Particle Acceleration by Magnetic Reconnection

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MFU V, Corsica, October 5-9, 2015

CR acceleration: exciting challenges

Standard processes – e.g. **1st Fermi in shocks**: difficulties to explain particle acceleration and very high energy emission (TeV) in very compact regions (variability) in:

- pulsars
- AGN cores
- BHBs (microquasars)
- GRB and AGN relativistic jets

magnetically dominated -> shocks weak

This talk

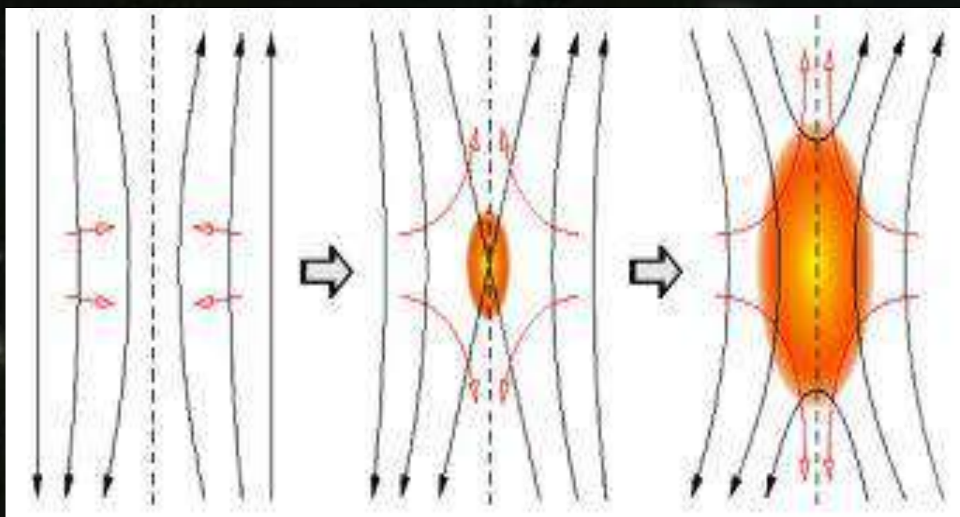
Particle acceleration by magnetic reconnection:

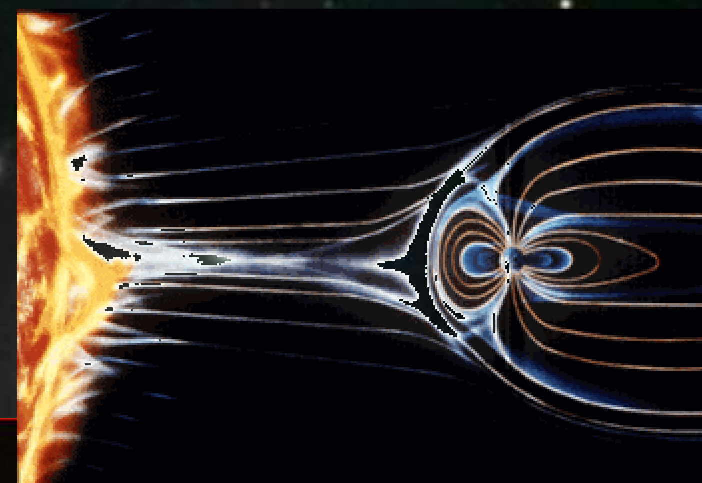
➡ **powerful acceleration mechanism**

➡ **can explain very high energy & neutrino emission**

COSMIC MAGNETIC RECONNECTION

Directly observed:



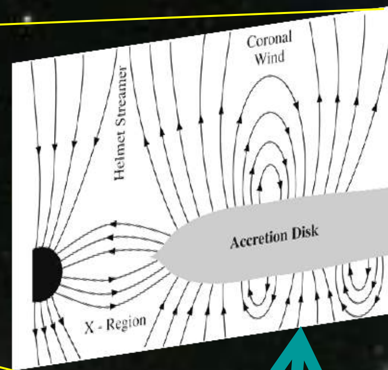


magnetotail

Solar corona

Reconnection is FAST !

$$V_{rec} \sim V_A$$



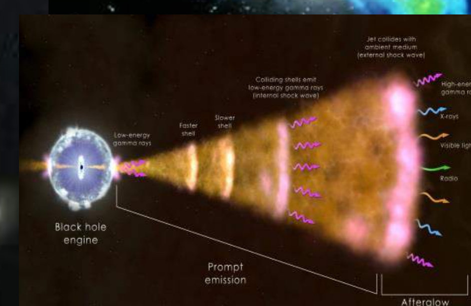
Accretion disk coronae

Stellar Xray Flares

Star Formation and ISM

Reconnection also beyond Solar System

AGN & GRB Jets

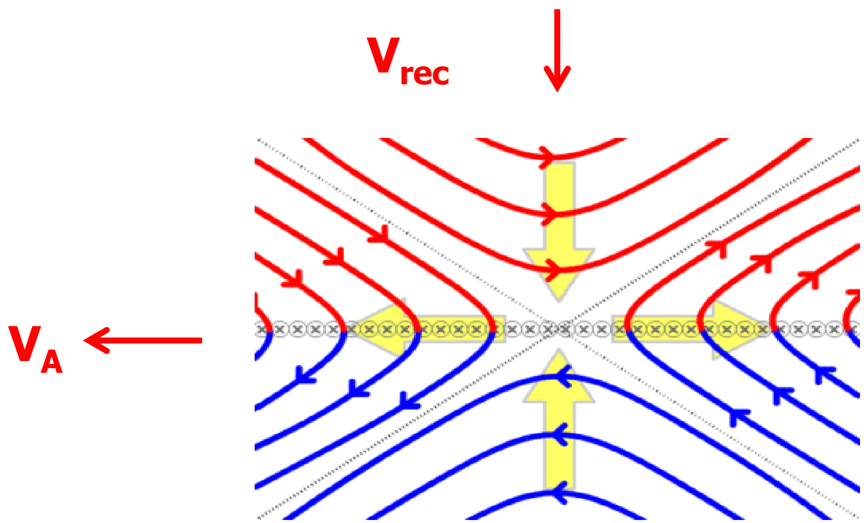


Pulsars

Accreting NS and SGRs

Fast Magnetic Reconnection Models

- **Petschek model (1964): X-point configuration**



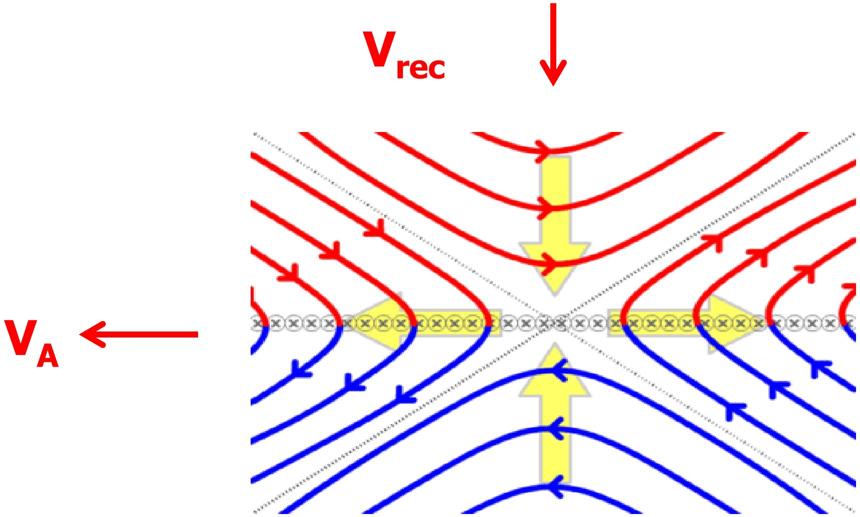
$$V_{rec} \sim v_A \, \pi/(4 \ln S)$$

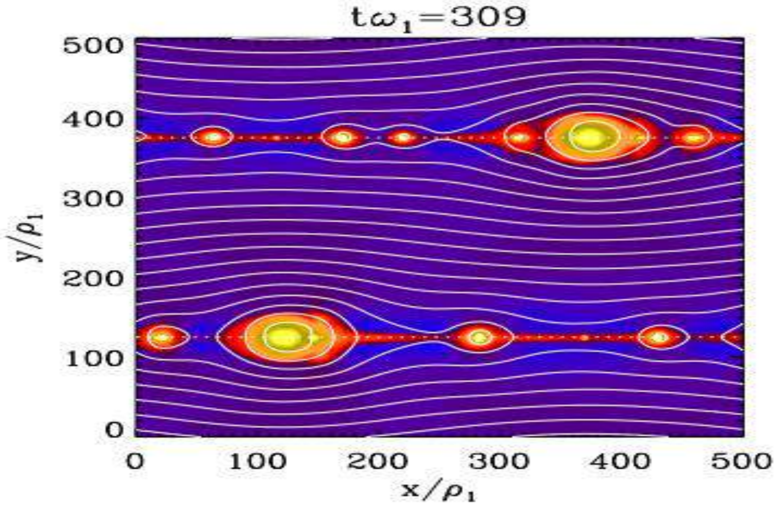
$$S = L \, v_A/\eta$$

Unstable and collapse to (Sweet-Parker) slow reconnection (Biskamp'96): **unless *collisionless* ($L \sim \lambda_{e,mfp}$) *pair* plasma with localized** η (e.g. Sturrock 1966; Birn+01, Yamada+10; Forbes+)

Fast Magnetic Reconnection Models

- **Petschek model (1964): X-point configuration**



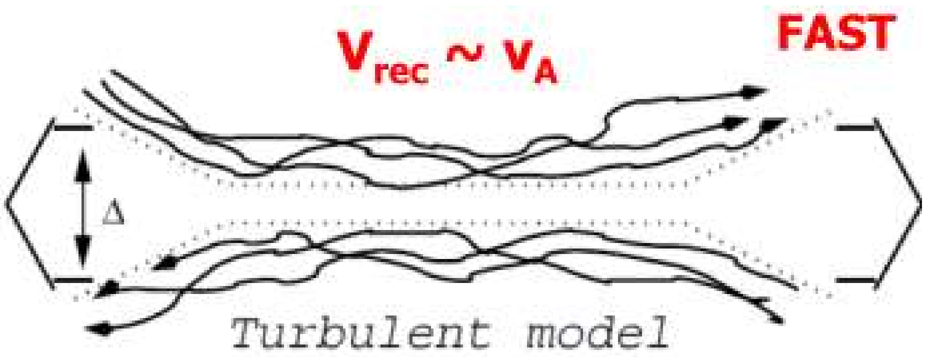


(2D PIC simulations: magnetic islands, e.g. Drake+ 2006; Cerutti+13, **Sironi's talk**)

Unstable and collapse to (Sweet-Parker) slow reconnection (Biskamp'96): **unless *collisionless* ($L \sim \lambda_{e,mfp}$) *pair* plasma with localized** η (e.g. Sturrock 1966; Birn+01, Yamada+10; Forbes+)

Fast Reconnection in collisional flows

TURBULENT RECONNECTION (Lazarian & Vishniac 1999):

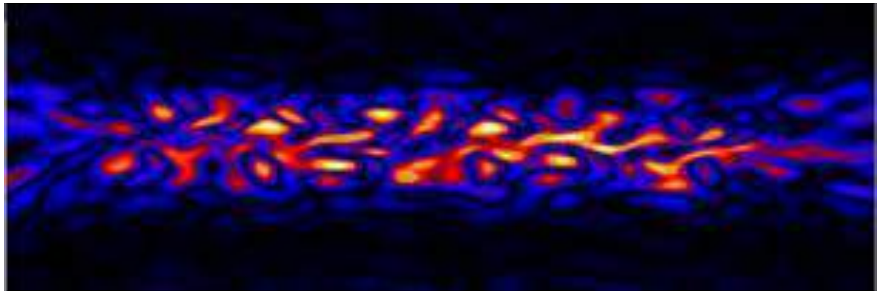


Magnetic lines wandering: many simultaneous reconnection events

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

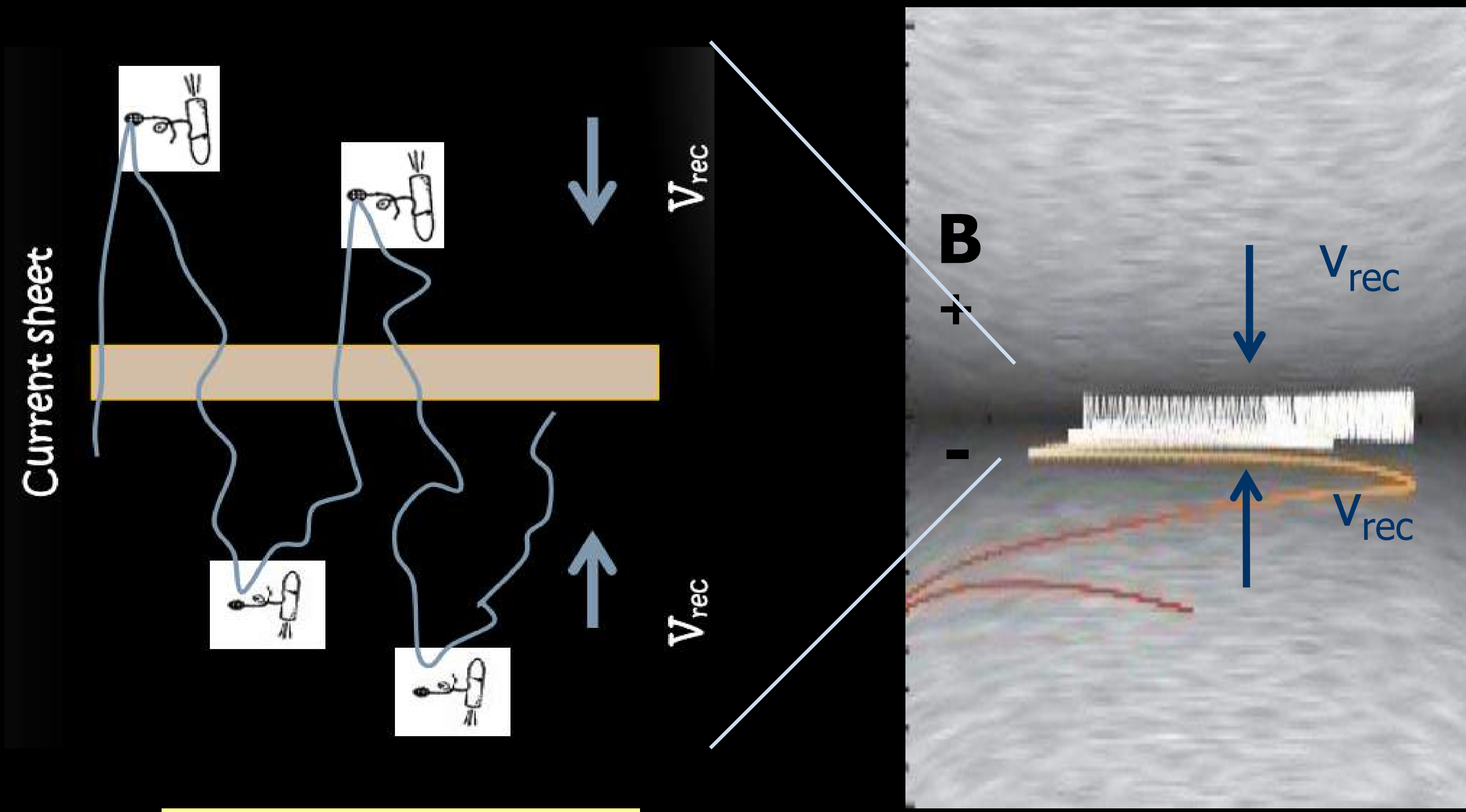
- ✓ **Reconnection layer : THICKER**
- ✓ **THREE-DIMENSIONAL**

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



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

1st-order FERMI ACCELERATION @ RECONNECTION SITE

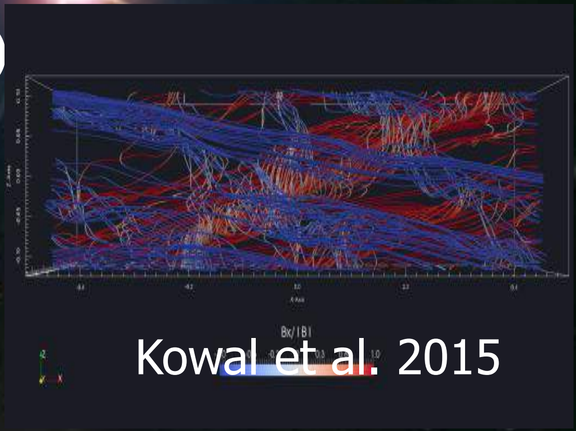


$<\Delta E/E> \sim v_{rec}/c$

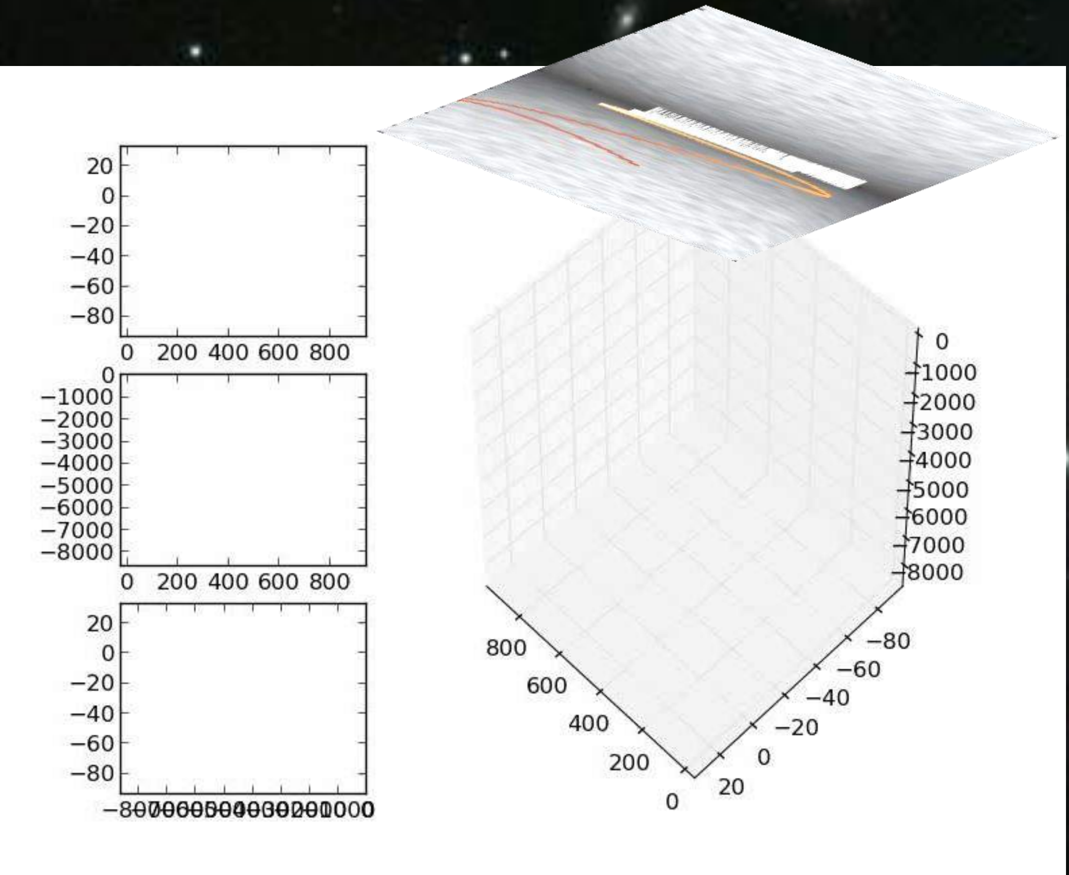
de Gouveia Dal Pino & Lazarian 2005

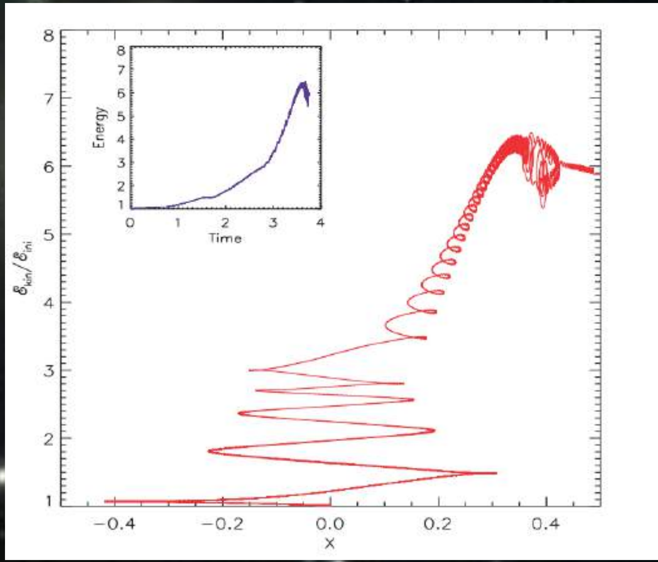
1st-order FERMI ACCELERATION BY RECONNECTION

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



Kowal et al. 2015





thanks Khiali

Kowal, de Gouveia Dal Pino & Lazarian, ApJ 2011

Probing Reconnection as powerful mechanism to accelerate particles

To probe analytical results → numerical simulations:

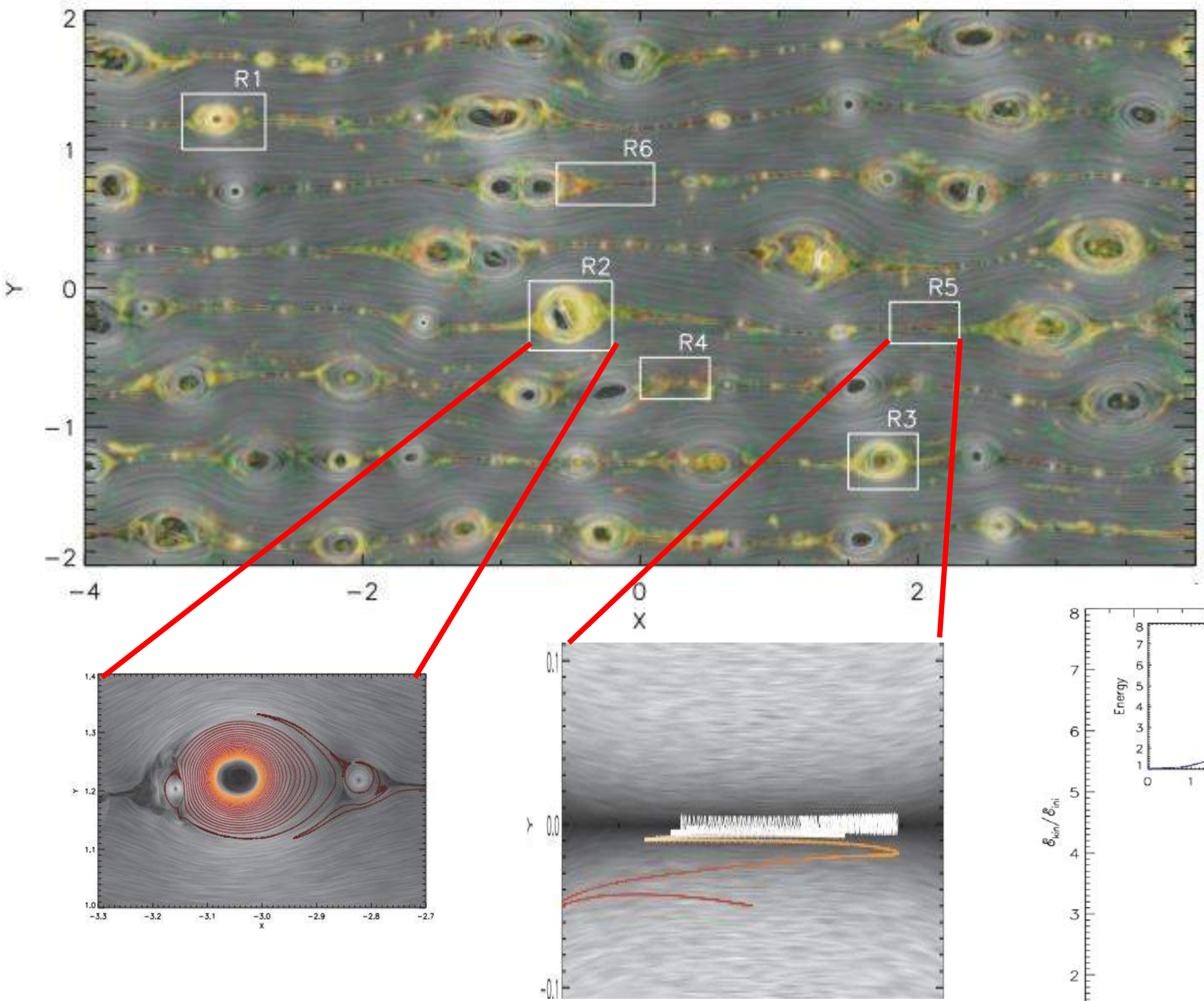
- Most simulations of particle acceleration by magnetic reconnection: **2D collisionless plasmas (PIC)** @ scales (e.g. Drake+; Zenitani & Hoshino; Cerutti, Uzdensky+; Sironi & Spitkovsky):

  few plasma inertial length ~ 100 c/ω_p

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

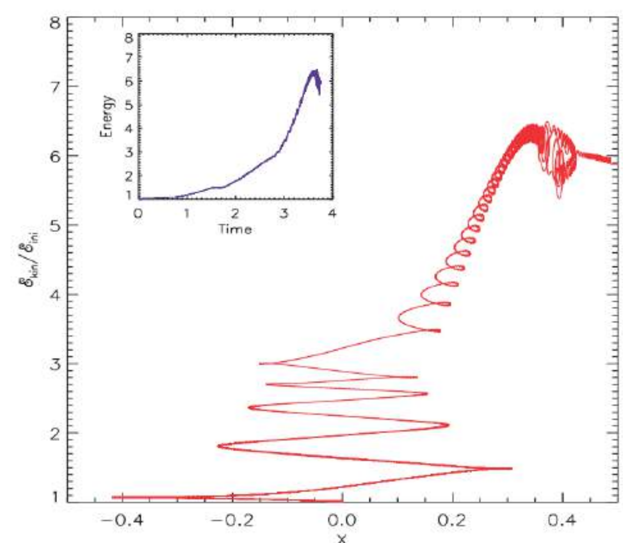
  → **MHD description → collisional reconnection**
  (Kowal, de Gouveia Dal Pino & Lazarian 2011, 2012; de Gouveia Dal Pino+ 2014, 2015)

Particle Acceleration in 2D MHD Reconnection



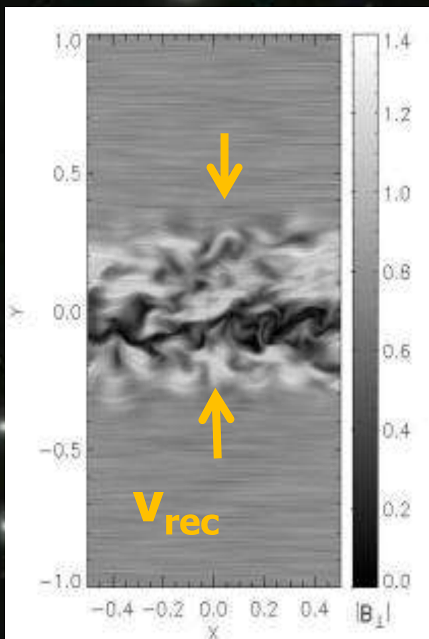
2D Multiple current sheets to compare with PIC simulations (e.g. Drake+10)

particles confined →
1st order Fermi:
$\Delta E/E \sim v_{rec}/v$

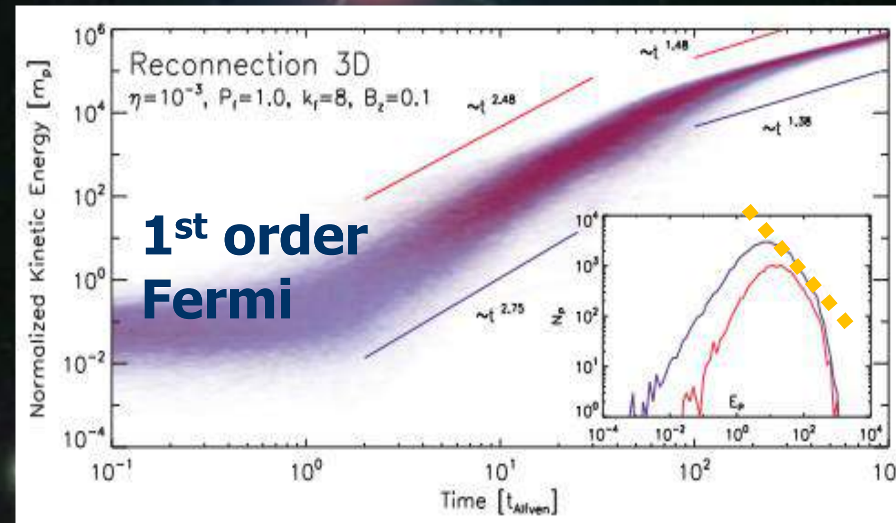


Kowal, de Gouveia Dal Pino, Lazarian 2011

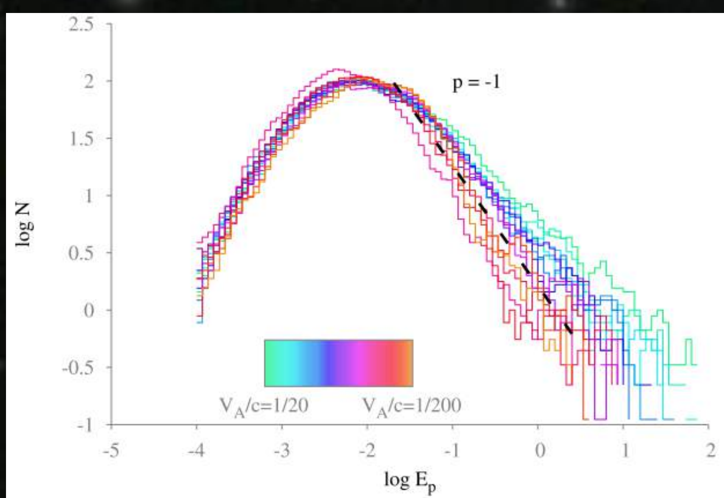
Magnetic Reconnection Acceleration: successful numerical testing in 3D MHD



current sheet with turbulence:
fast reconnection
(LV99)



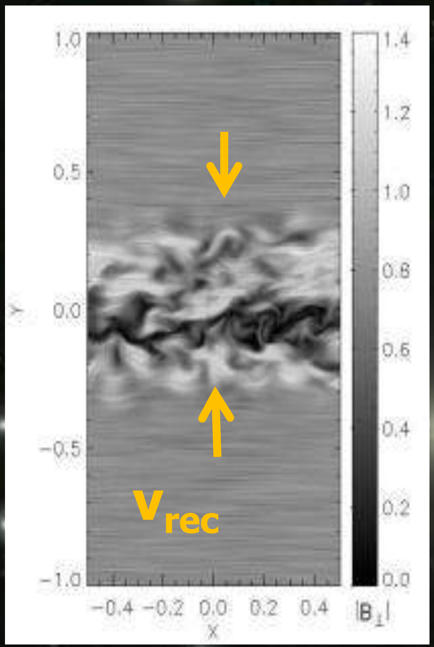
Kowal, de Gouveia Dal Pino, Lazarian, PRL 2012



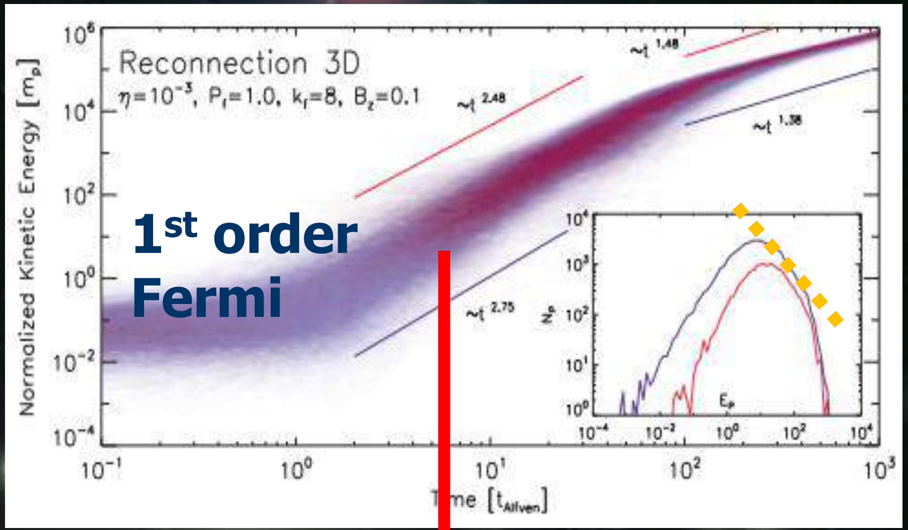
$N(E) \sim E^{-1-2}$

del Valle, de Gouveia Dal Pino, Kowal 2015

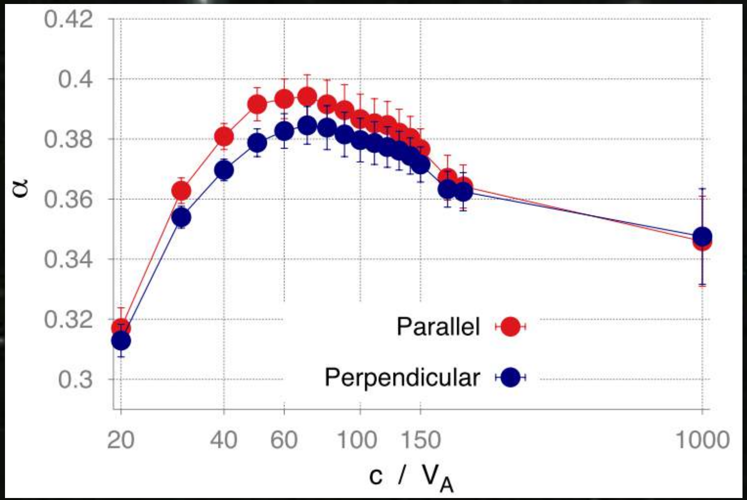
Magnetic Reconnection Acceleration: successful numerical testing in 3D MHD



current sheet with turbulence: fast reconnection (LV99)



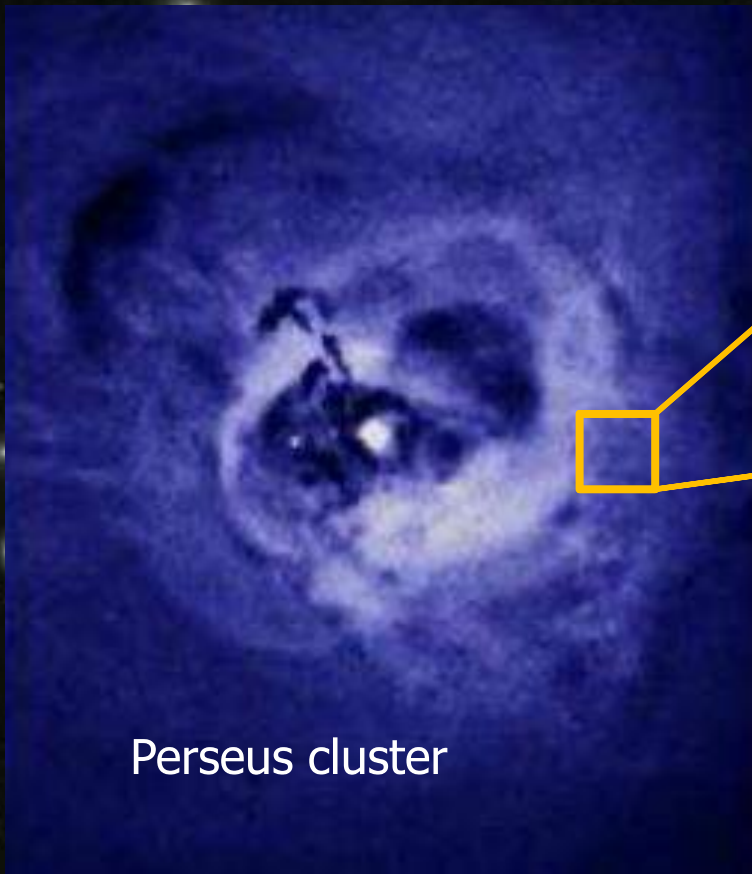
Kowal, de Gouveia Dal Pino, Lazarian, PRL 2012

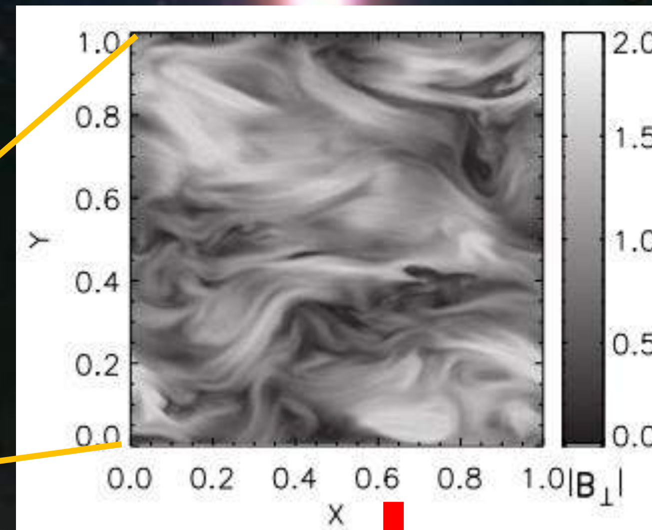


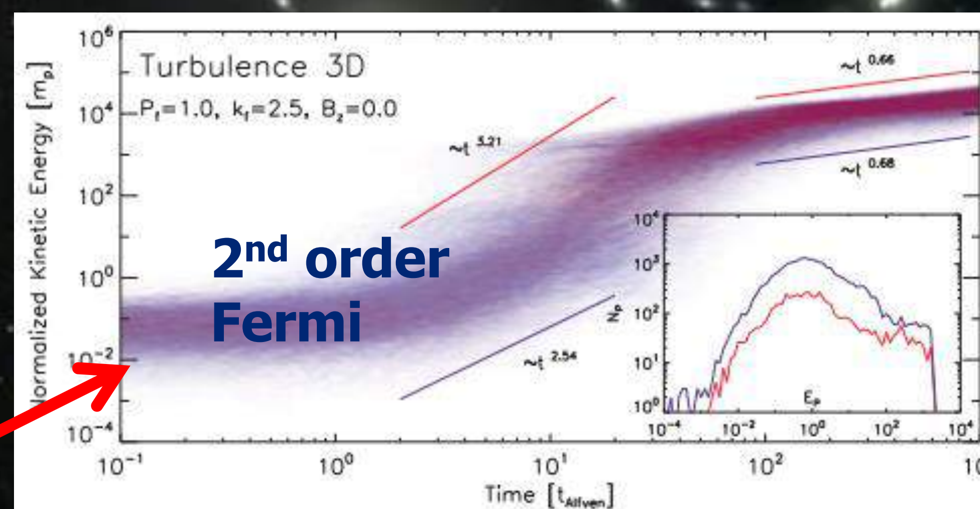
$\tau_{acc}^{-1} \sim E^{-0.4-0.3}$

del Valle, de Gouveia Dal Pino, Kowal 2015

Particle Acceleration in 3D MHD Pure Turbulence







scattering by approaching and receding magnetic irregularities

Kowal, de Gouveia Dal Pino, Lazarian, PRL 2012

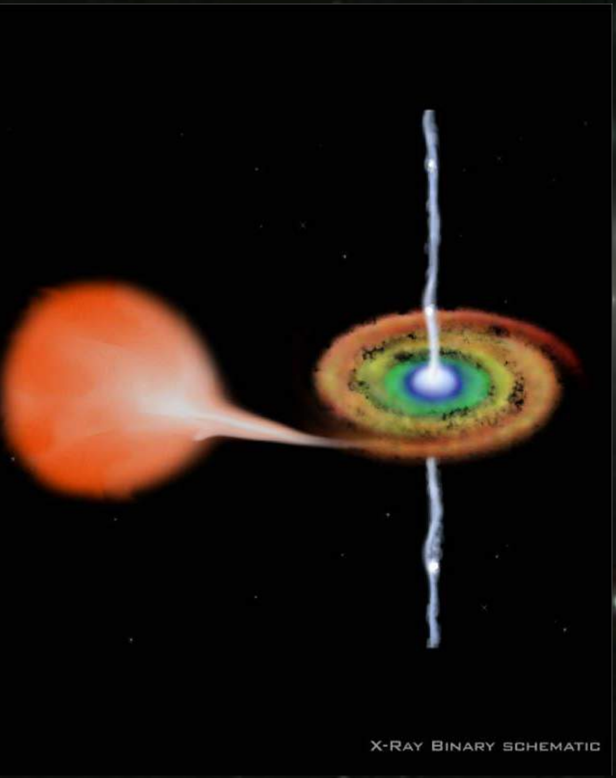
Reconnection acceleration beyond the SS

- Zenitani & Hoshino (2001-2007)
- de Gouveia Dal Pino & Lazarian (2003, 2005)
- Dmitruk, Matthaeus+ (2003)
- de Gouveia Dal Pino et al. (2010)
- 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)
- Khiali & de Gouveia Dal Pino (2015)
- del Valle, de Gouveia Dal Pino, Kowal (2015)
- de Gouveia Dal Pino & Kowal (2015)
- Uzdensky (2015)
- Guo et al (2015)
- Sironi, Petropoulou, Giannios (2015)….

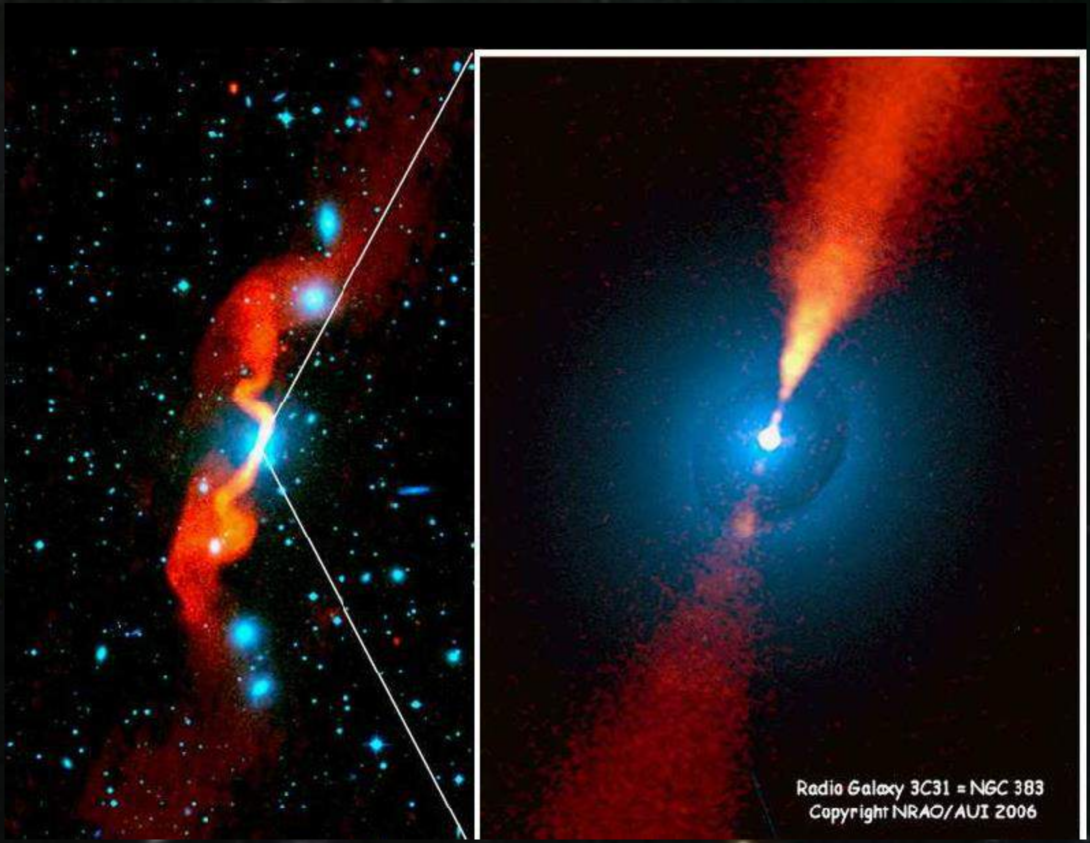
APPLICATION TO BHs and relativistic jets

Black Holes: Ubiquitious in Astrophysics

AGNs (blazars, radio-galaxies, seyferts)



Black Hole Binaries
(Microquasars)

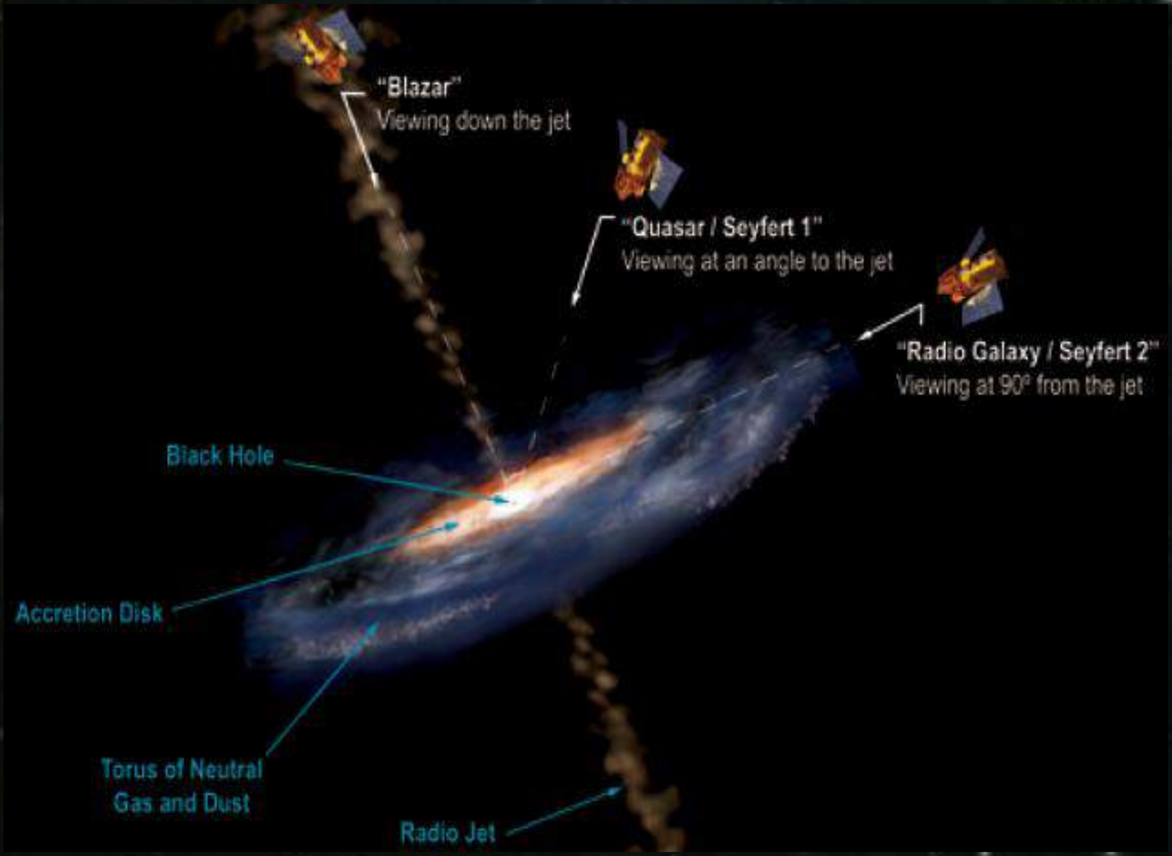


Gamma-Ray emission common in Blazars

BLAZARS: luminous AGNs

Jet ~ along the line of sight:

- Emission dominated by relativistic jet
- shock acceleration

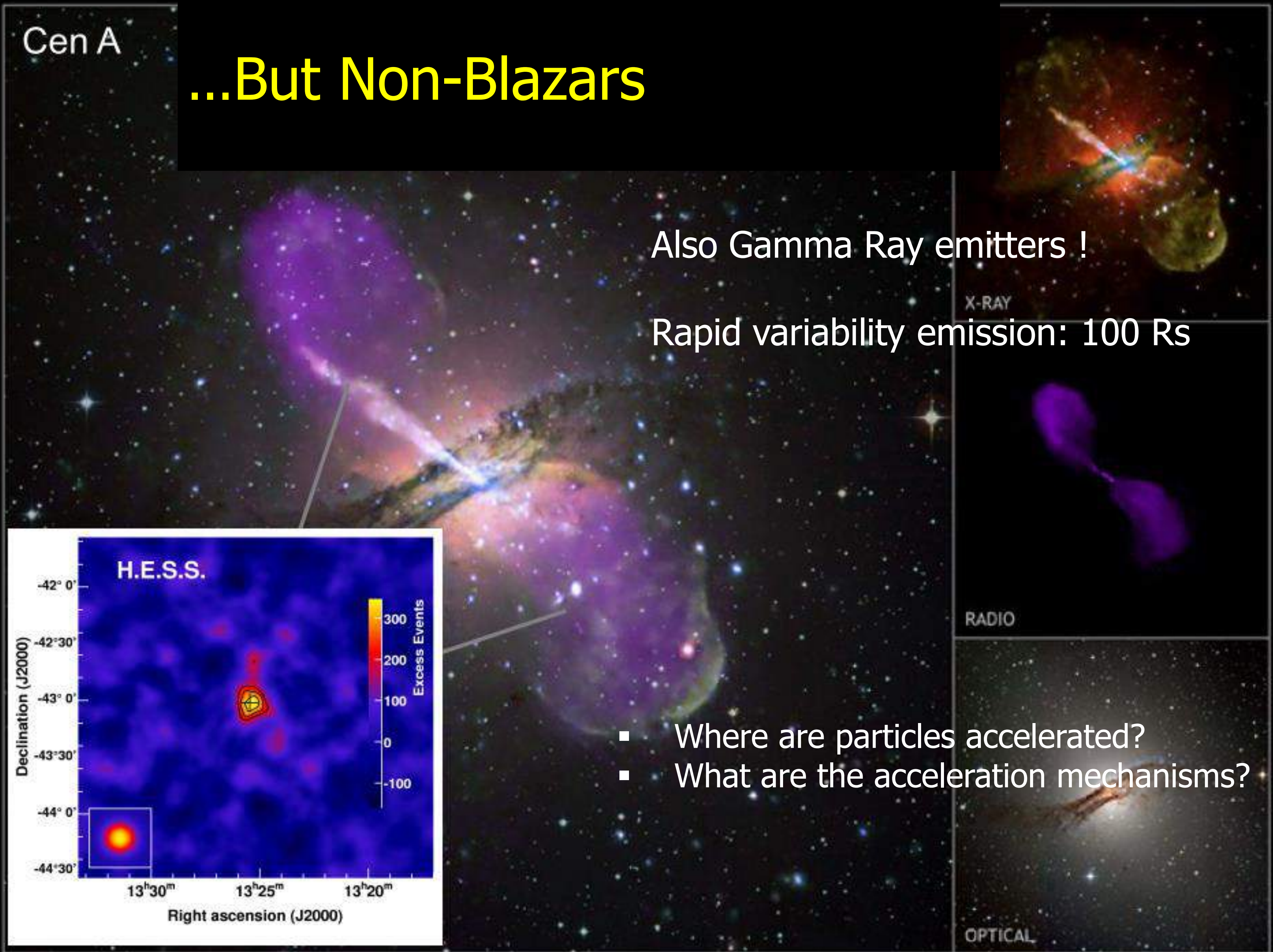


…But Non-Blazars

Also Gamma Ray emitters !

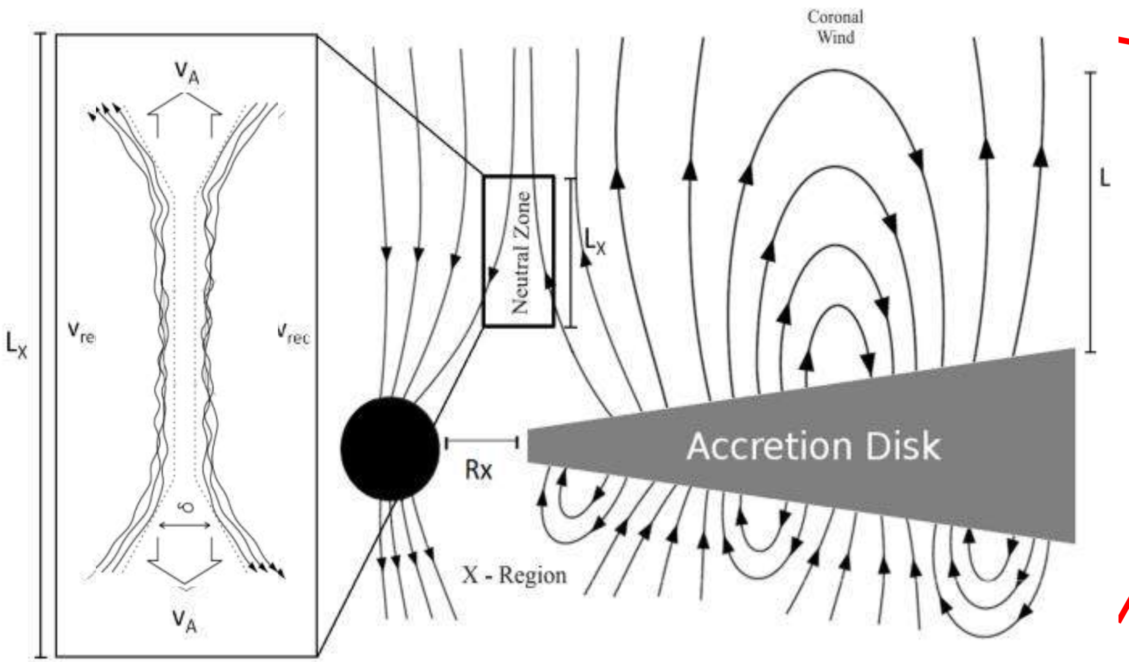
Rapid variability emission: 100 Rs

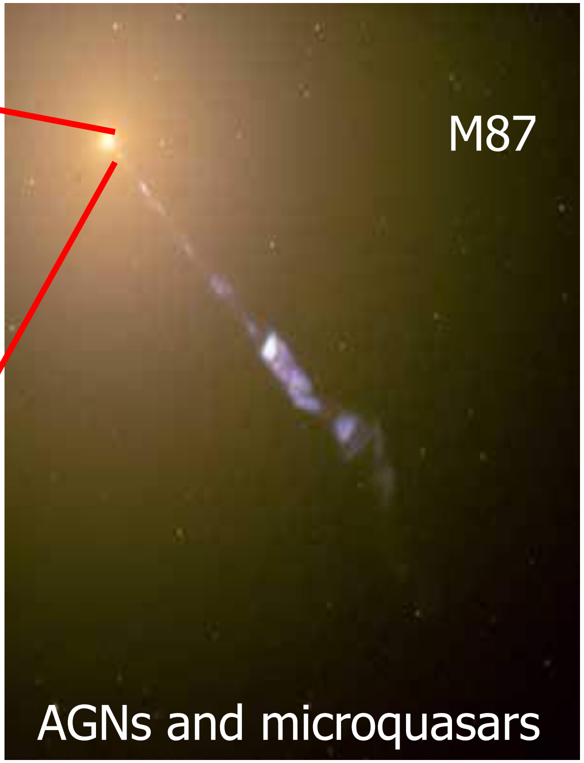
- Where are particles accelerated?
- What are the acceleration mechanisms?



Reconnection acceleration in the surrounds of BHs

Accretion disk/jet systems (AGNs & galactic BHs)



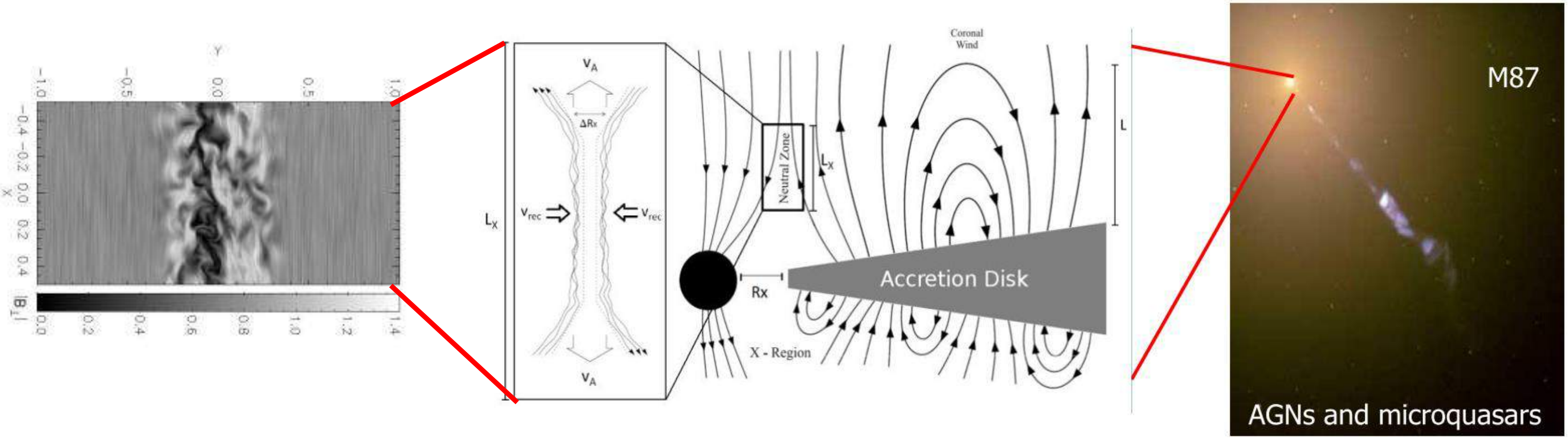


de Gouveia Dal Pino & Lazarian 2005; de Gouveia Dal Pino+2010

Reconnection acceleration in the surrounds of BHs

Revisited the model to evaluate reconnection power and acceleration -> apply to more than 200 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

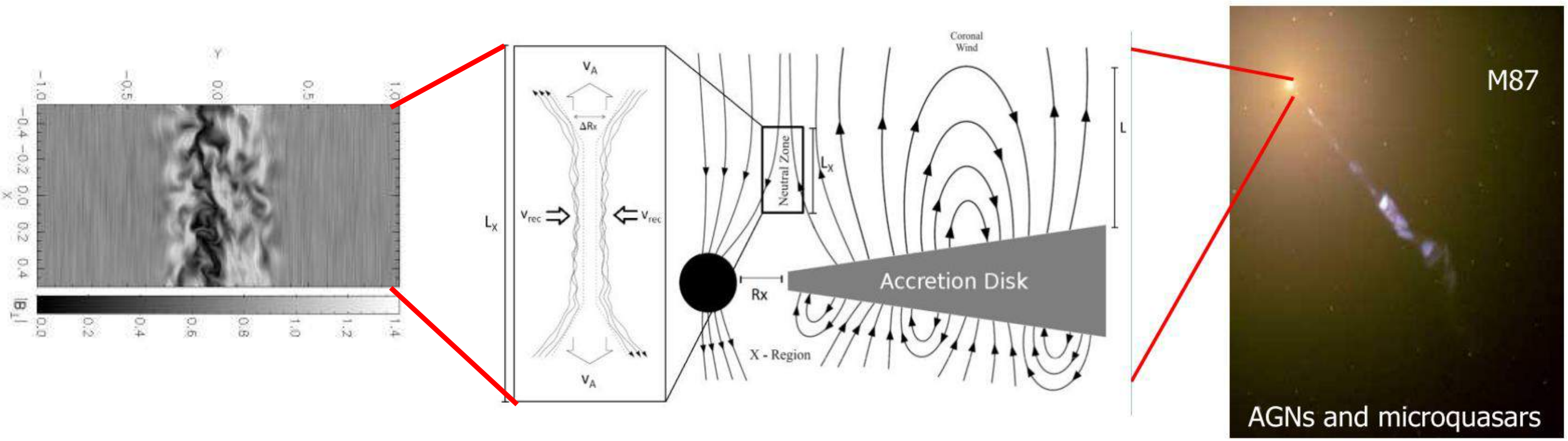


Kadowaki, de Gouveia Dal Pino, Singh, ApJ 2015
Singh, de Gouveia Dal Pino, Singh, ApJ Lett. 2015

Reconnection acceleration in the surrounds of BHs

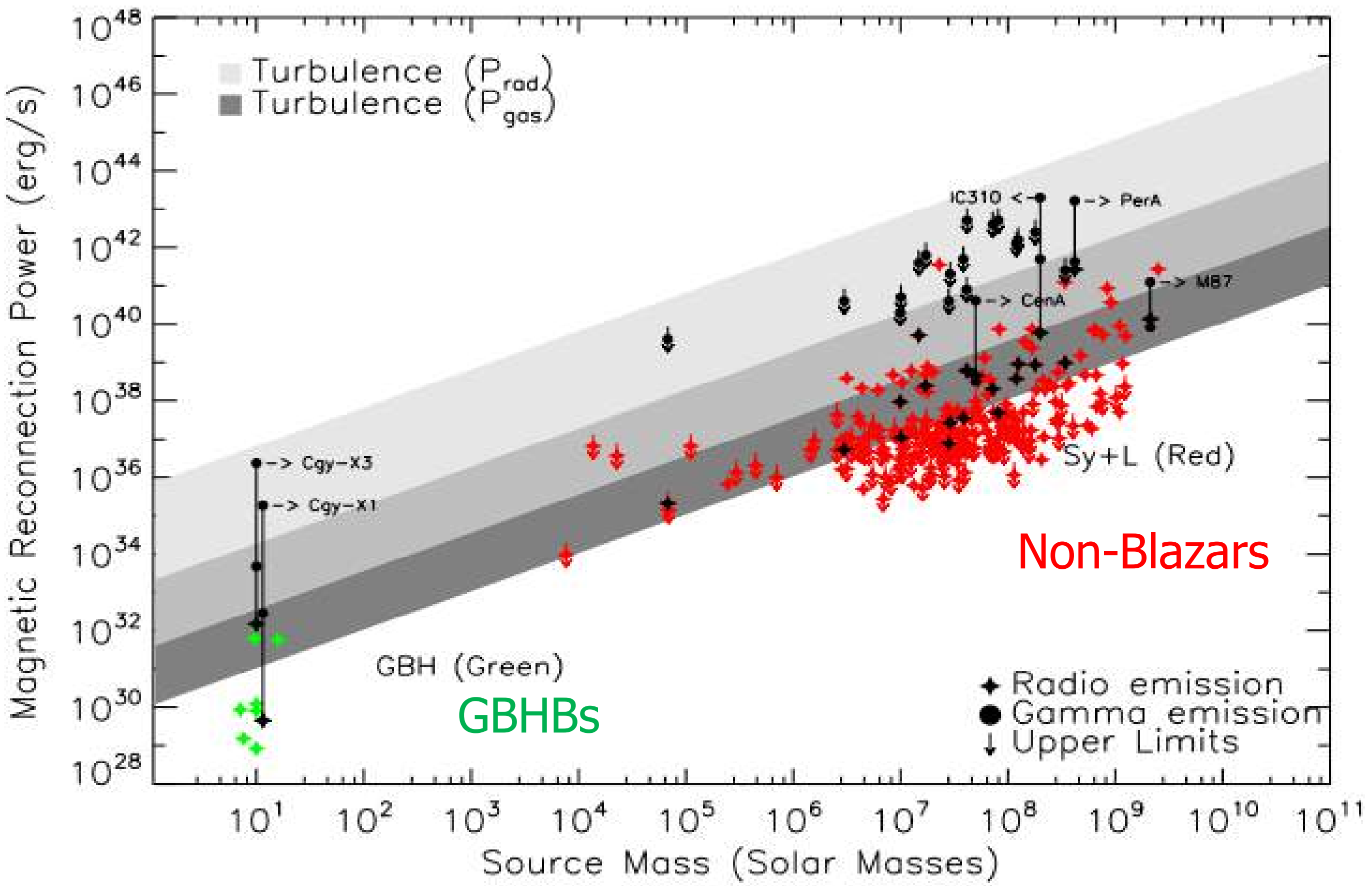
Magnetic Power

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



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

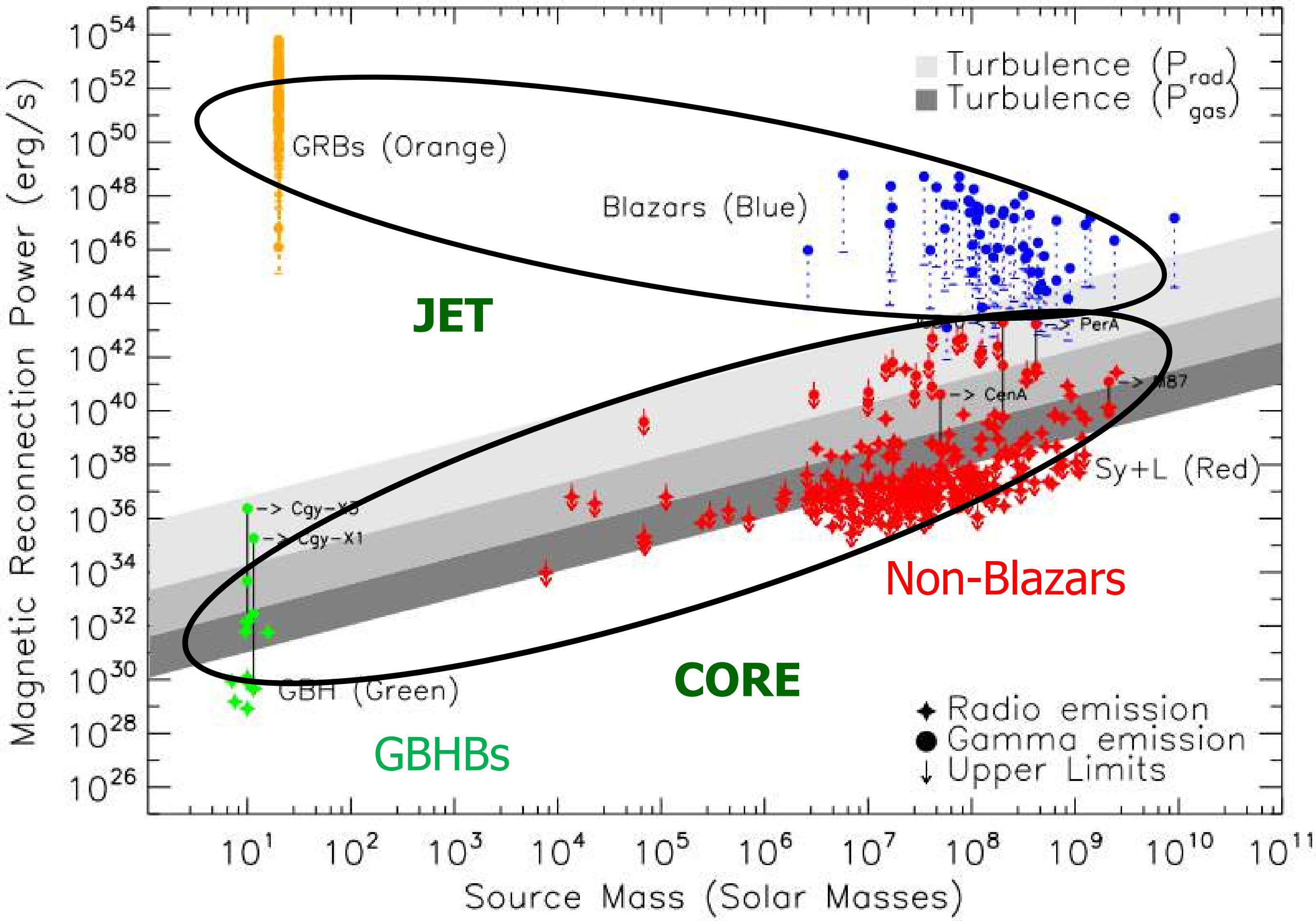
Magnetic Reconnection Power around BHs



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

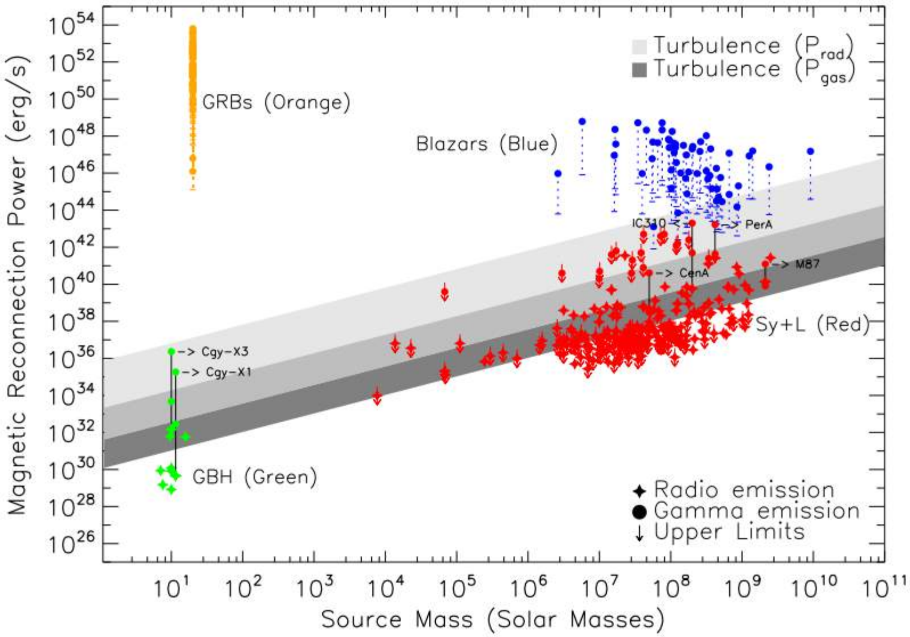
Kadowaki, de Gouveia Dal Pino, Singh, ApJ 2015
Singh, de Gouveia Dal Pino, Singh, ApJ Lett. 2015

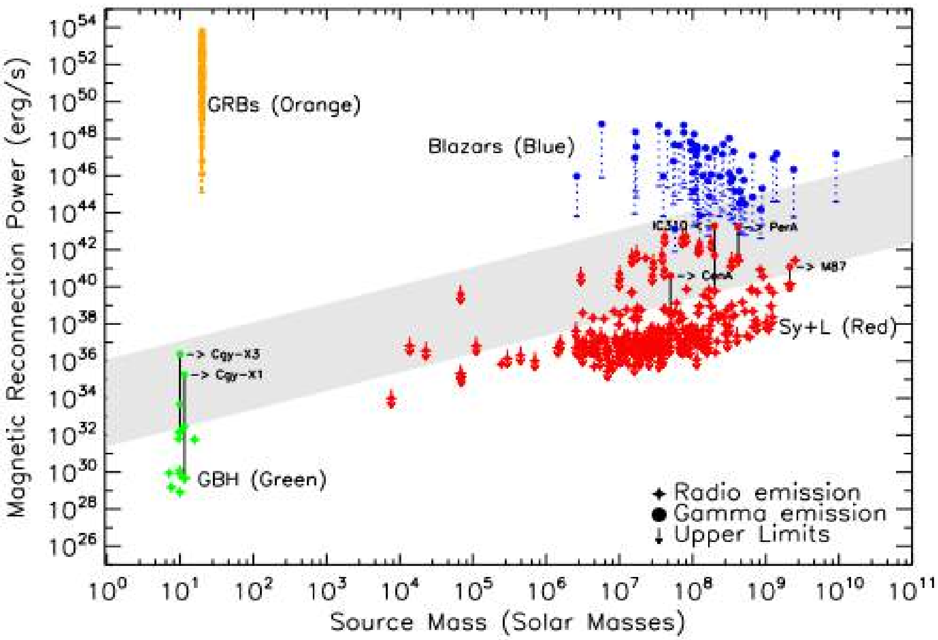
Magnetic Reconnection Power around BHs



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

Magnetic Reconnection around BHs works for different Accretion Disk Models





Standard accretion disk
Soft -> Hard

M-ADAF accretion disk
Hard -> Soft

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

Applied the reconnection acceleration model to build the SEDs of

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

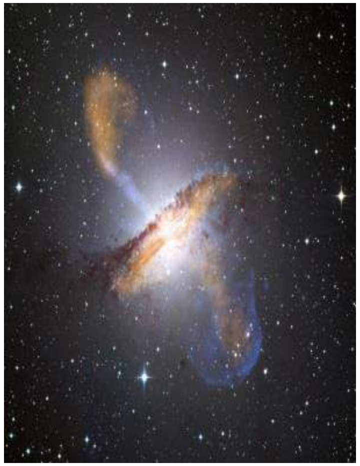
BHBs: Cyg X1 and Cyg X3

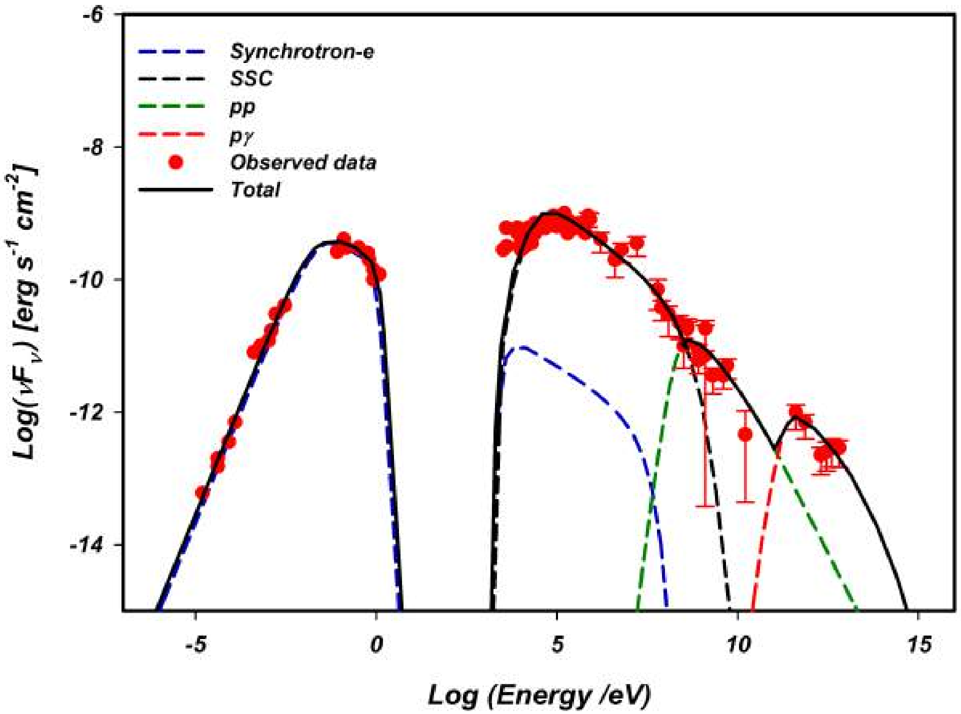
Reconnection Acceleration & Radiative Losses

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

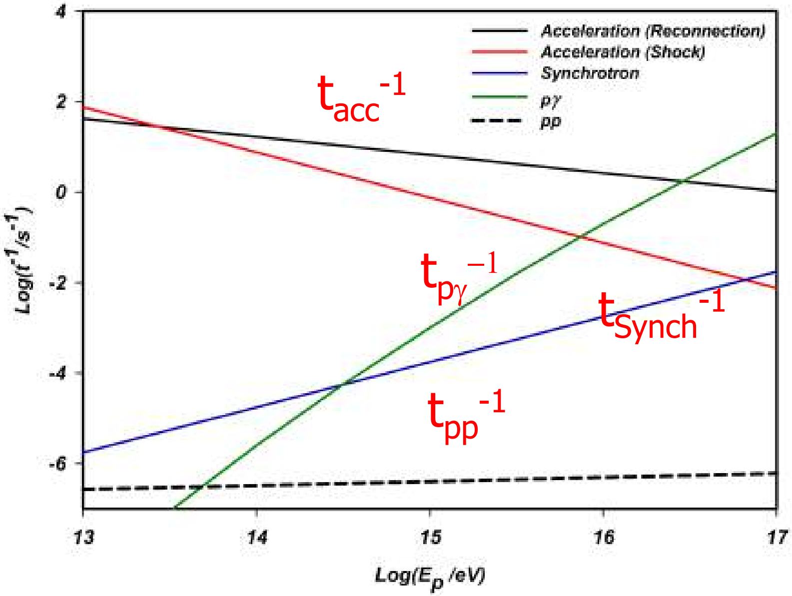
$$t_{acc} \sim t_{loss}(\text{Synchrotron, SSC, pp, p}\gamma)$$

Ex.: Radio-galaxy Cen A



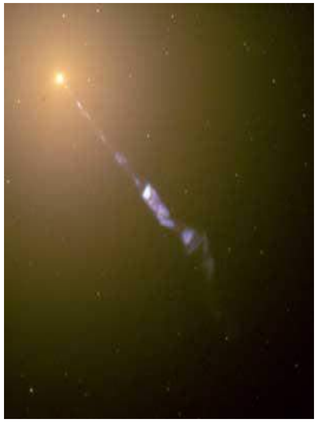


Spectral Energy Distribution



Khiali, de Gouveia Dal Pino, Sol 2015 (arXiv:1504.07592)

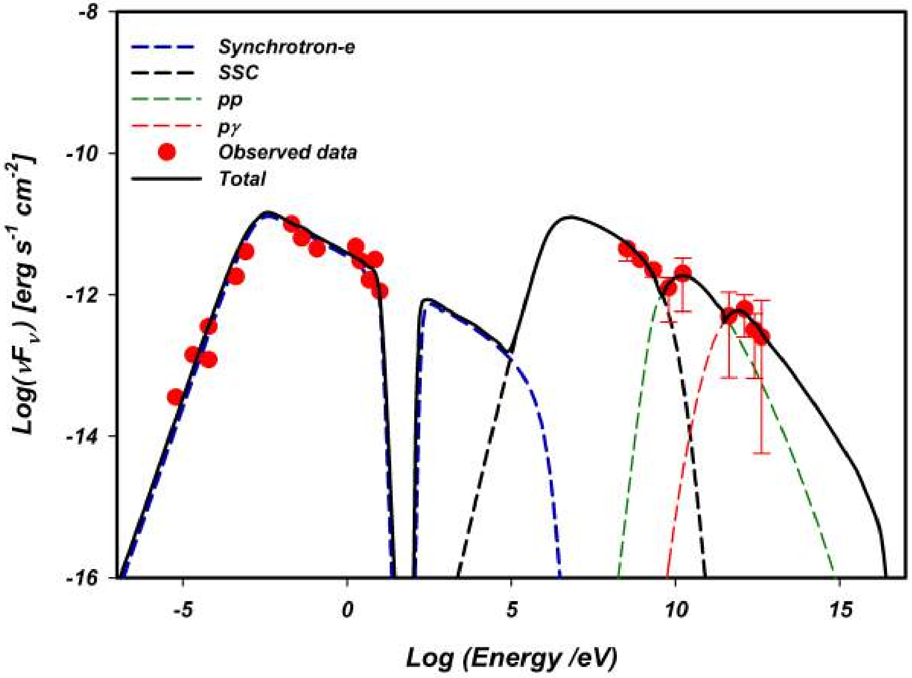
Reconnection Acceleration & Radiative Losses

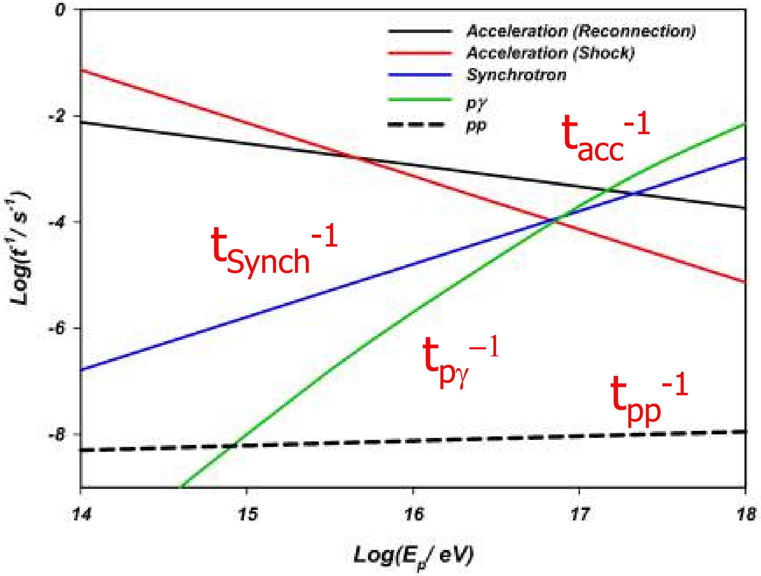


✓ **Cooling of the accelerated particles -> emission:**

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

Ex.: Radio-galaxy M87





Spectral Energy Distribution

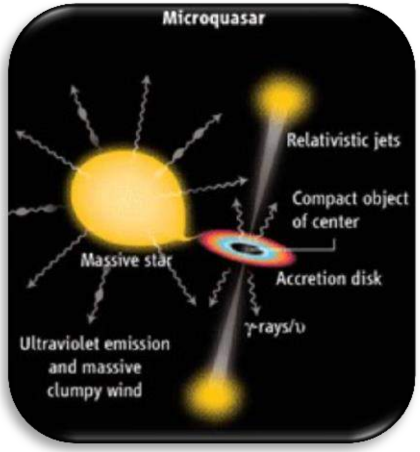
Khiali, de Gouveia Dal Pino, Sol 2015 (arXiv:1504.07592)

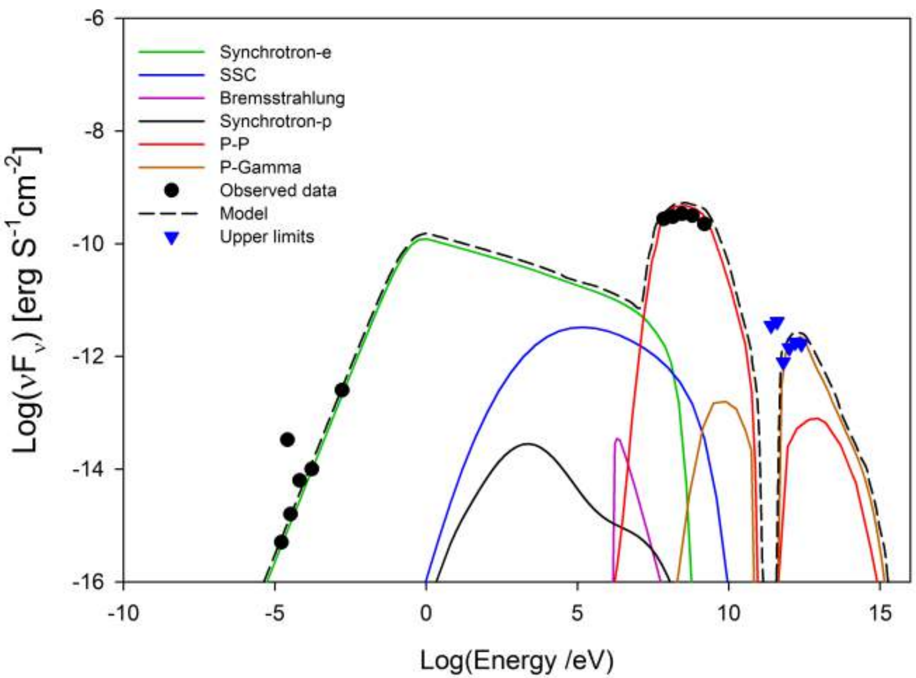
Reconnection Acceleration & Radiative Losses

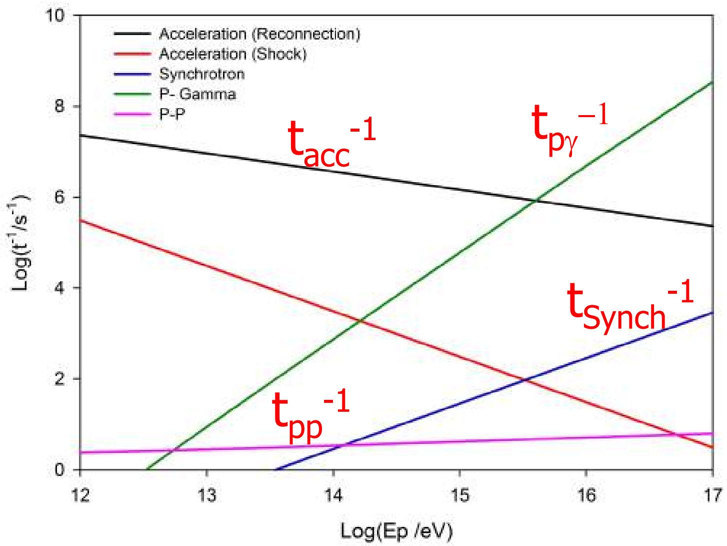
✓ **Cooling of the particles -> emission:**

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

Ex.: Galactic Black Hole Cyg X3



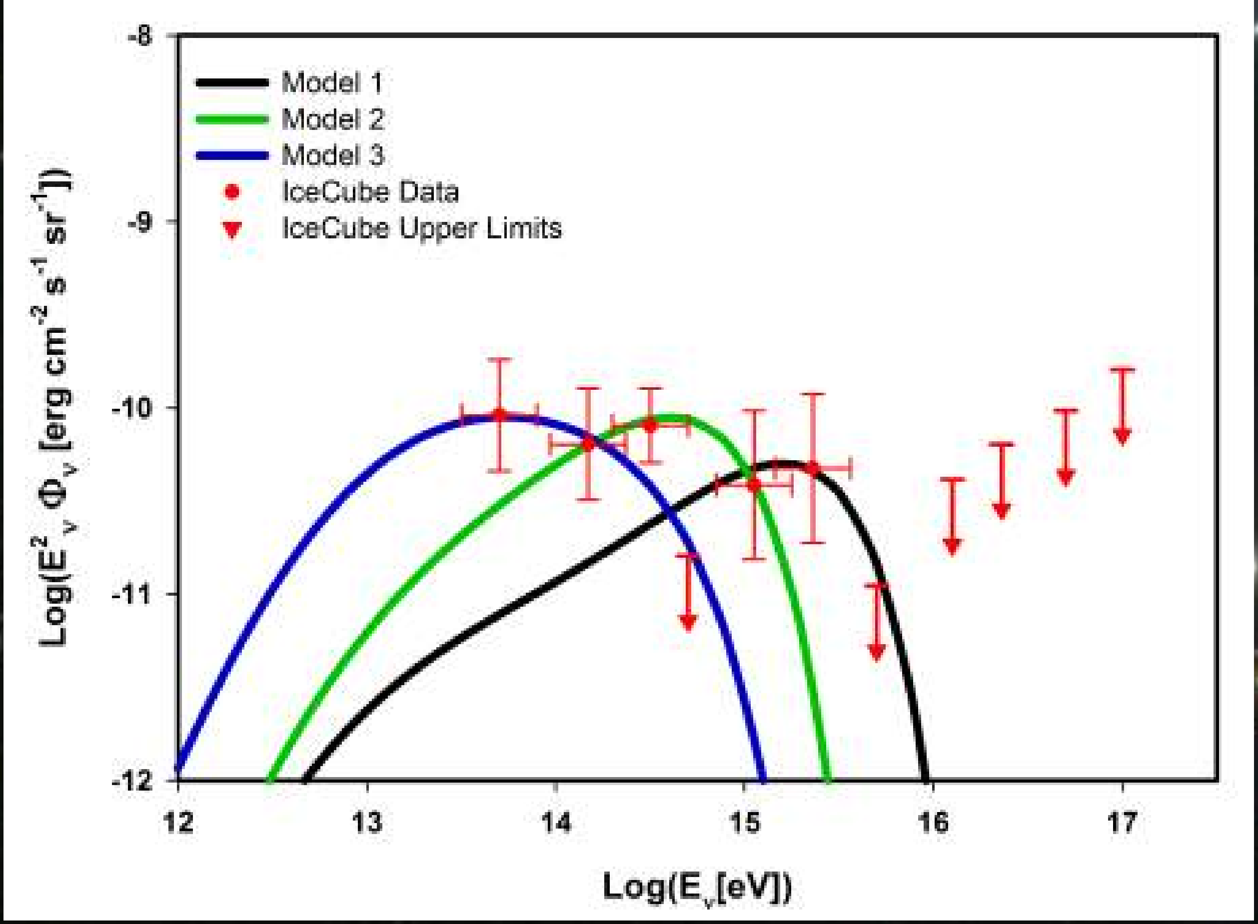




Spectral Energy Distribution

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

Neutrino emission from cores of low luminous AGNs due to reconnection acceleration



p + photons → π + p

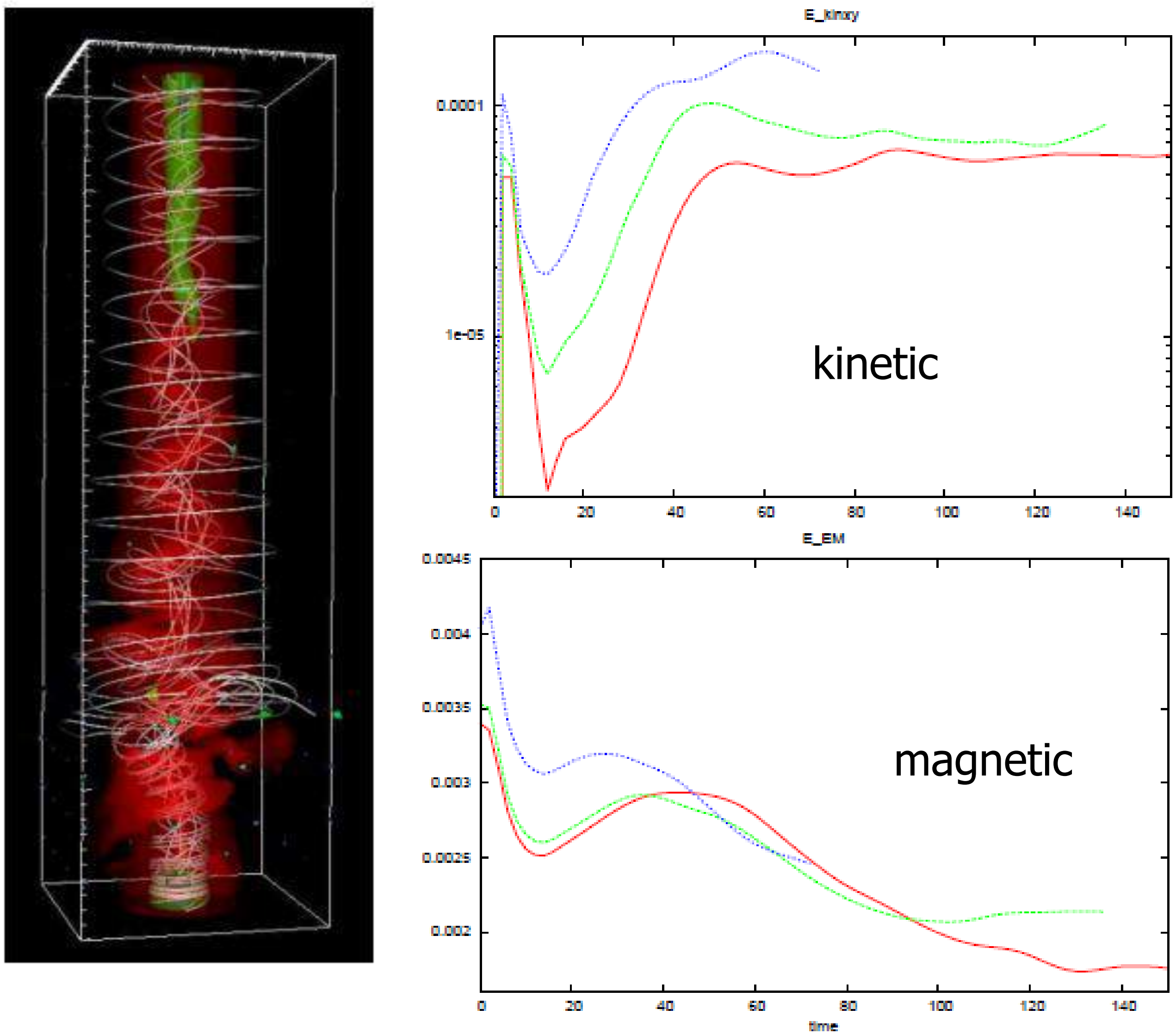
$\pi^o \rightarrow \gamma\gamma$

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

IceCube flux of Neutrinos

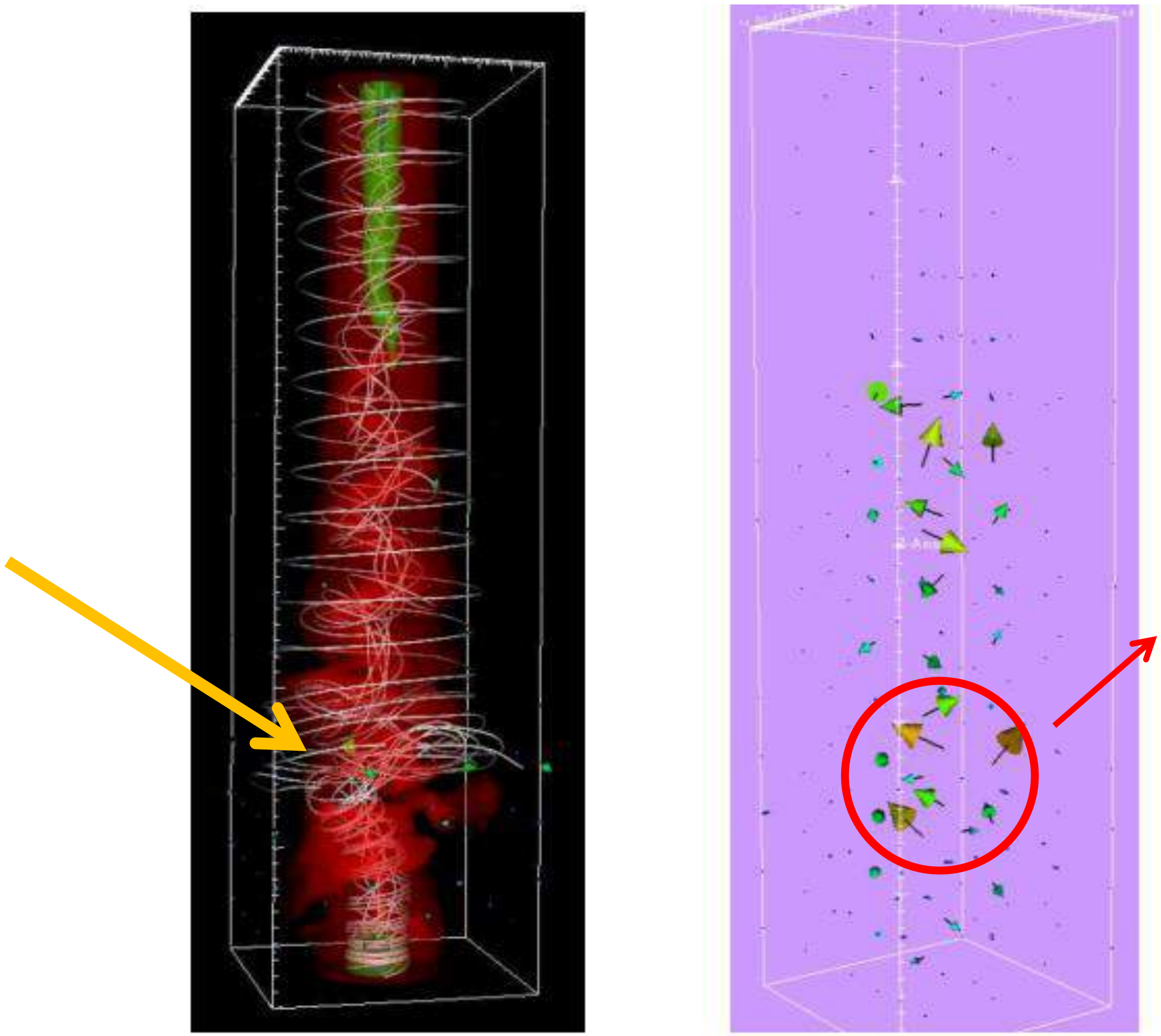
Khiali & de Gouveia Dal Pino, MNRAS 2015 (arxiv.1506.01063v1)

Reconnection driven by Kink in AGN & GRB Magnetically Dominated Relativistic Jets



Singh, Mizuno, de Gouveia Dal Pino (in prep.)

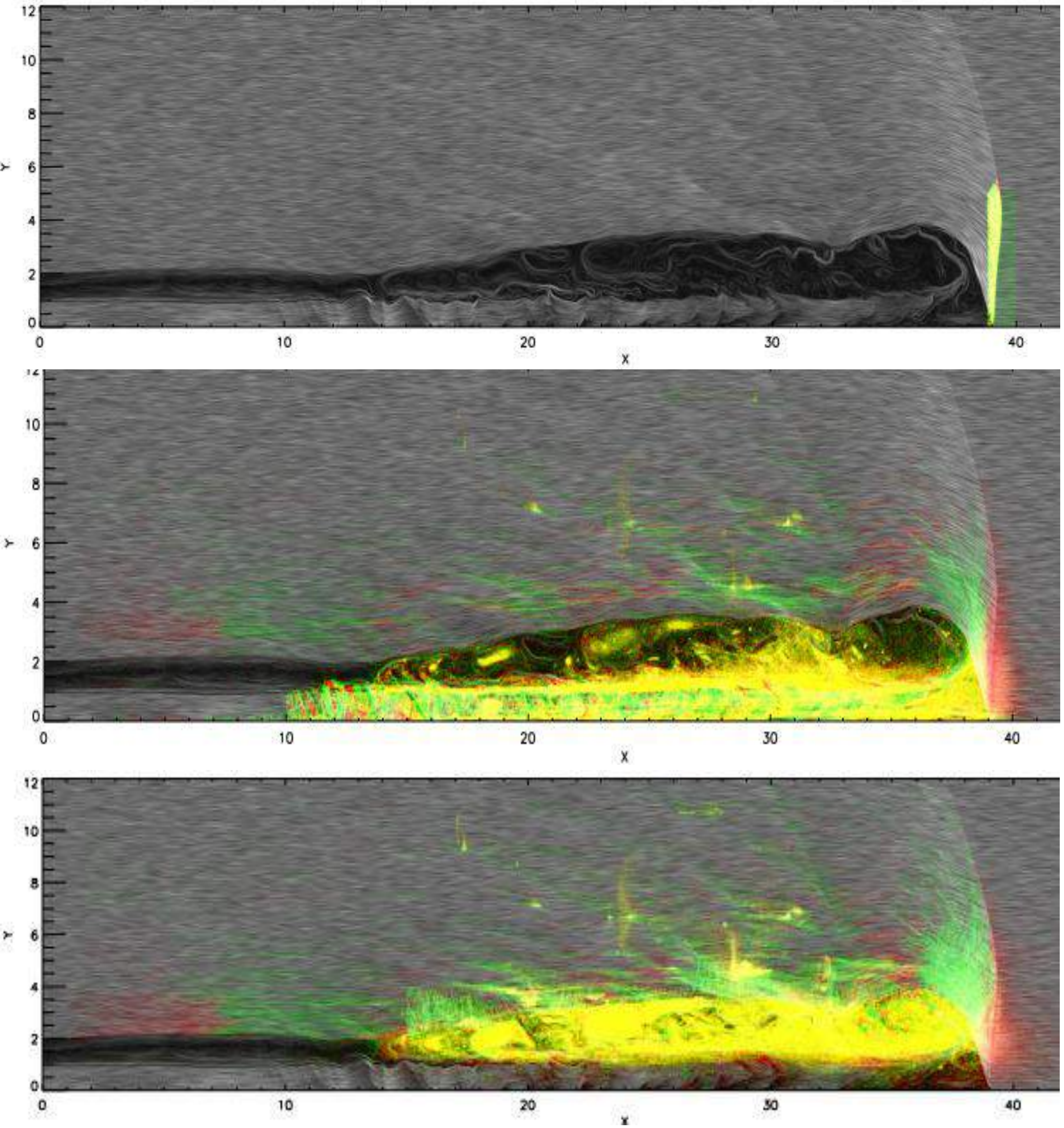
Reconnection driven by Kink in AGN & GRB Magnetically Dominated Relativistic Jets



Also sites for magnetic reconnection particle acceleration and gamma-rays!

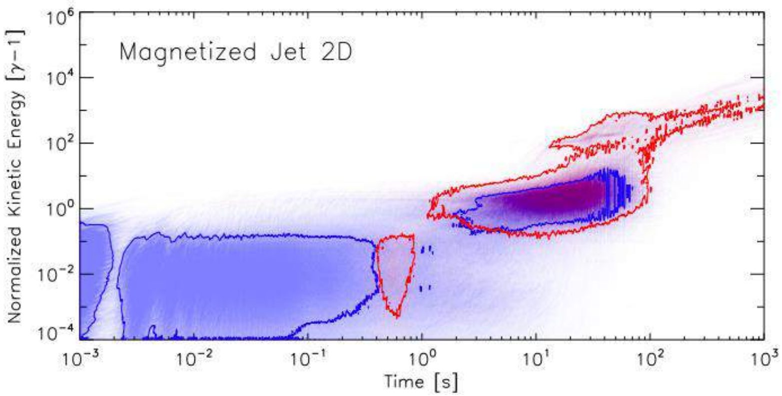
Singh, Mizuno, de Gouveia Dal Pino (in prep.)

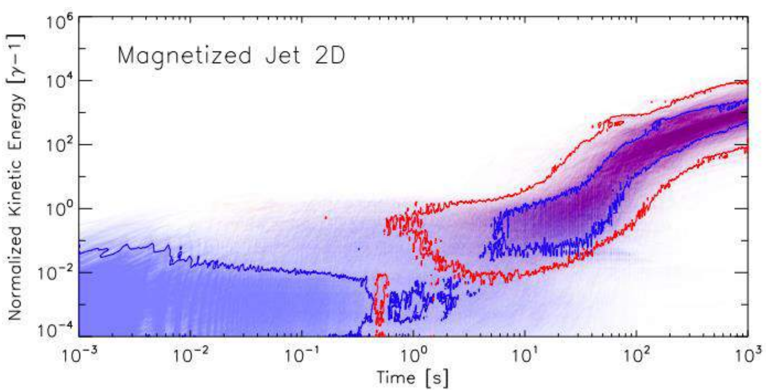
In situ 1st-order Fermi Relativistic MHD Reconnection x shock acceleration in Jets



Competing mechanisms

de Gouveia Dal Pino & Kowal, ASSL 2015





Summary

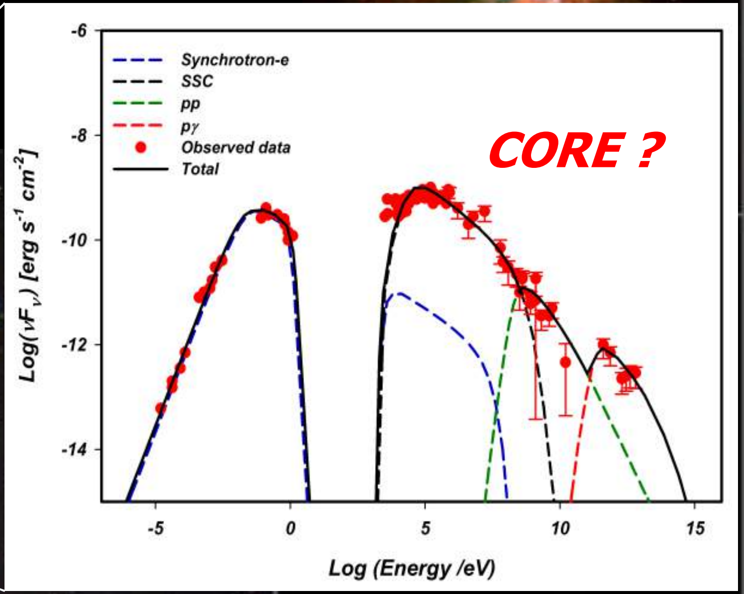
- ✓ Particles inserted in MHD current sheets with fast reconnection (e.g. driven by turbulence): exponential increase of energy in a 1st order Fermi acceleration (collisional ~ collisionless: $N(E) \sim E^{-1-2}$)
- ✓ Particle acceleration in 3D MHD reconnection is more efficient than in 2D
- ✓ Acceleration rate $t_{acc}^{-1} \sim E^{-0.4-0.3}$
- ✓ Acceleration by magnetic reconnection (numerically tested): can explain gamma-ray as coming from the *core* of BHBs and non-blazar AGNs
- ✓ The magnetic reconnection power matches well with the observed correlation of radio/gamma-ray luminosity versus BH mass for these sources over 10^{10} orders of magnitude
- ✓ Reconnection acceleration in the core -> SEDs of non-blazars and BHBs
- ✓ Magnetic reconnection acceleration may be important in magnetically dominated relativistic jets (AGNs & GRBs) (see also Sironi's talk)

Extra Slides

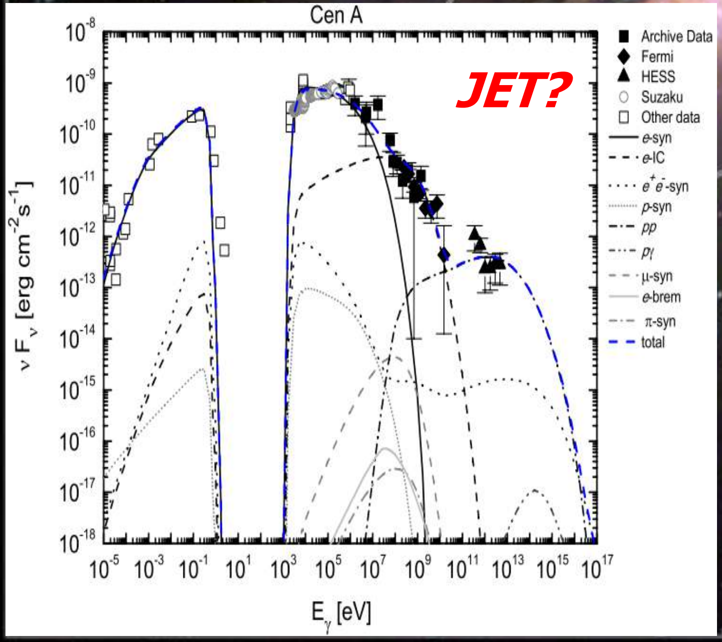
CTA & Mini-Array will locate the real region of acceleration and help to unveil the physics in the core/jet launching

Cen A

Is location of Gamma Emission in LLAGNs really in the core ?



Magnetic Reconnection Acceleration in the core?
(Khiali, de Gouveia Dal Pino, Sol 2015)



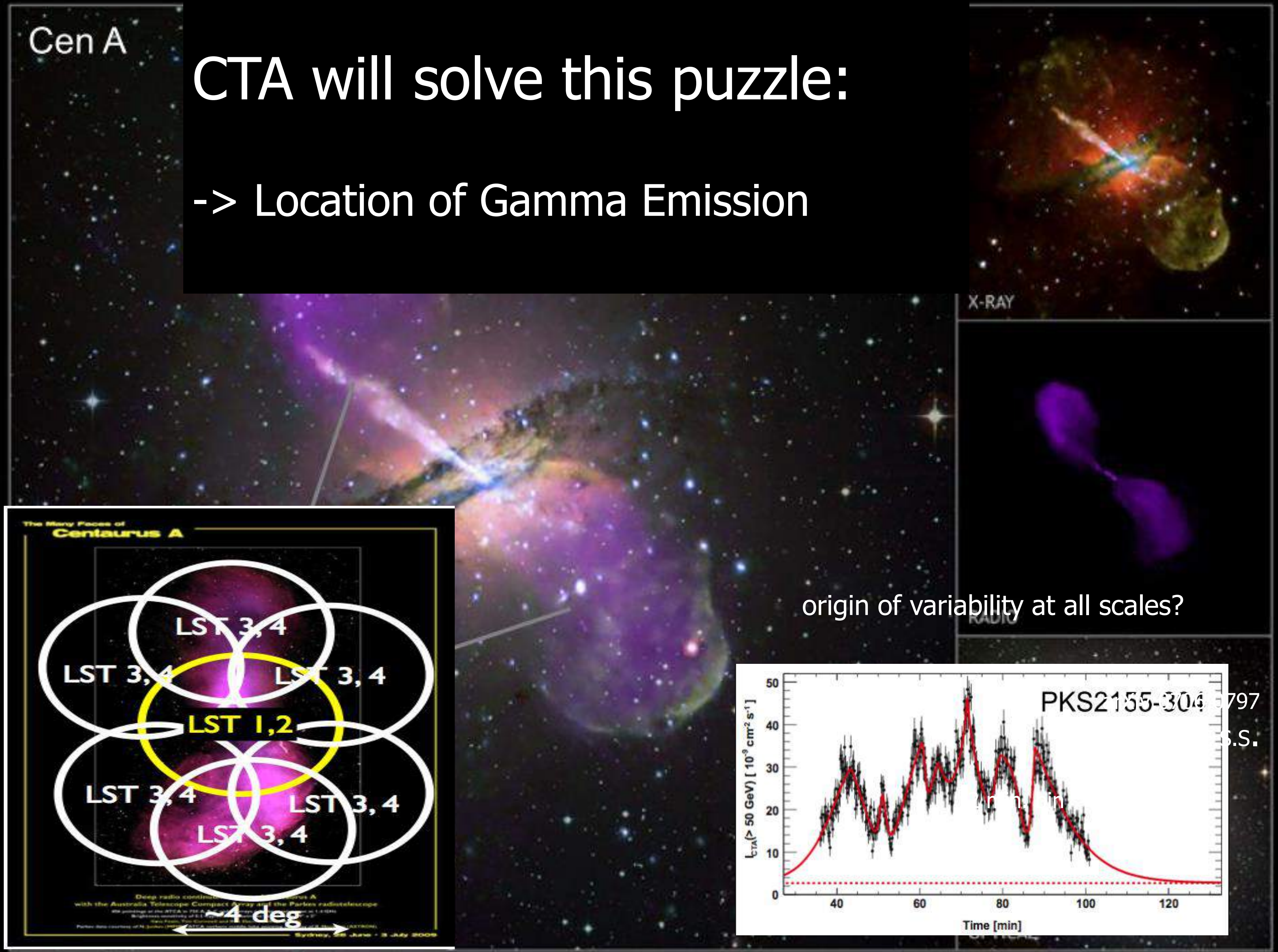
Shock Acceleration in the jet?
(e.g. Reynoso, Medina, Romero 2011)

OPTICAL

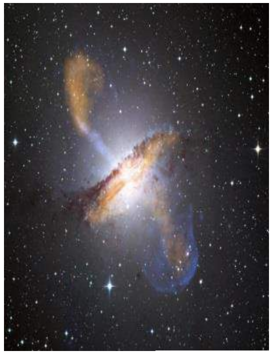
CTA will solve this puzzle:

-> Location of Gamma Emission

origin of variability at all scales?

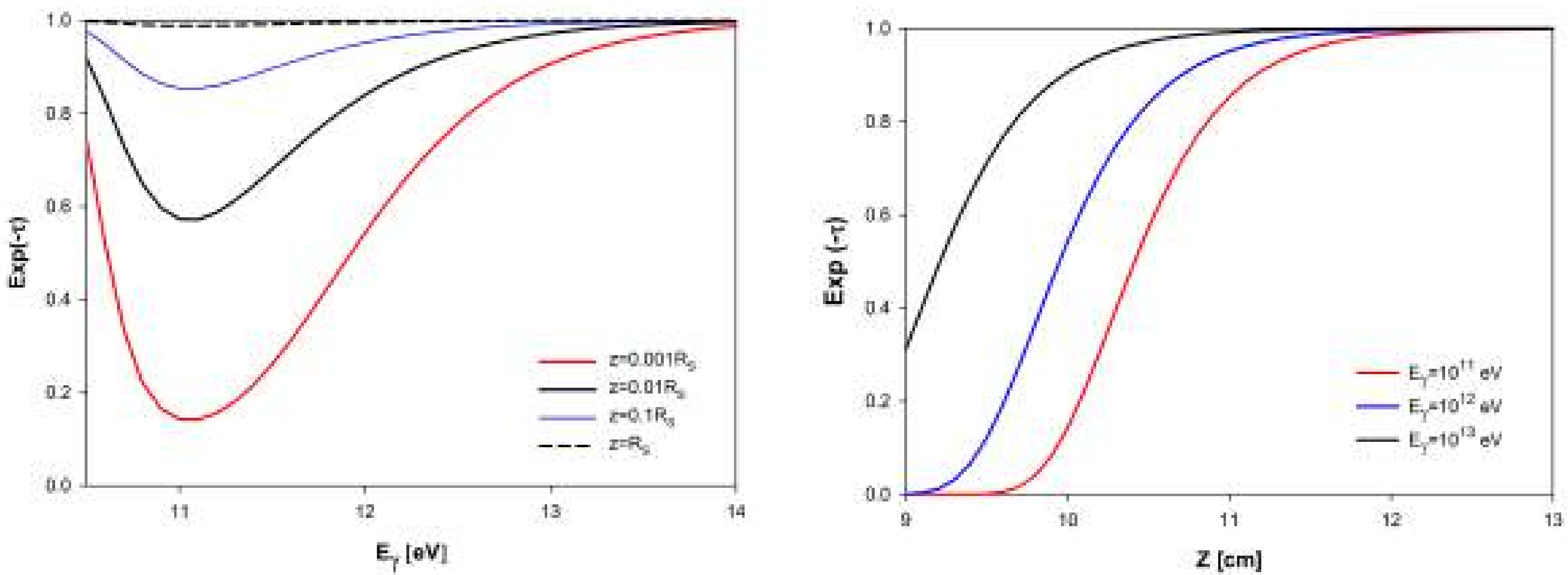


Reconnection Acceleration X Radiative Losses



- ✓ 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

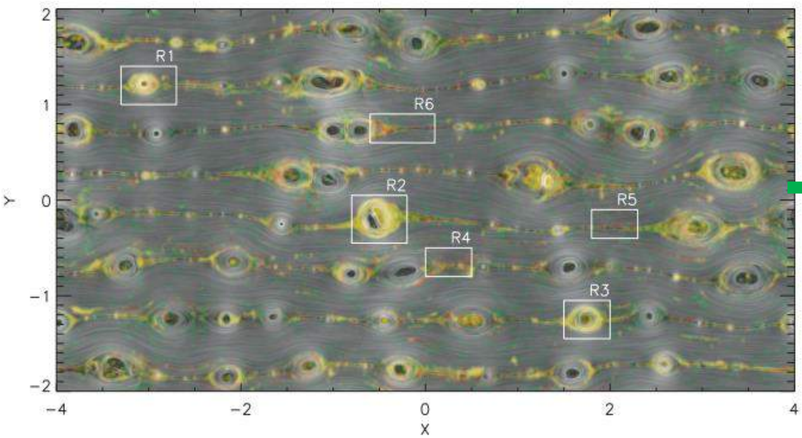


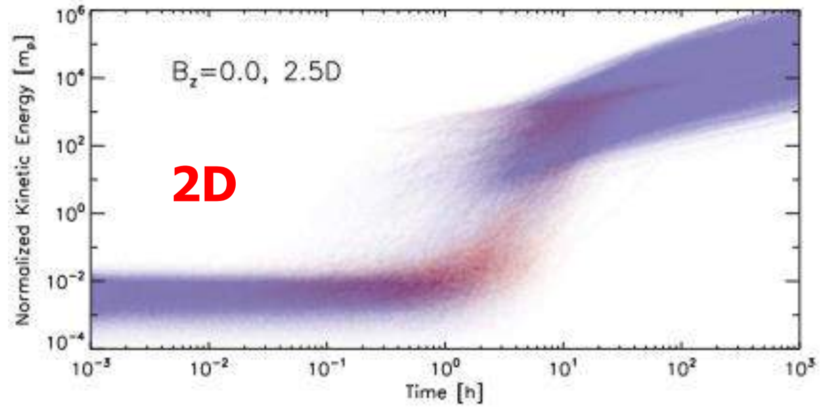
(a) Cen A (b) Cen A

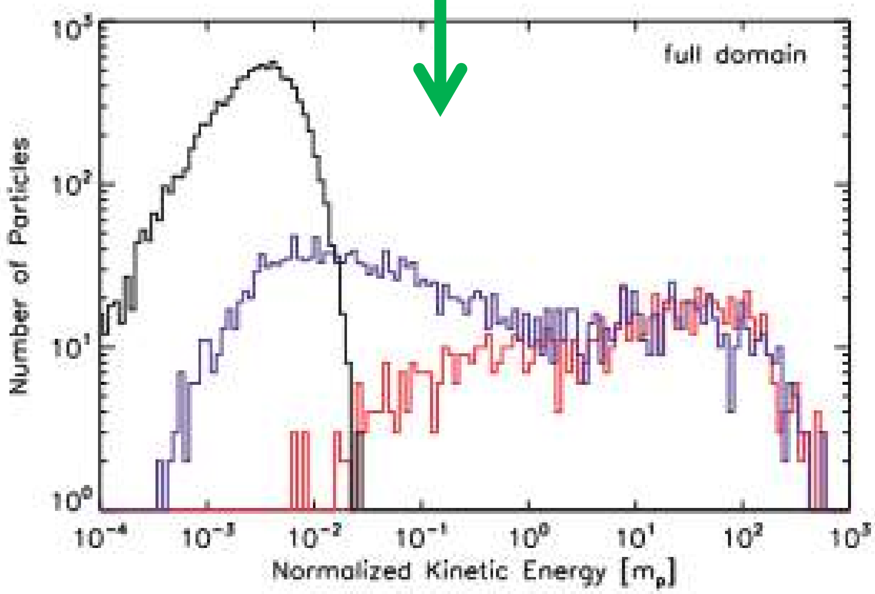
z>1 Rs -> NO absorption

Khiali, de Gouveia Dal Pino, Sol 2015

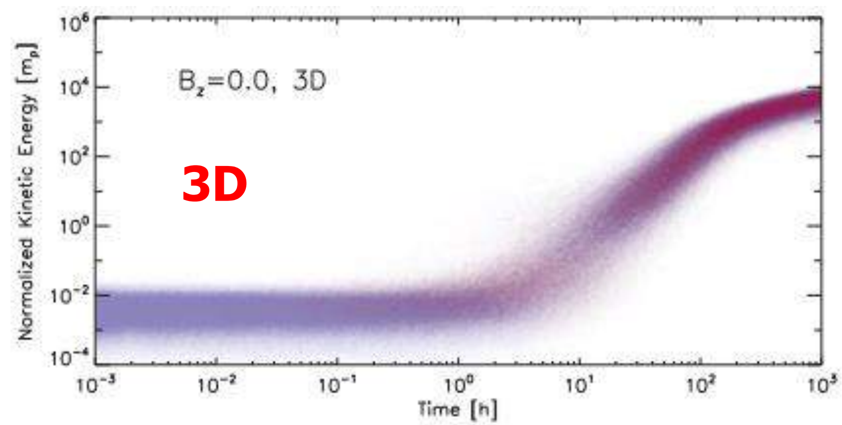
Particle Acceleration in 2D x 3D MHD Reconnection







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



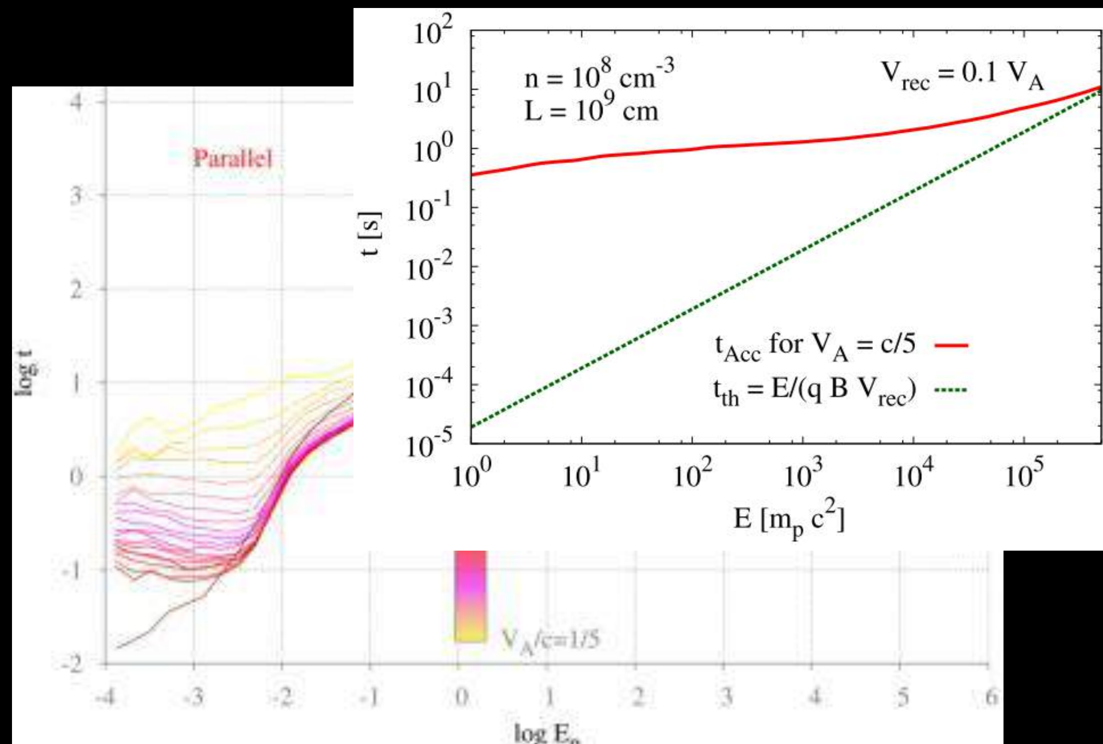
Energy growth w/ time

Particle Acceleration Time in Fast Reconnection

Particle acceleration time cannot be smaller than:

$$t_{acc,min} \sim t_g(\beta_{rec}) \sim \mathbf{E/e\ B\ c}\ \beta_{rec}$$

$t_{acc} \sim E^{0.4}$



AGNs:

R~10^{14} cm

B~10^4 G → v_A~c, $v_{rec} \sim 0.1 v_A$

E~ 10^{15} eV

t_{acc}~10 s << t_{pp}

Del Valle, de Gouveia Dal Pino, Kowal 2014

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