ASTROPHYSICAL JET MODELING

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1. **What** we mean by *jet* ?

> Astrohysical jets are collimated supersonic (relativistic) flows along which mass, momentum, energy and magnetic flux are channeled from several astrophysical objects to outer medium.

2. **Where** do we find *jets* ?

> Astrohysical jets are present in many astronomical objects, they span a wide range of spatial scales: on stellar scale we find them in the solar corona, in the first phases of stellar evolution (YSO) or in the last phases of stellar evolution (X-ray binaries, X-ray transients, Pulsars, GRBs …). On the extragalactic scale (AGN jets)
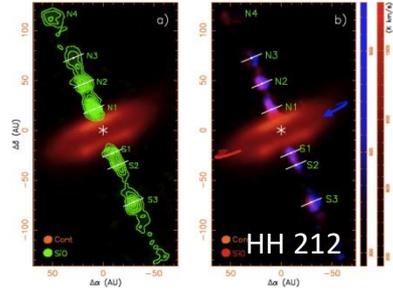
3. **Why** do we study *jets* ?

> On one side they can provide information about their sources, on the other side they may have a strong impact on the surrounding medium.
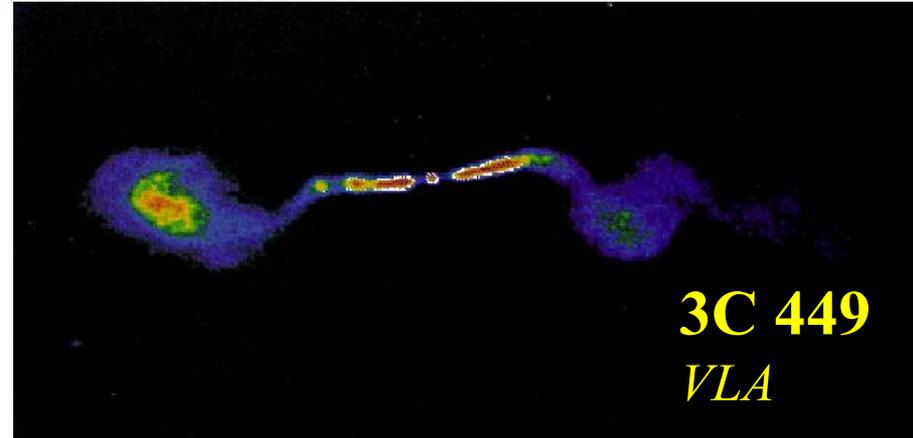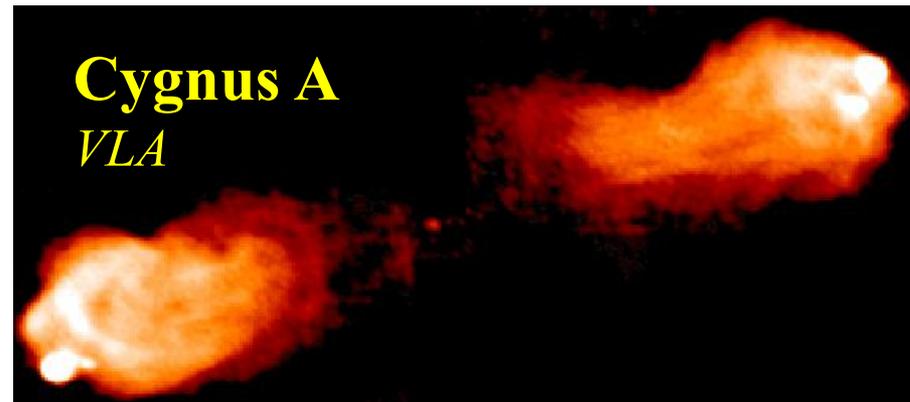
Stellar jets

AGN jets

HH 211

Ray & Ferreira, 2021

a)

b)

HH 212

3C 449
VLA

Crab nebula

X-ray: NASA/CXC/SAO
Optical: NASA/STSCI
IR: NASA/JPL/Caltech

Cygnus A
VLA

Similarities and differences

|	YSO jet <= pc	AGN jets > kpc
Central object	Star	SMBH
Radiation	Thermal	Non-Thermal
Spectrum	Optical, IR	Radio to gamma rays
Compositions	(e-,p+)	(e-,p+), (e-,e+), e.m.
Jet power	10^{30-33} erg/s	10^{40-47} erg/s
Mach Number	20-40	>> 1 (relativistic)
Density ratio (jet/am)	ca 1	<<1

The jet-disk paradigm
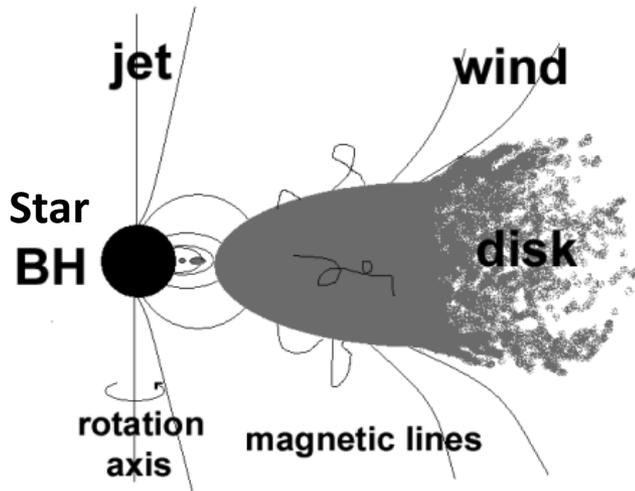
Ingredients:
- Central object creating a strong gravitational field
- Accretion disk
- Magnetic field (turbulent in the disk, ordered in magnetosphere)
- Strongly collimated outflow along the rotation axis
- Collimated wind arising from the disk

Accretion and ejection are strongly connected

How can we approach the jet physics?

~ 500 kpc   ~ 10kpc
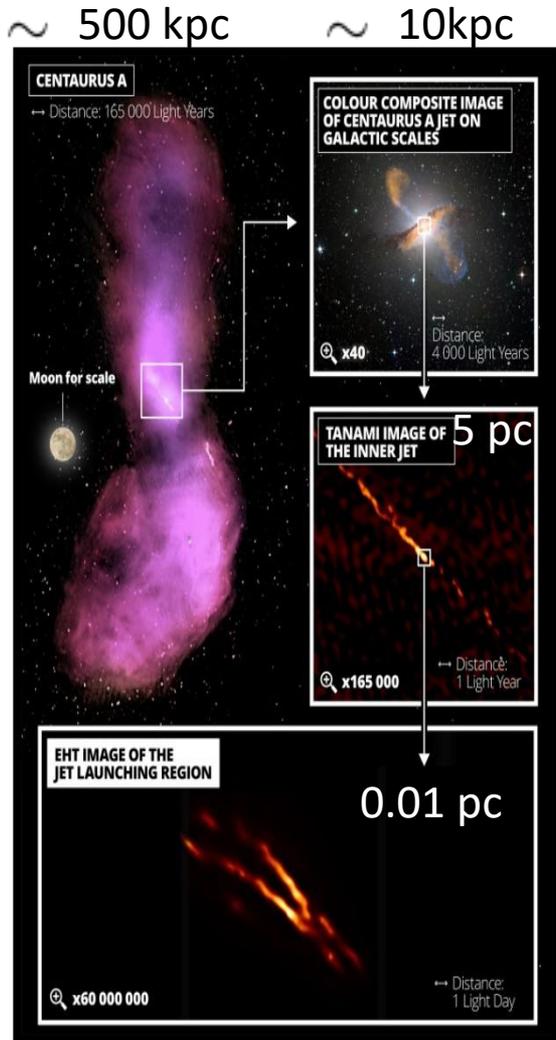
- **Launching phase**: acceleration from BH/disk and collimation   ~ 10^{15} cm

- **Propagation phase**: confinement and stability   ~ 1-100 kpc

- **Termination**: Termination interaction with external medium   > 100 kpc (3 x 10^{23} cm)

- **High-energy electron acceleration**   ~ 10^4 cm
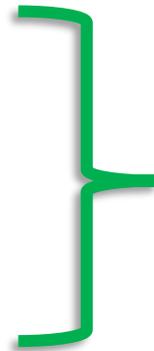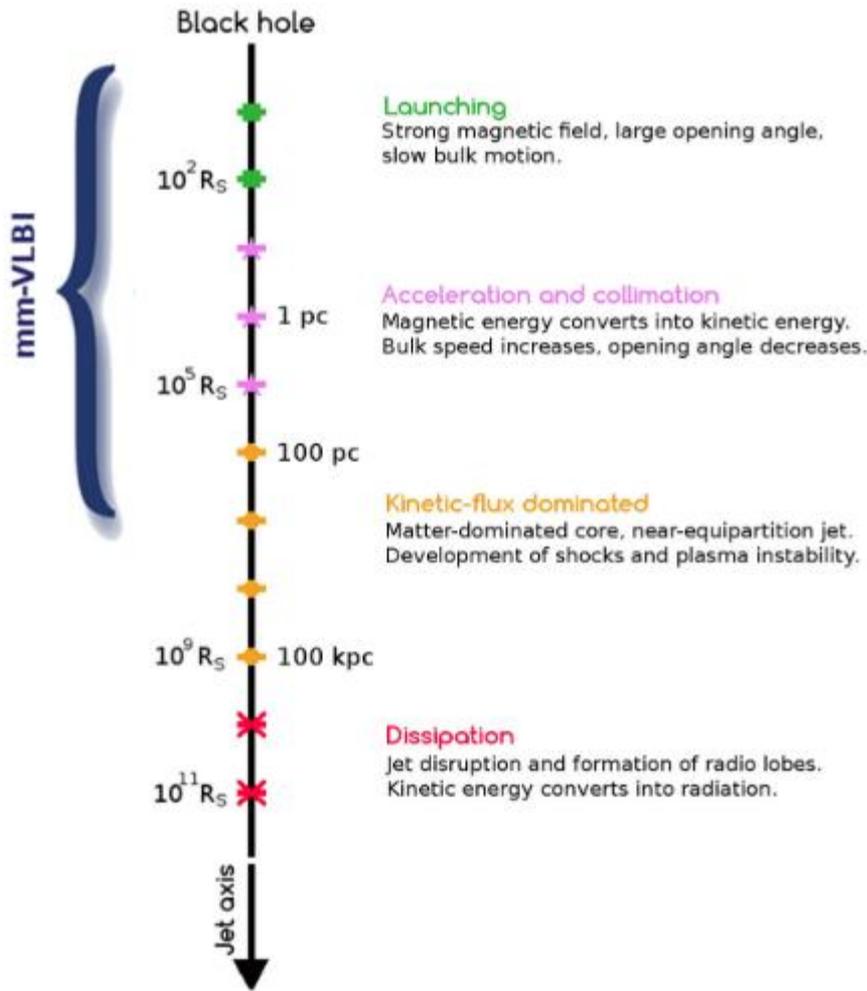
Launching phase:
Acceleration either from disk or BH
And collimation

Propagation phase:
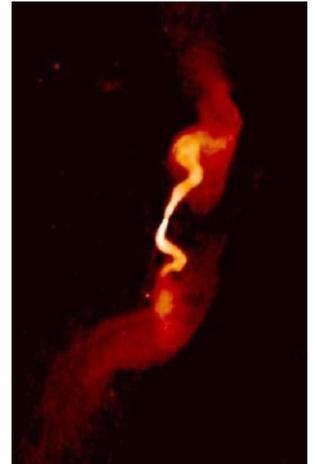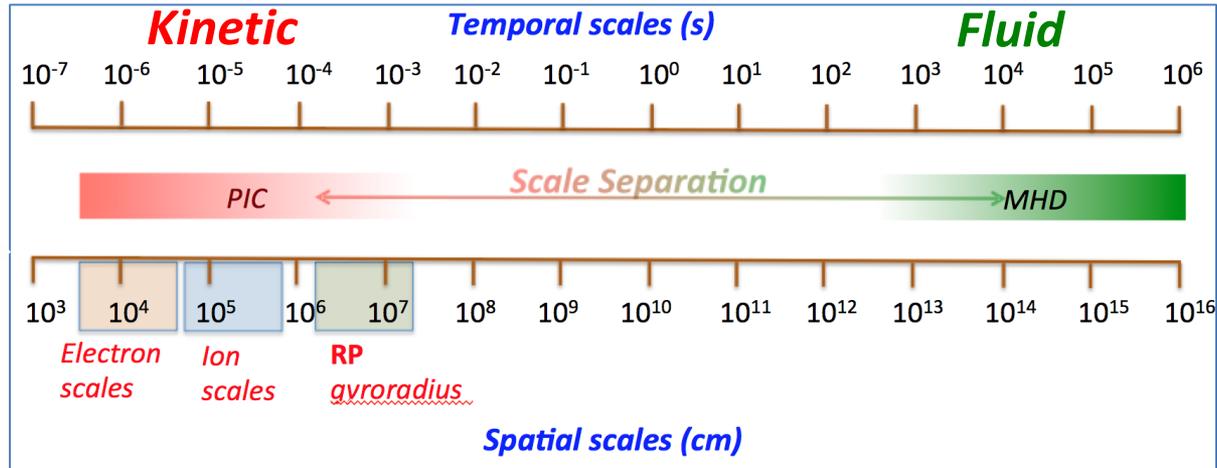Confinement and stability

Termination:
Interaction with external medium

Non thermal emission:
High energy electron acceleration

Modeling through relativistic MHD simulation

Astrophysical environments involve physical processes operating at *extremely different spatial* and *temporal scales*, and complex *interactions* between *plasmas* and *radiation*.

Kinetic | Temporal scales (s) | **Fluid**

10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6}

PIC ← Scale Separation → MHD

10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8} 10^{9} 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16}

Electron scales *Ion scales* **RP** *gyroradius*

Spatial scales (cm)

$10^{1} \rightarrow 10^{2}$ s

$10^{4} \rightarrow 10^{7}$ cm

How we can connect?

$10^{10} \rightarrow 10^{15}$ s

$10^{18} \rightarrow 10^{24}$ cm
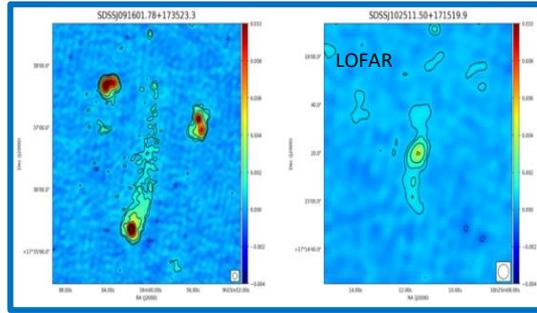
Particles acceleration
And radiation processes

Ideal MHD modeling
No resistivity, no viscosity
PLUTO code

Warning!!!

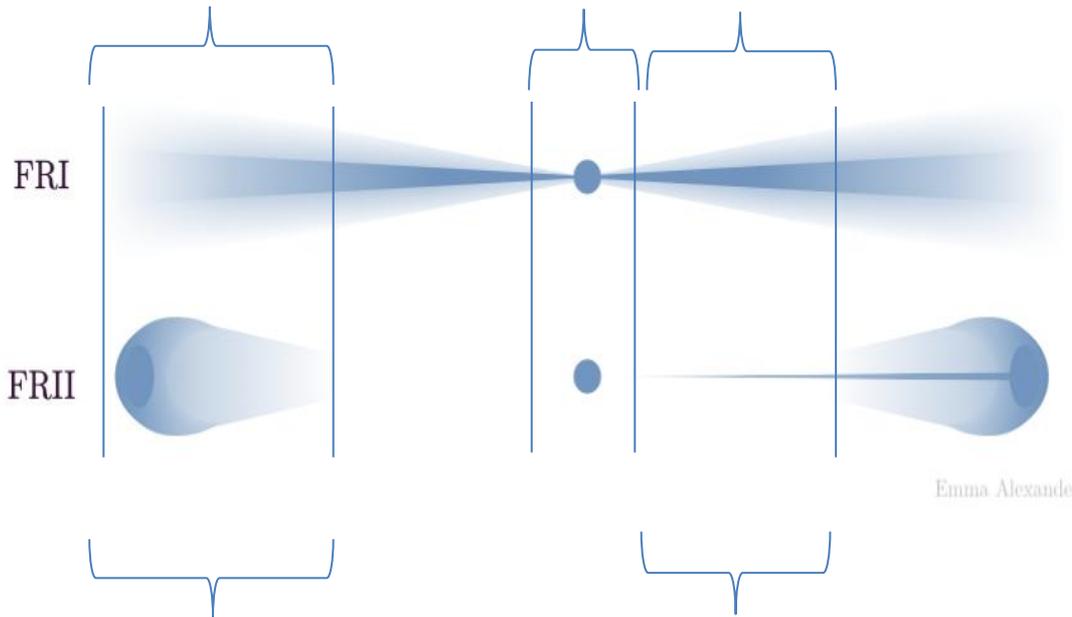Also the macrophysics involves a huge range of scale

LOFAR

Plume
Jet
Jet
3C 98
VLA
Plume
Hotspot
3C 31
VLA
Lobe
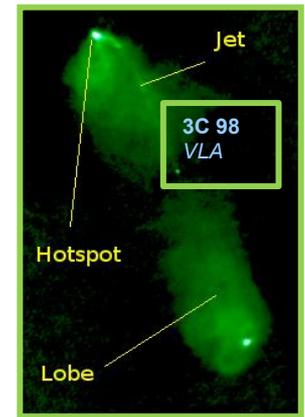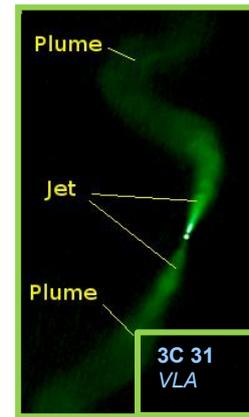
Multiscale approach

Turbulent propagation up to 100 kpc

Launching region 10^{15} cm

Propagation region with deceleration < 1 kpc

FRI

FRII

Emma Alexander

At the base all jets start relativistic with similar Lorentz factor (Giovannini+, 2001)

Termination shock, hot spot

Propagation region with No Deceleration 1-100 kpc

Launching phase

Main ingredients:
- Rotation
- Magnetic field

Spine   Sheath

Disk

Density distribution
(McKinney 2006)

Origin:
- BH (Blandford & Znajek 1977) → extraction of BH rotational energy
- Disk (Blandford & Payne 1982) → magnetocentrifugal acceleration

Magnetic field line

Accretion disk

Centrifugal force
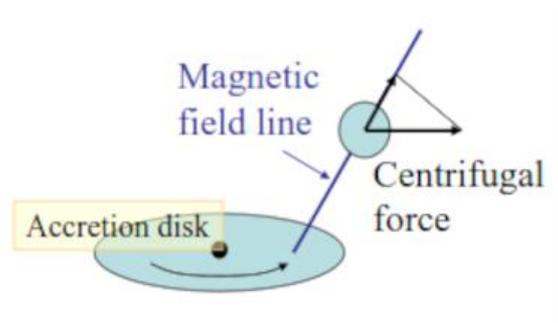
Many GRMHD simulations of jet formation (Port+,2019...) suggest that :
jet spine (Poynting flux jet) is driven by BZ process may be surrounded by a broad sheath wind driven by the magnetic field anchored in the accretion disk.

Open problem:
How the Poynting flux turn in a matter dominated jet?
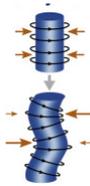Possibility: CD instability due to the toroidal magnetic field

Review Mizuno,2022

Propagation phase

The MHD ins. are very important in determining morphology, dynamics and emission properties of astrophysical jets.

KELVIN HELMHOLTZ
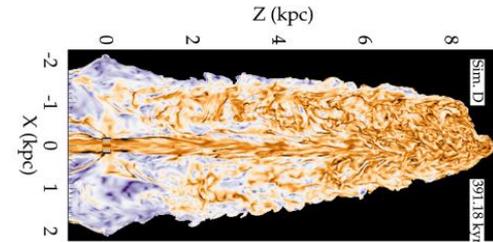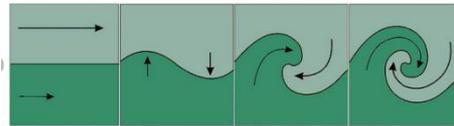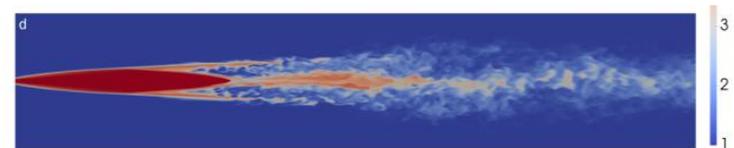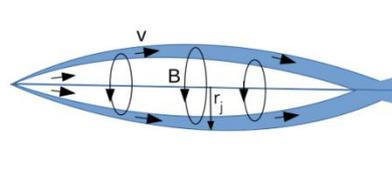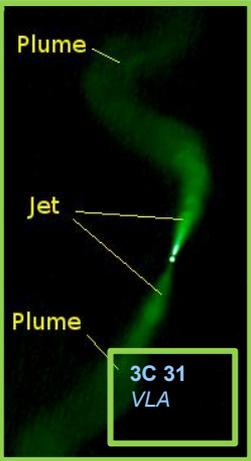

CURRENT DRIVEN
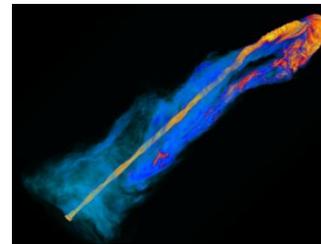
CENTRIFUGAL

Is it possible to decelerate a relativistic jet to sub-relativistic speed in the first kpc?

Plume

Jet

Plume

3C 31
VLA

Jet

3C 98
VLA

Hotspot

Lobe

Deceleration

Our purposes are to study

How entrainment develops

pc

kpc

Physical parameters

$M \gamma \rho$

ρ_e

Jet Mach number

Lorentz factor γ

Density ratio η

Constant external density inside the galaxy core
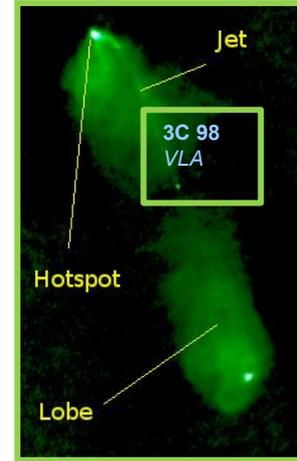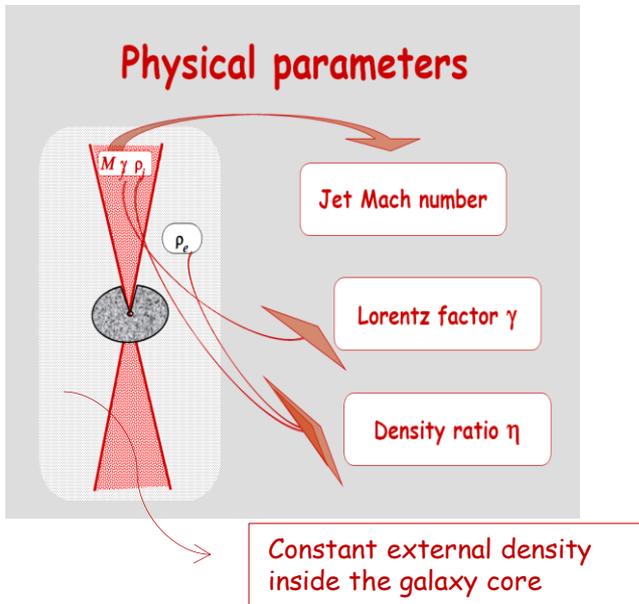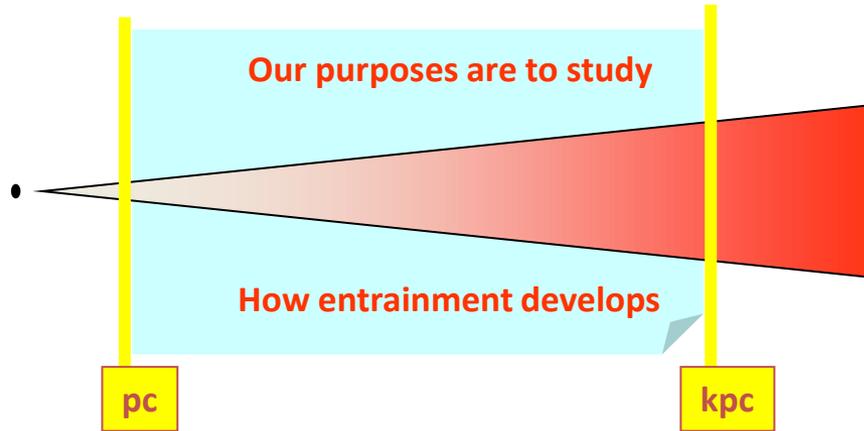
$$P_{\mathrm{j}} \sim h \left(\frac{\gamma}{10}\right)^2 \left(\frac{\eta}{10^{-4}}\right) \left(\frac{r_{\mathrm{j}}}{1\mathrm{pc}}\right)^2 \left(\frac{n_0}{1\mathrm{cm}^{-3}}\right) 1.22 \times 10^{43} \ \mathrm{erg} \ \mathrm{s}^{-1}$$

10

$10^{-2}, 10^{-4}$

$10^{43}, 10^{45}$ erg s^{-1}

Jet instabilities: growth length-scale increases
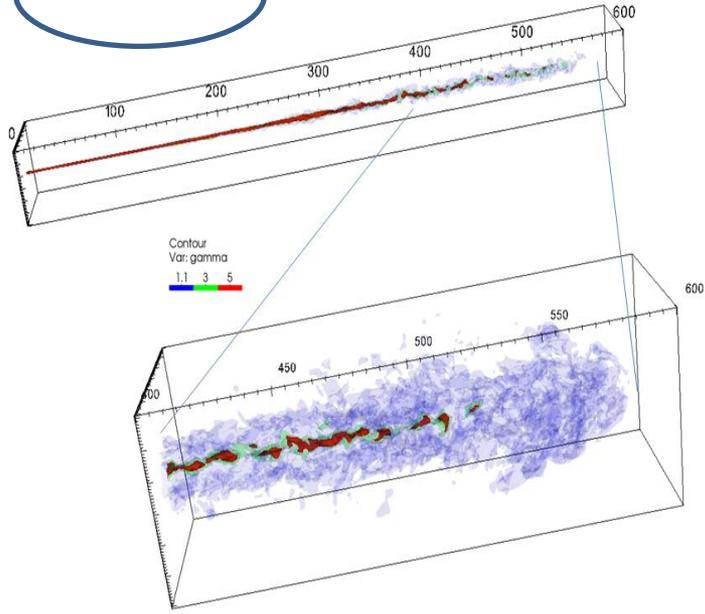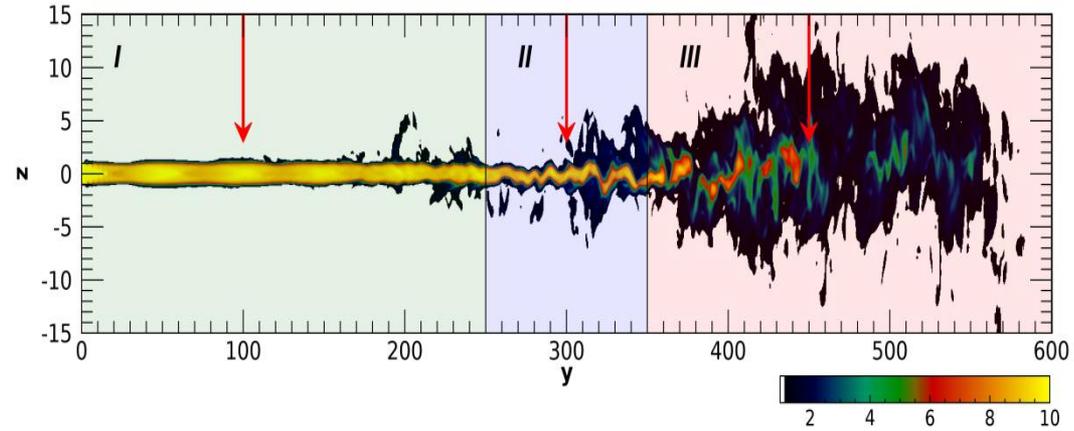with Lorentz factor and Mach number

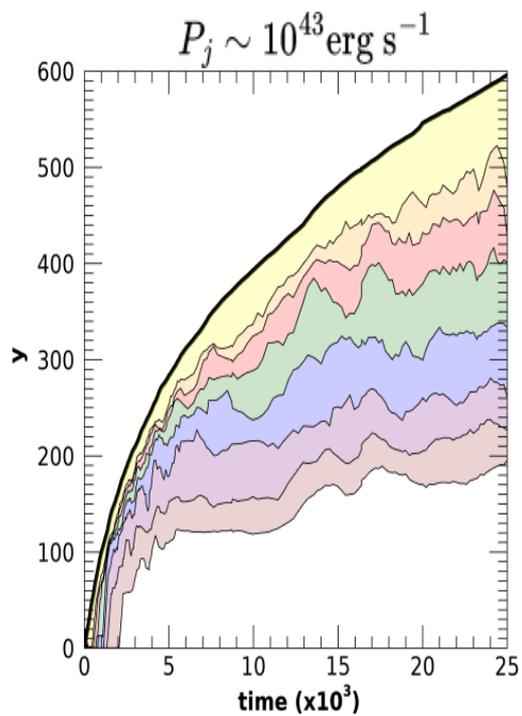Lorentz factor

$P_j \sim 10^{43} \text{erg s}^{-1}$

Non linear growth

Mixing and mass entrainment

Jet deceleration

Contour
Var: gamma
1.1 3 5

I ricollimation shocks

II growth of instabilities

III mixing and jet breaking

Rossi+, 2008,2020,2024

$P_j \sim 10^{43} \text{erg s}^{-1}$

$P_j \sim 10^{45} \text{erg s}^{-1}$
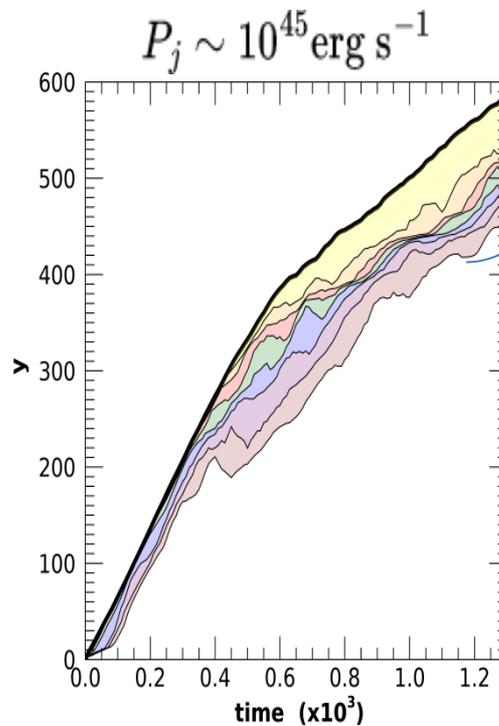
Each curve shows, as a function of time, the distance up to which relativistic material ($\gamma > 5$) carries more than certain fraction of the initial momentum flux: 70%,60%,50%......10%

Time unit: $\tau \sim 3.25 \left(\frac{r_j}{1\,\text{pc}} \right) \text{yr}$

$P_j \sim 10^{43} \text{erg s}^{-1}$

- Strong deceleration
- Strong entrainment
- Steady state
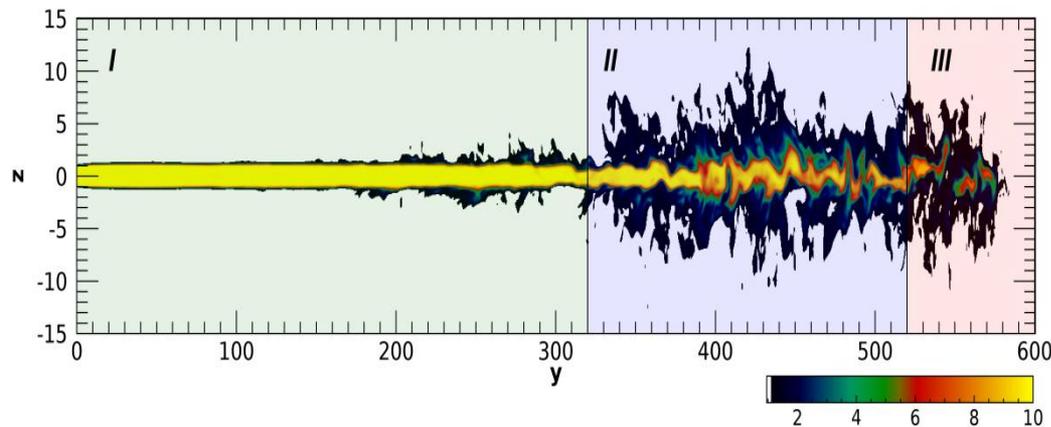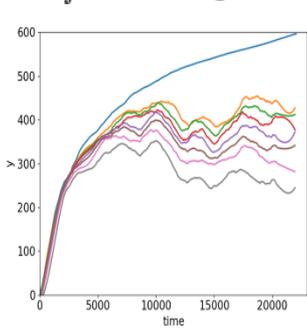
$P_j \sim 10^{45} \text{erg s}^{-1}$

- Weak deceleration
- Weak entrainment
- No Steady state
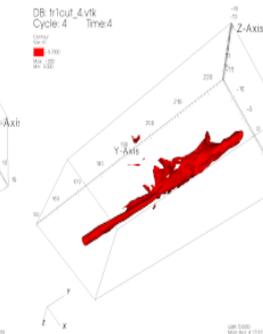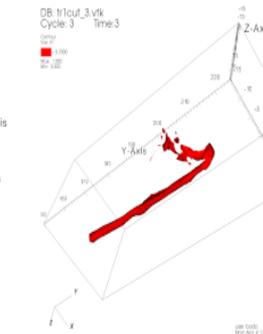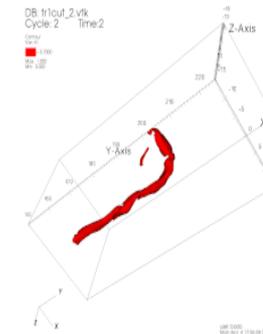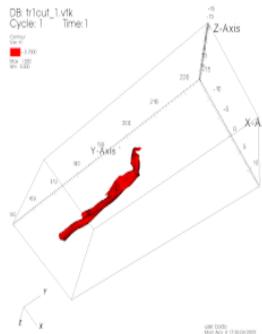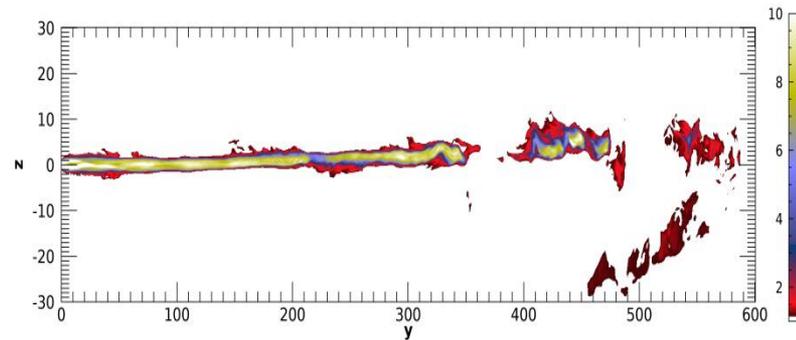
Magnetic effects
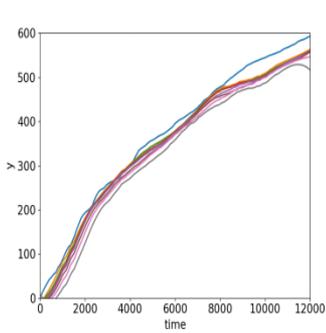
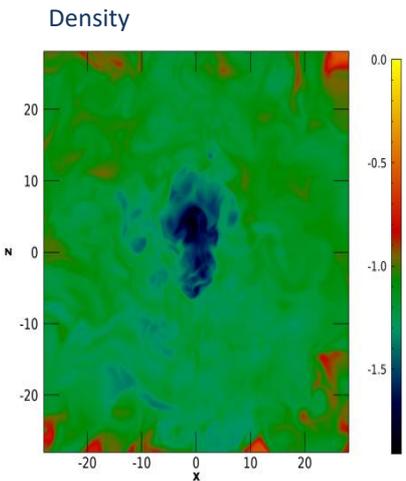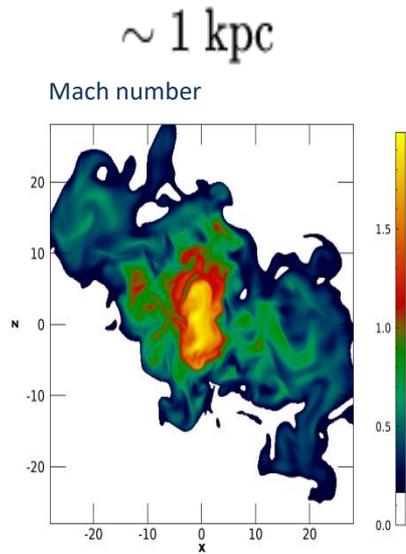$$P_j \sim 10^{43}\,\text{erg}\,\text{s}^{-1} \qquad \sigma = 10^{-2}$$
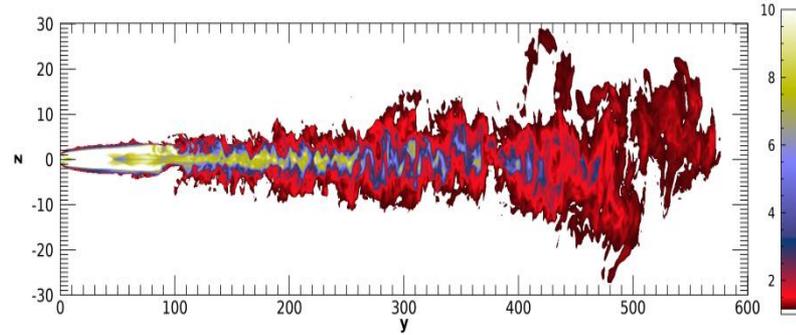
Magnetic field reduces entrainment, stabilizing KH inst. .
New inst. (current-driven) starts deforming the jet without deceleration.

$$P_j \sim 10^{43}\,\text{erg}\,\text{s}^{-1} \qquad \sigma = 10^{-1}$$
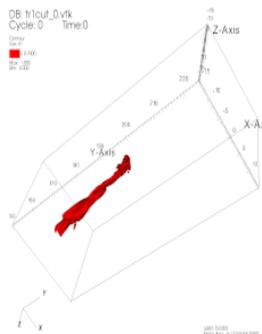
Turbulent propagation starting from 1 kpc
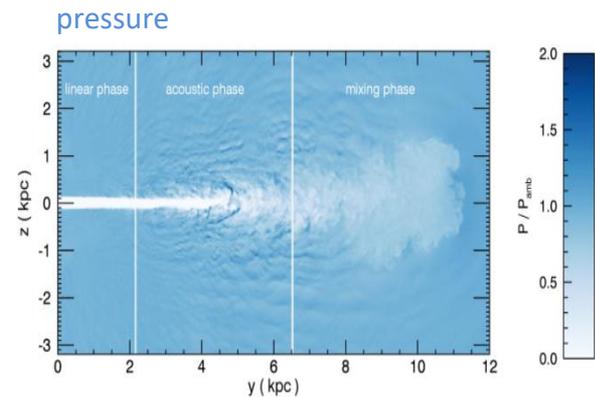
~ 1 kpc

Mach number

Density

Initial conditions:
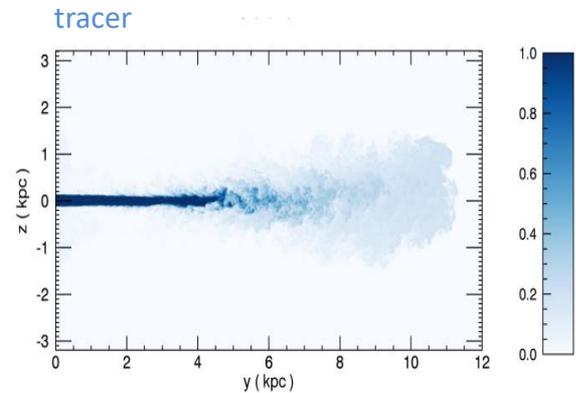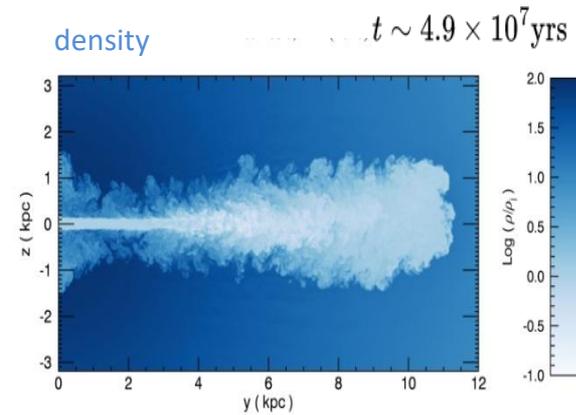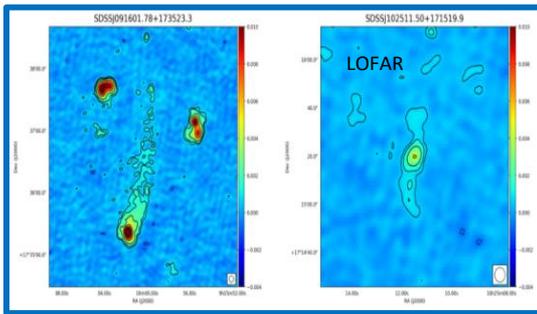
$$M \sim 2$$

$$\eta \sim 10^{-2}$$

$$\gamma \sim 1 - 2$$

We perform a set of simulations with similar conditions
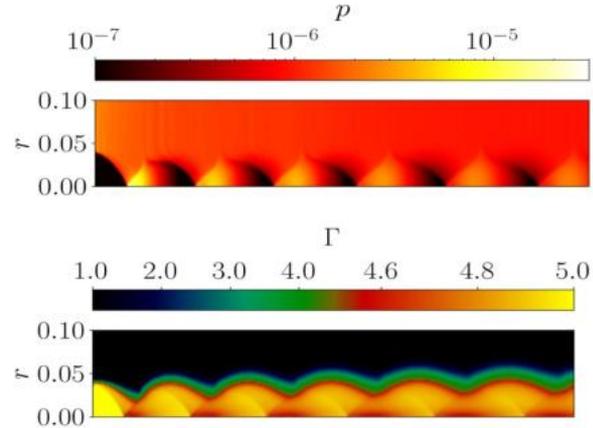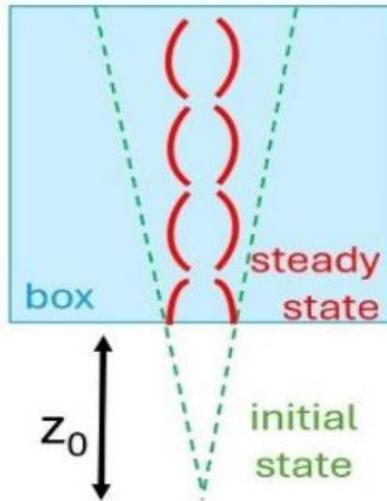
$$M = 4 \quad \text{(0.06 c)}$$

$$\eta = 10^{-2}$$

Non-relativistic with 3 different external density stratification (Massaglia et al. 2016)

density $\qquad t \sim 4.9 \times 10^{7}$ yrs

tracer

pressure

For the very low power jet (FR0) can we find a mechanism that stop the Jet at even smaller distance?

The external pressure or the wind surrounding the jet may collimate the jet inducing a series of recollimation shocks

$$\gamma = 5 \quad \nu = 7.6 \times 10^{-5} \quad L_j = 6.5 \times 10^{39} \text{ erg s}^{-1}$$

$$kT/mc^2 = 3.9 \times 10^{-5}$$

2D studies of recollimation process show a formation of a chain of recollimation shocks , but in 3D this structure results to be unstable. The mechanism is the centrifugal inst. Connected with the curvature of the fluid streamlines.

RECOLLIMATION SHOCKS AND FR0

Power 10^{40} erg s^{-1}
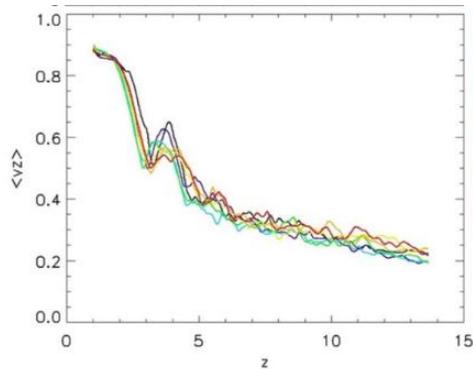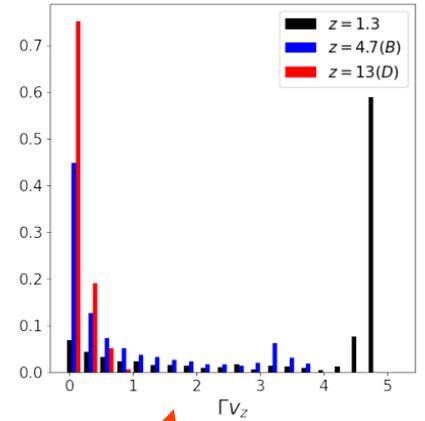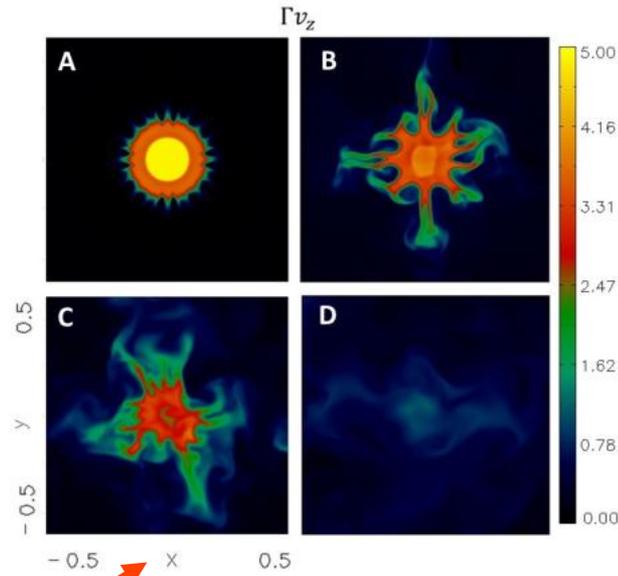
Entrainment

Quasi steady-state

Relativistic ($\gamma = 5$) up to about 3pc
Mildly relativistic up to about 10 pc
Subrelativistic at larger distances

Costa+, 2024,2025

What about Current-Driven instabilities?

Dissipation & Particles acceleration: from the acceleration process we expect that the toroidal magnetic field component is important → this may lead to current driven instabilities → formation of current sheets and magnetic reconnection region → Particles acceleration
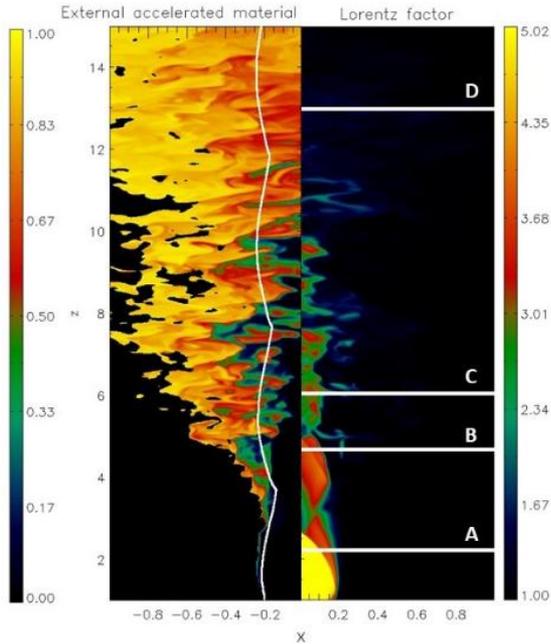
Jet morphologies: 3D simulations on a relativistic jet with a toroidal magnetic field show a complex dynamics with bendings and wigglings of the jet head.

Bodo+2013,2016,2019,2021,2022; Mignone+ 2010; Massaglia+,2019,2022
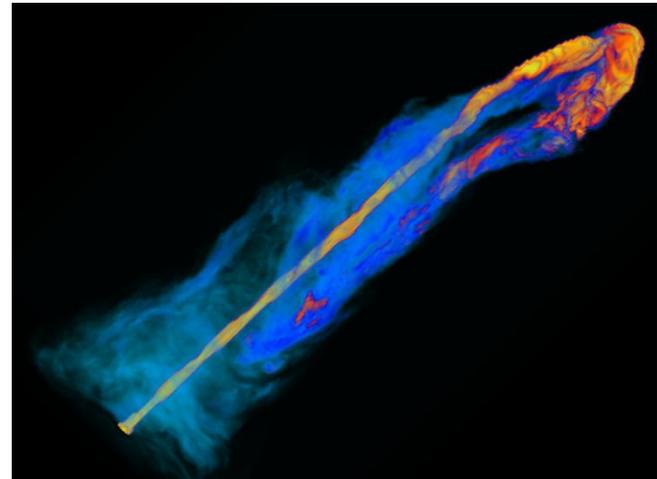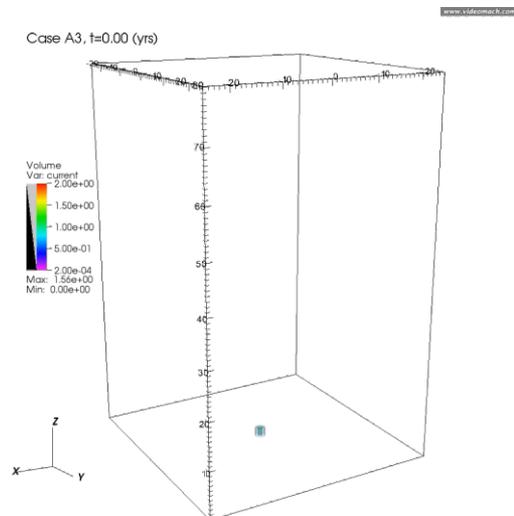
Termination phase

Jets deposit their energy either at the head (FRII) or gradually along their trajectory (FRI). this process has an impact on the ambient medium and may have consequences both for the host galaxies and for the intergalactic medium (jet feedback).

There are recent observational evidences that jets can have active recurrent phases
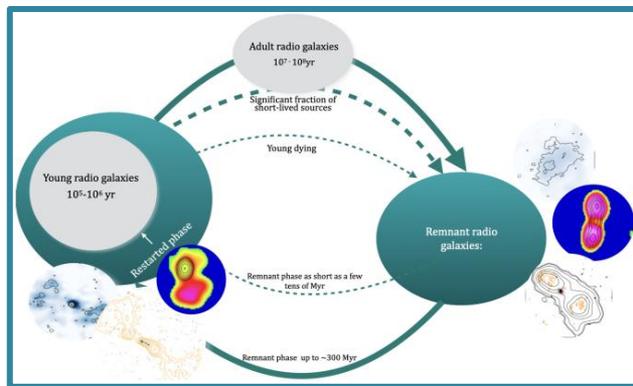
Morganti+ 2023

Ratnaparkhi+ 2026

From macro to micro physics

Jets with new hybrid scheme: macro-particle* + fluid

*to each macro-particle we associate a distribution function of non-thermal relativistic particles
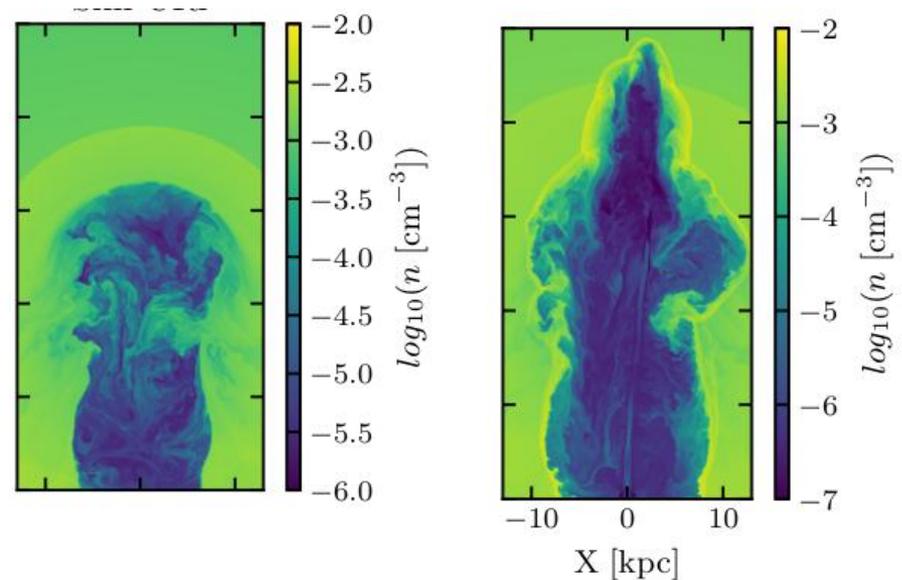
$$\frac{d\boldsymbol{x}_{\mathrm{p}}}{dt} = \boldsymbol{v}(\boldsymbol{x}_{\mathrm{p}})$$

Macro-particles move at the fluid velocity

$$\mathcal{N}(p, \tau) = \int d\Omega p^2 f_0 \approx 4\pi p^2 f_0$$

$$\frac{d\mathcal{N}}{d\tau} + \frac{\partial}{\partial E}\left[\left(-\frac{E}{3}\nabla_\mu u^\mu + \dot{E}_l\right)\mathcal{N}\right] = -\mathcal{N}\nabla_\mu u^\mu$$

Evolution equation for the distribution function
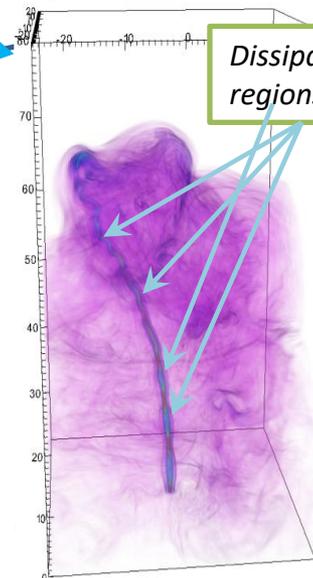
+

Energy losses, synchrotron, inverse Compton

Sub-grid model for acceleration at shocks (we take into account shock strength, orientation of magnetic field etc.)

Sub-grid model based on PIC simulations

Transport eq. for cosmic rays Parker1965, Jokipii &Parker 1970, Skilling 1975, Webb 1989.

Dissipation regions

Collisionless relativistic shocks

Relativistic magnetic reconnection

Vaydia+ 2018
Mukherjee+ 2021

How the RMHD models can talk to radioastronomers

RMHD eqs + particle transport eq
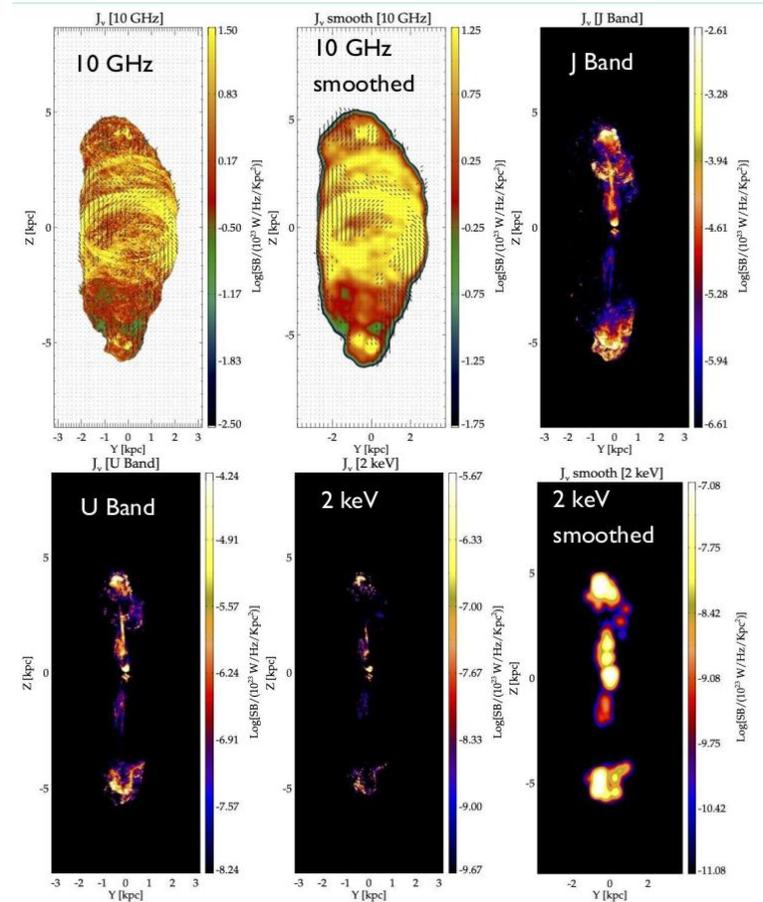
Spatial evolution
They move at fluid velocity
+

Spectral evolution
Radiative losses+sub-grid model for acceleration at shocks

Observational properties

… next

Bridging the gap between dynamical and radiative properties of jets is fundamental for comparing simulations with observations

This represents a challenge because of the huge scale differences.

Continuing to investigate sub-grid models in order to improve and to keep updated with the latest microphysical results.

Developing   a sub-grid model for particles acceleration at magnetic reconnection (Nurisso+ 2023, Suriano+ 2026)

……