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Simulations of relativistic jets and recollimation in extreme blazars

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PASTO
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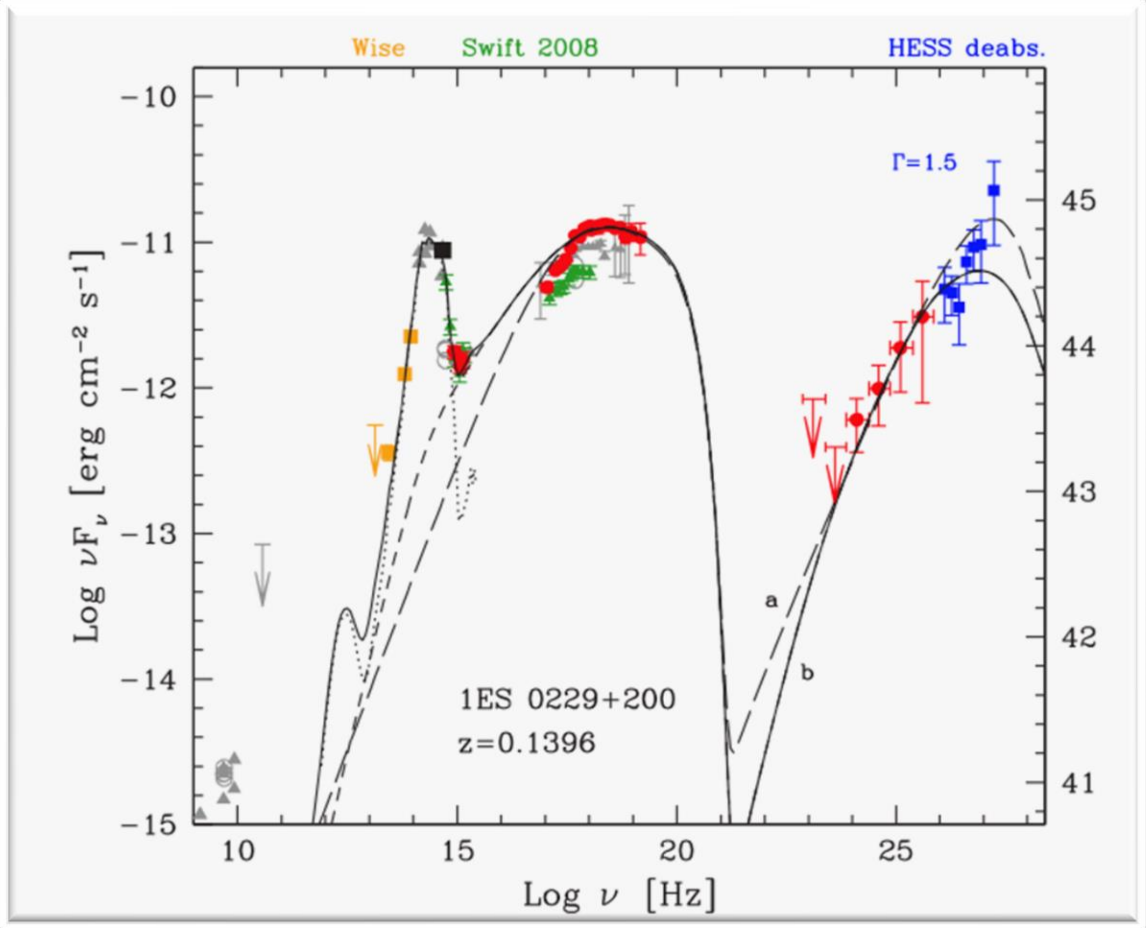
Simulations of relativistic jets and recollimation in extreme blazars

- Introduction: TeV blazars and simulations with PLUTO
- 2D relativistic MHD simulations with lagrangian particles for TeV blazars
- 2D → 3D simulations and turbulence

Extreme TeV blazars

Blazars with high energy peaked, hard spectrum.

Model: standard leptonic emission via synchrotron and SSC from electrons accelerated through DSA, but the slope is very hard!



Costamante et al. 2018
doi: 10.1093/mnras/sty857

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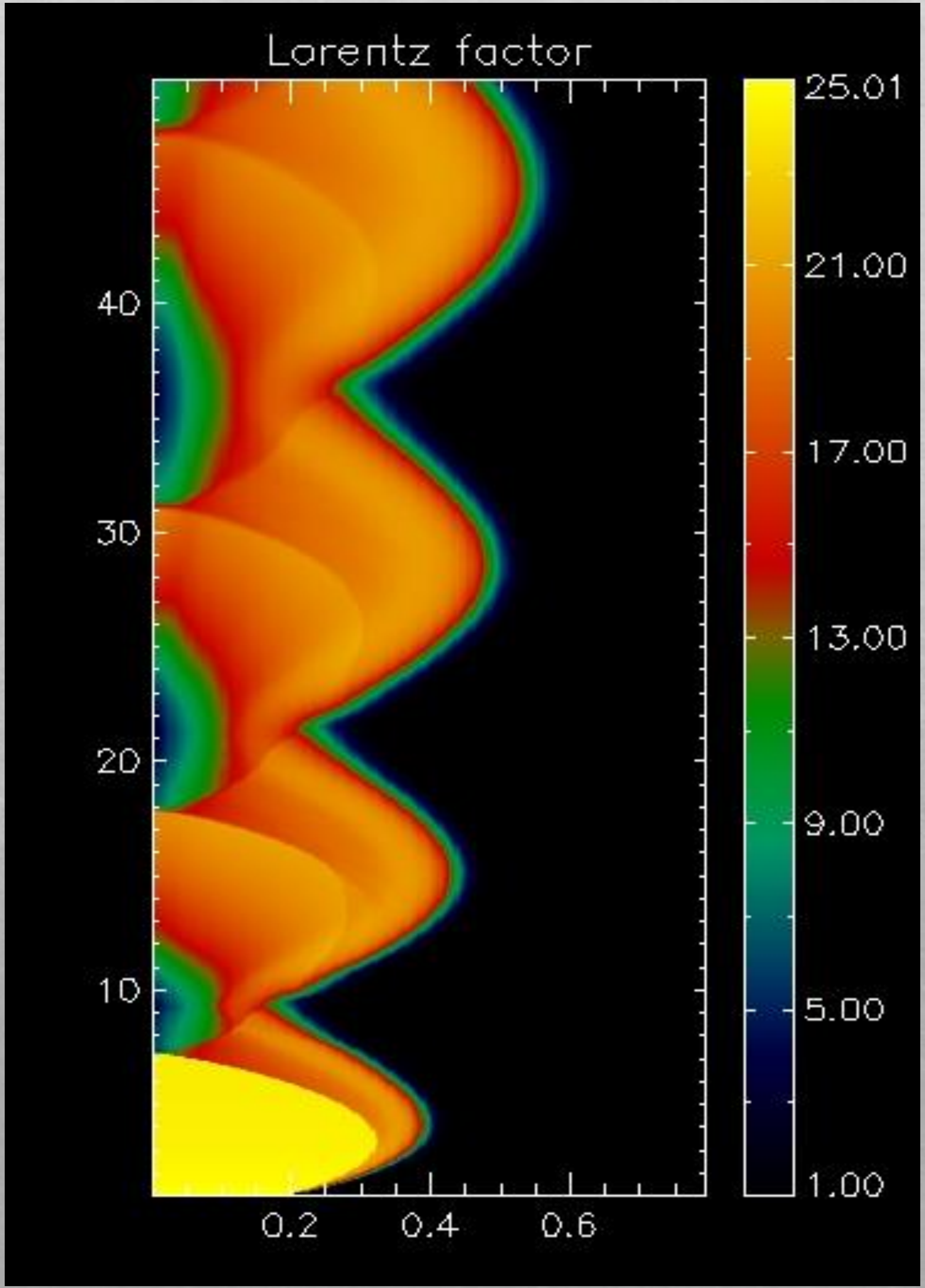

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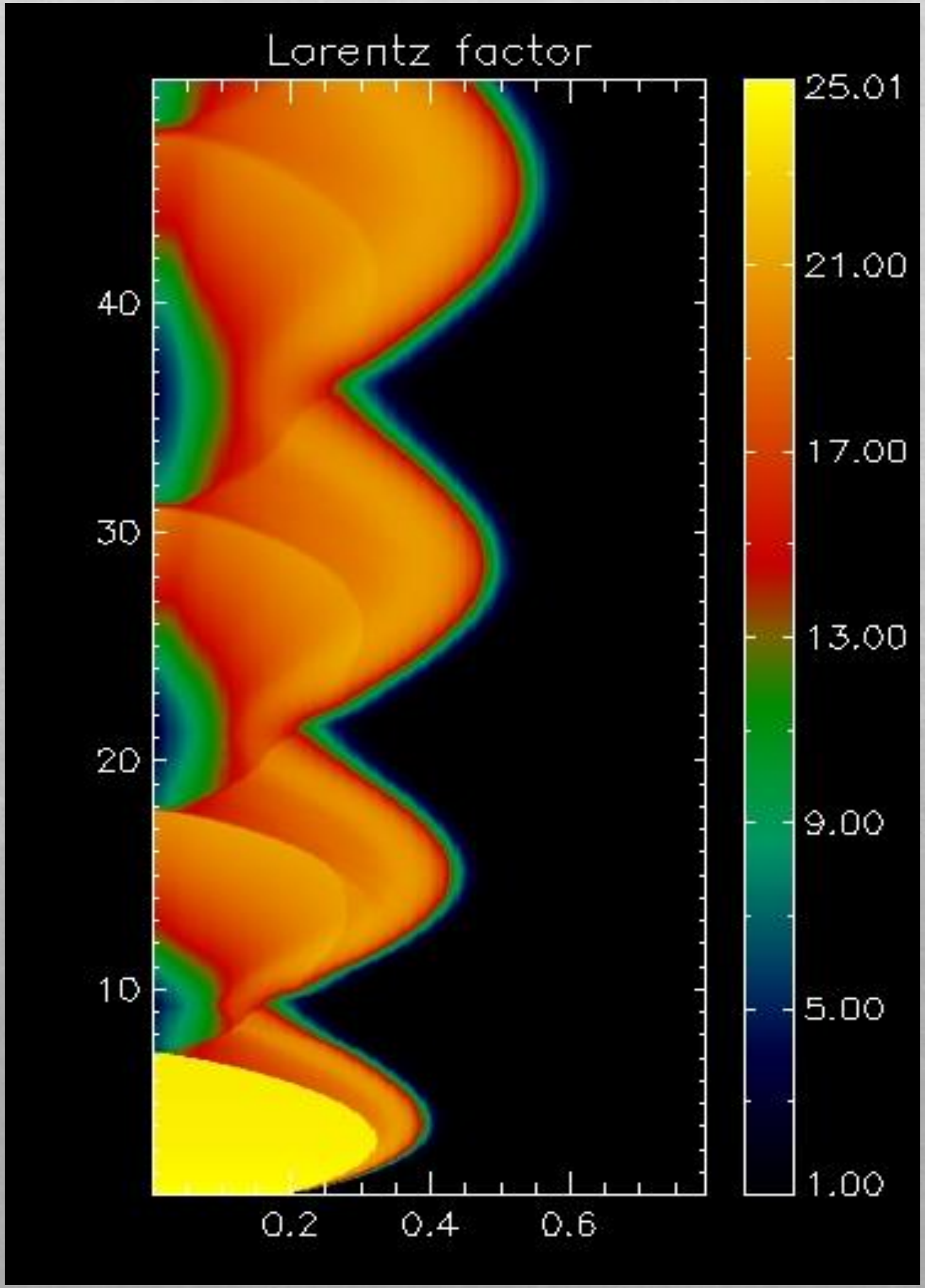
   BUT can it happen and work? (my research)

2. Other phenomenology? (the current part of my work)



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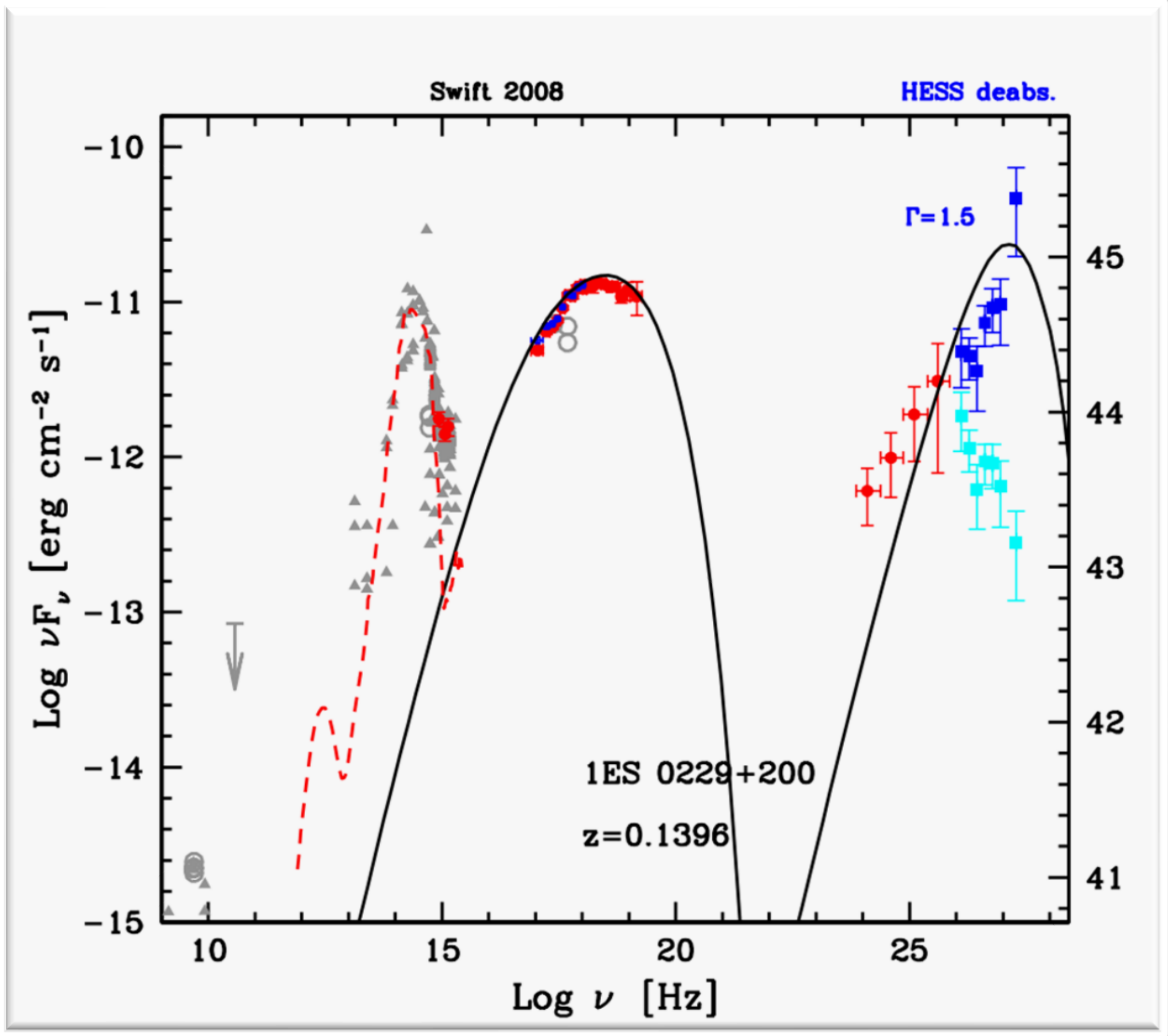
2. Other phenomenologies? (the current part of my work)
3. Would these work as acceleration mechanisms? (hear more from A. Sciaccaluga next)

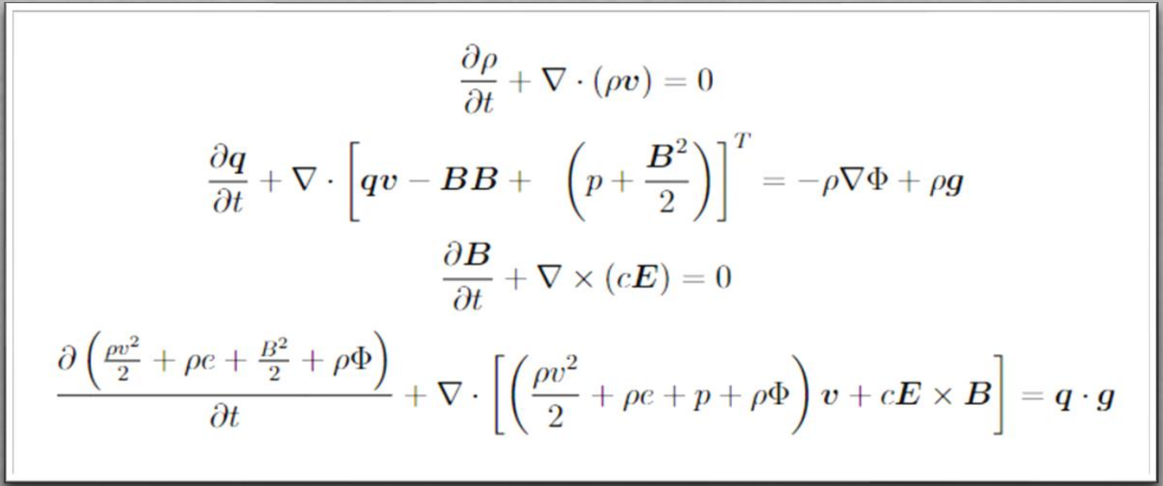


New fit from *Tavecchio et al. 2022.*

Plasma + Lagrangian particles simulations with PLUTO

Plasma:

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



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

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

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

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

ideal MHD for example

Plasma + Lagrangian particles simulations with PLUTO

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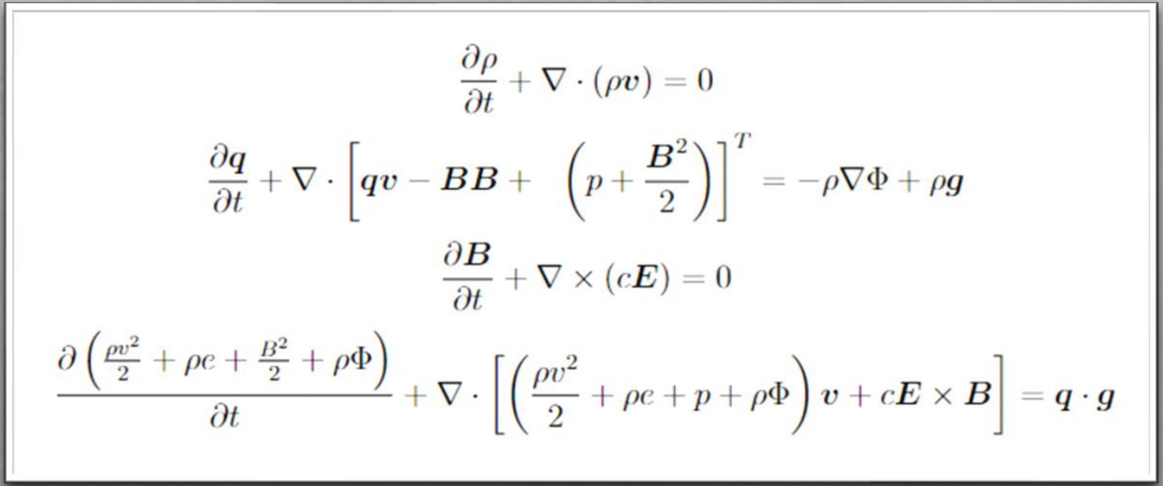

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Non-thermal particles: Lagrangian particle module

- Macroparticles of n real particles characterized by a spectral distribution
- They move following the fluid (fluid quantities at particle position is found via standard interpolation methods)
- No feedback on the fluid
- Energy distribution follows the CR transport equation (non diffusive)

Plasma + Lagrangian particles simulations with PLUTO

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$$
\begin{gathered}
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$$

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- They move following the fluid (fluid quantities at particle position is found via standard interpolation methods)
- No feedback on the fluid
- Energy distribution follows the CR transport equation (non diffusive)
- **After crossing shocks particles are accelerated and the distribution is updated**
- Non thermal emission via synchrotron and IC.
- More can be implemented

2D simulations with particles for TeV blazars

Setup compatible with TeV blazars

- Relativistic
- Low magnetized and B = $10^{-3} G$
- $p_e = p_{0e} \left(\frac{z}{z_0}\right)^{-1.8}$ and $p_{0j} \ll p_{0e}$ (underpressured)

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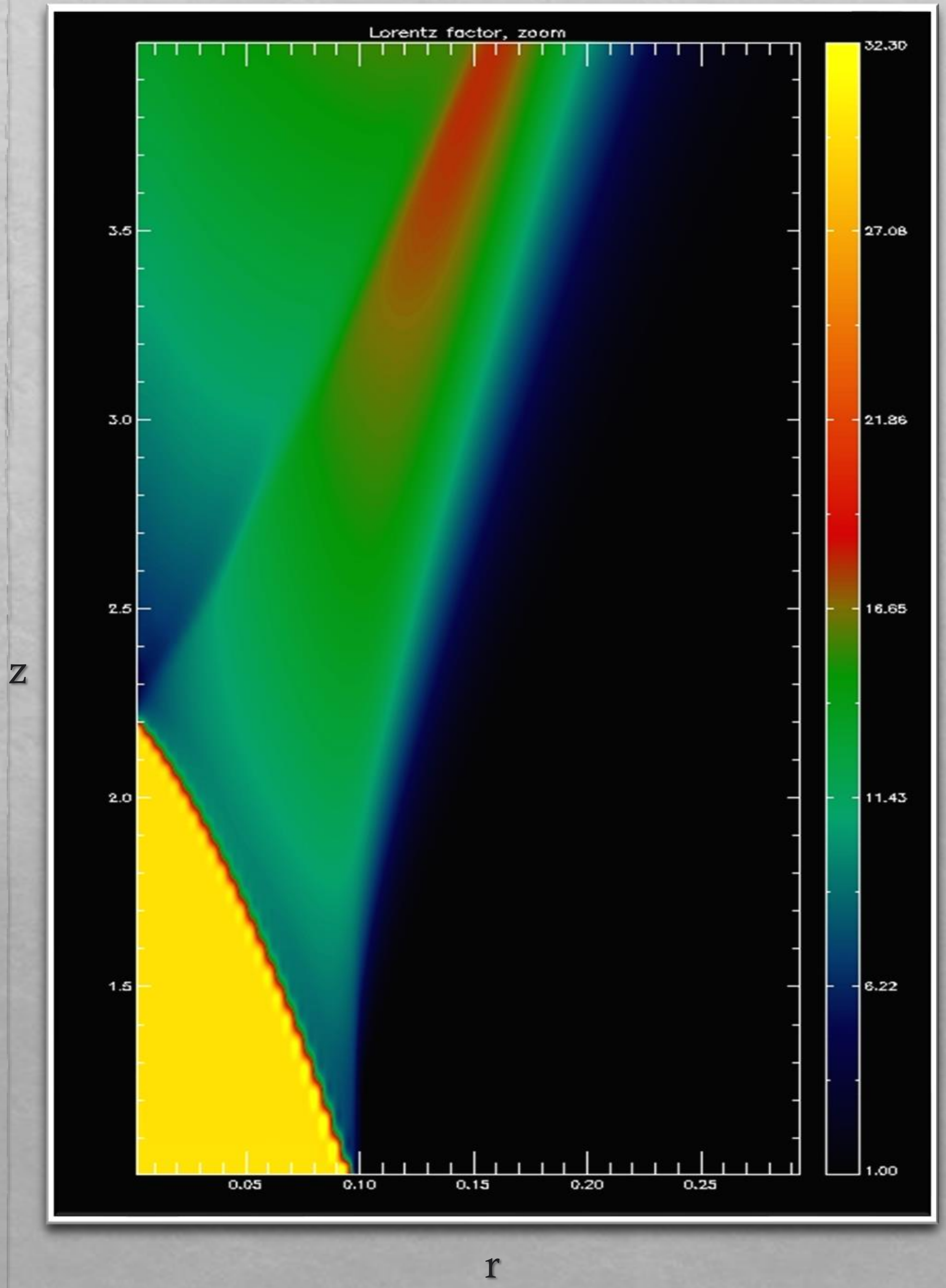

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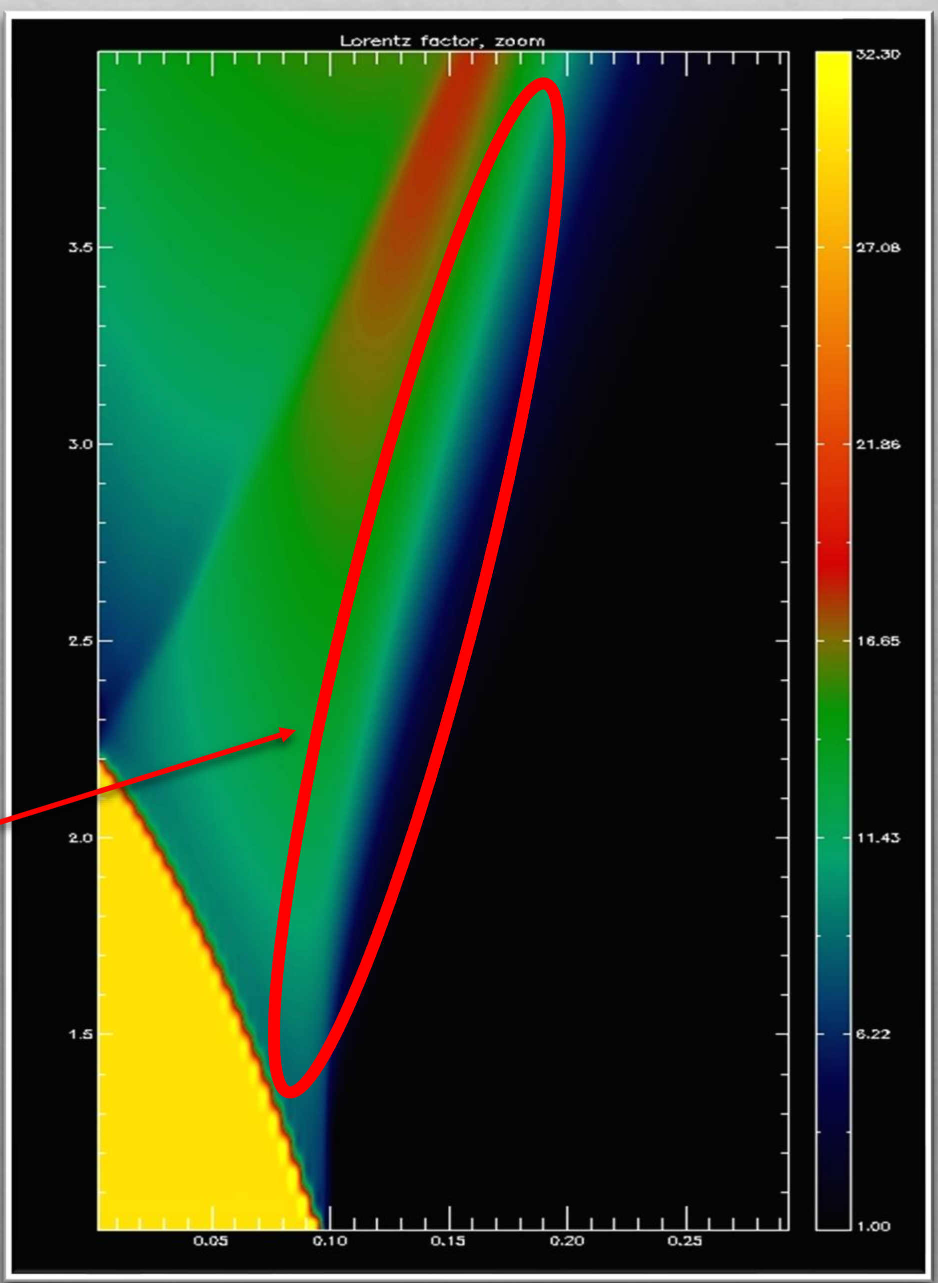

contact discontinuity

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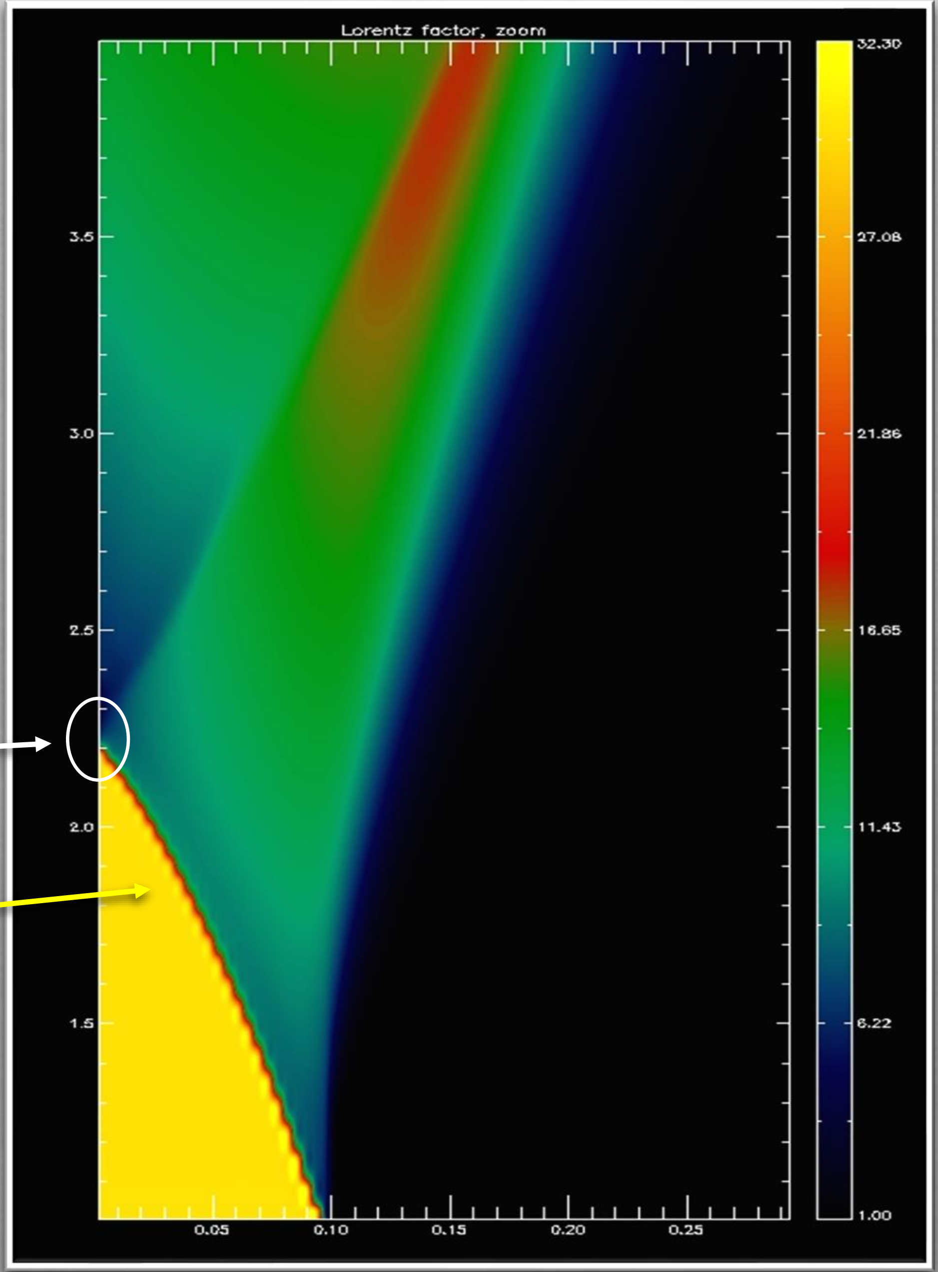

RECOLLIMATION POINT

recollimation shock

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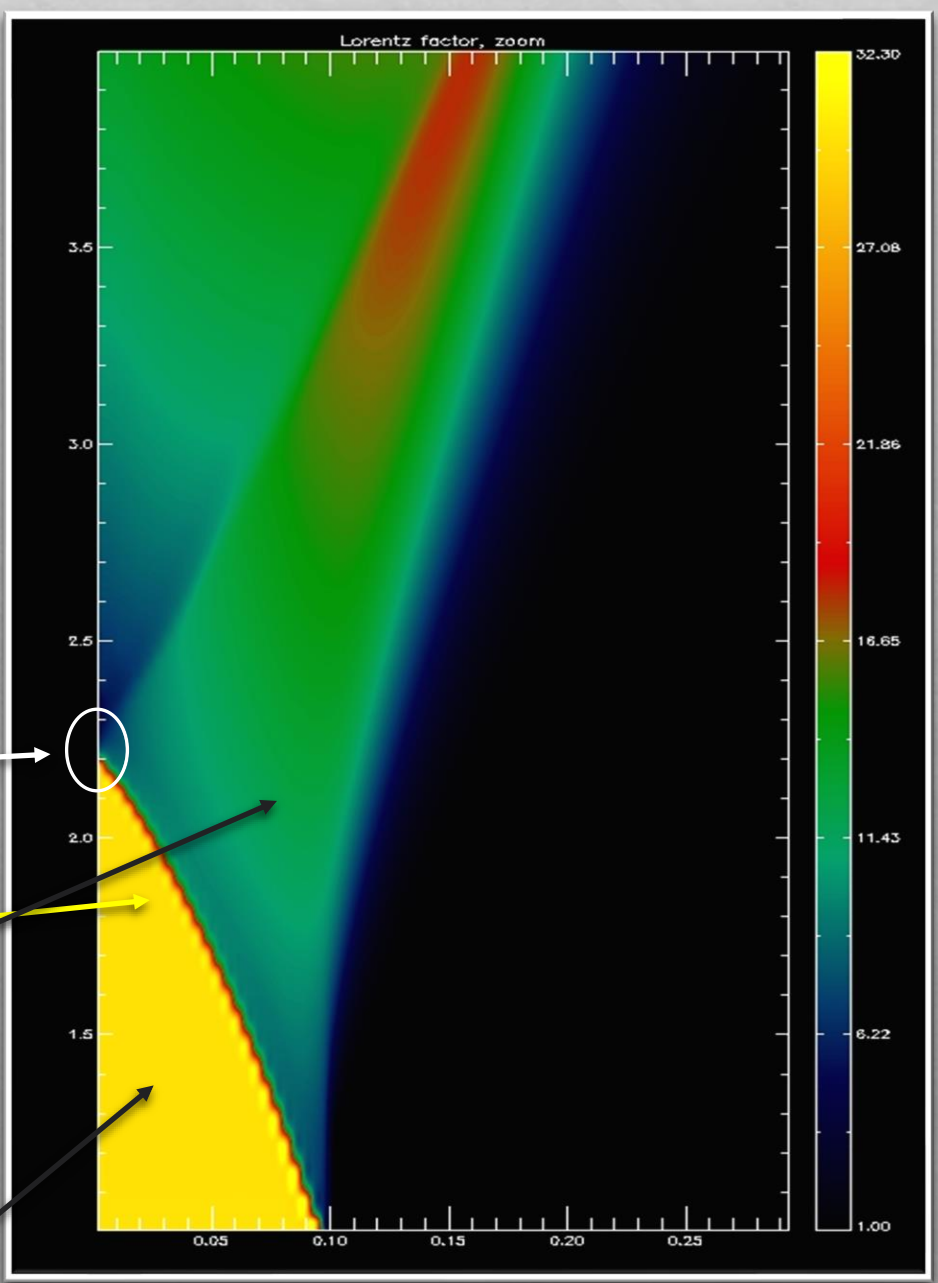

RECOLLIMATION POINT

recollimation shock

shocked jet / downstream

unshocked jet / upstream

2D simulations with particles for TeV blazars

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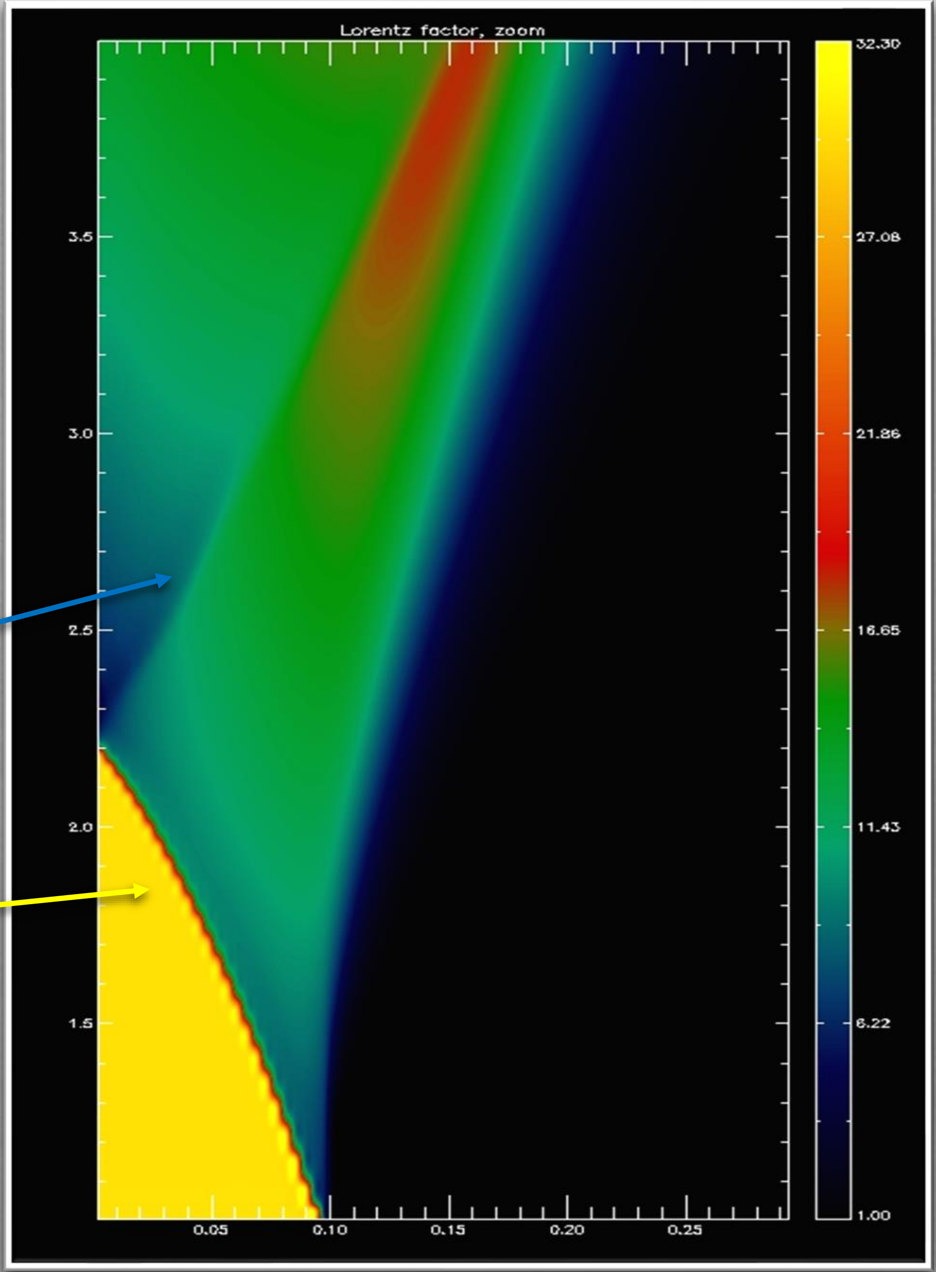


reflection shock: re-shocked jet

recollimation shock

2D simulations with particles for TeV blazars

Diffusive Shock Acceleration

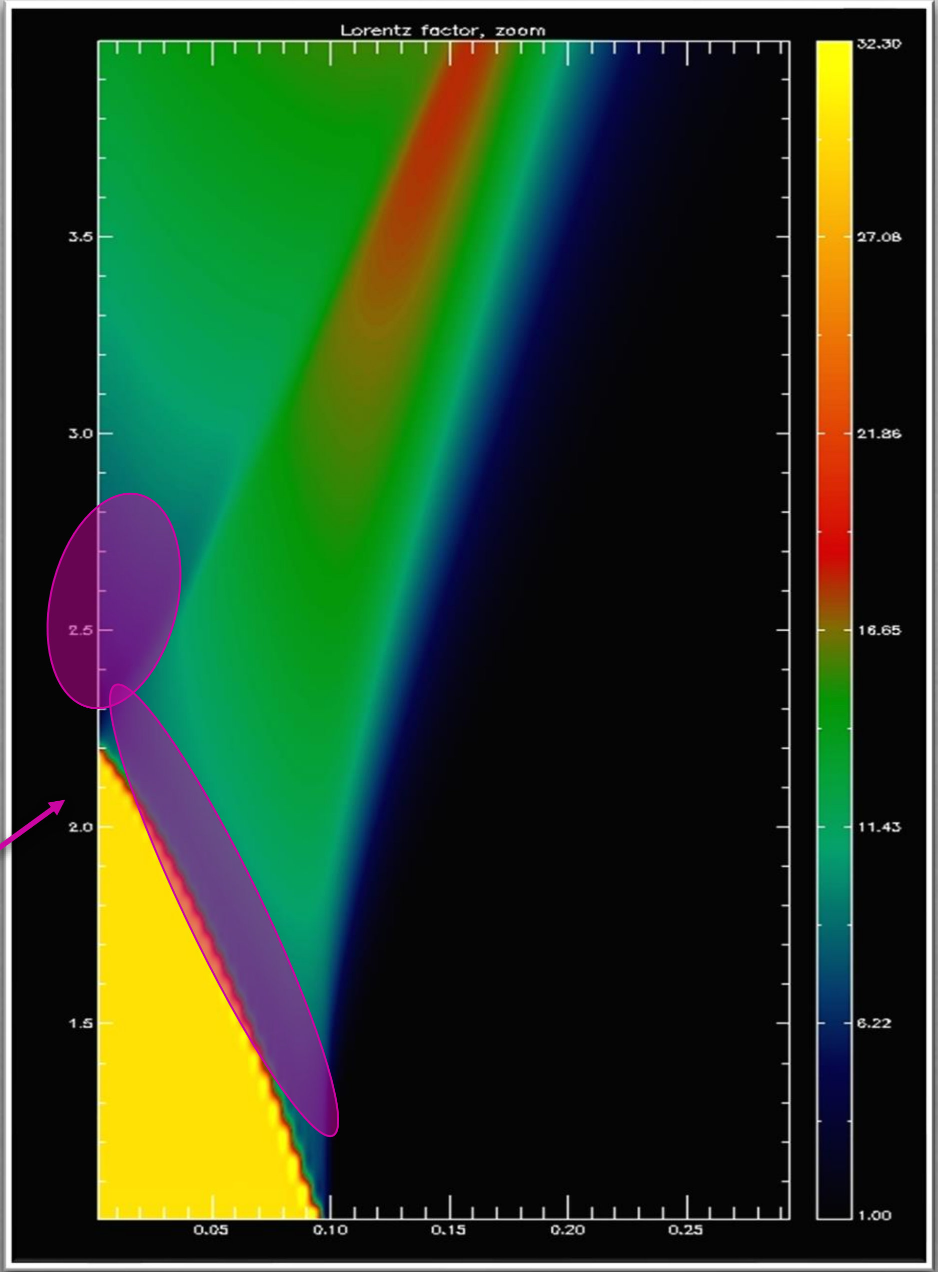
- $N_e(E) \propto E^{-2}$ for strong shocks
- efficient Fermi I acceleration mechanism:

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

- 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

2D simulations with particles for TeV blazars

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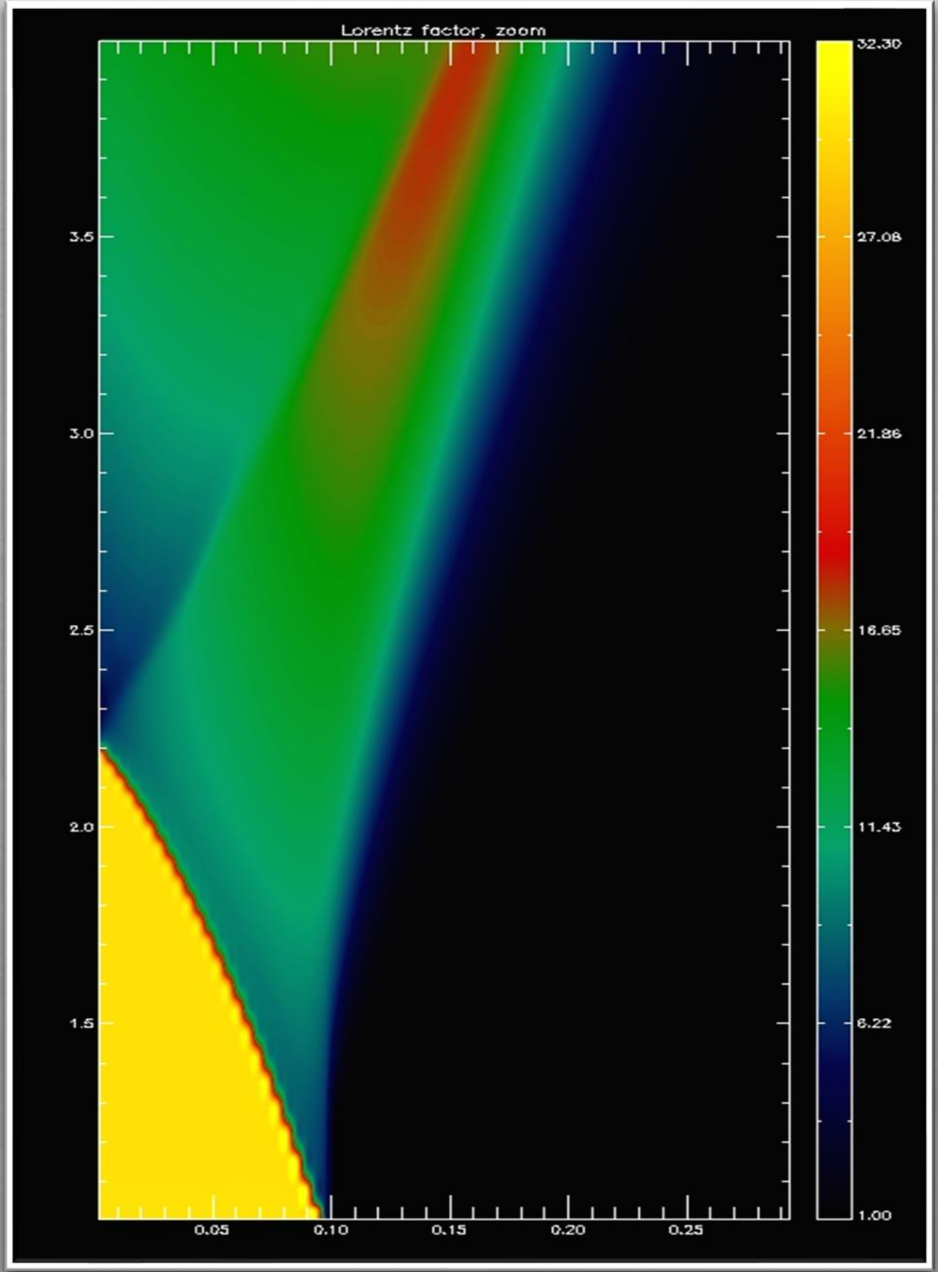
Non thermal particle injection

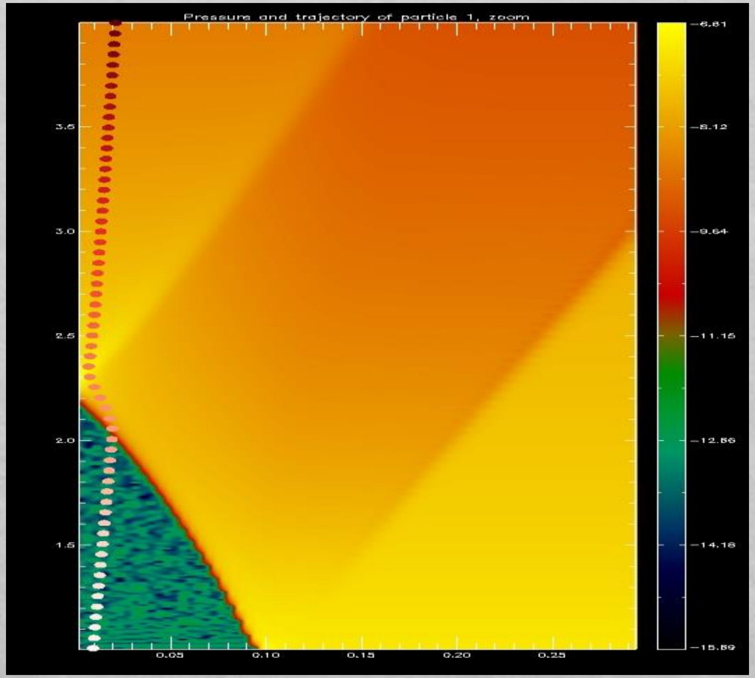
- Non thermal density and energy distribution are initialized to be small and mildly relativistic (we expect to have a population of pre-accelerated particles)
- Specifics have little impact on the results.

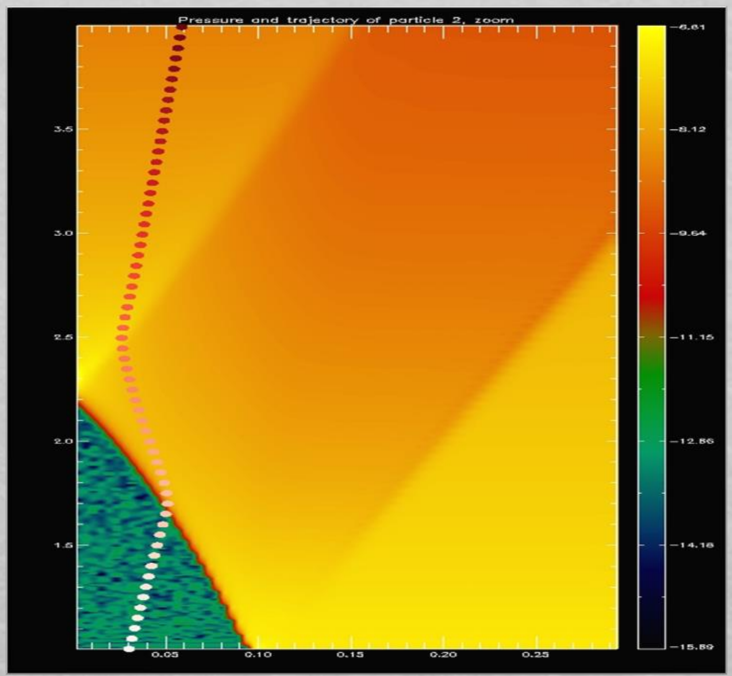


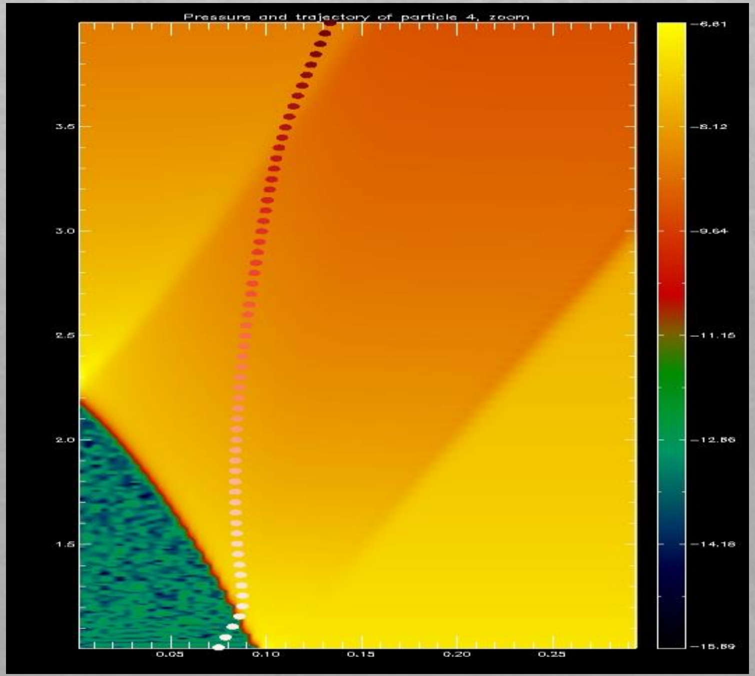
2D simulations with particles for TeV blazars

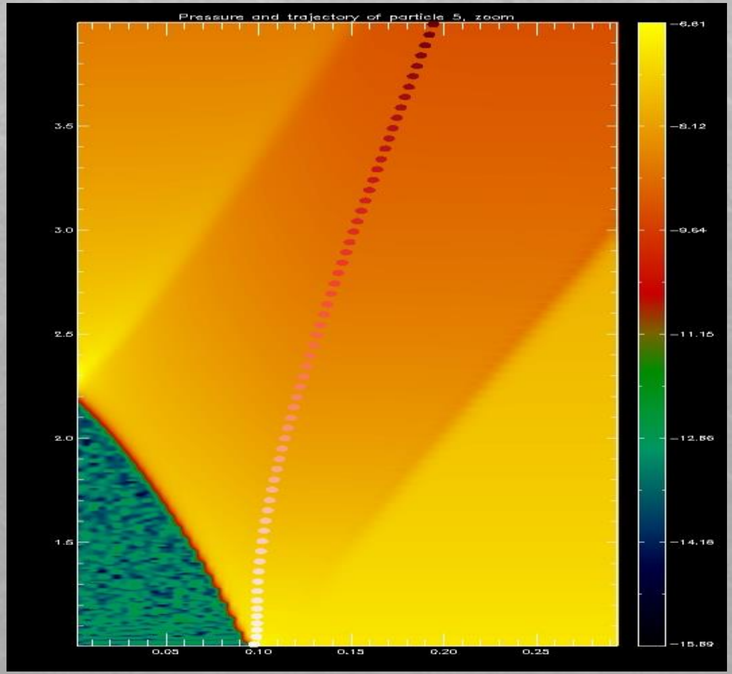
Results for different particles: 1, 2, 4, 5

- 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.





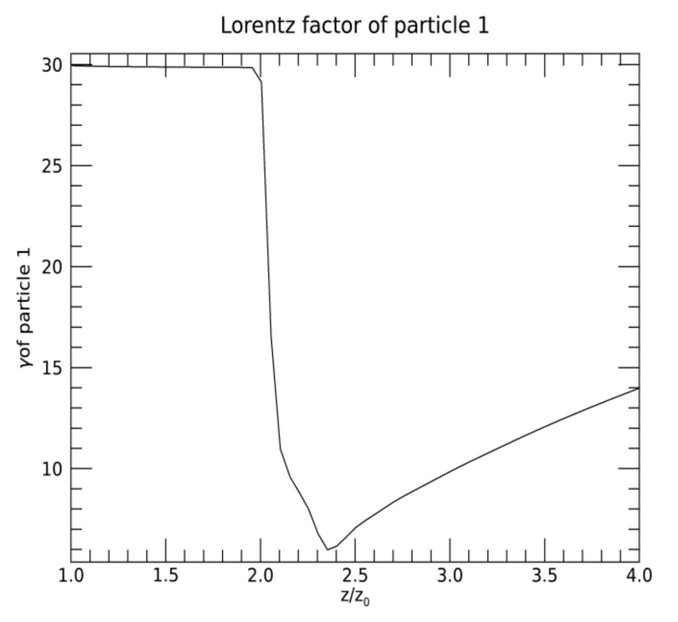


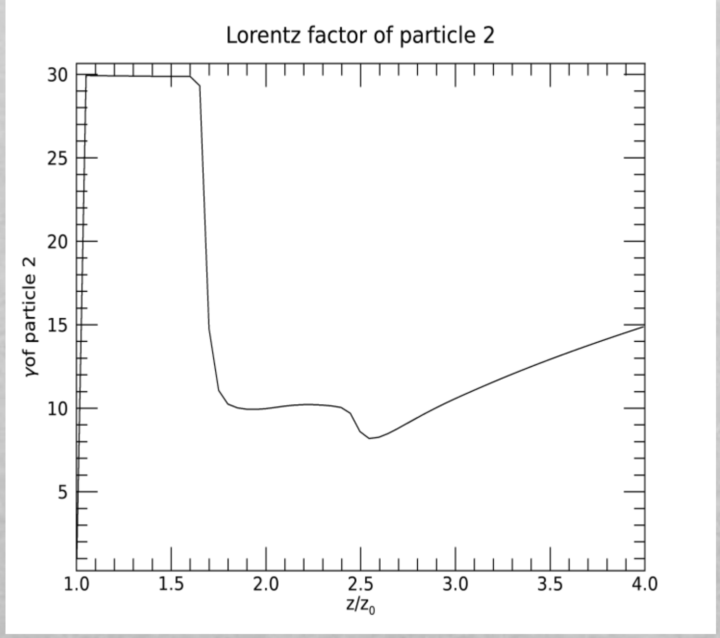


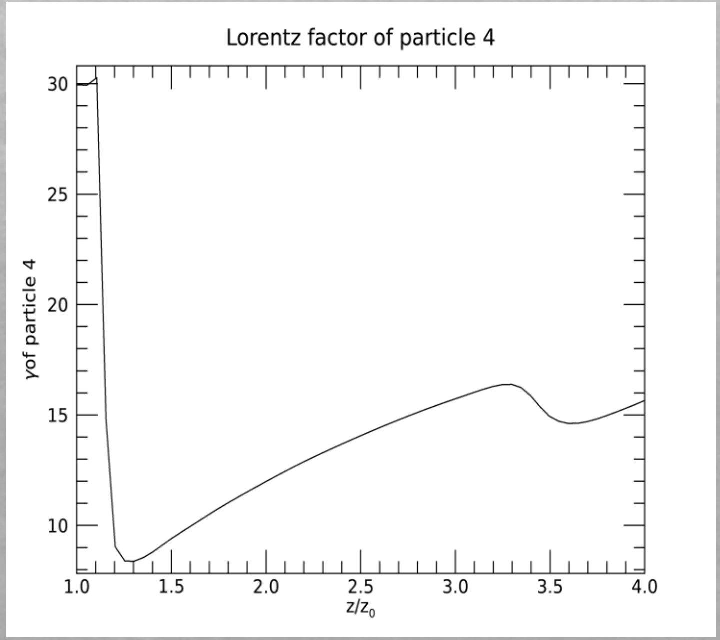
2D simulations with particles for TeV blazars

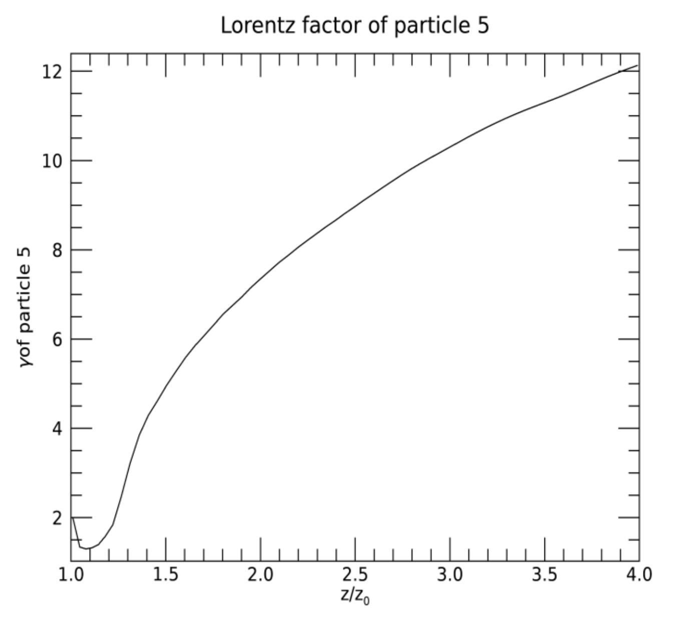
Results for different particles:

- 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.


Lorentz factor of particle 1


Lorentz factor of particle 2

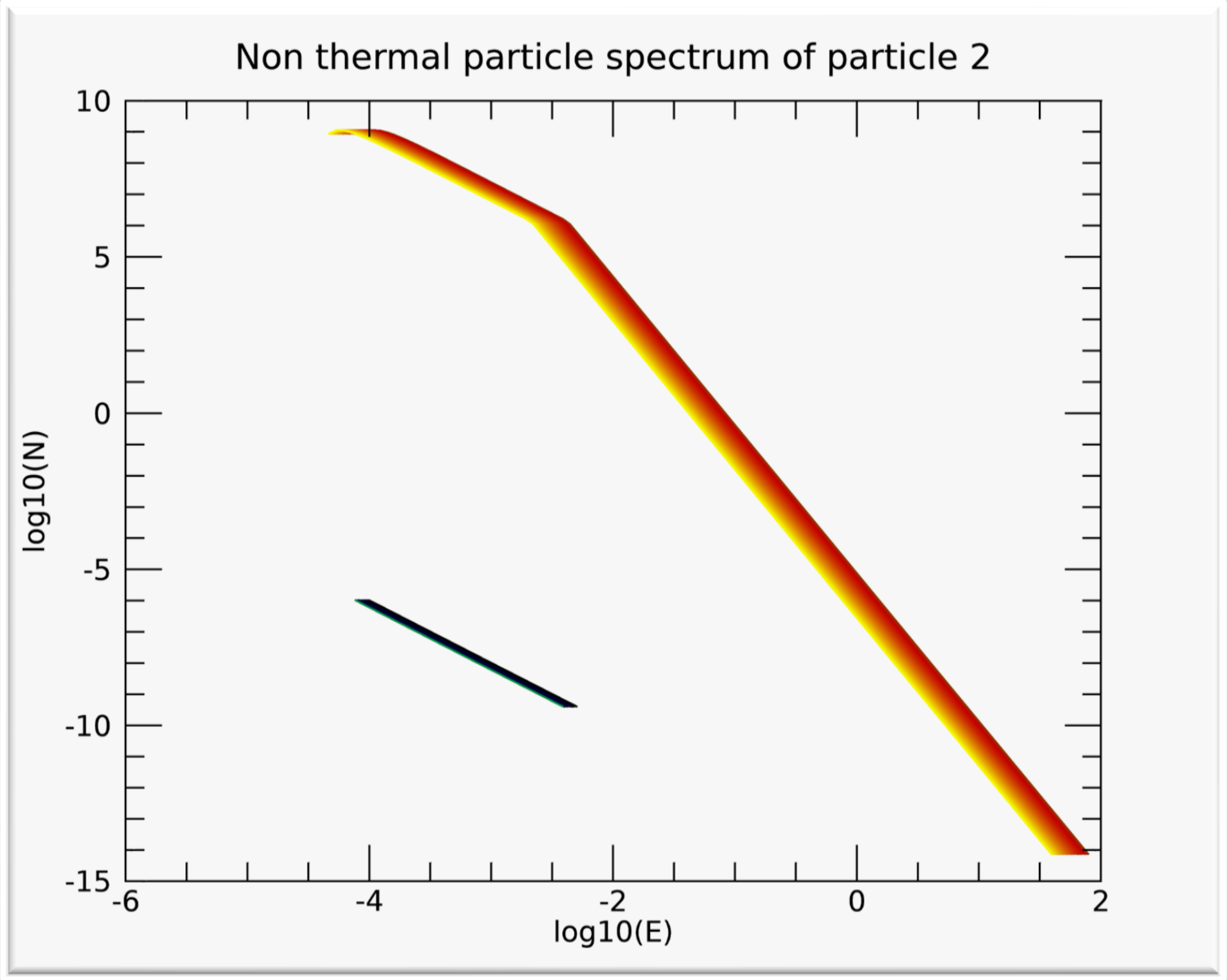

Lorentz factor of particle 4


Lorentz factor of particle 5

2D simulations with particles for TeV blazars

Energy distribution for macroparticle 2:

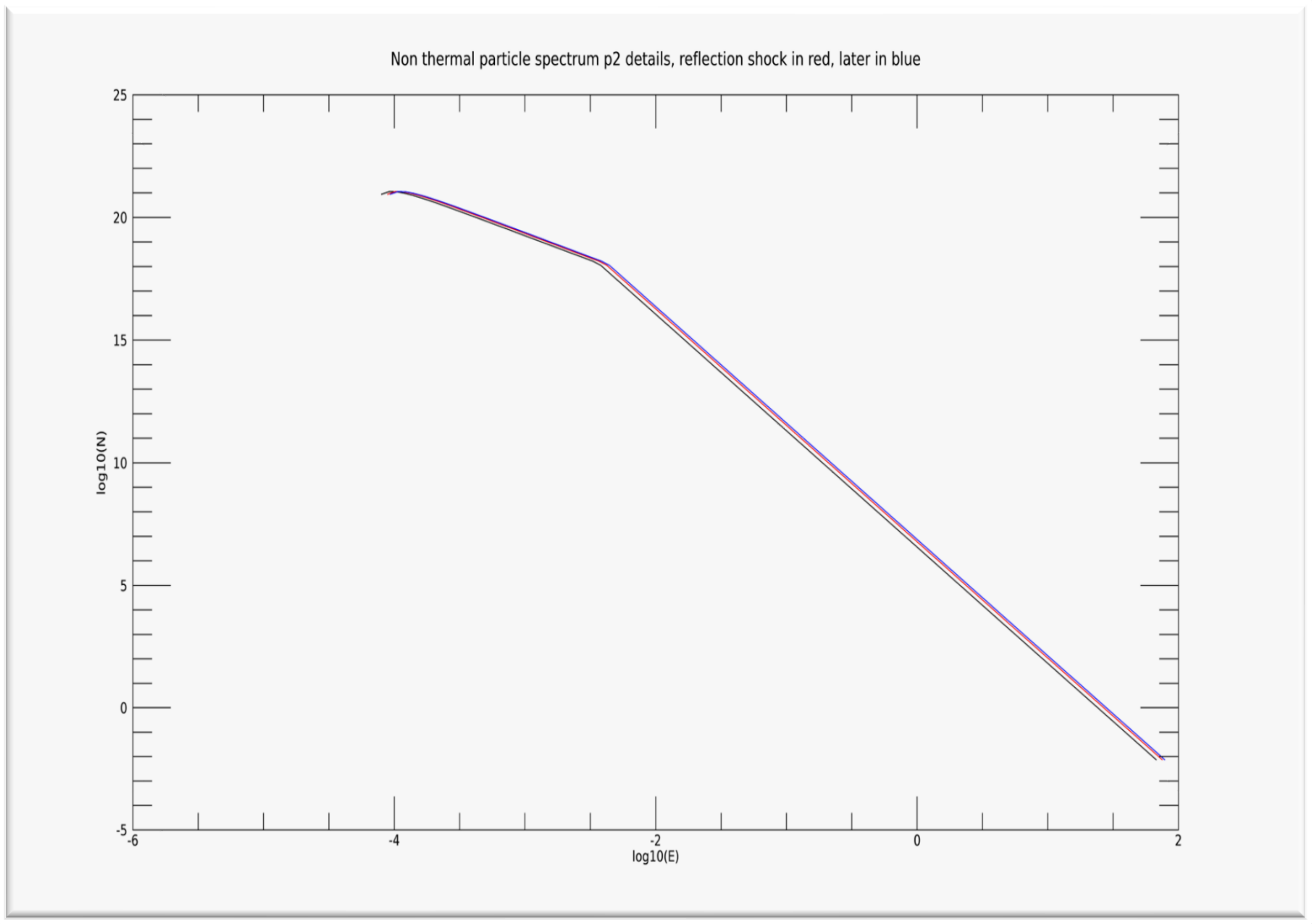
- energized from shocks



2D simulations with particles for TeV blazars

Energy distribution for macroparticle 2:

- energized from shocks
- but the reflection shock has no big impact on further acceleration.



2D simulations with particles for TeV blazars

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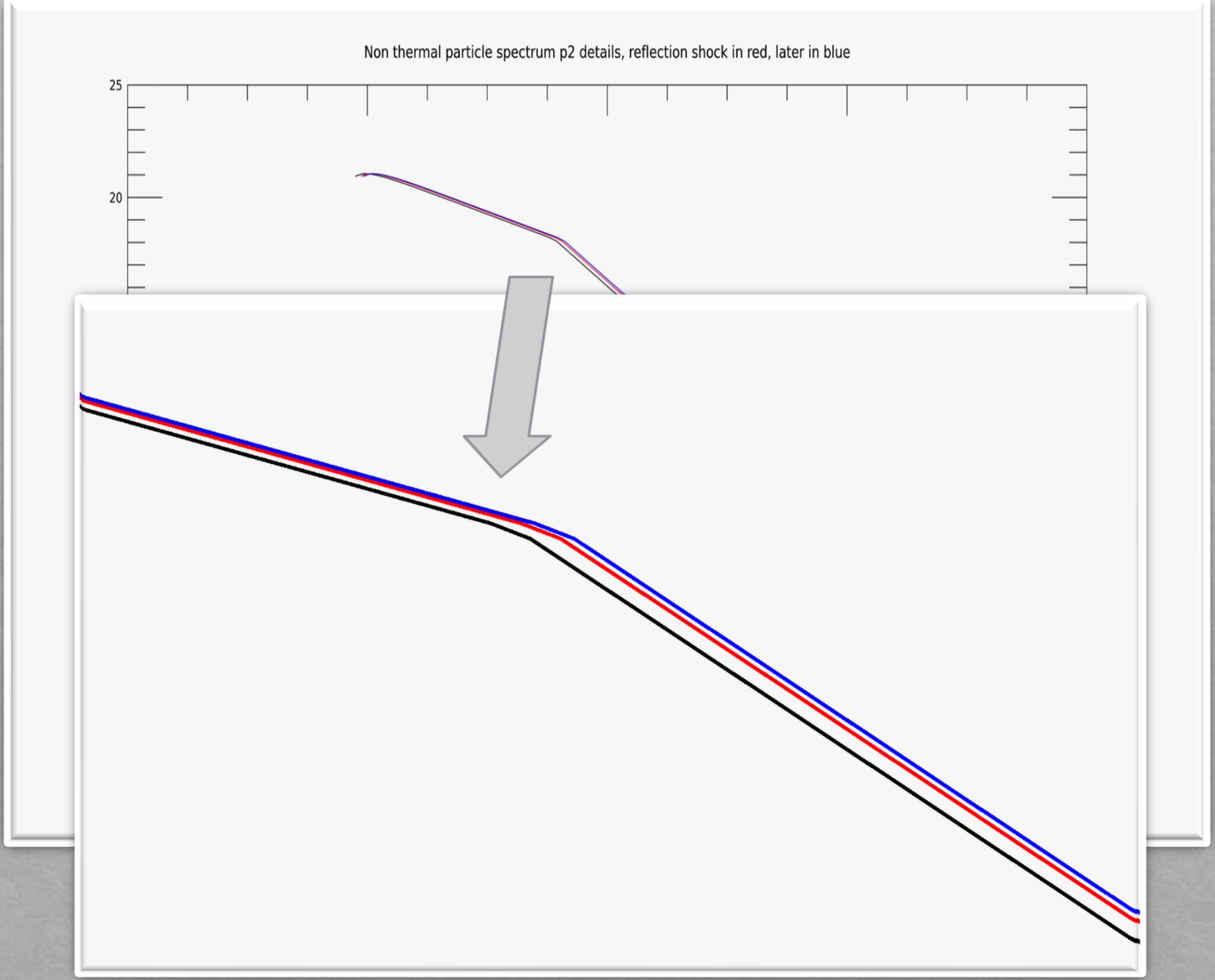
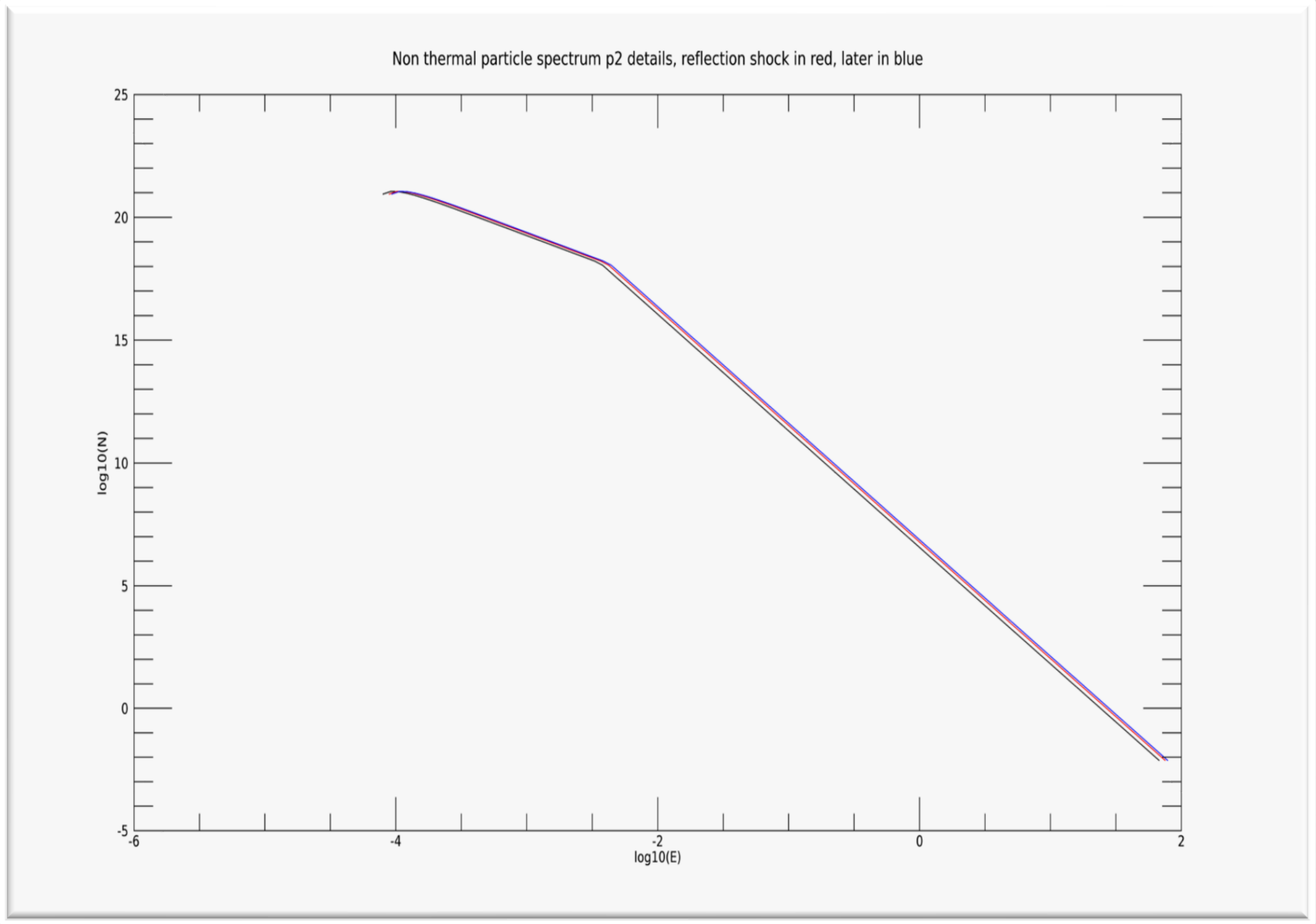


2D simulations with particles for TeV blazars

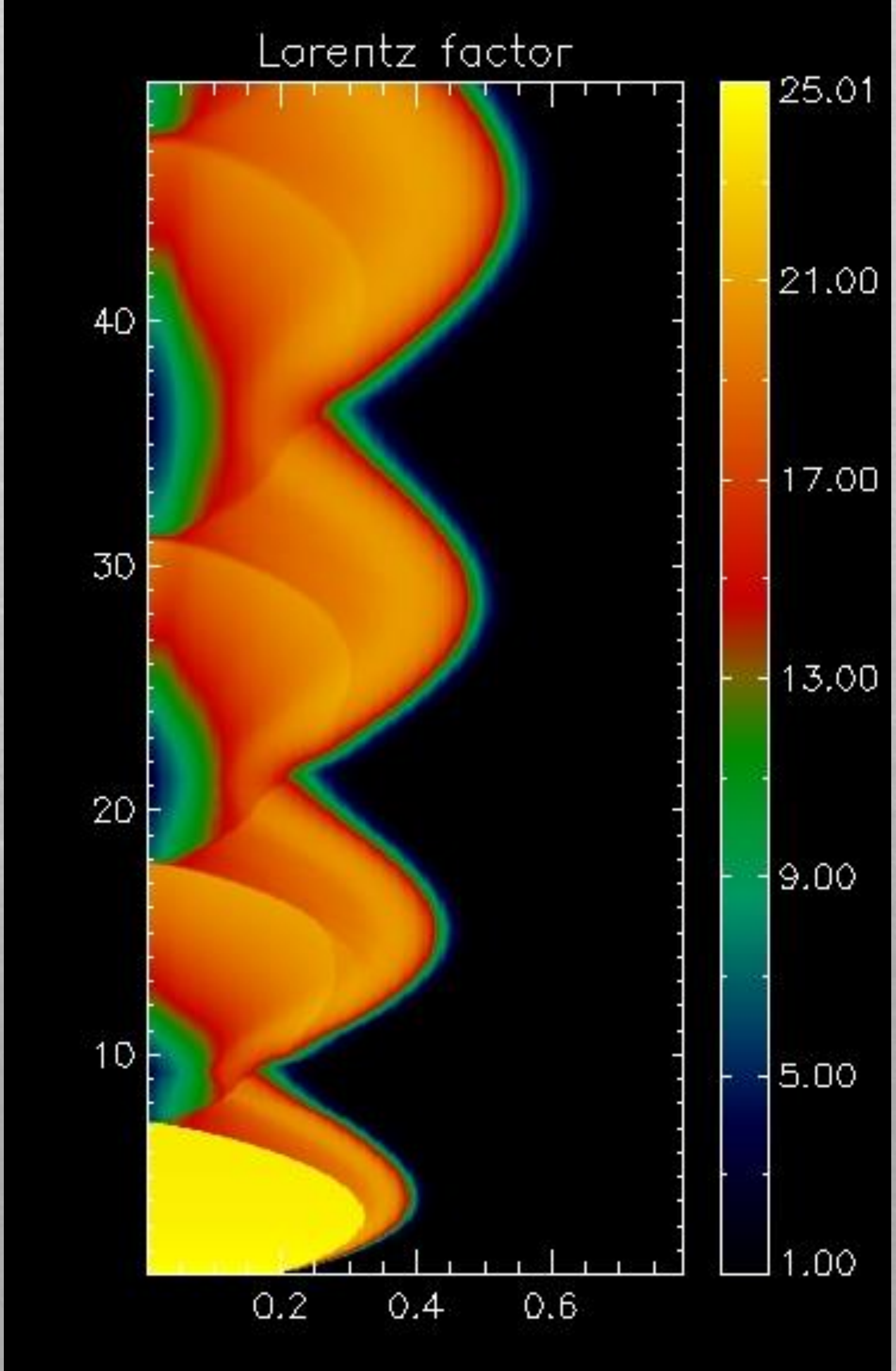
First result:

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



From 2D to 3D:
turbulence in low magnetized jets

1. A series of reconfinement and recollimation shocks might not be able to accelerate enough higher energy particles to produce the hard slope of the TeV blazars.

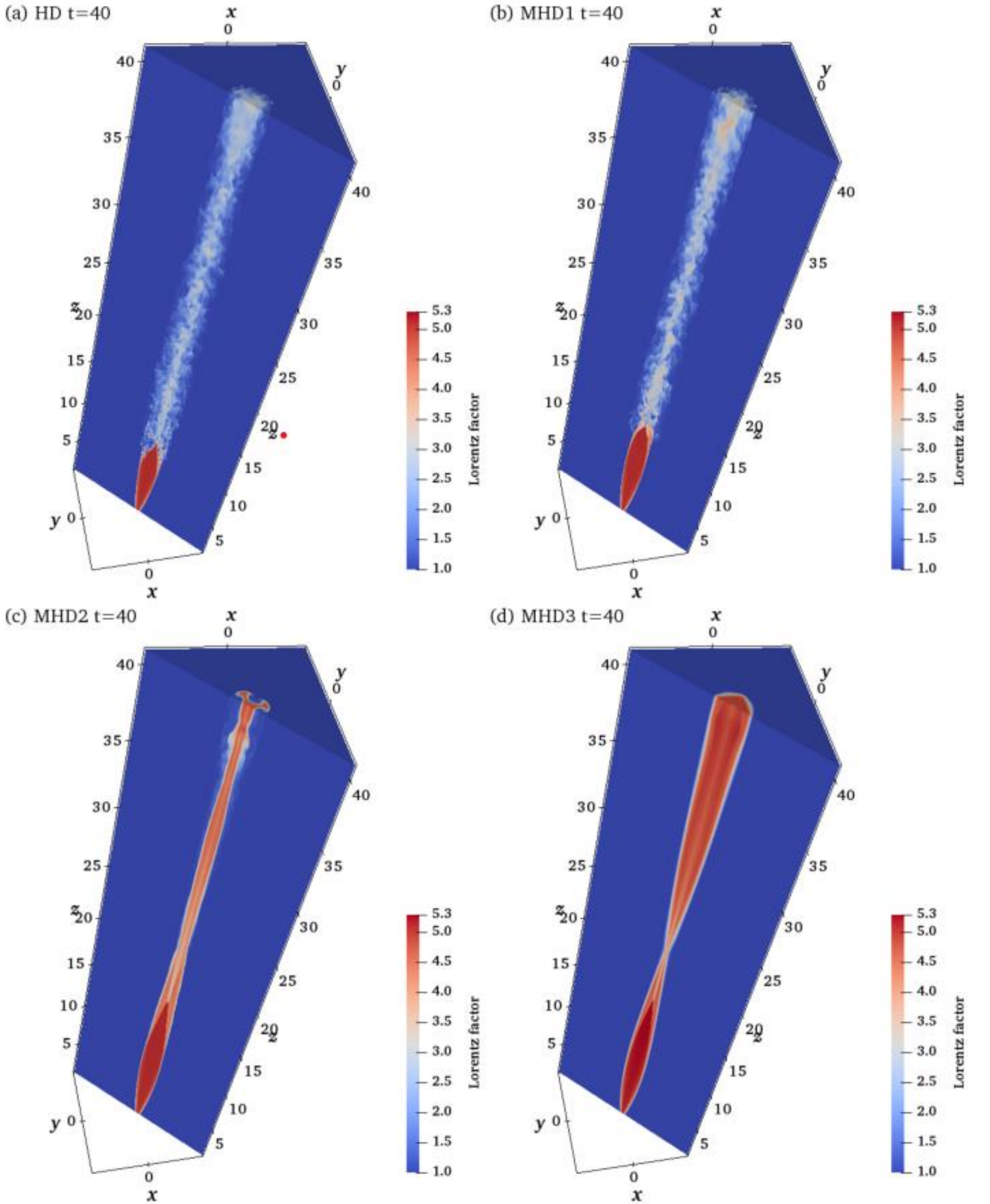


From 2D to 3D:
turbulence in low magnetized jets

1. A series of reconfinement and recollimation shocks might not be able to accelerate enough higher energy particles to produce the hard slope of the TeV blazars.

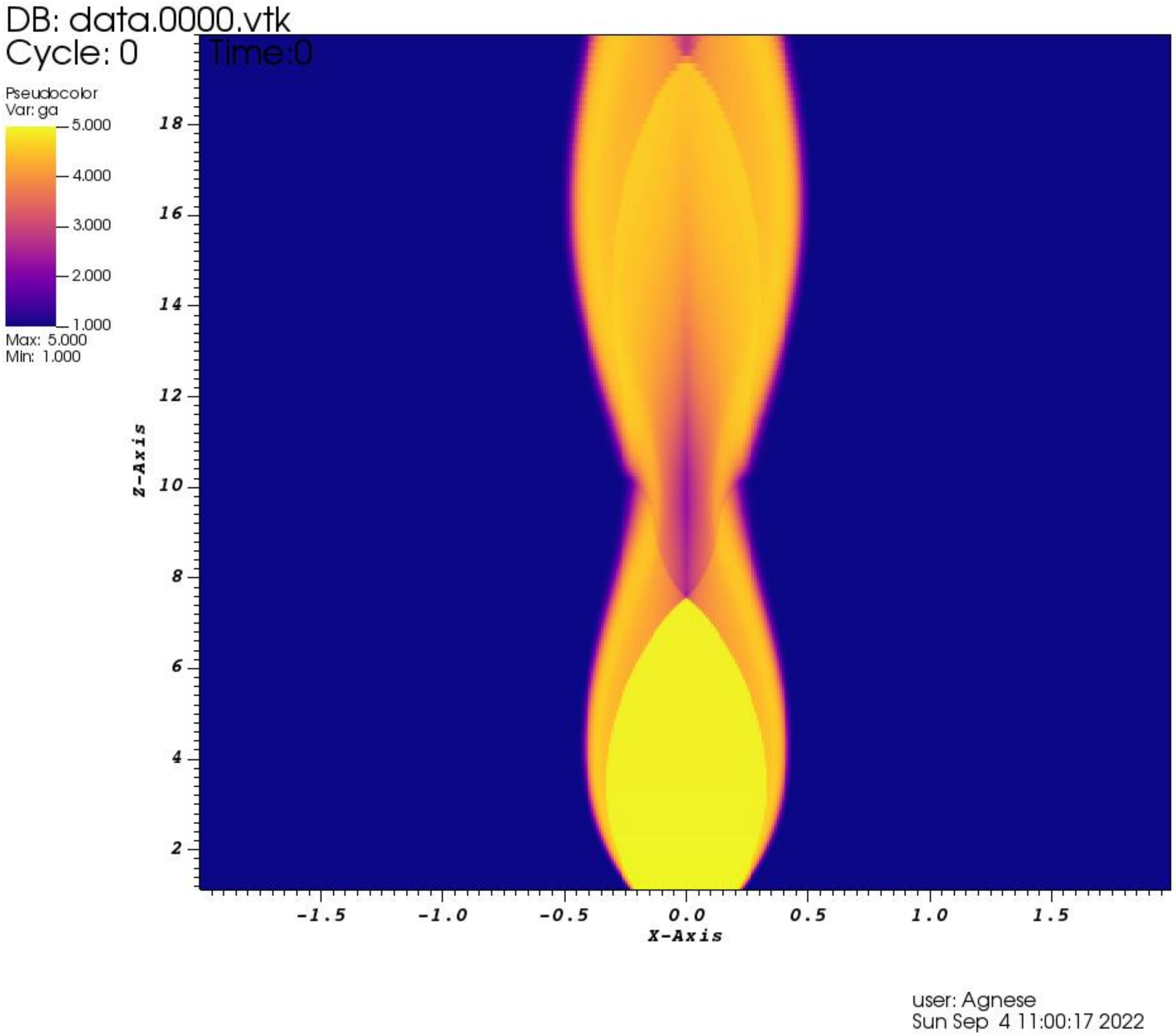
2. Instabilities that cannot be seen in 2D simulations might be relevant in reality:
   - Centrifugal instability caused by the recollimation shock → **turbulence in low magnetized jets** ($\sigma = \frac{B^2}{4\pi\omega} \leq 10^{-4}$)

Matsumoto, Komissarov, Gourgouliatos
doi:10.1093/mnras/stab828



What now?

3D RHD simulation starting from the **2D stationary solution** to check on turbulence developing with the PLUTO code:



2D stationary solution

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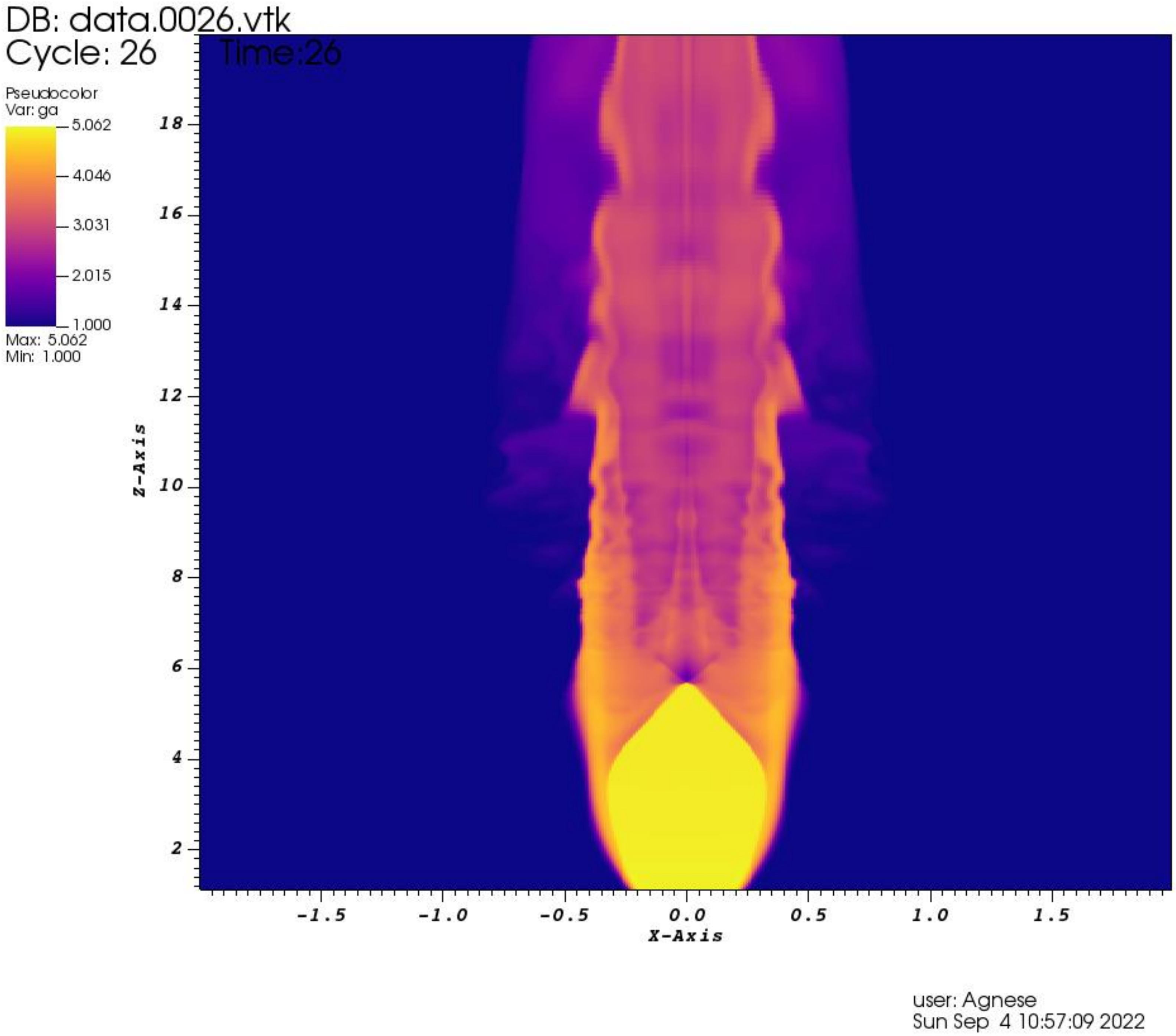
work in progress!



slice of the 3D simulation

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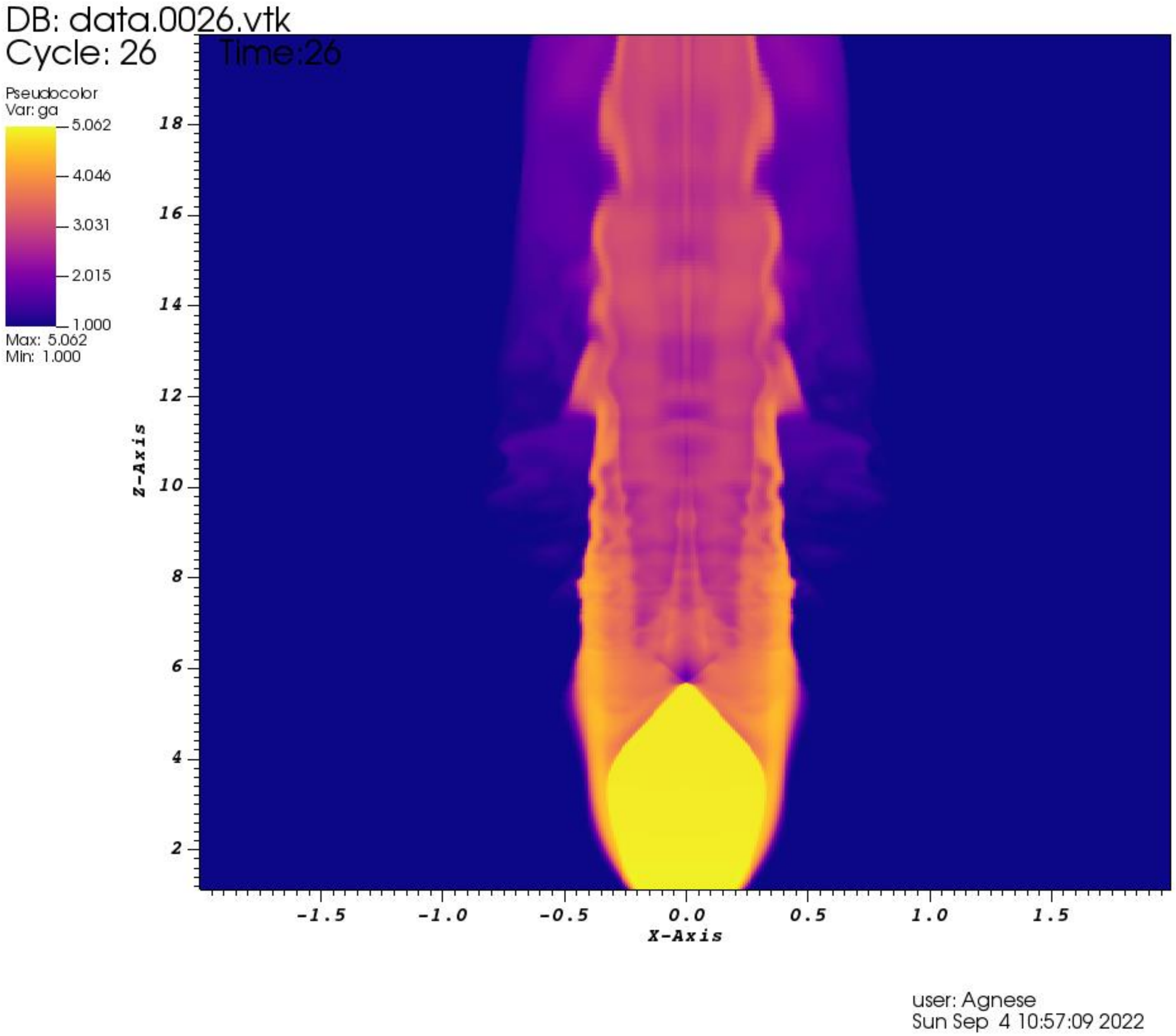


slice of the 3D simulation

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

Recollimation shocks in AGN jets

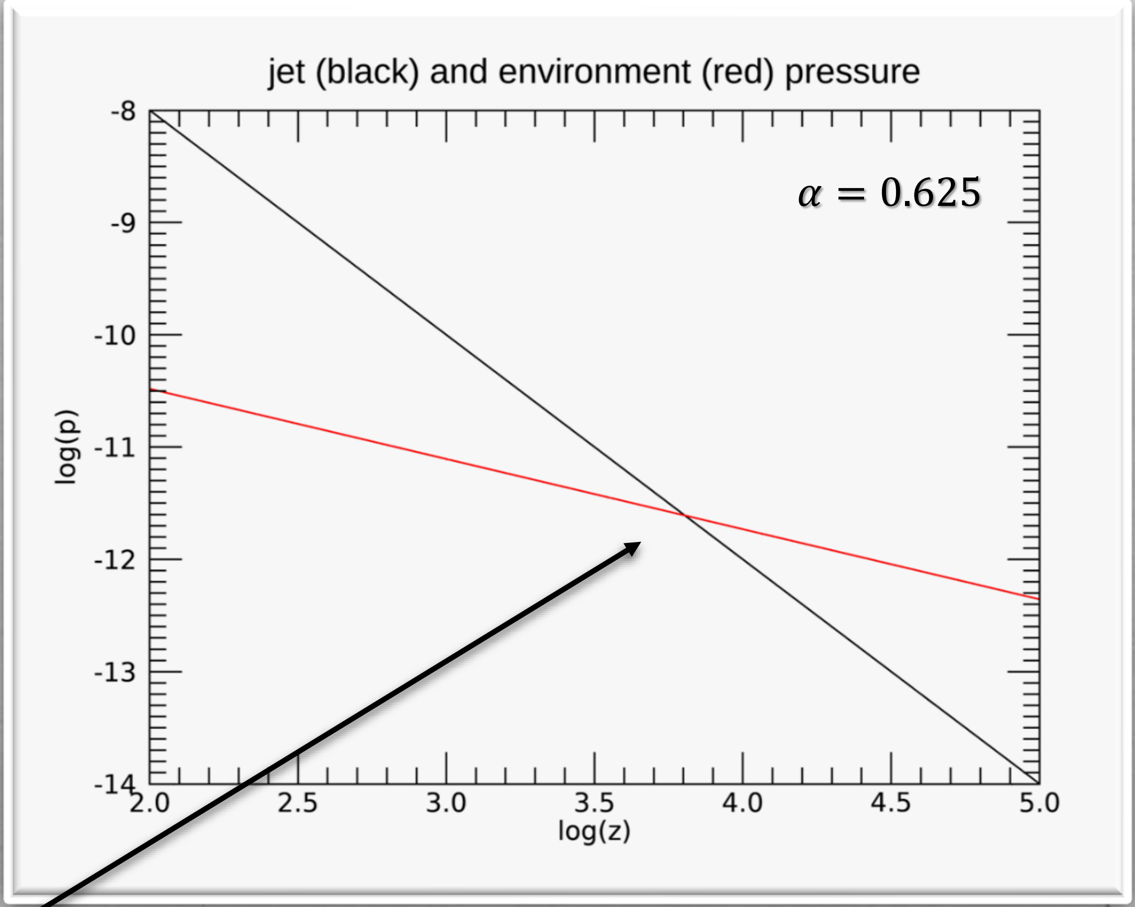
Relativistic AGN jets expand and cool adiabatically through the environment

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

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



$\underline{\alpha < 2}$

BACKUP
2D simulations with particles for TeV blazars

Dimensions:

$$z_0 = 0.1\,pc$$

$$r_0 = 0.1\,z_0 = 0.01\,pc$$

Plasma parameters:

$$\gamma = 30$$

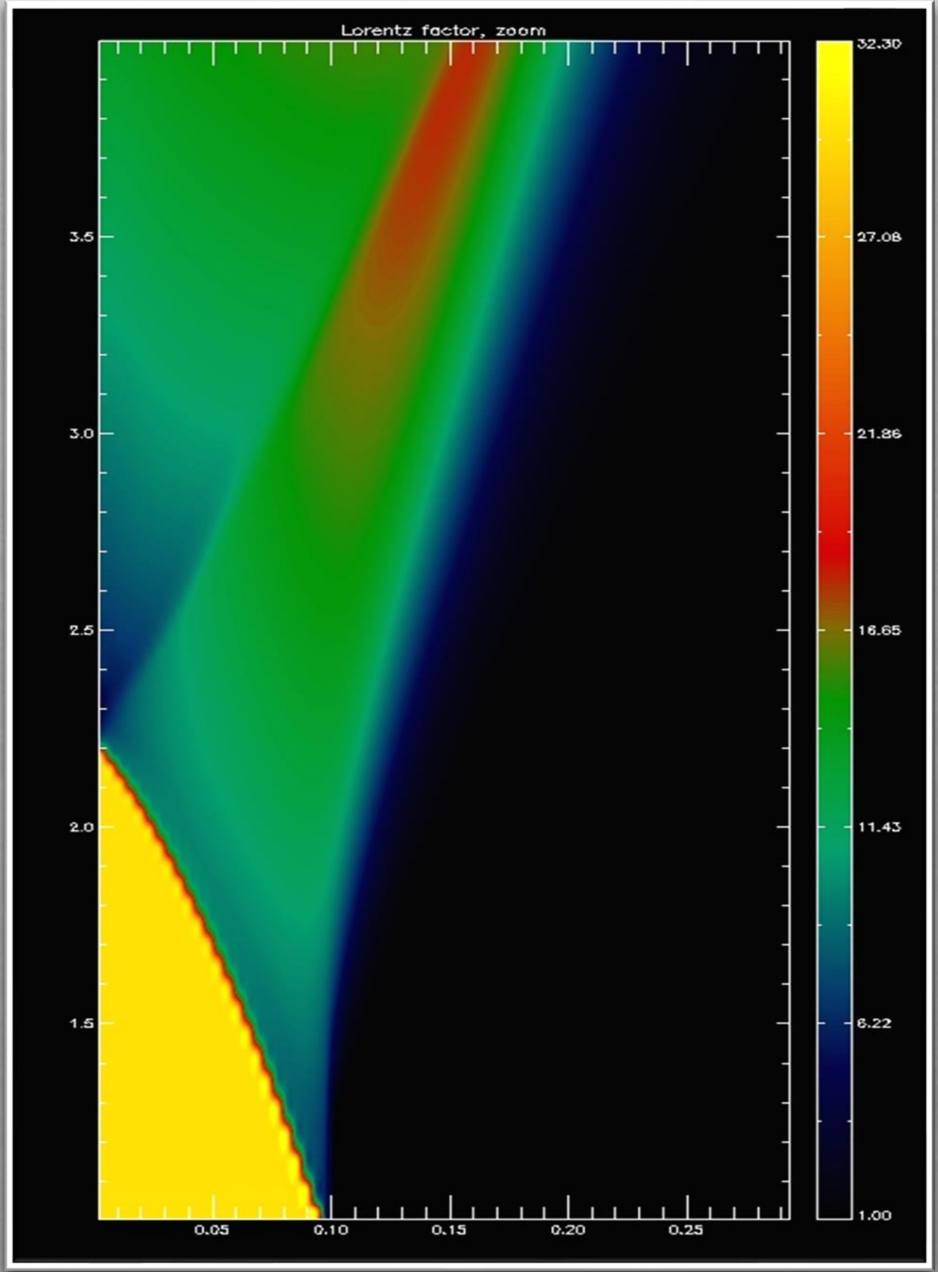
$$L_j = 10^{44} erg$$

$$B_0 = 3 \cdot 10^{-4} G \text{ poloidal}$$

$$p_{a,0} = 1 \;\; dyn/cm^2 \;\; and \;\; p_a = p_{a,0}\left(\frac{z}{z_0}\right)^{-1.8}$$

$$p_{j,0} = 10^{-7} p_{a,0}$$

$$n_a = 10^9 cm^{-3}$$



BACKUP
2D simulations with particles for TeV blazars

Particle parameters:

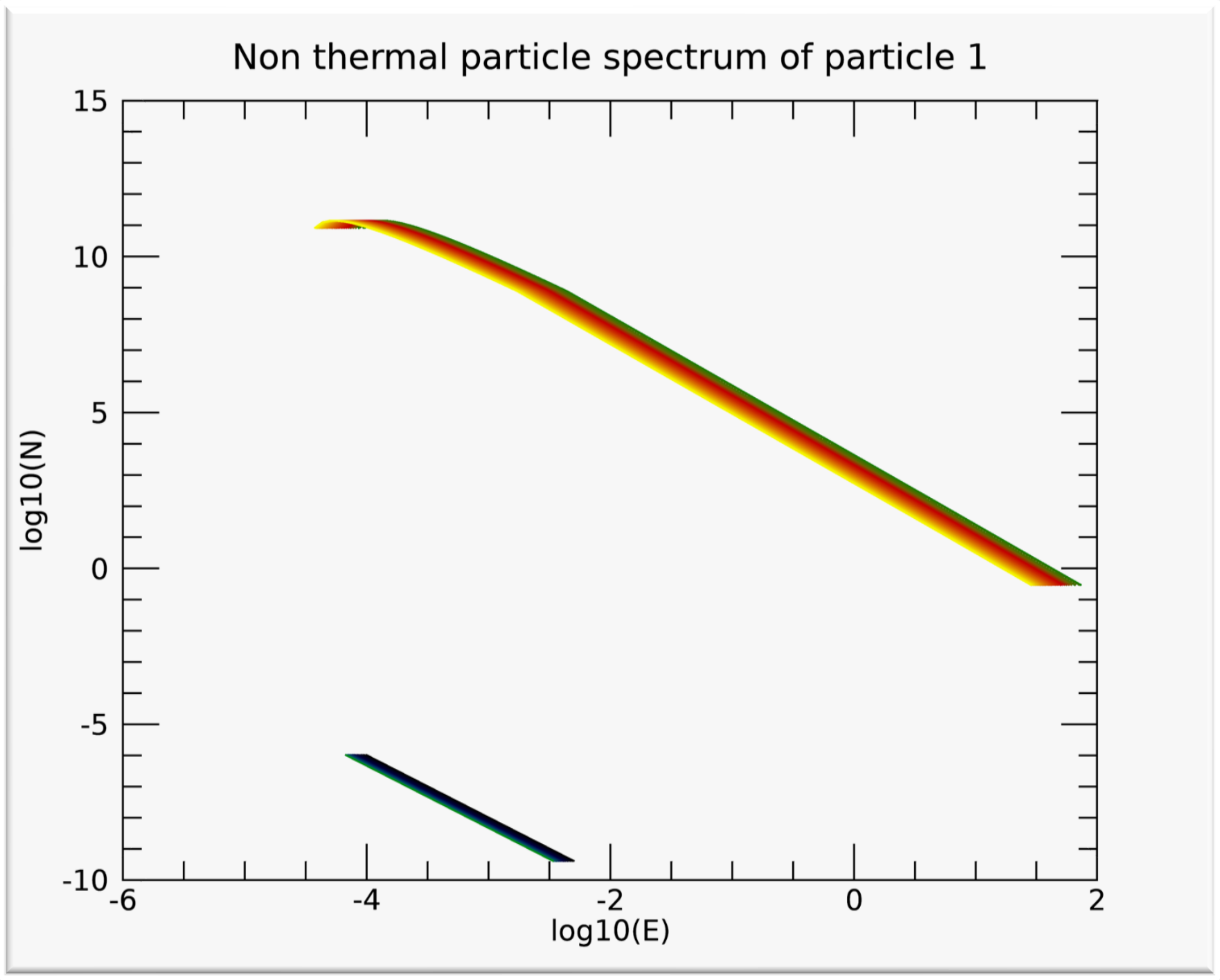
Initialization is meant to provide a minimal Lorentz factor for shock acceleration, because PLUTO itself still doesn't require any minimal energy (updated to be done):

Power law with:

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

Graph info

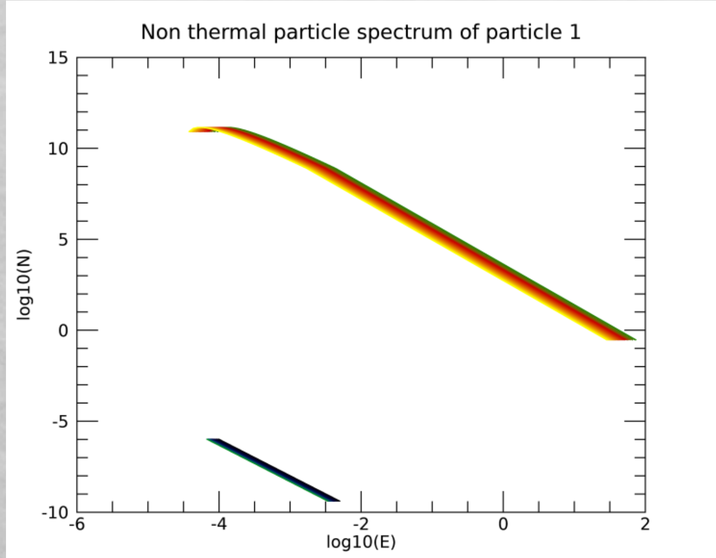
- Unit of measure of the energy is erg
- Acceleration up to $\gamma = 10^8$

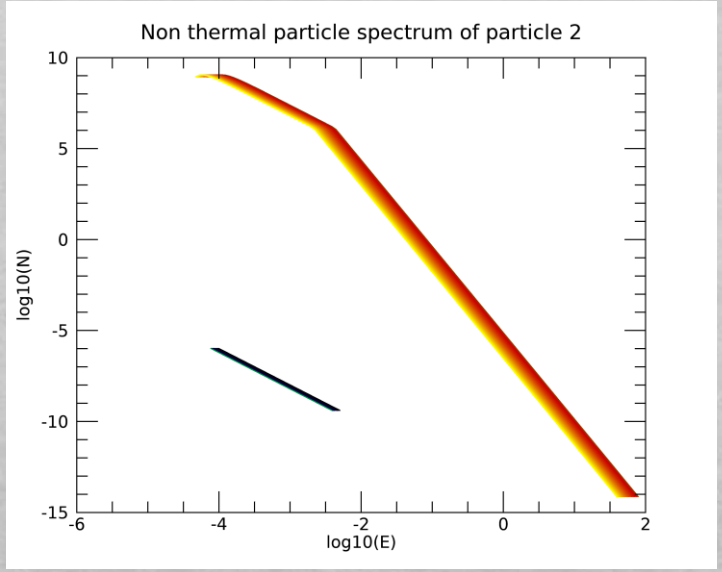


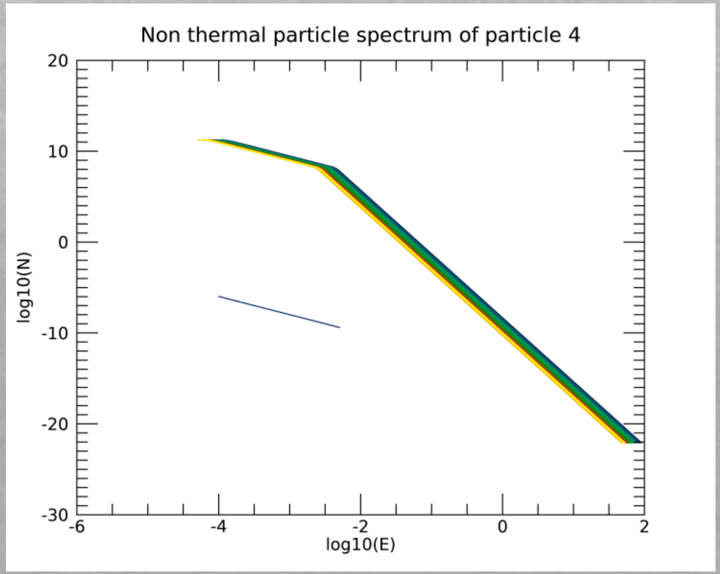
2D simulations with particles for TeV blazars

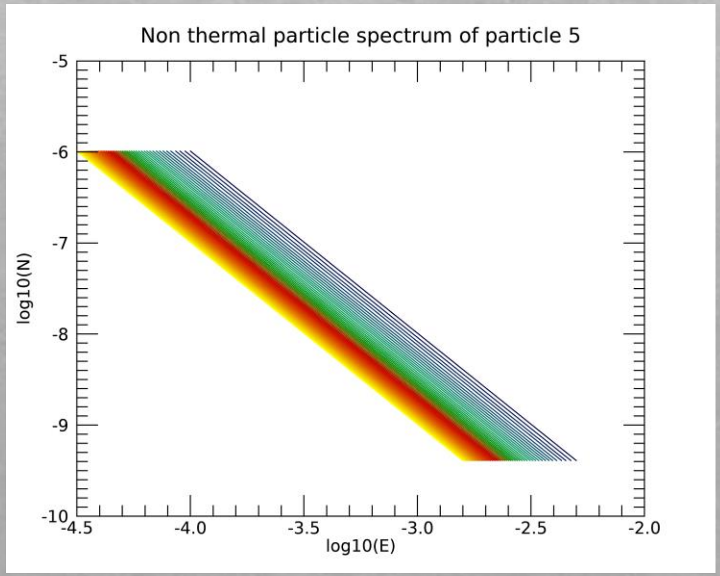
Results for different particles:

- 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.


Non thermal particle spectrum of particle 1


Non thermal particle spectrum of particle 2


Non thermal particle spectrum of particle 4


Non thermal particle spectrum of particle 5

2D simulations with particles for TeV blazars

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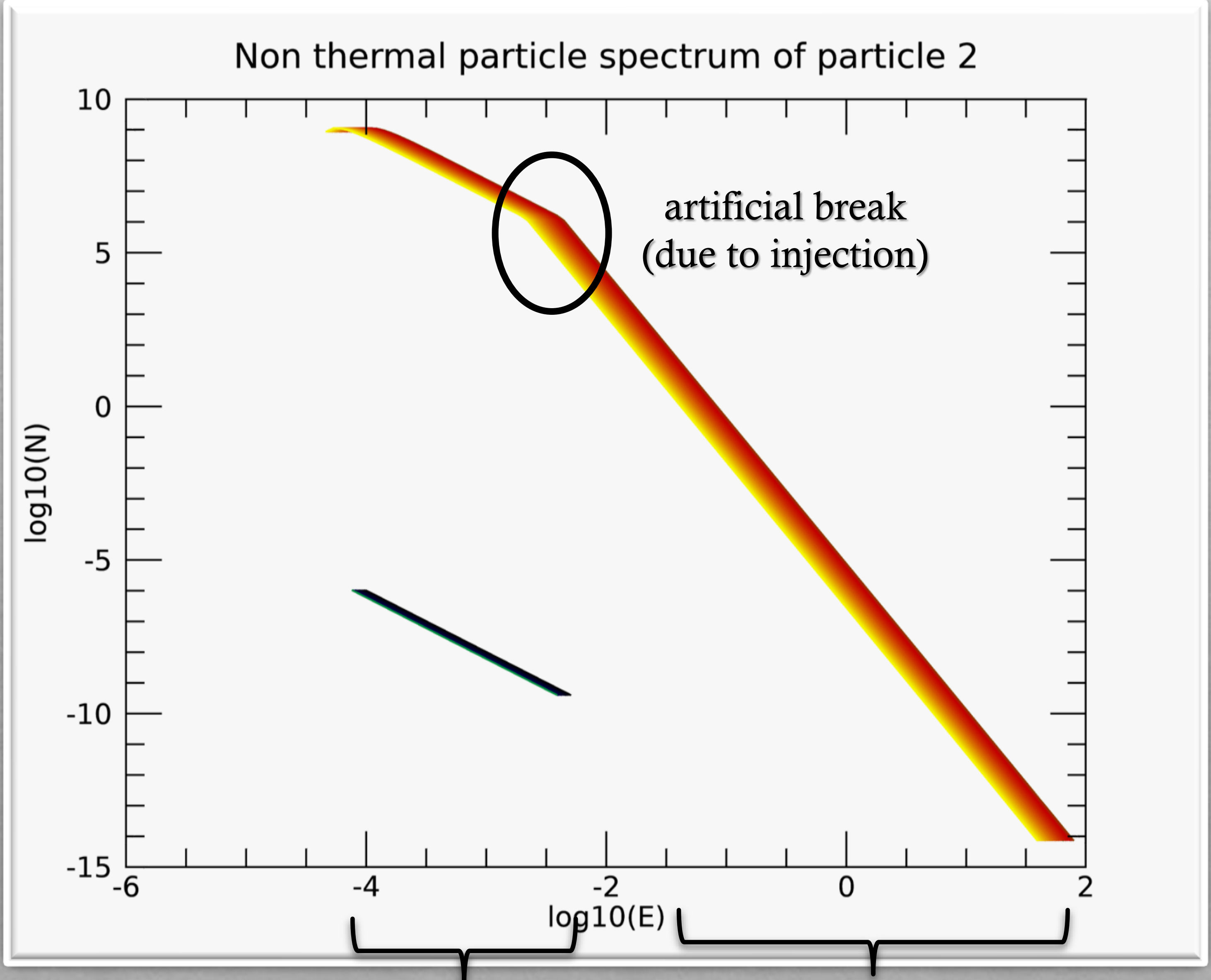
Non thermal particle spectrum of particle 2

artificial break
(due to injection)

injection

after the acceleration at shocks

BACKUP: 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