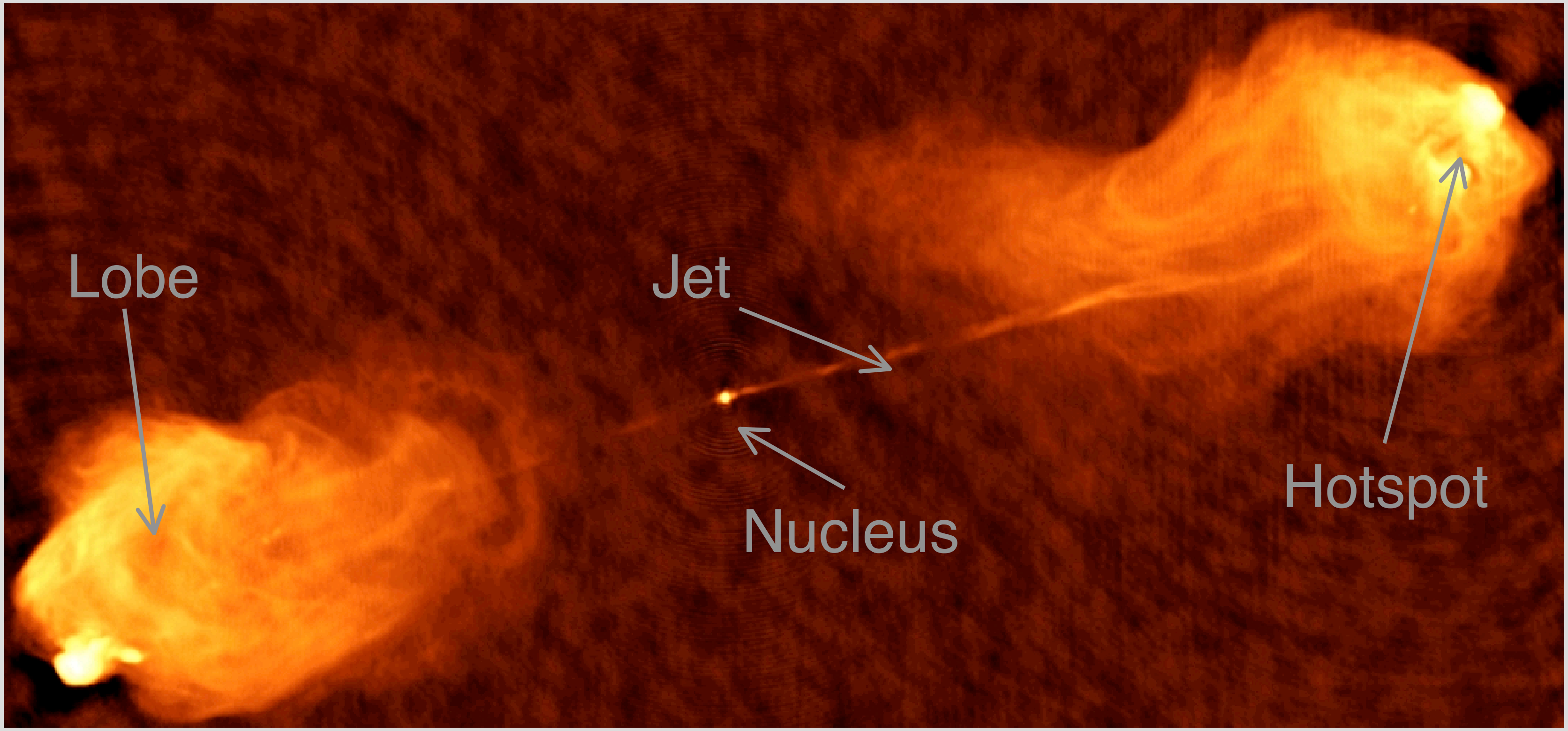
Radio Galaxies

High resolution observations of radio galaxies often show highly extended emission. Best known case: Cygnus A



Emission is synchrotron radiation

Physical extent can be large: typically several hundred kpc, though much smaller and larger examples exist

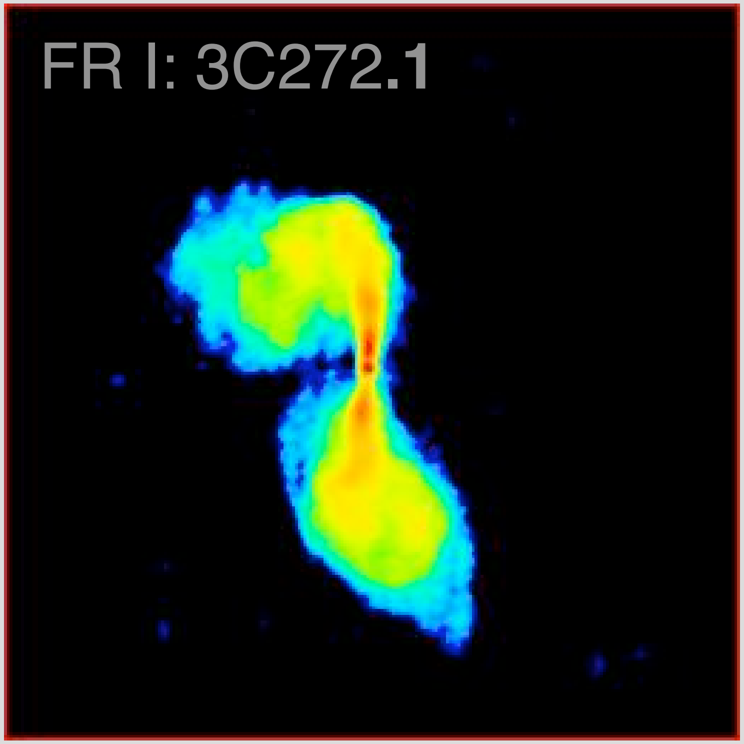
Observationally define two classes of radio galaxy:

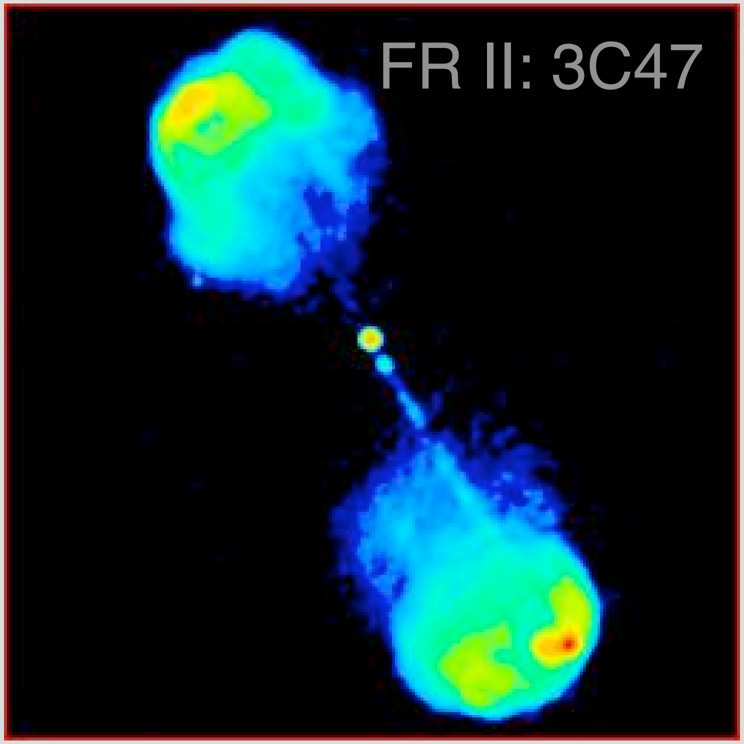
- **Fanaroff & Riley class I (FR-I)**

  Separation between the points of peak intensity in the lobes is *less* than half the largest size of the source

- **Fanaroff & Riley class II (FR-II)**

  Separation between the points of peak intensity in the lobes is *more* than half the largest size of the source





Morphological classification also divides radio galaxies into low radio power and high radio power classes:

- FR I: relatively low power sources
- FR II: more powerful sources

} Break power is about 10^{32} erg s^{-1} Hz^{-1} sr^{-1}

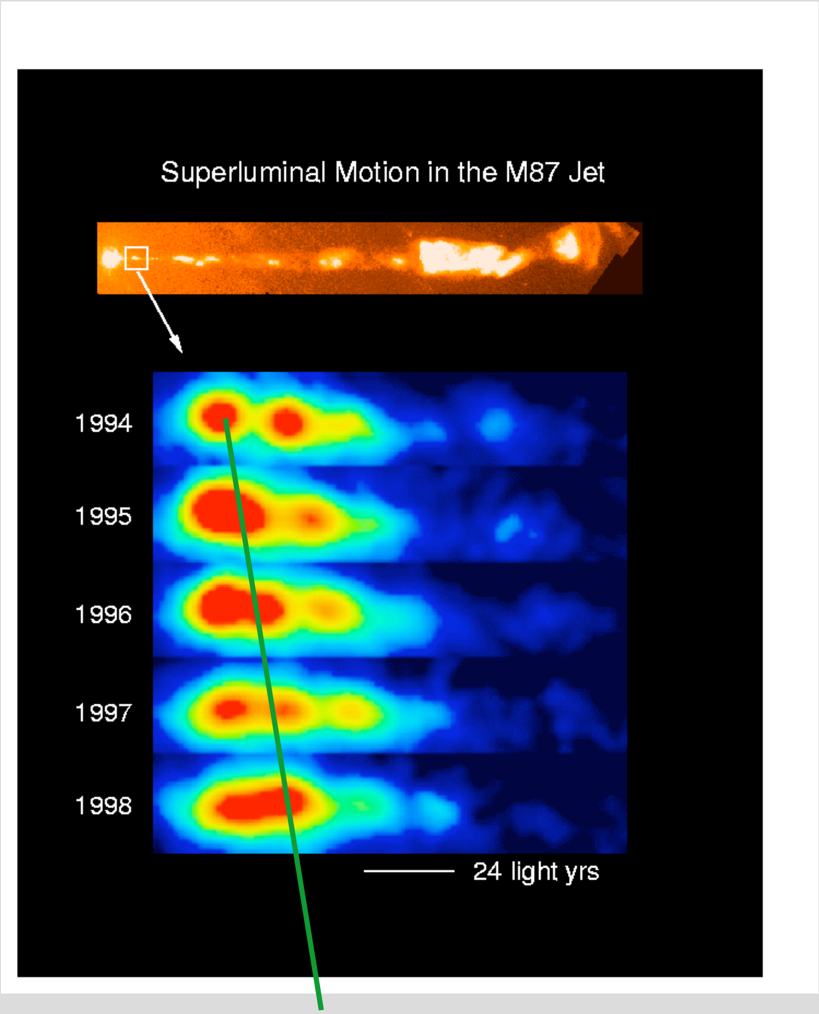
Different appearance probably reflects combination of power and environment…

Outflows from AGN could play an important role in galaxy and / or cluster formation:

- Provide energy source into ISM, intracluster medium
- May be more important than the radiation, which can escape the galaxy or cluster more easily

Apparent superluminal motion

On small scales, jets near the nucleus often show hotspots or `knots' which can be seen to move with time - e.g. M87:



Apparent velocity v ~ 6c

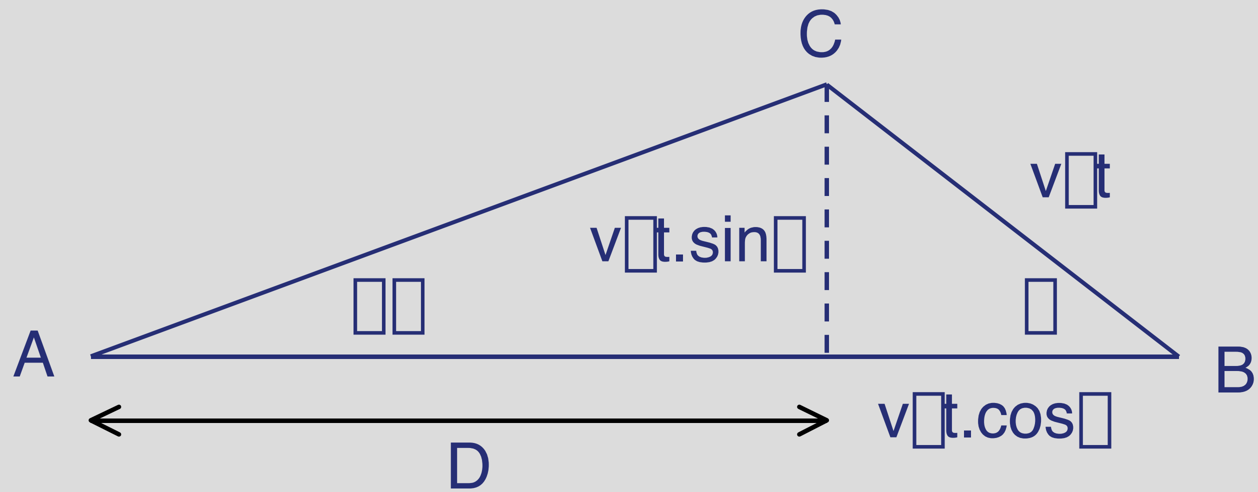
Not certain that the motion of these knots reflects physical speed of the jet.

But if it does, inferred velocity in the plane of the sky exceeds the speed of light.

Phenomenon of apparent **superluminal motion.**

Explanation of apparent superluminal motion

Explain apparent superluminal motion as an optical illusion caused by the finite speed of light. Consider a knot in the jet moving almost directly towards us at high speed:



Source at position B emits a blob of gas with velocity v, at an angle □ to the line of sight to an observer at position A.

A time □t later, the blob has moved to position C.

Observer does not know v or θ. Observer measures:

- Time difference between blob being ejected and reaching position C
- Angular separation between B and C. Assuming that the distance D to the source is known, this gives the projected separation

Angular separation: $\Delta\theta = \dfrac{v \Delta t \sin\theta}{D}$

Time difference as seen by the observer:

Let blob be emitted at time t = 0

Observer sees blob being emitted at time t_1:

$$t_1 = \frac{D + v \Delta t \cos\theta}{c}$$

Observer sees blob reach position C at time t_2:

$$t_2 = \Delta t + \frac{D}{c}$$

Time difference is: $$\Delta t = t_2 - t_1 = \Delta t + \frac{D}{c} - \frac{D + v\Delta t\cos\theta}{c}$$

$$= \Delta t\left(1 - \beta\cos\theta\right)$$

…where we have defined $\beta = v / c$

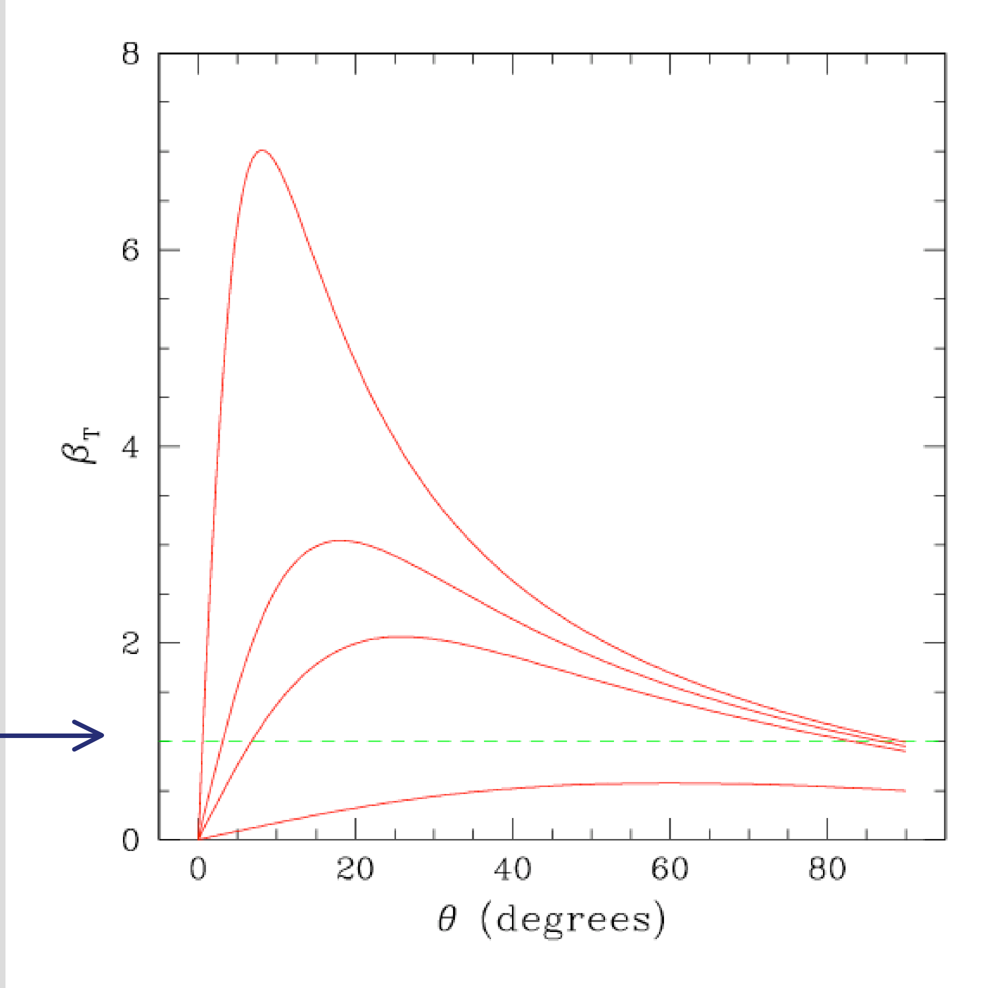
Observer infers a transverse velocity:

$$\beta_T \equiv \frac{v_T}{c} = \frac{1}{c} \times \frac{D\Delta\theta}{\Delta t} = \frac{v\sin\theta}{c\left(1 - \beta\cos\theta\right)} = \frac{\beta\sin\theta}{1 - \beta\cos\theta}$$

For β close to 1, and θ small, can clearly get an apparent transverse velocity $v_T > c$ (i.e. $\beta_T > 1$). e.g. $\beta = 0.99$, $\theta = 10$ degrees gives $\beta_T = 6.9$.

Apparent transverse velocity as a function of angle □ for different values of the true velocity: □ = 0.5, 0.9, 0.95, 0.99

Apparent superluminal motion



If real v > 0.9 c, apparent superluminal motion will be seen in majority of sources (assuming random orientations).

True velocity must exceed a critical value for superluminal motion to be observed (irrespective of orientation).

First find angle at which β_T is maximized:

$$\frac{\partial \beta_T}{\partial \theta} = \frac{\beta \cos\theta}{1 - \beta\cos\theta} - \frac{\beta^2 \sin^2\theta}{(1-\beta\cos\theta)^2} = 0$$

Solving this equation for $\theta = \theta_{max}$ gives: $\theta_{max} = \cos^{-1}\beta$

Substituting this back into the expression for β_T find:

$$\beta_T^{max} = \frac{\beta}{\sqrt{1-\beta^2}}$$

Set left hand side equal to one and solve for β:

$$1 - \beta_{min}^2 = \beta_{min}^2$$

$$\beta_{min} = \frac{\sqrt{2}}{2} = 0.707\ldots$$

Conclude: motion of jet does not need to be highly relativistic to observe superluminal motion

Actual properties of AGN jets are mostly unknown:

- Velocity
- Composition (e-p or e^--e^+)

Note: apparent superluminal motion is really a geometric effect - we have not appealed to any aspects of special relativity except for the restriction v < c.