Assessing cosmic ray feedback on relativistic jets

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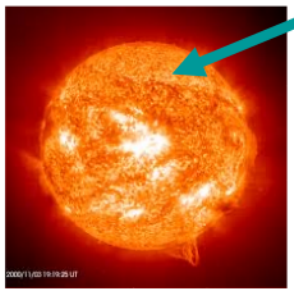
University of São Paulo, Brazil

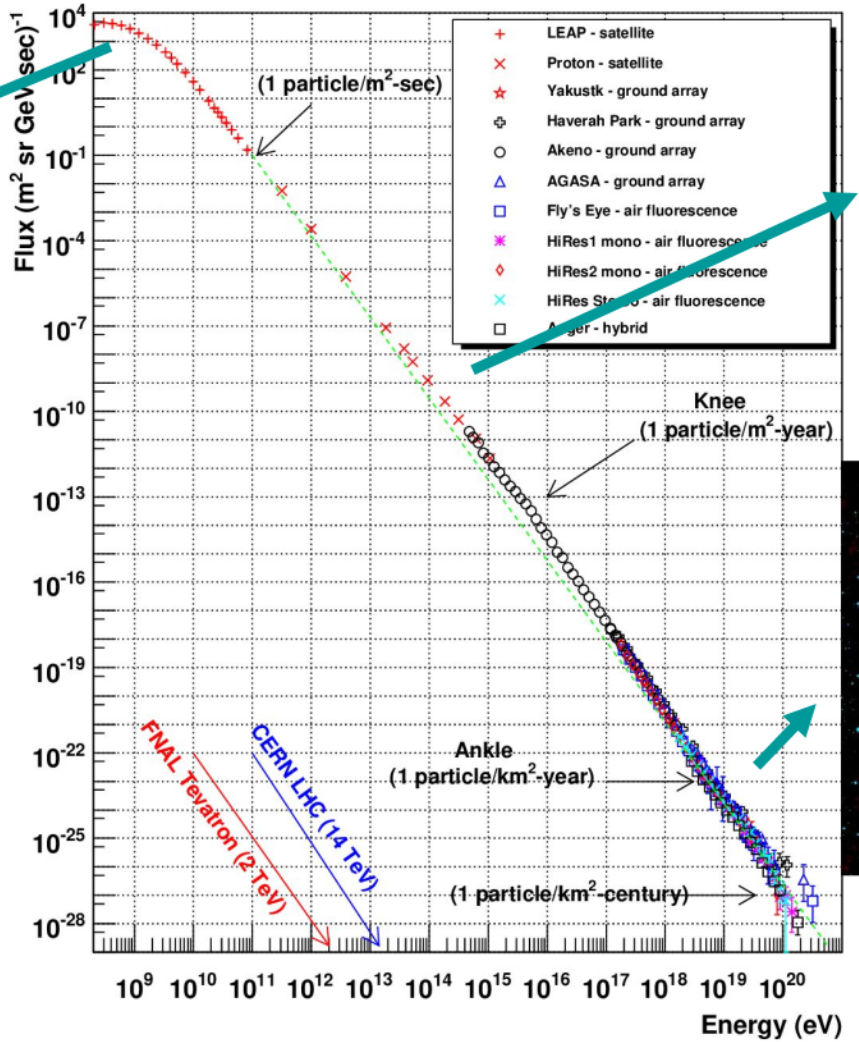
June 18, 2024

Outline

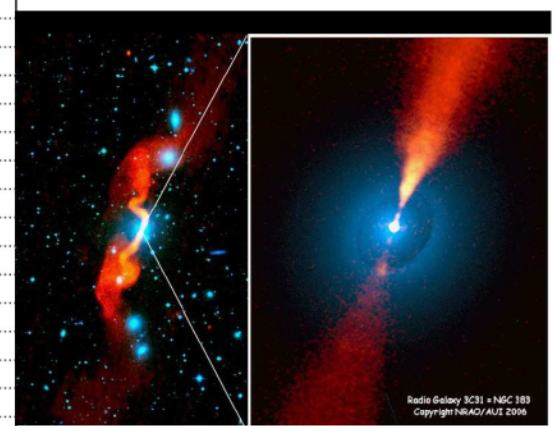
CR spectrum is not constant



Sun

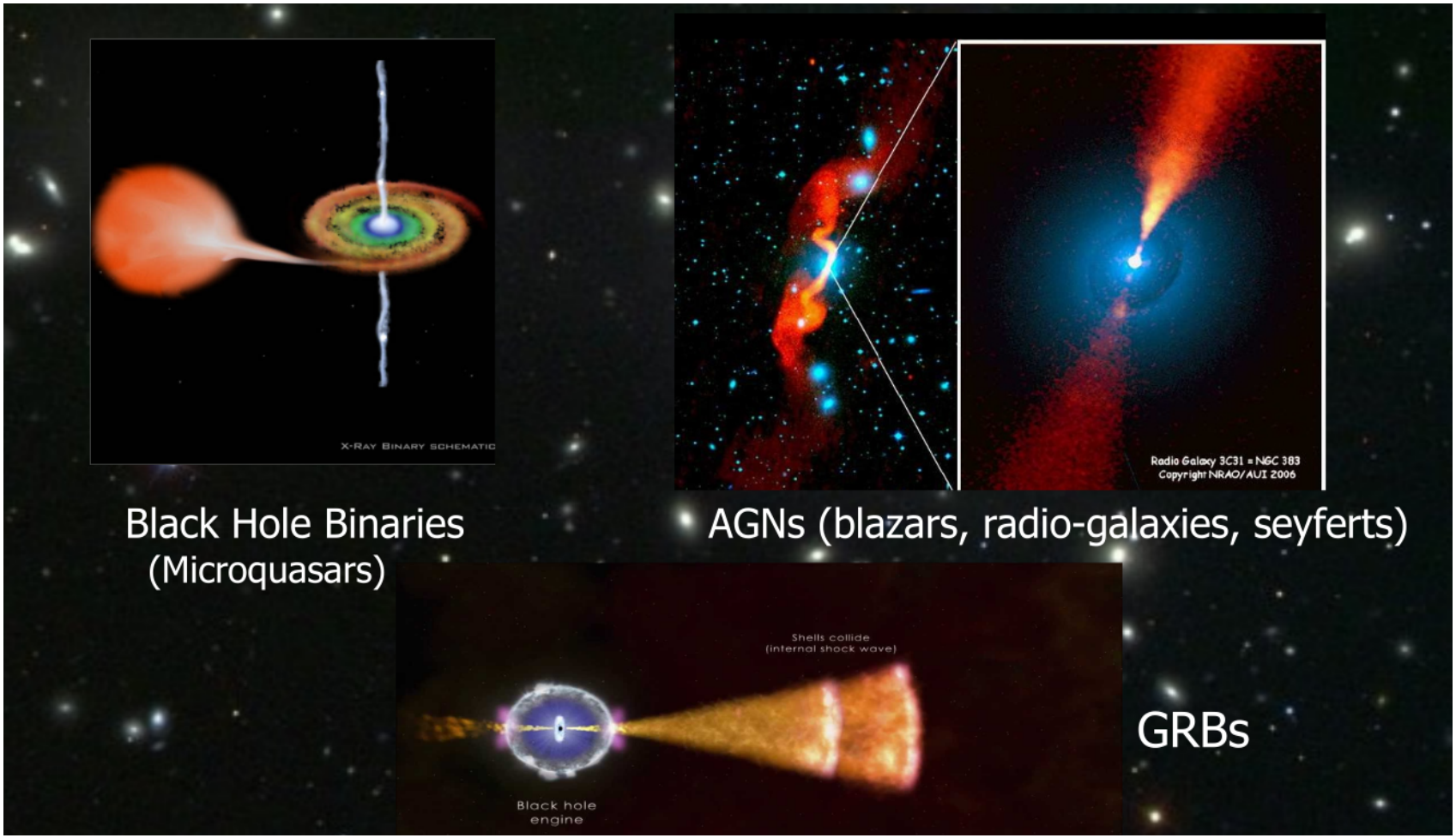


Milky Way

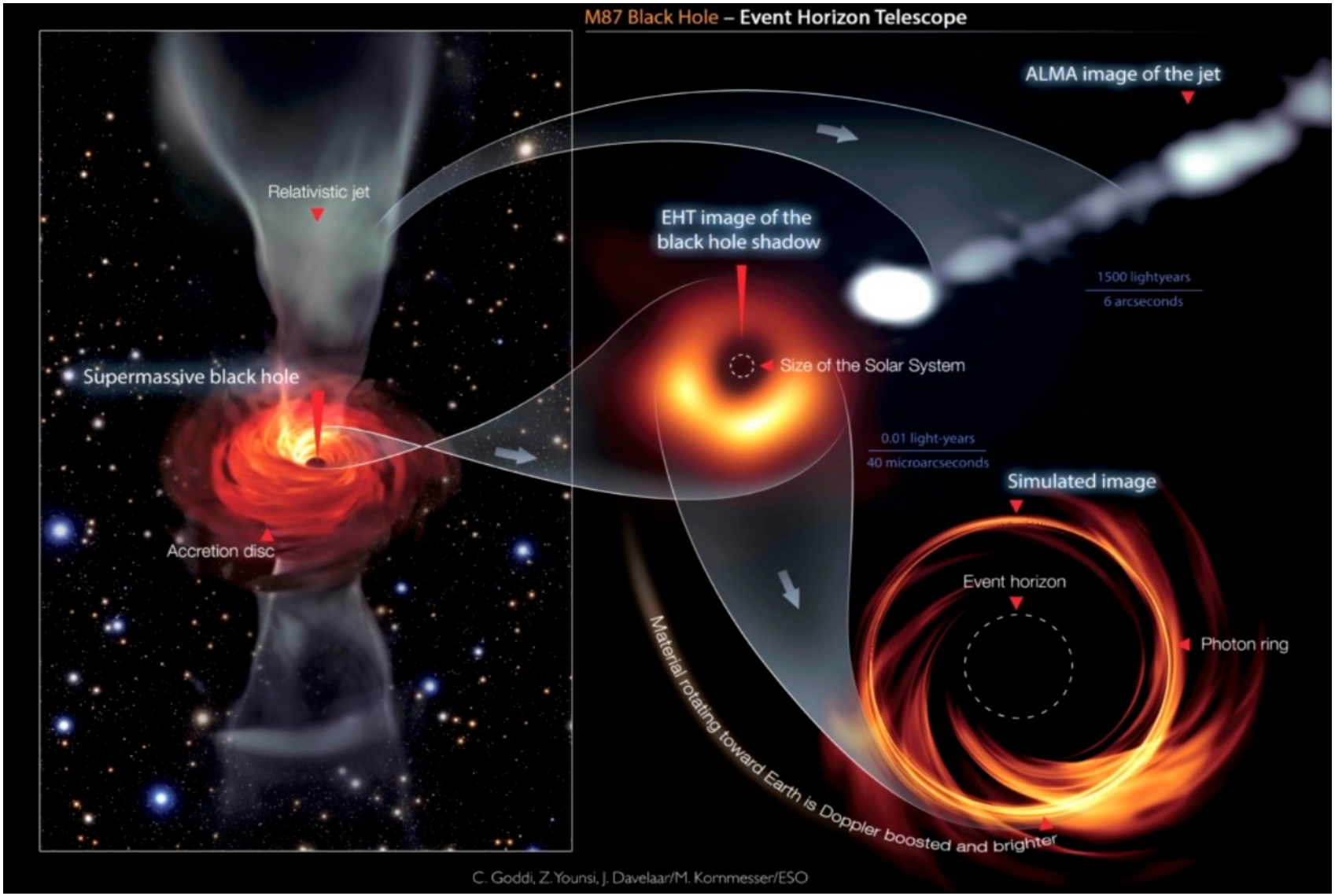


Active Galaxies

BHs are high-energy emitters



Astrophysical jets are born magnetically dominated



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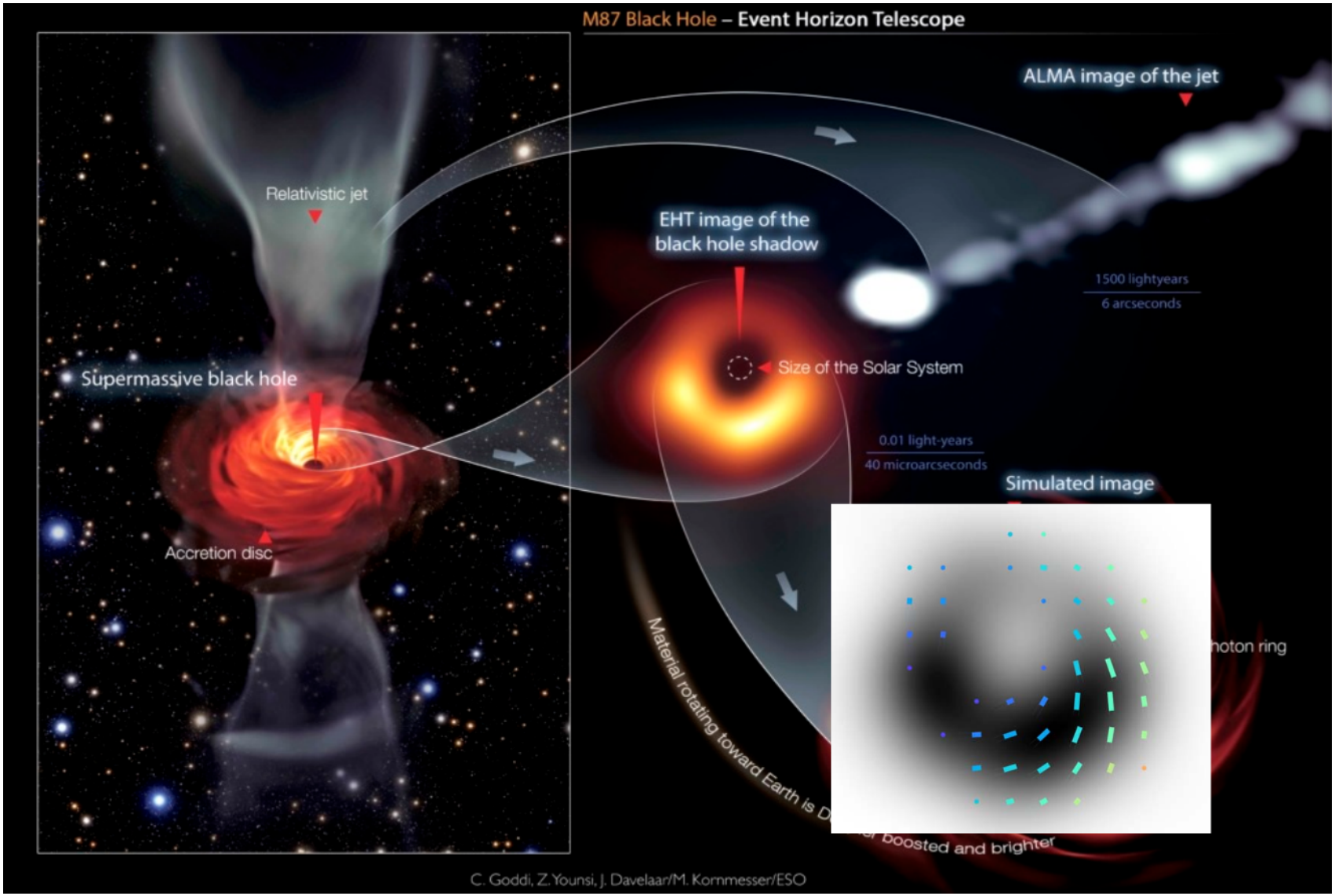
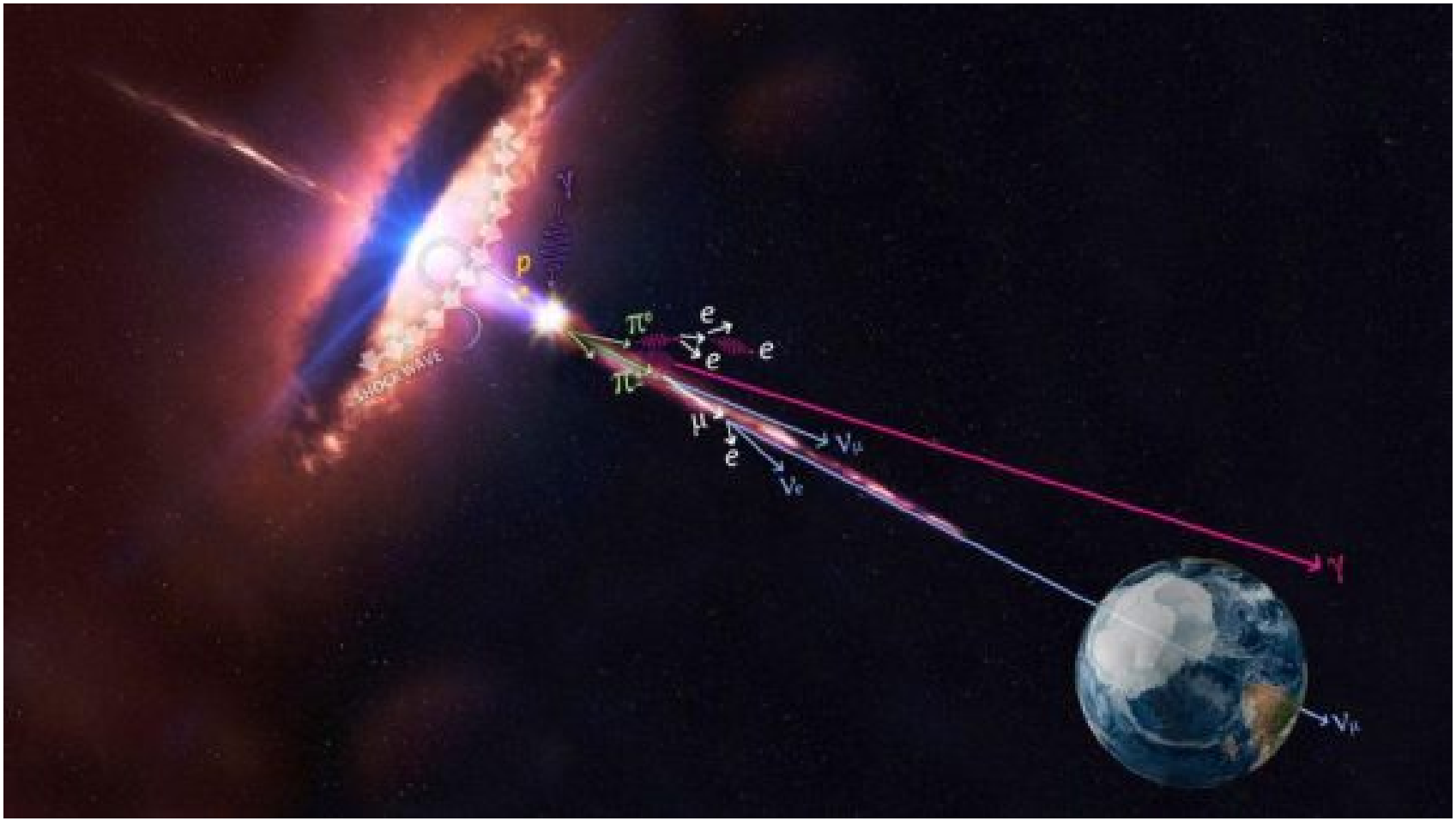


TXS0506+56: neutrinos followed by gamma rays

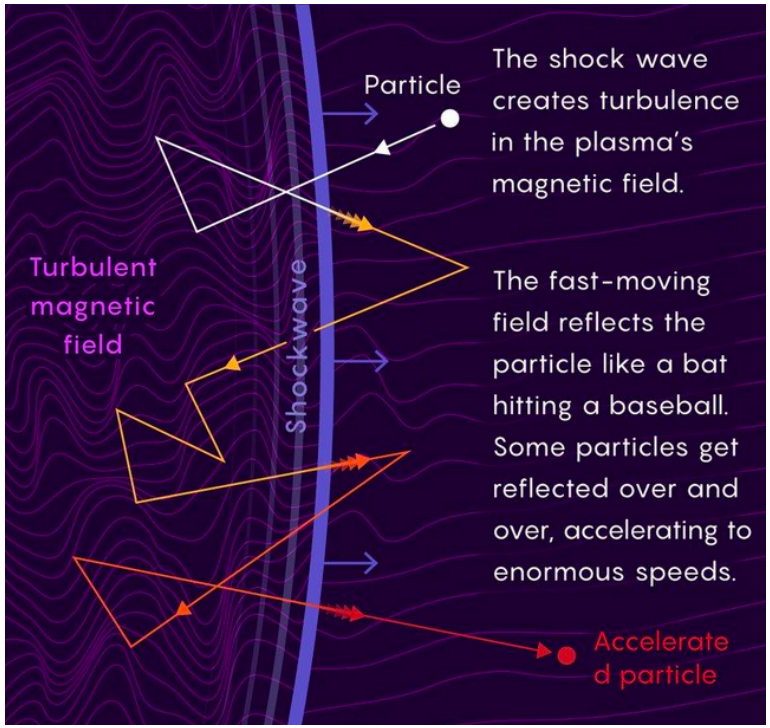


IceCube/NASA

Motivation

- Studying particle acceleration is essential to better understand the physical processes in VHE emitters.

Particle acceleration: 1st order Fermi process



Adapted from quantamagazine.org

[Bell, 1978]

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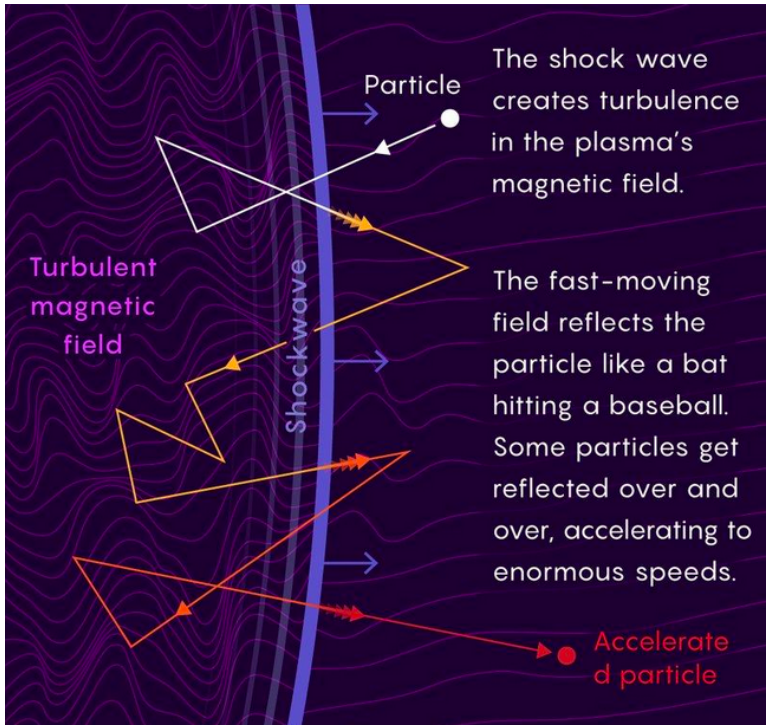

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$$\langle \Delta E/E \rangle \sim v_{sh}/c \qquad (1)$$

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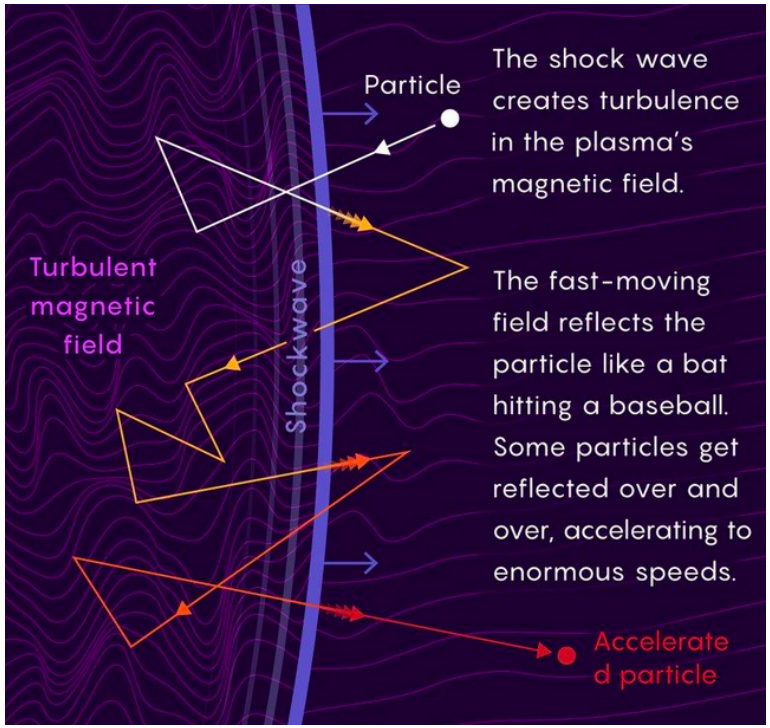

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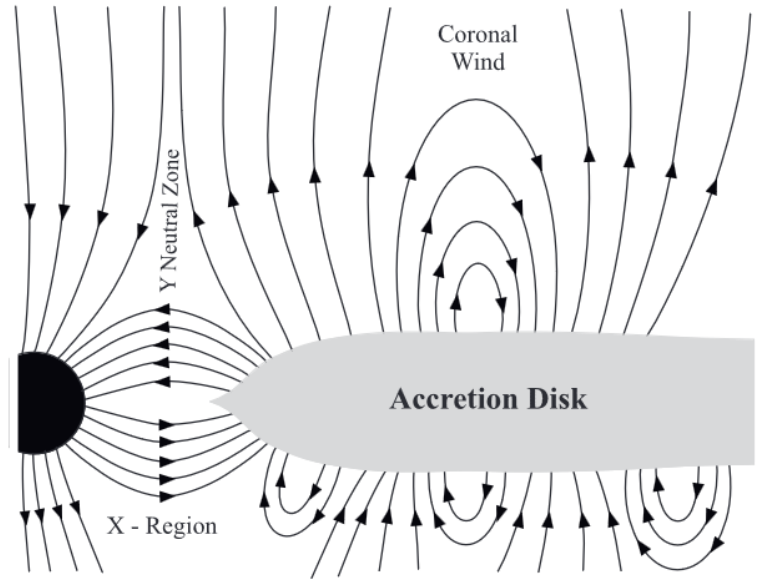

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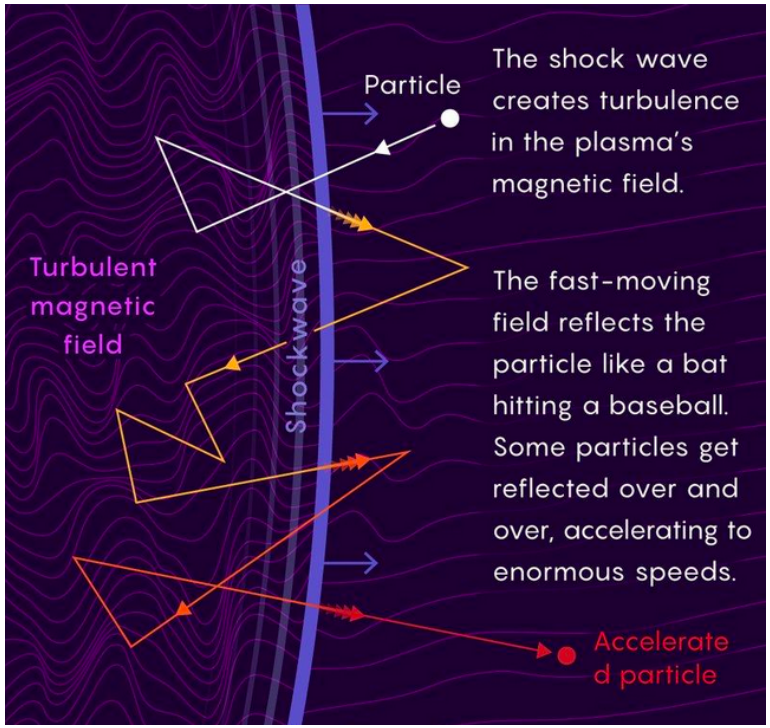

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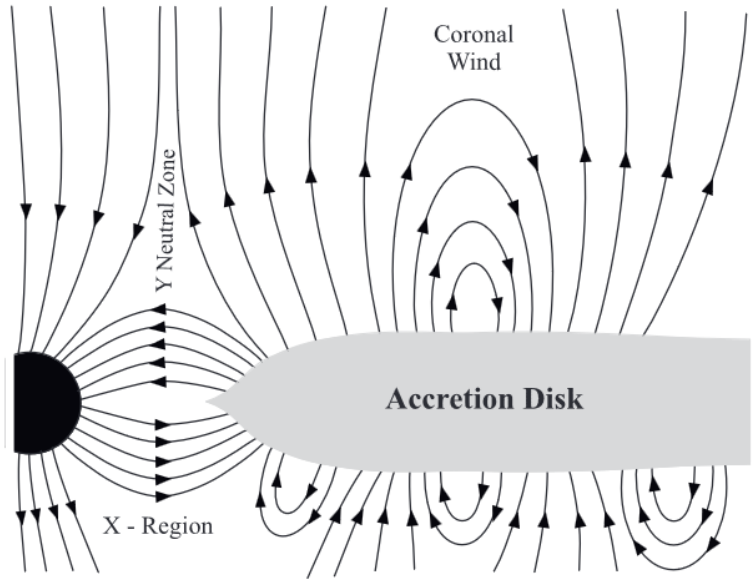

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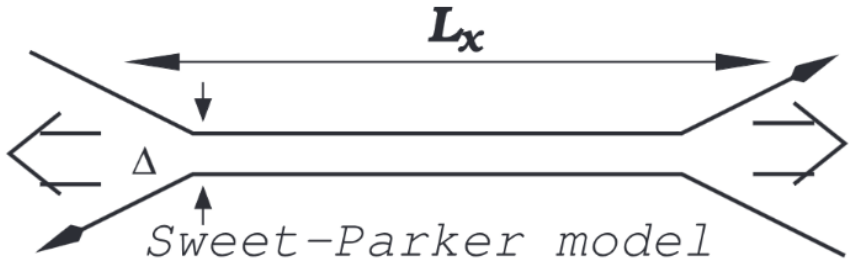
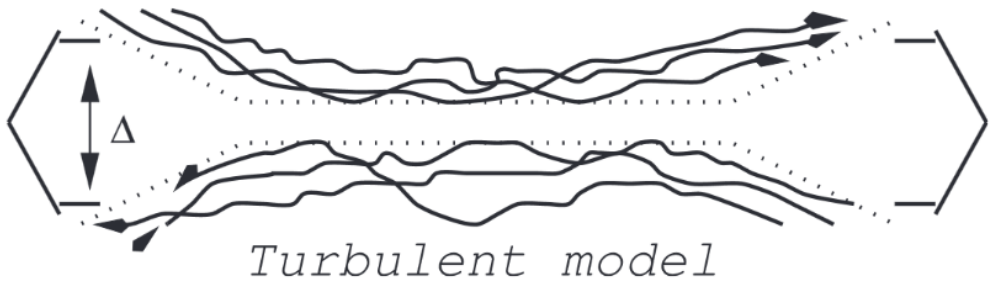
$$\langle \Delta E/E \rangle \sim v_{rec}/c \quad (2)$$

Magnetic Reconnection: slow and turbulent





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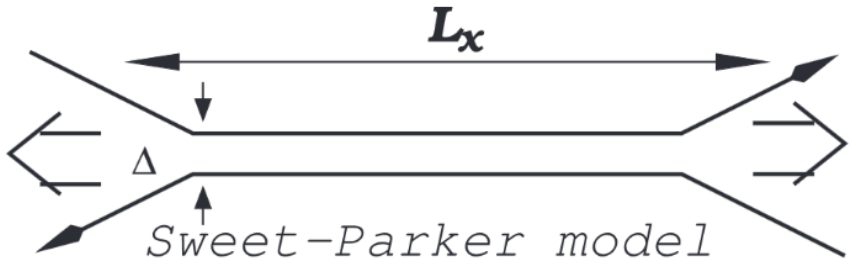

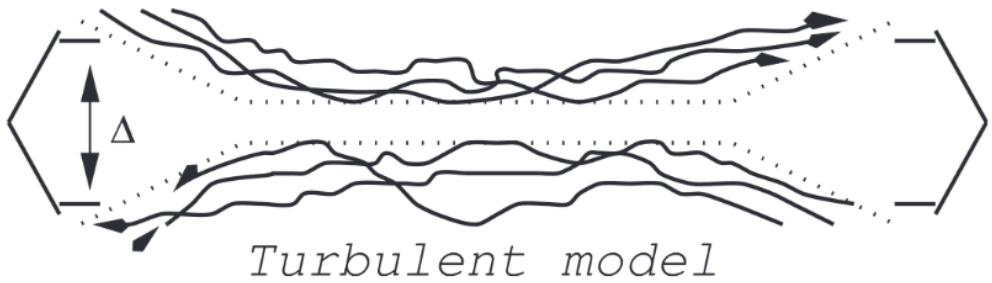

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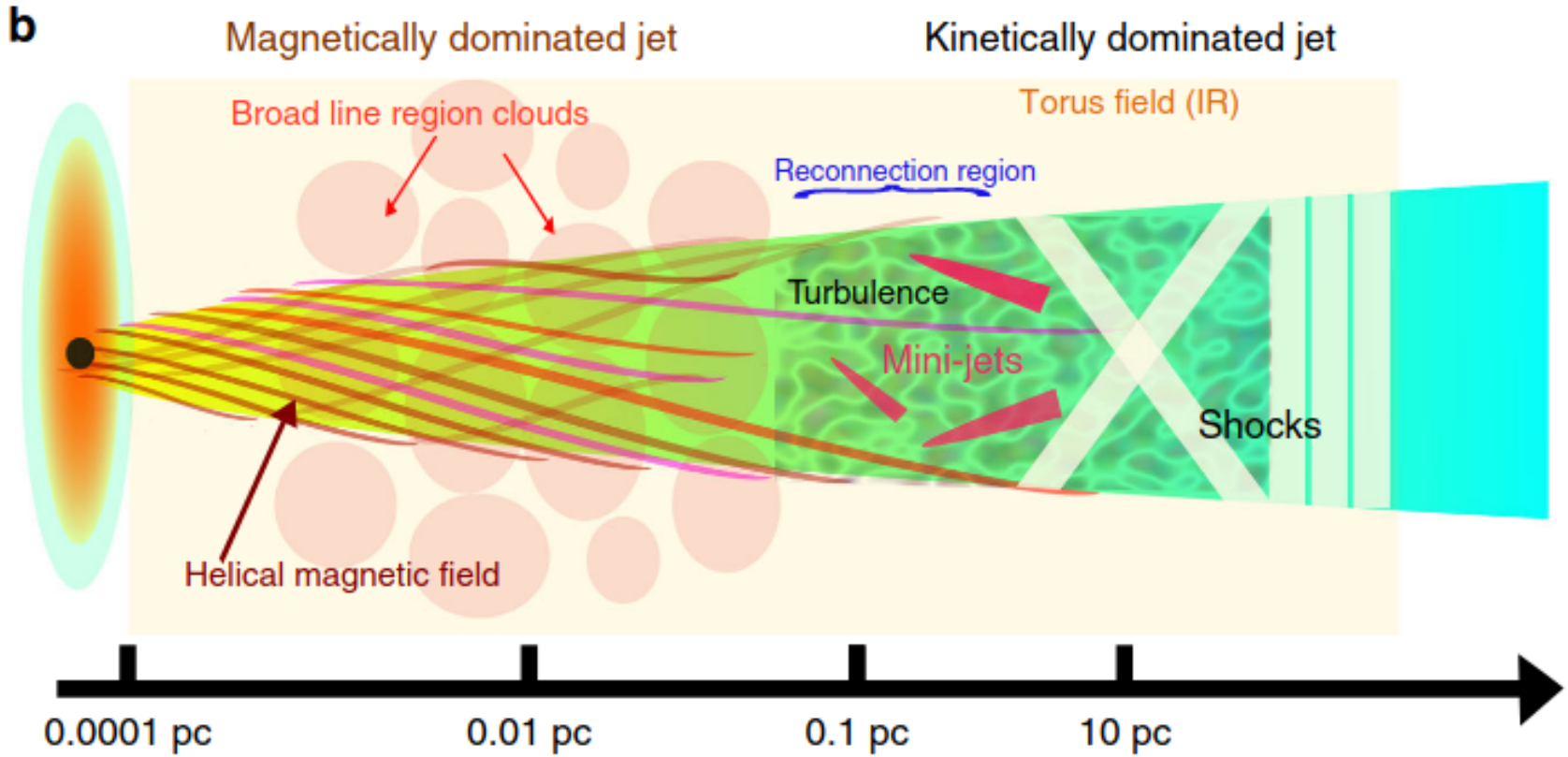
$$v_{rec} = v_A \min\left[\left(\frac{L}{L_i}^{1/2}\right), \left(\frac{L_i}{L}^{1/2}\right)\right] M_A^2 \tag{4}$$

Regions for both mechanisms are not the same



Adapted from [Shukla and Mannheim, 2020]

3D-RMHD simulations to study particle acceleration

RAISHIN [Mizuno et al., 2006] and PLUTO [Mignone et al., 2018] codes:

$$\frac{\partial}{\partial t}\begin{pmatrix} D \\ \mathbf{m} \\ E_t \\ \mathbf{B} \end{pmatrix} + \nabla \cdot \begin{pmatrix} D\mathbf{v} \\ w_t\gamma^2\mathbf{v}\mathbf{v} - \mathbf{b}\mathbf{b} + \mathbf{I}p_t \\ \mathbf{m} \\ \mathbf{v}\mathbf{B} - \mathbf{B}\mathbf{v} \end{pmatrix}^T = \begin{pmatrix} 0 \\ \mathbf{f}_g \\ \mathbf{v}\cdot\mathbf{f}_g \\ 0 \end{pmatrix}, \quad (5)$$

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$$\begin{pmatrix} b^0 \\ \mathbf{b} \\ w_t \\ p_t \end{pmatrix} = \begin{pmatrix} \gamma\mathbf{v}\cdot\mathbf{B} \\ \mathbf{B}/\gamma + \gamma(\mathbf{v}\cdot\mathbf{B})\mathbf{v} \\ \rho h + \mathbf{B}^2/\gamma^2 + (\mathbf{v}\cdot\mathbf{B})^2 \\ p + \frac{\mathbf{B}^2/\gamma^2 + (\mathbf{v}\cdot\mathbf{B})^2}{2} \end{pmatrix}. \quad (7)$$

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[Medina-Torrejón et al., 2023]:

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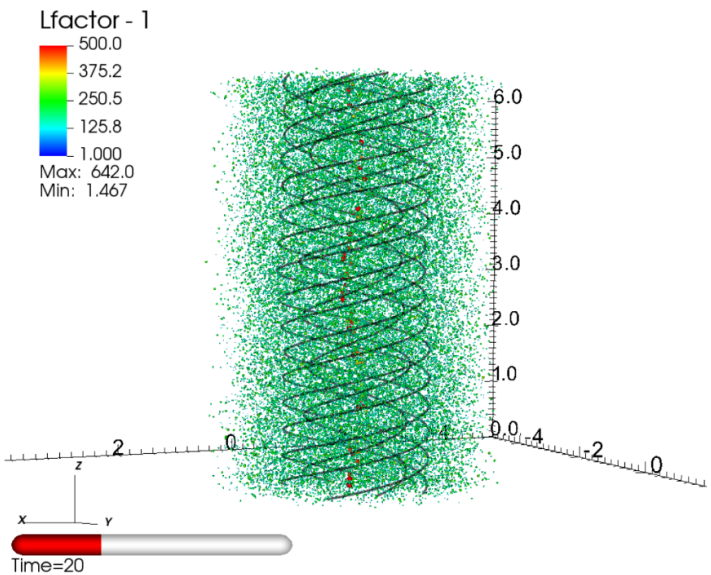

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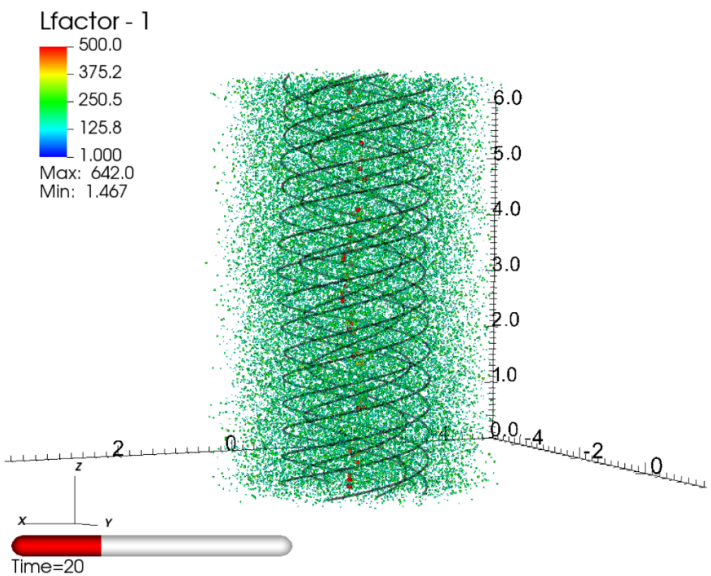

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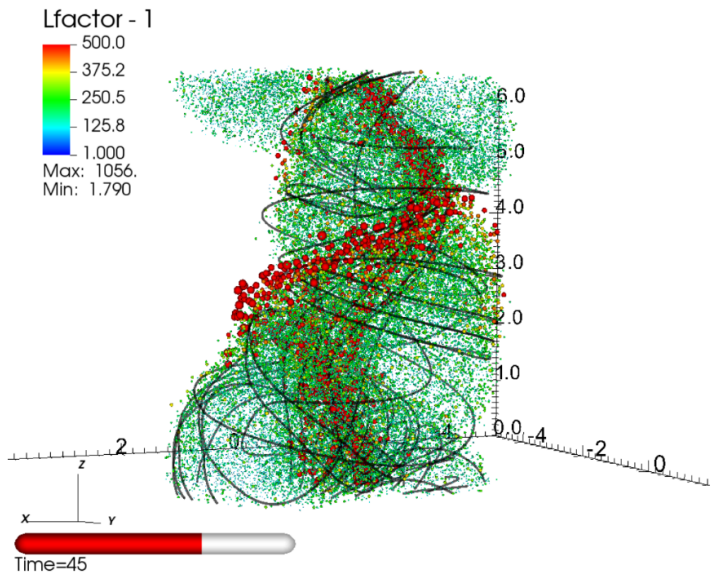

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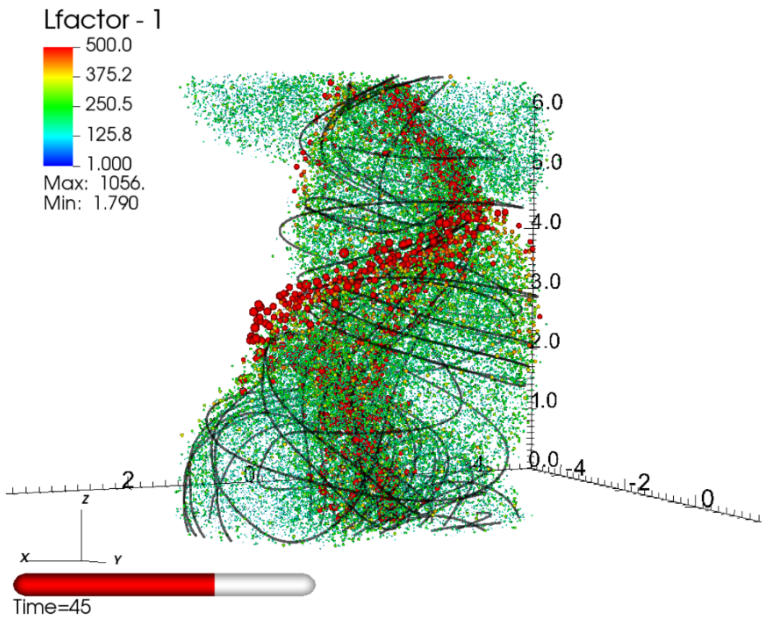

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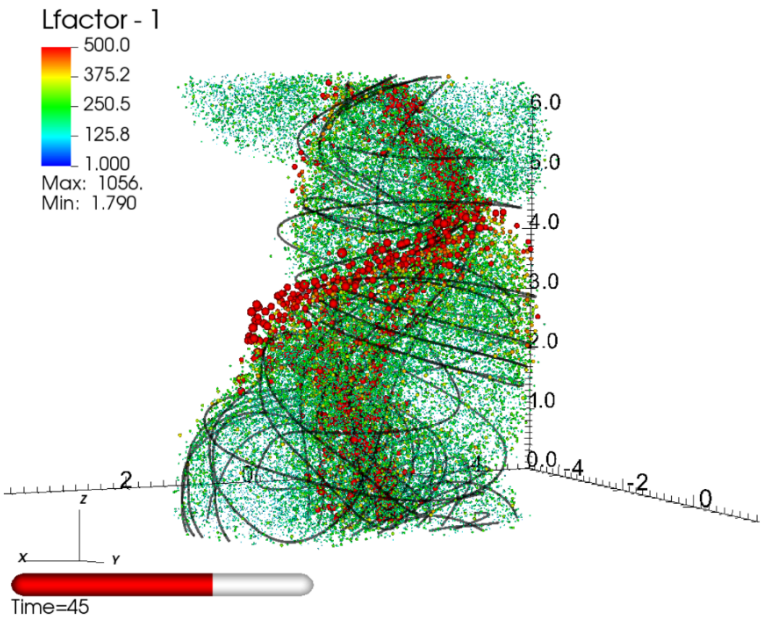

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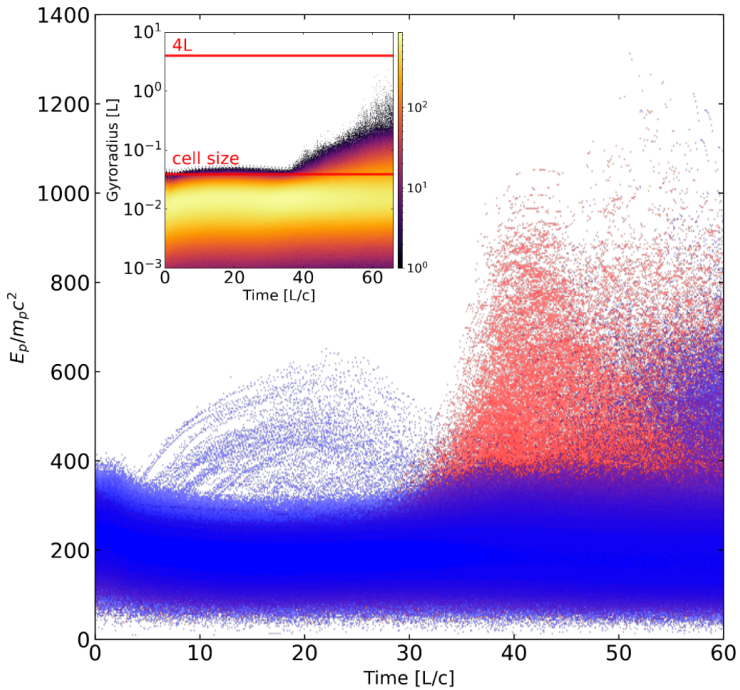

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- In short: particles accelerated by magnetic reconnection as the instability is fully developed.

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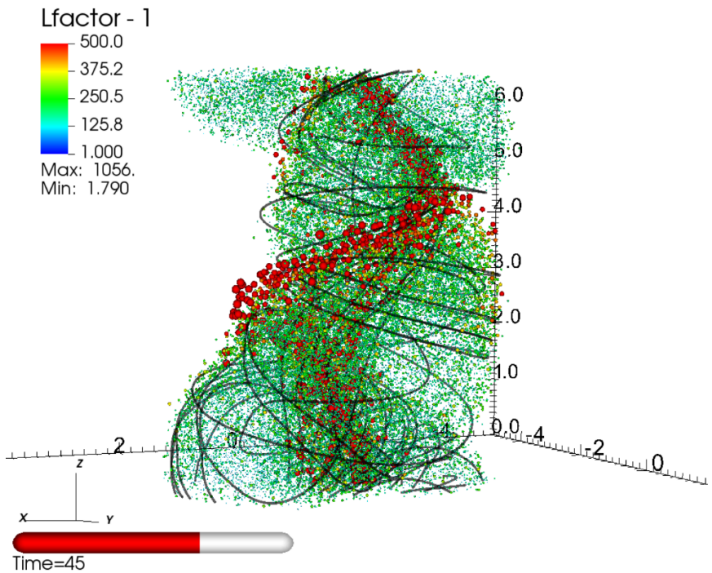

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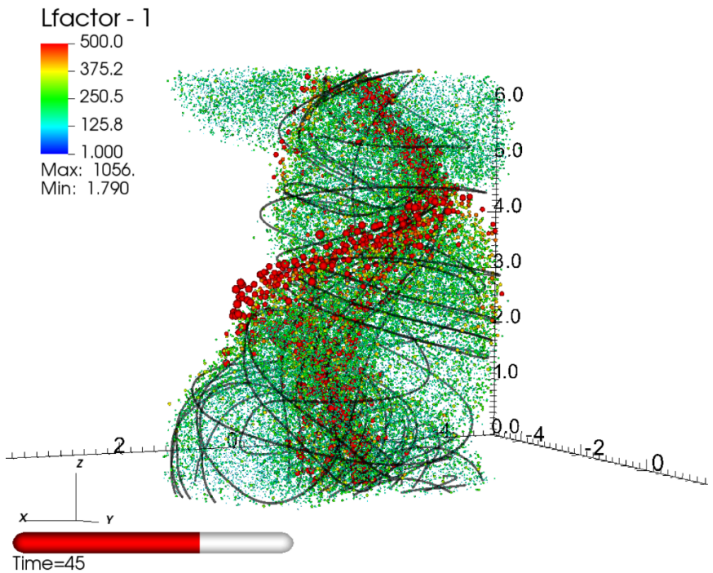

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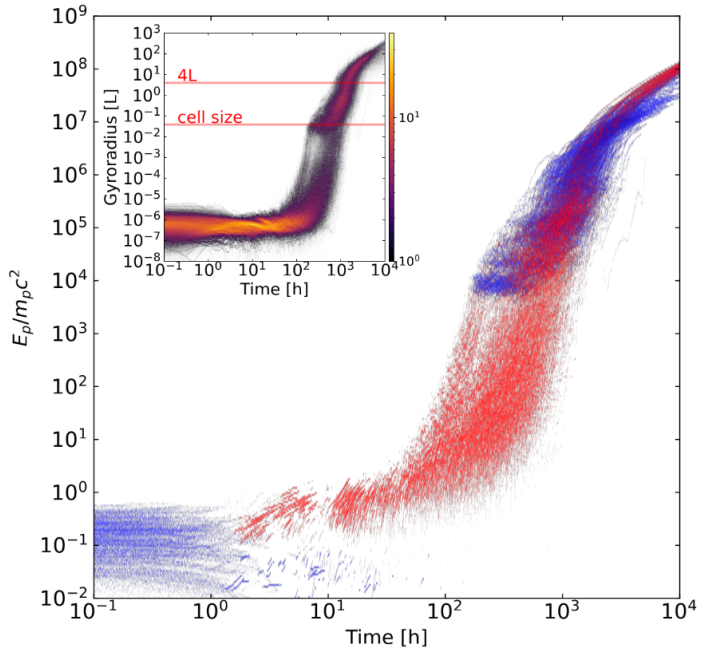

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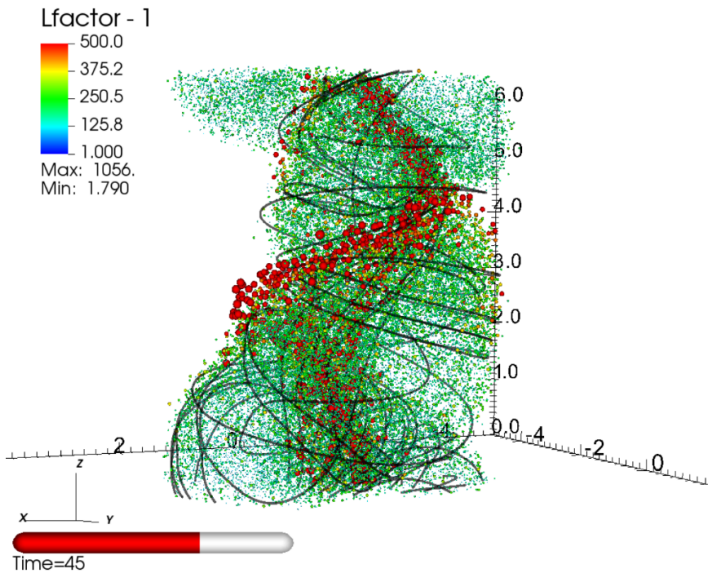

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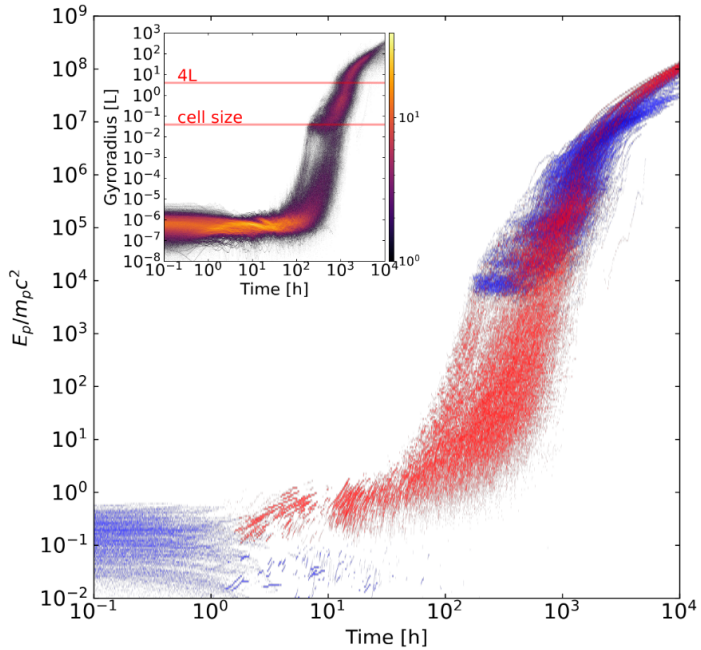

[Medina-Torrejón et al., 2023]

- In short: particles experience Fermi-like acceleration and reach a saturation energy.

Not included in the previous simulations

- How important is feedback in the particle-plasma interaction?

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Computing particle feedback with PLUTO: Post-processing

[Bai et al., 2015]:

$$\mathbf{F}_{CR} = \left(q_{CR}\mathbf{E}_0 + \frac{1}{c}\mathbf{J}_{CR} \times \mathbf{B} \right) \tag{8}$$

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$$W_{i\pm1} = \frac{1}{2}\left(\frac{1}{2} \pm \delta\right)^2; \qquad W_i = \frac{3}{4} - \delta^2, \tag{11}$$

with $\delta = (x_p - x_i)/\Delta x$ being the distance between the particle and the i-esimal zone, and $\delta \in [-1/2, 1/2]$.

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Strategy:

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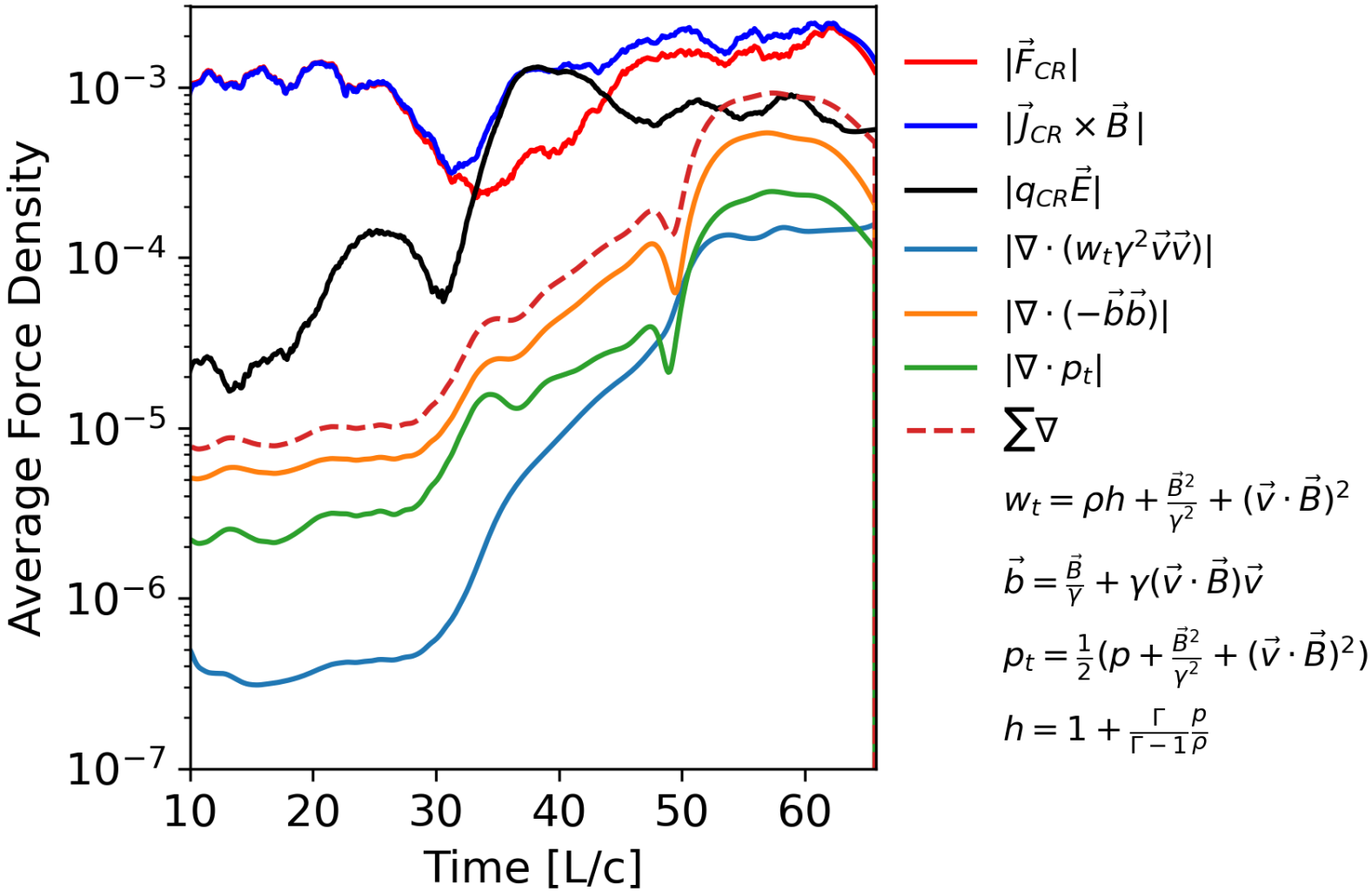
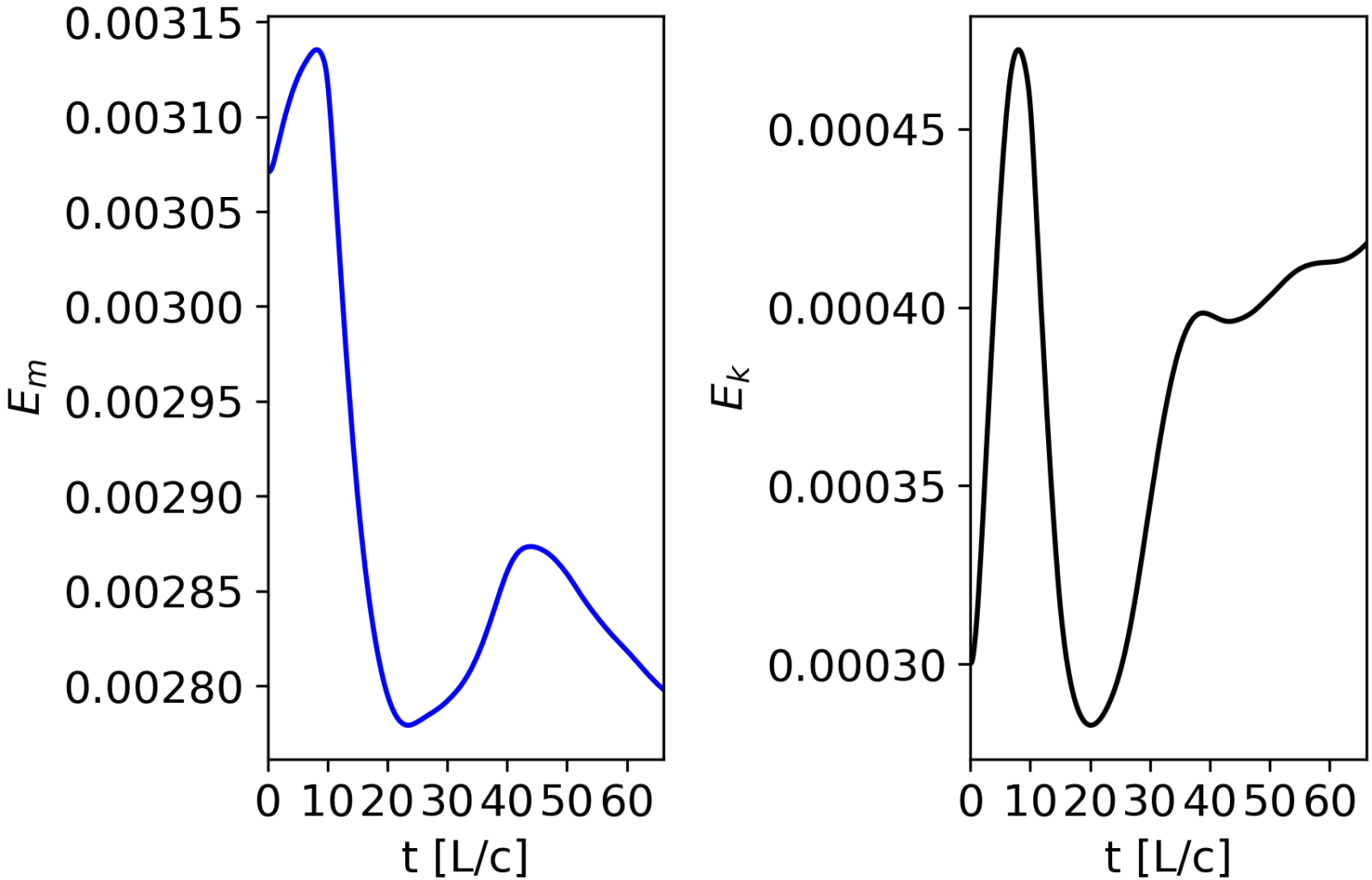
- Compute the Forces and work performed by the plasma:

$$\frac{\partial}{\partial t}\mathbf{m} + \nabla \cdot \left(w_t \gamma^2 \mathbf{vv} - \mathbf{bb} + \mathbf{I}p_t\right) = \mathbf{F}_{CR}, \tag{13}$$

$$\text{Work} = -\langle \mathbf{v}_{CR} \cdot \mathbf{F}_{CR} \rangle. \tag{14}$$



A. Carvalho et al. (in prep.)



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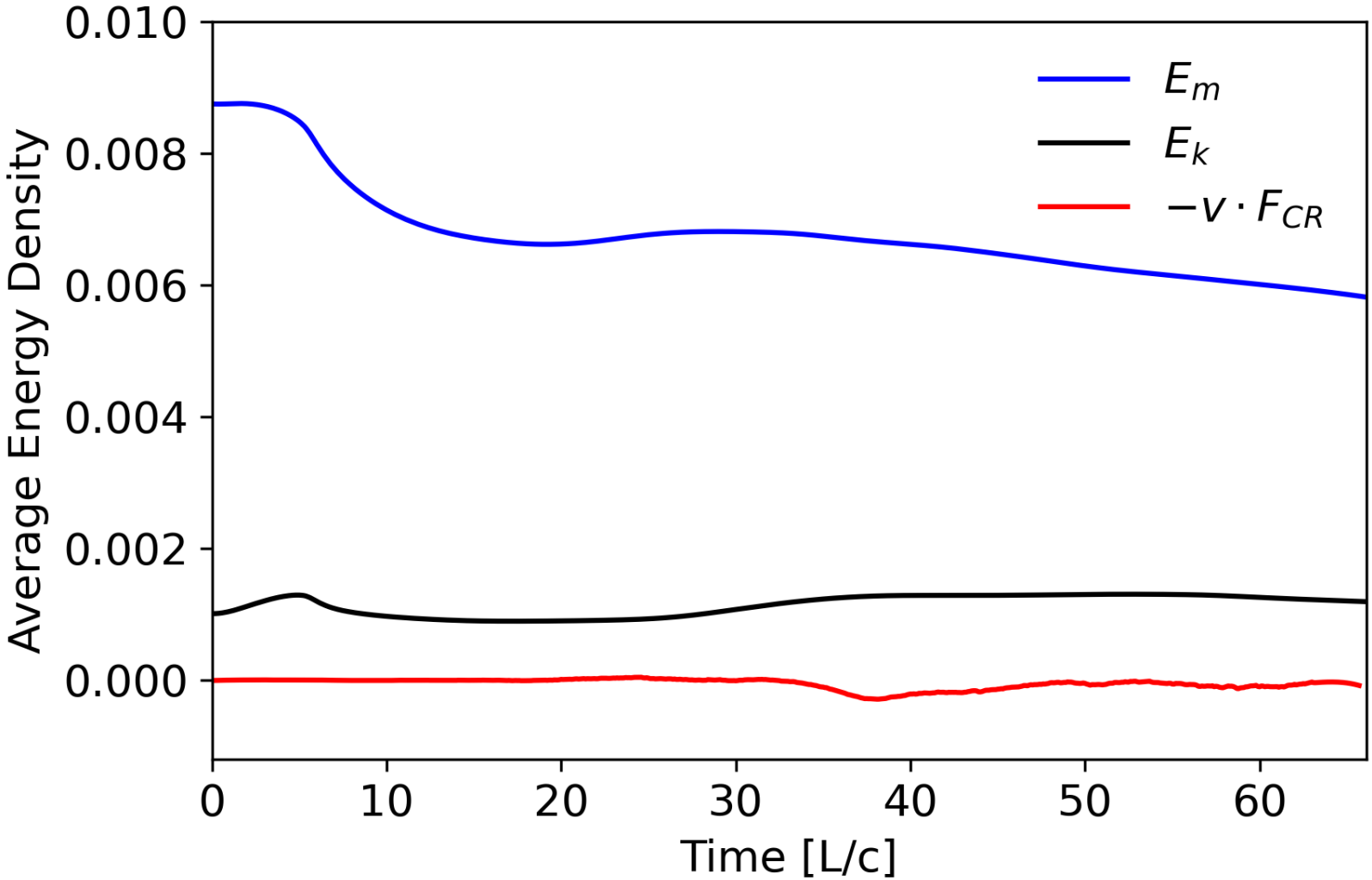

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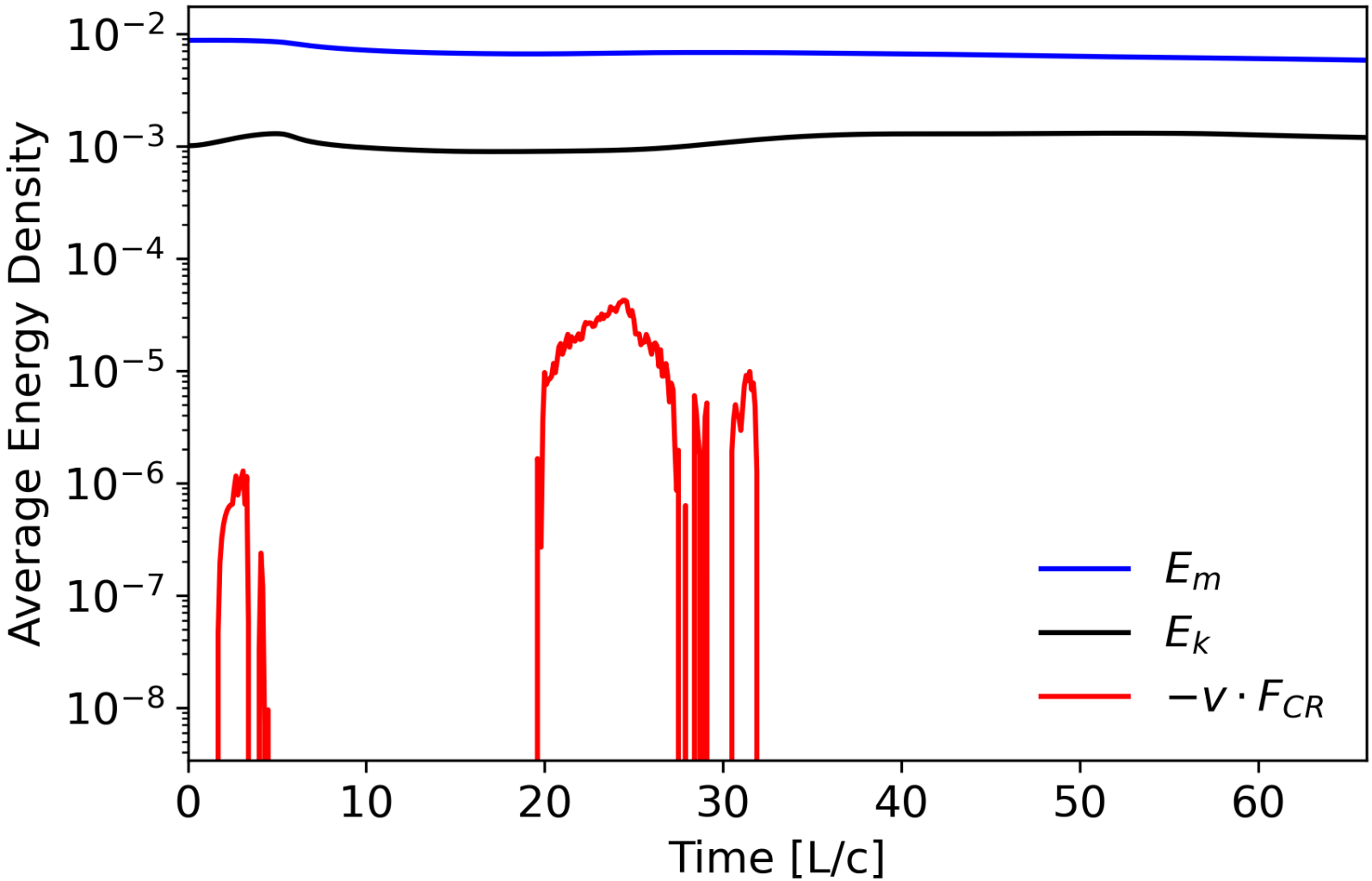

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