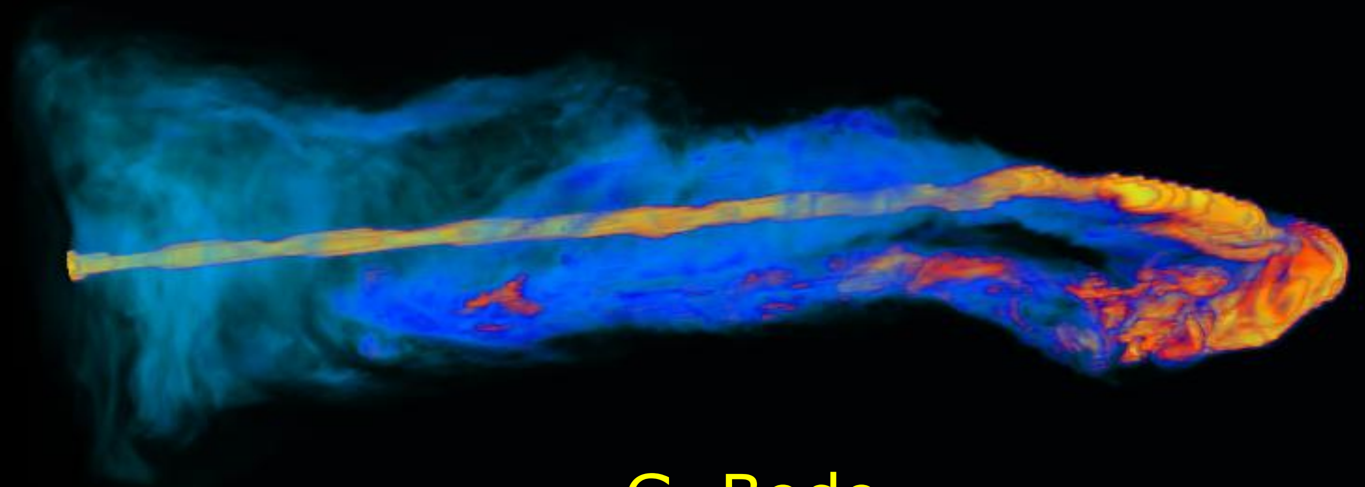
Instabilities of relativistic jets



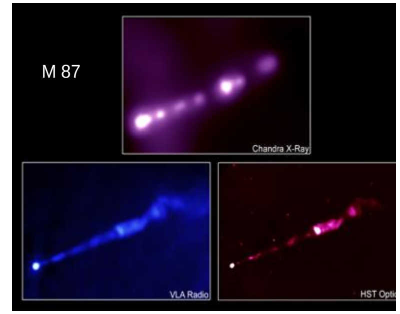
G. Bodo
INAF Osservatorio Astrofisico di Torino, Italy

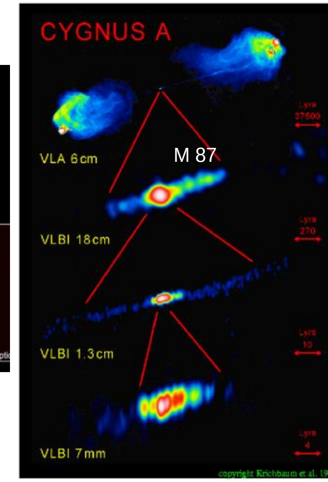
A. Mignone, P. Rossi, G. Mamatsashvili, S. Massaglia, A. Ferrari

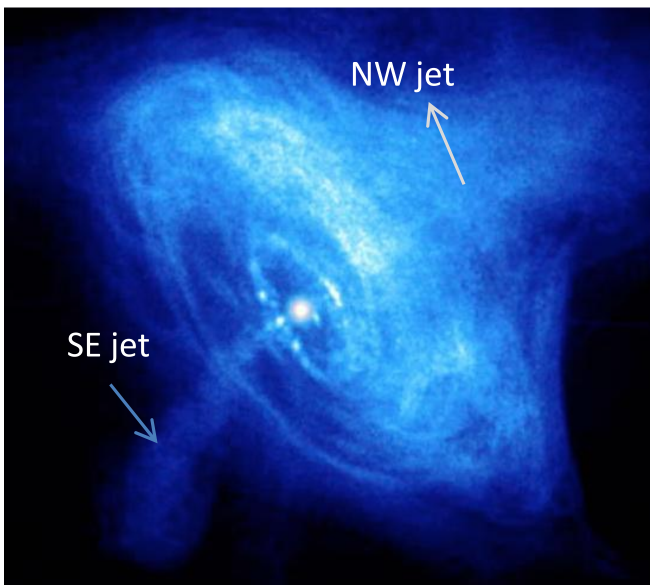
Universality of relativistic jet phenomenon

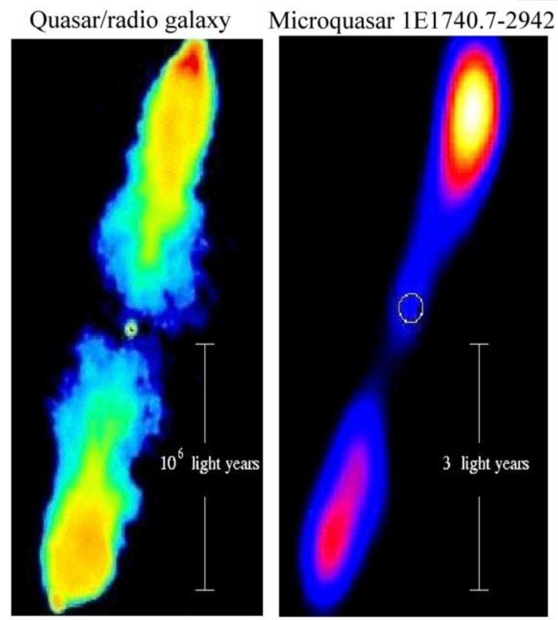
High energy sources

- AGN
- Microquasars
- GRB
- Pulsar wind nebulae









Similar physical processes may operate in all these objects

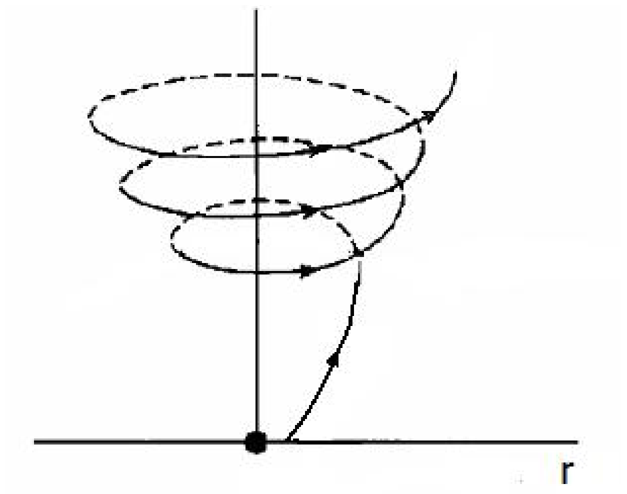
HOW JETS ARE ACCELERATED ?

Compact object + accretion disc

Current models for the jet acceleration are related to the interplay of magnetic field and rotation.

The flow starts as Poynting dominated->matter dominated at large distances

$$\sigma = \frac{B^2}{4\pi\gamma^2 c^2}$$



Blandford&Payne 1982

Twisted magnetic field

Velocity shear

Rotating jets

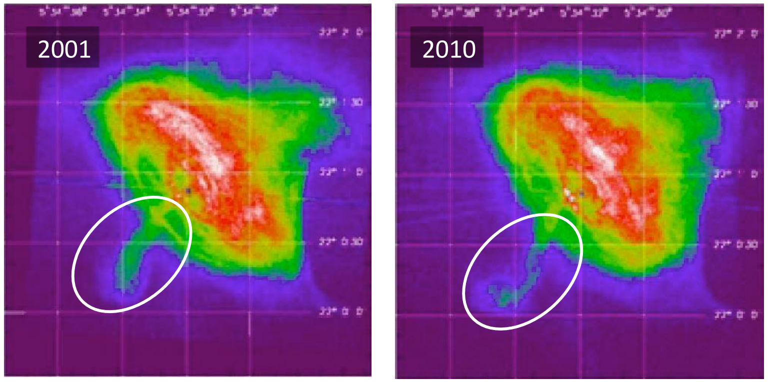
Instabilities

WHAT INSTABILITIES DO?

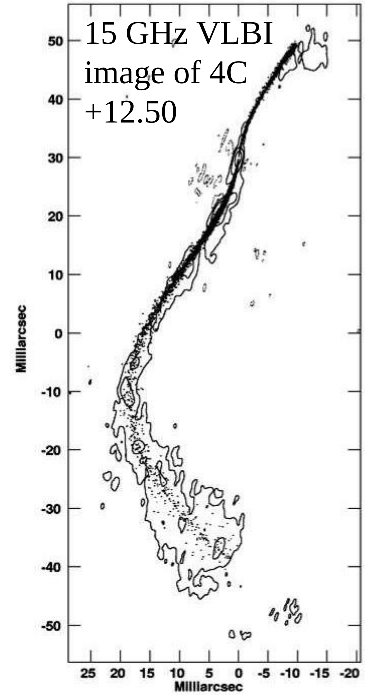
- Instabilities → dissipation → radiation
- Instabilities → morphologies
- Instabilities → momentum transfer, jet deceleration formation of velocity structures
- Instabilities → jet disruption

WHAT OBSERVATIONS TELL US ?

Morphological features in jets: knots, wiggling.

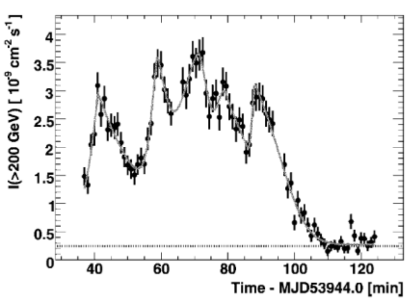


Crab Nebula



Ultra fast TeV variability in Blazars
Emitter compact and very large Lorentz factors
Very compact dissipation region

PKS2155-304 (Aharonian et al. 2007)
See also Mrk501, PKS1222+21



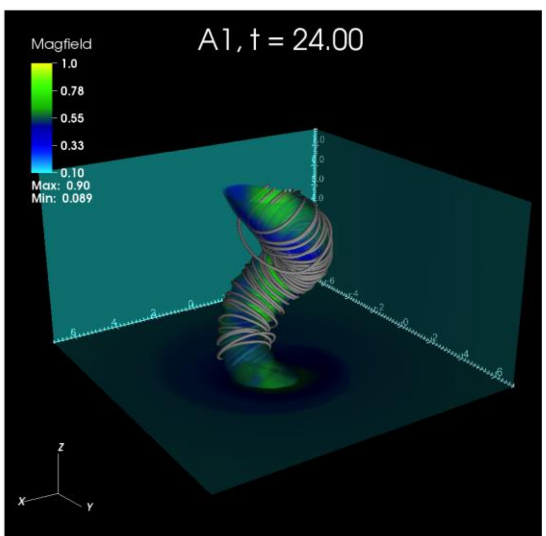
Velocity structure in jets
Fast spine surrounded by a slower layer

HOW DO WE STUDY INSTABILITIES?

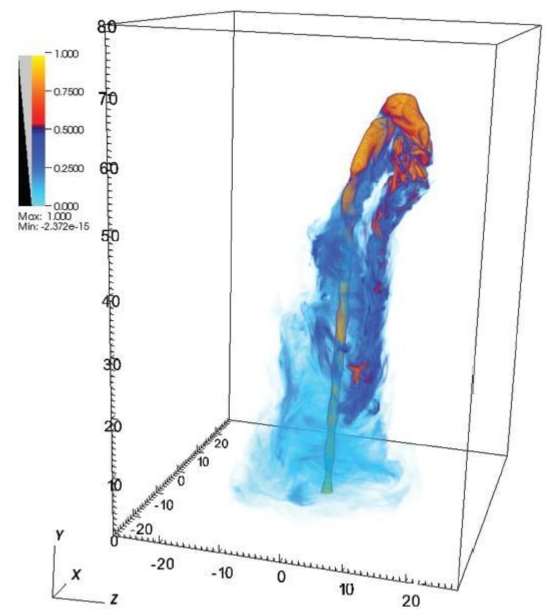
Linear analysis → What are the dominant modes of instabilities?
What are the driving forces?

Only valid when perturbations are small → NUMERICAL SIMULATIONS

LOCAL MODELS (small section of the jet)



GLOBAL MODELS (full jet propagation)



LINEAR ANALYSIS

EQUILIBRIUM

$$\rho\gamma^2 v_\phi^2 = \frac{1}{2r}\frac{d(r^2H^2)}{dr} + \frac{r}{2}\frac{dB_z^2}{dr},$$

Cold case
No pressure

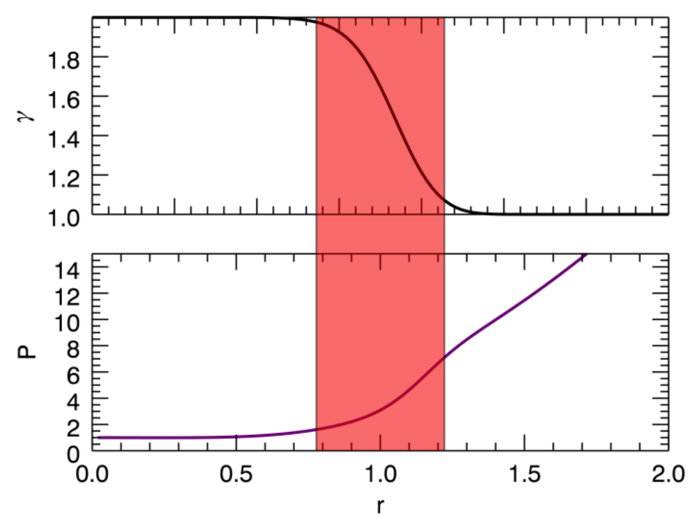
$$H^2 = B_\phi^2 - E_r^2$$

We consider a case where the current is concentrated inside the jet
return current very far from the jet

PARAMETERS

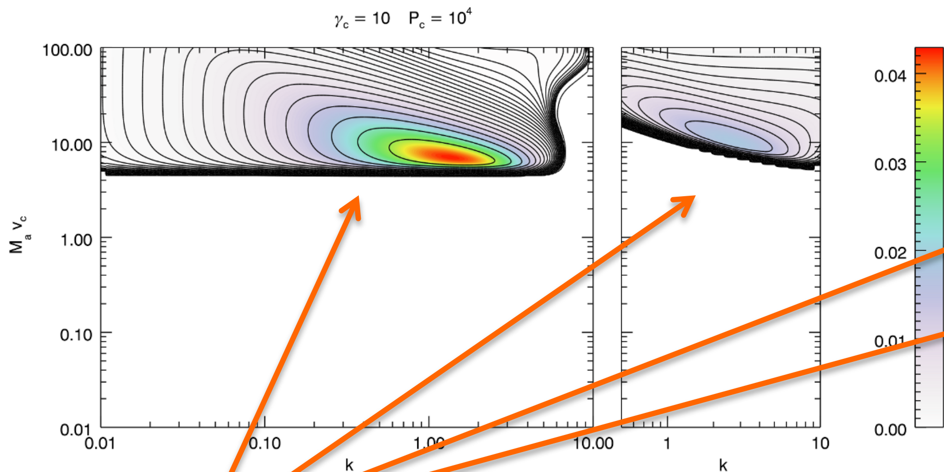
$$\sigma = \frac{B^2}{4\pi\gamma^2 c^2}$$ magnetization

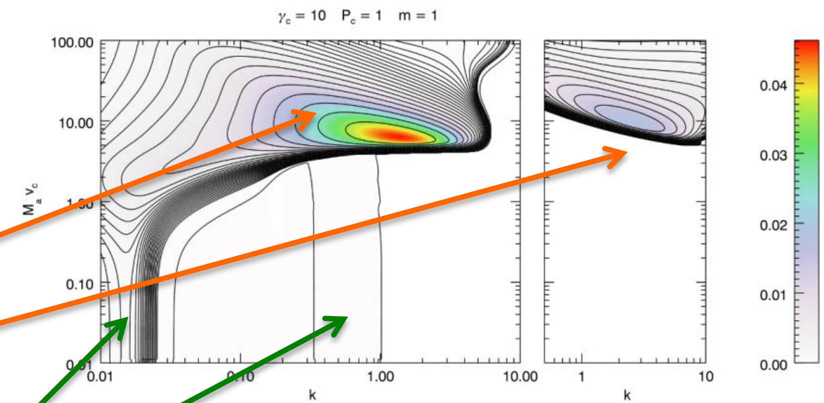
$$P = \frac{rB_z}{B_\phi}$$ Pitch



Bodo et al. 2013

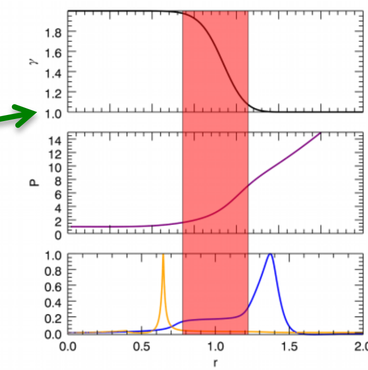
LINEAR ANALYSIS RESULTS





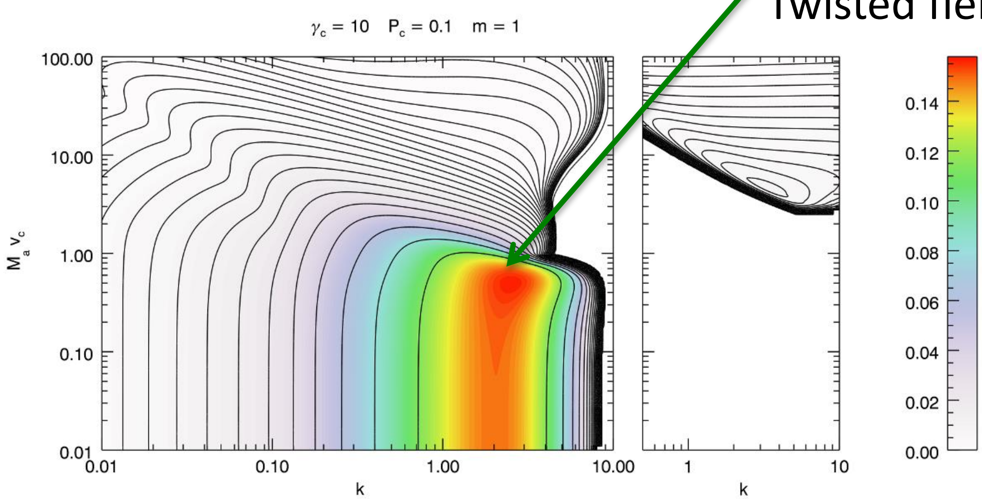
Kelvin Helmholtz
Velocity shear

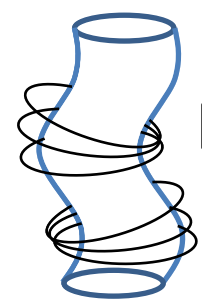
Current driven



$k\,P(r) = 1$

Twisted field

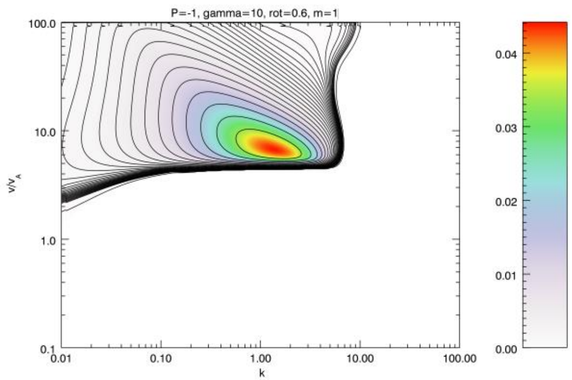


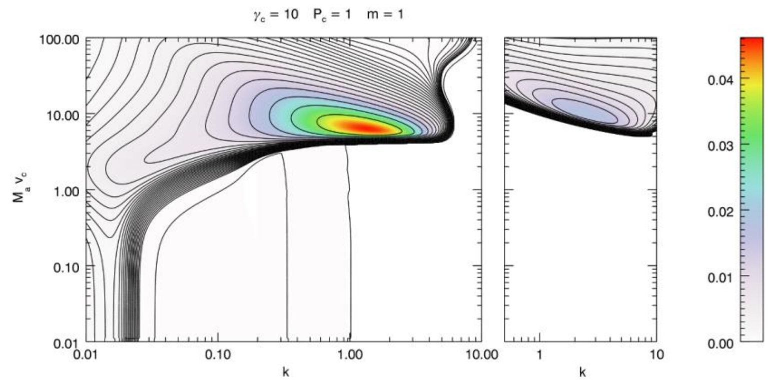


B

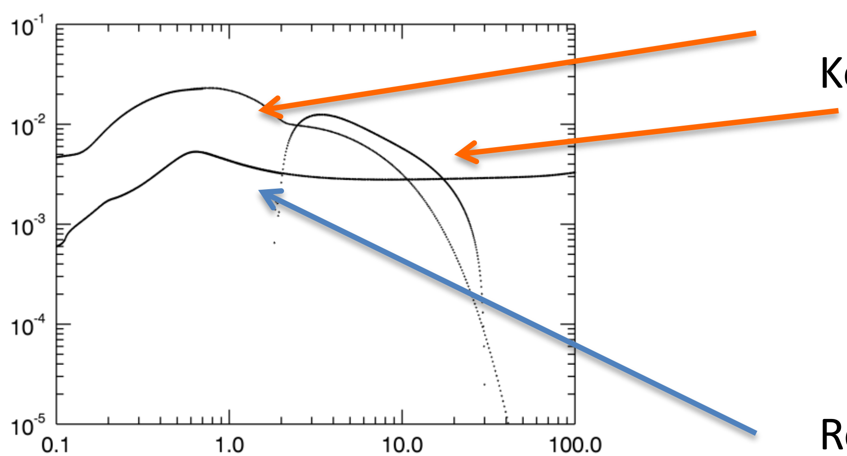
Kink modes
m=1

WHAT ABOUT ROTATION?





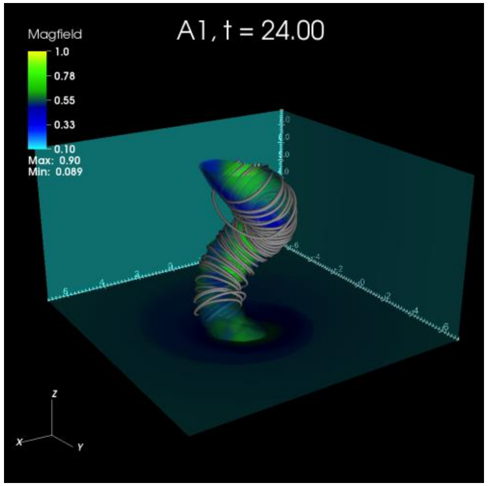
STABILIZATION OF CURRENT DRIVEN MODE, BUT NEW MODES



Kelvin Helmholtz

Rotation

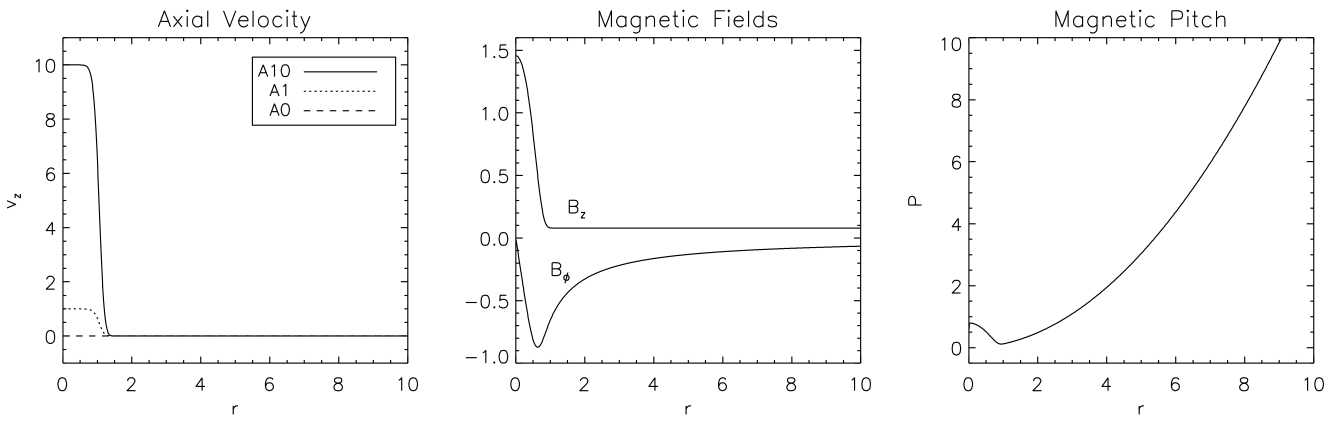
LOCAL ANALYSIS
(non relativistic, magnetically dominated jets)



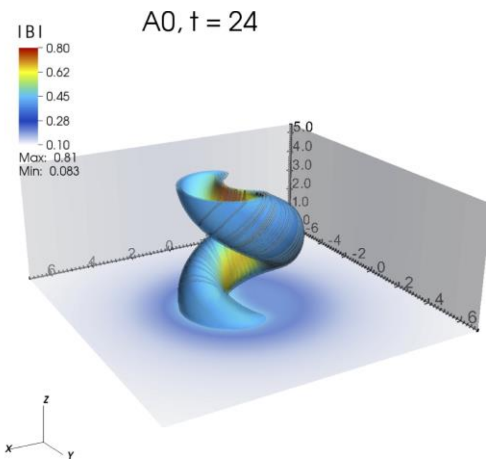
We take a local section of the jet,
periodic boundary conditions along the jet

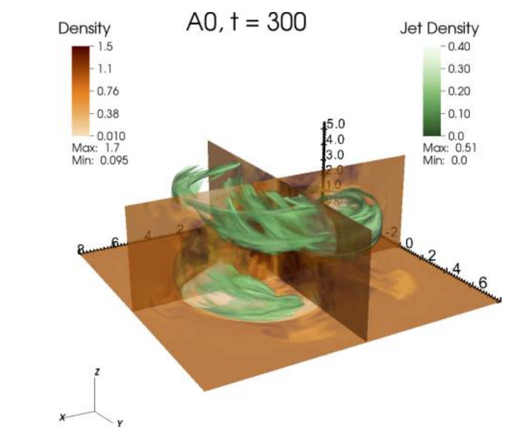
INITIAL EQUILIBRIUM (no rotation)

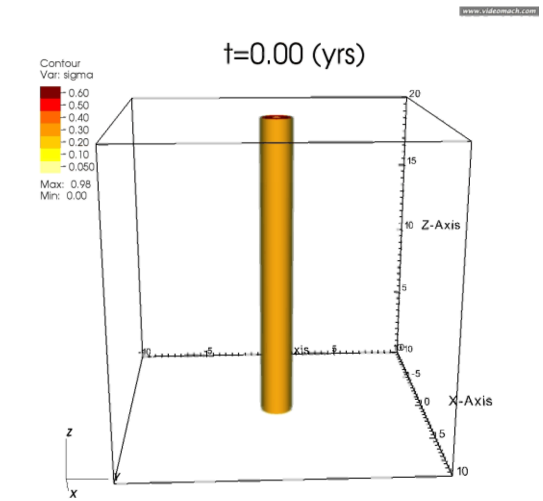
$$\cancel{\rho v_\phi^2} = \frac{1}{2r}\frac{d(r^2 B_\phi^2)}{dr} + \frac{r}{2}\frac{dB_z^2}{dr},$$

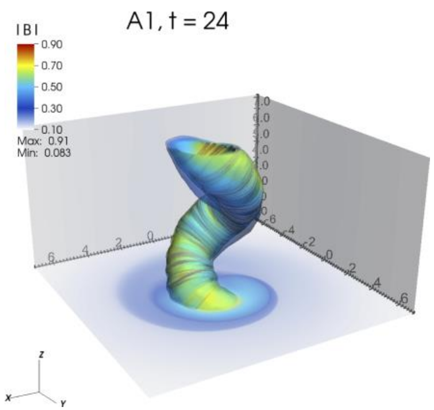


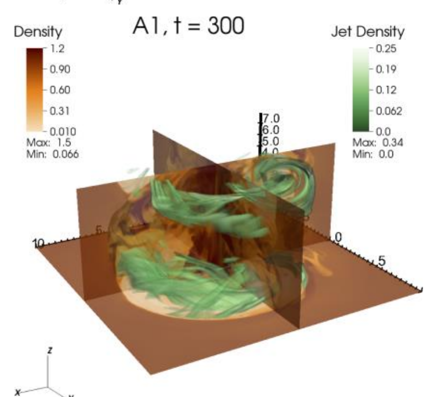
EVOLUTION

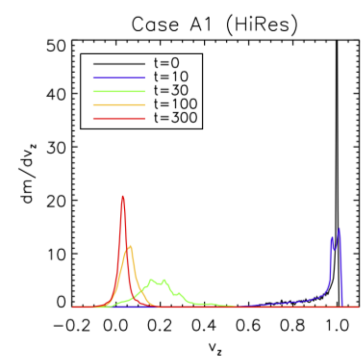

A0, t = 24
|B|
Max: 0.81
Min: 0.083

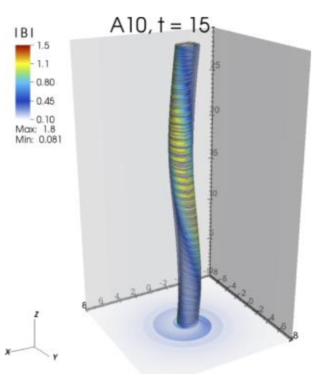

A0, t = 300
Density
Max: 1.7
Min: 0.095
Jet Density
Max: 0.51
Min: 0.0

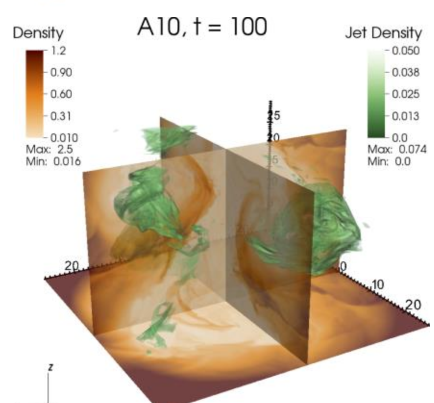

t=0.00 (yrs)
Contour
Var: sigma
Max: 0.98
Min: 0.00
Z-Axis
X-Axis

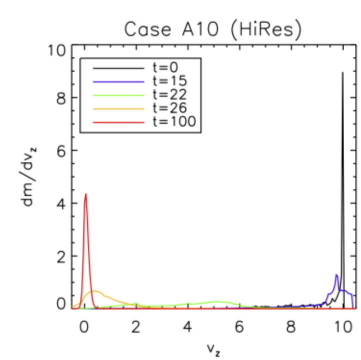

A1, t = 24
|B|
Max: 0.91
Min: 0.083


A1, t = 300
Density
Max: 1.5
Min: 0.066
Jet Density
Max: 0.34
Min: 0.0

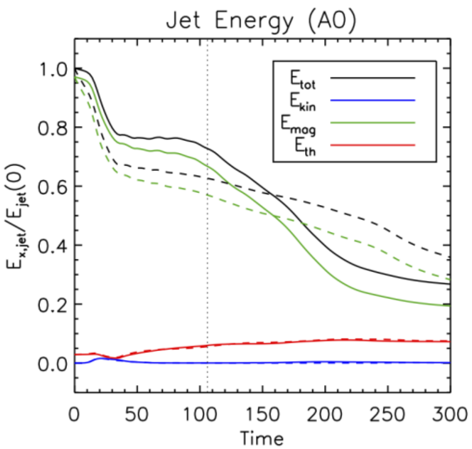

Case A1 (HiRes)
t=0
t=10
t=30
t=100
t=300
dm/dv_z
v_z

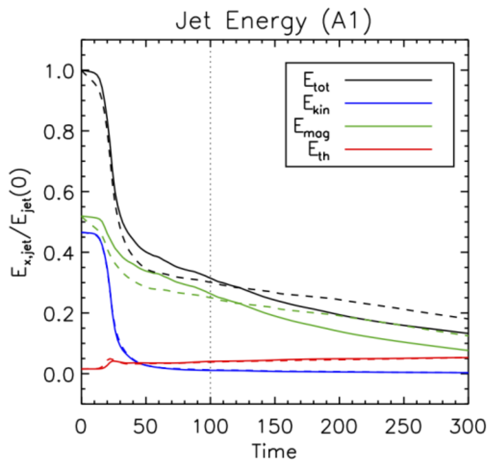

A10, t = 15
|B|
Max: 1.8
Min: 0.081

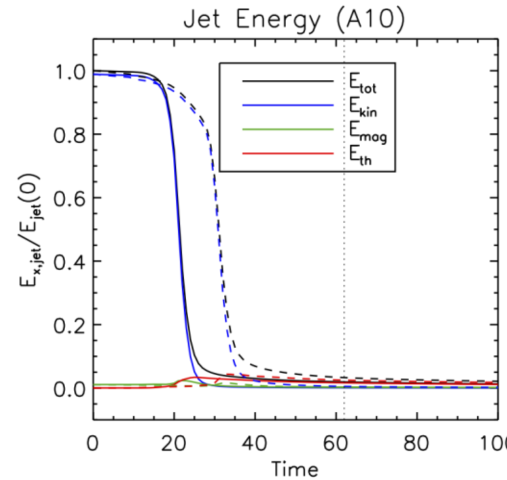

A10, t = 100
Density
Max: 2.5
Min: 0.016
Jet Density
Max: 0.074
Min: 0.0

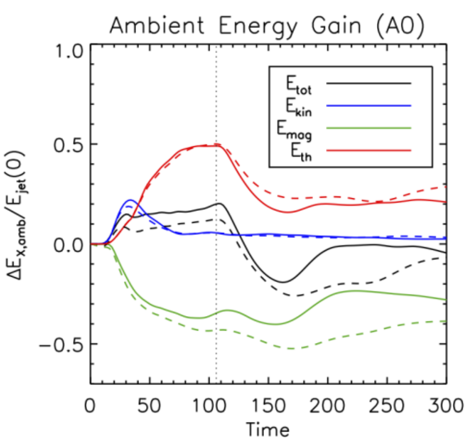

Case A10 (HiRes)
t=0
t=15
t=22
t=26
t=100
dm/dv_z
v_z

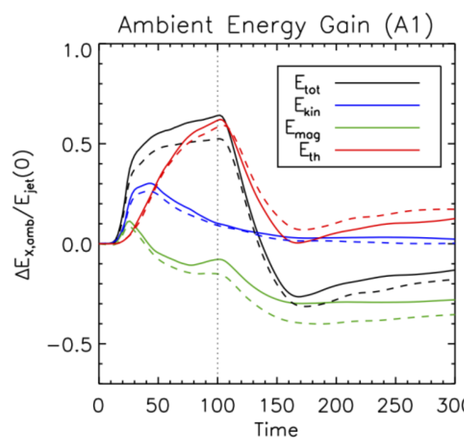
ENERGY EVOLUTION

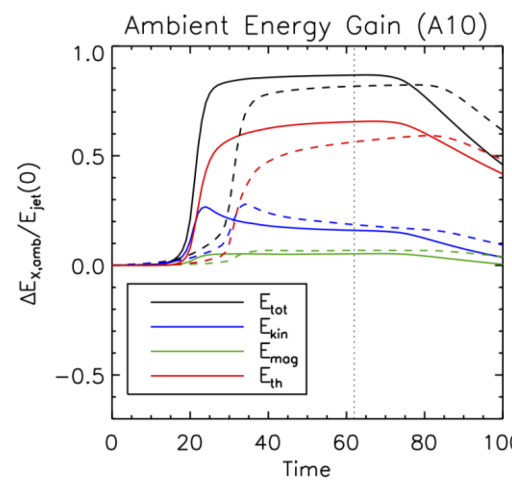




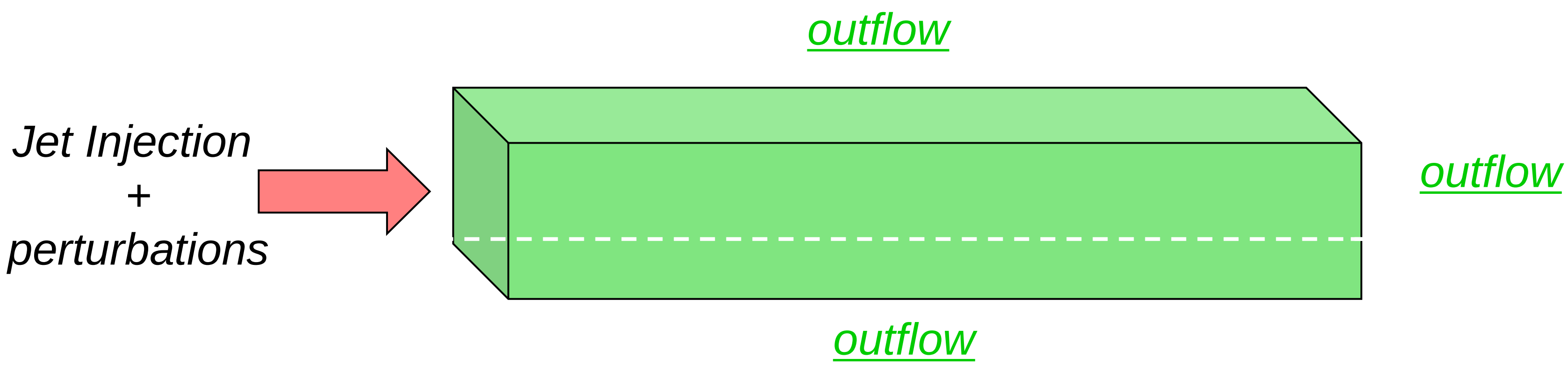




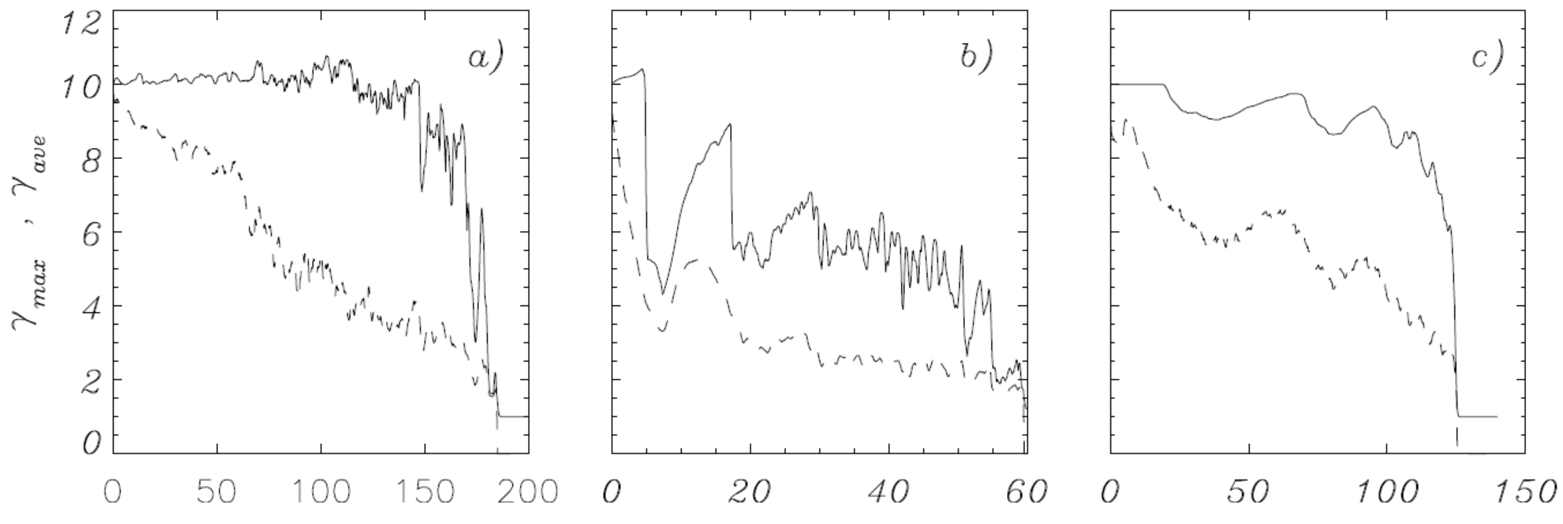




GLOBAL ANALYSIS – JET PROPAGATION



First case with no magnetic field: jet deceleration and formation of a spine layer structure
Turbulent structure driven by Kelvin-Helmholtz instabilities

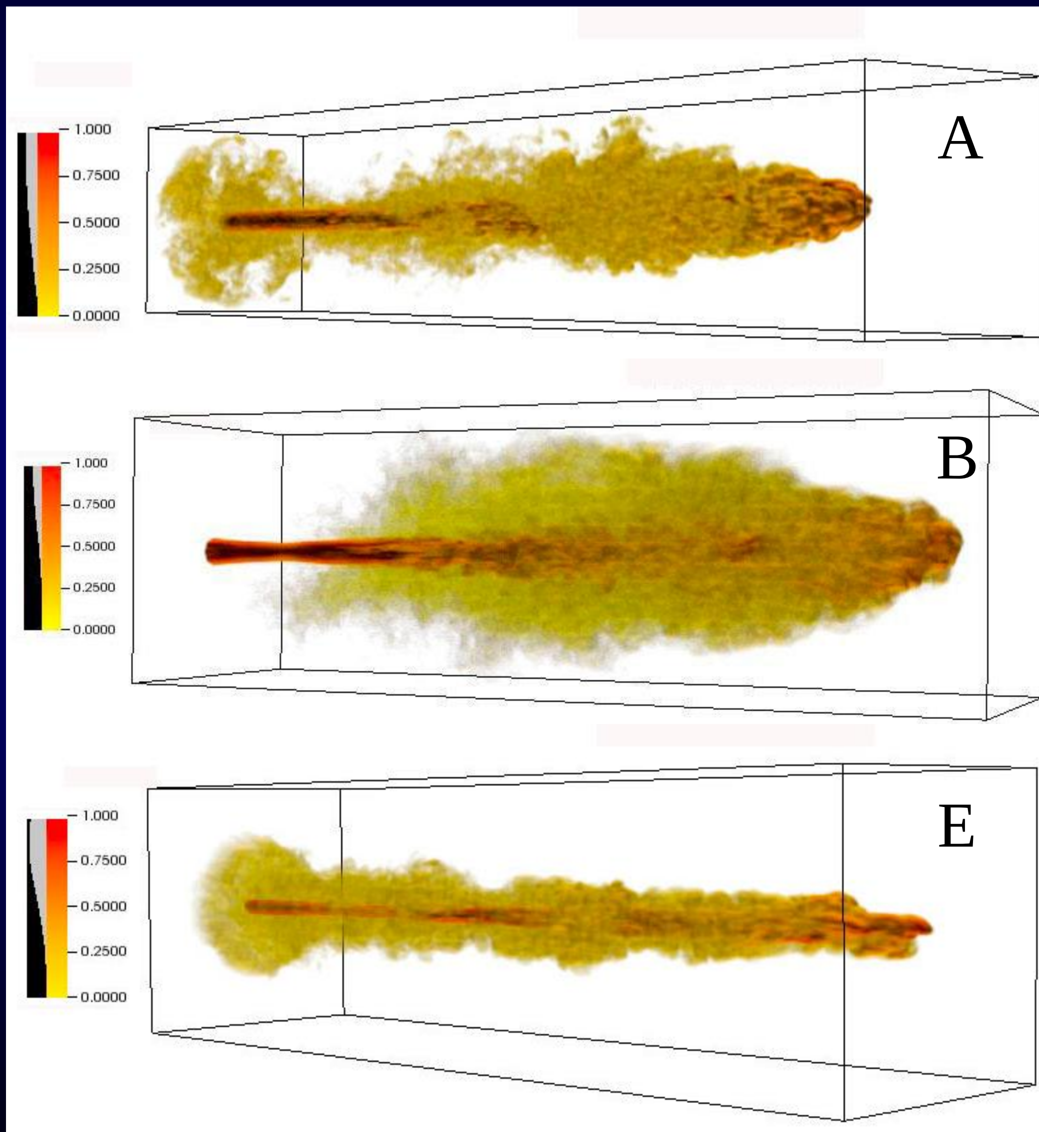


M=3 $\eta=10^2$

M=3 $\eta=10^4$

M=30 $\eta=10^2$

Mixing by shear instabilities



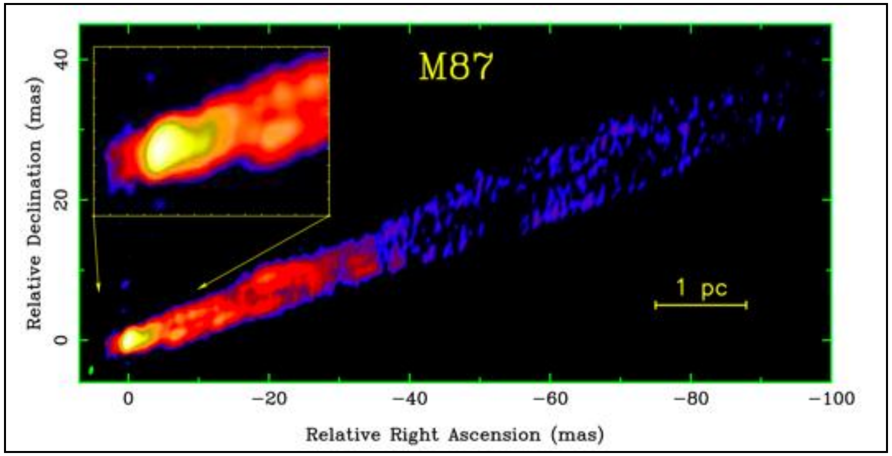
$\gamma = 10$, $M = 3$, $\eta = 10^2$

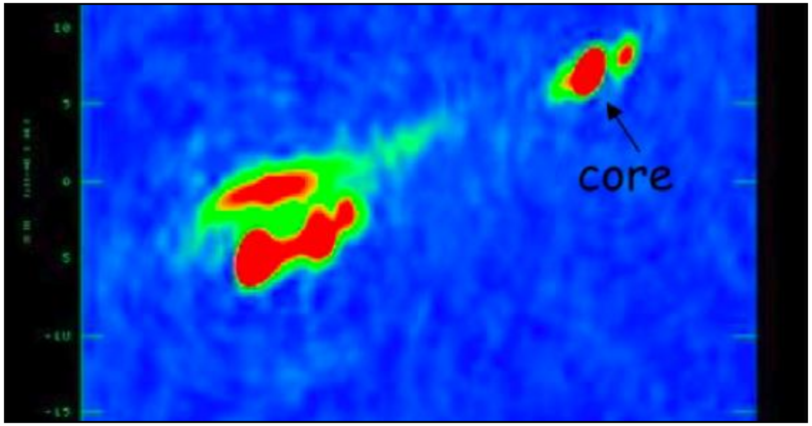
$\gamma = 10$, $M = 3$, $\eta = 10^4$
→Relativistic spine surrounded by a turbulent mixing layer

$\gamma = 10$, $M = 30$, $\eta = 10^2$

Comparison with observations

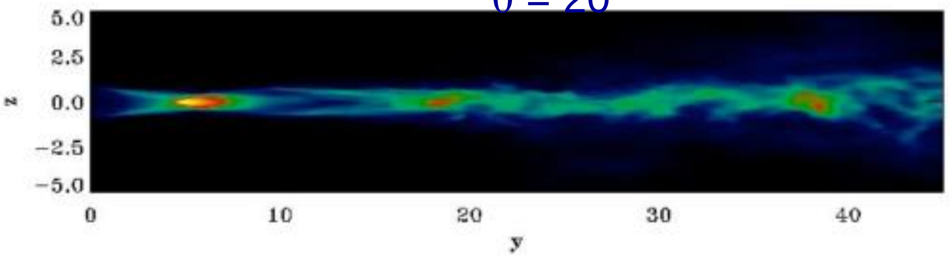
Emissivity integration along the line of sight
at different projection angles α



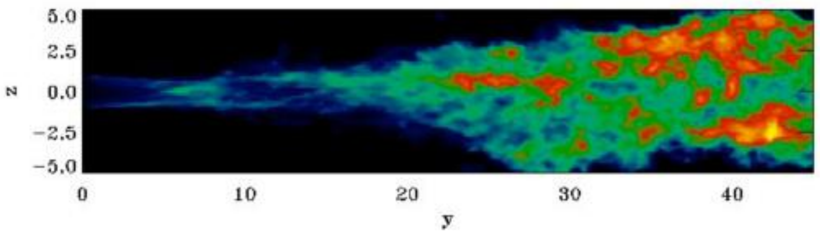


$$\delta = [\gamma(1-\beta\cos\theta)]^{-1}$$

$\theta = 20^o$

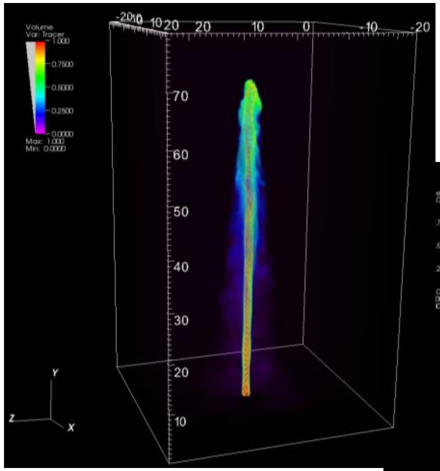


$\theta = 60^o$



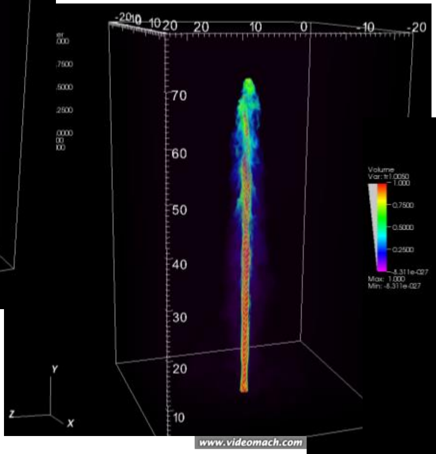
Magnetized Models:

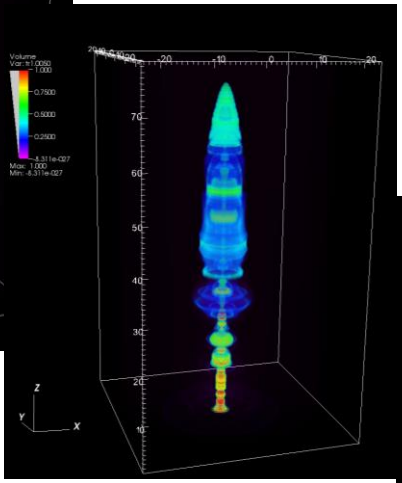
Tracer distribution



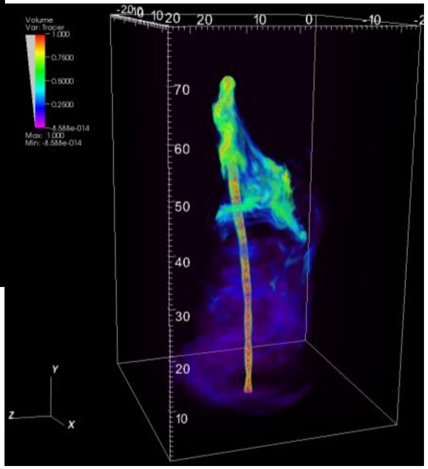
RHD
(Hydro)

Poloidal

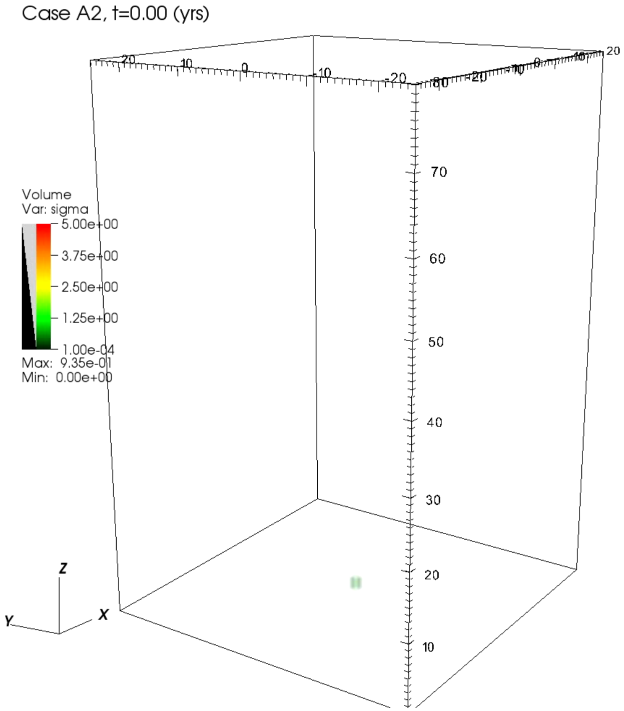




Toroidal 2D

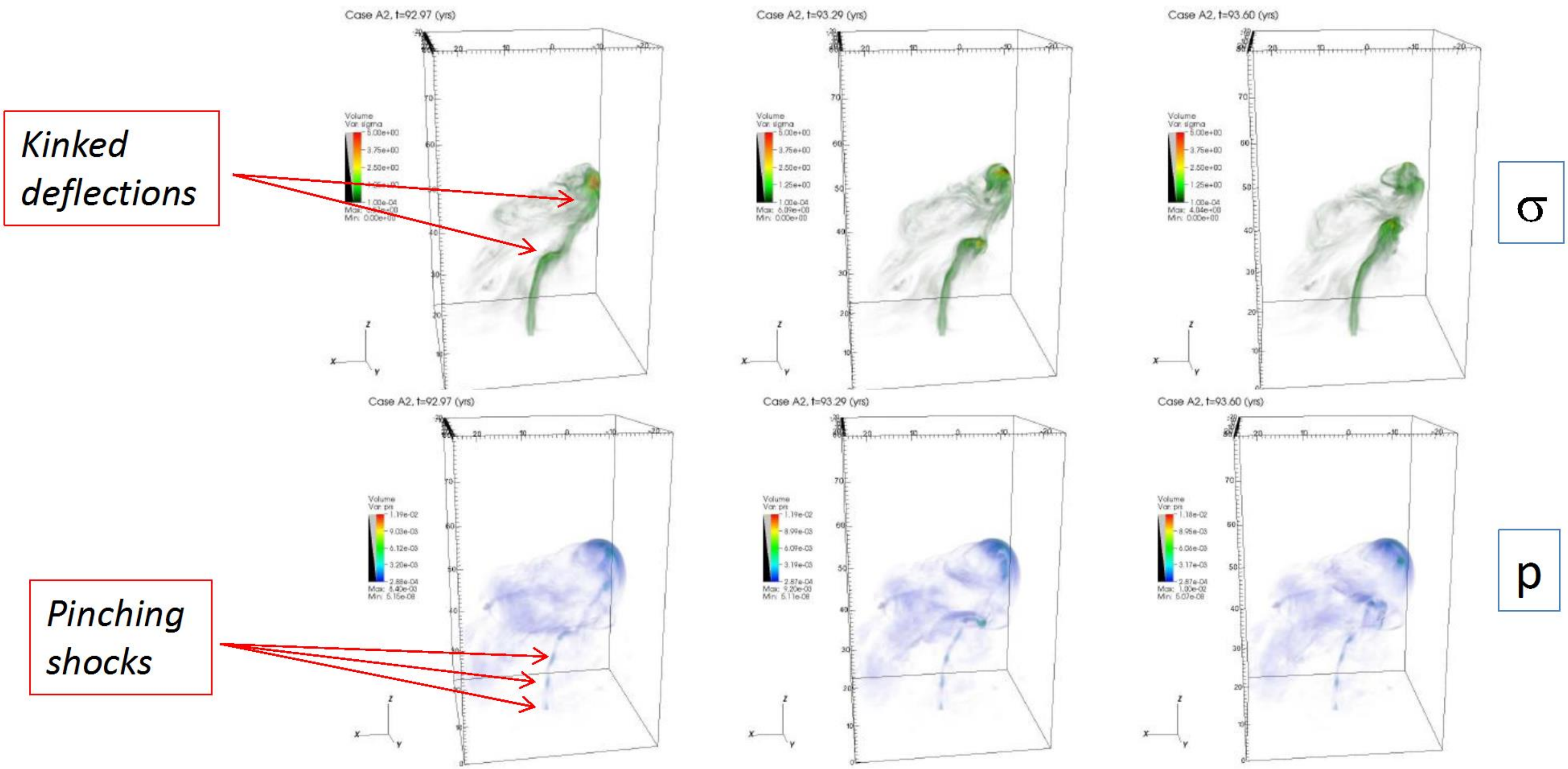


Toroidal 3D



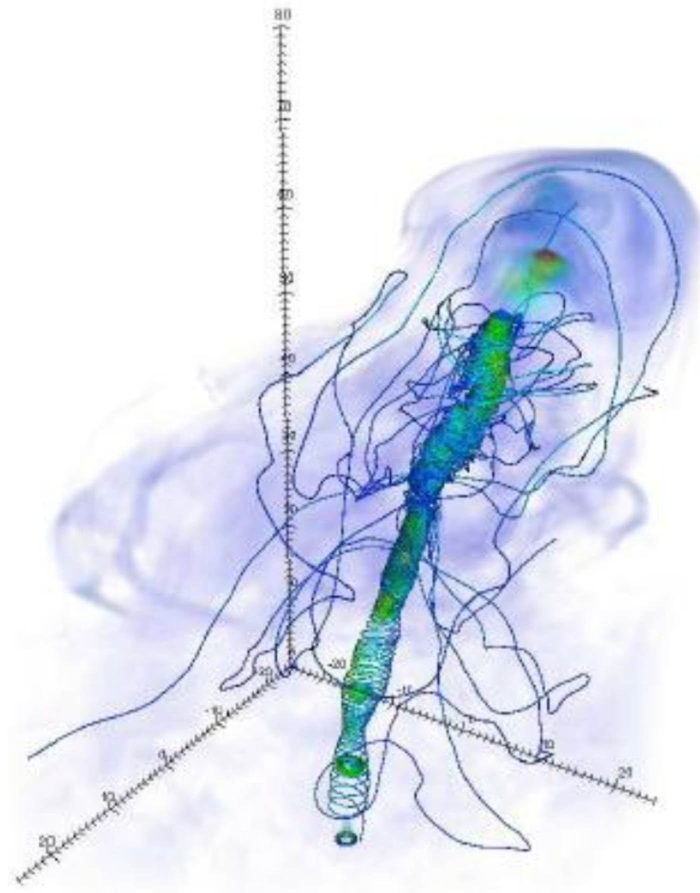
Jet Structure

- *Back-end regions:* quasi-periodic stationary pinch (m=0) shocks;
- *Front-end regions:* jet fragmentation at deflection sites forming short-lived unstable structures;



Magnetic Fields

- Magnetic field remains mainly toroidal or helical during the propagation;
- Azimuthal field “shields” the core preventing interaction with the surrounding[1].
- Poynting flux efficiently diverted at the termination shock and scattered via the backflow to feed the cocoon.
- Magnetic field dissipates and becomes turbulent in the cocoon (→ randomization[2])

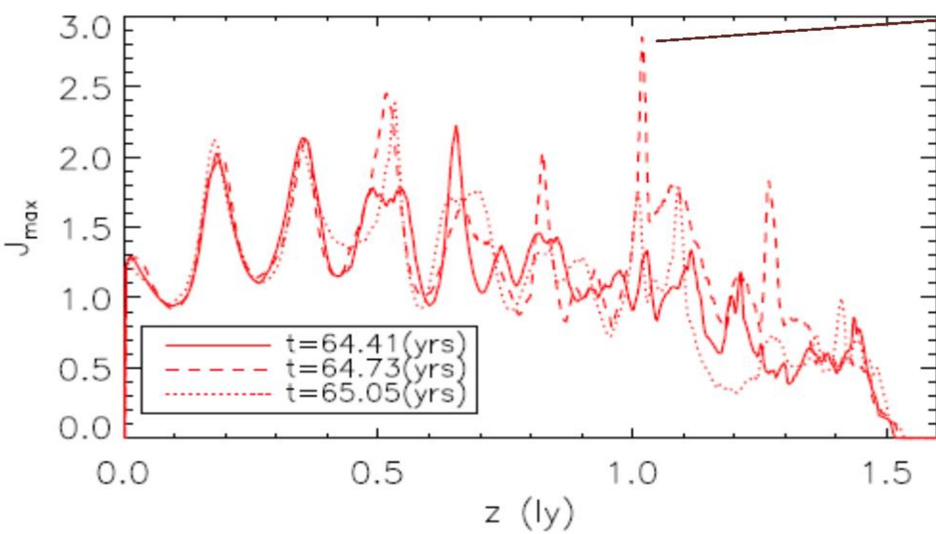


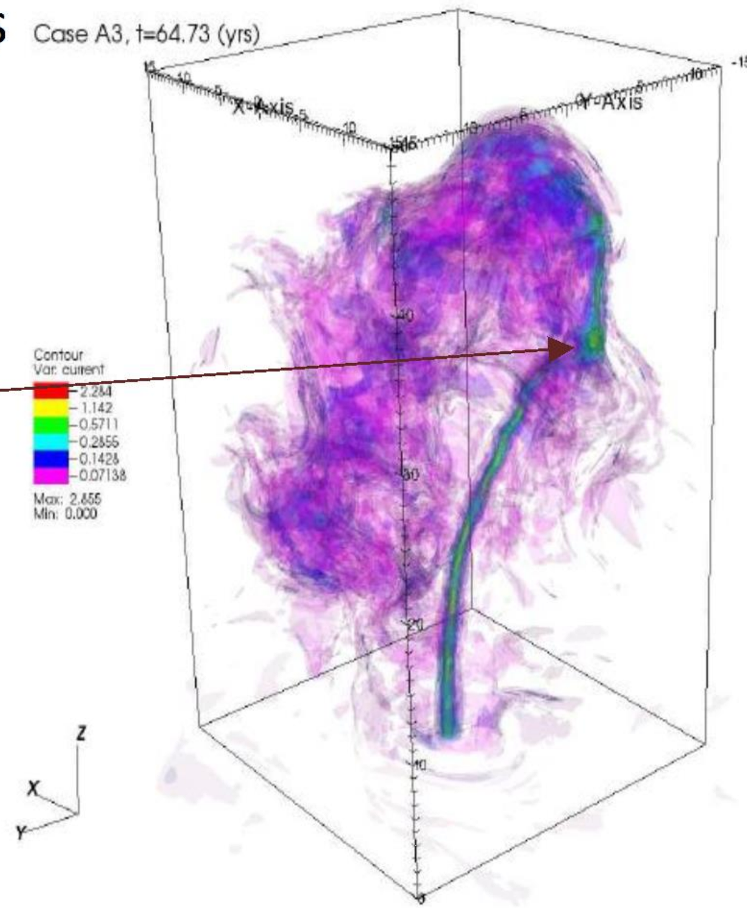
[1]Mignone et al, *MNRAS* (2010) 402, 7; [2]Porth et al., MNRAS (2013)

Current Sheets

- Current sheets localized in two regions:
  - at conical pinch shocks
    → quasi-steady, periodic
  - at jet "kinks" → short-lived episodes

- Magnetic reconnection
  → particle acceleration regions ?





THANK YOU