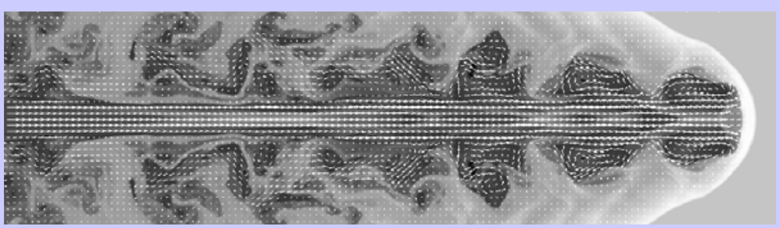
# Numerical Simulations of Relativistic Jets in AGNs


José Mª Martí

Departamento de Astronomía y Astrofísica

Universidad de Valencia (Spain)

Collaborators:
I. Agudo, M. Perucho (MPIfR, Bonn, Germany)
J.L. Gómez, M. Roca-Sogorb (IAA, Granada, Spain)
M. A. Aloy, L. Antón, J. M. Ibáñez, P. Mimica (UV, Valencia, Spain)
M. Hanasz (N. Copernicus Univ., Torun, Poland)
E. Müller (MPA, Garching, Germany)
J. A. Miralles (UA, Alicante, Spain)


Challenges of Relativistic Jets
Cracow, June 25-July 1, 2006

# Numerical simulations of relativistic jets in AGNs: Outline of the talk

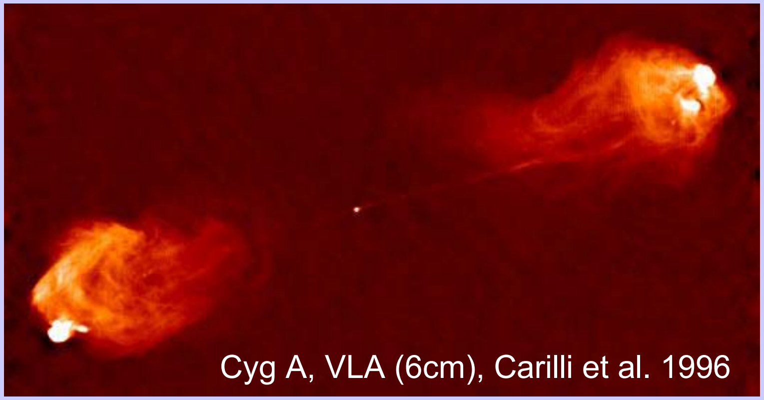
- Introduction
  - Extragalactic jets: three main regions
  - Standard model
  - Open questions

- Simulations of extragalactic jets
  - Large scale jets (long term sims., RMHD jets, FRIs)
  - Compact jets (superluminal radio sources, hydrodynamical shock-in-jet model, transversal structure)
  - K-H instabilities and extragalactic jets

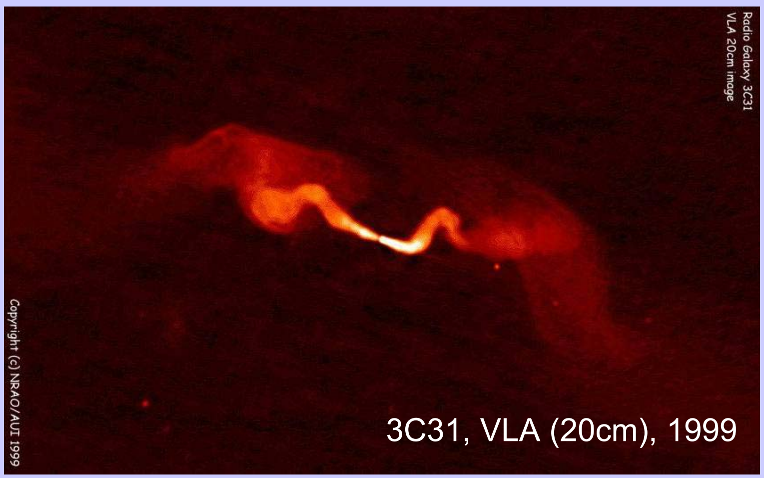
- Summary, conclusions, …

# Extragalactic jets: three main regions

Kpc scales: Morphological dichotomy based on jet power

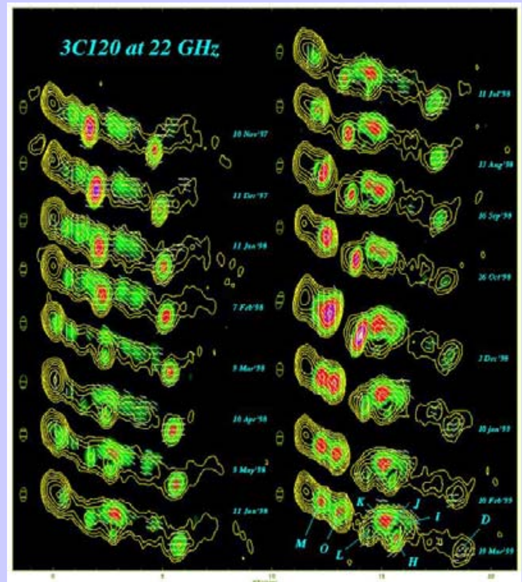


Cyg A, VLA (6cm), Carilli et al. 1996

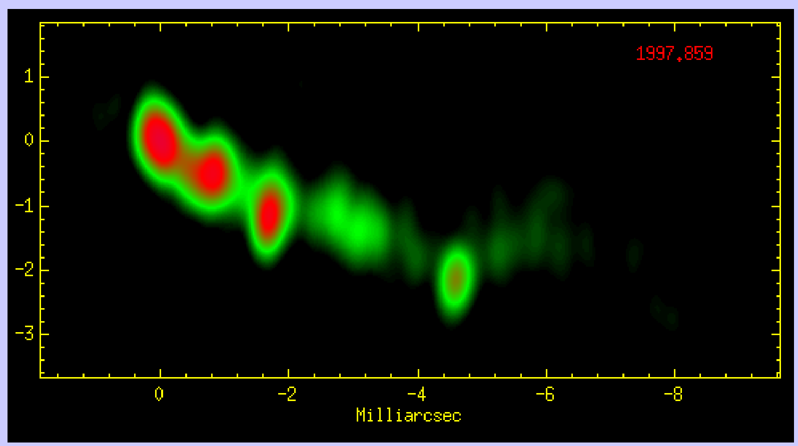



3C31, VLA (20cm), 1999

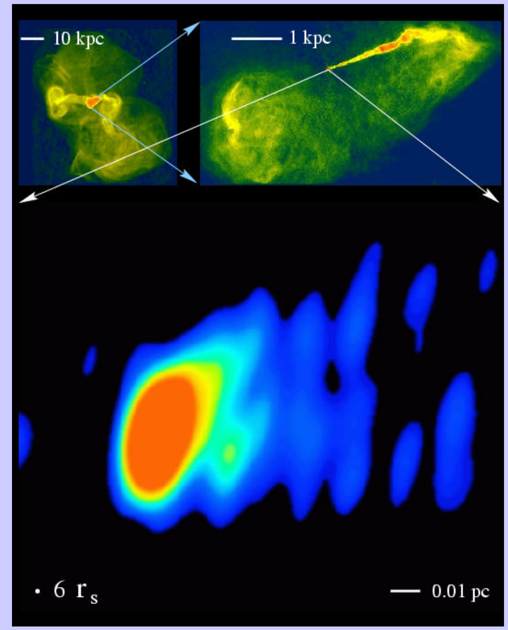
Pc scales: Superluminal motion, one-sidedness




3C120, VLBA
Gómez et al. 2000




Subpc scale: Collimation

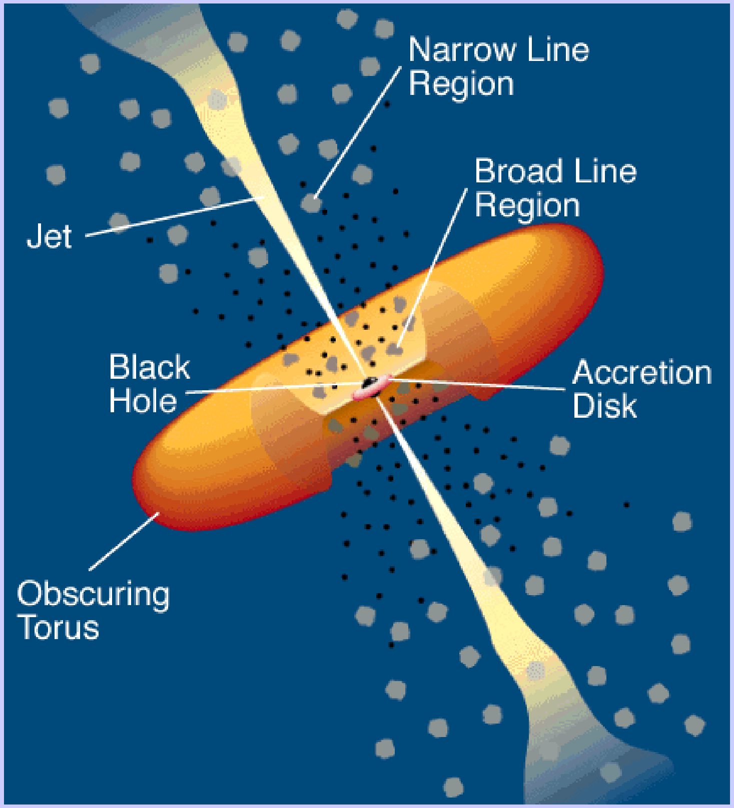



M87, VLA/VLBA
Junor et al. 1999

# Extragalactic jets: the standard model

The production of jets is connected with the process of accretion on supermassive black holes at the core of AGNs (see, e.g., Celotti & Blandford 2000)

- **Hydromagnetic acceleration** of disc wind in a BH magnetosphere (Blandford-Payne mechanism)
- **Extraction of rotational energy from Kerr BH** by magnetic processes (Blandford-Znajek mechanism, magnetic Penrose process)




Emission: **synchrotron** (responsible of the emission from radio to X-rays) **and inverse Compton** ($\gamma$-ray emission) from a relativistic (e+/e-, ep) jet (e.g., Ghisellini et al. 1998). Target photons for the IC process:

- Self Compton: synchrotron photons
- External Compton: disc, BLR, torus

Jets are relativistic, as indicated by:

- Superluminal motions at pc scales (due to the finite speed of propagation of light)
- One-sidedness of pc scale jets and brigthness asymmetries between jets and counterjets at kpc scales (due to Doppler boosting of the emitted radiation)

**Jets: Relativistic collimated ejections of thermal (e+/e-, ep) plasma + ultrarelativistic electrons/positrons + magnetic fields + radiation, generated in the vicinity of SMBH**

↓

(GENERAL) RELATIVISTIC MHD + ELECTRON TRANSPORT + RADIATION TRANSFER

# Extragalactic jets: open questions

miliparsec scale

Jet formation: hydromagnetic acceleration of disc wind ?
extraction of rotational energy from rotating BH → Connection with jet composition: ep, e+e-
Influence of radiative acceleration
Influence of hydrodynamic acceleration
Origin of the poloidal magnetic field

Acceleration: present numerical simulations fail to generate highly relativistic, steady jets
(several arguments point to Lorentz factor ≈few-20; IDV: Lorentz factor 100)

Jet composition

Origin of the ultrarelativistic particle distribution

parsec scale

Nature of the radio components: relativistic shocks ?
instabilities ?

Structure and kinematics of jets; magnetic field topology; role of the magnetic fields in the jet dynamics and emission

Kiloparsec scale

Stability on large scales

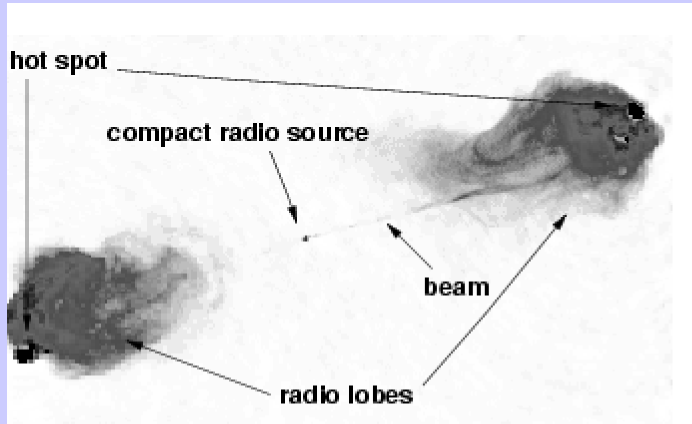
FRI/FRII morphological dichotomy: environment? Jet power? Composition? Formation mechanism? Accretion regime? Magnetic field?
KH instabilities?

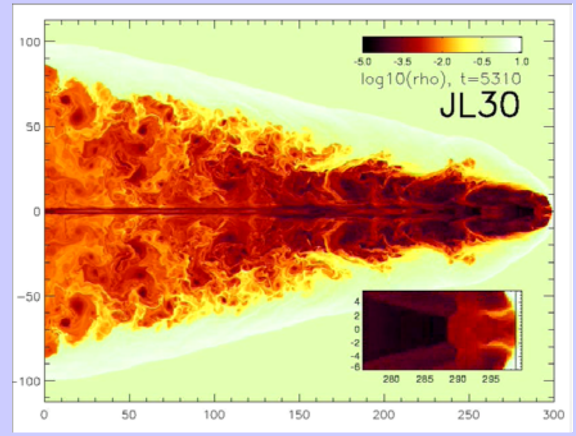
Role in galaxy and cluster evolution: heating

# Simulations of relativistic jets: kiloparsec scale jets I

Hydrodynamical non-relativistic simulations (Rayburn 1977; Norman et al. 1982) verified the basic jet model for classical radio sources (Blandford & Rees 1974; Scheuer 1974).
Two parameters control the morphology and dynamics of jets: the **beam to external density ratio** and the **internal beam Mach number**

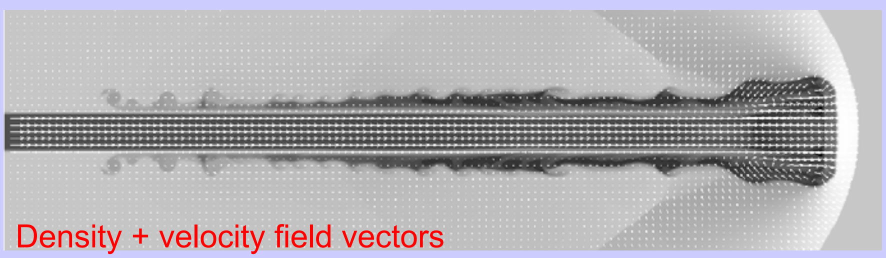
Morphology and dynamics governed by interaction with the external (intergalactic) medium. The simulations have allowed to identify the structural components of radio jets



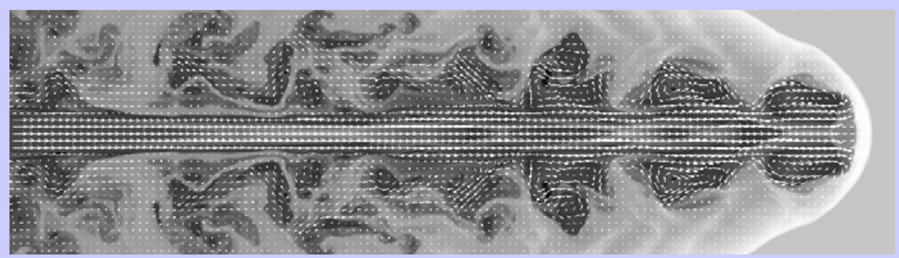

**First relativistic simulations**: van Putten 1993, Martí et al. 1994, 1995, 1997; Duncan & Hughes 1994

Relativistic, hot jet models




"featureless" jet + thin cocoons without backflow + stable terminal shock: naked quasar jets (e.g., 3C273)

Relativistic, cold jet models

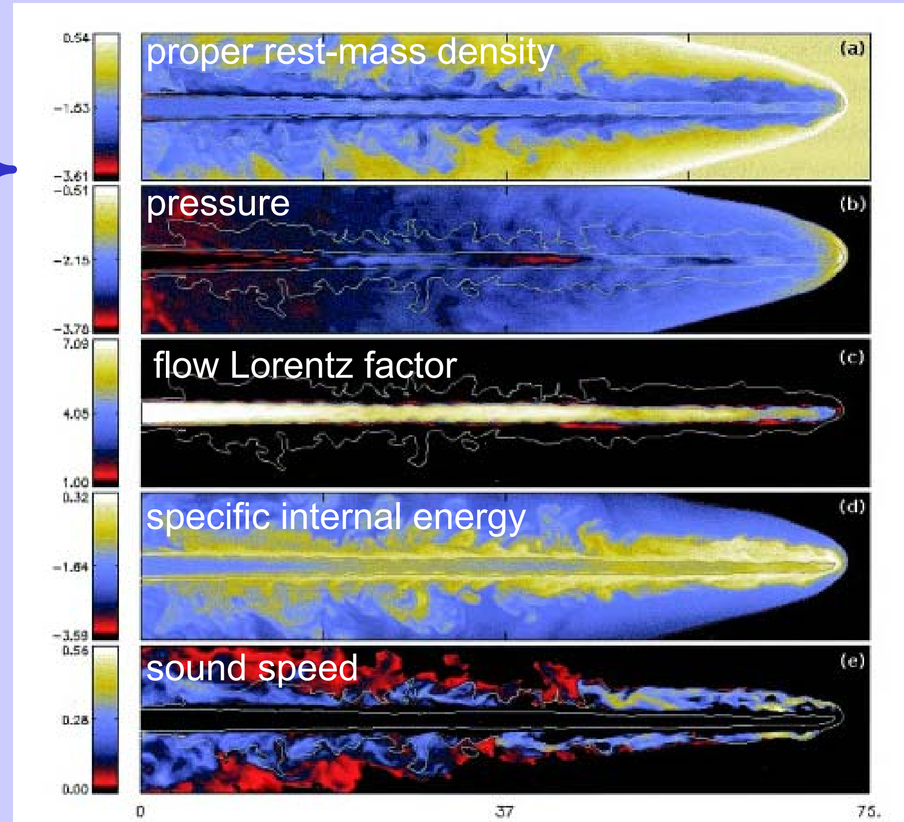


"knotty" jet + extended cocoon + dynamical working surface: FRII radio galaxies and lobe dominated quasars (e.g., Cyg A)

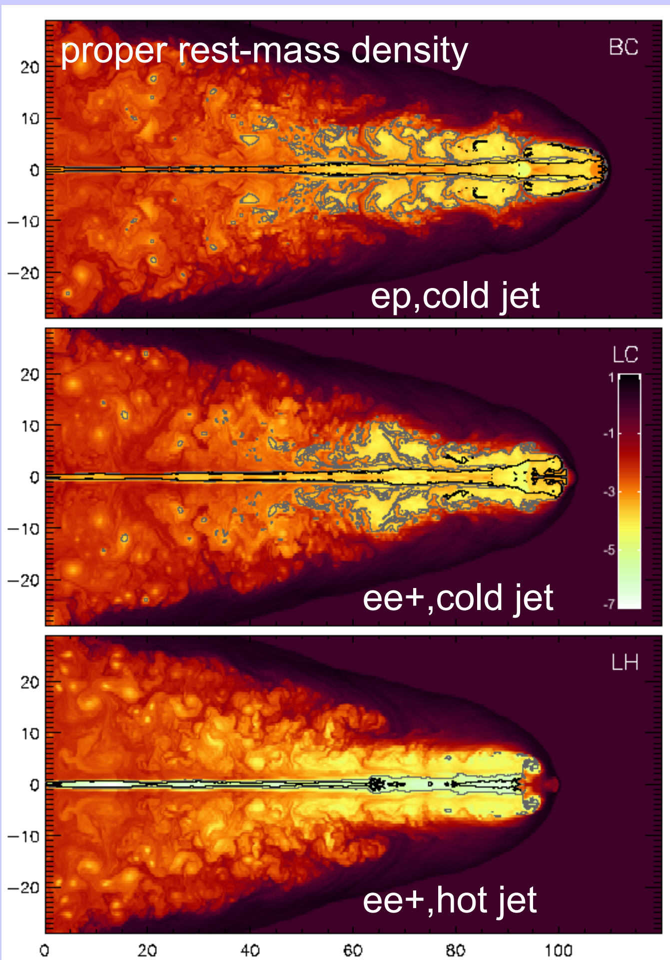
# Simulations of relativistic jets: kiloparsec scale jets II

3D simulations (Nishikawa et al. 1997, 1998; Aloy et al. 1999; Hughes et al. 2002, …):

- Simulations too short (mean jet advance speed too high; poorly developed cocoons)
- Two-component jet structure: fast (LoF ≈ 7) inner jet + slower (LoF ≈ 1.7) shear layer with high specific internal energy




Aloy et al. 1999



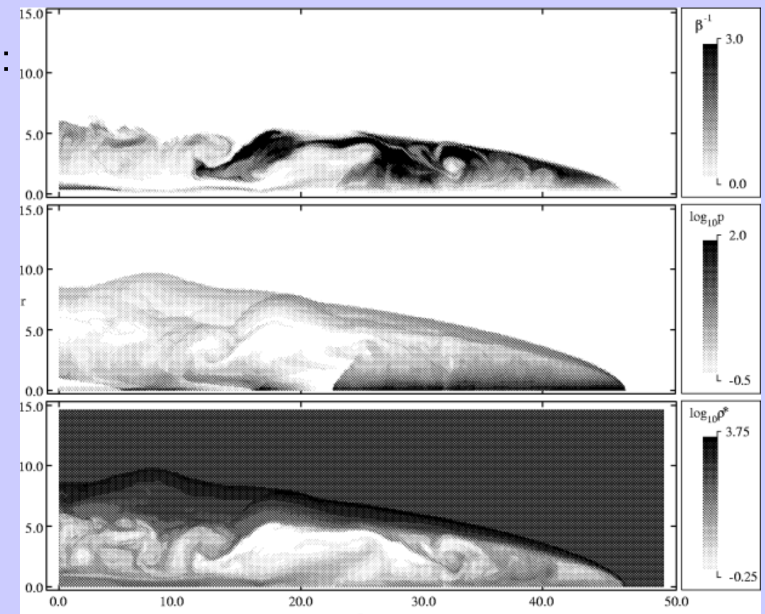

Long term evolution and jet composition (Scheck et al. 2002):

- Evolution followed up to 6 $10^6$ y (10% of a realistic lifetime).
- Realistic EoS (mixture of e-, e+, p)
- Long term evolution consistent with that inferred for powerful radio sources
- Relativistic speeds up to kpc scales
- Neither important morphological nor evolutionary differences related with the plasma composition

# Simulations of relativistic jets: RMHD sims of kpc jets

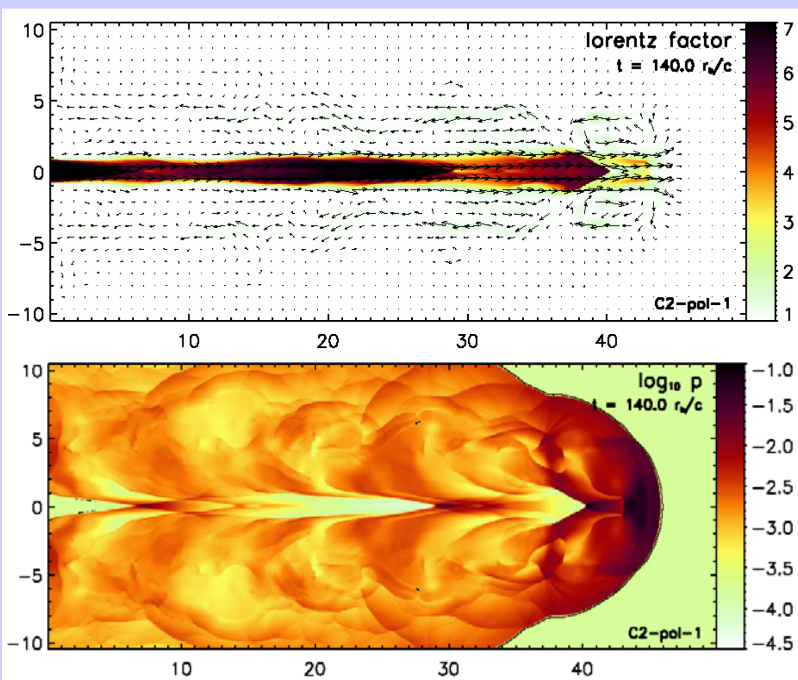
(Nishikawa et al. 1997, 1998; Komissarov 1999; Leismann et al. 2005)

Relativistic jet propagation along aligned and oblique magnetic fields (Nishikawa et al. 1997, 1998)




Relativistic jets carrying toroidal magnetic fields (Komissarov 1999):

- Beams are pinched
- Large nose cones (already discovered in classical MHD simulations) develop in the case of jets with Poynting flux
- Low Poynting flux jets may develop magnetically confining cocoons (large scale jet confinement by dynamically important magnetic fields)

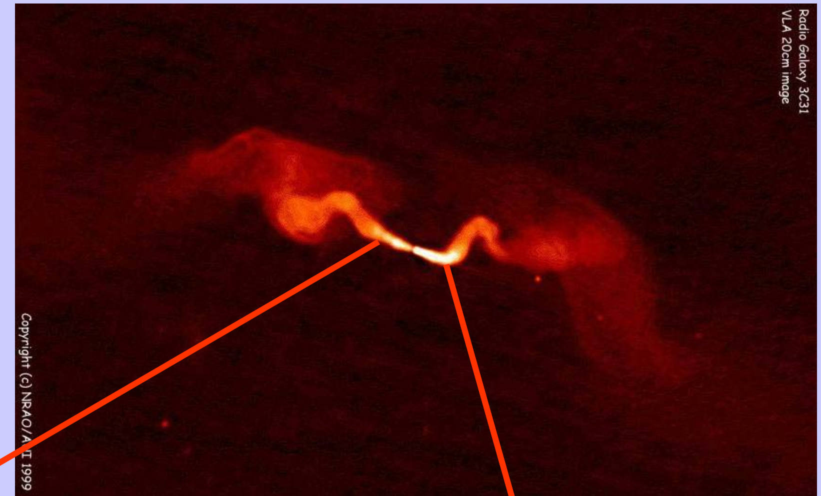



Models with poloidal magnetic fields (Leismann et al. 2005):

- The magnetic tension along the jet affects the structure and dynamics of the flow.
- Comparison with models with toroidal magnetic fields:
  - The magnetic field is almost evacuated from the cocoon. Cocoons are smoother.
  - Oblique shocks in the beam are weaker.

# Simulations of FRI jets: the case of 3C31

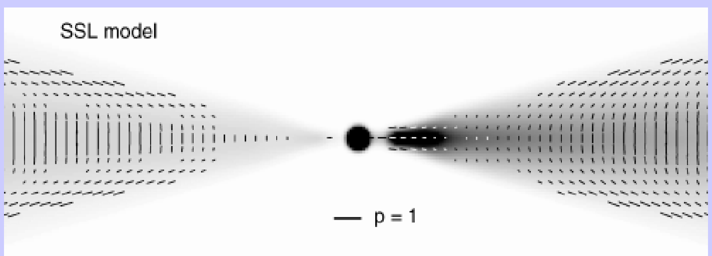
Laing & Bridle 2002a,b model

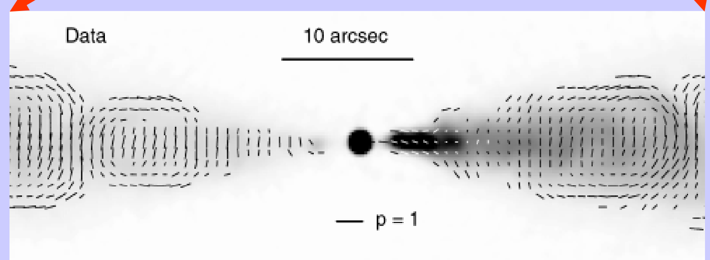



Assumptions

- Axisymmetric, time-stationary, relativistic jet
- Perfectly symmetric jet/counterjet system
- **Parameterized distributions of velocity, magnetic field and synchrotron emissivity**.

**Comparison with VLA total intensity and polarization data** allows to fix parameterizations.



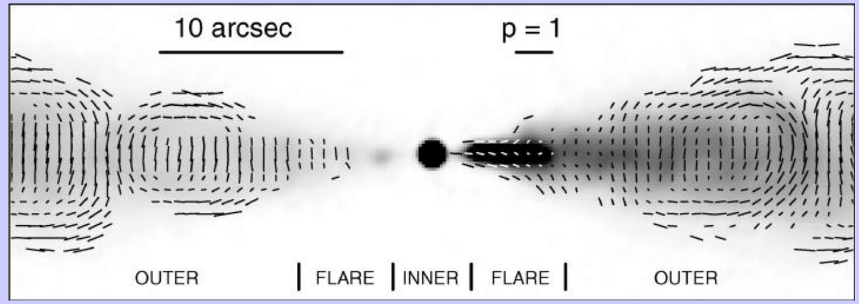




**Conservation of mass momentum and energy** to infer variations of pressure, density, Mach number and mass entrainment rate

- External density and pressure distributions are taken from Hardcastle et al. (2002)
- Pressure equilibrium with the external medium is assumed in the outermost studied region.

# Simulations of FRI jets: the case of 3C31

Laing & Bridle 2002a,b model

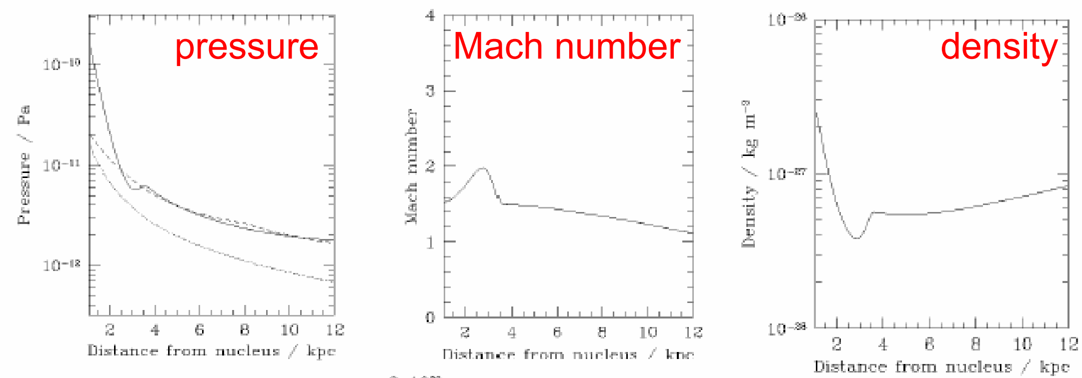



Results:

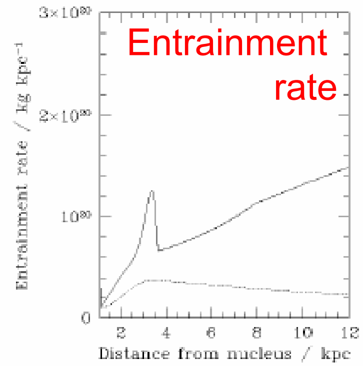
- Angle to the line of sight: 52º
- Jet axial structure: **inner, flaring and outer regions**
- Transversal structure: **spine + shear layer**
- **Spine velocity decreases** (from 0.9 to 0.25 c) due to entrainment after the **steady shock** (in the flare region)

Jet dynamics:

- **The jet is overpressured at the inlet and expands rapidly.**
- **Recollimation occurs when the jet becomes underpressured.**
- **Entrainment:** peak in the entrainment rate at the recollimation site; outwards the jet is slowly entrained and decelerates.




Laing & Bridle (2002b); Hardcastle et al. (2002)




Results confirm the FRI paradigm: free jet expansion, recollimation at shock, mass entrainment and deceleration to transonic speeds outwards

# Simulations of FRI jets: the case of 3C31. Testing Laing & Bridle's model

Perucho et al. 2006, in preparation

- The jet is injected according to the values in Laing & Bridle's model at 500 pc from the core.
- Purely leptonic jet with **L_*kin,j* ~ 10^44 erg/s**.
- Axisymmetric jet in cylindrical coord. (2D sim.); Physical domain: 18 kpc x 6 kpc
- Resolution: 8 cells/R_j (axial) x 16 cells/R_j (radial); 2880 x 1800 cells

| Component | Central density | Form factor | Core radius | Temperature |
|---|---|---|---|---|
| Galaxy | $n_c = 1.8\,10^5 \mathrm{m}^{-3}$ | $\beta_{atm,c} = 0.73$ | $r_c = 1.2\,\mathrm{kpc}$ | $T_c = 4.9\,10^6 K$ |
| Group | $n_g = 1.9\,10^3 \mathrm{m}^{-3}$ | $\beta_{atm,g} = 0.38$ | $r_g = 52\,\mathrm{kpc}$ | $T_g = 1.7\,10^7 K$ |

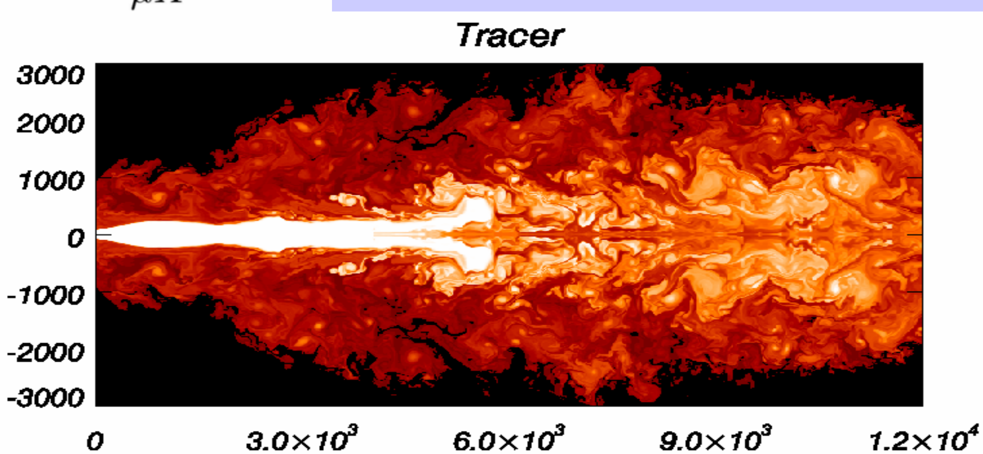
$$n_{ext}(r) = n_c \left(1 + \frac{r^2}{r_c^2}\right)^{-3\beta_{atm,c}/2} + n_g \left(1 + \frac{r^2}{r_g^2}\right)^{-3\beta_{atm,g}/2},$$

$$T = T_c + (T_g - T_c)\frac{r}{r_m} \quad (r < r_m)$$

$$T = T_g \quad (r \geq r_m),$$

$r_m$ = 7.8 kpc

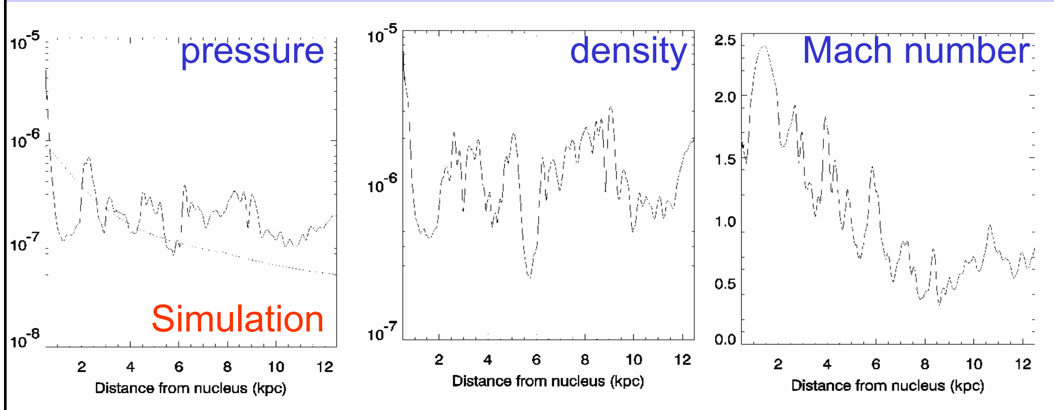
$$P_{ext} = \frac{k_B T}{\mu X} n_{ext}(r),$$

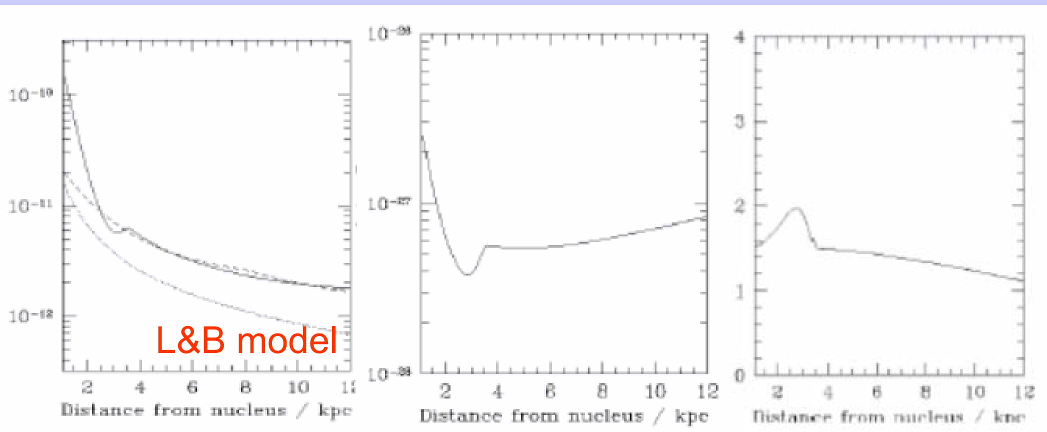


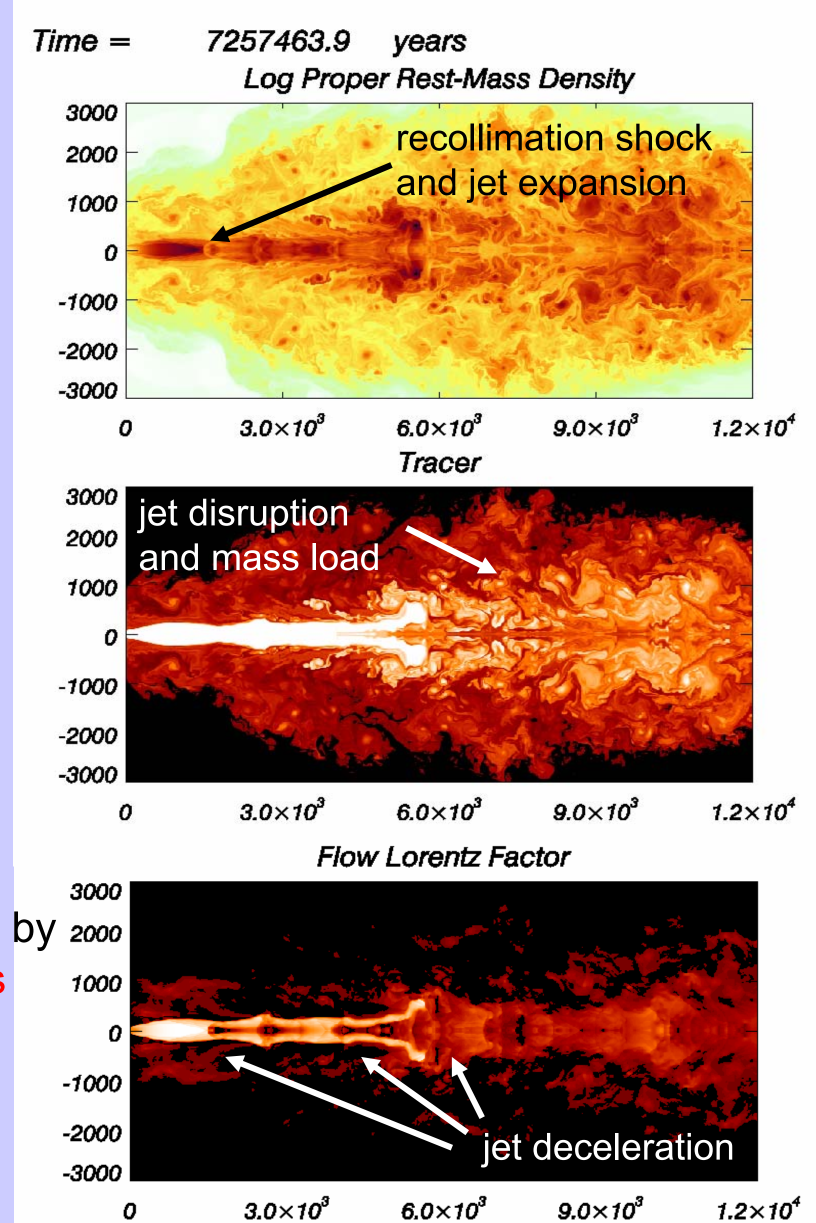

| | |
|---|---|
| Velocity ($v_j$) | $0.87\,c$ |
| Mach number ($M_j$) | 2.5 |
| Temperature ($T_j$, jet) | $4.1\,10^9$K |
| Temperature ($T_c$, ambient[1]) | $5.7\,10^6$K |
| Temperature ($T_g$, ambient[2]) | $1.7\,10^7$K |
| Density ($\rho_j$, jet) | $3\,10^{-30}$g/cm$^3$ |
| Density ($\rho_{a,c}$, ambient[1]) | $3\,10^{-25}$g/cm$^3$ |
| Density ratio ($\eta$) | $10^{-5}$ |
| Leptonic number ($X_l$, jet) | 1.0 |
| Specific int. energy ($\varepsilon_j$, jet) | $1.54\,c^2$ |
| Specific int. energy ($\varepsilon_{a,c}$, ambient[1]) | $1.57\,10^{-6}\,c^2$ |
| Specific int. energy ($\varepsilon_{a,g}$, ambient[2]) | $4.69\,10^{-6}\,c^2$ |
| Pressure ($P_j$, jet) | $6.91\,10^{-6}\,\rho_{a,c}\,c^2$ |
| Pressure ($P_{a,c}$, ambient[1]) | $8.84\,10^{-7}\,\rho_{a,c}\,c^2$ |
| Pressure ($P_{a,g}$, ambient[2]) | $3.07\,10^{-8}\,\rho_{a,c}\,c^2$ |
| Pressure ratio ($P_j/P_{a,c}$) | 7.8 |
| Adiabatic exponent ($\Gamma_j$, jet) | 1.38 |
| Adiabatic exponent ($\Gamma_a$, ambient) | 1.66 |
| 1D velocity estimation ($v_h^{1d}$) | $9.9\,10^{-3}$ c |
| Time unit ($1\,R_j/c$) | 60 pc/c ~ 195 yrs |

# Simulations of FRI jets: the case of 3C31. Testing Laing & Bridle's model

Perucho et al. 2006, in preparation



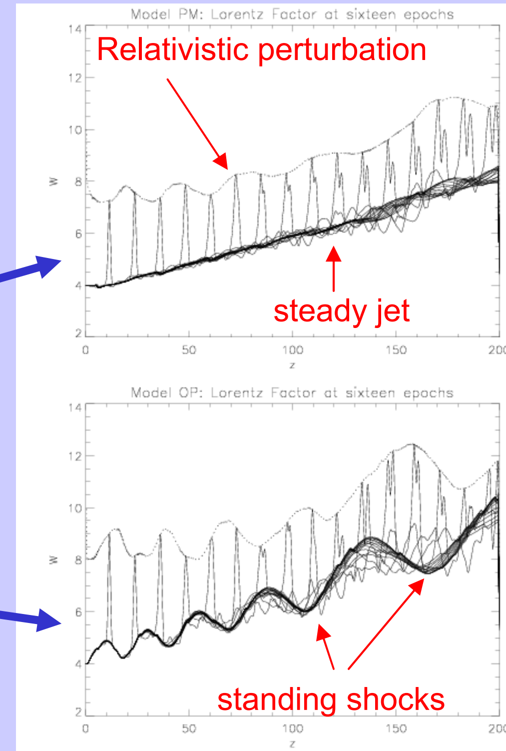




As in Laing & Bridle's model, the evolution is governed by adiabatic expansion of the jet, recollimation, oscillations around pressure equilibrium, mass entrainment and deceleration.

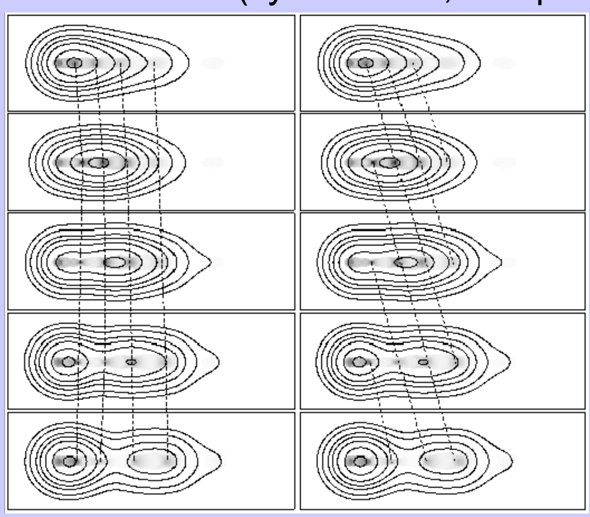
**Simulations confirm the FRI paradigm qualitatively**

# Simulations of relativistic jets: pc-scale jets and superluminal radio sources

Shok-in-jet model: steady relativistic jet with finite opening angle + small perturbation (Gómez et al. 1996, 1997; Komissarov & Falle 1996, 1997)


Radio emission (synchrotron; overpressured jet)



•**Convolved maps** (typical VLBI resolution; contours): core-jet structure with superluminal (8.6c) component

• **Unconvolved maps** (grey scale):

- Steady components associated to recollimation shocks
- dragging of components accompanied by an increase in flux
- correct identification of components (left panel) based on the analysis of hydrodynamical quantities in the observer's frame

**3D hydro+emission sims of relativistic precessing jets (including light travel time delays): Aloy et al. 2003**

# Relativistic hydrodynamics and emission models

**In order to compare with observations, simulations of parsec scale jets must account for relativistic effects (light aberration, Doppler shift, light travel time delays) in the emission**

**Basic hydro/emission coupling** (only synchrotron emission considered so far; Gómez et al. 1995, 1997; Mioduszewski et al. 1997; Komissarov and Falle 1997):

- Dynamics governed by the thermal (hydrodynamic) population
- Particle and energy densities of the radiating (non-thermal) and hydrodynamic populations proportional (valid for adiabatic processes)
- (Dynamically negligible) ad-hoc magnetic field with the energy density proportional to fluid energy density
- Integration of the radiative transfer eqs. in the observer's frame for the Stokes parameters along the LoS
  - Time delays: emission ($\varepsilon_\nu$) and absorption coefficients ( $\kappa_\nu$) computed at retarded times
  - Doppler boosting (aberration + Doppler shift):

$$\varepsilon^{ob}_{\nu^{ob}} = \delta^2 \varepsilon_\nu, \kappa^{ob}_{\nu^{ob}} = \delta^{-1}\kappa_\nu, \delta = \nu^{ob} / \nu = \delta(\Gamma, \cos\theta)$$

**Further improvements**:

- Include magnetic fields consistently (passive magnetic fields: Hughes 2006; RMHD models: work in progress by Roca-Sogorb et al.)
- Compute relativistic electron transport during the jet evolution to acount for adiabatic and radiative losses and particle acceleration of the non-thermal population (non-relativistic MHD sims.: Jones et al. 1999; R(M)HD sims: work in progress by Agudo et al.)
- Include inverse Compton to account for the spectra at high energies
- Include emission back reaction on the flow (important at high frequencies)

# Simulations of superluminal sources: interpreting the observations with the hydrodynamical shock-in-jet model

Isolated (3C279, Wehrle et al. 2001) and regularly spaced stationary components (0836+710, Krichbaum et al. 1990; 0735+178, Gabuzda et al. 1994; M87, Junor & Biretta 1995; 3C371, Gómez & Marscher 2000)

Variations in the apparent motion and light curves of components (3C345, 0836+71, 3C454.3, 3C273, Zensus et al. 1995; 4C39.25, Alberdi et al. 1993; 3C263, Hough et al. 1996)

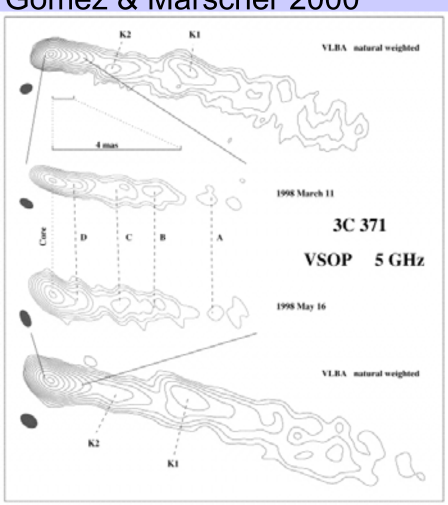
Coexistence of sub and superluminal components (4C39.25, Alberdi et al. 1993; 1606+106, Piner & Kingham 1998) and differences between pattern and bulk Lorentz factors (Mrk 421, Piner et al. 1999)

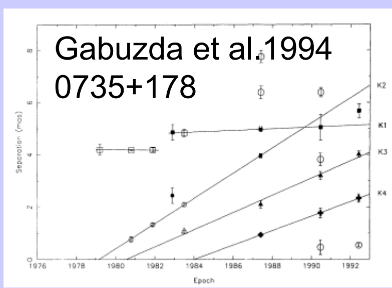
Dragging of components (0735+178, Gabuzda et al. 1994; 3C120, Gómez et al. 1998; 3C279, Wehrle et al. 1997)

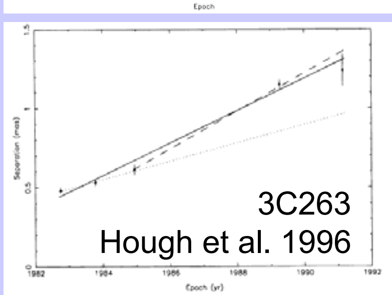
Trailing components (3C120, Gómez et al. 1998, 2001; Cen A, Tingay et al. 2001)

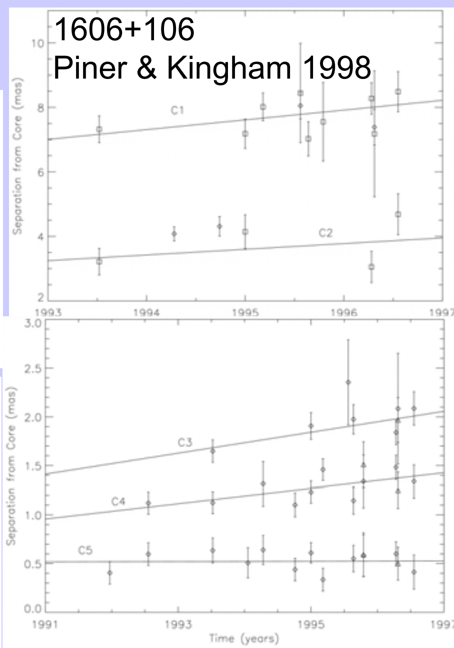
Pop-up components (PKS0420-014, Zhou et al. 2000)

3C371
Gómez & Marscher 2000

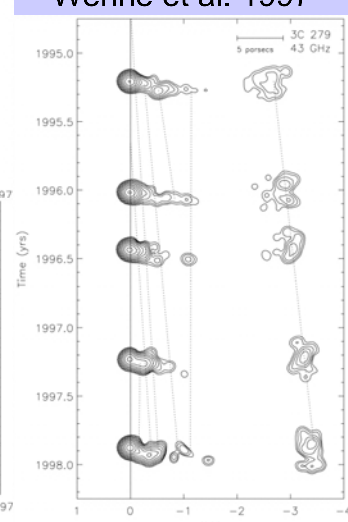


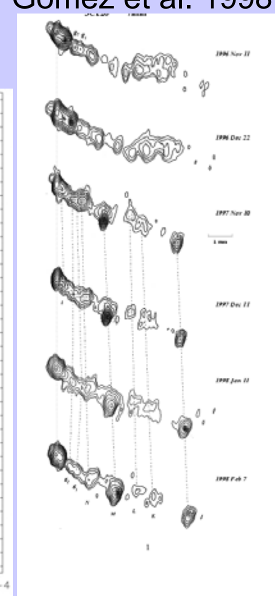




3C279
Wehrle et al. 1997



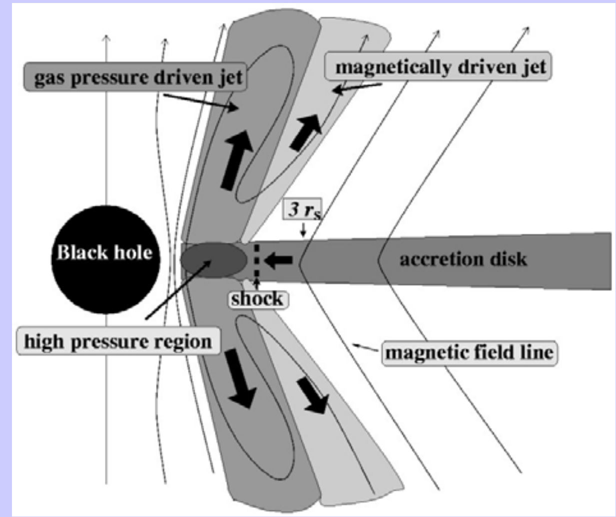

3C120
Gómez et al. 1998



# Observational signatures of jet stratification

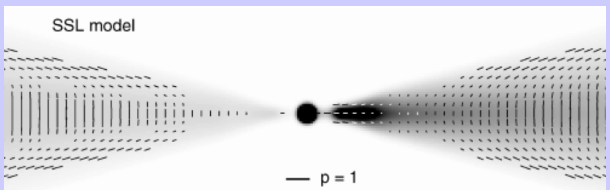
Two component jet models (fast jet spine + slower layers with different magnetic field structure)

- Appeared in some models of jet formation (e.g., Sol et al. 1989: inner relativistic e+/e- jet + thermal disk wind) and recent numerical simulations (Koide et al. 1998: slow magnetically driven jet + fast gas pressure driven jet)

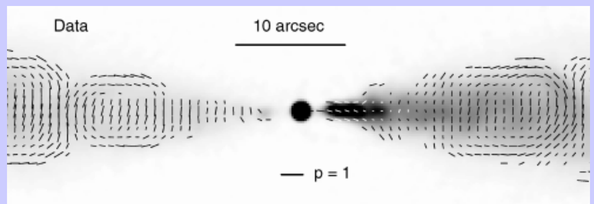



Koide et al. 1998

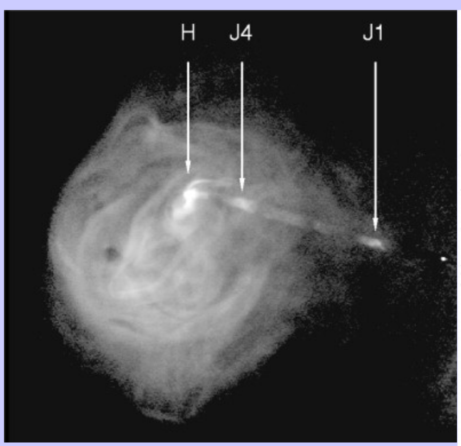
- Are invoked to fit the brightness distributions of FRI jets (Laing & Bridle 2002, and refs therein)

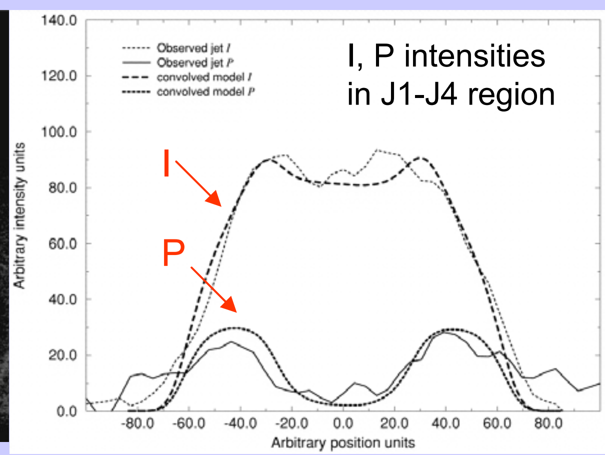



3C31, Laing & Bridle 2002

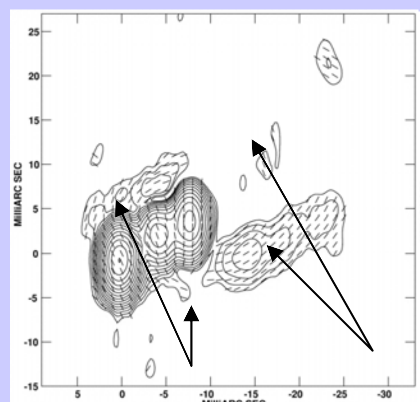



- FRIIs (3C353, Swain et al. 1998: low polarization rails; limb brightening)

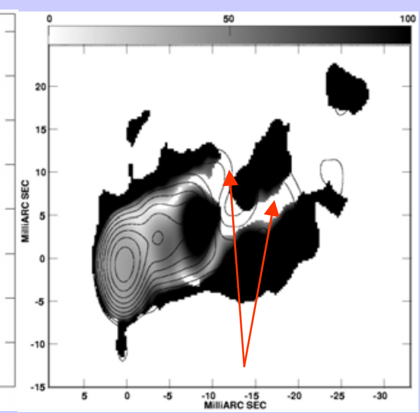



- Pc-scale jets (1055+018, Attridge et al. 1999)

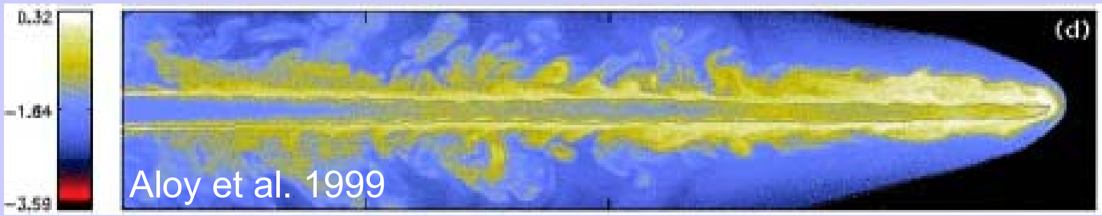


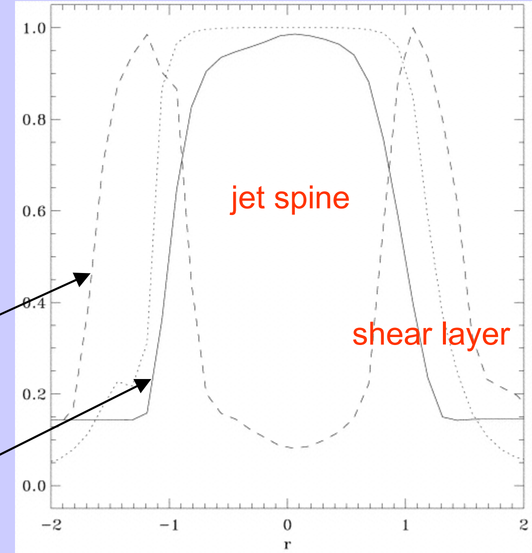

top /down asymmetry




low polarization rails

# Stratified jets 3D RHD + emission simulations




Transversal structure of the jet

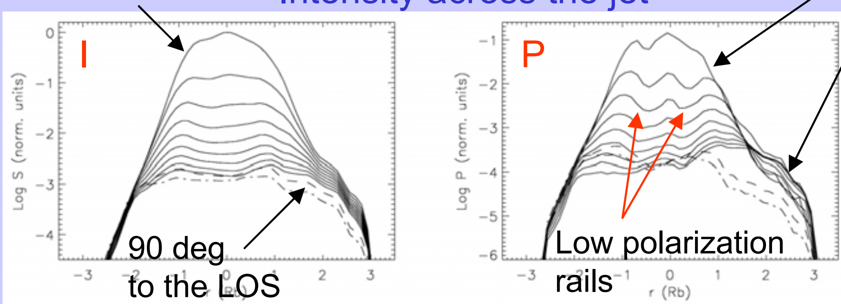
- High specific internal energy
- Relativistic, sheared flow

Magnetic field structure

- Jet spine: toroidal + radial (shocks) + random
- Shear layer: toroidal + aligned (shear) + random

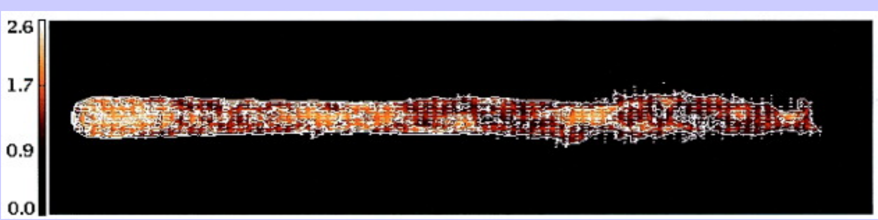
## Synchrotron emission

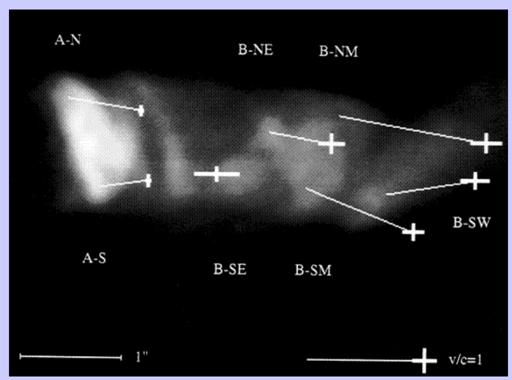
Aloy et al. 2000




- Low polarization rails
- Limb brightening
- Top/down asymmetry: the angle to the LOS (in the fluid frame) of the helical magnetic field has a top/down asymmetry affecting the synchrotron emission/absortion coeffs.

## Local variation of apparent motions




M87
Zhou et al. 1995

# Magnetic field structure in relativistic jets

work in progress by Roca-Sogorb et al.

Goals:

- Interpret the phenomenology of polarization radio maps (role of shear layers, shocks, magnetic field configurations,…)
- probe the dynamical importance of magnetic fields

RMHD model:

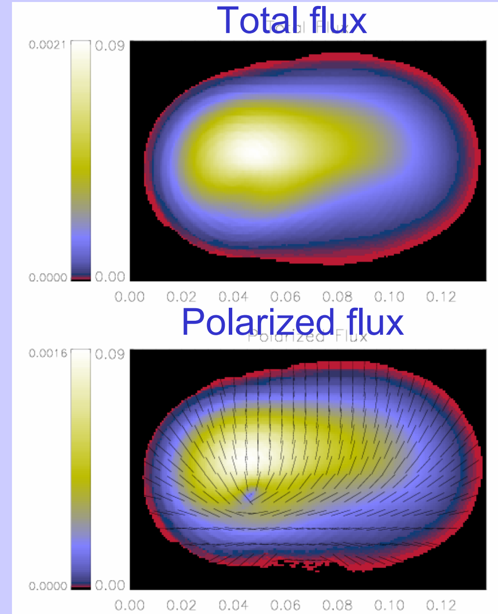
- Beam flow velocity: 0.99c
- (hydrodynamic) beam Mach number: 1.75
- Overpressured jet: beam-to-ambient hydrodynamic pressure = 2
- Equipartition helical magnetic field (pitch angle: 20º)

**Results confirm emission asymmetry variations as a function of the observer's angle to the LoS, θ'**
(Aloy et al. 2000)

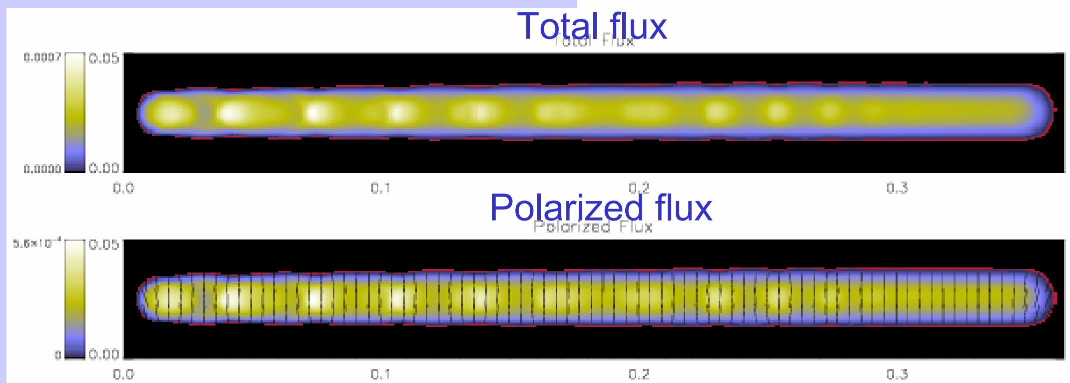
Work in progress include:

- Solution of the transversal equilibrium equation (e.g., Birkinshaw 1991) for different helical magnetic field configurations.
- Jets with toroidal velocity.

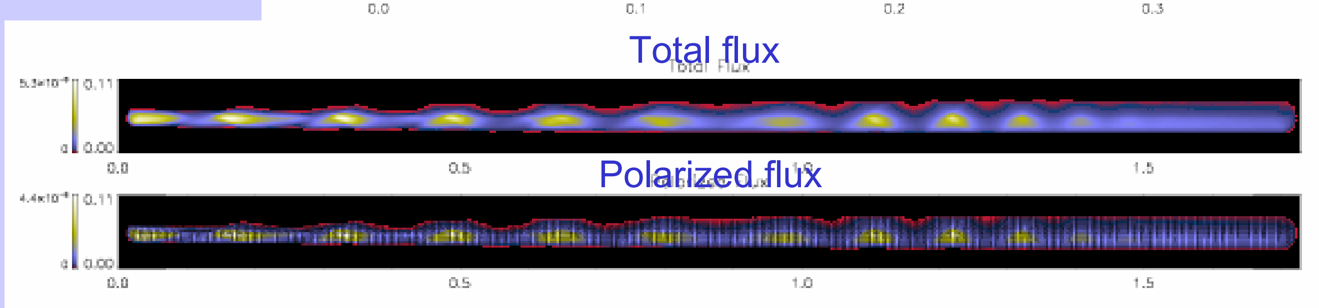
θ'




1.4º




8.1º




43.8º

# Kelvin-Helmholtz instabilities and extragalactic jets

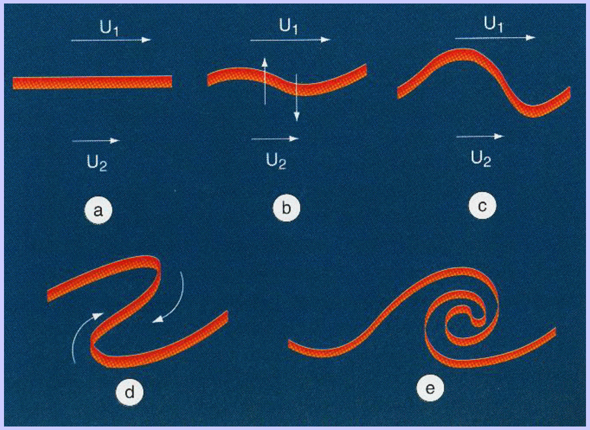
KH stability analysis is currently used to probe the physical conditions in extragalactic jets

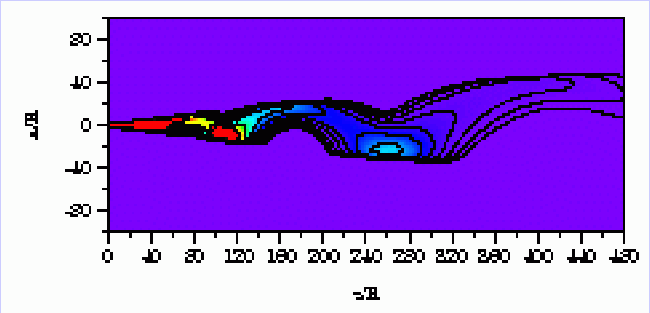
Linear KH stability theory:

- Production of radio components
- Interpretation of structures (bends, knots) as signatures of pinch/helical modes

Non-linear regime:

- Overall stability and jet disruption
- Shear layer formation and generation of transversal structure
- FRI/FRII morphological jet dichotomy



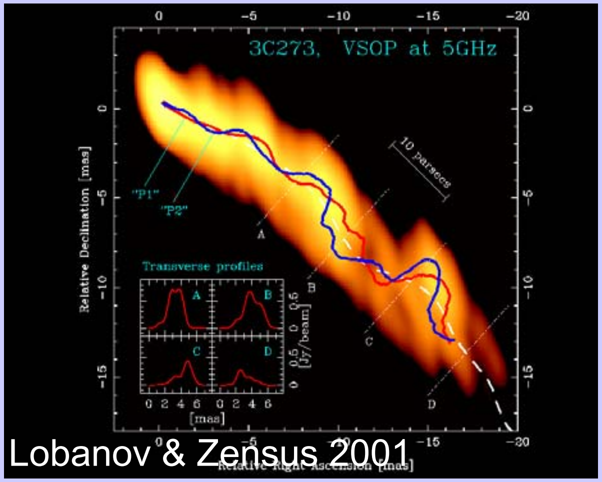
## Interpretation of parsec scale jets

Wavelike helical structures with differentially moving and stationary features can be produced by precession and wave-wave interactions (Hardee 2000, 2001)
[used to constrain the physical conditions in the inner jet of 3C120 (Hardee 2003, Hardee et al. 2005)]

## The 3C273 case

**1**. Emission **across** the jet resolved ➞ double helix inside the jet
**2**. Five sinusoidal modes are required to fit the double helix
**3**. The sinusoidal modes are then identified with instability modes (elliptical/helical body/surface modes) at their respective resonant wavelengths from which physical jet conditions are derived:

Lorentz factor: 2.1 ± 0.4; Mach number: 3.5 ± 1.4
Density ratio: 0.023 ± 0.012; Jet sound speed: 0.53 ± 0.16




Lobanov & Zensus 2001

# Kelvin-Helmholtz instabilities: non-linear regime

Perucho et al. 2004a,b

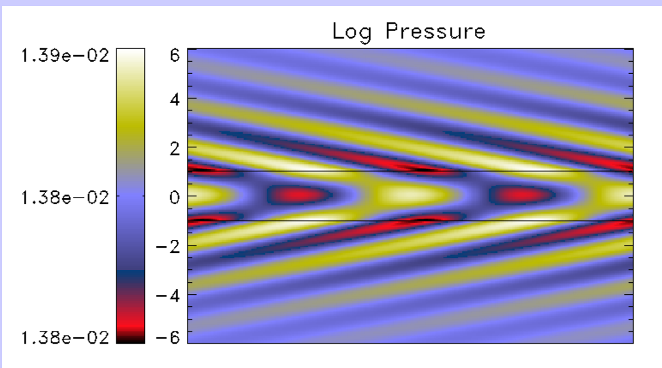
Goals of the study:

- Relativistic effects on the stability of jets
- Transition from linear to nonlinear stability
- Dynamics of jet disruption
- Long term evolution (jet disruption, shear layer formation, …)

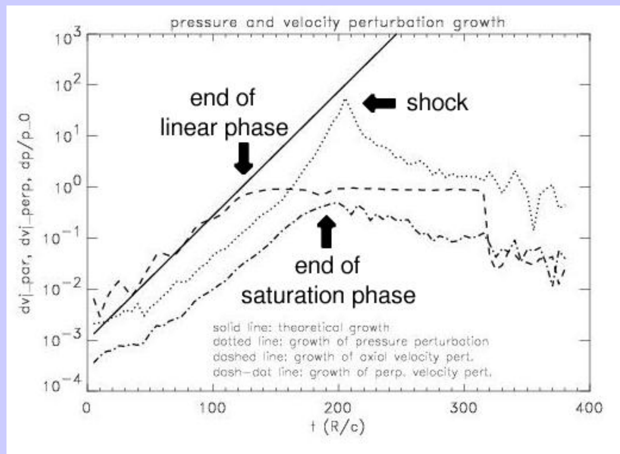
Numerical simulations:

- Planar (2D) symmetric (pinch) / antysymmetric (helical) modes
- Resolution: 400 zones/$R_j$ (transversal) x 16 zones/Rj (longitudinal)
- Initial conditions: steady jet + small amplitude perturbation (first body mode)
- Temporal approach

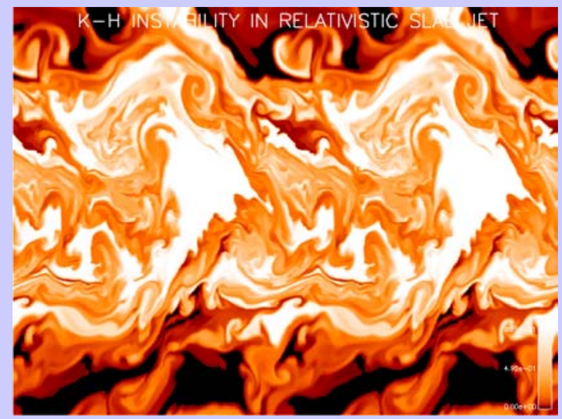
## Lorentz factor 5 model




Initial model

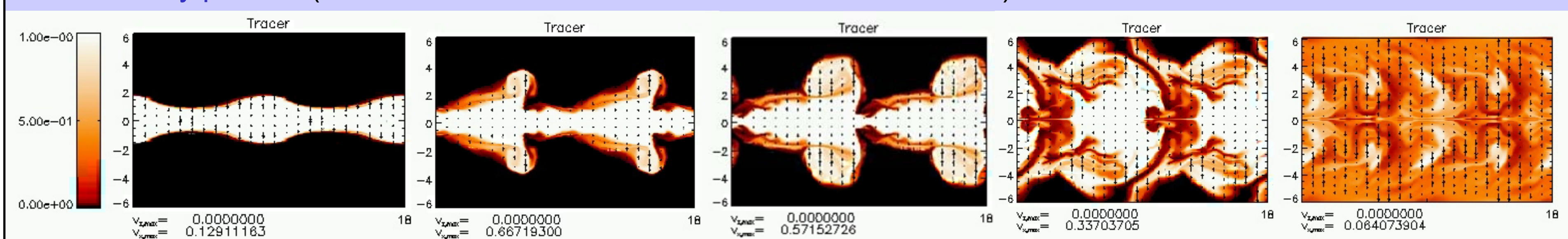



Linear phase




Non-linear evolution

Evolutionary phases (similar to Bodo et al. 1994 for non-relativistic flows):




Linear | Saturation | Pressure maximum | Mixing | Quasisteady

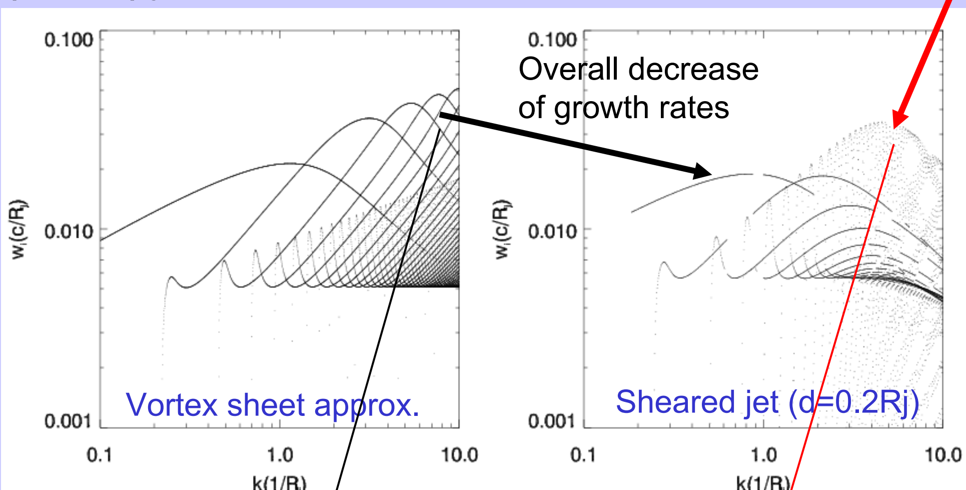
# K-H instabilities for relativistic sheared jets I: Linear regime

Perucho et al. 2005
Perucho et al. 2006, in prep.

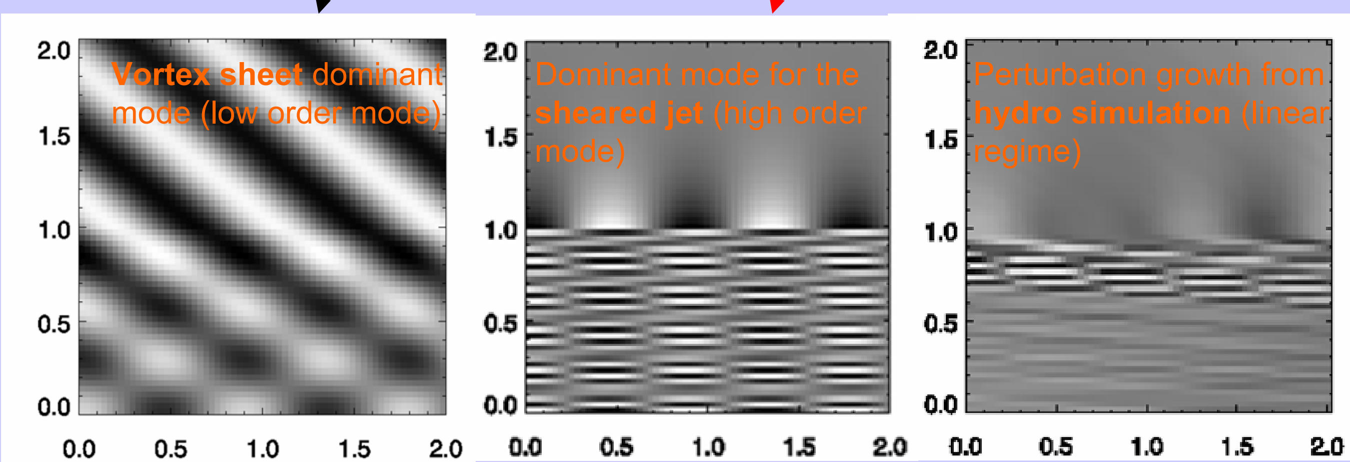
Goal: study the effects of shear in the (non-linear) stability of relativistic jets
More than 20 models analyzed by varying jet specific internal energy, Lorentz factor and shear layer width

**Growth rate vs. long. wavenumber for antisymmetric fundamental and body modes of a hot, relativistic (planar) jet model**

Shear layer resonances (peaks in the growth rate of high order modes at maximum unstable wavelength)




- **Resonant modes dominate in large Lorentz factor jets**
- Increasing the specific internal energy causes resonances to appear at shorter wavelengths
- Widening of the shear layer reduces the growth rates and the dominance of shear layer resonances → **optimal shear layer width that maximizes the effect**
- Widening of the shear layer causes the absolute growth rate maximum to move towards smaller wavenumbers and lower order modes



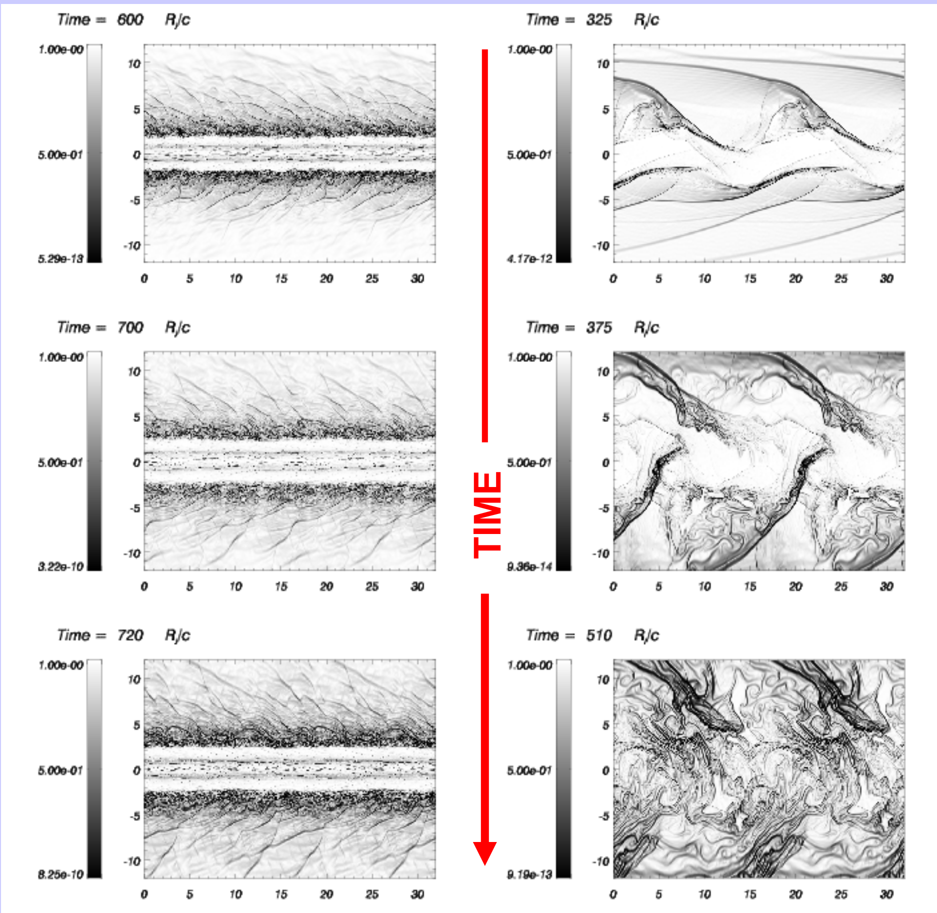

**Numerical simulations confirm the dominance of resonant modes in the perturbation growth**

# K-H instabilities for relativistic sheared jets II: Nonlinear regime

Perucho et al. 2005
Perucho et al. 2006, in prep.

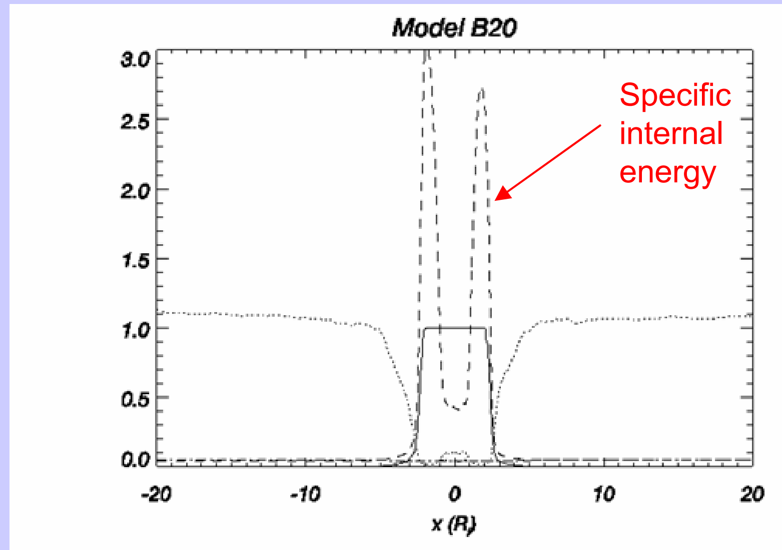
**Shear layer resonant modes suppress the growth of disruptive long wavelength instability modes**

Shear layer resonant modes dissipative most of their kinetic energy into internal energy close to the jet boundary generating **hot shear layers**




Sheared jet (d=0.2 Rj)
**Lorentz factor 20 jet**

Sheared jet (d=0.2 Rj)
**Lorentz factor 5 jet**




## Present results:

- offer a **natural explanation for the stability of powerful (FRII) jets**
- validate the interpretation of several observational trends involving **jets with transversal structure** (e.g., Aloy et al. 2000)

# Summary, conclusions,…I

- Kiloparsec scale jets: basic morphological and dynamical aspects understood
  advances in the comprehension of FRI jets

- Parsec scale jets: success of the relativistic hydrodynamical shock-in-jet model in interpreting the phenomenology of pc-scale jets and superluminal sources:

  isolated and regularly spaced components, variations in the apparent speed and light curves of components, coexistence of sub and superluminal components, differences between pattern and bulk Lorentz factors, dragging of components, trailing components, pop-up components

  observational signatures of jet stratification

  low polarization rails, limb brightening, top/down asymmetry, local variations of apparent speeds

- KH stability analysis: linear theory:

  interpretation of jet structure (bends, components) as signature of pinch/helical modes, derive physical parameters in jets

  non-linear (hydrodynamical) studies:

  transition to non-linear regime and phases in the perturbation development, non-linear stability and long-term quasi-steady state in terms of jet params., role of shear layers and shear layer resonant modes

# Summary, conclusions,…II

- Achievements:

  Steps in the combination of relativistic hydro + radiation transfer codes

- Further improvements:

  Include magnetic fields consistently (first steps given)

  Compute relativistic electron transport during the jet evolution to acount for adiabatic and radiative losses and particle acceleration of the non-thermal population

  Include inverse Compton to account for the spectra at high energies

  Include emission back reaction on the flow