Ultra-high-energy cosmic ray acceleration by magnetic reconnection in relativistic jets and the origin of very high energy emission

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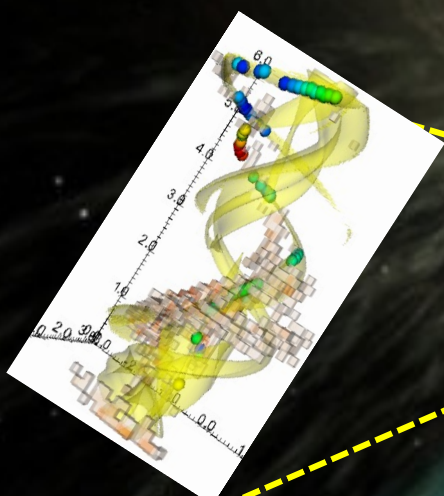
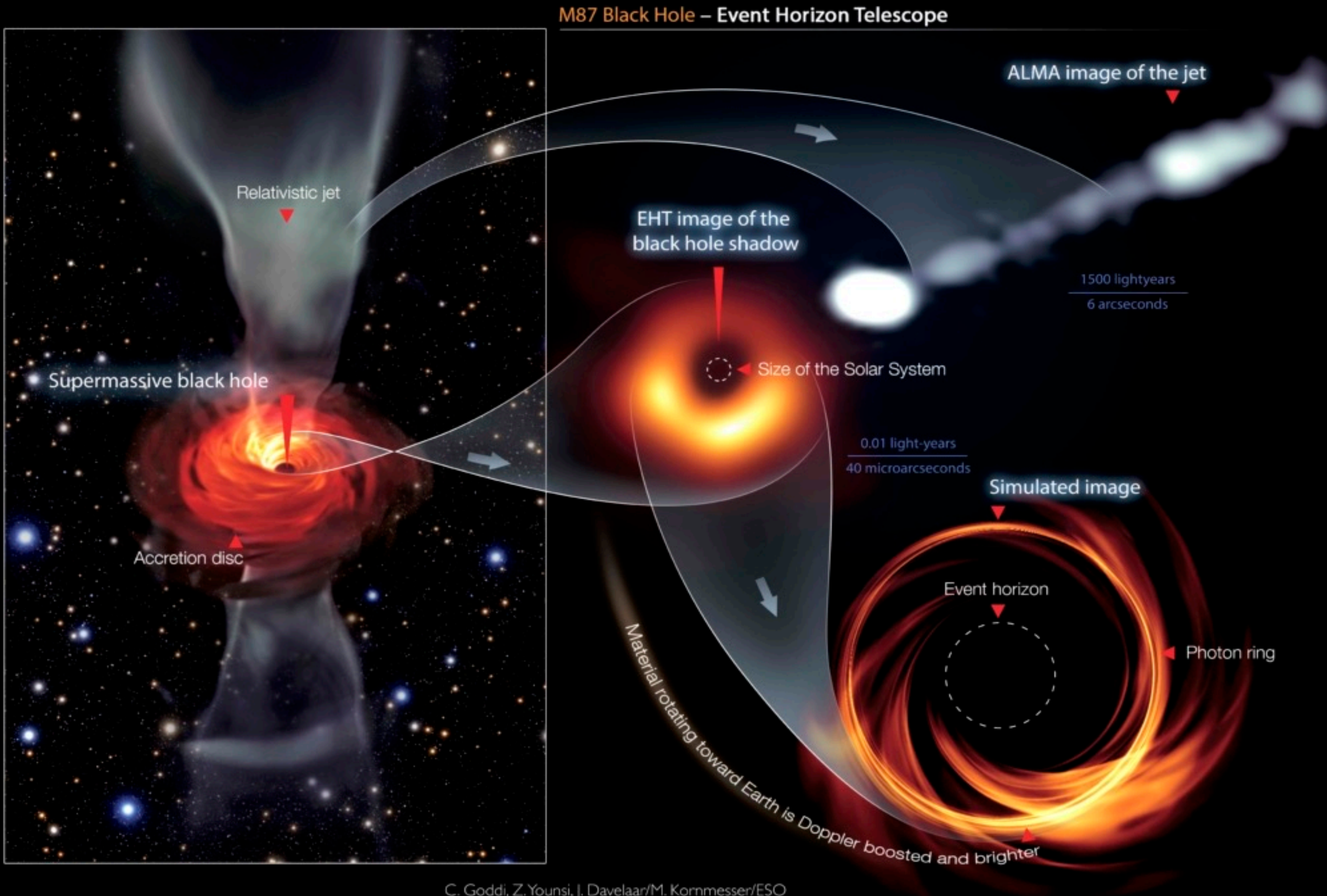
C. Singh



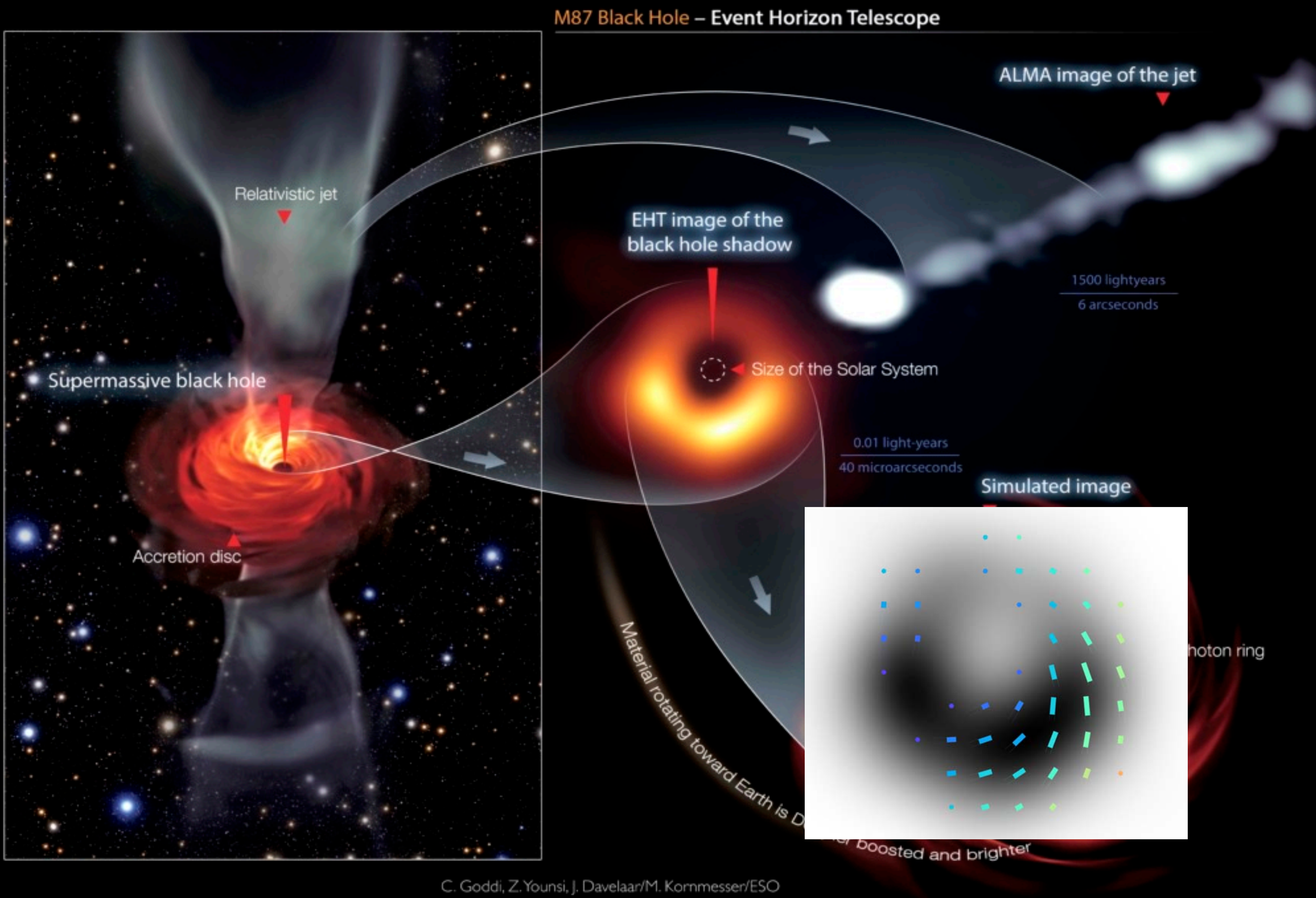
ICRC 2021, Germany, July 12-23, 2021, ONLINE

IAG USP

Relativistic jets are born magnetically dominated



Relativistic jets are born magnetically dominated



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

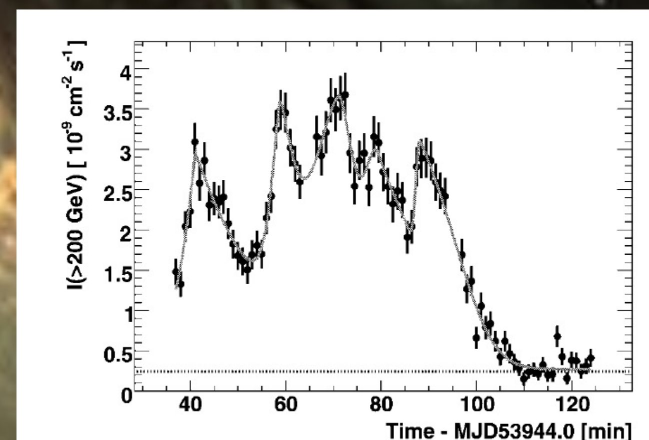
Blazars:
AGN jets point to line-of-sight

& most frequent
extragalactic
Gamma-ray emitters

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 $\Gamma_{em}>50$



Ex.: PKS2155-304 (Aharonian et al. 2007)

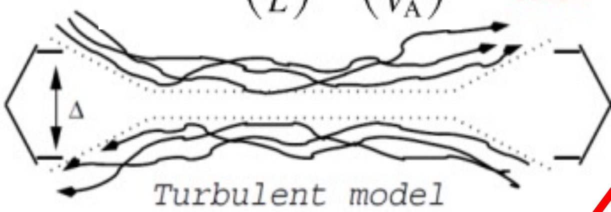
(also Mrk501, PKS1222+21, PKS1830-211)

(see e.g. Giannios et al. 2009)

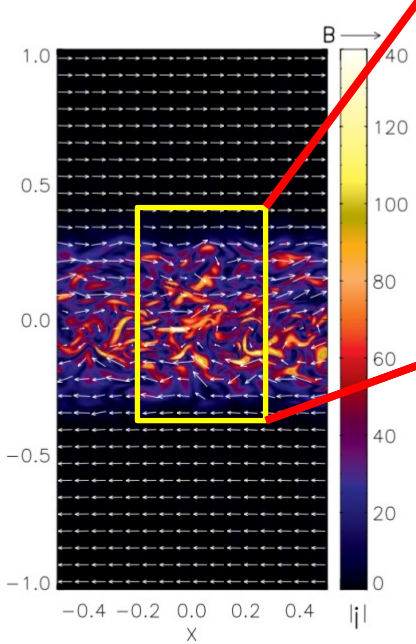
Particles are accelerated in 3D reconnection mainly by Fermi process (and turbulence makes reconnection FAST!)

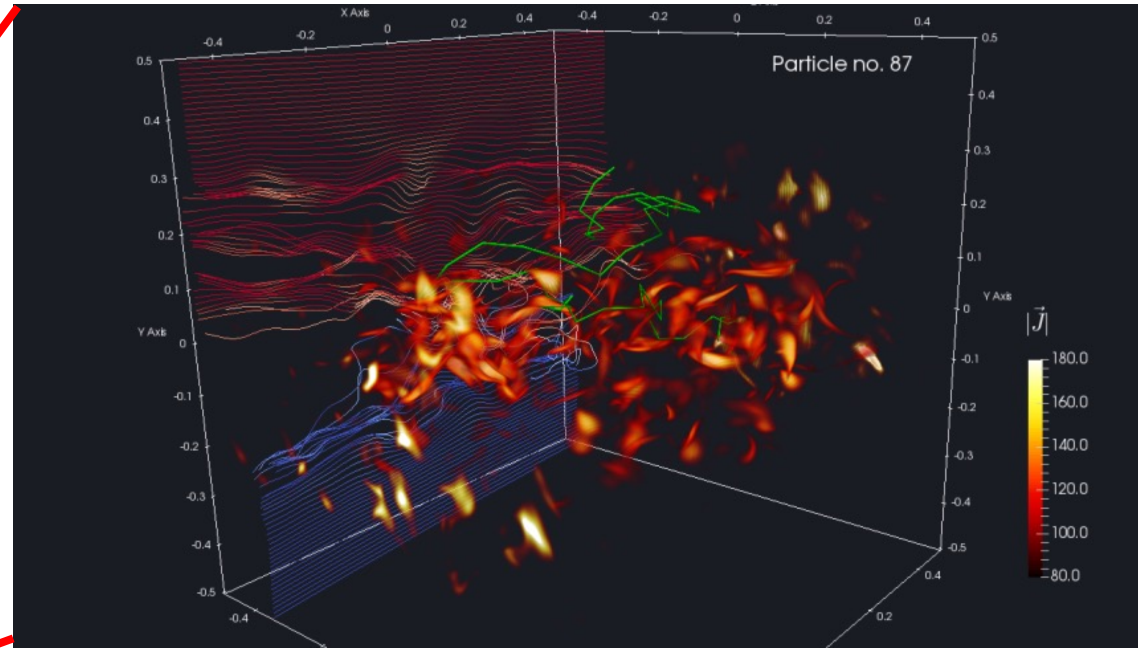
$$V_{rec} = V_A \left(\frac{l}{L}\right)^{1/2} \left(\frac{v_l}{V_A}\right)^2$$

FAST



(Lazarian & Vishniac 1999)





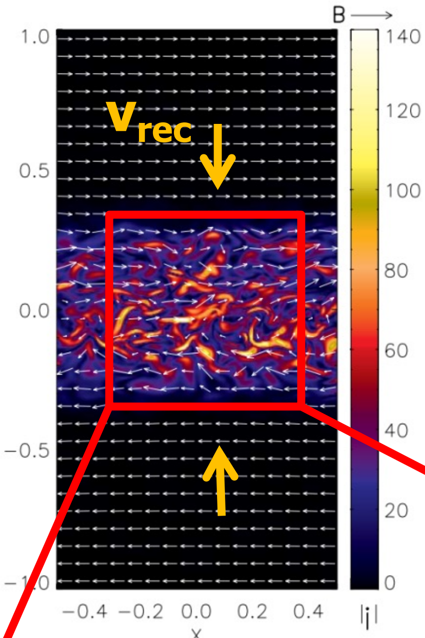
$$\frac{d}{dt}(\gamma\, m\, \mathbf{u}) = q(\mathbf{E} + \mathbf{u} \times \mathbf{B}) \rightarrow \frac{d}{dt}(\gamma m \boldsymbol{u}) = q\left[(\boldsymbol{u} - \boldsymbol{v}) \times \boldsymbol{B}\right]$$

de Gouveia Dal Pino & Lazarian A&A 2005;

Kowal, de Gouveia Dal Pino, Lazarian ApJ 2011; PRL 2012

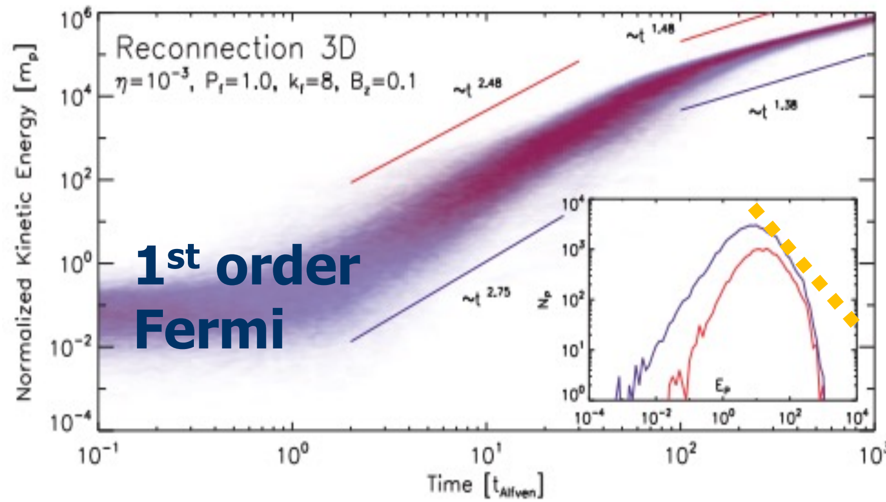
del Valle, de Gouveia Dal Pino, Kowal, MNRAS 2016

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



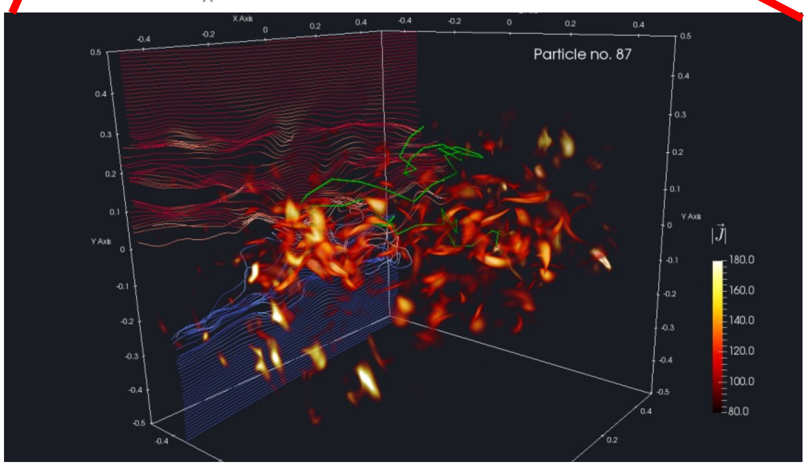
10,000 test particles

Injected in turbulent current sheet to make reconnection fast



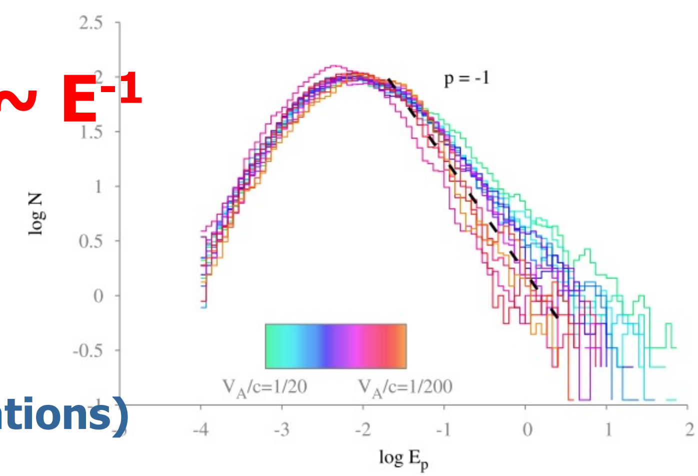
1^{st} order Fermi

Kowal, de Gouveia Dal Pino, Lazarian, PRL 2012



✓ **N(E) ~ E^{-1}**

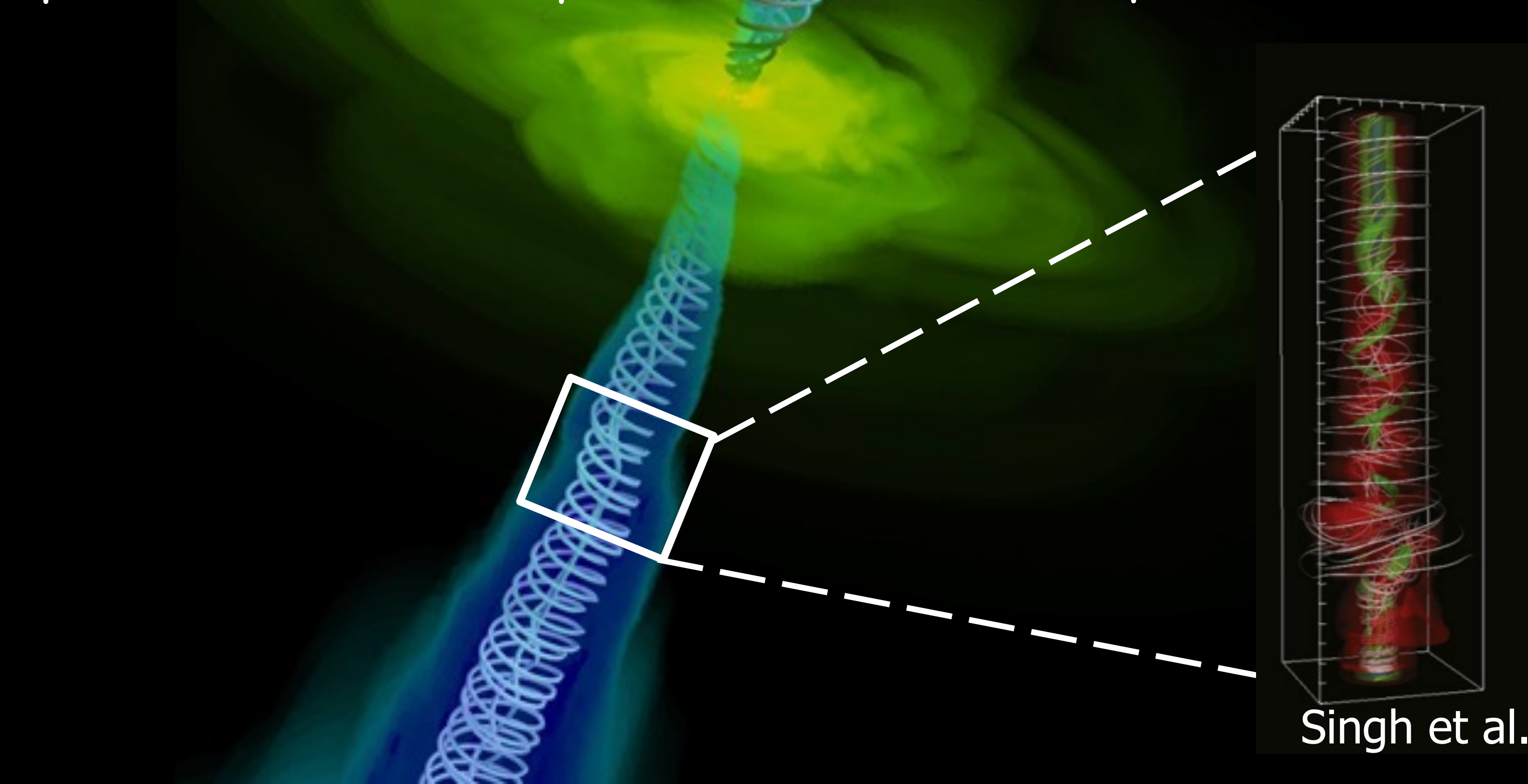
(~PIC simulations)



del Valle, de Gouveia Dal Pino, Kowal MNRAS 2016

In situ Reconnection Acceleration in Relativistic Jets

Global relativistic MHD (RMHD) simulations + test particles:
can probe particle acceleration to highest energies without doing extrapolations to macroscopic scales (which are required in PIC sims.)



Singh et al. 2016

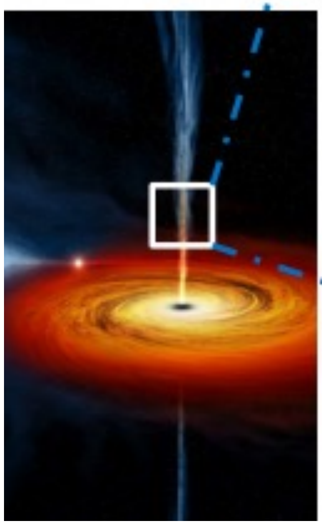
3D RMHD Simulations of Reconnection driven by Kink turbulence in Magnetically Dominated Relativistic Jets

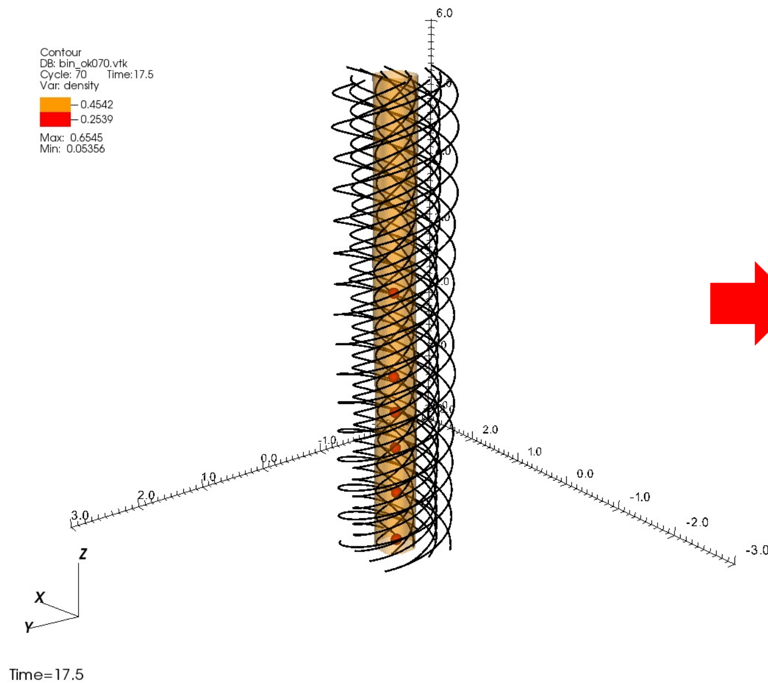
Precession perturbation causes lateral kink that distorts the plasma column:

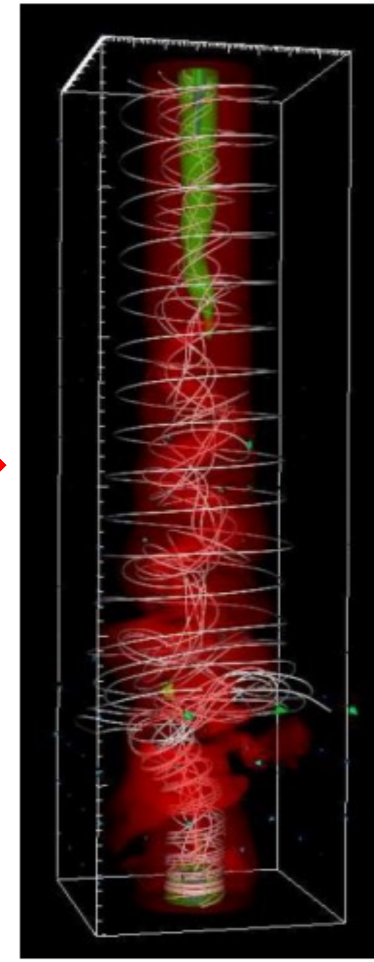
-> turbulence

-> **Reconnection!**

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







Singh, Mizuno, de Gouveia Dal Pino, ApJ 2016
Medina-Torrejon, de Gouveia Dal Pino+ ApJ 2021; Kadowaki, de Gouveia Dal Pino + ApJ 2021
(see also Bromberg & Tchekhovskoy 2015; Striani et al. 2016)

RMHD Simulations of Reconnection driven by Kink turbulence in Magnetically Dominated Relativistic Jets

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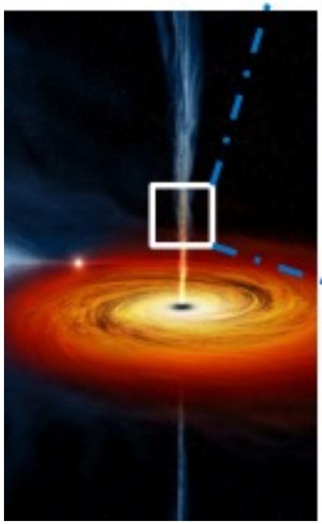

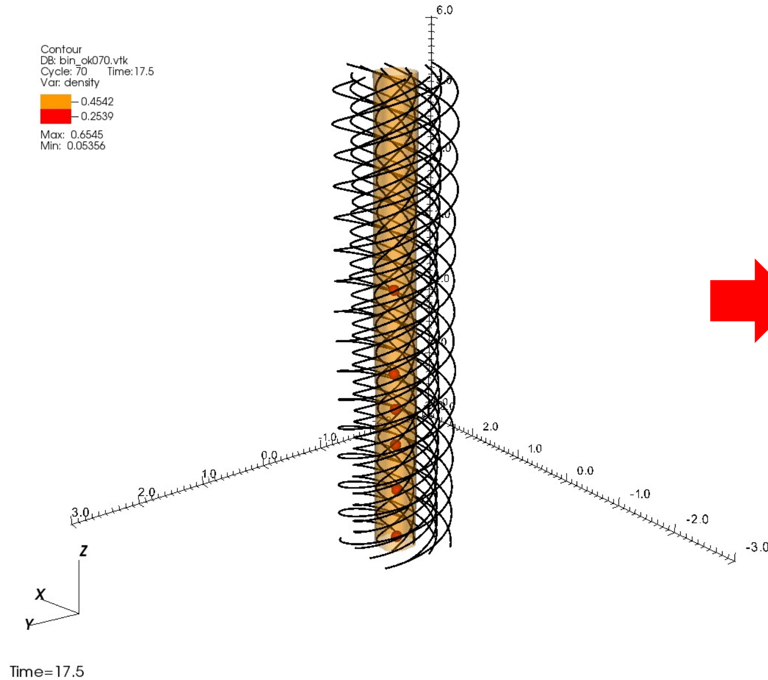

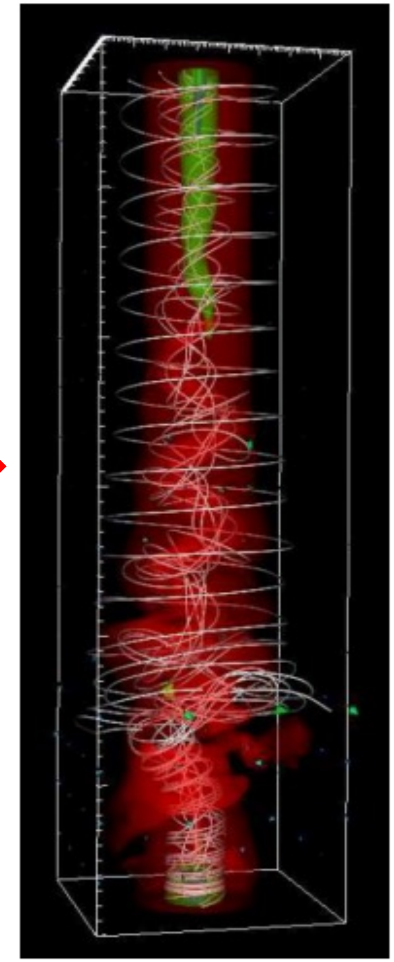

Singh, Mizuno, de Gouveia Dal Pino, ApJ 2016

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

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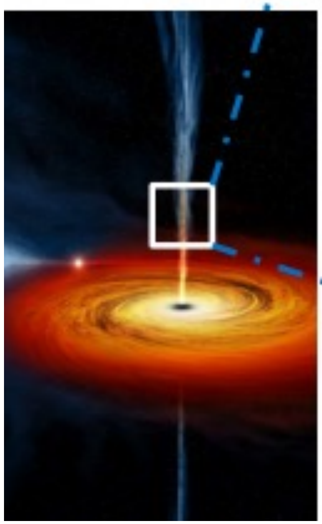
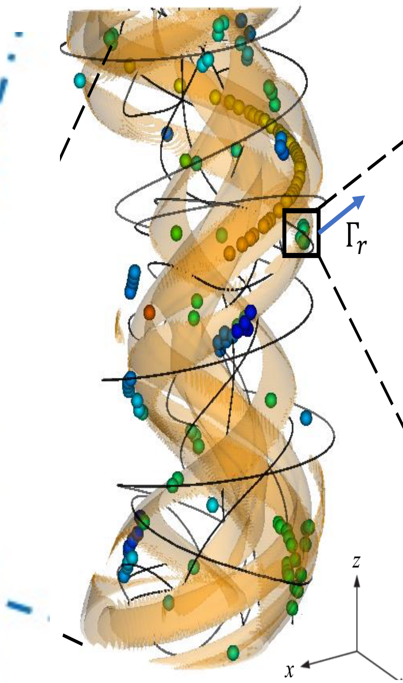
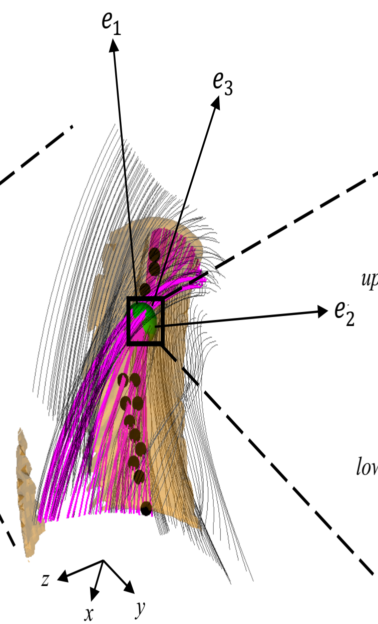
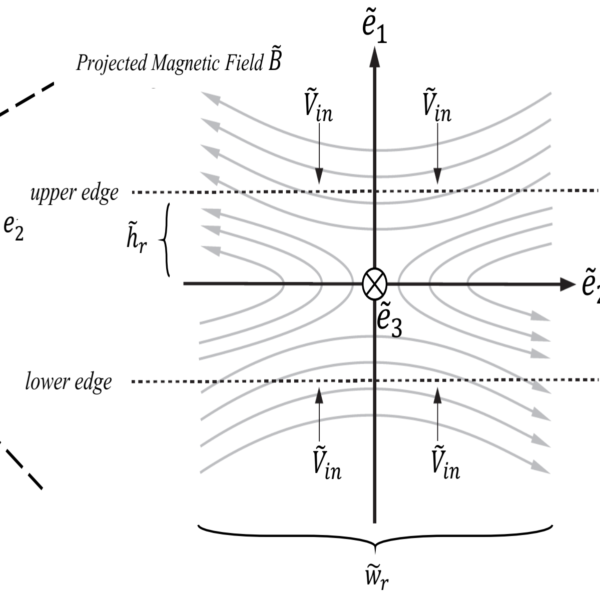


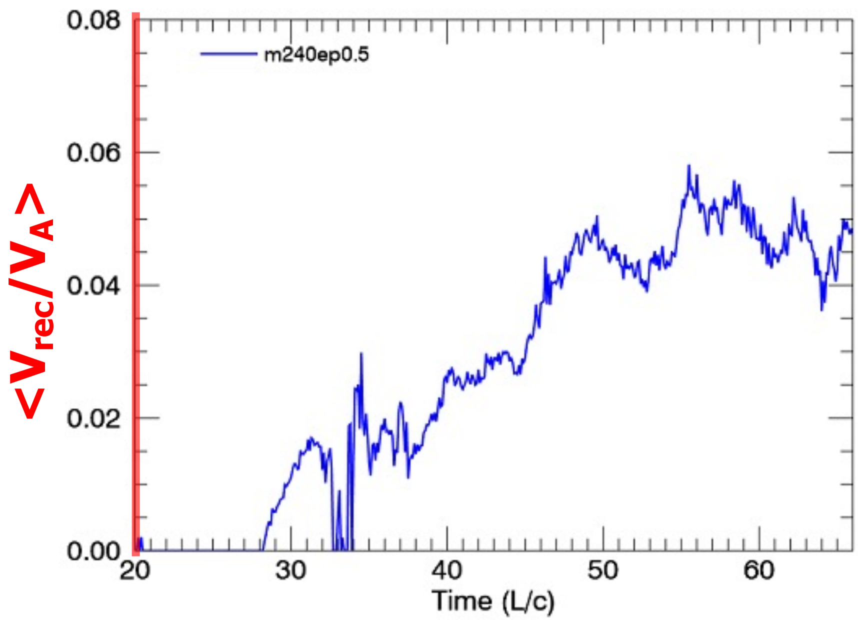




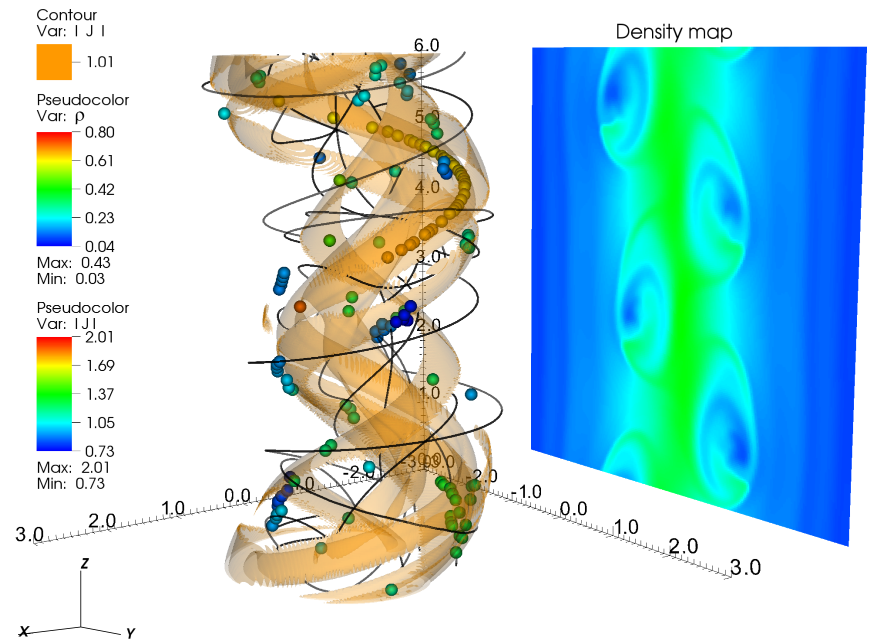


Kadowaki, de Gouveia Dal Pino, Stone ApJ 2018;
Kadowaki, de Gouveia Dal Pino, Medina-Torrejon +ApJ 2021

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



time



➢ $\langle V_{rec} \rangle \approx 0.05\ V_A$

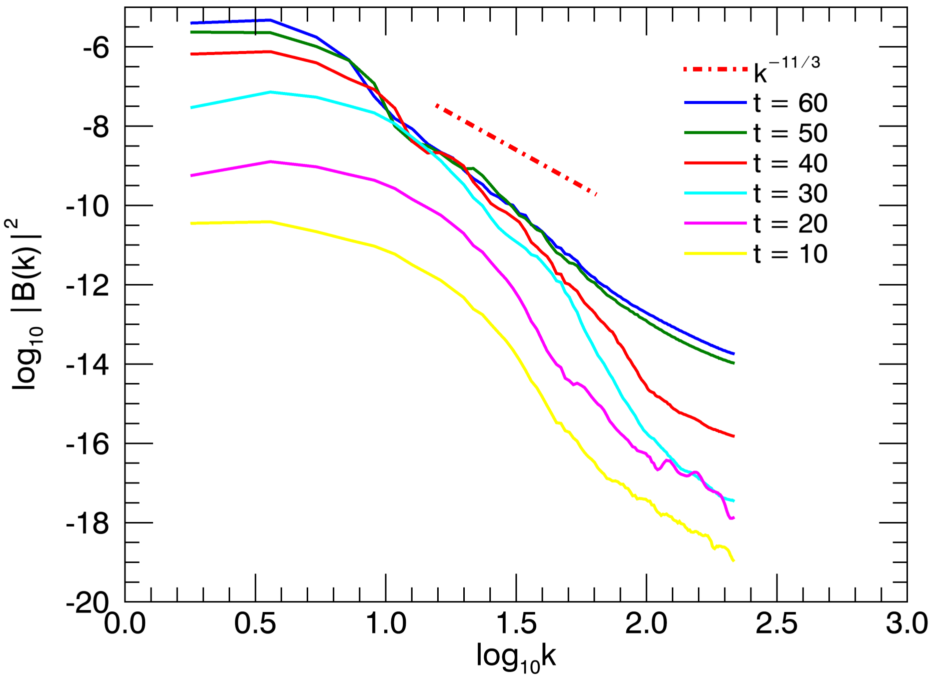
-> Fast reconnection: key to efficient particle acceleration

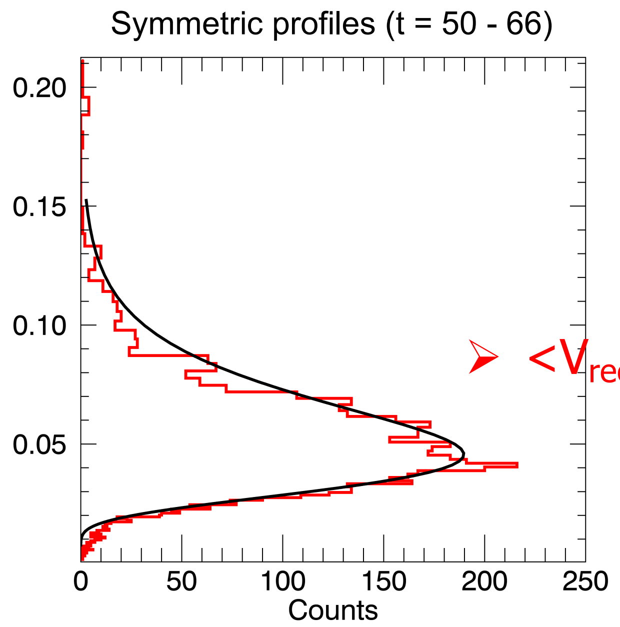
Kadowaki, de Gouveia Dal Pino, Medina-Torrejon + ApJ 2021

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}> ≈ 0.05 V_A

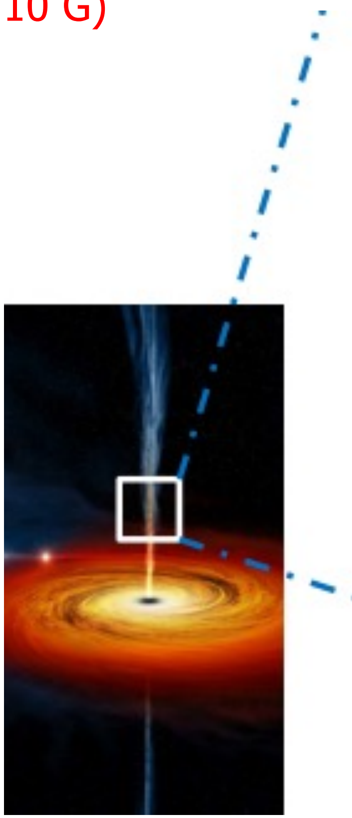
Kadowaki, de Gouveia Dal Pino, Medina-Torrejon +, ApJ 2021

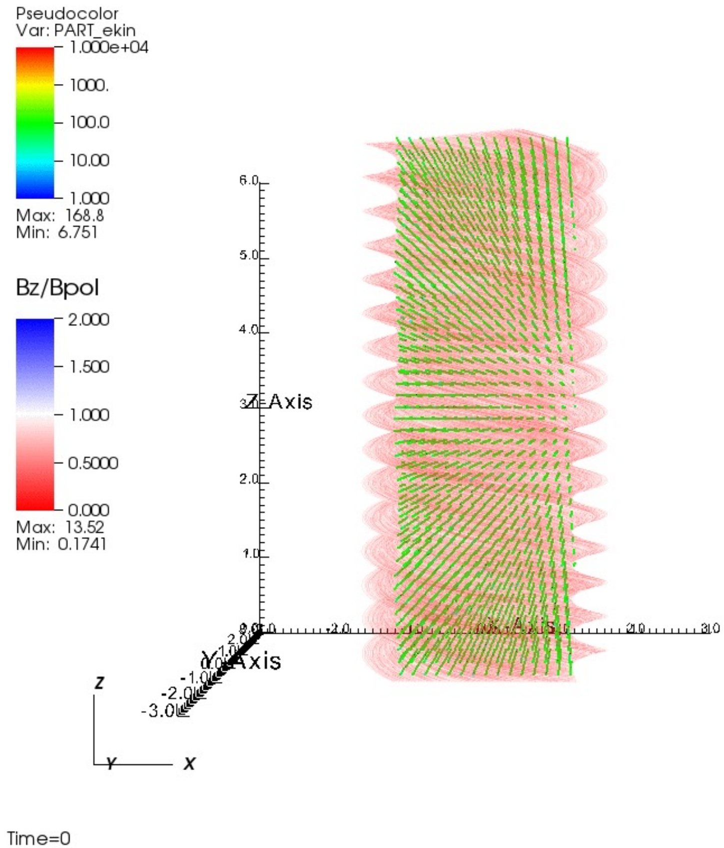
In situ acceleration of test particles by Magnetic Reconnection in Relativistic MHD Jets

L. Kadowaki

Injected test particles accelerated in reconnection sheets from:
~1 mc^2
(B~10 G)

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





Acceleration:

- curvature drift
- Fermi
- Magnetic drift

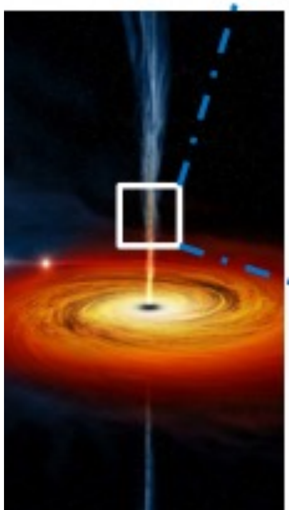
Medina-Torrejon, de Gouveia Dal Pino, Kadowaki+ ApJ 2021
Kadowaki et al. (in prep.)

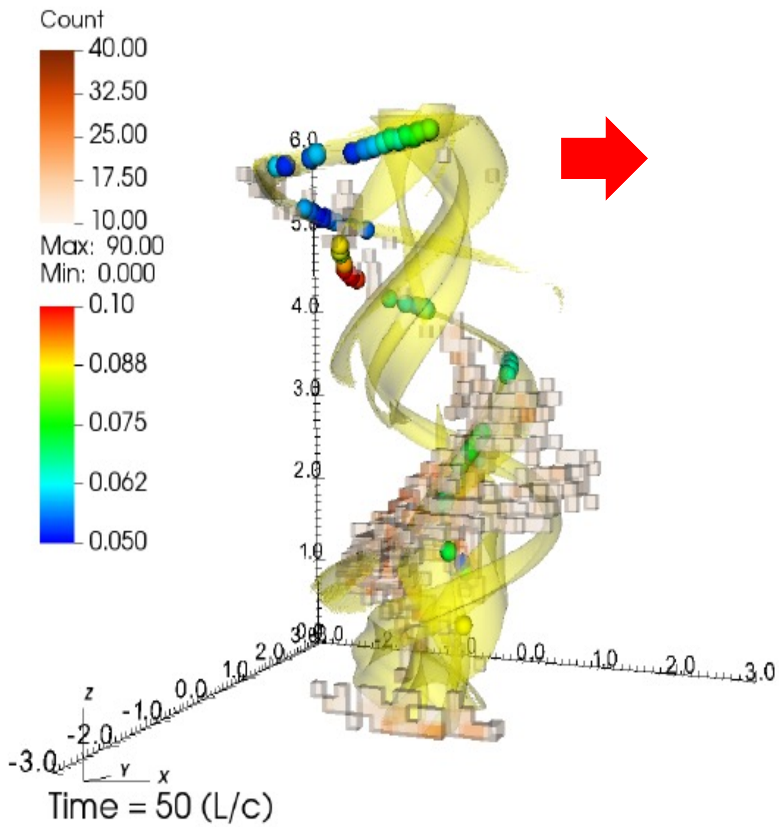
In situ acceleration of test particles by Magnetic Reconnection in Relativistic MHD Jets

T. Medina-Torrejon

Injected 1000 test particles accelerated in reconnection sheets from:
25 MeV=0.03 mc^2
to:
10^{18} - 10^{20} eV
at 0.1 pc scales
(B~ 0.1 -10 G)

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





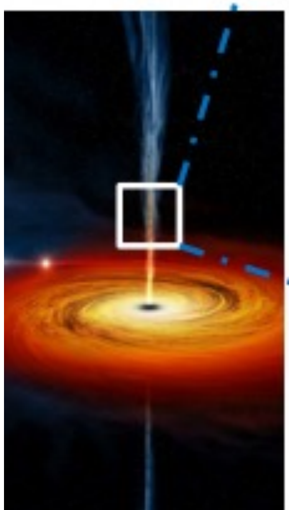
Medina-Torrejon, de Gouveia Dal Pino, Kadowaki+ ApJ 2021

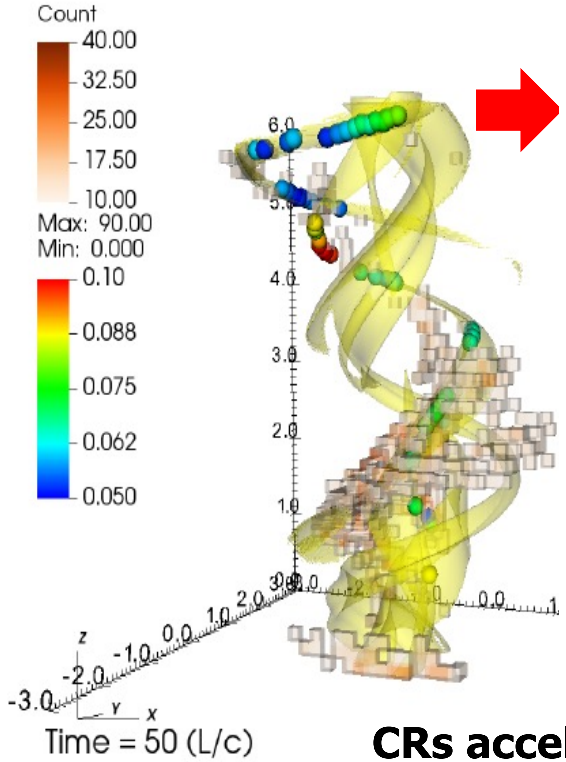
In situ acceleration of test particles by Magnetic Reconnection in Relativistic MHD Jets -> UHECRs

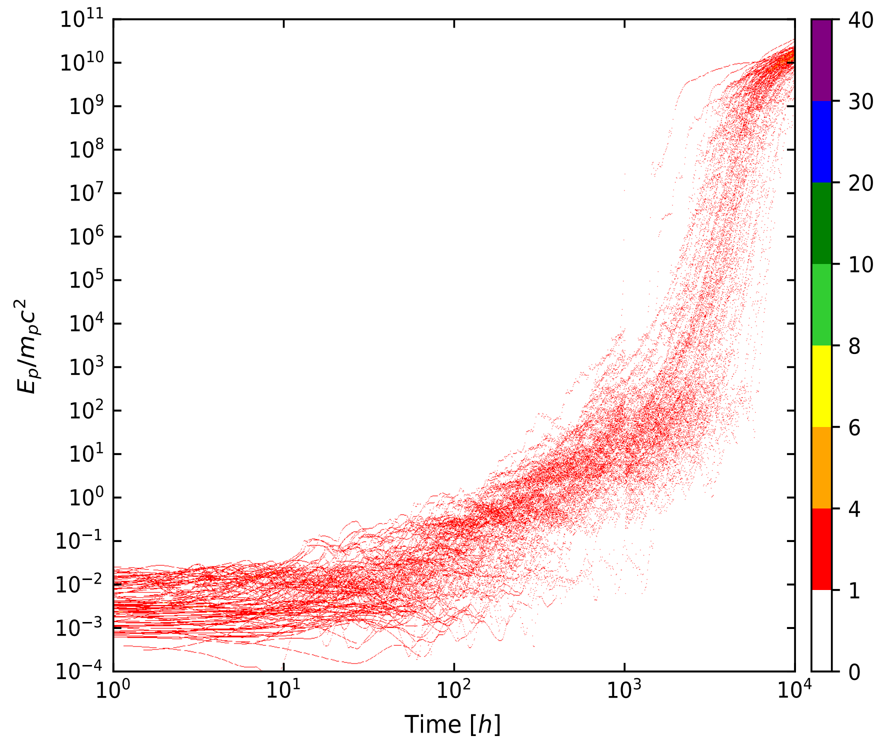
Injected 1000 test particles accelerated in reconnection regions from:
25 MeV=0.03 mc^2
to:
10^{18} - 10^{20} eV
at 0.1 pc scales
(B~ 0.1 -10 G)

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

B~ 10 G



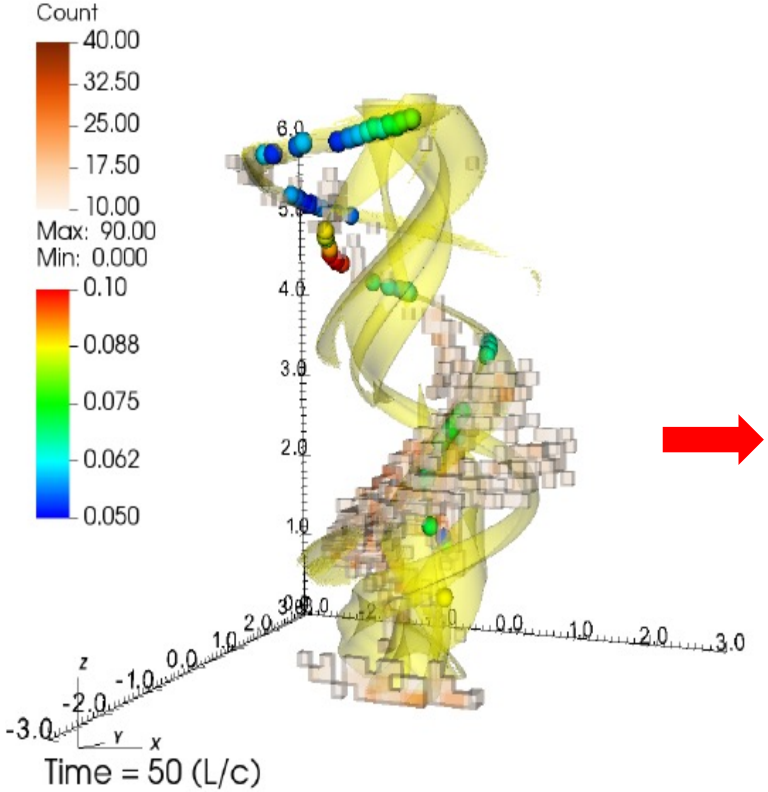


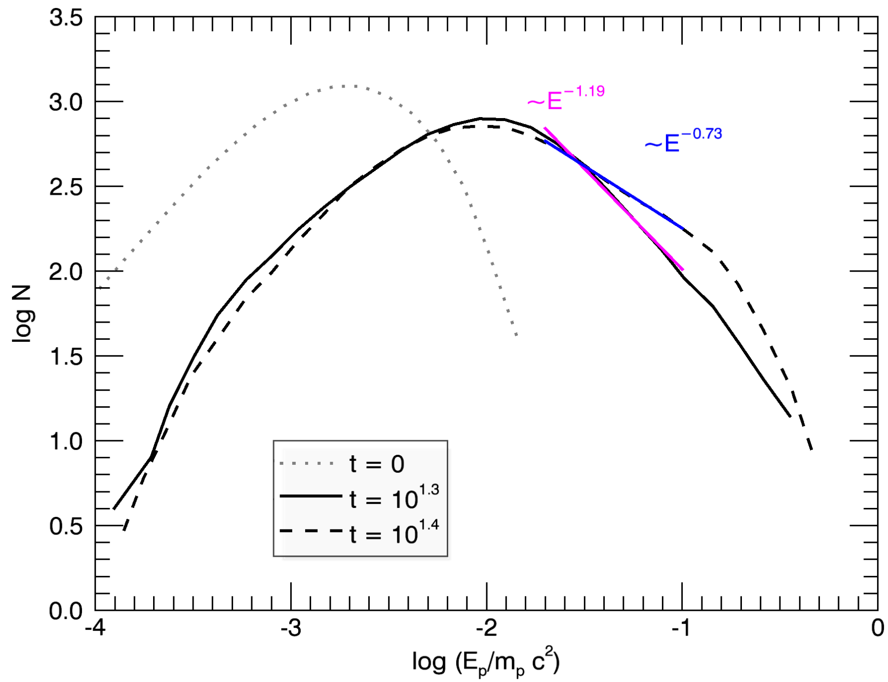


CRs accelerated to 10^{18} - 10^{20} eV: UHECRs !
-> energy enough to produce TeV Gamma-Rays and Neutrinos !!

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

Accelerated Particles Spectrum in the RMHD Jet



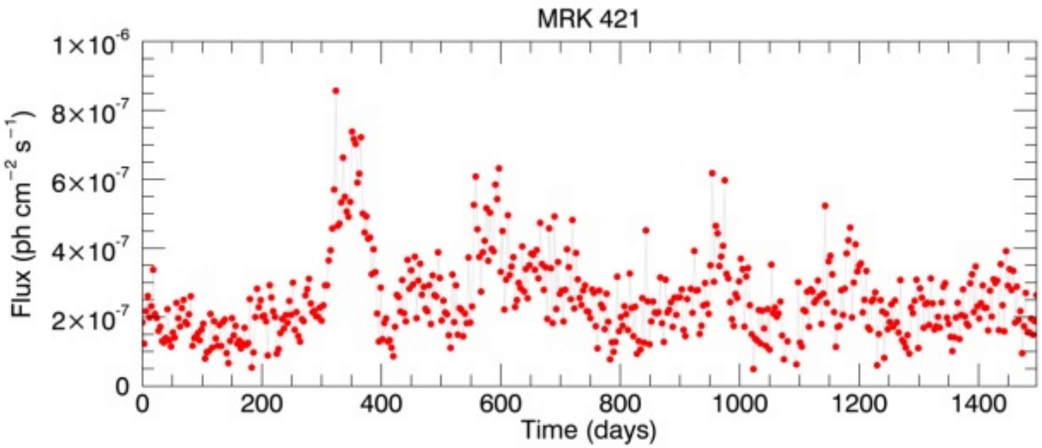


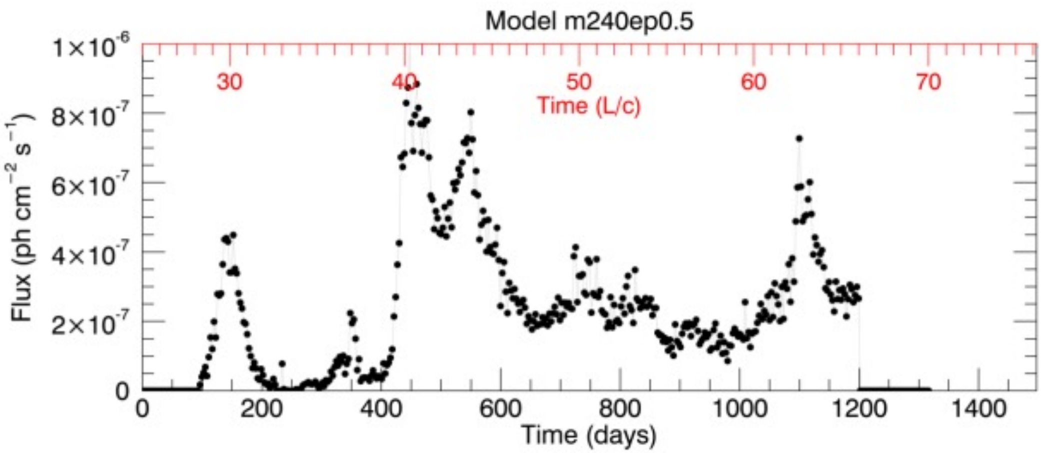
$N(E) \sim E^{-1.2}$

- Similar particle spectrum to PIC simulations and observations (but flatter due to absence of losses or feedback)

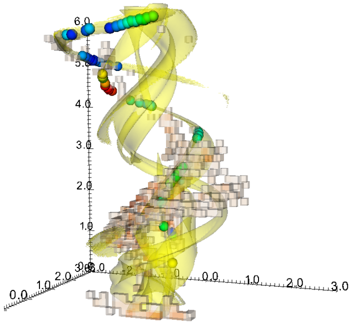
Medina-Torrejon, de Gouveia Dal Pino, Kadowaki +, ApJ 2021

Fast Reconnection able to explain observed gamma-ray flux & variability in Blazar Jet: ex. MRK421





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



- **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 driven by reconnection compatible with observed blazar flare

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

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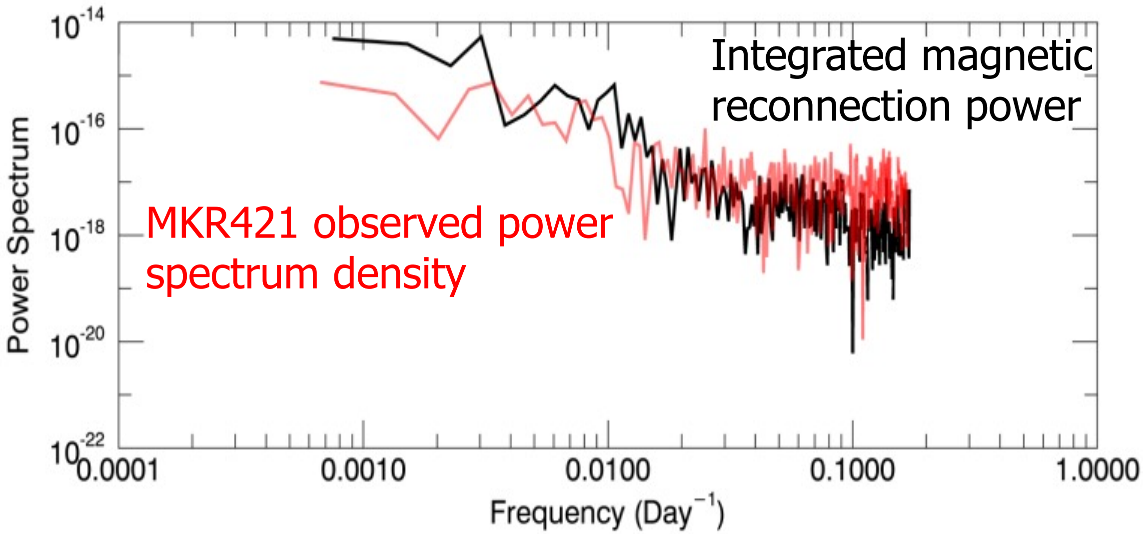
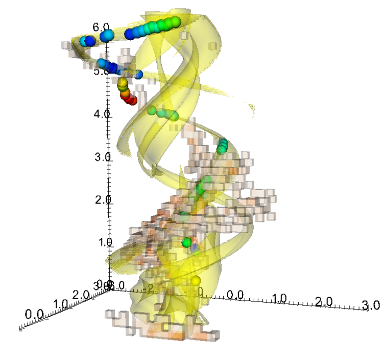


➢ **Observed gamma-ray flux** of MRK 421 Blazar (FERMI) (Kushwaha et al. 2017)



➢ **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

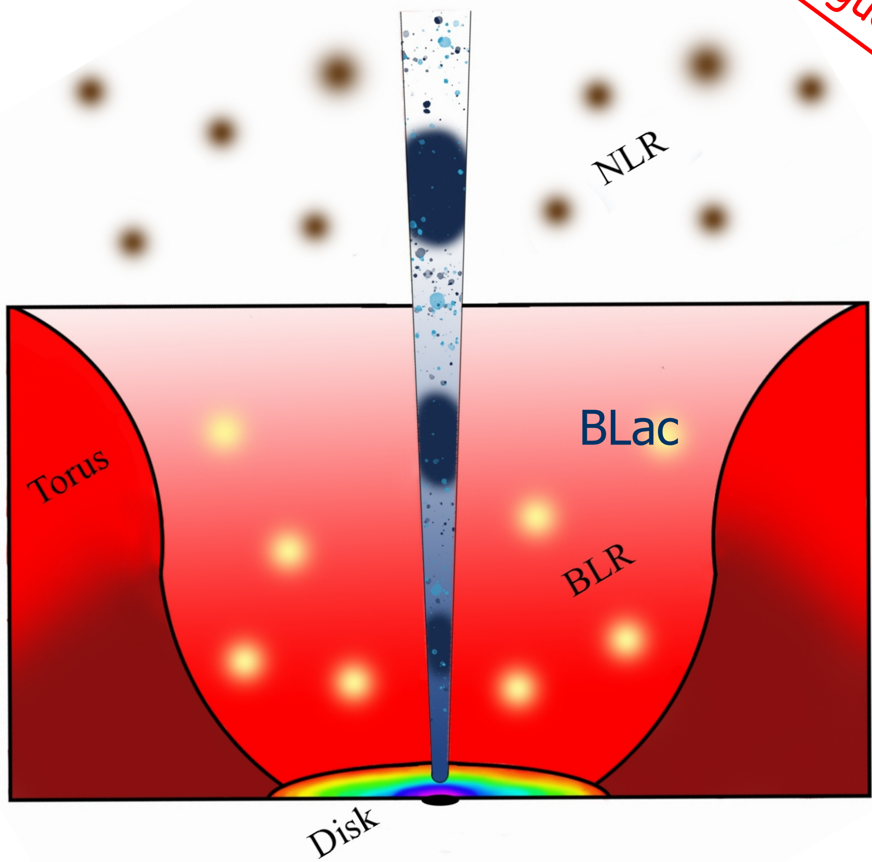
➢ Time variability and reconnection power compatible with observed blazar flare

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

Multi-zone Model based on Reconnection Acceleration for Blazars SED

PRELIMINARY

Rodriguez-Ramirez's talk in Session 25

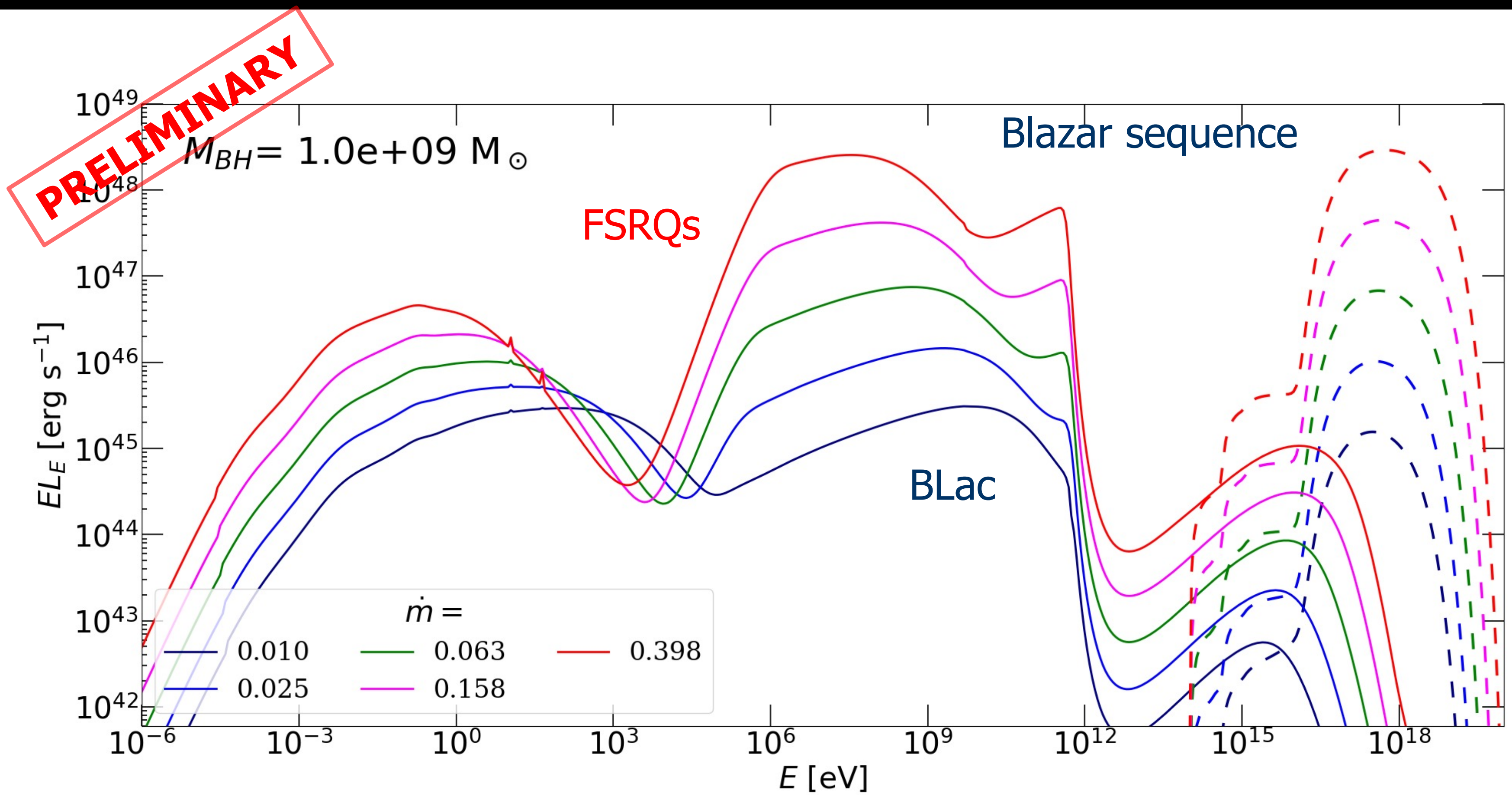


M. Cerutti's credit

Rodriguez-Ramirez et al. *in prep*. (2021)

J.C Rodriguez-Ramirez

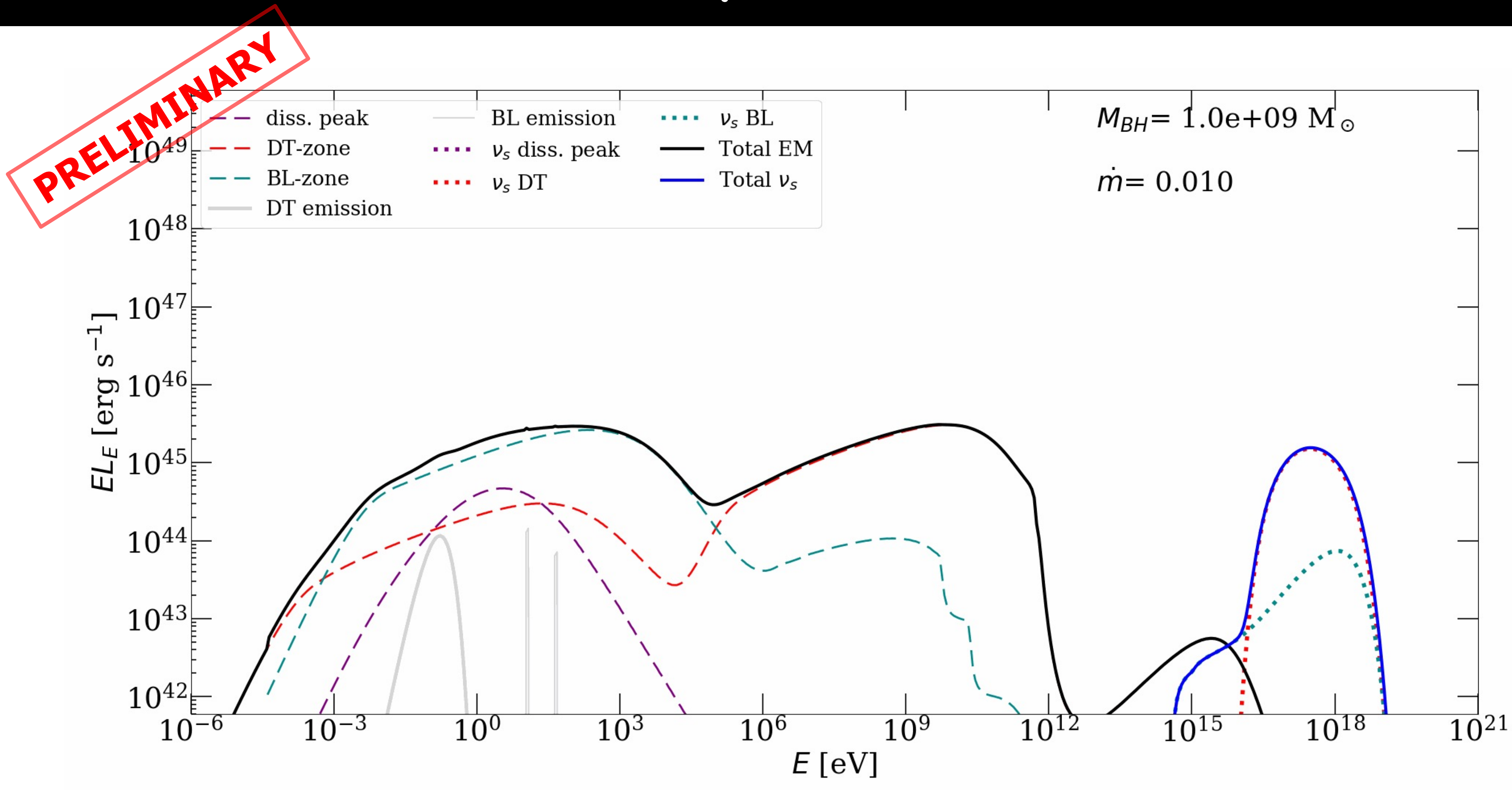
Multi-zone Model based on Reconnection Acceleration for Blazars SED



Three characteristic emission regions: **BLR**, **DT**, and **internal dissipation peak**

(see Rodriguez-Ramirez's talk in MM Session 25, this Conference)

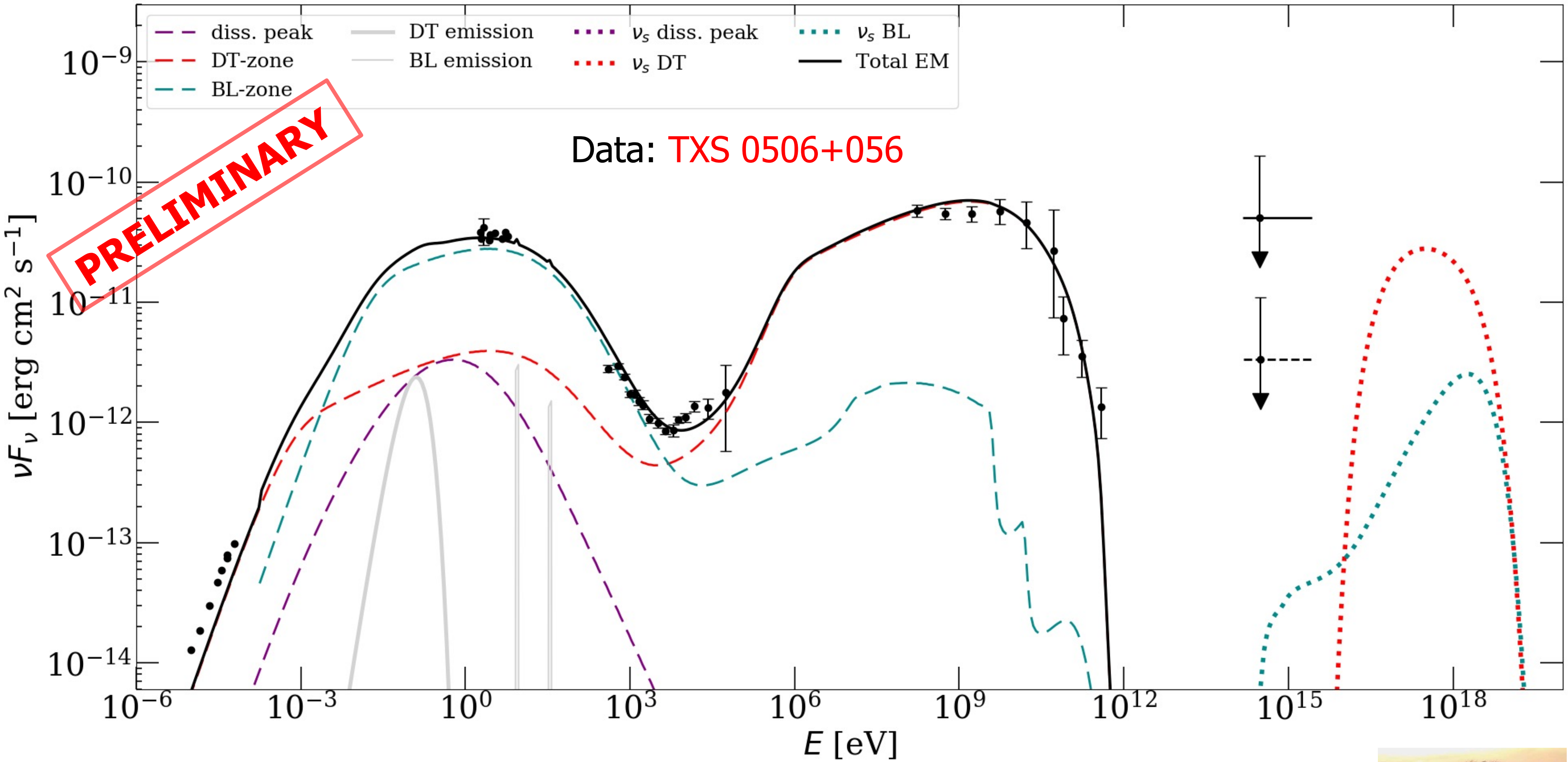
Multi-zone Model based on Reconnection Acceleration for Blazars SED



Three characteristic emission regions: **BLR**, **DT**, and **internal dissipation peak**

(See Rodriguez-Ramirez's talk in MM Session 25)

Multi-zone Model based on Reconnection Acceleration for TXS 0506+056



Three characteristic emission regions: **BLR**, **DT**, and **internal diss. peak**

(See Rodriguez-Ramirez's talk in MM Session 25, this conference)

Summary

- ✓ Reconnection acceleration of test particles in GLOBAL RMHD simulations of magnetically dominated Blazar jets produce UHECRs up to $\sim 10^{20}$ eV

- ✓ Able to explain gamma-ray emission variability and neutrinos (ex. Mrk 421, TXS0506+056)