CR Acceleration in Turbulent Magnetic Reconnection: applications to relativistic jets and accretion flows

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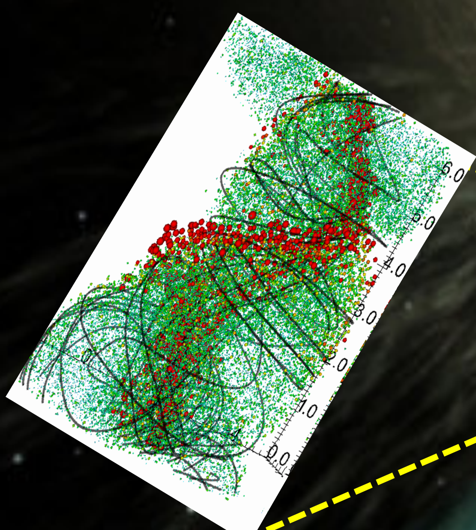
IAG - Universidade de São Paulo



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J. C. Rodriguez-Ramirez
C. Singh, J. Stone, G. Vicentin

CR Anistropy Workshop, Chicago, May 17th, 2023

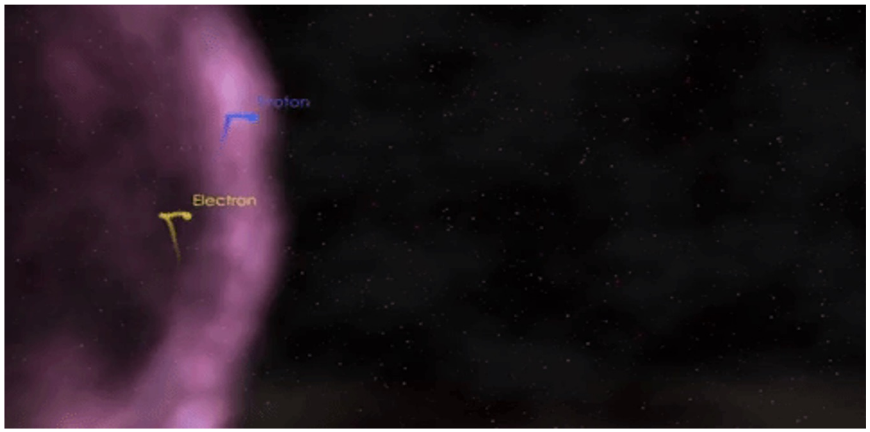
This talk

TURBULENT RECONNECTION ACCELERATION @ Magnetically dominated regions of BH relativistic jets and accretion flows (to solve current puzzles related CR acceleration and VHE emission):

- Overview of turbulent fast magnetic reconnection acceleration in **MHD flows**
- Reconnection acceleration of particles up to ultra-high-energies (UHECRs) from 3D relativistic MHD jet simulations + test particles (first time)
- Reconnection acceleration can explain observed emission in Blazar jets: variability, gamma-rays and neutrinos
- Reconnection acceleration in the accretion disks of BH sources

Particles are accelerated in reconnection sites mainly by Fermi process

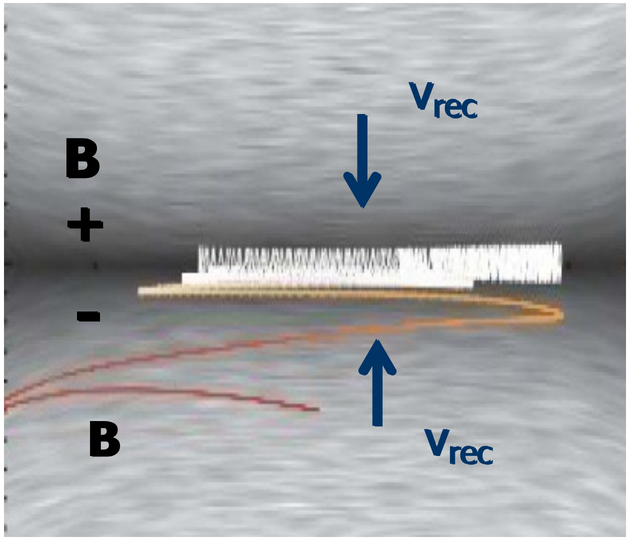
Shock Acceleration



1st-order Fermi (Bell 1978; Begelman & Eichler 1997)

$\langle \Delta E/E \rangle \sim v_{sh}/c$

Reconnection Acceleration



As in shocks: 1st-order Fermi
(de Gouveia Dal Pino & Lazarian 2005)

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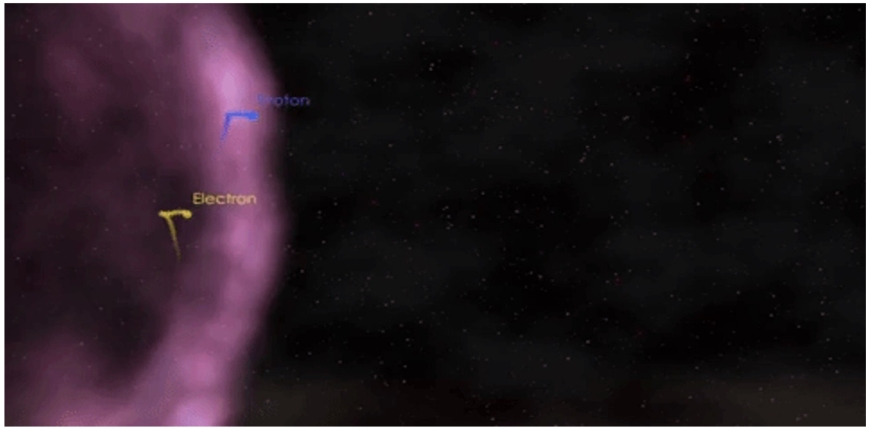
Shock Acceleration



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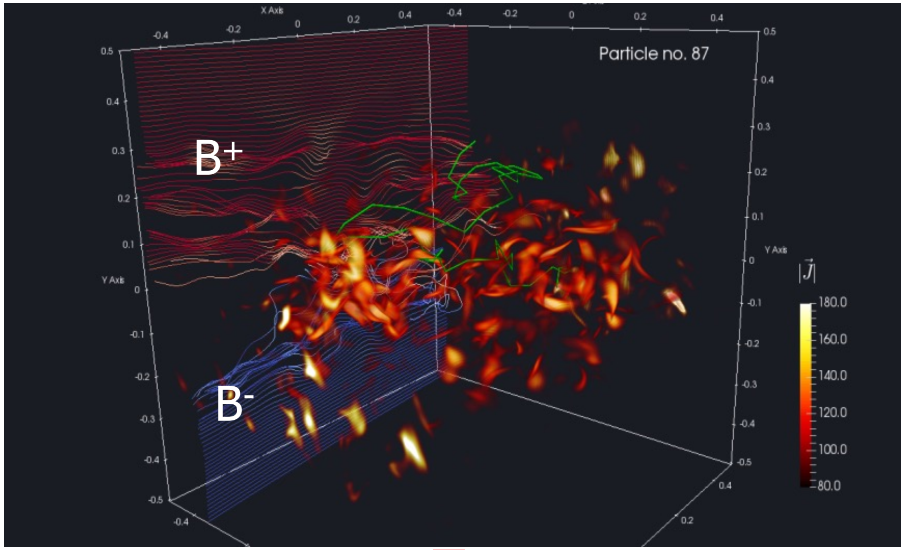

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(de Gouveia Dal Pino & Lazarian 2005;
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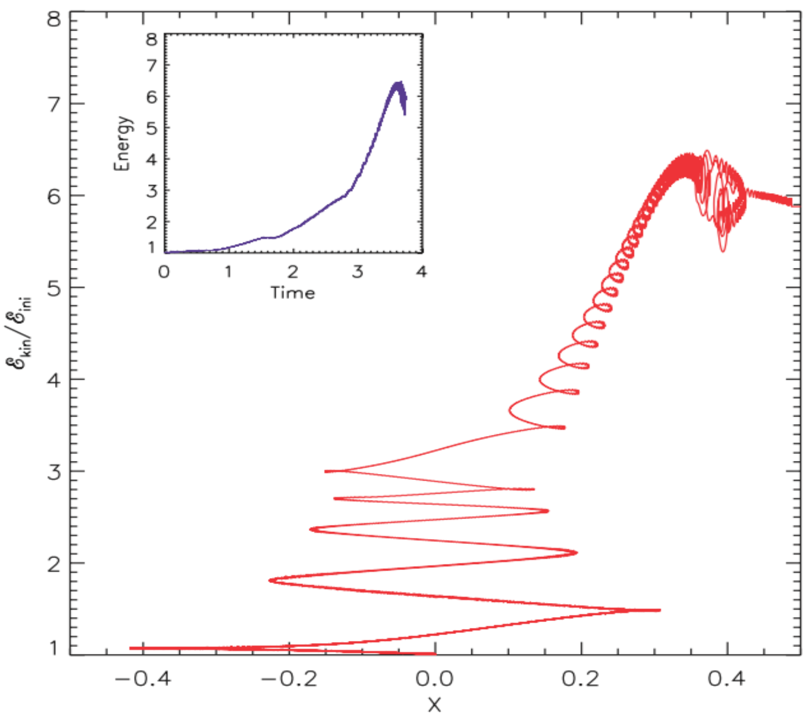
$<\Delta E/E> \sim v_{rec}/c$

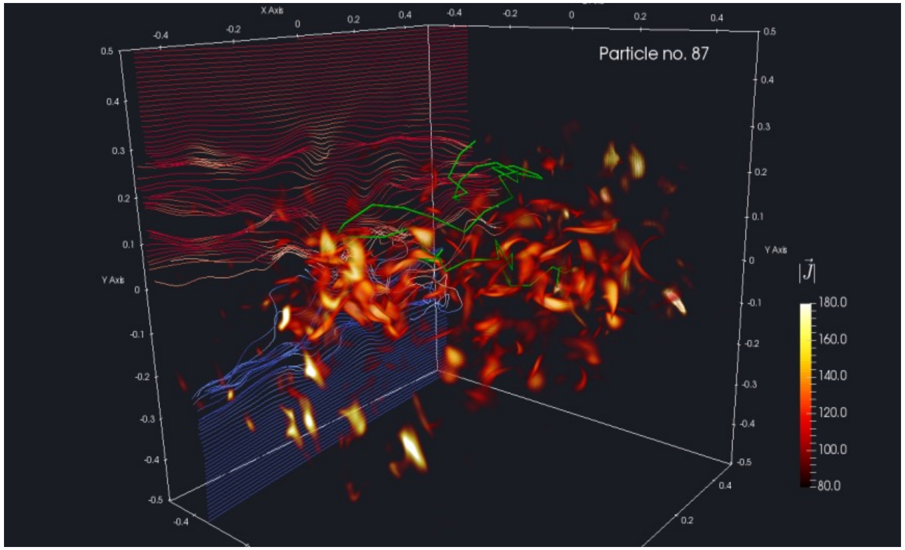
Particles are accelerated in reconnection sites mainly by Fermi process

Exponential energy growth in time



Kowal, de Gouveia Dal Pino & Lazarian, ApJ 2011

Reconnection Acceleration



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(de Gouveia Dal Pino & Lazarian 2005;
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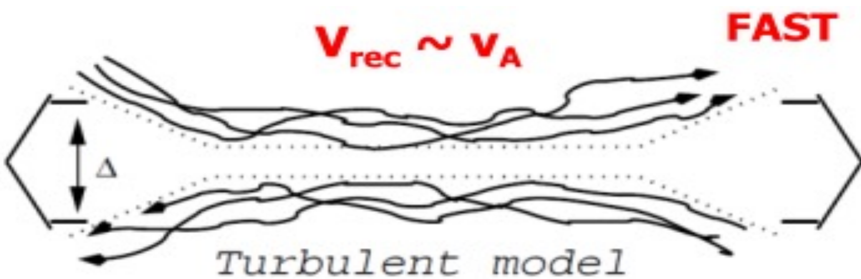
$$\langle \Delta E/E \rangle \sim v_{rec}/c$$

Turbulence drives Fast Reconnection in MHD flows

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

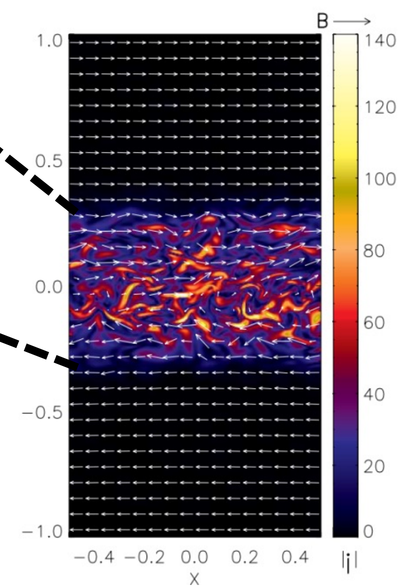
Magnetic lines wandering and slippage: many simultaneous reconnection events



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

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

Tested in 3D MHD numerical simulations (Kowal et al. 2009, 2012; 2015; 2019; 2020; Takamoto et al. 2015)



(Other descriptions: Shibata & Tanuma01; Loureiro+07; Bhattacharjee+09)

Particle Acceleration by Magnetic Reconnection probed with Numerical Simulations

- **2D and 3D kinetic plasmas (PIC):**

(e.g. Drake+ 06; Zenitani & Hoshino 01; 07; 08; Ji+ 11; Cerutti, Uzdensky+ 13; Li+ 15; Christie et al. 2019; Sironi & Spitkovsky 2014; Guo+2015; 16; 18; 21; Werner+ 17; 19; Sironi+18; Niskiwkawa et al. 2019, 2020; Comisso & Sironi 2019, 2020; Zhang et al. 2021, Davelaar et al. 2021; Sironi 2022…)

@ **scales: few plasma inertial length** ~ 100-1000 c/ω_p

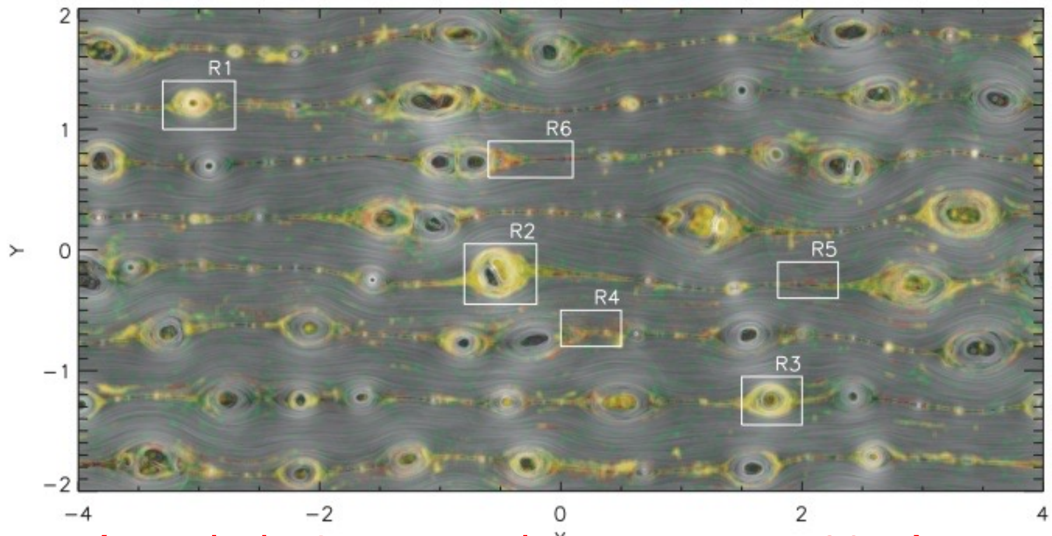
acceleration up to ~ few 1000 mc²

- **Larger-scale astrophysical systems** (e.g. BHBs, AGNs, GRBs):

3D MHD + test particles:

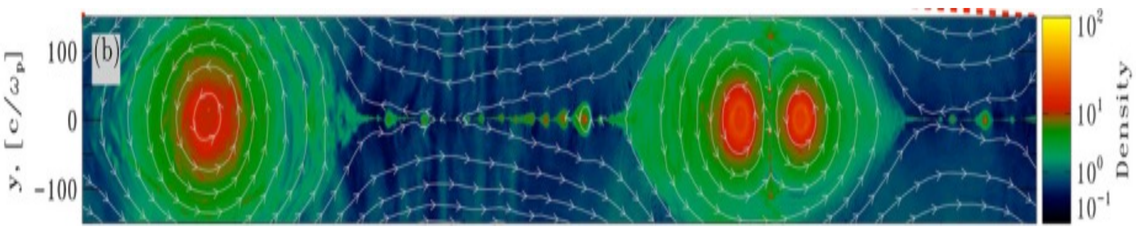
(Kowal, de Gouveia Dal Pino & Lazarian 2011, 2012; de Gouveia Dal Pino & Kowal 2015; del Valle et al. 2016; Beresnyak & Li 2016; de Gouveia Dal Pino+2018, 2019; Guo et al. 2019; Yang et al. 2020; Medina-Torrejon et al. 2021, Medina-Torrejon, de Gouveia Dal Pino, Kowal 2023, …)

Equivalence of particle acceleration in current sheets and merging plasmoids in 2D: Fermi



(Kowal, de Gouveia Dal Pino, Lazarian 2011)

2D MHD simulations of current sheets and plasmoids (driven by tearing mode)



(e.g. Sironi & Spitkovsky 2014)

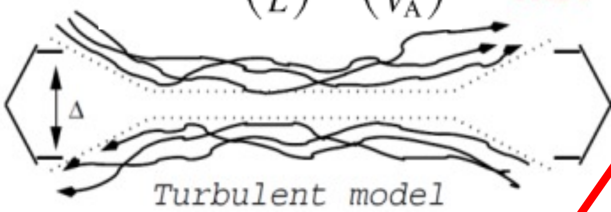
2D PIC simulations of plasmoids and X points (driven by tearing mode)

But plasmoids: just cross sections of 3D flux tubes reconnecting, and **particle acceleration is actually 3D !**

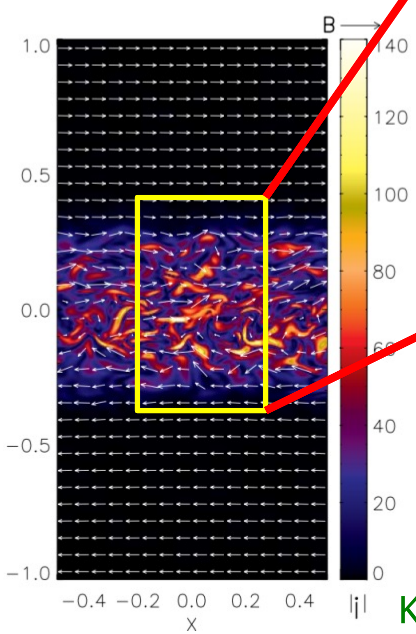
3D MHD Simulations with Test Particles
(with turbulence that makes reconnection fast)

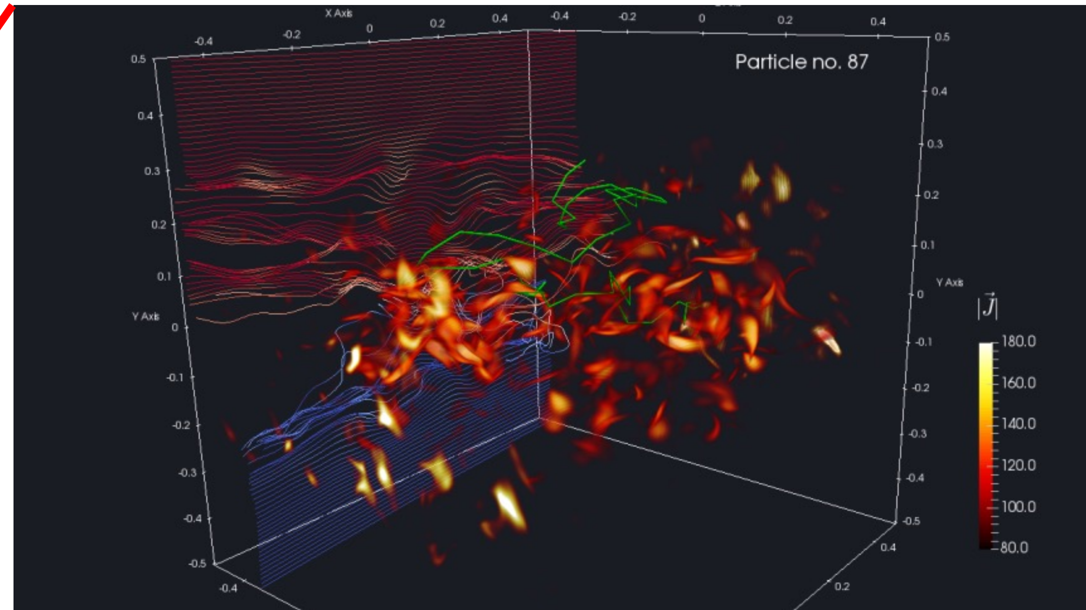
$$V_{\rm rec} = V_{\rm A}\left(\frac{l}{L}\right)^{1/2}\left(\frac{v_l}{V_{\rm A}}\right)^2$$

FAST



(Lazarian & Vishniac 1999)





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

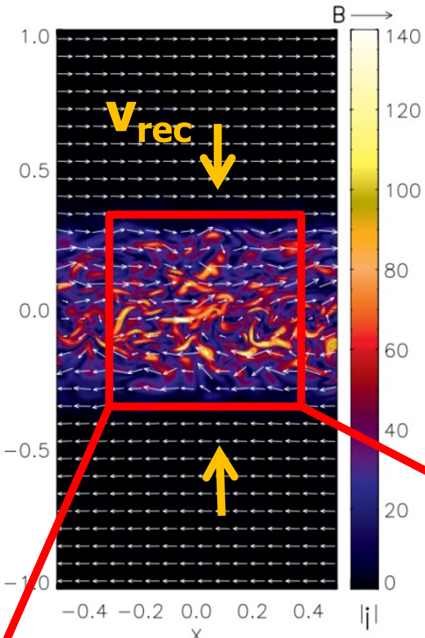
$\varepsilon = v \times B$

Neglect: $\varepsilon = \eta J$

(dominant in PIC simulations)

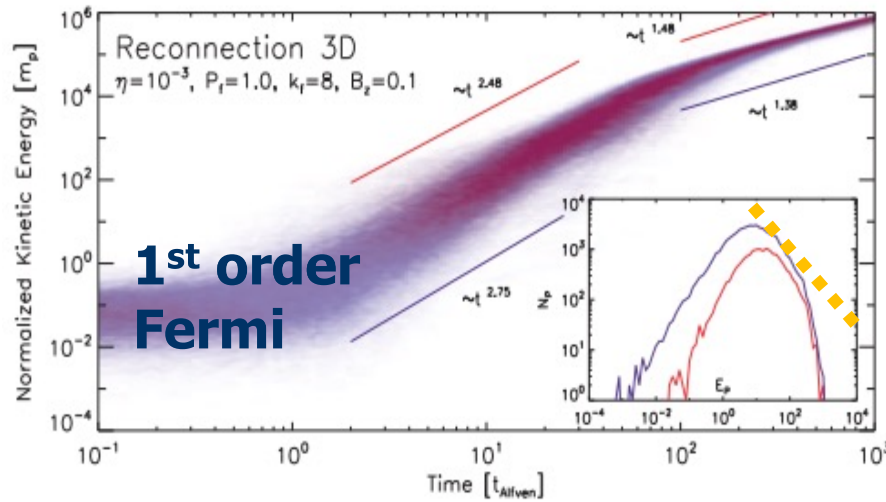
Kowal, de Gouveia Dal Pino, Lazarian PRL 2012
del Valle, de Gouveia Dal Pino, Kowal, MNRAS 2016

Fermi Reconnection Acceleration: successful numerical testing in 3D MHD turbulent Current Sheets

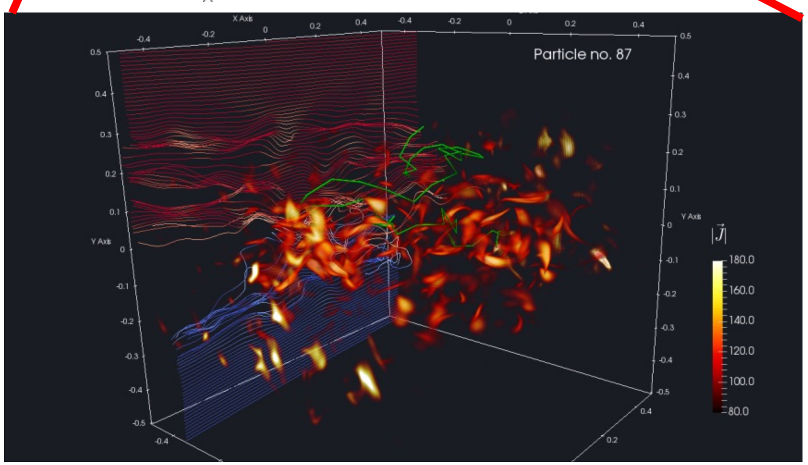


10,000 test particles

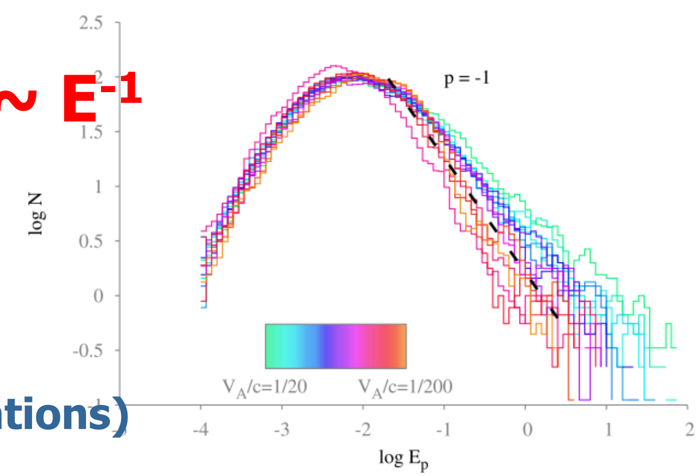
Injected in turbulent current sheet to make reconnection fast



Kowal, de Gouveia Dal Pino, Lazarian, PRL 2012



✓ N(E) ~ E^{-1}

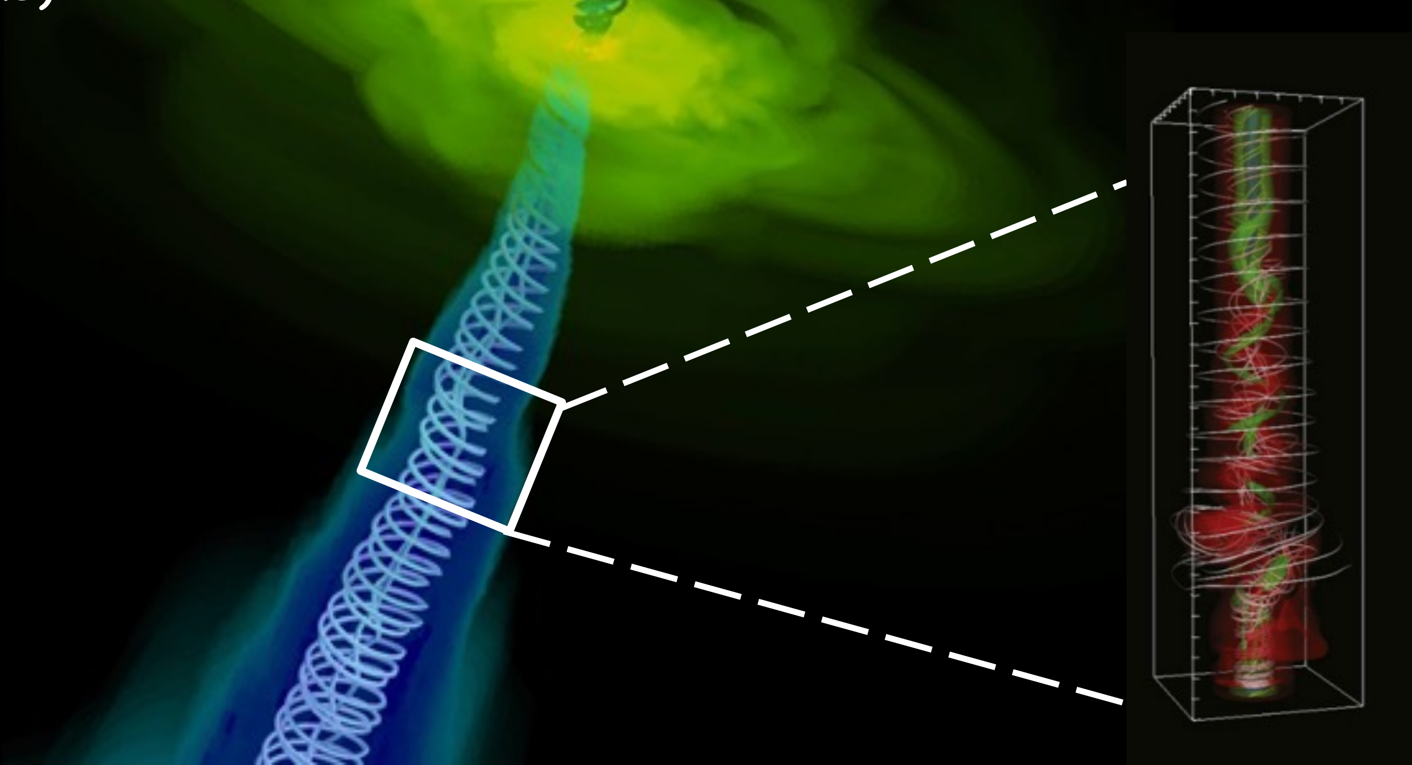


(~PIC simulations)

del Valle, de Gouveia Dal Pino, Kowal MNRAS 2016

<u>In situ</u> Reconnection Acceleration in Relativistic Jets

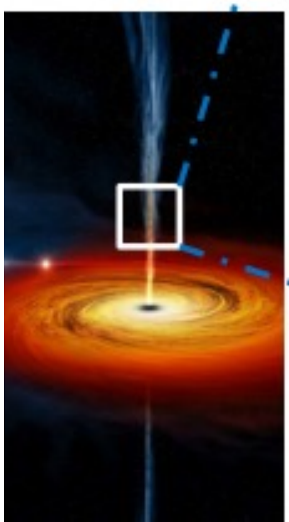
Relativistic MHD (RMHD) simulations + test particles:
can probe particle acceleration to highest energies without doing extrapolations (to macroscopic scales as it is required in PIC simulations)

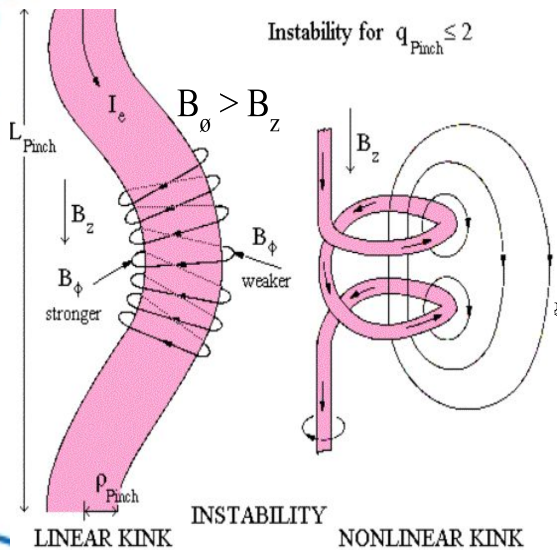


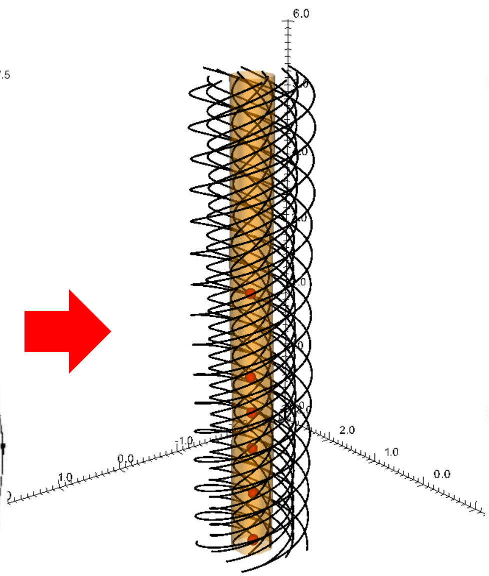
3D RMHD Simulations of Magnetically Dominated Relativistic Jets subject to Kink Instability

- RMHD Godunov (HLLE) based **RAISHIN** code (Mizuno et al. 2012)
- Precession perturbation -> **current-driven kink instability (CDKI)** -> **turbulence -> reconnection**

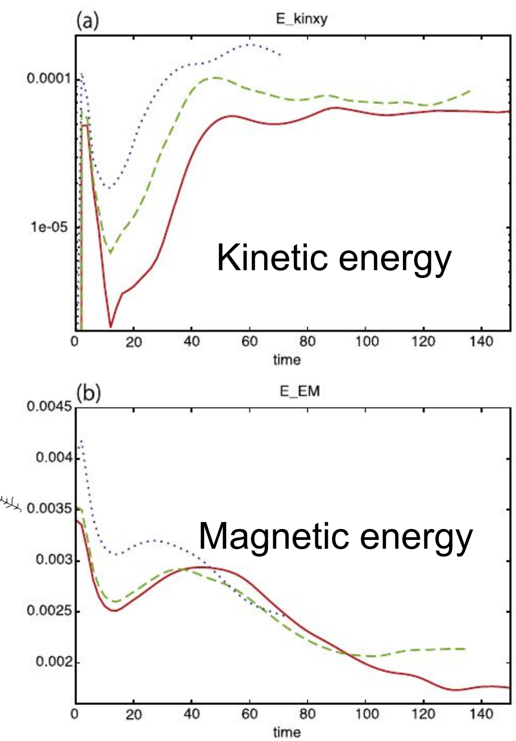
$$t_{\rm kink} \simeq \frac{2\pi R_{\rm j}}{c}\frac{B_p}{B_\phi}$$







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



Singh, Mizuno, de Gouveia Dal Pino, ApJ 2016
Medina-Torrejon, de Gouveia Dal Pino+ ApJ 2021
Kadowaki, de Gouveia Dal Pino + ApJ 2021

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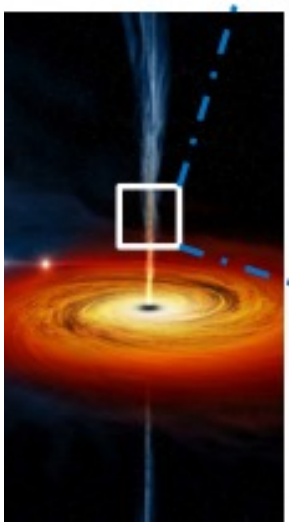

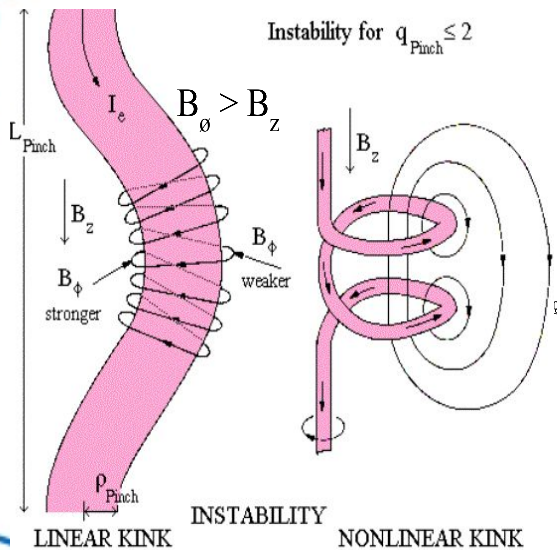

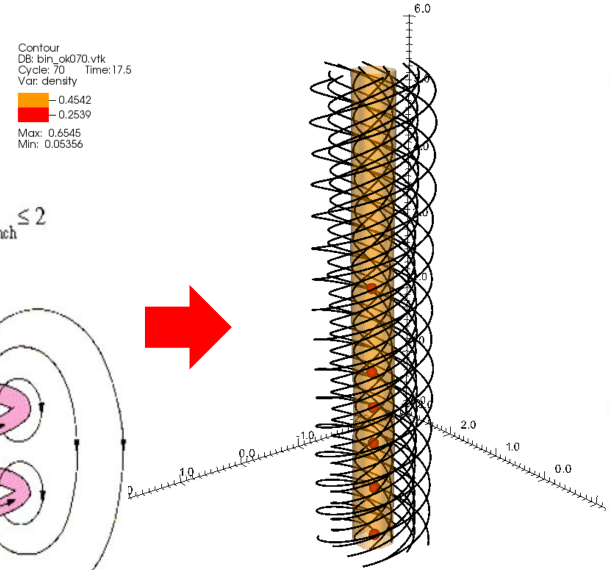

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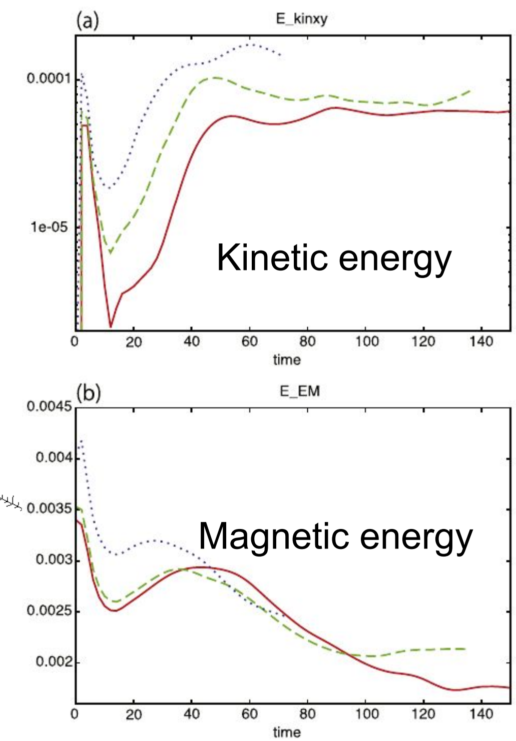
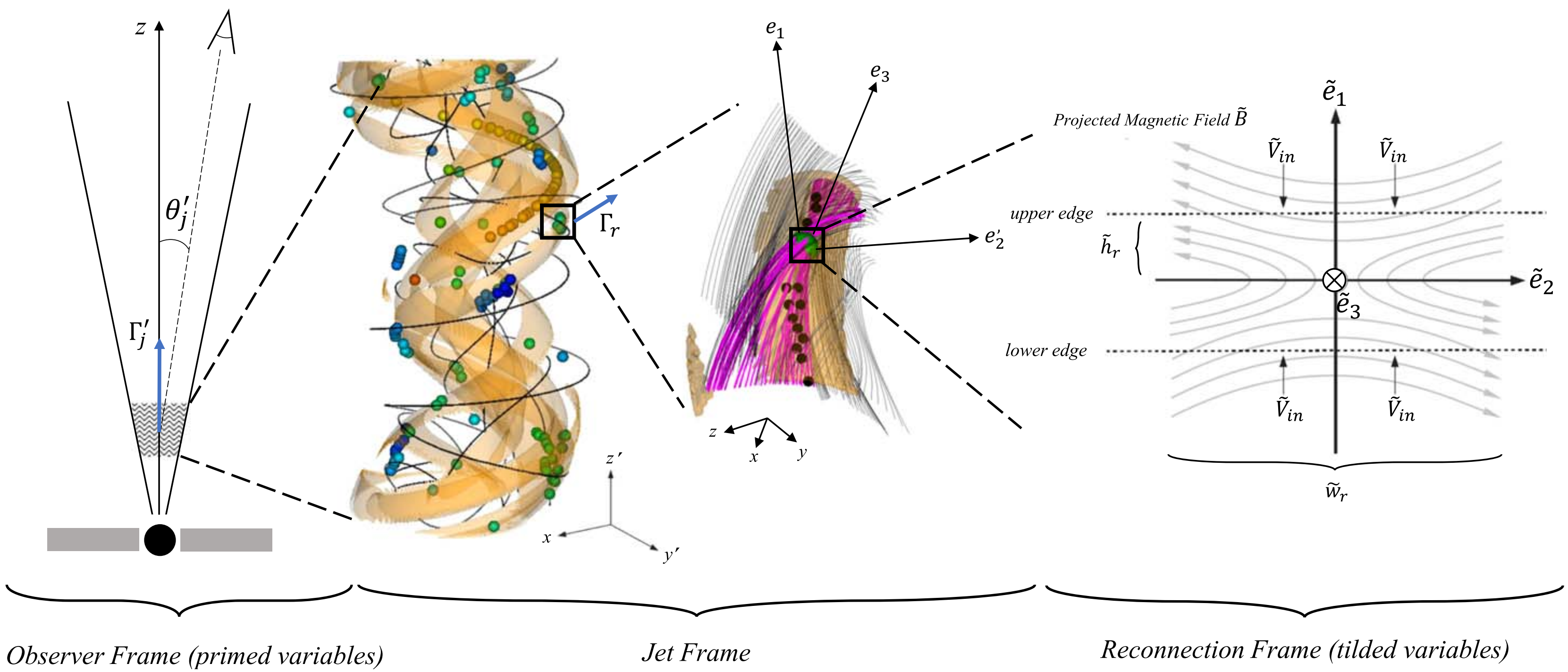


Singh, Mizuno, de Gouveia Dal Pino, ApJ 2016
Medina-Torrejon, de Gouveia Dal Pino+ ApJ 2021
Kadowaki, de Gouveia Dal Pino + ApJ 2021

Identification of Fast Reconnection driven by Kink in Relativistic Jets

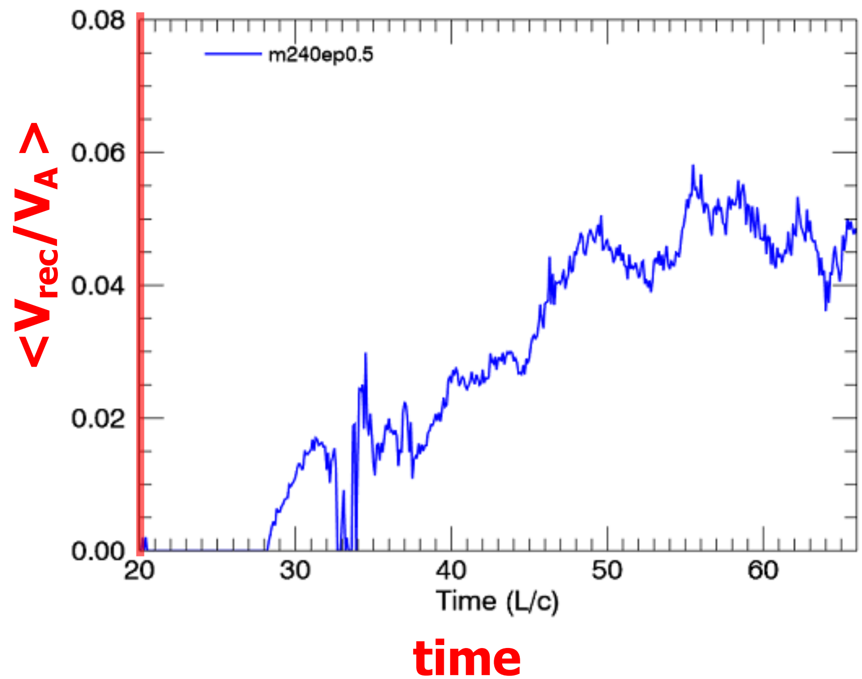
- Algorithm (as in Zhdankin et al. 2013) extended to 3D relativistic analysis

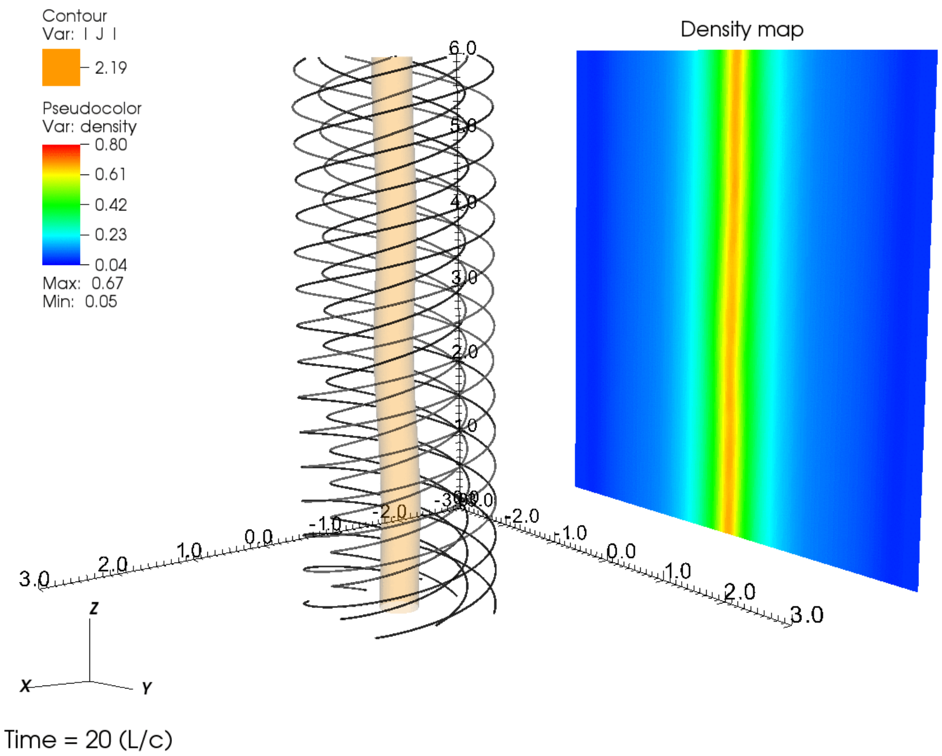


$$\left\langle \frac{V_{in}}{V_A} \right\rangle = \frac{1}{2}\left(\frac{V_{e_1}}{V_A}\bigg|_{lower} - \frac{V_{e_1}}{V_A}\bigg|_{upper} \right)$$

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

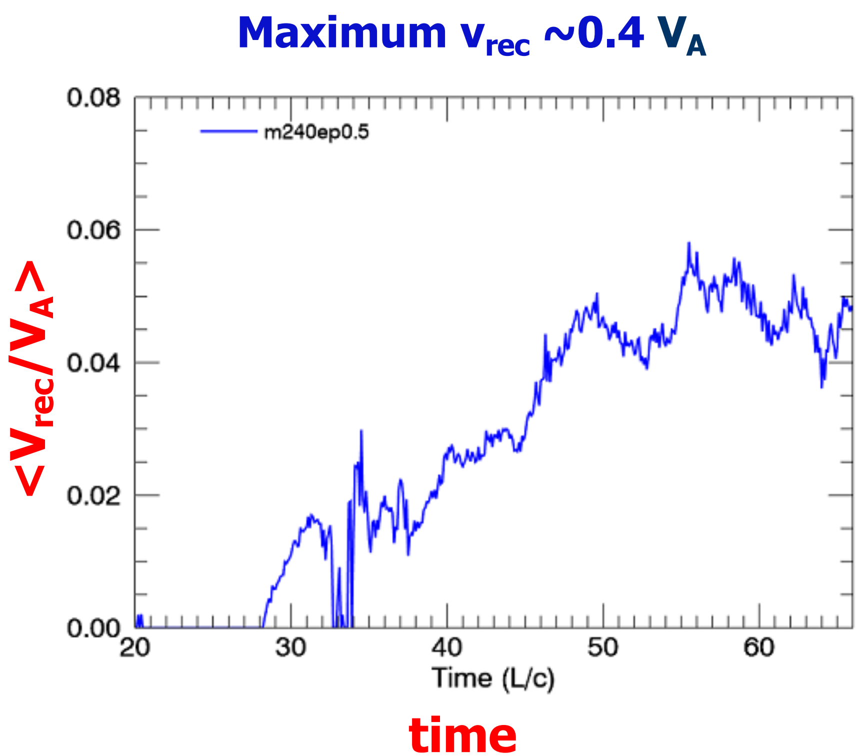
Fast Reconnection Rate driven by Kink instability in Relativistic Jets

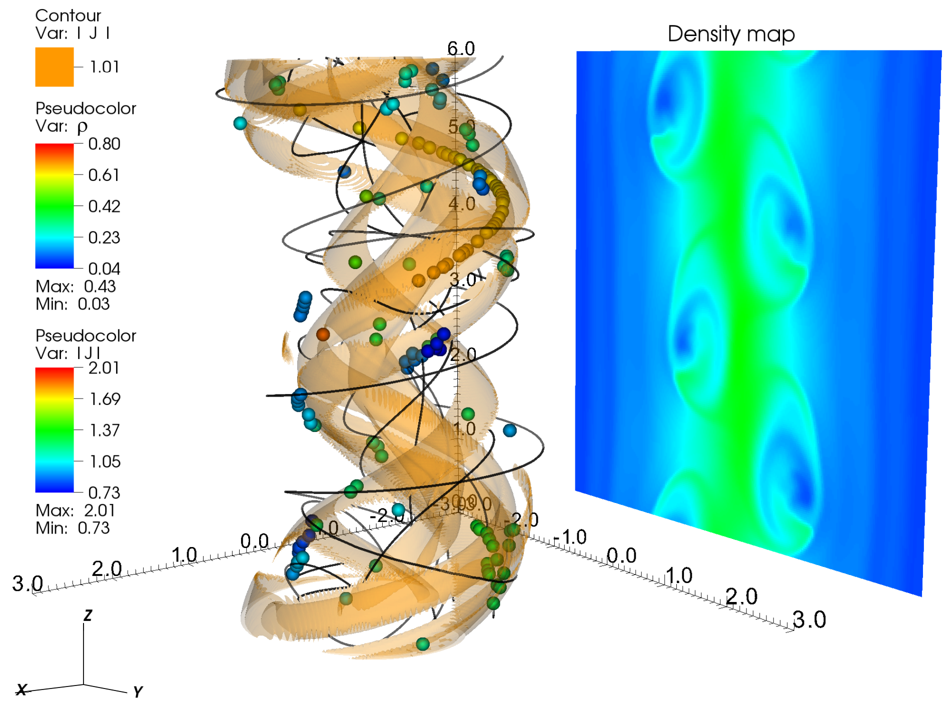




Kadowaki, de Gouveia Dal Pino, Medina-Torrejon +, ApJ 2021

Identification of Fast Reconnection Rate driven by Kink turbulence in Relativistic Jets





- $<V_{rec}> \approx 0.05\ V_A$

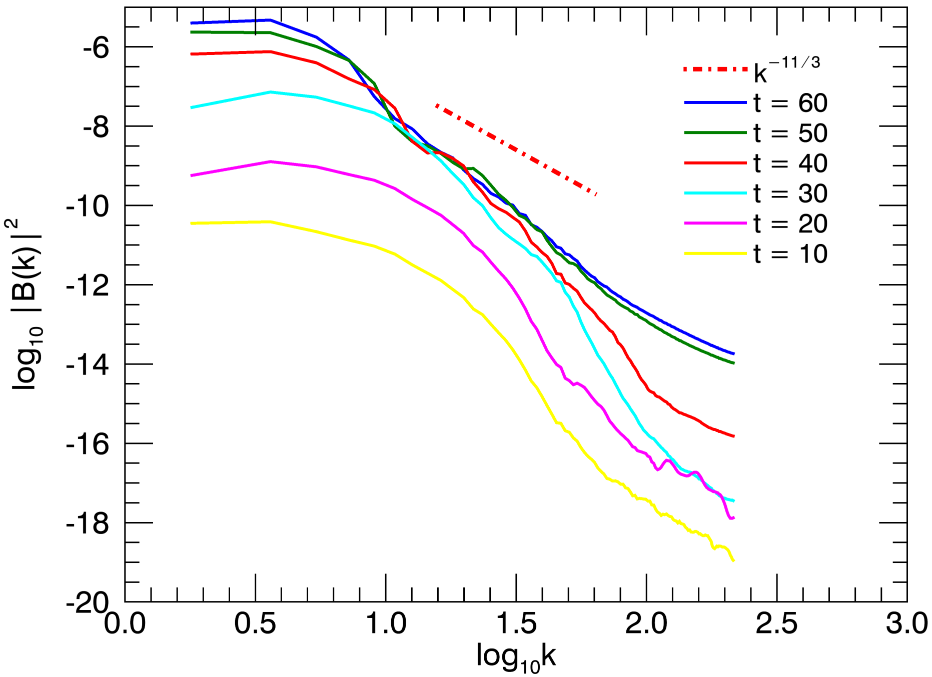
-> Fast reconnection: key for efficient particle acceleration

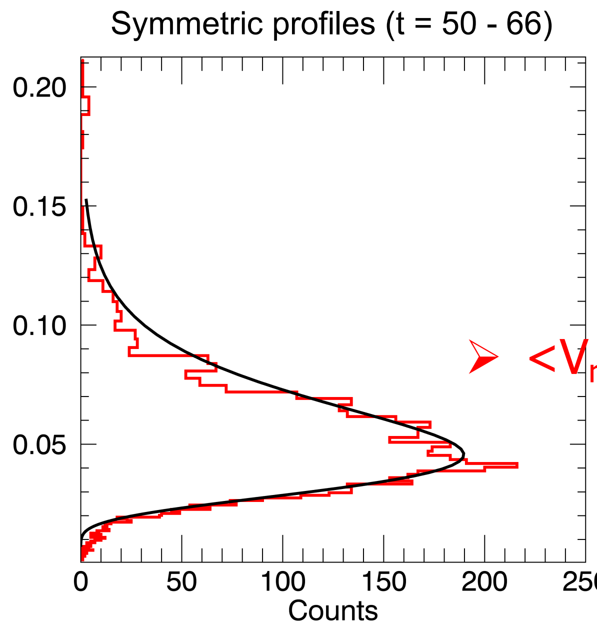
Kadowaki, de Gouveia Dal Pino, Medina-Torrejon + ApJ 2021

Fast Reconnection Rate driven by Kink instability turbulence in Relativistic Jets

- **Distribution of $<V_{rec}>$ follows log-normal:**
- **Magnetic field follows power law spectrum:**

TURBULENCE





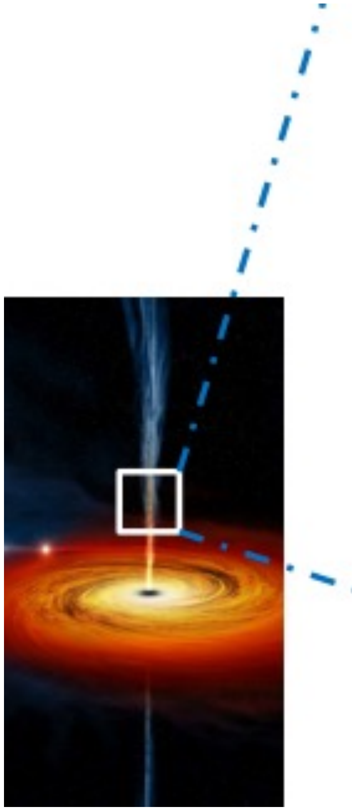
- $<V_{rec}> \approx 0.05\ V_A$

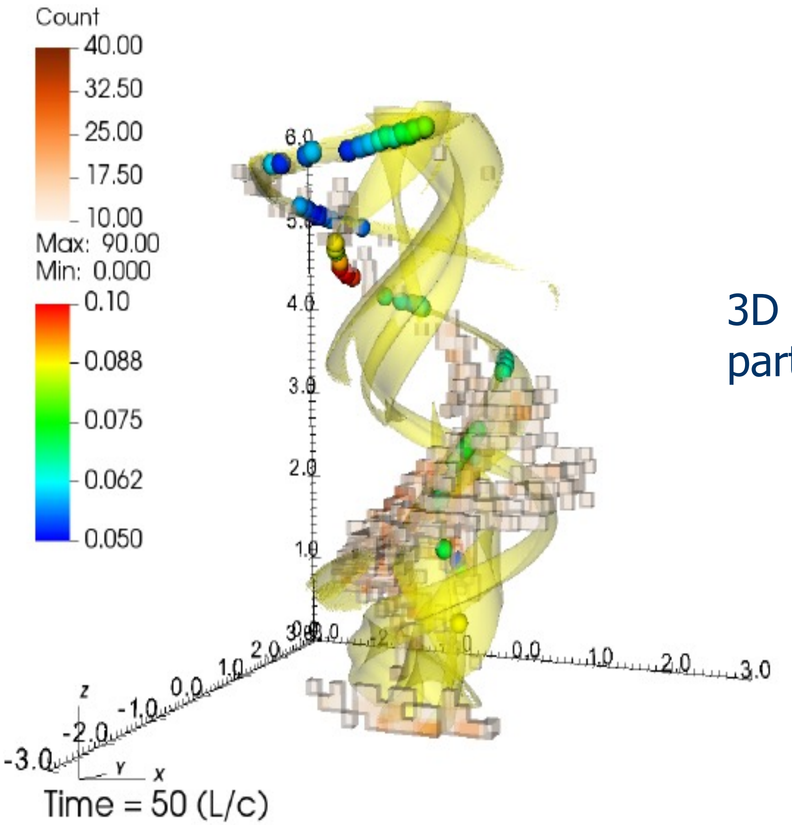
Kadowaki, de Gouveia Dal Pino, Medina-Torrejon +, ApJ 2021

In situ acceleration of test particles by Magnetic Reconnection in Relativistic MHD Jets

Injected 1000 test particles accelerated in reconnection sheets from:
25 MeV=0.03 mc^2

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





3D histogram of accelerated parttickles

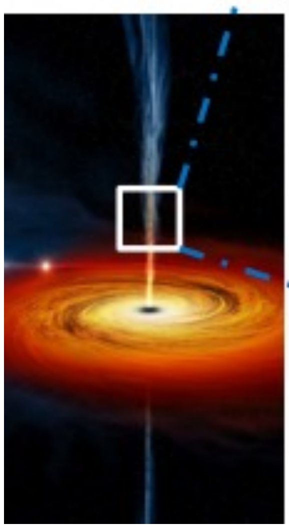
$E_p > 10^{-1} m_p c^2$

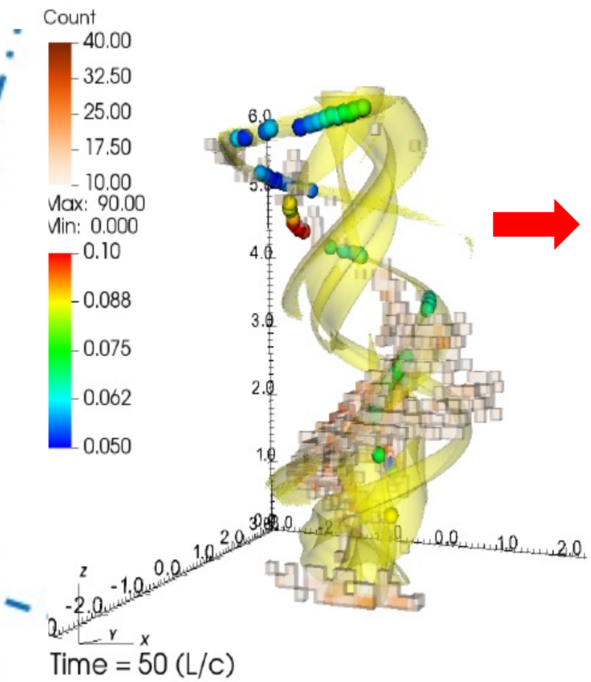
Medina-Torrejon, de Gouveia Dal Pino, Kadowaki+ ApJ 2021

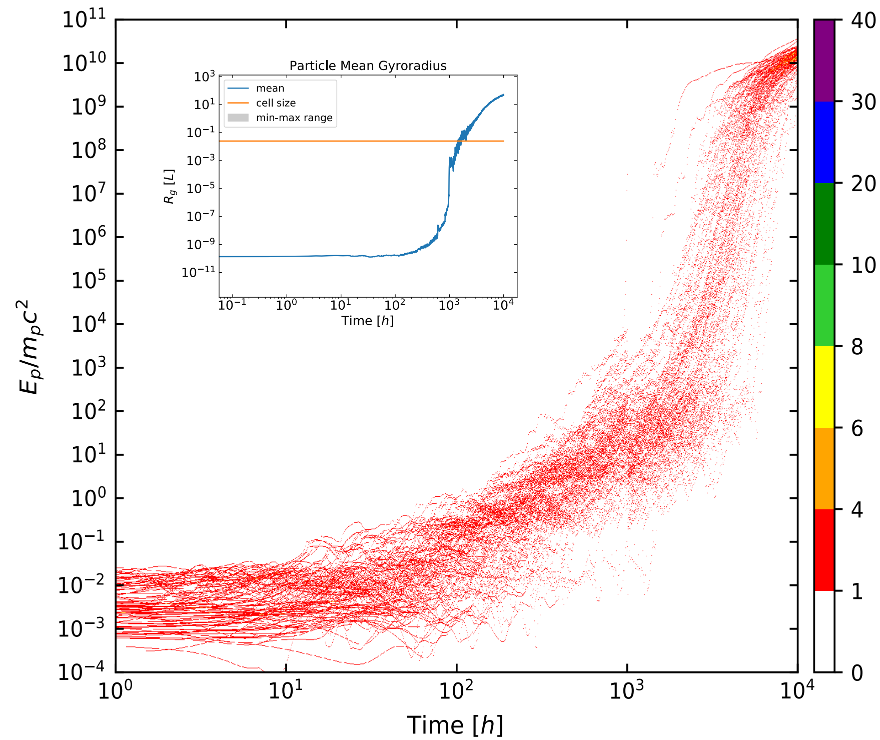
In situ acceleration of test particles by Magnetic Reconnection in Relativistic MHD Jets -> UHECRs

B~ 10 G

Particles accelerated over:
0.01-0.1 pc scales
(B~ 0.1 -10 G)







$L= 3.6\ 10^{-5}$ pc

Exponential regime:

$R_{L,max}$ ~10^{-4} pc E_{18}/B_{10G} ~ distorted jet diameter~4 L

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

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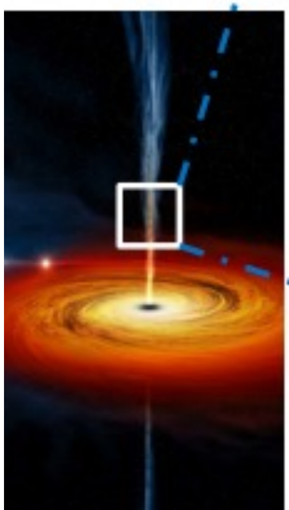

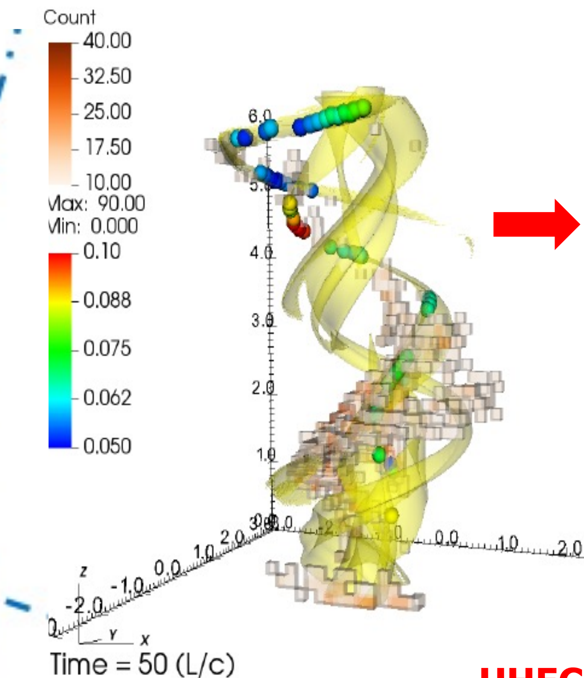

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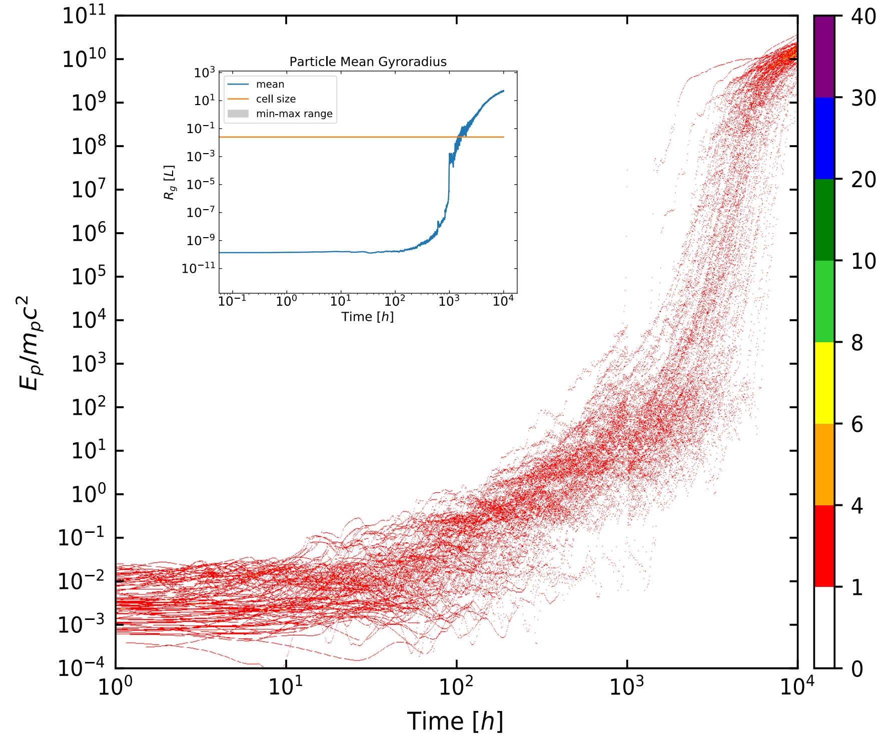
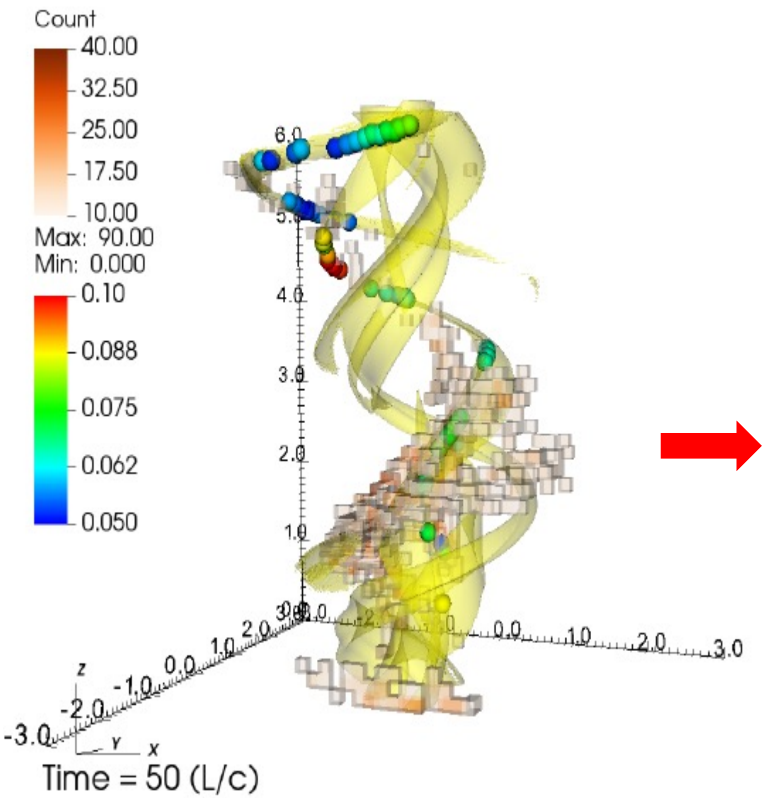
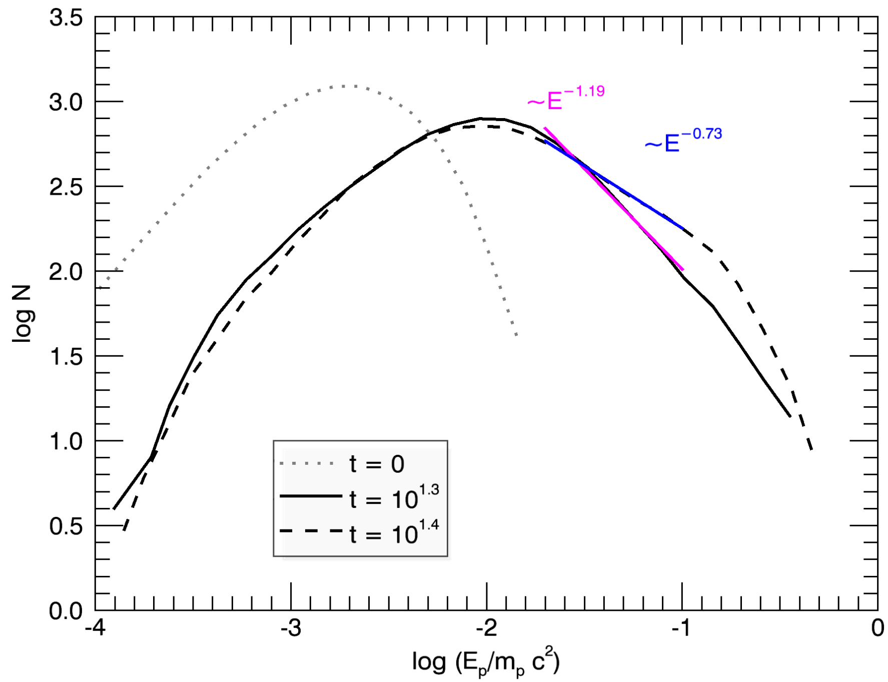


UHECRs: accelerated to 10^{18} - 10^{20} eV (B~ 0.1 -10 G)
-> more than enough to produce
TeV Gamma-Rays and Neutrinos !

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

Accelerated Particles Spectrum in the RMHD Jet





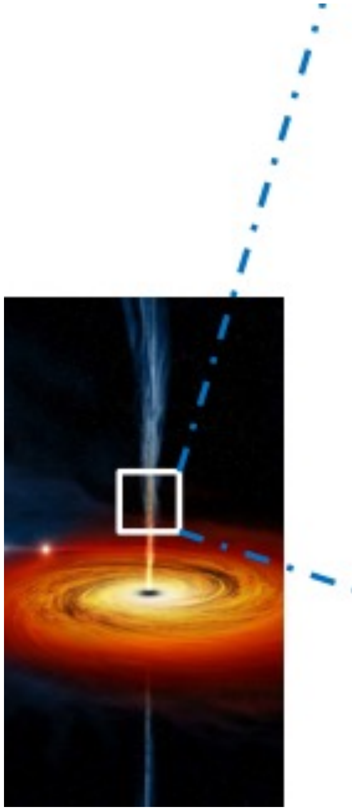
$$\boxed{N(E) \sim E^{-1.2}}$$

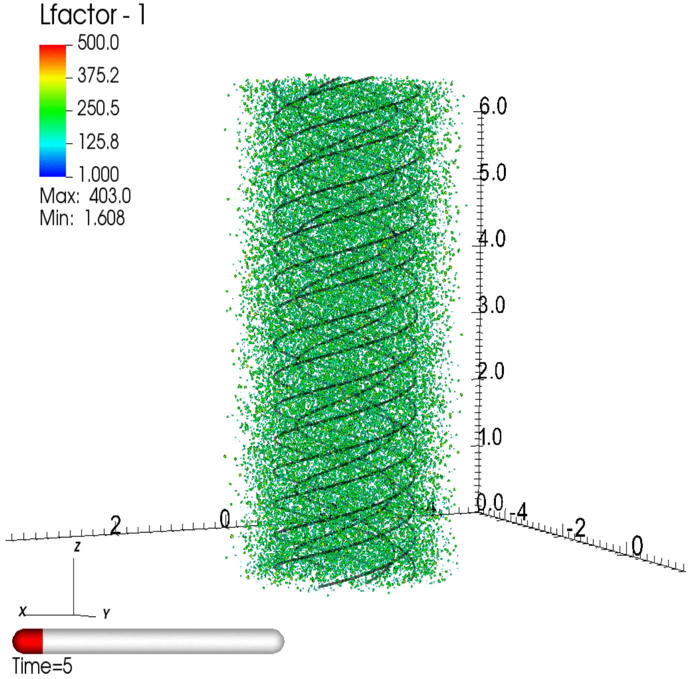
- Similar particle spectrum to PIC simulations, but flatter than observations due to absence of losses or feedback

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

Early Particle Acceleration using RMHD-PIC Simulations: δB/δt effects

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





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

Curvature drift
Fermi
Drift

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

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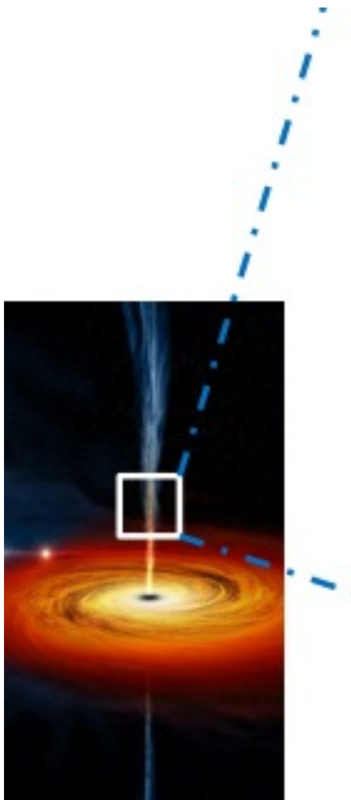

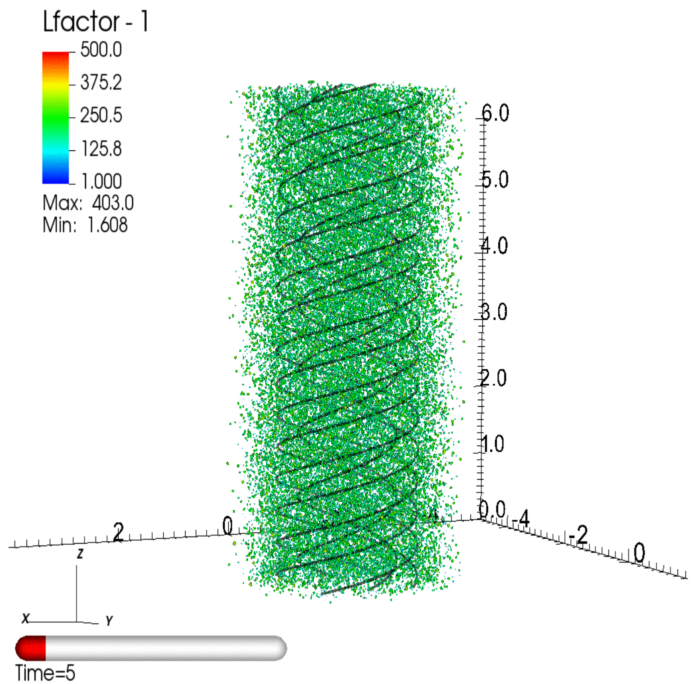

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Curvature drift
Fermi
Drift

Medina-Torrejon, de Gouveia Dal Pino, Kowal 2023

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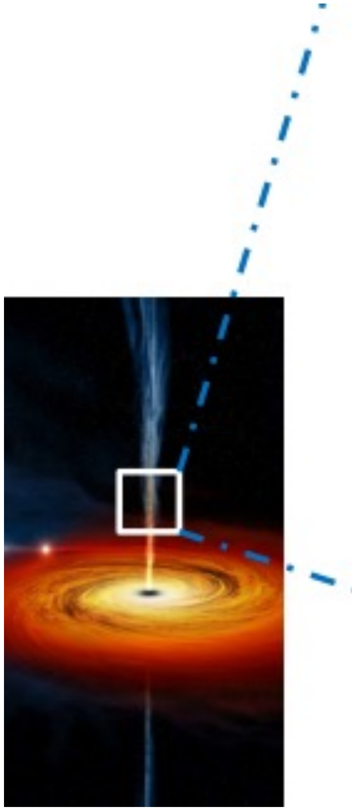
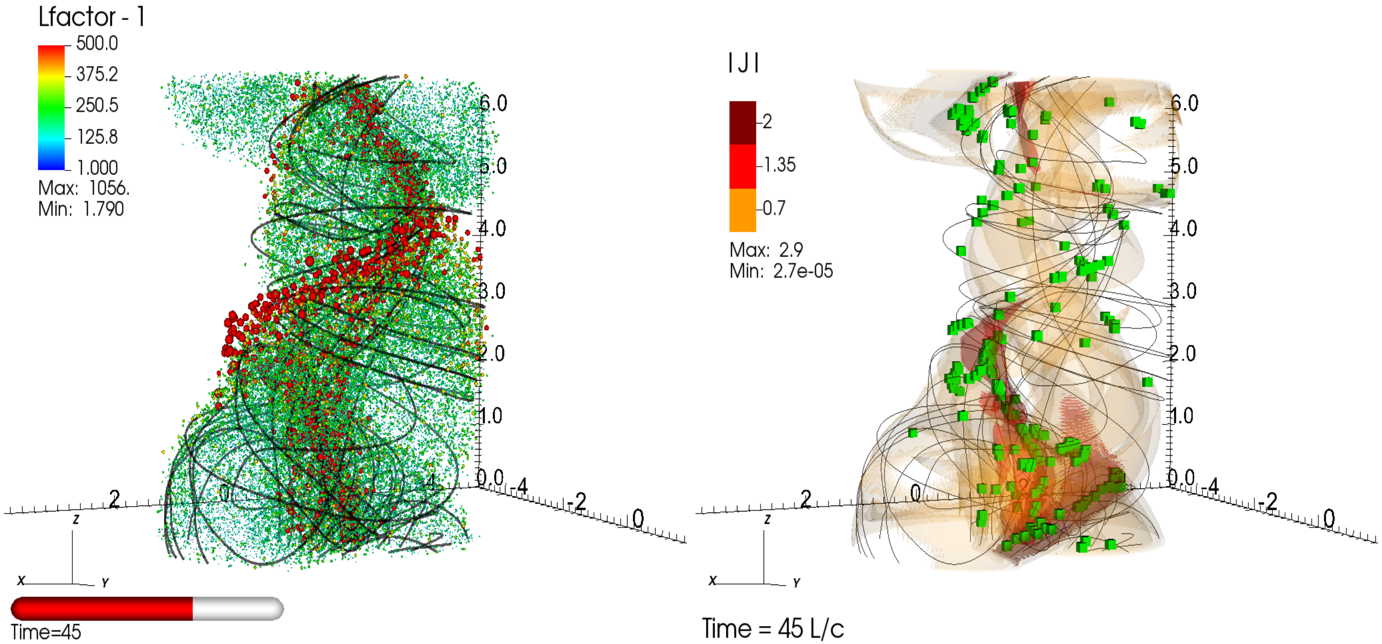
- Particles evolve with flow (Boris particle pusher method)
- 256^3 resolution

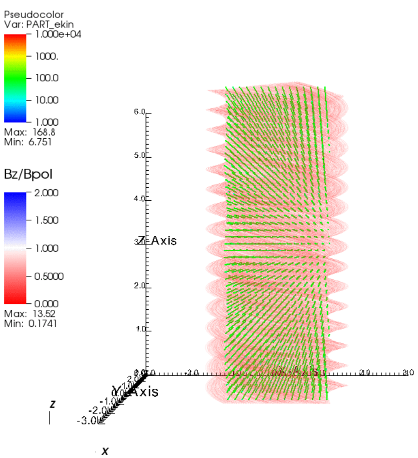




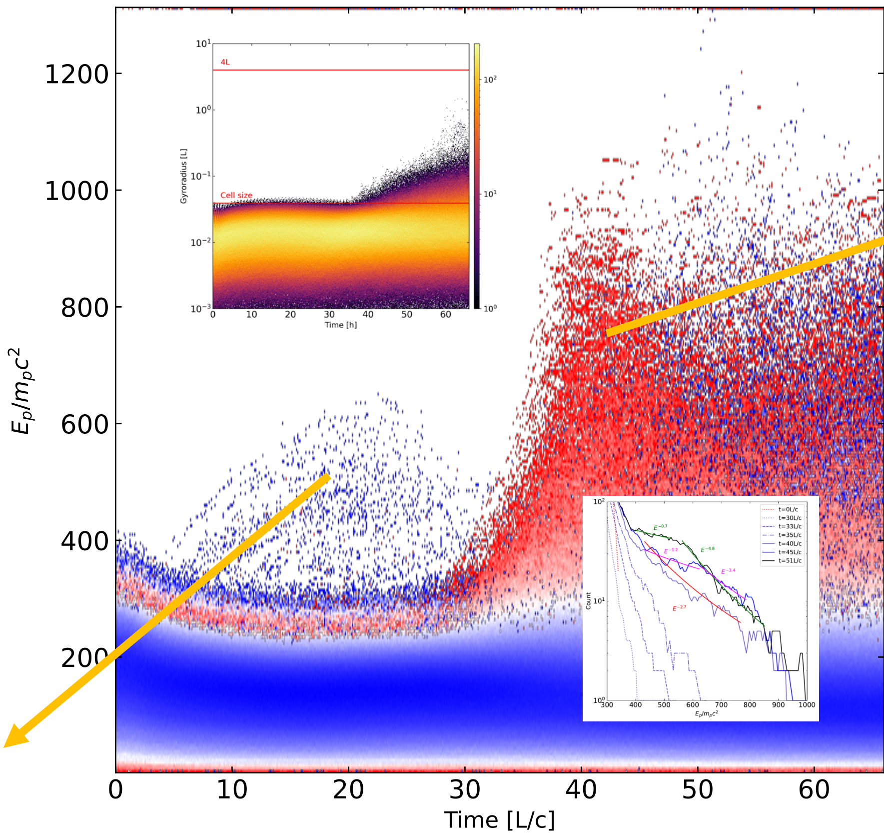
Particle acceleration ←→ Fast reconnection sites

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

Early Particle Acceleration using PIC-RMHD Simulations: δB/δt effects



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



curvature dirift

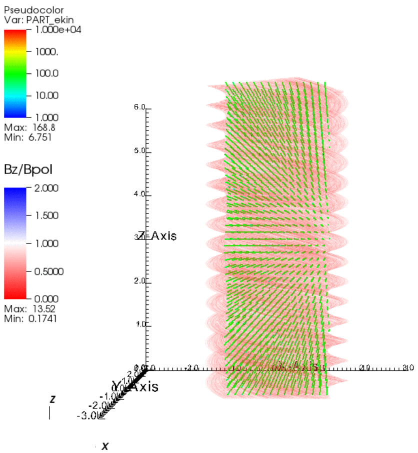
Reconnection acceleration

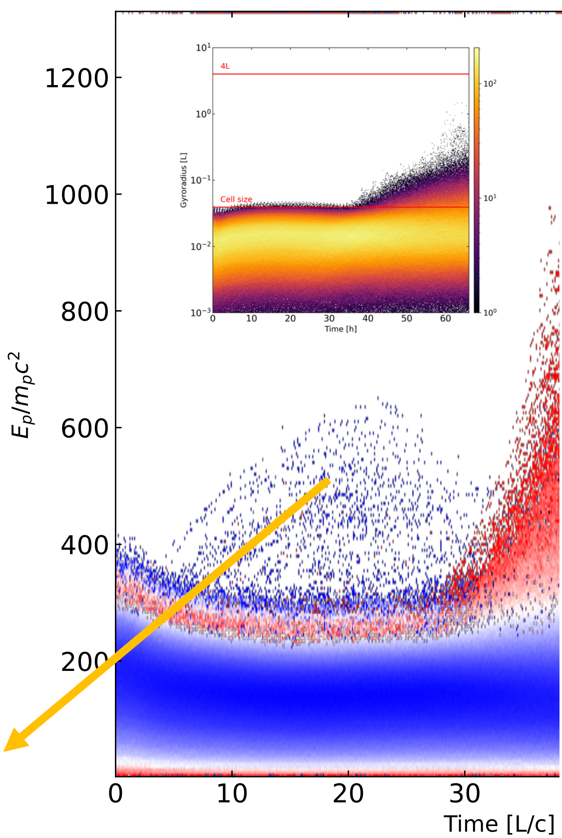
~ to RMHD+ test particles (Medina-Torrejon et al. 2021)

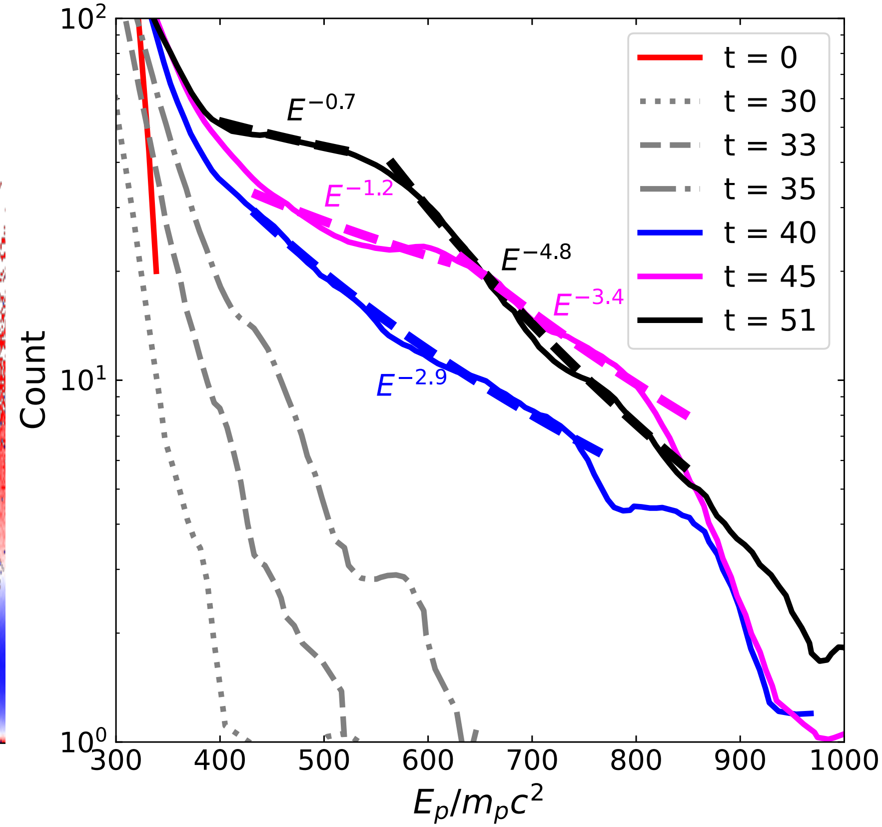
—> δB/δt effects: not important

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

Early Particle Acceleration using PIC-RMHD Simulations: δB/δt effects







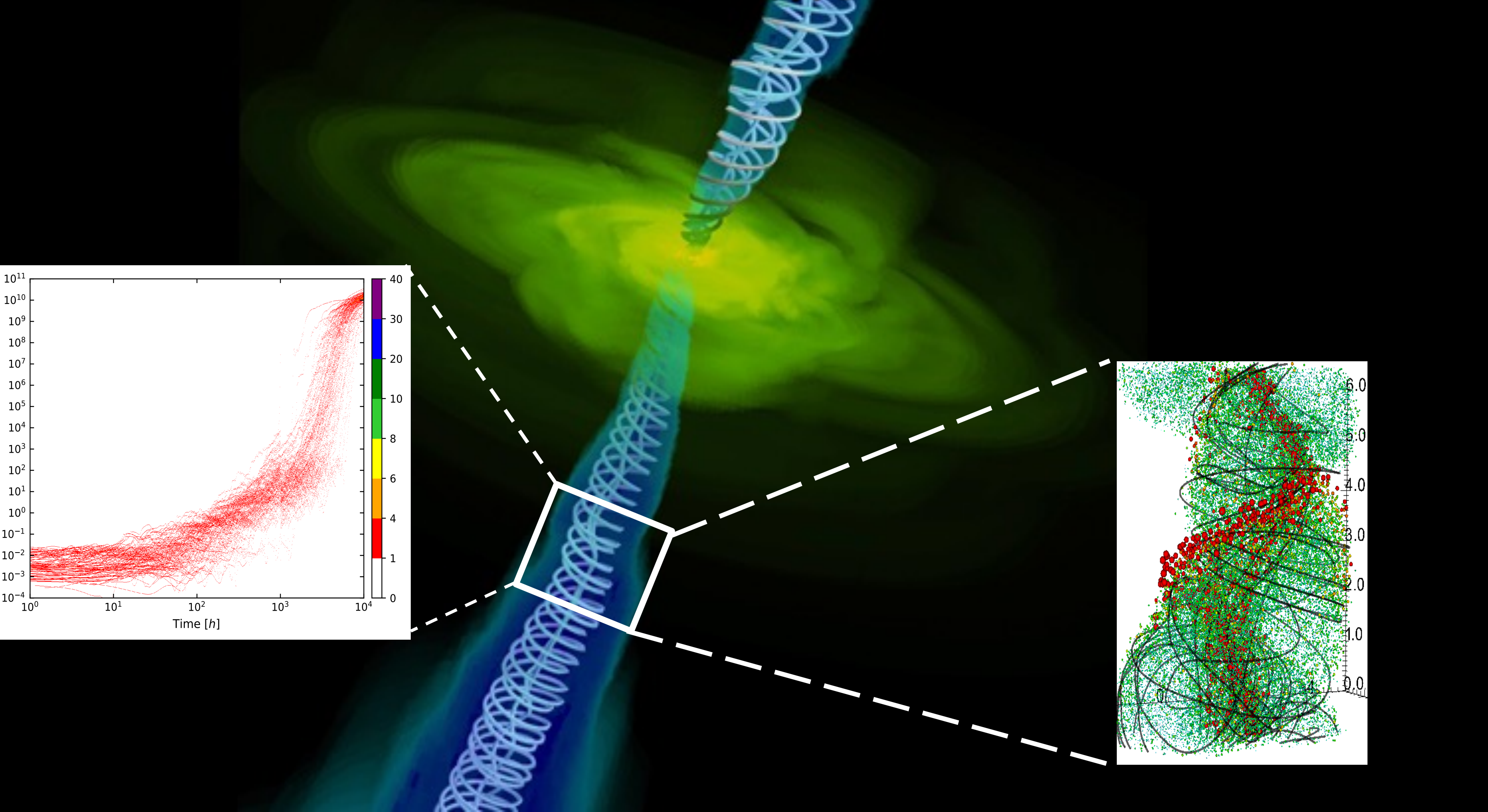
t= 60 L/c ~ 1 hr
L= 5 10^{-7} pc

curvature dirift

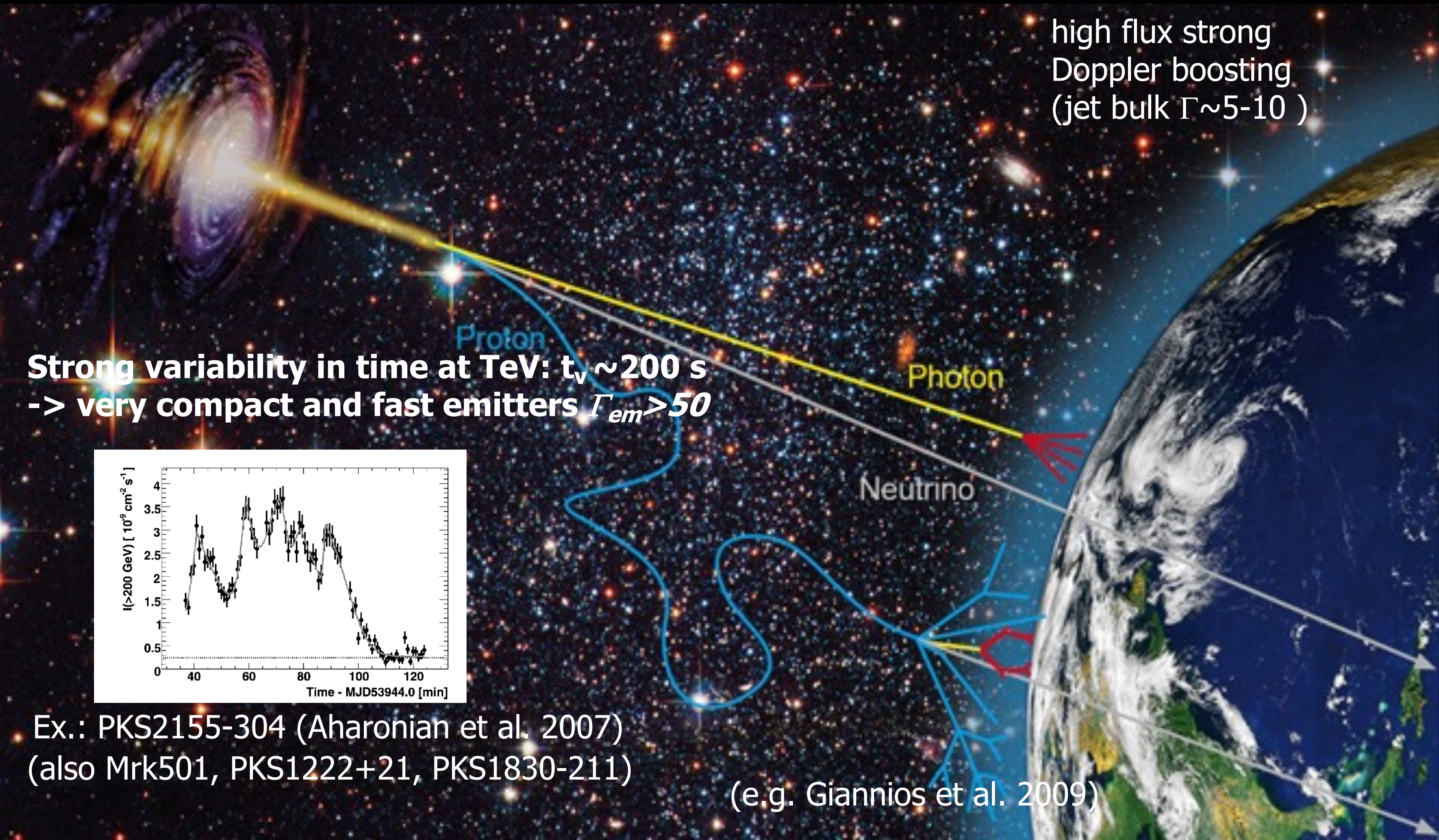
–> δB/δt effects: not important

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

Applications to Blazar AGN Jets VHE Phenomena



Reconnection Particle Acceleration: best candidate able to explain observed VHE gamma-ray flares in AGN BLAZAR Jets in magnetically dominated inner regions



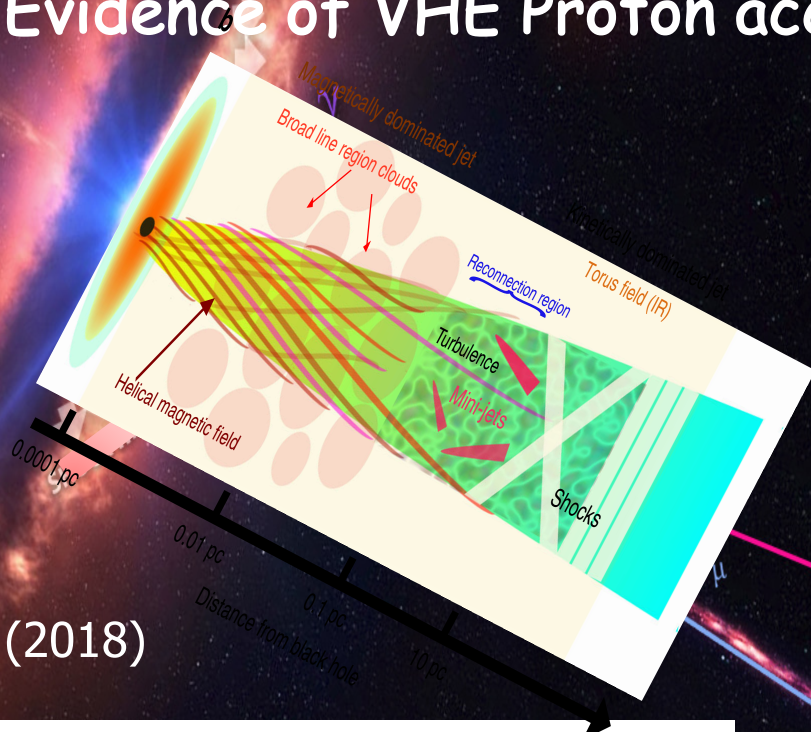
high flux strong Doppler boosting (jet bulk Γ~5-10)

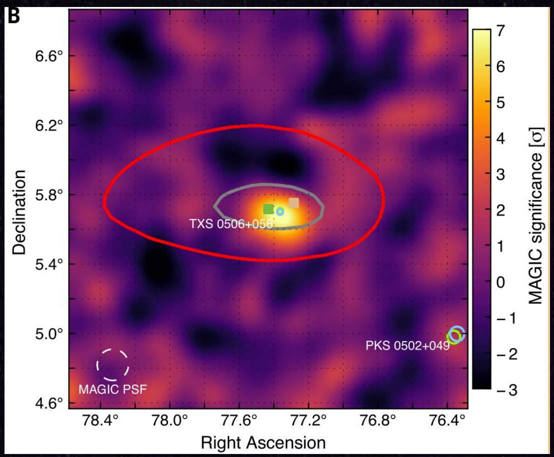
Strong variability in time at TeV: t_v ~200 s
-> very compact and fast emitters Γ_{em}>50

Ex.: PKS2155-304 (Aharonian et al. 2007)
(also Mrk501, PKS1222+21, PKS1830-211)

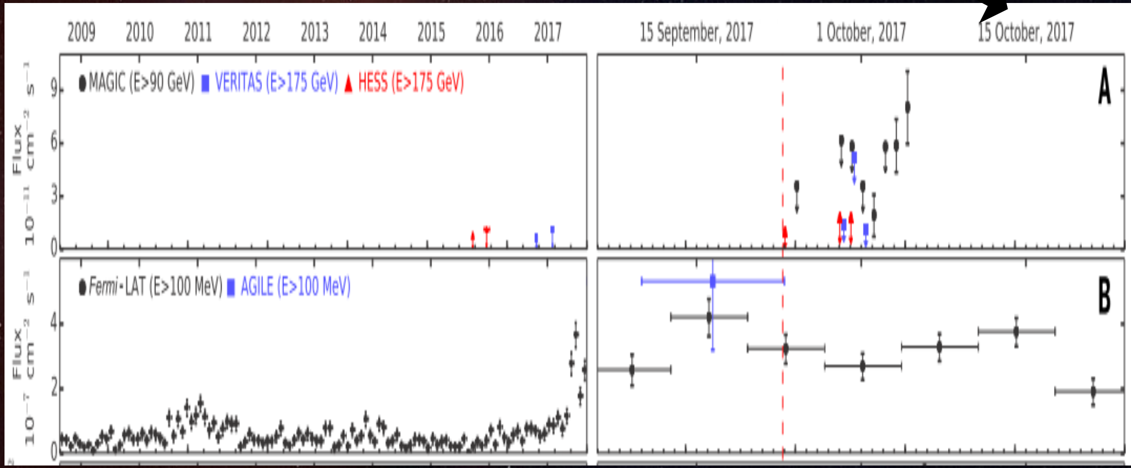
(e.g. Giannios et al. 2009)

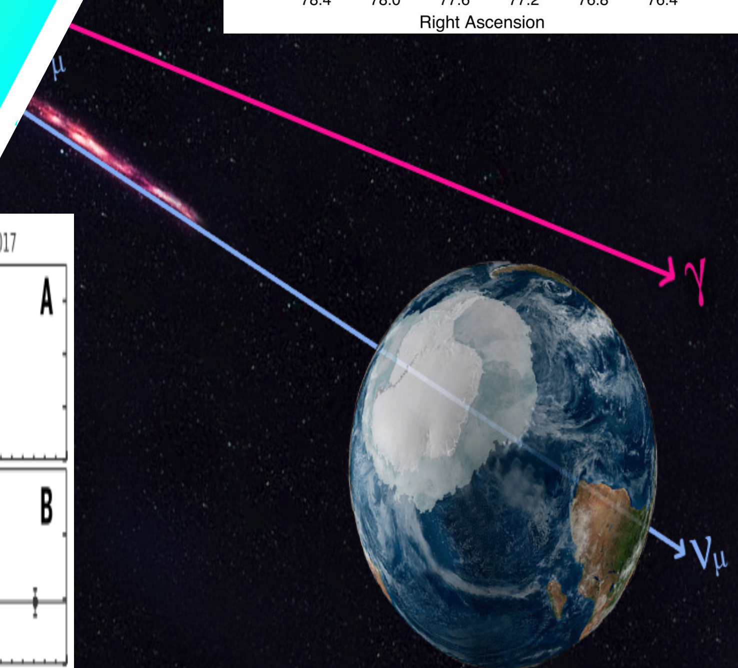
First simultaneous observation of gamma-ray flare and neutrino in AGN blazar TXS 0506+056: Evidence of VHE Proton acceleration



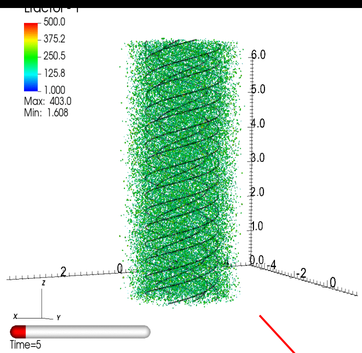


Science (2018)

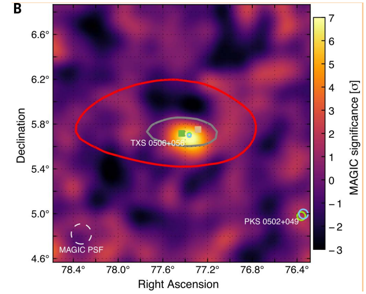




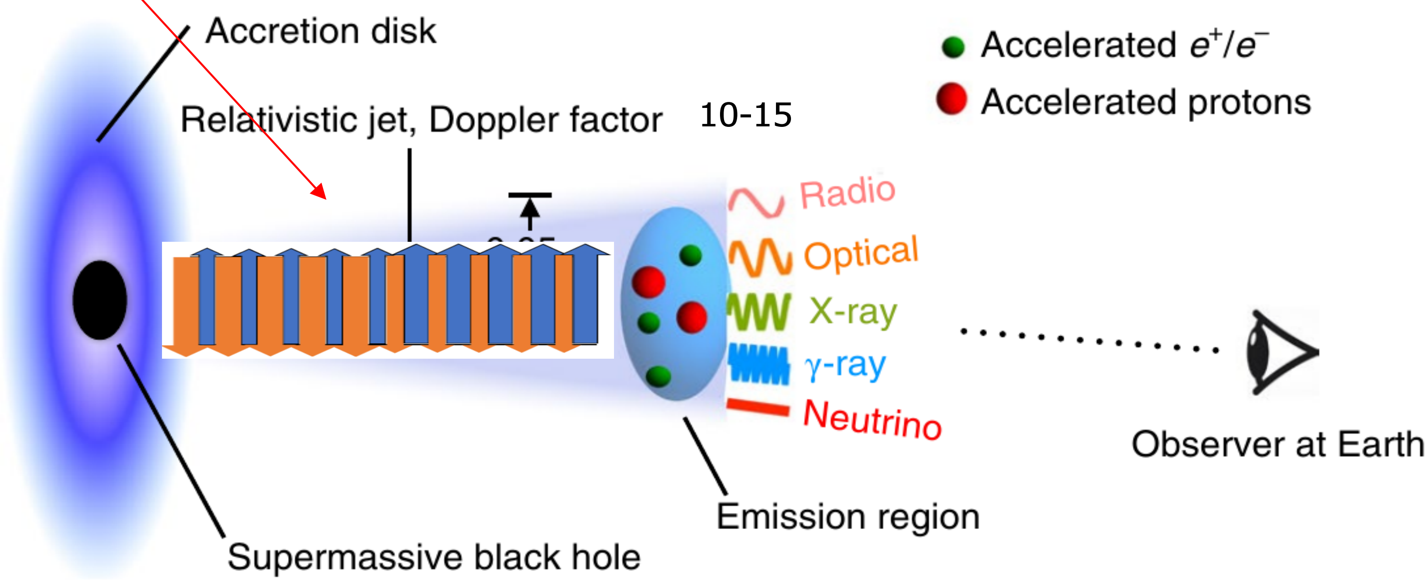
Leptonic-Hadronic Reconnection Acceleration for Relativistic Jets - VHE Losses



Blazar TXS 0506+056



(Aartsen et al. Science 2018)

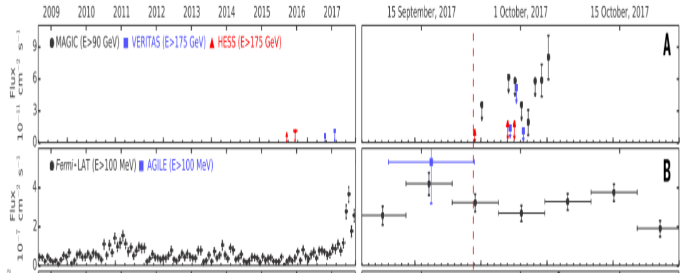


- ✓ Jet background described by **striped reconnection** model (Giannios & Uzdenzky 2019)
- ✓ Photon Field: due to internal dissipation

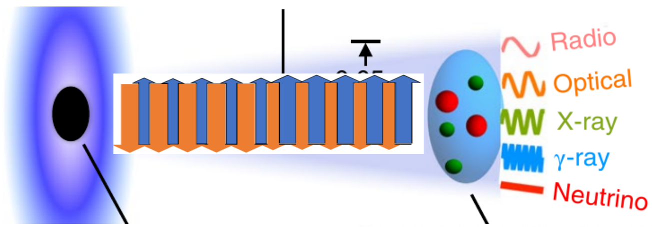
Rodriguez-Ramirez, de Gouveia Dal Pino et al. (2023, in prep.)

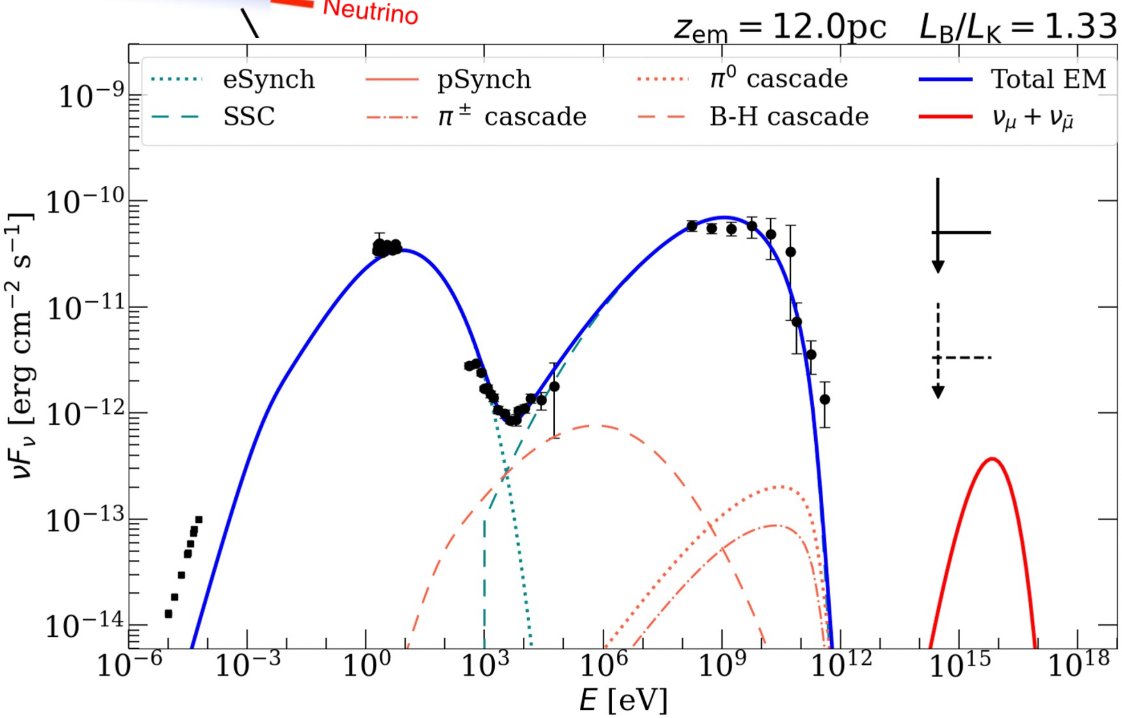
Lepto-Hadronic Model based on Reconnection Acceleration for Relativistic Jet

Blazar TXS 0506+056



(Aartsen et al. Science 2018)



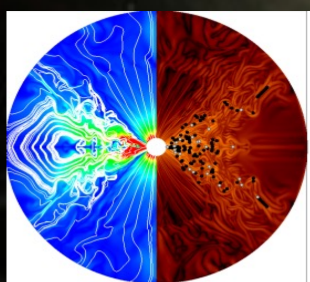


model predicts VHE γ-rays appearing later than neutrino emission, as observed!

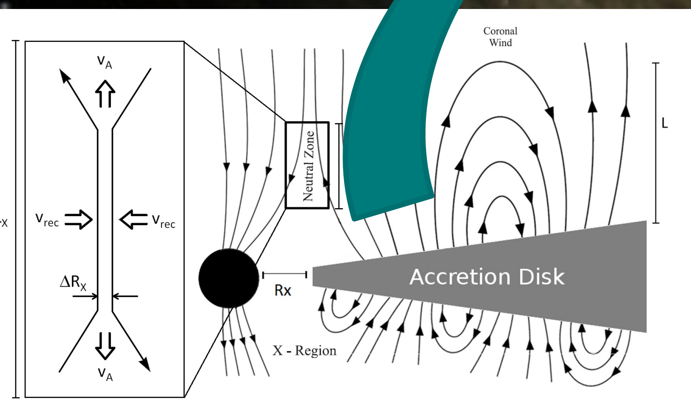
Rodriguez-Ramirez, de Gouveia Dal Pino et al. (2023, in prep.)

CR Reconnection Acceleration also possible in the core region of BHs

General Relativistic MHD + test particles

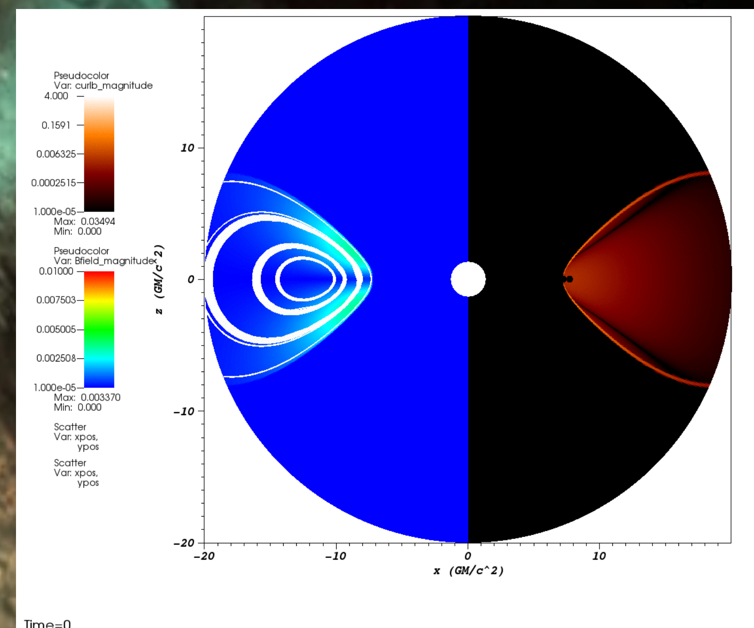


CR Reconnection Acceleration in the accretion flow of BH



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

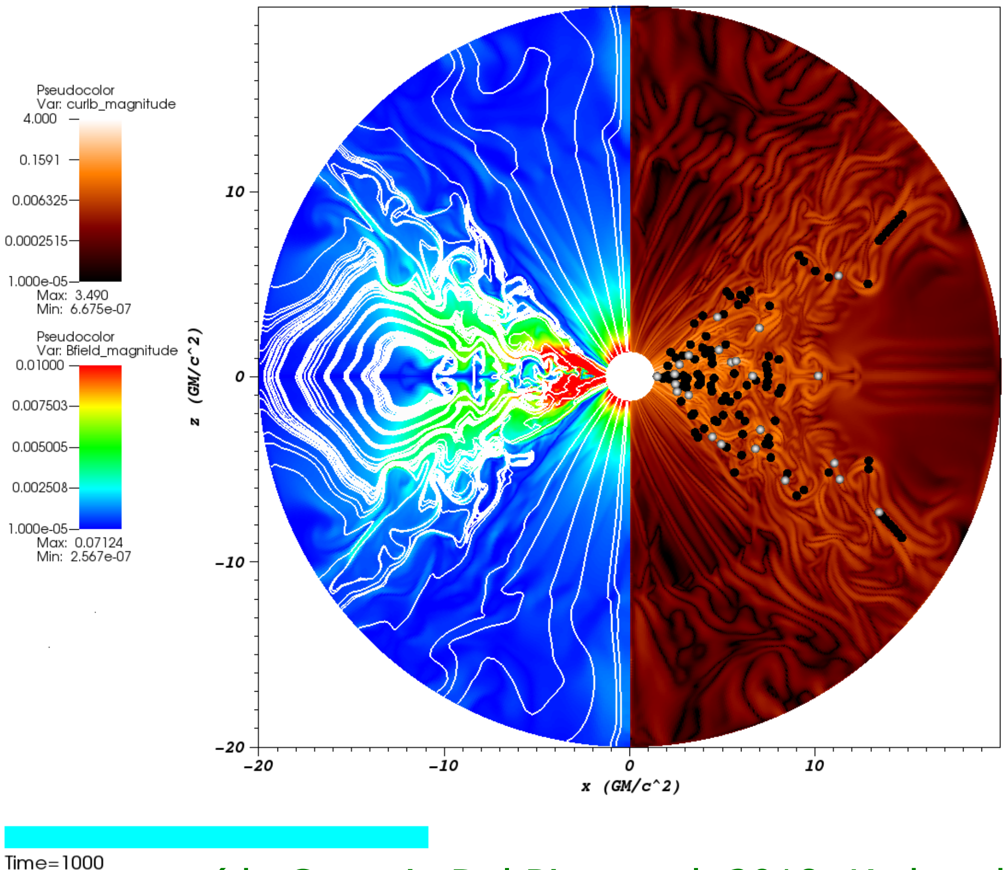
Athena++ code (Stone et al. 2020)

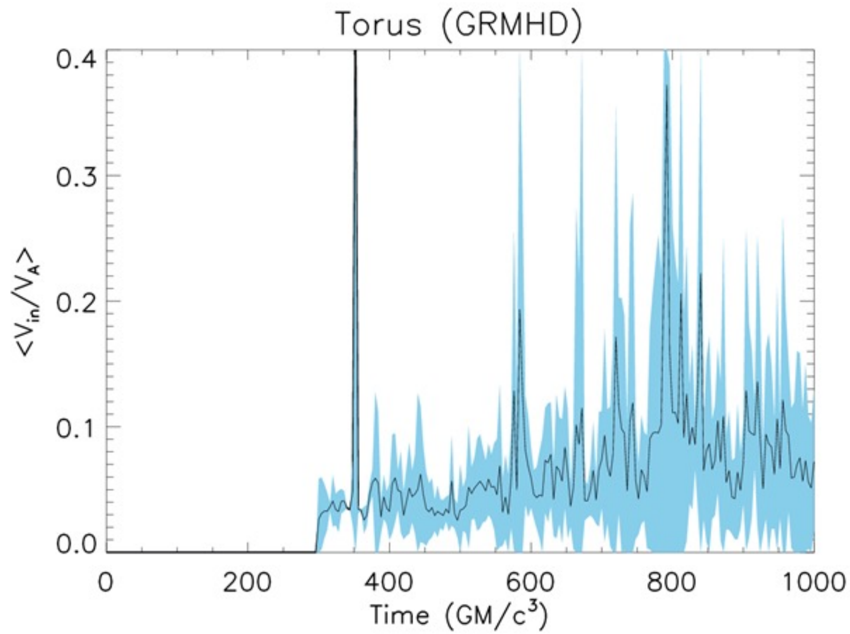


GRMHD simulations of accretion flows around BHs
reconnection driven by magneto-rotational turbulence

(de Gouveia Dal Pino et al. 2018; Kadowaki et al. 2019)

Fast Reconnection in GRMHD simulations of accretion flows around BHs driven by magneto-rotational instability turbulence



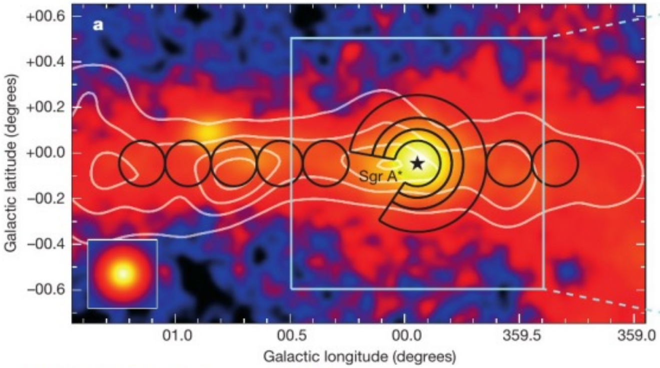


- Average reconnection velocities $<V_{rec}>\sim$ **0.05 V_A**

(de Gouveia Dal Pino et al. 2018; Kadowaki et al. 2019)

(See also: de Gouveia Dal Pino & Lazarian 2005; Koide & Arai 2008; Dexter, McKinney, Tcheckovskoy2014; Parfrey et al. 2015; Kadowaki + 2015; Singh + 2015; Pohl et al. 2016; de Gouveia Dal Pino+ 2018…)

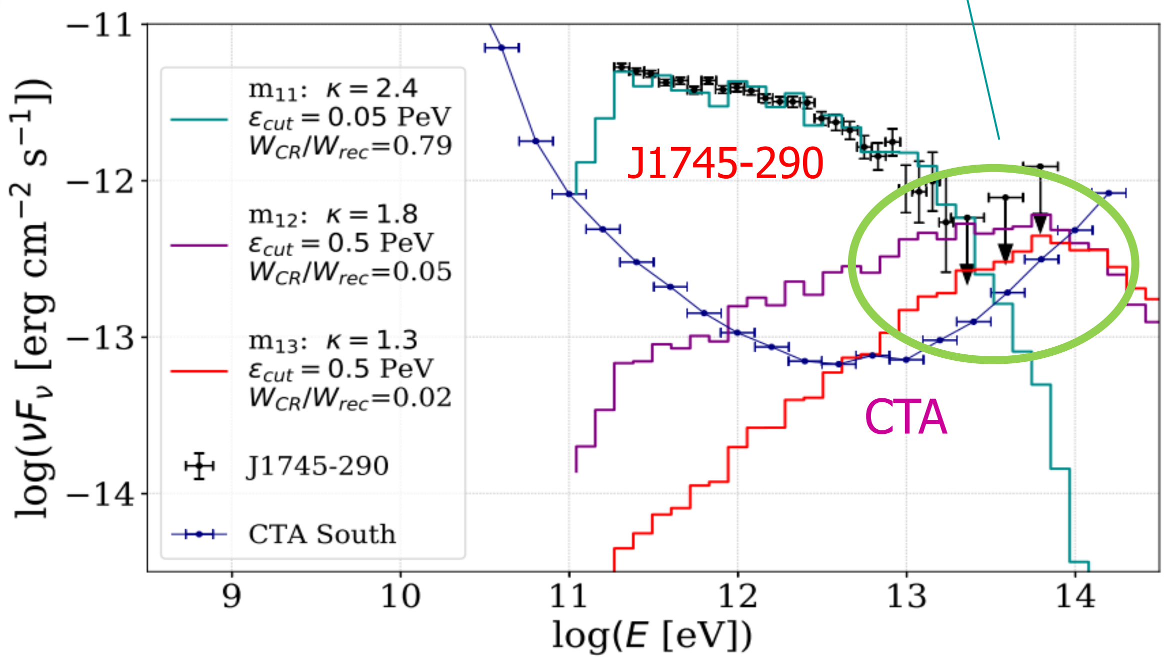
Ex. Galactic Center SgrA*: Reconnection acceleration and PeVatron emission

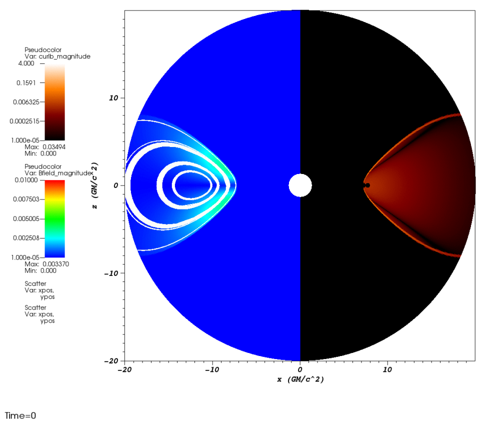


H.E.S.S. Nature 2016

PeVatron!

GRMHD + Radiative Transfer + CR cascading simulations





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

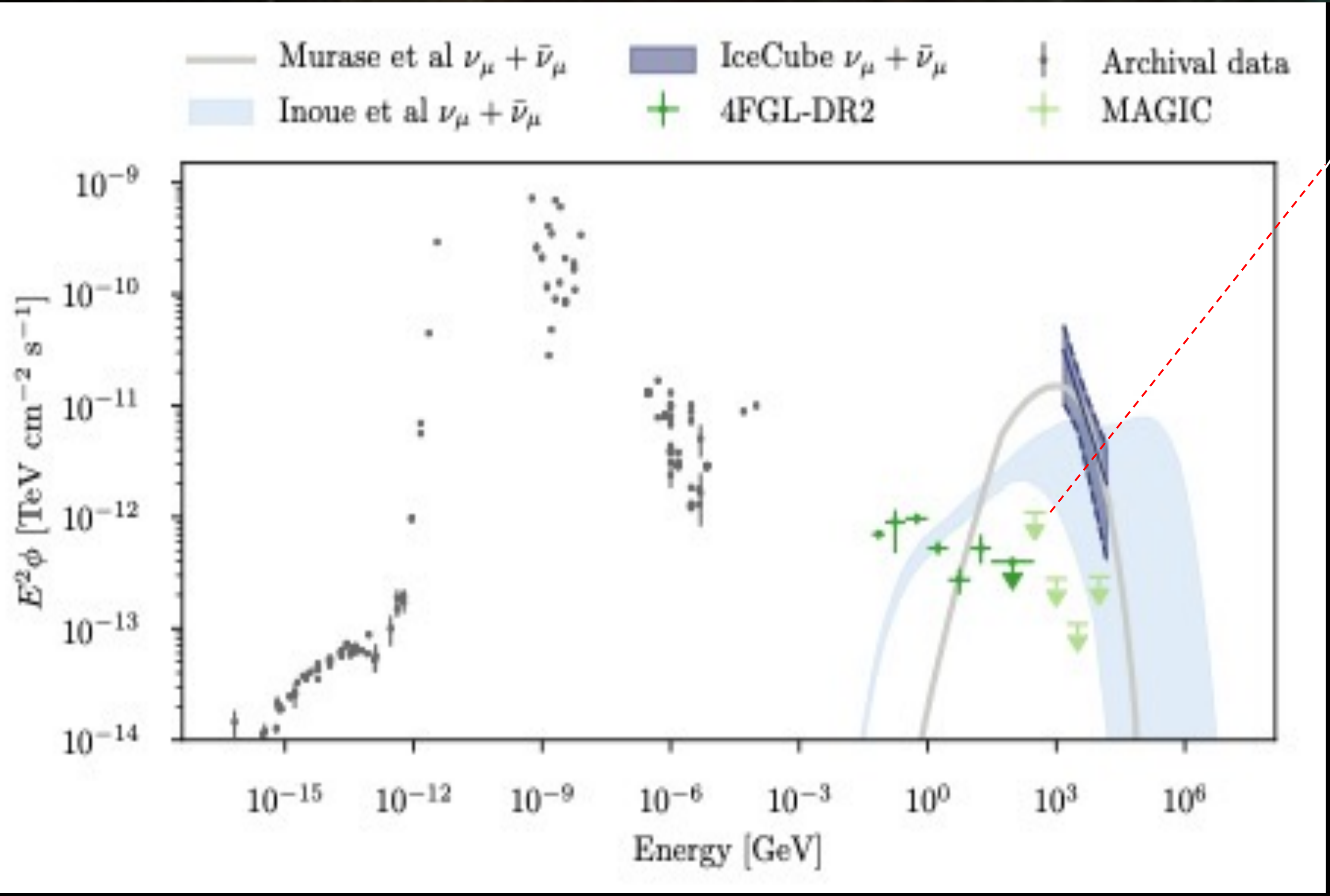
Summary

- ✓ In magnetized flows particles can be accelerated by turubulent driven fast magnetic reconnection via stochastic Fermi by $\varepsilon = v \times B$, and produce $N(E_p) \sim E^{-1.2}$
- ✓ Magnetic reconnection rates in MHD, RMHD and GRMHD simulations of turbulent systems $\langle v_{rec} \rangle \sim 0.05$ and peak values $> 0.1\ V_A$ (compatible with Lazarian & Vishniac 1999)
- ✓ Reconnection acceleration of protons GLOBAL RMHD simulations of magnetically dominated Blazar jets can produce UHECRs up to $\sim 10^{18}$ - 10^{20} eV (for B $\sim$ 0.1 – 10 G) -> may explain flare gamma-rays and neutrinos (ex.TXS0506+056)
- ✓ RMHD-PIC simulations ~ RMHD-test particle simulations: no important effects due to $\delta B/dt$
- ✓ Reconnection acceleration may be also important to explain VHE emission in core of BH sources: ex. SgrA* PeVatron, NGC1068?

To Dos

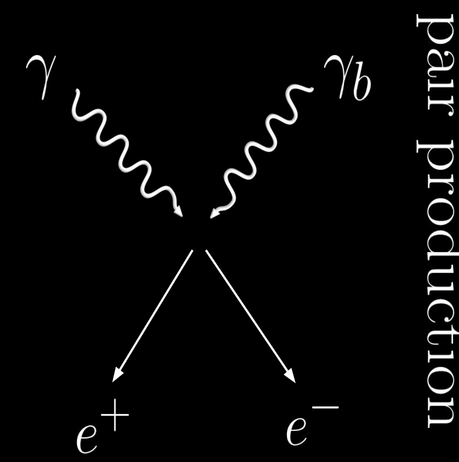
- Transition from PIC (resistive electric field) to MHD (ideal electric field) acceleration
- Signatures of polarization to probe reconnection ?
- RMHD+Radiative Transfer+CR Cascading: produce SED self-consistently (ex. NGC1068 ?)

Next to be tested:
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?)