Simulations of unstable recollimation shocks and Fermi-like particle acceleration

Agnese Costa, INAF Brera - Università degli Studi dell’Insubria

Alberto Sciaccaluga, INAF Brera - Dipartimento di Fisica di Genova

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2018-2022
DIPARTIMENTO
DI ECCELLENZA
MIUR

Overview

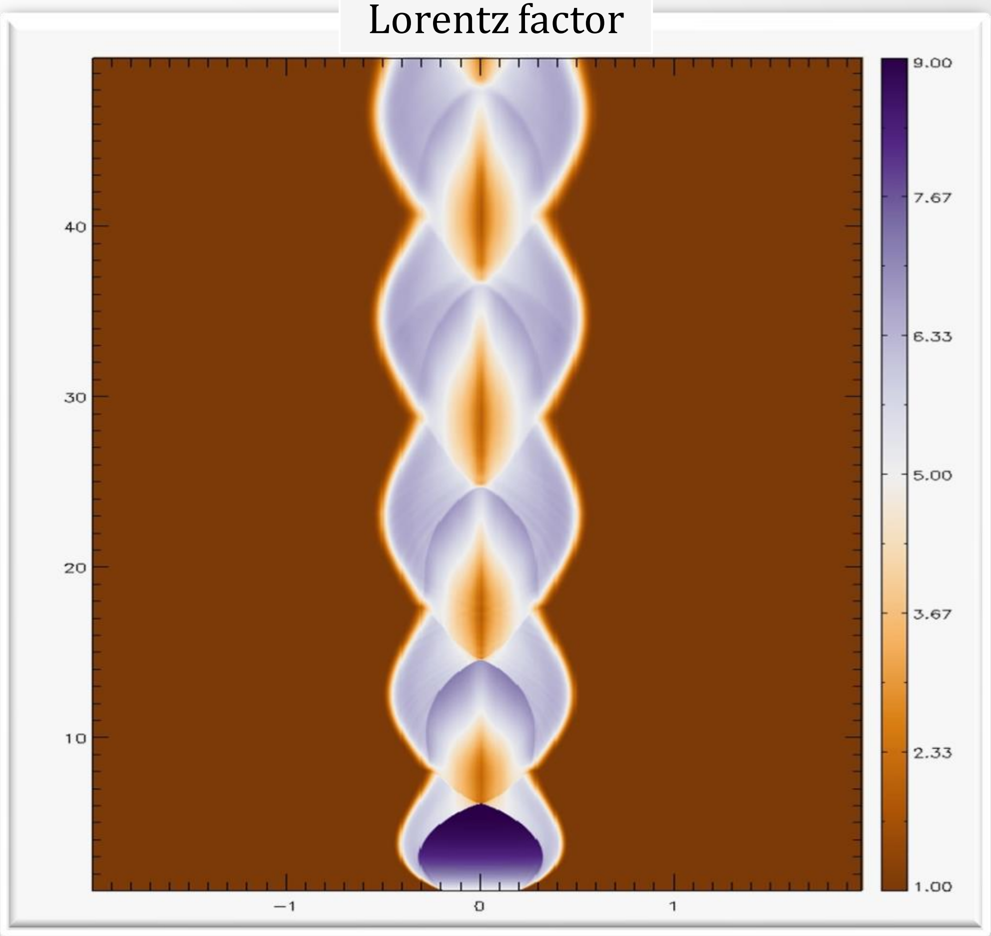
- Recollimation shocks in jets
- 3D vs 2D hydrodynamical jets
- Magnetized jets for extreme TeV blazars
- Extreme TeV blazars
- Hybrid DSA+SA model

Recollimation shocks in jets

Confinement due to flatter external pressure profile:

$$p_e \alpha\, z^{-\eta} \text{ with } \eta < 2$$

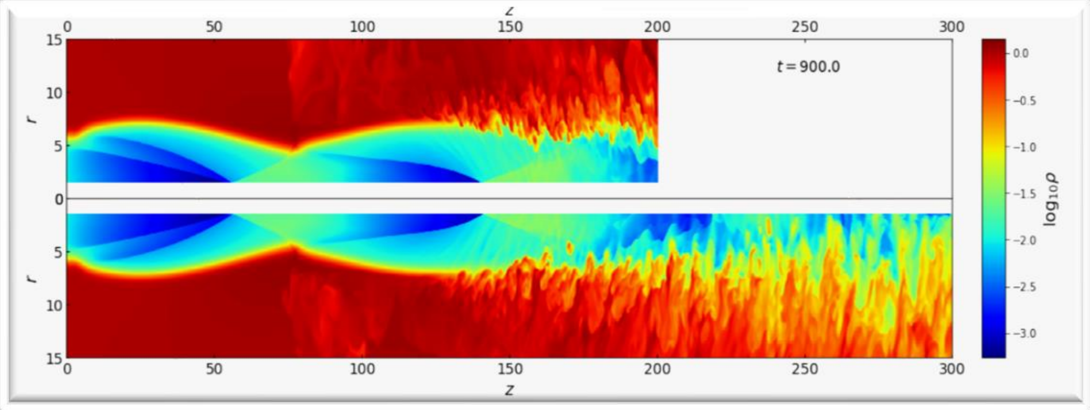
Well known Fermi I acceleration mechanism


Lorentz factor

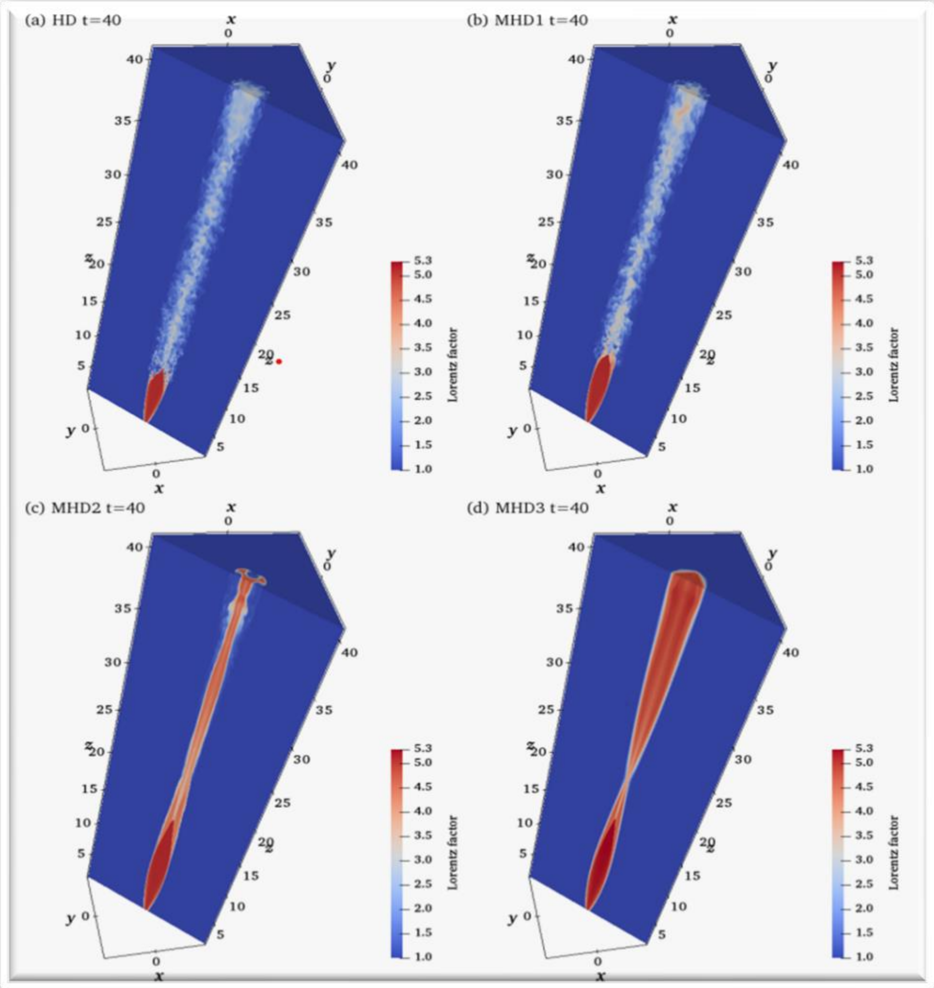
2D vs 3D (hydro)dynamical jets

Some instabilities cannot develop in 2D axisymmetry:

- CFI (/RTI) after the recollimation shock, in low magnetized jets ($\sigma = \frac{B^2}{4\pi\omega} \leq 10^{-4}$)
- RMI from the reflection shock



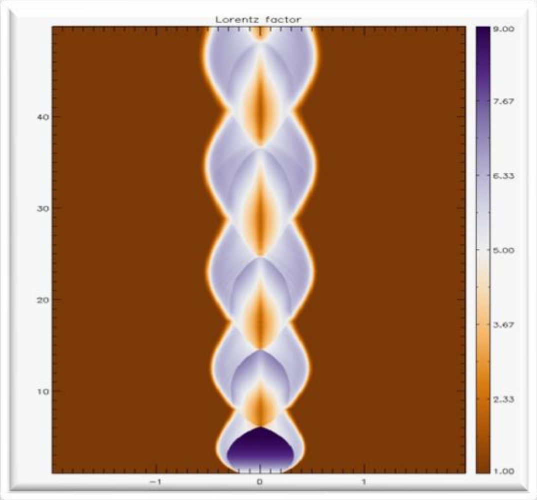
Abolmasov, Bromberg, 2022



Matsumoto, Komissarov, Gourgouliatos, 2021

3D hydrodynamical jets

3D started from the 2D steady state



Run for approximately 1.5 light crossing time of the domain (in z).

3D hydrodynamical jets

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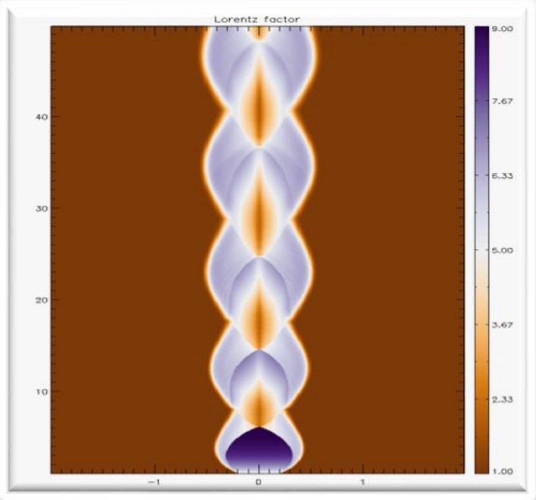

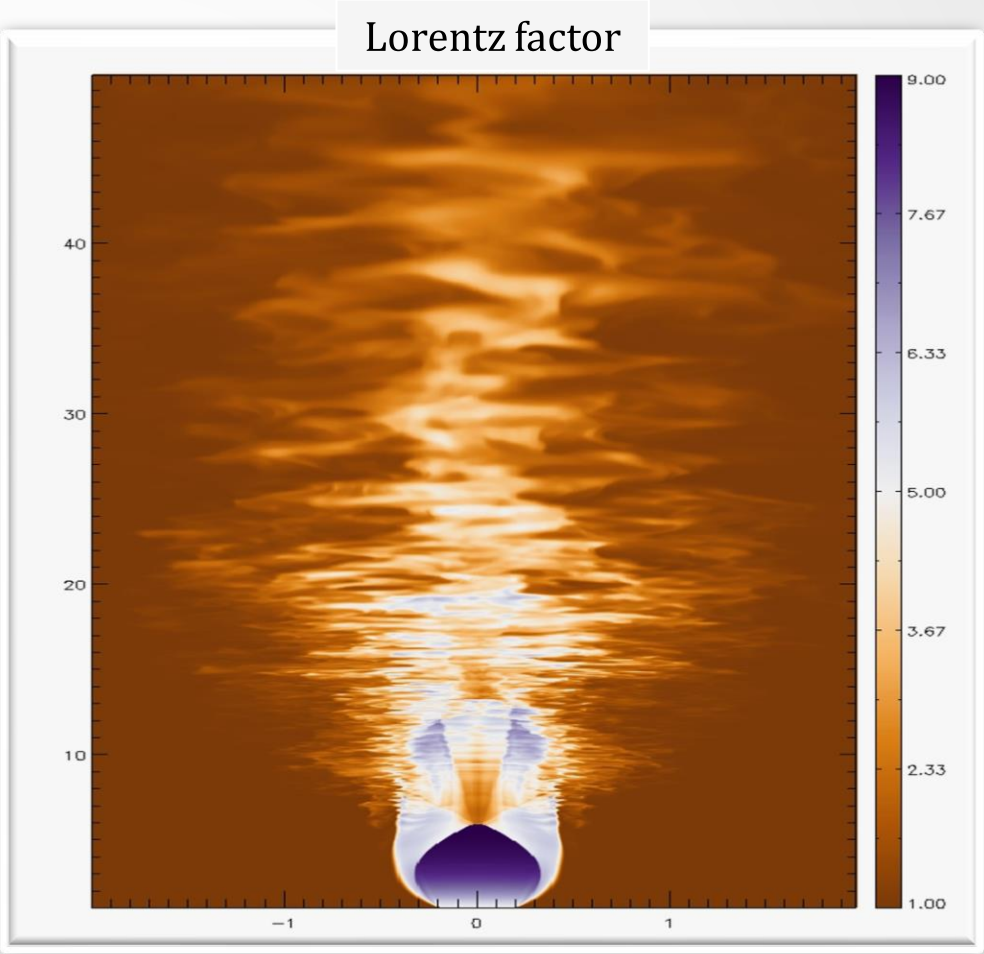
Lorentz factor

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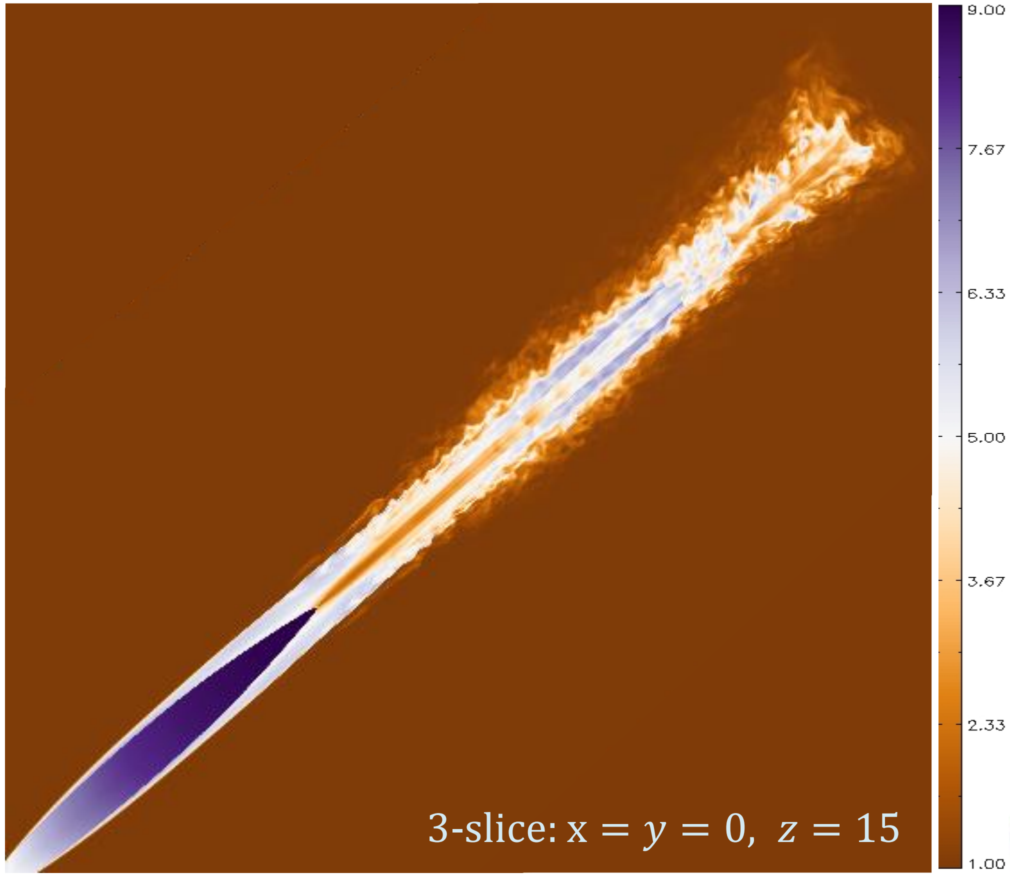
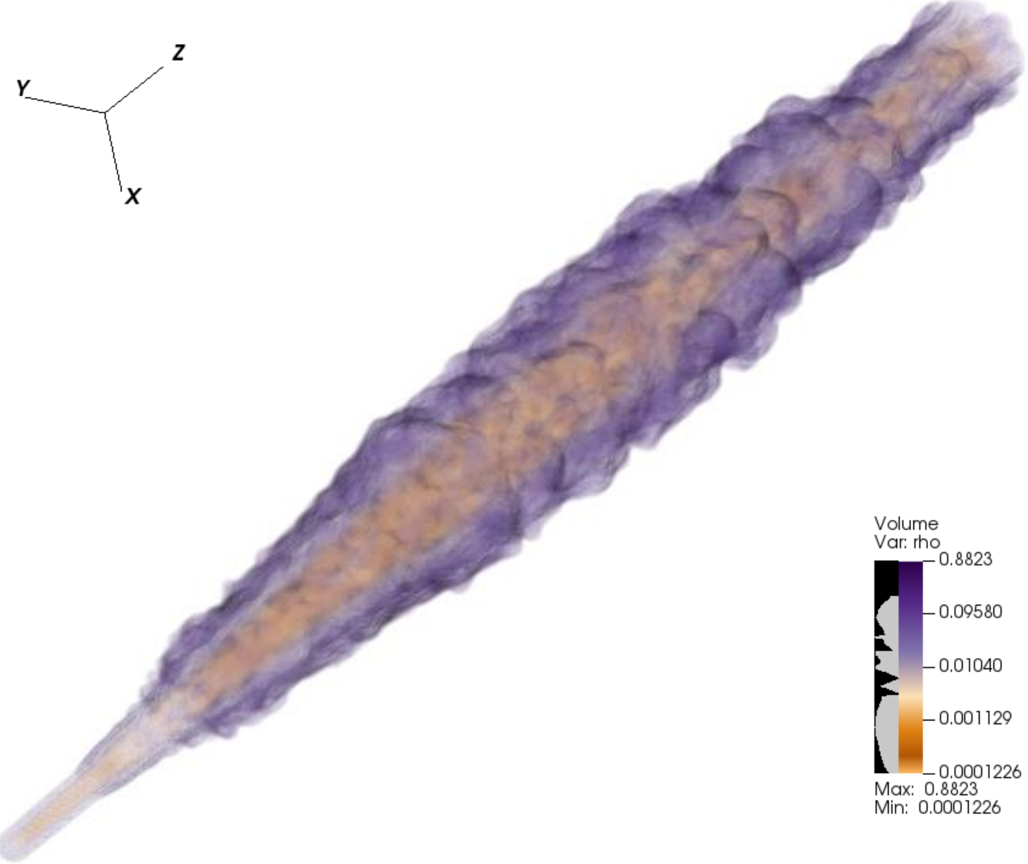
3D hydrodynamical jets

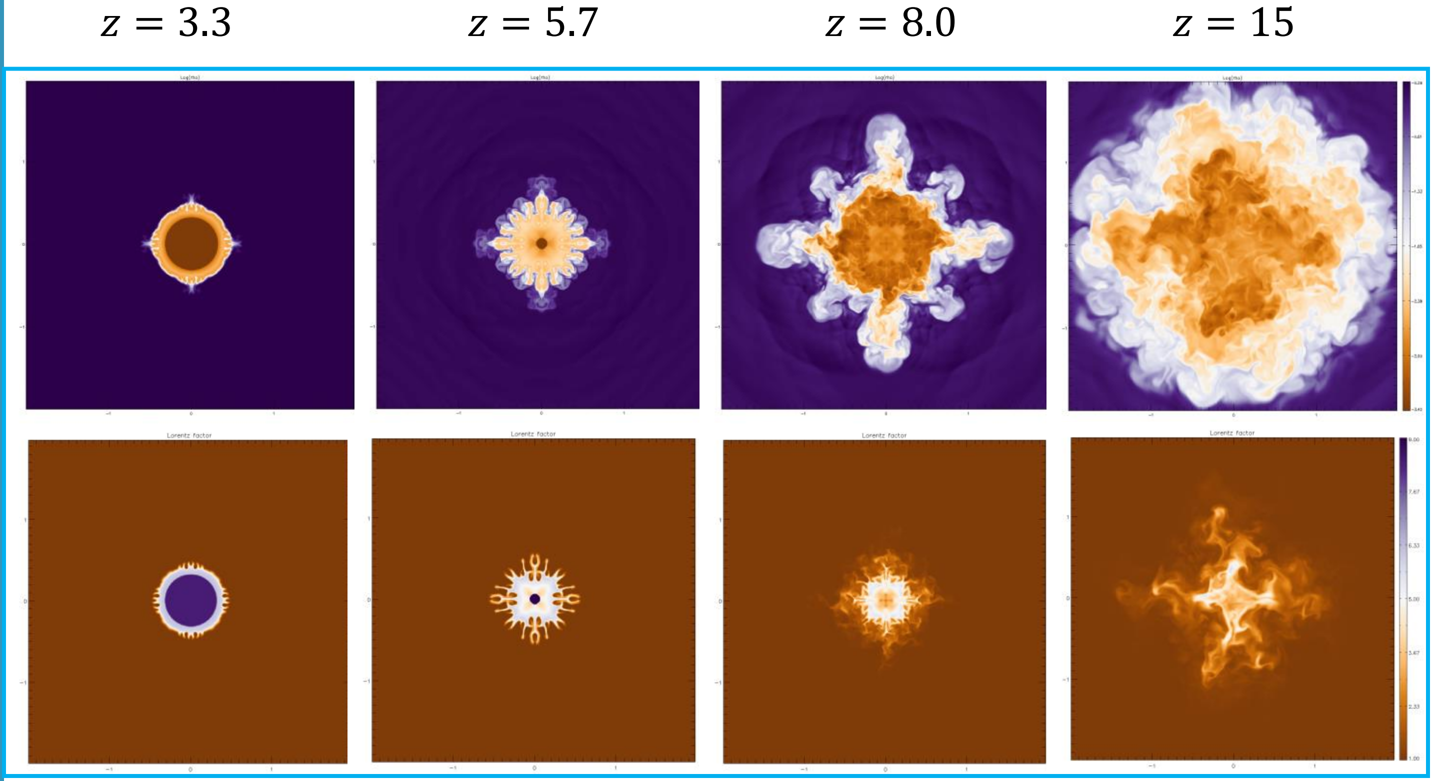
Lorentz factor

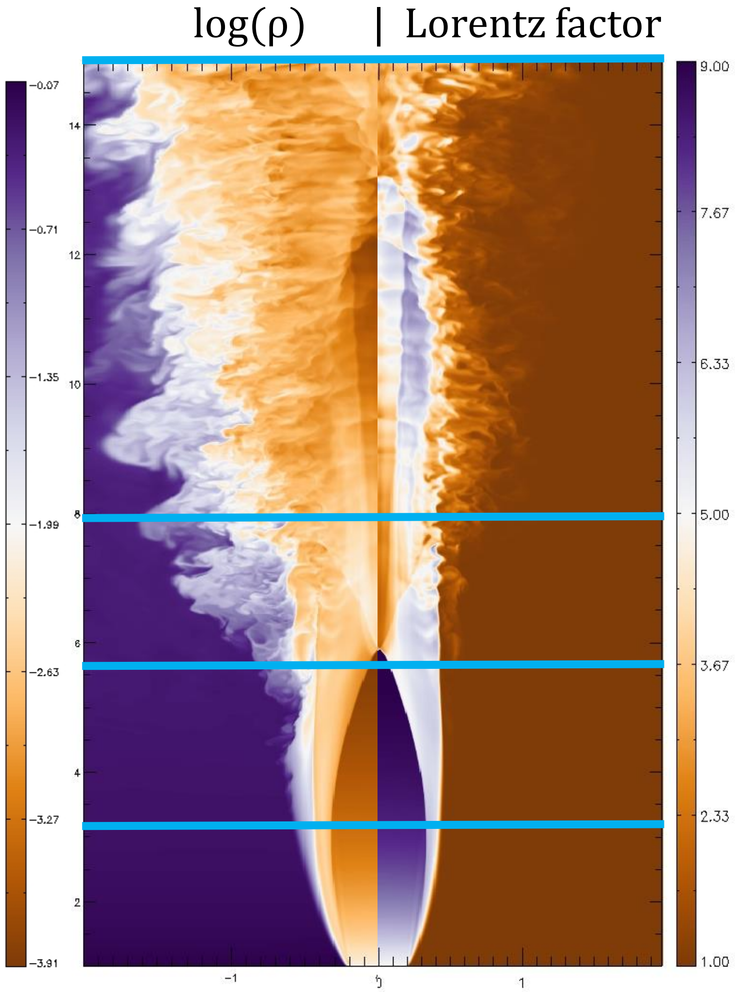

3-slice: $x = y = 0, \ z = 15$

Density



3D hydrodynamical jets





RTI at stages dominated by cartesian m=4
RMI dominates after the reflection shock and there is mixing
Turbulence develops and the jet is slowed after a few shocks.

3D hydrodynamical jets

1. Is the jet being disrupted by the instabilities?

2. Is there any sign of the KH instability?

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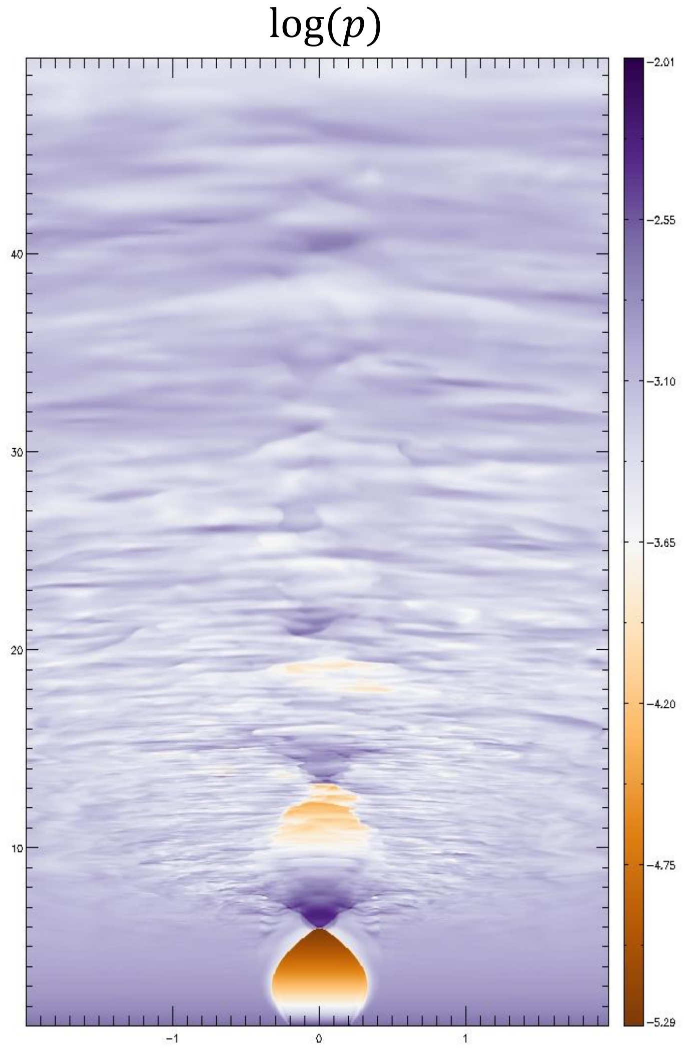
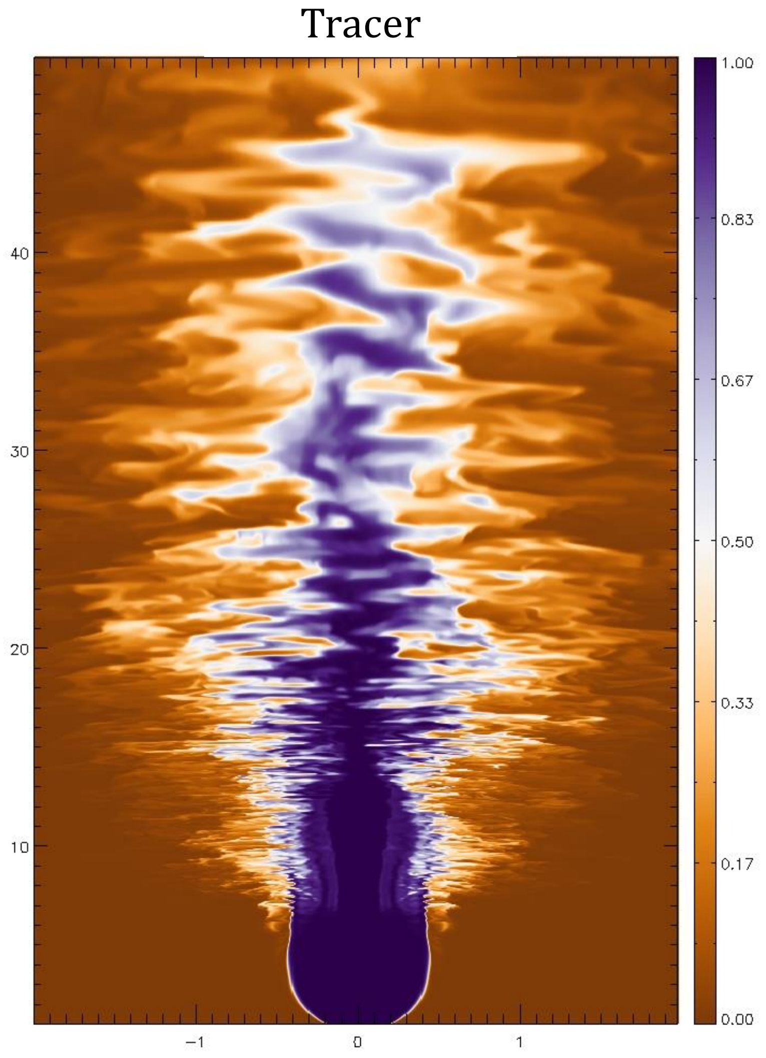


$\log(p)$

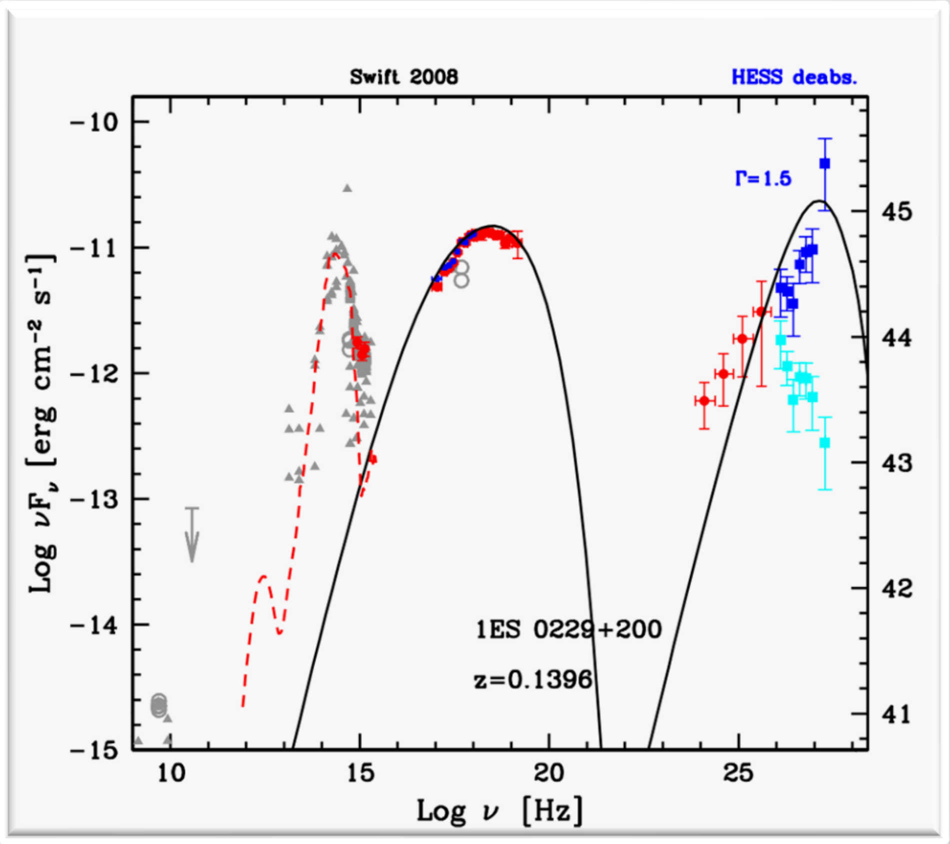


Tracer

Magnetized jets for TeV blazars

Setup

- high Lorentz factor
- low magnetization
- pc scale confined jet

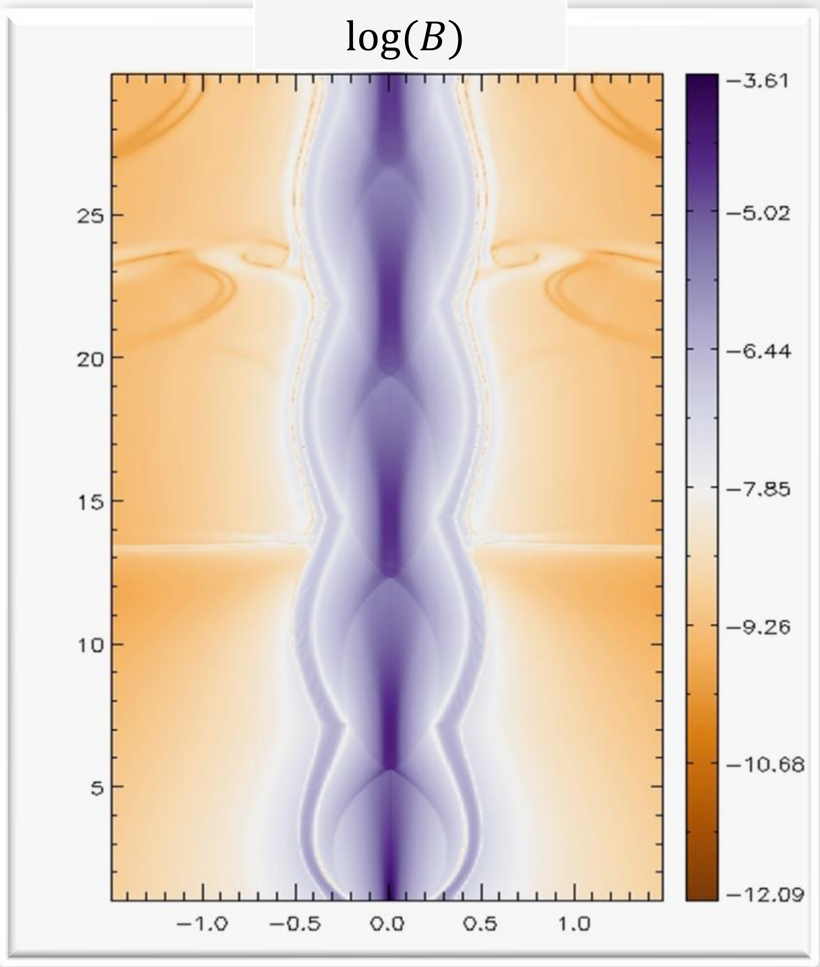


Tavecchio, Costa, Sciaccaluga, 2022

Magnetized jets for TeV blazars

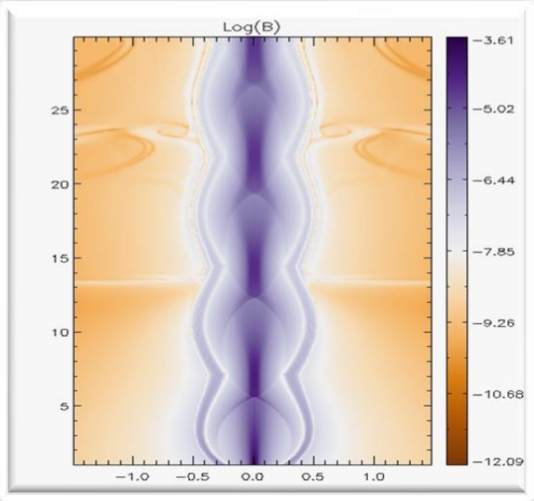
Setup

- high Lorentz factor: $\Gamma_0 = 5$
- **low magnetization:** $\sigma = 10^{-5}$
  $B_0 \simeq 3 \times 10^{-3}$ G
  poloidal and dumped outside the jet
- **pc scale confined jet**

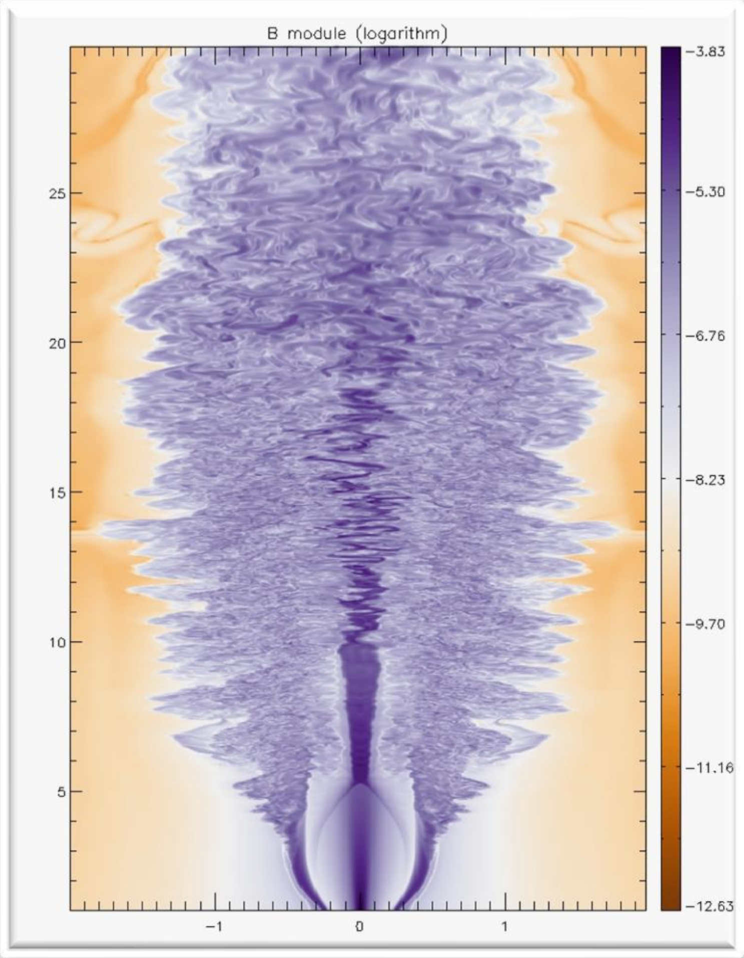


Magnetized jets for TeV blazars

3D started from the 2D steady state



Run for approximately 1 light crossing time of the domain (in z).

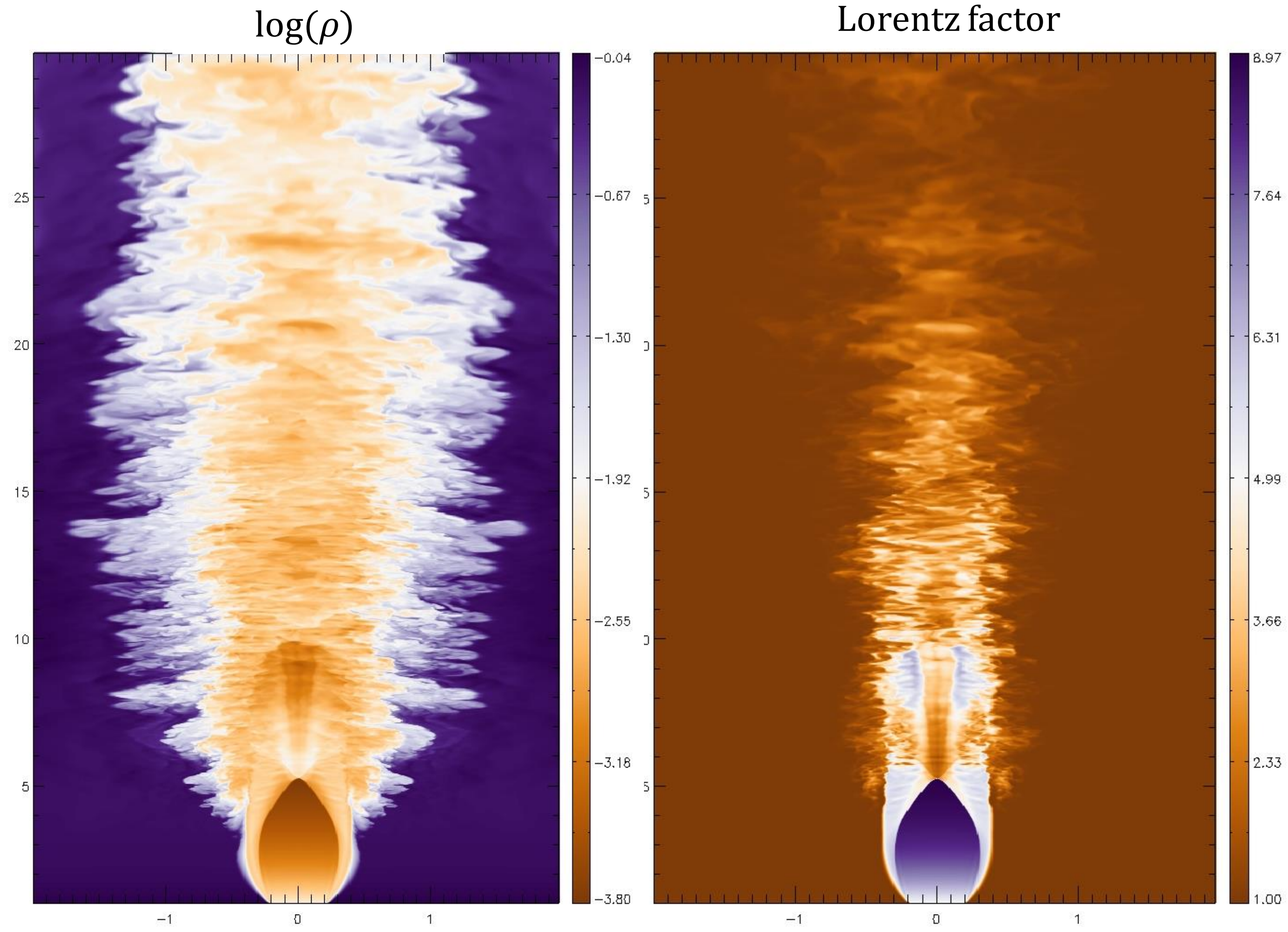


Magnetized jets for TeV blazars

1. Does the magnetic field stabilize the jet?

2. What’s the role of the magnetic field?

Magnetized jets for TeV blazars



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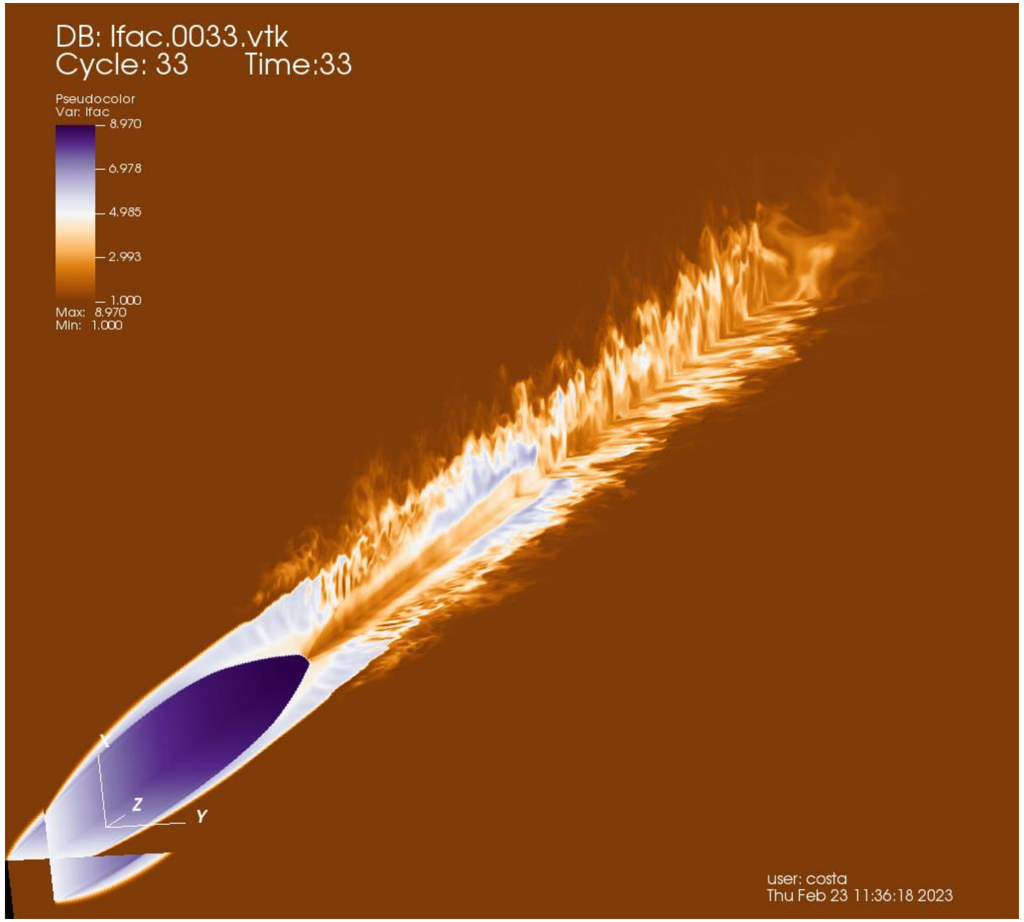

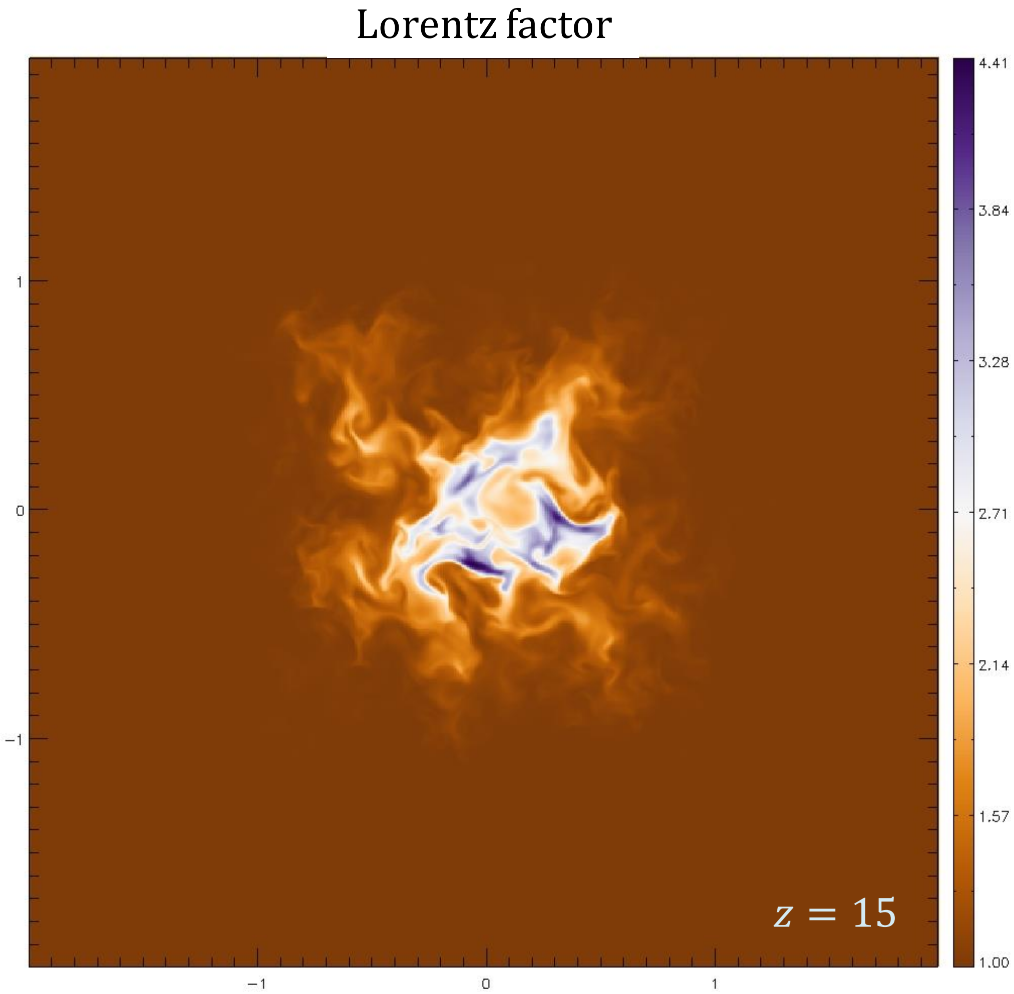
Lorentz factor

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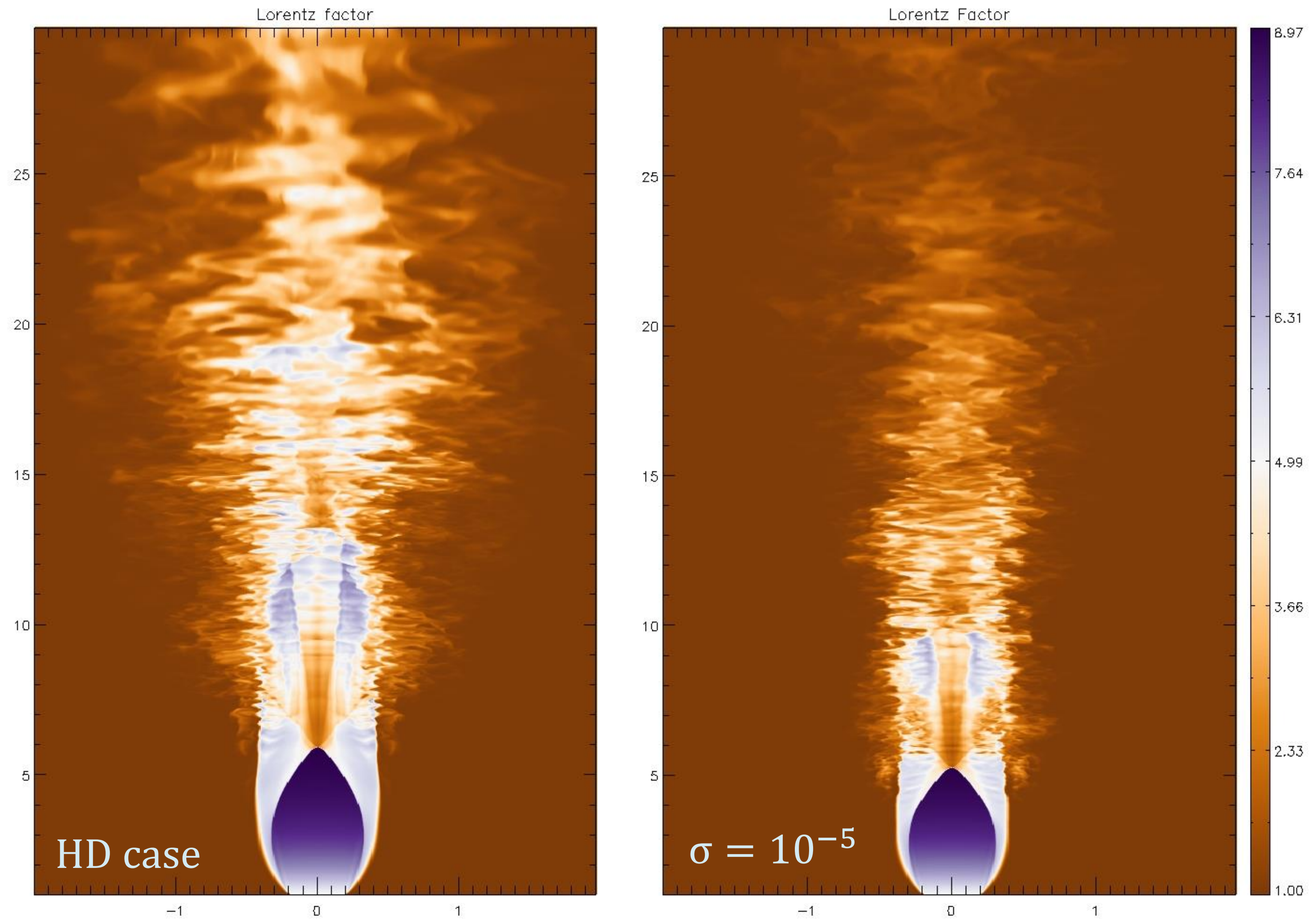


What’s next?

1. Does the magnetic field stabilize the jet?
2. What’s the role of the magnetic field?
3. What happens at higher magnetization?

   Two sets of simulations ongoing with $\sigma = 10^{-2}$ and $\sigma = 5 \times 10^{-1}$
4. The impact on particle acceleration

   Next set of simulations with particles added to the 3D unstable jet
5. Exploration of the parameters: e.g. higher Lorentz factor

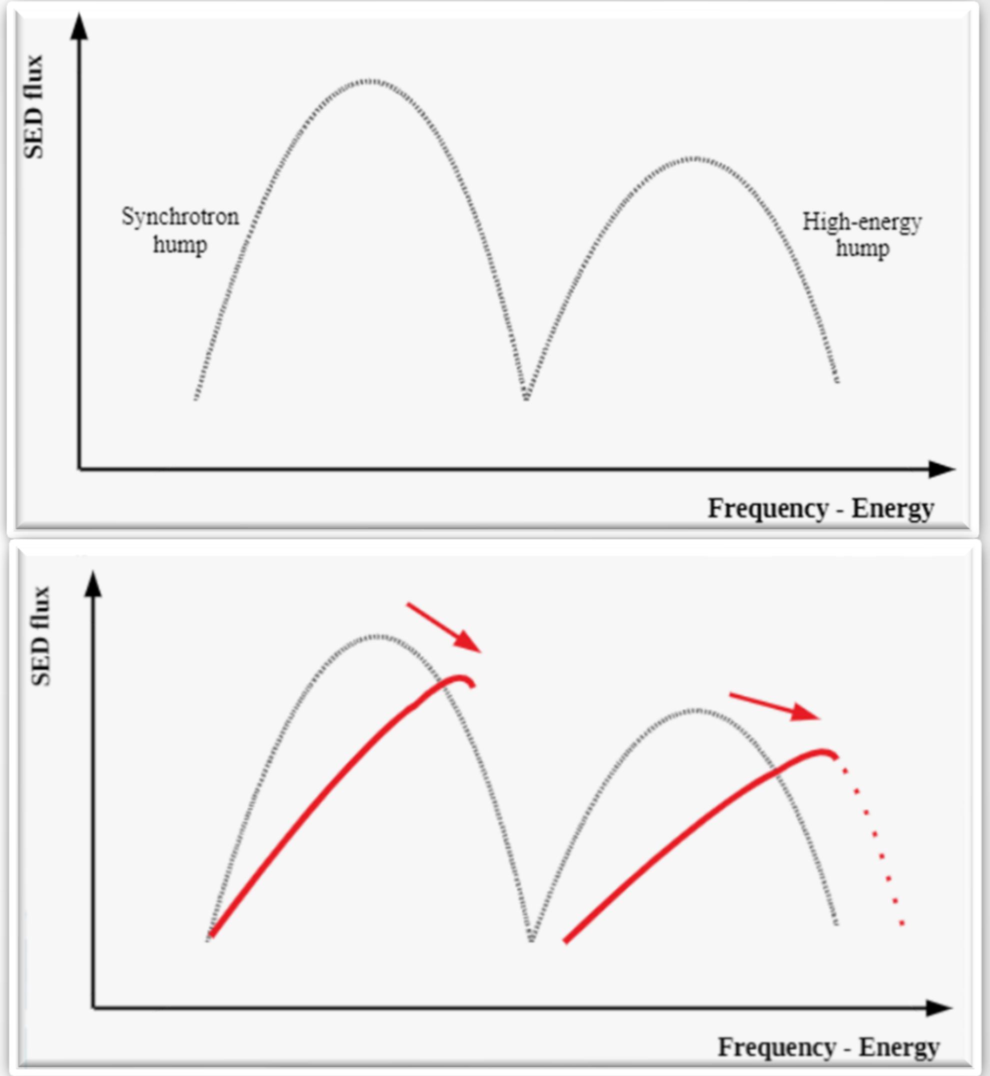
Extreme TeV BL Lacs

- Blazars can be classified on the synchrotron emission peak

- They form a sequence, whose end consists in the **Extreme TeV Bl Lacs**

- Their emission is not reproducible using single shock models

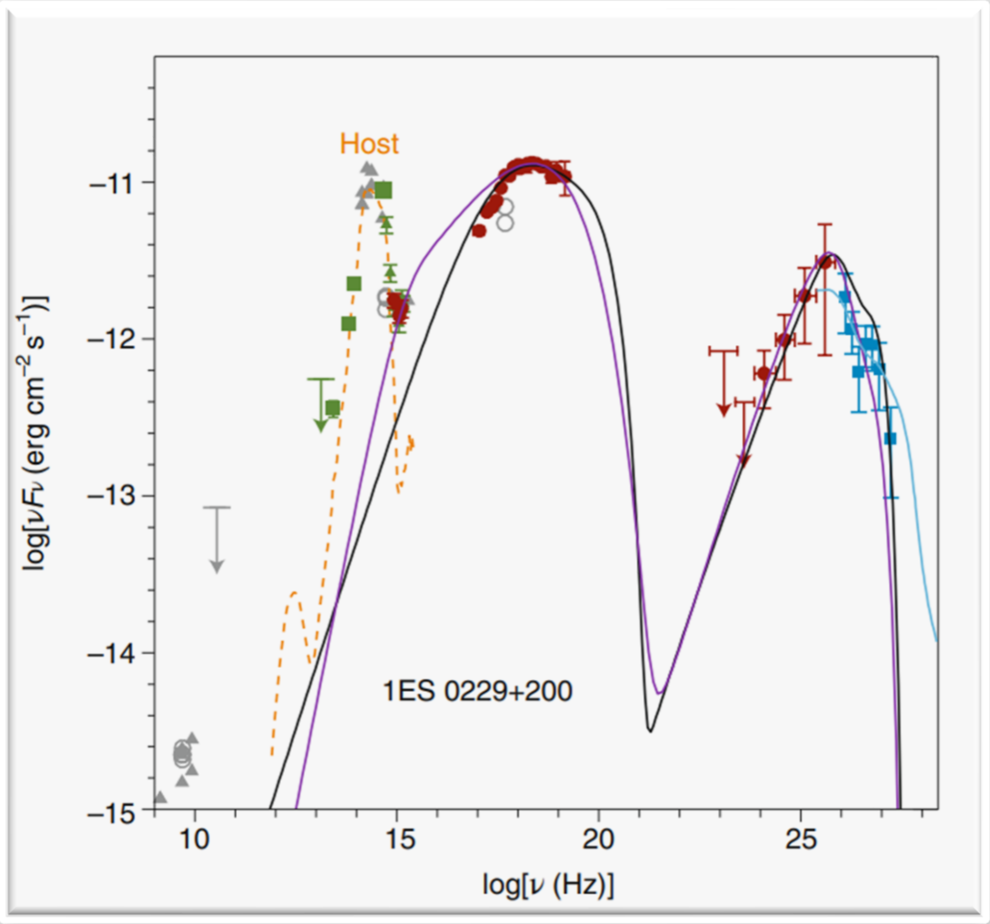
- Several alternatives have been proposed



Credits: Luca Foffano

Hybrid DSA+SA model

- Low magnetization is required
- Thermal plasma: recollimation shock + turbulence
- Non-thermal particles: diffusive shock acceleration + stochastic acceleration
- One zone Synchrotron Self Compton model



Biteau et al., 2020

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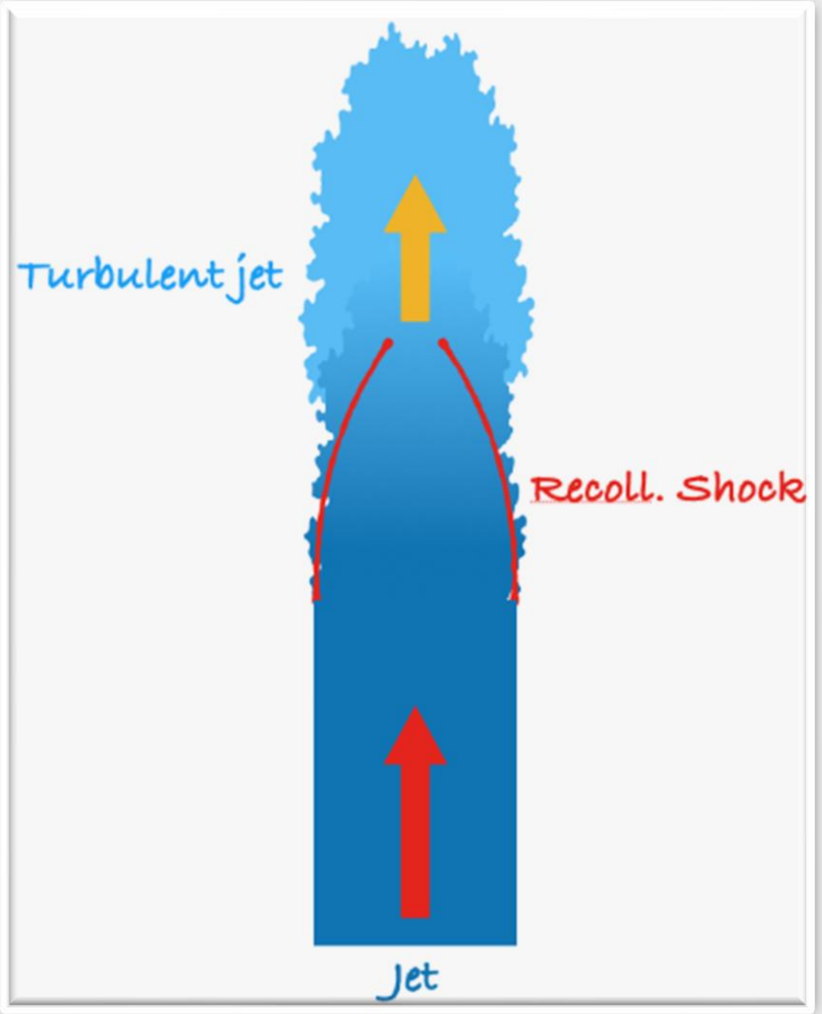

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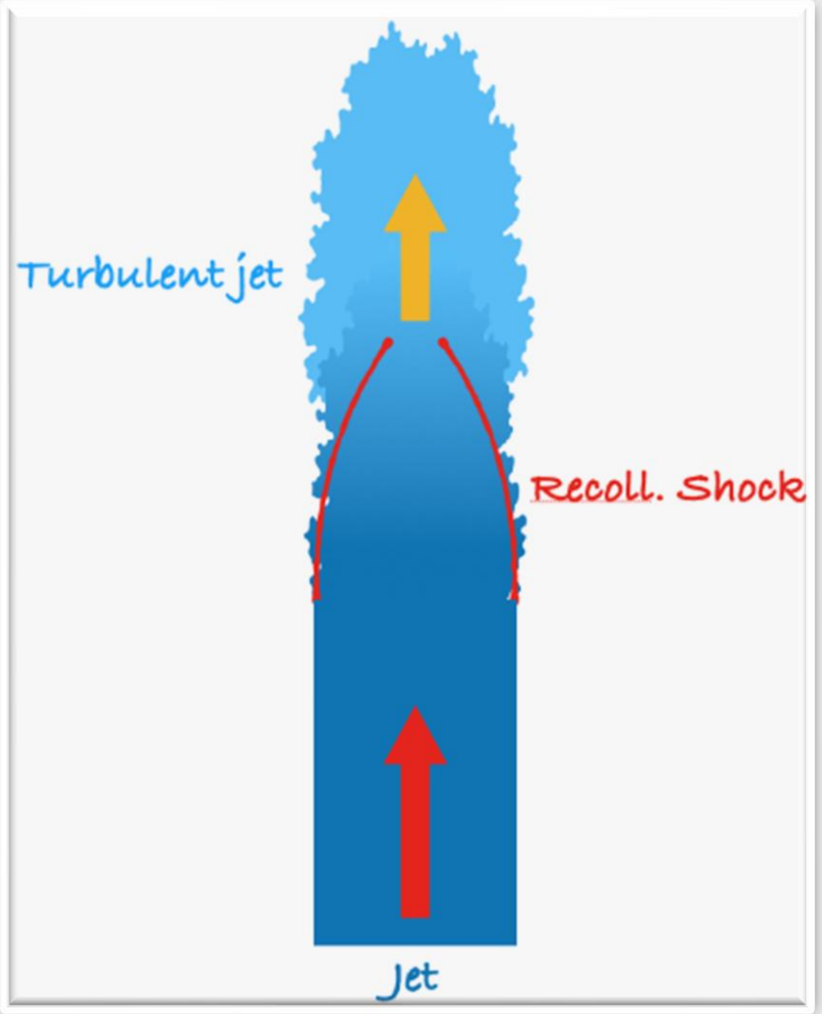

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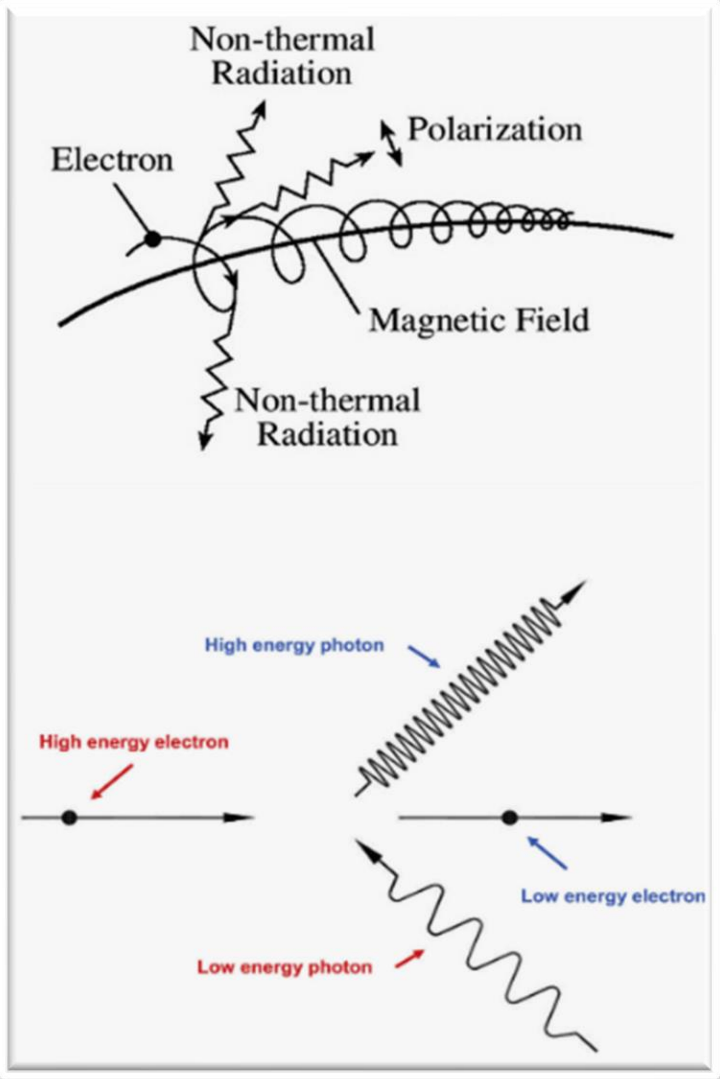
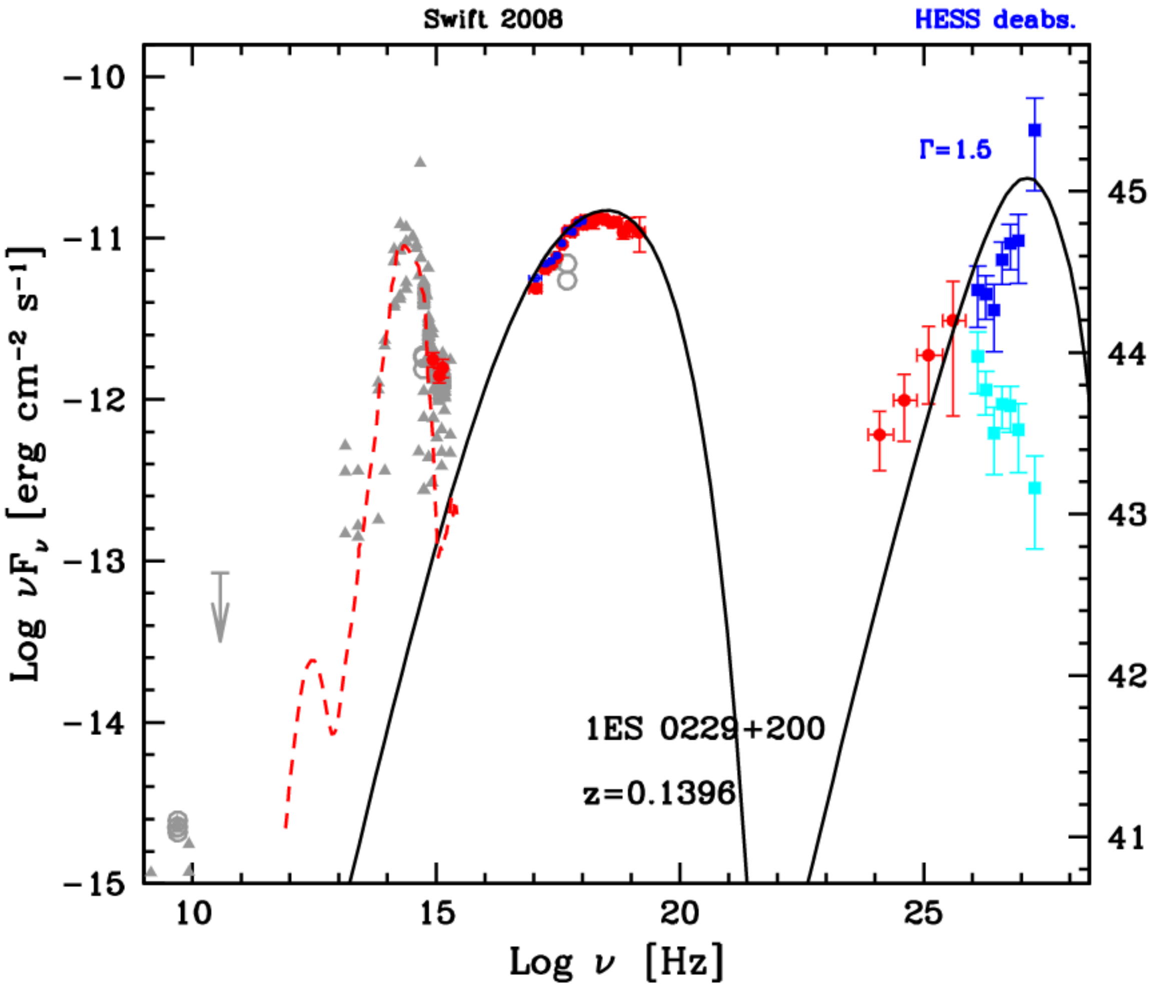


First attempt

- We assumed a constant turbulence spectrum
- The rise in the sub-TeV range is steeper than the data
- The ratio between the damping and the cascading time is much smaller than 1
- The **turbulence damping** is not negligible, it must be included in the model



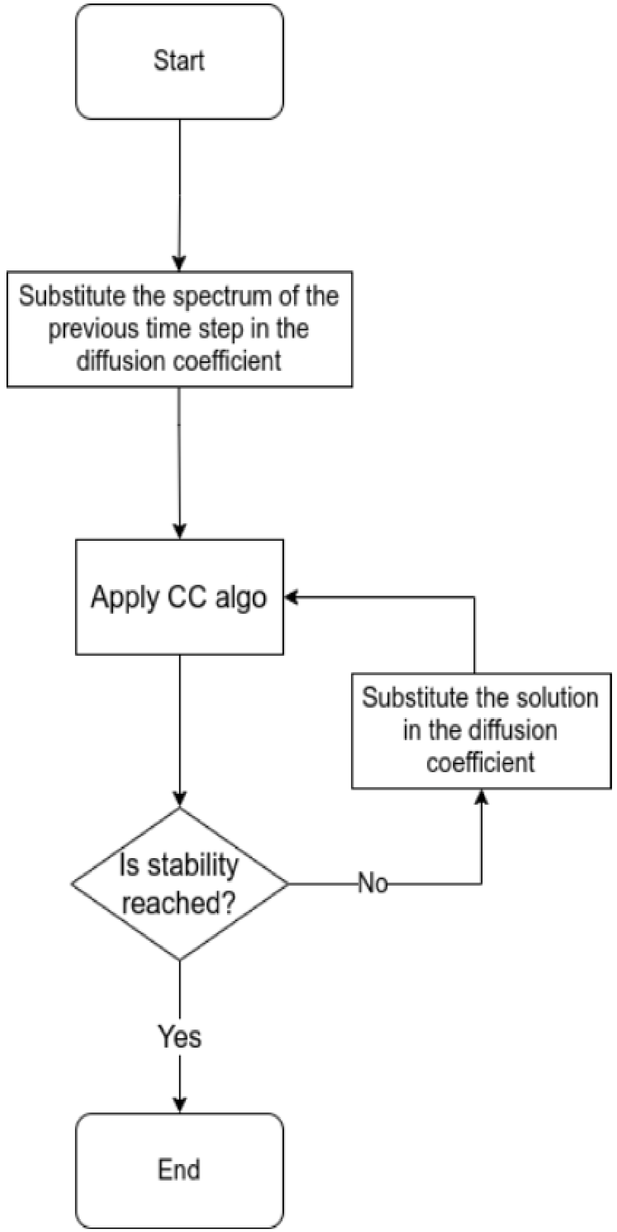
Numerical method

Assuming isotropy and homogeneity:

$$\begin{cases} \dfrac{\partial f}{\partial t} = \dfrac{1}{p^2}\dfrac{\partial}{\partial p}\left[p^2 D_p \dfrac{\partial f}{\partial p} + p^2 \left(\dfrac{\partial p}{\partial t}\right)_{\mathrm{rad}} f\right] + \dfrac{f}{t_{\mathrm{esc}}} + I_f \\ \dfrac{\partial Z}{\partial t} = \dfrac{1}{k^2}\dfrac{\partial}{\partial k}\left(k^2 D_k \dfrac{\partial Z}{\partial k}\right) + \Gamma Z + \dfrac{I_W}{k^2} \quad \text{with} \quad Z = \dfrac{W}{k^2} \end{cases}$$

- We must solve a system of two coupled **non-linear** Fokker-Planck equations
- We chose the robust Chang-Cooper algorithm, but it requires linearity
- We need a trick

the trick



Start

Substitute the spectrum of the previous time step in the diffusion coefficient

Apply CC algo

Is stability reached?

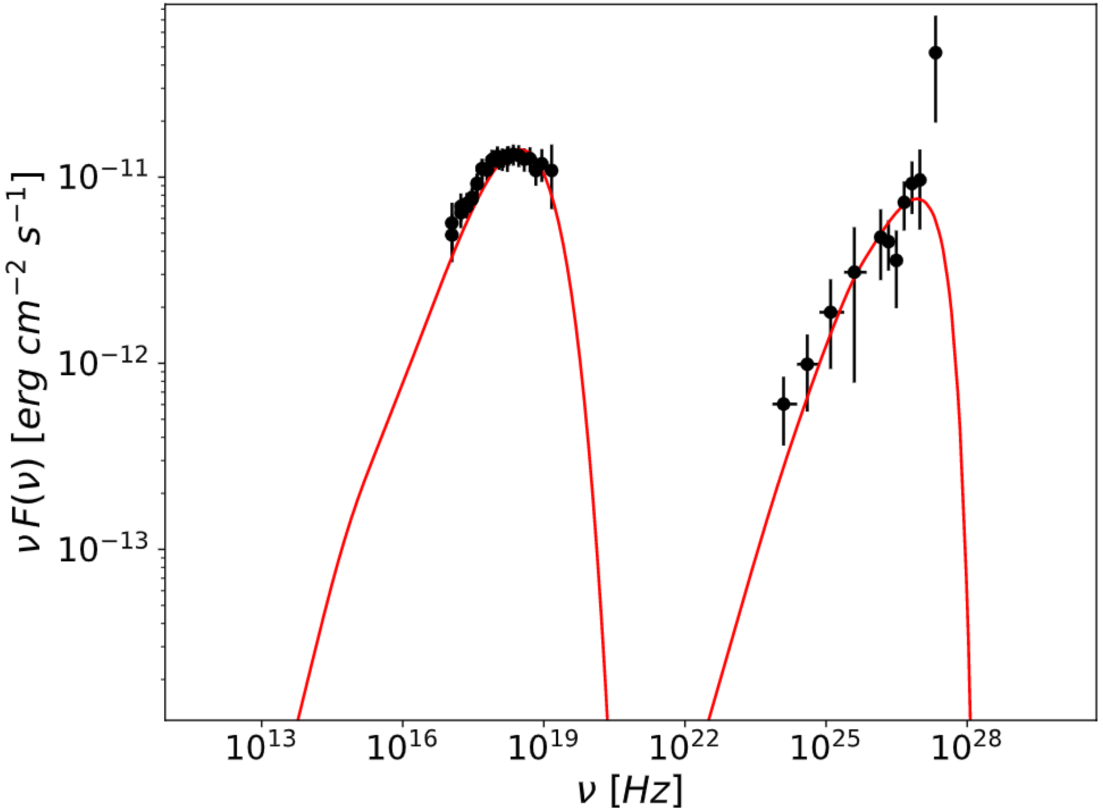
No

Substitute the solution in the diffusion coefficient

Yes

End

Second attempt



Sciaccaluga & Tavecchio, 2022

Downstream region radius
$R = 1.2 \times 10^{16}$ cm

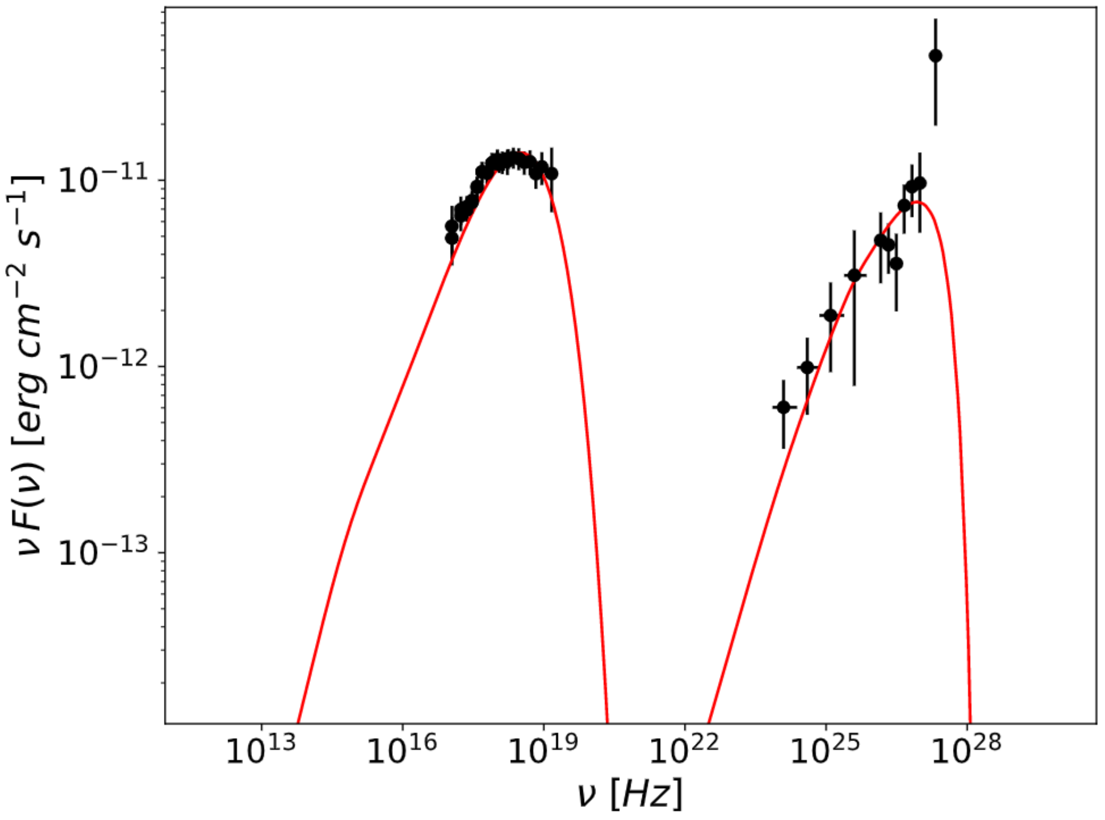
Alfvén velocity
$v_a = 2 \times 10^{9}$ cm/s

Mean magnetic field
$B = 15.9$ mG

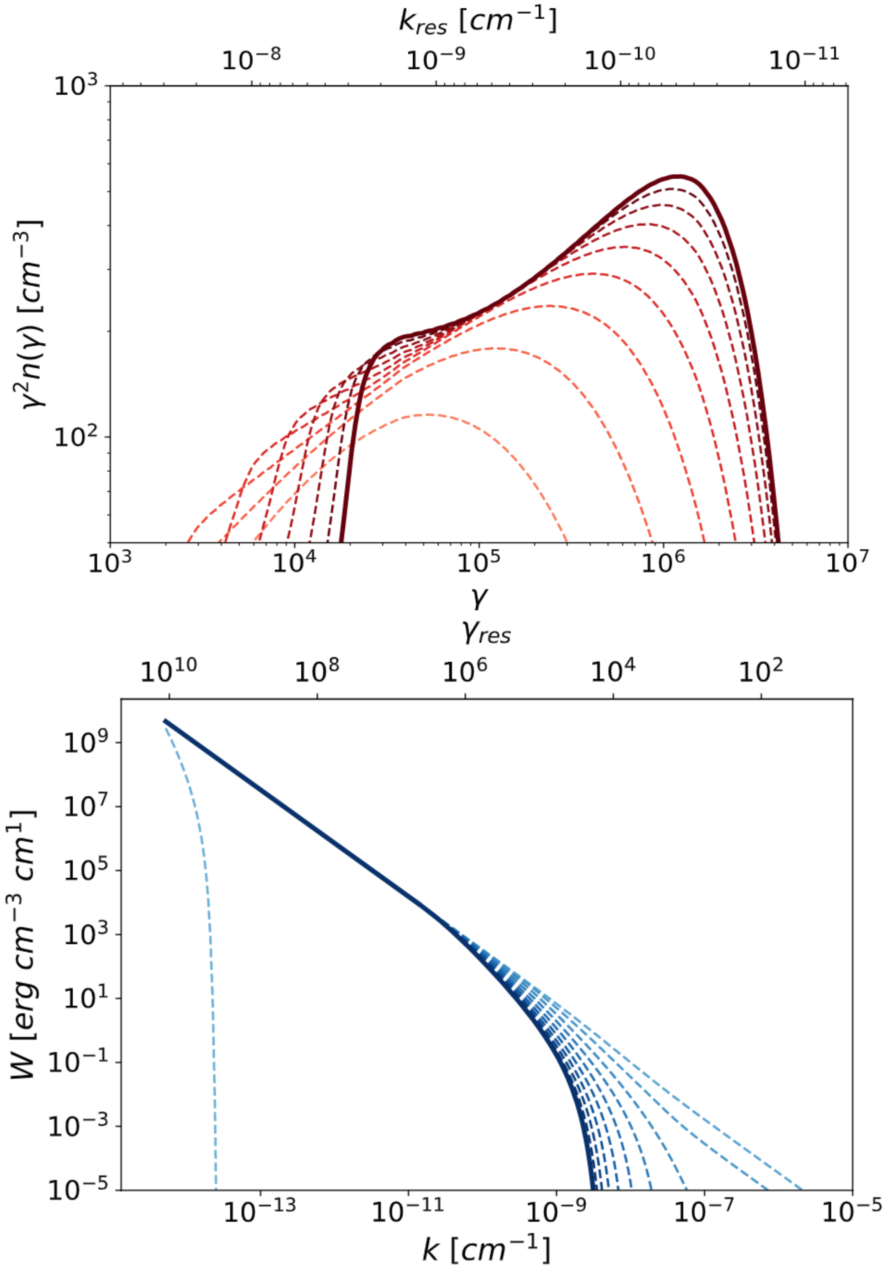
Injected electrons power
$P'_n = 7 \times 10^{39}$ erg/s

Injected turbulence power
$P'_W = 7 \times 10^{39}$ erg/s

Second attempt



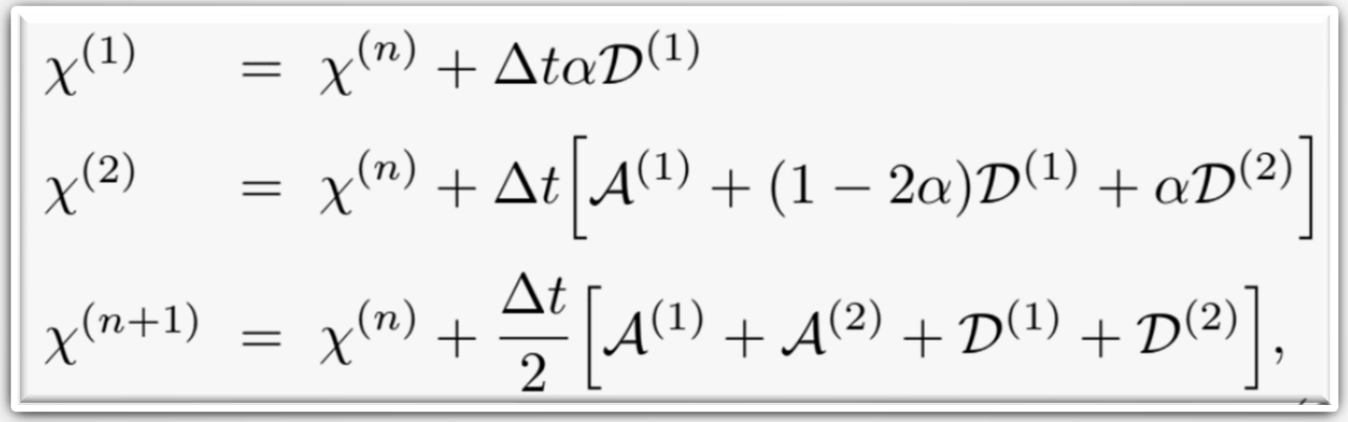
Sciaccaluga & Tavecchio, 2022



What’s next?

1) Implement a more sophisticated algorithm, i. e. **RK-IMEX**

PLUTO implementation?



$$
\begin{aligned}
\chi^{(1)} &= \chi^{(n)} + \Delta t \alpha \mathcal{D}^{(1)} \\
\chi^{(2)} &= \chi^{(n)} + \Delta t \left[\mathcal{A}^{(1)} + (1-2\alpha)\mathcal{D}^{(1)} + \alpha \mathcal{D}^{(2)} \right] \\
\chi^{(n+1)} &= \chi^{(n)} + \frac{\Delta t}{2} \left[\mathcal{A}^{(1)} + \mathcal{A}^{(2)} + \mathcal{D}^{(1)} + \mathcal{D}^{(2)} \right],
\end{aligned}
$$

Kundu et al., 2021

- More stable, since it treats the diffusive term implicitly and the convective term explicitly
- More accurate, in fact CC converges at first order rate, while RK-IMEX gives second order convergence

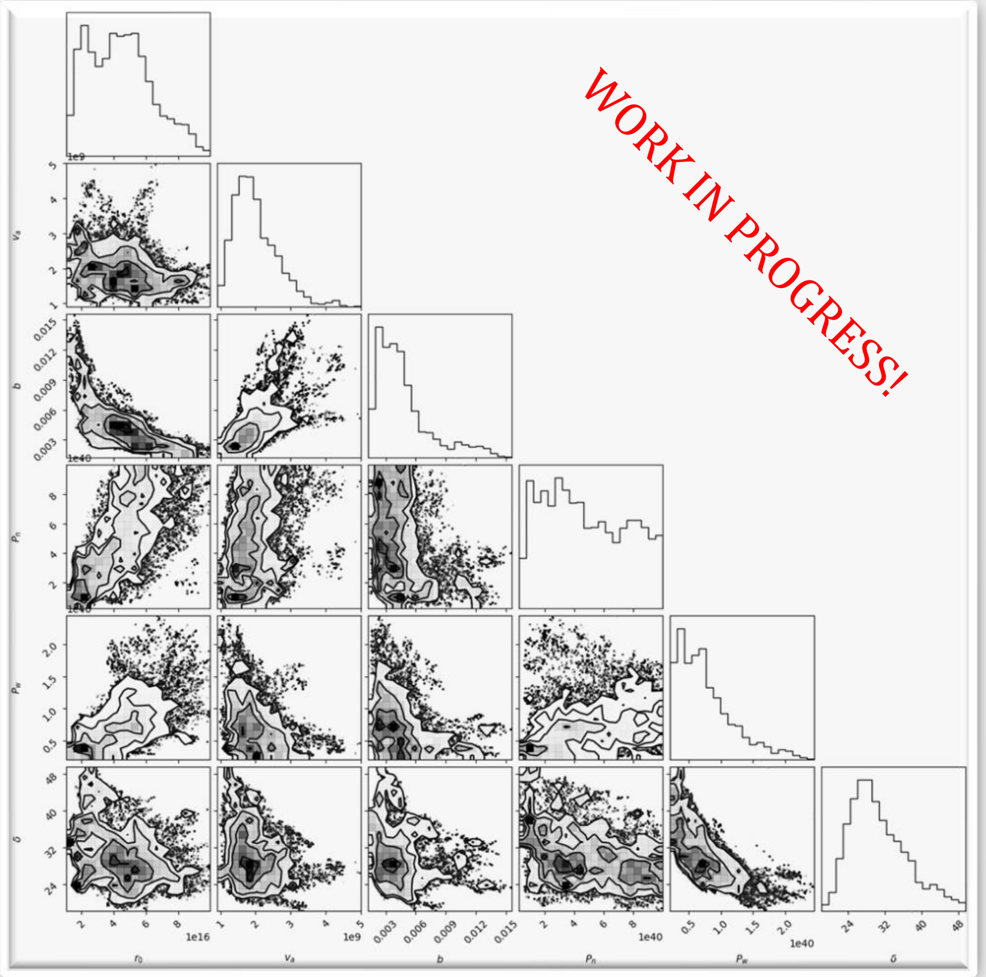
What’s next?

2) Fitting procedure, i. e. **MCMC**

- It is possible to get a “good fit” using different parameters, which is the best option?

- The “classical” approach does not work
  1. Complex parameters space
  2. CPU expensive function evaluation

- We are trying with an MCMC sampler



WORK IN PROGRESS!

Backup: main references

Zech A. & Lemoine M., 2021

Komissarov S. & Gourgouliatos K., 2017

Matsumoto et al., 2021

Abolmasov P. & Bromberg O., 2022

Backup: setup of the PLUTO simulations

Setup

- high Lorentz factor $\nrightarrow \Gamma_0 = 5$
- low magnetization → $\sigma = 10^{-5}$
- pc scale confined jet
  - $p_e \alpha\, z^{-0.5}$
- highly curved shock:
  - $\theta_0 = 0.2$
  - $p_{j,0} > p_{e,0}$ $(l_0 = 0.1\ \mathrm{pc})$
  - $\Gamma_0 = 5$
- $L_j = 10^{44}$ erg/s
- Taub equation of state

Magnetic field

$$B_0 \simeq 3 \times 10^{-3}\ \mathrm{G}$$

$$A_\phi = B_0 \frac{r}{\left(\sqrt{z^2 + (70r)^2} + z\right)\sqrt{z^2 + (70r)^2}}$$

Boundary conditions

- userdefined boundary at $z = 1$, with initial perturbation in density and pressure:

$$p = p_0(1 + \cos(\phi) \times 10^{-20})$$
$$\rho = \rho_0(1 + \sin(\phi) \times 10^{-20})$$

- reflective b.c. at $r = 0$ in 2D simulations,
- outflow otherwise.

Backup: setup of the PLUTO simulations

Grid

2D simulations are run on a 800×3700 (r, z) grid, with domain $[0,8] \times [1,30 \text{ or } 50]$, uniform only in $[-1.5,1.5] \times [1,15]$.

3D grid is cartesian, $680 \times 680 \times 3700$ in $[-4,4] \times [-4,4] \times [1,30 \text{ or } 50]$, uniform only in $[-1.5,1.5] \times [-1.5,1.5] \times [1,15]$.

Numerical methods

HLLD solver, Linear reconstruction, RK2 time stepping.

Constrained transport

Body force vector

Additional details for PLUTO users

In 2D RMHD simulations we used:
ASSIGN_VECTOR_POTENTIAL
UPDATE_VECTOR_POTENTIAL

In 3D we restarted from the 2D steady state, so we assigned B via
ASSIGN_VECTOR_POTENTIAL