Particle Acceleration by Reconnection and VHE emission

Around Black Holes and Relativistic Jets

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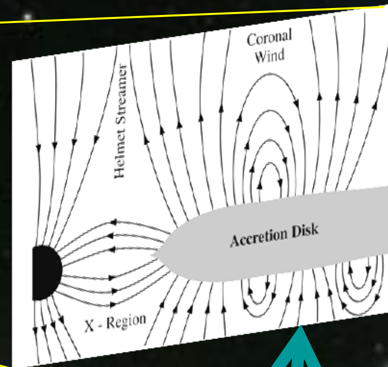
Y. Mizuno,
C. Singh

Deciphering the Violent Universe, Playa del Carmen, December 11-15, 2017

Reconnection beyond Solar System

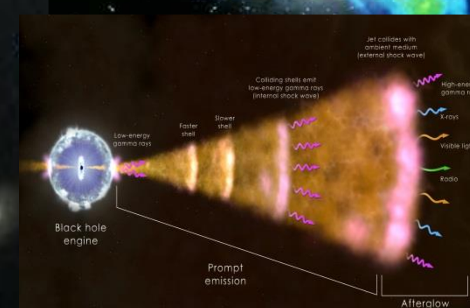


Accretion disk coronae

Stellar Xray Flares

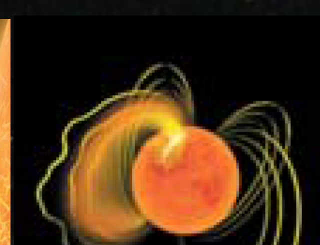
Star Formation and ISM

AGN & GRB Jets



Pulsars

Accreting NS and SGRs



This talk

MAGNETIC RECONNECTION an alternative:

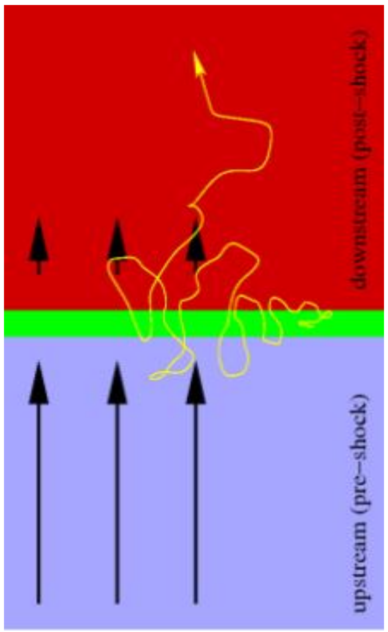
- Powerful relativistic particle acceleration

- Efficient conversion of magnetic energy -> into kinetic energy

- May explain very-high energy emission specially in BH sources and relativistic jets in magnetically dominated regions solving current puzzles

How particles are accelerated in reconnection sites?

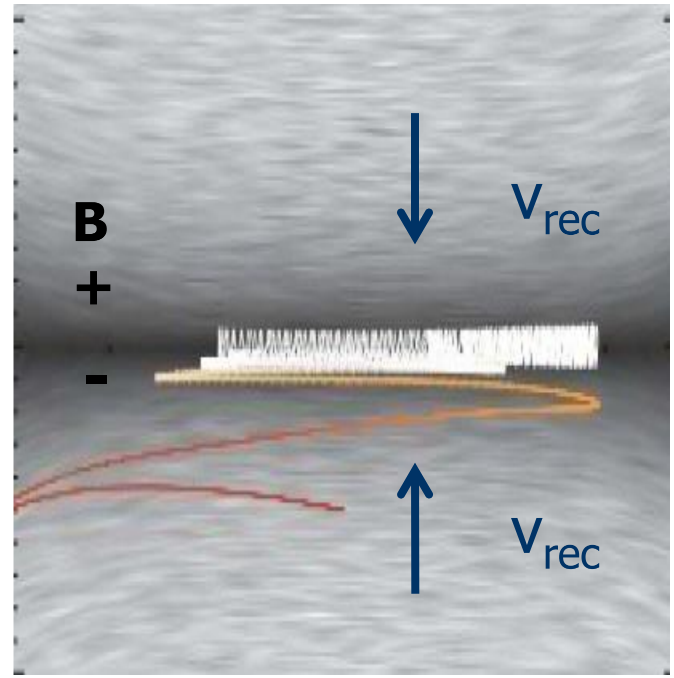
Shock Acceleration



1st-order Fermi (e.g.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, A&A 2005):

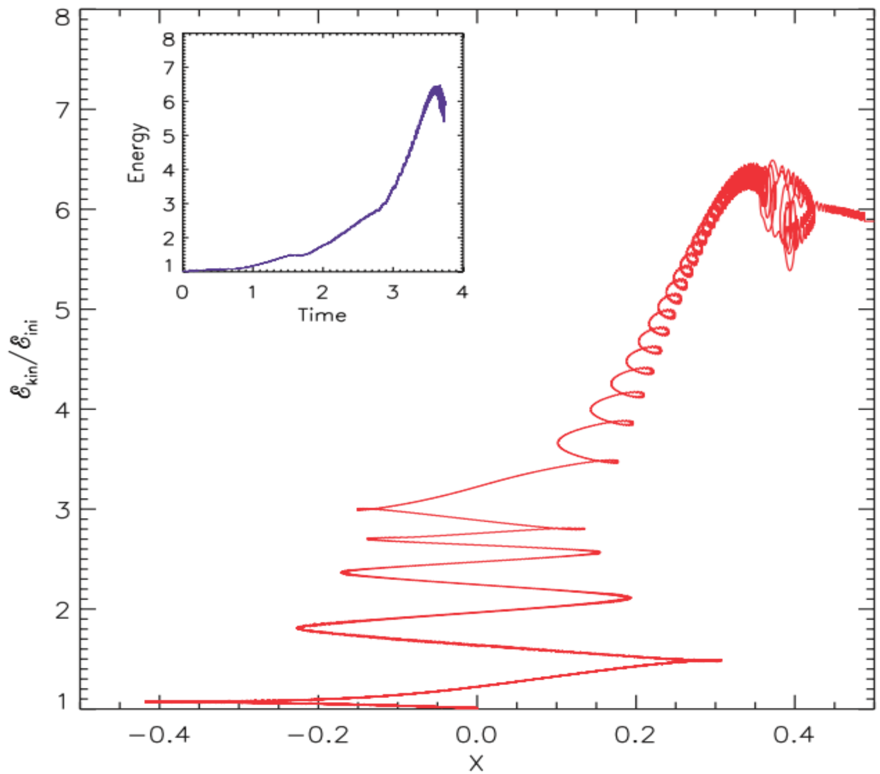
particles bounce back and forth between 2 converging magnetic flows

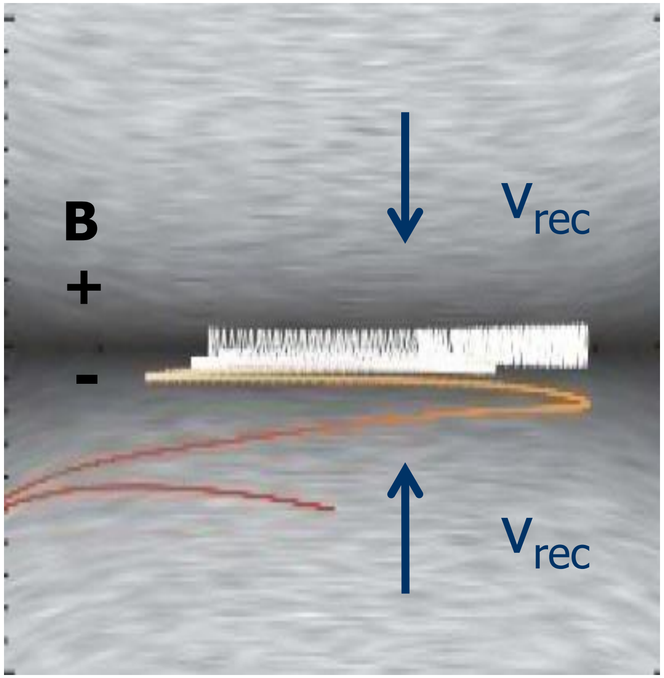
$$\langle \Delta E/E \rangle \sim v_{rec}/c$$

Particles are accelerated in reconnection sites in 1st-order Fermi

Reconnection Acceleration

Kowal's talk



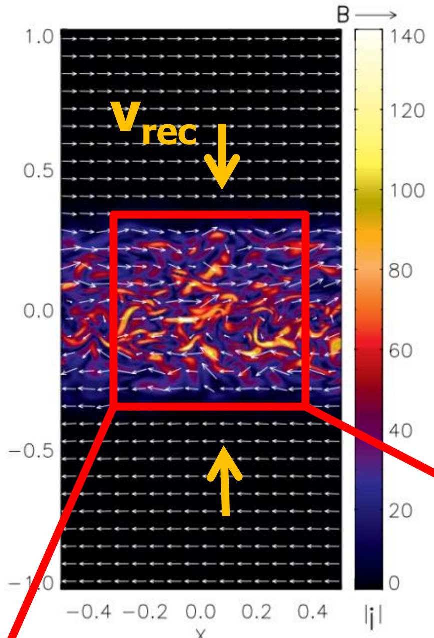


(Kowal, de Gouveia Dal Pino & Lazarian, ApJ 2011)

1st-order Fermi (de Gouveia Dal Pino & Lazarian, A&A 2005):
particles bounce back and forth between 2 converging magnetic flows

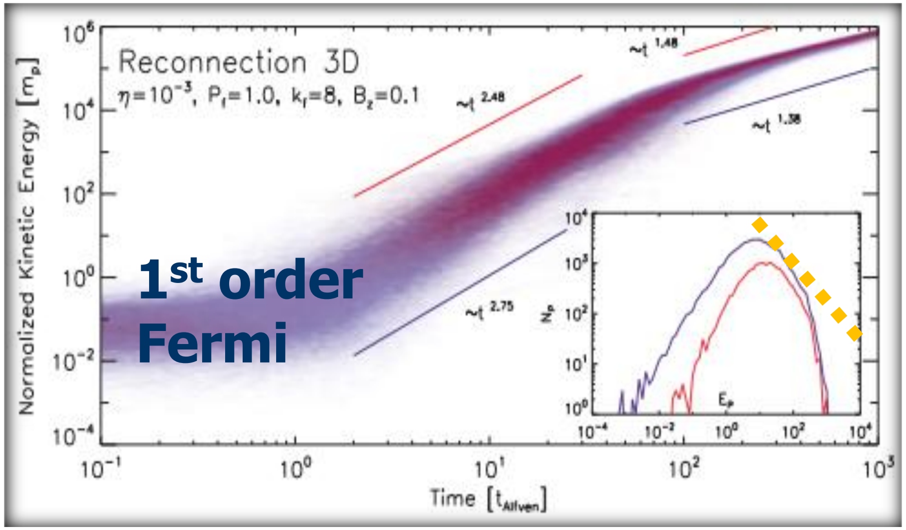
$\langle \Delta E/E \rangle \sim v_{rec}/c$

1st order Fermi Reconnection Acceleration: successful numerical testing in 3D MHD

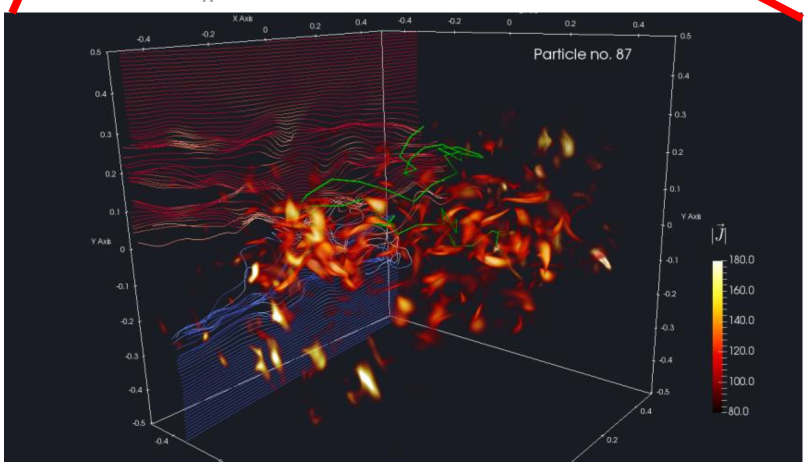


10,000 test particles

Injected in turbulent current sheet

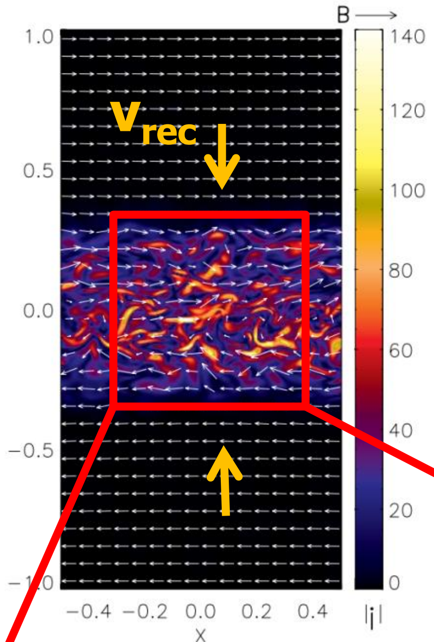


Kowal, de Gouveia Dal Pino, Lazarian, PRL 2012



del Valle, de Gouveia Dal Pino, Kowal MNRAS 2016

1st order Fermi Reconnection Acceleration: successful numerical testing in 3D MHD



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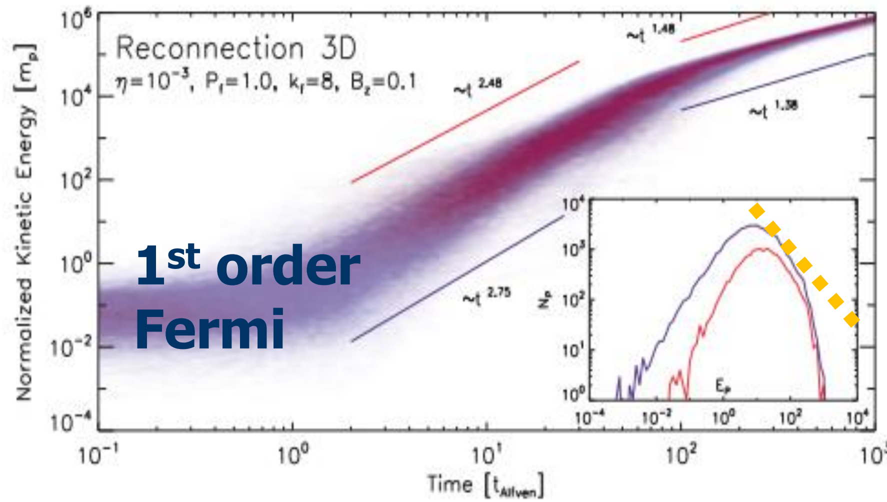
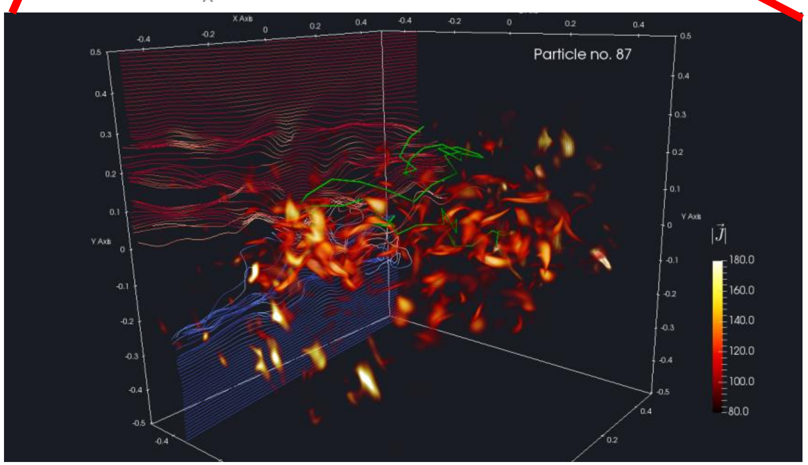
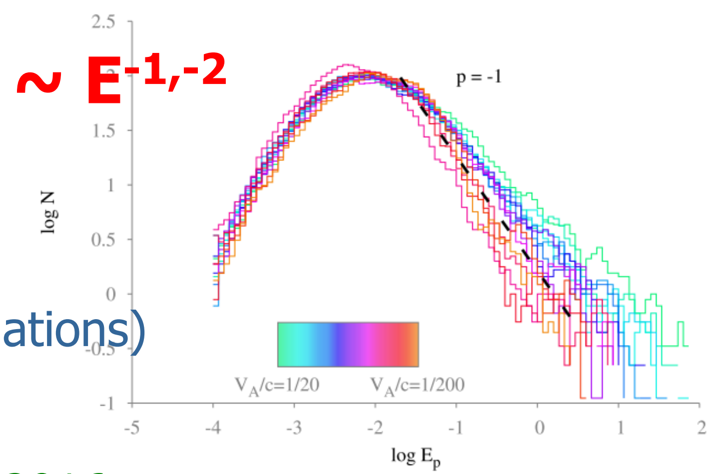


Kowal, de Gouveia Dal Pino, Lazarian, PRL 2012



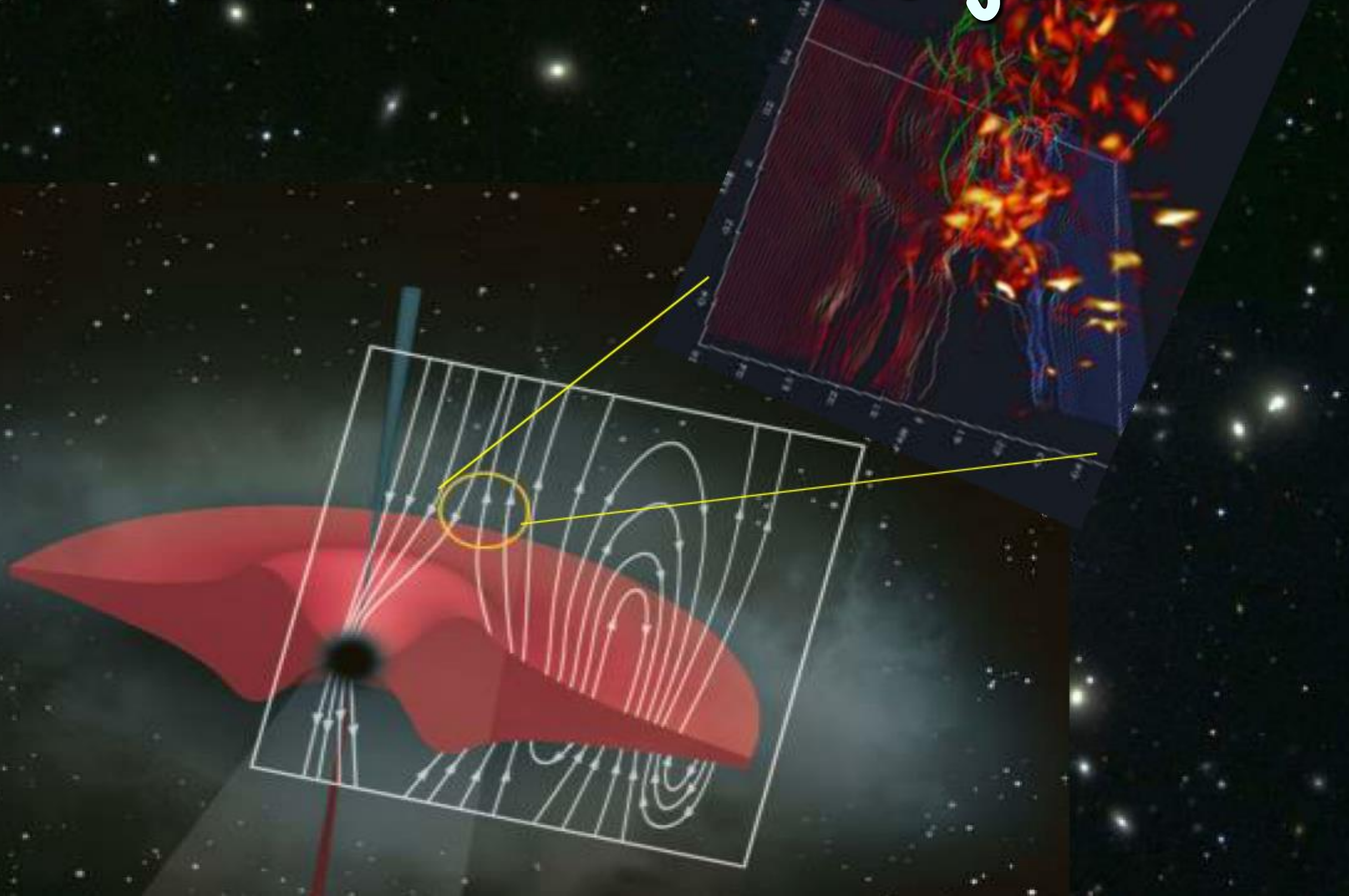
$N(E) \sim E^{-1,-2}$

(~PIC simulations)

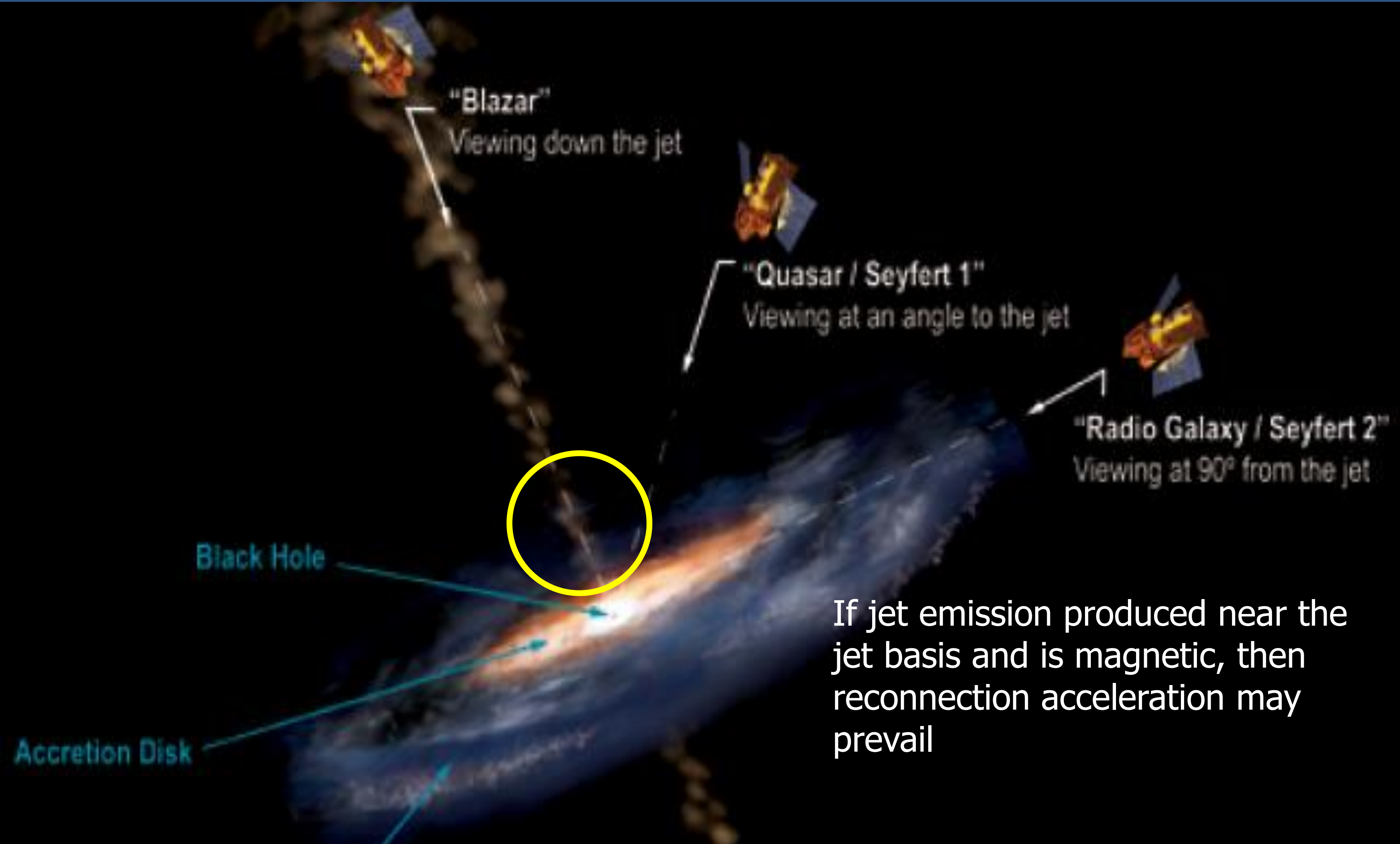


del Valle, de Gouveia Dal Pino, Kowal MNRAS 2016

Implication to BHs and relativistic jets



Reconnection Acceleration *along* Relativistic Jets



If jet emission produced near the jet basis and is magnetic, then reconnection acceleration may prevail

Very-rapid TeV Flares in *Blazar Jets* hard to explain with standard acceleration

- **Variation timescale:**

  t_v ~200 s < r_s/c ~ $3M_9$ hour

- For TeV emission to avoid pair creation $\gamma_{em}>50$ (Begelman, Fabian & Rees 2008)

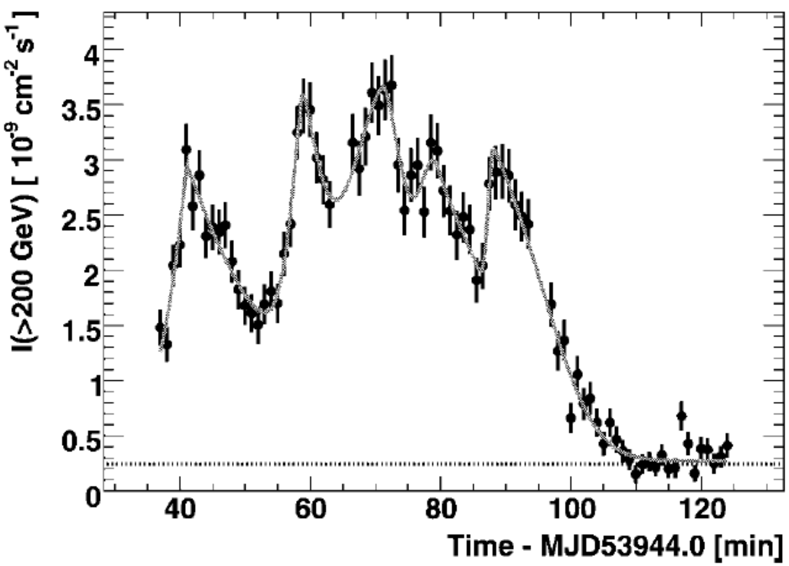
- But bulk jet γ ~ 5-10

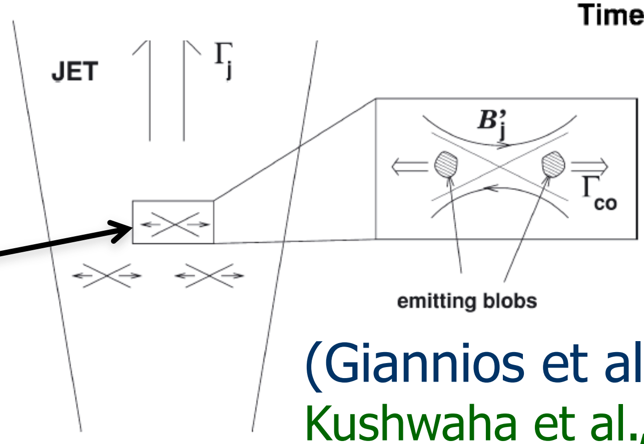
- **Emitter: compact** and/or extremely fast

- A proposed Model: **Reconnection** inside the jet

PKS2155-304 (Aharonian et al. 2007)

See also Mrk501, PKS1222+21, PKS1830-211

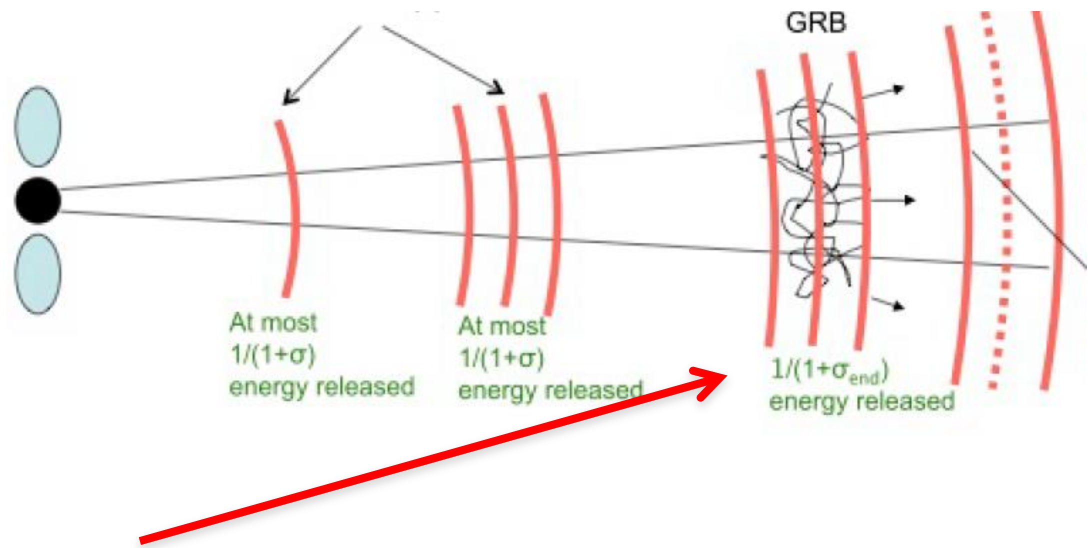




(Giannios et al. 2009; Kushwaha et al., MNRAS 2017)

GRB jet prompt gamma-ray emission may require reconnection acceleration too

Internal collision-induced magnetic reconnection turbulent model (ICMART) **(Zhang & Yan 2011):**



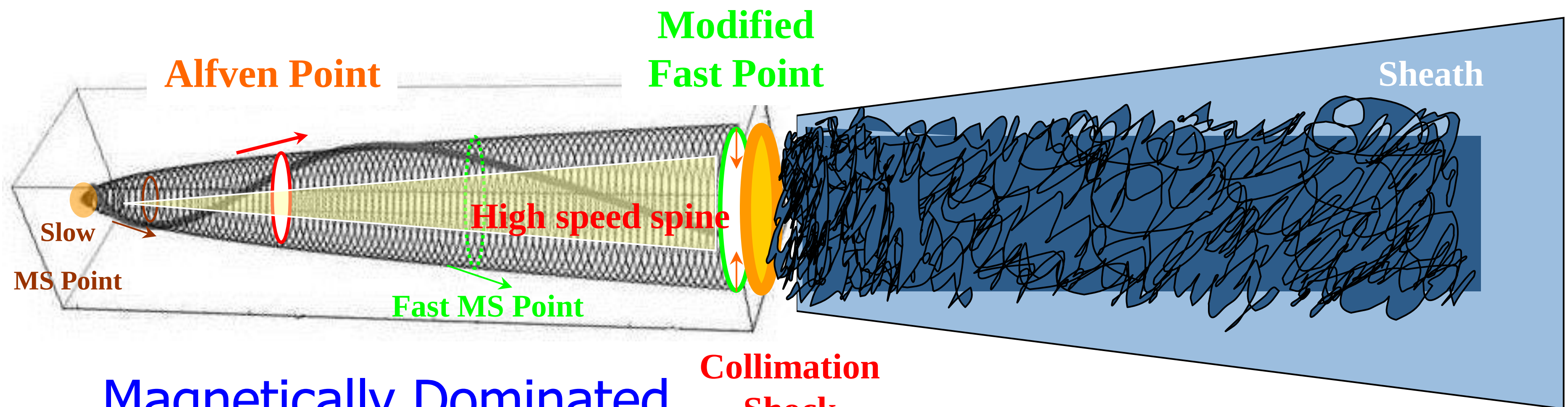
- GRB prompt emission: turbulence, magnetic reconnection, and particle acceleration via internal collisions of multiple launched parcels

(See also Giannios 2008; McKinney & Uzdensky 2012)

Inner Regions of AGN & GRB Jets: Magnetically dominated

Modified from D. Meier &
Y. Mizuno (courtesy)

~10 – $10^{2.5\pm0.5}$ r_S



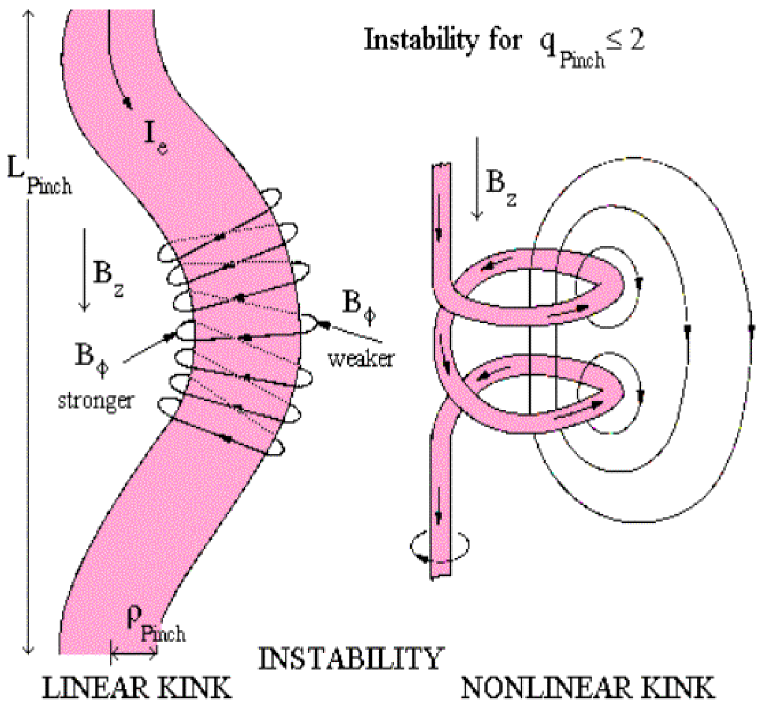
Magnetically Dominated

Kinetic Energy Flux Dominated

Current Driven Kink Instability

(Mizuno et al. 2012)

CD Kink Instability drives reconnection



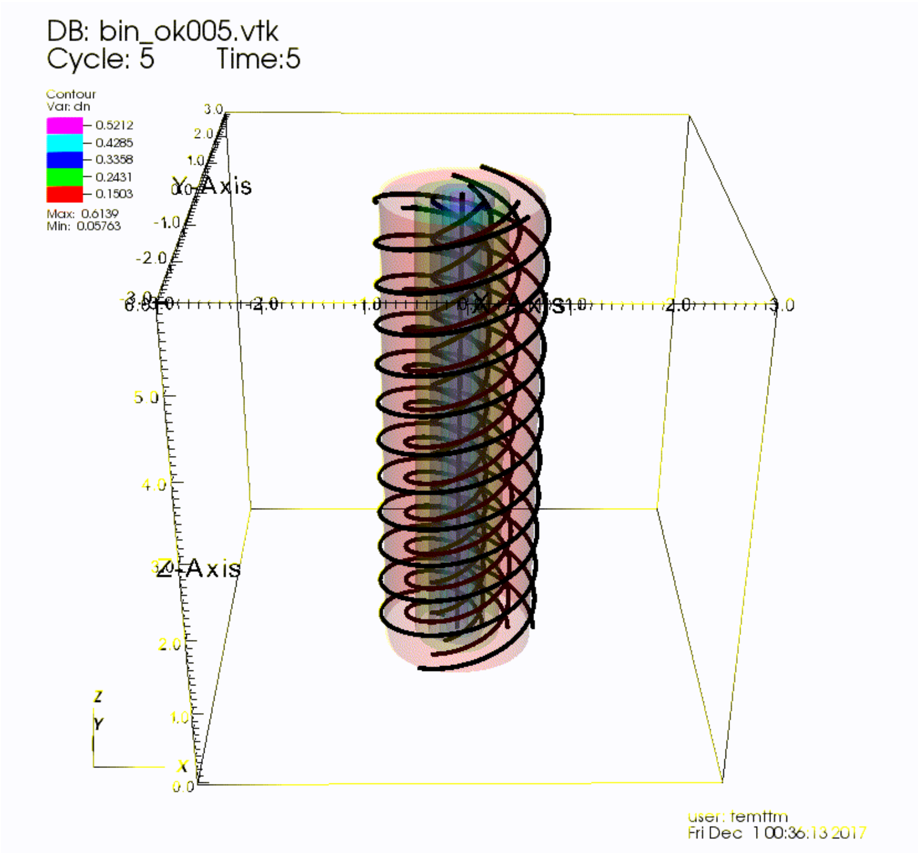
Schematic picture of CD kink instability

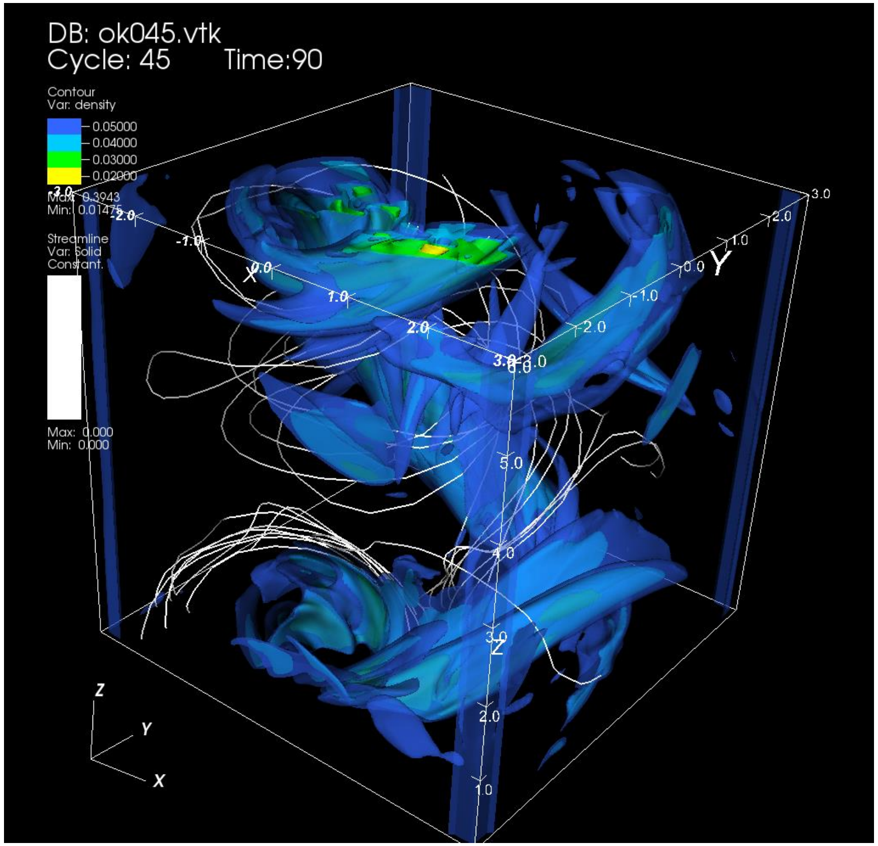
- Well-known instability in laboratory plasma (TOKAMAK) and astrophysical plasmas (Sun, jets, pulsars)
- In configurations with strong toroidal magnetic fields, current-driven (CD) kink mode (m=1) is unstable

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

- This instability excites large-scale helical motions that can strongly distort or even disrupt the system
- Distorted magnetic field structure may trigger **magnetic reconnection**

MHD Simulations of Reconnection driven by Kink in Magnetically Dominated Relativistic Jets (GRBs & AGNs)





Singh, Mizuno, de Gouveia Dal Pino, ApJ 2016

Torrejon, de Gouveia Dal Pino, Mizuno, Kadowaki, Singh in prep.

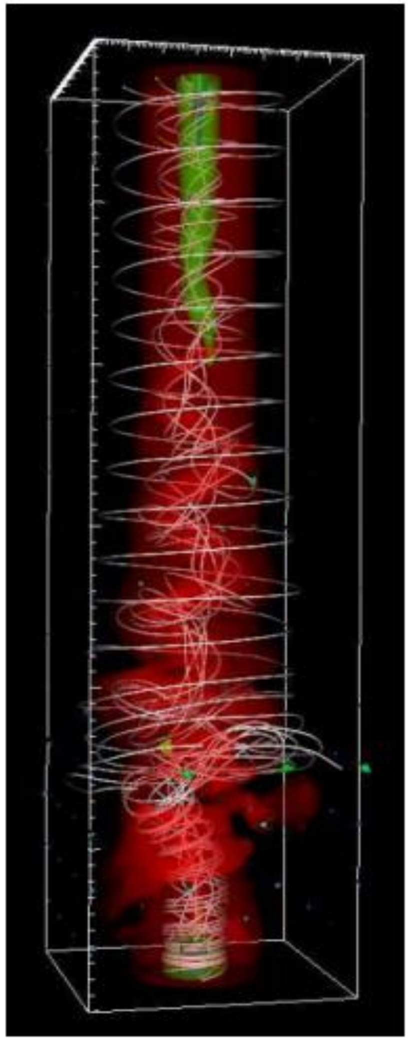
MHD Simulations of Reconnection driven by Kink in Magnetically Dominated Relativistic Jets (GRBs & AGNs)

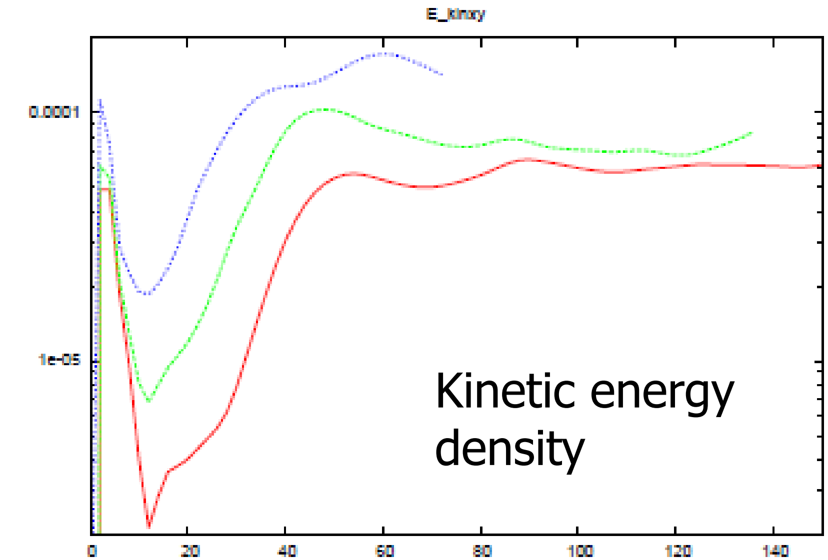
- Precession perturbation allows growth of CD kink instability with helical density distortion.

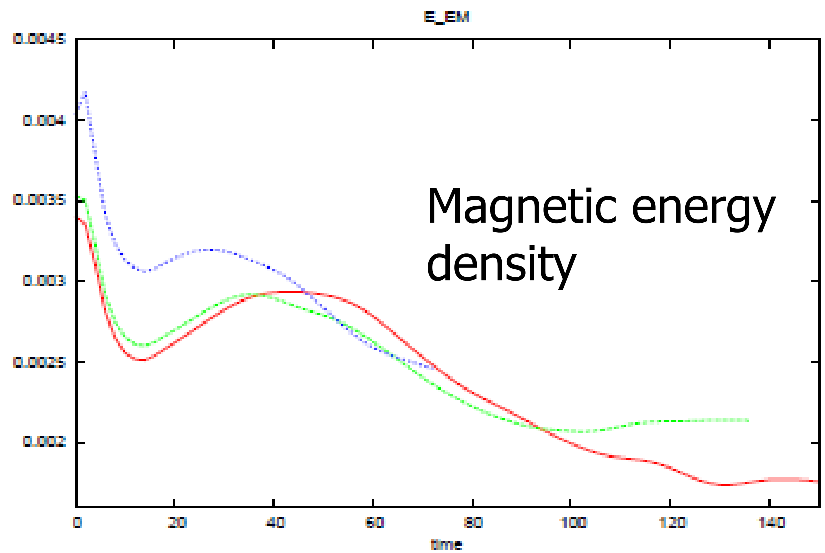
- Helical kink advected with the flow with continuous growth of kink amplitude in non-linear phase.

- Helical structure is disrupted

- ***Magnetic energy converted into kinetic***

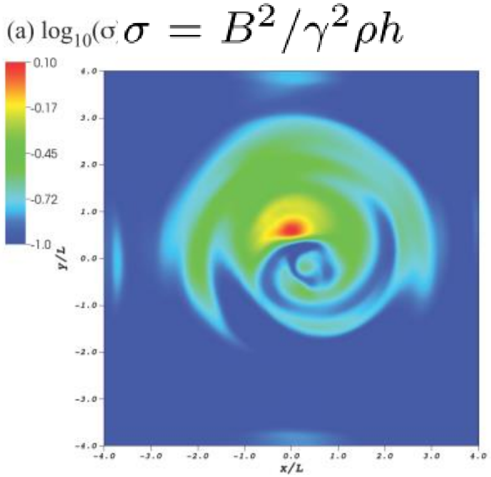




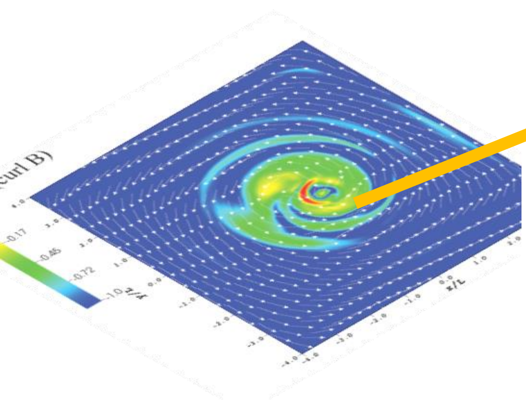


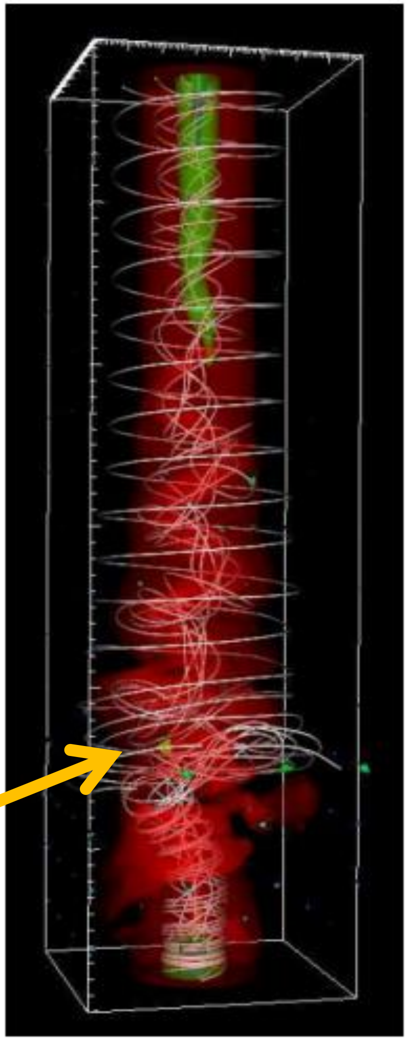
Singh, Mizuno, de Gouveia Dal Pino, ApJ 2016

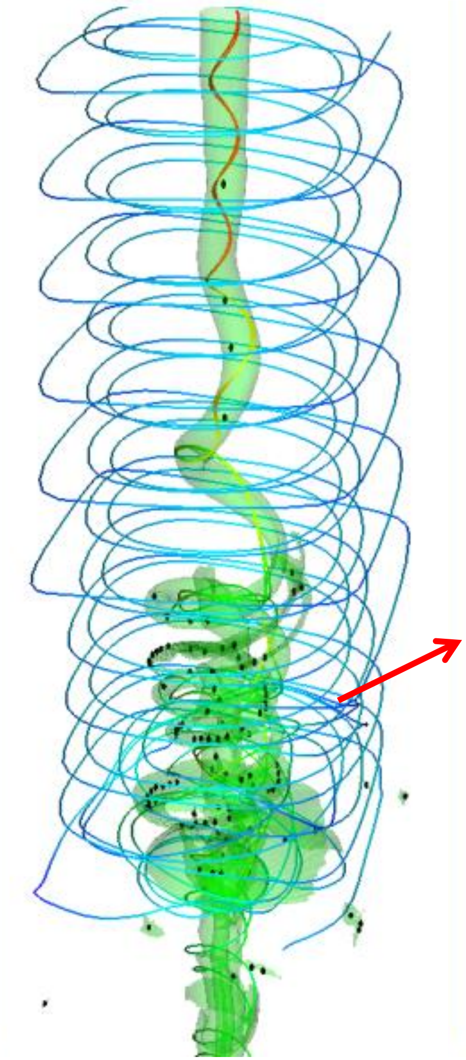
Reconnection driven by Kink in Magnetically Dominated Relativistic Jets (GRBs & AGNs)



$v_{rec} \sim 0.05\ v_A$







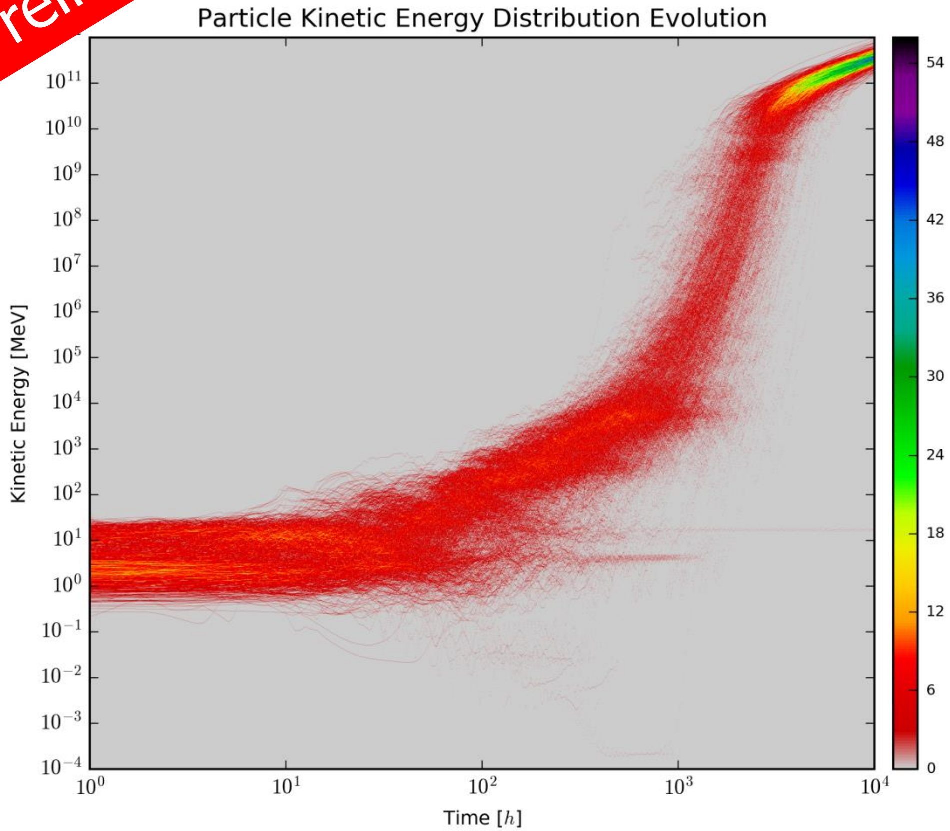
curl B = max

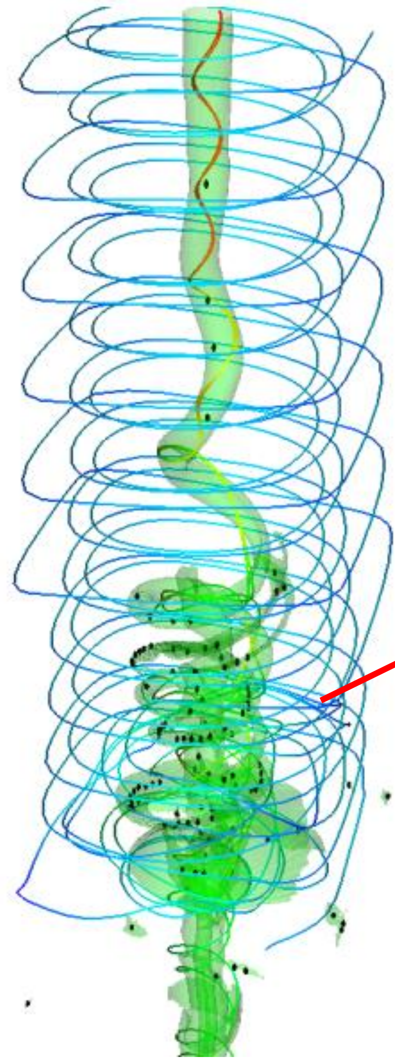
Sites for magnetic reconnection, dissipation, **particle acceleration** (and gamma-rays)!

Singh, Mizuno, de Gouveia Dal Pino, ApJ 2016

In situ Particle Acceleration by Reconnection in Relativistic Jets

Preliminary





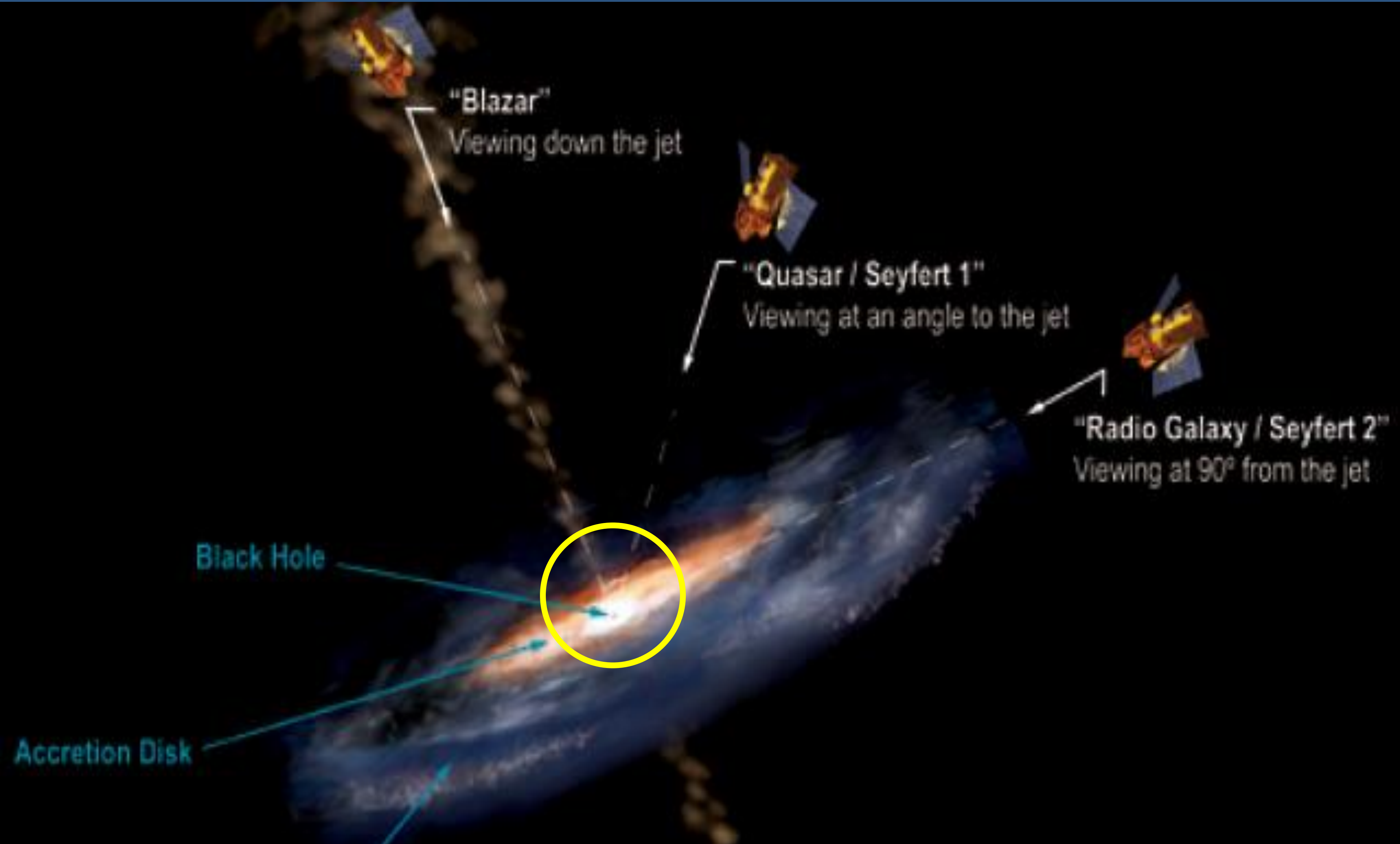
Injected 1000-10,000 test particles accelerated in current sheets:

10^4 MeV -> 10^{11} MeV very fast

-> may produce Gamma-rays!

Medina-Torrejon, de Gouveia Dal Pino, Kowal, Mizuno, Kadowaki, Singh, in prep.

Reconnection Acceleration *in the core region*



Few Low Luminous AGNs: gamma-ray emitters

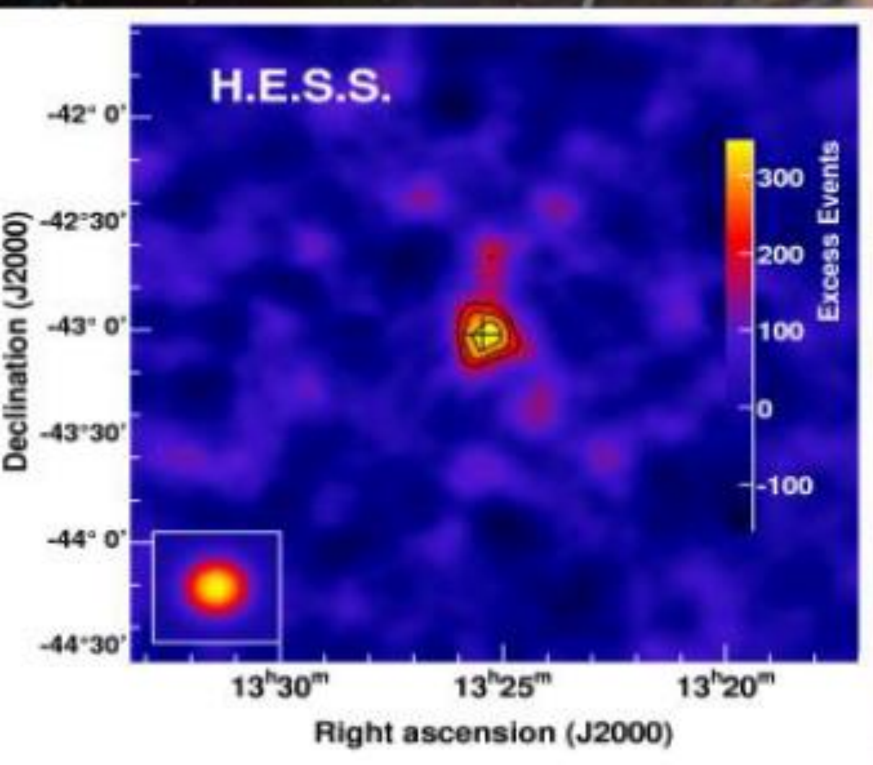
Ex. CenA

- ✓ *Is emission from core or jet ?*
- ✓ **Rapid variability emission:**
  size ~ c t $_{var}$~100 r$_s$

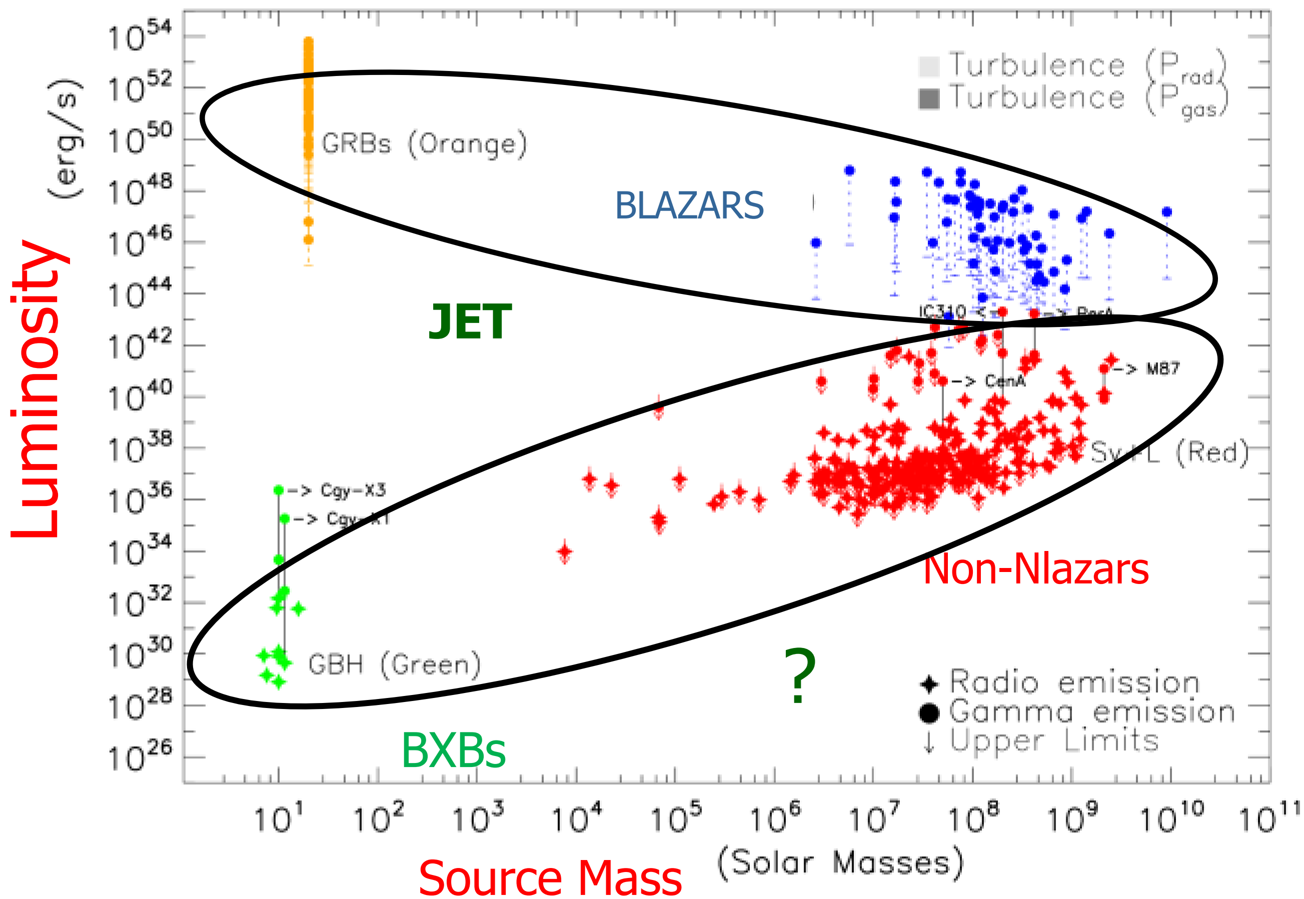
-> compact *emission: core?*

- ✓ ***If core:*** *magnetically dominated*

-> ***Reconnection acceleration?***

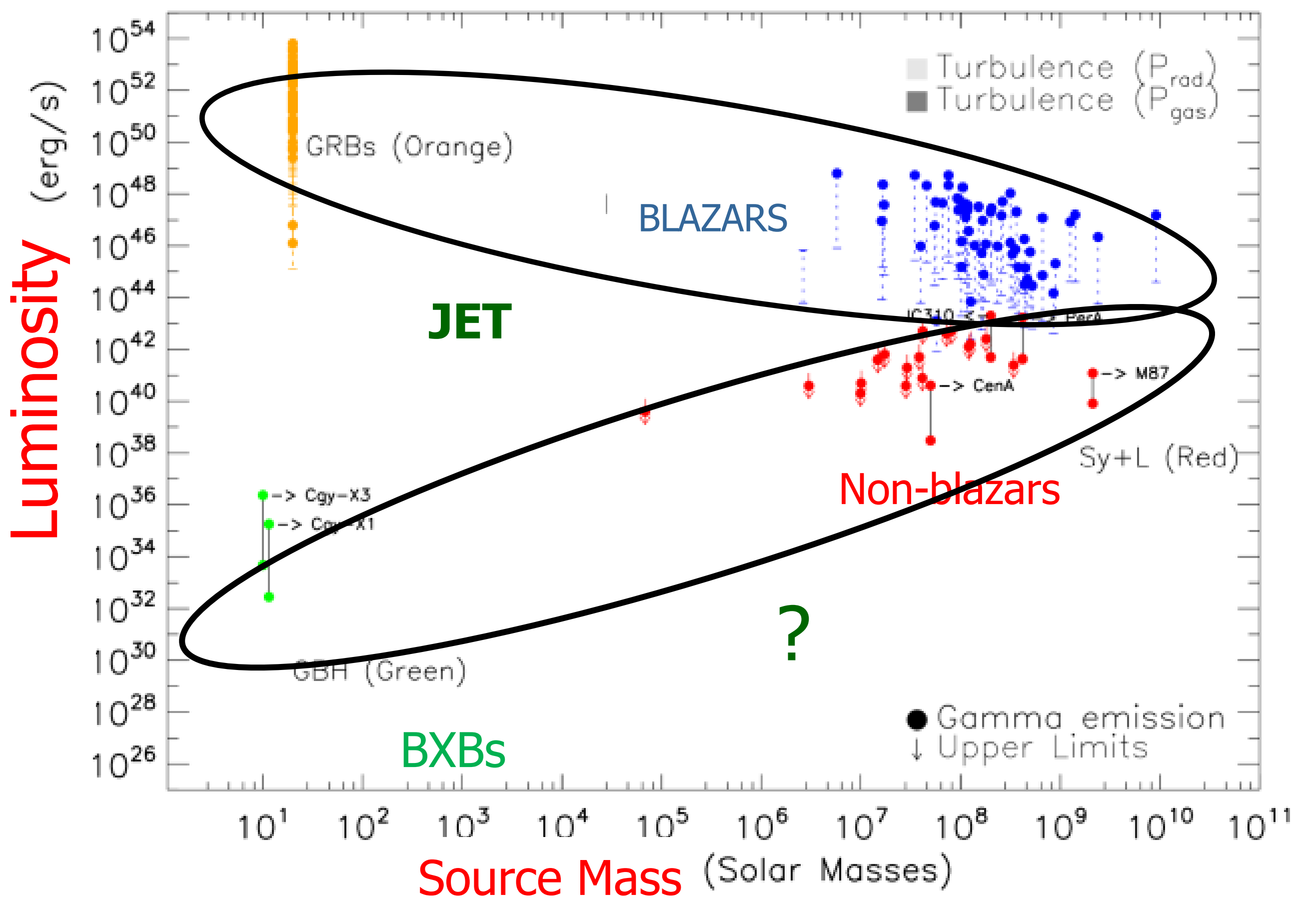


Radio and Gamma-Ray Power versus Mass



Kadowaki, de Gouveia Dal Pino, Singh, ApJ 2015
Singh, de Gouveia Dal Pino, Singh, ApJ Lett. 2015

Gamma-Ray Power versus Mass Correlations



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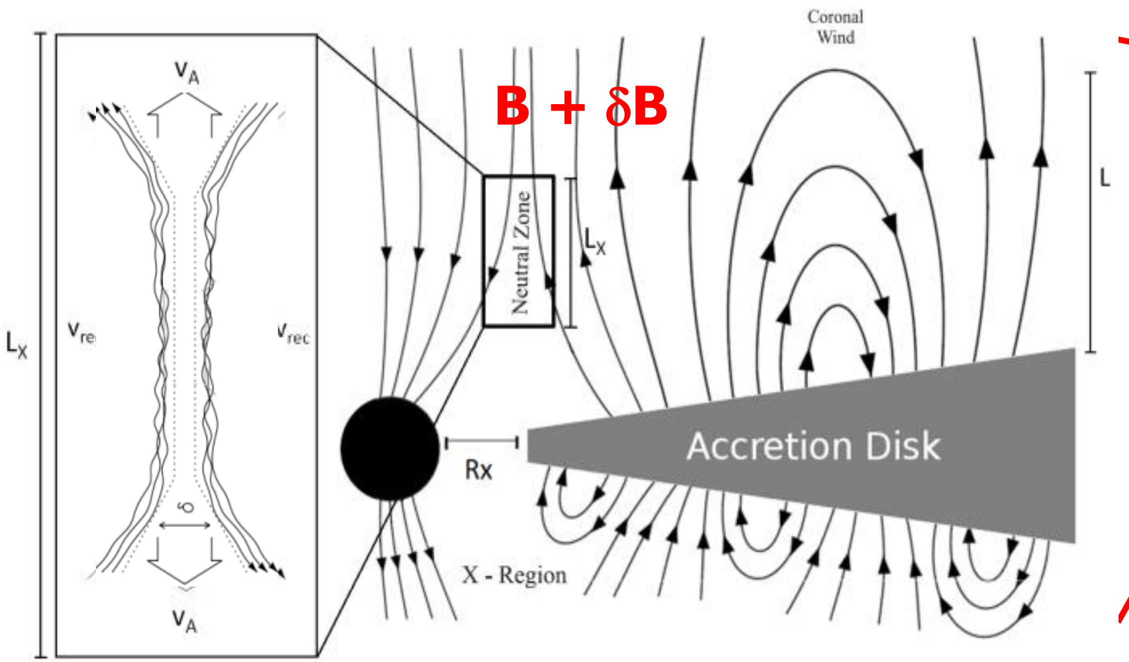
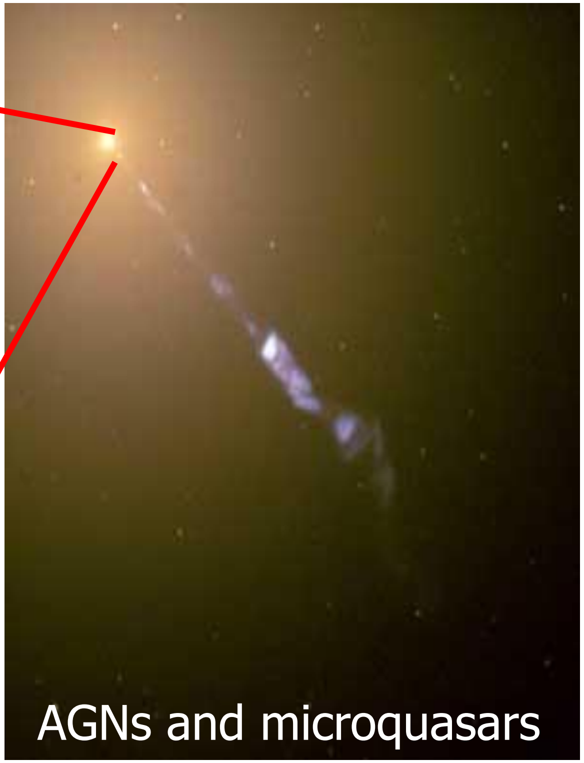
Reconnection acceleration in the surrounds of BHs ?

Accretion disk/jet systems (AGNs & galactic BHs)





de Gouveia Dal Pino & Lazarian 2005; de Gouveia Dal Pino+2010
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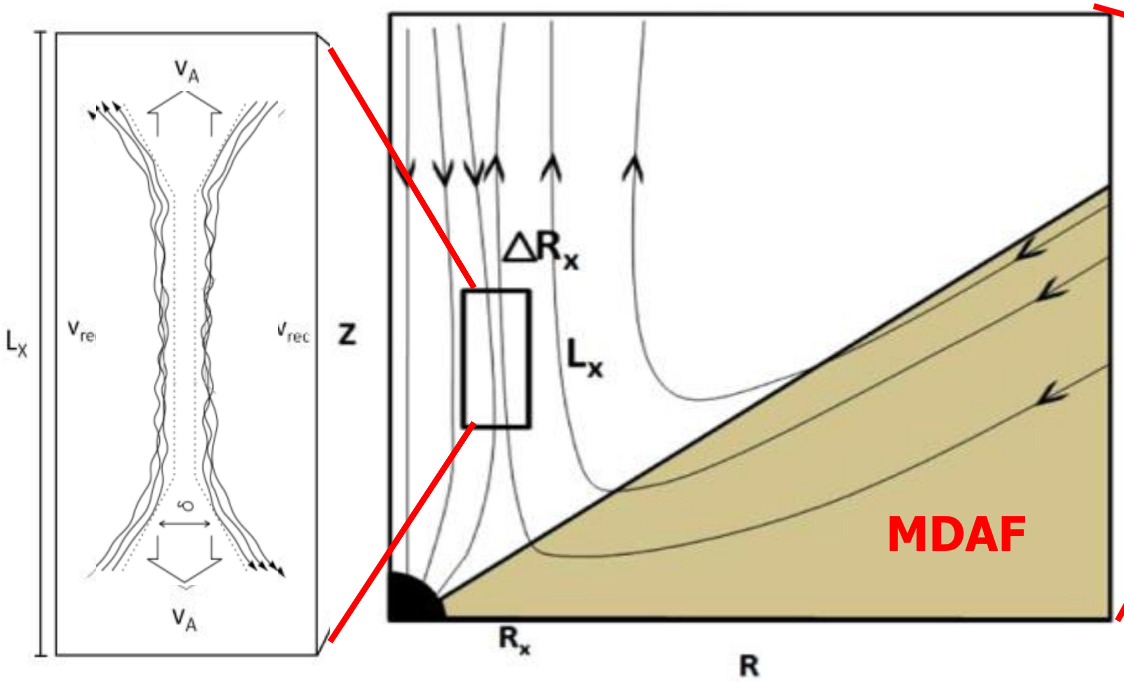

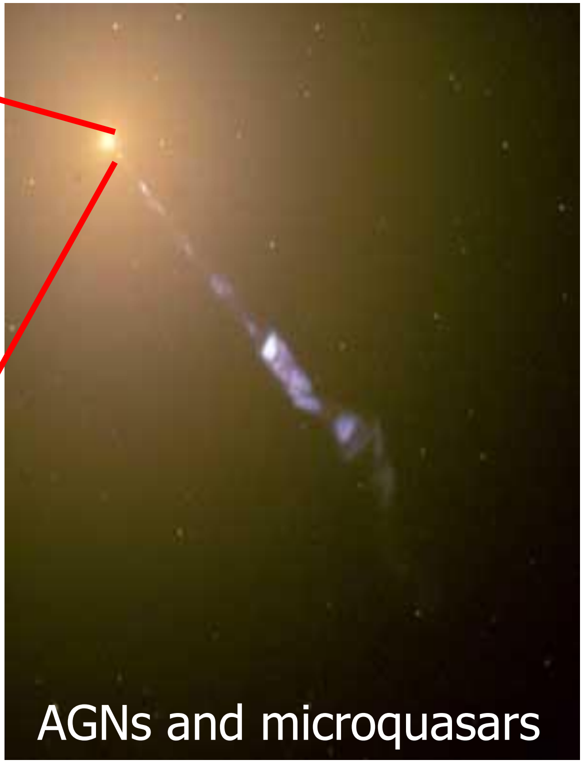

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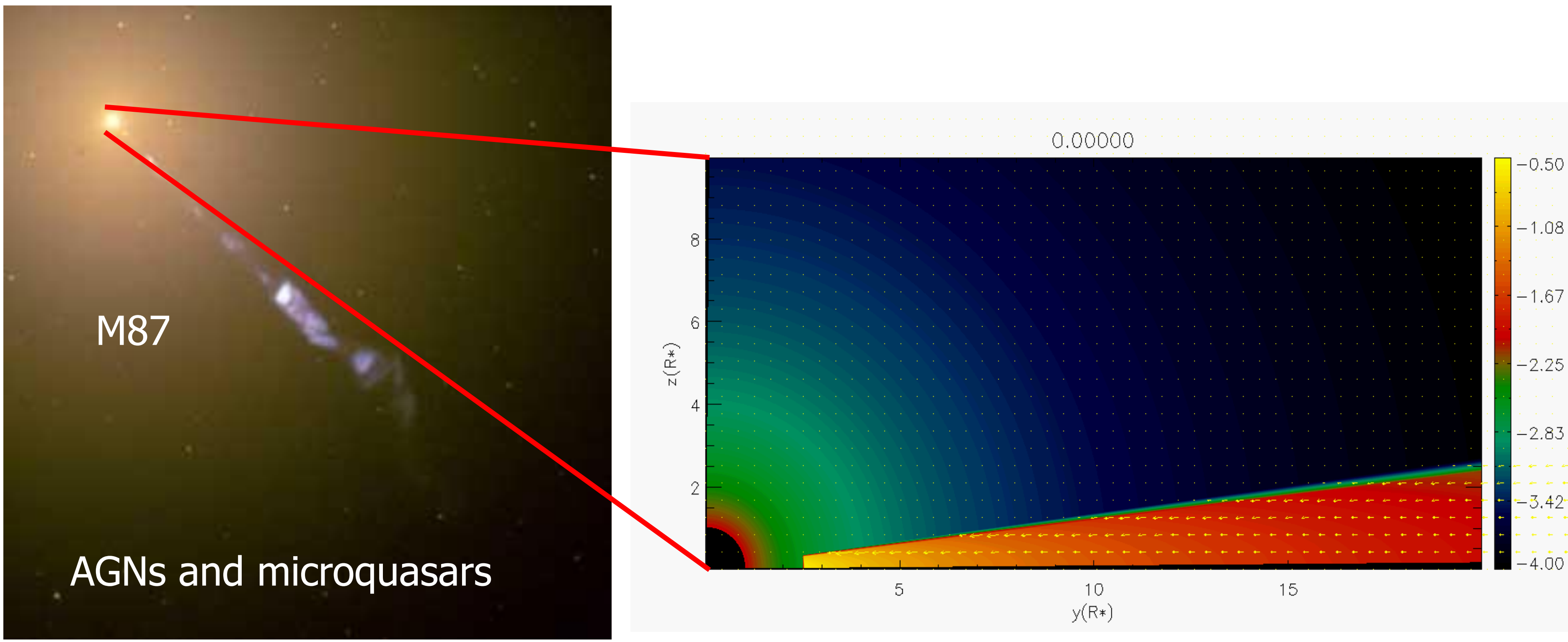
Evidence of Reconnection in MHD Simulations of accretion disk/corona around sources



Kadowaki, Master thesis 2011 (also Zani & Ferreira 2013; Romanova+)

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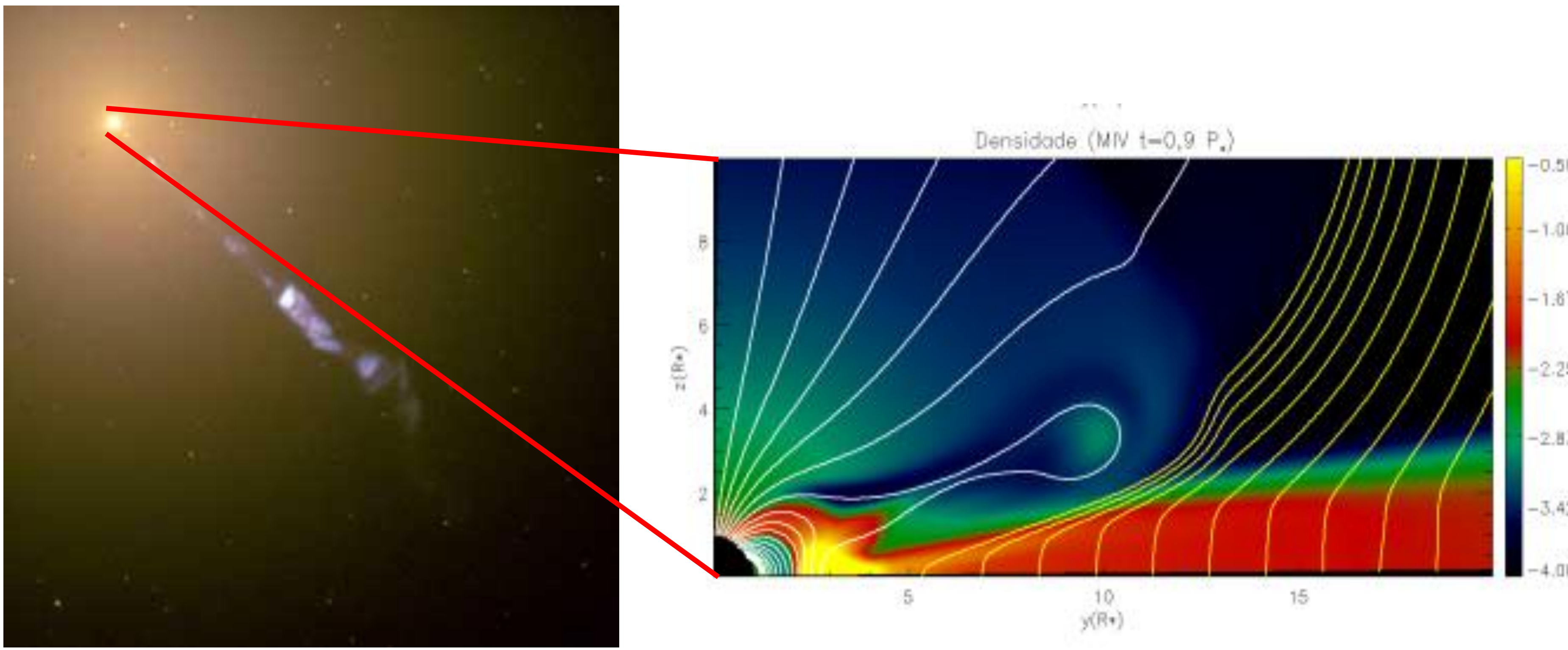

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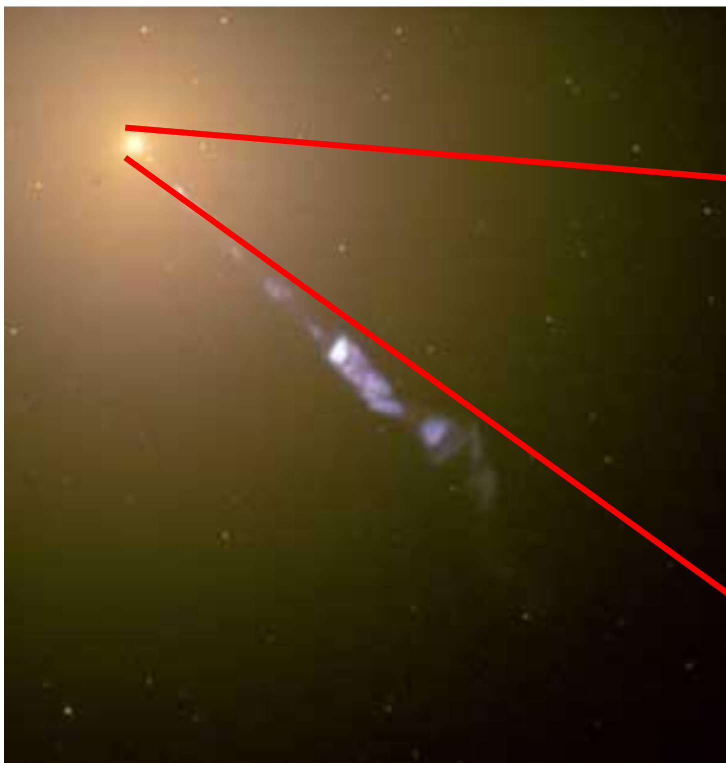
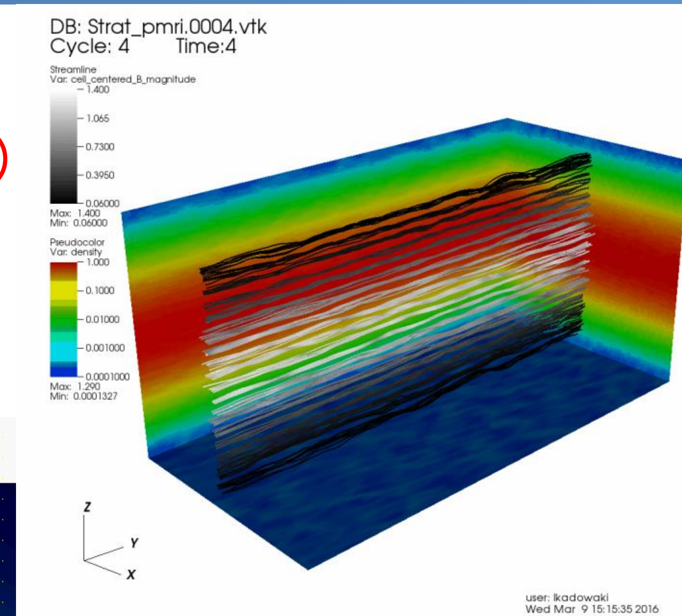
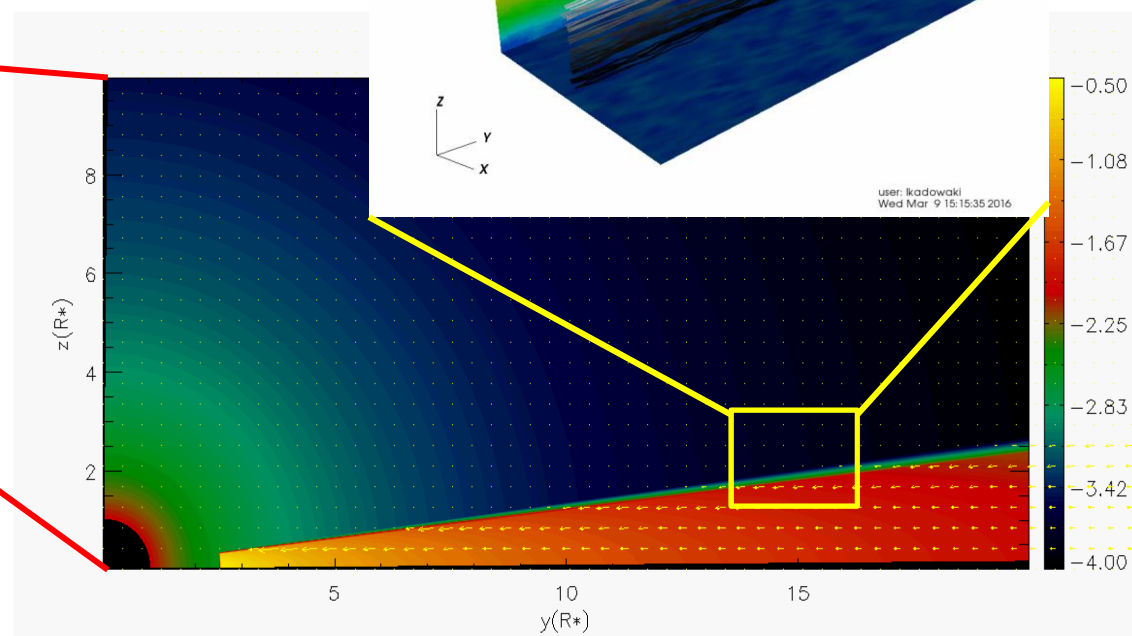
Kadowaki, de Gouveia Dal Pino, Stone (in prep.)







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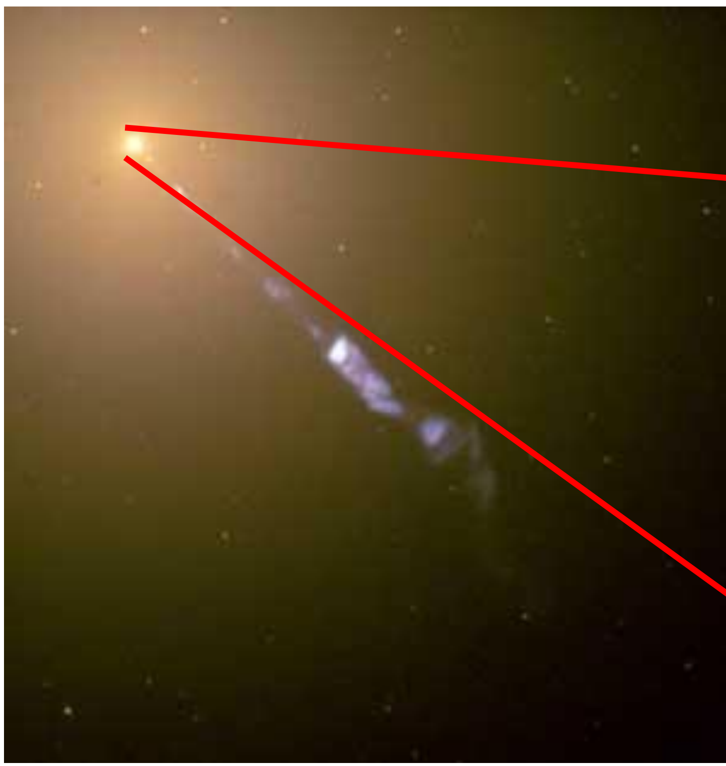
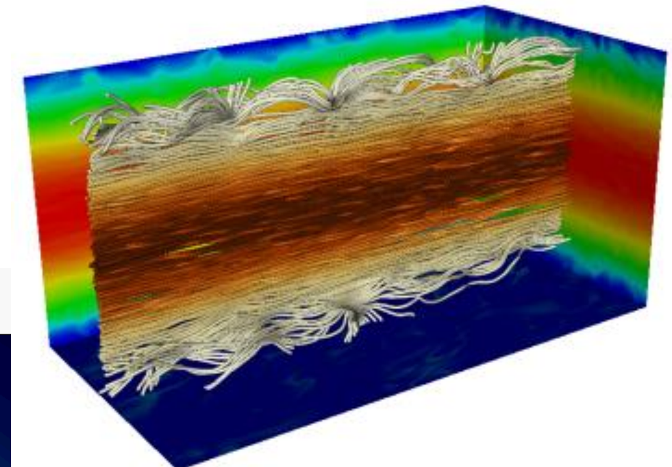
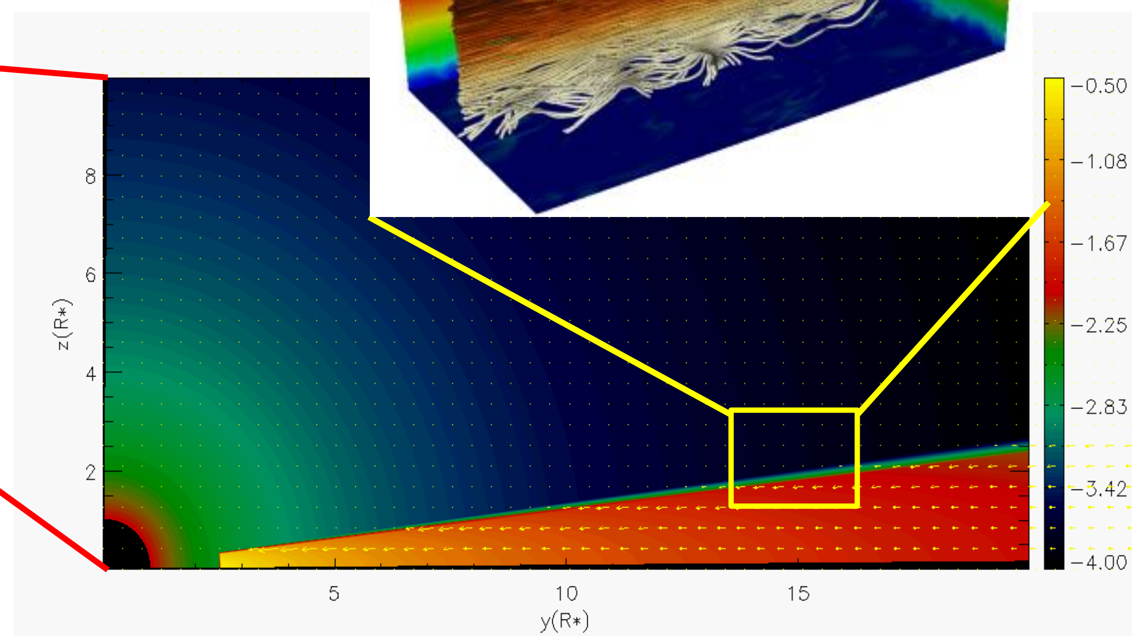
Evidence of Reconnection in MHD Simulations of accretion disk/corona around sources

Parker-Rayleigh-Taylor inst.

Kadowaki, de Gouveia Dal Pino, Stone (in prep.)







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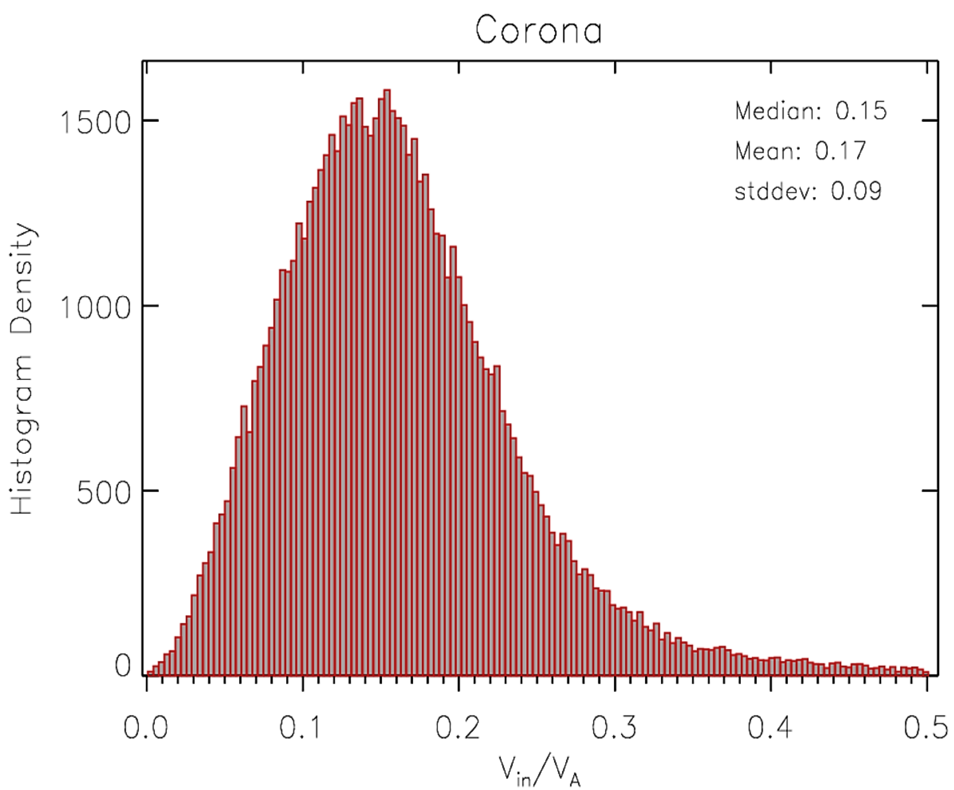
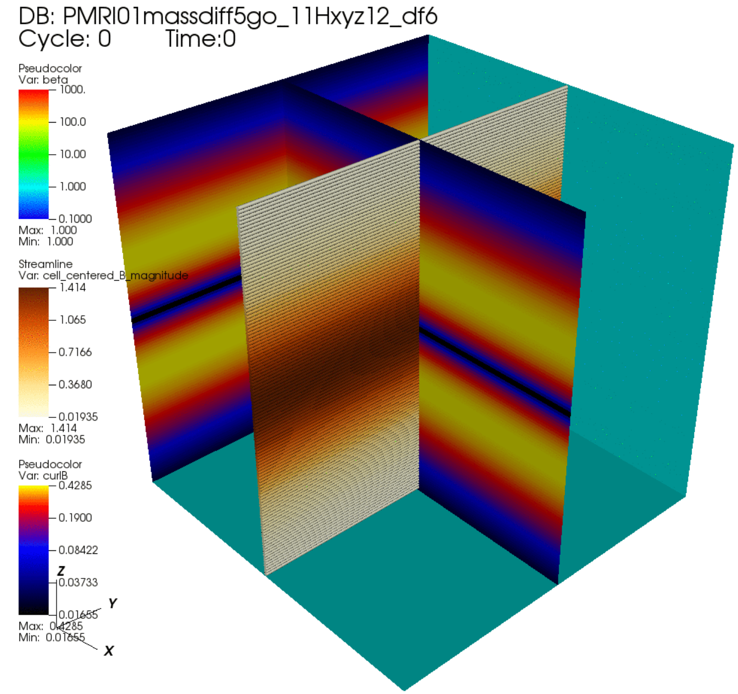
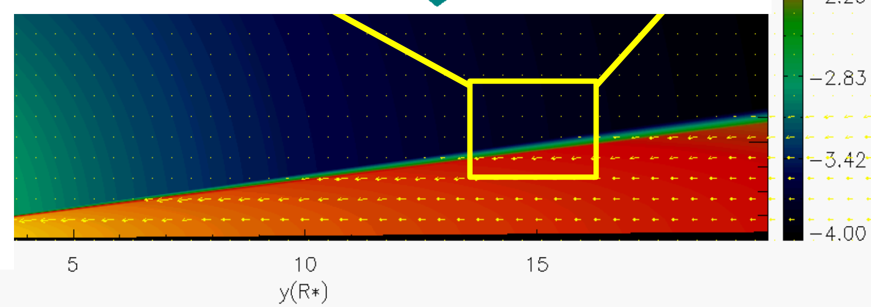




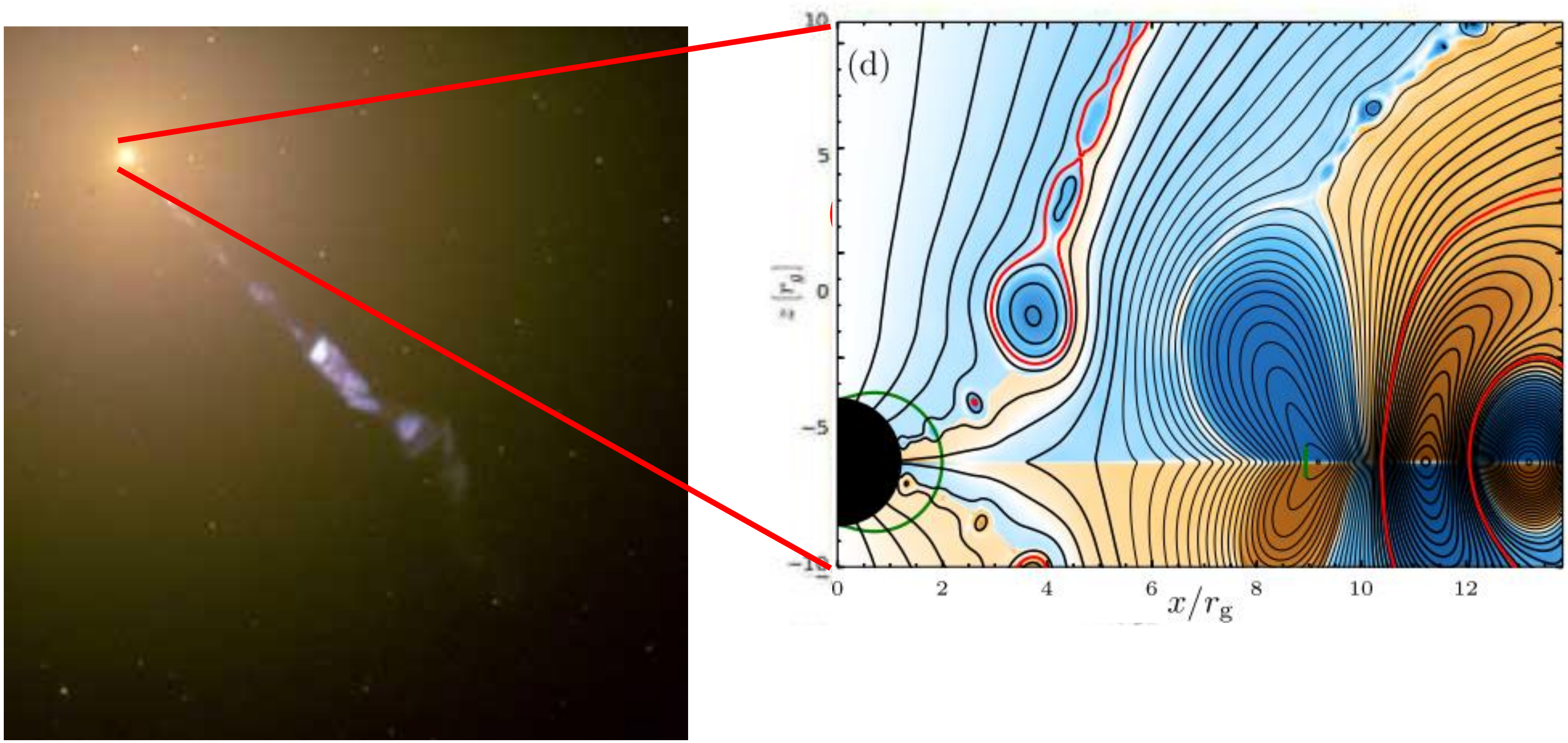


Reconnection velocity

-> Average reconnection velocity: 0.15 v_A

(3D MHD simulations with ATHENA - Kadowaki, de Gouveia Dal Pino, Stone, in prep.)

Evidence of Reconnection in MHD Simulations of accretion disk/corona around sources

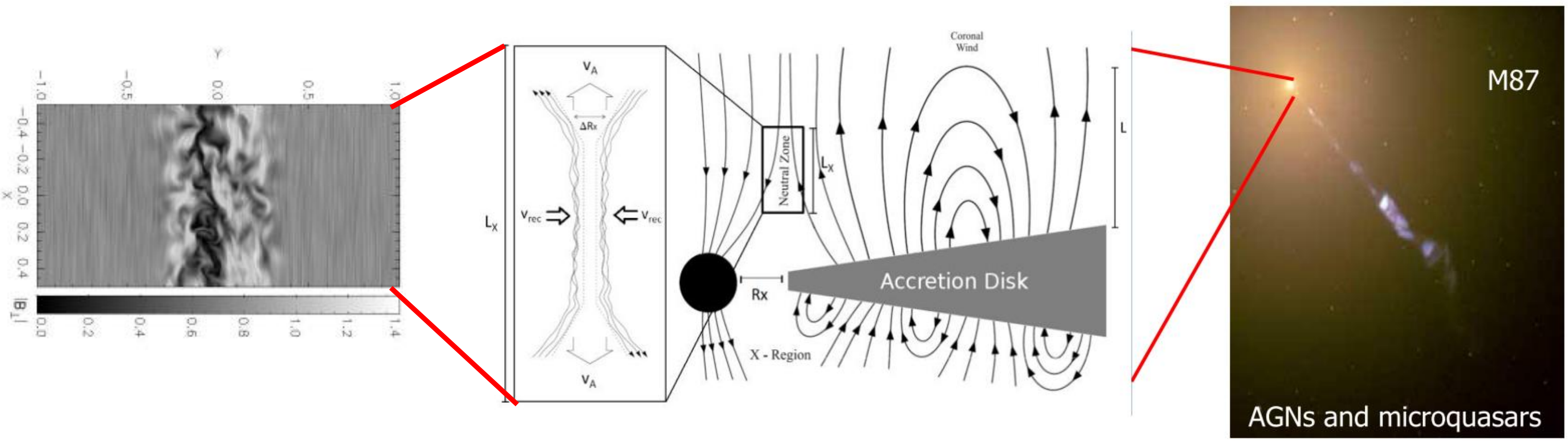


Reconnection seen in GRMHD simulations (Parfrey, Giannios, Beloborodov 2015; also Dexter, McKinney, Tcheckovskoy2014: Koide & Arai 2008; Pohl et al. 2016)

Reconnection acceleration in the surrounds of BHs

Magnetic Power released by fast reconnection

$$\dot{W}_B \simeq 1.66 \times 10^{35} \Gamma^{-\frac{1}{2}} r_X^{-\frac{5}{8}} l^{-\frac{1}{4}} l_X q^{-2} \dot{m}^{\frac{3}{4}} m \;\; erg/s$$



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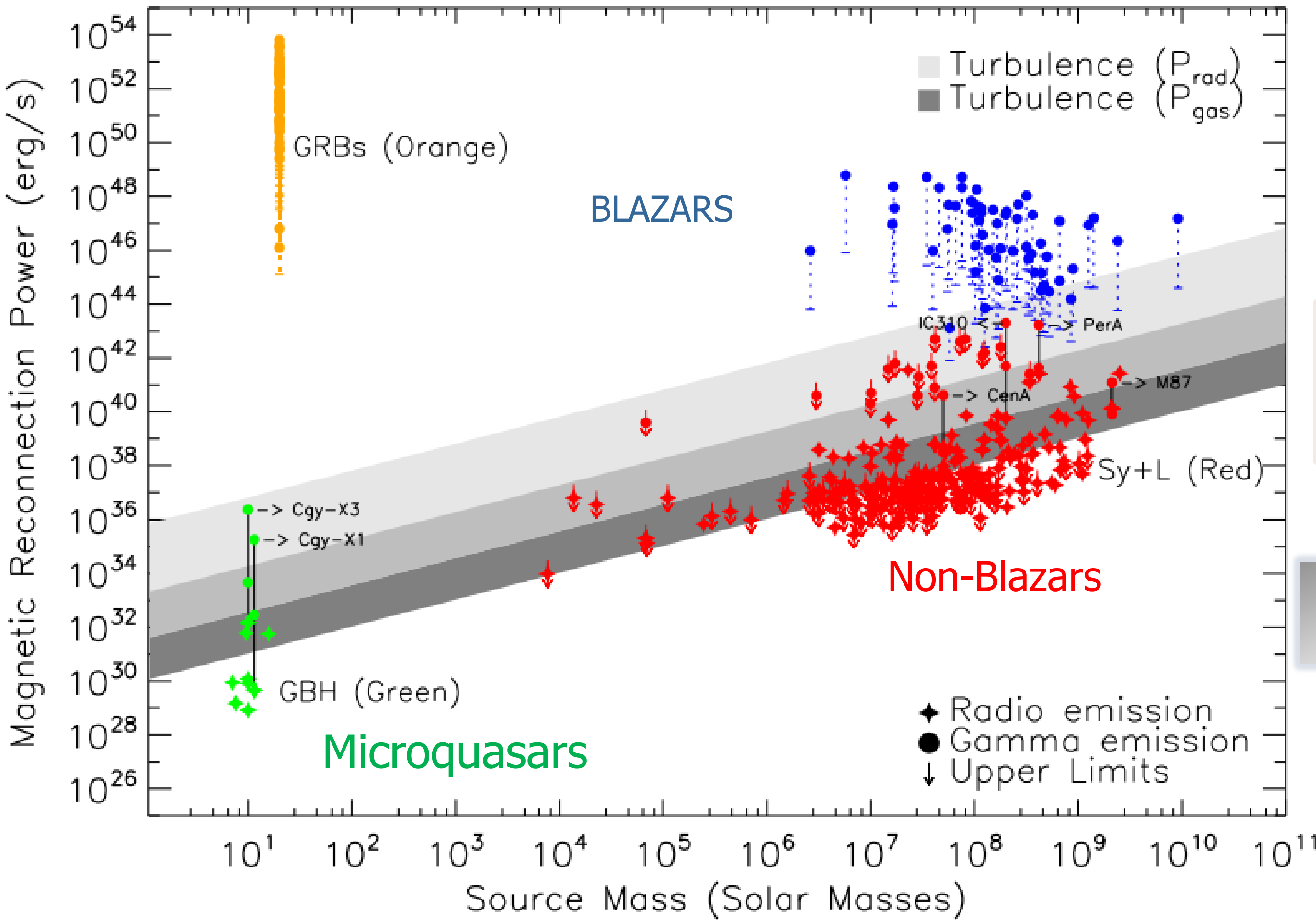
Magnetic Reconnection and Gamma-Ray emission around BHs

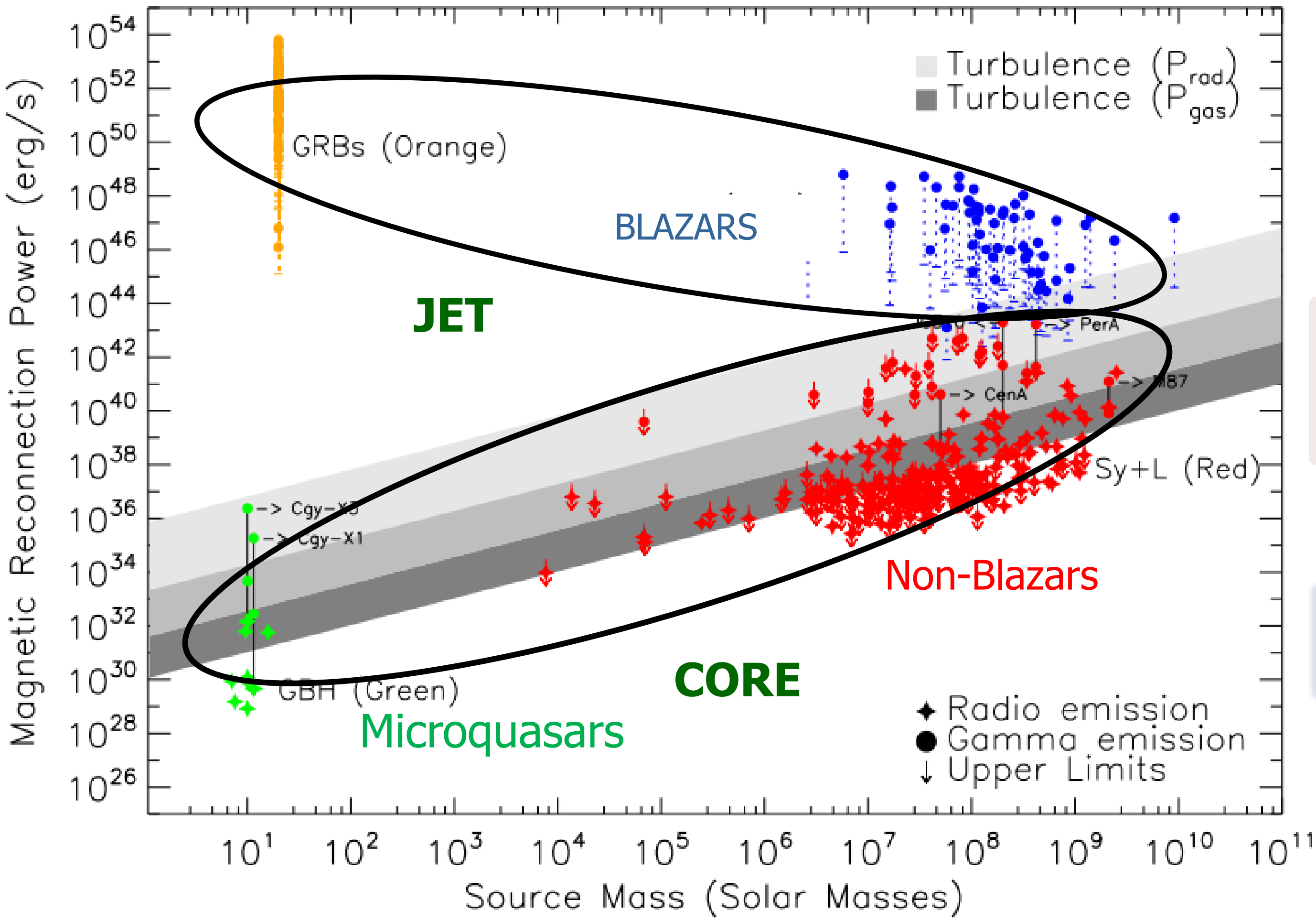


$0.0005 \le \dot{m} \le 1$
$1 \le l \le 18$
$l_x \le l$
$r_x = 6$
$\Gamma \sim 1$

L_X = 0.02 - 44 R_S
R_X = 1.1 - 186 R_S
m = 0.0005 - 0.05

Kadowaki, de Gouveia Dal Pino, Singh, ApJ 2015
Singh, de Gouveia Dal Pino, Singh, ApJ Lett. 2015

Magnetic Reconnection and Gamma-Ray emission around BHs



$0.0005 \leq \dot{m} \leq 1$
$1 \leq l \leq 18$
$l_x \leq l$
$r_x = 6$
$\Gamma \sim 1$

L_X = 0.02 - 44 R_S
R_X = 1.1 - 186 R_S
m = 0.0005 - 0.05

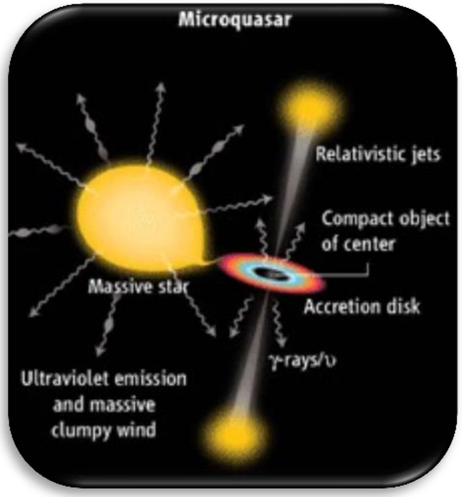
Kadowaki, de Gouveia Dal Pino, Singh, ApJ 2015
Singh, de Gouveia Dal Pino, Singh, ApJ Lett. 2015

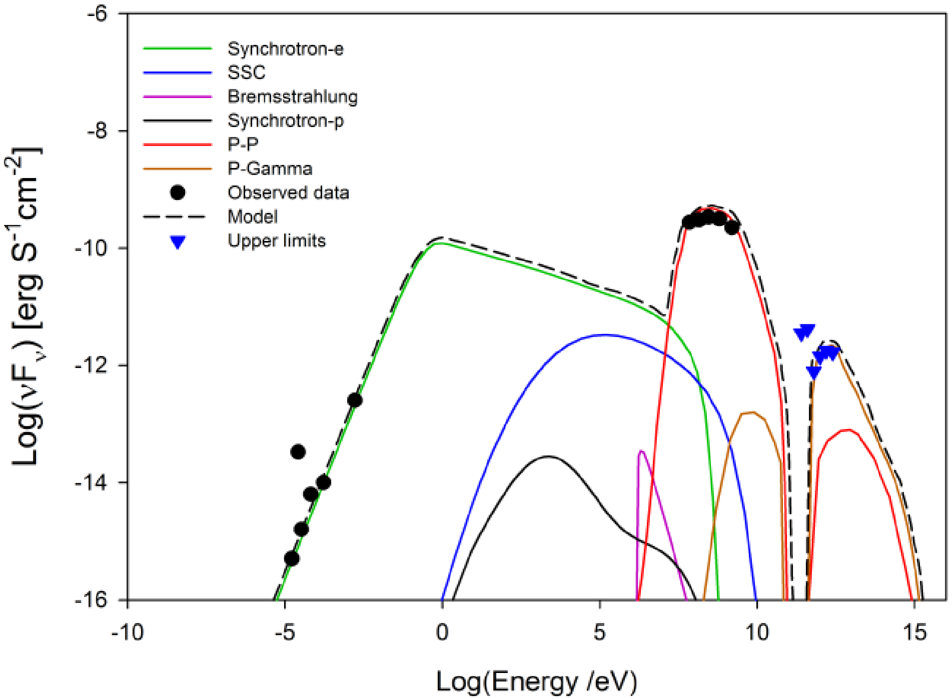
Reconnection Acceleration & Radiative Losses

- ✓ **Cooling of the accelerated particles -> emission:**

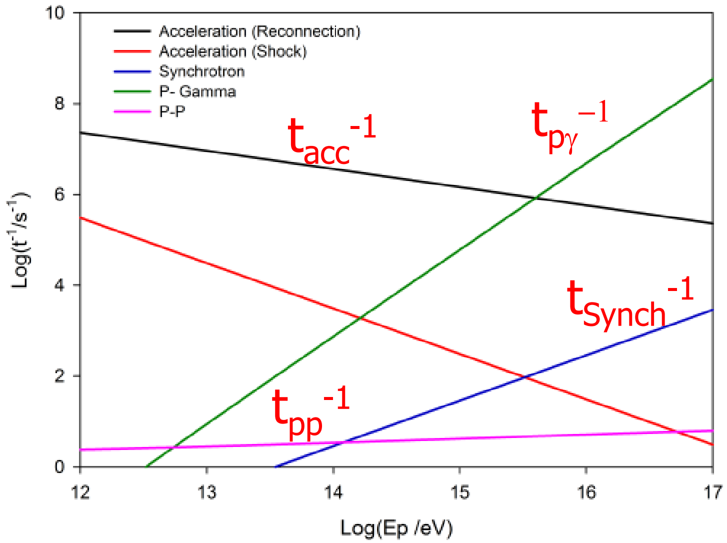
$t_{acc} \sim t_{loss}$(Synchrotron, SSC, pp, pγ)

Ex.: Galactic Black Hole Cyg X3





Spectral Energy Distribution (SED)

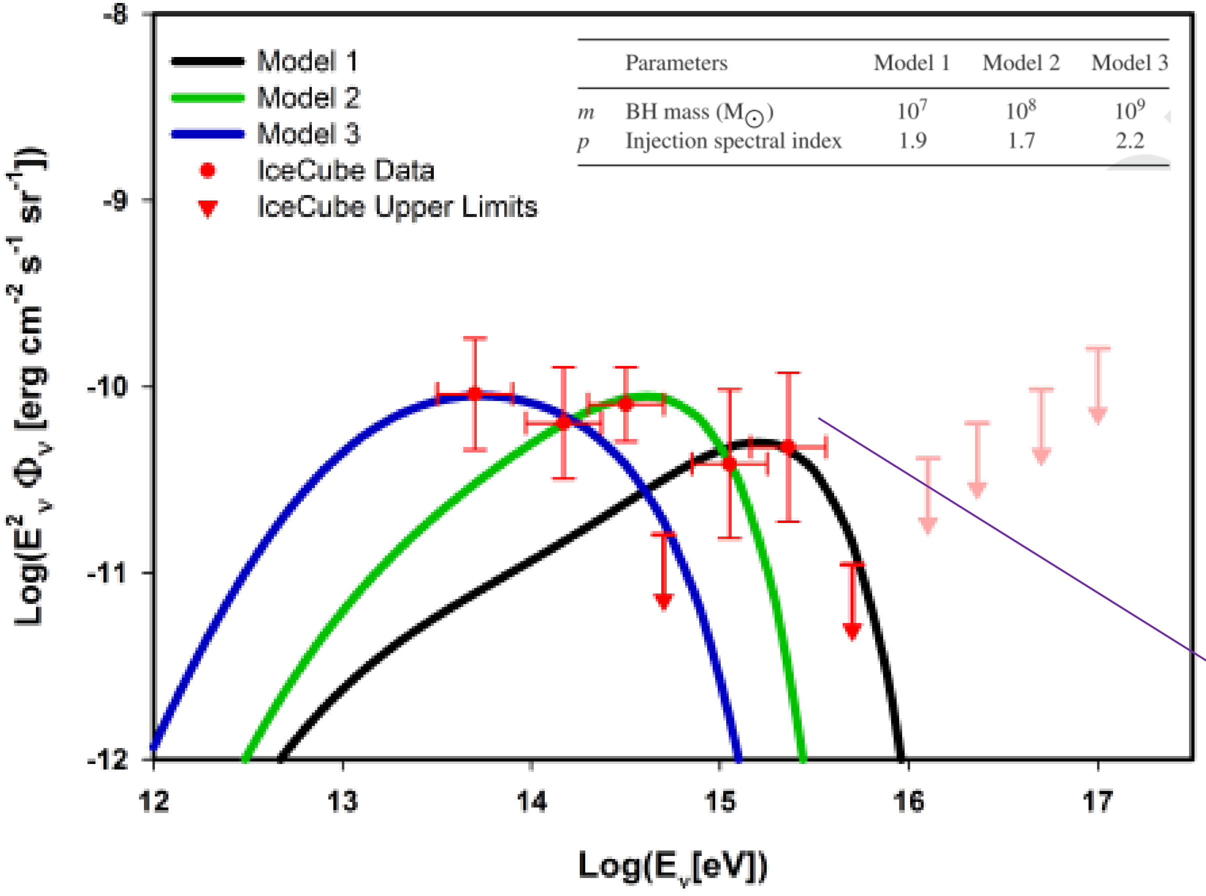


Khiali, de Gouveia Dal Pino, del Valle, MNRAS 2015

Summary

- ✓ Particles inserted in MHD current sheets with fast reconnection (e.g. driven by turbulence): exponential increase of energy in a 1st order Fermi acceleration: $N(E) \sim E^{-1}$ (similar to collisionless results)
- ✓ Acceleration by magnetic reconnection (numerically tested): may explain gamma-ray as coming from near *core* of BH binaries and low luminous AGNs
- ✓ Reconnection power matches well with the observed correlation of gamma-ray luminosity versus BH mass of microquasars and low-luminous (non-blazar) AGNs over 10 orders of magnitude in mass
- ✓ Reconnection acceleration also important along AGNs and GRBs jets to explain bursty gamma-ray emission
- ✓ Reconnection can be important in accretion/jet systems for particle acceleration, dissipation of magnetic energy and conversion into -> kinetic energy

Extra bonus: neutrino emission from *cores* of low luminous AGNs (z ~ 0 – 5.2) due to reconnection acceleration



p + photons → π + p

$\pi^o \rightarrow \gamma\gamma$

$\pi^\pm \rightarrow \mu^\pm \nu$

IceCube flux of Neutrinos

Khiali & de Gouveia Dal Pino, MNRAS 2016