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

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ElisaBete de Gouveia Dal Pino *IAG - Universidade de São Paulo*

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Collaborators: U. Barres de Almeida, M.V. del Valle, L. Kadowaki G. Kowal, A. Lazarian T. Medina-Torrejon Y. Mizuno, J.C. Ramirez-Rodriguez J. Stone, G. Vicentin

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Turbulence drives Fast Reconnection in 3D MHD flows Reconnection 13

Figure 5. 3D visualization of the current density magnitude, *|*J*|*, at *t* = 0 (left) and *t* = 2*.*0 (right) for the simulation with (Vicentin, Kowal, de Gouveia Dal Pino & Lazarian, ApJ 2024) $\sqrt{20}$ Dal Pino & Lazarian, An D024). 713 consistent with one of the most significant predictions \overline{r}

Two Parallel Worlds: Kinetic and MHD Reconnection Acceleration

Kinetic (**PIC)**

- Probes kinetic scales ~ 100 -1000 c/ $\omega_{\rm n}$ (microscopic: $10^{-10} - 10^{-17}$ orders smaller than real systems)
- Fast reconnection driven by tearing mode instability (plasmoids): **2D**
- Particle acceleration up to \sim **1000 mc²**
- Dominant electric field: resistivive h**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 \sim **10¹⁰ mc²**
- Dominant electric field: non-resistive –**vxB**
- **Fermi acceleration** dominates until Larmor radius > thickness of largest reconnection layers \sim 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

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

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

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ledina-Torrejon, d<mark>(</mark> Figure 13. Kinetic energy evolution for particles injected

Applications to Blazar HE Phenomena

Lepto-Hadronic Model based on Reconnection Acceleration for TXS 0506+056 Detection of gamma-rays and high-energy neutrinos ~290 TeV $f(x) = f(x) - f(x)$

Lepto-Hadronic Model based on Reconnection Acceleration for TXS 0506+056 from the blazar TXS 0506+056 (Aartsen et al. 2018).

(Aartsen et al. Science 2018)

- √ Jet at the transition from magnetically dominated to kinetically dominated: particle **acceleration controlled by reconnection** 3 hr nasZhmdc enq sgd γ − 0 ids& vghkd Z odZj uZktd −.-5 hr ZssZhmdc $\mathbf{B} = \mathbf{B} \mathbf{B}$ ticle within B. Using B. Usin
	- ü Jet background described by **striped reconnection** model (Giannios & Uzdenzky 2019)
	- \checkmark 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 **Emission scenario:** *Single-zone Lepto – Hadronic model for* **TXS 0506+056 neutrino flare** e. Al. de Gouveia Dal Pino et al. de Gouveia Dal Pino et al. de Gouveia Dal Pino et al. de Gouveia Dal Pino et
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Lepto-Hadronic Model based on Reconnection Acceleration for TXS 0506+056

Figure 7. Cooling time of the CR protons (source frame) which produce the Fermi reconnection acceler Fermi reconnection acceleration:

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

Xu & Lazarian 2023; de Gouveia Dal Pinno & Medina-Torrejon 2024 \mathcal{L} $\overline{0}$

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de Gouveia Dal Pino, Rodriguez-Ramirez+ 2024 (in prep.) location
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Lepto-Hadronic Model based on Reconnection Acceleration for TXS 0506+056

Figure 7. Cooling time of the CR protons (source frame) which produce the Fermi reconnection acceler Fermi reconnection acceleration: $\sum_{\mathbf{E}} 10^{-11}$

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t_{acc} \sim \frac{4\Delta}{cd_{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)}
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Xu & Lazarian 2023; de Gouveia Dal Pinno & Medina-Torrejon 2024 $\frac{10^{-4} \epsilon_0^2}{10^{-6}} \frac{1}{10^{-3}} \frac{1}{10^{6}}$ 23, $\frac{1}{10^{-14}}$

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- observed time delay
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TeV Spectral Spike of Mrk 501 explained by Spectral Spike of Mrk 501: explained by Reconnection Acceleration Reconnection Acceleration

Blazar Mrk 501: TeV spikes during X-ray high state

(Magic Coll. 2020)

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

TeV Spectral Spike of Mrk 501 explained by Reconnection Acceleration

Blazar Mrk 501

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

Rodriguez-Ramirez, Barres de Almeida, de Gouveia Dal Pino, Das-Cortes, Paiva (2024, in prep.) the appearance of the appearance of the TeV narrow feature. We discuss the TeV narrow feature. We discuss the α Rodriguez-Ramirez, Barres de Almeida, de Go ↵¹ 2*.*900 2*.*900 2*.*900 The overlaid curves are obtained through the two-zone jet-reconnection model discussed in the text. ^a "lg *x*" indicates the base 10 logarithm of the quantity *x*. $\mathcal{L}_{\mathcal{A}}$

Applications to accretion disk VHE Phenomena *Fast magnetic reconnection in turbulent accretion disks*Fast Reconnection in GRMHD simulations of accretion flows

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(See also: de Gouveia Dal Pino & Lazaria); Registration de Lazarian 2005; Registration de Lazarian 2005; Parf
2005; Desemble de Lazaria et al. 2015; Parfrey et al. 2014; Parfrey et al. 2014; Parfrey et al. 2015; Parfrey

around BHs driven by magneto-rotational instability turbulence

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 -> gamma ray emitter **WE COMBINE AND MILLION FULL EMISSION EMISSION COMPUTER (THE SET OF ALSO GAMMA-**

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

Galactic Center SgrA*: Reconnection acceleration driven by turbulent accretion flow -> gamma ray emitter **WE COMBINE AND MILLION FULL EMISSION EMISSION COMPUTER (THE SET OF ALSO GAMMA-**

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

Neutrinos and Gamma Rays from NGC1068 Neutrino Vannua NGC 11 VIII NGC106

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 Neutrino Vannua NGC 11 VIII NGC106

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 \therefore The emission may

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 \sim exponentially in time during Fermi: $t_{\rm acc} \sim$ 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

Reconnection in 3D MHD flows: 26 Auto 170 Auto 170 Au due to Turbulence

Fig. 10 Numerical simulations illustrating the violation of flux freezing. The **Turbulent flows violate flux freezing** $\ln n$ zarian 8. Vichniac 1000). fluid. From Eyink et al. 2013. (**Lazarian & Vishniac 1999**):

time and instead of a single line at earlier the field line in turbulent fluid. time, there are several progenitor lines μ (lines suffer Richardson diffusion) origin of magnetic field back tracked in

$\sqrt{2}$ and $\sqrt{2}$ and $\sqrt{2}$ magnetic field lines $\sqrt{2}$ at all $\sqrt{2}$ (Eyink et al., Nature 2013)

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

n_{RD} ∼ / v_l min (1, M_A ³) $H\left(\frac{N}{2}\right)$ is number of the turbulence. When the magnetic forces have made the magnetic forces have made to magnetic forces have made to the magnetic forces have made to magnetic forces have made to make $\frac{N}{2}$

(Lazarian 2005; Santos-Lima et al. 2010; Lazarian et al. 2012; 2012; 2021; Koshikumo et al. 2024). We found the non-trivial subset of α α account the change in the nature of the magnetic forces. azarian et al. 2012: 2012: 2021: Koshikumo \mathbf{A} under the hypothesis of incompressible turbulence (for \mathbf{A}

Turbulence drives Fast Reconnection in 3D MHD flows

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

Particles are accelerated in reconnection sites mainly by Fermi process

Reconnection Acceleration Exponential energy growth in time

1st-order Fermi de Gouveia Dal Pino & Lazarian, A&A 2005; del Valle, de Gouveia Dal Pino, Kowal, MNRAS 2016

$$
\frac{d}{dt}(\gamma m \mathbf{u}) = q(\mathcal{E} + \mathbf{u} \times \mathbf{B}) \quad \boxed{\varepsilon = -\mathbf{v} \times \mathbf{B}}
$$

 $\varepsilon = \eta J$ negligible

Particles are accelerated in reconnection sites also by Grad-B drift Particles are accelerated in recol tively large in \mathcal{L} f $\frac{1}{2}$

1st-order Fermi: particles bounce back and forth between 2 converging magnetic flows: shrinking loop: increases **p**∥ converging-center that can be used to diagnose the use of the use

(de Gouveia Dal Pino & Lazarian, A&A 2005) $\frac{1}{2005}$ \mathcal{Z} 003). The results are easily generalizable to $3-$

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

Shared magnetic field direction

$$
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 ∇B

1st-order Fermi: particles **Drift:** at larger Larmor radius bounce back and form between z and particle interacts with converging
converging magnetic flows: magnetic flow and gain energy <u>Particle with a successive with a successive shripting loop:</u> increases **p**<u></u>µ and second term corresponds term corresponds term corresponds term corresponds term corresponds to the second term corresponds term correspon particle interacts with converging particle interacted with conve The first term in Eq. (5) is the acceleration by the acceleration of the state of the state of the sta

converging magnetized flow and increases its perpendicular momentum *p*? as (Kowal, deGDP, Lazarian, PRL 2012; Lazarian et al. 2012) and arises from the first-order Fermi $m = 16$

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

