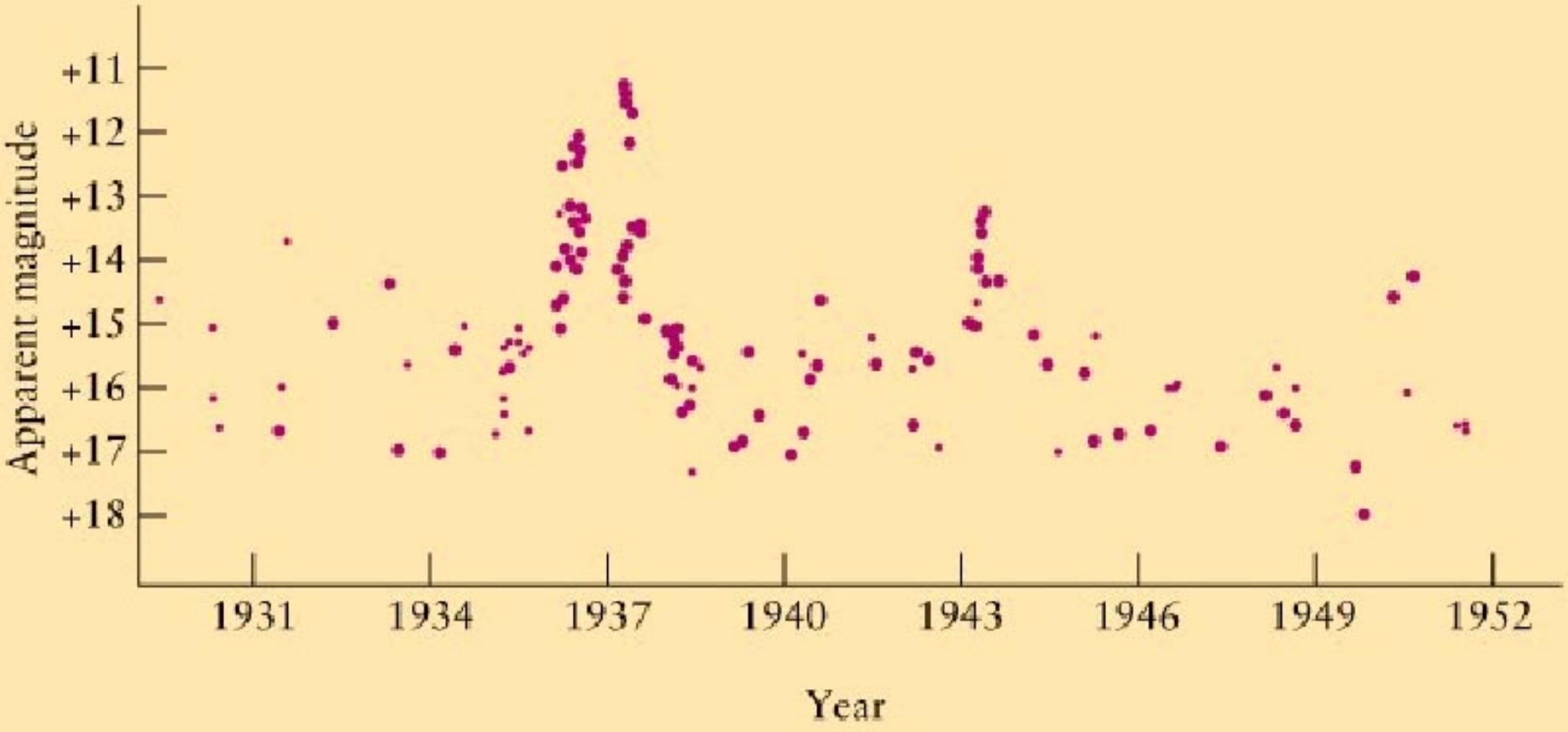


The quasar 3C273 is 2.6 billion light years away.

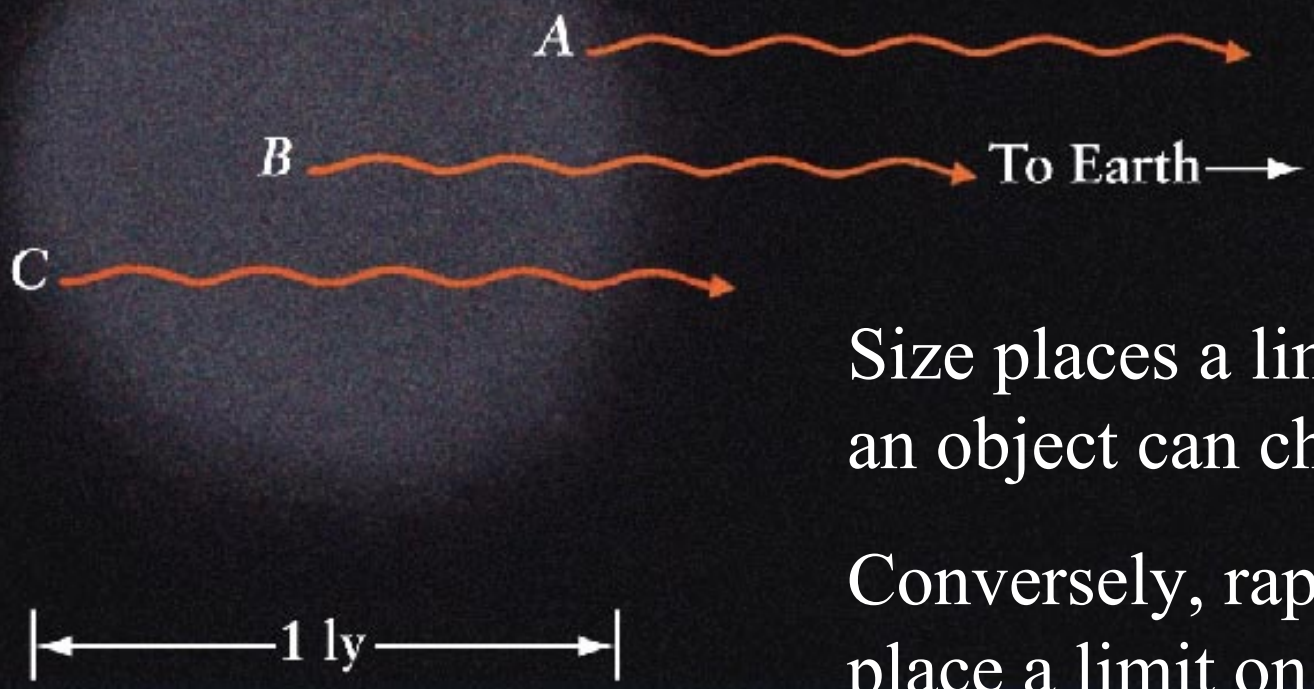
It looks dim, but must be extremely luminous to be visible as such distance.

The luminosity of 3C273 is more than one trillion times the entire energy output of our Sun, or 100 times the luminosity of our entire galaxy.

Quasars vary



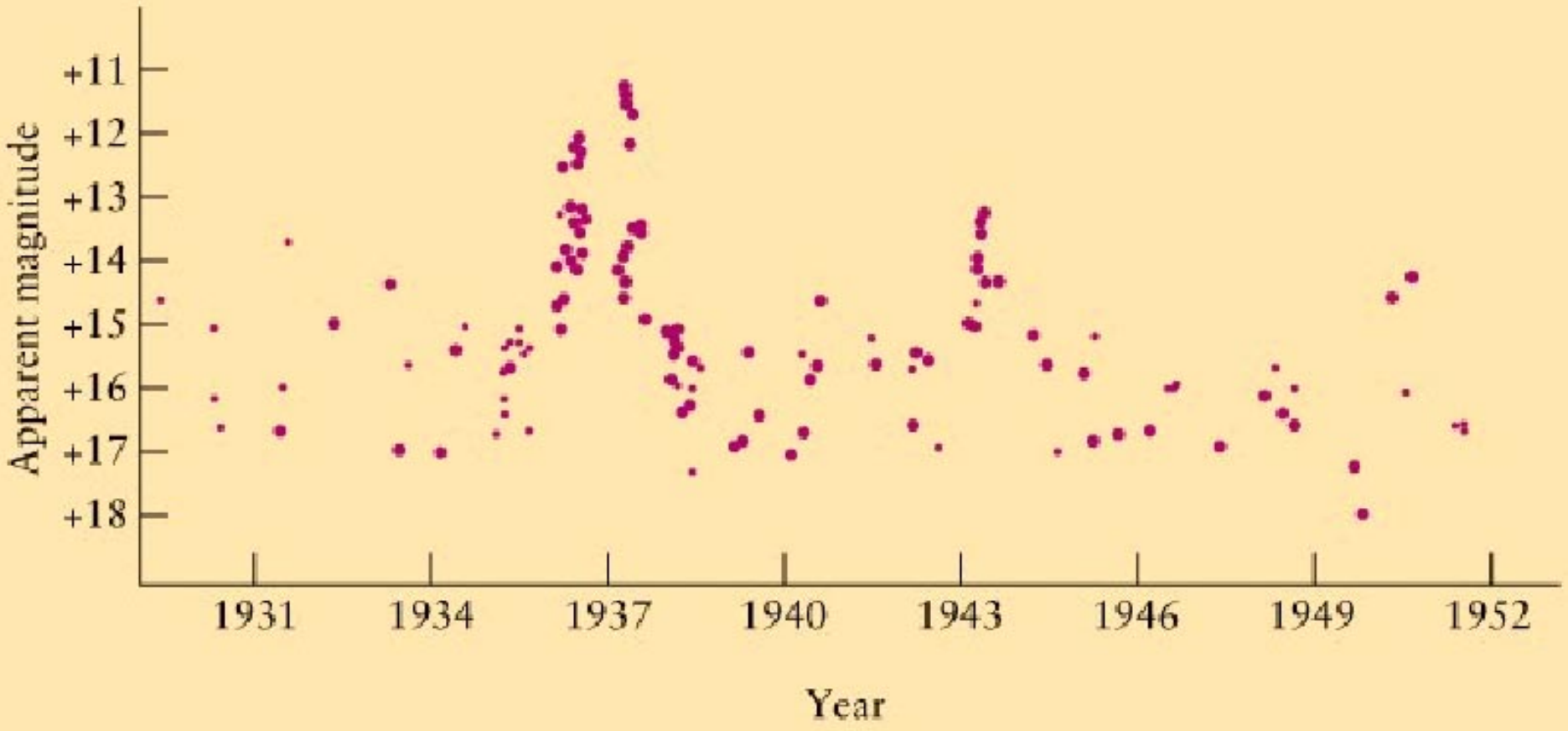
Quasar size



Size places a limit on how fast an object can change brightness.

Conversely, rapid variations place a limit on the size of the emitting object.

Quasars vary



The size of this quasar must be less than about one light year.

Quasar engine

- Quasars have 100 times the luminosity of our Galaxy
- The engine powering quasars is at most a few light years across

- **The only known engine which is powerful enough and compact enough is a black hole**
- Quasars contain supermassive black holes

A quasar varies in brightness by a factor of 2 in 10 days. What does this tell us about the quasar?

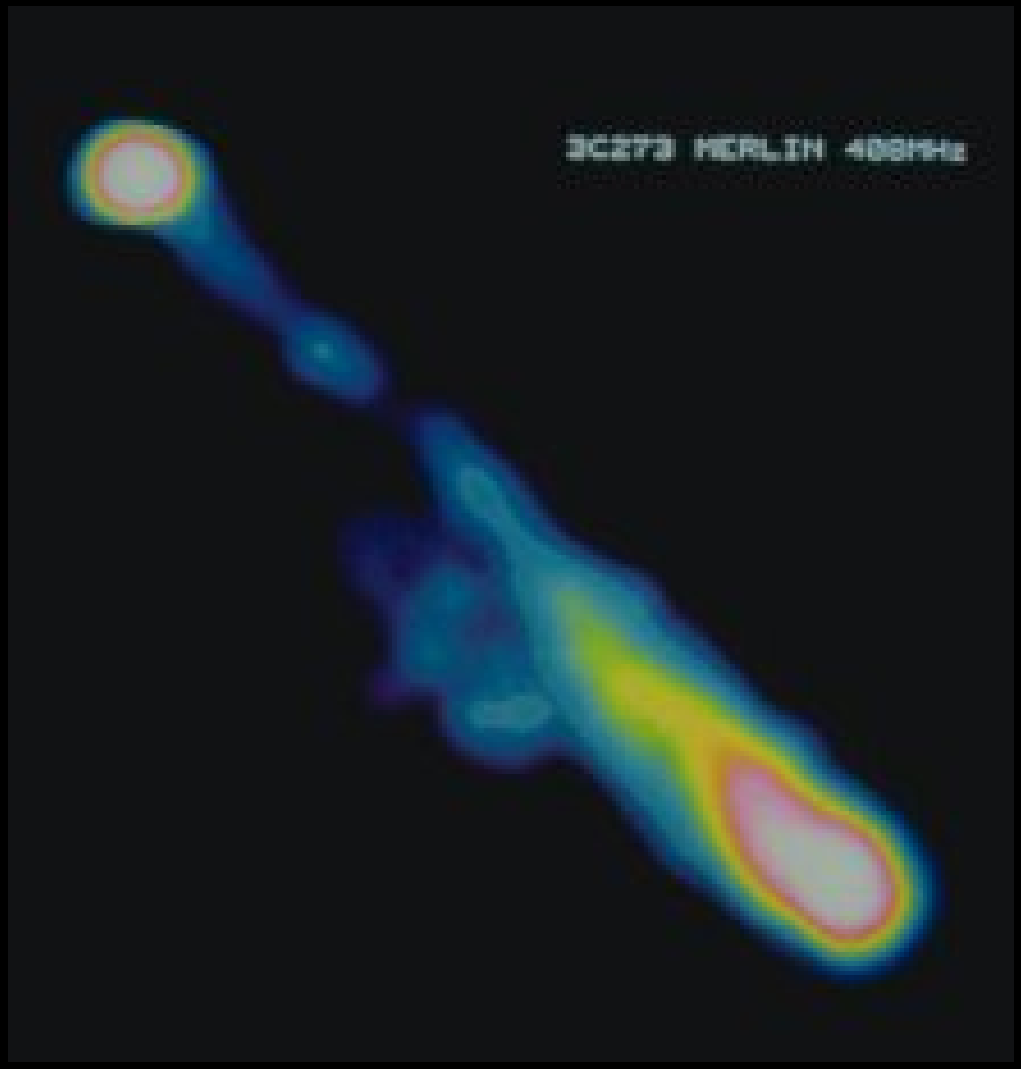
A) It has a large magnetic field.
B) It is quite small.
C) It must be highly luminous.
D) It cannot emit radio waves.

The luminosity of a quasar varies by a factor of 10 over 1 day. What does this tell us about the power source?

A) It cannot be less than 1 light day in diameter
B) It cannot be less than 10 light days in diameter
C) It cannot be more than 1 light day in diameter
D) It cannot be more than 10 light days in diameter
E) It cannot make up its mind

Quasar jets

Optical core →

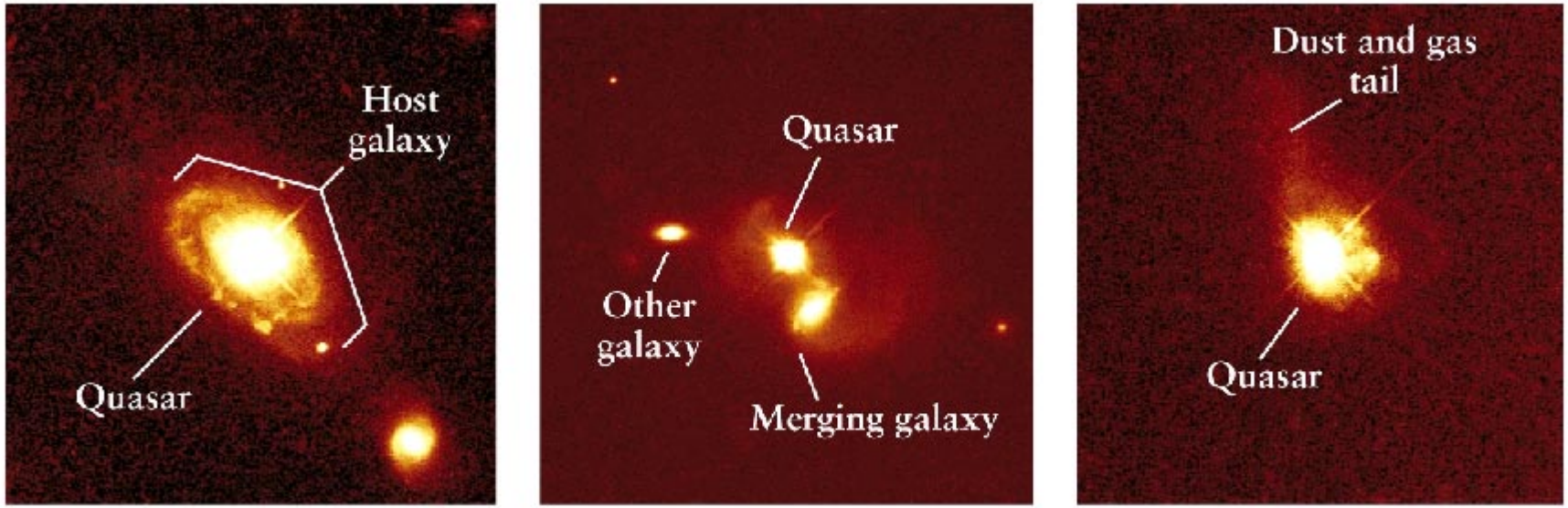


Radio jet →

Quasars

- object with a spectrum much like a dim star
- high red shift
- enormous recessional velocity
- huge distance (from Hubble's Law)
- enormously luminous
- compact physical size
- powered by supermassive black hole
- often produce huge jets

Quasars are the ultraluminous centers of distant galaxies.



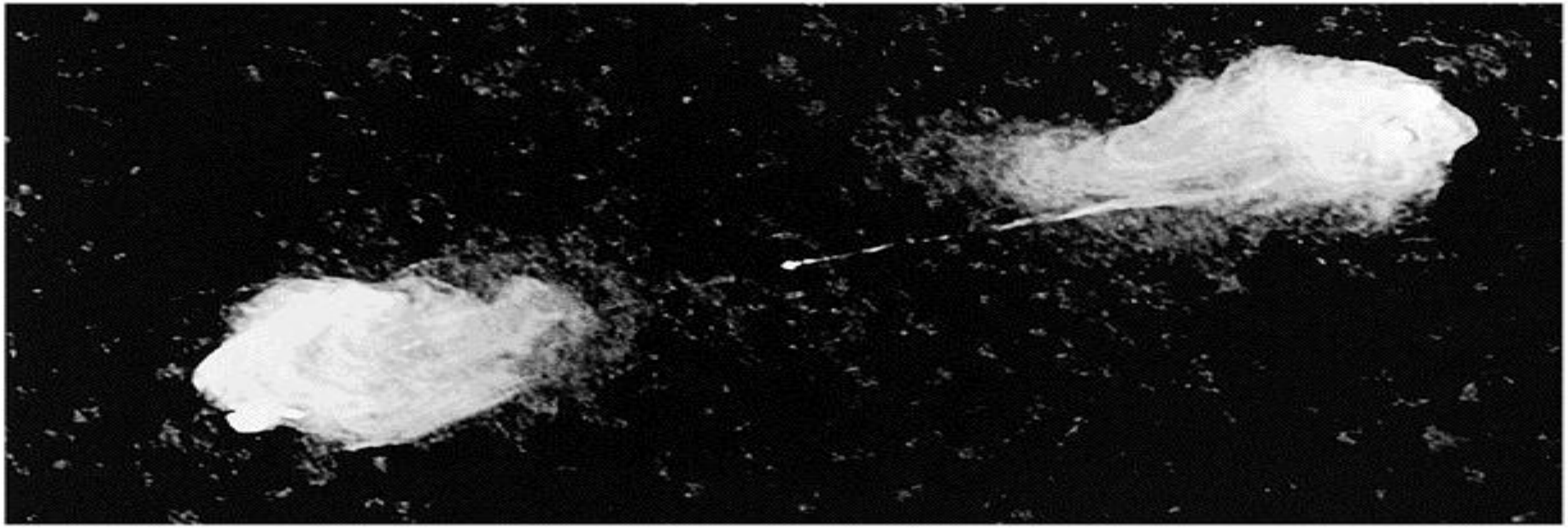
Quasars are often observed to be at the center of distant galaxies. The wispy material is likely gas that has been pulled out of the hot galaxy by gravitational interactions with nearby galaxies.

What is the radius of a 100 million solar mass black hole (non-rotating) such as those that exist at the centers of some quasars?

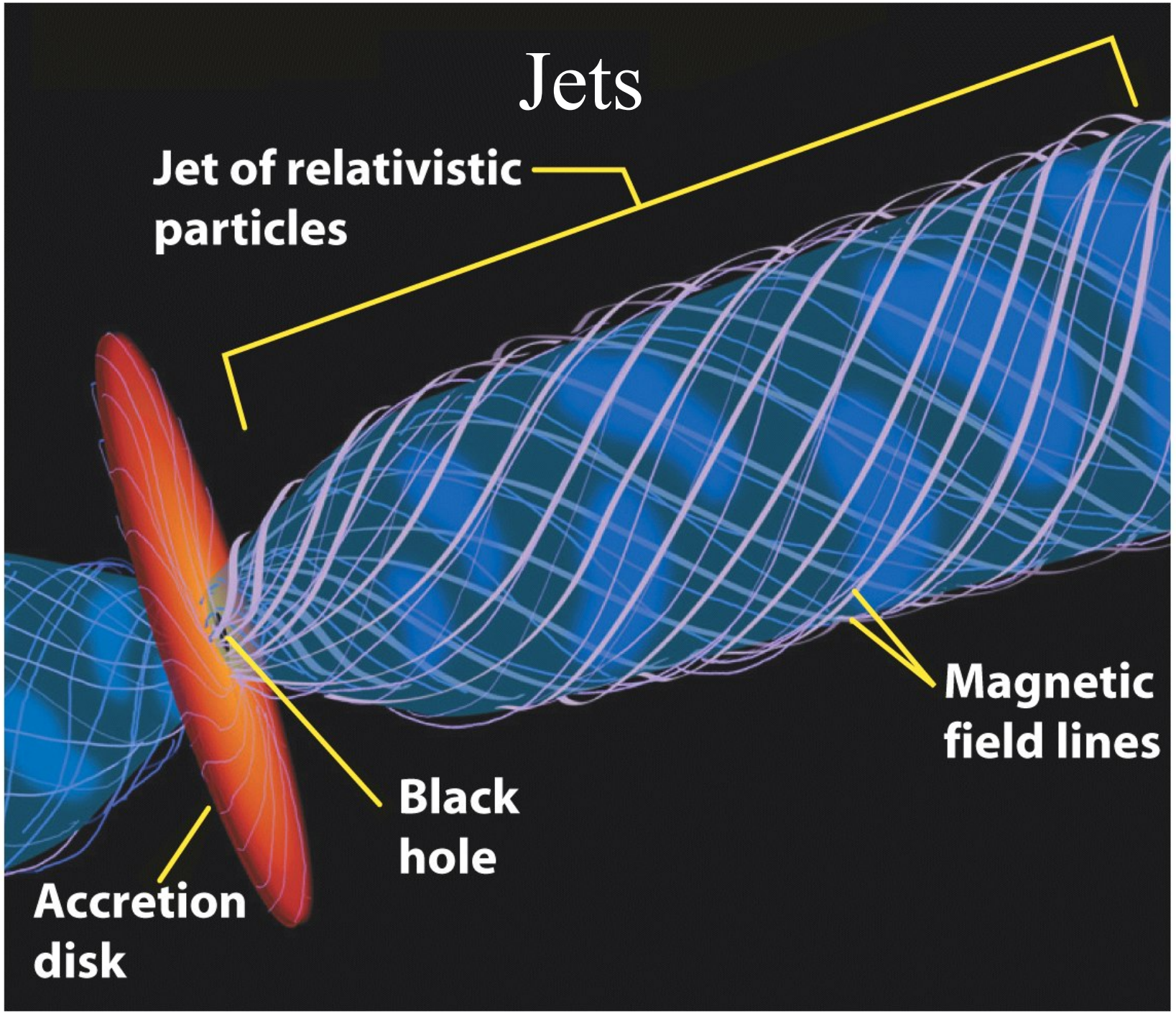
A) 10 km (neutron star)
B) 6000 km (Earth)
C) 1.5×10^8 km (AU)
D) 10^{13} km (light year)

Schwarzschild radius $= 3$ km (M/M_{Sun})

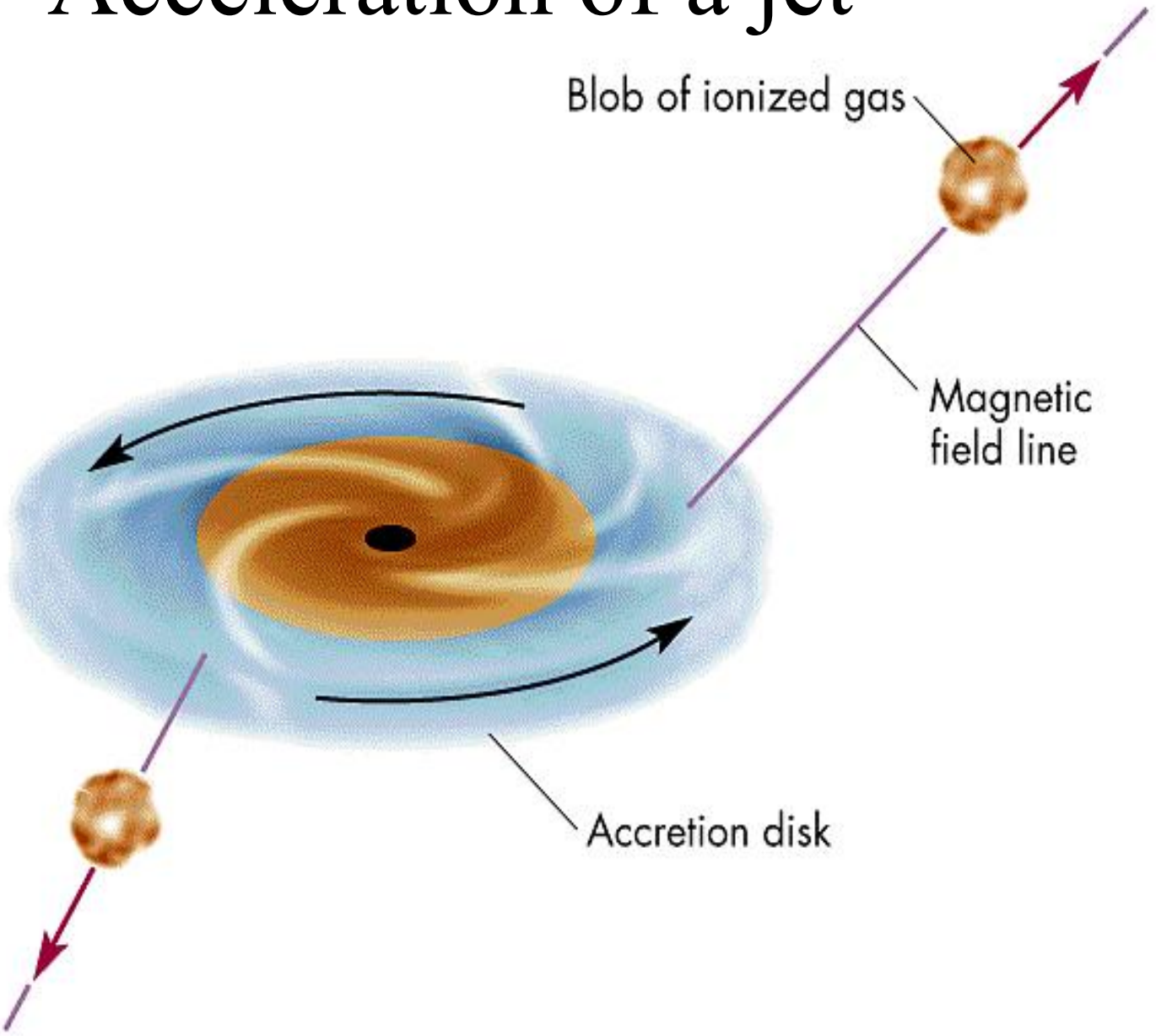
Jets



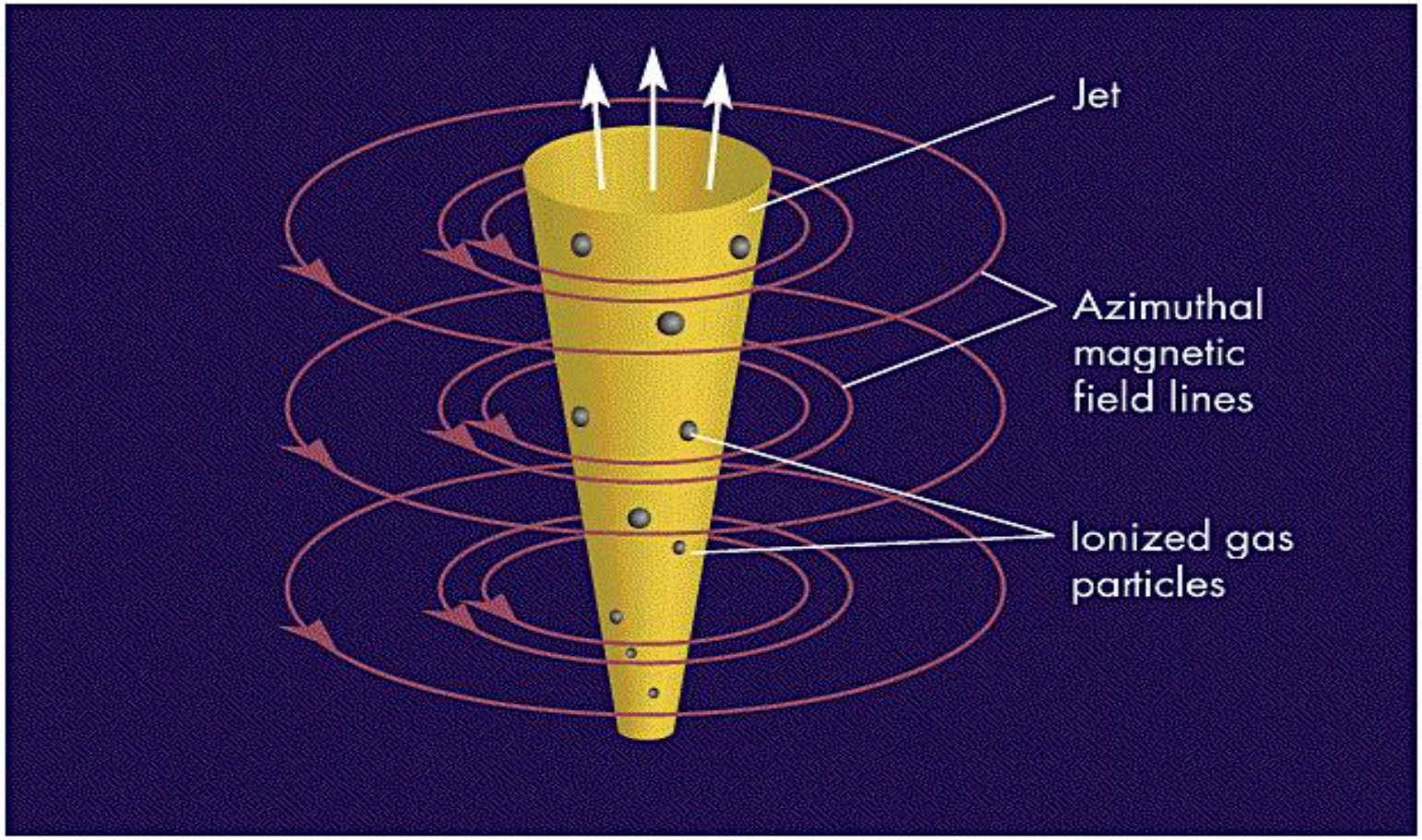
| -- Size of our Galaxy -- |


Jets
Jet of relativistic particles
Magnetic field lines
Black hole
Accretion disk

Acceleration of a jet



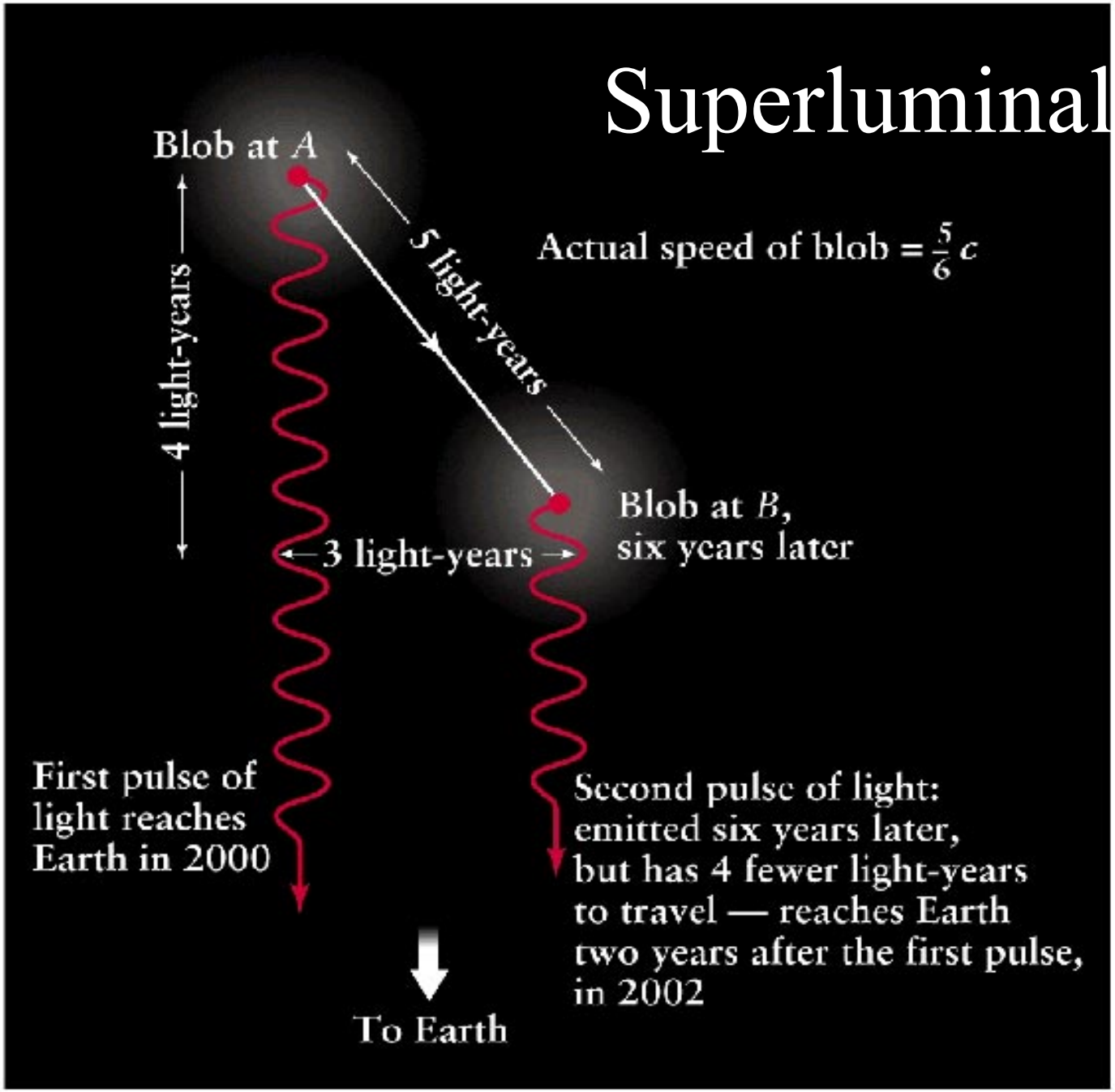
Collimation of a jet



Origin of jets is an unsolved problem

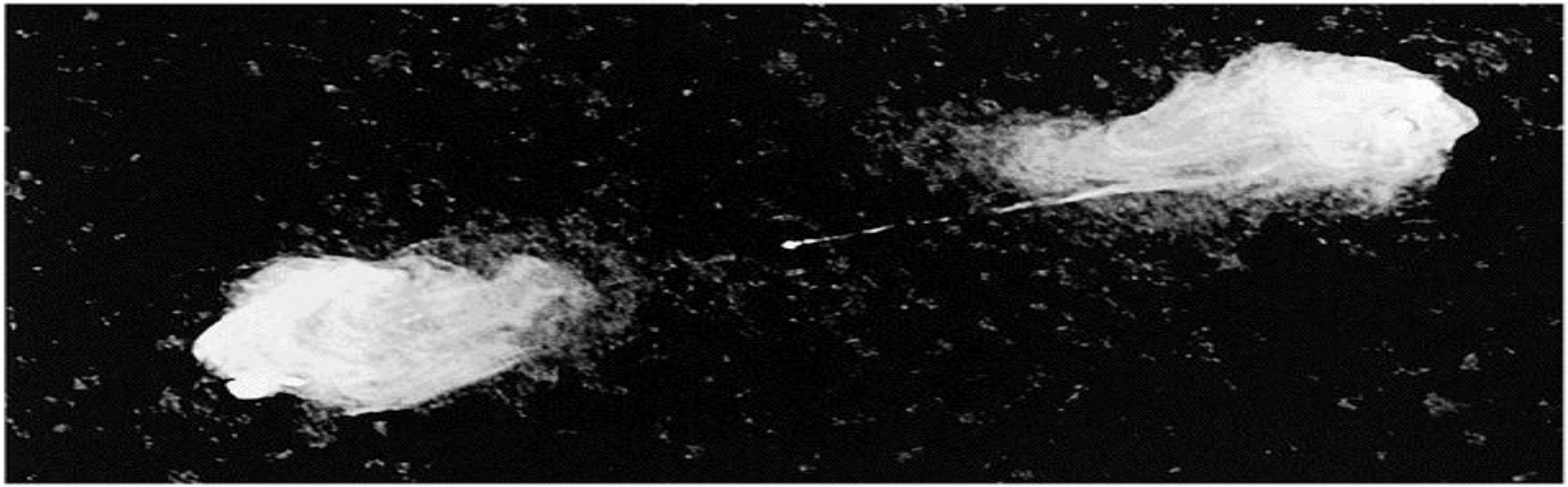
- The production and propagation of jets is a major topic in current research.

Superluminal motion



a View from above

What is the lifetime of this jet?



A) Not more than 150,000 years
B) Exactly 150,000 years
C) At least 150,000 years

| ---------- | = 150,000 light years

Evolution of Jets

- Jets from active galaxies are large and change slowly.
- Jets from solar-mass black holes are smaller, by the ratio of the black hole masses, and change more rapidly.
- It is possible to study the evolution of jets from solar-mass black hole.
- Show movie and then animation.

Black hole masses

- Two types of black holes
- Stellar mass black holes are up to 30 solar masses, formed in collapse of stars
- Supermassive black holes are 10^6-10^9 solar masses, found only in the nuclei of galaxies

- Is there anything in between?

Starburst galaxy – M82

M 82 (NGC 3034)

FOCAS (B, V, Hα)

Subaru Telescope, National Astronomical Observatory of Japan

March 24, 2000

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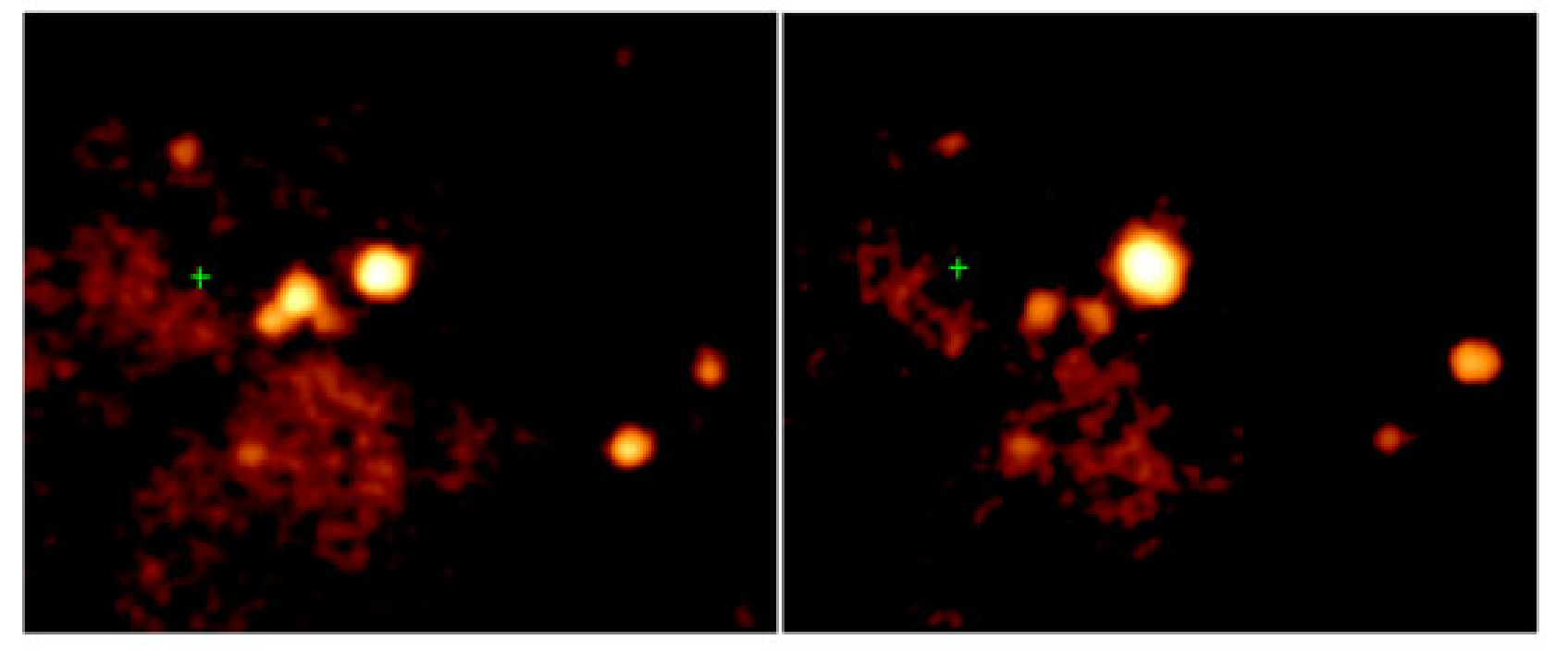
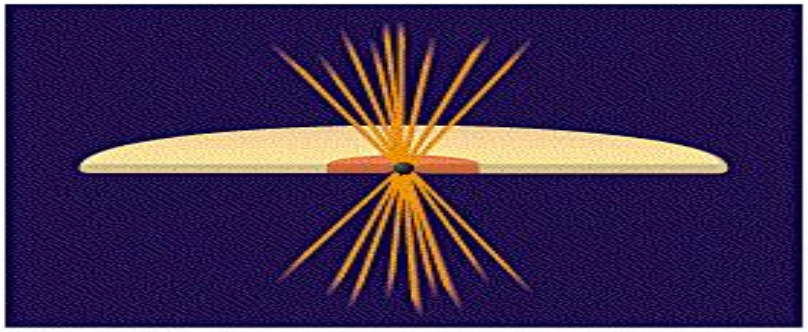
Starburst galaxy M82 in X-rays

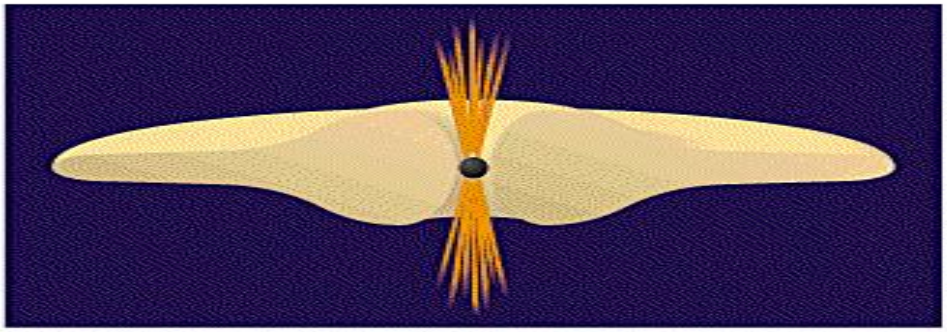


Green cross is center of galaxy
Bright X-ray source is 15,000,000 solar luminosities
From Eddington limit, looks like a 500 solar mass black hole

Beaming



A Thin disk: Slow accretion of matter

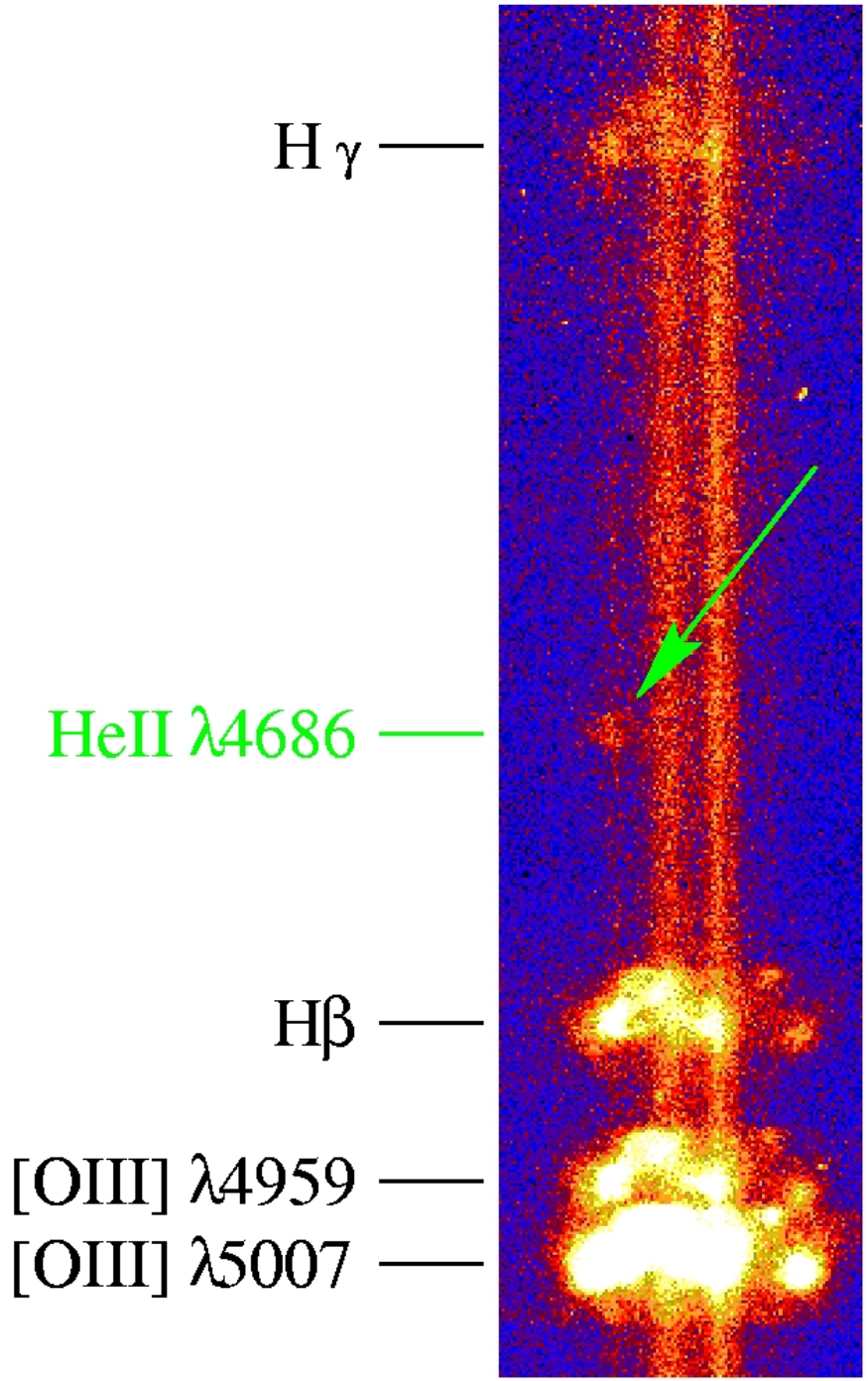


B Thick disk: Rapid accretion of matter

Is the source really as luminous as it looks or are the X-rays in a beam pointing towards us?

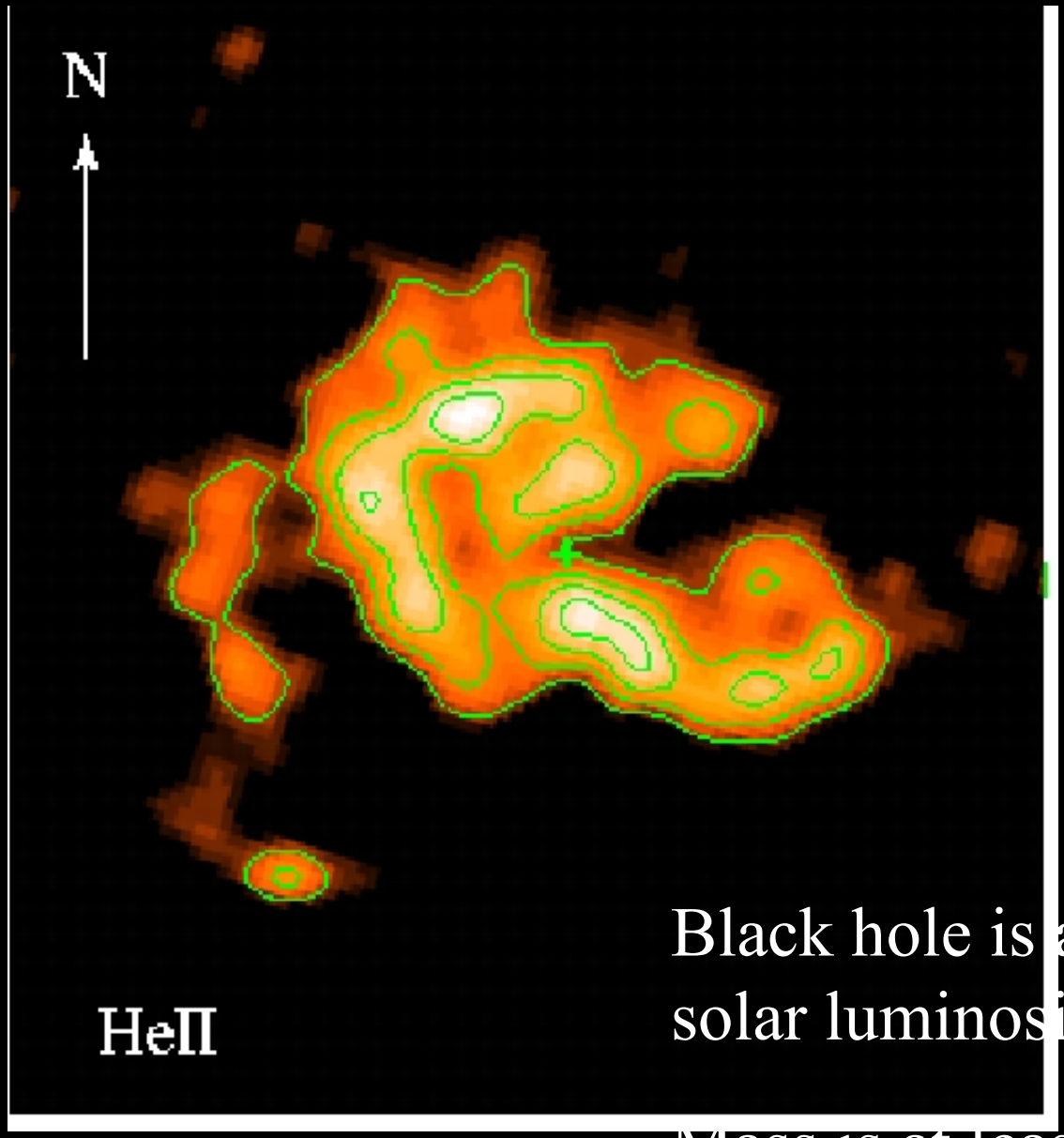
Nebula surrounding a BH

- X-rays from the BH ionize Helium in the nebula which causes the Helium to emit one particular spectral line
- By counting the number of photons in this spectral line of Helium, we can count the number of X-rays and find the true X-ray luminosity in all directions



Nebula around a black hole

Nebula around a black hole



Black hole is at least 750,000 solar luminosities.

Mass is at least 85 solar masses.

How do we know that quasars are no larger than the solar system?

A) The are too luminous to be very large.

B) The appear point like when viewed through a telescope.

C) The contain black holes.

D) The vary in brightness on time scales of days or weeks.

Black holes are invoked to explain quasars because

A) We can directly see matter falling across the event horizon

B) Quasars emit no light

C) Quasars are very distant

D) Black holes are very efficient and compact power generators

Review Questions

- How can we place an upper bound on the size of a quasar even if we can't resolve it with a telescope?
- How are jets accelerated?
- How are jets collimated?
- Do superluminal jets really move faster than the speed of light?
- Do the jets of stellar-mass black holes evolve faster or slower than the jets of supermassive black holes?
- How can the luminosity of a black hole be used to estimate its mass? Why is this method sometimes uncertain?
- Are there medium-sized black holes in the Universe?