

Midterm #1 Results

Average score = 84.5 /100

High score = 99 /100

Problem #1 had the lowest scores (especially part g).

Unit conversion on **Problem #4** was generally well done.

Today's Topics

Friday, April 24, 2026 (Week 12, Lecture 34) – Chapter 27.

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

Interlude 2 essay is due on [Gradescope](#) on Monday, April 27, 2026 by 9:00 AM

Problem Set #11 (optional/ungraded) is posted on [ExpertTA](#)

Edwin Hubble

Education background

- B. Sc. at U. of Chicago (math, astronomy, philosophy).
 - Gifted athlete: Basketball and track teams.
 - Rhodes Scholar (Oxford U., studied law).
 - Taught high school (Spanish, Physics, and Math).
 - PhD in Astronomy (U. of Chicago).
- ... served in WW1.

Discoveries

- Proved that the Milky Way is one of many galaxies.
 - Showed that Andromeda (M31) is outside of Milky Way.
- Studied many galaxies and classified them.
 - Spirals, ellipticals, and irregulars.
- Expansion of the universe.
 - Hubble's law (or Hubble-Lemaitre law).
 - Hubble did not fully believe that the universe is expanding.



[by J. Hagemeyer, 1931]

Edwin Hubble, 1889-1953

Hubble's Galaxy Classification

Three broad classes of galaxies:

- Spiral galaxies
- Elliptical galaxies
- Irregular galaxies

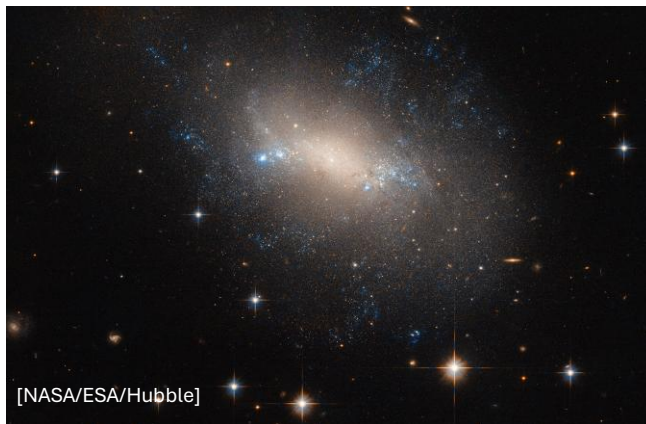
Size (mass and width)

- Spirals are medium size to large.
- Ellipticals can be very large.
- Irregulars tend to be smaller.



[NASA/ESA/Hubble]

UGC 12158 Spiral Galaxy



[NASA/ESA/Hubble]

NGC 2337 Irregular Galaxy

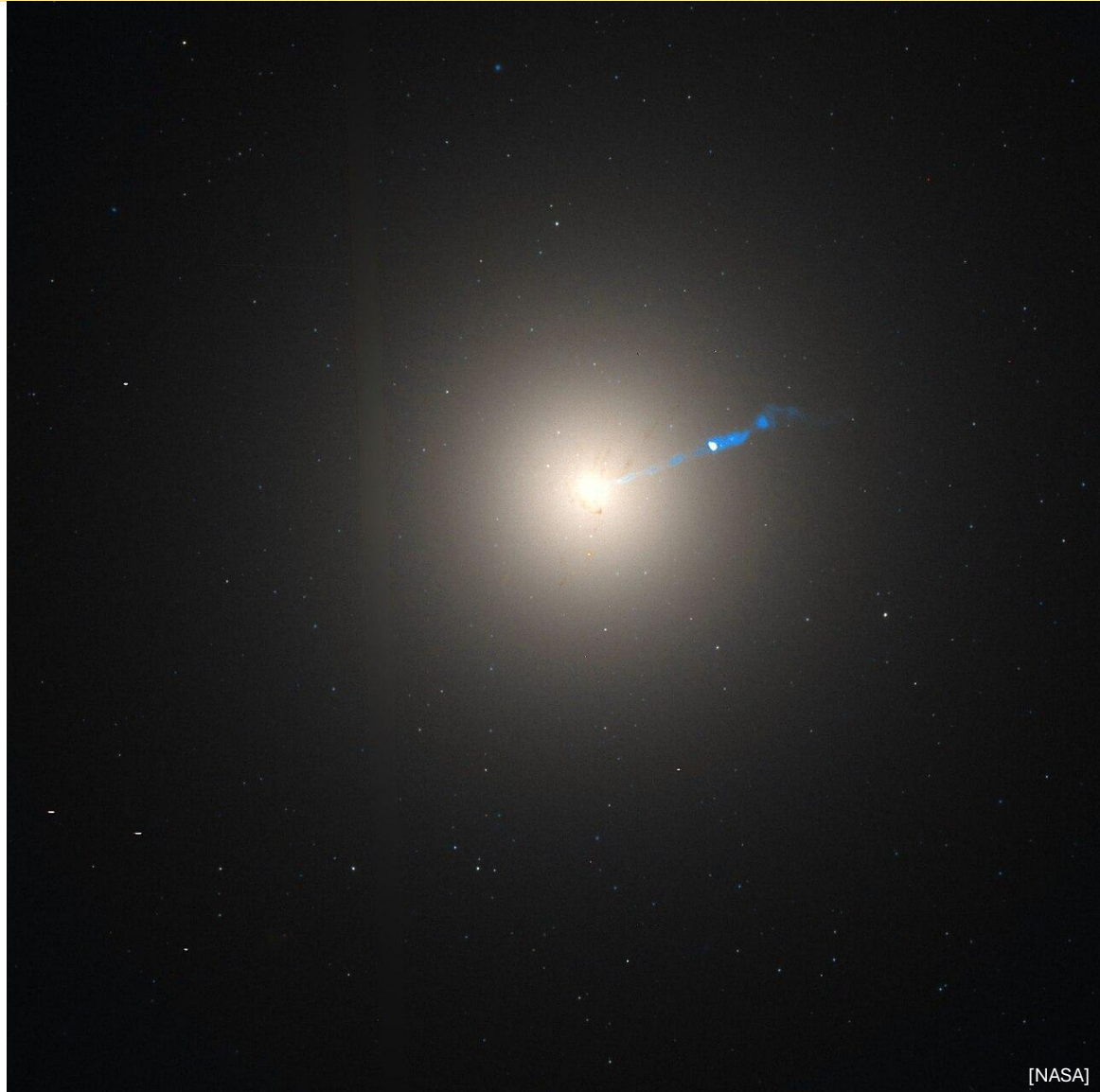


[NASA/ESA/Hubble]

IC 2006 Elliptical Galaxy

Elliptical Galaxies

- Roughly as common as spiral galaxies.
- Very little internal structure.
- Ellipsoidal shape.
- Size range: small to very large.
→ largest galaxies are elliptical.
- Most stars are very old.
- Very little gas and dust.
- Star orbits are disorganized and random.
→ Ellipticals are similar to the central bulge of a spiral galaxy.
- Mass often determined from gravitational lensing.



***M87 Elliptical Galaxy (53 million light years away)
(diameter=130,000 light years)***

Elliptical Galaxies

Giant elliptical galaxy
ESO 325-G004.

Distance

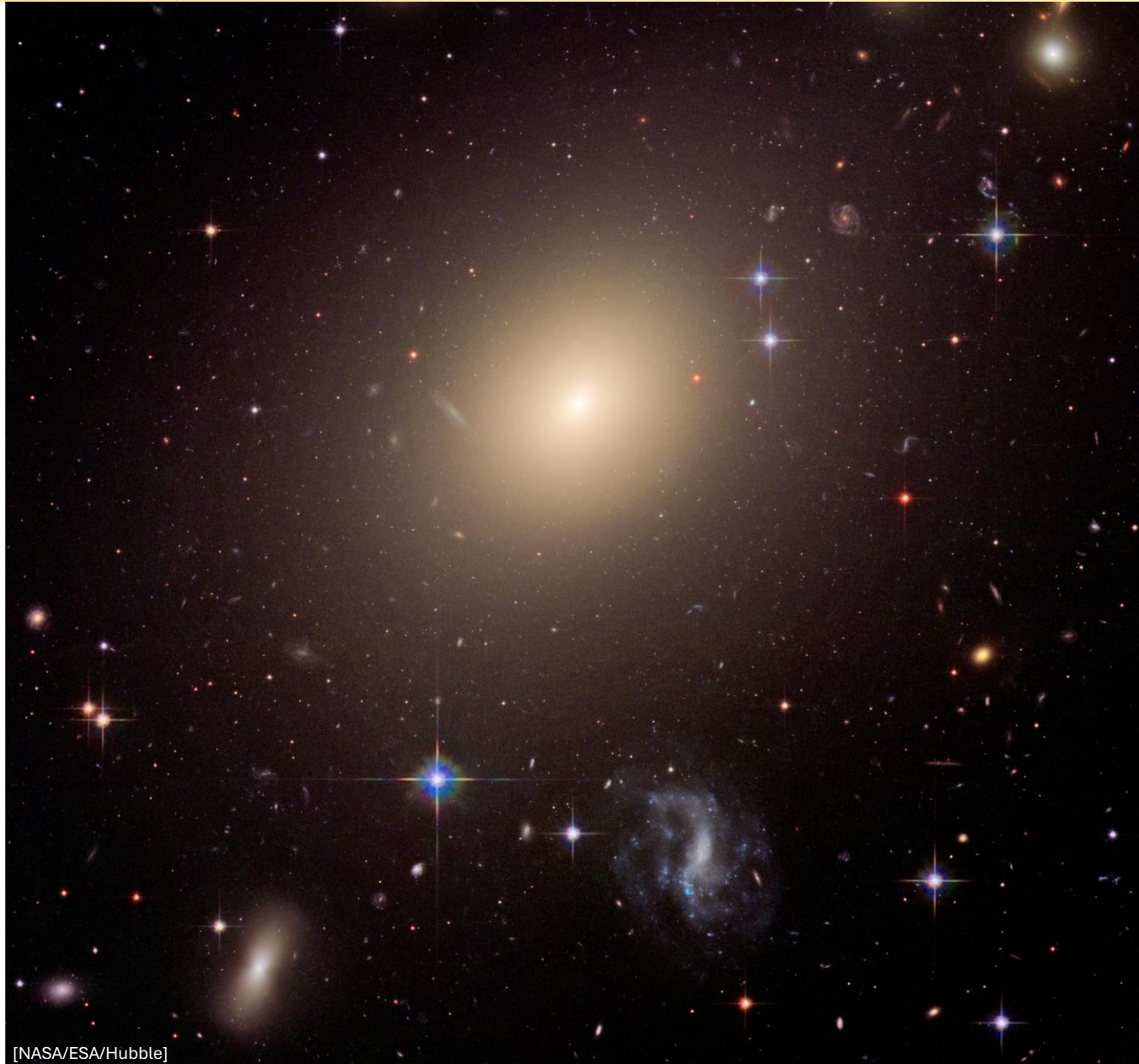
430-650 million light years

Diameter

400,000-500,000 light years

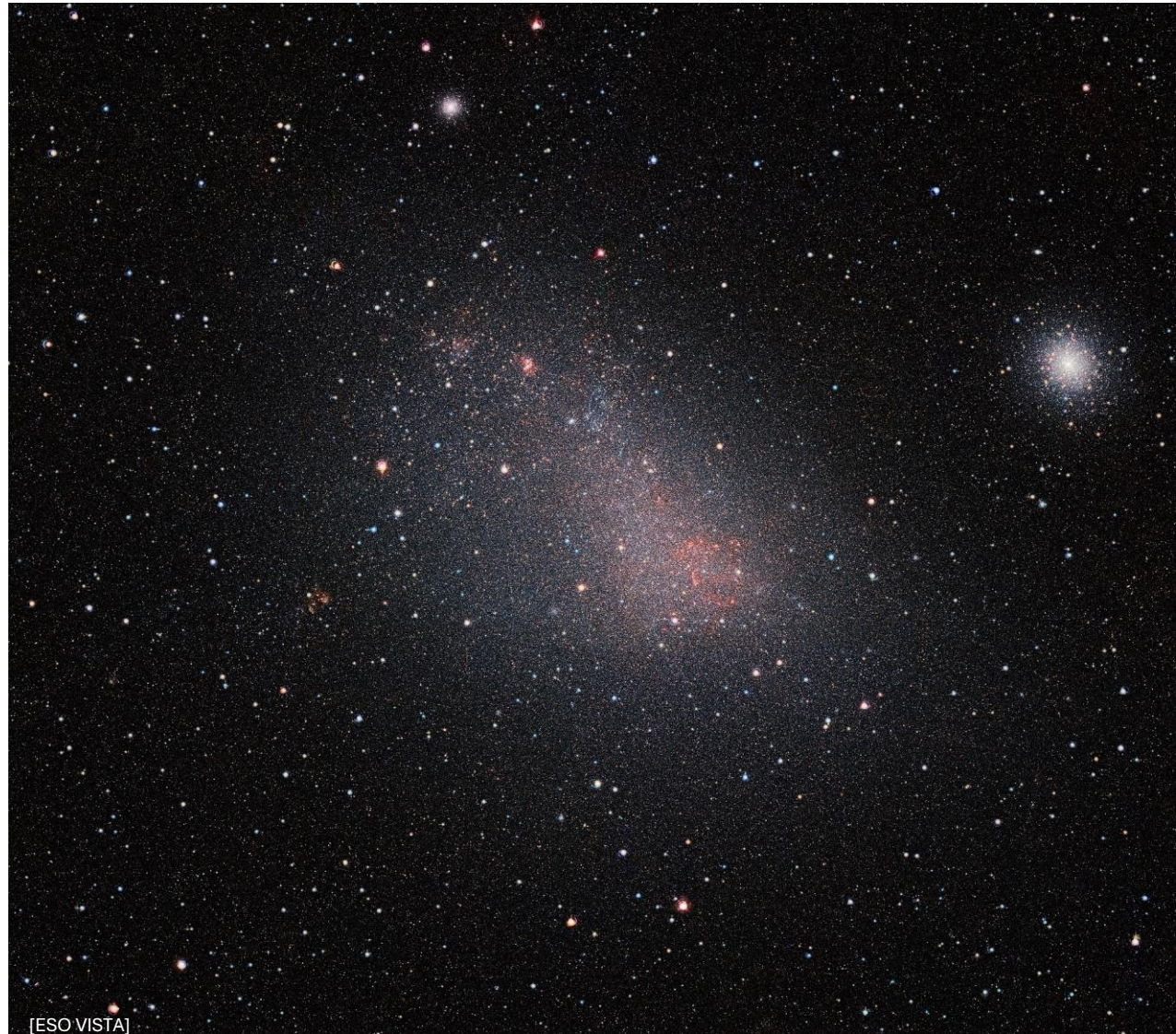
Mass

140 billion solar masses



Irregular Galaxies

- No defined shape.
- Tend to be smaller.
- Lots of gas; dust varies.
- Both old and young stars.



Small Magellanic Cloud (diameter=19,000 light years)

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

Mass-to-Light Ratio

Mass in units of M_{sun}

Luminosity in units of L_{sun}

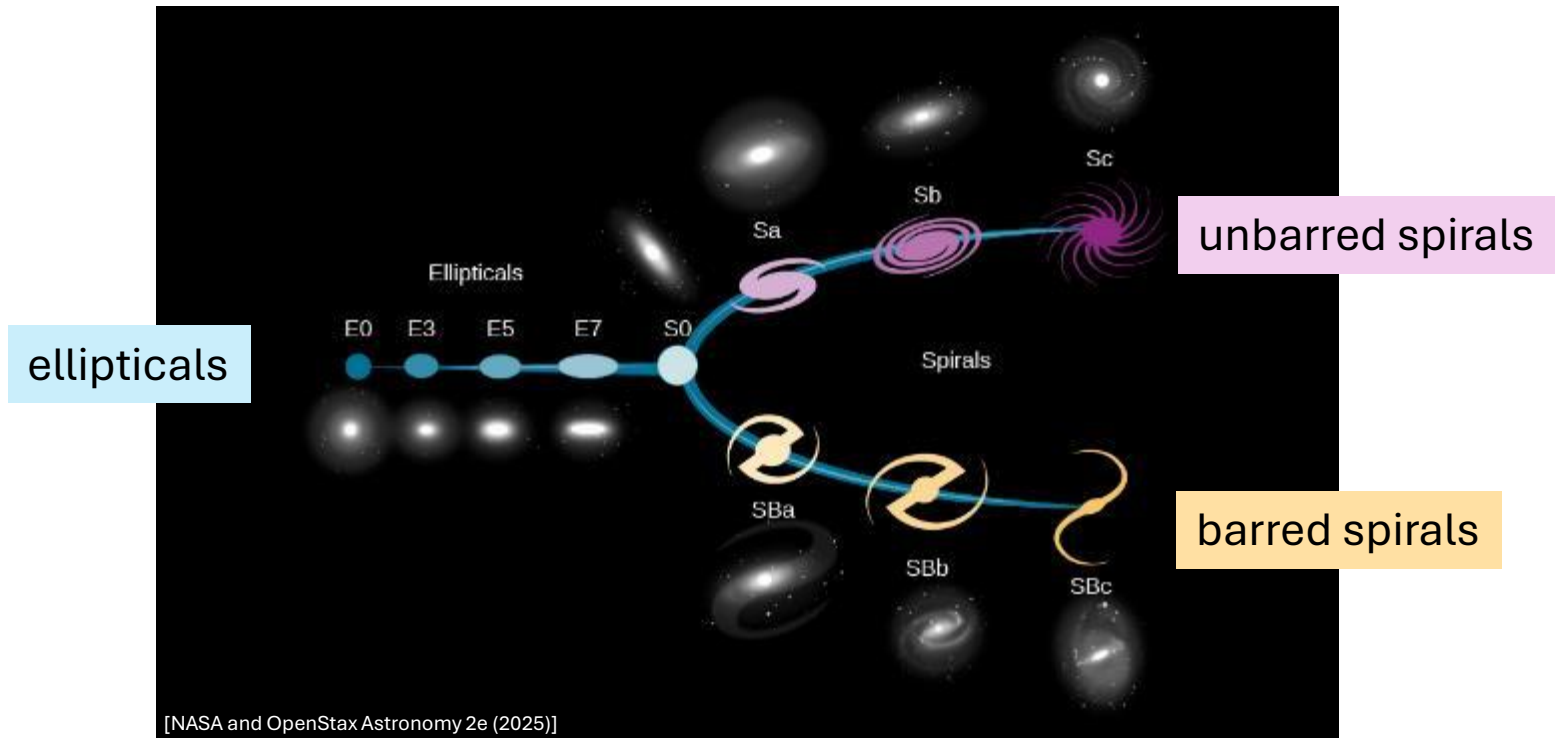
$$\text{Mass-to-Light ratio} = \frac{\text{Mass}}{\text{Luminosity}}$$

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



Hubble's Classification Scheme



Edwin Hubble's original classification of galaxies.

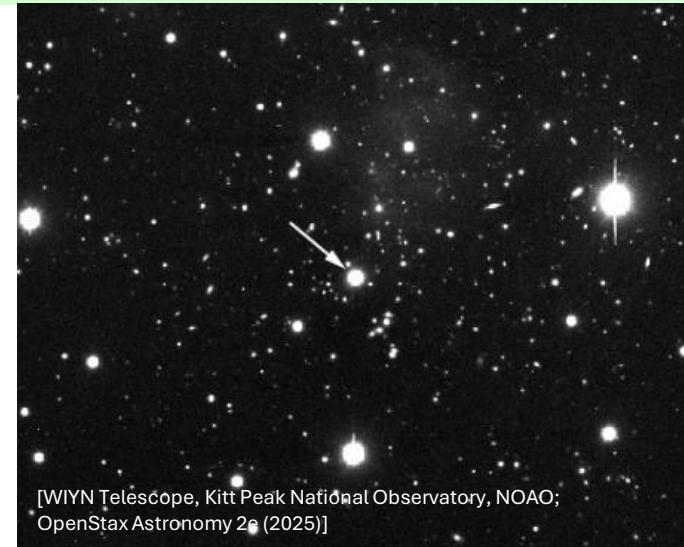
IMPORTANT: This “tuning fork” diagram does NOT represent galaxy evolution.
(though astronomers did try ... sort of like the H-R diagram)

PollEv Quiz: [PollEv.com/sethaubin](https://pollev.com/sethaubin)

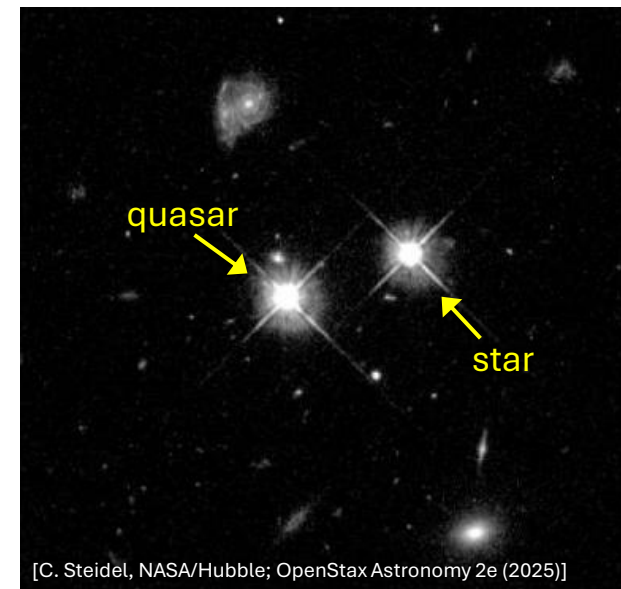
Quasars

- 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



[C. Steidel, NASA/Hubble; OpenStax Astronomy 2e (2025)]

Quasar Spectrum

- **Maarten Schmidt** discovered the primary clue for understanding quasars (in 1963).
- Quasars have a **very red-shifted spectrum**: Red shift is $0.06 \lesssim z \lesssim 10$.
- 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 $z = 0.15$)

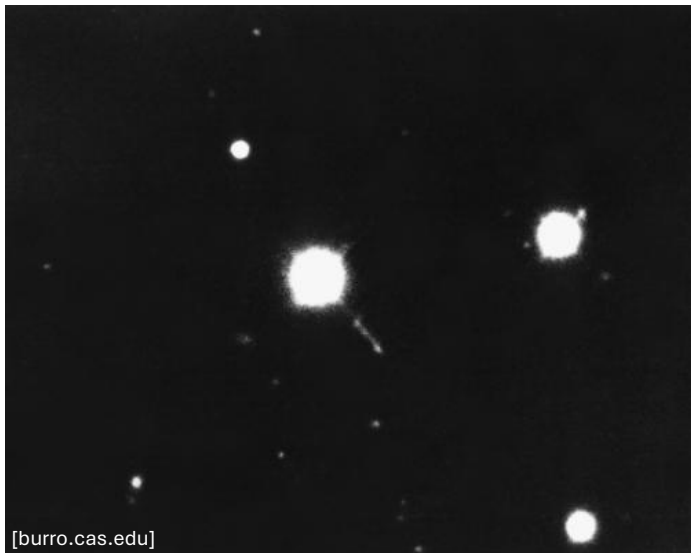
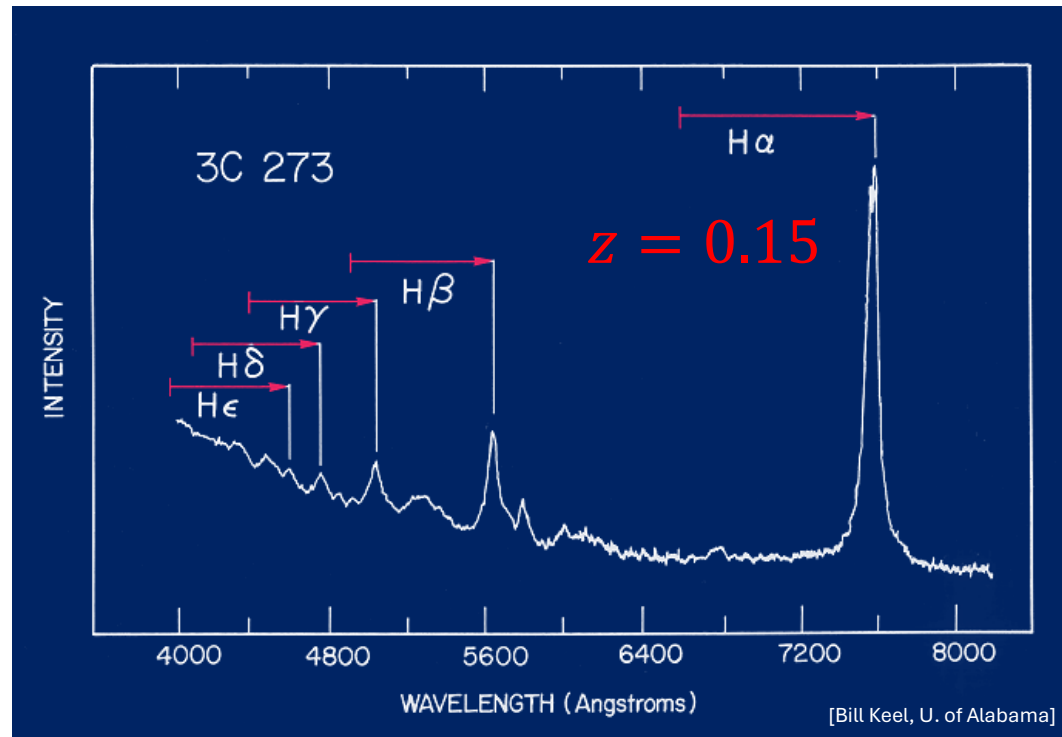


Photo of quasar 3C 273



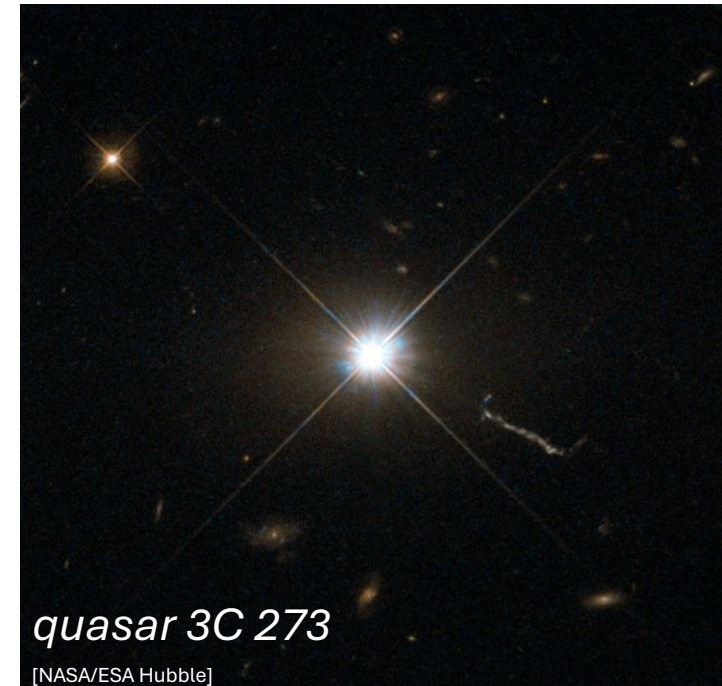
Visible spectrum of quasar 3C 273

Quasar Properties

- Quasars have an extremely high luminosity: $10L_{MW} < L_{quasar} < 10^5L_{MW}$.
(MW = Milky Way)
- Quasars are very far away: $10^9 \text{ light years} < \text{distance} < 13 \times 10^9 \text{ light years}$.
- 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)

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 - Implies that **quasars are very compact** with sizes of **light hours to light months**.
(Solar system diameter (Neptune) \approx 8 light hours)
- Quasars sometimes have **jets** 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.



Size of Quasars

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

0. An object 2 light days in size emits a sudden flash.



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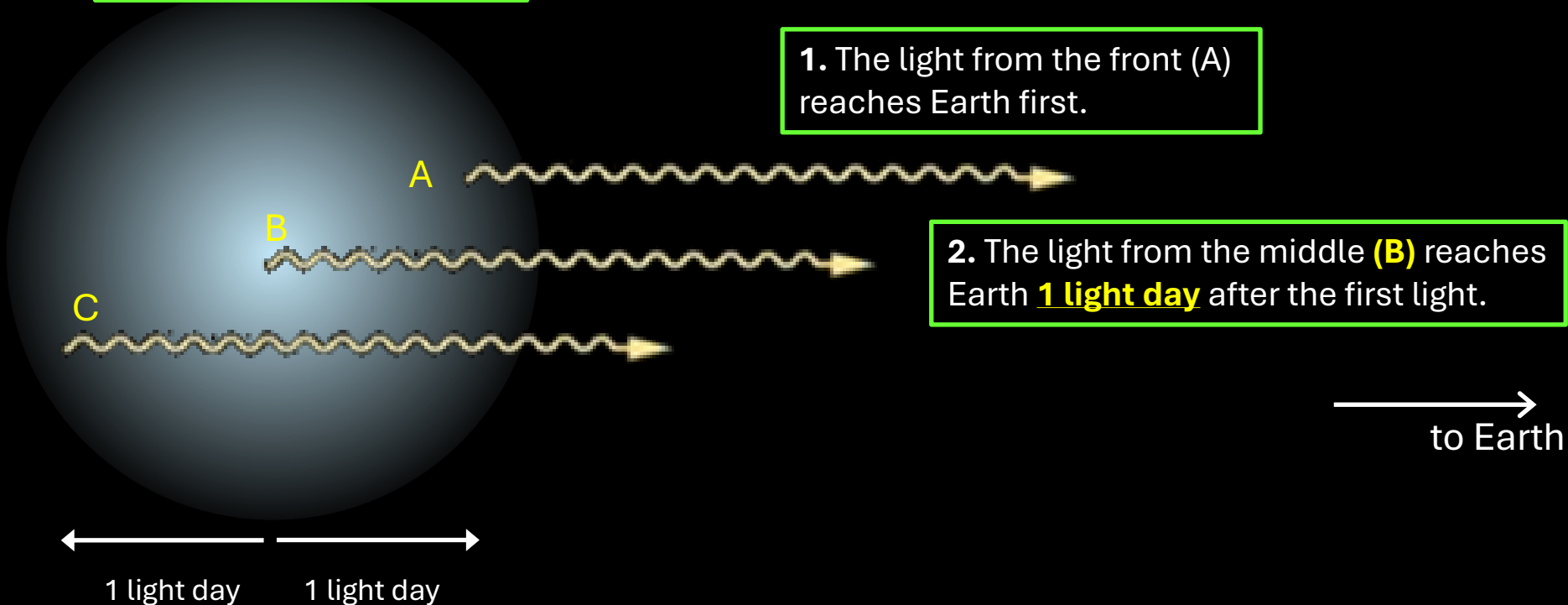
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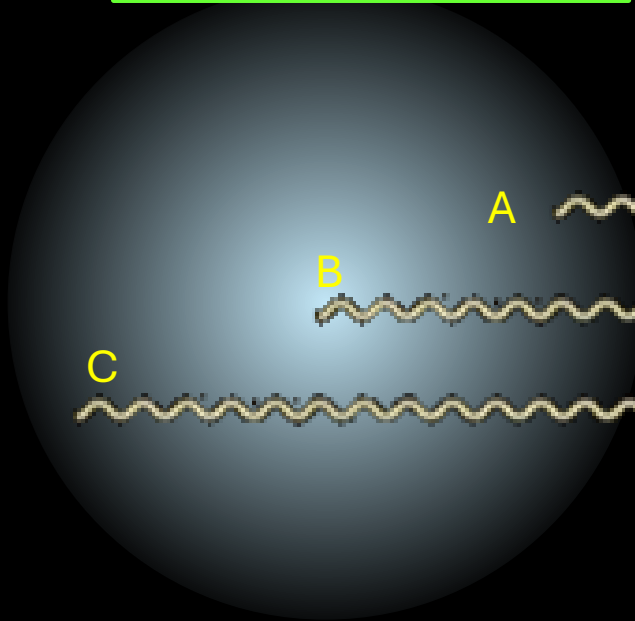
2. The light from the middle (B) reaches Earth **1 light day** after the first light.

3. The light from the rear (C) reaches Earth **2 light days** after the first light.

→
to Earth

1 light day

1 light day



What Are Quasars?

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



Supermassive black hole feeding on $10 - 1000 M_{\text{sun}}$ per year

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

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

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Milky Way “supermassive” black hole (Sagittarius A*) is much smaller.

→ Mass of only $4 \times 10^6 M_{\text{sun}}$.

→ About $1 M_{\text{Sun}}$ falls in every 1000 years.

What Are Quasars?

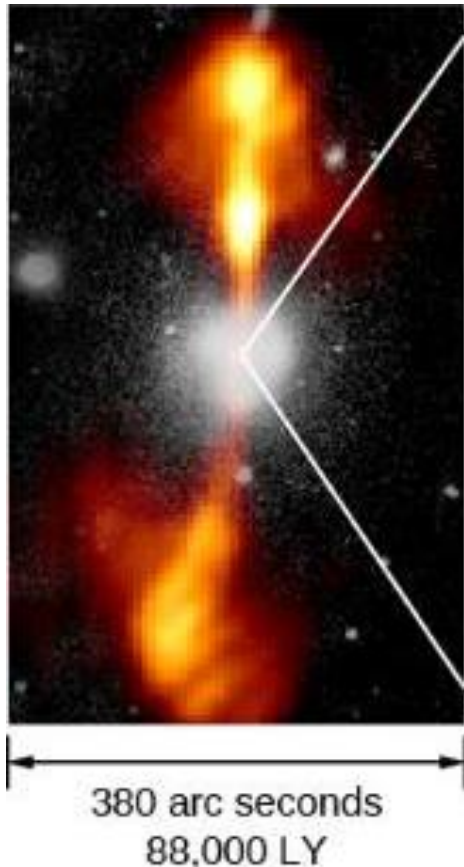
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Quasar = active galactic nucleus

(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

What Are Quasars?

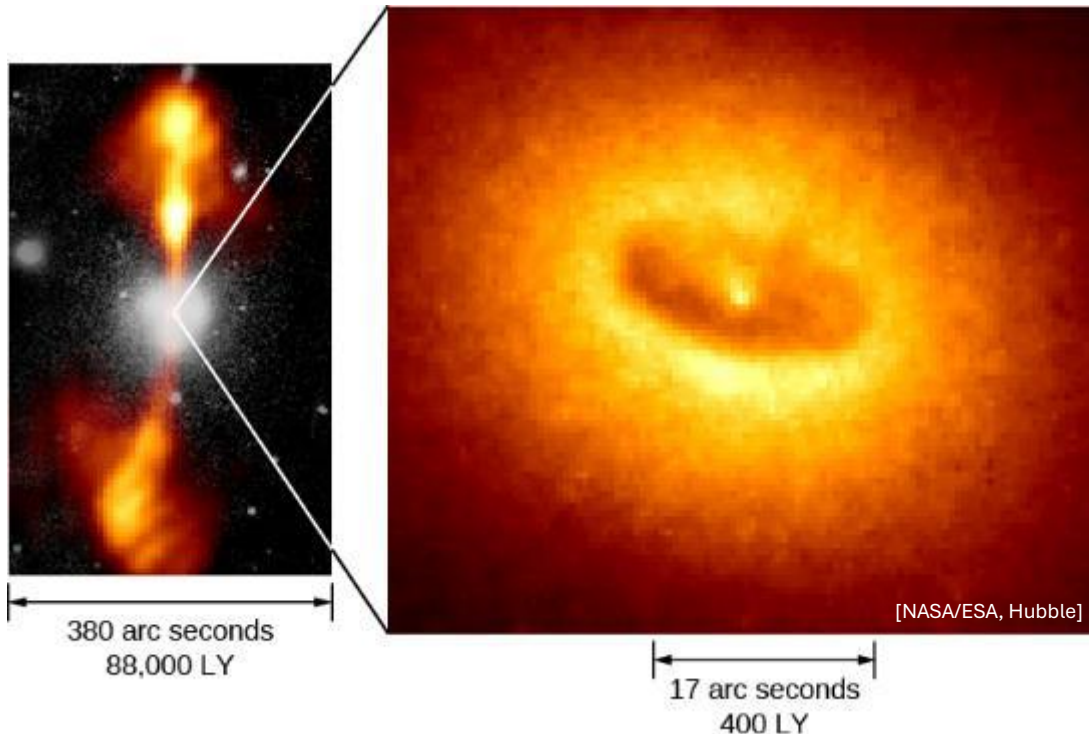
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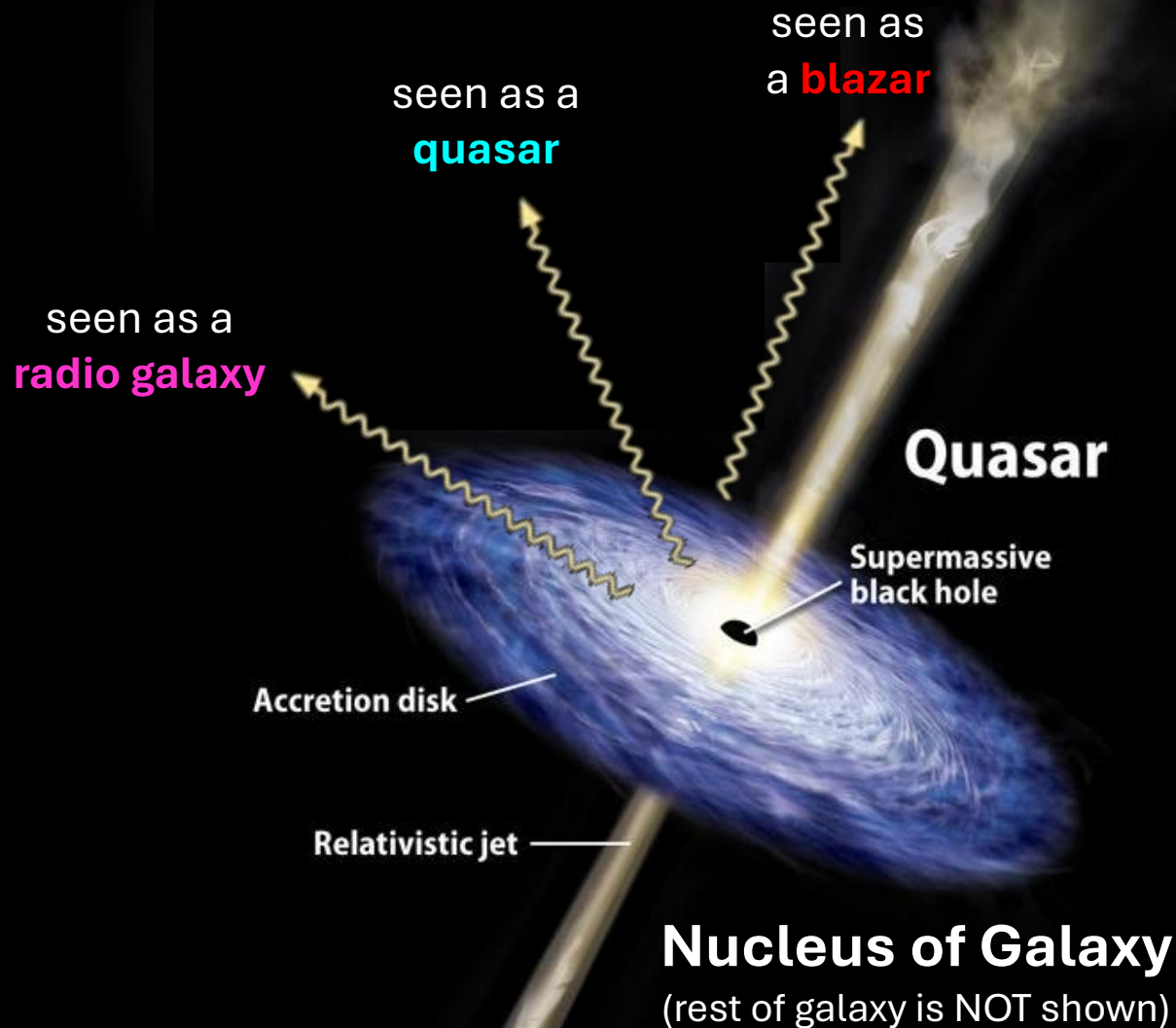
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Close-in (right) shows the accretion disk with a black hole at the center.

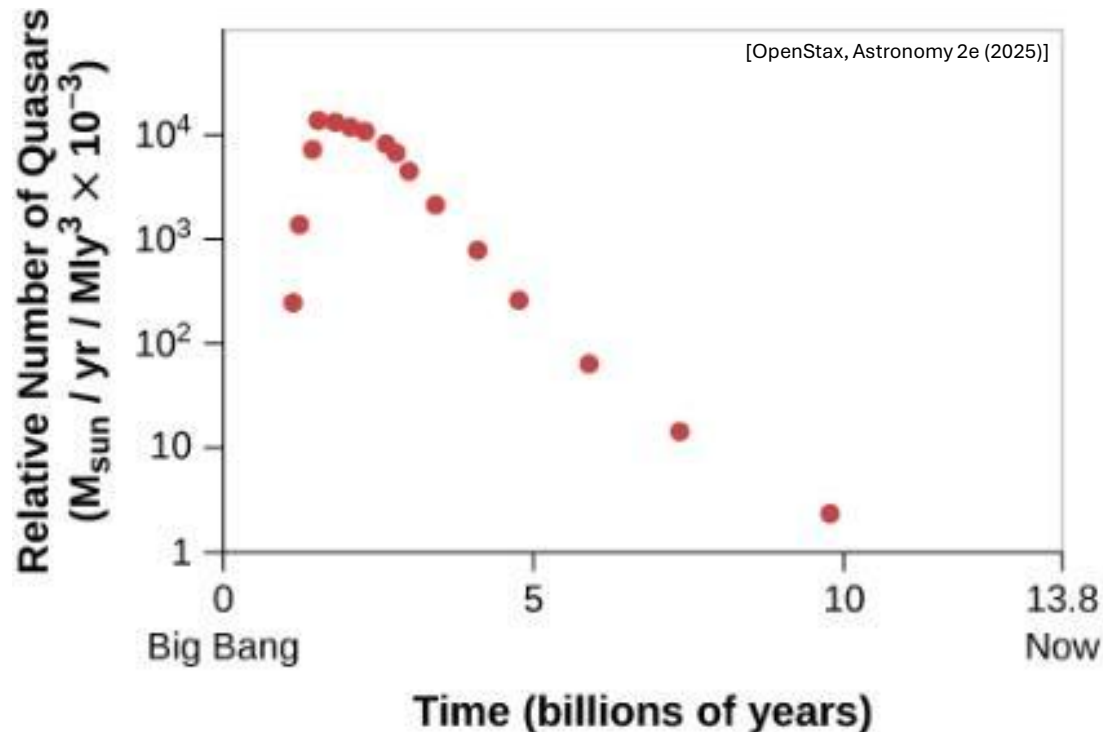
The “radio” jets (left) emanate from the black hole.

Quasar = Active Galactic Nucleus (AGN)



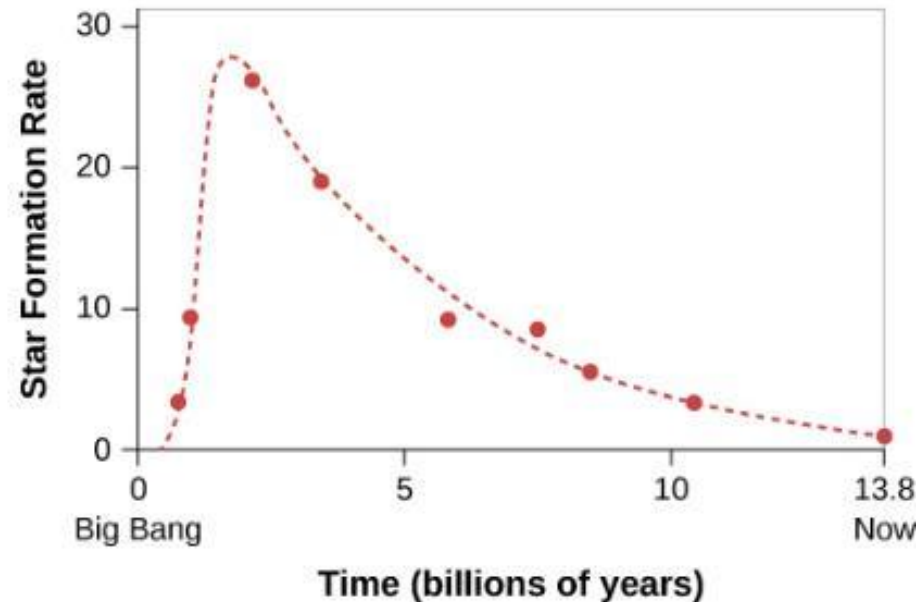
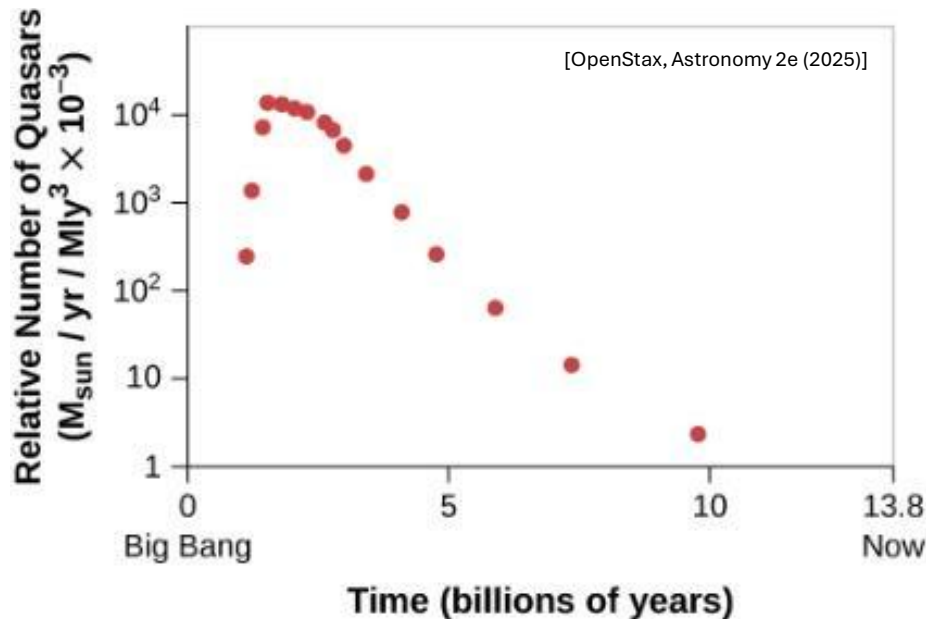
The Quasar Era

- 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.



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 - 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)

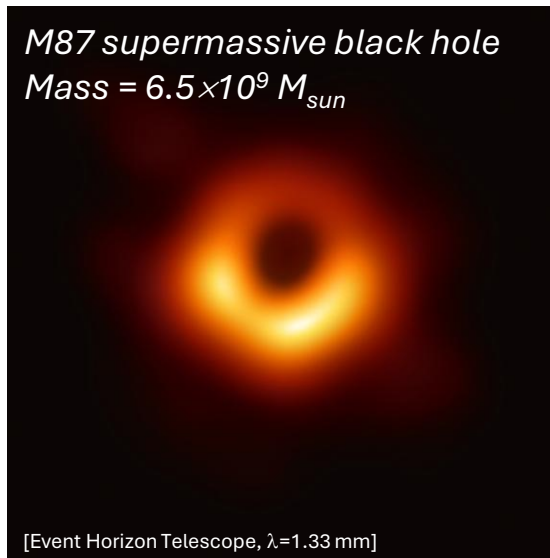
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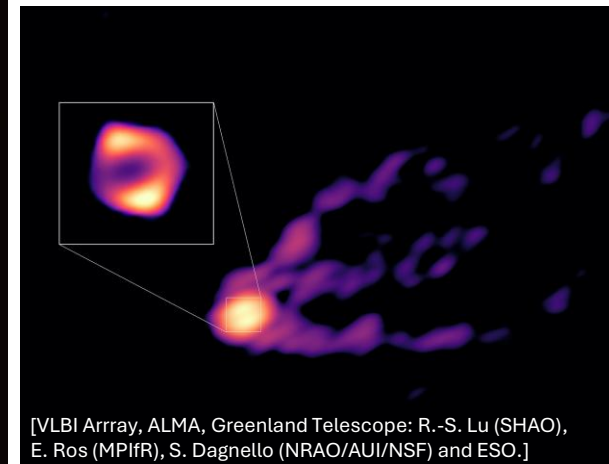
*M87 elliptical galaxy
+ jet from AGN*



*M87 supermassive black hole
Mass = $6.5 \times 10^9 M_{\text{sun}}$*



*M87 supermassive black hole
with radio jets emanating from it.*



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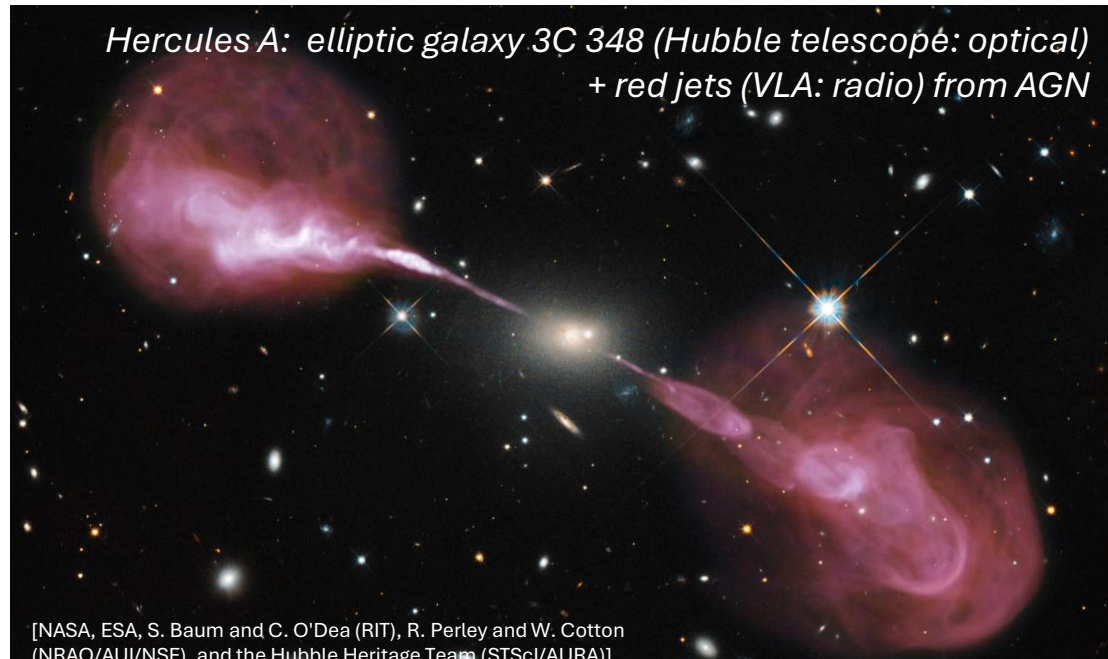
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*M87 elliptical galaxy
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[NASA, Hubble]

*Hercules A: elliptical galaxy 3C 348 (Hubble telescope: optical)
+ red jets (VLA: radio) from AGN*



[NASA, ESA, S. Baum and C. O'Dea (RIT), R. Perley and W. Cotton (NRAO/AUI/NSF), and the Hubble Heritage Team (STScI/AURA)]

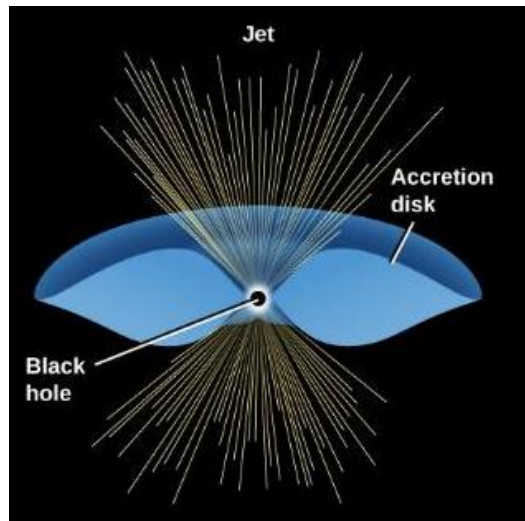
Accretion Disk and Jets

- 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.

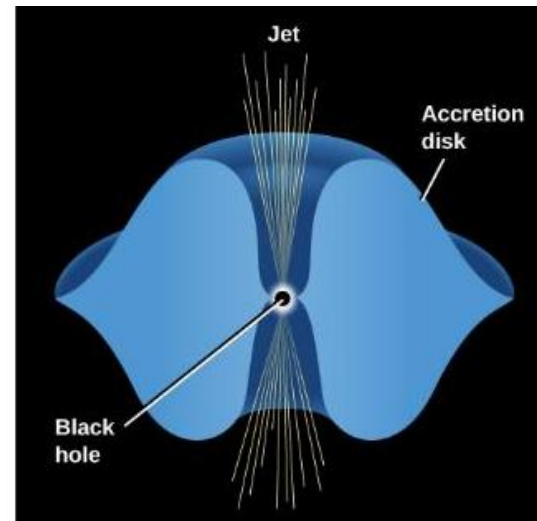


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thin disk → diffuse jets



thick disk → narrow jets

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

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.



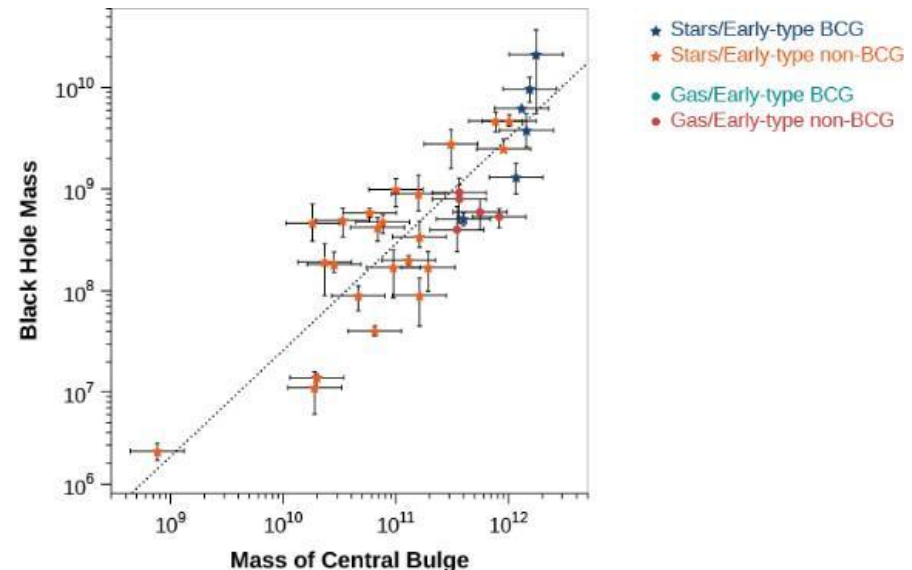
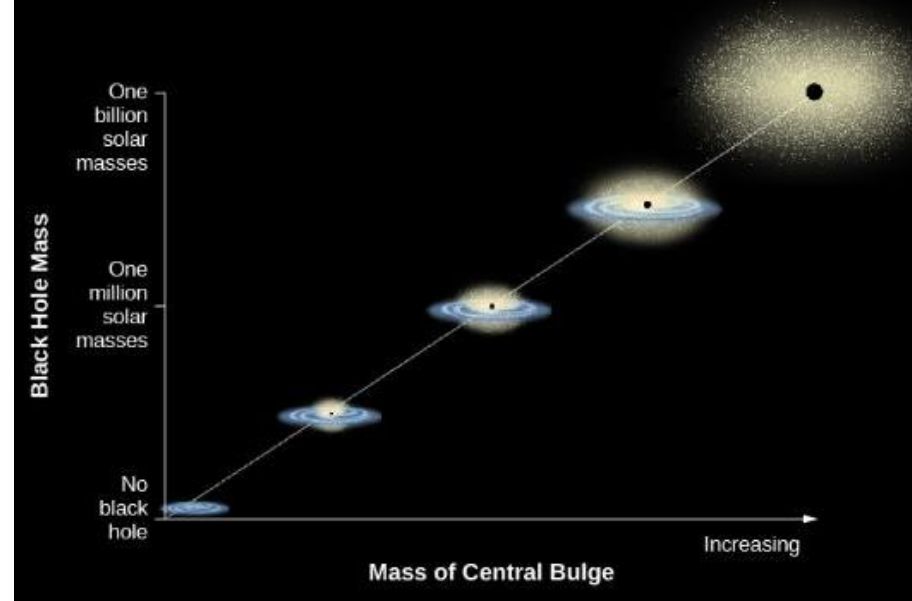
Galaxies & Supermassive Black Holes

- 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.

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- 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**.

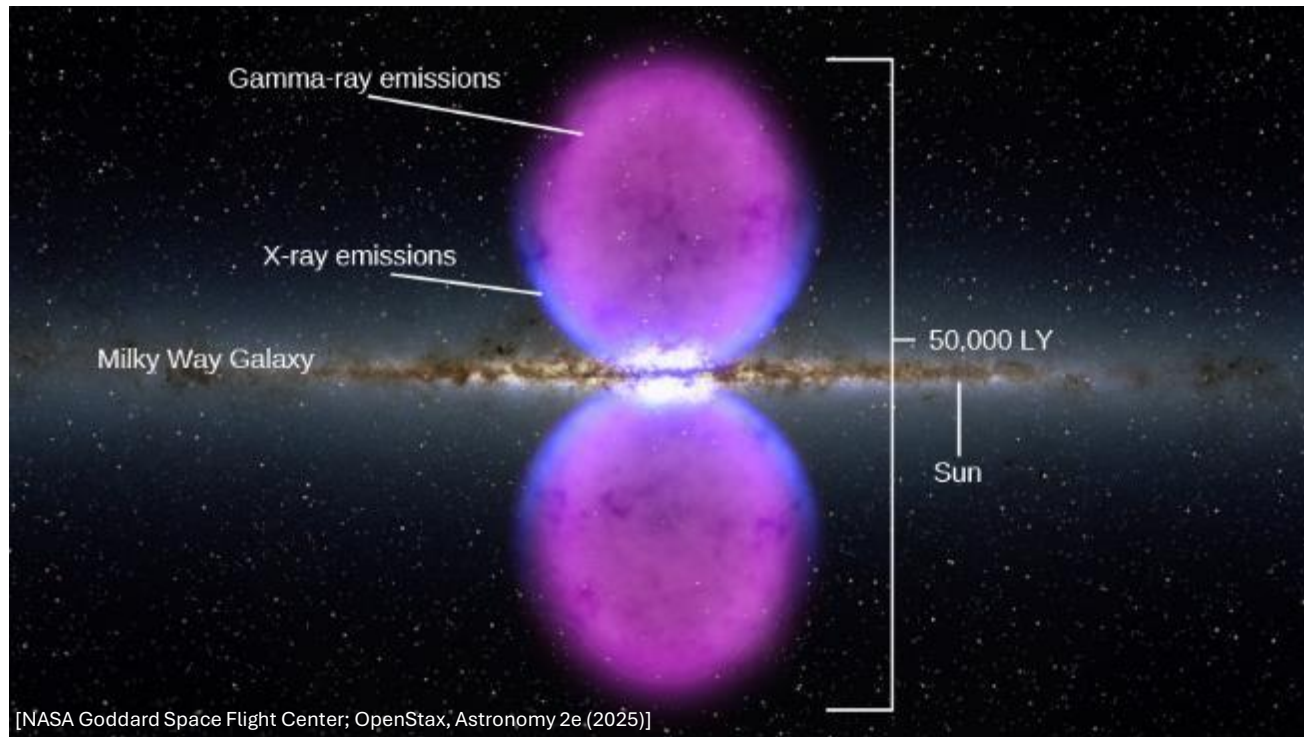
[OpenStax, Astronomy 2e (2025)]



[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.



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.