Particle Acceleration

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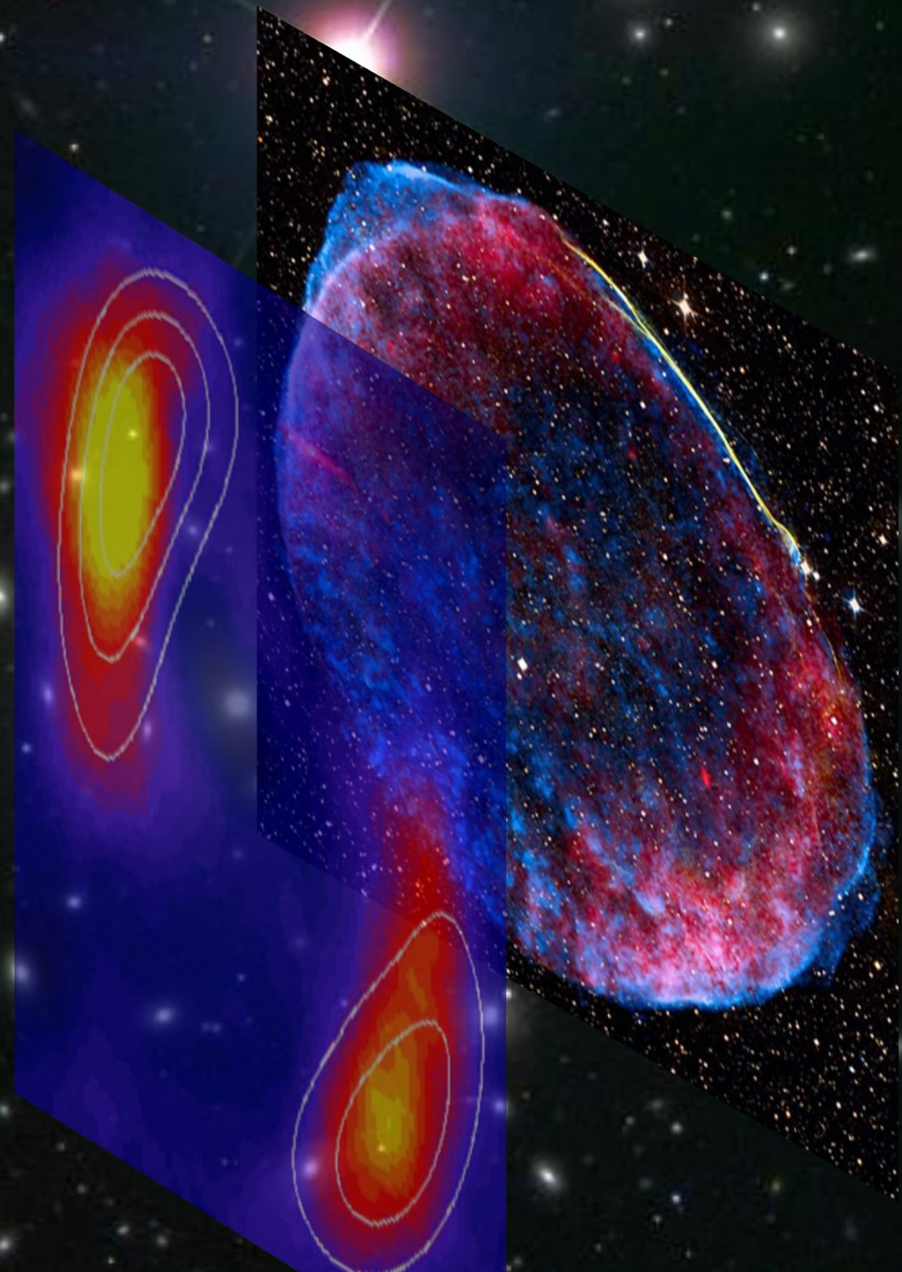
ISYA, Socorro, July 2018



Class 4

Part II

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- **Shock acceleration**
  - **Mirror Effect**
  - **2^{nd} Order Fermi Acceleration (turbulence)**
  - **Diffusive Shock Acceleration (1^{st} Order Fermi)**
- **Acceleration in Reconnection zones**
- **Astrophysical Sites**

Accelerated Particles – Cosmic Rays

High energy relativistic charged particles reaching the Earth's atmosphere (CRs):

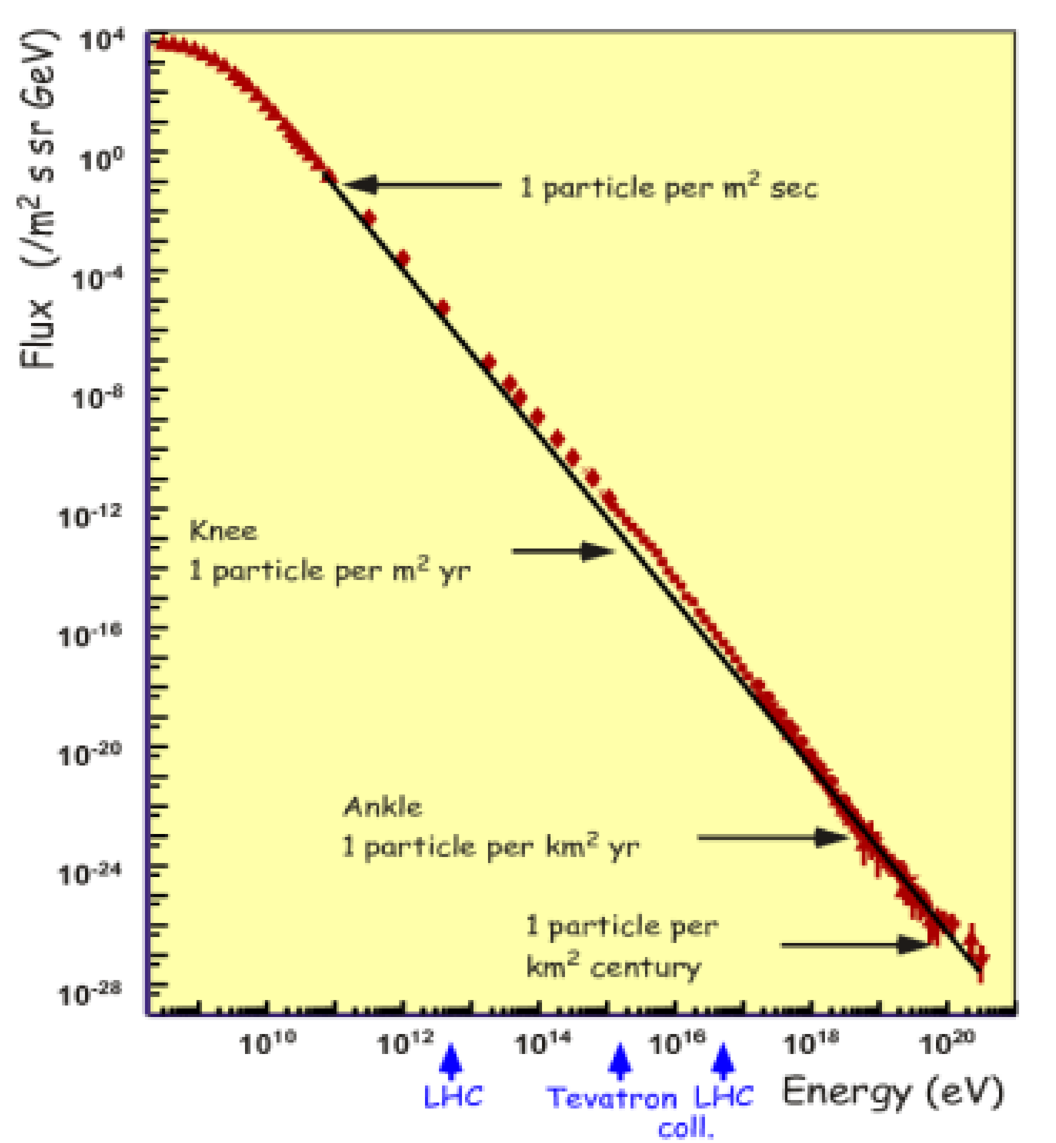
- **electrons** ~ 1%

- **protons** ~ 89%

- **heavier nuclei, mainly helium** ~ 10%

- **very few: antiparticles, muons, pions, kaons** (from interactions of CRs with the interstellar gas)

COSMIC RAY SPECTRUM



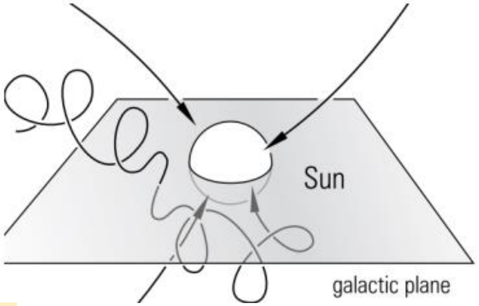
- **power law:**

$$N(E) \propto E^{-\gamma}$$

$$\gamma = 2.7 \quad \text{for} \quad 10^9\text{eV} < E < E_{knee},$$
$$\gamma = 3.0 \quad \text{for} \quad E_{knee} < E < E_{ankle},$$
$$\gamma = 2.7 \quad \text{for} \quad E_{ankle} < E < E_{GZK},$$

CRs and Magnetic Fields

Charged particles – circular orbits in Magnetic Field (MF):



- **gyro-radius (cyclotron) for relativistic particles :**

CGS

$$\frac{d\vec{p}}{dt} = \frac{q}{c}\mathbf{v} \times \mathbf{B} \rightarrow r_g = \frac{p}{qB} = \frac{\gamma m c\, v_\perp}{Ze\, B}$$

p: particle momentum

MKS

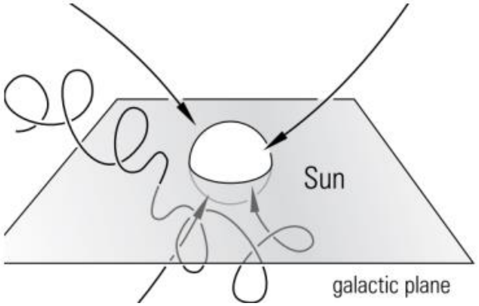
$$\frac{d\vec{p}}{dt} = q\mathbf{v} \times \mathbf{B} \rightarrow r_g = \frac{p}{qB} = \frac{\gamma m\, v_\perp}{Ze\, B}$$

γ : Lorentz factor

$$\frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

CRs and Magnetic Fields

$$r_g = \frac{p}{qB} = \frac{\gamma m\, v_\perp}{Ze\, B}$$



- **CRs with energies < 10^{15} eV**: sky distribution **ISOTROPIC**

- **Higher energy CRs:**

  are not as much deflected: **ANISOTROPIC**

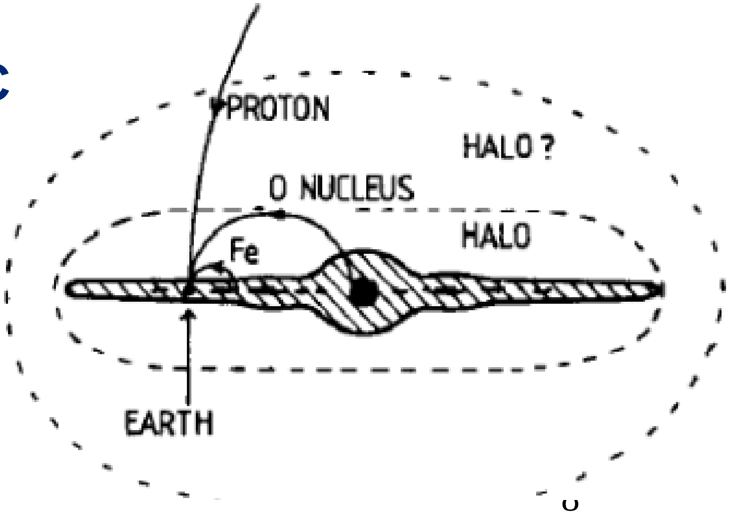
  Example:

  E = 10^{19} eV

  B = 2 μG → **r_g = 10 kpc**

  no correlation with galactic plane:

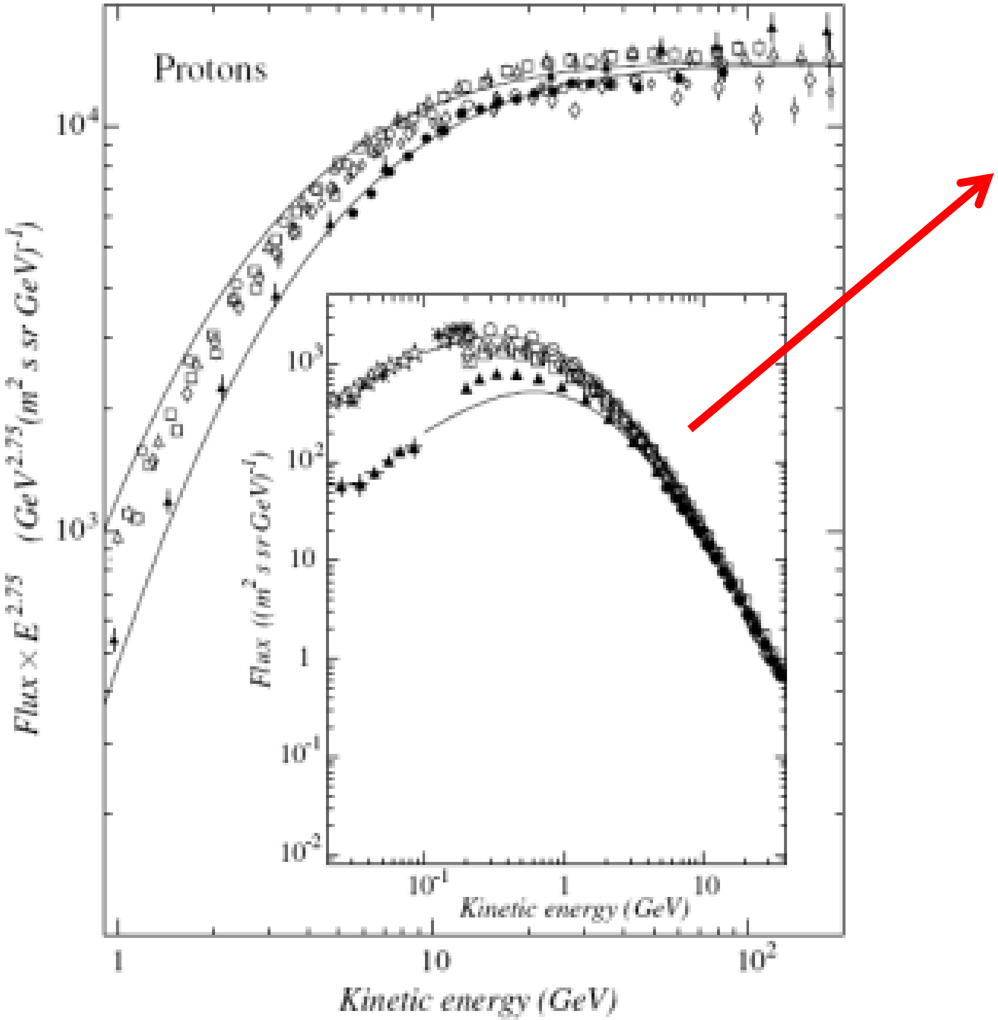
  -> **extragalactic origin**



What is the origin of the CRs ?

What are the acceleration mechanisms?

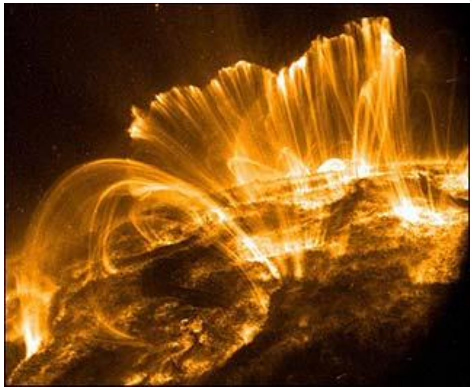
Ex.: CRs from the Sun



Power law spectrum at high energies

Possible mechanisms:

- Shock acceleration
- Magnetic Reconnection



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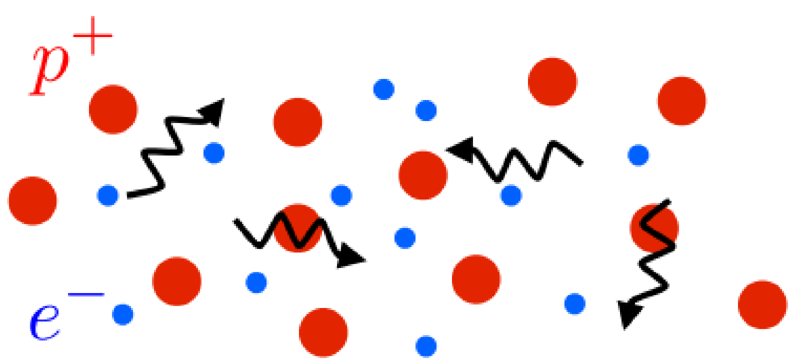
  - Mirror Effect
  - 2nd Order Fermi Acceleration (turbulence)
  - Diffusive Shock Acceleration (1st Order Fermi)
- Acceleration in Reconnection zones
- Astrophysical Sites

PLASMA & Cosmic Rays

MHD description applicable to most astrophysical plasma species

⬇

- ***BUT:* cosmic rays**
  - → need kinetic description
  - → and are coupled through waves with rest of the plasma



(Tchekhovskoy's cartoon)

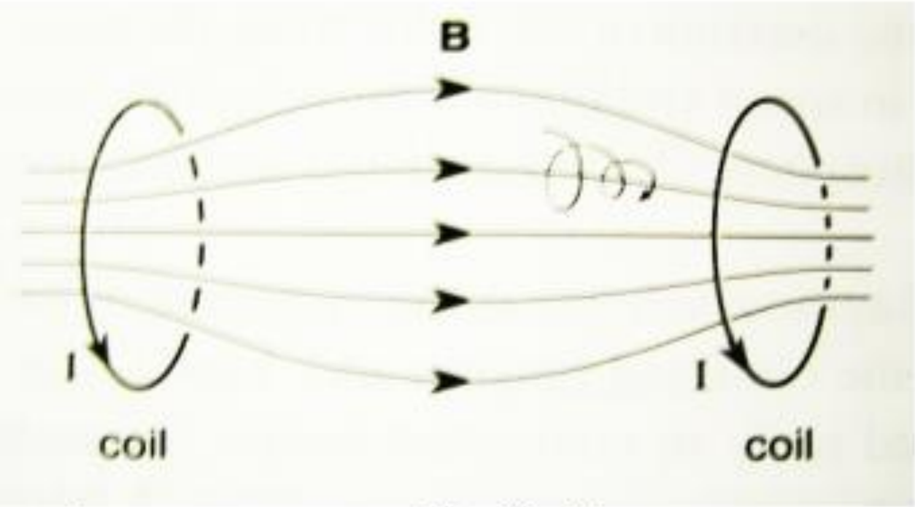
MIRROR EFFECT

particles entering regions of higher magnetic field strength are reflected backwards

- charged particles follow cyclotron orbits

  gyro-radius: $r_g = p_\perp / qB$

$$r_g = \frac{p}{qB} = \frac{\gamma m \; v_\perp}{Ze\,B}$$



Rule

The magnetic flux $\Phi = B \cdot \pi r_g^2 \;\propto v_\perp^2 / B$ through the particles' cyclotron circle is constant.

stronger magnetic field

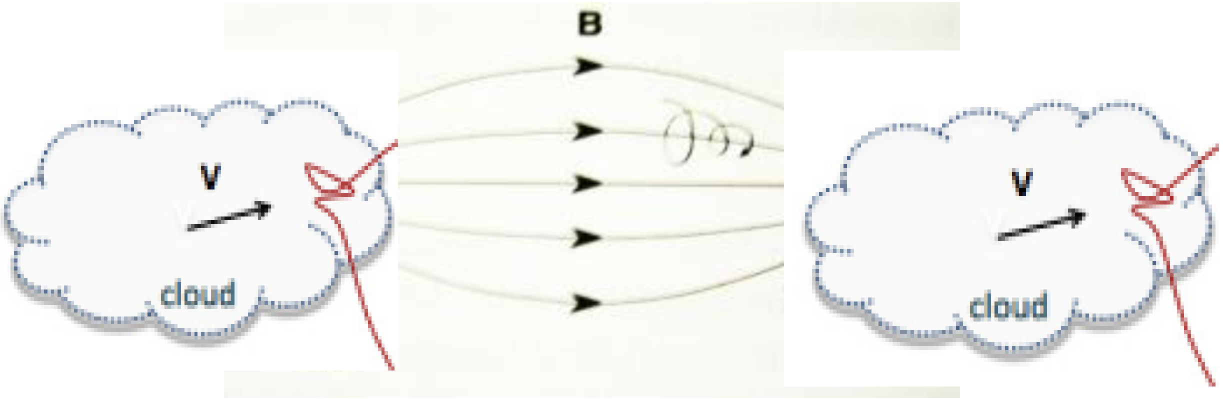
$\Rightarrow$ smaller gyro-radius, increased perpendicular velocity $v_\perp$

$\Rightarrow$ decrease of parallel velocity $v_\parallel$ (energy conservation)

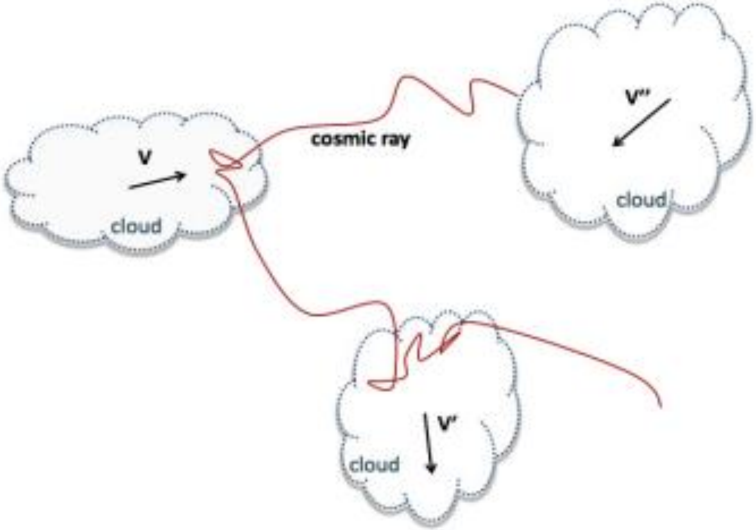
$\Rightarrow$ $v_\parallel \rightarrow 0$, then reflection

$$v = (v_{//}{}^2 + \; v_\perp^2 \;)^{1/2}$$

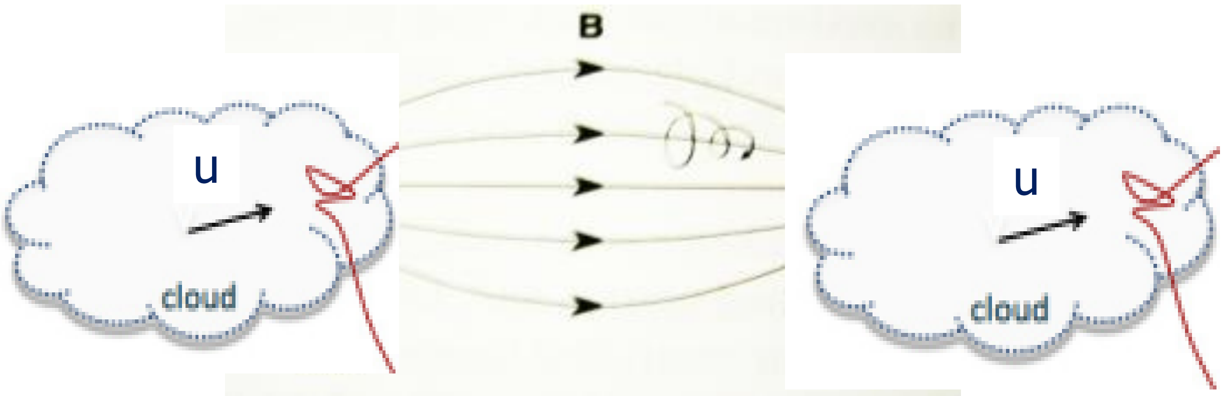
FERMI ACCELERATION



Fermi (1949): **could** CRs be produced via **random scattering with magnetized interstellar clouds?**



FERMI ACCELERATION

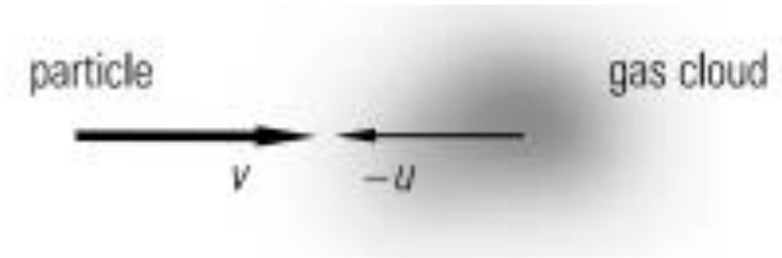


Frequency of head-on collisions > frequency of catch-up collisions

→ **net energy gain by particles**

FERMI ACCELERATION

Head-on collision:



- change in kinetic energy:

$$\Delta E = \tfrac{1}{2}m(v+u)^2 - \tfrac{1}{2}mv^2$$

Catch-up collision:

$$\Delta E_2 = \frac{1}{2}m(v-u)^2 - \frac{1}{2}mv^2$$

→ **Net energy gain:**

$$\Delta E = \Delta E_1 + \Delta E_2 :$$

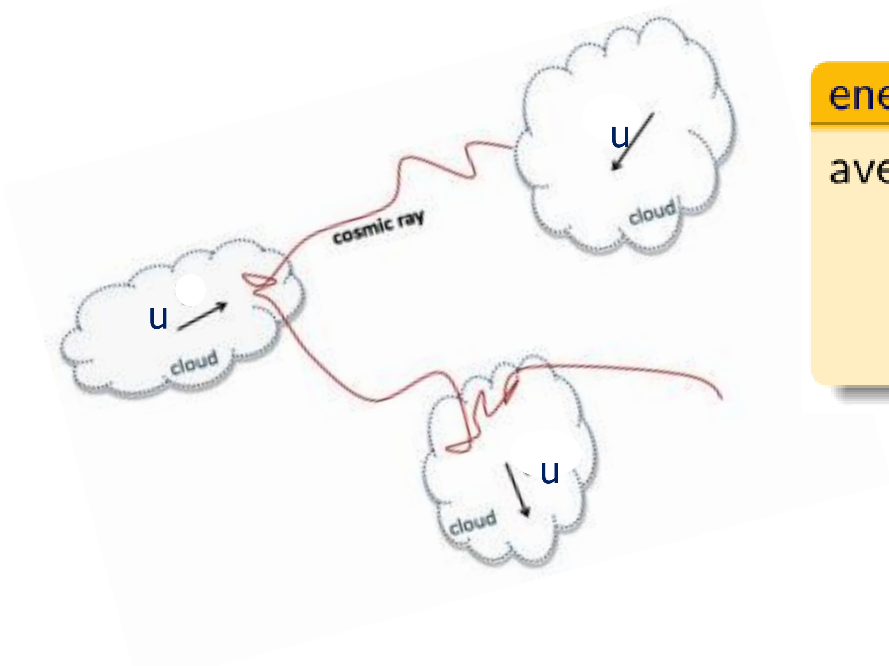
→

$$\boxed{\frac{\Delta E}{E} = 2\frac{u^2}{v^2}}$$

2nd Order Fermi

2^{nd} ORDER FERMI ACCELERATION

There is net energy gain per collision:



energy gain

average over all angles of incidence ϑ:

$$\left\langle \frac{\Delta E}{E} \right\rangle \propto \frac{u^2}{v^2}$$

u <<v ≈ c: the energy gain per collision is very small

Statistical reflection on many different clouds in a galaxy

- **Stochastic acceleration** in magnetized turbulent medium

2nd ORDER FERMI ACCELERATION

✓ Particles accelerated in this statistical process satisfy diffusion-loss equation (Fokker-Planck):

$$\frac{dN}{dt} \approx -\frac{\partial}{\partial E}[N(E,t)\alpha E] - \frac{N(E,t)}{\tau}$$

α =Acceleration rate $\alpha \equiv 4\nu(V/v)^2$

ν=1/Δt~ *v/L* (frequency collision)
V = u (clouds mean velocity)

τ = time a cosmic ray stays in the galaxy

➢ **Power Law spectrum:**

$$N(E) \approx N_0 E^{\underbrace{-(1+1/\alpha\tau)}_{\Gamma}}$$

2^{nd} ORDER FERMI ACCELERATION

Result: power law

$$N(E) \propto E^{-\Gamma}, \qquad \Gamma = \left(1 + \frac{1}{\alpha\tau}\right)$$

Nice, BUT:

$$\alpha \sim \langle V^2 \rangle / Lv = \langle V^2 \rangle / Lc$$

- L = 100pc = mean separation between clouds (scatterers)
- <V> = 10 km/s = clouds average velocity
- $\tau = 2\times10^{7}$anos = time CRs stay in the Galaxy

$$\frac{1}{\alpha\tau} = \frac{3\times10^{20}cm \times 3\times10^{10}cm/s}{10^{12}cm^2/s^2 \times 6\times10^{14}s} \simeq 1.5\times10^{4} \quad !!!$$

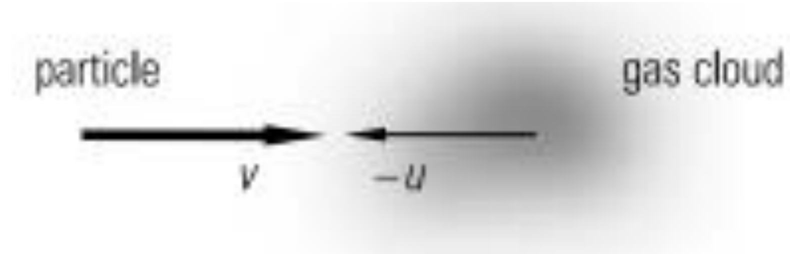
Thus: Γ calculated >> observed Γ ~ 2.7 !!

→ **2^{nd} ORDER FERMI: too slow !**

We need 1st ORDER FERMI ACCELERATION

REMEMBER :

Head-on collisions:



→ Net energy gain:

relativistic calculation →

$$\Delta E \propto E, \qquad \frac{\Delta E}{E} = 2\frac{uv}{c^2} + \frac{u^2}{c^2} \overset{v \approx c}{=} \underbrace{2\frac{u}{c}}_{\text{1st order}(\pm)} + \underbrace{\frac{u^2}{c^2}}_{\text{2nd order}}$$

↳ **1st Order Fermi**

Thus we need scattering in a CONVERGING FLOW:
→ acceleration in a SHOCK does this (Bell 1978) !!

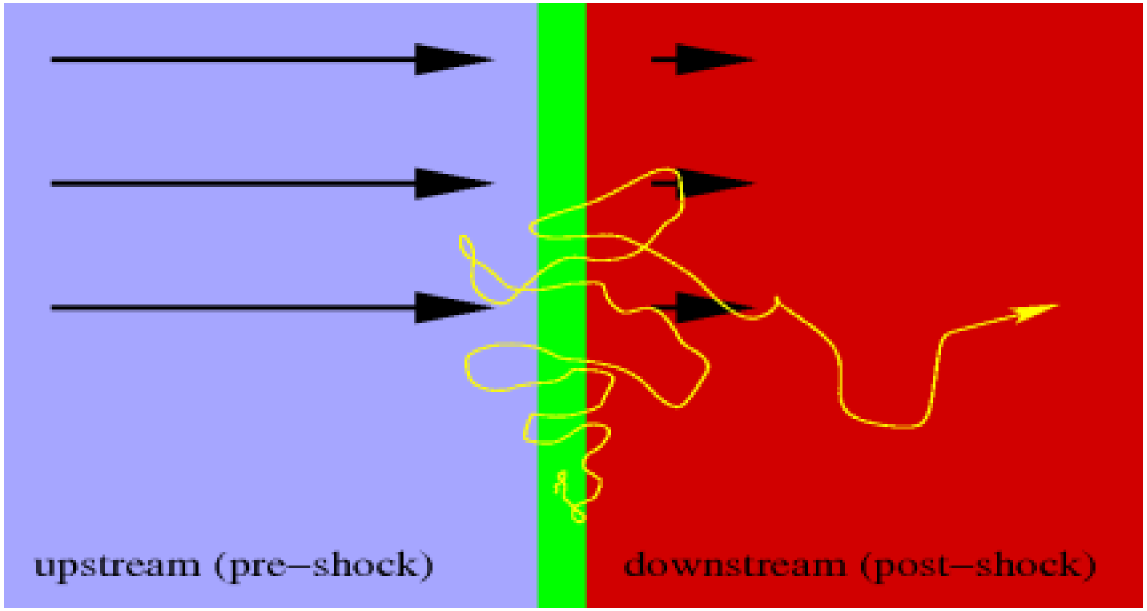
DIFFUSIVE SHOCK ACCELERATION

picture in the rest frame of the shock front

Assume for simplicity:

- Adiabatic shock
- B// v for simplicity

B



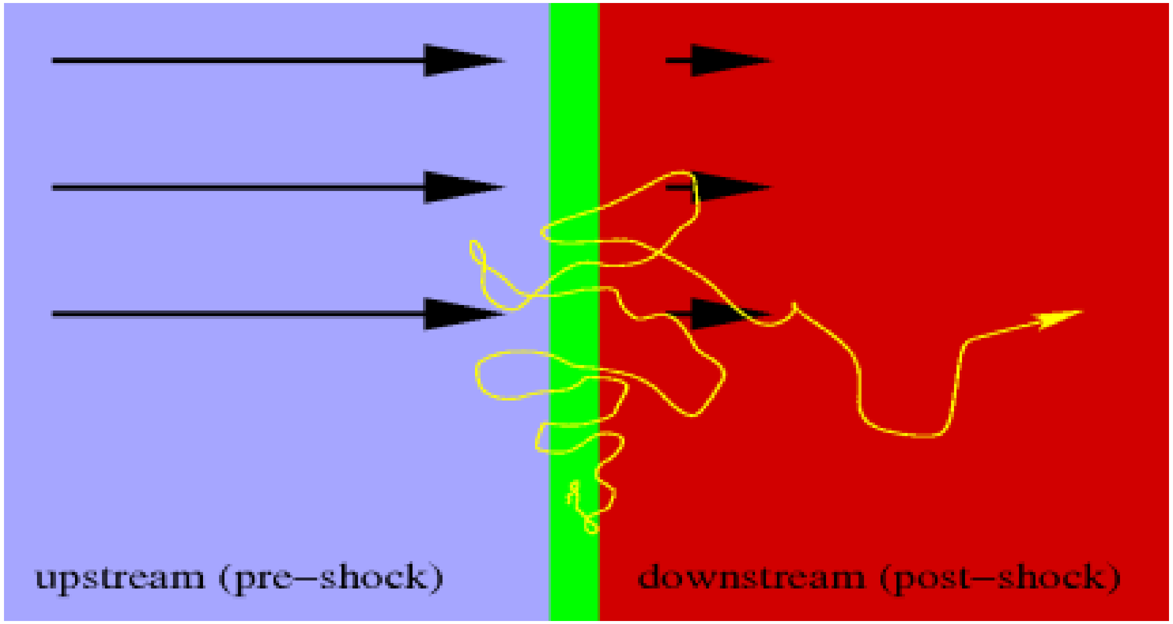
• Particles with higher velocity than the plasma flow may travel against the stream and cross the shock back to upstream (unshocked region)

• They scatter and interact with magnetic field fluctuations (Alfven waves)

• Shock contains **converging** scatterers because particles experience **higher (head-on)** collision velocities **upstream t**han **(catch-up)** collisions **downstream**

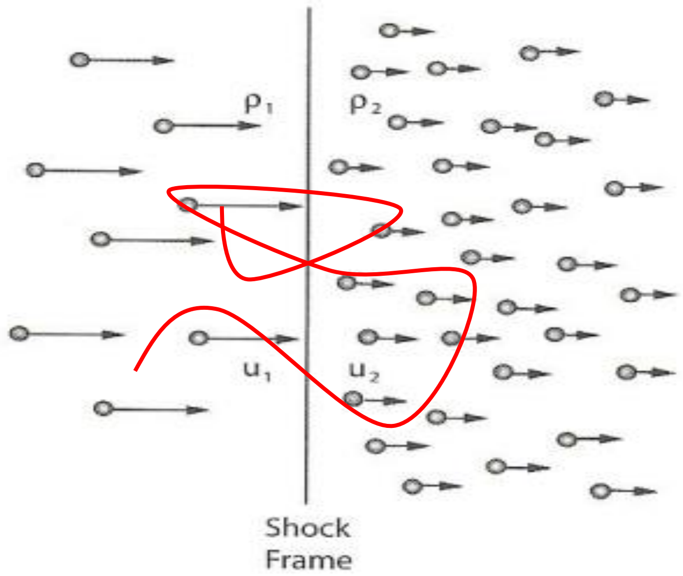
DIFFUSIVE SHOCK ACCELERATION

picture in the rest frame of the shock front



- reflection in upstream ⇒ energy gain $\propto v_{\mathrm{up}}/c$
- reflection in downstream ⇒ smaller energy loss $\propto v_{\mathrm{down}}/c$
- repetition until particle is not scattered back upstream

DIFFUSIVE SHOCK ACCELERATION



Every round trip: particle executes one catch-up and one head-on

→ **Average energy gain:**

$$\frac{\langle \Delta E \rangle}{E} \approx \frac{2(u_1 - u_2)}{v} = \frac{2\Delta u}{v}$$

➡ **1st order in ~u/c !**

→ **Fermi I more efficient than Fermi II !!**

DIFFUSIVE SHOCK ACCELERATION

Calculating the spectrum (Bell 1978):

$\beta = E/E_o = 1 + \Delta E/E_o$: new energy/ collision, or: $\beta = 1 + \frac{2\Delta u}{v}$

P= probability that particle remains in the acceleration regime after one collision (probability that it returns to upstream to be accelerated again)

-> After *k* collisions, the number of particles still scattering *N*:

$$N = N_0 \mathcal{P}^k$$

$$E = E_0 \beta^k$$

Thus, eliminating *k*:

$$\frac{N}{N_0} = \left(\frac{E}{E_0}\right)^{\ln \mathcal{P} / \ln \beta} \rightarrow dN = KE^{\ln \mathcal{P} / \ln \beta - 1}\, dE$$

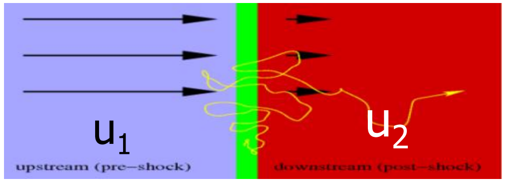
DIFFUSIVE SHOCK ACCELERATION

P= probability that particles remain in the acceleration region after one collision (that they return back to upstream from downstream):

- number of particles (with ~ c) crossing shock/area/time: $\frac{1}{4}Nc$

- steady state, the number of particles crossing back to upstream: $\frac{1}{4}Nc - u_2 N$

→ $$\mathcal{P} = \frac{\frac{1}{4}Nc - u_2 N}{\frac{1}{4}Nc} = 1 - \frac{4u_2}{c}$$



Thus: $\ln \mathcal{P} = \ln\left(1 - \frac{4u_2}{c}\right) \approx -\frac{4u_2}{c}$ **and** $\ln \beta = \ln\left(1 + \frac{2\Delta u}{c}\right) \approx \frac{2\Delta u}{c}$

for STRONG adiabatic shock → M>>1 → $u_1/u_2 = 4$

$$\frac{\ln \mathcal{P}}{\ln \beta} = \frac{-4u_2}{2(u_1 - u_2)} = -\frac{2}{3}$$

➡ $$dN(E) = KE^{-5/3}\,dE$$!!!

Observed γ ~ 2.7

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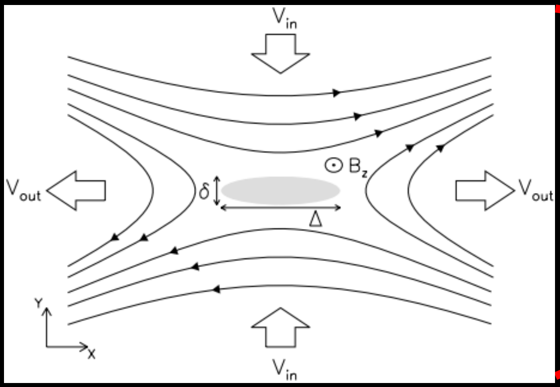
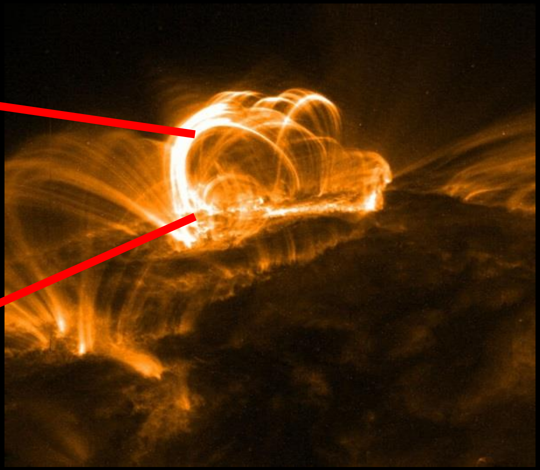
Reconnection & Particle Acceleration

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





✓ **Solar/stellar flares**

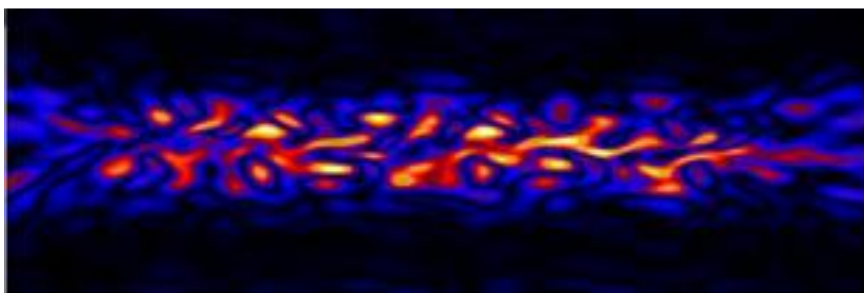
→ **Can reconnection lead to direct particle acceleration?**

Fast Reconnection in MHD flows

Turbulence drives FAST RECONNECTION

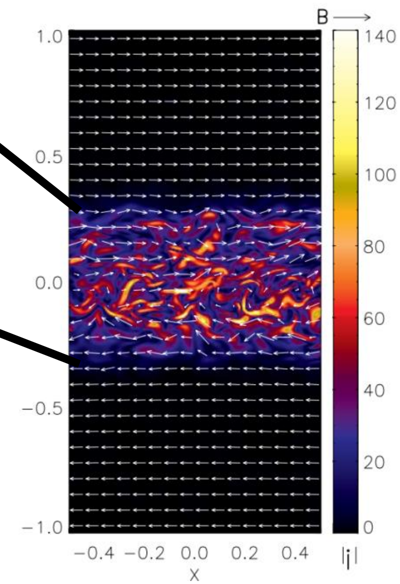
(Lazarian & Vishniac 1999; Eyink et al. 2011)

Magnetic lines wandering: many simultaneous reconnection events



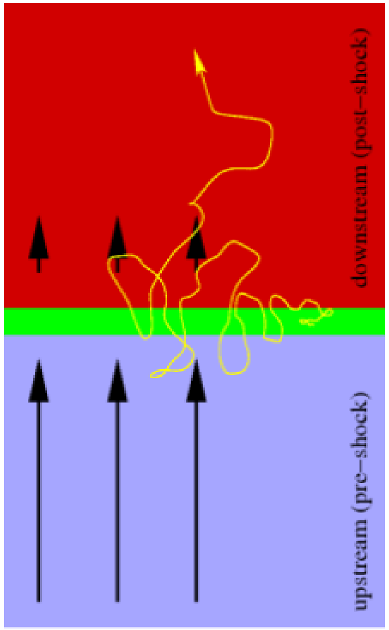
$$V_{\rm rec} = V_{\rm A}\left(\frac{l}{L}\right)^{1/2}\left(\frac{v_l}{V_{\rm A}}\right)^{2}$$

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



How particles can be accelerated in reconnection sites?

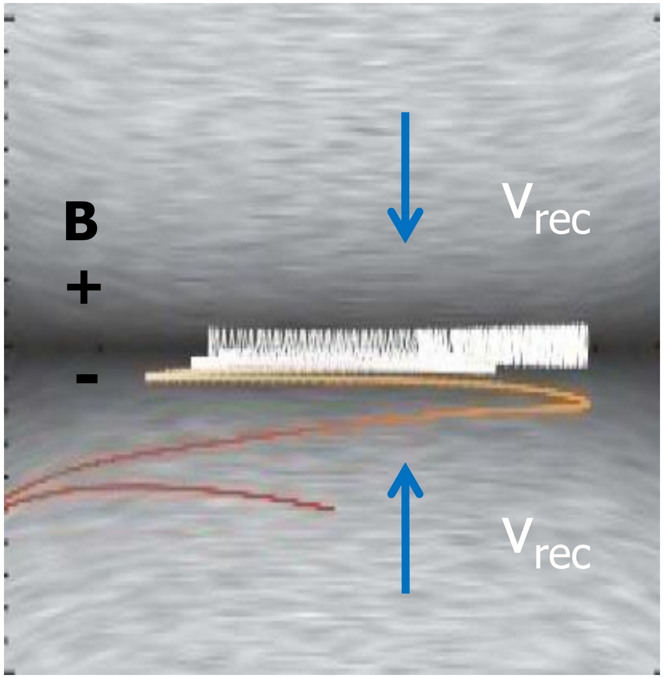
Shock Acceleration



1st-order Fermi
(Bell 1978):

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

Reconnection Acceleration

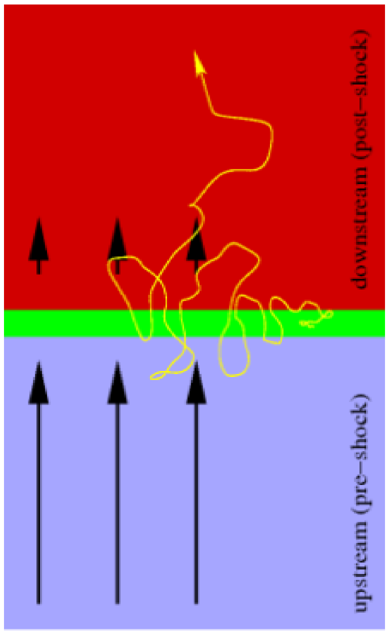


As in shocks: 1st-order Fermi !!
(de Gouveia Dal Pino & Lazarian, A&A 2005):

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

How particles can be accelerated in reconnection sites?

Shock Acceleration



1st-order Fermi
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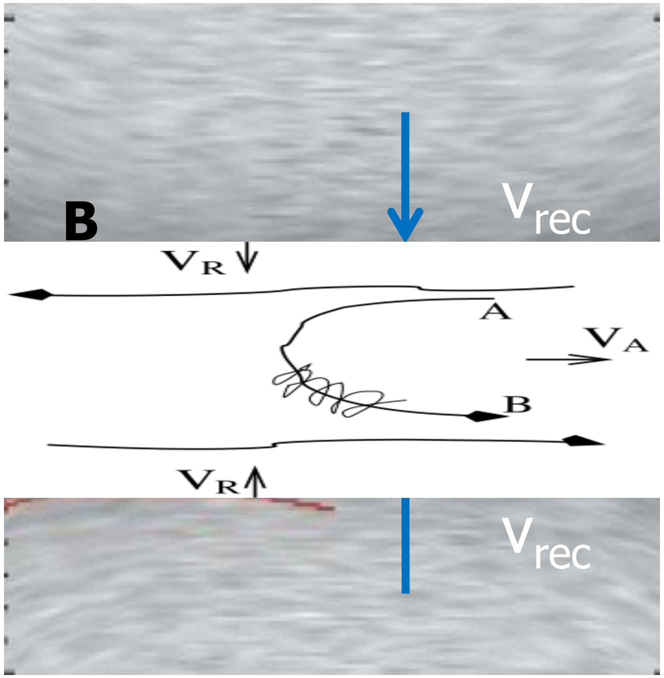
Reconnection Acceleration



As in shocks: 1st-order Fermi
(de Gouveia Dal Pino & Lazarian, A&A 2005):

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

1st-order FERMI ACCELERATION @ RECONNECTION SITE

Similar derivation as in shock acceleration we obtain
1st-order Fermi (de Gouveia Dal Pino & Lazarian 2005):

$$\langle \Delta E/E \rangle \sim 8 v_{rec}/3c$$

✓ Particle Spectrum?
(see also de Gouveia Dal Pino & Kowal 2015)

$$N(E) \sim E^{-5/2}$$

Testing Particle Acceleration by Reconnection using MHD Simulations with test particles

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

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

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

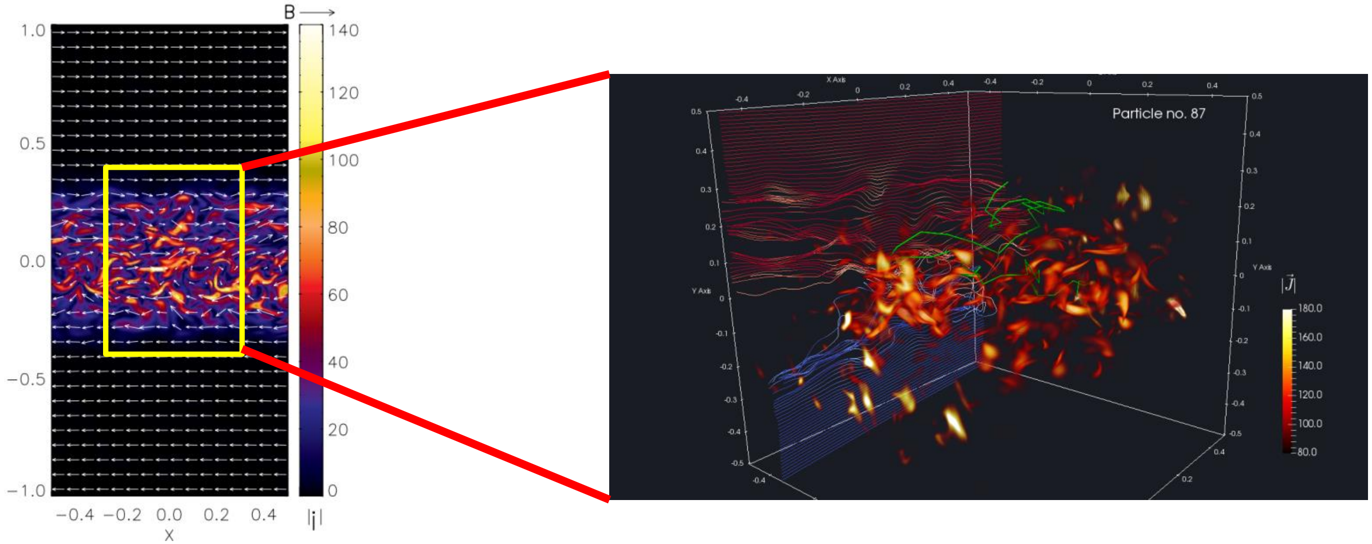
- 2nd order Godunov scheme with HLLD solver (Kowal et al. 2007, 2009)

- f: random force term responsible for injection of turbulence
- We perform numerical simulations of magnetic reconnection site simulated with MHD eqs. assuming isothermal plasma

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

Particle Acceleration by Reconnection using MHD Simulations with test particles

Current sheet with turbulence to make fast reconnection

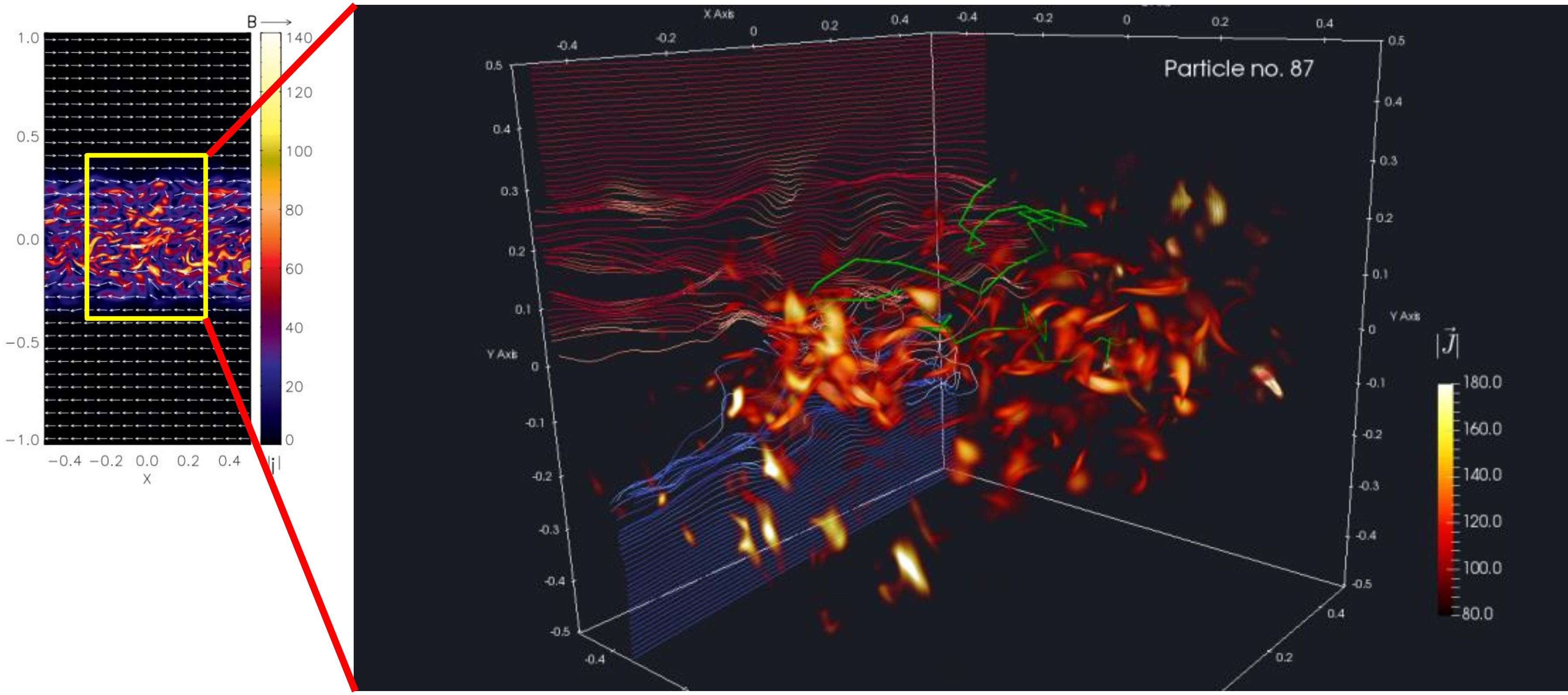


- **Inject test particles** in the MHD domain of reconnection and follow their trajectories (6th order Runge-Kutta-Gauss):

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

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

Particle Acceleration by Reconnection using MHD Simulations with test particles



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

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

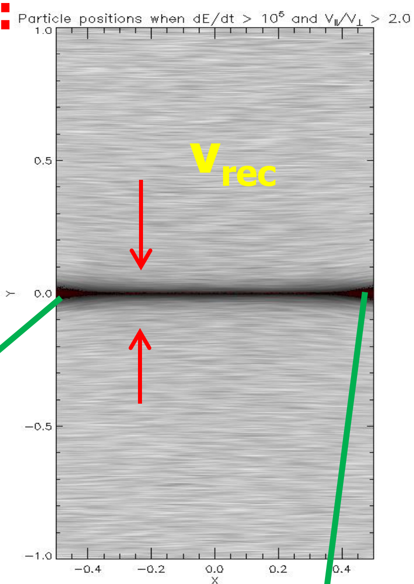
Test particle acceleration simulation in MHD Reconnection site

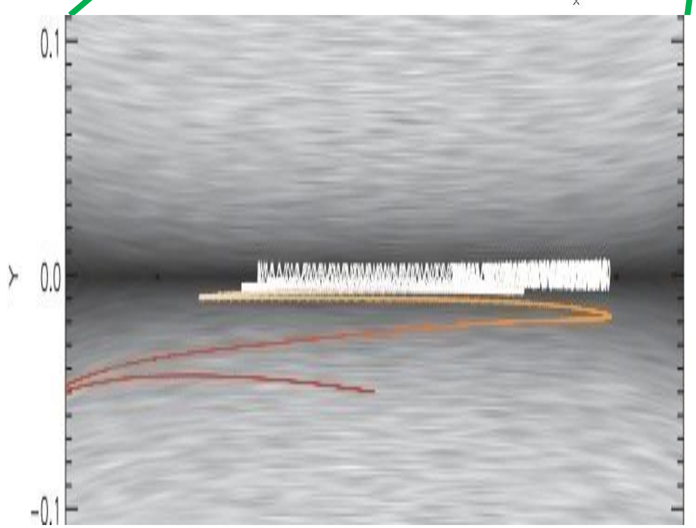
- **Single Particle test:**

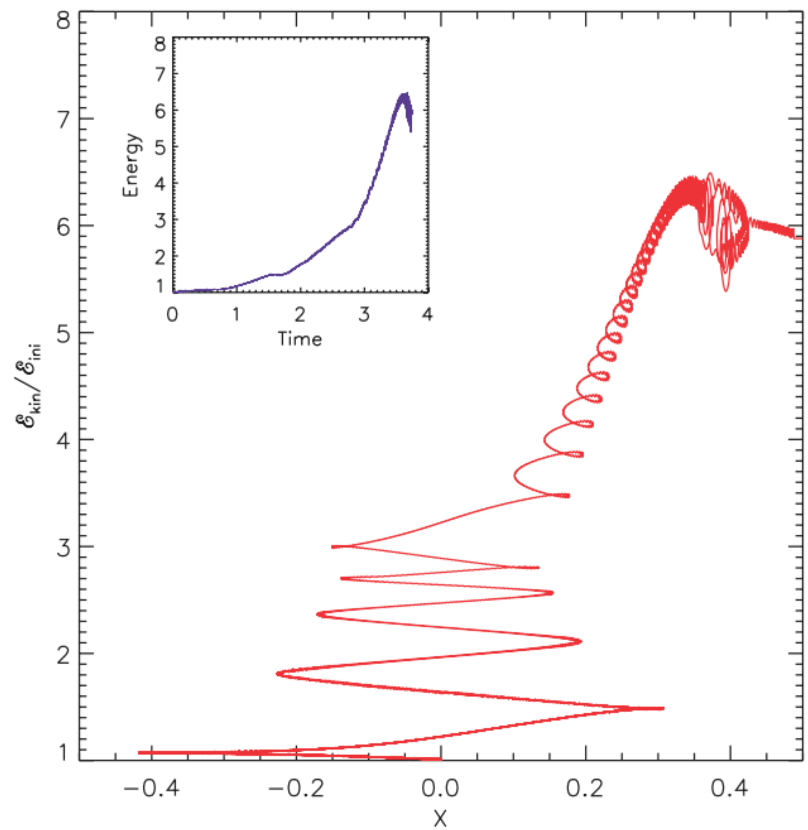
Resistive Sweet-Parker current sheet:

Particle is confined → 1^{st} order Fermi:

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

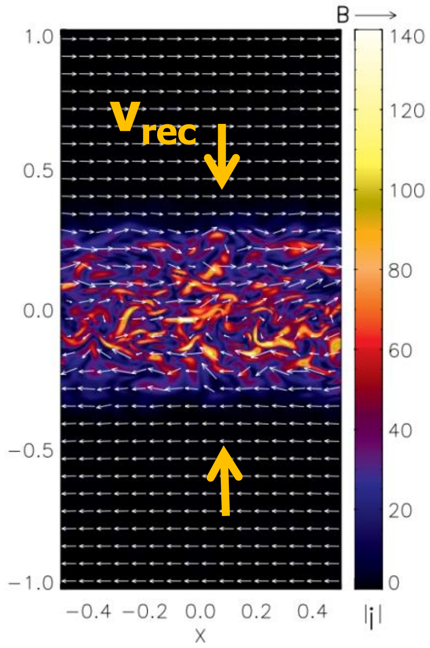






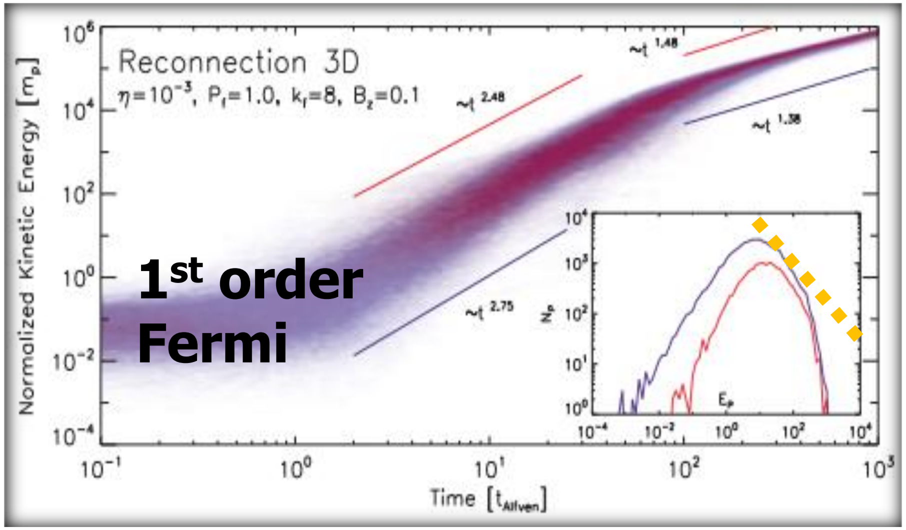
Exponential growth in energy (Kowal, de Gouveia Dal Pino, Lazarian 2011)

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



10,000 test particles

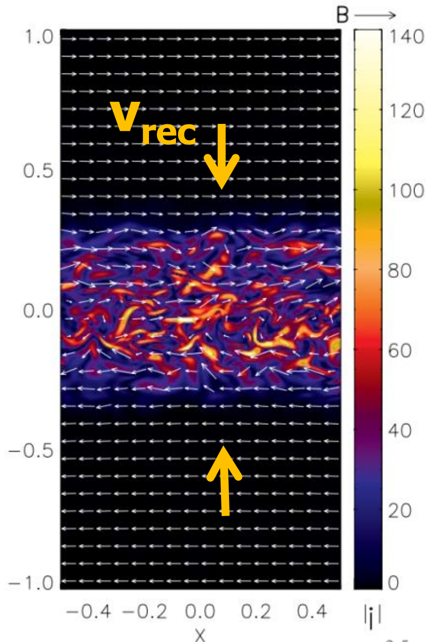
Injected in turbulent current sheet



Kowal, de Gouveia Dal Pino, Lazarian, PRL 2012

del Valle, de Gouveia Dal Pino, Kowal MNRAS 2016

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



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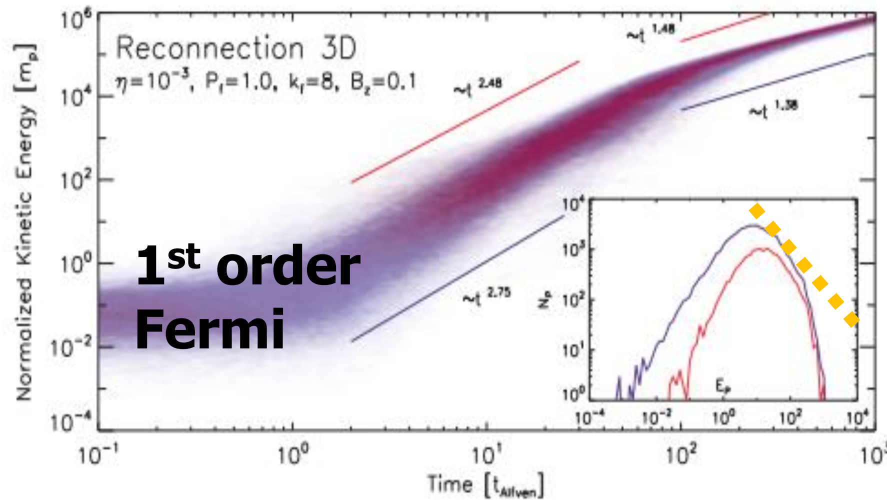
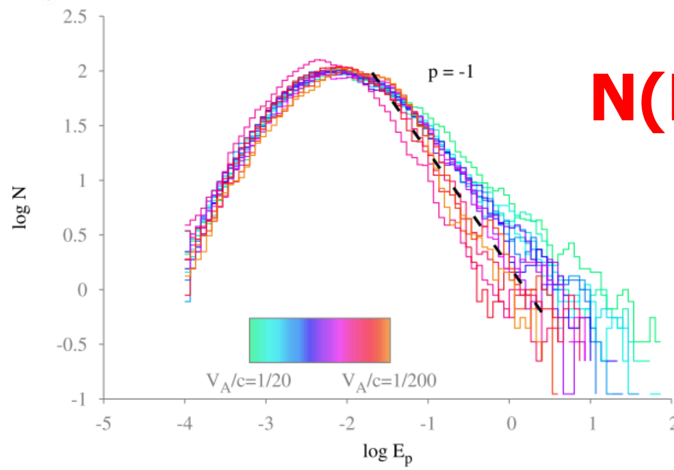


Kowal, de Gouveia Dal Pino, Lazarian, PRL 2012



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

Similar to PIC simulations

del Valle, de Gouveia Dal Pino, Kowal MNRAS 2016

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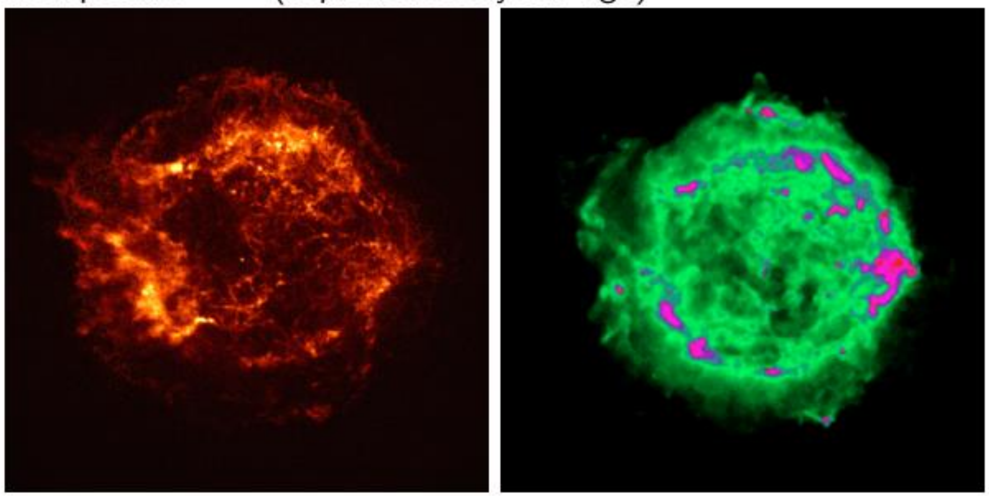
SHOCK ACCELERATION SITES

Supernova Remnants (SNRs):

Cassiopeia A (exploded 300 years ago)



x-ray picture - hot gas | radio picture - synchrotron radiation

- **SN II eject shell – shock front**

  $M = 10\ M_{sol}$
  $v = 100$ km/s
  SN rate = 10^{-2} yr^{-1}

➢ **Power output:**

$$P_{SN} = 5 \times 10^{42}\ \mathrm{J\ yr^{-1}}$$

- **Power to accelerate CRs in the Galaxy:**

  galactic radius: $R \sim 15$ kpc
  thickness: $D \sim 0.2$ kpc
  CRs energy density: $\rho_E = 1$ eV cm^{-3}

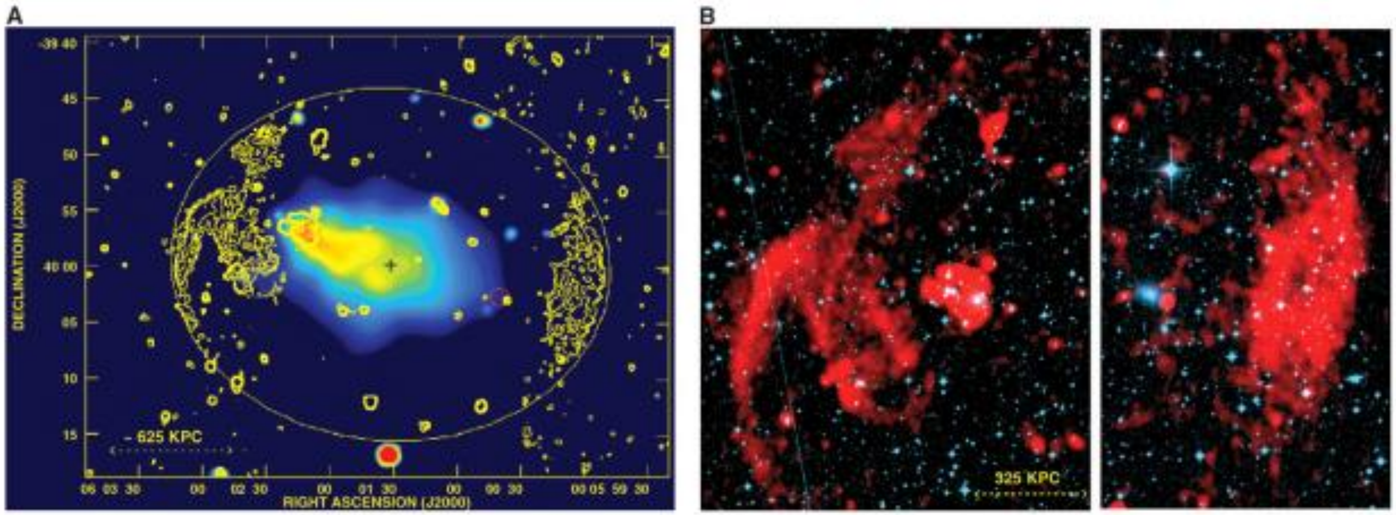
$$P_{CR} = 2 \times 10^{41}\ \mathrm{J\ yr^{-1}}$$

SNRs more than sufficient to account for galactic CRs

SHOCK ACCELERATION SITES

Merging clusters of galaxies:

Galaxy cluster Abell 3376



Bagchi et al. 2006

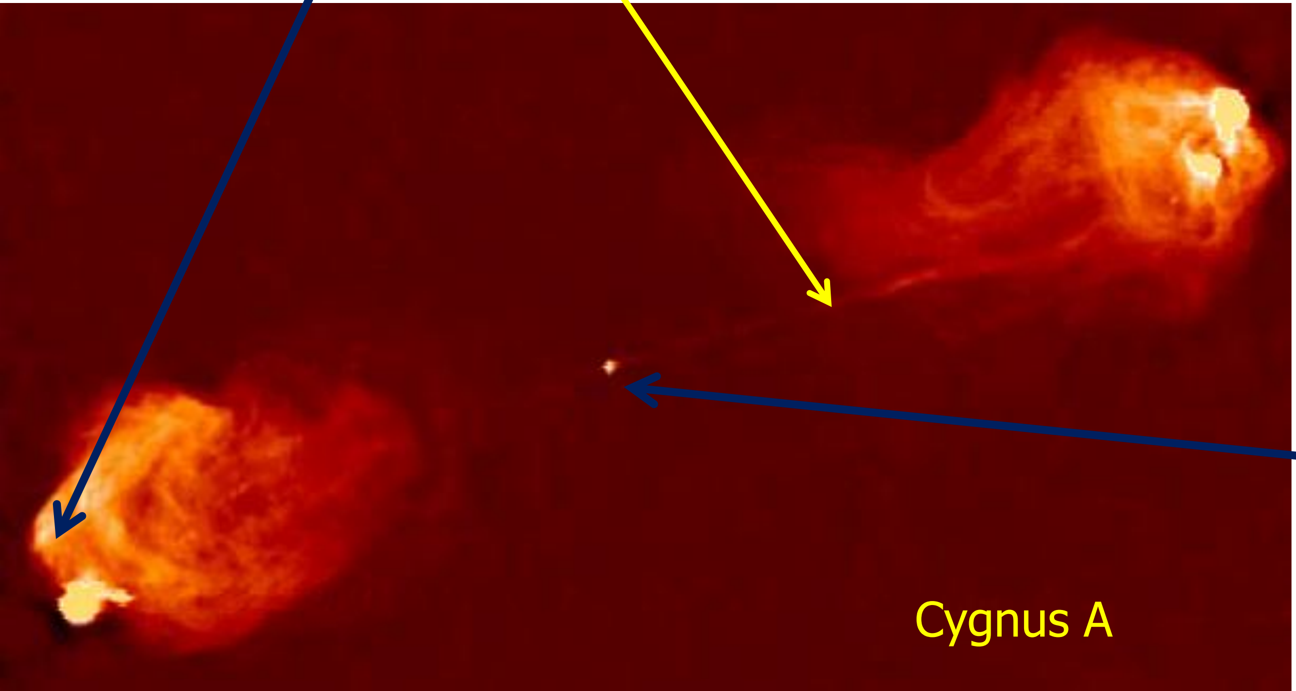
- Mpc-scale supersonic radio-emitting shockwaves
- radio sources (synchrotron radiation..) may be acceleration sites boosting particles up to 10^{19} eV ???
- hints to subcluster merger activities

ACCELERATION SITES

Astrophysical Jets:

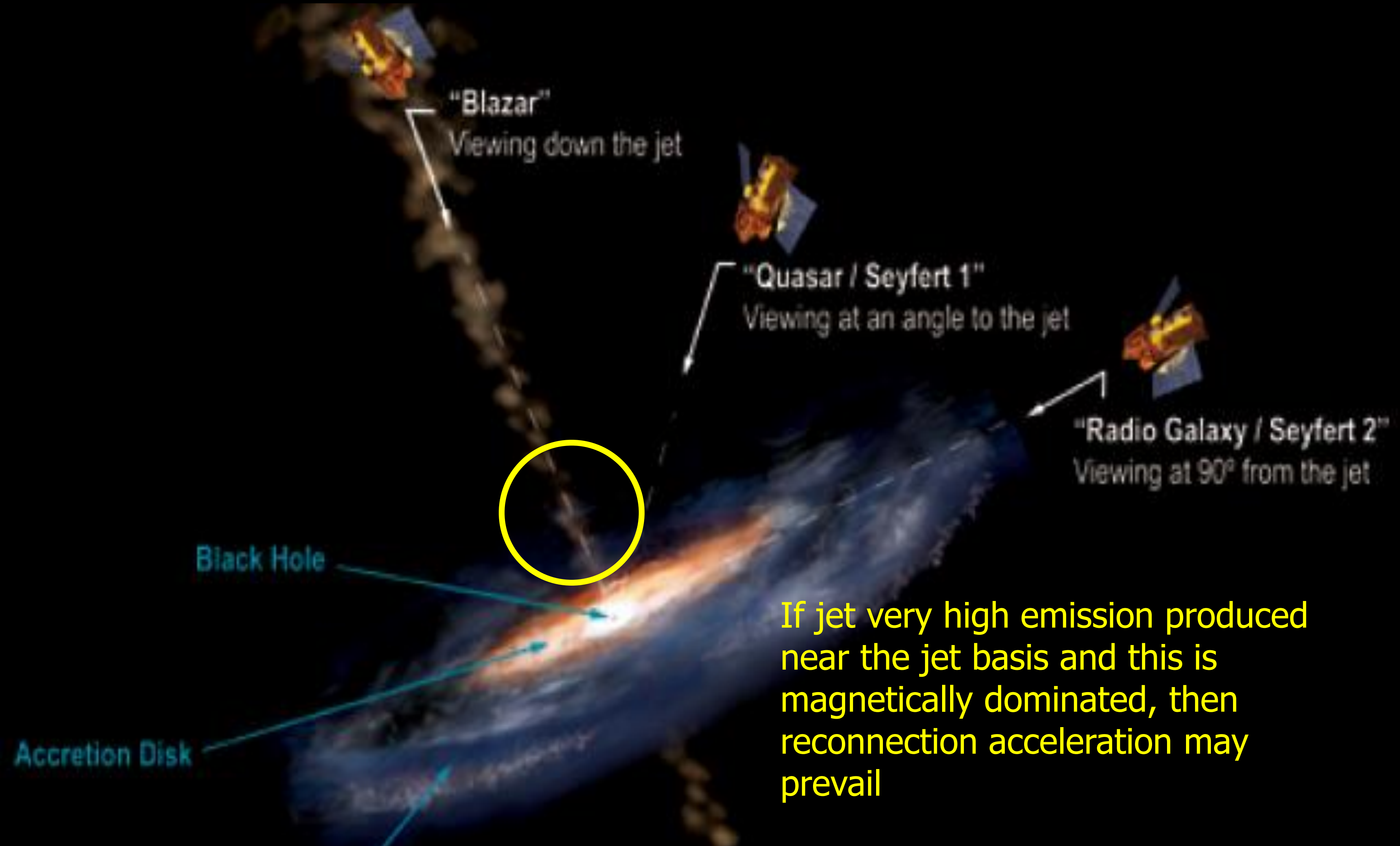
Shock Acceleration:
in internal shocks
and terminal shocks (hot spots)

Synchrotron radiation evidences
Particle acceleration in these shocks



Acceleration by
Magnetic
Reconnection ?

Reconnection Acceleration *can be important in magnetically dominated regions as* Relativistic Jets and surrounds of Black Holes



If jet very high emission produced near the jet basis and this is magnetically dominated, then reconnection acceleration may prevail

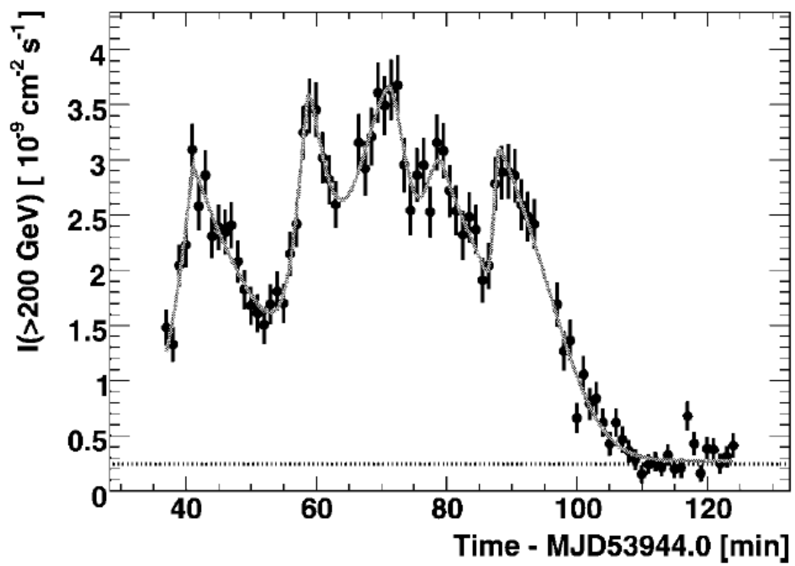
Very-rapid 10^{12}eV Flares in *Blazar Jets* hard to explain with shock acceleration

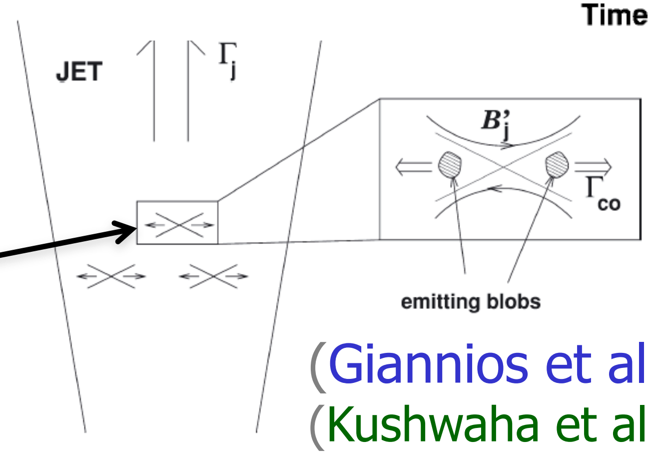
Variation timescale:

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

- TeV emission to avoid pair creation $\Gamma_{em}>50$ (Begelman, Fabian & Rees 2008)
- bulk jet $\Gamma \sim$ 5-10
- **Emitter: compact**
  and/or extremely fast
- **Only model that can explain:**
  Reconnection acceleration

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





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

Press Release – SCIENCE TODAY!!

Multimessenger observations of a
flaring blazar TXS 0506+056
coincident with
high-energy neutrino IceCube-170922A
for the first time !!

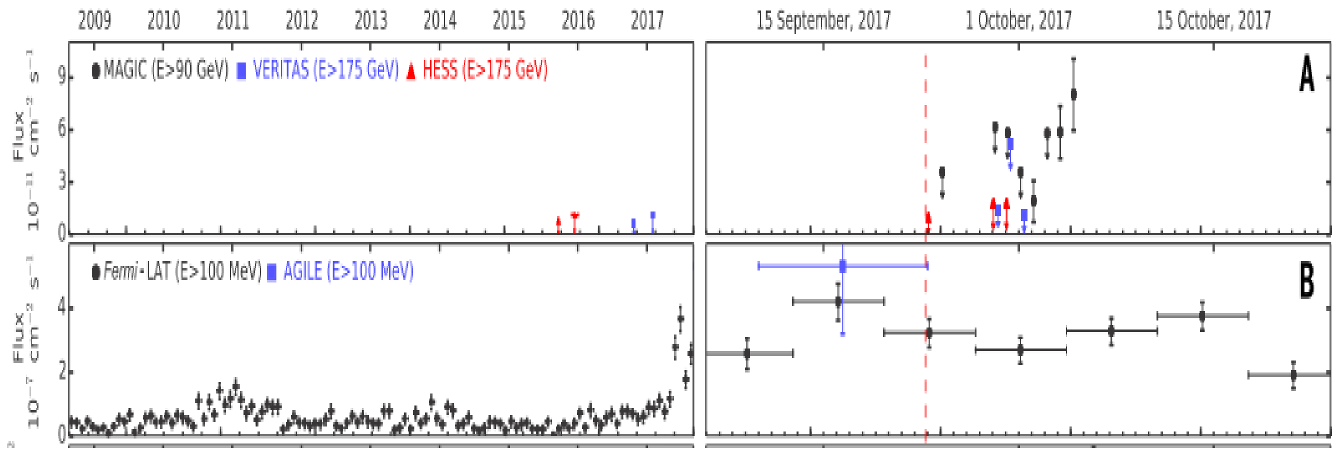
Gamma-ray and neutrino observation in blazar

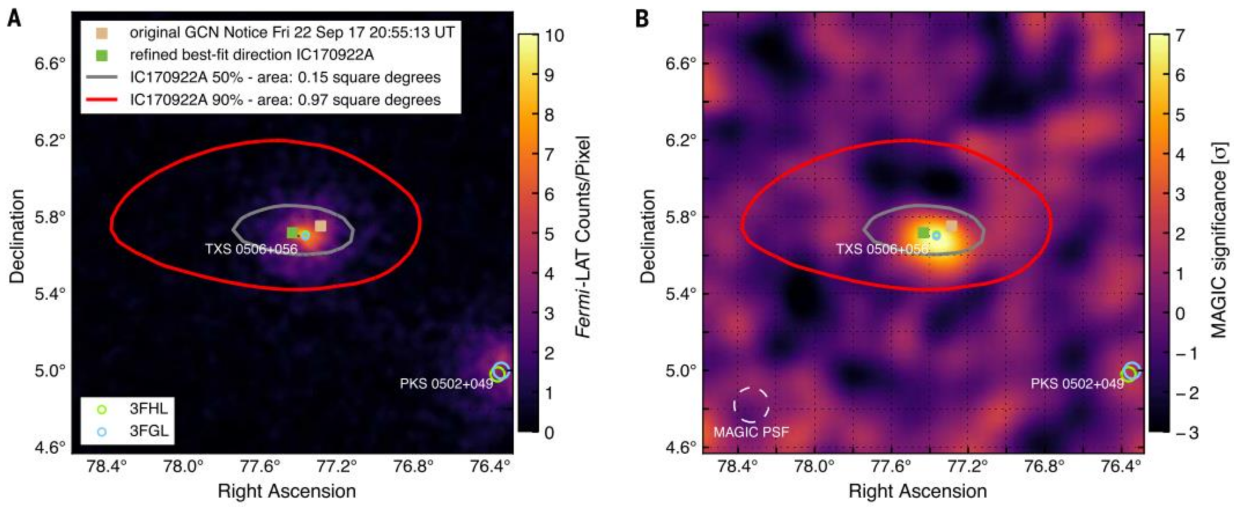
✓ **Neutrinos and gamma-rays are produced by high energy CRs :**

p + photons → π + p

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

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

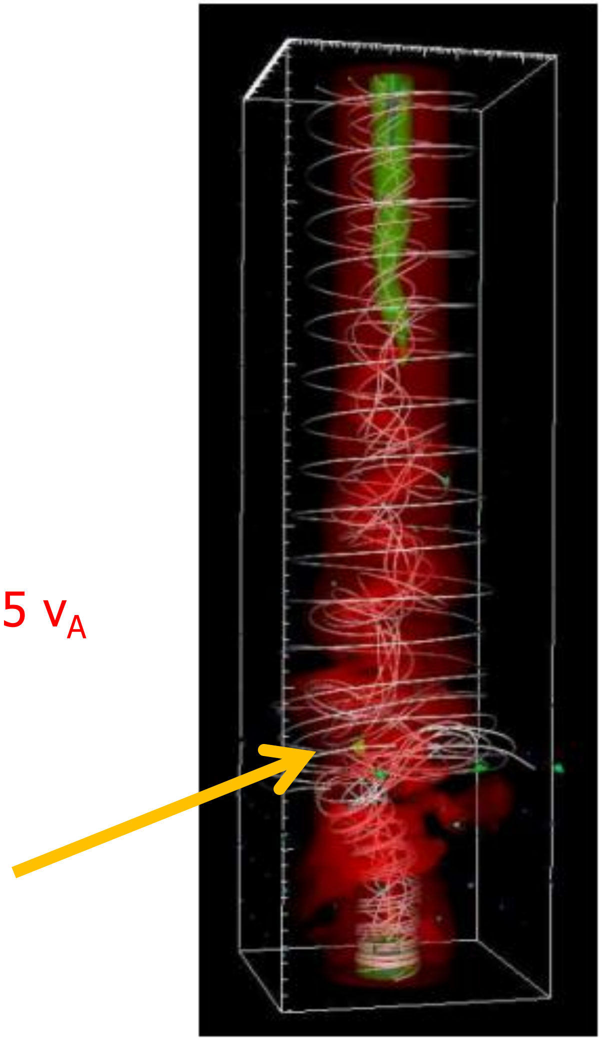


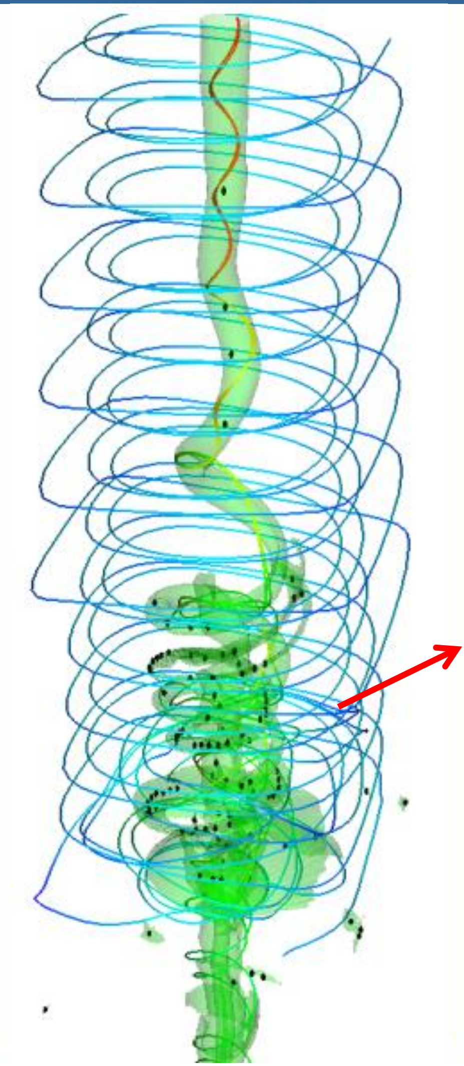


✓ Observed by IceCube, Fermi - LAT, MAGIC, HAWC, H.E.S.S, VLA, etc **(Science, 11 july, 2018)**

MHD Simulations of Reconnection driven in Magnetically Dominated Relativistic Jets

$v_{rec} \sim 0.05\ v_A$



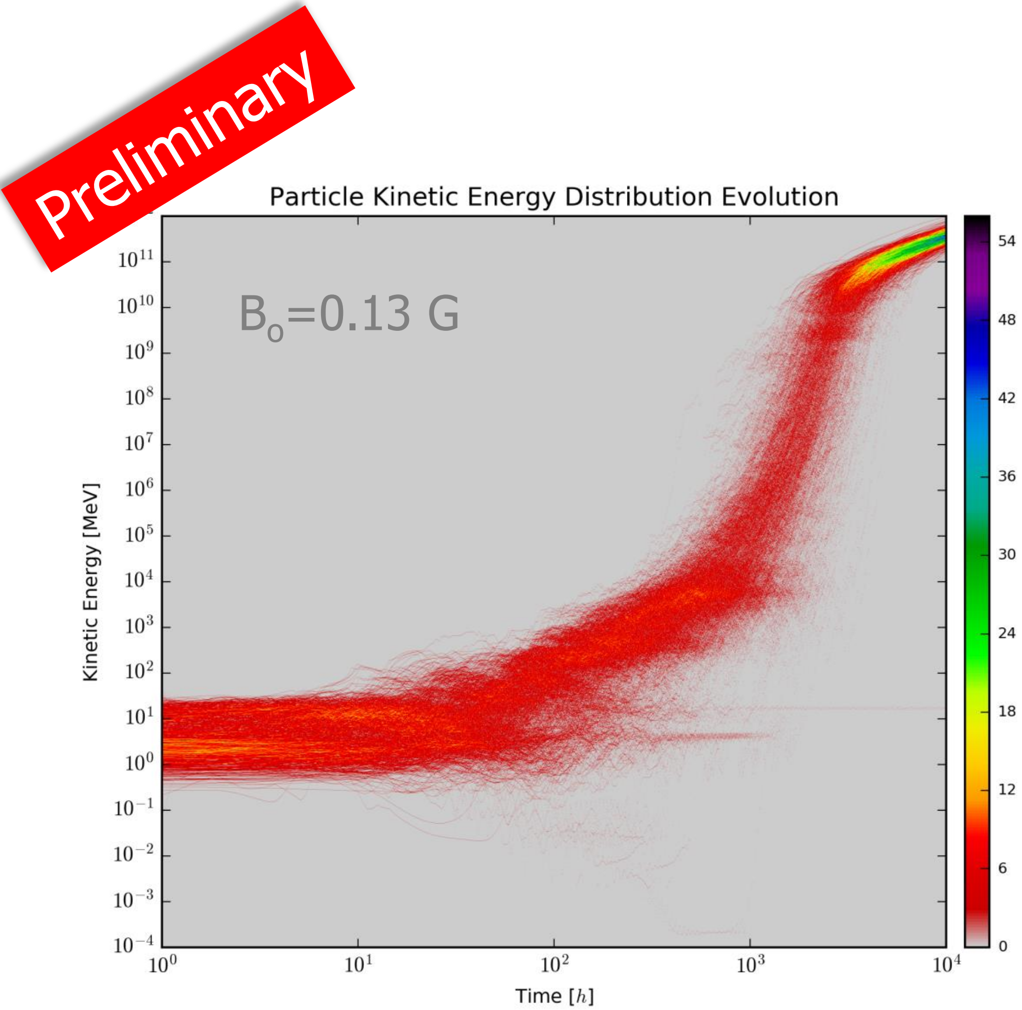


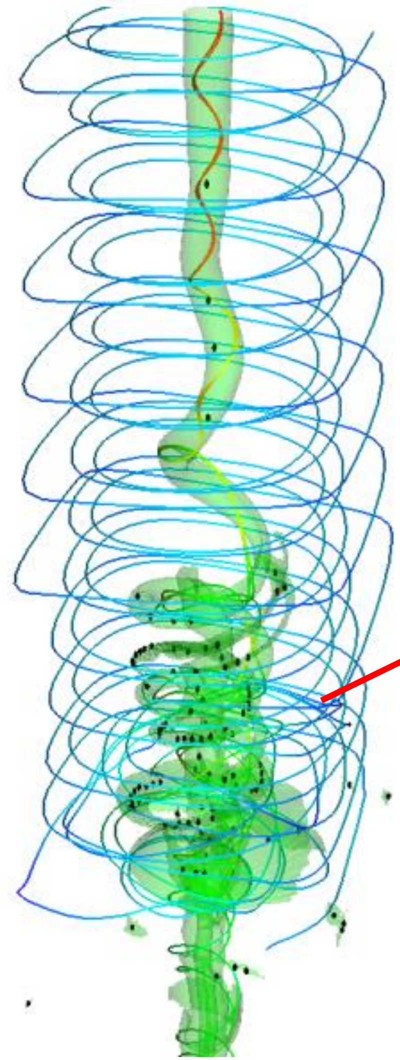
curl B = max

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

Singh, Mizuno, de Gouveia Dal Pino, ApJ 2016

Test Particle simulations of Acceleration by Reconnection in Relativistic Jets





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

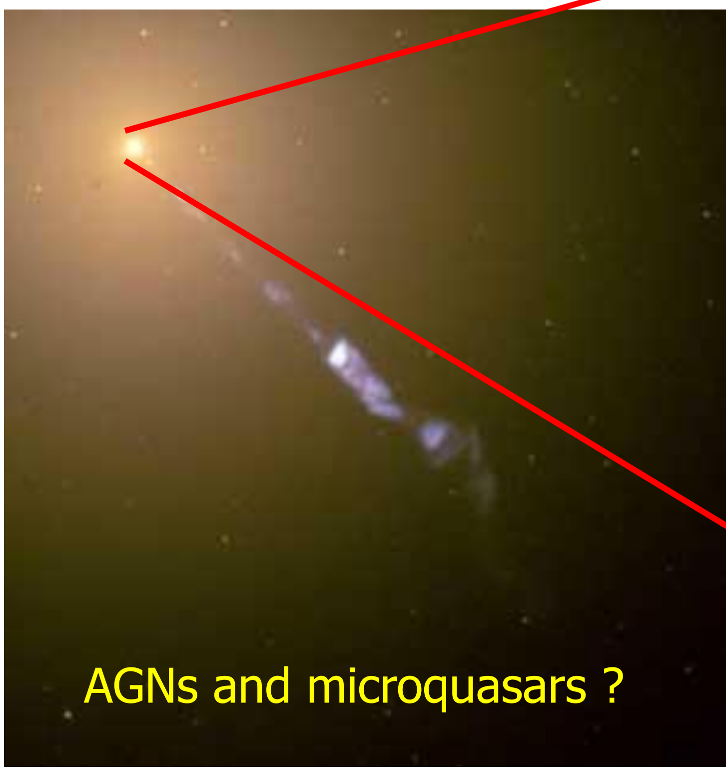
10^4 MeV -> 10^{17} - 10^{19} eV very fast at sub-pc distances (B=0.13 -13 G)

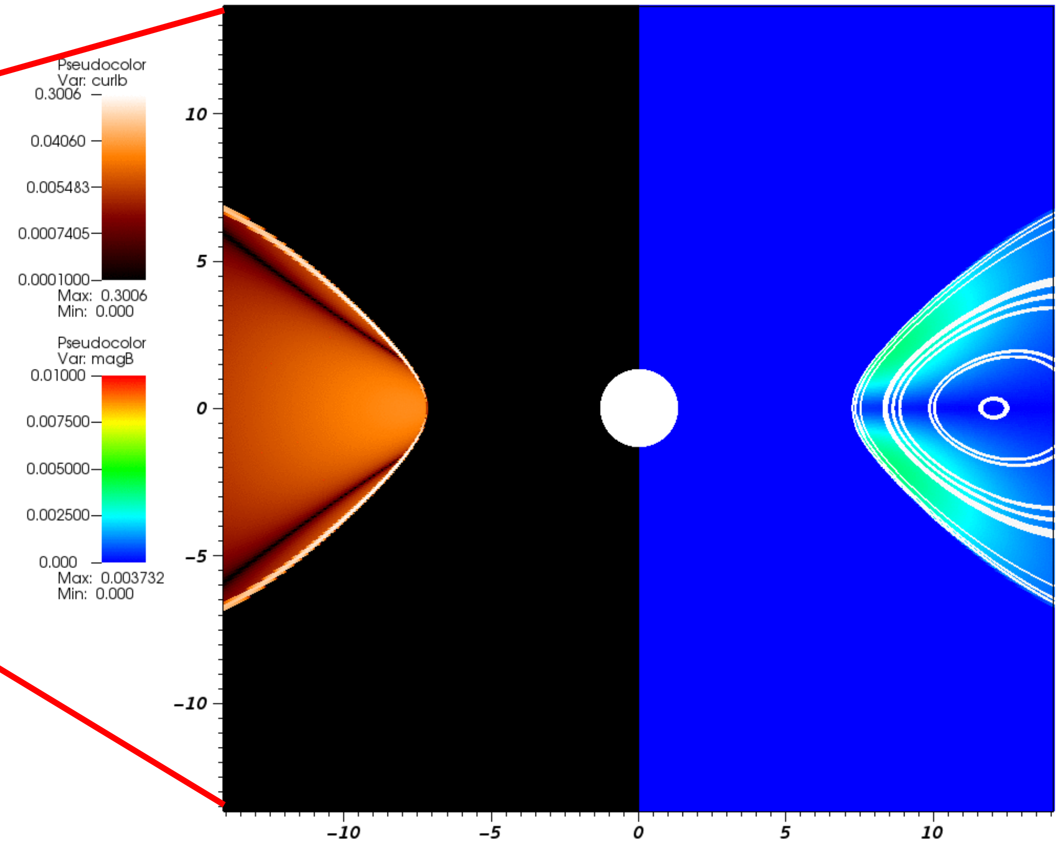
-> may produce Gamma-rays and neutrinos!

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

Evidence of Reconnection in general relativistic MHD Simulations of accretion disk/corona around BHs

Kadowaki, de Gouveia Dal Pino & Stone, 2018b (Athena++ code)





Sites of particle acceleration and non-thermal emission ??

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…and references inside the presentation…