Astrophysical Objects

Active Galaxies

Based on: An introduction to modern Astrophysics chapter 28

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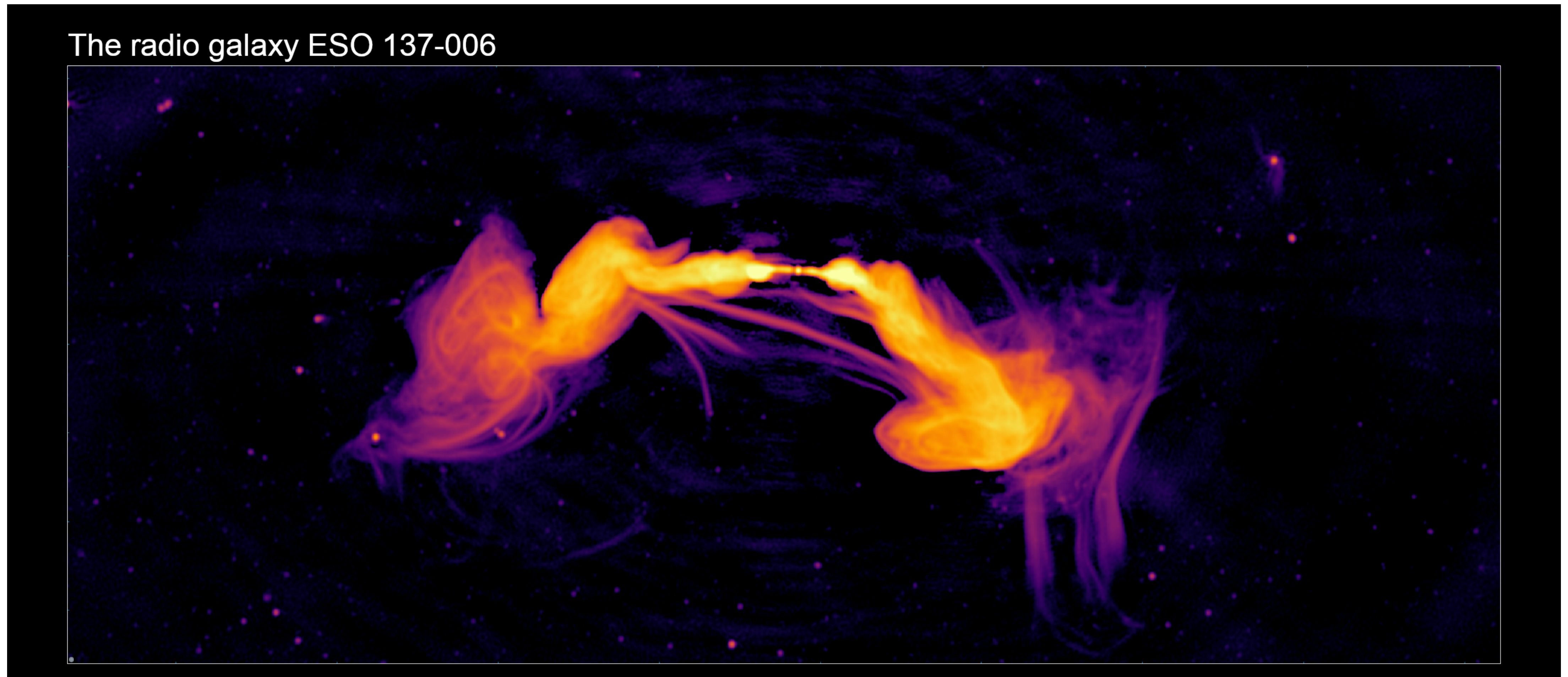
Radio lobes and jets

There is a basic division of active galaxies into objects that are **radio-loud** and those that are **radio-quiet**.

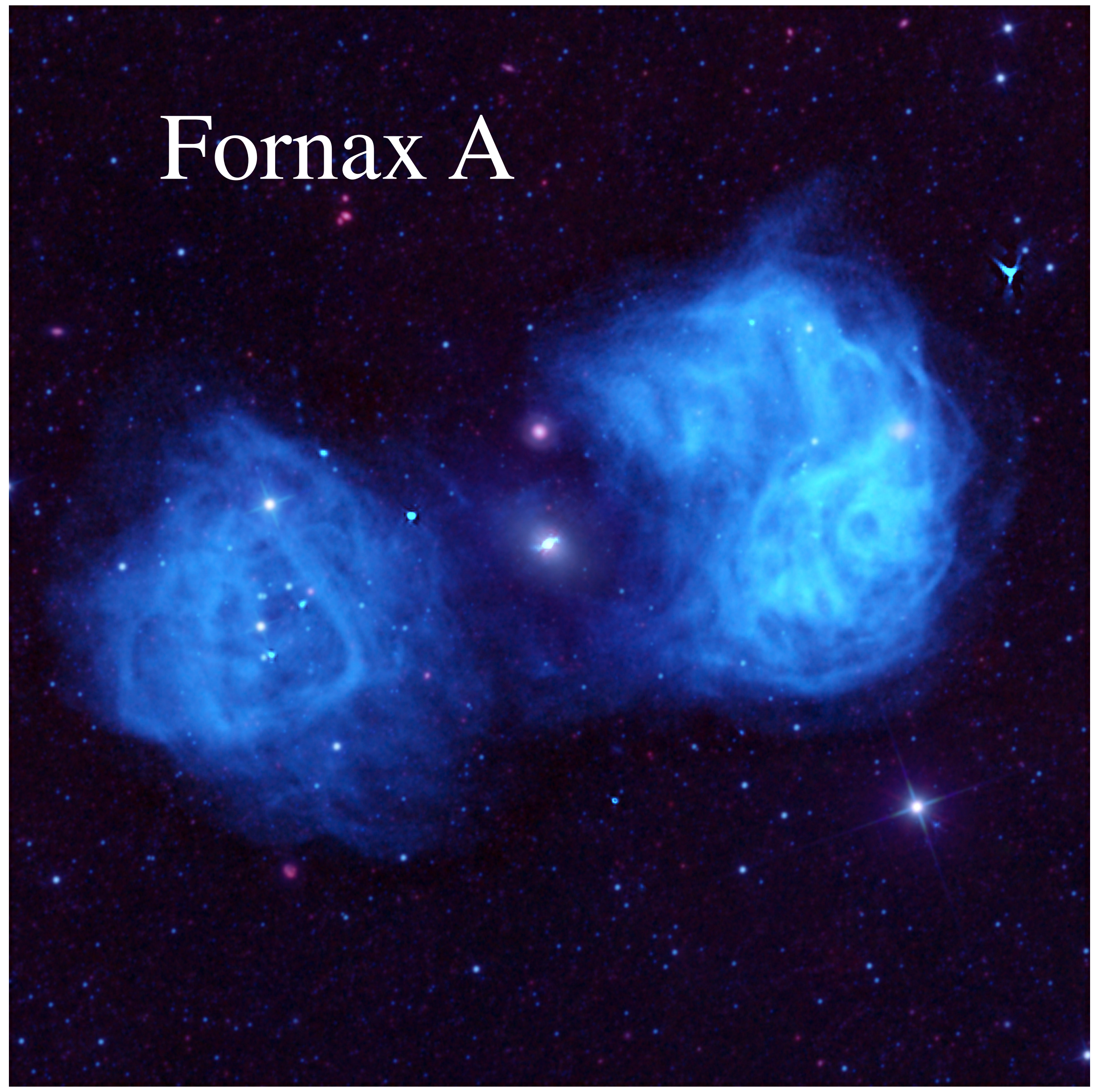
Radio-loud sources usually consist of a **radio core, one or two detectable jets, and two dominant radio lobes**.

The **radio-quiet sources are less luminous at radio wavelengths** by a factor of 10^3 to 10^4, consisting of a weak radio core and perhaps a feeble jet.

The **increased level of activity** in radio-loud AGNs is not confined to radio wavelengths, however; they also tend to be about three times **brighter in X-rays** than their radio-quiet cousins.



"Collimated synchrotron threads linking the radio lobes of ESO 137-006", M. Ramatsoku et al. 2020, A&A
MeerKAT Radio Telescope image at 1000 MHz
Image credits: Rhodes University / INAF / SARAO



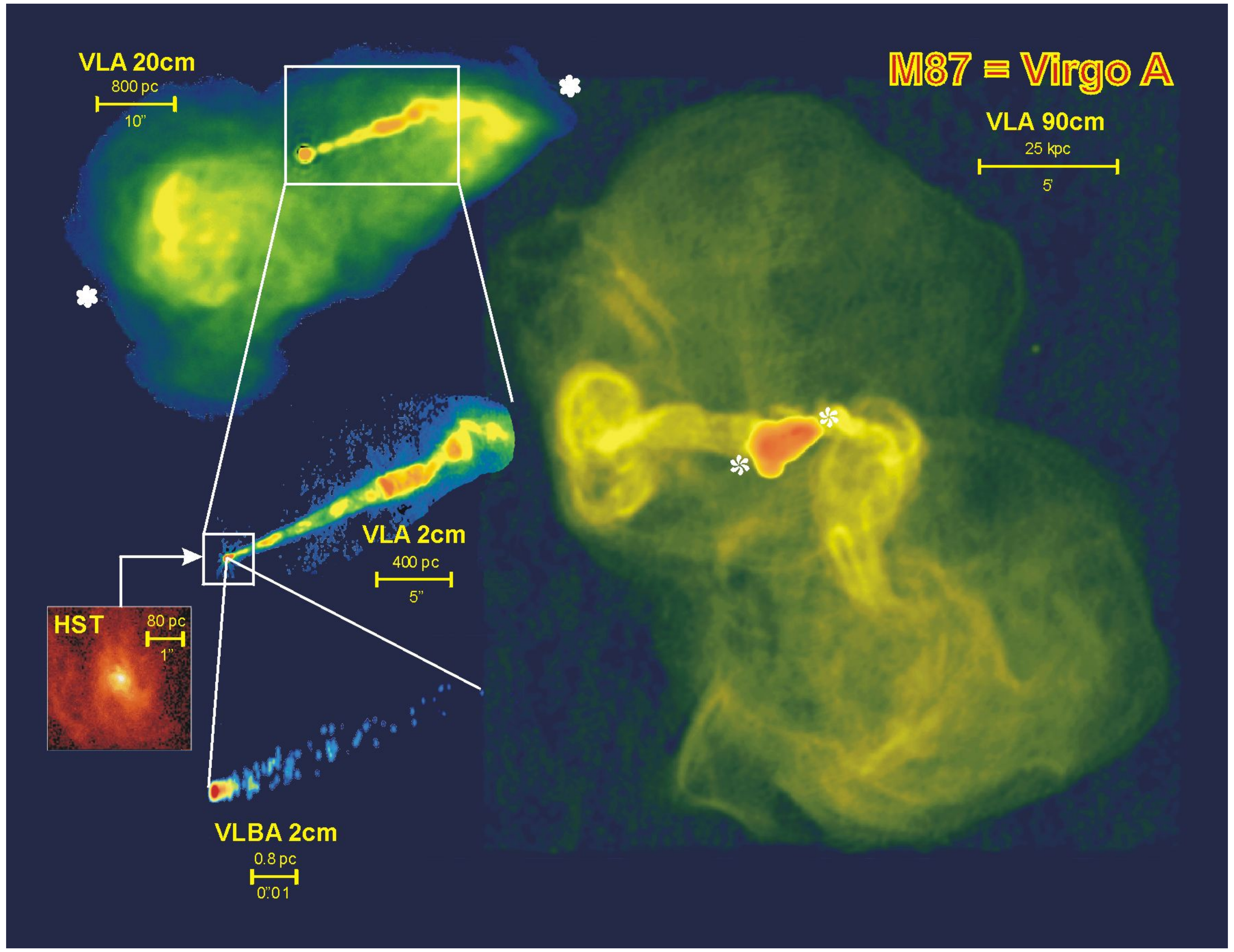
Jets

The **radio lobes are produced by jets of charged particles ejected from the central nucleus of the AGN at relativistic speeds.**

These particles are accelerated away from the nucleus in two opposite directions, **powered by the energy of accretion and/or by the extraction of rotational kinetic energy from the black hole** via the Blandford–Znajek mechanism.

The jet must be electrically neutral overall, but it is not clear whether the **ejected material consists of electrons and ions or an electron–positron plasma.** The latter, being less massive, would be more easily accelerated.

The disk's magnetic field is coupled ("frozen in") to this flow of charged particles. The resulting magnetic torques may remove angular momentum from the disk, which would allow the accreting material to move inward through the disk.



Jets

The incredible **narrowness and straightness of some jets** means that a **collimating process** must be at work **very near the central engine powering the jet**. A thick, hot accretion disk around the black hole could provide natural collimation by funneling the outflowing particles, as shown in Fig. 29. Because the accreting material retains some angular momentum as it spirals inward through the disk, it will tend to pile up at the smallest orbit that is compatible with its angular momentum.

Inside this **"centrifugal barrier" there may be a relatively empty cavity** that can act as a nozzle, **directing the accreting gases outward along the walls of the cavity.**

However, producing highly relativistic jets, as frequently observed, appear to be difficult to accomplish with this nozzle mechanism.

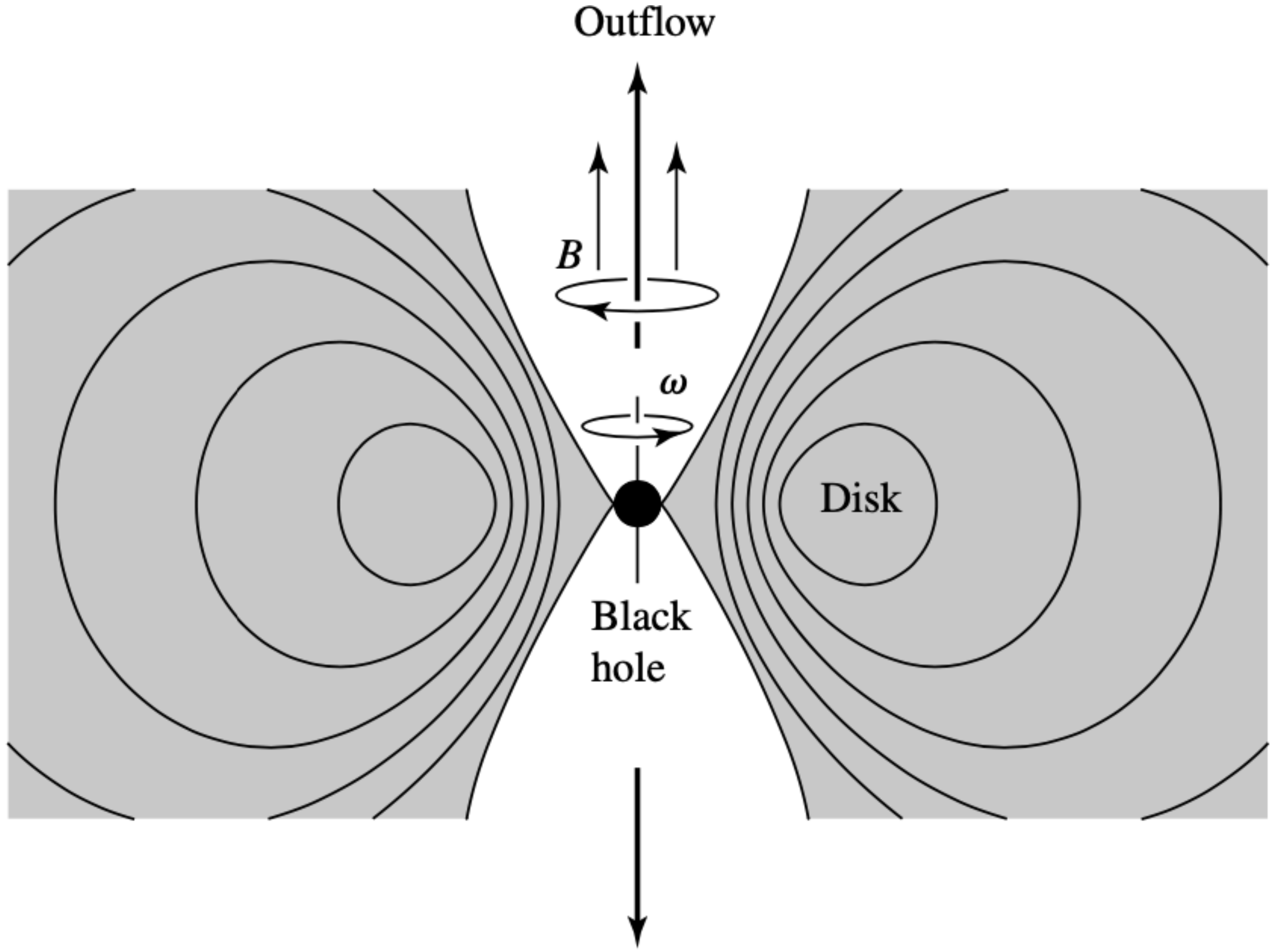


FIGURE 29 A schematic showing the collimation of outflowing material by a thick, hot accretion disk. The loops represent contours of constant disk density.

Jets

Alternatively, **magnetohydrodynamic (MHD) effects could play an important role** in accelerating and collimating the relativistic flows. Unfortunately, details of MHD mechanisms have not yet been fully developed either. -> the jet launching mechanism is part of active research.

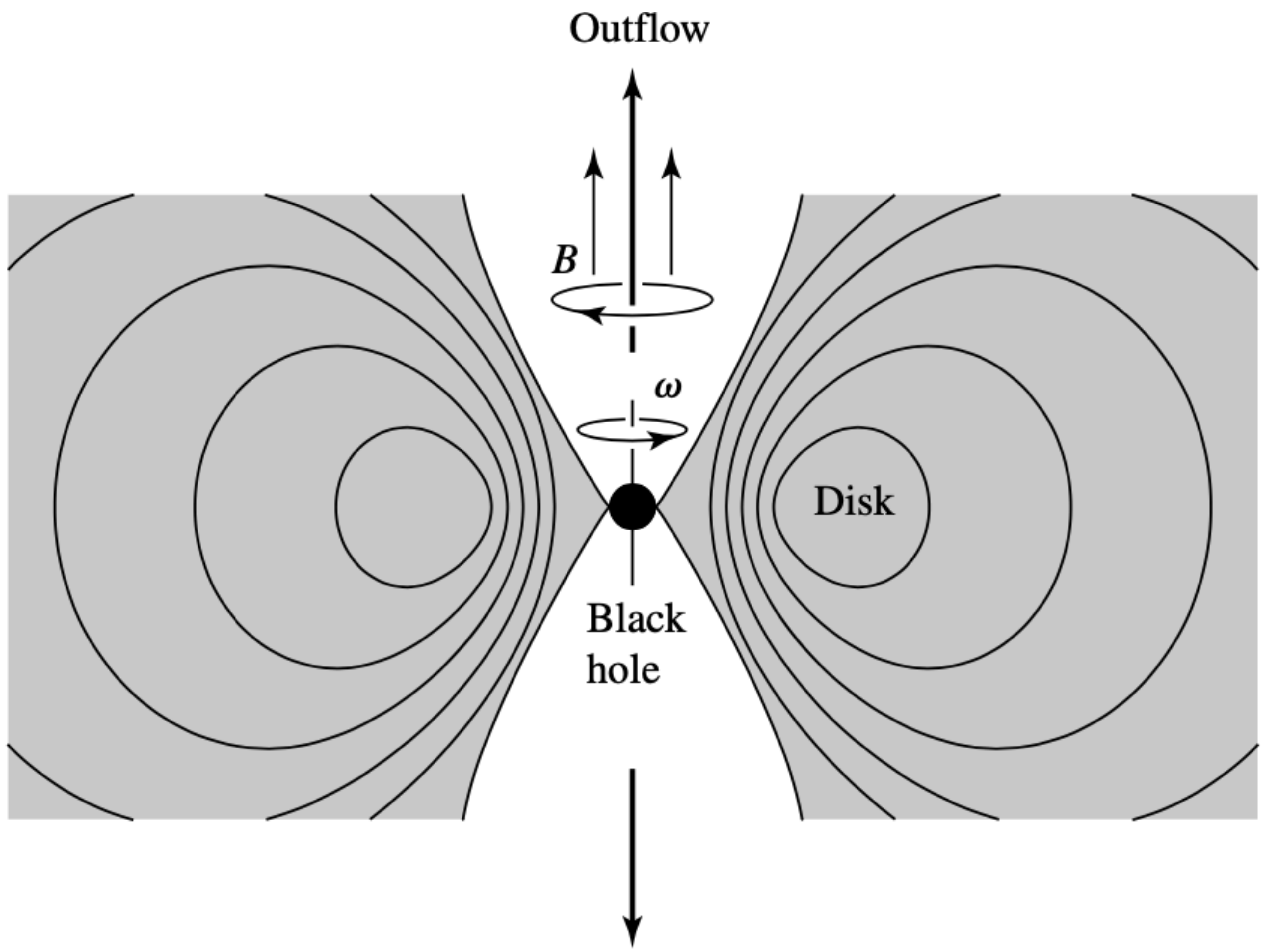
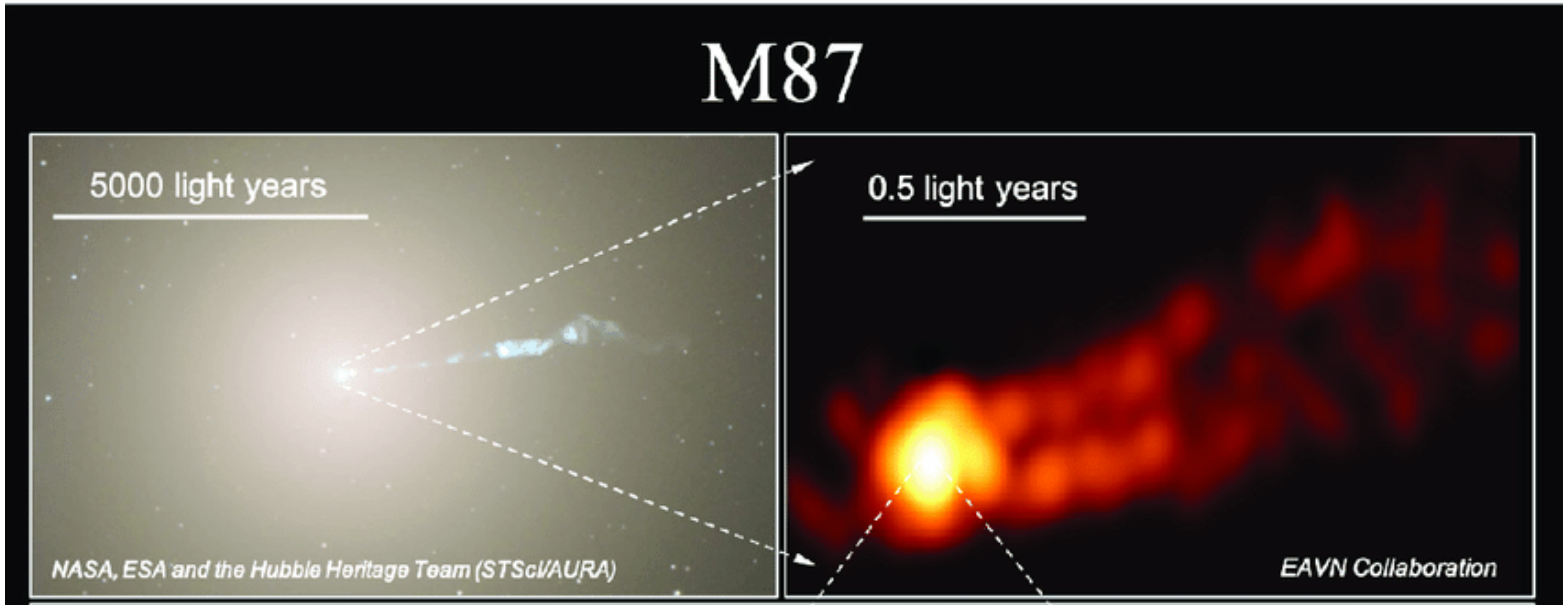


FIGURE 29 A schematic showing the collimation of outflowing material by a thick, hot accretion disk. The loops represent contours of constant disk density.

Jets



Some accretion discs produce jets of twin, highly collimated, and fast outflows that emerge in opposite directions from close to the disc.

The **direction of the jet ejection is determined either by the angular momentum axis of the accretion disc or the spin axis of the black hole.**

The jet production mechanism and indeed the jet composition on very small scales are not understood at present due to the **resolution of astronomical instruments being too low**. The jets have their most obvious observational effects in the radio waveband, where **very-long-baseline interferometry** can be used to study the synchrotron radiation they emit at resolutions of sub-parsec scales.

However, they radiate in all wavebands from the radio through to the gamma-ray range via the **synchrotron and the inverse-Compton scattering process**, and so AGN jets are a second potential source of any observed continuum radiation.

https://en.wikipedia.org/wiki/Active_galactic_nucleus

Radio lobes

As a jet of material travels outward, its energy primarily resides in the **kinetic energy of the particles**. As the jet encounters **resistance as it moves trough the interstellar medium** within the host galaxy and the **intergalactic medium** beyond. ->The **material at the head of the jet is slowed, and a shock front forms** there. The **accumulation and deceleration of particles** at the shock front cause the directed energy of the jet to become disordered as the particles **"splash back" to form a large lobe** in which the energy may be shared equally by the **kinetic and magnetic energy**.

Extensive **numerical simulations are required to model the process**. Figure 30 shows a series of computer simulations of jets with various initial energies working their way through the intergalactic medium.

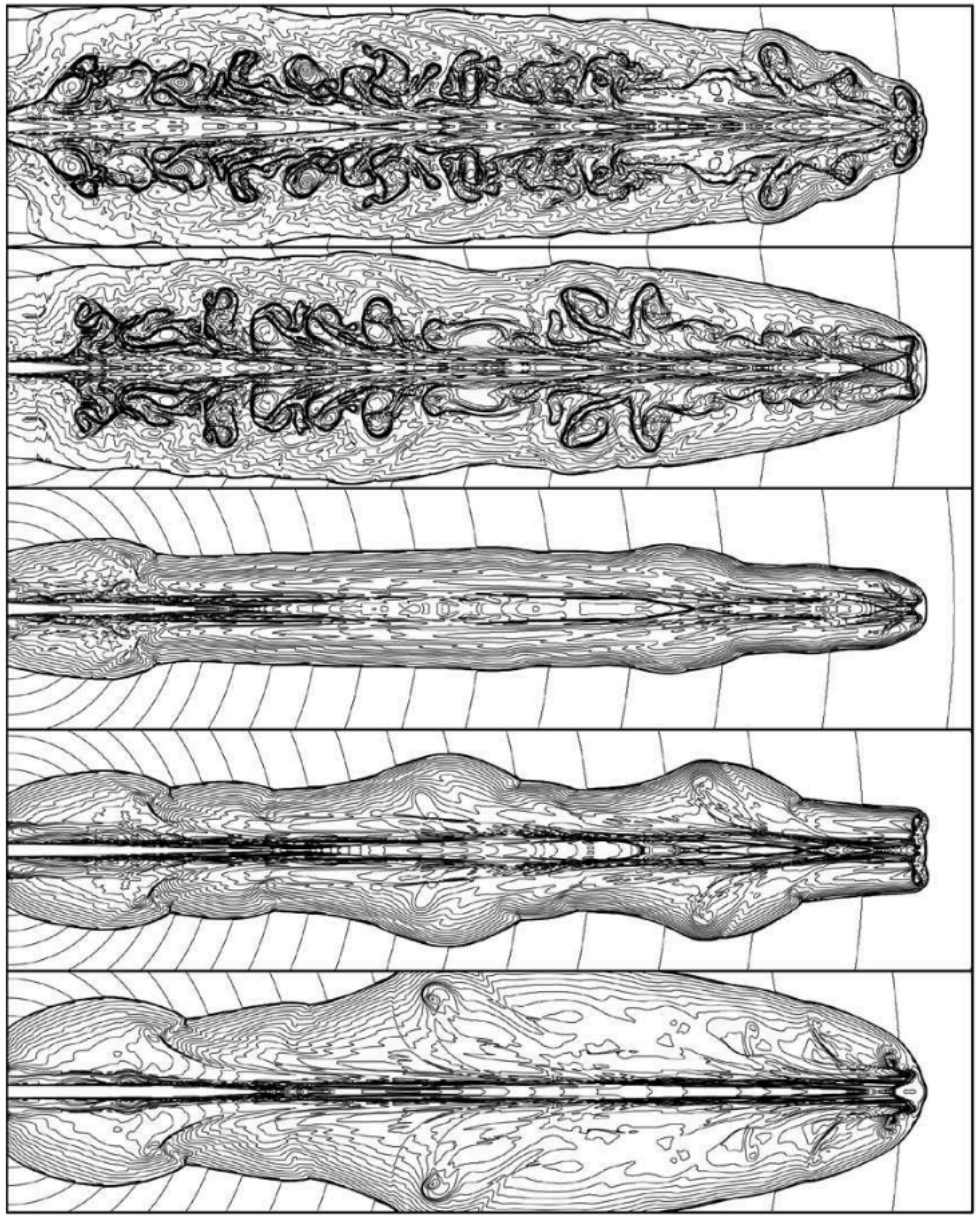
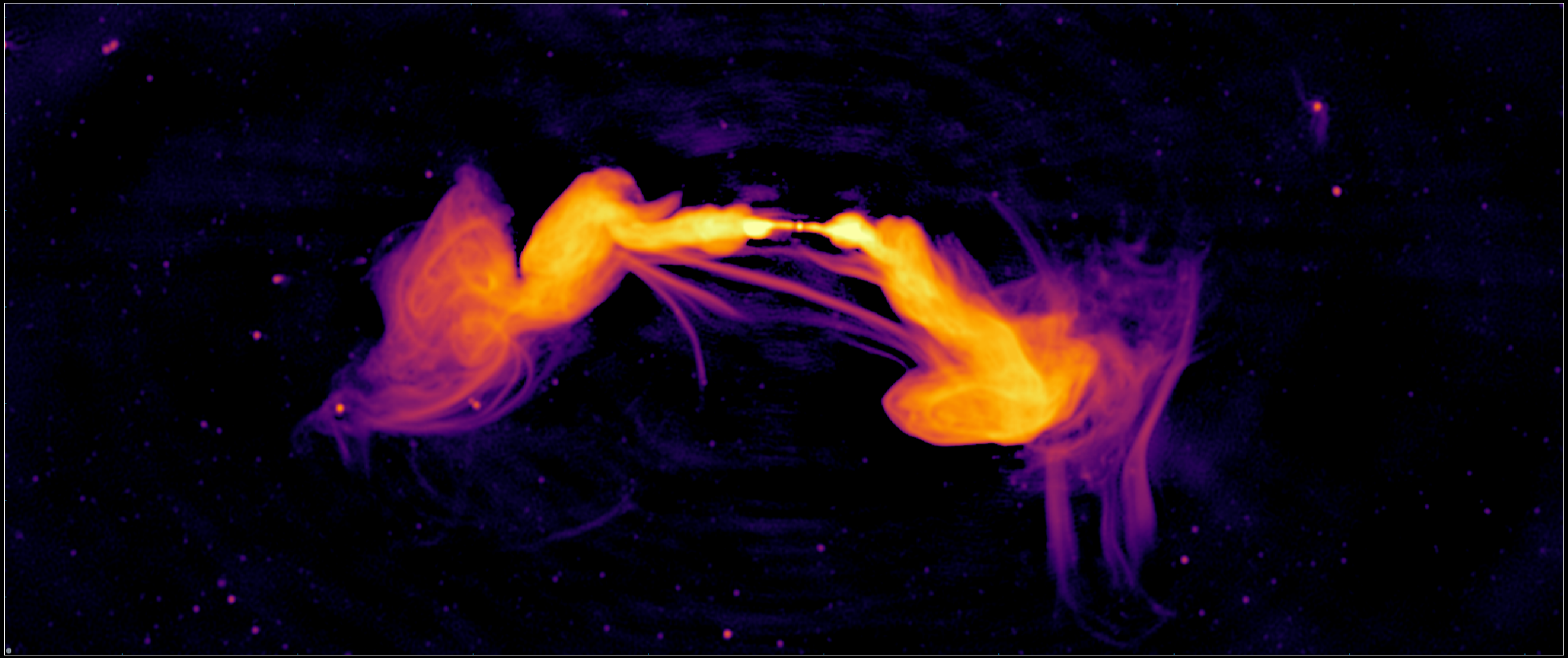


FIGURE 30 Numerical simulation of electron–positron plasma jets moving through the intergalactic medium, which is assumed to be decreasing in density with increasing distance from the source of the jets (left-hand side of each frame). The frames correspond to initial Lorentz factors (γ) at the source of the jets of (a) 2.0, (b) 2.5, (c) 5.0, (d) 7.0, and (e) 10.0. Somewhat different behaviors are seen in the simulations when the jet material is assumed to be composed of electrons and protons. (Figure from Carvalho and O'Dea, *Ap. J. Suppl.*, *141*, 371, 2002.)

Radio lobes

The radio galaxy ESO 137-006



"Collimated synchrotron threads linking the radio lobes of ESO 137-006", M. Ramatsoku et al. 2020, A&A
MeerKAT Radio Telescope image at 1000 MHz
Image credits: Rhodes University / INAF / SARAO

Radio lobes

The motion of the charged particles and the magnetic fields within the lobes of radio-loud objects contain an **enormous amount of energy**. For Cygnus A, the energy of each lobe is estimated to be approximately 10^{53} to 10^{54} J, equivalent to the energy liberated by 10^{7} supernovae.

Cyg A - radio galaxy (AGN)

Radio lobes

Example 3.1. Assuming that each radio lobe of Cyg A contains an energy of $E_{lobe} = 10^{53}$ J, and adopting h = $[h]_{WMAP} = 0.71$ for the values given in Example 1.1 (calculating the luminosity from the radio Flux) for Cyg A, the lifetime of the radio lobes can be estimated. With Cyg A's radio luminosity of $L_{radio} = 4.8 \times 10^{37}$ W, the time to radiate away the energy stored in its radio lobes is

$$t_{\text{lobe}} = \frac{E_{\text{lobe}}}{L_{\text{radio}}} = 66 \text{ Myr}.$$

Generally, the lifetime of the radio emission from radio lobes ranges from **10^7 to more than 10^8 years.**

Radio lobes

The average strength of the magnetic field in the lobes can be estimated by making the common assumption that the energy is shared equally between the kinetic and magnetic energy. The magnetic energy stored per unit volume is um = $B^2/2\mu_0$. If the volume of the lobe is V_{lobe}, then

$$\frac{1}{2}E_{\text{lobe}} = u_m V_{\text{lobe}} = \frac{B^2 V_{\text{lobe}}}{2\mu_0}$$

Or

$$B = \sqrt{\frac{\mu_0 E_{\text{lobe}}}{V_{\text{lobe}}}}.$$

Radio lobes

Example 3.2: Assume that each of Cyg A's radio lobes can be modeled as a sphere of radius R = 8.5 kpc = 2.6 × 10^{20} m, characteristic of the size of the lobes. With $E_{lobe} = 10^{53}$ J, the average value of the magnetic field in the lobes is estimated to be

$$B = \sqrt{\frac{\mu_0 E_{\rm lobe}}{\frac{4}{3}\pi R_{\rm lobe}^3}} \approx 41 \text{ nT}.$$

A value of order **10 nT** is typical of the **bright emission regions** ("hot spots" that are a few kpc across) found in radio lobes. In **diffuse radio lobes**, the value may be more than an order of magnitude **smaller**, while the field strength in the **radio core is probably around 100 nT.**

Accelerating the charged particles in jets

The observations of jets are made possible by inefficiencies in the transport of particles and energy out to the radio lobes. The spectra of the radio lobes and jets follow a power law, with a typical spectral index of $\alpha \simeq 0.65$. **The presence of power-law spectra and a high degree of linear polarization strongly suggest that the energy emitted by the lobes and jets comes from synchrotron radiation**.

The **loss of energy by synchrotron radiation is unavoidable**, and in fact the **relativistic electrons in jets will radiate away their energy after just 10,000 years** or so.

This **implies that there is not nearly enough time for particles to travel out to the larger radio lobes;** for example, for the large radio galaxy 3C 236, the journey would take several million years, even at the speed of light. This long travel time and the long lifetime of radio lobes **imply that there must be some mechanism for accelerating particles in the jets and radio lobes.**

As one possibility, **shock waves may accelerate charged particles by magnetically squeezing them,** reflecting them back and forth inside the shock. **Radiation pressure may also play a role**, but it alone is not enough to generate the necessary acceleration.

Superluminar velocities

Although the standard model of jets and radio lobes requires a steady supply of charged particles moving at relativistic speeds, evidence for such high velocities is difficult to obtain. **The absence of spectral lines in a power-law spectrum means that the relativistic velocity of the jet material cannot be measured directly** but must be inferred from indirect evidence. The most compelling argument for relativistic speeds involves radio observations of material ejected from the cores of several AGNs with so-called **superluminal velocities**. This effect is observed within about 100 pc of the AGN's center and probably continues farther out.

Superluminar velocities

Example 3.3. Figure 31 is a radio view of the core of the quasar **3C 273** that shows a blob of radio emission moving away from the nucleus with an angular velocity of $\mu = 0.0008'' \text{ yr}^{-1}$. **Assuming that the radio knot is traveling in the plane of the sky,** perpendicular to the line of sight, and using a distance of $d = 440h^{-1}$ Mpc for 3C 273, the ***apparent*** **transverse velocity** of the blob away from the nucleus is,

$$v_{\text{app}} = d\mu = 1.67 \times 10^9 h^{-1} \text{ m s}^{-1} = 5.57 h^{-1} c.$$

If $h=[h]_{\text{WMAP}}$, we find that $\mathbf{v_{app} = 7.85\ c}$. This is clearly **unphysical**, and so the assumption of motion perpendicular to the line of sight must be wrong.

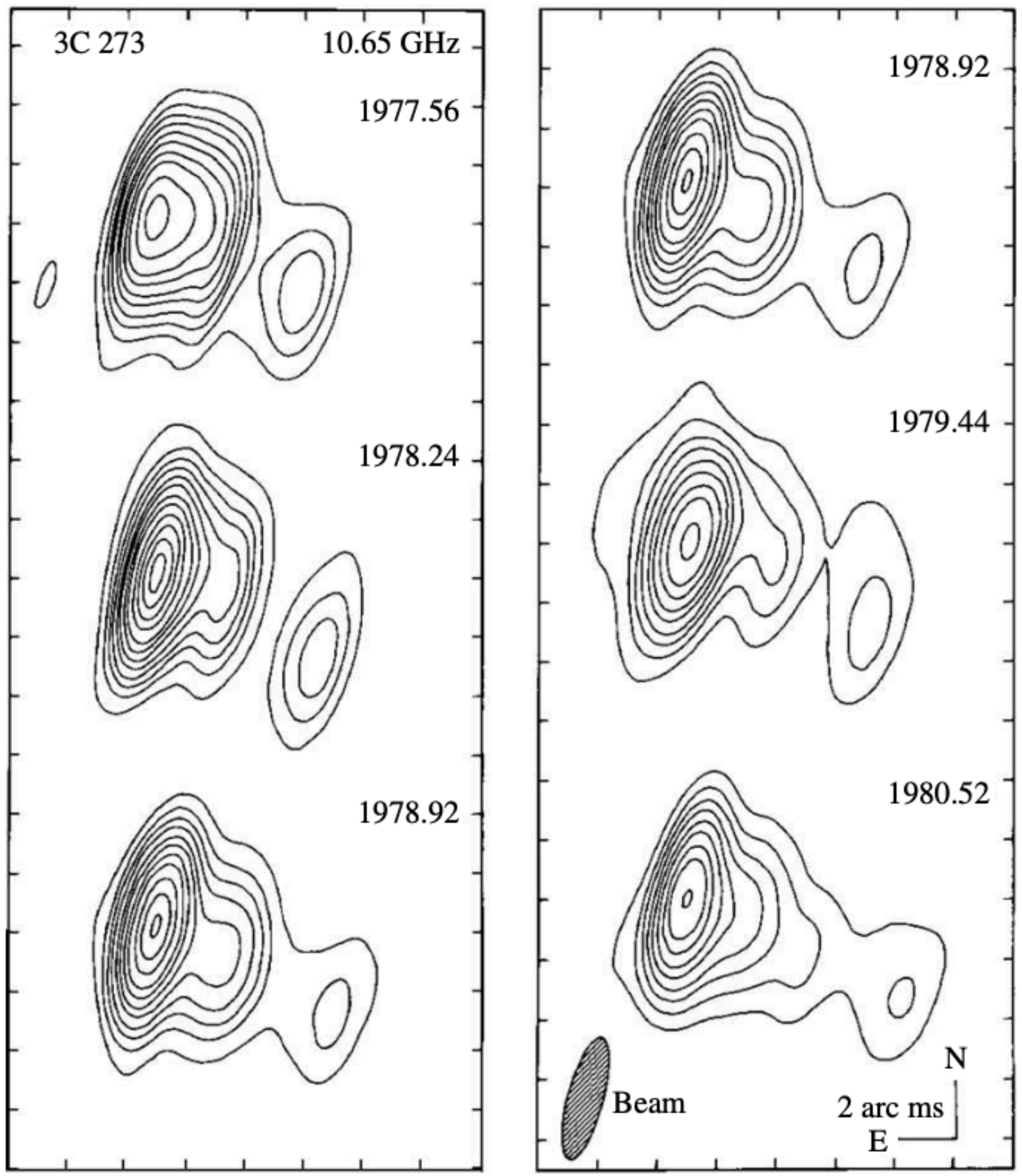


FIGURE 31 The motion of a radio-emitting knot ejected from the core of the quasar 3C 273. The dates of the observations are recorded as fractions of a year, and the third image has been repeated for clarity. (Figure adapted from Pearson et al., *Nature*, *290*, 365, 1981. Reprinted by permission from *Nature*, Vol. 290, pp. 365–368. Copyright 1981 Macmillan Magazines Limited.)

Superluminar velocities

Figure 32 shows how the motion of the knot toward the observer can resolve this dilemma. Suppose a source is traveling with a velocity v (the actual speed of the source, not its apparent speed) at an angle ϕ measured from the line of sight.

A photon is emitted along the line of sight at time t = 0 when the source is a distance d from Earth. At a later time (t_e), another photon is emitted when the distance to Earth is $d - vt_e \cos \phi$. The first photon reaches Earth at time t_1, where

$$t_1 = \frac{d}{c}.$$

The second photon arrives at Earth at time

$$t_2 = t_e + \frac{d - vt_e \cos \phi}{c}.$$

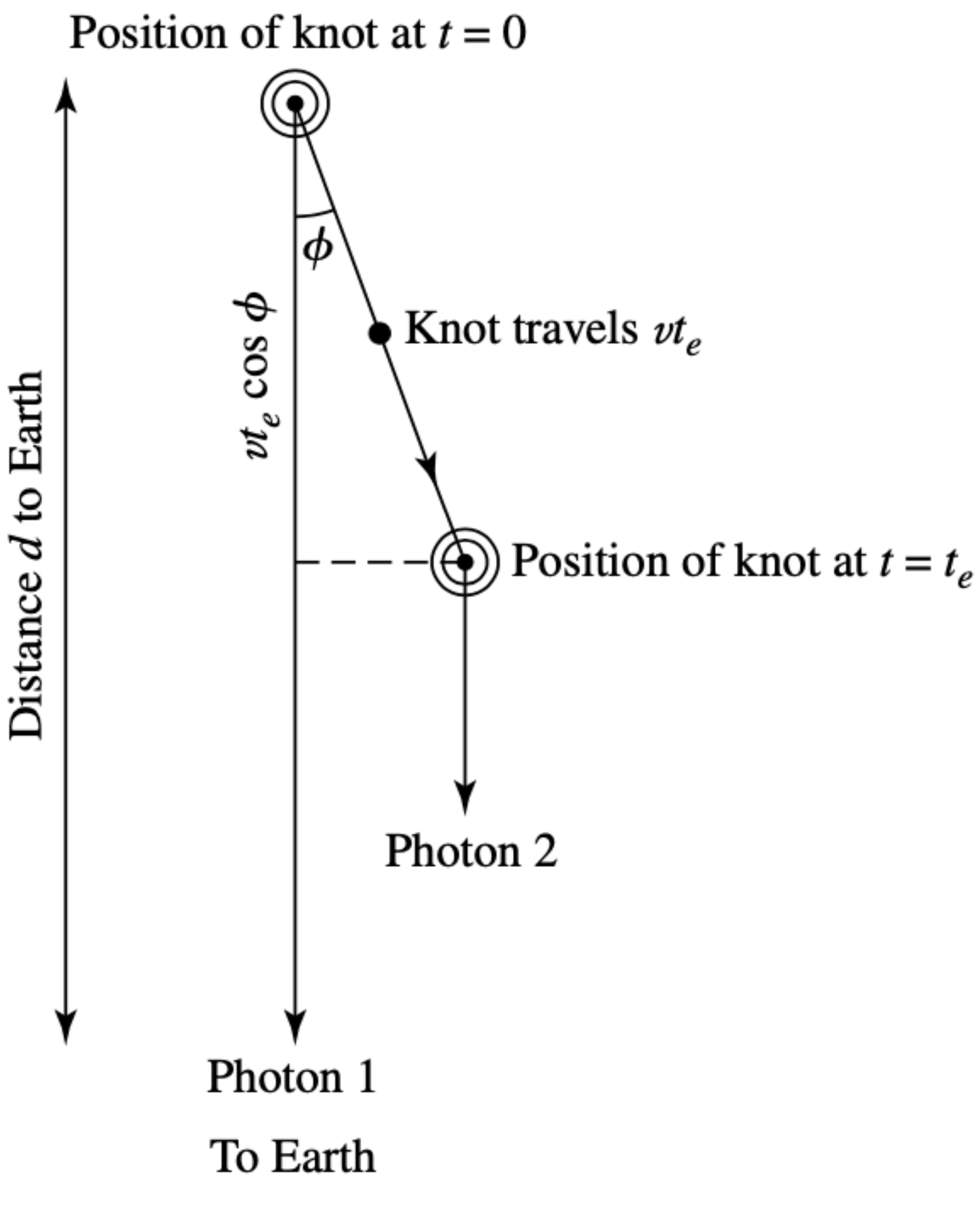


FIGURE 32 Two photons emitted at $t = 0$ and $t = t_e$ by a source moving with speed v.

Superluminar velocities

The time on Earth between the reception of the two photons is thus

$$\Delta t = t_2 - t_1 = t_e \left(1 - \frac{v}{c}\cos\phi\right),$$

a time that is *shorter* than t_e. The apparent transverse velocity measured on Earth is then

$$v_{\rm app} = \frac{v t_e \sin\phi}{\Delta t} = \frac{v \sin\phi}{1 - (v/c)\cos\phi}.$$

Solving this for v/c results in

$$\boxed{\frac{v}{c} = \frac{v_{\rm app}/c}{\sin\phi + (v_{\rm app}/c)\cos\phi}.}$$

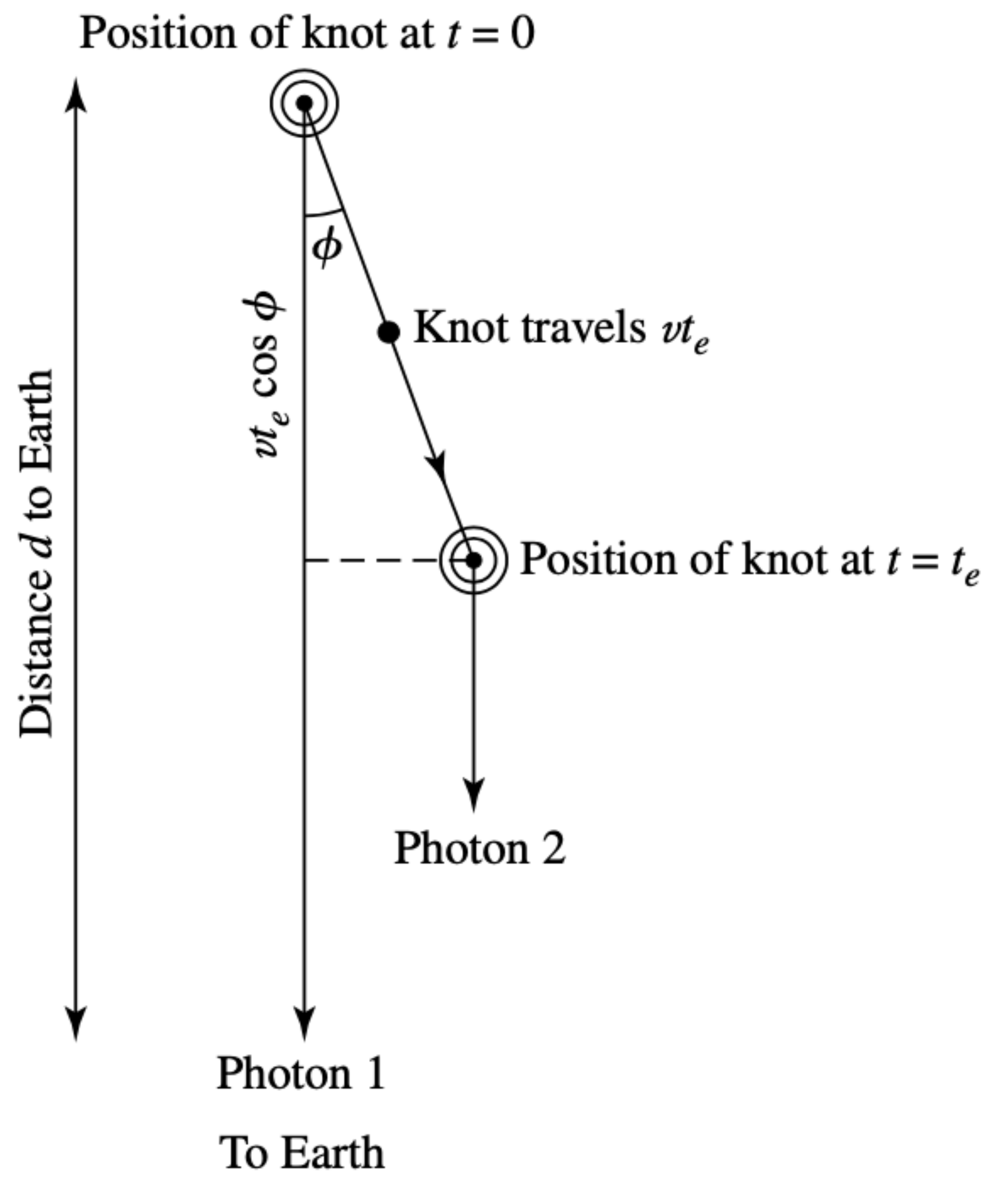


FIGURE 32 Two photons emitted at $t = 0$ and $t = t_e$ by a source moving with speed v.

Superluminar velocities

If v/c < 1 for angles satisfying

$$\frac{v_{\text{app}}^2/c^2 - 1}{v_{\text{app}}^2/c^2 + 1} < \cos\phi < 1,$$

and that the smallest possible value of v/c for the source is

$$\frac{v_{\min}}{c} = \sqrt{\frac{v_{\text{app}}^2/c^2}{1 + v_{\text{app}}^2/c^2}},$$

which occurs at an angle ϕmin given by

$$\cot\phi_{\min} = \frac{v_{\text{app}}}{c}.$$

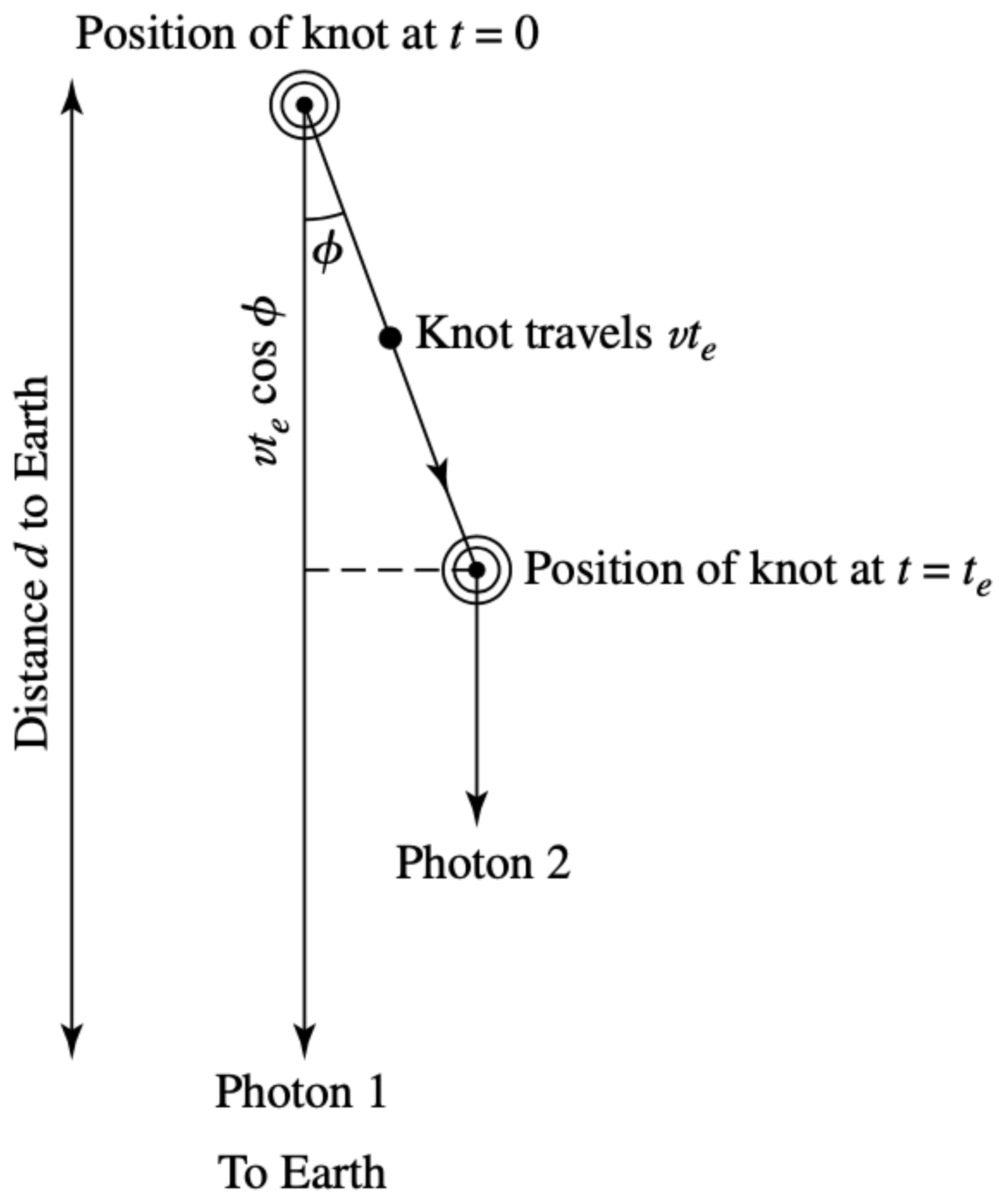


FIGURE 32 Two photons emitted at $t = 0$ and $t = t_e$ by a source moving with speed v.

Superluminar velocities

This minimum value of v/c corresponds to a minimum Lorentz factor source of

$$\gamma_{\min} = \frac{1}{\sqrt{1 - v_{\min}^2/c^2}} \simeq \sqrt{1 + v_{\mathrm{app}}^2/c^2} = \frac{1}{\sin\phi_{\min}}.$$

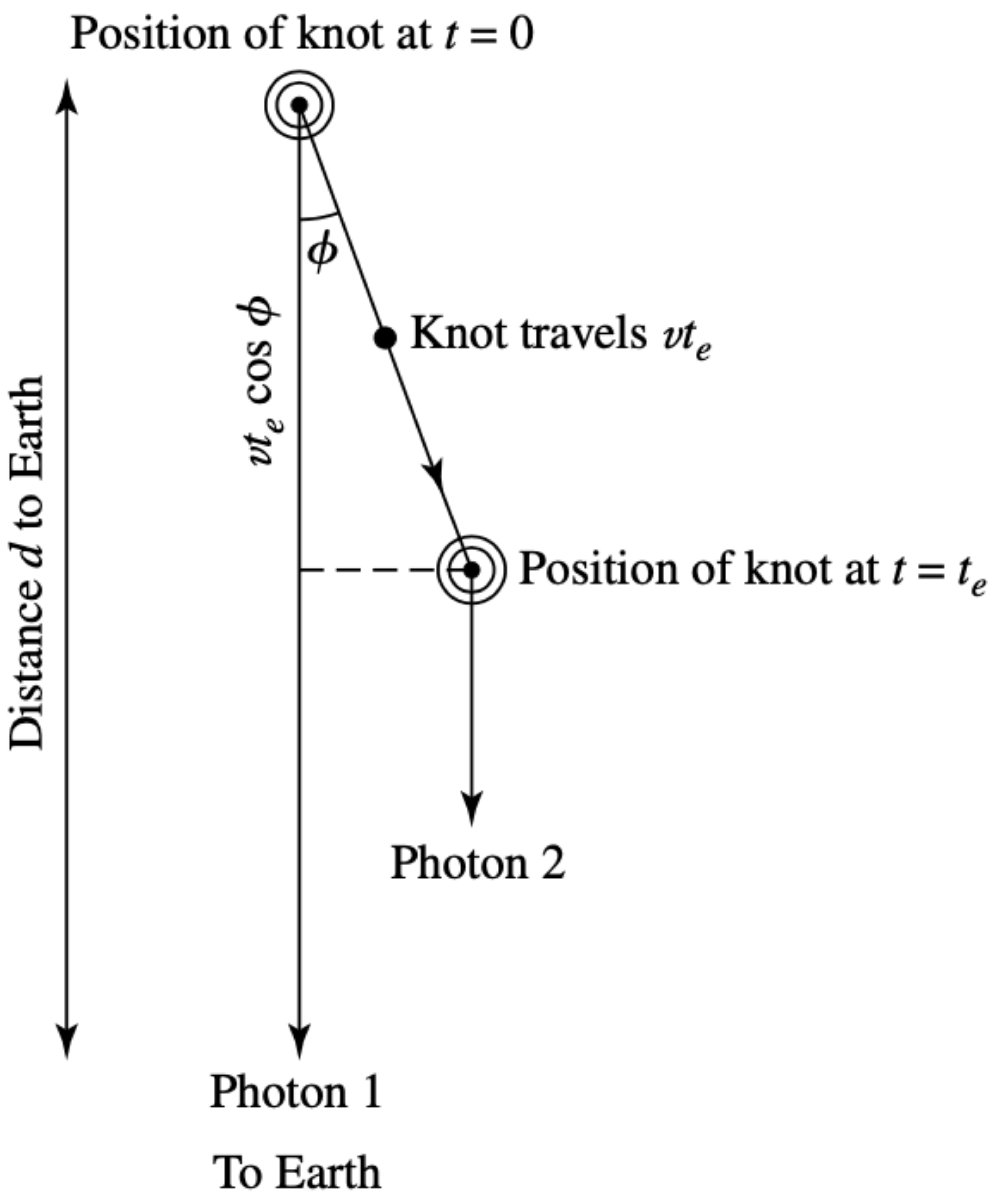


FIGURE 32 Two photons emitted at $t = 0$ and $t = t_e$ by a source moving with speed v.

Superluminar velocities

Example 3.4. Referring to Example 3.3, since the actual speed of the radio knot ejected by 3C 273 must be less than c, as required by special relativity, ϕ must be less than

$$\phi_{\min} = \cot^{-1}\left(\frac{v_{\text{app}}}{c}\right) = 7.26^\circ.$$

That is, the knot must be approaching Earth within 7.26° of the line of sight. The lower limit of the knot's speed is v_{min} = 0.992 c. Therefore, γ_{min} = 7.92.

The minimum value of the Lorentz factor inferred for other superluminal sources ranges between γ_{min} = 4 and 12 for h=[h]$_{WMAP}$. 3C273 and similar examples provide compelling evidence that the central cores of AGNs can **accelerate material to relativistic speeds**.

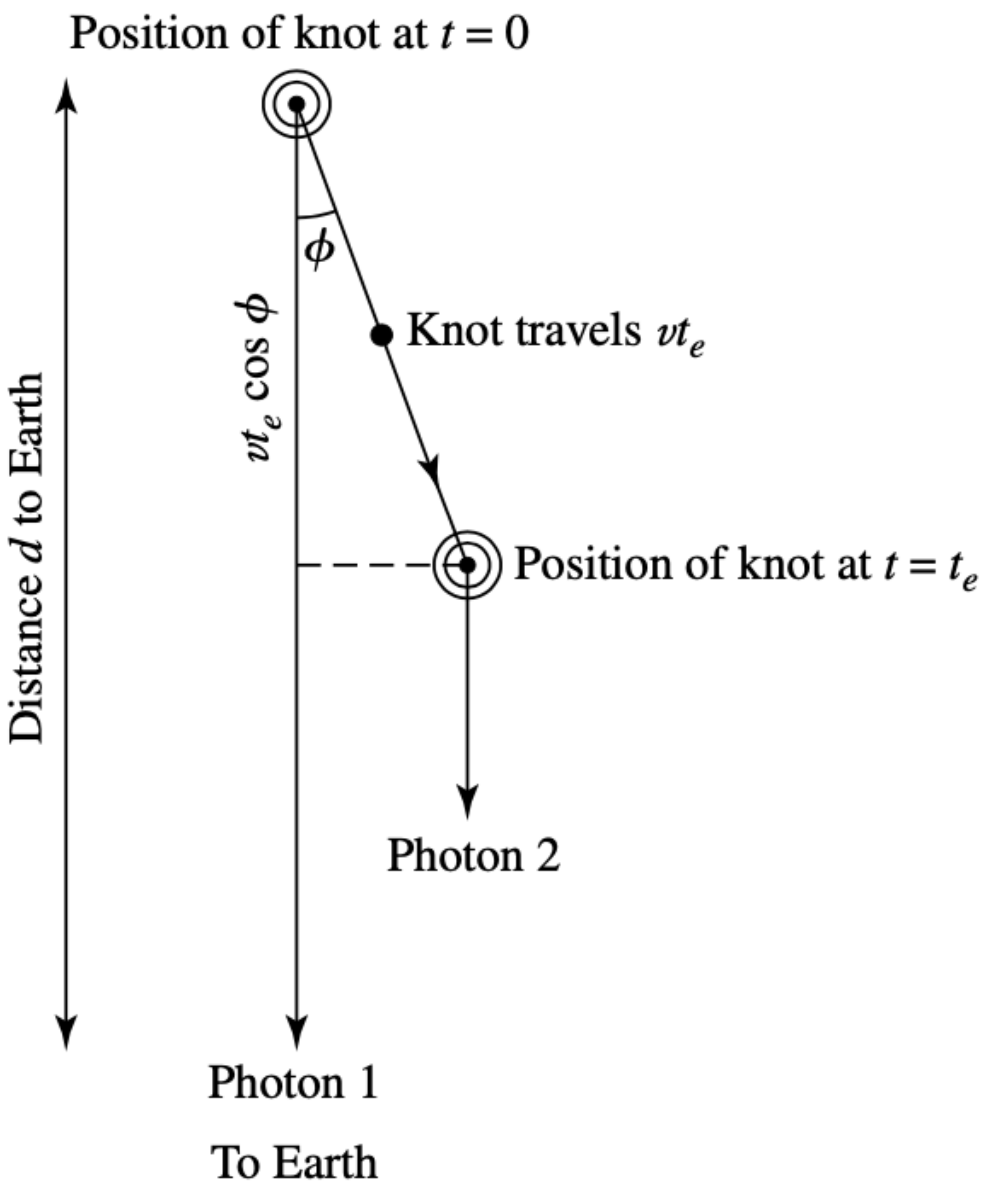


FIGURE 32 Two photons emitted at $t = 0$ and $t = t_e$ by a source moving with speed v.

Relativistic beaming

The **headlight effect** will be involved whenever a source of light moves with a **relativistic speed ($\gamma \gg 1$)**.

All of the **light emitted** into the **forward** hemisphere **in the rest frame of the source** is **concentrated into a narrow cone in the observer's rest frame.** The cone's half-angle, θ , is given by $\sin\theta = 1/\gamma$.

$$\gamma_{\min} = \frac{1}{\sqrt{1 - v_{\min}^2/c^2}} \simeq \sqrt{1 + v_{\mathrm{app}}^2/c^2} = \frac{1}{\sin\phi_{\min}}.$$

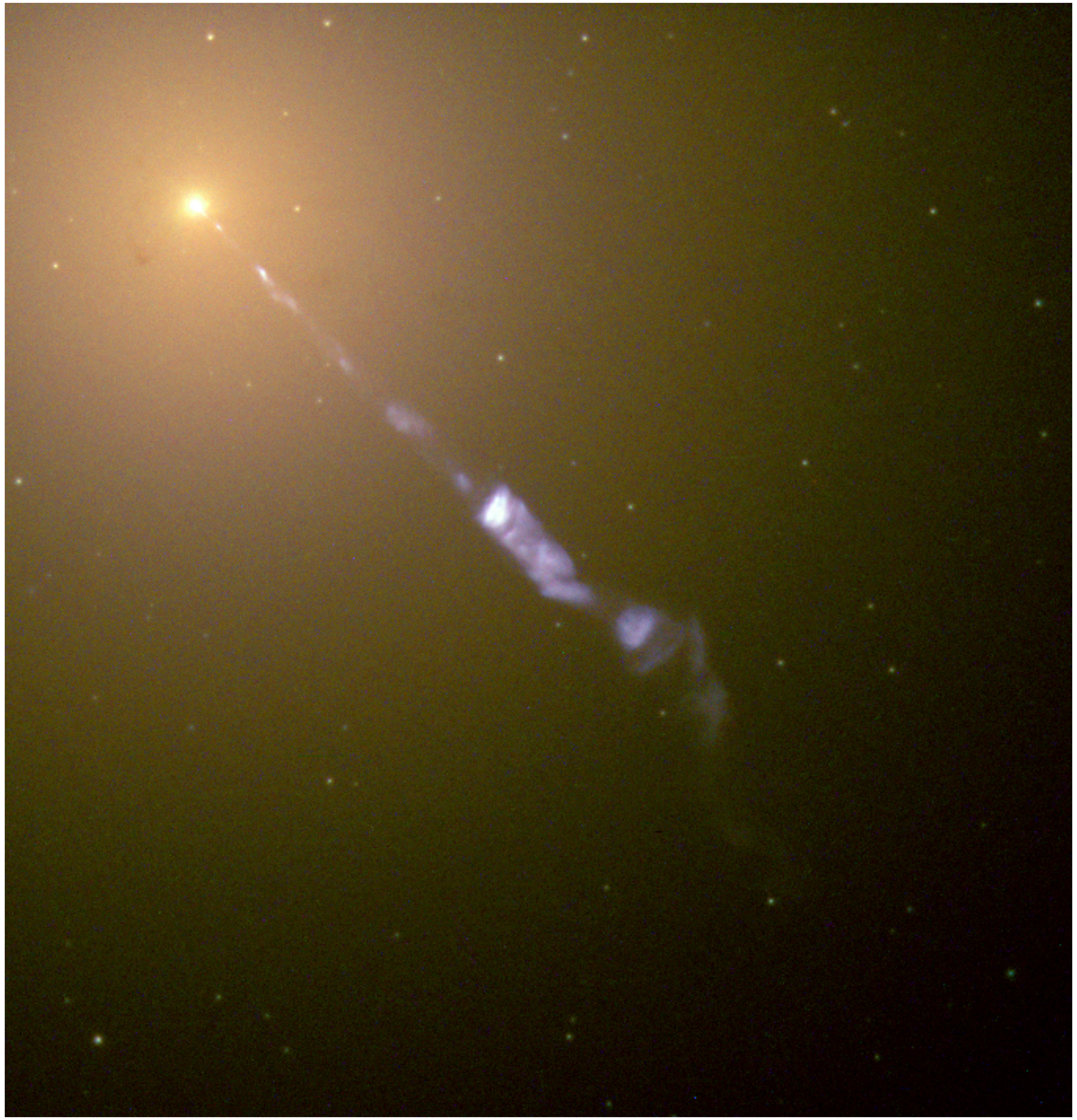
Comparing this with shows that if the source is approaching Earth with a relativistic velocity within the angle $\phi_{\min}$ of the line of sight, this **relativistic beaming effect will cause it to appear much brighter than expected** and it will appear to be moving with a **superluminal speed** across the plane of the sky.

Interestingly, nearly all AGNs showing superluminal motions are **surrounded by large, dim halos that may be radio lobes seen end-on. Blazars** may be quasars or radio galaxies viewed with the **jet coming directly (or nearly so) toward the observer.** Their very rapid time variability could then be exaggerated by the relativistic Doppler shift. Any luminosity variations due to a source within the relativistic jet would be observed to occur approximately 2γ times more rapidly by astronomers on Earth.

Relativistic beaming

Conversely, a **relativistic source moving away from us will appear unusually dim.**

All of the **jets showing superluminal motion are one-sided**, even when the AGNs exhibit two radio lobes. It is expected that the central engines of AGNs produce two oppositely directed jets; however, **relativistic beaming seems to explain why the jets appear to be only one-sided.**



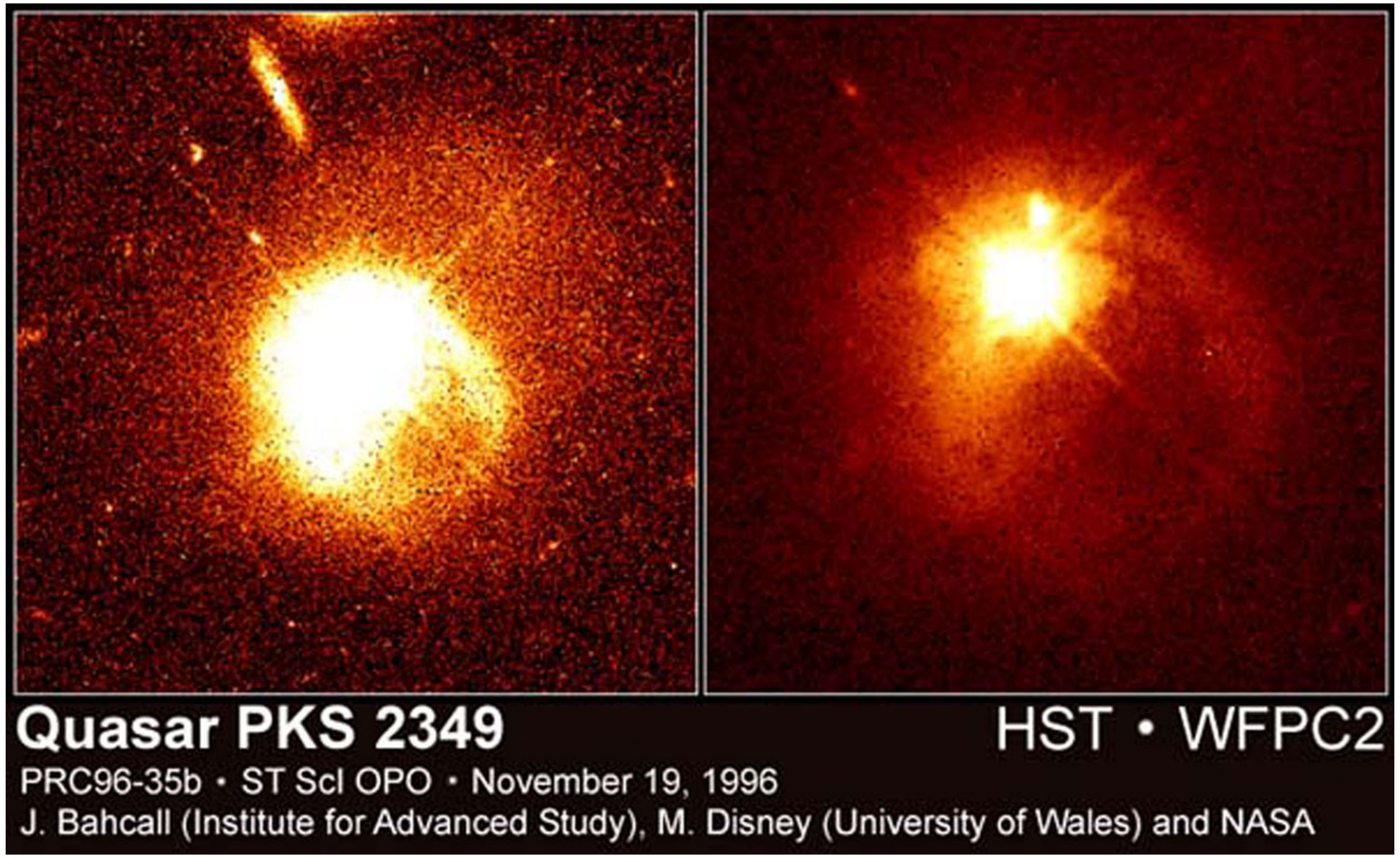
M87

Fuel sources for AGN

Seyfert galaxy **NGC 4151**

The **galactic companions of AGNs** may play an important role in supplying them with the fuel. Most **Seyferts (at least 90%) are spiral galaxies, and many have close neighbors with whom they may be interacting. Gravitational perturbations** produce the distorted appearance frequently seen in those Seyferts close enough to be studied, as evidenced by the appearance of bars and/or outer rings. These interactions could produce **gravitational torques on the gas in a Seyfert galaxy,** drastically **reducing its angular momentum and sending the gas plunging into the galactic center.** The result would be the delivery of a fresh supply of fuel to the Seyfert nucleus to be **accreted by the black hole.** The concentration of gas could also result in a **burst of star formation around the nucleus.** Furthermore, if a **merger with a galactic companion** occurs, the subsequent disruption could produce an **elliptical galaxy with an active nucleus,** resulting in a young **radio galaxy.**

Fuel sources for AGN



Mergers are certainly important for quasars as well. Some **low-redshift quasars show evidence of past interactions**, and mergers were undoubtedly more common in the early universe than they are today. Since **galaxies are believed to have contained more gas when they were young**, mergers may have resulted in the infall of large amounts of gas that could have contributed to the growth of a central supermassive black hole as the gas simultaneously fueled its activity. In addition, **mergers probably resulted in the coalescing of supermassive black holes**, producing even **larger central engines**. As the masses of the black holes grew, so did the number of quasars and their energy output, until the fuel powering the engines was largely consumed.

Fuel sources for AGN

What happens when a quasar runs out of fuel?

In broad terms, the diminishing fuel supply of an energetic object could lead to its transformation into a **less luminous form**. For example, **Cen A has huge radio lobes** (Fig) but **is a weak radio source**. It was probably much more luminous in the past but is **now fading away**.

On the other hand, a **lesser luminosity could be explained by a less massive black hole** rather than a smaller accretion rate.

Our **Milky Way** does not have a 10^8 M⊙ black hole at its center, although there is a more modest one of 3.7 × **10^6 M⊙** . If, as has been conjectured, every large galaxy comparable to the Milky Way has a supermassive black hole of at least 10^6 M⊙, then **low-level galactic activity may be a common occurrence.**

Fuel sources for AGN

One large impediment to understanding the evolution of active galaxies is our current **lack of knowledge about their lifetimes.**

Some researchers find that **around $z = 2$,** the **number of luminous AGNs decreases toward the present-day** epoch with a characteristic decay time of $\tau \simeq 2h^{-1}$ Gyr. However, this is only an ***upper limit* to the lifetime** of an AGN.

A single AGN may remain active this long, or the individual lifetimes may be much shorter, say **between 10^7 and 10^8 years, the typical timescale needed to radiate away the energy stored in a radio lobe.** In this latter case, τ would describe the statistical changes in a population of active galaxies, rather than the behavior of a single individual.

A galaxy may then experience just one, or several, brief episodes of activity during its history as mergers refuel the central engine. It may be that Seyfert galaxies experience recurring episodes of activity, for example.