# Particle Acceleration II: by Magnetic Reconnection

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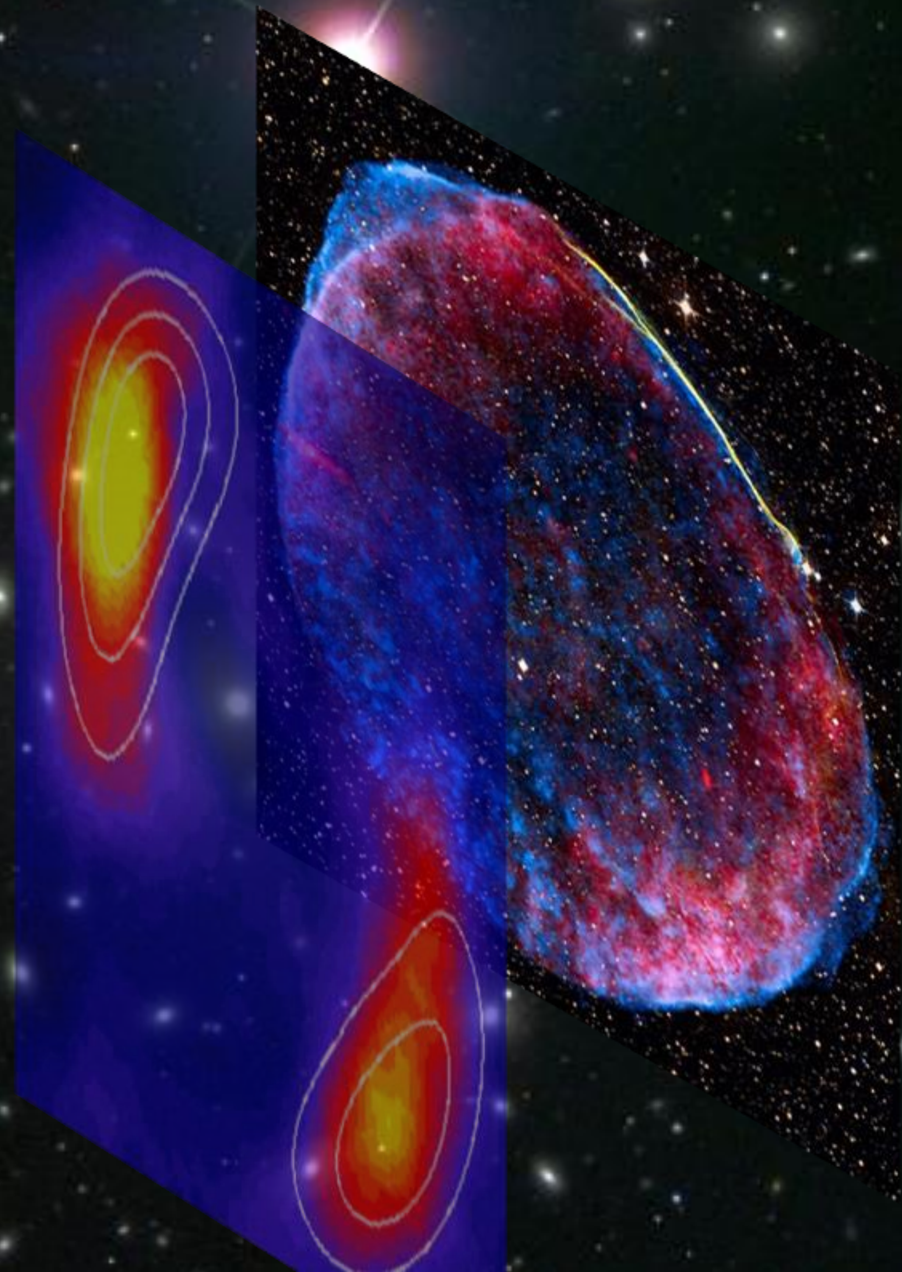


# CR acceleration: new challenges

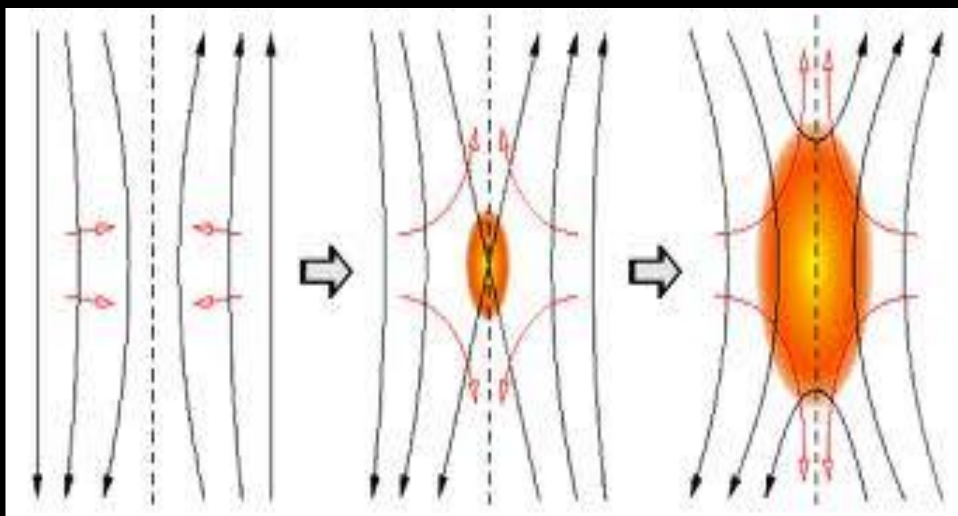
- ✓ **UHECRs** - extragalactic astrophysical sources origin: birth of compact objects, GRBs, AGNs, ICM medium? mechanism?

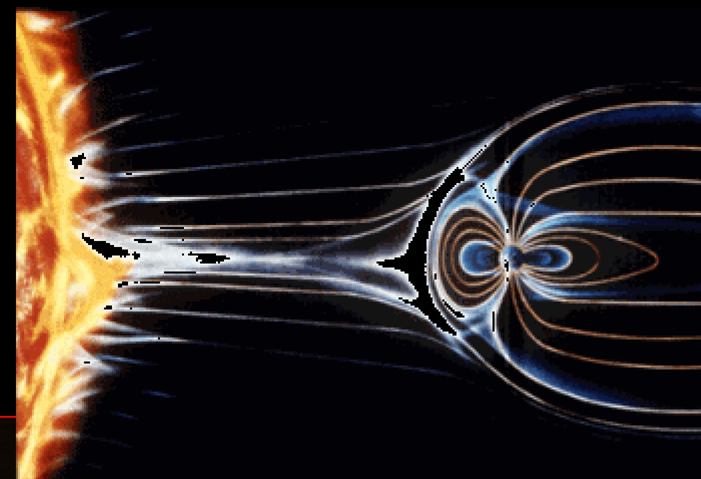
- ✓ **Very high energy observations of pulsars, AGNs and GRBs** (Fermi, Swift, HESS, VERITAS, MAGIC):

  → compact magnetized emission regions: sometimes shocks absent

# MAGNETIC RECONNECTION?

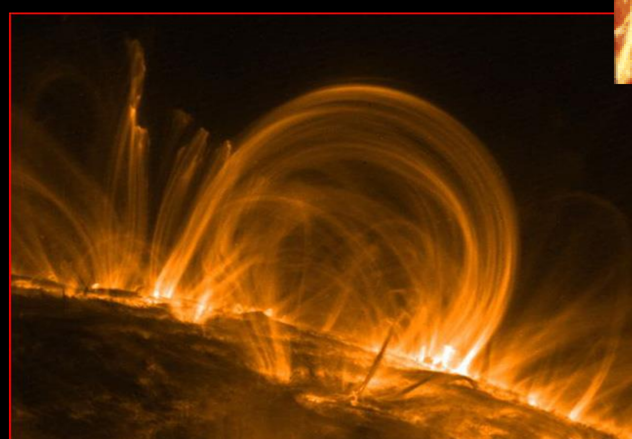
**Approach of magnetic flux tubes of opposite polarity:**





magnetotail

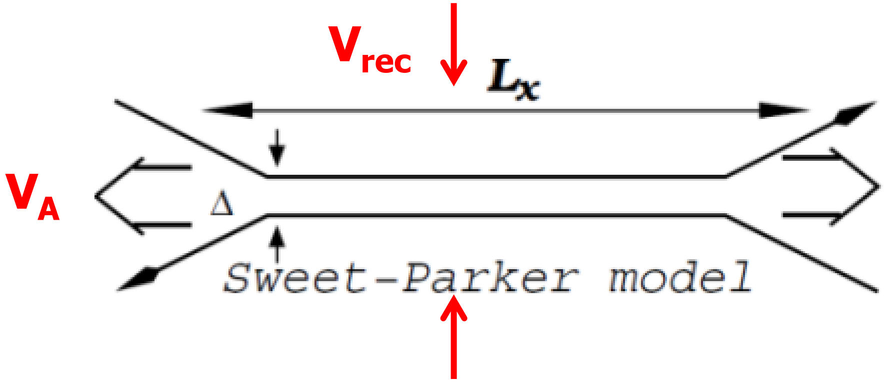
Solar corona



**Reconnection is FAST !**

# Magnetic Reconnection Models

- **Standard Sweet-Parker (57-58) reconnection: SLOW**

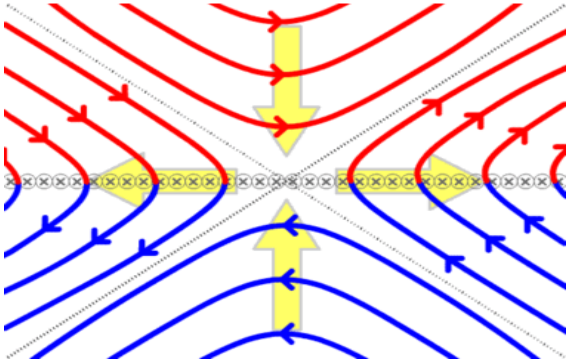



$V_{rec} \sim v_A (\Delta/L)$

$S = L\, v_A/\eta$

$V_{rec} \sim v_A S^{-1/2} << 1$

- **Petschek (1964): X-point configuration -> FAST**



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

**Unstable and collapse to S-P** (Biskamp'96) unless ***collisionless pair*** **plasma** with localized η (Sturrock 1966; Birn+01, Yamada+10).

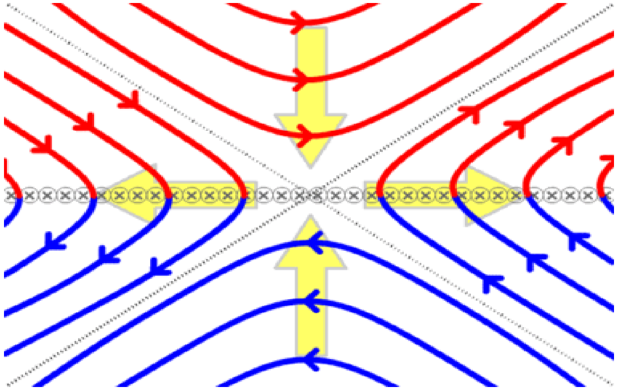
# Magnetic Reconnection Models

- **Petschek-X-point configuration in *collisionless* pair plasmas (L ~$\lambda_{e,mfp}$):**

**→ $\delta_{ion} = v_A/\omega$ > S-P diffusion scale $\Delta_{SP} = (L\eta/v_A)^{1/2}$**

**At these scales Hall effect important:**

$$\vec{v}_e = \vec{v}_i - (\vec{v}_i - \vec{v}_e) \simeq \vec{v} - \frac{\vec{J}}{n_e e}$$



**→ $v_e \times B$ term in Ohm's law:**

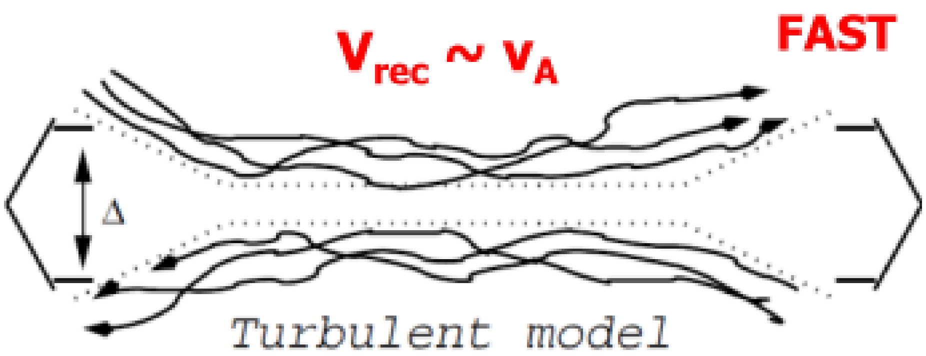
$$\vec{E} = -\frac{\vec{v}_e}{c} \times \vec{B} + \frac{m_e}{e}\vec{g} - \frac{1}{n_e e}\vec{\nabla} p_e + \eta \vec{J}$$

→ sustains X-point -> **FAST reconnection**

(Shay et al. 1998, 2004, Yamada et al. 2006)

# Ubiquitous Fast Magnetic Reconnection

**TURBULENT RECONNECTION** (Lazarian & Vishniac 1999):



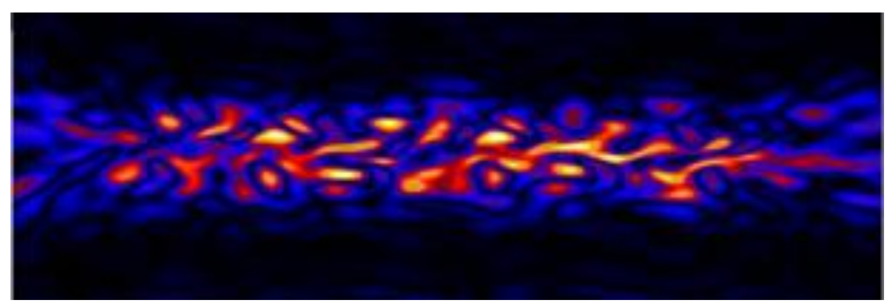

**B dissipates on a small scale $\lambda_{||}$: many simultaneous reconnection events**

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

**(does not depend on $\eta$)**

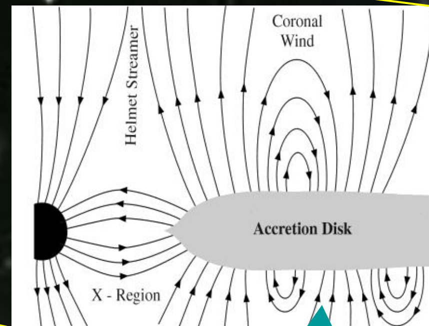
- ✓ **Reconnection layer : THICKER**
- ✓ **THREE-DIMENSIONAL**

**Successfully tested in numerical simulations** (Kowal et al. 2009, 2012)



(Similar description: Loureiro+07; Shibata & Tanuma01; Uzdensky+10)

# Reconnection beyond Solar System

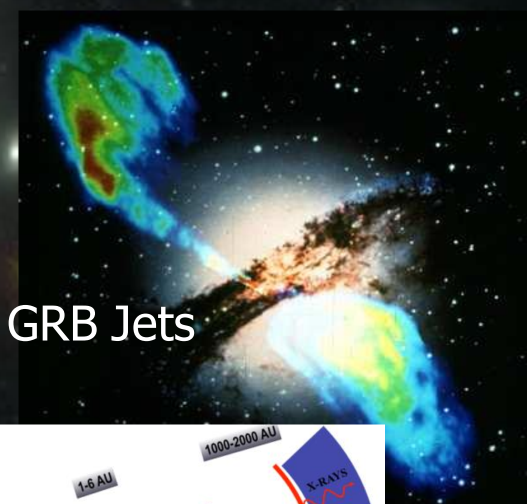


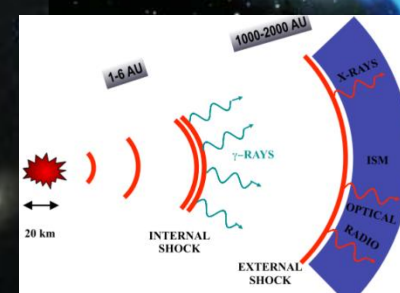

Accretion disk coronae

Stellar Xray Flares

Star Formation and ISM

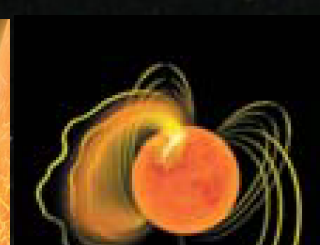
AGN & GRB Jets






Pulsars

Accreting NS and SGRs



# Reconnection Beyond the Solar System

Stellar X-ray flares (Cassak+08; Shibata+05)

Young stellar objects (van Ballegooijen94; Hayashi+1996; Goodson+1997; Feigelson & Montmerle'99; Uzdensky+'02; 04; de Gouveia Dal Pino+'10; D'Angelo & Spruit'10)

Interstellar medium and star formation (Zweibel89; Lesch & Reich92; Brandenburg & Zweibel95; Lazarian & Vishniac99; Heitsch & Zweibel03; Lazarian05; Santos-Lima+10, 12, 13; Leao+13)

Accreting neutron stars & white dwarfs (Aly & Kuijpers90; van Ballegooijen 1994; Warner & Woudt02)

Accretion disk coronae (Galeev+79; Haardt & Maraschi91; Tout & Pringle96; Romanova+98; Di Matteo+99; de Gouveia Dal Pino & Lazarian01, 05; Liu+03; Schopper et al. 1998; Uzdensky & Goodman08; Goodman & Uzdensky08; de Gouveia Dal Pino+10)

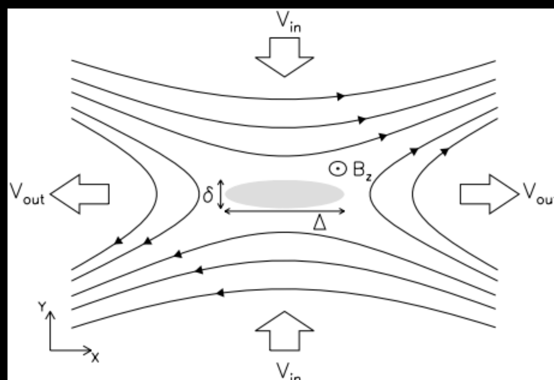
Pulsar magnetospheres and winds (Coroniti90; Michel94; de Gouveia Dal Pino & Lazarian01; Blasi+01; Lyubarsky & Kirk01; Lyubarsky03; Kirk & Skjæraasen03; Contopoulos07; Arons07; P´etri & Lyubarsky07; Spitkovsky08; Lyutikov10; Cerutti+13)

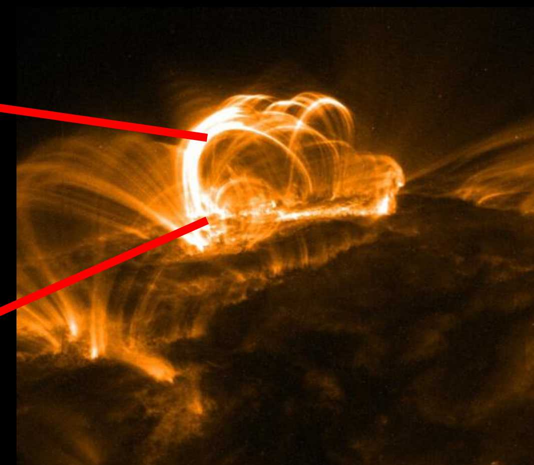
SGRs (Thompson & Duncan95, 01; Lyutikov 03, 06; Uzdensky08; Masada+10)

Relativisitc jets (microquasars/AGNs/GRBs) (Romanova & Lovelace92; Larrabee+03; Lyutikov+03; Jaroschek+04; Giannios10; Giannios+09, 10; de Gouveia Dal Pino+10; Nalewajko et al. 2010); Spruit et al. 2001; Lyutikov & Blackman01; Lyutikov & Blandford02; Drenkhahn &Spruit02; Giannios & Spruit05, 06, 07; Rees & M´esz´aros 2005; Uzdensky & MacFadyen06; McKinney & Uzdensky10; 12; Uzdensky11; Zhang & Yan09).

# Reconnection & Particle Acceleration

Reconnection breaks the magnetic field topology -> releases magnetic energy into plasma in short time -> explains bursty emission

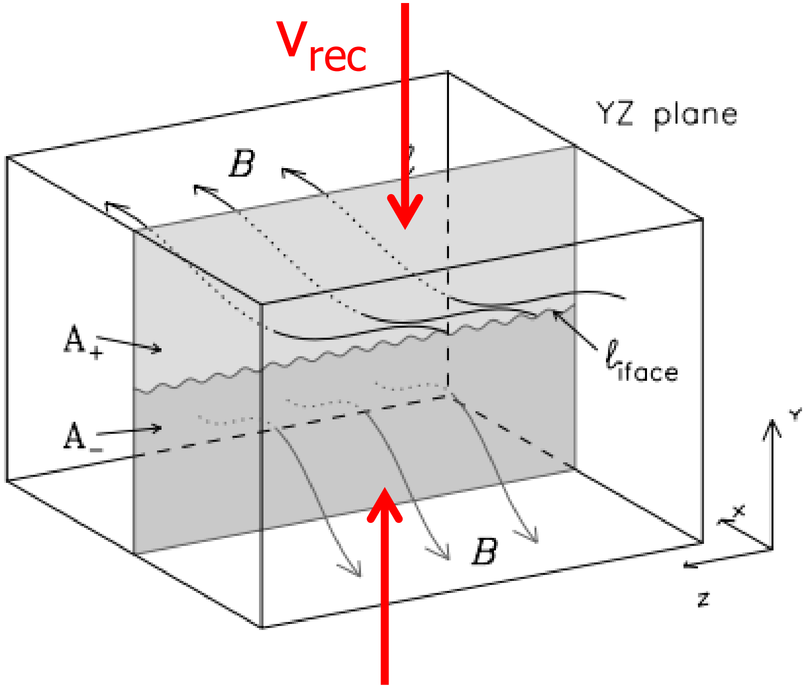


✓ **Solar/stellar flares** produced by fast **reconnection**
✓ **Particle acceleration** connected with flares

→ **Can reconnection lead to direct particle acceleration?**

# Reconnection & Particle Acceleration



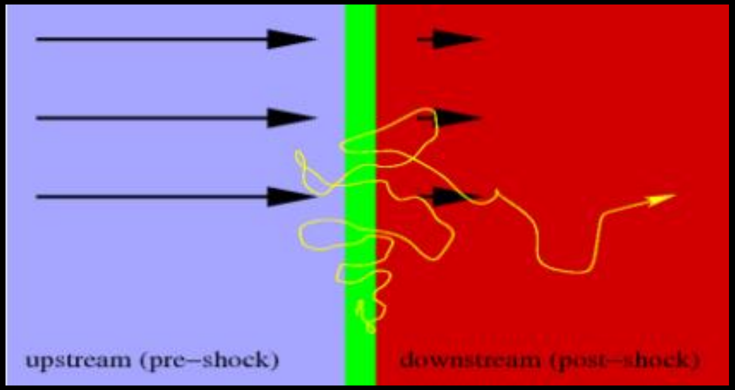

**Particle acceleration in reconnection site:**

due to advective electric field directed along z-axis (linear)

$\mathbf{e_z = v_{rec}\, B/c}$ → **reconnection electric field**

# 1st-order FERMI ACCELERATION @ RECONNECTION SITE

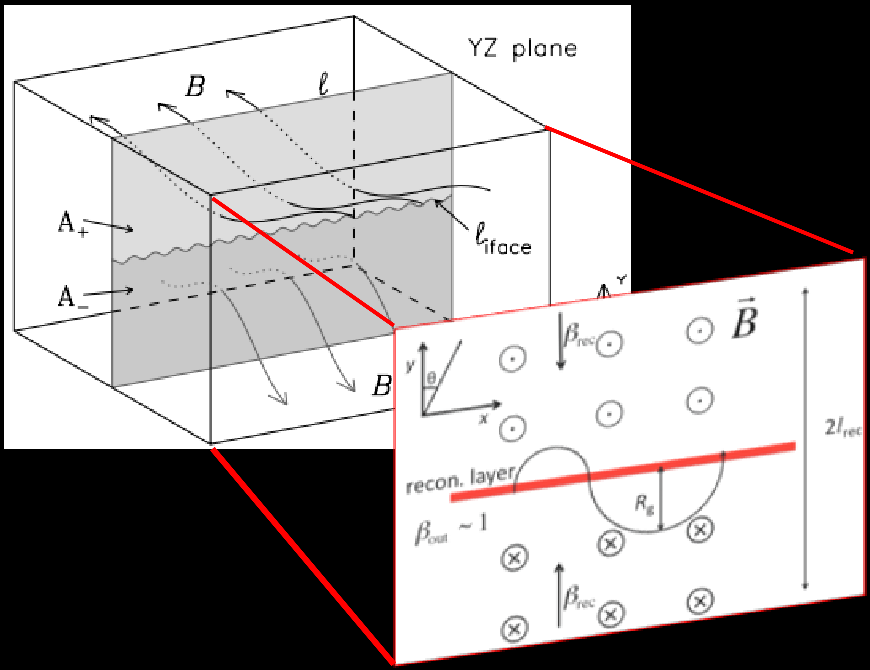
## Shock Acceleration




1st-order Fermi (Bell+1978):

**<ΔE/E> ~ v/c**

## Reconnection Acceleration



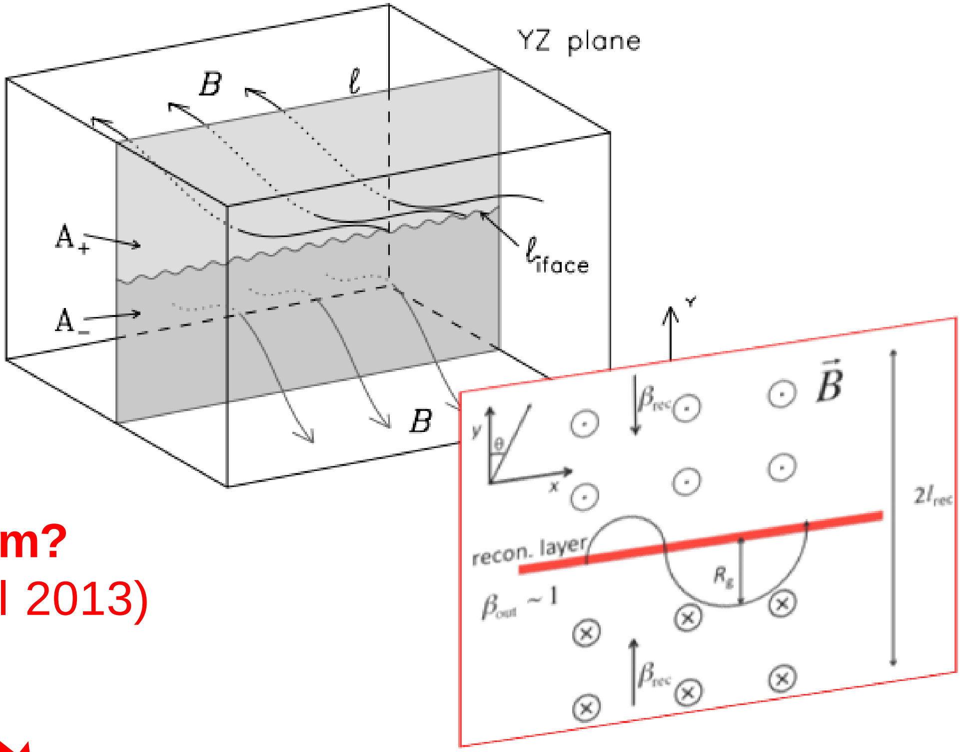

**1st-order Fermi (de Gouveia Dal Pino & Lazarian 2005):**
particles bounce back and forth between 2 converging flows

**$<\Delta E/E> \sim 8v_{rec}/3c$**

# 1st-order FERMI ACCELERATION @ RECONNECTION SITE

**1st-order Fermi (de Gouveia Dal Pino & Lazarian 2005):**

$<\Delta E/E> \sim 8v_{rec}/3c$




✓ **Particle and Synchrotron Spectrum?**
(see also de Gouveia Dal Pino & Kowal 2013)

$N(E) \sim E^{-5/2} \rightarrow S_\nu \sim \nu^{-0.75}$

**Radio flares in galactic BHs**

✓ **Relax the assumption considered above that particle escapes rate ~ shock (Drury 2012) →**

$N(E) \sim E^{-(r+2)/(r-1)}$ , $r = \rho_2/\rho_1$ → $N(E) \sim E^{-2-1}$

# Reconnection a powerful mechanism to accelerate particles?

**To probe analytical results → numerical simulations:**

- Most 2D simulations of particle acceleration by magnetic reconnection: **collisionless plasmas (PIC)** @ scales (e.g. Drake+; Zenitani & Hoshino):

  **few plasma inertial length ~ 100 $c/\omega_p$**

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

  → **MHD description → collisional resistive reconnection**

# MHD Simulations of Reconnection Particle Acceleration

?

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$\rho \left( \frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla \right) \mathbf{u} = -c_s^2 \nabla \rho + (\nabla \times \mathbf{B}) \times \mathbf{B} - \rho \nabla \Psi + \mathbf{f}$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \eta_{\mathrm{Ohm}} \nabla^2 \mathbf{B}$$

- $2^{nd}$ order shock capturing Godunov scheme with HLLD solver (Kowal et al. 2007, 2009)

- f: isotropic, non-helical, solenoidal, delta correlated in time random force term (responsible for injection of turbulence)

# Probing Particle Acceleration by Reconnection with Numerical MHD Simulations

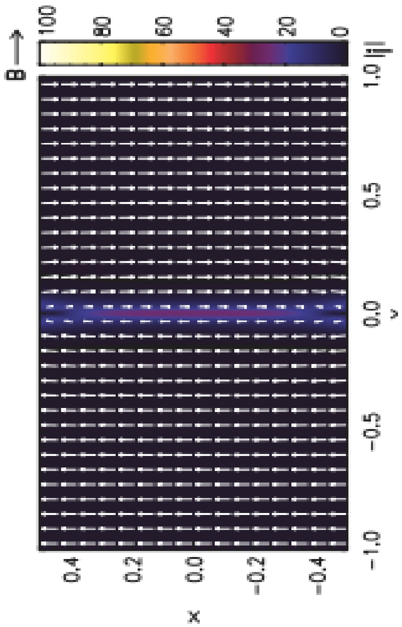
- **Isothermal MHD equations solved:** second-order Godunov scheme and HLLD Riemann solver (Kowal et al. 2007, Kowal et al 2009)

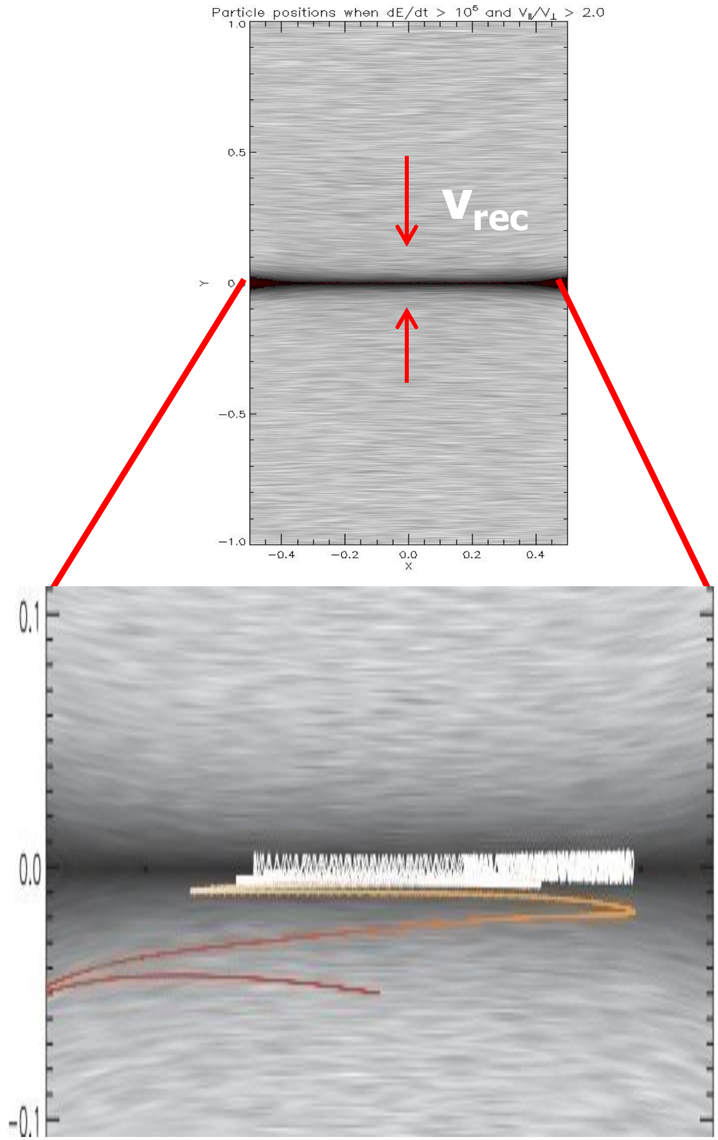
- **Test particles injected** in the MHD domain of reconnection and their trajectories followed:

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

**Kowal, de Gouveia Dal Pino, Lazarian 2011; 2012**

# Particle Acceleration in MHD Reconnection



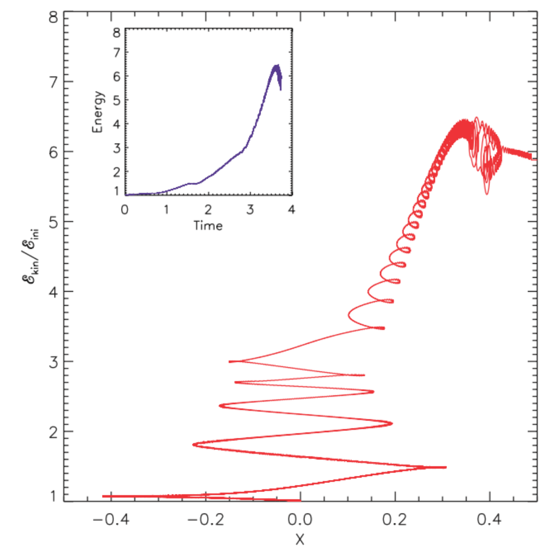




**Resistive Sweet-Parker Current Sheet:**

particles confined

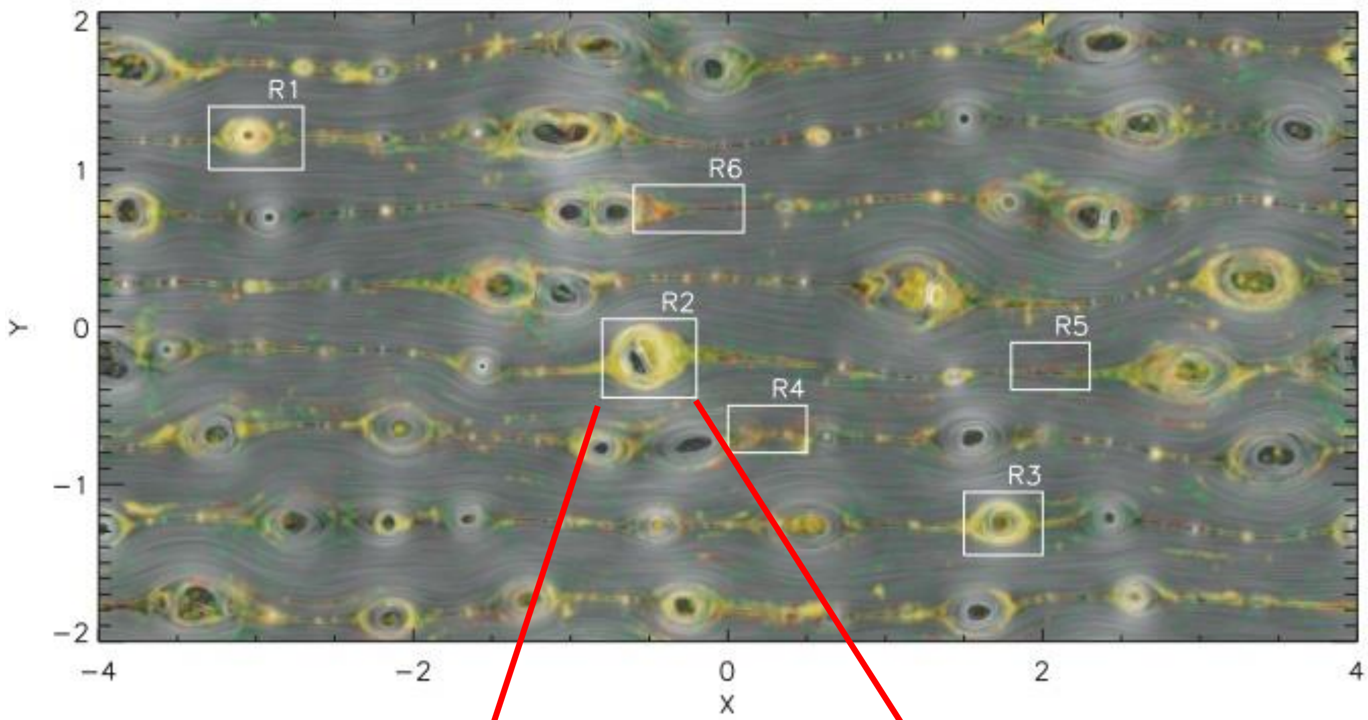
→ 1$^{st}$ order Fermi:

$\Delta E/E \sim v_{rec}/v$




Confirming
de Gouveia Dal Pino
& Lazarian (2005)

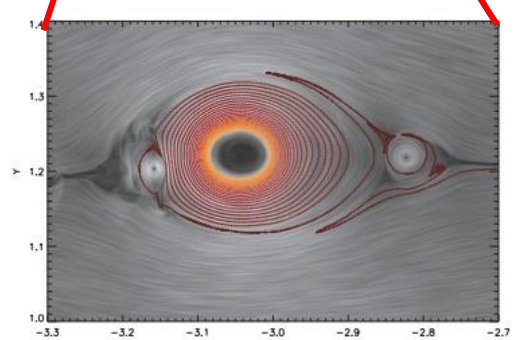
# Particle Acceleration in 2D MHD Reconnection

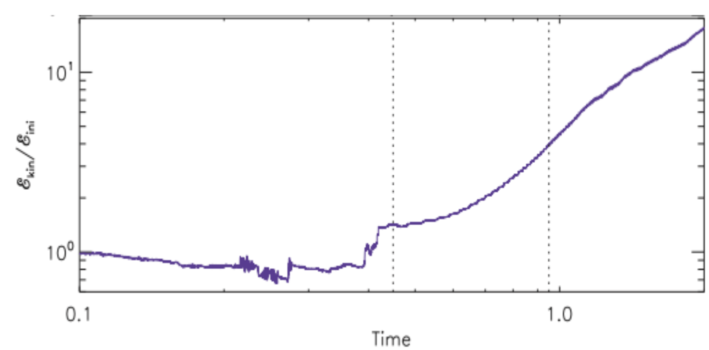



**2D Multiple current sheets**

**v fluctuations:** to allow reconnection and islands formation

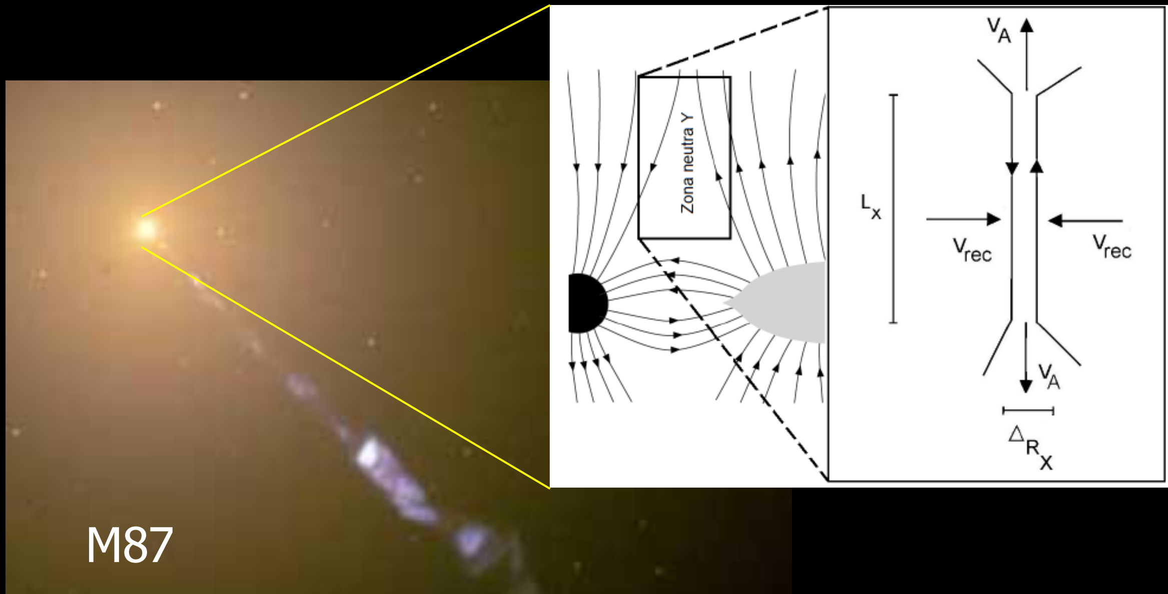
**Merging islands:** particles confined → $1^{st}$ order Fermi

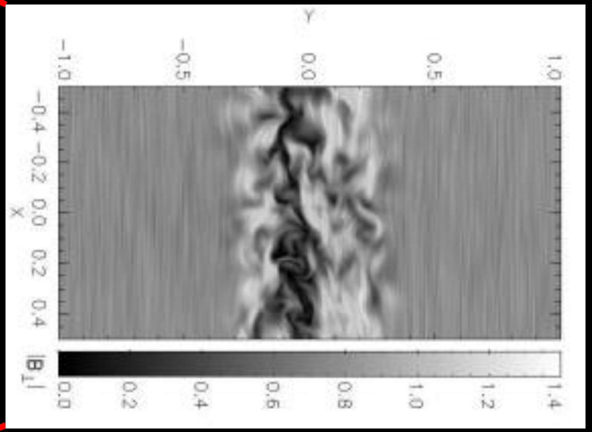


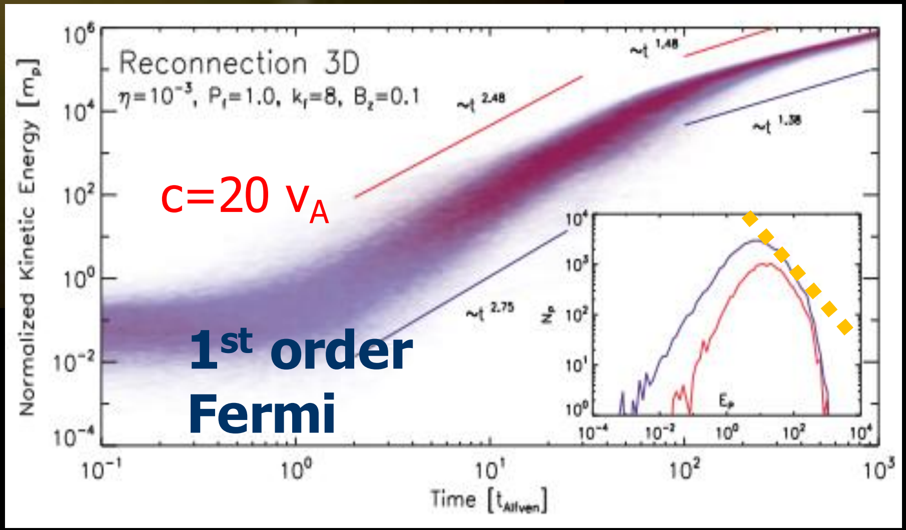

Kowal, de Gouveia Dal Pino, Lazarian 2011 (see also Drake)

# Particle Acceleration in 3D MHD Fast reconnection



current sheet with turbulence ➡ **fast reconnection**




Exponential growth of energy

**N(E) ~ $E^{-1}$**

Kowal, de Gouveia Dal Pino, Lazarian 2012

# Particle Maximum Energy in Fast Reconnection

✓ **Particle can no longer be confined within the reconnection region when:**

$$r_g = E/B\,e\,c > l_{rec} \rightarrow E_{max} \sim l_{rec} c\,e\,B = 9.\,10^{12}\,\mathrm{eV}\,l_{rec,cm}\,B_G$$

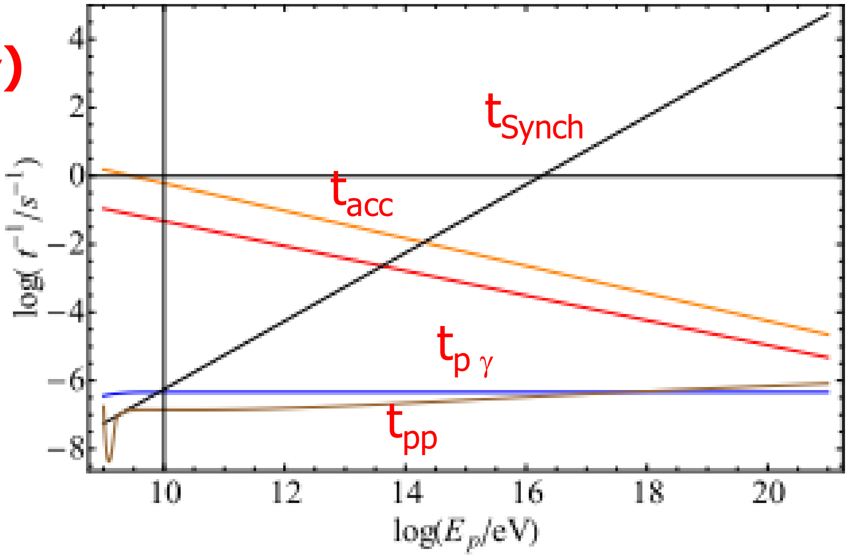
✓ **Cooling of the particle** is fast enough to inhibit further acceleration:

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

**AGN M87**:

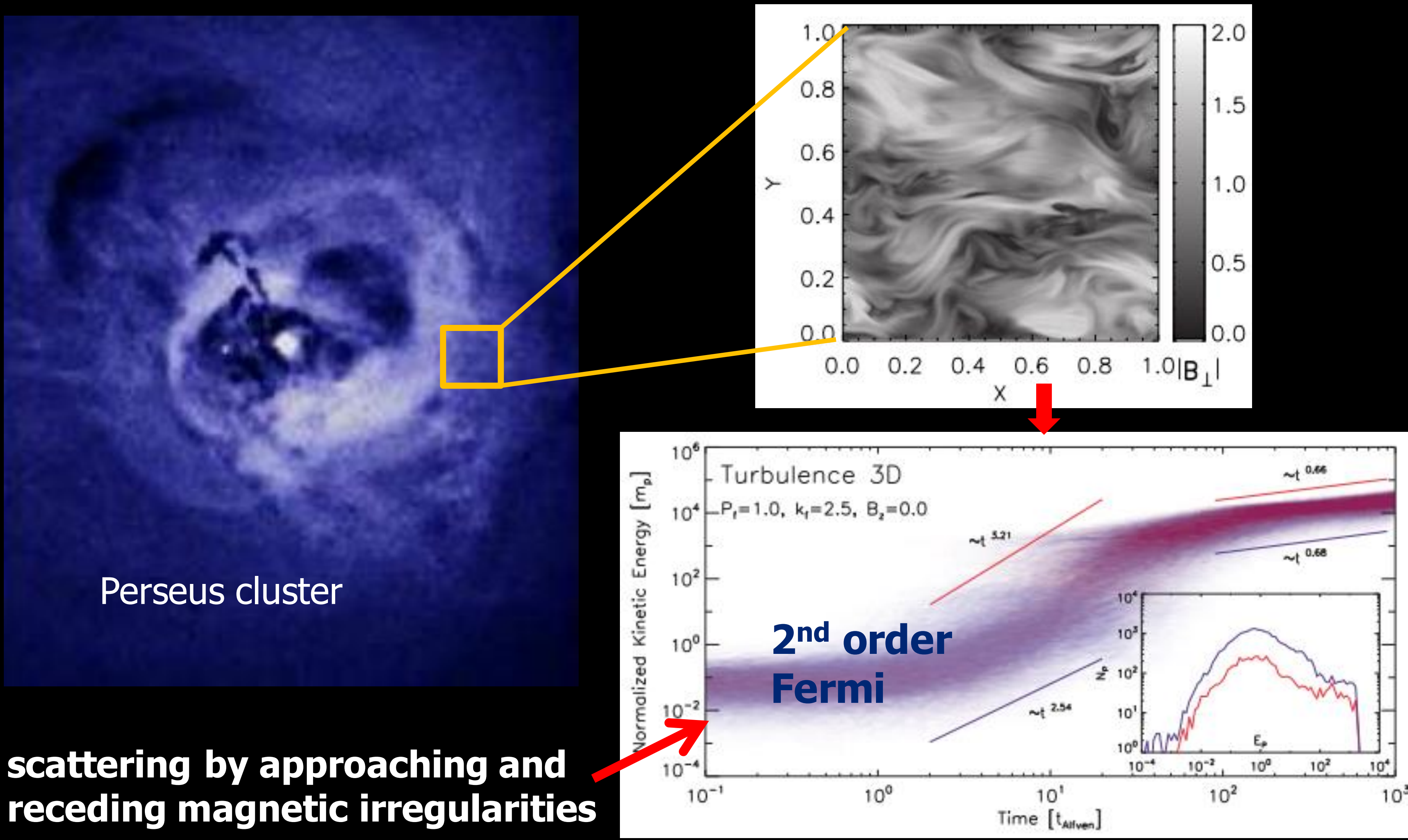
if $B \sim 10^5$ G, $v_{rec} \sim 0.1 v_A$

$E_{max} \sim 10^{15}$ eV




Khiali, de Gouveia Dal Pino, del Valle, Sol (20130

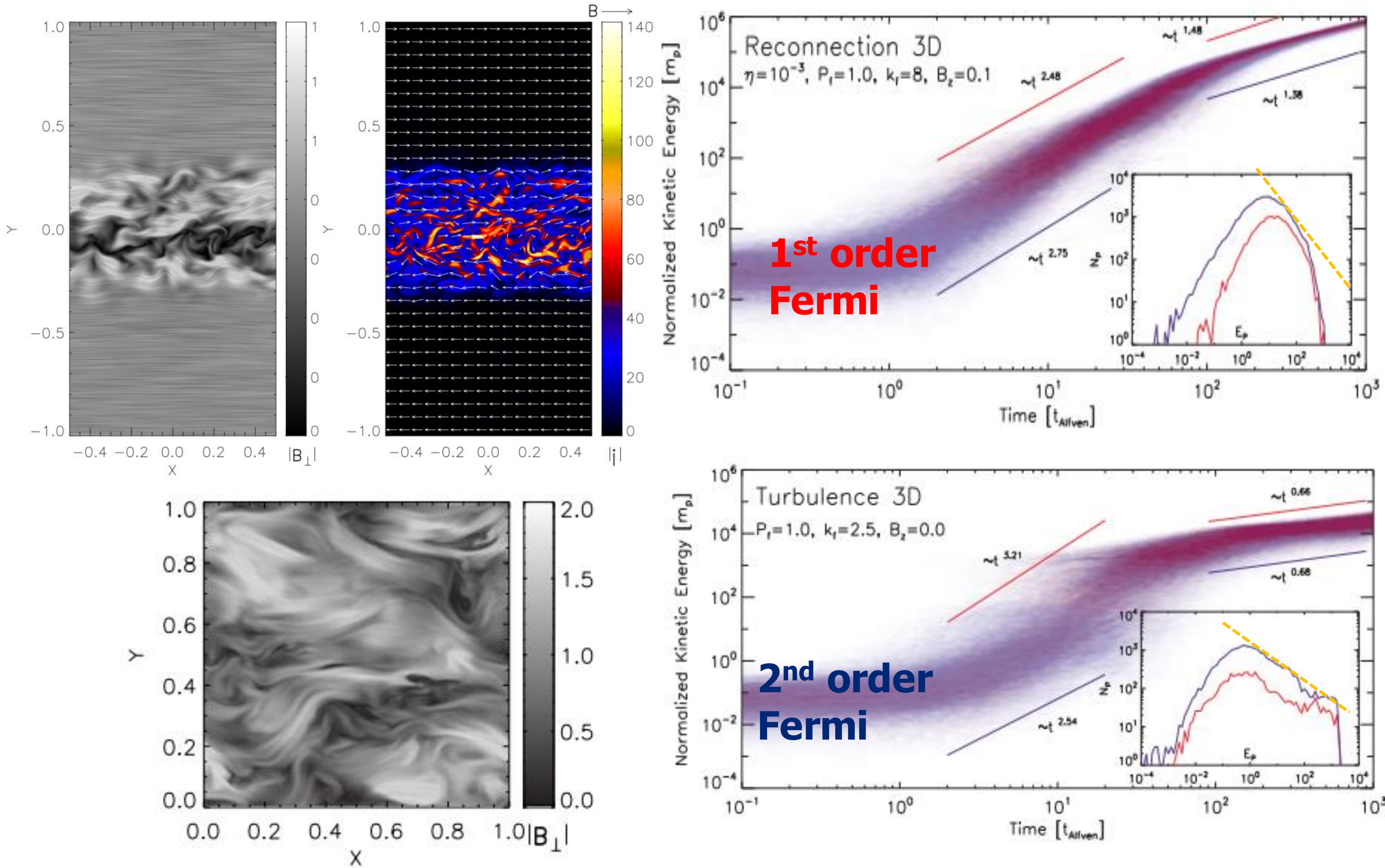
# Particle Acceleration in pure turbulence




**scattering by approaching and receding magnetic irregularities**

Kowal, de Gouveia Dal Pino, Lazarian, 2012

# Turbulent reconnection versus Turbulence




Kowal, de Gouveia Dal Pino, Lazarian, 2012

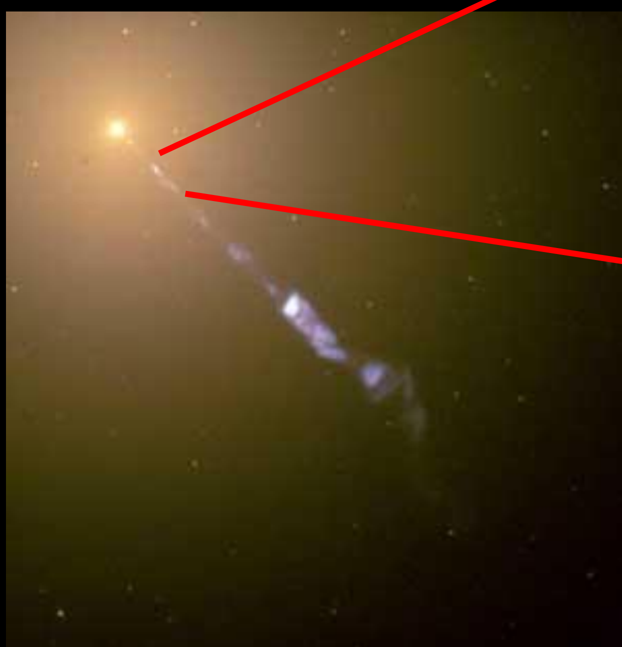

APPLICATIONS

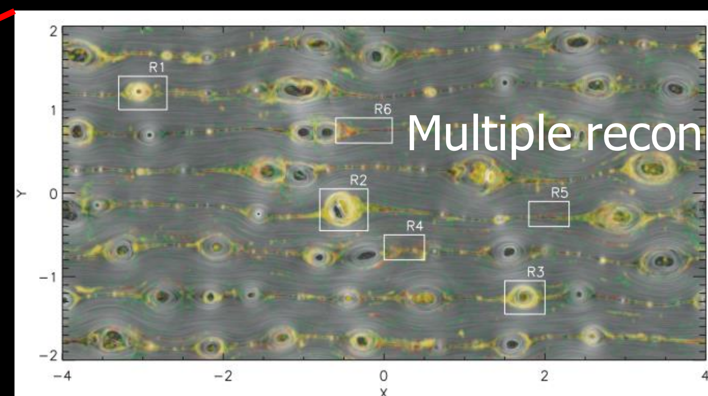
# Reconnection Acceleration of UHECRs in GRB & AGN jets?

**Assuming multiple field reversals along jet** (separated by ~ c $t_{rot}$ )
→ **1st-order Fermi acceleration** (Giannios 2010):

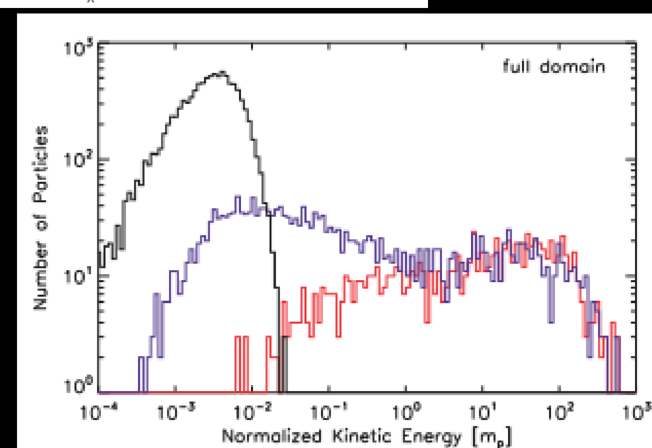
$$E_{\rm M}^{\rm conf} = 6 \times 10^{19} \frac{\epsilon_{-1} L_{52}^{1/2}}{\Gamma_{2.5}} \ {\rm eV}$$

→ **UHECRs**



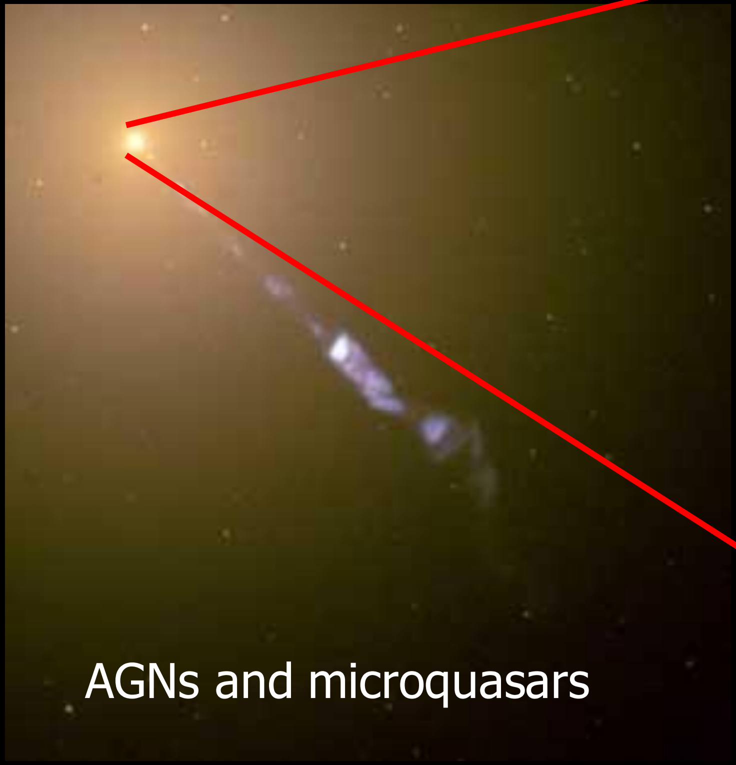


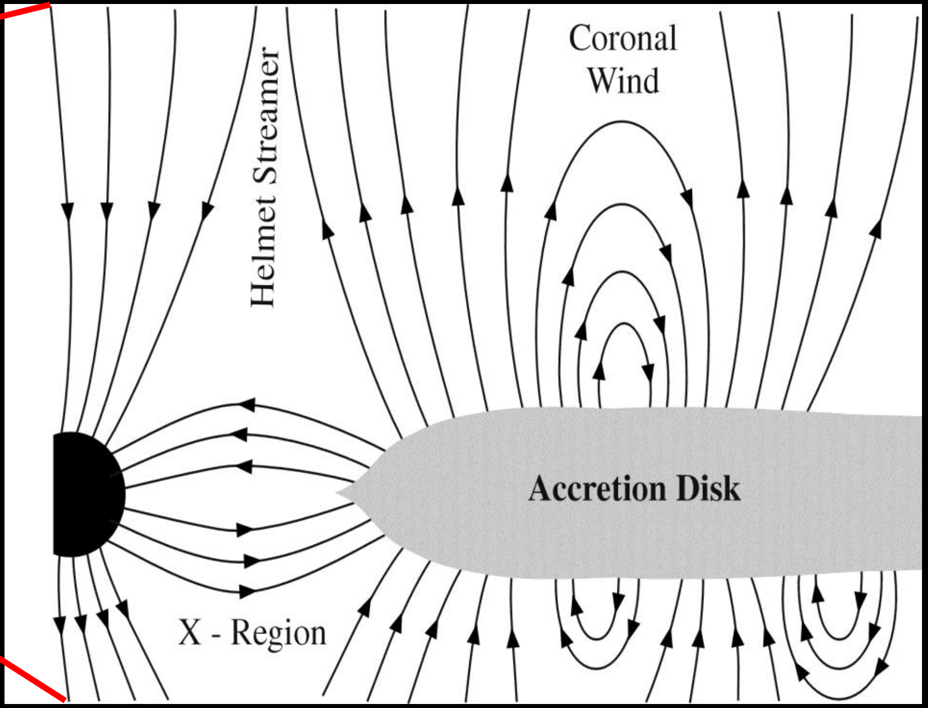

Multiple reconnection layers



# Reconnection acceleration in accretion disk corona ?

## Accretion disk/Jet systems (AGNs & galactic BHs)



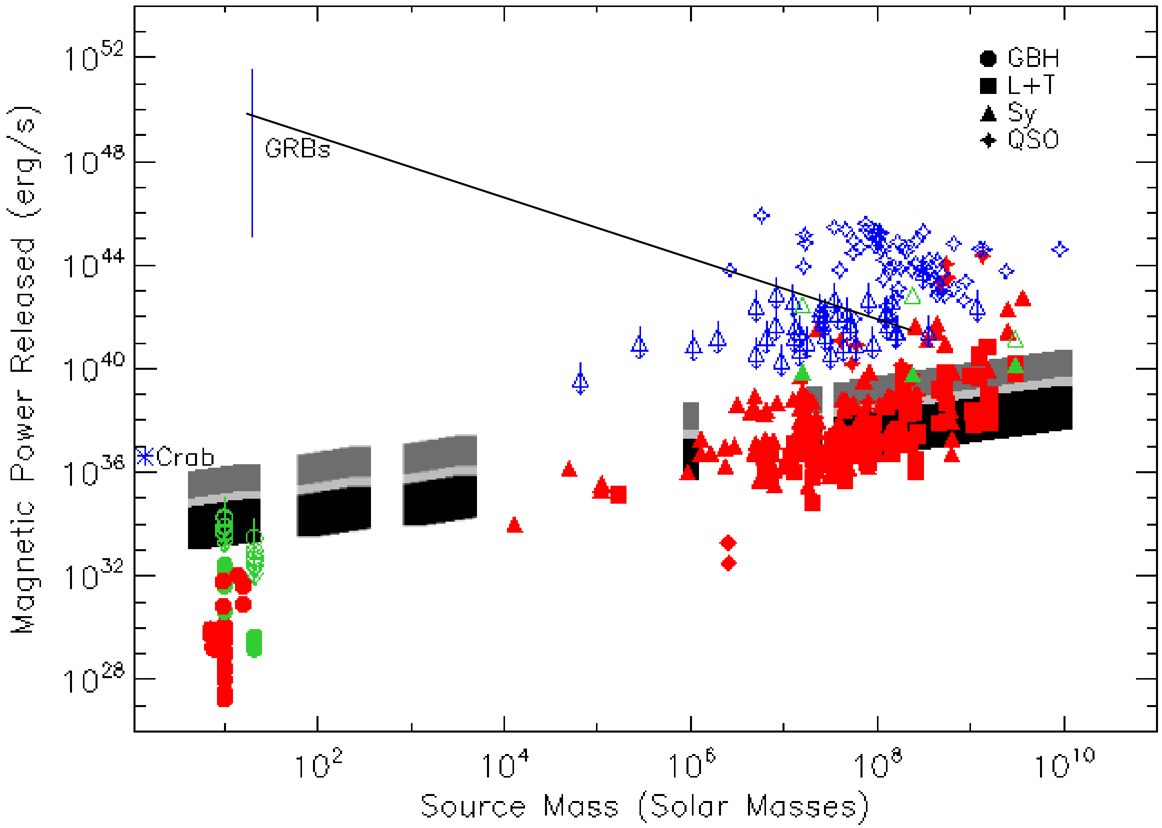




de Gouveia Dal Pino & Lazarian 2005, de Gouveia Dal Pino+2010

# Power Released by Fast Reconnection

$$\dot{W}_B \cong 1,6 \times 10^{35} \alpha_{0.5}^{-19/16} \beta_{0.8}^{-9/16} M_{14}^{19/32} R_{X,7}^{-25/32} l_{100}^{11/16} \quad erg/s$$

Radio + Gamma Emission




**Explains fundamental plane of Merloni+2003)**

de Gouveia Dal Pino, Piovezan & Kadowaki, 2010
Kadowaki & de Gouveia Dal Pino 2013

# Relativistic Reconnection

**Fast reconnection in relativistic environments**: $v_{rec} \sim v_A \rightarrow c$

**Theoretical grounds** (Blackman & Field 1994; Lyubarsky 2005; Lyutikov & Uzdensky 2003; Jaroschek et al. 2004; Hesse & Zenitani 2007; Zenitani & Hoshino 2008; Zenitani et al. 2009; Komissarov 2007; Coroniti 1990; Lyubarsky & Kirk 2001):

- **Sweet–Parker relativistic reconnection** (Lyubarsky 05): **SLOW**

  → $v_{rec} << c$

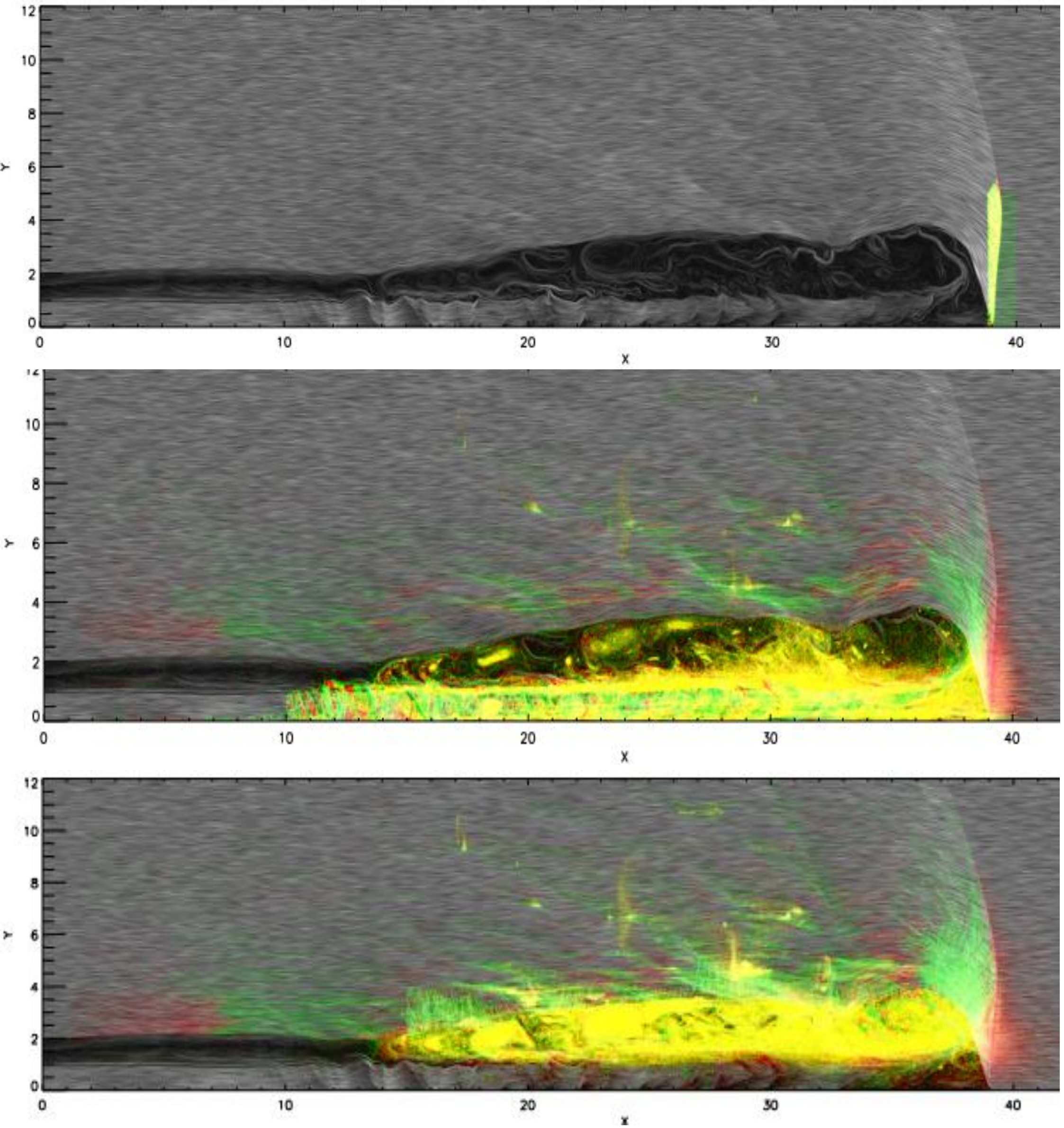
- **X-point (Petschek) relativistic reconnection: FAST**

  → $v_{rec} \simeq \pi/4 \ln S$, $S \equiv Lc/\eta$

- **Numerical advances: in relativistic collisionless Petschek's reconnection only**:

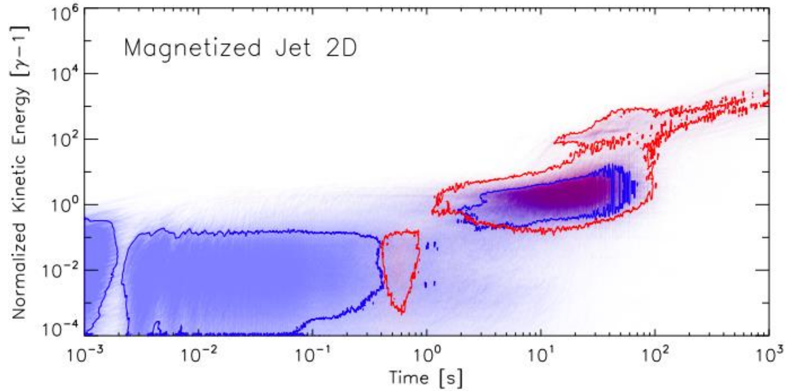
  → confirmed analytical theory

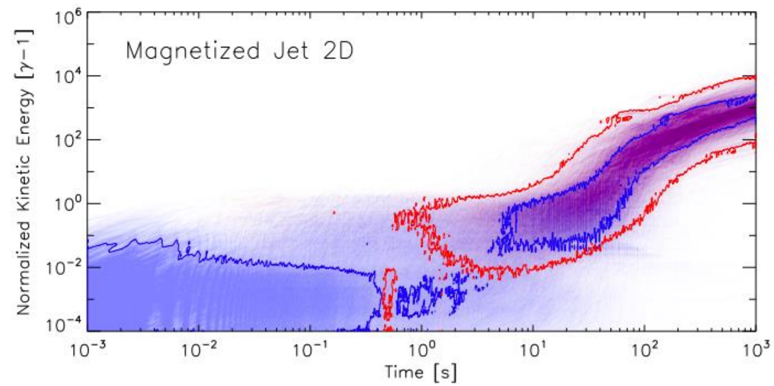
# *In situ* 1st-order Fermi Relativistic MHD Reconnection x shock acceleration




## Competing mechanisms

de Gouveia Dal Pino & Kowal 2013



# What is Next?

## Particle acceleration in:

- ✓ **Relativistic MHD fast reconnection with turbulence** (e.g. de Gouveia Dal Pino & Kowal 2013)

- ✓ **Relativistic reconnection electron-ion, high energy density, radiative plasmas** (e.g. Uzdenski 2011):

→ **open fundamental issues** → **SGRs, GRBs, AGNs,...?**


CTA – Cherenkov Telescope Array

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