Propagation and stability of relativistic jets

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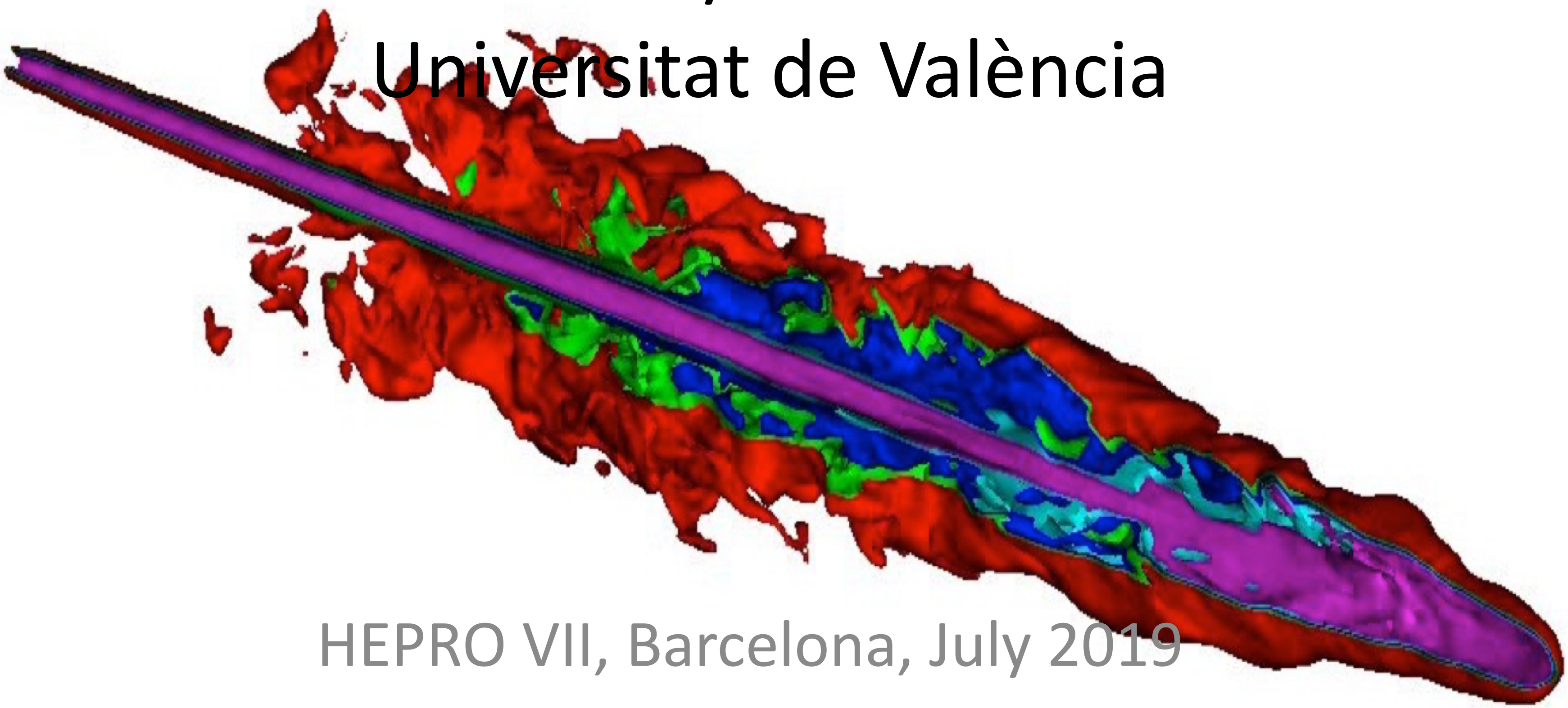
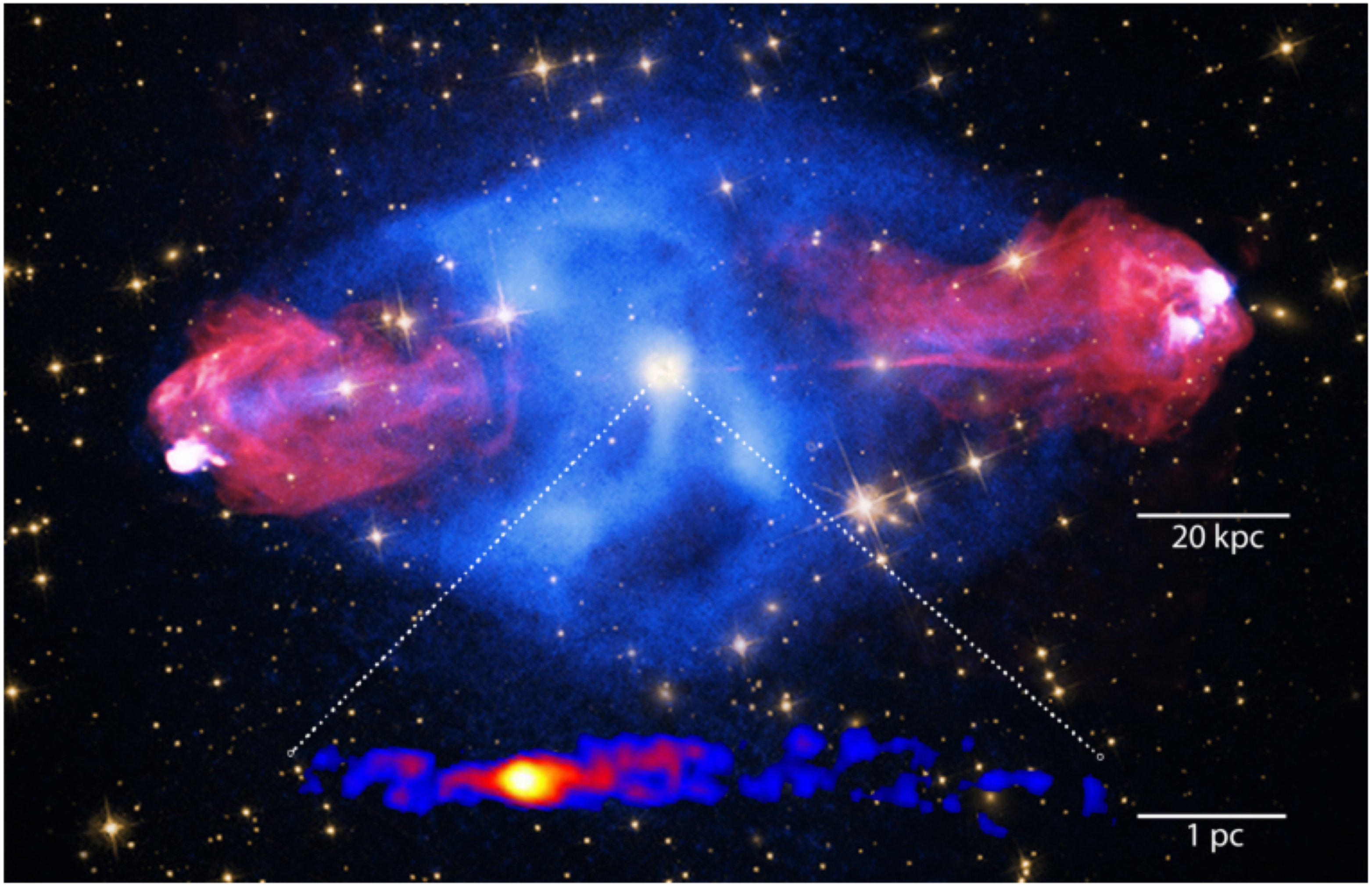


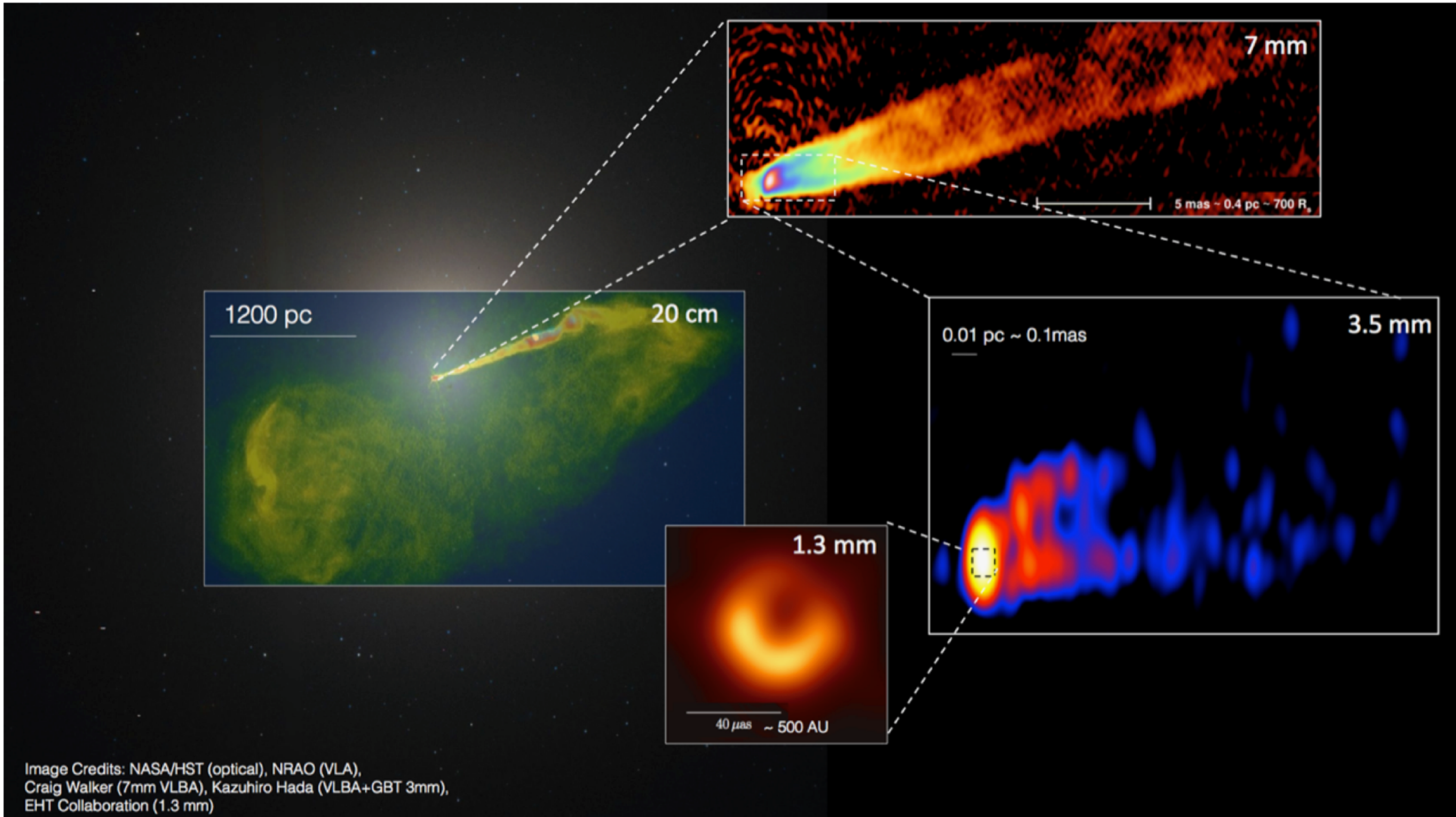
HEPRO VII, Barcelona, July 2019

Extragalactic jets



X-ray: NASA/CXC/SAO; Optical: NASA/STScI; Radio: NSF/NRAO/AUI/VLA; VLBI inset: Boccardi et al. 2017. Blandford et al. 2018.

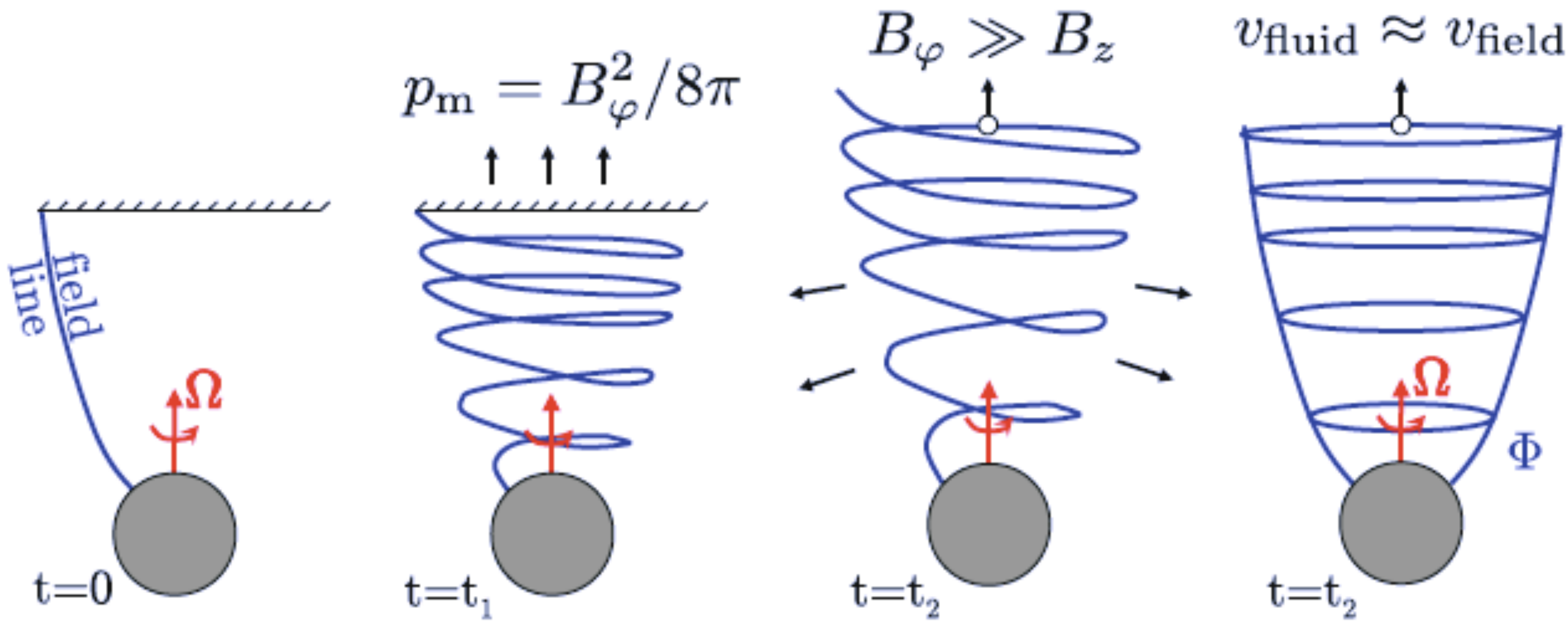
Extragalactic jets



Formation

- Blandford-Znajek

Tchekhovskoy 2012



- The jets probably form from the extraction of rotational energy from the SMBH.
- The toroidal component is dominant. It cannot be constant across the jet cross-section.

Equations

$$T^{\mu\nu} = \rho h^* u^\mu u^\nu + p^* g^{\mu\nu} - b^\mu b^\nu$$

b_μ is the magnetic field in the fluid rest-frame

$h^* = h + |b|^2/\rho$ the gas plus field enthalpy,

$p^* = p_{\rm gas} + |b|^2/2$

$$|b|^2 = b_\alpha b^\alpha = B^2/\gamma^2 + (\mathbf{v}\cdot\mathbf{B})^2$$

conservation equations:

$$\nabla_\mu T^{\mu\nu} = 0 \qquad \nabla_\mu(\rho u^\mu) = 0.$$

mass:

$$\frac{\partial \gamma\rho}{\partial t} + \nabla_i(\gamma\rho v^i) = 0,$$

momentum:

$$\frac{\partial \gamma^2 \rho h^* v^i}{\partial t} + \nabla_j(\gamma^2 \rho h^* v^i v^j + p^* \delta^{ij} - b^i b^j) = 0$$

$$i, j = 1, 2, 3$$

$$b^i = B^i/\gamma + v^i \gamma(\mathbf{v}\cdot\mathbf{B})$$

energy:

$$\frac{\partial(\rho h^* \gamma^2 - p^* - b^0 b^0 - \rho\gamma)}{\partial t} + \nabla\cdot(\rho h^* \gamma^2 \mathbf{v} - b^0 \mathbf{b} - \rho\gamma\mathbf{v}) = 0, \quad b^0 = \gamma(\mathbf{v}\cdot\mathbf{B})$$

field equations:

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla\times\mathbf{E} = 0, \qquad \nabla\cdot\mathbf{B} = 0. \qquad \mathbf{E} = -\mathbf{v}\times\mathbf{B}$$

Are jets unstable?

Linear perturbation:

$$X(r) \longrightarrow X_0(r) + X_1(r,\phi,z,t) \qquad X = \mathbf{v},\, \rho,\, p,\, \mathbf{B}$$

Linearized momentum equation:

$$\frac{\partial}{\partial t}\left[\gamma_0^2(\rho h)_1 - P_1 + 2\gamma_0^4\,(\mathbf{v}\cdot\mathbf{v}_1)\,(\rho h)_0\right] + \nabla\cdot\left[\gamma_0^2(\rho h)_1\mathbf{v} + 2\gamma_0^4\,(\mathbf{v}\cdot\mathbf{v}_1)\,(\rho h)_0\mathbf{v} + \gamma_0^2(\rho h)_0\mathbf{v}_1\right]$$
$$+\frac{\partial}{\partial t}\left[B_0^2(\mathbf{v}\cdot\mathbf{v}_1) + (1+v^2)\mathbf{B}_0\cdot\mathbf{B}_1 - (\mathbf{v}\cdot\mathbf{B}_1 + \mathbf{v}_1\cdot\mathbf{B}_0)\mathbf{v}\cdot\mathbf{B}_0/c\right]$$
$$+\nabla\cdot\left[2(\mathbf{B}_0\cdot\mathbf{B}_1)\mathbf{v} + B_0^2\mathbf{v}_1 - (\mathbf{v}\cdot\mathbf{B}_0)\mathbf{B}_1 - (\mathbf{v}\cdot\mathbf{B}_1)\mathbf{B}_0 - (\mathbf{v}_1\cdot\mathbf{B}_0)\mathbf{B}_0\right] = 0.$$

Linearized energy equation:

$$\gamma_0^2(\rho h)_0\left[\frac{\partial\mathbf{v}_1}{\partial t} + (\mathbf{v}\nabla)\mathbf{v}_1\right] + \nabla P_1 + \frac{\mathbf{v}}{c^2}\frac{\partial P_1}{\partial t} - (\mathbf{j}_0\times\mathbf{B}_1) - (\mathbf{j}_1\times\mathbf{B}_0) = 0,$$

Linearized field equations:

$$\nabla\cdot\mathbf{B}_1 = 0$$

$$\nabla\times\mathbf{E}_1 = -\frac{\partial\mathbf{B}_1}{\partial t}, \qquad \mathbf{E}_1 = -\mathbf{v}\times\mathbf{B}_1 - \mathbf{v}_1\times\mathbf{B}_0.$$

Yes, they are

Non-magnetized jets ($\mathbf{B} = 0$):

- No rotation ($\mathbf{v} = v^z \mathbf{e}_z$):
  - No expansion ($\partial v^r / \partial t = 0$): KHI
  - Expansion ($\partial v^r / \partial t \neq 0$): RTI
- Rotation ($\mathbf{v} = v^\phi \mathbf{e}_\phi + v^z \mathbf{e}_z$):
  - No expansion ($\partial v^r / \partial t = 0$): KHI
  - Expansion ($\partial v^r / \partial t \neq 0$): CFI

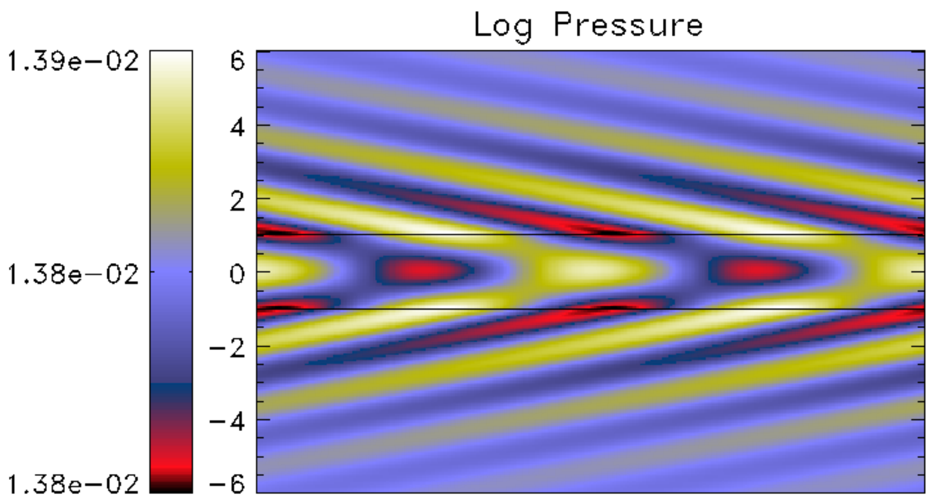
Magnetized jets (all non-expanding cases):

- No rotation ($\mathbf{v} = v^z \mathbf{e}_z$):
  - KHI
  - CDI + KHI
  - CDI/pressure-driven instability
- Rotation($\mathbf{v} = v^\phi \mathbf{e}_\phi + v^z \mathbf{e}_z$):
  - Centrifugal buoyancy

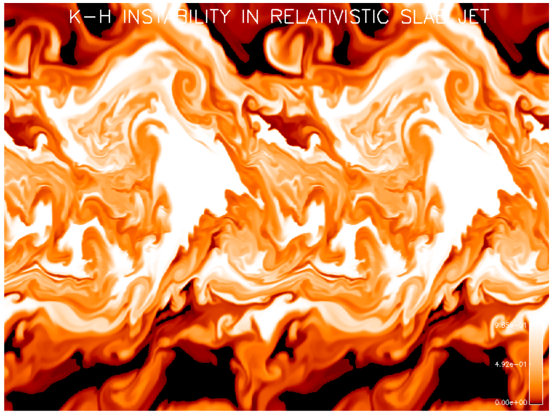
$$X_1(r, \phi, z, t) \; = \; X_1(r) \exp(i(\omega t \pm m\phi - k_z z))$$

KH instability

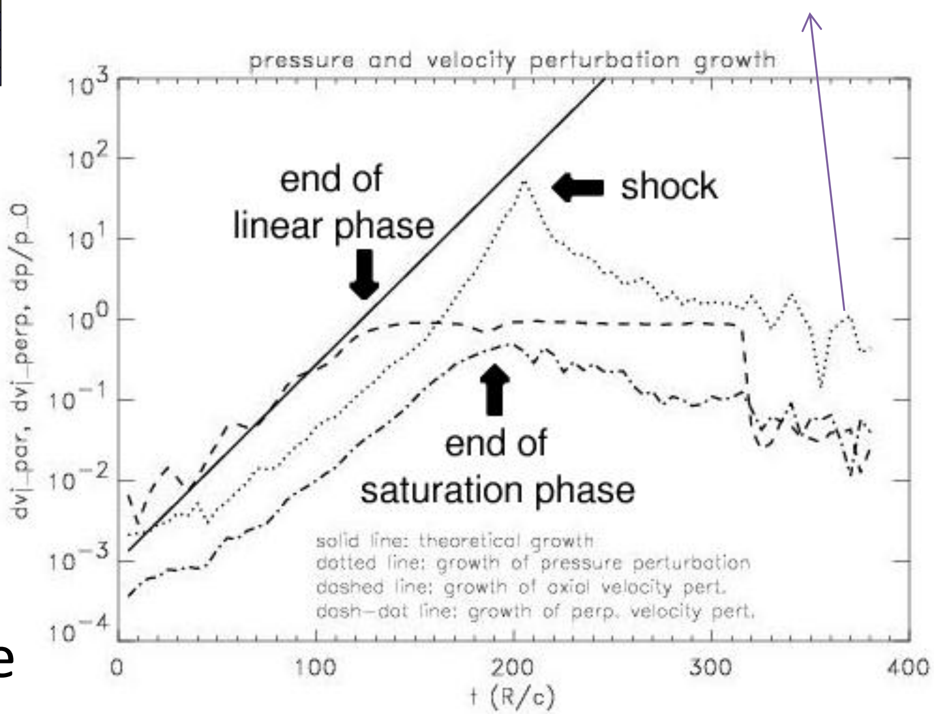
Perucho et al. (2004a, 2004b)



Initial model

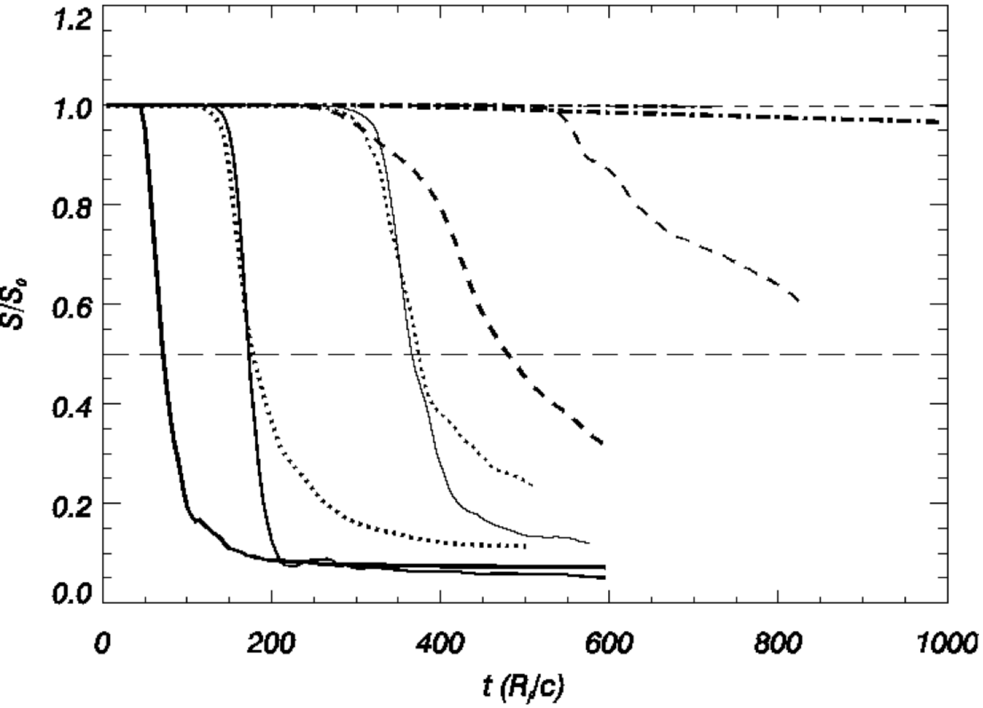


- Parameters:
  - Lorentz factor.
  - Rest-mass density contrast.
  - Specific internal energy.
  - Pressure equilibrium.



Linear phase

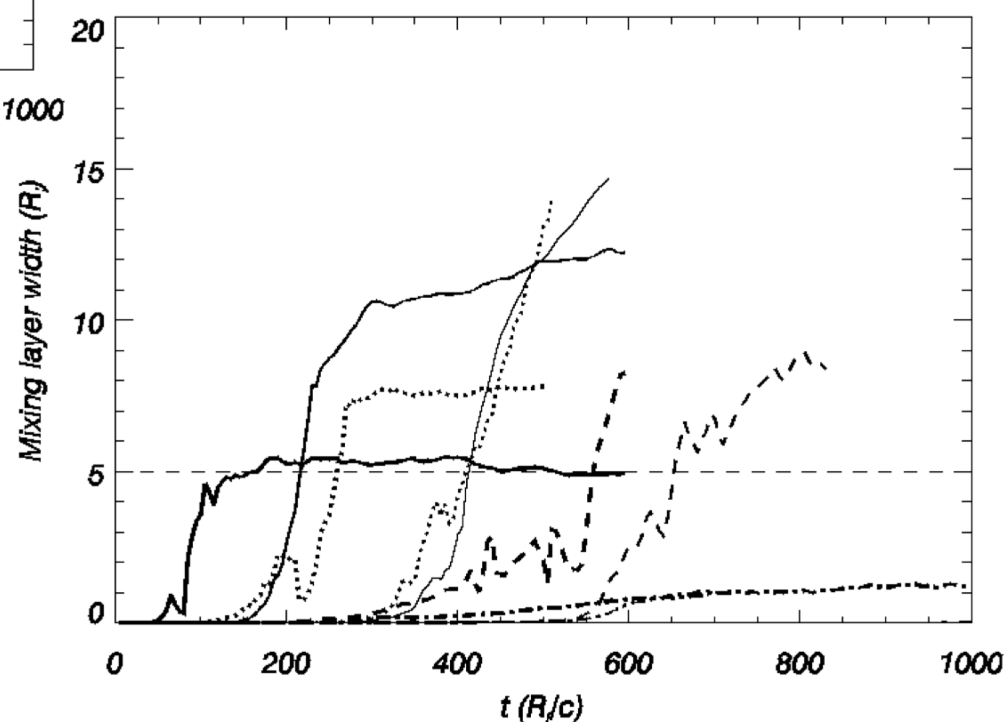
KH instability



Perucho, Martí, Hanasz (2005), Perucho et al. (2010):

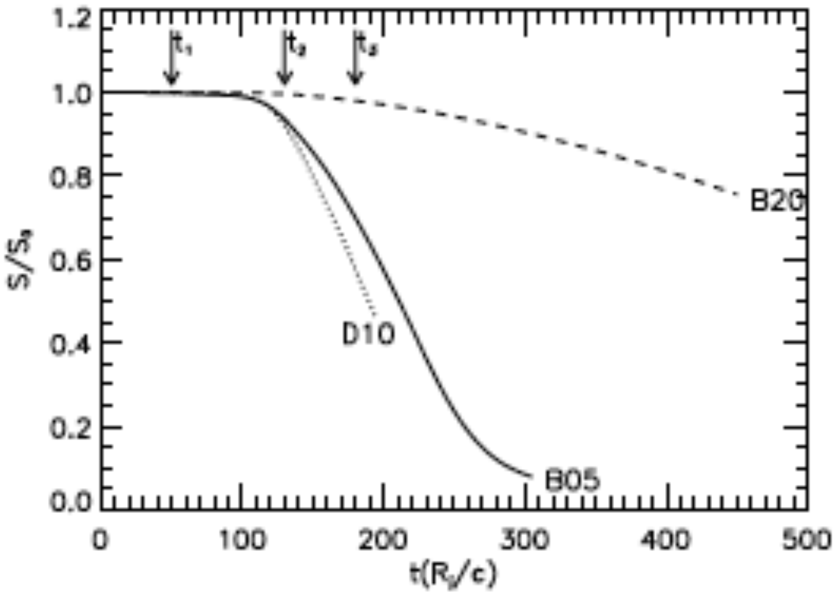
KH instability. The disruption process can be slow if the growing modes have small wavelengths.

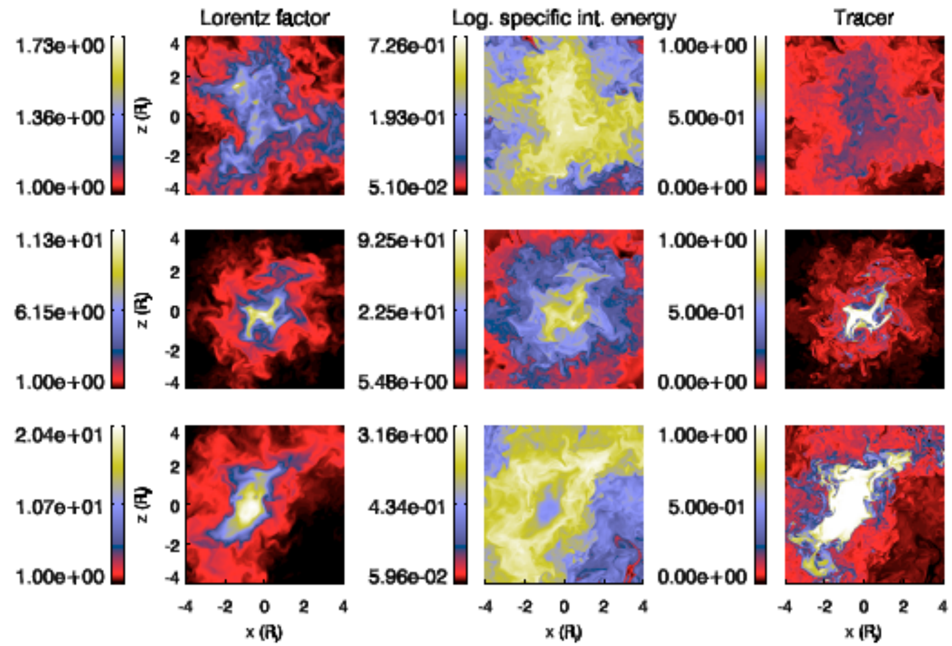
2D simulations of temporal evolution of KH instabilities in relativistic flows.

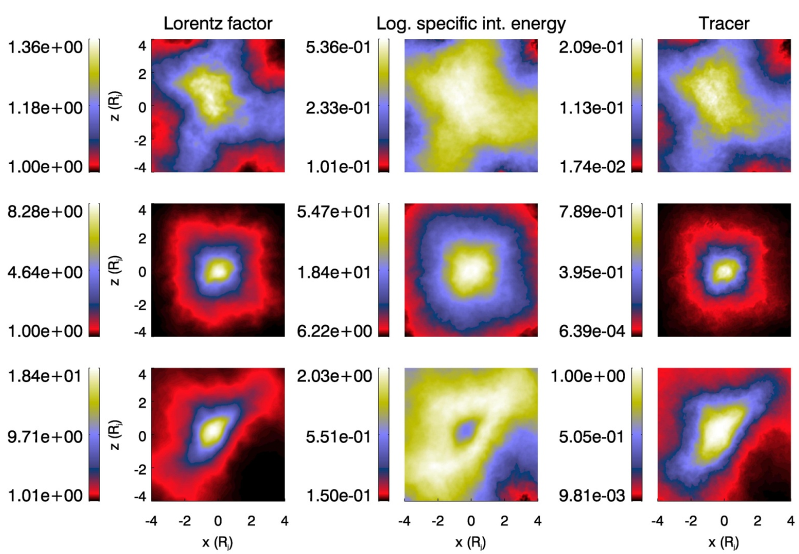


Deceleration distance 300 pc – 3 kpc

KH instability







cold

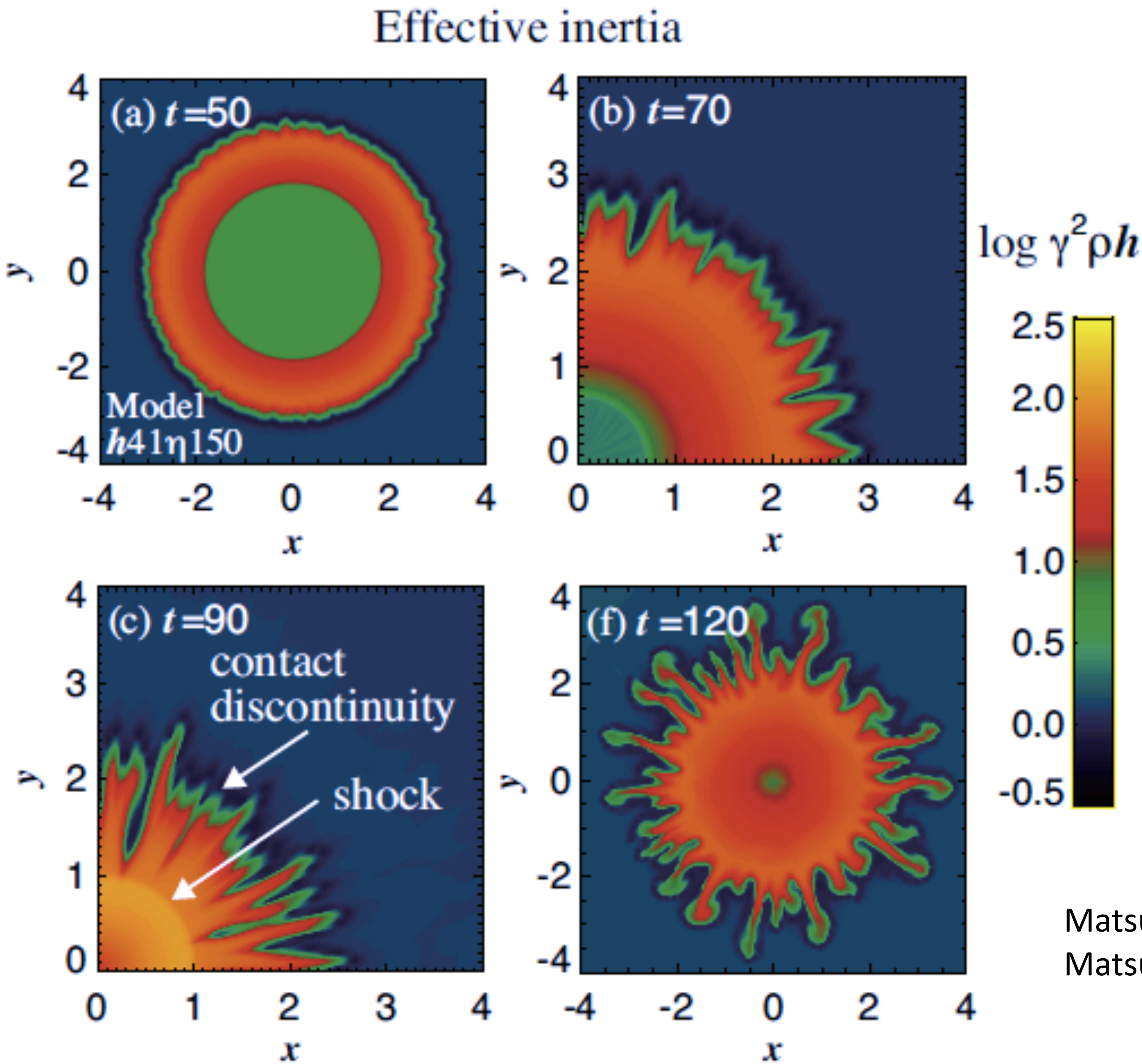
hot

cold

Lorentz factor

Perucho et al. 2005, 2010: KH instability. The disruption process can be slow if the growing modes have small wavelengths.

Rayleigh-Taylor instability



criterion

$$\frac{\rho_1 h_1' \gamma_1^2}{\rho_2 h_2' \gamma_2^2} > 1,$$

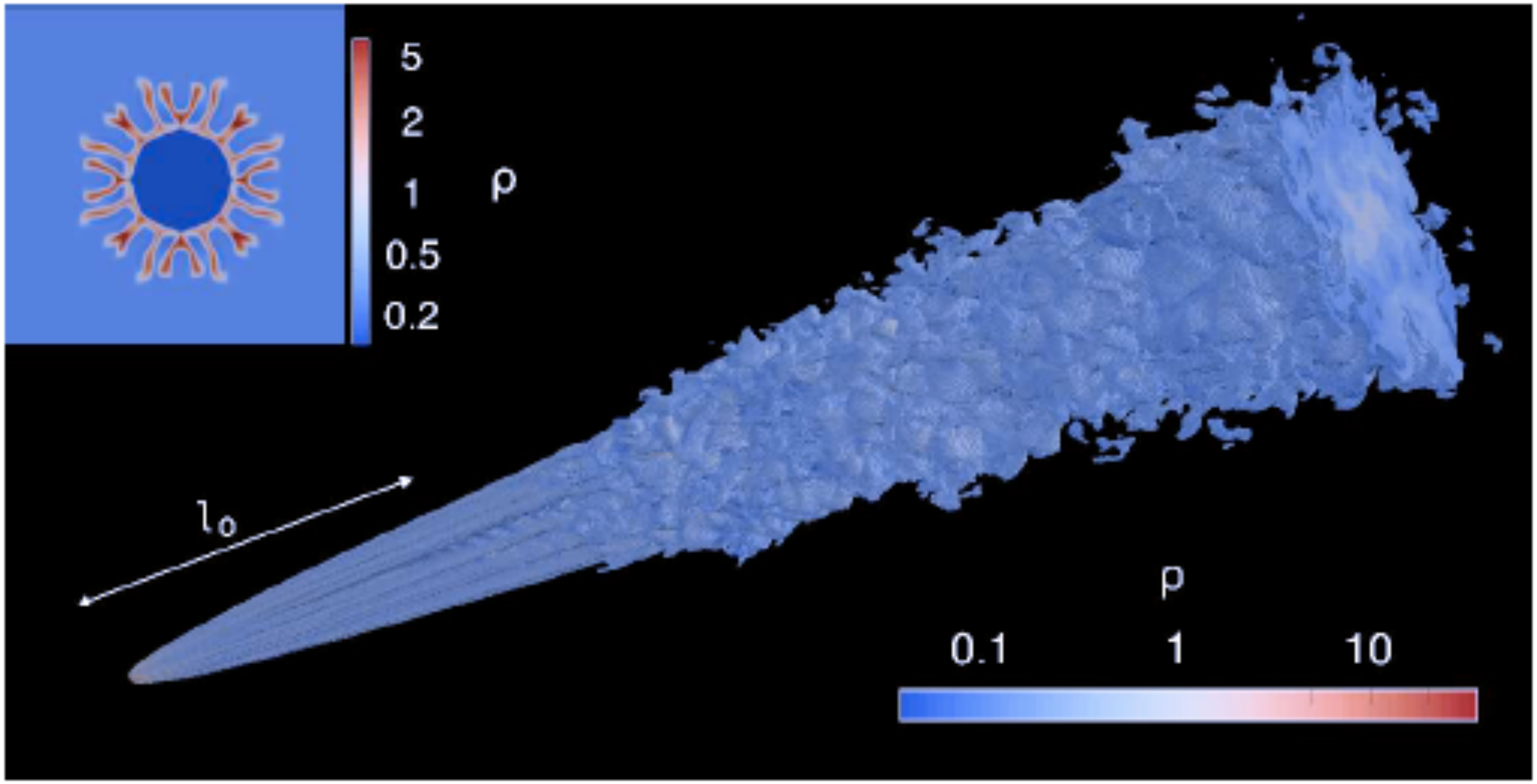
$$h' := 1 + \frac{\Gamma^2}{\Gamma - 1}\frac{p}{\rho},$$

1: jet
2: ambient medium

Matsumoto & Masada 2013
Matsumoto, Aloy, Perucho 2017

Centrifugal instability

Gourgouliatos & Komissarov 2018 a,b



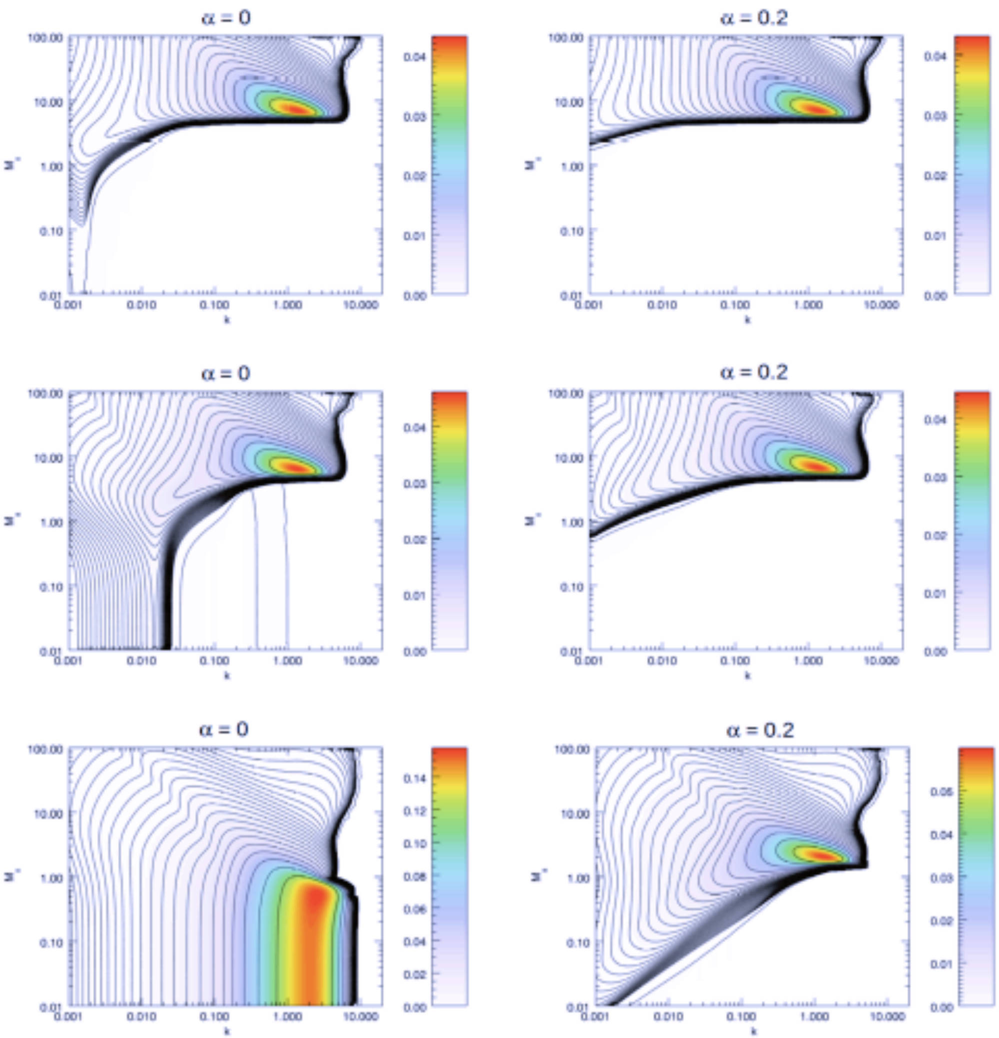
criterion:

$$\Psi_2 - \Psi_1 < 0, \quad \Psi = \rho h \gamma^2 (\Omega R^2)^2,$$

$$\frac{d \ln \Psi}{d \ln R} < M^2, \qquad M = \gamma \Omega R / (\gamma_s c_s),$$

reduces to RTI when Ω is continuous across the discontinuity $\rho_2 h_2 \gamma_2^2 - \rho_1 h_1 \gamma_1^2 < 0,$

Current driven instability



$\gamma = 10$

M_a is the total to magnetic energy ratio.

Left column: no rotation.
Right column: rotation.

Top to bottom: poloidal to toroidal dominating field.

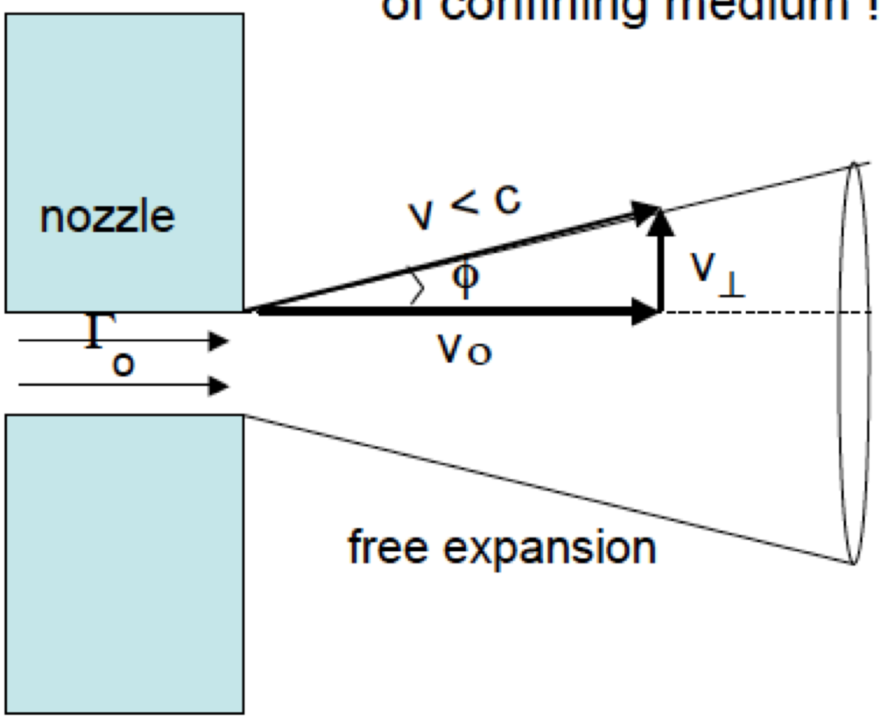
$M_a = 1$ sets the limit between the KHI and the CDI

Bodo et al. (2013, 2016, 2019)

Axial field, super-Alfvénic flows, differential rotation (Bodo et al. 2013, 2016, 2019).
Current-free shear layers stabilize short wavelengths (Kim et al. 2017, 2018).
In force-free jets, a shear in the toroidal field is also stabilizing (Istomin & Pariev 1994, 1996).

Large-scale collimation

Even sub-sonic (sub-fast-magnetosonic) relativistic jets can remain collimated in the absence of confining medium !



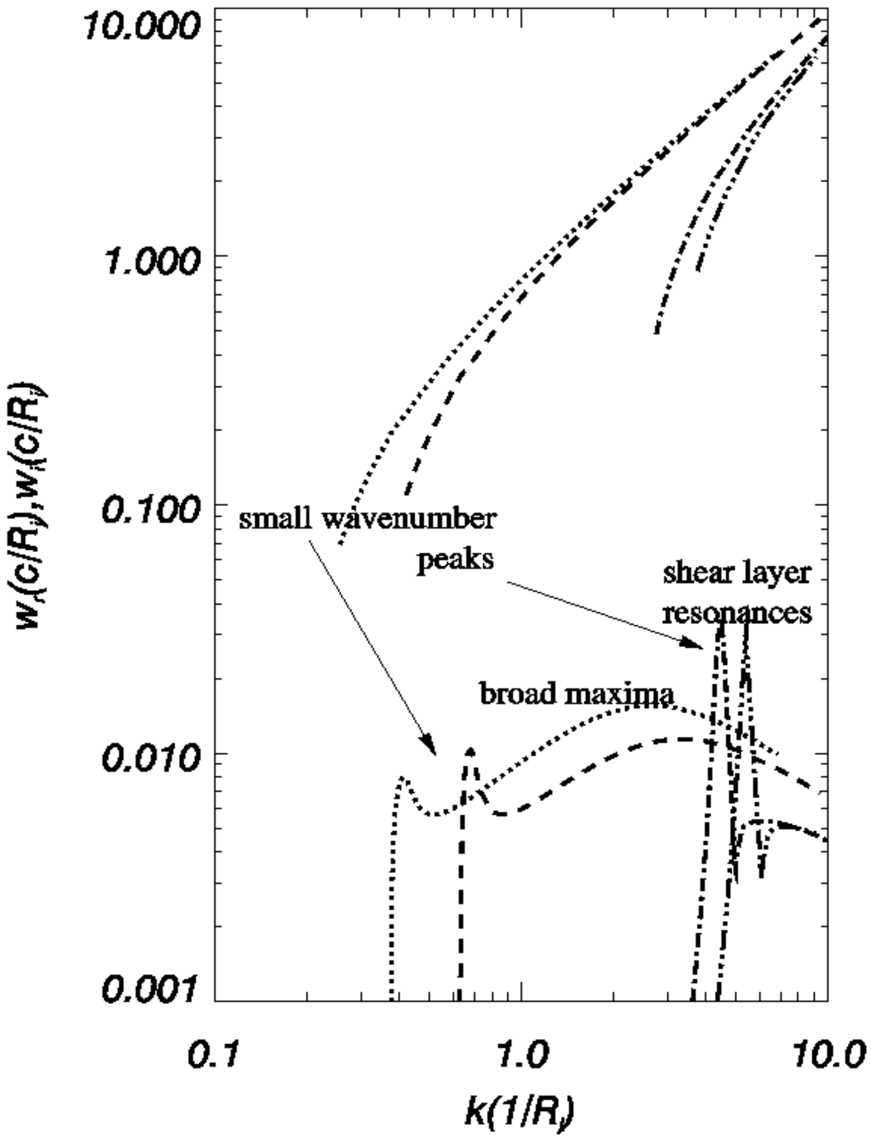
$$v^2 = v_0^2 + v_\perp^2$$

$$\phi \simeq v_\perp / v_0, \;\; v < c$$

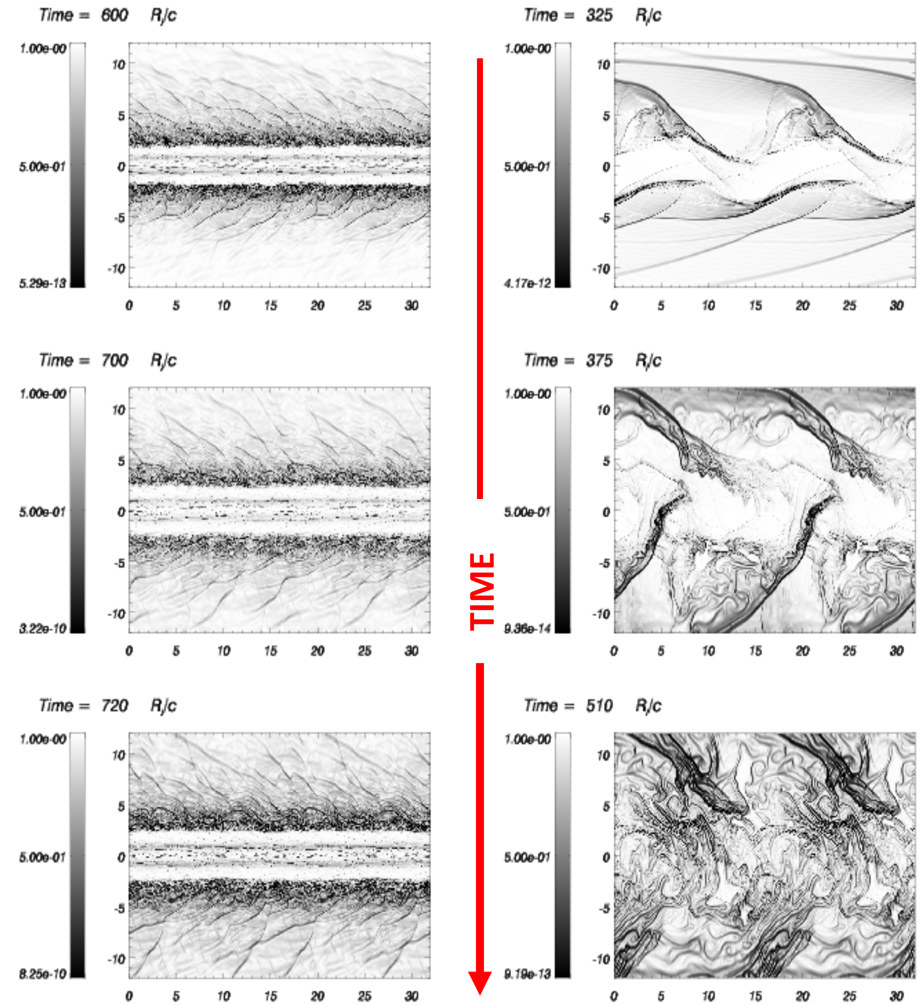
$$\boxed{\phi < 1/\Gamma_0}$$

credit: S.S. Komissarov

Unexpected collaborations



Perucho et al. 2005, 2007

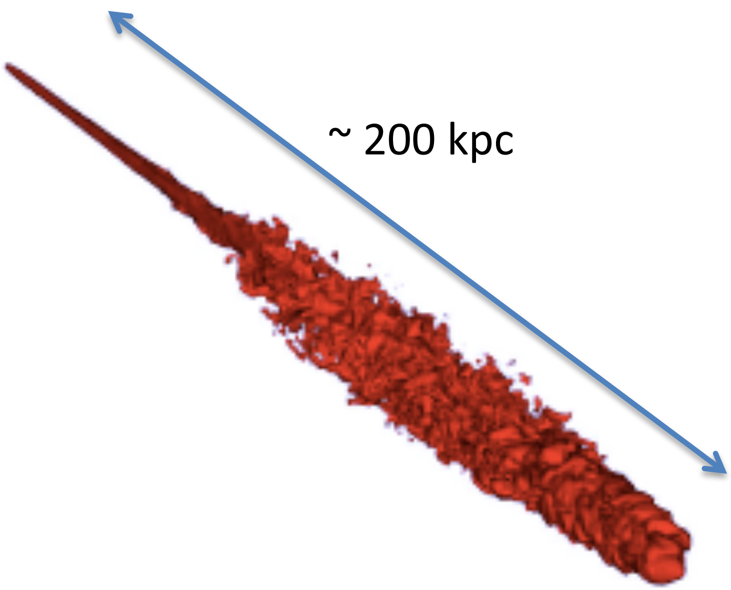


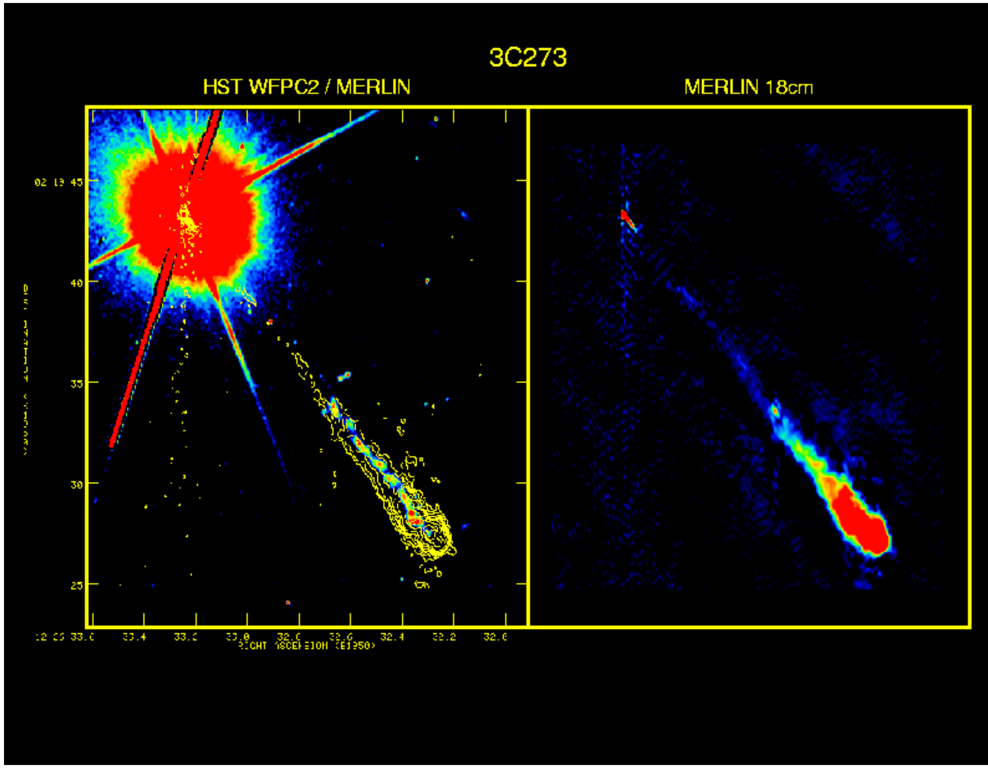
Sheared jet (d=0.2 Rj)
Lorentz factor 20

Sheared jet (d=0.2 Rj)
Lorentz factor 5

See also short λ saturation (Hardee 2011)

Unexpected collaborations

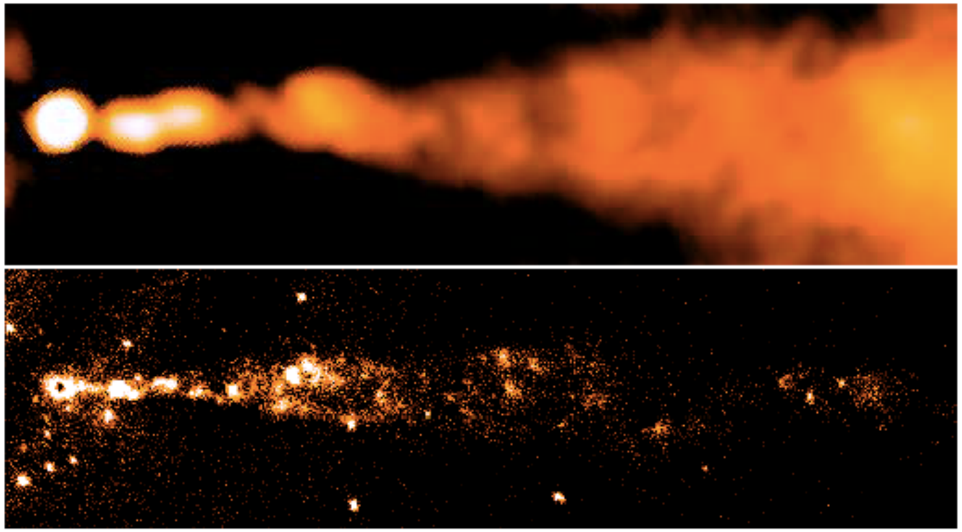




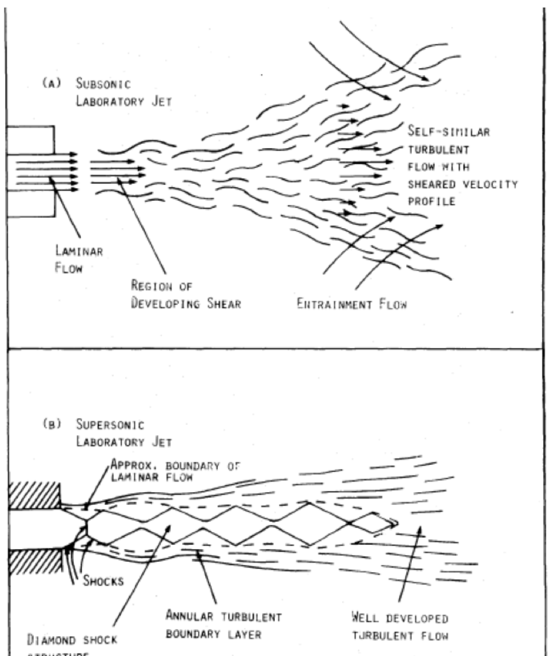
A small (linear) oscillation of the jet head can enhance jet propagation velocity due to the induced obliquity of the terminal shock.

Perucho, Martí, Quilis 2019

Mass-load and deceleration

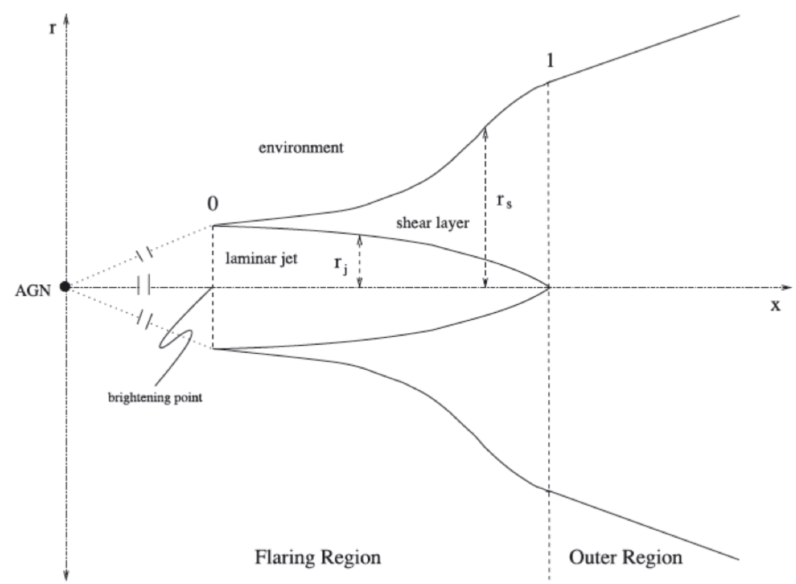


Worrall et al. 2008, Goodger et al. 2010, Wykes et al. 2013, 2015, Müller et al. 2014.
Possible interaction with obstacles in Centaurus A: Clouds, O/B type stars?



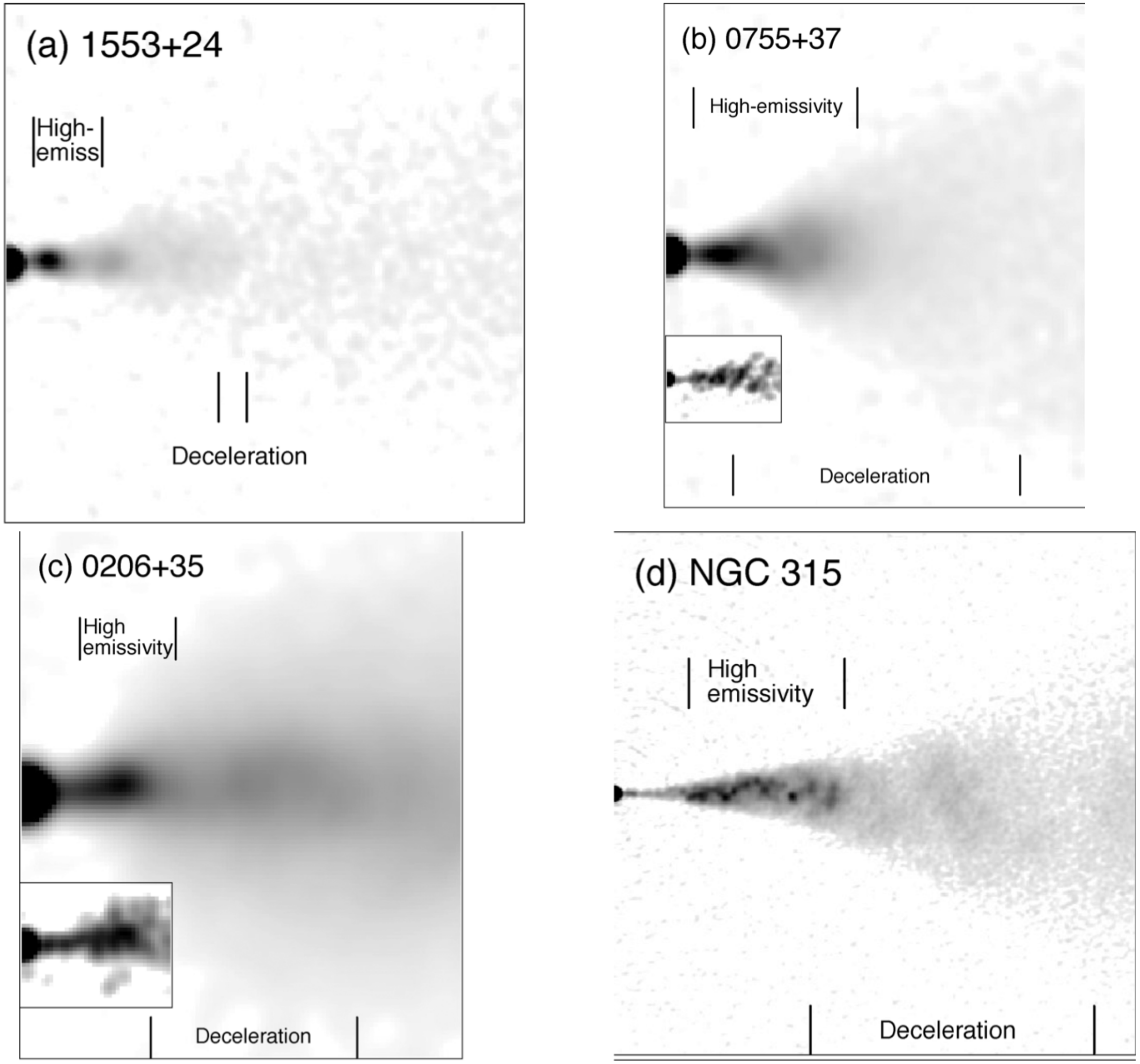
Bicknell 1984

Shear-layer loading by turbulent mixing.

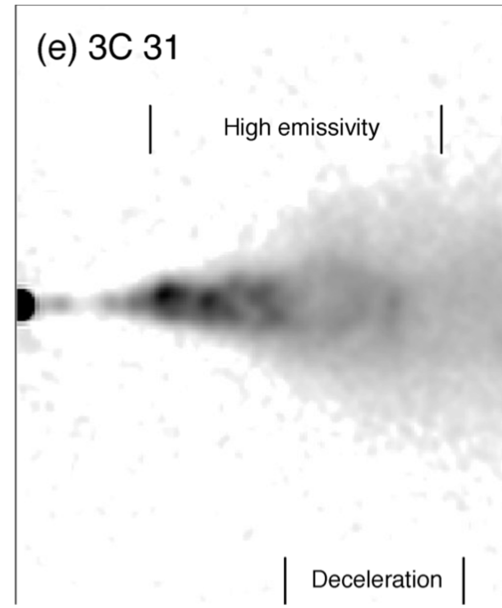


Wang et al. 2009

Deceleration of FRI jets



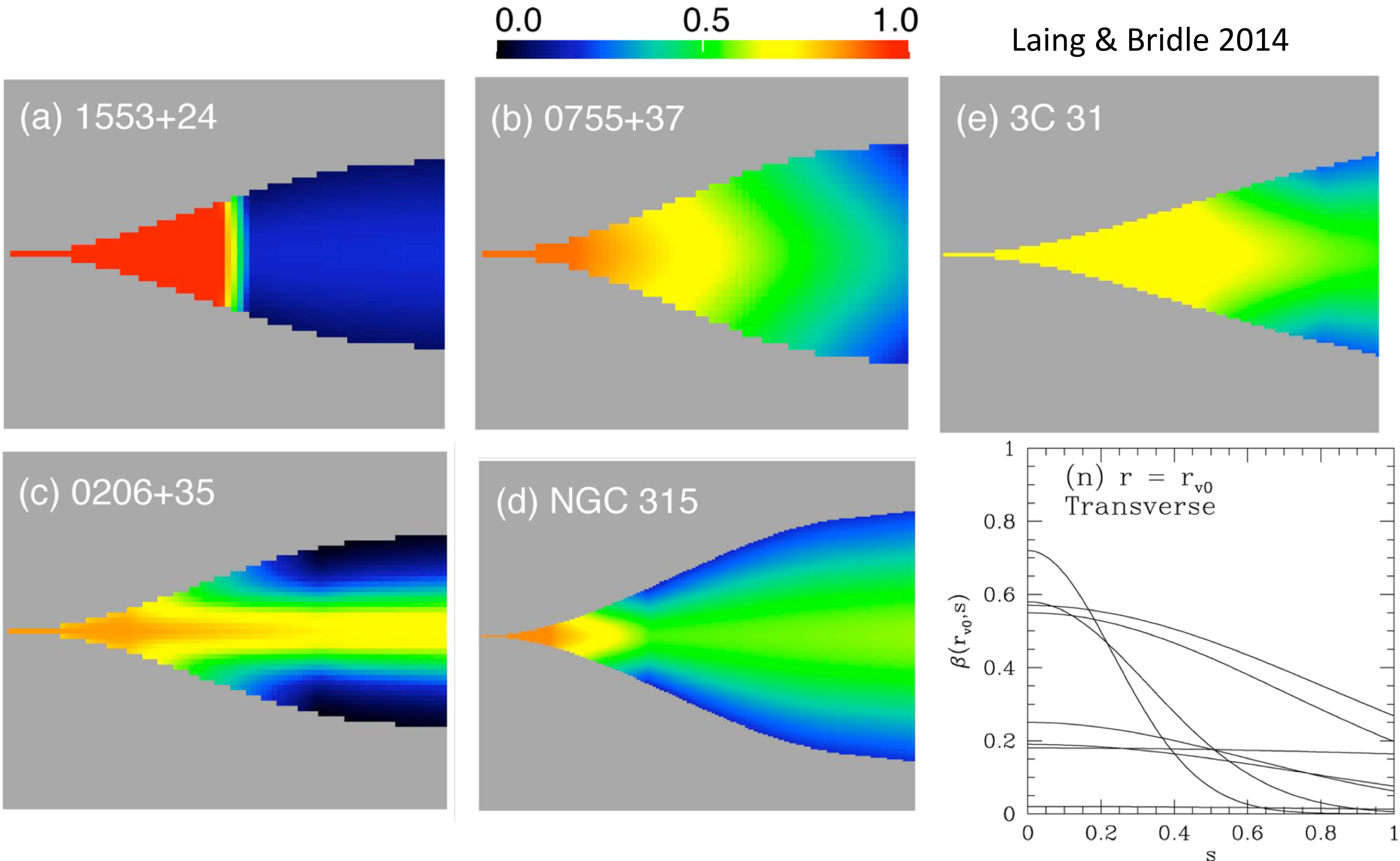
Laing & Bridle 2014

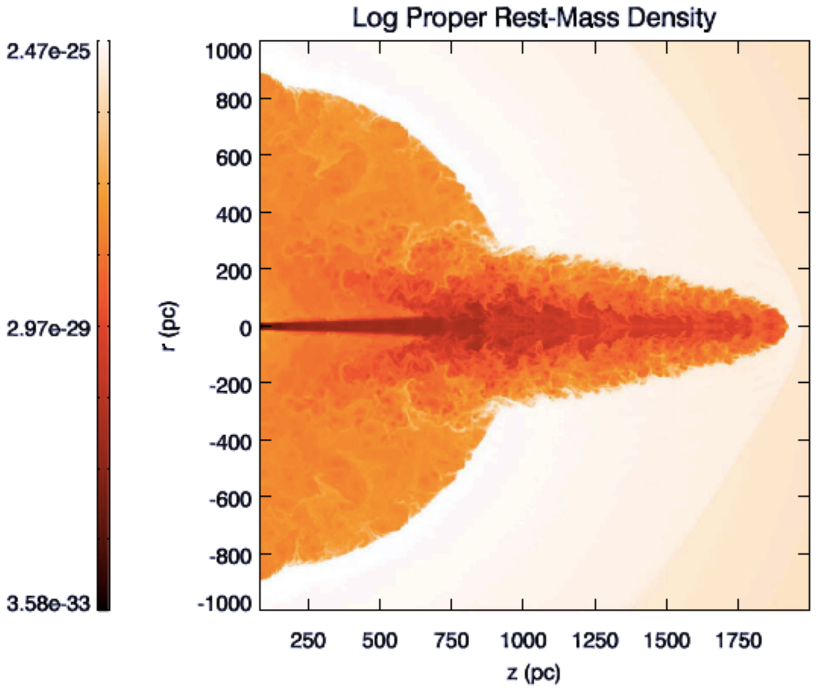


Kharb et al. (2012) find X-ray emission from these regions In 15/21 FRI’s (nine X-ray jets).

Deceleration of FRI jets

Laing & Bridle 2014





Following Komissarov (1994), Bowman et al. (1996), we performed simulations of FRI jets with a source term in mass accounting for mass-load from stellar wind.

King density profile.

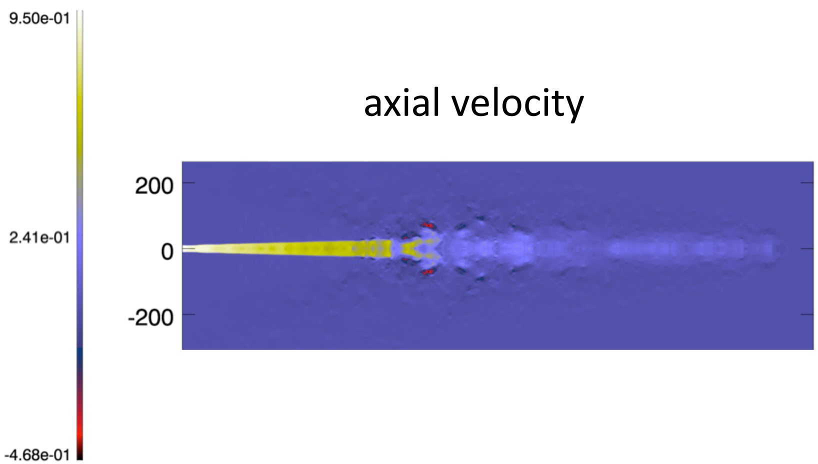
$$n_{ext} = n_c \left(1 + \frac{r^2}{r_c^2}\right)^{-3\beta_{atm,c}/2}$$

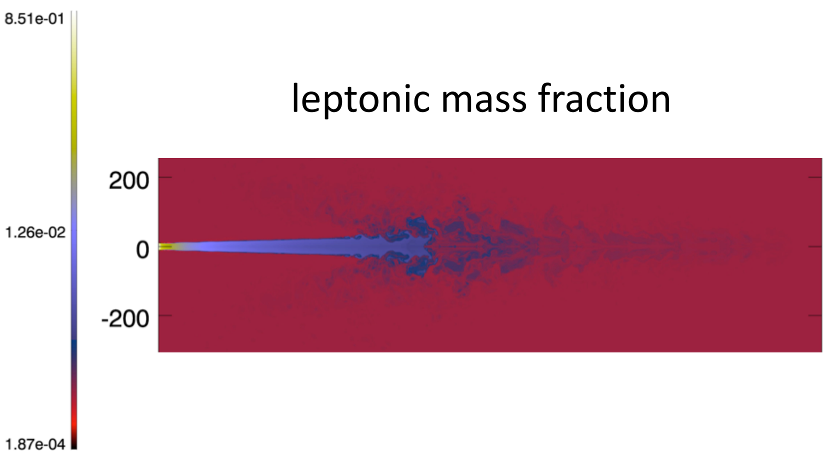
Deprojected Nuker profile (Lauer et al. 2007).

$$S_\rho = q_0 \left(\frac{r_b}{r}\right)^\gamma \left(1 + \left(\frac{r}{r_b}\right)^\alpha\right)^{(\gamma-\beta)/\alpha}$$

The stars are assumed to be all the same, with stellar mass losses 10^{-11}-10^{-12} $M_\odot yr^{-1}$.

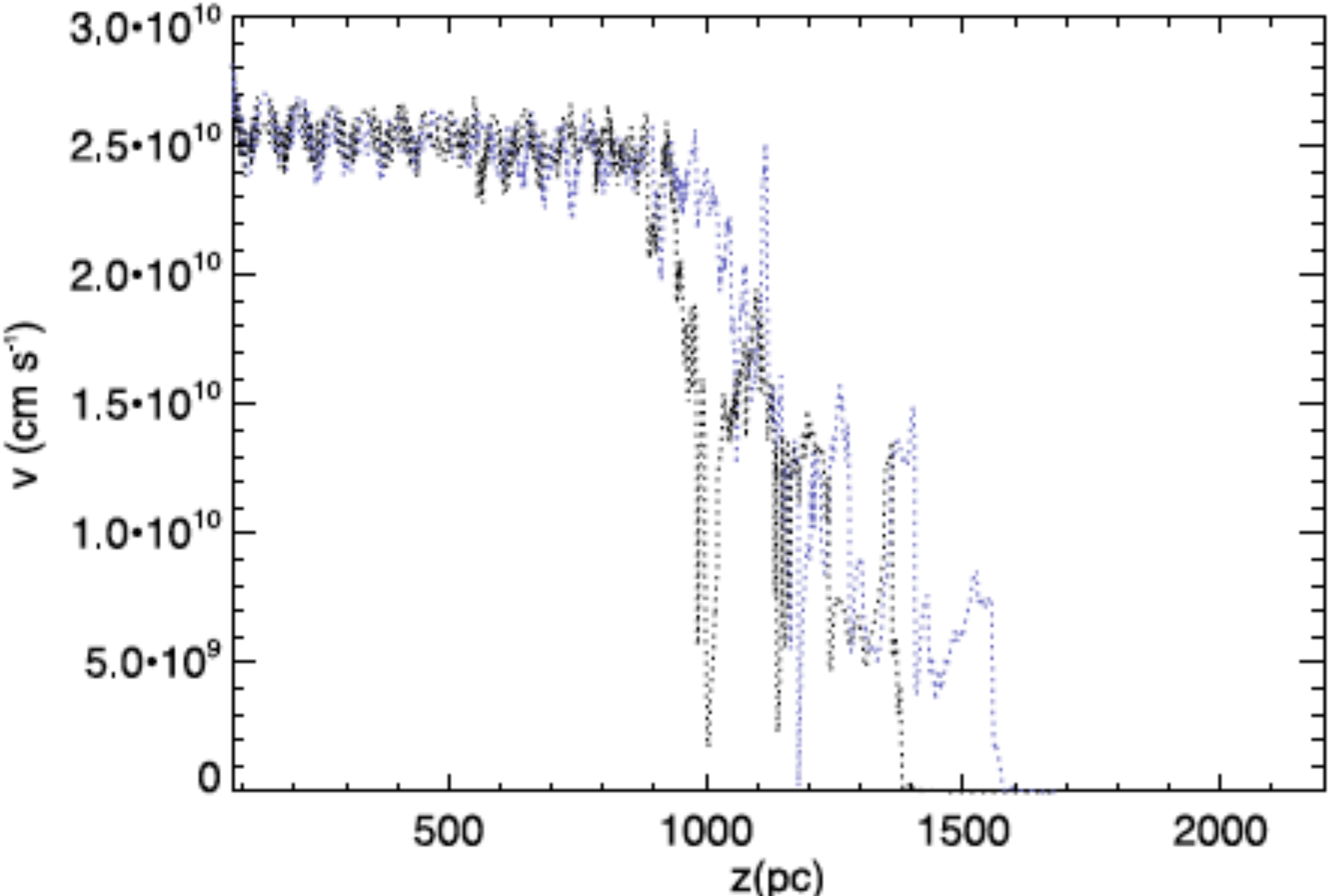
injection point at 80 pc – initial jet radius 10 pc





Perucho, Martí, Laing, Hardee 2014

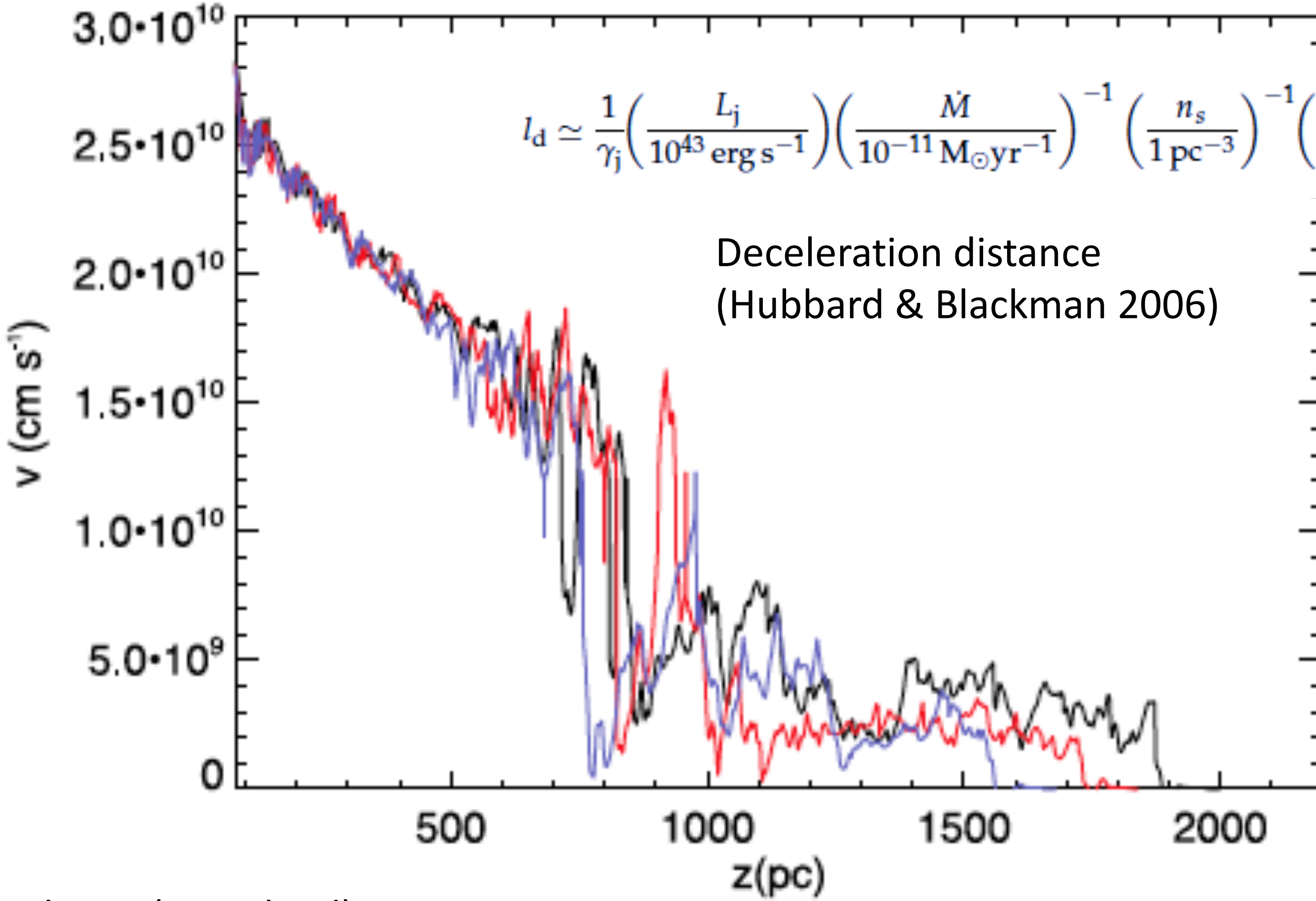
Deceleration: mass load by stellar winds



Jet velocity (less or no load)

Perucho, Martí, Laing, Hardee 2014

Deceleration: mass load by stellar winds



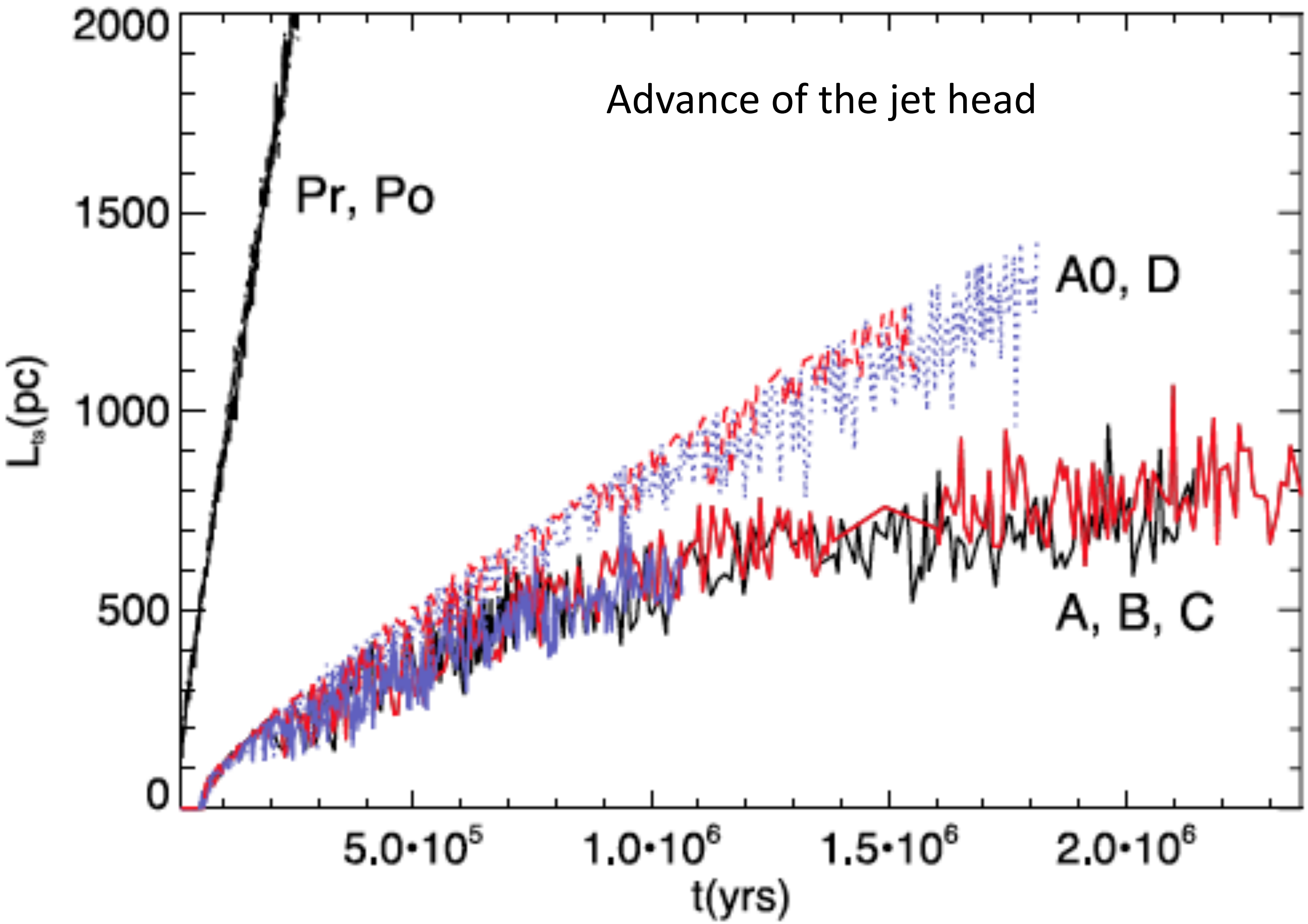
$$l_{\rm d} \simeq \frac{1}{\gamma_{\rm j}}\left(\frac{L_{\rm j}}{10^{43}\,{\rm erg\,s^{-1}}}\right)\left(\frac{\dot{M}}{10^{-11}\,{\rm M_{\odot}yr^{-1}}}\right)^{-1}\left(\frac{n_{\rm s}}{1\,{\rm pc^{-3}}}\right)^{-1}\left(\frac{R_{\rm j}}{10\,{\rm pc}}\right)^{-2} 10^2\,{\rm kpc},$$

Deceleration distance
(Hubbard & Blackman 2006)

Jet velocity (mass load)

Perucho, Martí, Laing, Hardee 2014

Deceleration: mass load by stellar winds



Perucho, Martí, Laing, Hardee 2014

RMHD simulations: 1D code

Komissarov et al. 2015

The approximation is valid as long as:

- the radial dimension of the flow is much smaller than the axial one (quasi-one-dimensional approximation):
- the flow is relativistic in the axial direction:

Consistency with the 1D version of the divergence free condition:

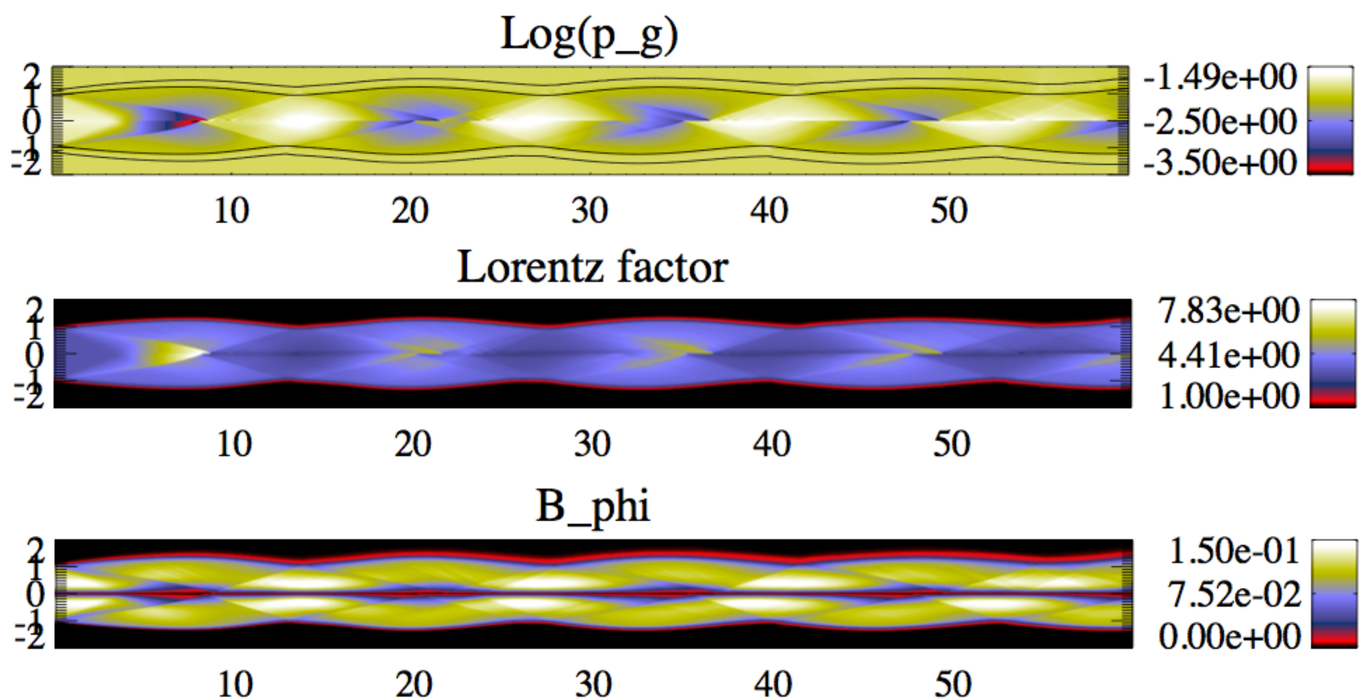
$$r \ll z$$
$$v^r, v^\phi \ll v^z \sim c$$
$$B^r \ll B^\phi, B^z$$

Under these conditions, the steady-state equations of RMHD can be accurately approximated by the 1D time-dependent equations, with the axial coordinate acting as *temporal* coordinate

Model HP03
Martí et al. 2016

Top half-panels:
2D time-dependent sims.

Bottom half-panels:
Q1D approximation



Jet deceleration (RMHD): equilibrium

Martí, MNRAS, 2015b

Top-hat profiles for **density**, **axial flow velocity** and **axial magnetic field**:

$$\rho(r) = \begin{cases} \rho_j, & 0 \leqslant r \leqslant 1 \\ 1, & r > 1, \end{cases}$$

$$v^z(r) = \begin{cases} v^z_j, & 0 \leqslant r \leqslant 1 \\ 0, & r > 1, \end{cases}$$

$$B^z(r) = \begin{cases} B^z_j, & 0 \leqslant r \leqslant 1 \\ 0, & r > 1, \end{cases}$$

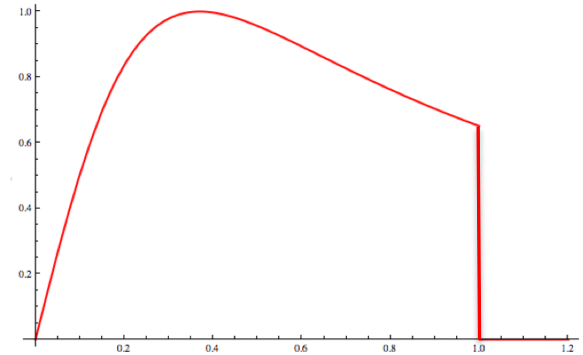
Toroidal magnetic field:

$$B^\phi(r) = \begin{cases} \dfrac{2B^\phi_{j,\mathrm{m}}(r/R_{B^\phi,\mathrm{m}})}{1+(r/R_{B^\phi,\mathrm{m}})^2}, & 0 \leqslant r \leqslant 1 \\ 0, & r > 1. \end{cases}$$

Units: $R_j = 1$

$c = 1$

$\rho_a = 1$



$$p^* = p(\rho, \varepsilon) + \frac{b^2}{2}$$ (total pressure: thermal + magnetic)

$$W = \frac{1}{\sqrt{1-v^2}}$$ (flow Lorentz factor)

$$h^* = h(\rho, \varepsilon) + \frac{b^2}{\rho}$$ (total specific enthalpy)

$$(b^0, \vec{b}) = \left(W(\vec{v}\cdot\vec{B}), \frac{\vec{B}}{W} + W(\vec{v}\cdot\vec{B})\,\vec{v} \right)$$

(magnetic field four-vector in the comoving frame)

$h(\rho, \varepsilon)$: specific enthalpy

ε : specific internal energy

Transversal equilibrium:

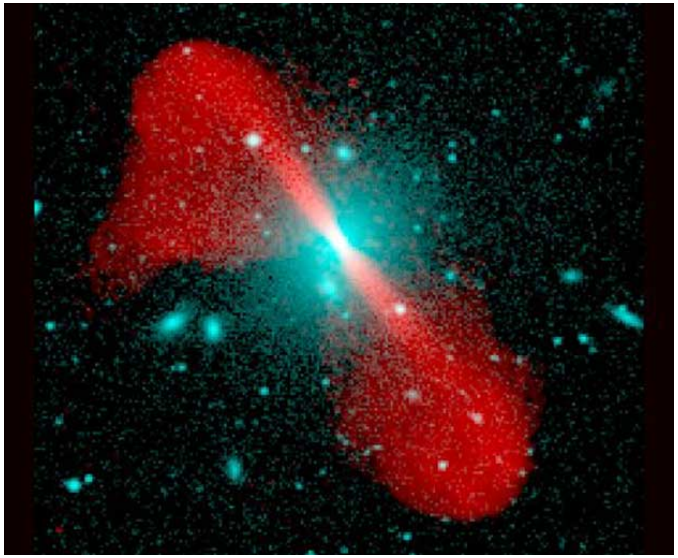
$$\frac{dp^*}{dr} = \frac{\rho h^* W^2 (v^\phi)^2}{r} - \frac{(b^\phi)^2}{r}$$

Stellar mass-load: setup

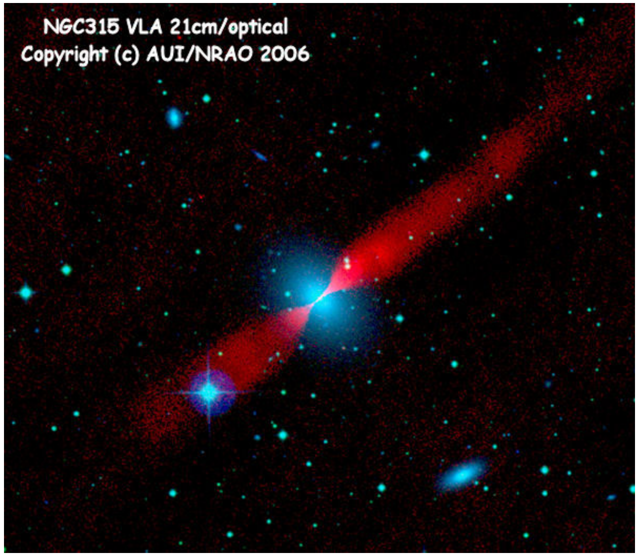
Jet power: $L_j = (\rho_j h_j W_j + \overline{B^{\phi}}_j) v^j A_j c^2,$

1.e43 erg/s

3C 296
A. Bridle



NGC 315
A. Bridle



Ambient pressure: $$p_a(z) = p_{a,0}\left(1 + \left(\frac{z}{r_c}\right)^2\right)^{-1.095},$$ r_c = 200 / 500 pc $R_{j,0}$ = 1 pc

Stellar wind mass-load: $$Q(z) = Q_0\left(1 + \left(\frac{z+z_0}{r_{c,s}}\right)^2\right)^{-1.095},$$

$Q_0 = 10^{-11}\,M_\odot \dot{y}r^{-1}$

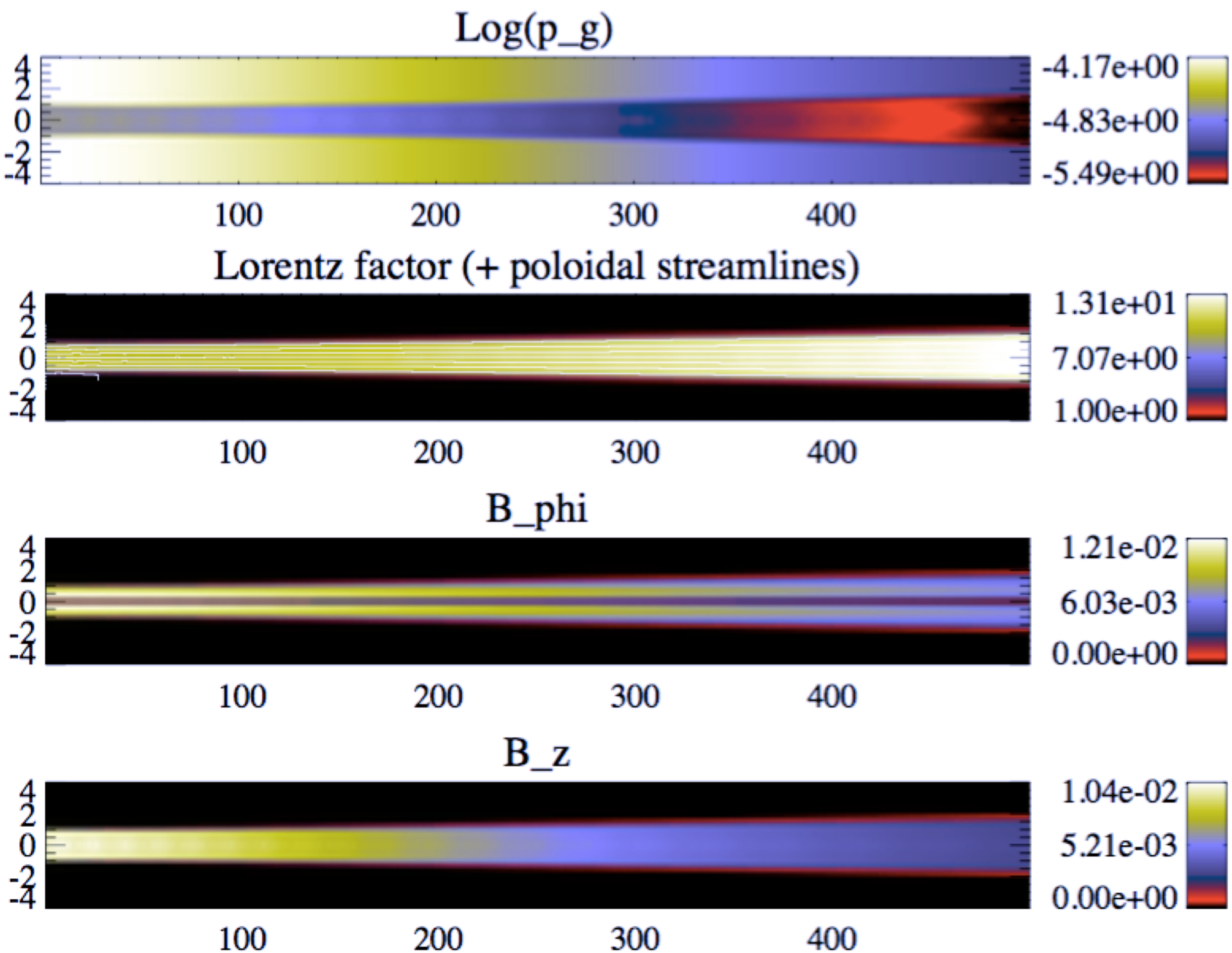
$Q_0 = 10^{-9}\,M_\odot yr^{-1}$

$r_{c,s}$ = 500 pc

Jet composition: Leptonic.
Stellar wind: electron-proton.

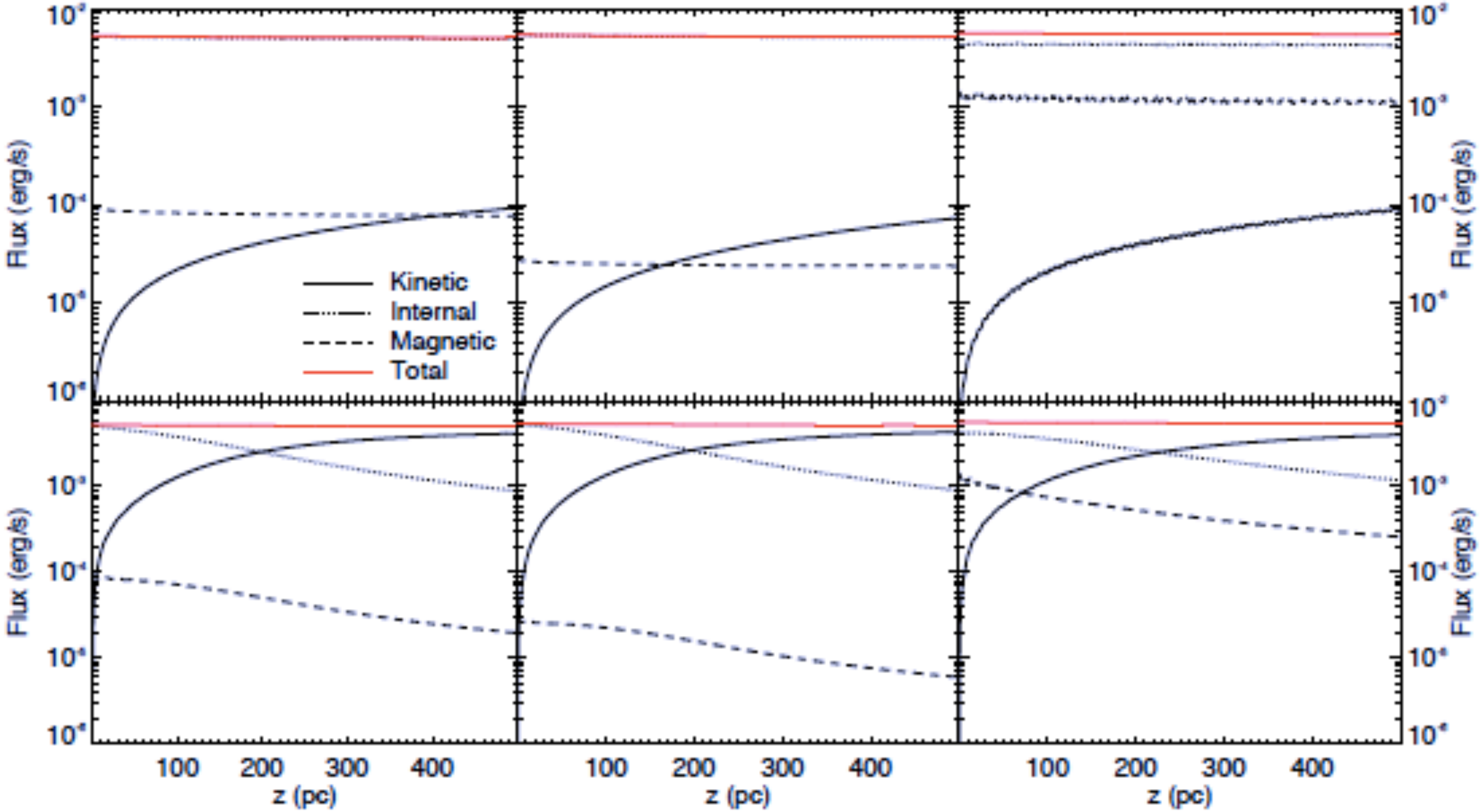
Perucho, Martí, Anglés, Laing, in preparation

Results

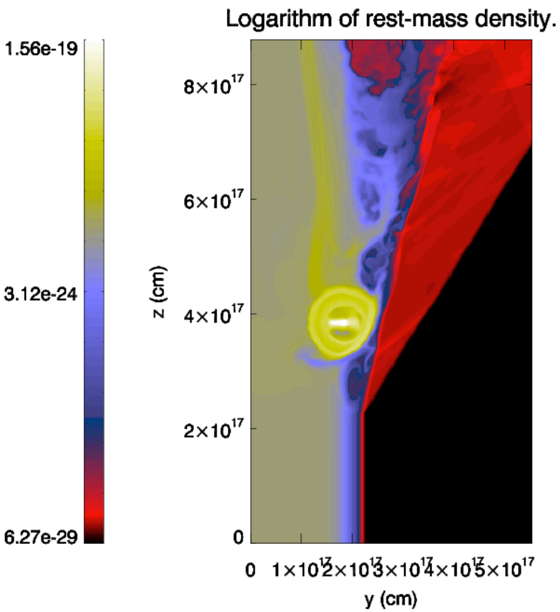


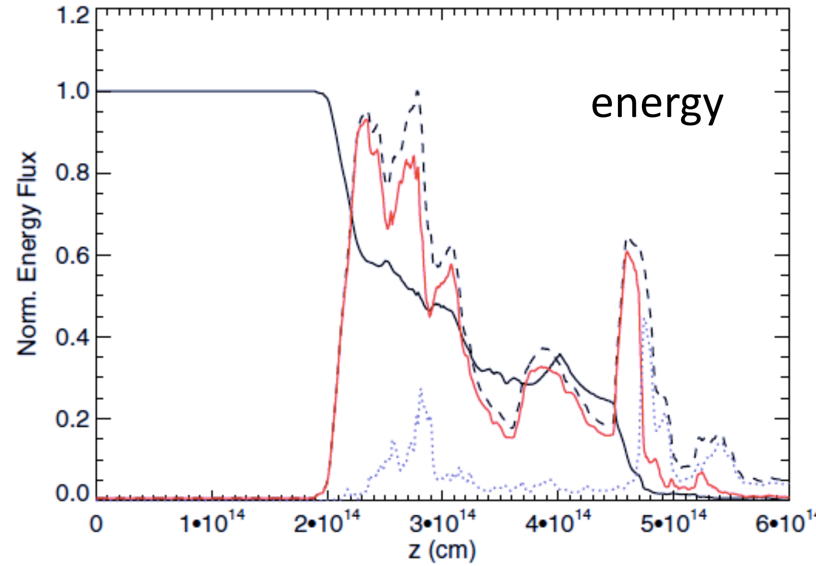
Perucho, Martí, Anglés, Laing, in preparation

Energy fluxes

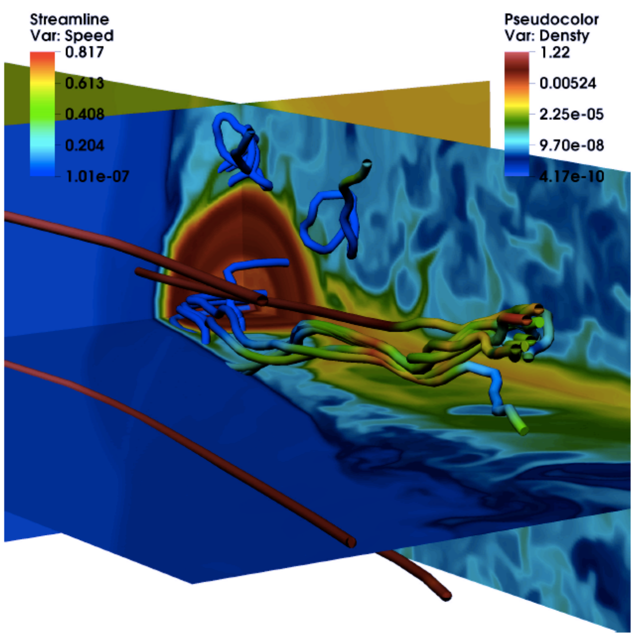


Deceleration: mass load by stellar winds





Bosch-Ramon, MP & Barkov (A&A, 2012)

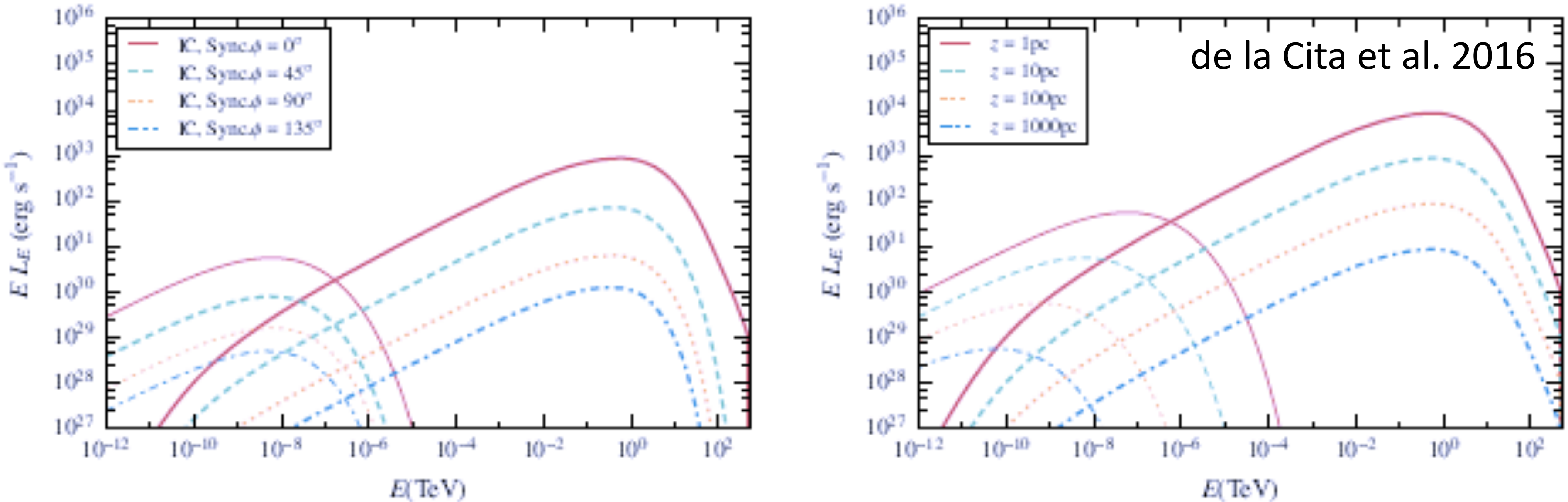


3D simulation of a stellar-wind entering the jet at z ≈100 pc.

Shock propagating towards the jet axis. Upstream wave in the shear layer.

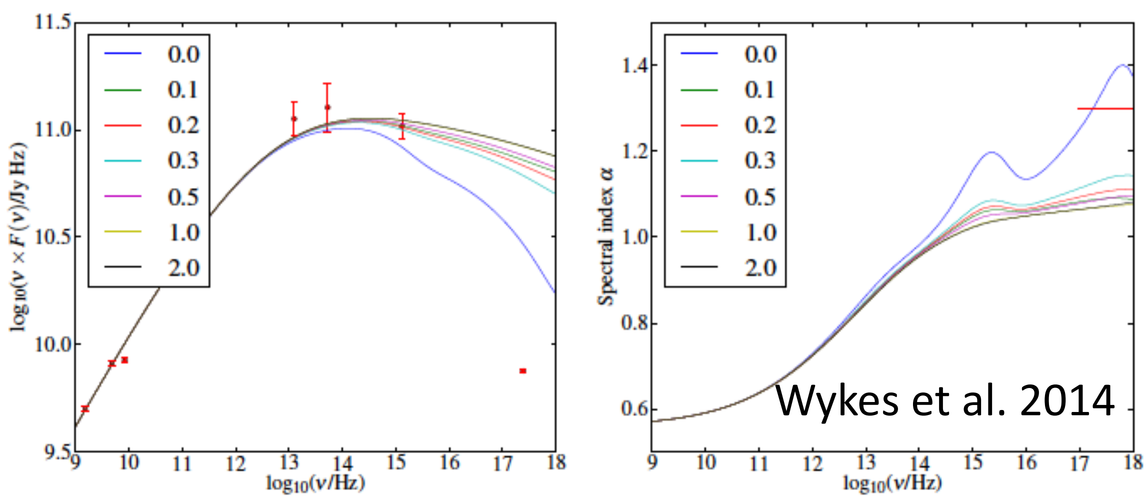
Perucho, Bosch-Ramon & Barkov (A&A, 2017)

Deceleration: mass load by clouds



de la Cita et al. 2016

(see also Bednarek & Protheroe 1997, Barkov et al. 2010, 2012, Araudo et al. 2013, Wykes et al. 2013, Khangulyan et al. 2013, Vieyro et al. 2017, Torres-Albà & Bosch-Ramon 2019,…)



Wykes et al. 2014

8x10^8 stars in the jet in Cen A. Particle acceleration at the interaction sites could explain the high-energy emission from the jet.

$$\sim 2.3 \times 10^{-3}\, M_{\odot}\, \mathrm{yr}^{-1}$$

Total mass entrainment given by the model.

Global effect of mass-load

steady-state equations:

$$\partial_z(\gamma\rho v^z) = q,$$
$$\partial_z(\gamma\rho h^* v^z v^z + p^* - b^z b^z) = g^z,$$
$$\partial_z(\rho h^* \gamma^2 v^z - b^0 b^z - \gamma\rho v^z) = v^z g^z,$$

energy conservation:

$$\frac{\Delta\left[(\rho\gamma v^z)(h\gamma - 1)R_j^2\right]}{\Delta z} + \frac{\Delta\left[(B^\phi)^2 v^z R_j^2\right]}{\Delta z} = 0.$$

mass conservation:

$$\Delta(\rho\gamma v^z R_j^2)/\Delta z = qR_j^2$$

dropping the magnetic term*:

$$(\rho\gamma v^z)_0 \frac{\Delta(h\gamma)}{\Delta z} = (1 - (h\gamma)_0)q$$

≤ 1 (~ 1)

$$\frac{\Delta h}{h_0} = \frac{q\Delta z}{(\rho\gamma v^z)_0}\left(\frac{1}{(h\gamma)_0} - 1\right) - \frac{\Delta\gamma}{\gamma_0}.$$

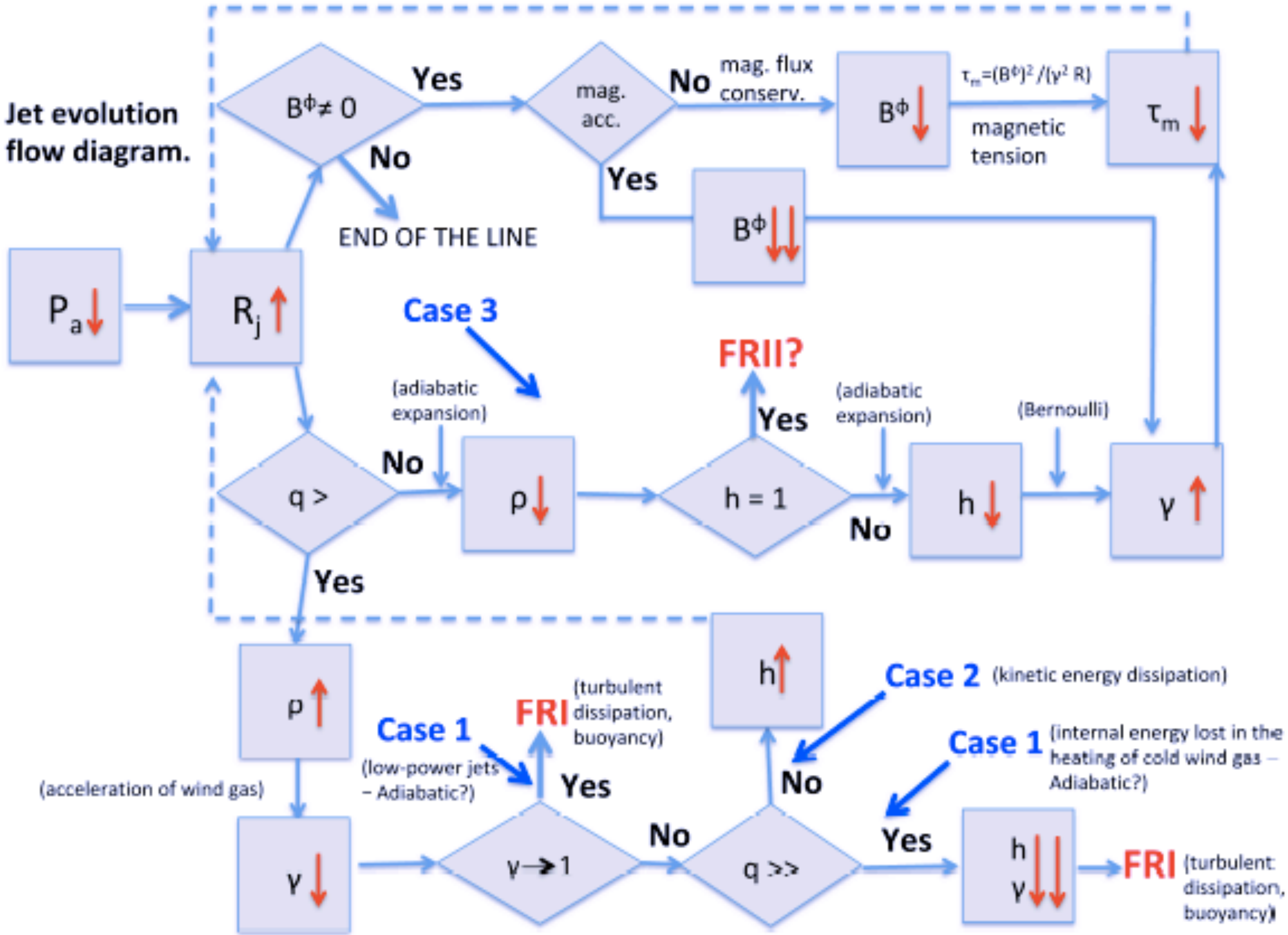
Global effect of mass-load

In terms of the ratio of loaded mass to the initial mass flux:

1. Strong relative mass-load ($q\Delta z \gg (\gamma\rho v^z)_0$): In this case $\Delta h < 0$ and the conservation equation tells us that the initial jet enthalpy is transferred to the entrained flow.
2. Mild relative mass-load ($q\Delta z \sim (\gamma\rho v^z)_0$): In this case Δh could be both smaller than or larger than zero, depending on the value of the terms accounting for deceleration (so the initial jet enthalpy can grow).
3. Small relative mass-load ($q\Delta z \ll (\gamma\rho v^z)_0$): In this case, we could neglect the source term q in the conservation equation above, and would be left with the Bernoulli expression for adiabatic evolution: $h\gamma = constant$, where expansion of a hot jet flow translates into acceleration.

$$\rho_{j,0}\,\gamma_{j,0}\,c > 6.7\times 10^{-31}\left(\frac{\dot{M}}{10^{-12}\mathrm{M}_\odot\mathrm{yr}^{-1}}\right)\left(\frac{n_s}{10\,\mathrm{pc}^{-3}}\right)\left(\frac{\Delta z}{1\,\mathrm{kpc}}\right)^3\left(\frac{\tan(\alpha)}{\tan(1^\circ)}\right)^2\left(\frac{R_{j,0}}{1\,\mathrm{pc}}\right)^{-2}\,\mathrm{g\,cm}^{-3},$$

Summary



Jet evolution flow diagram.
$B^{\phi} \neq 0$
Yes
No
END OF THE LINE
mag. acc.
No
mag. flux conserv.
B^{ϕ}
$\tau_m = (B^{\phi})^2 / (\gamma^2 R)$
magnetic tension
τ_m
Yes
B^{ϕ}
P_a
R_j
Case 3
FRII?
(adiabatic expansion)
Yes
(adiabatic expansion)
(Bernoulli)
q >
No
ρ
h = 1
No
h
γ
Yes
ρ
h
Case 2
(kinetic energy dissipation)
(turbulent dissipation, buoyancy)
FRI
Case 1
(low-power jets – Adiabatic?)
Yes
No
Case 1
(internal energy lost in the heating of cold wind gas – Adiabatic?)
(acceleration of wind gas)
γ
γ→1
No
q >>
Yes
h
γ
FRI
(turbulent dissipation, buoyancy)

You can also read..

Review

Dissipative processes and their role in the evolution of radio galaxies

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