The dynamics of turbulent jets

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FRI sources → Turbulent jets, entrainment

Bicknell 1984, 1986; Komissarov 1990; De Young 1993

Numerical simulations → Hypersonic jets

High power **FRII sources**

The jet dumps its energy at its termination, hot spot, cocoon

Lack of resolution, limited dynamic range of simulations, not suited for turbulence

Increase in computational power makes feasible such simulations
Nawaz et al 2014, 2016; Massaglia et al 2016

↓

We started a systematic study of low power turbulent jets

Simulations setup

Non relativistic jet -- At first no magnetic field

Cartesian grid **512x1280x512** grid points

64x120x64 Physical domain in units of the jet radius

Uniform for |x|, |z| < 10 stretched in the outer parts

In the inner region we have 10 points per jet radius

External medium

$$\rho = \frac{\rho_0}{(1 + r/r_c)^{\alpha}}$$

Temperature increases outward

$$r = \sqrt{x^2 + y^2 + z^2}$$ Spherical radius

r_c core radius $= 40\ r_j$ $\alpha = 2$

Non dimensional parameters:

Mach number $M = v_j / c_{sj}$

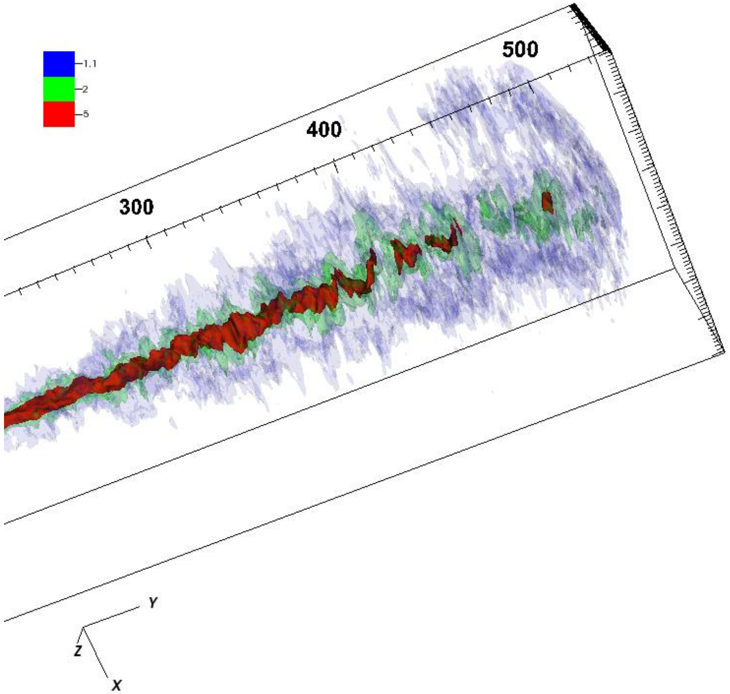
density ratio $\eta = \rho_j / \rho_0$

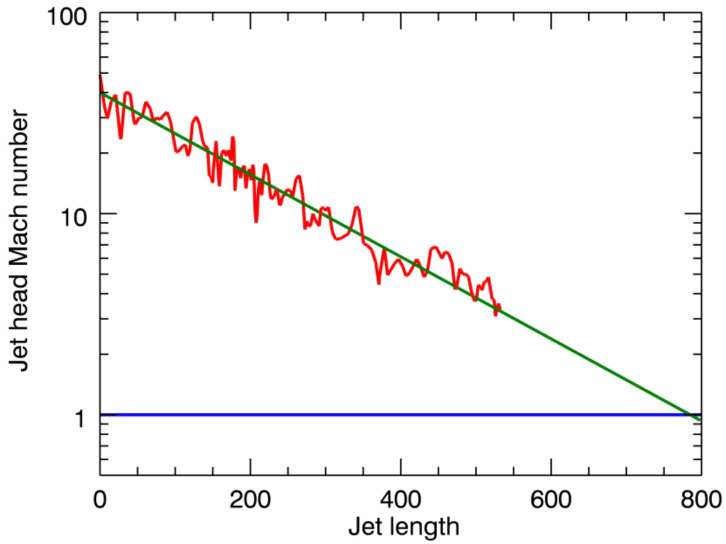
Deceleration to subrelativistic velocities

FRI jets at small scale are relativistic

Our simulations are non relativistic

Our point of injection is after the deceleration to subrelativistic velocities has occurred





Units

We express the jet parameters as functions of the external values

Galactic core radius r_c = 4 kpc

$$\rho_j = 0.01 \left(\frac{\eta}{0.01}\right) \left(\frac{\rho_c}{1\ \mathrm{cm}^{-3}}\right) \mathrm{cm}^{-3}$$

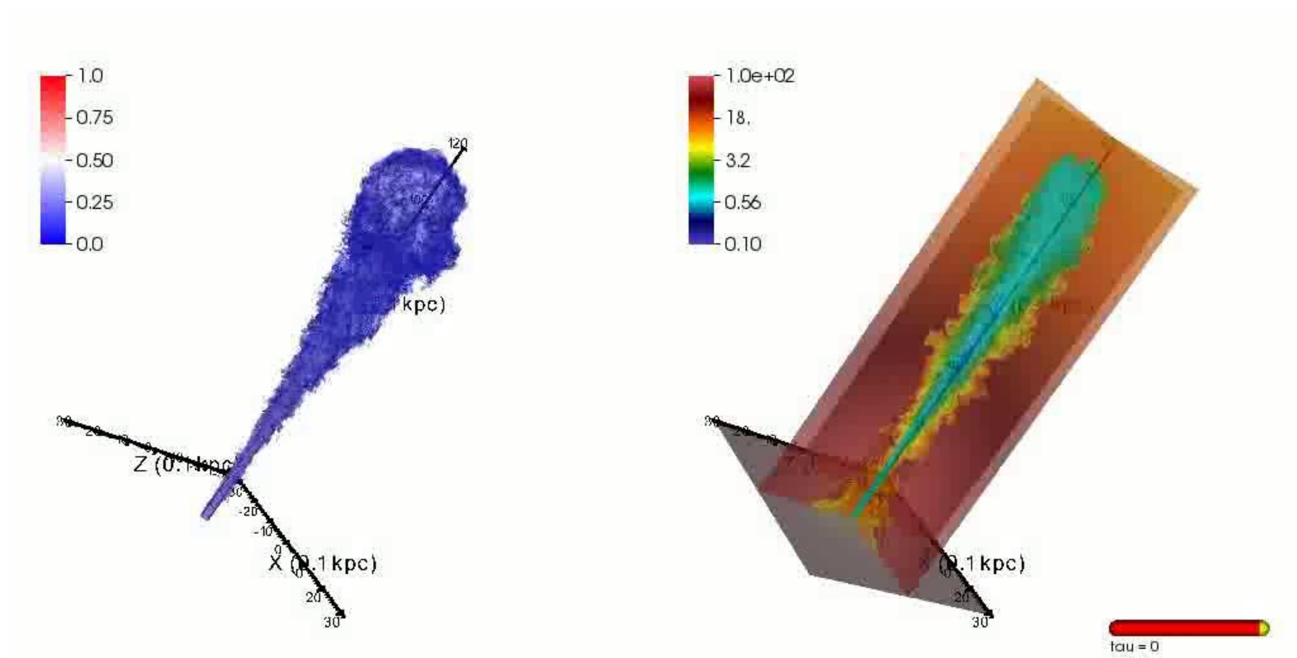
$$v_j = 5.1 \times 10^8 M \left(\frac{T_c}{0.2\ \mathrm{keV}}\right)^{1/2} \left(\frac{\eta}{0.01}\right)^{-1/2} \left(\frac{P_j}{P_c}\right)^{1/2} \mathrm{cm\ s}^{-1}.$$

$$\mathcal{L}_{\mathrm{kin}} = 1.1 \times 10^{42} \left(\frac{r_j}{100\ \mathrm{pc}}\right)^2 \left(\frac{\rho_c}{1\ \mathrm{cm}^{-3}}\right) \left(\frac{T_c}{0.2\ \mathrm{keV}}\right)^{3/2} \times \left(\frac{M}{4}\right)^3 \left(\frac{\eta}{0.01}\right)^{-1/2} \left(\frac{P_j}{P_c}\right)^{3/2} \mathrm{erg\ s}^{-1}.$$

$$\tau = \frac{r_j}{c_{sj}} = 7.7 \times 10^4 \left(\frac{r_j}{100\ \mathrm{pc}}\right) \left(\frac{T_c}{0.2\ \mathrm{keV}}\right)^{-1/2} \times \left(\frac{\eta}{0.01}\right)^{1/2} \left(\frac{P_j}{P_c}\right)^{-1/2} \mathrm{yr}.$$

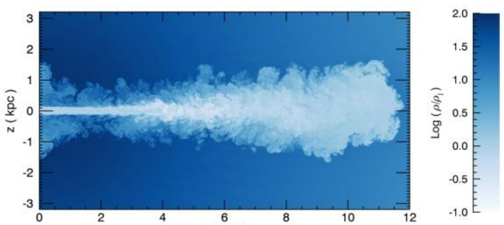
Our simulations cover a time interval of about 100-1000 time units corresponding to 10^7 - 10^8 years

M=4 $\eta = 0.01$ **L_j = 1.1 x 10^{42} erg/s**



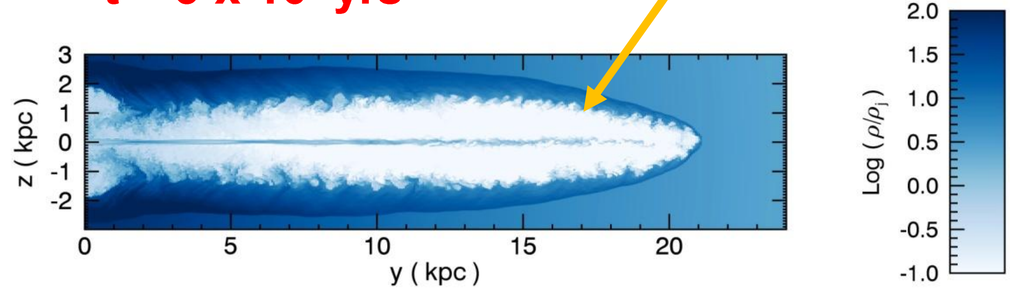
Animation at https://www.dropbox.com/s/zrqcf8htsjrhfqm/HD.mp4?dl=0

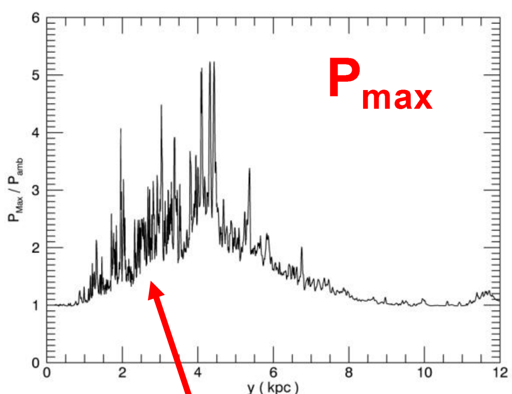
$L_j = 1.1 \times 10^{42}$ erg/s
M=4 η=0.01
$t = 5 \times 10^7$ yrs

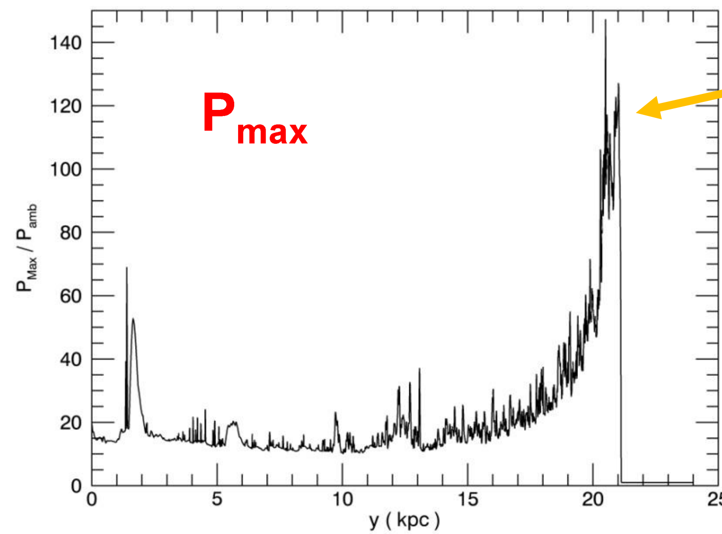


$L_j = 1.1 \times 10^{44}$ erg/s
M=40 η=0.01
$t = 3 \times 10^6$ yrs

Cocoon

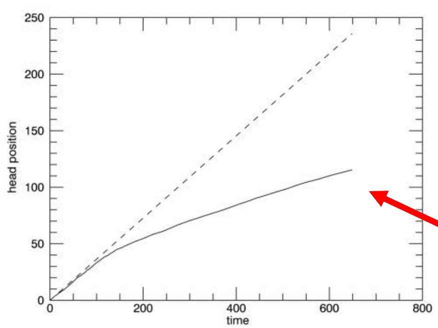






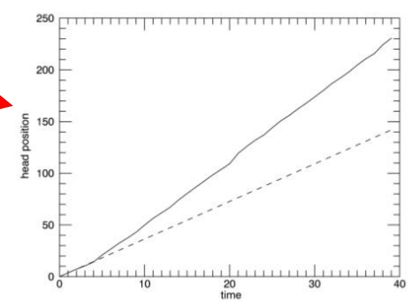
Mach disk
Hot Spot

Transition to turbulence



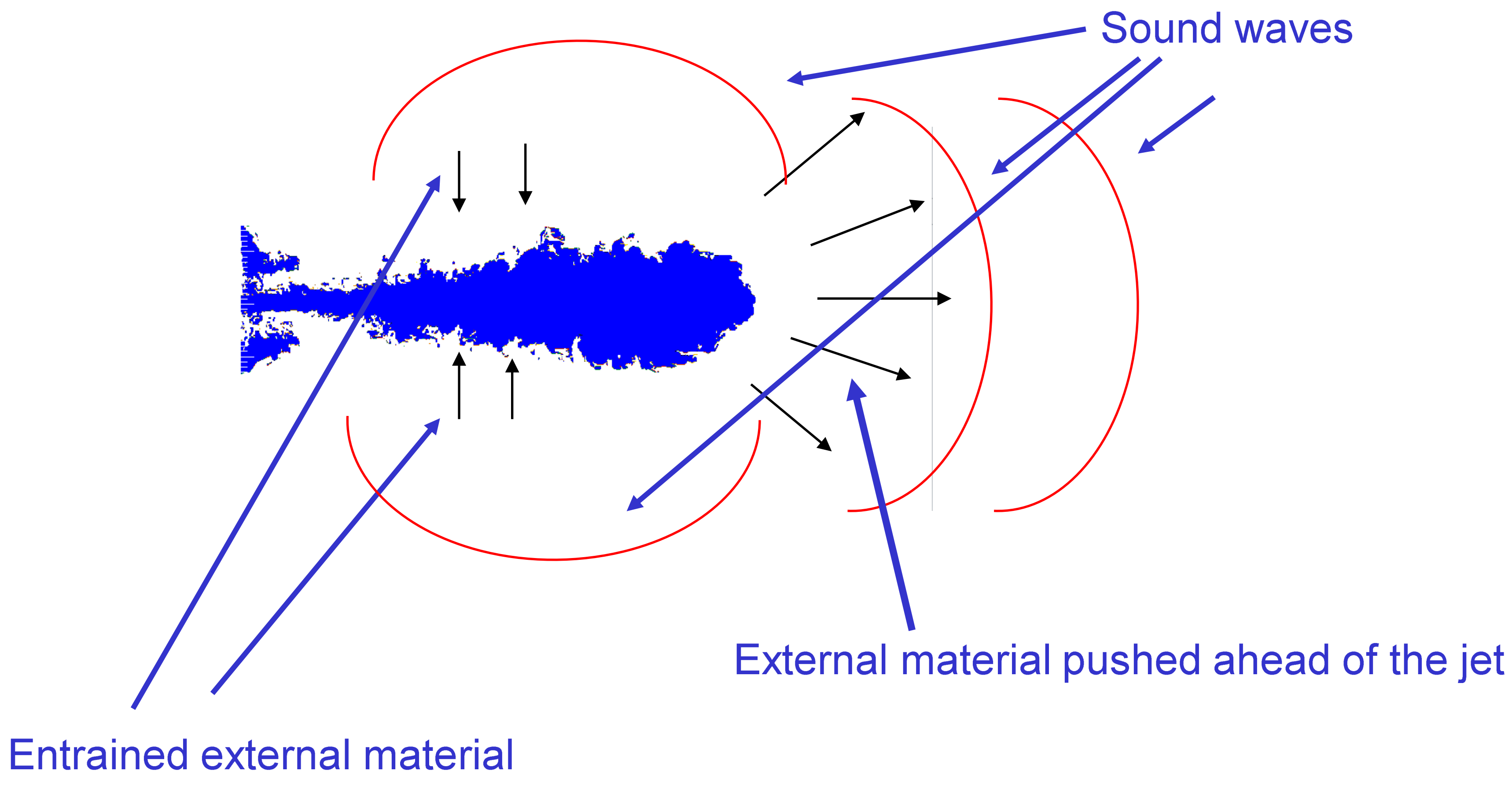
Jet head position

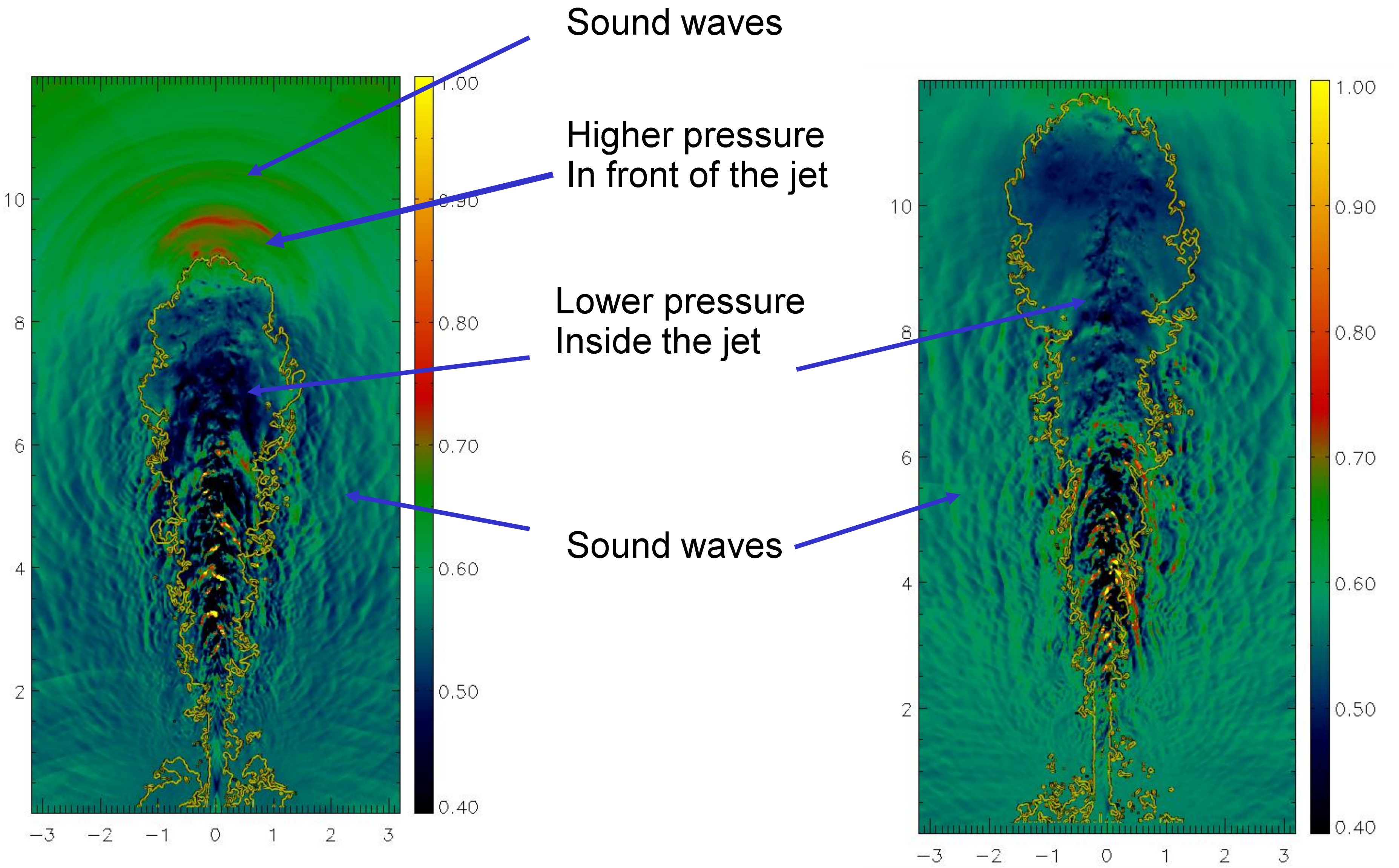
$V_h \sim 500$ km/s



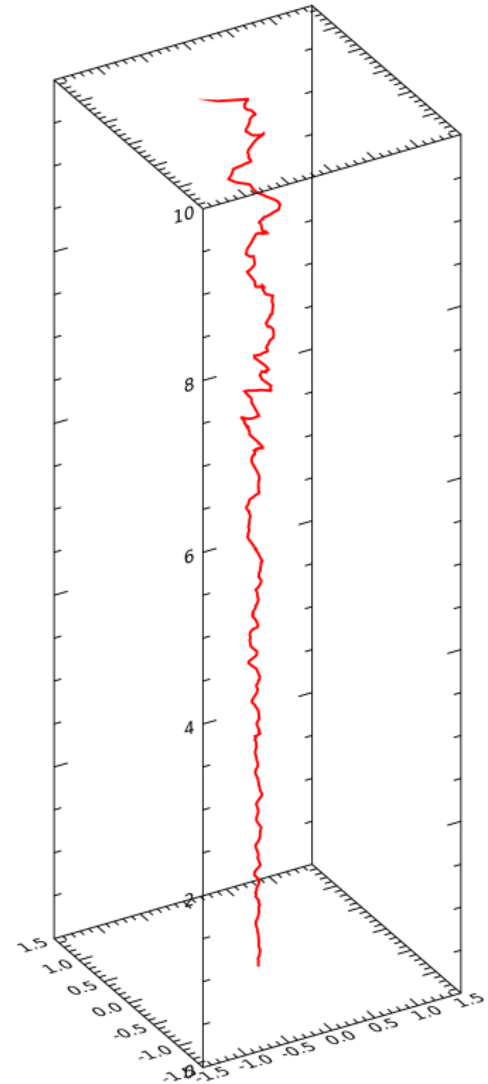
Jet effects on the ambient medium

The jet advances and expands at subsonic velocities
The external region that feels the presence of the jet is larger ~ c_s t



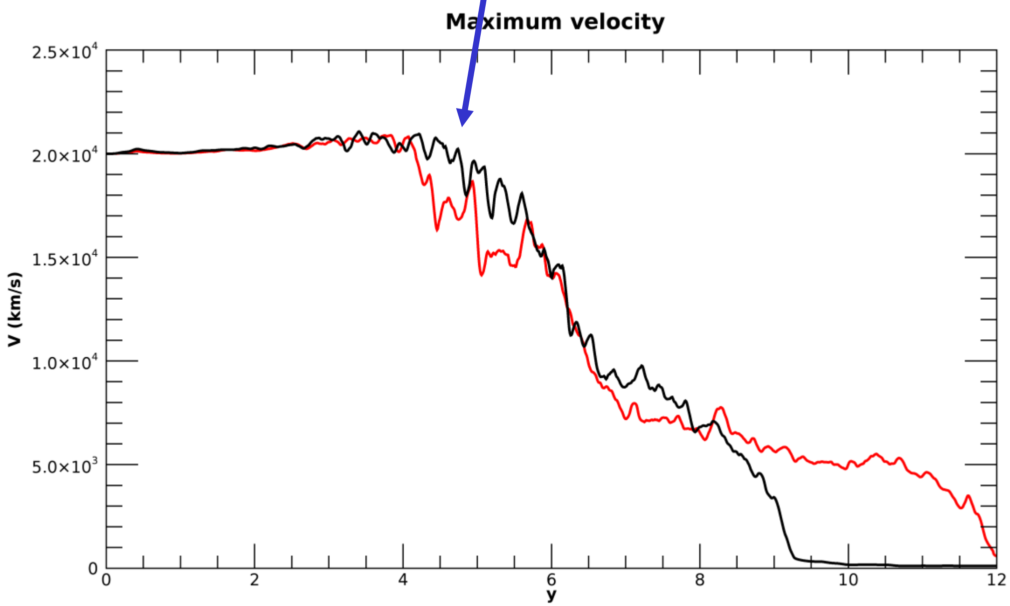

Sound waves
Higher pressure
In front of the jet
Lower pressure
Inside the jet
Sound waves
10
8
6
4
2
−3
−2
−1
0
1
2
3
1.00
0.90
0.80
0.70
0.60
0.50
0.40

Jet axis



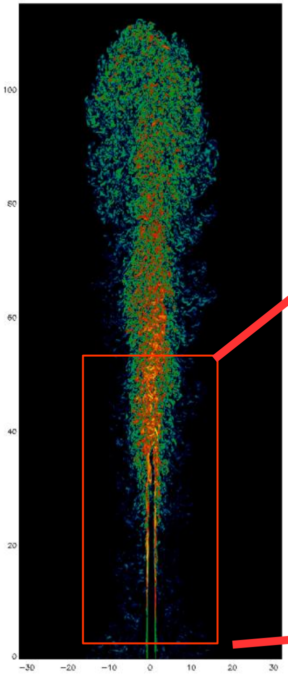
Transition to turbulence

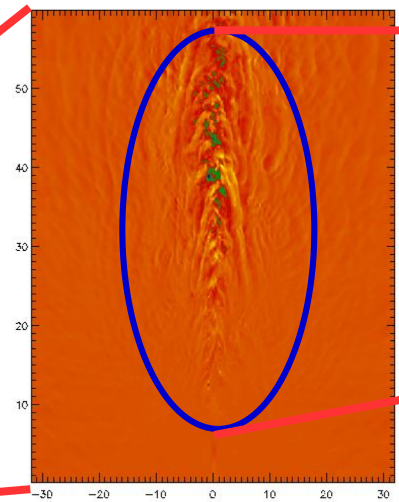
Jet deceleration



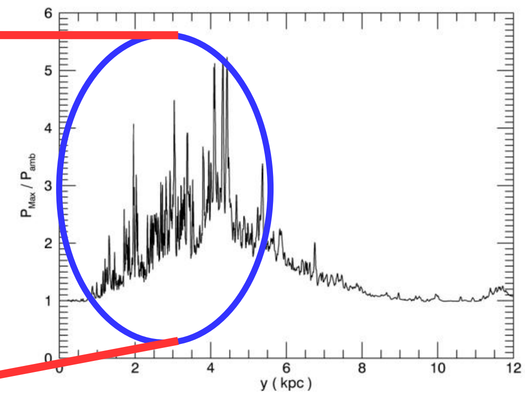
Transition to turbulence

Vorticity

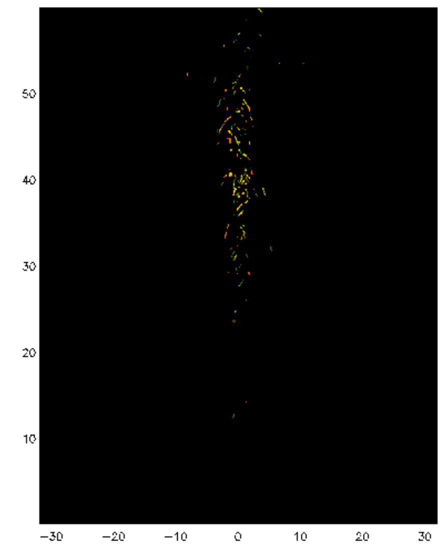




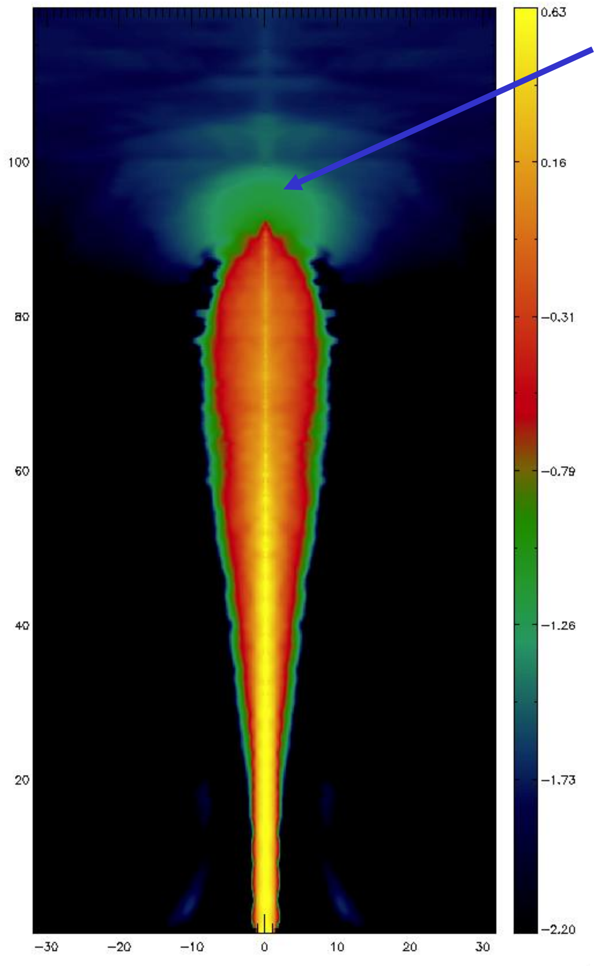
Pressure



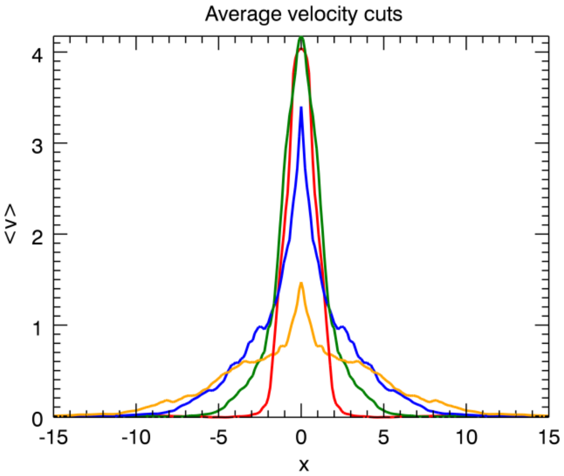
Dissipation through weak shocks



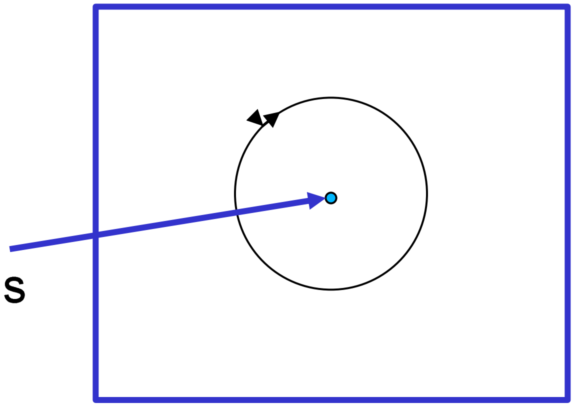
The mean flow



External material displaced in front of the jet

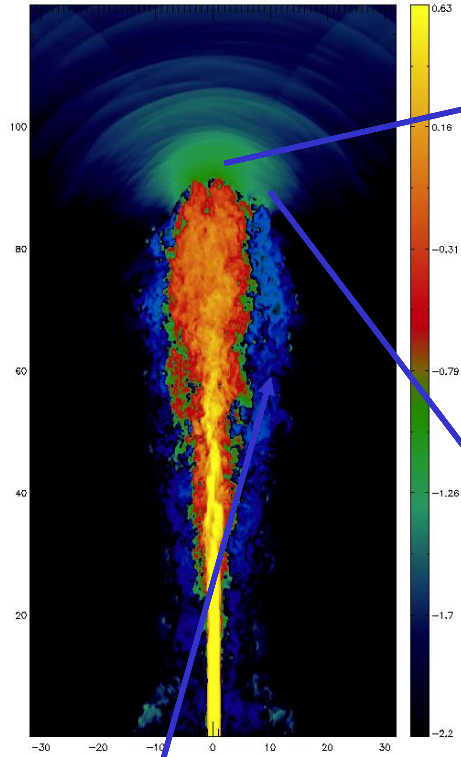


Mean quantities are obtained by averaging over the azimuthal direction

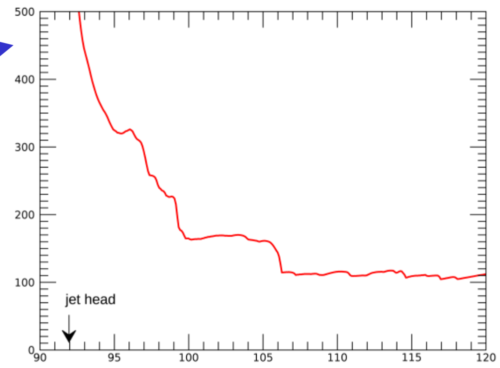


jet axis

Transverse cut of the computational domain

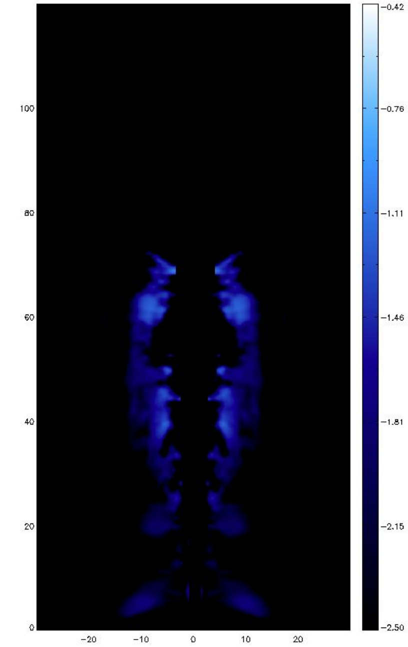


Longitudinal velocity

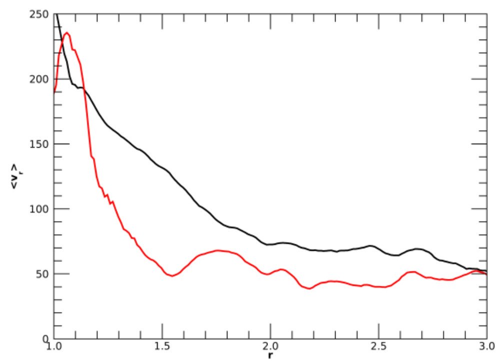


V_y (y) along the axis

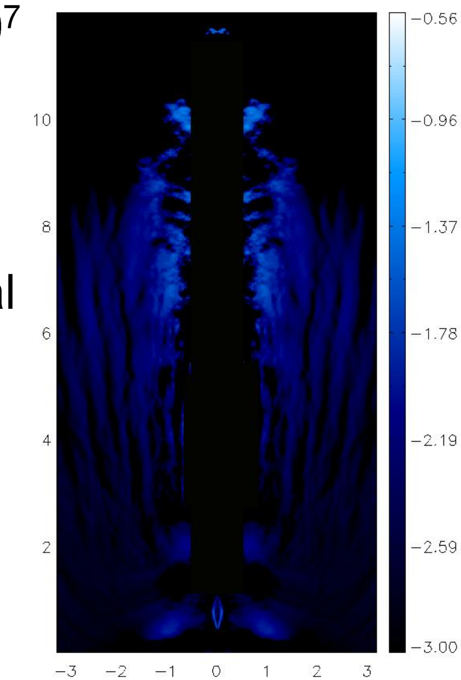
$t=3.5\times10^7$ yrs



Radial velocity



$t=5.2\times10^7$ yrs



Backflow
(mainly external material)
weakens with time

Negative radial velocity

entrainment

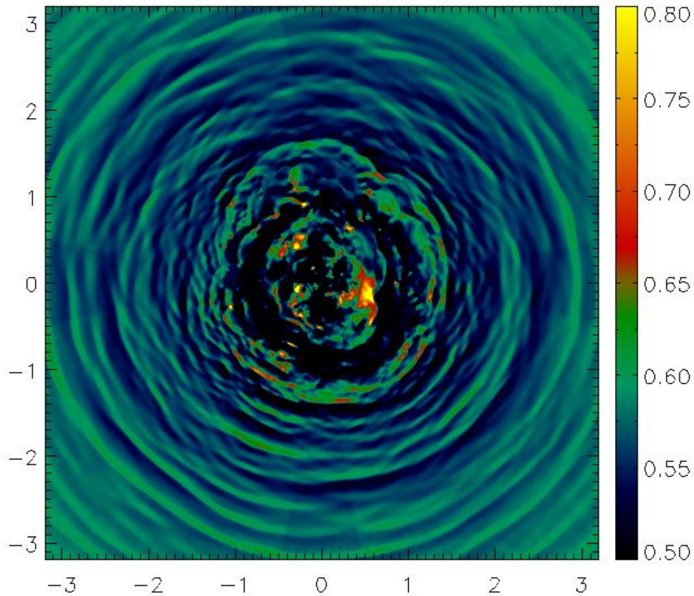
from
200-300 km/s
to few km/s

At the end of the simulation we see that
the mass in the jet region is a small fraction
of the mass that was present at the beginning
All the mass has been displaced.

Sound waves

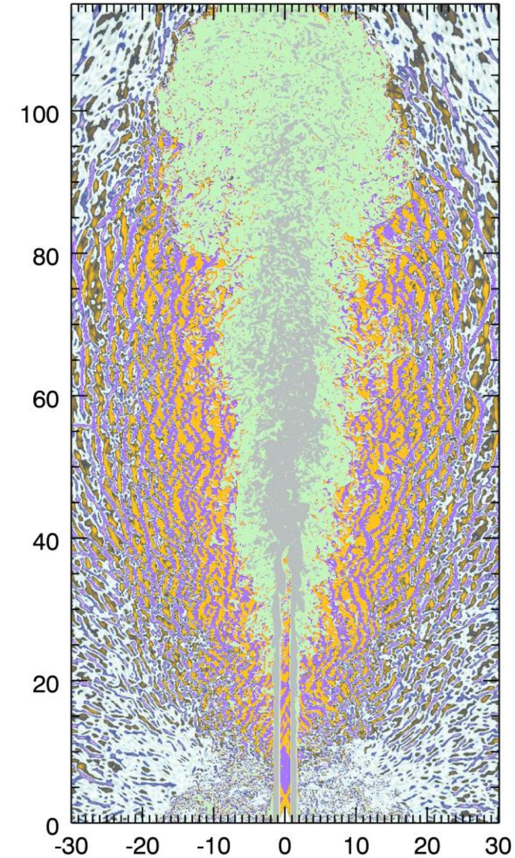
Pressure

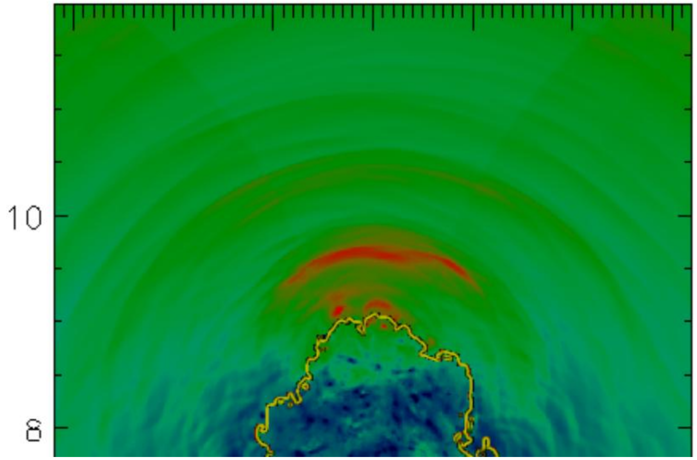
t=3.5x10^{7} yrs

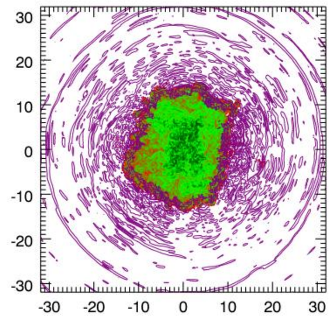


t=5.2x10^{7} yrs

Vorticity (green) and Divergence of velocity field

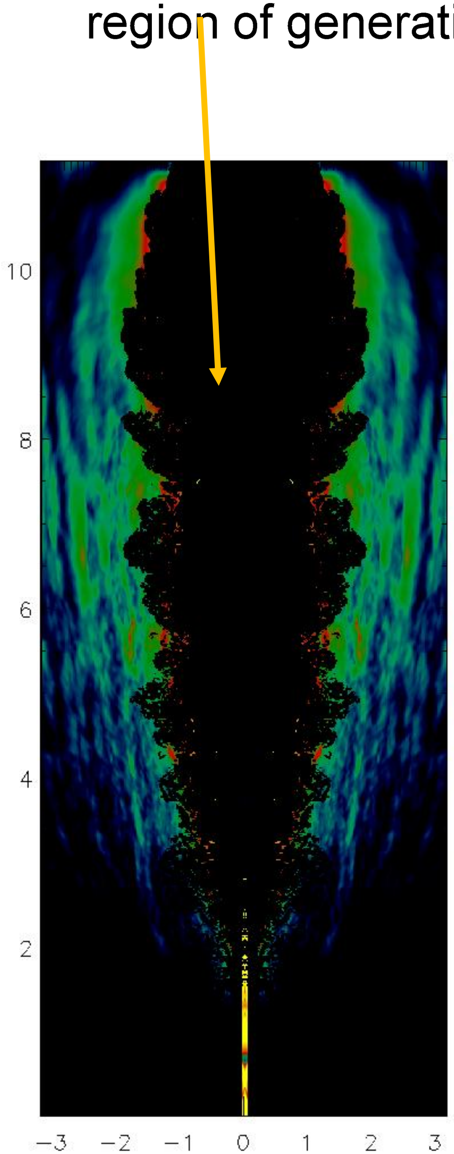






Generation of sound waves by turbulence and turbulent jets
Lightill 1952
Tam and Burton 1984
(eddies moving at supersonic velocities)
Chagelishvili et al. 1997
(conversion of vortices in waves
In shear flows)

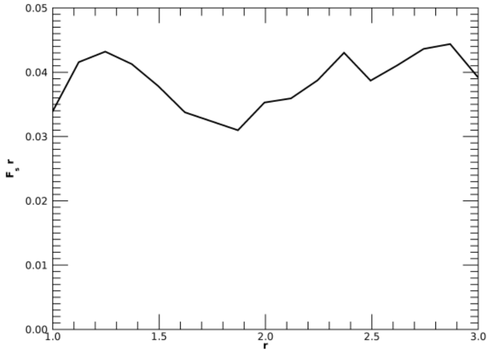
We cut out the region of generation



Sound energy flux

$$F_s = \rho c_s^3 \left\langle \left(\frac{\delta p}{p} \right)^2 \right\rangle$$

Integrating over a cylinder around the jet we get and efficiency of about 30%



The MHD case

Similar setup, but we inject with the jet a toroidal field

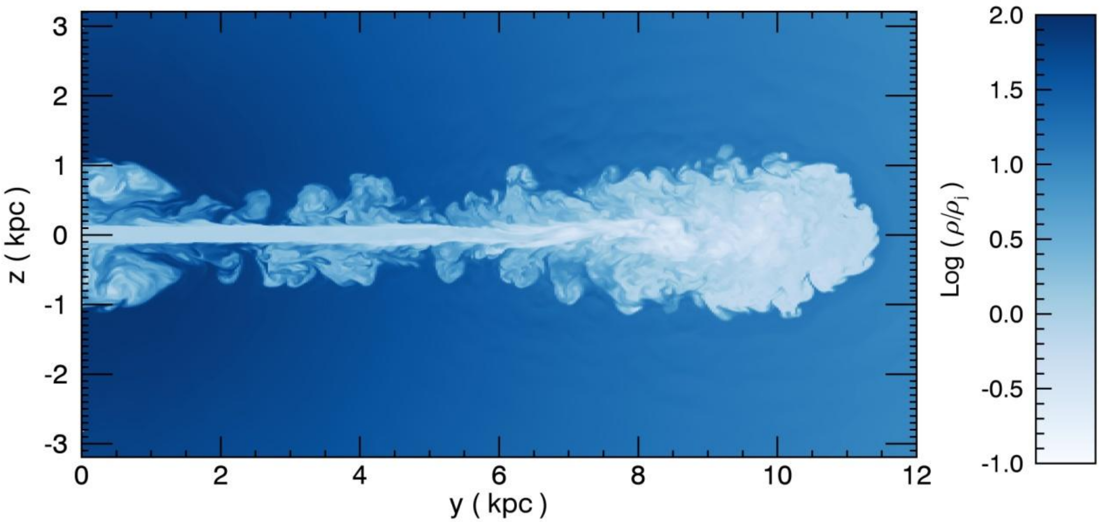
Additional parameter: β is the ratio of gas pressure to magnetic pressure

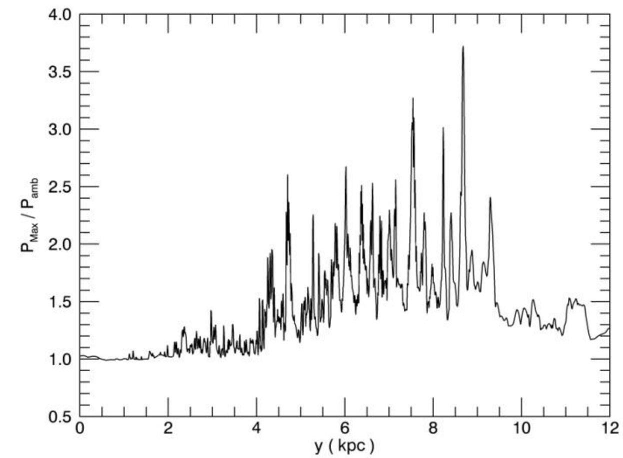
We consider values of β larger than unity.

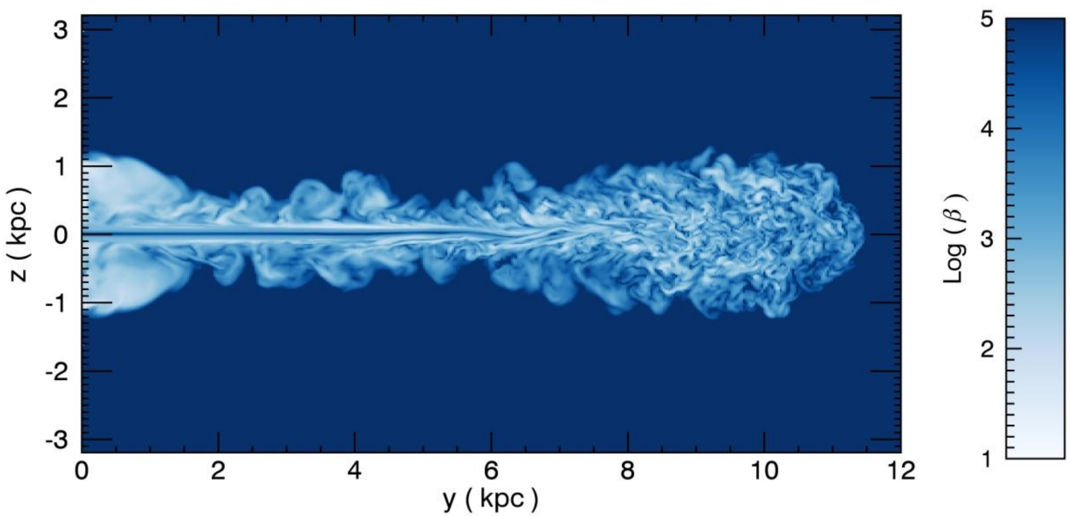
Poynting flux negligible with respect to the kinetic energy flux

We will discuss two cases: $\beta = 100$ and $\beta = 3$

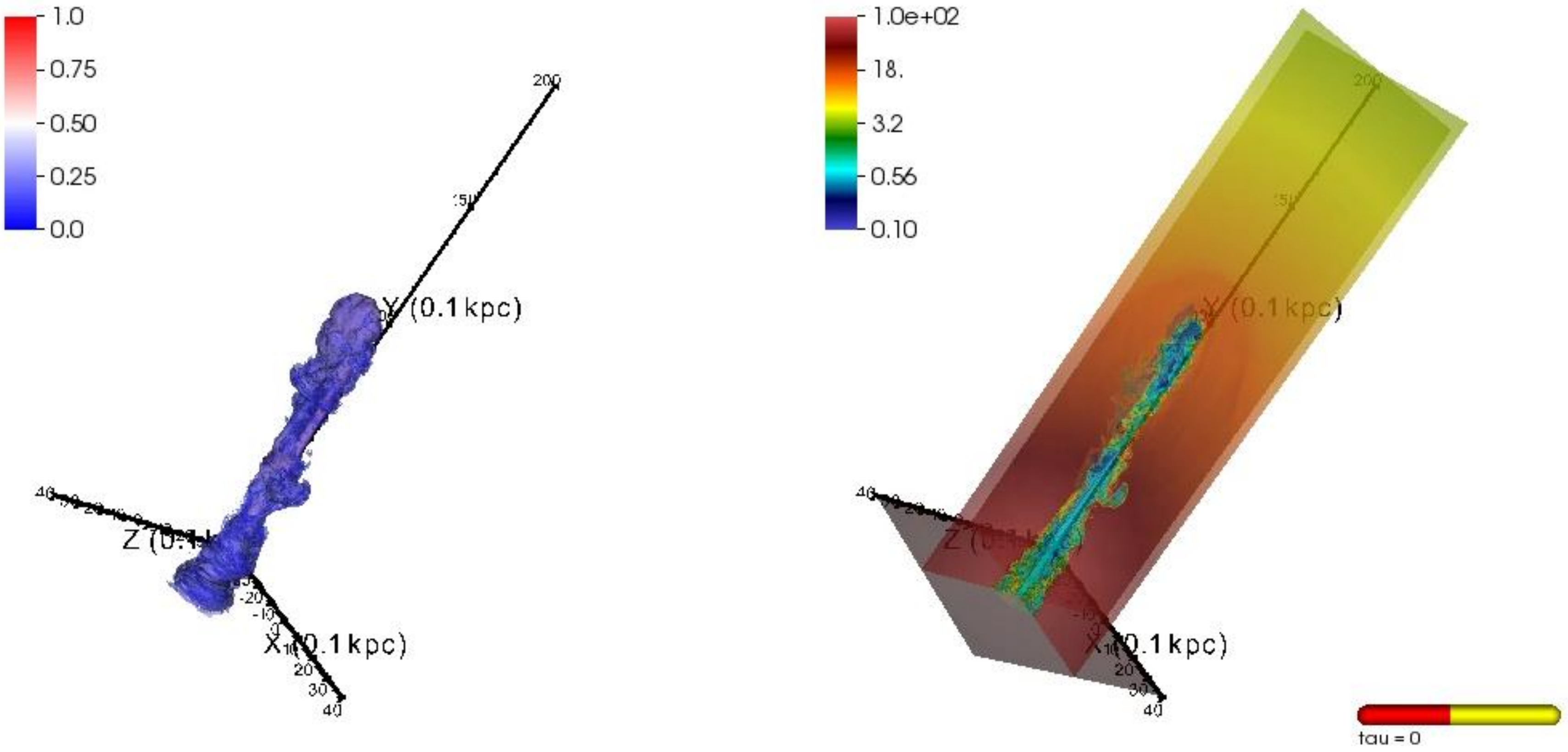
$M=4 \quad \eta=10^{-2} \quad \beta = 100 \quad L_j = 1.1 \times 10^{42}$



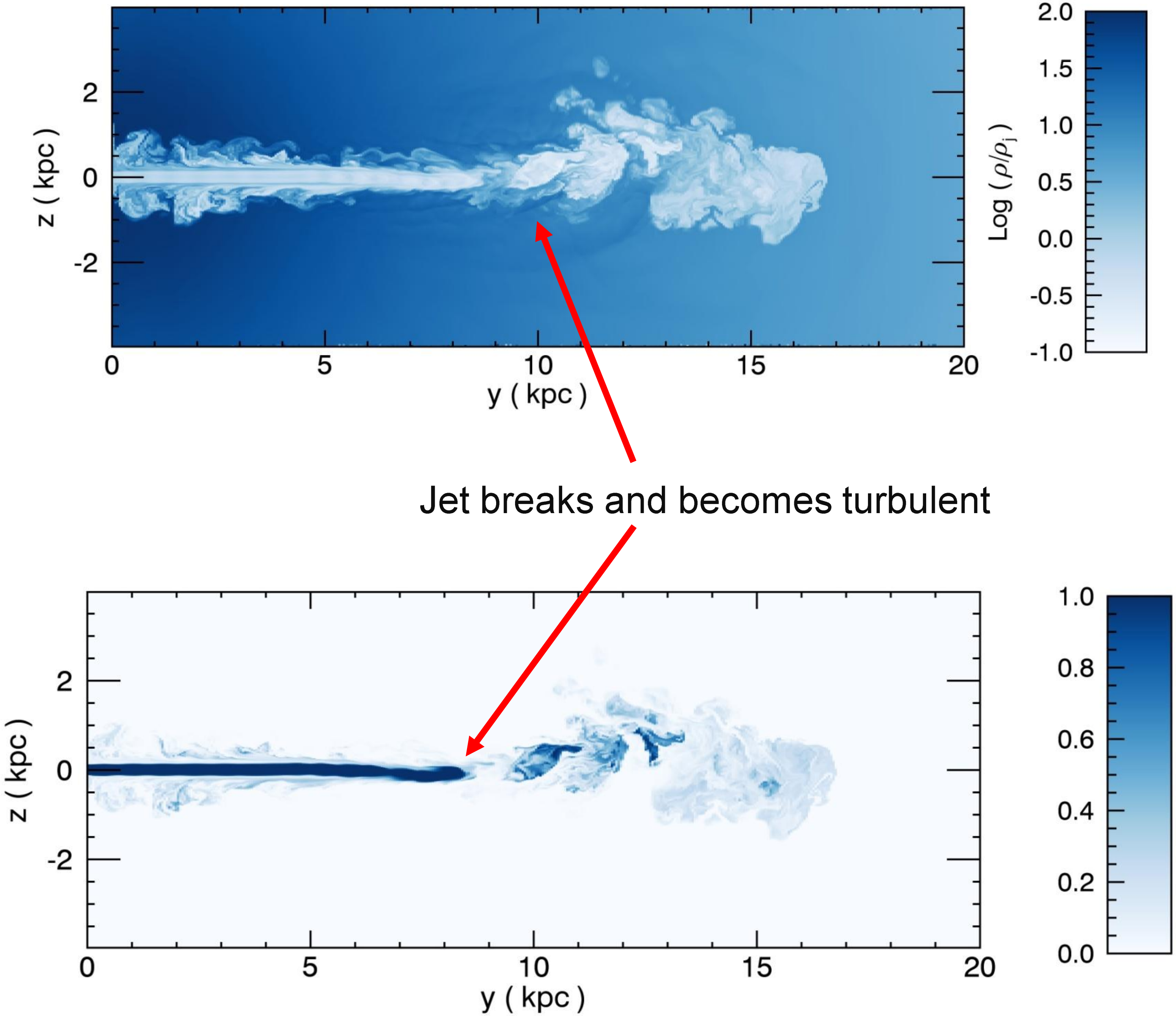




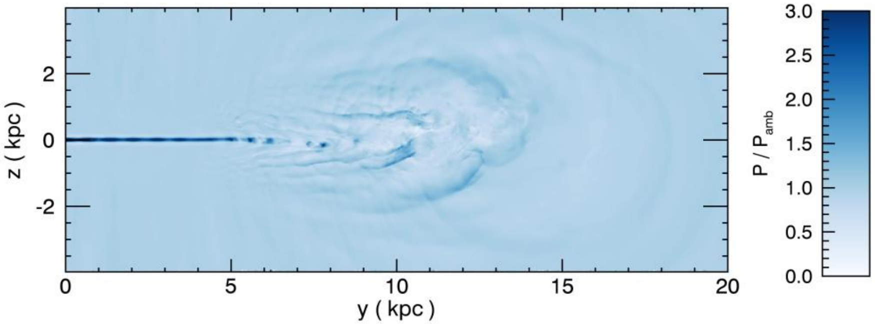
$M=4$ $\eta=10^{-2}$ $\beta = 3$ $L_j = 1.1 \times 10^{42}$



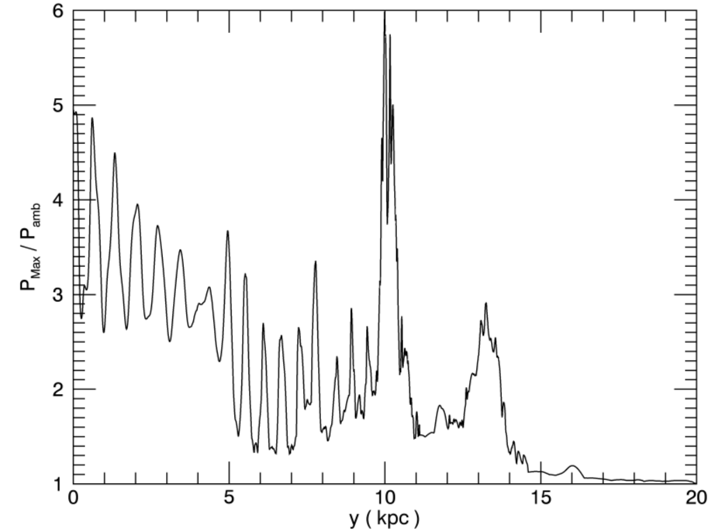
Animation at **https://www.dropbox.com/s/j72em5szy3paryz/MHD.mp4?dl=0**



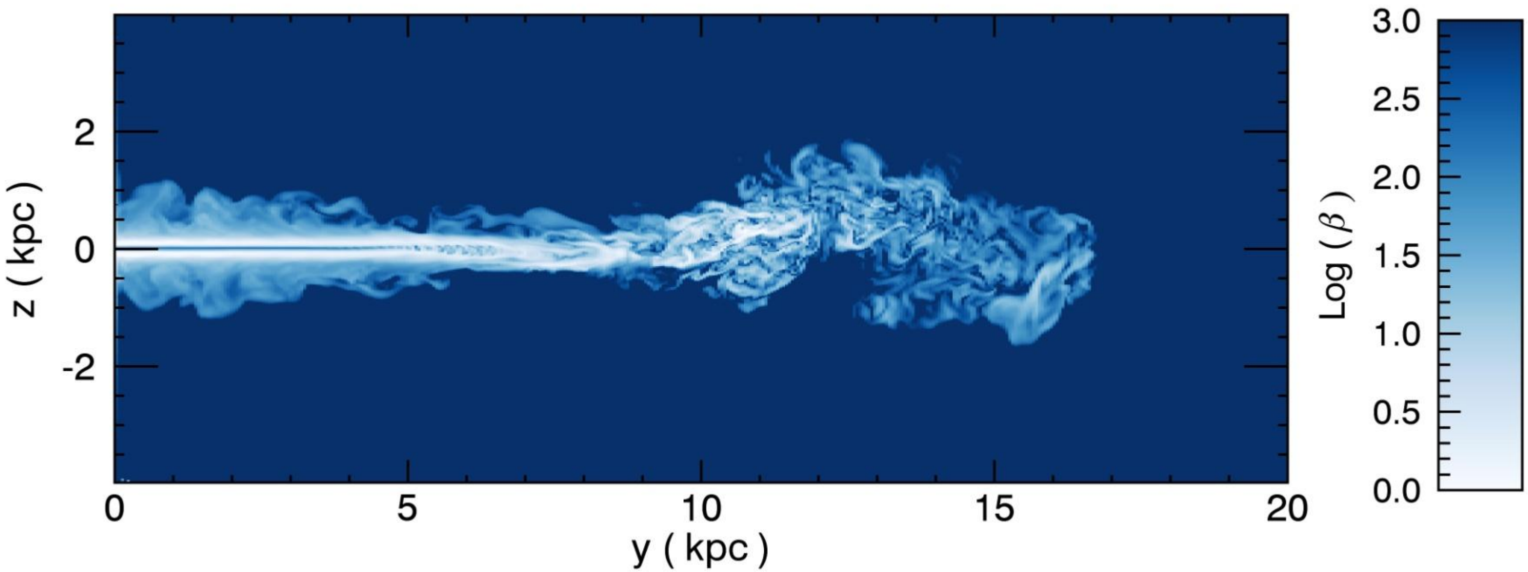
z (kpc)
y (kpc)
Log (ρ/ρ_j)
Jet breaks and becomes turbulent
z (kpc)
y (kpc)



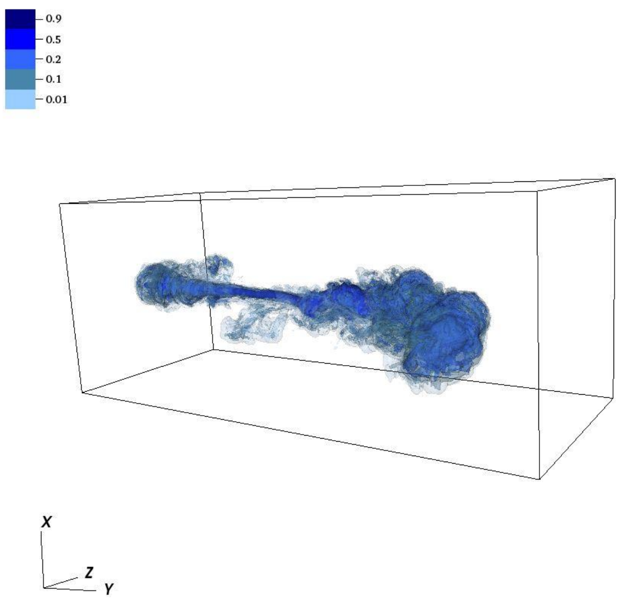
z (kpc)
y (kpc)
P / P_{amb}

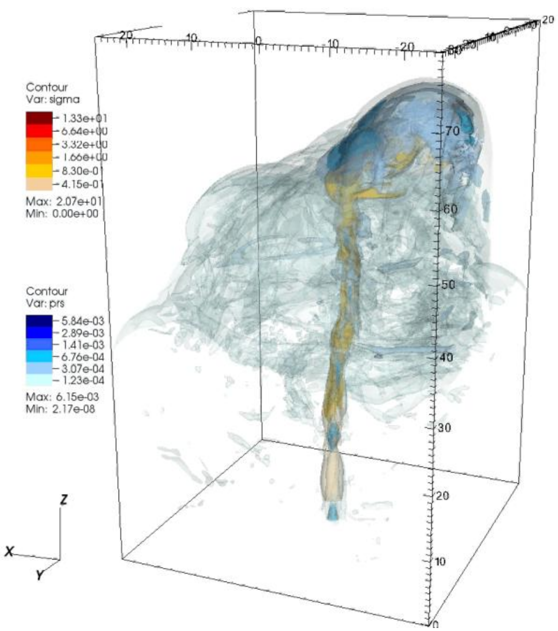


P_{Max} / P_{amb}
y (kpc)



z (kpc)
y (kpc)
Log (β)





In the MHD case different kind of instabilities lead to the transition to turbulence.

Current driven instabilities

We got similar jet wiggling in Mignone et al. 2010 for a high power relativistic jet, in that case the jet was not disrupted.

Conclusions

We have examined how turbulent jets may induce motions and transfer energy to the ambient medium

In particular generation of sound waves

Somewhat different behaviour for the MHD case: effect of current driven kink instabilities