

Reading: OpenStax, Chapter 27, all sections

Previously: **Galaxy Distances and Motions**

- By using variable stars and other “standard candles” we can measure the distance to other galaxies across the known Universe
- The Cosmic Distance Ladder
- The ‘Hubble Law’ - we live in an expanding universe

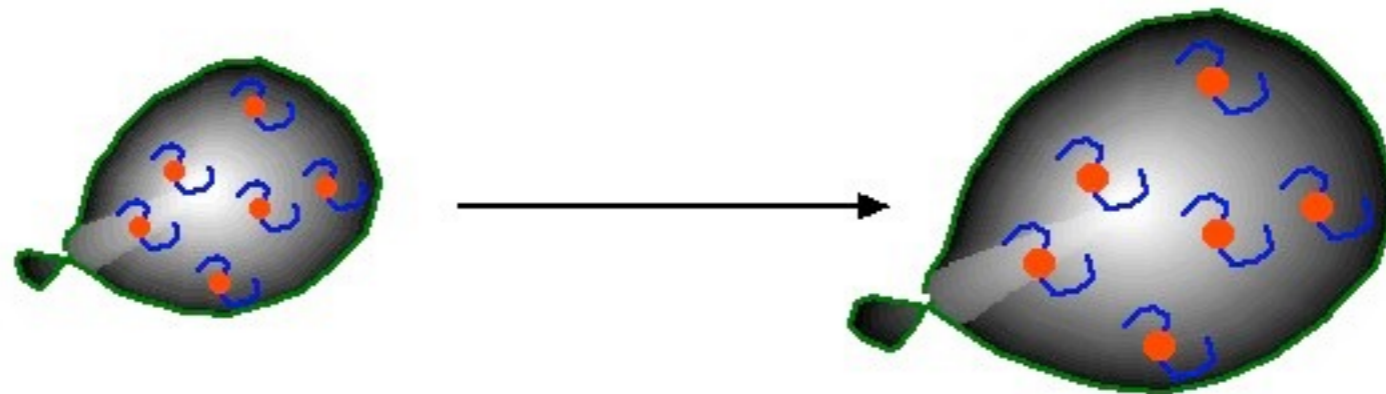
Today: **Quasars, Active Galaxies, and Monster Black Holes**

- Discovery of quasars — distant objects that are very bright (Hubble Law and redshift — receding very fast and very far away)
- “Active Galaxies” show evidence for high-energy phenomena in and around a small central engine that drives enormous structures
- Supermassive black holes as the engine for AGN phenomena

if **ALL** distant galaxies are moving away from us,
are we at the center of the Universe?

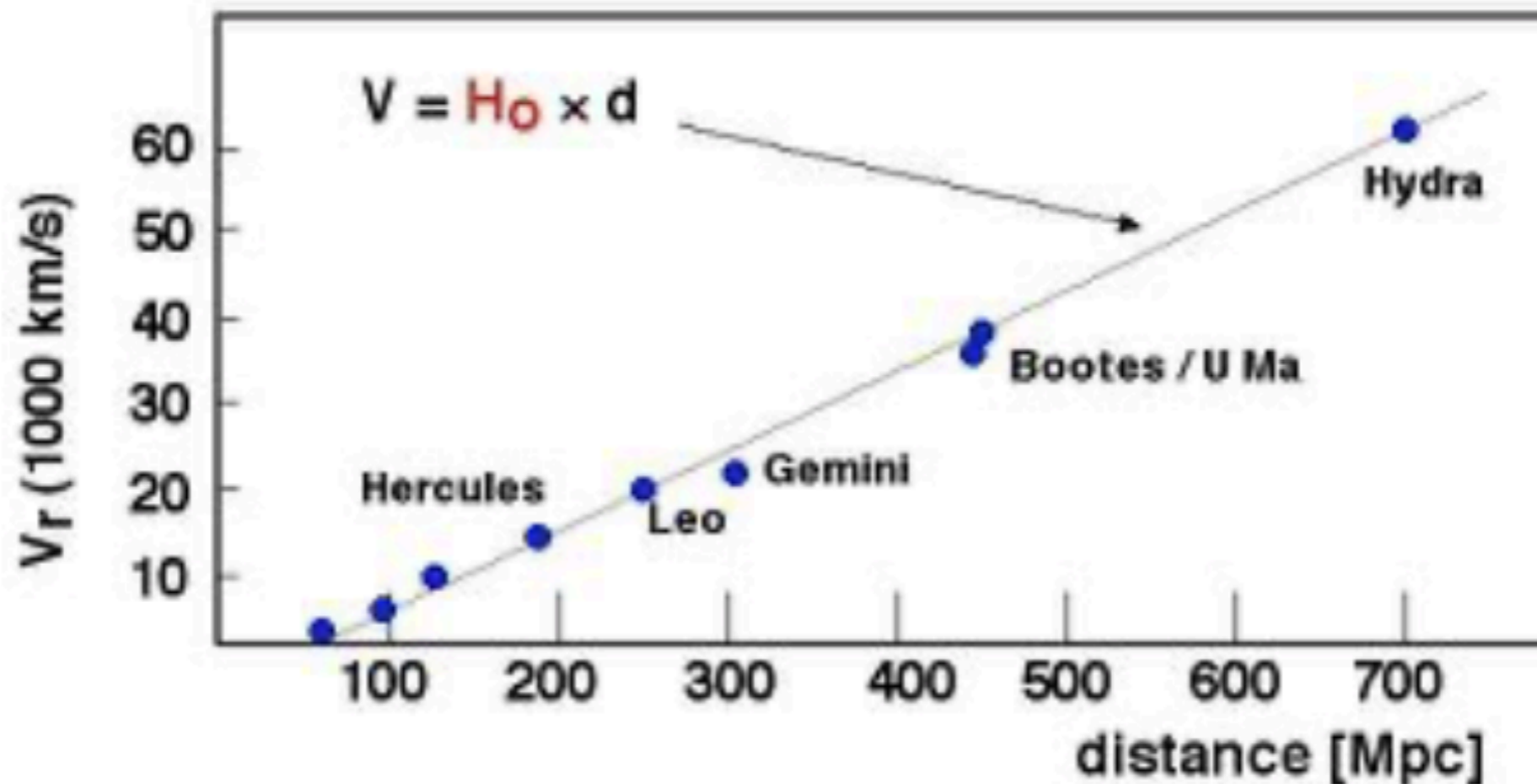
NO!

- in an **Expanding Universe**
- all galaxies move away from each other
- farther galaxies move faster ($V \propto d$)



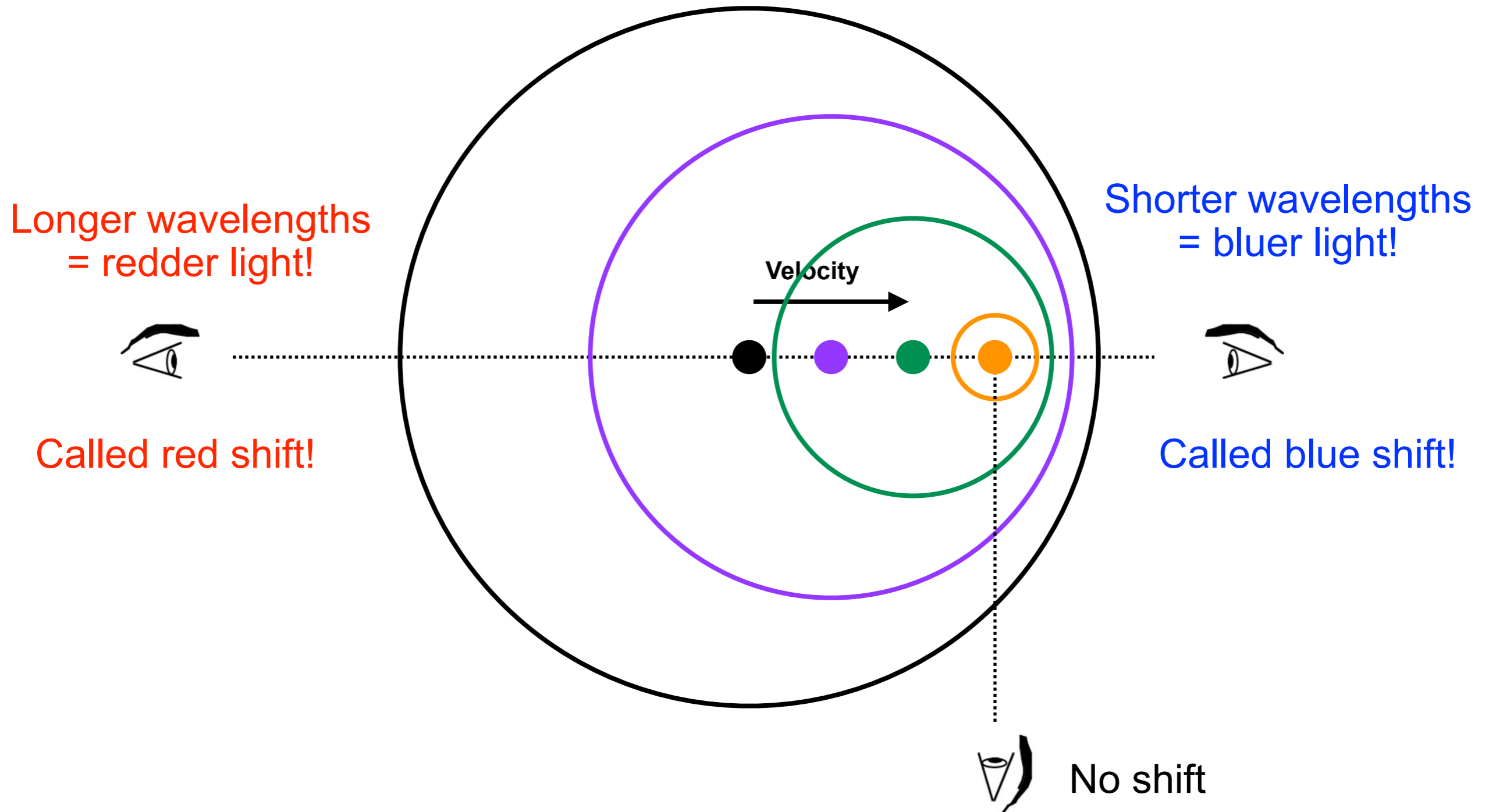
- *Expansion gentle on small scales:*
Andromeda shows **blue** shift

Hubble expansion: further objects are receding faster



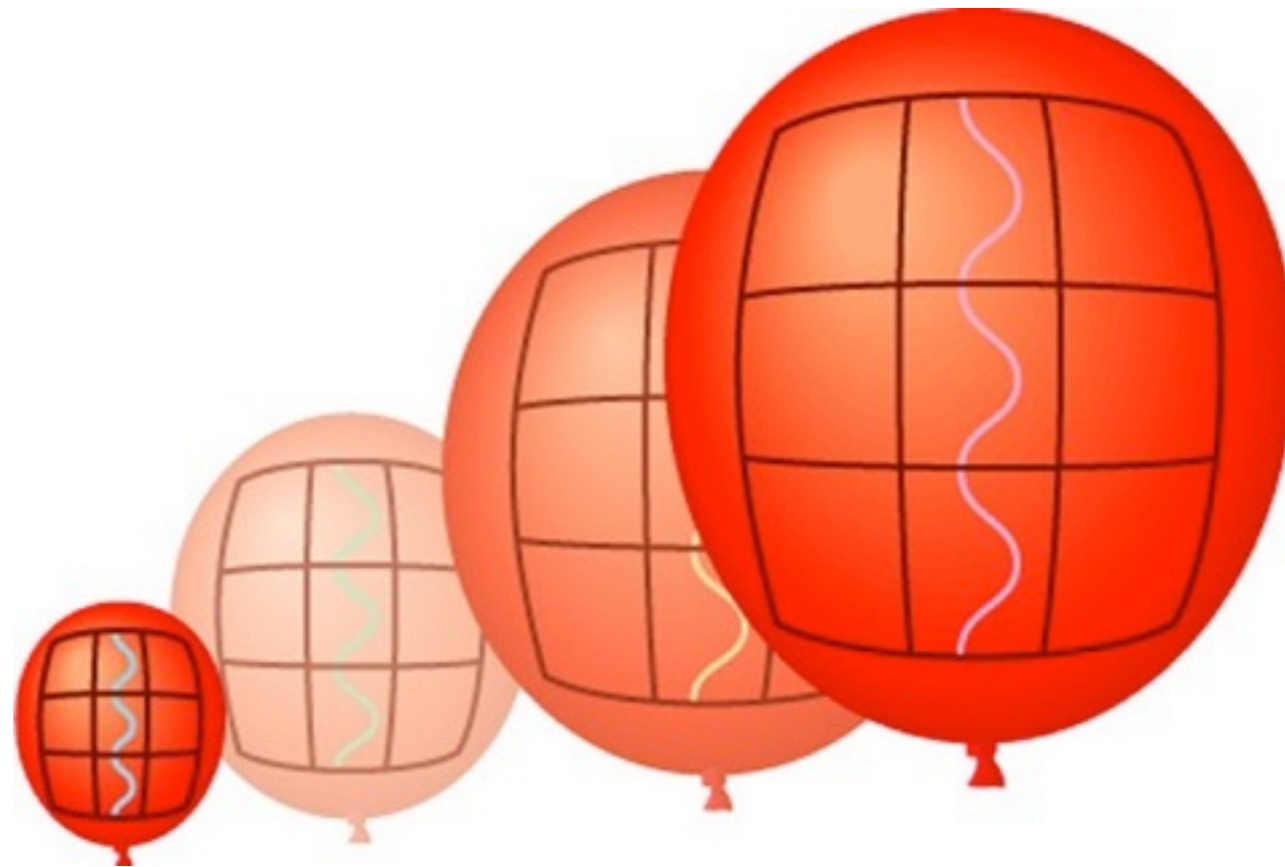
How do we know this? Redshift!

Brief review of redshift



Cosmological redshift

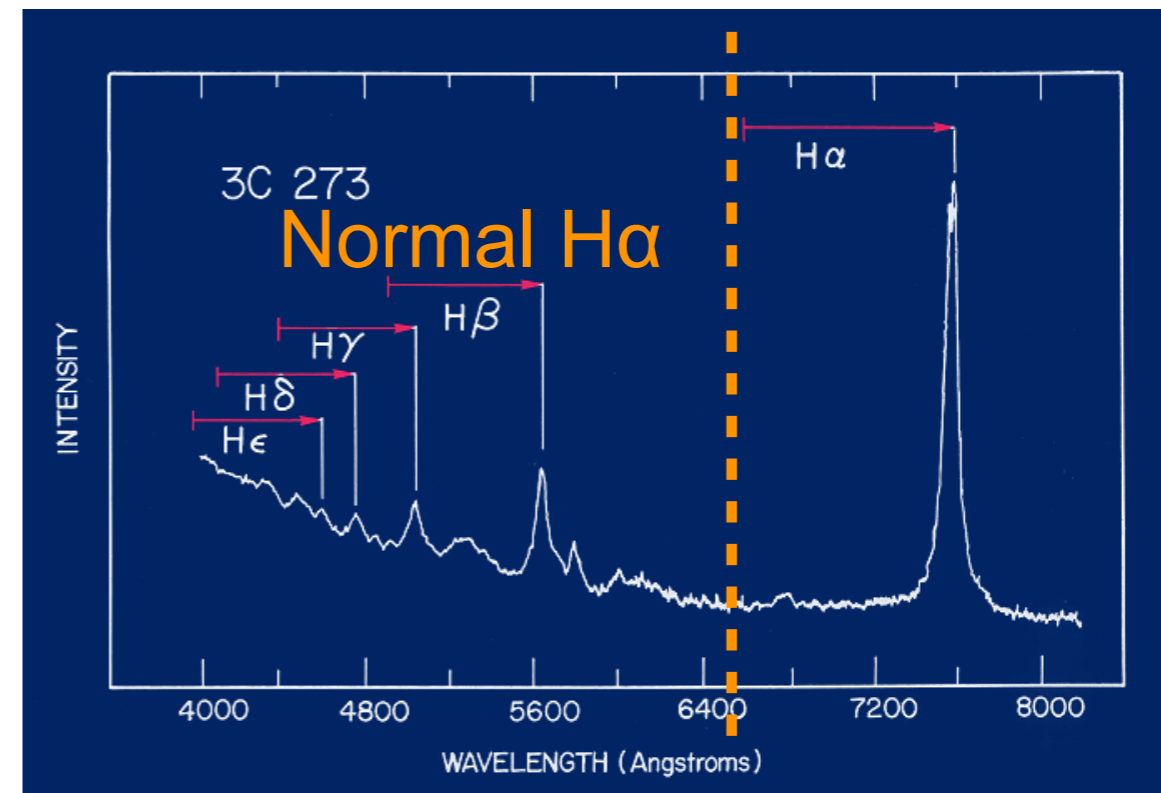
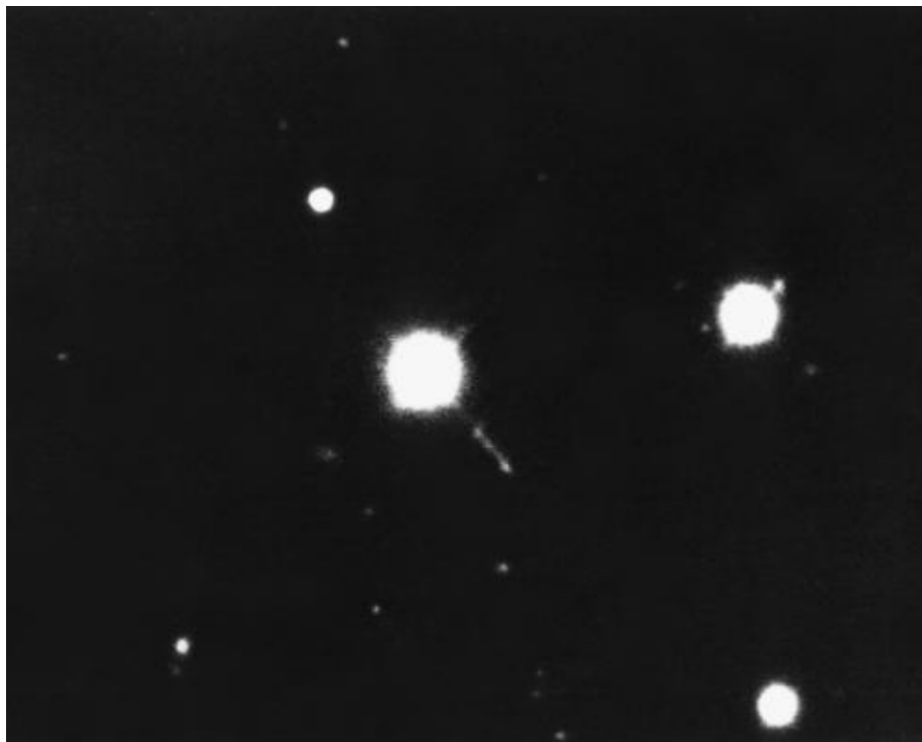
- Things further away have higher redshift
- This is actually caused by the “stretching” of space
- Light is stretched along with space



Discovery of Quasars

1950s — surplus of WWII radar equipment led to discovery of “radio stars”

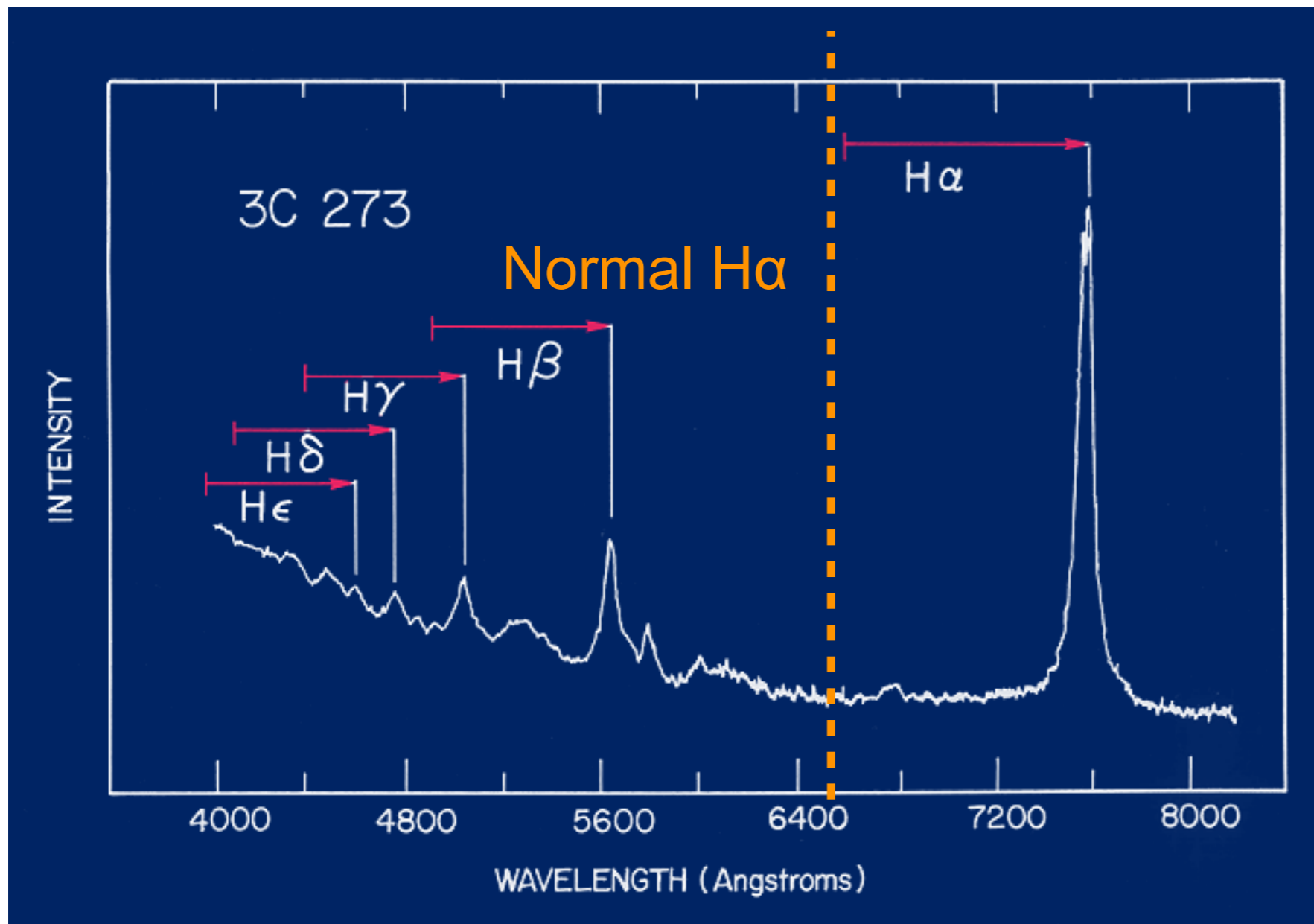
- Quasars or QSO — Quasi Stellar Radio Source:
 - Weird spectra — not star-like even though point sources and had strong radio emission
 - Emission lines at unusual wavelengths — same spacing as Hydrogen lines but (red)shifted (this was a major clue!)



Quasars



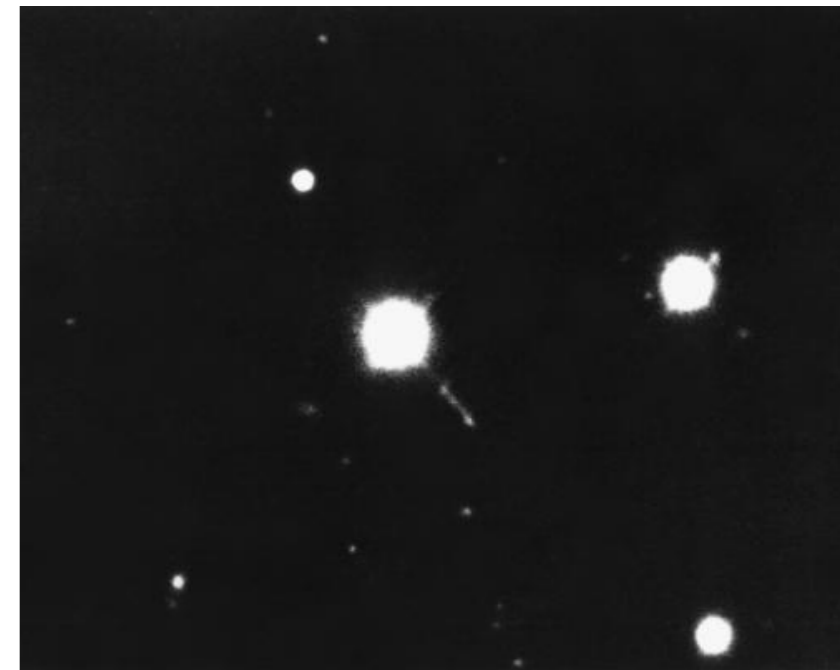
3C 273



- **Redshift means that 3C 273 is receding at 15% of the speed of light!!!**
- **Can't be within our galaxy — would easily escape**
- **Must be VERY far away (high redshift = large distance)**

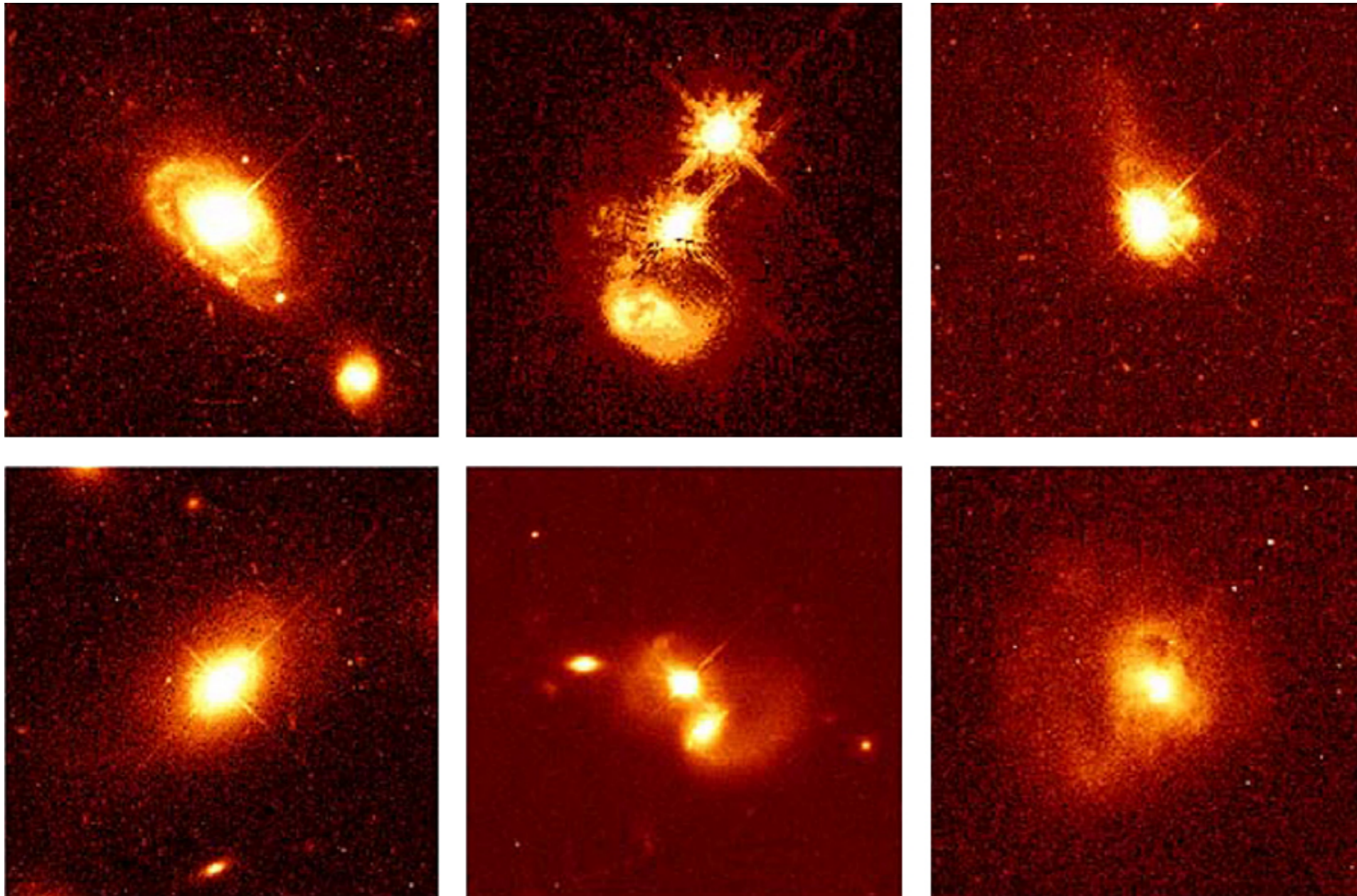
Quasars

- The Hubble Law says that they are at the edge of the observable universe!
- Large Redshift + modest apparent brightness:
 - QSOs are extremely luminous (can't be due to nuclear fusion!)
 - $L \sim 10^{11}$ to $10^{15} L_{\text{sun}}$
 - Huge luminosity in a tiny package



Quasars (contd.)

- Quasars were observed to be associated with galaxies
- Observed (crucially by the Hubble Space Telescope) to be located at the center of galaxies
- Can outshine host galaxies by factors of $> 10-100!!!$

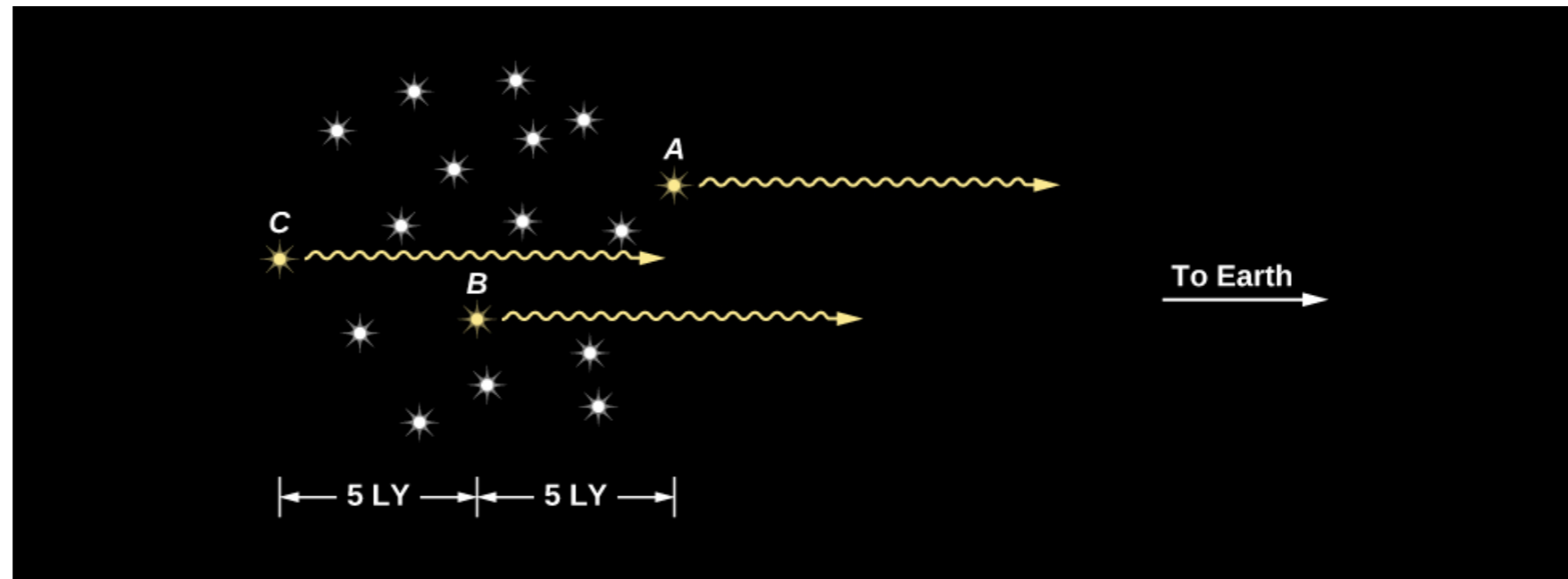


Quasars (contd.)

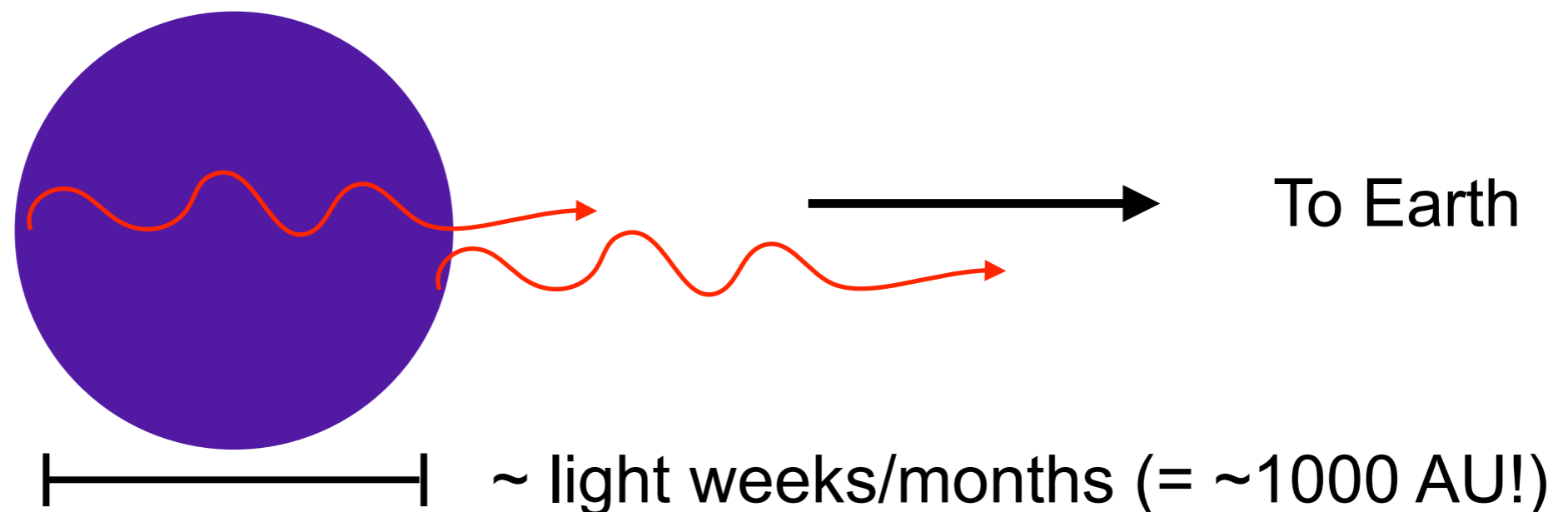
- Appear at the centers of both elliptical and spiral galaxies
- Also bright in X-rays and infrared
- Not always bright in radio
- Large variability over short timescales
 - brightness changes in days to months
 - central engine smaller than a few **light-weeks** across in some cases
 - = a few thousand **A.U.**
 - = **0.03 pc!**

Variability timescale tells us about the size of the emitting region

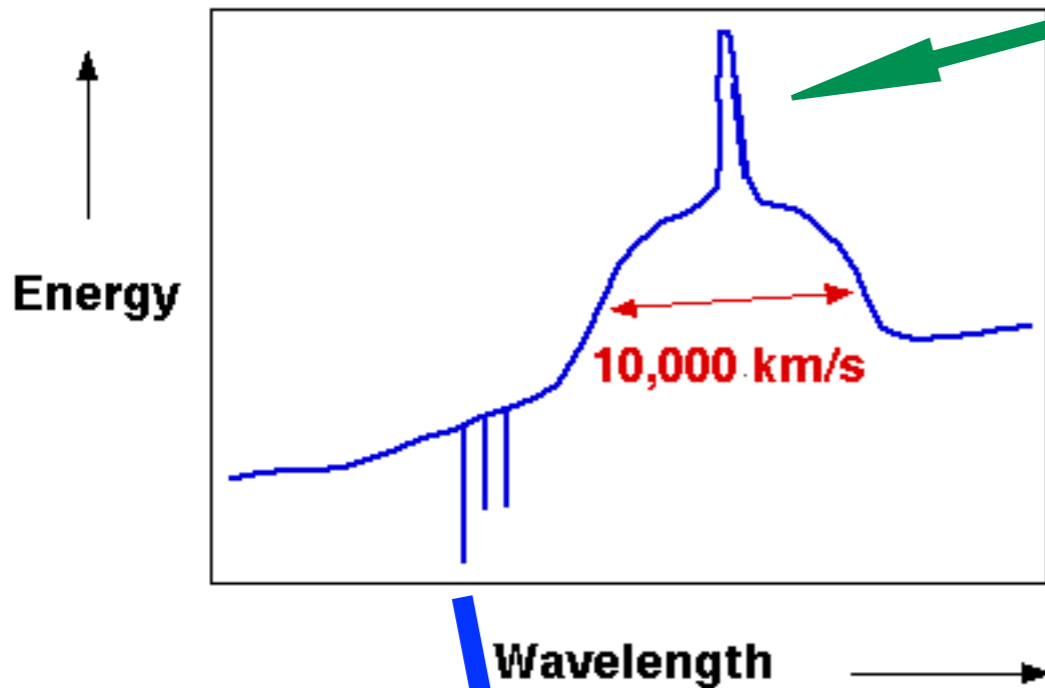
Cluster



Quasar



Quasar Spectral Lines:



- Narrow Line Region

$$\Delta v \sim 200 \text{ km/s}$$

- “normal” galaxy matter

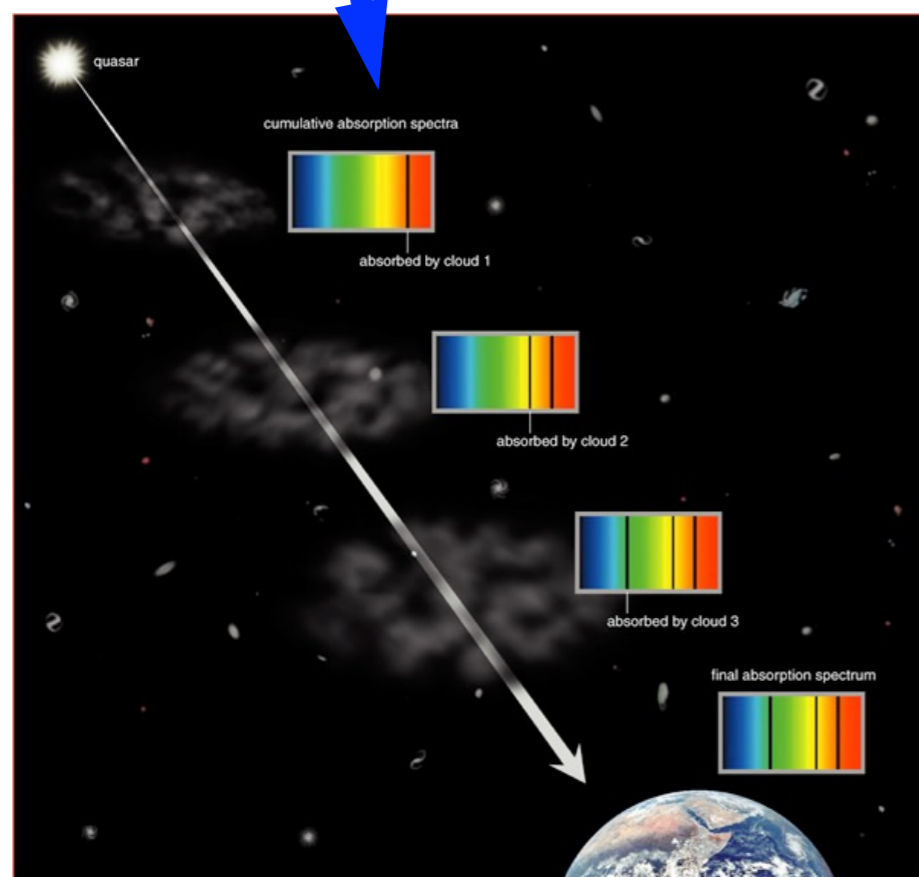
- Broad Line Region:

$$\Delta v \sim 10,000 \text{ km/s}$$

- gas clouds moving at high speed near QSO center

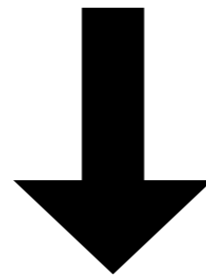
- Narrow Absorption Lines

- redshift always less than QSO
- intervening matter closer to us than QSO



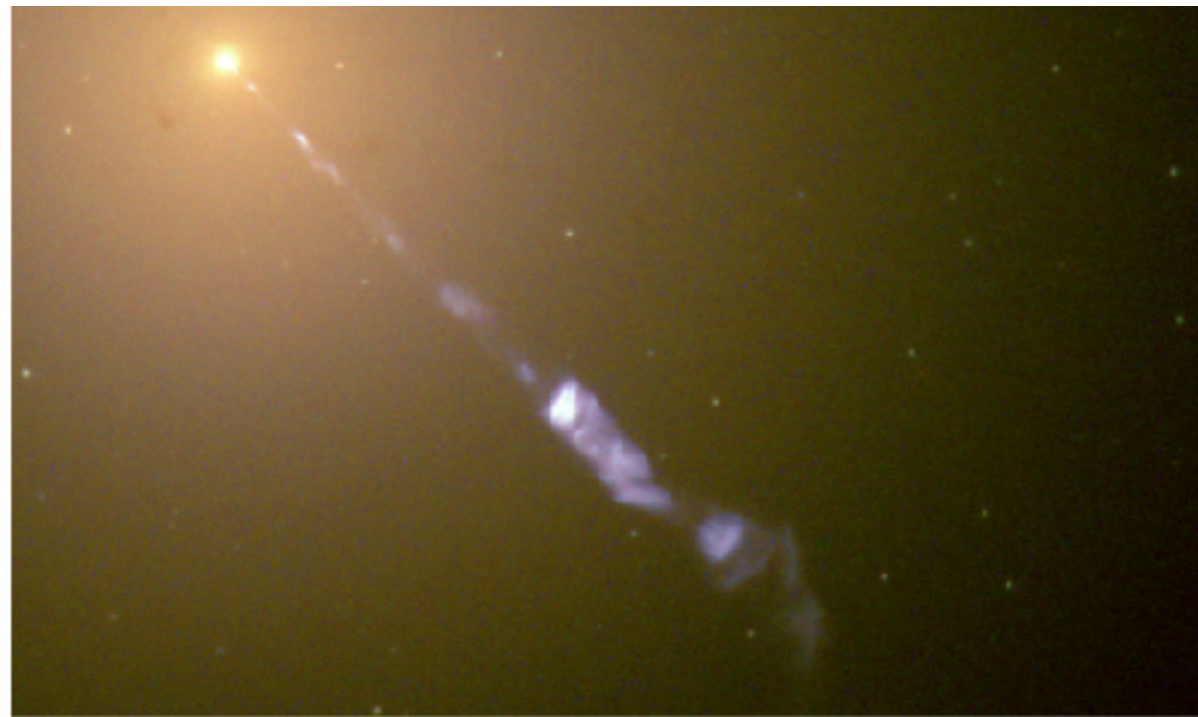
Let's summarize key properties of quasars

- **Very distant — large redshift, receding near speed of light**
- **Very luminous — can easily outshine host galaxies and we can see them from very far away**
- **Small in size — in some cases, not much larger than the Solar System!**

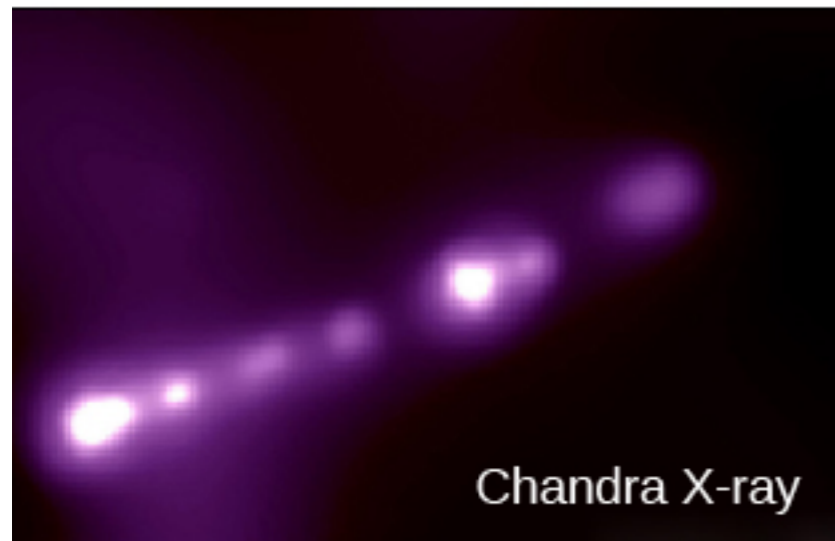


Something capable of producing outrageous amounts of energy in a very small region

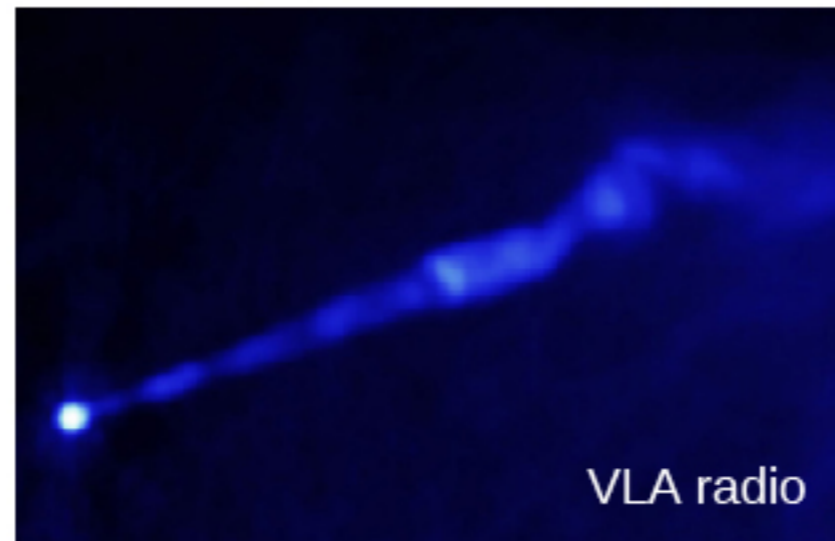
Earlier evidence for these odd objects



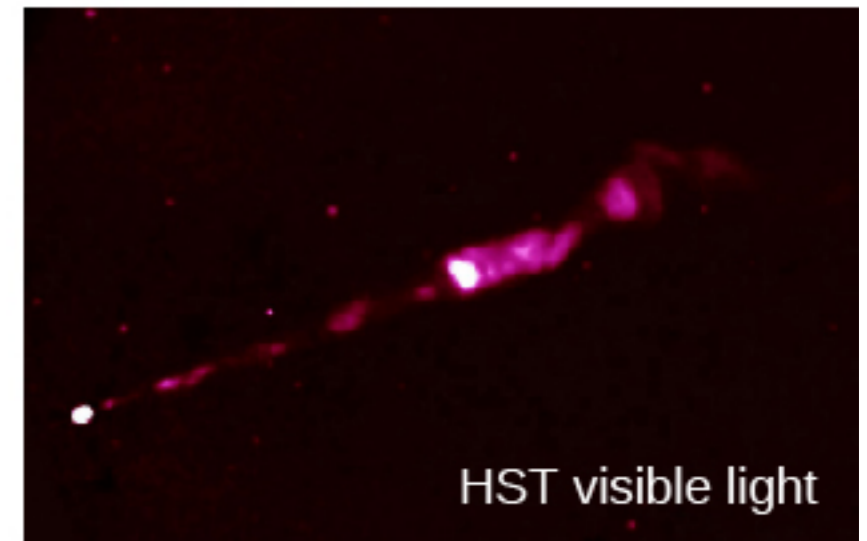
M87



Chandra X-ray



VLA radio



HST visible light

- Jets were observed as early as 1918 associated with galaxy M87
- Eventually, found associated with other quasar type objects

Quasar properties

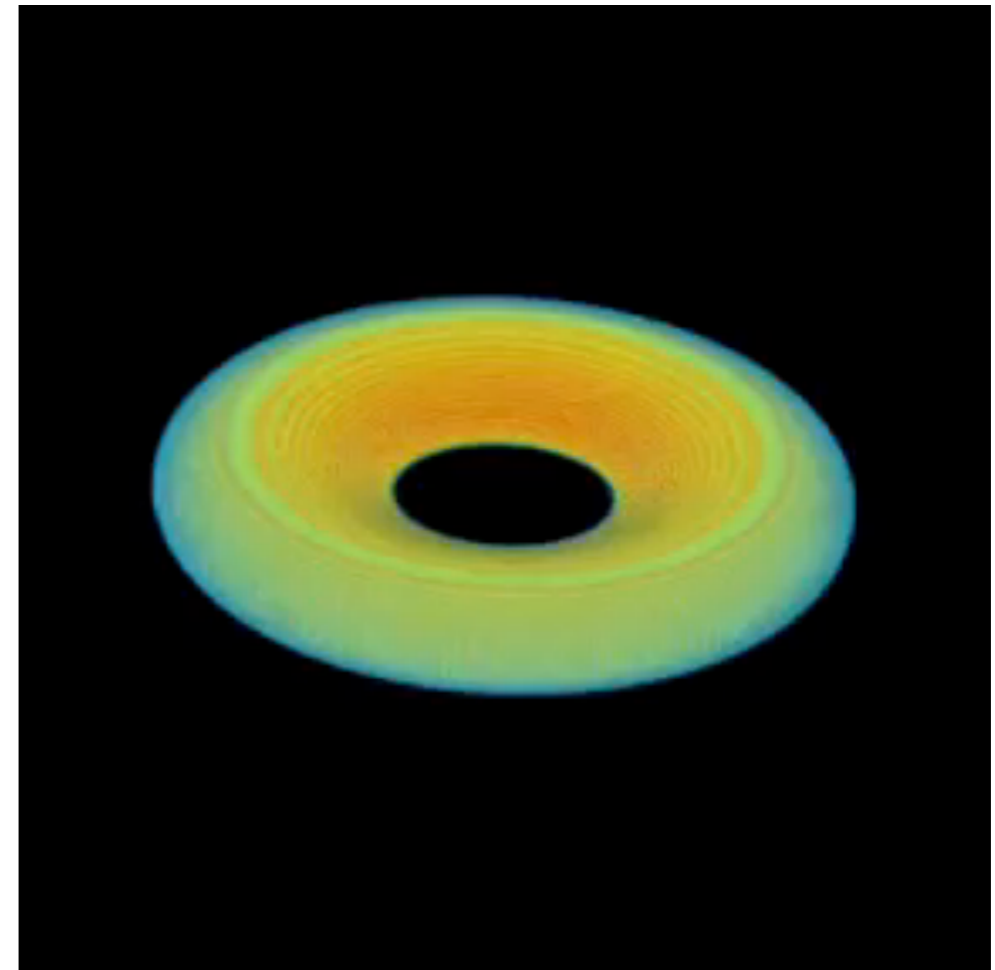
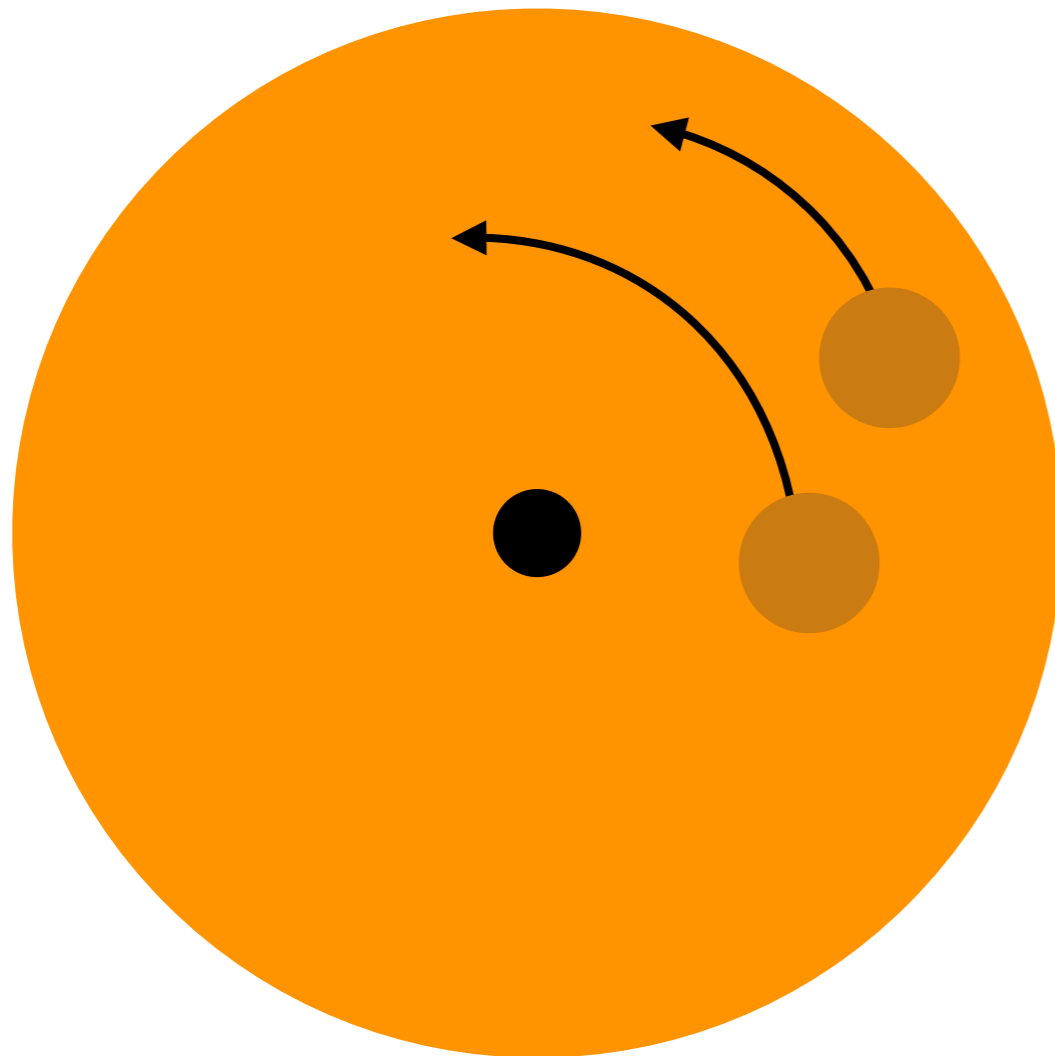
- **Very distant** — large redshift, receding near speed of light
- **Very luminous** — can easily outshine host galaxies and we can see them from very far away
- **Small in size** — in some cases, not much larger than the Solar System!
- **Jets of gas being emitted at close to the speed of light**

*Answer: Supermassive
Black Holes!*



NASA

Why so luminous?



- Turbulence causes collisions between gas
 - This transports angular momentum away
 - Gas then falls inward toward black hole
 - Energy released from gravitational infall — high luminosity!
- 10% of $M_{\text{in}}c^2$**
- 

How much is 10% of rest mass energy?

- Assume (modest) $10 M_{\text{Sun}}$ swallowed in one year
- $E_{\text{out}} = 0.1 \times M_{\text{in}} c^2$
- $E_{\text{out}} = 0.1 \times 10 \times (1.99e33) \times (3.0e10)^2$

$$E_{\text{out}} \sim 10^{54} \text{ erg} = 10^{20} \text{ Suns!}$$

Brief aside (for fun)



- In Star Trek, Romulans used a (small) black hole to power their engines
- This would indeed be more powerful than a nuclear fusion reactor ($< 1\%$)
- (But the Star Fleet reactors relied on anti-matter matter collisions which should be 100% efficient — even better than black holes!)

But not all supermassive black holes appear in *quasars*

Active Galactic Nuclei (AGNs)

- share properties of QSOs and normal galaxies
- lots of energy from **non-thermal** sources

- Seyfert Galaxies: spirals with point-like nuclei

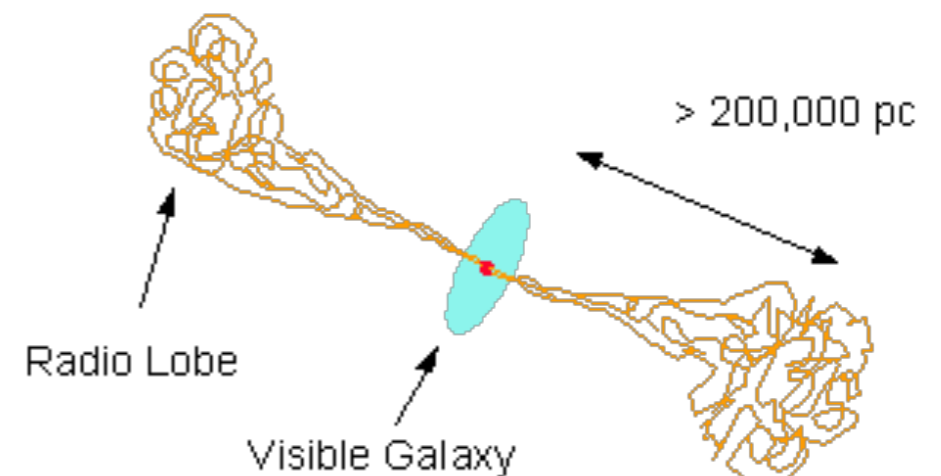
- $L \sim 10^{11} L_{\text{sun}}$
- “rapid” variations
- broad emission lines (5000 km/s)
- a few % of all spirals

- BL Lac objects: minor-league QSOs

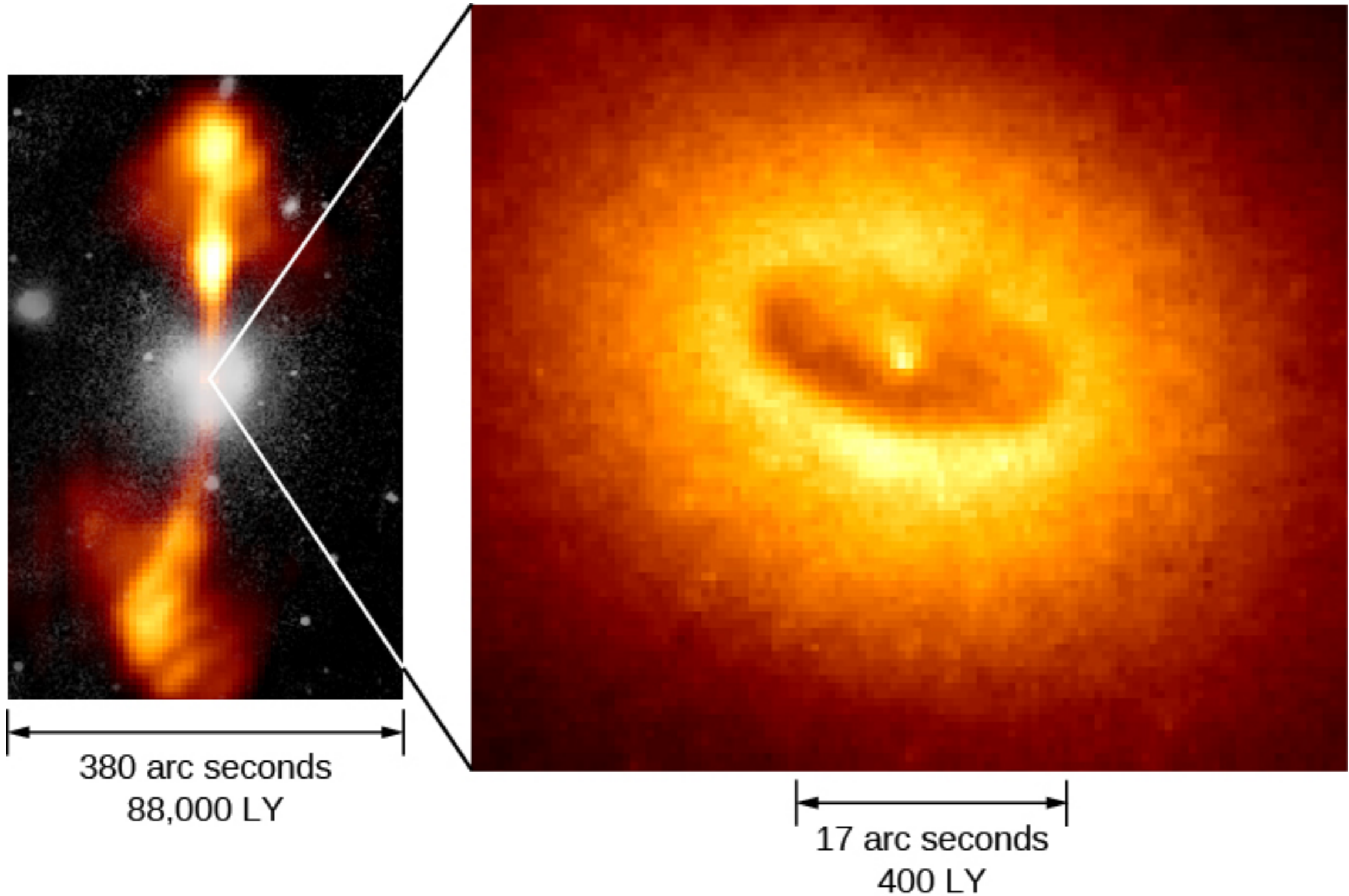
- stellar appearance
- sometimes violent variability (“Blazars”)
- no spectral lines; faint fuzz at high redshift, UV+X-ray

- Radio Galaxies: ~10% of AGNS

- double-lobed radio sources
- tight jets

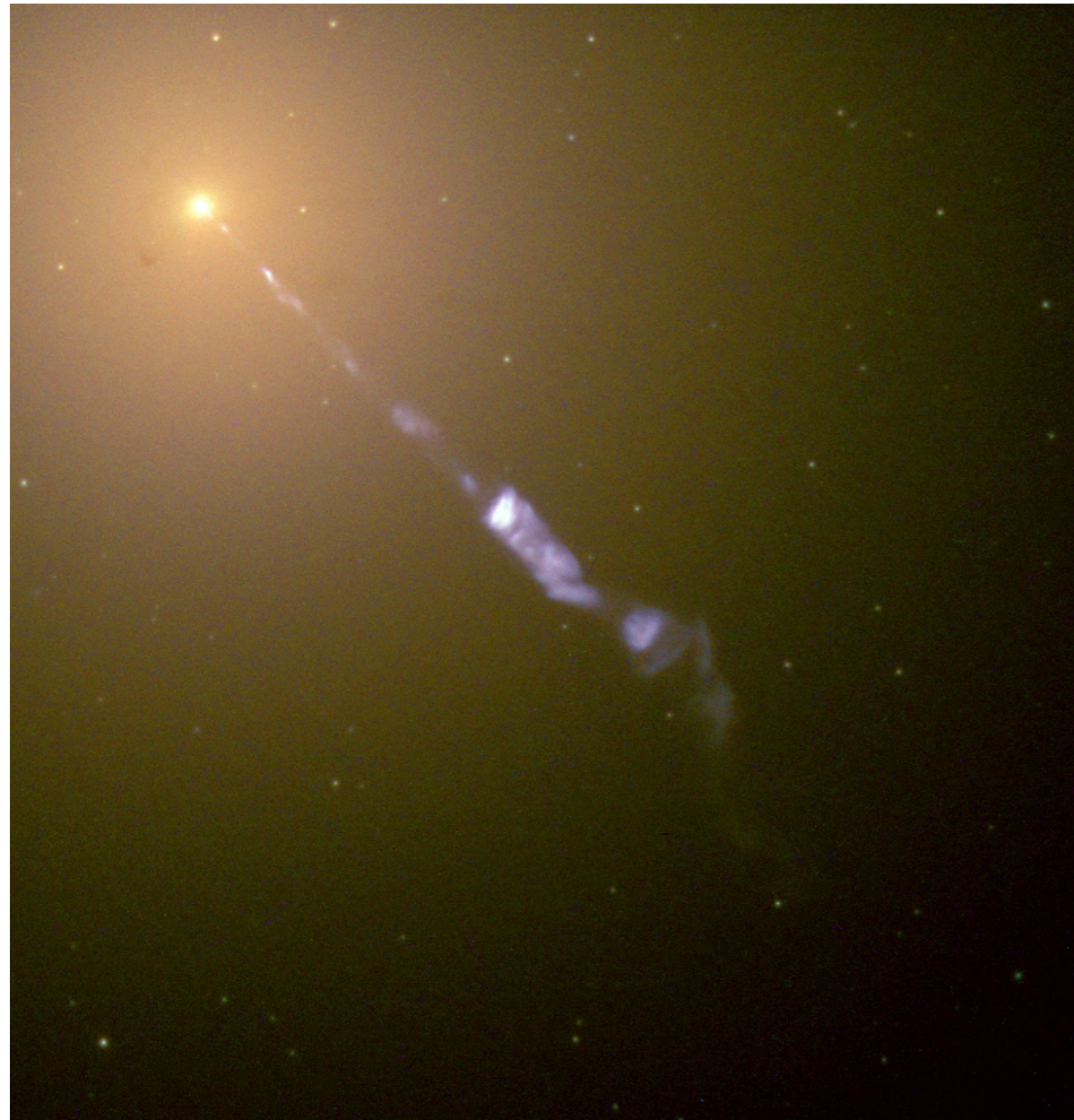


NGC 4261

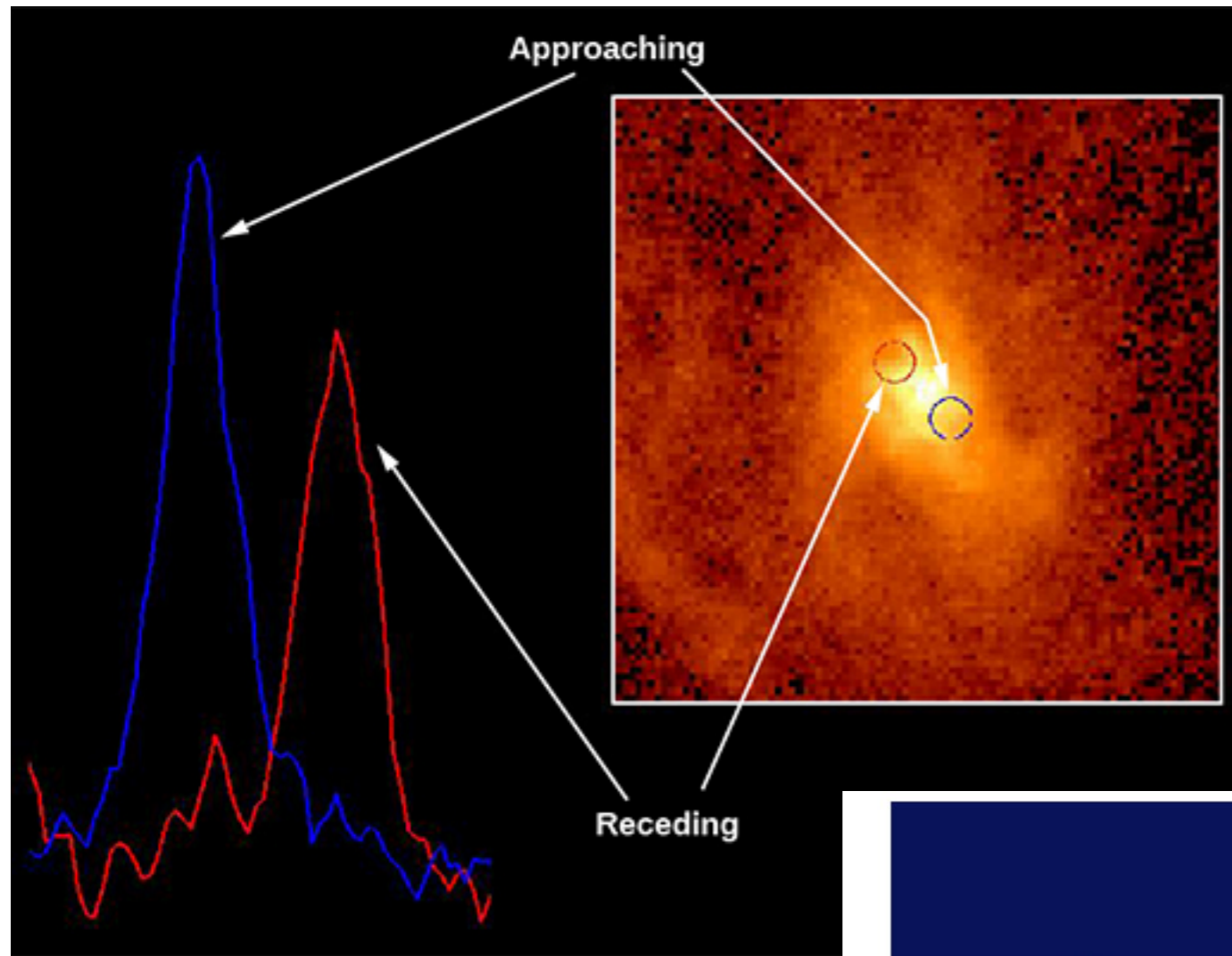


M87 - elliptical galaxy with 3.5 billion M_{sun} black hole at the center!

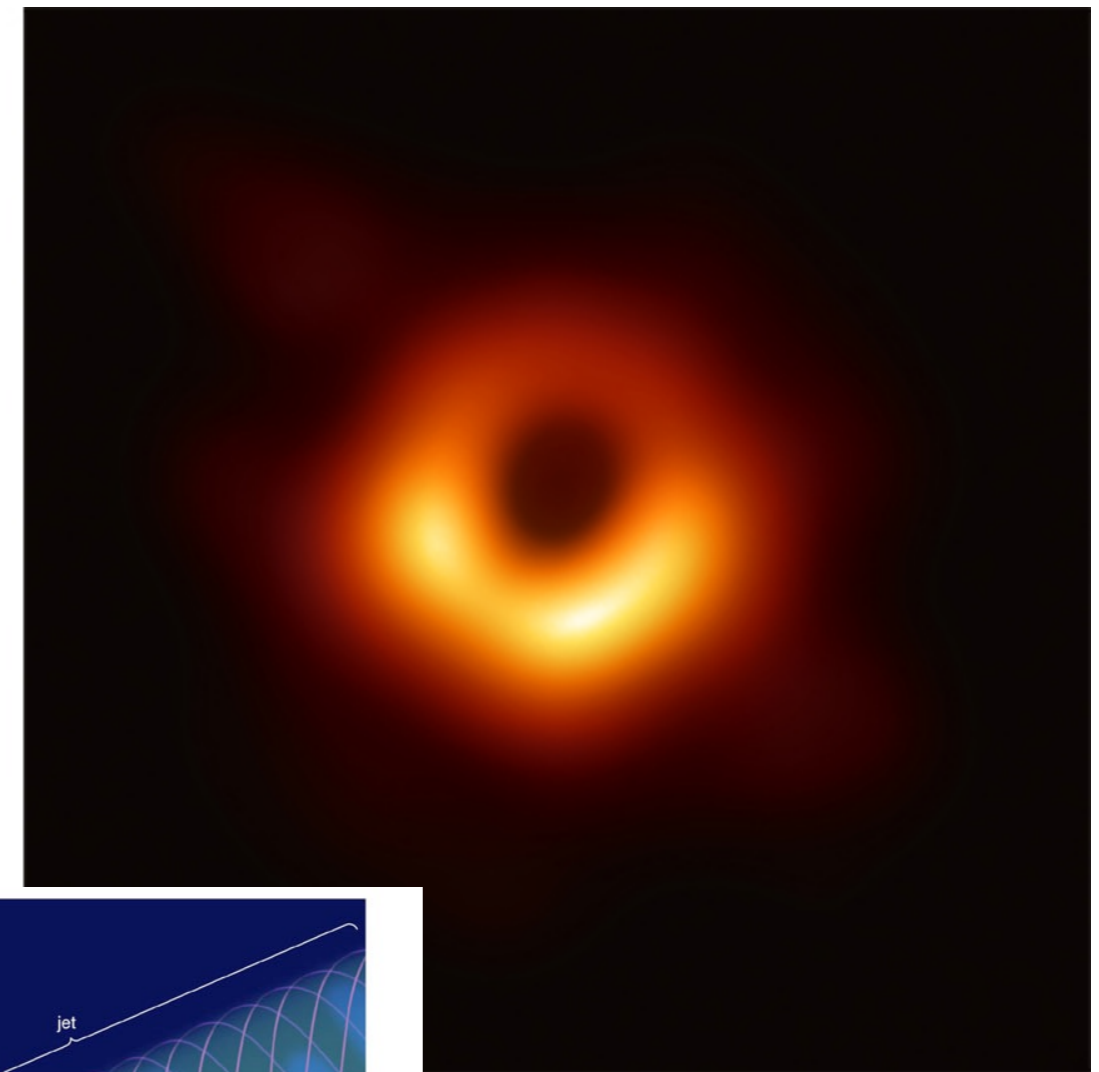
SIZE COMPARISON:
THE M87 BLACK HOLE
AND
OUR SOLAR SYSTEM



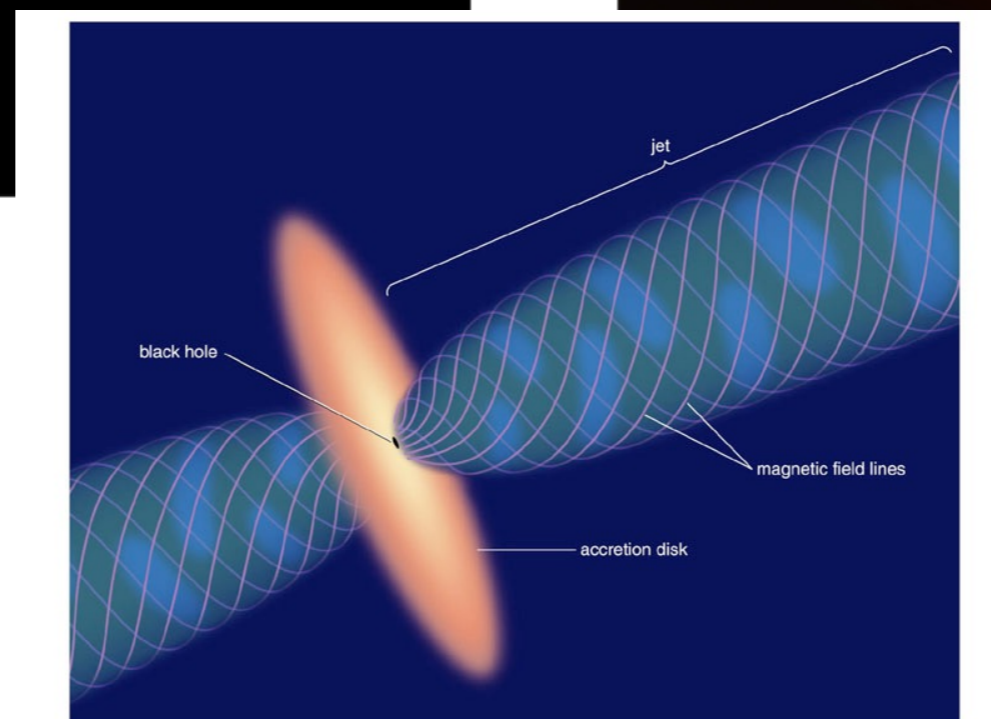
M87 - signature of an accretion disk



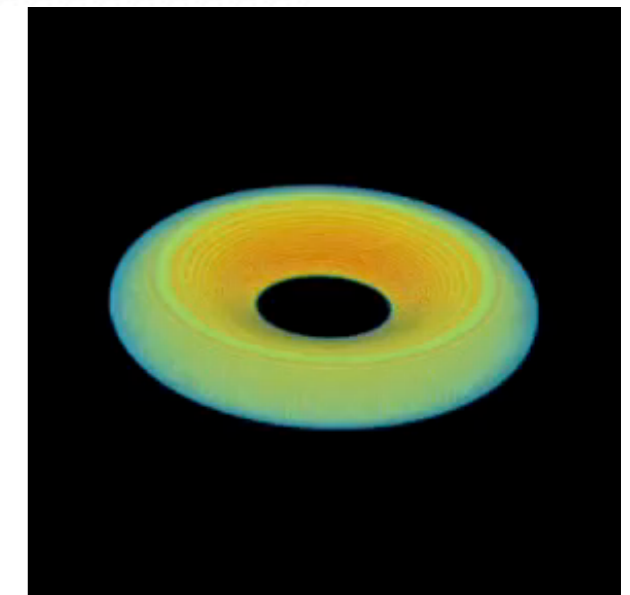
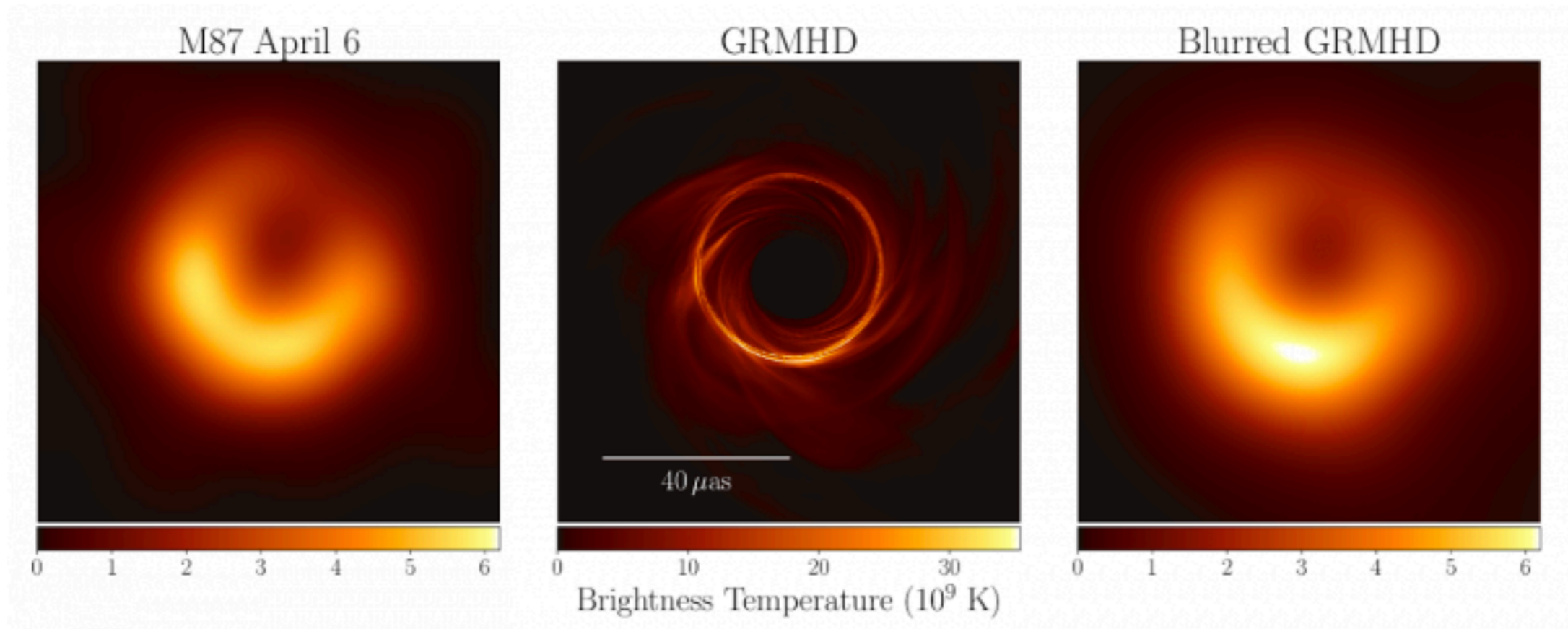
(a)



(b)



M87 - direct comparison between theory and observations



Take a closer look at AGN features

- Common Features of AGNs:
 - high luminosity
 - rapid variability = small size
 - → compact, efficient central engine
- Diverse Features of AGNs:
 - radio loud / radio quiet
 - broad lines / narrow lines
 - jets / no jets
 - UV-Xray / no UV-Xray

Unified model of AGNs:

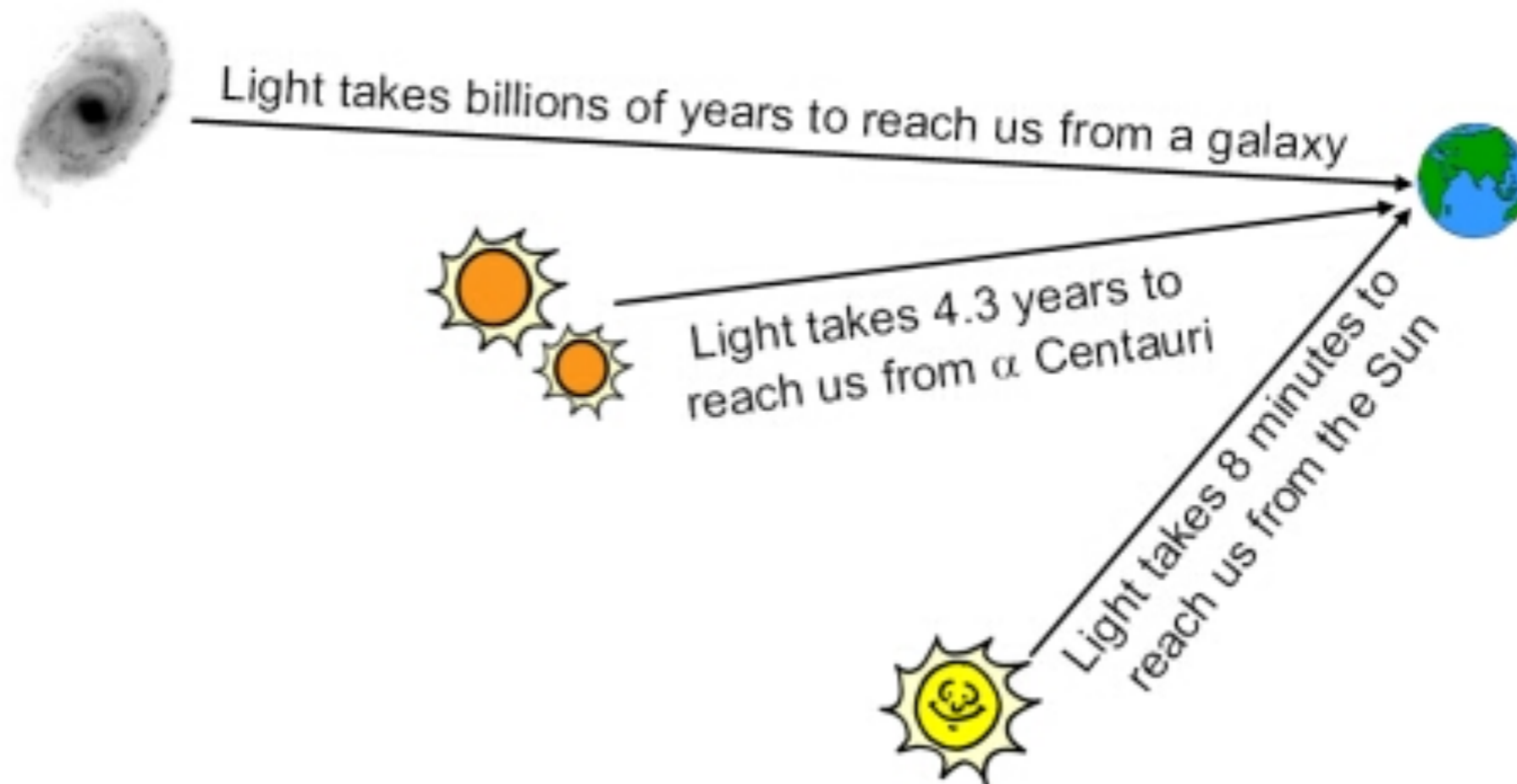
it's all a matter of *inclination*

- Edge-on: see disk edge
 - Radio galaxies, Seyferts
- Tilted: see hot disk
 - Quasars
- Face-on: bore-sight on BH
 - BL Lac

- More distant objects appear to be more active
- Activity in closer AGN is much less (though still a LOT)
- All galaxies (including our Milky Way) likely have a black hole at their centers. (or at least, most galaxies!)

Brief aside: Look-back Time

- More distant galaxies - longer time for light to reach us
- We see distant galaxies as they were when light left them



The brightest quasars (i.e., the most active AGN) existed in the early Universe. Things have since "quieted down"

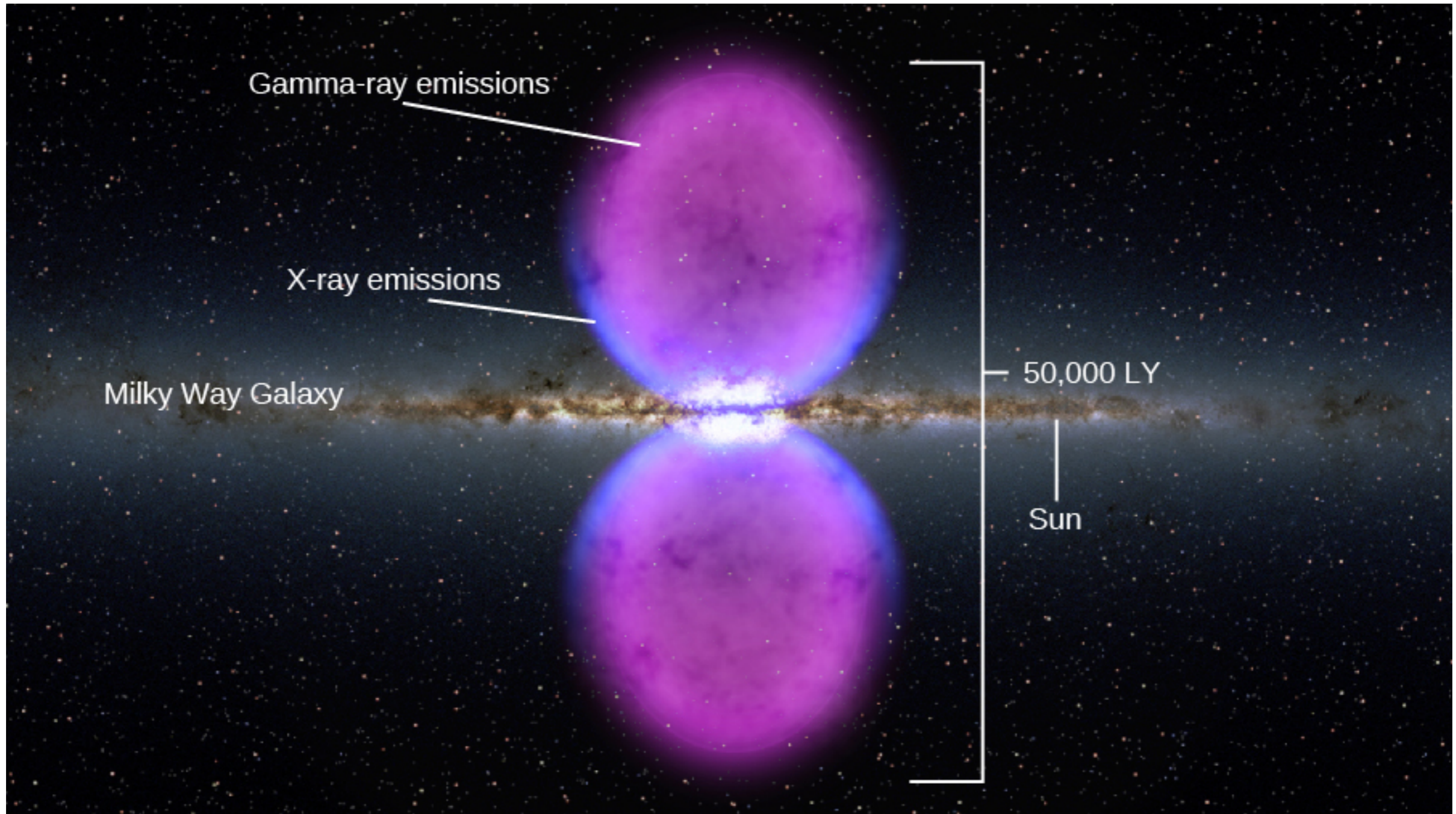
Unified model of AGNs:

it's all a matter of *inclination*

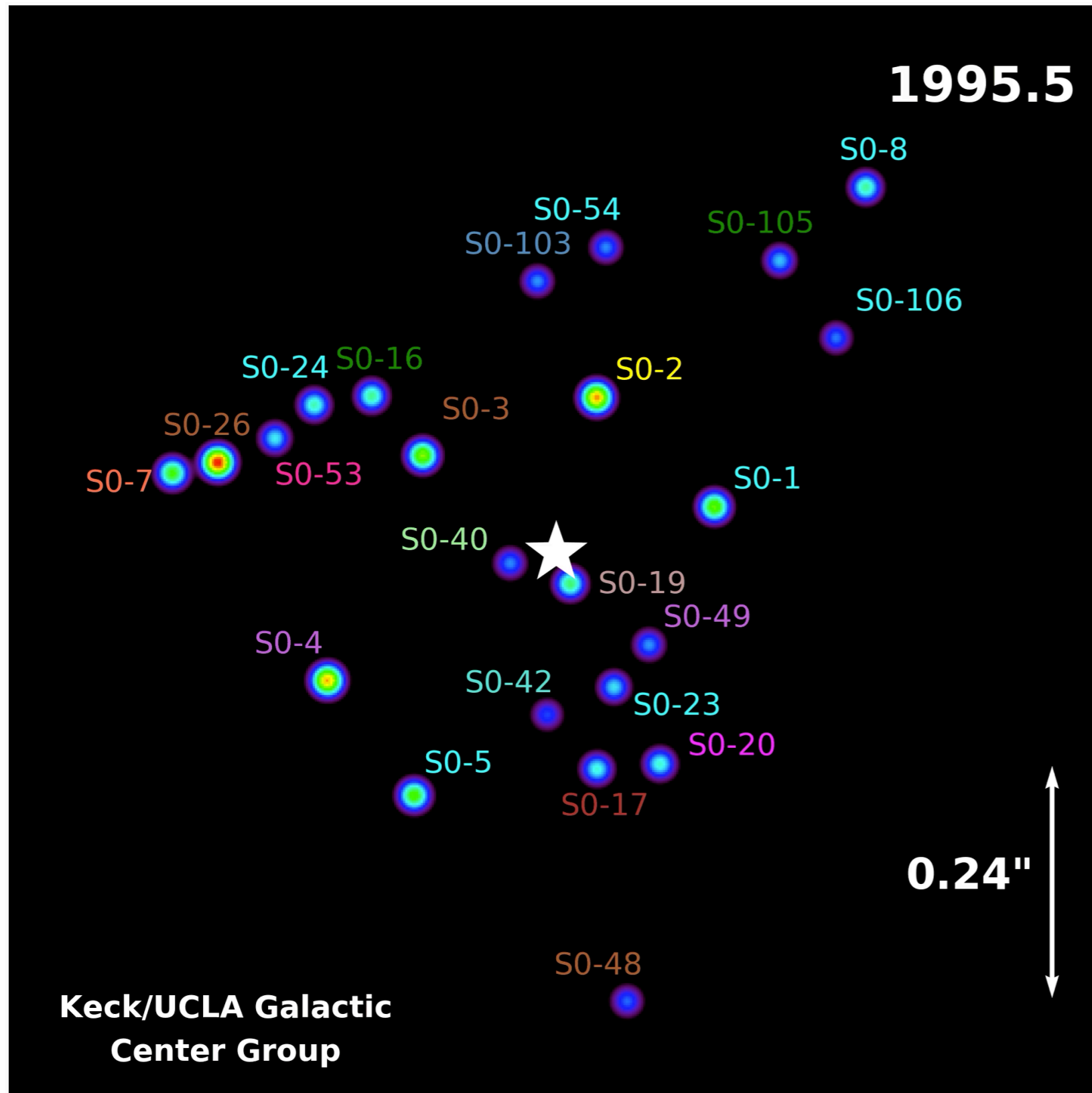
- Edge-on: see disk edge
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 - Quasars
- Face-on: bore-sight on BH
 - BL Lac

- More distant/younger objects appear to be more active
- Activity in closer/older AGN is much less (though still a LOT)
- All galaxies (including our Milky Way) likely have a black hole at their centers. (or at least, most galaxies!)

Our own supermassive black hole



Our own supermassive black hole



- Mass is (only) 2.6 million M_{Sun}
- Not very active — very low luminosity (for an AGN)

Unified model of AGNs:

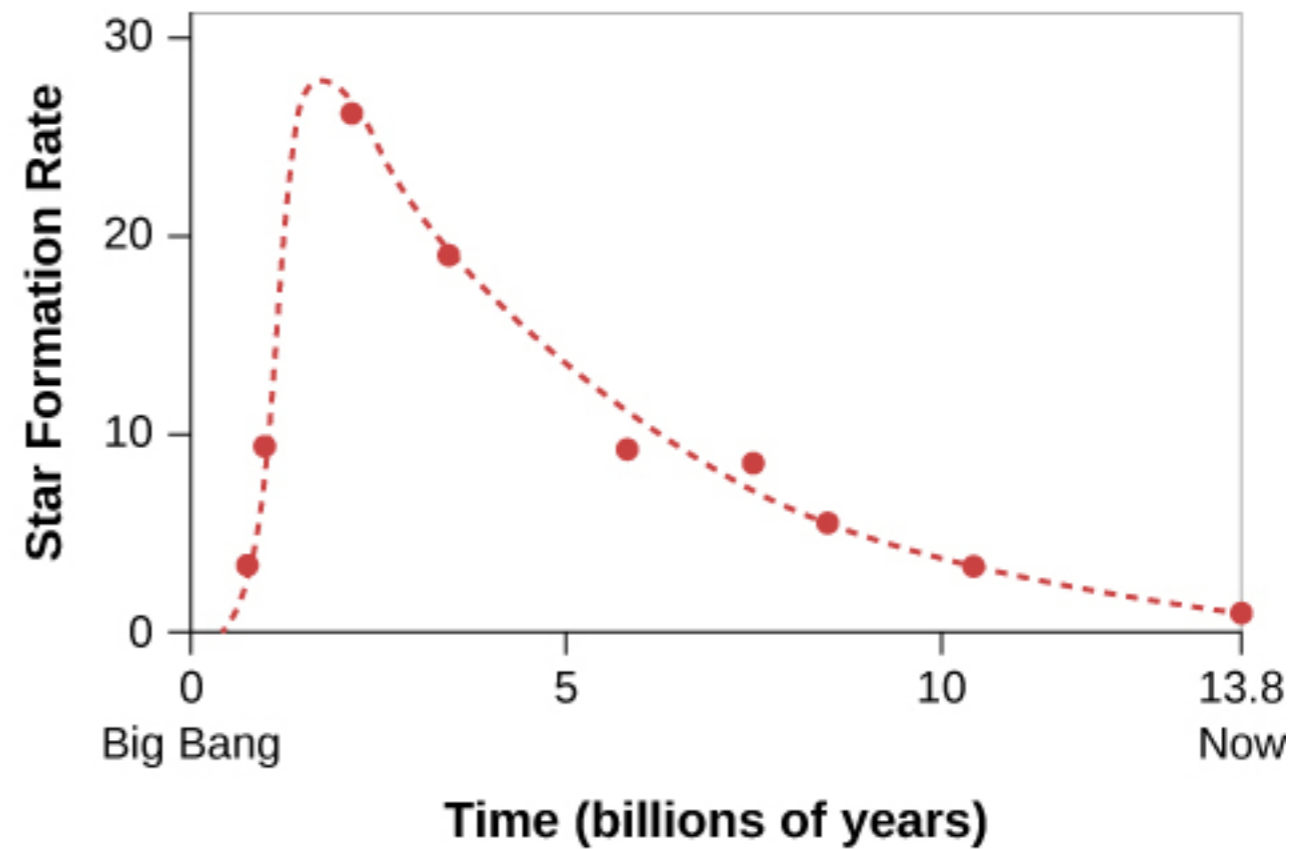
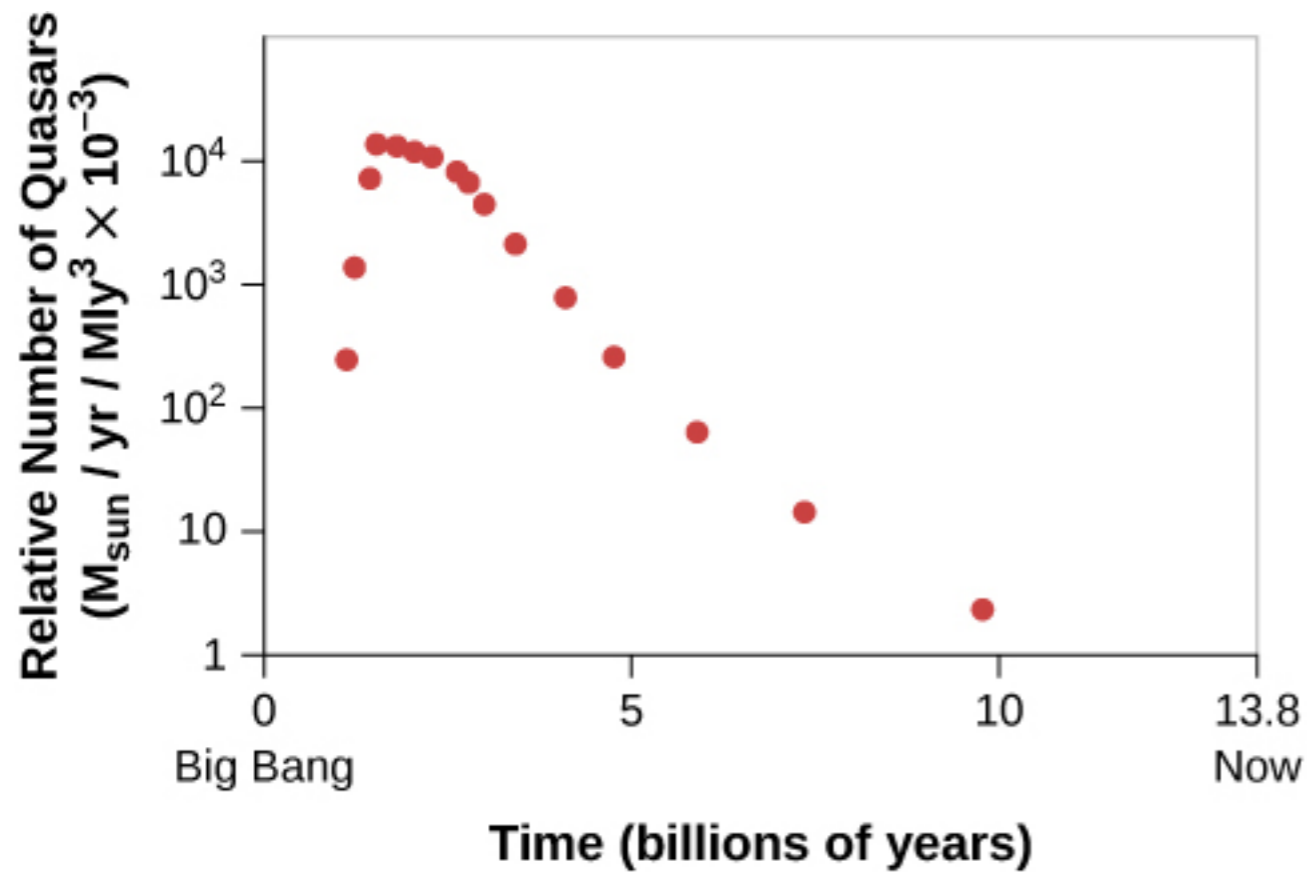
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Why??

- More distant objects appear to be more active
- Activity in closer AGN is much less (though still a LOT)
- All galaxies (including our Milky Way) likely have a black hole at their centers. (or at least, most galaxies!)

Early on, gas that had not yet formed stars accreted onto the black holes



One final thought (actually an open question)

