Particle Acceleration by Magnetic Reconnection & production of gamma-rays in Relativistic Jets and Accretion disks

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Collaborators:
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T. Medina-Torrejon
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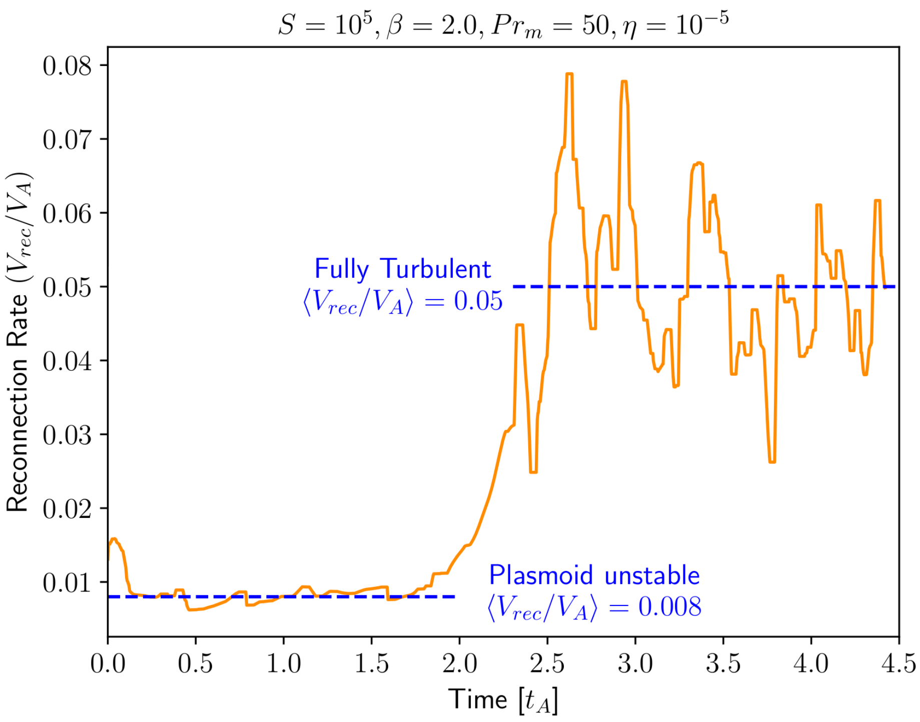
J. Stone, G. Vicentin

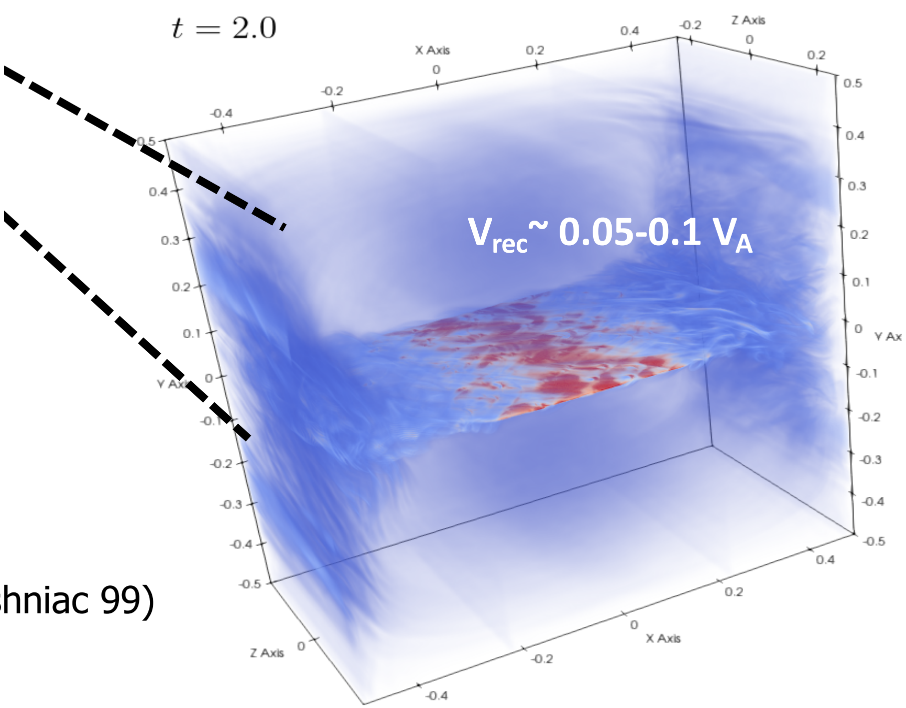
Gamma-Ray 2024 Workshop, Milan, September 3rd, 2024

Turbulence drives Fast Reconnection in 3D MHD flows

(See poster G. Vicentin et al.)



Dominance of turbulence over tearing (plasmoid) reconnection



$$V_{\rm rec} = V_{\rm A} \left(\frac{l}{L}\right)^{1/2} \left(\frac{v_l}{V_{\rm A}}\right)^2$$

(Lazarian-Vishniac 99)

(Vicentin, Kowal, de Gouveia Dal Pino & Lazarian, ApJ 2024)

Two Parallel Worlds: Kinetic and MHD Reconnection Acceleration

Kinetic (PIC)

- Probes kinetic scales ~ 100-1000 c/ω_p (microscopic: 10^{-10} – 10^{-17} orders smaller than real systems)
- Fast reconnection driven by tearing mode instability (plasmoids): **2D**
- Particle acceleration up to ~**1000 mc^2**
- Dominant electric field: resistivive η**J**
- **3D: Fermi acceleration and/or drift? no consensus**
- **3D:** Power law spectrum due to **drift acceleration ?**

(e.g. Comisso & Sironi 2019; Zhang et al 2021, 2023; Sironi 2022; Chernoglazov et al 2023; Gou et al. 2019; 2023)

Solves injection energy problem: initial acceleration of CRs -> caution needed to extrapolate to large scales

MHD

- Probes macroscopic astrophysical scales
- Fast reconnection driven by turbulence (**3D**) (**K-H; MRI, Kink CDKI, tearing, etc)**
- Particle acceleration up to ~**10^{10} mc^2**
- Dominant electric field: non-resistive –**vxB**
- **Fermi acceleration** dominates until Larmor radius > thickness of largest reconnection layers ~ injection scale of turbulence
- **drift acceleration beyond that**
- Power law spectrum determined by **Fermi and drift acceleration**

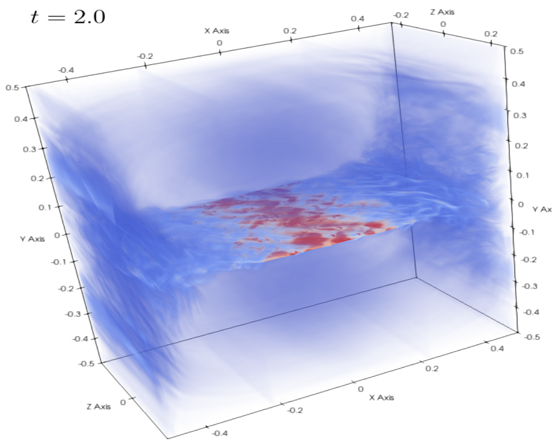
(Kowal, deGDP & Lazarian 2011; 2012; de Gouveia Dal Pino & Kowal 2015; del Valle et al. 2016; Kadowaki et al 2021; Medina-Torrejon et al 2021, 2023)

Solves saturation energy of CRs: final acceleration

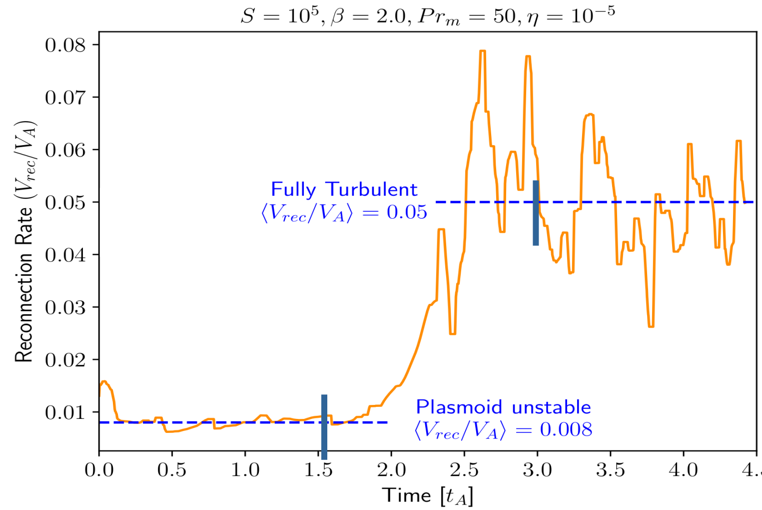
High Resolution Reconnection Acceleration in 3D Resistive MHD Current Sheets with test particles

$S = 10^5$, $\eta = 10^{-5}$

Vicentin, Kowal, de Gouveia Dal Pino & Lazarian, ApJ 2024



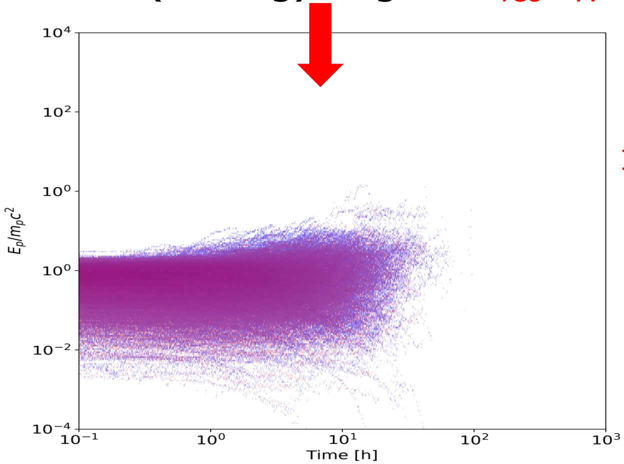
$\Delta x = \Delta y = \Delta z = 1/1024$



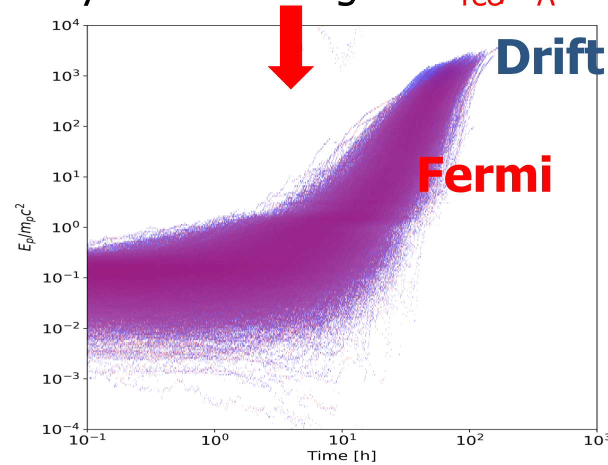
Plasmoid (tearing) regime $v_{rec}/v_A \sim 0.01$

Fully turbulent regime $v_{rec}/v_A \sim 0.07$

$t_{plasma}=1.5$



10,000 test particles

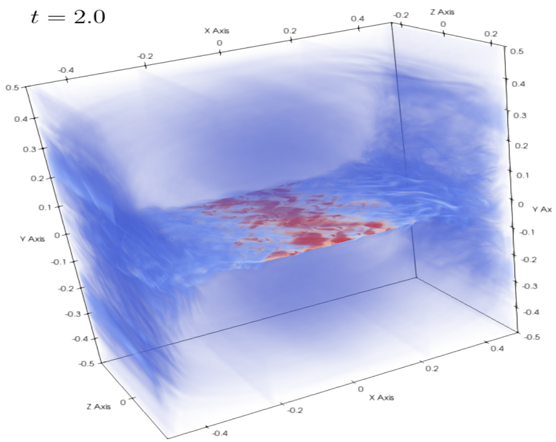


$t_{plasma}=2.8$

High Resolution Reconnection Acceleration in 3D Resistive MHD Current Sheets with test particles

$S = 10^5, \ \eta = 10^{-5}$

Vicentin, Kowal, de Gouveia Dal Pino & Lazarian, ApJ 2024



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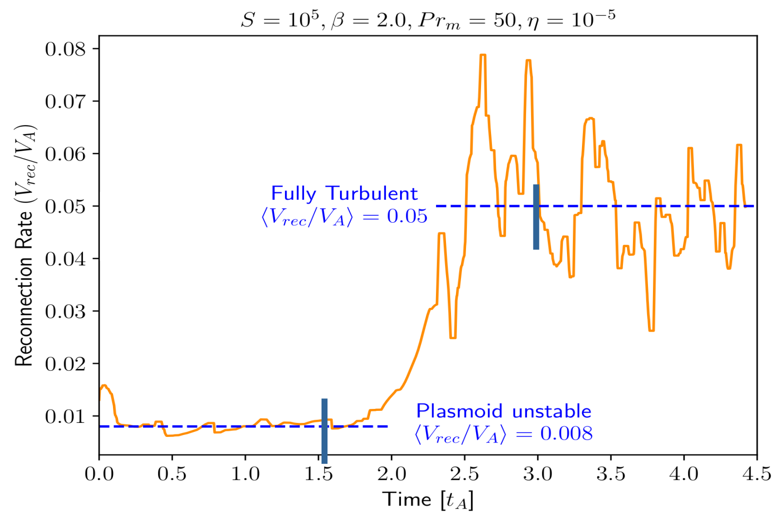

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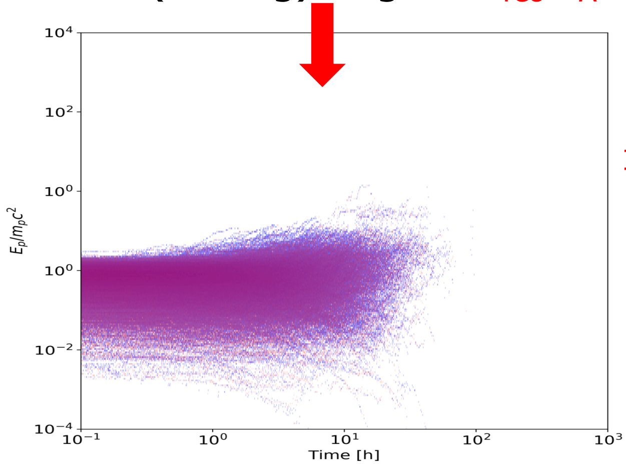
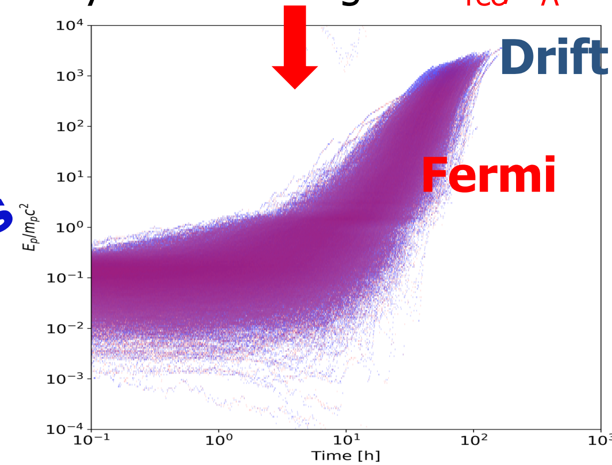


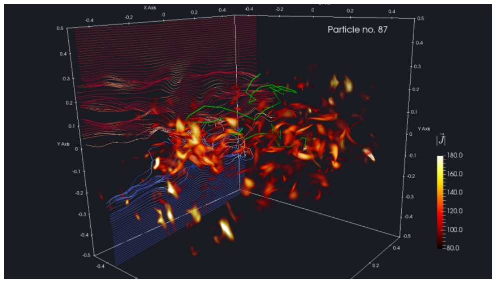
10,000 test particles

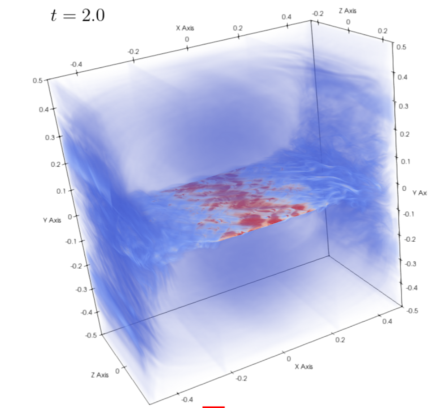
In progress

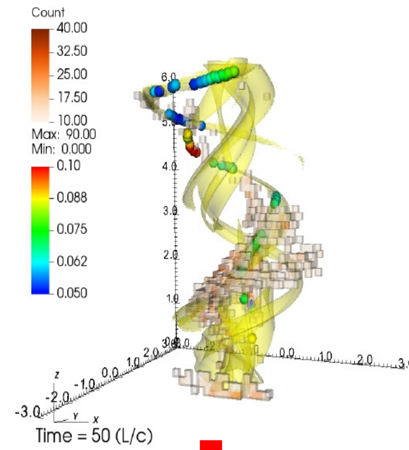


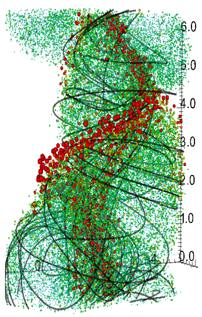
$t_{plasma} = 2.8$

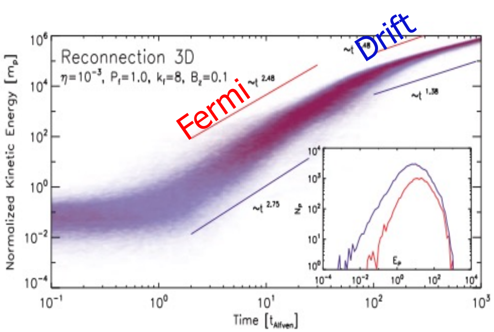
Agreement from MHD turbulent CS to turbulent jets

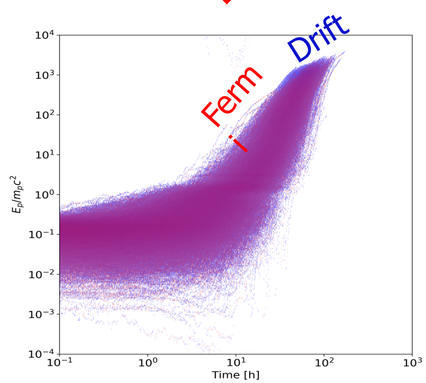


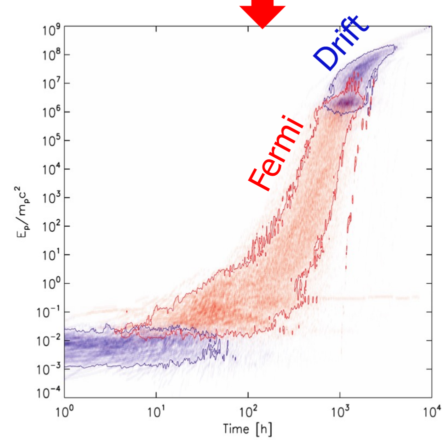


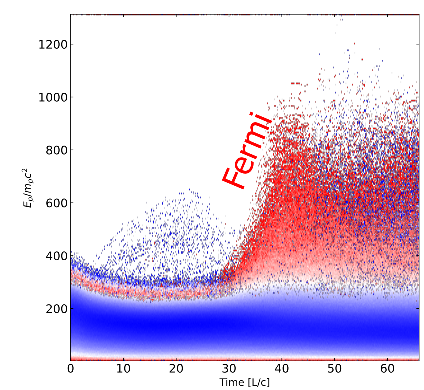












Kowal, dGDP, Lazarian, PRL 2012

Vicentin, dGDP, Kowal & Lazarian (in prep.)

Medina-Torrejon, dGDP+ ApJ 2021

Medina-Torrejon, dGDP, Kowal ApJ 2023

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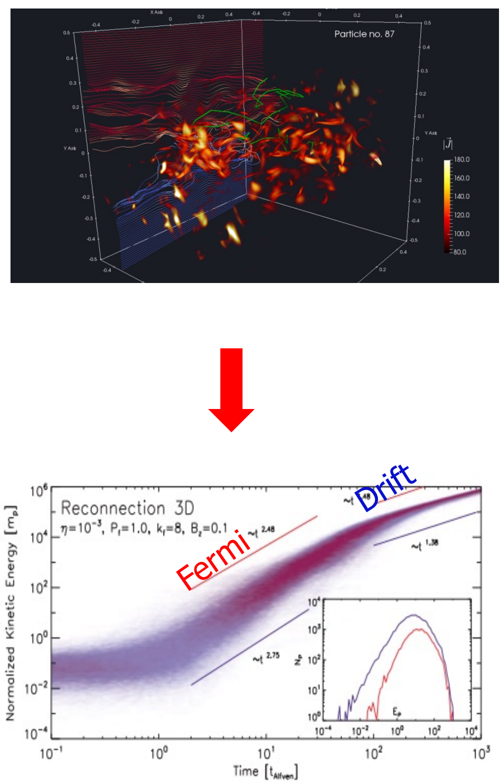

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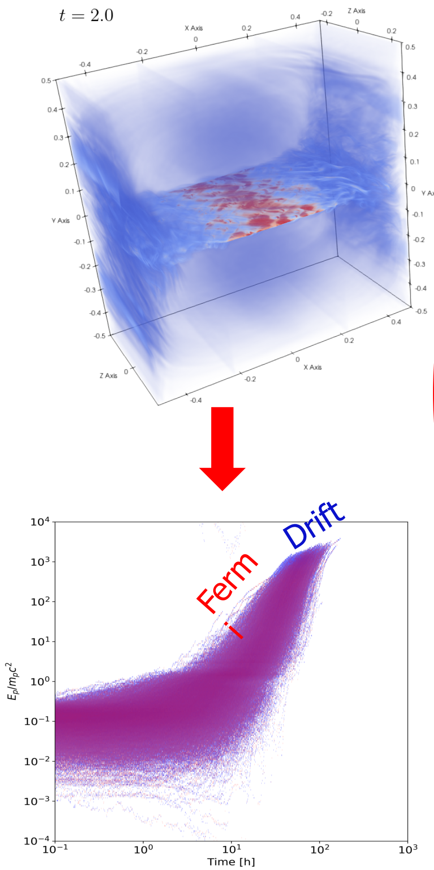

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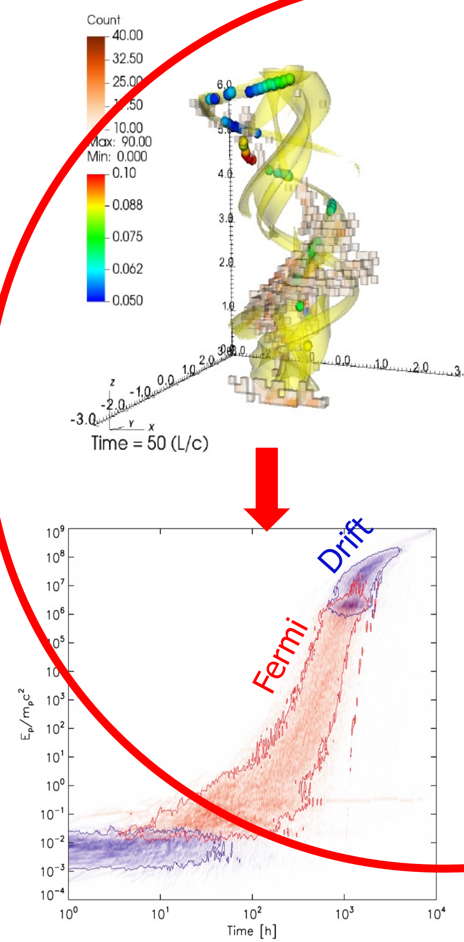
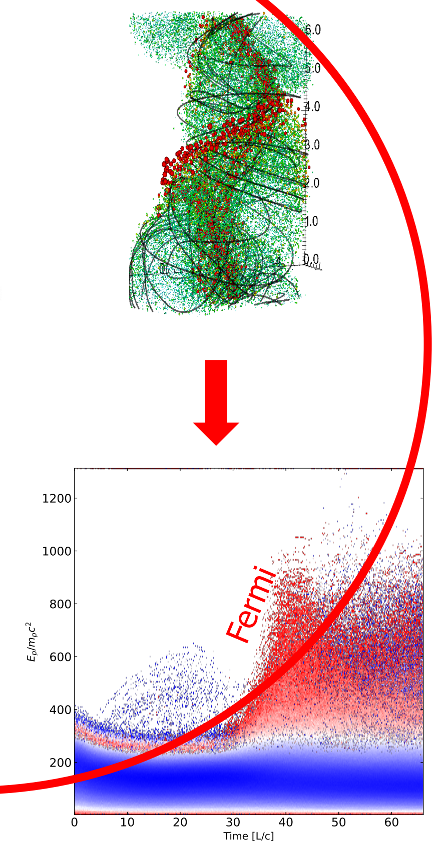
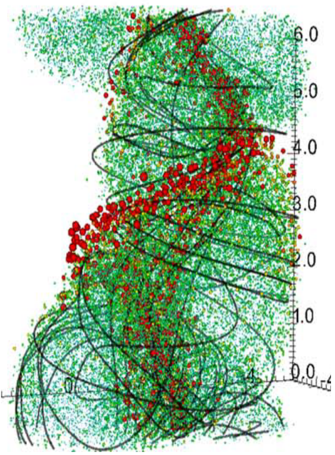


Medina-Torrejon, dGDP+ ApJ 2021



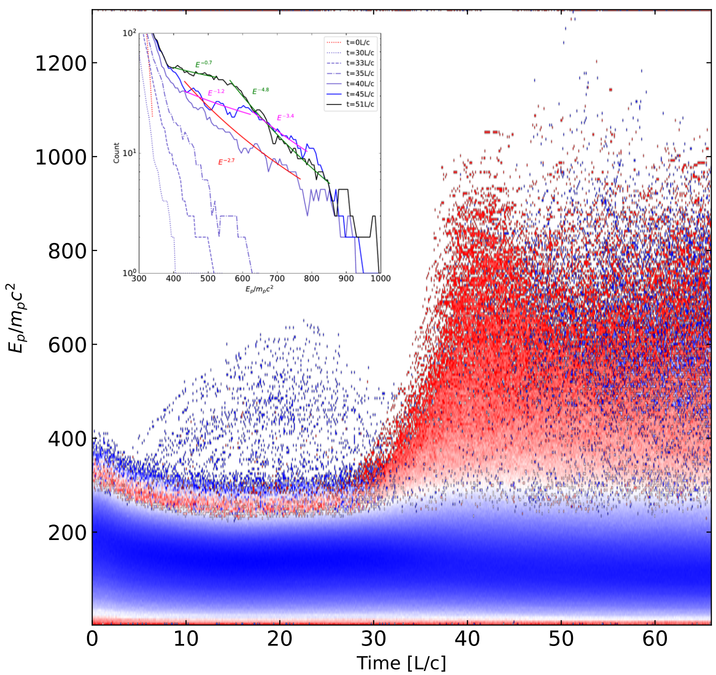
Medina-Torrejon, dGDP, Kowal ApJ 2023

Magnetic Reconnection Particle Acceleration from 3D-MHD Simulations of Relativistic Jets



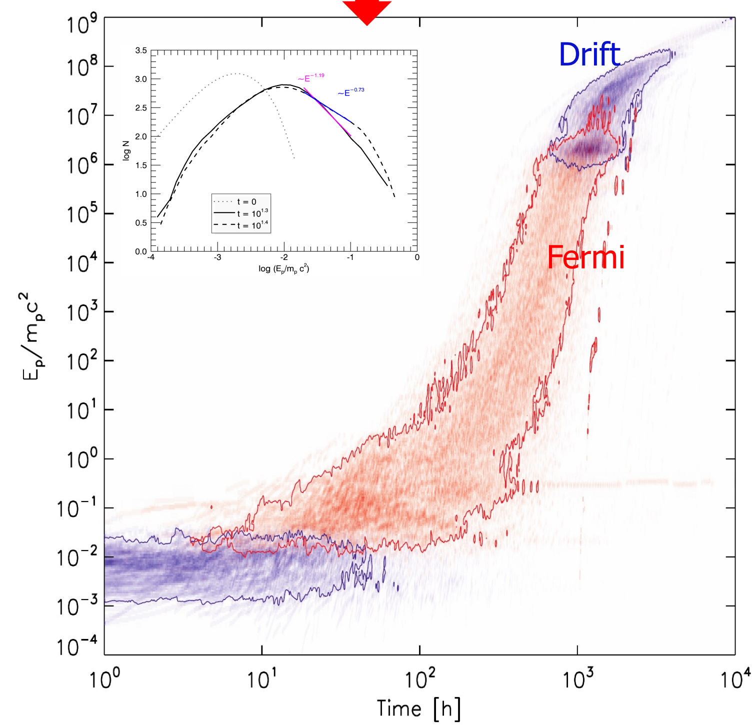
t= 60 L/c ~ 1 hr
L= 5 10^{-7} pc

RMHD-PIC



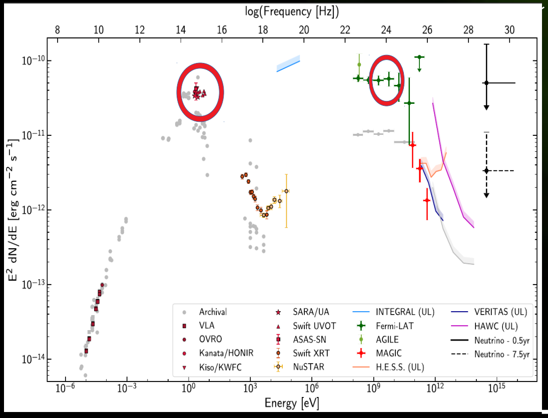
Medina-Torrejon, de Gouveia Dal Pino, Kowal, ApJ 2023

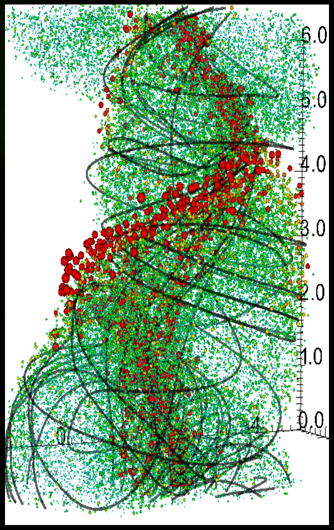
RMHD+test particles



Medina-Torrejon, dGDP+ ApJ 2022

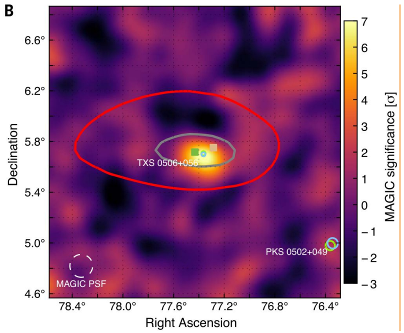
Applications to Blazar VHE Phenomena



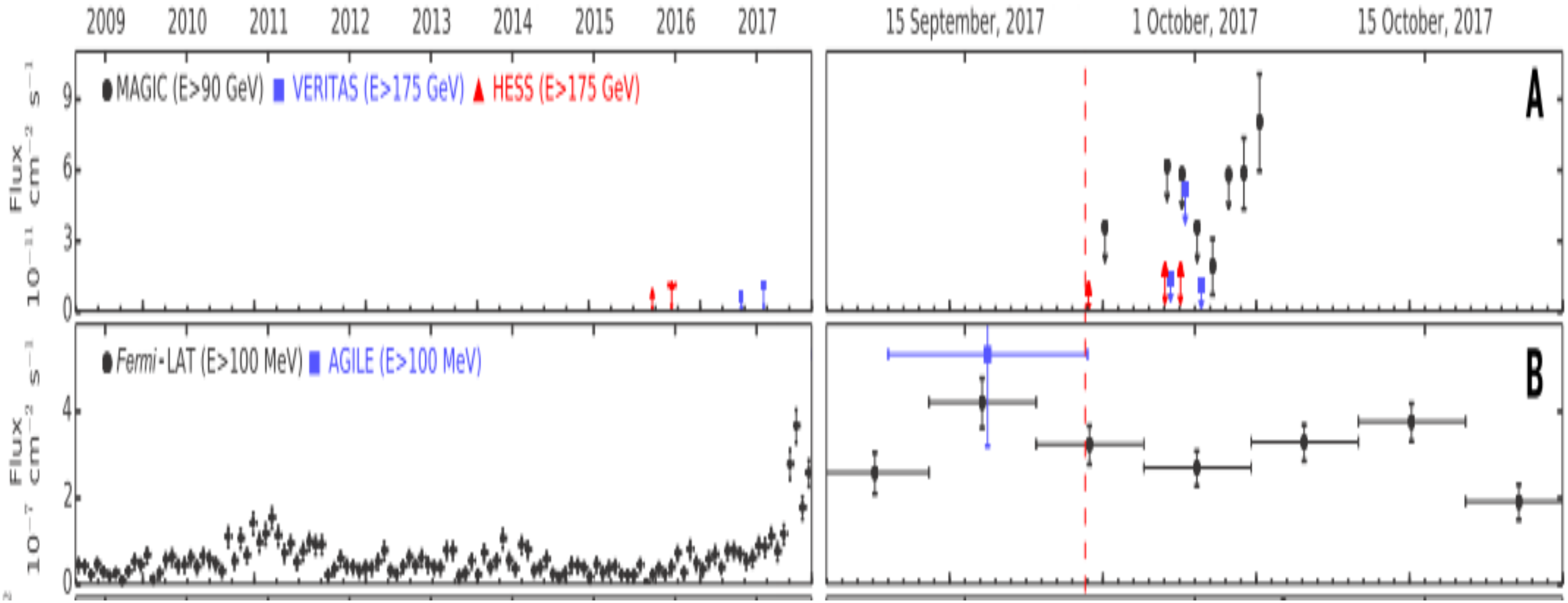


Lepto-Hadronic Model based on Reconnection Acceleration for TXS 0506+056

Blazar TXS 0506+056



(Aartsen et al. Science 2018)



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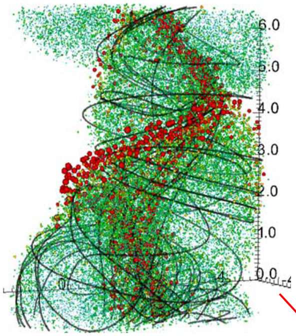

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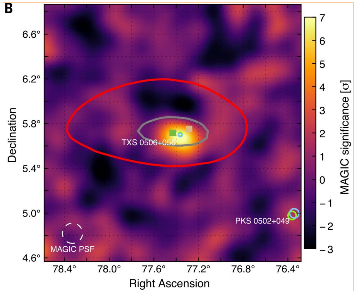

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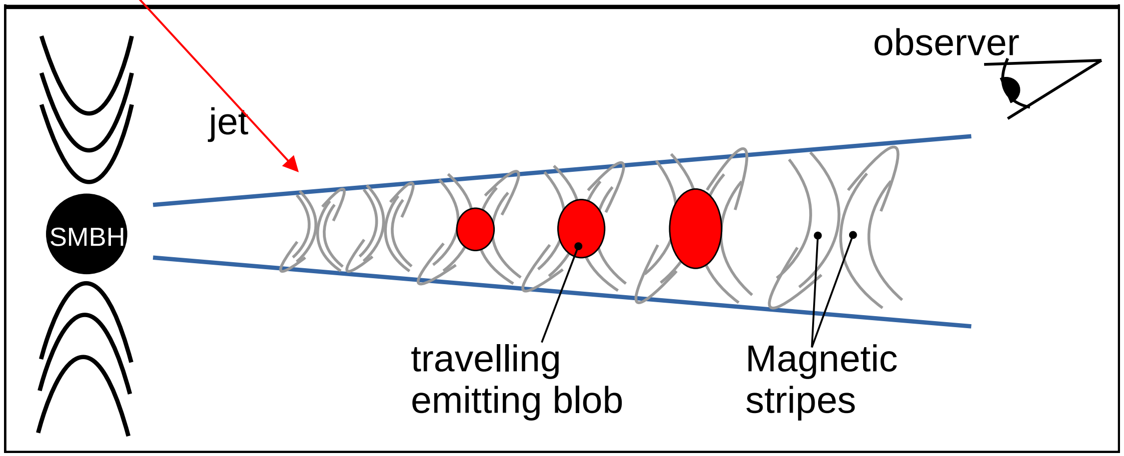
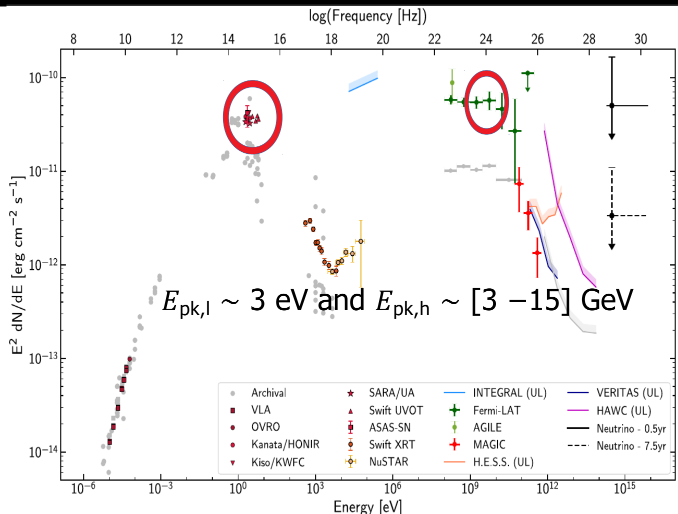


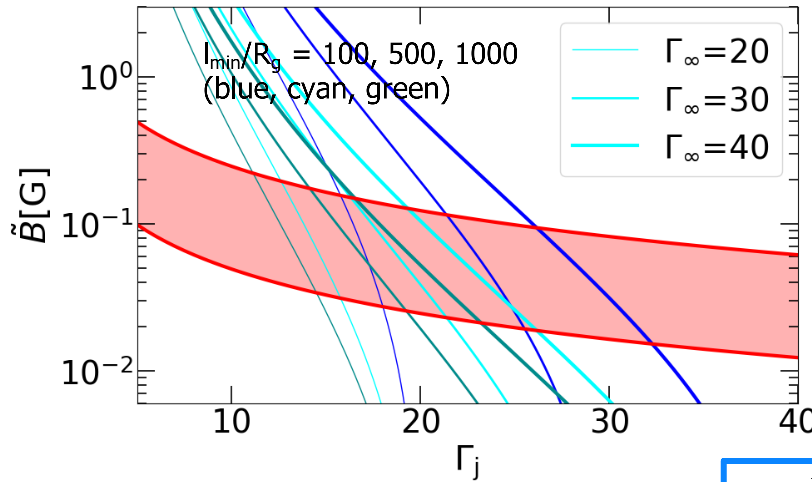
- ✓ Jet at the transition from magnetically dominated to kinetically dominated: **particle acceleration controlled by reconnection**
- ✓ Jet background described by **striped reconnection** model (Giannios & Uzdenzky 2019)
- ✓ Photon Field: due to internal dissipation -> Synchrotron photons

de Gouveia Dal Pino, Rodriguez-Ramirez+ (2024, in prep.)

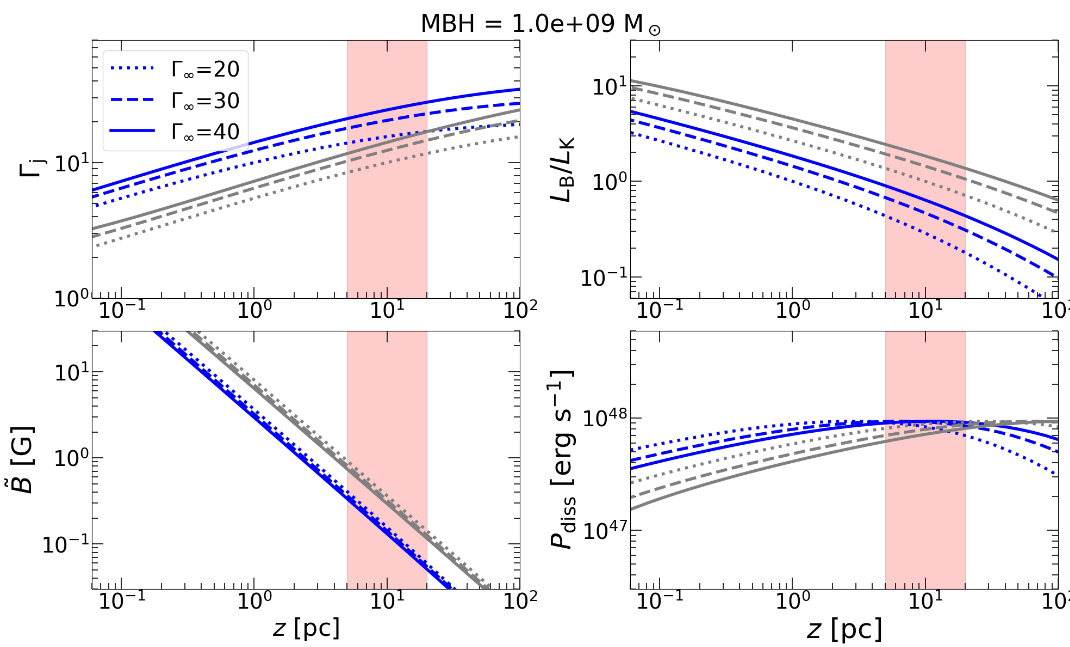
Lepto-Hadronic Model based on Reconnection Acceleration for TXS 0506+056



Blazar TXS 0506+056 (Aartsen et al. 2018, Science)



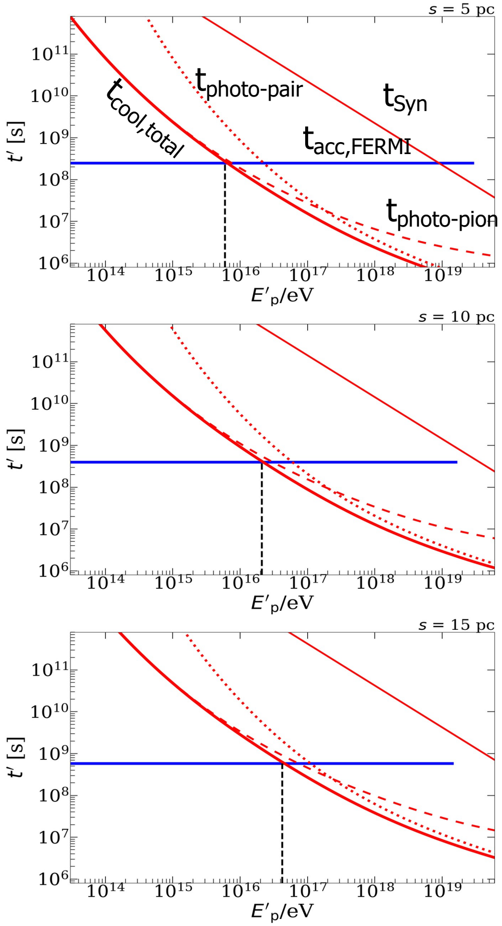
$$B' = \frac{E^2_{\mathrm{pk},\ell}}{E_{\mathrm{pk,h}}} \frac{m_e c}{e\hbar} \frac{(1+z)}{\Gamma_j}$$

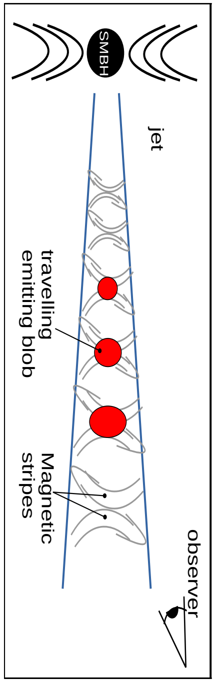


Jet properties from reconnection stripe model

Pink band: constrained by B-Γ_j space

Lepto-Hadronic Model based on Reconnection Acceleration for TXS 0506+056





Fermi reconnection acceleration:

$$t_{acc} \sim \frac{4\Delta}{c d_{ur}} \qquad d_{ur} \approx \frac{2\beta_{rec}(3\beta_{rec}^2 + 3\beta_{rec} + 1)}{3(\beta_{rec} + 0.5)(1 - \beta_{rec}^2)}$$

$\Delta t = 0.44$ yr.

Xu & Lazarian 2023;
de Gouveia Dal Pinno & Medina-Torrejon 2024

de Gouveia Dal Pino, Rodriguez-Ramirez+ 2024 (in prep.)

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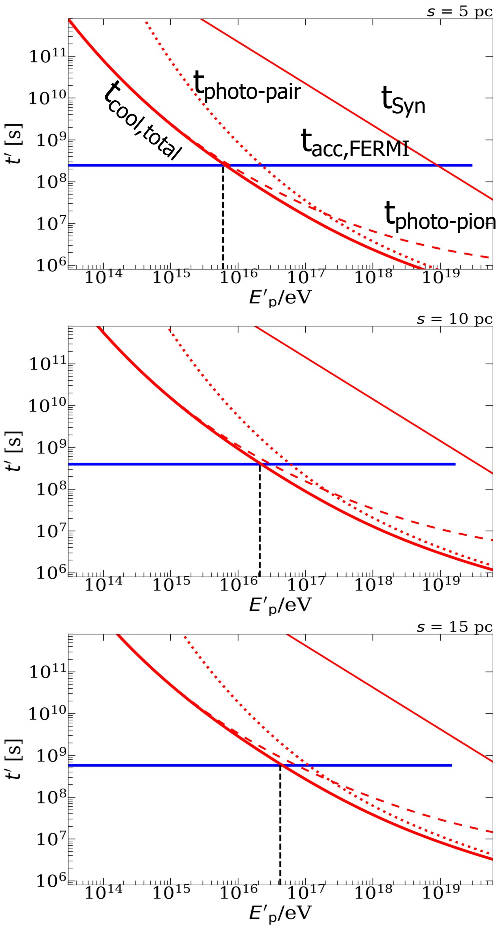

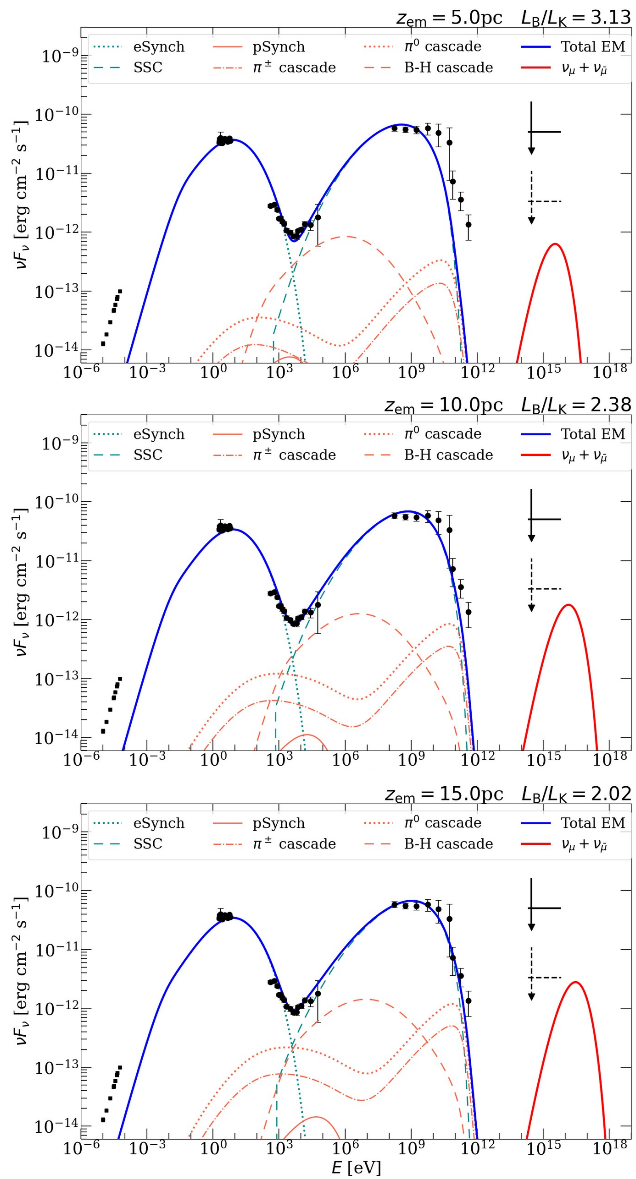

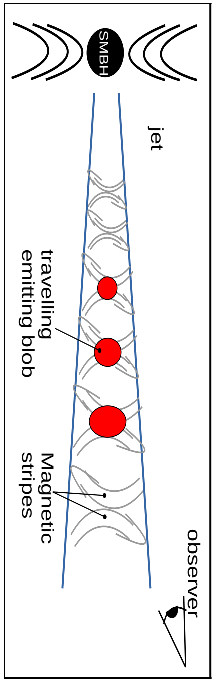

Model produces:

- neutrinos and VHE (photo-pion)
- observed time delay between VHE γ-rays appearing later than neutrino $\Delta t = 0.44$ yr.

de Gouveia Dal Pino, Rodriguez-Ramirez+ 2024 (in prep.)

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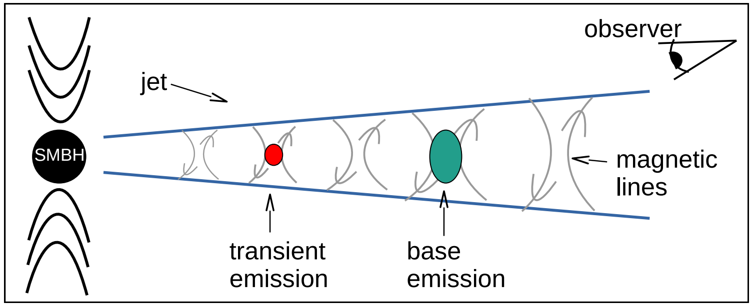
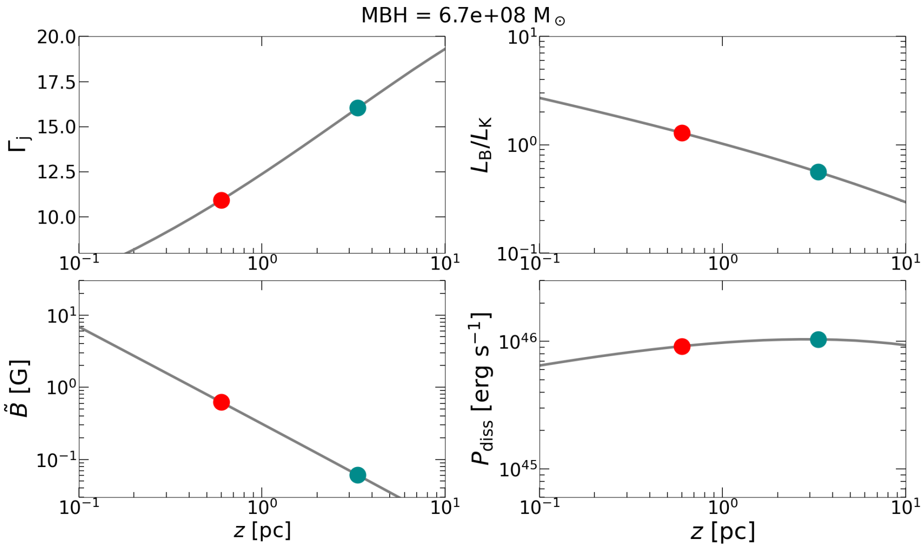
Xu & Lazarian 2023;
de Gouveia Dal Pinno & Medina-Torrejon 2024

TeV Spectral Spike of Mrk 501 explained by Reconnection Acceleration

Blazar Mrk 501: TeV spikes during X-ray high state (Magic Coll. 2020)



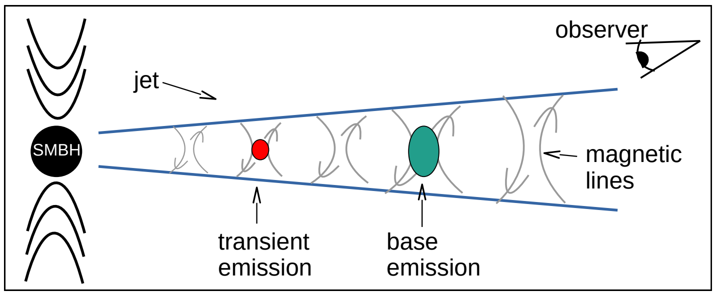


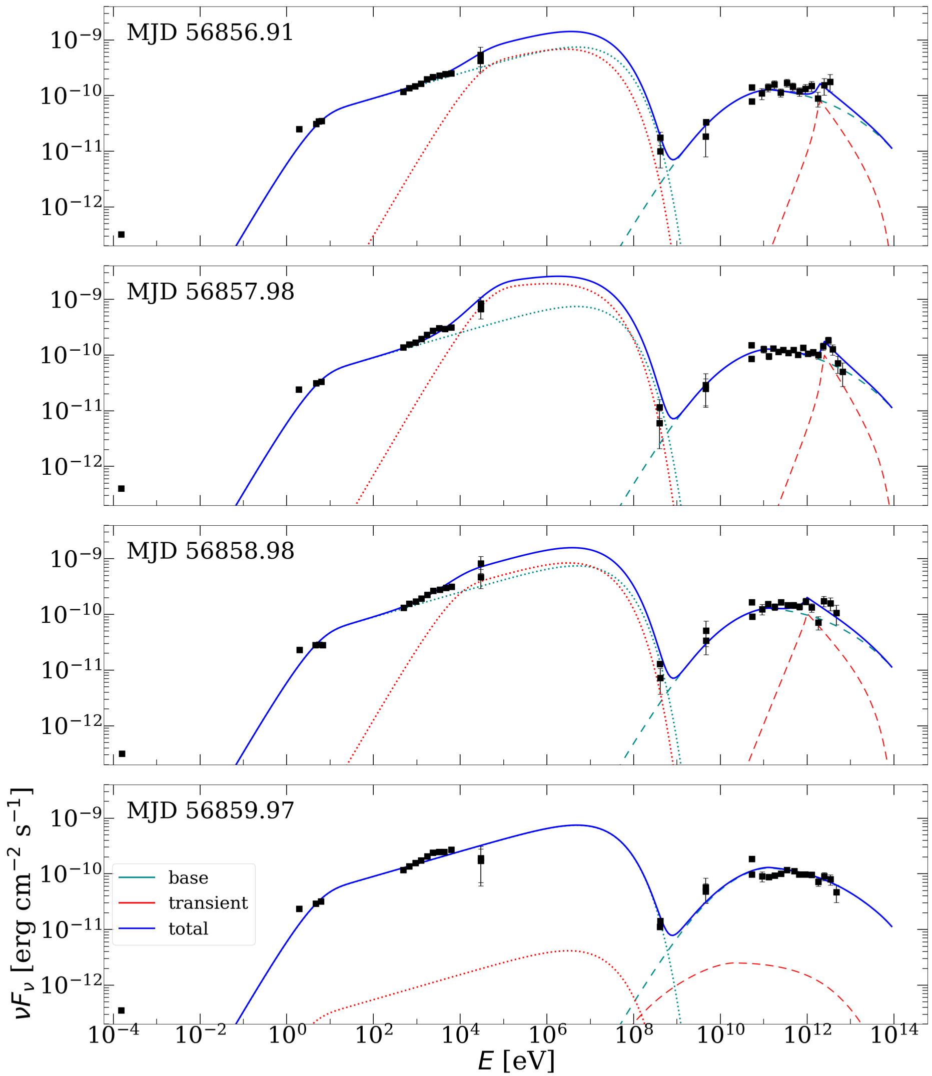
- ✓ Jet at the transition from magnetically dominated to kinetically dominated: **particle acceleration by reconnection**
- ✓ Same jet background model: **striped reconnection** (Giannios & Uzdenzky 2019)
- ✓ Two-zone model (electron Syn & SSC):
  - base quiescent emission
  - transient emission (inner magnetized region)

Rodriguez-Ramirez, Barres de Almeida, de Gouveia Dal Pino, Das-Cortes, Paiva (2024, in prep.)

TeV Spectral Spike of Mrk 501 explained by Reconnection Acceleration

Blazar Mrk 501

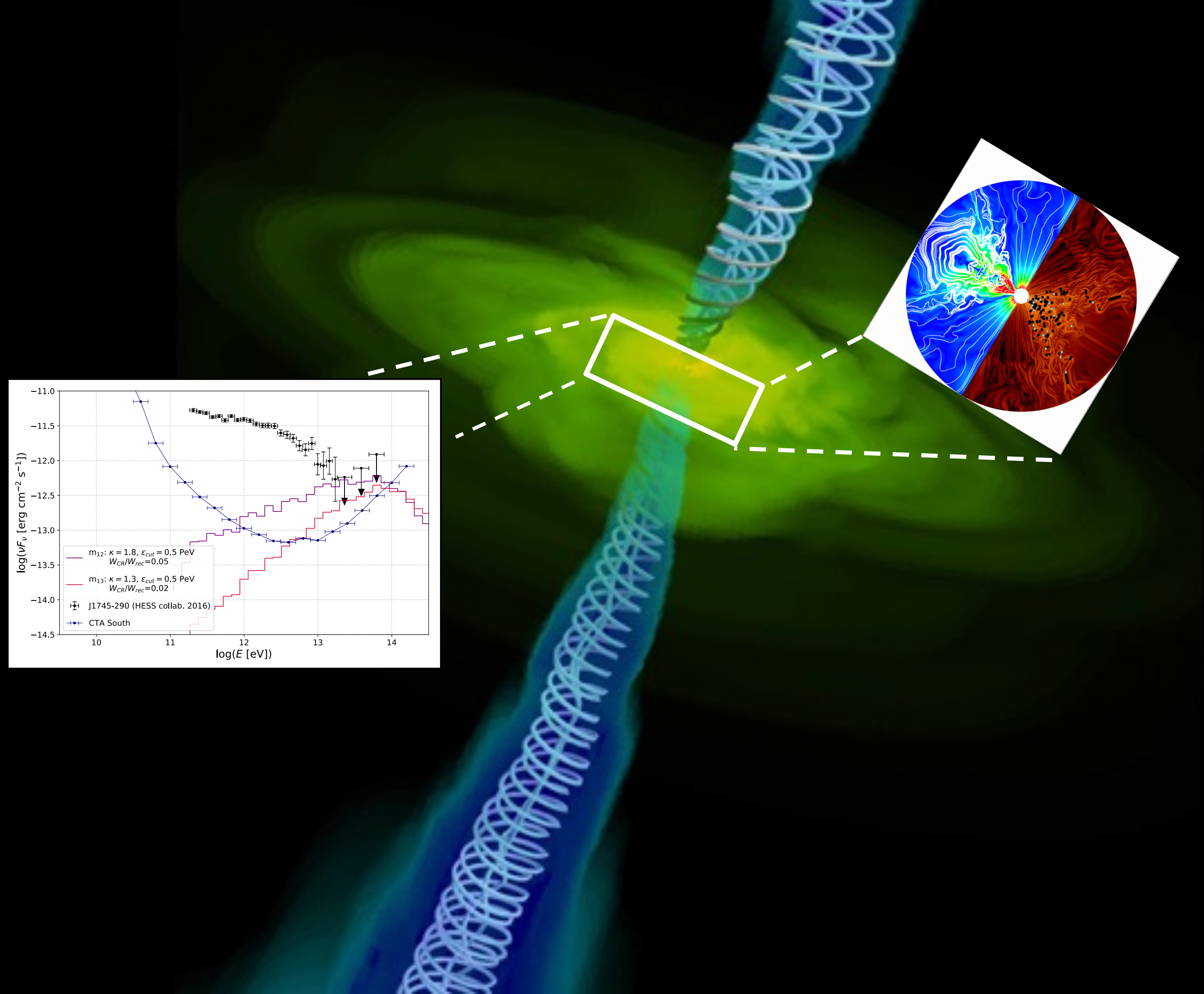




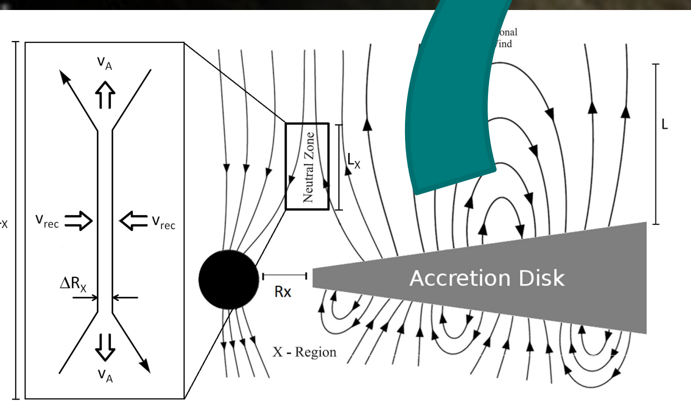
TeV spikes: explained by a leptonic transient emission in a compact zone, located in a more magnetized and slower flow compared to the region that produced quiescent SED component.

Rodriguez-Ramirez, Barres de Almeida, de Gouveia Dal Pino, Das-Cortes, Paiva (2024, in prep.)

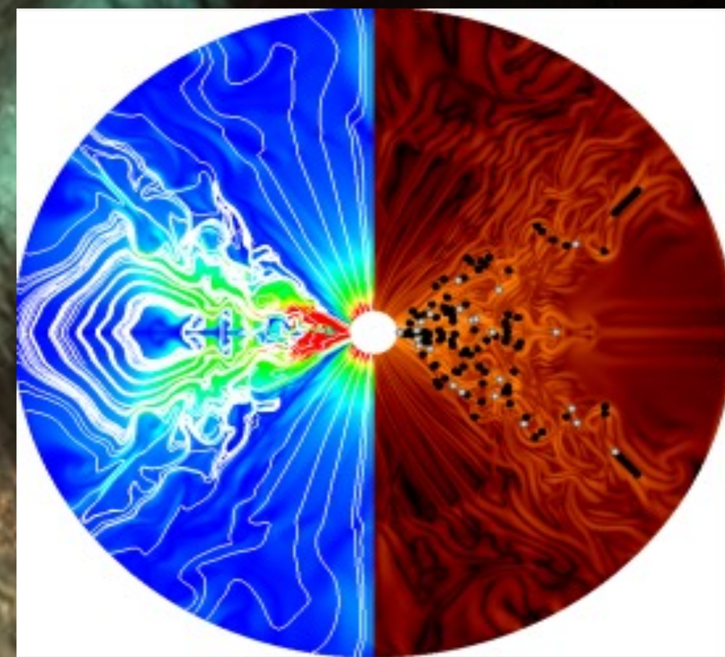
Applications to accretion disk VHE Phenomena



CR Reconnection Acceleration in the accretion flow of BHs



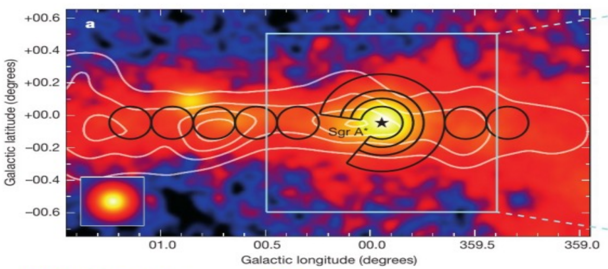
de Gouveia Dal Pino & Lazarian, A&A 2005
de Gouveia Dal Pino, Piovezan, Kadowaki A&A 2010
Kadowaki, de Gouveia Dal Pino & Singh, ApJ 2015
Singh, de Gouveia Dal Pino & Kadowaki, ApJ 2015



GRMHD simulations of accretion flows around BHs
reconnection driven by magneto-rotational turbulence

(de Gouveia Dal Pino et al. 2020; Kadowaki et al. 2018; Vincentin+ in pr.)

Galactic Center SgrA*: Reconnection acceleration driven by turbulent accretion flow



H.E.S.S. Nature 2016

GRMHD:

Axi-symmetric HARM code Gammie et al. (2003)

+

Radiative Transfer:

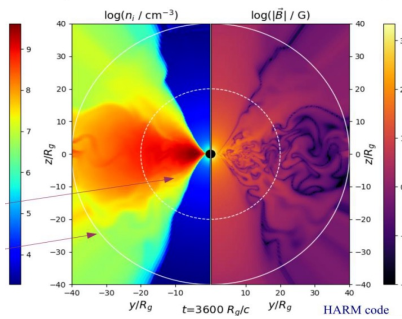
GRMONTY code Dolence et al. (2009)

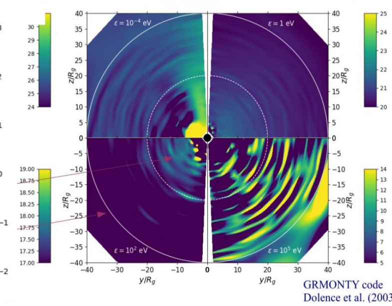
+

Propagation of CR Accelerated by Reconnection :

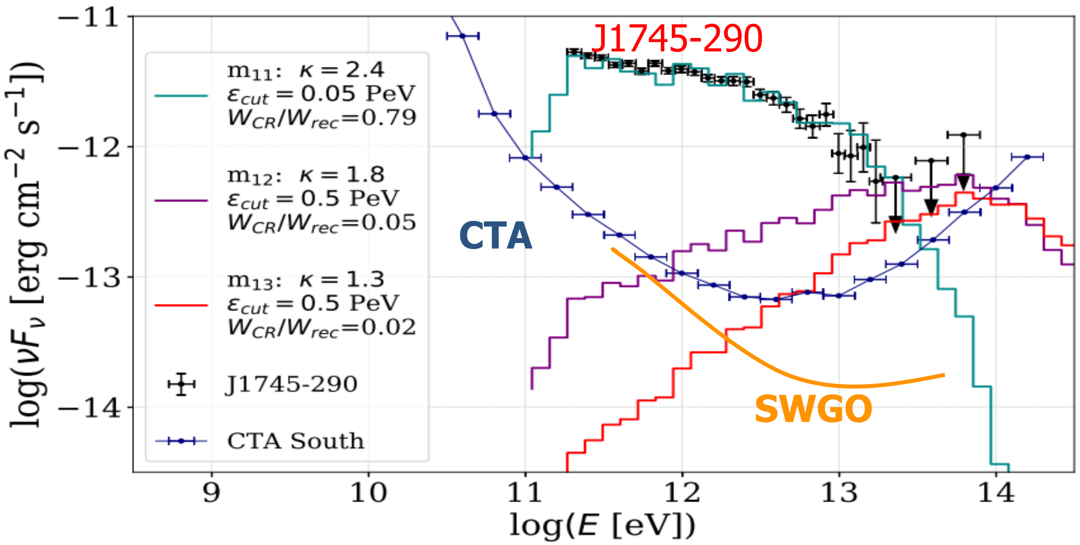
CRPropa3 code Alves Batista et al. (2016)

=





To probe hadronic Emission/absorp (TeVs)



Rodriguez-Ramirez, de Gouveia Dal Pino, Alves-Batista, ApJ 2019

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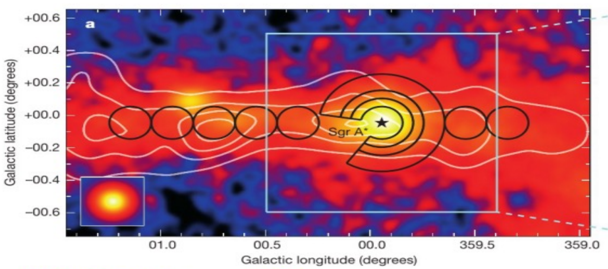

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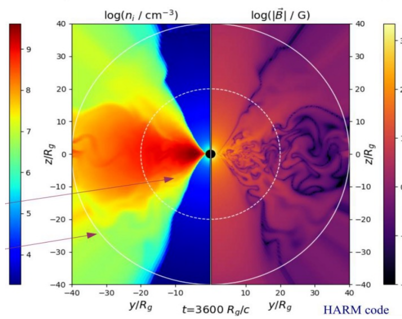
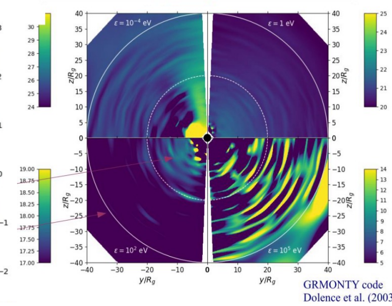
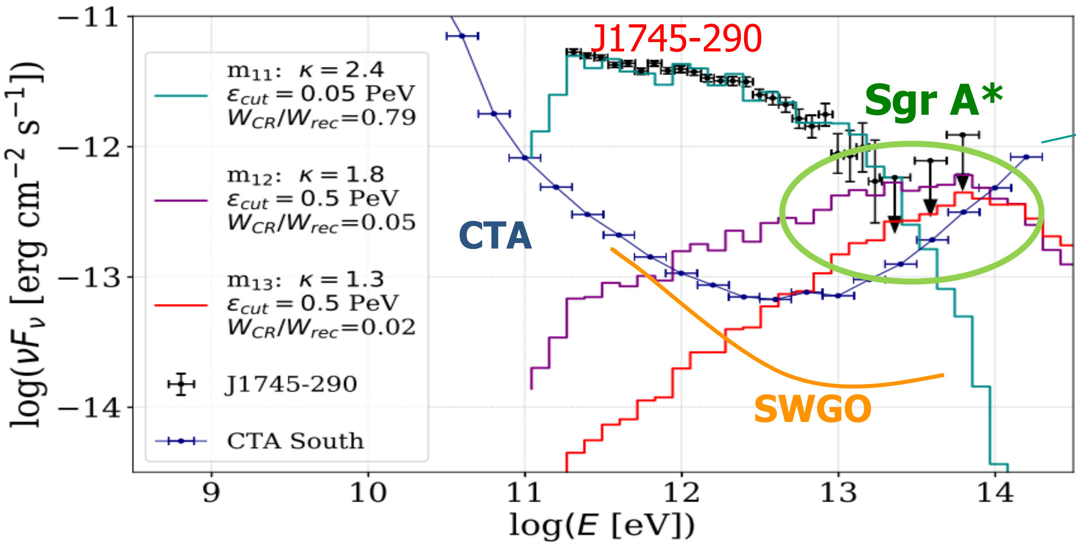




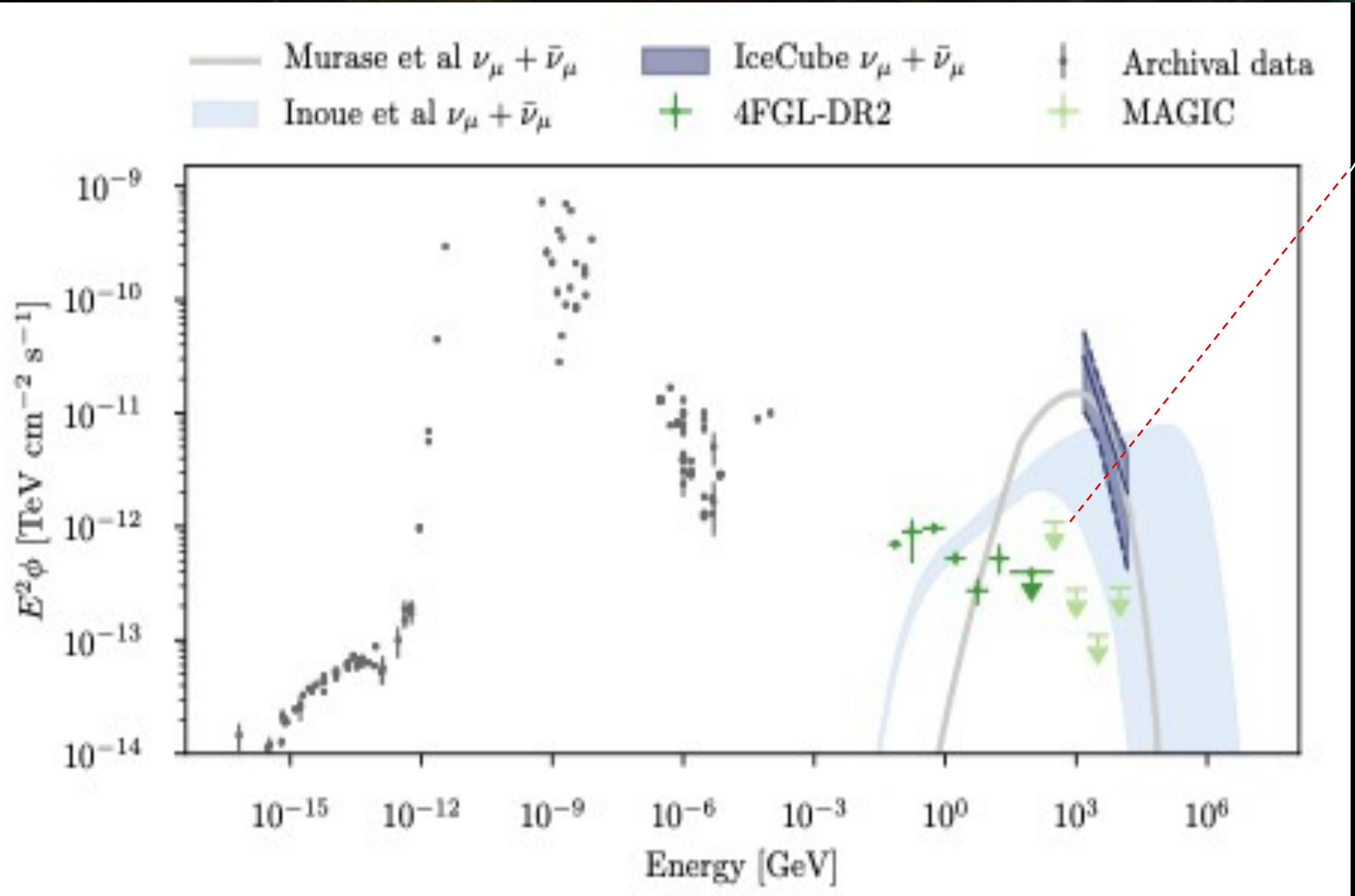
To probe hadronic Emission/absorp (TeVs)



PeVatron!

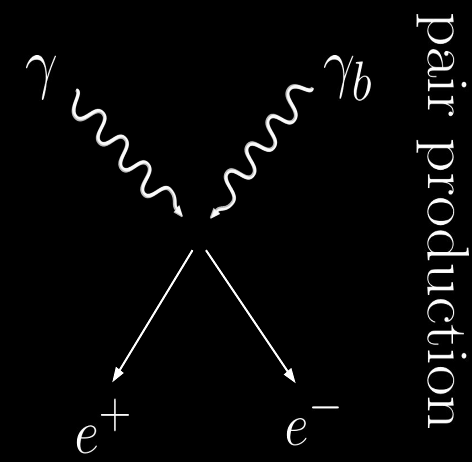
Rodriguez-Ramirez, de Gouveia Dal Pino, Alves-Batista, ApJ 2019

Neutrinos and Gamma Rays from NGC1068



(IceCube Collaboration, 2022, Science)

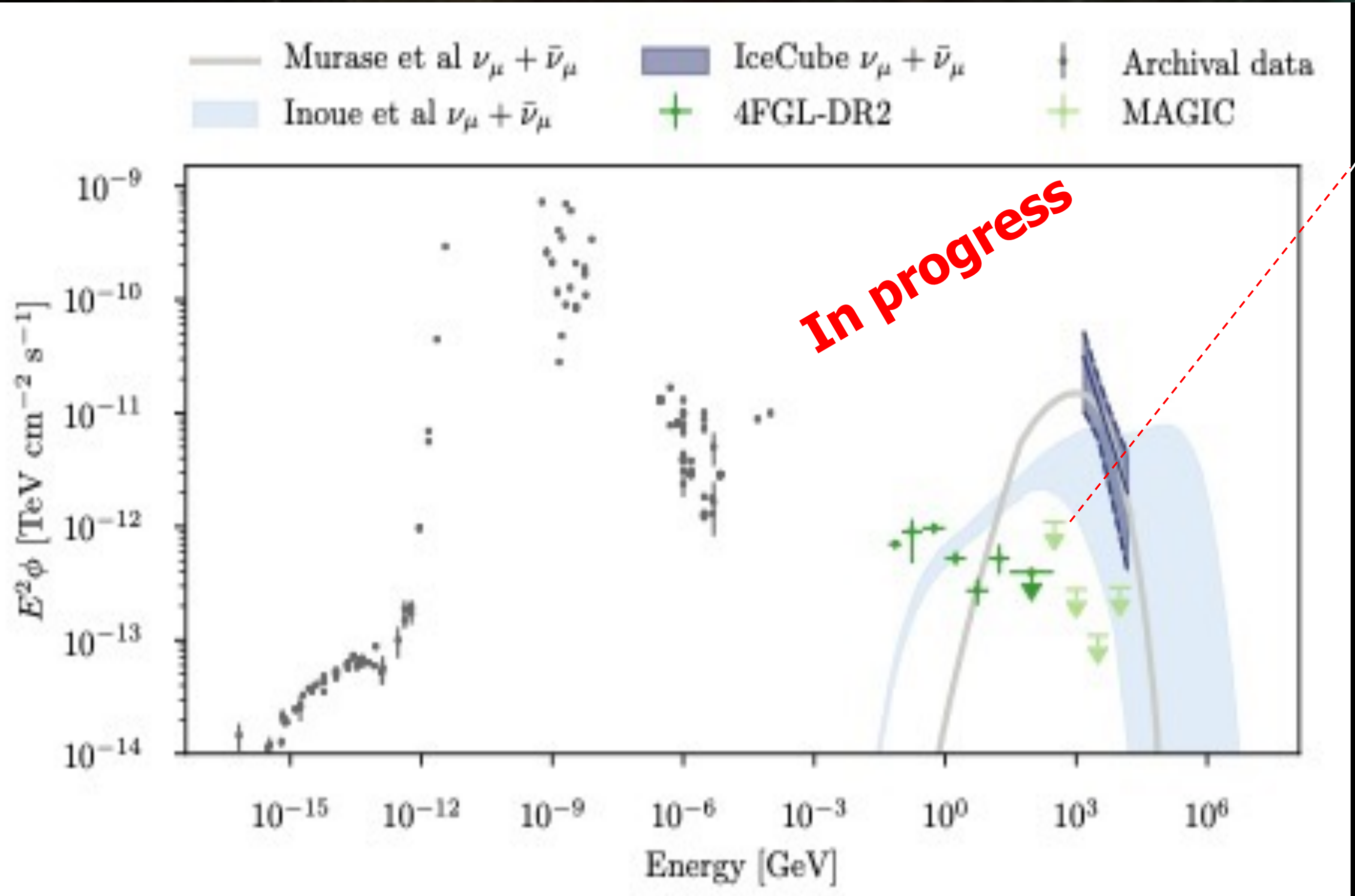
The absence of γ rays indicates auto-absorption due to a dense photon field



$\therefore$ The emission may

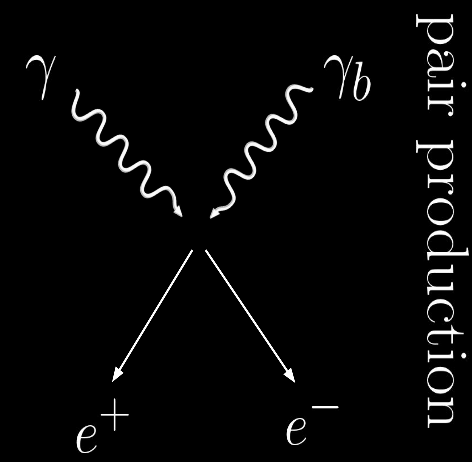
come from the core of the AGN (reconnecrtion acceleration?)

Neutrinos and Gamma Rays from NGC1068



(IceCube Collaboration, 2022, Science)

The absence of γ rays indicates auto-absorption due to a dense photon field



∴ The emission may

come from the core of the AGN (reconnecrtion acceleration?)

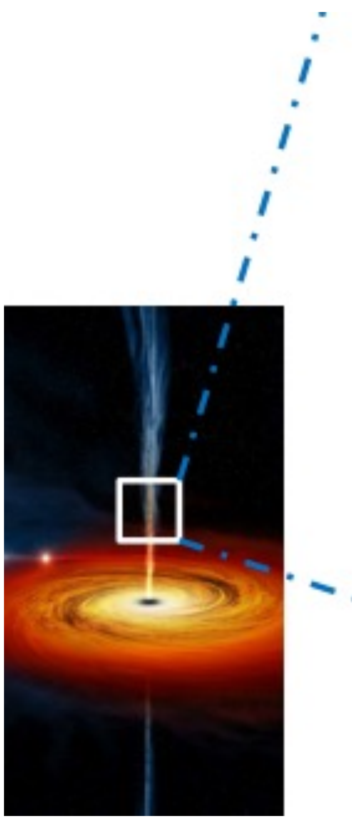
Summary

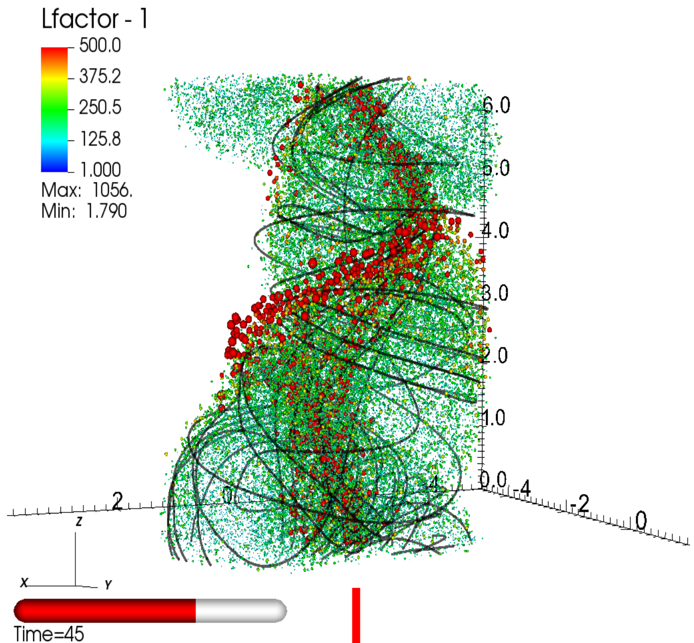
- 3D MHD simulations of particle acceleration driven by turbulent reconnection align with theory predictions: dominance of Fermi over drift process up to large saturation energy, in contrast to recent 3D PIC predictions (Sironi 2022; Zhang, Giannios & Sironi 2023)
- Particle energy grows ~ exponentially in time during Fermi: t_{acc} ~ independent of E, in contrast to drift: $t_{acc} \sim E$ (very inefficient to accelerate at large energies)
- Magnetic reconnection particle acceleration model applied to blazar TXS 0506+056 **explains VHE and neutrino emission and observed time delay**
- Magnetic reconnection particle acceleration model applied to blazar Mrk 501 explains **TeV spikes as due to** transient leptonic emission (located in a more magnetized and slower region than the one that produces the quiescent component of the SED)
- Reconnection acceleration in turbulent accretion flows around BHs may also explain VHE phenomena (e.g. SgrA*, and maybe NG1068 ?....)

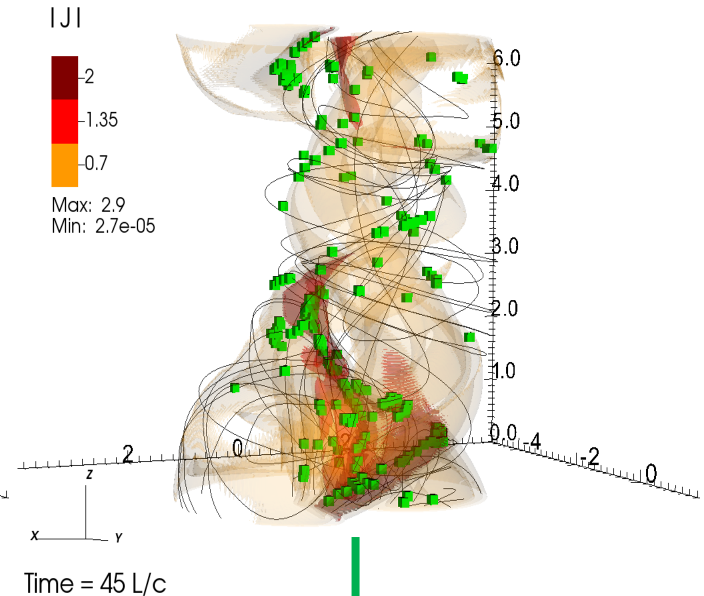
EXTRA SLIDES

Magnetic Reconnection Particle Acceleration from 3D-MHD Simulations of Relativistic Jets

- RMHD-PIC PLUTO code Godunov Based (HLLD) (Mignone et al. 2018)
- Particles evolve with flow (Boris particle pusher method)
- 256^3 resolution





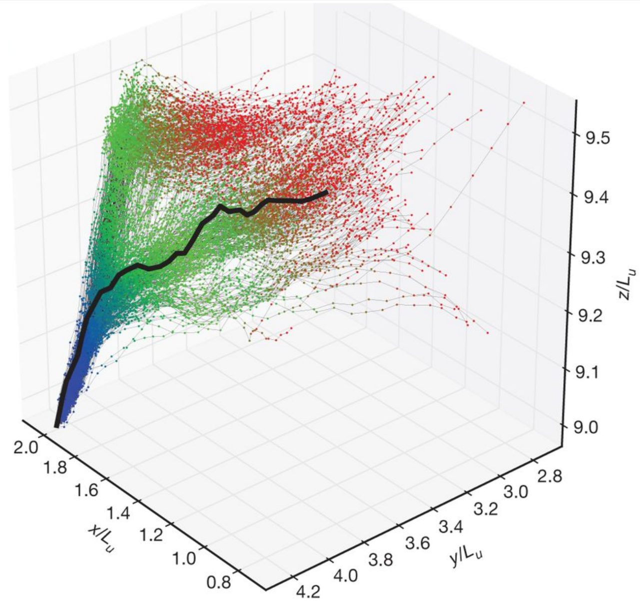


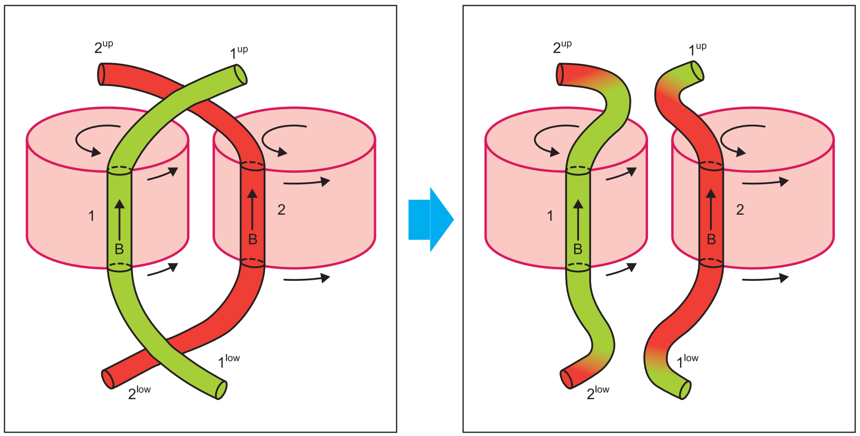
Accelerated Particles (red) ←→ Fast reconnection sites

CORRELATE quite well !

Medina-Torrejon, de Gouveia Dal Pino, Kowal, ApJ 2023

Reconnection in 3D MHD flows: due to Turbulence





Turbulent flows violate flux freezing (**Lazarian & Vishniac 1999**): origin of magnetic field back tracked in time and instead of a single line at earlier time, there are several progenitor lines (lines suffer Richardson diffusion)

(Eyink et al., Nature 2013)

Plasma does not stay in same magnetic field line, but diffuses -> enabling **reconnection diffusion**

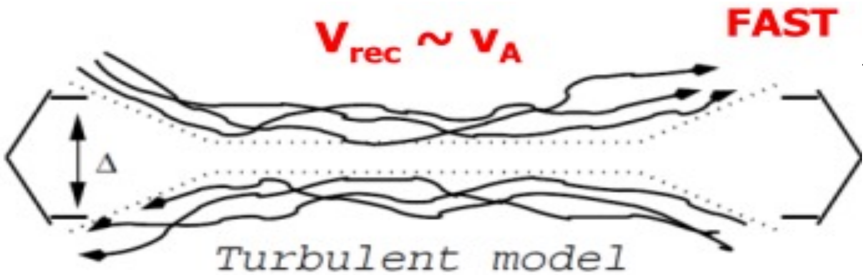
$$\eta_{RD} \sim l\, v_l \min(1, M_A^3)$$

(Lazarian 2005; Santos-Lima et al. 2010; Lazarian et al. 2012; 2012; 2021; Koshikumo et al. 2024)

Turbulence drives Fast Reconnection in 3D MHD flows

(Lazarian & Vishniac 1999; Eyink et al. 2011; 2013; Lazarian et al. 2020)

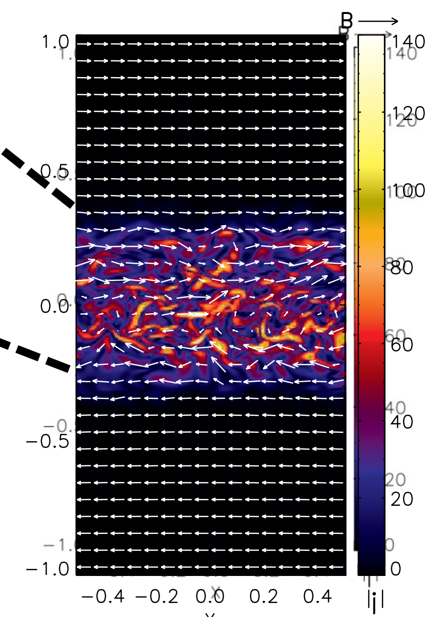
Magnetic lines wandering and slippage: many simultaneous reconnection events



$$V_{rec} = V_A \left(\frac{\eta}{L V_A}\right)^{-1/2} \left(\frac{\Delta}{L}\right)^{-1/2}$$

$$V_{rec} = V_A \left(\frac{l}{L}\right)^{1/2} \left(\frac{v_l}{V_A}\right)^{2}$$

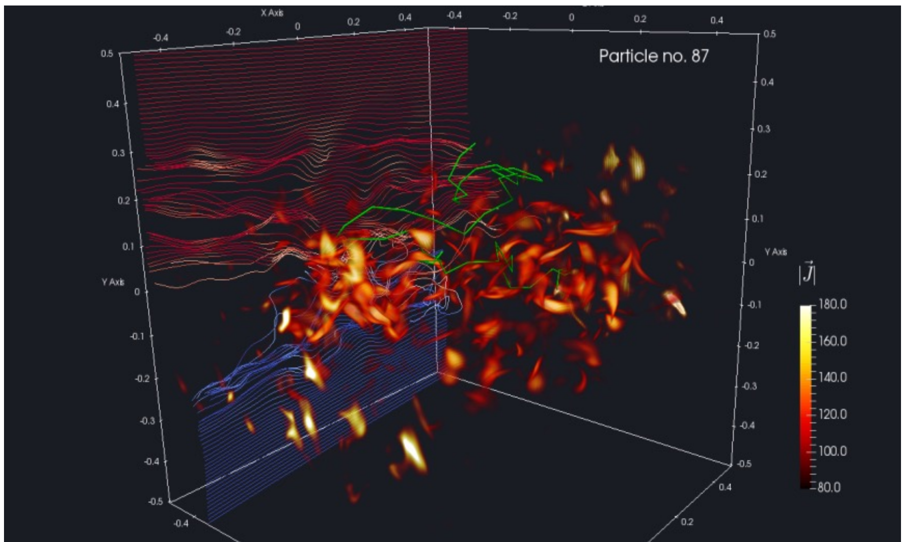
Tested in 3D res-MHD ($S_{max}=10^6$) **numerical simulations** (Kowal+2009, 2012; 2015; 2019; 2020; Takamoto+2015; Oishi+2015; Beresnyak2017; Vicentin +2024)



$V_{rec} \sim$ 0.01-0.1 V_A

Particles are accelerated in reconnection sites mainly by Fermi process

Reconnection Acceleration

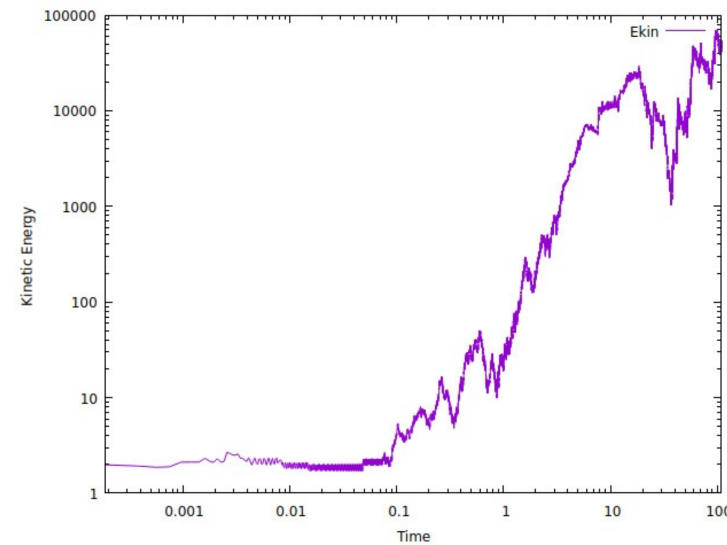


1st-order Fermi

de Gouveia Dal Pino & Lazarian, A&A 2005;
del Valle, de Gouveia Dal Pino, Kowal, MNRAS 2016

$<\Delta E/E> \sim v_{rec}/c$

Exponential energy growth in time



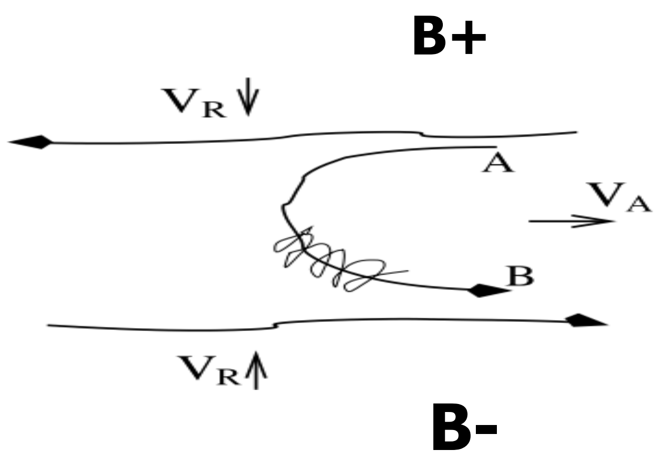
$$\frac{d}{dt}(\gamma m \mathbf{u}) = q(\varepsilon + \mathbf{u} \times \mathbf{B})$$

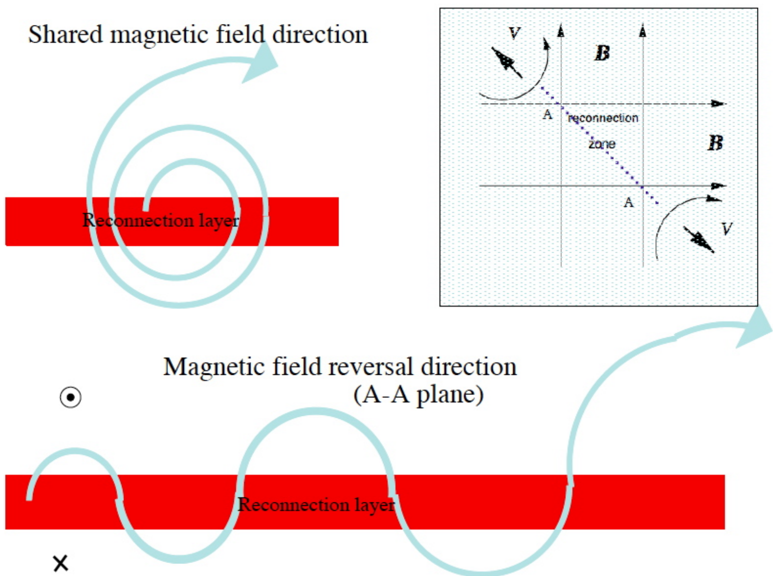
$$\varepsilon = -v \times B$$

$\varepsilon = \eta J$ *negligible*

Particles are accelerated in reconnection sites also by Grad-B drift

$$\mathbf{v}_g = \frac{v_\perp^2 \mathbf{b}}{2\Omega_{ce}} \times \frac{\nabla B}{B}$$





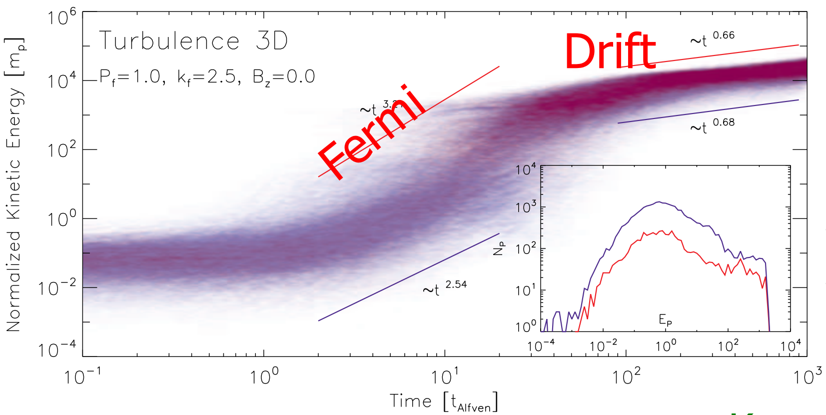
1st-order Fermi: particles bounce back and forth between 2 converging magnetic flows: shrinking loop: increases **p‖**

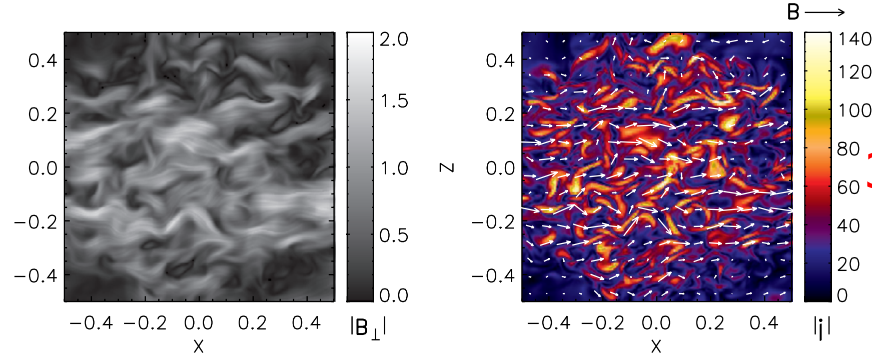
Drift: at larger Larmor radius particle interacts with converging magnetic flow and gain energy during every gyration: increases **p⊥**

(de Gouveia Dal Pino & Lazarian, A&A 2005)

(Kowal, deGDP, Lazarian, PRL 2012; Lazarian et al. 2012)

3D MHD X 3D PIC Reconnection Acceleration in *PURE* Turbulence: similar results different interpretation

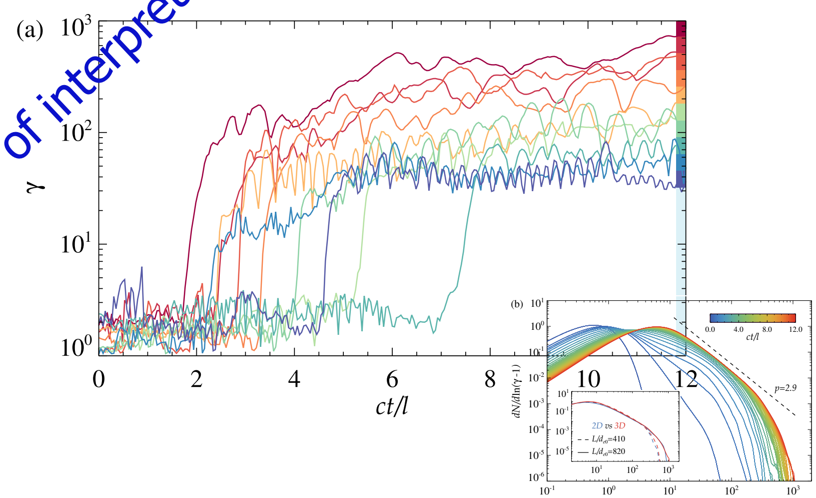


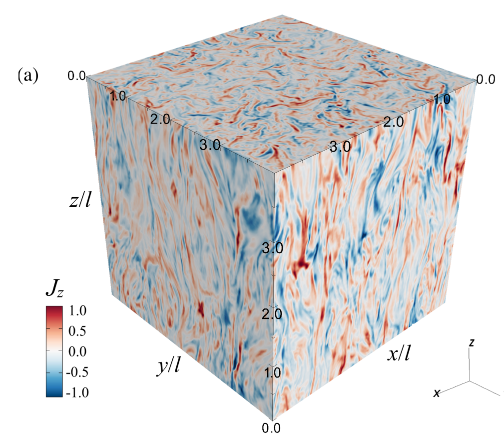


3D MHD

Kowal, de Gouveia Dal Pino, Lazarian, PRL 2012

A matter of interpretation?





3D PIC

Comisso & Sironi, PRL 2019