Class 17 : Jets!

ASTR350 Black Holes (Spring 2022)

Cole Miller

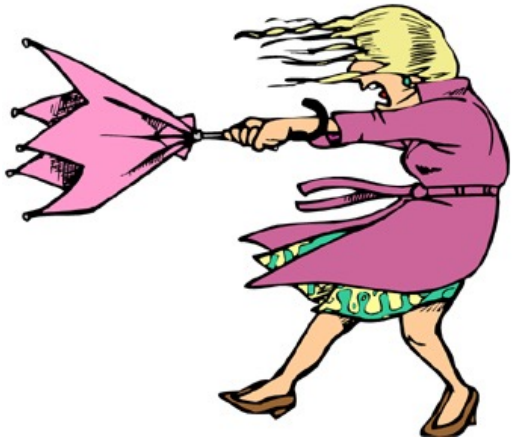
RECAP

- Observed Properties of active galactic nuclei (AGN)
  - Radio observations ➔ relativistic jets
  - Optical/UV observations ➔ accretion disk (+ maybe jet)
  - X-ray observations ➔evidence for emission close to BH

- Most of the emitted electromagnetic radiation occurs in optical, UV and X-ray for supermassive black holes (AGN)
- AGN can be very luminous- the observed range is very large 10^{39}-10^{48} ergs/sec (or 10^{6}-10^{15} times the luminosity of the sun) ***if*** the emission is ~isotropic

Jets…

These are non-relativistic jets



shock as airplane velocity
exceeds the speed of sound

This class

- **Relativistic** jets
  - The radio galaxy “zoo”
  - The one sidedness of jets
  - Ultra high resolution imaging of jets
  - How do we really know they are *relativistic*?
    - 'Superluminal' motion

Two uses of the word relativistic

1) the particles in the jet are moving close to the speed of light

2) the jet itself is moving close the speed of light

Basic Schema of AGN

The 4 essential ingredients are

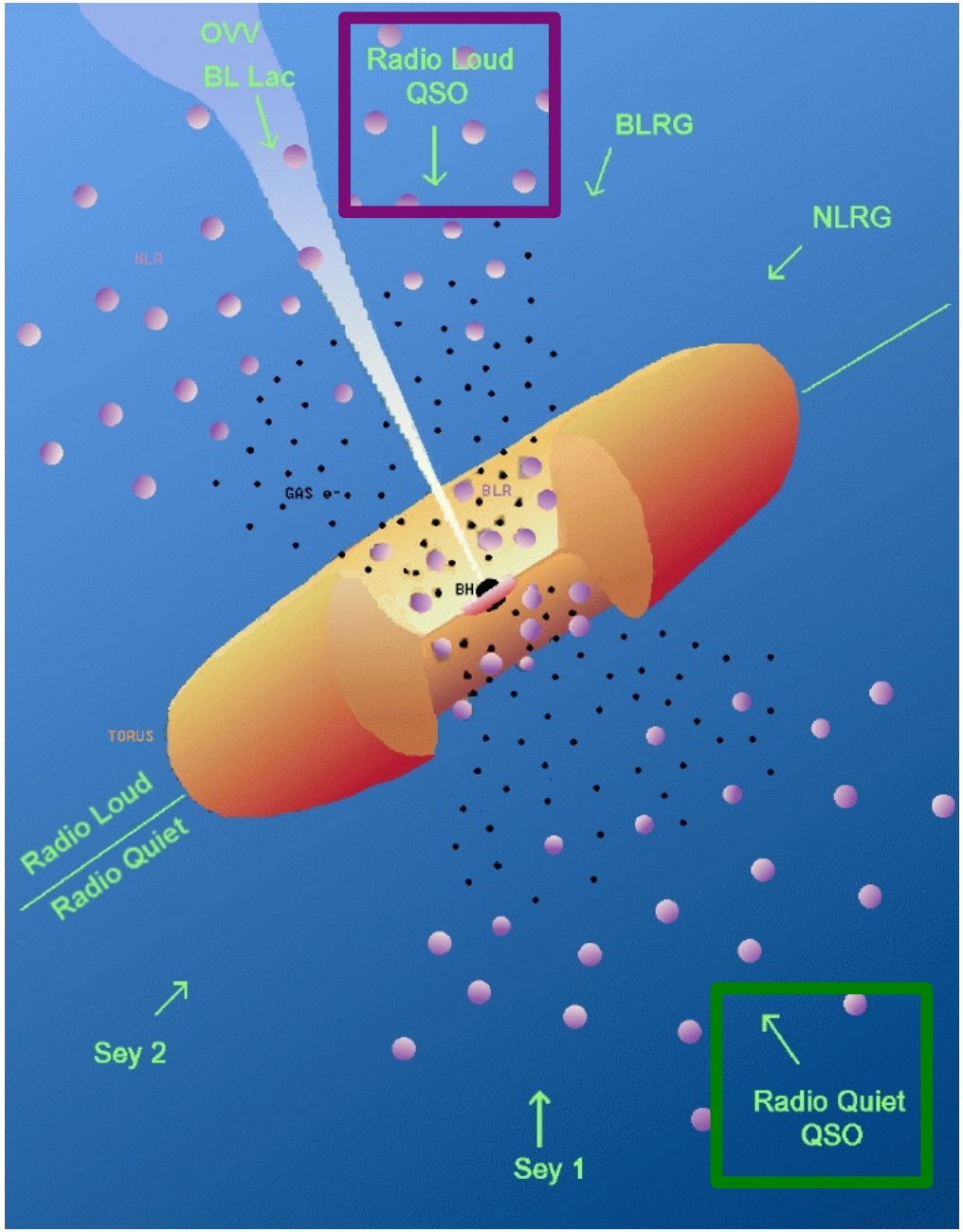
- The black hole, (surely spinning),
- The inflow (almost certainly in the form of a disk),
- The relativistic jet (that derives from the region around the black hole).
- Material far from the BH that absorbs and emits photons.

The difficulty of the problem is that there are interactions between all pairs of elements and determining the character and strength of these interactions.(adapted from R. Blandford)

Standard View of AGN

- Standard 'view' of an AGN in the 'Unified Model' (Urry and Padovani)

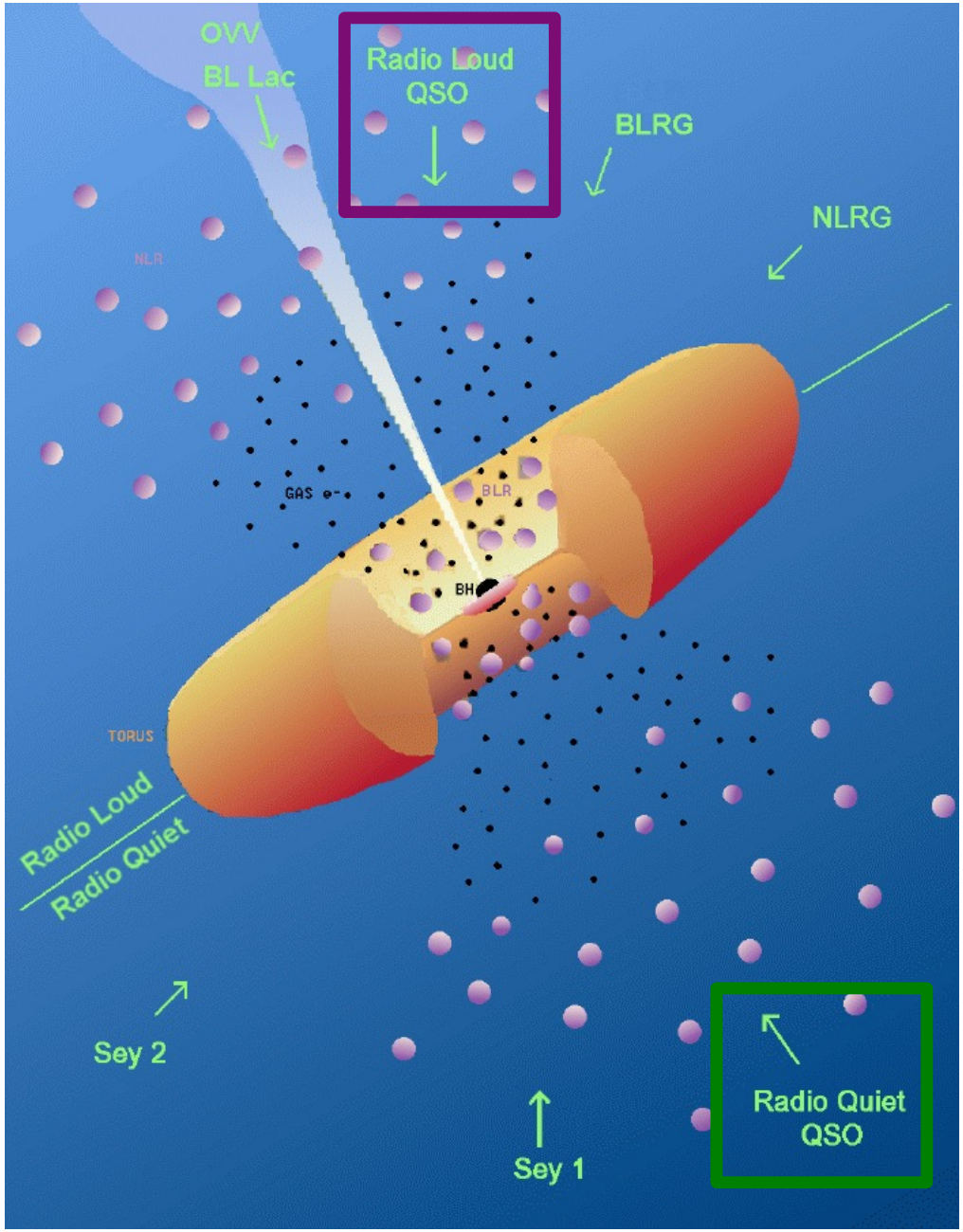
- In this model there are 2 basic classes of AGN
  - radio loud (with jets)
  - radio quiet
- All the other apparent differences are due to orientation effects (e.g. which way we look at the object) (scale is logarithmic)
- *Unified model is 1st order model*- lots of variance in the parameters
  - physical nature of the obscuring torus not understood



Notice all the strange names

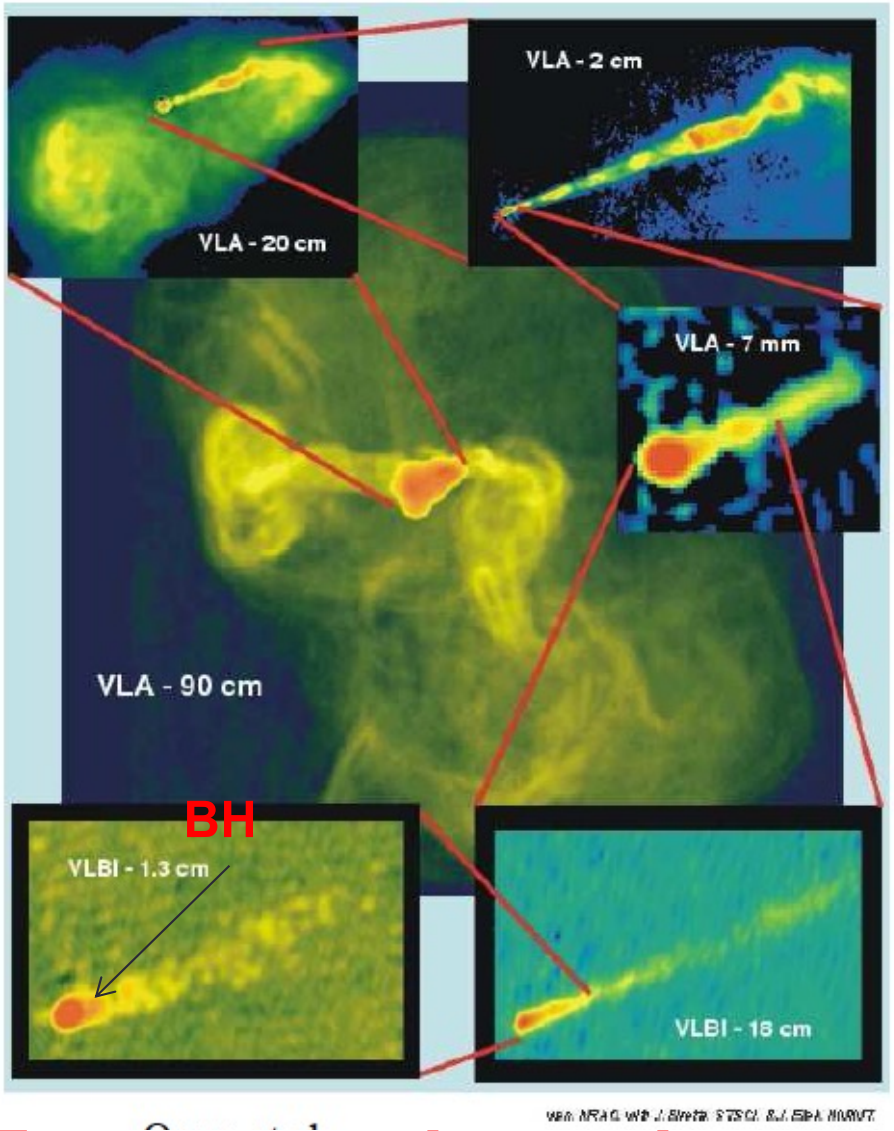
- NLRG- narrow line radio galaxy
- BLRG- broad line radio galaxy
- Seyfert 1 and 2
- OVV and Bl Lac (blazars)

- We will try to NOT use these names and knowing them is NOT necessary.
- However the names carry some information, e.g., whether the object is a radio source or not and the angle of the observer to the 'torus' which blocks optical and UV light from the region of the black hole.



Basic Questions

- How/where/why are jets formed, accelerated and collimated?
- In which form is energy extracted and transported?
- How do they relate to gas inflow/accretion disk?
- How do they propagate?
- How/where/why do they dissipate?
- What is their relation to environment ?
- What fraction of the total luminosity is produced by the jets?
- Are BHs necessary to produce them ?



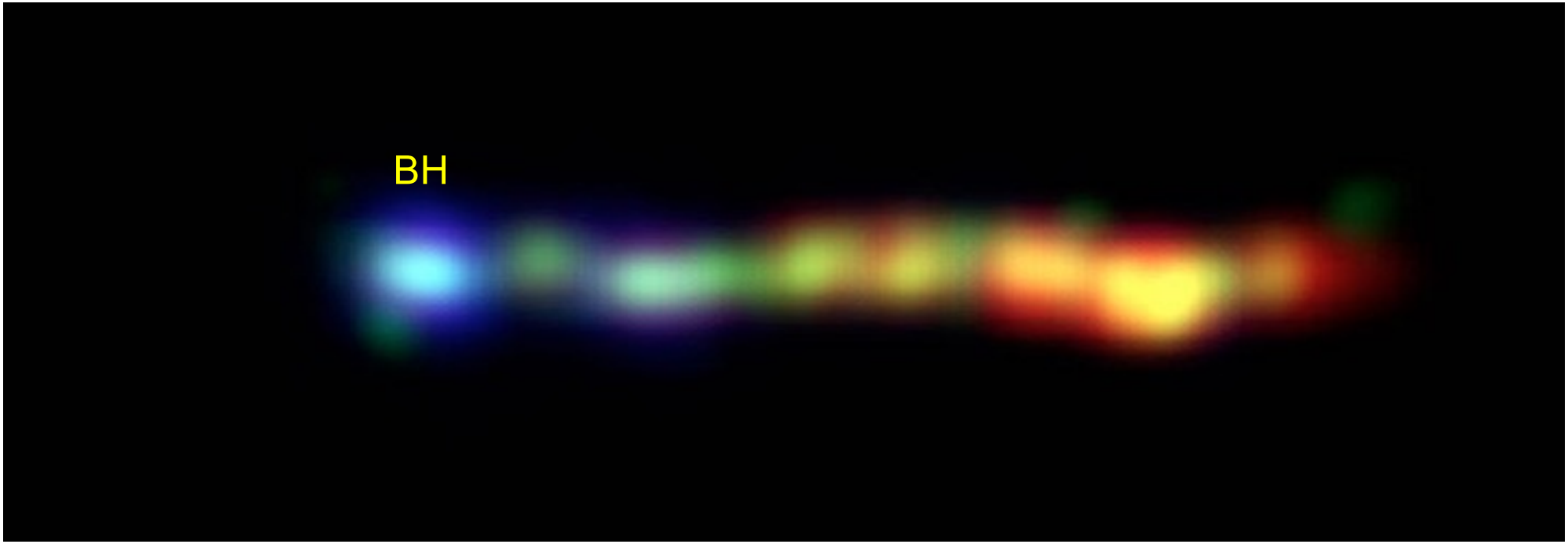
Enormous dynamic range in M87 over 0.2-2×10^5 ly – position angle does not change

I : Relativistic Jets

- Observed properties of jets:
  - Often single-sided (e.g. M87/Virgo-A)
  - Clearest in radio emission, but emit across electromagnetic spectrum (radio to gamma-ray)
  - Often fairly (but not exactly) straight
  - Always connect back to 'core' of galaxy where BH is
  - Some start dim and then brighten to edge…
  - Some start bright and then darken to edge…
  - And some are just weird!
- see rogue's gallery in next slides

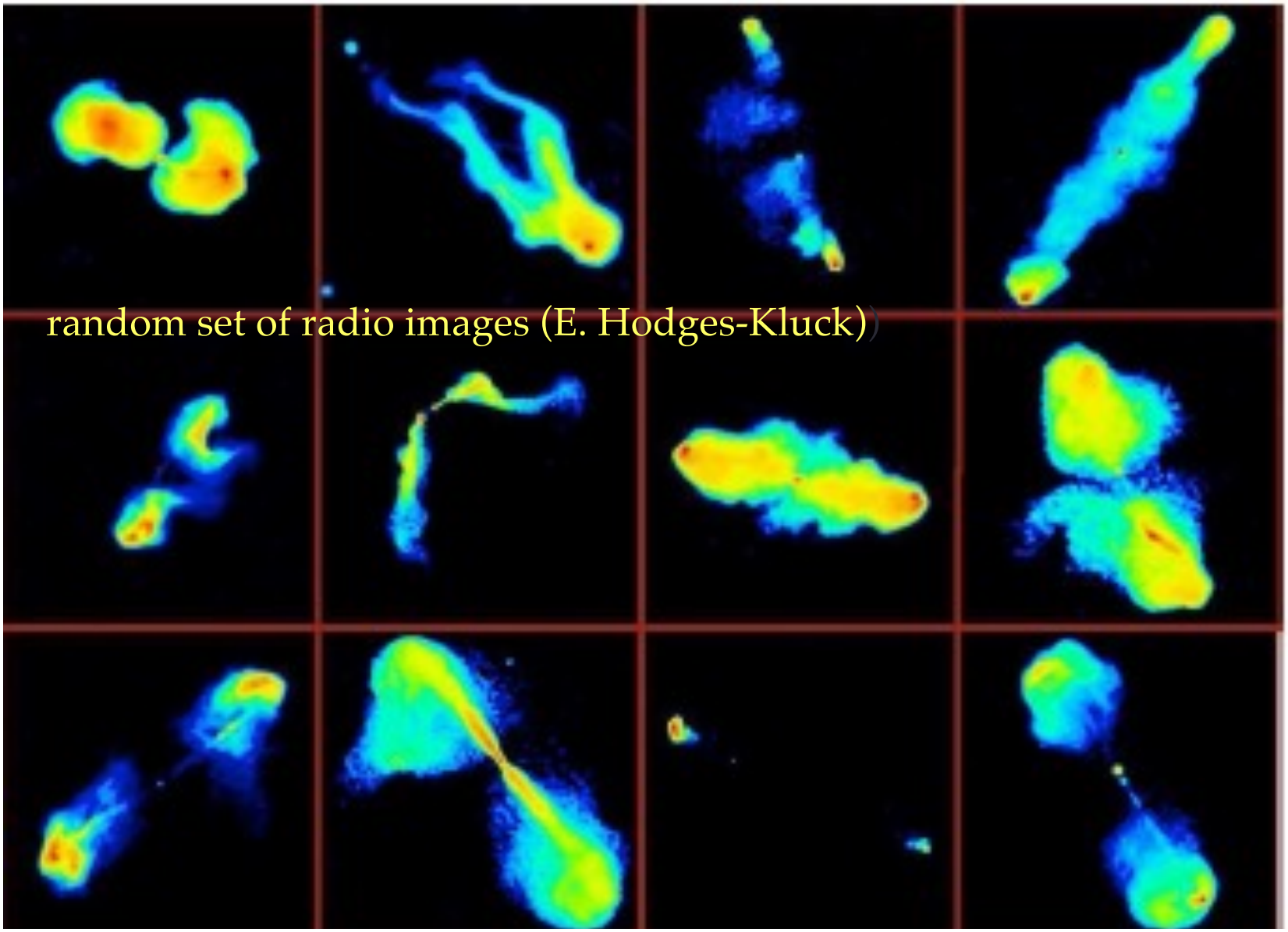
Jets are fantastic places to study particle acceleration and propagation and relativistic phenomena

3C273 jet
X-ray blue ,optical white, radio red
strong variations in spectral shape with position



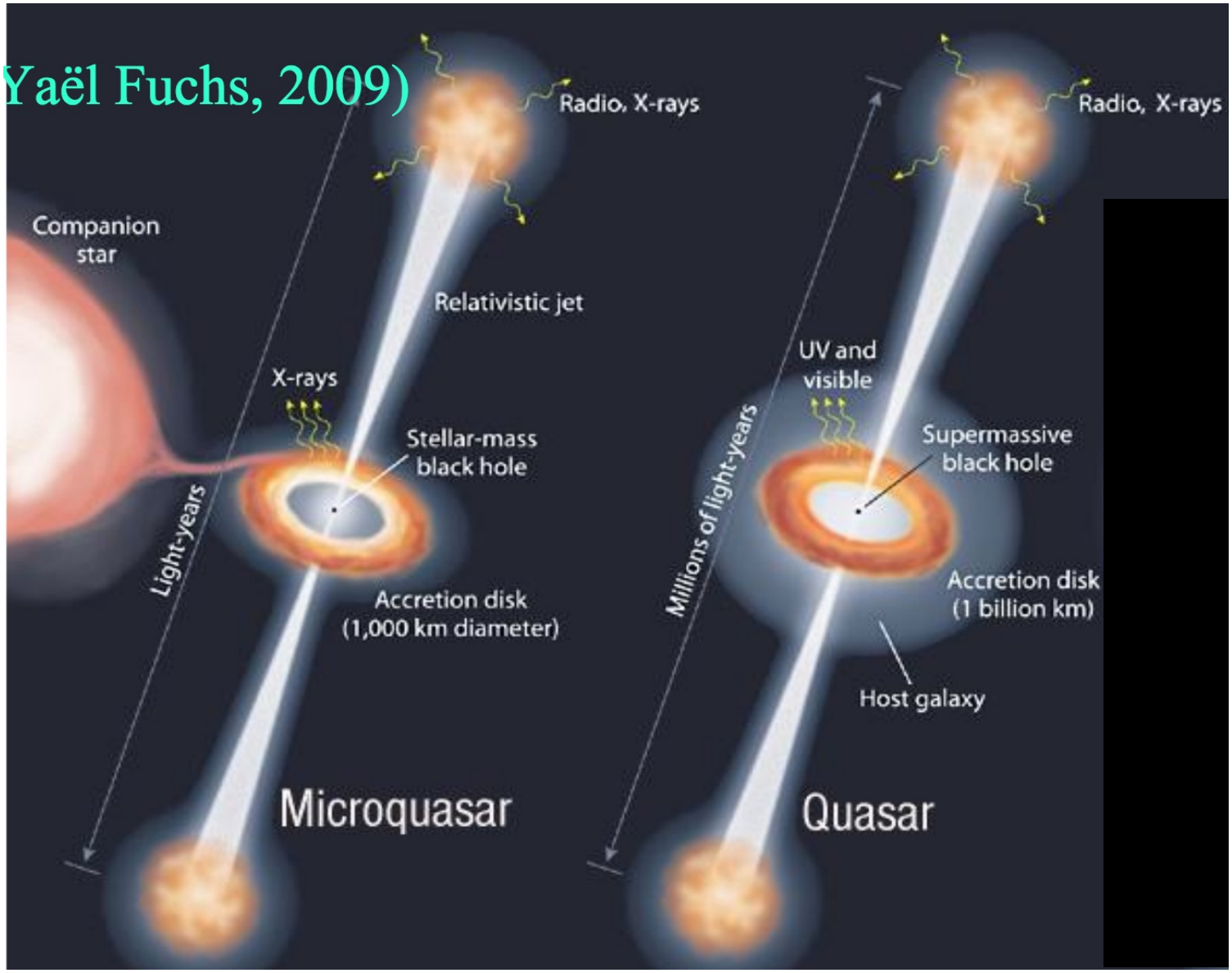
Rogue's Gallery of Radio Images of Jets

- Lots of interesting shapes, sizes



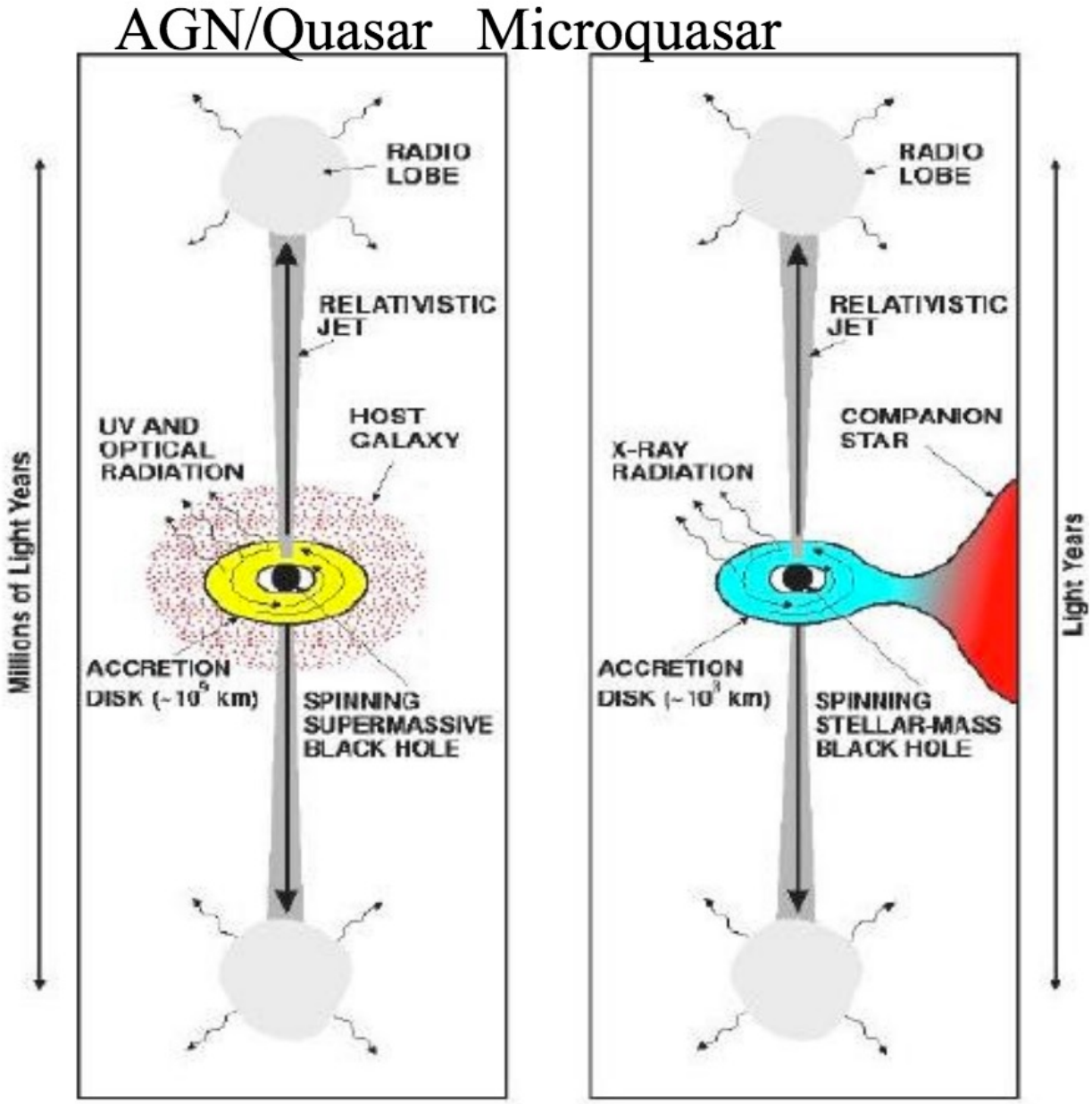
Black Holes with Jets

Can have jets in both stellar mass BH and supermassive BHs



Relativistic Jets

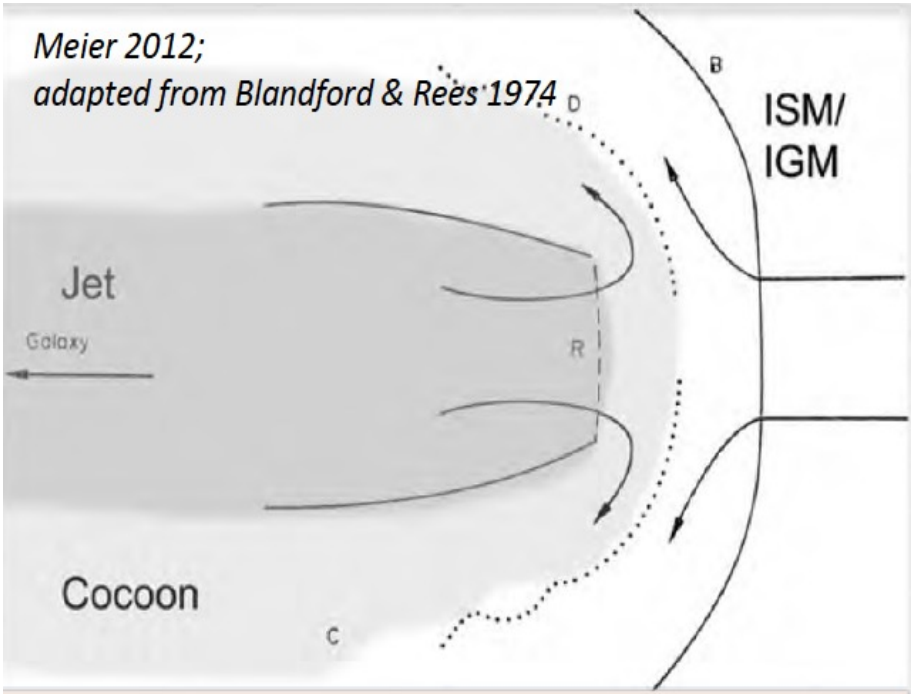
Can occur in stellar mass **and** supermassive black holes but the scales are dramatically different



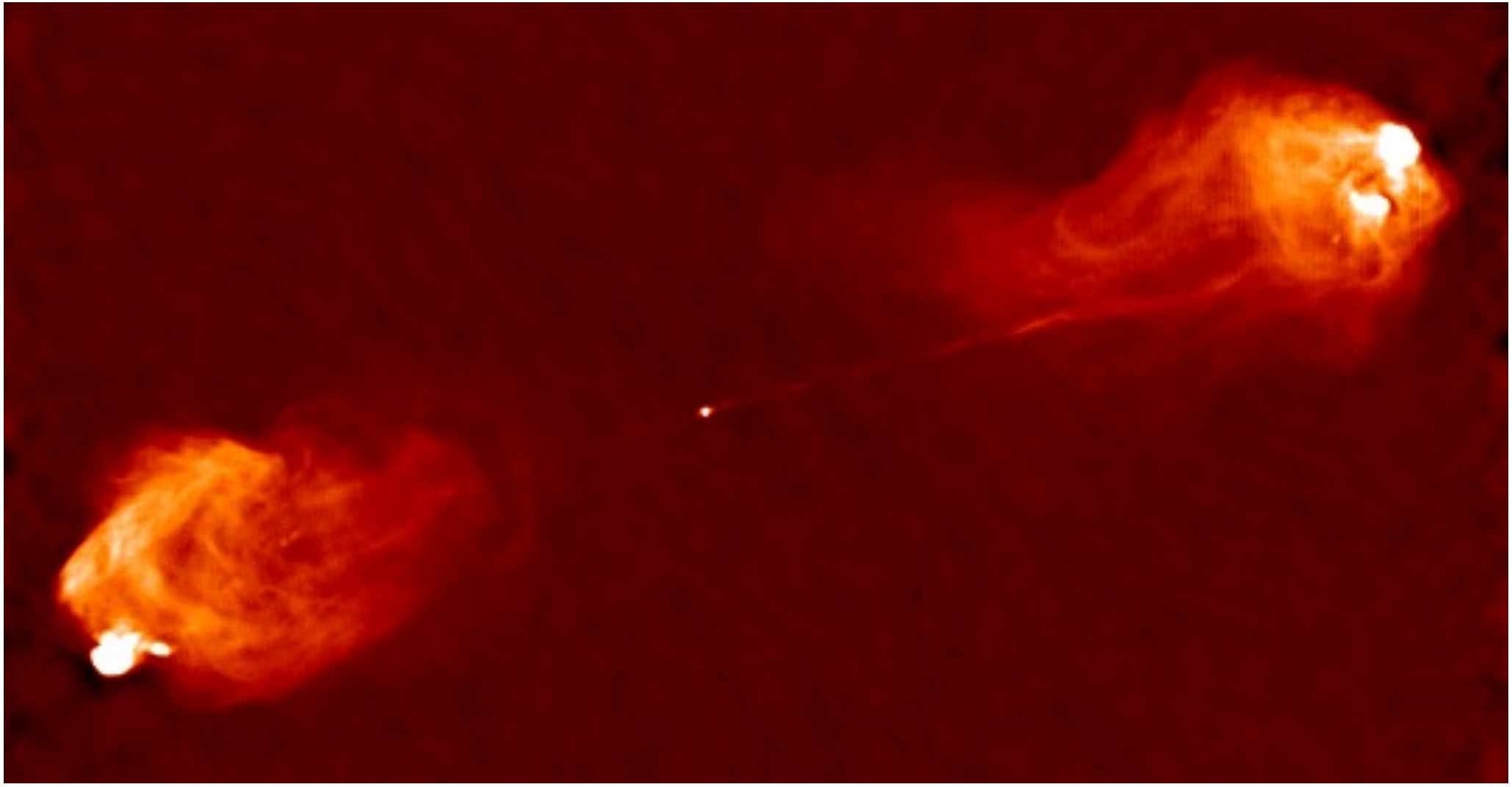
J. Beall

Jets are clearly seen to interact with surrounding matter

- “Hot spots” in radio emission correspond to the point where the jet “splashes” (shocks!) against surrounding matter
- Jets can bend/twist if they hit interstellar gas clouds
  - Can see shock waves and other disturbances in surrounding matter (often best seen in X-rays)



Jet drills its way through the dense ISM filling a cavity with hot plasma. This is



Fundamental Questions

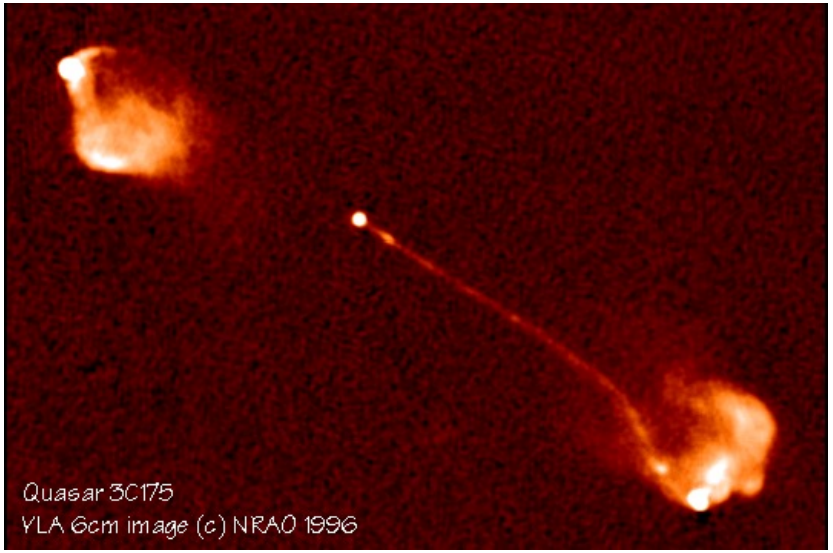
- What is the jet launching process (what controls the on-and-off switch) and how is that related to the central object
- What is the jet emission mechanism (what mechanisms convert the jet power into X/γ-ray radiation at high efficiency)
- What is the jet composed of and how much energy does it have
- How does relativity affect things

What do we see with high resolution?

- jets are knotty And the knots move … very fast!
- Often appear to be traveling at v>c !
  - Conflict with special relativity?
  - No! In fact, this is a dramatic *confirmation* of special relativity!

II : Relativistic effects

- One sidedness of jets



- Looks strange!
- Why would such powerful jets be created asymmetrically?
- In fact, this is **illusion** created by relativistic beaming
- Approaching jets appears much brighter than receding one
- Correcting for this, jets may be symmetric

II : Relativistic beaming

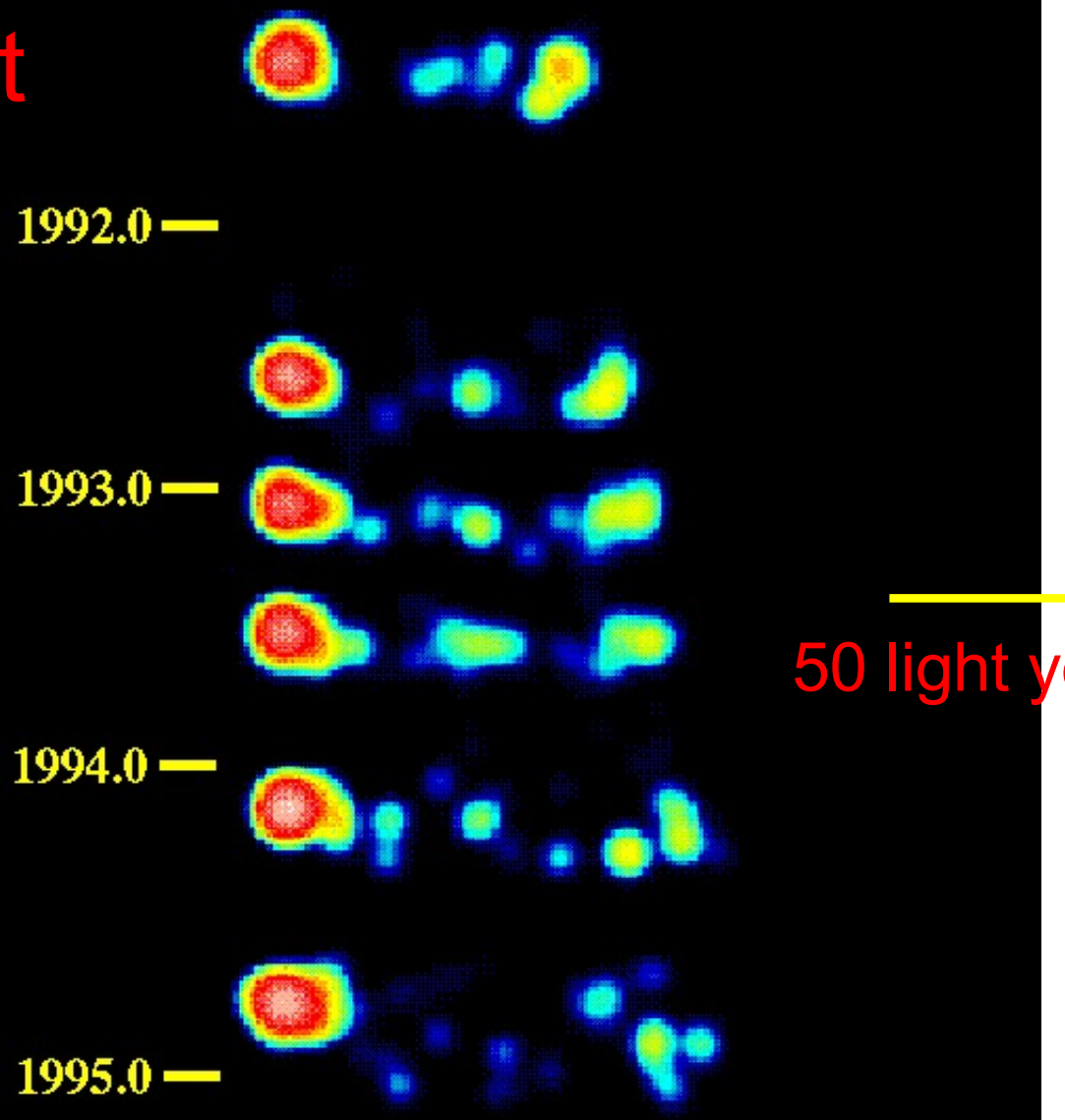
- There are 3 terms when the jet is coming toward us
  - the energy of the photons is blue shifted increasing their apparent energy
  - aberration proportional to γ (rain drops)
  - time dilation γ

  - All these work together to make the jet seem much more energetic and one sided

Superluminal Motion

3C 279 inner jet

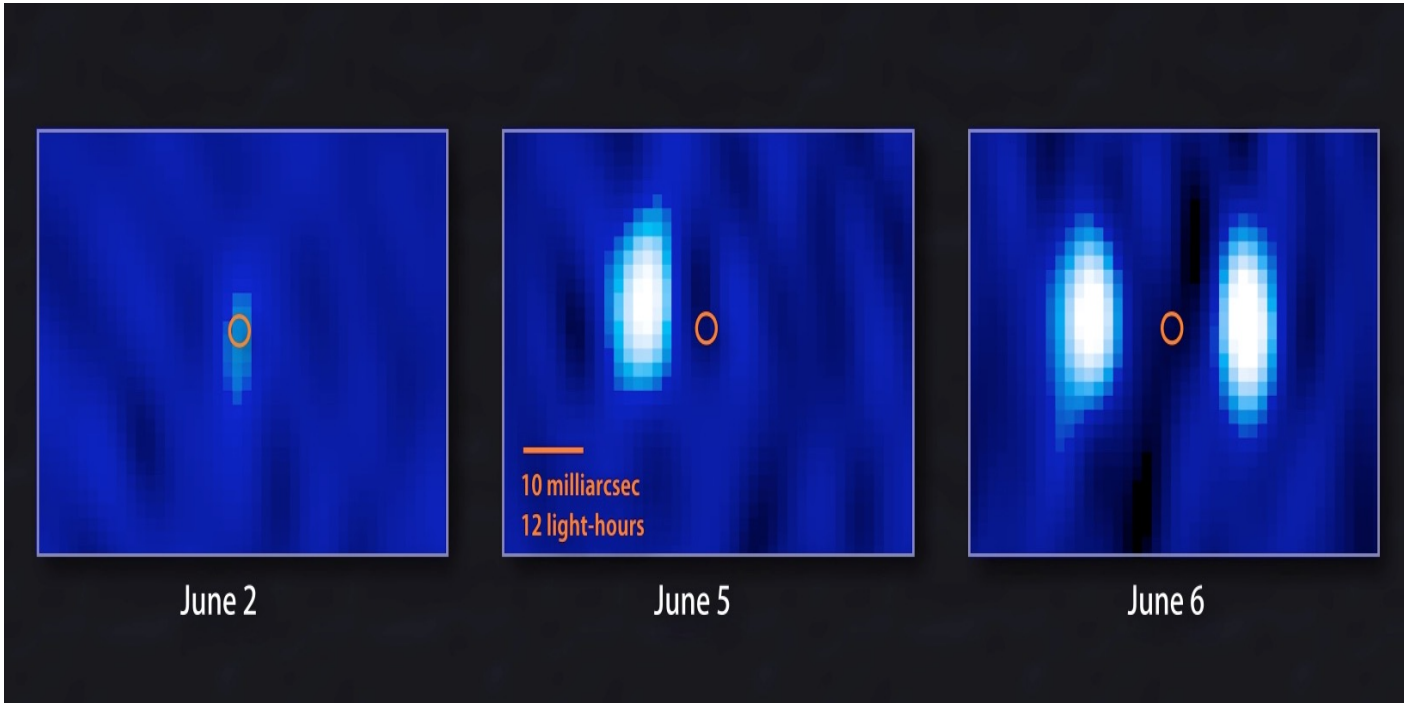
Ch*anging*
with time

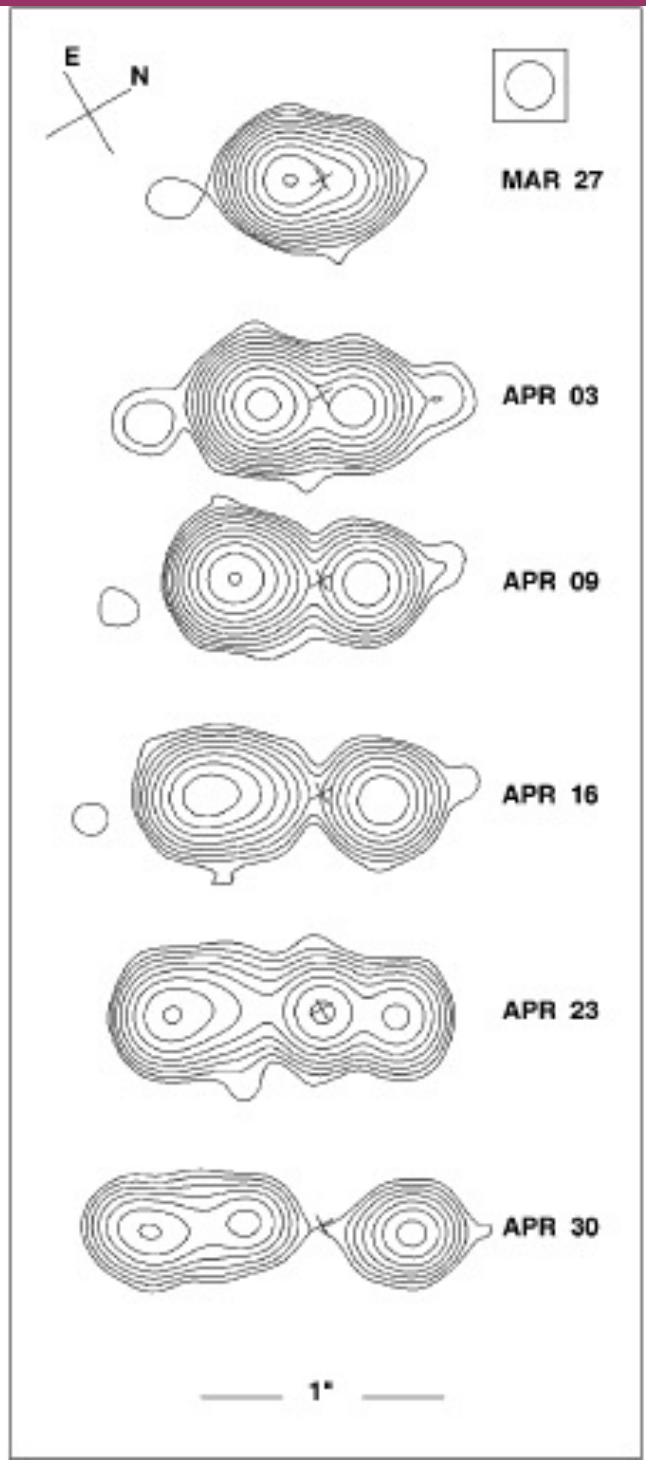


Galactic Black Holes

- Radio images of 2 galactic black holes with jets
- These objects, called microquasars, show highly variable jets which exhibit 'superluminal' expansion in their radio images
- The *apparent* velocities range from 15-1.7c

see Mirabel and Rodriguez Annu. Rev. Astron. Astrophys. 1999. 37:409–43 for more information



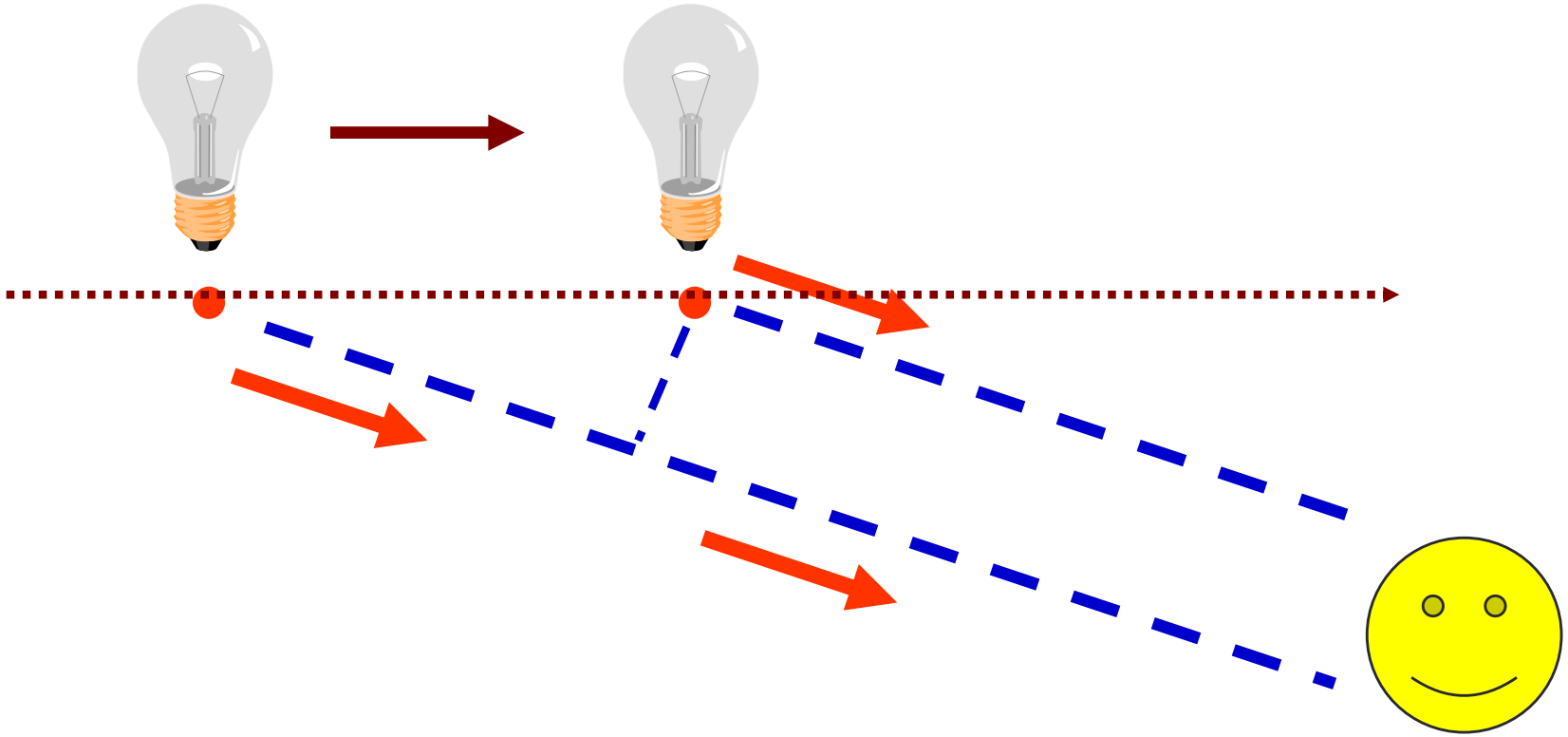


How Can Something Appear to Move Faster Than Light?? (Superluminally)

- It's a consequence of geometry and special relativity
- *Nothing is really moving greater than the speed of light*
- In order for this effect to be visible
  - need small angle to line of sight (e.g. jet pointing more or less towards us)
  - true velocity close to **c**

Superluminal motion

assume the source is the illustrated light bulb which is moving to the right, and the smiley face is the observer

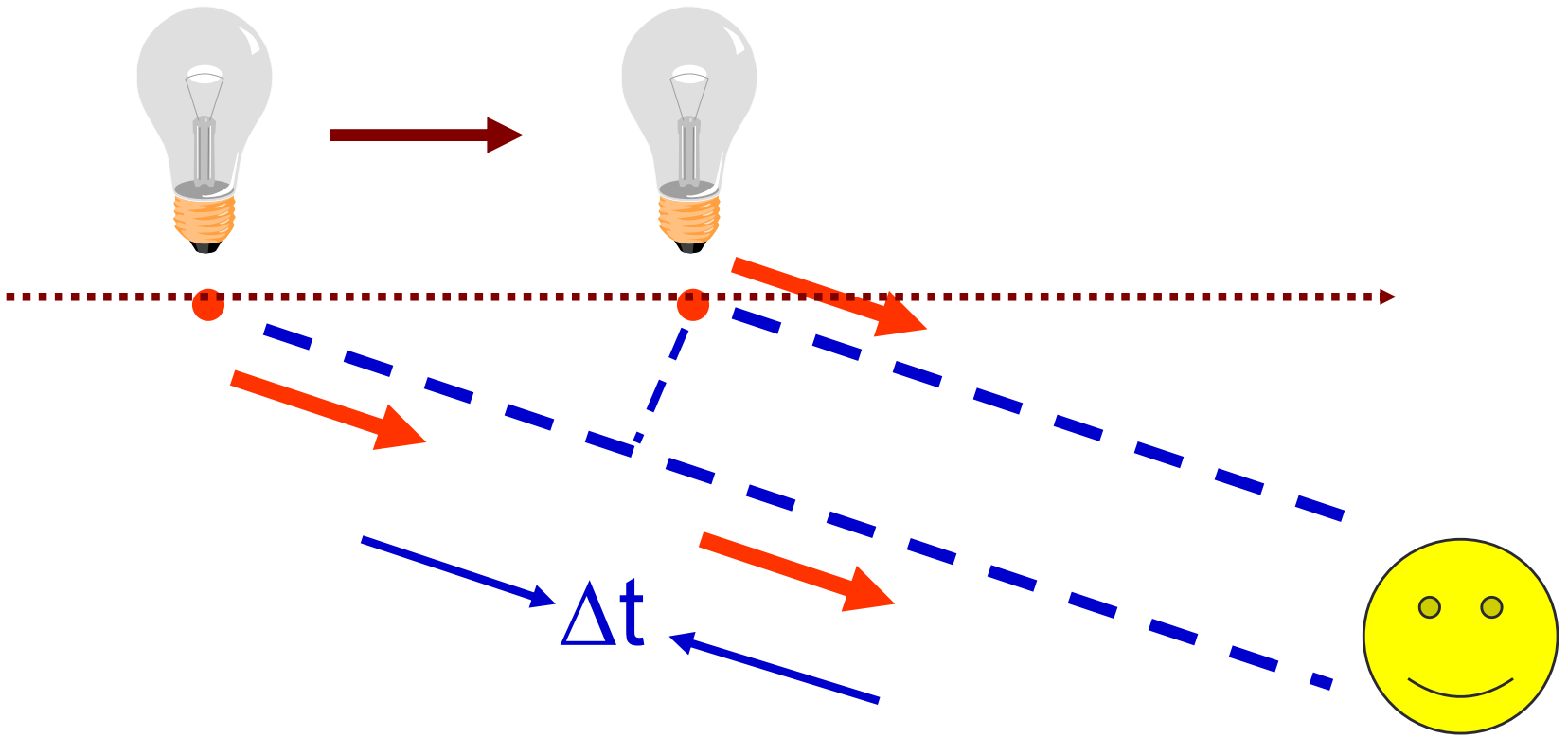


From C.M. Urry

the arrows show the light rays coming from the source to us

Superluminal motion

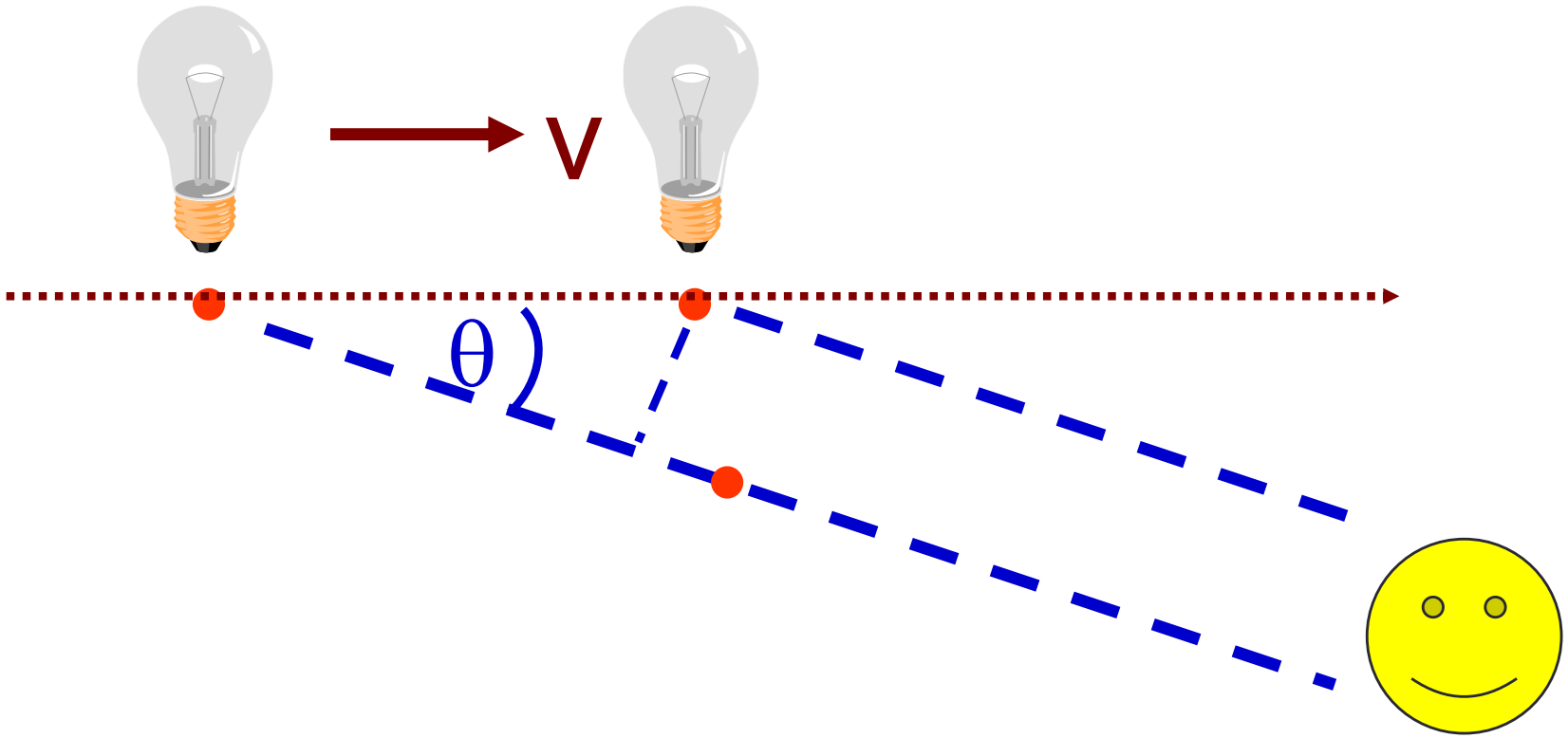
assume the source is the illustrated light bulb which is moving to the right, and the smiley face is the observer



From C.M. Urry

the arrows show the light rays coming from the source to us and Δt is the time between 2 bursts of light

$$\text{observed speed } v_{obs} = \frac{v \sin\theta}{(1 - \boldsymbol{v/c} \cos\theta)}$$



This is called Doppler beaming- if the angle is small and v/c is large can get v_{obs}>c (v is the true velocity of the object)

Doppler beaming effects

Appearances:

- Events happen faster: $\Delta t_{obs} = \delta^{-1} \Delta t_{em}$
- Radiation is blue-shifted: $\nu_{em} = \delta \nu_{em}$
- Superluminal velocity: $v_{obs} = v \sin\theta/(1-\beta\cos\theta)$

  $= v \gamma\delta \sin\theta$
- Intensity is much higher: $I_{obs} = \delta^3 I_{em}$
- From C.M. Urry $\delta = [\gamma (1 - \beta \cos\theta)]^{-1}$

  where $\gamma = (1- \beta^2)^{-1/2}$ and $\beta = v/c$

Jets are Nature's Demonstration of Special Relativity

- Superluminal Jets are pointing at us!
  - Many more must point elsewhere
  - these are "radio galaxies"
- Outflow speeds v~c

Jets are Nature's Demonstration of Special Relativity

- Superluminal Jets are pointing at us!
  - The energy of the photons is boosted by a large factor (δ)- this makes such jets gamma-ray sources
  - Objects with jets pointing at us are called Blazars

Relativistic Jets

High luminosity, superluminal motion, rapid variability and high γ-ray luminosity

- The effects of beaming are **dominant** - changing both the observed energetics of the system and the observed energy of the photons emitted
- $L_{obs}=4\pi\delta^4 L$; $\delta = \Gamma(1-\beta\cos\theta)^{-1}$

  $\Gamma=\mathrm{sqrt}(1-\beta^2)^{-1}$ $\beta=v/c$

the spectrum depends on the slope of the spectrum

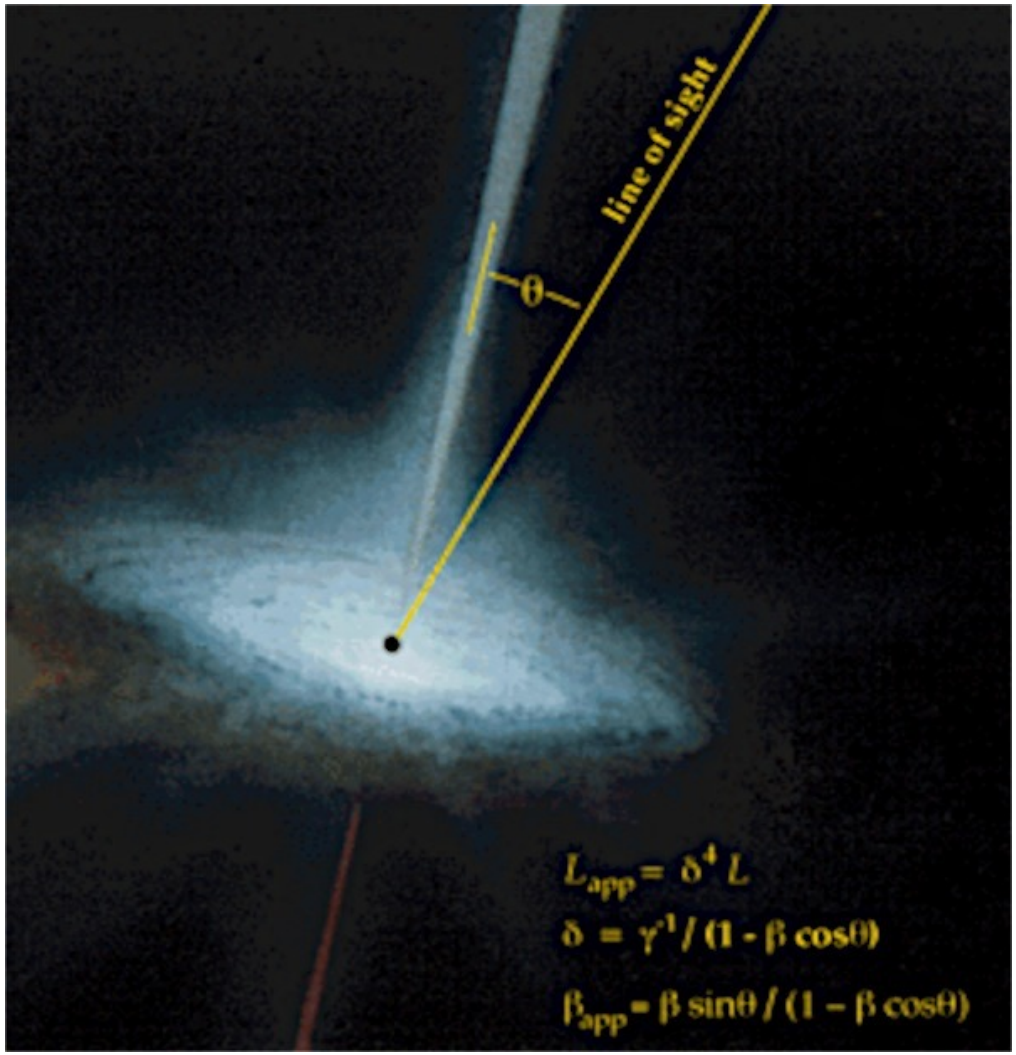
($F_\nu=\nu^{-\alpha}$) $F_0=F_{emit}\delta^{3+\alpha}$

typical opening angles of the jets

$\theta\sim 1/\Gamma$

Faster than light motion

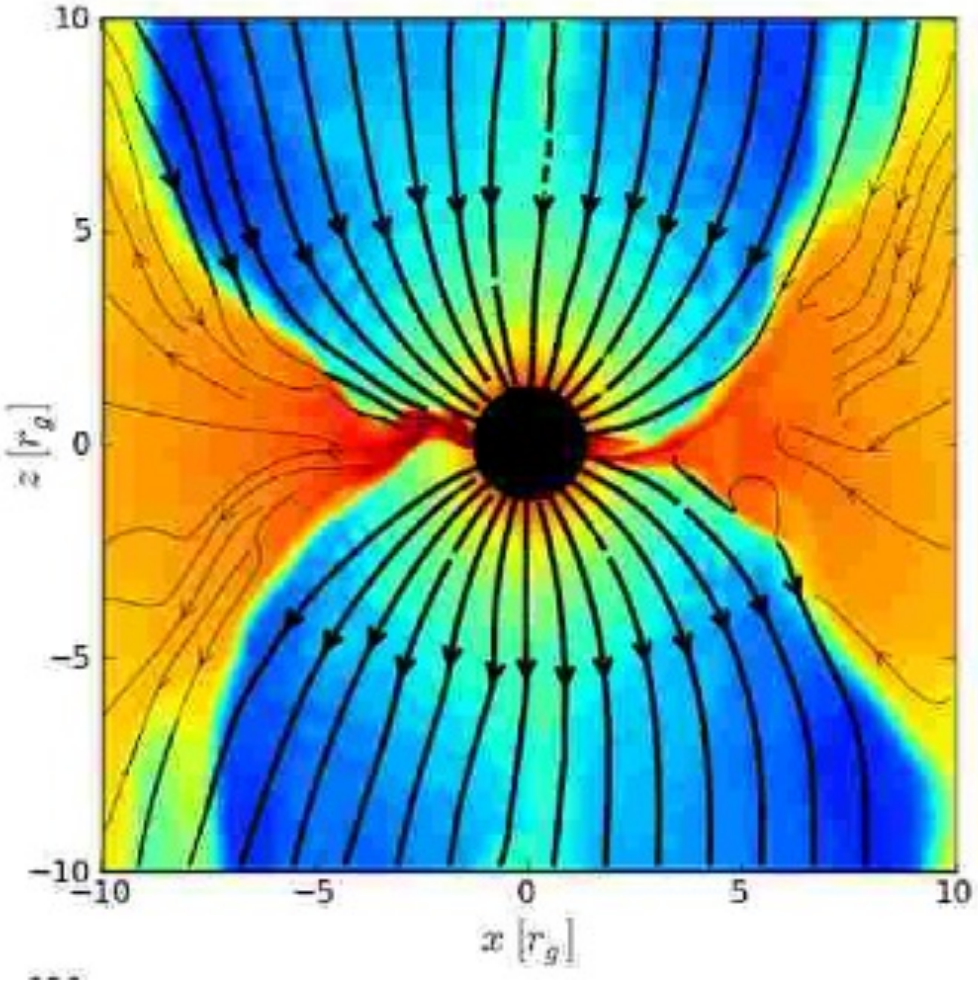
$\beta_{apparent}=(\beta\sin\theta)/(1-\beta\cos\theta)$



III : Formation of Jets

- Jets are accelerated and collimated in the immediate environment of the black hole
- Currently favored theoretical model…
  - Central spinning black hole-jet powered by the magnetic extraction of the black hole's spin energy.
  - Threaded by magnetic field generated by accretion disk
  - Then… black hole rotation twists fields into "coils" which expand away from black hole
  - Energy comes from black hole rotation
  - Example of a Penrose Process (magnetic form attributed to Blandford & Znajek 1977)
- Explains why some AGN have no/weak jets
  - need both the black hole spin and the magnetic field!
  - If you lack either ingredient, no jets.

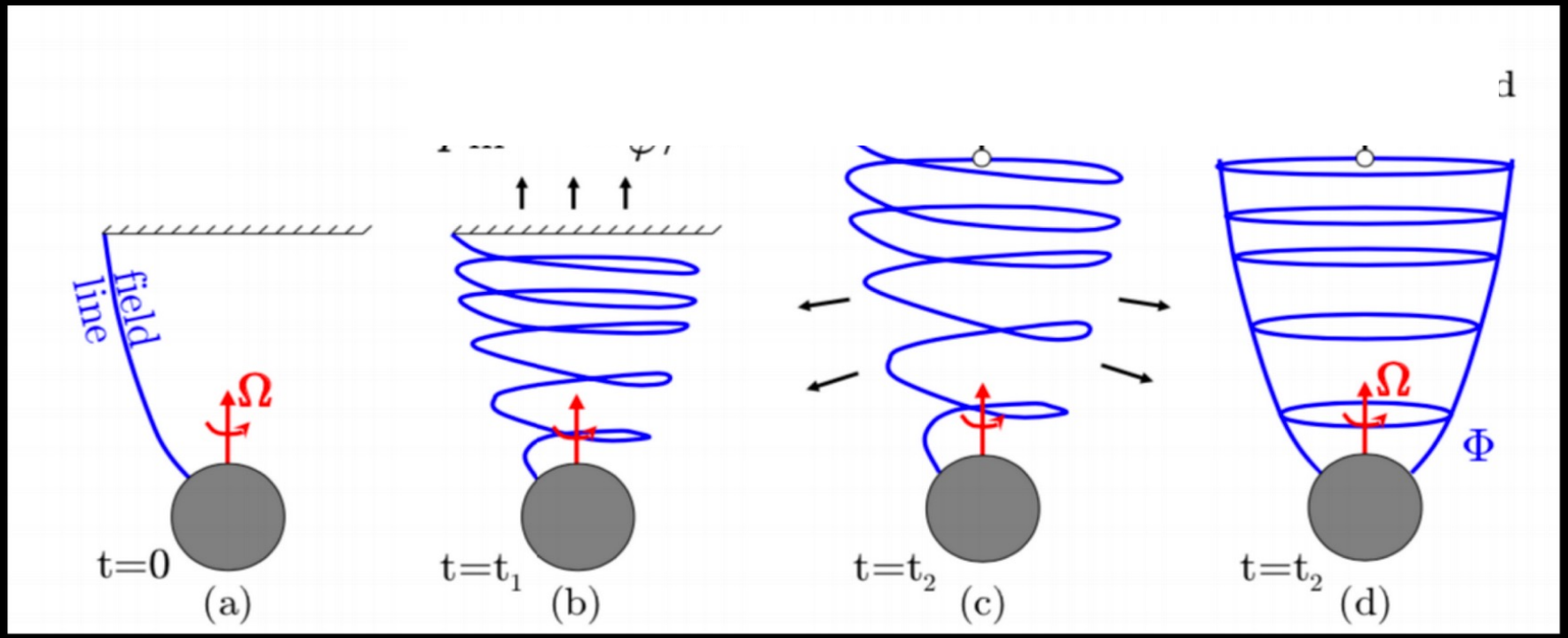
MAGNETIC FIELD STRUCTURE OF A JET



Maybe How it Works

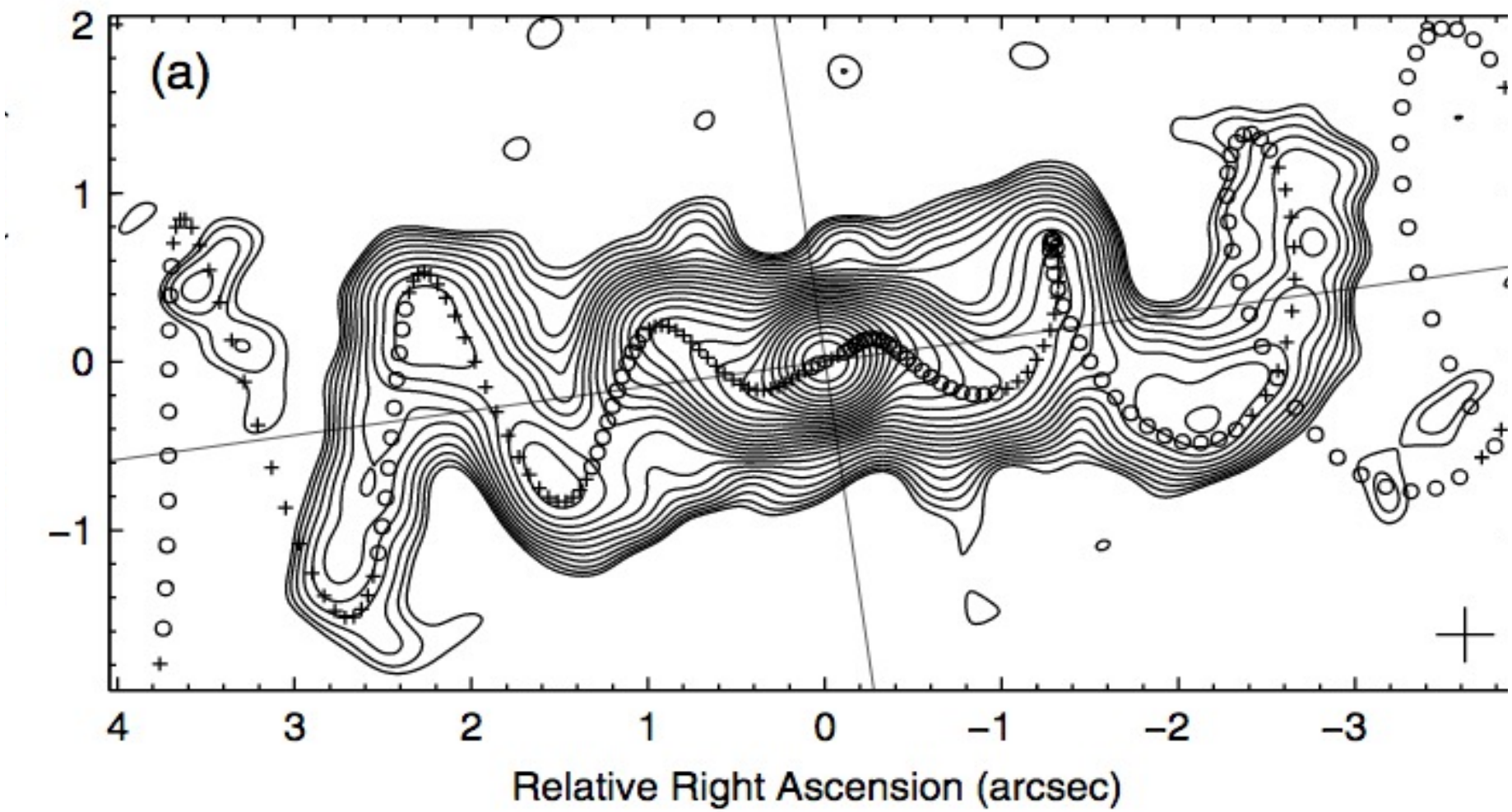
Powering relativistic jets

Credit: Tchekhovskoy

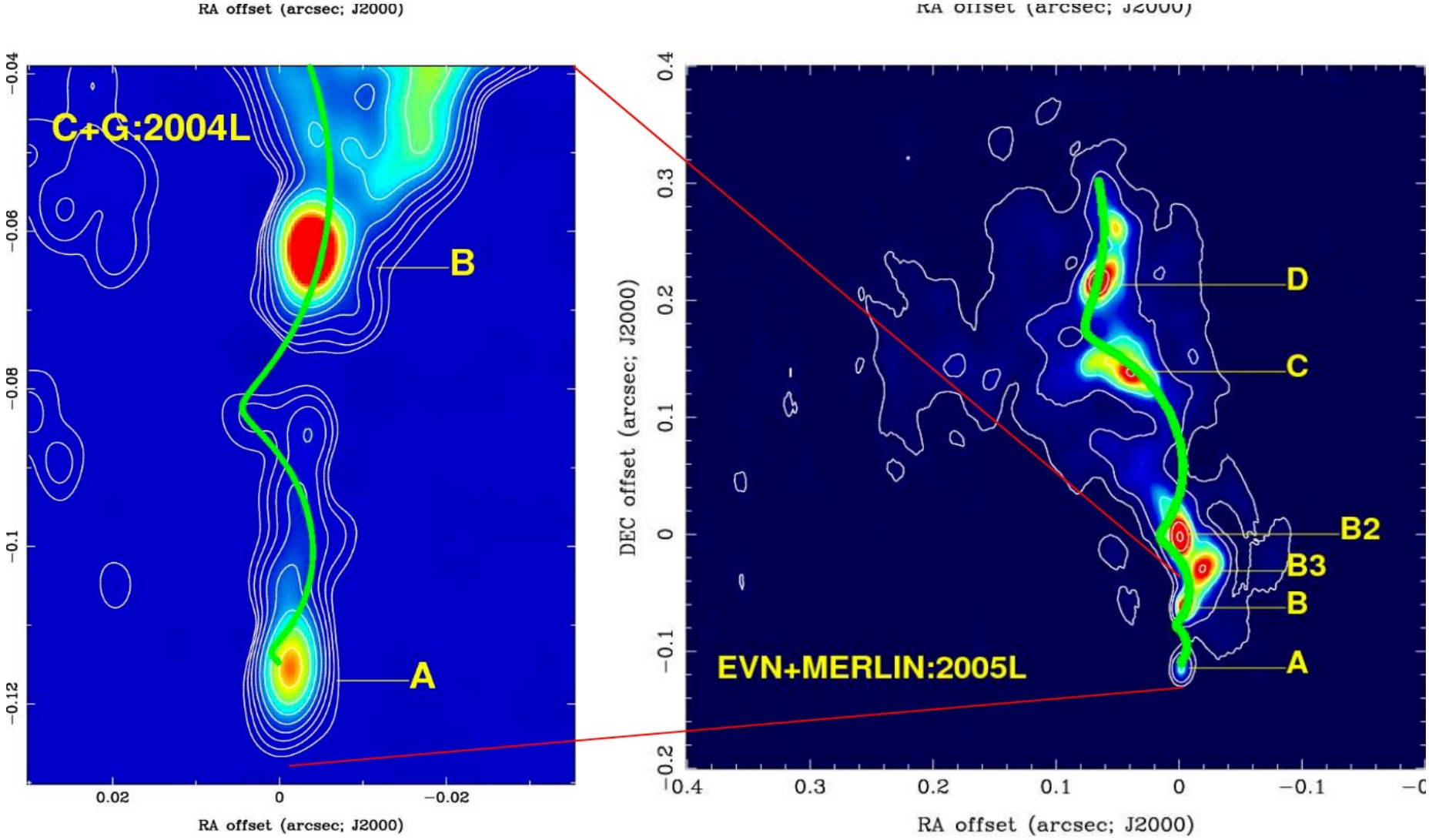


BZ '77 (slow rotation)

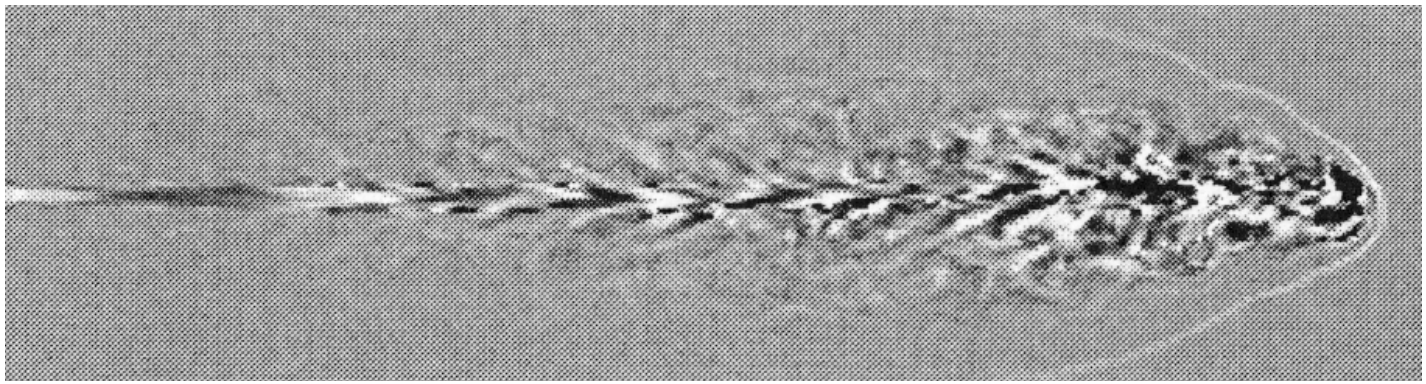
Radio Image of Helical Jet in a Galactic Black Hole



What do the Data Look Like- Radio Images for a Quasar

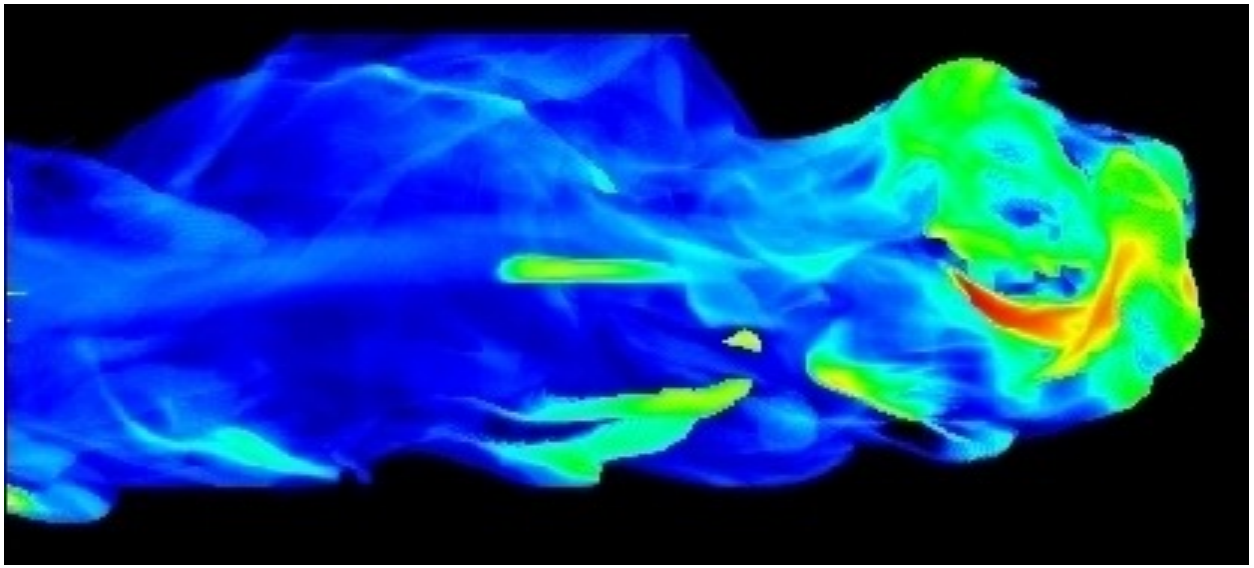


Numerical Models

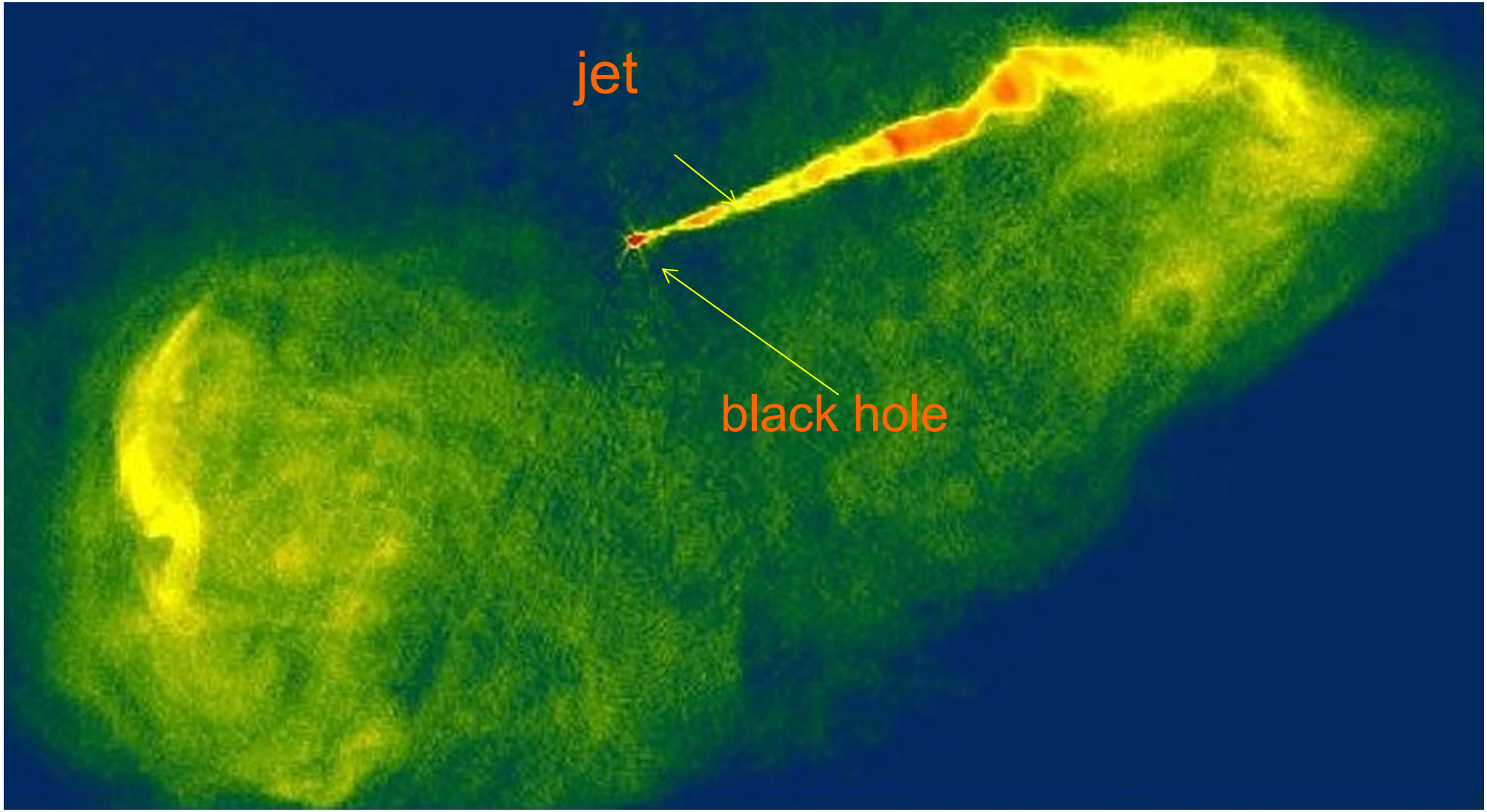


Numerical model

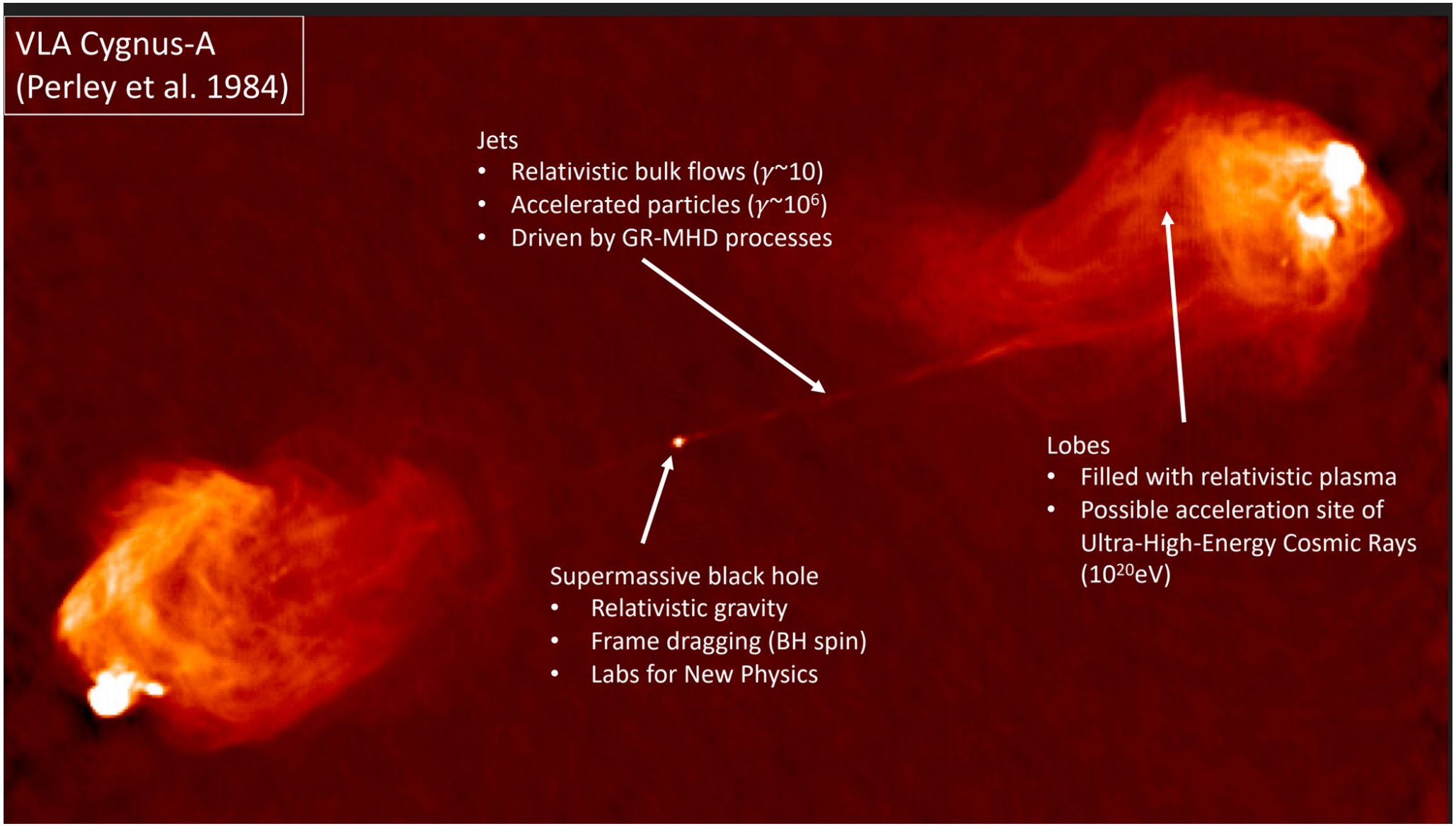
Radio image

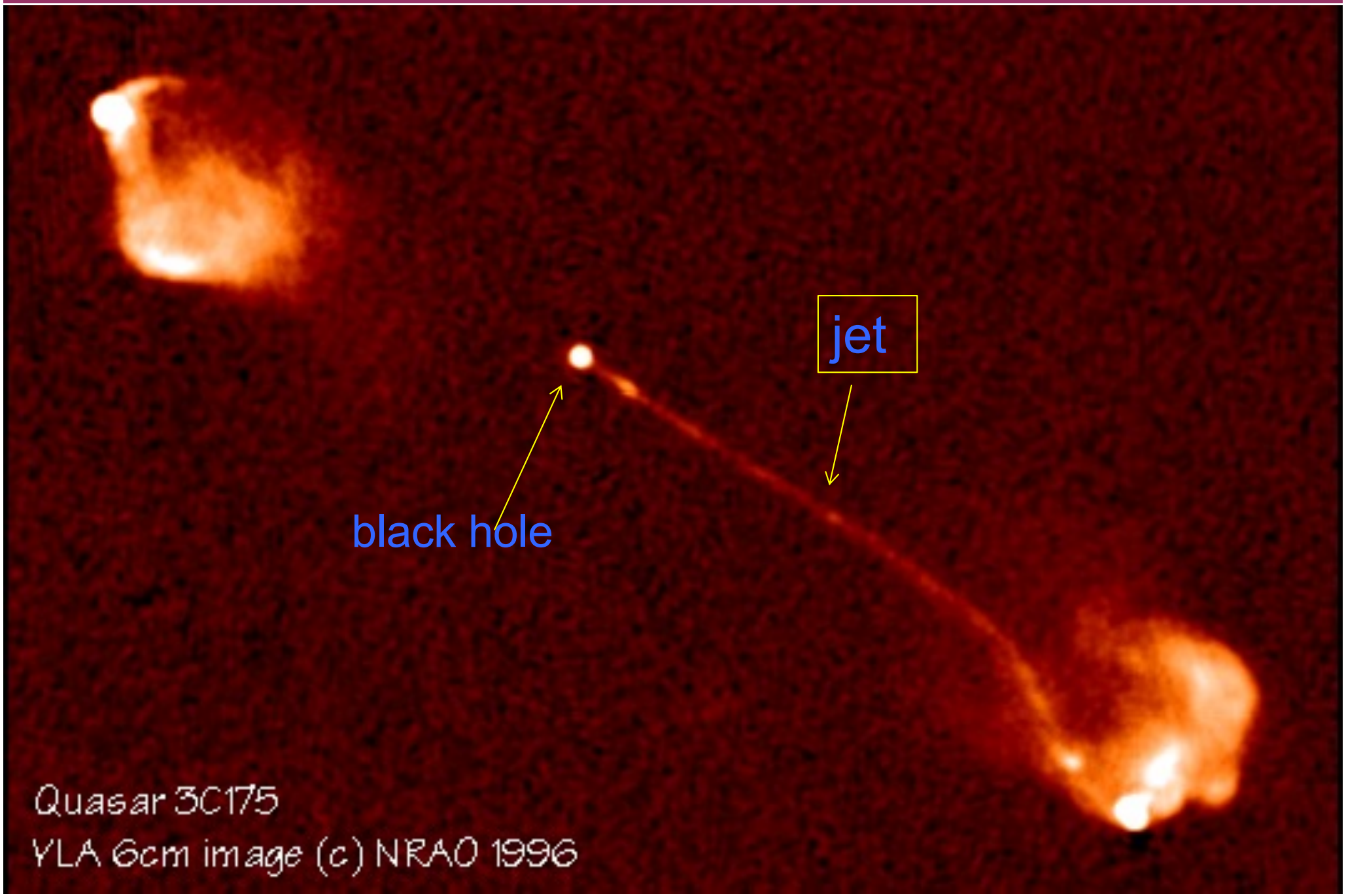


M87/Virgo A (3C274)

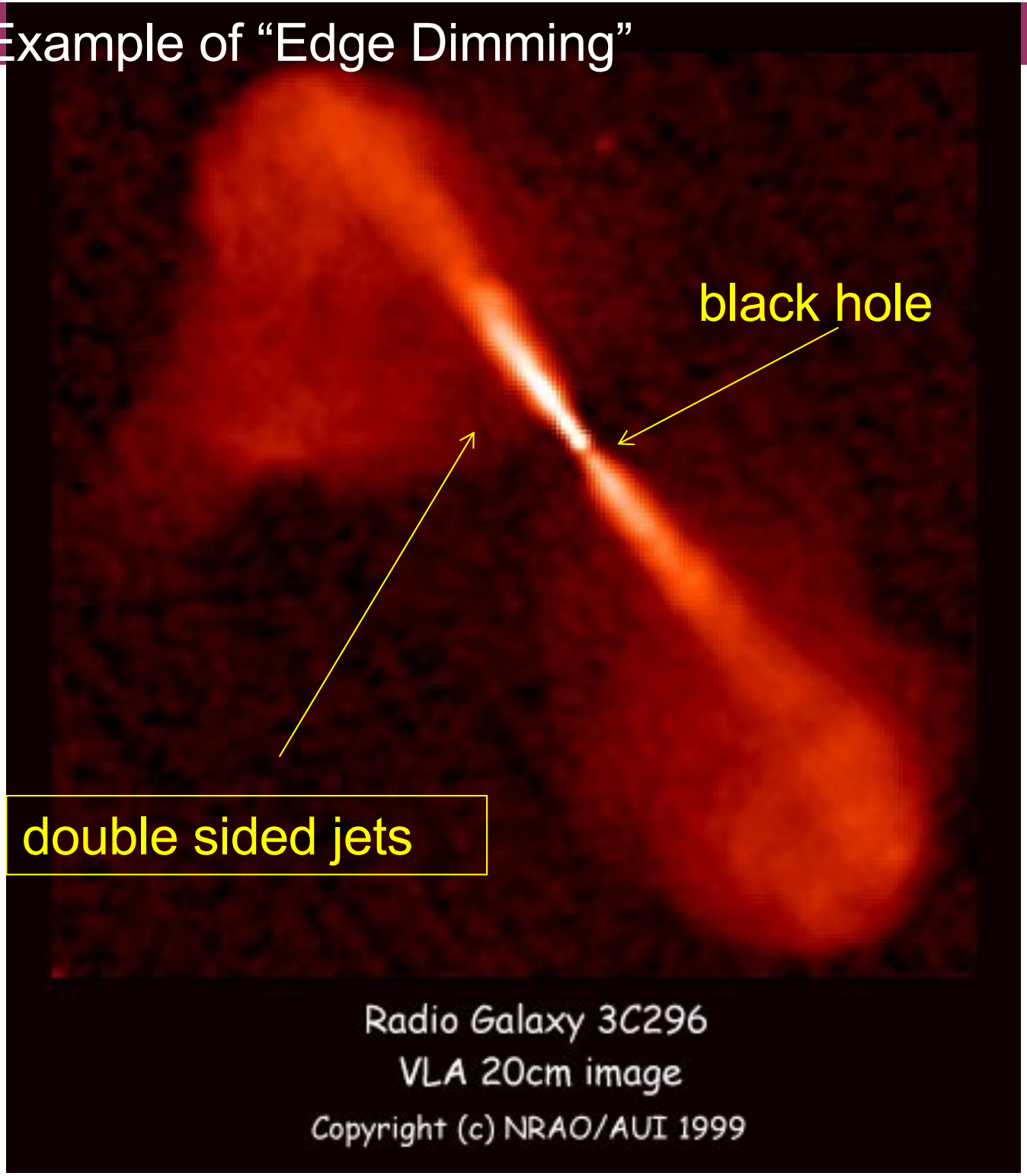


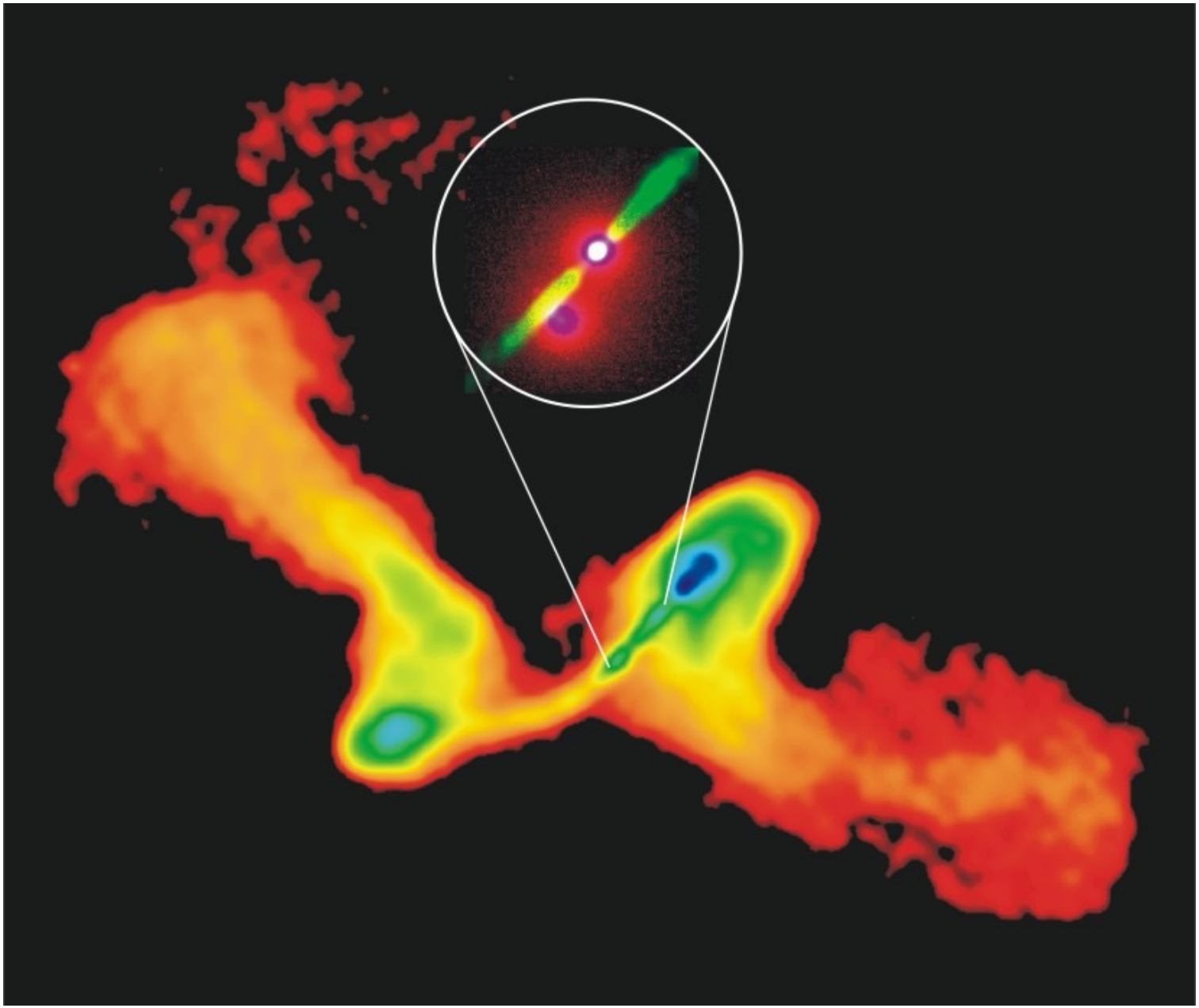
Cygnus A


VLA Cygnus-A
(Perley et al. 1984)
Jets
• Relativistic bulk flows (γ~10)
• Accelerated particles (γ~10^6)
• Driven by GR-MHD processes
Supermassive black hole
• Relativistic gravity
• Frame dragging (BH spin)
• Labs for New Physics
Lobes
• Filled with relativistic plasma
• Possible acceleration site of Ultra-High-Energy Cosmic Rays (10^{20}eV)

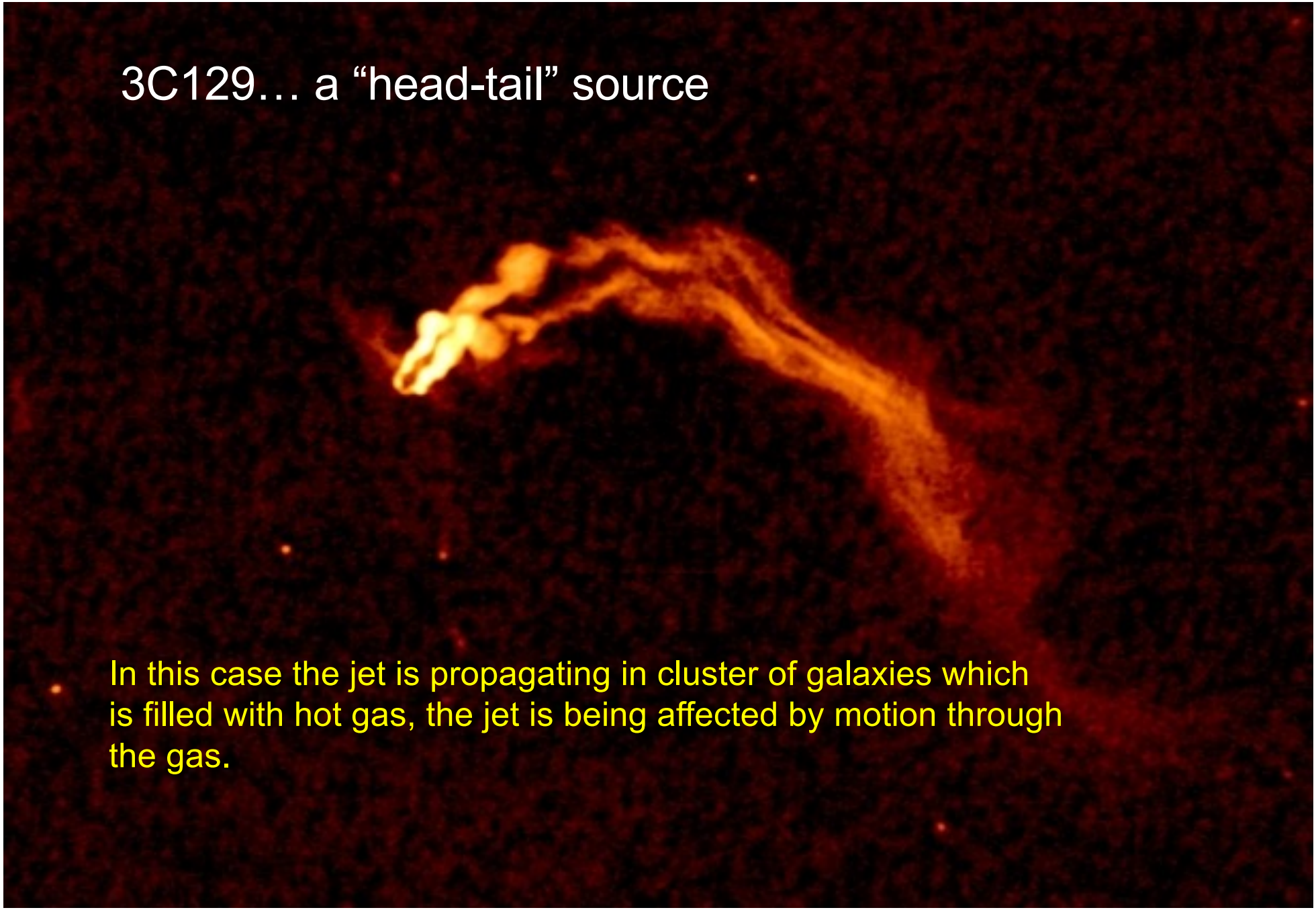

jet
black hole
Quasar 3C175
VLA 6cm image (c) NRAO 1996

3C296 Example of “Edge Dimming”

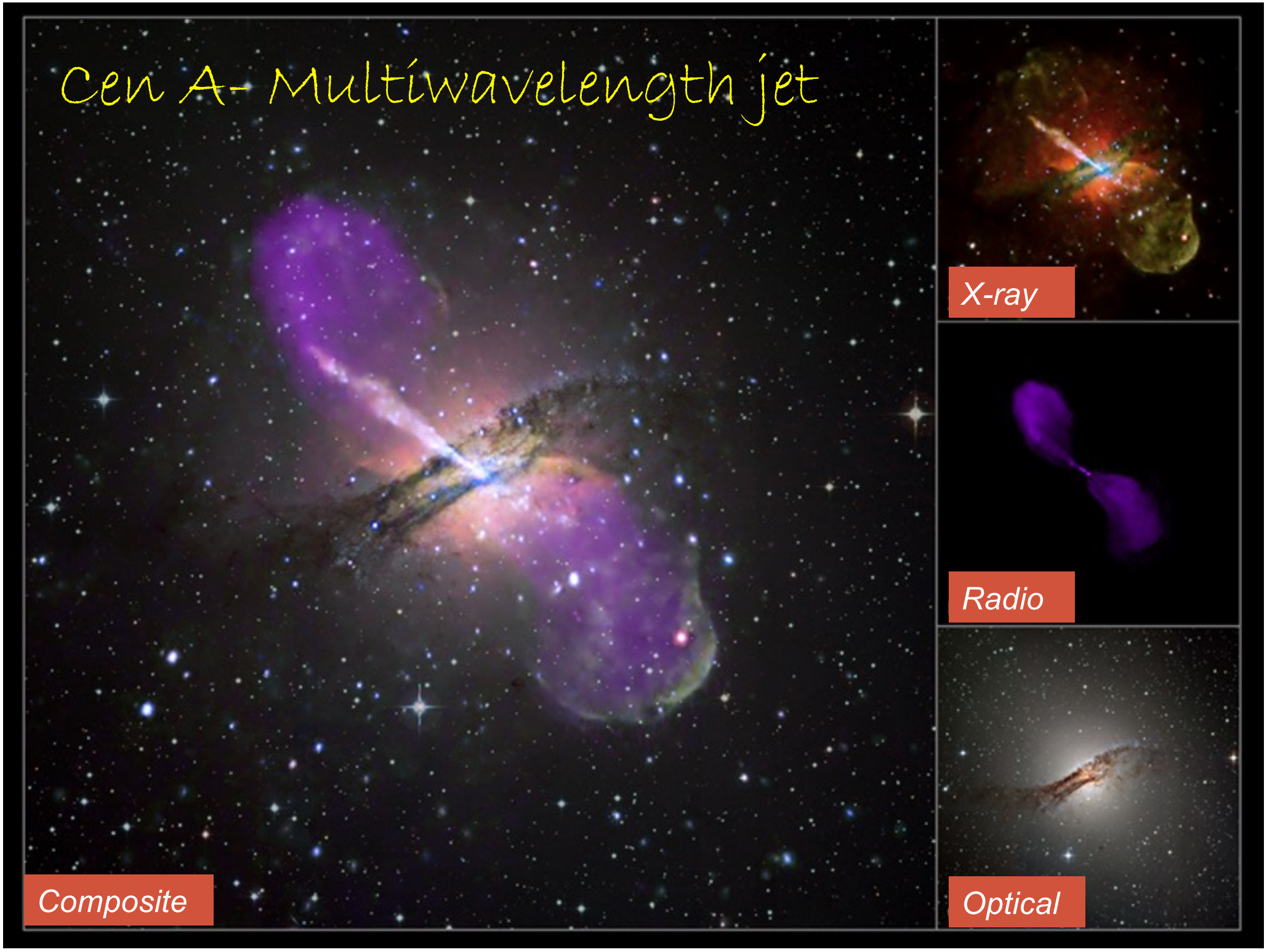


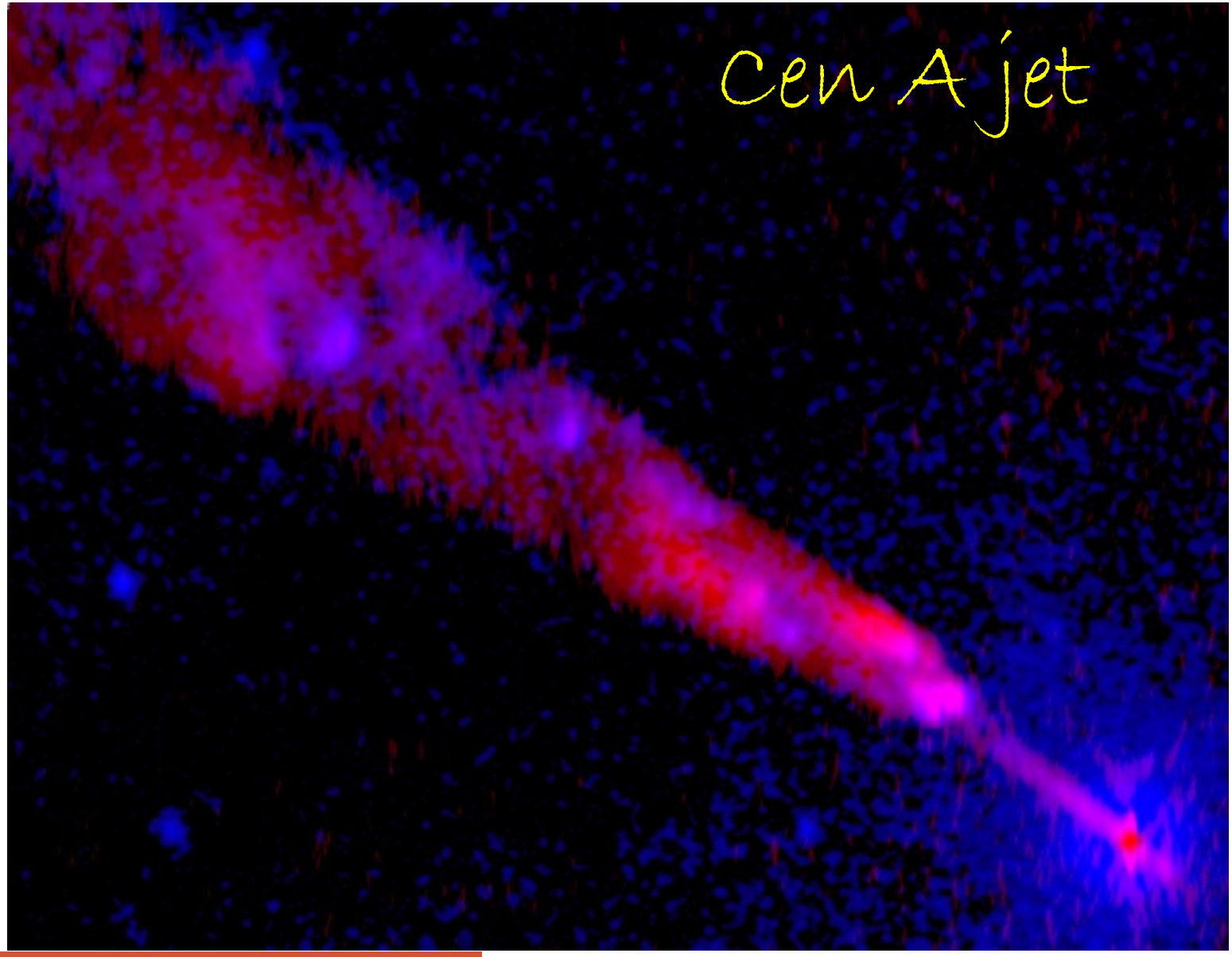


3C129… a “head-tail” source



In this case the jet is propagating in cluster of galaxies which is filled with hot gas, the jet is being affected by motion through the gas.


Cen A- Multiwavelength jet
X-ray
Radio
Optical
Composite



Optical, X-ray composite