Magnetic Reconnection & Acceleration around BHs and Jets

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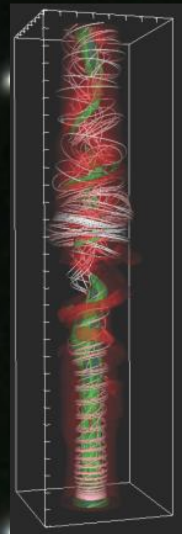
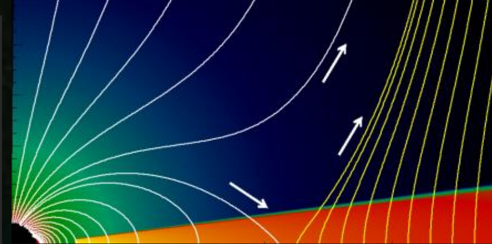
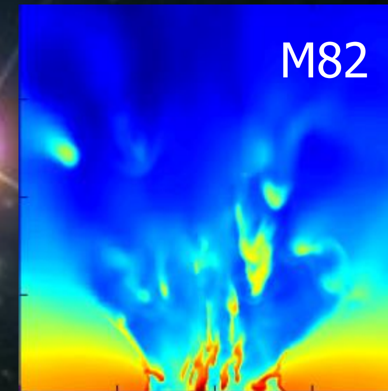
Goethe University, ITP, October, 2016

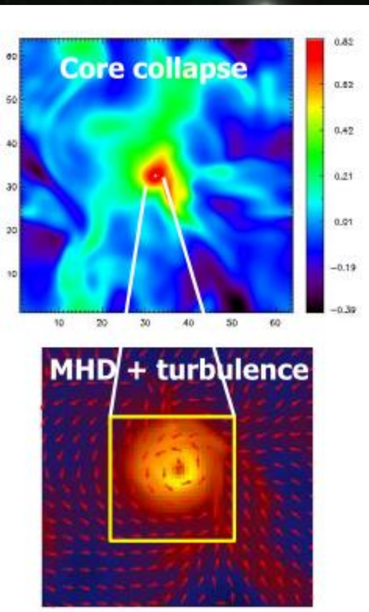




Jets & accretion disks



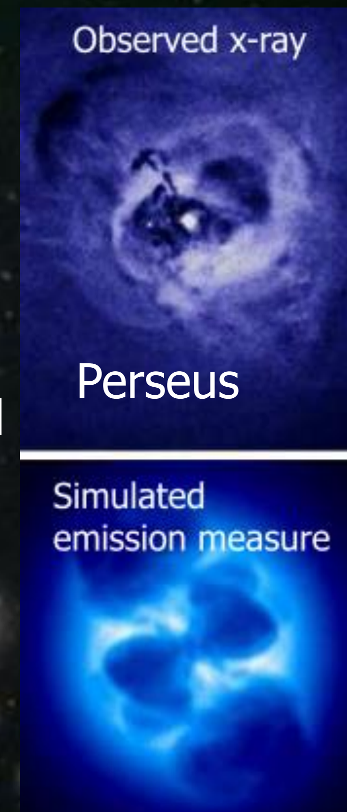
SN driven galactic winds



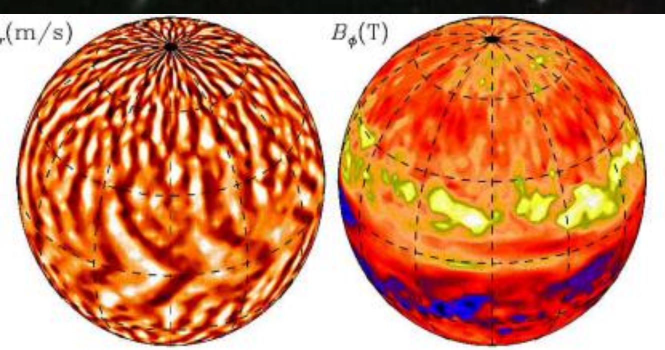
Star Formation-Clouds-SNR-turbulence connection

MHD processes

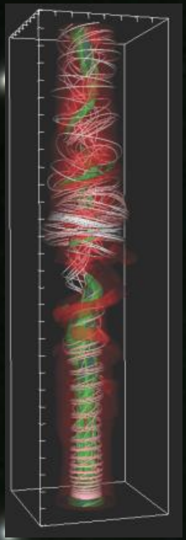
AGN/Star formation feedback in clusters & gal

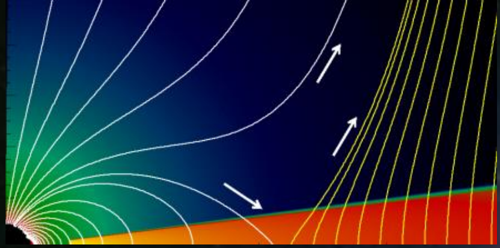


Sun & Stars

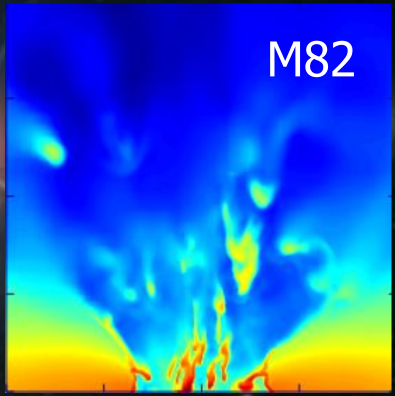


- ✓ Turbulence
- ✓ Particle Acceleration
- ✓ Magnetic reconnection
- ✓ Magnetic flux transport
- ✓ Collisionless MHD
- ✓ Dynamos (solar & MIS, IGM)
- ✓ Relativistic MHD

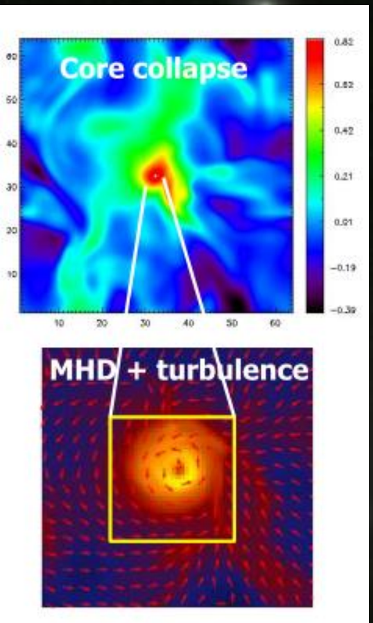




Jets & accretion disks



SN driven galactic winds



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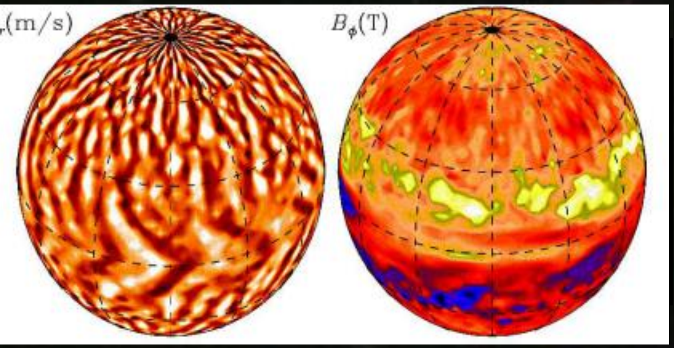

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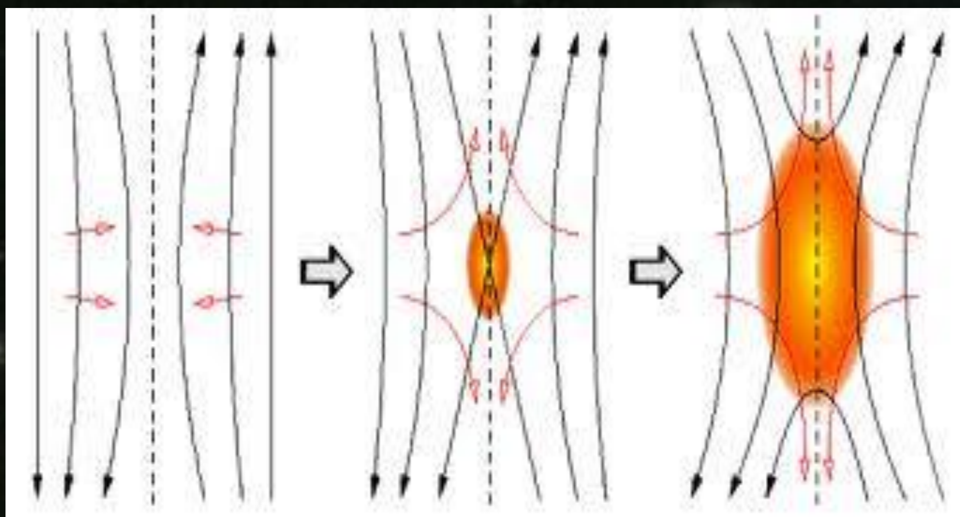
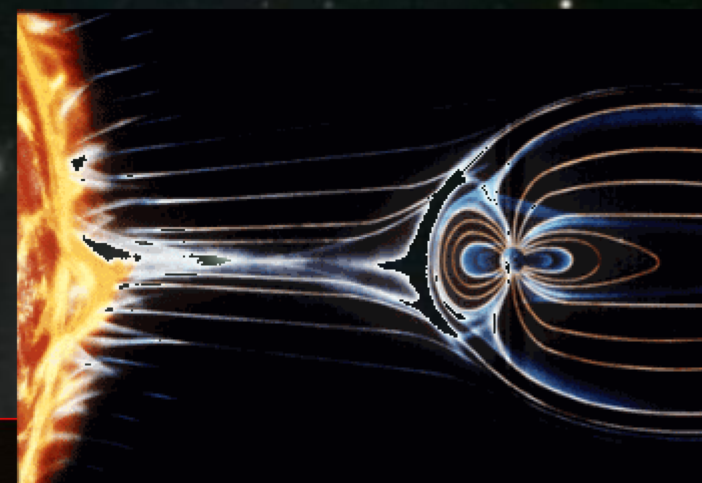
COSMIC MAGNETIC RECONNECTION

Directly observed:



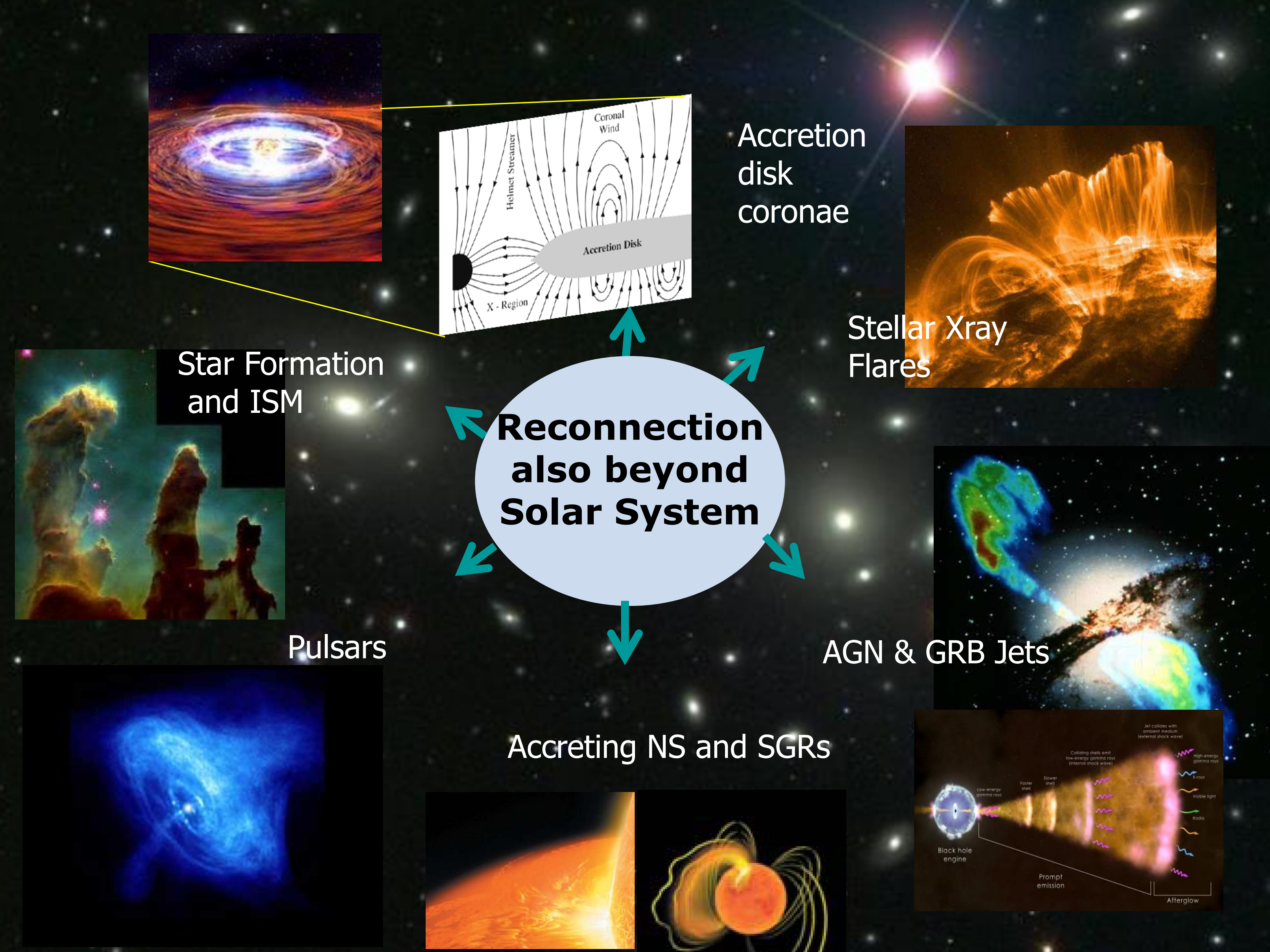


magnetotail

Solar corona

Reconnection is FAST !

$$V_{rec} \sim V_A = B/(4\pi\rho)^{1/2}$$


Reconnection also beyond Solar System
Accretion disk coronae
Coronal Wind
Helmet Streamer
Accretion Disk
X - Region
Stellar Xray Flares
Star Formation and ISM
AGN & GRB Jets
Pulsars
Accreting NS and SGRs
Black hole engine
Prompt emission
Afterglow

Reconnection may be the key to solve another problem

Particle acceleration in compact sources: new challenges

- pulsars
- Black Hole sources
- GRB and AGN relativistic jets

Standard process –> **Fermi acceleration in shocks**:

difficulties to explain relativistic particles origin and associated very high energy emission (up to TeV) occurring in very compact regions in:

magnetically dominated ? -> shocks weak

This talk

Fast magnetic reconnection and Particle acceleration:

- ➡ Review in (collisional) MHD flows
- ➡ surrounds of BHs & relativistic jets
- ➡ its implications for very high energy (VHE), & neutrino emission, conversion of magnetic into kinetic energy

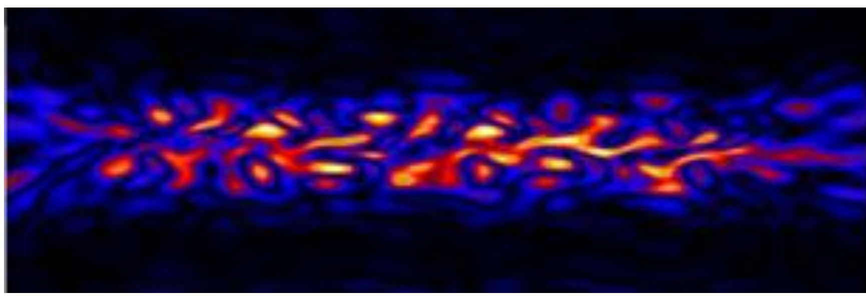
Fast Reconnection in MHD flows

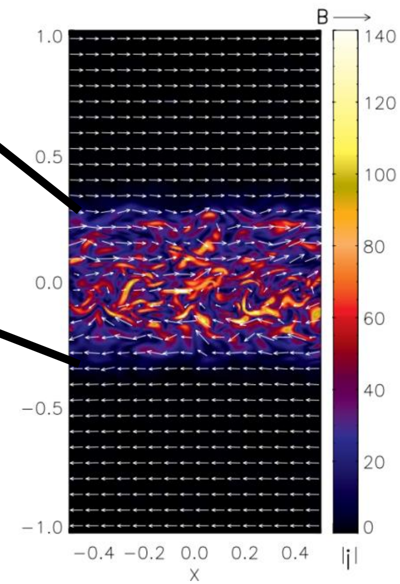
Turbulence drives FAST RECONNECTION !

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

Magnetic lines wandering: many simultaneous reconnection events

Successfully tested in numerical simulations (Kowal et al. 2009, 2012; Takamoto et al. 2015)





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

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

Reconnection a powerful mechanism to accelerate particles

This has been tested with → numerical simulations:

- Most simulations of particle acceleration by magnetic reconnection: **2D collisionless (kinetic) plasmas (PIC)** (e.g. Drake+ 06; Zenitani & Hoshino 01; 07; 08; Cerutti, Uzdensky+ 13; Li+ 15) **and 3D** (Sironi & Spitkovsky 2014; Guo+2015; 16)
  @ scales:

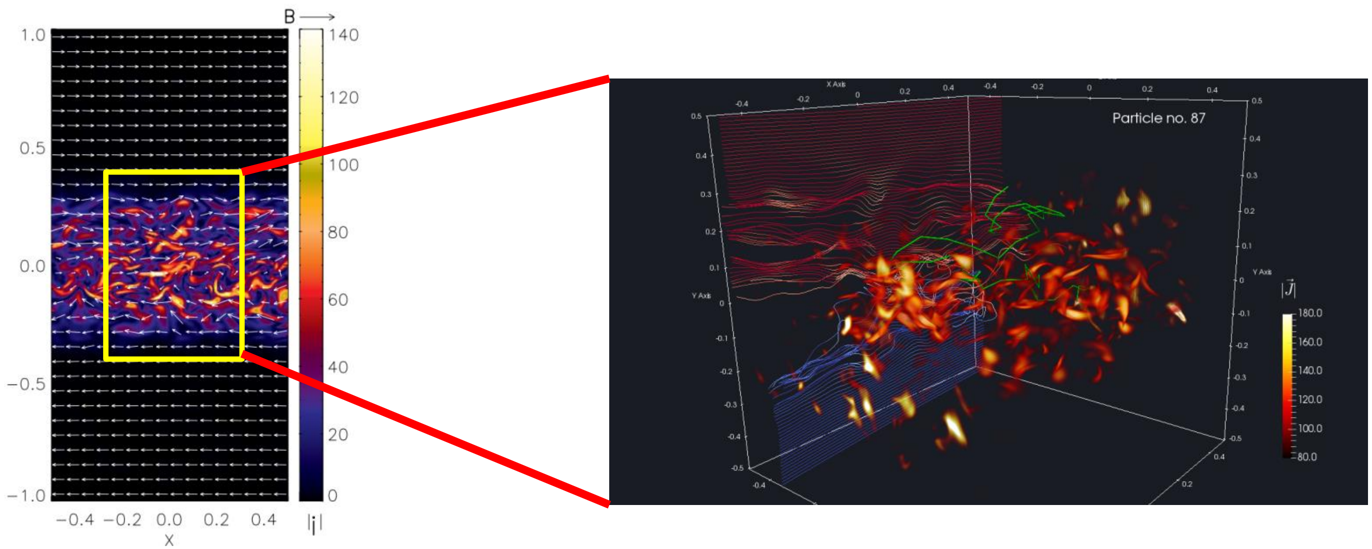
  few plasma inertial length ~ 100-1000 c/ω_p

- **Larger-scale astrophysical systems (AGNs, BHBs):**

  → **MHD description → collisional reconnection**
  (Kowal, de Gouveia Dal Pino & Lazarian 2011, 2012; de Gouveia Dal Pino+ 2014, 2015; del Valle et al. 2016)

Particle Acceleration by Reconnection using MHD Simulations with test particles

- **Isothermal MHD equations to build reconnection domain:** second-order Godunov scheme and HLLD Riemann solver (Kowal et al 2009)

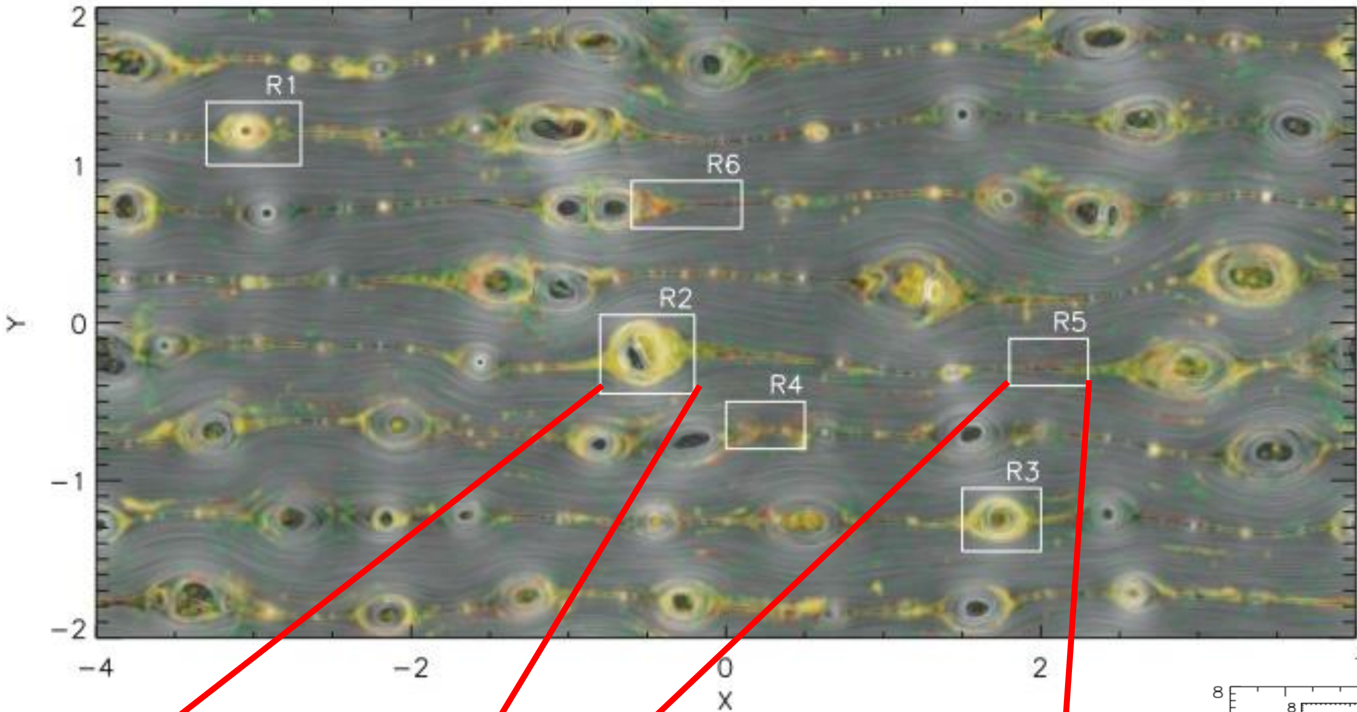


- **Inject test particles** in the MHD domain of reconnection and follow their trajectories (6^{th} order Runge-Kutta-Gauss):

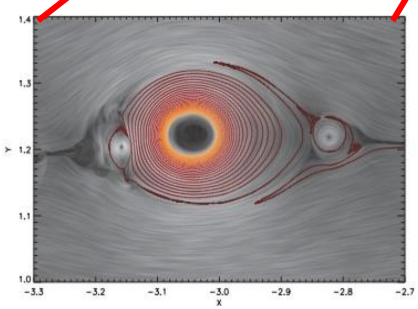
$$\frac{d}{dt}(\gamma\, m\, \mathbf{u}) = q(\mathbf{E} + \mathbf{u} \times \mathbf{B}) \rightarrow \boxed{\frac{d}{dt}(\gamma m \boldsymbol{u}) = q\left[(\boldsymbol{u} - \boldsymbol{v}) \times \boldsymbol{B}\right]}$$

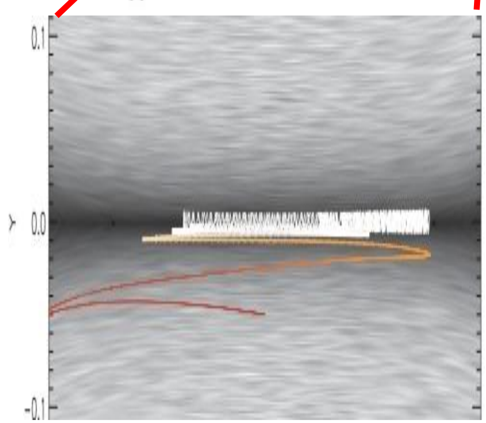
Kowal, de Gouveia Dal Pino, Lazarian 2011; 2012

Particle Acceleration in 2D MHD Reconnection

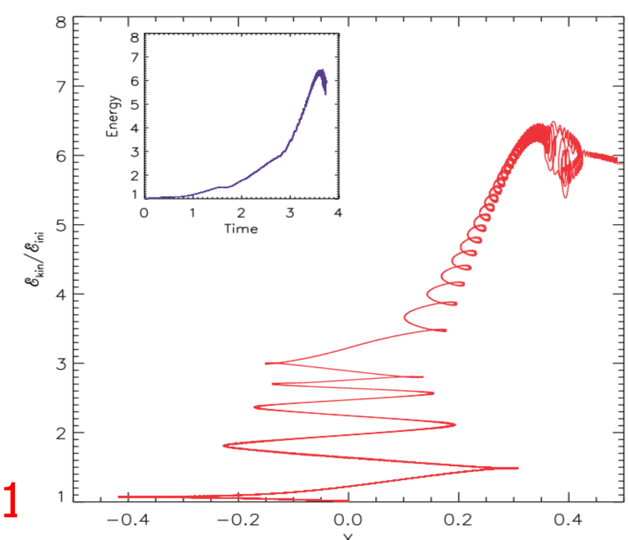


2D Multiple current sheets
to compare with
PIC simulations





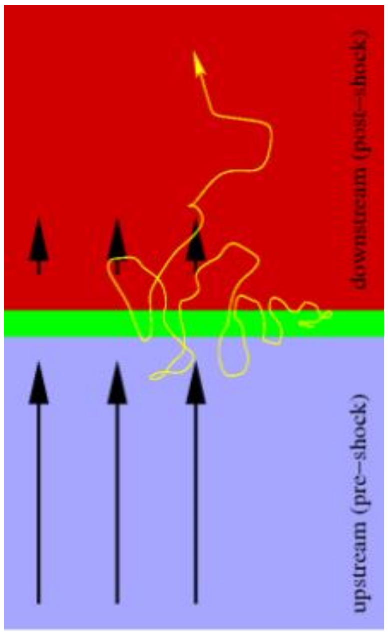
Kinetic energy increase



Kowal, de Gouveia Dal Pino, Lazarian, ApJ 2011

Interpretation of Particle Acceleration in reconnection sites

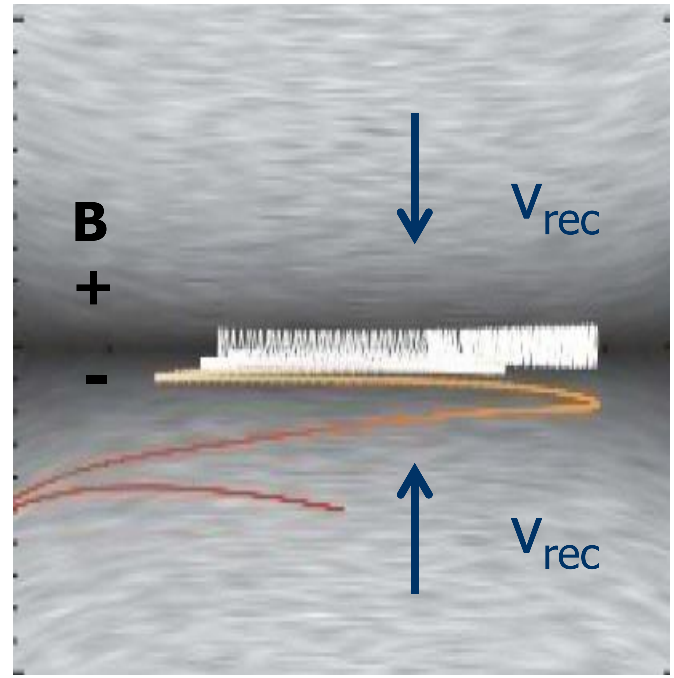
Shock Acceleration



1st-order Fermi (e.g.Bell+1978)

$<\Delta E/E> \sim v_{sh}/c$

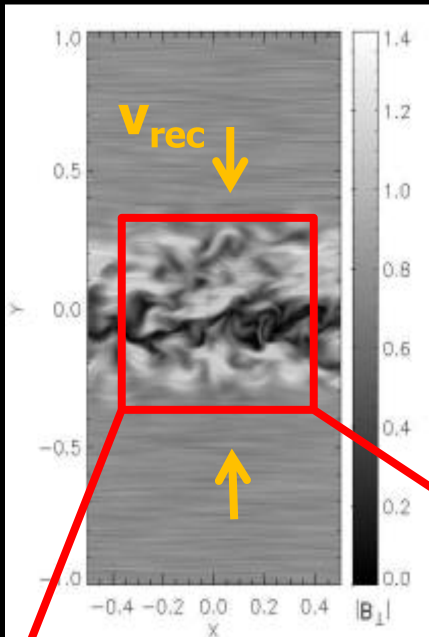
Reconnection Acceleration



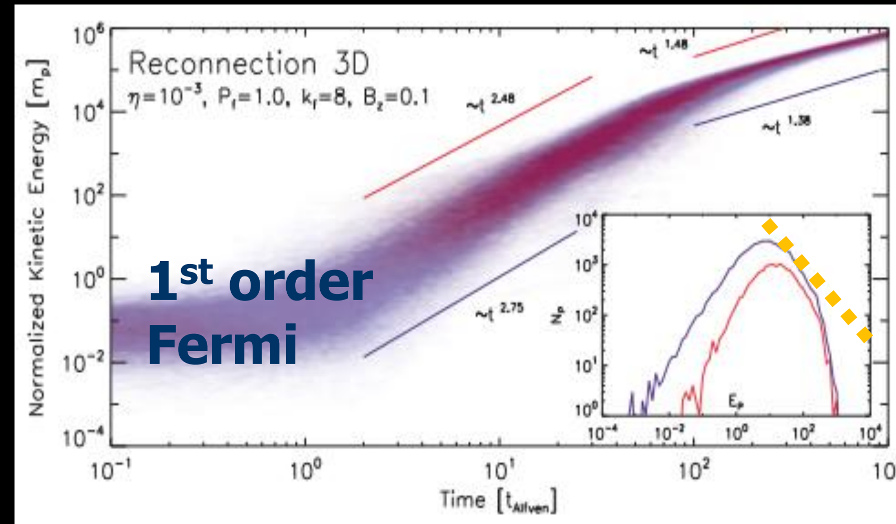
1st-order Fermi (de Gouveia Dal Pino & Lazarian, A&A 2005):
particles bounce back and forth between 2 converging magnetic flows

$<\Delta E/E> \sim v_{rec}/c$

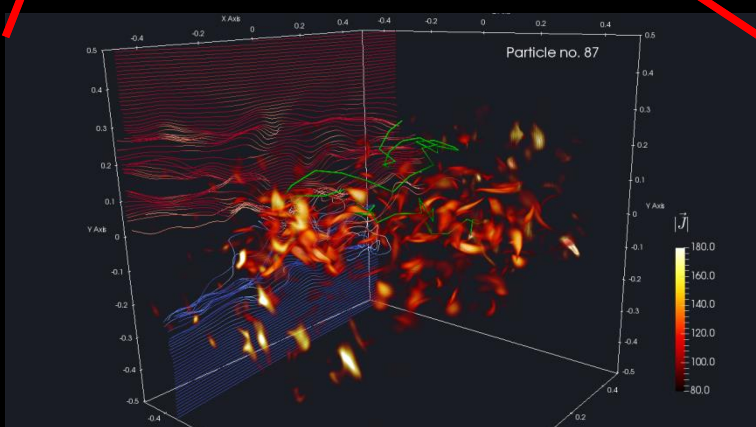
1st order Fermi Reconnection Acceleration: successful numerical testing in 3D MHD



current sheet with turbulence:
fast reconnection (LV99)

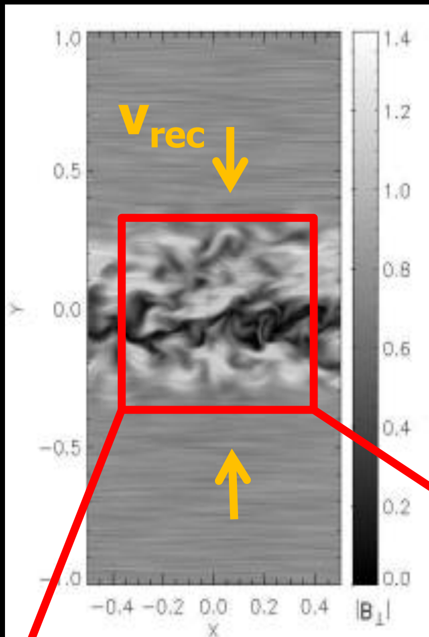


Kowal, de Gouveia Dal Pino, Lazarian, PRL 2012



- ✓ **Acceleration more efficient in 3D than in 2D**

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



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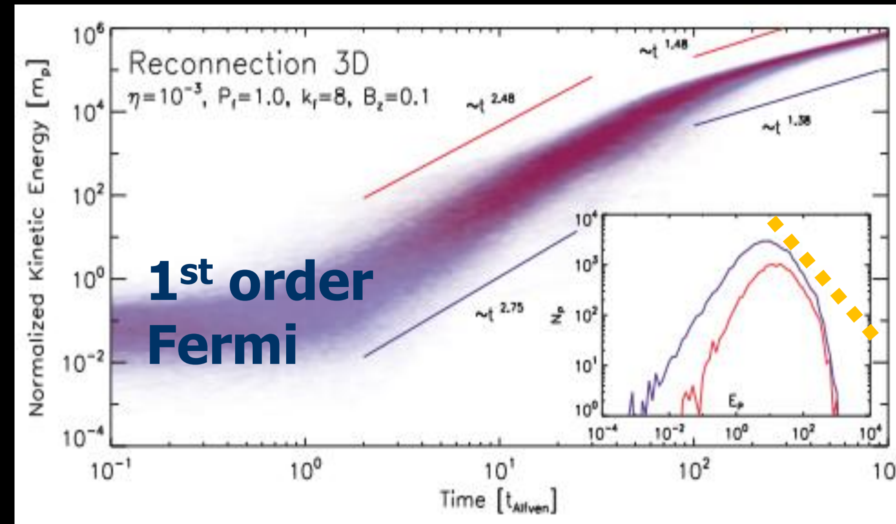
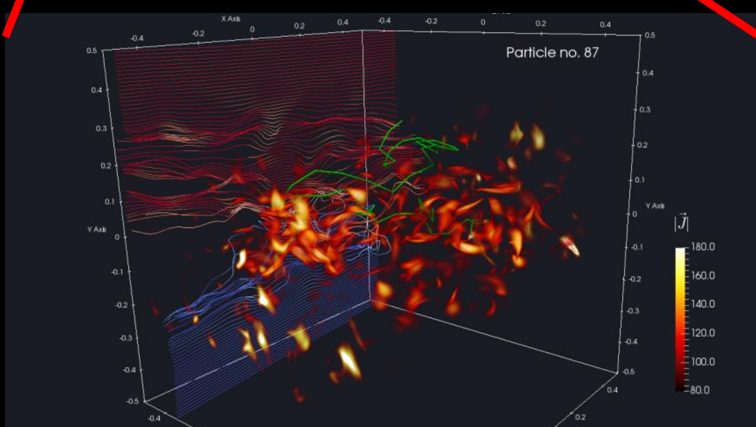
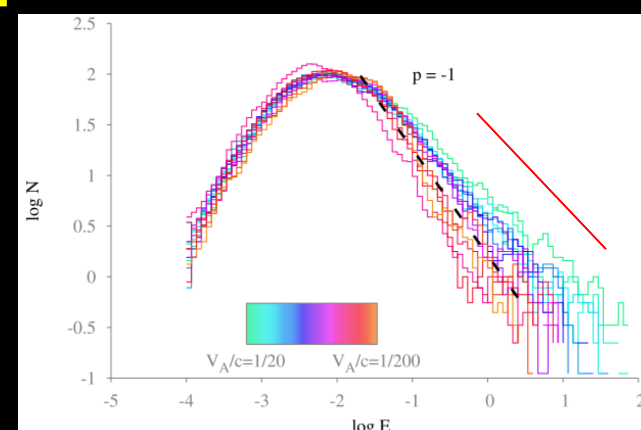


Kowal, de Gouveia Dal Pino, Lazarian, PRL 2012

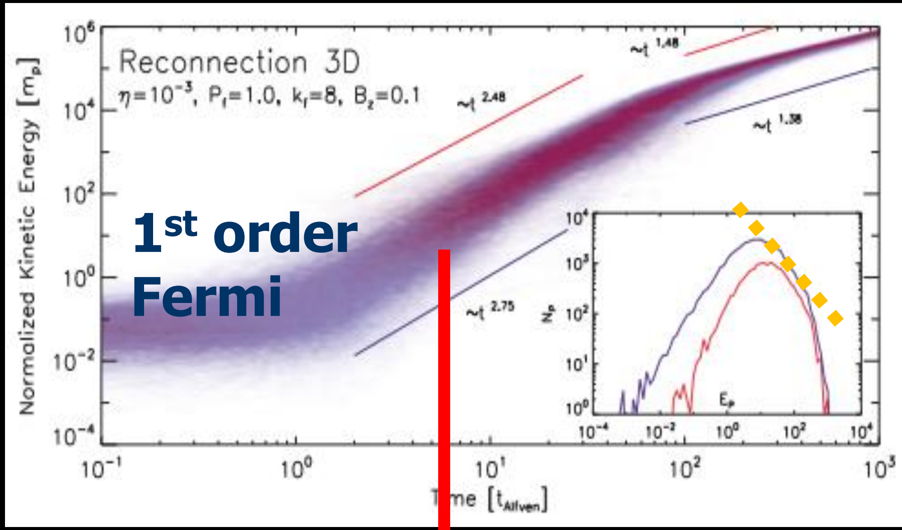


$N(E) \sim E^{-1,-2}$

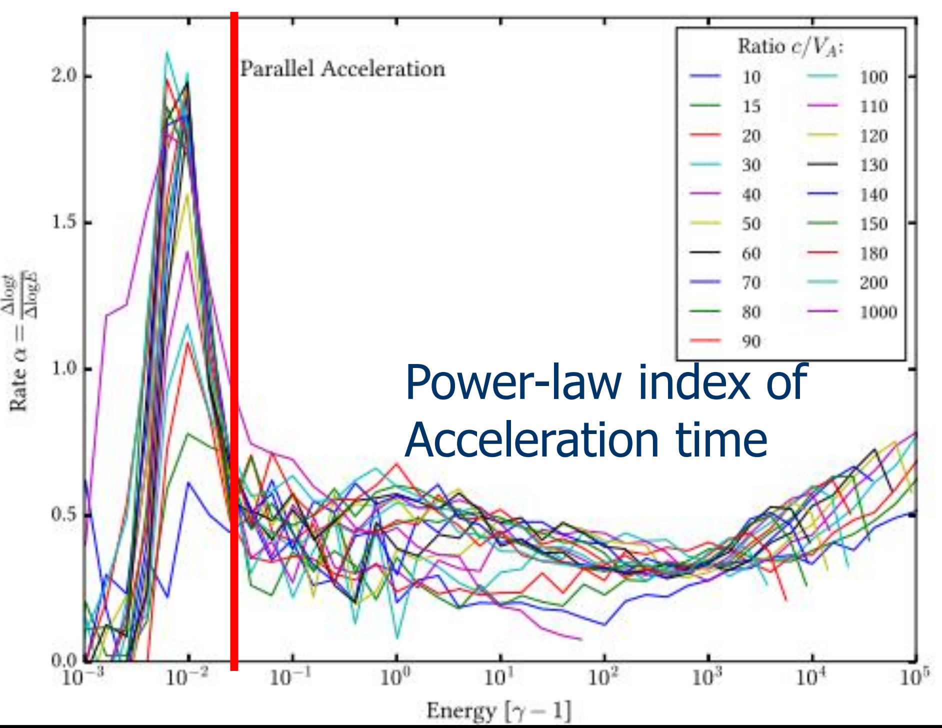


del Valle, de Gouveia Dal Pino, Kowal MNRAS 2016

3D MHD Reconnection Acceleration tested for different values of v_A/c = 1/10 – 1/1000



Kowal, de Gouveia Dal Pino, Lazarian, PRL 2012



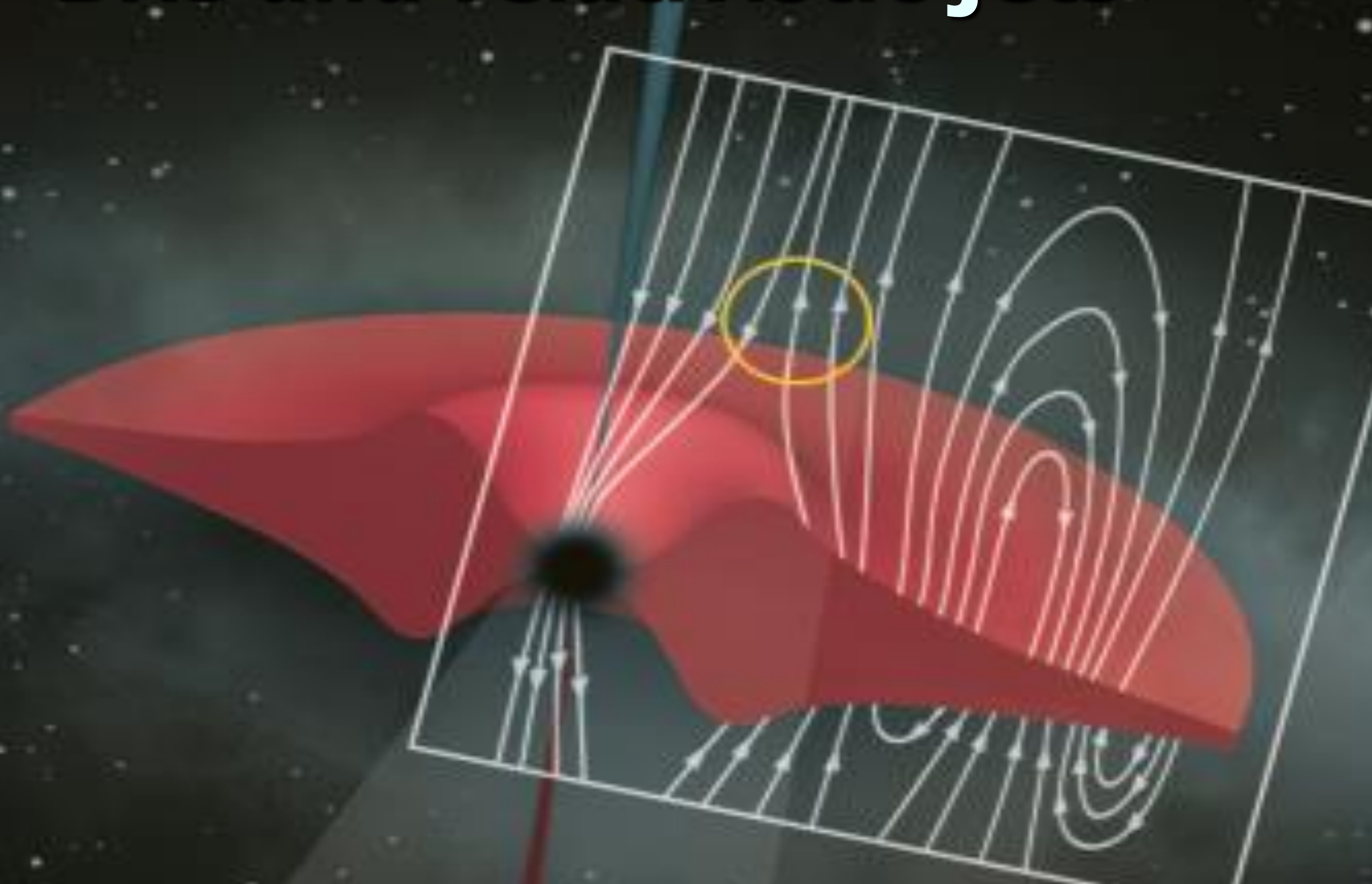
$\tau_{acc} \sim E^{0.45 +- 0.15}$

del Valle, de Gouveia Dal Pino, Kowal MNRAS 2016

Reconnection acceleration beyond the SS

- Zenitani & Hoshino (2001-2007)
- de Gouveia Dal Pino & Lazarian (2003, 2005)
- Dmitruk, Matthaeus+ (2003)
- de Gouveia Dal Pino et al. (2010)
- Kowal, de Gouveia Dal Pino, Lazarian (2011, 2012)
- Giannios+ (2009), Giannios, 2010, 2013)
- del Valle, Romero et al. (2011)
- Cerutti et al. (2013)
- de Gouveia Dal Pino, Kowal & Lazarian (2014)
- Cerutti, Werner, Uzdensky, Begelman (2014)
- Lyutikov (2014)
- Wu+ (2014)
- Dexter+ (2014)
- Werner+ (2014)
- Sironi & Spitkovsky (2014)
- Singh, de Gouveia Dal Pino, Kadowaki (2015)
- Kadowaki, de Gouveia Dal Pino, Singh (2015)
- Khiali, de Gouveia Dal Pino, del Valle (2015)
- Khiali, de Gouveia Dal Pino, Sol (2015)
- de Gouveia Dal Pino & Kowal (2015)
- Khiali & de Gouveia Dal Pino (2016)
- del Valle, de Gouveia Dal Pino, Kowal (2016)
- de Gouveia Dal Pino & Kowal (2015)
- Uzdensky (2015)
- Guo et al (2015)
- Sironi, Petropoulou, Giannios (2015)
- Singh, Mizuno, de Gouveia Dal Pino (2016)….

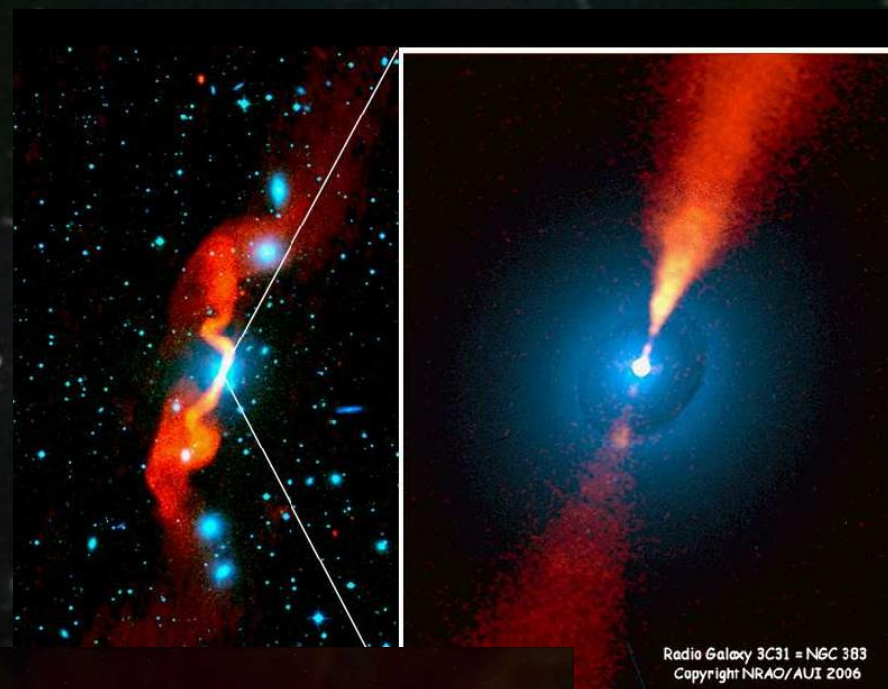
Application to BHs and relativistic jets

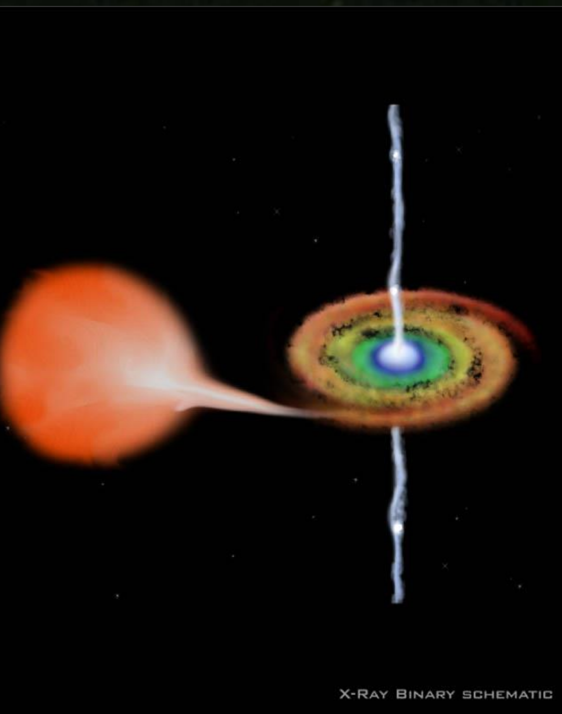


Black Hole sources are accelerators

(specially of cosmic rays >10 ^{17} eV) and VHE emitters

AGNs (blazars, radio-galaxies, seyferts)

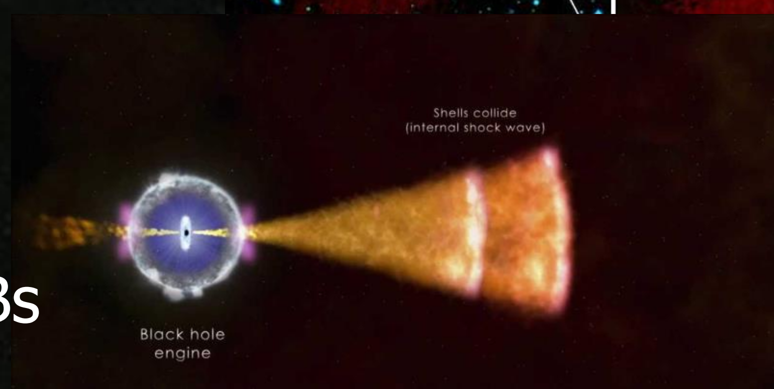




Black Hole Binaries

(Microquasars)

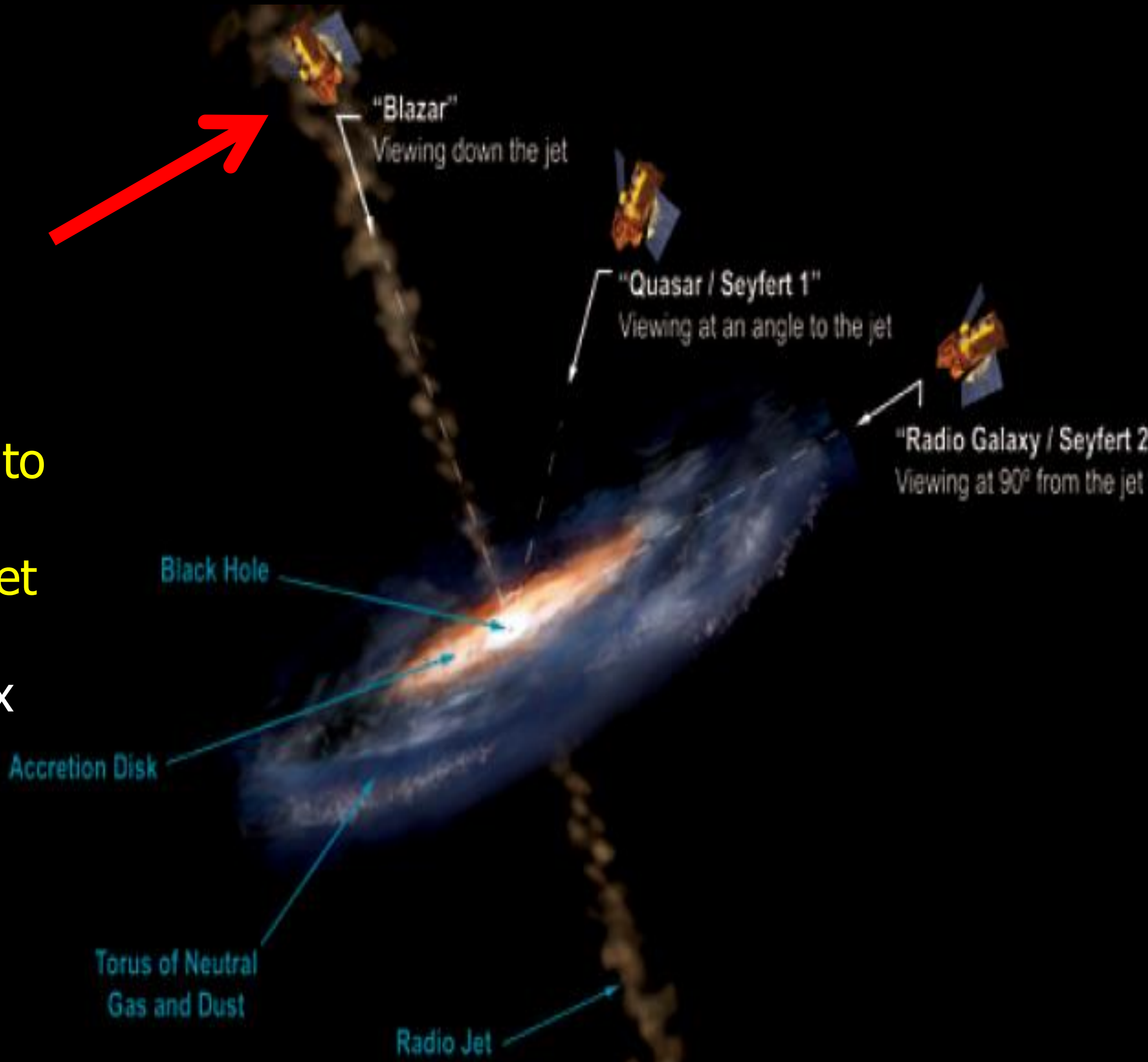
GRBs



VHE emission more common in Blazars

High Luminous AGNs

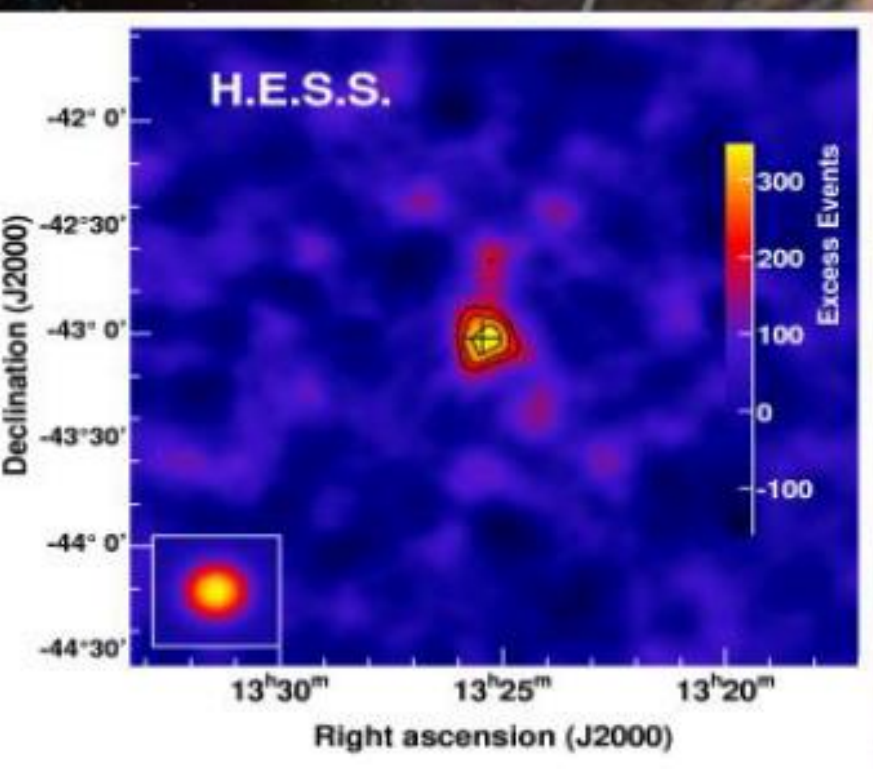
- ✓ Jet ~ along our line of sight
- ✓ VHE Emission (poor resolution): attributed to particle acceleration ***along*** the relativistic jet
- ✓ with apparent high flux due to strong Doppler boosting (γ~5-10)
- ✓ shock acceleration in kinetic-dominated flux



...*But*
a few Non-Blazars Low Luminous AGNs

- ✓ **Also Gamma Ray emitters**
- ✓ Jet does not point to the line of sight
- ✓ no significant Doppler boosting !

CenA



✓ ***Does it come from core or jet ?***

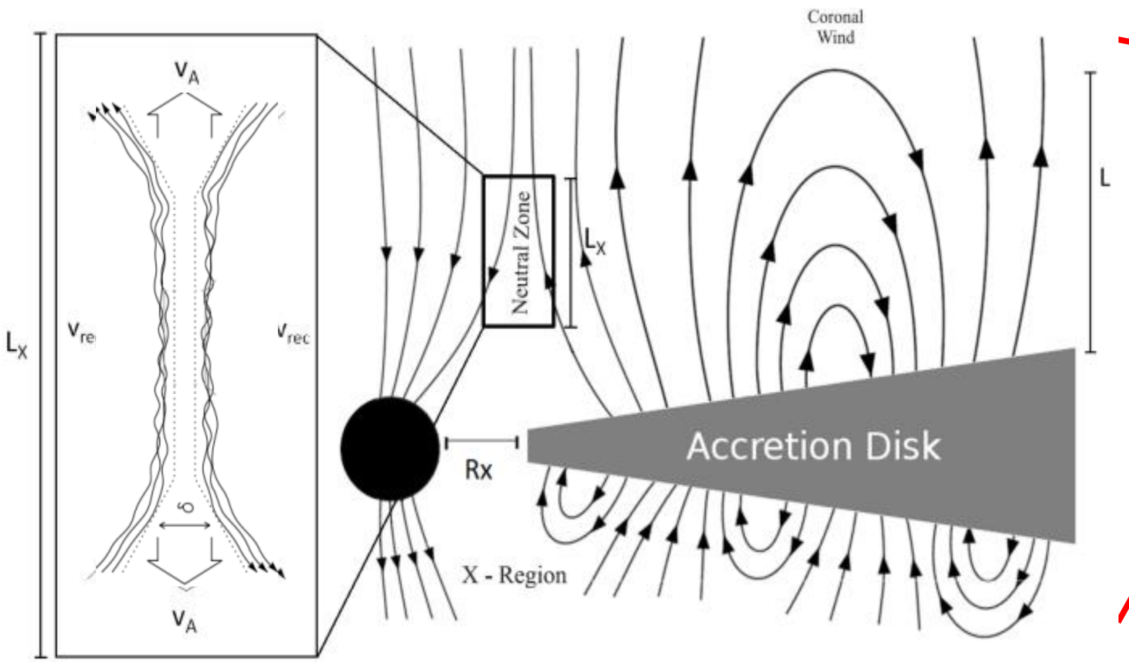
✓ **Rapid variability emission: ~100 r_s**
-> compact *emission (core)?*

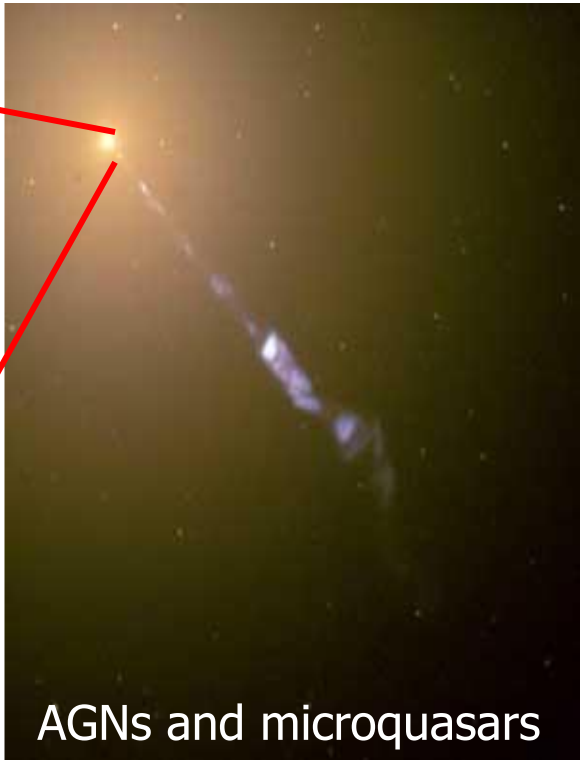
- Where are particles accelerated?
- Is acceleration magnetically dominated?

Reconnection Acceleration?

Reconnection acceleration in the surrounds of BHs ?

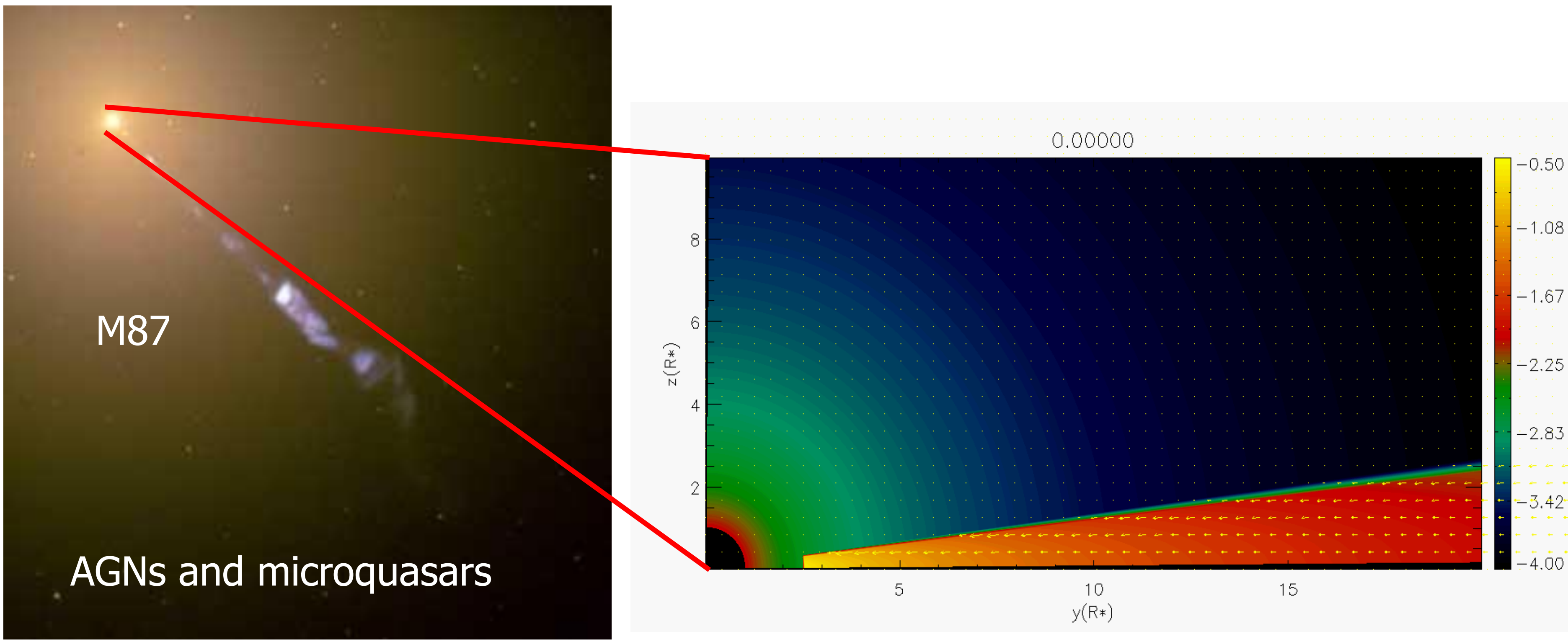
Accretion disk/jet systems (AGNs & galactic BHs)





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

Evidence of Reconnection in MHD Simulations



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

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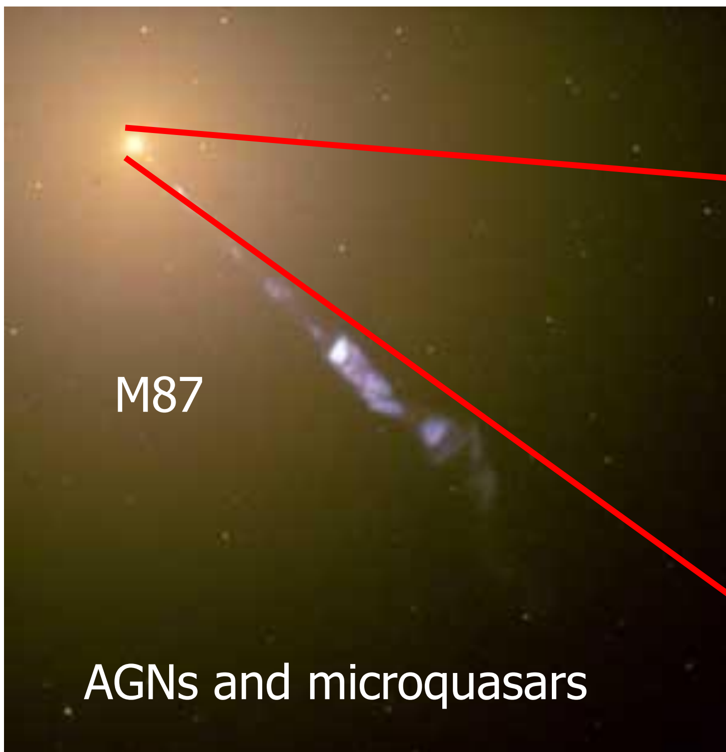

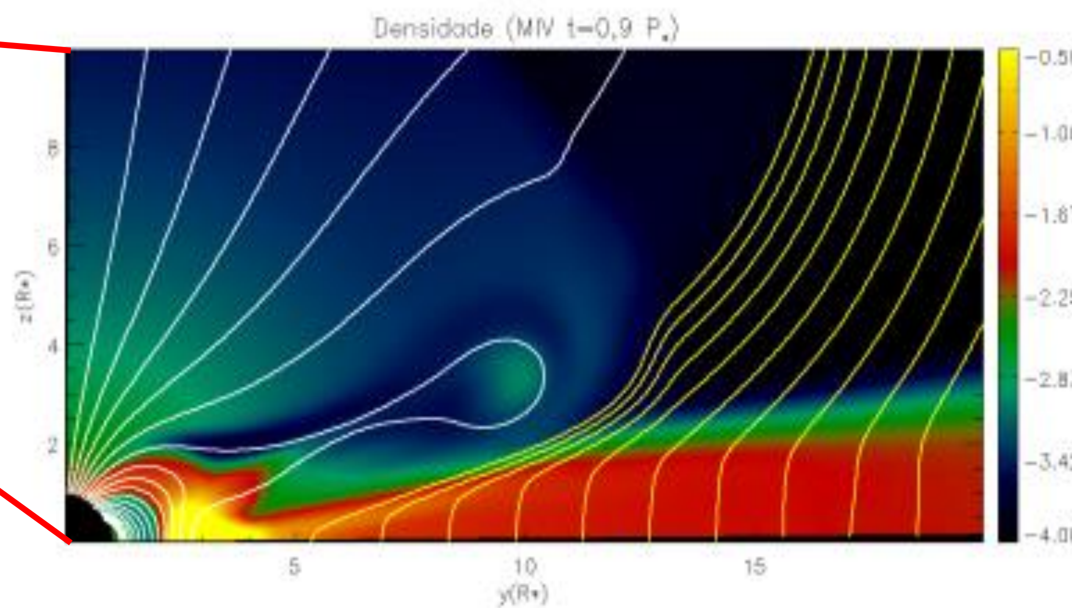

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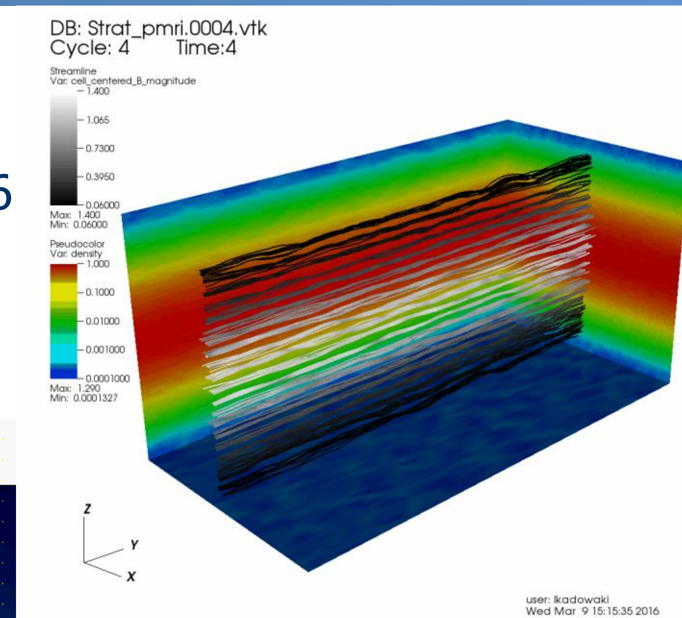
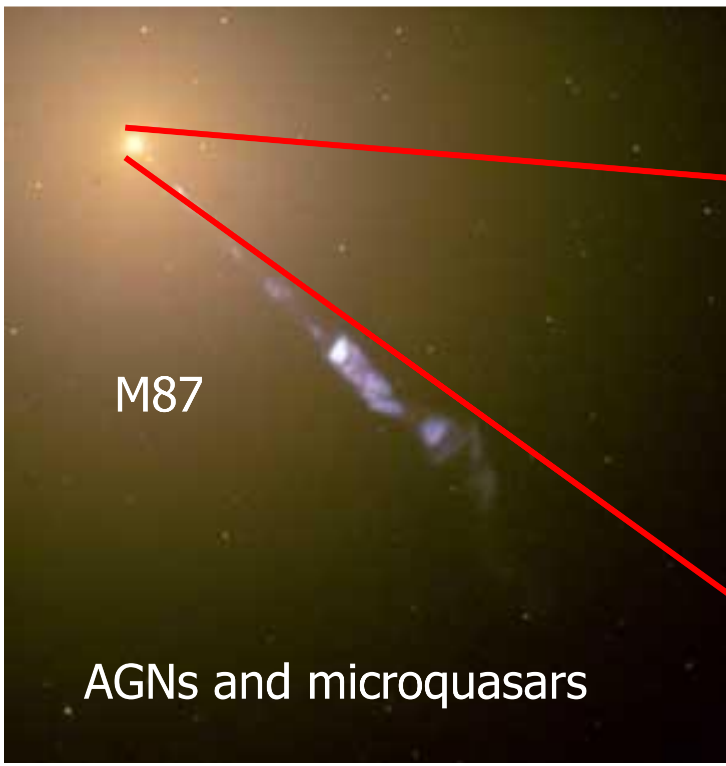
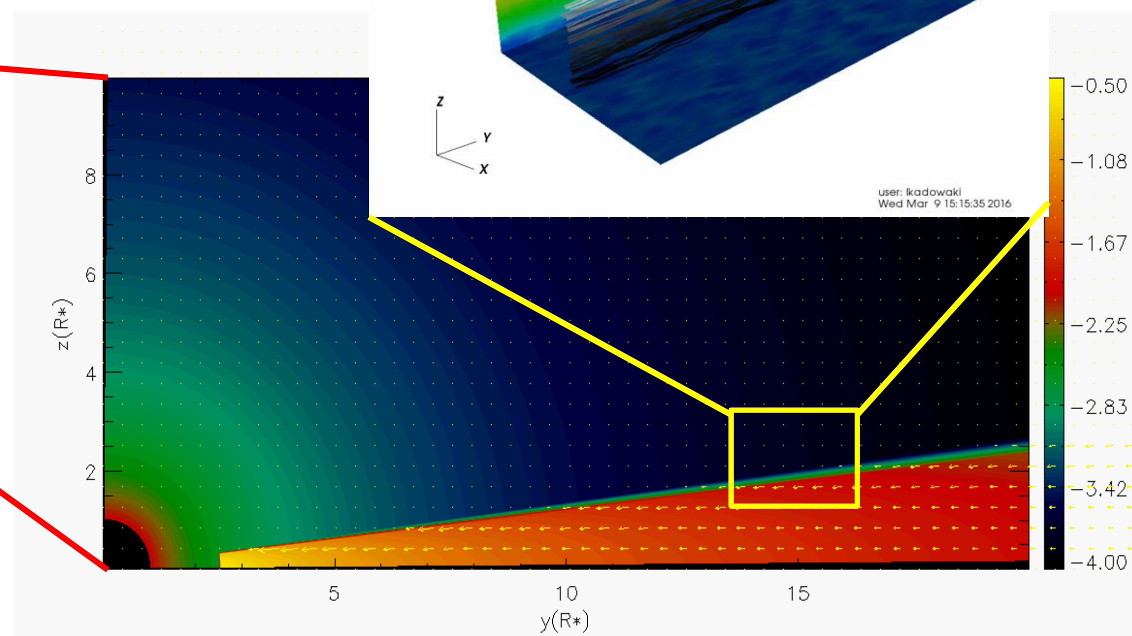
Evidence of Reconnection in MHD Simulations

Kadowaki, de Gouveia Dal Pino, Stone 2016







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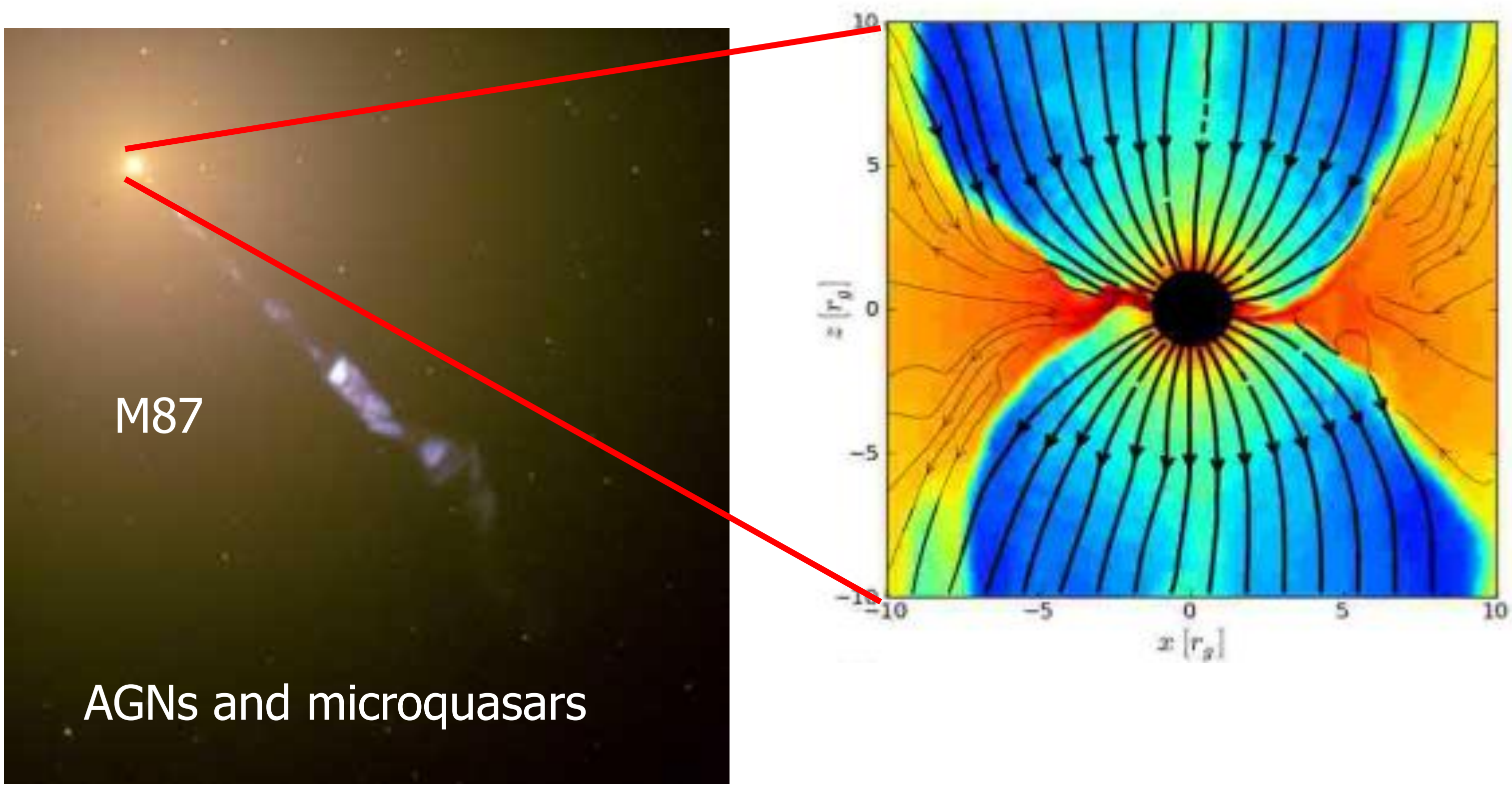
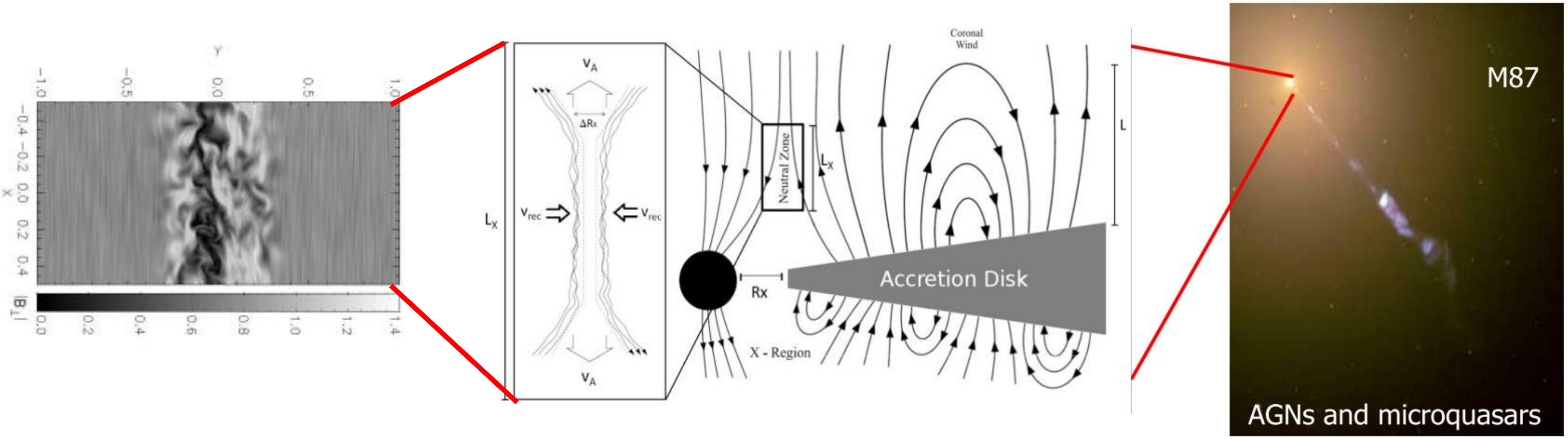


Dexter, McKinney et al. 2014: reconnection seen in GRMHD simulations (also Koide & Arai 2008)

Reconnection acceleration in the surrounds of BHs

Revisited the model to evaluate reconnection power and acceleration -> apply to more than 230 sources:

- Different accretion disk models (Shakura-Sunyaev; MDAF)
- Coronal model by Liu et al. (2002, 2003).
- Fast reconnection in the surrounds of the BH driven by turbulence



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

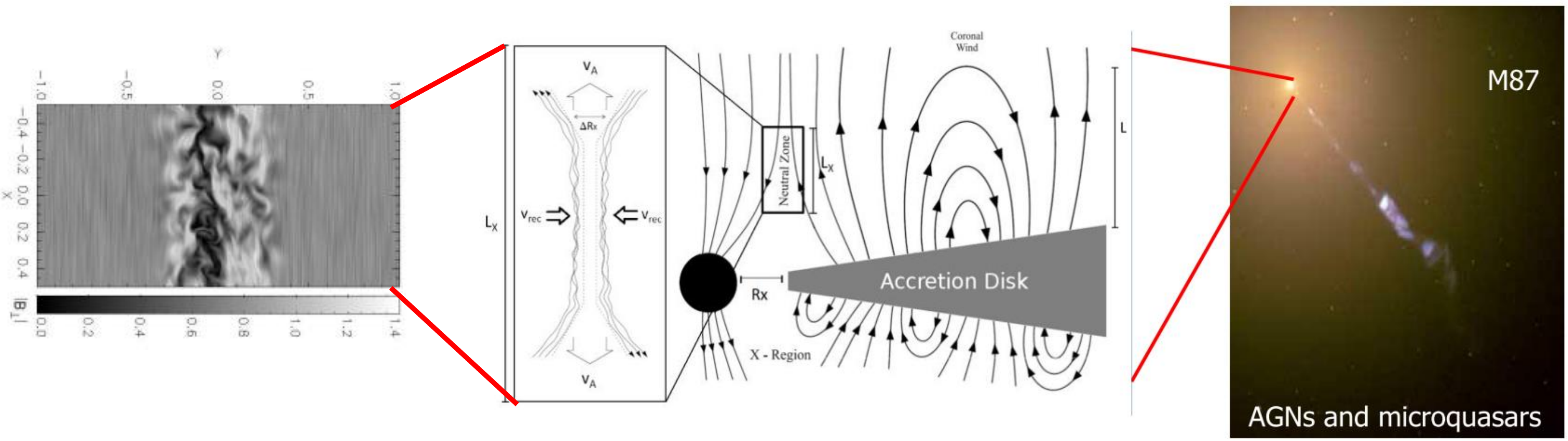
Reconnection acceleration in the surrounds of BHs

$$B \cong 9.96 \times 10^{8} r_X^{-1.25} \xi^{0.5} m^{-0.5} \quad \mathrm{G}$$

$$W \cong 1.66 \times 10^{35} \psi^{-0.5} r_X^{-0.62} l^{-0.25} l_X q^{-2} \xi^{0.75} m \quad \mathrm{erg\,s^{-1}}$$

$$\Delta R_X \cong 2.34 \times 10^{4} \psi^{-0.31} r_X^{0.48} l^{-0.15} l_X q^{-0.75} \xi^{-0.15} m \quad \mathrm{cm}$$

$$n_c \cong 8.02 \times 10^{18} \psi^{0.5} r_X^{-0.375} l^{-0.75} q^{-2} \xi^{0.25} m^{-1} \quad \mathrm{cm^{-3}}$$

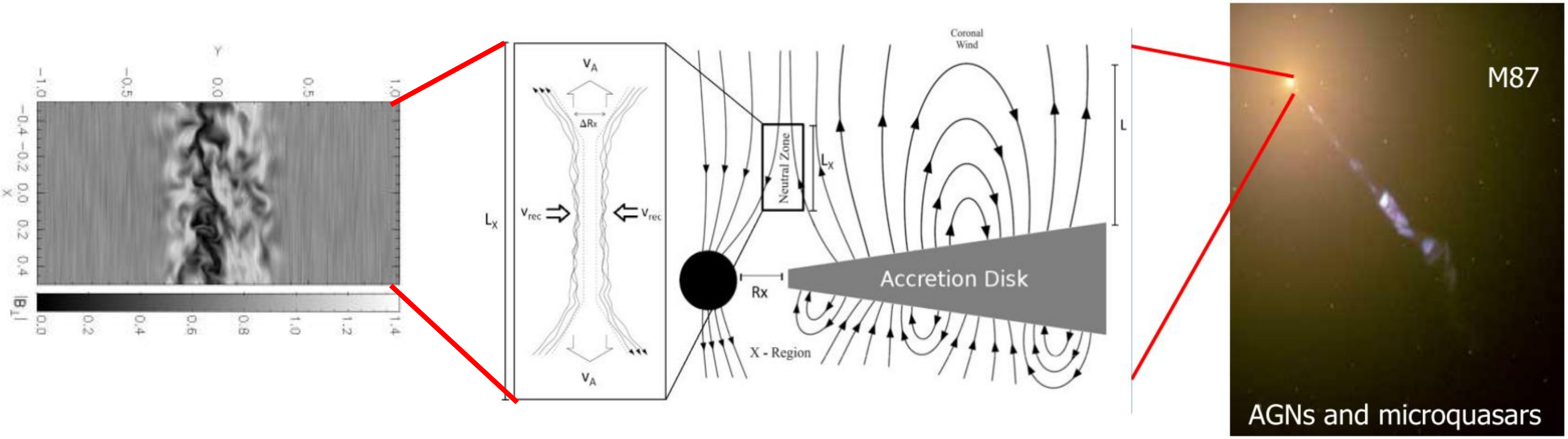


Kadowaki, de Gouveia Dal Pino, Singh, ApJ 2015
Singh, de Gouveia Dal Pino, Singh, ApJ Lett. 2015

Reconnection acceleration in the surrounds of BHs

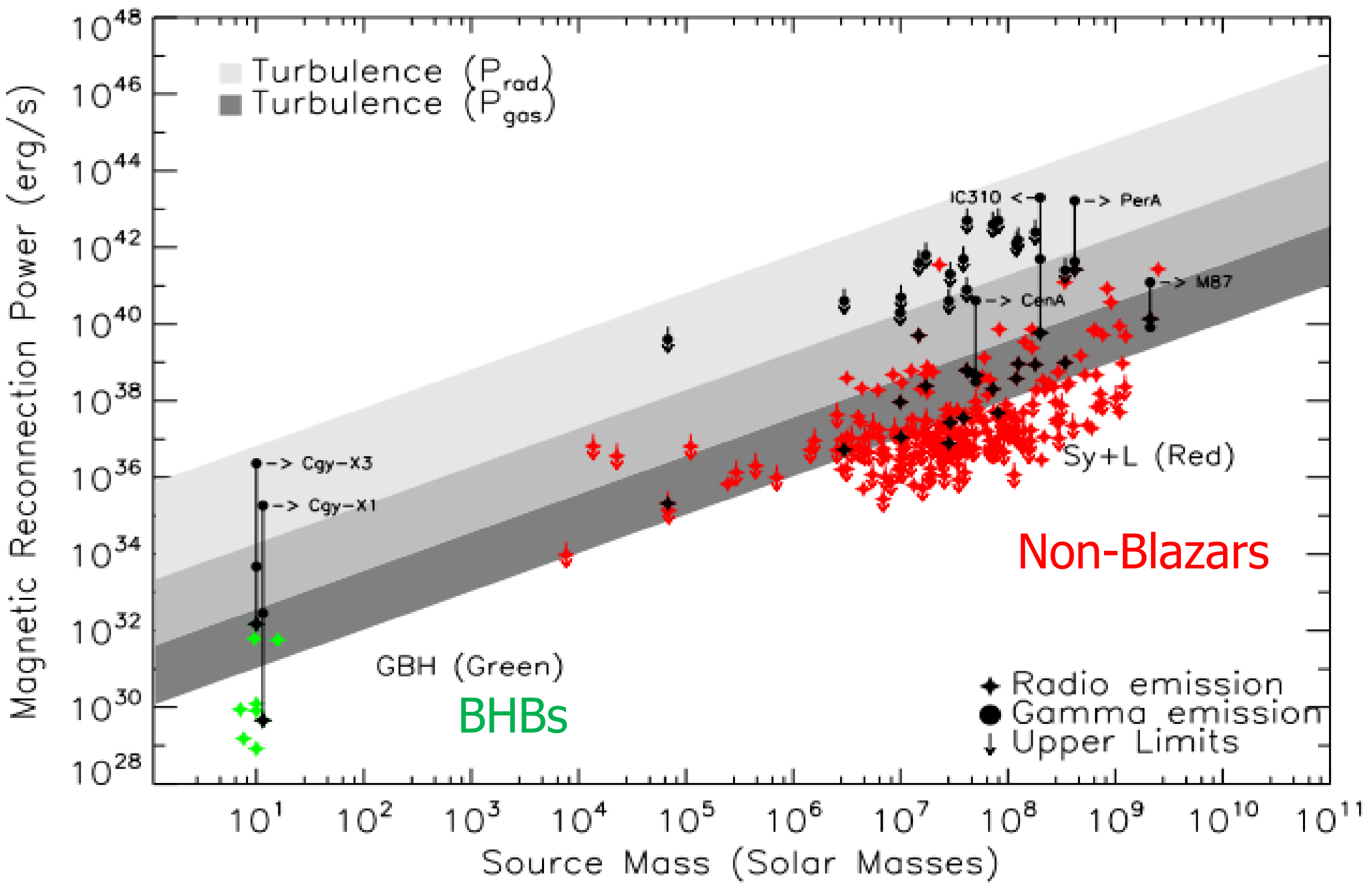
Magnetic Power

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



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

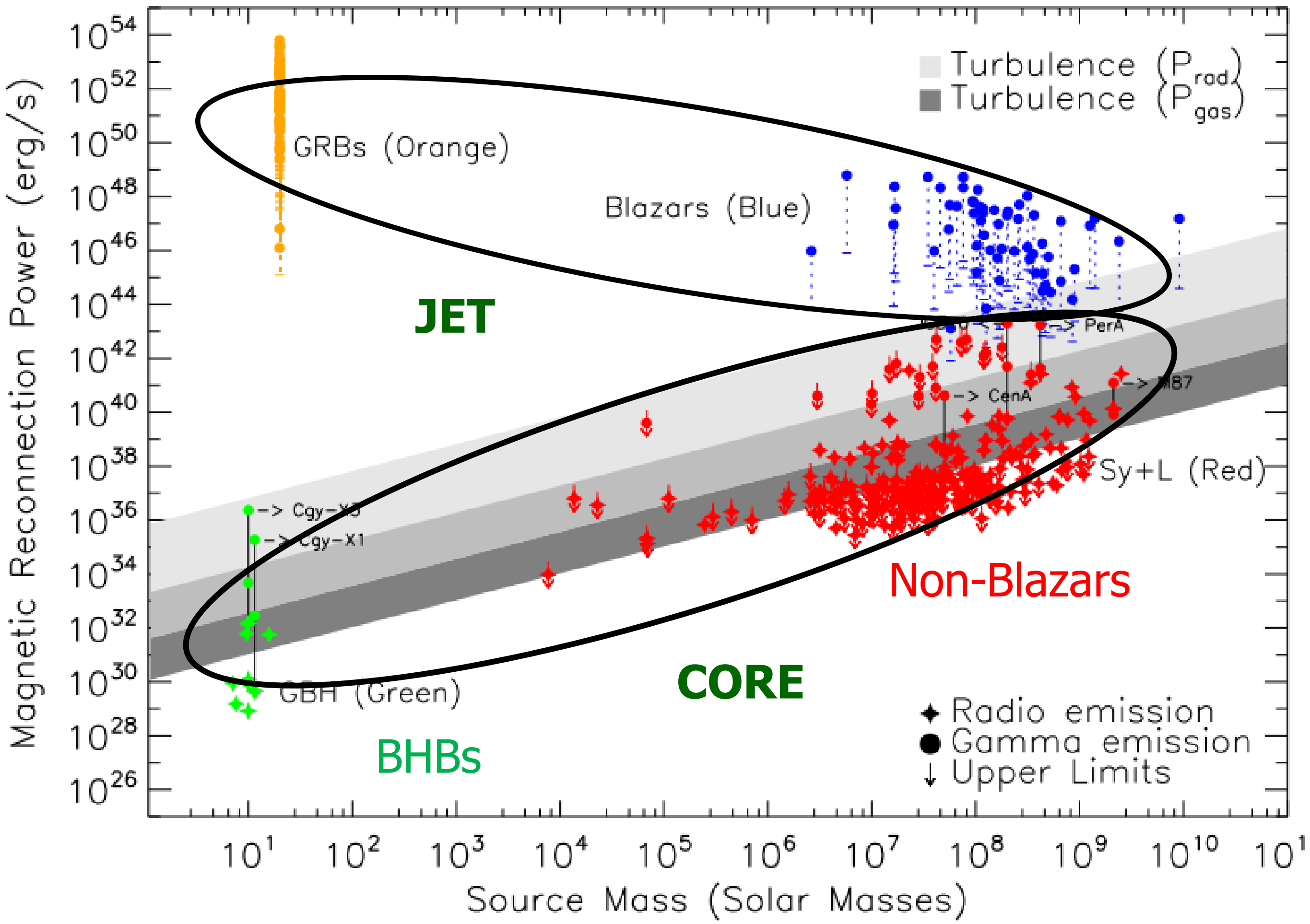
Magnetic Reconnection Power around BHs



$0.0005 \leq \dot{m} \leq 1$
$1 \leq l \leq 18$
$l_X \leq l$
$r_X = 6$
$\Gamma \sim 1$

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

Magnetic Reconnection Power around BHs



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

Also applied the reconnection acceleration model in the *core* to build the full SPECTRUM of

Non-Blazars: CenA, M87, PerA, 3C110

(Khiali, de Gouveia Dal Pino, Sol, arXiv:1504.07592)

Microquasars: Cyg X1 and Cyg X3

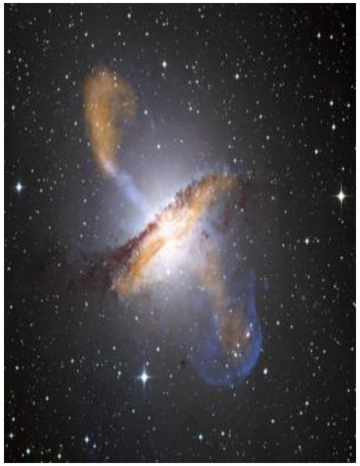
(Khiali, de Gouveia Dal Pino, del Valle, MNRAS 2015)

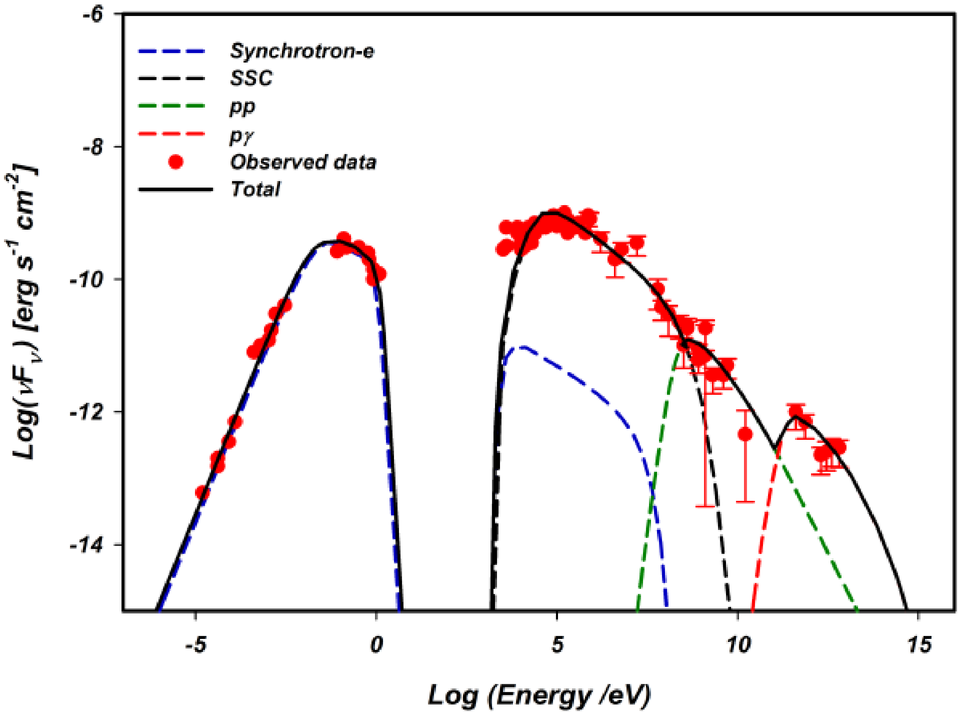
Reconnection Acceleration & Radiation from the core

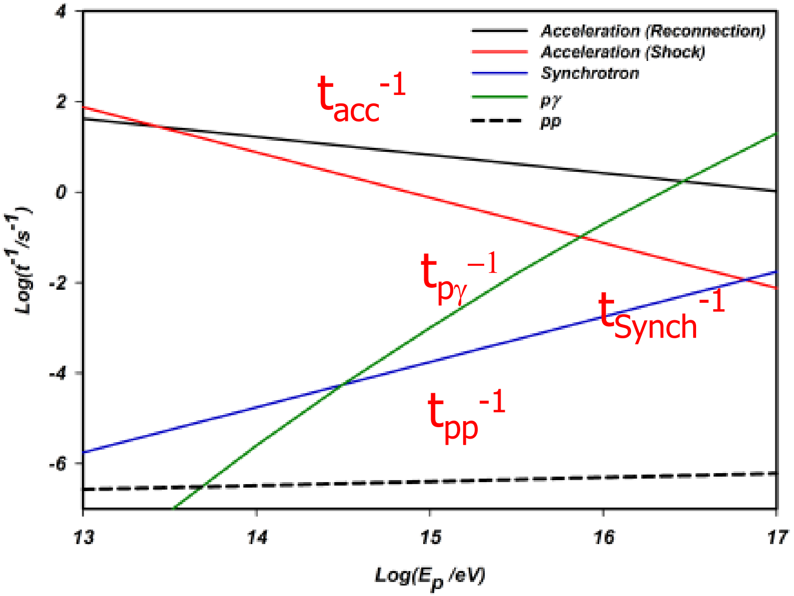
- ✓ **Cooling of the accelerated particles -> emission:**

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

Ex.: Radio-galaxy Cen A



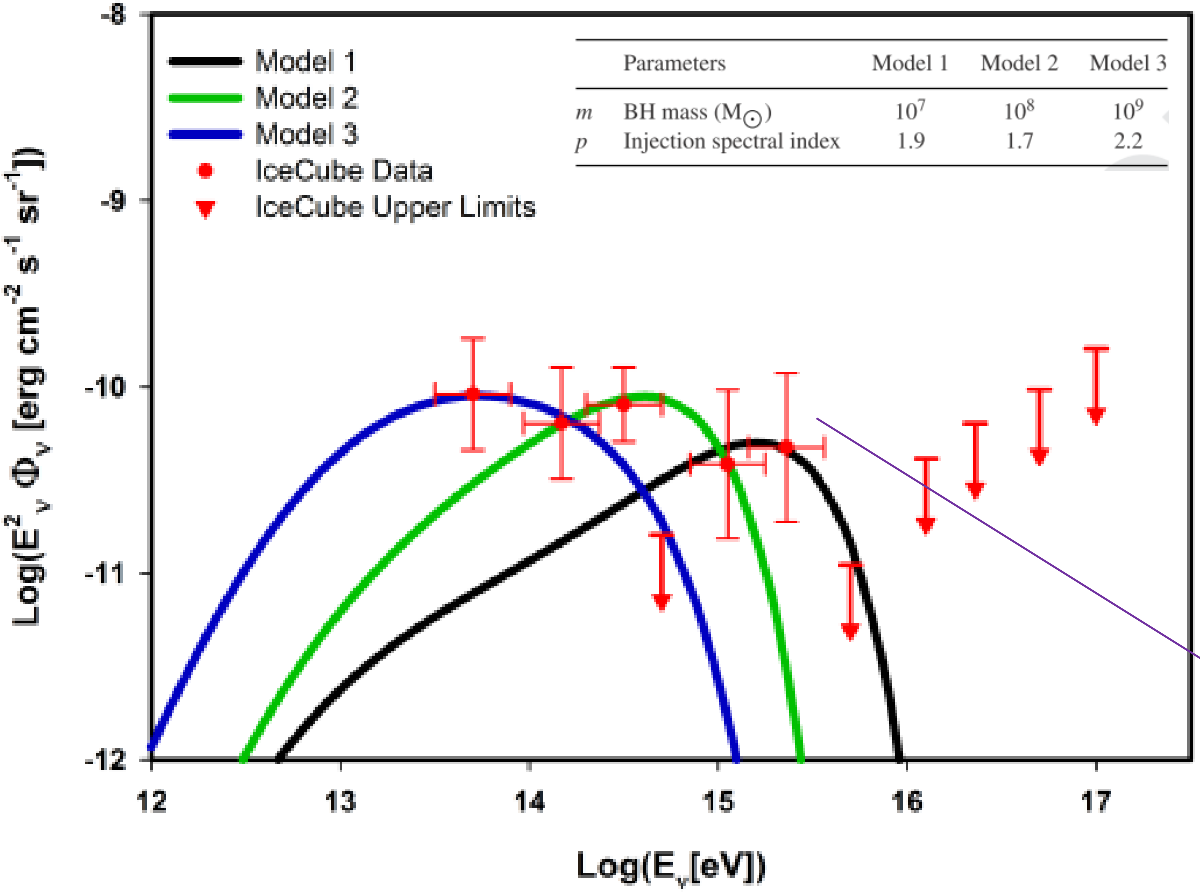




Spectral Energy Distribution

Khiali, de Gouveia Dal Pino, Sol 2015 (arXiv:1504.07592); Khiali, de Gouveia Dal Pino, del Valle, MNRAS 2015

Neutrino emission from ***cores*** of low luminous AGNs (z ~ 0 – 5.2) due to reconnection acceleration



$p + \text{photons} \rightarrow \pi + p$

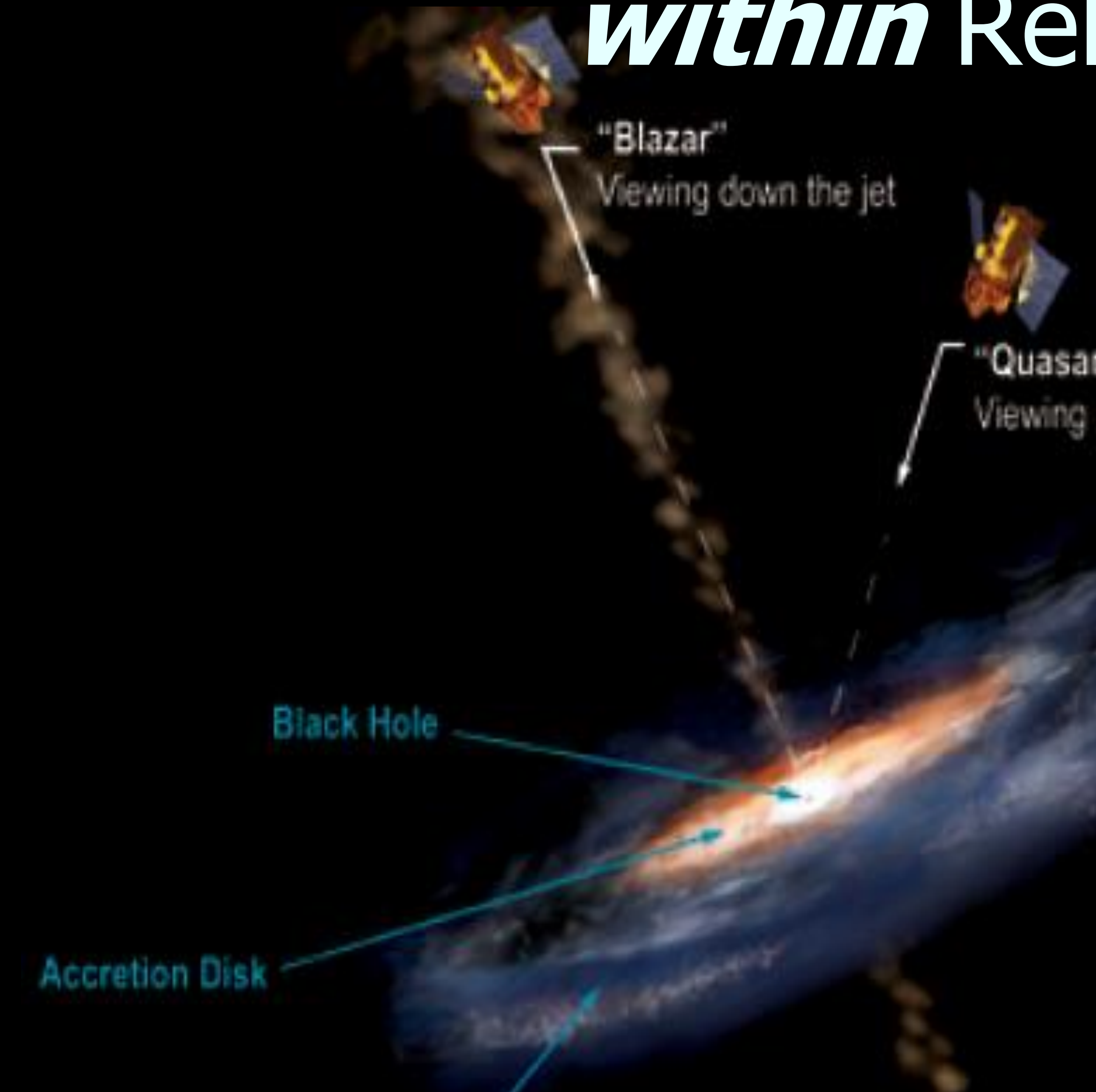
$\pi^o \rightarrow \gamma\gamma$

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

IceCube flux of Neutrinos

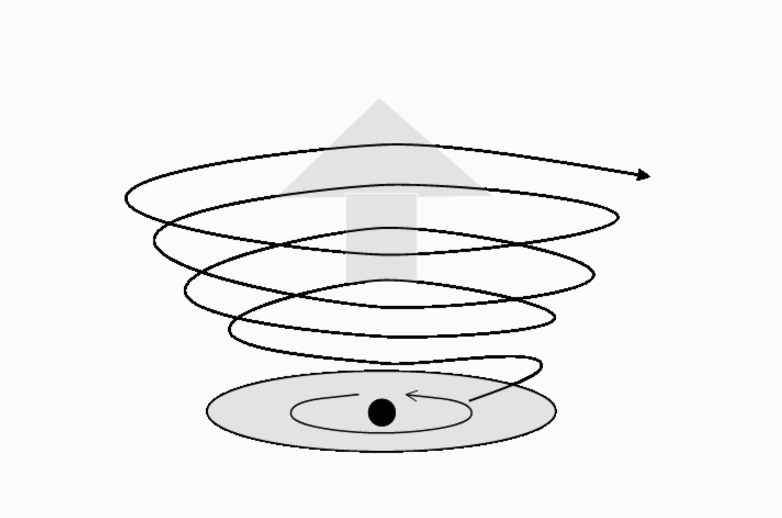
Khiali & de Gouveia Dal Pino, MNRAS 2015

Reconnection Acceleration ***within*** Relativistic Jets



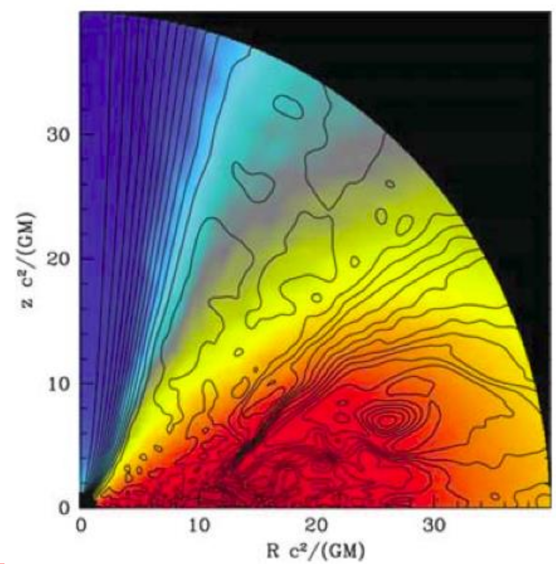
If jet emission produced near the core and jet is magnetic, then reconnection acceleration may prevail

Are Jets born magnetically dominated?



Magneto-centrifugal acceleration by helical field arising from the accretion disk (Blandford & Payne)

Or powered by BH spin (Blandford-Znajek)



GRMHD simulations (e.g., McKinney 06)

Major Problem 1:

Most energy in Poynting Flux (magnetic field)

➡ Need rapid conversion (dissipation) to kinetic:

Requires RECONNECTION?

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

- **Variation timescale:**

  $t_v \sim 200$ s < $r_s/c \sim 3M_9$ hour

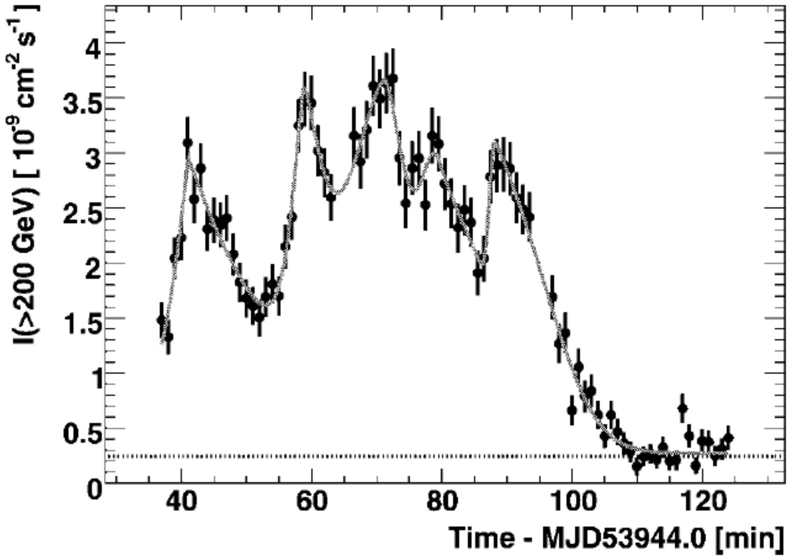
- For TeV emission to avoid pair creation $\gamma_{em} > 50$ (Begelman, Fabian & Rees 2008)

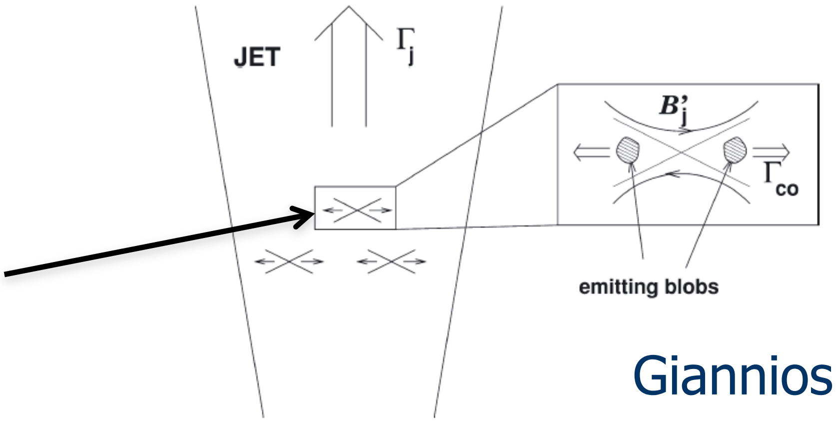
- But bulk jet $\gamma \sim$ 5-10

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

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

PKS2155-304 (Aharonian et al. 2007)
See also Mrk501, PKS1222+21



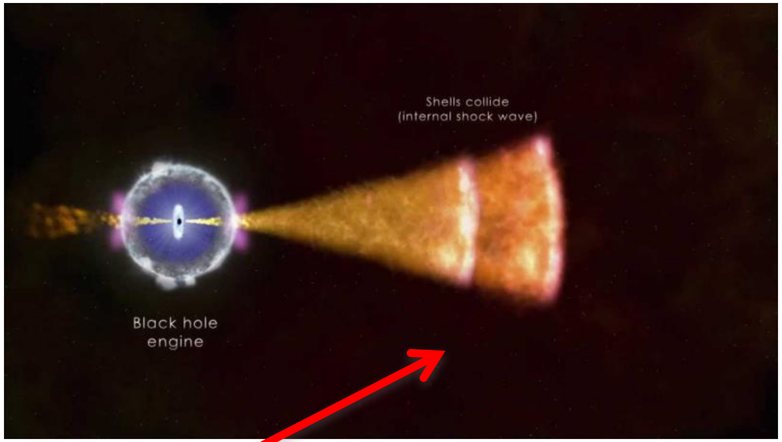


Giannios et al. (2009)

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

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

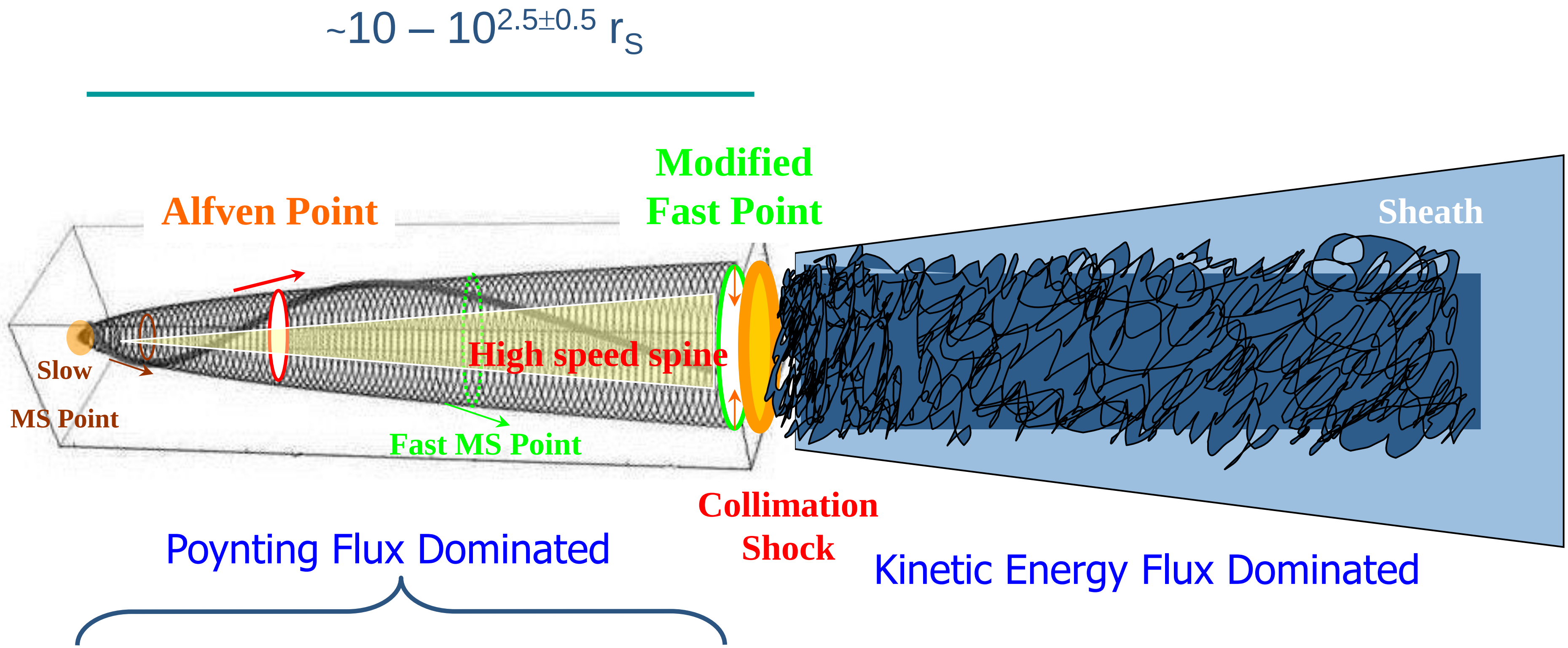
- **GRB prompt emission: turbulence, magnetic reconnection, and particle acceleration via internal collisions of multiple launched parcels**



(See also Gianios 2008; McKinney & Uzdensky 2012)

Regions of AGN & GRB Jet Propagation

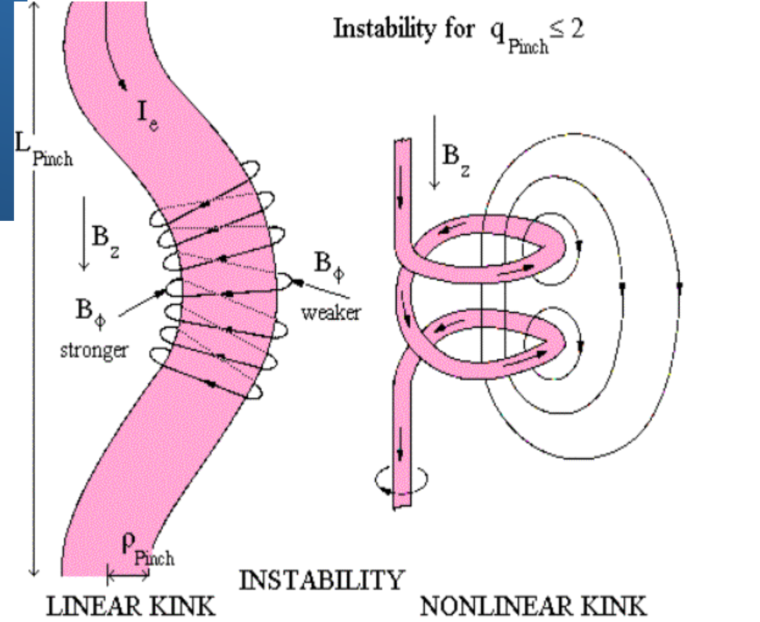
Modified from D. Meier & Y. Mizuno (courtesy)



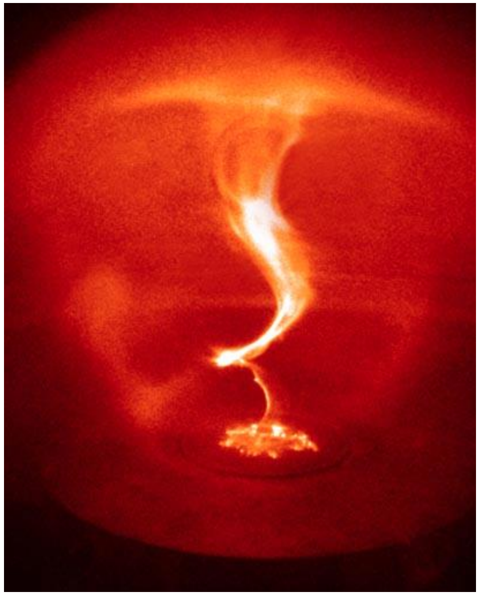
Current Driven Kink Instability
(Mizuno et al. 2012)

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



Schematic picture of CD kink instability



Kink instability in lab plasma (Moser & Bellan 2012)

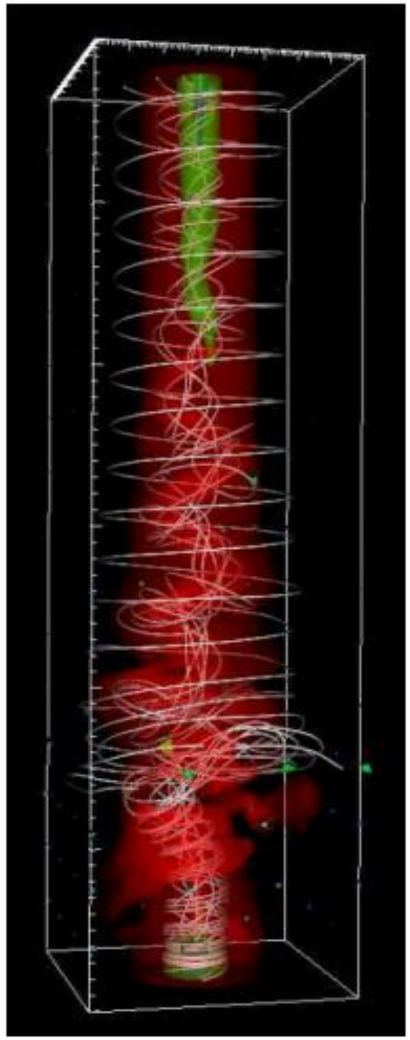
MHD Simulations of Reconnection driven by Kink in Magnetically Dominated Relativistic Jets (GRBs & AGNs)

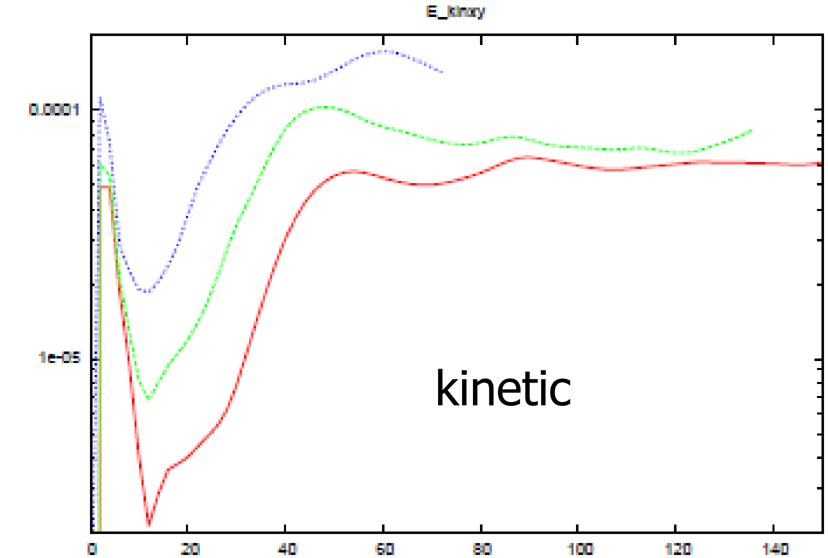
- Precession perturbation allows growth of CD kink instability with helical density distortion.

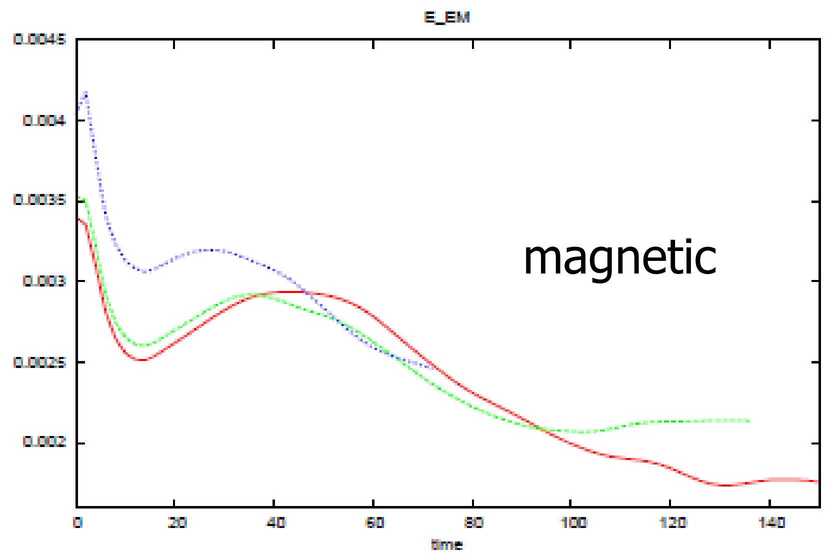
- Helical kink advected with the flow with continuous growth of kink amplitude in non-linear phase.

- Helical structure is disrupted

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



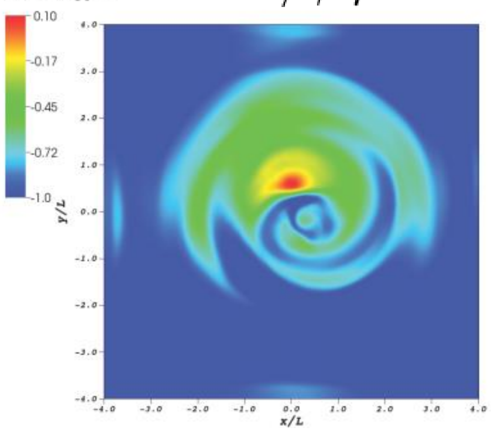




Singh, Mizuno, de Gouveia Dal Pino, ApJ 2016

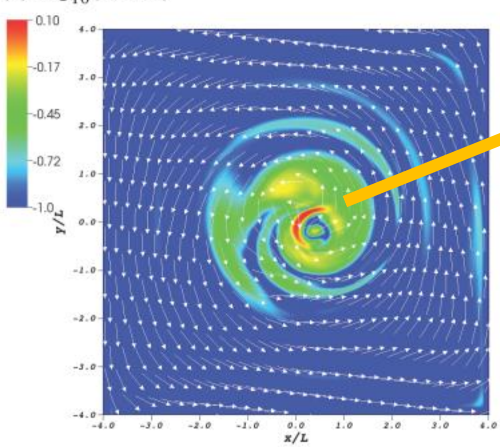
Reconnection driven by Kink in Magnetically Dominated Relativistic Jets (GRBs & AGNs)

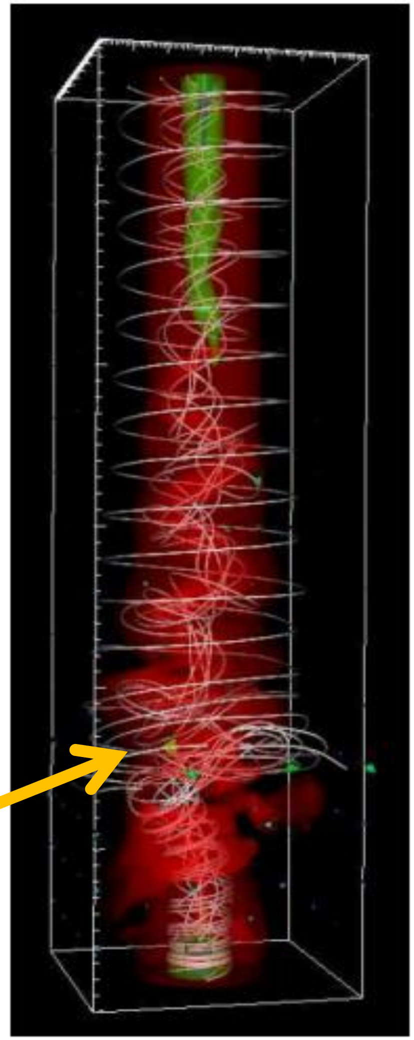
(a) $\log_{10}(\sigma$ $\sigma = B^2/\gamma^2 \rho h$



$v_{rec} \sim 0.05\ v_A$

(b) $\log_{10}$(curl B)





curl B = max

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

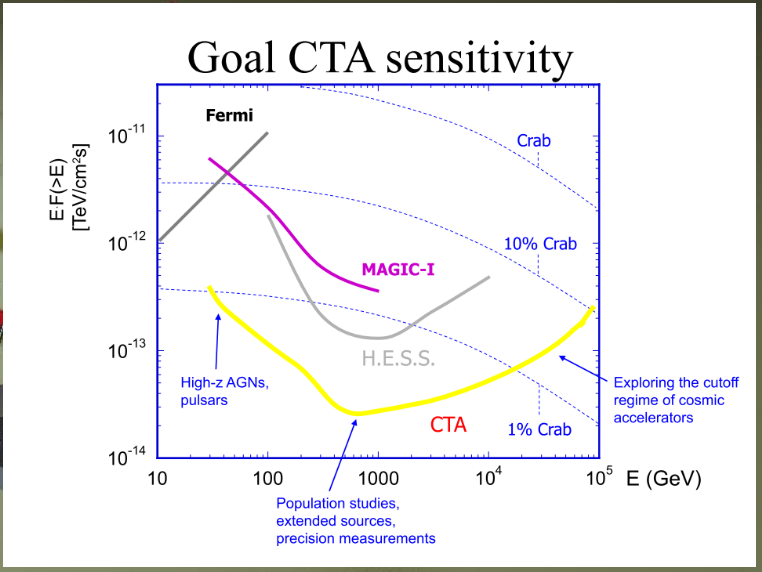
Singh, Mizuno, de Gouveia Dal Pino, ApJ 2016

Summary

- ✓ Reconnection can be important in accretion/jet systems for particle acceleration, dissipation of magnetic energy and conversion MDF -> KDF
- ✓ Fermi particle acceleration by turbulent magnetic reconnection (numerically tested): can explain gamma-ray of microquasars and non-blazar AGNs as coming from the *core*
- ✓ The magnetic reconnection power matches well with the observed correlation of radio/gamma-ray luminosity versus BH mass of microquasars and non-blazar AGNs over 10 orders of magnitude in mass
- ✓ Reconnection acceleration in the core -> SEDs of non-blazars and microquasars
- ✓ Reconnection in magnetically dominated relativistic jets can be triggered by CD Kink instability, can explain rapid variability and possibly drive Fermi acceleration and gamma-ray emission too

CTA: Cherenkov Telescope Array

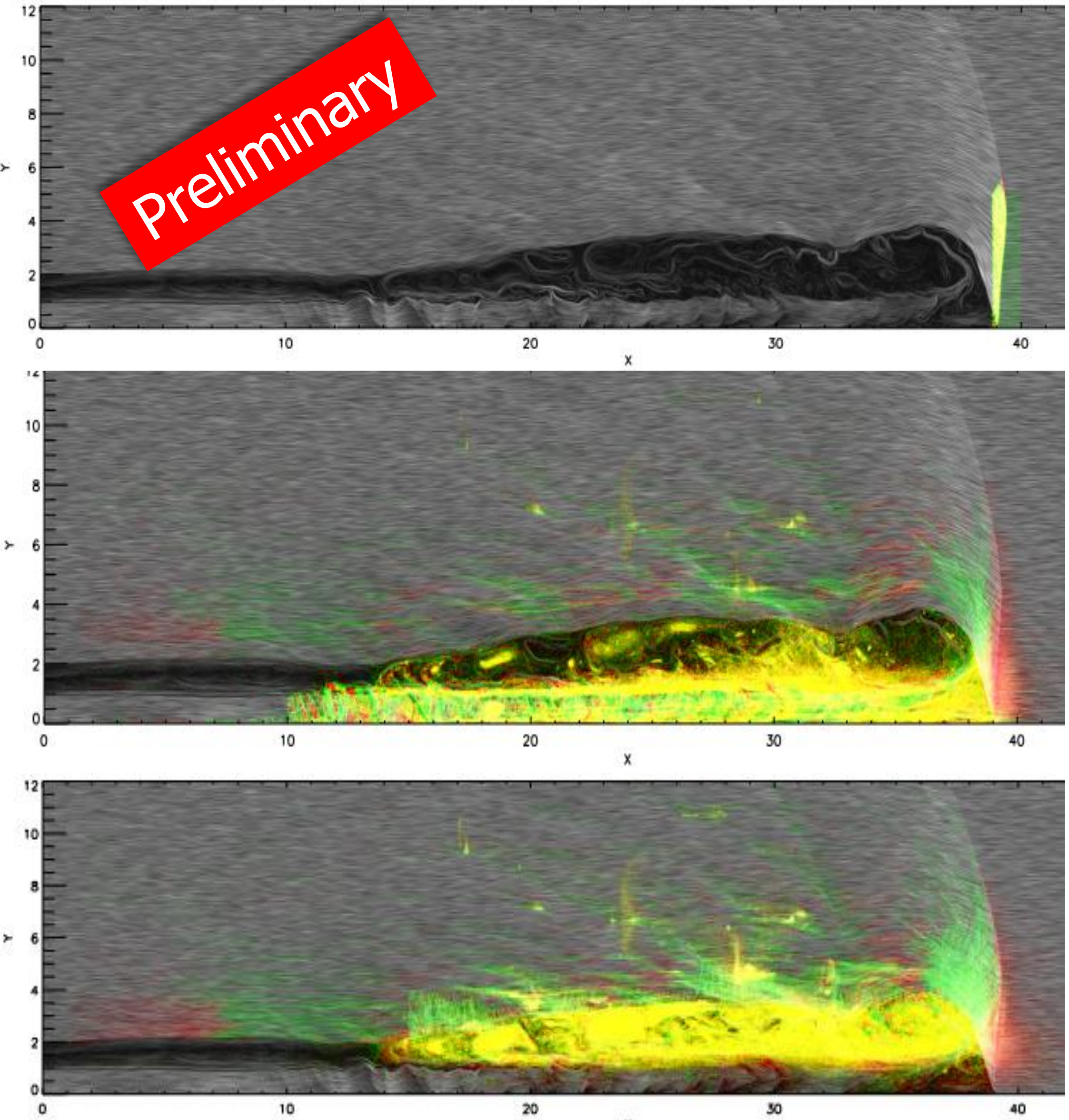
ASTRI Mini-Array



CTA & ASTRI Mini-Array will locate the real region of acceleration and help to unveil the physics in the core/jet launching

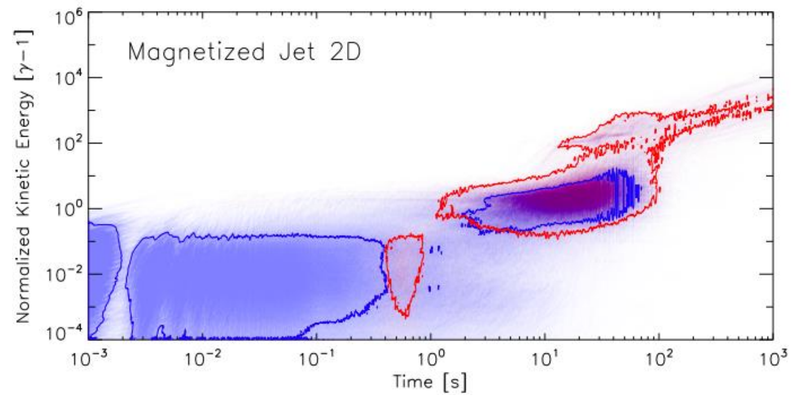
EXTRA SLIDES

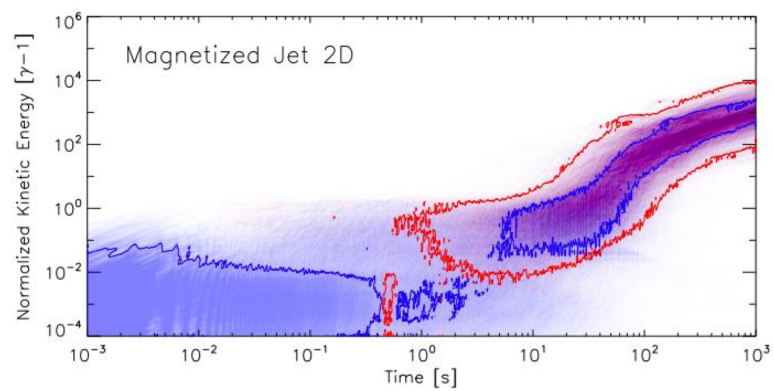
In situ 1st-order Fermi Relativistic MHD Reconnection x shock acceleration in Jets



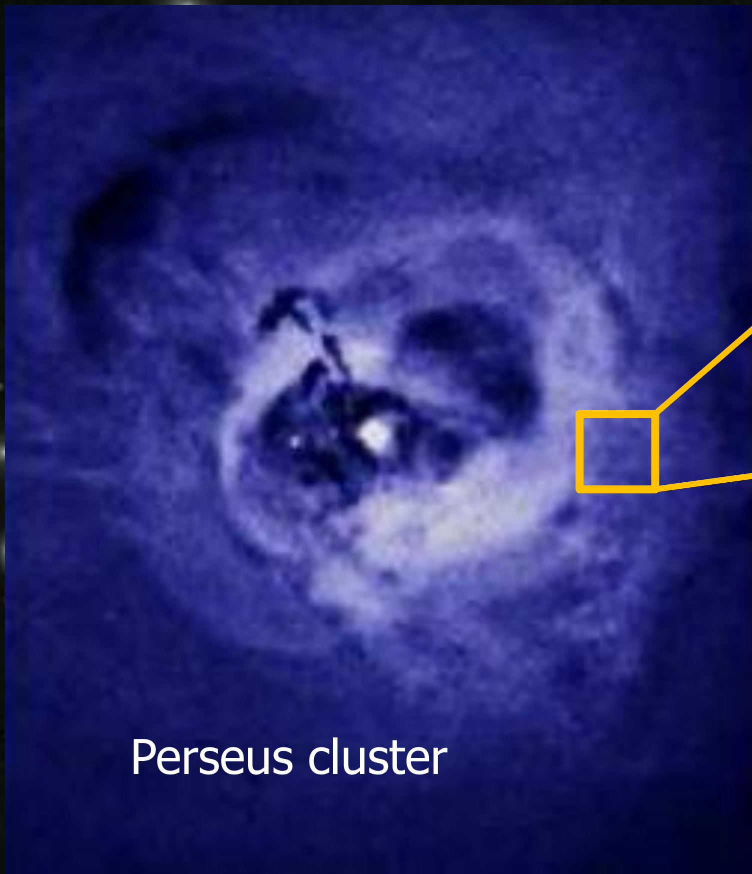
Competing mechanisms

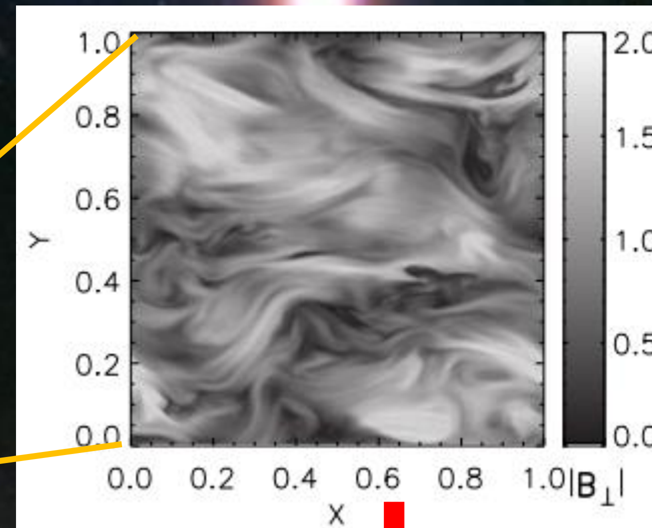
de Gouveia Dal Pino & Kowal, ASSL 2015

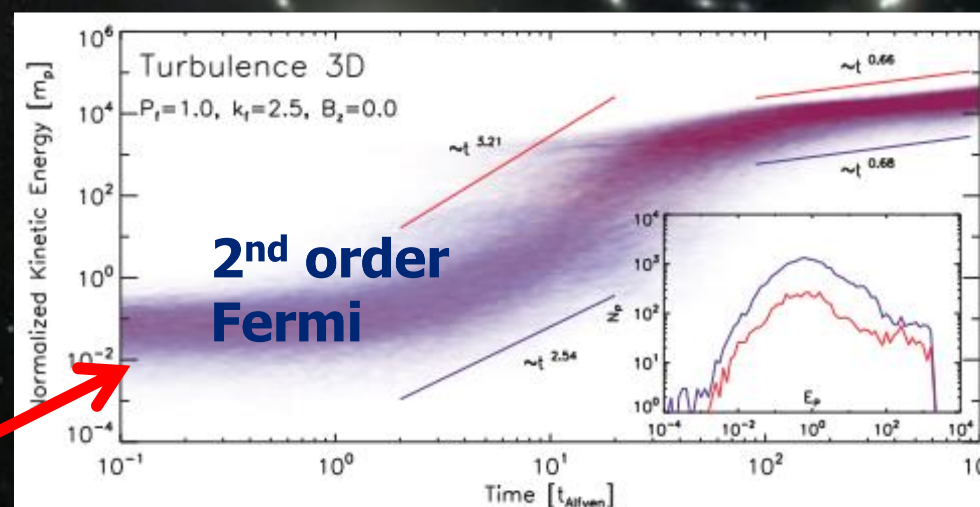




Particle Acceleration in 3D MHD Pure Turbulence



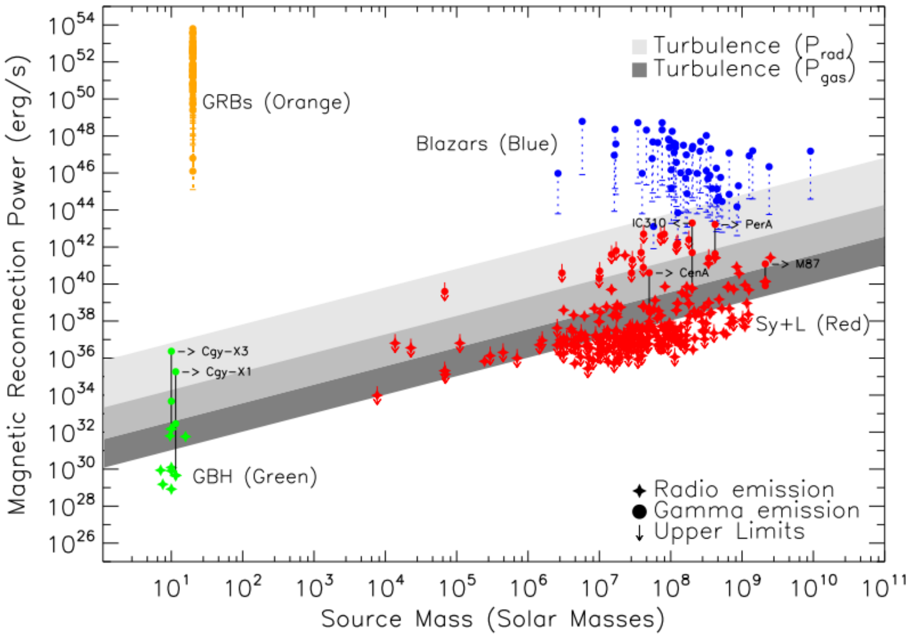


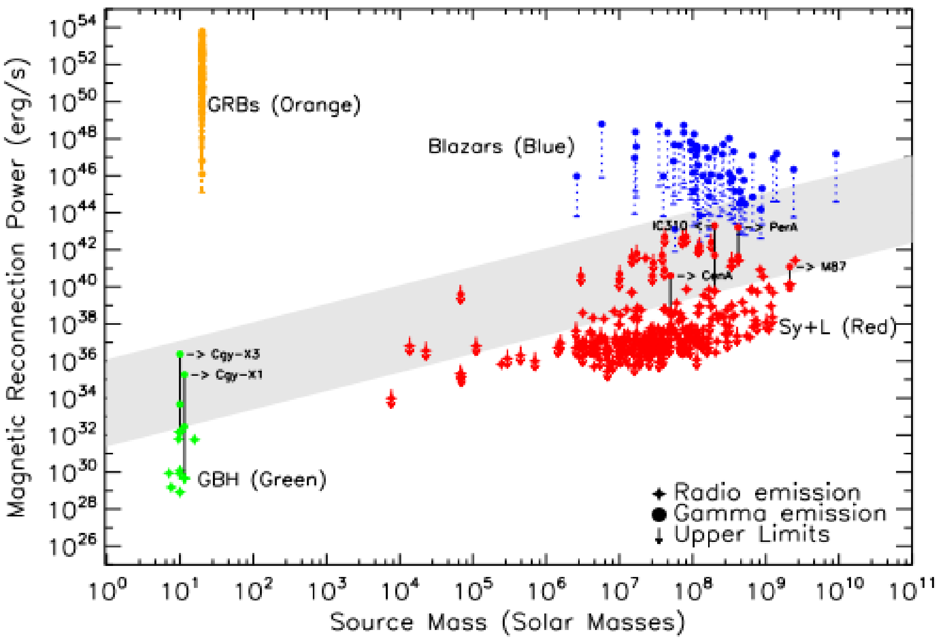


scattering by approaching and receding magnetic irregularities

Kowal, de Gouveia Dal Pino, Lazarian, PRL 2012

Magnetic Reconnection around BHs works for different Accretion Disk Models





Standard accretion disk

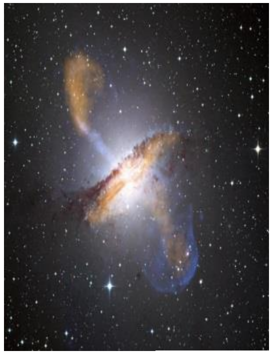
Soft -> Hard

MDAF accretion disk

Hard -> Soft

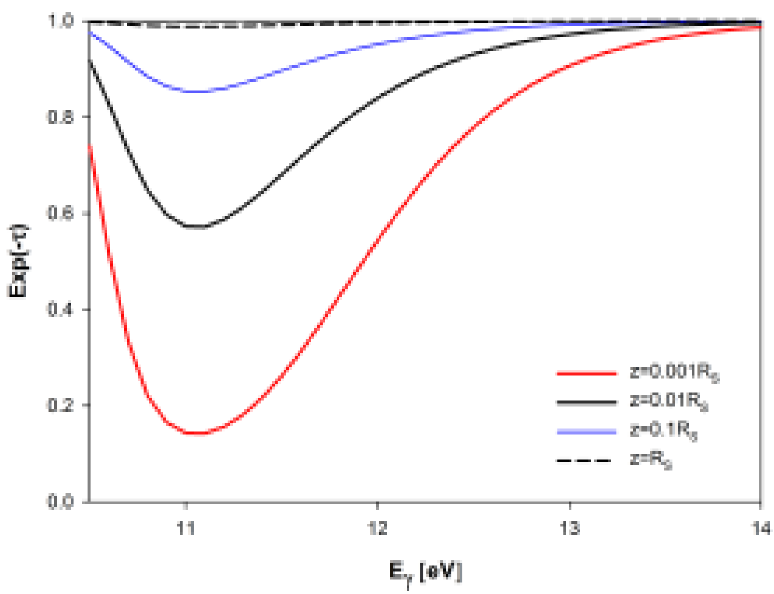
Kadowaki, de Gouveia Dal Pino, Singh, ApJ 2015;
Singh, de Gouveia Dal Pino, Kadowaki, ApJL 2015

Reconnection Acceleration X Radiative Losses

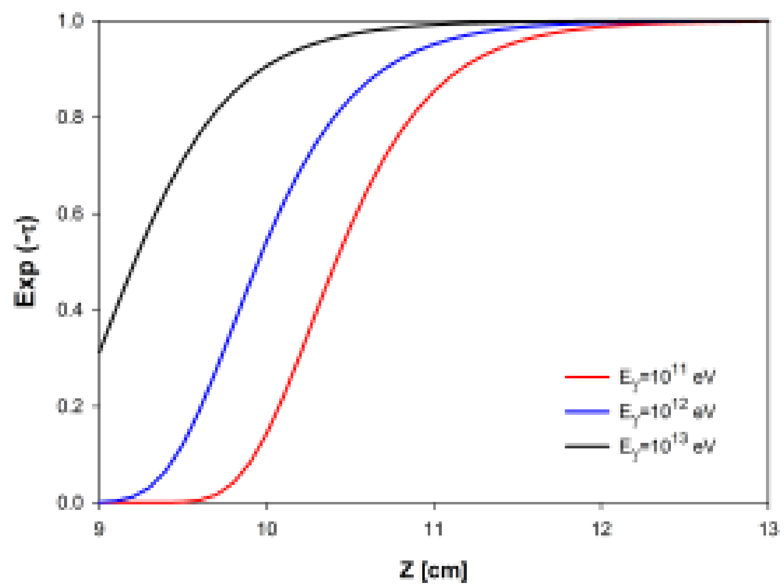


✓ γ-ray flux absorption by pair production as function of energy and height z above the plane of the accretion disk

Ex.: **Radio-galaxy Cen A**



(a) Cen A



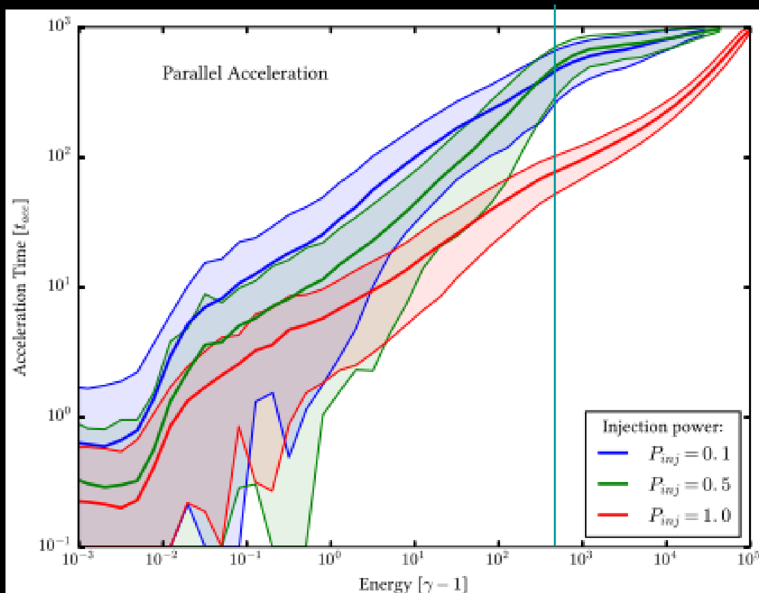
(b) Cen A

z>1 Rs -> NO absorption

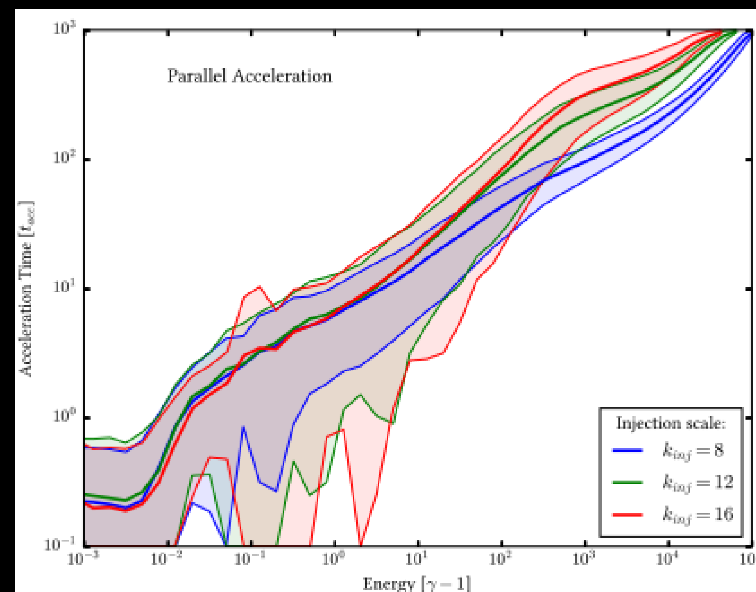
Khiali, de Gouveia Dal Pino, Sol 2015

3D MHD Reconnection Acceleration tested for different parameters of **turbulence**

Acceleration time X E for different turbulence injection power P_{inj}



Acceleration time X E for different turbulence injection scale $1/k_{inj}$

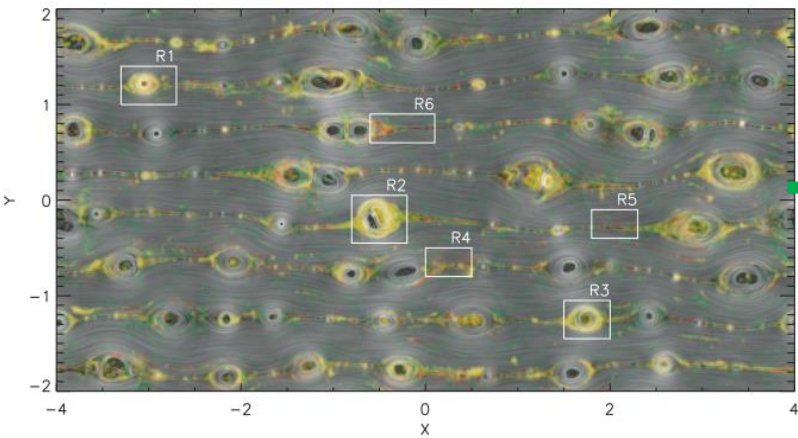


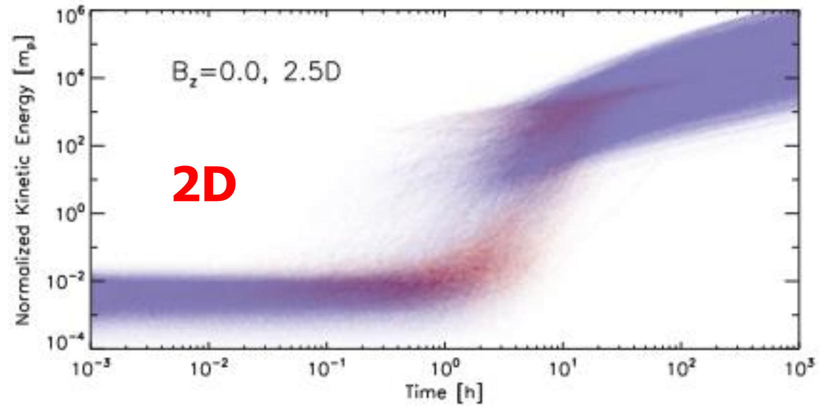
✓ **Acceleration time -> weak dependence with parameters of turbulence**

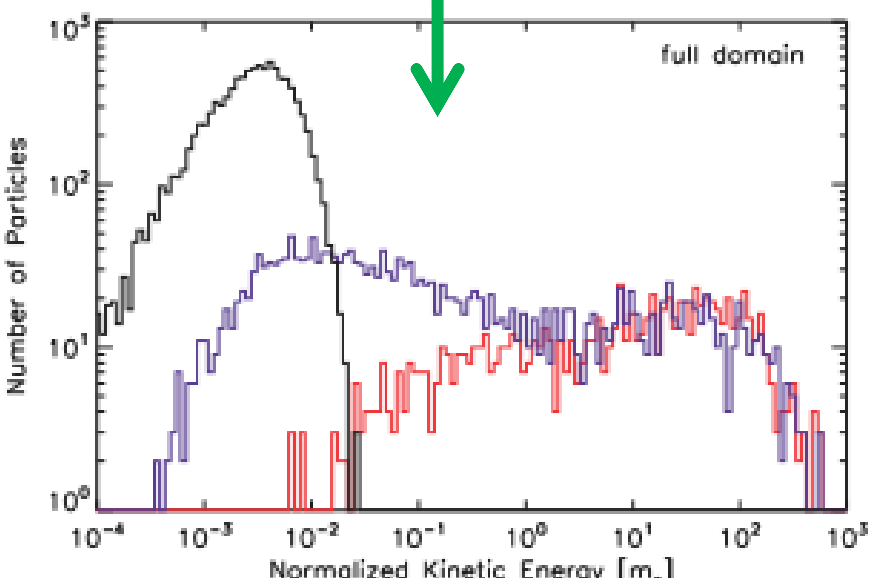
-> Compatible with the fact that turbulence is just the driving mechanism of fast reconnection in the large scale current sheet

(del Valle, de Gouveia Dal Pino, Kowal 2016)

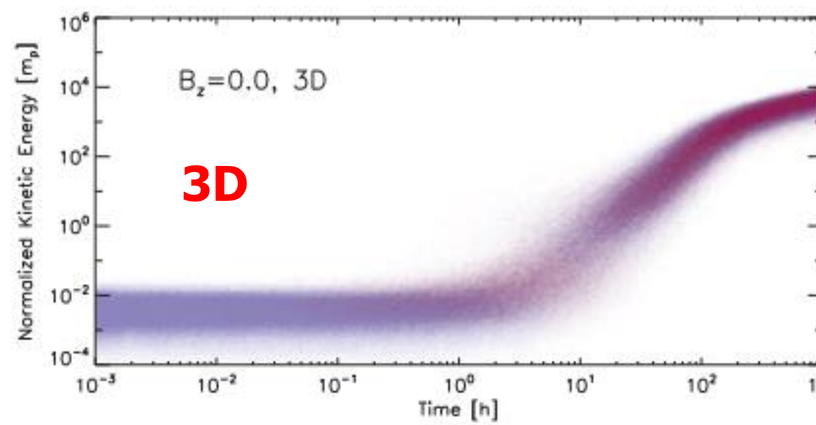
Particle Acceleration in 2D x 3D MHD Reconnection







Particle spectrum in 2D mulitple CS
(1 hr after injection)



Energy growth w/ time