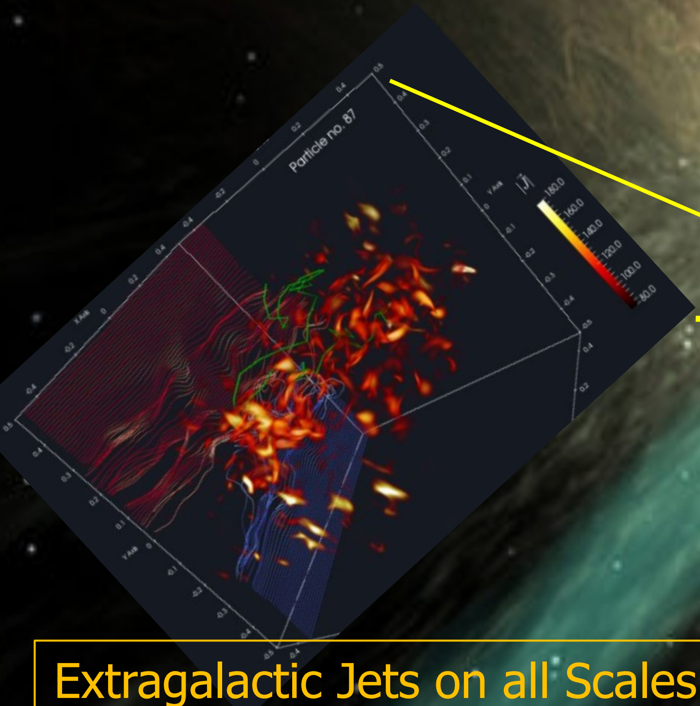
Probing Particle Acceleration to Ultra High Energies by Reconnection in Blazars & Origin of Very High Energy Emission

ElisaBete de Gouveia Dal Pino

IAG – Universidade de São Paulo



Collaborators:
L. Kadowaki,
G. Kowal,
T. Medina-Torrejon,
Y. Mizuno,
J. C. Rodriguez-Ramirez,
C. Singh

Extragalactic Jets on all Scales Conference, June 14-18, 2021, ONLINE

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

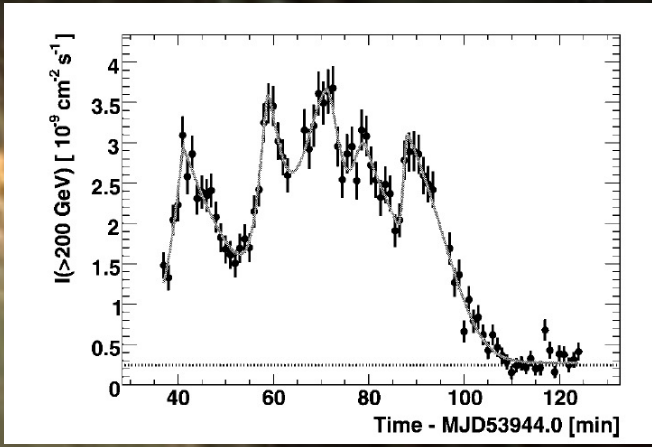
Blazars:
Jets point to line-of-sight

& 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 $\Gamma_{em}>50$

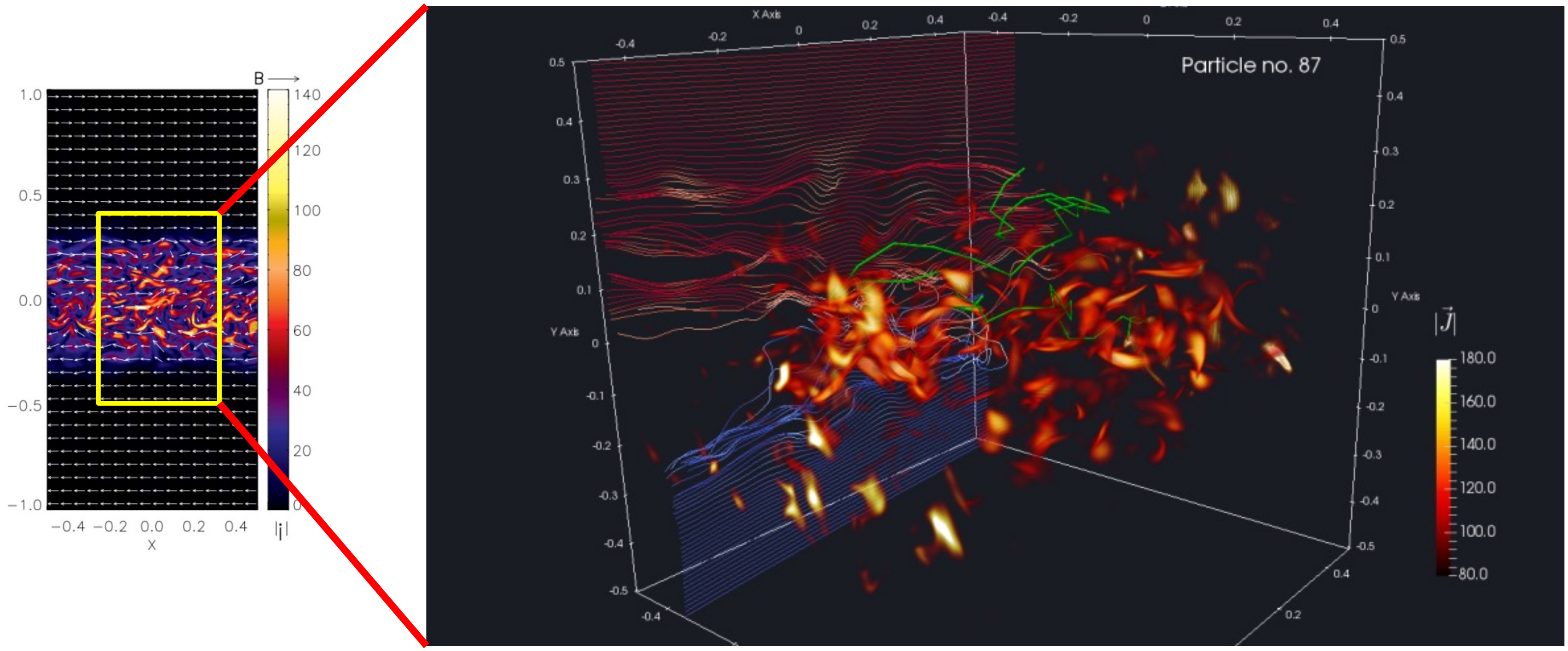


Ex.: PKS2155-304 (Aharonian et al. 2007)

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

Particles are accelerated in reconnection sites mainly by stochastic & Fermi process

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



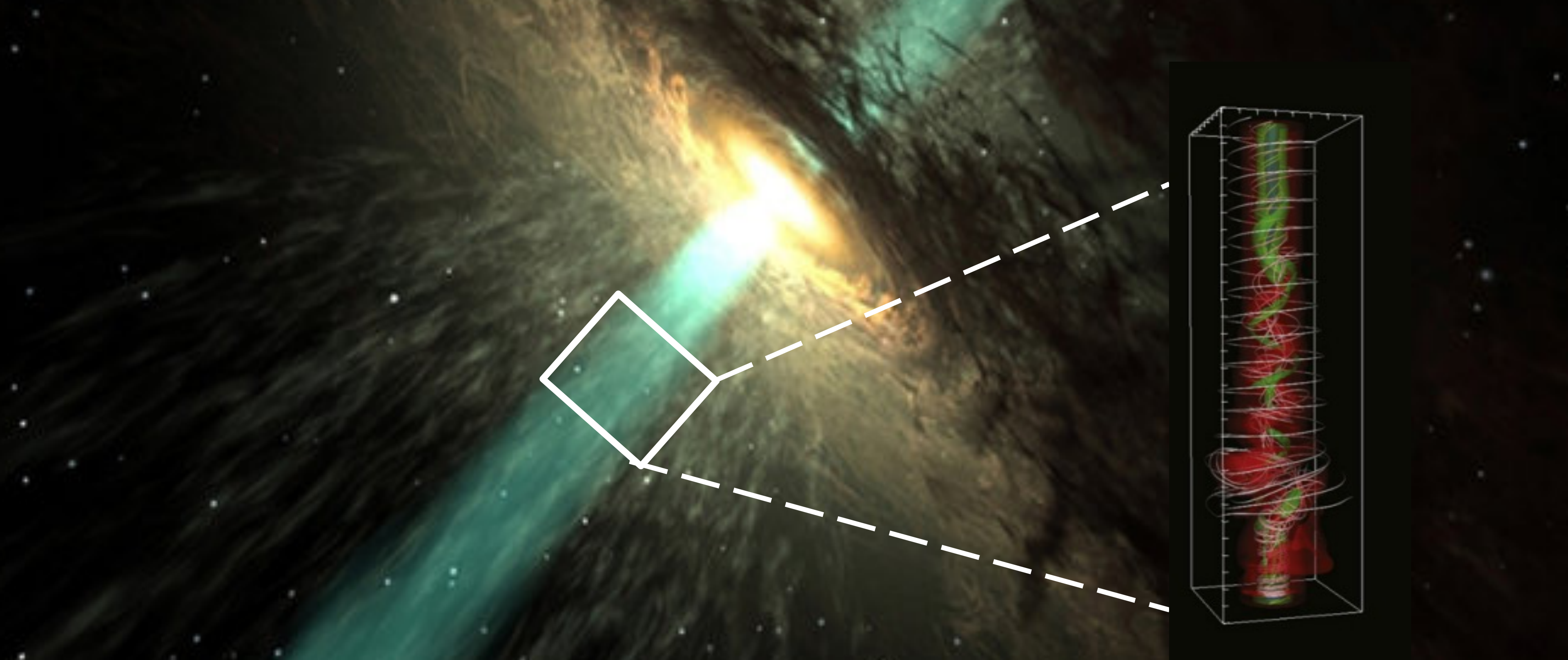
de Gouveia Dal Pino & Lazarian A&A 2005;

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

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

In situ 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 required in PIC simulations)

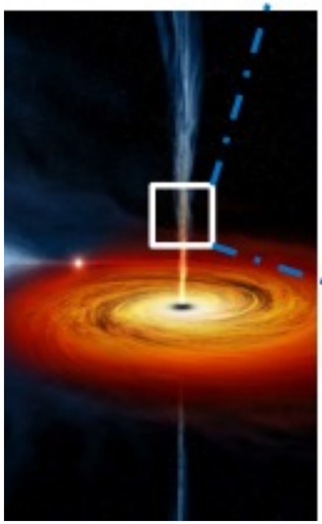


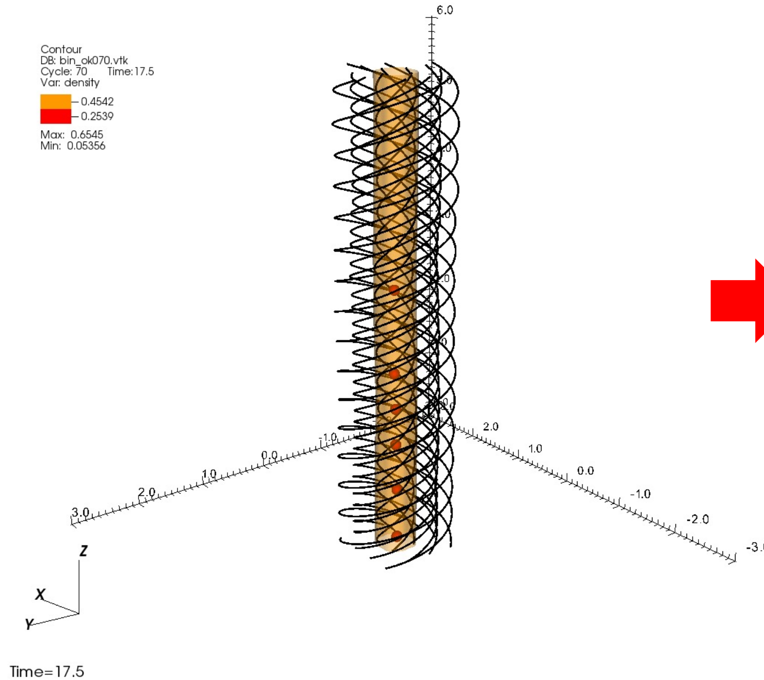
RMHD Simulations of Reconnection driven by Kink turbulence in Magnetically Dominated Relativistic Jets

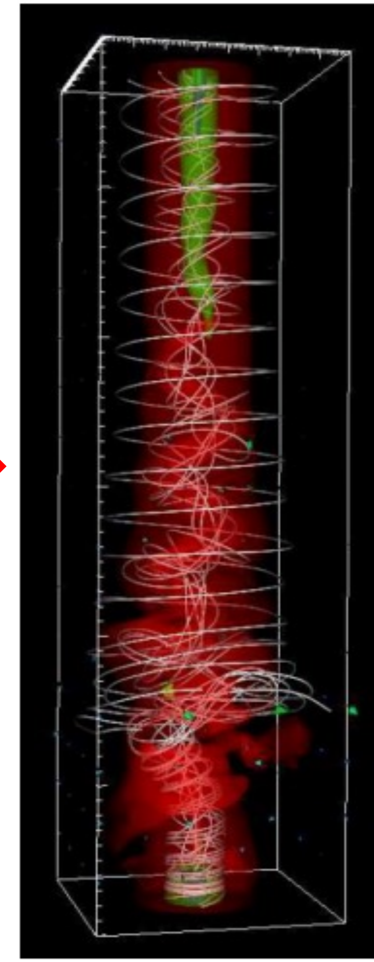
Precession perturbation causes lateral kink that distorts the plasma column:
-> turbulence

-> **Reconnection!**

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





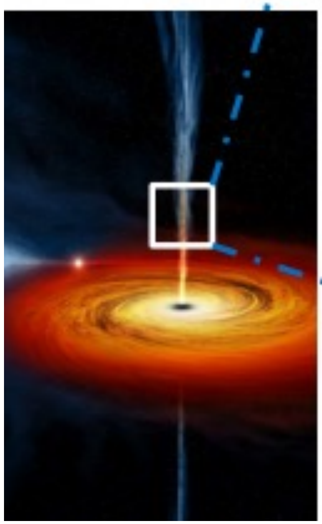


Singh, Mizuno, de Gouveia Dal Pino, ApJ 2016
Medina-Torrejon, de Gouveia Dal Pino+ 2021; Kadowaki, de Gouveia Dal Pino + 2021
(see also Bromberg & Tchekhovskoy 2015; Striani et al. 2016)

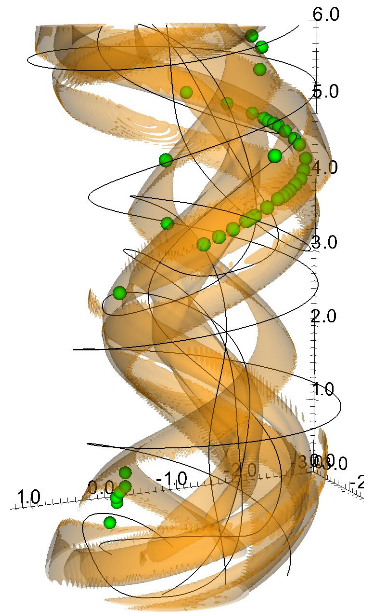
RMHD Simulations of Reconnection driven by Kink turbulence in Magnetically Dominated Relativistic Jets

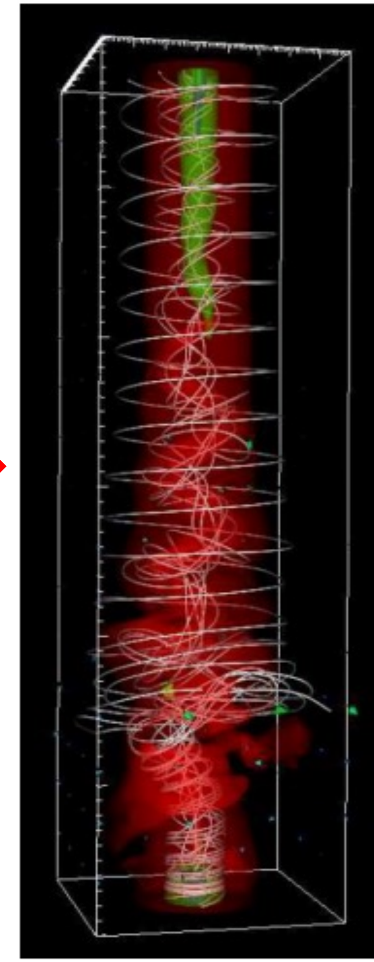
Precession perturbation causes lateral kink that distorts the plasma column:
-> turbulence

-> **Reconnection!**



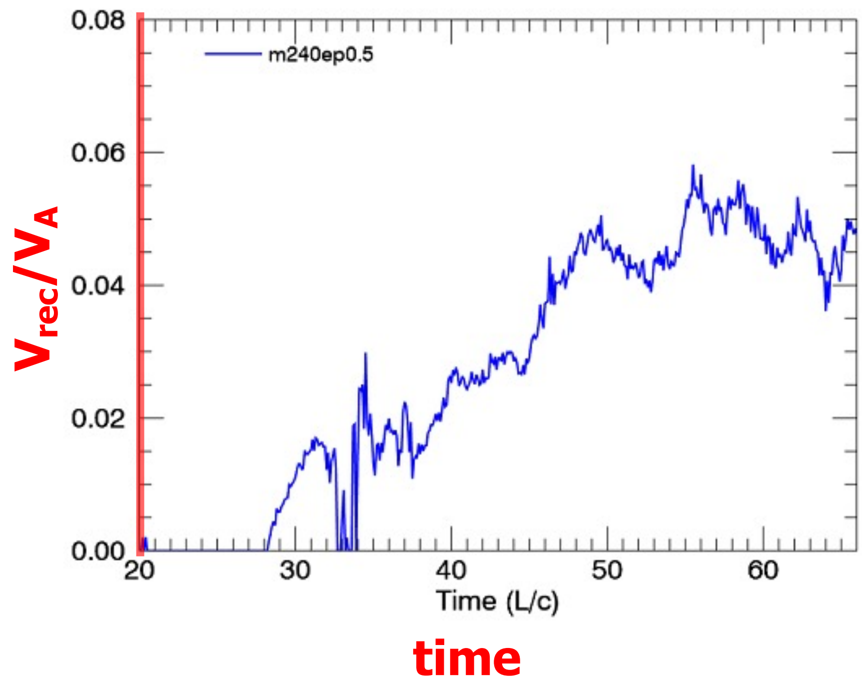
$\sigma = B^2/\gamma^2 \rho h$ ~1

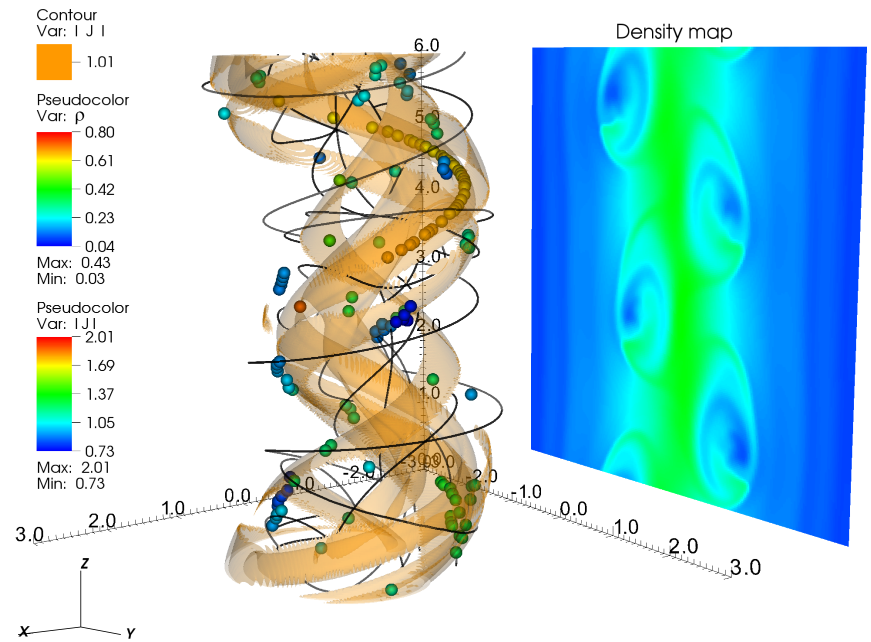




Singh, Mizuno, de Gouveia Dal Pino, ApJ 2016
Medina-Torrejon, de Gouveia Dal Pino+ 2021; Kadowaki, de Gouveia Dal Pino + 2021
(see also Bromberg & Tchekhovskoy 2015; Striani et al. 2016)

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





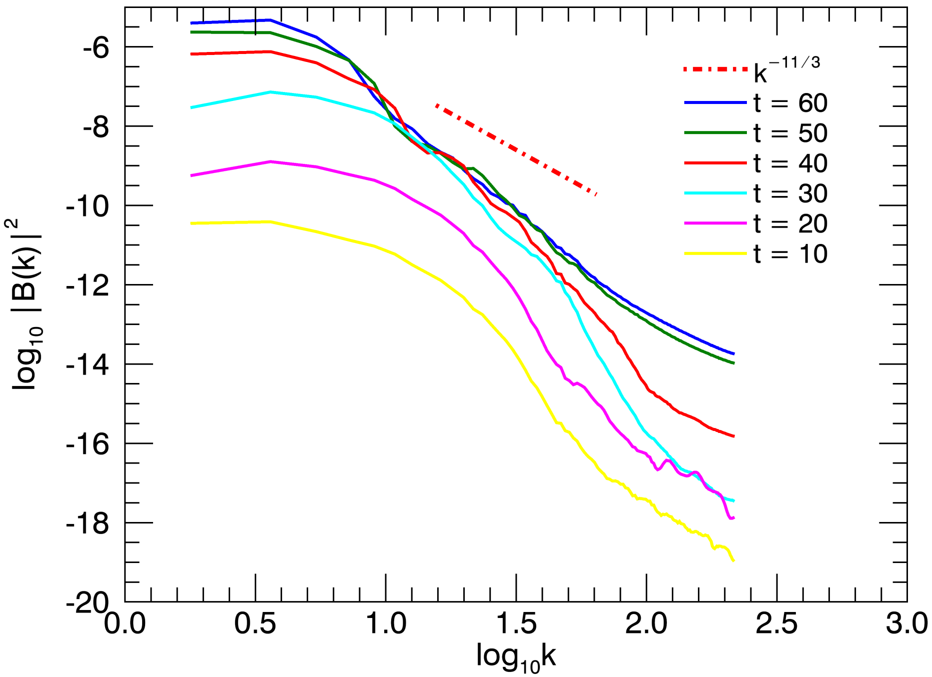
➢ $\langle V_{rec} \rangle \approx 0.05\, V_A$

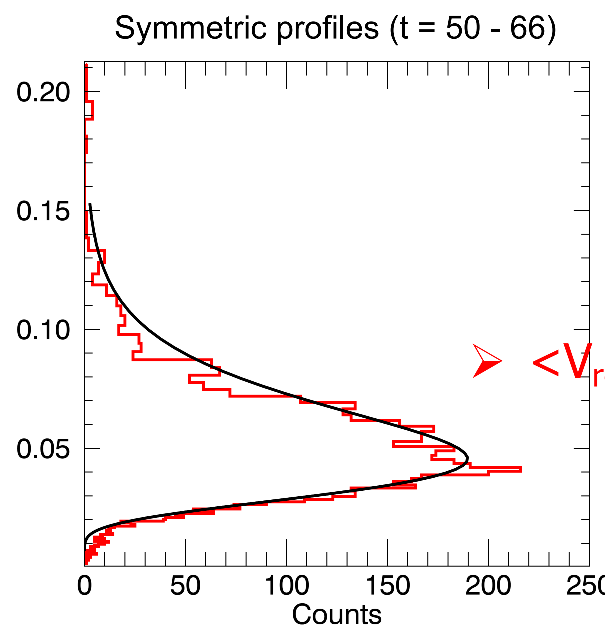
-> Fast reconnecton: key to particle acceleration

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

Fast Reconnection Rate driven by Kink instability turbulence in Relativistic Jets

- **Distribution of $\langle V_{rec} \rangle$ follows log-normal**
- **Magnetic field follows power law spectrum: TURBULENCE**





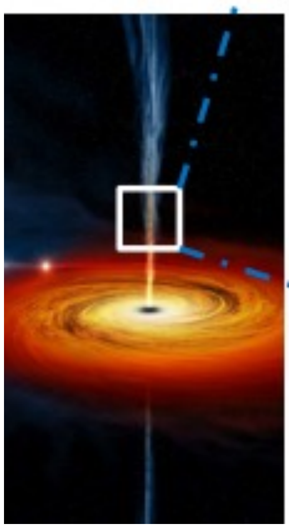
- $\langle V_{rec} \rangle \approx 0.05\ V_A$

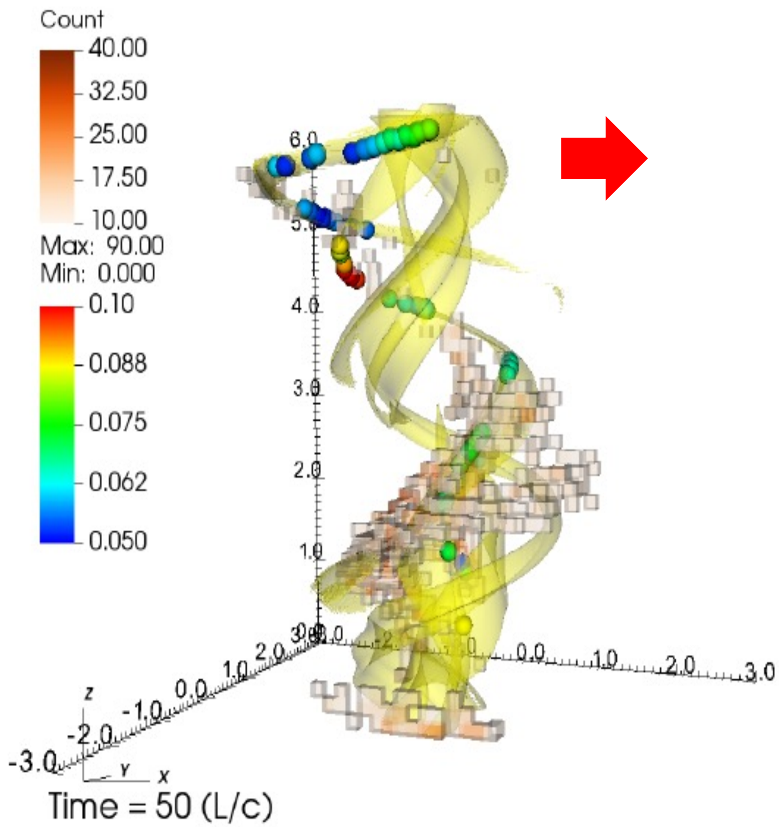
Kadowaki, de Gouveia Dal Pino, Medina-Torrejon +, ApJ 2021

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
to:
10^{18} - 10^{20} eV
at 0.1 pc scales
(B~ 0.1 -10 G)

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





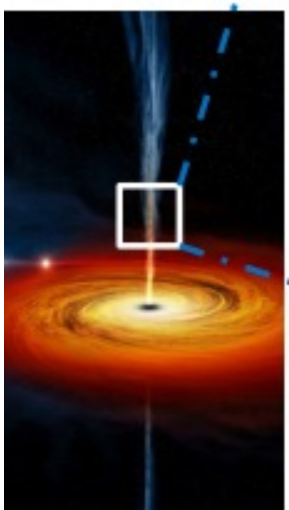
Medina-Torrejon, de Gouveia Dal Pino, Kadowaki+ ApJ 2021

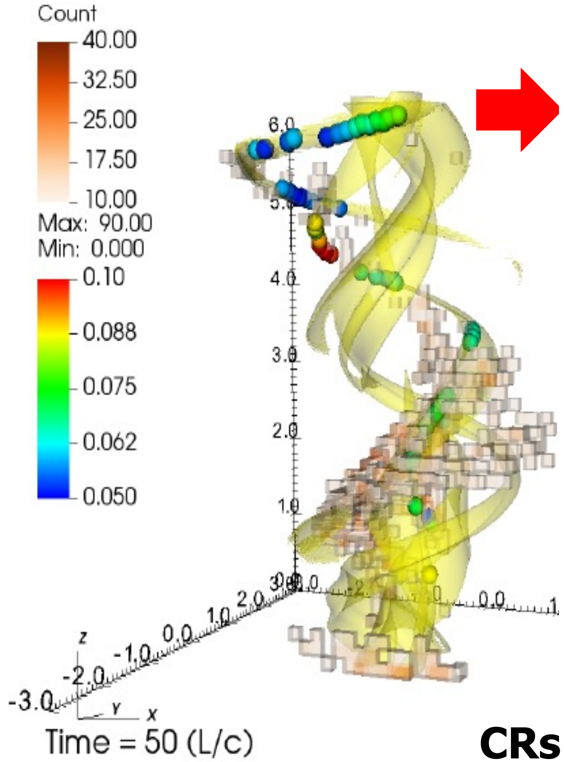
In situ acceleration of test particles by Magnetic Reconnection in Relativistic MHD Jets -> UHECRs

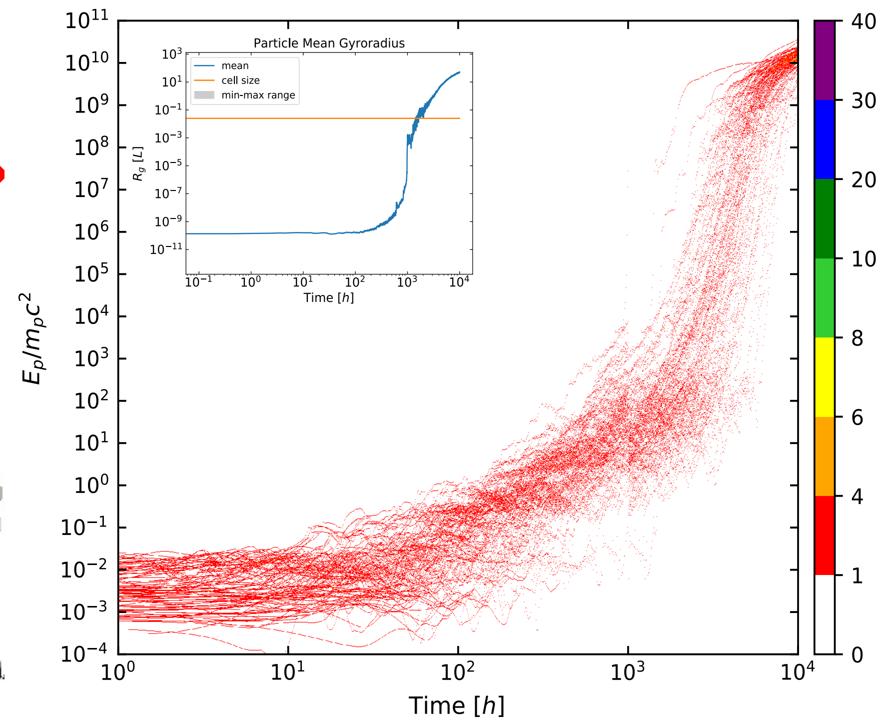
Injected 1000 test particles accelerated in reconnection regions from:
25 MeV=0.03 mc^2
to:
10^{18} - 10^{20} eV
at 0.1 pc scales
(B~ 0.1 -10 G)

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

B~ 10 G



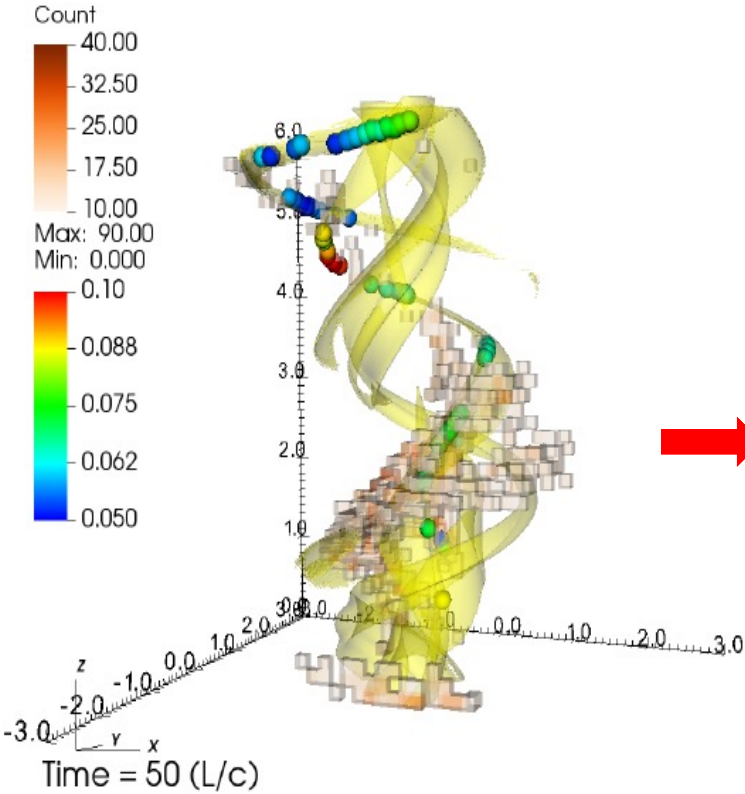


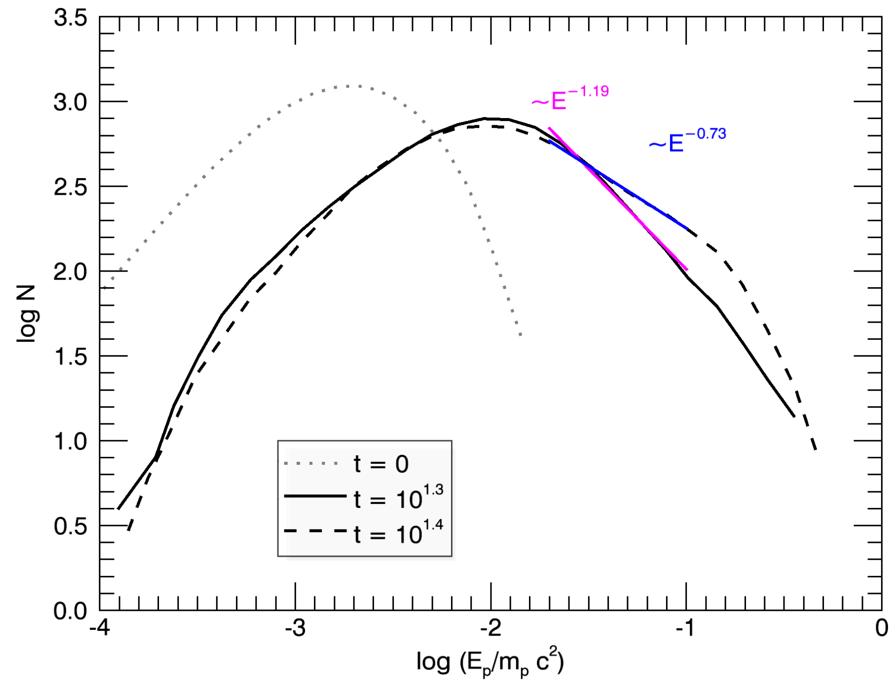


CRs accelerated to 10^{18} - 10^{20} eV,
-> energy enough to produce TeV Gamma-Rays and Neutrinos !!

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

Accelerated Particles Spectrum in the RMHD Jet



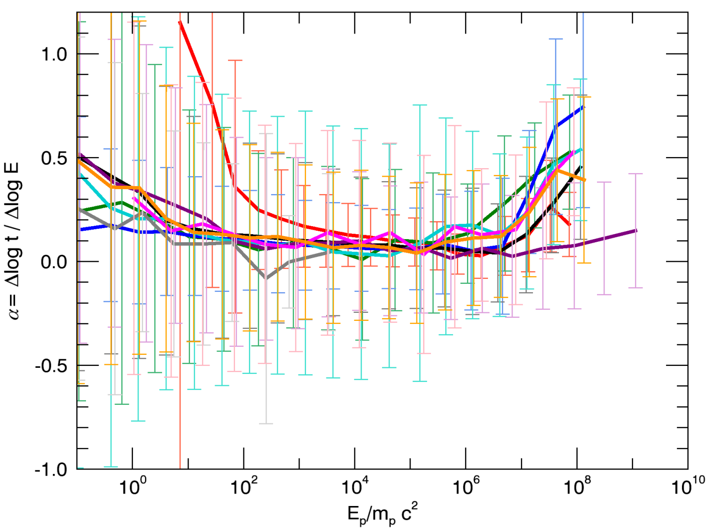


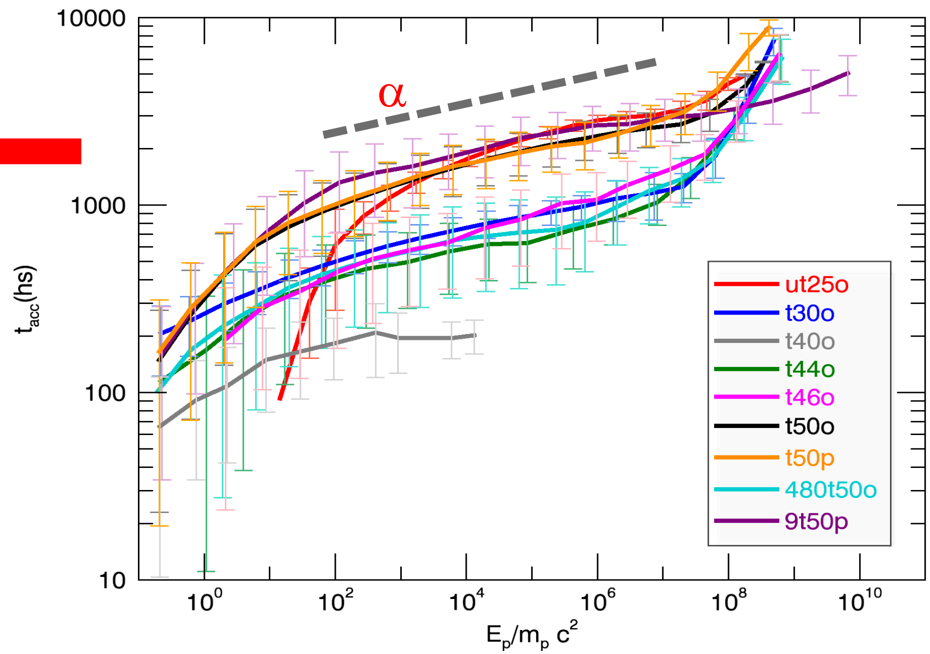
$N(E) \sim E^{-1.2}$

- 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

Acceleration time of particles by Magnetic Reconnection in RMHD Jet

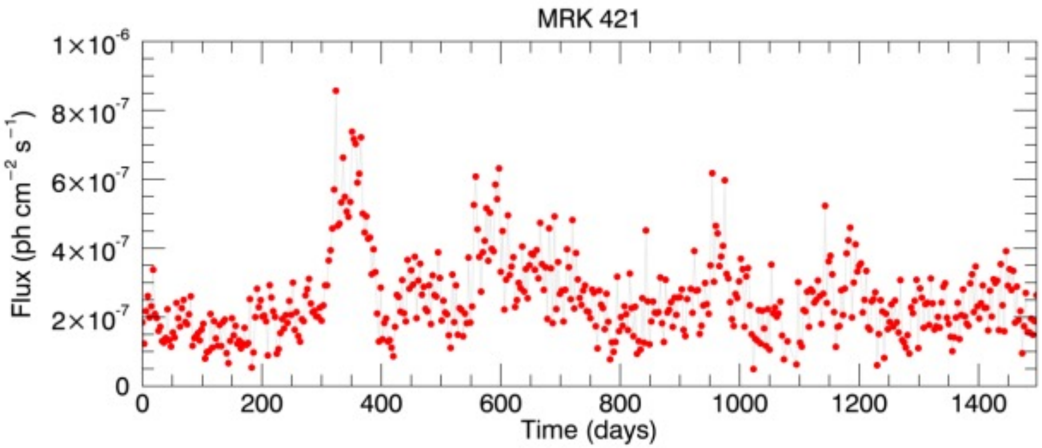


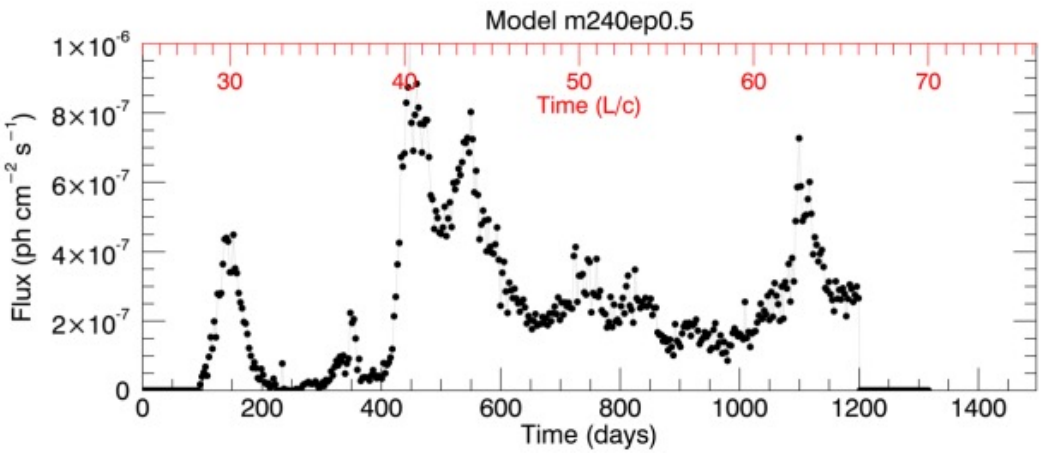


α~0.1 ➡ $t_A \propto E^{0.1}$

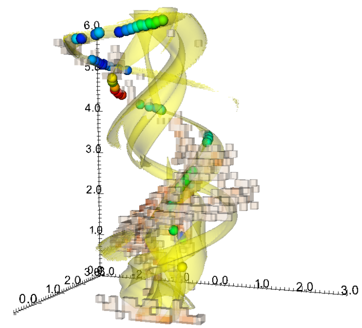
Medina-Torrejon, de Gouveia Dal Pino, Kadowaki +, ApJ 2021

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)

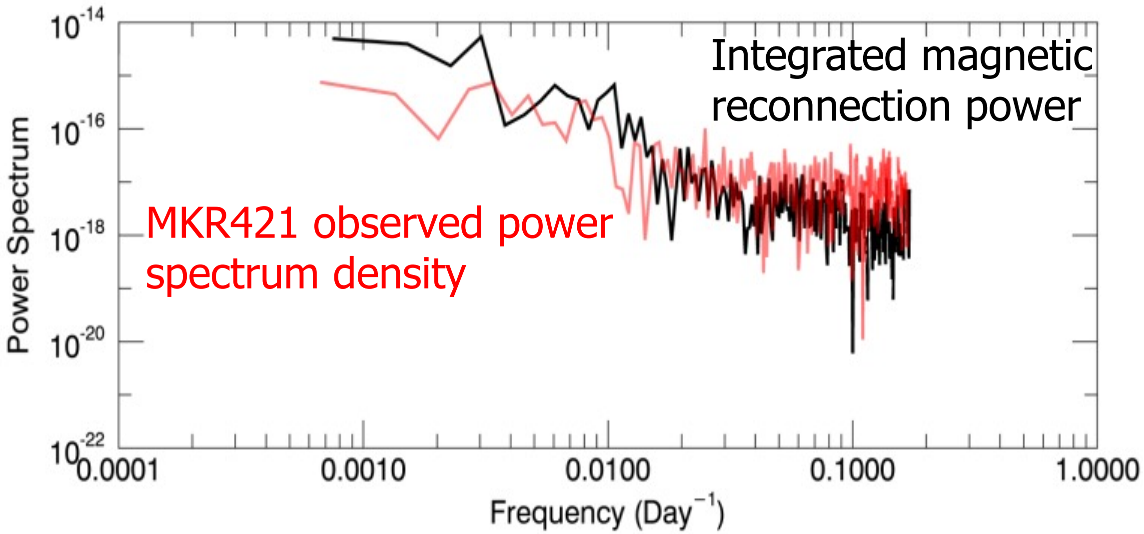


- **Simulated flux variability**
  - Magnetic field: 3.7 G
  - Doppler: $\delta=5$
  - Height of the Jet: $\approx$ 0.1 pc
  - High density regions: $\approx 7\ 10^2\ cm^{-3}$
  - Photon energy: 0.1 - 300 GeV

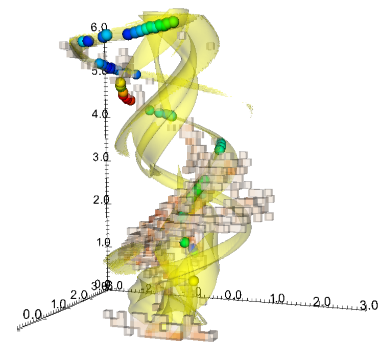
- Time variability driven by reconnection compatible with observed blazar flare

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

Fast Reconnection 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)



- **Simulated flux variability**
  - Magnetic field: 3.7 G
  - Doppler: $\delta=5$
  - Height of the Jet: $\approx$ 0.1 pc
  - High density regions: $\approx 7\ 10^{2}\ cm^{-3}$
  - Photon energy: 0.1 - 300 GeV

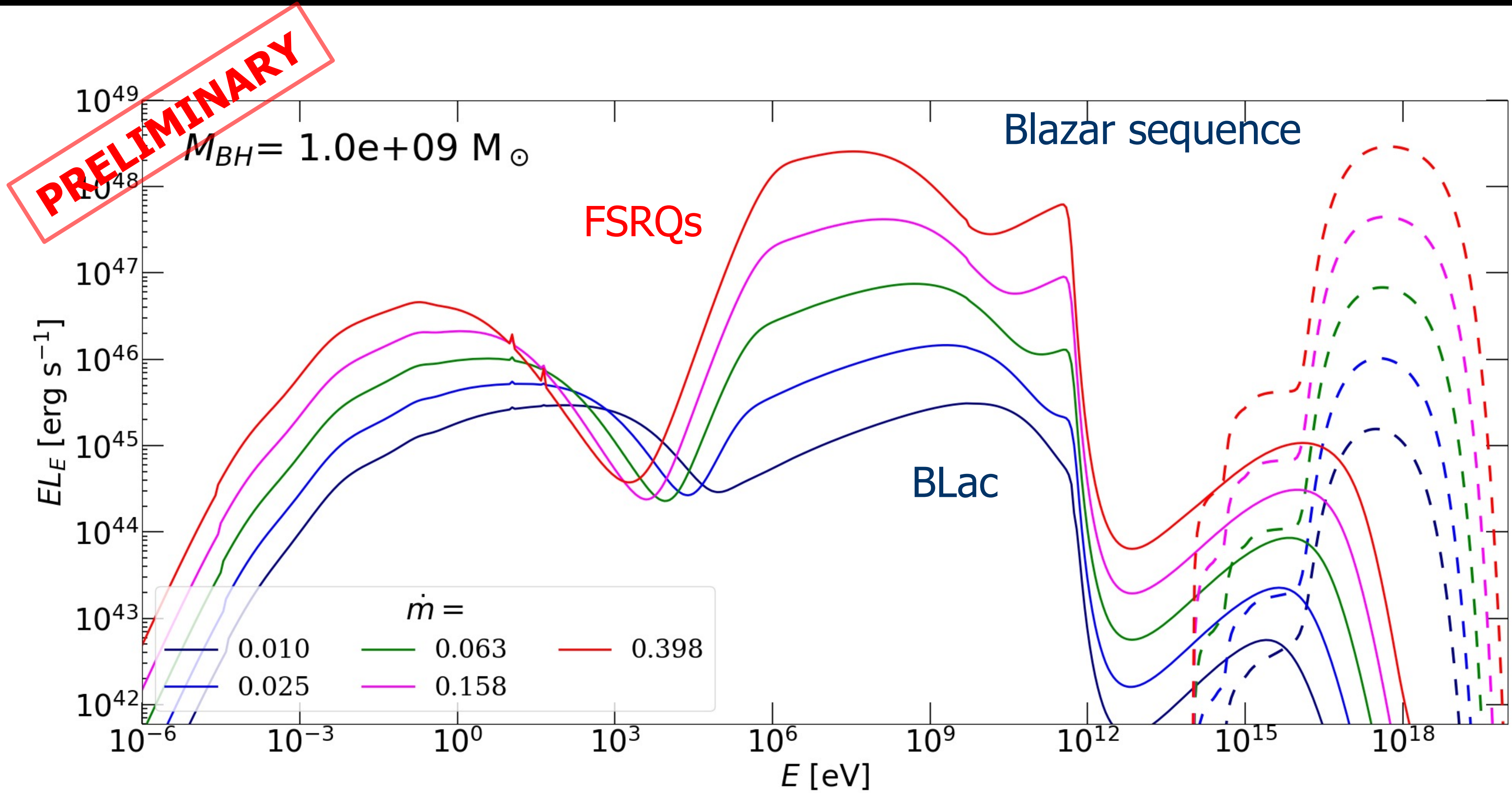
- Time variability and reconnection power compatible with observed blazar flare

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

Summary

- ✓ In magnetized plasmas particles can be accelerated by fast magnetic reconnection (e.g. driven by turbulence) by stochastic Fermi + drift: $N(E) \sim E^{-1.2}$
- ✓ We find similar magnetic reconnection rates in MHD, RMHD and GRMHD simulations of turbulent systems $v_{rec} \sim 0.05$ (compatible with fast reconnection theory, Lazarian & Vishniac 1999)
- ✓ Reconnection acceleration rate: $\tau_A^{-1} \sim E^{-\alpha}$ ($\alpha \sim 0.1$ in RMHD and $\alpha \geq 0.2$ in MHD)
- ✓ Time variability and magnetic reconnection power from global RMHD simulations compatible with observations of Blazars @ gamma-ray band (ex. Mrk 421)
- ✓ Reconnection acceleration of test particles in GLOBAL RMHD simulations of magnetically dominated Blazar **jets** produce CRs up to $\sim 10^{20}$ eV -> may explain flare gamma-ray emission and neutrinos

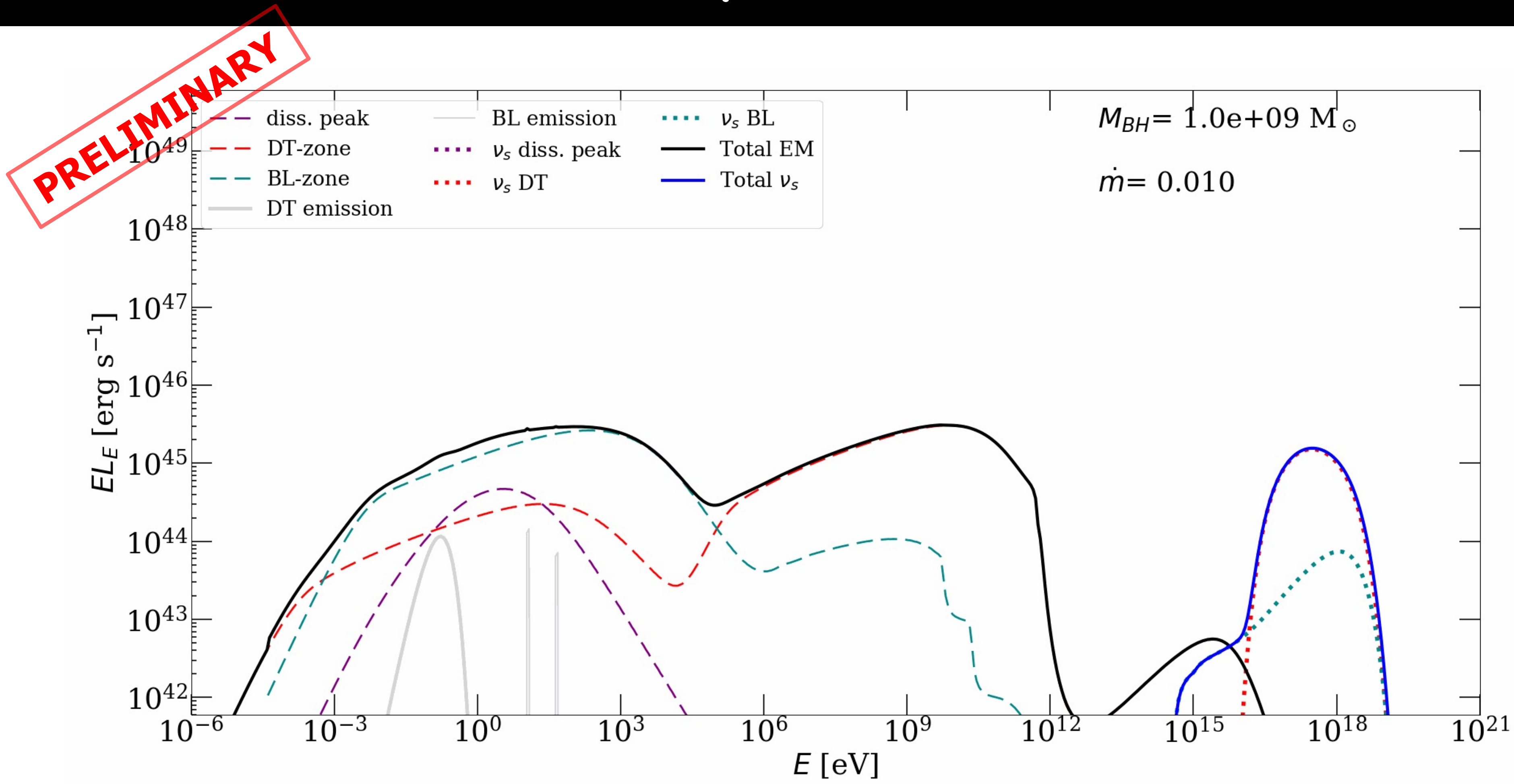
Multi-zone Model based on Reconnection Acceleration for Blazars SED



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

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

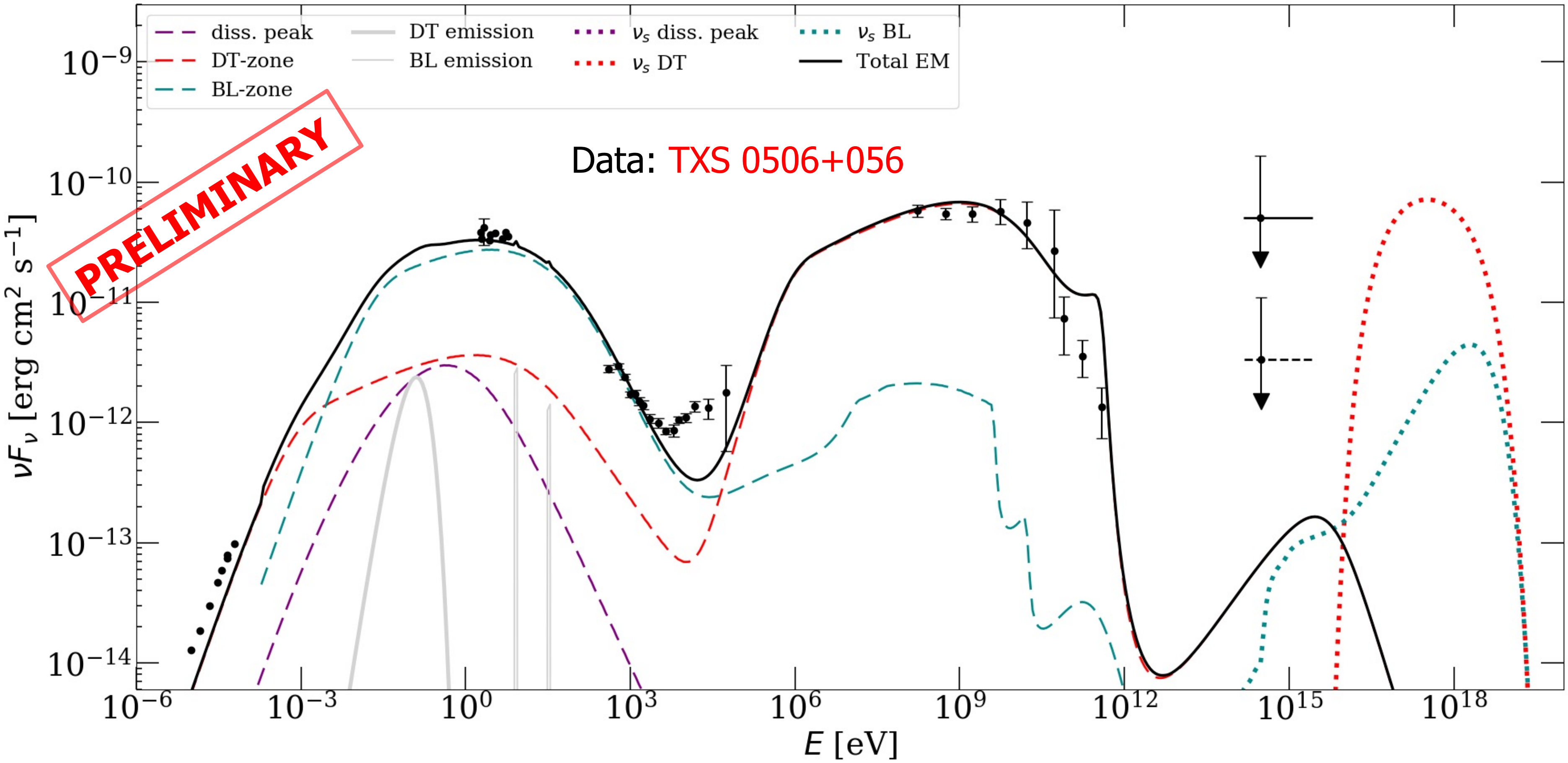
Multi-zone Model based on Reconnection Acceleration for Blazars SED



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

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

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



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

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