Simulations of relativistic jets and recollimation in extreme blazars

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Hands-on the Extreme Universe with High Energy Gamma-ray data,
20.07.2022

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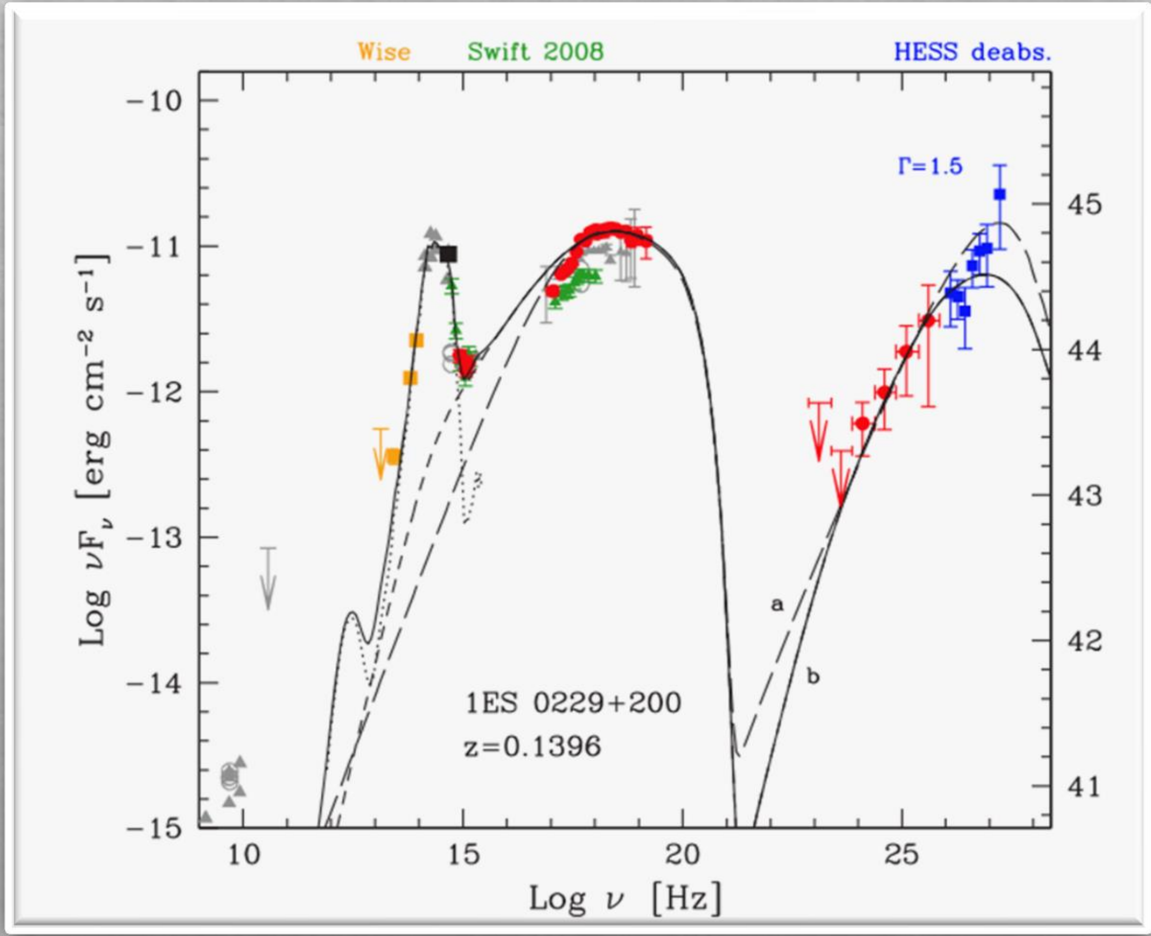
- Introduction: TeV blazars and simulations with PLUTO
- 2D relativistic MHD simulations with lagrangian particles for TeV blazars
- 2D → 3D simulations and turbulence

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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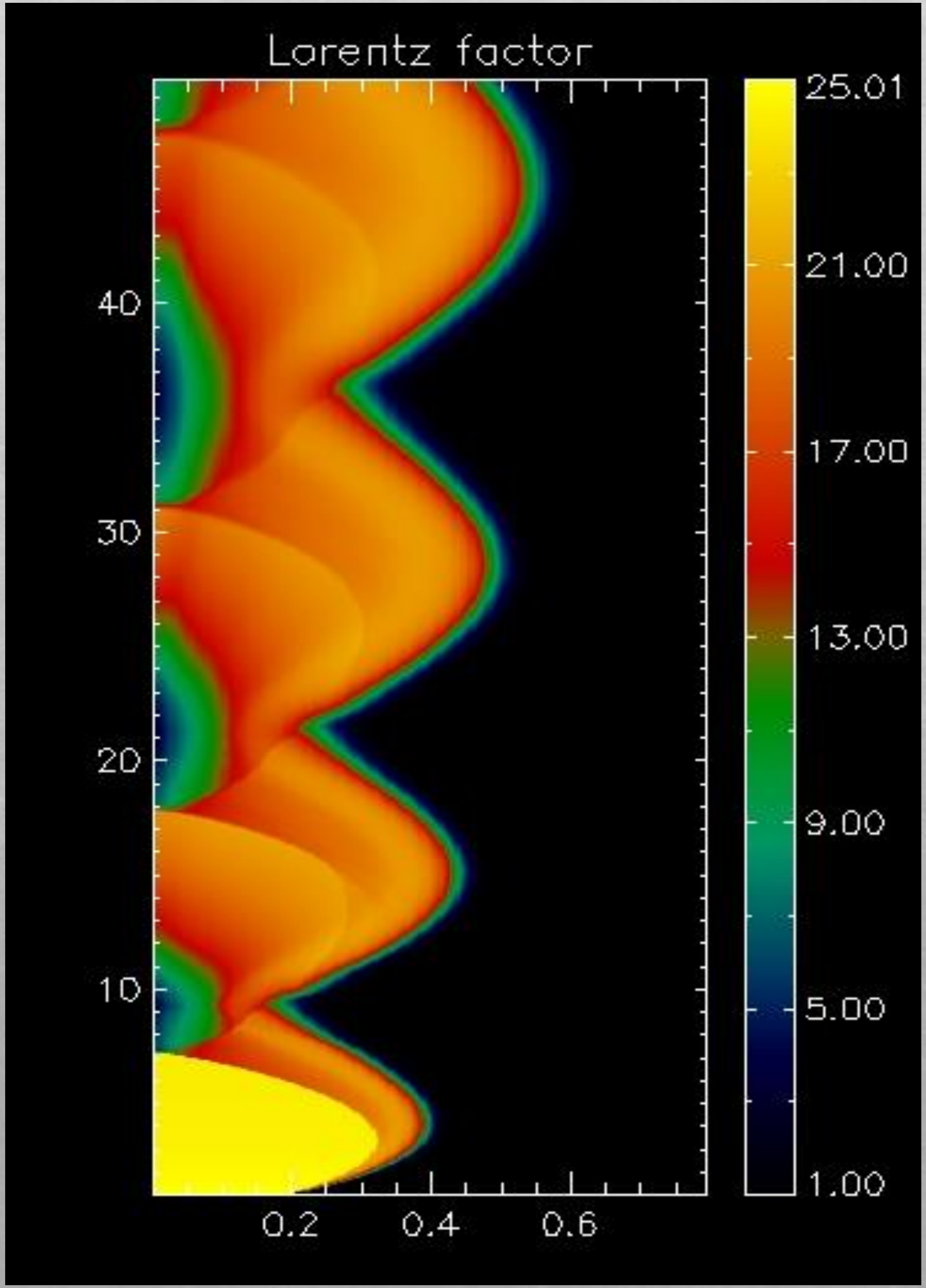
1. Current guess: due to a series of recollimation and reflection shocks (Zech A., Lemoine M., 2021, doi:10.1051/0004-6361/202141062)



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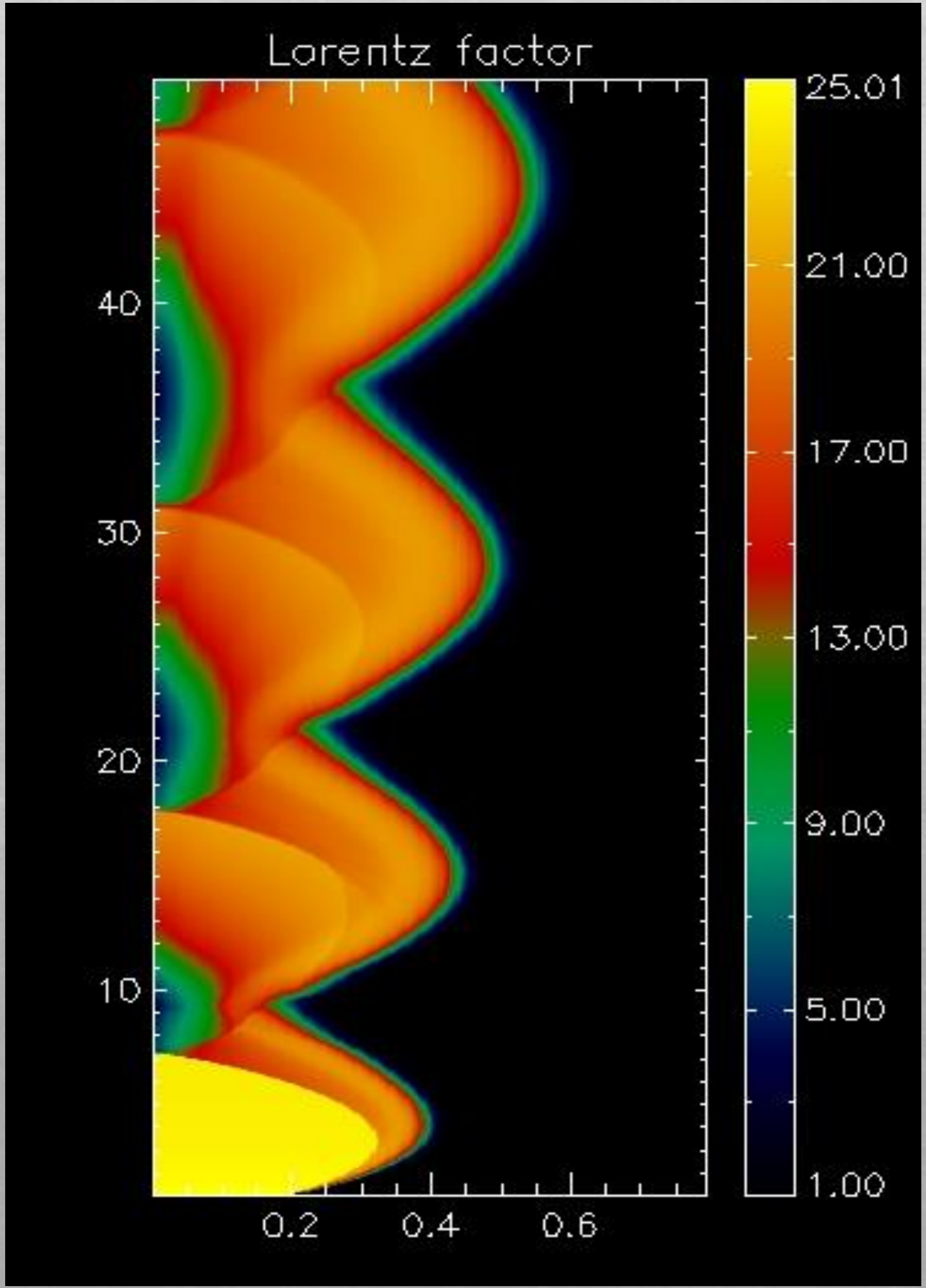
   BUT can it happen and work? (my research)

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



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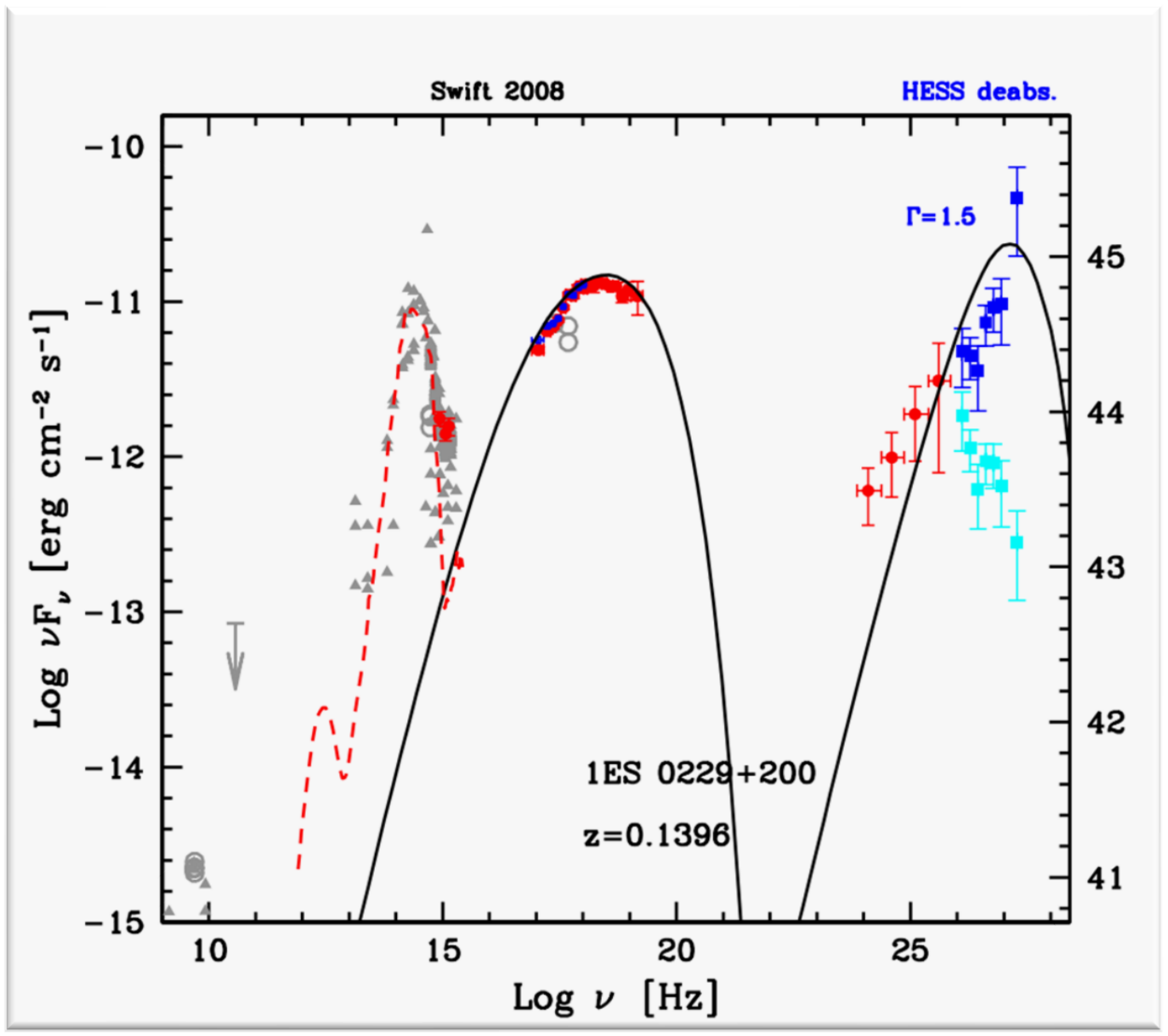
3. Would these work as acceleration mechanisms? (hear more from A. Sciaccaluga next)



New fit from *Tavecchio et al. 2022 in prep.*

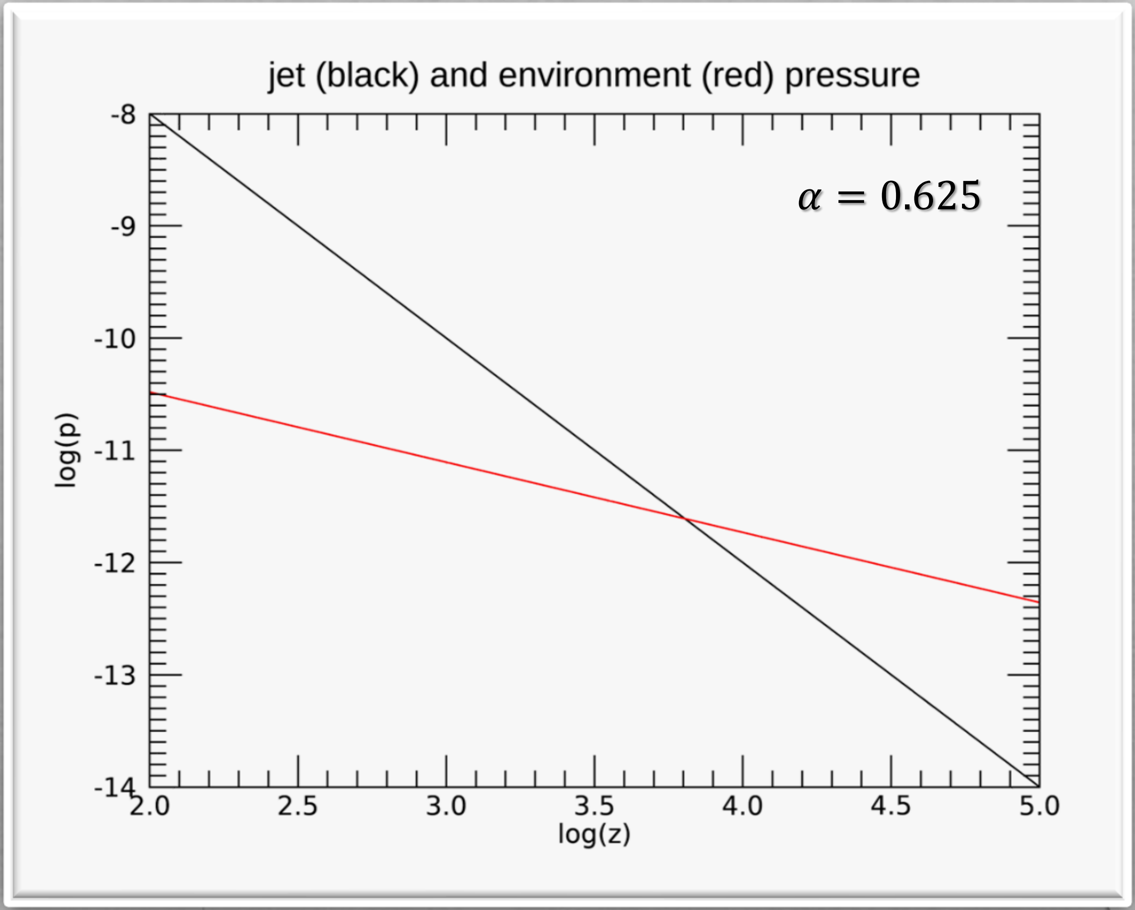
Recollimation shocks in AGN jets

Relativistic AGN jets expand and cool adiabatically while going though the environment

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

while the environment follows a general power law

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



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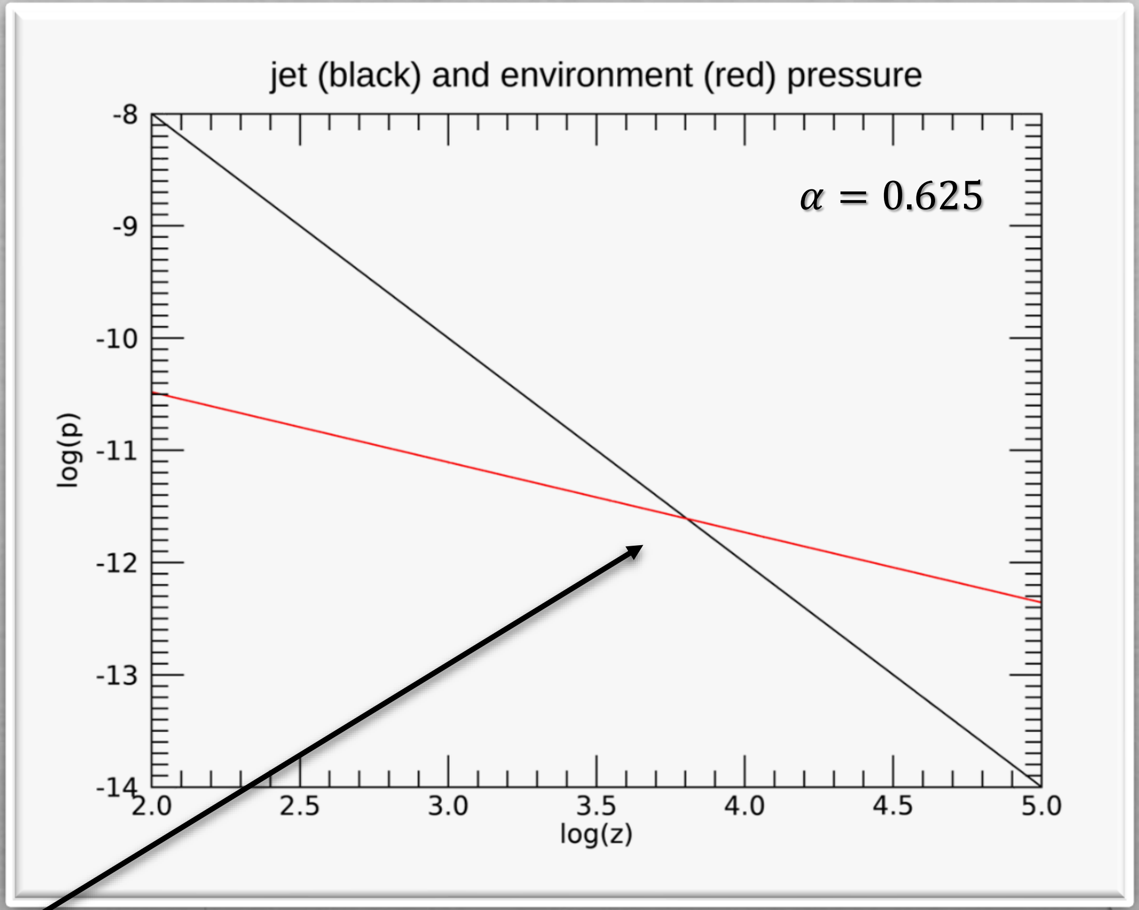
When there is a pressure unbalance in favour of the environment the jet undergoes a recollimation process that is supersonic and waves/shocks form



$\alpha < 2$

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

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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)

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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)
- **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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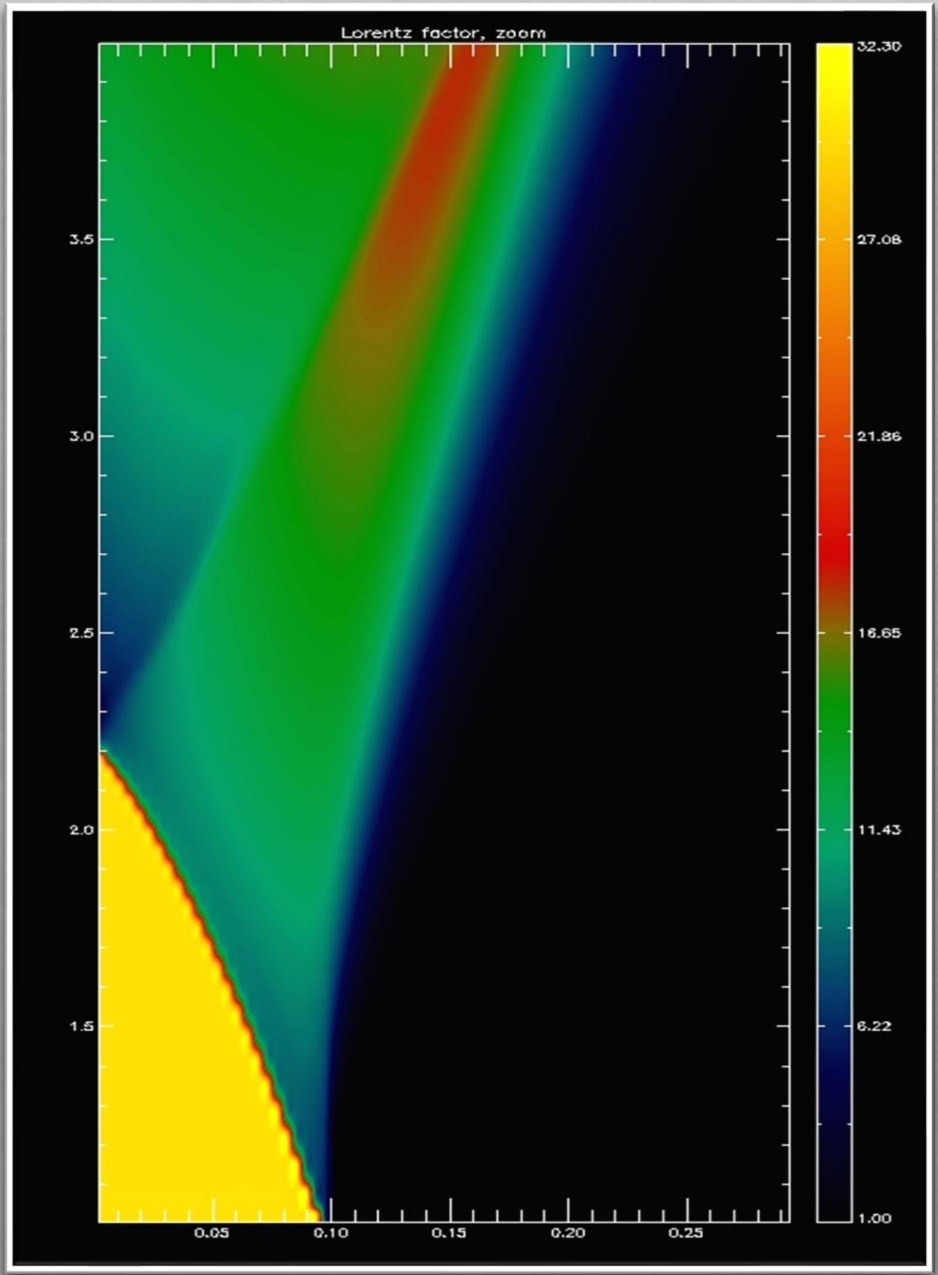

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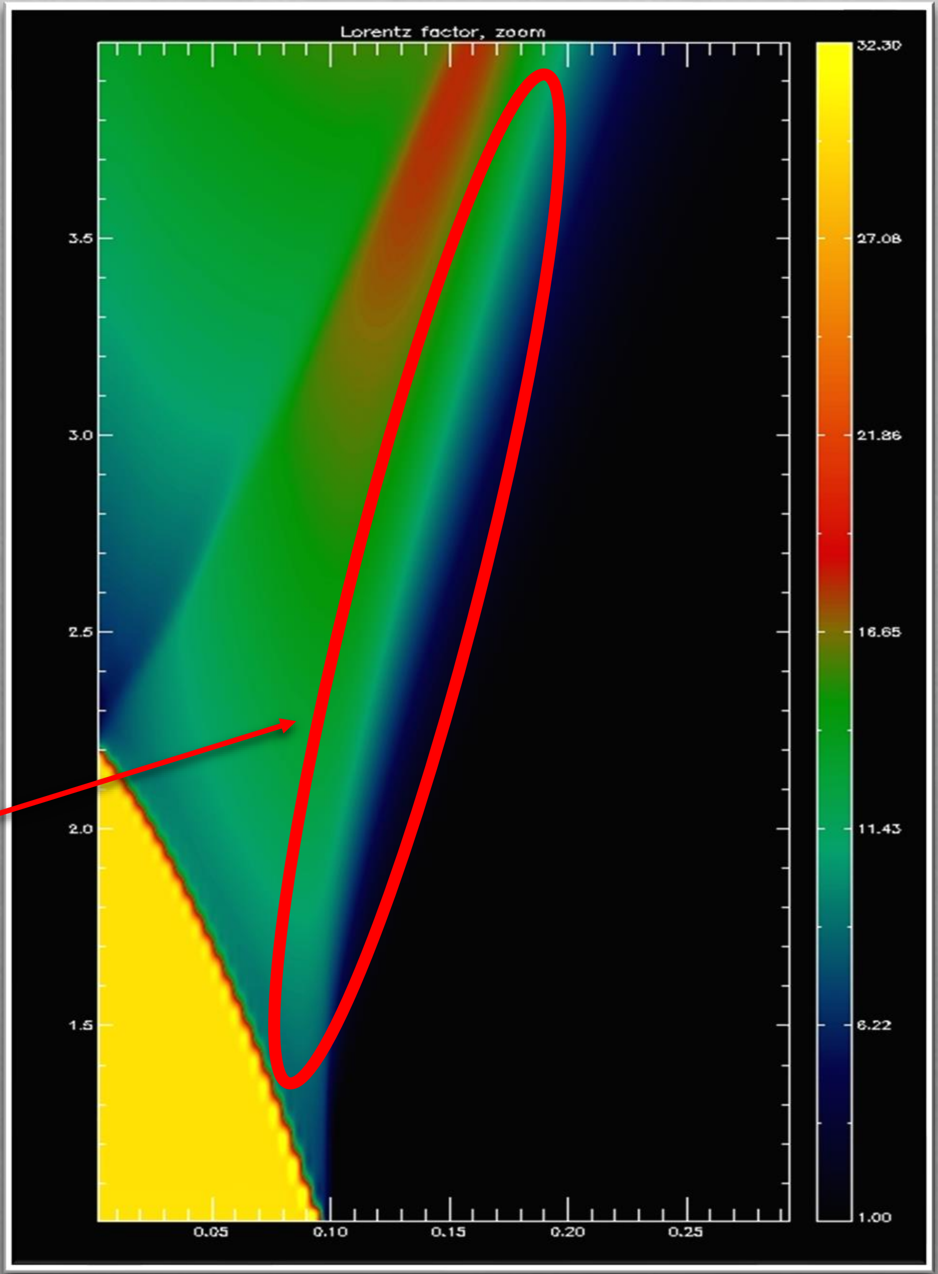

contact discontinuity

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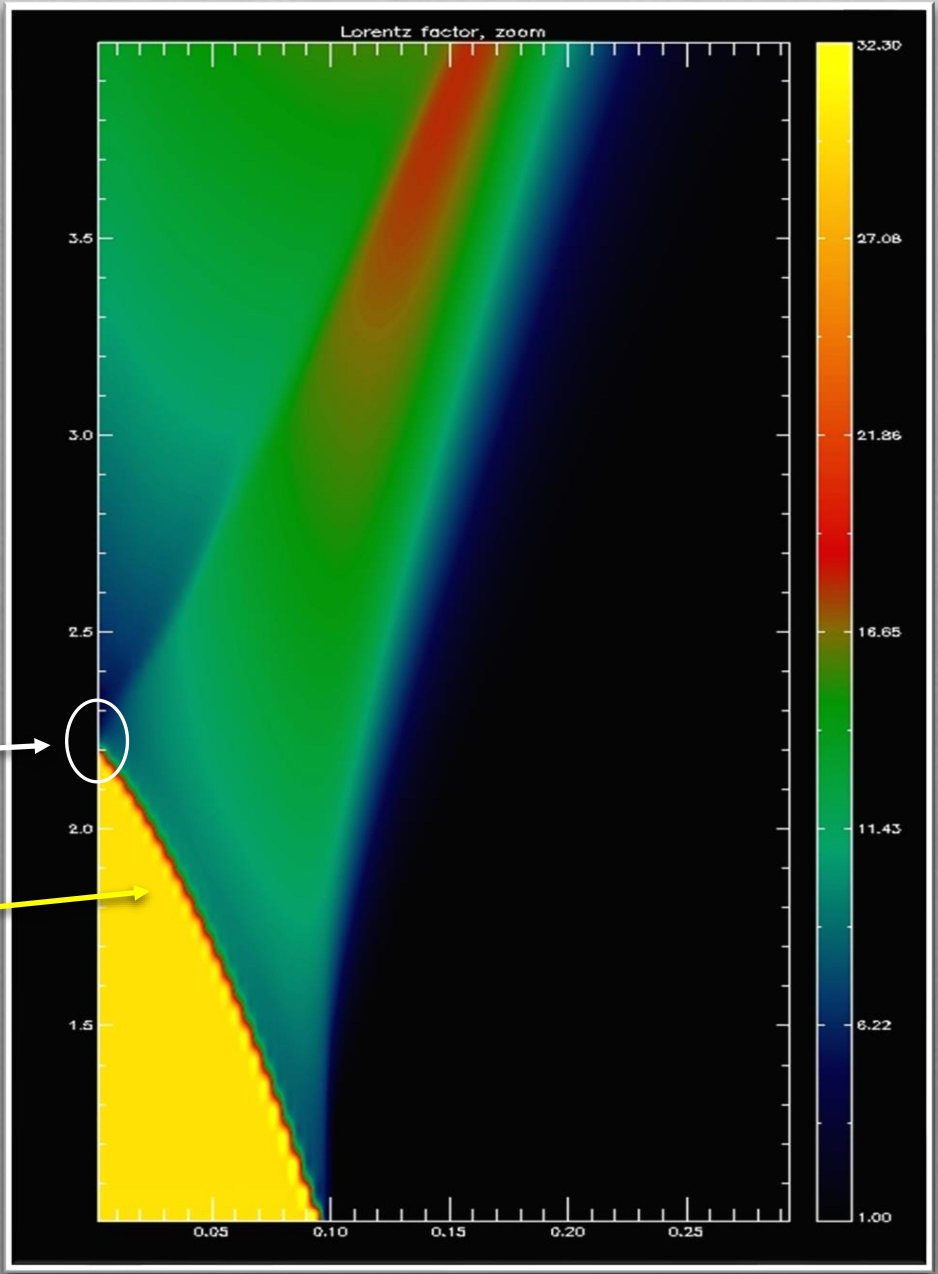
RECOLLIMATION POINT

recollimation shock



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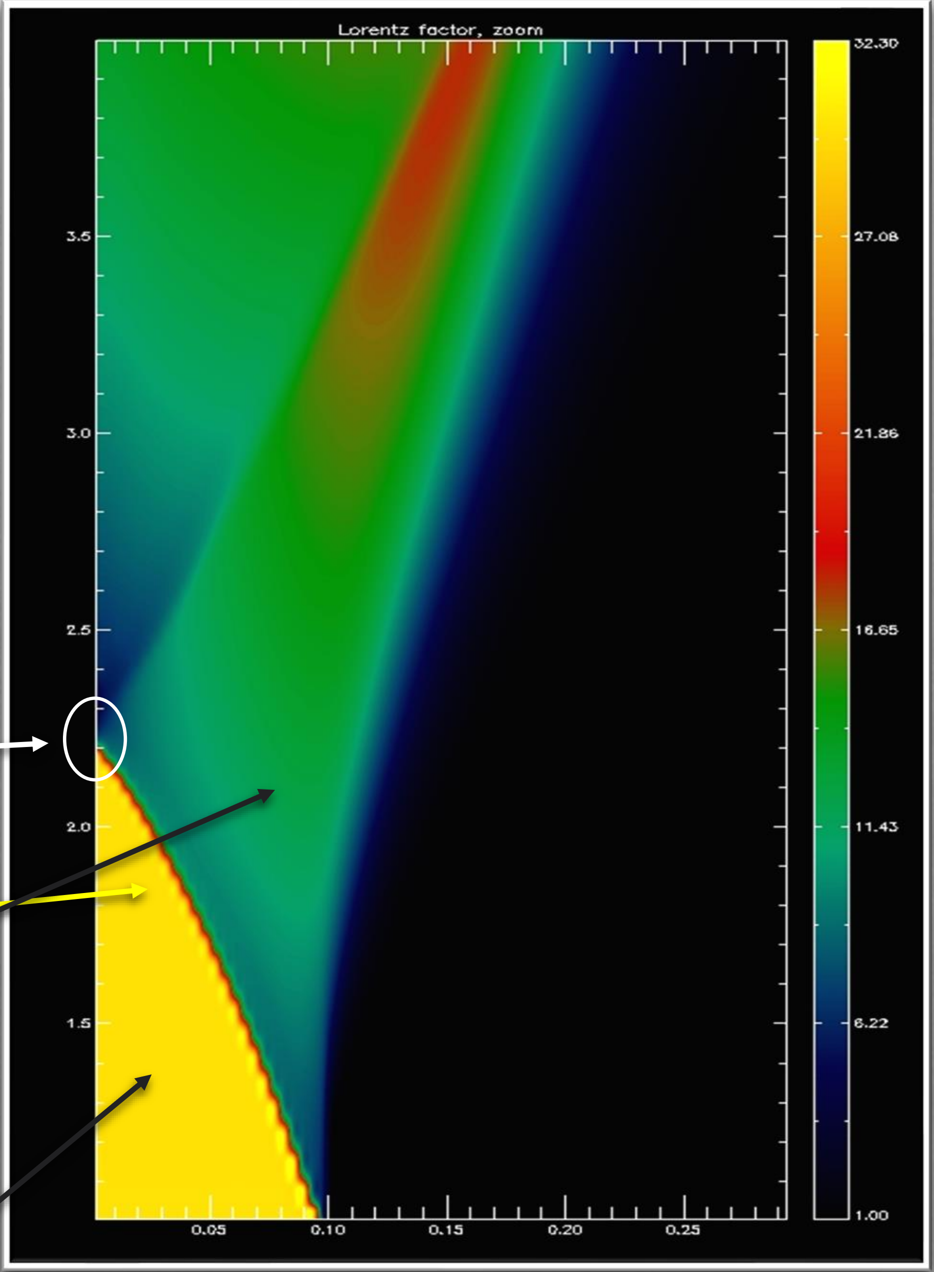
RECOLLIMATION POINT

recollimation shock

shocked jet / downstream

unshocked jet / upstream



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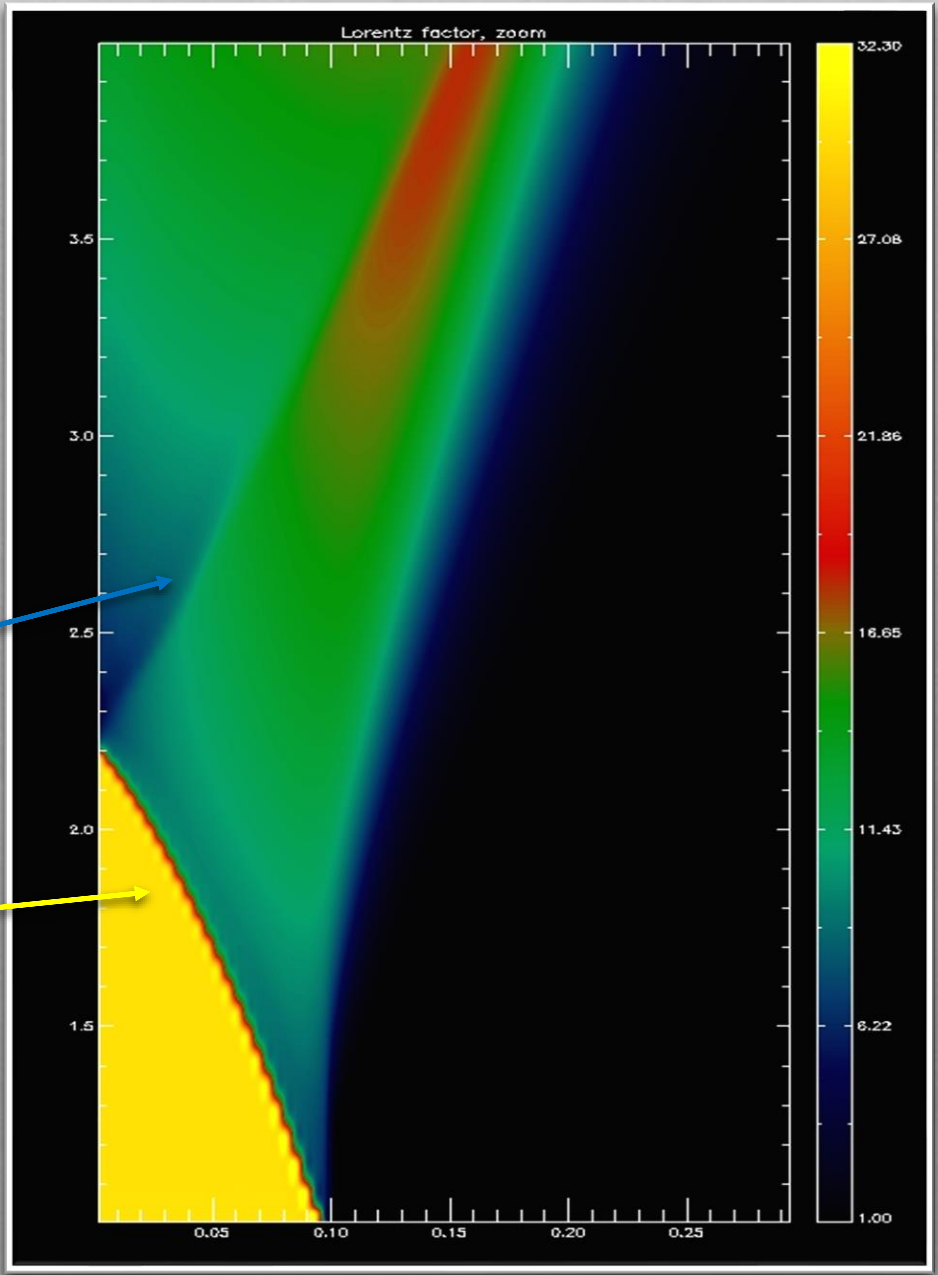
reflection shock: re-shocked jet

recollimation shock



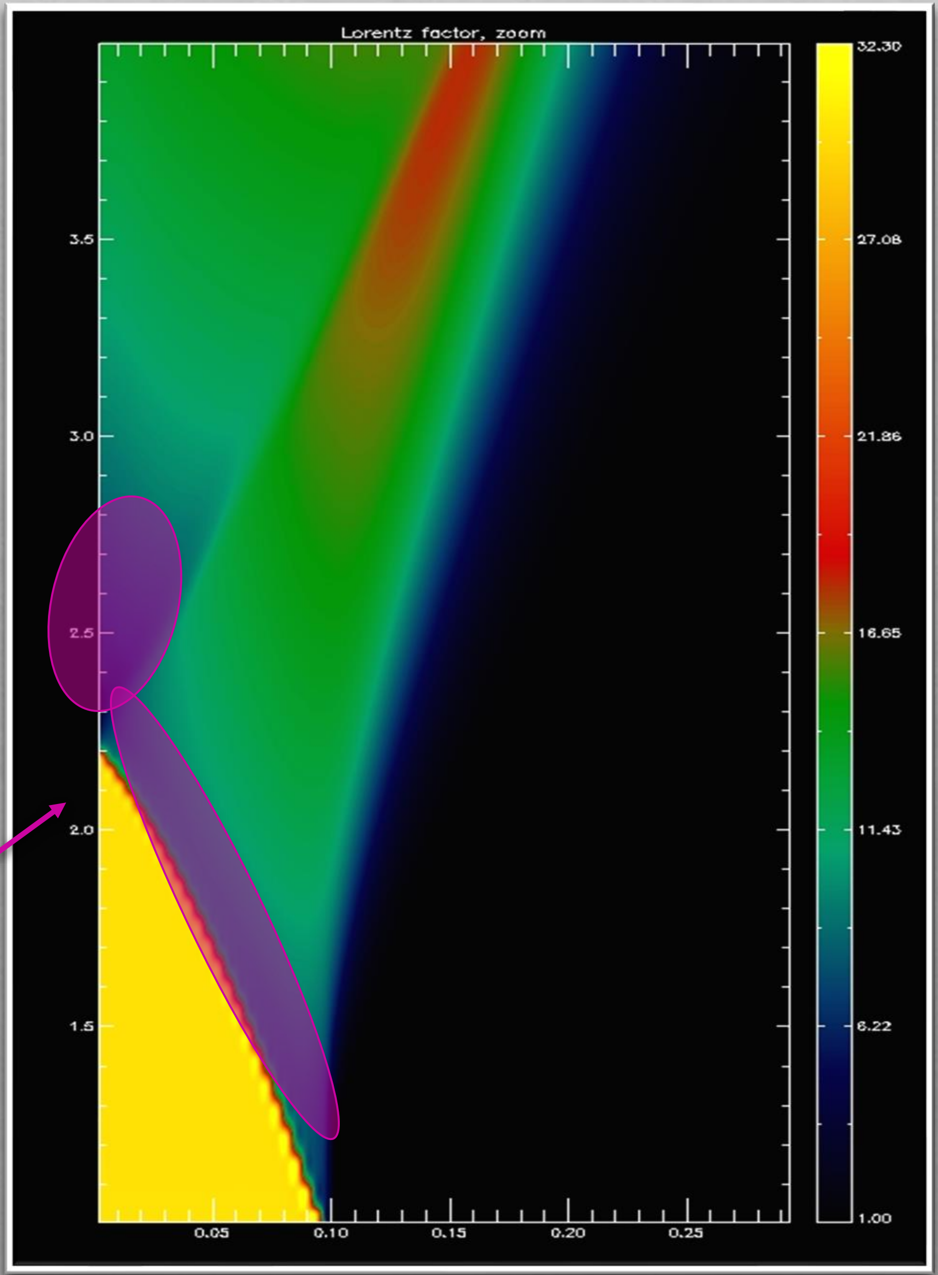
2D simulations with particles for TeV blazars

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 also)



acceleration sites in recollimation-reflection shocks

2D simulations with particles for TeV blazars

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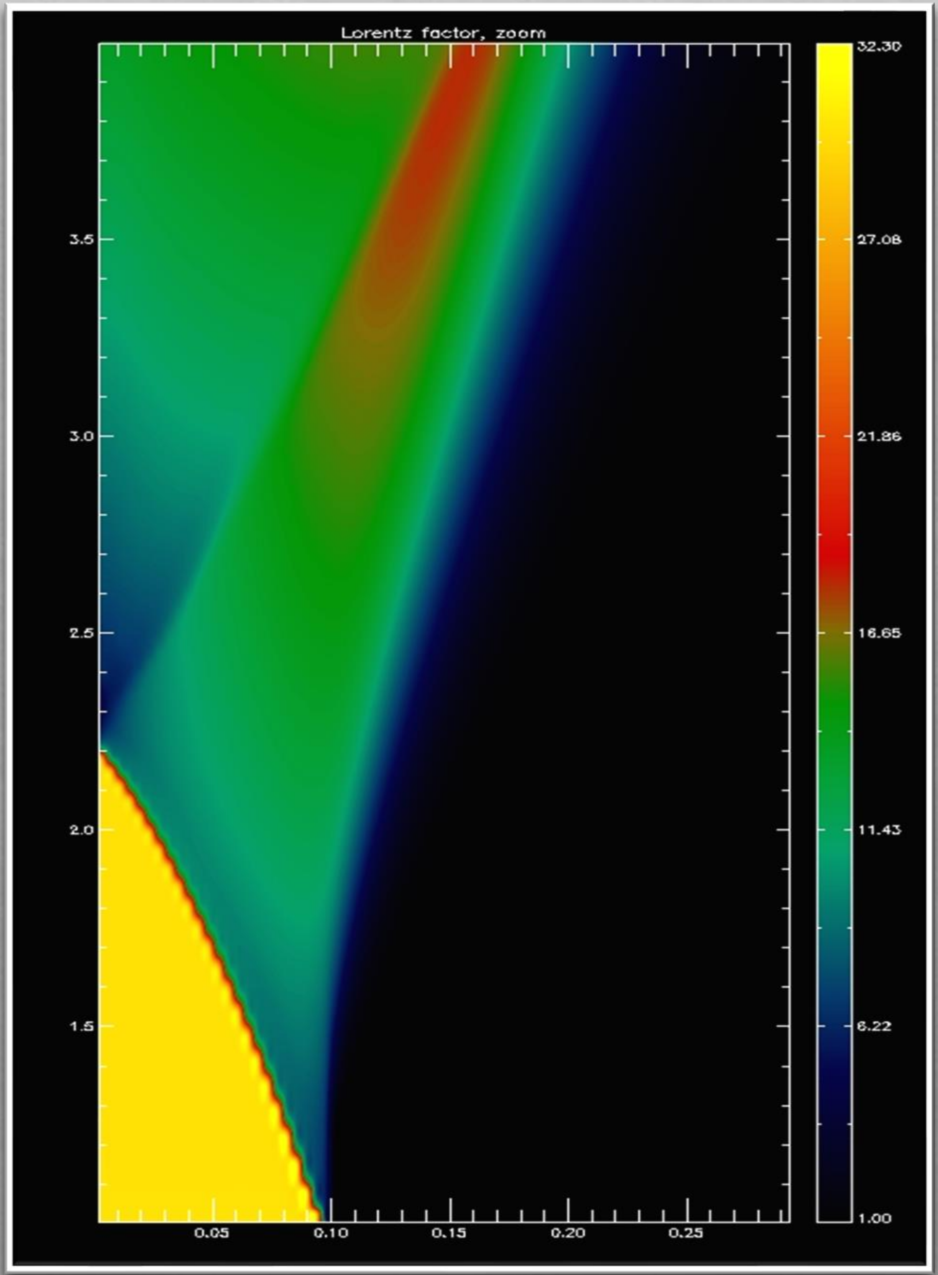
Non thermal particle injection

- Real particle density at injection is:

$$\frac{n_{nth}}{n_{th}} = 10^{-2}$$

- Energy distribution at injection is

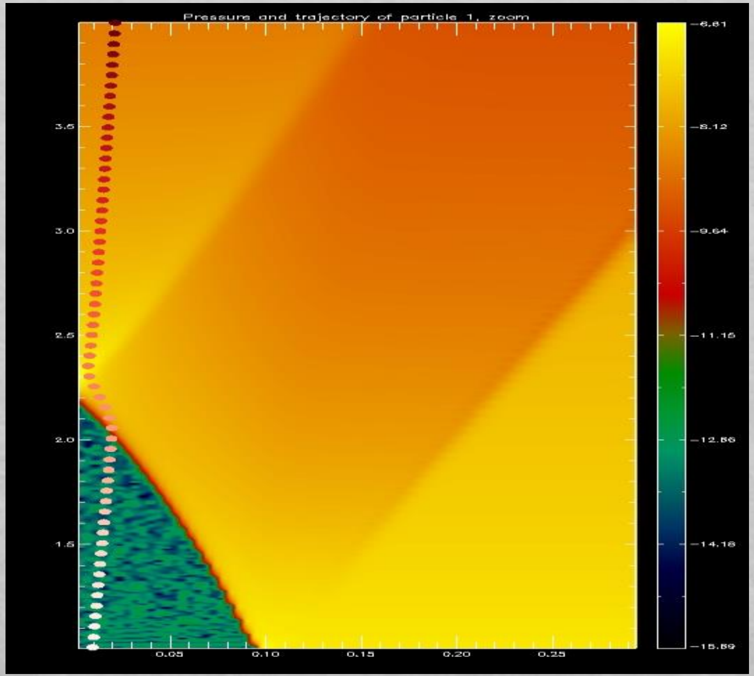
$$N_e(E) \propto \mathrm{E}^{-2} \text{ with } \gamma_e \in [10^2, 5 \cdot 10^3]$$

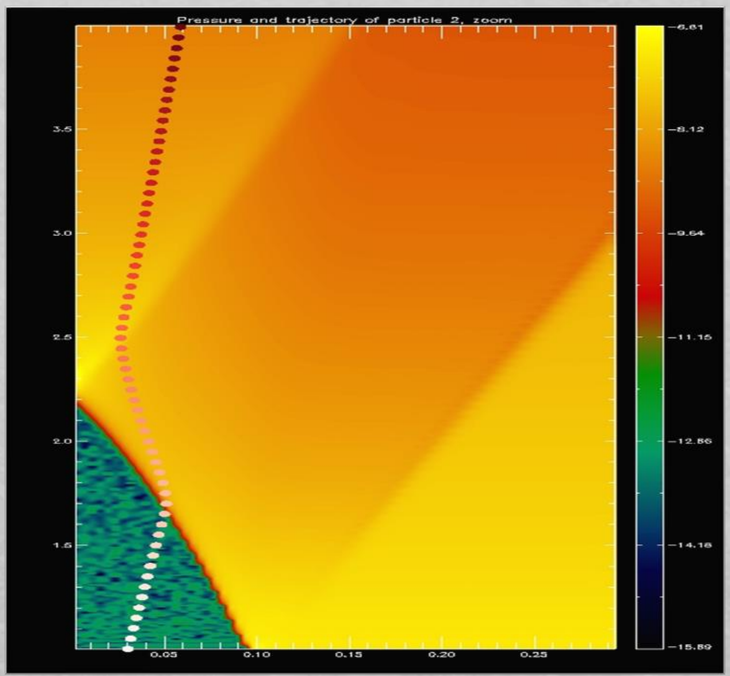


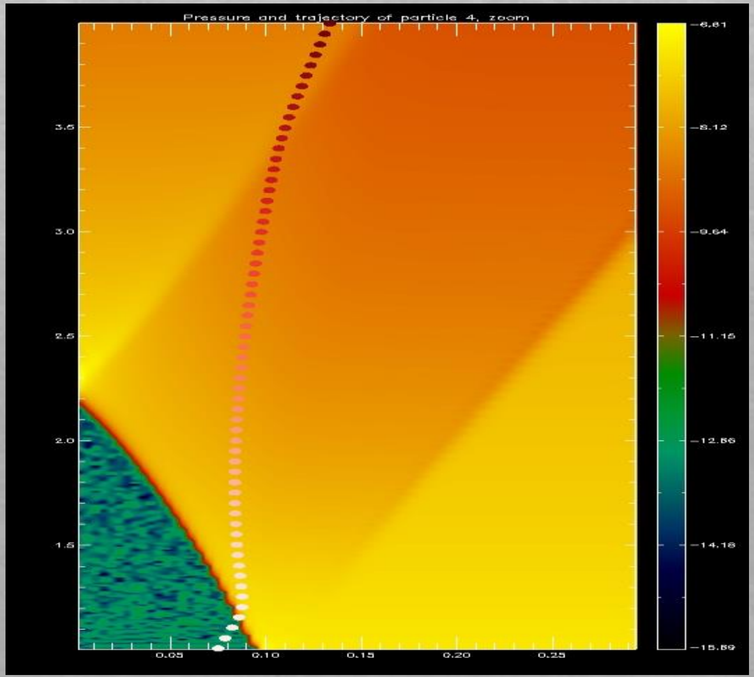
2D simulations with particles for TeV blazars

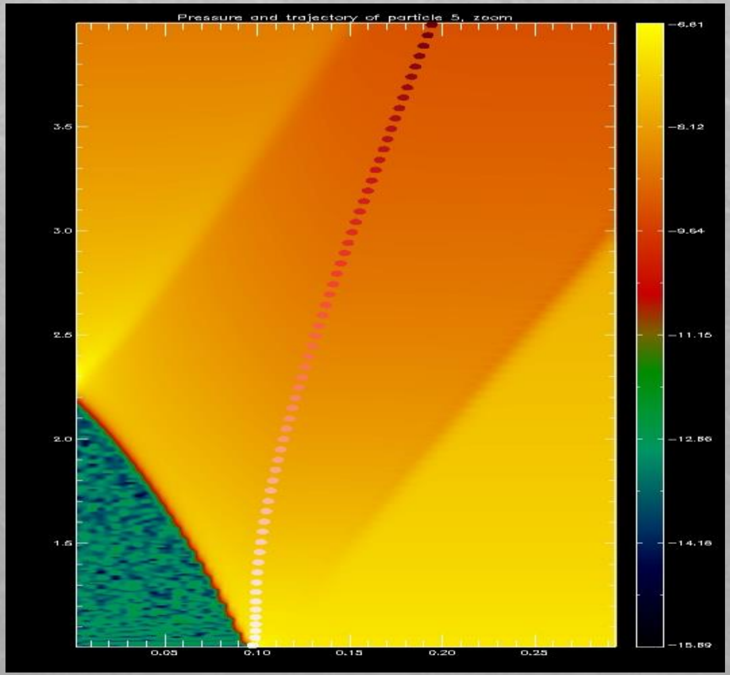
Results for different particles:

- Particle 1 is shocked near the axis and soon is reshocked
- Particle 2 experiences two, well distinct, shocks
- Particle 4 experiences a first weak recollimation shock and… what about the reflection shock?
- Particle 5 is not shocked at all probably.





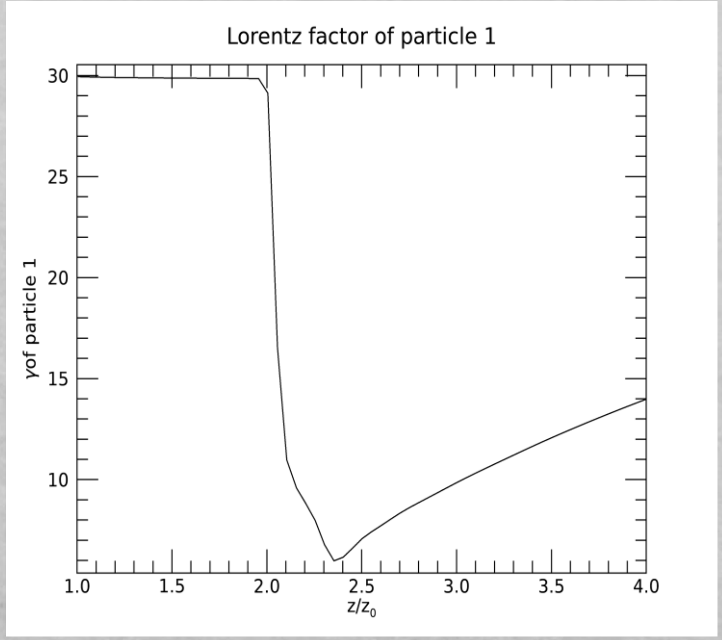


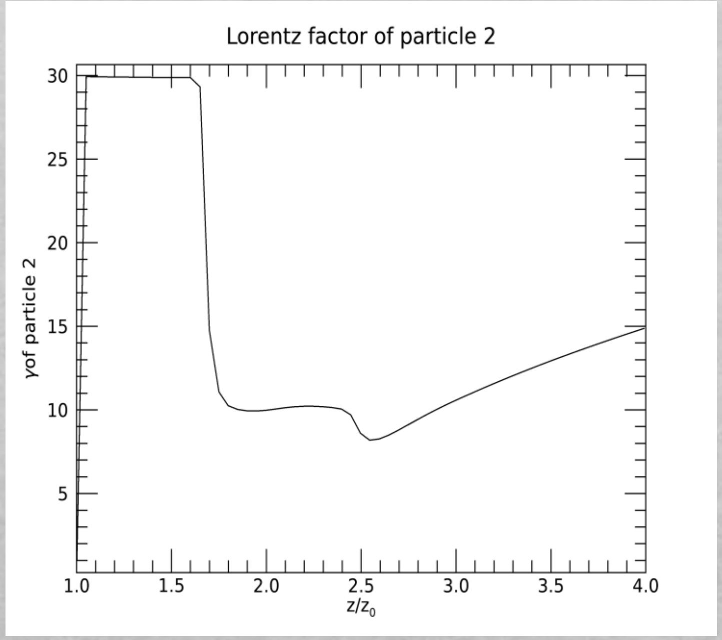


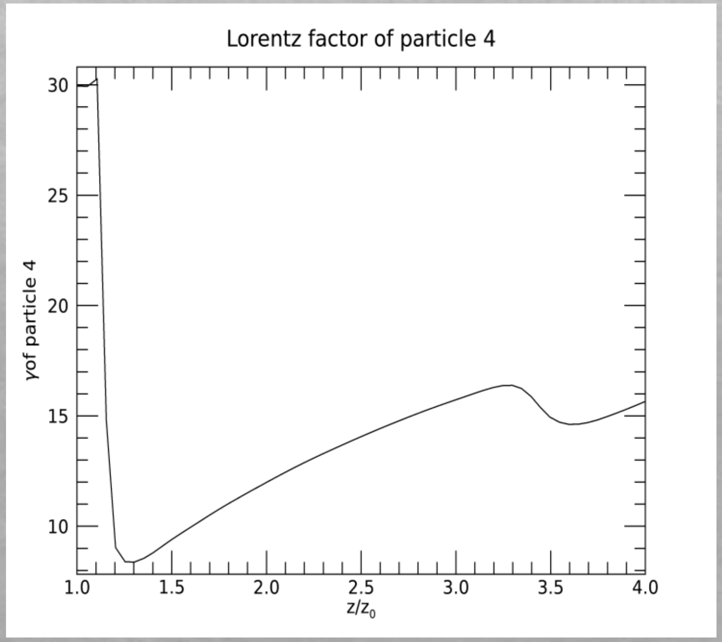
2D simulations with particles for TeV blazars

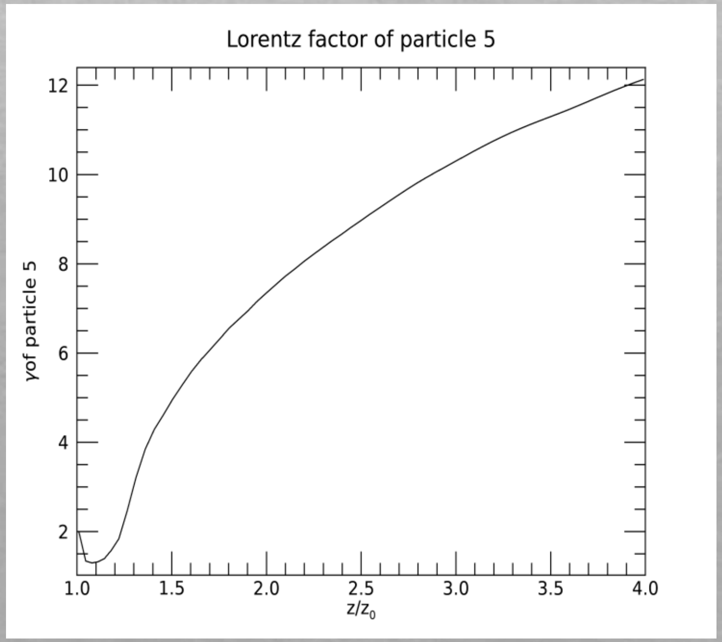
Results for different particles:

- 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.







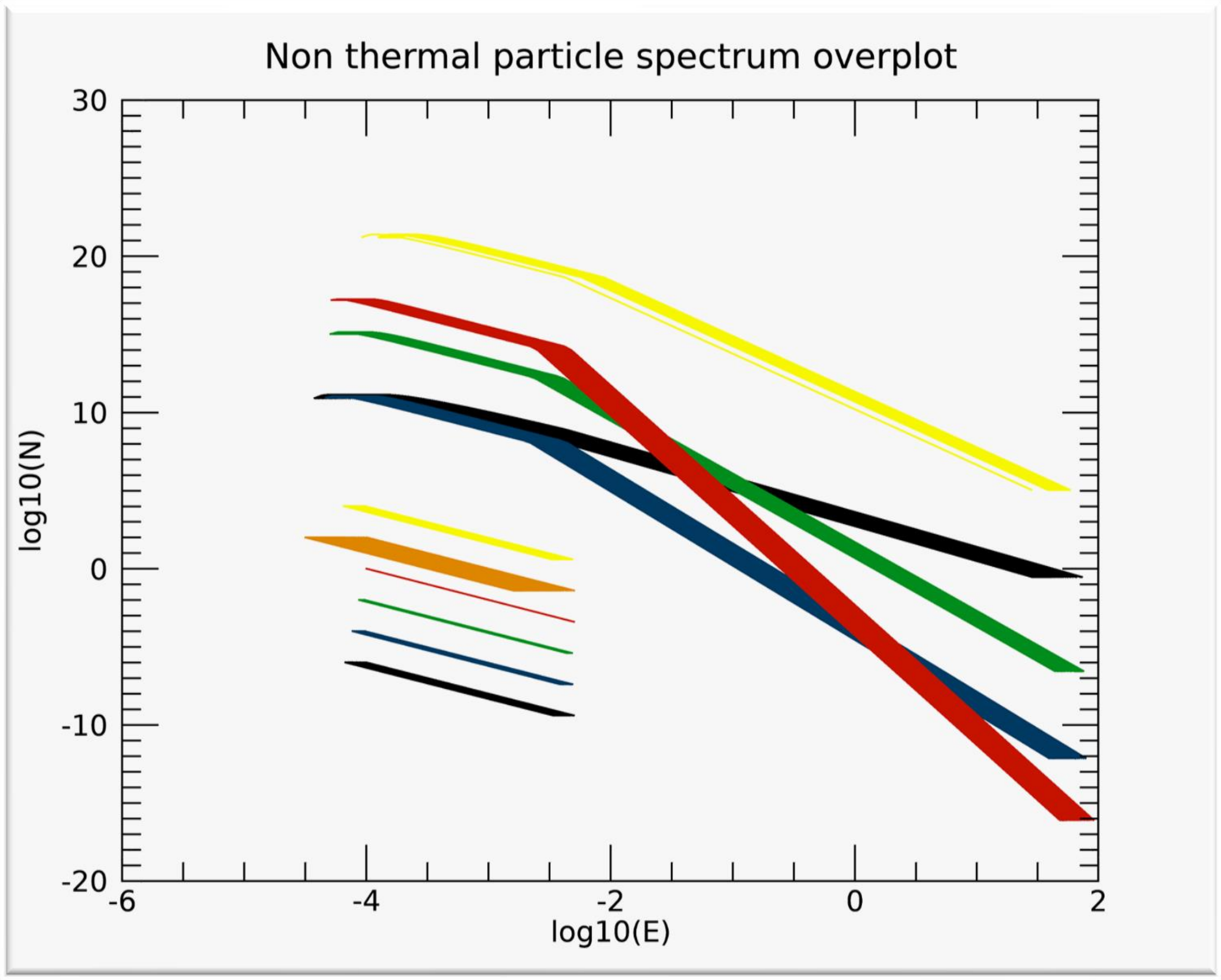


2D simulations with particles for TeV blazars

Results for different particles:

(bold lines=update of the energies)

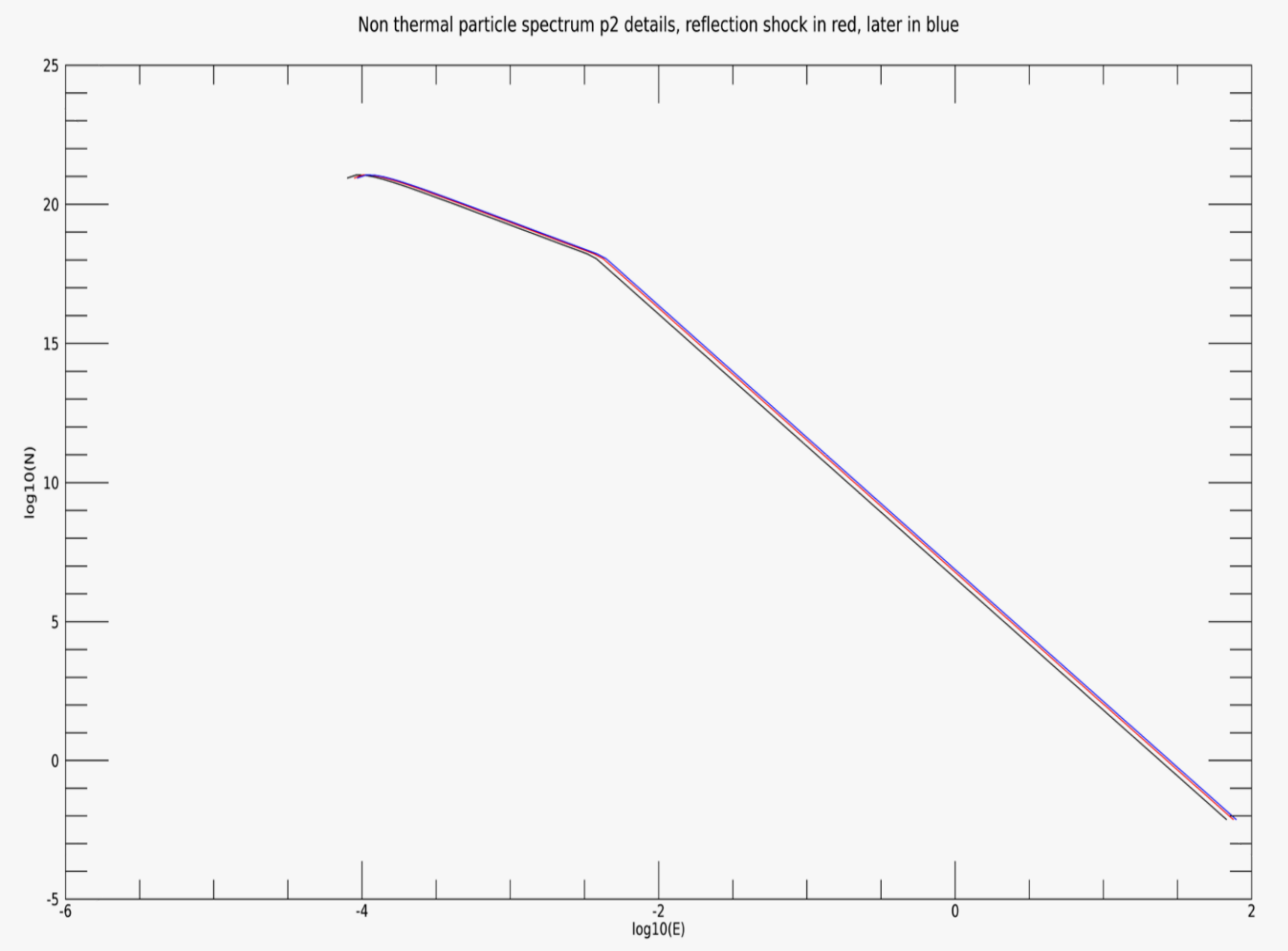
- **Particle 1** crosses the strongest shocks
- **Particle 2** experiences two weaker shocks.
- **Particle 4** experiences even weaker shocks.
- **Particle 5** does not capture the shock.



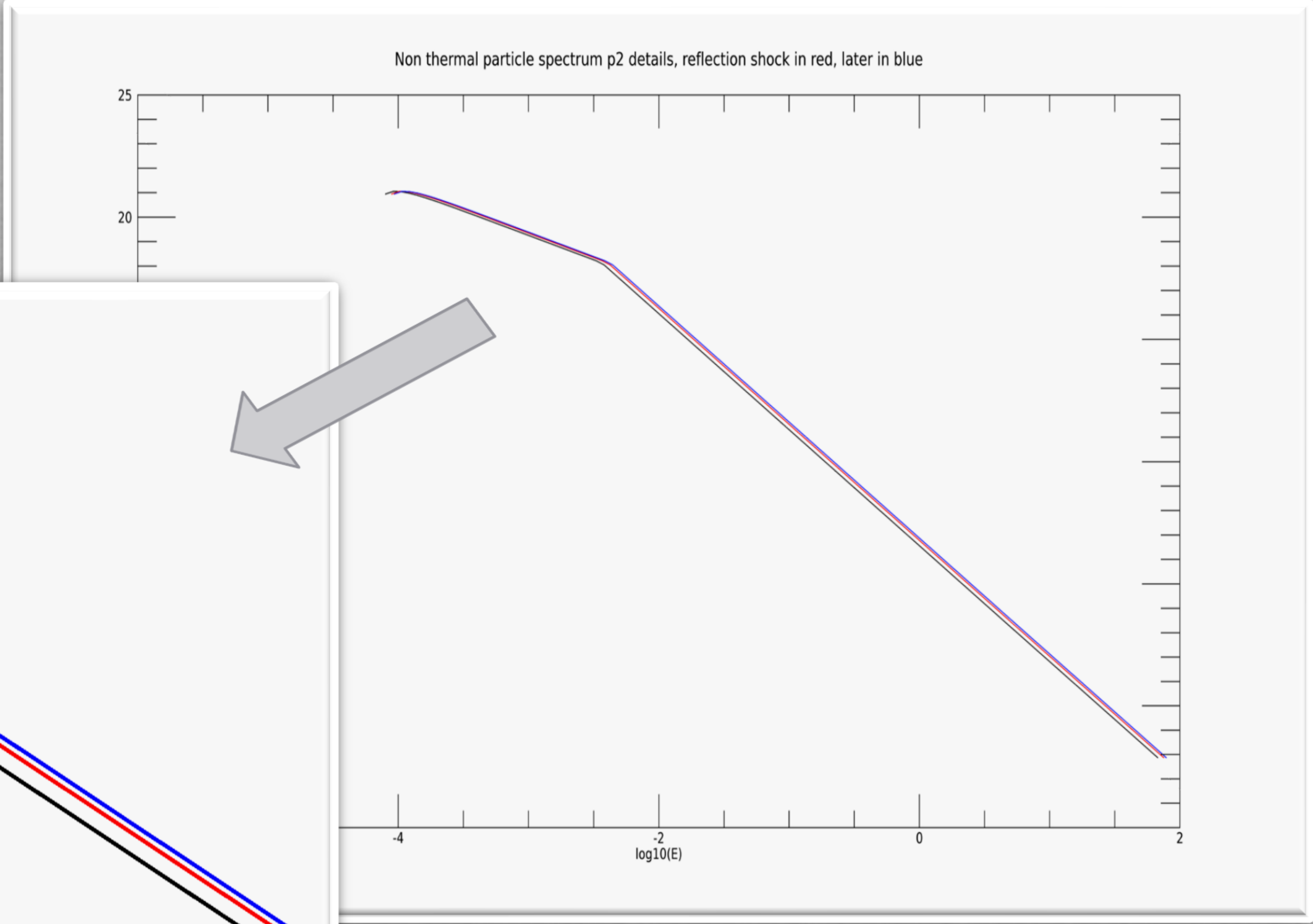
2D simulations with particles for TeV blazars

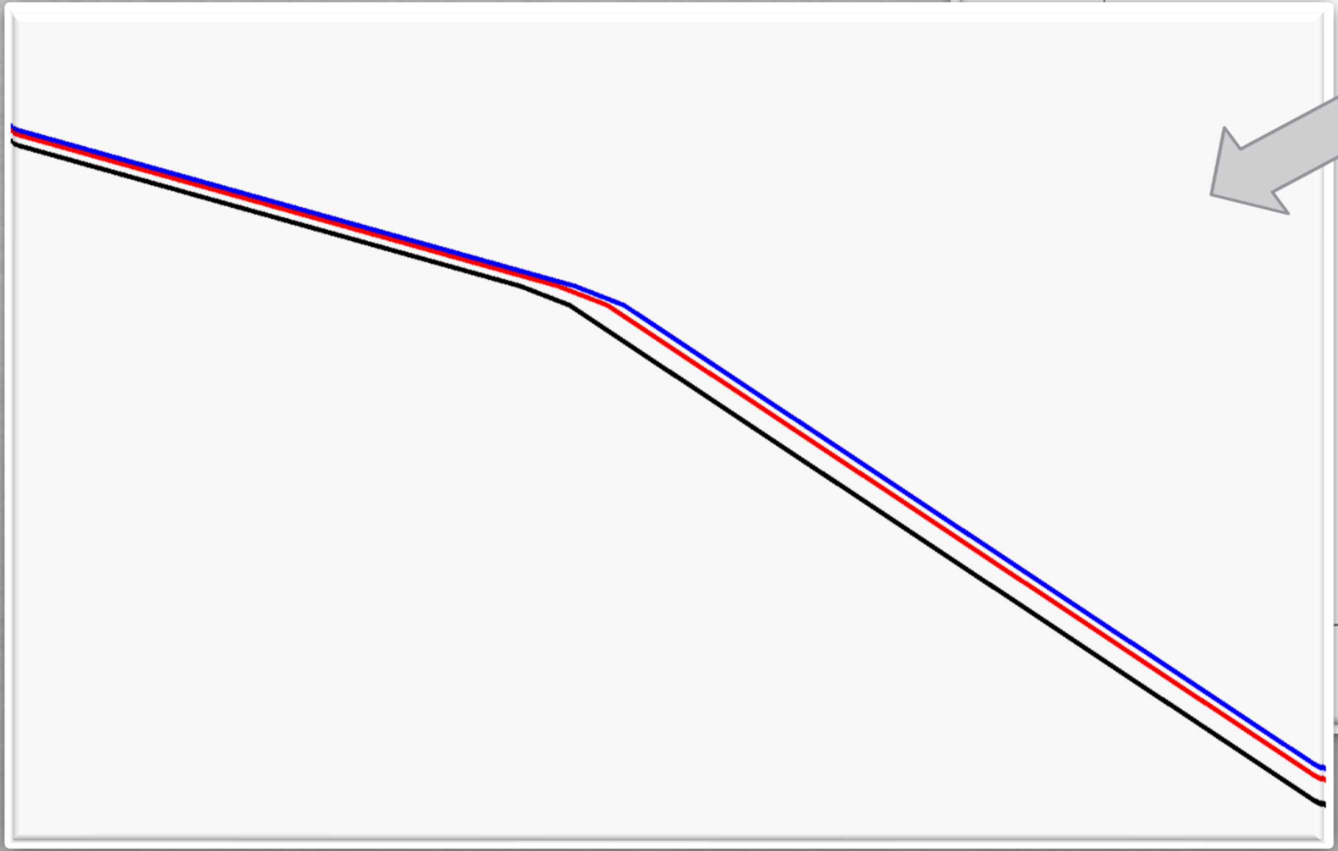
Observations:

- recollimation shocks are stronger at the recollimation point ($\mathbf{v} \cdot \hat{n}$ is bigger)
- the distribution of the accelerated electrons weakly depends on the injection
- the distribution of the accelerated electrons depends on the injection only weakly
- The reflection shock has no big relevance on the acceleration.



2D simulations with particles for TeV blazars

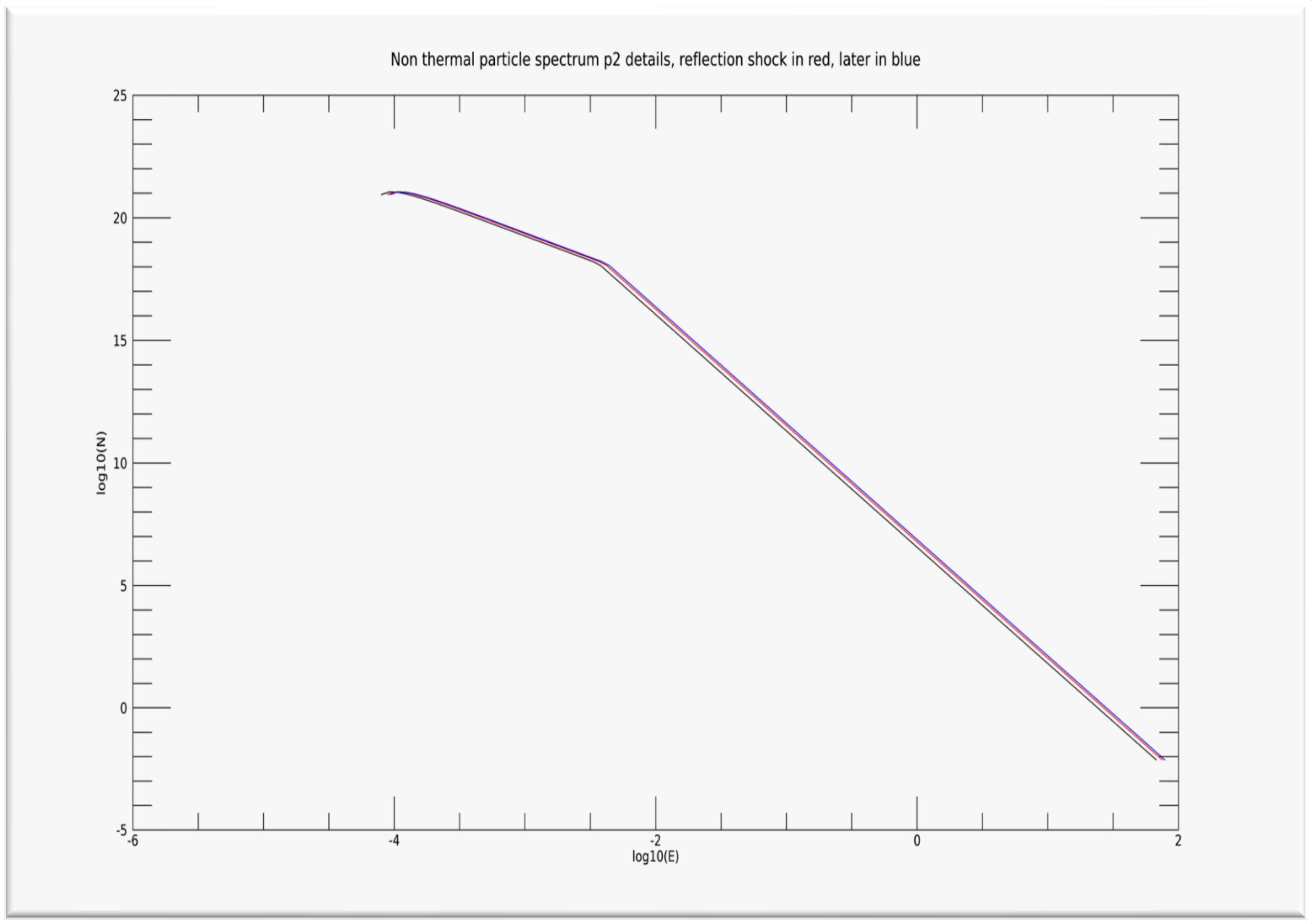




2D simulations with particles for TeV blazars

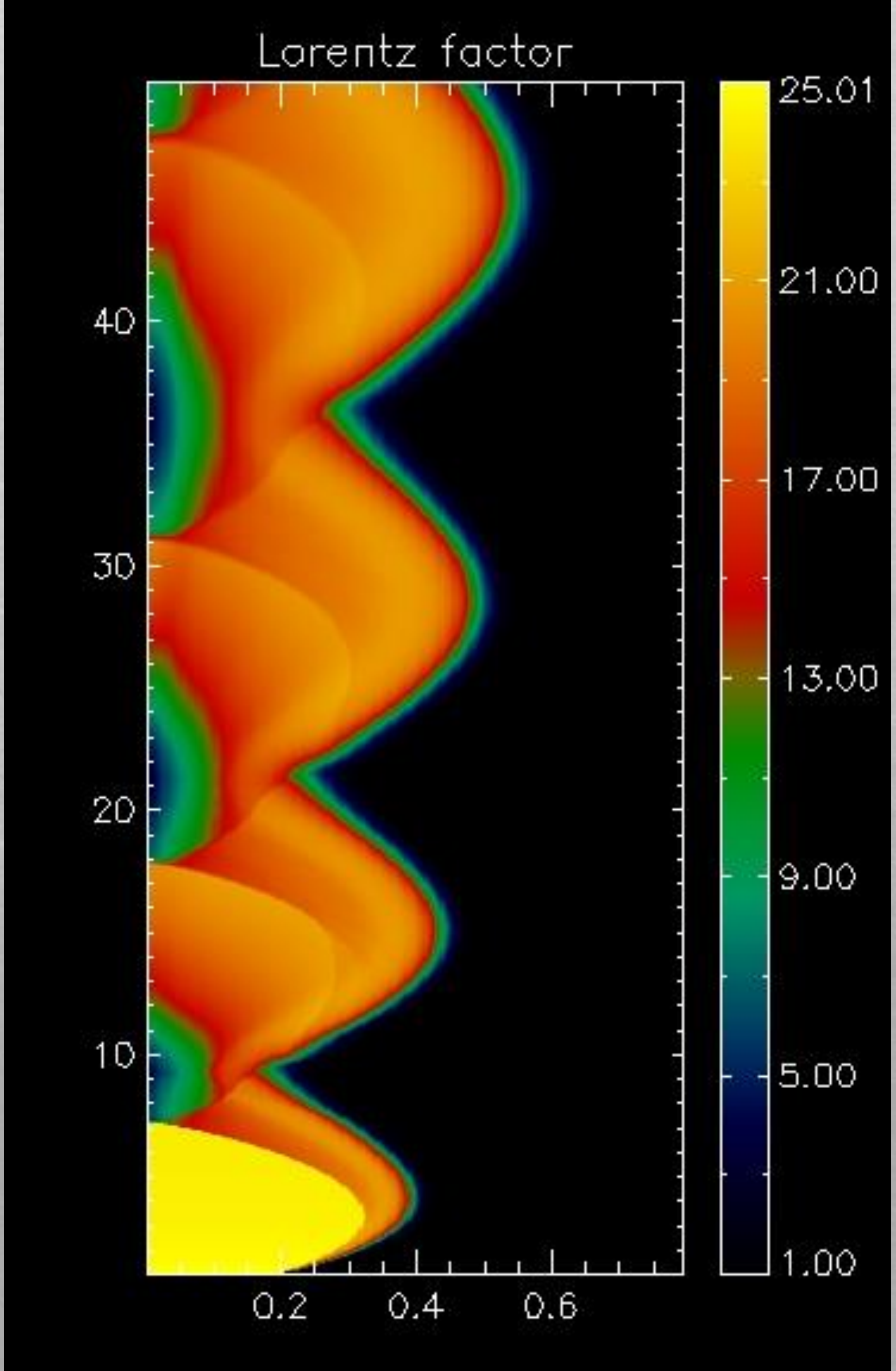
Conclusion 1:

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.

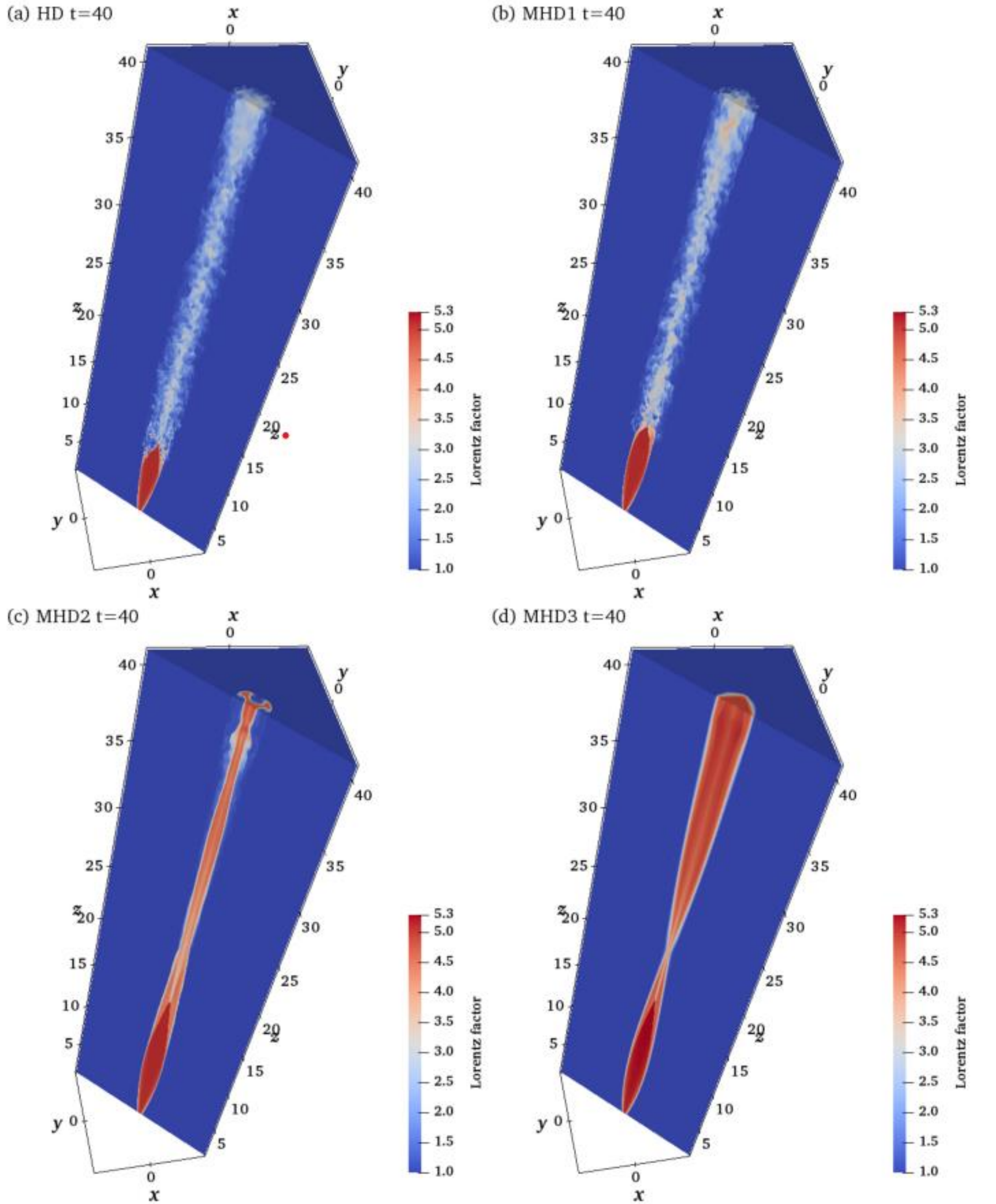


From 2D to 3D:
turbulence in low magnetized jets

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.

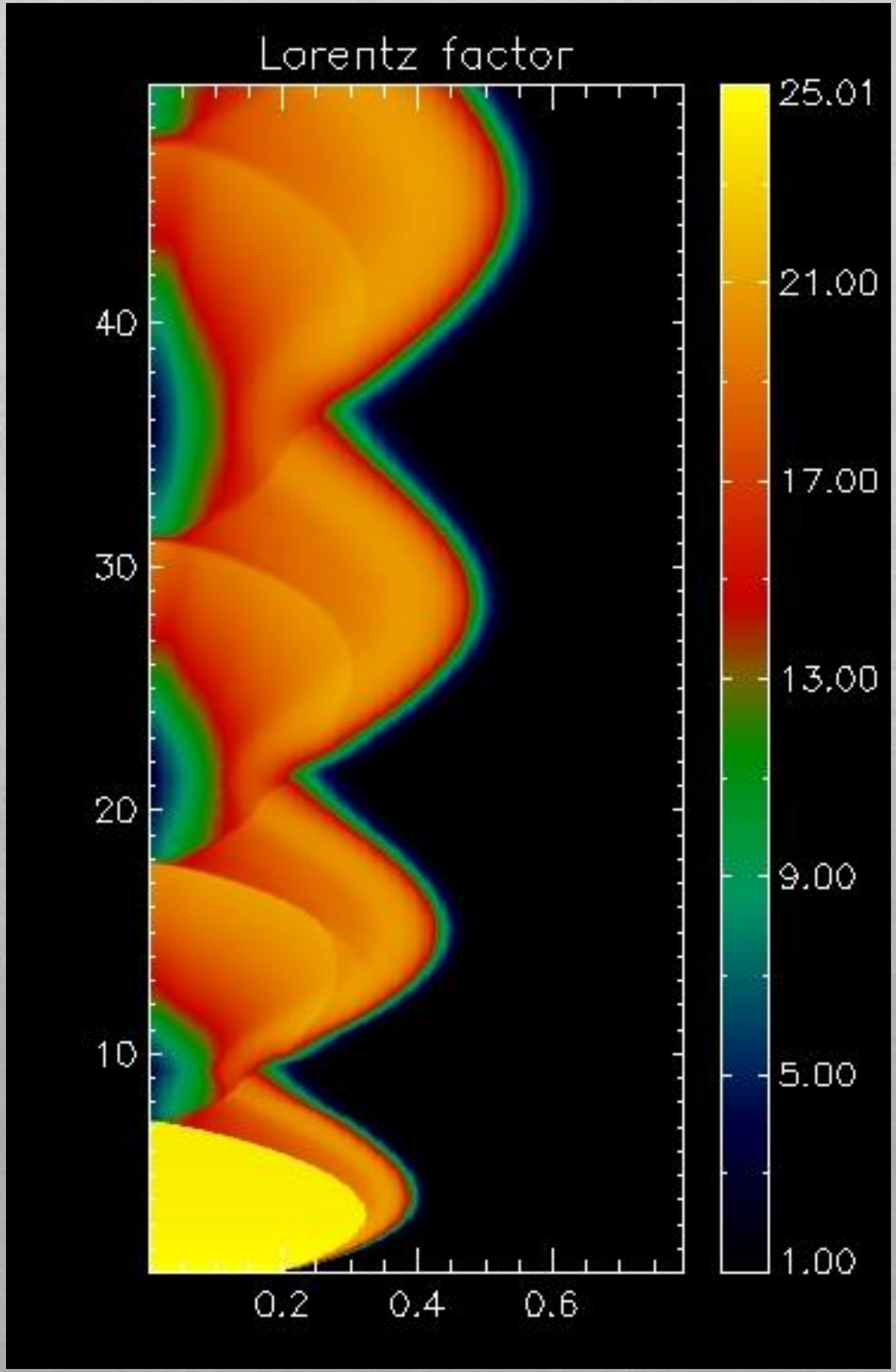
2. Instabilities that cannot be seen in 2D simulations might be relevant in reality:
   - Centrifugal instability caused by the recollimation shock → **turbulence in low magnetized jets** ($\sigma = \frac{B^2}{4\pi\omega} \leq 10^{-4}$)

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



What’s next?

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

The end!

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Thank you for your kind attention