Relativistic Jets in Astrophysics

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MAX-PLANCK-GESELLSCHAFT

Course info

- Aim: To give an introduction to the phenomenon of relativistic outflows in the Universe. The emphasis is on jets from supermassive black holes. Qualitative descriptions of physical processes instead of rigorous mathematical treatment.
- Forms of study: 7 lectures, two sets of exercises. Need to pass the final exam in order to pass the course. Worth 4 credits.
- Exercises count towards the final mark by 25% (still need to pass the exam).
- The course wiki-page: tube.utu.fi/courses/doku.php?id=xfys4281
    - I'll put the slides here together with some useful links
- This is a new course. It means that
    - there are no lecture notes available (yet)
    - you *really* should ask questions, if something is not clear
    - feedback is *very* welcome

Reading material

- The course does not follow any single book. It is mainly based on the following literature:
  - DeYoung: The Physics of Extragalactic Radio Sources (2002)
    - Ch. 1-4, 6-9, 12
  - Belloni (ed.): The Jet Paradigm (2010, available from Springer in electronic form)
    - Ch. 1, 4, 7, 9, 10
  - Rybicki & Lightman: Radiative Processes in Astrophysics (1979)
    - Ch. 4,6,7
- Download these articles:
  - Marscher: Jets in Active Galactic Nuclei (2010; Ch. 7 of the Belloni book) www.bu.edu/blazars/paperstodownload/marscher_bellonibook.pdf
  - Mirabel & Rodriguez: Sources of Relativistic Jets in the Galaxy (1999) http://arxiv.org/abs/astro-ph/9902062

Additional reading material

- Text books:
  - Krolik: Active Galactic Nuclei (1999)
  - Hughes & Bregman (ed.): Relativistic Jets (2006)
  - Hughes (ed.): Beams and Jets in Astrophysics (1986)
  - Pacholczyk: Radio Astrophysics (1970)
- Conference proceedings:
  - If someone is interested in reading research papers, an up to date review of current blazar research can be found in Savolainen, Ros, Porcas, & Zensus (eds.): “Fermi meets Jansky – AGN in radio and Gamma-rays” (2010; the whole book is available at http://www.mpifr-bonn.mpg.de/div/vlbi/agn2010/PdfFiles/fmj2010_complete.pdf)

(Tentative) course plan

- 1. lecture (30.11. 12:00, XVII)
    - Introduction – jets in the cosmic landscape
- 2. lecture (1.12. 10:00, XVIII)
    - Relativistic effects
- 3. lecture (2.12. 12:00, XVIII)
    - Radiative processes in jets
- 4. lecture (5.12. 14:00, XVI)
    - Jet launching, acceleration, collimation
- 1. demonstrations (7.12. 12:00, XVII)

(Tentative) course plan

- 5. lecture (8.12. 10:00, XVIII)
  - Observed structures in jets, opacity effects, instabilities, shock waves
- 6. lecture (9.12. 12:00, XVIII)
  - Deriving the physical properties of jets from observations
- 7. lecture (12.12. 14:00, XVI)
  - Blazars and blazar models
- 2. demonstrations and Q&A session (14.12. 12:00, XVII)
- Exam (16.12. 12:00, XVIII)

1. lecture
Introduction - jets in the cosmic landscape

Outline

- General jet characteristics
- History of astrophysical jets
- Jets from active galactic nuclei
    - morphologies, spectra, classification
- Jets from X-ray binaries
- Jets from gamma-ray bursts

Some definitions, conventions, units

- Definitions:
  - Lorentz factor $\Gamma=(1-\beta^2)^{-1/2}$ where $\beta=v/c$
  - gravitational radius of a BH: $R_g = 2GM_{BH}/c^2$
- Positive convention for spectral index
- Units:
  - (radio) flux density: 1 Jy = 10^{-26} W m^{-2} Hz^{-1}
  - magnetic flux density: 1 G = 10^{-4} T
  - energy: 1 erg = 10^{-7} J

What is an astrophysical jet?

- Definition: Jet is a collimated outflow of matter from an astronomical object. Length > 4x width of the outflow (Bridle 1982).
- Jets are ejected from a variety of celestial objects:
    - Young stellar objects
    - Neutron stars
    - Stellar mass black holes (Galactic X-ray binaries)
    - Supermassive black holes (AGN)
    - Forming black holes (Gamma-ray bursts)

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Jets with highly relativistic speeds

Relativistic jets - properties

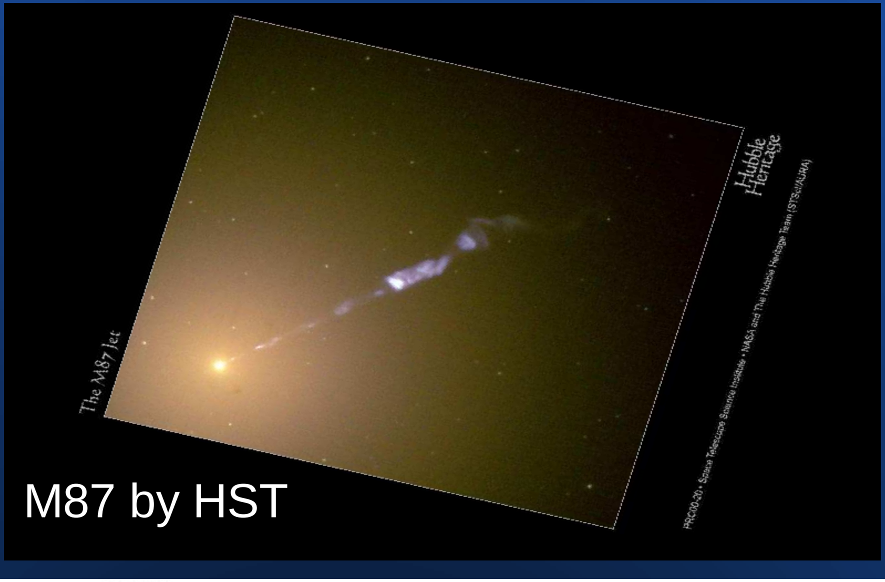
- Highly relativistic jets are launched from accreting black holes (“central engine”), probably through magnetic processes. The jets extract potential energy of the accreting matter and/or rotational energy of BH.
- Jets transport energy and angular momentum from central engine to remote locations and provide feedback to ISM/IGM
- They are fast: Lorentz factors ~ a few to a few tens for AGN and microquasars, and >100 for GRBs
- High Lorentz factors mean that special relativistic effects are important (especially “beaming” of radiation into small cone)
- Jet phenomenon bridges many orders of magnitude in size: forming in size scale of R_g and extending up to 10^9-10^{10} R_g

Relativistic jets - radiation

- Synchrotron radiation - Non-thermal electrons + B-field
- X-Rays/Gamma-rays:
  - inverse Compton scattering - Non-thermal electrons + photon field
  - hadronic emission processes (?) - relativistic protons
- Very high luminosities (10^{44}-10^{47} erg/s in quasars) and total energies ($>10^{60}$ ergs stored in large extragalactic radio sources; total lifetime energy output up to 10^{62} ergs)
- Jets contain highly relativistic charged particles and magnetic fields → need efficient acceleration mechanisms ("How does nature do it so easily?")

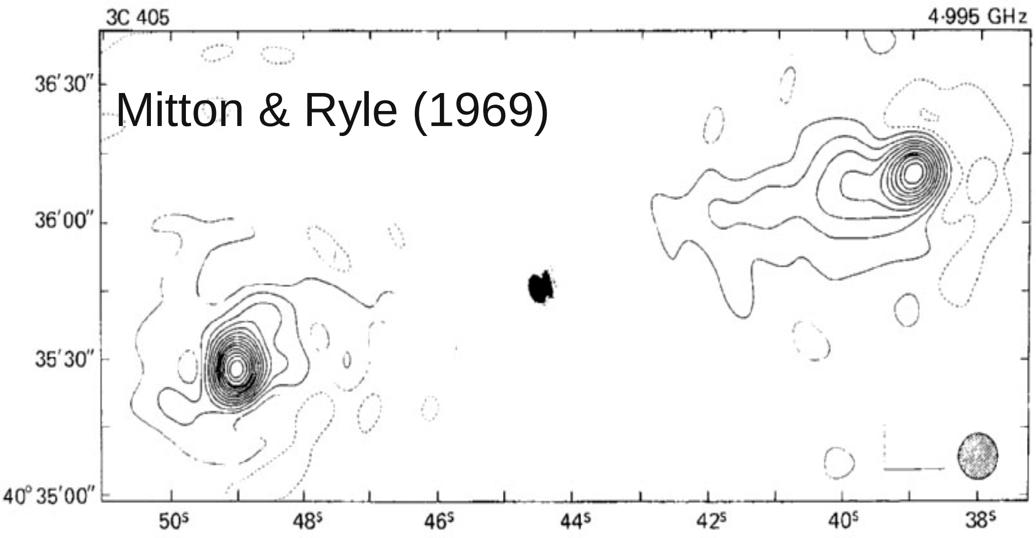
Understanding jets requires both classical and quantum mechanics as well as special and general relativity.

Historical note 1



M87 by HST

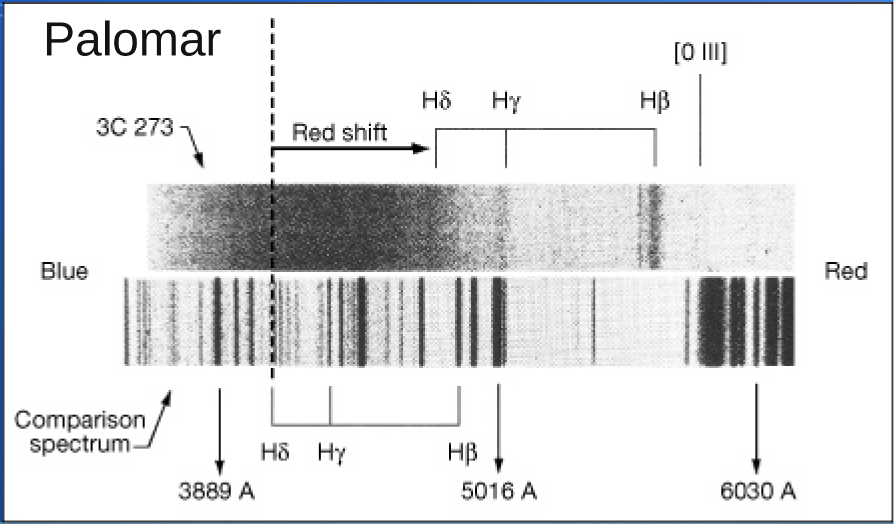
- First recorded observation: “a curious straight ray” in M87 by Curtis in 1918
- 1953: Jennison & Das Gupta discover double lobed structure of Cyg A
- In the 1960s: *radio interferometry* demonstrated that extended radio emission, consisting of lobes, hot spots and jets, is seen in many galaxies



Mitton & Ryle (1969)

Historical note 2

- In 1963: Identification of a radio source 3C273 with a quasi-stellar object with redshift of 0.158 → discovery of quasars
- In late 1970s VLA becomes operational and reveals detailed morphologies of extragalactic radio sources



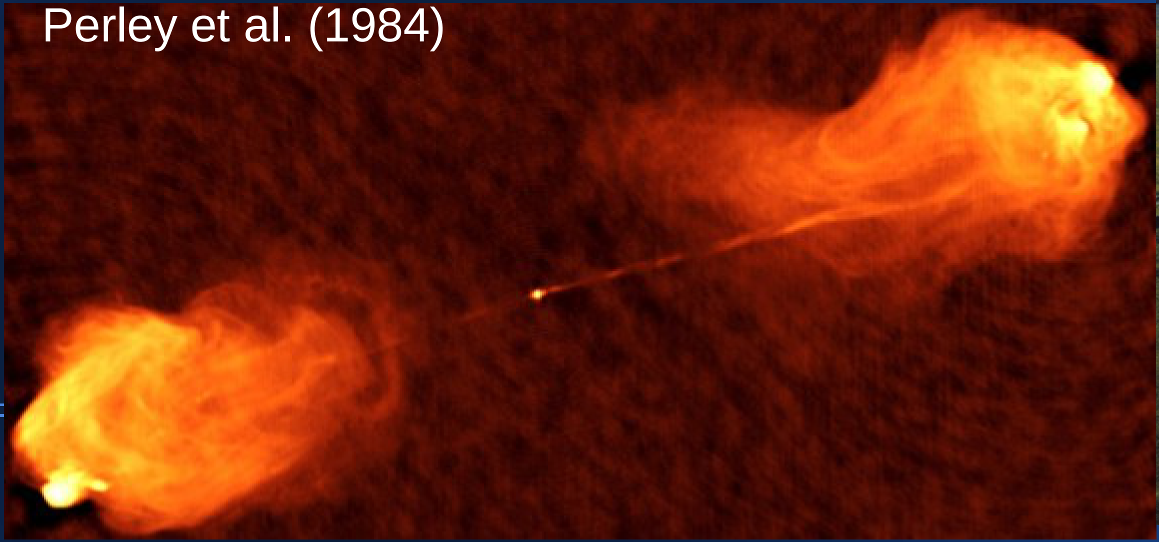
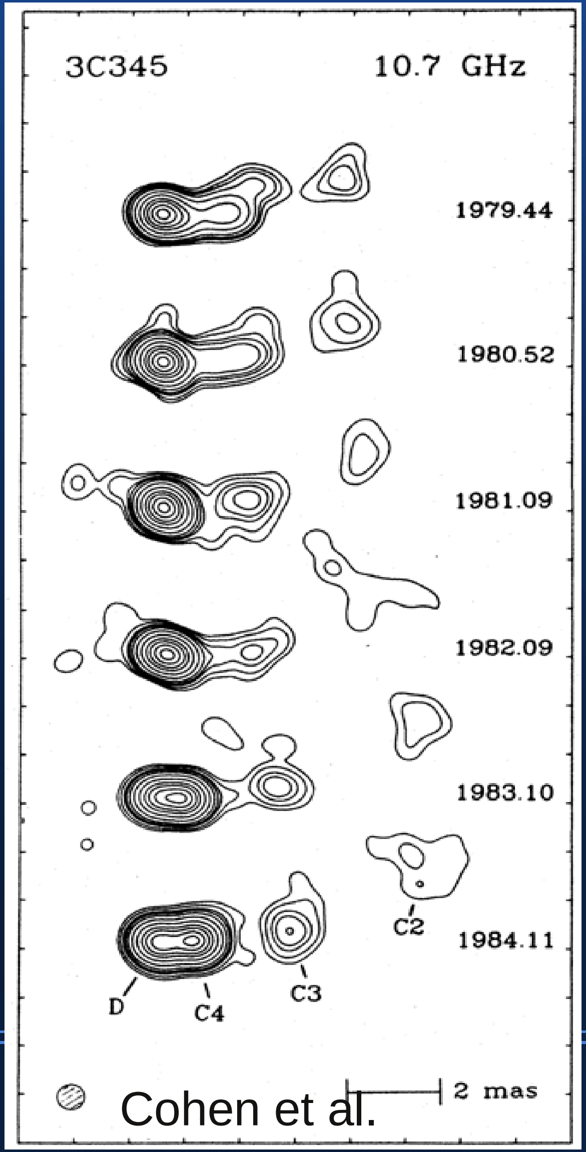

Perley et al. (1984)


Image courtesy of NRAO/AUI

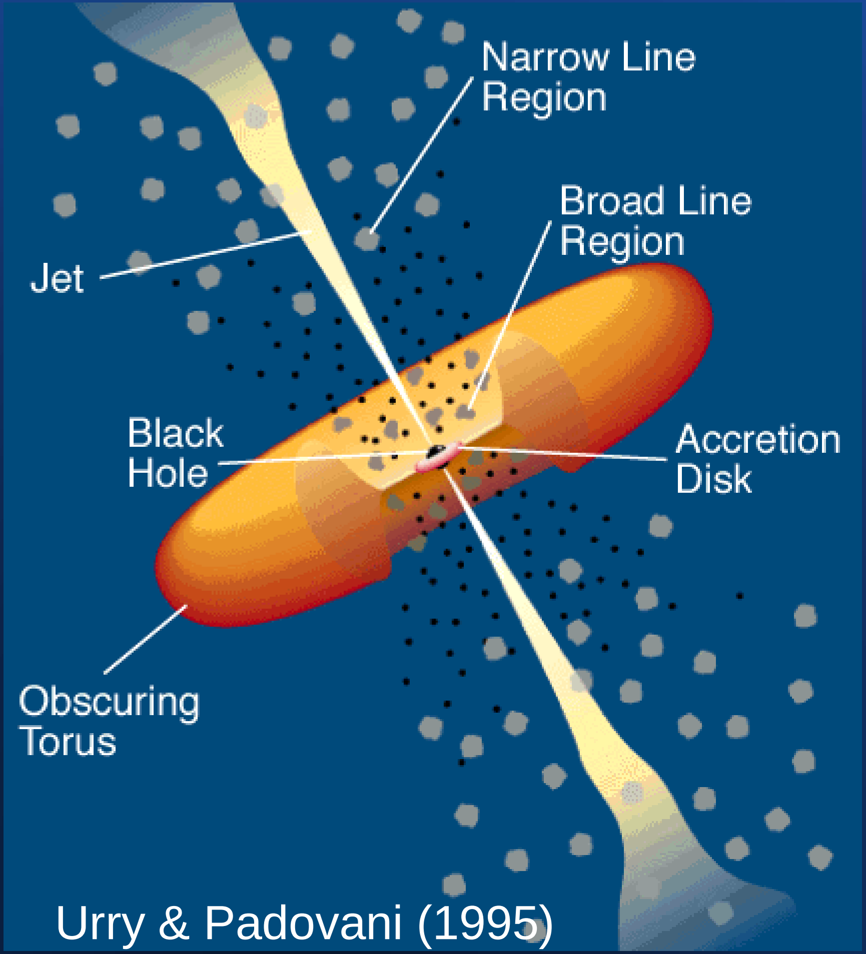
Historical note 3
Relativistic motion



Cohen et al.

- 1960s: short observed variability time scales of radio sources create “Compton catastrophe” problem – the solution is invoking relativistic motion towards the observer
- Rees (1966): relativistic outflow and prediction of superluminal motion
- Shapiro et al.; Cohen et al. (1971): First detections of superluminal motion in 3C273 and 3C279 using *very long baseline interferometry* → relativistic jets
- EGRET in the 1990s: radio-loud AGN are also gamma-ray emitters. Fast gamma-ray variability → independent evidence of relativistic motion
- Discovery of microquasars in the Milky Way (Mirabel 1994)
- Long GRBs have very high Lorentz factor jets

Jets from active galactic nuclei



Urry & Padovani (1995)

- Launched from vicinity of a supermassive BH
- ~10% of AGN are radio-loud i.e. have prominent jets – weak jets may be more common
- AGN jets can extend from ~10^{-4} pc to several hundred kpc in size
- Jet composition is unknown (normal or pair plasma) and so is the dominant energy carrier (relativistic protons, cold protons, cold electrons, Poynting flux)
- Jets powers:10^{43}-10^{47} erg/s
- Jet power integrated over radio source lifetime: 10^{57}-10^{62} erg !

Radio galaxies - morphologies

- Compact sources

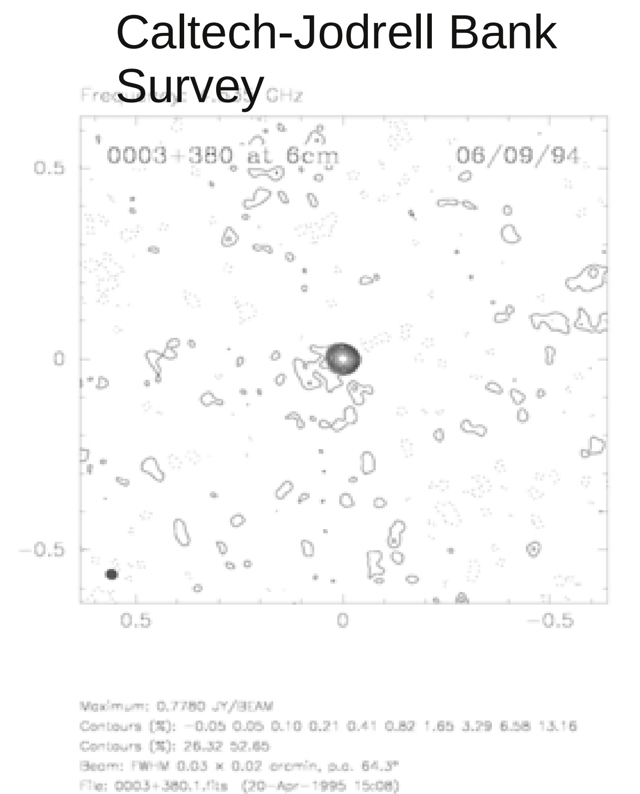

Caltech-Jodrell Bank Survey

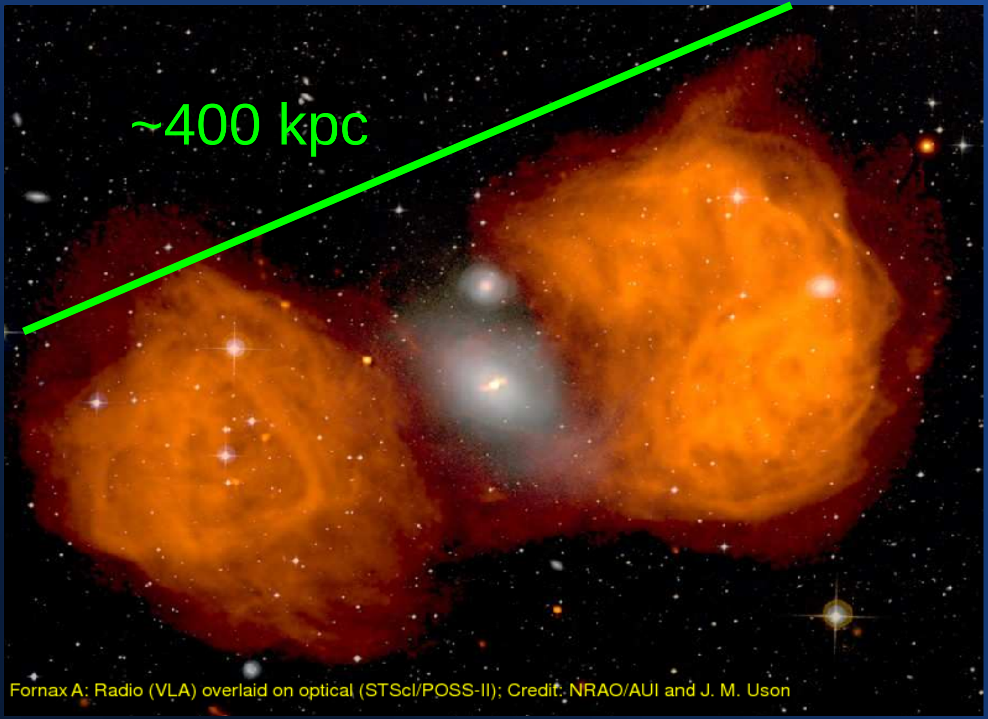
Image courtesy of NRAO/AUI

- Extended sources – one-sided

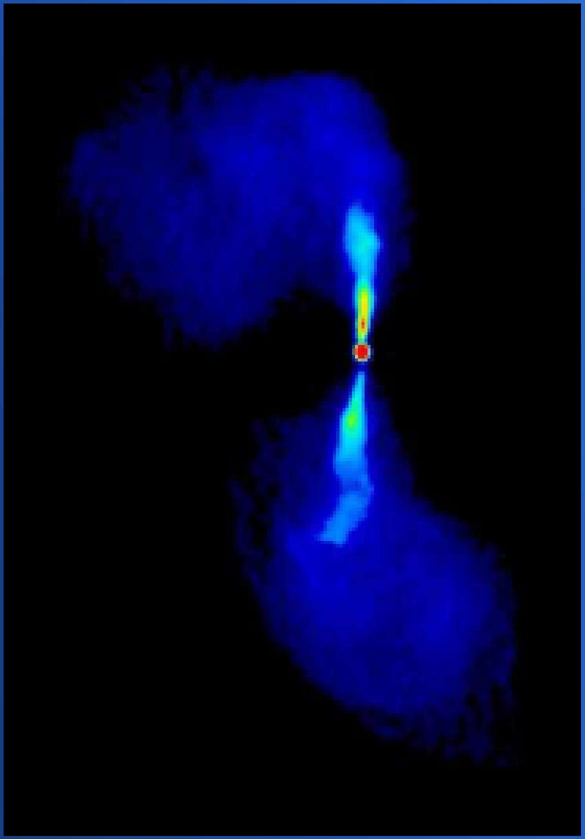
(NGC6251 -“Blowtorch”)

Radio galaxies - morphologies

- Extended sources – double sided



Fornax A in radio+optical
(NRAO/AUI, J. Uson)

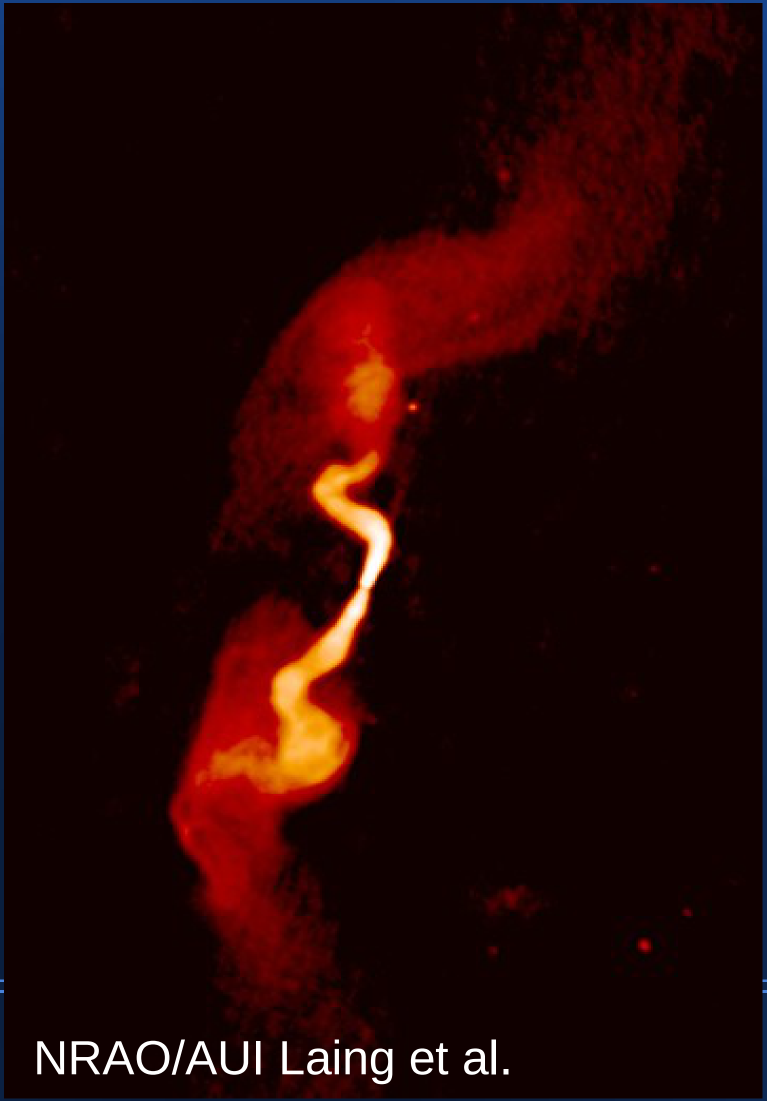


M84 with VLA (Laing & Bridle 1987)

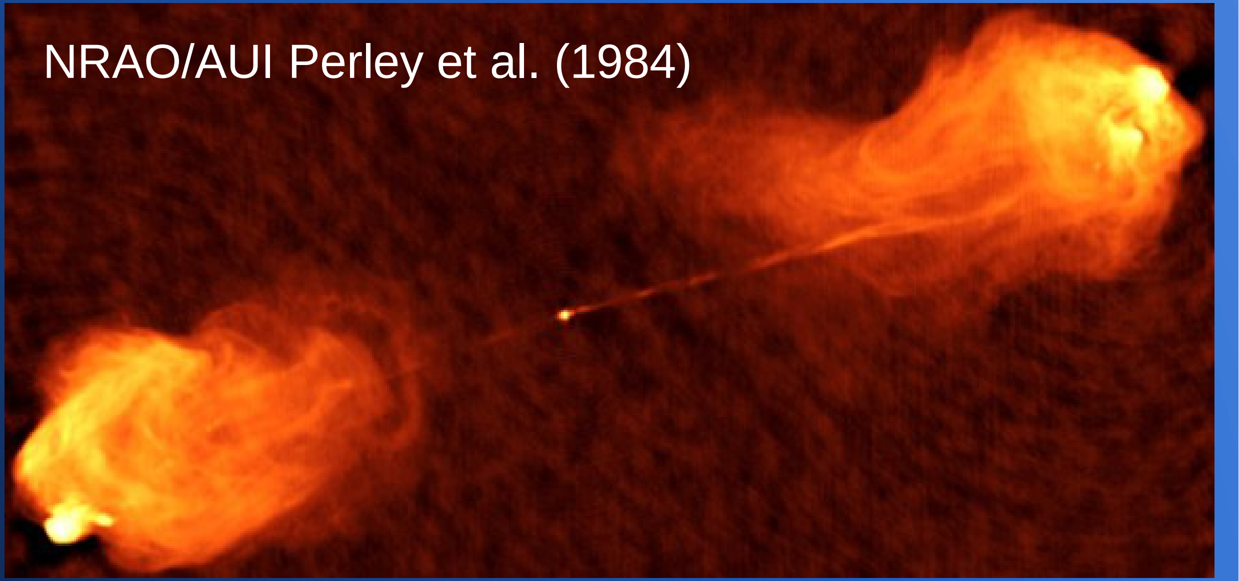
Radio galaxies – FRI/FRII dichotomy

- Fanaroff & Riley (1974): Connection between radio galaxy luminosity and morphological type
- FRI: Prominent two-sided jets, brighter towards center, often distorted with bends → 1.4 GHz luminosities below 10^{25} W/Hz
- FRII: Double-lobed, edge-brightened, prominent hot-spots; relatively weak, straight, one sided jets → 1.4 GHz luminosities over 10^{25} W/Hz

Radio galaxies – FRI/FRII dichotomy



NRAO/AUI Laing et al.



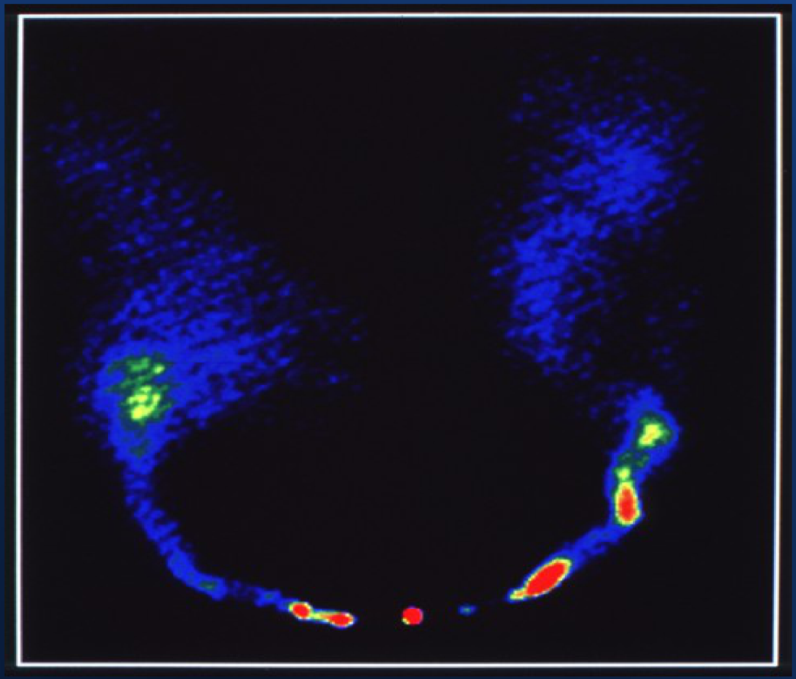
NRAO/AUI Perley et al. (1984)

FR-II (Cyg A)

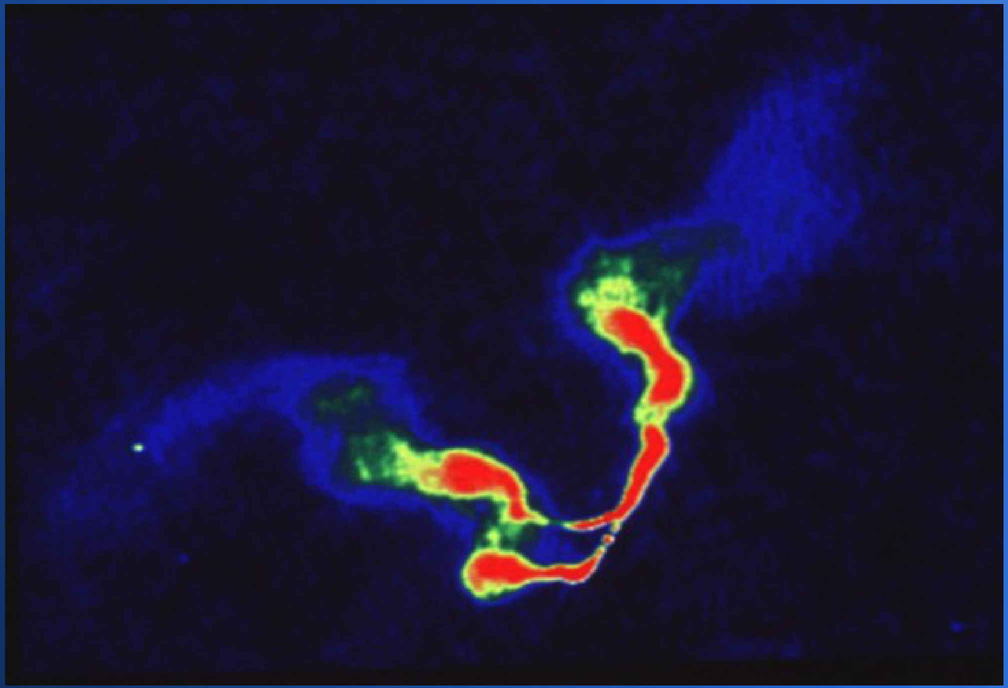
FR-I (3C31)

Radio galaxies - morphologies

- Extended sources – peculiar morphologies



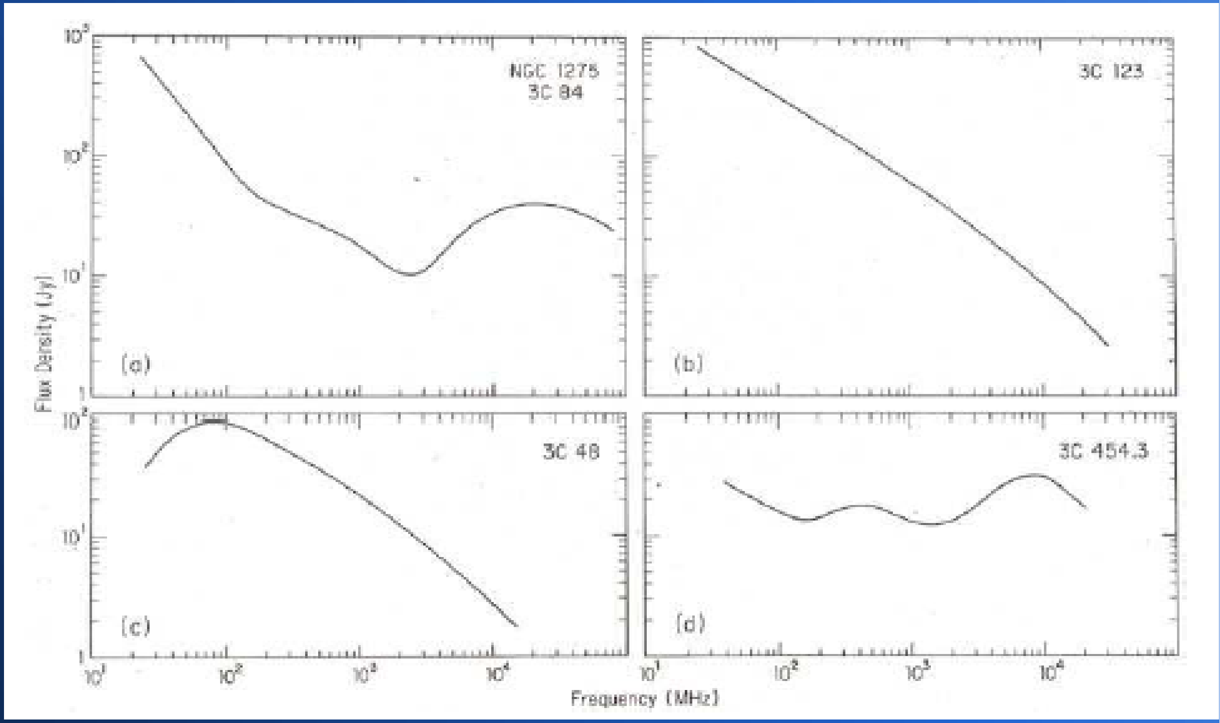
NGC 1265- Narrow angle tailed radio galaxy



3C75 – Two twin jets

Radio galaxies - spectra

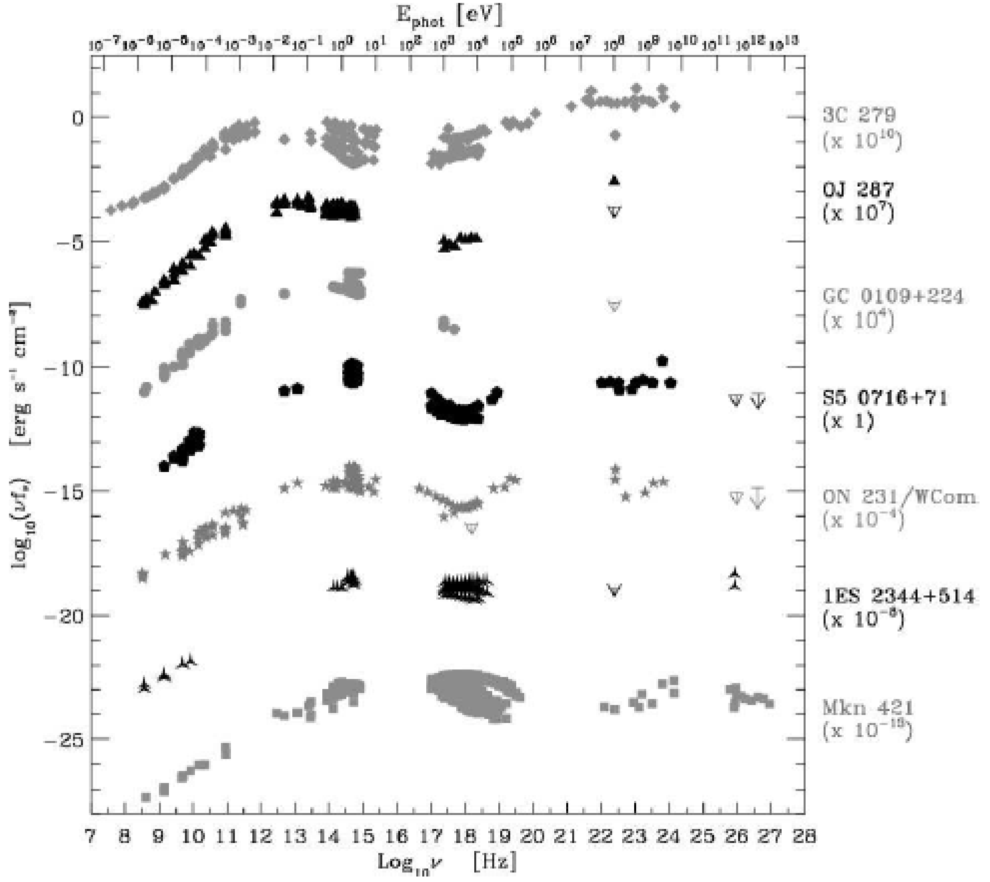
- Synchrotron radiation from different parts of the jet/lobes
- Self-absorption turnover frequency depends on B and rel. particle density → high frequency turnover requires compact emission region
- Steep spectra from radio lobes
- Flat spectrum from sources where the parsec-scale jet dominates



Kellermann & Owen (1988)

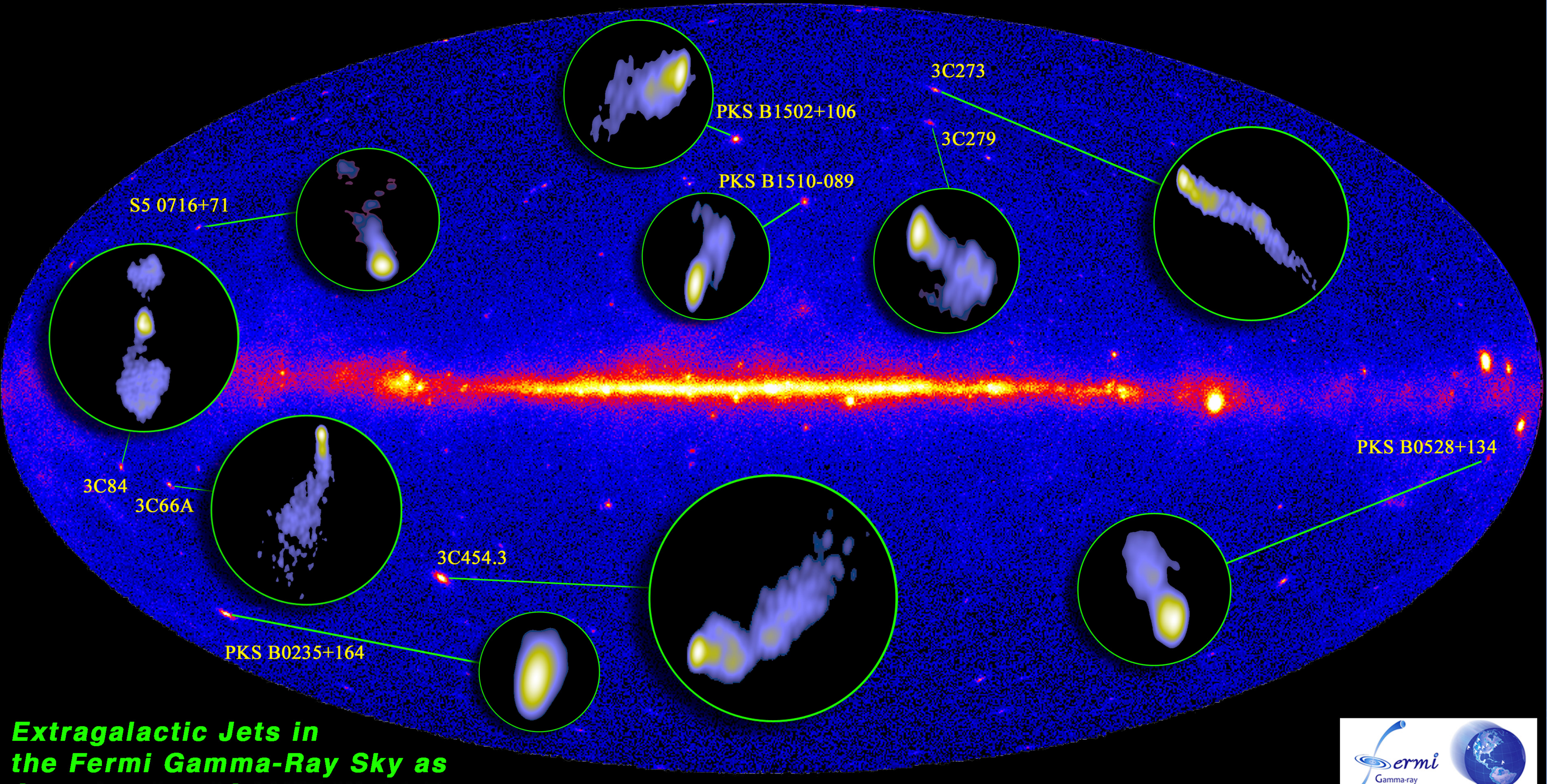
Blazars

- AGN with relativistic jets seen almost end-on
- Flat-spectrum radio quasars and BL Lac objects
- Jet emission enhanced due to relativistic effects by a factor of thousands
- Broad-band spectral energy distribution dominated by non-thermal emission from the jet
- Emission from radio up to TeV gamma-rays!



(Fiorucci, Ciprini & Tosti, 2004)

Blazar dominate the extragalactic gamma-ray sky



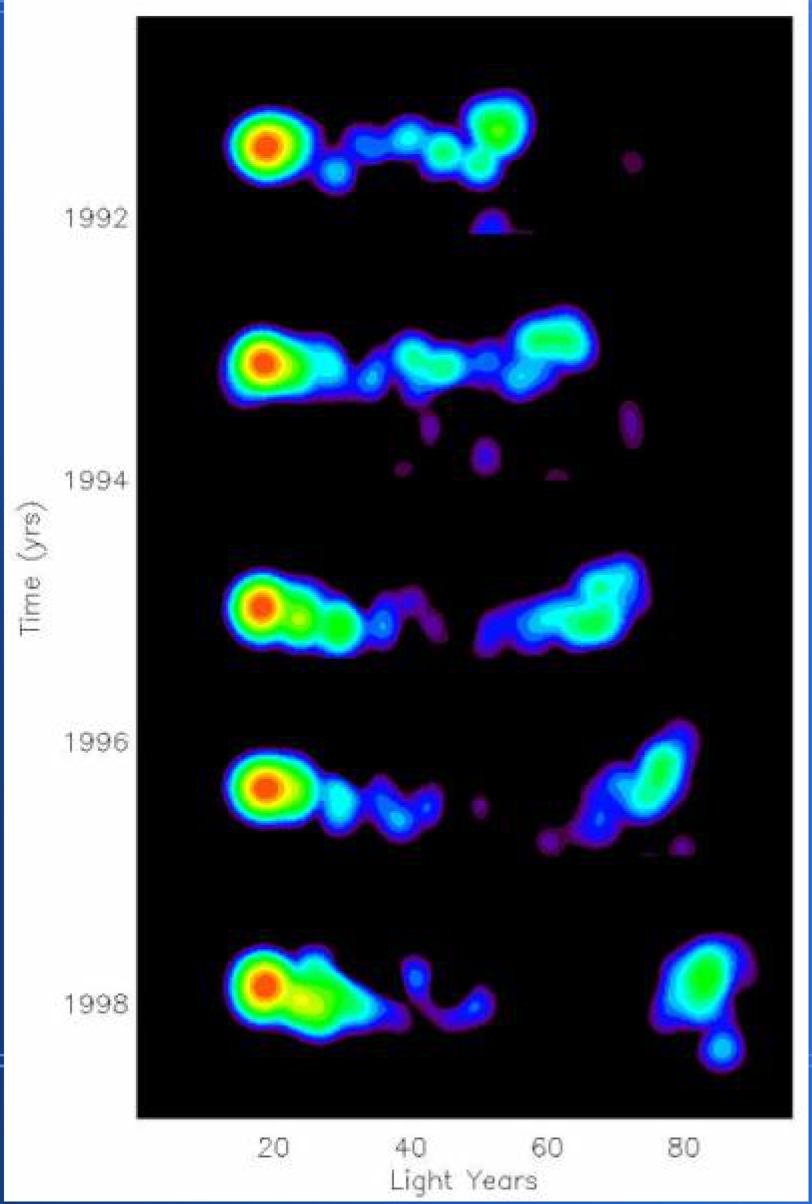
Extragalactic Jets in the Fermi Gamma-Ray Sky as Seen by the MOJAVE VLBA Program

Fermi Gamma-ray Space Telescope

MOJAVE - VLBA

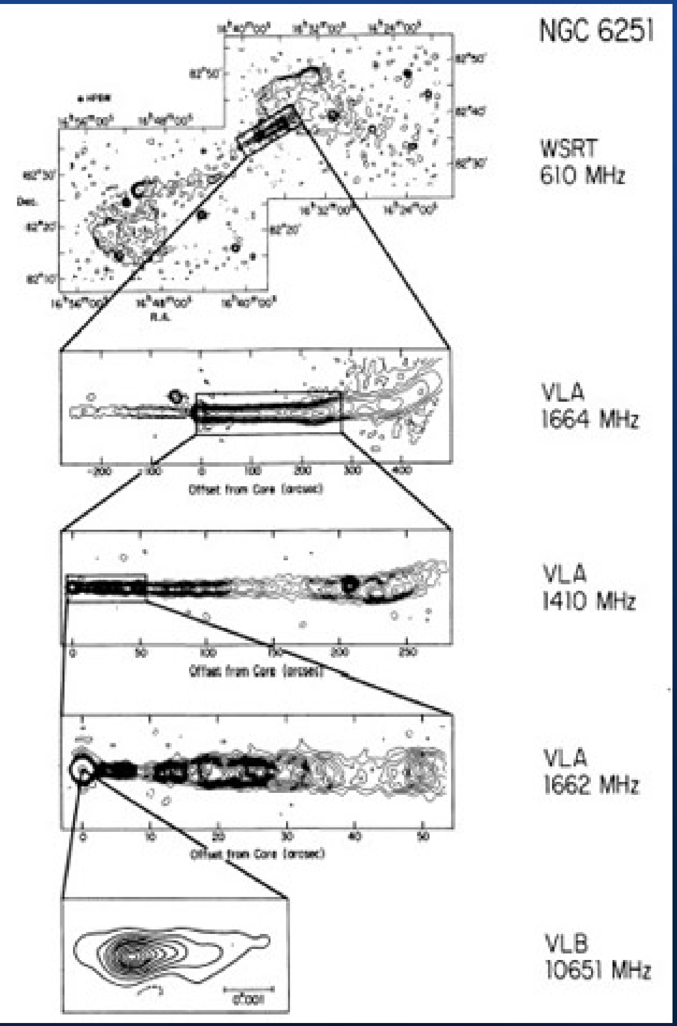
Superluminal motion

- If relativistically moving object is seen in a small angle with respect to its direction of motion, its observed velocity may appear higher than *c*! Observation of such apparent superluminal speeds is an evidence for relativistic bulk motion.
- Routinely observed in blazars on parsec scales using VLBI techiques.

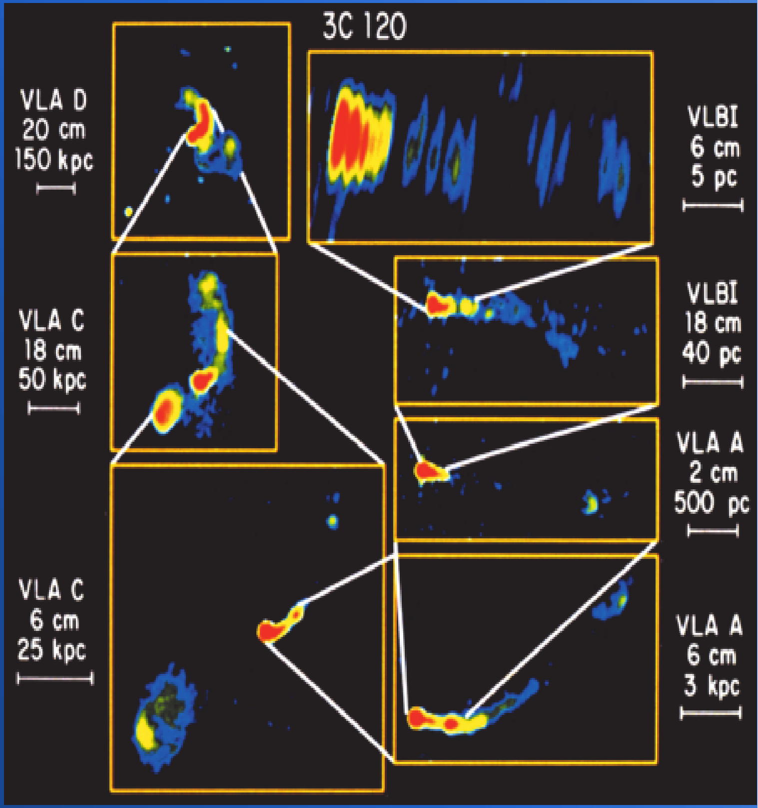


MOJAVE movie of 1222+216

Jets from the central engine to lobes

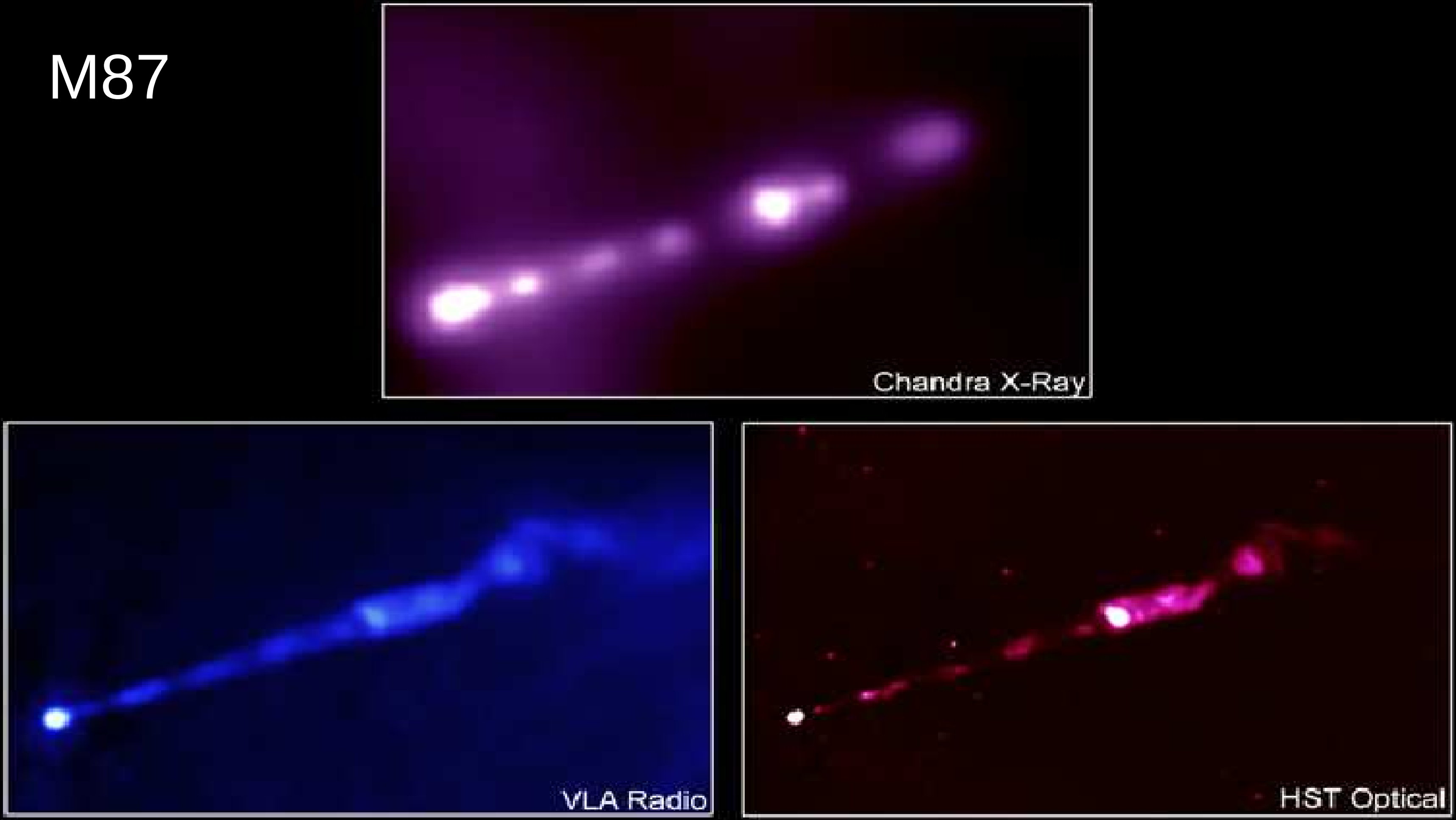


- Using radio interferometers with different baseline lengths and observing at different frequencies, it is possible to “zoom in” the jet.
- In the smallest scales, VLBI reveals proper motion. The large radio lobes are fed by a relativistic jet!



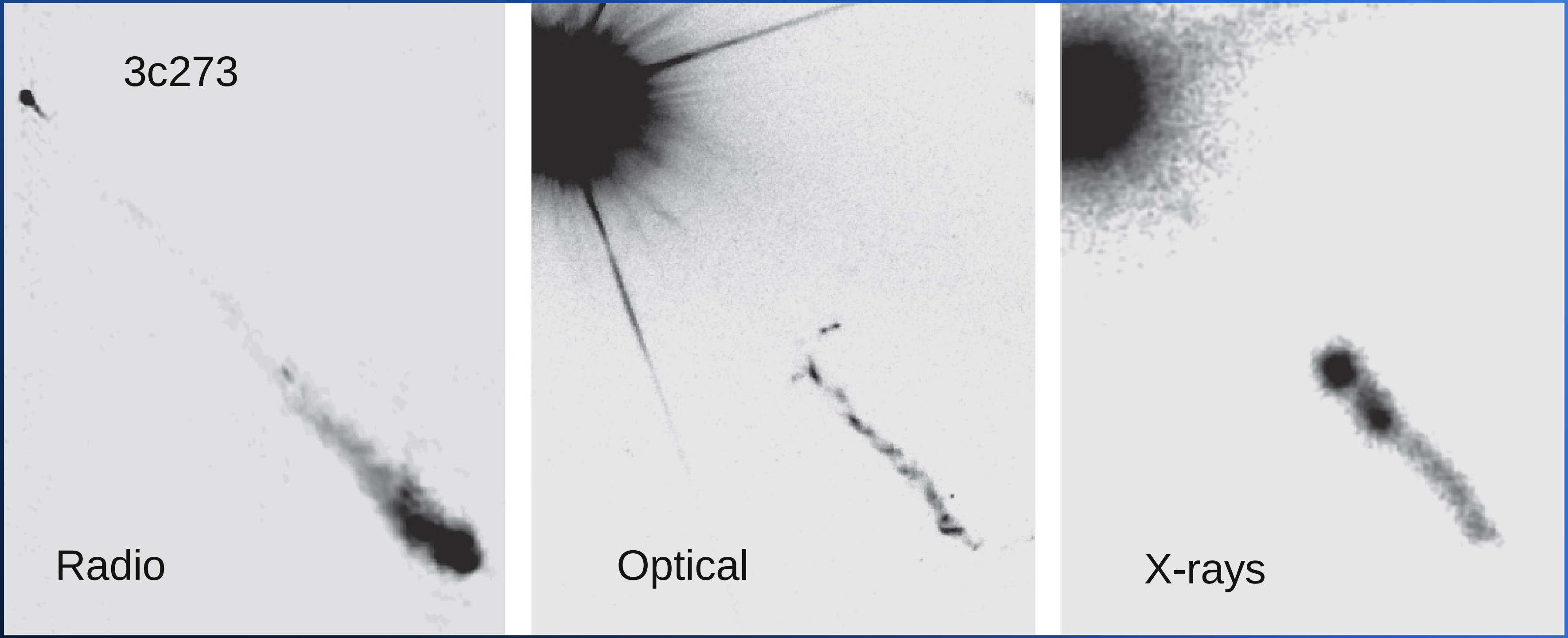
Large scale jets in optical and X-rays

M87



Credit: X-ray: NASA/CXC/MIT/H.Marshall et al. Radio: F. Zhou, F.Owen (NRAO), J.Biretta (STScI)
Optical: NASA/STScI/UMBC/E.Perlman et al.

Large scale jets in optical and X-rays



- Cooling time of the electrons radiating optical synchrotron emission is too short compared to distance from BH to kpc-scale jet. In-situ particle acceleration required!

AGN jets – Classification summary

- Classification based on morphology and radio spectrum:
- 1. Powerful double-lobed radio galaxies with hotspots and a steep radio spectrum falling toward higher frequencies (Fanaroff-Riley class II, FR II)
- 2. Weaker steep-spectrum, double-lobed radio galaxies without leading hotspots (FR I types)
- 3. Core-dominated flat-spectrum sources (Blazars: quasars and BL Lac objects)
- 4. Compact steep-spectrum sources (CSS sources) and gigahertz-peaked spectrum sources (GPS sources); no large-scale radio structure; morphological classification term: compact symmetric objects (CSOs) → Young radio galaxies?

Observing technique and frequency strongly affects sample composition (e.g., low-frequency flux density limited surveys tend to select steep-spectrum sources. Flat-spectrum sources are classical targets for Very-Long-Baseline Interferometry (VLBI) observations, which are sensitive to compact emission.

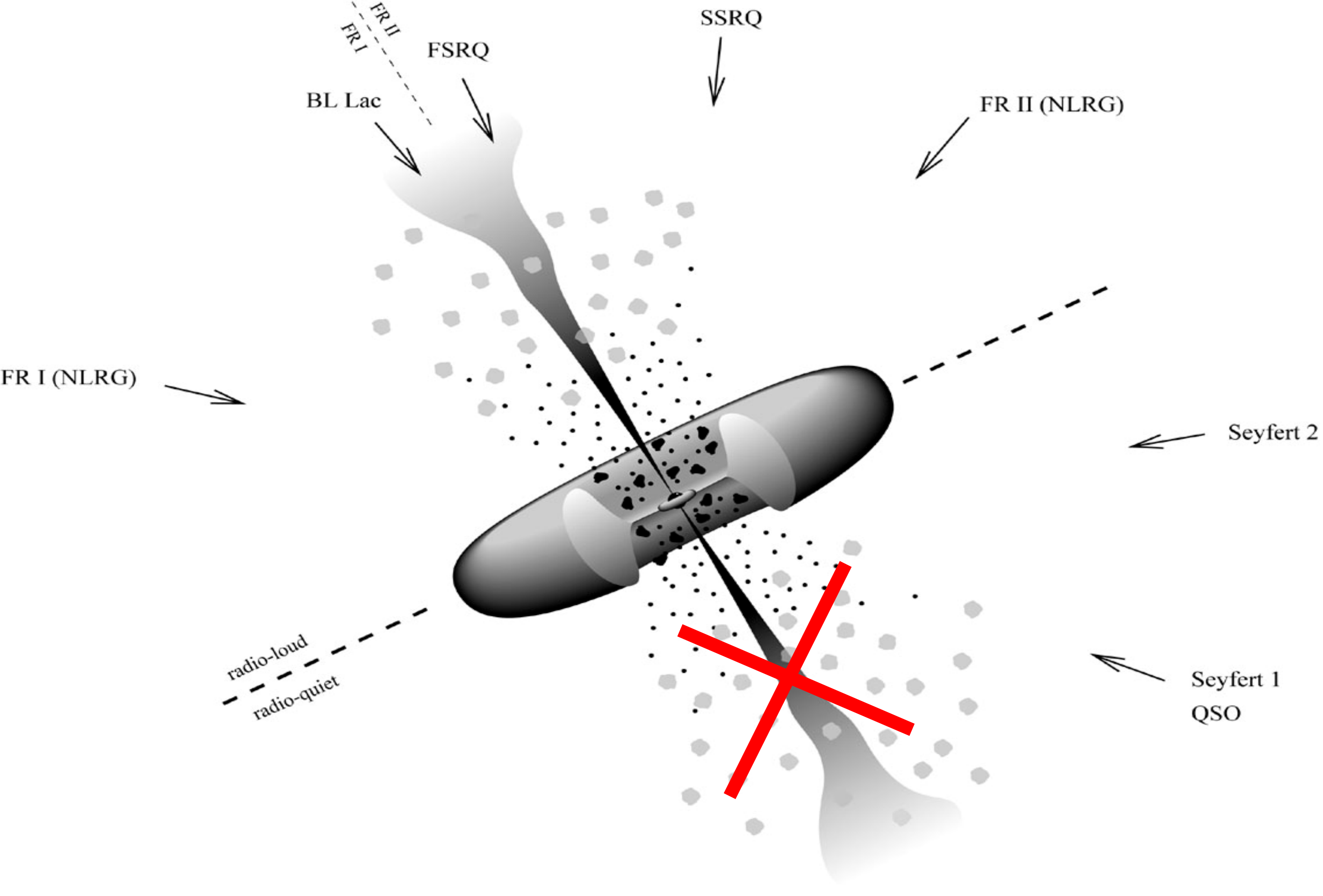
Courtesy of Kadler & Wilms

AGN unification

- Jet vs. no jet
- Different viewing angles
- FSRQ – FRII ?
- BL Lac – FRI ?

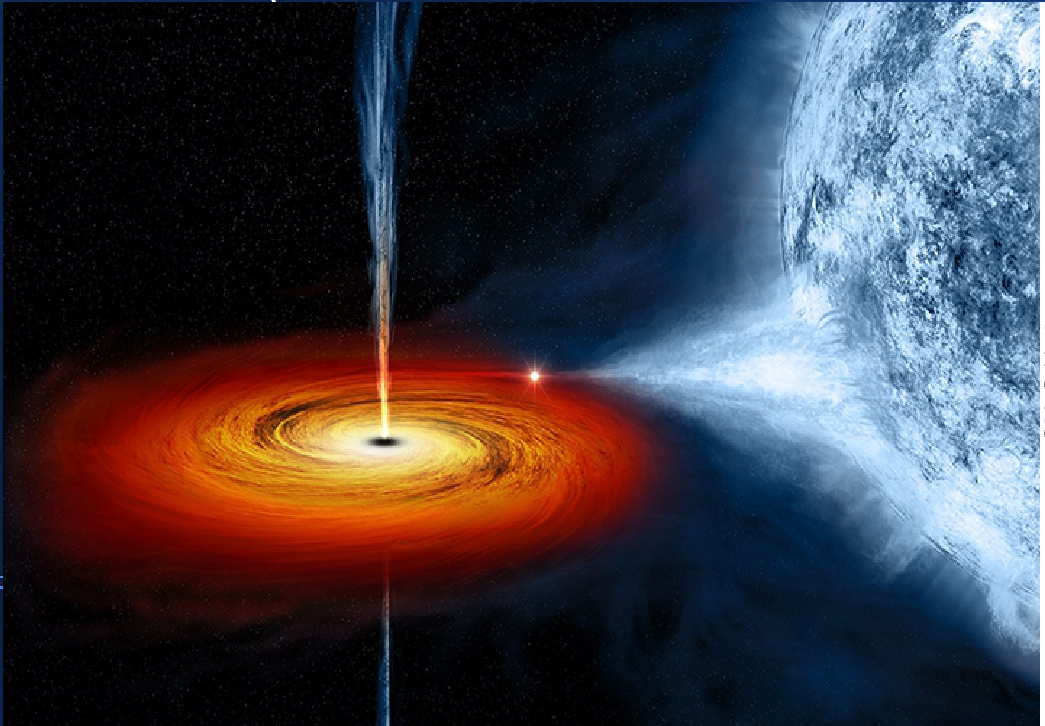
Urry & Padovani (1995),

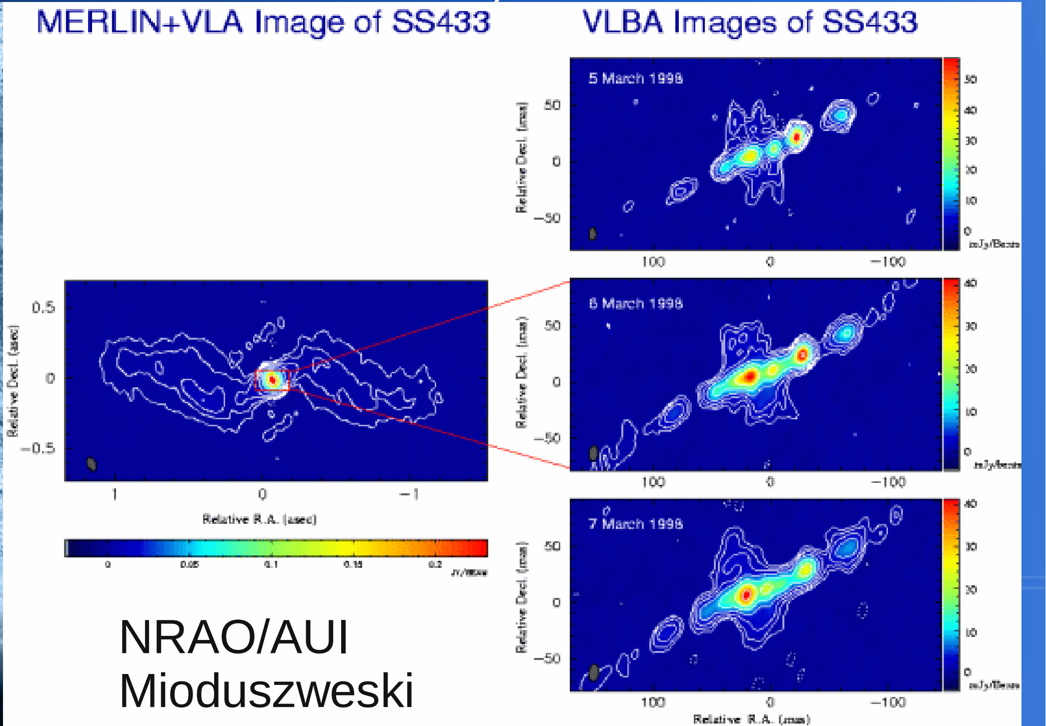
Barthel (1989)



Jets from galactic X-ray binaries

- Binary star systems with a compact object (BH or neutron star) accreting material from its companion
- Bright X-ray emitters: thermal emission from optically thick, geometrically thin accretion disk and Comptonizing corona
- Can produce (radio-emitting) jets, especially if the compact object is a BH (but some neutron stars do it as well, see Cir X-1)



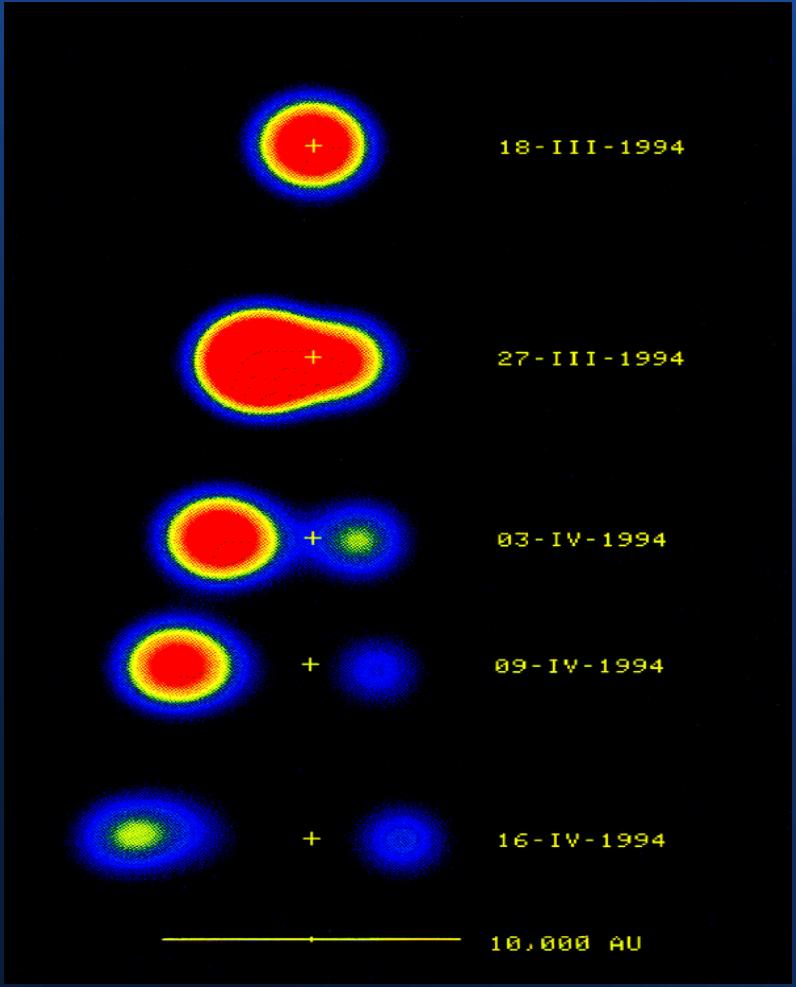


MERLIN+VLA Image of SS433

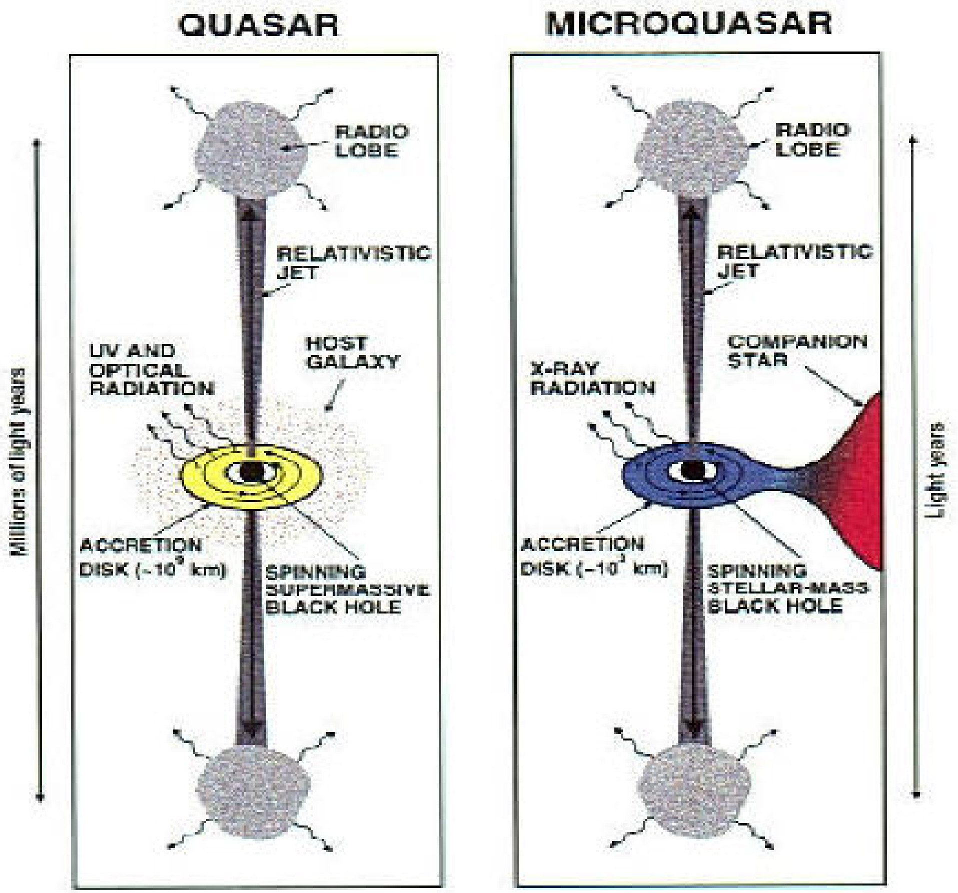
VLBA Images of SS433

NRAO/AUI
Mioduszweski

Relativistic motion in XRBs – Microquasars

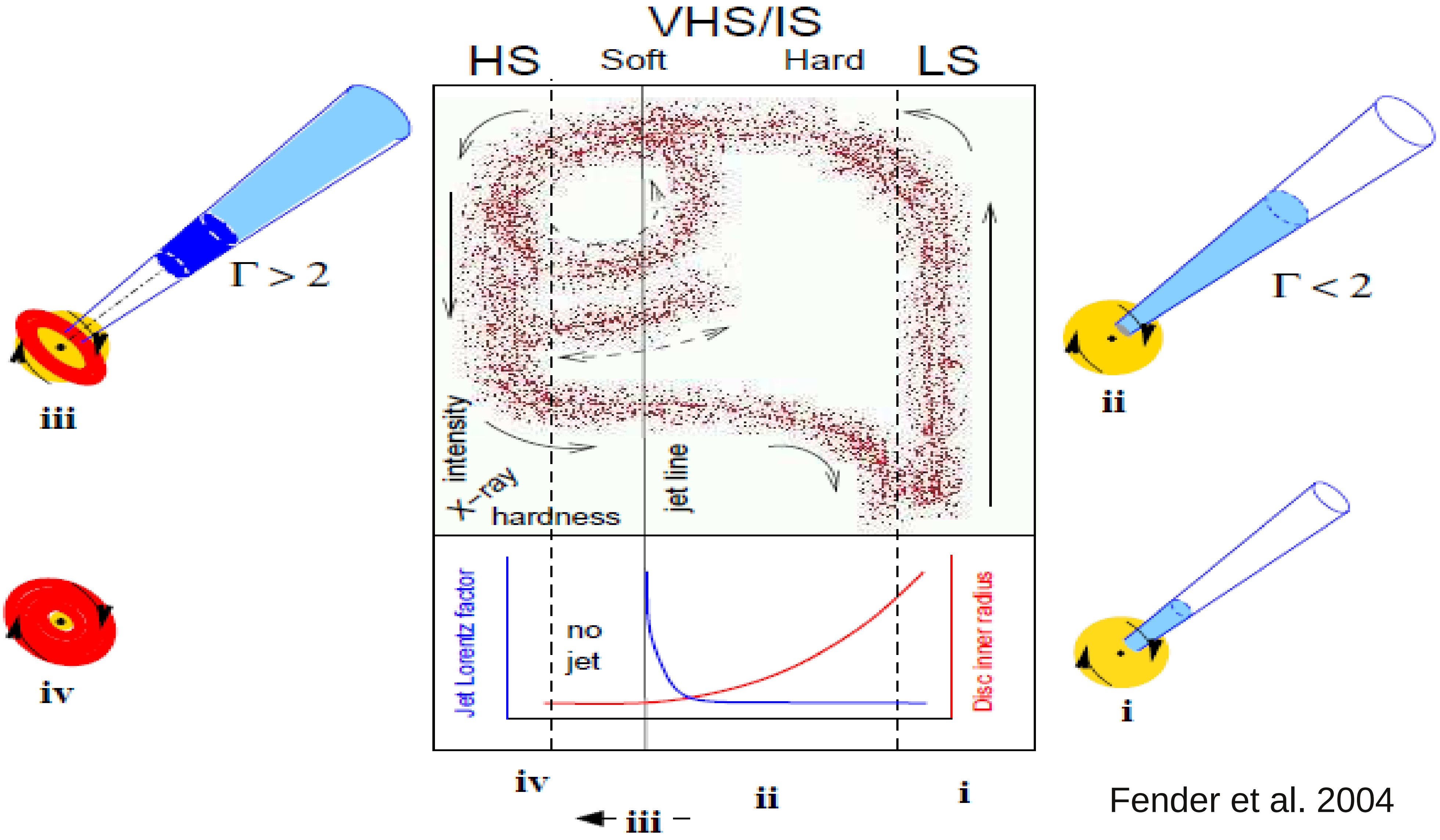


GRS 1915+105, first discovered superluminal source in our Galaxy (Mirabel & Rodriguez, Nature 1994)



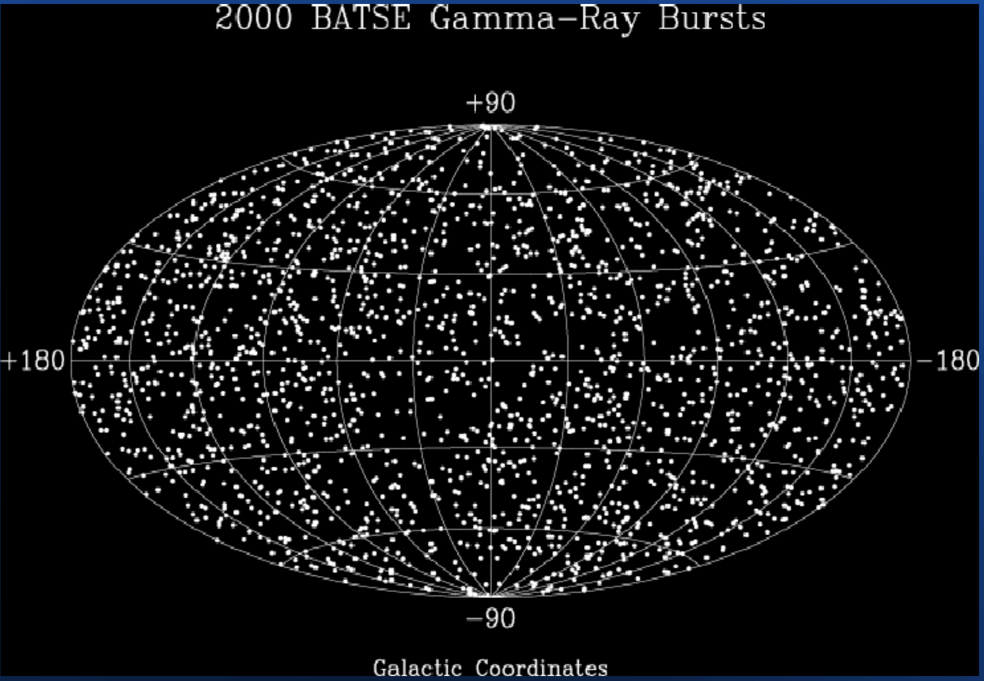
Mirabel 1999

Disc-jet coupling in X-ray binaries



Fender et al. 2004

Gamma-ray bursts



- BATSE: uniform distribution over sky. Redshift measurements from afterglows confirm cosmological distances.

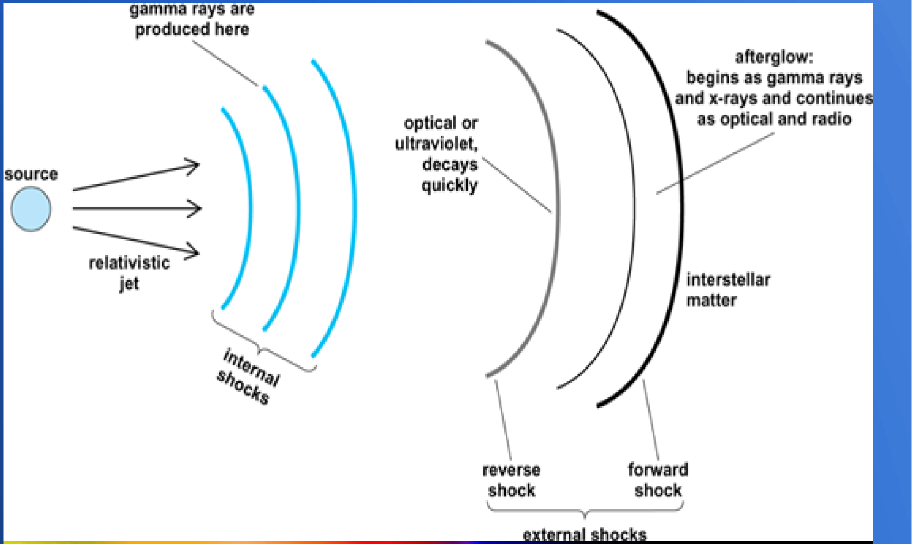
- GRBs are extreme events:
  - bulk of energy emitted in the 0.1-1 MeV range
  - durations from ms to 1000s
  - Very broad continuum spectrum
  - Energy release of 10^{51}-10^{54} erg if isotropic emitters!
- Bimodal distribution of burst duration:
  - Long bursts (>2s) from core-collapse supernovae
  - Short bursts (<2s) possibly from neutron star mergers

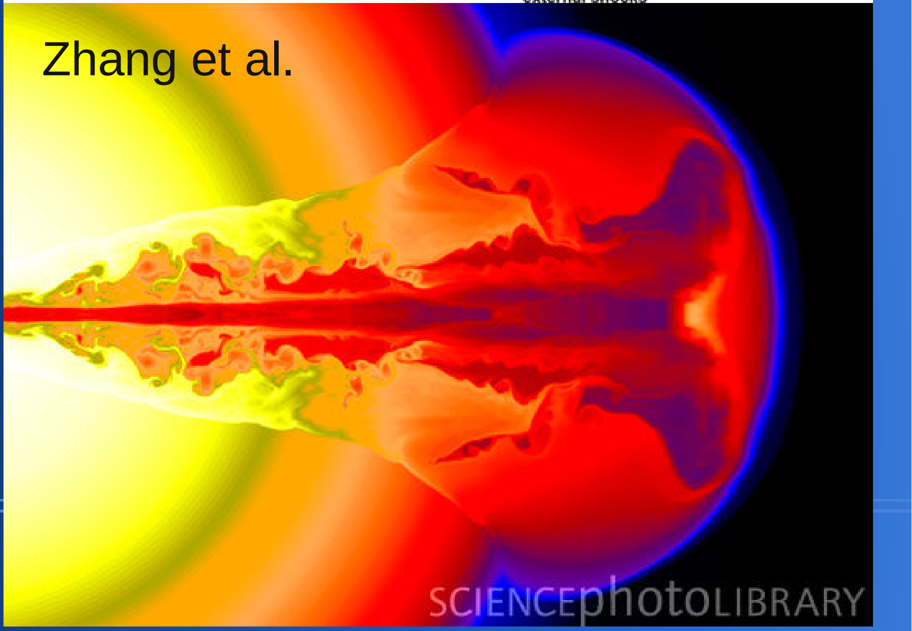
Relativistic motion in GRBs

- Fast time scale of variability of energy release of $>10^{50}$ erg in 1 MeV photons creates “compactness problem”: variability time scale restricts the emission region size and makes the photon density so high that the optical depth for pair production >> 1
- Solution: relativistic beaming
  - increases the inferred size of the emission region by factor of Γ^2
  - reduces the photon energy in the source frame
- $\Gamma > 100$ required explain observations

Internal shocks

- Prompt emission from GRBs most likely due to “internal shocks”: the central engine emit irregular flow and shells traveling at different speeds collide creating shocks and efficiently converting flow energy into internal energy.
- Internal energy is radiated away by synchrotron and inverse Compton mechanisms
- Finally the flow hits external medium, decelerates and emits an afterglow

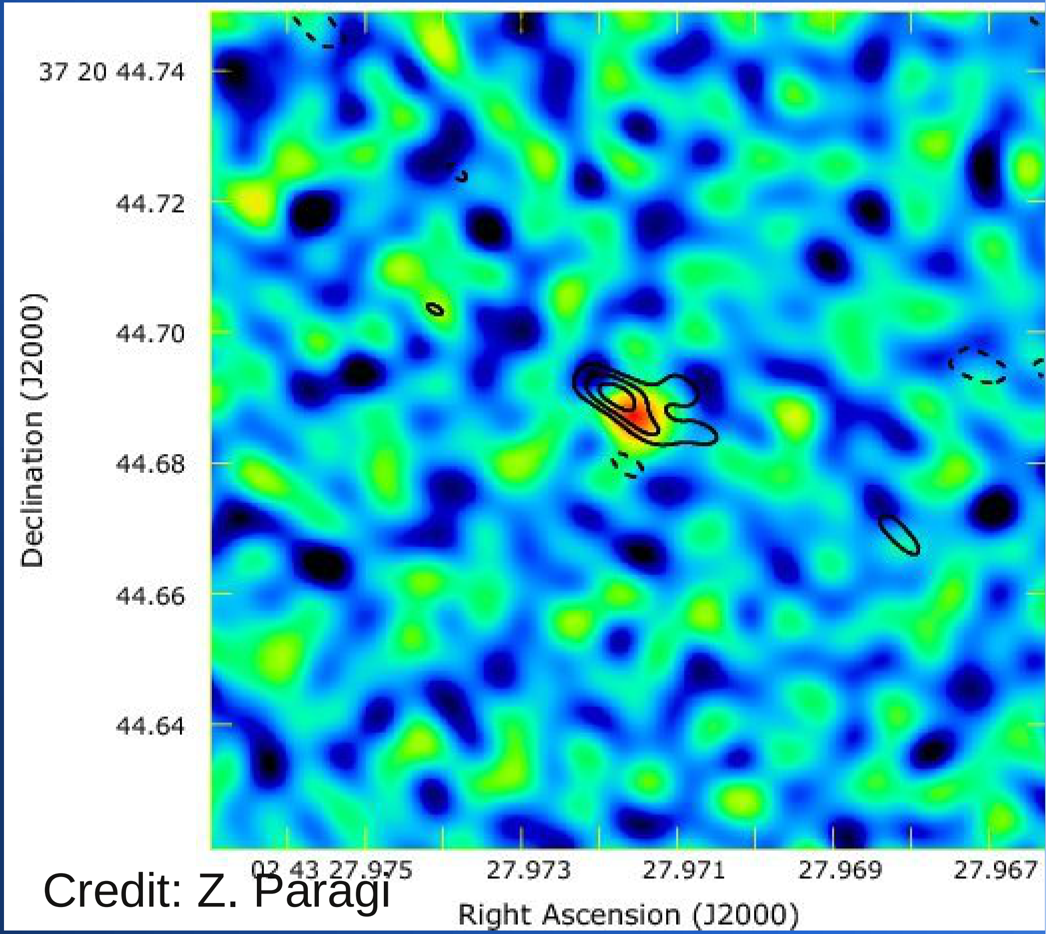




Zhang et al.

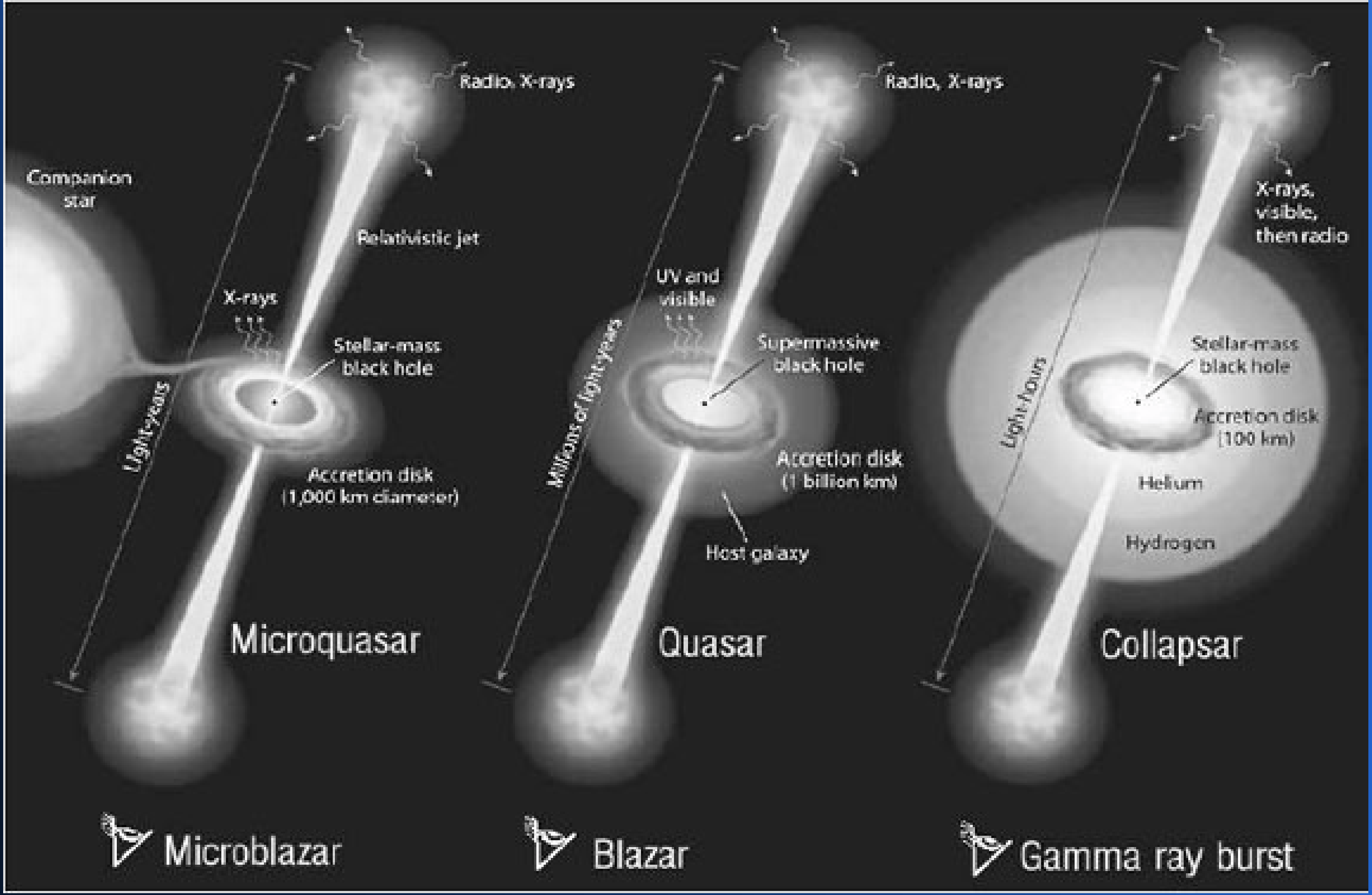
Jets from gamma-ray bursts?

- Is the relativistically moving material in form of jets?
- Consequences of jets:
  - Total emitted energy ~5×10^{50} instead of up to 10^{54}
  - Observed event rates smaller than true rates
  - Can explain breaks in the light curves
- Elongated radio emission observed from supernova with VLBI (Paragi et al. Nature 2010)



Credit: Z. Paragi

Summary: Relativistic jets from different astrophysical systems



Mirabel

Major open questions

- How are jets formed, accelerated and collimated? Is the jet energy extracted from the spin of the BH or from the accreting matter?
- What is the matter content of the jets?
- How the jet remain stable over large distances?
- How the jets influence ISM and IGM?
- How is the high energy gamma-ray emission produced?

Current lines of research

- Observational
    - across the electromagnetic spectrum
- Theoretical
- Computational
    - significant advances expected