Today's Topics

Friday, April 25, 2025 (Week 12, Lecture 33) – Chapter 27.

1. Galaxy types
2. Quasars
3. Active galactic nuclei

Problem Set #11 is due on ExpertTA on Friday, May 2, 2025, by 9:00 AM

Interlude 2 essay is due on Gradescope on Monday, April 28, 2025 by 9:00 AM

Properties of Galaxy Classes

Characteristics of the Different Types of Galaxies

Characteristic	Spirals	Ellipticals	Irregulars
Mass (M_{Sun})	10^9 to 10^{12}	10^5 to 10^{13}	10^8 to 10^{11}
Diameter (thousands of light-years)	15 to 150	3 to >700	3 to 30
Luminosity (L_{Sun})	10^8 to 10^{11}	10^6 to 10^{11}	10^7 to 2×10^9
Populations of stars	Old and young	Old	Old and young
Interstellar matter	Gas and dust	Almost no dust; little gas	Much gas; some have little dust, some much dust

[OpenStax, Astronomy 2e (2025), Table 26.1]

Mass-to-Light Ratio

Mass in units of M_{sun} Luminosity in units of L_{sun}

$$\text{Mass-to-Light ratio} = \frac{Mass}{Luminosity}$$

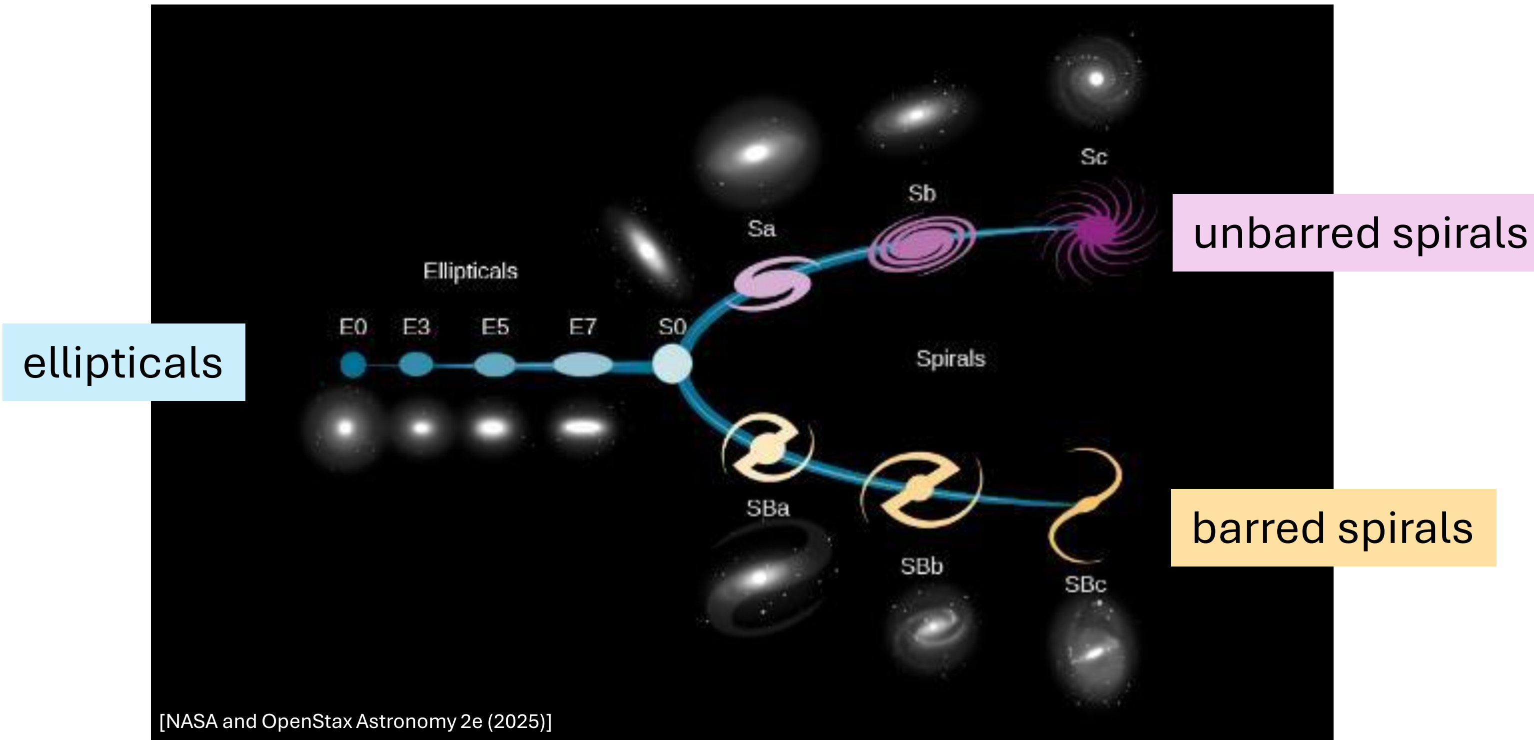
Characteristic	Spirals	Ellipticals	Irregulars
Mass-to-light ratio in the visible part	2 to 10	10 to 20	1 to 10
Mass-to-light ratio for total galaxy	100	100	?

Includes dark matter

[OpenStax, Astronomy 2e (2025), Table 26.1]

PollEv Quiz: PollEv.com/sethaubin

Hubble's Classification Scheme



Edwin Hubble's original classification of galaxies.

IMPORTANT: This "tuning fork" diagram does NOT represent galaxy evolution.

(though astronomers did try … sort of like the H-R diagram)

Quasars

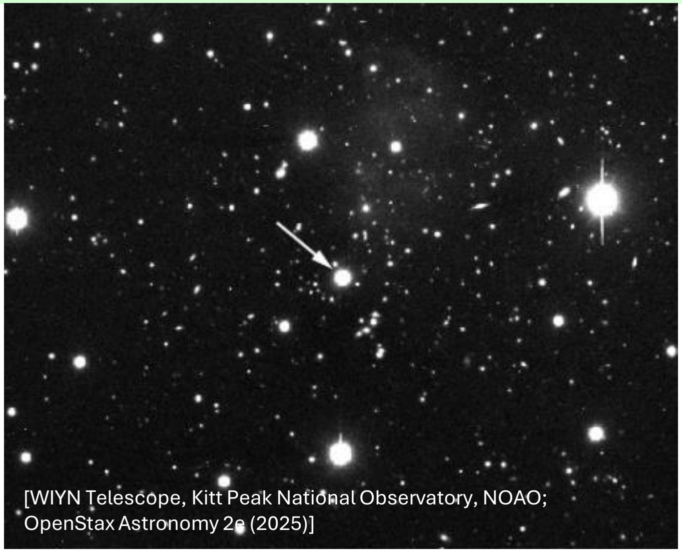
- Quasi-Stellar Radio Source (or quasar) are *point-like* intense **radio sources.**
  → discovered in the 1950s (using WW2 radar/radio equipment).

- In the visible, they look like faint blue-ish stars.

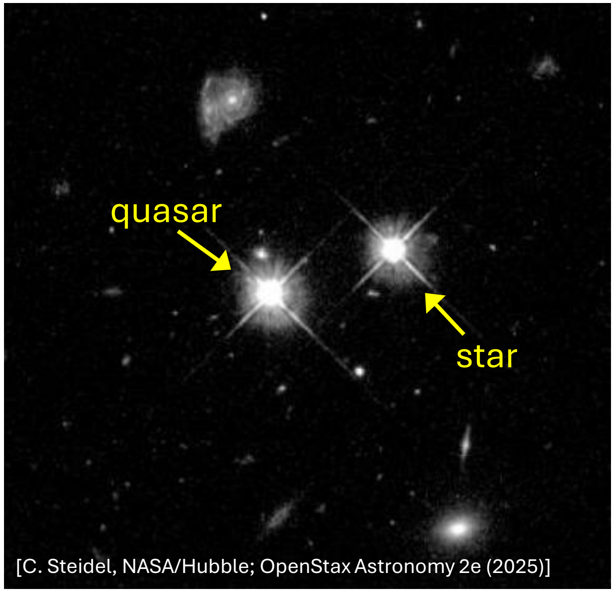
- Except stars typically do not emit much in the radio part of the spectrum.

- They are quite **numerous** and distributed **uniformly** over the sky.

→ What are **quasars**?



Quasar PKS 1117-248



Quasar Spectrum

- **Maarten Schmidt** discovered the primary clue for understanding quasars (in 1963).
- Quasars have a **very red-shifted spectrum**: Red shift is $\mathbf{0.06 \lesssim z \lesssim 10}$.
- A velocity of 15% of *c* is very large (quasar 3C 273): v= 45,000 km/s.
  → Quasars are extragalactic.
- Hubble's law
  → $d = v/H = 2 \times 10^9$ light years.
  (for $z = 0.15$)

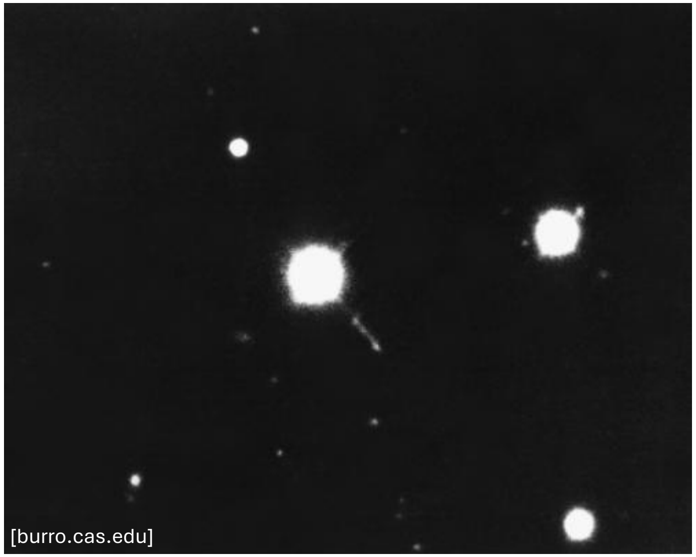
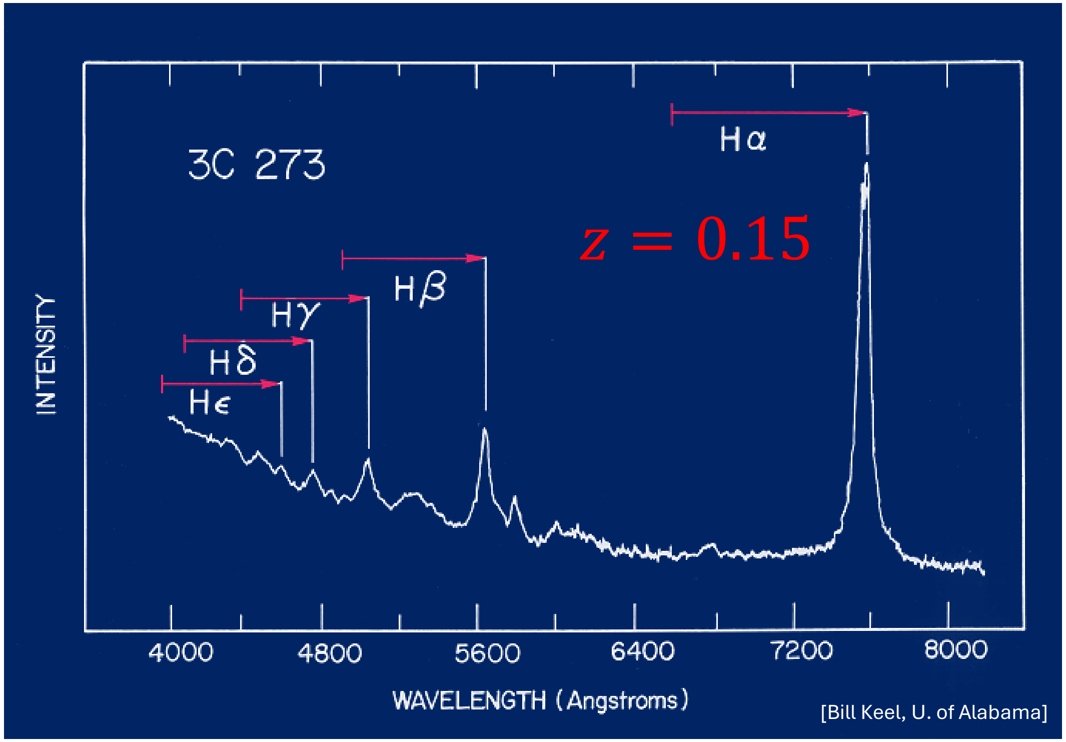


Photo of quasar 3C 273



Visible spectrum of quasar 3C 273

Quasar Properties

- Quasar have an extremely high luminosity: $10LMW < L_{quasar} < 10^5 L_{MW}$.
  (MW = Milky Way)

- Quasars are very far away: $10^9\ light\ years < \ distance\ < 13 \times 109\ light\ years$.

- Over 900,000 discovered so far: they are distributed uniformly over the sky.

- Quasar luminosity varies on short time scales: hours to months.
  → Implies that **quasars are very compact**
  with *sizes of* ***light hours to light months***.
  (Solar system diameter (Neptune) $\approx$ 8 light hours)

Quasar Properties

- Quasar have an extremely high luminosity: $10LMW < L_{quasar} < \ 10^5 L_{MW}$.
  (MW = Milky Way)

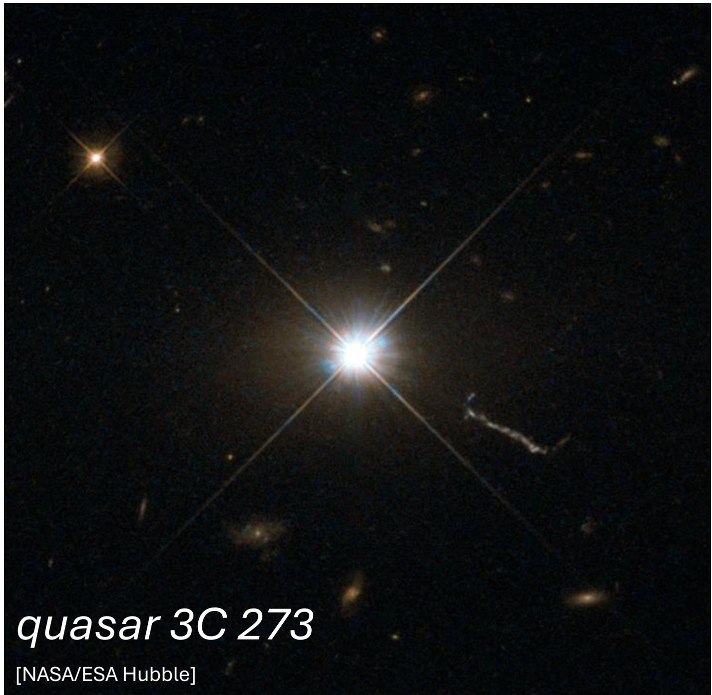
- Quasars are very far away: $10^9 \ light \ years < \ distance \ < 13 \times 109 \ light \ years$.

- Over 900,000 discovered so far: they are distributed uniformly over the sky.

- Quasar luminosity varies on short time scales: hours to months.
  → Implies that **quasars are very compact** with *sizes of **light hours to light months***.
  (Solar system diameter (Neptune) ≈ 8 light hours)

- Quasar sometimes have **<u>jets</u>** of material spewing out of them.
  → These tend to have stronger radio emissions.

- Only 10% of quasars have strong radio emissions. The other 90% have weaker radio emissions.

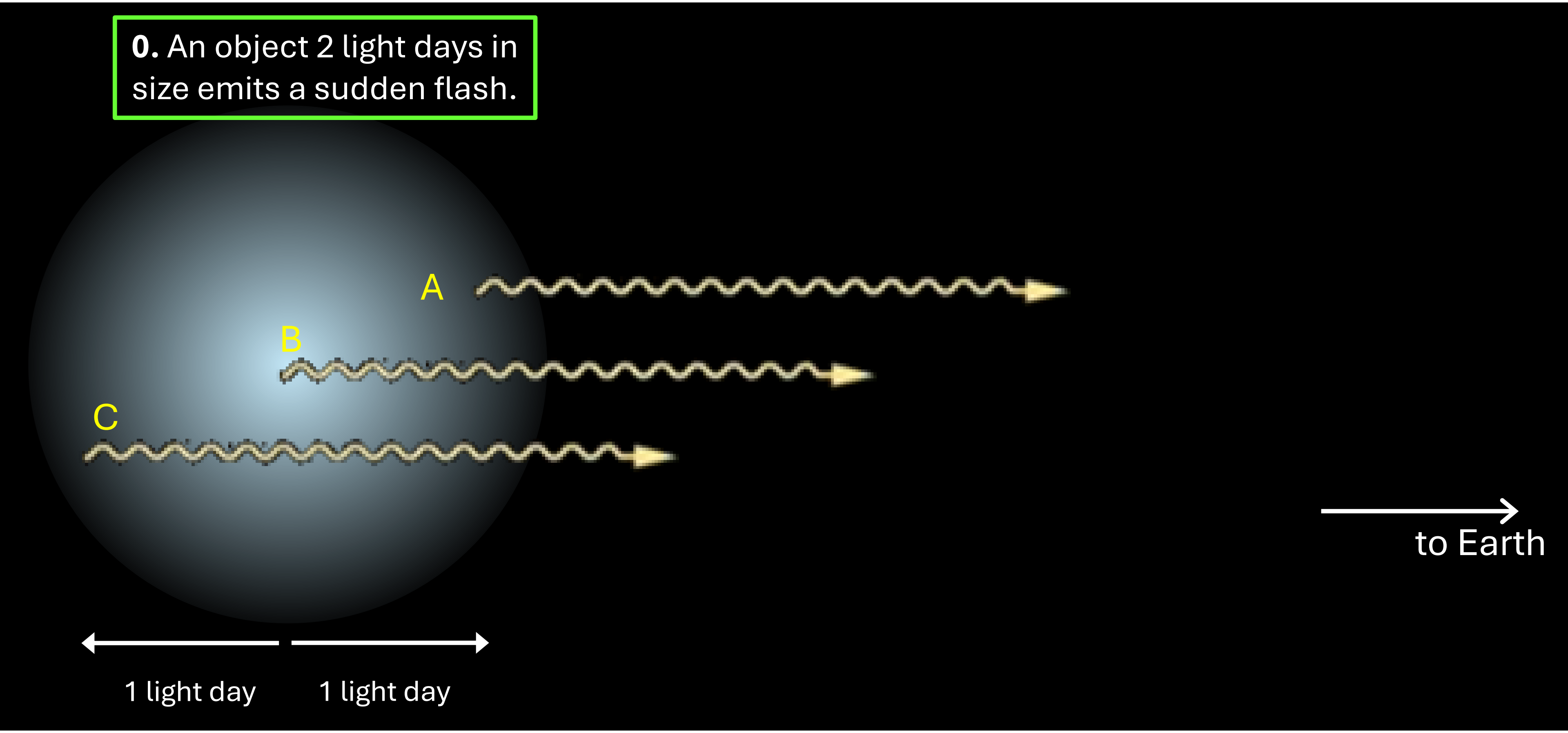


quasar 3C 273

[NASA/ESA Hubble]

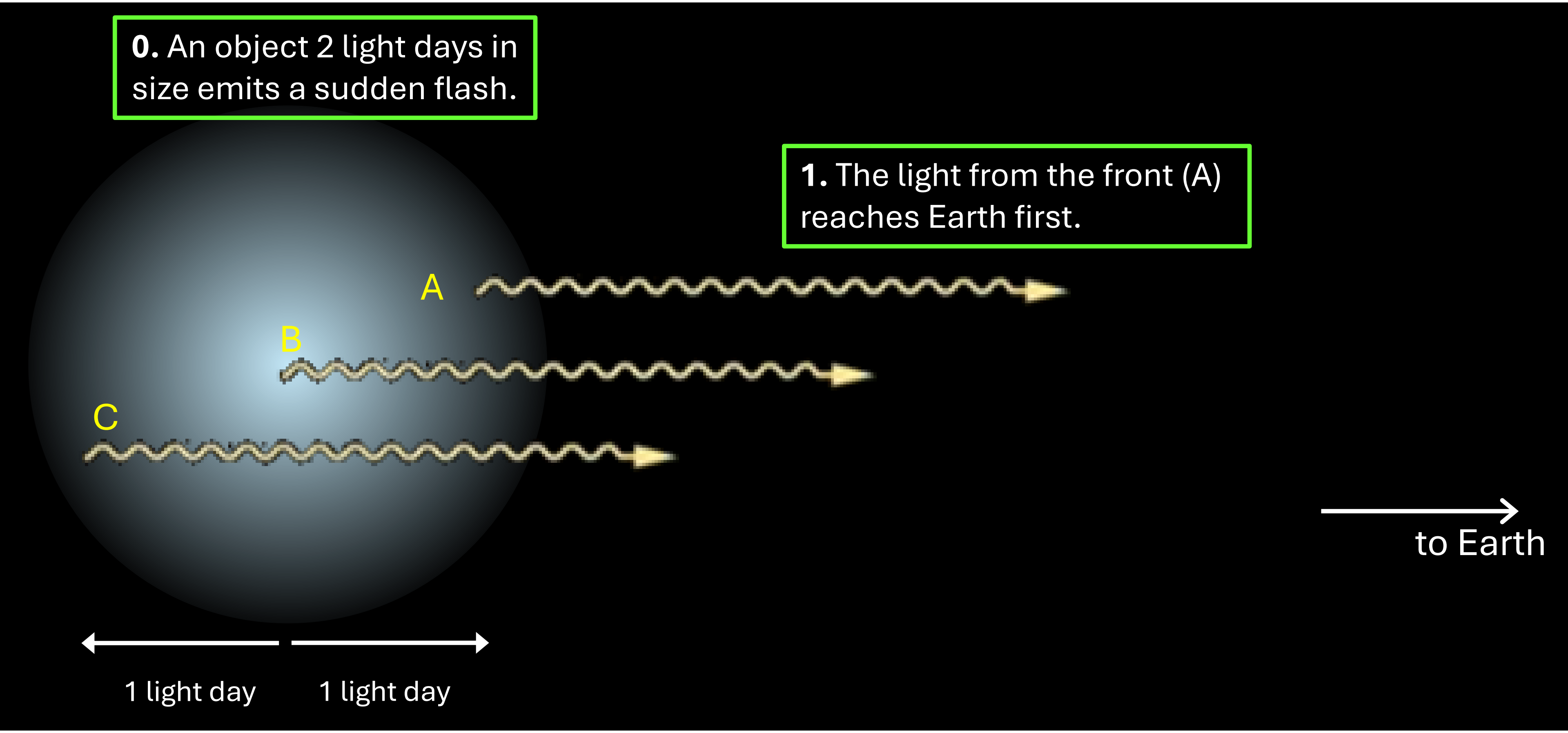
Size of Quasars

The size of a distant light source determines the timescale for apparent brightness variations as seen on Earth.



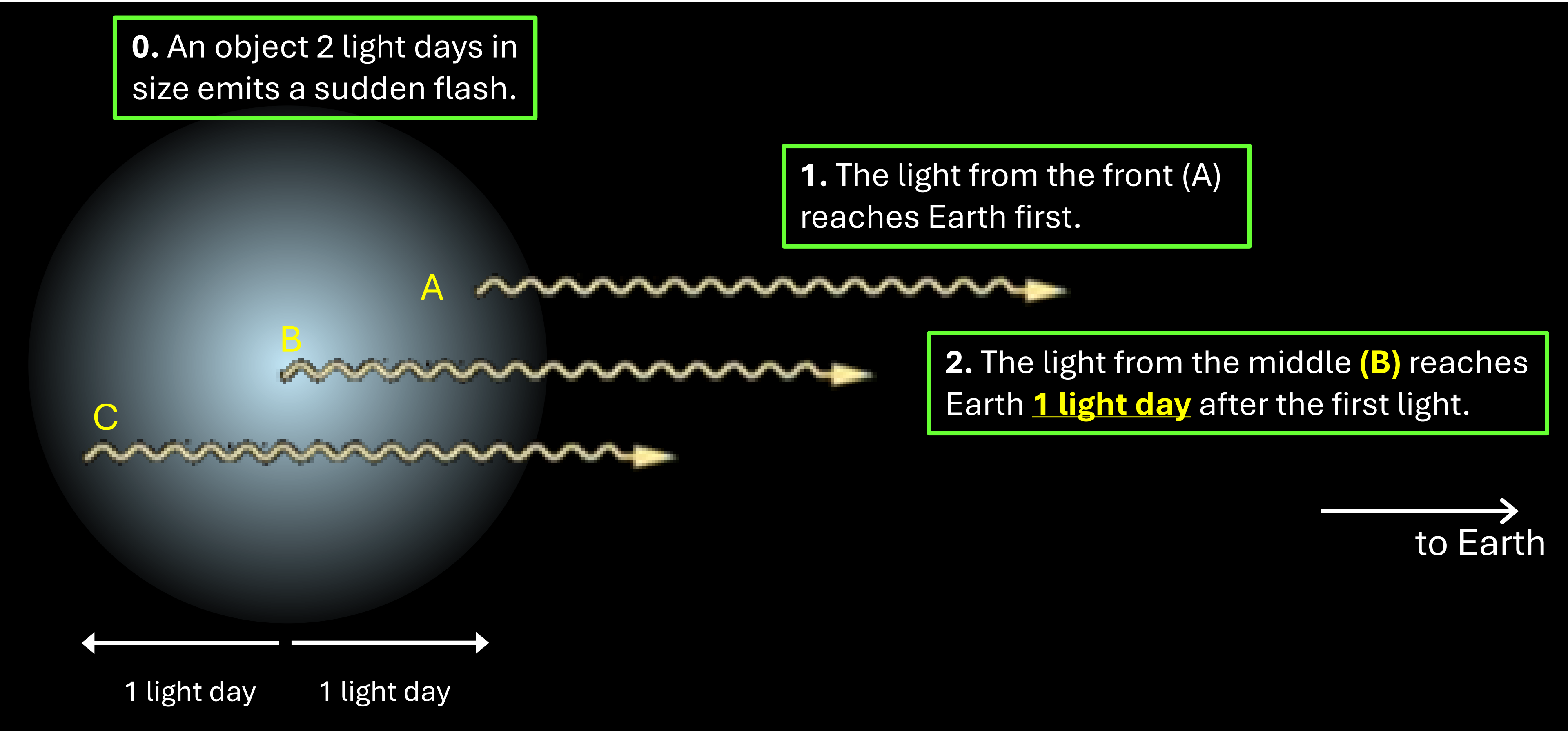
Size of Quasars

The size of a distant light source determines the timescale for apparent brightness variations as seen on Earth.



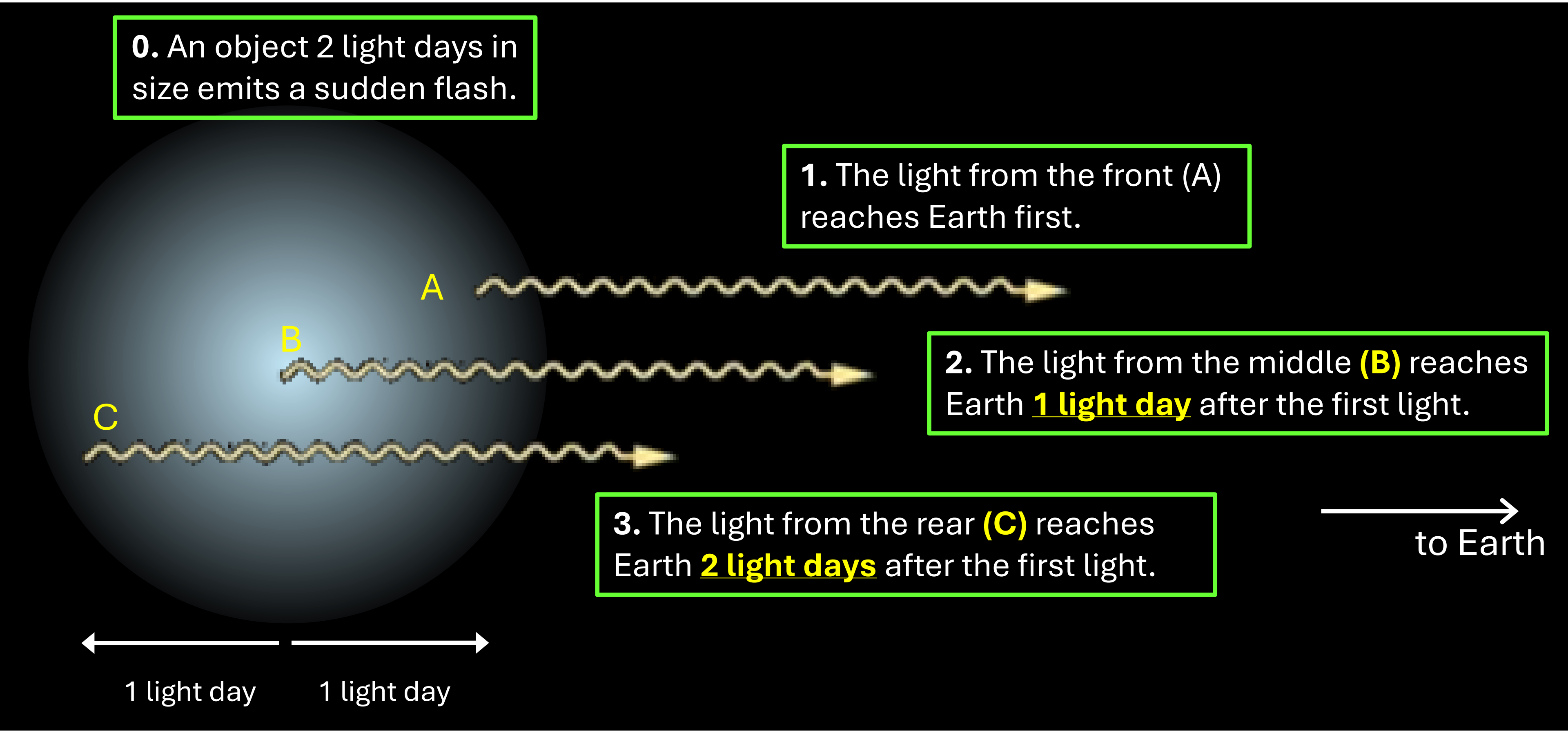
Size of Quasars

The size of a distant light source determines the timescale for apparent brightness variations as seen on Earth.



Size of Quasars

The size of a distant light source determines the timescale for apparent brightness variations as seen on Earth.



What Are Quasars?

- ✓ 1000 times luminosity of Milky Way
- ✓ Size of the solar system

Supermassive black hole feeding on 10 – 1000 M_{sun} per year

→ Gravitational potential energy is converted to radiation.
(efficiency: 6% – 32%)

→ Supermassive black hole with mass of 10^9 M_{sun} or larger needed.

What Are Quasars?

- ✓ 1000 times luminosity of Milky Way
- ✓ Size of the solar system

Supermassive black hole feeding on 10 – 1000 M_{sun} per year

→ Gravitational potential energy is converted to radiation.
(efficiency: 6% – 32%)

→ Supermassive black hole with mass of 10^9 M_{sun} or larger needed.

Milky Way “supermassive” black hole (Sagittarius A*) is much smaller.
→ Mass of only 4×10^6 M_{sun}.
→ About 1 M_{Sun} falls in every 1000 years.

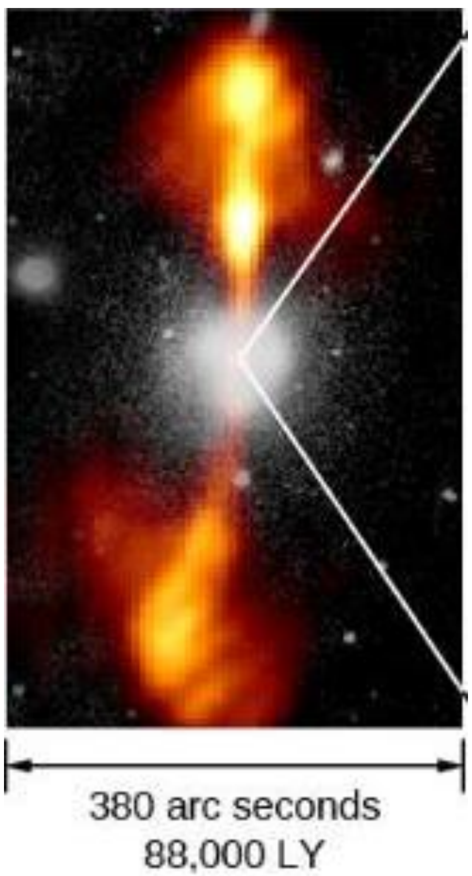
What Are Quasars?

- ✓ 1000 times luminosity of Milky Way
- ✓ Size of the solar system

Supermassive black hole feeding on 10 – 1000 M_{sun} per year

→ Gravitational potential energy is converted to radiation. (efficiency: 6% – 32%)

→ Supermassive black hole with mass of 10^9 M_{sun} or larger needed.



Quasar = active galactic nucleus

(with a "feeding" supermassive black hole)

NGC 4261 active elliptical galaxy (not a quasar but a model for one)
(Virgo Cluster of galaxies, distance 100 million light years)
White = optical emission
Orange = Radio emission

[NASA/ESA, Hubble]

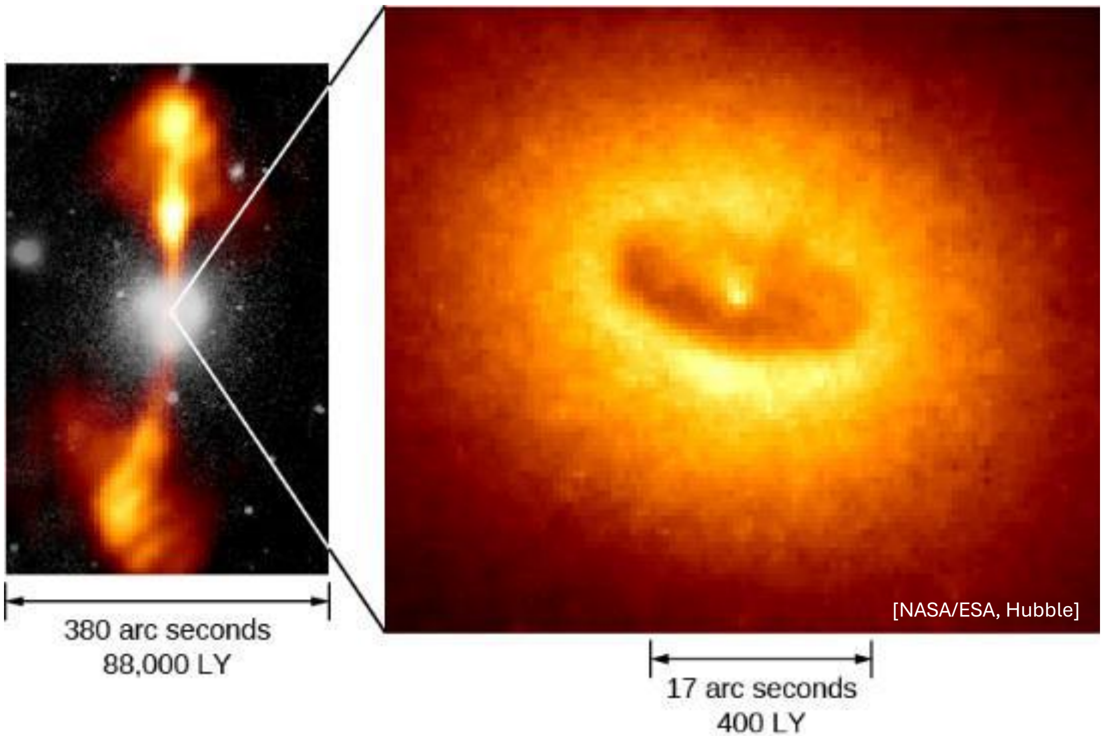
What Are Quasars?

- ✓ 1000 times luminosity of Milky Way
- ✓ Size of the solar system

Supermassive black hole feeding on 10 – 1000 M_{sun} per year

→ Gravitational potential energy is converted to radiation. (efficiency: 6% – 32%)

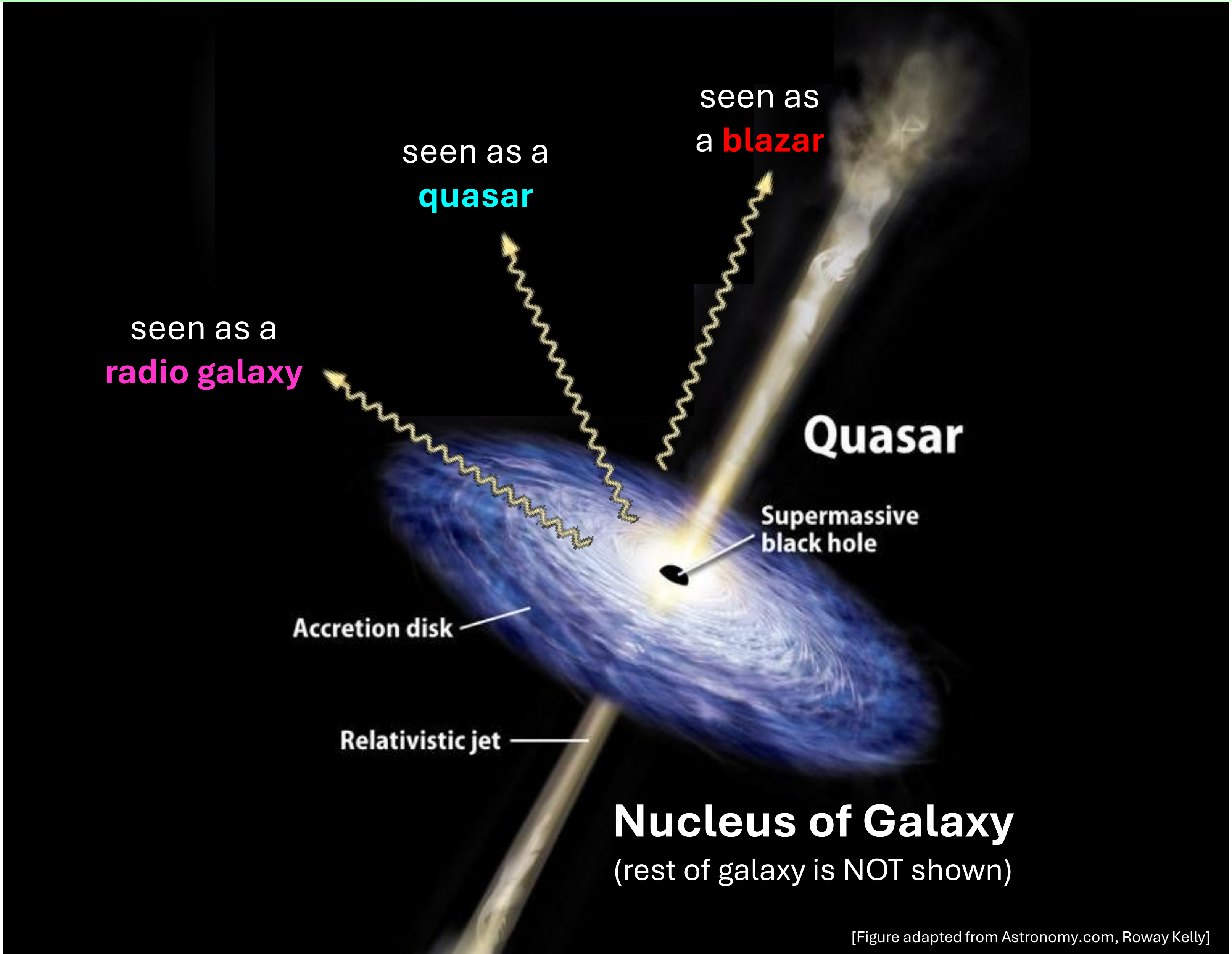
→ Supermassive black hole with mass of 10^9 M_{sun} or larger needed.



Close-in (right) shows the accretion disk with a black hole at the center.

The “radio” jets (left) emanate from the black hole.

Quasar = Active Galactic Nucleus (AGN)

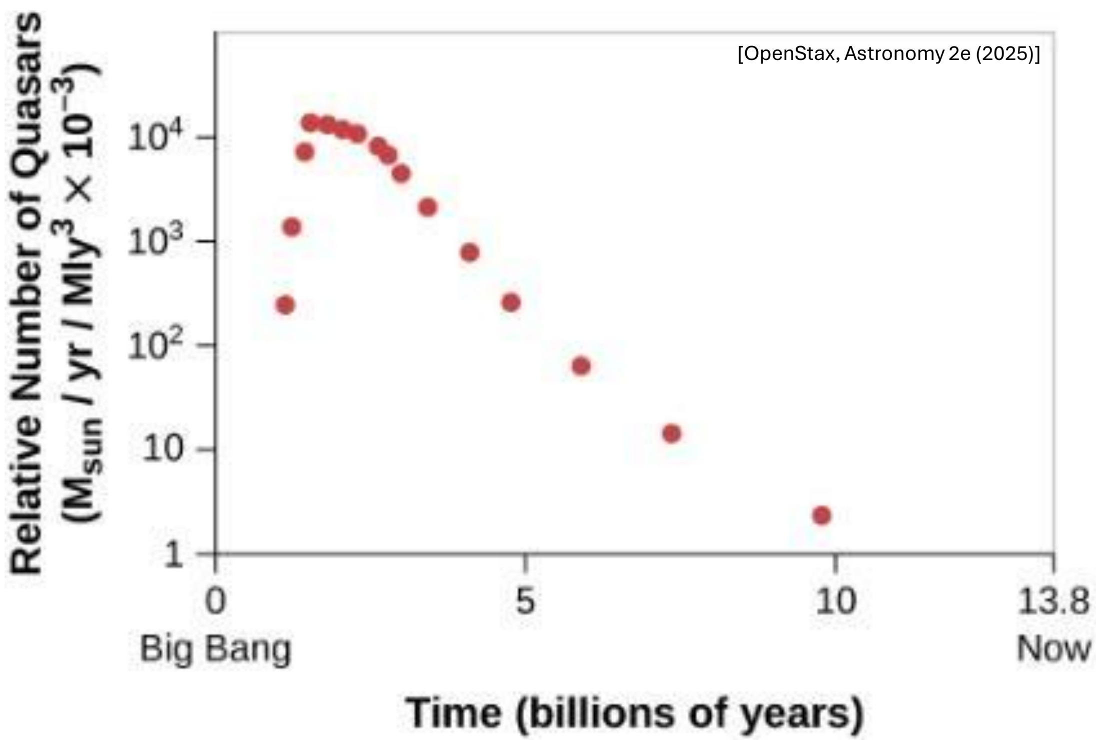


[Figure adapted from Astronomy.com, Roway Kelly]

The Quasar Era

- Quasars existed primarily in the **early universe** (peaks at 2 billion years after Big Bang).
  → Galaxies are forming.
  → There is a lot of material (gas) for an accretion disk to feed supermassive black hole.

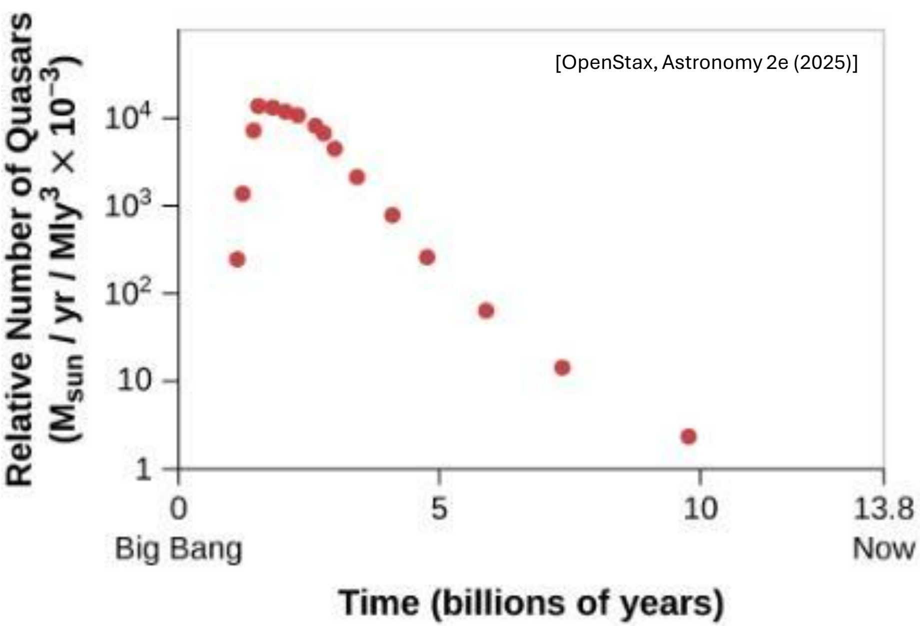
- The early universe had more **galaxy-galaxy collisions**.
  → More collisions because galaxies are closer together.
  → Collisions can put more material closer to supermassive black hole.

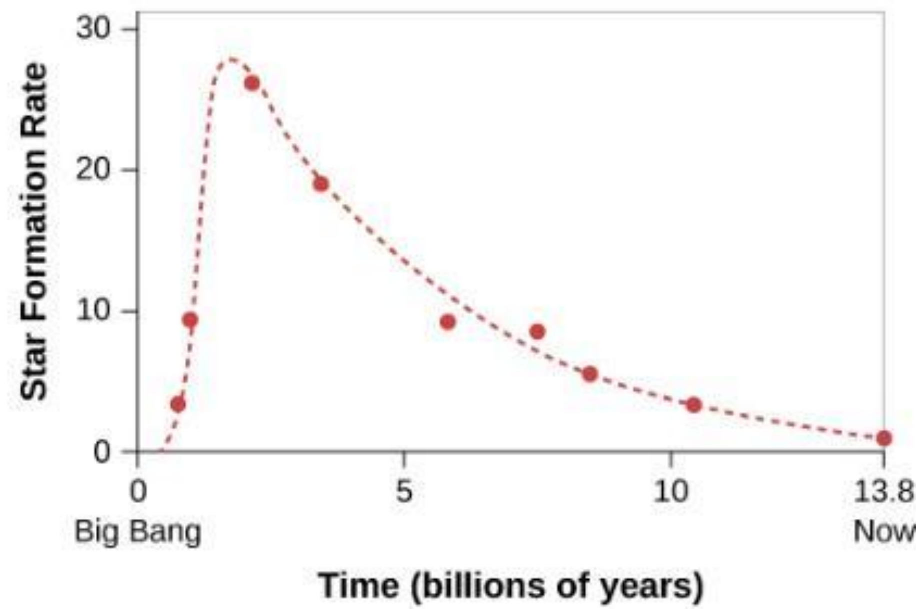


The Quasar Era

- Quasars existed primarily in the **early universe** (peaks at 2 billion years after Big Bang).
  → Galaxies are forming.
  → There is a lot of material (gas) for an accretion disk to feed supermassive black hole.
  → These conditions also favor star formation (peaks at 2 billion years after Big Bang).

- The early universe had more **galaxy-galaxy collisions**.
  → More collisions because galaxies are closer together.
  → Collisions can put more material closer to supermassive black hole.
  → These conditions also favor star formation.





Active Galactic Nucleus (AGN)

An AGN is a supermassive black hole that is emitting lots of radiation (radio, visible, x-ray), because it is feeding on its accretion disk.

→ All quasars are AGNs.

→ Not all AGNs are quasars.

→ Quasars are very active AGNs.

→ AGNs typically have jets of material emitted along the spin axis of the black hole.

→ The Milky Way supermassive black hole (Sagittarius A*) is NOT an AGN at present.

Active Galactic Nucleus (AGN)

An AGN is a supermassive black hole that is emitting lots of radiation (radio, visible, x-ray), because it is feeding on its accretion disk.

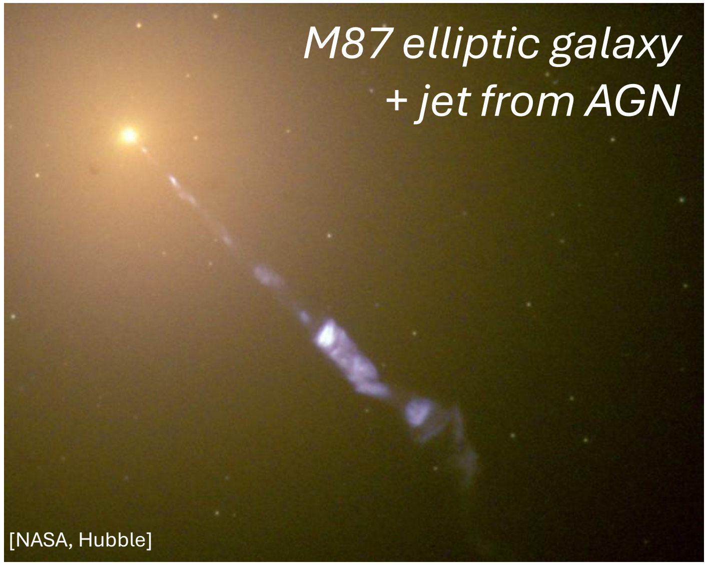
→ All quasars are AGNs.

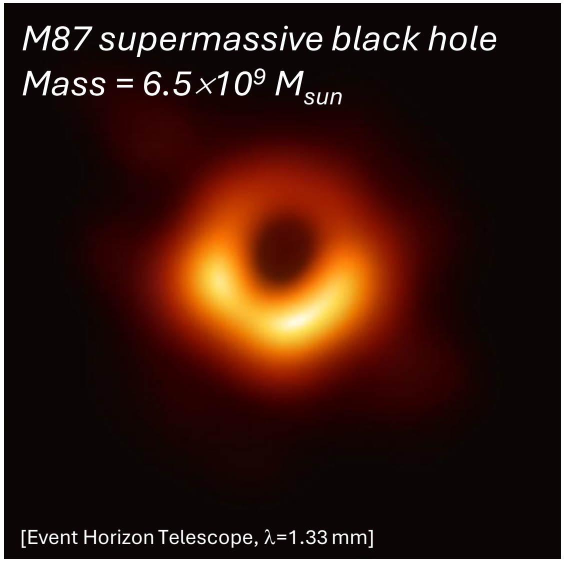
→ Not all AGNs are quasars.

→ Quasars are very active AGNs.

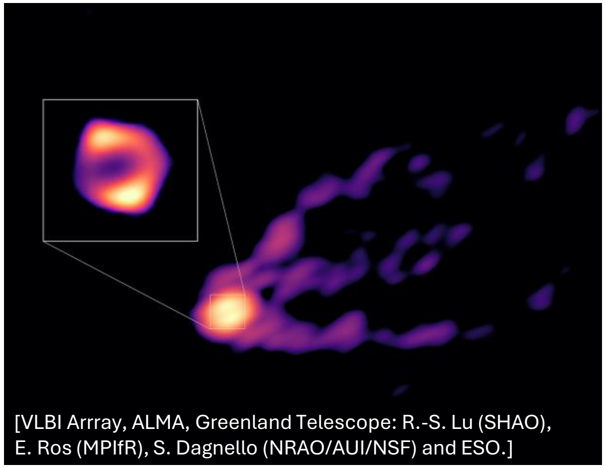
→ AGNs typically have jets of material emitted along the spin axis of the black hole.

→ The Milky Way supermassive black hole (Sagittarius A*) is NOT an AGN at present.





M87 supermassive black hole with radio jets emanating from it.



Active Galactic Nucleus (AGN)

An AGN is a supermassive black hole that is emitting lots of radiation (radio, visible, x-ray), because it is feeding on its accretion disk.

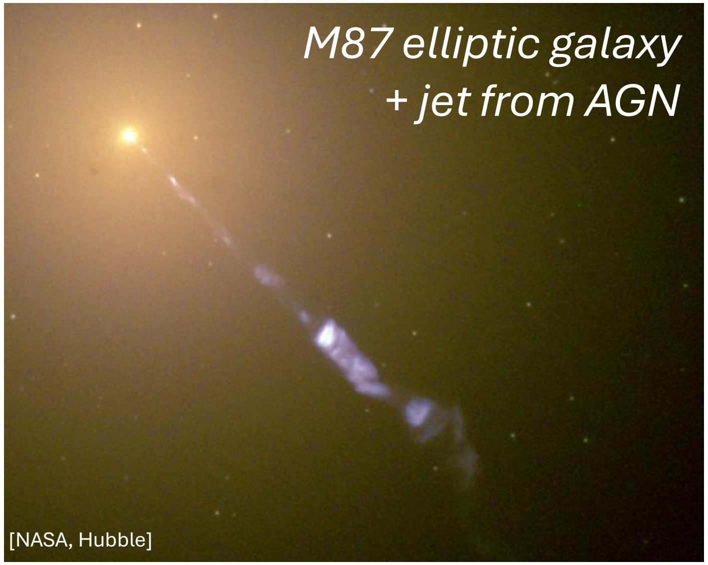
→ All quasars are AGNs.

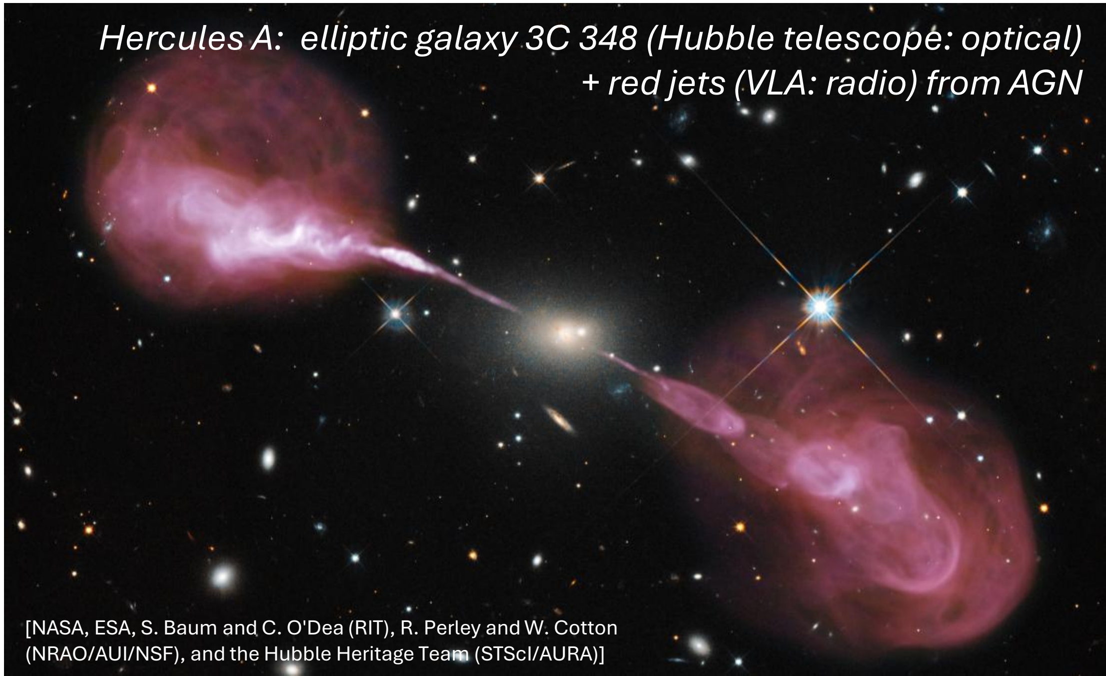
→ Not all AGNs are quasars.

→ Quasars are very active AGNs.

→ AGNs typically have jets of material emitted along the spin axis of the black hole.

→ The Milky Way supermassive black hole (Sagittarius A*) is NOT an AGN at present.





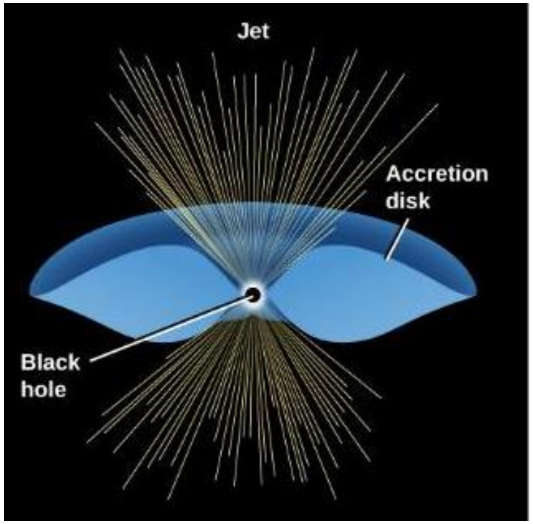
Accretion Disk and Jets

- Accretion disk is relatively well understood.
- As material (gas, dust, stars) orbits the black hole, friction heats up the material.
  - → Millions of degrees → black body radiation.
  - → Efficient conversion of gravitational energy to radiation.
  - → Radiation can push material outward away from accretion disk, which can lead to star formation away from black hole.
  - → If radiation is too intense, it can also turn off star formation in the central part of galaxy.

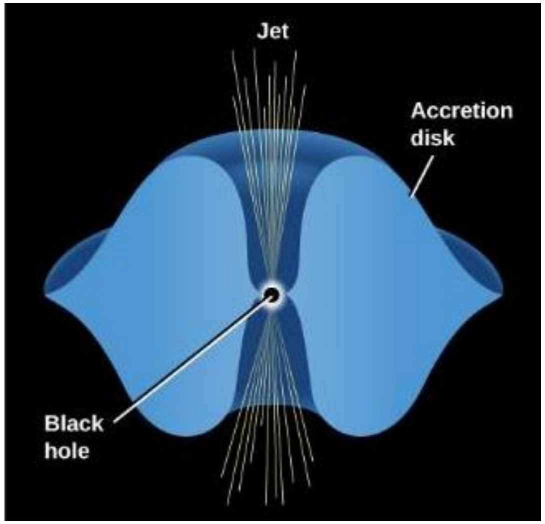
[NASA, JPL, CalTech]

Accretion Disk and Jets

- Accretion disk is relatively well understood.
- As material (gas, dust, stars) orbits the black hole, friction heats up the material.
  - → Millions of degrees → black body radiation.
  - → Efficient conversion of gravitational energy to radiation.
  - → Radiation can push material outward away from accretion disk, which can lead to star formation away from black hole.
  - → If radiation is too intense, it can also turn off star formation in the central part of galaxy.



thin disk → diffuse jets



thick disk → narrow jets

- Jet formation is along black hole and accretion disk rotation axis.
  → Jet formation is NOT that well understood.

[OpenStax, Astronomy 2e (2025)]

How does a black hole “eat” a star?

- The star’s orbit decays due to friction with accretion disk gas and emission of gravitational waves.
- As the star gets close to the black hole **tidal forces** deform it.
- Once the star is inside the “Roche limit”, it becomes part of the accretion disk, which eventually falls into black hole.

  → Material gets very hot from friction, so black hole region will get momentarily brighter.

[NASA/CXC/M. Weiss; OpenStax, Astronomy 2e (2025)]

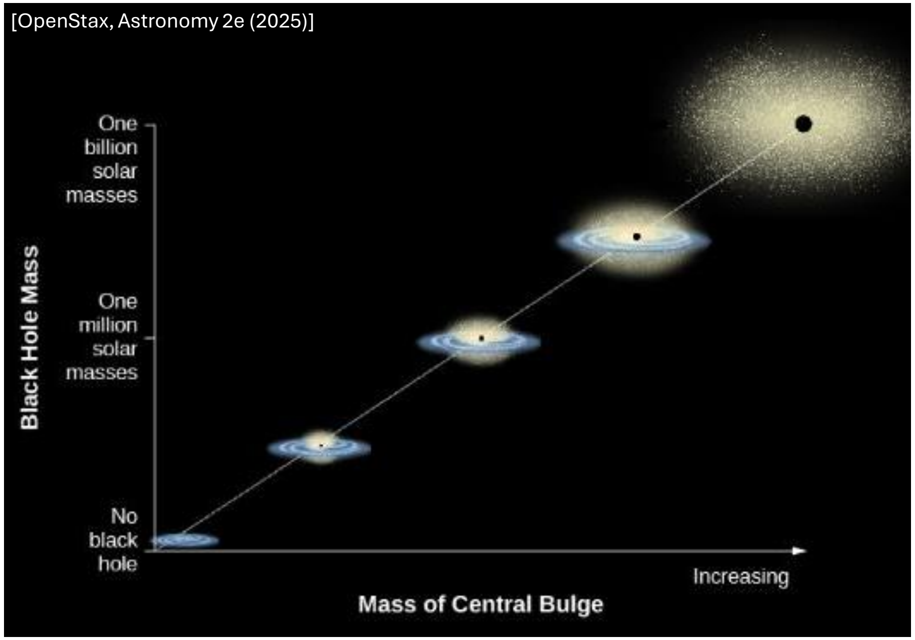
Galaxies & Supermassive Black Holes

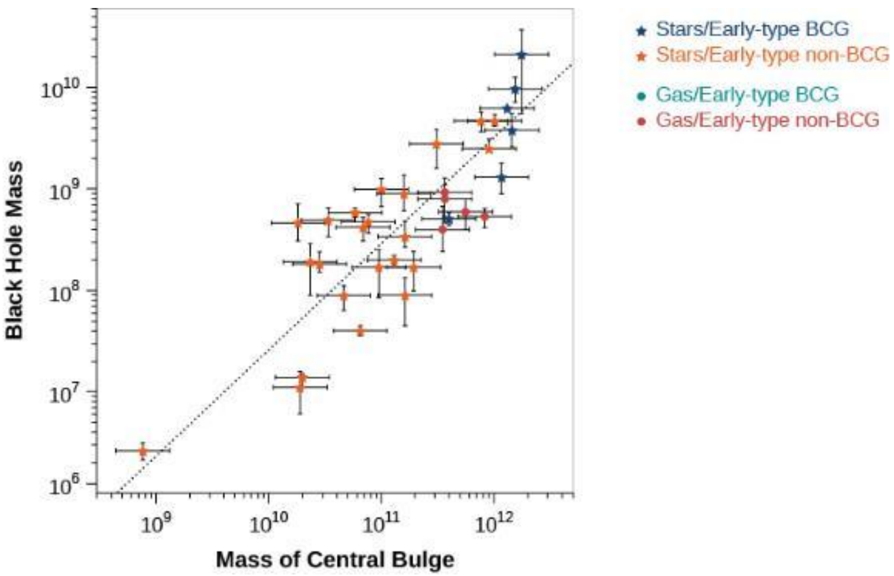
- As far as we can tell, all galaxies have a supermassive black hole at their nucleus.

- The origin of these black holes is uncertain.
  → Perhaps, a high density of material coalesced into a black hole.
  → Perhaps the universe was born with primordial black holes.

Galaxies & Supermassive Black Holes

- As far as we can tell, all galaxies have a supermassive black hole at their nucleus.
- The origin of these black holes is uncertain.
  → Perhaps, a **high density** of material coalesced into a black hole.
  → Perhaps the universe was born with **primordial** black holes.
- The supermassive black hole tends to have **1/200th of the mass** of its host galaxy.
  → The "why" is not well understood.
- The supermassive black hole can **foster star formation** in its vicinity, but if it gets too active, then it can also **turn off star formation**.

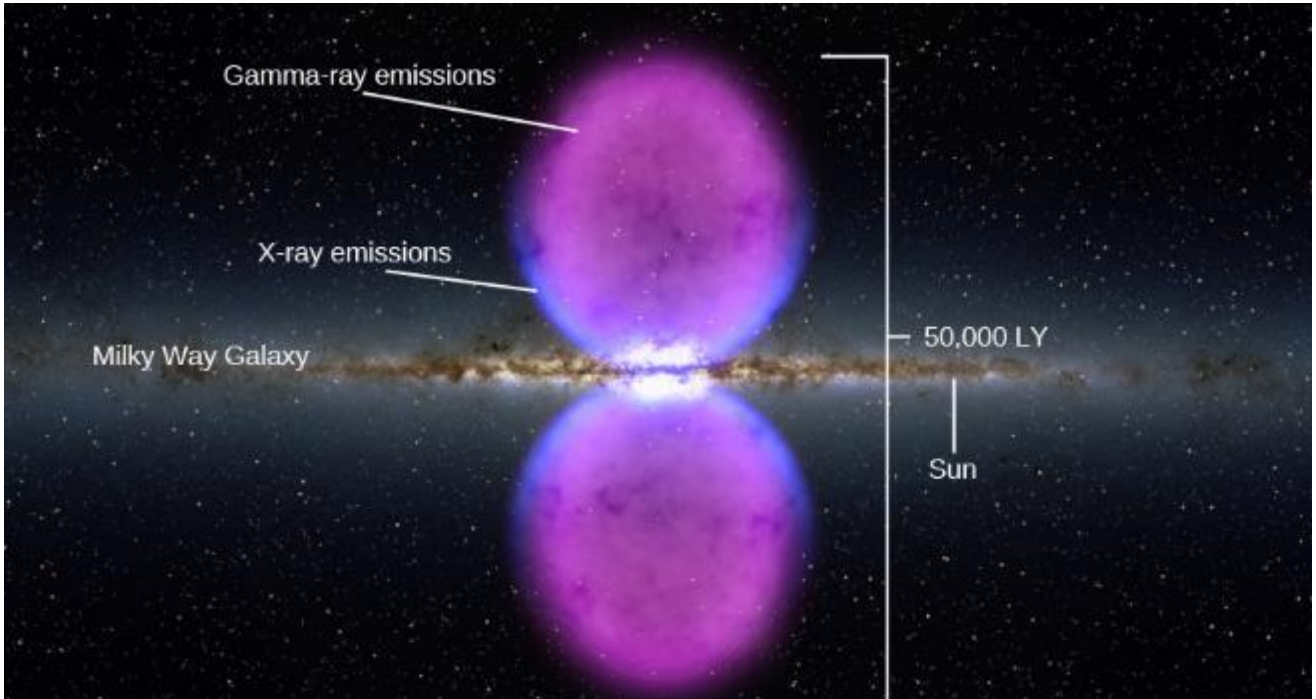




[OpenStax, Astronomy 2e (2025)]

Milky Way's Supermassive Black Hole

The Milky Way's supermassive black hole was probably much more active in the past.



[NASA Goddard Space Flight Center; OpenStax, Astronomy 2e (2025)]

Fermi Bubbles in the Galaxy: Giant bubbles shining in gamma-ray light lie above and below the center of the Milky Way Galaxy, as seen by the Fermi satellite.

→ The gamma-ray and X-ray image is superimposed on a visible-light image of the inner parts of our Galaxy.

→ The bubbles may be evidence that the supermassive black hole at the center of our Galaxy was more quasar-like a few million years ago.