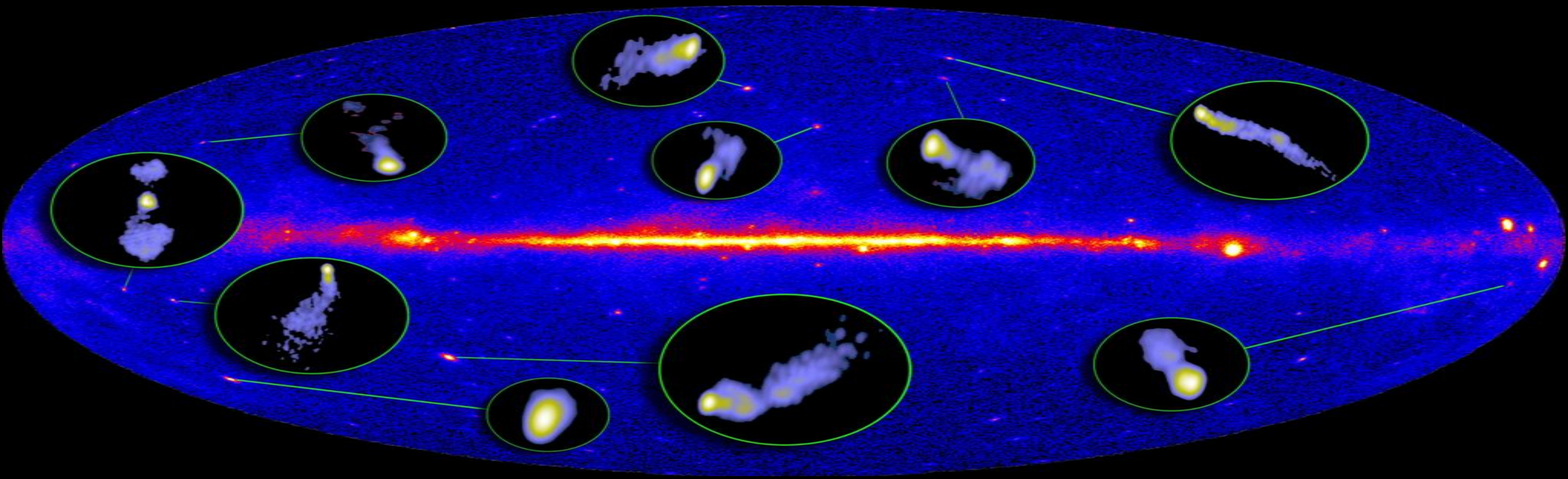
Extragalactic jets from the point of view of radio astronomy



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LLAMA

NAT
Núcleo de Astrofísica Teórica

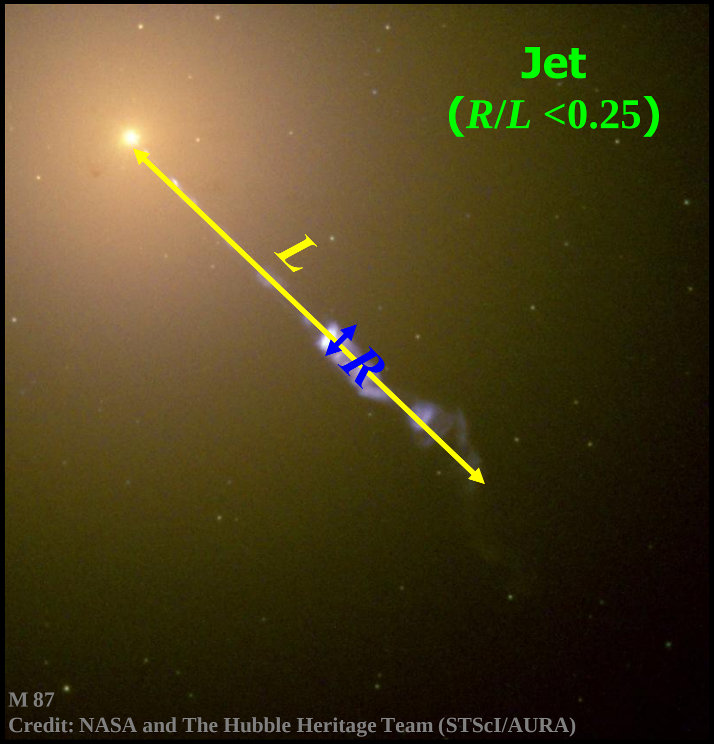
XVI IAG/USP Advanced School on Astrophysics
Radioastronomy, Galaxies and Clusters at High-z
November 4-9, 2012 – Itatiba,SP, Brazil

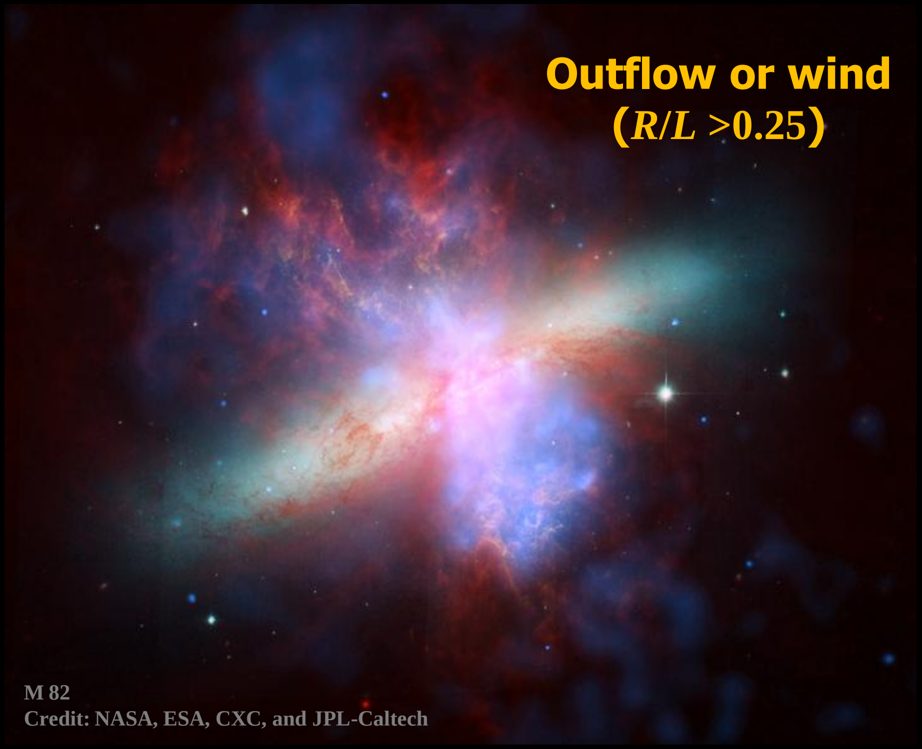
Outline

- Astrophysical jets: a basic overview
- Extragalactic jets in radio frequencies
- Jet kinematics of parsec-scale radio jets
- Some statistical aspects of parsec-scale radio jets
- Deriving structural parameters of VLBI jet components
- Final remarks

Astrophysical jets: a basic overview

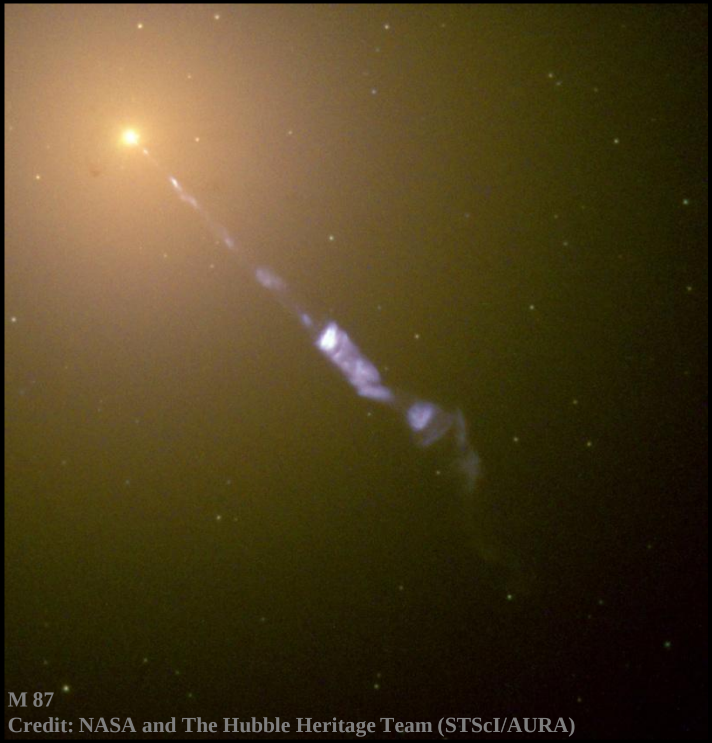
- What is an astrophysical jet???
- Basically, a stream of particles. According to Bridle & Perley (1984), to be termed jet, the candidate must be:
    i. at least four times as long as it is wide;





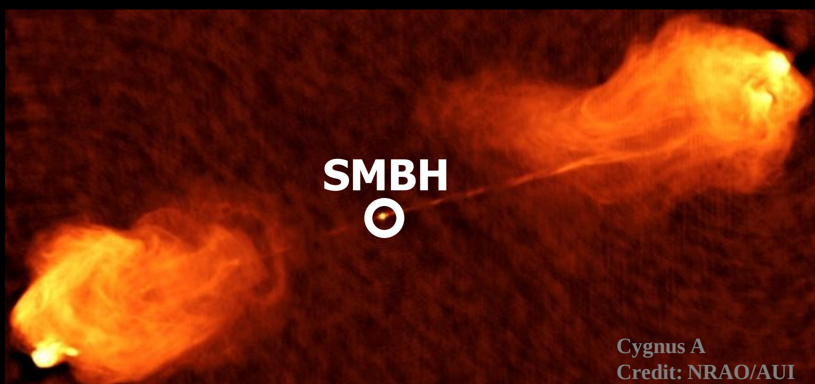
Astrophysical jets: a basic overview

- According to Bridle & Perley (1984), to be termed jet, the candidate must be:
  ii. separable at high resolution from other standard structures either spatially or by brightness contrast;

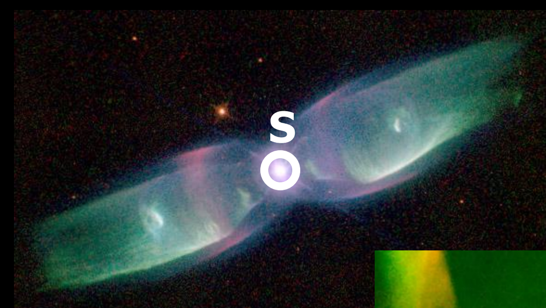


Astrophysical jets: a basic overview

- According to Bridle & Perley (1984), to be termed jet, the candidate must be:
  - iii. aligned with the compact core when the former is close to it;

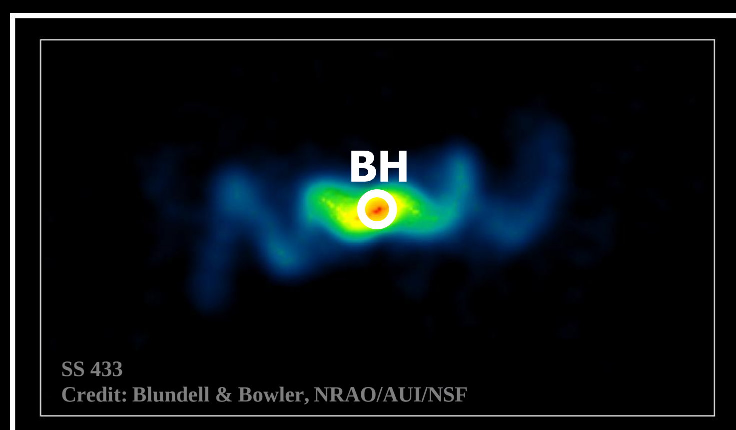


Cygnus A
Credit: NRAO/AUI

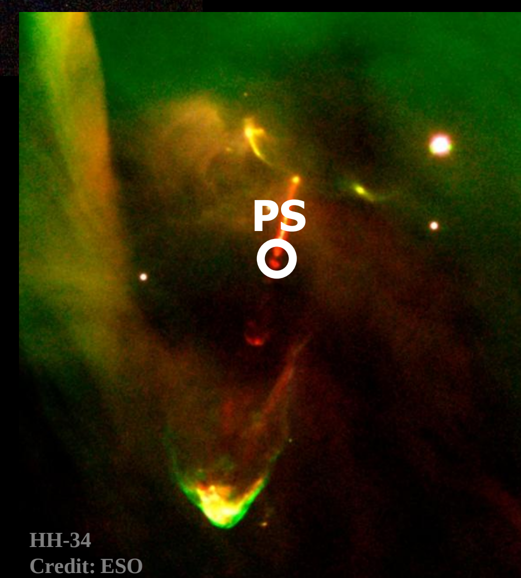


M2-9
Credit: Bruce Balick (University of Washington), Vincent Icke (Leiden University, The Netherlands), Garrelt Mellema (Stockholm University), and NASA

Crab Nebulae
Credit: NASA, HST, CXC, ASU/J. Hester et al.



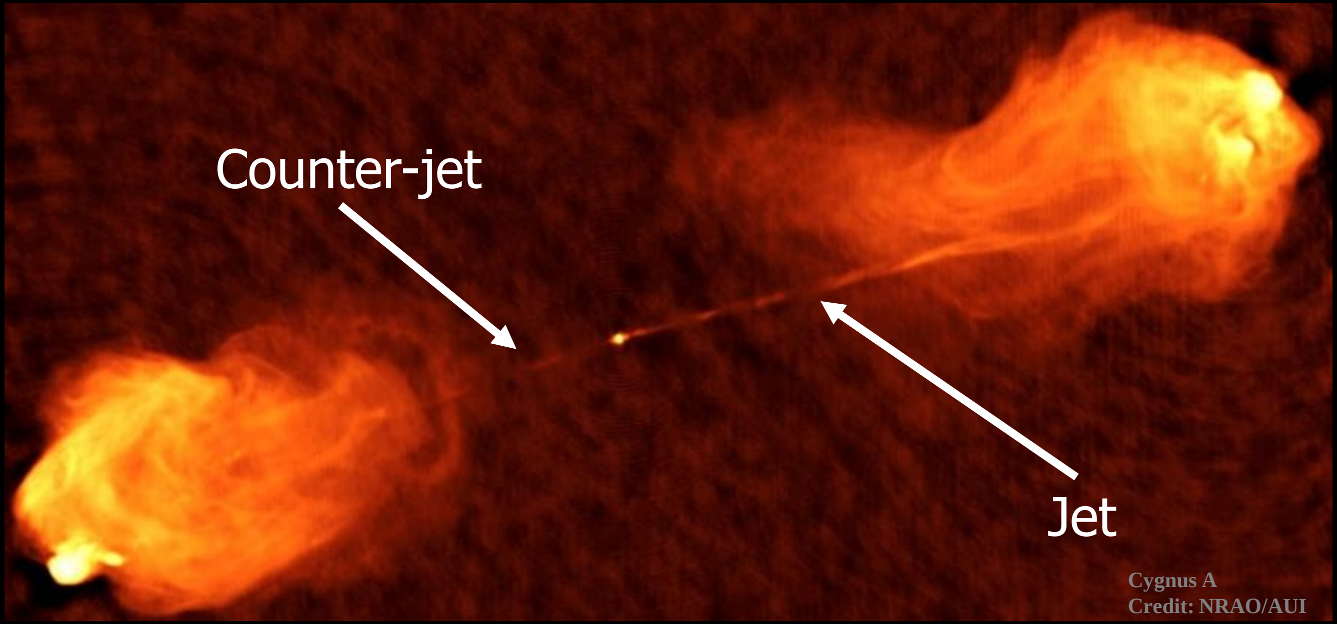
SS 433
Credit: Blundell & Bowler, NRAO/AUI/NSF



HH-34
Credit: ESO

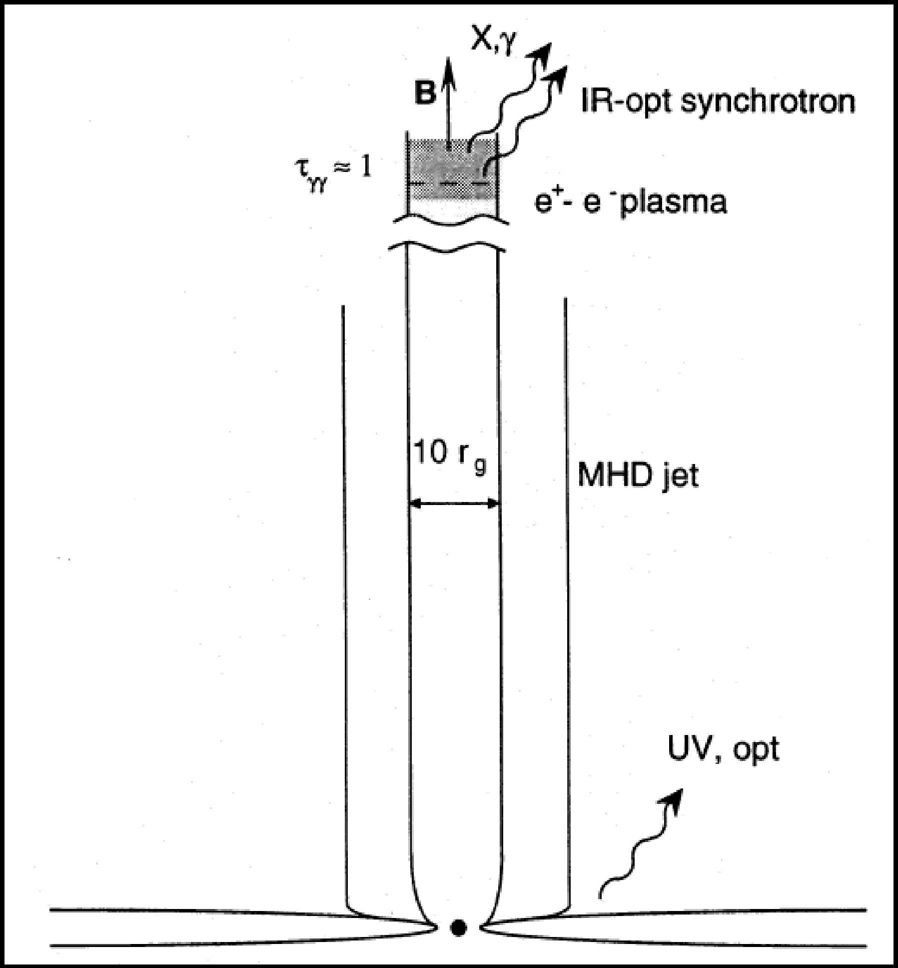
Astrophysical jets: a basic overview

- Let me include an extra item:
    iv. to be termed jet, the candidate must be pointing toward an hypothetical observer; otherwise, it is a counter-jet.



Astrophysical jets: a basic overview

- A plenty of models (e.g., Blandford & Znajek 1977, Blandford & Payne 1982; Shu et al. 1994; Livio et al. 2003; de Gouveia dal Pino & Lazarian 2005);
- Basic ingredients behind jet formation:
  - Accretion disc;
  - Central object dominating the dynamics of the disc;
  - Large scale magnetic field;
  - BH rotation (???).

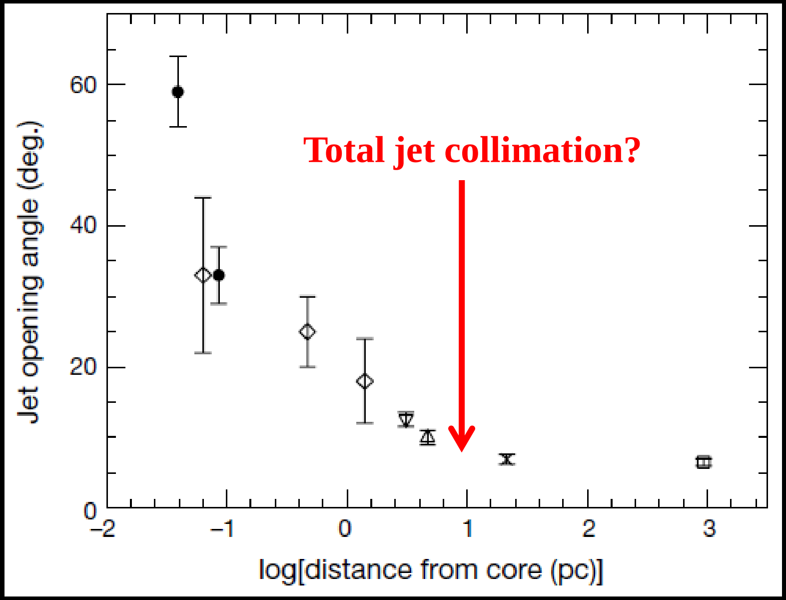


Marcowith, Henri & Pelletier (1995)

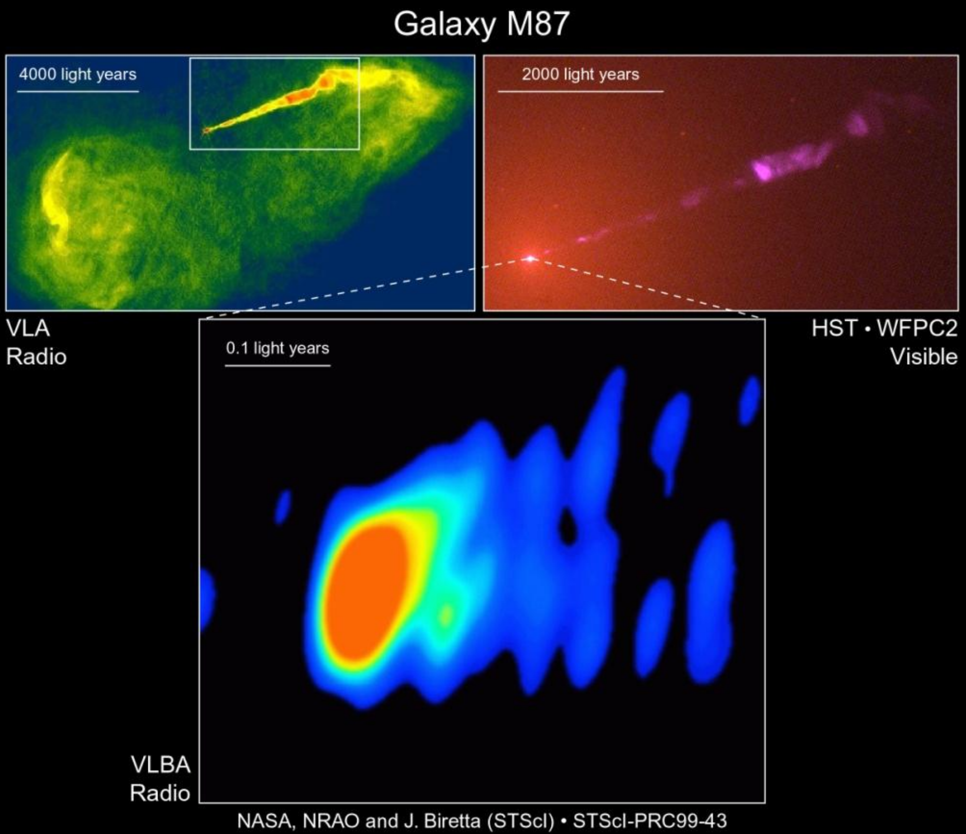
Astrophysical jets: a basic overview

- Jet is not necessarily collimated at all scales;

Jet collimation process in M87 (Junor, Biretta & Livio 1999):



(Junor, Biretta & Livio 1999, Nature, 401, 891)



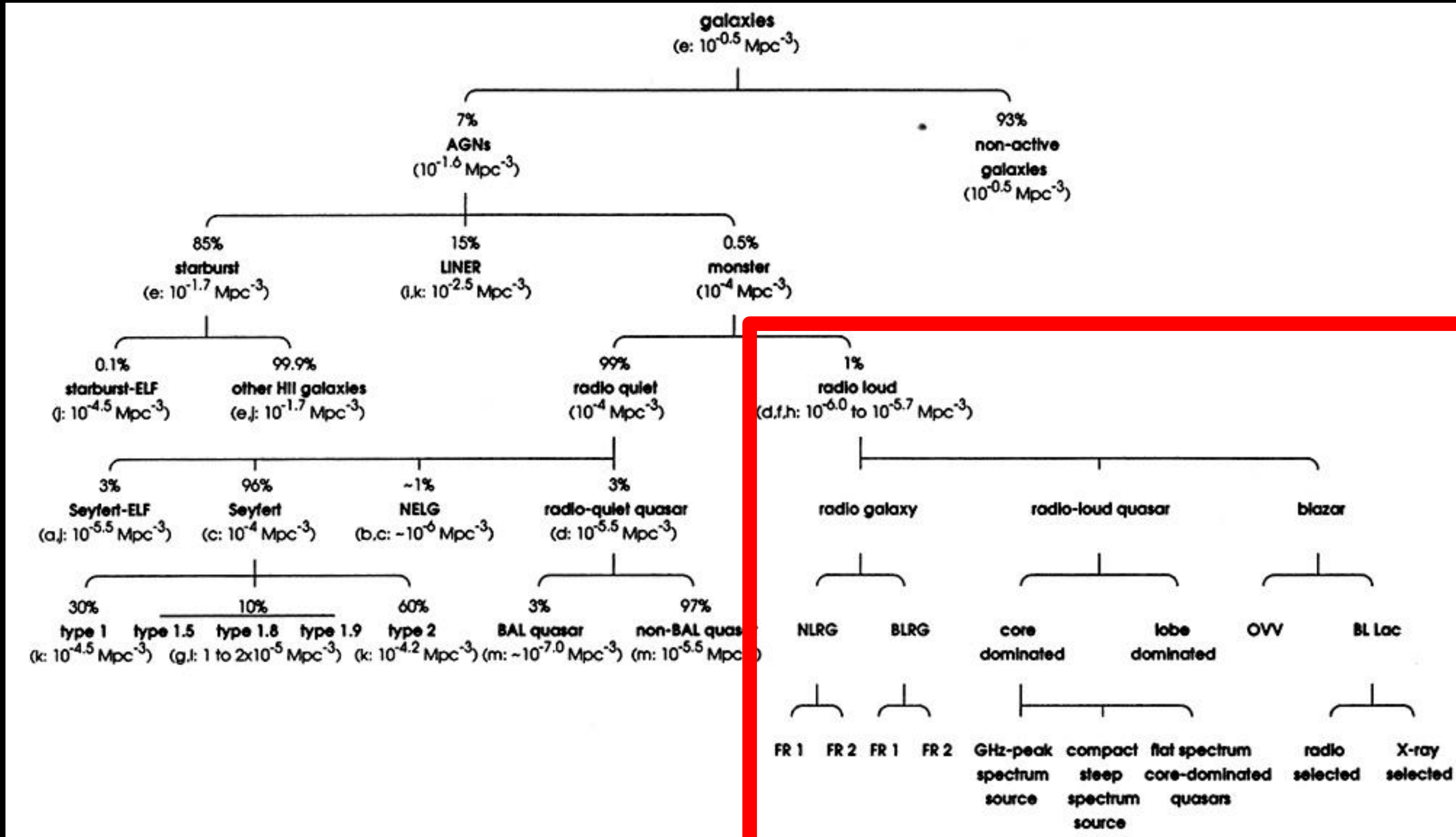
Extragalactic jets in radio frequencies

- Let us concentrate our discussion on extragalactic jets…
- Where can these jets be found???

Basically in radio-loud AGNs!

For a general review on unified model for radio-loud sources, see Urry & Padovani (1995).

Extragalactic jets in radio frequencies



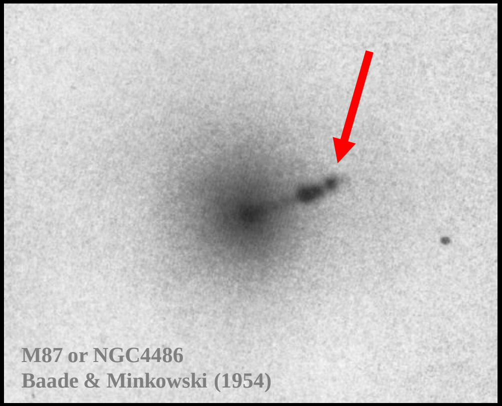
a: Allen et al. 1991
b: Antonucci 1993
c: Edelson 1987
d: Hawkins & Véron 1993
e: Huchra 1977
f: Osterbrock 1987
g: Osterbrock & Dahari 1983
h: Peacock, Miller & Longair 1986
i: Reichert et al. 1992
j: Soifer et al. 1986
k: Spinoglio & Malkan 1989
l: Ulvestad & Wilson 1984
m: Weymann, Carswell & Smith 1981

AGN = active galactic nucleus
BAL = broad-absorption line
BCDG = blue compact dwarf galaxy
BL Lac = BL Lac object
BLRG = broad-line radio galaxy
ELF = extremely luminous far-infrared galaxy
FR 1 = Fanaroff - Riley class I radio galaxy
FR 2 = Fanaroff - Riley class II radio galaxy
LINER = low-ionization nuclear emission-line region galaxy
NELG = narrow emission line galaxy (aka narrow-line X-ray galaxy). Most likely obscured Seyfert galaxies.
NLRG = narrow-line radio galaxy
OVV = optically-violent variable quasar

(Roy 1994)

Extragalactic jets in radio frequencies

- A (very) brief historical timeline about extragalactic jets…
- First noted observationally in M87 (Curtis 1918) and analyzed later by Baade & Minkowski (1954);



- At radio frequencies:
  - Jet-like feature detected by Hazard et al. (1963) using lunar occultation method (two components – core and jet – separated by ~20”);
  - Detection of two components in M87 by Miley et al. (1970): one coinciding with the optical nucleus, while the other with the tip of the optical jet;
  - First detection of superluminal motions in parsec-scale jets obtained by Whitney et al. (1971) and Cohen et al. (1971).

Extragalactic jets in radio frequencies

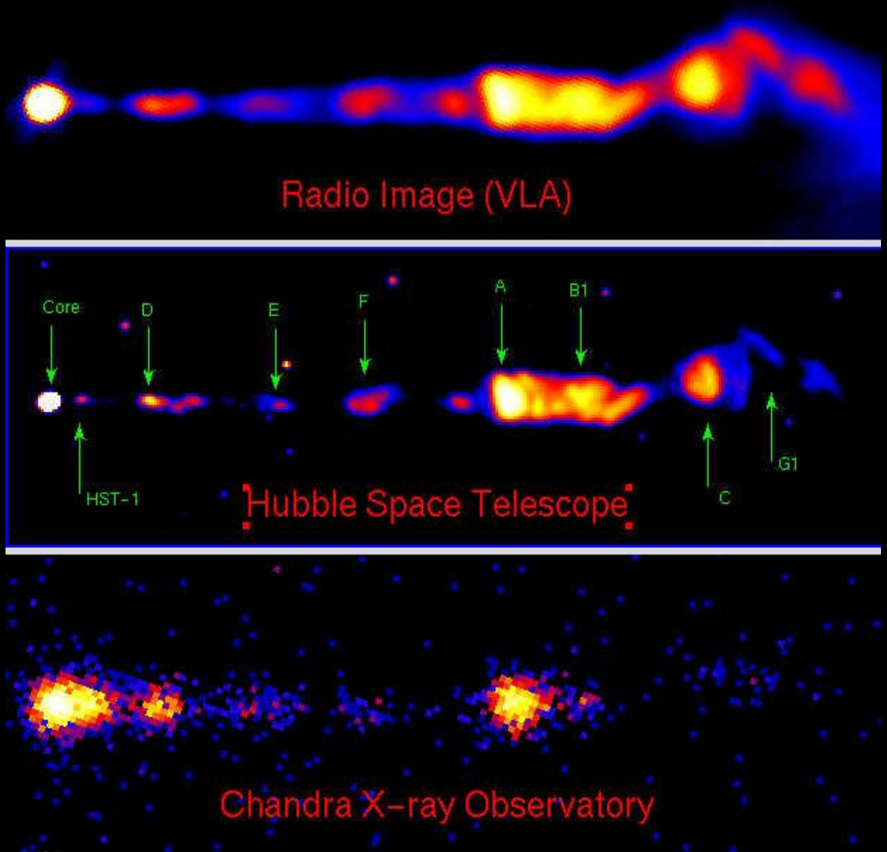
- Kiloparsec-scale jets may be detected at different wavelengths (e.g., Lelievre et al. 2004; Jester et al. 2007; Worrall 2009):

But this is not the rule!!!

(less than 20 extragalactic jets has optical counterpart detected)

Why?

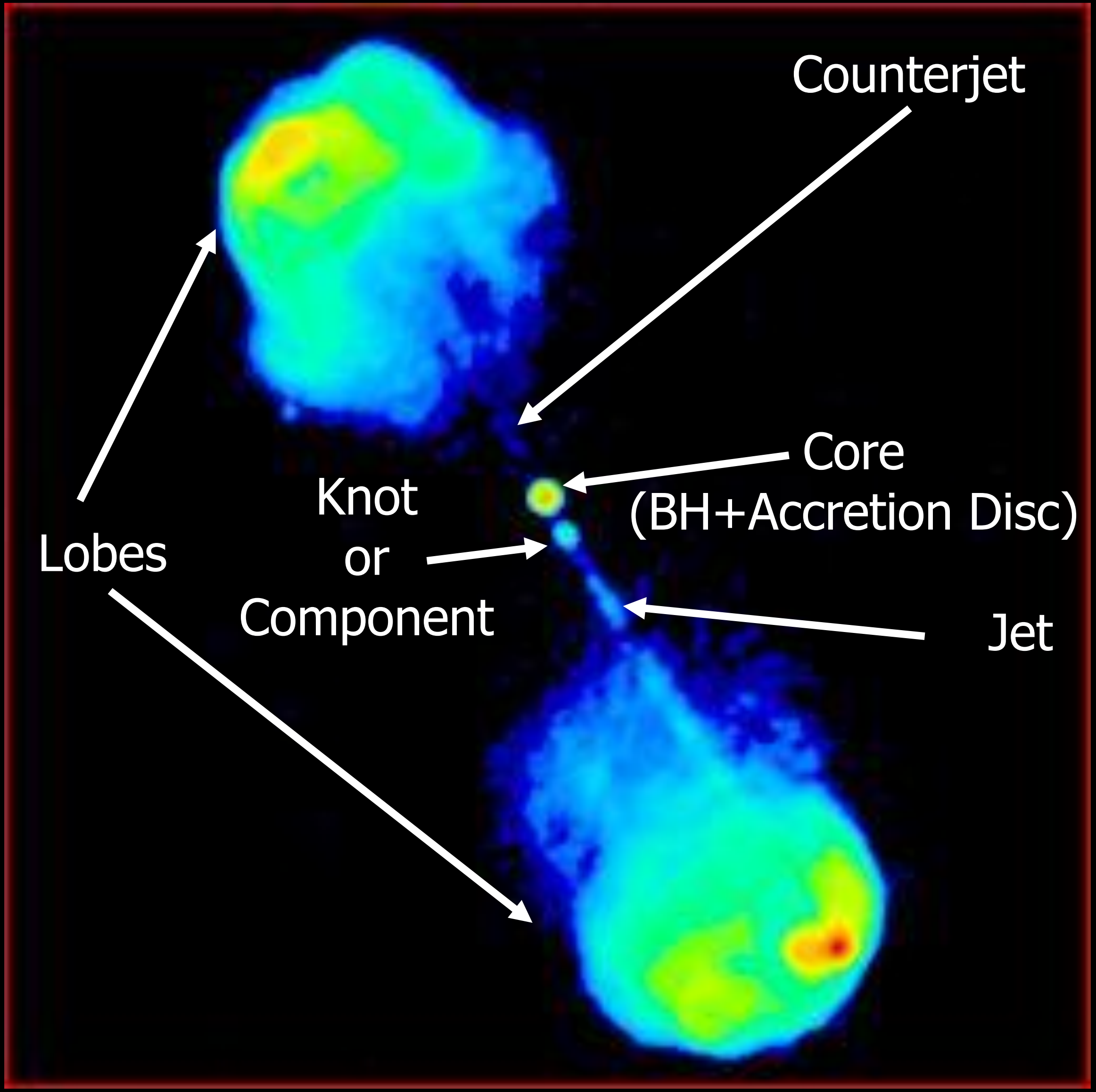
As they are associated to powerful radio sources, relativistic beaming may be playing a significant role on detection (e.g., Scarpa & Urry 2002; Jester 2003).



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

Extragalactic jets in radio frequencies

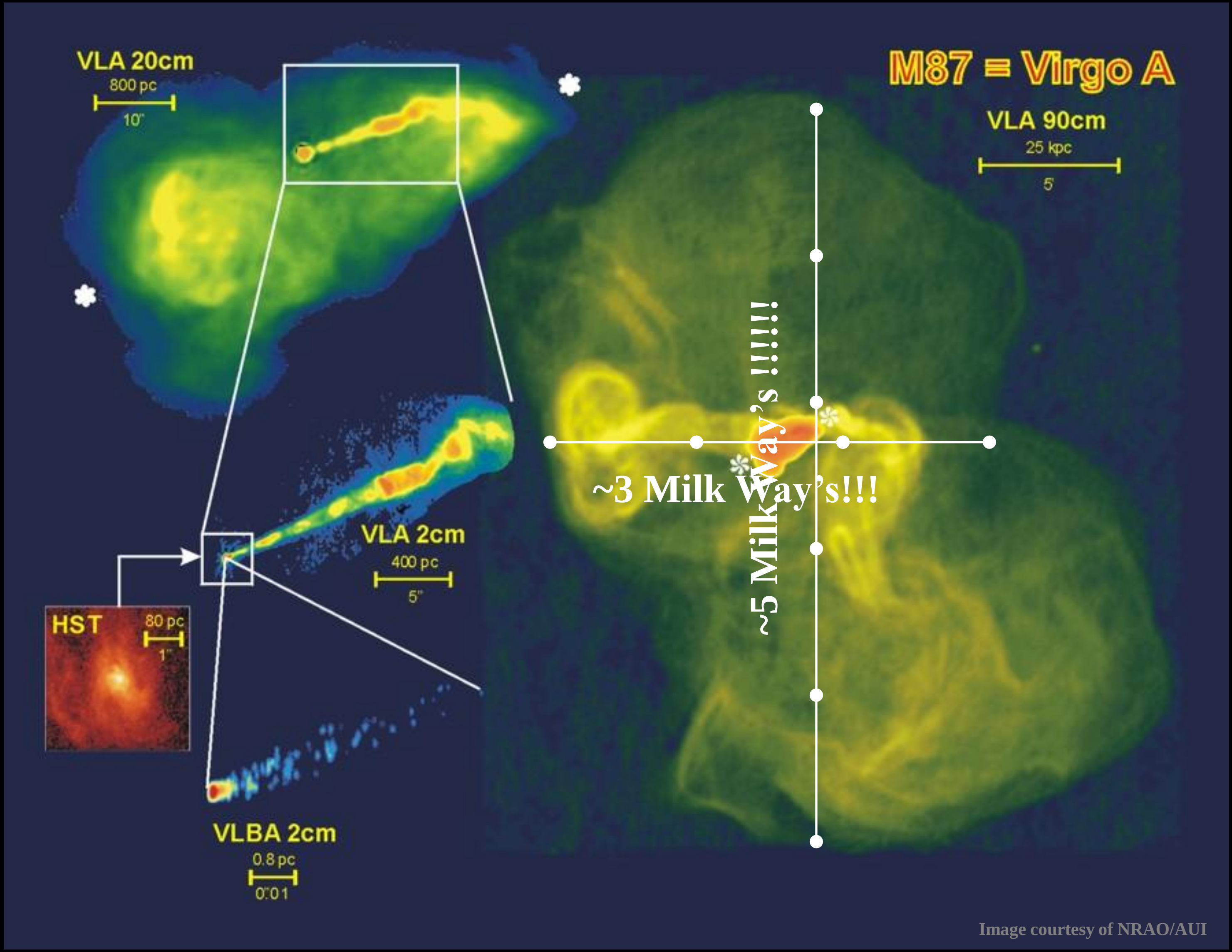
Typical radio morphology of a kiloparsec-scale jet



3C47
Credit: http://www.jb.man.ac.uk/atlas/object/3C47.html

Extragalactic jets in radio frequencies

But it can be much more complex: morphology dependence with scale



Extragalactic jets in radio frequencies

- How obtain radio maps of extragalactic jets at kpc-scale?
- Single dish observation???

No! Poor angular resolution...

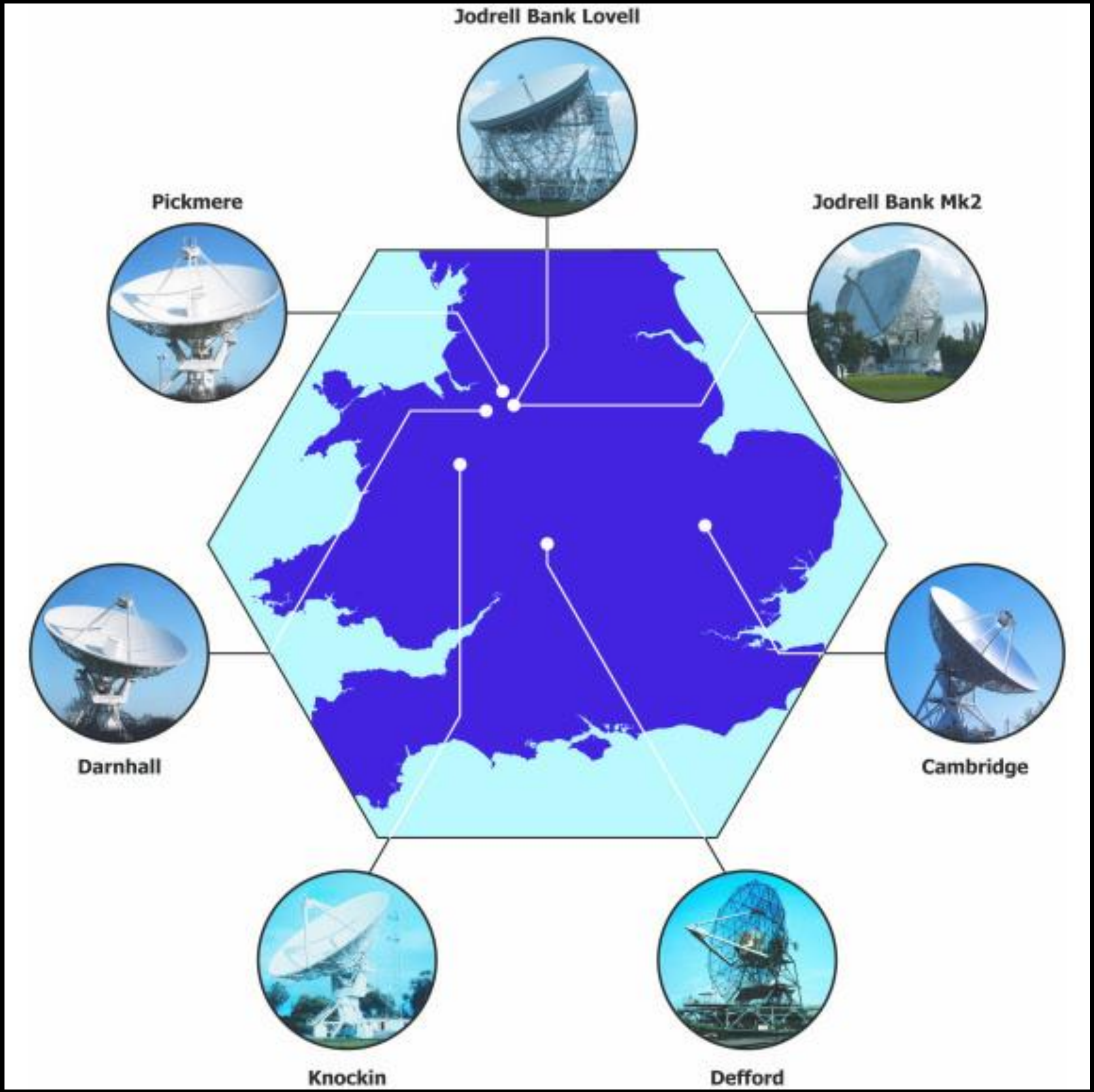
$$\theta = 1{,}22 \frac{\lambda}{D} \text{ rad}$$

e.g., for λ = 1.36 cm (22 GHz) and D = 13.7 m, $\theta \sim 4'$
(worse than typical human eye's resolution)

- What to do?
- Array of telescopes…

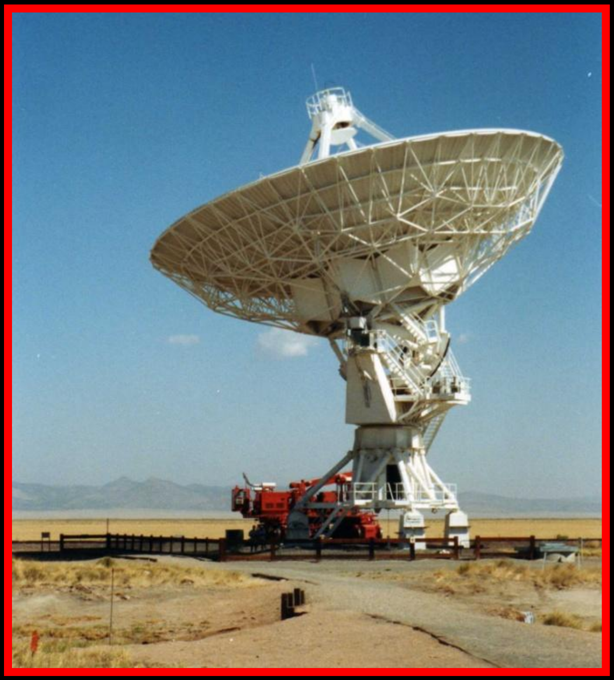
Australia Telescope Compact Array (ATCA)

Extragalactic jets in radio frequencies



Multi-Element Radio-Linked Interferometer (MERLIN)

Extragalactic jets in radio frequencies

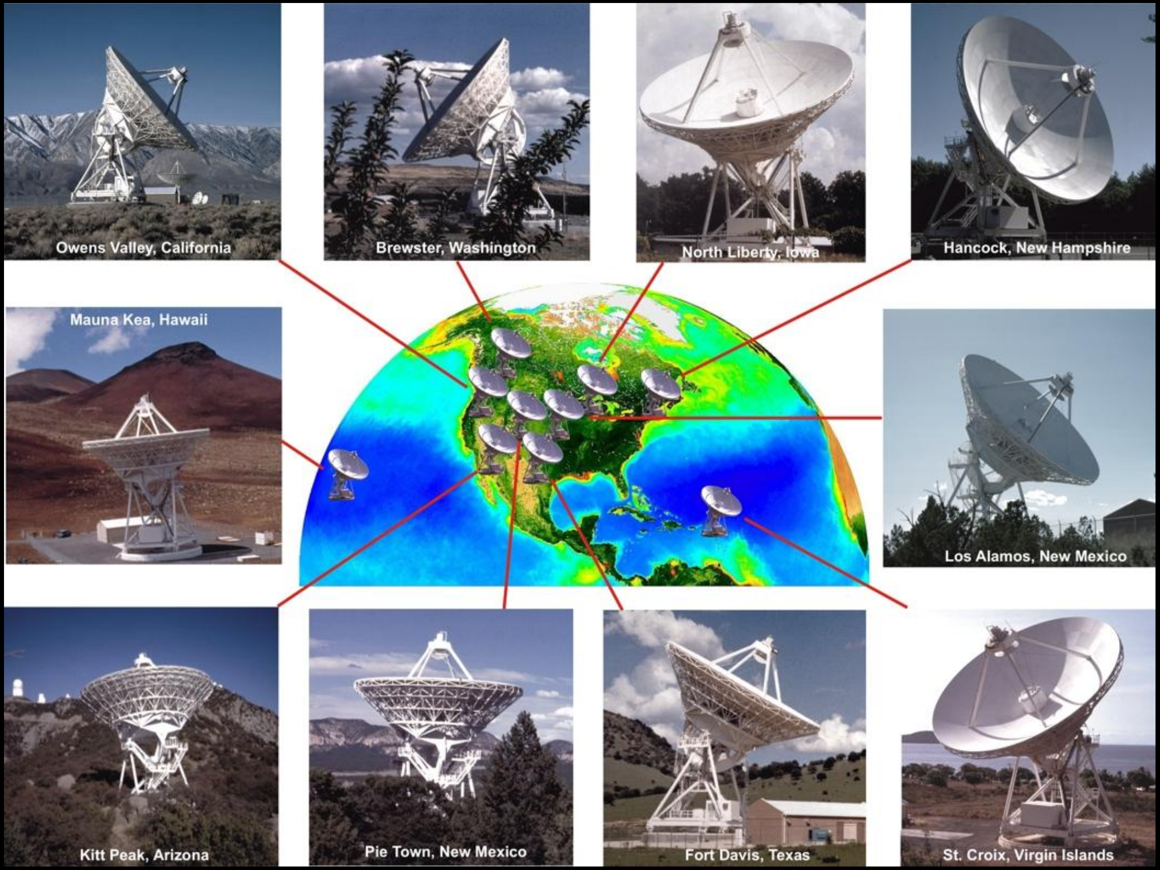


Very Large Array (VLA)

Jet kinematics of parsec-scale radio jets

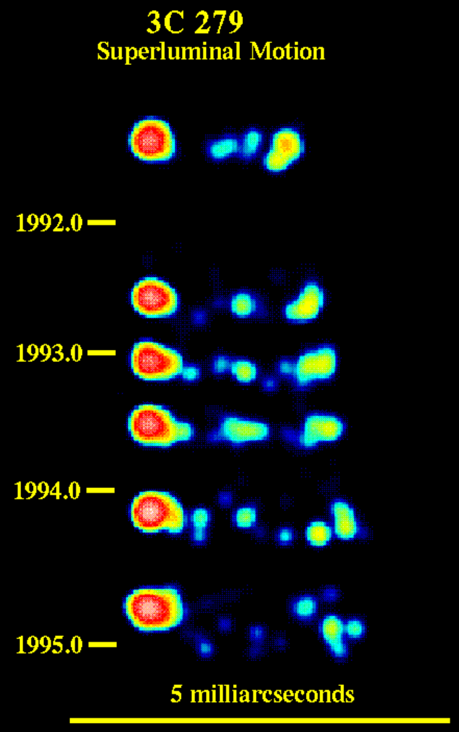
- How obtain radio maps of extragalactic jets at pc-scale?
- Array of radio telescopes separated at continental distances: Very Large Baseline Interferometry (VLBI).

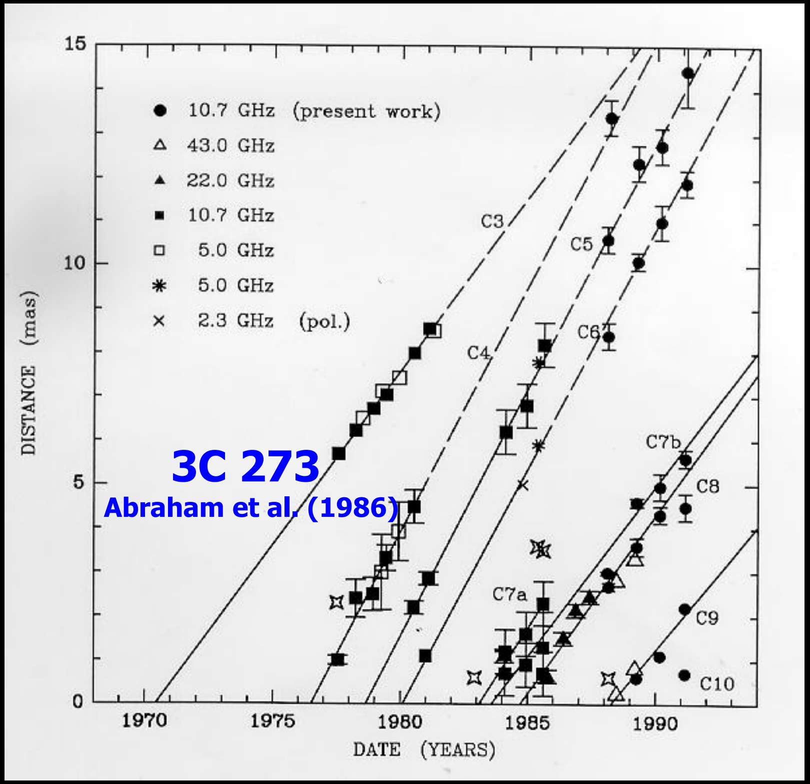
Very Large Baseline Array (VLBA)



Jet kinematics of parsec-scale radio jets

- Proper motion (μ):
  - Core-component angular separation as a function of time;
  - Unit (in VLBI): mas/ano;



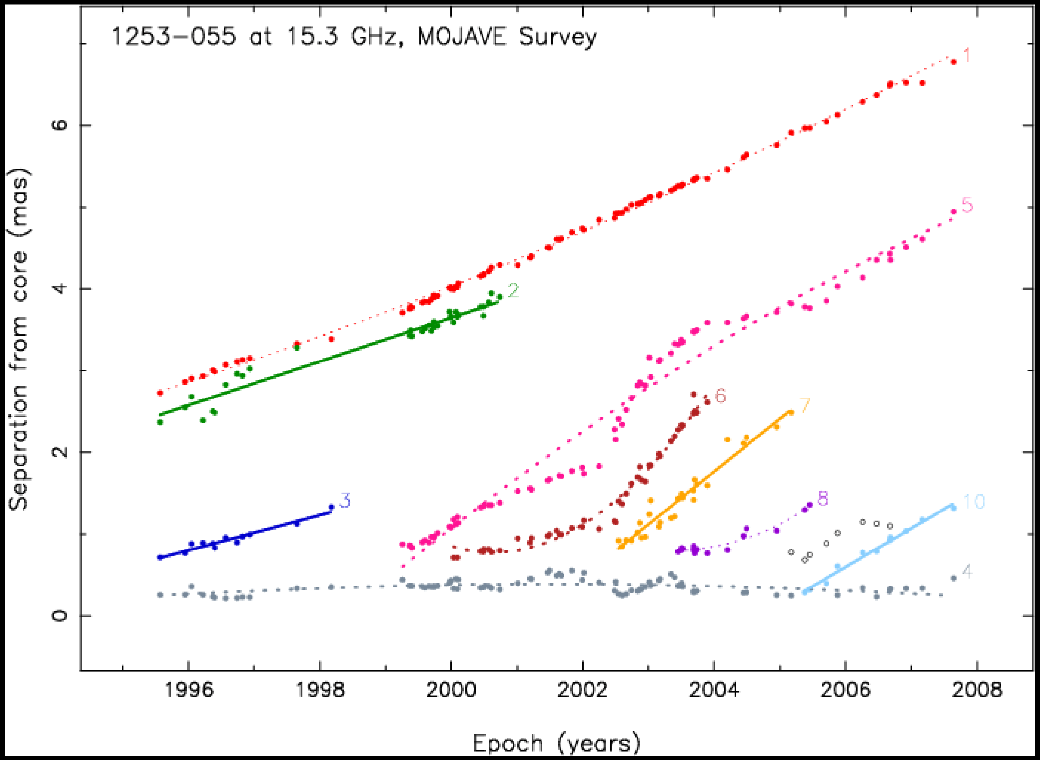


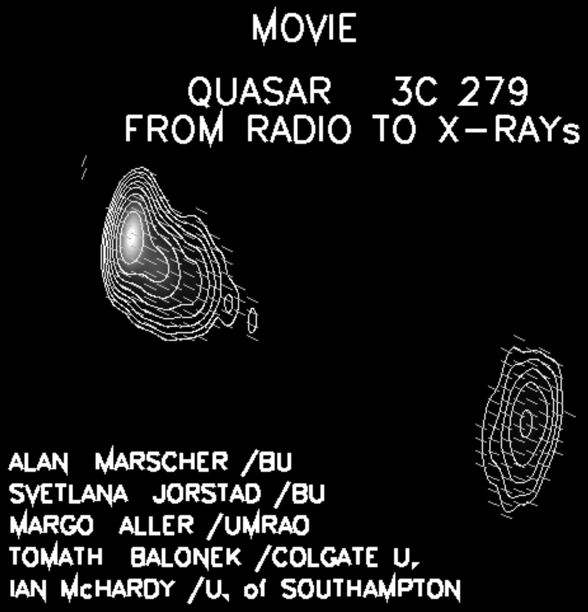
- Apparent speed(β_{app}):
  - Source distance must be known;
  - Some cosmology must be assumed a prior;

$$\beta_{\mathrm{app}} = \frac{D_{\mathrm{L}}}{(1+z)} \frac{\mu}{c}$$

Jet kinematics of parsec-scale radio jets

- Another example: the quasar 3C 279.





- 3C 279 is one of the AGNs that exhibits superluminal motions in its jet.

Jet kinematics of parsec-scale radio jets

- Superluminal motions:
  - First detected in quasars 3C 273 e 3C 279 (Whitney et al. 1971; Cohen et al. 1977; Cotton et al. 1979);

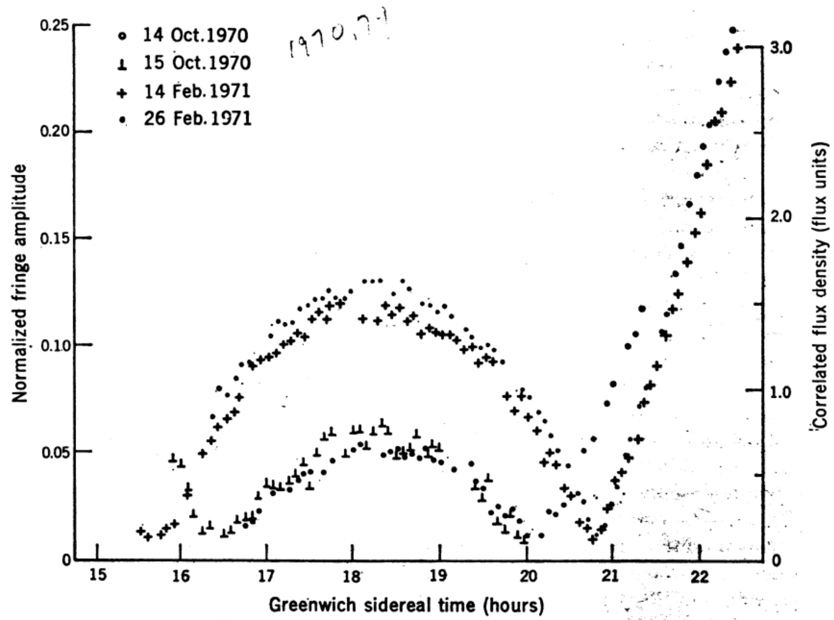


Fig. 1. Fringe-amplitude data from observations of 3C 279 with the Goldstone-Haystack interferometer. Each point is based on 110 seconds of integration.

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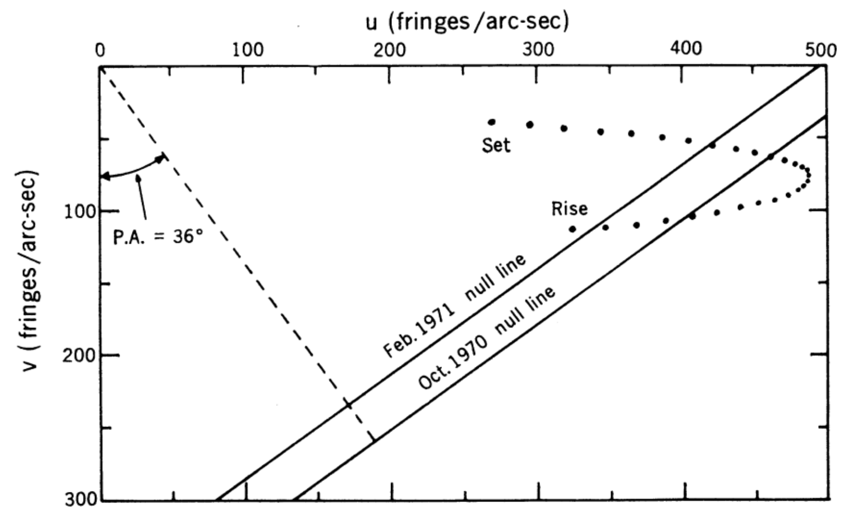

Fig. 4. The *u-v* plane (*1*) representation of the Goldstone-Haystack observations of 3C 279. The dotted curve shows the interferometer resolution at 15-minute intervals from 15 hours 30 minutes to 22 hours 30 minutes Greenwich sidereal time. The solid lines connect the times at which nulls were observed in October 1970 and in February 1971. The distances from the origin to the solid lines are inversely proportional to the separations of the components of the putative double source at the two times of observation. [The position angle (*P.A.*) was assumed to remain constant.]

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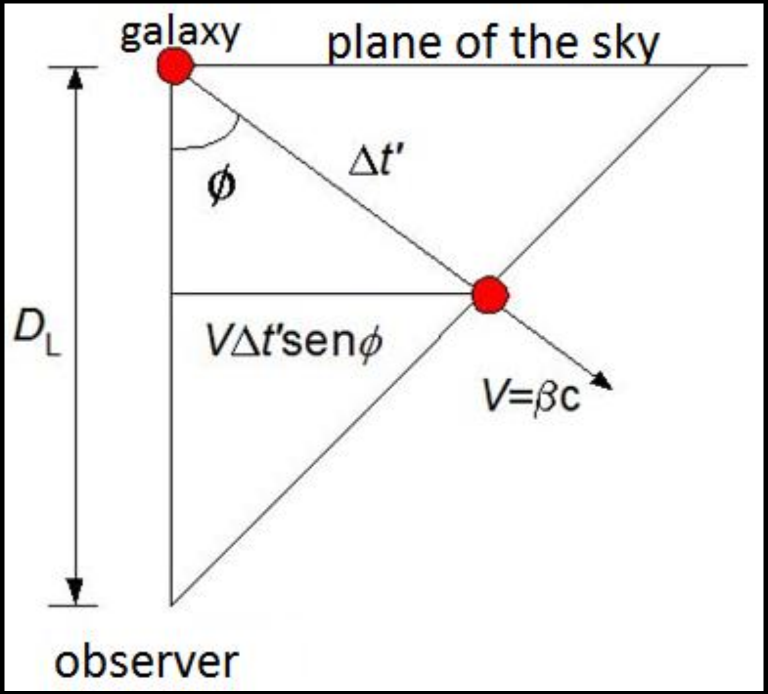
  - Whitney et al. (1971): angular displacement of 1.55 ± 0.03 mas in four months $\Rightarrow$ $\beta_{app} = v/c = 10 \pm 3$!

Jet kinematics of parsec-scale radio jets

- Superluminal motions:
  - Detected in several objects later;
  - Typical apparent speeds range from 3 e 10*c*, reaching ~50*c* (Lister et al. 2009);
  - Reason: component moving close to l.o.s. with $v{\sim}c$ (Rees 1966);
  - Component ejected at time $t_0 = 0$;
  - Emitted radiation at t_0 is detected by an observer at a luminosity distance D_L after an interval Δt:

$$\Delta t = t_1 - t_0 = \frac{D_L}{c}$$



Jet kinematics of parsec-scale radio jets

- Component recedes a distance (from the core) of $V\Delta t'$ after an interval $\Delta t'$, producing a projected displacement on the plane of the sky:

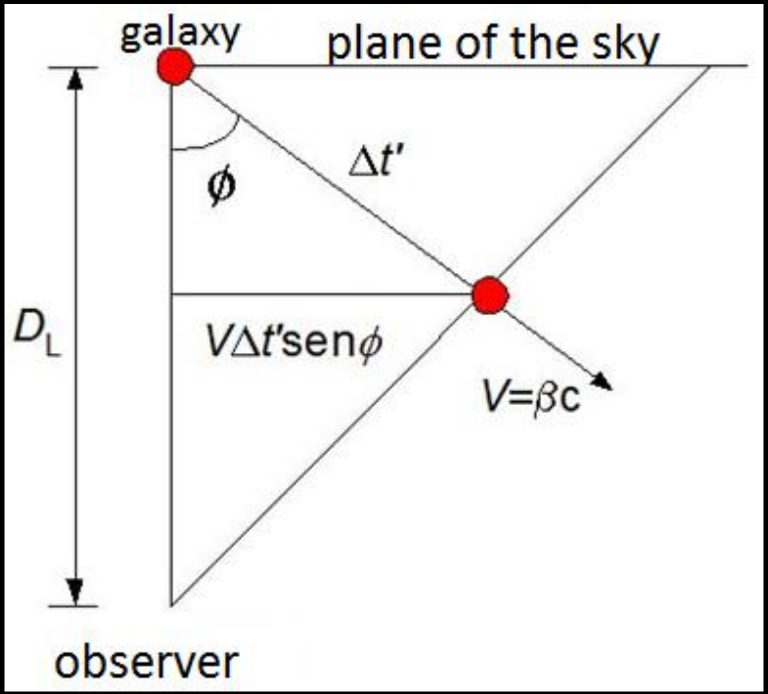
$$L_{\rm proj} = V\Delta t' \sin\phi$$

- Radiation emitted after $\Delta t'$ will be detected by the observer at instant t_2:

$$t_2 = \Delta t' + \frac{(D_{\rm L} - V\Delta t' \cos\phi)}{\rm c}$$

- The elapsed time between t_2 e t_1 corresponds to:

$$\Delta t = t_2 - t_1 = \Delta t'(1 - \beta\cos\phi)$$

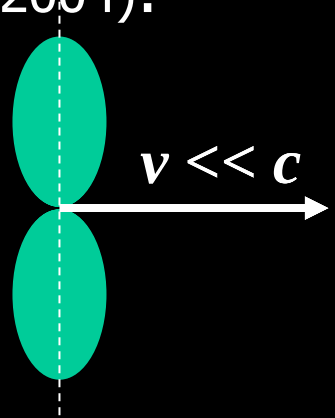


- Thus, the apparent speed of the jet knot is given as:

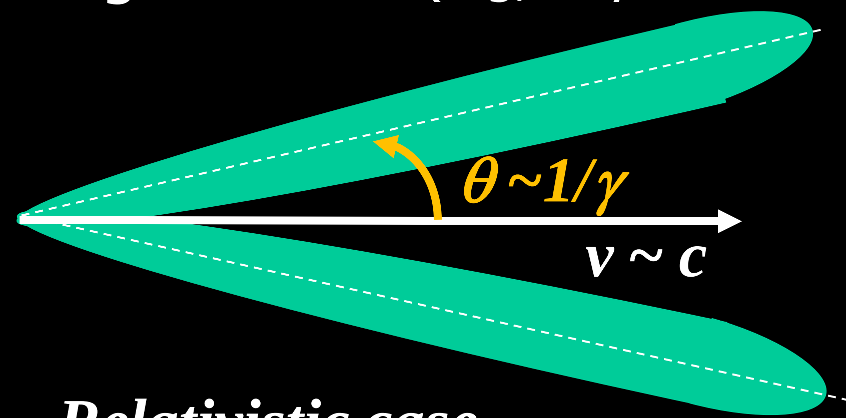
$$\beta_{\rm app} = \frac{L_{\rm proj}}{{\rm c}\Delta t} = \frac{\beta\sin\phi}{(1 - \beta\cos\phi)}$$

Jet kinematics of parsec-scale radio jets

- Other consequences of relativistic motions are the beaming and Doppler boosting effects (e.g, Rybicki & Lightman 2004):



Non-relativistic case



Relativistic case

$$\gamma = \left(1-\beta^2\right)^{-1/2} \equiv \text{Lorentz factor}$$

$$\delta = \frac{1}{\gamma\left(1-\beta\cos\phi\right)} \equiv \text{Doppler boosting factor}$$

$\uparrow v \Rightarrow \uparrow \gamma \Rightarrow \downarrow \theta \Rightarrow$ **Beaming**

$\uparrow v \Rightarrow \uparrow \gamma \Rightarrow \uparrow \delta \Rightarrow$ **Doppler boosting**

- Blandford & Lind (1985): $S_{obs} = S_0 \delta^p$

$p = 2 + \alpha$ *(continuous jet)*
$p = 3 + \alpha$ *(clumpy jet)*
$S_\nu \propto \nu^{-\alpha}$

Some statistical aspects of parsec-scale radio jets

- MOnitoring of Jets in Active Galactic Nuclei with VLBA Experiments (MOJAVE) (e.g., Lister et al. 2009):
  - To investigate the pc-scale jet kinematics of a complete flux-density-limited sample of 135 AGNs in the northern sky at 2 cm;
  - Analyzed data set spans 13 years of observations since 1994 (observations are still ongoing);
  - Kinematical parameters of jet knots derived from (u,v)-plane, assuming two-dimensional Gaussian shape for them (mainly elliptical Gaussians for core and circular ones for components);
- Important! MOJAVE team provides a public archive of images and other products related to those jets (http://www.physics.purdue.edu/MOJAVE/index.html).

Some statistical aspects of parsec-scale radio jets

- Some specific results concerning jet kinematic (Lister et al. 2009):

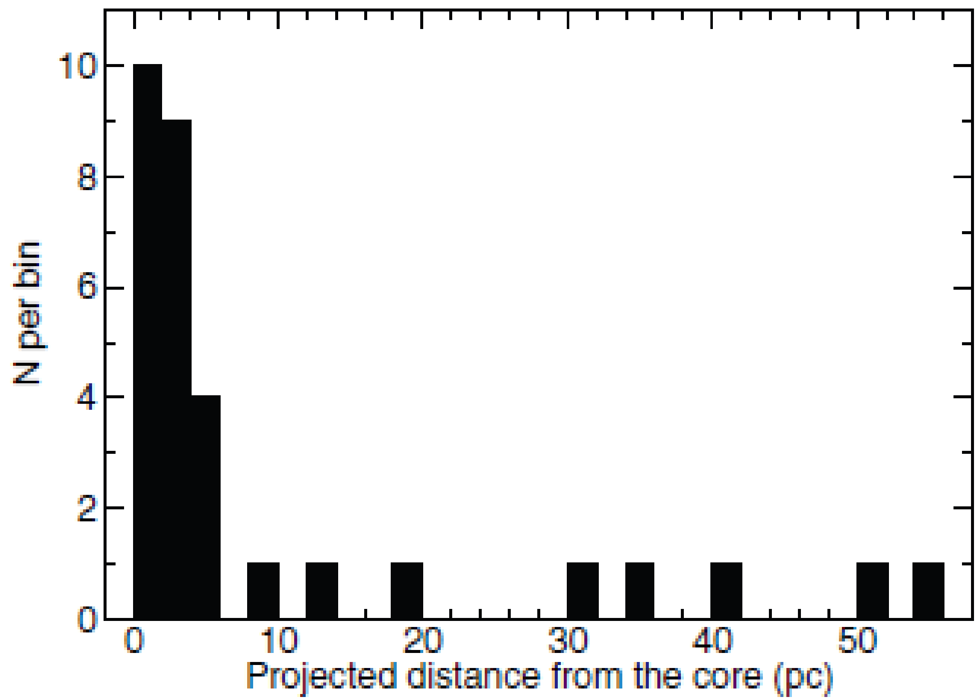


Figure 5. Distribution of projected distance from the core for LPS jet features in the MOJAVE sample.

Low pattern speed knots located mostly inside 8 pc from the core.

Standing shocks in the flow or low viewing angle effect?

Some statistical aspects of parsec-scale radio jets

- Some specific results concerning jet kinematic (Lister et al. 2009):

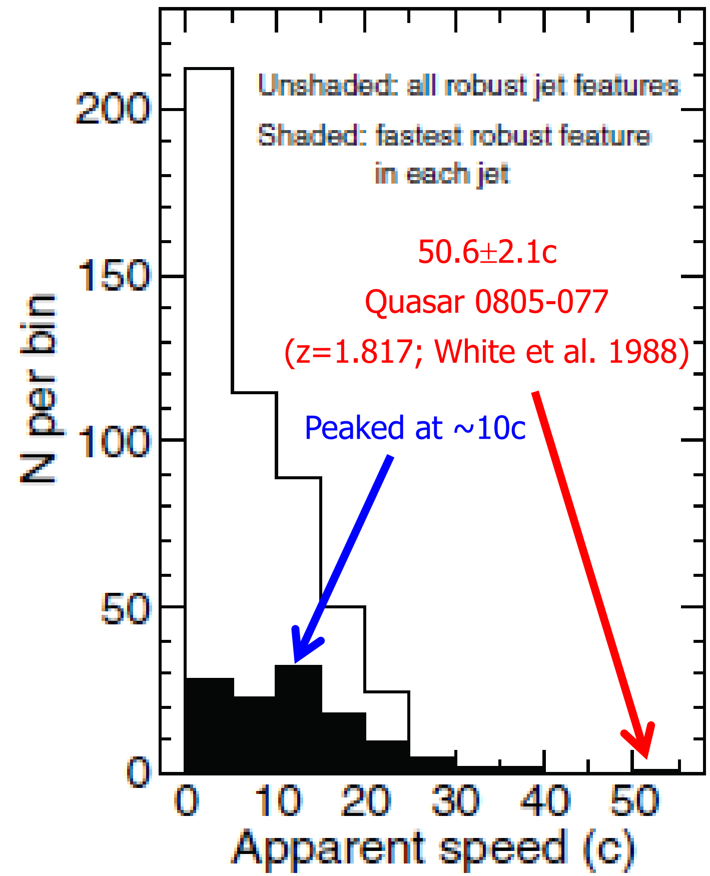


Figure 7. Distribution of apparent speed for 502 robust jet features in MOJAVE AGN with measured redshifts. The shaded histogram represents the distribution of the fastest robust feature in each jet.

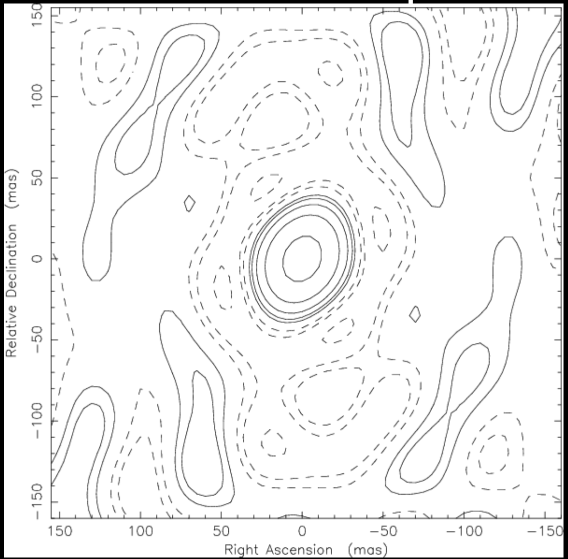
See also Piner et al. (2012)

Deriving structural parameters of VLBI jet components

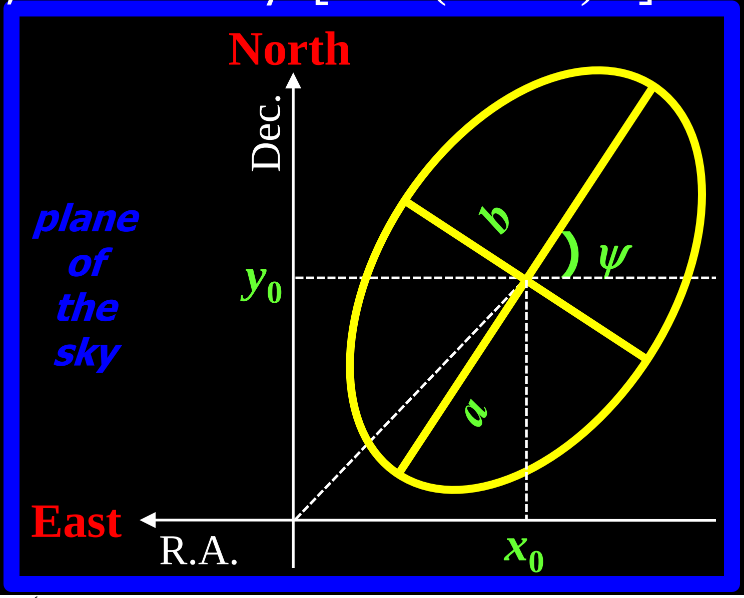
- Regular model fitting tasks used in the analyses of interferometric images suffer from some limitations:
  - Impossibility to fit simultaneously more than 4 components;
  - Gradient-based fitting methods (prone to find a local minimum solution if we do not choose appropriately the initial parameters);
  - Depend on initial guess for the model parameter values;
  - Number of components is not constrained by the own fitting procedure.
- How to overcome such limitations?
- Cross-entropy method for continuous multi-extremal optimization (Rubenstein 1999; Kroese et al. 2006; Caproni et al. 2009; Monteiro et al. 2010, 2011, Caproni et al. 2011, 2012);

Deriving structural parameters of VLBI jet components

- Caproni et al. (2011, ApJ, 736, 68):
  - ➢ CE model fitting implemented to work out in the image plane;
  - ➢ Shape of the jet knots modeled as 2D elliptical Gaussian sources;
    - ✓ Why? Dirty beam usually has elliptical shape (convolution between elliptical 2D Gaussian and punctual source ⇒ 2D elliptical source);
    - ✓ Gaussian parameters: intensity (I_0) and center coordinates (x_0 and y_0) of the peak, major axis (a), eccentricity [$\varepsilon = (1-b^2/a^2)^{1/2}$] and structural position angle (ψ);



(Vermeulen et al. 2006, A&A, 447, 489)



$$I(x,y) = I_0 e^{-1/2\left\{a^{-2}\left[(x-x_0)\cos\psi+(y-y_0)\sin\psi\right]^2+b^{-2}\left[-(x-x_0)\sin\psi+(y-y_0)\cos\psi\right]^2\right\}}$$

Deriving structural parameters of VLBI jet components

- If there are N_s sources in an image with N_{pixel} pixels, there are $6N_s$ parameters to be determined;
- How is it done via CE technique?
  i. Choice of the upper and lower limits for the tentative values of the Gaussian parameters, keeping them fixed during optimization processes;

$$
\begin{gathered}
x_{\min} \le x_i \le x_{\max} \\
y_{\min} \le y_i \le y_{\max} \\
a_{\min} \le a_i \le a_{\max} \\
\varepsilon_{\min} \le \varepsilon_i \le \varepsilon_{\max} \\
\psi_{\min} \le \psi_i \le \psi_{\max} \\
I_{0_{\min}} \le I_{0_i} \le I_{0_{\max}} \\
\left(1 \le i \le N_s\right)
\end{gathered}
$$

Deriving structural parameters of VLBI jet components

ii. Normal random generation of the initial parameter sample composed of N tentative solutions, based on the mean of the pre-defined limits given in i):

considering just one source! $\Rightarrow$

$$\mathbf{X}_{ij}(0) = \begin{pmatrix} x_1 & y_1 & a_1 & \varepsilon_1 & \psi_1 & I_{0_1} \\ x_2 & y_2 & a_2 & \varepsilon_2 & \psi_2 & I_{0_2} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{N-1} & y_{N-1} & a_{N-1} & \varepsilon_{N-1} & \psi_{N-1} & I_{0_{N-1}} \\ x_N & y_N & a_N & \varepsilon_N & \psi_N & I_{0_N} \end{pmatrix}$$

iii. Selection of the N_{elite}-best sample based on the minimization of the merit function S_{prod} among N tentative solutions above:

$$S_{prod}(k) = \bar{R}(k) \times \frac{1}{N_{pixel}} \left\{ \sum_{m=1}^{N_{pixel}} \left[R_m(k) - \bar{R}(k) \right]^2 \right\},$$

where:

$$\bar{R}(k) = \frac{1}{N_{pixel}} \left[\sum_{m=1}^{N_{pixel}} R_m(k) \right].$$

$$R_m(k) = \left[I_m - M_m(k) \right]^2$$

Model versus data (observation)

Deriving structural parameters of VLBI jet components

iv. Random generation of updated parameter samples from the previous best N_{elite} candidates to be evaluated in the next iteration k:

$$\mathbf{X}_{ij}(k) = \overline{p}_j^{elite}(k-1) + \sigma_j^{elite}(k-1) G_{ij},$$

where:

$$\overline{p}_j^{elite}(k-1) = \frac{1}{N_{elite}} \sum_{i=1}^{N_{elite}} \mathbf{X}_{ij}^{elite}(k-1);$$

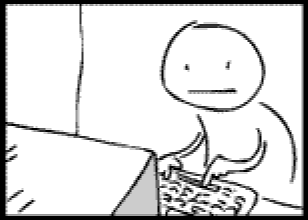
$$\sigma_j^{elite}(k-1) = \sqrt{\frac{1}{\left(N_{elite}-1\right)} \sum_{i=1}^{N_{elite}} \left[\mathbf{X}_{ij}^{elite}(k-1) - \overline{p}_j^{elite}(k-1)\right]^2};$$

$G_{ij} \equiv$ is matrix with random numbers generated from a zero-mean normal distribution with standard deviation of unity.

v. Optimization process repeats Steps (ii) and (iv) while, e.g., $k \le k_{\max}$.

Deriving structural parameters of VLBI jet components

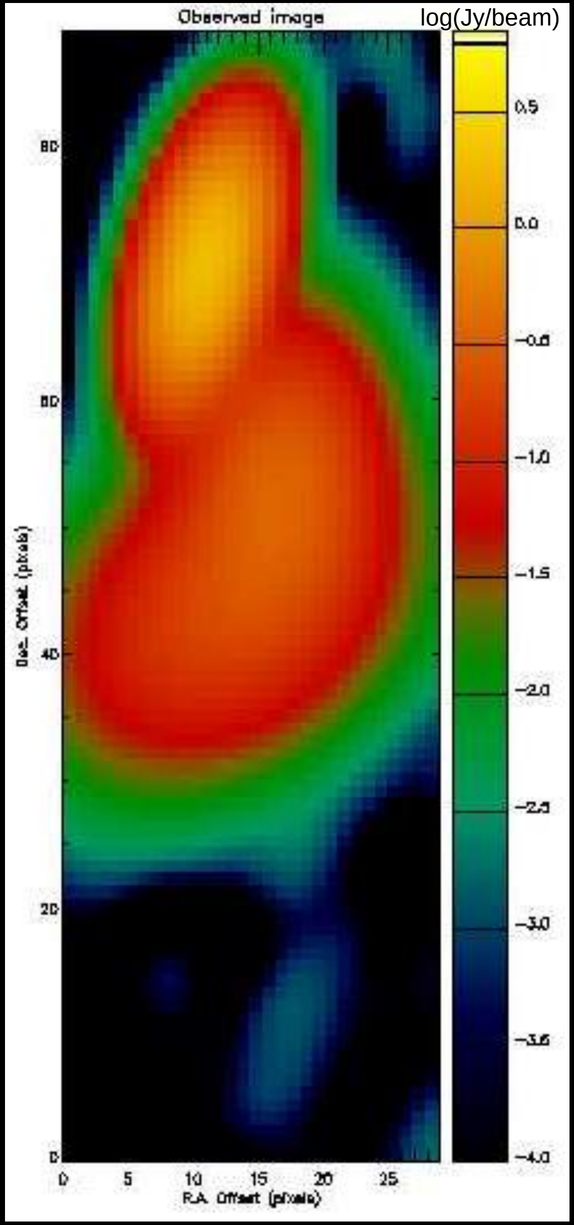
- Some remarks concerning CE:
  - ➢ It is a heuristic method (no proof on convergence for continuous optimizations);
  - ➢ Therefore, it needs (a lot of!) validation tests to assure that convergence to the optimal solutions can be reached:
    - ✓ Influence of the CE parameters (e.g, N, N_{elite}, etc.);
    - ✓ Stopping optimization criteria (maximum iteration, RMS, etc.);
    - ✓ (The most suitable) merit function;
- A lot of computational work to obtain trustful results…



- Validation tests can be found in Caproni et al. (2011).

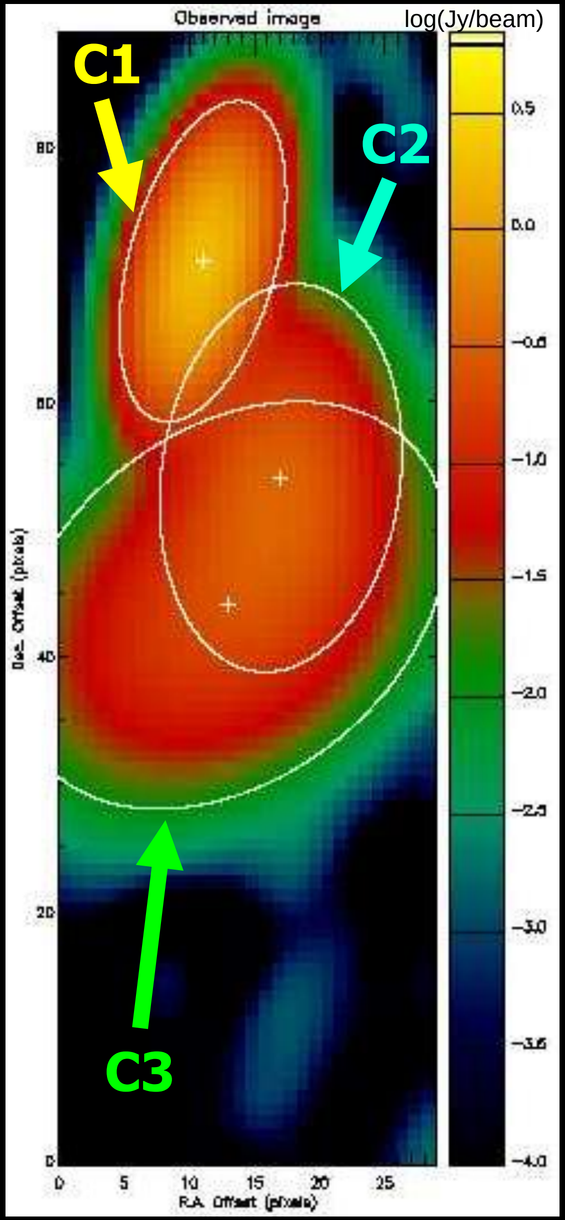
Deriving structural parameters of VLBI jet components

- A quiz (to check if you are not sleeping)… ☺
- How many source components are present in the following image?
- Answer: three sources.
- Indeed, it is difficult to assure this from visual inspection only…



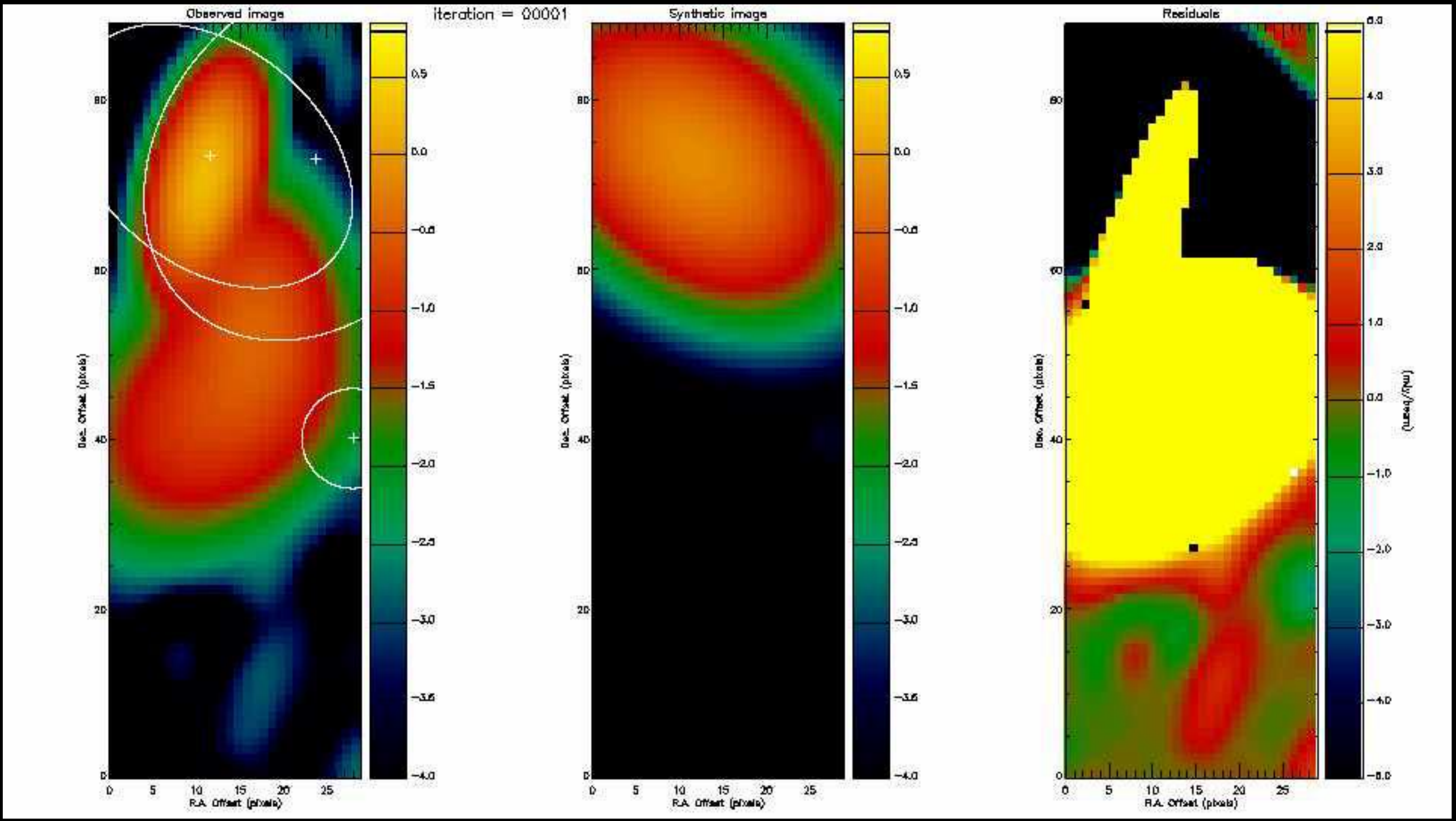
Deriving structural parameters of VLBI jet components

- Validation test J1:
  - Three sources;
  - Brightest component (C1): 2 Jy/beam (~3883·RMS);
  - Dimmest source (C3): 0.2 Jy/beam (~388·RMS);
  - Eccentricity varies from 0.7 to 0.9;
  - Some degree of superposition between C3 and C2 (~583·RMS);
  - 18 parameters to be optimized!
  - N = 3645 and N_{elite} = 20.



Deriving structural parameters of VLBI jet components

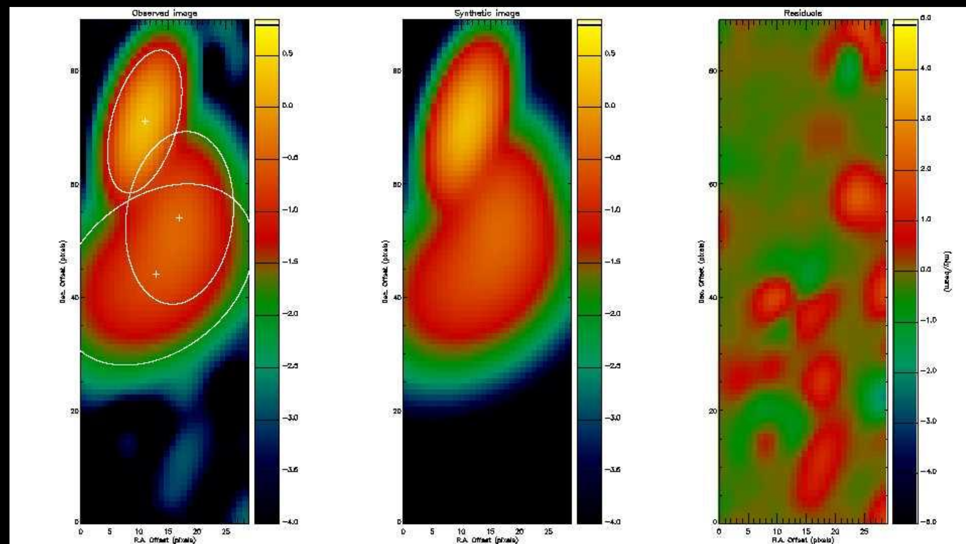
- Validation test J1:



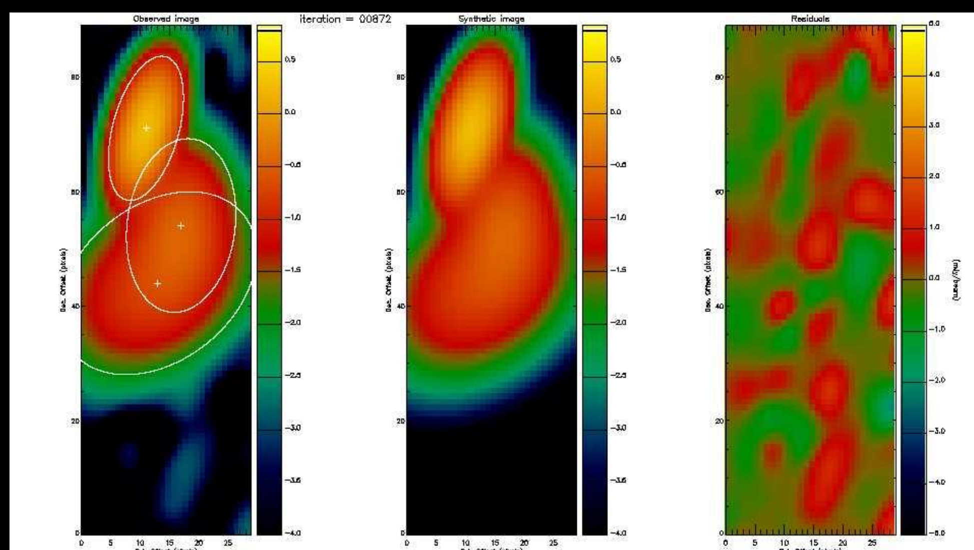
Deriving structural parameters of VLBI jet components

- Validation test J1: RMS level reached!!!

Control image

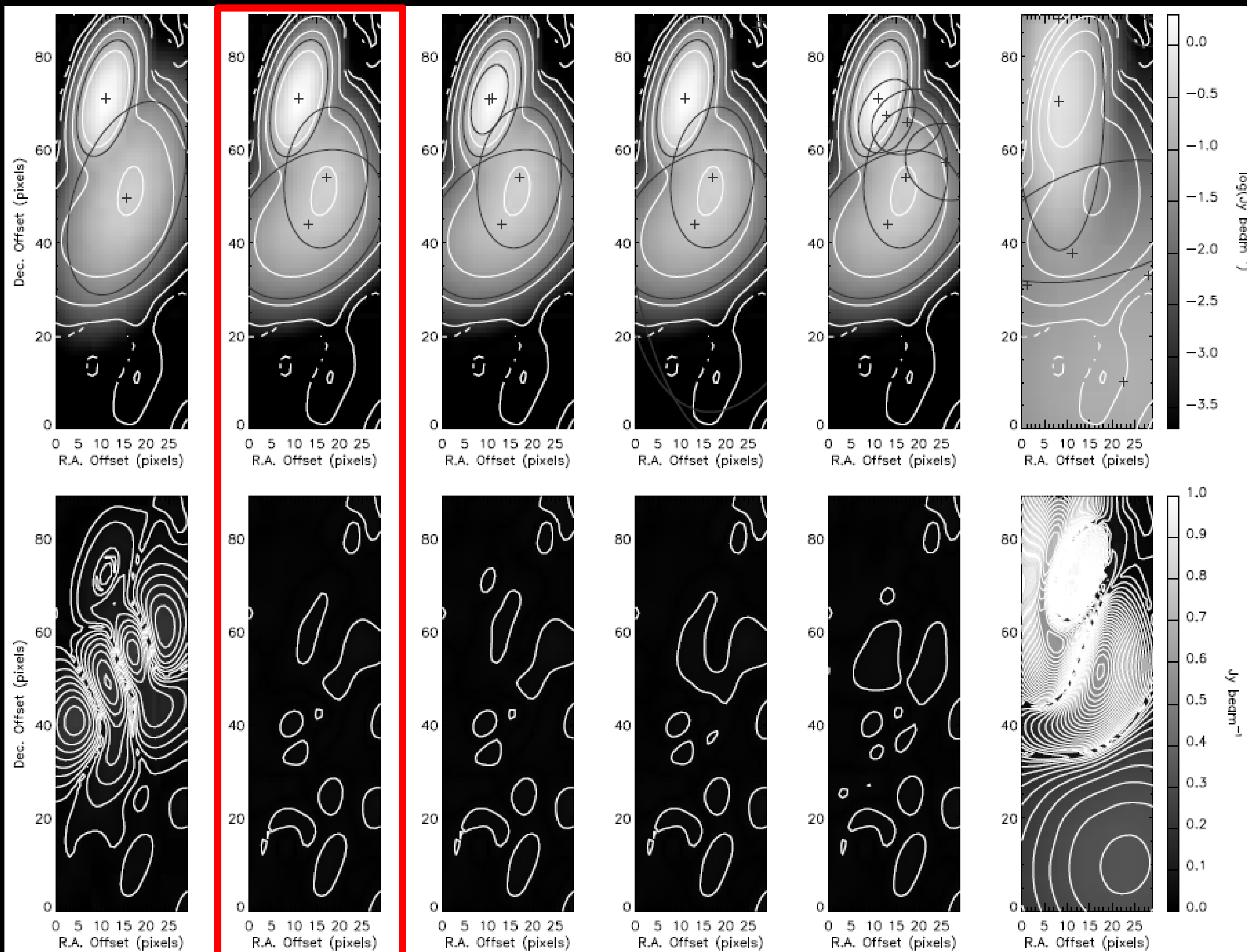


Optimized image



Deriving structural parameters of VLBI jet components

Three sources (J1 jet) – Caproni et al. (2011)

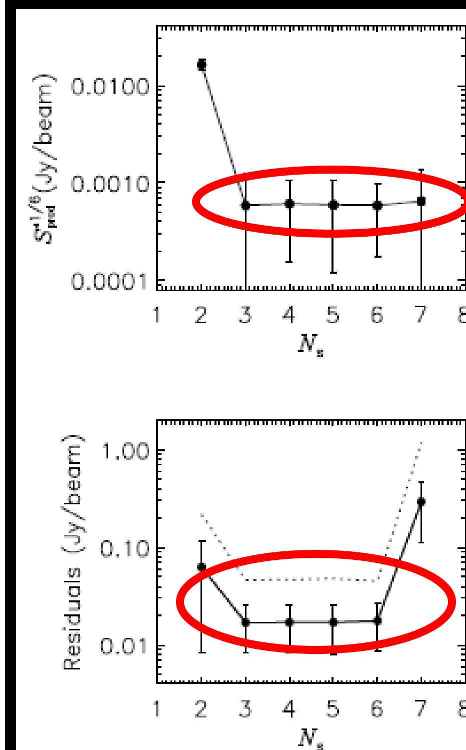


Contour lines: image

Gray-scale image: CE image

Elipses: FWHM

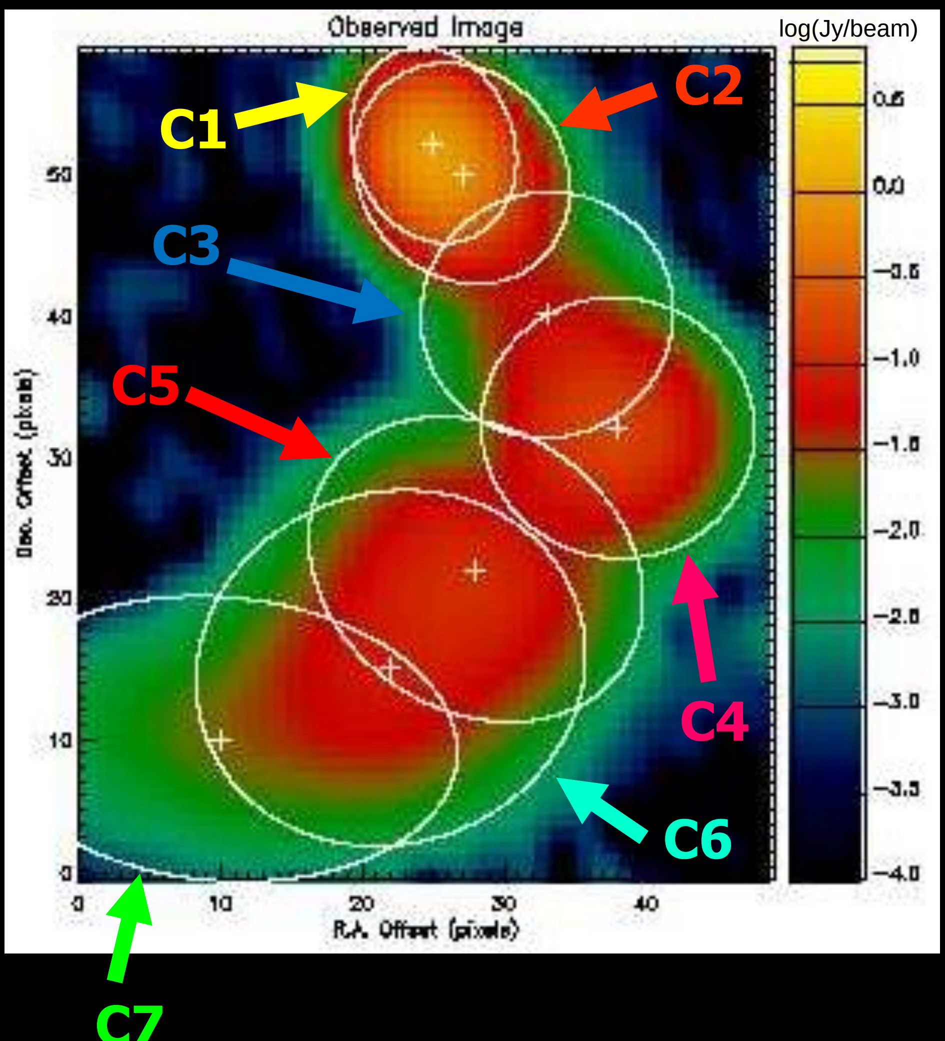
Crosses: Peak position



More than 3 sources do not improve the fit!

Deriving structural parameters of VLBI jet components

- Validation test J7:



- Seven sources;
- Brightest component (C1): 0.85 Jy/beam (~1836·RMS);
- Dimmest source (C7): 20 mJy/beam (~43·RMS);
- Eccentricity varies from 0.25 to 0.8;
- High degree of superposition:
  - between C1 and C2 (~713·RMS);
  - C6 (~173·RMS) with C7 and C5 (~216·RMS);
- Some degree of superposition between C3 (~108·RMS) and C4 (~432·RMS);
- 42 parameters to be optimized!
- N = 22050 and N_{elite} = 20.

Deriving structural parameters of VLBI jet components

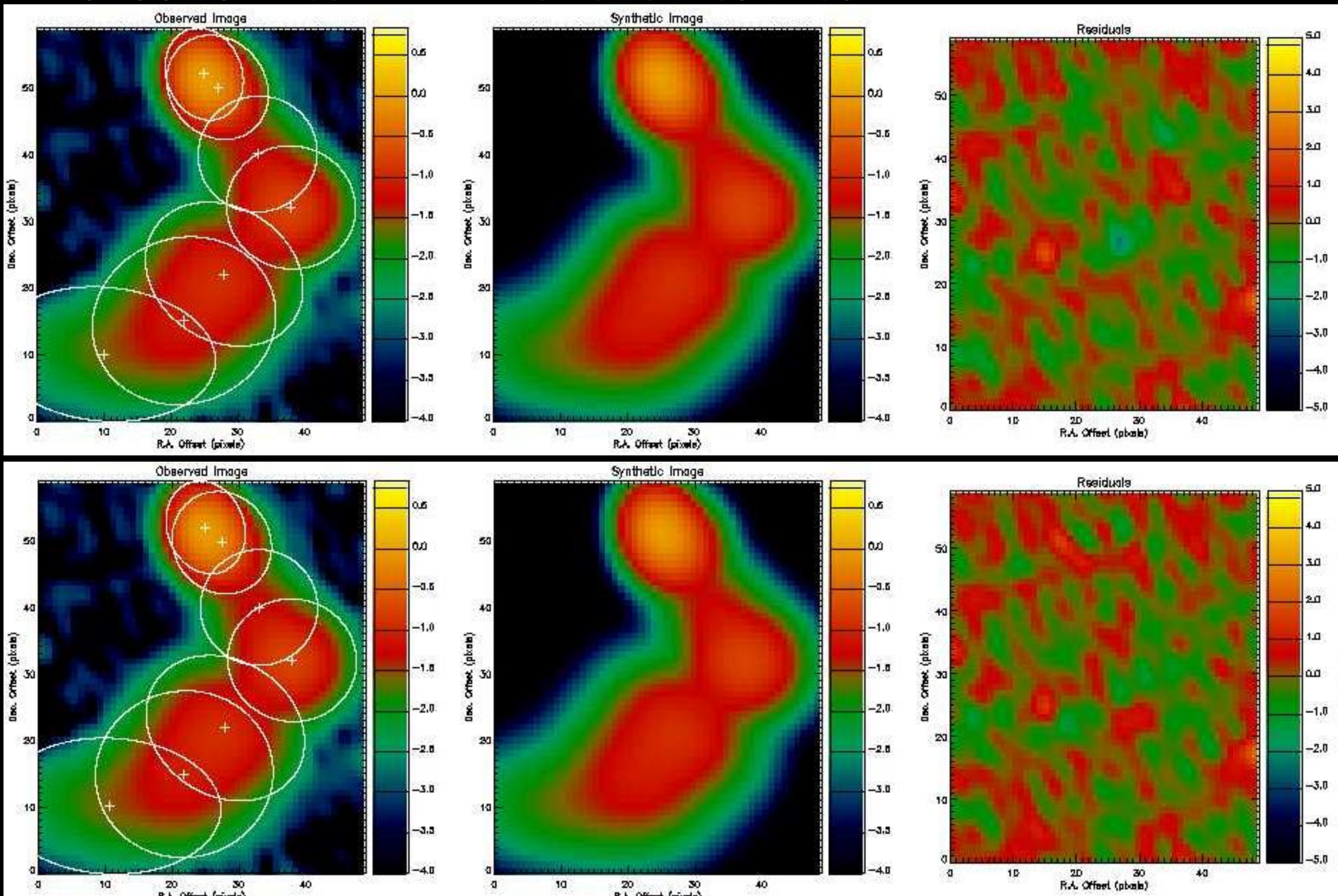
- Validation test J7:

Deriving structural parameters of VLBI jet components

- Validation test J7: RMS level reached!!!

Control image

Optimized image



Final remarks

- Astrophysical jets:
  - ➢ Found in several objects in the Universe;
  - ➢ Formation is not fully understood yet;
  - ➢ Impact on ISM (IGM): AGN feedback, X-ray bubbles, etc.
- Extragalactic jets:
  - ➢ Few detected in optical or X-ray wavelengths;
  - ➢ Generally associated to radio-loud AGNs;
  - ➢ Relativistic flows at parsec-scale (even at kiloparsec-scales in some cases);
  - ➢ Beaming and Doppler-boosting effects;
- Jet kinematic studies at parsec-scale:
  - ➢ VLBI studies: necessity of good coverage in (u,v)-plane, as well as time monitoring;
  - ➢ (Traditional) model fitting:
    - ✓ Dependence on number of components assumed in model-fitting;
    - ✓ Limitation in the number of components fitted simultaneously;
  - ➢ CE technique:
    - ✓ Able to recover the parameters of the sources with a similar accuracy to that obtained from the traditional AIPS task IMFIT when the image is relatively simple;
    - ✓ Presents superior performance for more complex images;
    - ✓ Quantitative estimate of the number of individual components present in a VLBI image;