Particle acceleration in relativistic explosive reconnection events

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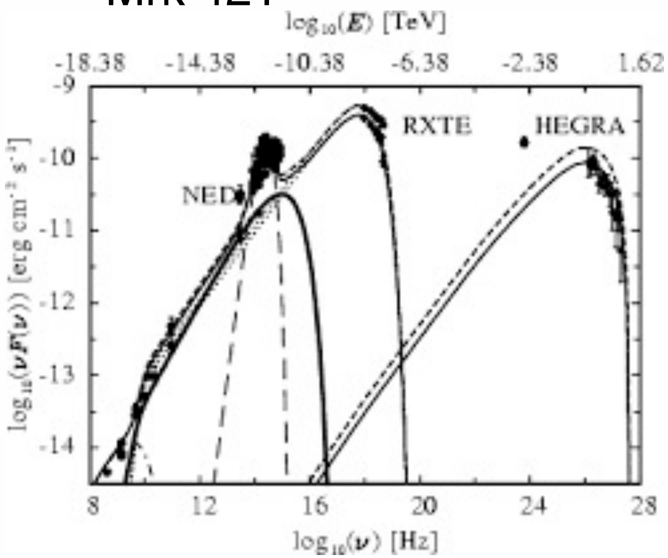
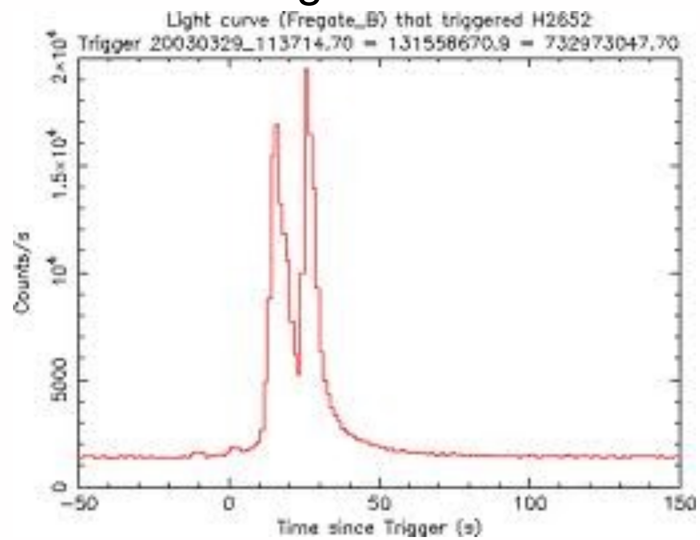
High energy sources: non-thermal particles, **fast variability (= very fast acceleration)**

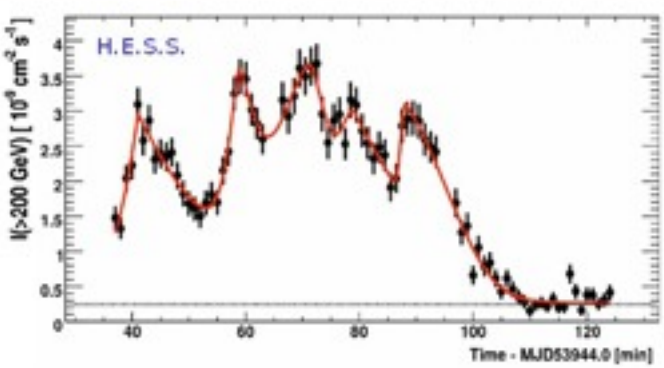
Mrk 421

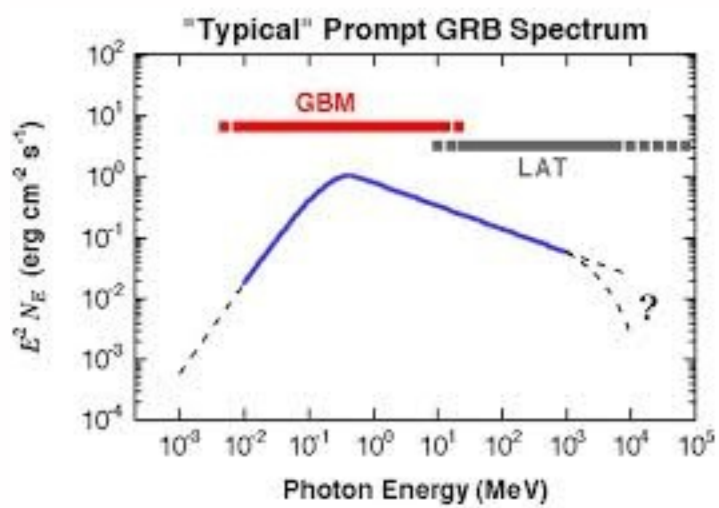


GRB light curve



blazar PKS 2155-304





Requirements on acceleration mechanism

- Power law distribution $$\frac{dn}{d\gamma} \propto \gamma^{-\alpha}$$

α sometimes is smaller than 2!

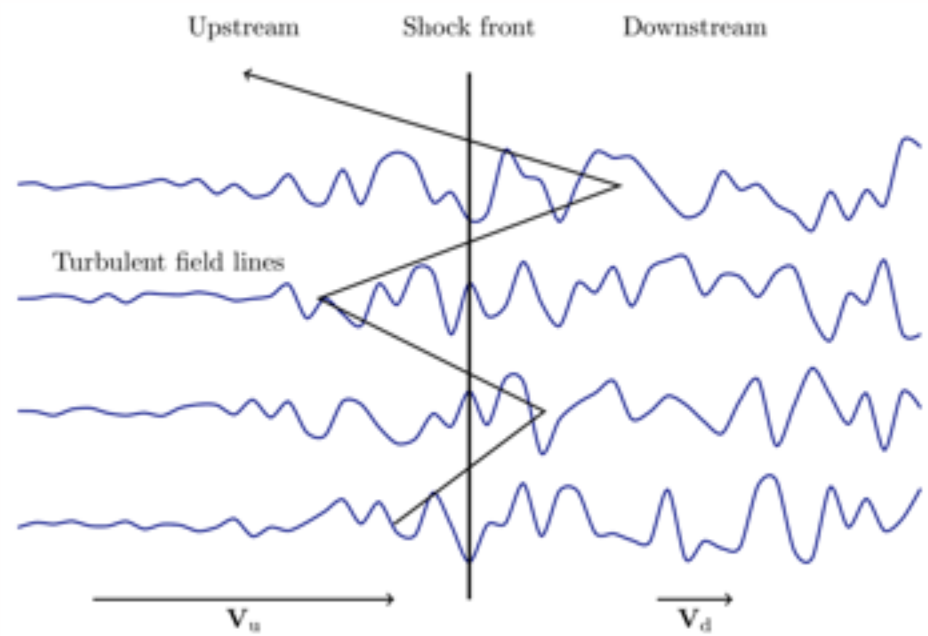
$$\alpha \sim 2 \pm \epsilon$$

- Very large Lorentz factors $\gamma_{\rm max} \sim 10^7 - 10^9$

- **Variability on (shorter!) than light travel times**
- **Very efficient (very fast) acceleration**

Shocks: acceleration by Fermi

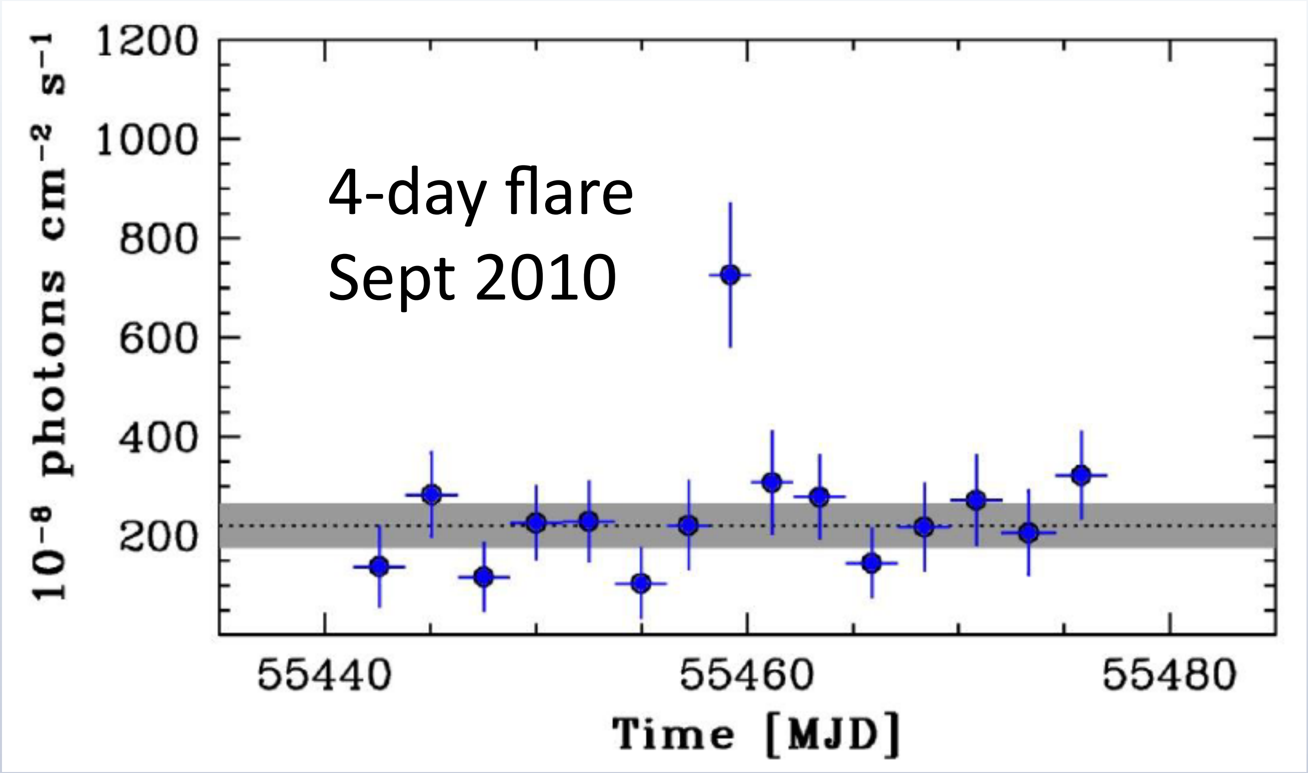
- **Acceleration is slow, on time-scales >> gyration**
- (Drift acc. might be faster - but it does not work)



$$\alpha = 2 + \epsilon$$ - Just from shock compression

Microscopic property from macroscopic parameters!

Crab nebula flares!

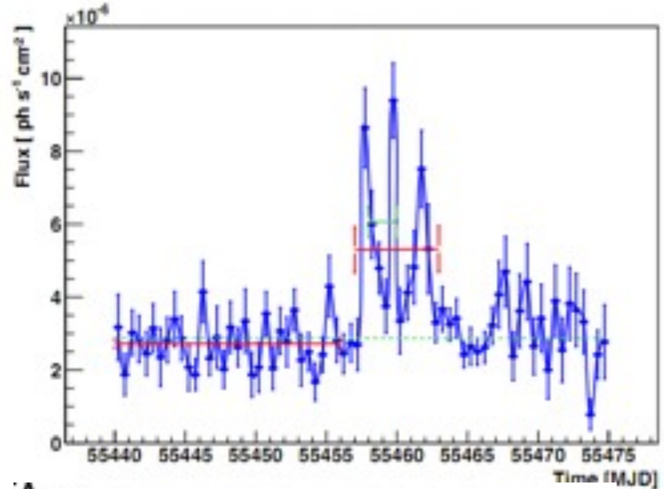


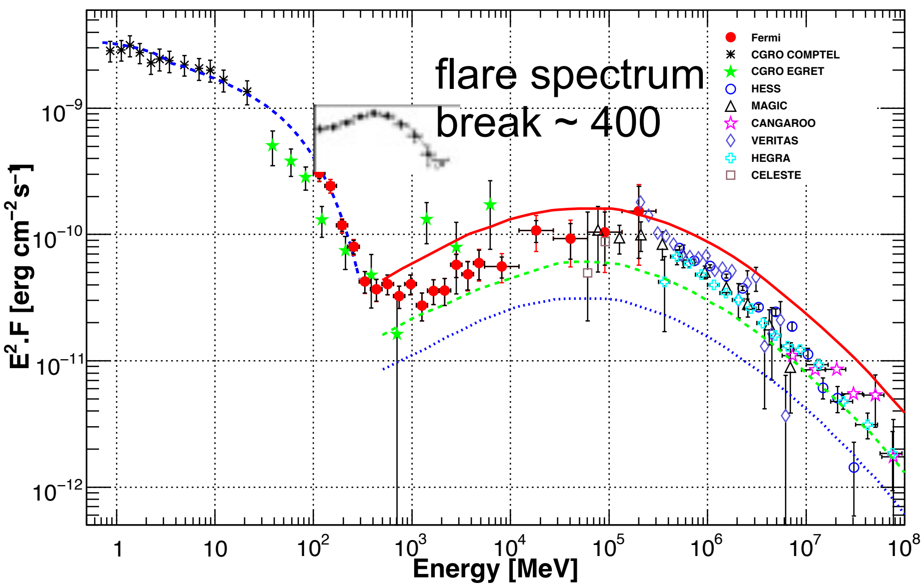
Tavani et al. 2011

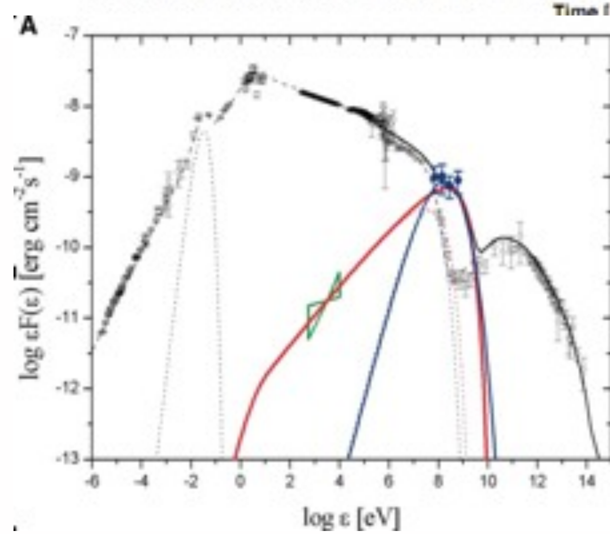
Many aspects of AGNs and GRBs models are based on Crab nebula.
Pulsar = very small AGN

Crab flares

- Few times per year
- Random
- Flux increase by 40
- 100 MeV - 1GeV
- lasts for a day (<< dynamical time)
- periodicity?







Nearly monoenergetic!

Upper limit to synchrotron frequency

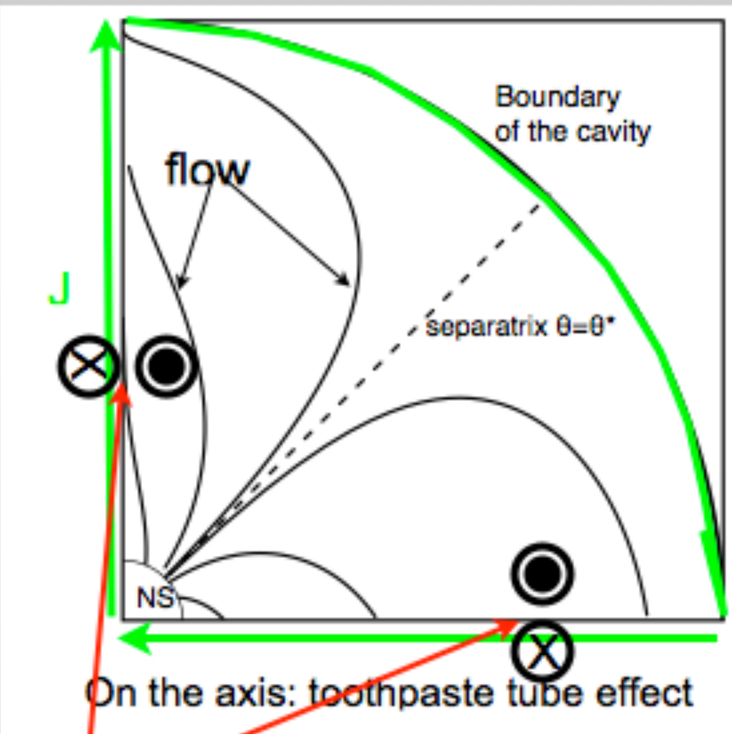
Accelerating E-field < B-field

$$eEc = \eta eBc = \frac{4e^4}{9m^2c^3}B^2\gamma^2$$

$$E_p = \frac{27}{16\pi}\,\eta\,\frac{mhc^3}{e^2} = 236\,\eta\,\mathrm{MeV}.$$

- Same as Fermi acceleration on inverse gyroscale (requires very efficient scattering, stochastic acceleration: eta << 1)
- **Typically eta < 10^{-2} for stochastic shock acceleration: this excludes stochastic acceleration schemes.**

High sigma model of pulsar wind nebulae *(Lyutikov 2010)*

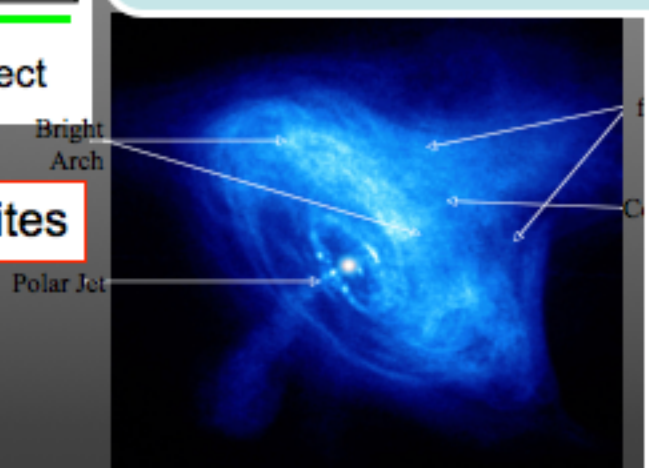


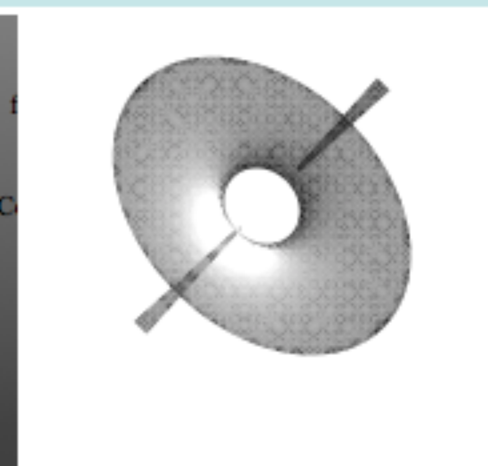
Two possible reconnection sites

- *Lyutikov (2010): 100 MeV is still too much.*
- *Ideal flow in the bulk, dissipation on boundary*
- "We propose that [...] the excessive magnetic flux is destroyed in a reconnection-like process"

High sigma model of PWNe

- No shocks! (Acceleration in reconnection)
- Relativistic bulk motion of emitting plasma



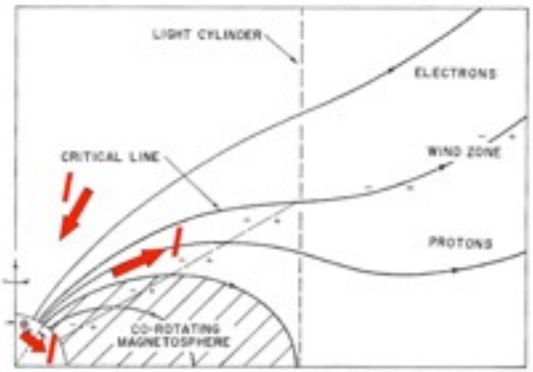


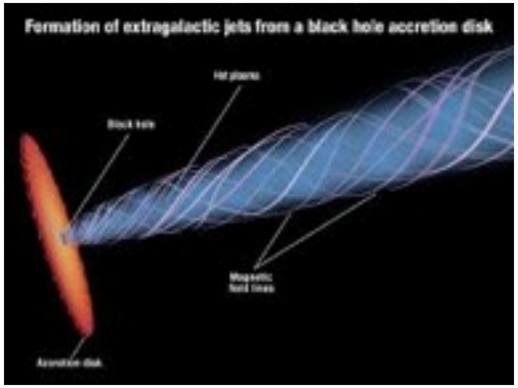
Very demanding conditions on acceleration

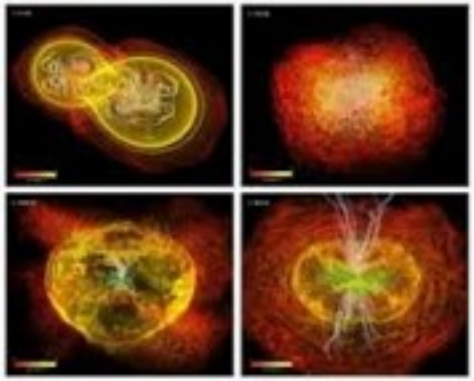
- Acceleration by E ~ B (energy gain & loss on one gyro radius)
- **on macroscopic scales >> skin depth**
  - acceleration size ~ thousands skins
  - acceleration size ~0.1 -1 of the system size (in Crab)
- Few particles are accelerated to radiation-reaction limit - gamma ~ 10^9 for Crab flares (**NOT** all particles are accelerated)
- Slow accumulation of magnetic energy, spontaneously triggered dissipation
- (relativistic bulk motion)

Magnetically-dominated plasmas

- Pulsar winds,AGN jets, GRBs are magnetically driven



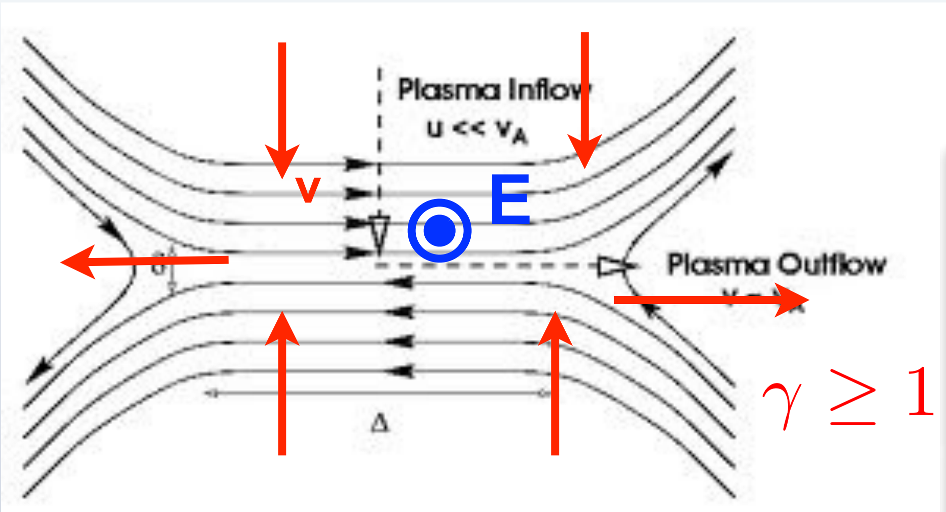




- At launch $\sigma = \frac{B^2}{4\pi\rho c^2} \gg 1$
- Most energy in B-field
- Can be used to accelerate particles directly (without converting into mechanical bulk motion, shocks, field regeneration)
- AGN jets and GRBs may accelerate particles via reconnection events

(Lyutikov & Blackman 2001, Lyutikov 2003, Lyutikov & Blandford 2003)

Relativistic Reconnection



$$\sigma = \frac{B^2}{4\pi \rho c^2} \gg 1$$

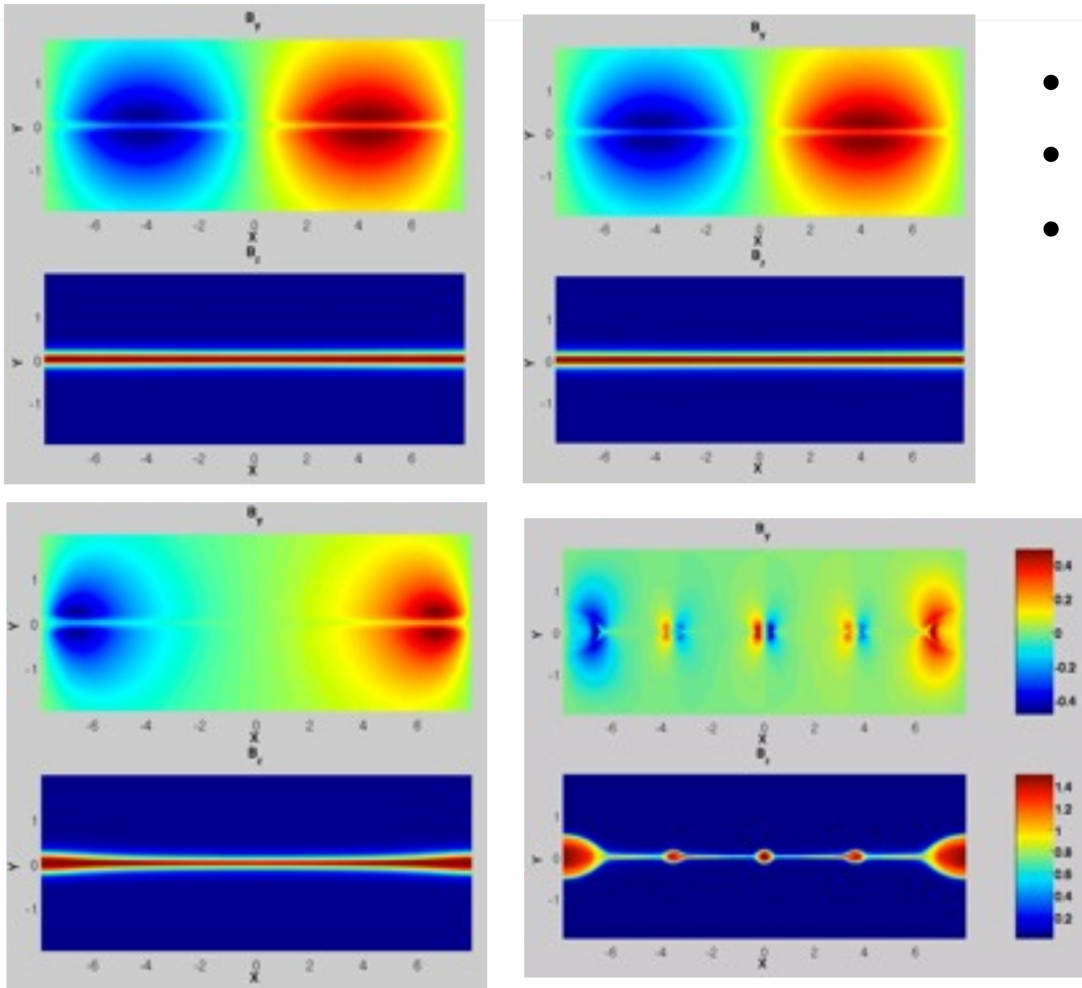
Reconnection in sigma >> 1 plasma: inflow and outflow can be relativistic E ~ (v_{in}/c)B

(Lyutikov&Uzdensky, Lyubarsky)

New plasma physics regime: sigma >> 1 plasma.

- **What are dynamic and dissipative properties of such plasmas? - very different from laboratory and space plasmas.**
- Pulsar winds, AGN & GRB jets and magnetospheres of BHs
- Alfven velocity is highly relativistic $v_A = \sqrt{\frac{\sigma}{1+\sigma}} \to 1$
    - E-field is dynamically important
    - charge density is important

Tearing mode in force-free plasma



Lyutikov 2003
Komissarov +, 2006

- massless resistive plasma
- anisotropic conductivity
- tearing ~ non-relativistic

$$B^2/(4\pi c^2) \sim \rho$$

$$\Gamma \sim \sqrt{\tau_\eta \tau_A}$$

Particle acceleration?...

- Highly magnetized, sigma >> 1, shocks are weak, not likely to be efficient accelerators.
- All the energy in the B-field: accelerate particles directly via **reconnection.**
- Reconnection was a "…" word in high energy astrophysics

Some (most?) particles in high energy sources are accelerated by magnetic reconnection (and not shocks)

How to make a flare

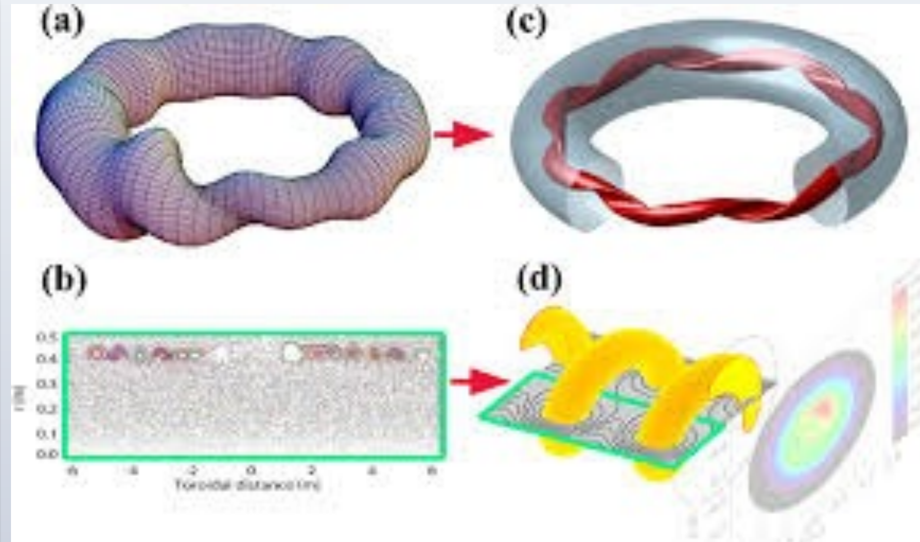
- Store magnetic energy
- Dissipate magnetic energy on light travel time

Accumulation of magnetic energy: Woltjer-Taylor plasma relaxation

- Topology: helicity (twistiness of magnetic field lines)
- Helicity accumulates on largest scales and is better conserved than energy
- Plasma reaches force-free state with

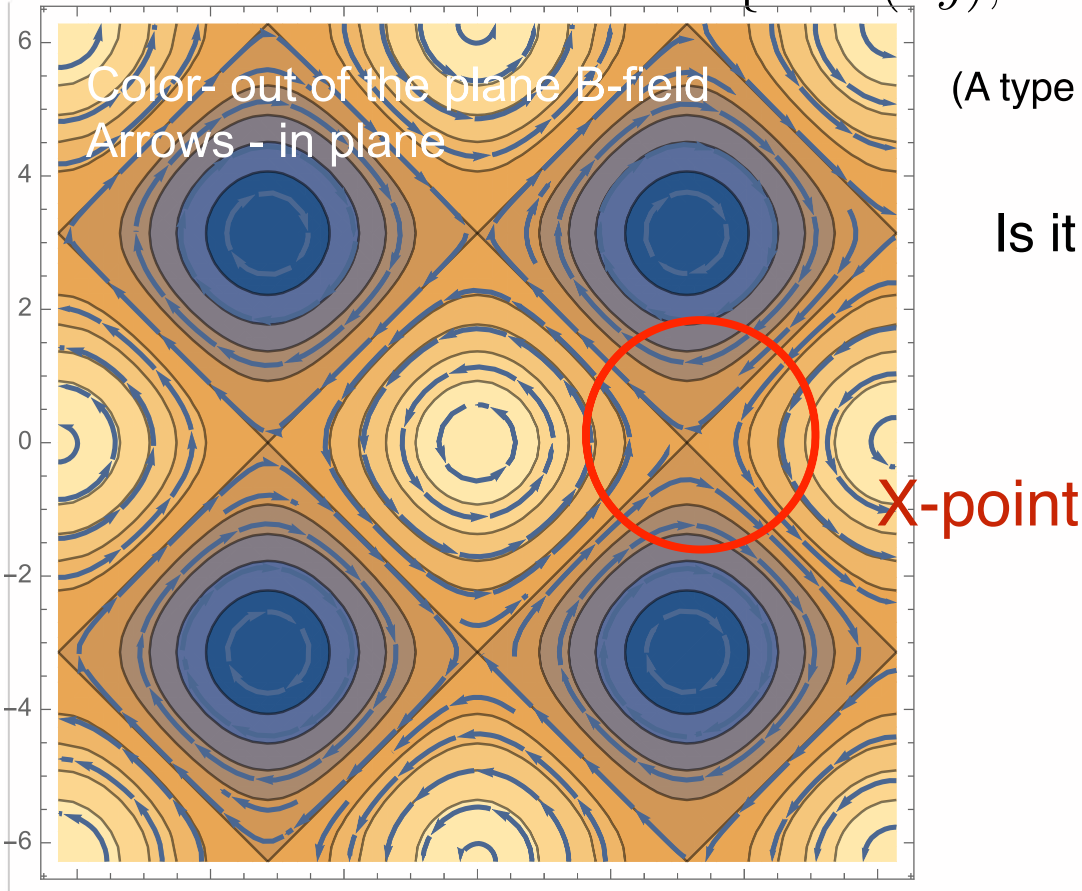
$$\mathbf{J} = \alpha \mathbf{B}$$
$$\alpha - \text{constant}$$

- Plasma currents tend to form 2D structures



2D force-free state with $\alpha - \text{constant}$

$$\mathbf{B} = \{-\sin(\alpha y), \sin(\alpha x), \cos(\alpha x) + \cos(\alpha y)\} B_0$$



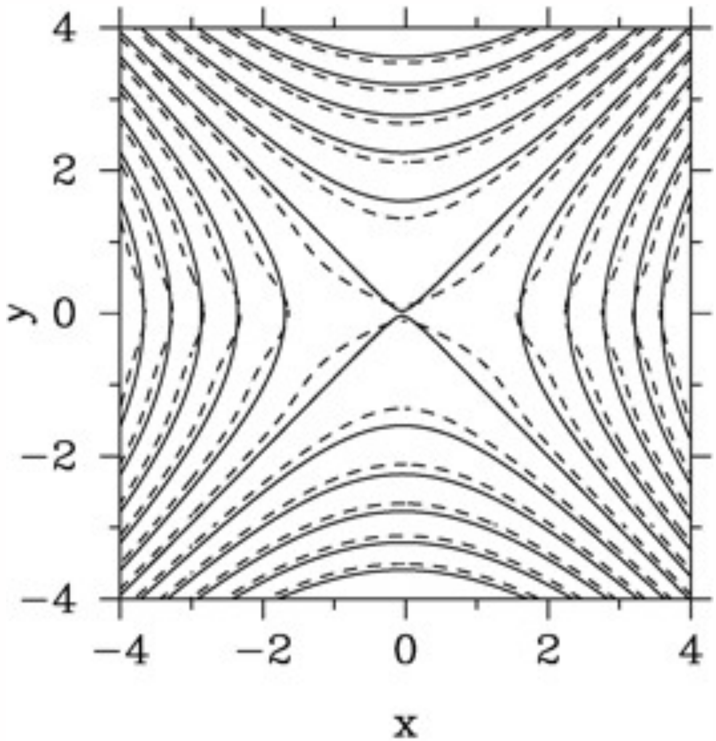
(A type of the “ABC” flow)

Is it stable?

- Detailed investigation of stability using analytical, relativistic fluid-type and PIC simulations (Lyutikov, Komissarov & Sironi, in prep.)

1.The X-point

- Unstressed X-point is stable to **short** wave length perturbation

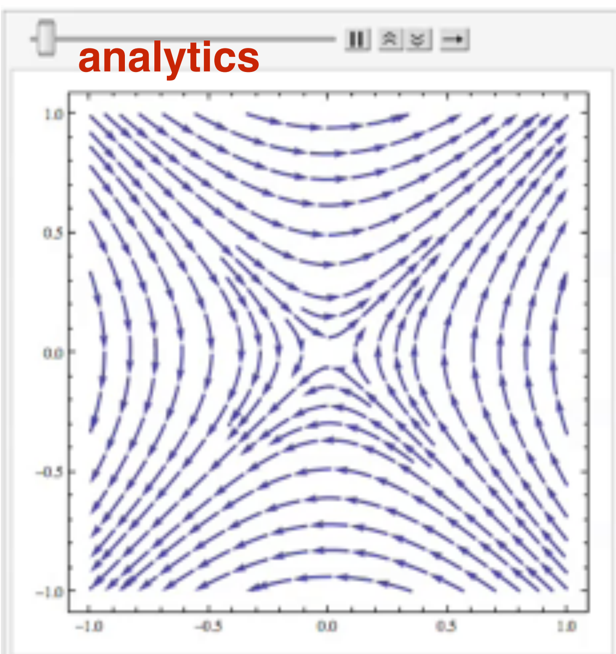


Collapse of stressed magnetic X-point in force-free plasma (a la Syrovatsky)

Dynamics force-free:

- infinitely magnetized plasma:
- currents & charges ensure **EB** =0, no particle inertia

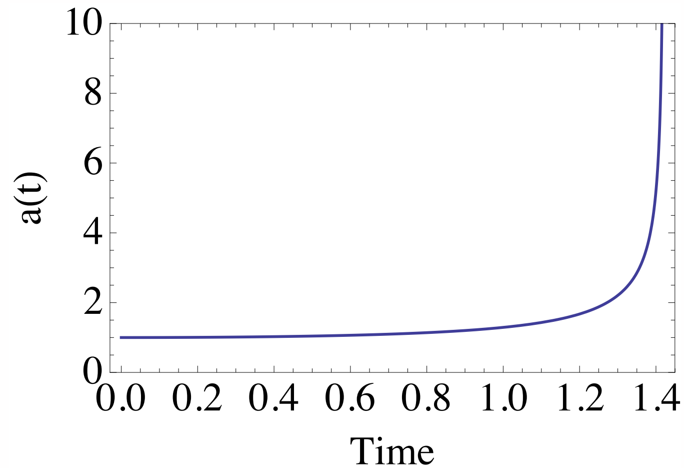
$$\sigma = \frac{B^2}{4\pi\rho c^2} \gg 1$$



$$\mathbf{B} = \left\{ \frac{a^2}{\lambda^2}\frac{y}{L}B_\perp, \frac{x}{La^2}B_\perp, B_0 \right\}$$

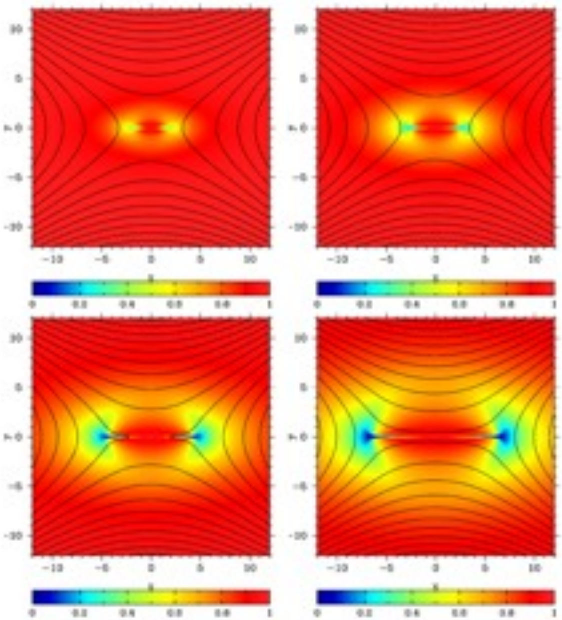
$$\mathbf{E} = \left\{ \frac{yB_0}{c}, \frac{xB_0}{c}, -\frac{x^2\lambda^2 + y^2 a^4}{cL\lambda^2 a^2} \right\} \partial_t \ln a$$

$$\partial_t^2 \ln a = \mathcal{A}\left(\frac{a^4 - \lambda^2}{\lambda^4}\right), \ \mathcal{A} = \frac{c^2}{L^2}\frac{B_\perp^2}{B_0^2}$$



- **explosive** dynamics on Alfven time
- slow initial evolution
- Starting with smooth conditions
- Finite time singularity

- Relativistic force-free simulations of X-point collapse:

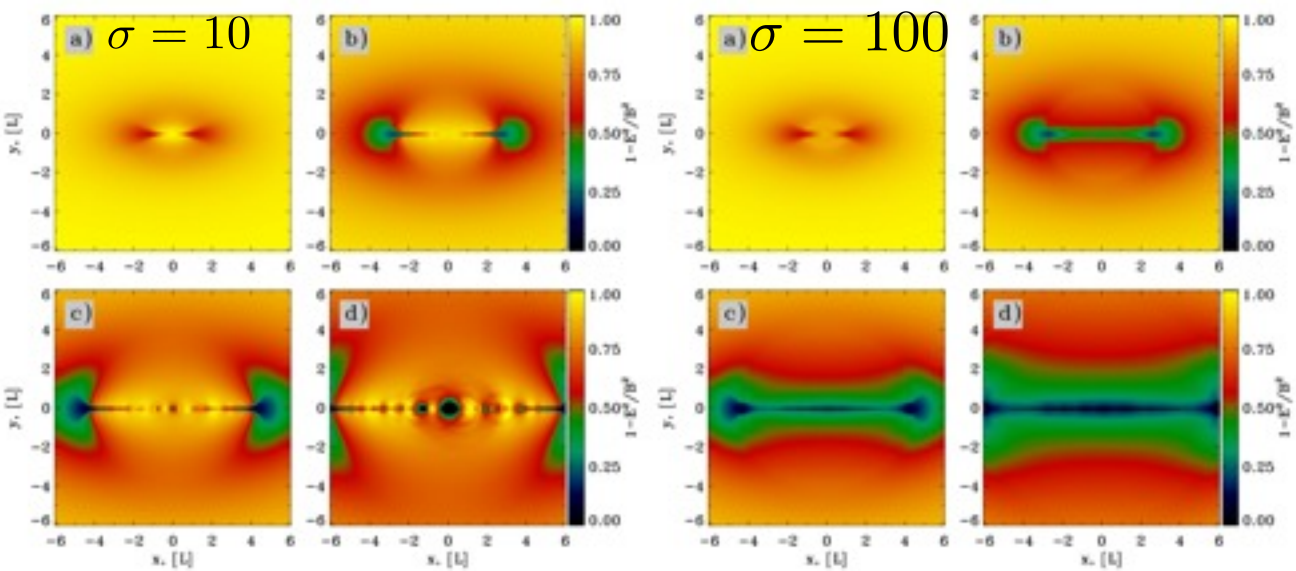


The color-coded image shows the value of $B^2 - E^2$, contours – the magnetic field lines.

(Komissarov)

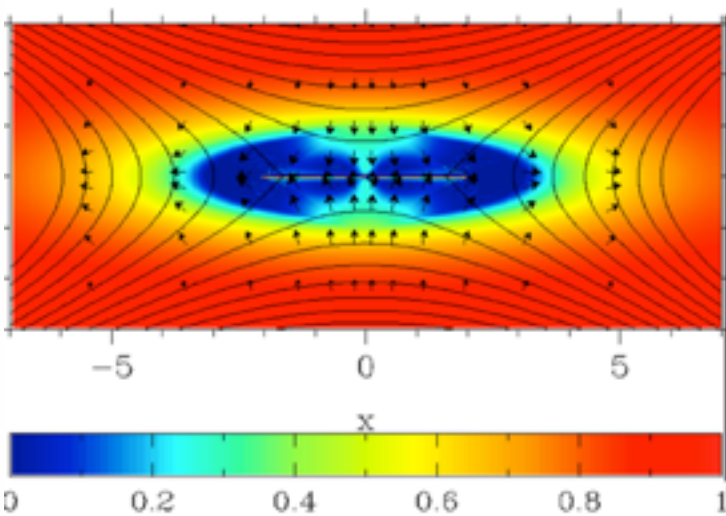
Large areas of E>B appear

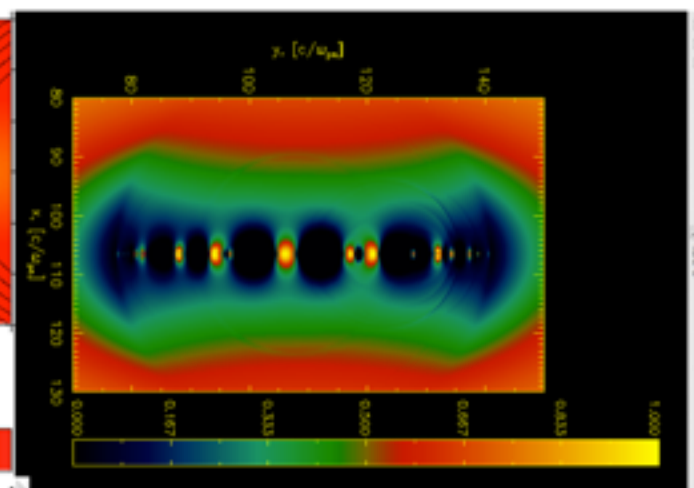
PICs



(Sironi)

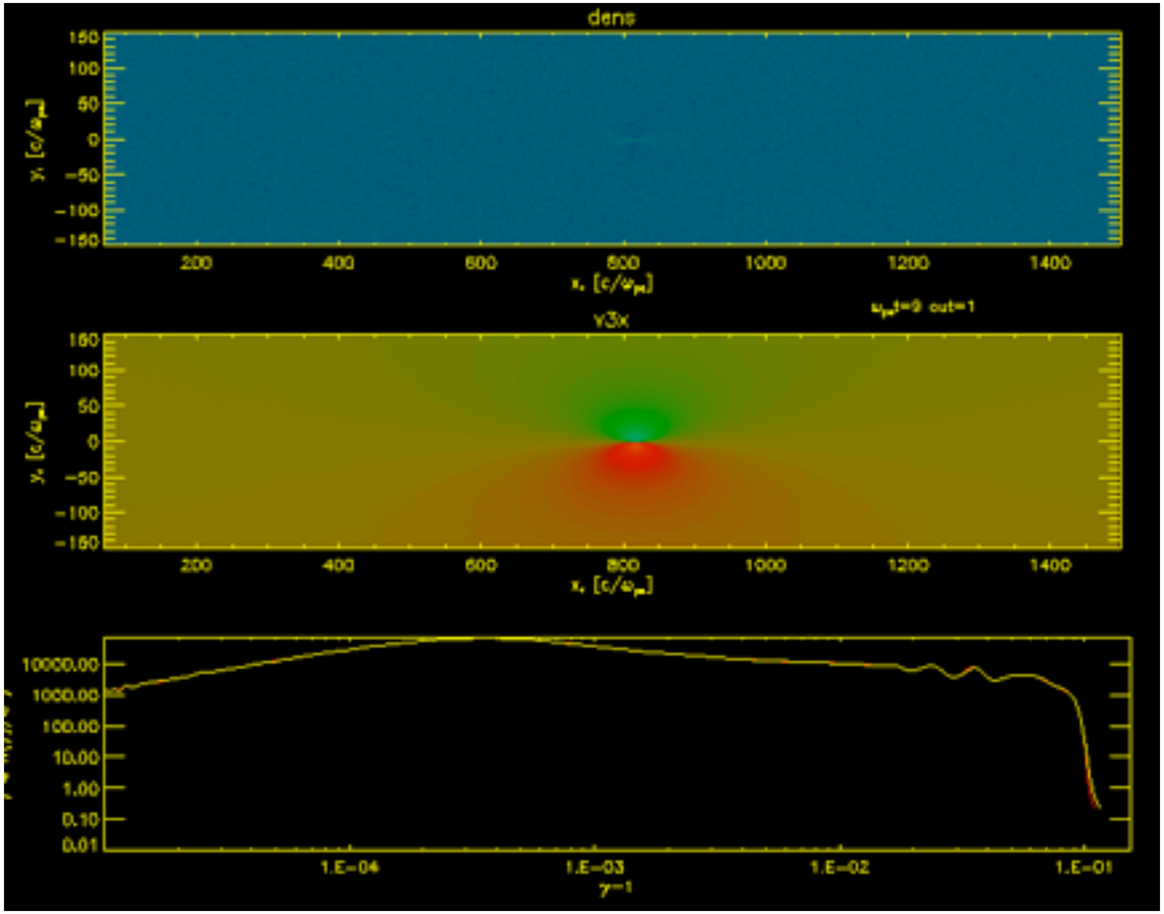
High-sigma PICs and fluid simulations agree





Large region of E~B, growing with time
High sigma PICs look similar to force-free

Can produce power-laws



PIC simulations by Sironi

Acceleration in X-point collapse

- Highly efficient acceleration by E ~ B
- Acceleration starts abruptly, when reaching **charge starvation.**
  - During collapse current density grows

$$J_z \approx \frac{c}{4\pi}\frac{B_\perp}{L}a(t)^2$$

  - But J< 2 n e c - not enough particles to carry the current

$$curl\mathbf{B} = \frac{4\pi}{c}\mathbf{J} + \partial_t \mathbf{E}/c$$

  - E-field grows
  - Condition for charge starvation: $a(t) > \sqrt{\frac{L}{\delta}\frac{1}{\sigma^{1/4}}}$ (not too demanding for Crab)

Acceleration in X-point collapse

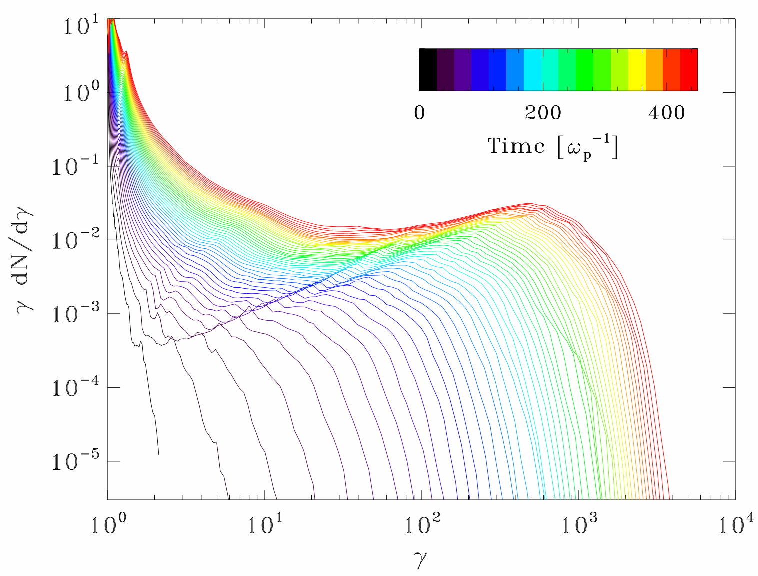
- Very hard spectrum: alpha =-1.
- All the energy is in the high energy particles
- All particles are accelerated (the acceleration region grows with the speed of light)

$$\sigma = \frac{B^2}{4\pi\rho c^2}$$

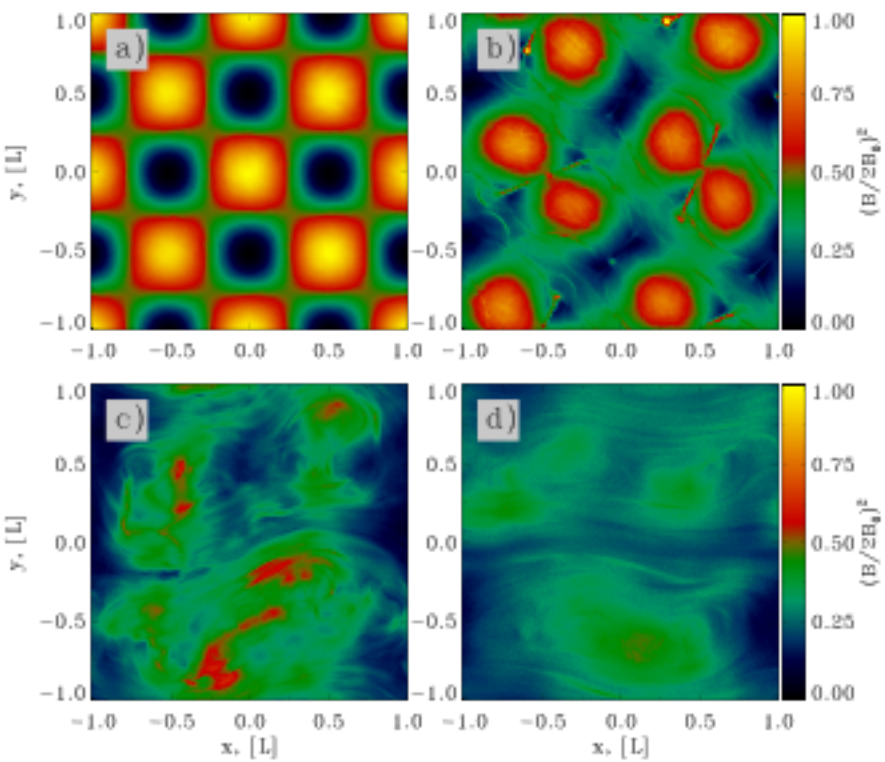
$$\gamma_{max} \leq \sigma$$

- But we need gamma ~ 10^9

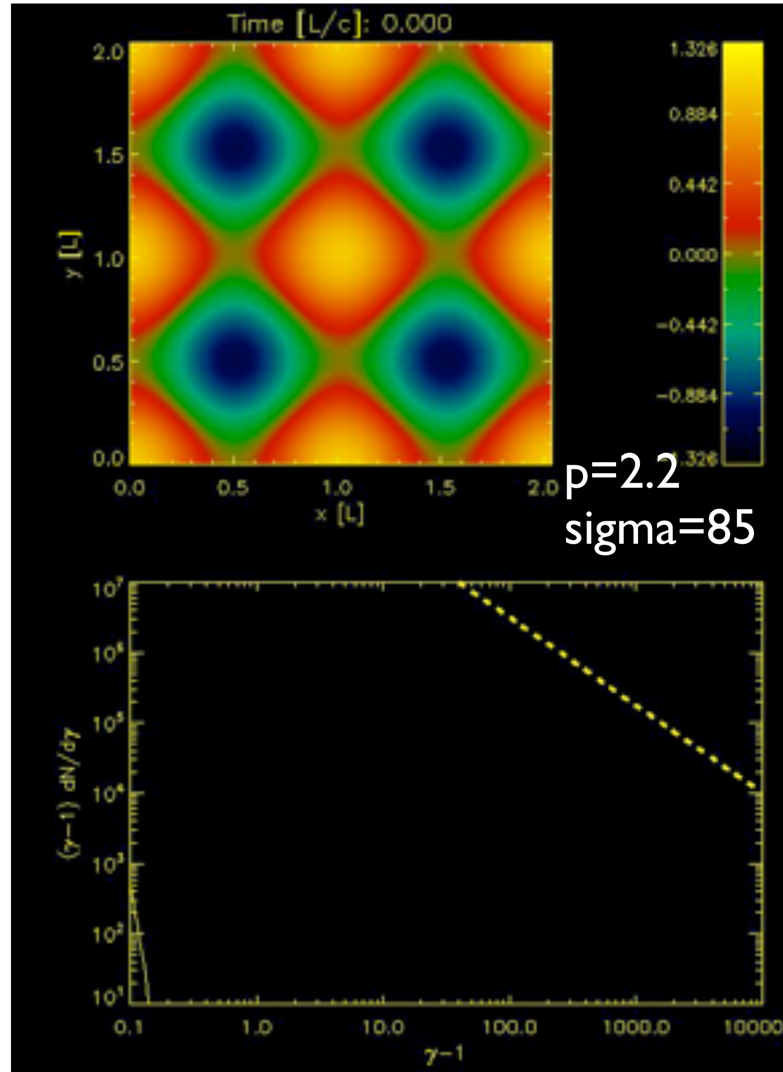
NO



2.Collapse of a system of magnetic islands



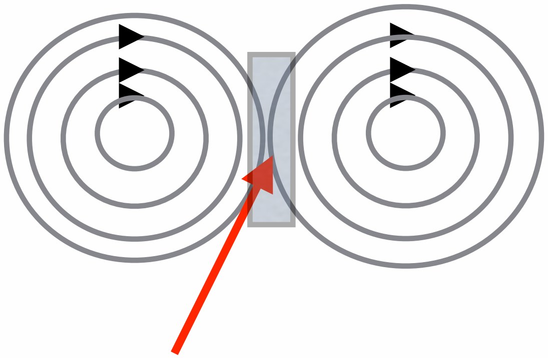
The first panel is at time=5.625, second at 11.25 , third at 16.875 and fourth at 22.5



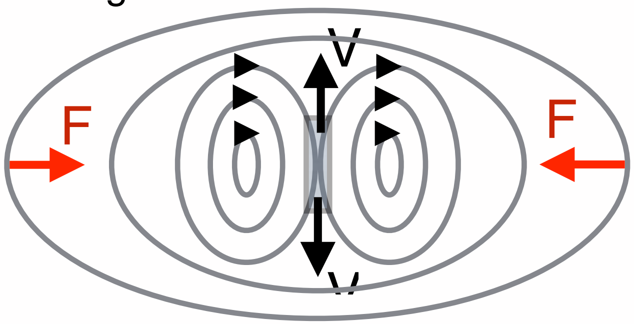
Quasi-stable configuration that destroys itself on light travel times!

- A set of magnetic islands is quasi-stable: Initially it survives for many dynamical times = energy is slow accumulated
- There is a period of violent instability
  - X-point collapse
  - Merger of magnetic islands
- Large fraction of magnetic energy is dissipated

Island merger: forced reconnection

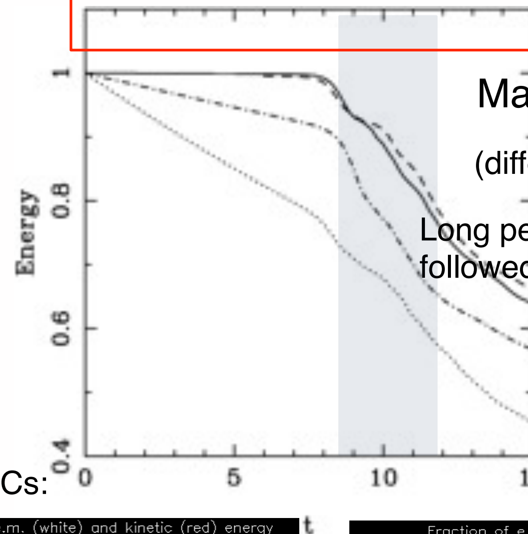


Tearing-like reconnection -> common envelope



Forced reconnection

50% of magnetic energy in a **whole** volume dissipated on light travel time

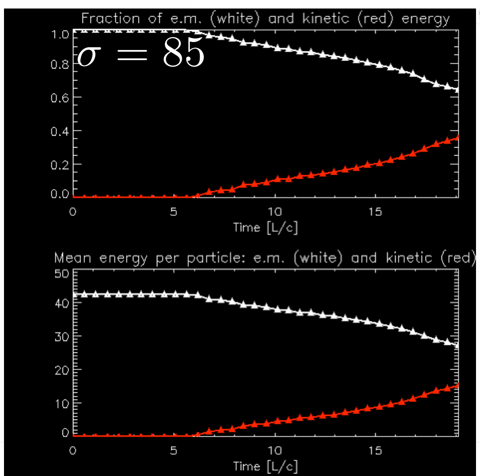


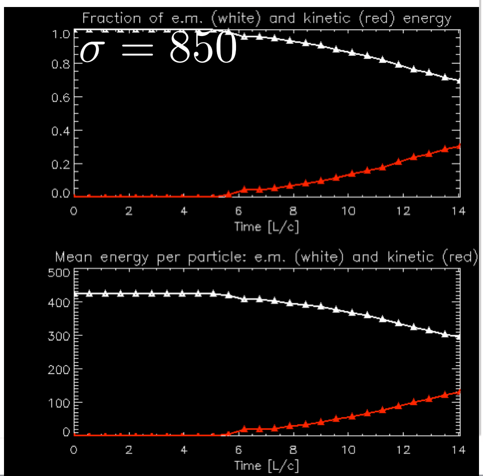
Magnetic energy

(different resistivities)

Long period of slow growth followed by explosive merger

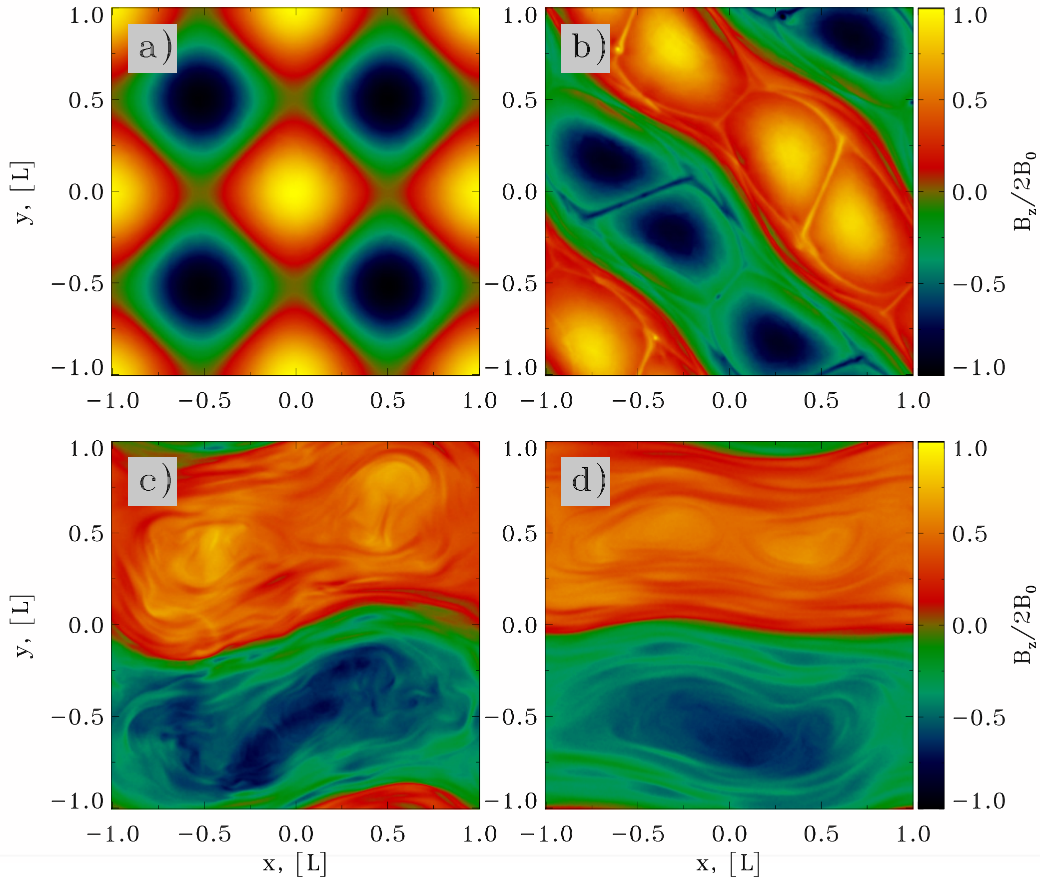
PICs:





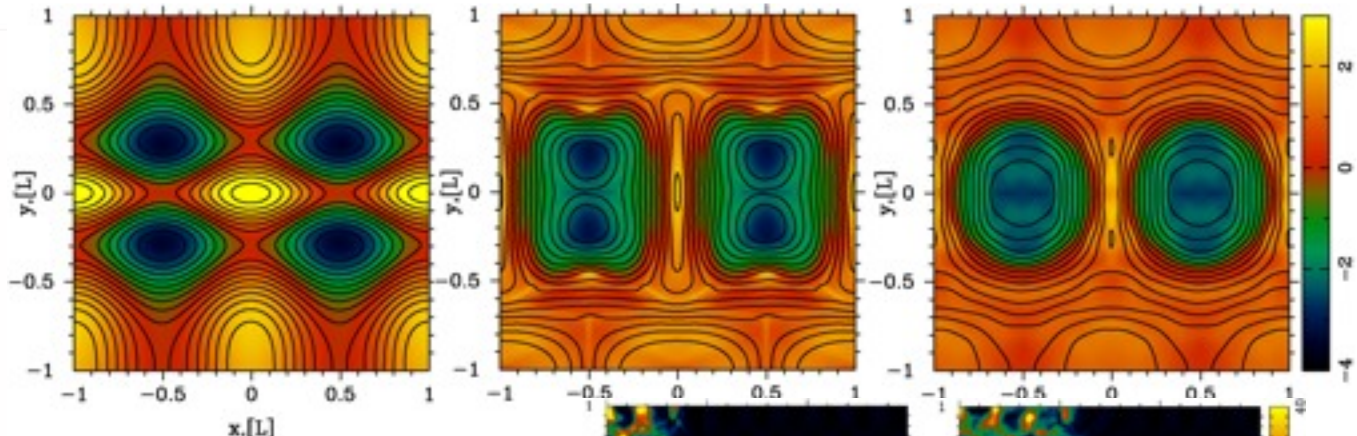
Inverse cascade? Probably not

- Merger of islands into larger ones, up to box size
- Large fraction of magnetic energy (~50%) is dissipated in each step

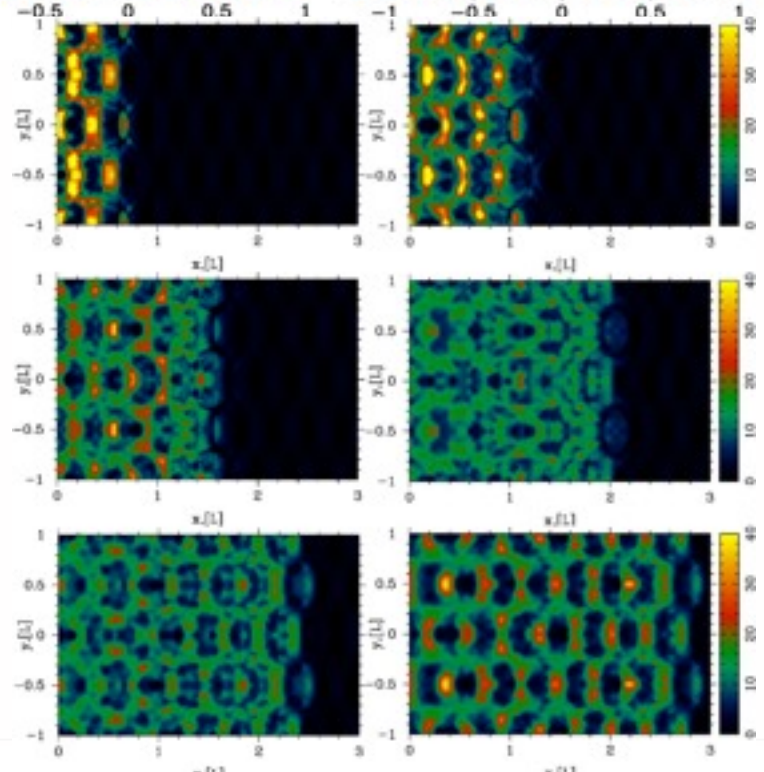


2.b island merger triggered by external perturbation

Stressed magnetic islands:

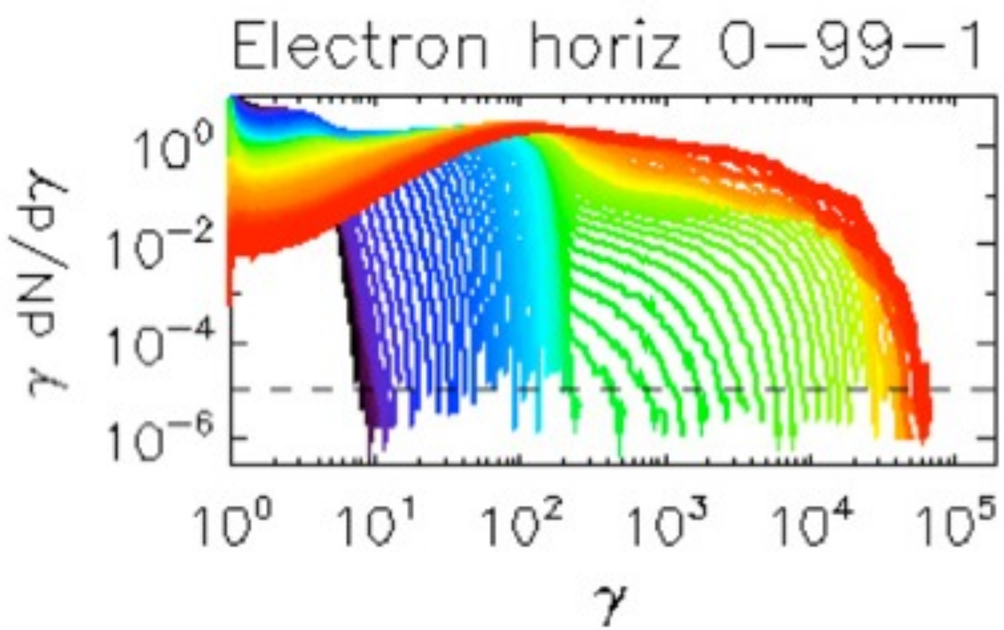


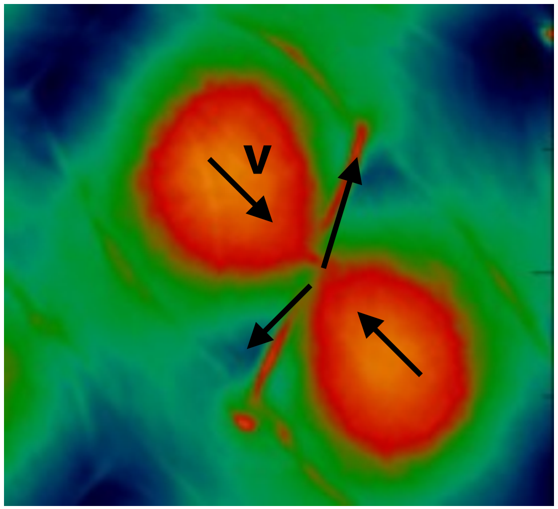
- Two ways to trigger fast reconnection:
  - development of tearing-like mode
  - external compression



Particle acceleration in island merger

- For sigma < 100 spectrum is soft, few particles are accelerated to gamma >> sigma

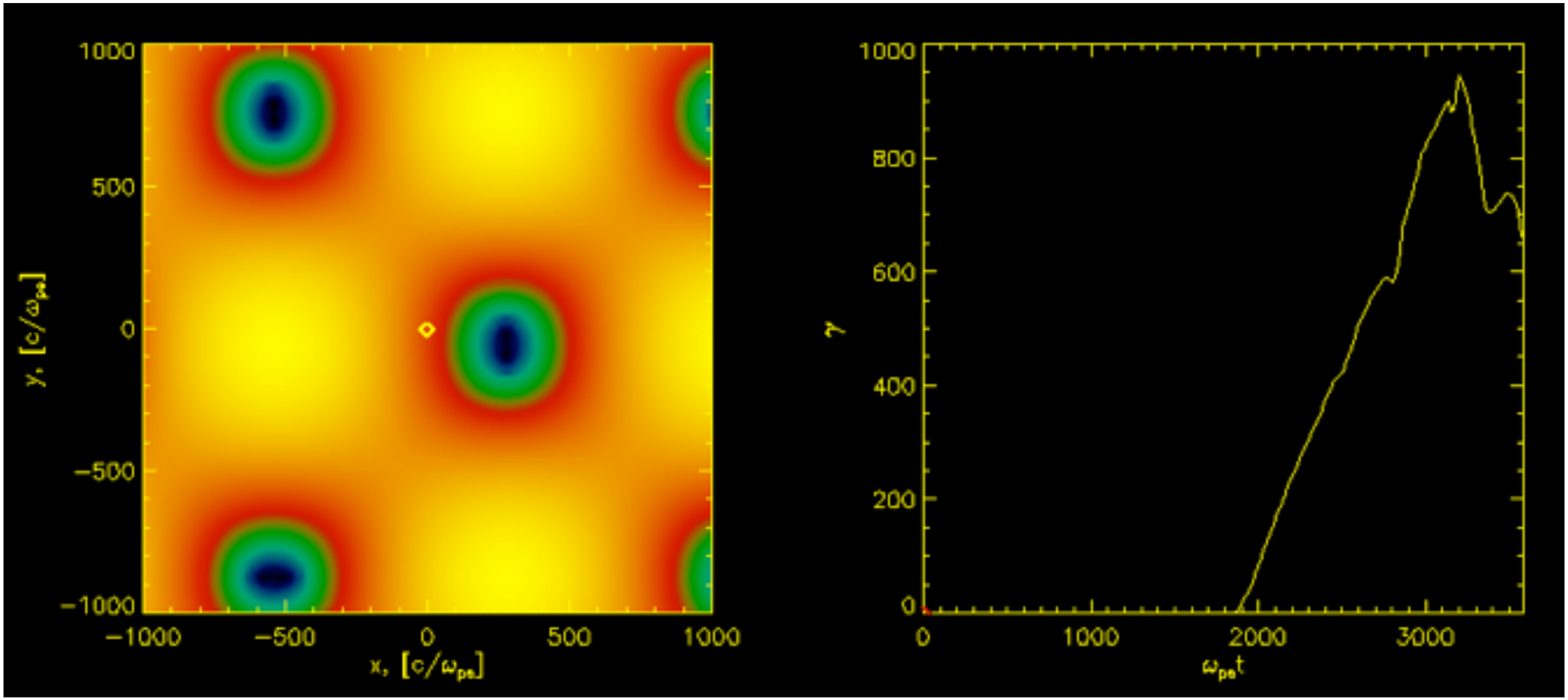




Sweet-Parker-like picture

Most particles leave via jets, only few chosen one stay accelerated

Particles are accelerated by the reconnecting E-field near X-point

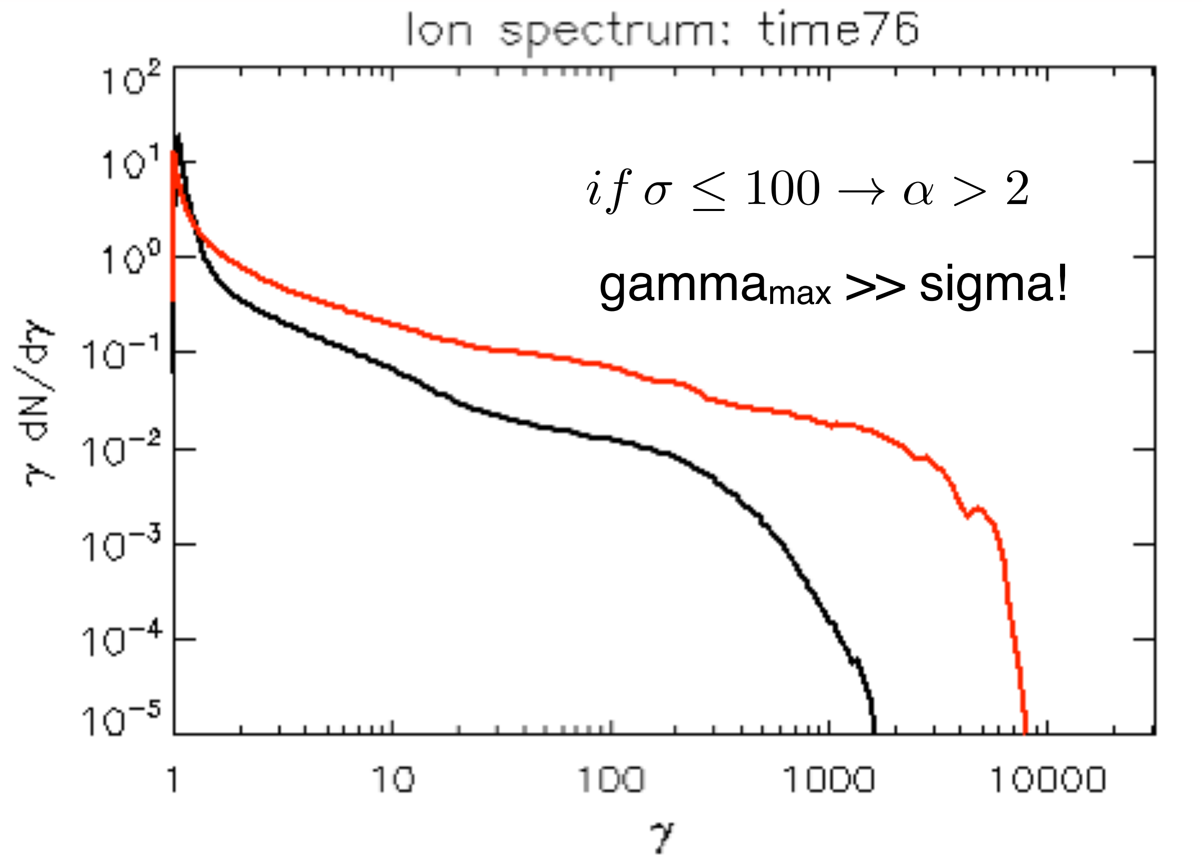


$$E \sim B \propto t$$

$$\epsilon \propto t^2$$

Spectra as functions of sigma

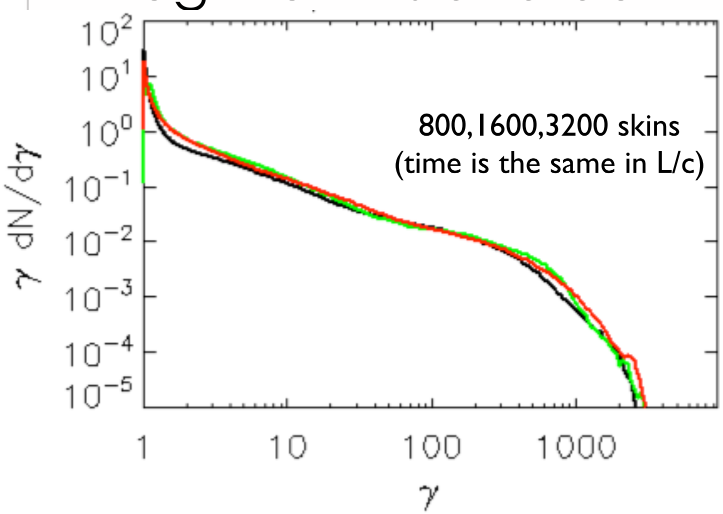
- comparison of spectra between avg sigma=85 and 850
- slope is harder for higher sigma -> running in energy issues

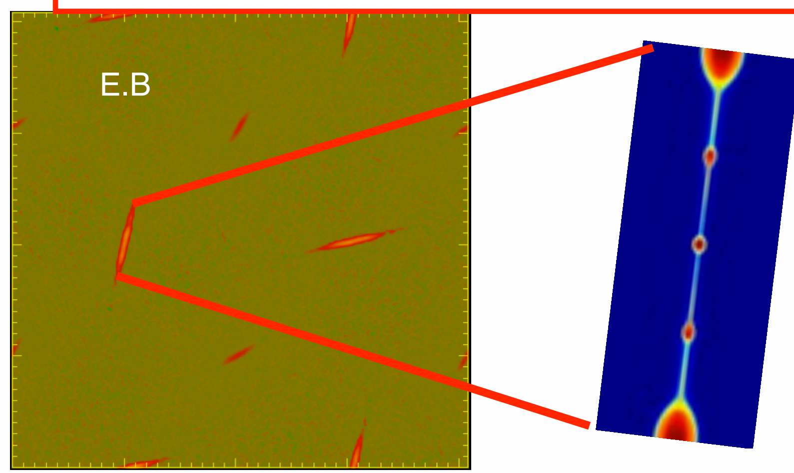


gamma ~ 10^9?

- Potential available $\Phi \sim BL$
- (just need to collapse at ~ c at scale L)
- It seems, for large L the forced reconnection changes a regime -> island dominate

L>L_{crit} - plasmoid instability of current sheet





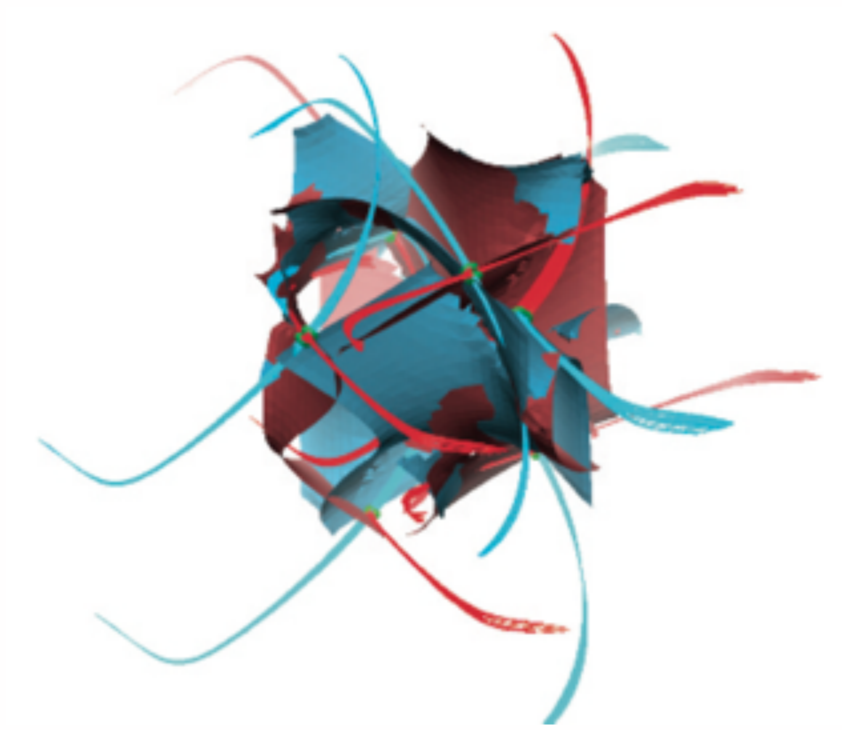
- Acceleration seems to drop down beyond some L
- Optimal regime: sigma ~ 100, L/delta ~ 100-1000

$\alpha > 2$

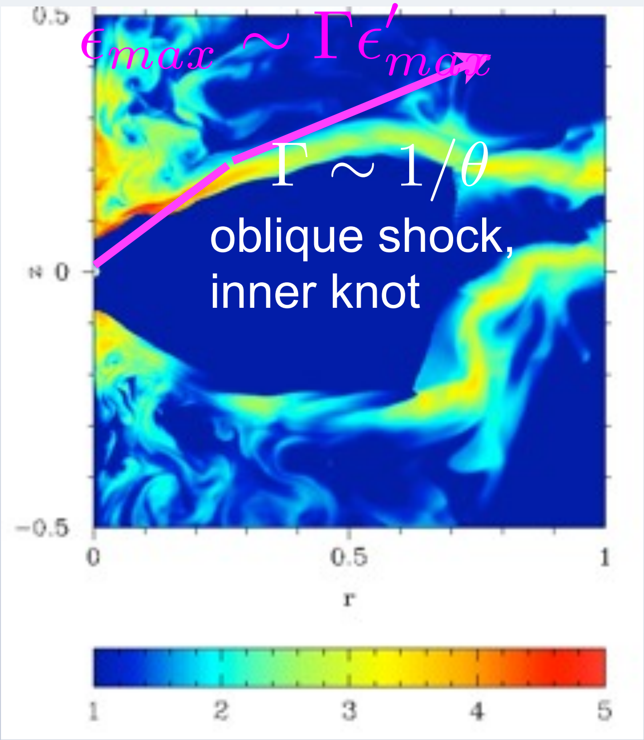
E ~ B

To do: full 3D ABC flow

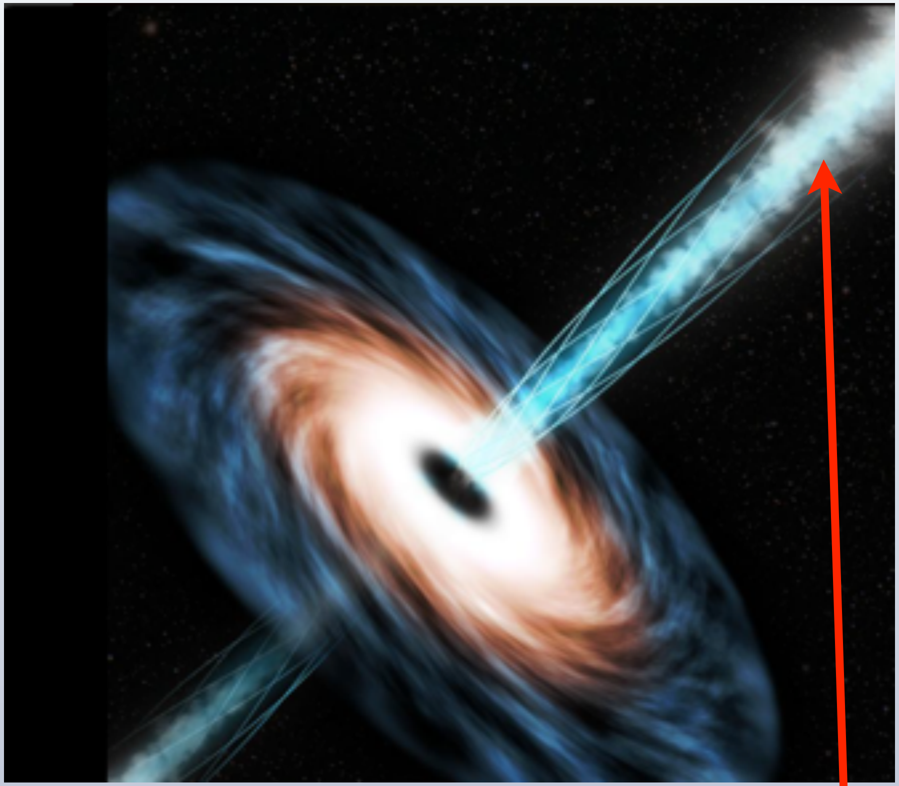
- Plasmoid instability can be stabilized by weak guiding field
- (Not too much)
- Non-zero guiding field at X-point



Where in Crab and AGNs?



Komissarov & Lyutikov, 2011



- Dissipation zone @ r < 1pc (approximately where $B'_\phi \sim B'_p$)

Conclusion

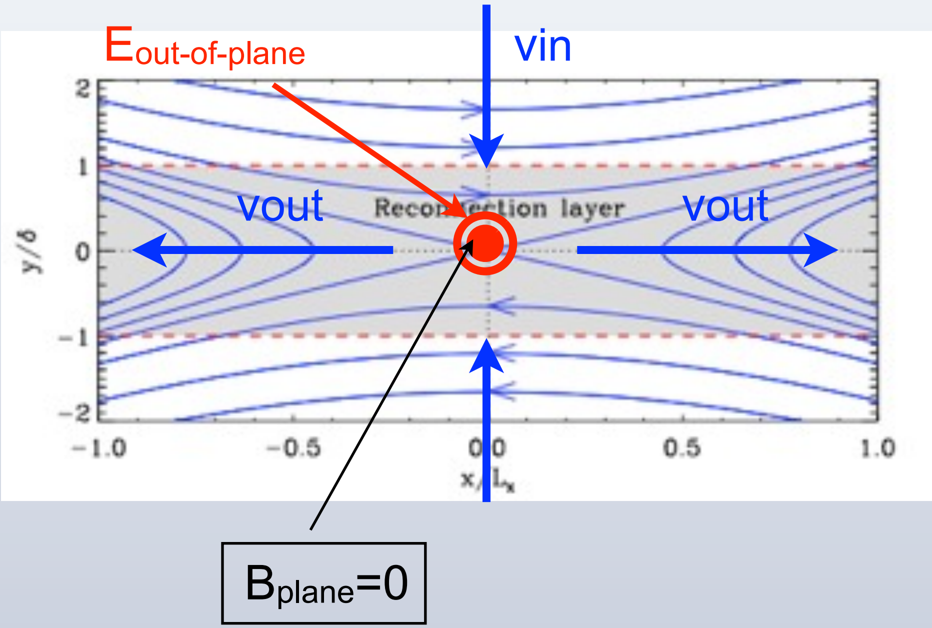
Reconnection in magnetically-dominated plasma

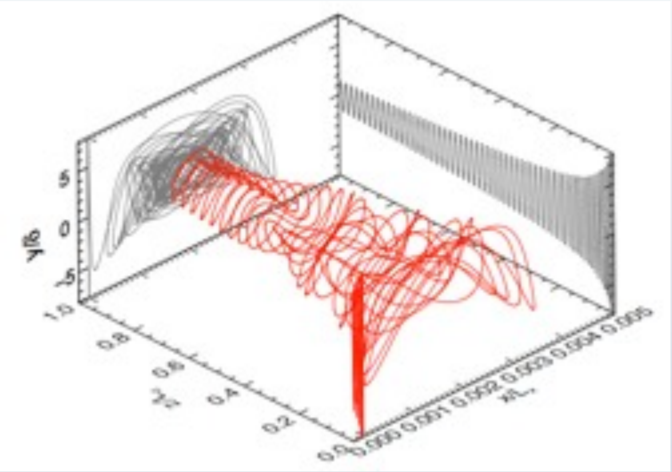
- **can proceed explosively**
- **efficient particle acceleration**
- **is an important, perhaps dominant for some phenomena, mechanism of particle acceleration in high energy sources.**

Best case scenario for Crab

- Pulsar produces $\sigma_w \sim 10^6$ (polar angle-dependent)
- Partial dissipation
  $\sigma_{post-shock} \sim 10^2, \gamma_{post-shock} \sim 10^4$
- Explosive collapse
  $\gamma_{flare} = 100\sigma_{post-shock}\gamma_{post-shock} \sim 10^8$

Compare with Colorado group





Uzdensky et al.: Accelerate in a region where B is small, with E >B, emit where B is large.

- Tearing mode instability of current sheet.
- All scales related to delta - smallish potential @ skin
- Large island merger: inflow velocities << c
- All particles accelerated (gamma < sigma)