Cosmic Ray Acceleration by Magnetic Reconnection

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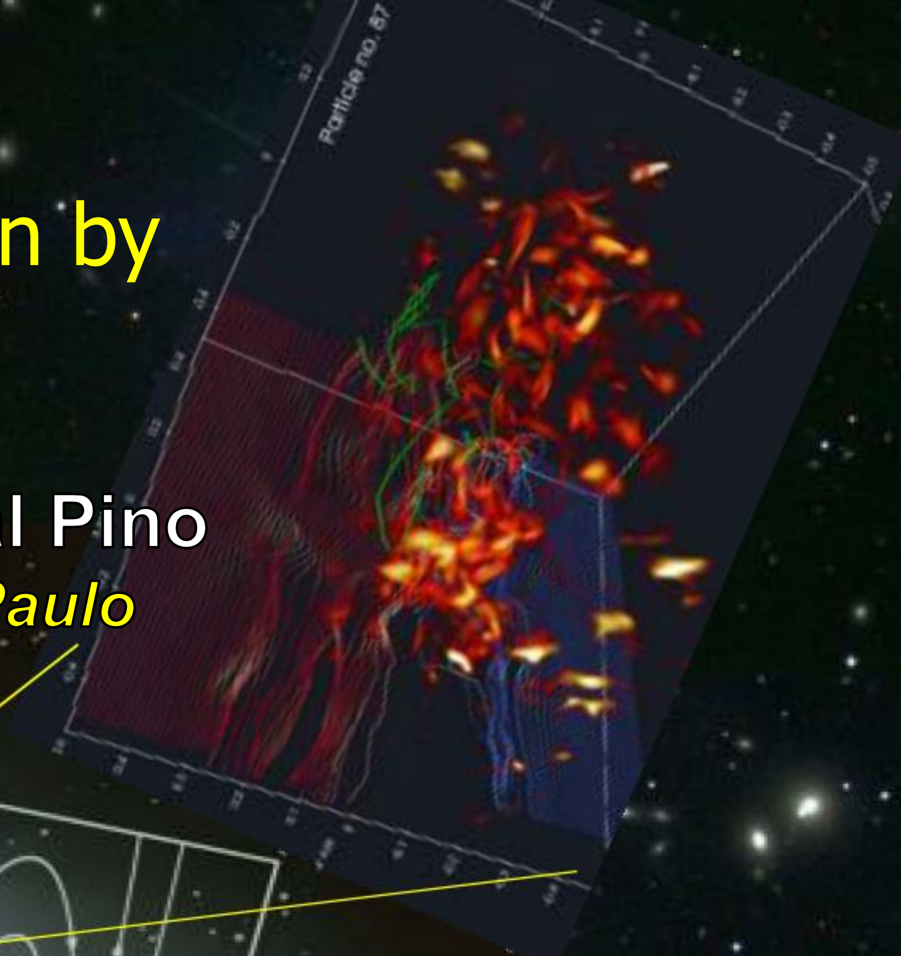
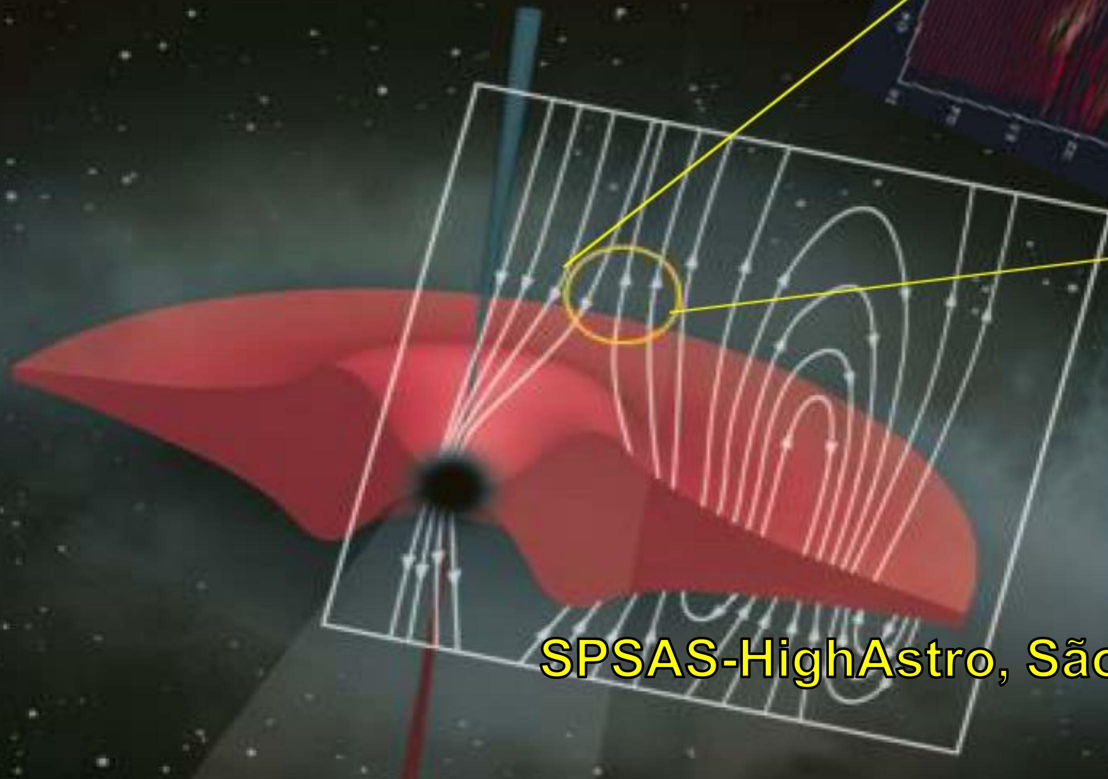
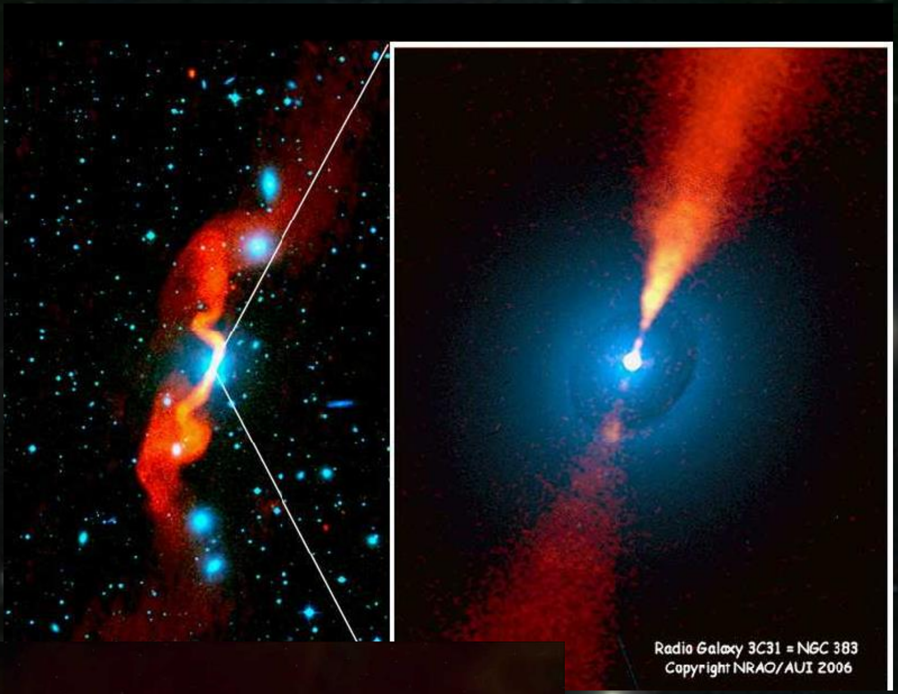


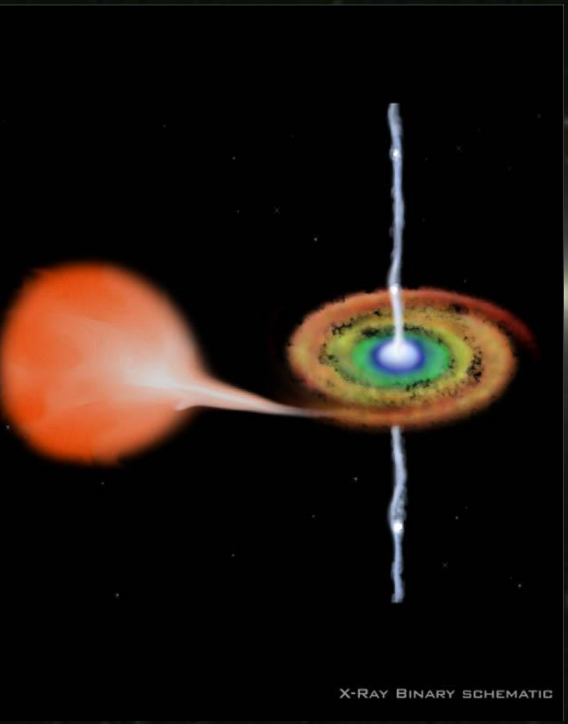


SPSAS-HighAstro, São Paulo, May 30, 2017

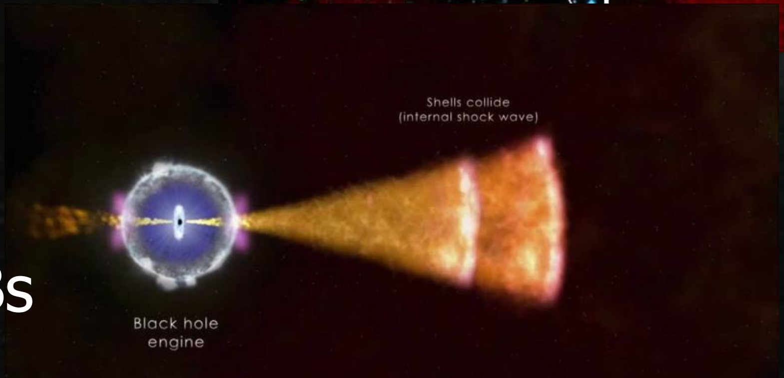
Black Hole sources are Cosmic Ray (CR) accelerators and Very High Energy (VHE) emitters

AGNs (blazars, radio-galaxies, seyferts)





Black Hole Binaries
(Microquasars)



GRBs

Particle acceleration in compact sources: new challenges

- Some Black Hole sources & jets
- Pulsar wind nebulae

If acceleration regions are magnetically dominated
-> shocks weak

Standard particle **Fermi acceleration in shocks**:

-> may fail to explain relativistic particles origin and associated very high energy emission (up to TeV) occurring in very compact regions

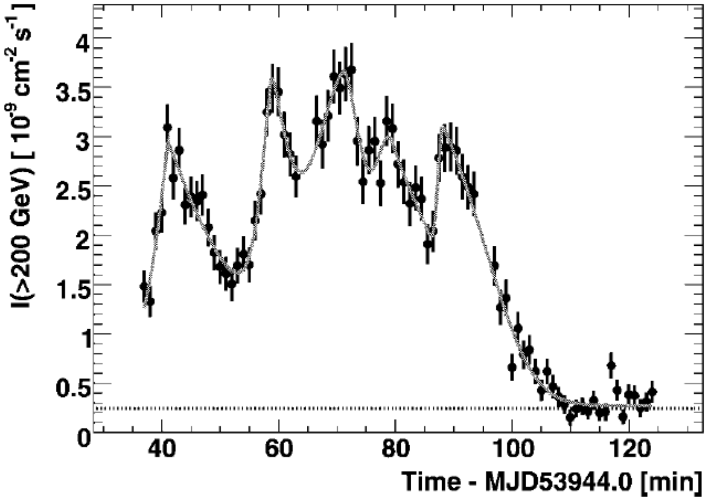
Alternative mechanism -> *Magnetic reconnection*

Observational Properties of high energy emission of these sources

- Often non-thermal power-law spectra -> efficient **non-thermal particle acceleration** yielding high energy power law-tail

- Intense rapid gamma-ray flares (e.g. 200s TeV flares in blazars)
  → **short time variability**

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



Can **magnetic reconnection** explain these properties?
YES !

This key talk

MAGNETIC RECONNECTION an alternative:

- Powerful relativistic particle acceleration

- May explain gamma-ray emission

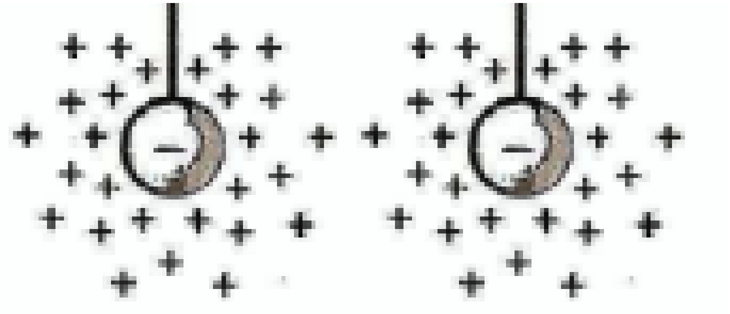
- Dissipation of magnetic energy -> conversion into kinetic energy

PLASMA in a nutshell

- Plasma **quasi-neutral gas of charged particles** (electrons+ions):

$$n_e \sim Z\, n_i$$

with long range ***collective interactions*:**



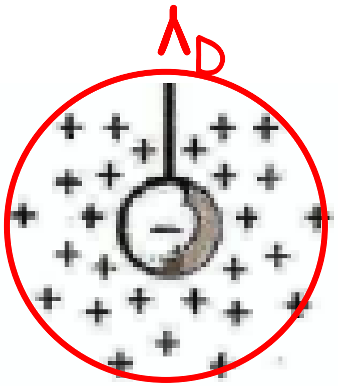
(binary collisions not important)

- Over **90% of visible matter in Universe**: *PLASMA*

Tips - plasma parameters

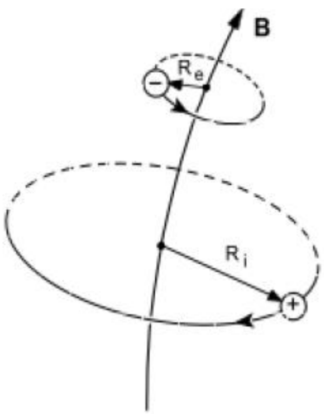
- Debye length

$$\lambda_D \simeq \frac{v_{th}}{\omega_{pe}} \simeq \left(\frac{KT_e}{4\pi n_e e^2}\right)^{1/2} = 7\ cm\ (T_e/n_e)^{1/2}$$



- Plasma frequency

$$\omega_{pe} = \left(\frac{4\pi n_e e^2}{m_e}\right)^{1/2} \simeq 5.6 \times 10^4 n_e^{1/2} \quad s^{-1}$$



- Cyclotron radius

$$r_L = \frac{p}{ZeB} \qquad r_L = 33.36\ \mathrm{km} \left(\frac{p}{\mathrm{GeV/c}}\right) \left(\frac{1}{Z}\right) \left(\frac{\mathrm{G}}{B}\right)$$

- Alfven velocity

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

PLASMA @ different scales

- **Intermediate - *microscopic scales*** : $l >> \lambda_D$

  kinetic theory describes the collective behaviour of the many charged particles by means of particle distribution functions (**Folker-Planck equation**):

  $$f_{e,i}(r,v,t)$$

- **Large – *macroscopic scales*** : $L >> \lambda_{mfp} \sim r_L$

  effectively **collisional** -> fluid description: size and time scales are large enough → possible to apply AVERAGES over microscopic quantities: over collective plasma oscillations and collective cyclotron motions **(MHD equations)**

  ⬇

- **Applicable to most astrophysical plasma species**

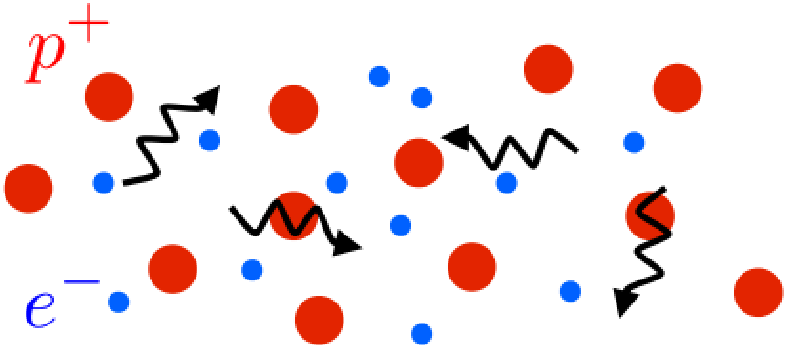
PLASMA & Cosmic Rays

MHD description applicable to most astrophysical plasma species

- ***BUT:* cosmic ray component is *collisionless***

  → need kinetic description

  → and is coupled through waves with rest of the plasma

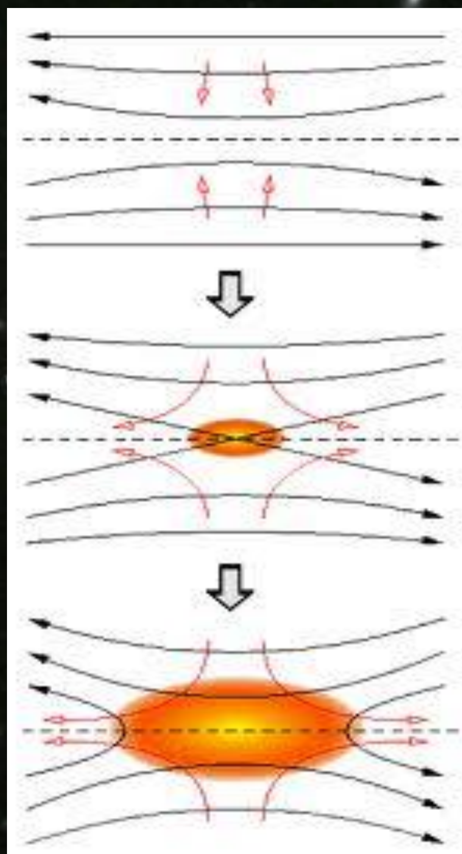


(Tchekhovskoy's cartoon)

Let us start ….
with Cosmic Ray Acceleration by Magnetic Reconnection

WHAT IS MAGNETIC RECONNECTION ?

Approach of magnetic flux tubes of opposite polarity with finite resistivity (η ~1/conduction): **RECONNECT**



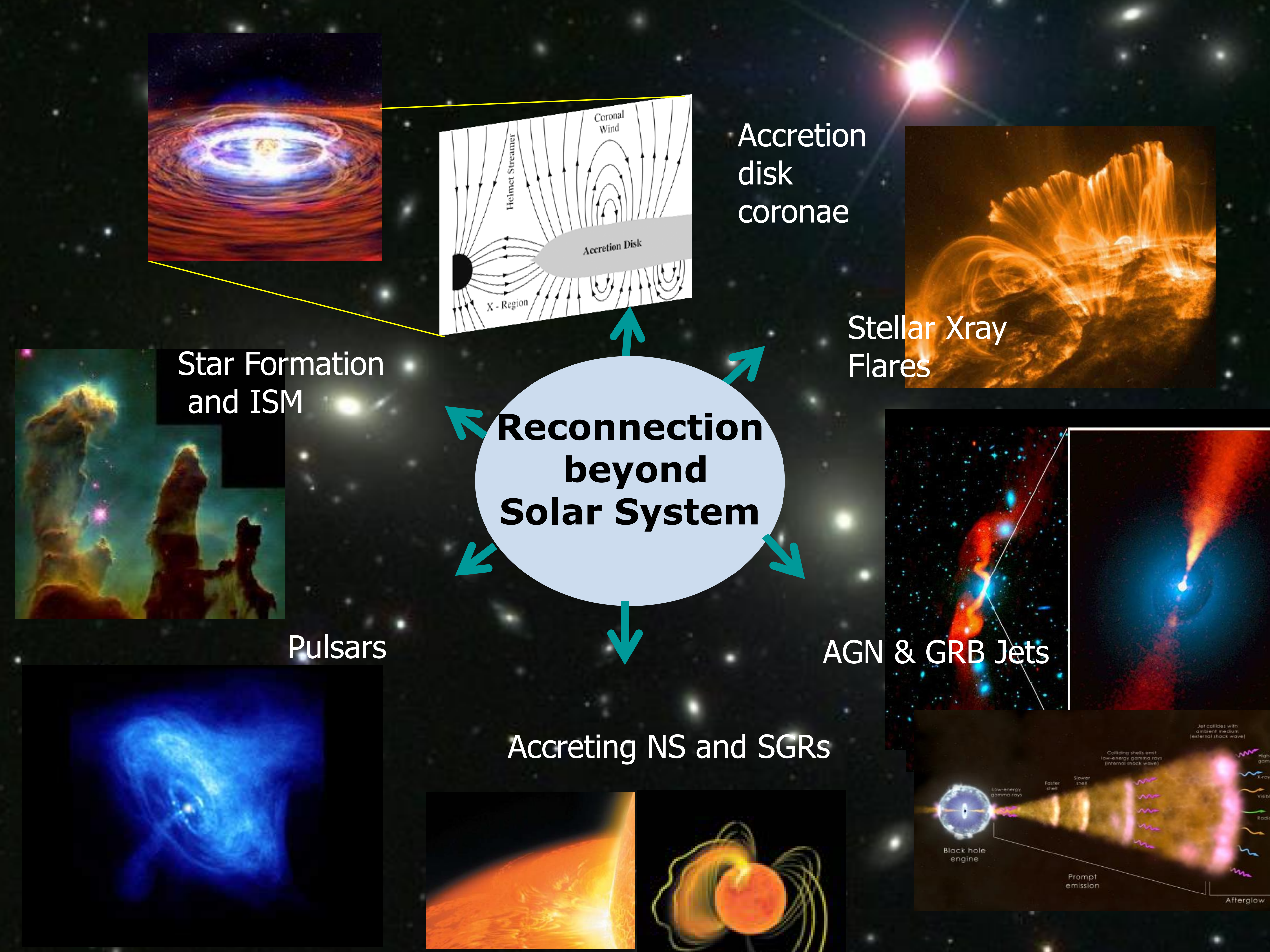
$$J \sim \frac{2Bc}{\Delta}$$

Earth magnetotail

Solar corona

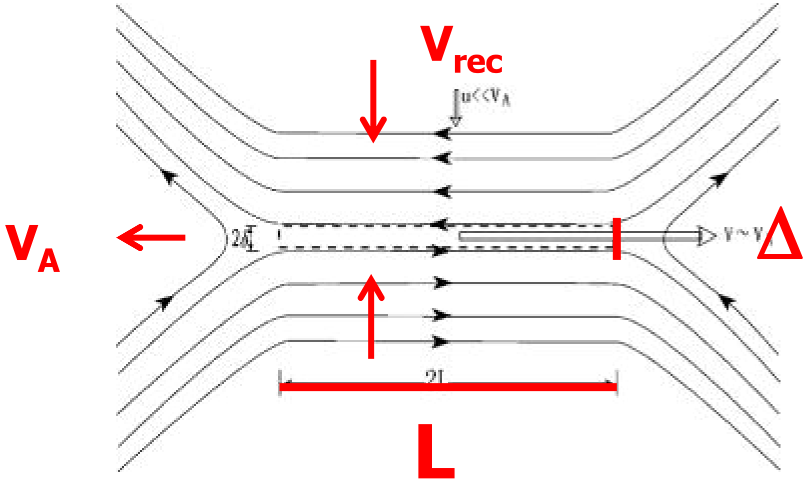
Reconnection is FAST in these environments !

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


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

Magnetic Reconnection Models

- **Sweet-Parker (1957) reconnection:**



From mass flux conservation:

$$V_{rec} \sim v_A\,(\Delta/L)$$

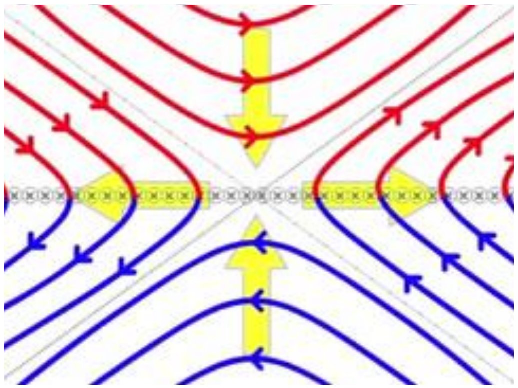
But $\Delta/L << 1$

In fact $S = L\,v_A/\eta >> 1$

$V_{rec} \sim v_A\,S^{-1/2} << 1$ → **SLOW reconnection**

Magnetic Reconnection Models

Petschek (1964): X-point configuration ->



Δ → $\Delta \sim L$

L

Then reconnection rate is FAST:

$$V_{rec} \sim \pi v_A / 4 \ln S$$

Where $S = L v_A/\eta \gg 1$

BUT*: unstable and evolves to Sweet-Parker** (Biskamp'96) ***unless:

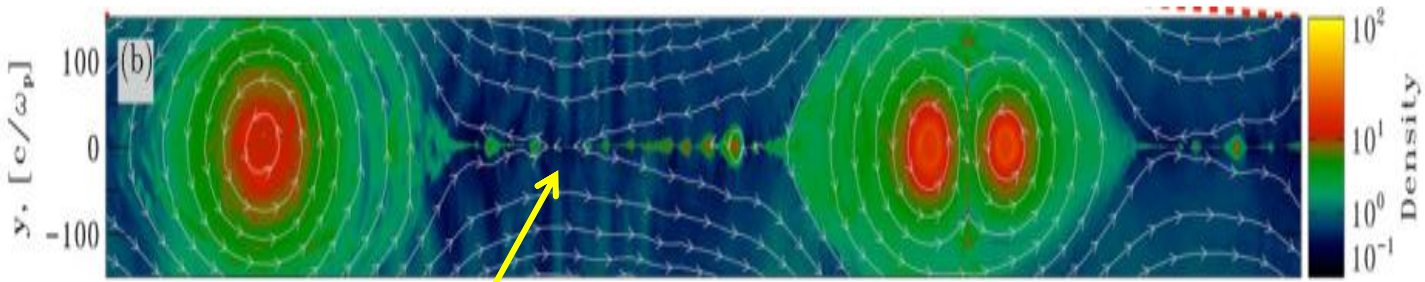
***pair* plasma at kinetic scales** with localized resistivity η

Magnetic Reconnection Models

Petschek X-point configuration -> arises naturally in kinetic *(collisionless)* ion-e^- or e^+e^- *pair* plasma with localized η

- **Kinetic simulations**: 2-dimensional (2D) Particle In Cell **(PIC)** simulations of e^+e^- *pair* plasma :

few plasma inertial length ~ 100-1000 c/ω_p



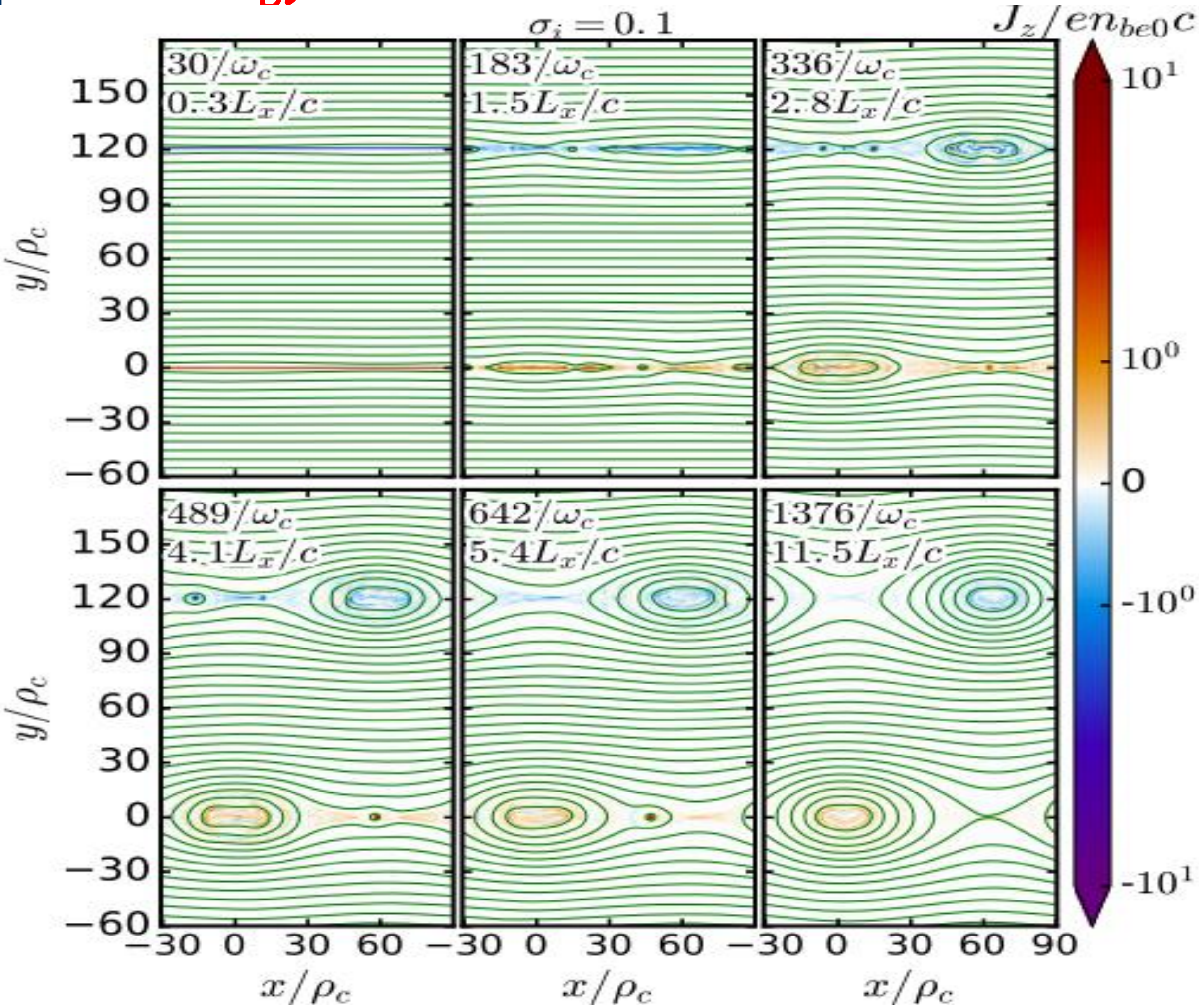
X-point

(Sironi & Spitkovsky 14)

Current sheet: unstable to **tearing mode** and break up into chain of **plasmoids** (or islands)

Magnetic Reconnection Models

- **Kinetic simulations**: 2D **PIC** simulations of **ion-e^-** pair plasma (up to 3000 λ_D):



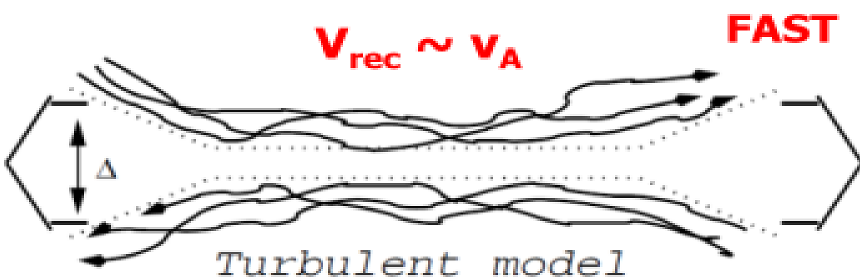
(Werner, Uzdenzky et al. 2017)

Fast Reconnection in MHD flows

Turbulence drives FAST RECONNECTION !

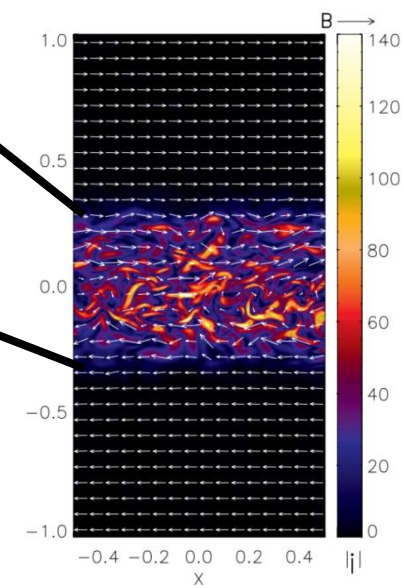
(Lazarian & Vishniac 1999; Eyink et al. 2011)

Magnetic lines wandering: many simultaneous reconnection events



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

Tested in 3D numerical simulations (Kowal et al. 2009, 2012; Takamoto et al. 2015)



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

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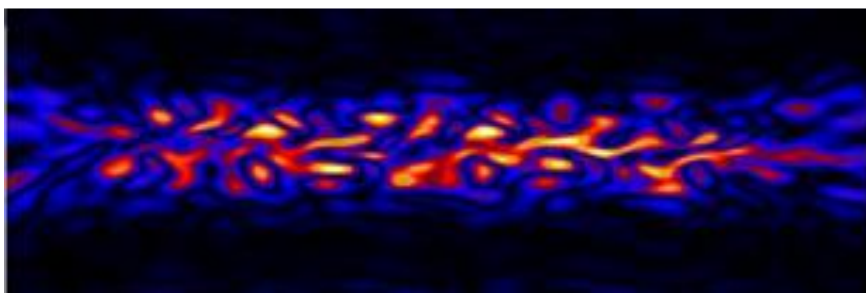

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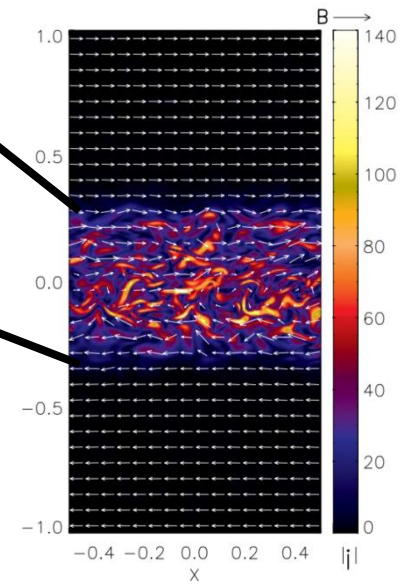

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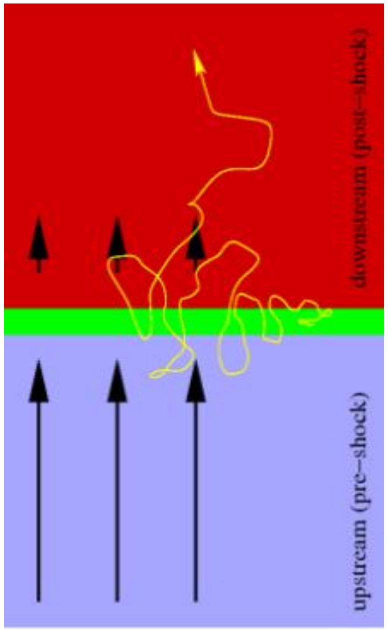
(Alternative~descriptions: Shibata & Tanuma01; Loureiro+07; Bhattacharjee+09)

Particle Acceleration by Reconnection

- **Released magnetic energy by reconnectio**n -> into heating and particle motion (kinetic energy)
- **30%–40%** of magnetic energy converted into particle kinetic energy (PIC simulations, e.g. Werner et al. 2017)
- **Laboratory plasmas: ~50%** goes into kinetic particle acceleration (Yamada+ 2015)

How particles are accelerated in reconnection sites?

Shock Acceleration



1st-order Fermi (e.g.Bell+1978; Begelman & Eichler 1997)

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

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

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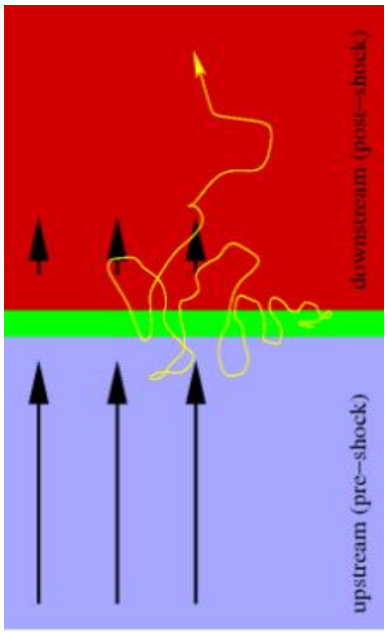

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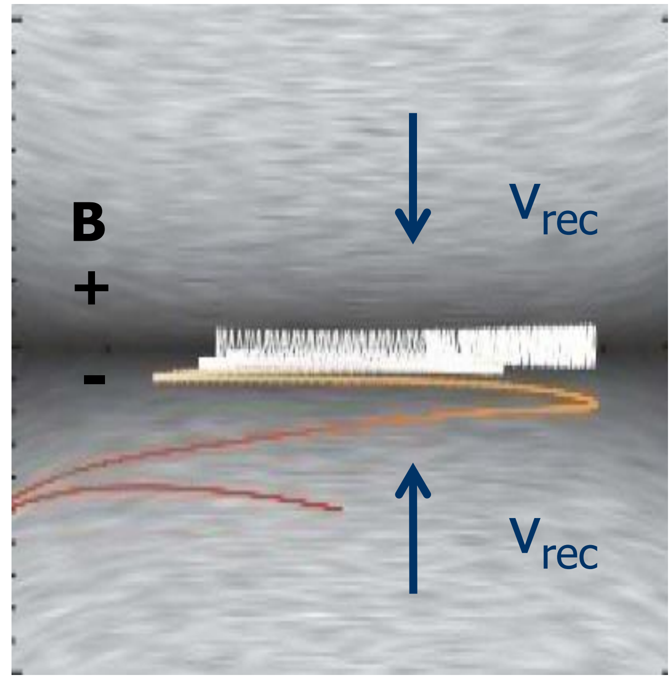
Reconnection Acceleration



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

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

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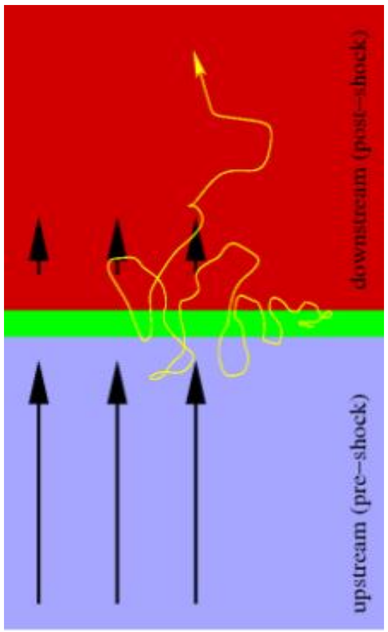

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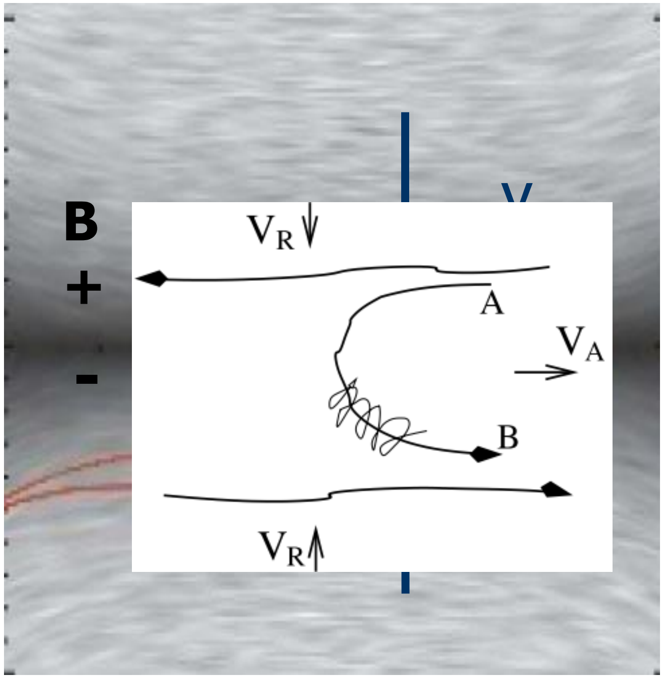

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particles bounce back and forth between 2 converging magnetic flows

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

Particle Acceleration by Reconnection probed with numerical simulations

- Most simulations of particle acceleration by magnetic reconnection: **2D 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; Werner+ 17)

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

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

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

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0, \quad (5)$$

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot \left[\rho \boldsymbol{v} \boldsymbol{v} + \left(a^2 \rho + \frac{B^2}{8\pi} \right) I - \frac{1}{4\pi} \boldsymbol{B} \boldsymbol{B} \right] = \boldsymbol{f}, \quad (6)$$

$$\frac{\partial \boldsymbol{A}}{\partial t} + \boldsymbol{E} = 0, \quad (7)$$

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

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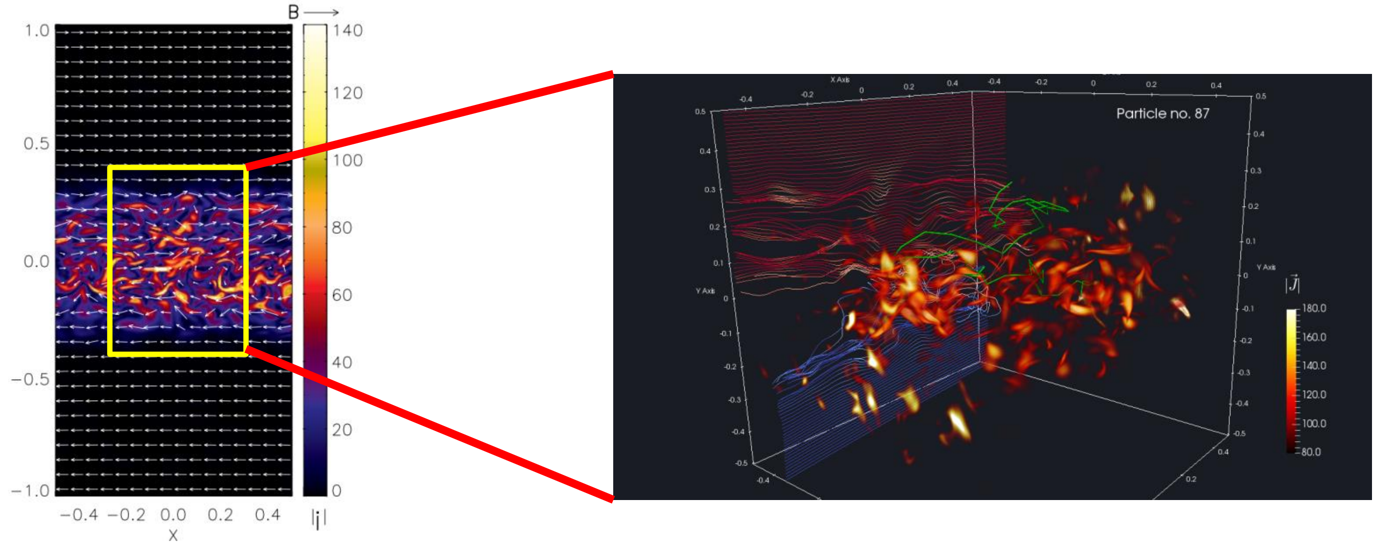
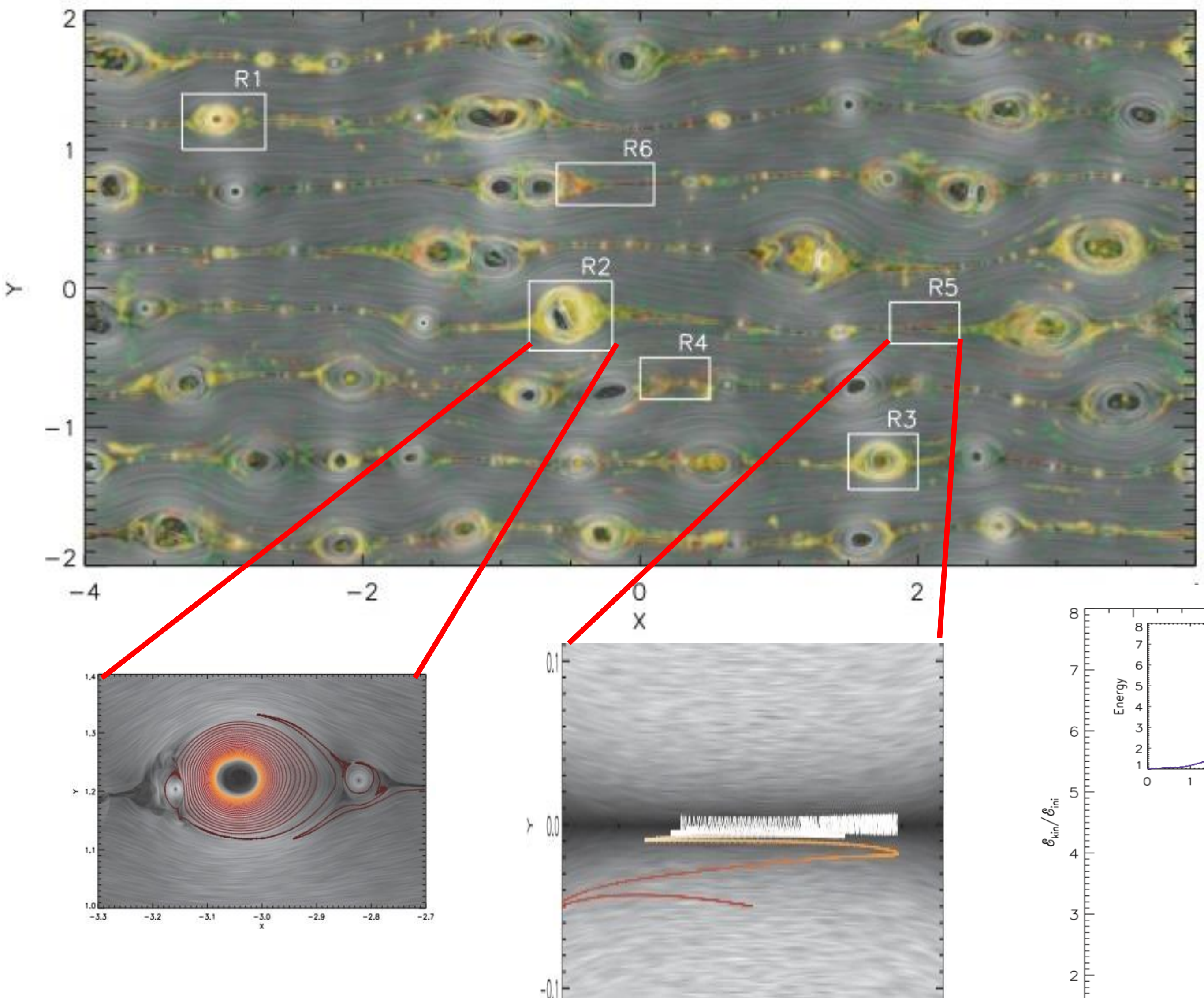


- **Inject test particles** in the MHD domain of reconnection and follow their trajectories (6^{th} order Runge-Kutta-Gauss):

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

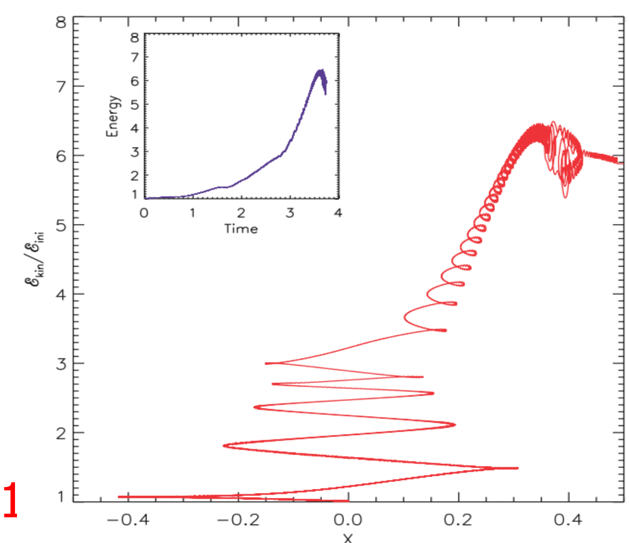
Kowal, de Gouveia Dal Pino, Lazarian ApJ 2011; PRL 2012

Particle Acceleration in 2D MHD Reconnection



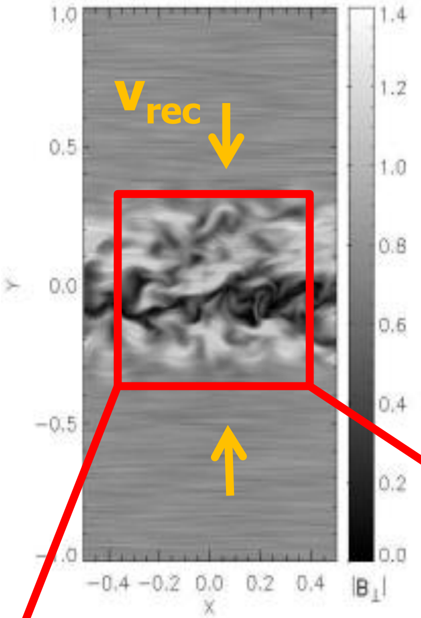
2D Multiple current sheets to compare with PIC simulations

Kinetic energy increase

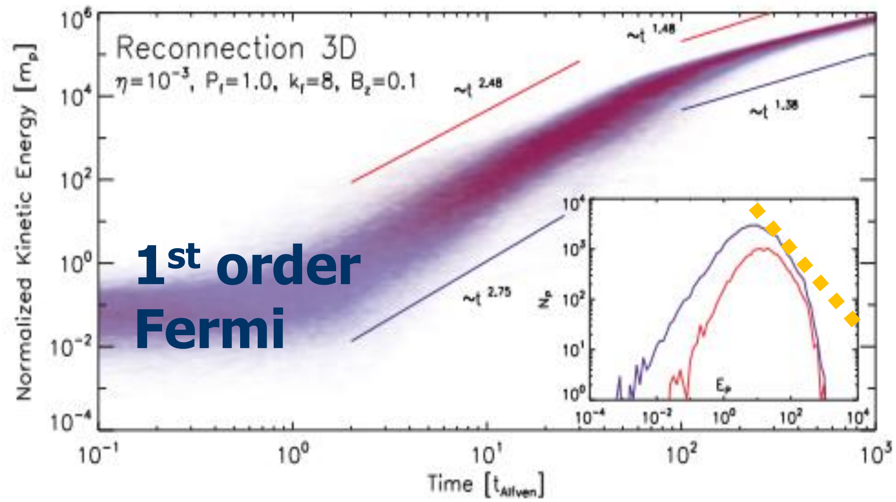


Kowal, de Gouveia Dal Pino, Lazarian, ApJ 2011

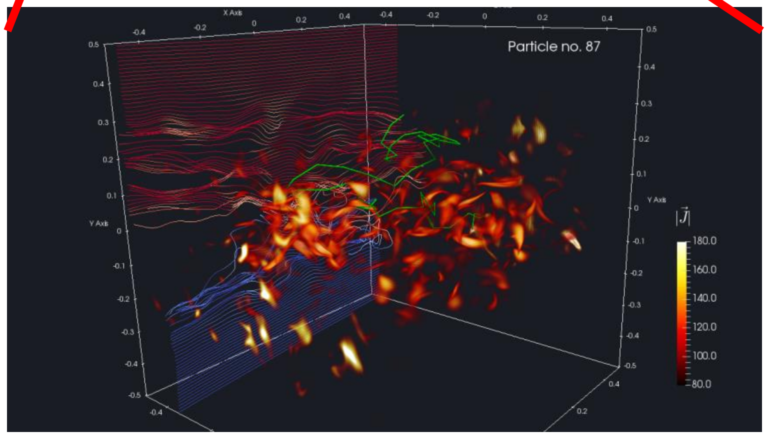
1st order Fermi Reconnection Acceleration: successful numerical testing in 3D MHD



current sheet with turbulence:
fast reconnection (LV99)



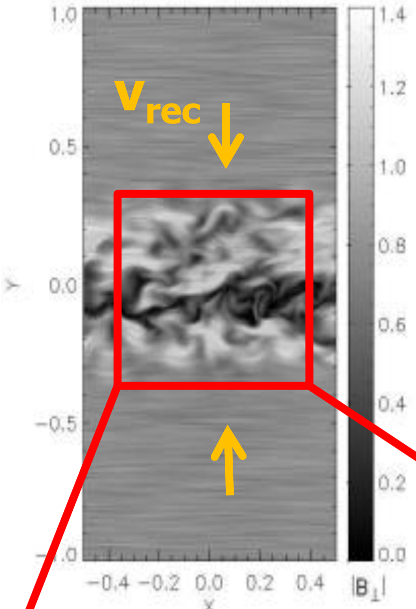
Kowal, de Gouveia Dal Pino, Lazarian, PRL 2012



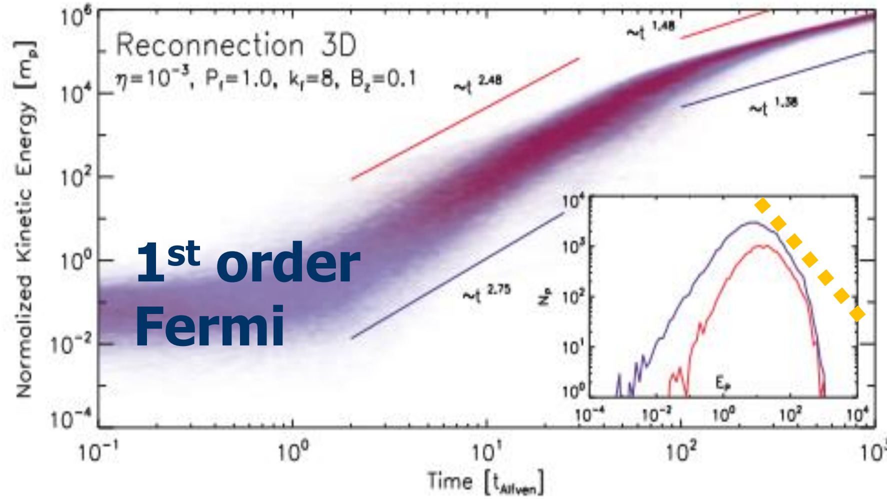
$$E_{\max} \simeq e l_{\mathrm{acc}} B$$

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

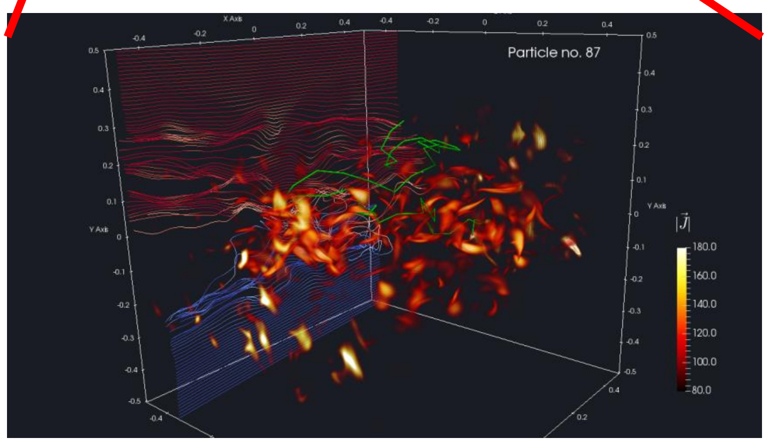
1st order Fermi Reconnection Acceleration: successful numerical testing in 3D MHD



current sheet with turbulence to make fast reconnection

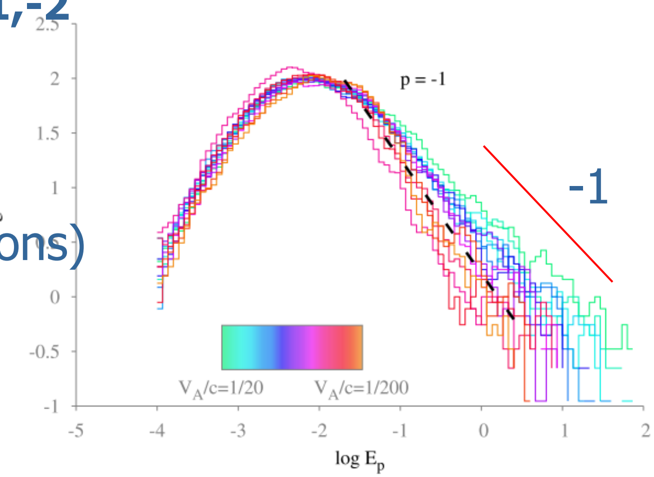


Kowal, de Gouveia Dal Pino, Lazarian, PRL 2012



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

(~PIC simulations)

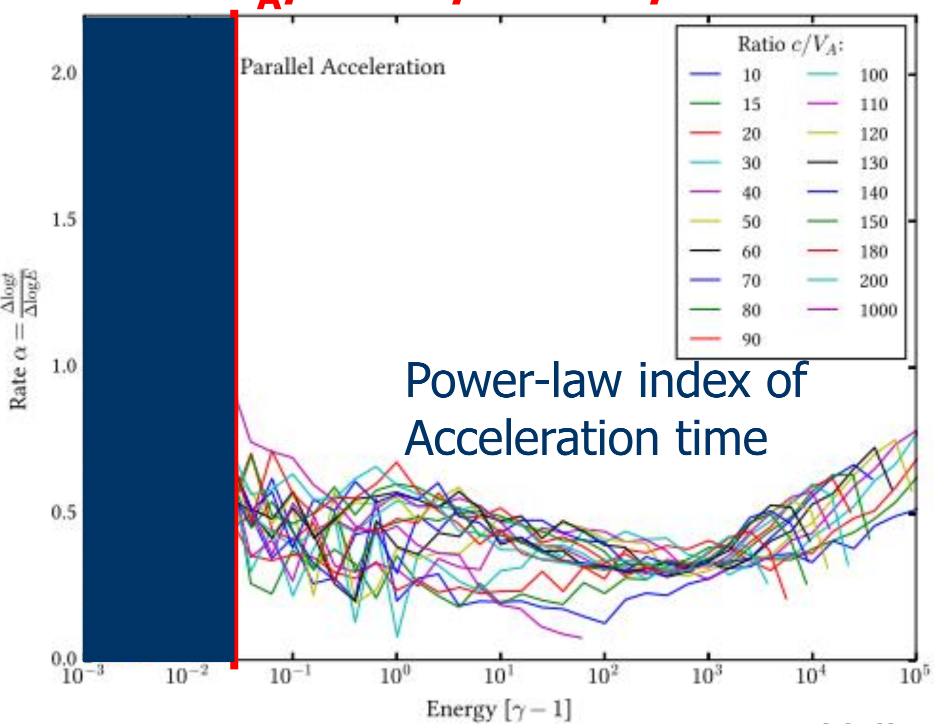


Valle, de Gouveia Dal Pino, Kowal MNRAS 201

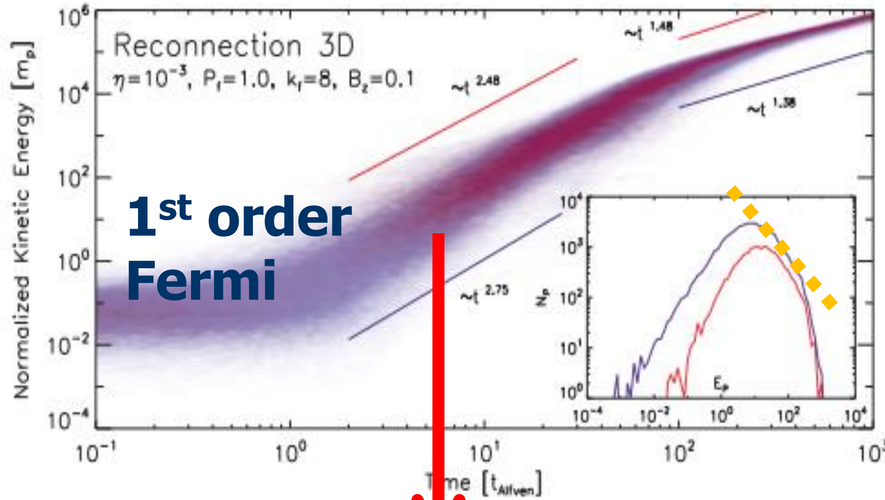
3D MHD Reconnection Acceleration tested for different values of reconnection velocity

Kowal, de Gouveia Dal Pino,Lazarian, PRL 2012

v_A/c = 1/10 – 1/1000



Power-law index of Acceleration time



1st order Fermi

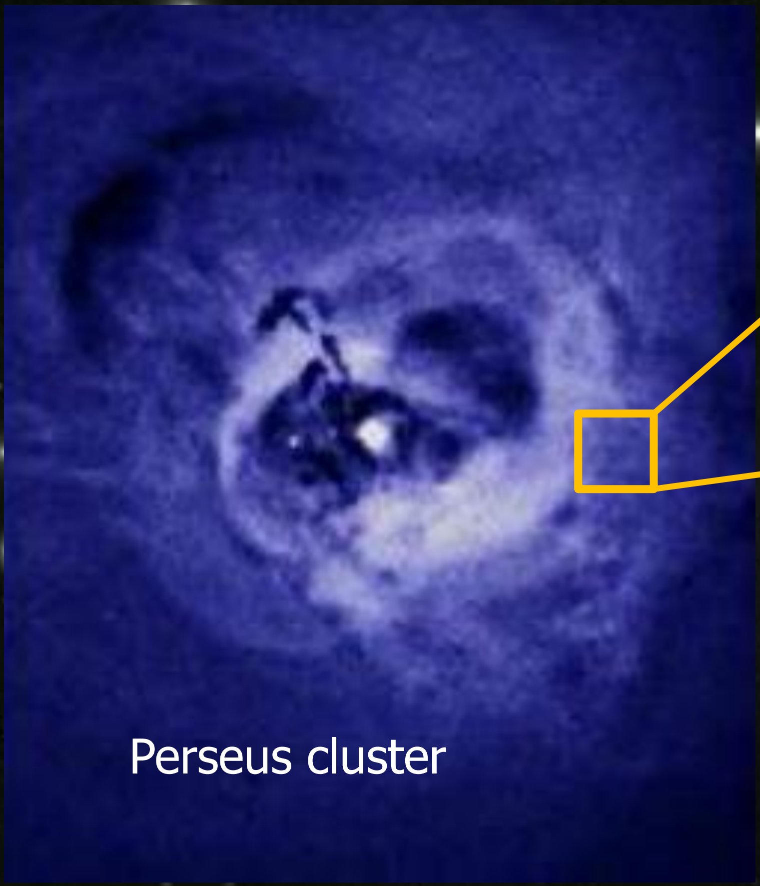
Reconnection acceleration time (nearly independent of turbulent parameters that drive fast fast reconnection):

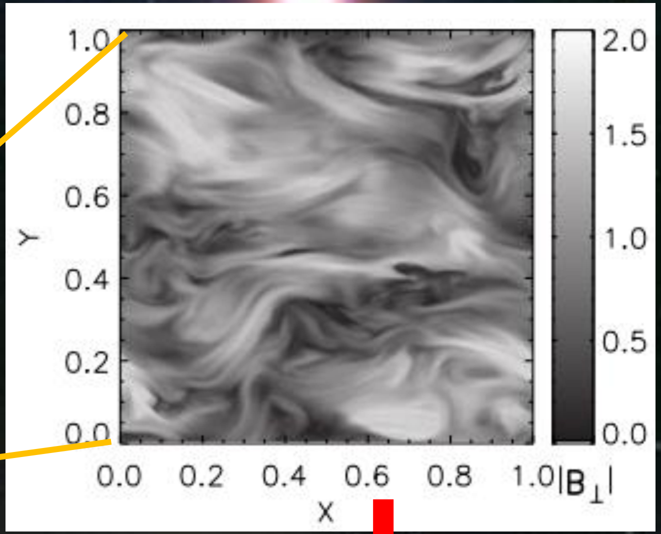
$$\tau_{acc} \sim E^{0.45+-0.15}$$

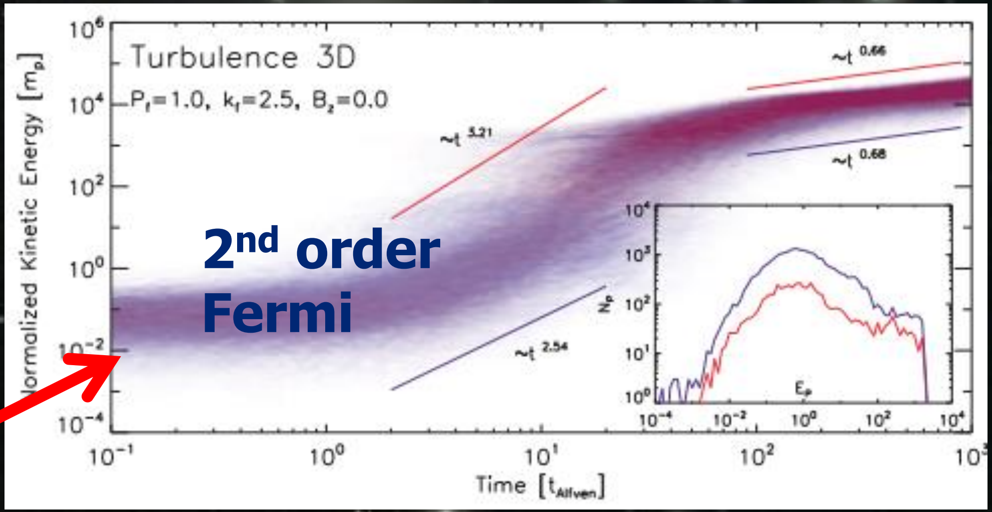
$$(\tau_{min} \sim e / B)$$

Valle, de Gouveia Dal Pino, Kowal, 2016 MNRAS

Particle Acceleration in 3D MHD Pure Turbulence



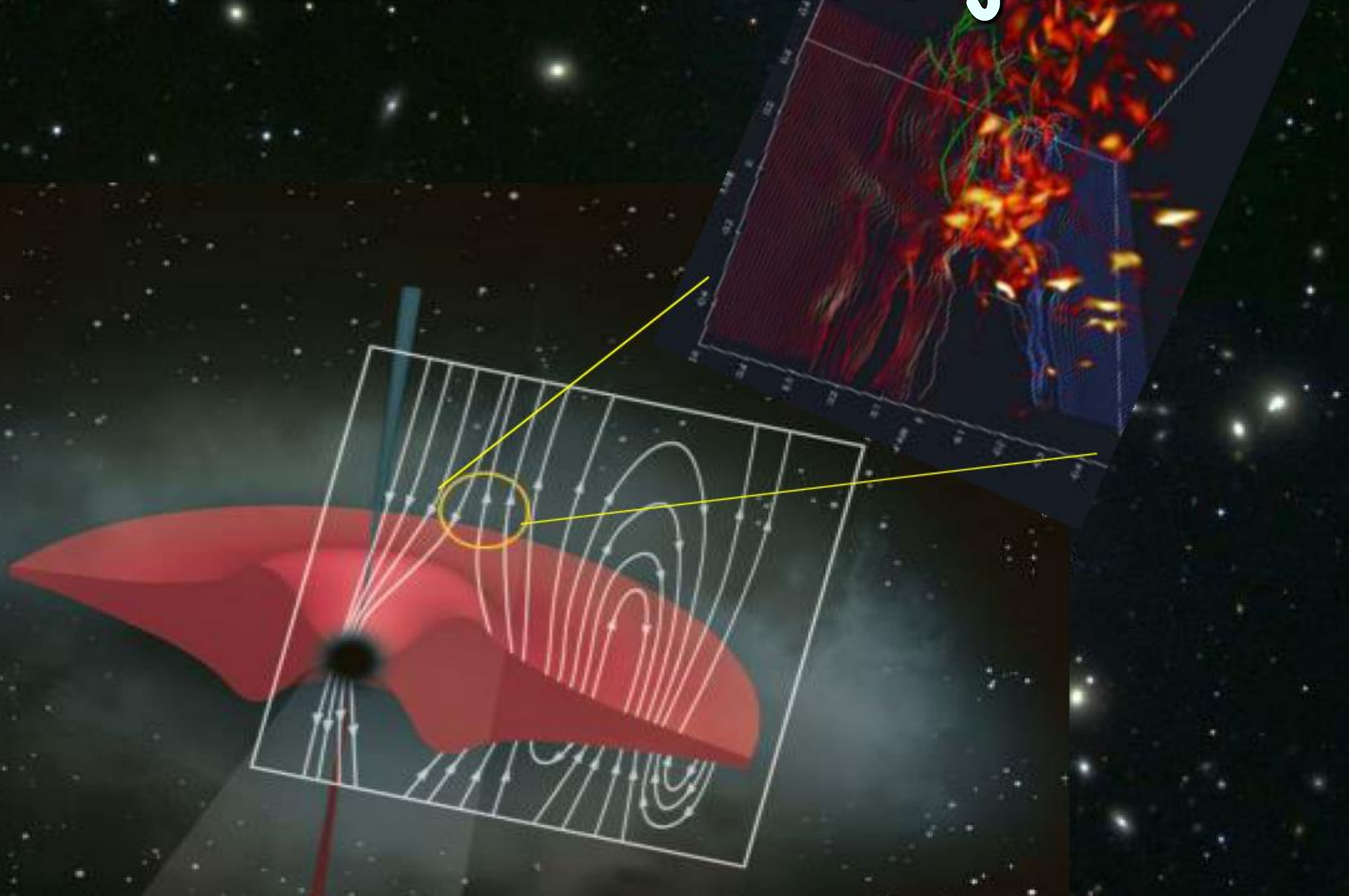




scattering by approaching and receding magnetic irregularities

Kowal, de Gouveia Dal Pino, Lazarian, PRL 2012

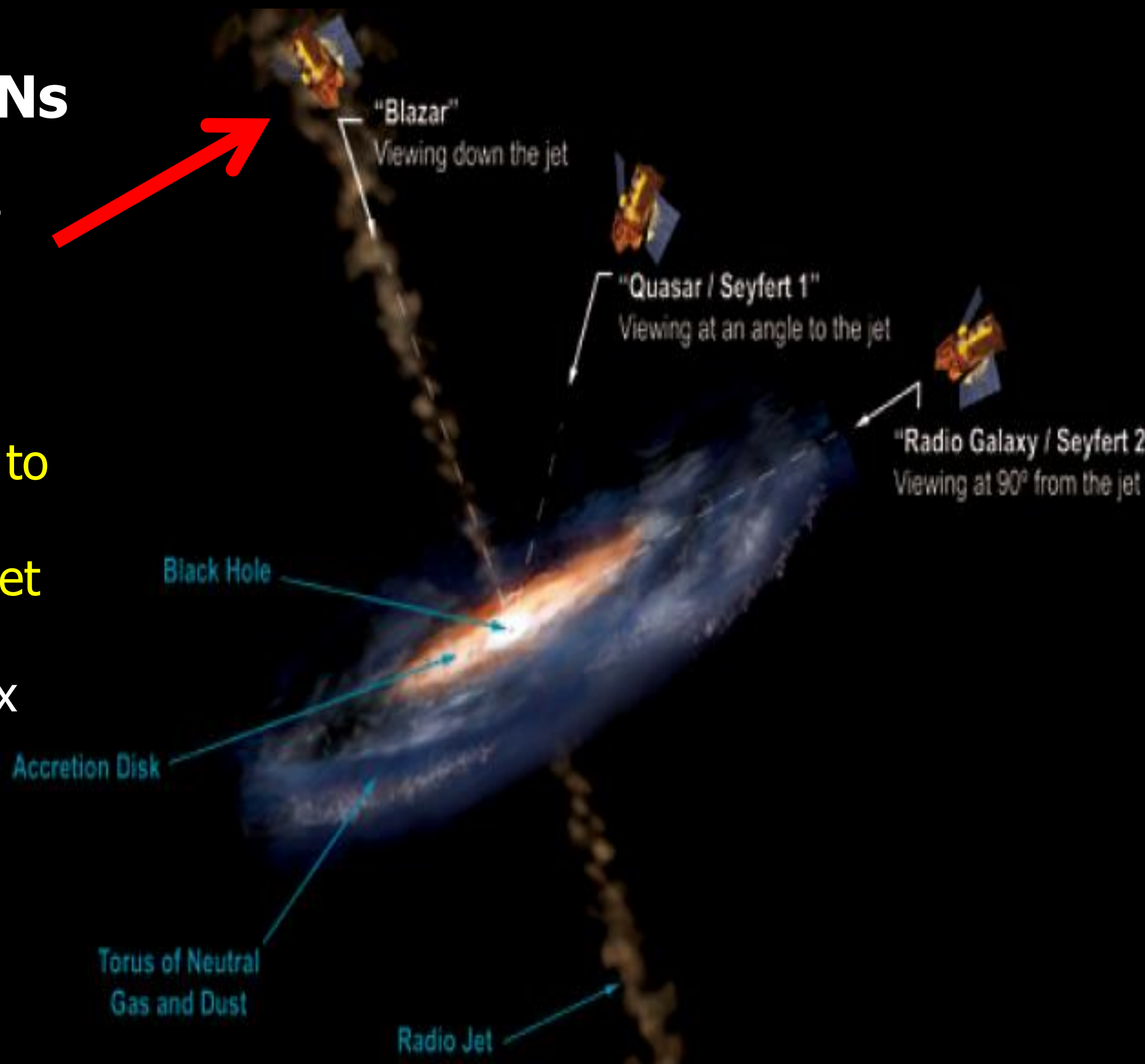
Implication to BHs and relativistic jets



VHE emission much more common in *Blazars*

High Luminous AGNs

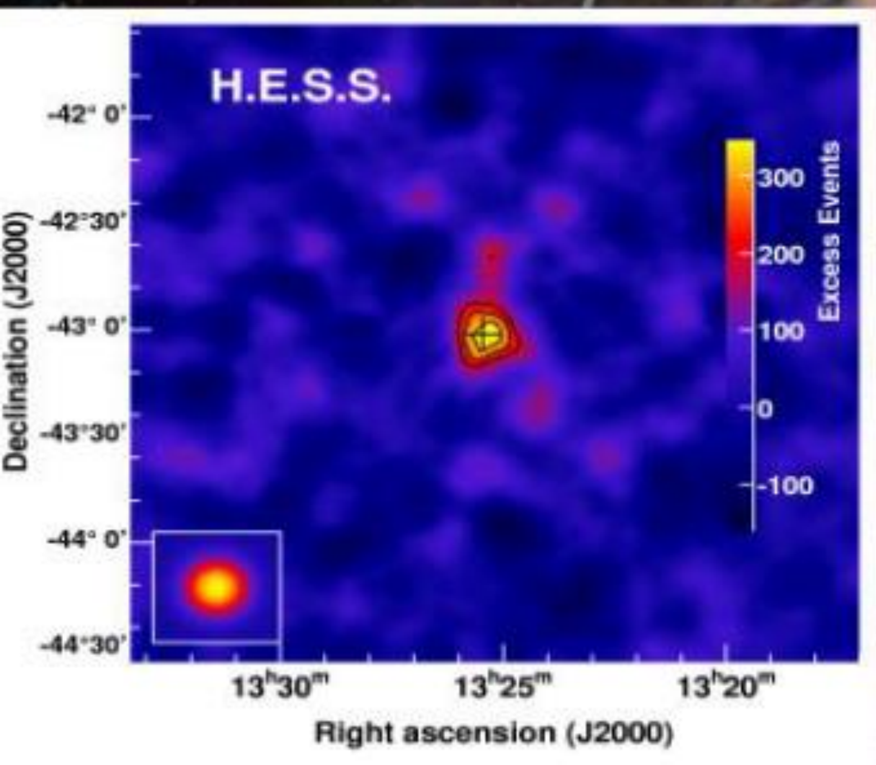
- ✓ Jet ~ along our line of sight
- ✓ VHE Emission (poor resolution): attributed to particle acceleration ***along*** the relativistic jet
- ✓ with apparent high flux due to strong Doppler boosting (γ~5-10)
- ✓ shock acceleration in kinetic-dominated flux



...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



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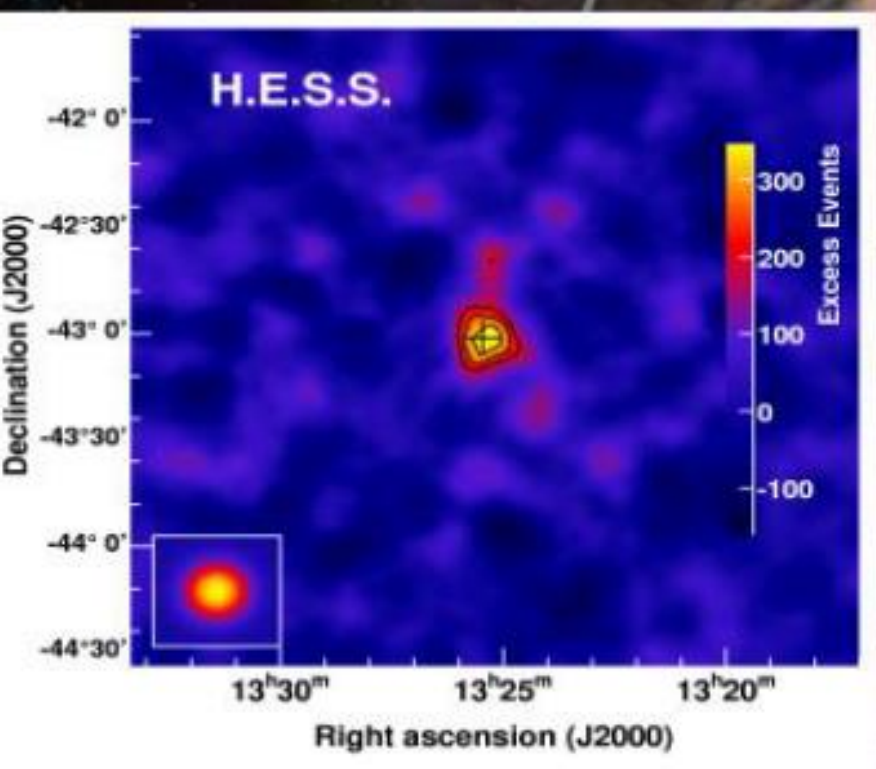


✓ ***Does it come from core or jet ?***

✓ **Rapid variability emission:**
size ~ c t_{var}~100 r_s

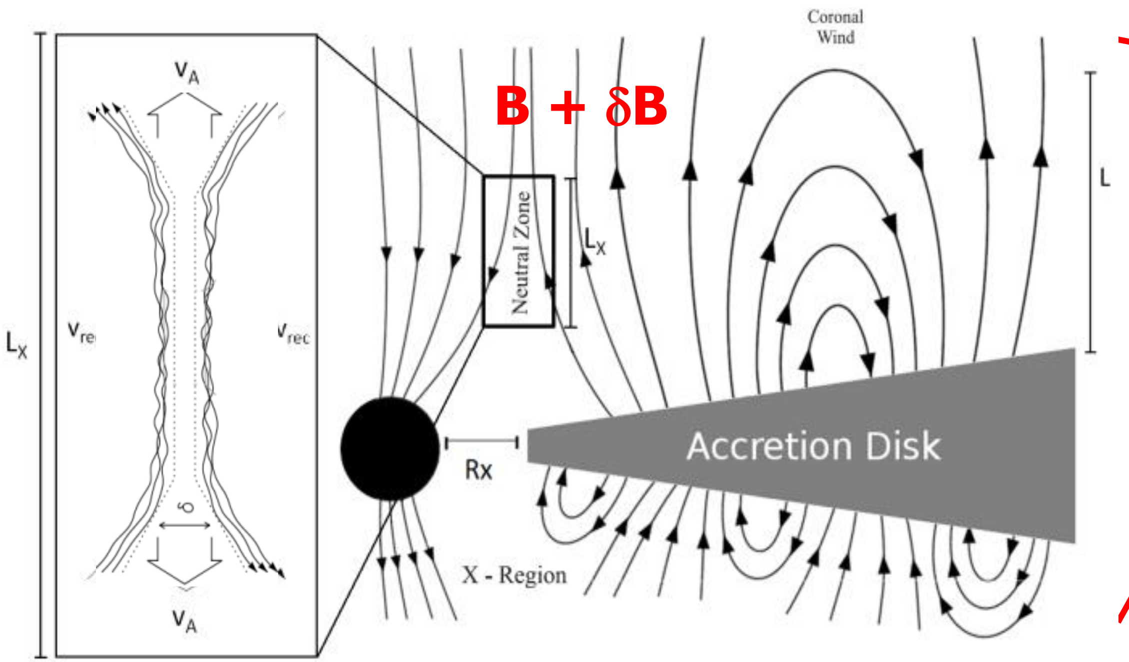
-> compact *emission (core)?*

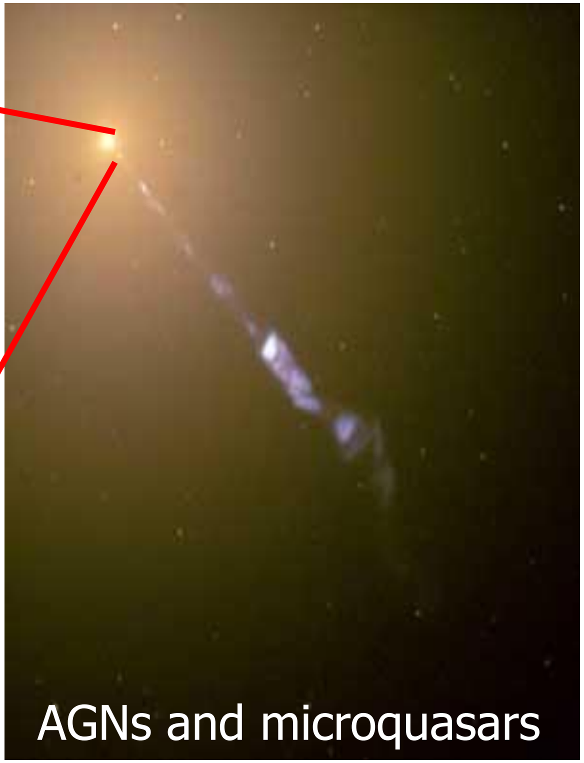
- Where are particles accelerated?
- Is acceleration magnetically dominated?

Reconnection Acceleration?

Reconnection acceleration in the surrounds of BHs ?

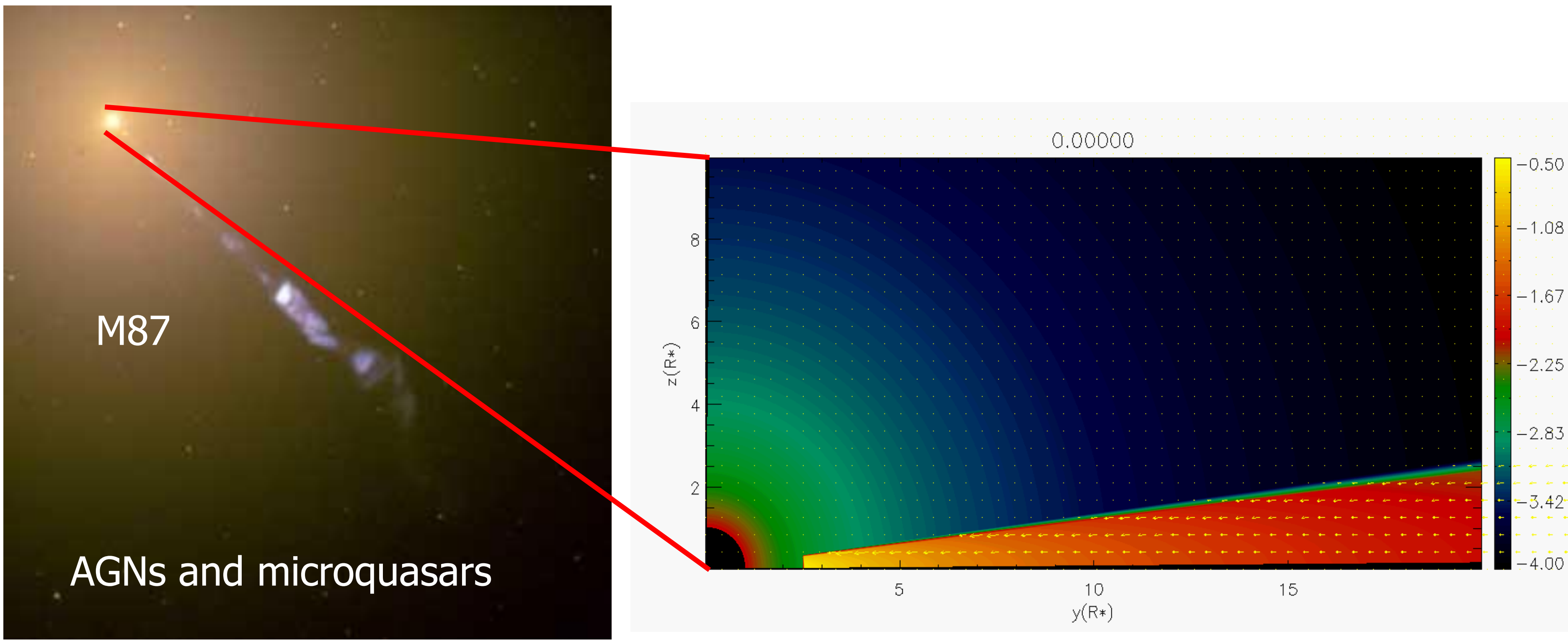
Accretion disk/jet systems (AGNs & galactic BHs)





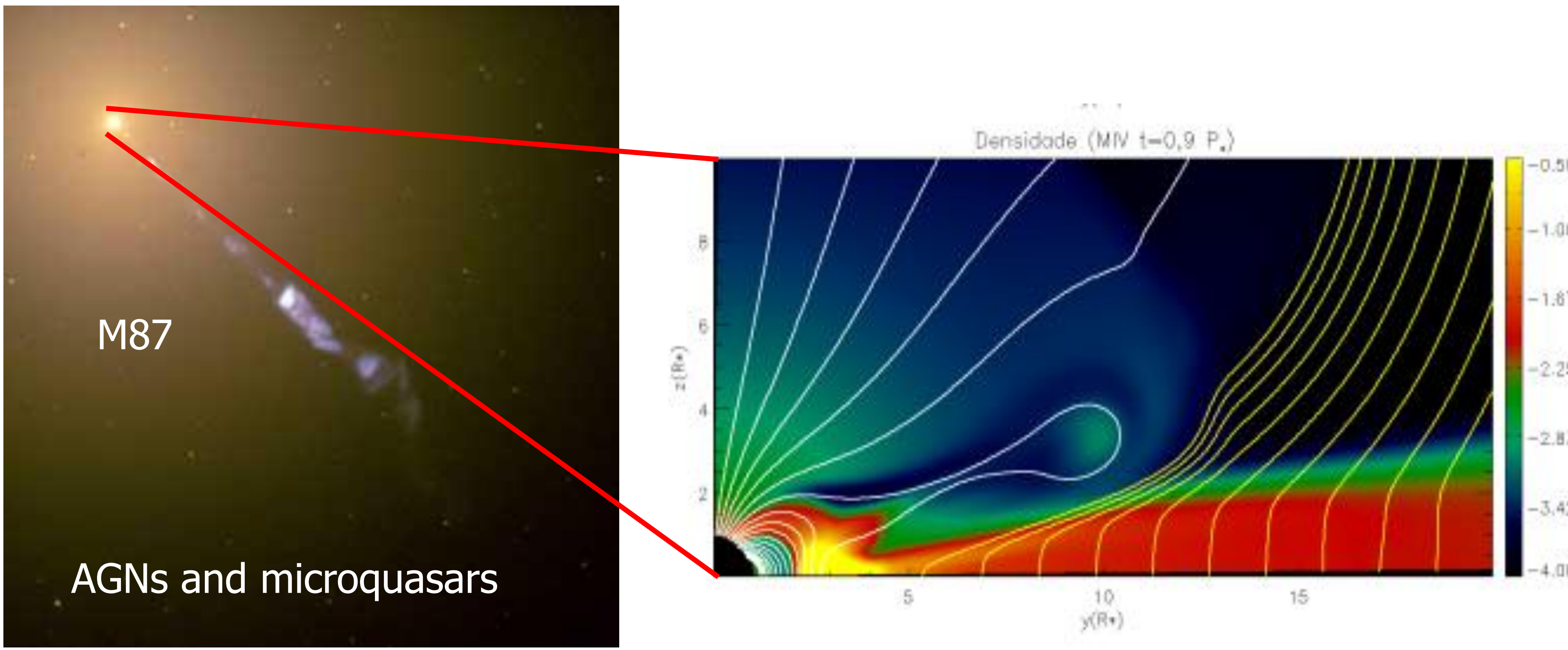
de Gouveia Dal Pino & Lazarian 2005; de Gouveia Dal Pino+2010

Evidence of Reconnection in MHD Simulations



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

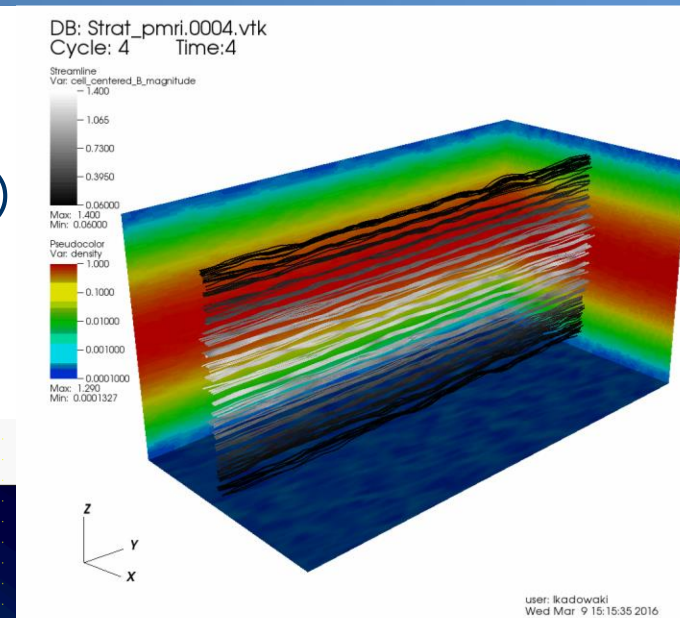
Evidence of Reconnection in MHD Simulations

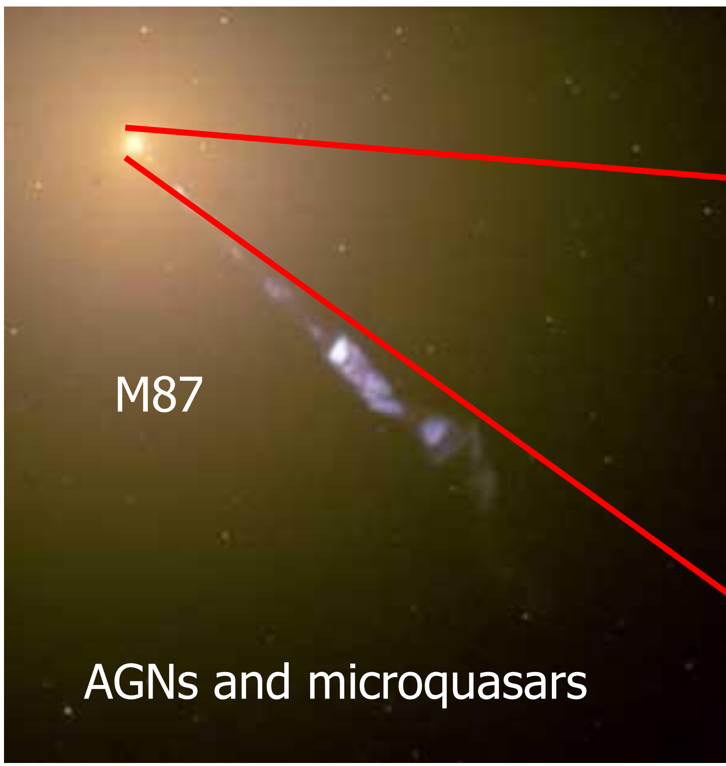


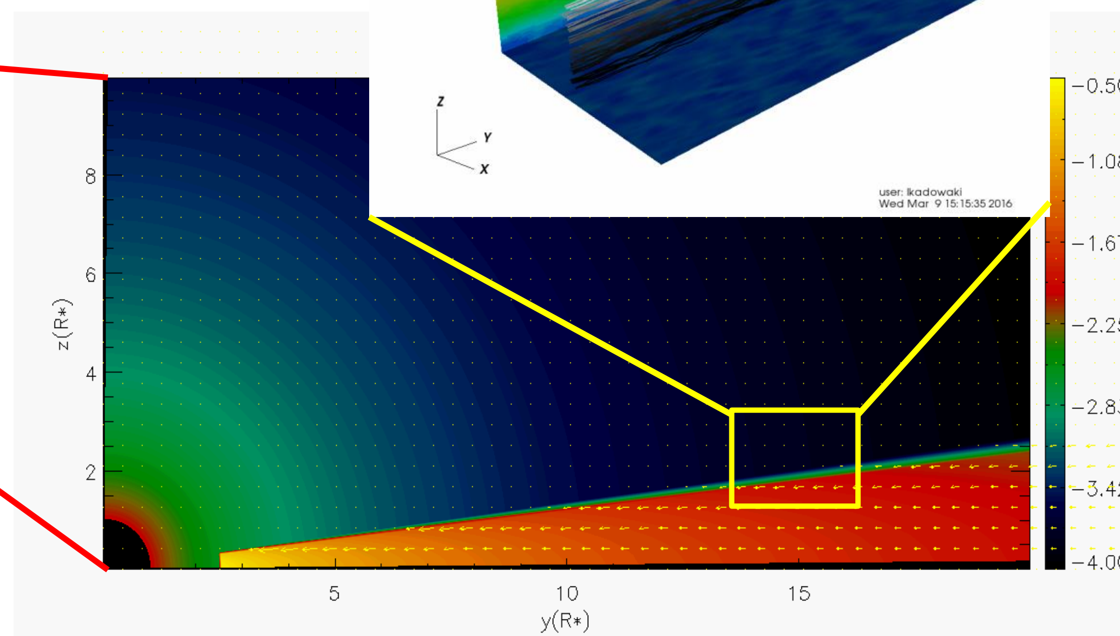
Kadowaki, Master thesis 2011 (also Zani & Ferreira 2013; Romanova+)

Evidence of Reconnection in MHD Simulations

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



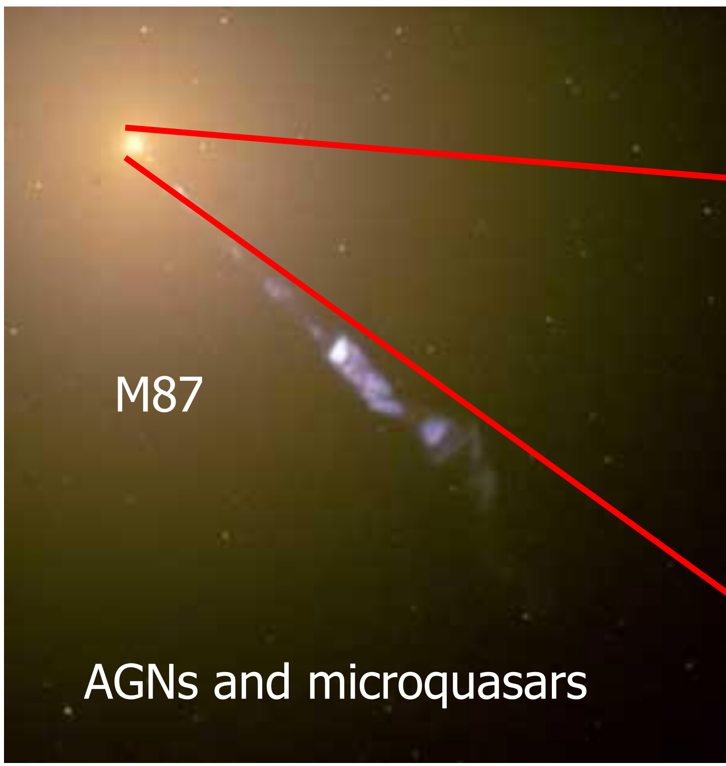


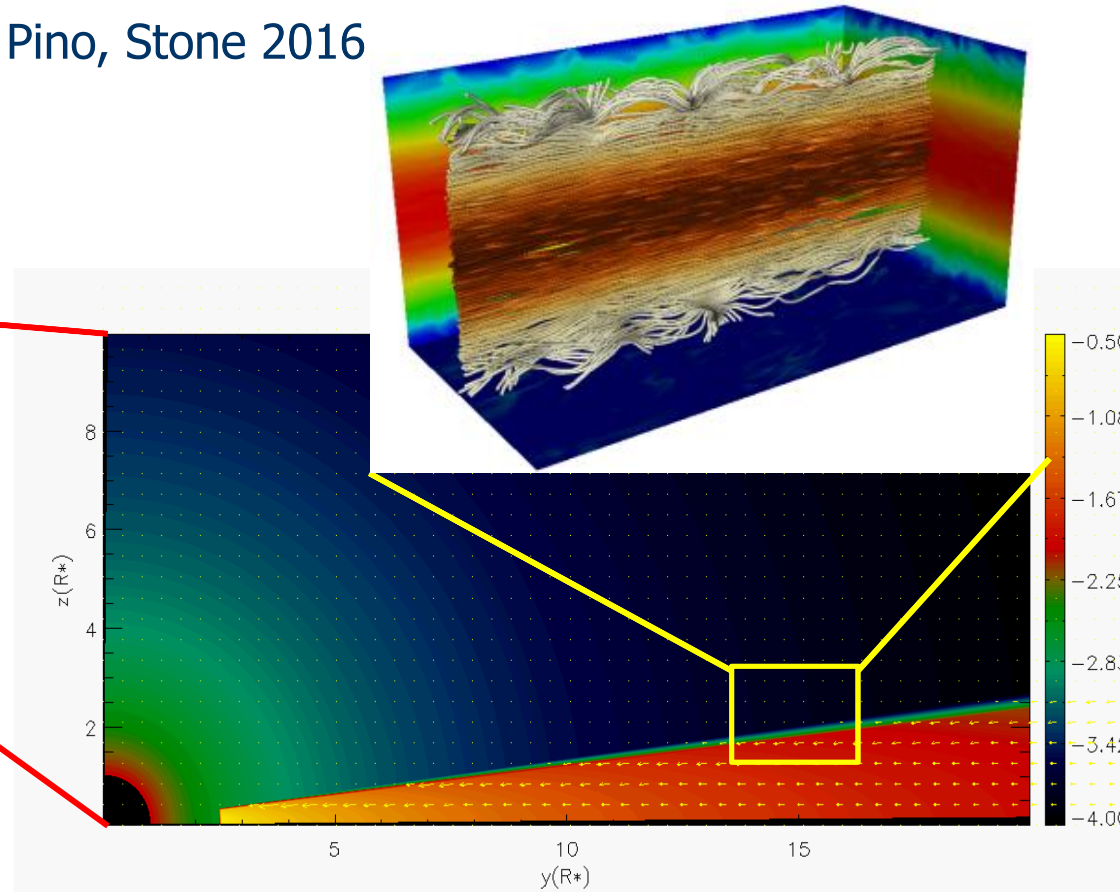


Kadowaki, Master thesis 2011 (also Zani & Ferreira 2013; Romanova+)

Evidence of Reconnection in MHD Simulations

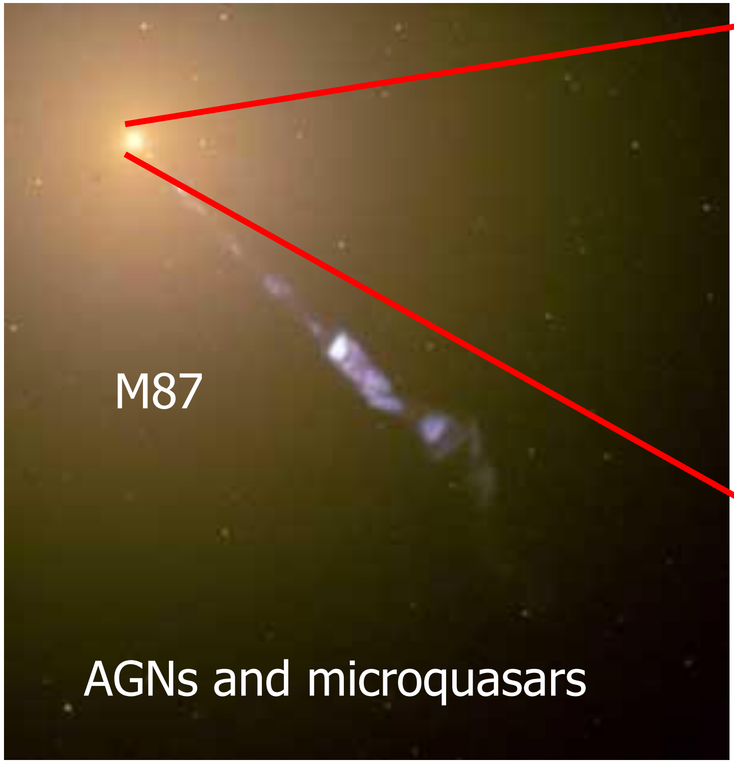
Kadowaki, de Gouveia Dal Pino, Stone 2016

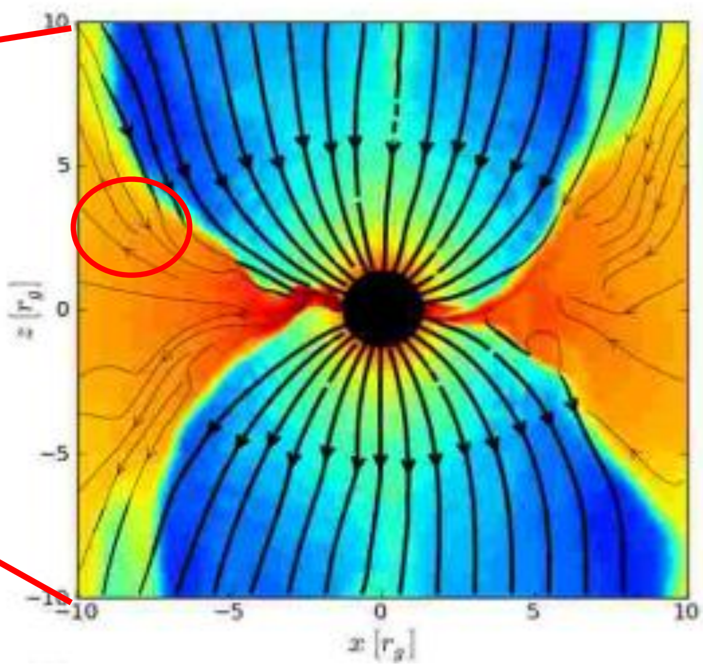




Kadowaki, Master thesis 2011 (also Zani & Ferreira 2013; Romanova+)

Evidence of Reconnection in MHD Simulations



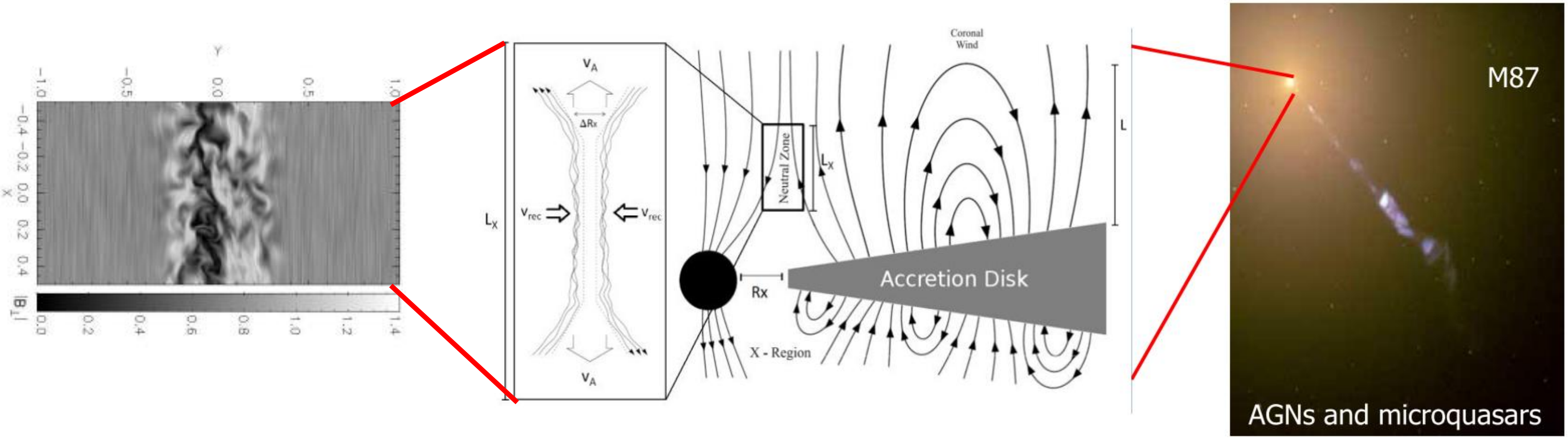


Dexter, McKinney, Tcheckovskoy et al. 2014: reconnection seen in GRMHD simulations (also Koide & Arai 2008; Pohl et al. 2016)

Reconnection acceleration in the surrounds of BHs

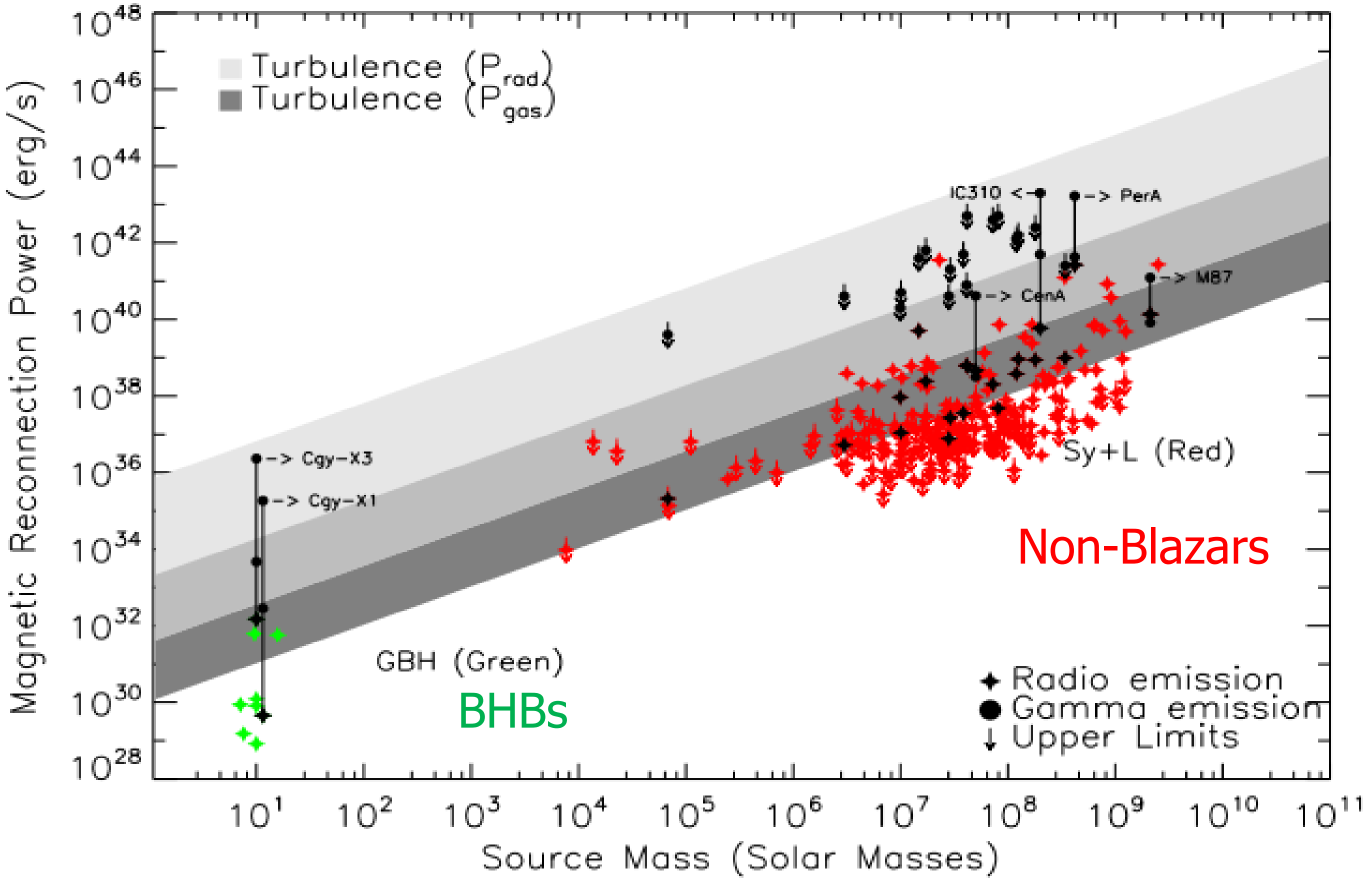
Magnetic Power released by fast reconnection

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



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

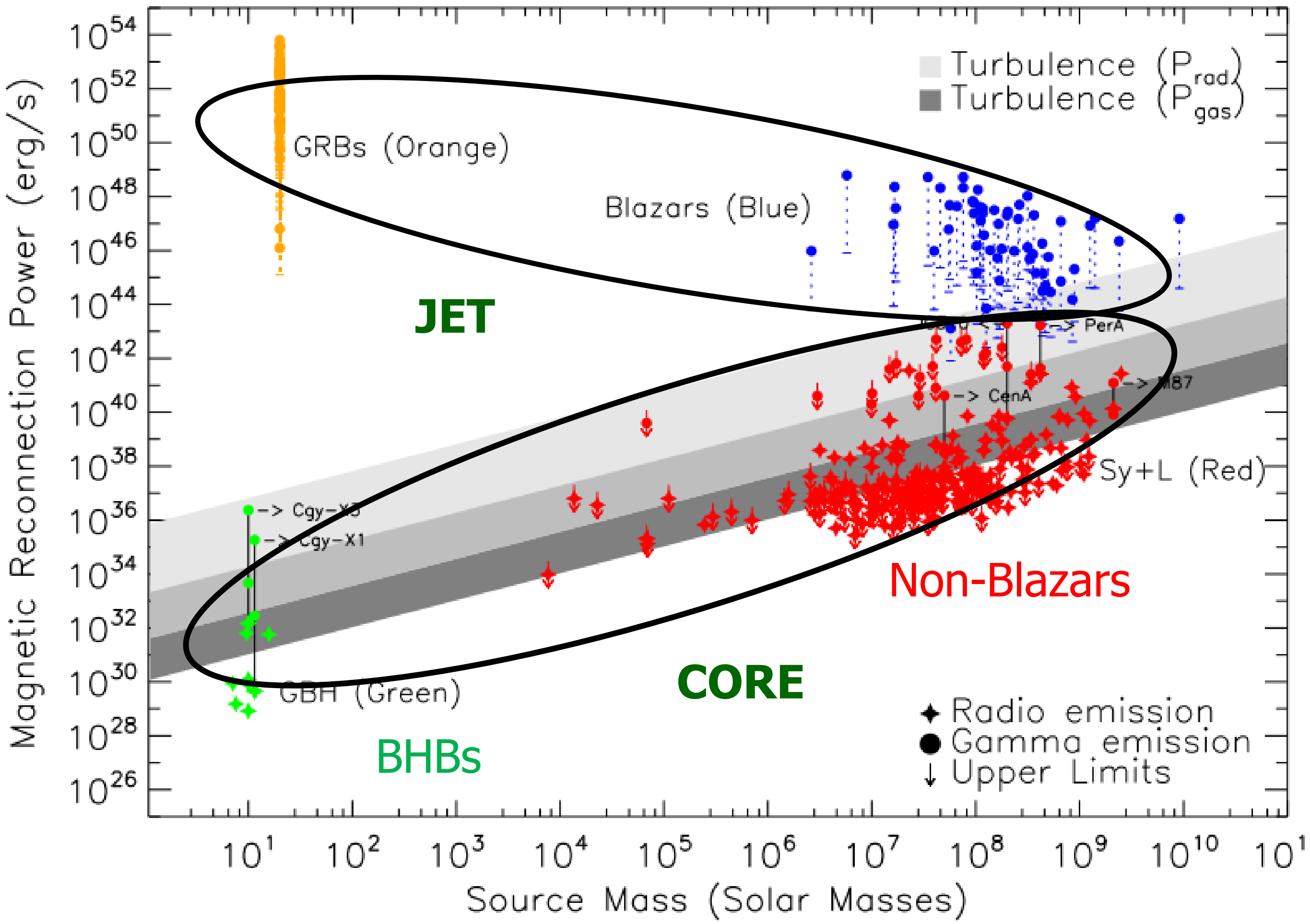
Magnetic Reconnection Power around BHs



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

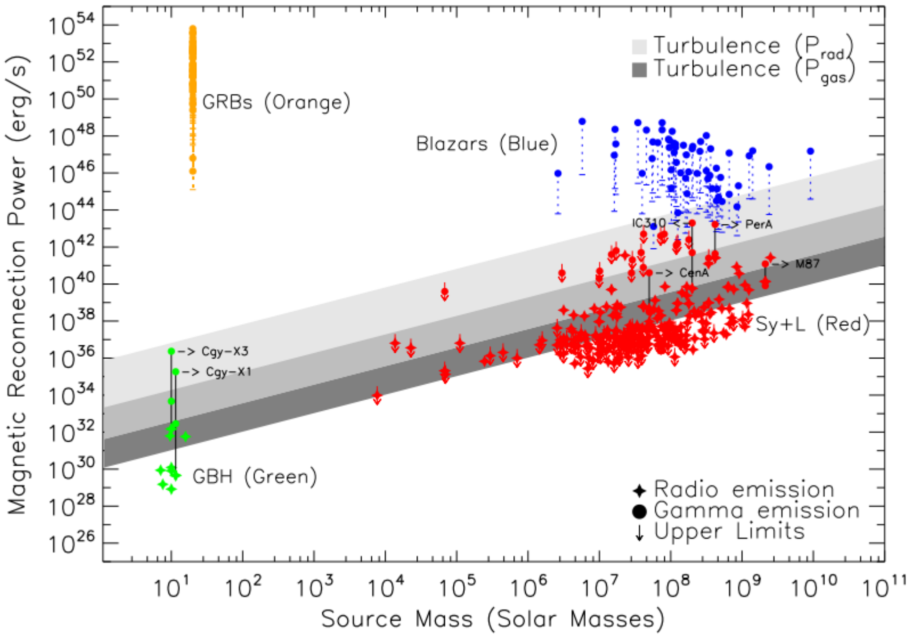
Kadowaki, de Gouveia Dal Pino, Singh, ApJ 2015
Singh, de Gouveia Dal Pino, Singh, ApJ Lett. 2015

Magnetic Reconnection Power around BHs



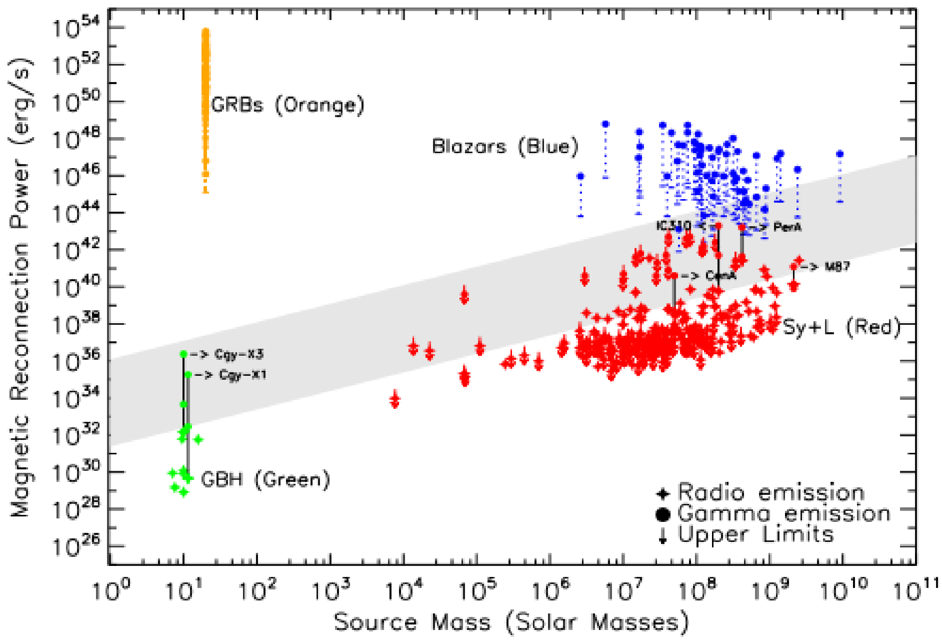
Kadowaki, de Gouveia Dal Pino, Singh, ApJ 2015
Singh, de Gouveia Dal Pino, Singh, ApJ Lett. 2015

Magnetic Reconnection around BHs works for different Accretion Disk Models



Standard accretion disk

Soft -> Hard

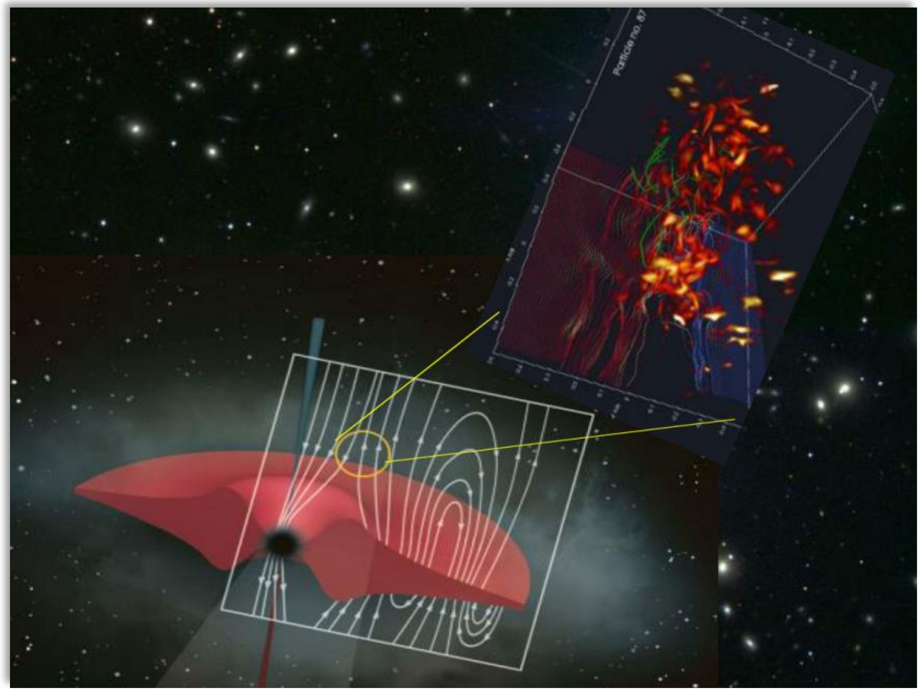


MDAF accretion disk

Hard -> Soft

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

Applying 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)

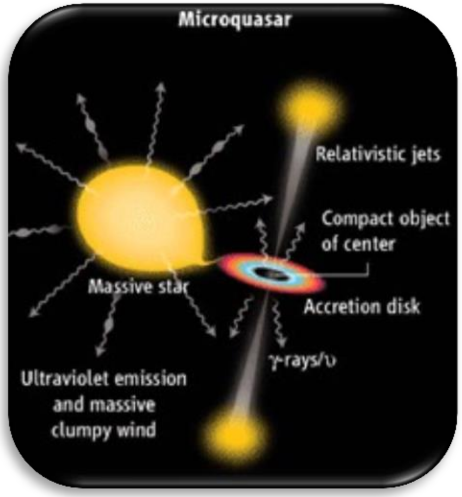
Microquasars (BH binaries): Cyg X1 and Cyg X3
(Khiali, de Gouveia Dal Pino, del Valle, MNRAS 2015)

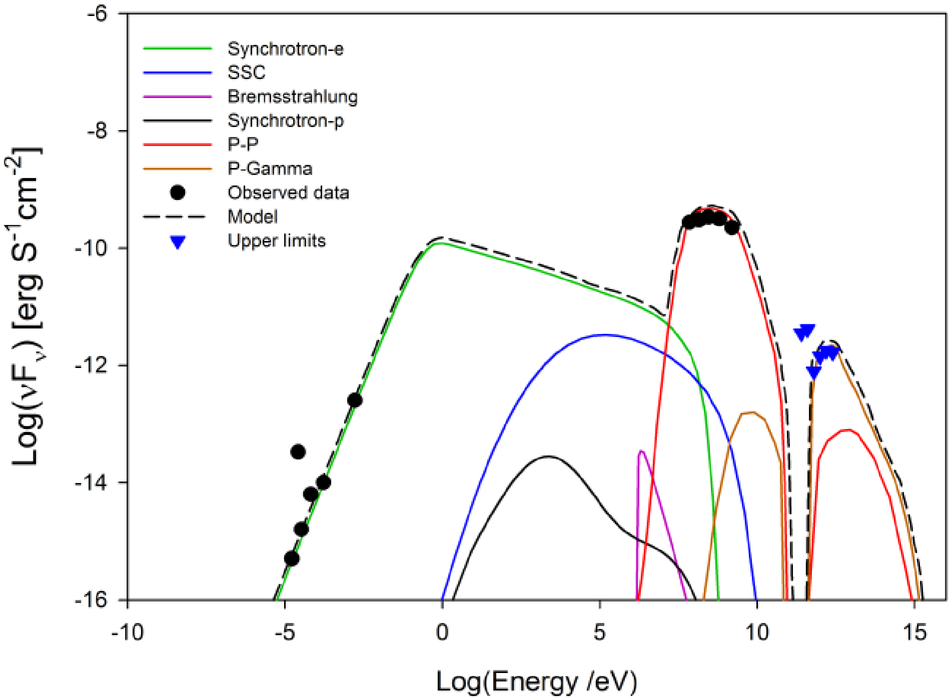
Reconnection Acceleration & Radiative Losses

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

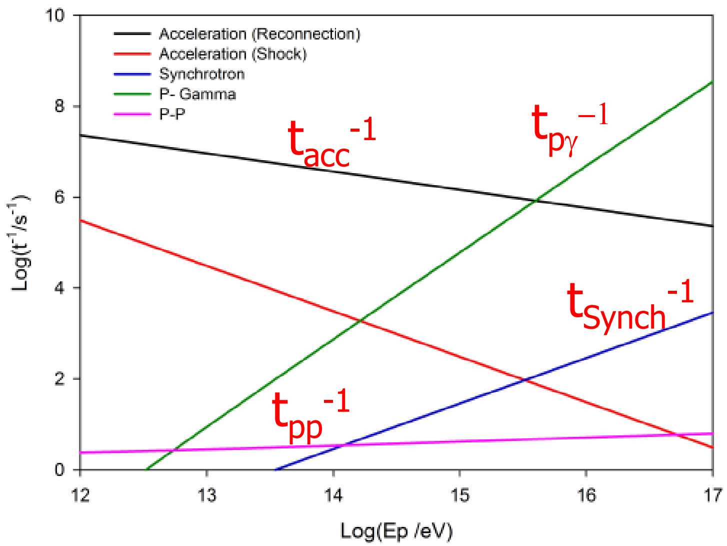
$$t_{acc} \sim t_{loss}(\text{Synchrotron, SSC, pp, p}\gamma)$$

Ex.: Galactic Black Hole Cyg X3



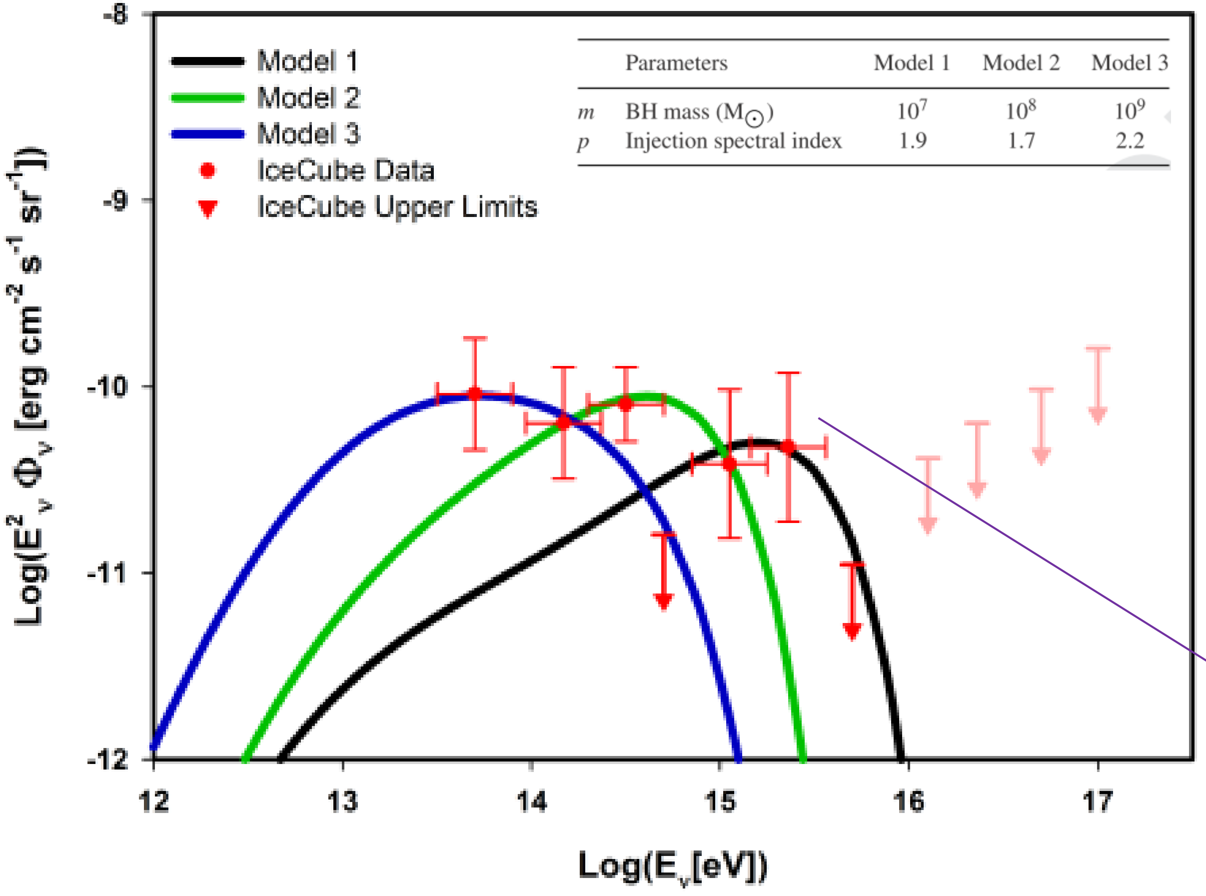


Spectral Energy Distribution (SED)



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 + photons → $\pi + p$

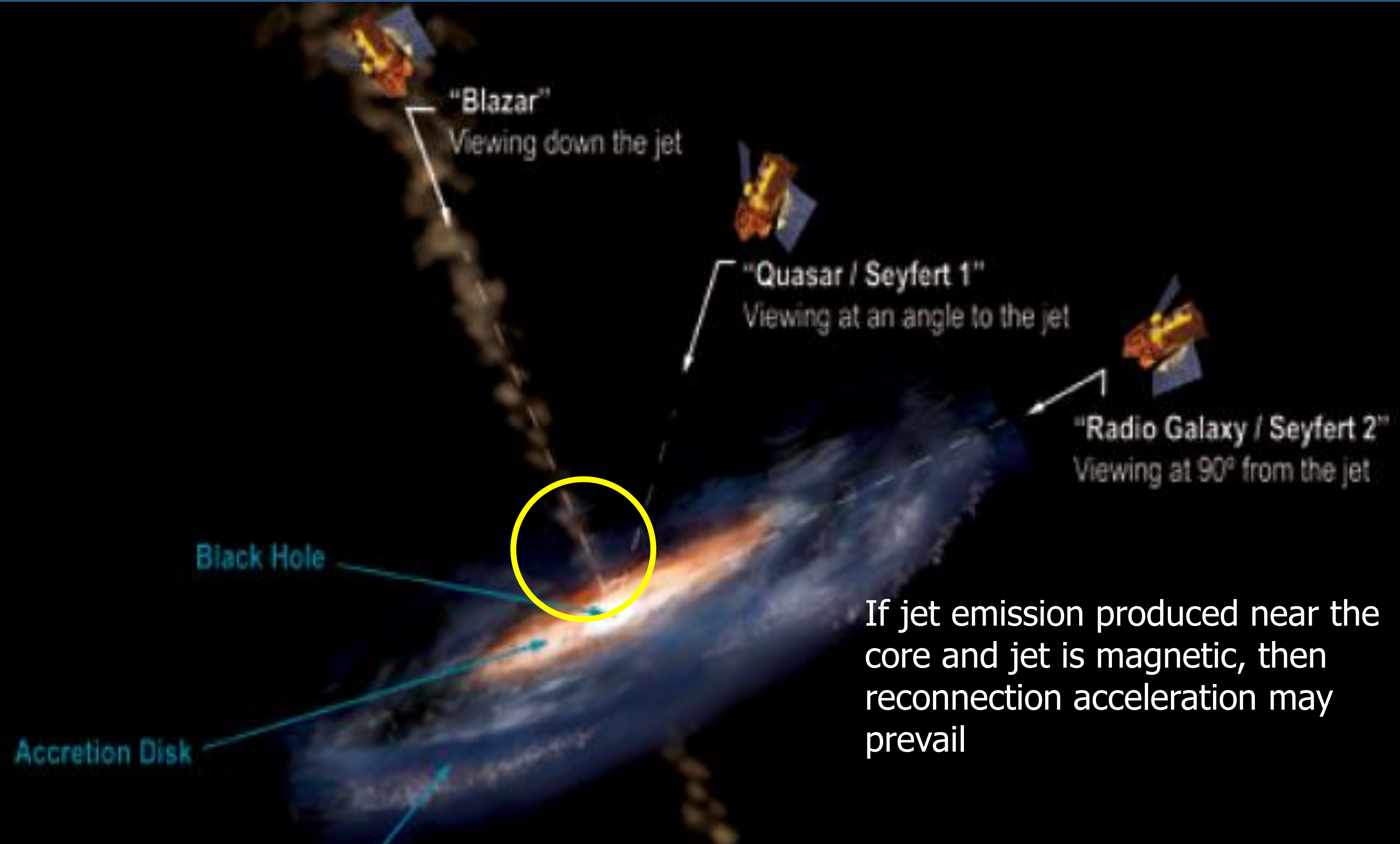
$\pi^o \rightarrow \gamma\gamma$

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

IceCube flux of Neutrinos

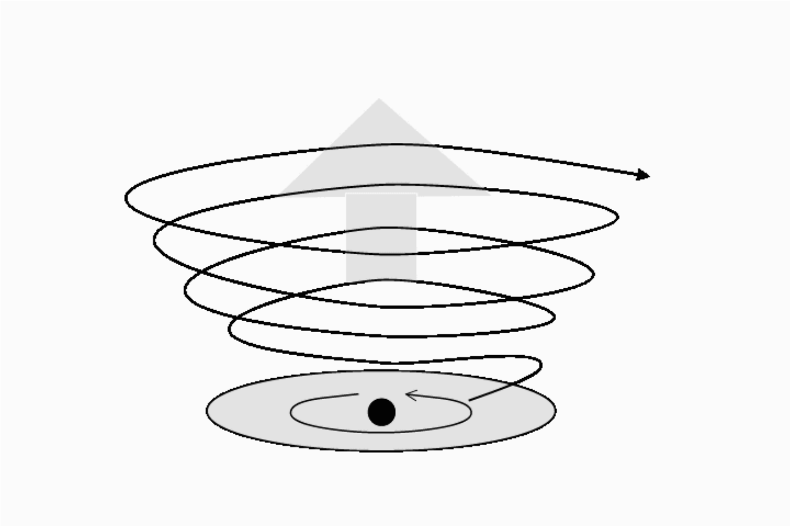
Khiali & de Gouveia Dal Pino, MNRAS 2015

Reconnection Acceleration **along** Relativistic Jets

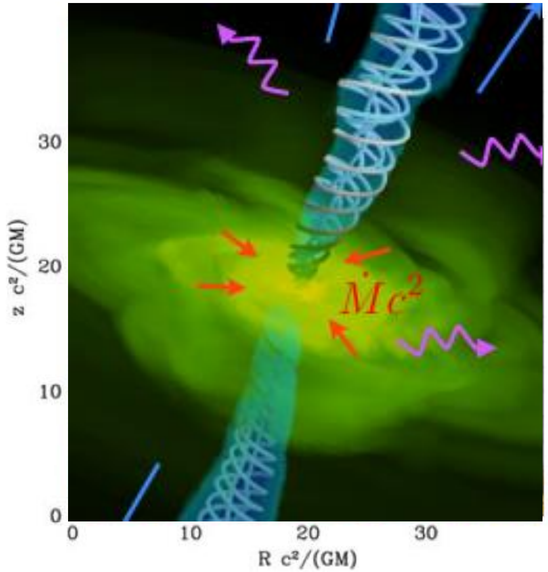


If jet emission produced near the core and jet is magnetic, then reconnection acceleration may prevail

Jets possibly 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; Tchekhovskoy 2015)

Major Problem:

Most energy in 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)

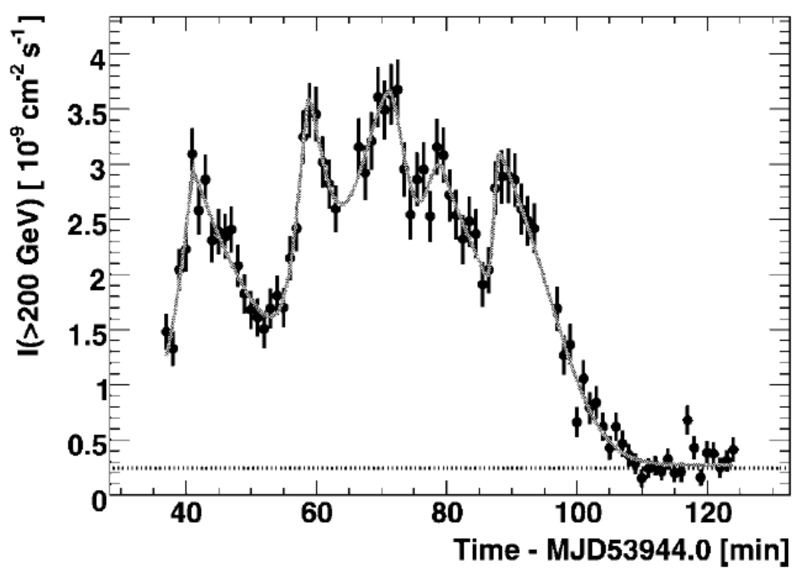
- But bulk jet $\gamma \sim$ 5-10

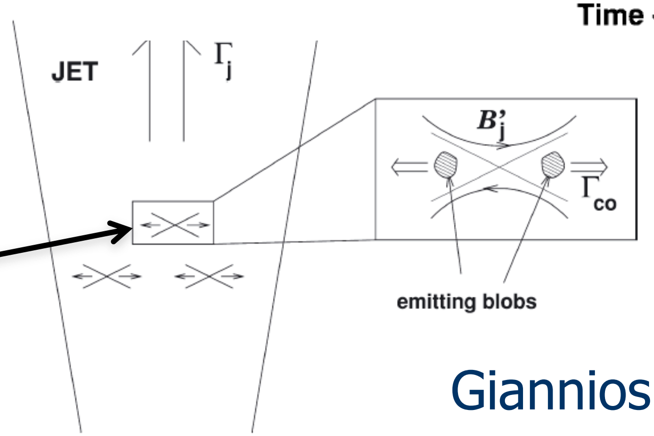
- **Emitter: compact** and/or extremely fast

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

PKS2155-304 (Aharonian et al. 2007)

See also Mrk501, PKS1222+21, PKS1830-211

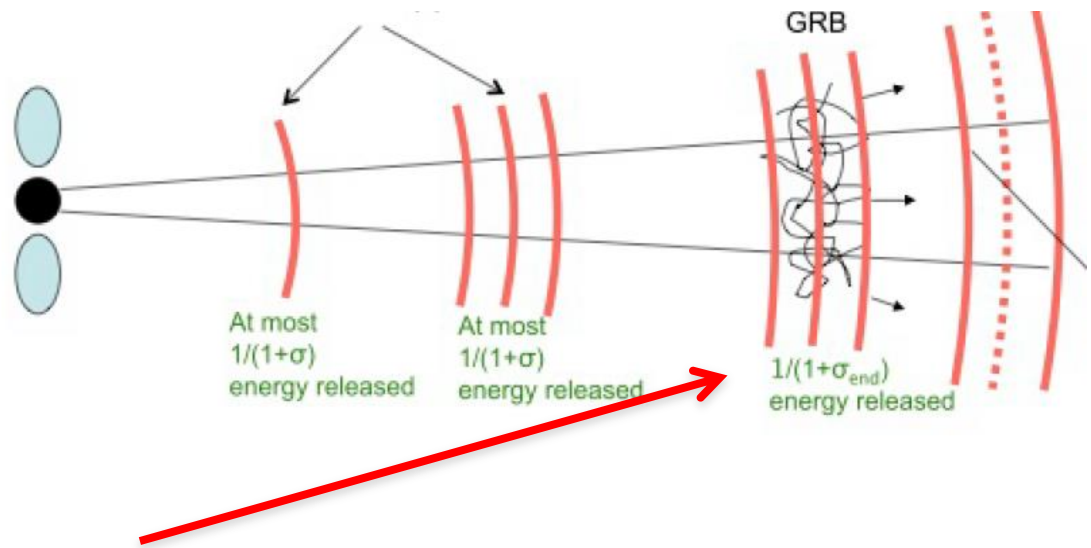




Giannios et al. (2009)

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

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



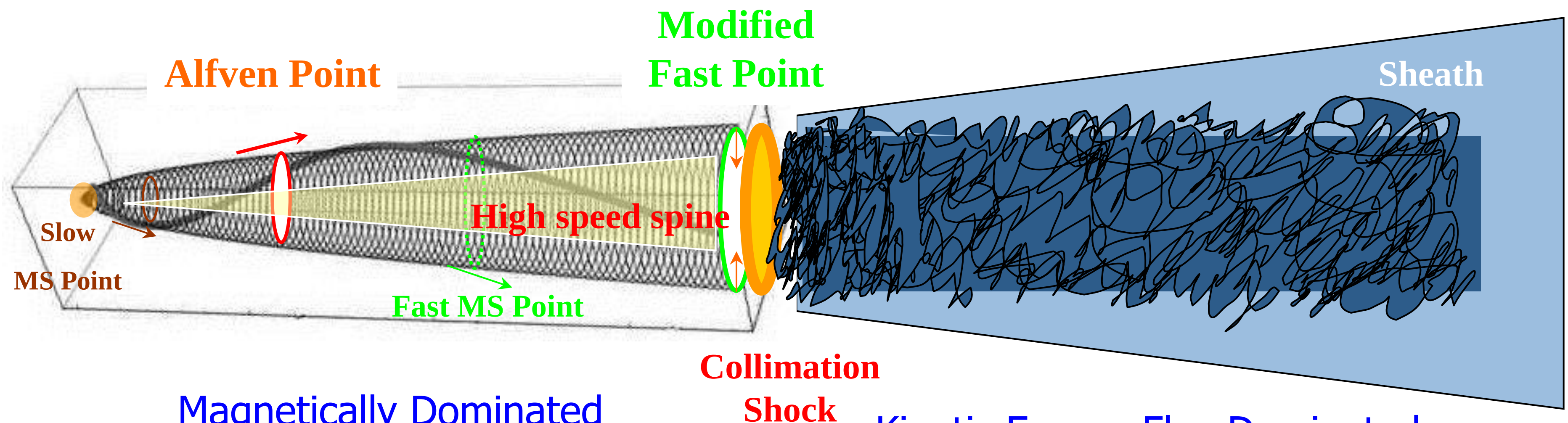
- GRB prompt emission: turbulence, magnetic reconnection, and particle acceleration via internal collisions of multiple launched parcels

(See also Giannios 2008; McKinney & Uzdensky 2012)

Regions of AGN & GRB Jet Propagation

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

~10 – $10^{2.5\pm0.5}$ r_S



Magnetically Dominated

Kinetic Energy Flux Dominated

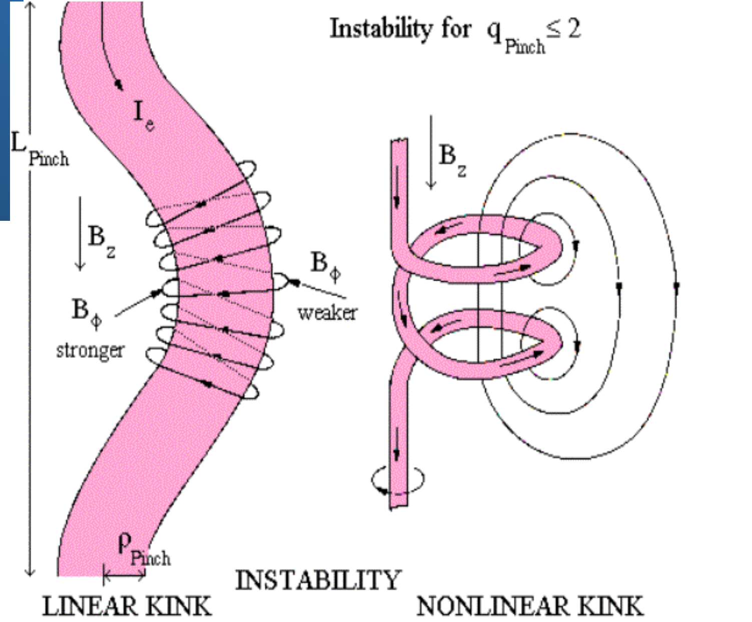
Current Driven Kink Instability
(Mizuno et al. 2012)

CD Kink Instability

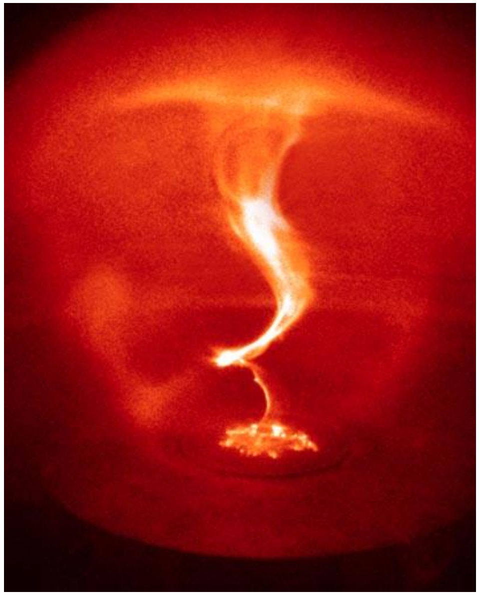
- Well-known instability in laboratory plasma (TOKAMAK) and astrophysical plasmas (Sun, jets, pulsars)
- In configurations with strong toroidal magnetic fields, current-driven (CD) kink mode (m=1) is unstable

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

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

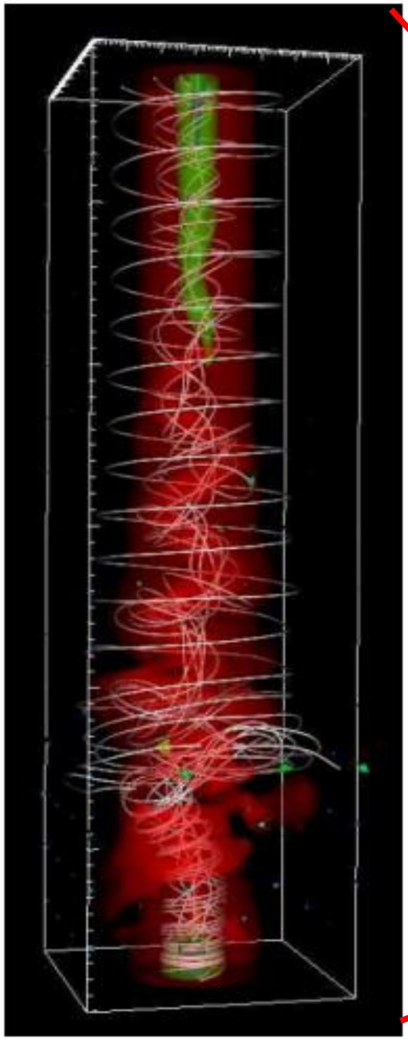


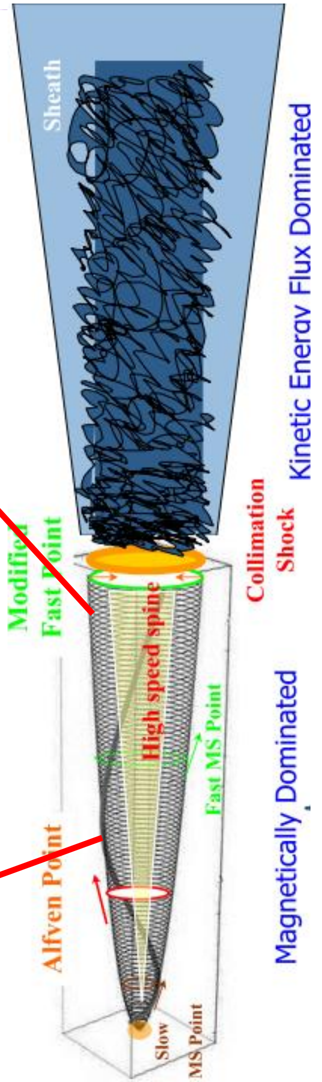
Schematic picture of CD kink instability



Kink instability in lab plasma (Moser & Bellan 2012)

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





Singh, Mizuno, de Gouveia Dal Pino, ApJ 2016

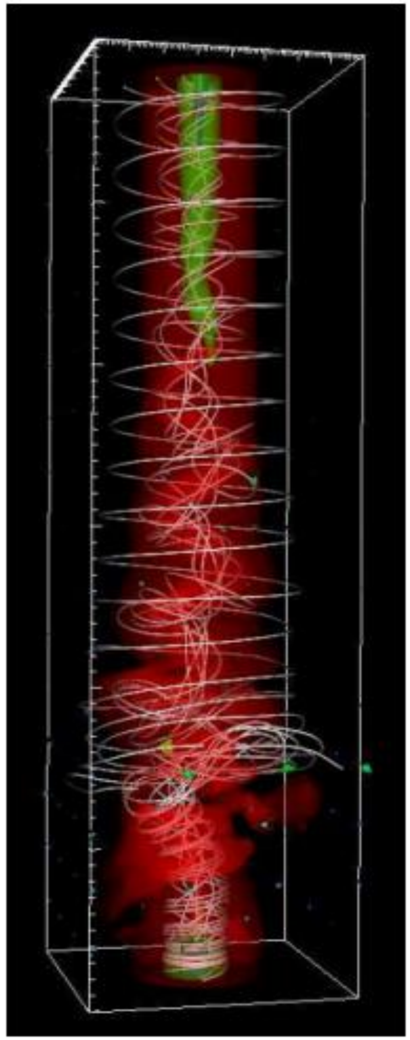
MHD Simulations of Reconnection driven by Kink in Magnetically Dominated Relativistic Jets (GRBs & AGNs)

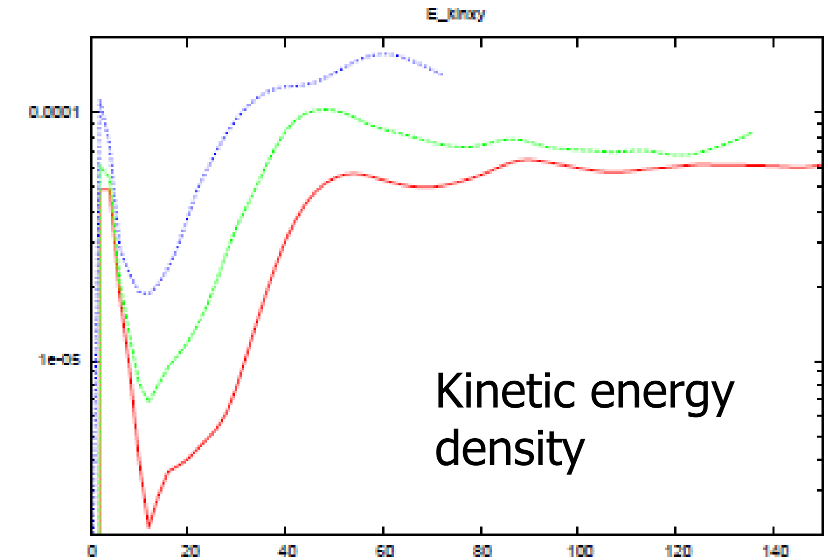
- Precession perturbation allows growth of CD kink instability with helical density distortion.

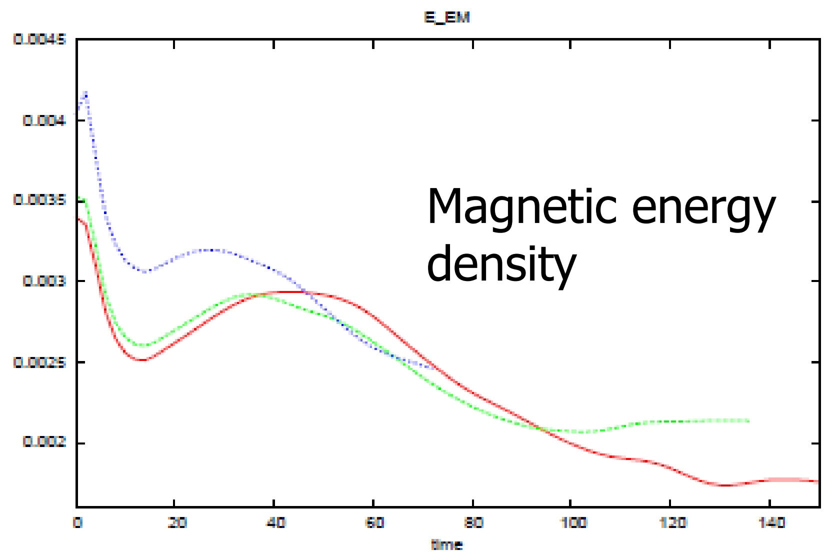
- Helical kink advected with the flow with continuous growth of kink amplitude in non-linear phase.

- Helical structure is disrupted

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



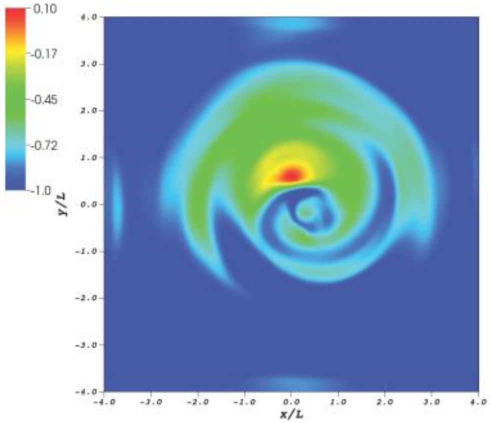




Singh, Mizuno, de Gouveia Dal Pino, ApJ 2016

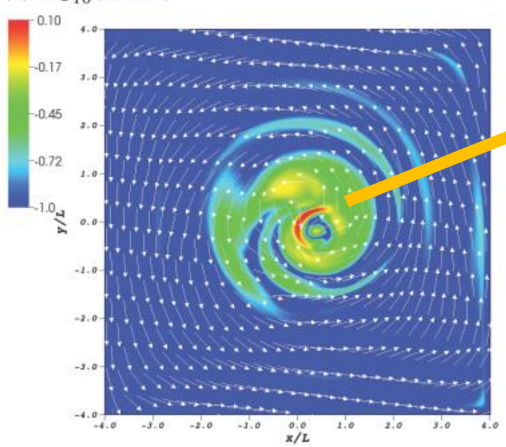
Reconnection driven by Kink in Magnetically Dominated Relativistic Jets (GRBs & AGNs)

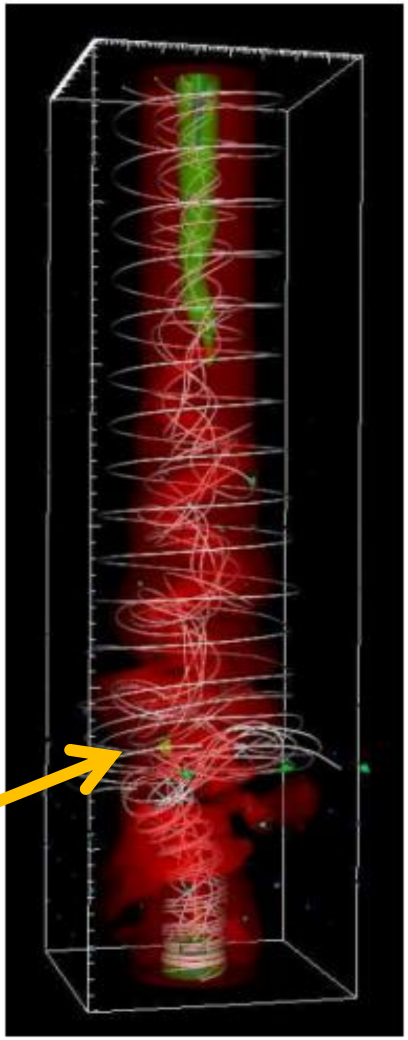
(a) $\log_{10}(\sigma$ $\sigma = B^2/\gamma^2 \rho h$

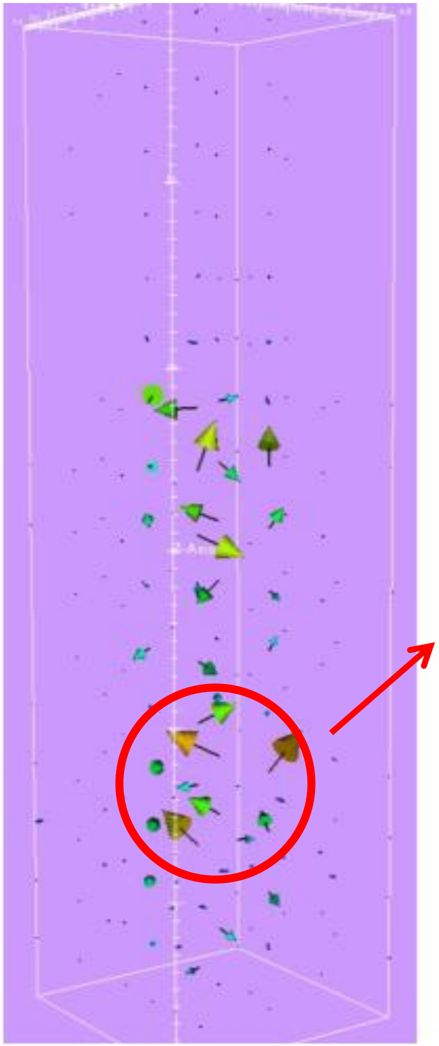


$v_{rec} \sim 0.05\ v_A$

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





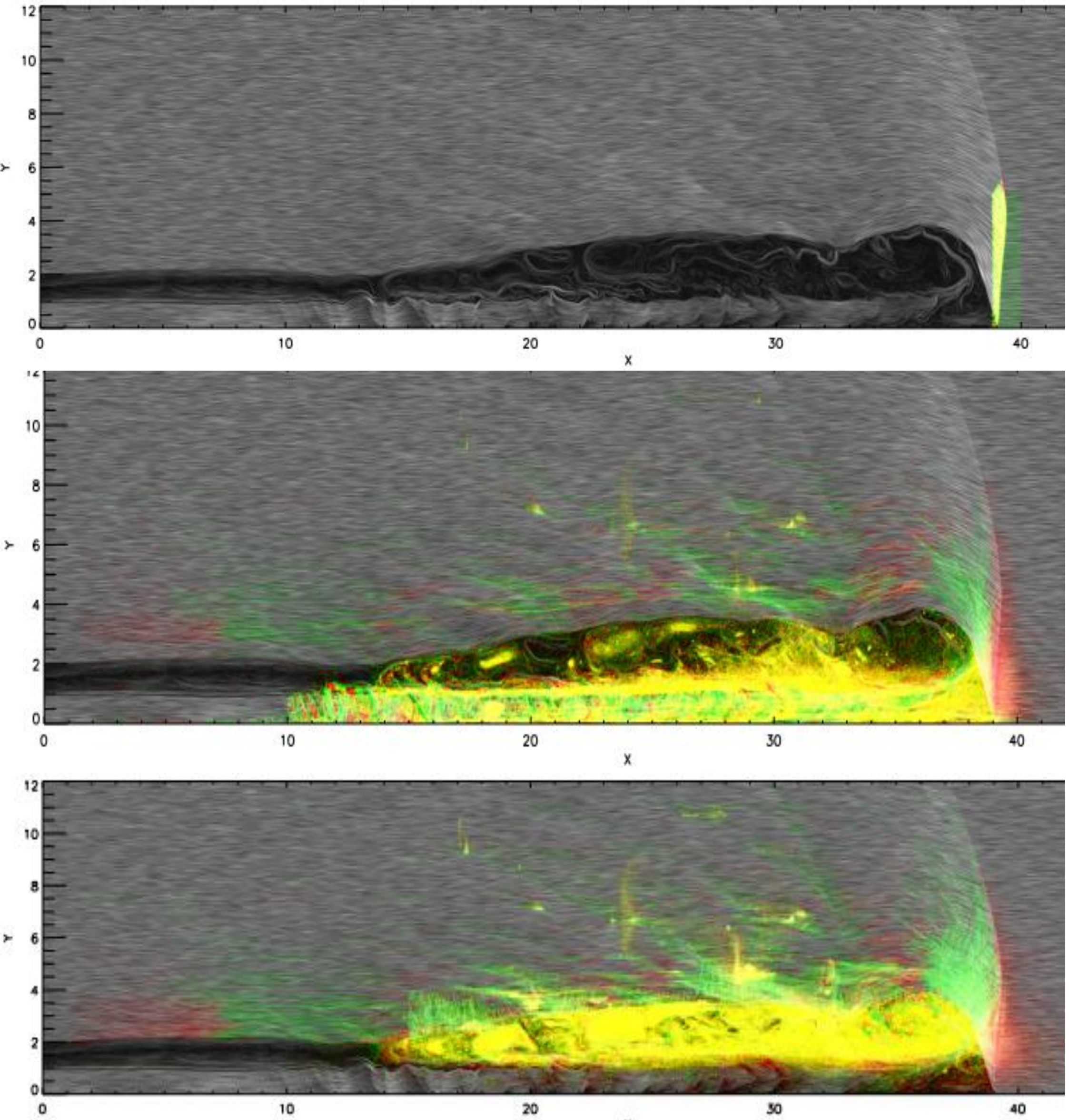


curl B = max

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

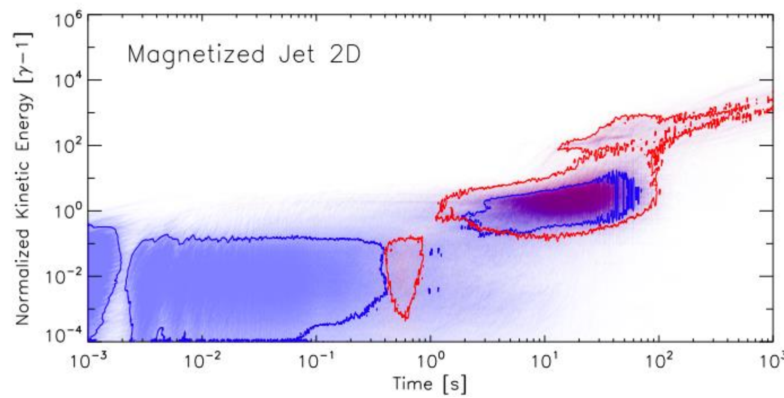
Singh, Mizuno, de Gouveia Dal Pino, ApJ 2016

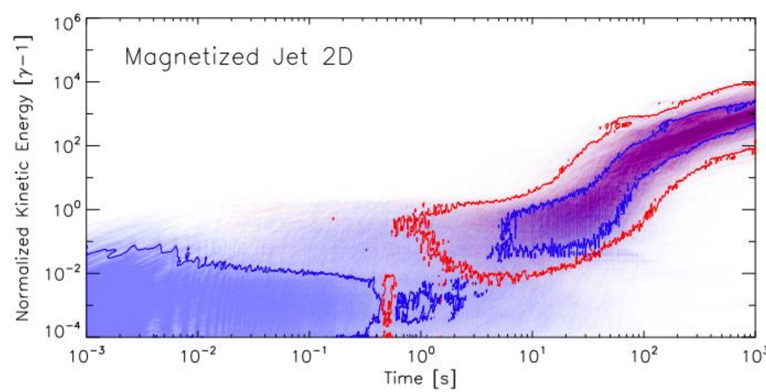
In situ 1st-order Fermi Relativistic MHD Reconnection x shock acceleration in Jets



Competing mechanisms

de Gouveia Dal Pino & Kowal, ASSL 2015





Summary

- ✓ Reconnection can be important around BHs for particle acceleration, dissipation of magnetic energy and conversion Magnetic -> Kinetic
- ✓ Particles trapped in current sheets with fast reconnection (e.g. driven by turbulence): exponential increase of energy in a 1st order Fermi acceleration: $N(E) \sim E^{-1}$
- ✓ Fermi particle acceleration by turbulent magnetic reconnection (numerically tested): can explain gamma-ray of BH binaries 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 BH binaries and non-blazar AGNs over 10 orders of magnitude in BH mass
- ✓ Reconnection acceleration can be also important in magnetically dominated regions of relativistic blazars and GRBs jets

postdoc & phd positions in my group

@ IAG-USP (FAPESP):

http://www.iag.usp.br/astri/en/opportunities