The Properties of AGN Jets - Comparison with HH Jets

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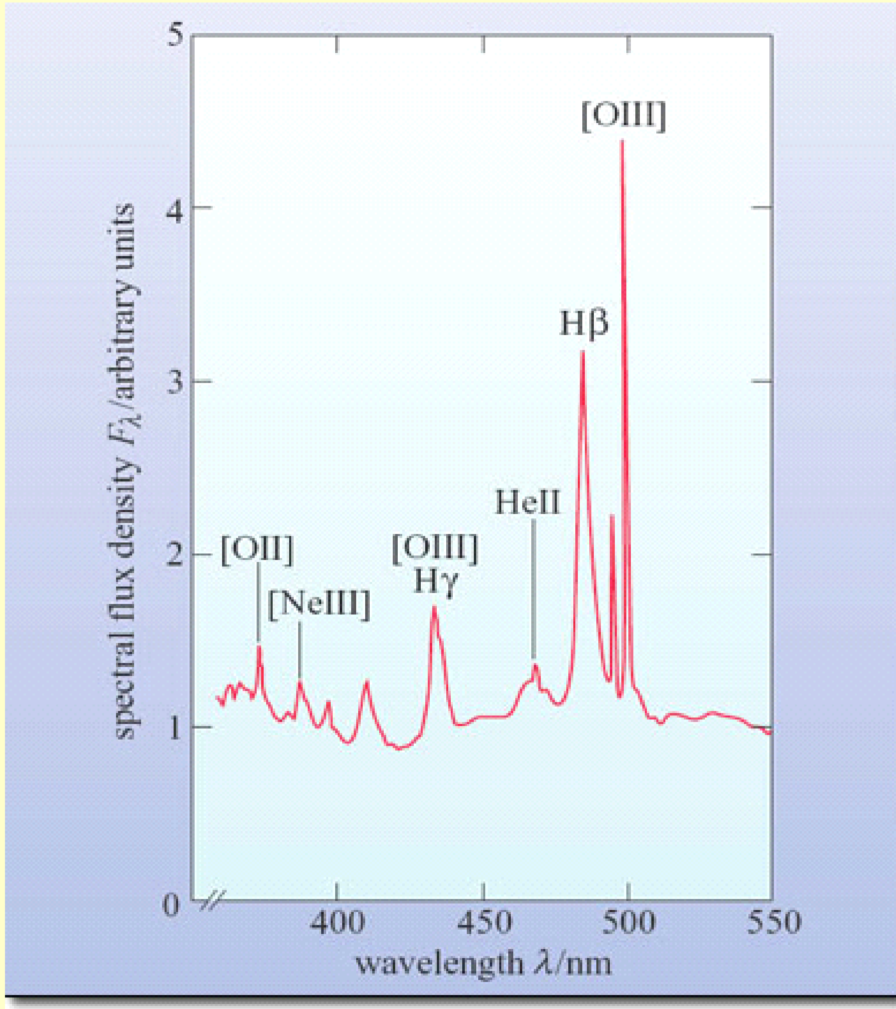
Overview

- AGNs: general properties
- Jets in radio galaxies
- On the AGN jets acceleration
- Why AGN jets come in two flavors? The role of instabilities
- Summary

Active Galaxies

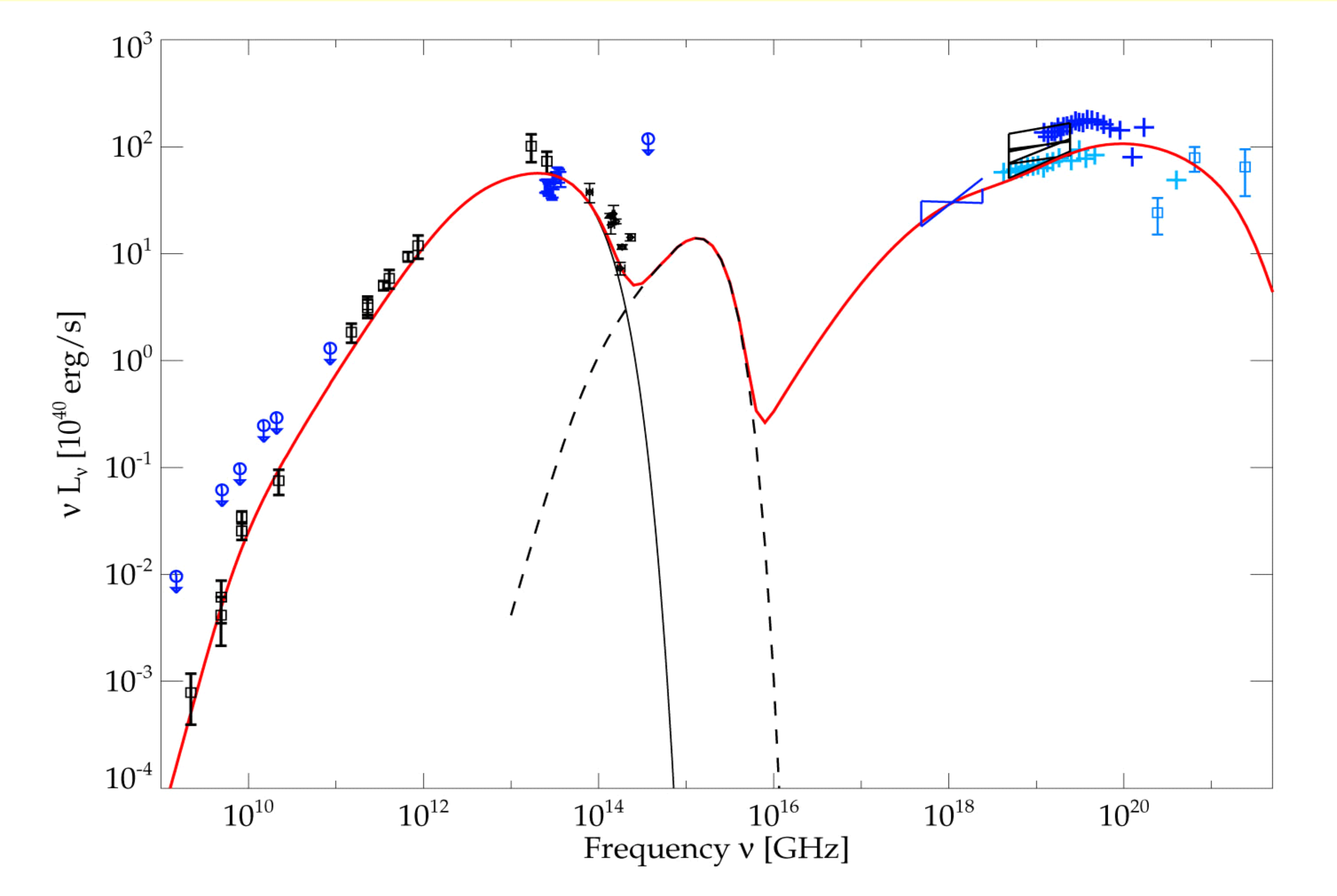
About 1% of the galaxies of the Local Universe show:

- **strong and broad emission lines, consistent with velocity dispersion of several thousand kilometers per second for the emitting gas**



Active Galaxies

- Non-thermal emission extending from the radio to the X-rays and gamma bands



SED of Cen A
(Prieto et al. 2007)

Active Galaxies

The dominant contribution to the total luminosity is not from stars but from an Active Nucleus

R ~ 30 kpc

R ~ 2 kpc

R ~ 10^{-5} kpc

M87

AGN Zoology

Radio quiet AGNs: **No jets**

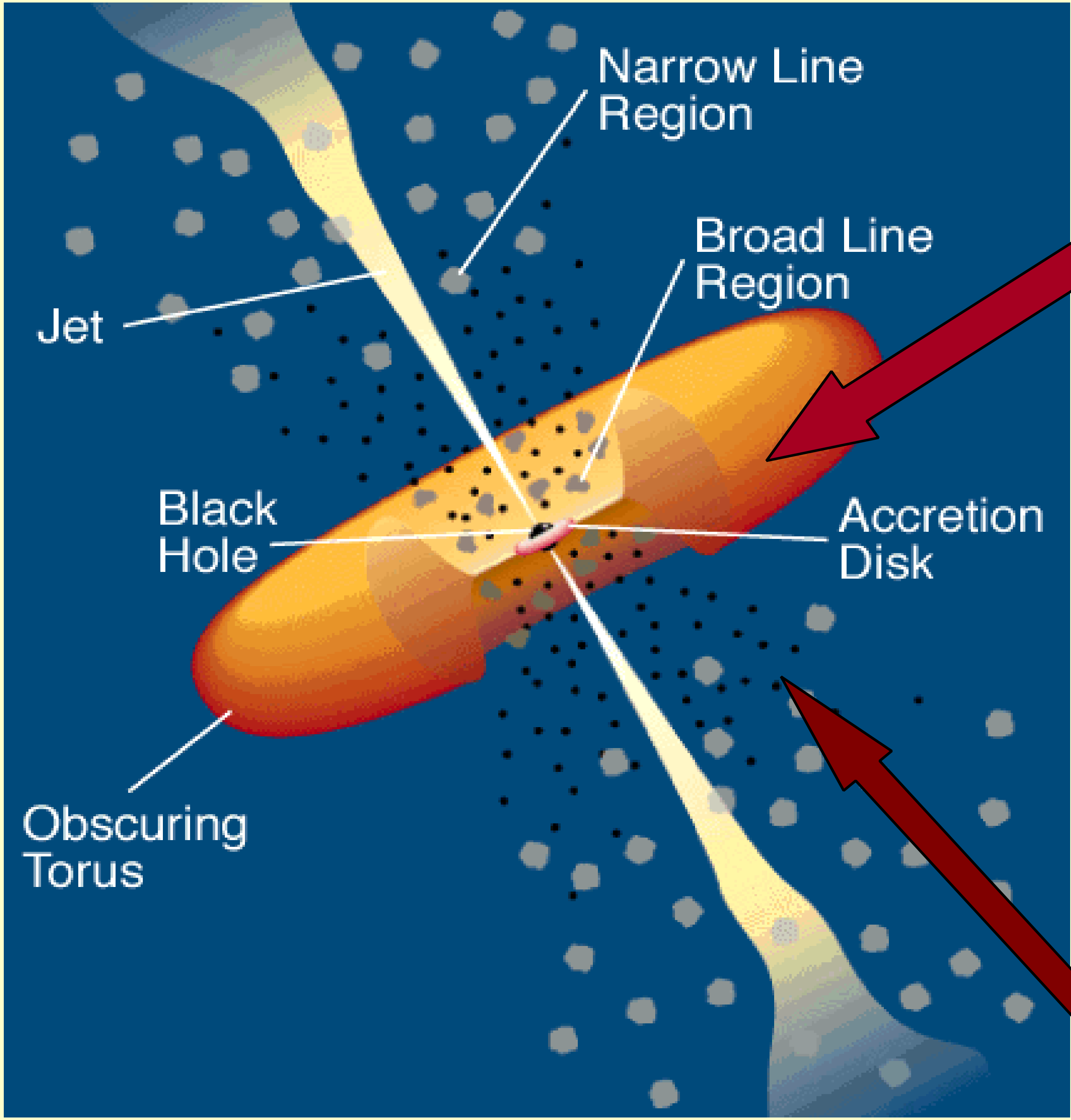
- Seyfert I galaxies (SyI) (BLR, $\sim 10^4$ km/s)
- Seyfert II galaxies (SyII) (NLR, $\leq 10^3$ km/s)
- Radio Quiet Quasars (QSOs)

Radio loud AGNs: **Jets**

- Radio galaxies
- Radio Quasars
- BL Lac Objects
- Optically Violent Variables (OVV's)

Radio loudness parameter: $R = L_{5GHz}/L_B > 10$

The AGN Unified Model



radio galaxy/
radio quasar
(jet),
SyII/QSO
(no jet)

narrow lines

NLR, L~0.1kpc

broad lines

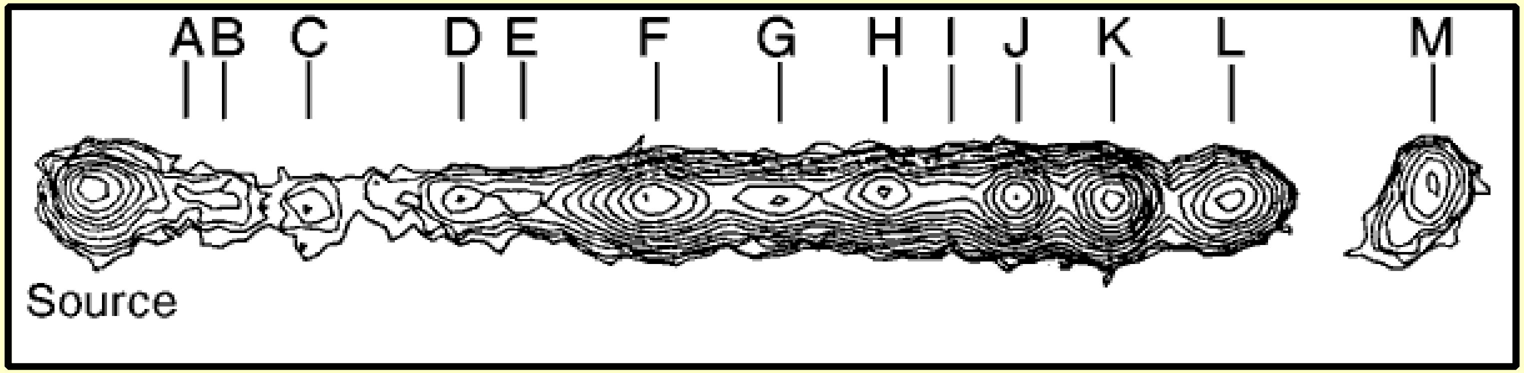
(Urry & Padovani, 1995)

OVV/BLLac (jet), SyI/QSO (no jet)

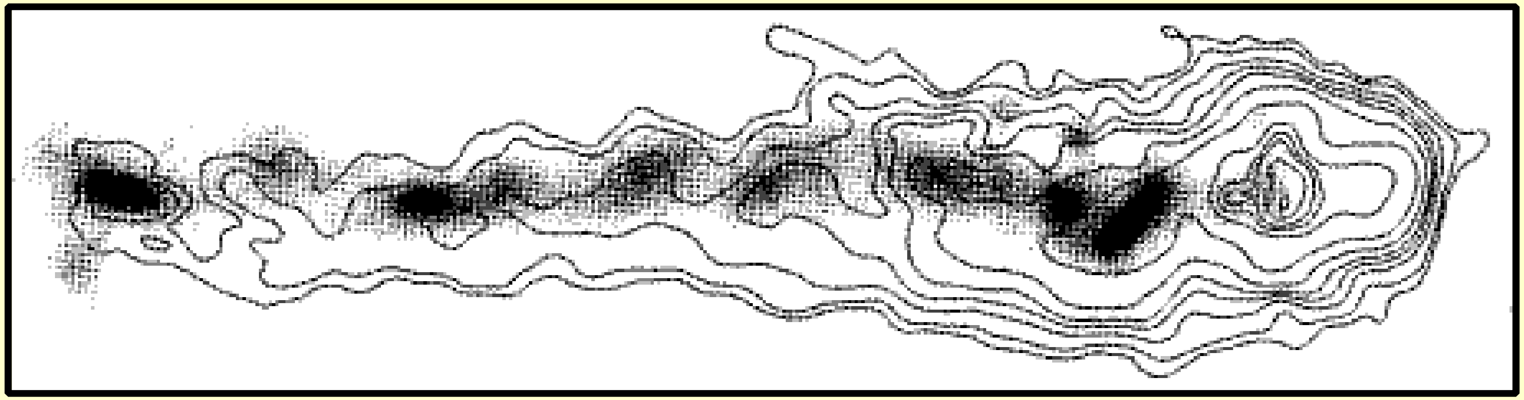
AGN and YSO Jets

- Comparison of radio-loud AGN with YSOs: both have jets!
- Focus on <u>Radio Galaxies</u>

HH34 optical



3C 273 Radio+ optical

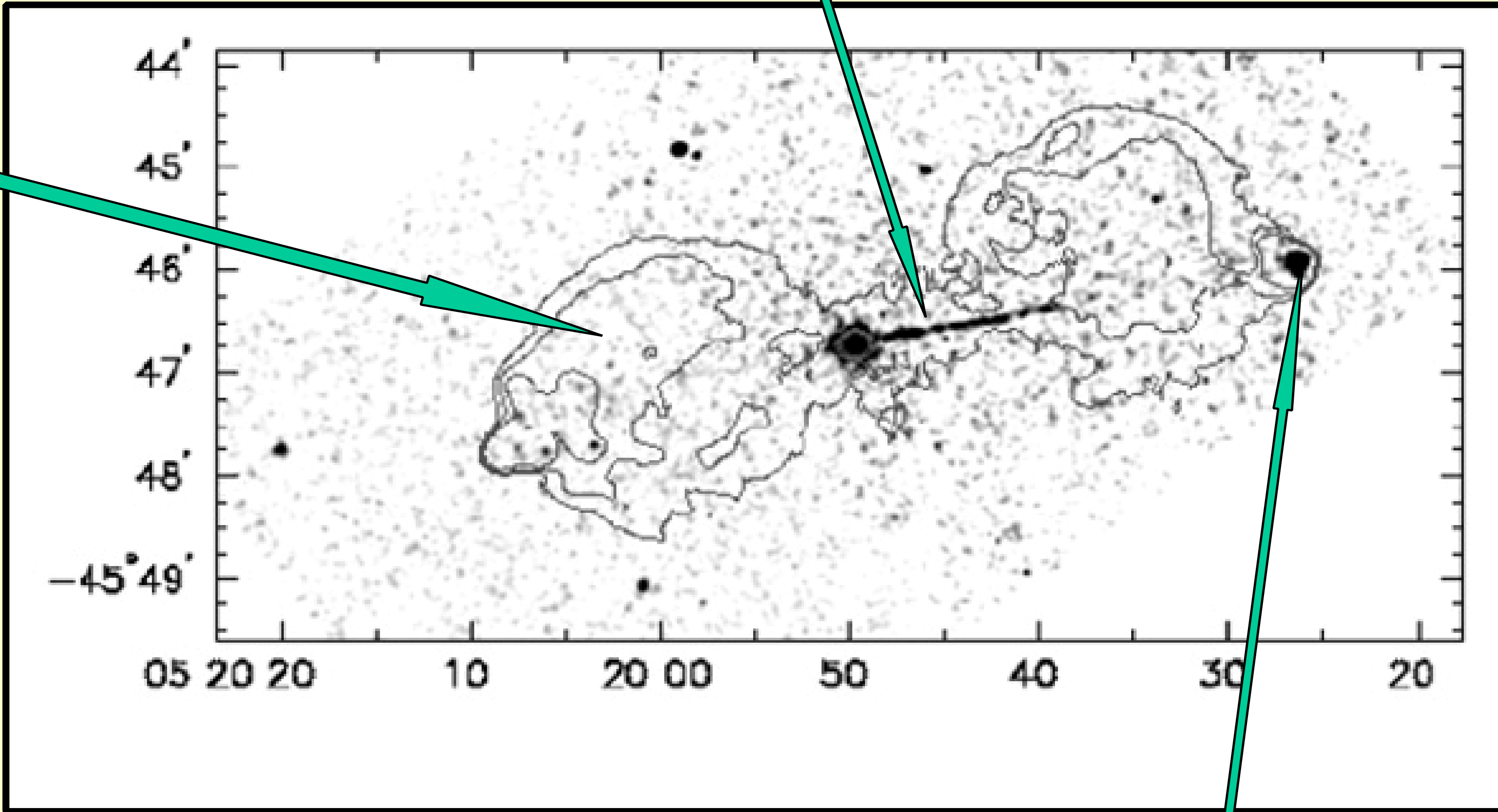


About Radio Galaxies

Synchrotron Radio to X-rays

Radio emission
Synchrotron:
$F(\nu) \propto \nu^{-\alpha}$
$\alpha \sim 0.5$

Electron power
law distribution
$n(E) \propto E^{-p}$
$p=2\alpha+1$



Pictor A (z=0.035)
Nucleus to hot-spot ~ 270 kpc
jet ~ 120 kpc

Radio: synchrotron X-rays: synchrotron+SSC

Radio Galaxies: Main facts

What we observe:

- Radio luminosity: 10^{41}-10^{44} ergs s^{-1}
- Size: a few kpc – some Mpc
- Morphologies
- Polarization degree: about 1%-30%

What we derive (but do not know for sure!):

- Life timescale: 10^{7}-10^{8} ys
- Magnetic field: 10 – 10^{3} μG
- Kinetic power: 10^{42}-10^{47} ergs s^{-1}
- Jet Mach number: M>1
- Jet velocity: possibly relativistic
- Jet density: 10^{-5}-10^{-3} cm^{-3}
- Jet composition: e-p vs e^{+}-e^{-}(?)

Radio Galaxies: Main facts

Why these uncertainties in constraining the basic parameters?:

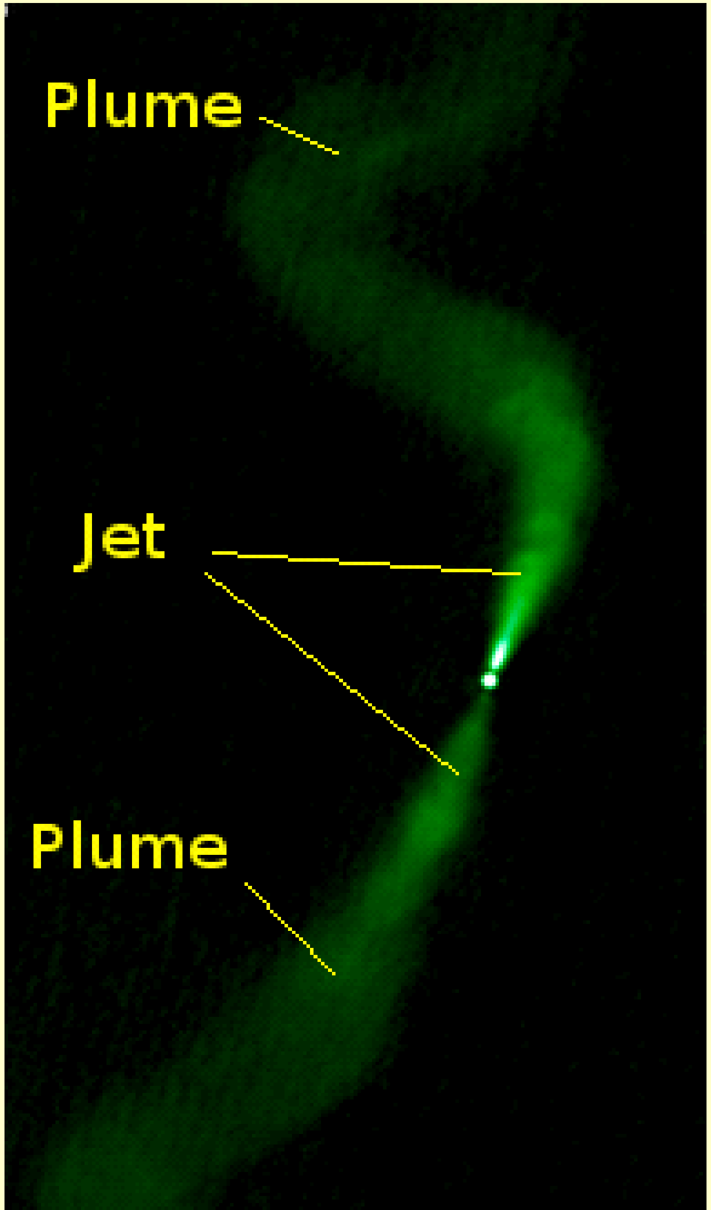
Absence of any line in the radiation spectrum!

Parameters are constrained by indirect means:

- Magnetic field: by minimum energy condition (equipartition)
- Kinetic power: work done against the ambient
- Jet Mach number: indication of shocks
- Jet velocity: jet one-sidedness
- Jet density: jet numerical modelling

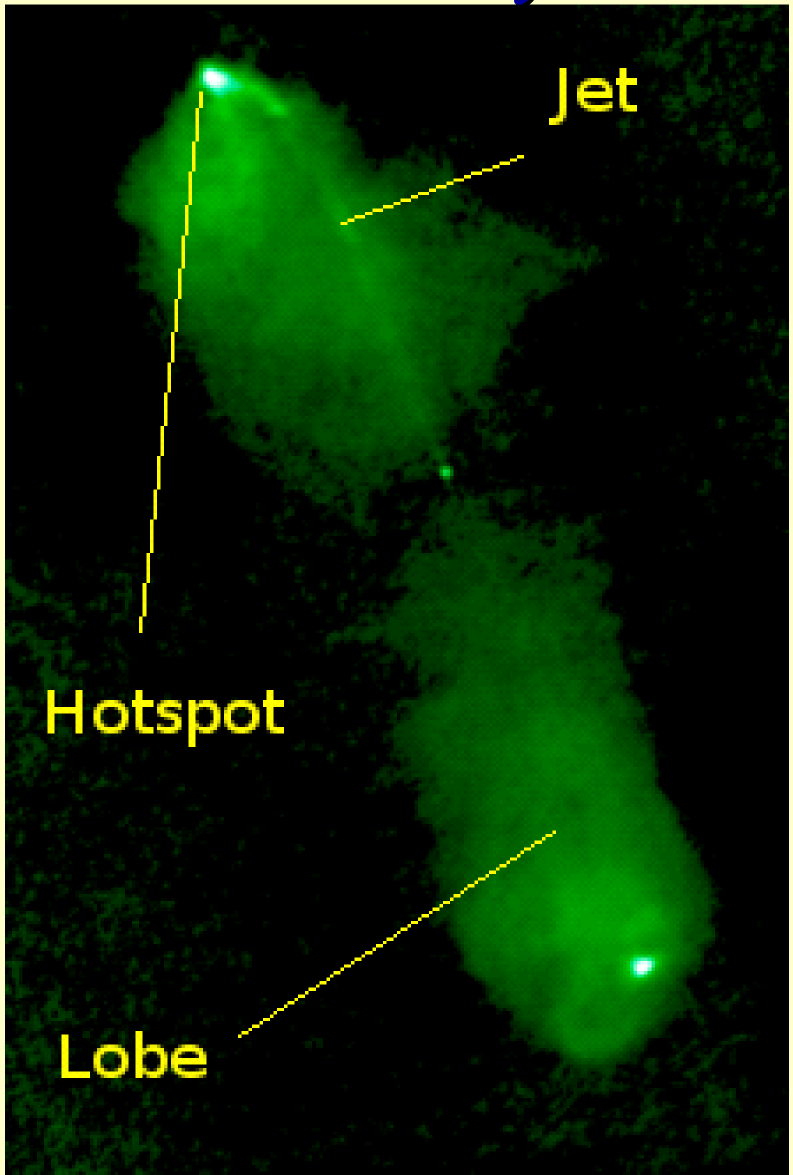
Observed morphologies:
The Fanaroff-Riley classification

FR I or jet dominated



3C 31
VLA

FR II or lobe dominated (classical doubles)



3C 98
VLA

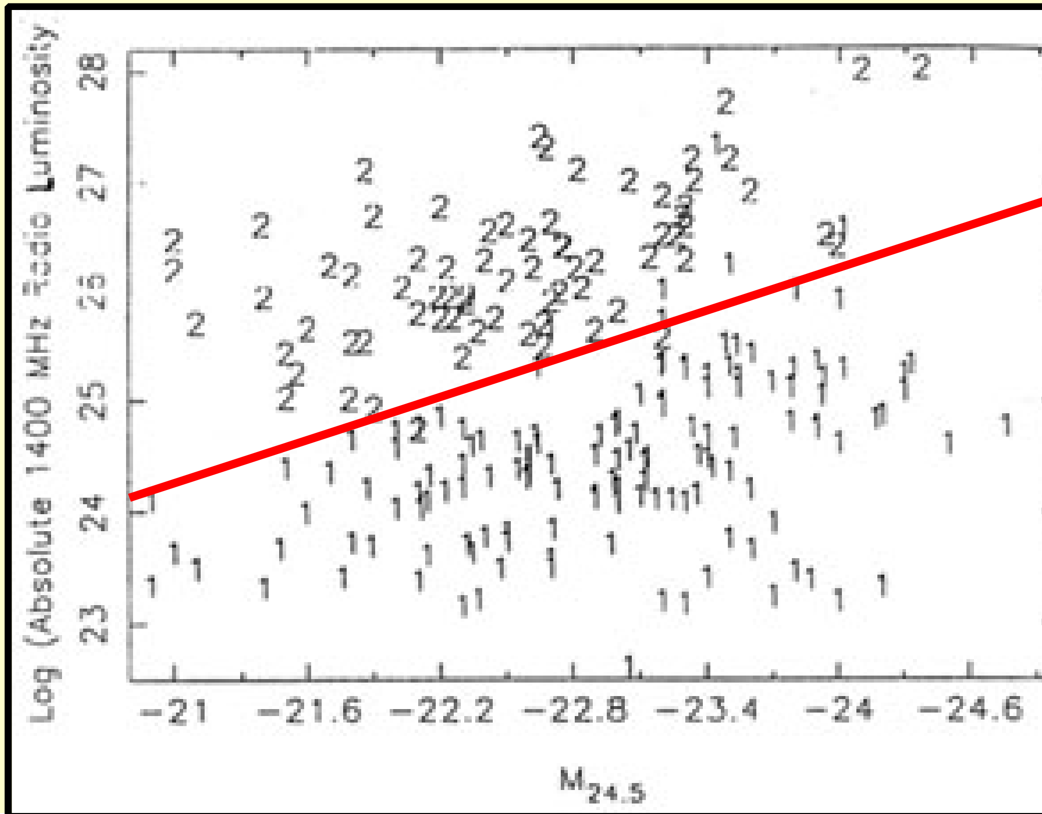
FR II only have Hot-spots!

- **FR I:** Jet dominated emission, two-sided jets, found in rich clusters, weak-lined galaxies, less powerful
- **FR II:** Lobe dominated emission, one-sided jets, isolated or in poor groups, strong emission lines galaxies, more powerful

Radio vs optical luminosities:

$$L_R \propto L_{opt}^{1.7}$$

(Owen & Ledlow 1994)
Environment plays a role?



Jet composition

- **YSO jets:**
  are made of ordinary matter, we observe emission lines of H, He and metals coming from the jet's medium.

- **AGN jets:**

1. ordinary proton-electron plasma;
2. e^--e^+ dominated plasma;
3. Poynting flux jets.

Jet composition

AGN jets:

- The work done by the jets against the ambient to inflate lobes and cocoon favors the electron/proton jets interpretation (Shankar et al. 2008);
- e^--e^+ jets suffer strong inverse Compton losses off the CMB (e.g. Harris & Krawczynski 2006)
- Jets can be Poynting-dominated up to $\sim$1000 r_g but become kinetically-dominated further away (Sikora et al. 2005, Giannios and Spruit 2008: kink instability?, Vlahakis talk)

Jet acceleration

YSO jets:

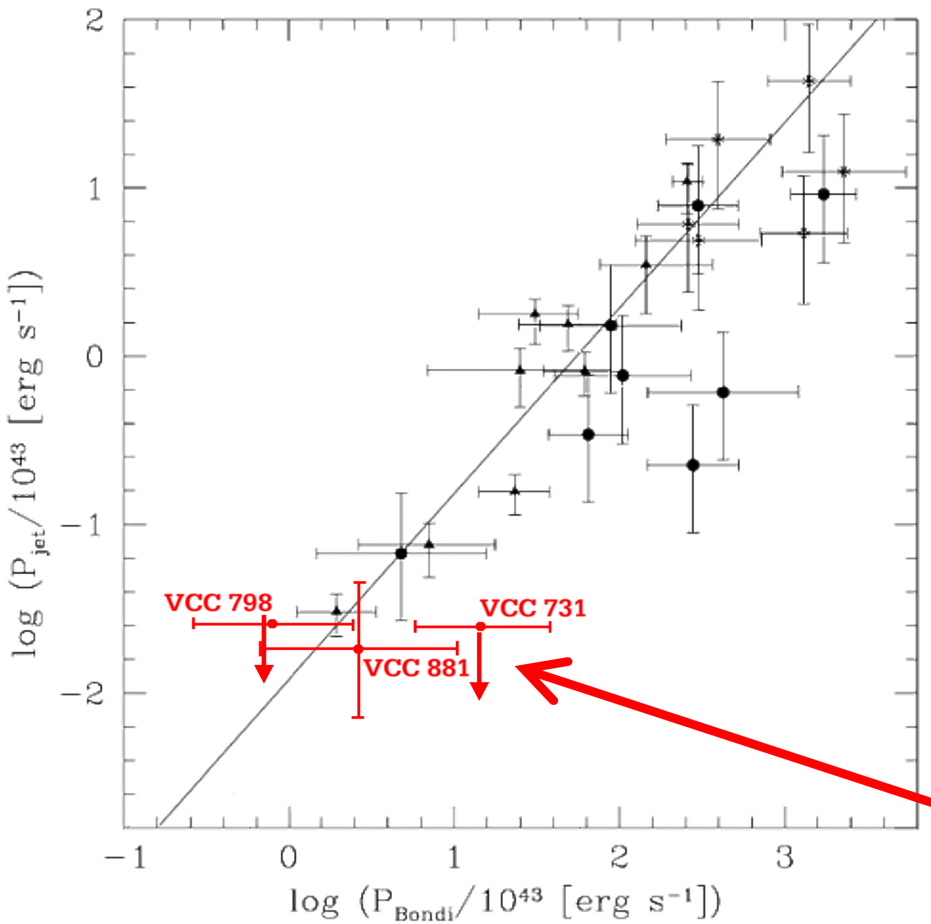
MHD-wind acceleration models, driven by the mass accretion rate through a disk, with likely a stellar wind component (MAES).

AGN jets:

- Jet energy extracted from the rotating SMBH (Blandford & Znajek 1977), need of a strong magnetic field threading the SMBH;
- Jet kinetic energy originating from the accretion energy (e.g. Livio et al. 1999)

Accretion and jets

Correlation found between the accretion onto BH and the jet kinetic power (Allen et al. 2006, Heinz et al. 2007)



(Balmaverde et al. 2008)

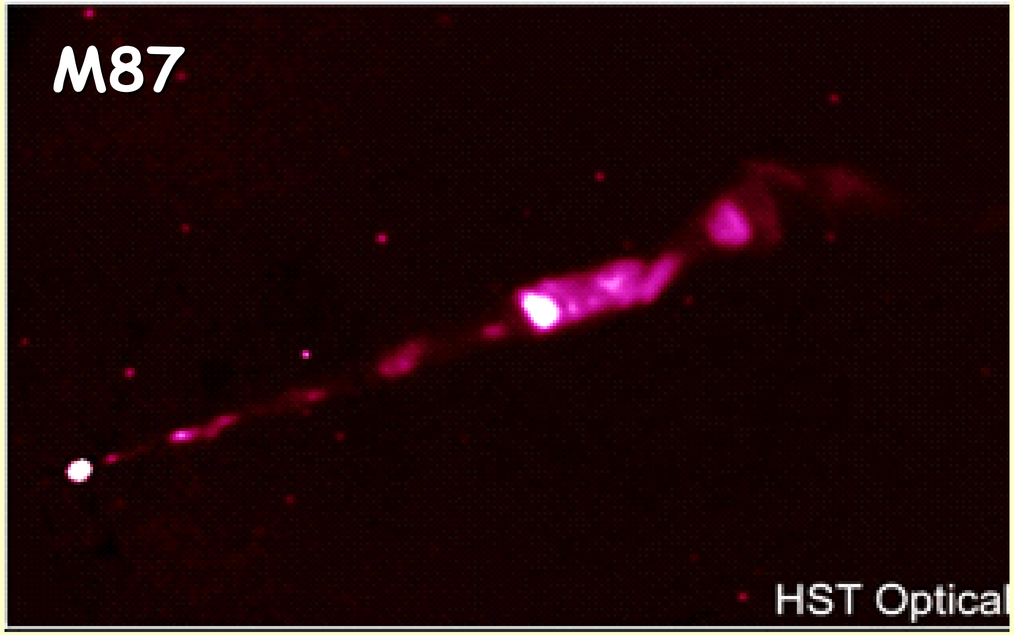
$$1)\ P_B = \dot{M}_B c^2, \quad \dot{M}_B = \frac{\pi G^2 \rho_B M_{BH}^2}{c_s^3}$$

$$2)\ L_j = 3\times 10^{45} f^{3/2} L_{151MHz}^{6/7}\ erg\ s^{-1}$$

(Willot et al. 1999)

Radio quiet

AGN-YSO Jets Comparison



Jets in radiogalaxies:

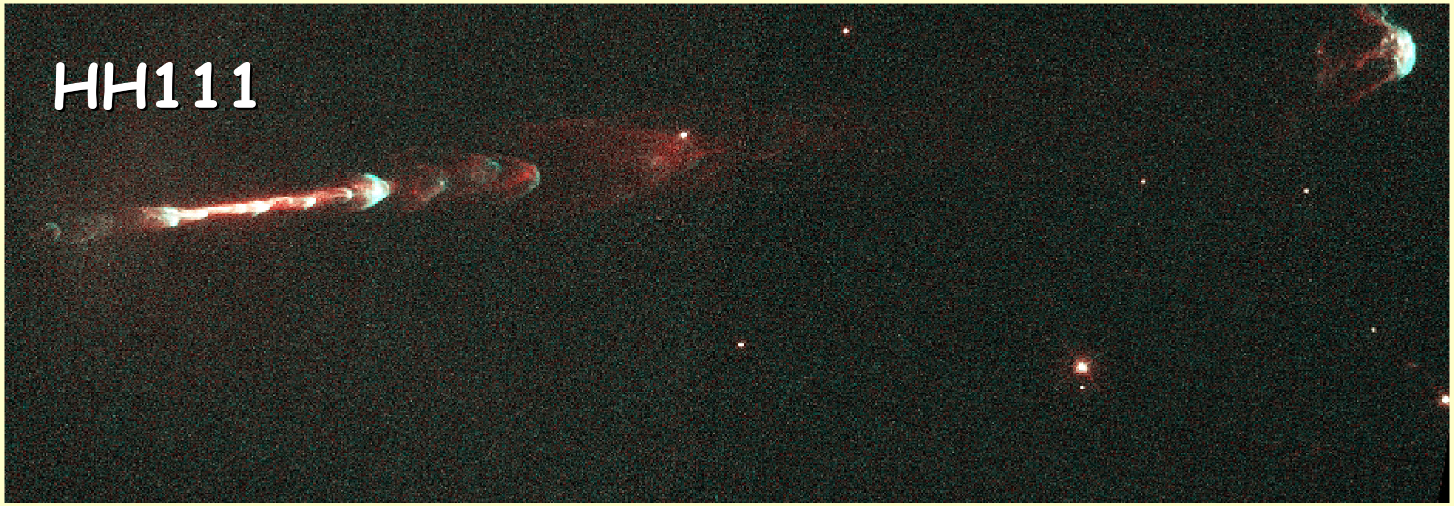
Radiation: non-thermal

Shocks: likely

Line emission: no

Composition: $e^{-}p$(?)

<u>FRI/FRII dichotomy: yes</u>



YSO jets:

Radiation: thermal

Shock emission:yes

Line emission: yes

Composition: e^{-}-p

<u>Dichotomy: no</u>

Assumptions:

- AGN jet acceleration is governed by the accretion rate through an accretion disk in a relativistic regime (e.g. Camenzind 1998 in steady state, Koide et al. 1999 simulations GRMHD).
- AGN jets can be Poynting dominated in the sub-parsec region, but are matter-dominated beyond

Aim:

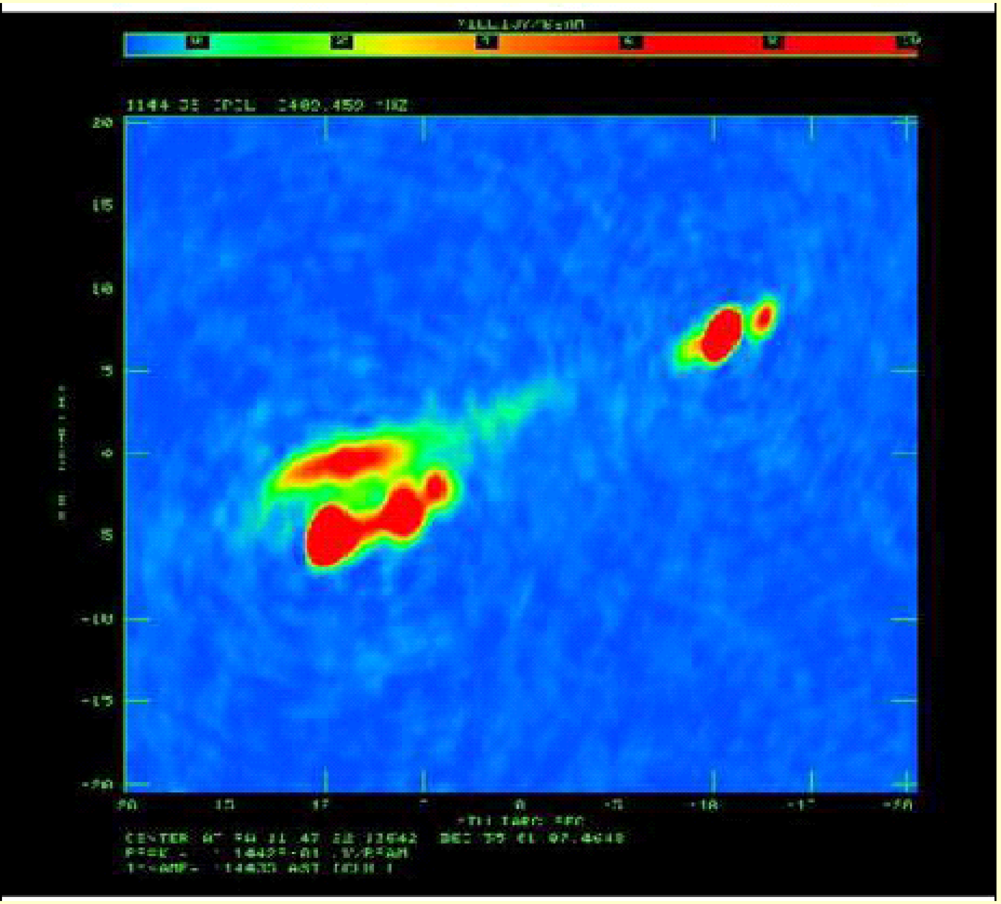
- Why are radio jets dichotomic? (and YSO jets are not?)

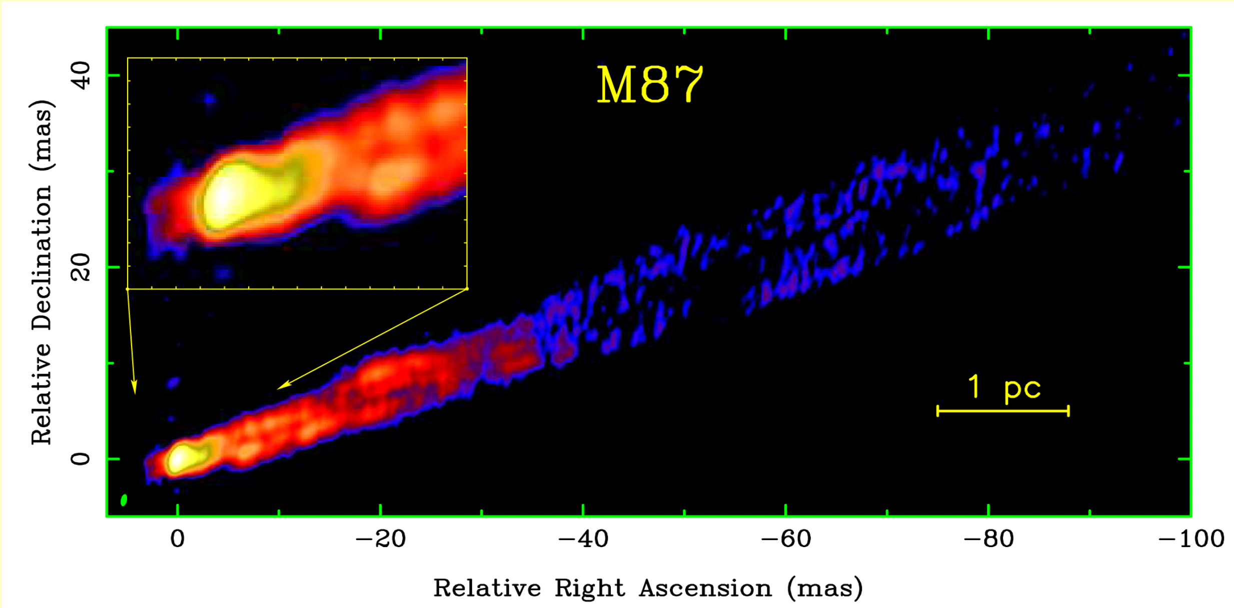
Radio Galaxies: More facts

- FR I and FR II have different kpc-scale morphologies and radio power but are similar on the parsec scale, where the jet bulk Lorentz factor is in the range γ=3-10 (e.g. Giovannini et al. 2001)
- FR I sources are non-relativistic at kpc scales
- FR I radiogalaxies, about 10 VLBI sources, show limb-brightened radio emission at parsec scales

Limb-brightening

B2 1144+35





About FR I / FR II Dichotomy

- **Intrinsic explanations:**

1. Differences in jet composition (e^+-e^- for FR I sources, Reynolds et al. 1996a);
2. Difference in the central engine (a fast spinning BH yields FR II jets, Meier 1999)
3. ADAF produce FR I (and BL Lacs), while 'standard' accretion discs FR II (and quasars) (Reynolds et al. 1996b).

- **Extrinsic explanation:**

1. Jets are similar close to the source (apart from power); weaker jets are decelerated by instabilities and/or entrainment to produce FR Is, stronger jets remain stable to form FR IIs (Komissarov 1990, Bicknell 1995, Bowman et al. 1996, Laing 1996, Rossi et al. 2008).

FRI jets braking

Problem: jet deceleration from the VLBI to VLA scale (Bowman et al. 1996, Laing et al. 2003)

VLBI

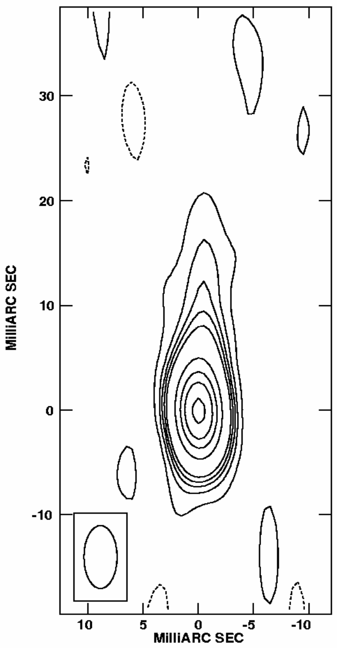
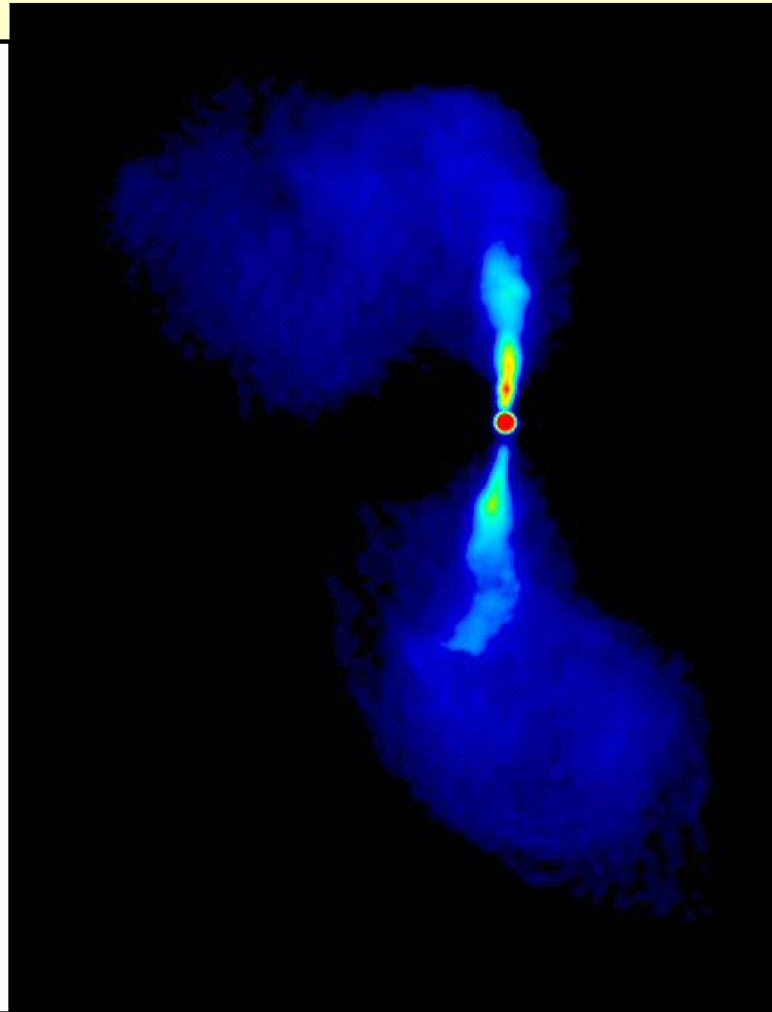


Fig. 13.— Global VLBI image of 1222+13 (3C272.1) at 1.7 GHz. The HPBW is 6 × 3 mas in PA 0°. The noise level is 0.5 mJy/beam and levels are: -1, 1, 3, 5, 7, 10, 30, 50, 70, and 100 mJy/beam.

VLA



FRI jets limb-brightening

"Spine-layer" velocity structure of the jet: inner core with high Lorentz factor surrounded by a slower external layer (e.g. Chiaberge et al. 2000, Piner & Edwards 2004)

$$P_{observed} = P_{emitted} \times \left[\gamma\left(1-\beta\cos\theta\right)\right]^{-(2+\alpha)} = P_{emitted} \times \delta^{-(2+\alpha)}$$

For θ (angle jet to line-of-sight) large enough the spine emission is "de-boosted". Possibilities:

1) **The jet has a spine-layer structure from its origin (care about its stability, Mizuno poster);**
2) **this structure results from interaction with the ambient medium via instabilities.**

Jet instability and braking in FRIs

Jet instabilities: linear growth $\tau_{\mathrm{KH}} \sim 2\pi\, M_{\mathrm{J}}\, R_{\mathrm{J}} / c_{\mathrm{s}}$

Nonlinear growth: $\tau_{\mathrm{KH}} \leq 10\, R_{\mathrm{J}} / c_{\mathrm{s}}$

Mixing and mass entrainment

Jet braking

Limb-brightening

Jet instabilities and braking in FRIs

3D nonlinear evolution of Kelvin-Helmholtz instabilities in relativistic hydro jets (Rossi et al. 2008). Relativistic equation set:

$$\frac{\partial}{\partial t}\begin{pmatrix} \rho\gamma \\ w\gamma^2 v_k \\ w\gamma^2 - p \\ \rho\gamma f \end{pmatrix} + \sum_i \frac{\partial}{\partial x_i}\begin{pmatrix} \rho\gamma\, v_i \\ w\gamma^2 v_k v_i + p\delta_{ki} \\ w\gamma^2 v_i \\ \rho\gamma\, f v_i \end{pmatrix} = 0$$

p=gas pressure, w=enthalpy, ρ=rest mass density, γ=Lorentz factor, f=tracer

Parameter space:

Case	γ	M	η	pts/beam	$L_x \times L_y \times L_z$	$N_x \times N_y \times N_z$
A	10	3	10^2	20	$50 \times 150 \times 50$	$324 \times 1200 \times 324$
B	10	3	10^4	20	$60 \times 75 \times 60$	$344 \times 600 \times 344$
C	10	3	10^4	12	$50 \times 75 \times 50$	$172 \times 300 \times 172$
D	10	30	10^4	20	$50 \times 150 \times 50$	$324 \times 1050 \times 324$
E	10	30	10^2	12	$24 \times 200 \times 24$	$144 \times 560 \times 144$

η = ambient-to-jet (proper) density ratio

M = Mach number

Perturbation introduced at the jet inlet.

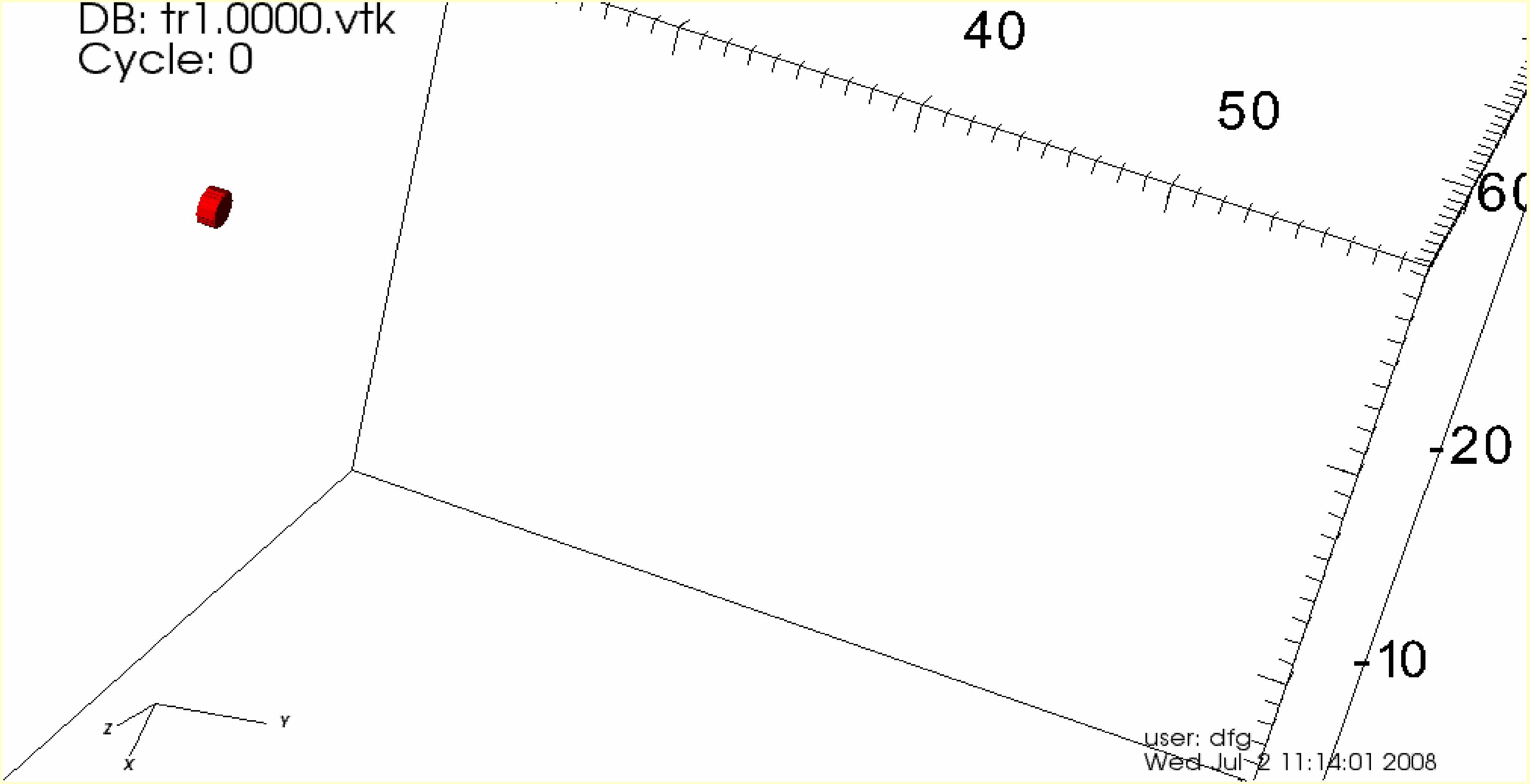
The temporal evolution of the system studied numerically with the code PLUTO (Mignone et al. 2007, PPM module)

Numerical simulations: Results

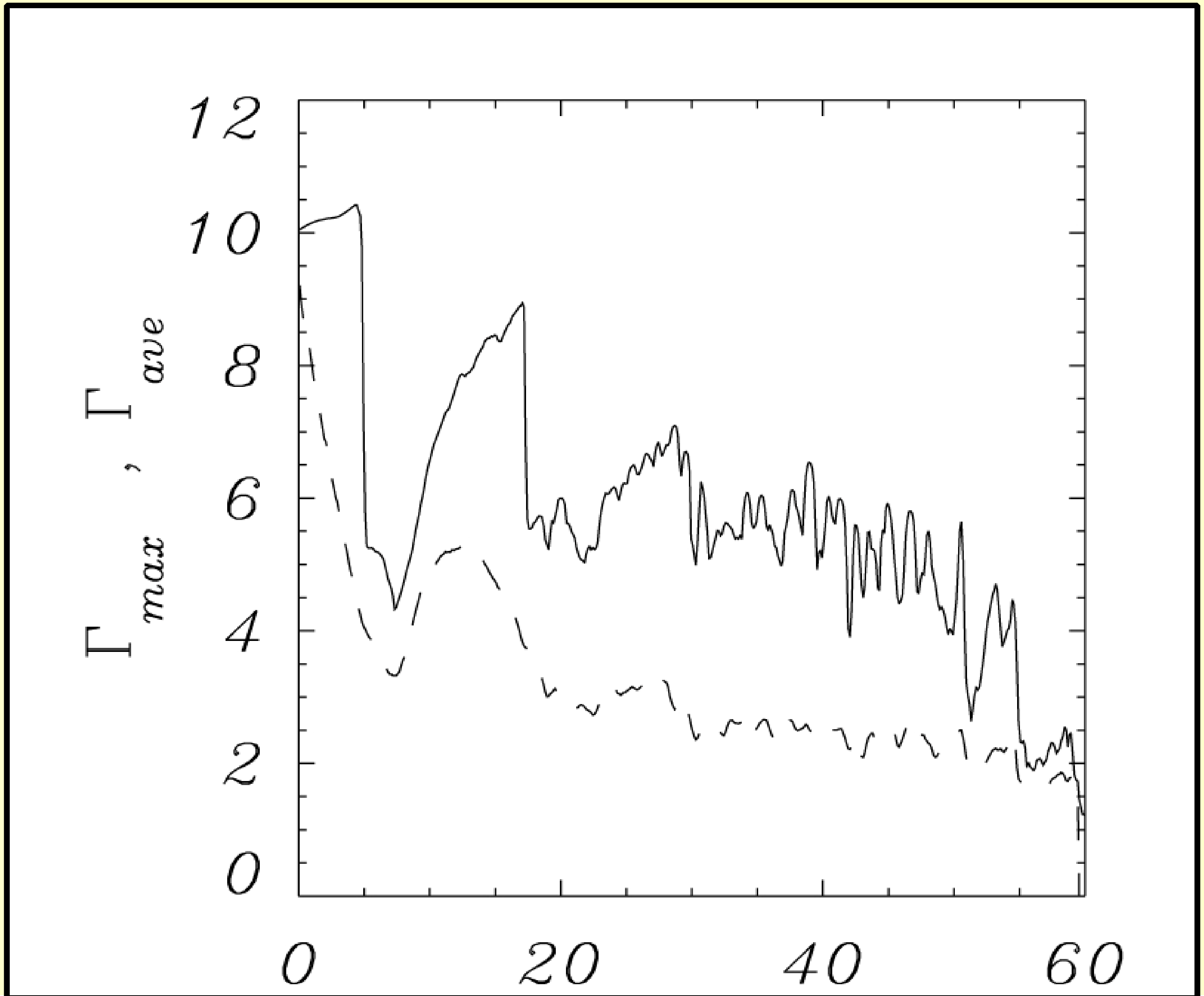
- The dominant parameter in determining the instability evolution and the entrainment properties is the ambient-to-jet density contrast η.
- Lighter jets suffer stronger slowing down in the external layer that in the central part
- Presence of a central spine at high Lorentz factor

$$\frac{\rho_{amb}}{\rho_{jet}} = 10^4, \quad M = \frac{v_j}{c_s} = 3, \ \gamma = 10$$

By Petros & Andrea



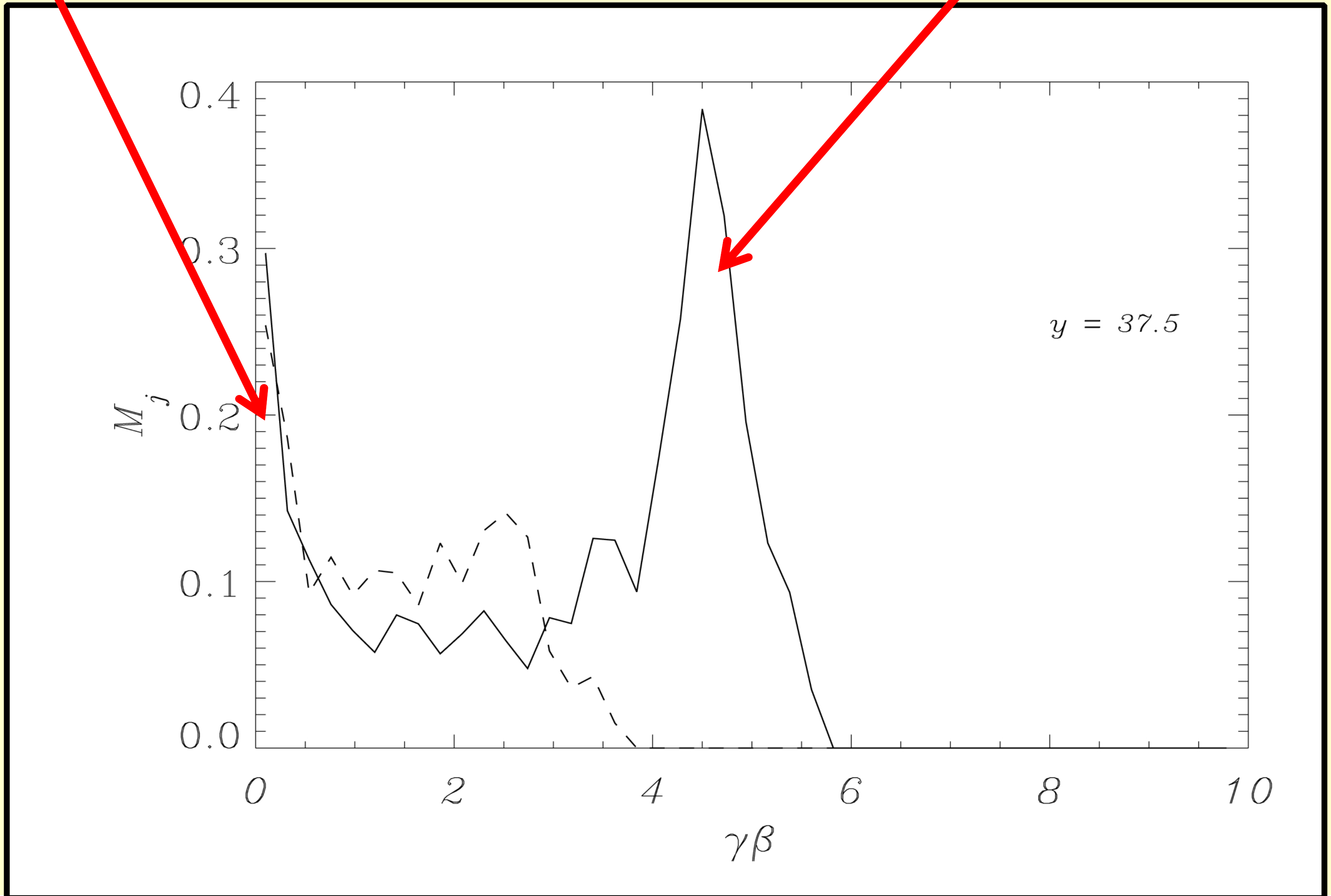
Longitudinal behavior of maximum and averaged Lorentz factor



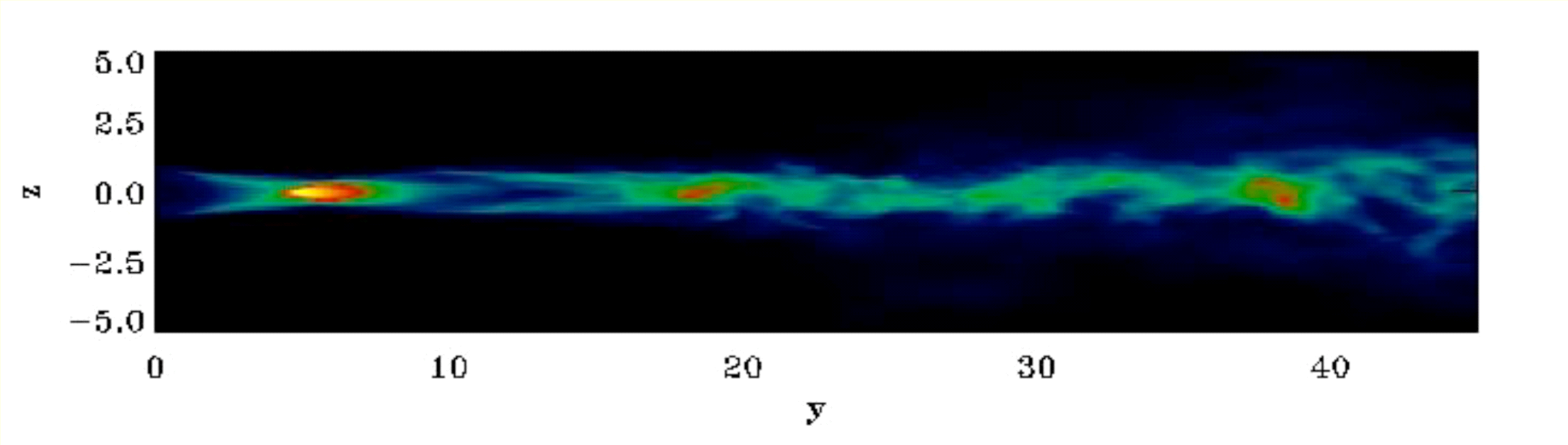
“Spine-layer” structure formation:

Layer: Jet mass at γβ ~ 0.2

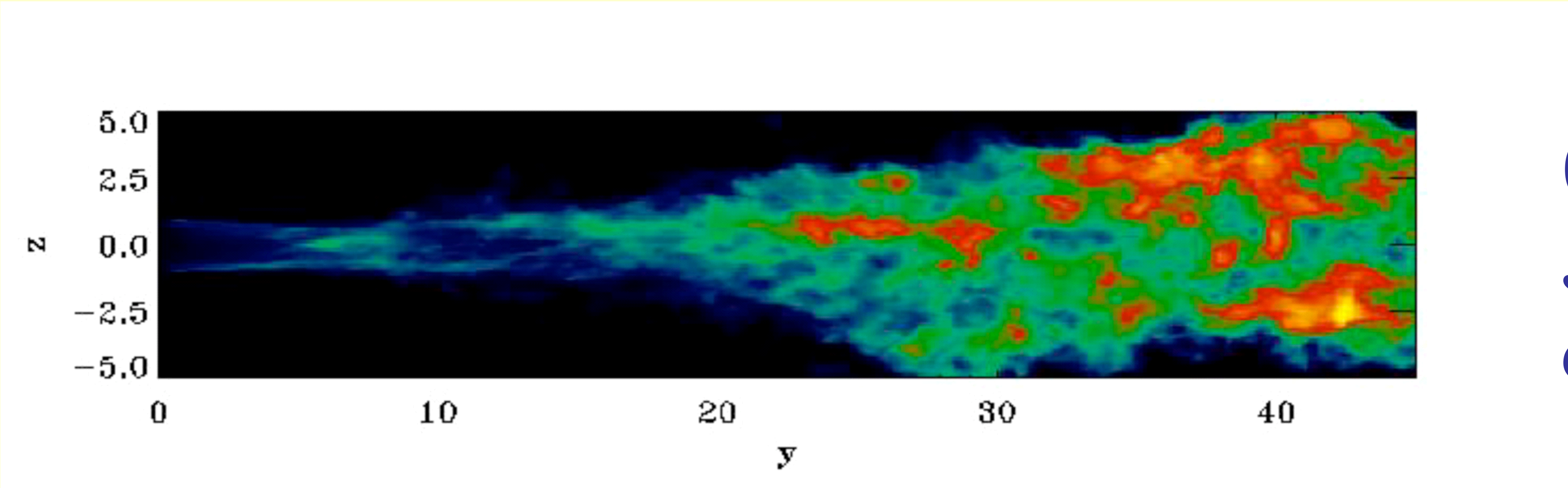
Spine: Jet mass at γβ ~ 5



"Spine-layer" structure formation: synthetic VLBI maps = radio emissivity $\propto$ proper density $\times$ $\delta^{-(2+\alpha)}$



$\theta = 20°$: Spine boosted



$\theta = 60°$: Spine deboosted

- **KHI in low density jets would produce jet braking, FRI-like morphologies, and limb brightening at VLBI scales**
- **This is consistent with the low kinetic power of FRI sources (e.g. Celotti 2003). The critical kinetic power:**

$$P_j^* \approx 10^{44} \left(\frac{r_j}{1pc} \right)^2 \left(\frac{\gamma}{10} \right)^2 \left(\frac{n_{amb}}{1cm^{-3}} \right) \left(\frac{\eta^*}{10^3} \right)^{-1} \; erg\, s^{-1}$$

- **FRI jets would have a density contrast ambient-to-jet exceeding 10^3**

Hint for YSO jets

- Not-dichotomic
- In this scheme, YSO jets would be similar to FRIIs:
  presence of a final working surface and a cocoon seen in the infrared (Bally's talk)
- The moderate density contrast jet-to-ambient would reduce instability growth

Summary

- The jet power appear to be connected to the accretion power onto the central SMBH
- FRI/FRII dichotomy can be intepreted by the evolution of KHI
- The dominant parameter is the density contrast ambient/jet