Simulating the recollimation shocks, instabilities and particle acceleration in relativistic jets

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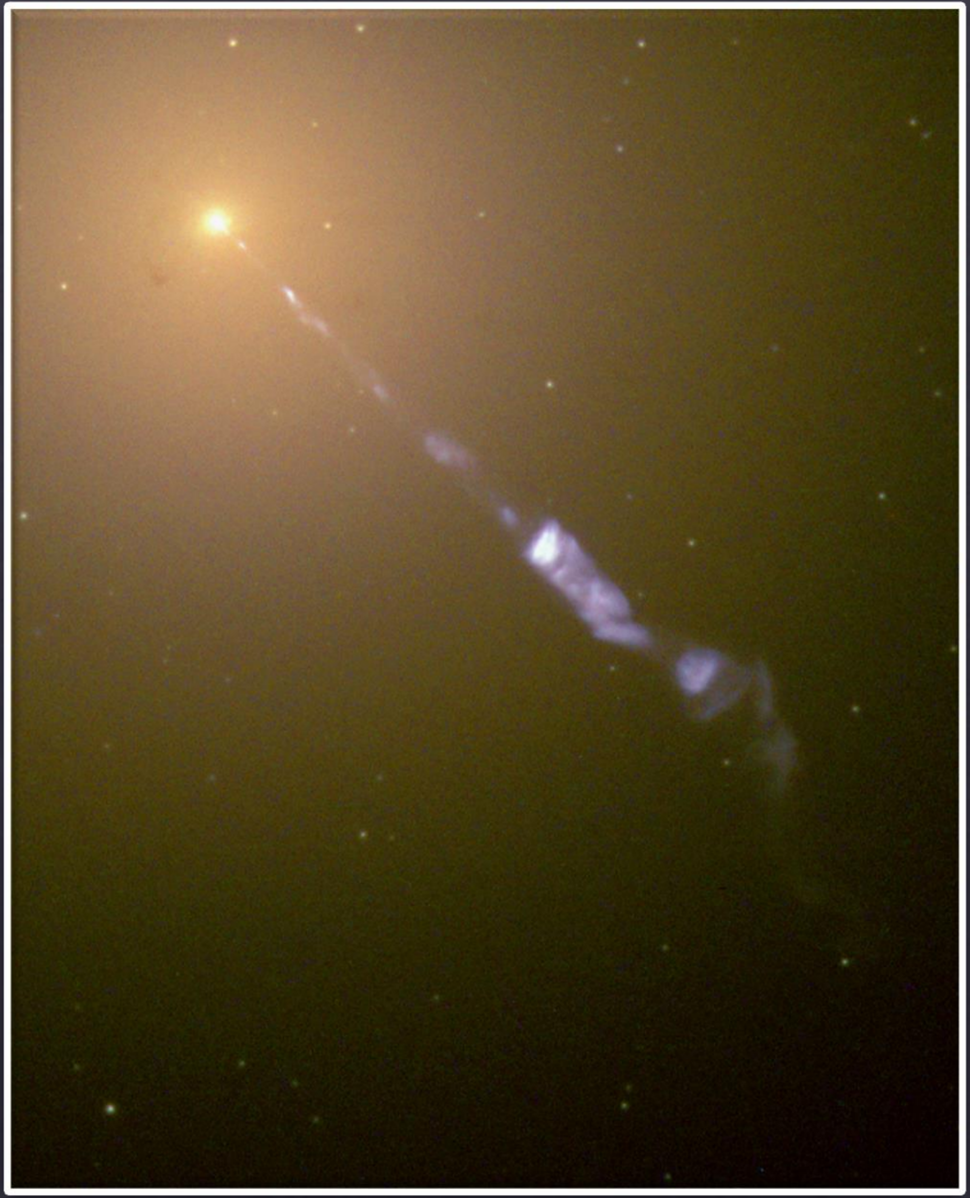
Overview

- Introduction: relativistic jets, shocks and instabilities
- TeV blazars
- 2D vs 3D simulations

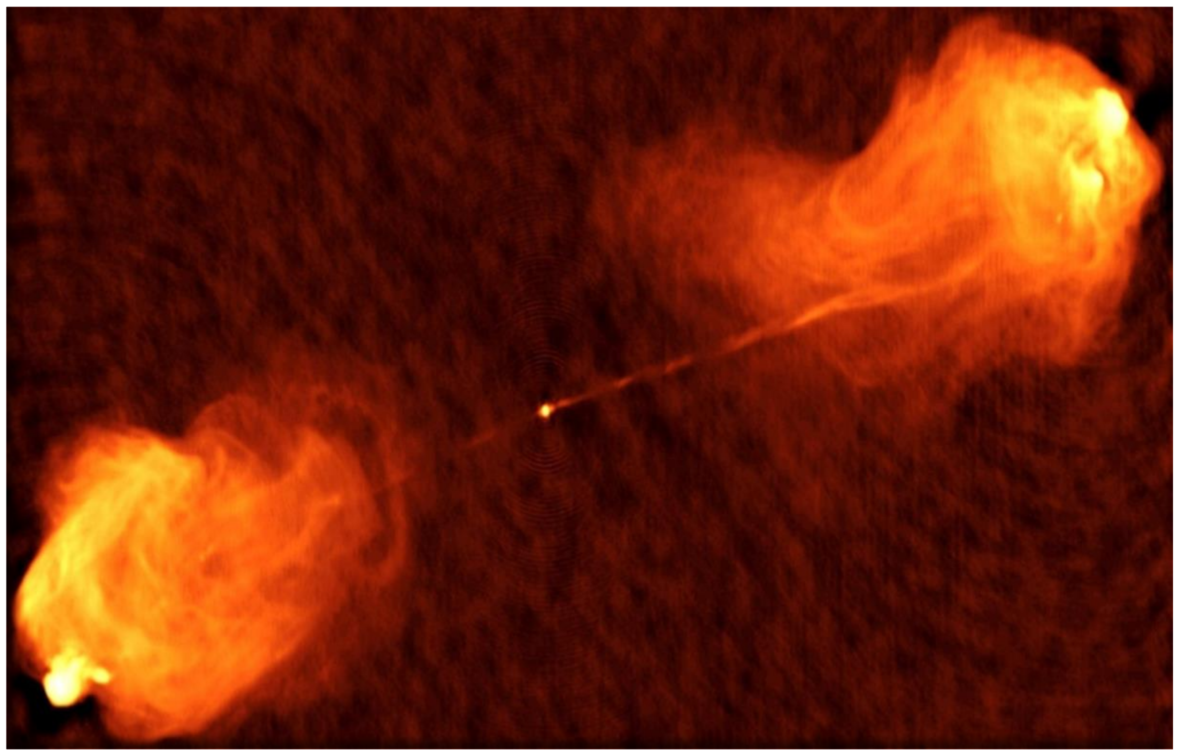
Relativistic AGN jets

- Plasma made of ions + electrons (or pairs)
- Launched to relativistc speed
- Powerful and long
- Bright: from thermal to non thermal emission, broad in frequencies.
- Complex and various phenomenology.

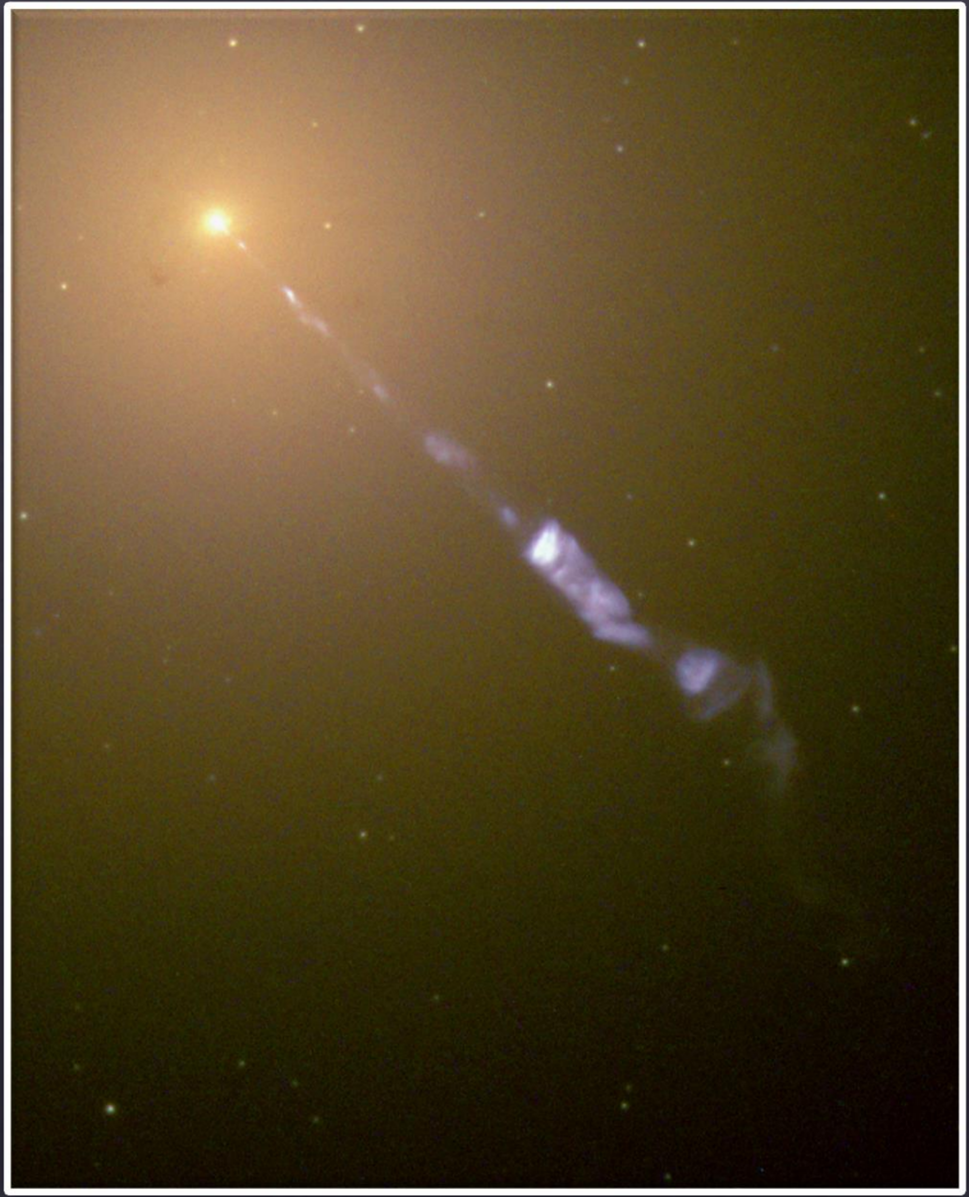


M87, *NASA and The Hubble Heritage Team*

Relativistic AGN jets



Cygnus A, *NRAO, Radio*



M87, *NASA and The Hubble Heritage Team, optical*

Many open questions!

main properties?

launching

MIT Kavli Institute for Astrophysics and Space Research

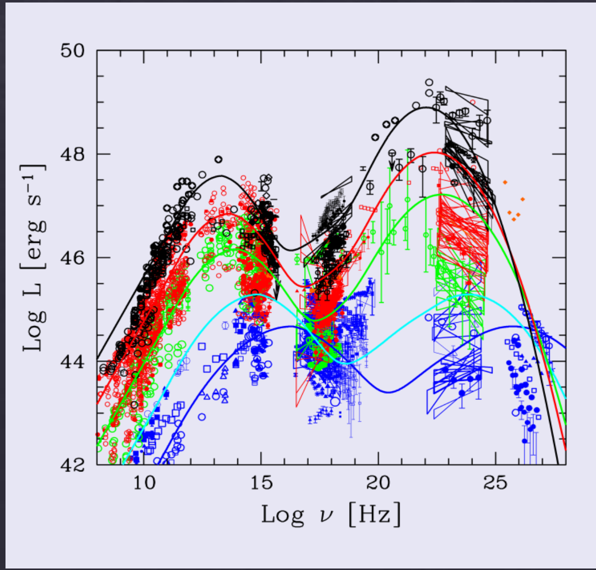
?

?

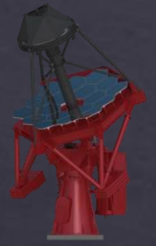
particle acceleration

injection of non thermal particles: pre-acceleration

non thermal emission



transport (and beaming for blazars)



Credit to CTAO

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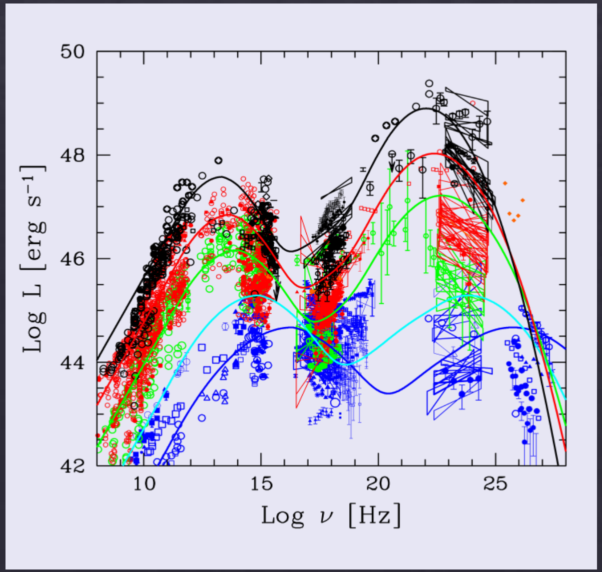

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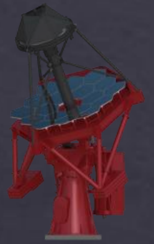


Credit to CTAO

Acceleration in jets

- shocks
- magnetic reconnection
- turbulence

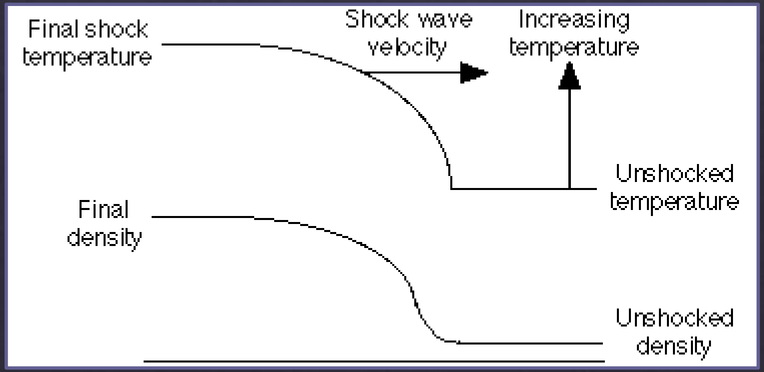
Acceleration in jets

- shocks
- magnetic reconnection
- turbulence
- and more!

Acceleration in jets

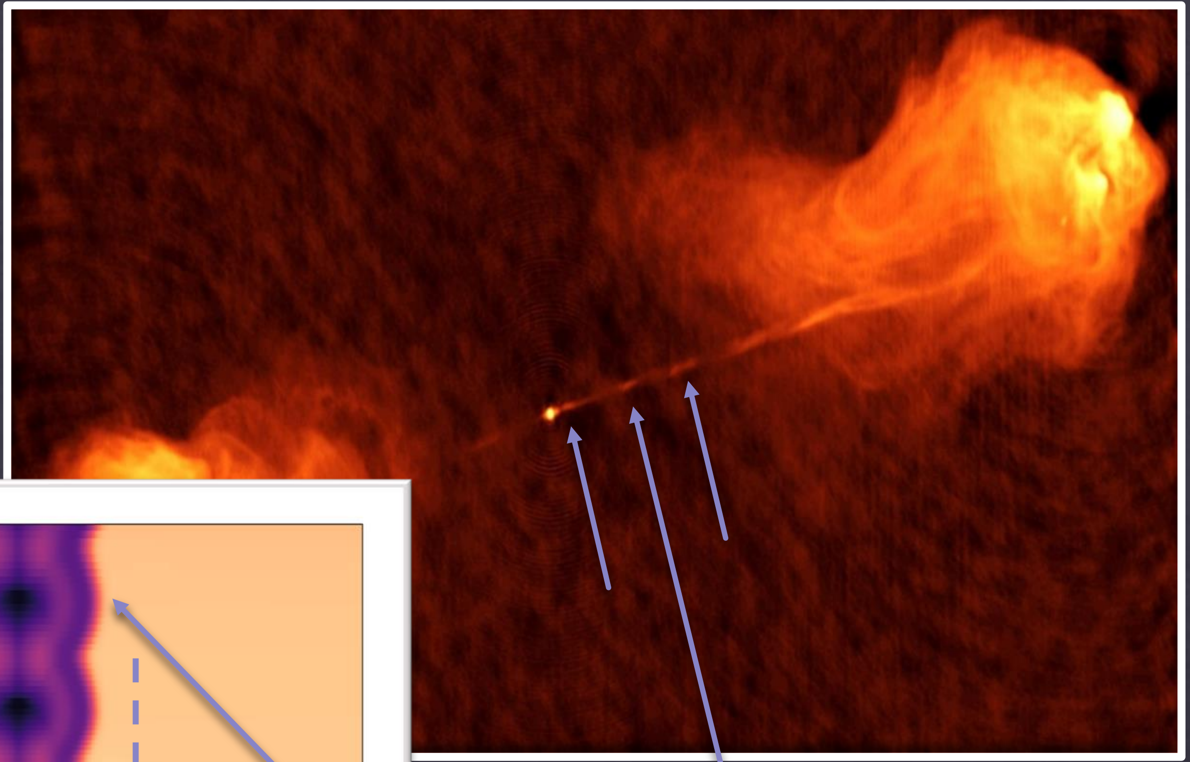
shocks

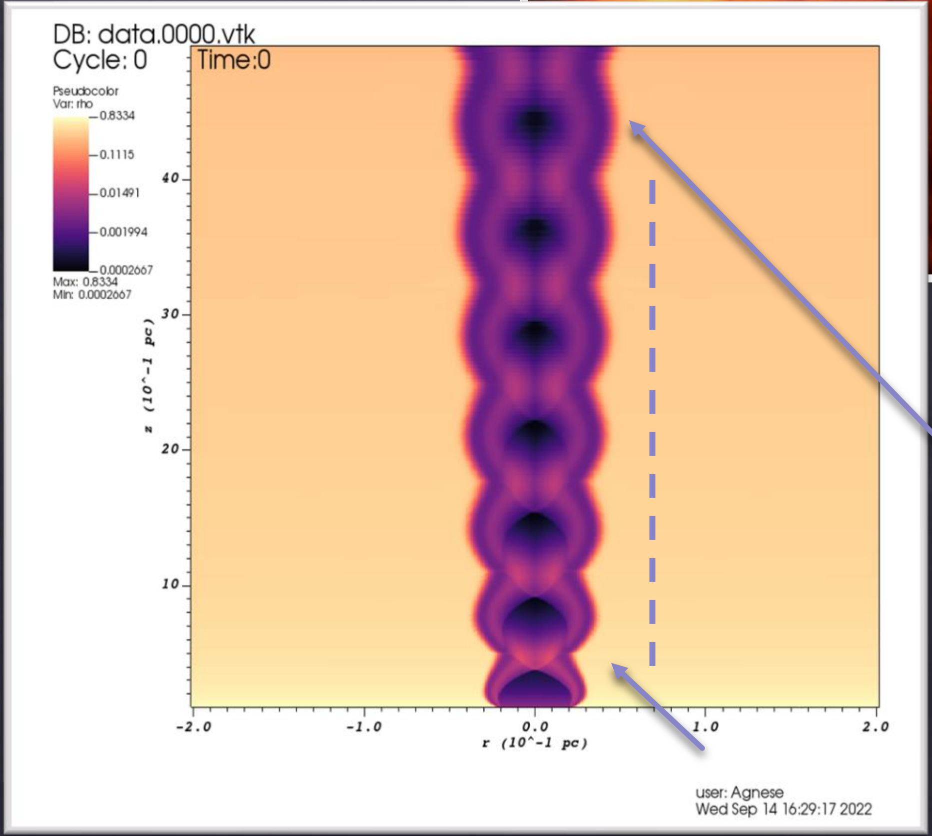
- loss of continuity in the termodynamical quantities and **B** (ρ, p, **v**, **B**)
- it happens as a perturbation moves through the fluid with supersonic speed
- it converts bulk kinetic energy into thermal energy: p and ρ increase



Acceleration in jets

shocks



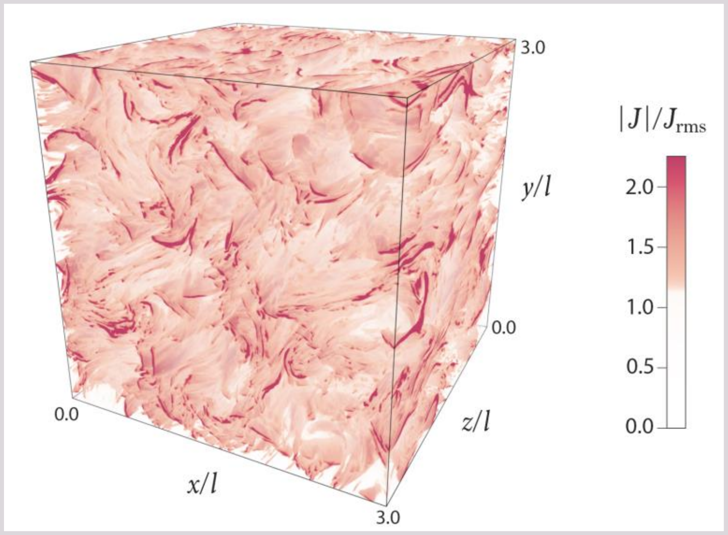


Recollimation shocks caused by the pressure of the external medium

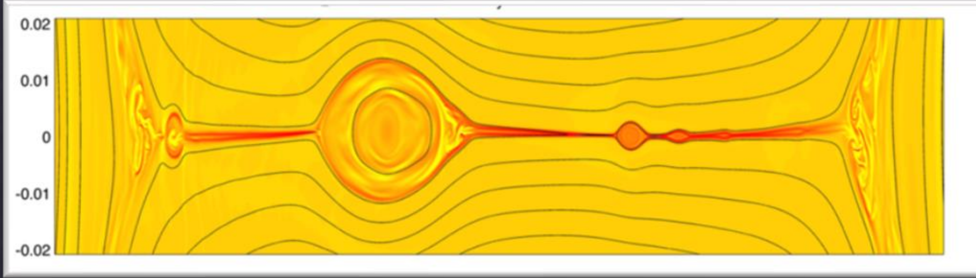
Efficient acceleration of particles:

$$\frac{<\Delta E>}{E} \propto \frac{v}{c}$$

Acceleration in jets



Comisso L., Sironi, L., 2022



Bhattacharjee et al. (2009); simulations by Y.-M. Huang

magnetic reconnection

- Relevant for mildly and highly magnetized jets
- Studied through particle in cell (PIC) simulations
- Strongly coupled with turbulence

Acceleration in jets

- Fermi acceleration, second order efficient

$$\frac{<\Delta E>}{E} \propto \left(\frac{\mathrm{v}}{\mathrm{c}}\right)^2$$

turbulence

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- Grows from instabilities: at both large and microscopic scales.

turbulence

and instabilities!

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turbulence and instabilities!

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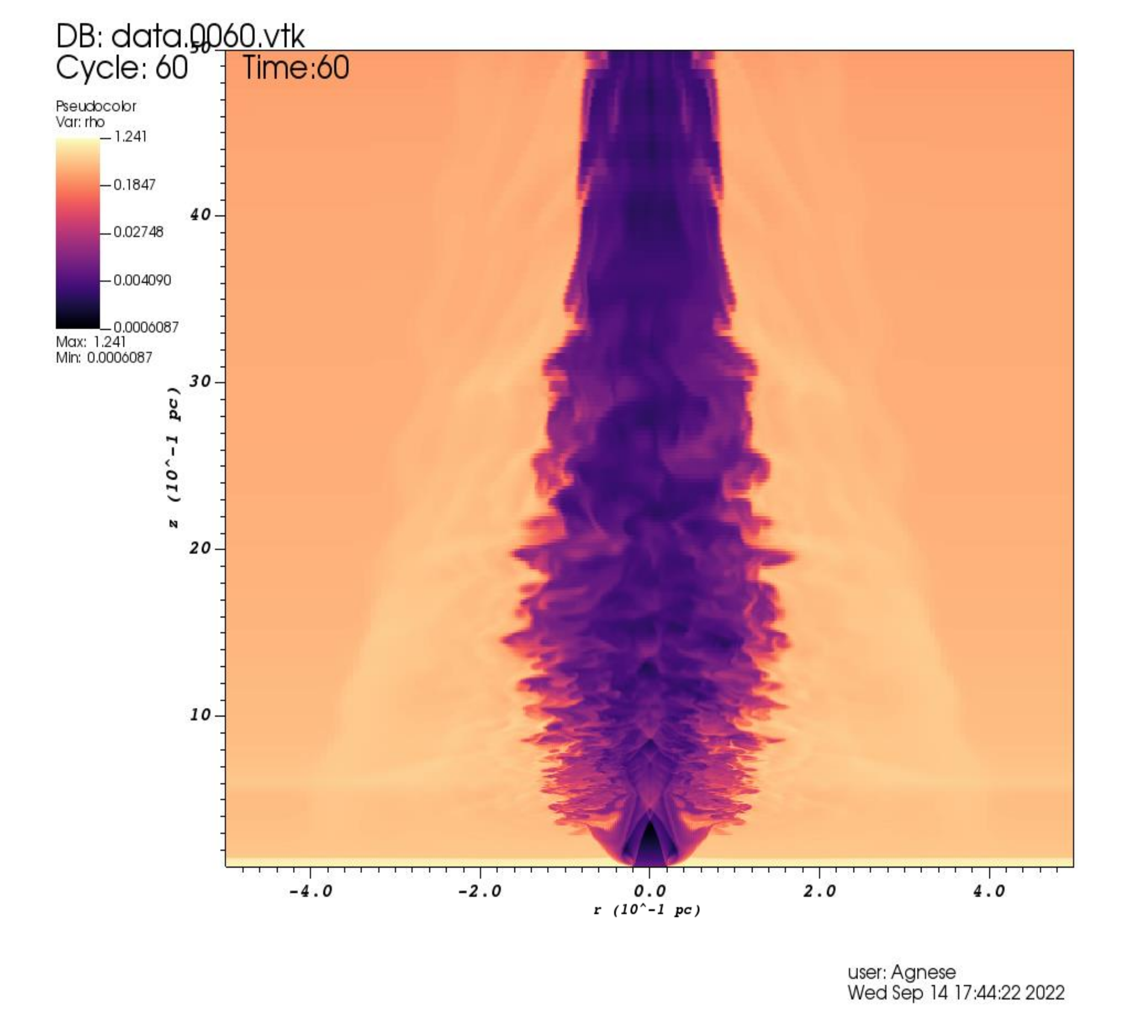

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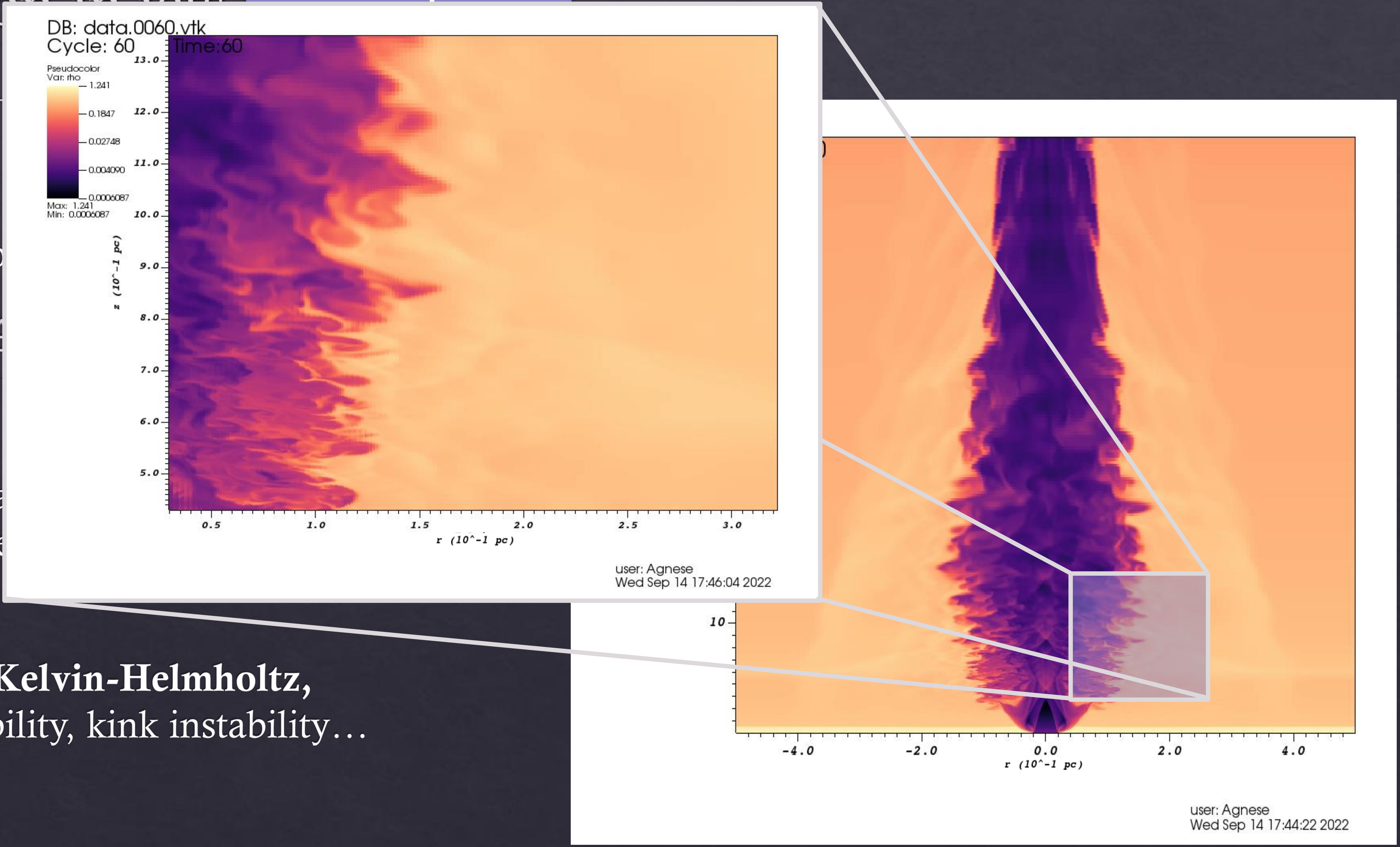
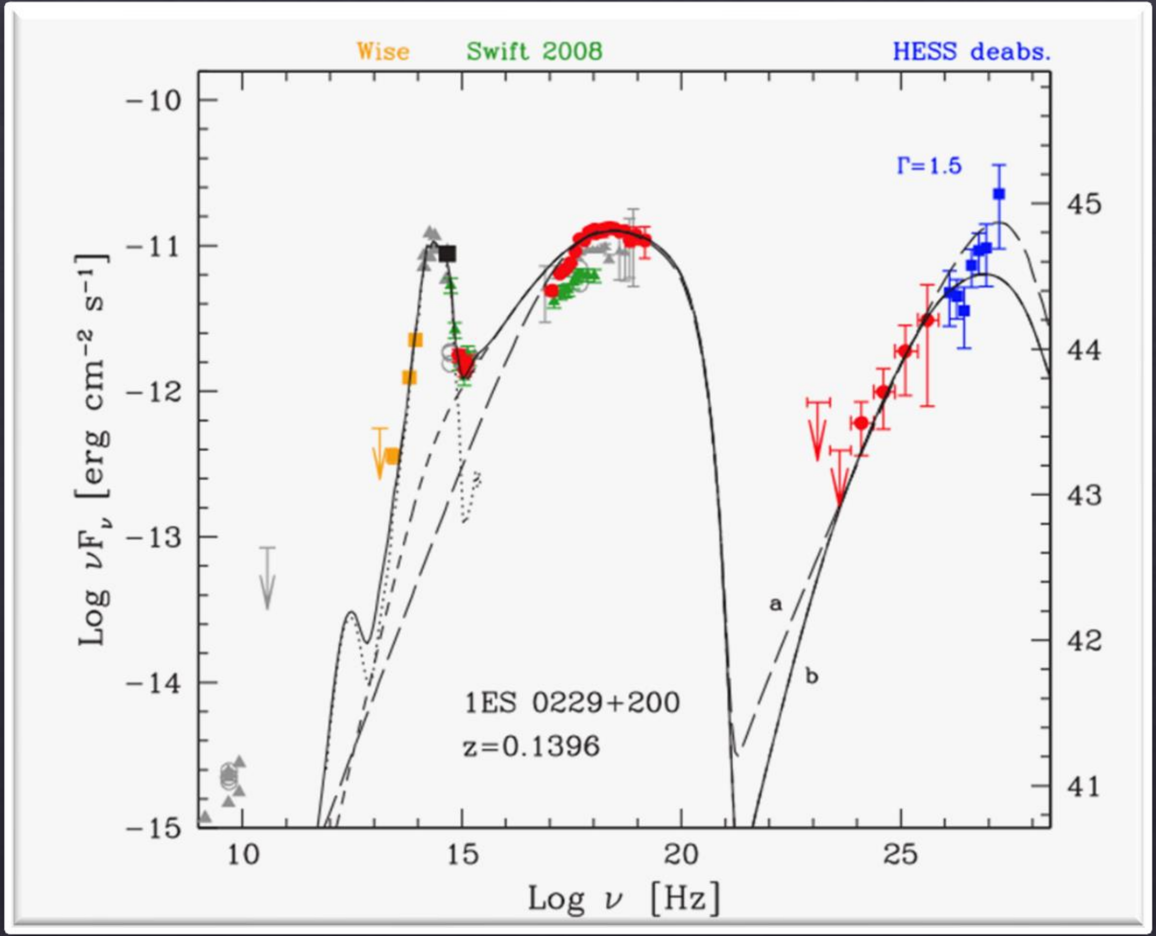


Extreme TeV blazars

Blazars with high energy peaked, hard spectrum.

What's the acceleration process of the emitting particles?



Costamante et al. 2018

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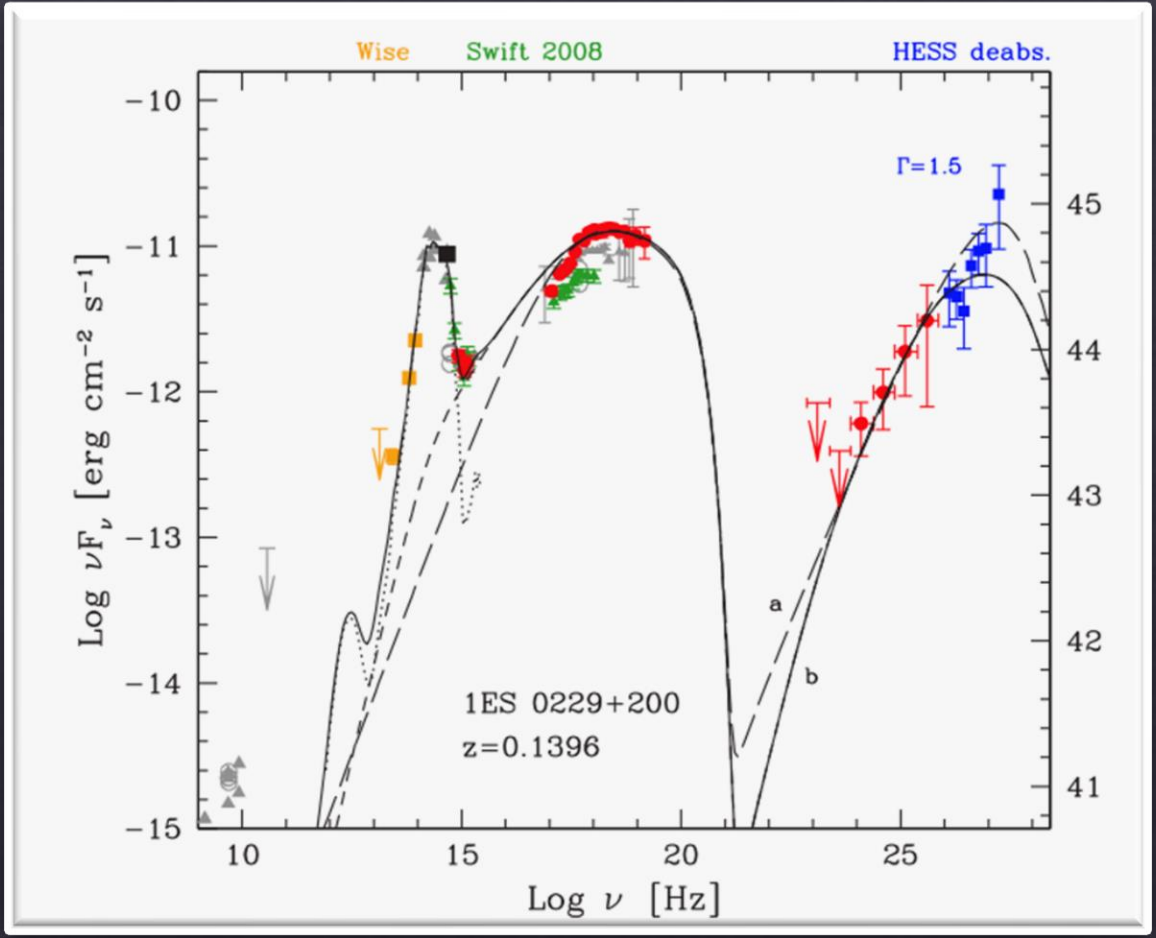

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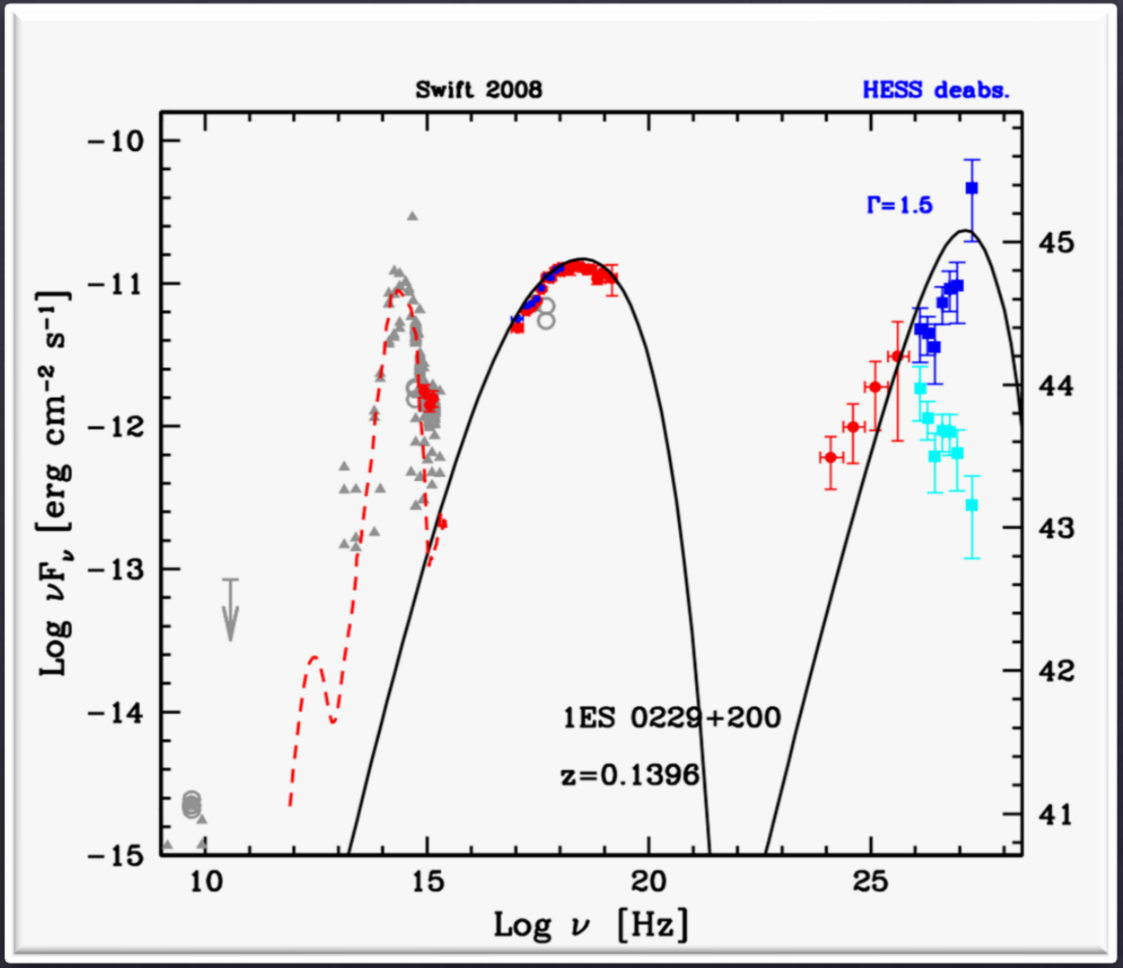
2. Recollimation shock + turbulence

   (supported from 3D simulations)



Tavecchio et al., 2022

Plasma + Lagrangian particles simulations with the PLUTO code

Non-thermal particles: Lagrangian particle module

- Macroparticles of n real particles characterized by a spectral distribution

Plasma

Conserv… capturin… method

… feedback on

… the CR … usive)

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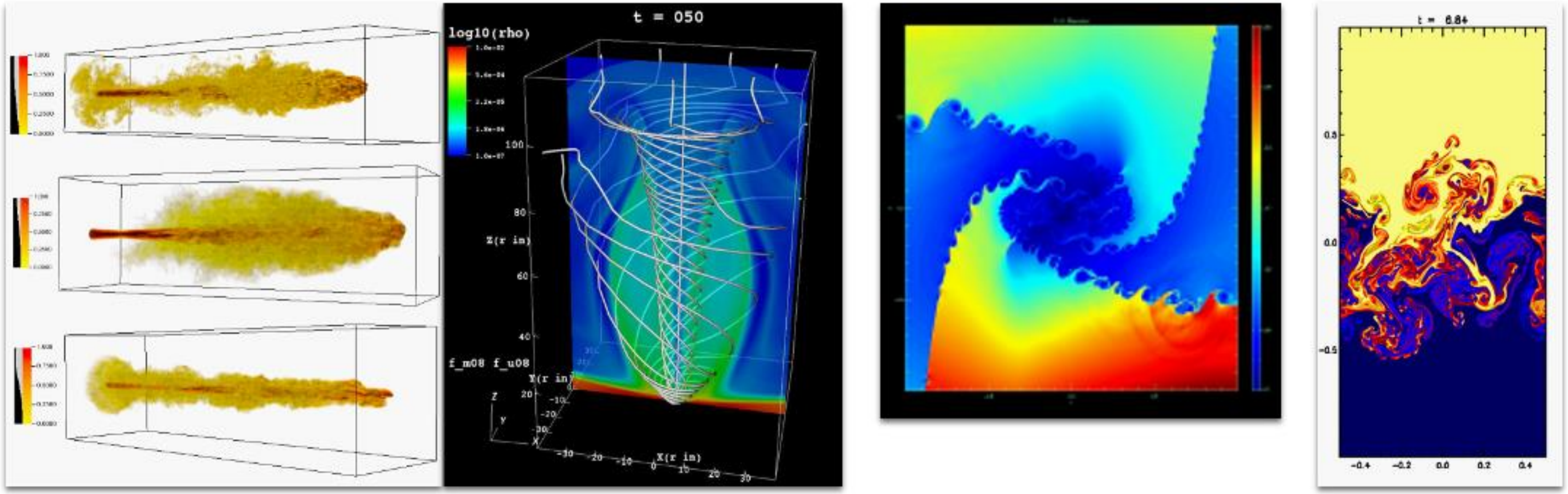
The PLUTO Code



The PLUTO Code for Astrophysical GasDynamics

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Plasma + Lagrangian particles simulations with the PLUTO code

http://plutocode.ph.unito.it/

Plasma:

Conservation equations evolved with shock-capturing finite volume (or finite difference) methods

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0$$

$$\frac{\partial \boldsymbol{q}}{\partial t} + \nabla \cdot \left[\boldsymbol{q}\boldsymbol{v} - \boldsymbol{B}\boldsymbol{B} + \left(p + \frac{\boldsymbol{B}^2}{2}\right)\right]^T = -\rho \nabla \Phi + \rho \boldsymbol{g}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} + \nabla \times (c\boldsymbol{E}) = 0$$

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ideal MHD for example

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Non-thermal particles: Lagrangian particle module

- Macroparticles of n real particles characterized by a spectral distribution
- Transported by the fluid: no feedback on the fluid
- Energy distribution follows the CR transport equation (non diffusive)

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ideal MHD for example

Non-thermal particles: Lagrangian particle module

- Macroparticles of n real particles characterized by a spectral distribution
- Transported by the fluid: no feedback on the fluid
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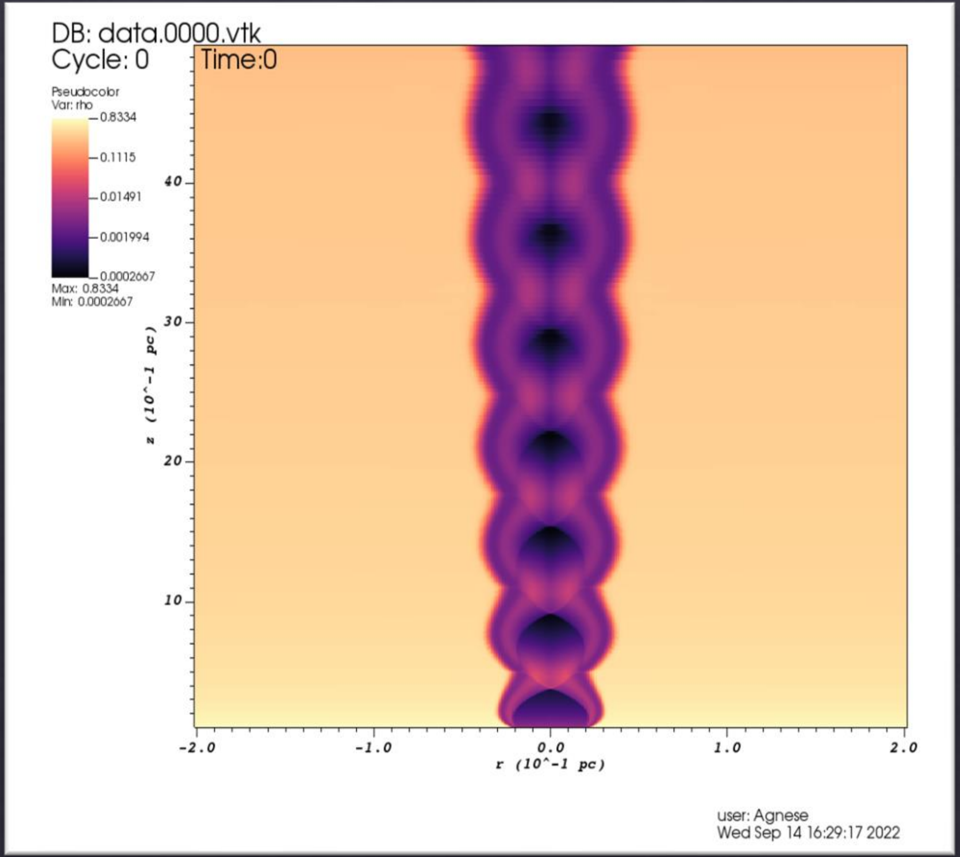
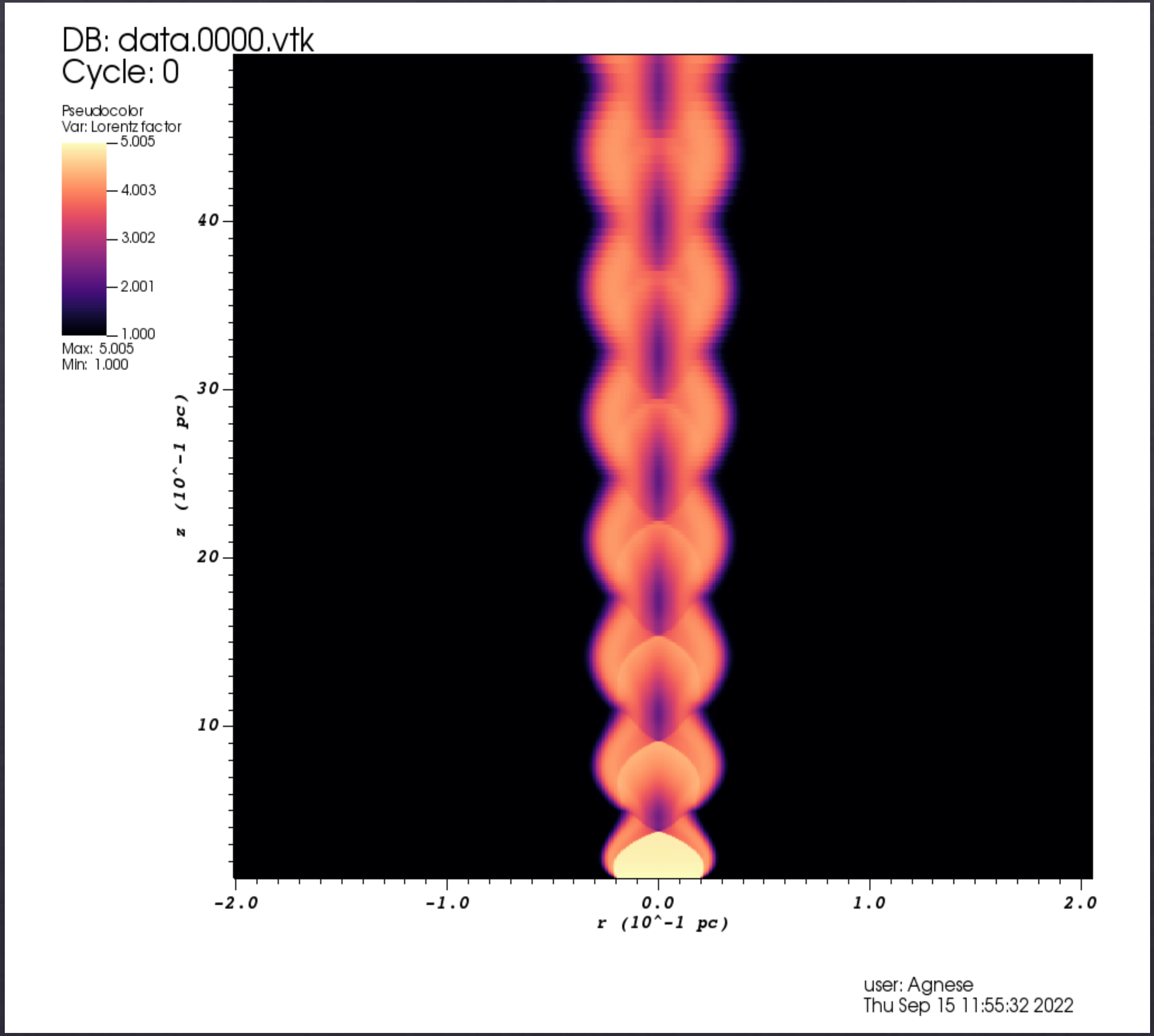
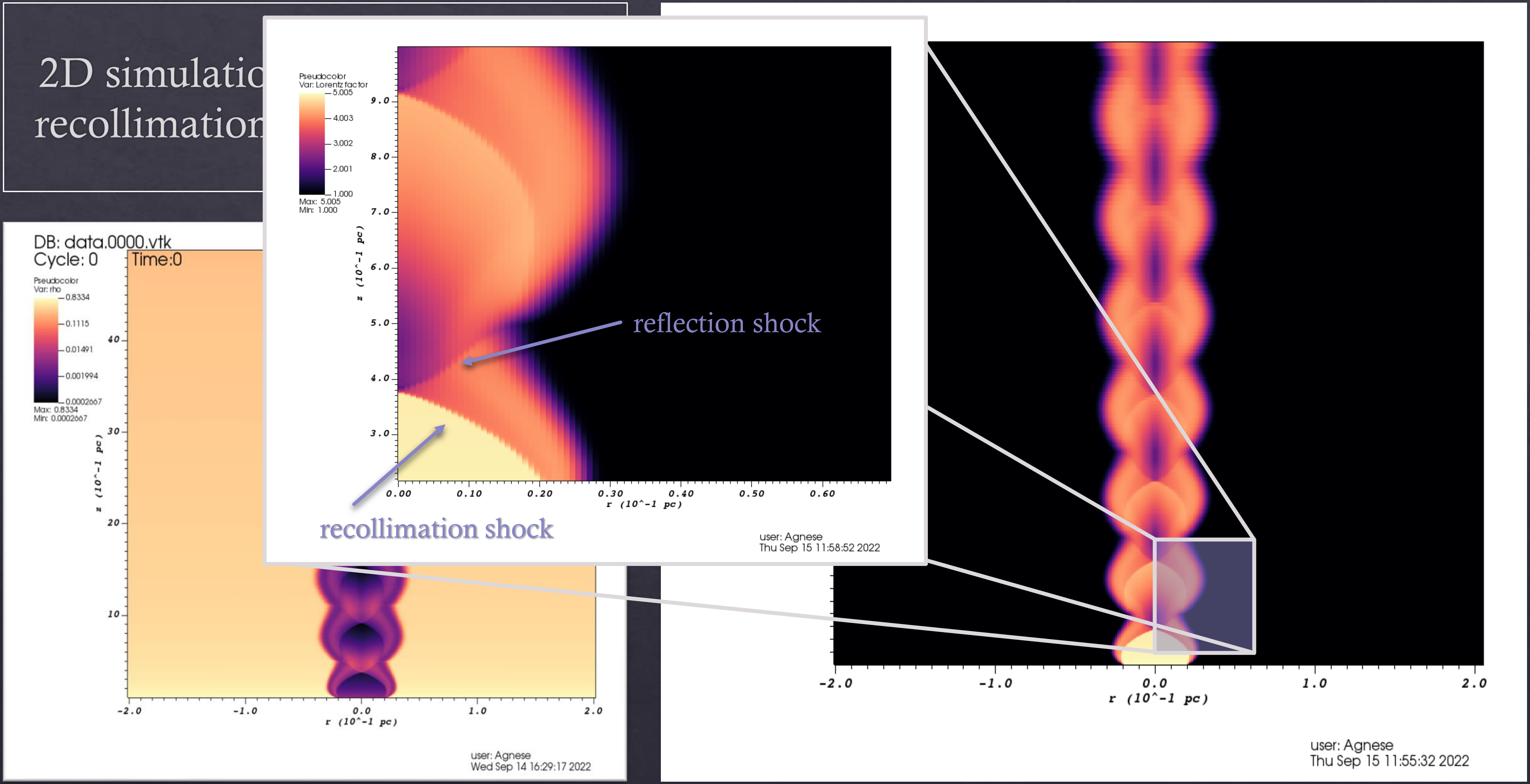
- **Particle acceleration at shocks**
- Non thermal emission via synchrotron and IC.

2D simulations for Tev blazars: recollimation+reflection shocks



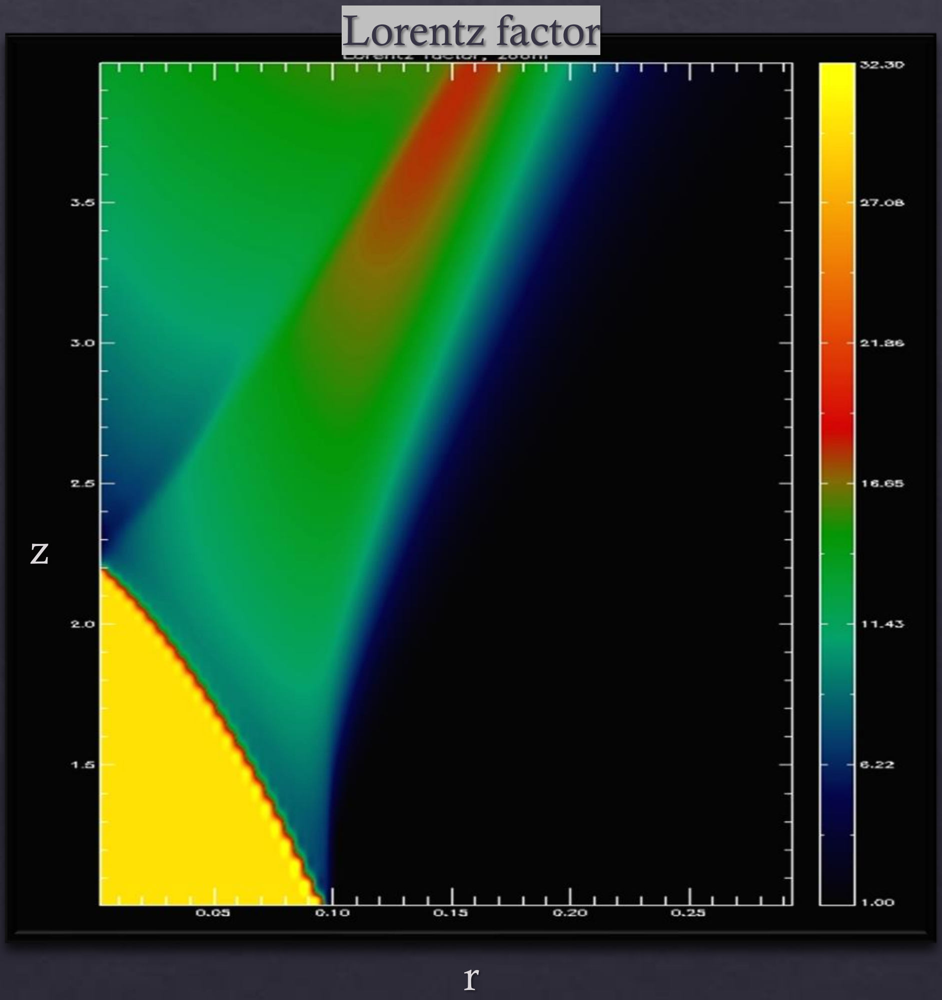


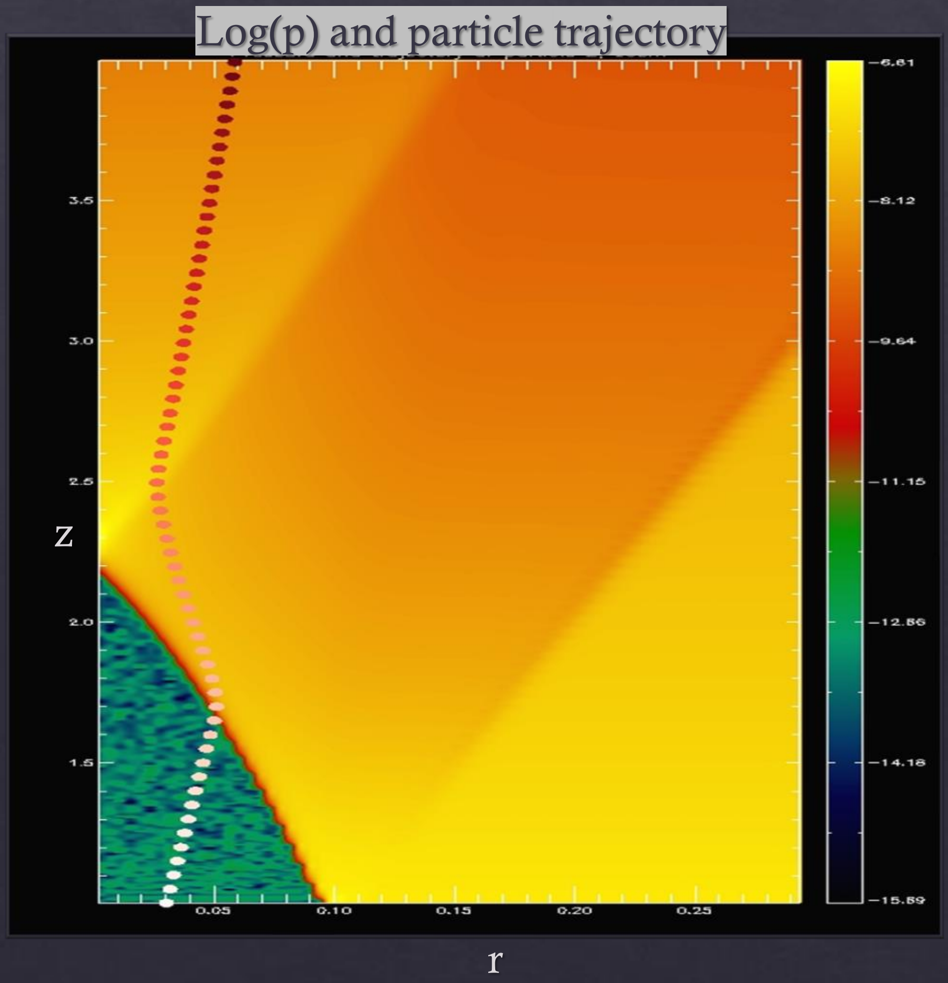
2D simulatio
recollimation



2D simulations for TeV blazars: particle acceleration at rec+ref shocks

- Relativistic MHD module + Lagrangian particles
- Focus on 1 recollimation + 1 reflection shock

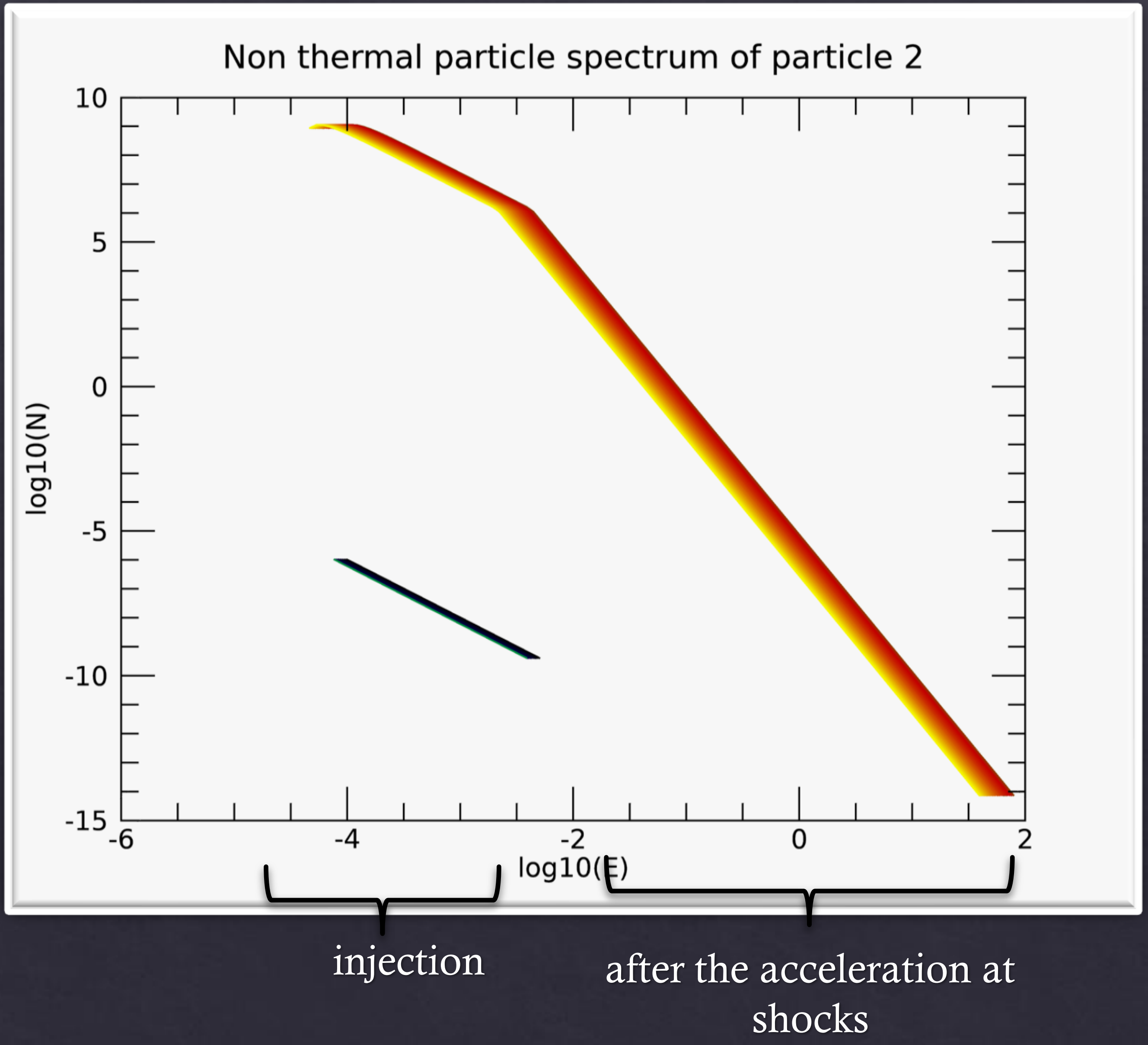




2D simulations for TeV blazars: particle acceleration

Energy distribution for macroparticle 2:

- energized from shocks



2D simulations for TeV blazars: particle acceleration

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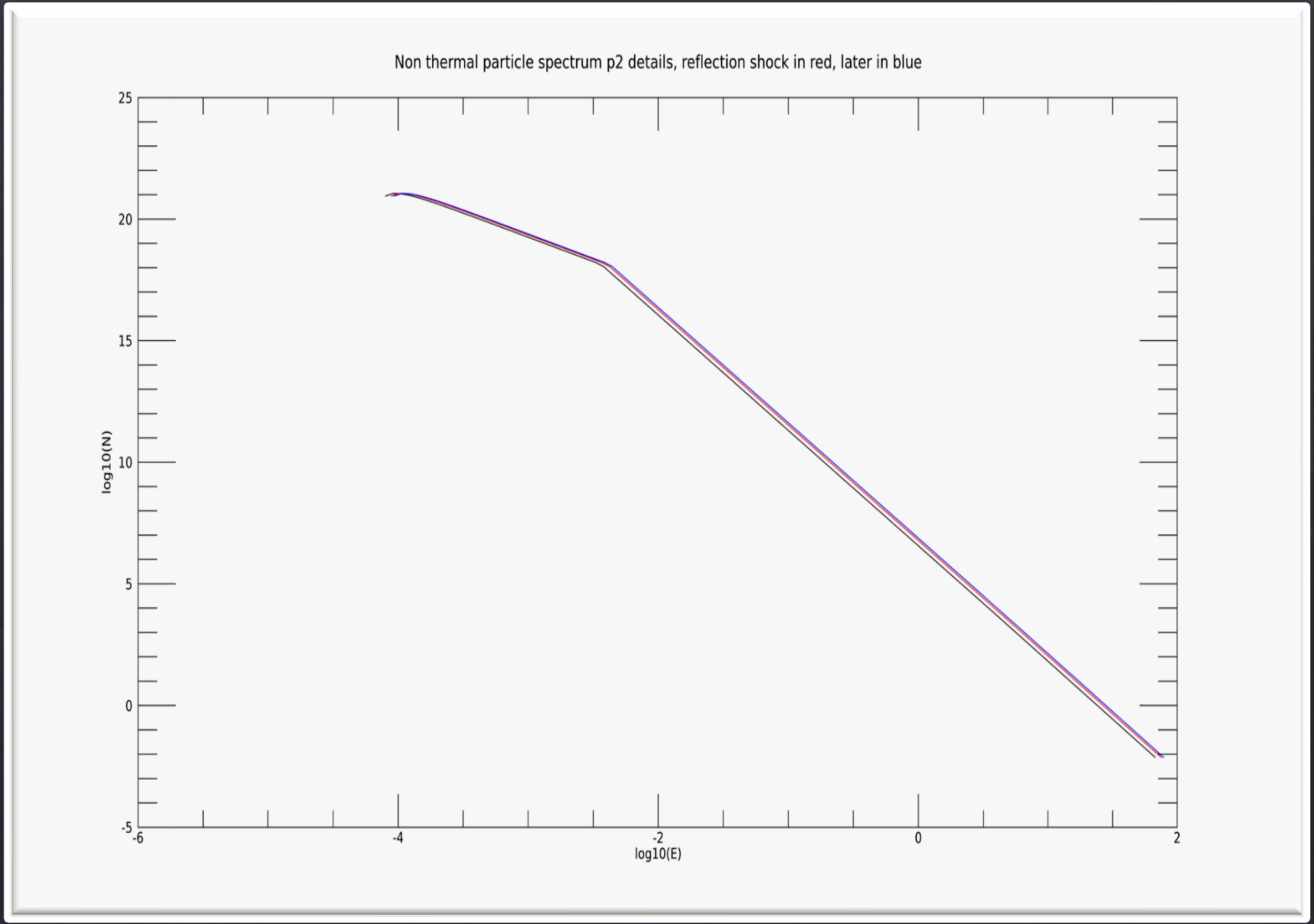

2D simulations for TeV blazars: particle acceleration

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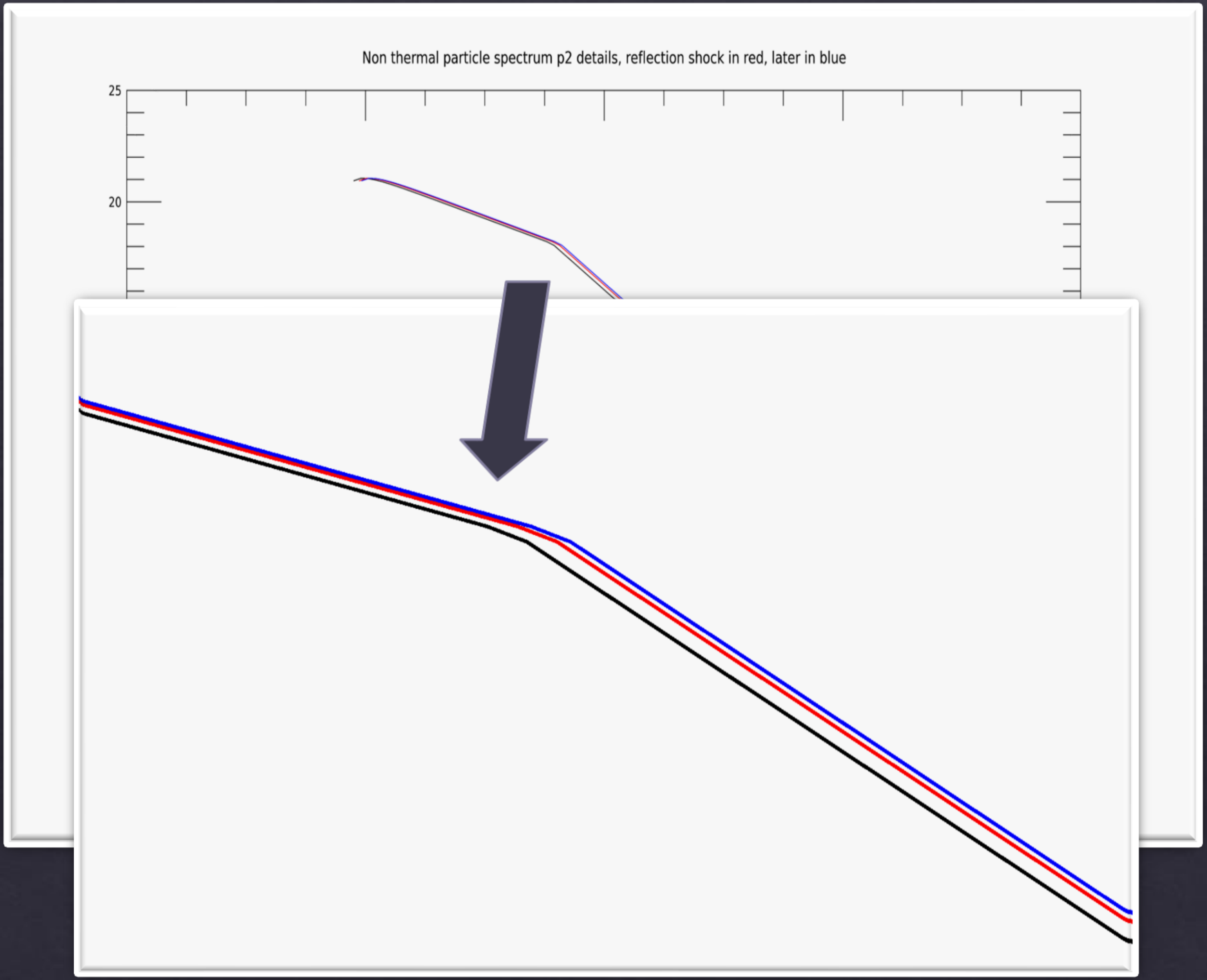
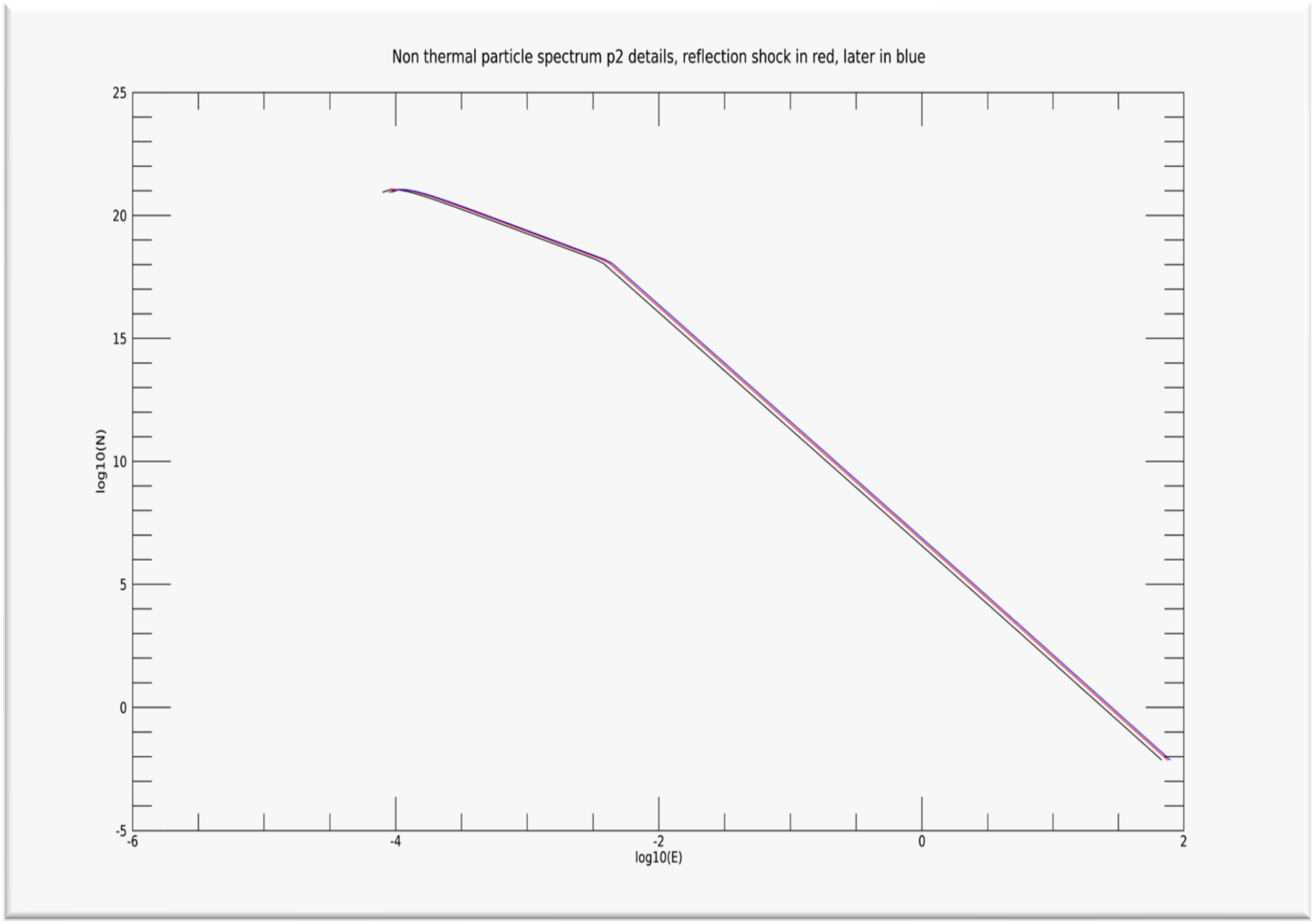


2D simulations for TeV blazars: particle acceleration

First result:

Subsequent shocks might not be able to accelerate further the electrons !

In tension with the current modeling of TeV blazars



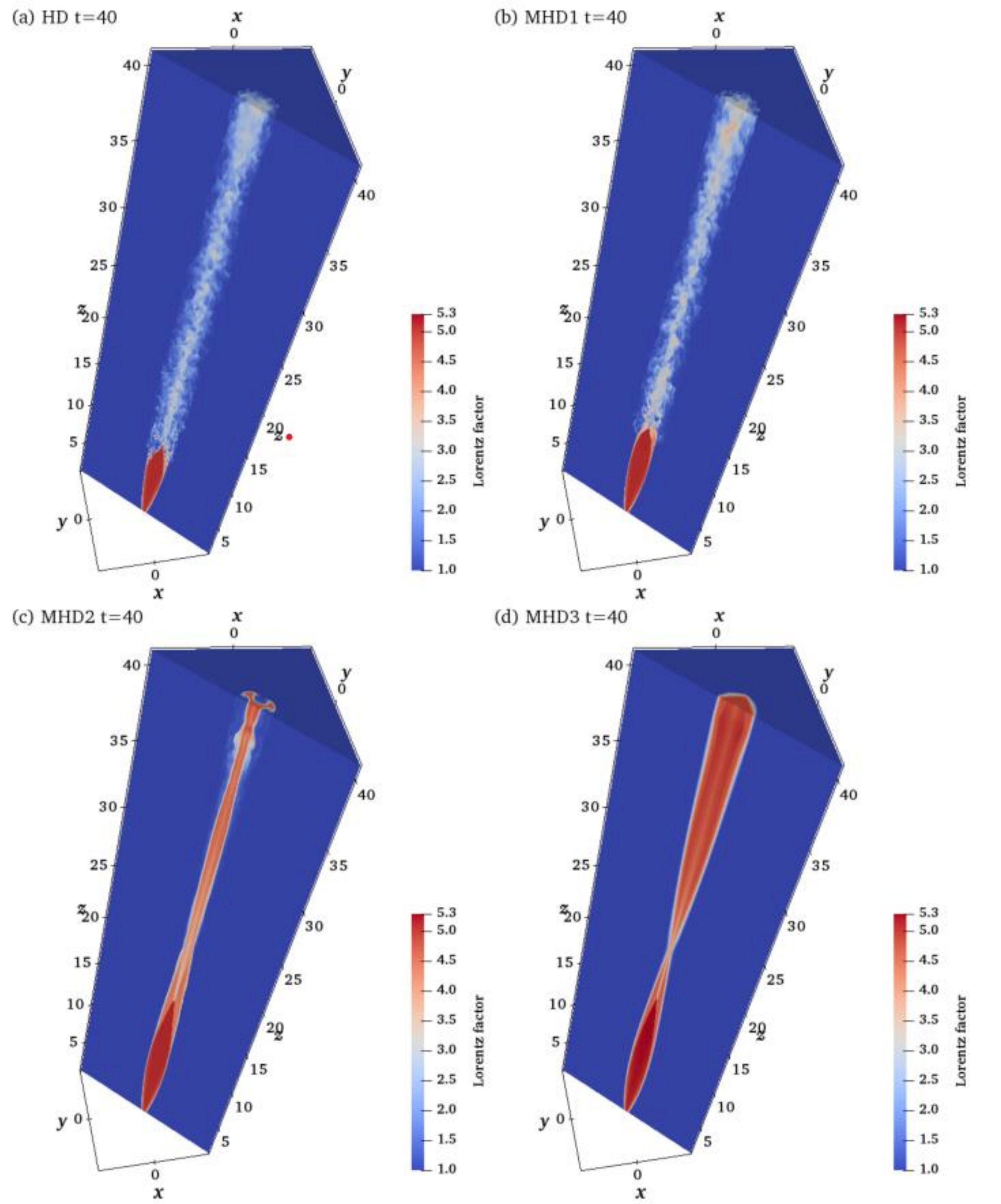
3D simulations for TeV blazars: turbulence in low magnetized jets

1. Instabilities **cannot develop completely** in 2D axisymmetry
2. Some don't develop at all in 2D, but they exist!

3D simulations for TeV blazars: turbulence in low magnetized jets

1. Instabilities **cannot develop completely** in 2D axisymmetry
2. Some don't develop at all in 2D, but they exist!
   - Centrifugal instability caused by the recollimation shock → **turbulence in low magnetized jets** ($\sigma = \frac{B^2}{4\pi\omega} \leq 10^{-4}$)

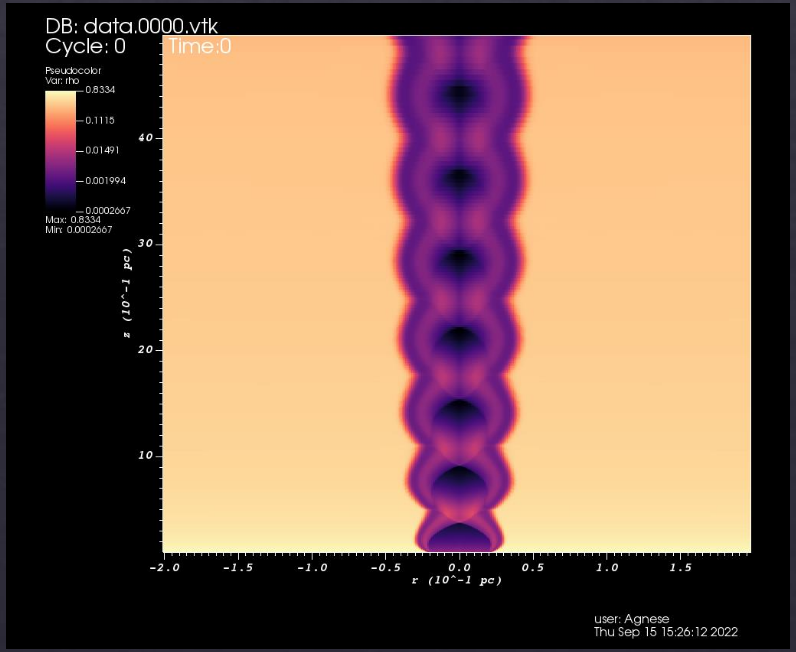
Matsumoto, Komissarov, Gourgouliatos, 2021

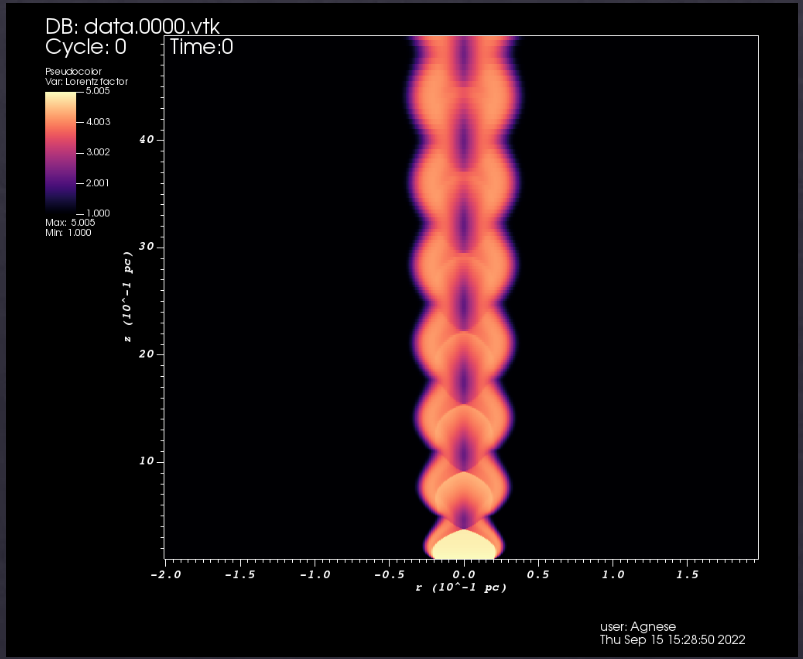


3D simulations for TeV blazars: what now?

3D RHD simulation to check on turbulence developing

From the 2D stationary solution:

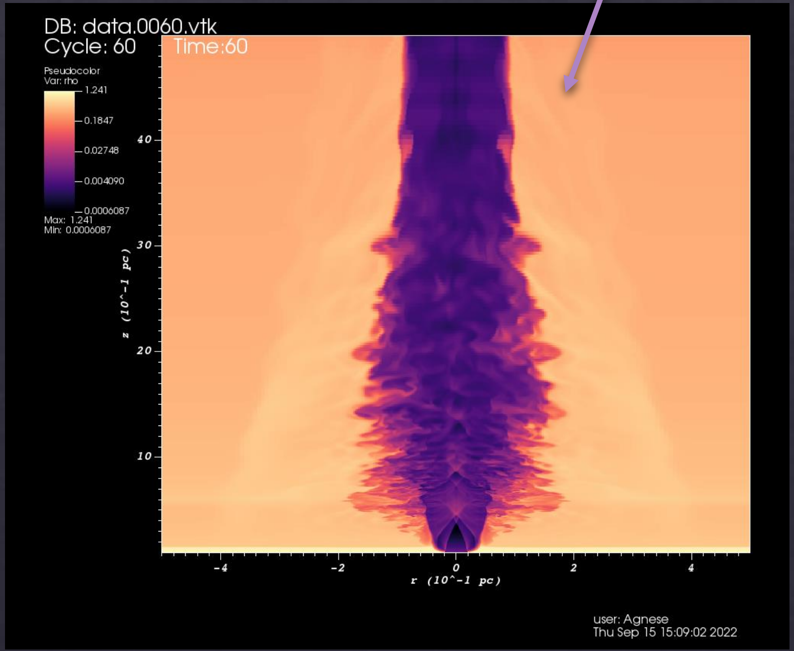


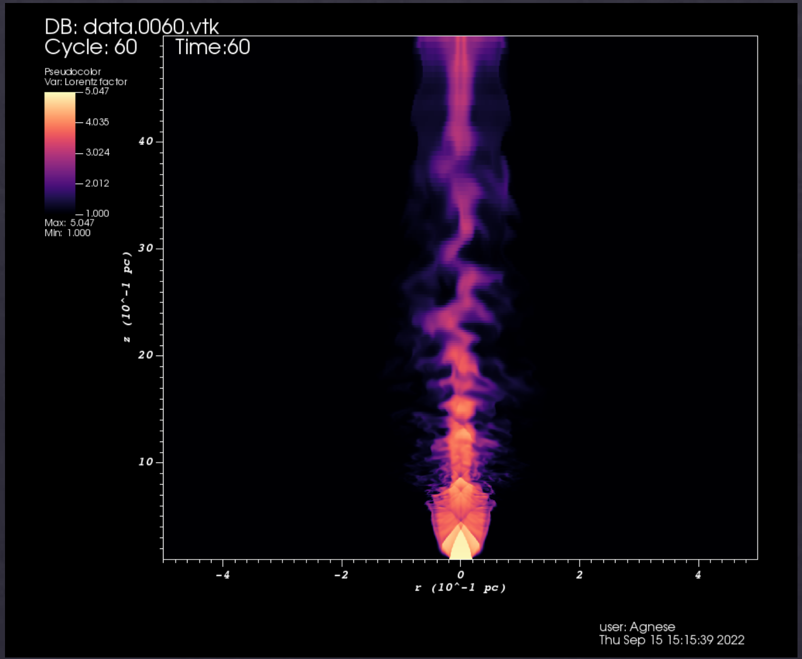


3D simulations for TeV blazars: what now?

3D RHD simulation to check on turbulence developing

From the 2D stationary solution to the 3D simulation:





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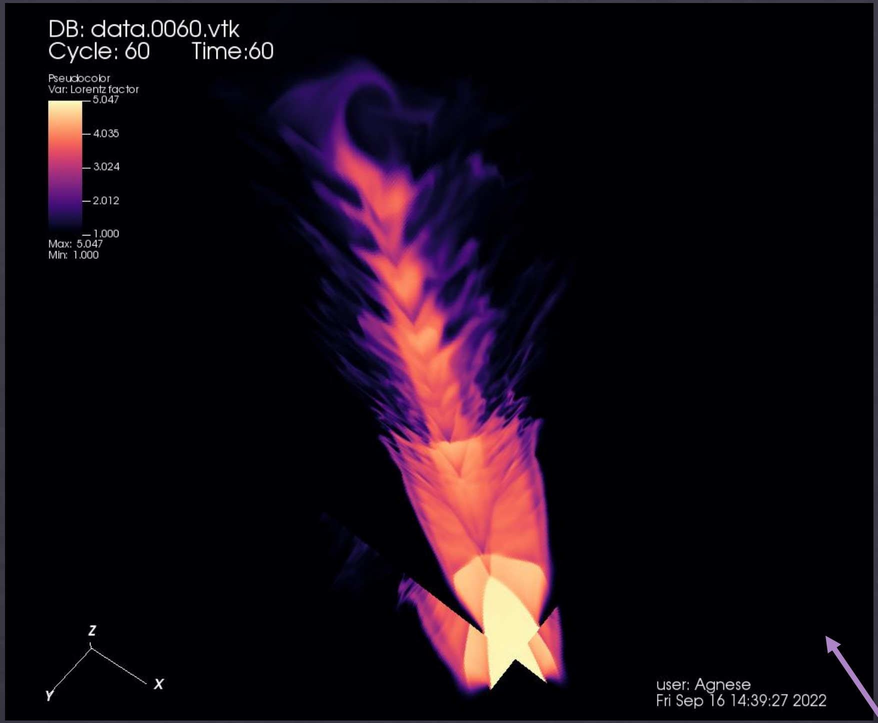
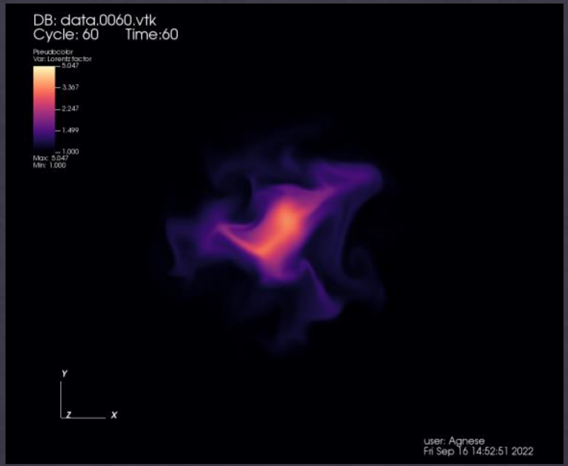
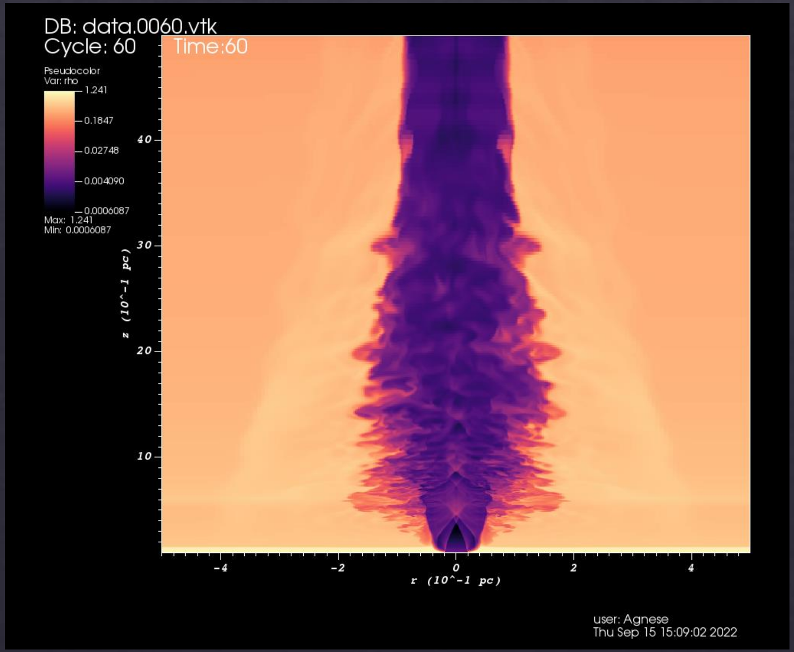


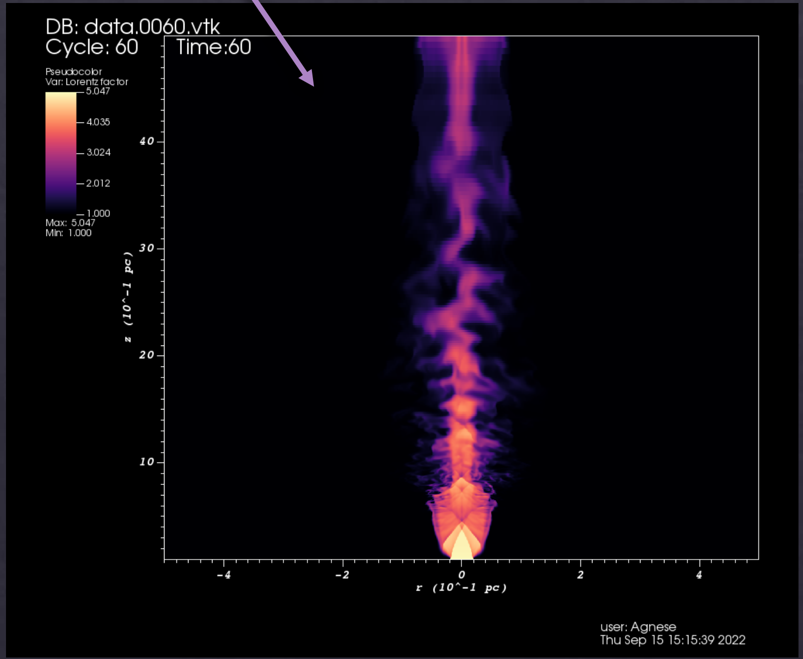


From the 2D stationary solution to the 3D simulation:

- the jet becomes turbulent
- CFI+KH instabilities?
- More complex shock structure
- …

Work in progress!





What’s next?

- 3D RHD to 3D Relativistic MHD to check on turbulence developing
- Particle acceleration (and sync+IC emission) in the 3D final setup

The end!

The end!

Thank you for your kind attention

BACKUP: Recollimation shocks in AGN jets

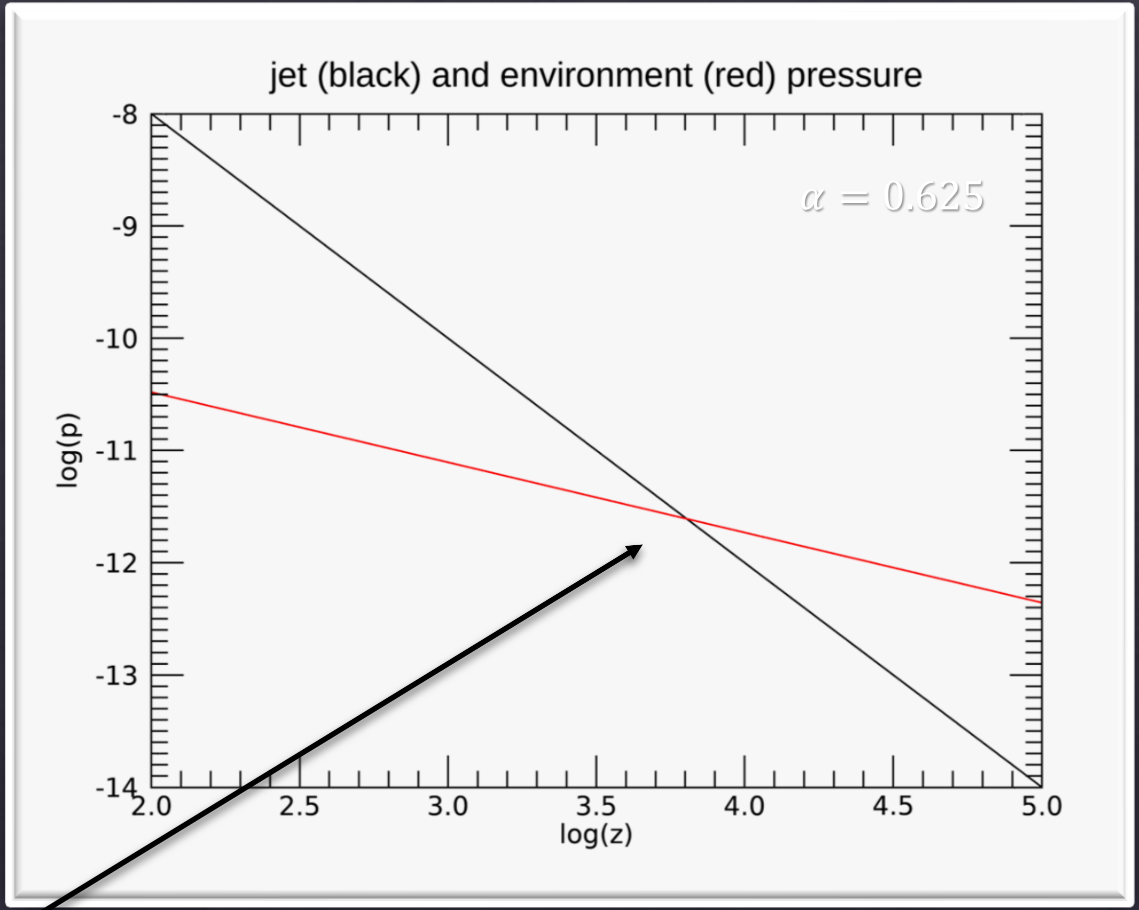
Relativistic AGN jets expand and cool adiabatically through the environment

$$p_j = p_{0j}\left(\frac{\sqrt{z^2+r^2}}{z_0}\right)^{-2}$$

while the environment pressure follows a general power law decaying with distance from the central engine

$$p_e = p_{0e}\left(\frac{z}{z_0}\right)^{-\alpha}$$

When there is a pressure unbalance in favour of the environment the jet undergoes a recollimation process that is supersonic and waves/shocks form



$\alpha < 2$

BACKUP: 2D simulations with particles for TeV blazars

Diffusive Shock Acceleration

- $N_e(E) \propto E^{-2}$ for strong shocks
- efficient Fermi I acceleration mechanism:

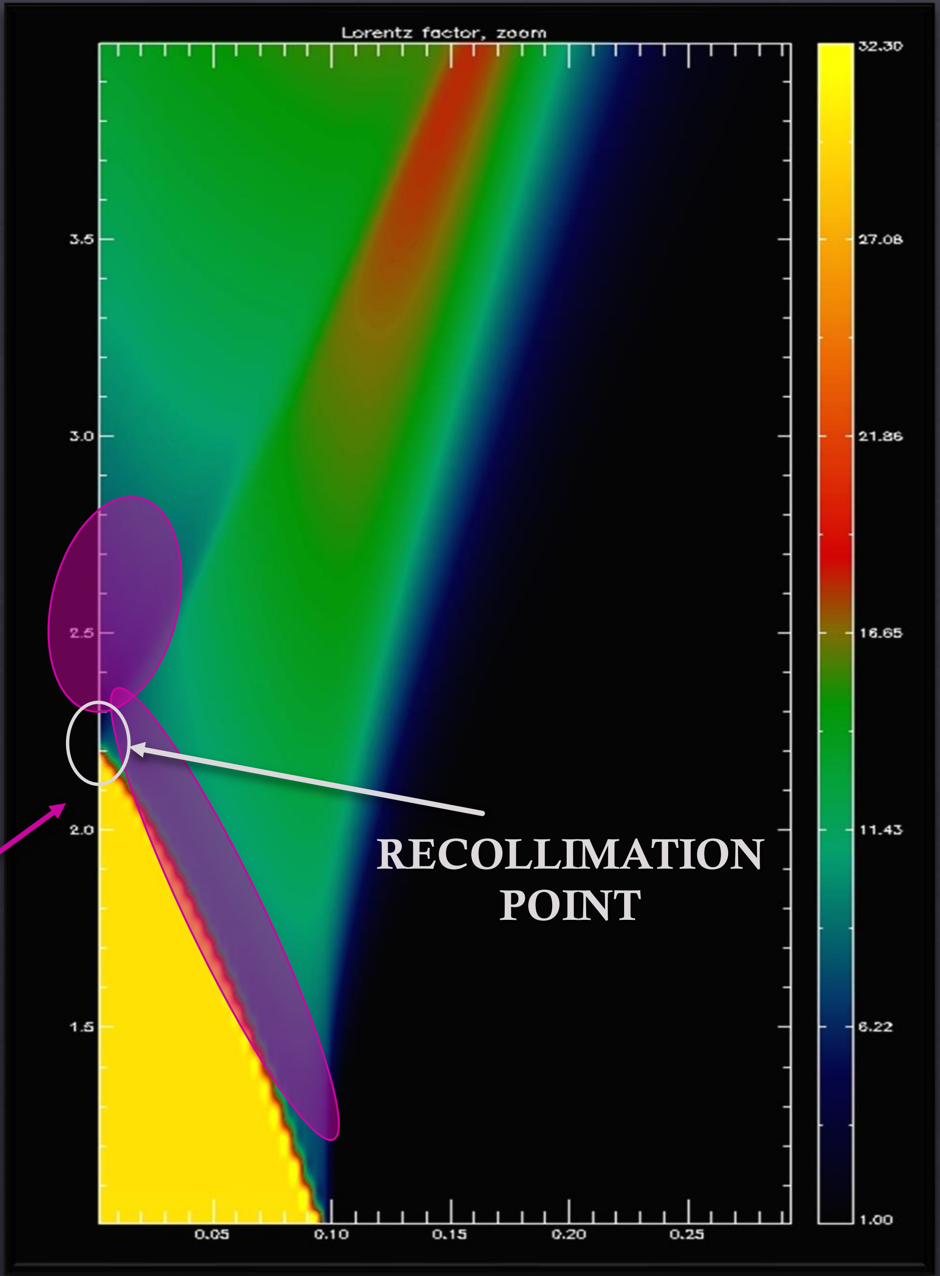
$$\frac{<\Delta E>}{E} \propto \frac{\mathrm{v}}{\mathrm{c}}$$

- good for low magnetized jets (otherwise magnetic reconnection too)

In recollimation and reflection shocks the shock surface is curved and the angle between the upstream velocity and the surface is variable

- the strength of the shock increases towards the recollimation point.

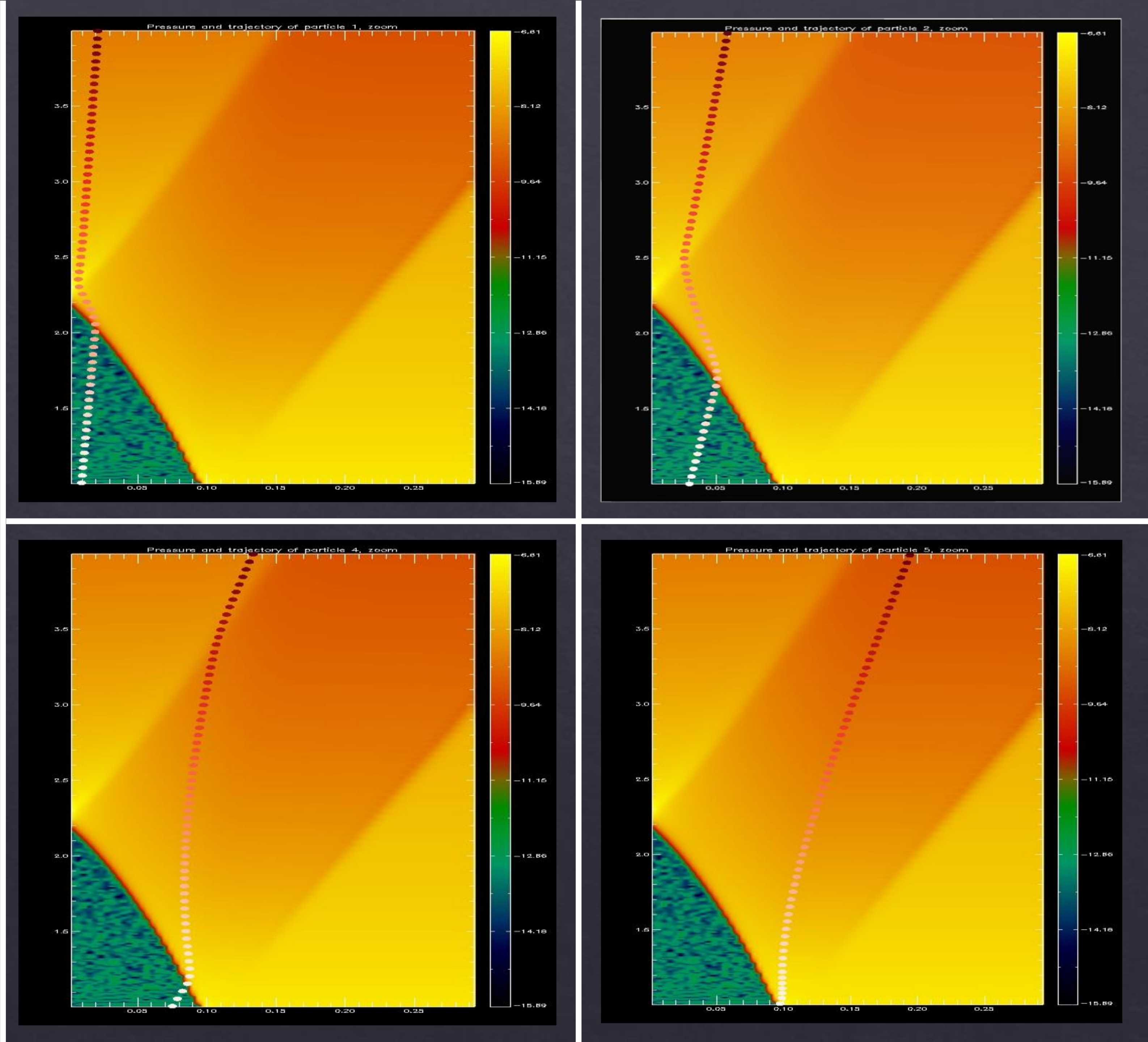
acceleration sites in recollimation-reflection shocks



BACKUP: 2D simulations with particles for TeV blazars

Results for different particles: 1, 2, 4, 5

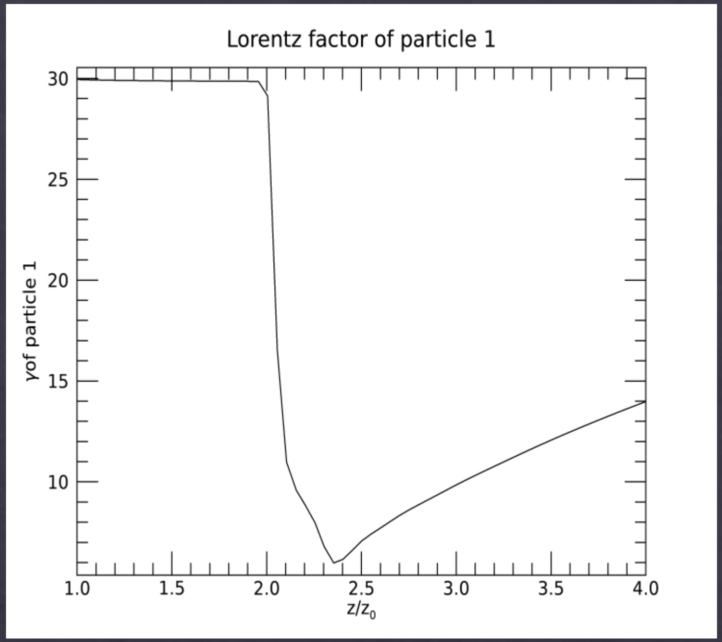
- The particles follow the plasma, so they undergo shocks of varying strength depending on the direction of the shock surface, and of the plasma velocity, at their position.
- Particles are accelerated the most near the axis, near the recollimation point.
- The reflection shock is stronger at the axis as well.

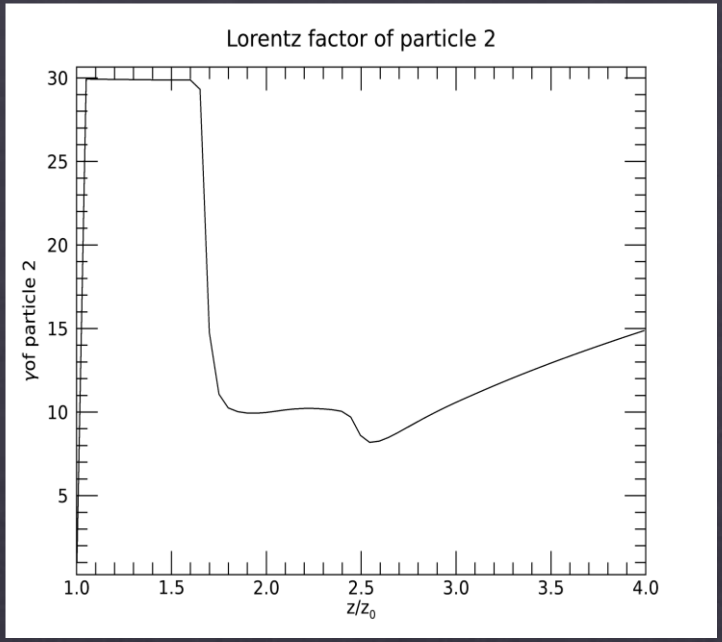


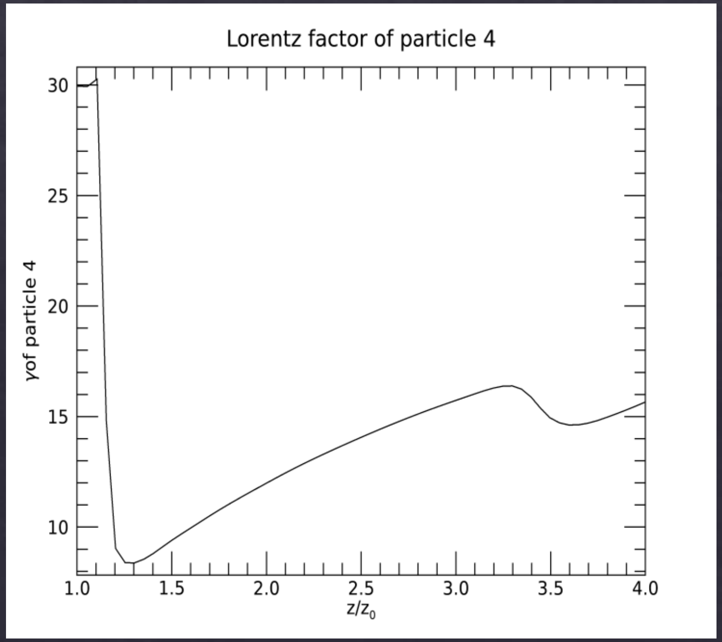
BACKUP: 2D simulations with particles for TeV blazars

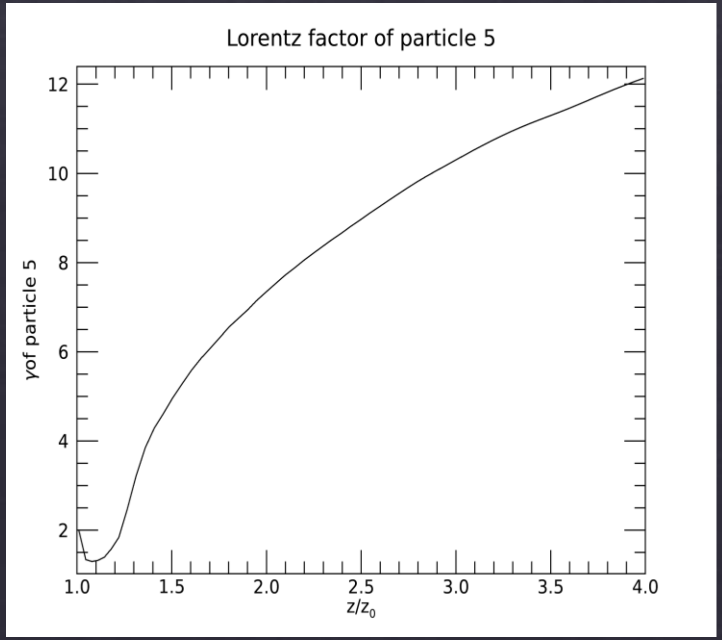
Results for different particles:

- Particle 1 is shocked near the axis and soon is reshocked
- Particle 2 experiences two, well distinct, shocks
- Particle 4 experiences two, well distinct, shocks
- Particle 5 seems to be faintly shocked at the beginning and then is accelerated from the increasing background velocity.





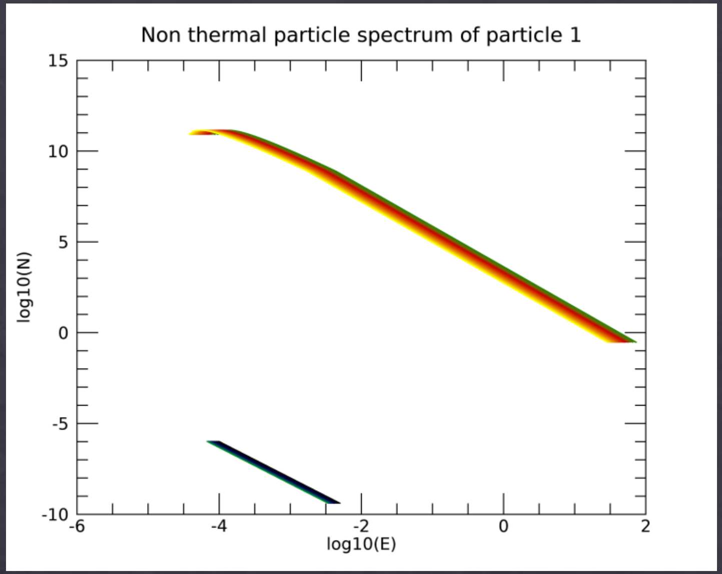


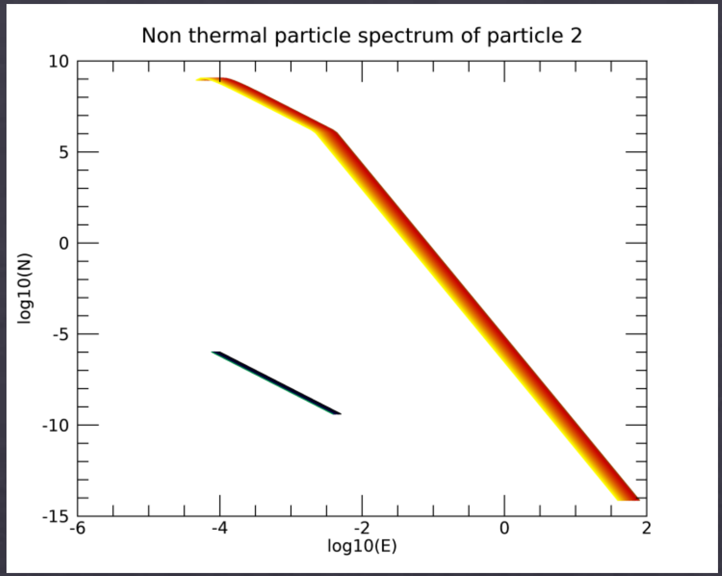


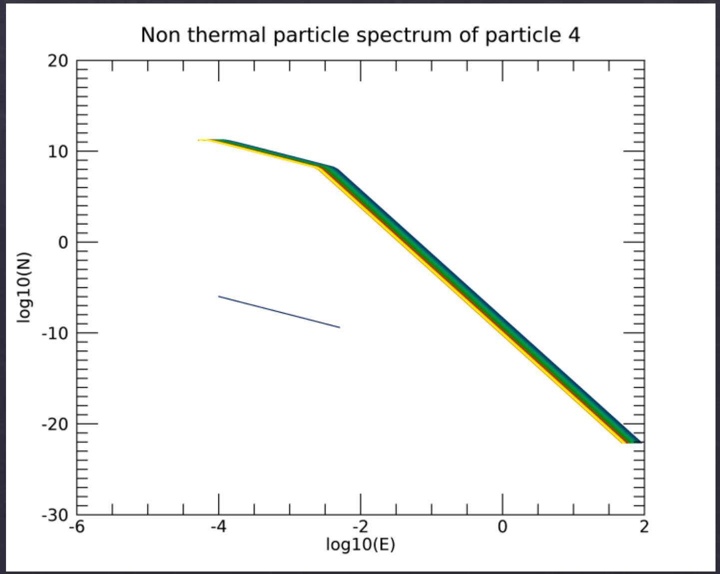
BACKUP: 2D simulations with particles for TeV blazars

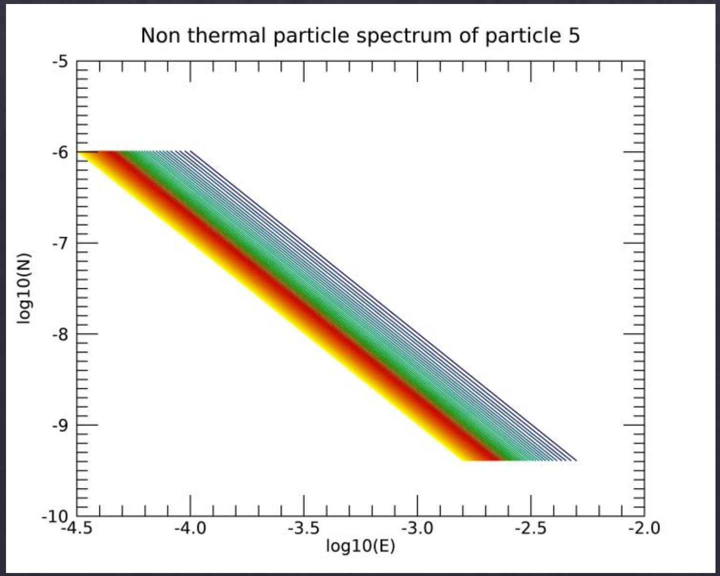
Results for different particles:

- Particle 1 crosses the strongest shocks
- Particle 2 experiences weaker shocks.
- Particle 4 experiences even weaker shocks.
- Particle 5 does not capture the shock: the injected particle distribution is only updated.









BACKUP: 2D simulations with particles for TeV blazars

Particle parameters:

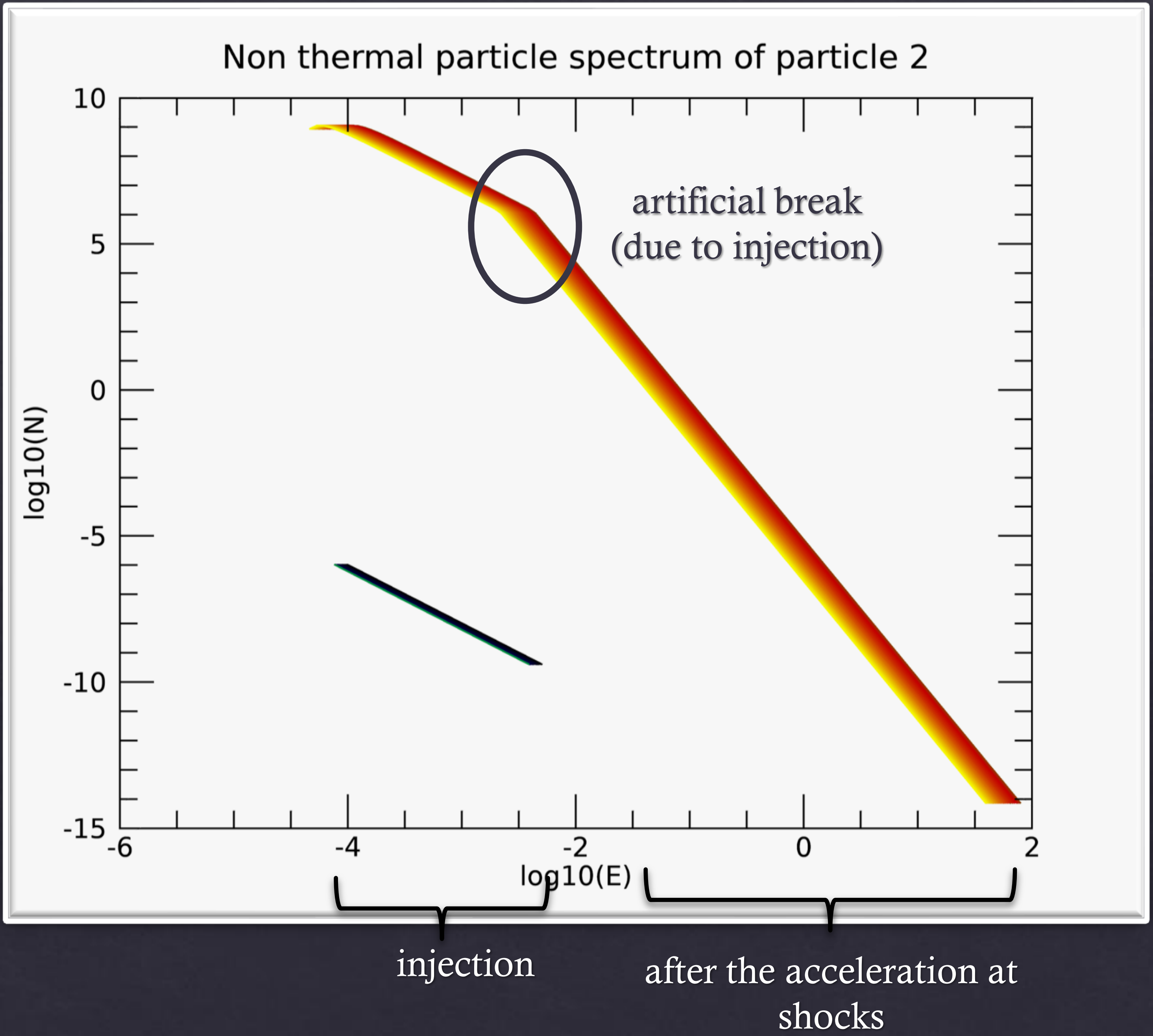
Initialization is meant to provide a minimal Lorentz factor for shock acceleration, because PLUTO itself still doesn't require any minimal energy (updated to be done):

Power law with:

- $\gamma_{nth,0} = (10^2, 5 \cdot 10^3)$
- $n_{nth,0} = 10^{-10} cm^{-3}$

Graph info

- Unit of measure of the energy is erg
- Acceleration up to $\gamma = 10^8$



BACKUP: main references

Vaidya B. et al., 2018 for the details of the implementation of diffusive shock acceleration in PLUTO and all its sources.

Zech A., Lemoine M., 2021 for the emission model of TeV blazars

Komissarov S., Gourgouliatos K., 2017 for 3D relativistic HD simultations of turbulence in recollimated jets

Matsumoto et al., 2021, for 3D relativistic MHD simultations of turbulence in recollimated jets