The role of stars on FRI jet deceleration

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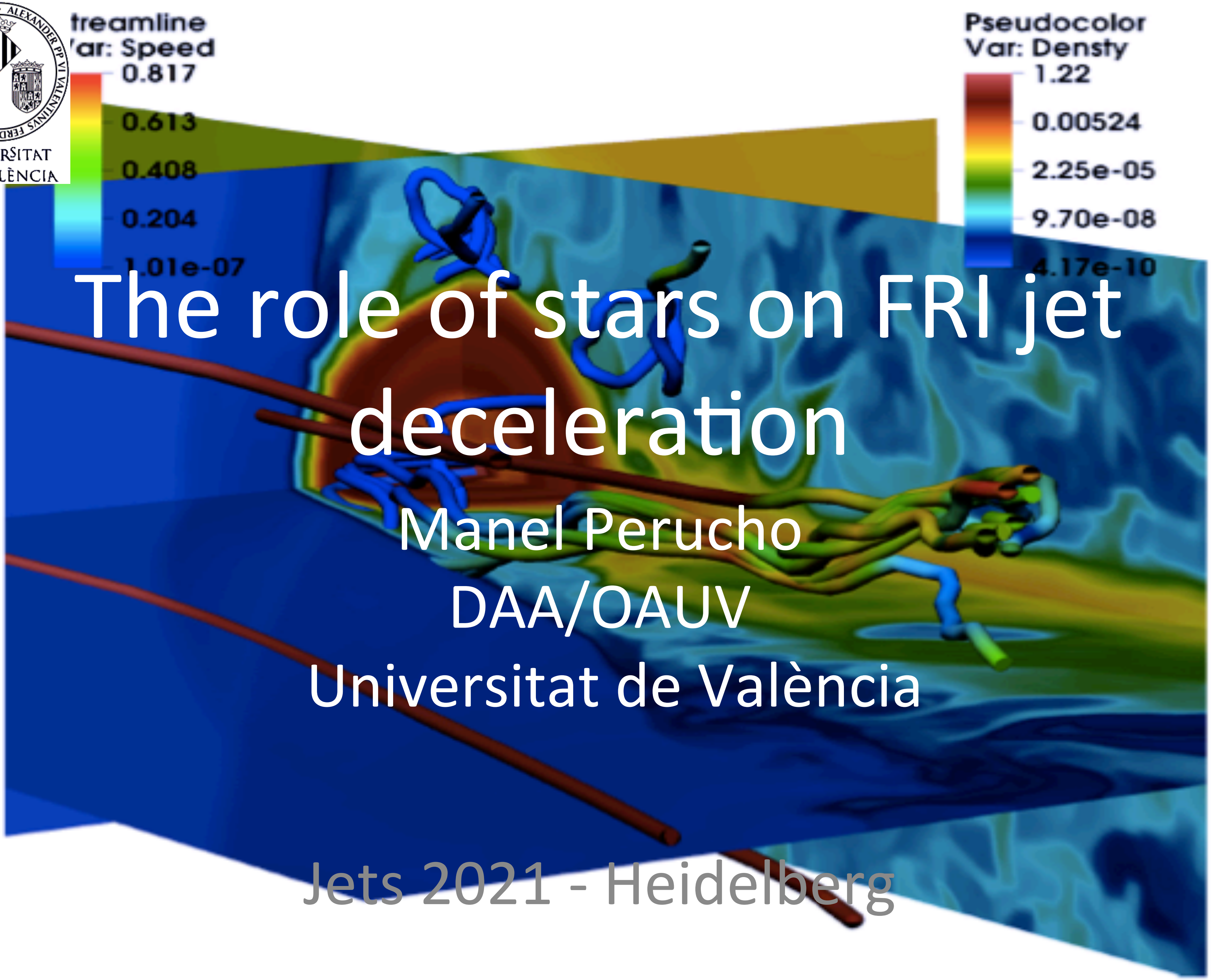
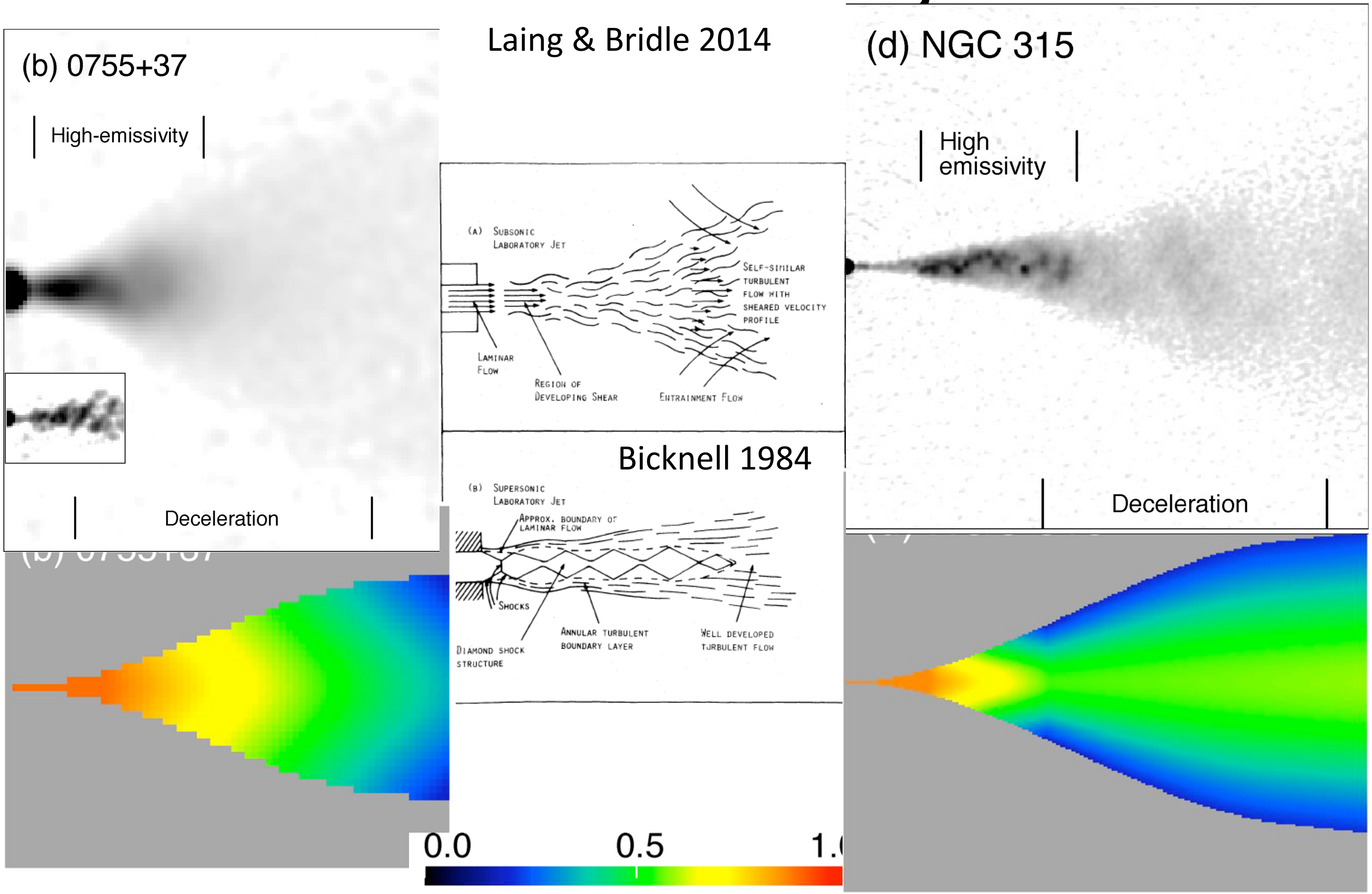
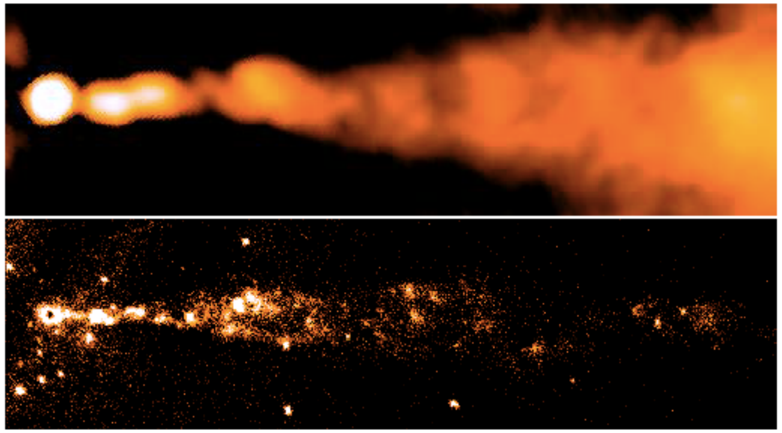


Deceleration of FRI jets



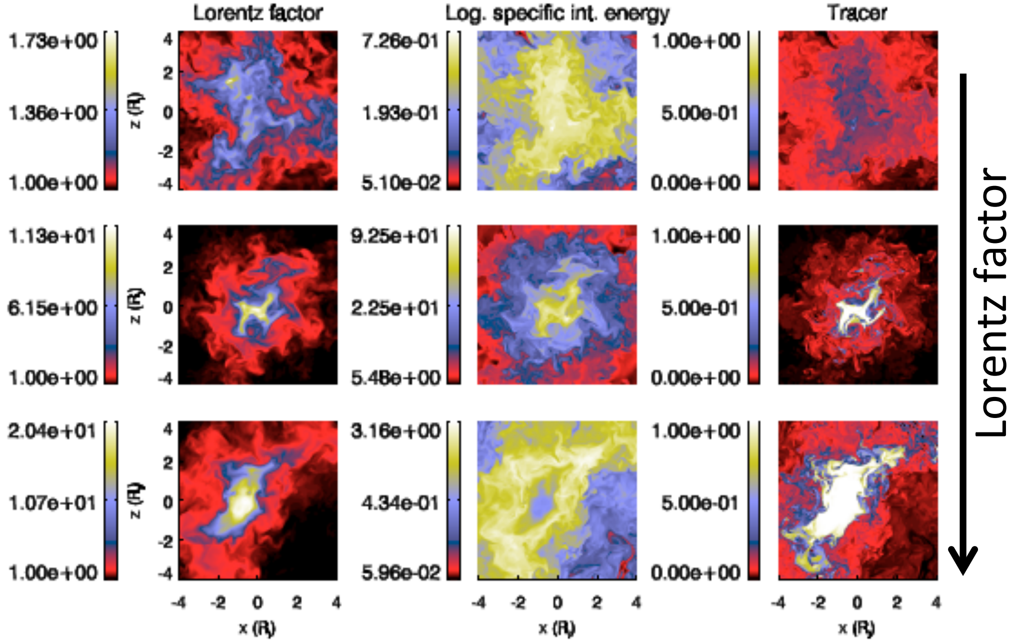
Kharb et al. (2012) also found X-ray emission from these regions in 15/21 FRI's.

Instabilities

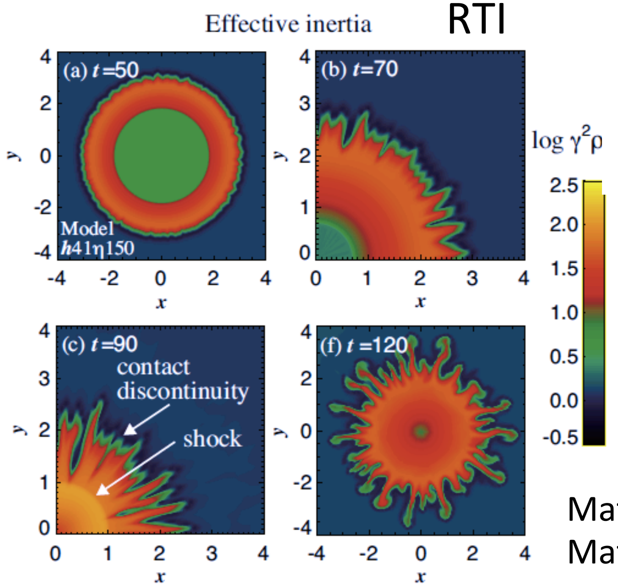


Komissarov 1994, Bowman et al. 1996, Worrall et al. 2008, Goodger et al. 2010, Wykes et al. 2013, 2015. Stellar winds?

Perucho et al. 2005, 2010. KHI



RTI

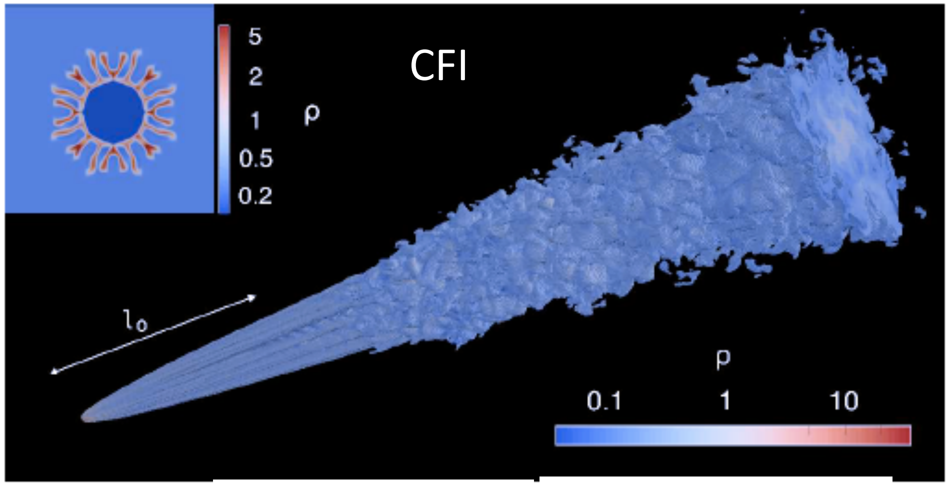


$$\frac{\rho_1 h_1' \gamma_1^2}{\rho_2 h_2' \gamma_2^2} > 1,$$

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

Matsumoto & Masada 2013
Matsumoto, Aloy, Perucho 2017

CFI

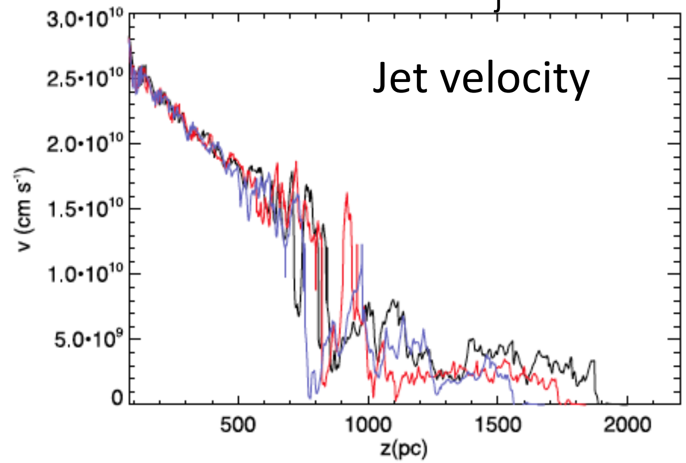


$$\Psi_2 - \Psi_1 < 0, \qquad \Psi = \rho h \gamma^2 (\Omega R^2)^2,$$

Gourgouliatos & Komissarov 2018 a,b

Deceleration: mass load by stellar winds

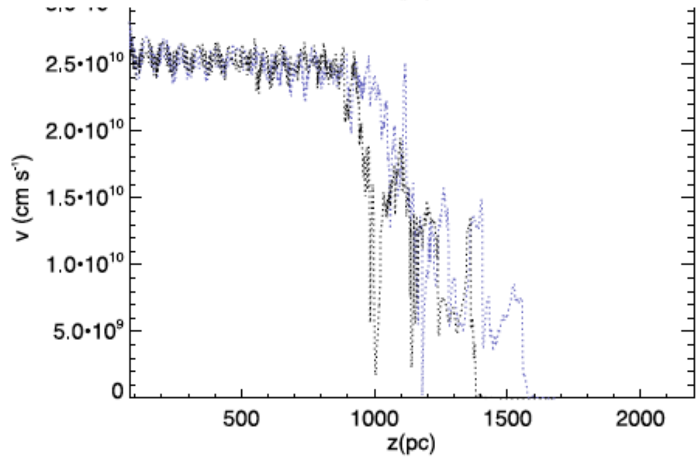
$L_j \sim 10^{42}$ erg/s



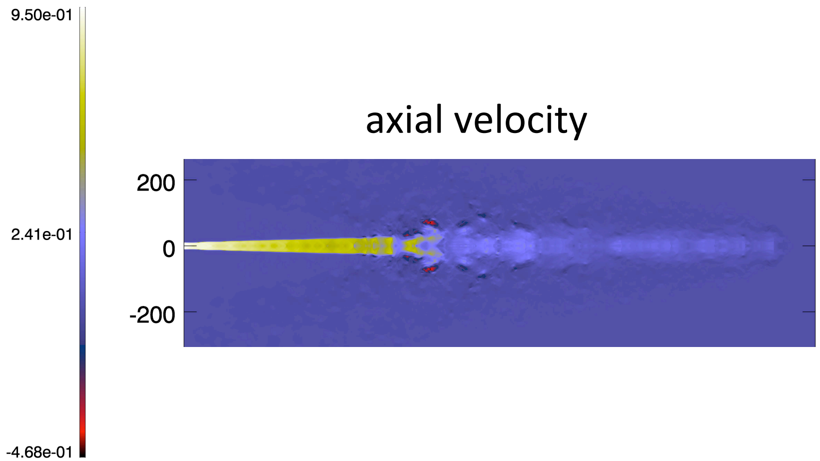
Following Komissarov (1994), Bowman et al. (1996), we performed simulations of FRI jets with a source term in mass accounting for mass-load from stellar wind.

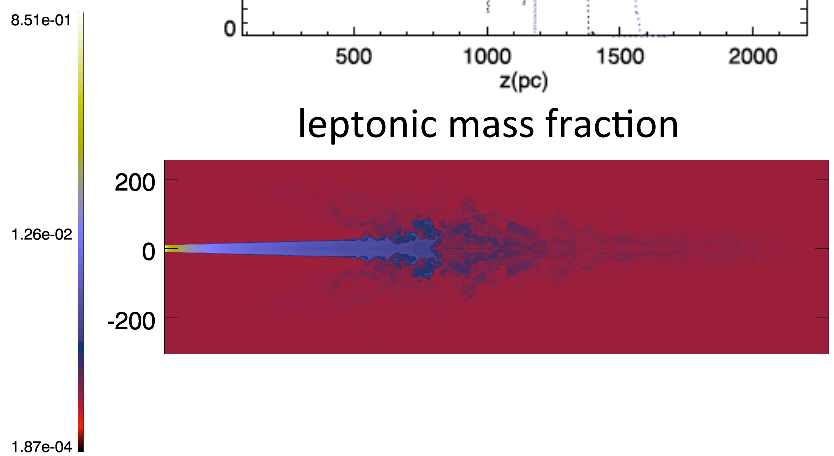
King density profile. $$n_{ext} = n_c \left(1 + \frac{r^2}{r_c^2}\right)^{-3\beta_{atm,c}/2}$$

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

RMHD simulations: 1D code – mass-load

The approximation is valid as long as:

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

Komissarov, Porth, Lyutikov (2015)

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

SIMULATION SETUP

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

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

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

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

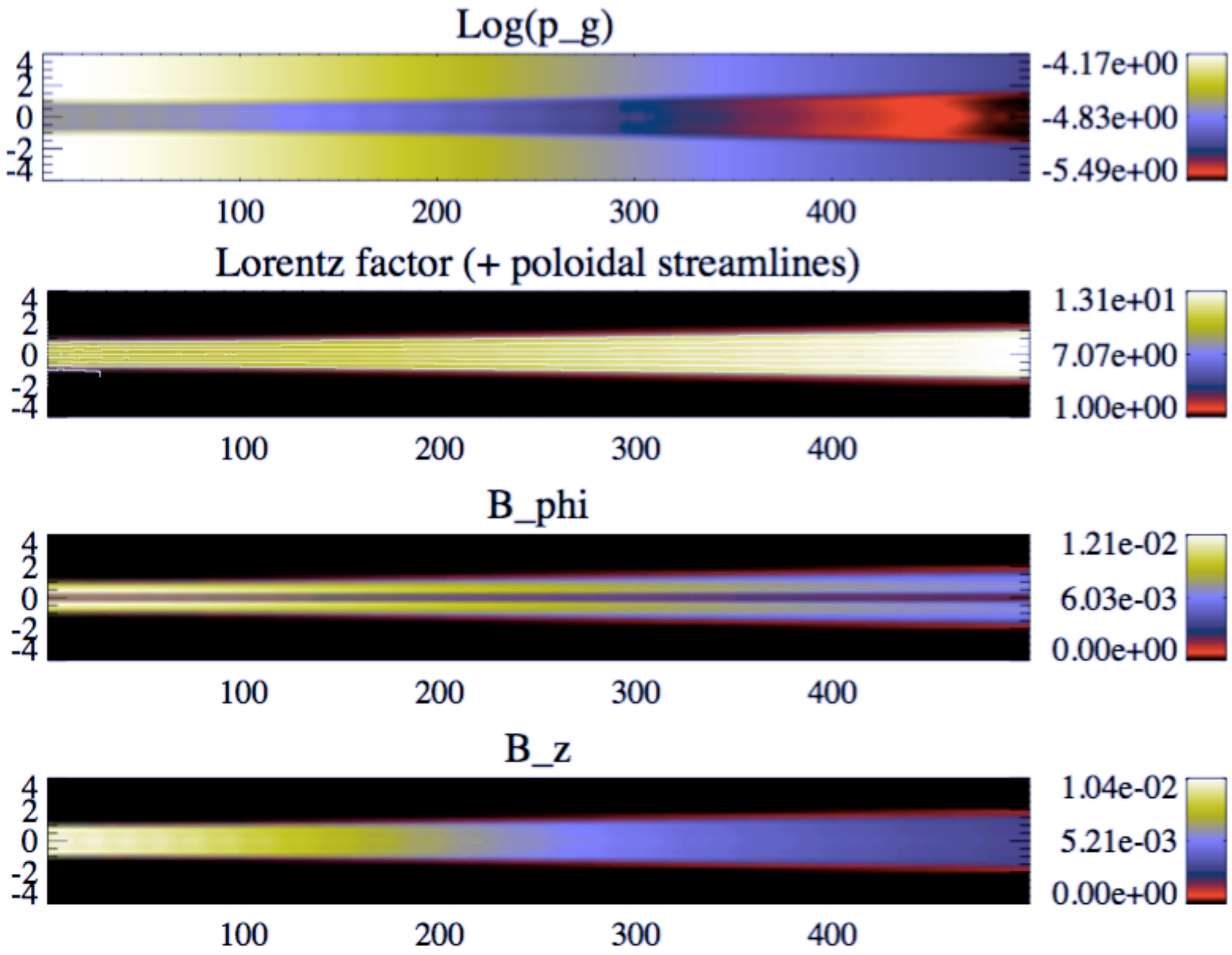
$R_{j,0}$ = 1 pc
L_J = 1.e43 erg/s

$Q_0 = 10^{-11}\,\mathrm{M_\odot yr^{-1}}$
$Q_0 = 10^{-9}\,\mathrm{M_\odot yr^{-1}}$

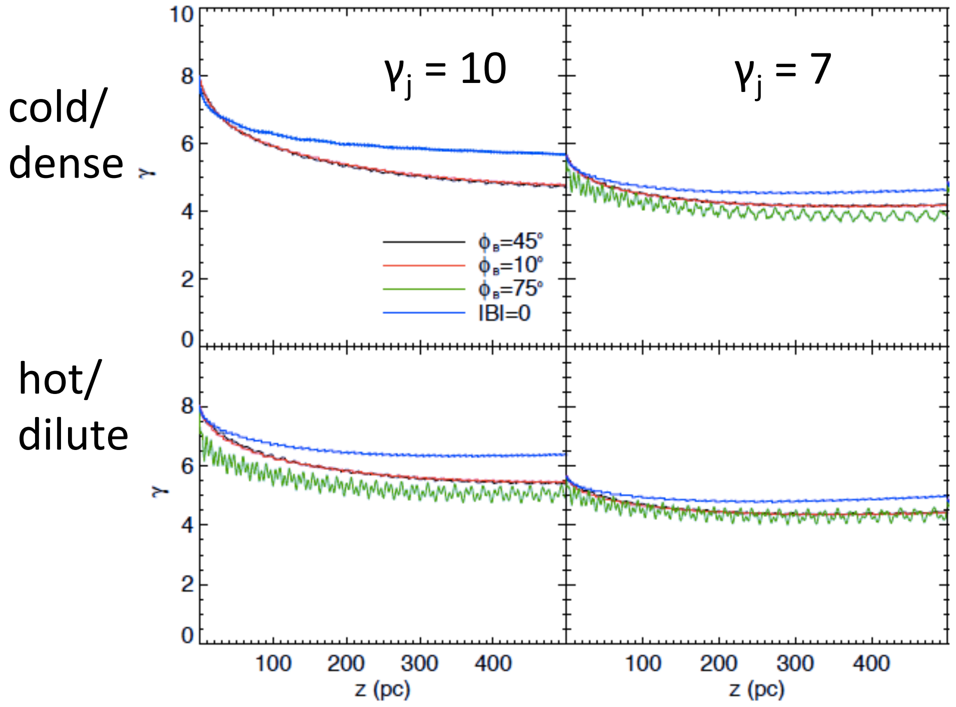
r_c = 200 / 500 pc
$r_{c,s}$ = 500 pc

Anglés, Perucho, Martí, Laing, MNRAS, 2021

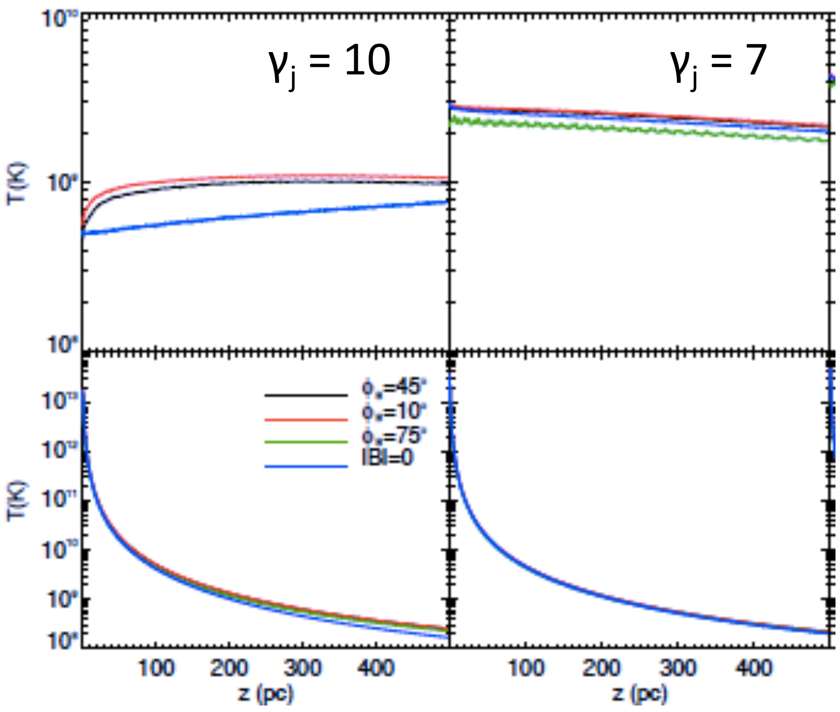
Results



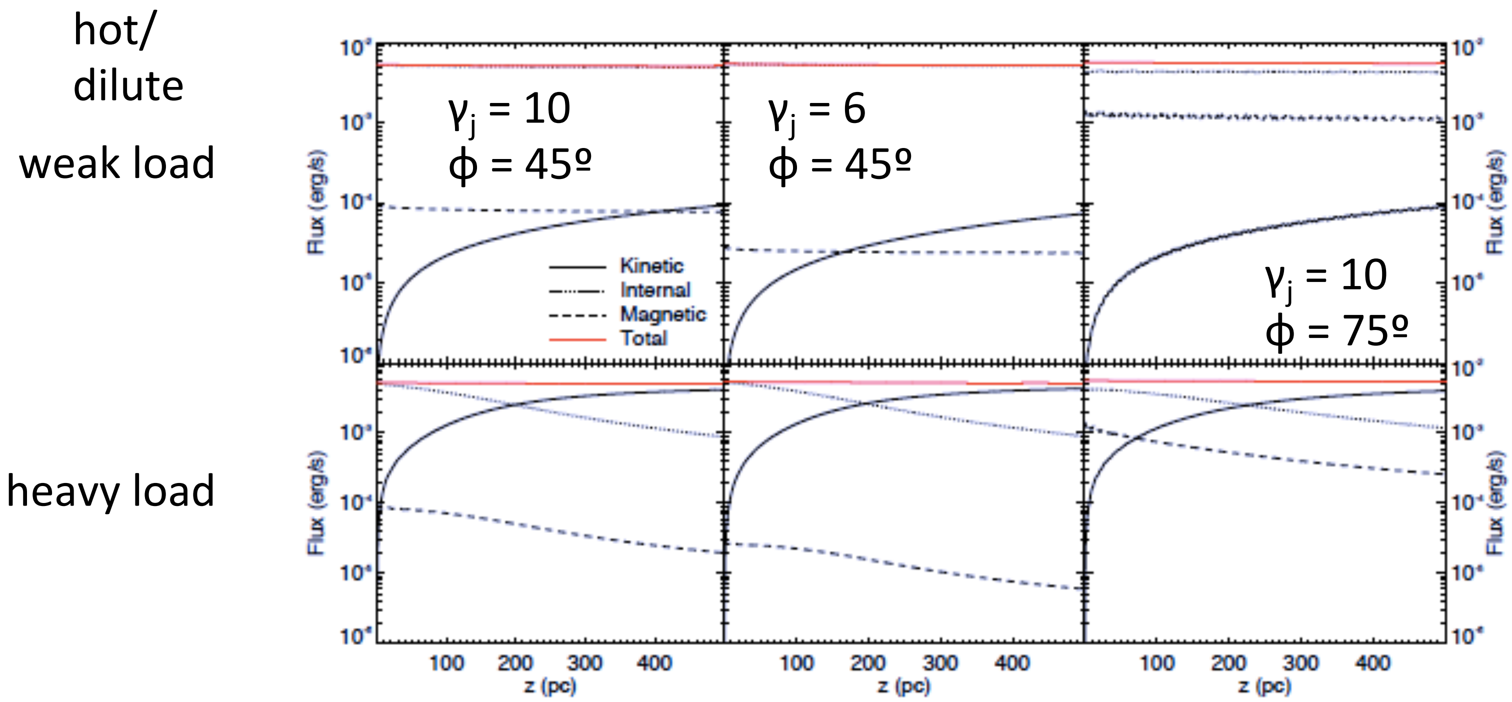
Anglés, Perucho,Martí, Laing, MNRAS, 2021



cold/
dense
hot/
dilute
γj = 10
γj = 7
γ
z (pc)
ϕB=45°
ϕB=10°
ϕB=75°
IBI=0

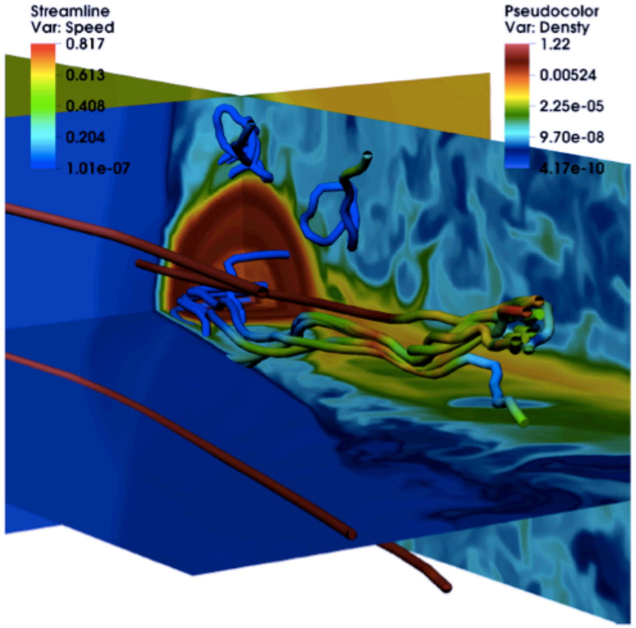


γj = 10
γj = 7
T(K)
z (pc)
ϕB=45°
ϕB=10°
ϕB=75°
IBI=0



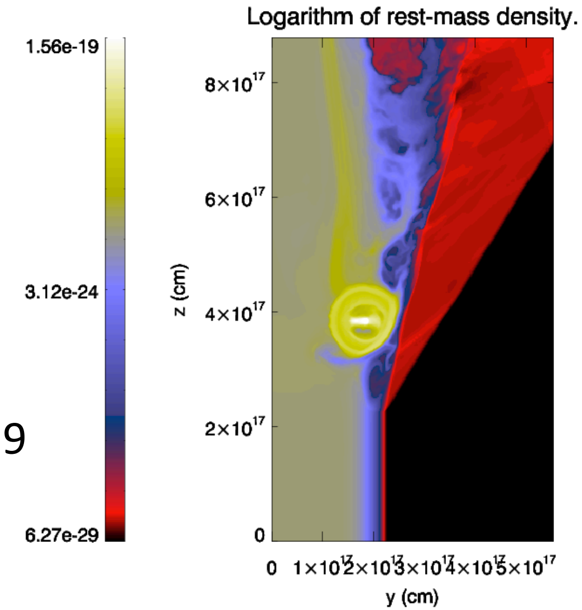
hot/
dilute
weak load
heavy load
γj = 10
ϕ = 45º
γj = 6
ϕ = 45º
γj = 10
ϕ = 75º
Flux (erg/s)
z (pc)
Kinetic
Internal
Magnetic
Total

Stars as triggers of mixing and deceleration



Perucho, Bosch-Ramon, Barkov
A&A 2017

see Araudo et al. 2013
Vieyro et al. 2017
Torres-Albà & Bosch-Ramon 2019
for detailed studies on jet-star interactions



number of interactions per unit time

$$\mathcal{N}_{\rm p} \sim n_{\rm s}(z)\, v_{\rm s}(z)\, \frac{S_{\rm j}(z)}{z}, \qquad S_{\rm j}(z) \sim \pi\, R_{\rm j}(z)\, z$$

$$\mathcal{N}_{\rm p} \sim 3\times10^{-4} \left(\frac{n_{\rm s}(z)}{1\,{\rm pc}^{-3}}\right) \left(\frac{v_{\rm s}(z)}{10^7\,{\rm cm\,s^{-1}}}\right) \left(\frac{R_{\rm j}(z)}{1\,{\rm pc}}\right) {\rm pc}^{-1}\,{\rm yr}^{-1}.$$

One interaction every 3×10^2-10^3 yr if $R_j \approx 10$ pc and $n_s \approx 0.1$ -1 pc^{-3}

Perucho, 2020, MNRAS Lett.

Interaction scales

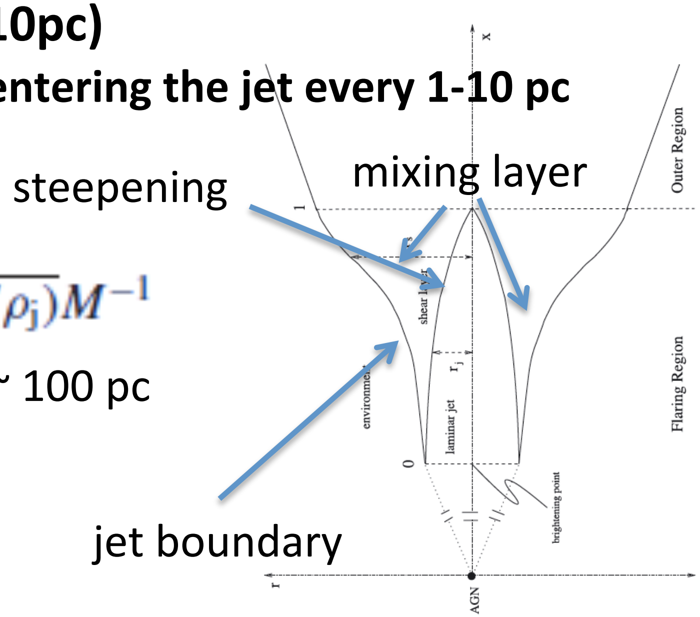
$$R_{\rm int} = 2.14\times10^{12}\left(\frac{\dot{M}_{\rm w}}{10^{-11}\,{\rm M_\odot\,yr^{-1}}}\right)^{1/2}\left(\frac{v_{\rm w}}{10\,{\rm km\,s^{-1}}}\right)^{1/2}\times \left(\frac{L_{\rm j}}{10^{43}\,{\rm erg\,s^{-1}}}\right)^{-1/2}\left(\frac{v_{\rm j}}{c}\right)^{-1/2}\left(\frac{h_{\rm j}}{c^2}\right)^{1/2}\left(\frac{R_{\rm j}}{1\,{\rm pc}}\right)\,{\rm cm},$$

If $t_p = R_{int}/v_s$, with v_s = 100 km/s

Shear layer of 1-10% of the jet radius: $10^{17\text{-}18}$ cm / 10^7 cm/s ~ $10^{3\text{-}4}$ yr

$10^{3\text{-}4}$ yr > 3×10^2-10^3 yr ! (R_j = 10pc)

The process could thus be continuous with one star entering the jet every 1-10 pc



mixing layer expansion (De Young 1993) $\propto \sqrt{(\rho_{\rm ISM}/\rho_{\rm j})}M^{-1}$

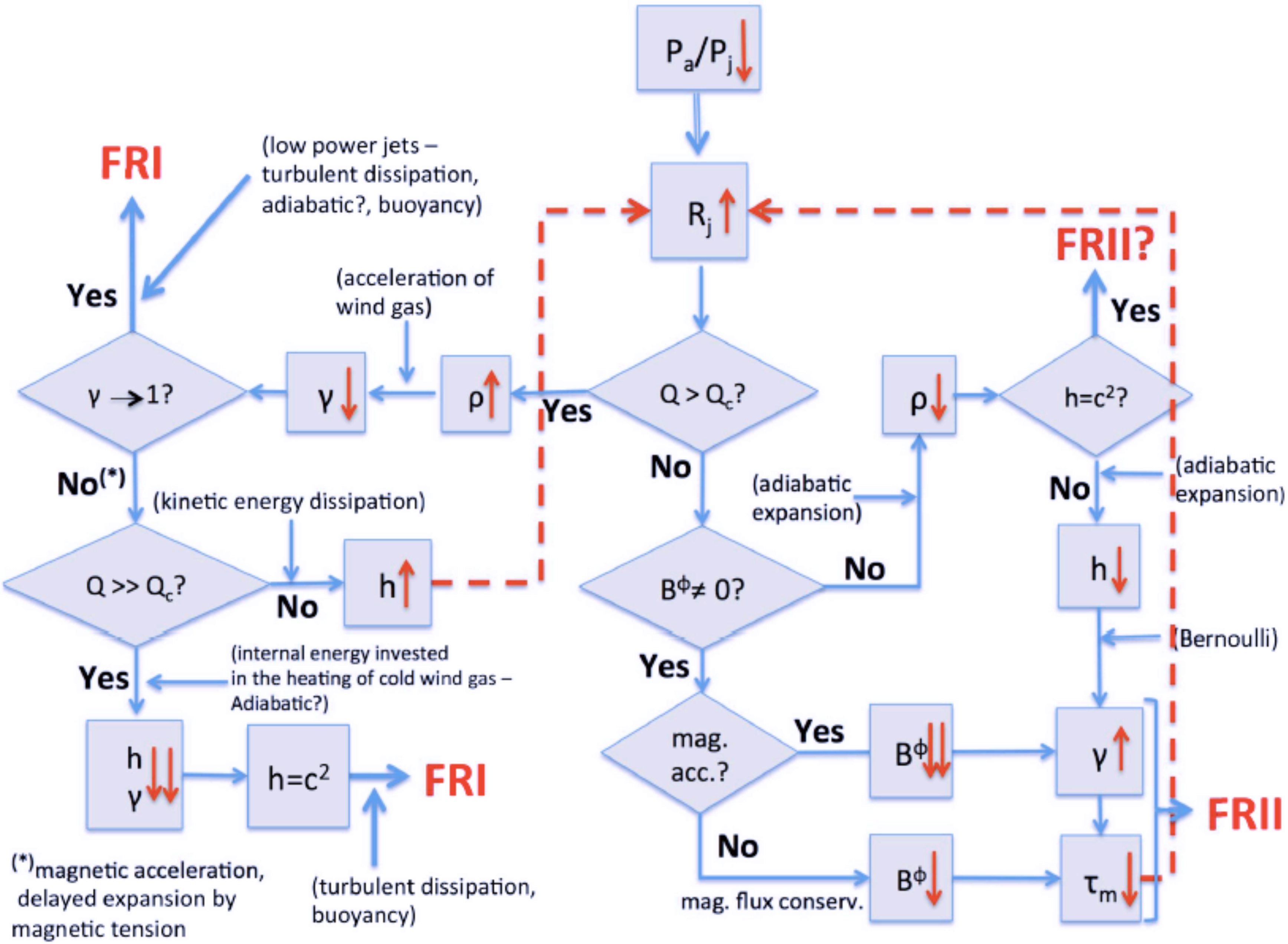
In FRI sources, the mixing layer expands across the jet ~ 100 pc along ~ 3 kpc (Wang 2009, Laing & Bridle 2014):

0.03 c → 10^4 yr

Summary

- Mass load by stellar winds seems to be insufficient to decelerate classical FRIs with the stellar populations in elliptical galaxies.
- They can, however, strongly affect jet composition and the distribution of energy fluxes (particle dominated).
- The process can dissipate a significant amount of kinetic energy.

- Deceleration can be caused by the continuous disturbance of the jet surface by entering/exiting stars and clouds.



Anglés, Perucho,Martí, Laing, MNRAS, 2021

Observability

The value of R_{int} would represent, for M87, 10^{-2} μas – 0.1 mas (for the largest bubbles).

The latter is below the resolution achieved at 15-43 GHz (Kovalev et al. 2007, Walker et al. 2018) and around that at 86 GHz (Kim et al. 2018).

However, the regions observed at those frequencies are compact and the expected number of large bubbles is therefore strongly reduced if compared to larger scales.

Flaring:

The number of simultaneous interactions is given by $N_{\rm int} \propto n_{\rm s}(z)\, V_{\rm j} \propto n_{\rm s}(z)\, R_{\rm j}(z)^2$

The jet expands with z^k, with k>1 at the flaring region.
If the number of stars drops with an exponent smaller than 2k, then the number of interactions and, thus, the global energy dissipation produced by jet-star interactions would grow with distance in this region, as a plausible cause for the observed flaring (e.g., Laing & Bridle 2014).