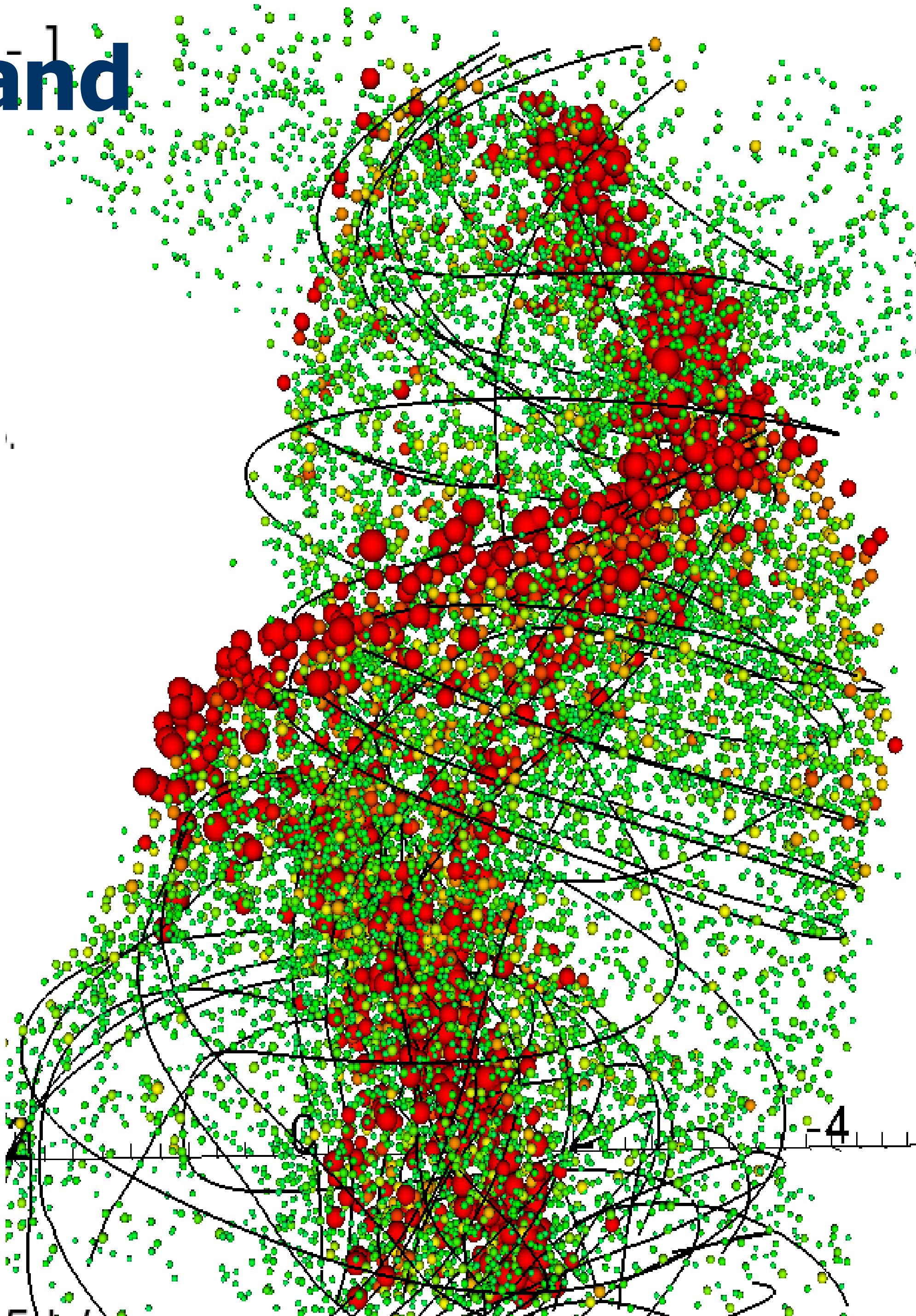
Key Processes in Cosmic-Ray and Gamma-Ray Acceleration and Propagation

Elisabete M. de Gouveia Dal Pino
IAG/USP – Universidade de São Paulo



Collaborators:
Lucas Barreto-Mota
Luis Kadowaki
Greg Kowal
Alex Lazarian
Tania Medina-Torrejon
Luana Passos-Reis
Petros Stefanou
Juan C. Rodriguez-Ramirez
Giovani Vicentin

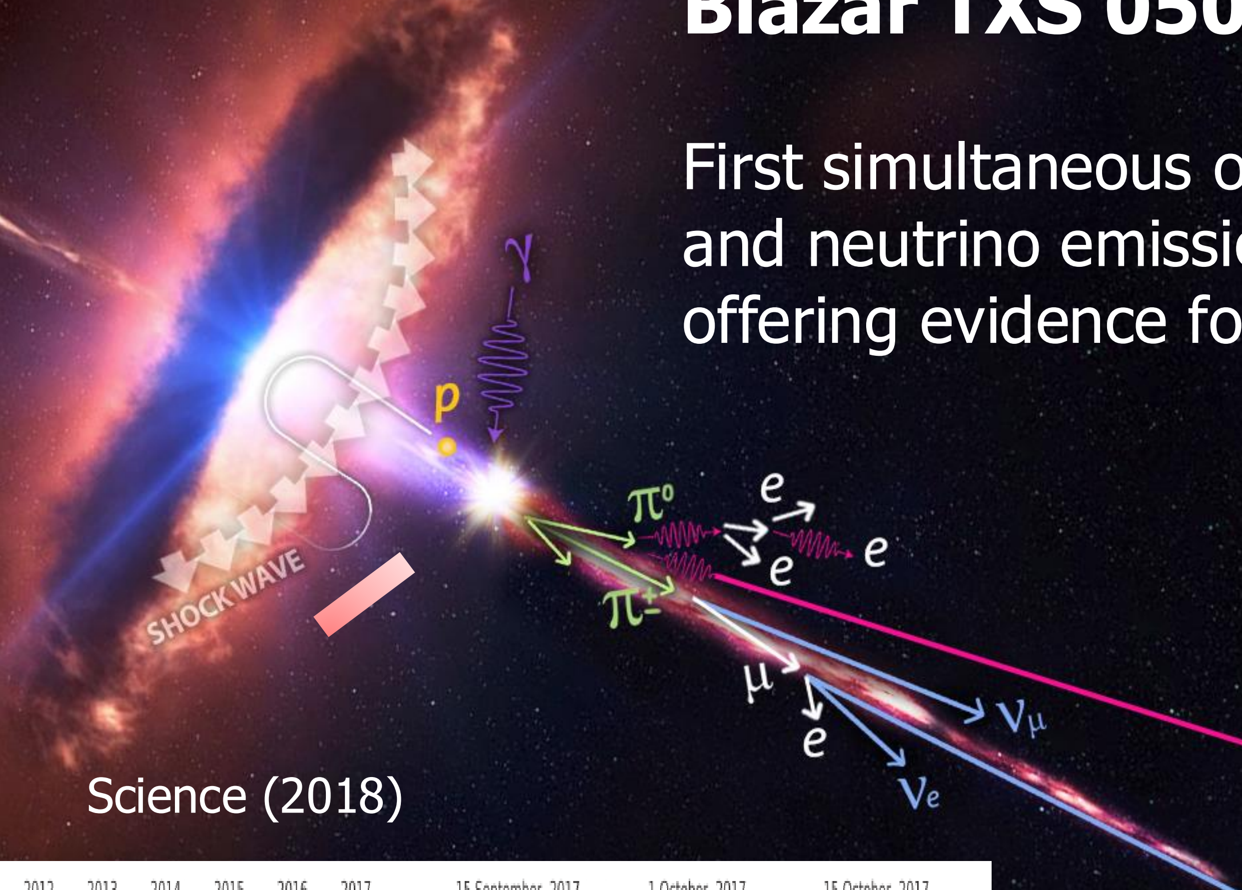
Sexten, Italy, July 20-24, 2026

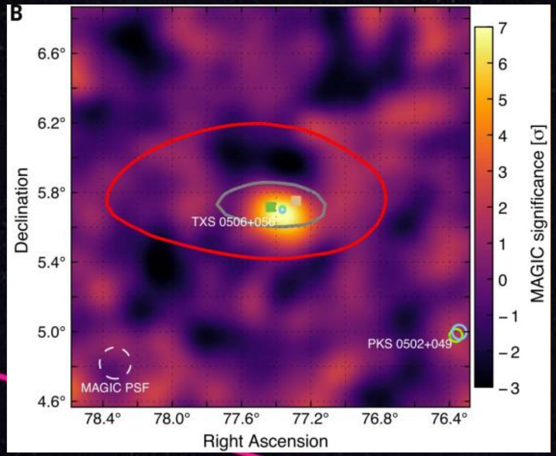
Clues from Observations

Blazar TXS 0506+056

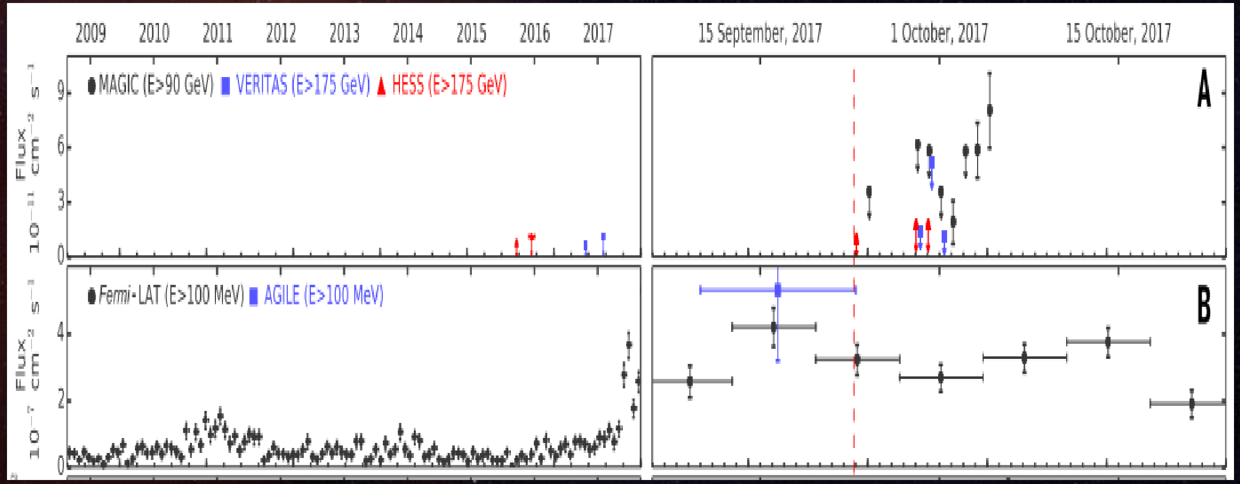
AGN Jets

First simultaneous observation of γ-ray flare and neutrino emission in AGN blazar jet -> offering evidence for VHE Protons





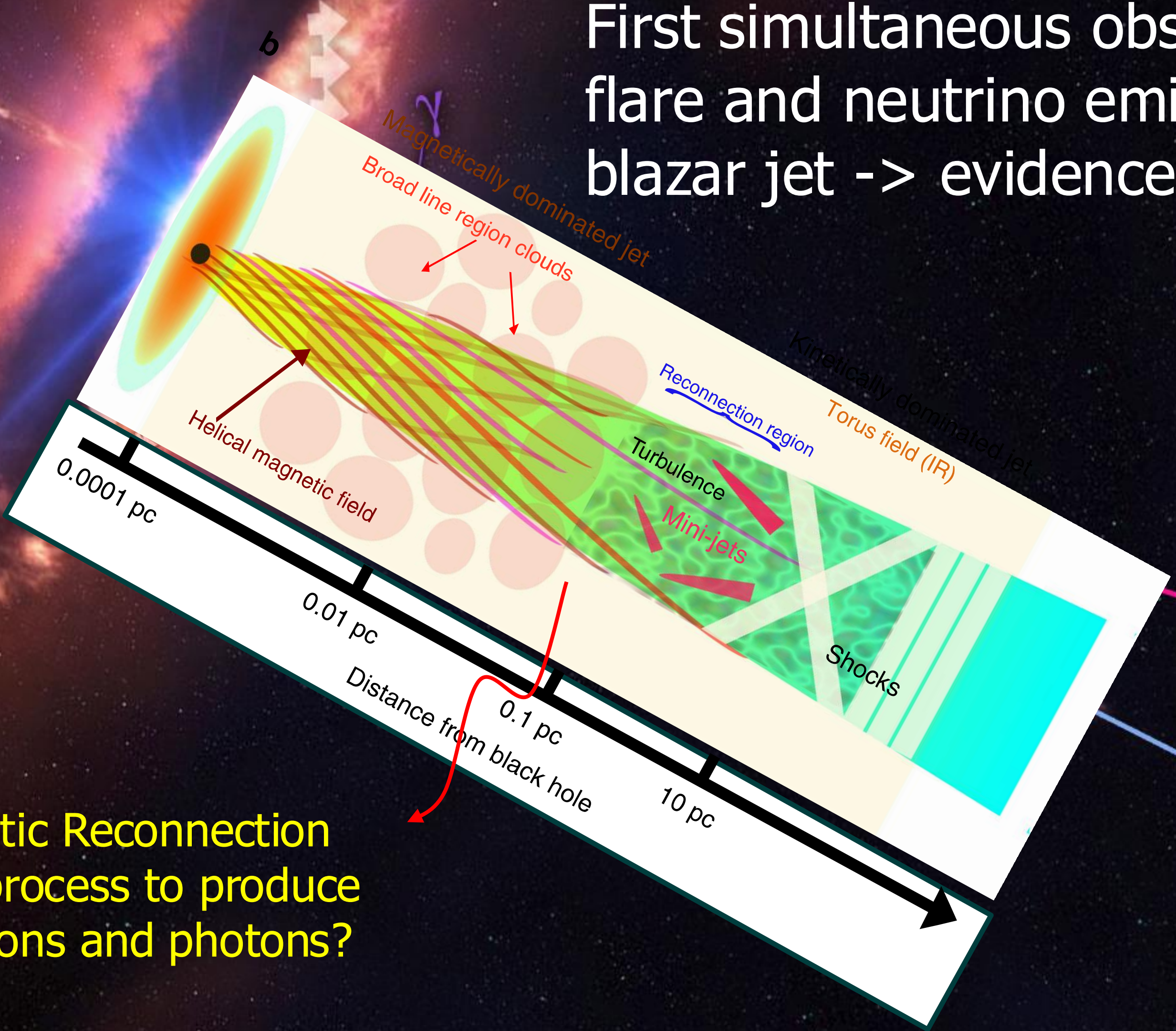
Science (2018)

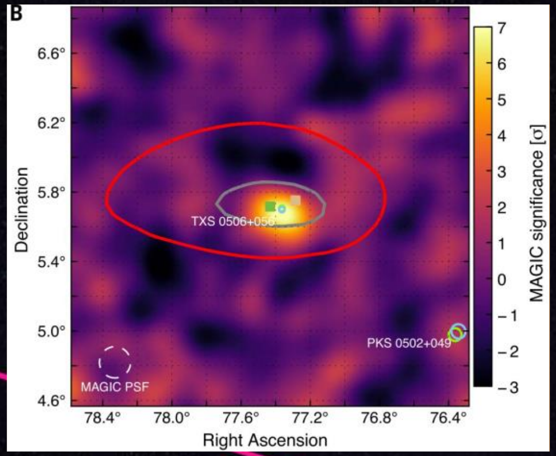


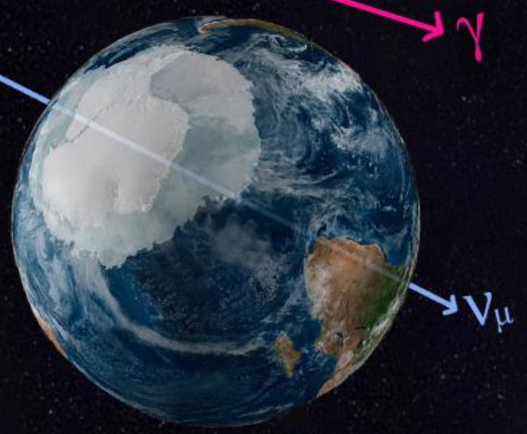
AGN Jets

Blazar TXS 0506+056

First simultaneous observation of γ-ray flare and neutrino emission in AGN blazar jet -> evidence of VHE Protons

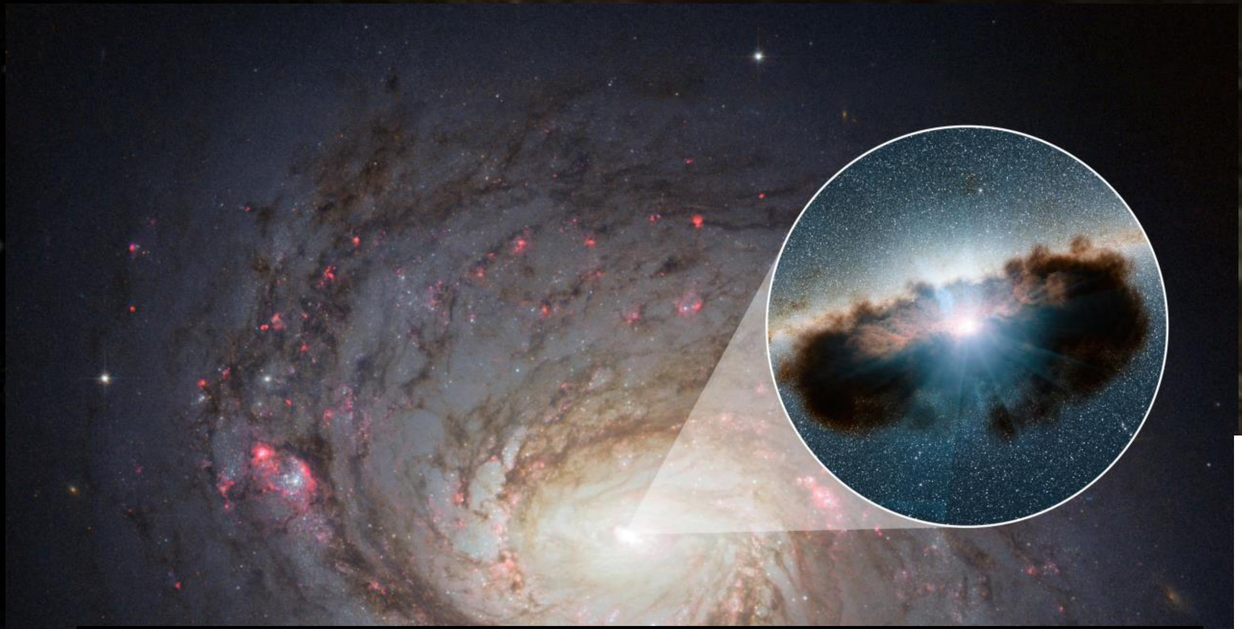


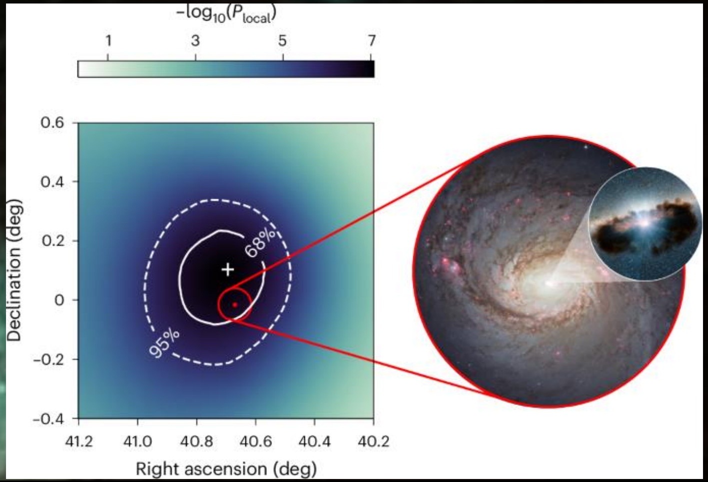




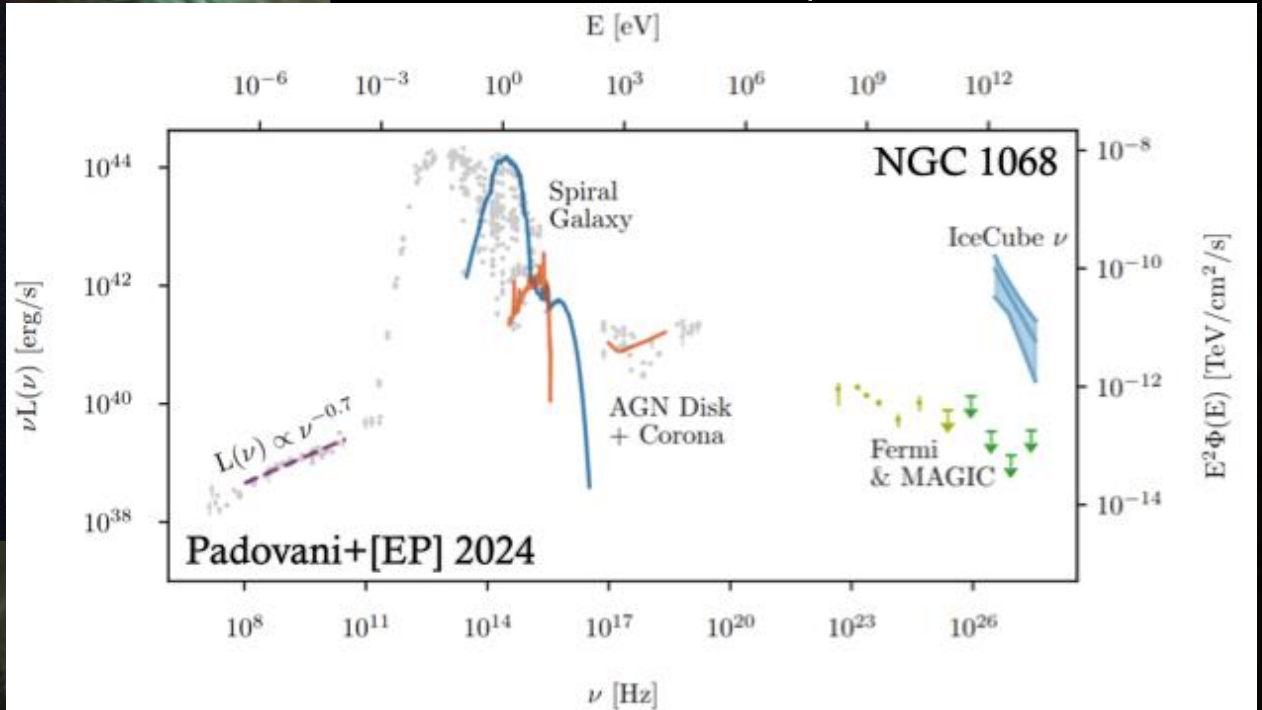
Is Magnetic Reconnection the key process to produce VHE protons and photons?

Neutrino Excess and Gamma Ray Absorption in AGN NGC1068





IceCube collaboration, Science 2022

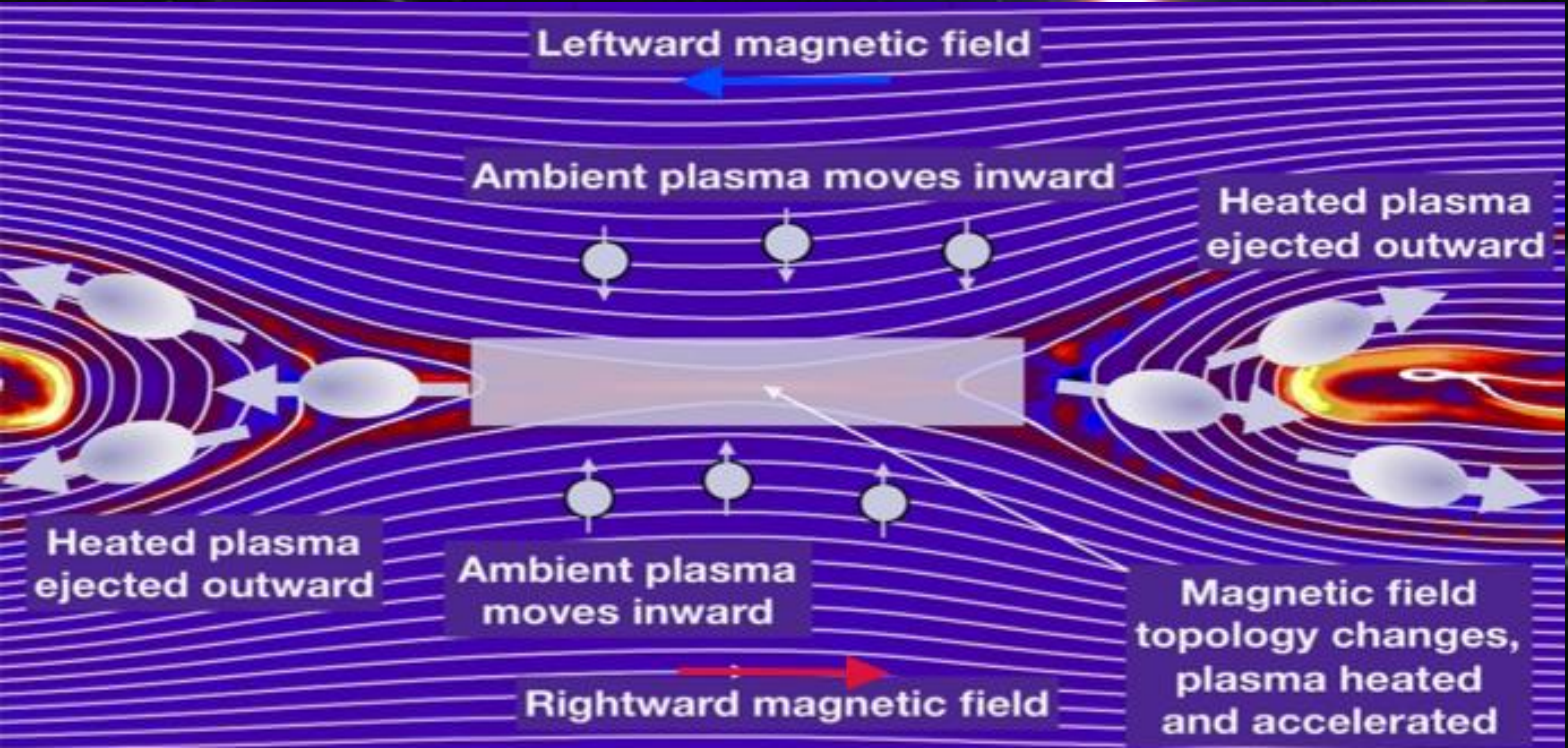


Neutrinos: a clue for the acceleration of protons to VHE

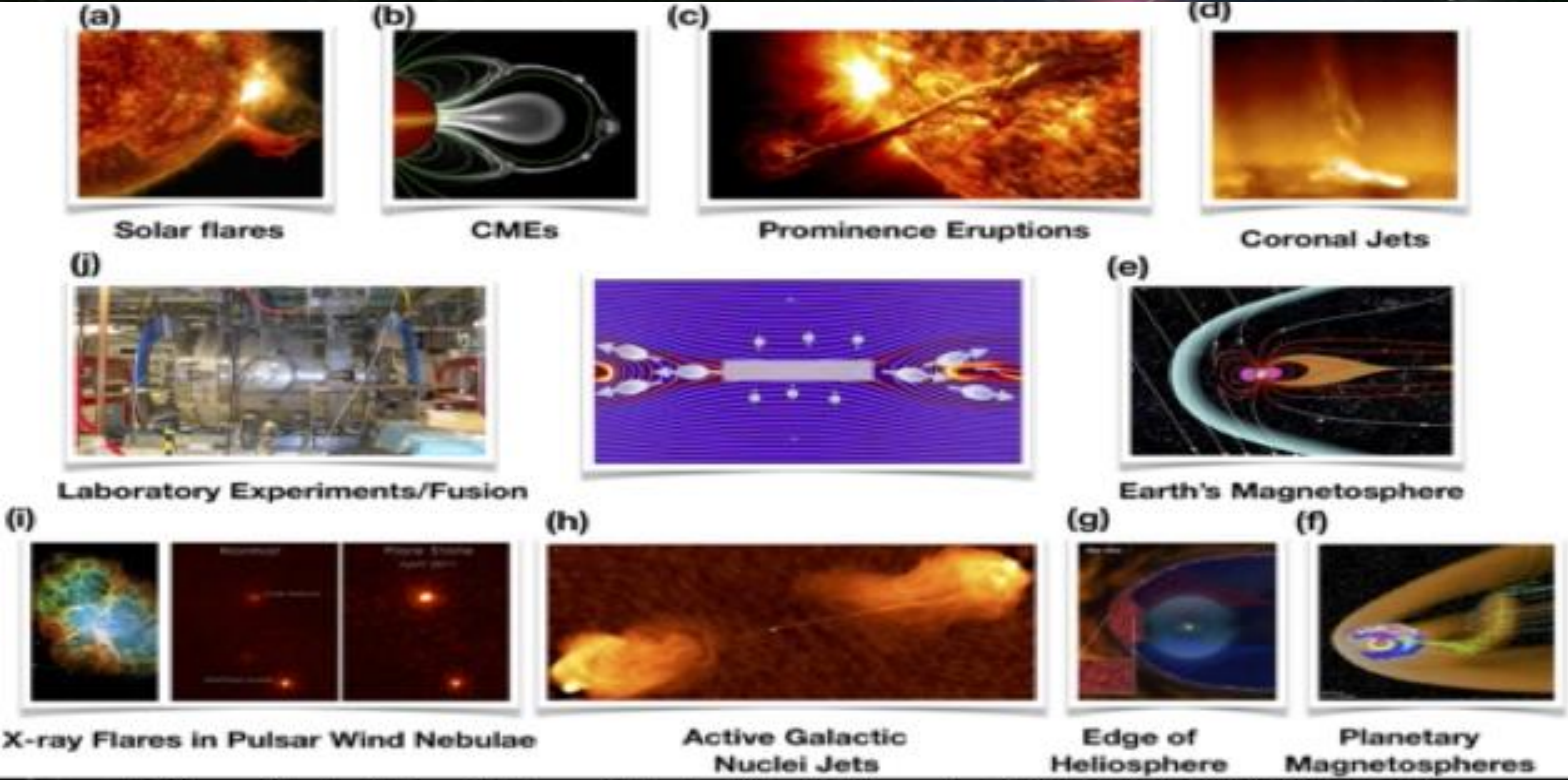
Gamma-ray absorption suggests: emission comes from magnetized nuclear region of the AGN

Can magnetic reconnection explain VHE acceleration and emission?

Magnetic Reconnection



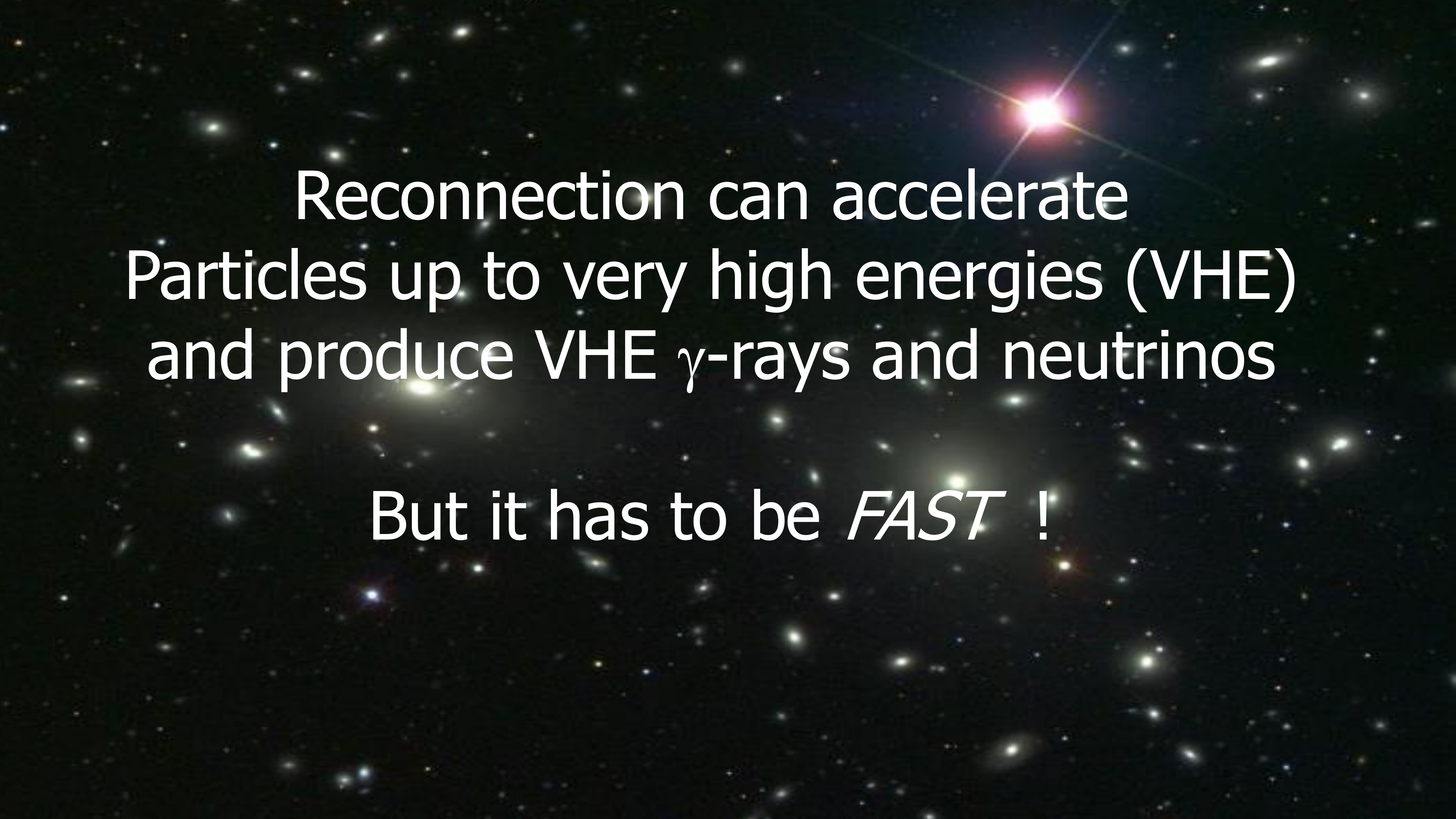
Fast Magnetic Reconnection Ubiquitous



This talk

MAGNETIC RECONNECTION key process for CR acceleration and VHE emission:

- Overview of fast magnetic reconnection mechanisms
- Overview of first-order Fermi particle acceleration by reconnection
- Reconnection acceleration at Kinetic (PIC) versus MHD scales
- Turbulence-driven Reconnection **(TDR)** acceleration of particles in MHD: up to ultra-high-energies (UHECRs) **without extrapolations**
- Applications of Turbulent-driven reconnection **(TDR)** acceleration to AGN sources (core and jets) explain **neutrino and gamma-rays**
- Key processes on **CR propagation**: Lucas Barreto-Mota & Petros Stefanou's talks


Reconnection can accelerate
Particles up to very high energies (VHE)
and produce VHE γ-rays and neutrinos
But it has to be *FAST* !

Two ways to make reconnection fast

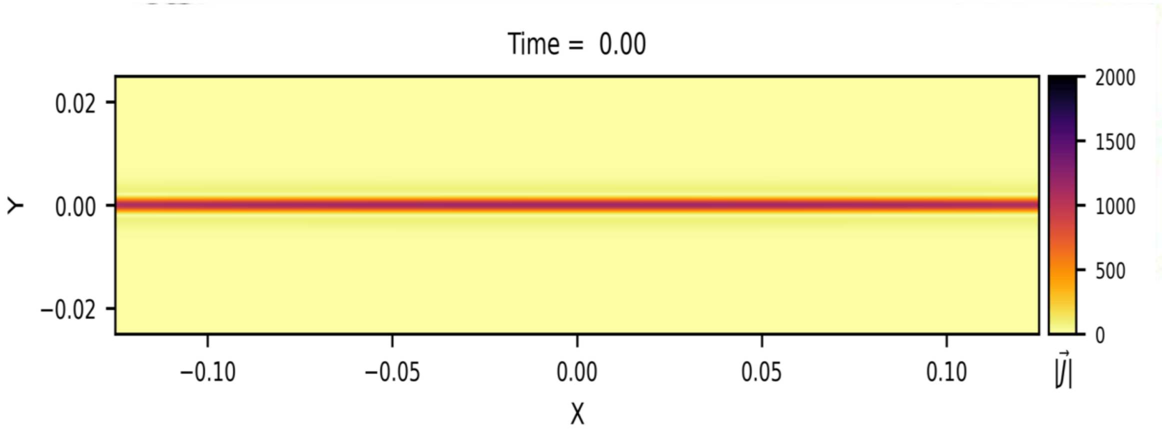
- Resistive Tearing mode instability (or “plasmoid-mediated”)

- Turbulence-Driven Reconnection (TDR): resistive independent

Best-Resolved 2D MHD Simulations of Tearing Mode/Plasmoid Reconnection

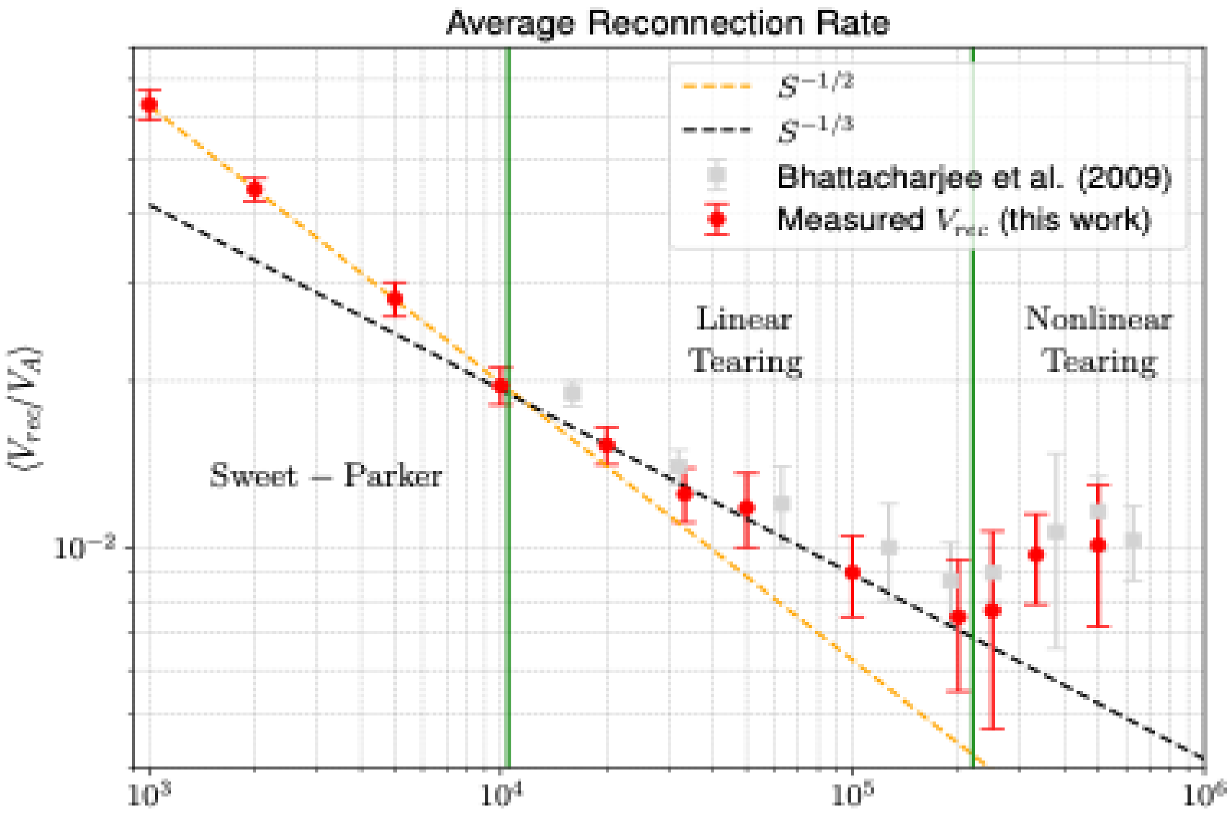
Simulation of a current layer:

S= 3.3 10^5 and 65,536^2 grid points



- **$1 \times 10^4 < S < 3 \times 10^5$** -> tearing reconnection **slow and resistive-dependent:**

$$V_{rec} \sim S^{-1/3}$$



$$S = LV_A/\eta$$

Vicentin, Kowal, de Gouveia Dal Pino & Lazarian, ApJ 2026

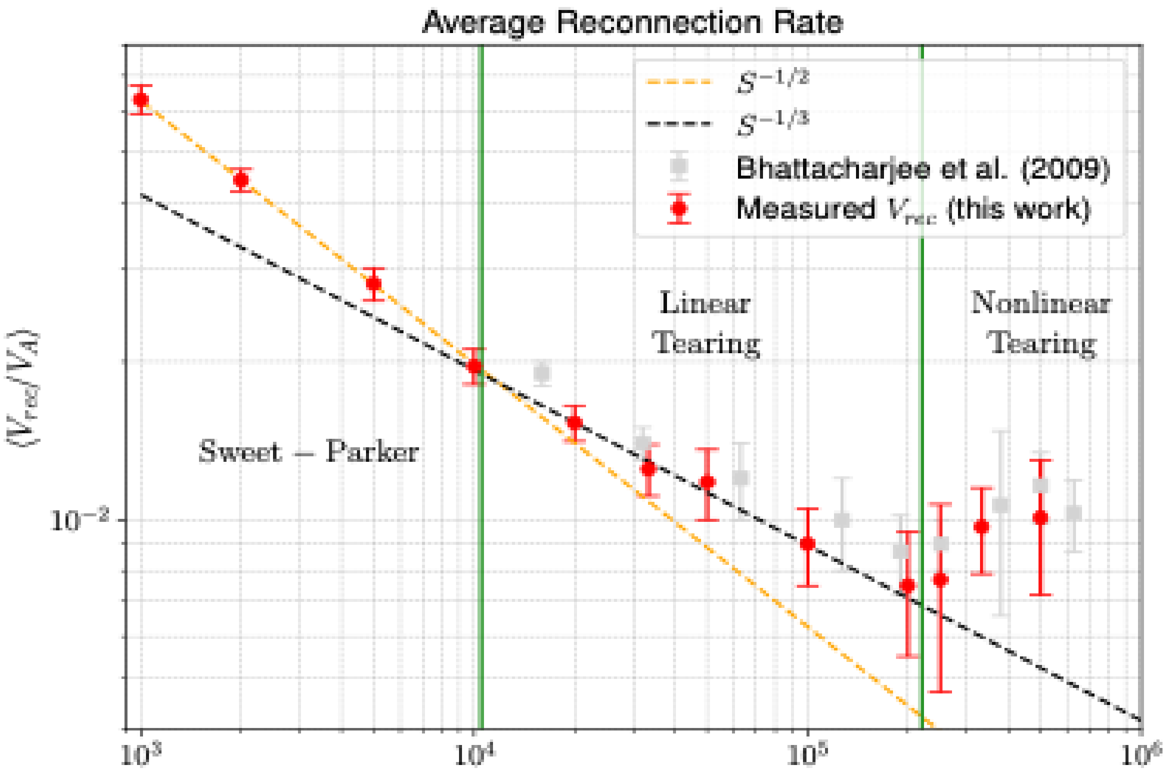
Best-Resolved 2D MHD Simulation of Tearing Mode/Plasmoid Reconnection

- ➔ **Plasmoid Reconnection: RESISTIVIVE-DEPENDENT AND SLOW up to S_c ~ 3.3 × 10^5**

- ➔ Contradicts earlier reports of "**UNIVERSAL**" fast $V_{rec} \sim 0.01\, V_A$ for S_c ~ 10^4 (Bhattacharjee et al. 2009; Loureiro et al. 2012)

- ➔ **At large S > 2 x 10^5: Re >> 1 and Reconnection occurs in TURBULENT REGIME!**

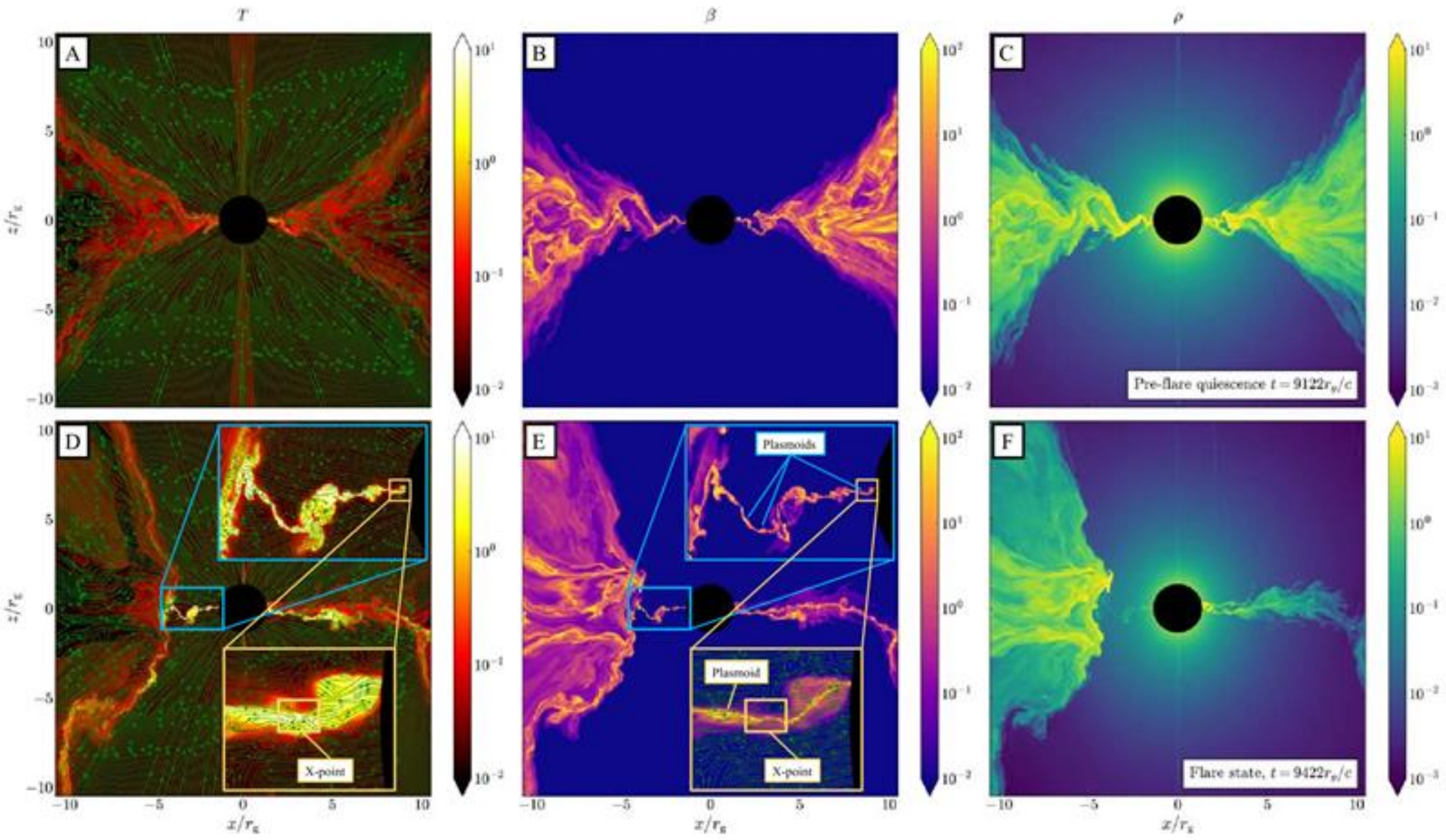
$$Re \sim Pr_m^{-1} S^{1-\alpha} \text{ with } \alpha \in [0, 1/2]$$



$$S = LV_A/\eta$$

Vicentin, Kowal, de Gouveia Dal Pino & Lazarian, ApJ 2026

Insights from 3D GRMHD simulations



Ripperda et al. (2022)

3D General Relativistic MHD simulations of Magnetically Arrested Disc (MAD) performed by Ripperda et al. (2022) with the GRMHD code H-AMR (Liska et al. 2019).

"Plasmoid" structures found in the accretion flow w/ v_{rec} ~0.01.

But, are they plasmoids (driven by explicit or numerical resistivity), or simply turbulent eddies?

Fortunately there is another way to make FAST Reconnection in MHD Flows:

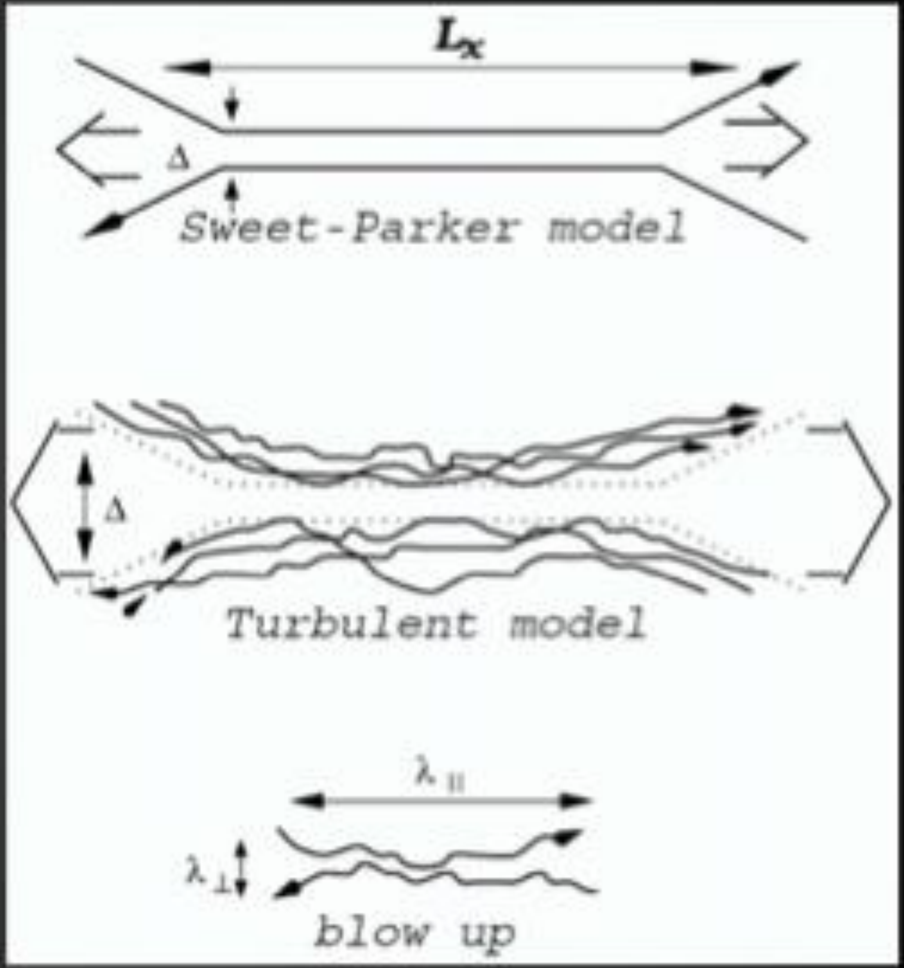
Turbulence-Driven Reconnection (TDR)

Turbulent Reconnection is Fast and Resistive-Independent

Turbulence – Lazarian-Vishniac (1999)

- **3D stochastic geometry** → turbulent field-line wandering broadens the outflow; the rate is set by turbulence, not by resistivity.
- **Simultaneous reconnection events** ("$L/\lambda_{//}$" patches). The sheet breaks into ~$L/\lambda_{//}$ independent reconnection sites along the guide/mean-field direction.
- **B dissipates on a small parallel scale $\lambda_{//}$ set by turbulence statistics.** With critical balance, $\lambda_{//}$ follows the cascade anisotropy (e.g., $k_{//} \propto k_{\perp}^{2/3}$), fixing patch length and multiplicity.
- **Ohmic resistivity is enough** (no kinetic prerequisite). Dissipation is **localized** within each patch; the **global rate** is boosted by the **many simultaneous** patches, making it effectively **independent of S.**

$$\boxed{\frac{V_{\rm rec}}{v_A} \approx \left(\frac{l_{\rm inj}}{L}\right)^{1/2} M_A^2, \qquad \frac{\Delta}{L} \approx \left(\frac{l_{\rm inj}}{L}\right)^{1/2} M_A^2}$$



Turbulent Reconnection @ Relativistic Regime

- **Relativistic replacement of speeds**
  Use $v_A = c\sqrt{\sigma/(1+\sigma)}$; for finite-amplitude driving use proper velocities $u = \gamma v \Rightarrow M_A \equiv u_{\rm inj}/u_A$.

magnetization $\sigma = B^2 / 4\pi w$, where
$w = \rho c^2 + p\,\Gamma / (\Gamma - 1)$ is enthalpy density

- **Same geometry, same core scaling … with a modifier:**

$$\boxed{\frac{V_{\rm rec}}{v_A} \approx \left(\frac{l_{\rm inj}}{L}\right)^{1/2} M_A^2 f_A(\sigma, M_A) \quad (M_A \lesssim 1)}$$

Takamoto & Lazarian (2017)
Takamoto et al. (2018)

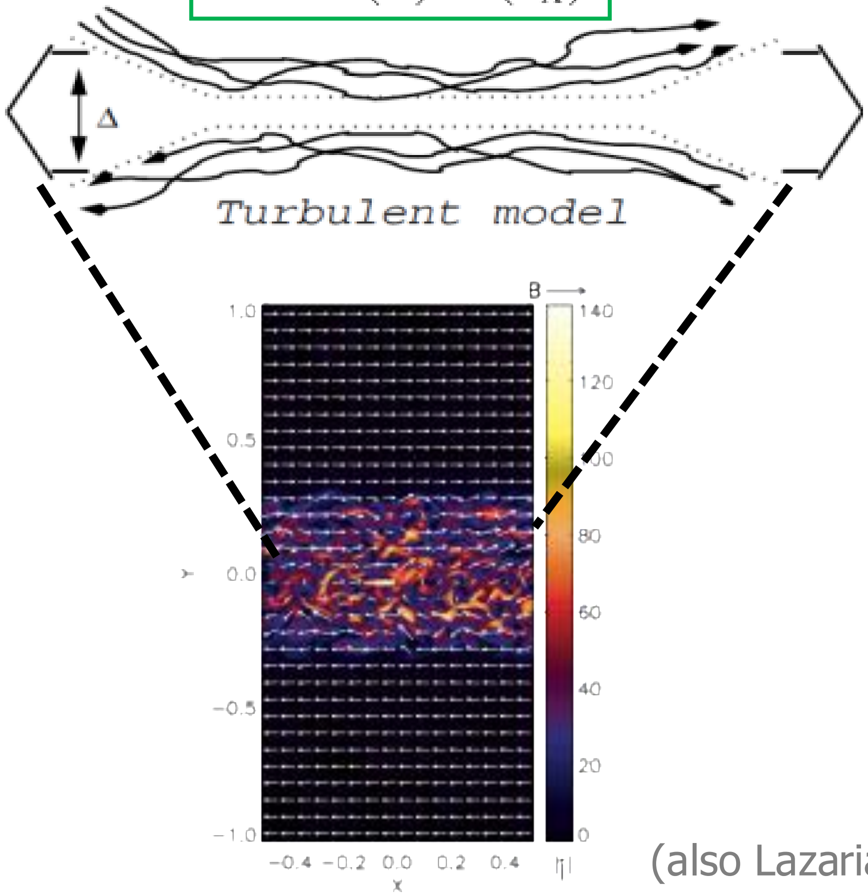
  Field-line wandering still sets Δ; independent of S as in LV99.
- **Compressibility / mode-coupling effect.**
  High magnetization ($\sigma \gtrsim 1$) enhances Alfvén–fast coupling; only the Alfvénic share thickens the layer $\Rightarrow f_A \downarrow$ with σ and with turbulent amplitude.
- **Rate behavior in practice.**
  For small M_A: LV99 $M_A^{\ 2}$ law holds. As M_A grows, rate saturates at ~0.05–0.1 v_A (up to ~0.2 v_A if $l_{\rm inj} \approx L$), then can decline as compressible power dominates.
- **Turbulent anisotropy.**
  Alfvénic component remains GS95-like (critical balance) → line-wandering logic intact; strong coupling can mildly steepen the $k_{/\!/} - k_\perp$ relation but does not re-introduce S-dependence.

Fast Reconnection driven by Turbulence in 3D MHD Flows Successfully Tested

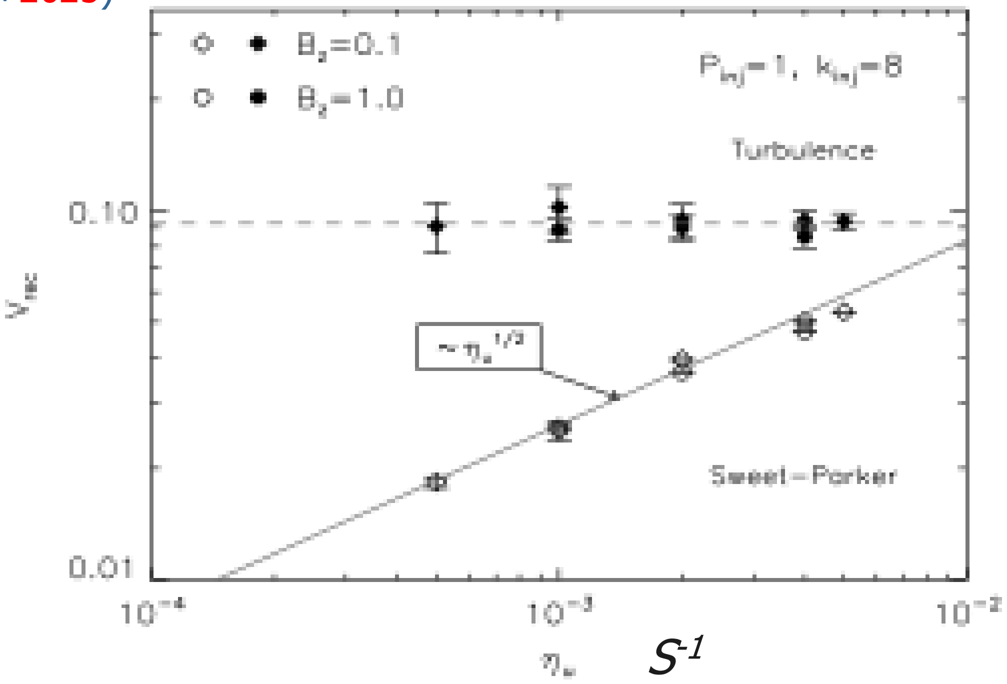
Lazarian & Vishniac 1999

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

FAST



Tested in 3D res-MHD (S_{max}<2x10^6) numerical simulations (Kowal+2009, 2012; 2015; 2019; 2020; Eyink et al. 2013; Takamoto+2015; Oishi+2015; Beresnyak 2017; Vicentin +2025)



RESISTIVITY-INDEPENDENT & FAST

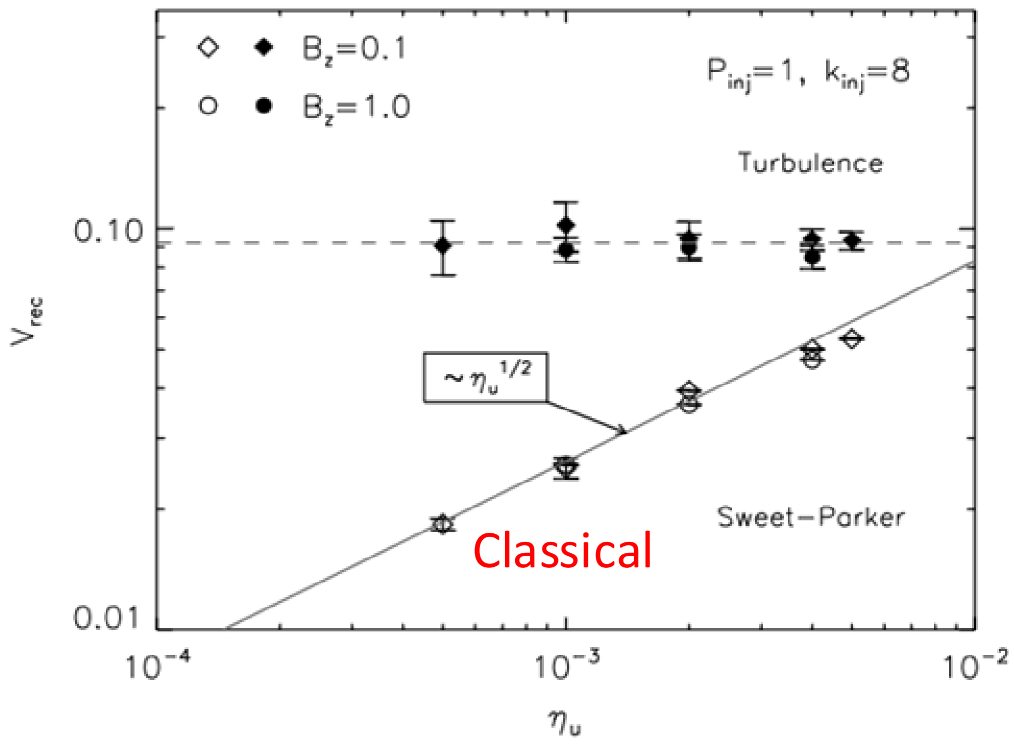
V_{rec}~ 0.05-0.1 V_A

- Confirmed dependence on the turbulent injection power and scale

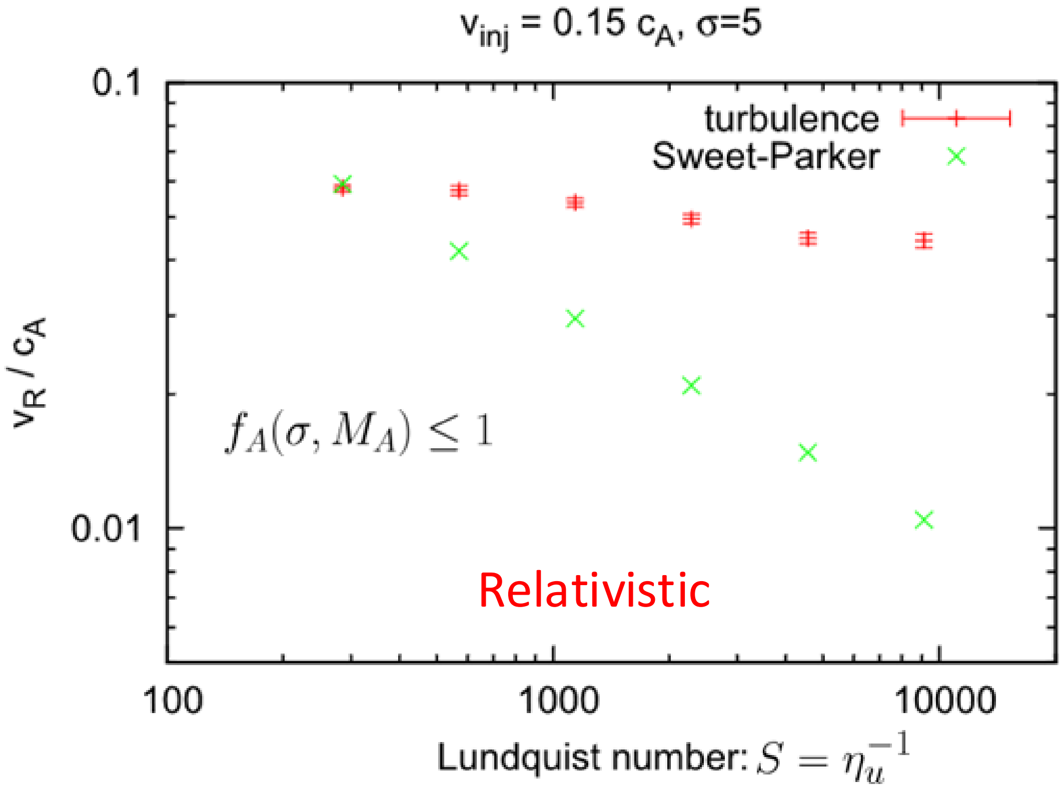
(also Lazarian et al. 2020 for review)

Reconnection driven by Turbulence: Fast and Resistive-independent

The Lazarian & Vishniac theory numerically tested in 3D MHD simulations both in classical (Kowal et al. 2009, 2017, 2020, Kadowaki et al. 2018, Vicentin et al. 2025) and relativistic (Takamoto et al. 2015, Kadowaki et al. 2019, 2021) regimes.

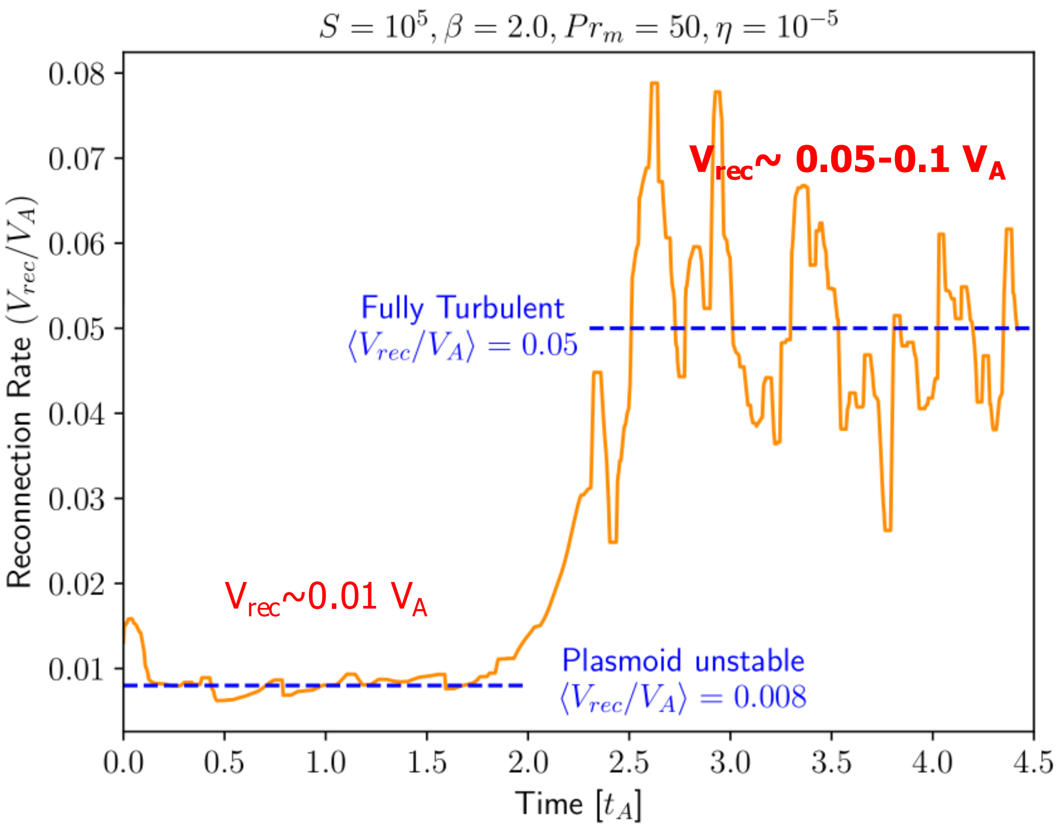


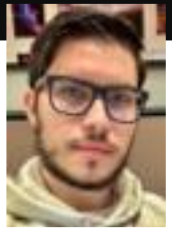
Kowal et al. (2009)

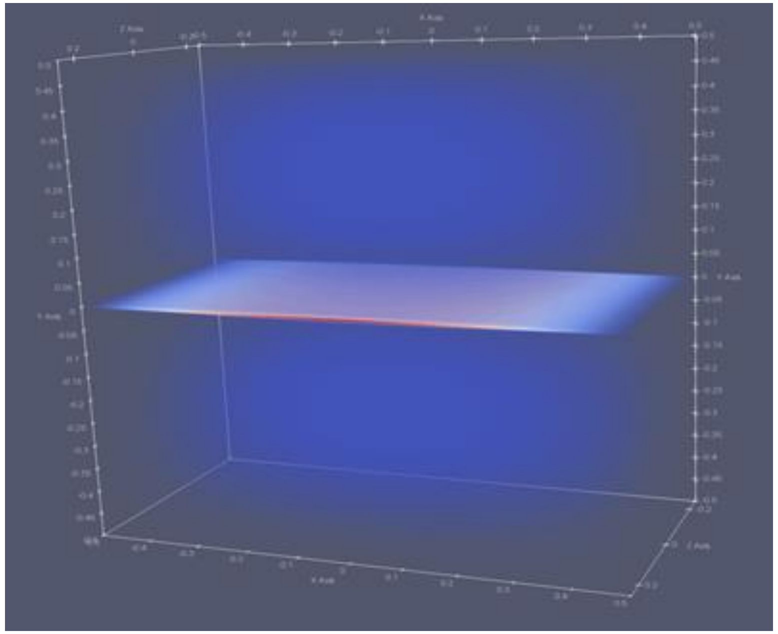


Takamoto et al. (2015)

Plasmoid Reconnection x Turbulence-Driven Reconnection in MHD Flows







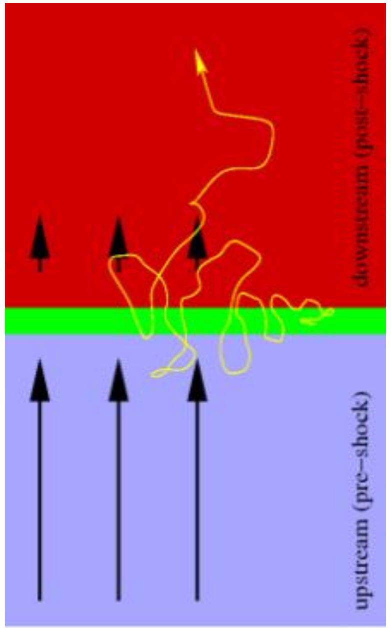
Reconnection is faster during fully turbulent regime compared to plasmoid phase

Vicentin, Kowal, de Gouveia Dal Pino & Lazarian, ApJ 2025

Cosmic Ray Acceleration by Reconnection

How particles are accelerated in reconnection sites?

Shock Acceleration

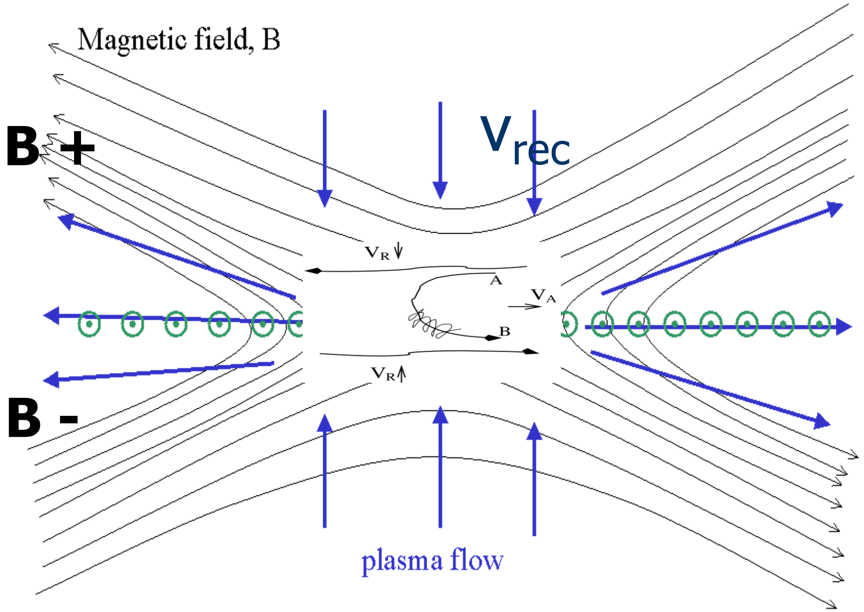


1st-order Fermi:

(Bell 1978; Begelman & Eichler 1997)

$$\left\langle \frac{\Delta E}{E} \right\rangle \sim \frac{v_{sh}}{c}$$

Reconnection Acceleration



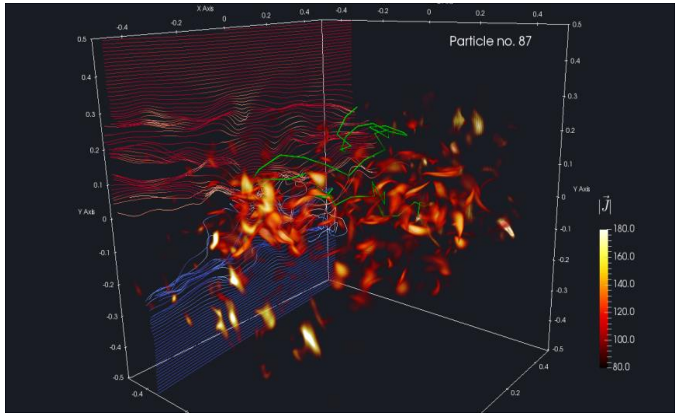
As in shocks: 1st-order Fermi:

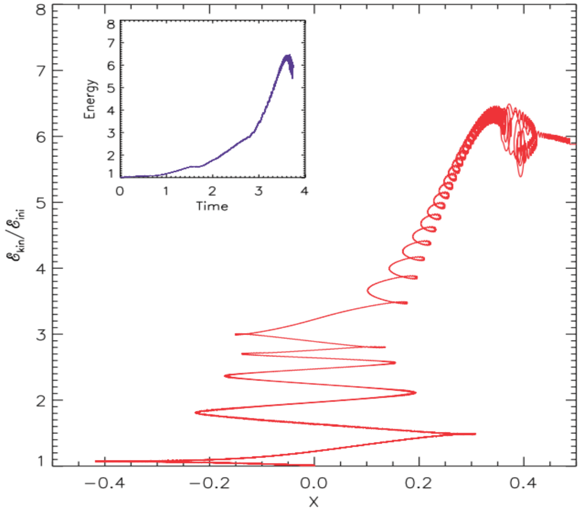
(de Gouveia Dal Pino & Lazarian, 2005)

$$\left\langle \frac{\Delta E}{E} \right\rangle \sim \frac{v_{\rm rec}}{c}$$

Particles are Accelerated in Reconnection Sites first by FERMI and then by Grad-B Drift

de Gouveia Dal Pino & Lazarian, A&A 2005





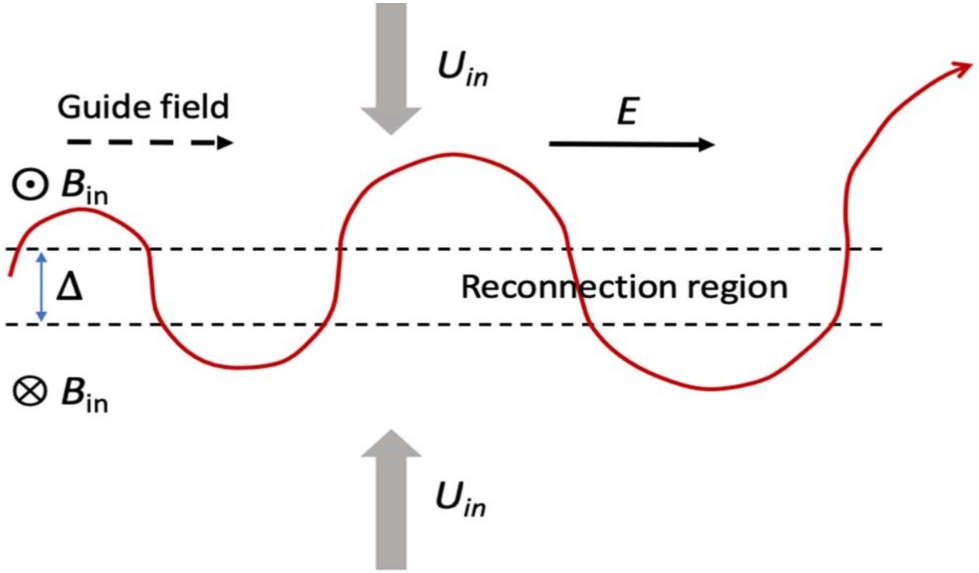
1[ST]-ORDER FERMI: particles bounce back and forth between 2 converging magnetic flows: increases **p∥ and p⊥**

$$\left\langle \frac{\Delta E}{E} \right\rangle \sim \frac{V_{\rm rec}}{c}$$

Acceleration time: E-independent

(See also Drake et al. 2006, Kowal et al. 2011; Guo et al. 2019)

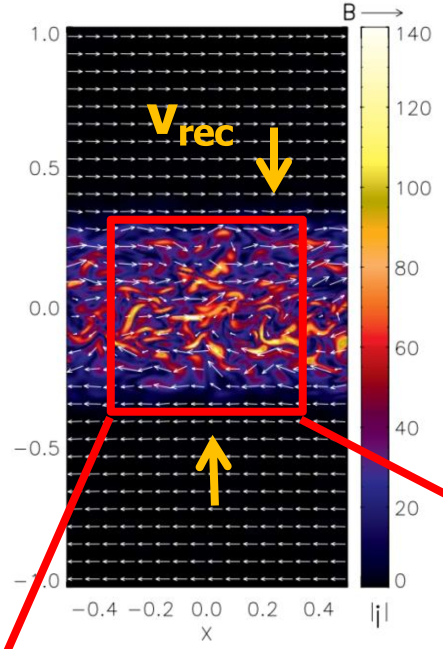
Kowal, de Gouveia Dal Pino, Lazarian, PRL 2012
Lazarian et al. 2012

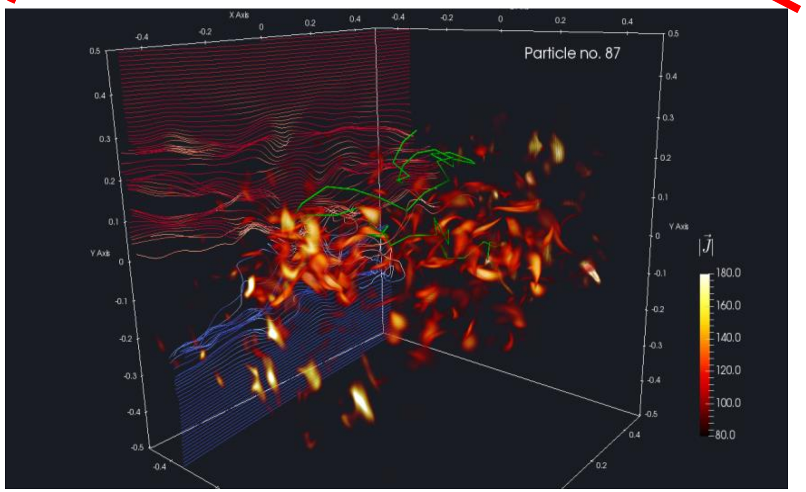


DRIFT: outside current sheet, at Larmor radius >Δ, particle interacts with magnetic field gradient and gain energy during every gyration: increases **p⊥**

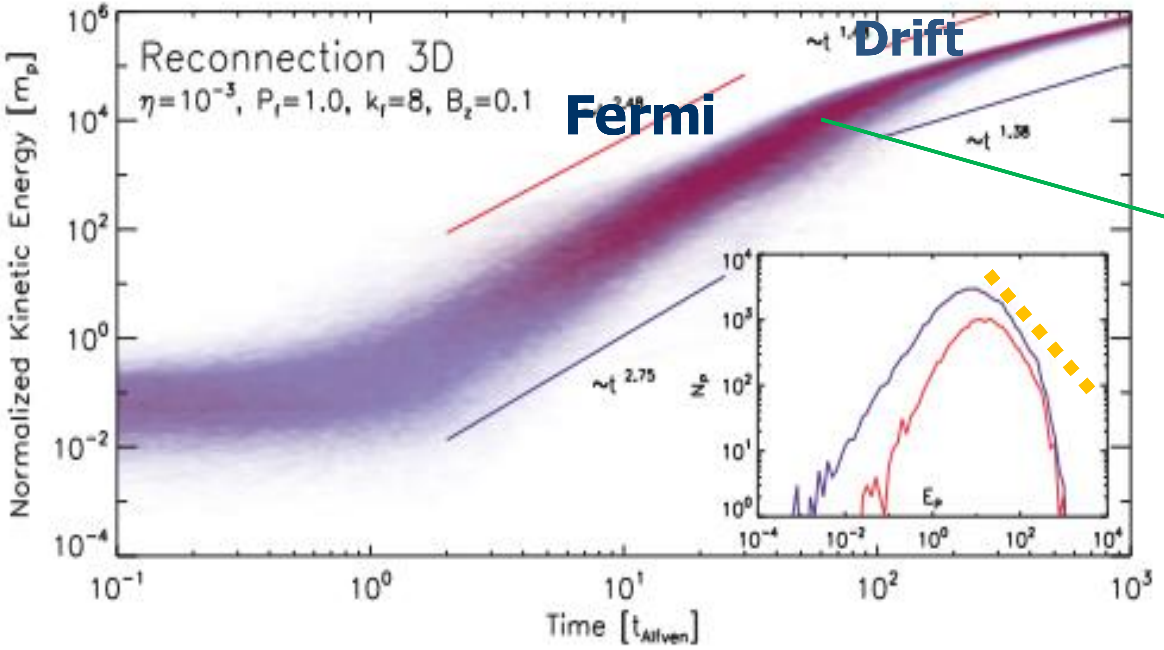
(see also del Valle, de Gouveia Dal Pino, Kowal, MNRAS 2016
Zhang, Giannios & Sironi, ApJ 2021)

Turbulent-Driven Reconnection (TDR) Acceleration in 3D MHD Simulations of Current Sheets with Test Particles





10,000 test particles



$r_{g,max}$ = Δ_{max} ~l_{inj}

N(E) ~ E^{-1}

(~PIC simulations)

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

$E = -\boldsymbol{v} \times \boldsymbol{B}$
(neglect: $\varepsilon = \eta J$)

$$\boxed{\frac{d}{dt}(\gamma m \boldsymbol{u}) = q[(\boldsymbol{u} - \boldsymbol{v}) \times \boldsymbol{B}]}$$

Kowal, de Gouveia Dal Pino, Lazarian, PRL **2012**
del Valle, de Gouveia Dal Pino, Kowal MNRAS **2016**

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 instability** (plasmoid 2D)

(e.g. Sironi & Spitkovsky 2014; 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**

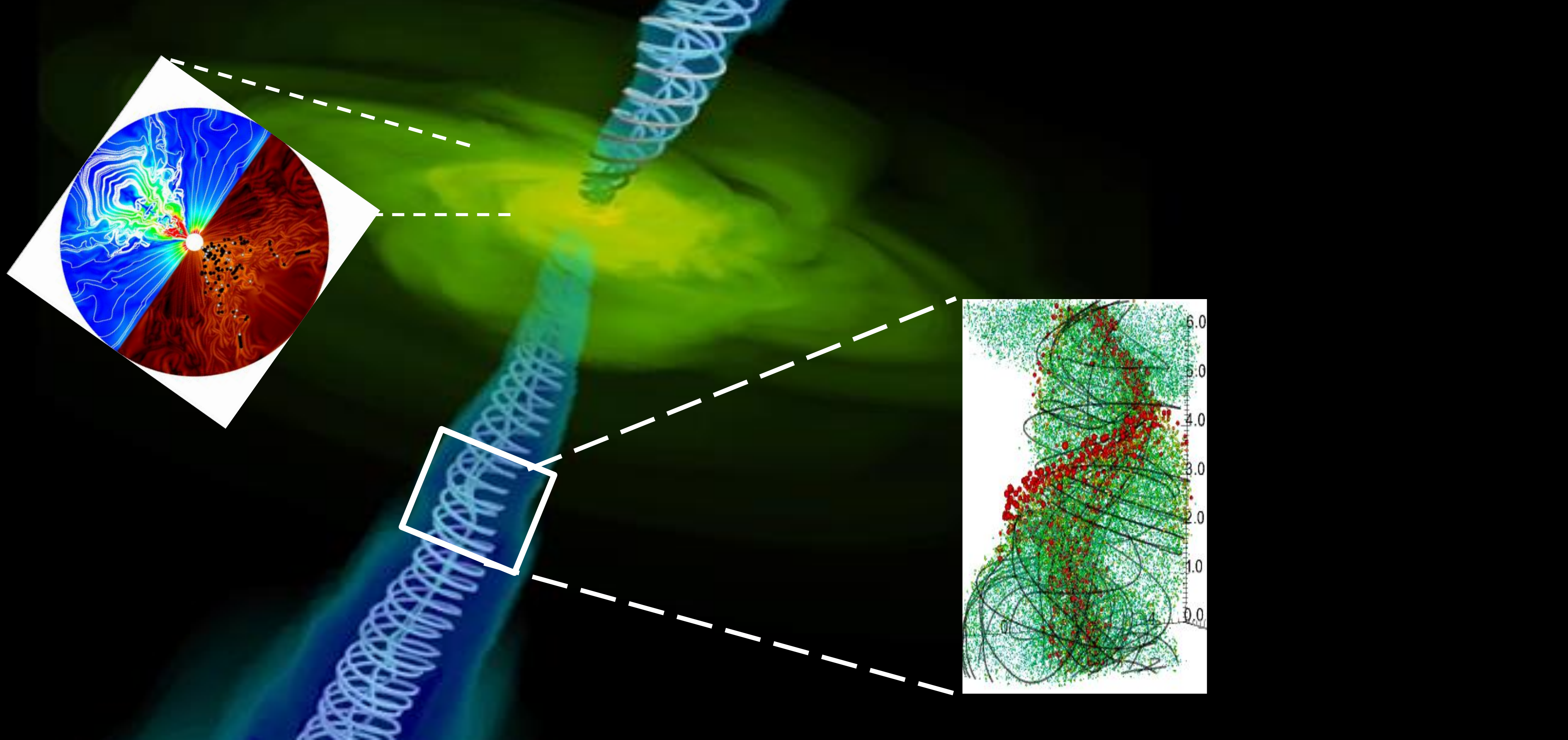
MHD

- Probes macroscopic astrophysical scales
- **Fast reconnection driven by turbulence (3D)**

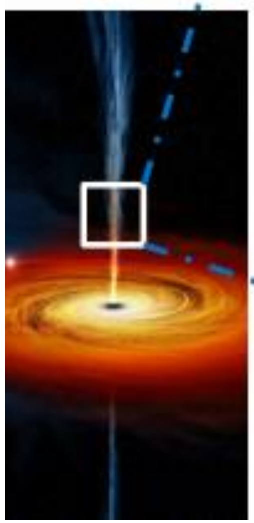
(Kowal, deGDP & Lazarian 2011; 2012; deGDP & Kowal 2015; del Valle, deGDP et al. 2016; Kadowaki, deGDP et al 2021; Medina-Torrejon, deGDP et al 2021, 2023; dGDP & Medina-Torrejon 2026)

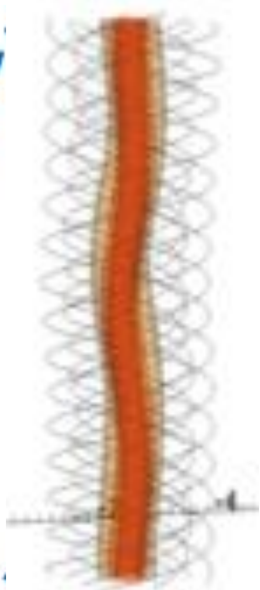
Solves saturation energy of CRs: final acceleration

Implications of Turbulence Driven Reconnection (TDR) for CR Acceleration and VHE emission in Relativistic Jets and Accretion Flows

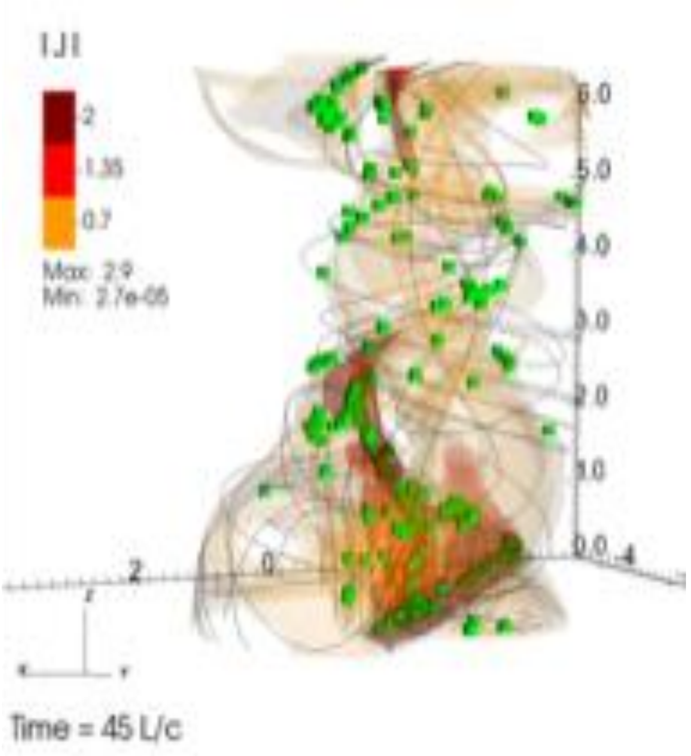


Kink Instability Drives Turbulence and Fast Magnetic Reconnection in Relativistic MHD Jets





Kink instability drives turbulence

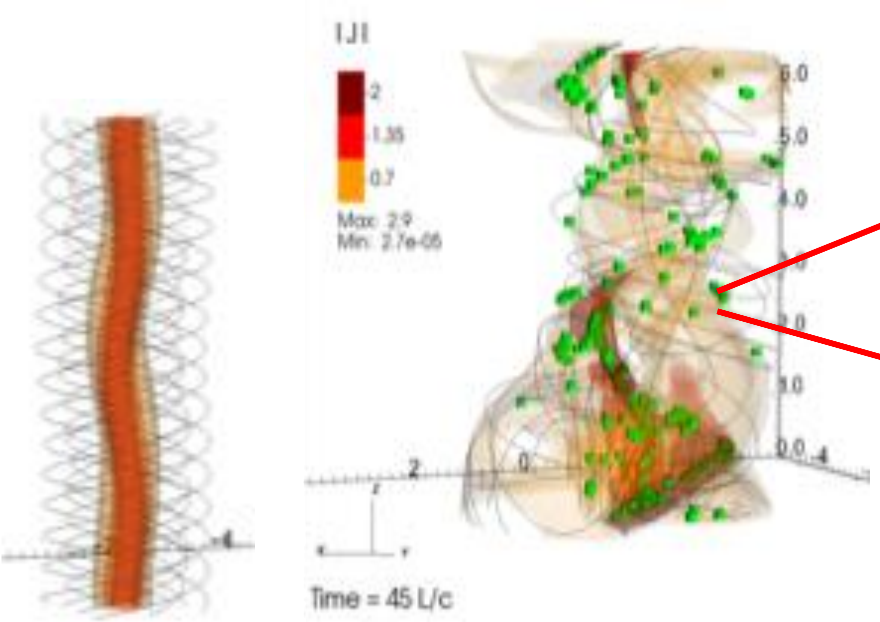


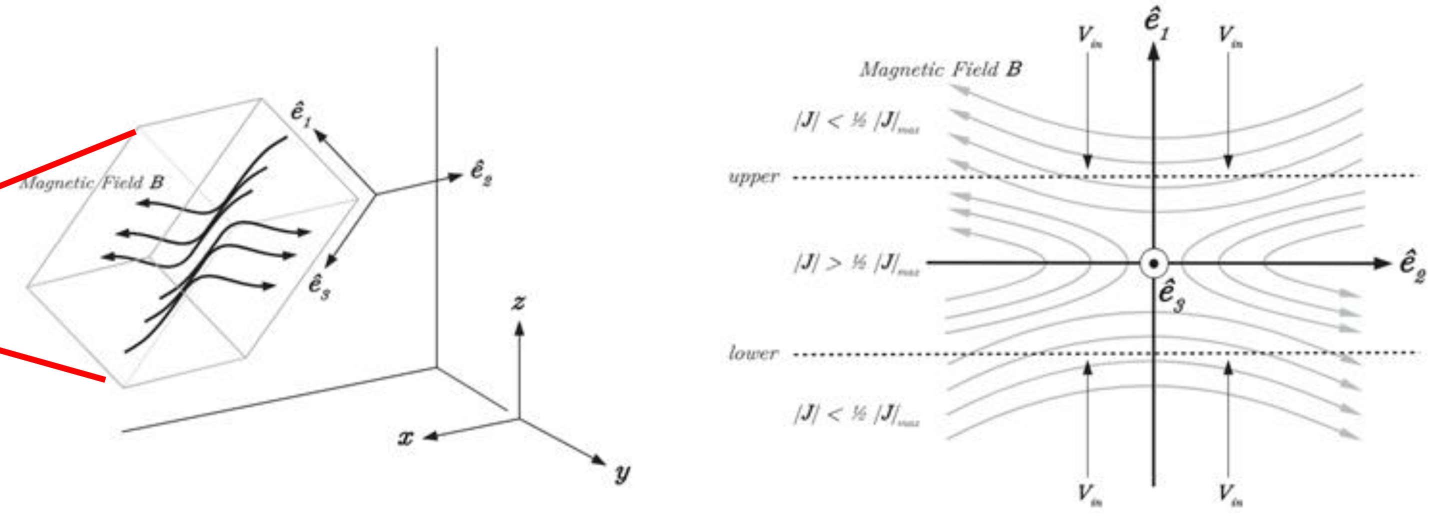
Reconnection sites form due to turbulence
(B~ 0.1 -10 G)

Kadowaki, de Gouveia Dal Pino, Stone, ApJ 2018;
Kadowaki, de Gouveia Dal Pino, Medina-Torrejon +ApJ 2021

Identification of Turbulence-Driven Fast Reconnection layers (CS) in Relativistic MHD Jets

- Detection algorithm of reconnection layers (as in Zhdankin et al. 2013) extended to 3D relativistic analysis

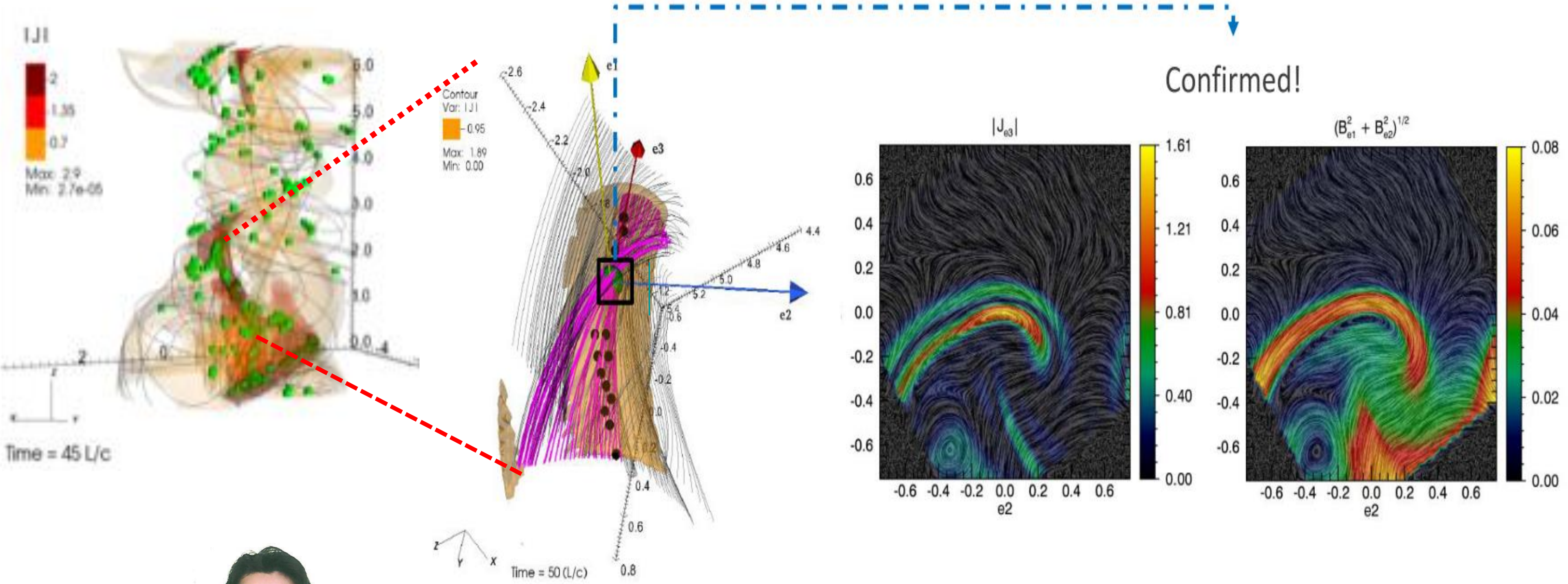




- Identify J_{max}
- Measure local v_{in}
- Measure local Δ

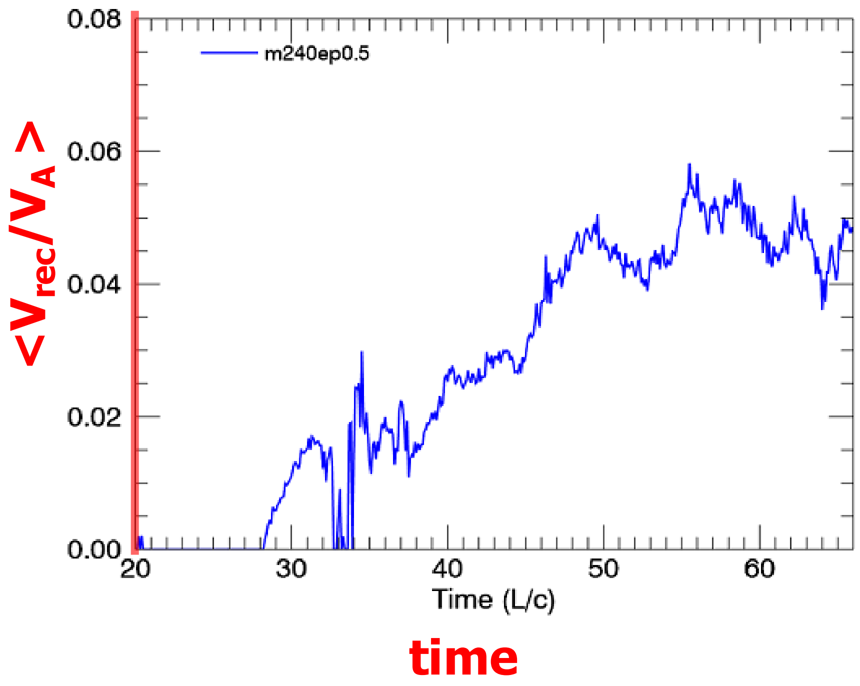
Kadowaki, de Gouveia Dal Pino, Stone, ApJ 2018;
Kadowaki, de Gouveia Dal Pino, Medina-Torrejon +ApJ 2021

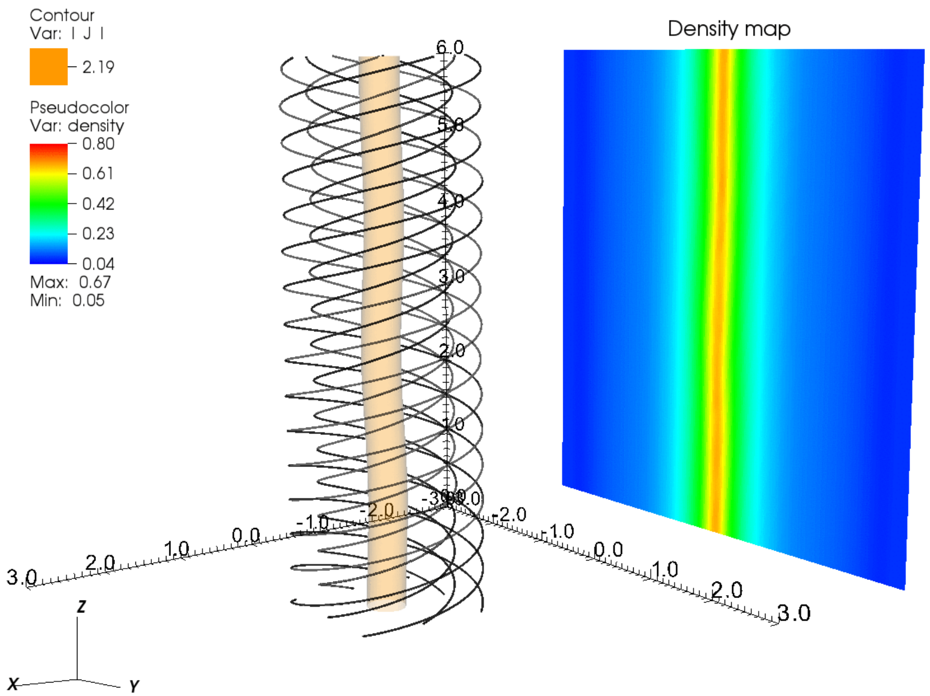
Identification of Fast Reconnection driven by Kink in Relativistic Jets



Kadowaki, de Gouveia Dal Pino, Medina-Torrejon + ApJ 2021

Fast Reconnection Rate driven by Kink Turbulence in Relativistic Jets

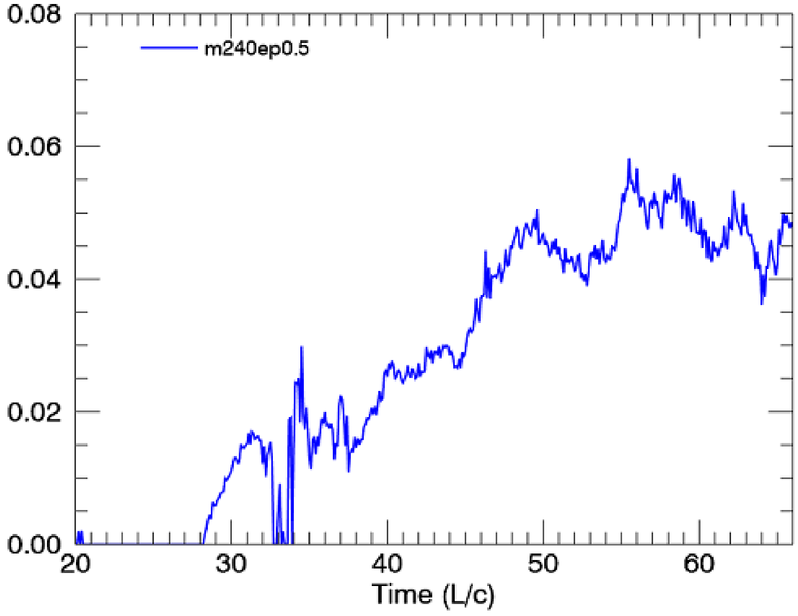




Kadowaki, de Gouveia Dal Pino +, ApJ 2021

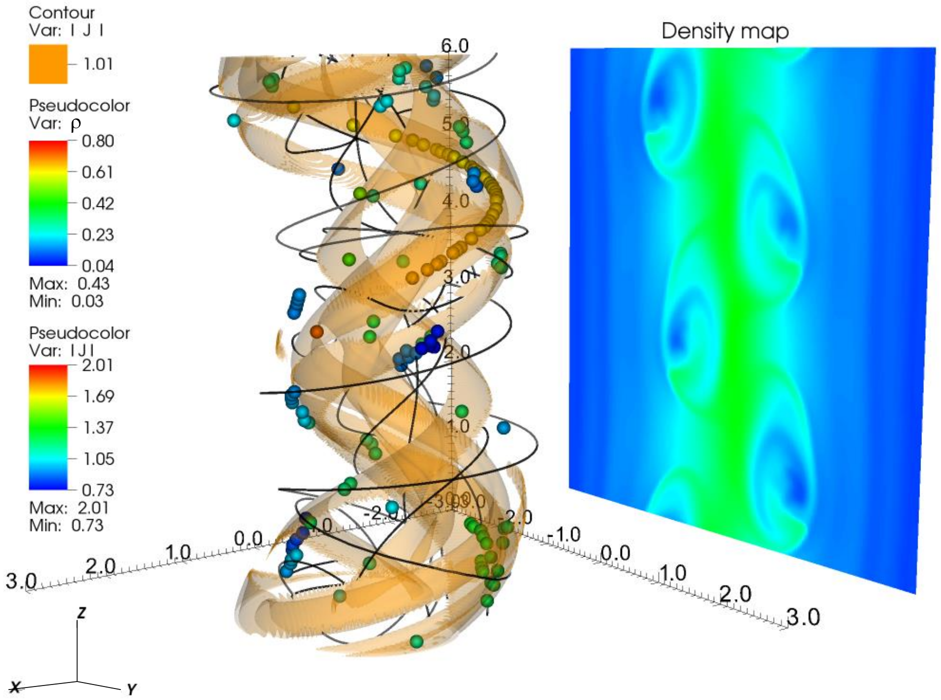
Fast Reconnection Rate driven by Kink Turbulence in Relativistic Jets

Maximum v_{rec} ~0.4 V_A



$<V_{rec}/V_A>$

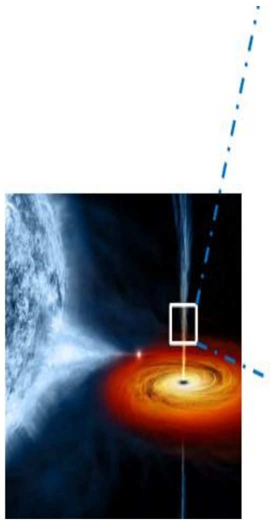
time



➢ $<V_{rec}> \approx 0.05\ V_A$ -> Fast reconnection: key for efficient particle acceleration

Kadowaki, de Gouveia Dal Pino + ApJ 2021

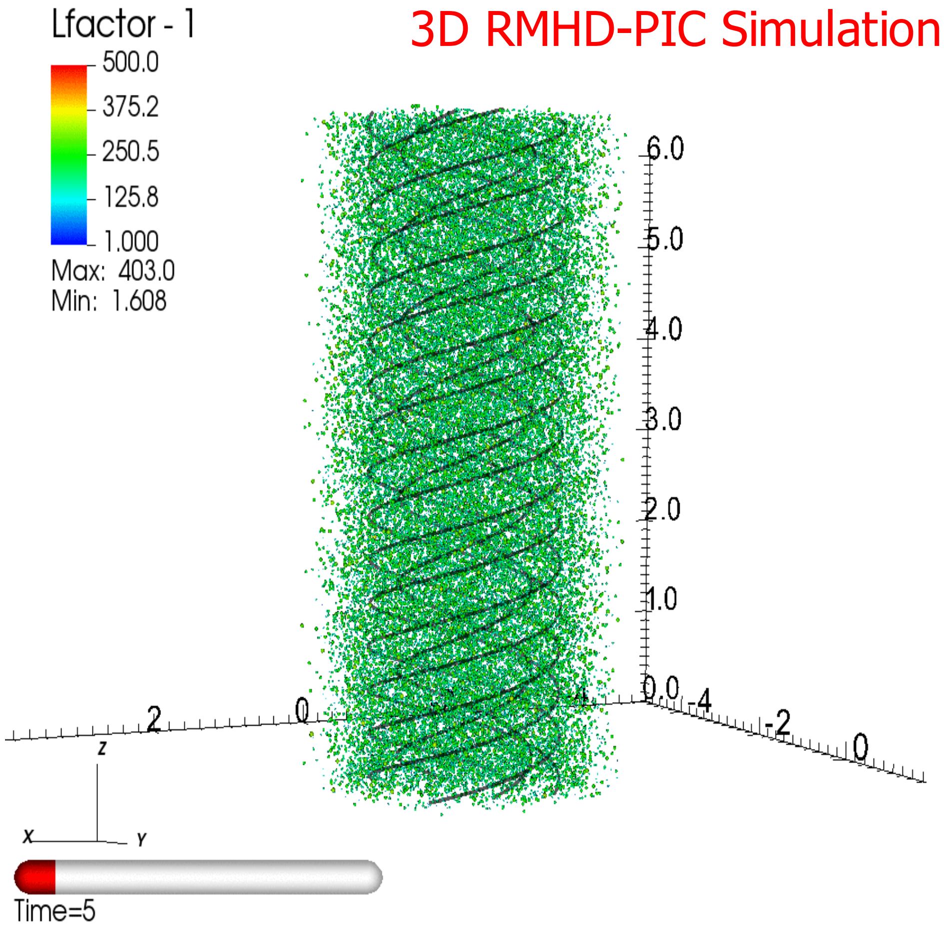
Early Acceleration of Particles by Turbulence-Driven Reconnection (**TDR**) with Particles Evolving with Relativistic Jet



(σ~1)

(B~ 0.1 G)

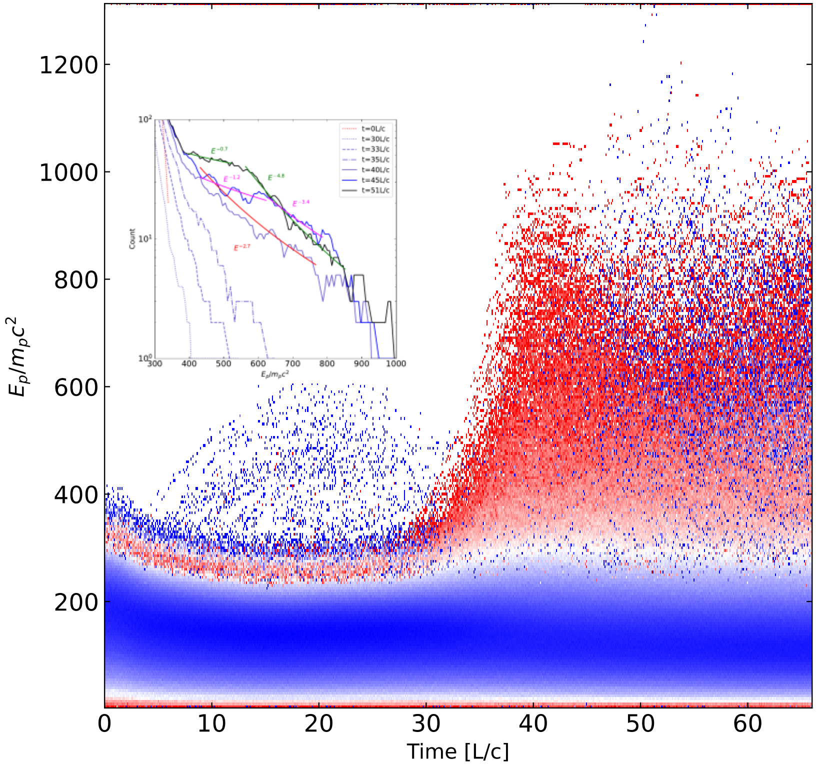
3D RMHD-PIC Simulation



$\sigma = B^2/\gamma^2 \rho h$ ~1

L= 5 10^{-7} pc

B~ 0.1 G



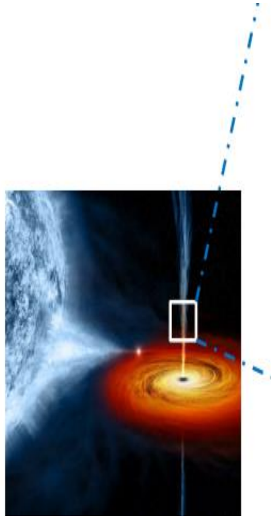
L= 5 10^{-7} pc

Particles accelerated for:

t= 60 L/c ~ 1 hr

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

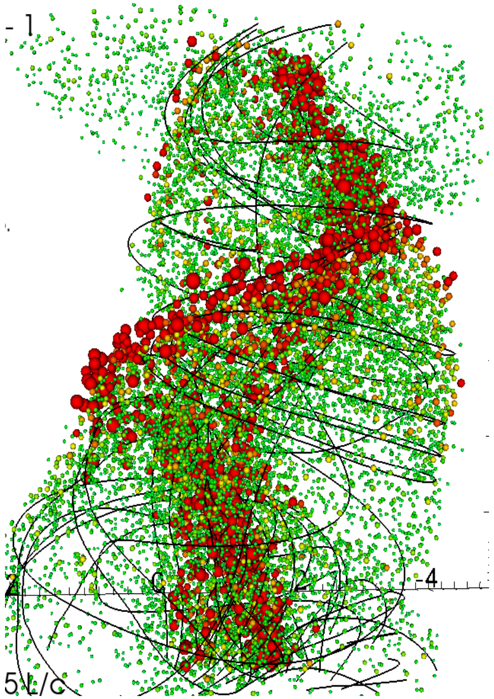
Early Acceleration of Particles by Turbulence-Driven Reconnection (**TDR**) with Particles Evolving with Relativistic Jet

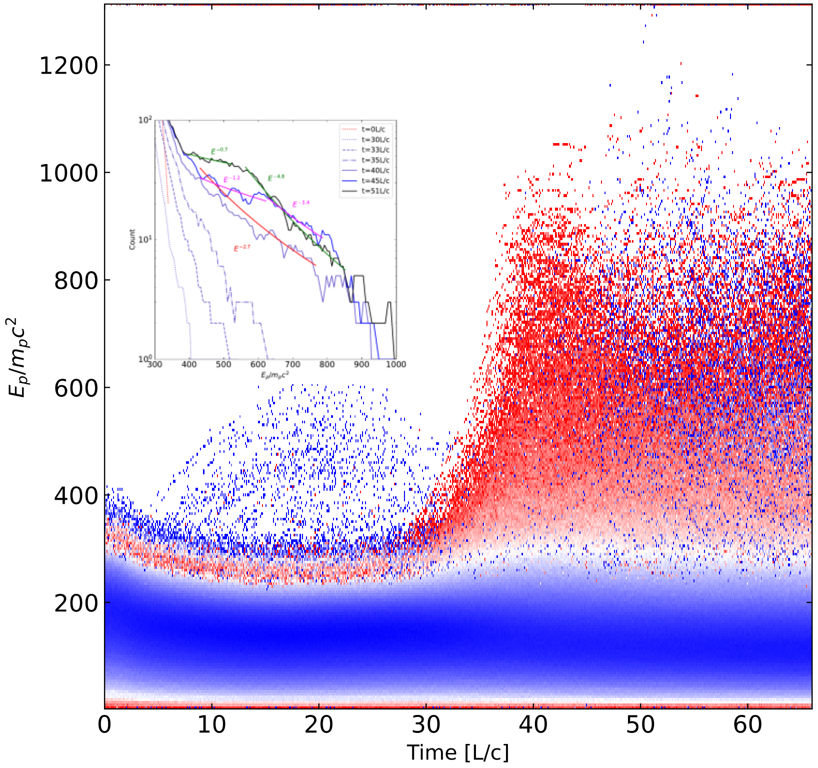


(σ~1)

(B~ 0.1 G)

3D RMHD-PIC Simulation





L= 5 10^{-7} pc

Particles accelerated for:

t= 60 L/c ~ 1 hr

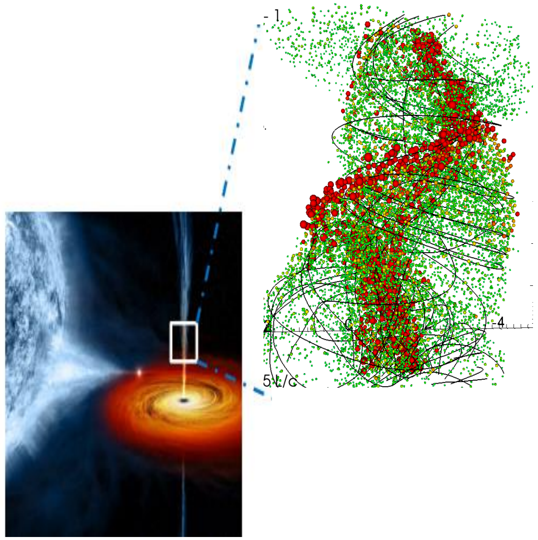
$\sigma = B^2/\gamma^2\rho h$ ~1

L= 5 10^{-7} pc

B~ 0.1 G

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

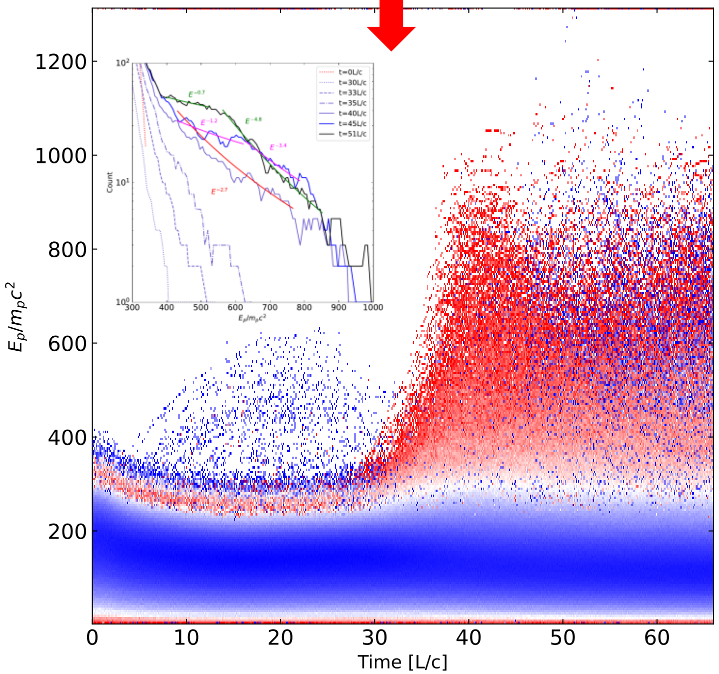
Acceleration of test particles by Turbulence-Driven Reconnection (**TDR**) in Relativistic MHD Jets continues up to VHE and UHEs



(B~ 0.1 G)

(σ~1)

3D RMHD-PIC scale probes initial acceleration



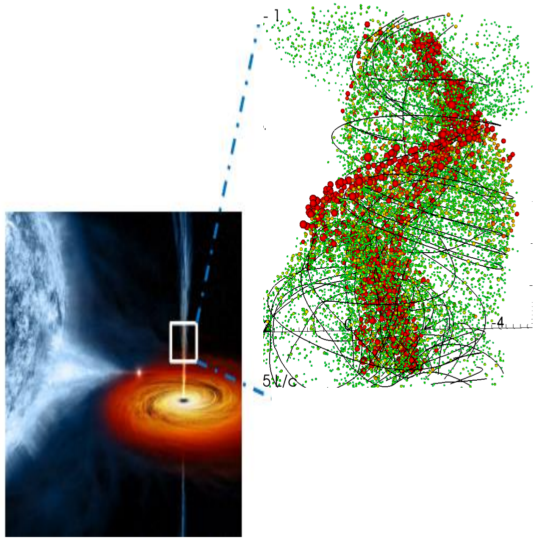
L= 5 10^{-7} pc
Particles accelerated for: t= 60 L/c ~ 1 hr

L= 3.6 10^{-5} pc
Particles accelerated over: 0.01-0.1 pc scale

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

Medina-Torrejon, de Gouveia Dal Pino+ ApJ 2021

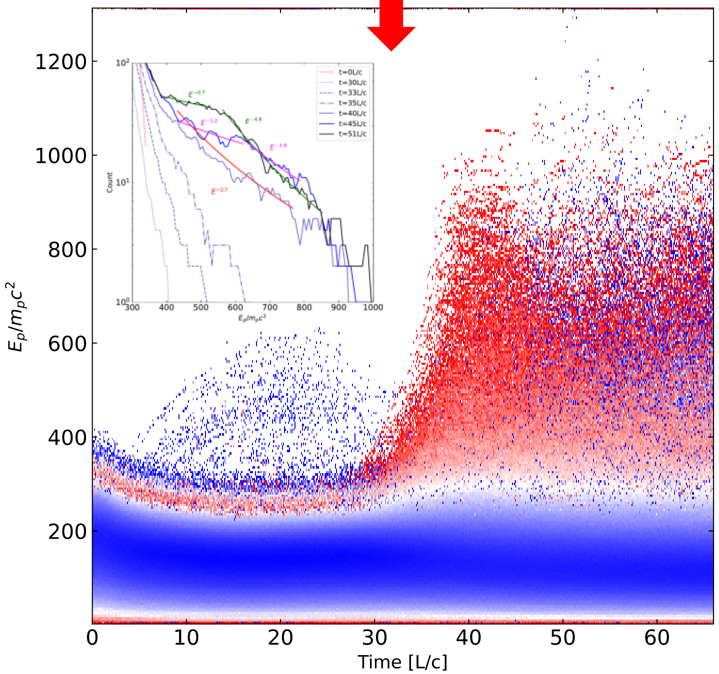
Acceleration of test particles by Turbulence-Driven Reconnection (**TDR**) in Relativistic MHD Jets continues up to VHE and UHEs



(B~ 0.1 G)

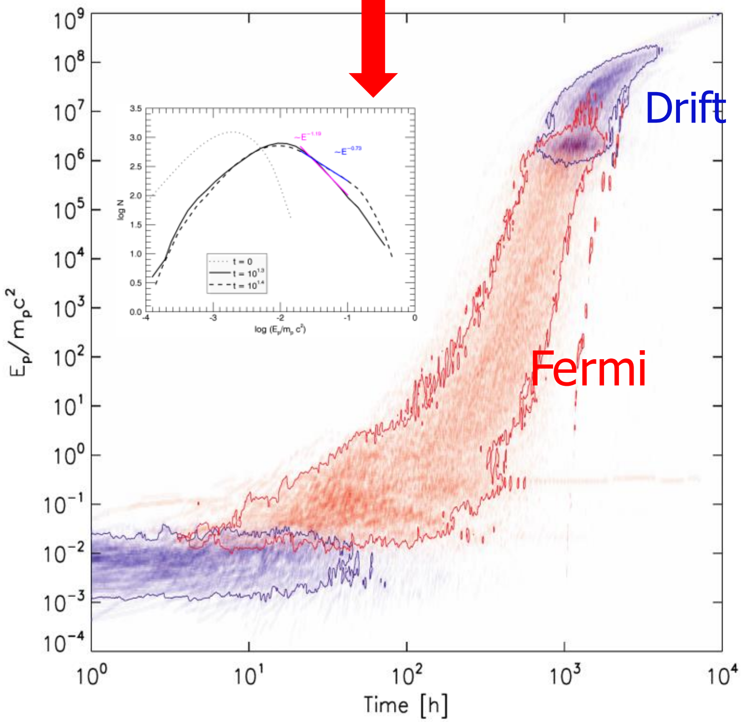
(σ~1)

3D RMHD-PIC scale probes initial acceleration



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

3D RMHD scale probes maximum acceleration

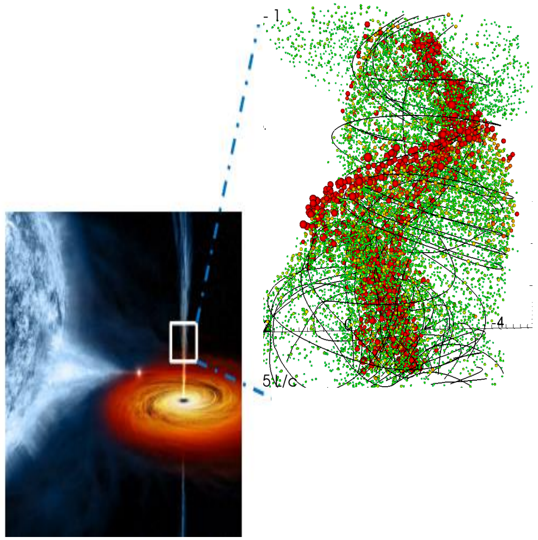


L= 3.6 10^{-5} pc
Particles accelerated over: 0.01-0.1 pc scale

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

Medina-Torrejon, de Gouveia Dal Pino+ ApJ 2021

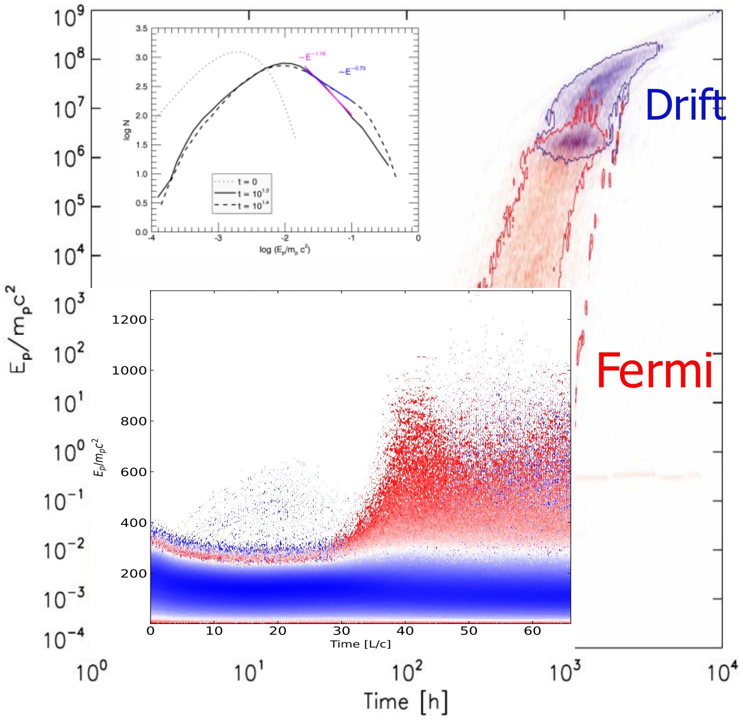
Acceleration of test particles by Turbulence-Driven Reconnection (**TDR**) in Relativistic MHD Jets continues up to VHE and UHEs



3D RMHD-PIC scale probes initial acceleration

Particles undergo exponential Fermi acceleration up to VHE within turbulent reconnection layers whose sizes span from the small resistive scale to the turbulence injection scale.

3D RMHD scale probes maximum acceleration



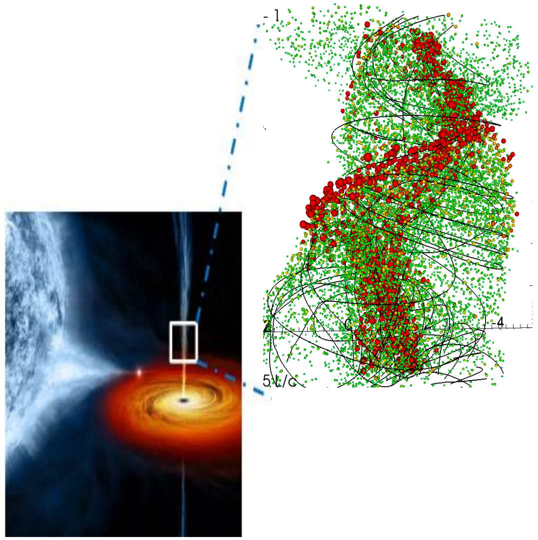
L= 5 10^{-7} pc
Particles accelerated for: t= 60 L/c ~ 1 hr

L= 3.6 10^{-5} pc
Particles accelerated over: 0.01-0.1 pc scale

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

Medina-Torrejon, de Gouveia Dal Pino+ ApJ 2021

Acceleration of test particles by Turbulence-Driven Magnetic Reconnection in Relativistic MHD Jets continues up to VHE and UHEs

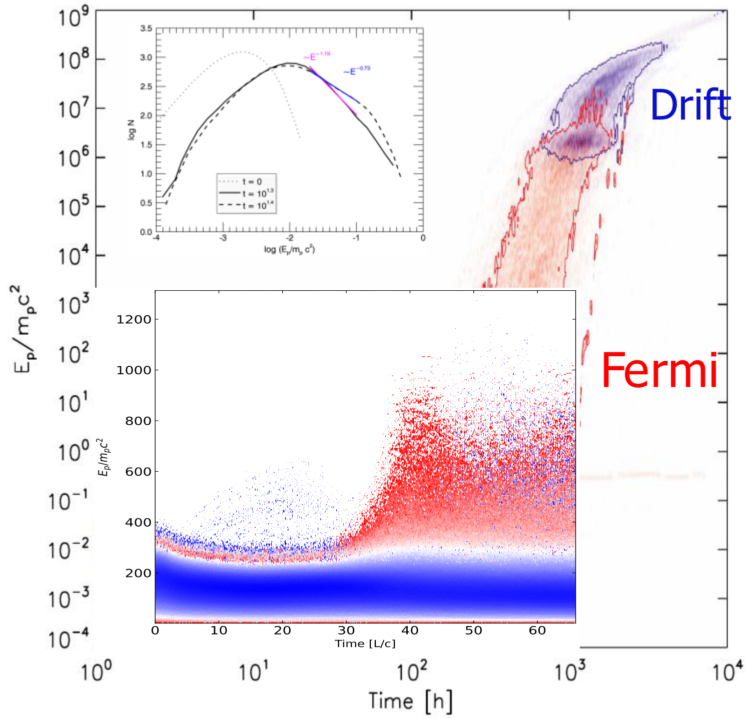


3D RMHD-PIC scale probes initial acceleration

Particles undergo exponential Fermi acceleration up to VHE within turbulent reconnection layers whose sizes span from the small resistive scale to the turbulence injection scale.

Particles accelerated up to 10^{17} eV -> energy enough to produce TeV Gamma-Rays and Neutrinos !

3D RMHD scale probes maximum acceleration

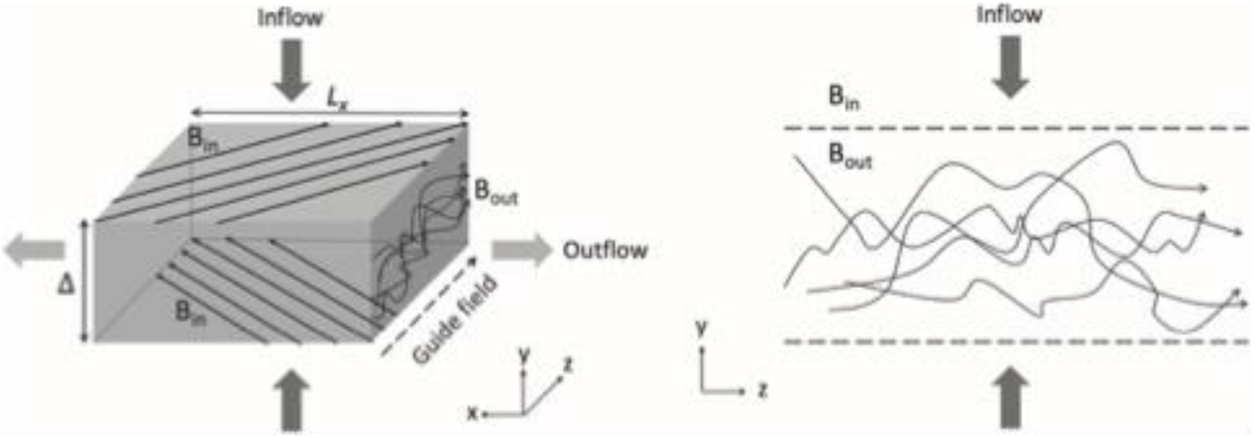


L= 3.6 10^{-5} pc
Particles accelerated over: 0.01-0.1 pc scale

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

Medina-Torrejon, de Gouveia Dal Pino+ ApJ 2021

Acceleration time in turbulence-driven reconnection a crucial parameter



(a) (b)

- $t_{acc,Fermi}$ ~ *constant w/* E_p
- *But depends on* v_{in}, Δ *and* θ

$$\text{Condition I (small } \theta, \text{small } v_{in}) : \ t_{acc} \sim \frac{3\Delta}{\sin\theta v_{in}},$$

$$\text{Condition II (large } \theta, \text{small } v_{in}) : \ t_{acc} \sim \frac{3\Delta}{2v_{in}},$$

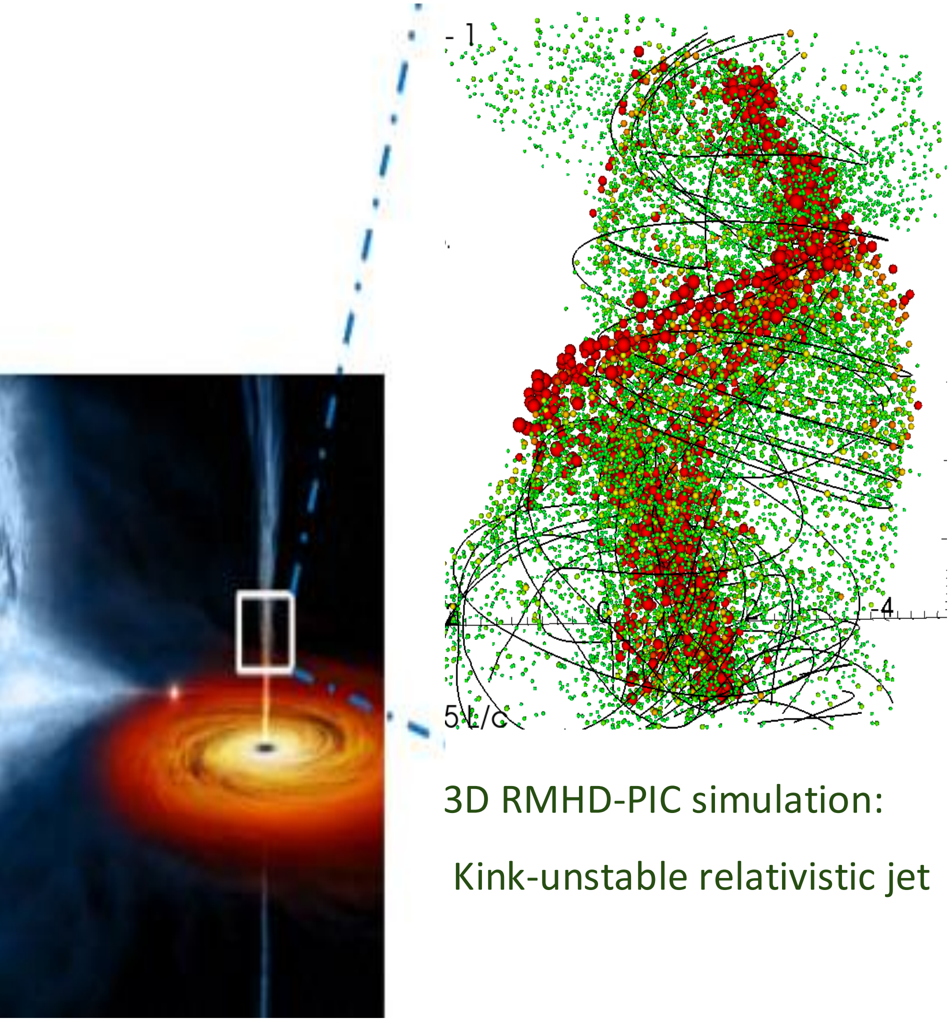
$$\boxed{\text{Condition III (large } \theta, \text{large } v_{in}) : \ t_{acc} \sim \frac{4\Delta}{c d_{ur}},}$$

Fastest reconnection acceleration

$$d_{ur} \approx \frac{2\beta_{in}(3\beta_{in}^2 + 3\beta_{in} + 1)}{3(\beta_{in} + 0.5)(1 - \beta_{in}^2)} \qquad \beta_{in} = v_{in}/c$$

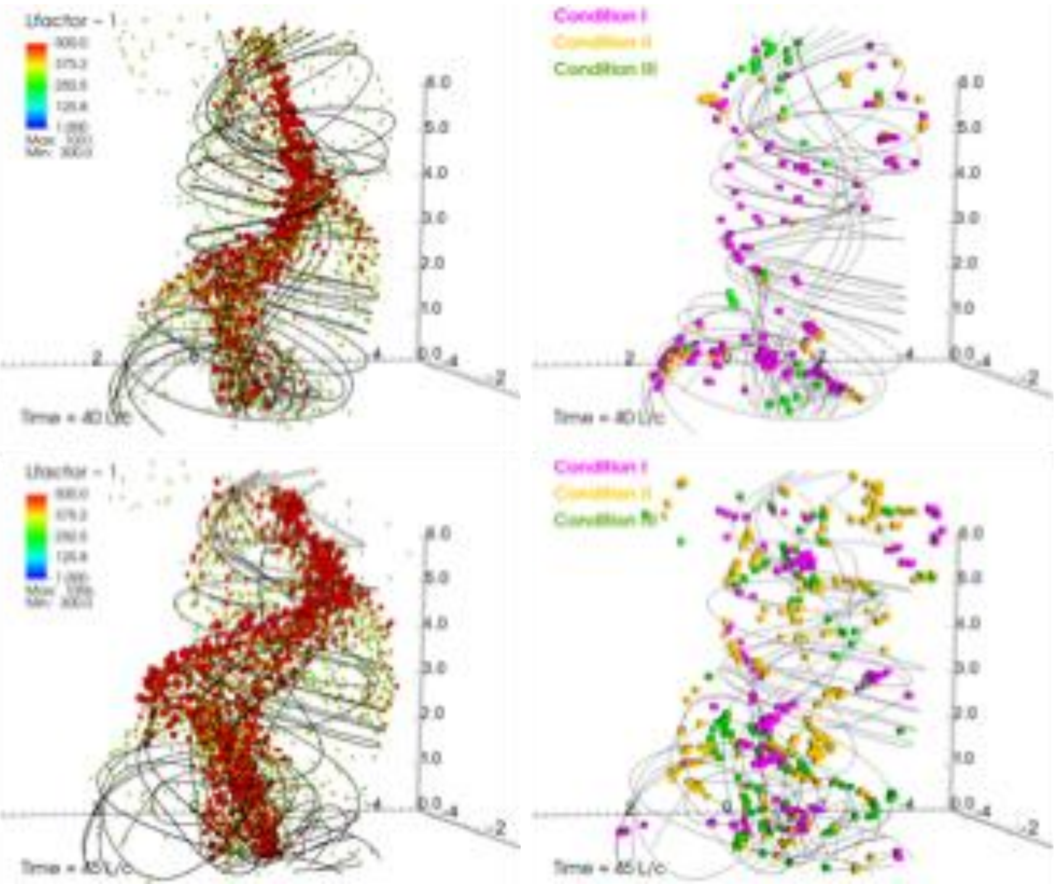
Xu & Lazarian, ApJ 2023

Particle Acceleration time in turbulence driven reconnection



3D RMHD-PIC simulation:

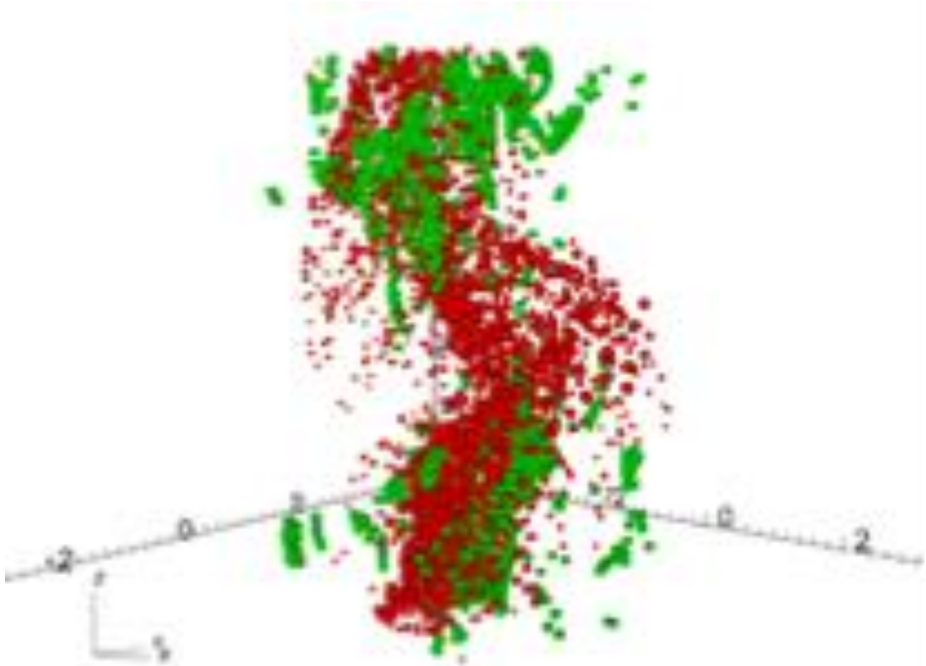
Kink-unstable relativistic jet

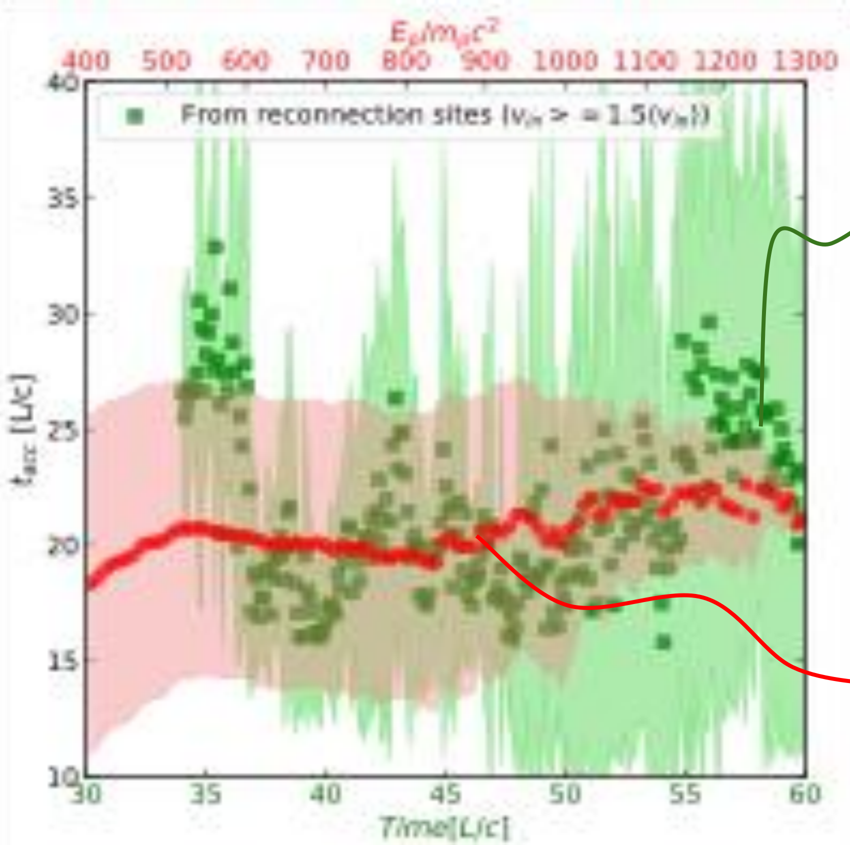


Medina-Torrejon, de Gouveia Dal Pino+, *ApJ*, (21, 23)

de Gouveia Dal Pino & Medina-Torrejon, *ApJ*, (2026)

Particle Acceleration time in turbulence driven reconnection





$$\boxed{t_{acc} \sim \frac{4\Delta}{c d_{ur}}}$$

$$d_{ur} \approx \frac{2\beta_{in}(3\beta_{in}^2 + 3\beta_{in} + 1)}{3(\beta_{in} + 0.5)(1 - \beta_{in}^2)},$$

(Xu & Lazarian, 2023)

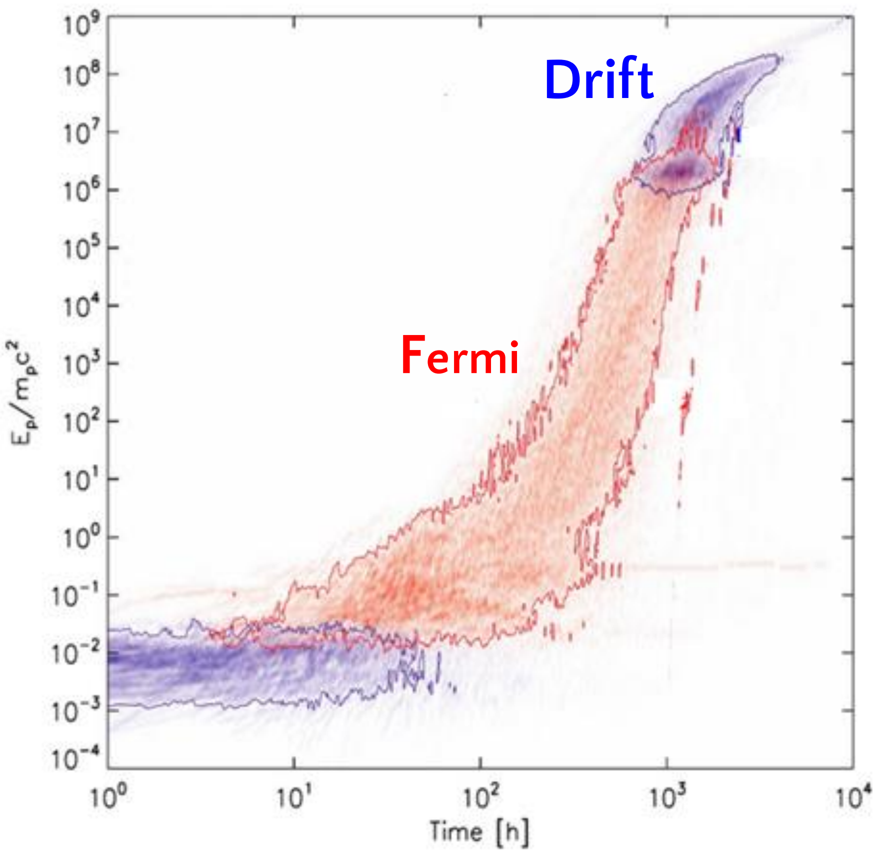
$$\boxed{t_{acc} = \frac{E_p}{dE_p/dt}}$$

de Gouveia Dal Pino & Medina-Torrejon, *ApJ* (2026)

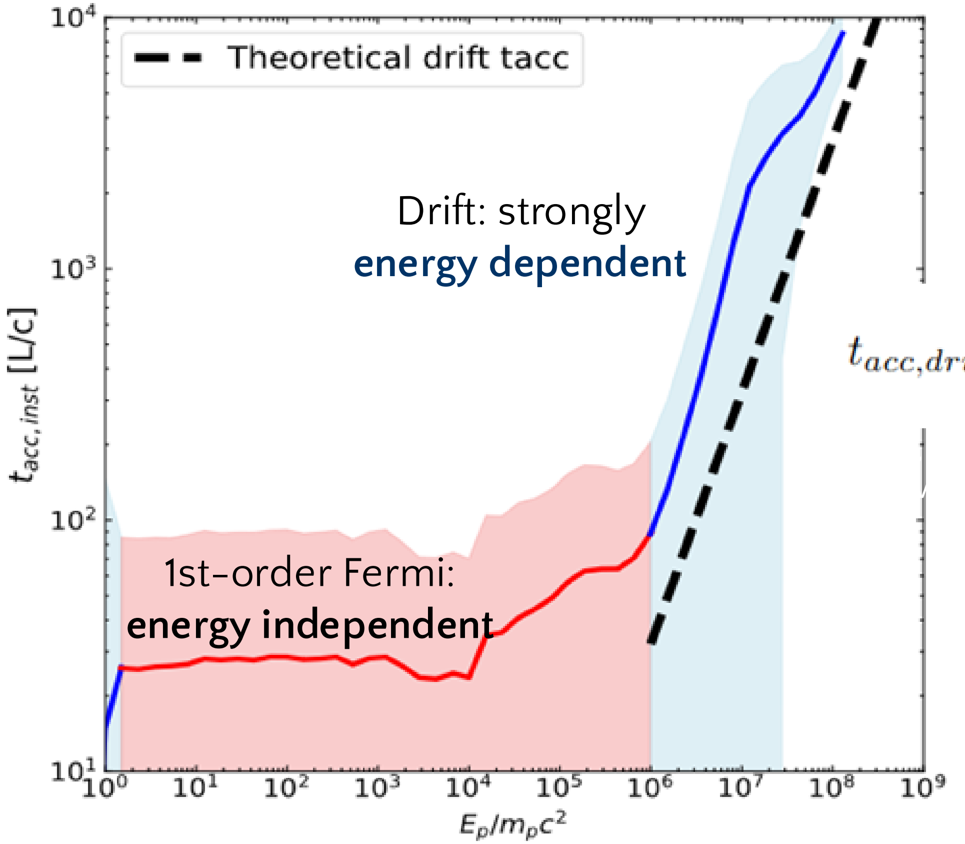
Acceleration Time inside CS: independent of E (as expected from Fermi acceleration)

Particle Acceleration time in turbulence driven reconnection

Medina-Torrejon, de Gouveia Dal Pino et al., *ApJ*, (2021; 2023)



de Gouveia Dal Pino & Torrejon, *ApJ*, (2026)



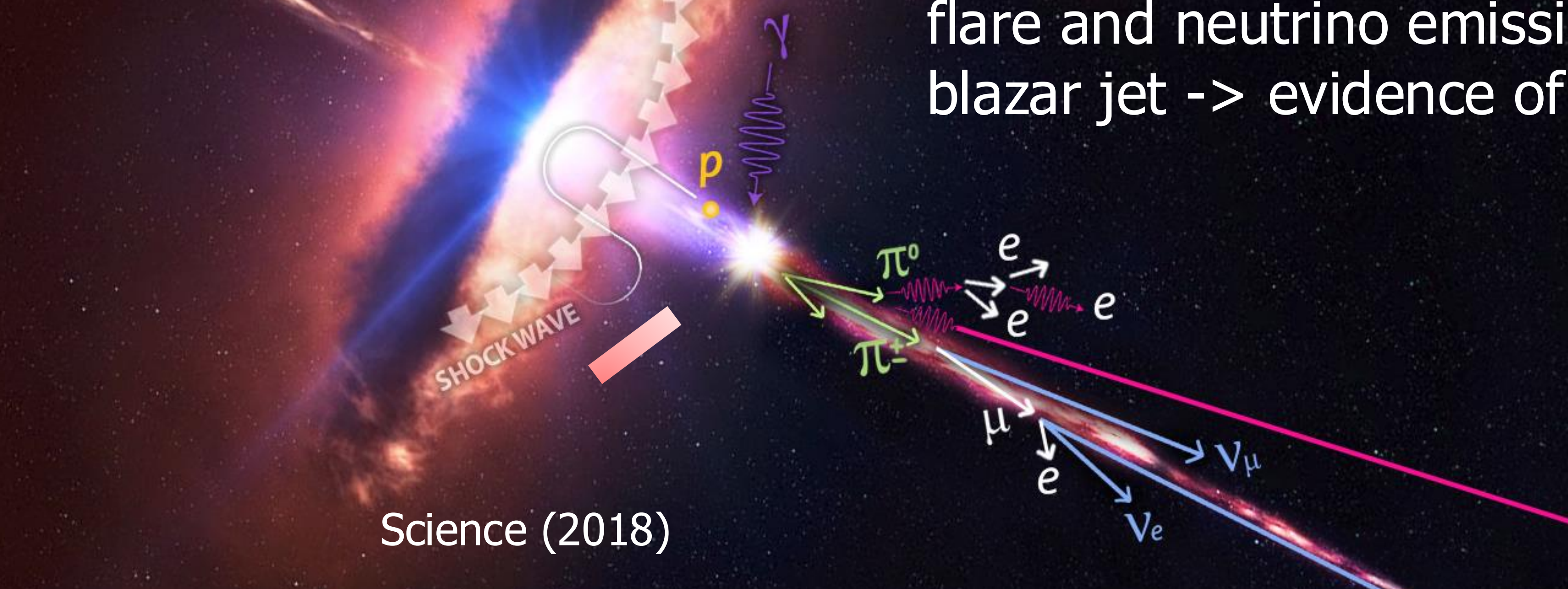
$$t_{acc,drift} \simeq \frac{E_p}{qBv_{rec}}$$

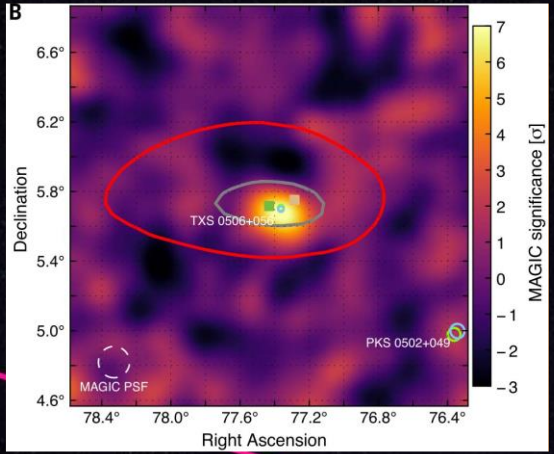
Fermi acceleration within CS is dominant up to VHE: important to shape VHE emission spectrum: in contrast to recent works based on extrapolation from microscopic PIC simulations, suggesting **drift acceleration as dominant** (e.g., **Zhang, Sironi, Giannios, 2021**)

Blazar TXS 0506+056

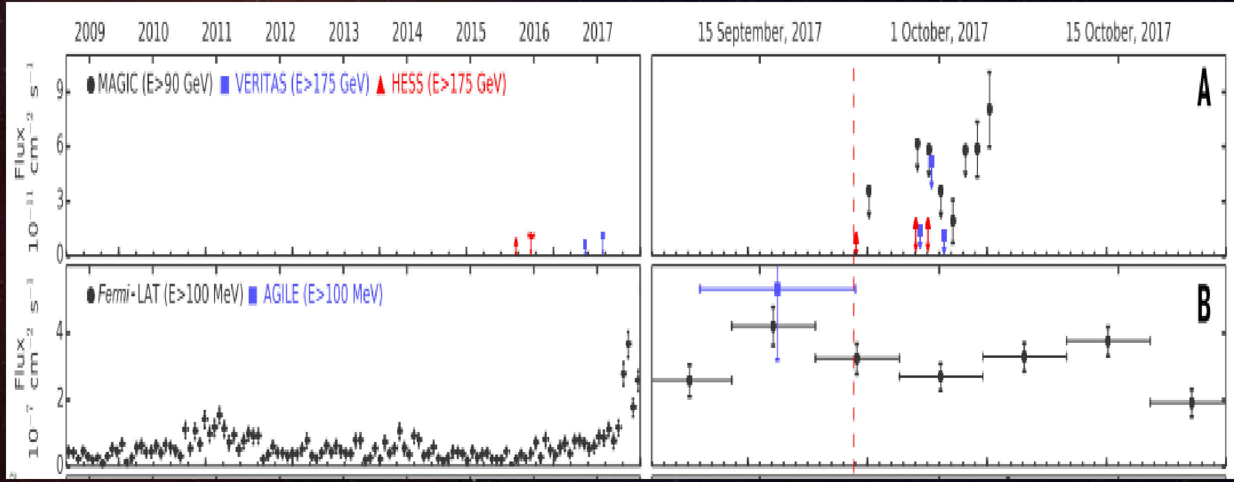
First simultaneous observation of γ-ray flare and neutrino emission in AGN blazar jet -> evidence of VHE Protons

AGN Jets





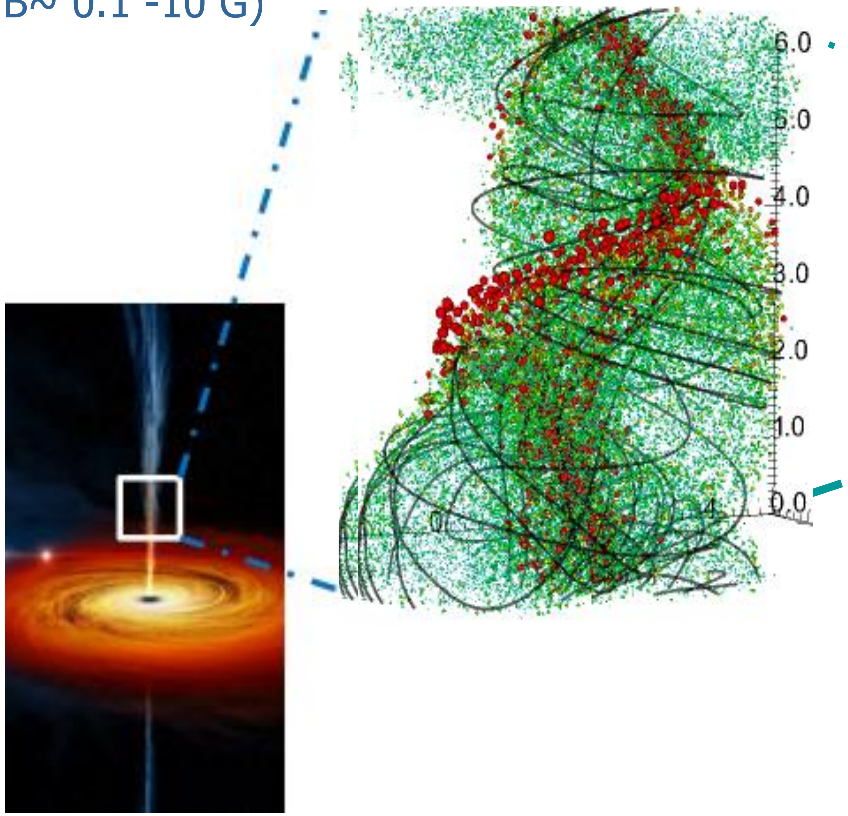
Science (2018)

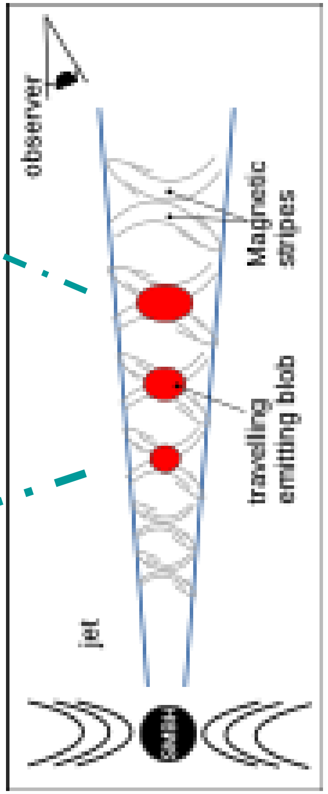


Turbulence-Driven Reconnection (TDR) Fermi Acceleration Model of Relativistic Jet to explain Very High Energy (VHE) emission

$$\sigma = B^2/\gamma^2 \rho h \sim 1$$

(B~ 0.1 -10 G)



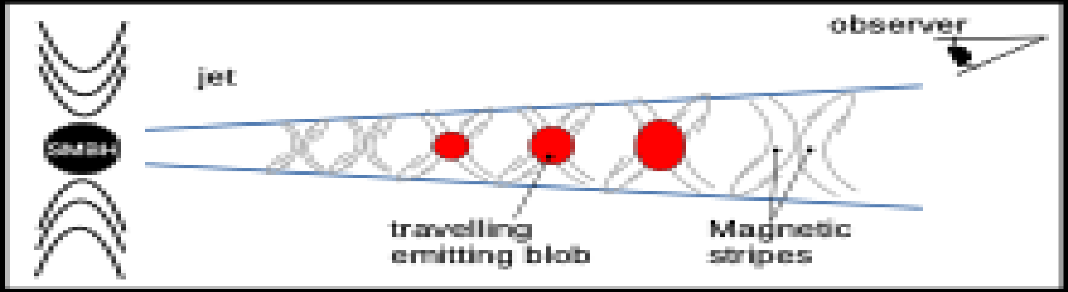


Background reconnection: stripped jet model (Giannios & Usdenszki 2019) embedded in turbulence which makes reconnection fast

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

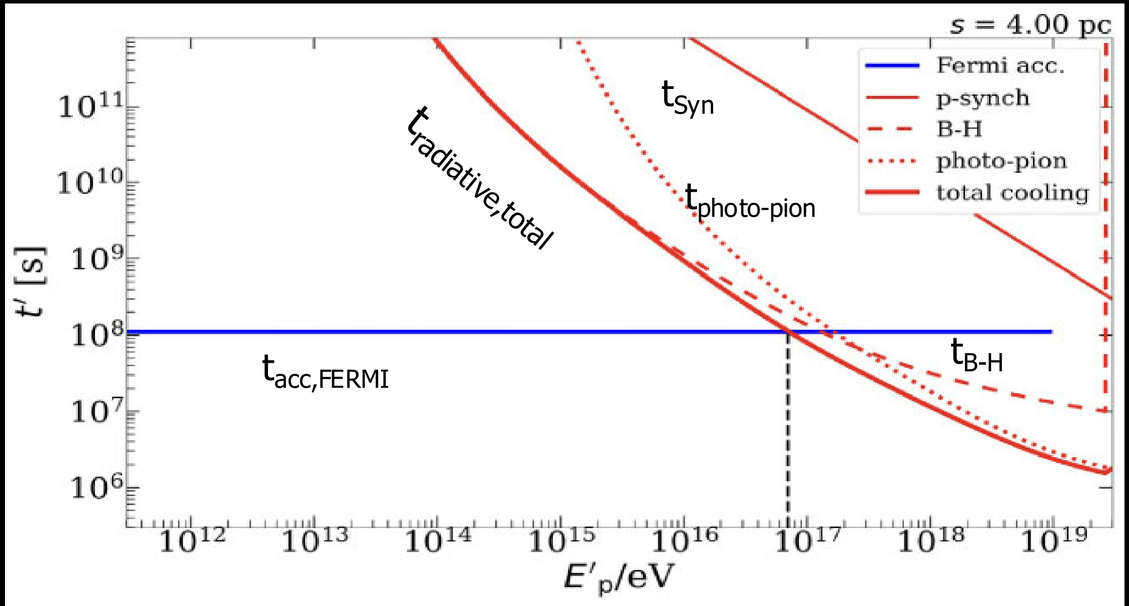
de Gouveia Dal Pino, Rodriguez-Ramirez, del Valle MNRAS 2025

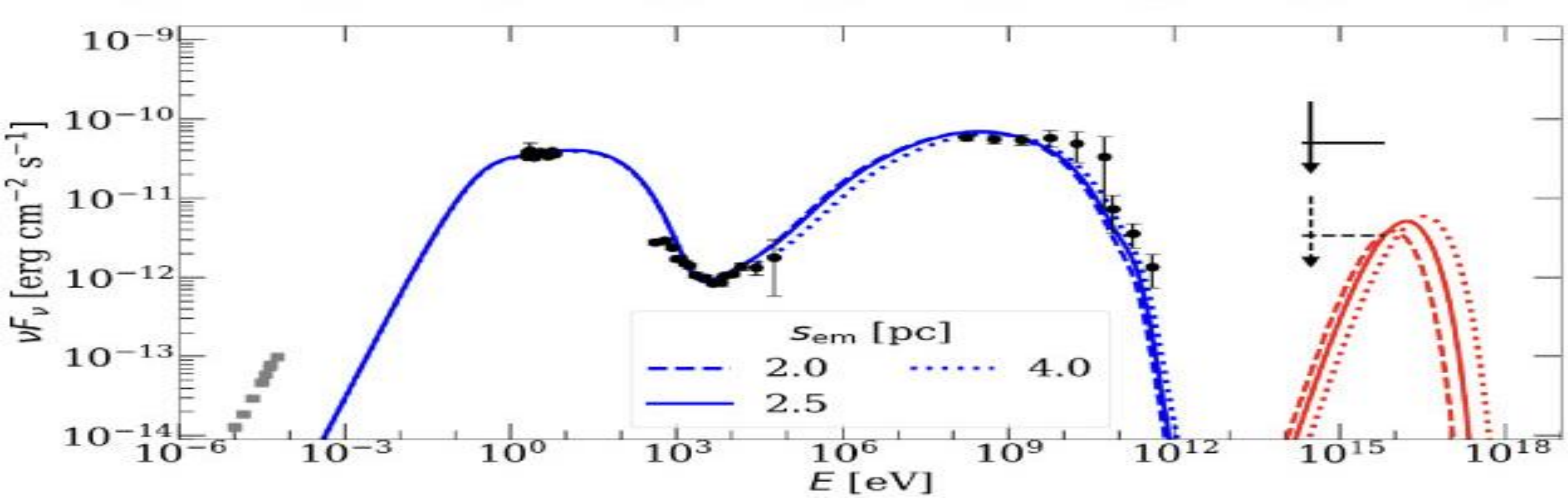
Turbulence-Driven Reconnection (**TDR**) Fermi Acceleration for TXS 0506+056



(Xu & Lazarian, ApJ 2023)

- **Fermi t_{acc}~ constant w/ E_p**
  (de Gouveia Dal Pino & Lazarian 2005)
- $t_{acc} \sim \frac{4\Delta}{c d_{ur}}$ Fast reconnection





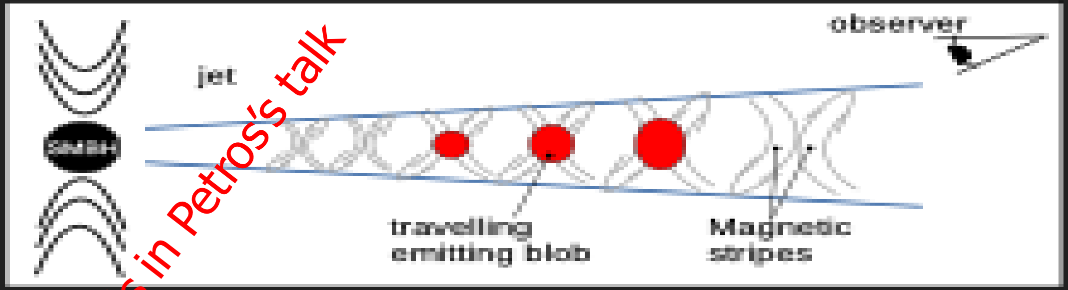
Model produces:

- neutrinos and VHE (photo-pion)
- observed time delay between VHE γ-rays appearing later than neutrino

Δt = 0.44 yr.

de Gouveia Dal Pino, Rodriguez-Ramirez, del Valle MNRAS 2025

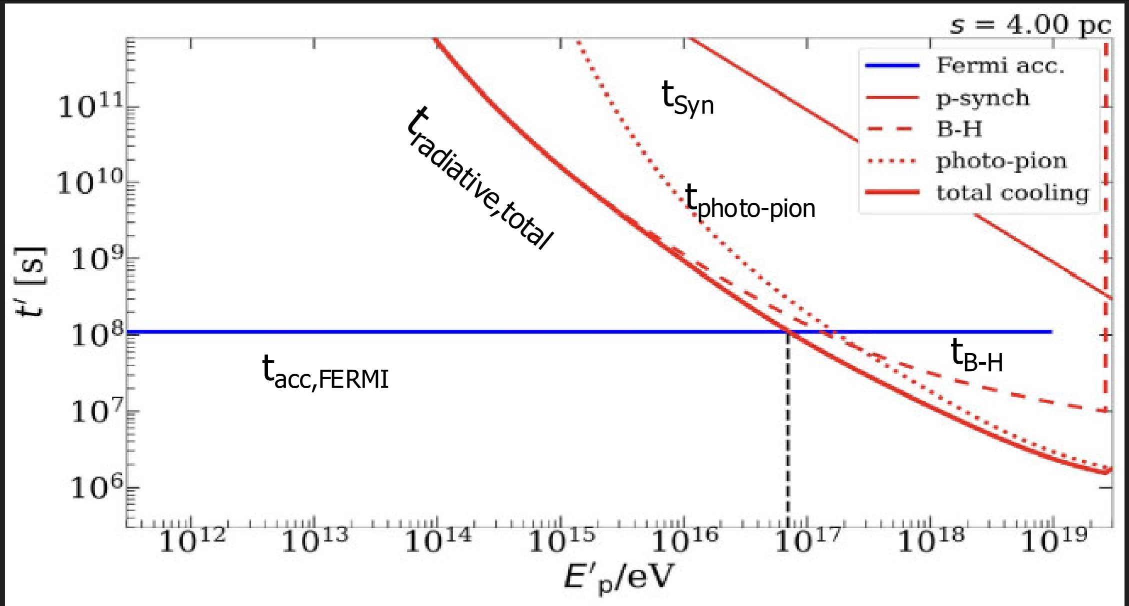
Turbulence-Driven Reconnection (**TDR**) Fermi Acceleration for TXS 0506+056

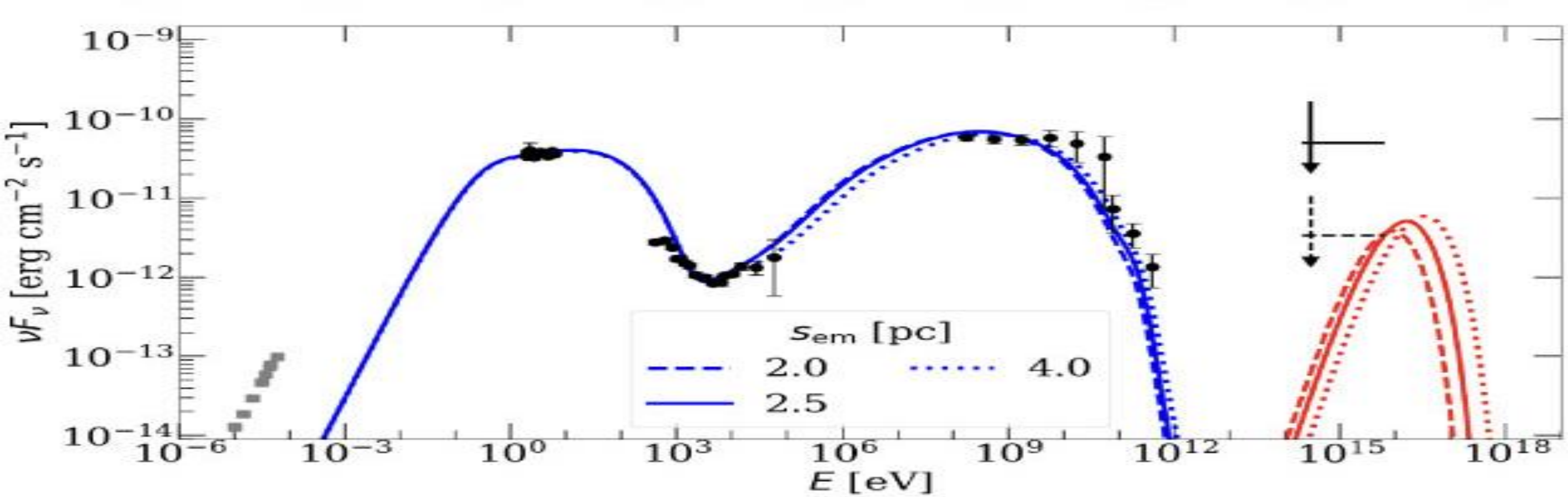


More details in Petros's talk

(Xu & Lazarian, ApJ 2023)

- **Fermi t_{acc}~ constant w/ E_p** (de Gouveia Dal Pino & Lazarian 2005)
- $t_{acc} \sim \frac{4\Delta}{c d_{ur}}$ Fast reconnection





Model produces:

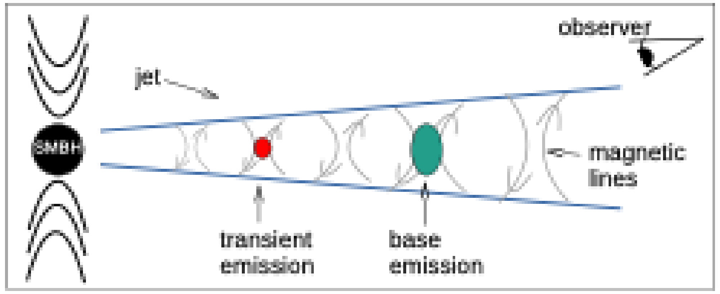
- neutrinos and VHE (photo-pion)
- observed time delay between VHE γ-rays appearing later than neutrino

Δt = 0.44 yr.

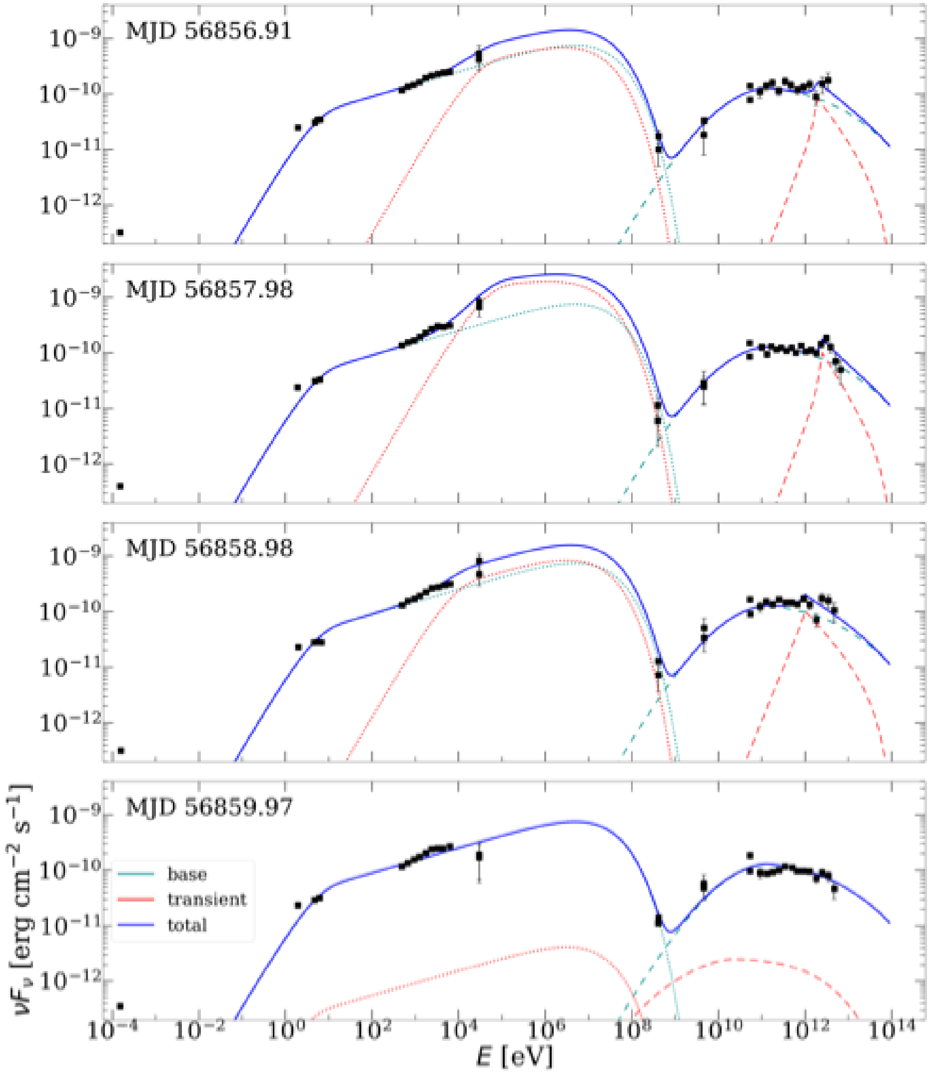
de Gouveia Dal Pino, Rodriguez-Ramirez, del Valle MNRAS 2025

TeV Spectral Spike of Mrk 501 explained by Turbulence-Driven Reconnection (TDR) Fermi Acceleration

Blazar Mrk 501

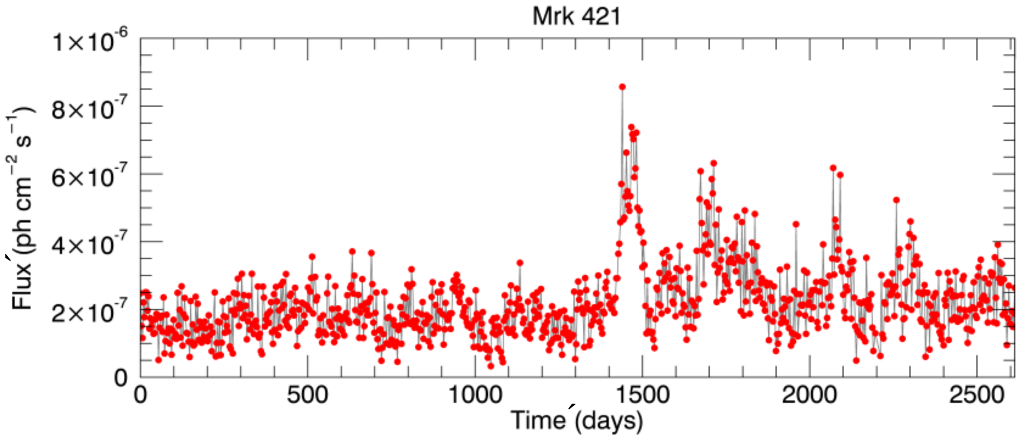


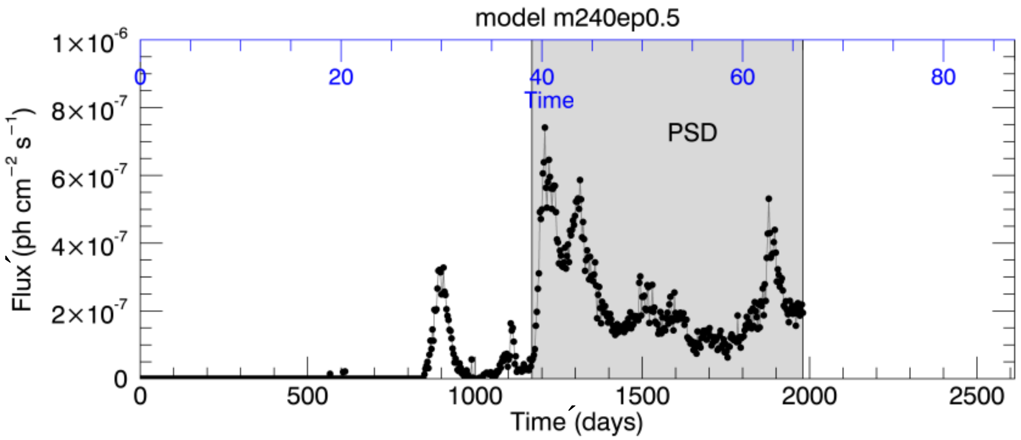
TeV spikes: **explained by a leptonic transient emission in a compact zone, located in a more magnetized and slower flow compared to the region that produced quiescent SED component.**



Formiga-Paiva, de Gouveia Dal Pino, Rodriguez-Ramirez, Barres de Almeida, & Diaz-Cortes, JHEAp 2026

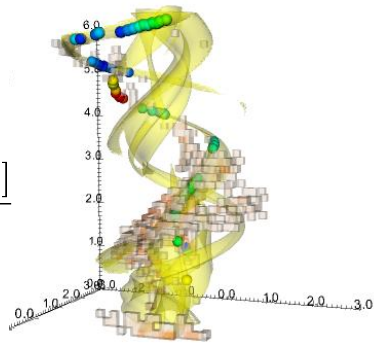
Fast Turbulent-Driven Reconnection (TDR) able to explain observed gamma-ray flux & variability in Blazar Jet: ex. MRK421





➢ **Observed gamma-ray flux** of MRK 421 Blazar (FERMI) (Kushwaha et al. 2017)

$$t_0 = \frac{\delta' \Delta t'_{obs}[cgs]}{\Delta t[c.u.]}$$



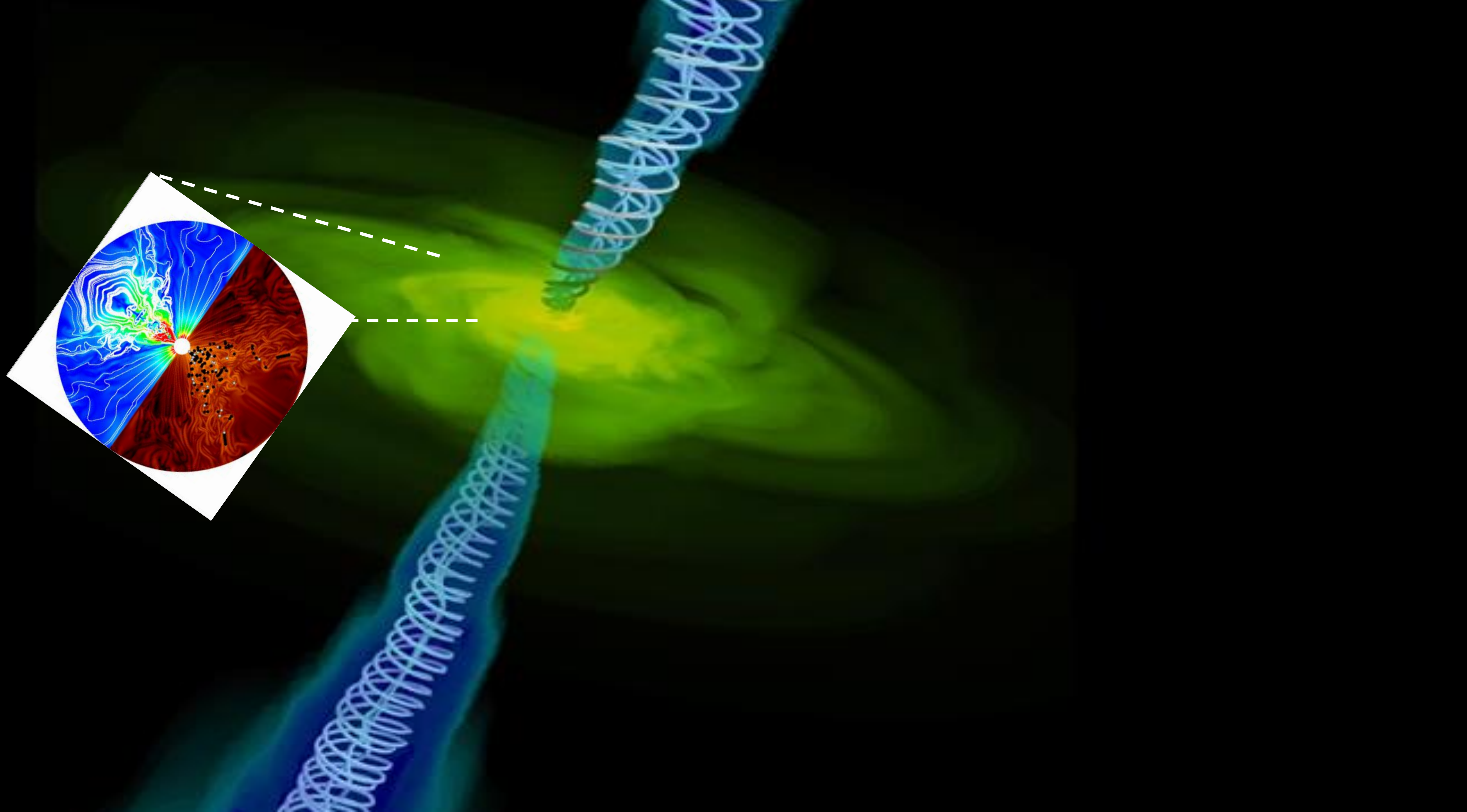
➢ **Simulated flux variability**

- Magnetic field: 3.7 G
- Doppler: δ=5
- Height of the Jet: ≈ 0.1 pc
- High density regions: ≈ 7 10^2 cm^{-3}
- Photon energy: 0.1 - 300 GeV

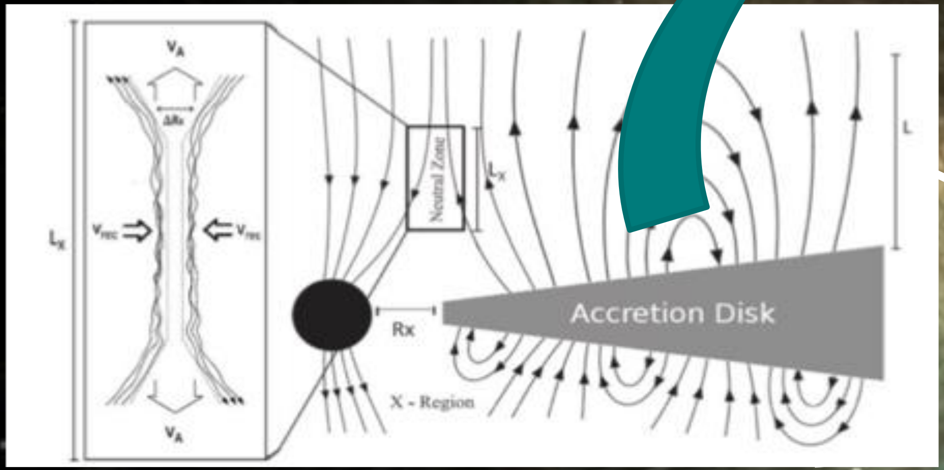
➢ Time variability and reconnection power compatible with observed blazar flare

Kadowaki, de Gouveia Dal Pino, Medina-Torrejon, Kowal, Mizuno & Kushwaha ApJ 2021

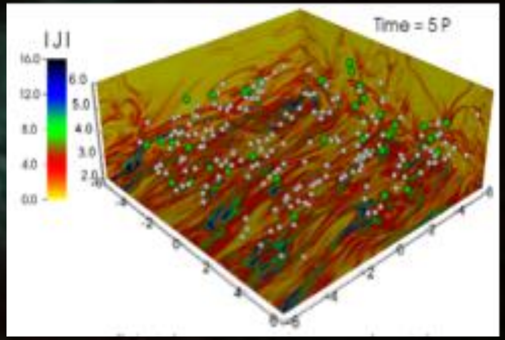
Turbulence-Driven Magnetic Reconnection (TDR) in Accretion Flows around Black Holes

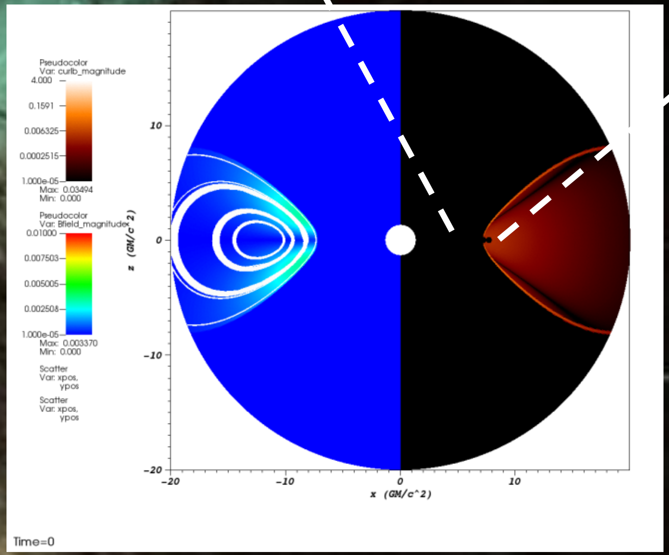


Turbulence-Driven Reconnection Acceleration in the accretion flow of BH



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;
Khiali & de Gouveia Dal Pino, MNRAS 2016

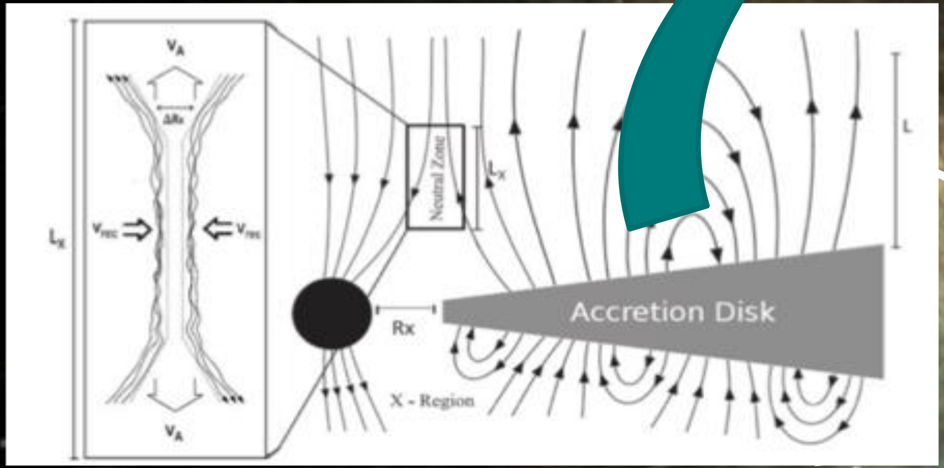


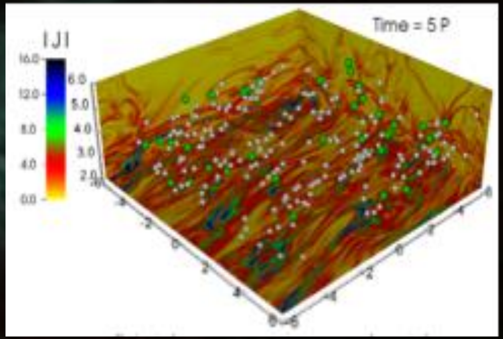


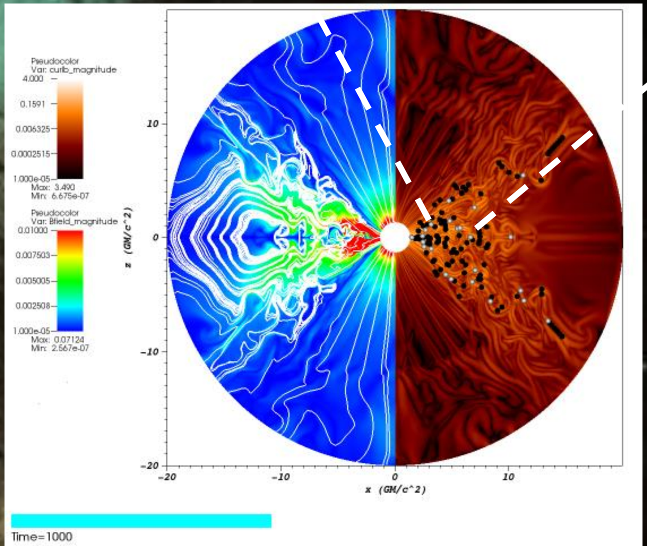
GRMHD simulations of accretion flows around BHs reconnection driven by magneto-rotational turbulence

Kadowaki, de Gouveia Dal Pino, Stone ApJ 2018;
de Gouveia Dal Pino et al. 2018; Kadowaki et al. 2019;
Rodriguez-Ramirez, deGDP, Alves-Batista MNRAS 2019; Vicentin et al., in prep.

Turbulence-Driven Reconnection Acceleration in the accretion flow of BH







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
Khiali & de Gouveia Dal Pino, MNRAS 2016

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

Kadowaki, de Gouveia Dal Pino, Stone ApJ 2018;
de Gouveia Dal Pino et al. 2018; Kadowaki et al. 2019;
Rodriguez-Ramirez, deGDP, Alves-Batista MNRAS 2019; Vicentin et al., in prep.

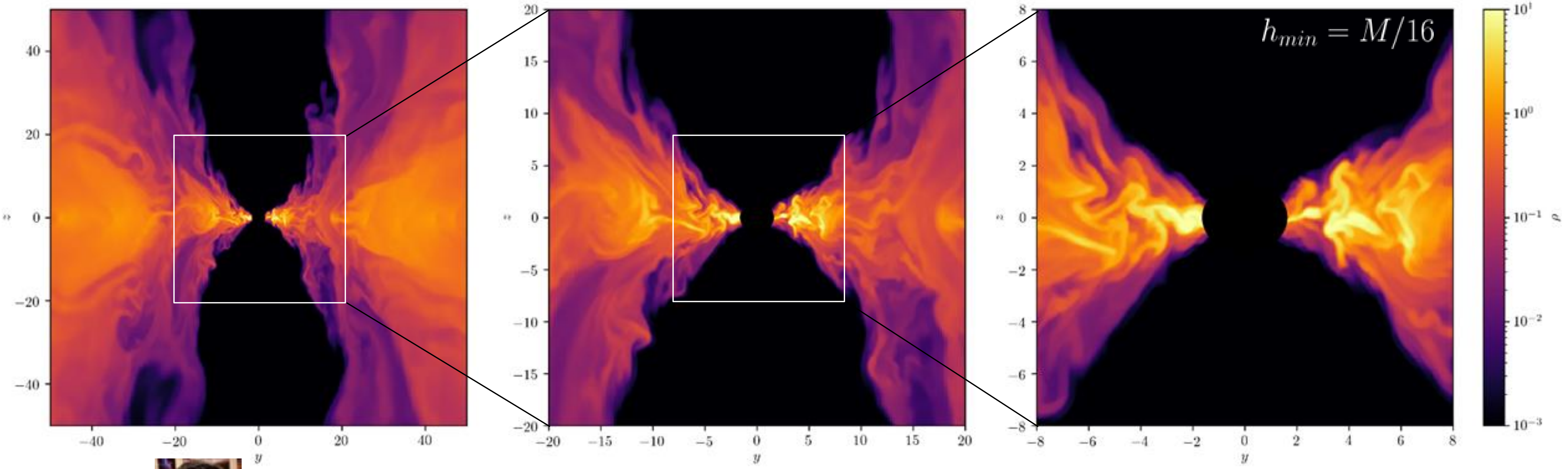
3D GRMHD Simulation of Turbulence Driven Reconnection (TDR) in Accretion Flows around BHs

3D GRMHD simulation of a MAD accretion flow.

3D domain (CSK): (x, y, z) ∈ [-1024M, 1024M]^3, with 8 refinement levels.

Best uniform resolution in the inner magnetized subdomain (x, y, z) ∈ [-8M, 8M]^3.

FM torus, MAD, a = 0.9375

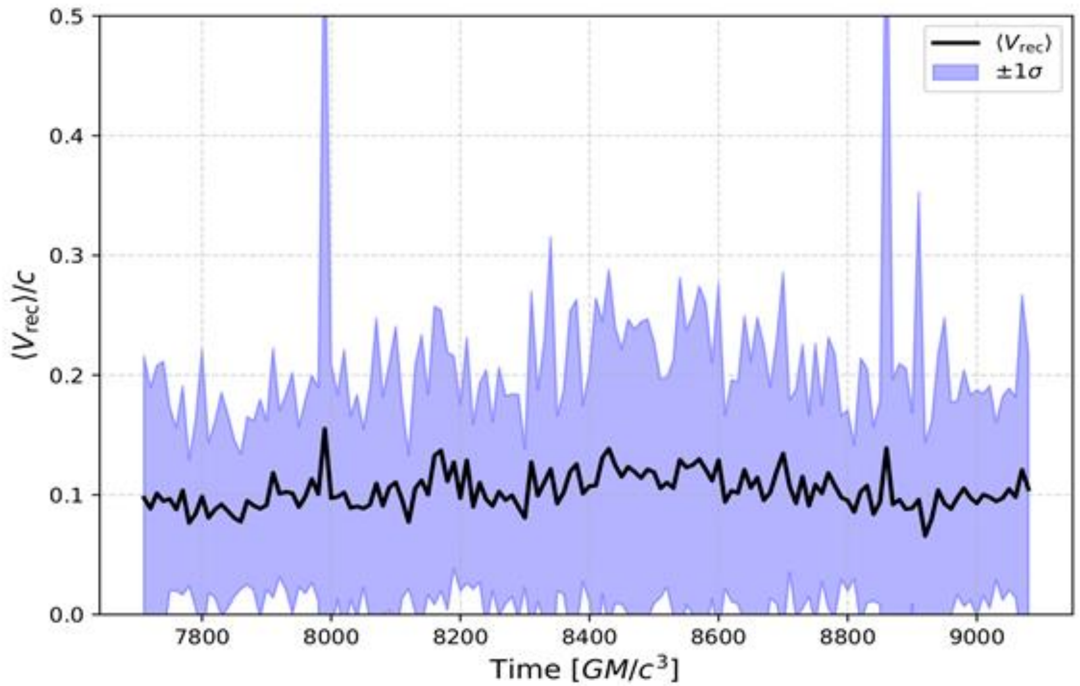


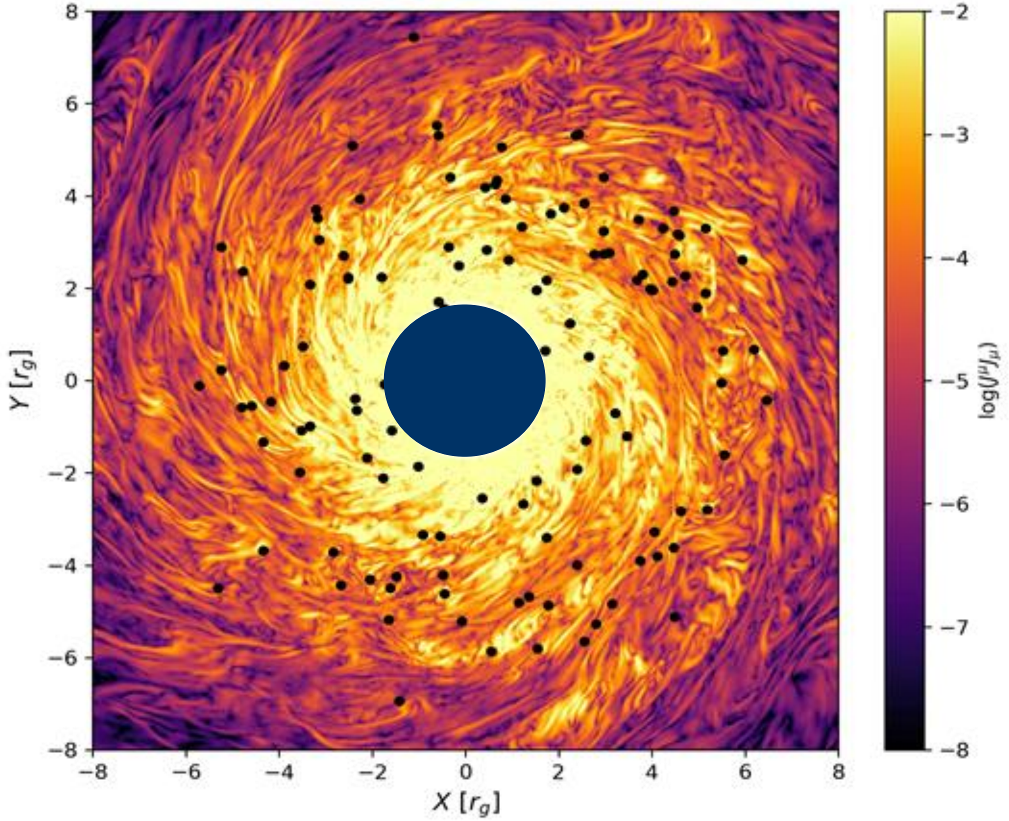
Vicentin, de Gouveia Dal Pino, Wong, Medeiros & Stone, *in prep.*

3D GRMHD Simulation of Turbulence Driven Reconnection (TDR) in Accretion Flows around BHs

MHD turbulence induced by MRI instability. Fully-developed MRI and turbulence at t > 7700 M. High-resolution (h = M/32).

Application of the detection algorithm for magnetic reconnection sites (Kadowaki et al. 2018, 2021) modified to account for GRMHD effects.



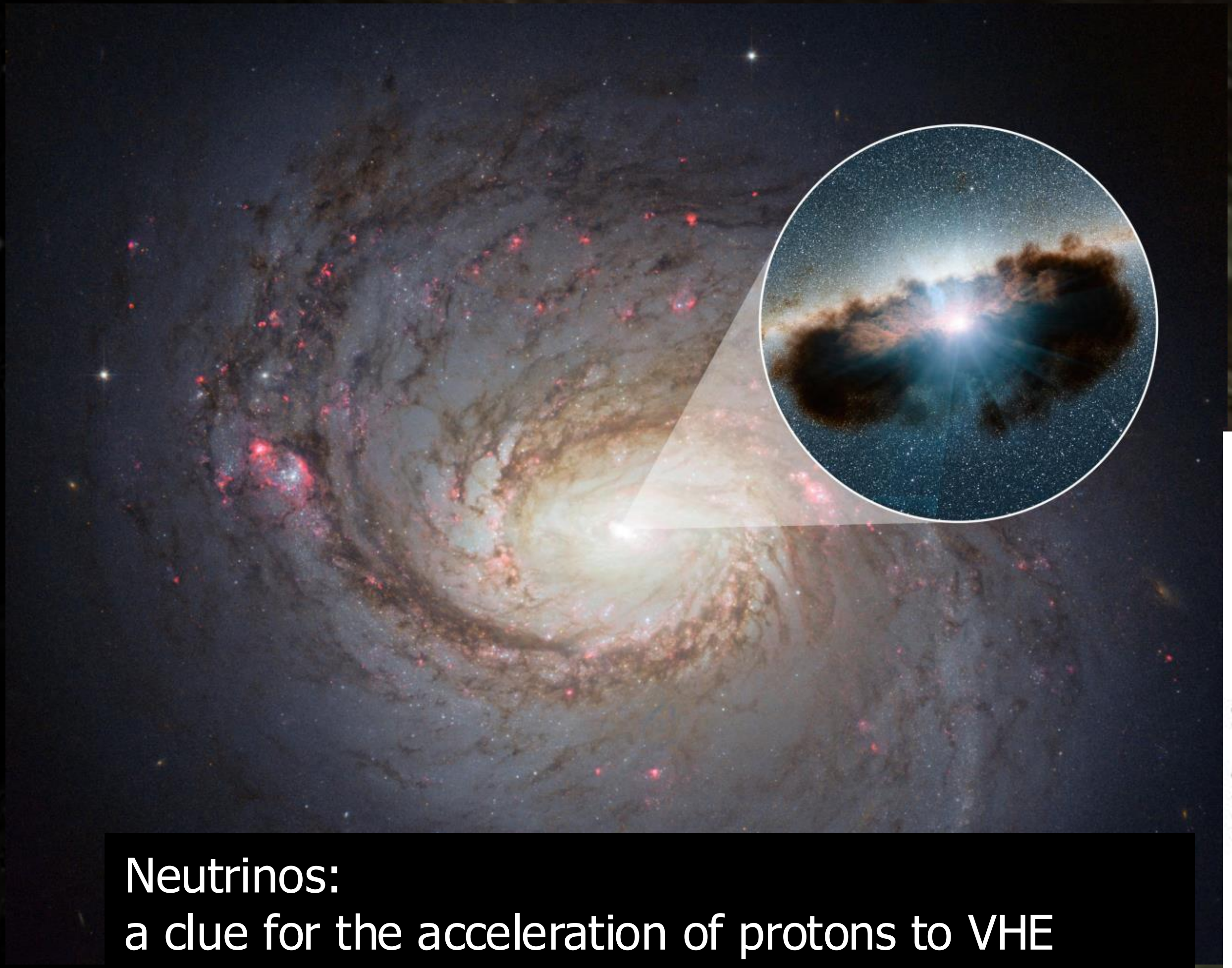


17212 confirmed reconnection sites only here !

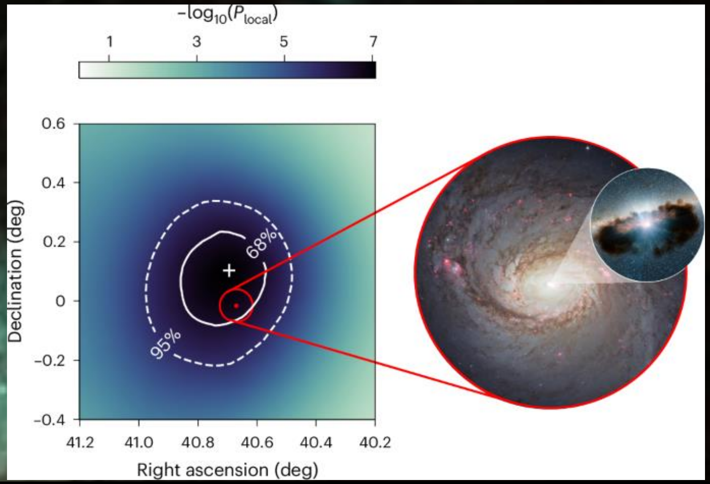
$\langle v_{rec} \rangle$ >> 0.01 (of the plasmoid reconnection in Ripperda et al. 2022)

Vicentin, de Gouveia Dal Pino, Wong, Medeiros & Stone, *in prep*

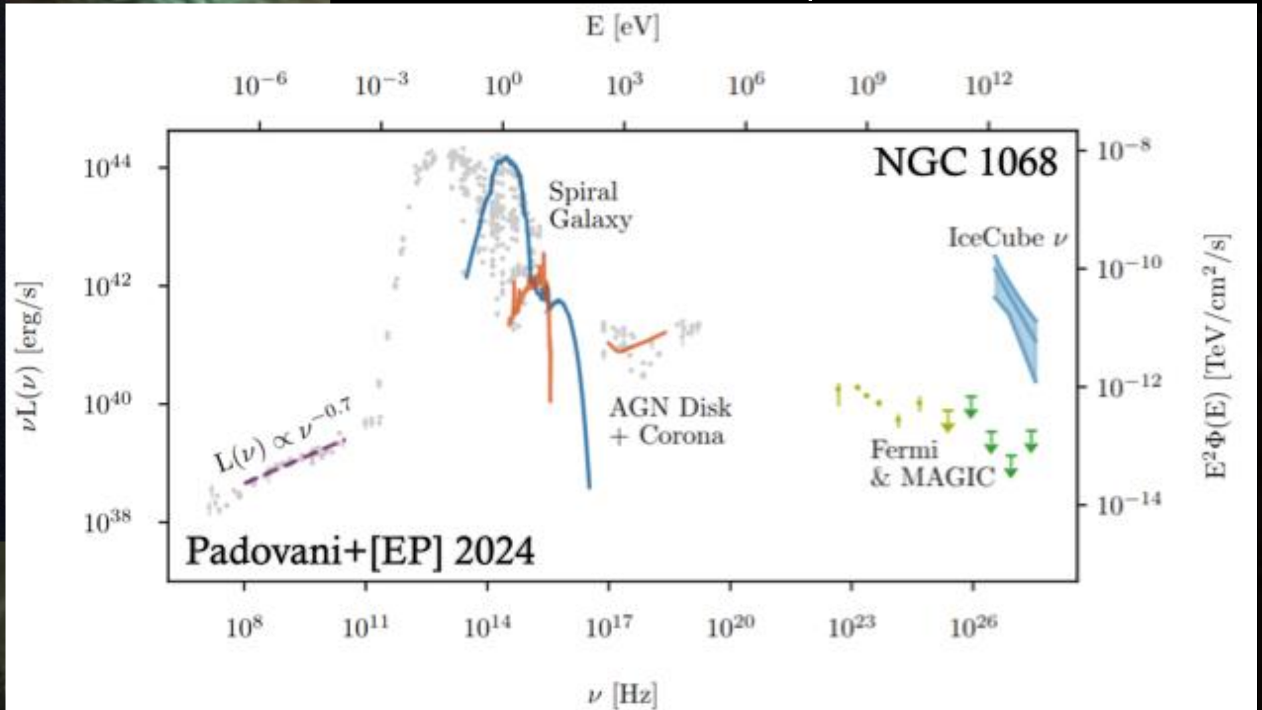
Neutrino Excess and Gamma Ray Absorption in AGN NGC1068



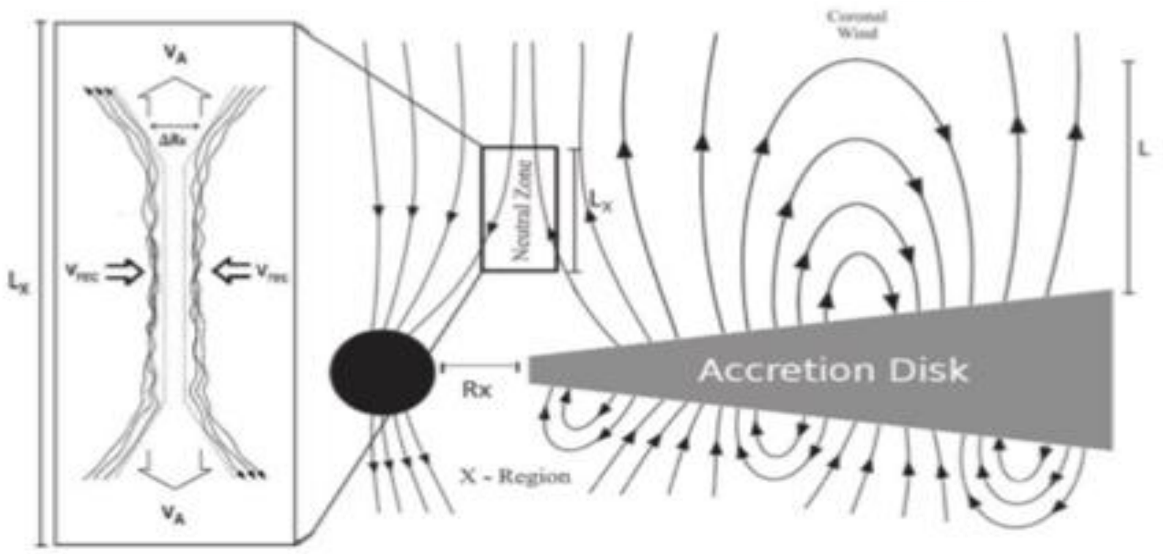
Neutrinos:
a clue for the acceleration of protons to VHE



IceCube collaboration, Science 2022



Turbulence-driven Reconnection (TDR) Fermi Acceleration Model for NGC1068



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

$$B_c \simeq 9.96 \times 10^8 r_X^{-5/4} \dot{m}^{1/2} m^{-1/2} \text{ G.}$$

$$T_c \simeq 2.73 \times 10^9 \Gamma^{1/4} r_X^{-3/16} l^{1/8} q^{-1} \dot{m}^{1/8} \text{ K.}$$

$$n_c \simeq 8.02 \times 10^{18} \Gamma^{1/2} r_X^{-3/8} l^{-3/4} q^{-2} \dot{m}^{1/4} m^{-1} \text{ cm}^{-3}.$$

$$\Delta R_X \simeq 11.6 \Gamma^{-5/4} r_X^{31/16} l^{-5/8} l_X q^{-3} \dot{m}^{-5/8} m \text{ cm.}$$

$$\dot{W}_B = 1.66 \times 10^{35}\ \Gamma^{-1/2}\ r_X^{-5/8}\ l^{-1/4}\ l_X\ q^{-2}\ \dot{m}^{3/4}\ m,$$

$$T_d \simeq 3.71 \times 10^7 \alpha^{-0.25} r_X^{-0.37} m^{0.25} \text{ K}$$

$$q = [1 - (\frac{3R_{sch}}{R_X})^{1/2}]^{1/4}, \qquad \Gamma = (1 + (\frac{v_{A0}}{c})^2)^{-1/2}$$

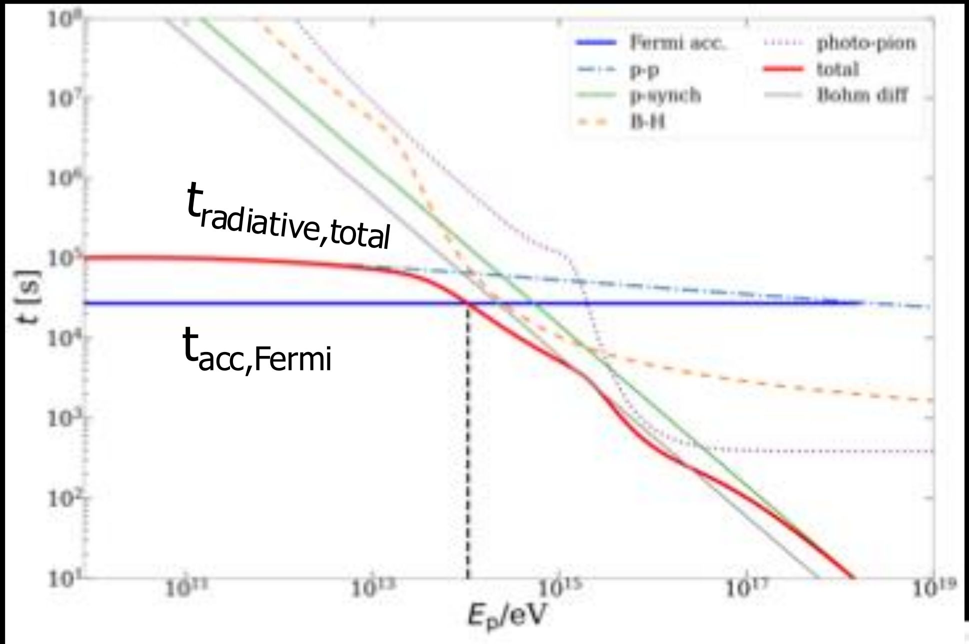
m	Black Hole Mass ($M/M_\odot$)	6.7×10^6	From observations
$\dot{m}$	Accretion Rate ($\dot{M}/\dot{M}_{\rm Edd}$)	0.55	
d	Distance (Mpc)	$\simeq 10.1$	
z	Redshift	~ 0.00379	
v_r	Radial Velocity (km s^{-1})	1137 ± 3	
l	Coronal Magnetic Flux Tube Height ($L/R_{\rm Sch}$)	7.5 (15 R_g)	Assumed
l_x	Height of reconnection region ($L_x/R_{\rm Sch}$)	6.5 (13 R_g)	
r_x	Inner radius of disc ($R_x/R_{\rm Sch}$)	3.2 (6.5 R_g)	
B_c	Coronal Magnetic Field (G)	6.5×10^4	From Model
n_c	Coronal particle number density (cm^{-3})	6.1×10^{11}	
T_c	Coronal Temperature (K)	5.4×10^9	
T_d	Temperature of Disc (K)	1.1427×10^6	
ΔR_X	Width of the current sheet (cm)	3.5×10^{10} $(0.02 R_s = 0.04 R_g)$	
$\dot{W}_B$	Reconnection Power (erg s^{-1})	7.9307×10^{42}	

Passos-Reis, de Gouveia Dal Pino, Rodriguez-Ramirez, Vicentin, JHEAp (subm)

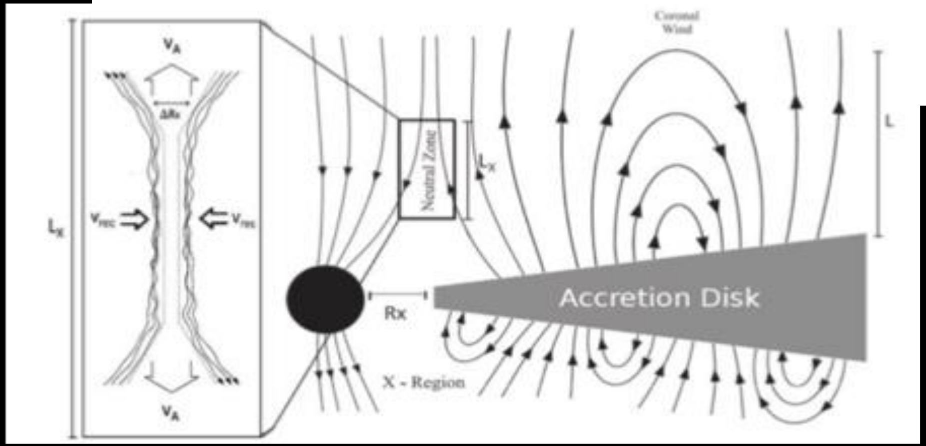
Radiation Fields:

- **BlackBody Radiation from the Disk (Optical and UV)**
- **X-rays from the coronae**

Turbulence-driven Reconnection (TDR) Fermi Acceleration Model for NGC1068

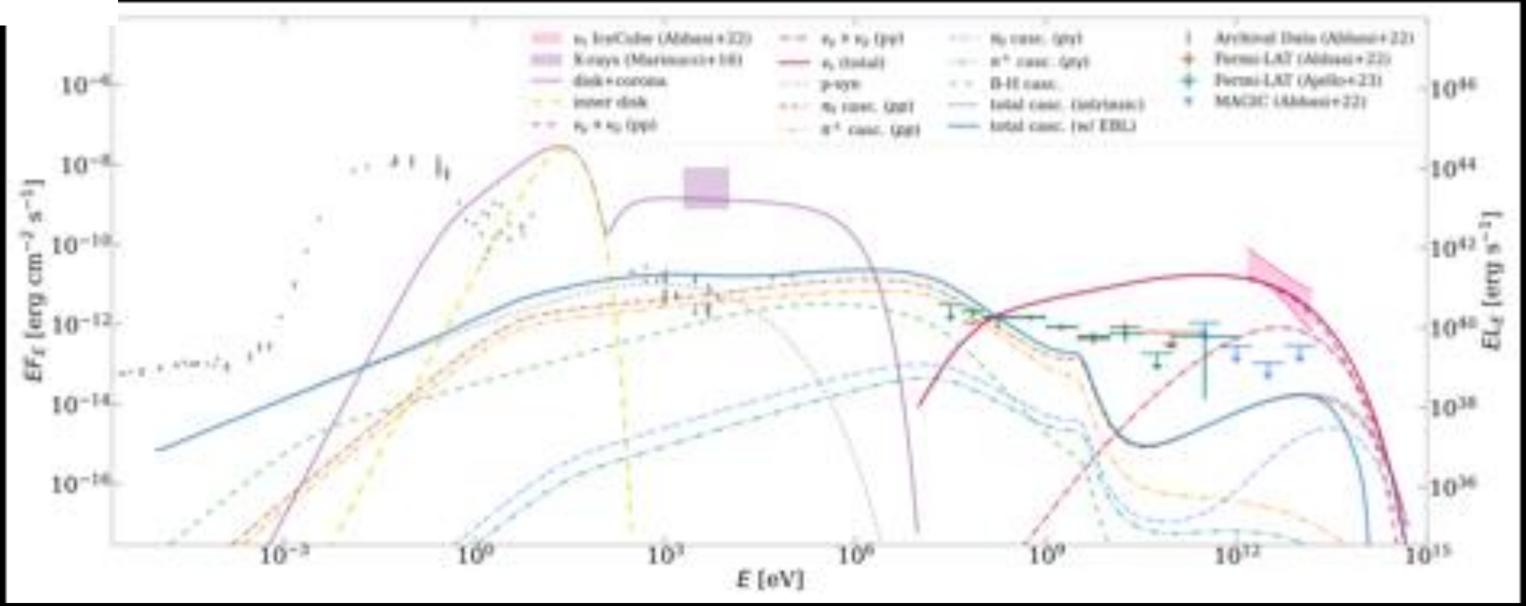


de Gouveia Dal Pino & Lazarian, A&A 2005
de Gouveia Dal Pino, Piovezan, Kadowaki, A&A 2010
Kadowaki, de Gouveia Dal Pino & Singh, ApJ 2015



- **Fermi t_{acc}~ constant w/ E_p** (de Gouveia Dal Pino & Lazarian 2005)
- $$t_{\rm acc} \approx \frac{4\Delta R_X}{c d_{\rm ur}}$$ Fast reconnection

(Xu & Lazarian, ApJ 2023)



Passos-Reis, de Gouveia Dal Pino, Rodriguez-Ramirez, Vicentin, subm. JHEAp 2026

Summary

Exercice of caution when making direct extrapolations from PIC simulations at kinetic scales to large scales without looking at MHD results

- Tearing/Plasmoid mediated reconnection at kinetic scales enables fast local reconnection; **not a system-size solution**
- Tearing/Plasmoid mediated reconnection in 2D MHD: resistive-dependent and slow up to **$S_c \sim 3 \times 10^5$** : $\boxed{\frac{V_{rec}}{V_A} \sim S^{-1/3}}$
- Turbulence-driven reconnection (**TDR**) (LV99): *RESISTIVE-INDEPENDENT AND FAST* $\boxed{V_{rec} = V_A \left(\frac{l}{L}\right)^{1/2} \left(\frac{v_l}{V_A}\right)^2}$; in Relativistic MHD: multiply by $f_A(\sigma, M_A) \leq 1$
- 3D MHD simulations of particle acceleration driven by turbulent reconnection (**TDR**): dominance of Fermi over drift acceleration up to large saturation energy (**in contrast to 3D PIC extrapolations)**
- In TDR: particle energy grows ~ exponentially in time in Fermi: **t_{acc} ~ cte w/ E_p** , in contrast to Drift: $t_{acc} \sim E_p$ (very inefficient to accelerate at large energies)
- Acceleration time within TDR reconnection layers – Fermi mechanism: $\boxed{t_{acc} \sim \frac{4\Delta}{c d_{ur}}}$
- Signatures of **turbulence-driven reconnection (TDR) Fermi acceleration** in magnetically dominated systems at high energy (flare) emission in systems like: NGC1068, TXS 0506+056, Mrk 501, Mrk421 (coming CygX3…)
- More studies on transition from kinetic to MHD turbulence-driven reconnection **(TDR)** acceleration required