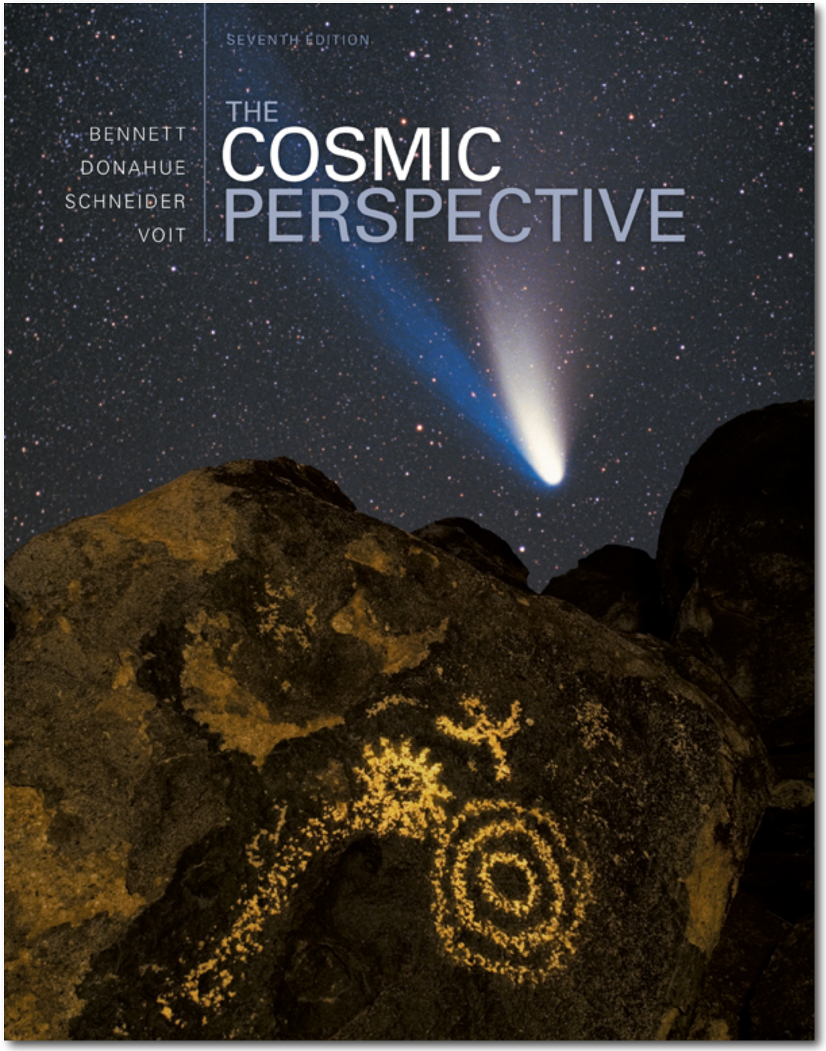
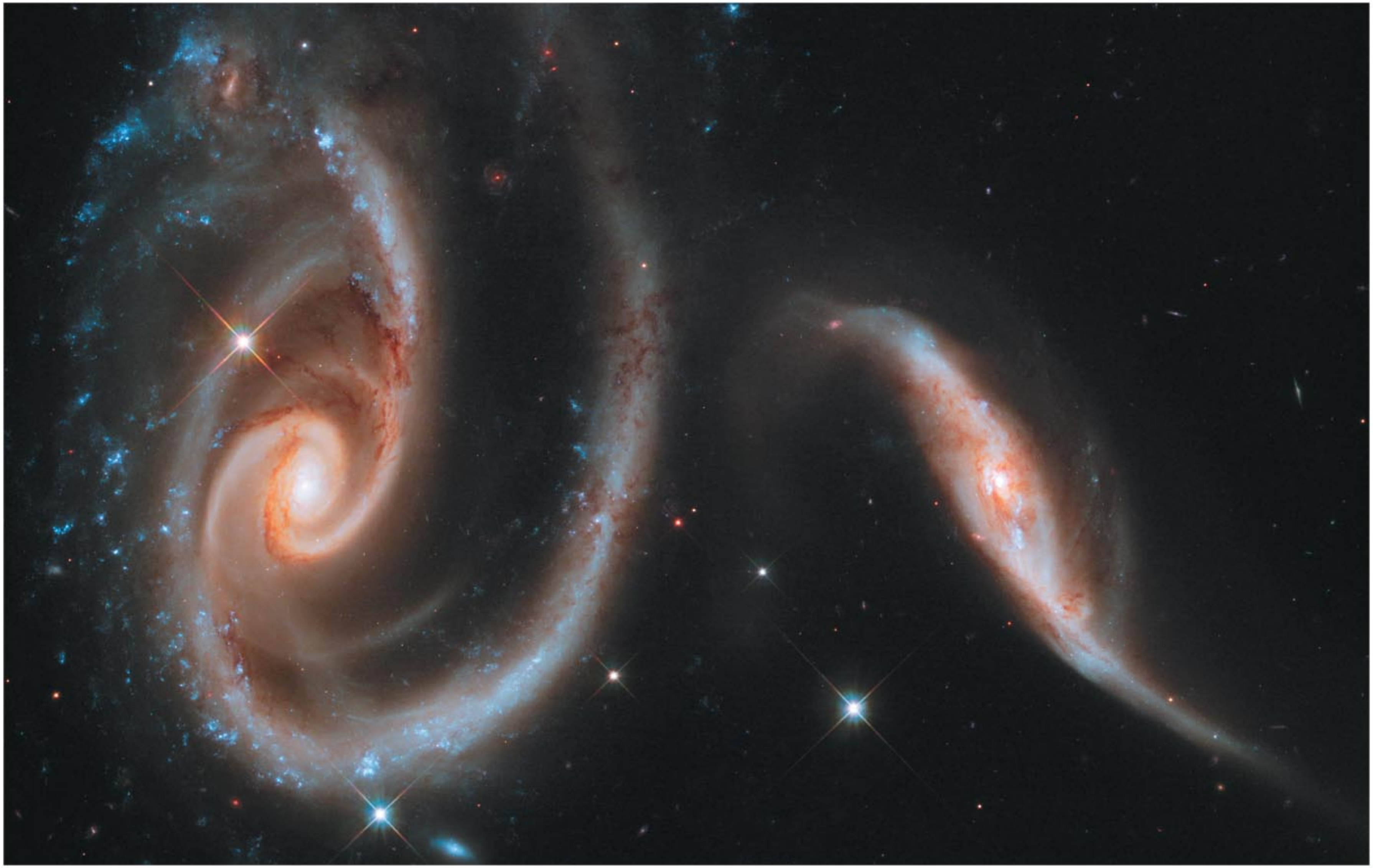
The Cosmic Perspective

Seventh Edition



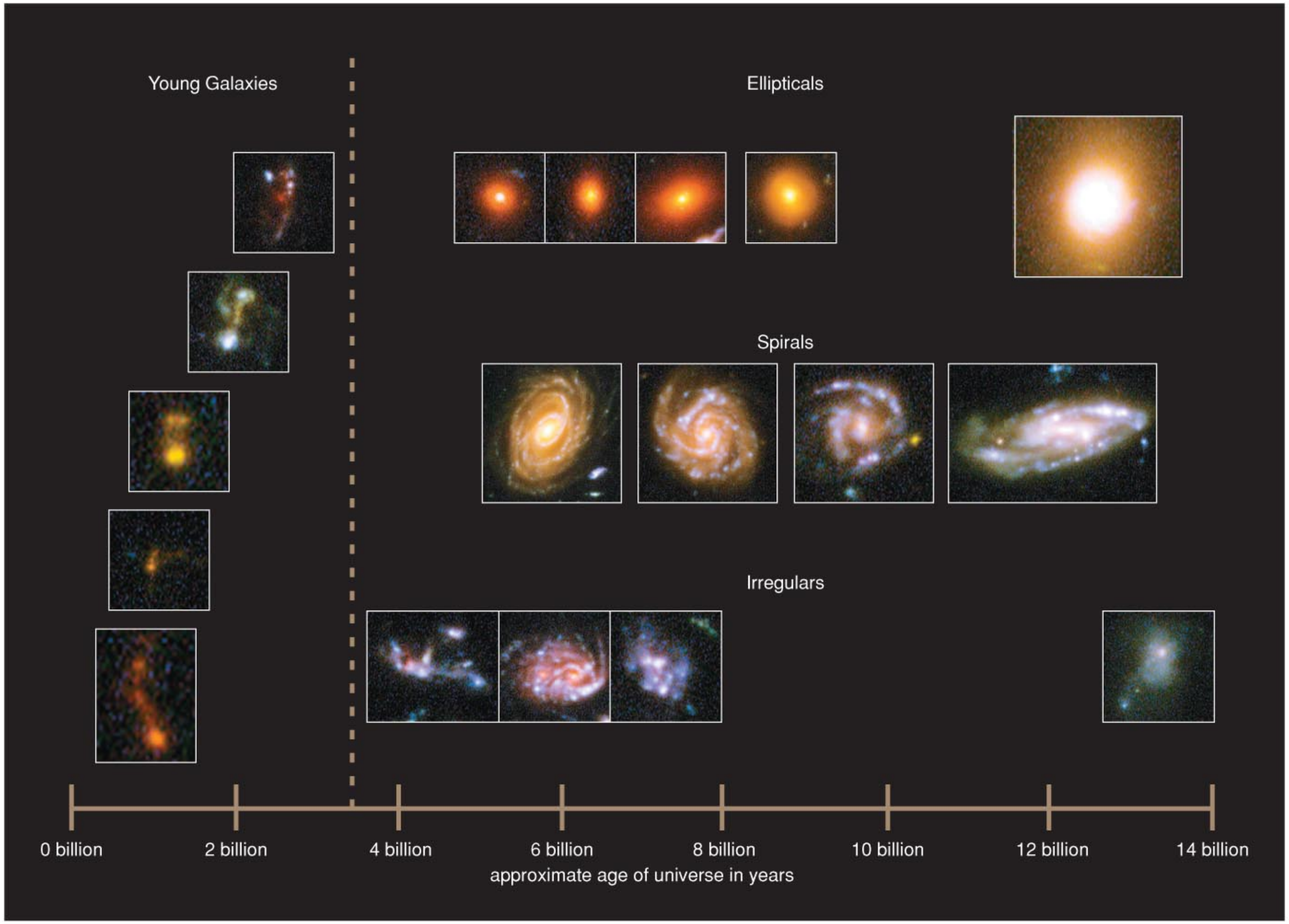
Galaxy Evolution

Galaxy Evolution

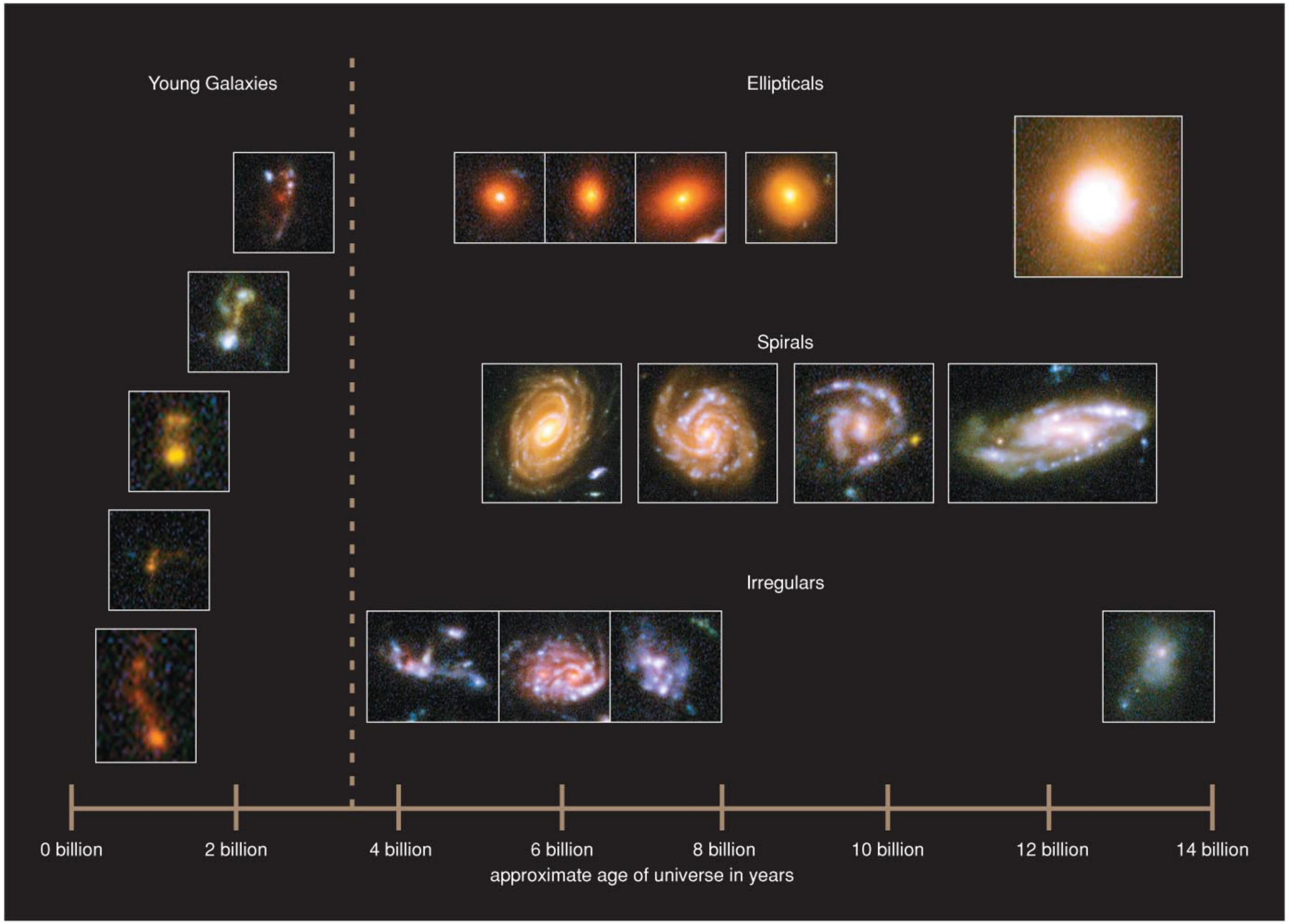


21.1 Looking Back Through Time

- Our goals for learning:
  - **How do we observe the life histories of galaxies?**
  - **How do we study galaxy formation?**



By looking back through time we can study how galaxies first formed and how they evolved and why there is such a variety of galaxy types.



Based on Hubble Space Telescope observations we find that the first galaxies formed at about 1 billion years after the Big Bang. Our galaxy also probably started forming during this time. Several stars in the halo of our galaxy are about 13 billion years old.

Galaxy Formation

- Galaxies form from the collapse of ***protogalactic clouds***.
- Hydrogen and helium gas in these clouds formed the first stars.

- Supernova explosions from the first stars kept much of the gas from forming stars.
- Leftover gas settled into a spinning disk due to the ***conservation of angular momentum***.

NGC 4414

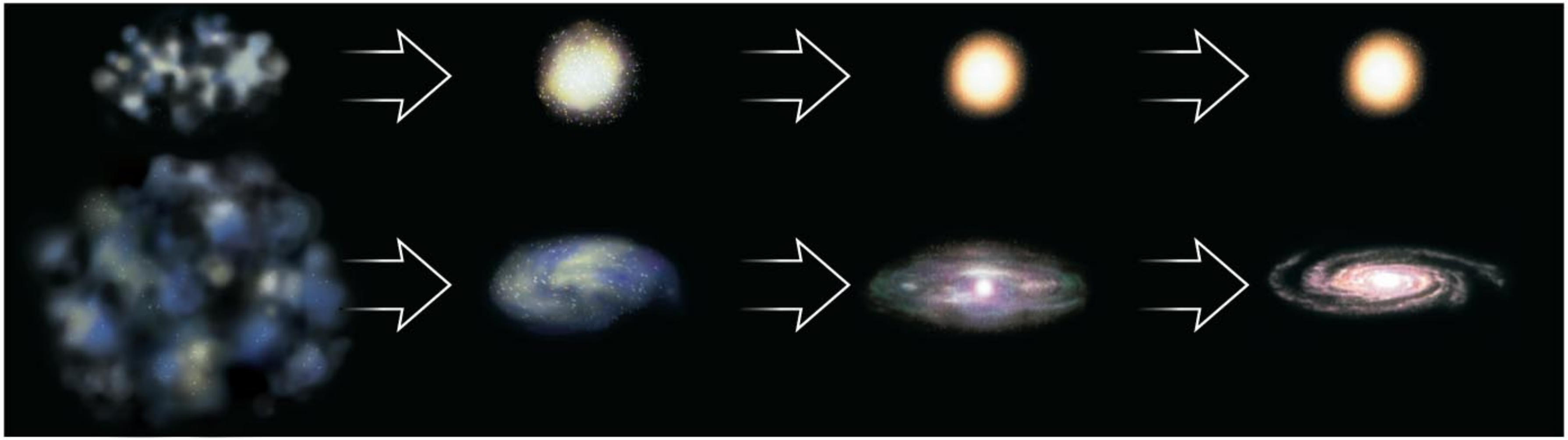
M87

- But why do some galaxies end up looking so different?

21.2 The Lives of Galaxies

- Our goals for learning:
  - **Why do galaxies differ?**
  - **What are starbursts?**

Why do galaxies differ?

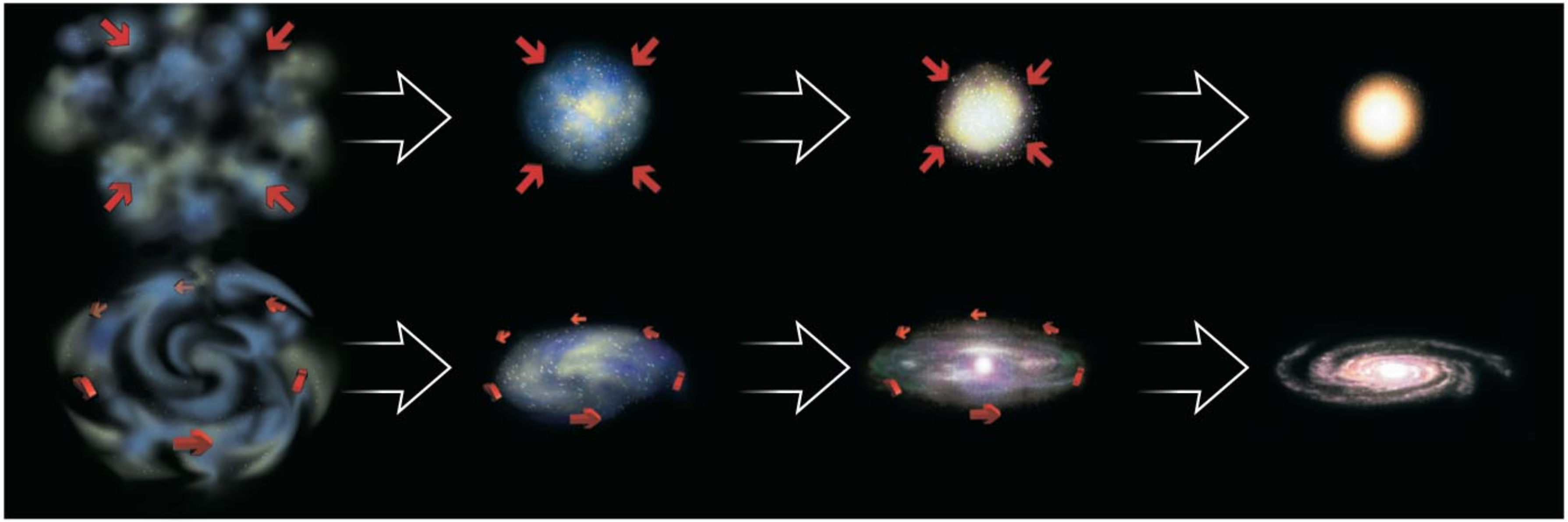


b The gas density of a galaxy's protogalactic clouds may determine whether it ends up spiral or elliptical.

1. Birth Conditions (rotation, density)

2. Mergers

Conditions in Protogalactic Cloud?

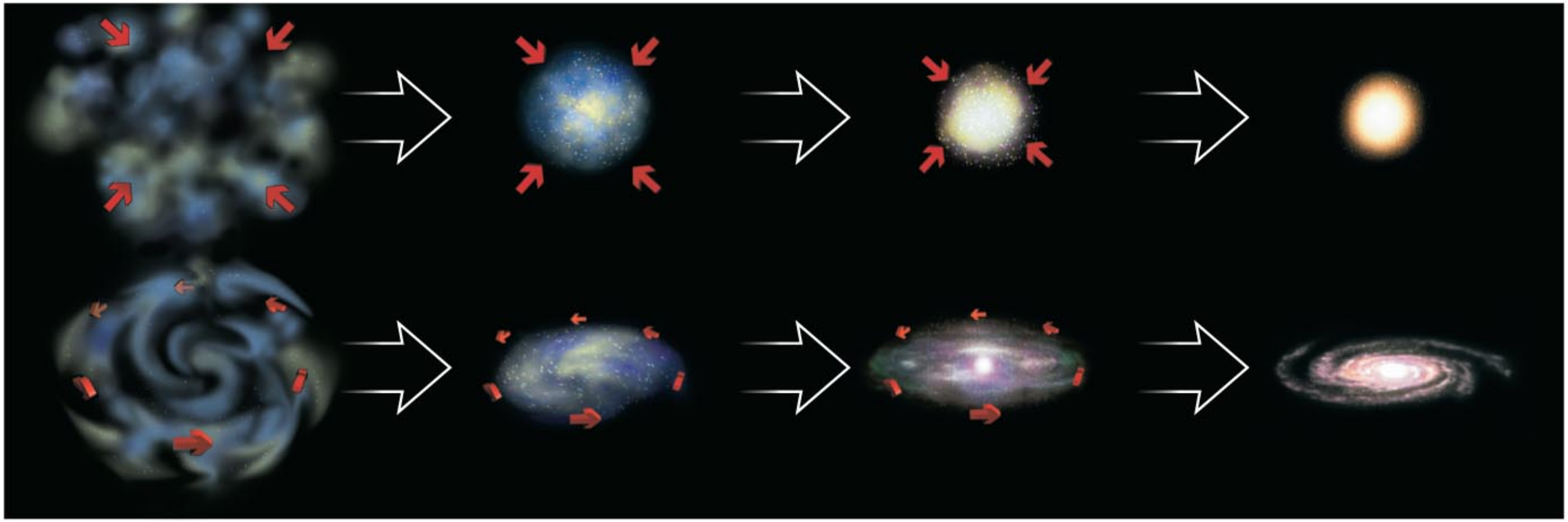


a The angular momentum of a galaxy's protogalactic-cloud system may determine whether it ends up spiral or elliptical.

Interactive Figure

- ***Spin:*** The initial angular momentum of the protogalactic cloud could determine the size of the resulting disk. Protogalactic clouds with **large spin** are likely to form a disk and the resulting galaxy will be **spiral**.

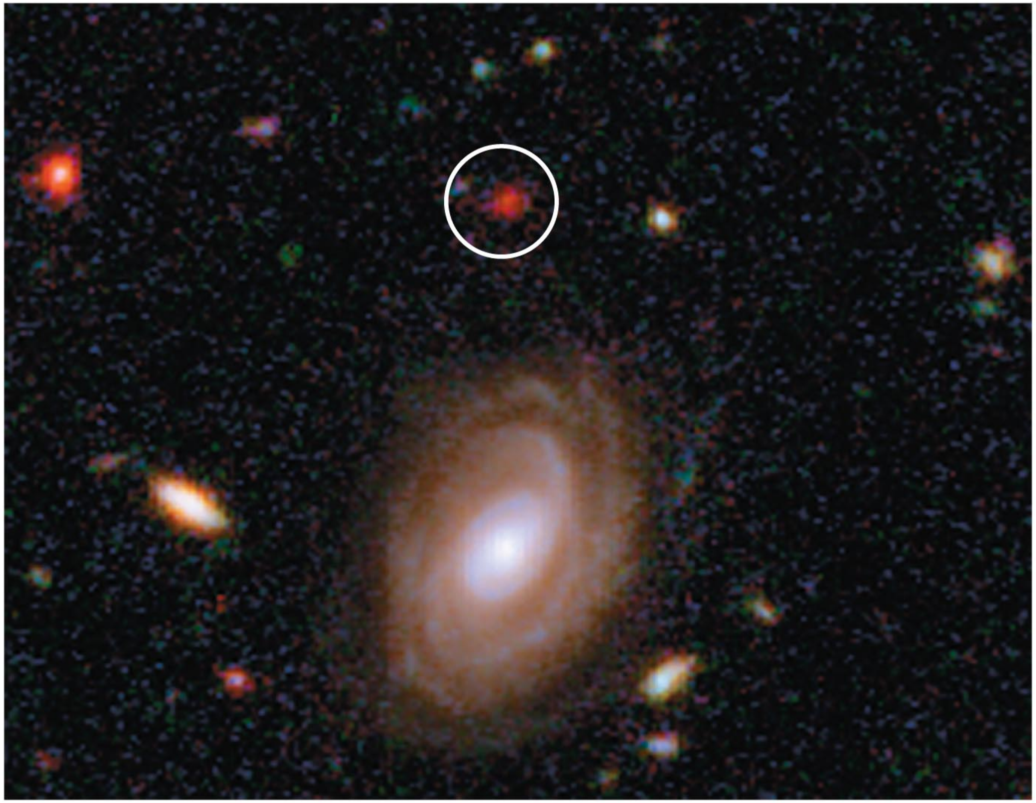
Conditions in Protogalactic Cloud?



a The angular momentum of a galaxy's protogalactic-cloud system may determine whether it ends up spiral or elliptical.

- ***Density:* Elliptical galaxies could come from dense protogalactic clouds** that were able to radiate energy and cool, forming stars before gas settled into a disk.

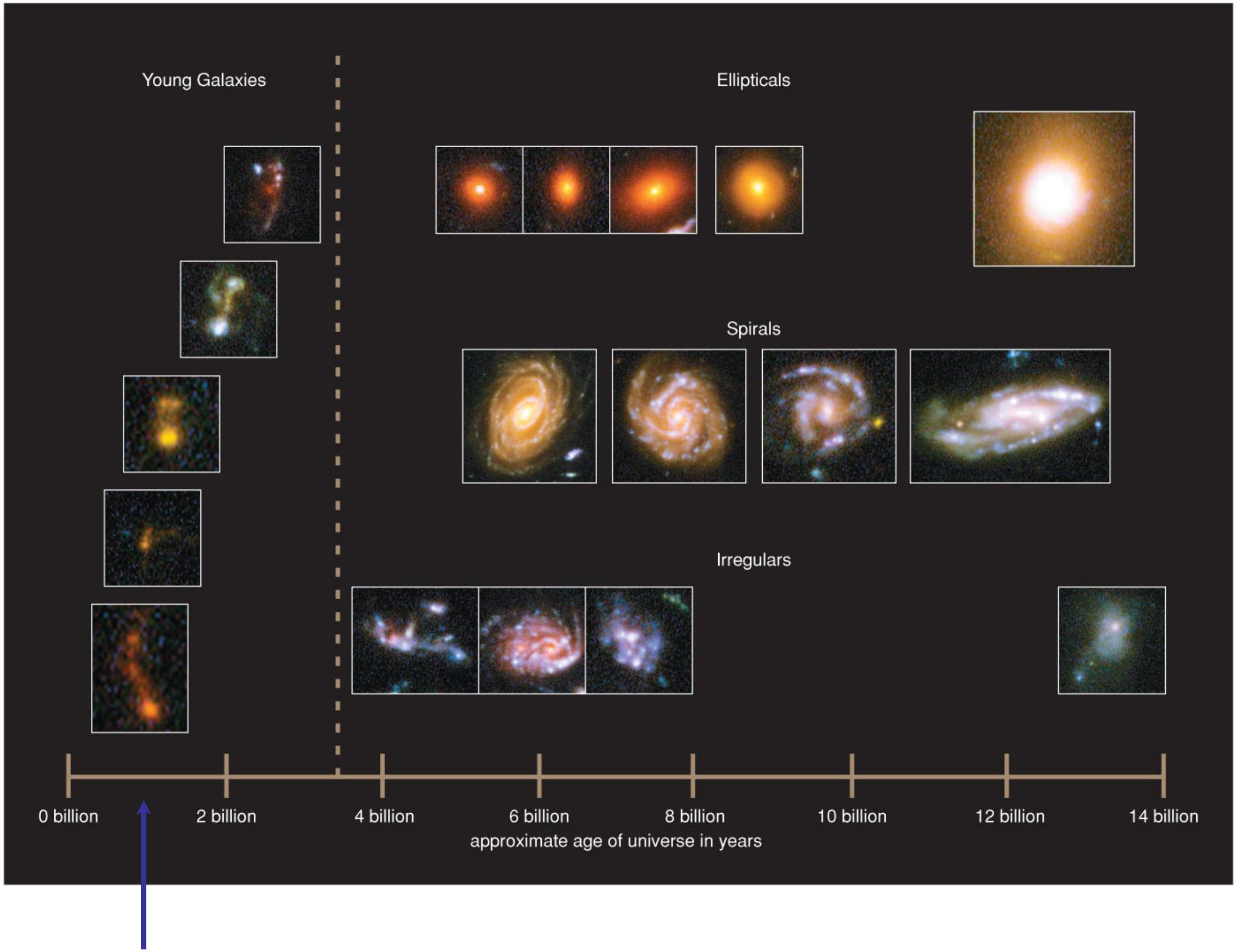
Distant Red Ellipticals



- Observations of some distant red elliptical galaxies support the idea that most of their stars formed very early in the history of the universe.

[redacted]

- We must also consider the effects of collisions.

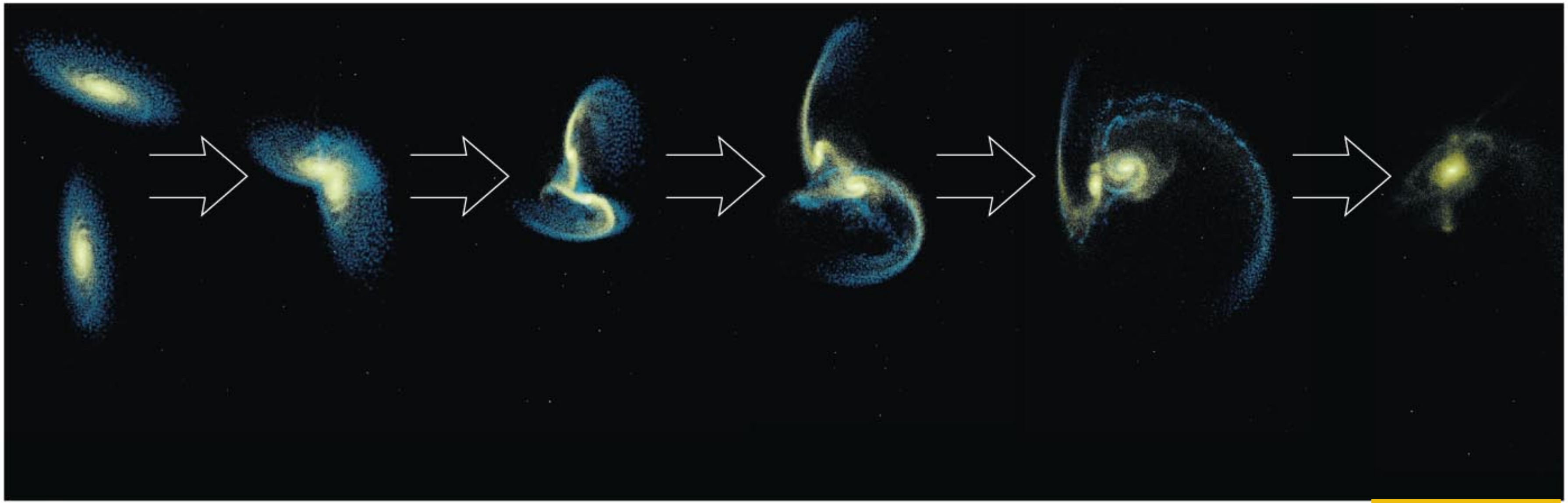


- Collisions were much more likely early in time because galaxies were closer together.

This collision between two spiral galaxies stripped out two long tidal tails of stars . . .

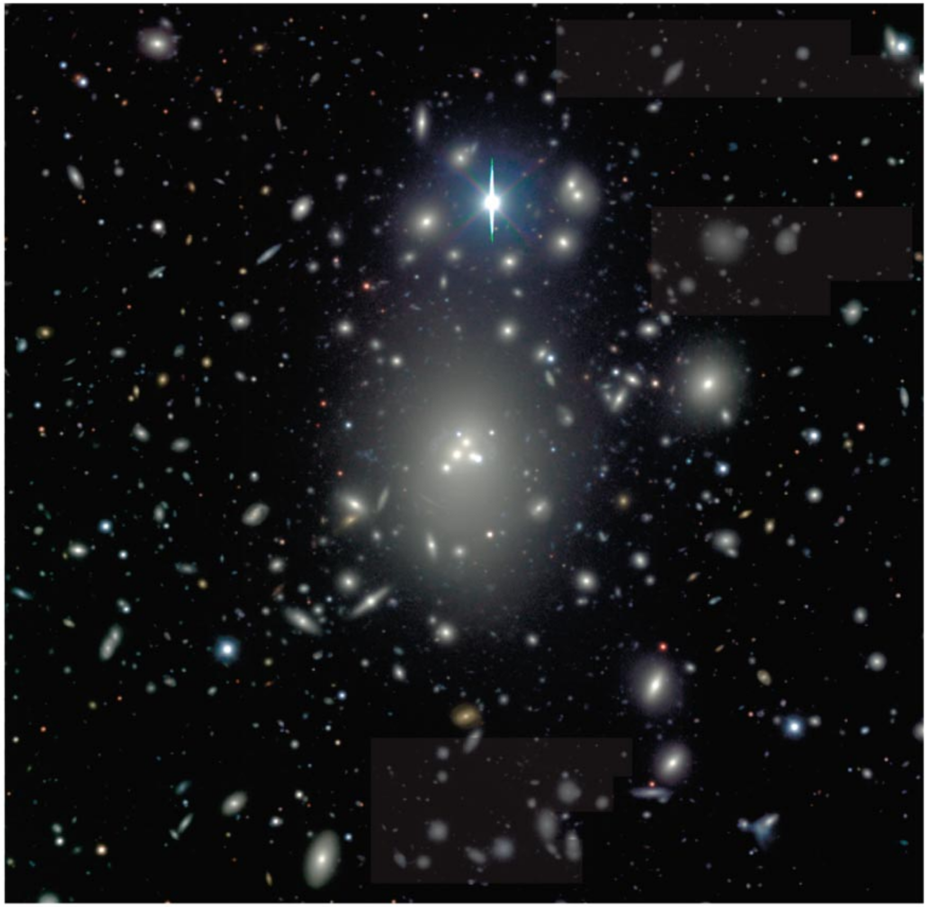
. . . and triggered a burst of star formation, producing many young blue star clusters.

- The collisions we observe nearby trigger bursts of star formation.



Interactive Figure

- Modeling such collisions on a computer shows that two spiral galaxies can merge to make an elliptical.



- A **large fraction of elliptical galaxies** is found **near the centers of clusters** of galaxies where we expect the merger rate to be higher due to the larger density of galaxies.
- Giant elliptical galaxies at the centers of clusters seem to have consumed a number of smaller galaxies. This is because of multiple mergers near the center of the cluster.

Starburst galaxies are galaxies with large star formation rates (~ 100 $M_\odot$/year). They form stars so quickly that they would use up all their gas in less than a billion years.

Visible-light image

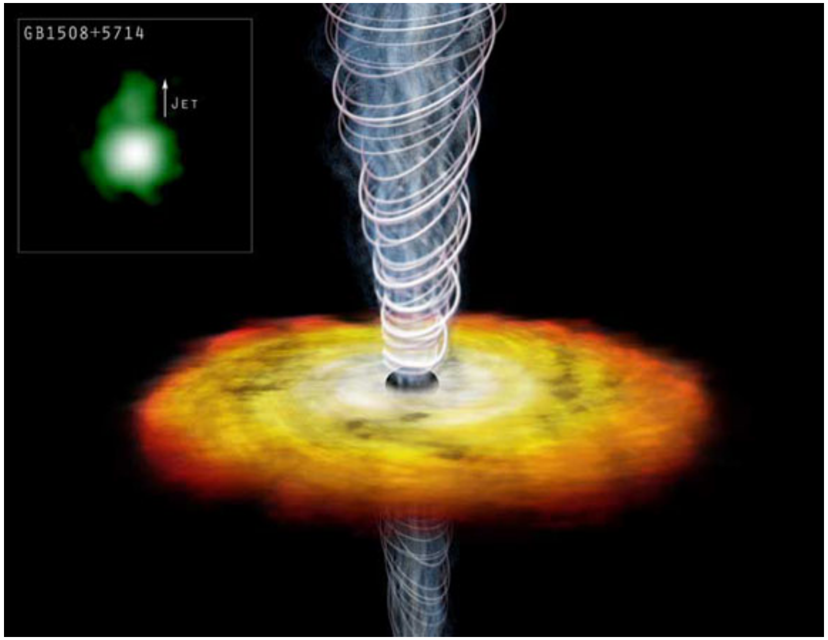
Interactive Figure

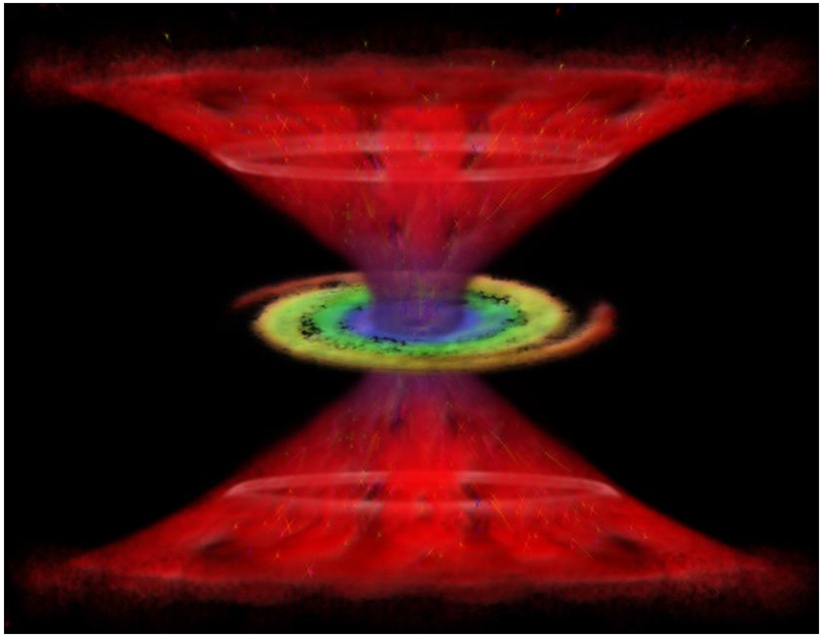
- Supernova explosions in starburst galaxies can drive galactic winds. A galactic wind in a small galaxy can drive away most of its gas.

21.3 Quasars and Other Active Galactic Nuclei

- Our goals for learning:
  - **How are quasars powered?**
  - **Do supermassive black holes really exist?**
  - **How do quasars let us study gas between the galaxies?**

Quasars and Active Galaxies



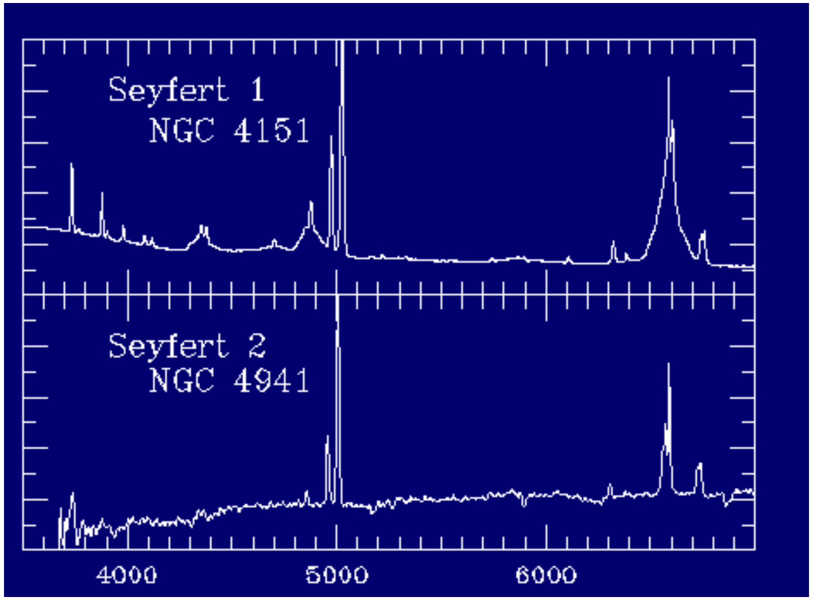


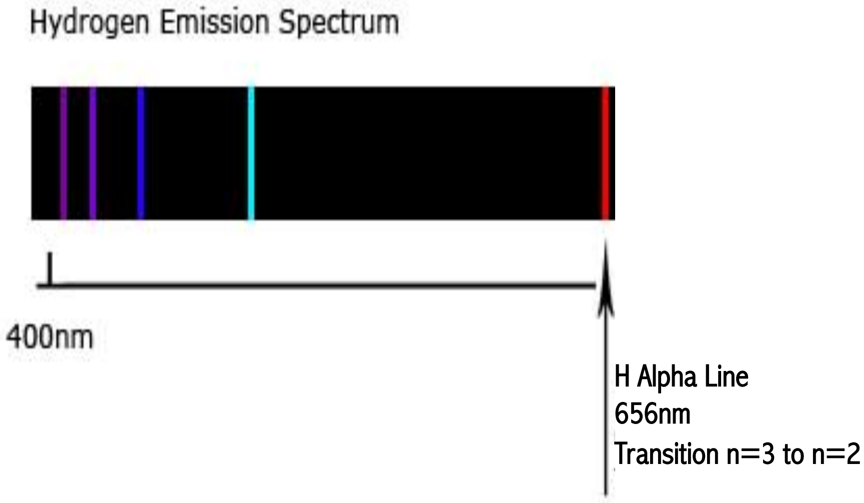
The Discovery of Active Galactic Nuclei

Carl Seyfert at the Mount Wilson observatory in California first observed that a few percent of **spiral galaxies** contain intense blue nuclei. Such spiral galaxies are now called **Seyfert galaxies.**

The spectra of Seyfert galaxies show strong emission lines of the type typically produced by ionized gas.

The Discovery of Active Galactic Nuclei





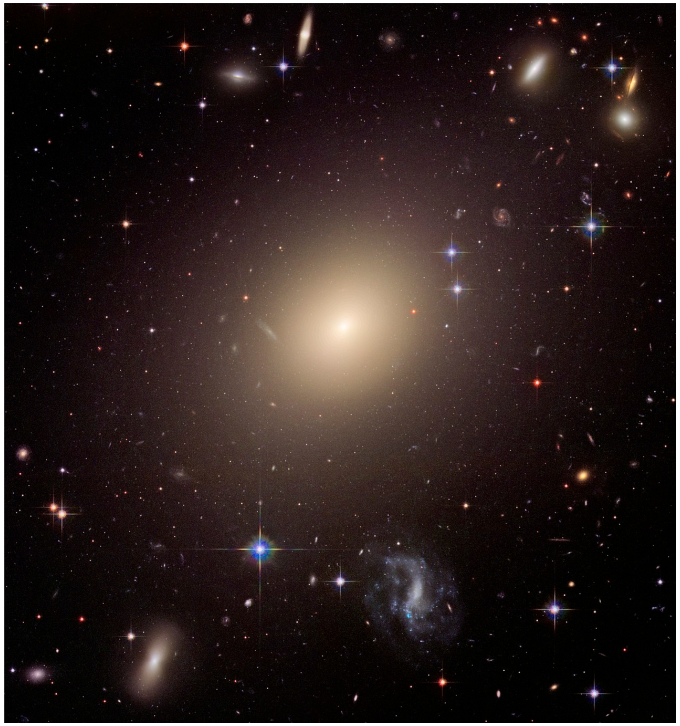
Seyfert galaxies are observationally grouped into ones that show broad and narrow emission lines (**Type I Seyferts**) and ones that show only narrow emission lines (**Type II Seyferts**)

The **narrow lines** are thought to be produced by low density ionized gas with $n_e \sim 10^3$ - $10^6 \mathrm{cm}^{-3}$ producing forbidden narrow lines with widths of ~100 km/s

The **broad lines** are thought to come from higher density ionized gas with $n_e > 10^9$ cm^{-3} producing permitted lines with widths of up to 10^4 km/s

The Discovery of Active Galactic Nuclei

The Armenian astronomer Markarian discovered that some **elliptical galaxies** also harbor bright nuclei.



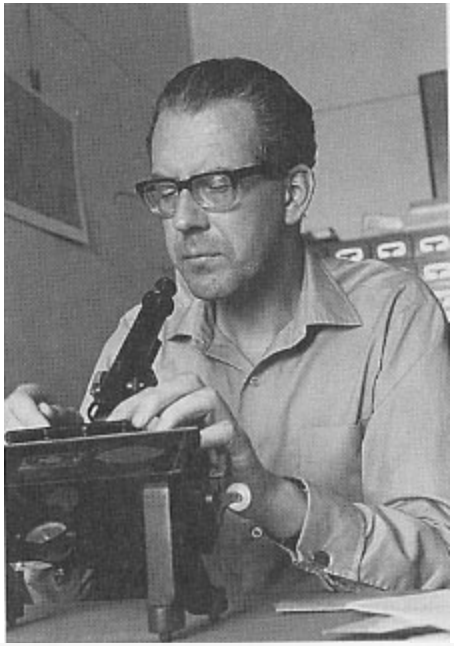
The giant elliptical galaxy ESO 325-G004

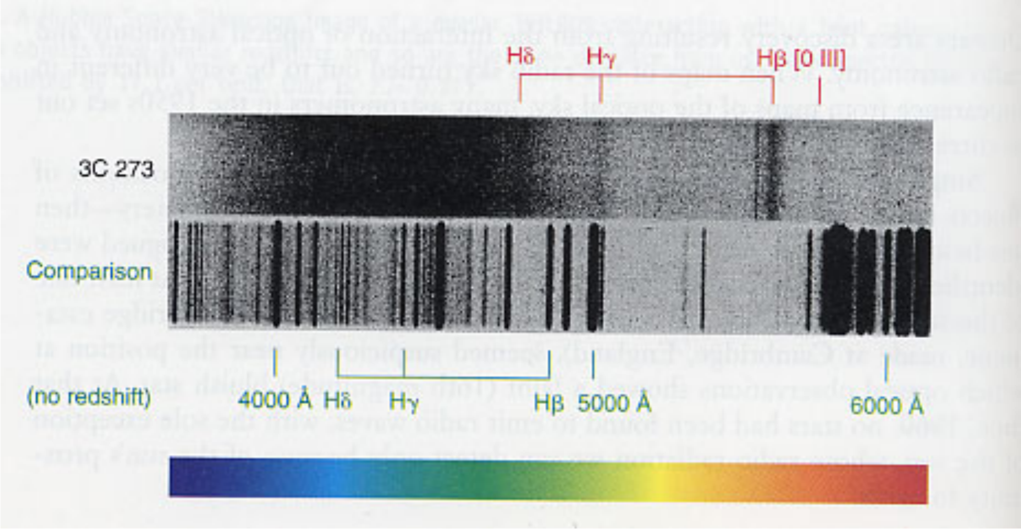
The Discovery of Quasars

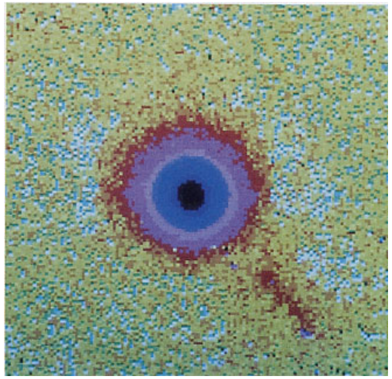
In 1963 Hazard using the Parkes Radio Telescope obtained an accurate position of the **radio source 3C 273.**

The accurate position of 3C 273 allowed Maarten Schmidt to locate the optical counterpart of 3C 273 and obtain its optical spectrum.

The first breakthrough that led to the understanding of **quasars** was the realization by Maarten Schmidt that the emission lines detected in 3C 273 were significantly redshifted Balmer lines.



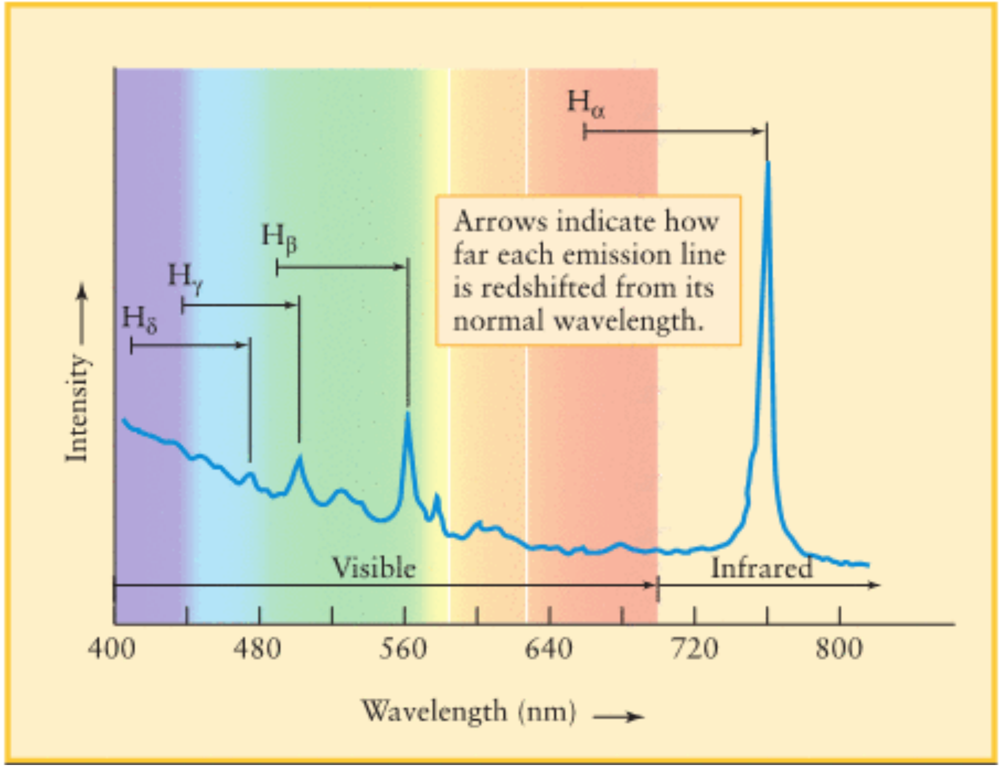




3C 273

The Discovery of Quasars

The large distances of quasars was revealed by their redshifts.



Maarten Schmidt from Caltech first realized that the emissions lines in 3C 273 were significantly redshifted Balmer lines.

Schmidt determined that 3C 273 has a redshift of $z = 0.158$ which corresponds to a comoving distance of $\sim 2 \times 10^9$ ly.

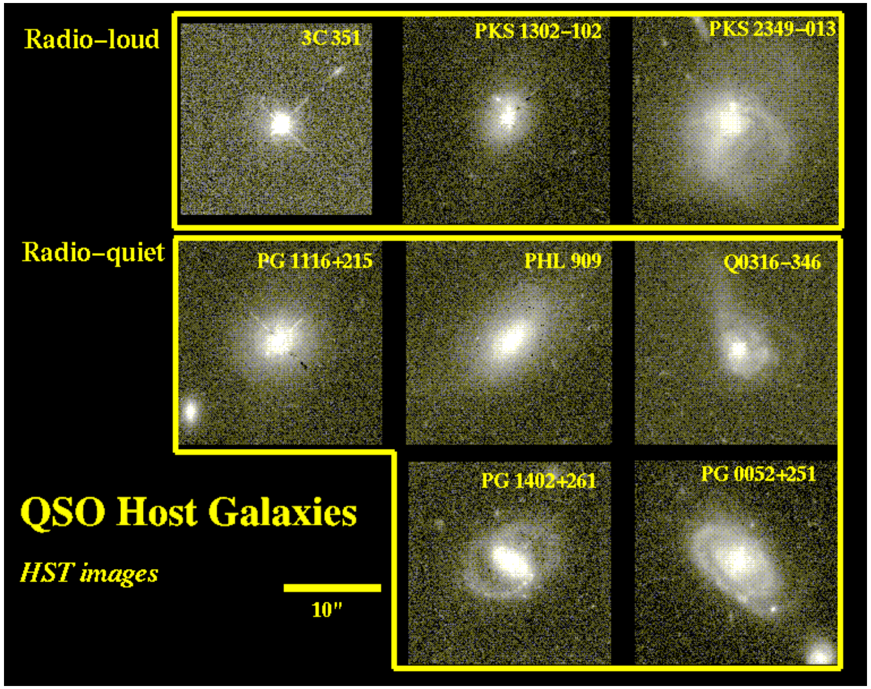
The Discovery of Quasars

Quasars are more luminous versions of Seyfert galaxies. HST observations found that quasars reside in galaxies.

About 10% of quasars are **radio loud** and ~90% **radio quiet**.

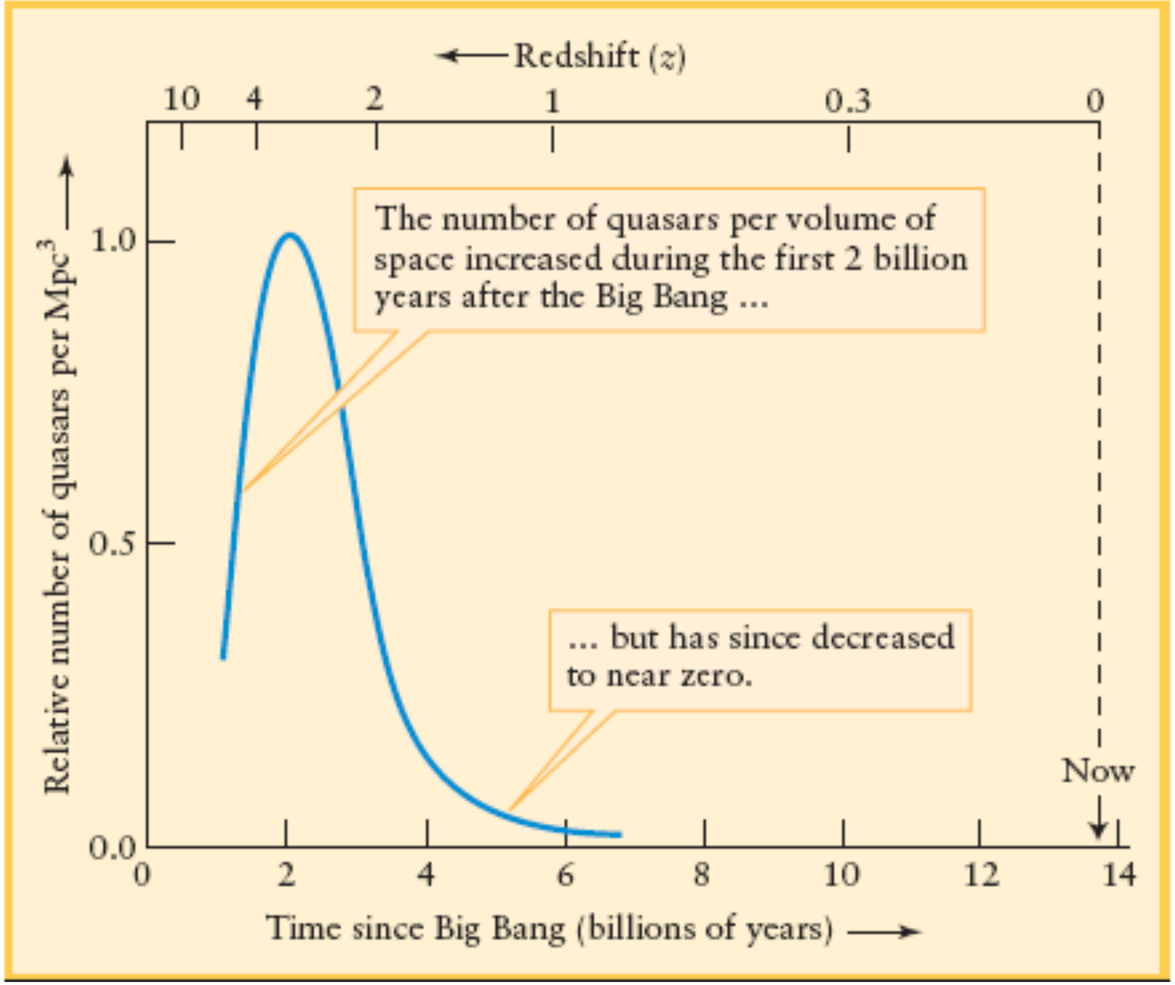
Quasar luminosities are calculated from distances inferred from redshifts, the apparent brightnesses and using the inverse square law.

The average luminosity of 3C 273 is about 10^{40} watts ($L_{\odot} \sim 3.9 \times 10^{26}$ watts and $L_{\text{Milky Way}} \sim 10^{37}$ watts)



Most **radio-loud quasars** reside in the centers of **elliptical galaxies**. Nearby ($z < 0.2$) radio-quiet quasars reside mostly in spiral galaxies and distant ($z > 0.2$) radio-quiet quasars reside in either spiral or elliptical galaxies.

Evolution of Quasars

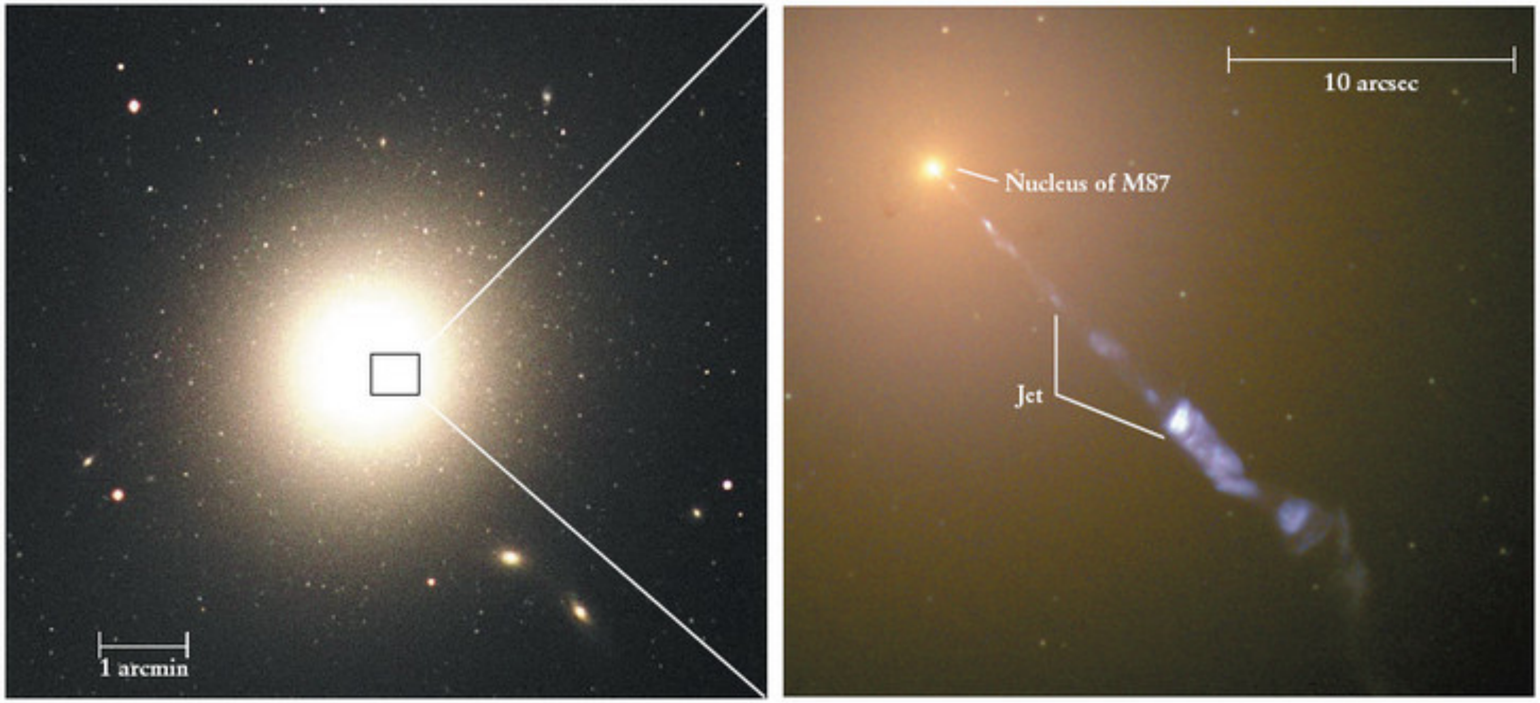


The number of quasars per volume of space increased during the first 2 billion years after the Big Bang ...

... but has since decreased to near zero.

There are no quasars nearby. The nearest quasar known is ~ 800 million ly away. The number density of quasars peaked around redshift of 3-4 corresponding to a look back time of about 10 billion years.

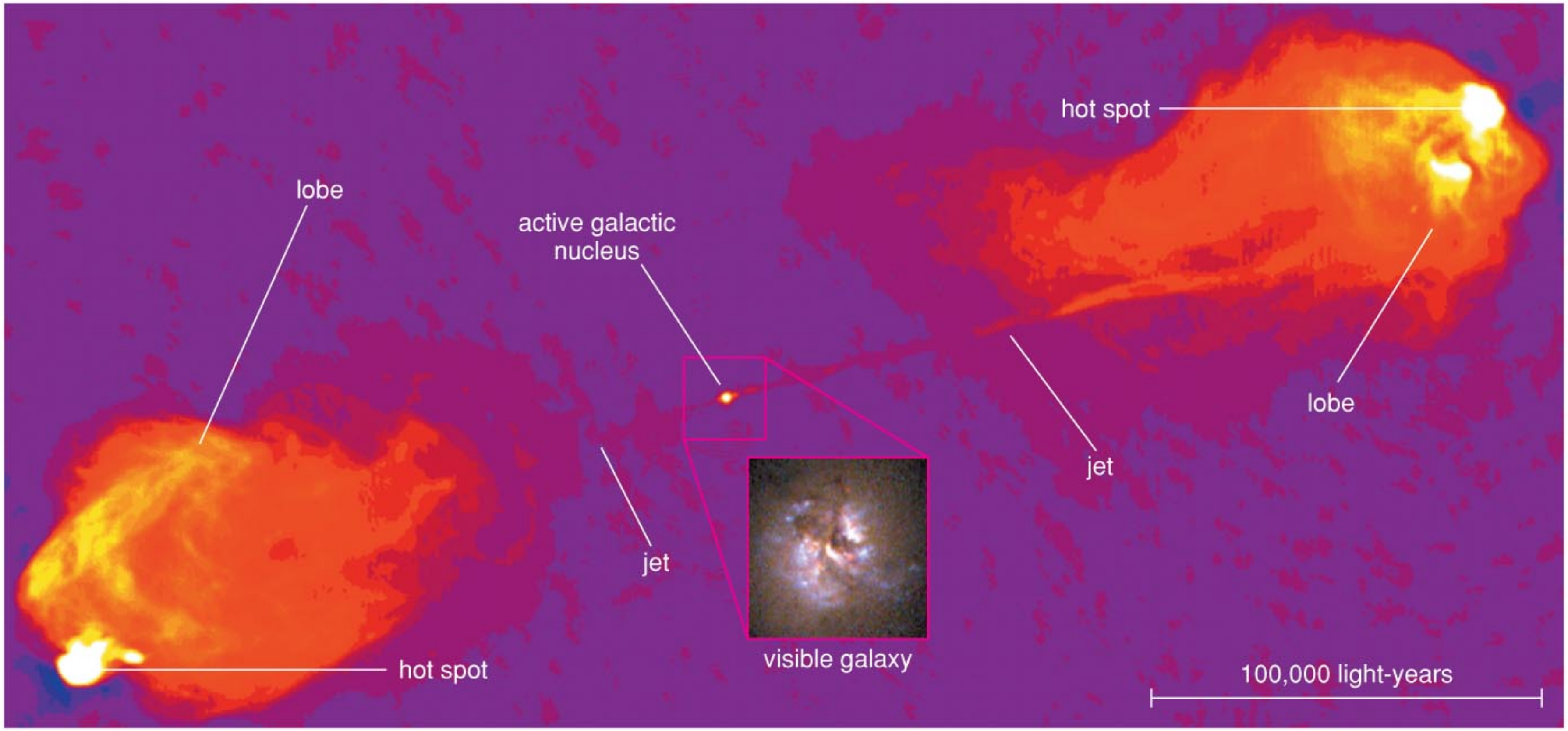
Radio Galaxies



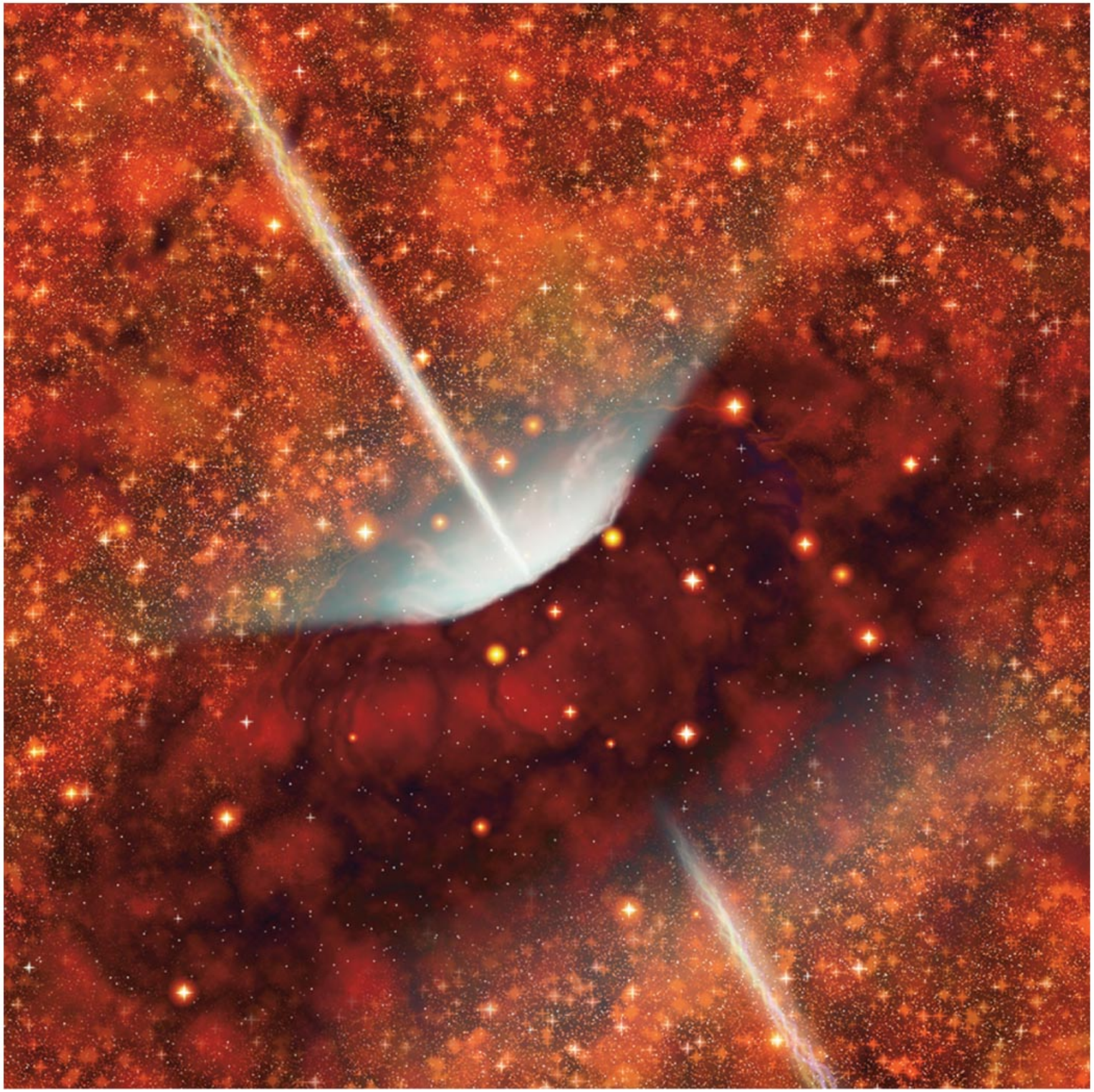
(a) The giant elliptical galaxy M87

(b) A shorter exposure reveals M87's jet

Certain galaxies (especially elliptical ones) have strong radio sources in their centers and resemble dim radio-loud quasars. Such galaxies that emit large amounts of radio waves are called **radio galaxies.** In the center of elliptical galaxy M87 lies a strong compact radio (core size ~ 7 ly) source. A jet extends outwards some 5000 ly.



- ***Radio galaxies*** contain active nuclei shooting out vast jets of plasma that emits radio waves coming from electrons that move at near light speed.



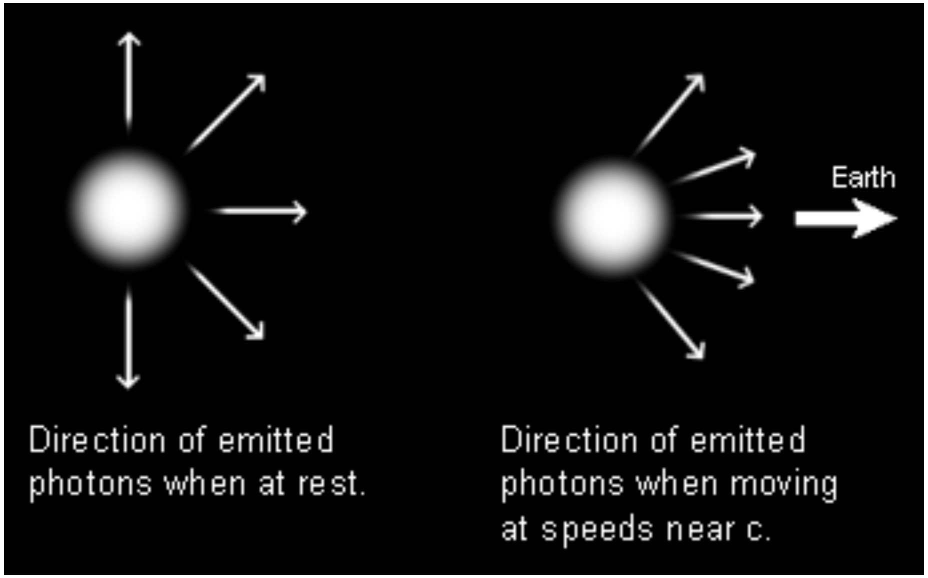
- Radio galaxies don't appear as quasars because dusty gas clouds (torus) block our view of the accretion disk.

Beaming

The luminosity of a jet is increased due to various relativistic effects including beaming and time dilation.

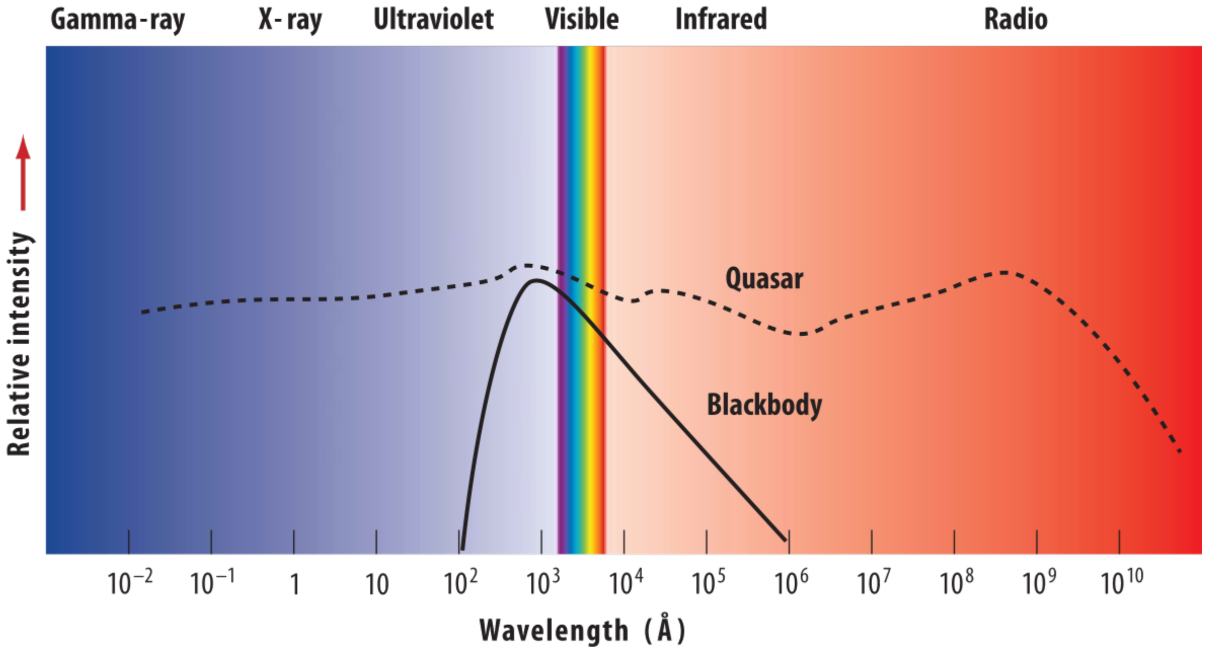
Beaming Angle:
Half of the opening angle is $\theta = 1/\gamma$,

$$\gamma = \frac{1}{\sqrt{1-\left(\frac{v}{c}\right)^2}}$$



A sphere at rest emits photons in all directions (not all are shown). If the sphere is moving at relativistic speed, then we would observe these same photons to be emitted from a cone centered around the direction of motion.

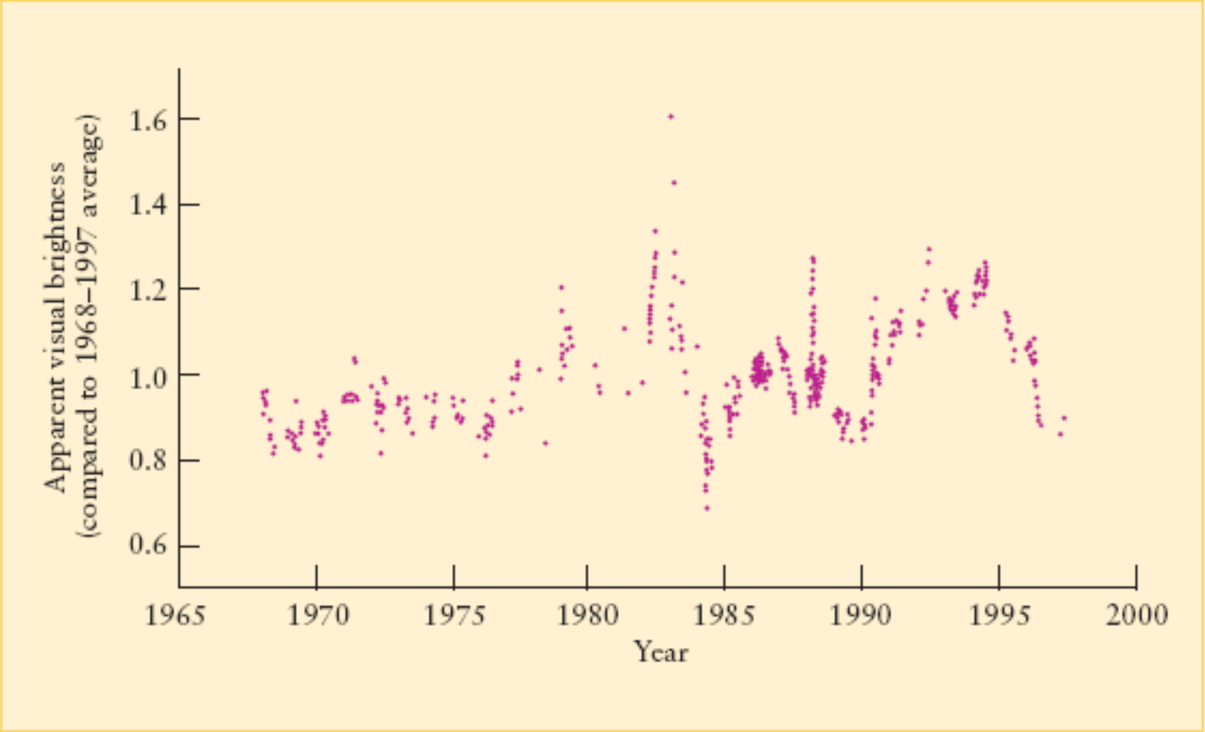
Properties of AGN



The surface of **stars emit approximately blackbody radiation** whose spectrum has a characteristic shape and peaks at shorter wavelengths for hotter bodies.

A spectrum of a quasar, however, shows that energy **is distributed over a much broader range of wavelengths**. This is because several regions of different temperature contribute to the total spectrum and also because some of the emission comes from processes (such as synchrotron radiation) that do not have a well-defined temperature.

Variability of AGN



This graph shows variations over a 29-year period in the apparent brightness of the quasar 3C 273. One property that is common in most types of AGN is variability. If a source of size D_{source} varies significantly over a time interval t_{var} (rest frame) then the size of the source is smaller than the distance light travels in that time interval.

$D_{source} < c\, t_{var} = ct_{obs}/(1+z)$, were t_{var} and t_{obs} are in the objects rest frame and observed frame, respectively.

Eddington Limit

A quasar consists of a supermassive black hole that accretes material through an accretion disk. The accretion disk radiates as it is heated up. The amount a disk can radiate is limited to a maximum luminosity called the **Eddington Luminosity**.

If the disk radiates above the Eddington limit, radiation pressure produced by outgoing photons in the disk will overcome the pressure produced by gravity as material is accreted onto the black hole.

$$L_{\mathrm{Edd}} = 30{,}000\left(\frac{M_{\mathrm{BH}}}{M_{\mathrm{solar}}}\right)L_{\mathrm{solar}}$$

M_{BH} = mass of the black hole

M_{solar} = solar mass

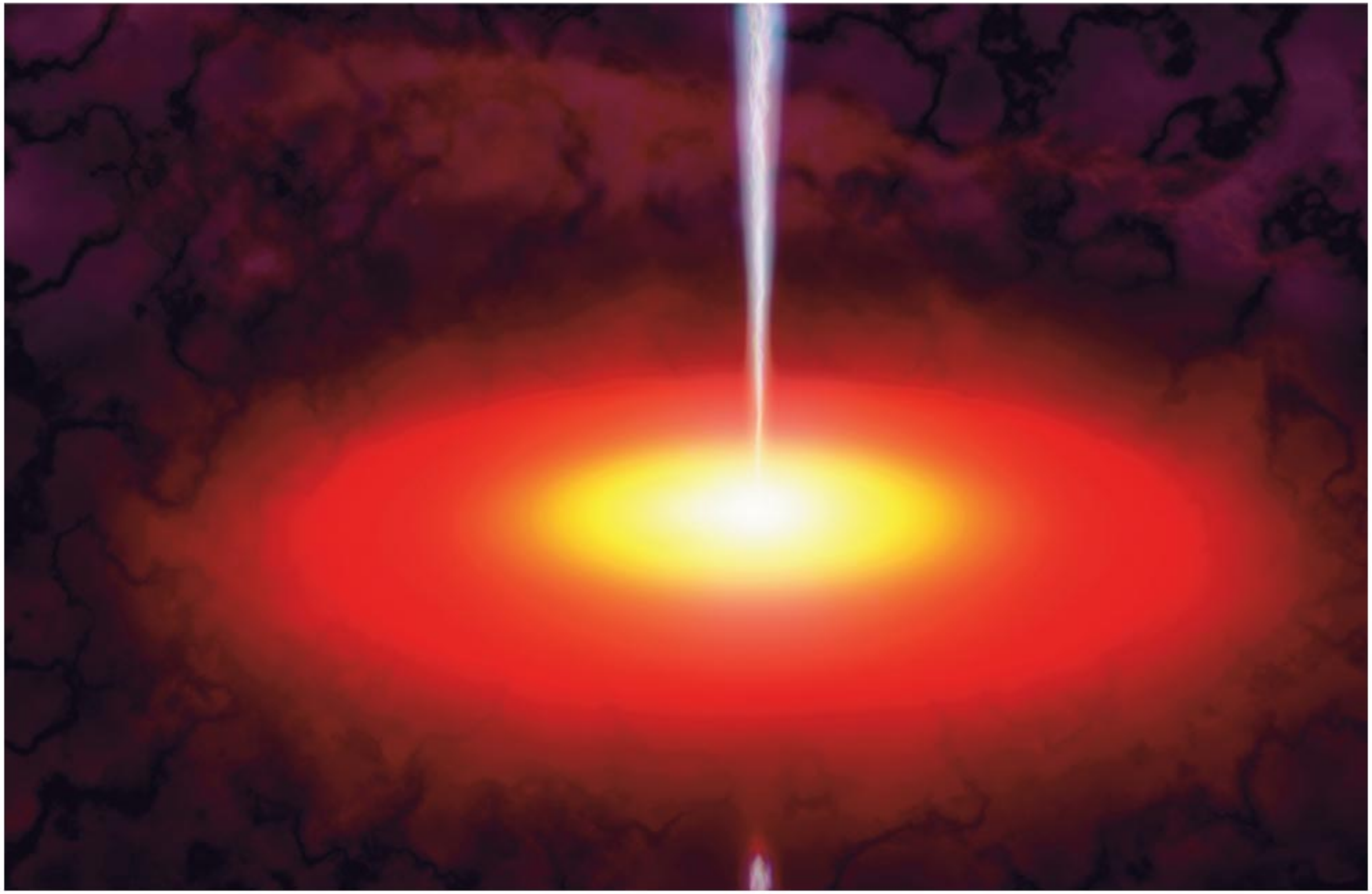
L_{solar} = solar luminosity

$$L_{\mathrm{solar}} = 3.839 \times 10^{26} W$$

$$M_{solar} = 2 \times 10^{30} kg$$

Characteristics of Active Galaxies

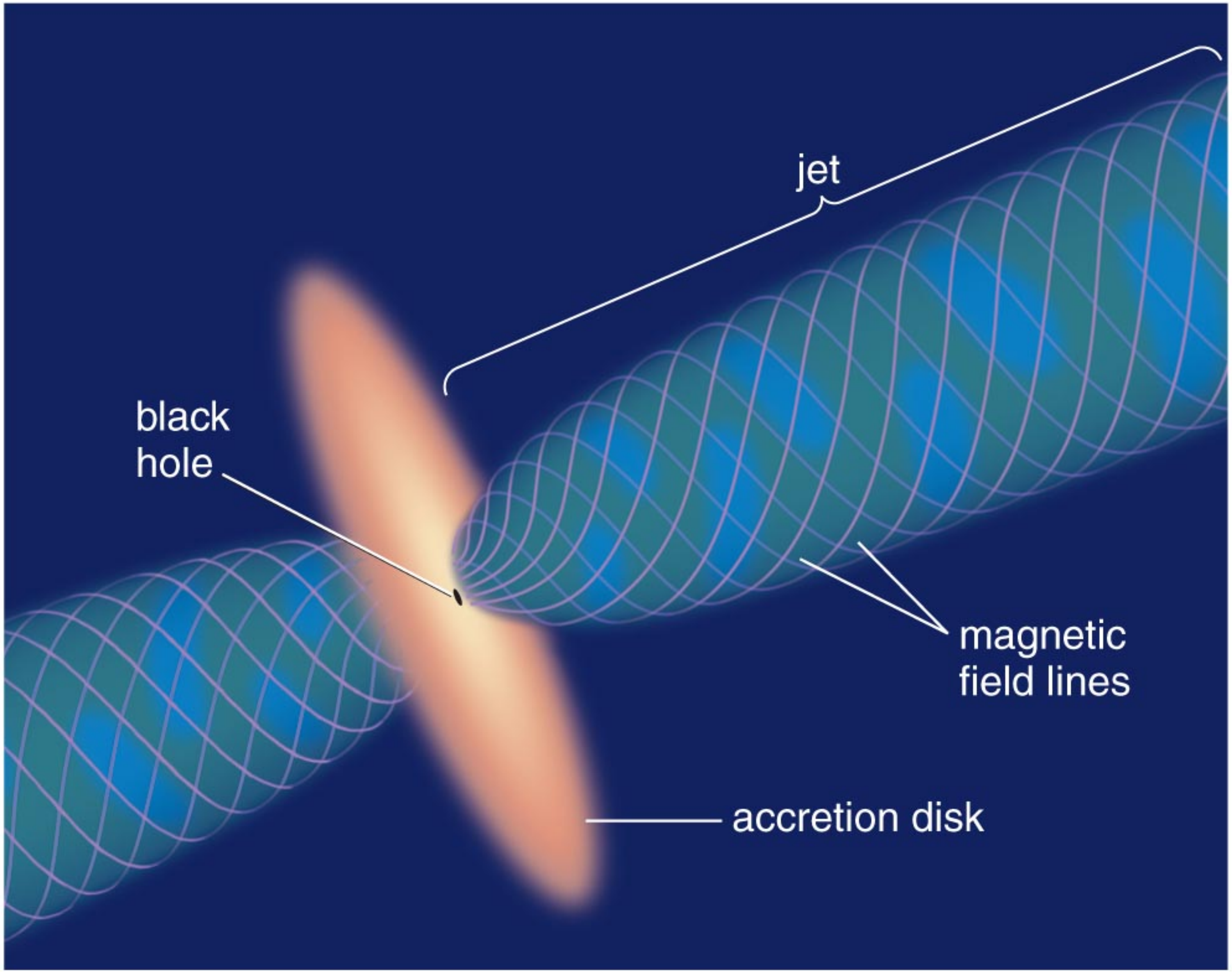
- Their luminosities can be enormous ($>10^{12}\ L_{\mathrm{Sun}}$).
- Their luminosities can rapidly vary (come from a space smaller than solar system).
- They emit energy over a wide range of wavelengths (contain matter with a wide temperature range).
- Some galaxies drive jets of plasma at near light speed.



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

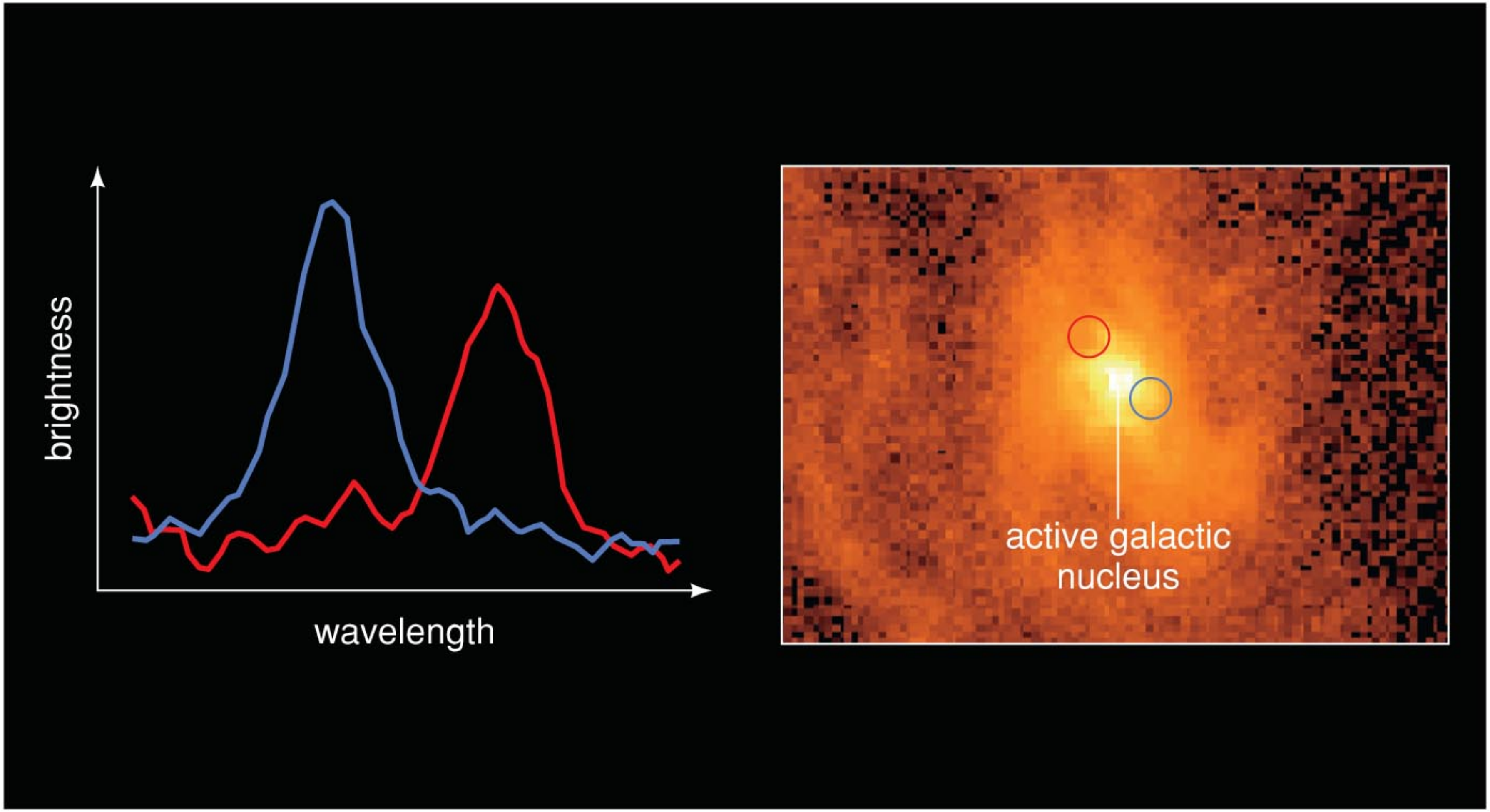
Energy from a Black Hole

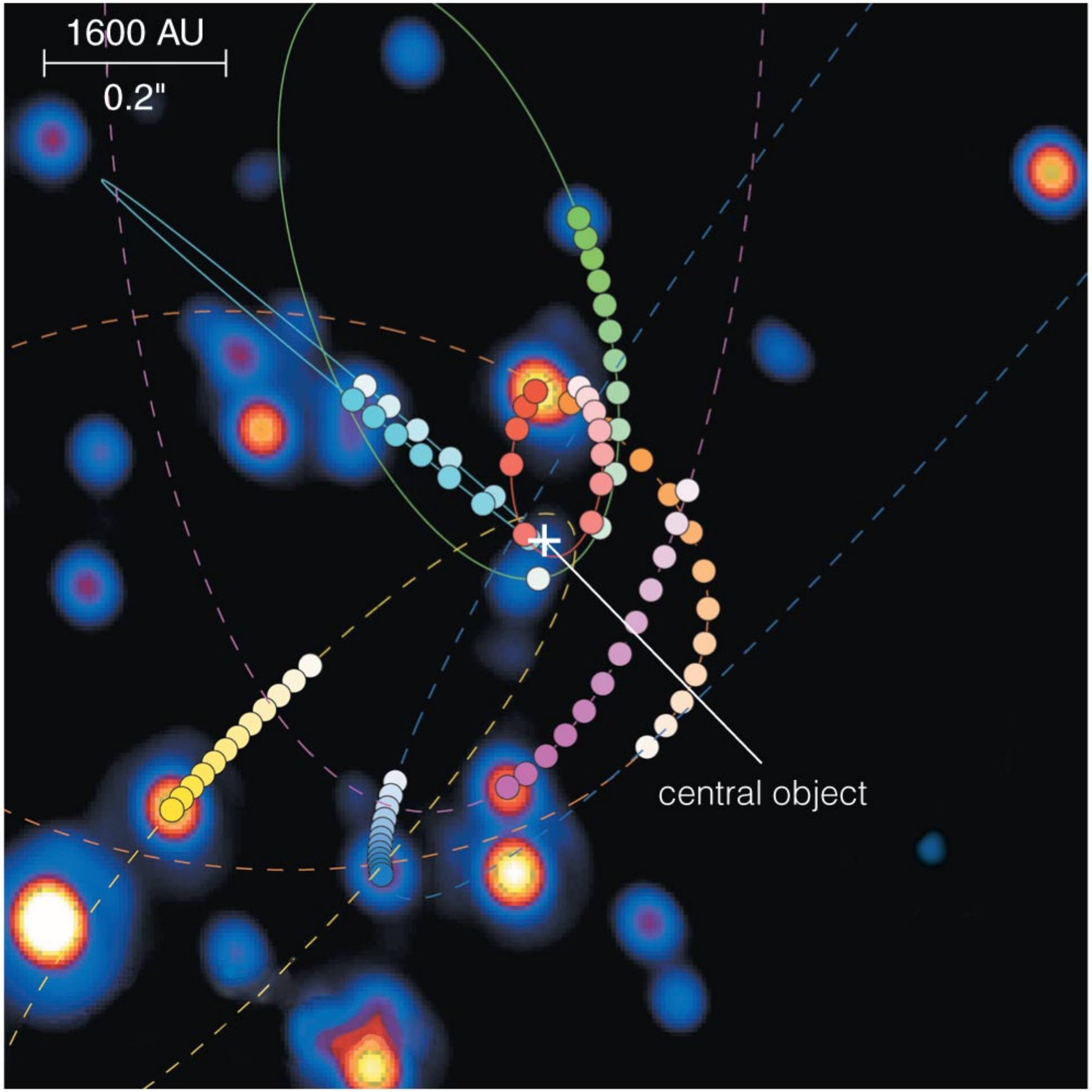
- **Gravitational potential energy of matter falling into black hole turns into kinetic energy**.
- Friction in an accretion disk turns kinetic energy into thermal energy (heat).
- Heat produces thermal radiation (photons).
- This process can convert 10 to 40% of the infalling mass into radiation.



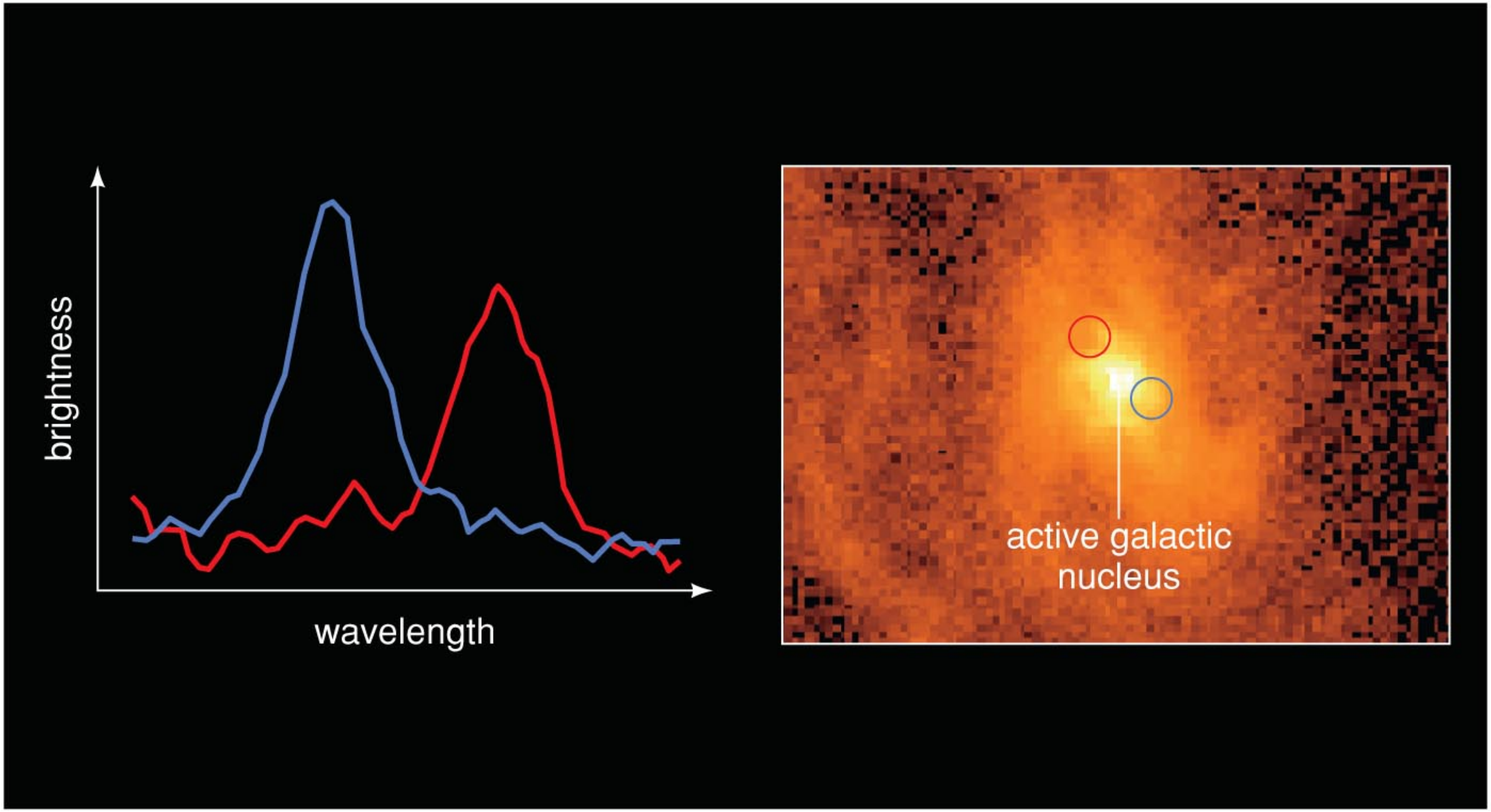
- Jets are thought to come from twisting of magnetic field in the inner part of accretion disk.

Do supermassive black holes really exist?





- Orbits of stars near the center of the Milky Way indicate a black hole with mass of 4 million M_{Sun}.

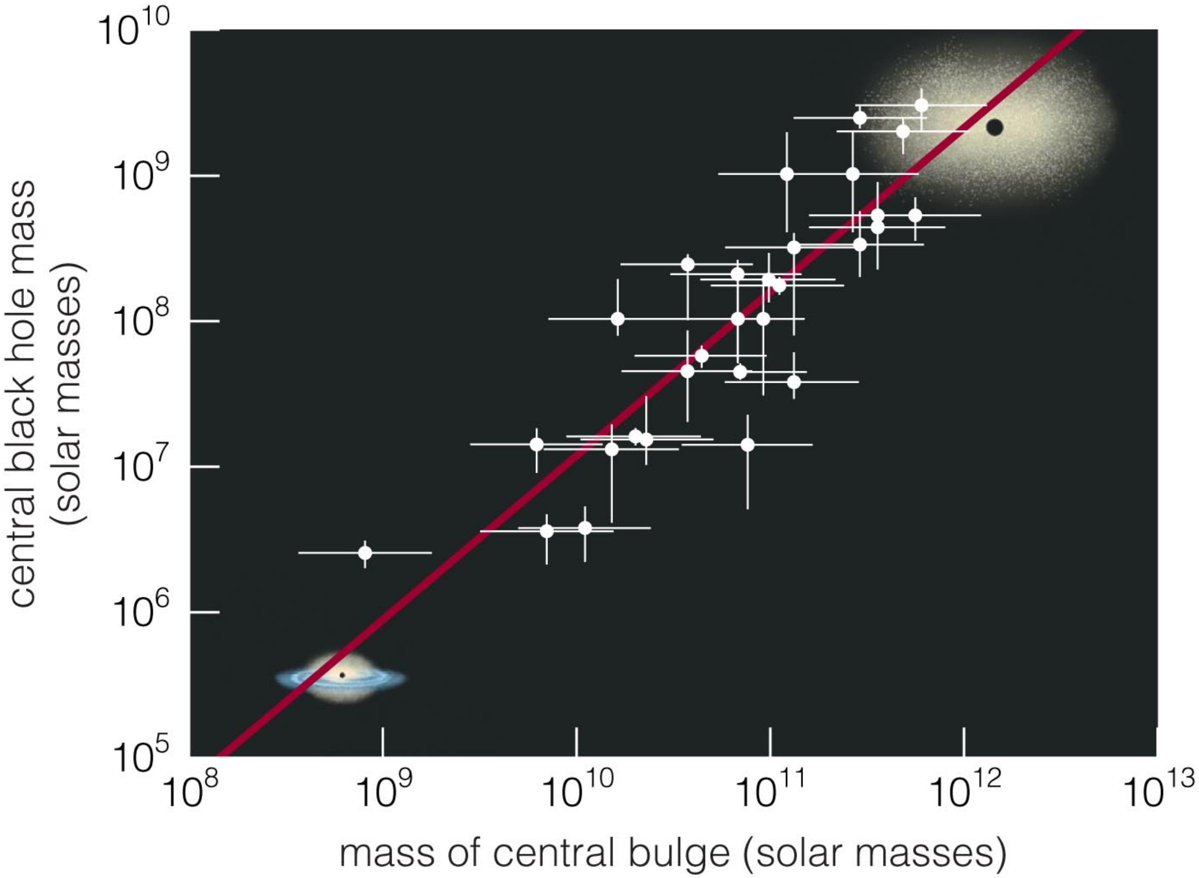


- The orbital speed and distance of gas orbiting the center of Galaxy M87 indicate a black hole with mass of 6 billion M_{Sun}.

Black Holes in Galaxies

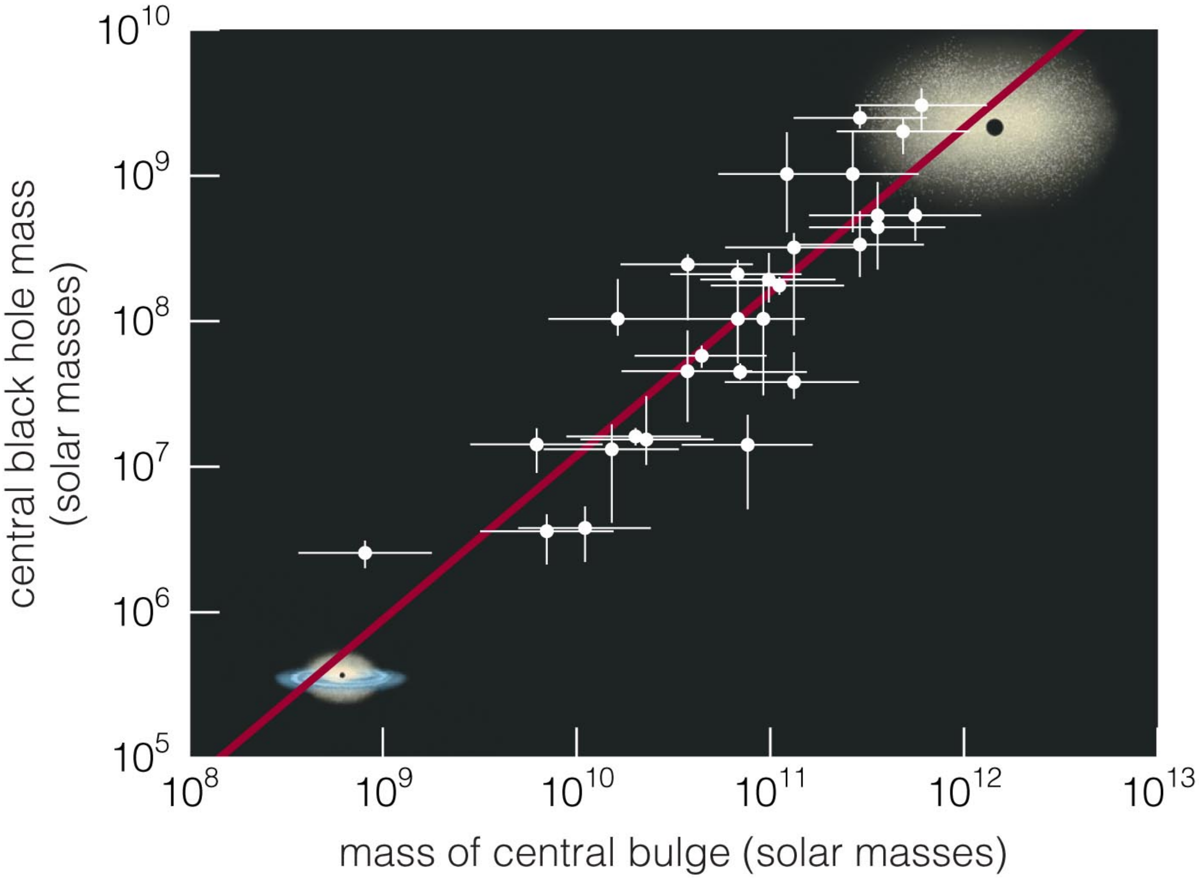
- Many nearby galaxies—perhaps all of them—have supermassive black holes at their centers.
- These black holes seem to be dormant active galactic nuclei.
- All galaxies may have passed through a quasar-like stage earlier in time.

Galaxies and Black Holes



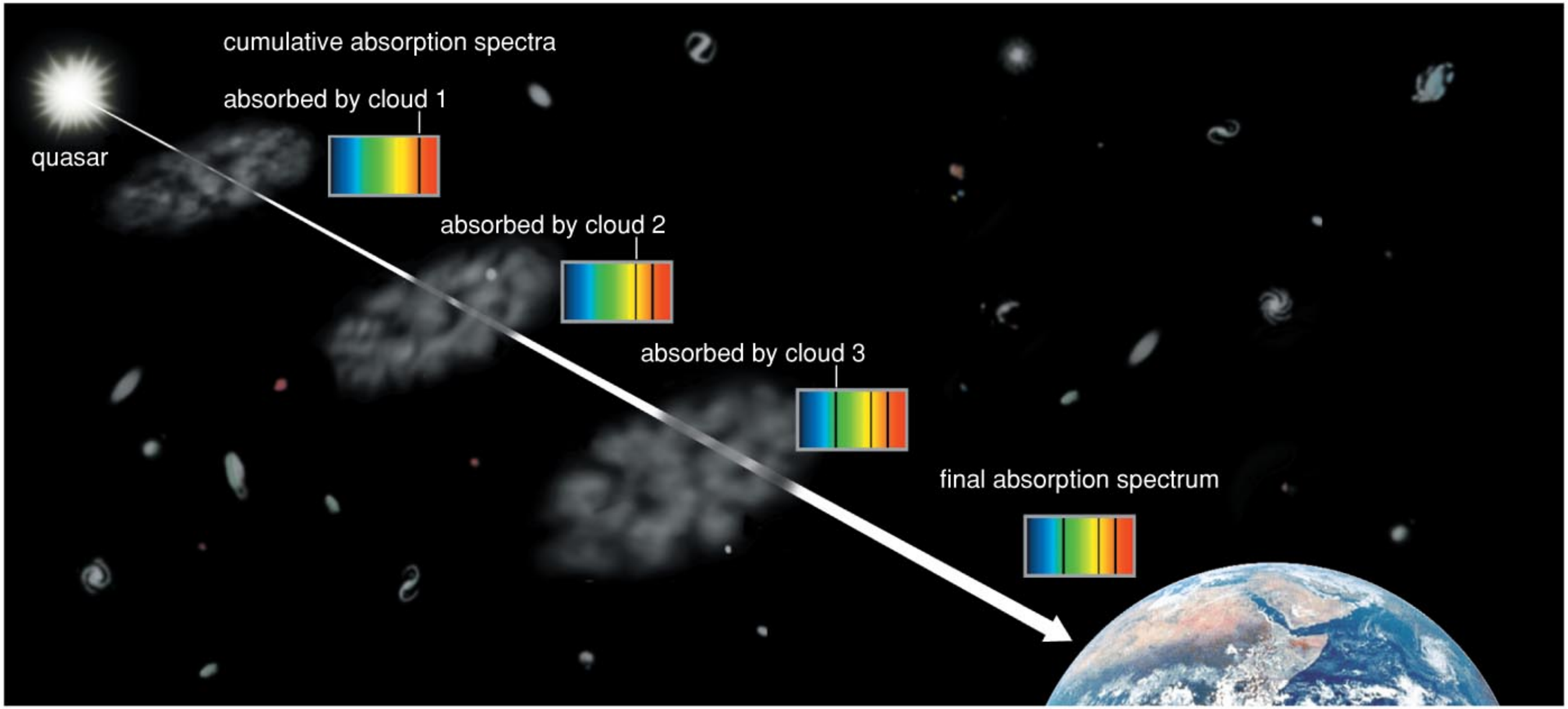
- The mass of a galaxy's central black hole is closely related to the mass of its bulge.

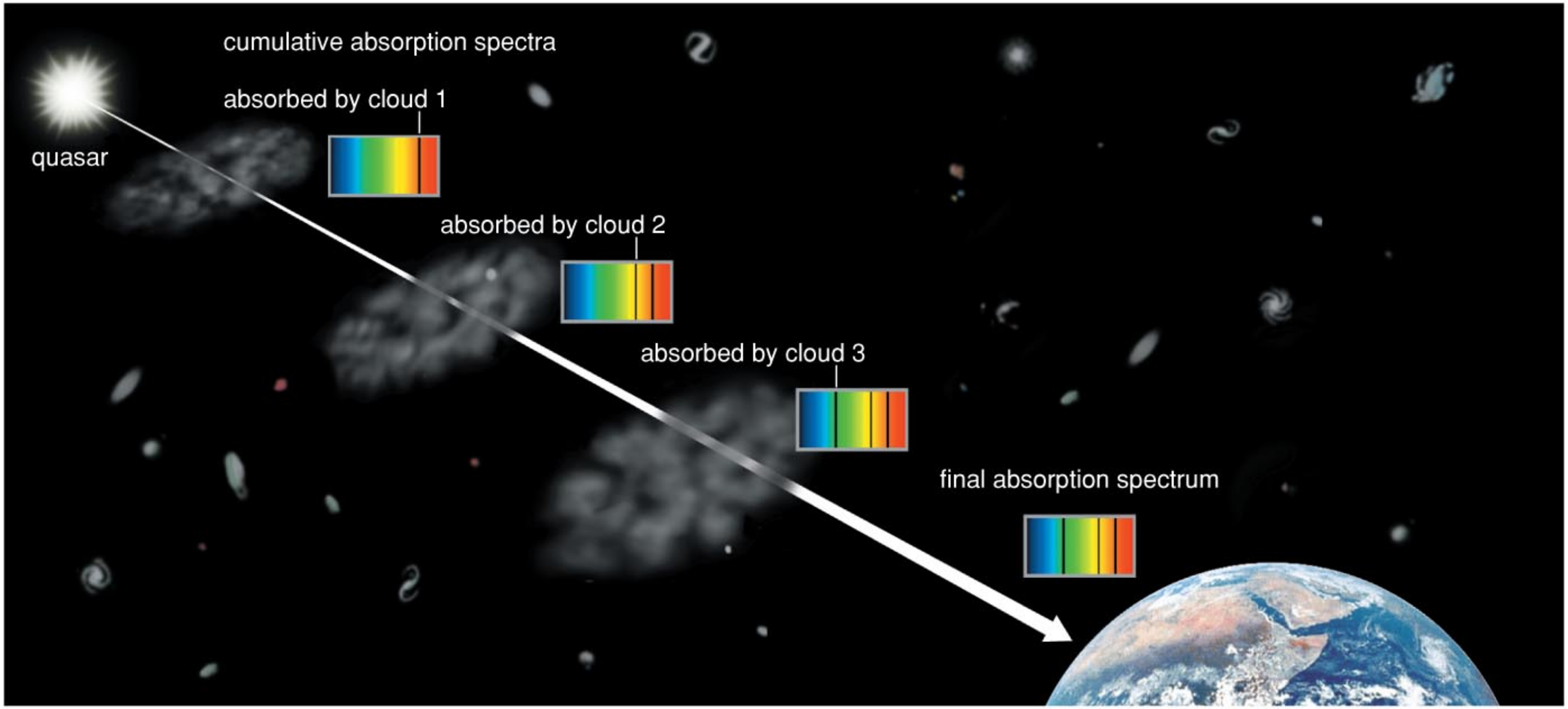
Galaxies and Black Holes



- The development of the central black hole must be somehow related to galaxy evolution.

How do quasars let us study gas between the galaxies?





- Gas clouds between a quasar and Earth absorb some of the quasar's light.
- We can learn about protogalactic clouds by studying the absorption lines they produce in quasar spectra.

What have we learned?

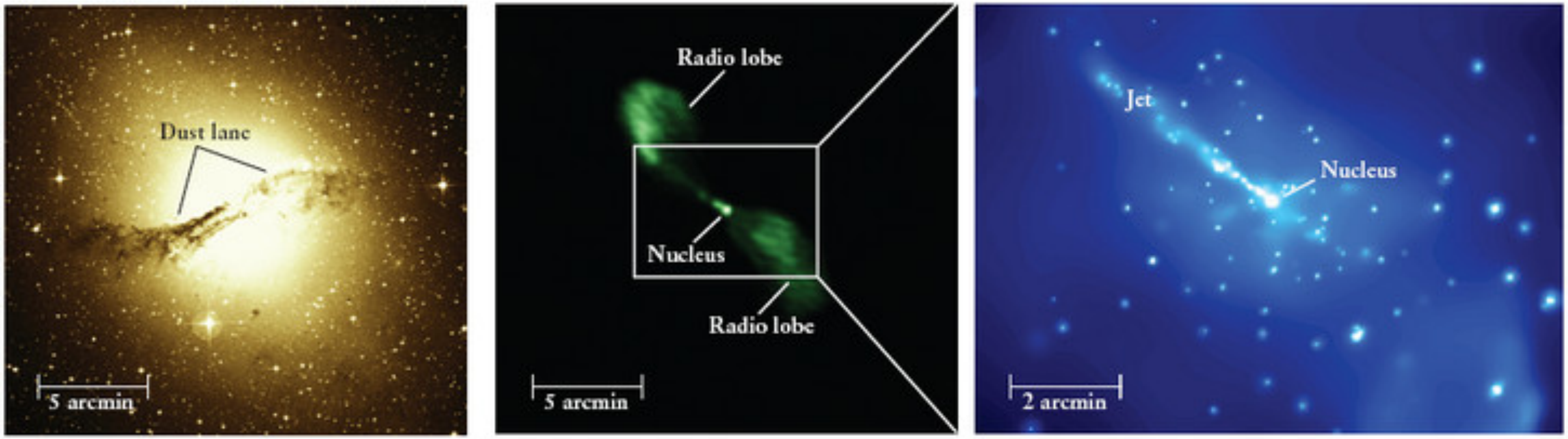
- **How are quasars powered?**
  - Active galactic nuclei are very bright objects seen in the centers of some galaxies, and quasars are the most luminous type.
  - The only model that adequately explains the observations holds that supermassive black holes are the power source.

What have we learned?

- **Do supermassive black holes really exist?**
  - Observations of stars and gas clouds orbiting at the centers of galaxies indicate that many galaxies, and perhaps all of them, have supermassive black holes.
- **How do quasars let us study gas between the galaxies?**
  - Absorption lines in the spectra of quasars tell us about intergalactic clouds between those quasars and Earth.

EXTRA

Jets and Radio Lobes in Radio Galaxies



(a) Centaurus A: light from stars
R I **V** U X G

(b) Centaurus A: radio lobes
R I V U X G

(c) An X-ray-emitting jet emanates from the nucleus
R I V U **X** G

Images of radio galaxy Centaurus A. **Jets of charged particles** are often ejected from the centers of radio galaxies. When these jets collide with dense clouds in the intergalactic medium they convert their kinetic energy into electromagnetic radiation that appears as bright **lobes** on either side of the galaxy.

The emission from the jets and lobes is partially polarized supporting the model of relativistic charged particles being accelerated in these jets. The distance between the lobes can be >10 times larger than the size of the galaxy.

Eddington Limit

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M_{BH} = mass of the black hole

M_{solar} = solar mass

L_{solar} = solar luminosity

$L_{\mathrm{solar}} = 3.839 \times 10^{26} W$

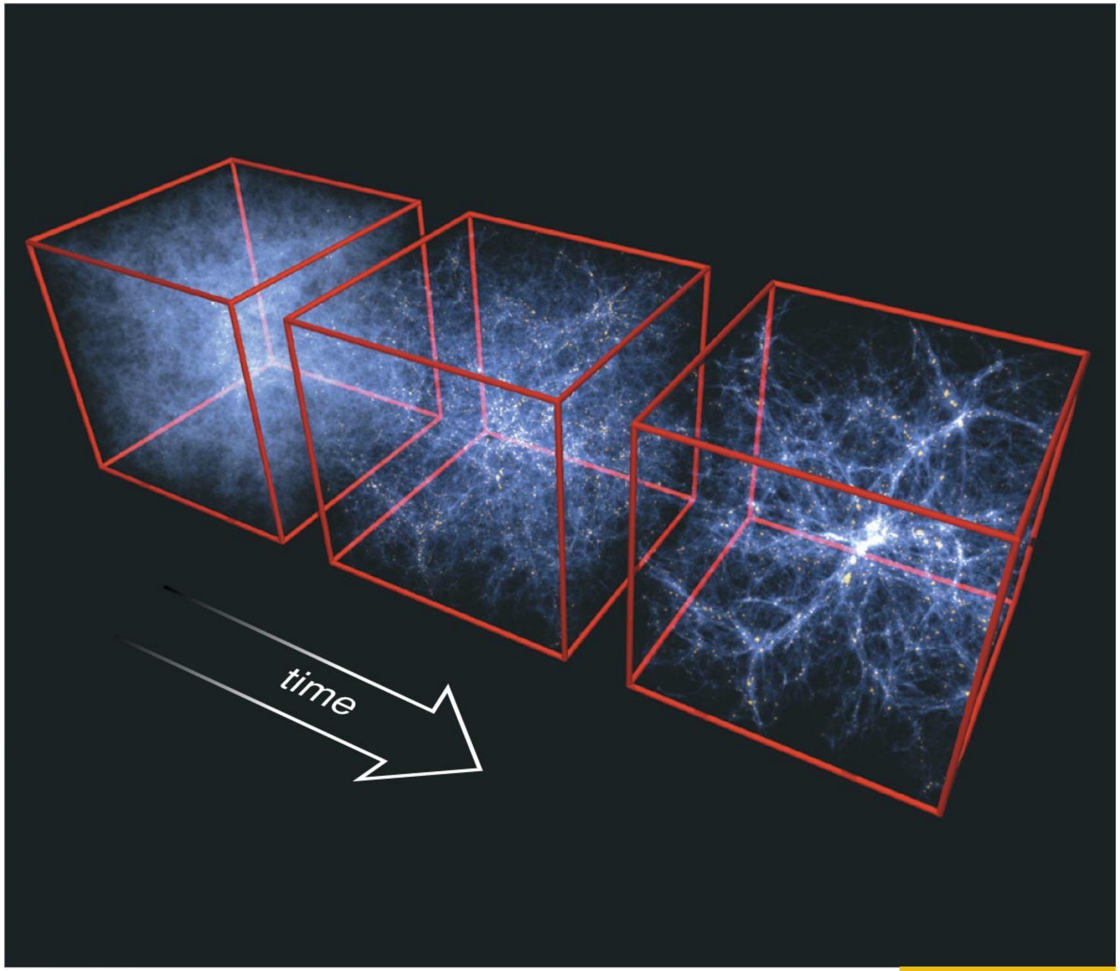
$M_{solar} = 2 \times 10^{30} kg$

Example: Estimate the black hole mass of 3C 273. $L_{3C273} = 10^{13}L_{\odot}$

Since the true luminosity of 3C 273 (L_{3C273}) must be less than L_{Edd} its black hole mass (M_{3C273}) is greater than :

$M_{3C273} > L_{3C273}\, M_{\odot}/(30{,}000L_{\odot})$.

We can study galaxy formation with numerical simulations



Interactive Figure

- Our best models for galaxy formation assume:
  - Matter originally filled all of space almost uniformly.
  - Gravity of denser regions pulled in surrounding matter.