High-Energy Astrophysics and Numerical Simulations

- Master Thesis in Physics -

[Curriculum Astrofisica - Fisica Teorica]

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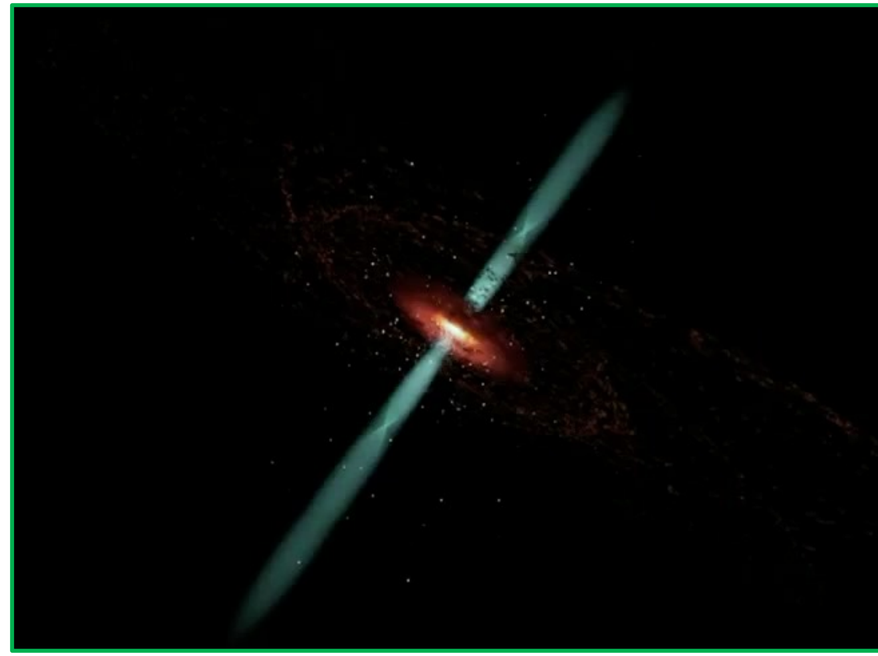
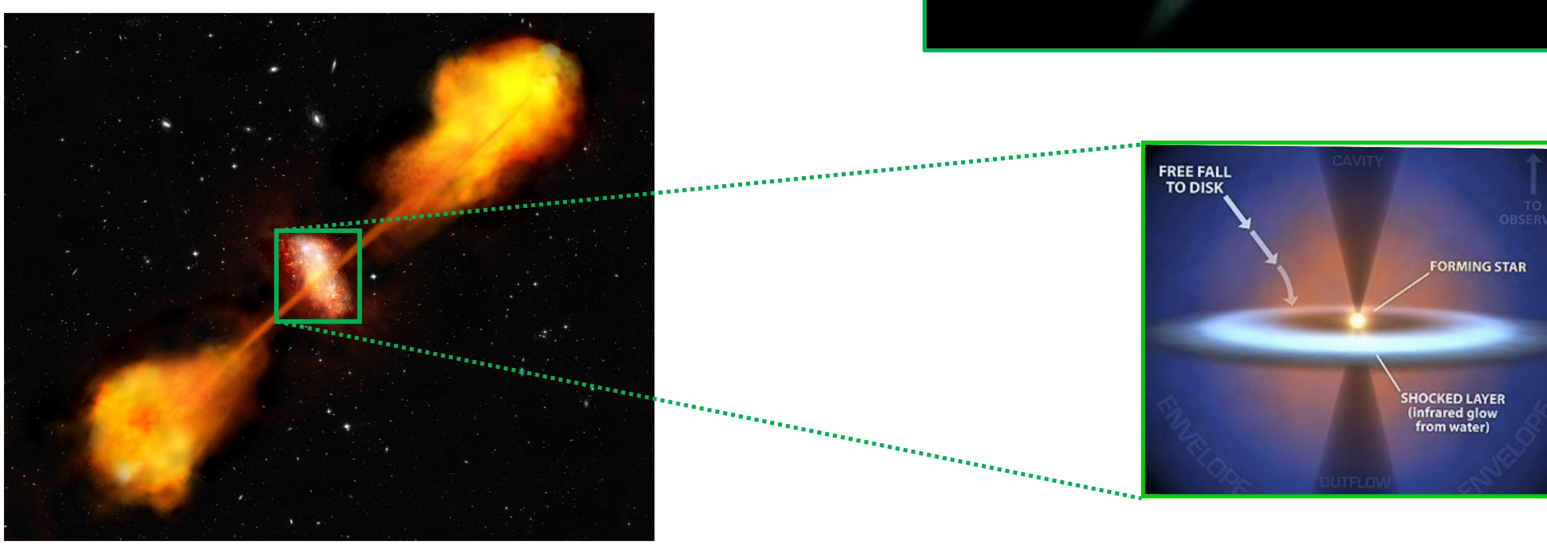
Physical Goals

Investigation of high-energy astrophysical environments characterized by relativistic flows, non-thermal emission signatures:

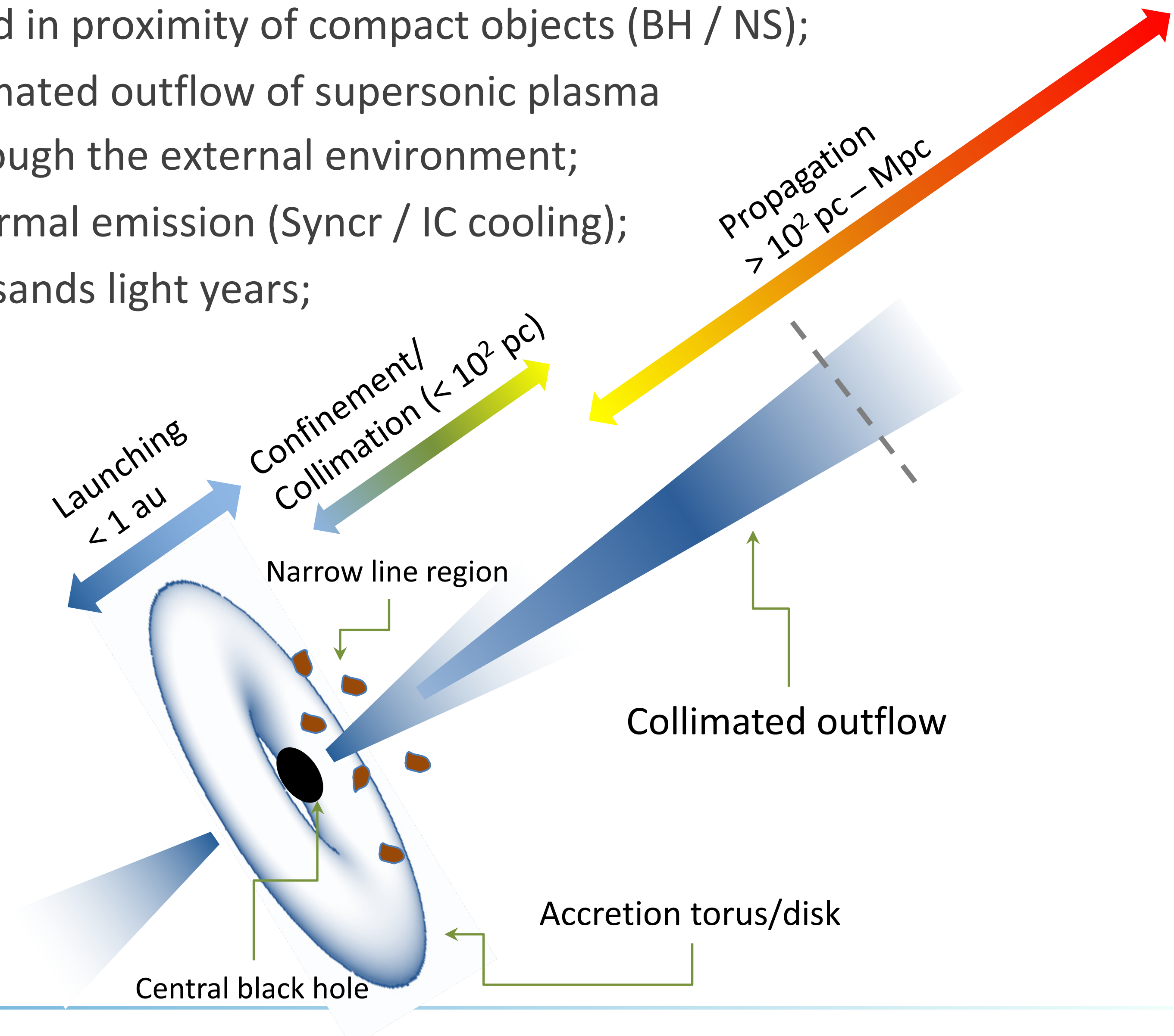
- Relativistic jets from Active Galactic Nuclei (AGN) / Pulsar Wind Nebuale (PWN) / Gamma Ray Burst (GRB);
- Accretion Disks;
- Particle acceleration;





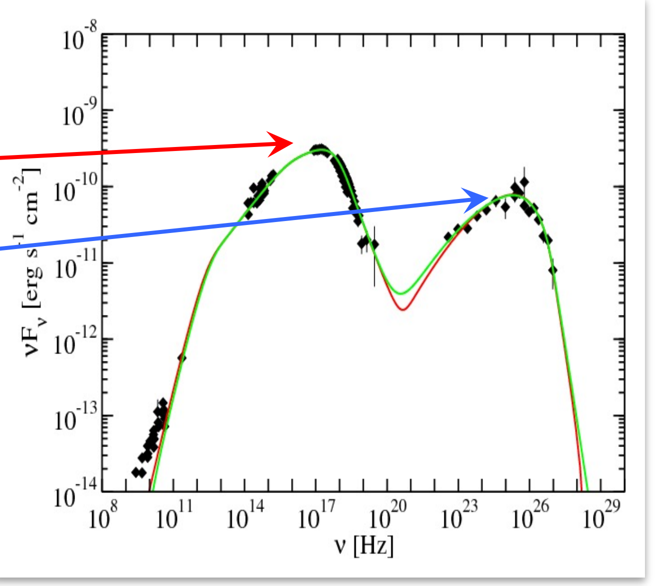
Relativistic Jets

- Jets are launched in proximity of compact objects (BH / NS);
- Relativistic collimated outflow of supersonic plasma propagating through the external environment;
- Feature non-thermal emission (Syncr / IC cooling);
- Survive for thousands light years;

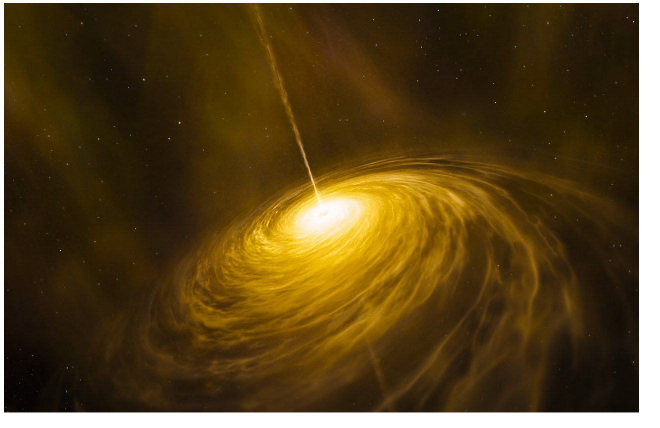


AGN Jets: Emission

- Spectral energy distribution (SED) features two broad humps:
  - *lower energy peak* (in the mm-UV band) → synchrotron emission
  - *higher energy peak* (X- and γ-rays) → inverse Compton scattering.



- Strong variability (blazars) on timescales < day → very compact emission regions where a sizeable fraction of the jet energy flux must be dissipated.

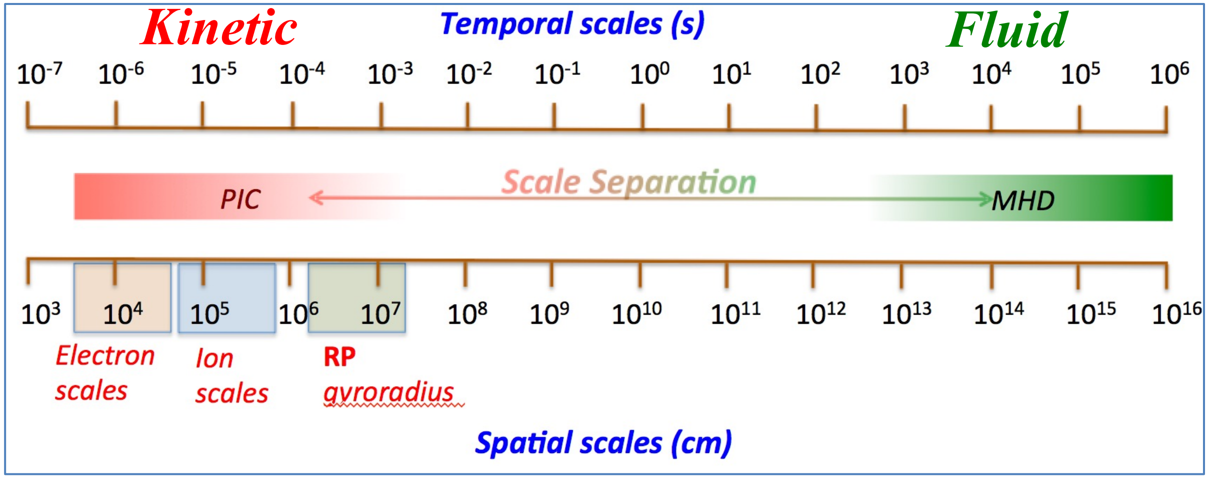


- Part of this energy becomes available to accelerate particles to ultra-relativistic energies.

Challenge: Scale Separation

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

- Current computational *modeling* is still *largely fragmented* under the limited range of applicability of different models.



- A **large gap** stretches from theory to a clear interpretation of the observations of high-energy astrophysical sources.

Numerical Simulations

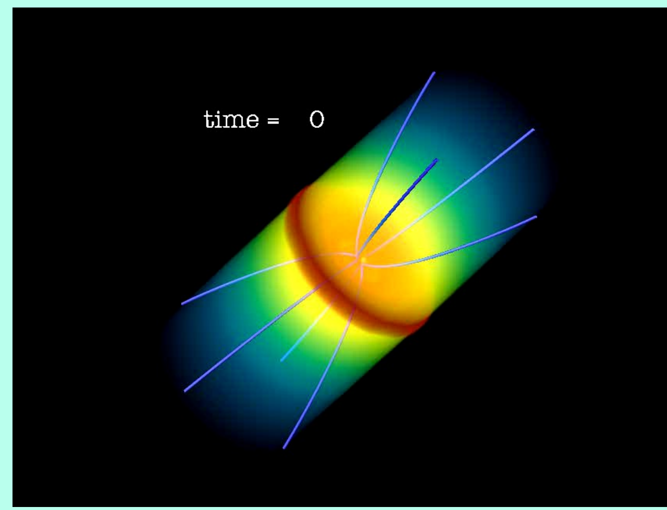
- Owing to the complexities of the equations and their nonlinear behavior, theoretical models based on astrophysical fluids / plasma are approached by means of numerical simulations;
- Results are compared with observation → validation of theoretical models.

Theoretical Model

$$
\begin{aligned}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) &= 0 \\
\frac{\partial (\rho \boldsymbol{v})}{\partial t} + \nabla \cdot \left(\rho \boldsymbol{v}\boldsymbol{v}^T\right) + \nabla p &= \nabla \cdot \Pi \\
\frac{\partial E}{\partial t} + \nabla \cdot \left[(E+p)\,\boldsymbol{v}\right] &= \nabla \cdot (\boldsymbol{v} \cdot \Pi) + \nabla \cdot \boldsymbol{F}_c
\end{aligned}
$$

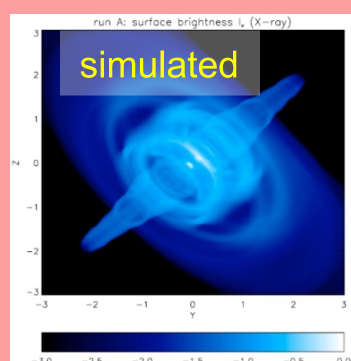
Parameter Dependence

Numerical Simulations



Results Analysis

Observational Comparison



Model Equations

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho\mathbf{u}) = 0 \qquad \text{(Mass cons.)}$$

$$\frac{\partial (\rho\mathbf{u})}{\partial t} + \nabla\cdot\left[\rho\mathbf{u}\mathbf{u} - \frac{\mathbf{B}\mathbf{B}}{4\pi} + \left(p + \frac{\mathbf{B}^2}{8\pi}\right)\mathsf{I}\right] = 0 \qquad \text{(Momentum cons.)}$$

$$\frac{\partial E}{\partial t} + \nabla\cdot\left[\left(E + p + \frac{\mathbf{B}^2}{8\pi}\right)\mathbf{u} - \frac{(\mathbf{u}\cdot\mathbf{B})}{4\pi}\mathbf{B}\right] = 0 \qquad \text{(Energy cons.)}$$

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla\cdot(\boldsymbol{u}\boldsymbol{B} - \boldsymbol{B}\boldsymbol{u}) = 0 \qquad \text{(Mag. flux cons.)}$$

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho\mathbf{u}) = 0 \qquad \text{(Continuity)}$$

$$\rho\left(\frac{\partial}{\partial t} + \mathbf{u}\cdot\nabla\right)\mathbf{u} + \nabla p - \frac{1}{c}\mathbf{J}\times\mathbf{B} = 0 \qquad \text{(Eq. of motion)}$$

$$\frac{\partial (\rho e)}{\partial t} + \nabla\cdot(\rho e\,\mathbf{u}) + p\nabla\cdot\mathbf{u} = 0 \qquad \text{(Thermodynamics I law)}$$

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla\times\mathbf{E} = 0 \qquad \text{(Faraday)}$$

- MHD suitable for describing plasma at large scales;
- Good first approximation to much of the physics, even when some of the conditions are not met.
- Draw some intuitive conclusions concerning plasma behavior without solving the equations in detail.
- Fluid equations are hyperbolic partial differential equations, also known as *hyperbolic* conservation laws.

$$\mathbf{J} = \frac{c}{4\pi}\nabla\times\mathbf{B} \qquad \text{(Ampere)}$$

$$\mathbf{E} + \frac{\mathbf{u}}{c}\times\mathbf{B} = 0 \qquad \text{(Ohm)}$$

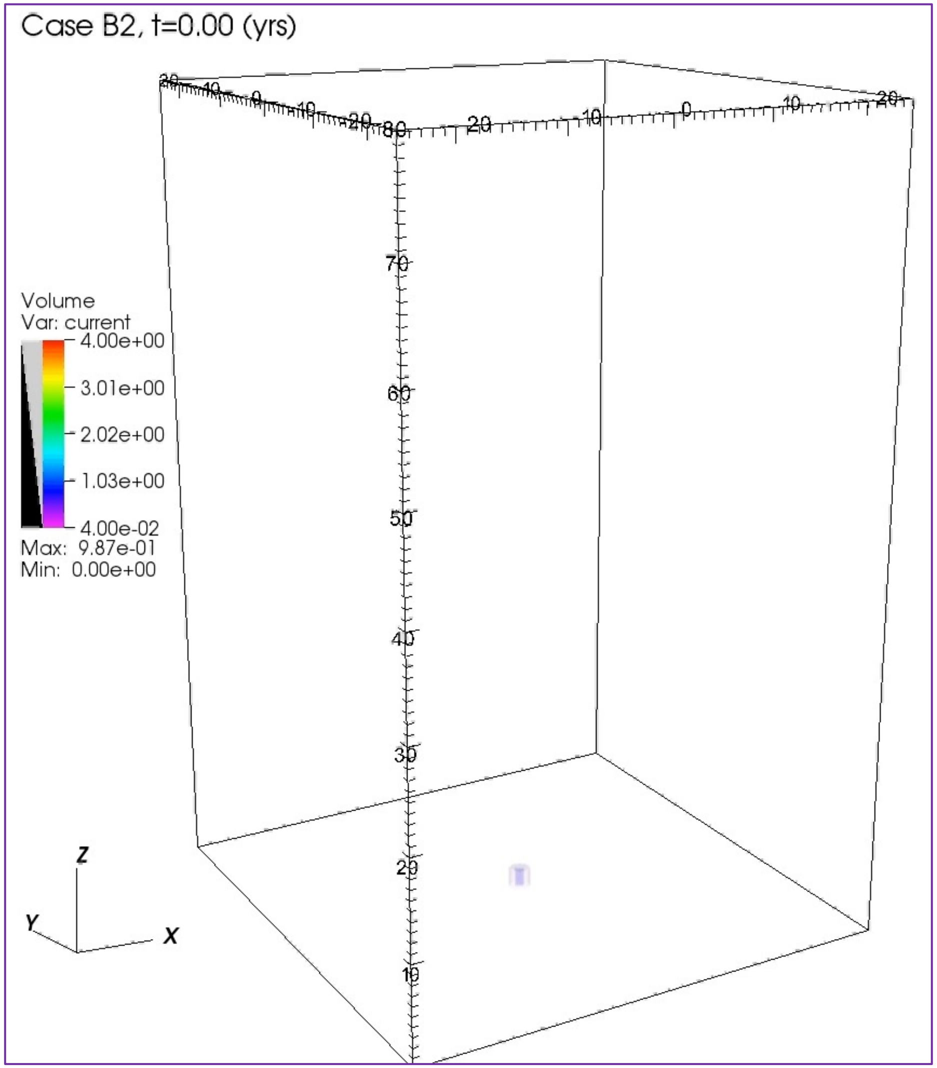
$$\nabla\cdot\mathbf{B} = 0 \qquad \text{(Divergence} - \text{free)}$$

$$\rho e = \rho e(\rho, p) \qquad \text{(EoS/Closure)}$$

Jet Propagation: Open Questions

Jet propagation still accompanied by a number of unsresolved questions:

- What is causing the difference in the observed morphologies ? (FRI-FRII)
- How do jet loose collimation and decelerate ? → dissipation problem.
- Are jets Poynting- or kinetically-dominated ?
- What is accelerating particles to ultra-relativistic energies ? What is causing strong variability ?
- Where does emission originate rom ?
- What fraction of the jet energy becomes available to accelerate particles to ultra-relativistic energies ?



Jet Instabilities

- Jets may be prone to three types of instabilities,

Kelvin-Helmholtz (KHI):

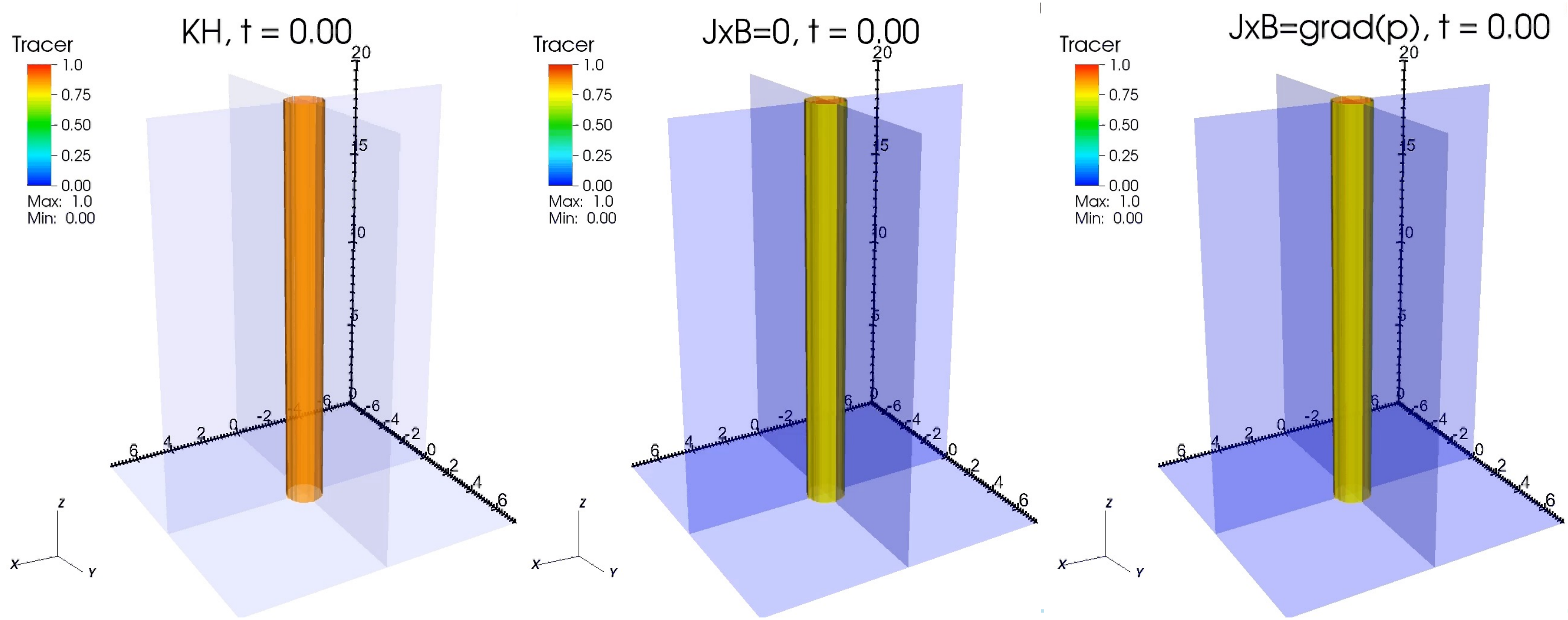
driven by relative velocity shear → mixing, momentum & energy transfer, entrainment .

Current-Driven (CDI) :

driven by || component of current, small pitch → helical deformation.

Pressure-Driven (PDI):

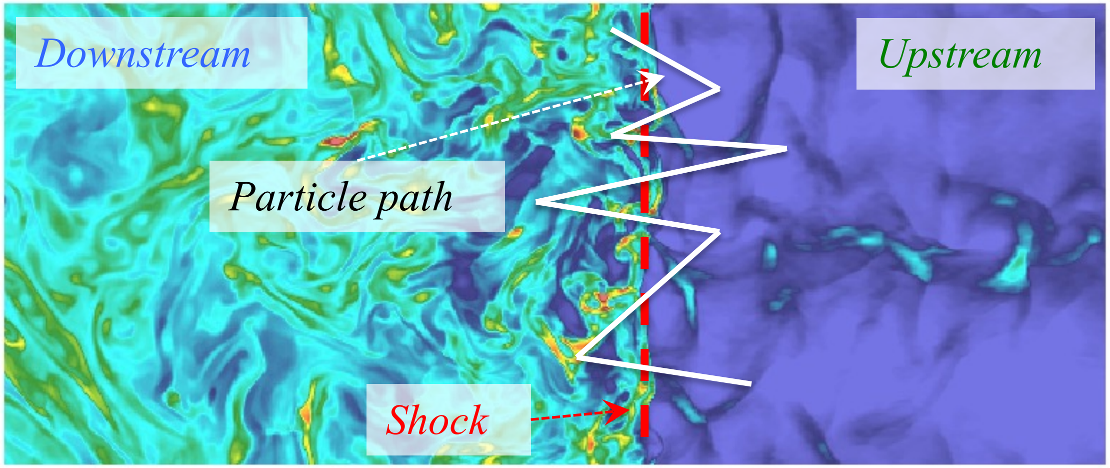
driven by the ⊥ component of current → interchange modes (like RT)



Particle Acceleration at Shocks

- Diffusive Shock Acceleration (DSA) commonly invoked to explain production of high energy Cosmic Rays (CR) at shock waves.

- Acceleration of charged particles when being repeatedly scattered across a shock front;



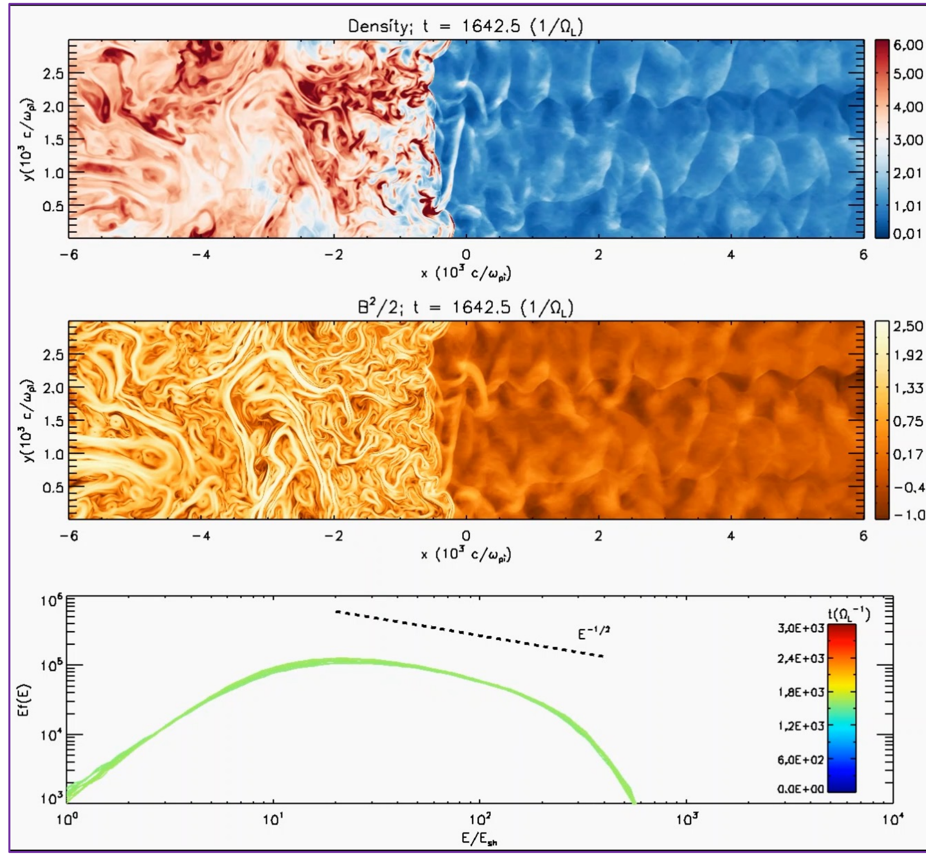
- Important in many astrophysical models (e.g. solar flares and SNR).

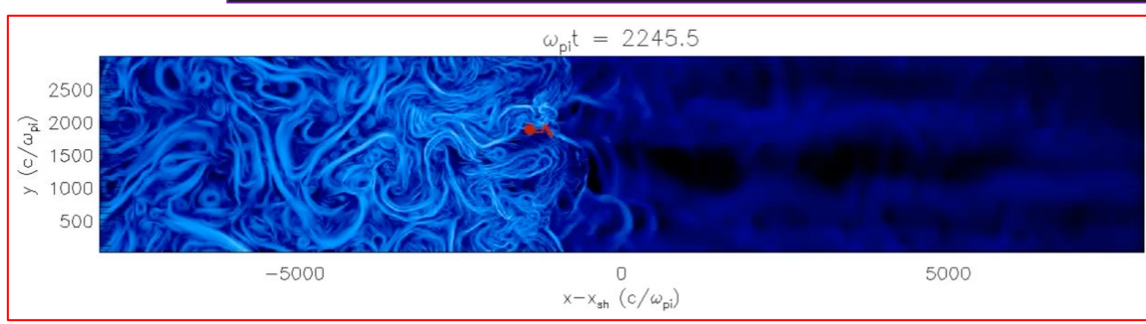
- Scattering comes from magnetic field irregularities (acting as magnetic mirrors) / Alfvén waves → Requires substantial magnetic field amplification → Bell instability

- Steady-state DSA theory predicts spectrum dN/dE = f(E) ≈ $E^{-3/2}$ (for non-relativistic shocks)

Particle Acceleration at Shocks

- CR scattered by local turbulent magnetic field irregularities.
- Accelerated CRs drift with respect to the upstream fluid and the instability typically quickly enters its strongly nonlinear stage.
- Particles spectrum broadens in time, extending substantially to the high energy side.
- A high-energy power-law tail builds up[1,2], with spectral slope consistent with -3/2.
- The high-energy tail extends to higher energies with time, with a exponential energy cutoff.





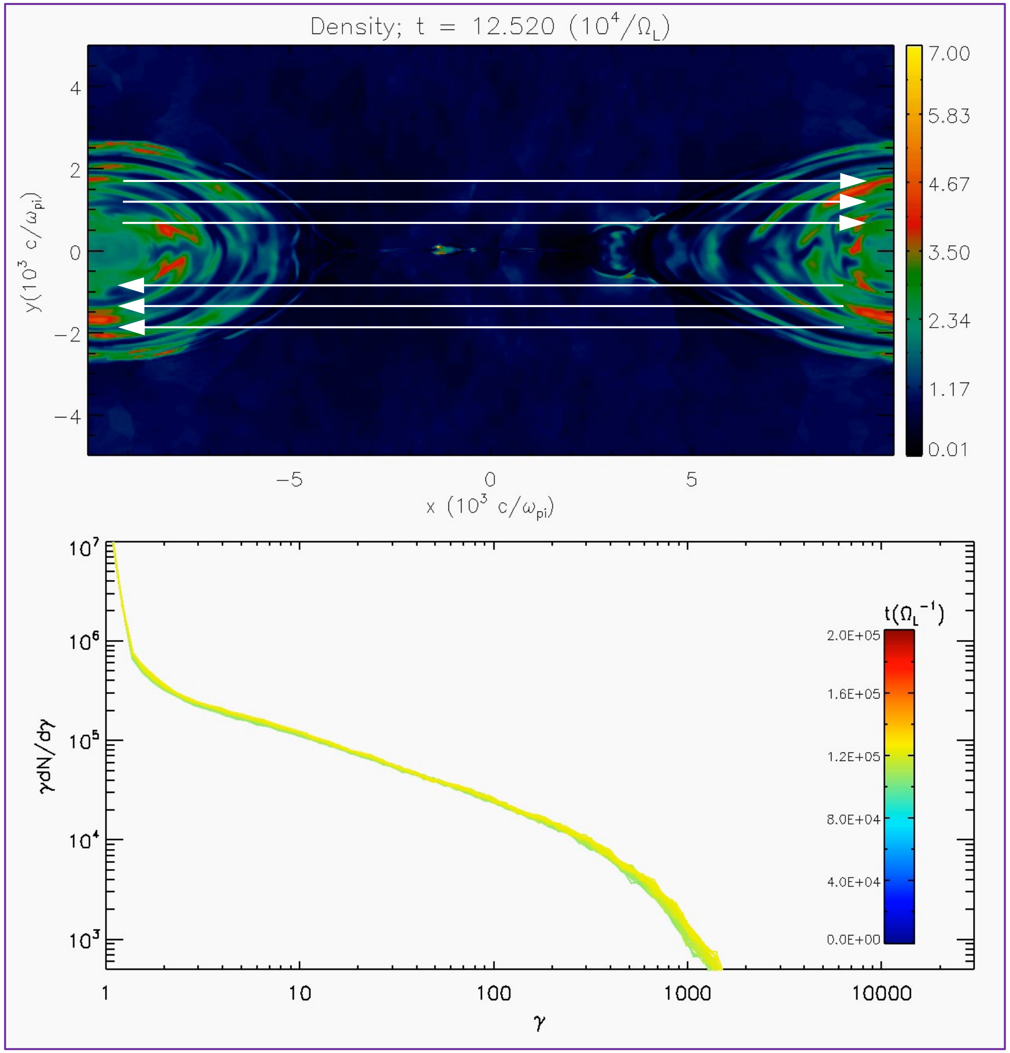
[1]Bai et al. ApJS (2015) 809:55, [2]Mignone et al. ApJS (2018) 859:13

Particle acceleration at current sheets

- Magnetic reconnection: topological rearrangement of magnetic field lines with opposite polarity → efficient dissipation of magnetic energy into heat, kinetic energy and particle acceleration.

- Spectrum: $$\frac{dN}{d\gamma} = N_0 \left(\frac{\gamma}{\gamma_0}\right)^{-p}$$

- Simulations predict particles spectra with a power law with slope p ≈ 4 for σ=1; p ≤ 2 for σ≥10 (harder than in relativistic shocks[1])



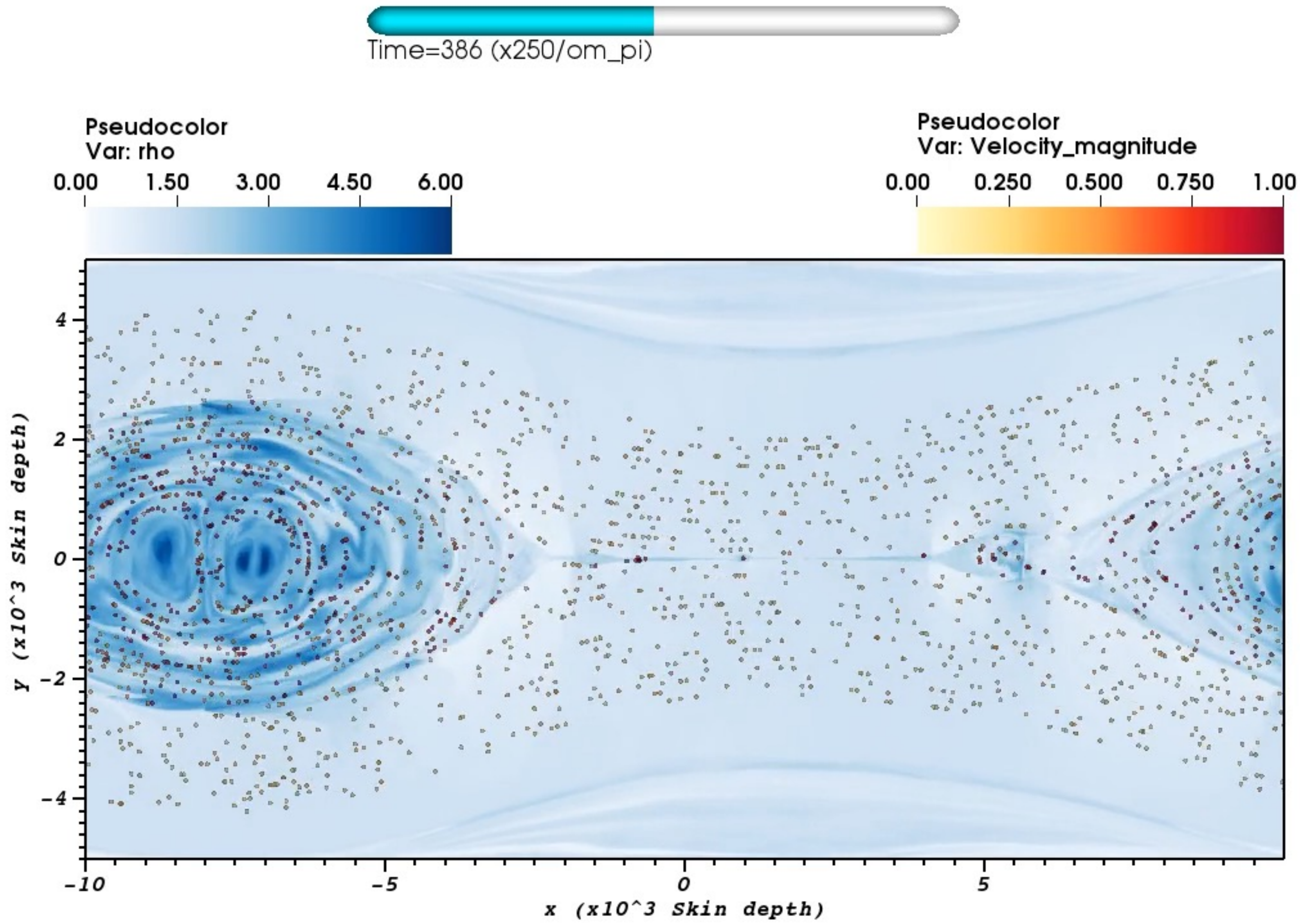
[1]Siron & Spitkovsky. ApJL (2014)

Particle acceleration at current sheets

2D / 3D numerical simulation of relativistic reconnection + test particles;

Three main acceleration mechanisms:

1. ***X-point***
2. ***Island merging***
3. ***1st-order Fermi***

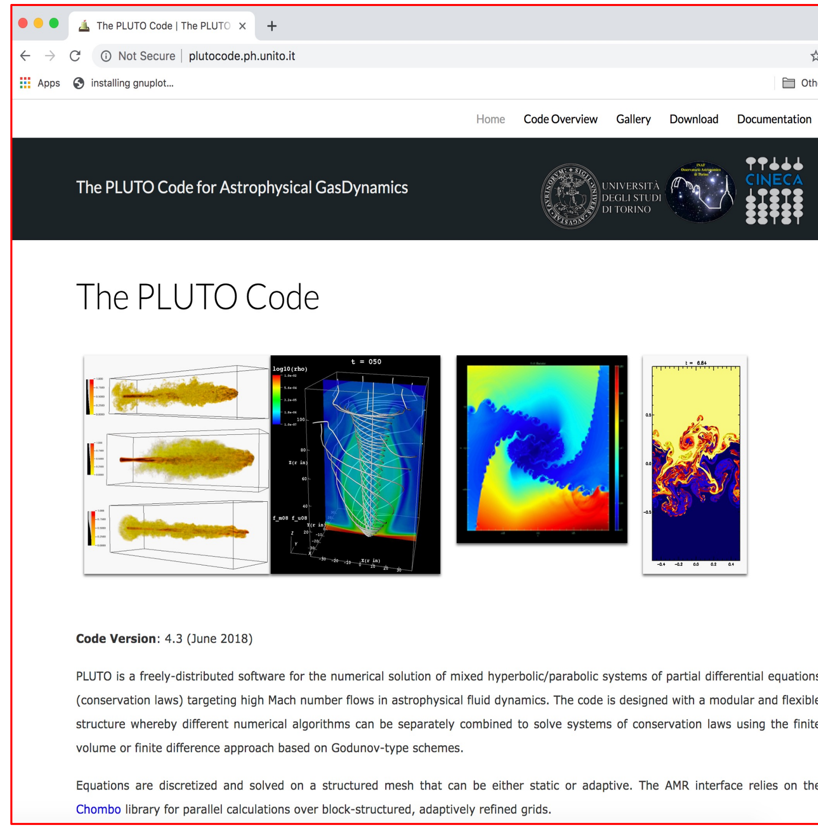


Tools: the PLUTO Code

- PLUTO[1,2] is a modular parallel code providing a *multi-physics* as well as a *multi-algorithm* framework for solving the equations of gas and plasma dynamics in astrophysics;

- *Target*: multidimensional *compressible* plasma with high Mach numbers:

  – Compressible Euler/Navier Stokes;
  – Newtonian (ideal/resistive) magnetohydrodynamics (MHD);
  – Special Relativistic hydro and MHD;
  – Heating/cooling processes, chemical netword, …
  – Particle physics



- Freely distributed at http://plutocode.ph.unito.it (v. 4.3)

[1]Mignone et al. ApJS (2007), 170, 228-242; [2]Mignone et al, ApJS (2012), 198, 7

Thesis Requirements

Several physical area can convey into an astrophysical problem,

- Dynamics (Newton's laws);
- Electromagnetism;
- Thermodynamics;
- Fluid dynamics / Plasma physics;
- Radiative Processes;
- (Special) Relativity;

Also, acquaintance with Linux-like operative system is required:

- Knowledge or know-how of Linux shell;
- Basic knowledge of C or C++ programming;
- Employment of a pc essential;

Thesis Flowchart

- For the thesis, an astrophysical problem of interest is chosen (jet propagation / jet instabilities / particle acceleration).
- Student contribution to the subject must be original.
- Reading of most relevant work on the topic is the 1st step.
- The model is constructed and understood;
- Numerical simulations are performed.
- Data analysis is through python / IDL (or other) is crucial in order to understand / interpret the results;
- Conclusions are drawn.

~9 months

Algorithm Development

- Upon request, the topic can be more numerically-oriented;
- This rerquires code development to implement specific numerical methods that are essential for the problem at hand.
- In this case, intermediate / advance knowledge of C / C++ is necessary.

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Thank you for your attention

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