Jet Deceleration in Radio Galaxies and the FR Dichotomy

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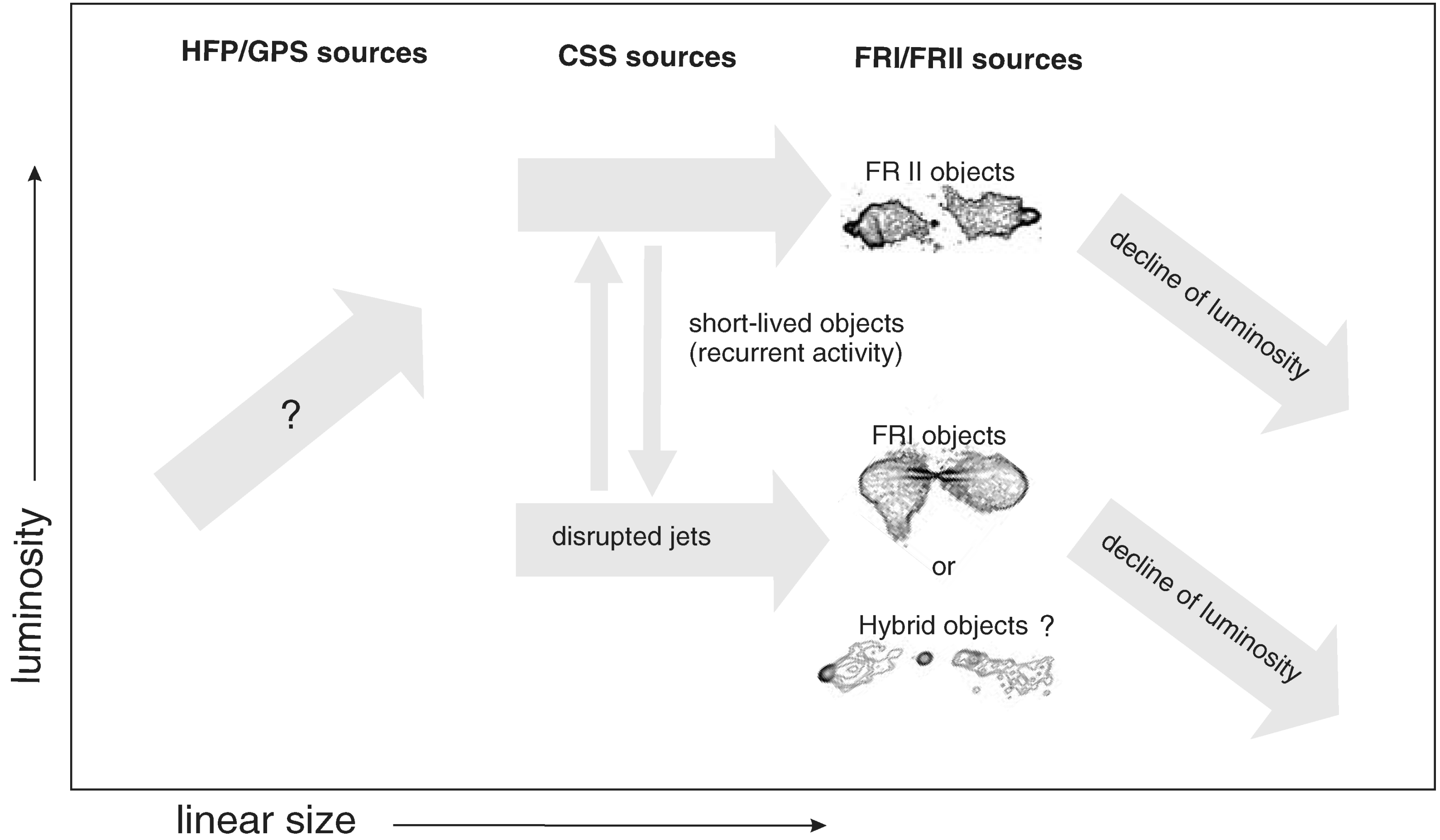
Extragalactic Relativistic Jets: Cause and Effect.

Bangalore, October 16th 2015.

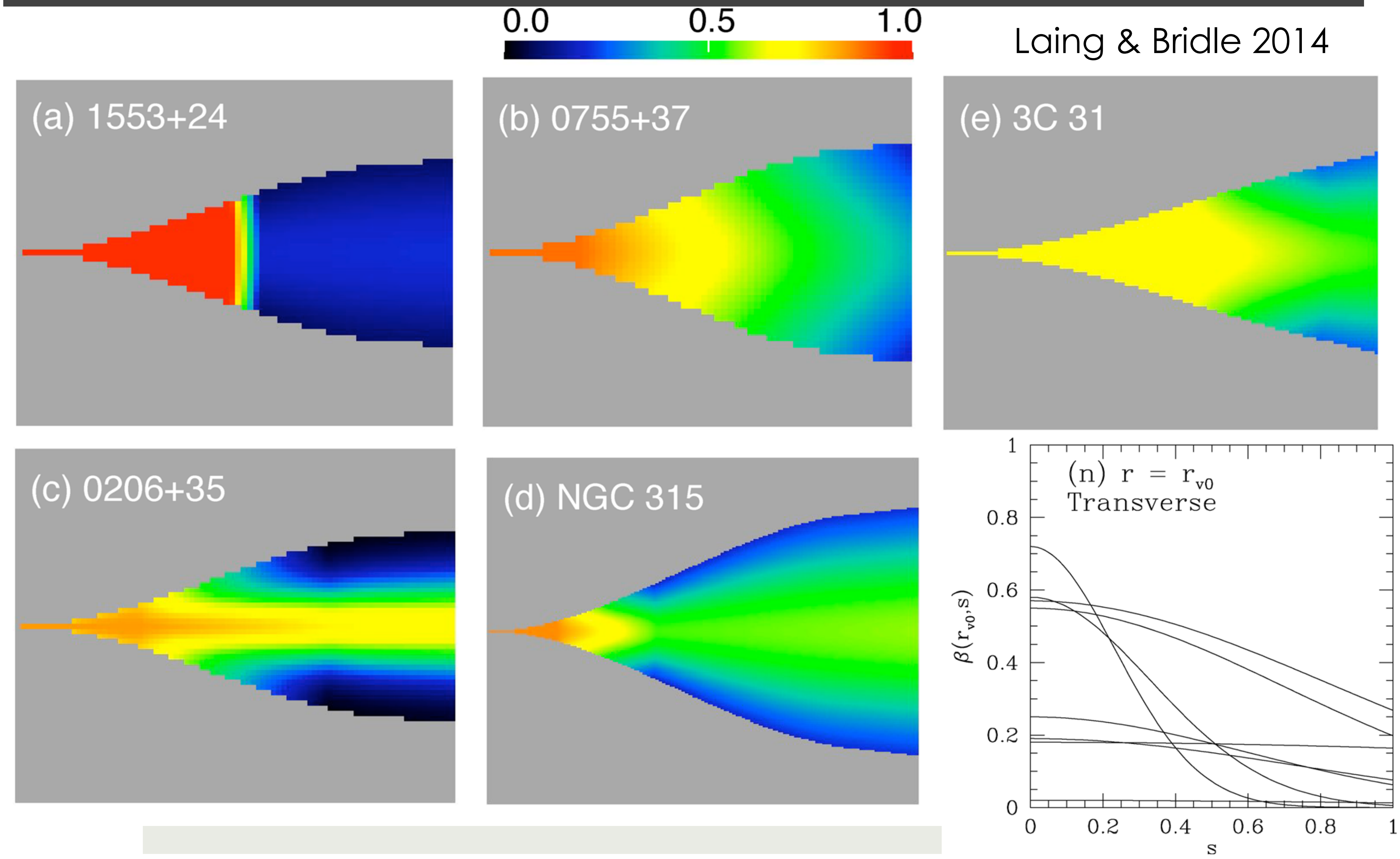
Radio-source evolution: PD diagram



From Kunert-Bajraszewska et al. (2010)

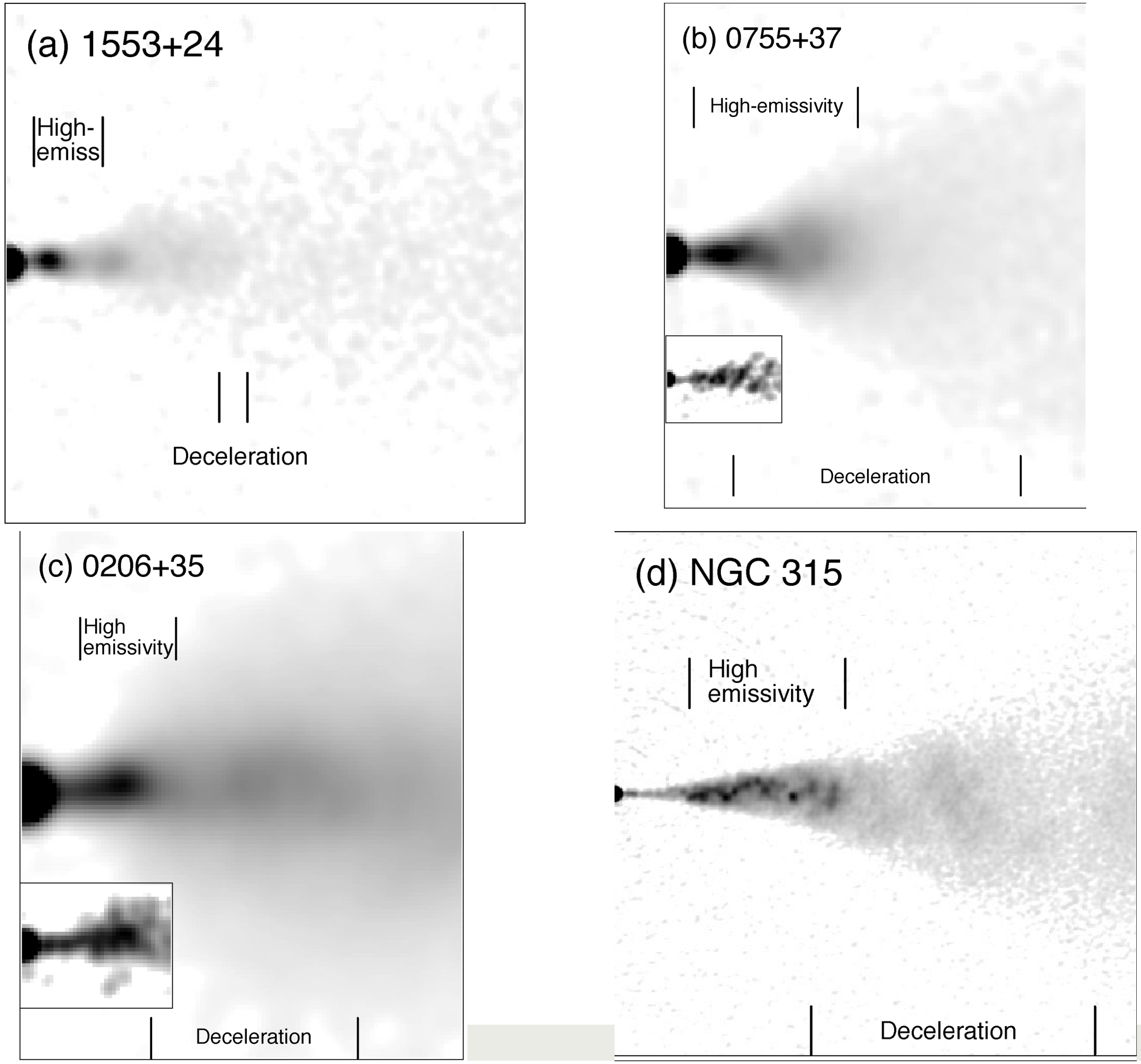
Deceleration of FRI jets

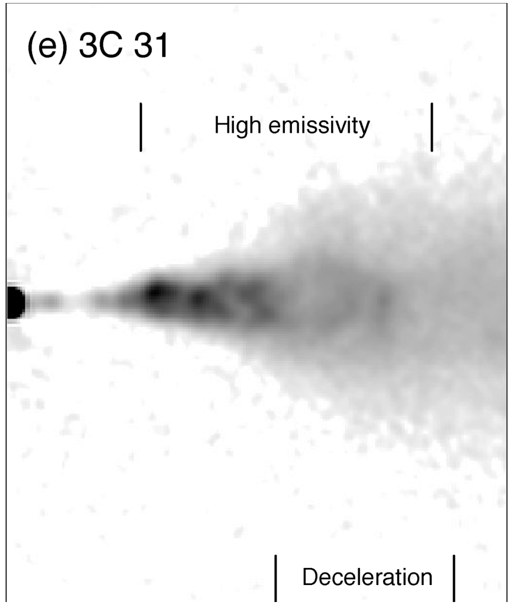
Laing & Bridle 2014



Deceleration of FRI jets

Laing & Bridle 2014



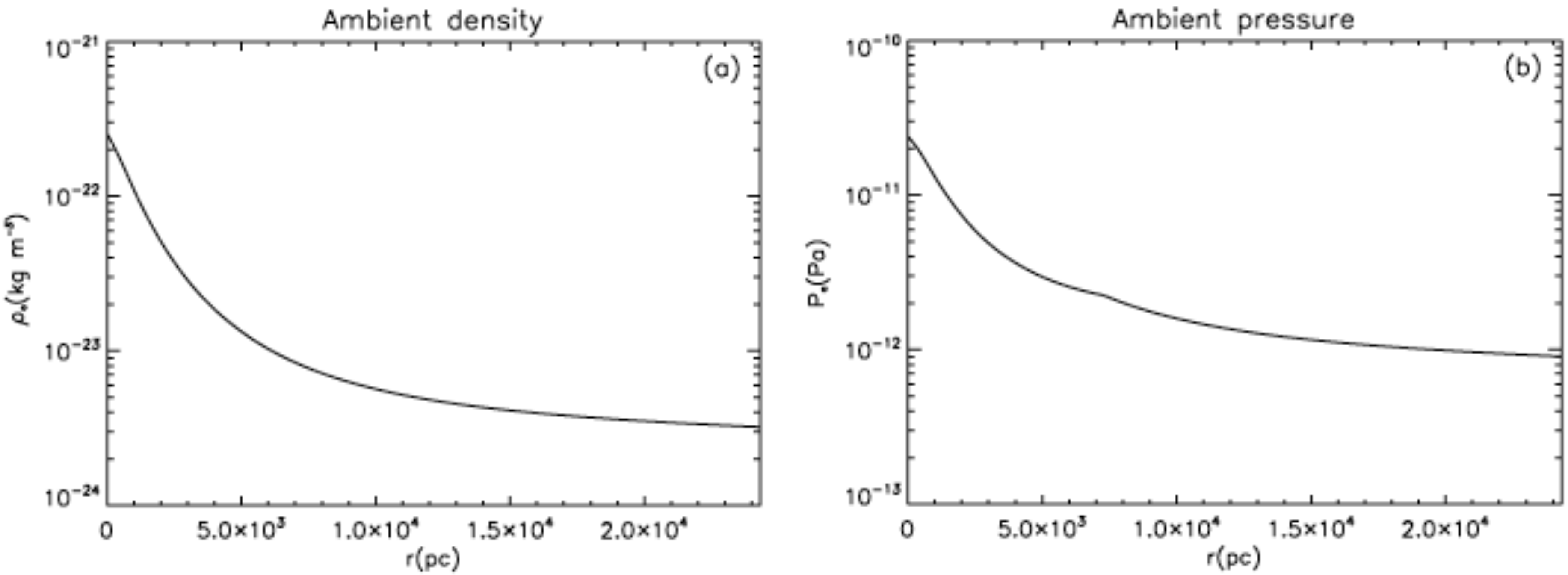


Kharb et al. (2012) find X-ray emission from these regions In 15/21 FRI's (nine X-ray jets).

Deceleration: role of the ambient medium

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

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

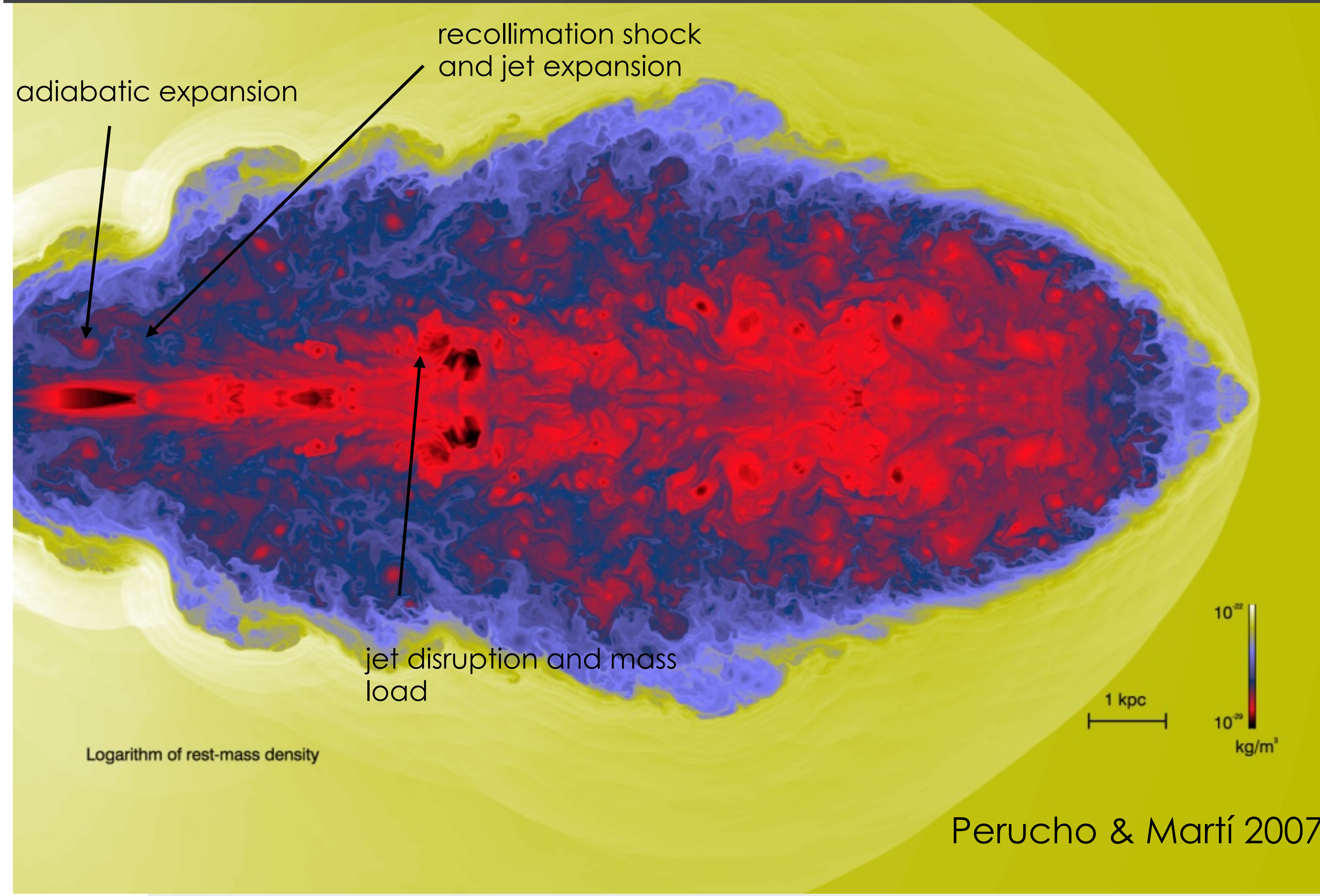


Perucho & Martí (2007)

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

From Hardcastle et al. (2002)

Deceleration: role of the ambient medium

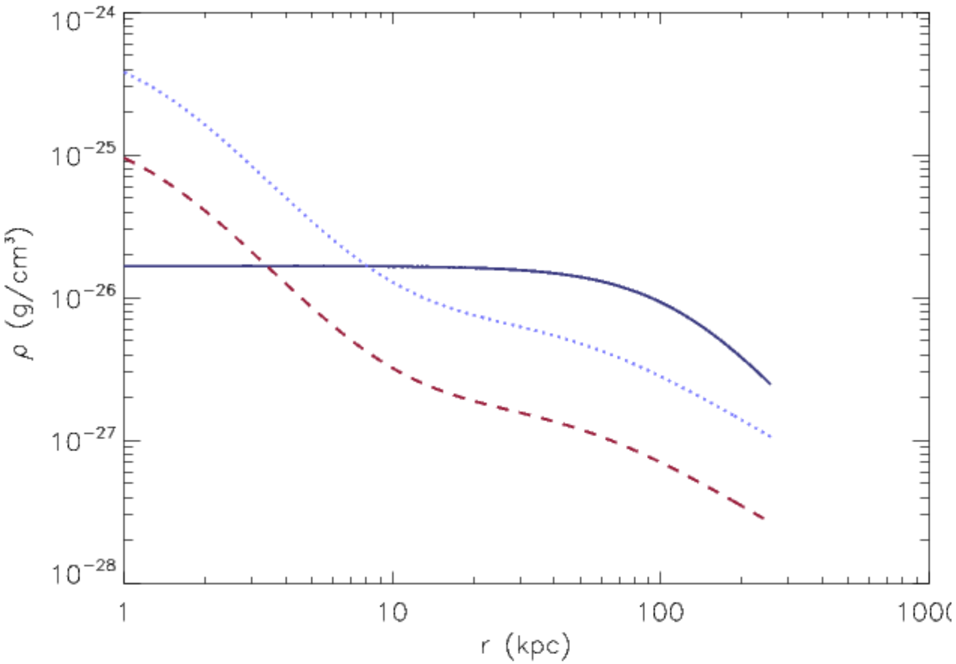


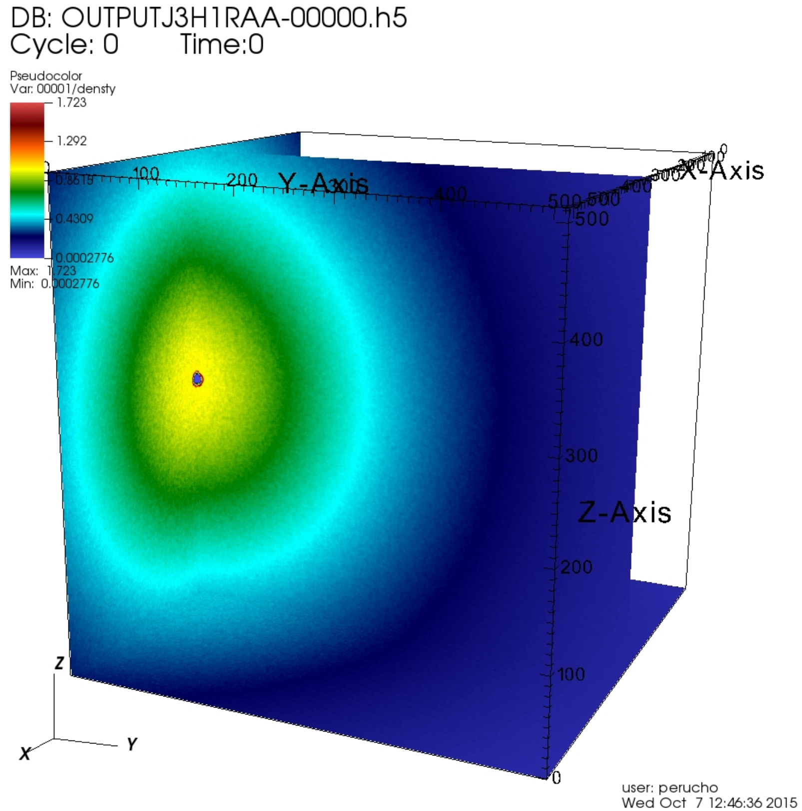
Deceleration: ambient medium and instabilities

dashed-red line: ambient density profile in the 2D simulations.

solid-blue line: ambient density profile in the 3D simulation.

$L_j = 10^{46}$ erg/s, $\rho_j = 10^{-4}\ \rho_{a,0}$, $\rho_{e,j} = 0.8\ m_p/cm^3$, $v_j = 0.92$ c, $T_a = 5\ 10^7$ K.

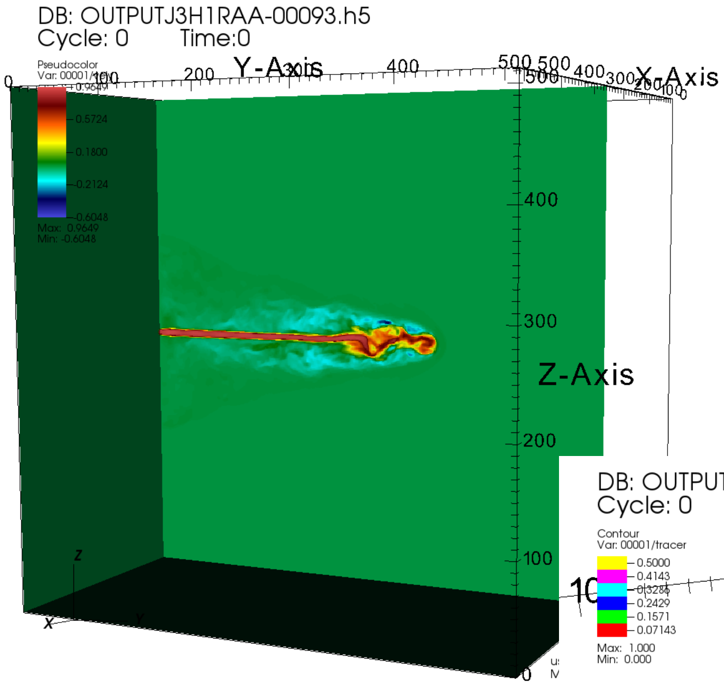


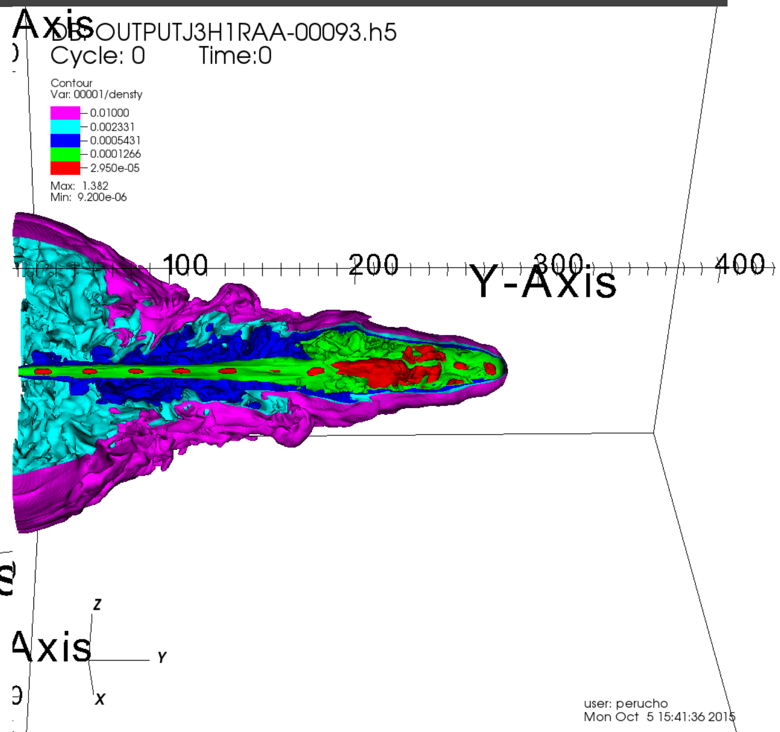


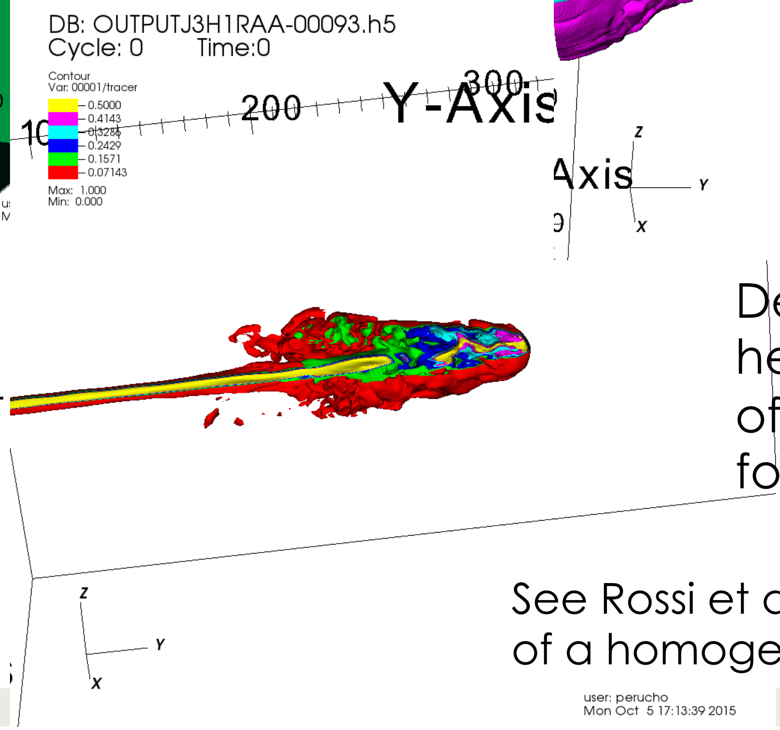
Perucho et al., in preparation

Ratpenat is a HRSC, 3D RHD code that combines MPI and OMP parallelization. It includes **a relativistic equation of state**, which allows us to introduce different populations of particles.

Deceleration: ambient medium and instabilities





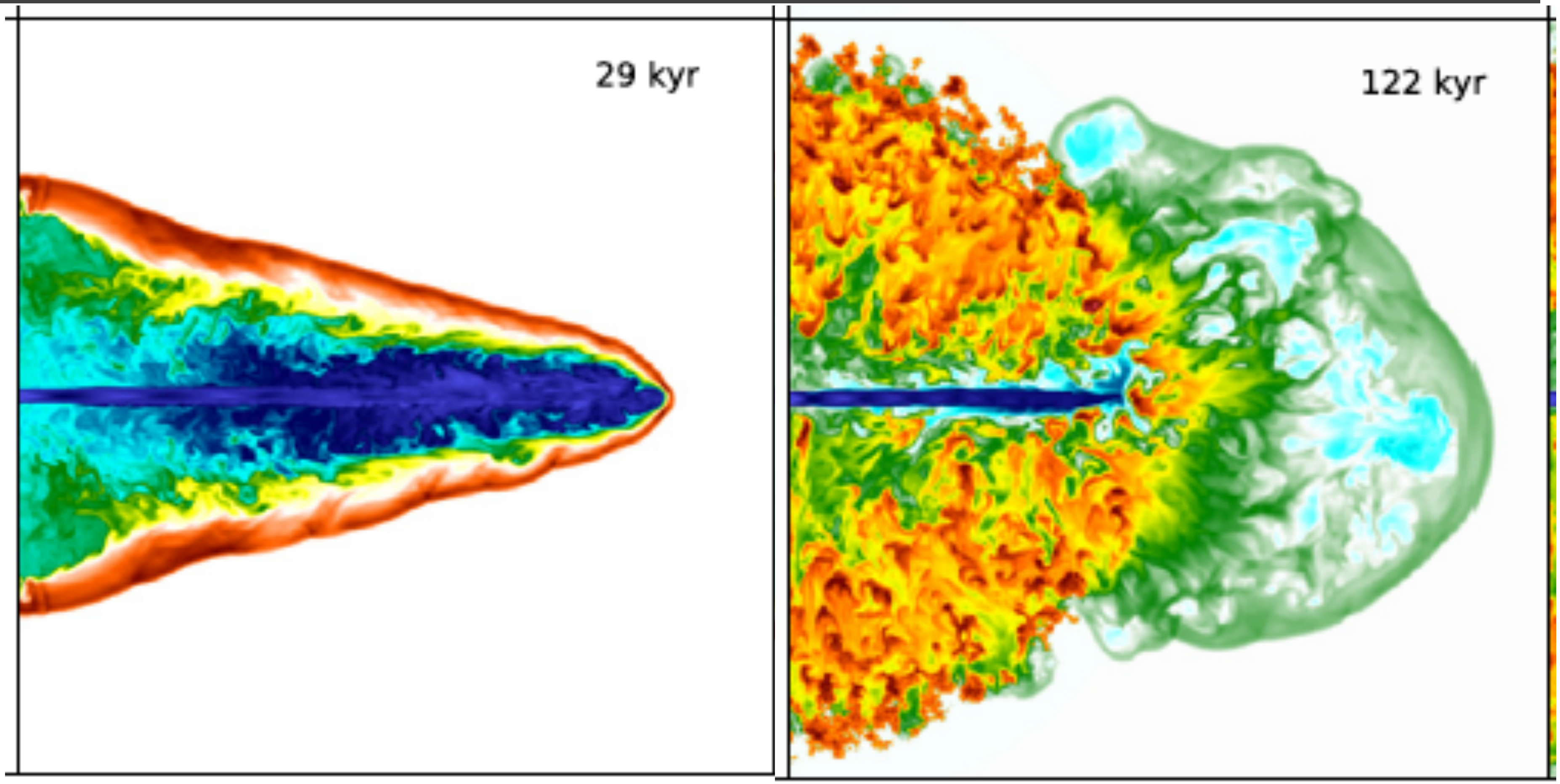


The jet develops pinching and (induced) helical instabilities and it is disrupted beyond the density core.

Deceleration of the jet head and development of fat lobes is expected following this disruption.

See Rossi et al. (2008) for the case of a homogeneous ambient medium.

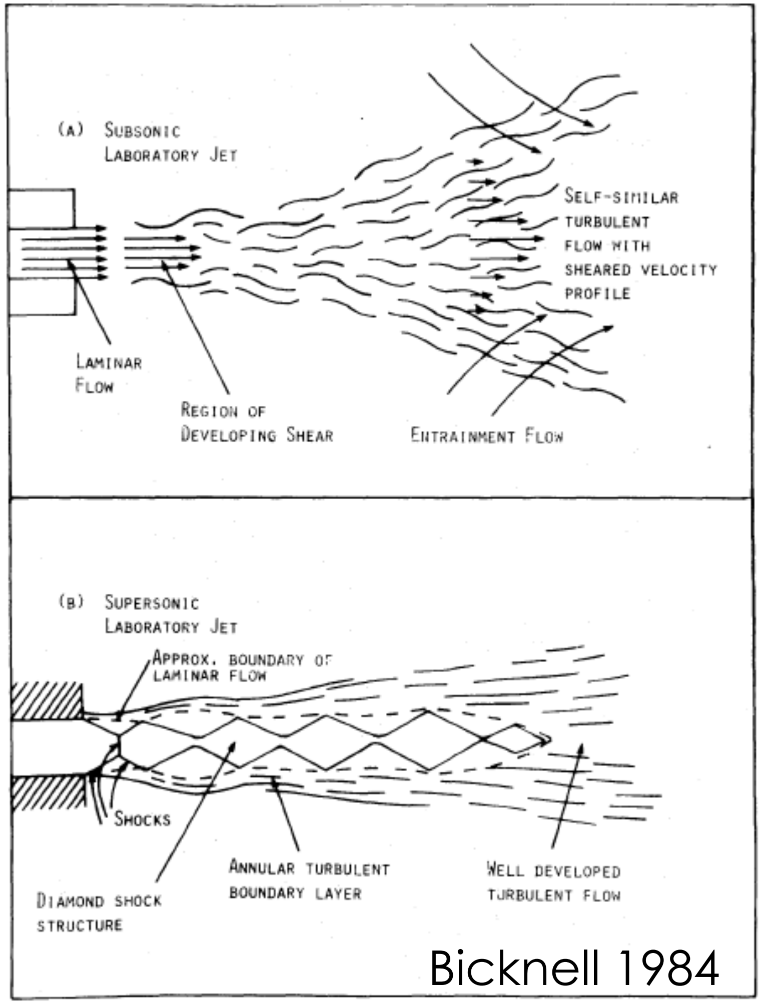
Deceleration: inhomogeneous media



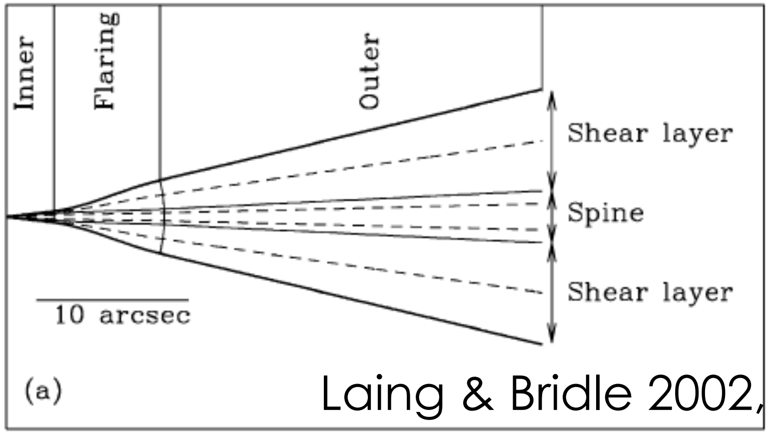
Wagner & Bicknell (2011)
Wagner et al. (2012)

Homogeneous versus clumpy medium

Deceleration: instabilities



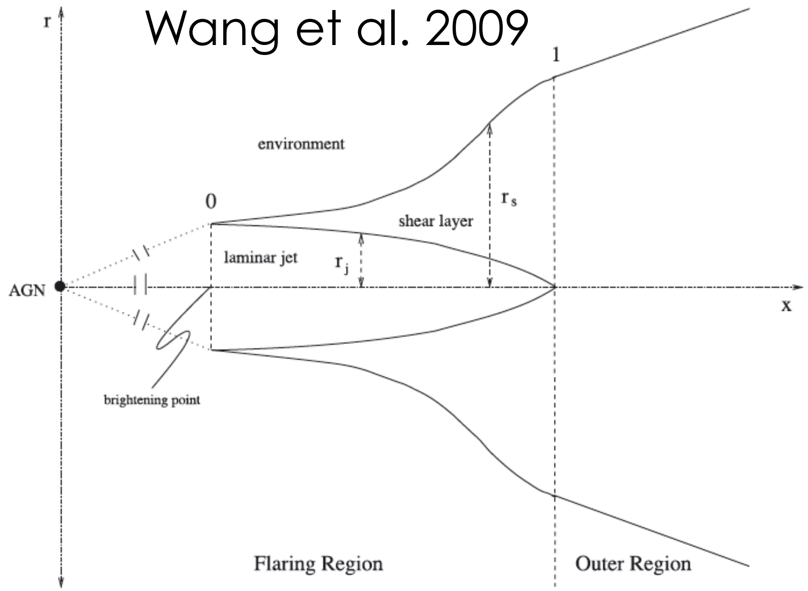
Bicknell 1984



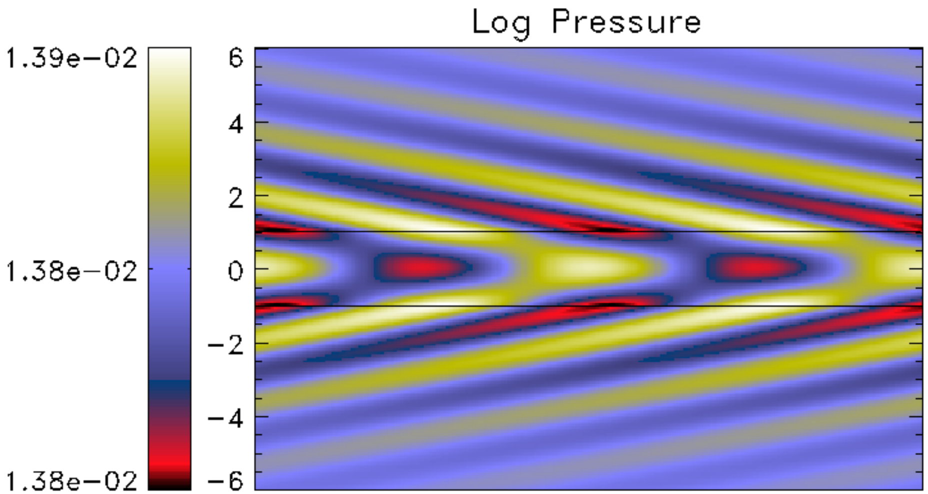
Laing & Bridle 2002, 2014

Shear-layer loading by turbulent mixing.

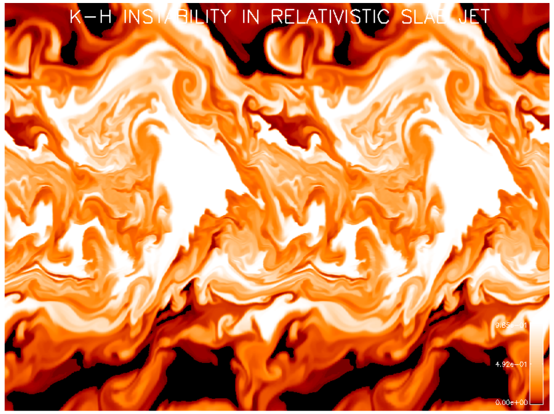
Wang et al. 2009

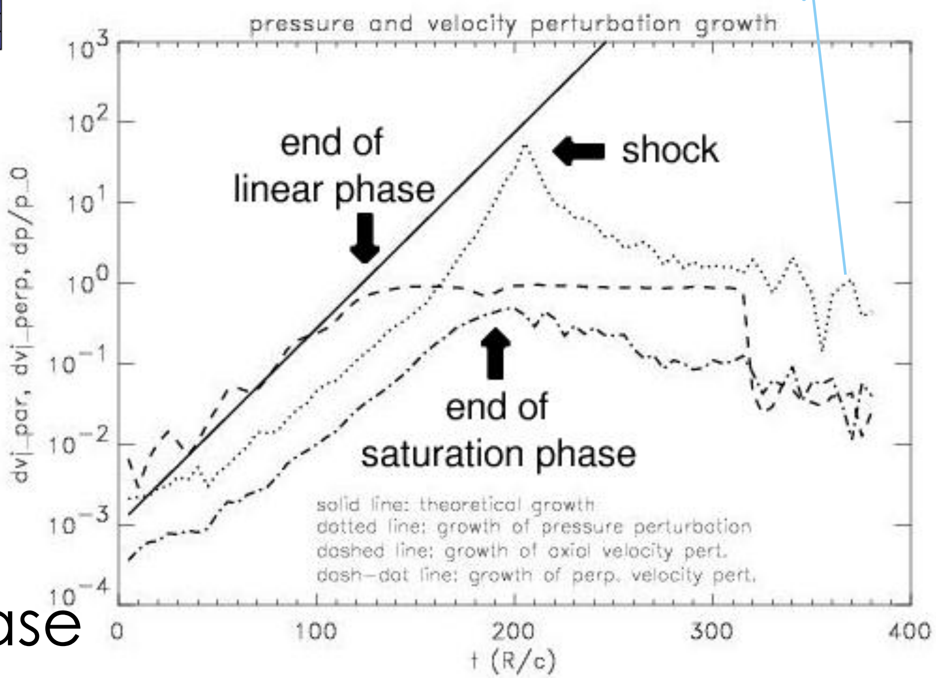


Deceleration: instabilities



Initial model

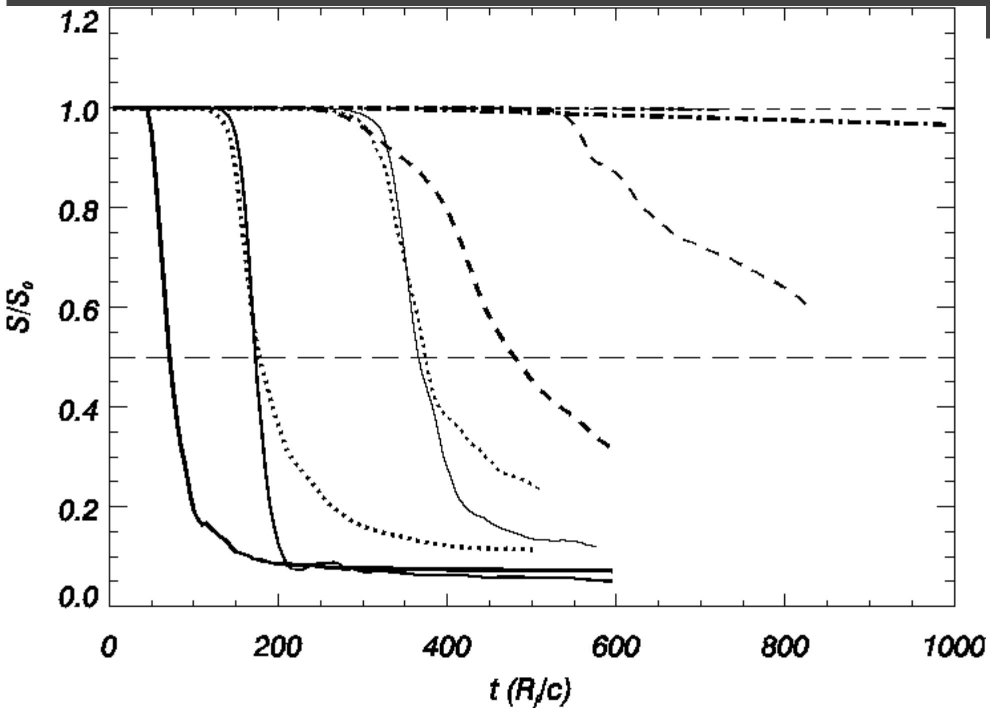




- Parameters:
  - Lorentz factor.
  - Rest-mass density contrast.
  - Specific internal energy.
  - Pressure equilibrium.

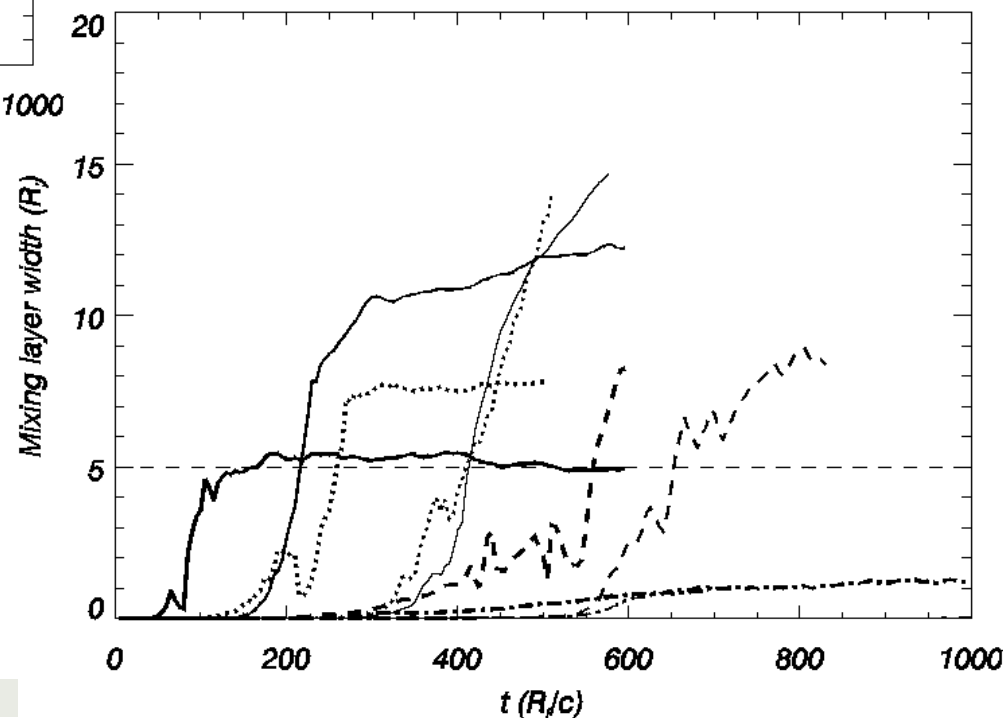
Linear phase

Deceleration: instabilities



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

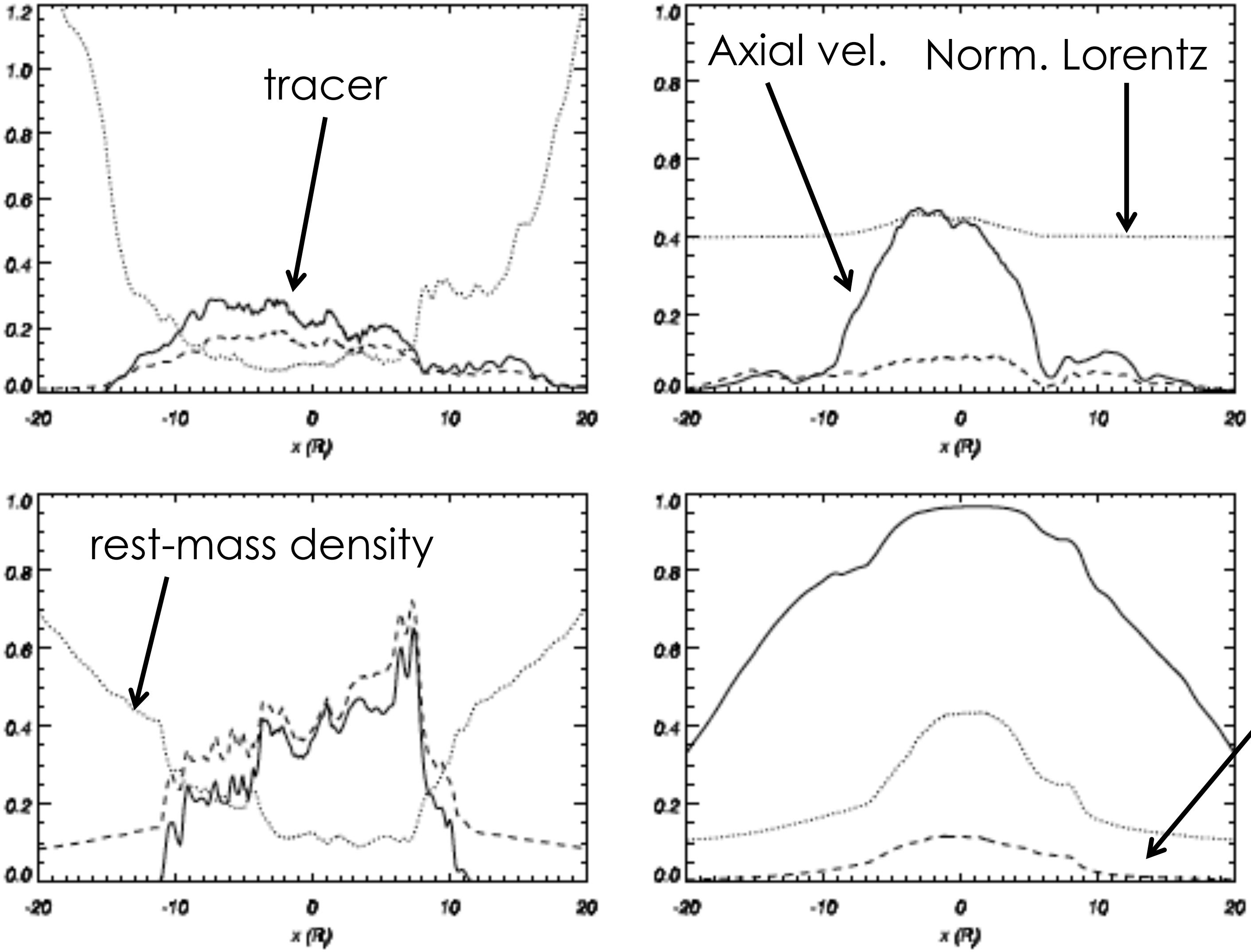
KH instability. The disruption process can be slow if the growing modes have small wavelengths.



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

Deceleration distance 300 pc – 3 kpc

Deceleration: instabilities



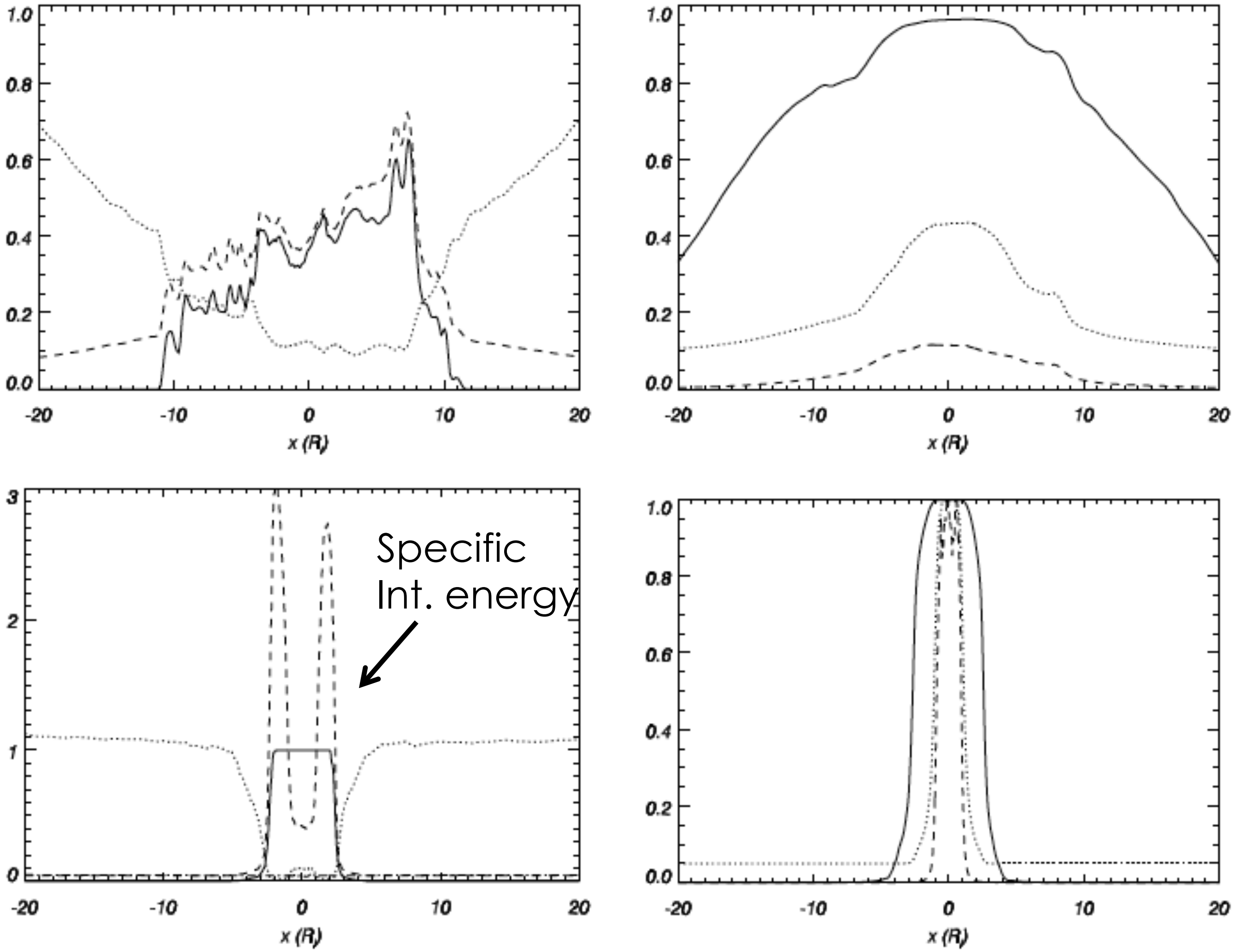
Profiles across the jet in 2D simulations.

Norm. Momentum In the axial direction

Left panel (thermodynamical quantities): solid line, tracer; dotted line, rest mass density; dashed line, specific internal energy.

Right panels solid line, longitudinal velocity; dotted line, lorentz factor normalized to the initial value in the jet dashed line, longitudinal momentum normalized to the initial value in the jet.

Deceleration: instabilities



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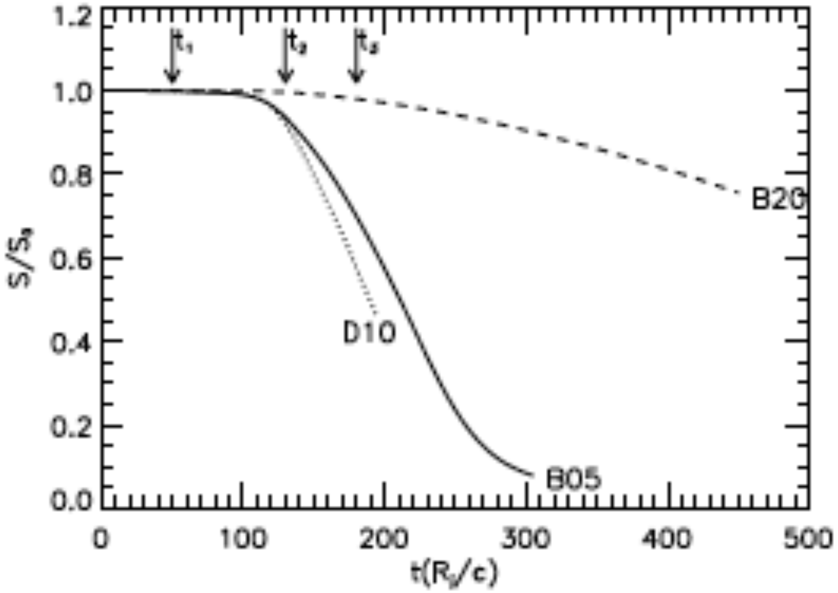
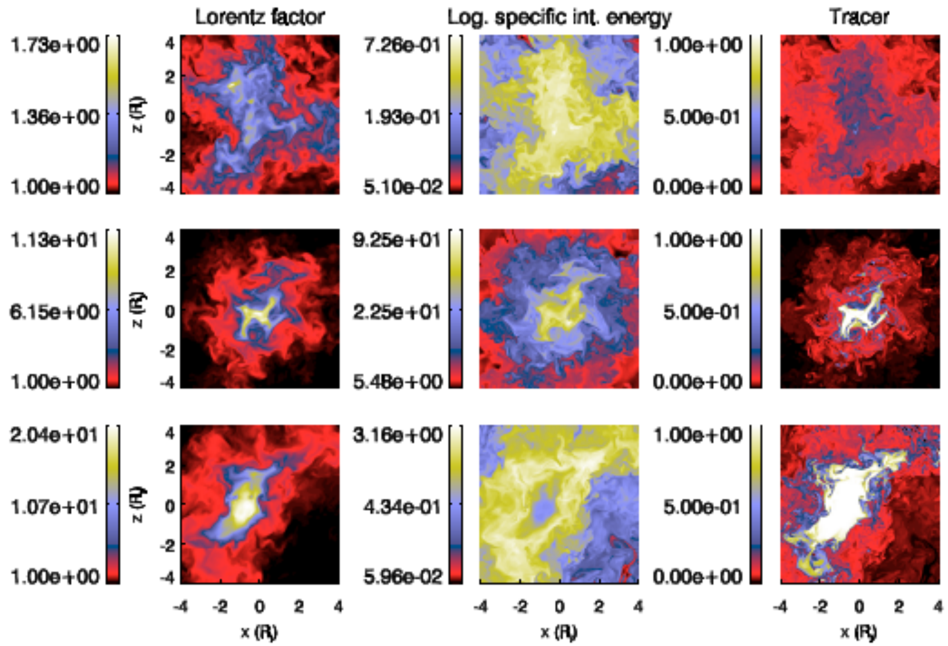
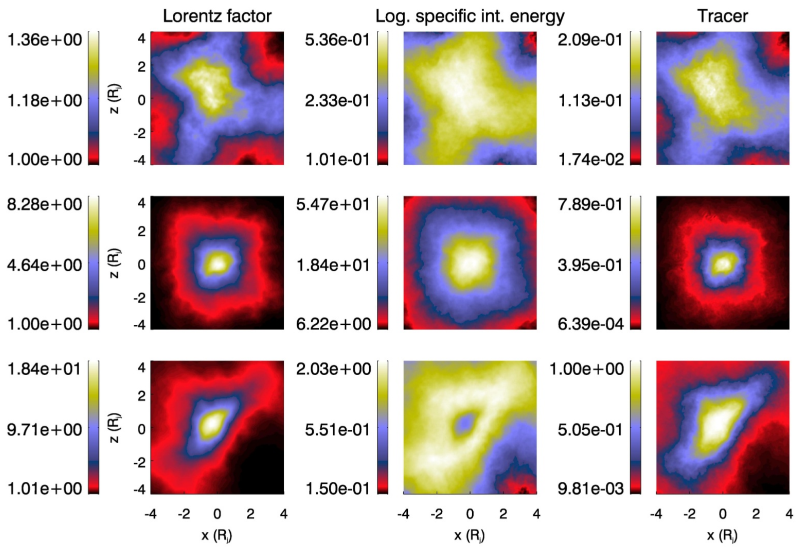
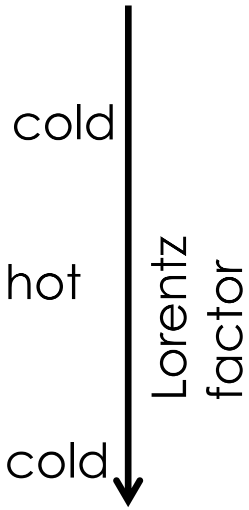
Deceleration: instabilities





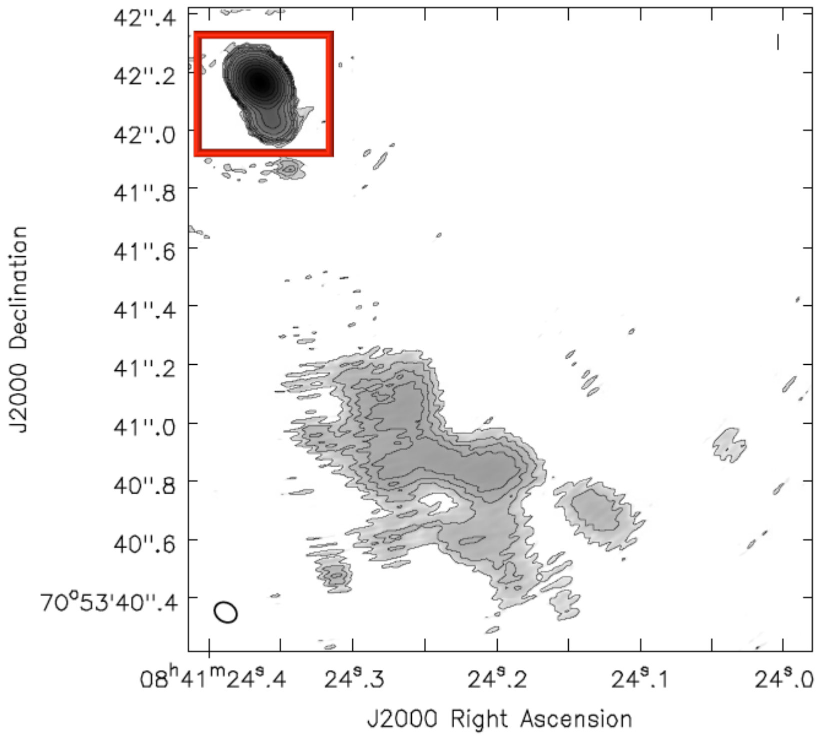


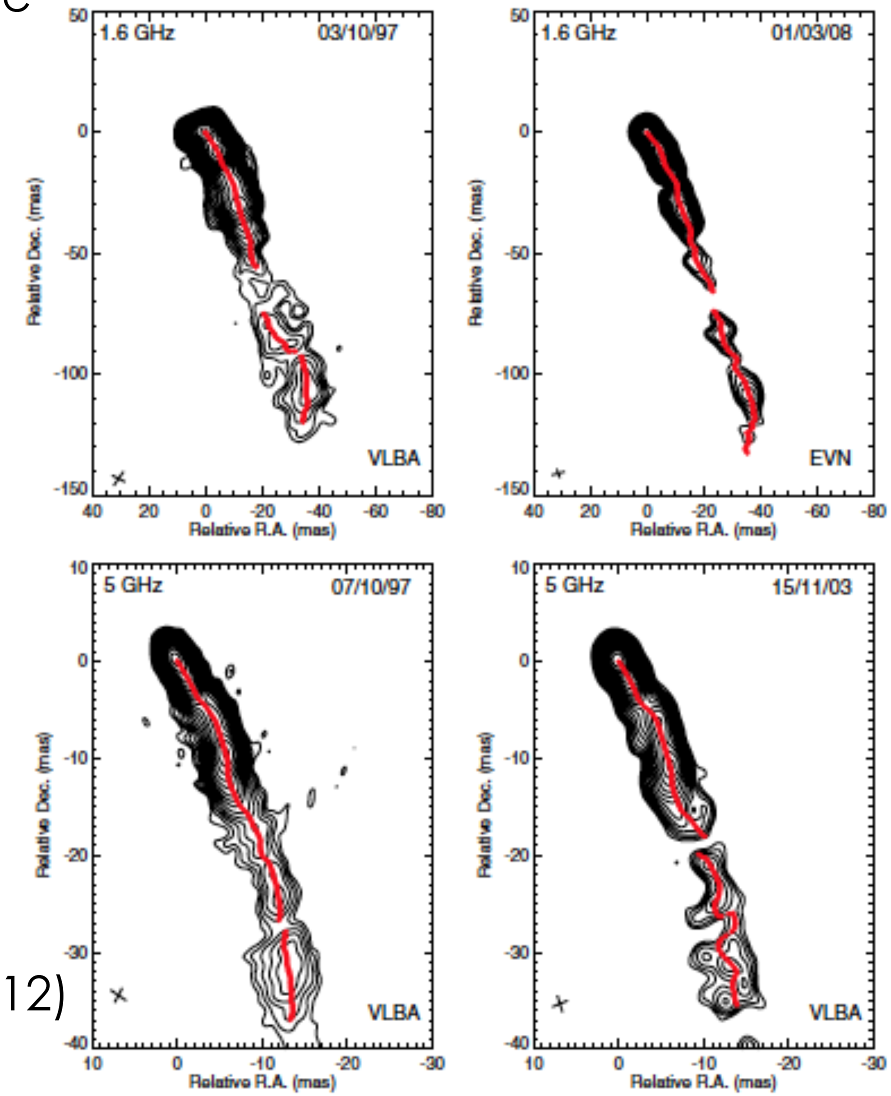


Perucho et al. 2005, 2010: KH instability. The disruption process can be slow if the growing modes have small wavelengths.

Deceleration: instabilities

0836+710: The jet is possibly disrupted by the growth of instabilities.

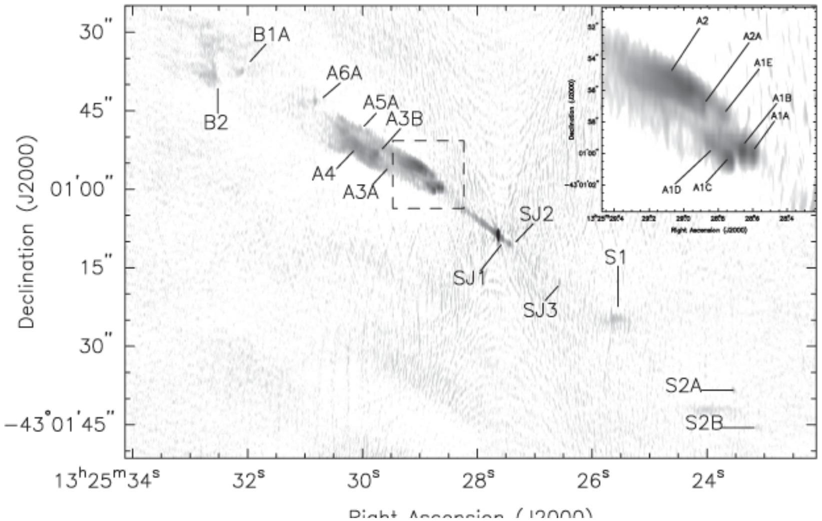


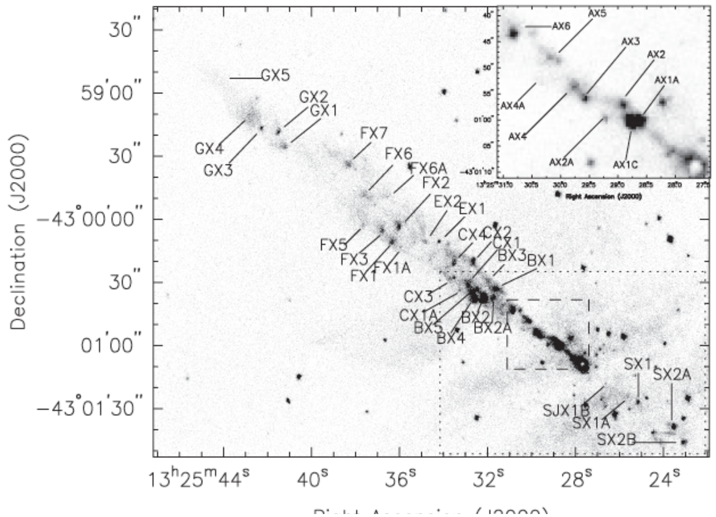


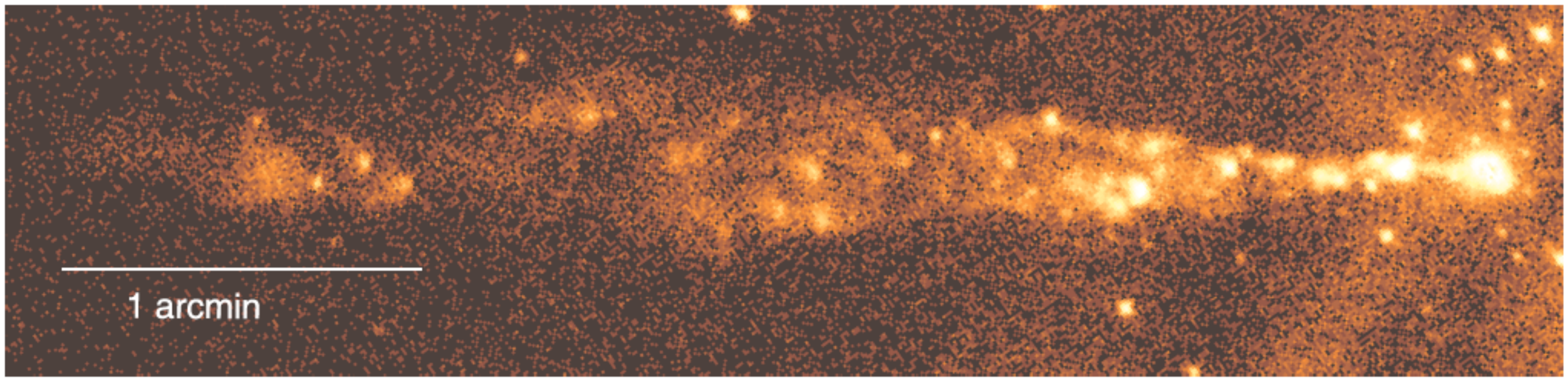
MP, Kovalev, Lobanov, Hardee, Agudo (2012)
MP, Martí-Vidal, Lobanov, Hardee (2012)

Deceleration: mass load by stellar winds

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?



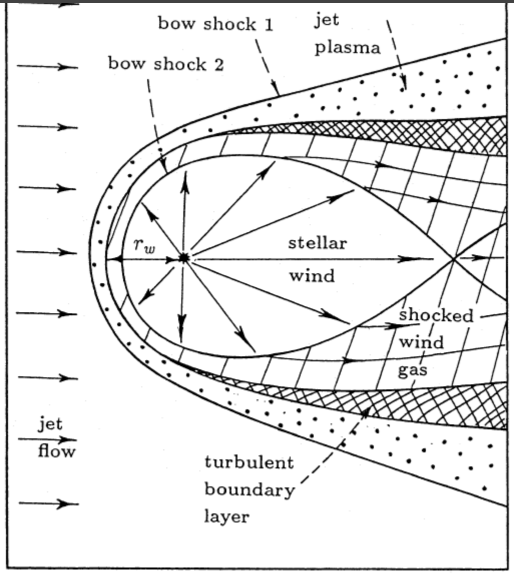




SEE TALK BY S. WYKES

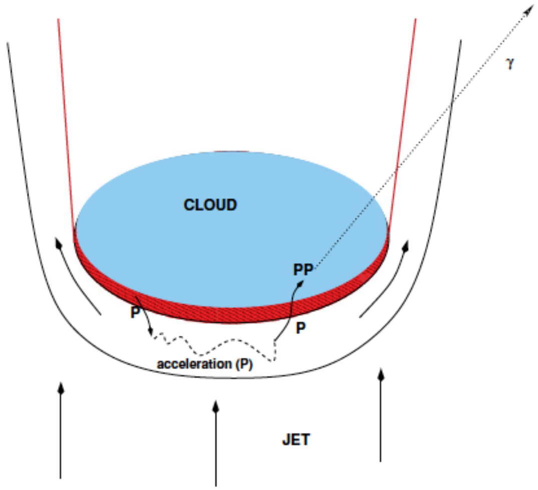
FIG. 1.—A 0.8–3 keV unsmoothed rotated image of the six *Chandra* exposures comprising the Cen A VLP, with 0.492 × 0.492 arcsec² pixels.

Deceleration: mass load by stellar winds

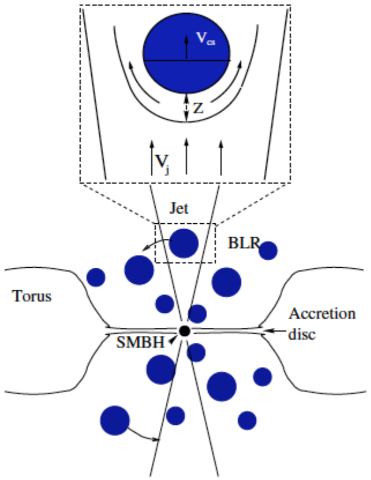


FRI deceleration due to mass-load of stellar wind gas?

Komissarov 1994 (RHD problem),
Bowman, Leahy & Komissarov 1996,
Hubbard & Blackman 2006



Interaction between jets and clouds invoked to explain high-energy emission: Bednarek, Protheroe 1997
Araudo et al. 2010
Barkov et al. 2010, 2012
Wykes et al. 2013, 2015

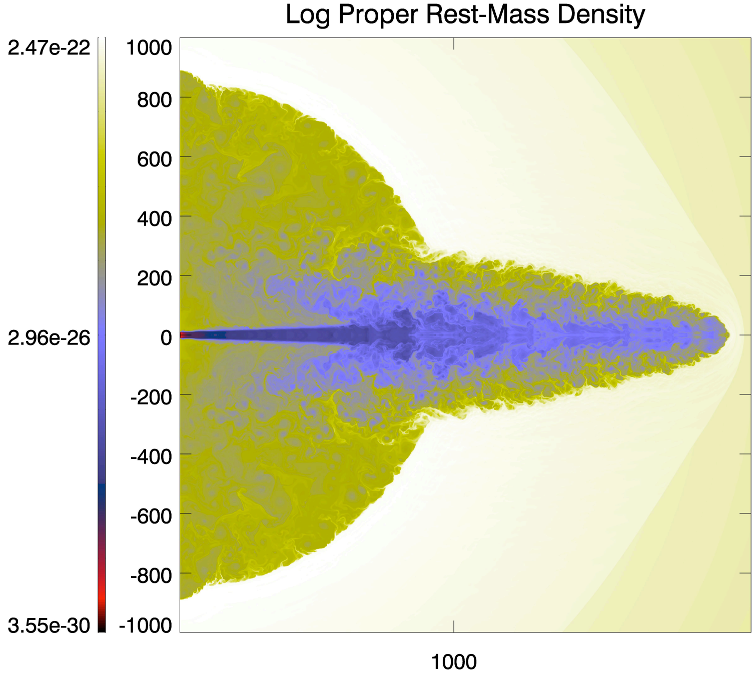


Deceleration: mass load by stellar winds

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.

Laing & Bridle (2002) studied this case in 3C31 (10^{44} erg/s): concluded it was not enough to decelerate the jet flow.

Model	Velocity $[c]$	Density $[g/cm^3]$	Temperature $[K]$	P_j/P_{am}	L_k [erg/s]	q_0 $[g\,yr^{-1}\,pc^{-3}]$	Jet length [kpc]	t_{sim} [Myrs]
Po	0.99	9.65×10^{-30}	3×10^9	17.6	10^{44}	4.95×10^{22}	2.2	-
Pr	0.99	9.65×10^{-30}	3×10^9	17.6	10^{44}	4.95×10^{22}	2.2	-
A0	0.95	3×10^{-33}	3×10^{11}	0.54	5×10^{41}	0	1.5	1.6
A	0.95	3×10^{-33}	3×10^{11}	0.54	5×10^{41}	4.95×10^{22}	2.1	24.0
B	0.95	3×10^{-34}	3×10^{12}	0.54	5×10^{41}	4.95×10^{22}	2.0	21.0
C	0.95	3×10^{-35}	3×10^{13}	0.54	5×10^{41}	4.95×10^{22}	1.8	19.0
D	0.95	3×10^{-35}	3×10^{13}	0.54	5×10^{41}	4.95×10^{21}	1.8	18.0



injection point at 80 pc – initial jet radius 10 pc

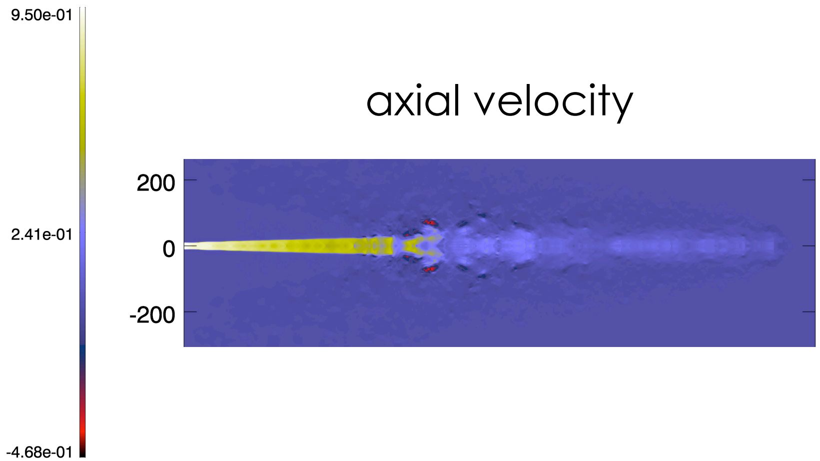
King density profile.

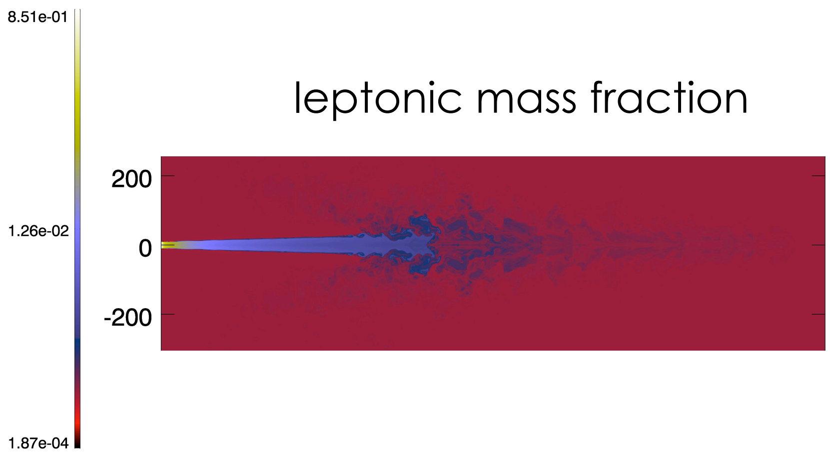
$$n_{ext} = n_c \left(1 + \frac{r^2}{r_c^2}\right)^{-3\beta_{atm,c}/2}$$

Deprojected Nuker profile (Lauer et al. 2007).

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

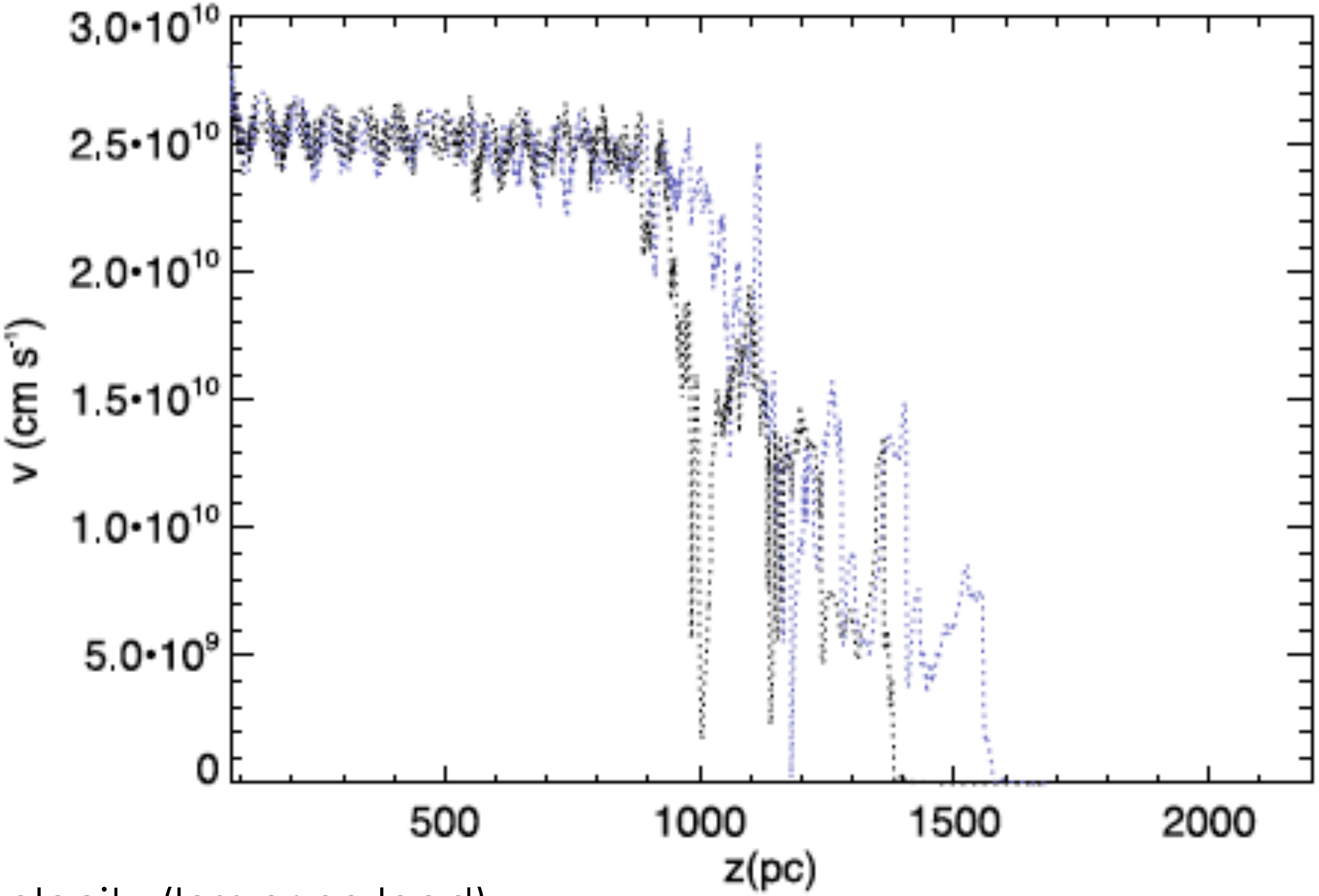
The stars are assumed to be all the same, with stellar mass losses 10^{-11}-10^{-12} $M_{\odot}yr^{-1}$.





Perucho, Martí, Laing, Hardee 2014

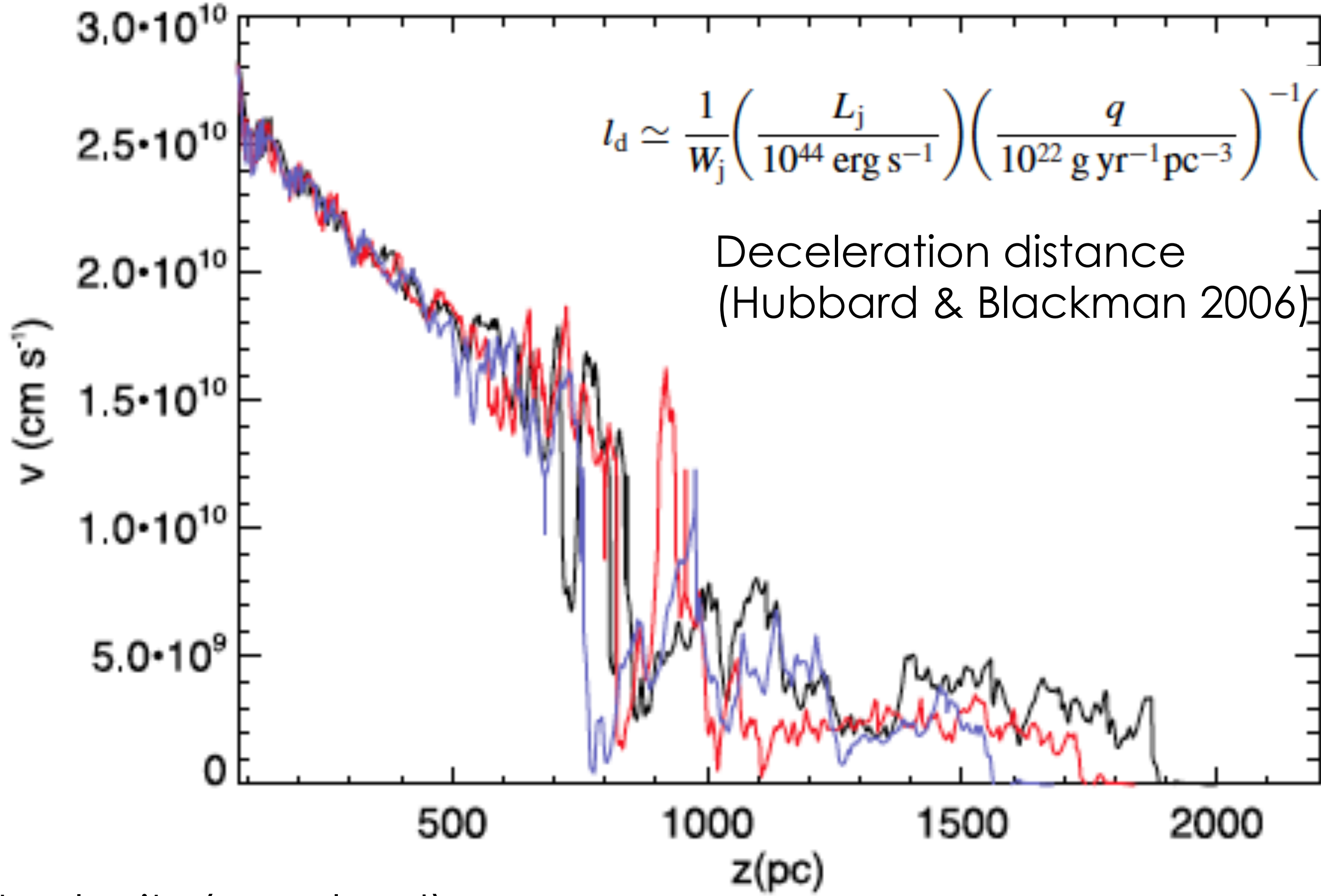
Deceleration: mass load by stellar winds



Jet velocity (less or no load)

Perucho, Martí, Laing, Hardee 2014

Deceleration: mass load by stellar winds



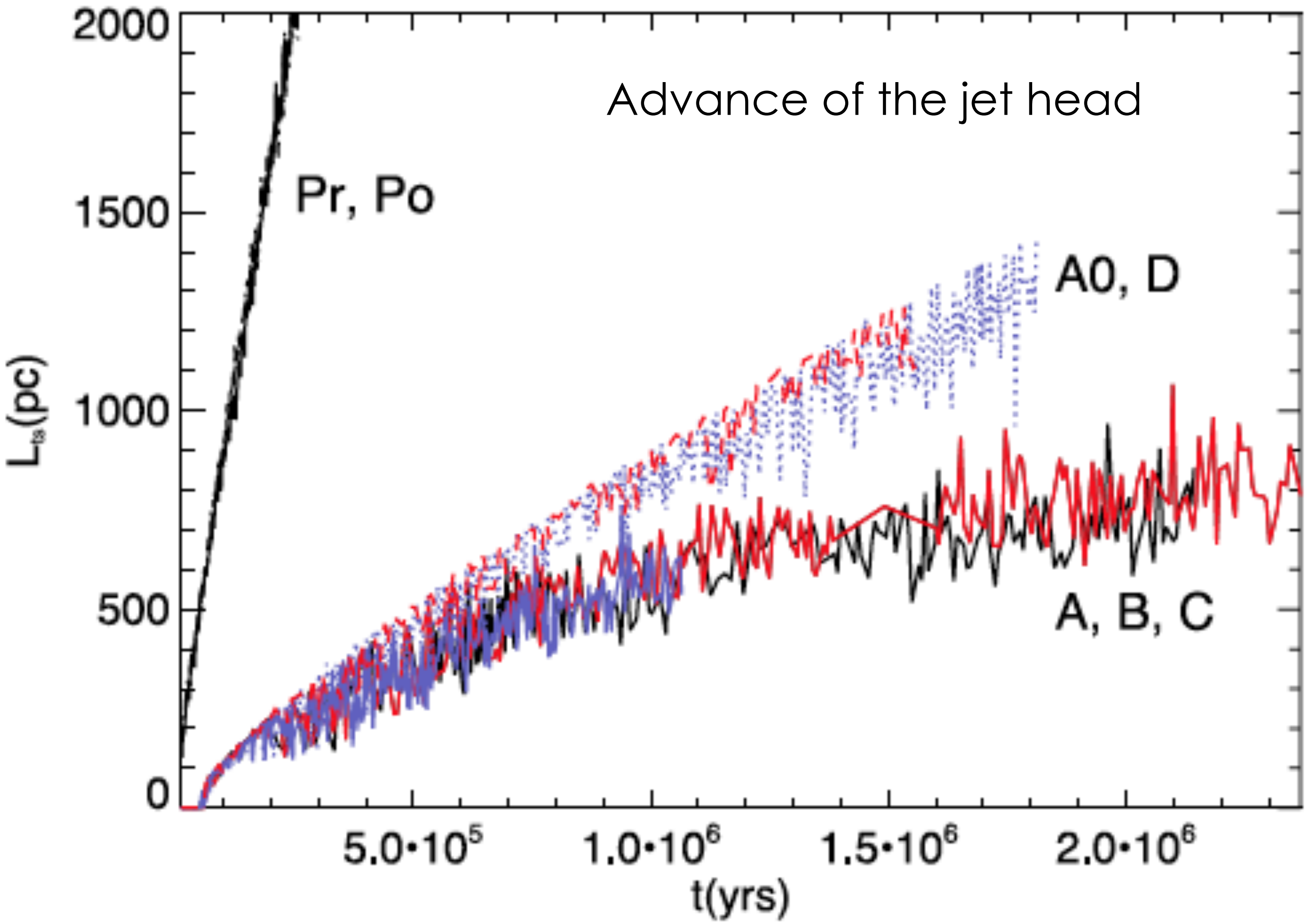
$$l_{\rm d} \simeq \frac{1}{W_{\rm j}}\left(\frac{L_{\rm j}}{10^{44}\,{\rm erg\,s^{-1}}}\right)\left(\frac{q}{10^{22}\,{\rm g\,yr^{-1}pc^{-3}}}\right)^{-1}\left(\frac{R_{\rm j}}{10\,{\rm pc}}\right)^{-2}\,{\rm Mpc}$$

Deceleration distance
(Hubbard & Blackman 2006)

Jet velocity (mass load)

Perucho, Martí, Laing, Hardee 2014

Deceleration: mass load by stellar winds

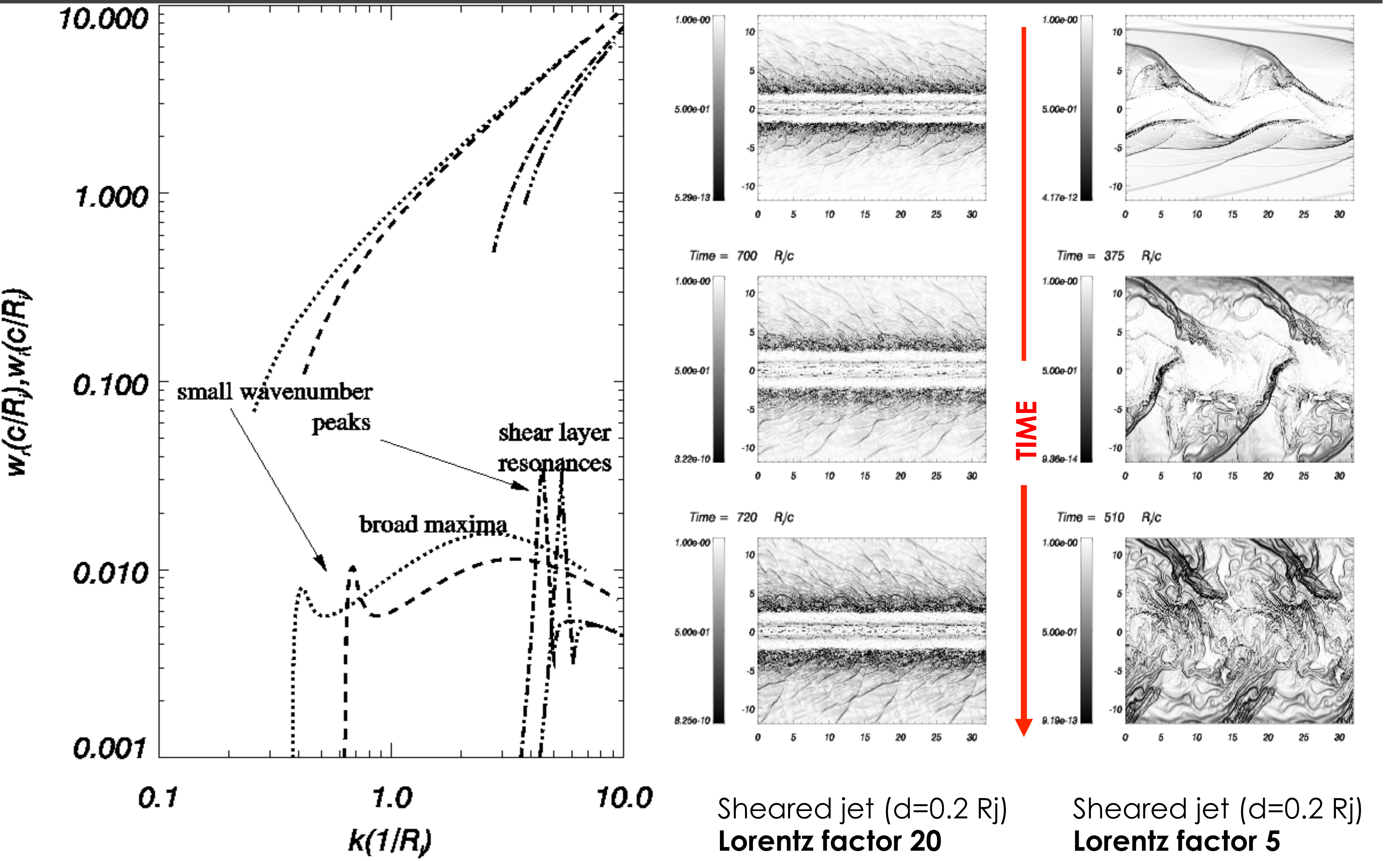


Perucho, Martí, Laing, Hardee 2014

Conclusions

- Jet power and environmental properties (including stellar population) seem to determine the evolution of radio-sources.
- Jet deceleration:
  - Strong recollimation shocks in steep density gradients (not tremendously favoured by the observations).
  - Small scale instabilities in jets with $L_j \sim 10^{43-44}$ erg/s can cause mixing, dissipation, increase of internal energy and subsequent expansion within the expected FRI deceleration scales.
  - Long wavelength instabilities can cause the disruption of powerful jets in the long-term (possibly also the flaring of the inner spine in FRI's?).
  - Mass load by stellar winds and clouds can efficiently decelerate low-power AGN jets with $L_j \sim 10^{41-42}$ erg/s (Seyfert, LLAGN galaxies?), if the stellar population is old with weak stellar winds.

Deceleration: instabilities



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)