Magnetic Reconnection in Relativistic Jets and Accretion Flows around Black Holes

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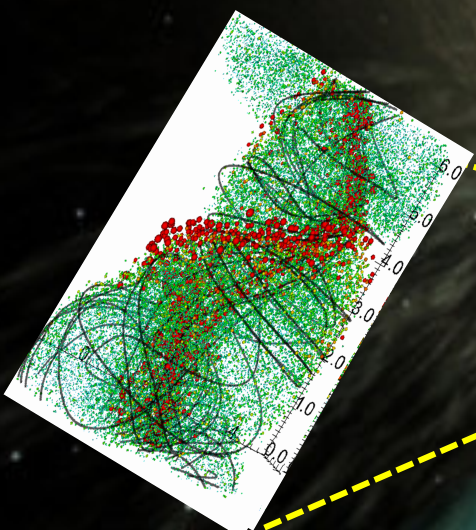

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Y. Mizuno
J. C. Rodriguez-Ramirez
C. Singh, J. Stone, G. Vicentin

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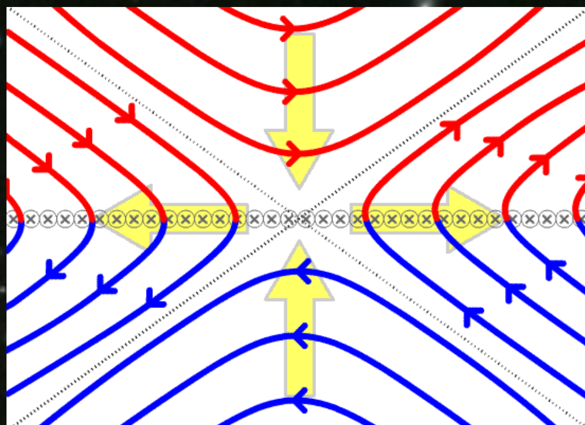
MAGNETIC RECONNECTION

Approach of magnetic flux tubes of opposite polarity with finite resistivity (η): **RECONNECT**



Δ

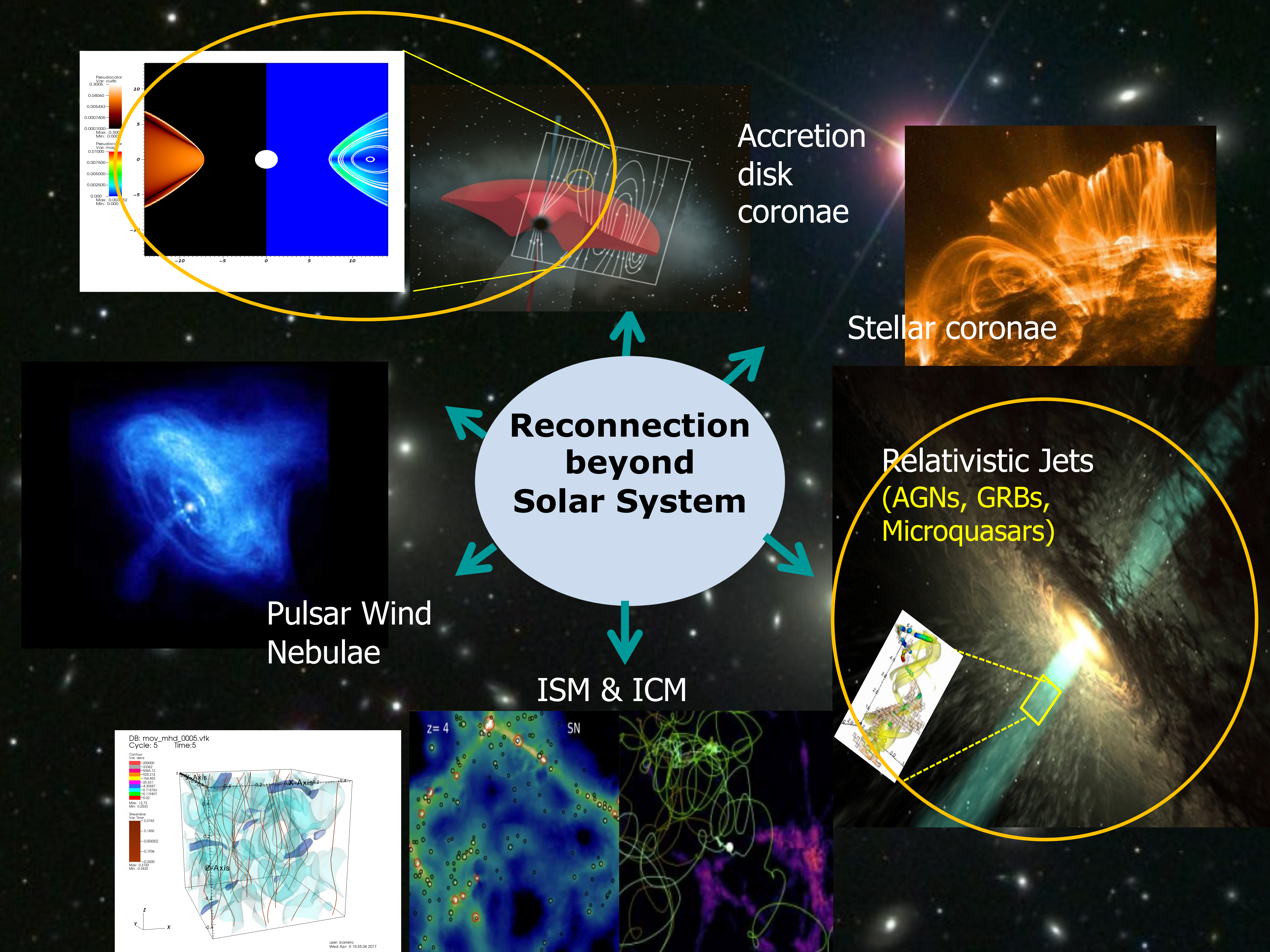
$$\vec{J} = \frac{c}{4\pi}\vec{\nabla}\times\vec{B} \sim \frac{2B}{\Delta}\frac{c}{4\pi}$$

Earth magnetotail

Solar corona

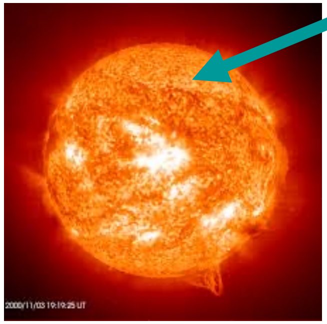
Reconnection is *FAST* in these environments

-> $\boldsymbol{v_{rec} \sim V_A = B/(4\pi\rho)^{1/2}}$

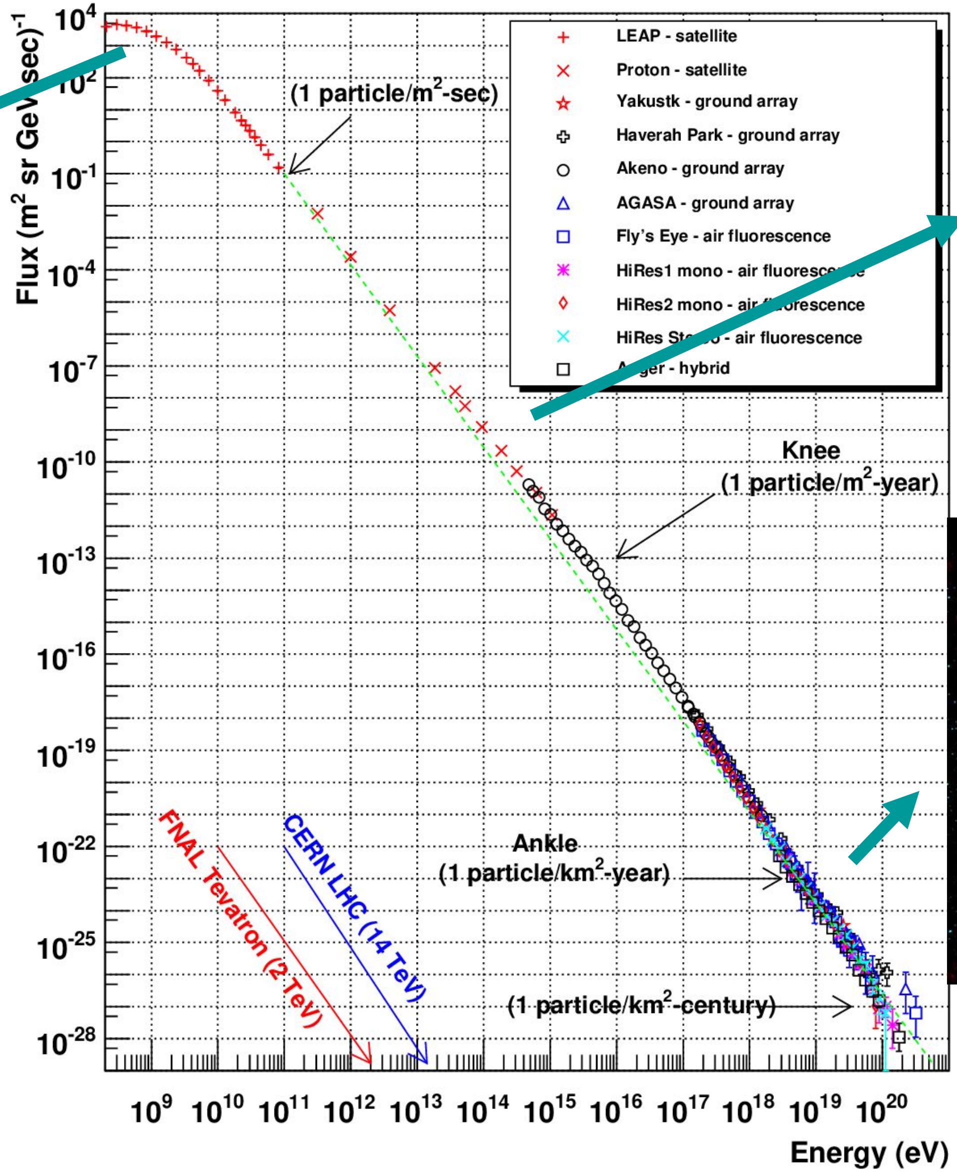

Accretion disk coronae
Stellar coronae
Reconnection beyond Solar System
Relativistic Jets
(AGNs, GRBs, Microquasars)
Pulsar Wind Nebulae
ISM & ICM

Facts & Challenges

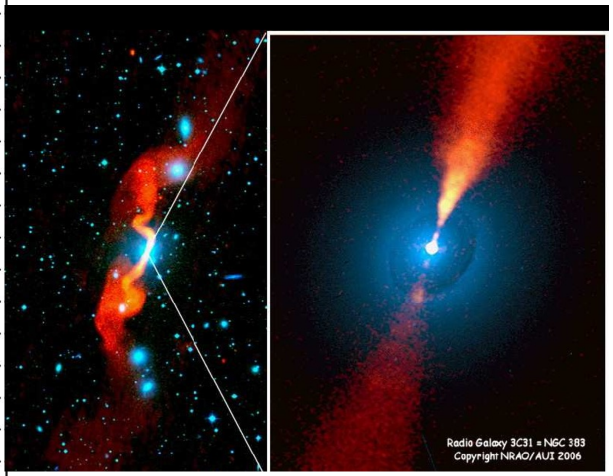
Cosmic Ray Spectrum



Sun

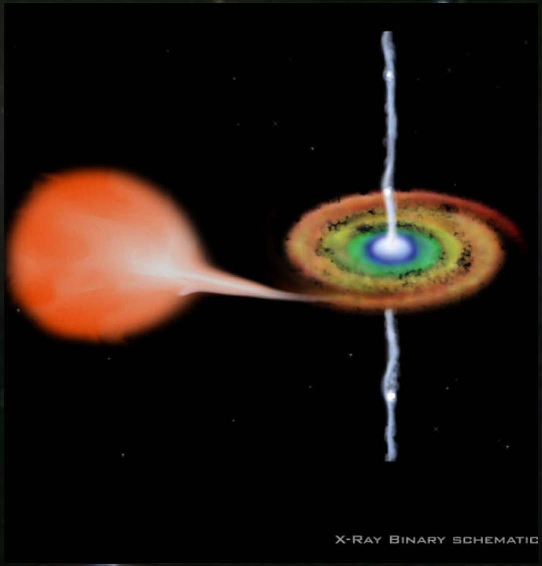


Milky Way

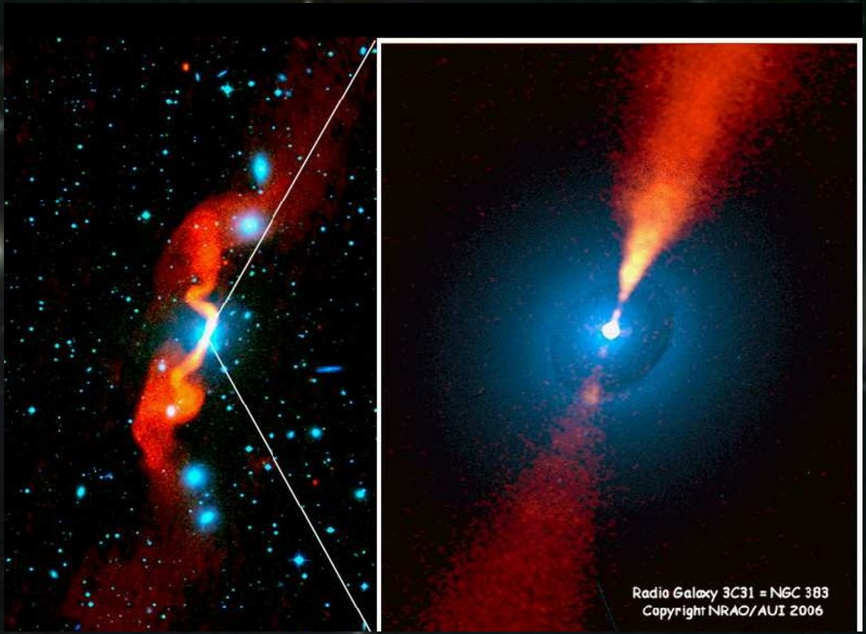


Active Galaxies

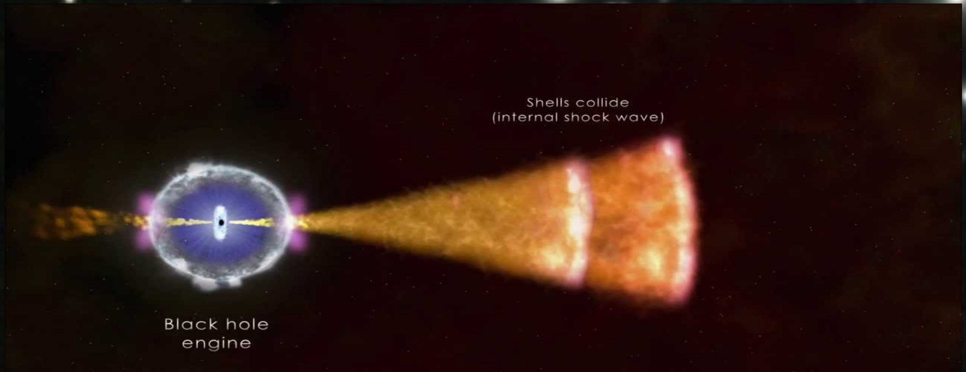
Black Hole Sources: Cosmic Ray accelerators $\geq 10^{15}$ eV and very high energy emitters >TeVs



Black Hole Binaries
(Microquasars)

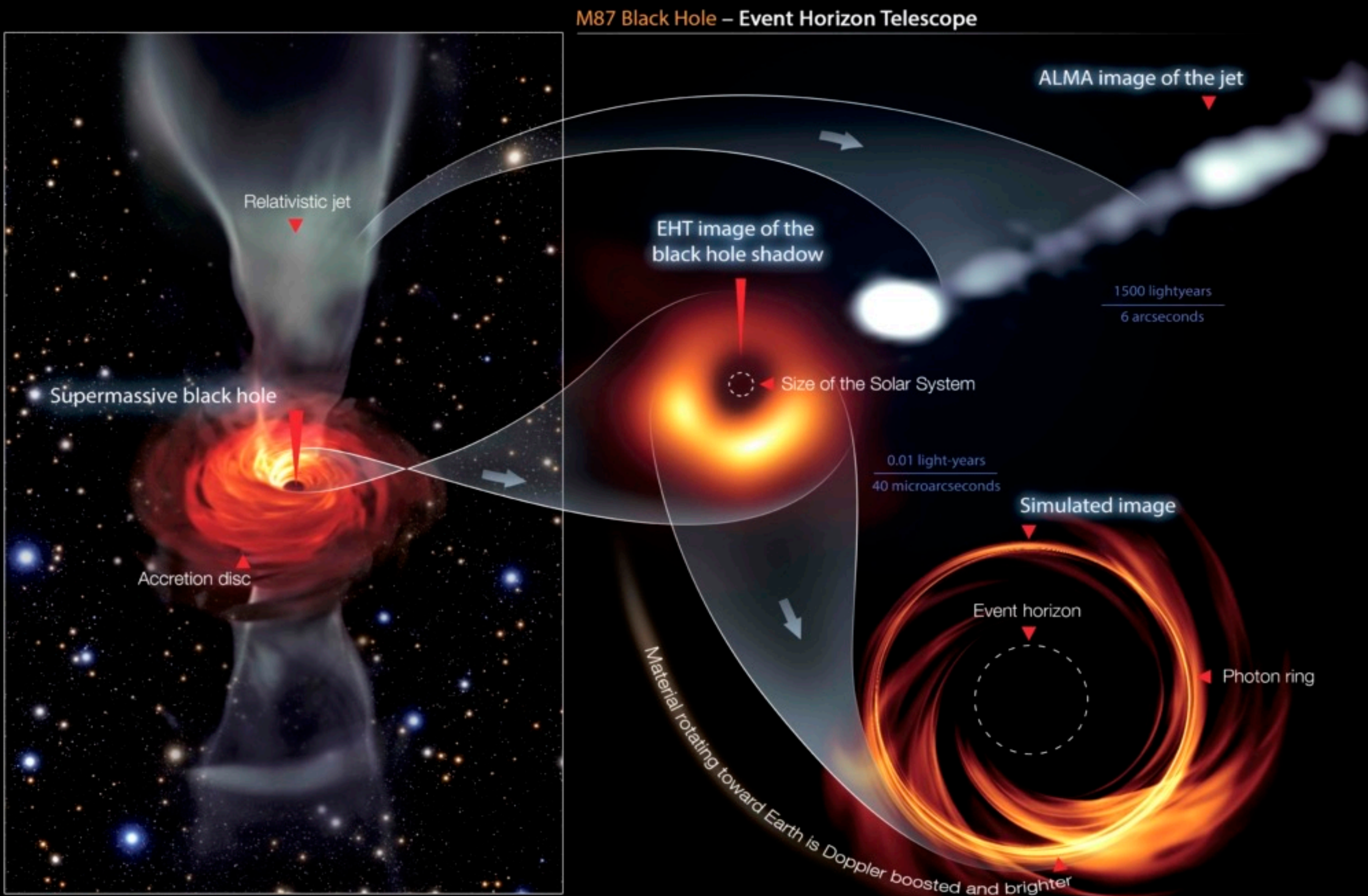


AGNs (blazars, radio-galaxies, seyferts)



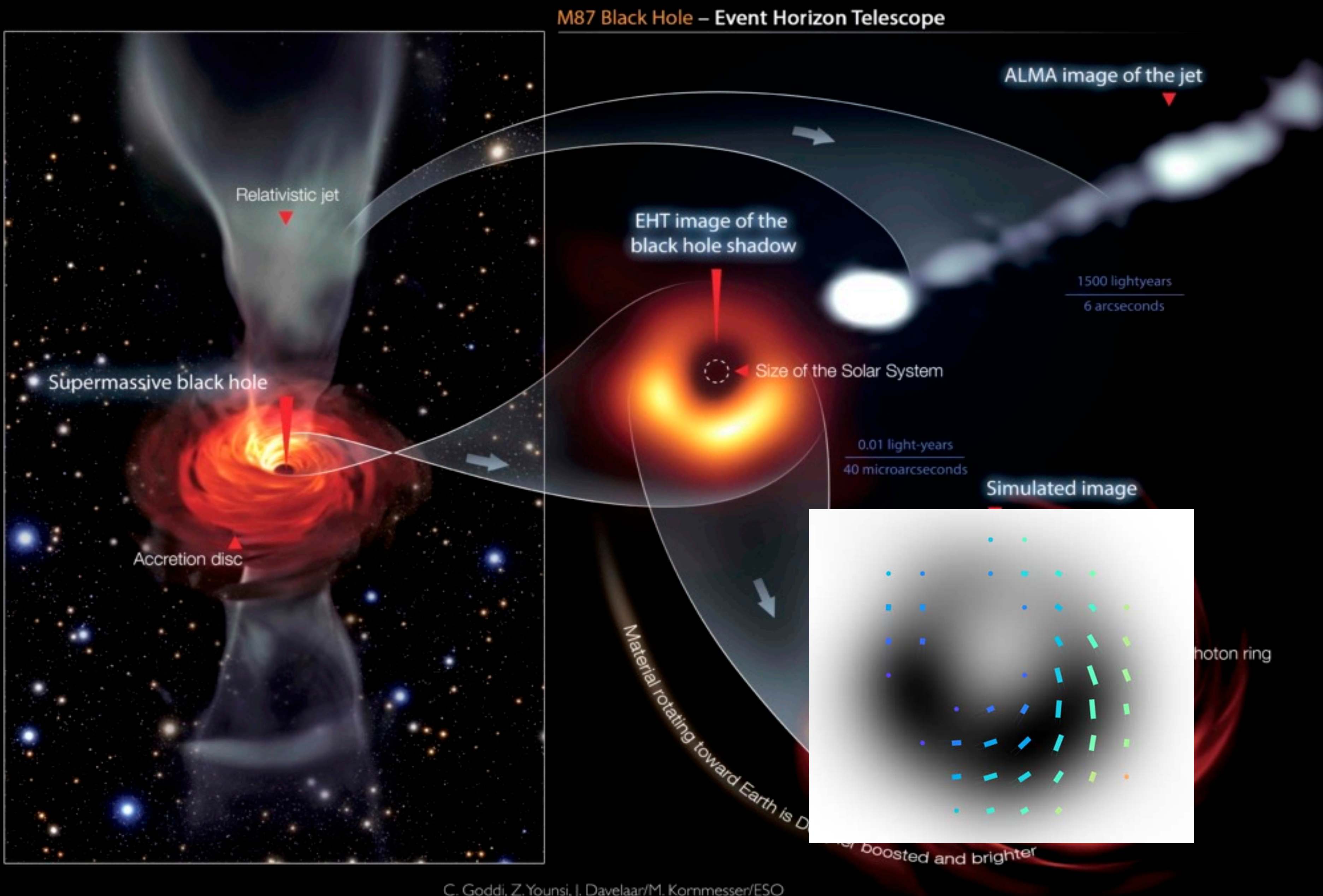
GRBs

Relativistic jets are born magnetically dominated

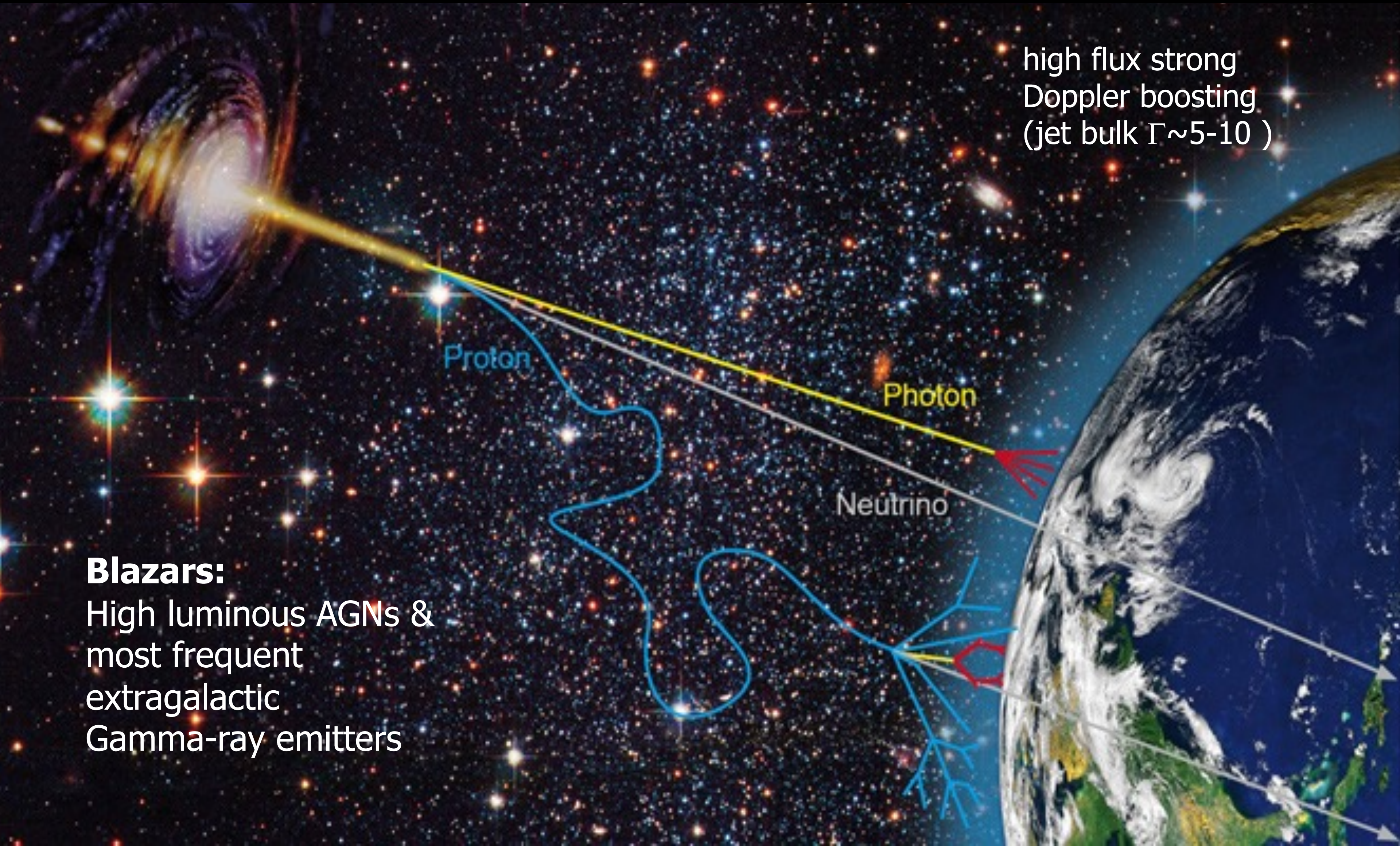


C. Goddi, Z. Younsi, J. Davelaar/M. Kornmesser/ESO

Relativistic jets are born magnetically dominated



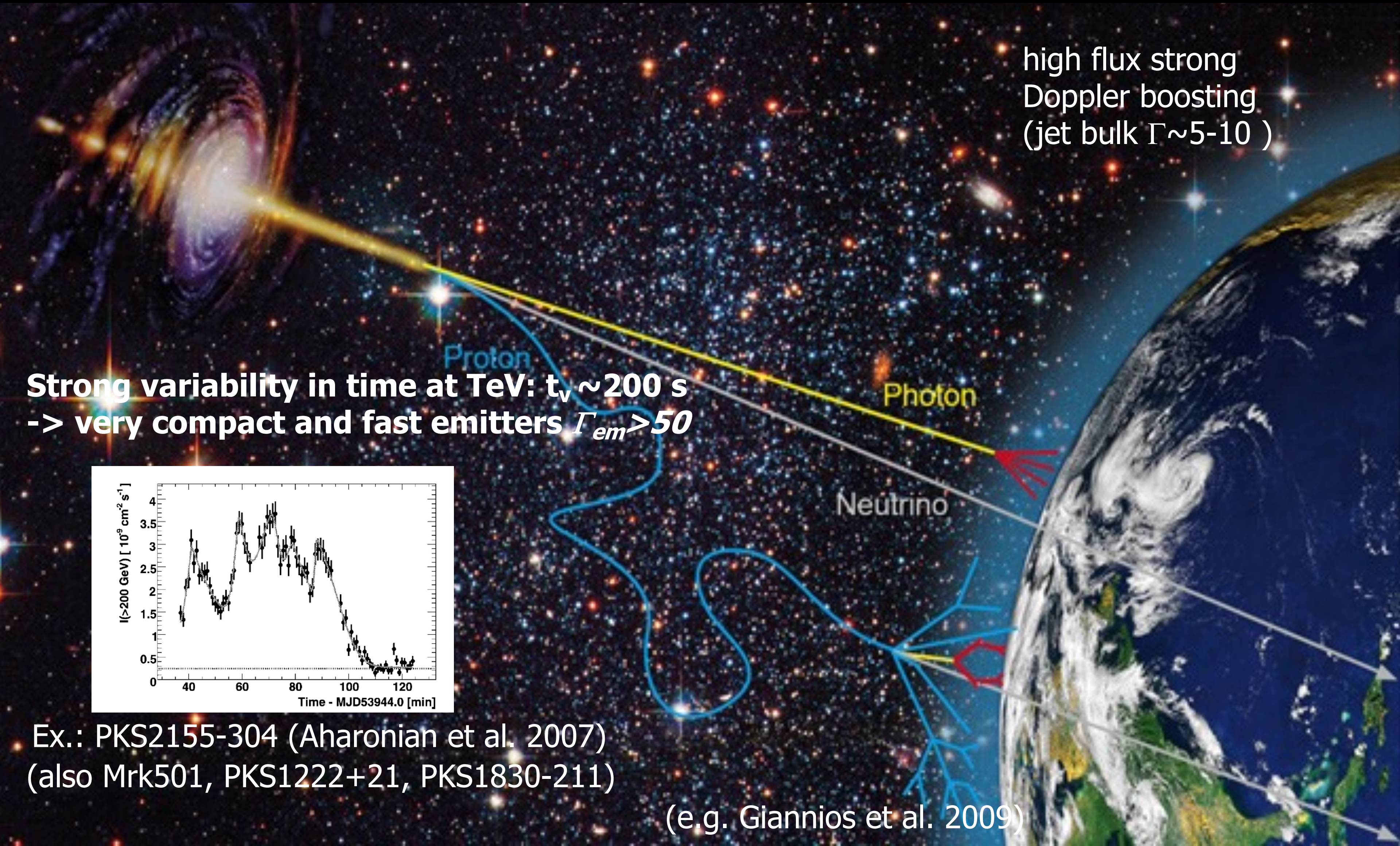
Challenge to explain observed gamma-ray flares in AGN BLAZAR Jets?



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

Blazars:
High luminous AGNs & most frequent extragalactic Gamma-ray emitters

Challenge to explain observed gamma-ray flares in AGN BLAZAR Jets?



high flux strong Doppler boosting (jet bulk $\Gamma \sim 5\text{-}10$)

Strong variability in time at TeV: $t_v \sim 200$ s -> very compact and fast emitters $\Gamma_{em} > 50$

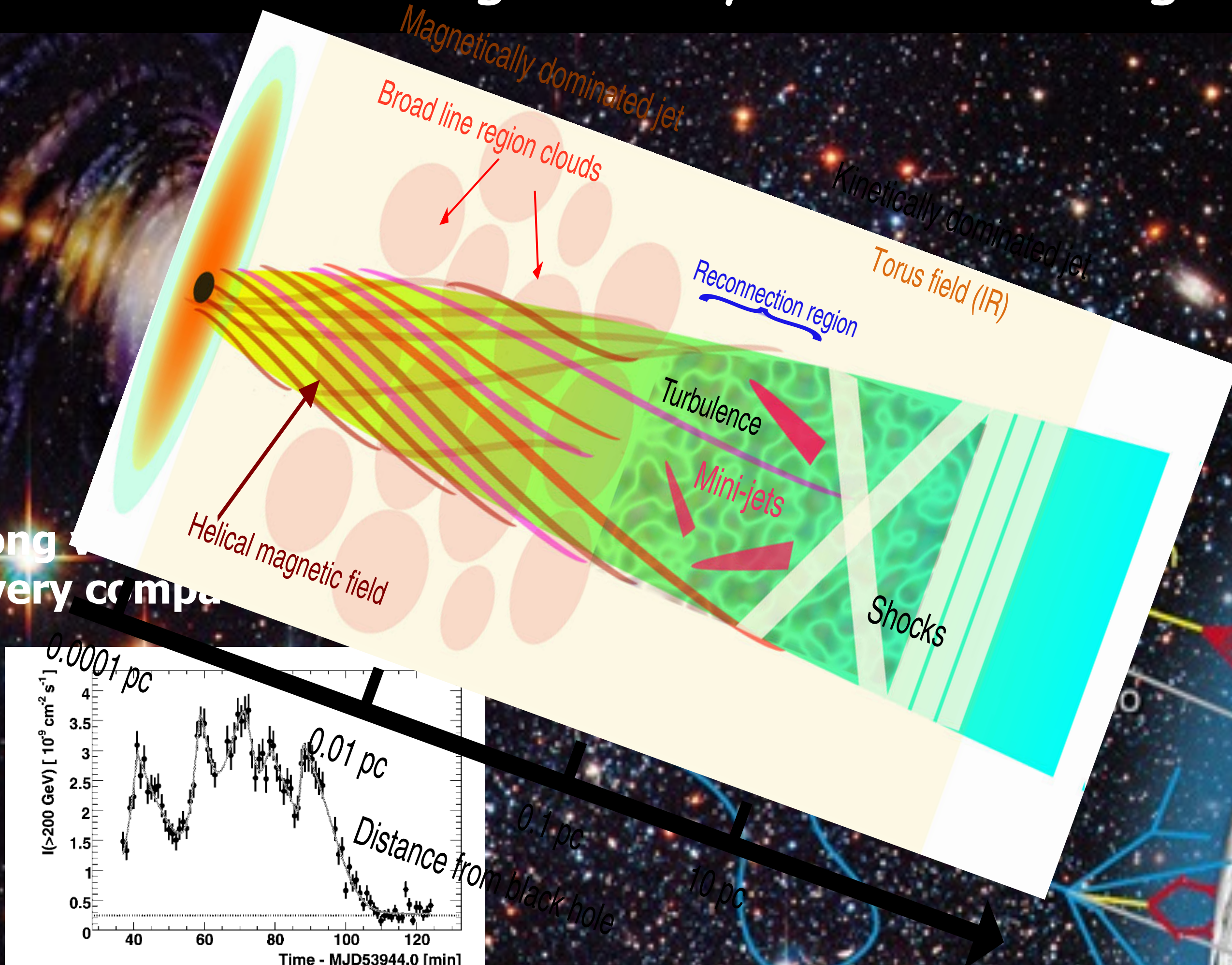
Ex.: PKS2155-304 (Aharonian et al. 2007)
(also Mrk501, PKS1222+21, PKS1830-211)

(e.g. Giannios et al. 2009)

Reconnection Particle Acceleration: best mechanism able to explain gamma-ray flares in AGN BLAZAR Jets in magnetically dominated regions

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

Strong
-> very c mpa



Ex.: PKS2155-304 (Aharonian et al. 2007)
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(e.g. Giannios et al. 2009)

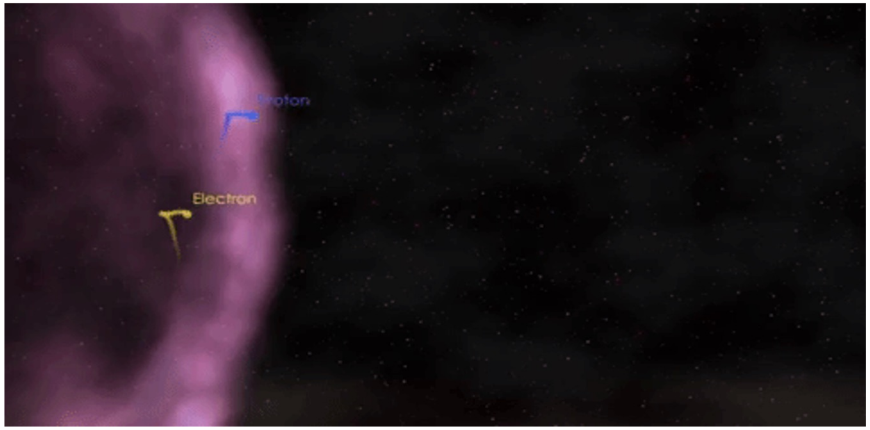
This talk

PARTICLE ACCELERATION BY RECONNECTION @ magnetically dominated regions of black hole relativistic jets and accretion flows (to solve current puzzles related CR acceleration and very high energy emission):

- Overview of fast magnetic reconnection acceleration in **MHD flows driven by turbulence**
- Reconnection acceleration of particles up to ultra-high-energies (UHECRs) from 3D relativistic MHD jet simulations + test particles
- 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

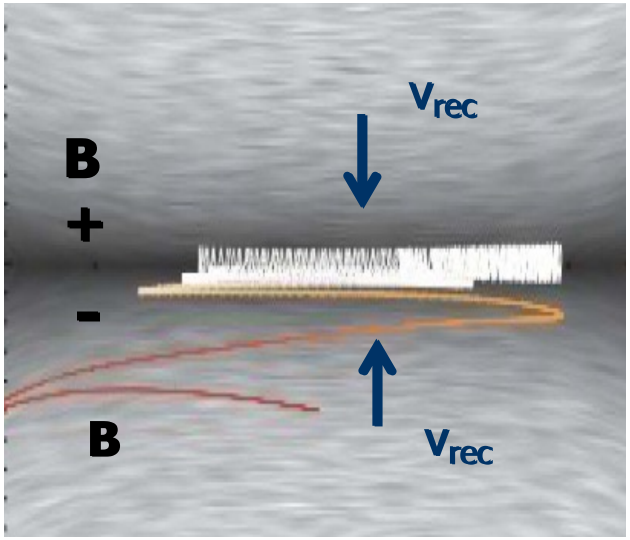
Shock Acceleration



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

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

Reconnection Acceleration

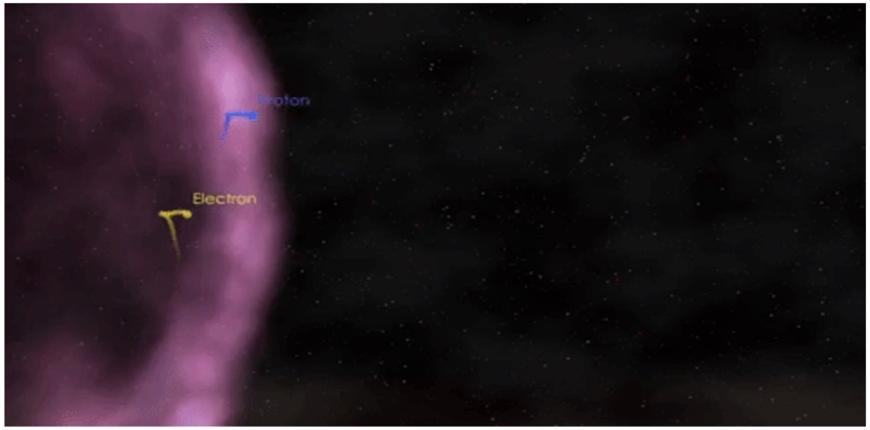


As in shocks: 1st-order Fermi
(de Gouveia Dal Pino & Lazarian 2005)

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

Particles are accelerated in reconnection sites mainly by Fermi process

Shock Acceleration



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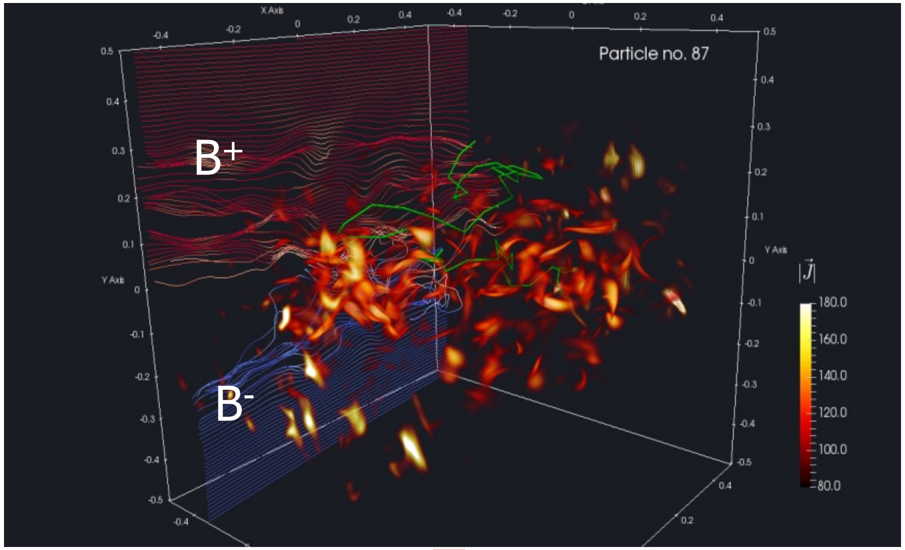
Reconnection Acceleration

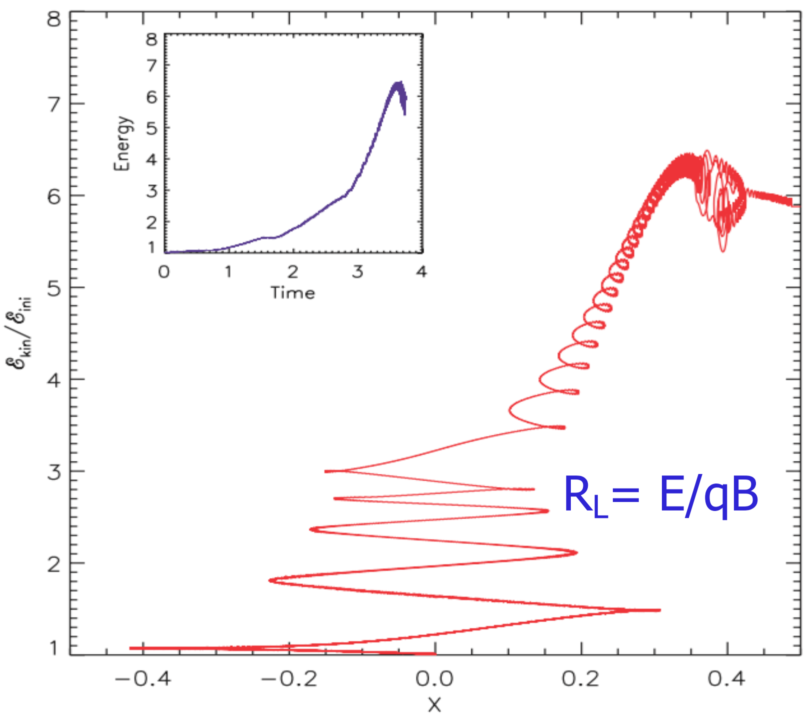


As in shocks: 1st-order Fermi
(de Gouveia Dal Pino & Lazarian 2005;
del Valle, de Gouveia Dal Pino, Kowal 2016)

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

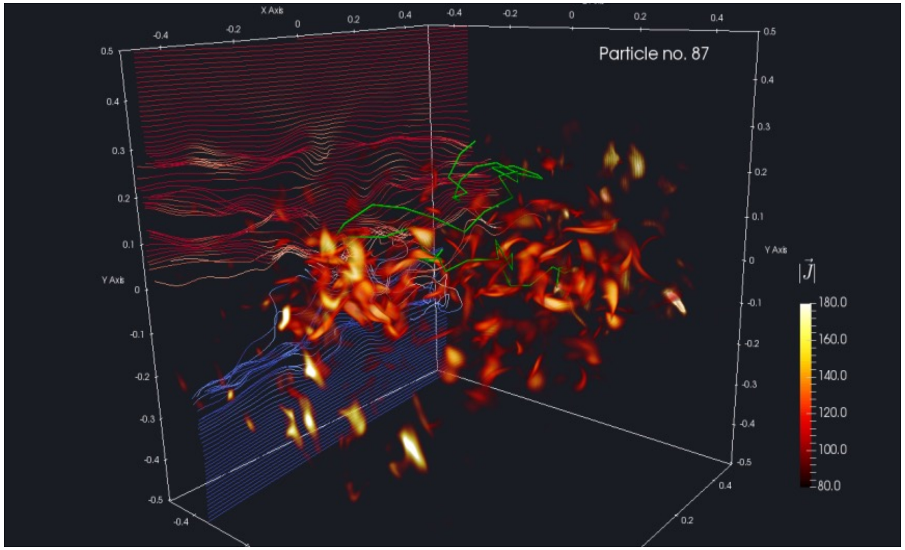
Particles are accelerated in reconnection sites mainly by Fermi process

Exponential energy growth in time



Kowal, de Gouveia Dal Pino & Lazarian, ApJ 2011

Reconnection Acceleration



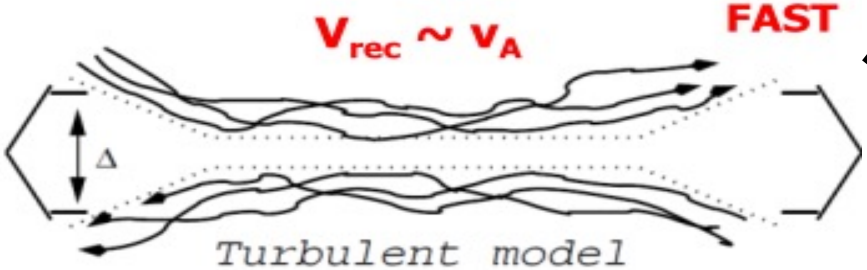
As in shocks: 1st-order Fermi
(de Gouveia Dal Pino & Lazarian 2005;
del Valle, de Gouveia Dal Pino, Kowal 2016)

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

Turbulence drives Fast Reconnection in MHD flows

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

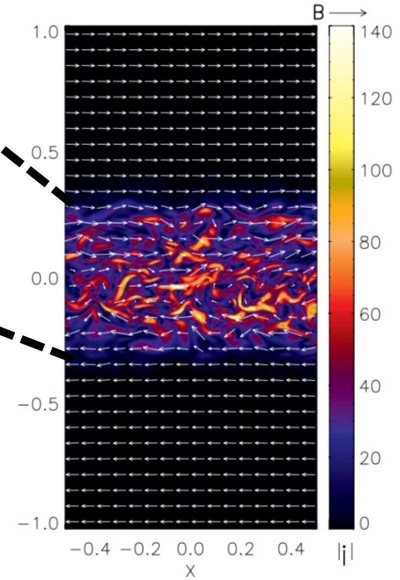
Magnetic lines wandering and slippage: many simultaneous reconnection events



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

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

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; 22; Werner+ 17; 19; Sironi+18; Niskiwkawa et al. 2019, 2020; Comisso & Sironi 2019, 2020; Zhang et al. 2021, Davelaar et al. 2021; Sironi 2022; Zhang et al 2023; …)

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

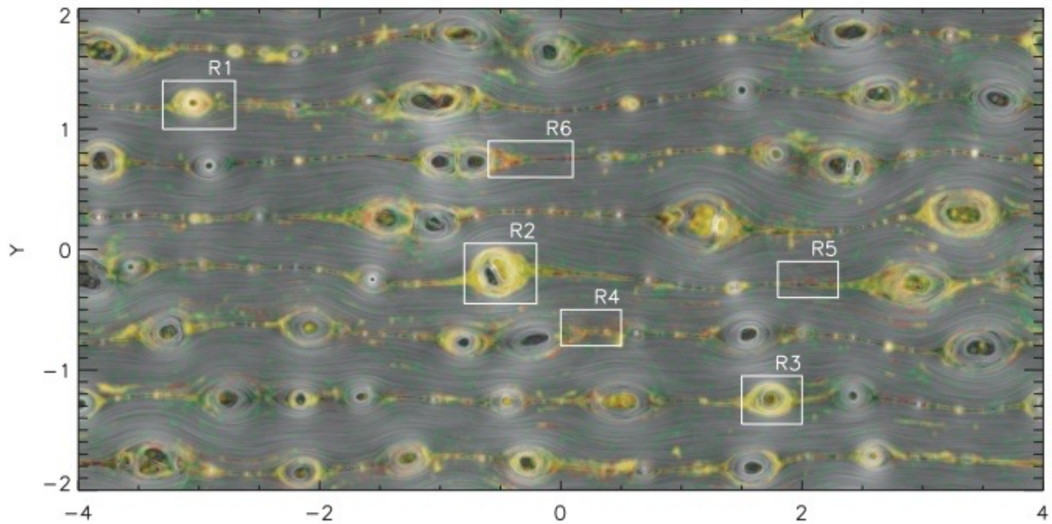
  acceleration up to ~ few 1000 mc^2

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

  3D MHD + test particles:

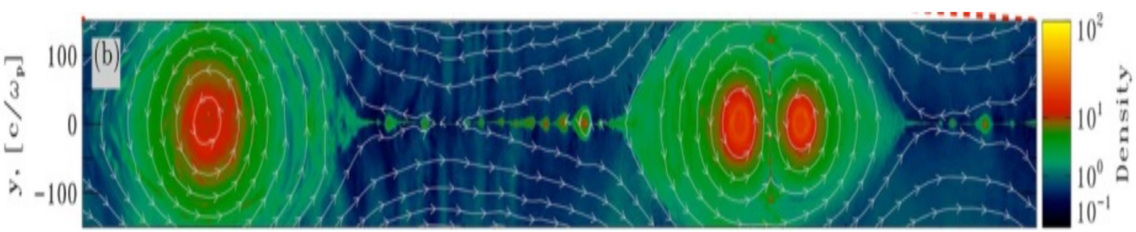
  (Kowal, de Gouveia Dal Pino & Lazarian 2011, 2012; de Gouveia Dal Pino & Kowal 2015; del Valle et al. 2016; Beresnyak & Li 2016; de Gouveia Dal Pino+2018, 2019; Guo et al. 2019; Yang et al. 2020; Medina-Torrejon et al. 2021; Medina-Torrejon, de Gouveia Dal Pino, Kowal 2023, …)

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)

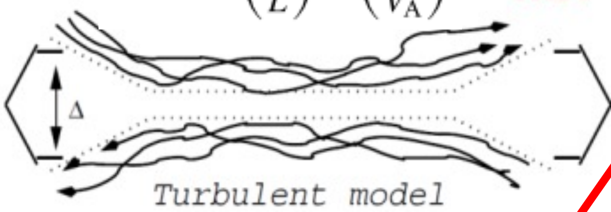
2D PIC simulations of plasmoids and X points (driven by tearing mode)

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

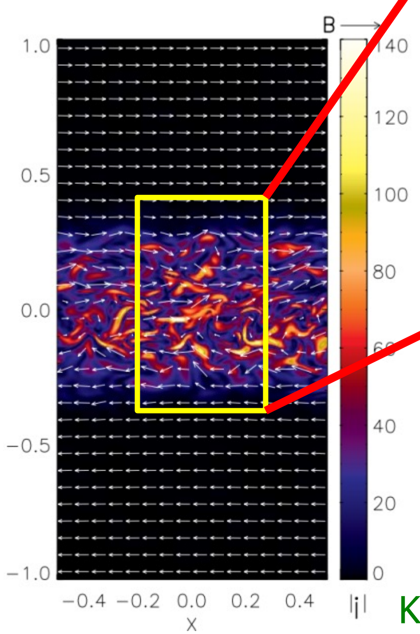
3D MHD Simulations with Test Particles (with turbulence that makes reconnection fast)

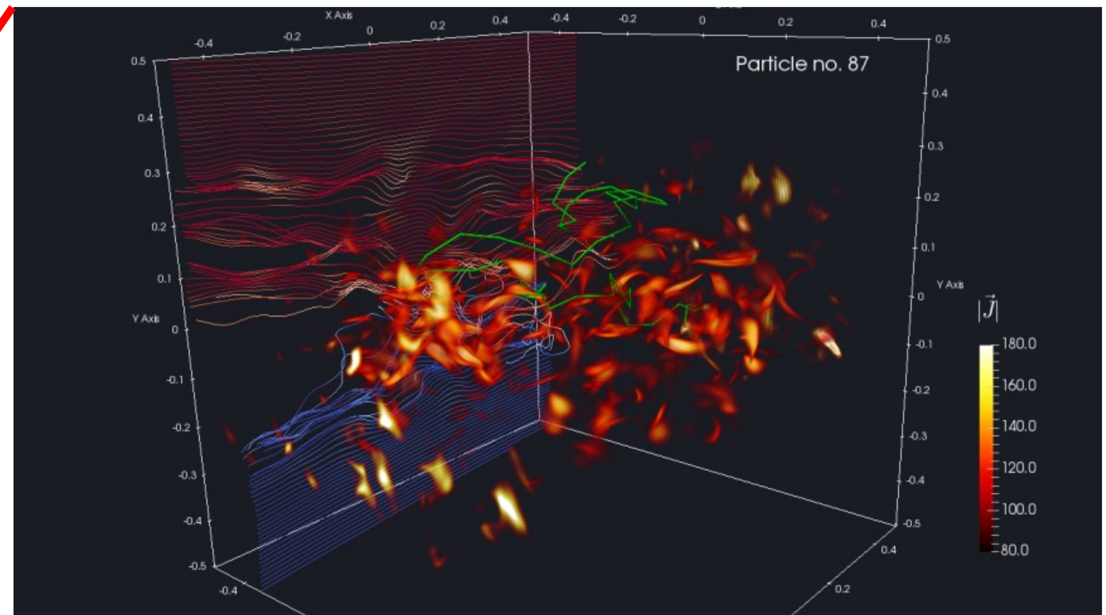
$$V_{\rm rec} = V_{\rm A}\left(\frac{l}{L}\right)^{1/2}\left(\frac{v_l}{V_{\rm A}}\right)^2$$

FAST



(Lazarian & Vishniac 1999)





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

$\varepsilon = -v \times B$

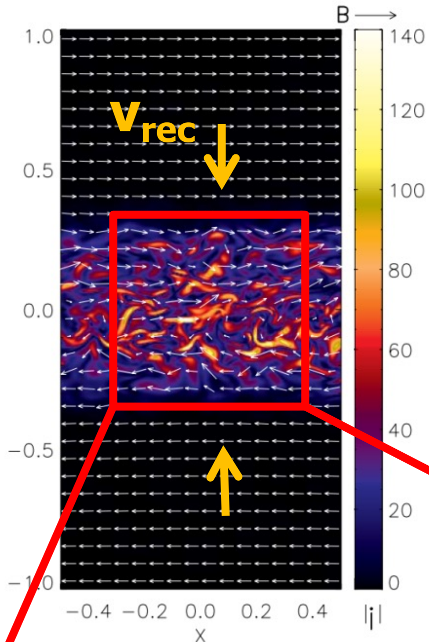
Neglect: $\varepsilon = \eta J$

(dominant in PIC simulations)

Kowal, de Gouveia Dal Pino, Lazarian PRL 2012

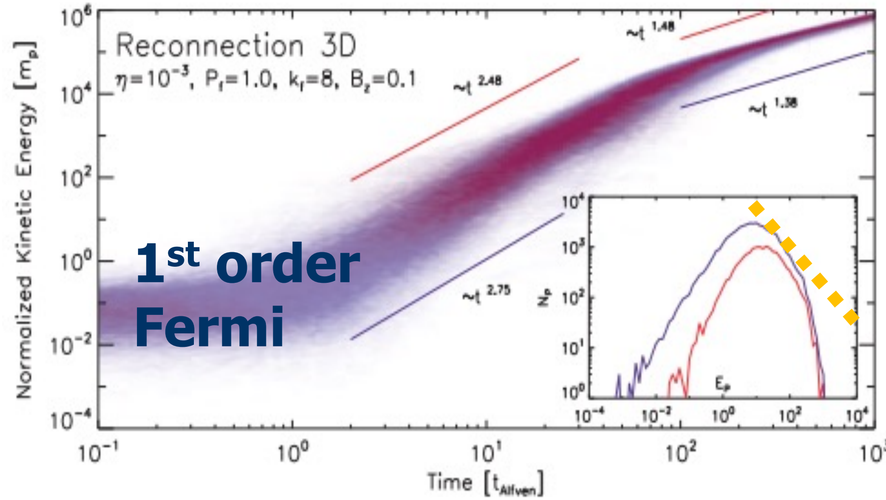
del Valle, de Gouveia Dal Pino, Kowal, MNRAS 2016

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

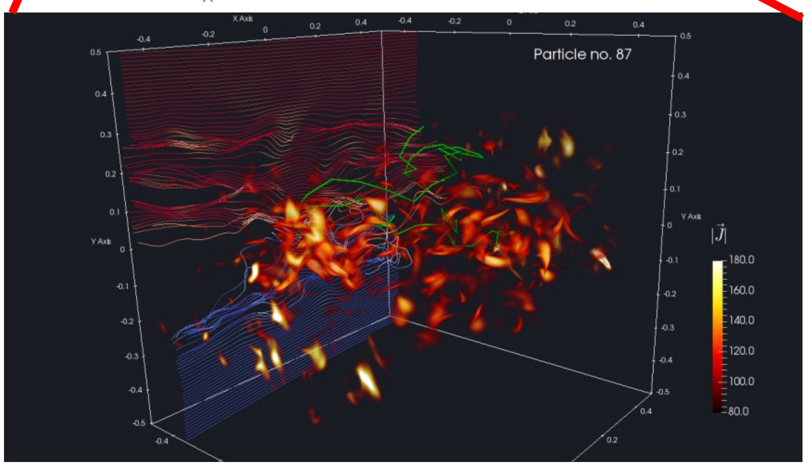


10,000 test particles

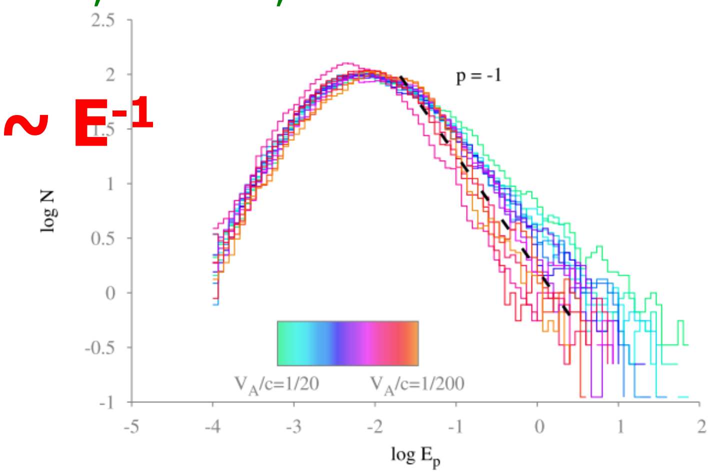
Injected in turbulent current sheet to make reconnection fast



Kowal, de Gouveia Dal Pino, Lazarian, PRL 2012



✓ **N(E) ~ E^{-1}**

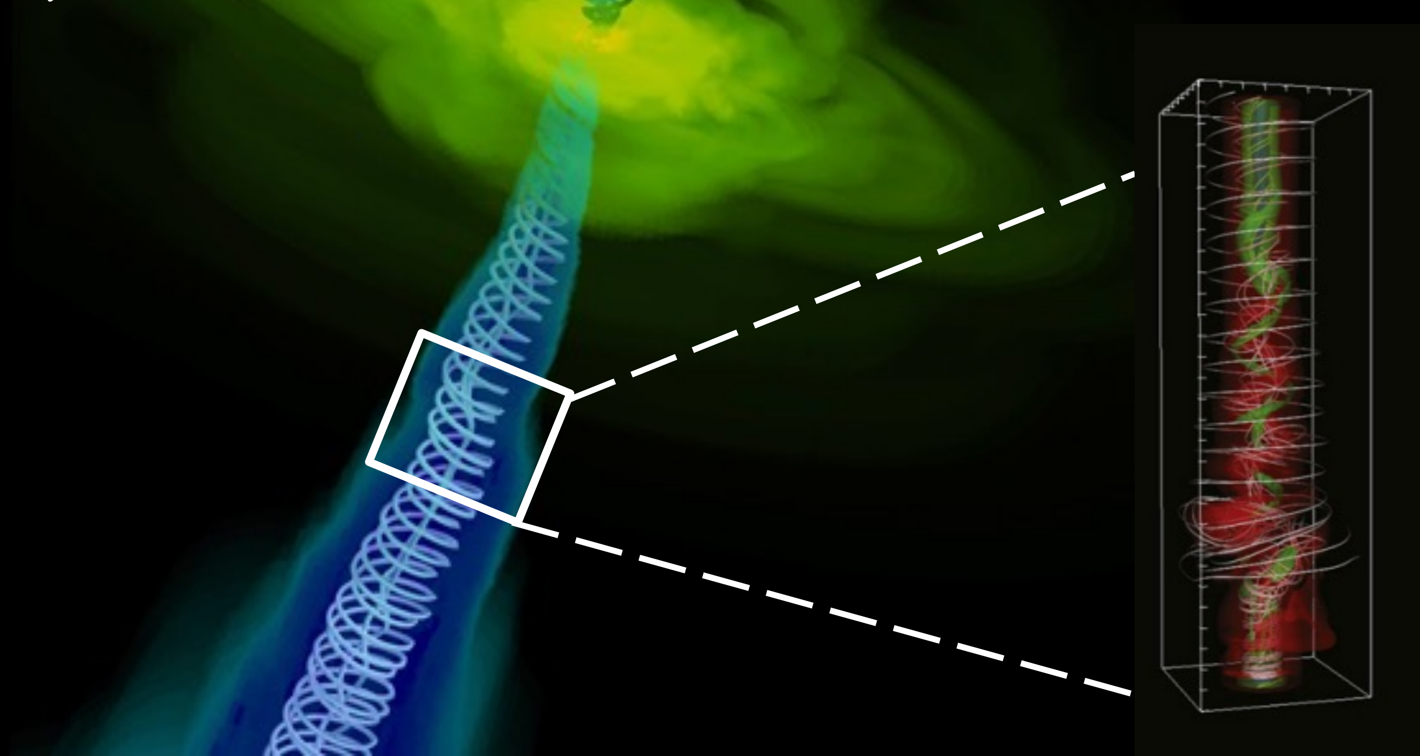


✓ **Signatures of Fermi acceleration**

del Valle, de Gouveia Dal Pino, Kowal MNRAS 2016

In situ Reconnection Acceleration in Relativistic Jets

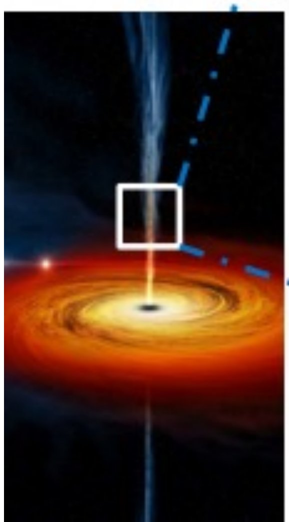
Relativistic MHD (RMHD) simulations + test particles:
can probe particle acceleration to highest energies without doing extrapolations (to macroscopic scales as it is required in PIC simulations)

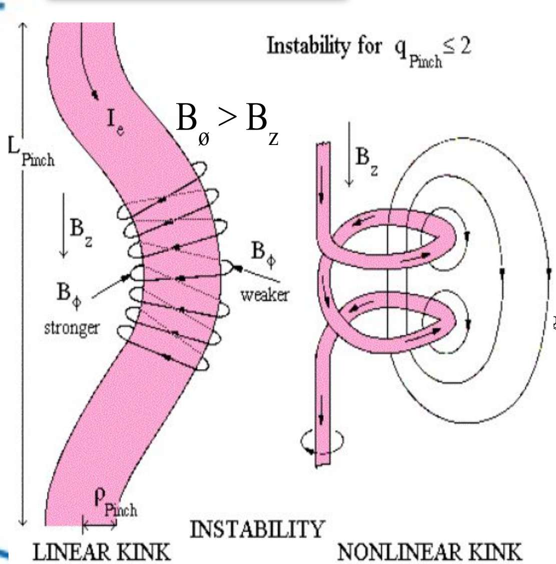


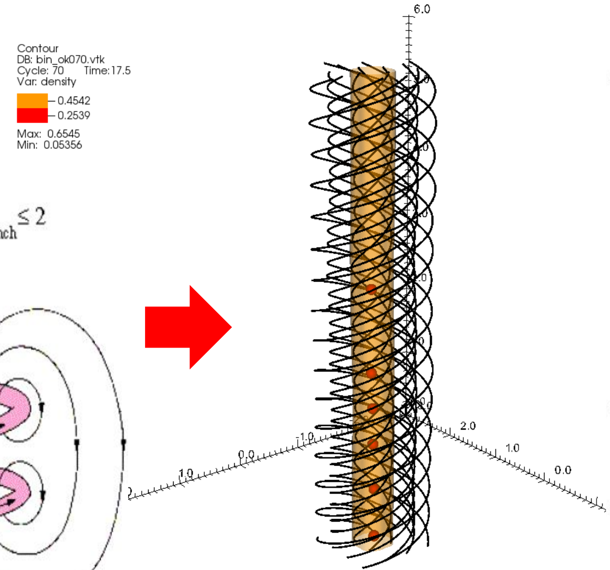
3D RMHD Simulations of Magnetically Dominated Relativistic Jets subject to Kink Instability

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

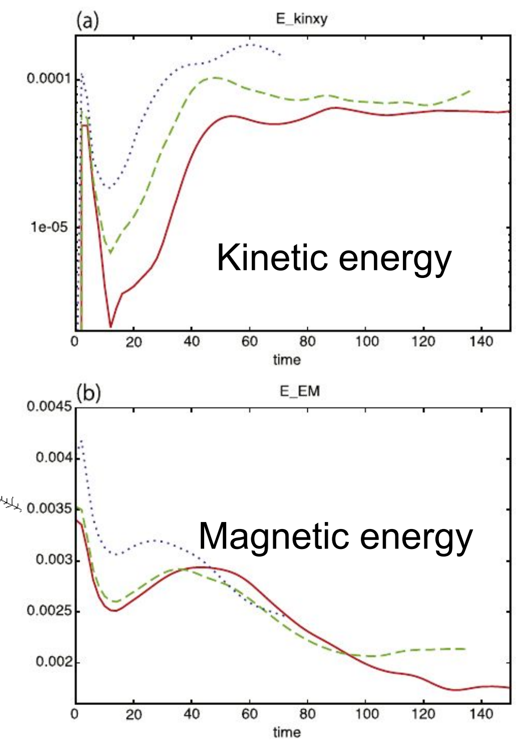
$$t_{\rm kink} \simeq \frac{2\pi R_{\rm j}}{c}\frac{B_p}{B_\phi}$$







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



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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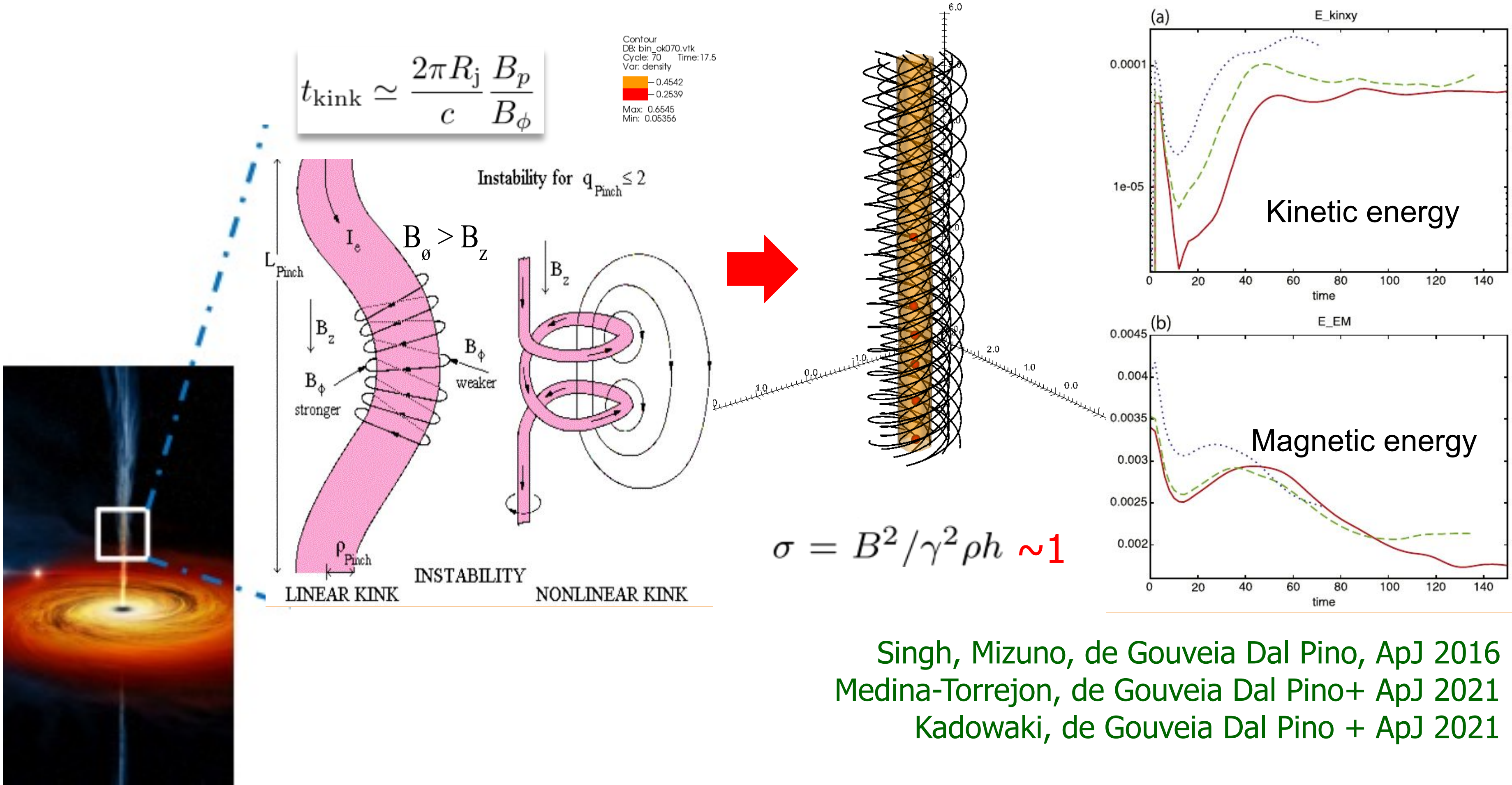
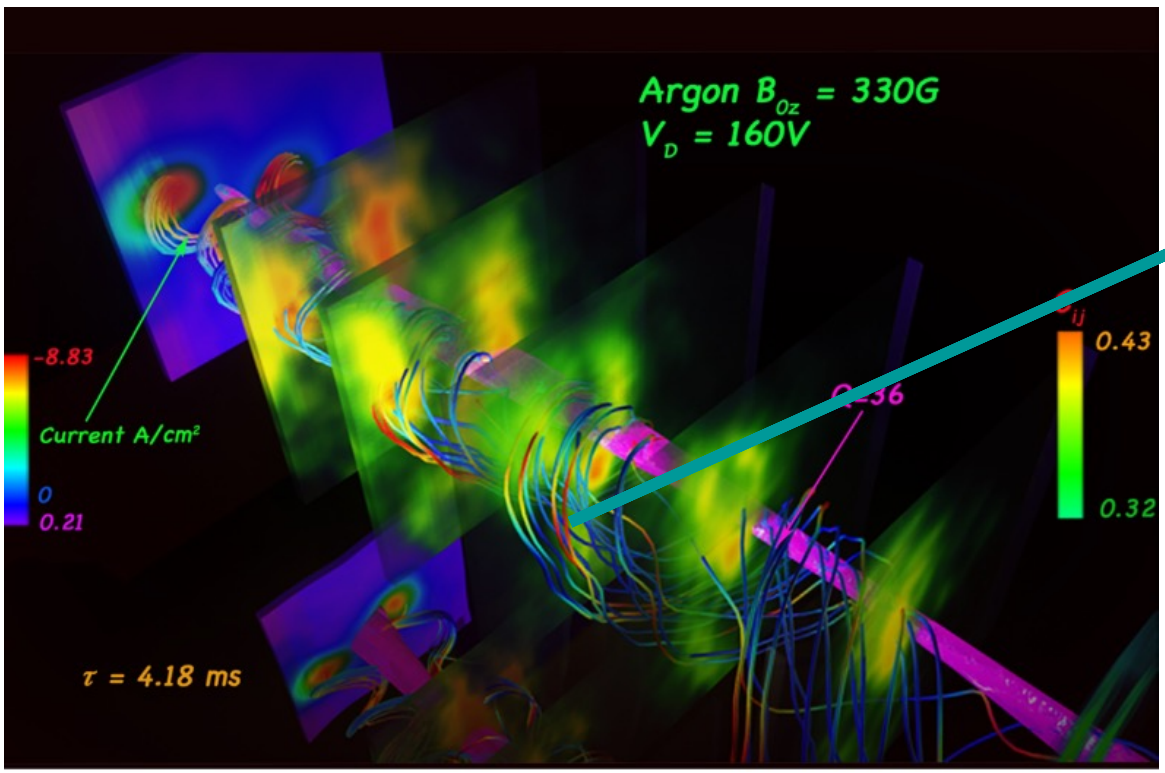


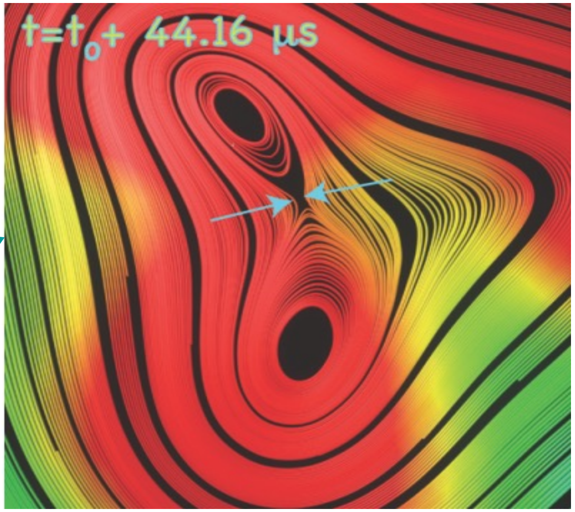
$\sigma = B^2/\gamma^2 \rho h$ ~1

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

Reconnection driven by CD Kink Instability in Laboratory

LAPD plasma column: 60 cm in diameter and 18 m long @ UCLA
(Gekelman et al., ApJ 2012)

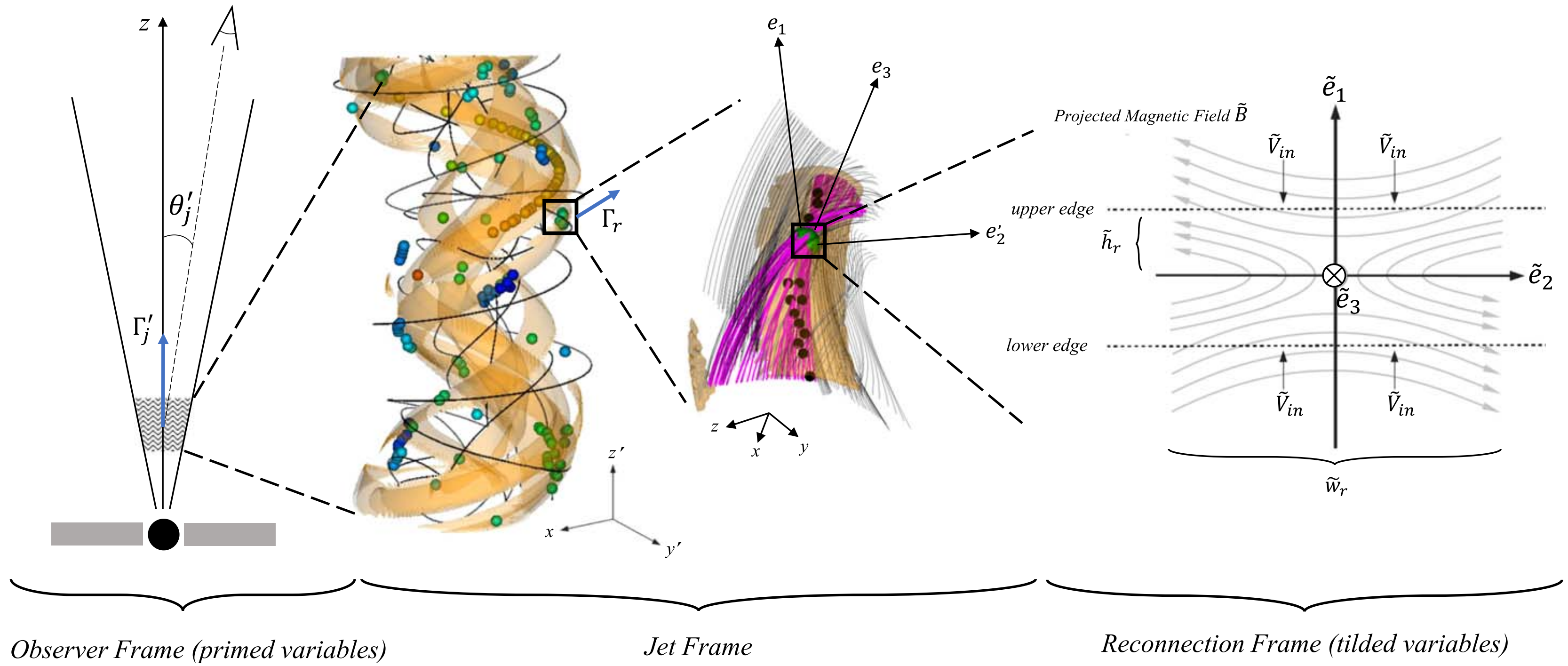




Magnetic flux ropes wrapped around each other develop kink instability that drives turbulent **reconnection -> patchy in space and bursty in time**

Identification of Fast Reconnection driven by Kink in Relativistic Jets

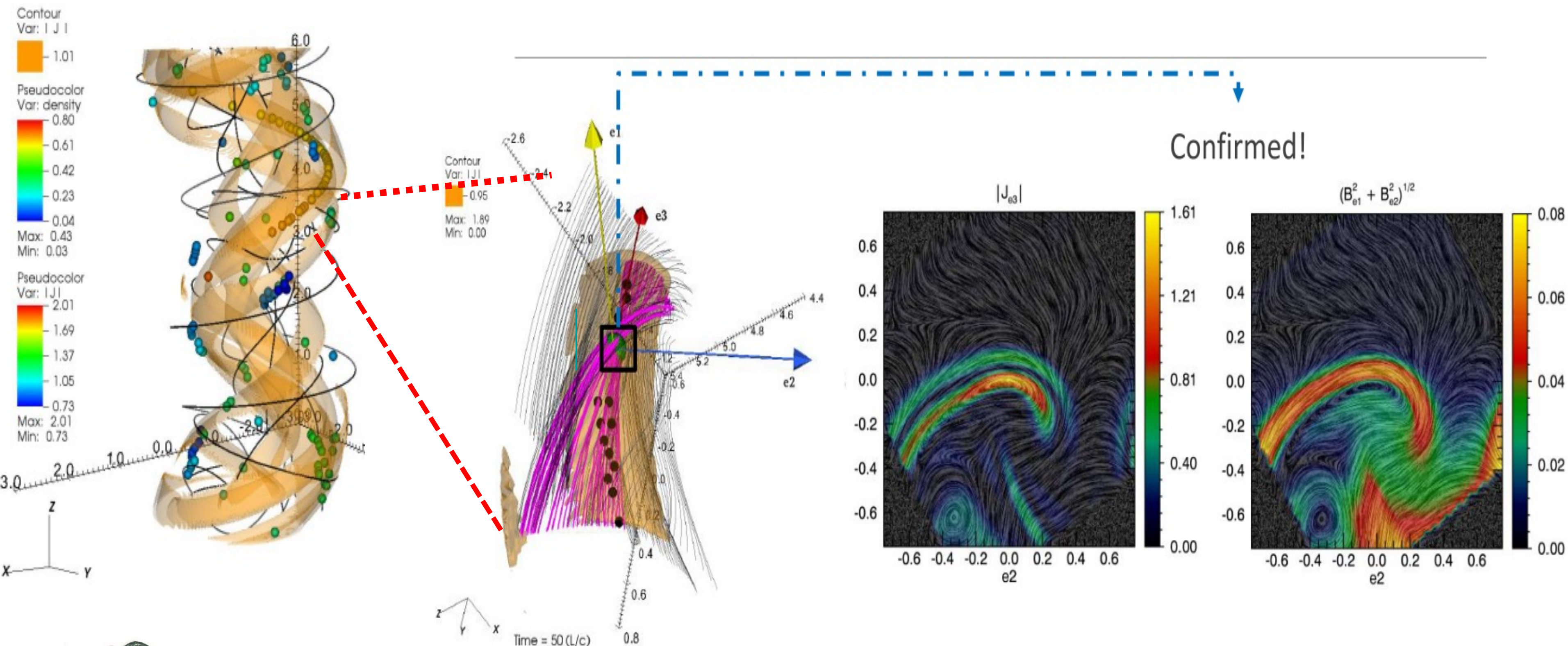
➢ Algorithm (as in Zhdankin et al. 2013) extended to 3D relativistic analysis



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

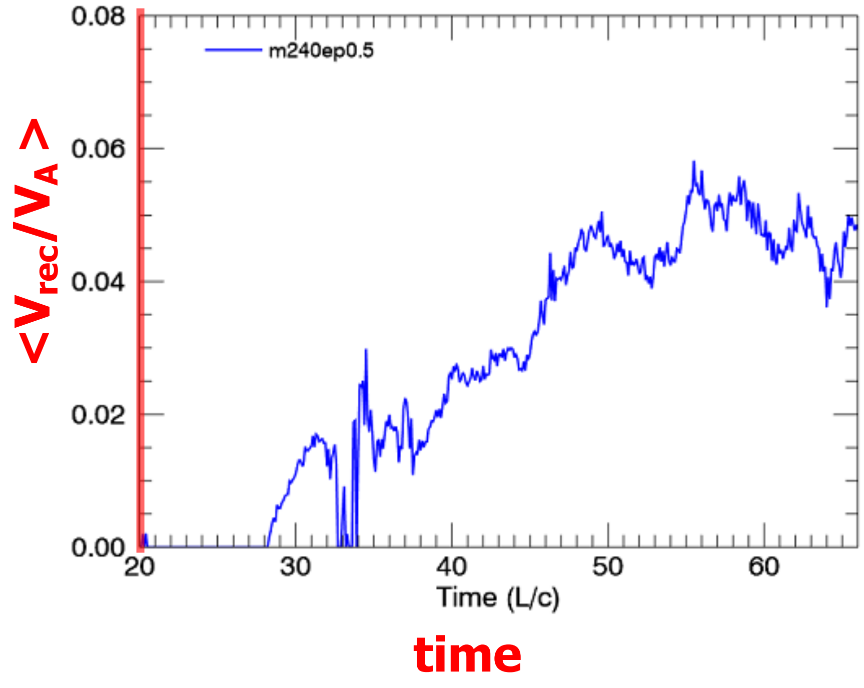
Kadowaki, de Gouveia Dal Pino, Stone ApJ 2018;
Kadowaki, de Gouveia Dal Pino, Medina-Torrejon +ApJ 2021

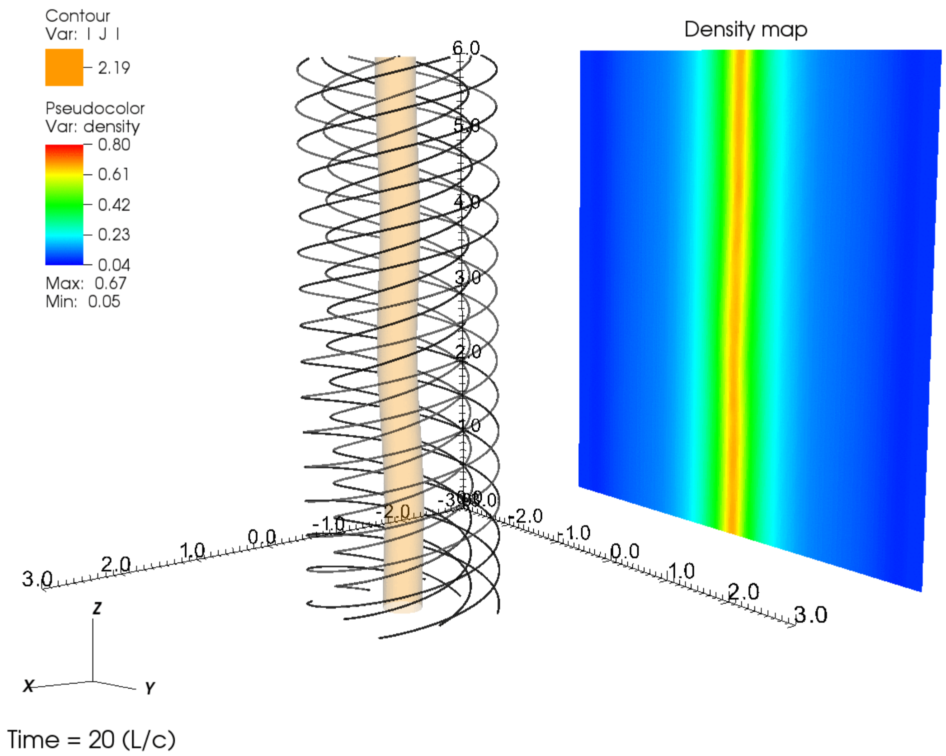
Identification of Fast Reconnection driven by Kink in Relativistic Jets



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

Fast Reconnection Rate driven by Kink instability in Relativistic Jets

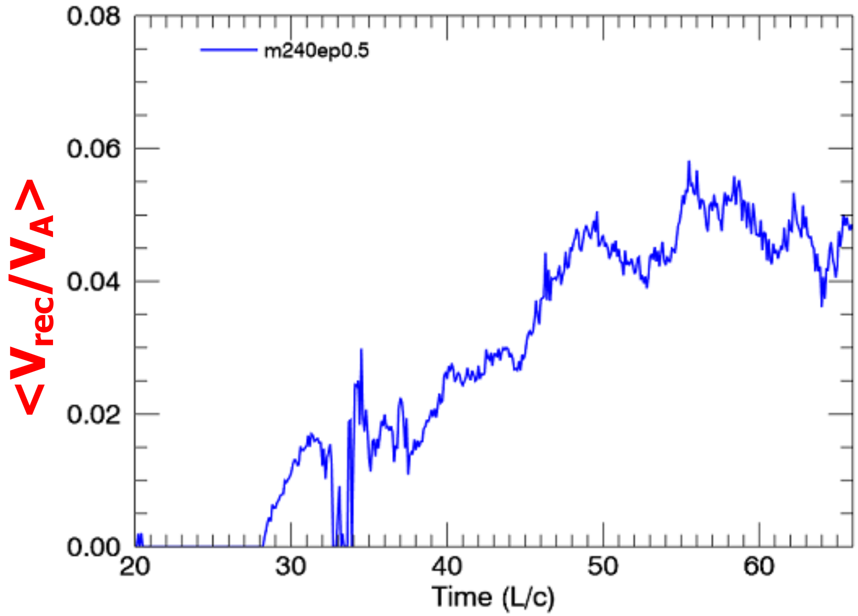




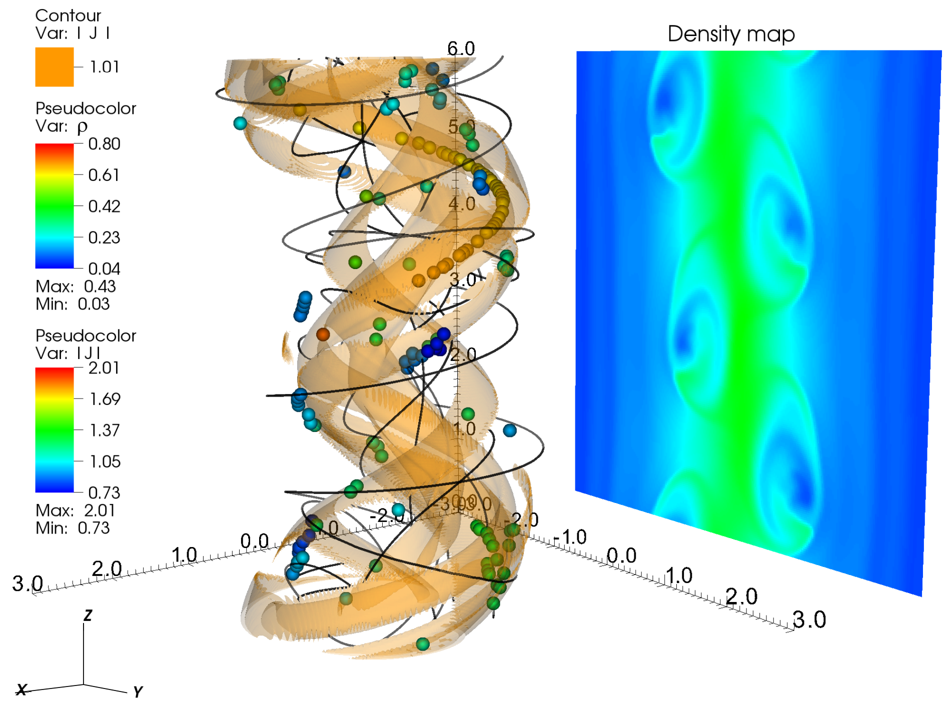
Kadowaki, de Gouveia Dal Pino, Medina-Torrejon +, ApJ 2021

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

Maximum v_{rec} ~0.4 V_A



time



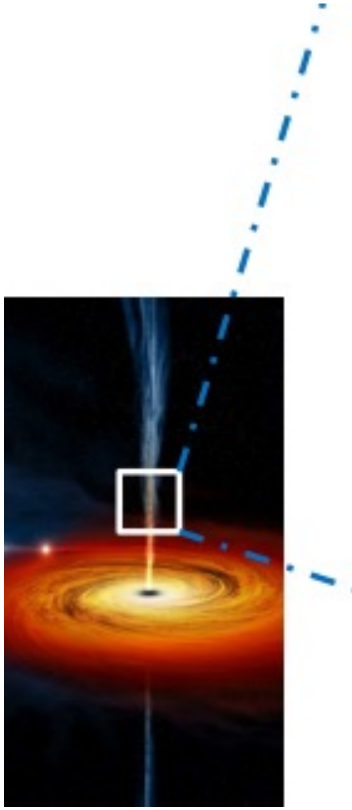
➢ $<V_{rec}> \approx 0.05\ V_A$ -> Fast reconnection: key for efficient particle acceleration

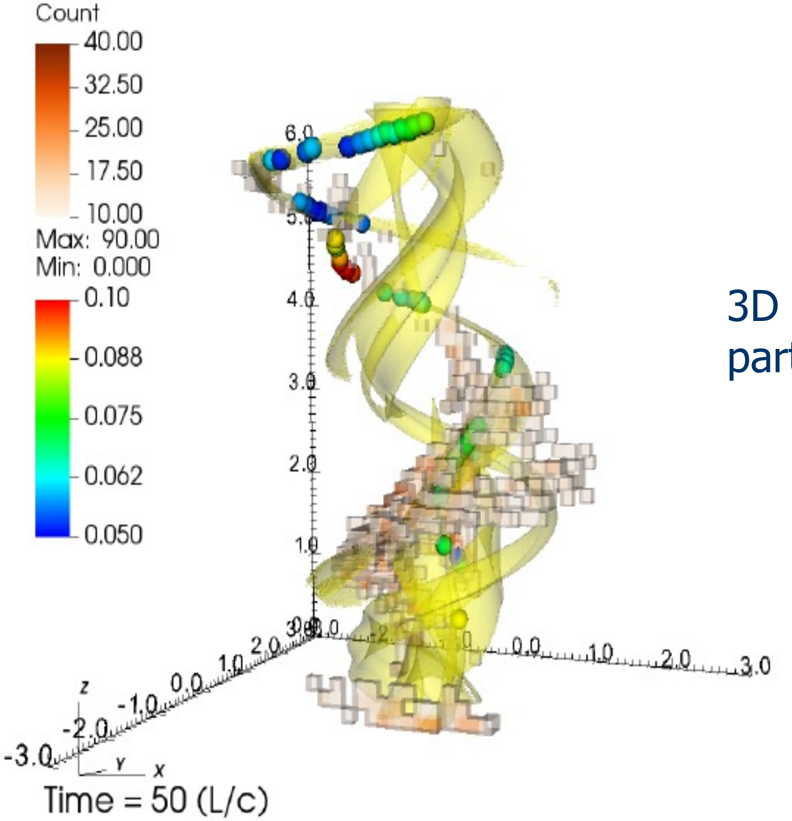
Kadowaki, de Gouveia Dal Pino, Medina-Torrejon + ApJ 2021

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





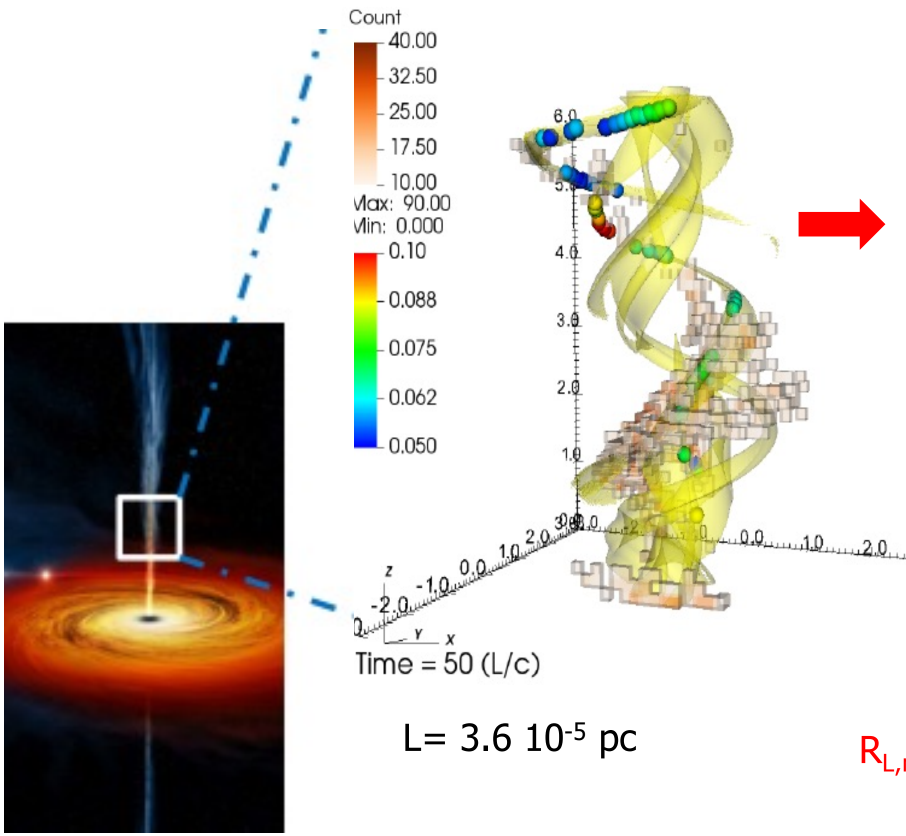
3D histogram of accelerated parttlicles

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

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

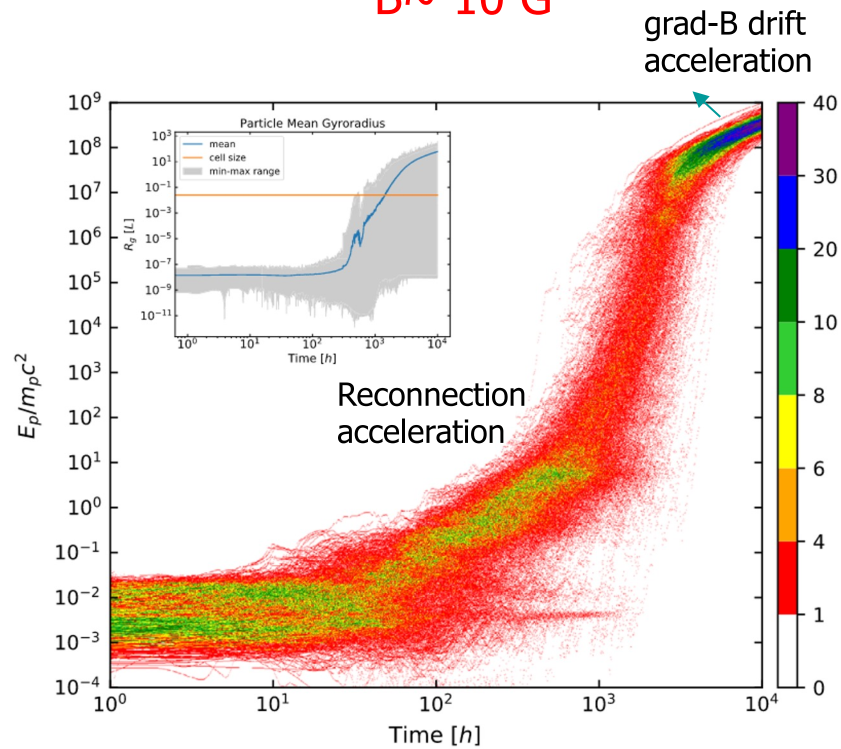
In situ acceleration of test particles by Magnetic Reconnection in Relativistic MHD Jets -> UHECRs

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



L= 3.6 10^{-5} pc

B~ 10 G



Exponential regime:

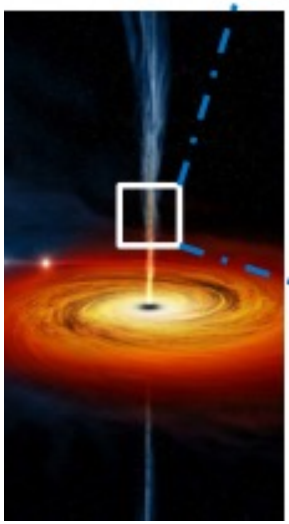
$R_{L,max}$ ~10^{-4} pc E_{18}/B_{10G} ~ distorted jet diameter~4 L

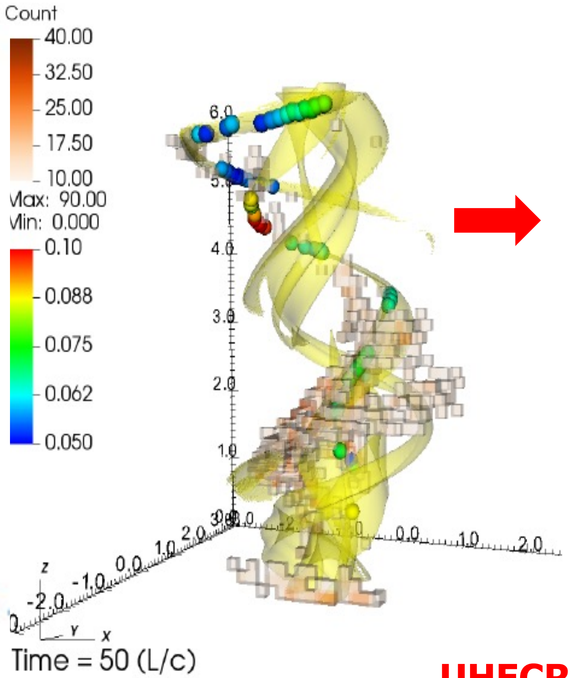
Medina-Torrejon, de Gouveia Dal Pino, Kadowaki+ ApJ 2021

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

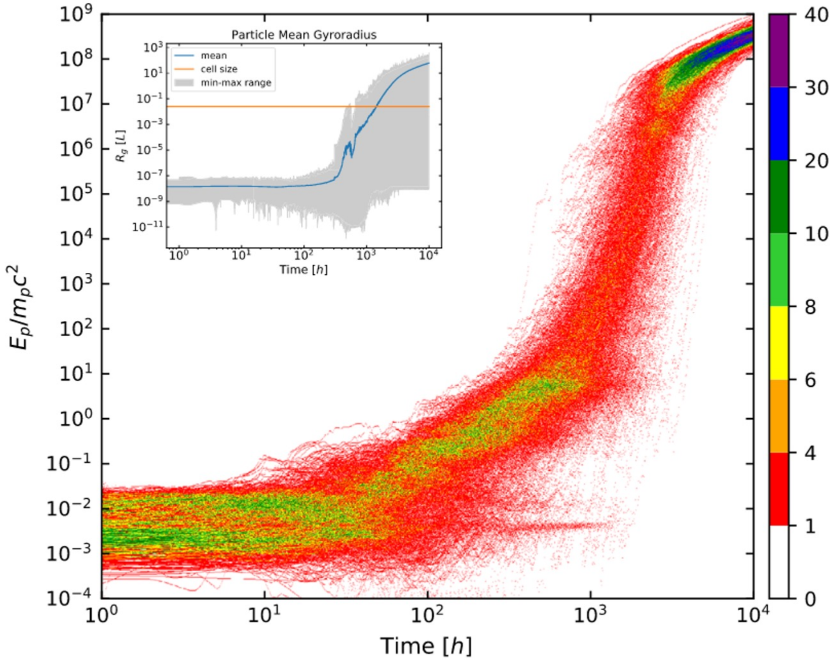
B~ 10 G

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





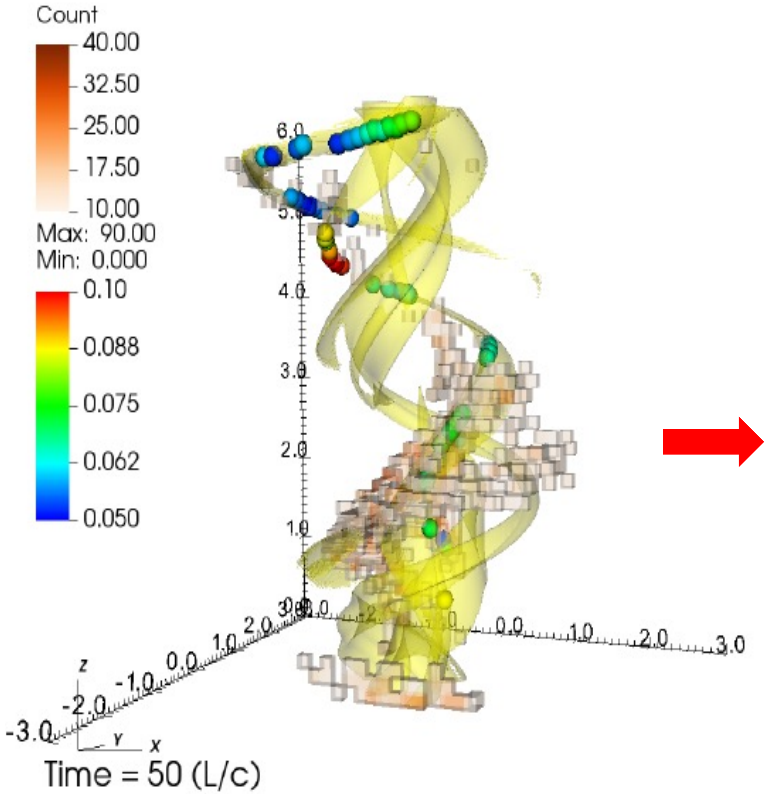
L= 3.6 10^{-5} pc

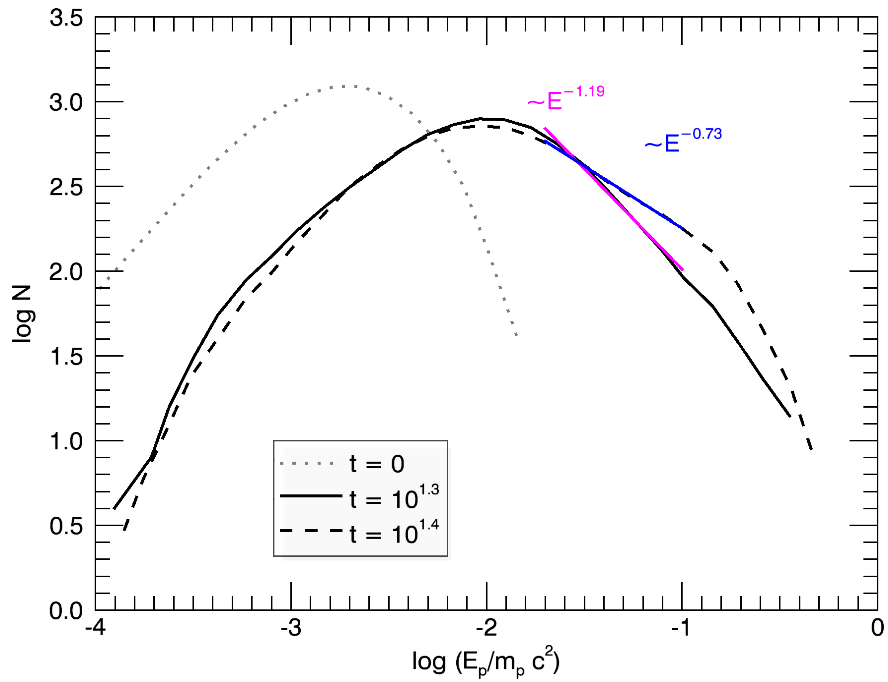


UHECRs: accelerated to 10^{18} - 10^{20} eV (B~ 0.1 -10 G)
-> more than enough to produce
TeV Gamma-Rays and Neutrinos !

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

Accelerated Particles Spectrum in the Relativistic MHD Jet





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

- 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

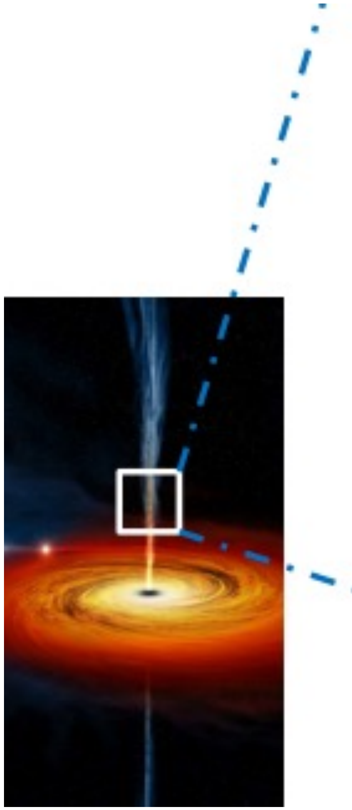
Early Particle Acceleration

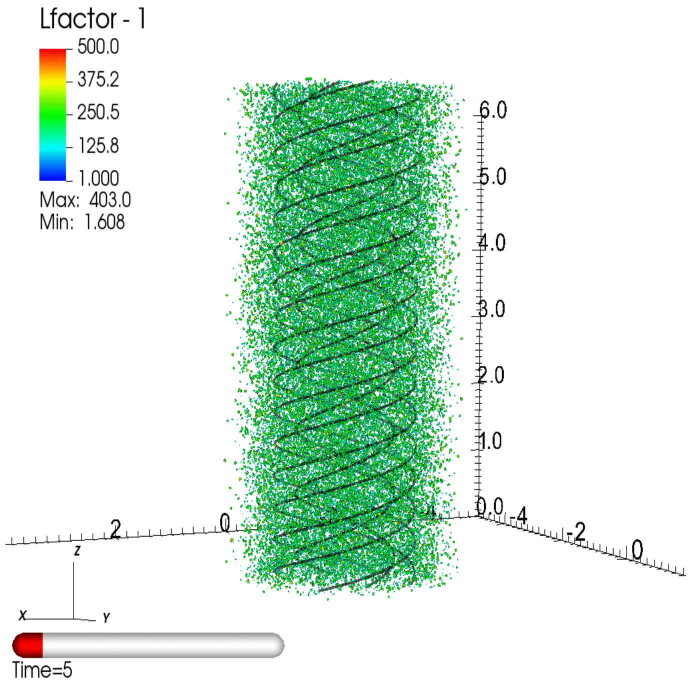
Transition from small to large scales

From PIC to MHD ?

Early Particle Acceleration using RMHD-PIC Simulations: $\delta B/\delta t$ 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
Magnetic-grad drift

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

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

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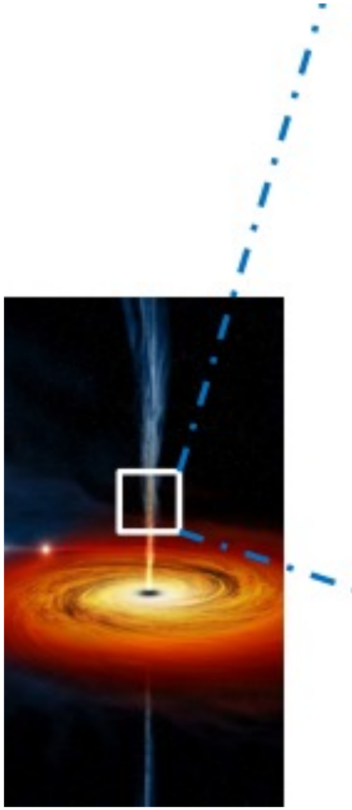

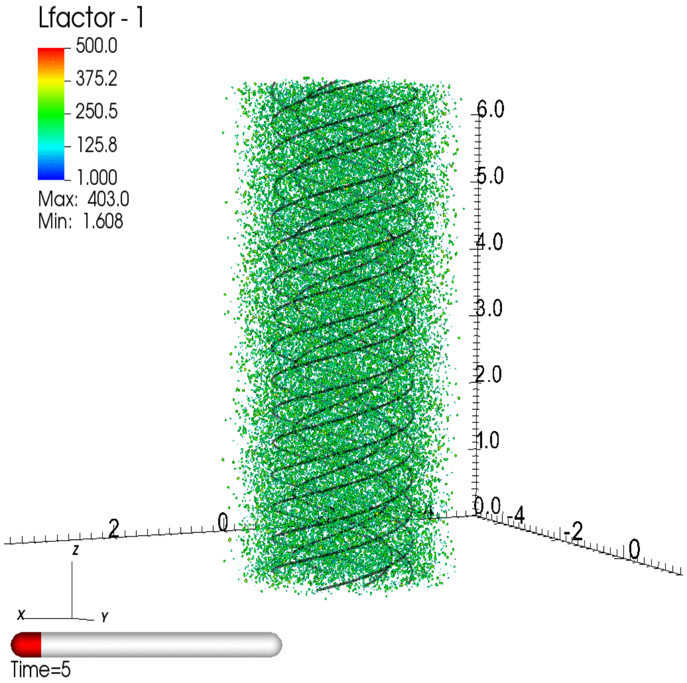

$\sigma = B^2/\gamma^2\rho h$ ~1

Curvature drift
Fermi
Magnetic-grad drift

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

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

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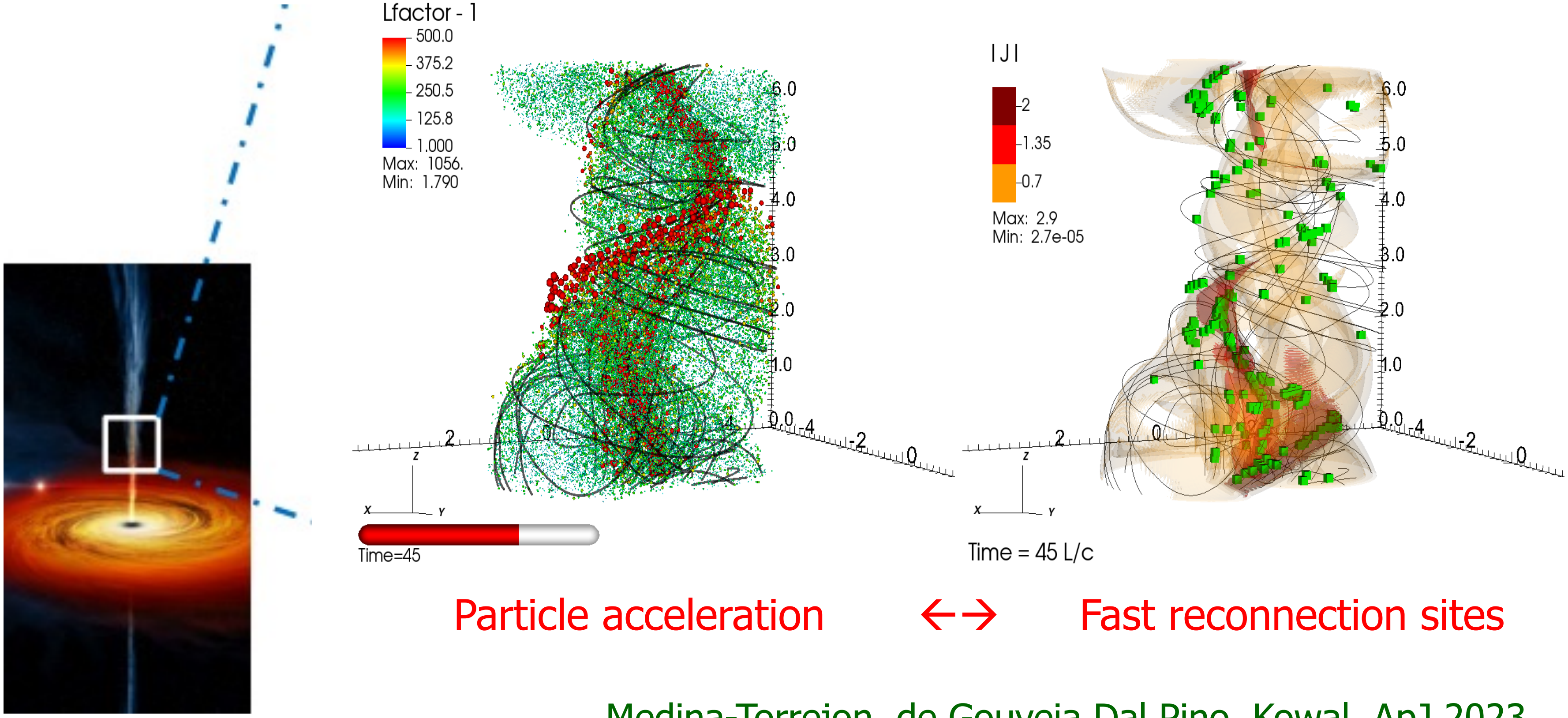
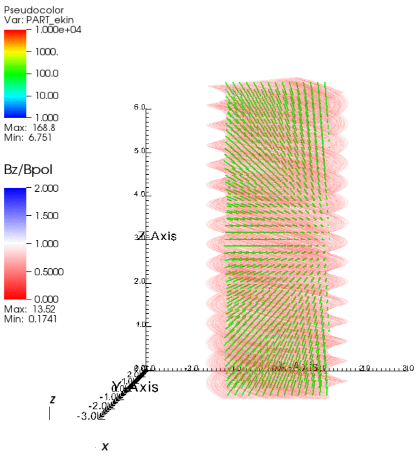
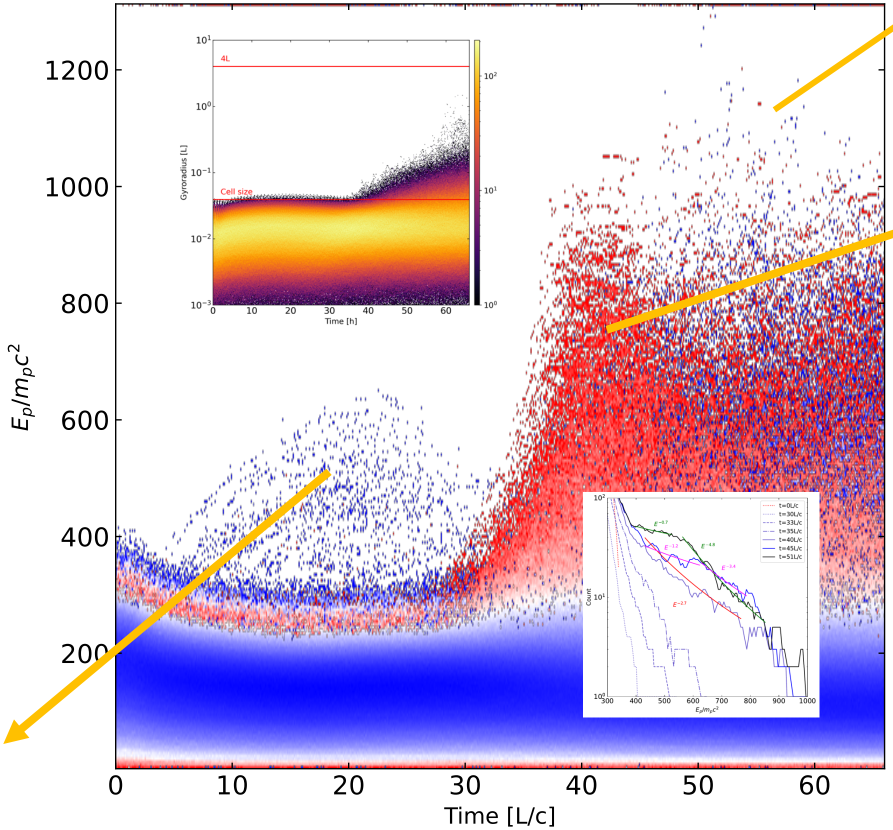


Particle acceleration ←→ Fast reconnection sites

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

Early Particle Acceleration using PIC-RMHD Simulations: $\delta B/\delta t$ effects





Magnetic-grad drift

Reconnection acceleration

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

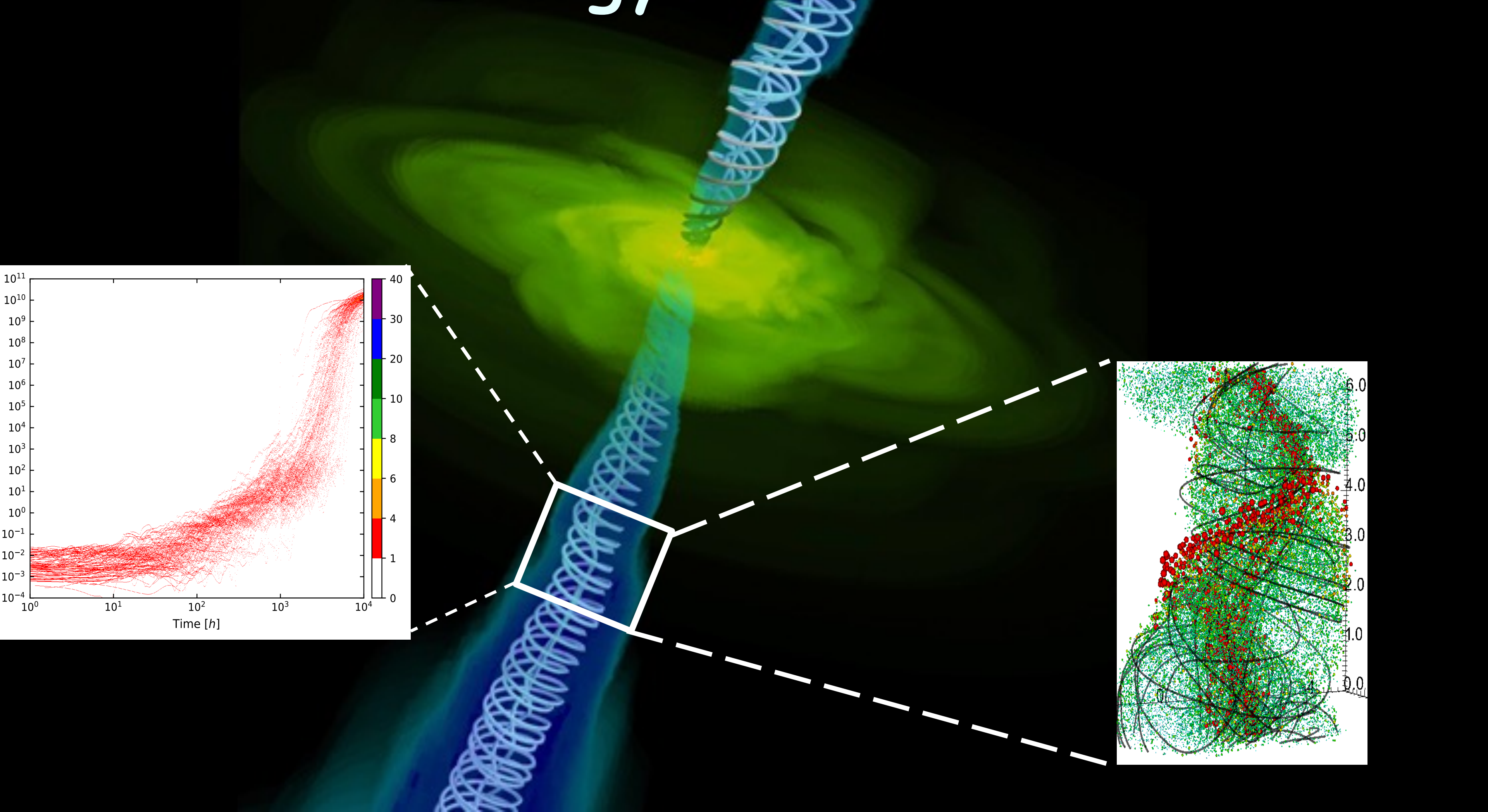
curvature dirift

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

–> $\delta B/\delta t$ effects: not important

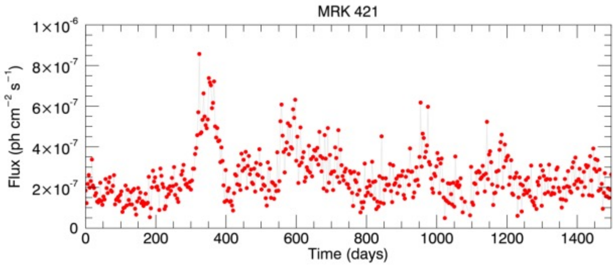
Medina-Torrejon, de Gouveia Dal Pino, Kowal, ApJ 2023

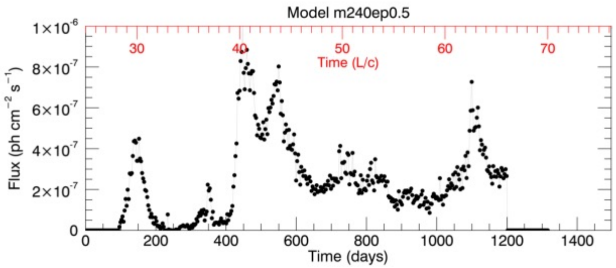
Applications to AGN Jet Very High Energy Phenomena



Fast Reconnection can explain observed gamma-ray flux & variability in Relativistic Jets

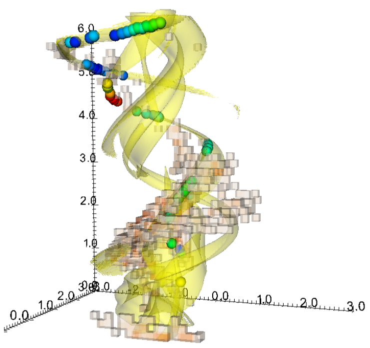
AGN Blazar: MRK421

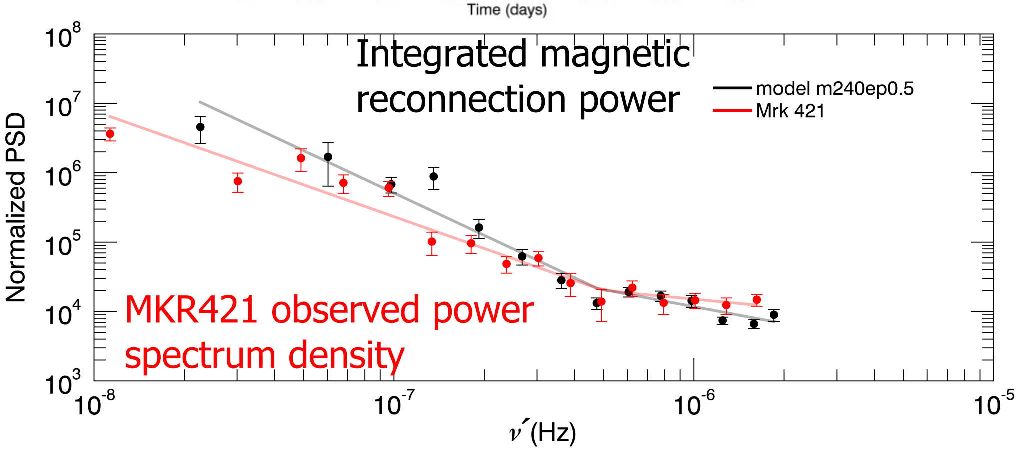




- **Observed gamma-ray flux** (FERMI)
  (Kushwaha et al. 2017)

- **Simulated**





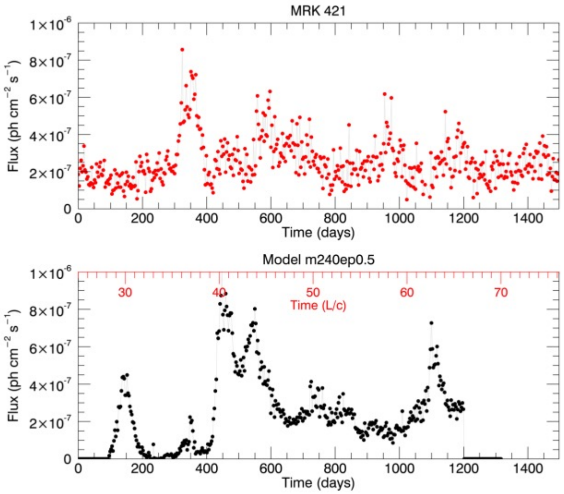
- **Simulated flux variability**
  - Magnetic field: 3.7 G
  - Doppler: $\delta \sim 5$
  - Height of the Jet: $\approx$ 0.1 pc
  - High density regions: $\approx 7\ 10^2\ cm^{-3}$
  - Photon energy: 0.1 - 300 GeV

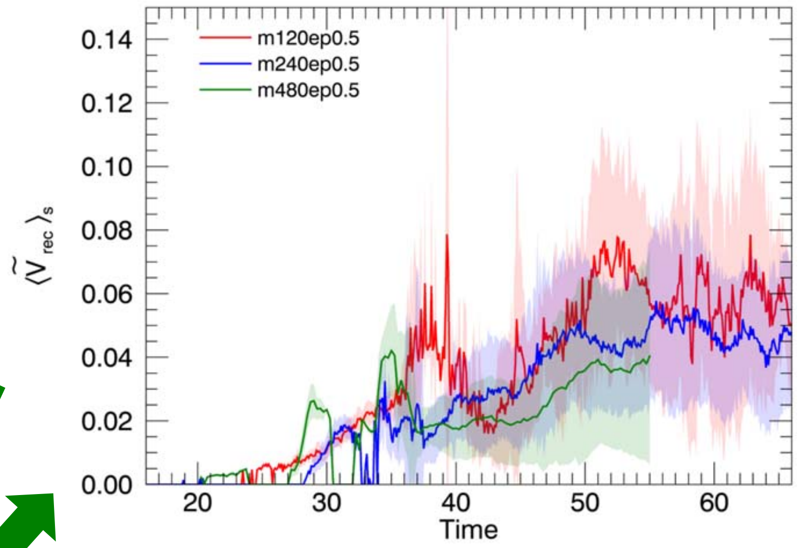
- Time variability and reconnection power compatible with observed blazar flaring

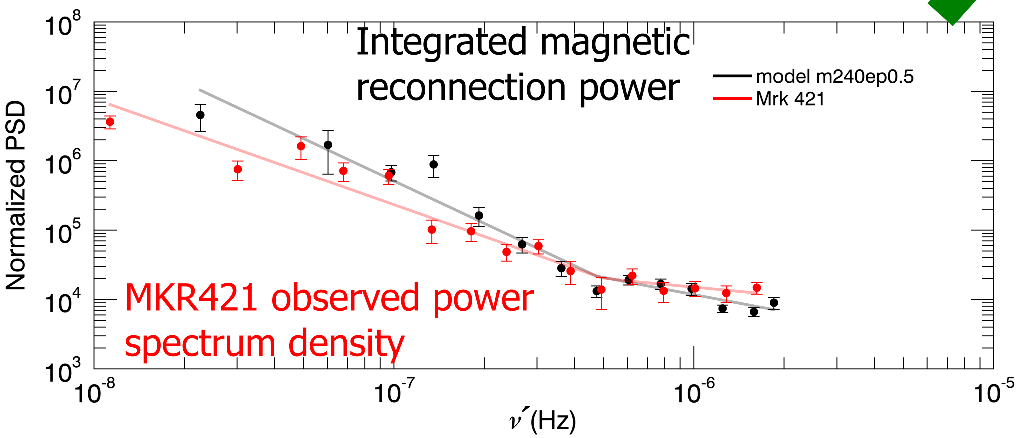
Kadowaki, de Gouveia Dal Pino, Medina-Torrejon+, ApJ 2021

Fast Reconnection can explain observed gamma-ray flux & variability in Relativistic Jets

AGN Blazar: MRK421





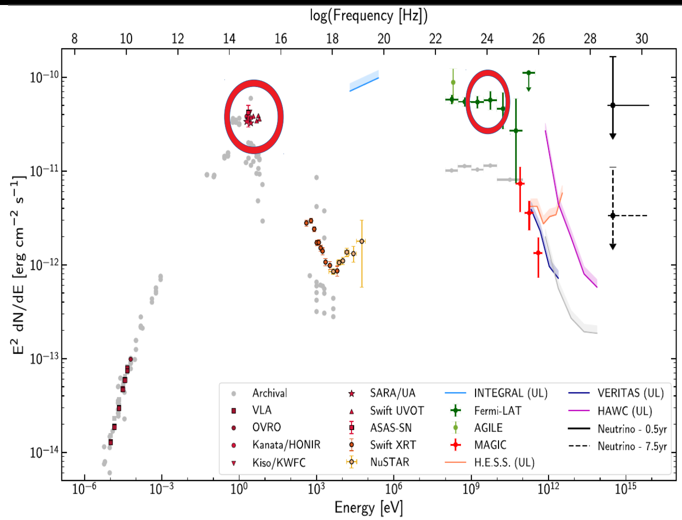


- **Simulated flux variability**
  - Magnetic field: 3.7 G
  - Doppler: δ=5
  - Height of the Jet: ≈ 0.1 pc
  - High density regions: ≈ 7 10^2 cm^{-3}
  - Photon energy: 0.1 - 300 GeV

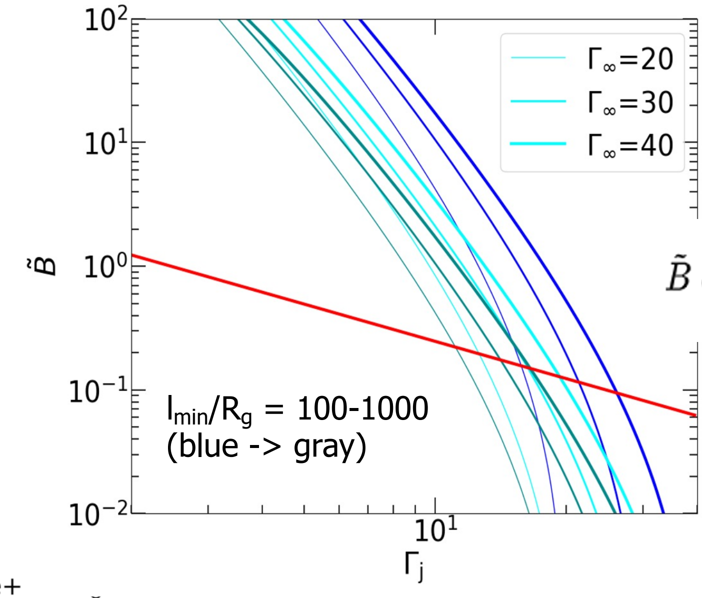
- Time variability and reconnection power compatible with observed blazar flaring

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

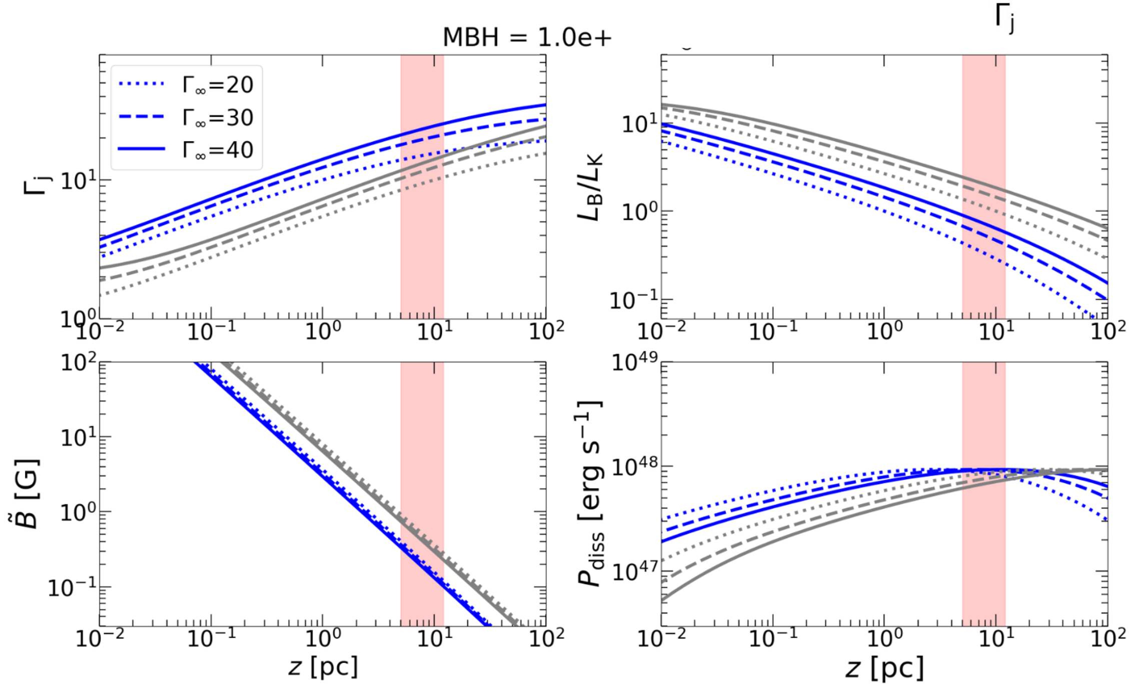
Lepto-Hadronic Reconnection Acceleration for Relativistic Jets - VHE Losses



Blazar TXS 0506+056 (Aartsen et al. 2018, Science)



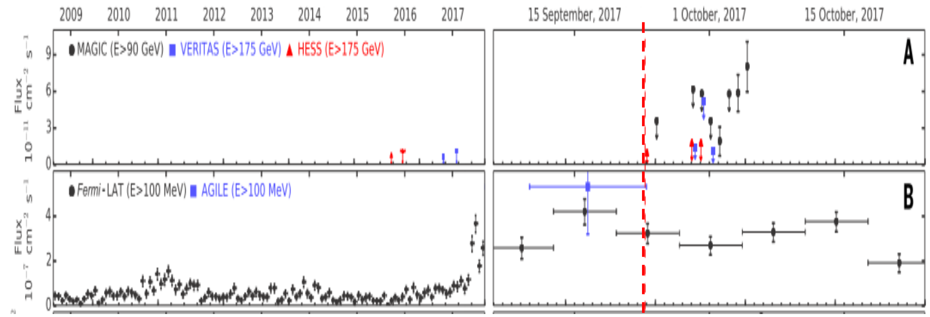
$$\tilde{B} \sim \frac{E_{\rm syn}^2}{E_{\rm SSC}} \frac{4\pi m_e c}{3eh} \frac{1+z}{\Gamma_{\rm j}}$$



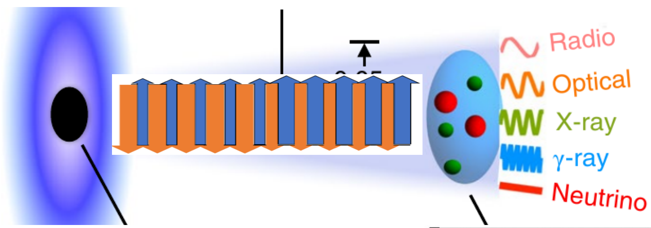
(Giannios & Uzdensky 2019)

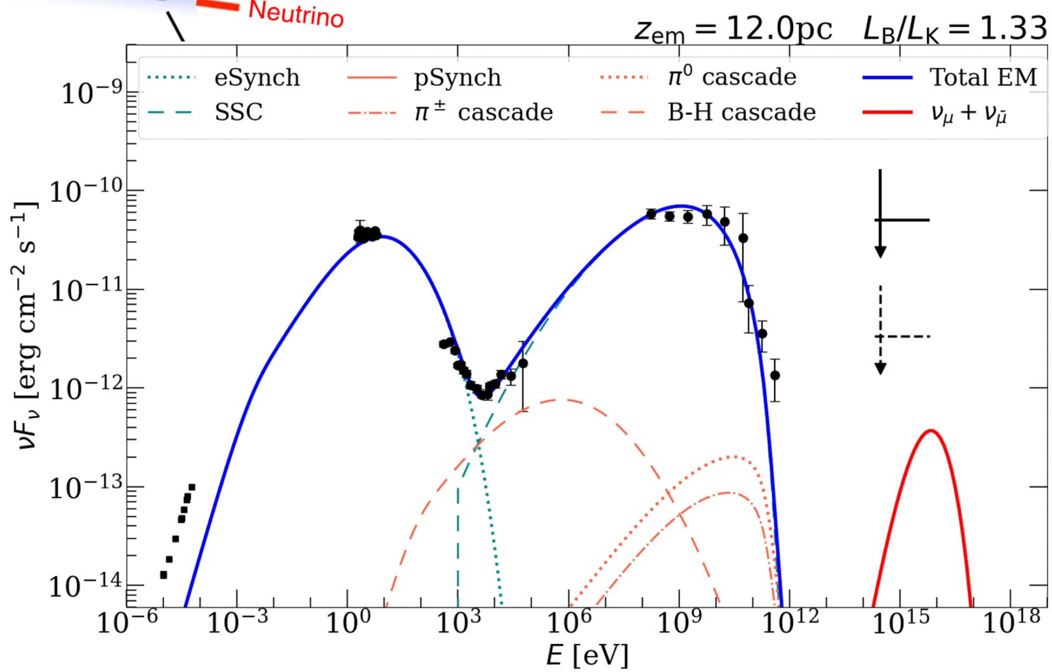
Emission Model based on Reconnection Acceleration for Relativistic Jet

Blazar TXS 0506+056



(Aartsen et al. Science 2018)



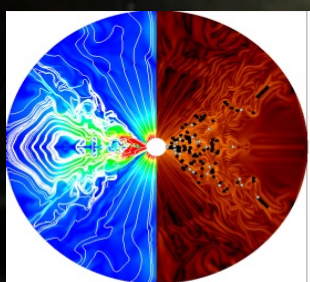


model predicts VHE γ-rays appearing later than neutrino emission, as observed!

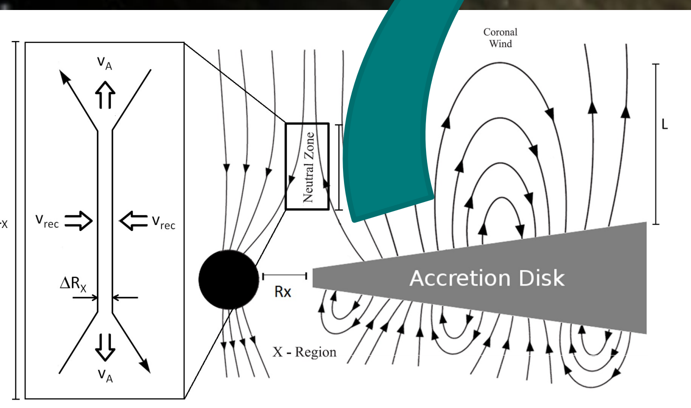
Rodriguez-Ramirez, de Gouveia Dal Pino et al. (2023, in prep.)

CR Reconnection Acceleration also possible in the core region of BHs

General Relativistic MHD + test particles

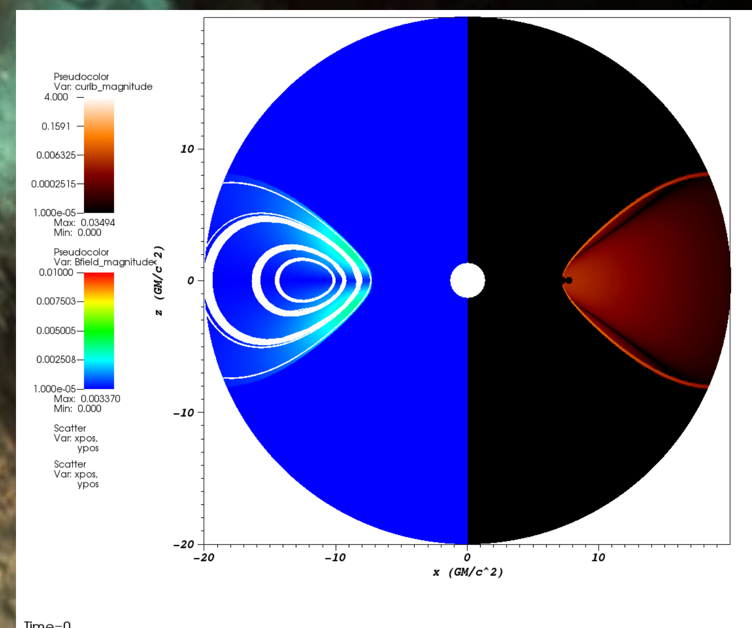


CR Reconnection Acceleration in the accretion flow of BH



de Gouveia Dal Pino & Lazarian, A&A 2005
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

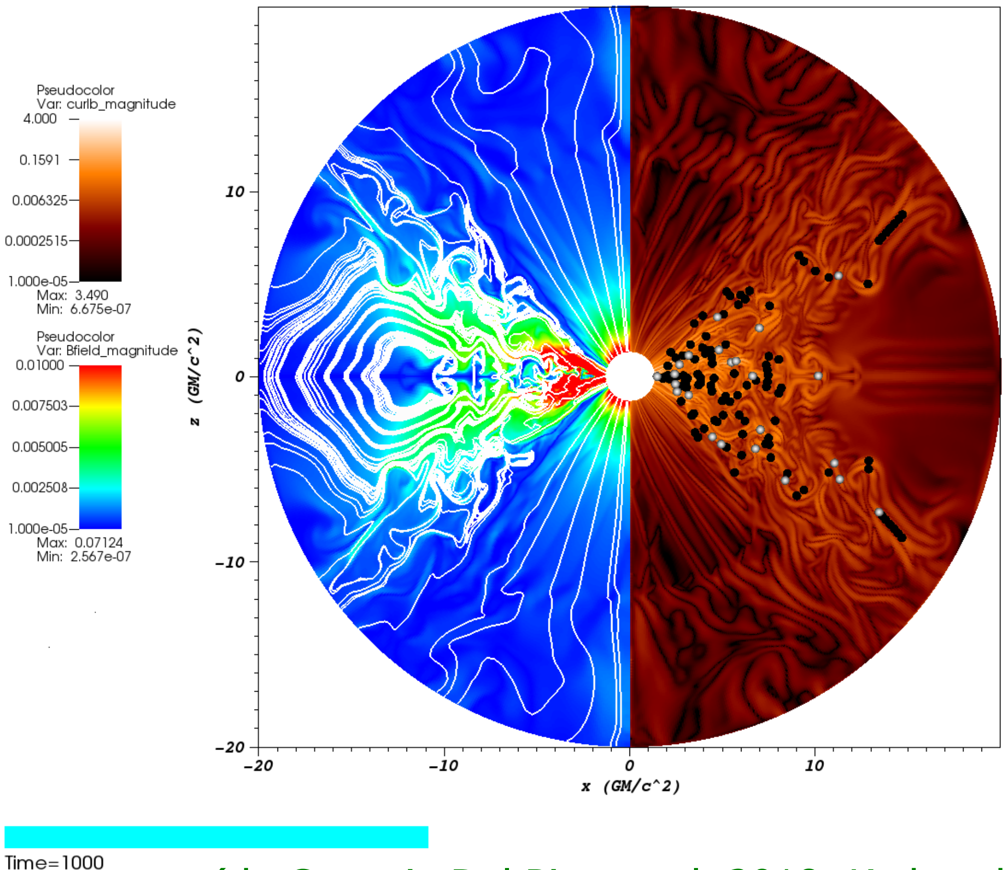
Athena++ code (Stone et al. 2020)

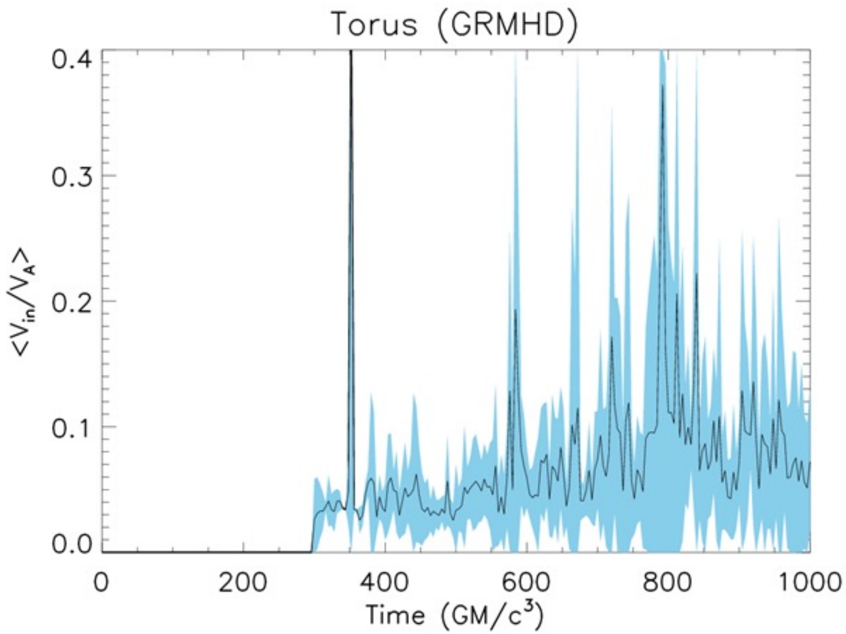


GRMHD simulations of accretion flows around BHs reconnection driven by magneto-rotational turbulence

(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



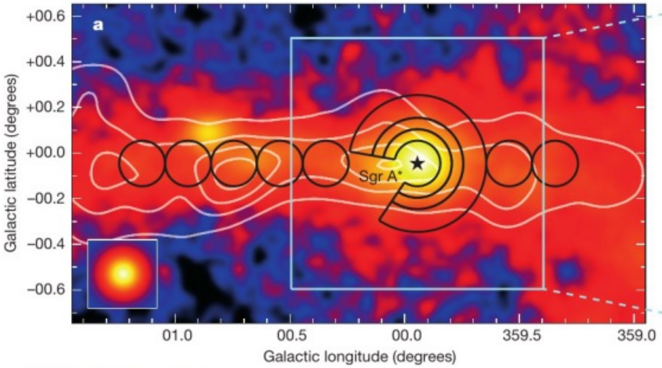


- Average reconnection velocities $<V_{rec}> \sim 0.05\ V_A$

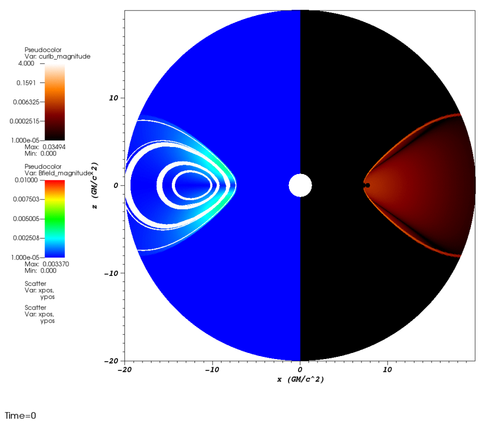
(de Gouveia Dal Pino et al. 2018; Kadowaki et al. 2019)

(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

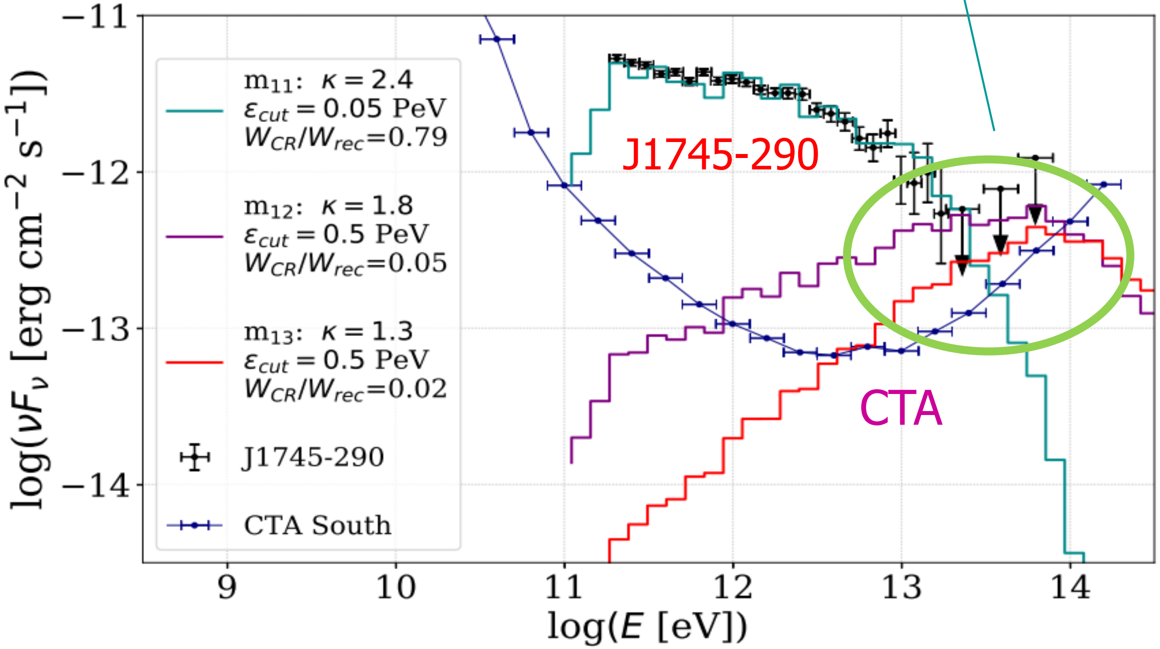


H.E.S.S. Nature 2016



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 (+ drift): $N(E) \sim E^{-1.2}$
- ✓ Magnetic reconnection rates in MHD, RMHD and GRMHD simulations of turbulent systems $\langle v_{rec} \rangle \sim 0.05$ (compatible with Lazarian & Vishniac 1999)
- ✓ Reconnection acceleration of protons GLOBAL RMHD simulations of magnetically dominated Blazar jets can produce UHECRs up to ~ 10^{18} - 10^{20} eV (for B ~ 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? (signatures of polarization?)