Relativistic pulsar winds: structure, shocks, reconnection

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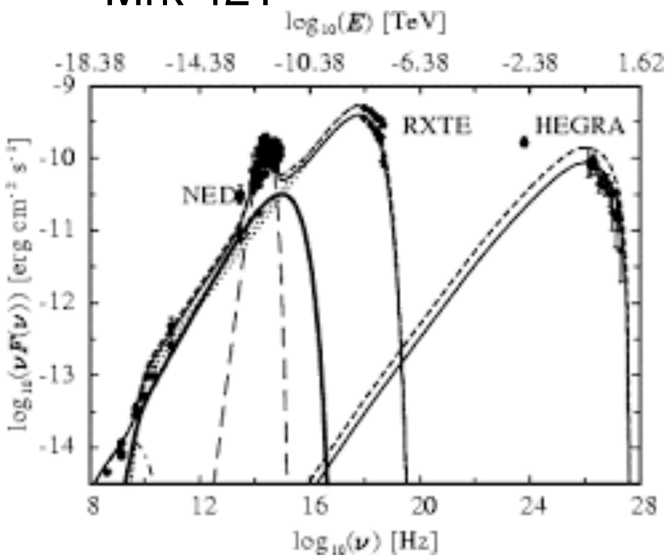
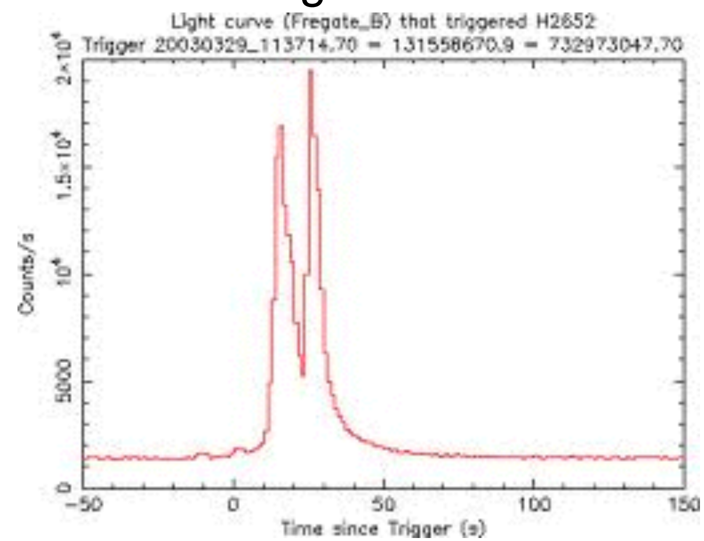
High energy sources: non-thermal particles, **fast variability (= very fast acceleration)**

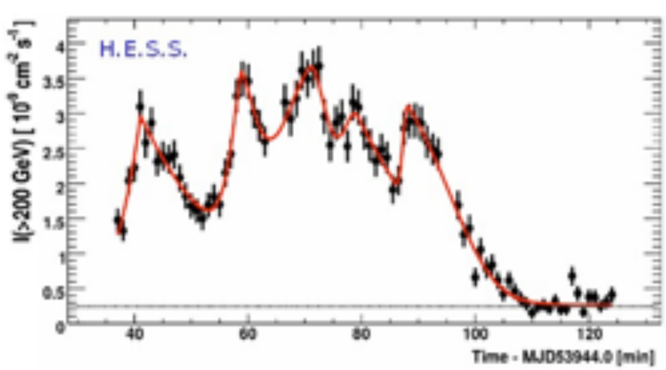
Mrk 421

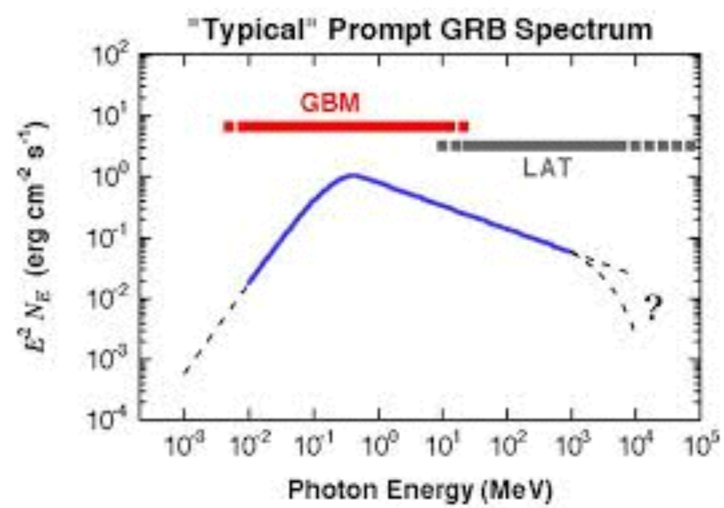


GRB light curve

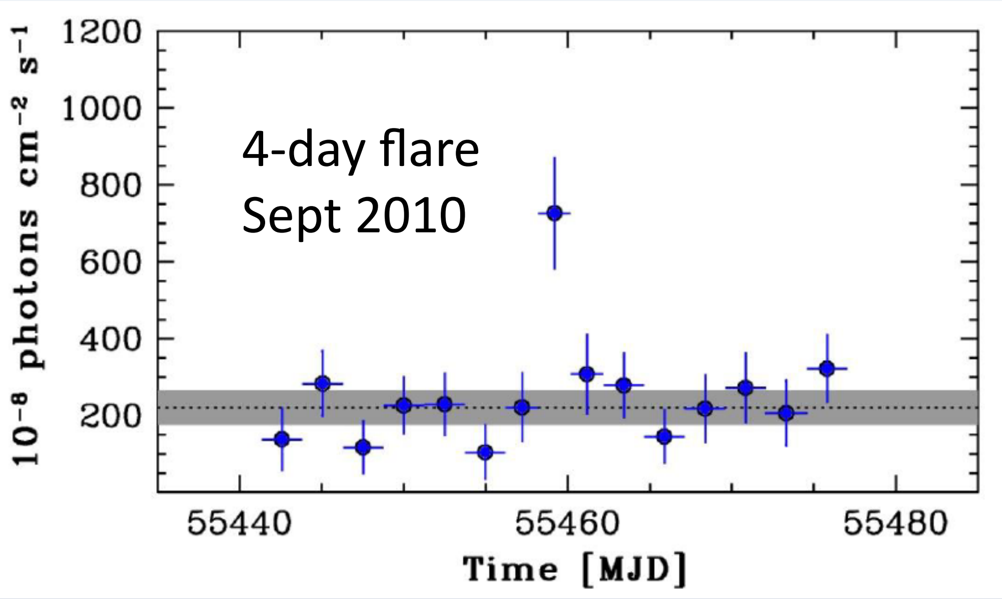


blazar PKS 2155-304





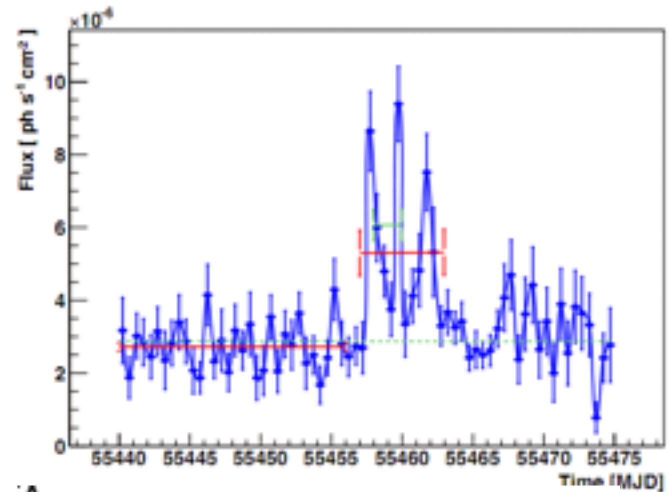
Crab nebula flares

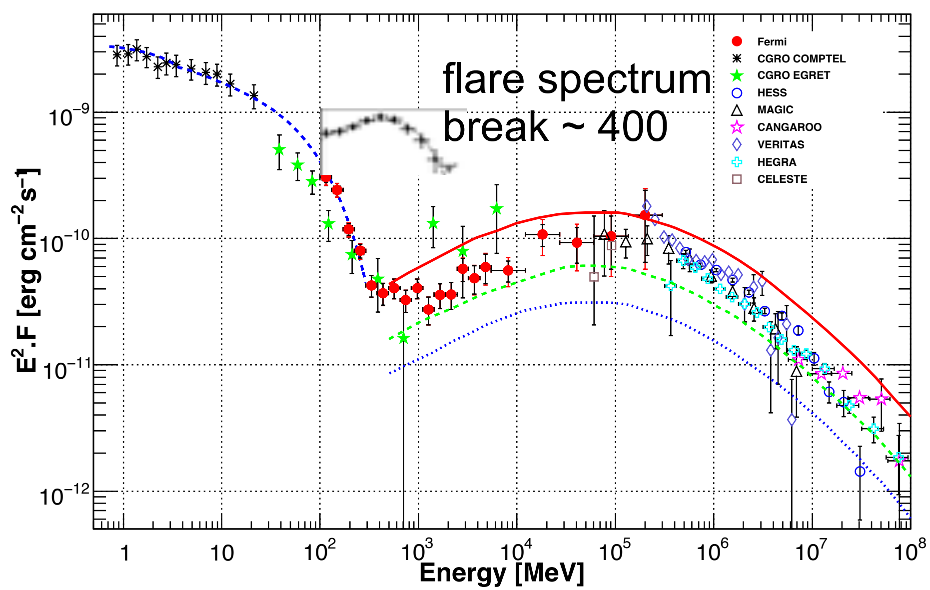


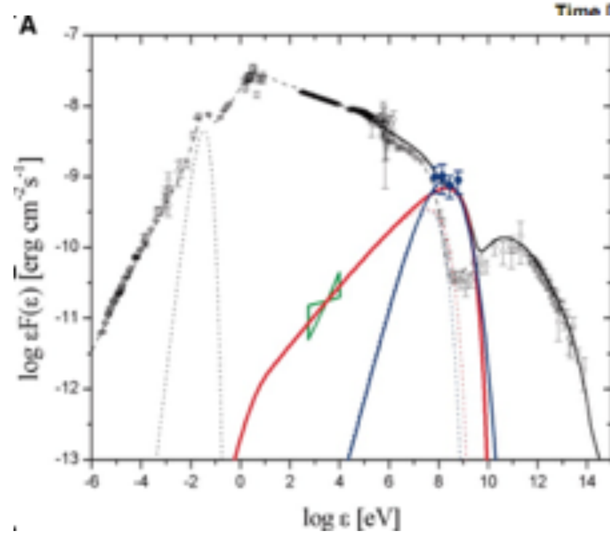
Tavani et al. 2011

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

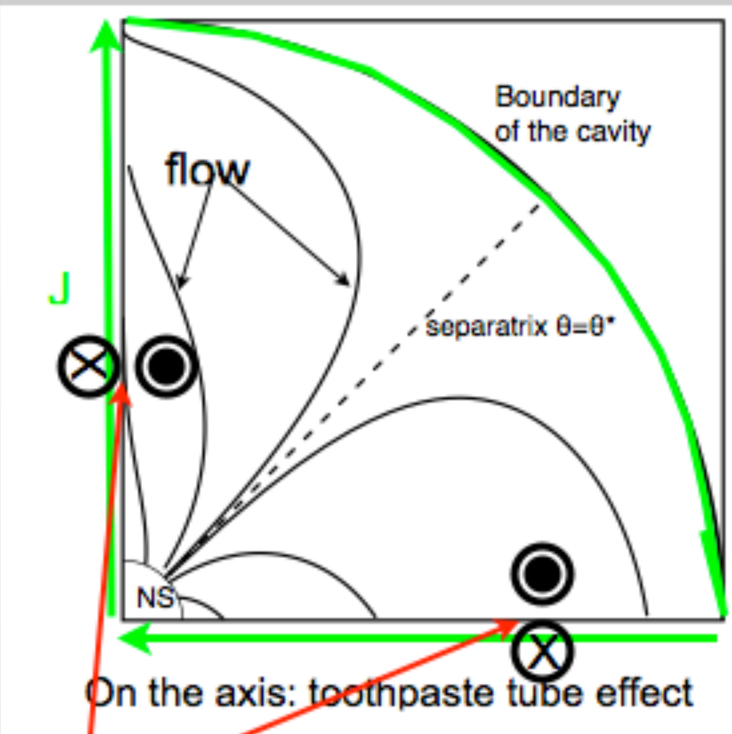
Accelerating E-field < B-field

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

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

- 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)*

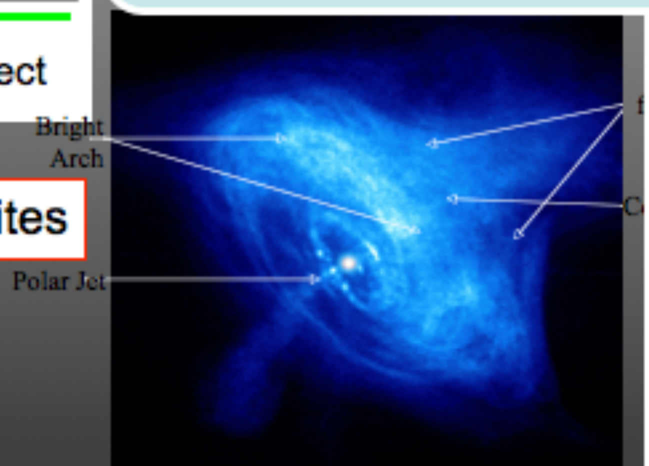


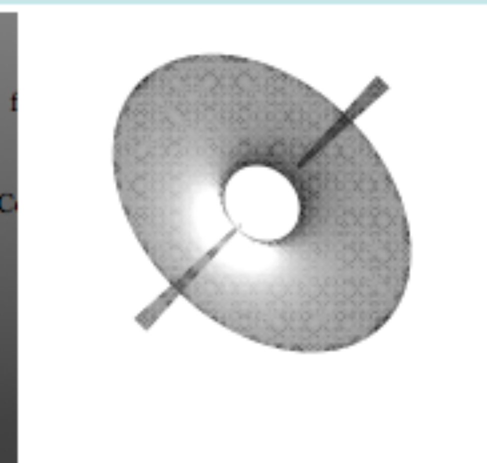
Two possible reconnection sites

- *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
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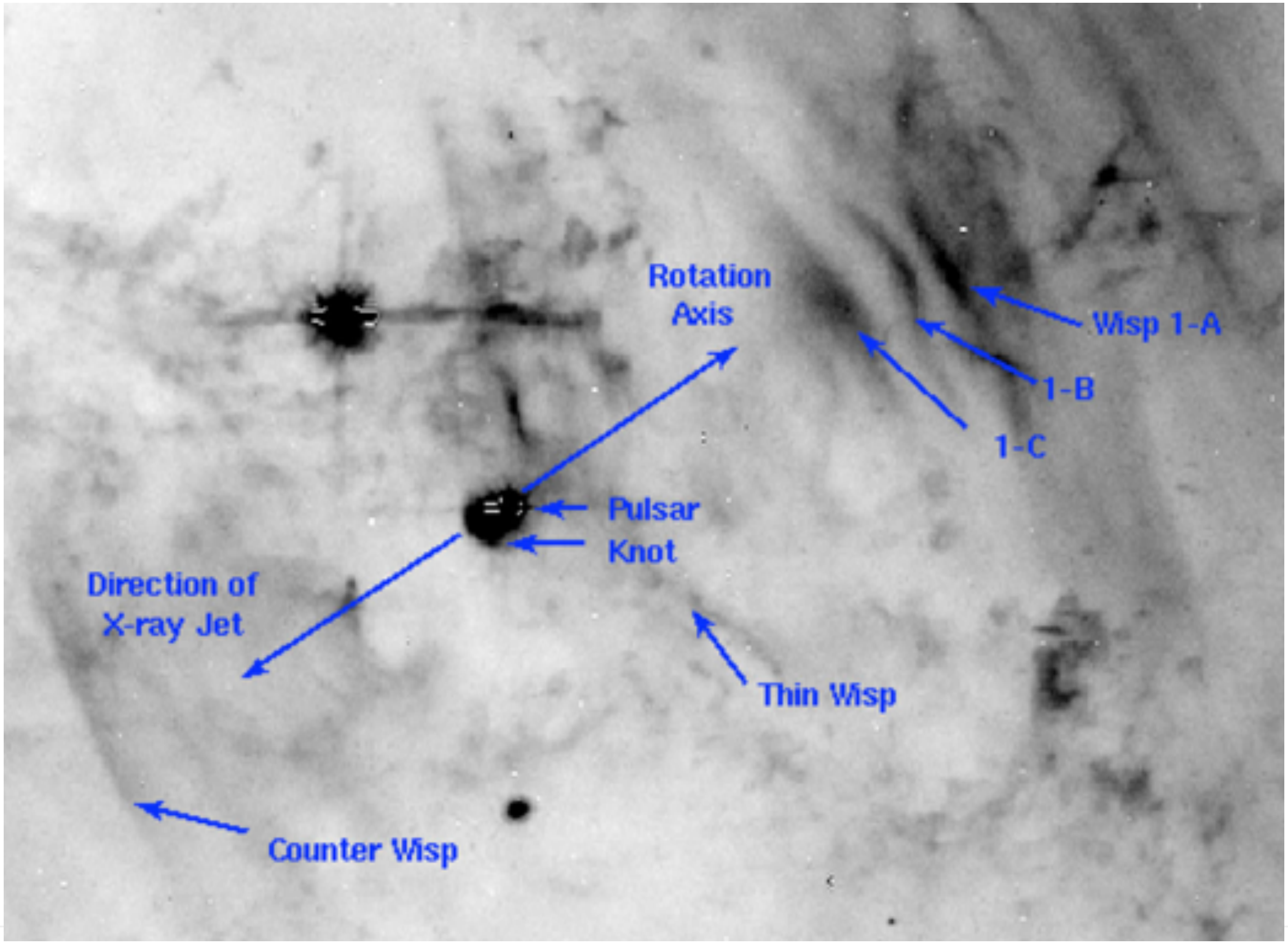
Explosive Reconnection in relativistic plasmas

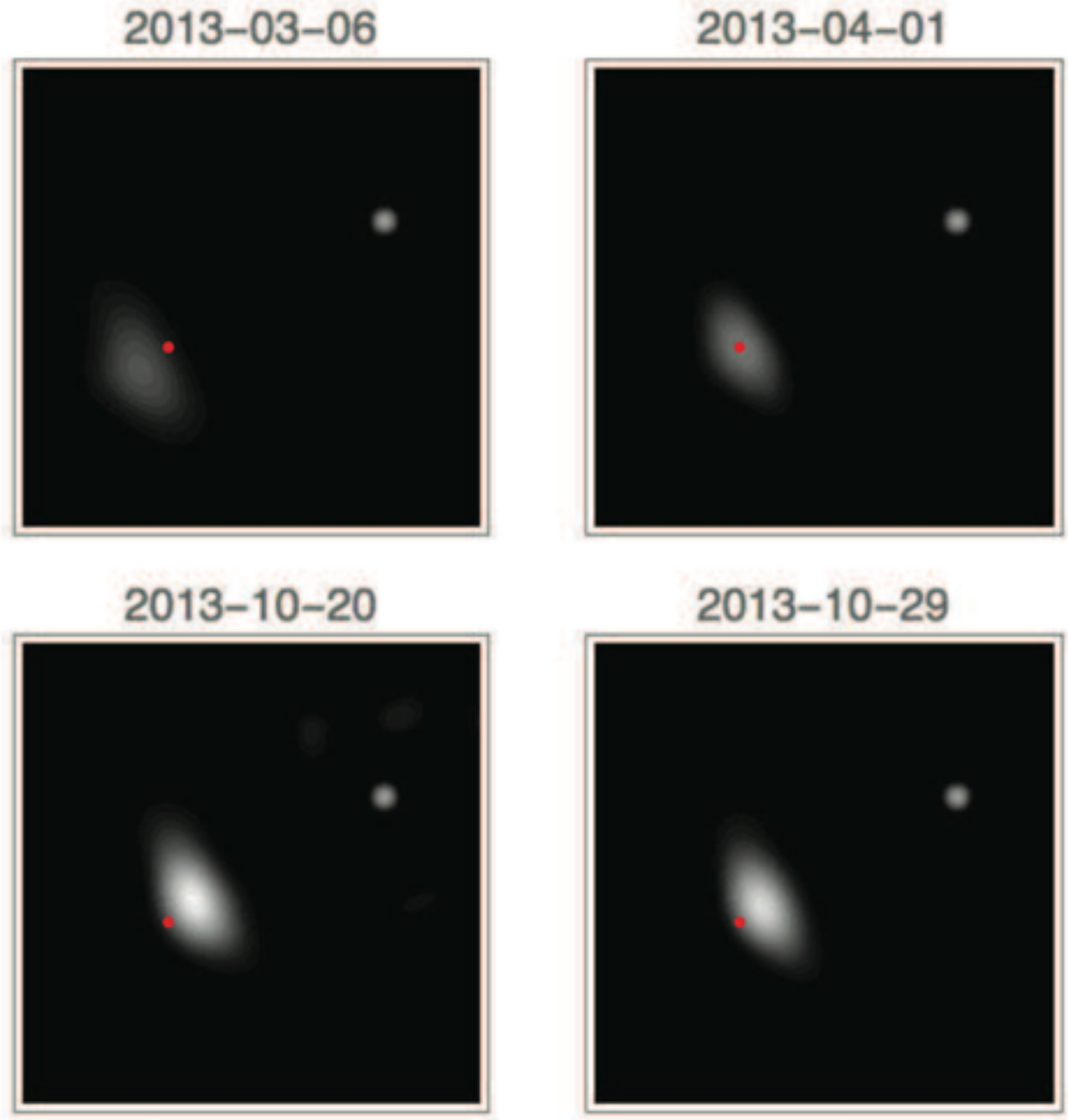
The inner knot of Crab nebula

The Crab Inner knot

Rudy +, 2015

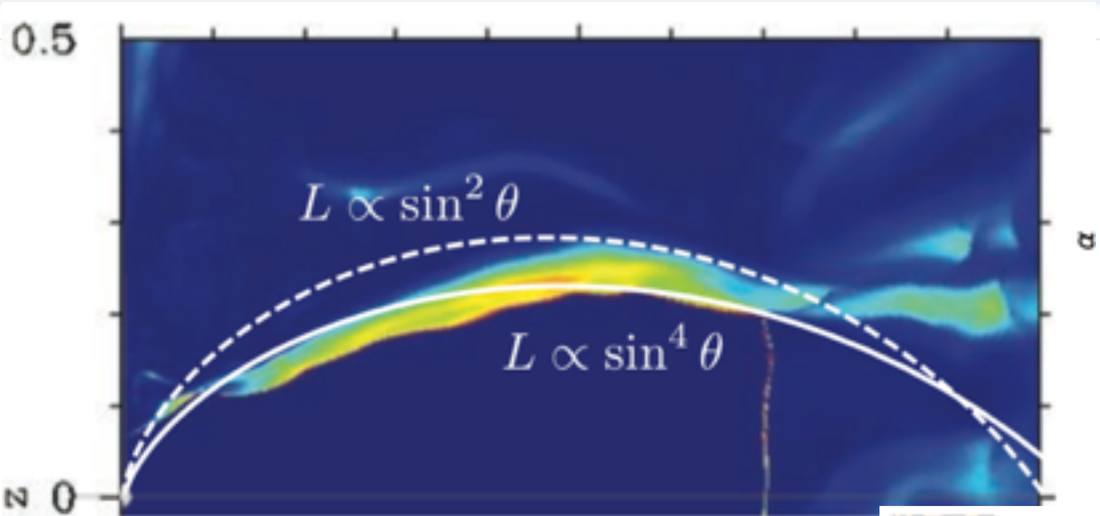


Scales ~ 0.5'' (light day)

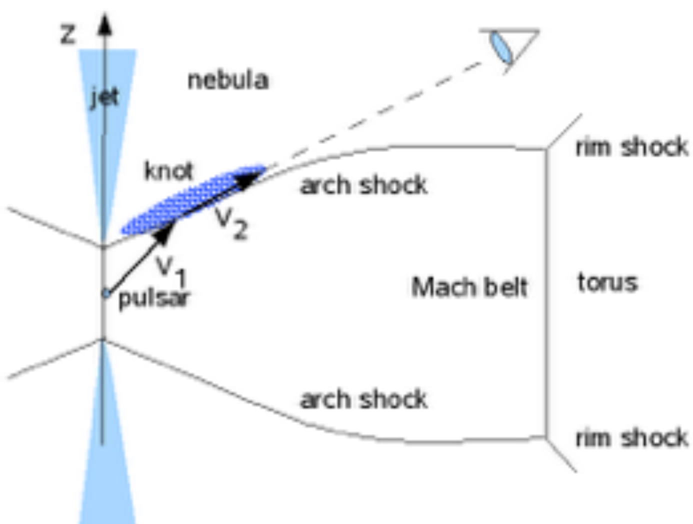


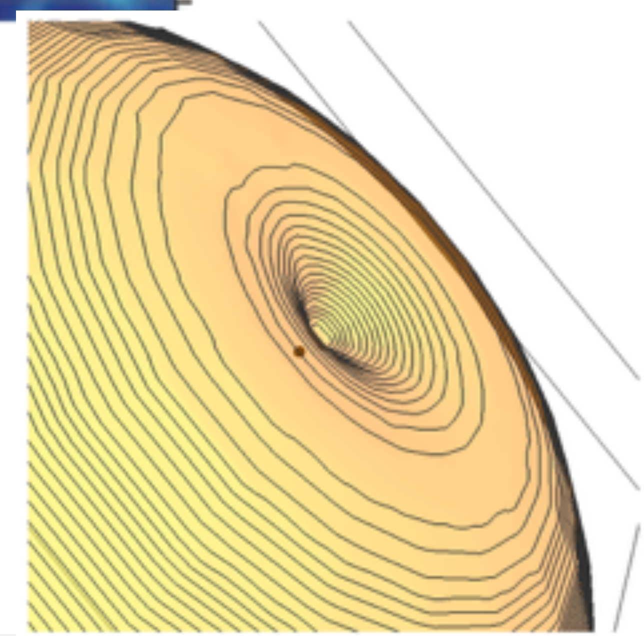
Rudy +, 2015

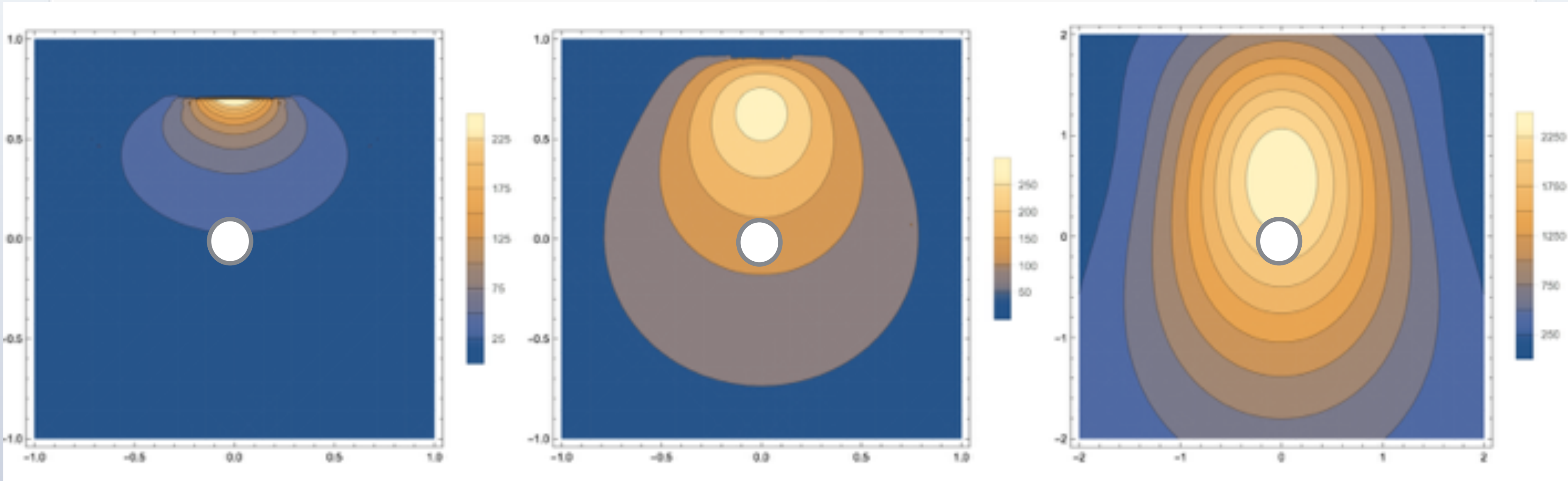
Shock modeling



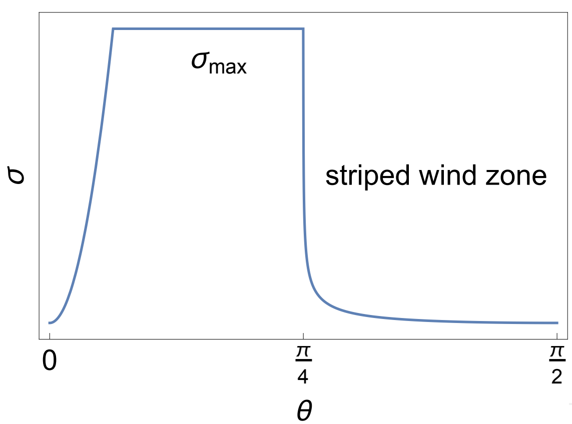
Kompaneets approximation

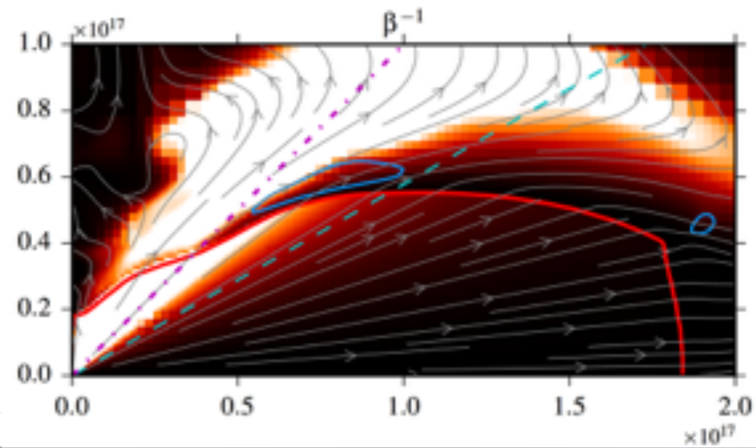






$\sigma = 0$ $\sigma = 1$ $\sigma = 10$





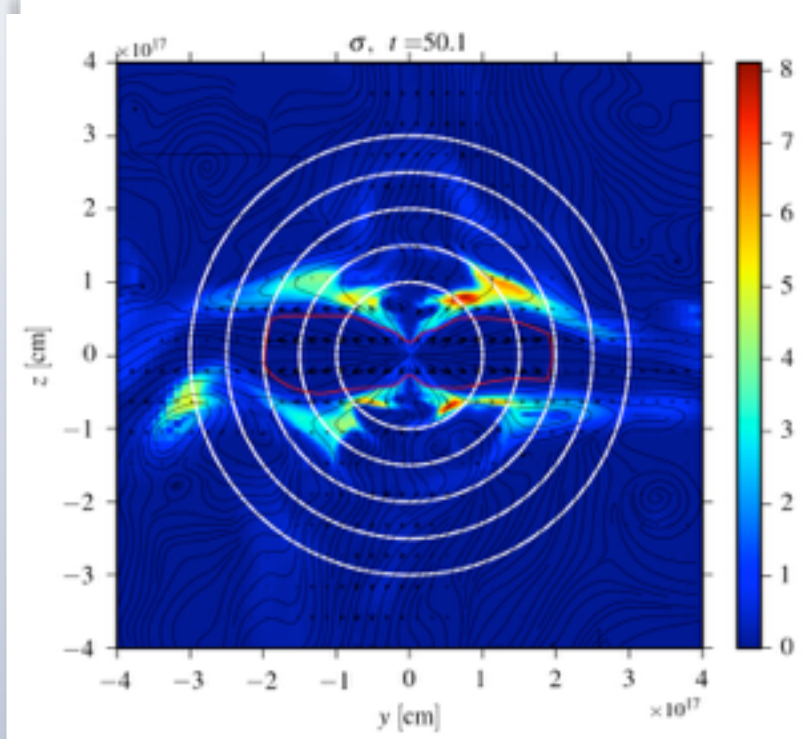
Inner knot

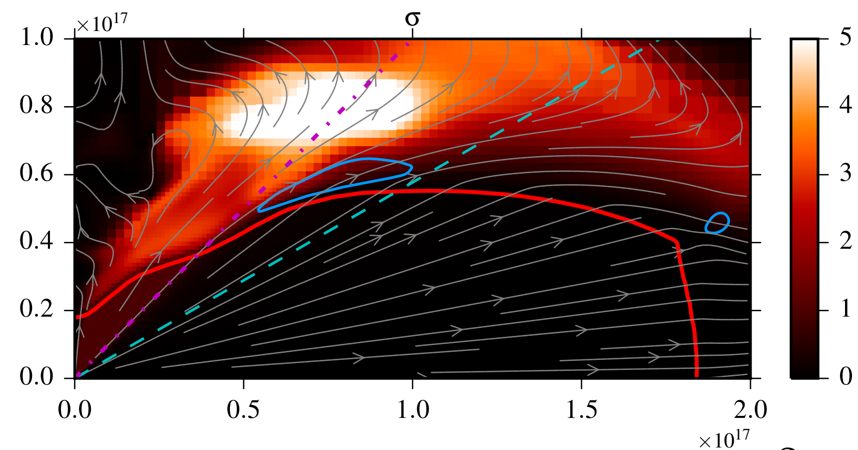
- **Location**: The knot is on the same side of the pulsar as the Crab jet, along the symmetry axis, on the opposite side as the brighter section of the Crab torus.
- **Size**: The knot size is comparable to its separation from the pulsar. Only models with $\sigma < 1$ agree
- **Elongation**: The knot is elongated in the direction perpendicular to the symmetry axis. Only models with $\sigma < 1$ agree
- **Brightness peak**: The observations indicate that the brightness peak is shifted in the direction away from the pulsar.
- **Polarization**: The knot polarization degree is high, and the electric vector is aligned with the symmetry axis.
- **Luminosity**: Taking into account Doppler beaming, the observed radiative efficiency of the inner knot is fairly low
- **Variability**: The knot flux is anticorrelated with its separation from the pulsar.

Not a sight of gamma-ray flares.

How to make Crab flare

Large scale simulations - formation of high-sigma regions





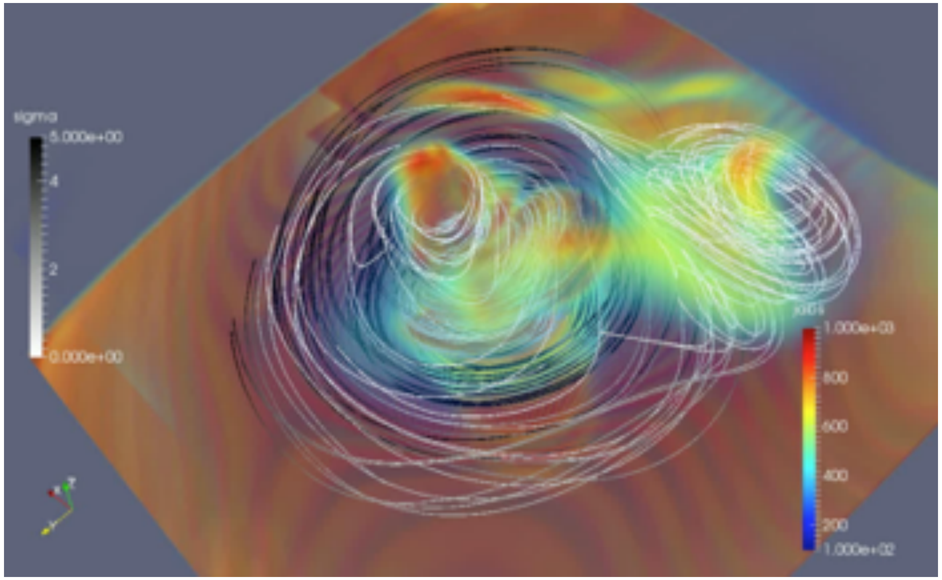
color: value of sigma,
Porth +, 2014

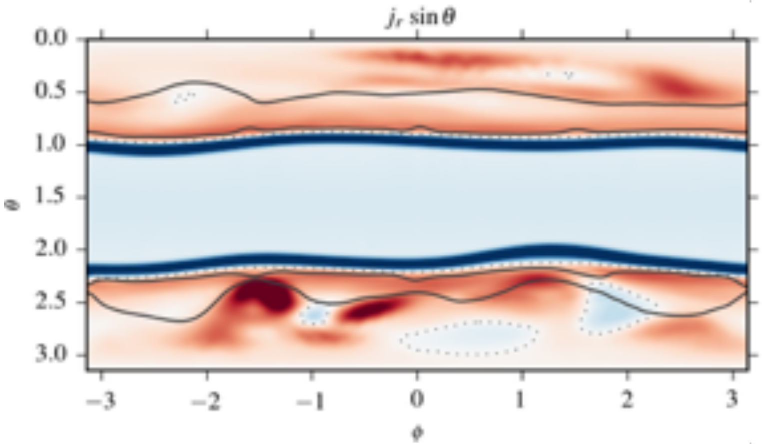
$$\sigma = \frac{B^2}{4\pi\rho c^2}$$

- Initially, in the simulations sigma ~ few, increases to ~40.
- Cranfill effect: **BΓrv ≈ constant**
- $\sigma_{\text{flare region}} \gg \sigma_{\text{shock}}$

Large scale simulations

- Toroidally-dominated B-field are unstable to large-scale kinks





Porth +, 2014

- Parallel currents attract. Can flux merger be the source of Crab flares?

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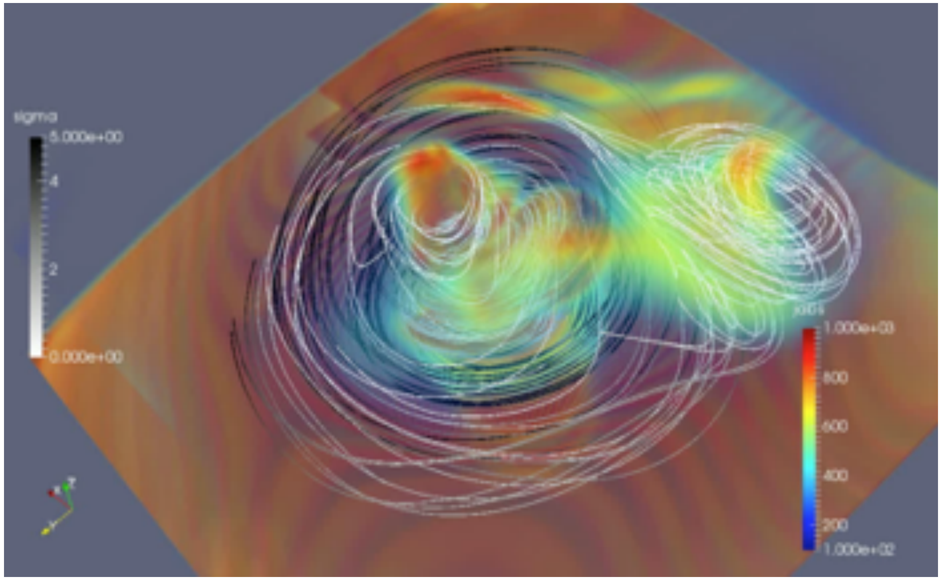

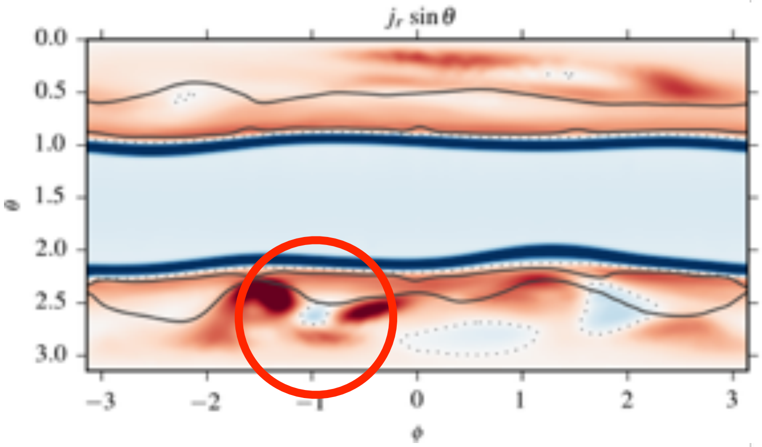

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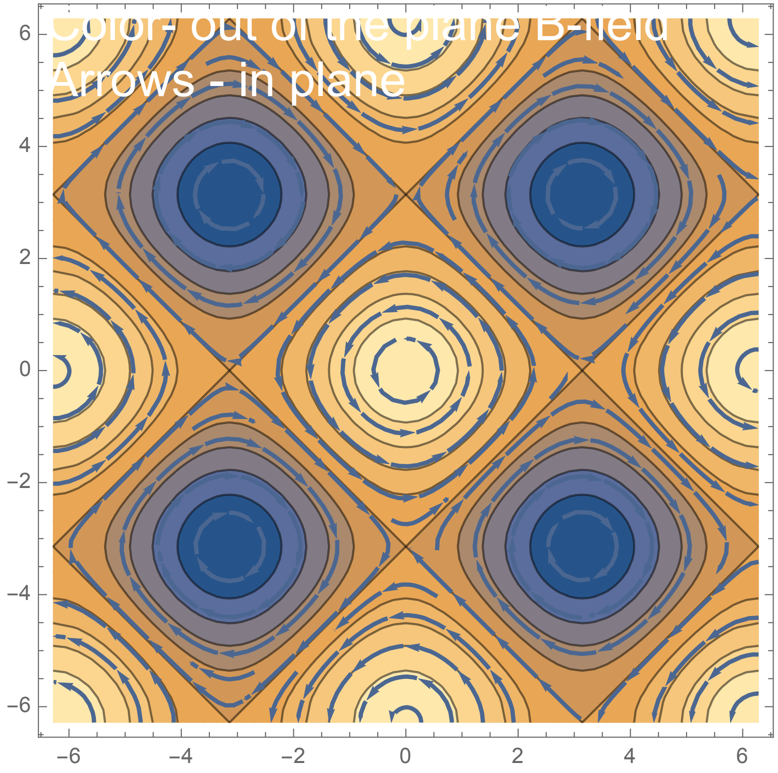
2D force-free state with $\alpha - \text{constant}$

$$\mathbf{B} = \{-\sin(\alpha y), \sin(\alpha x), \cos(\alpha x) + \cos(\alpha y)\} B_0$$ (A type of the "ABC" flow)



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- Similarity to Stanford group (Nalewajko's talk)

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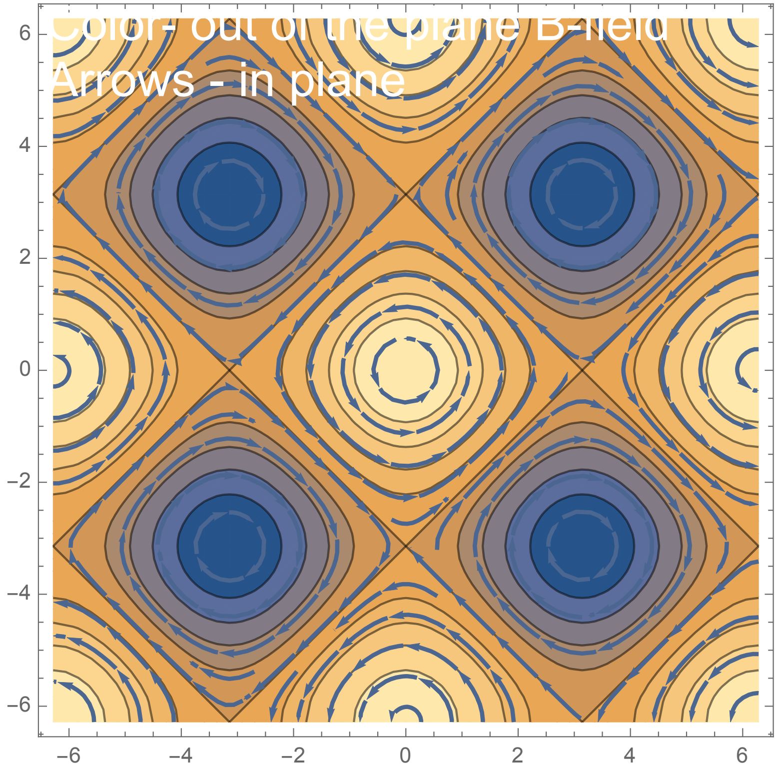

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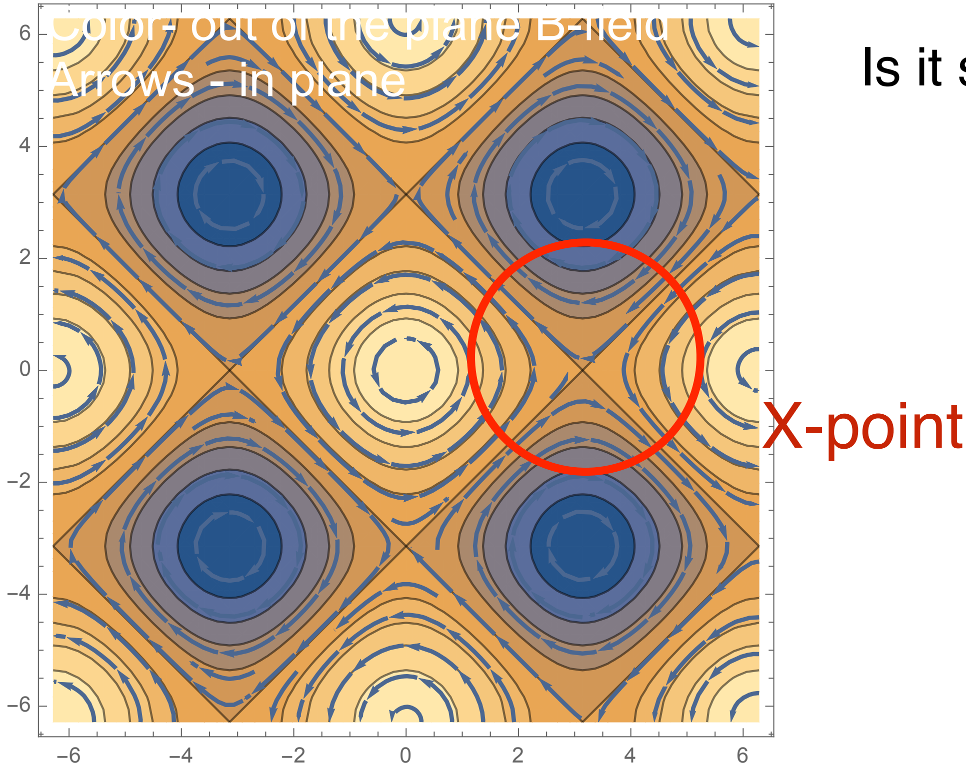

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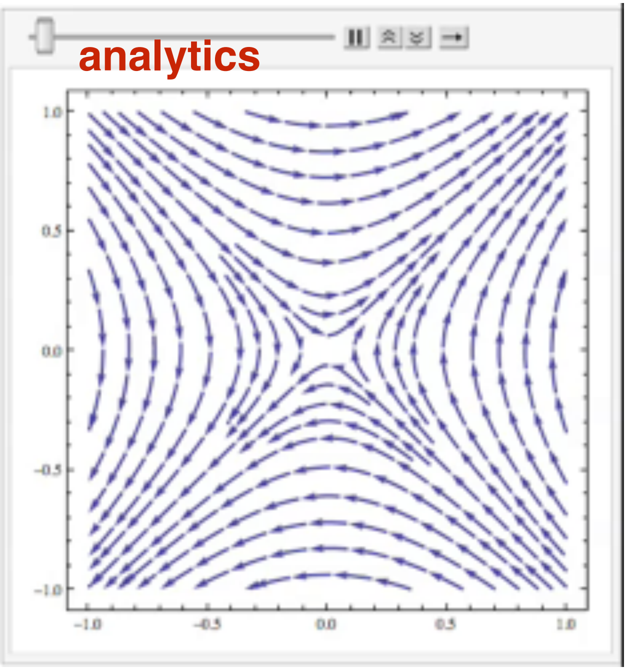
Collapse of stressed magnetic X-point in force-free plasma (a la Syrovatsky)

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

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



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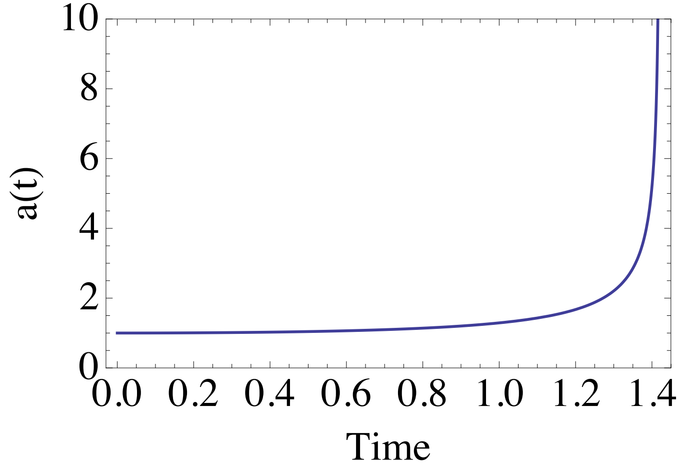

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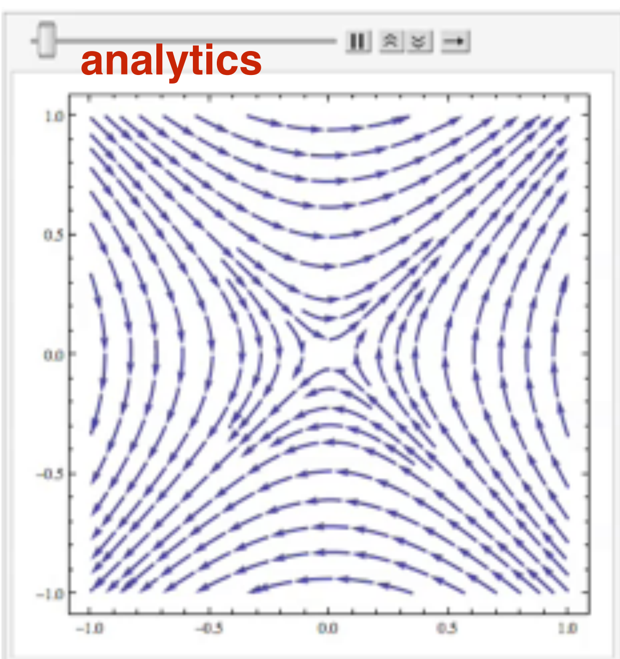

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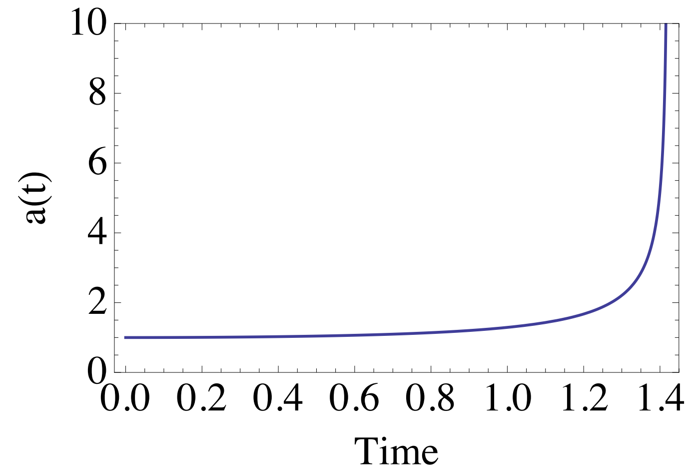

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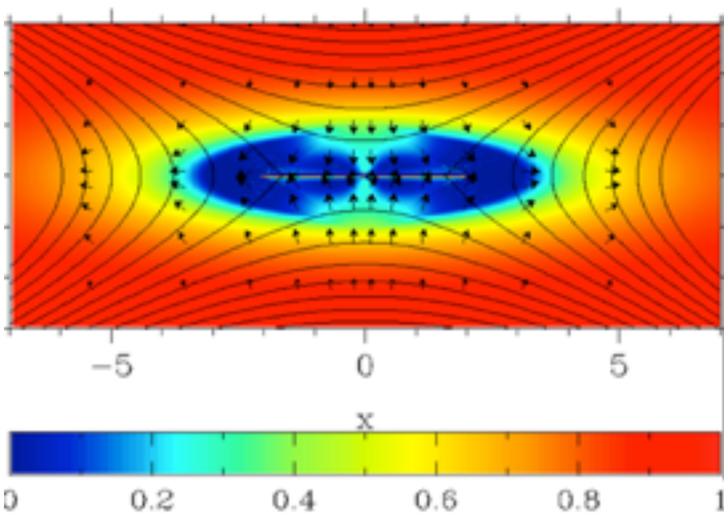
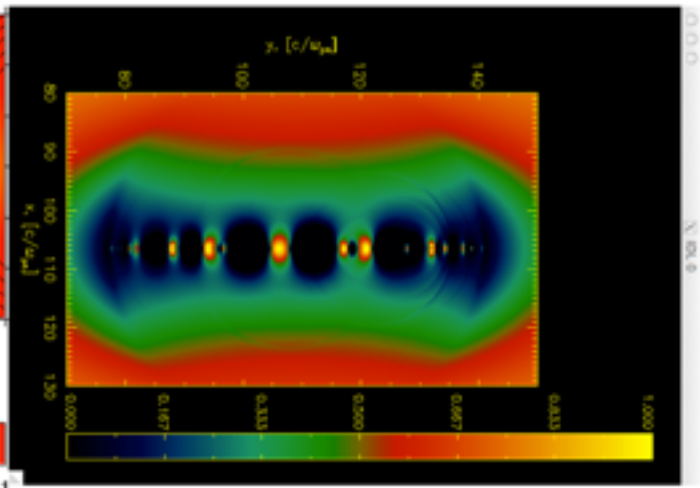
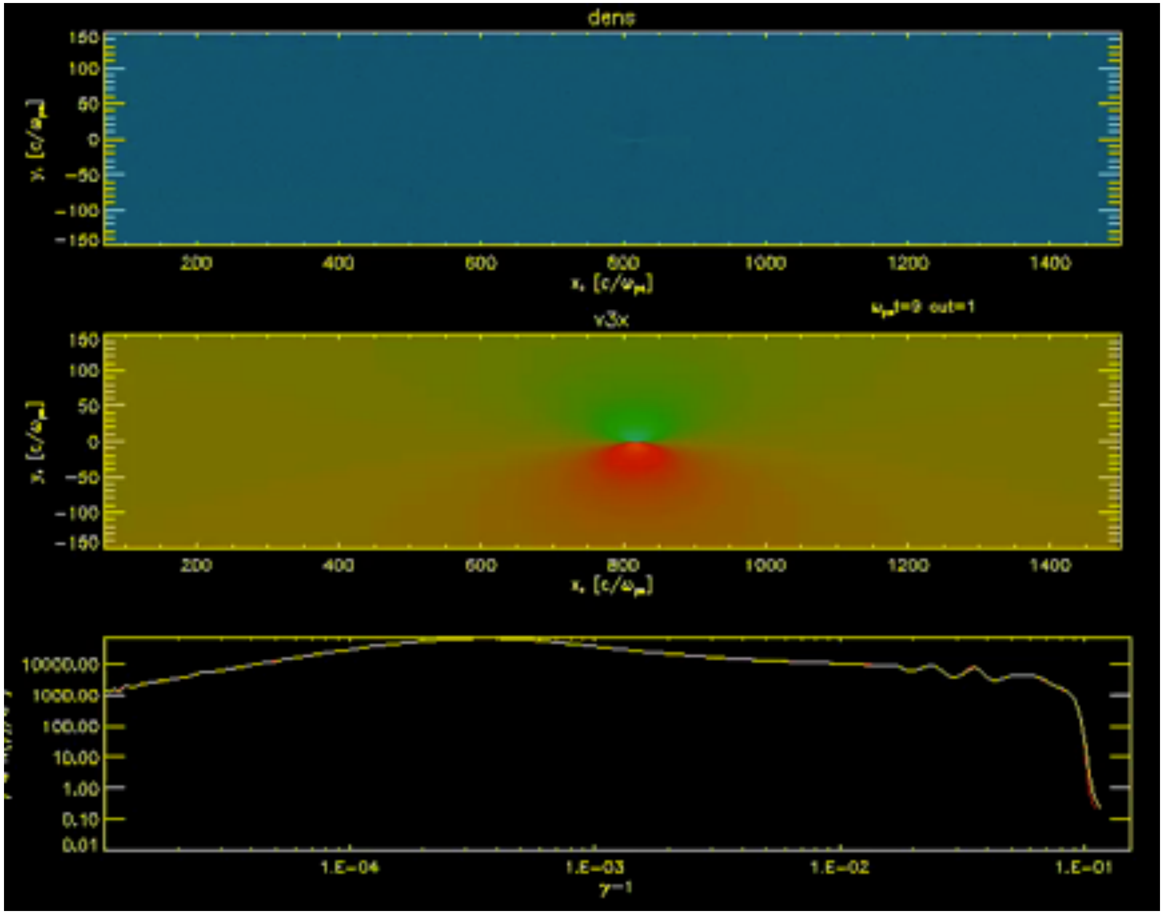
High-sigma PICs and fluid simulations agree





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

Can produce power-laws



PIC simulations by Sironi

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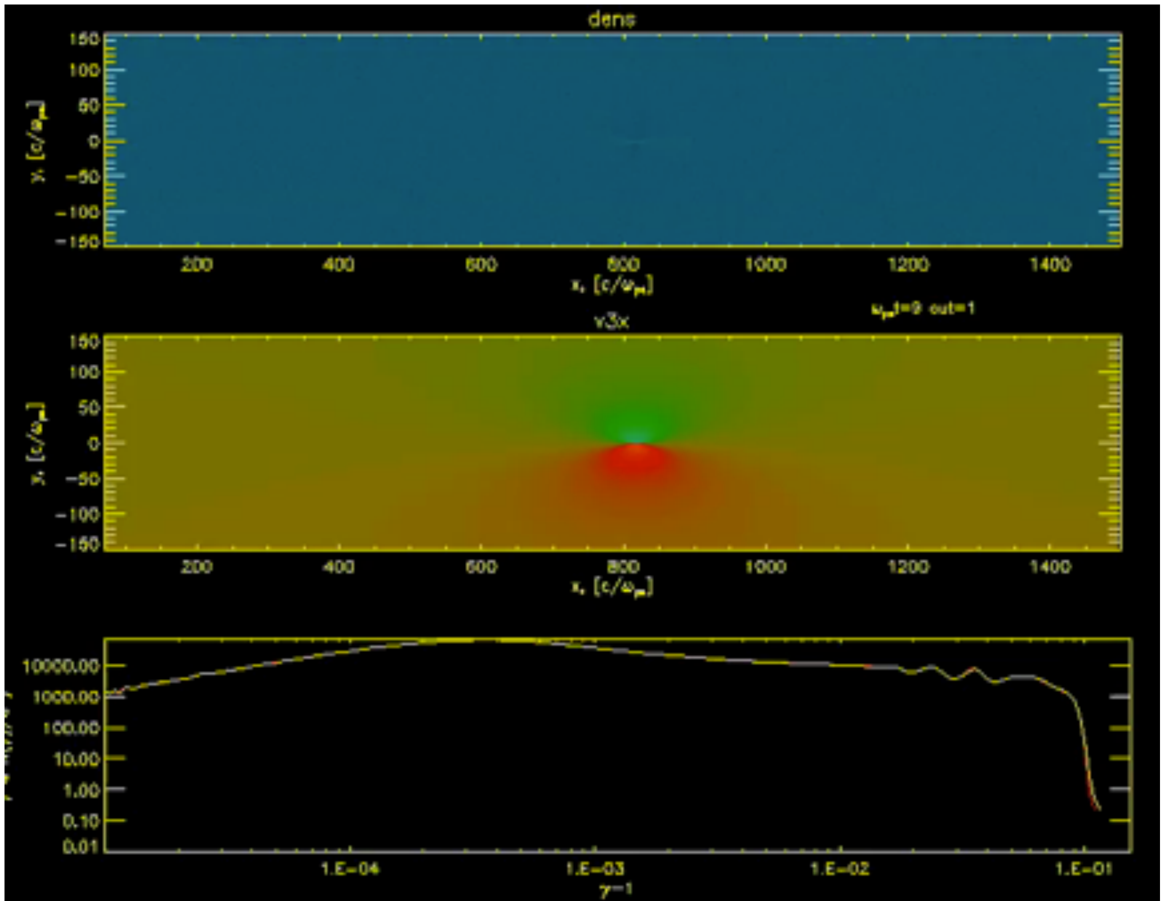


PIC simulations by Sironi

Acceleration in X-point collapse

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

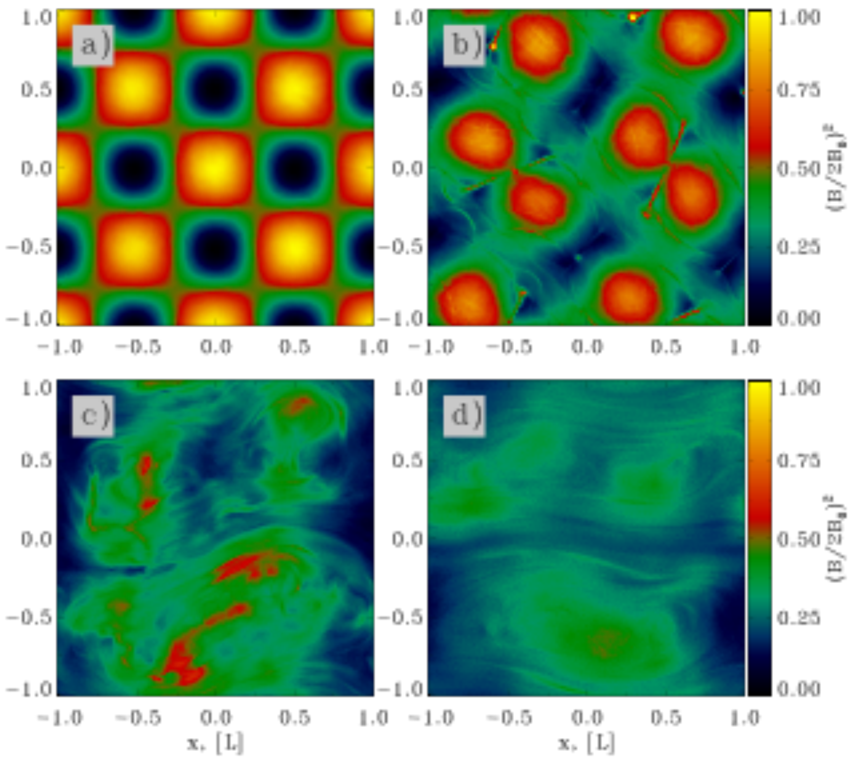
$$J_z \approx \frac{c}{4\pi}\frac{B_\perp}{L}a(t)^2$$

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

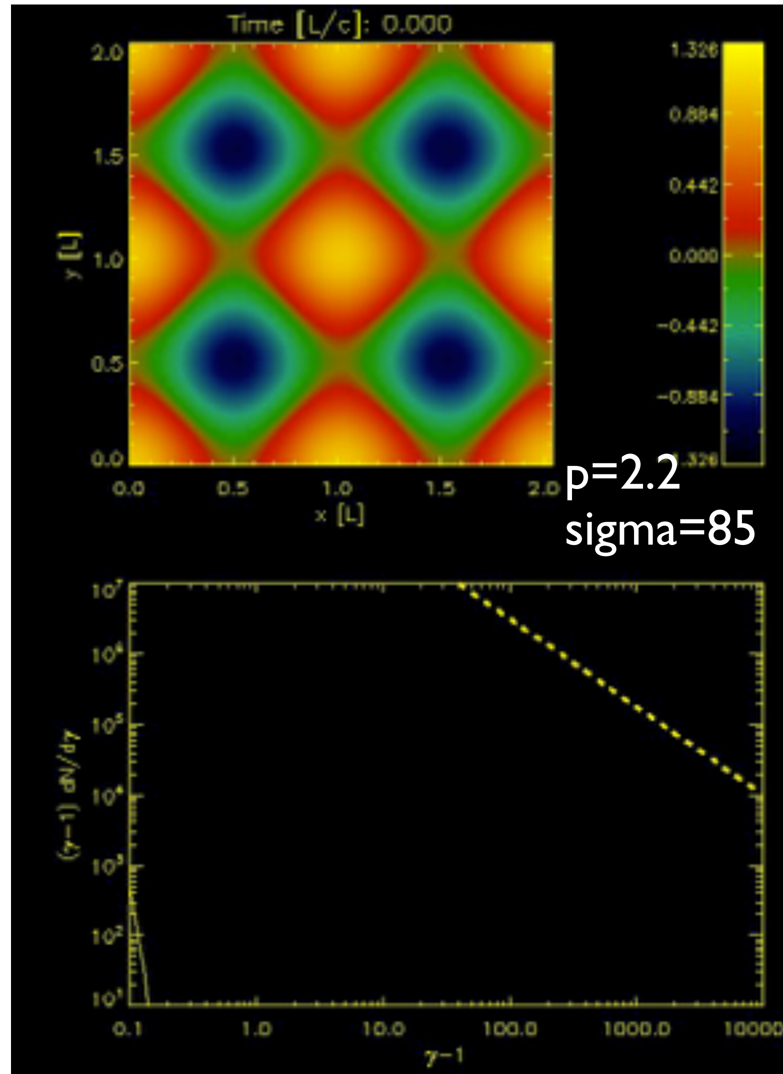
$$curl\mathbf{B} = \frac{4\pi}{c}\mathbf{J} + \partial_t \mathbf{E}/c$$

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

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



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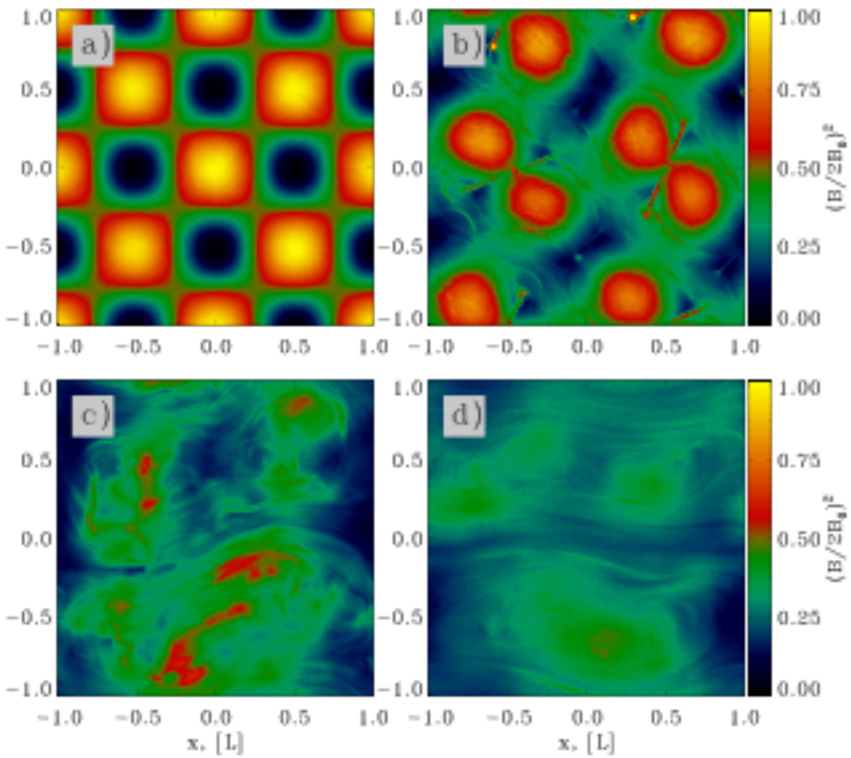

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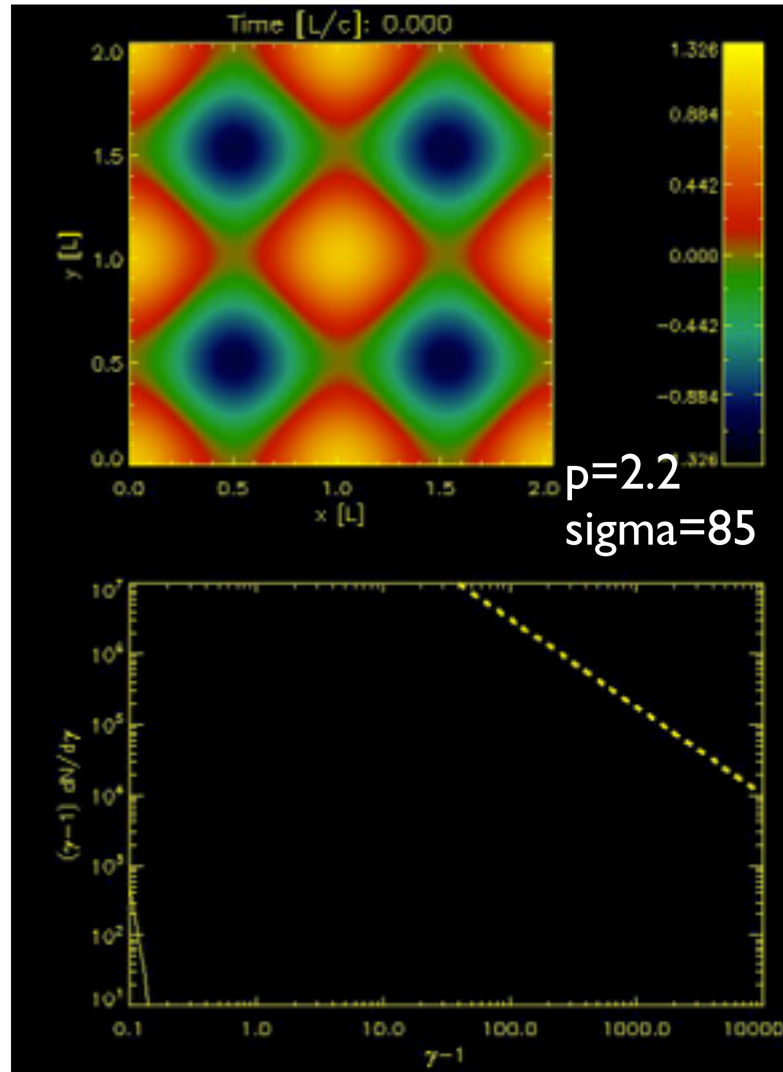
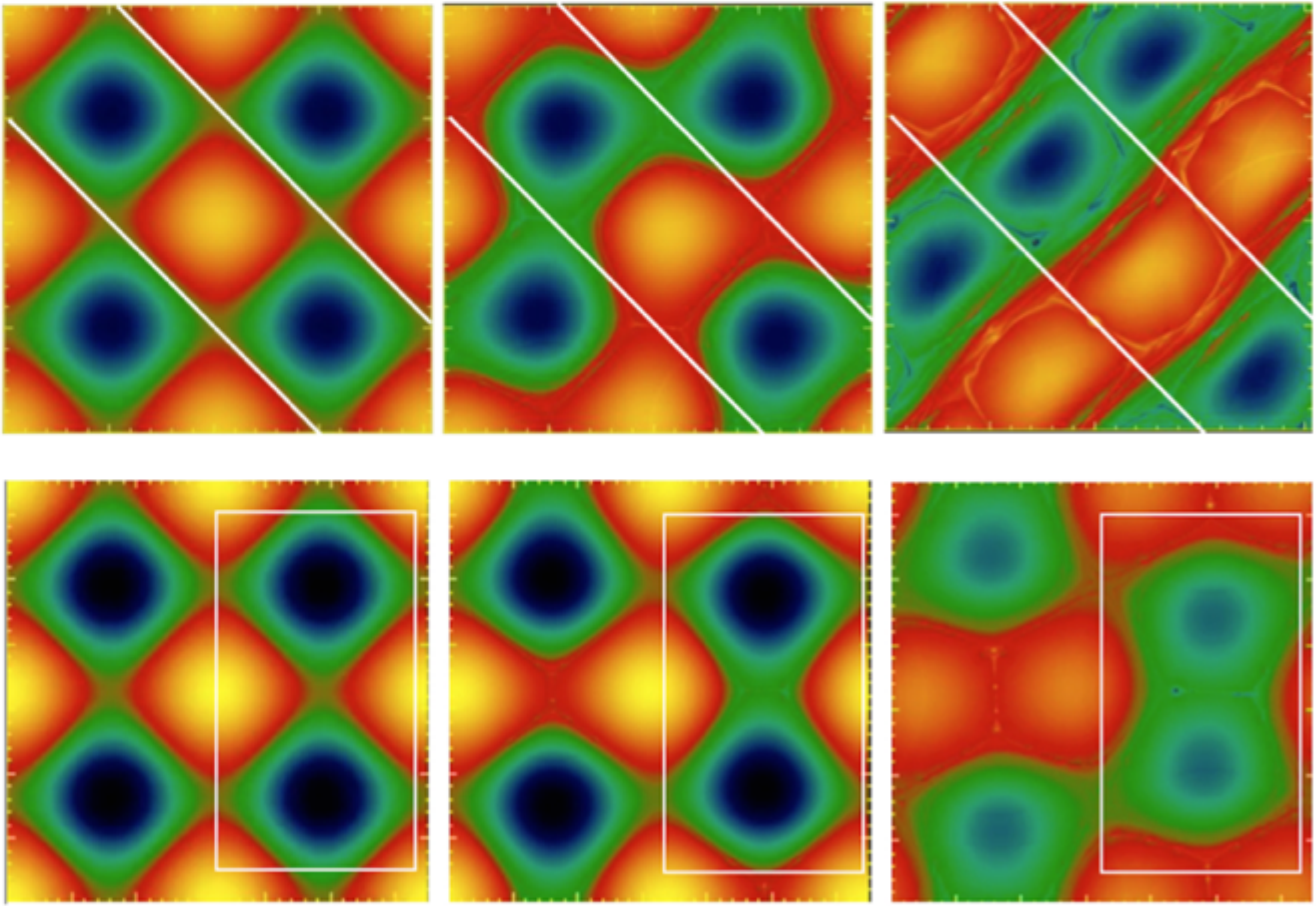
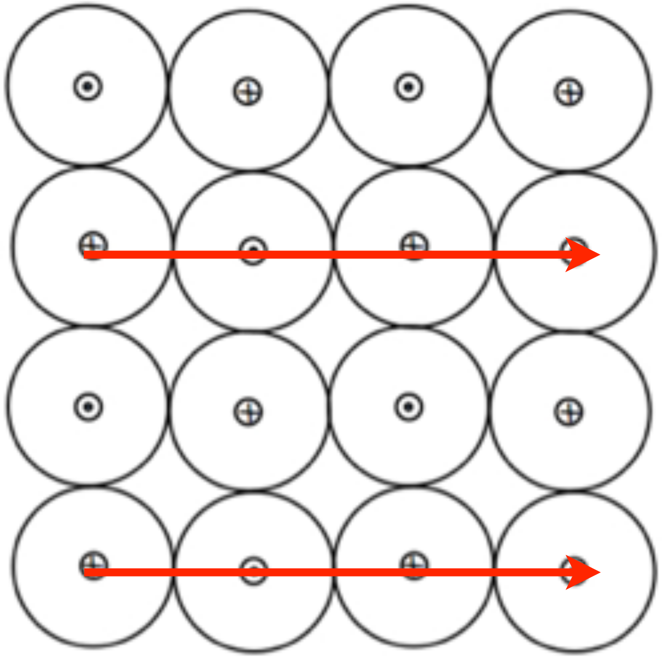
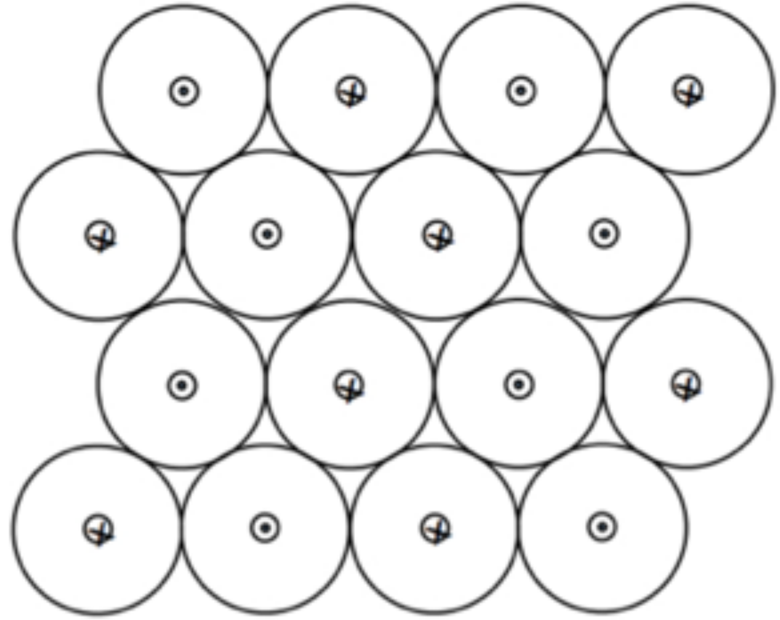
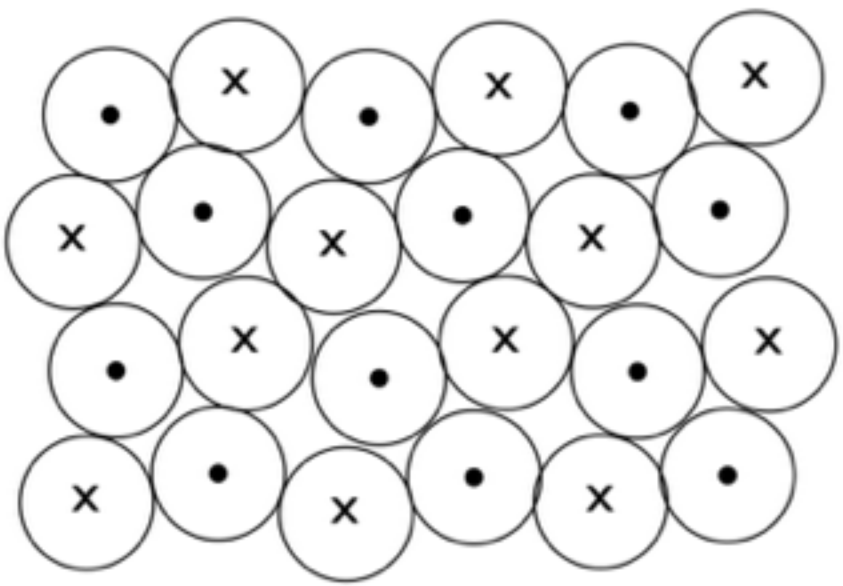
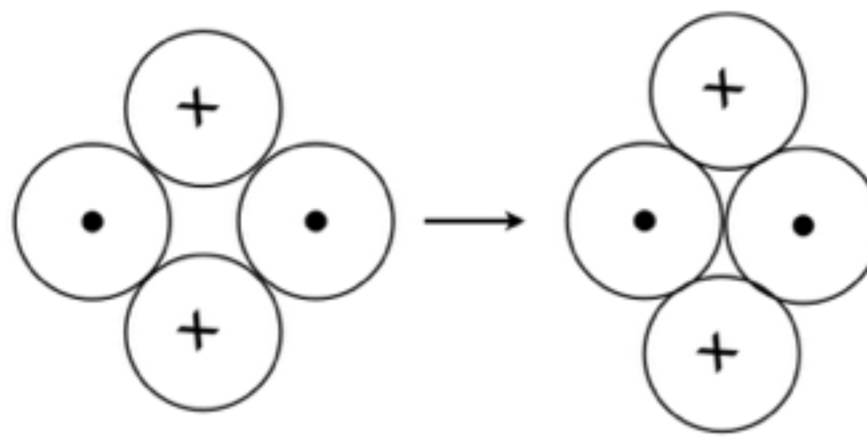




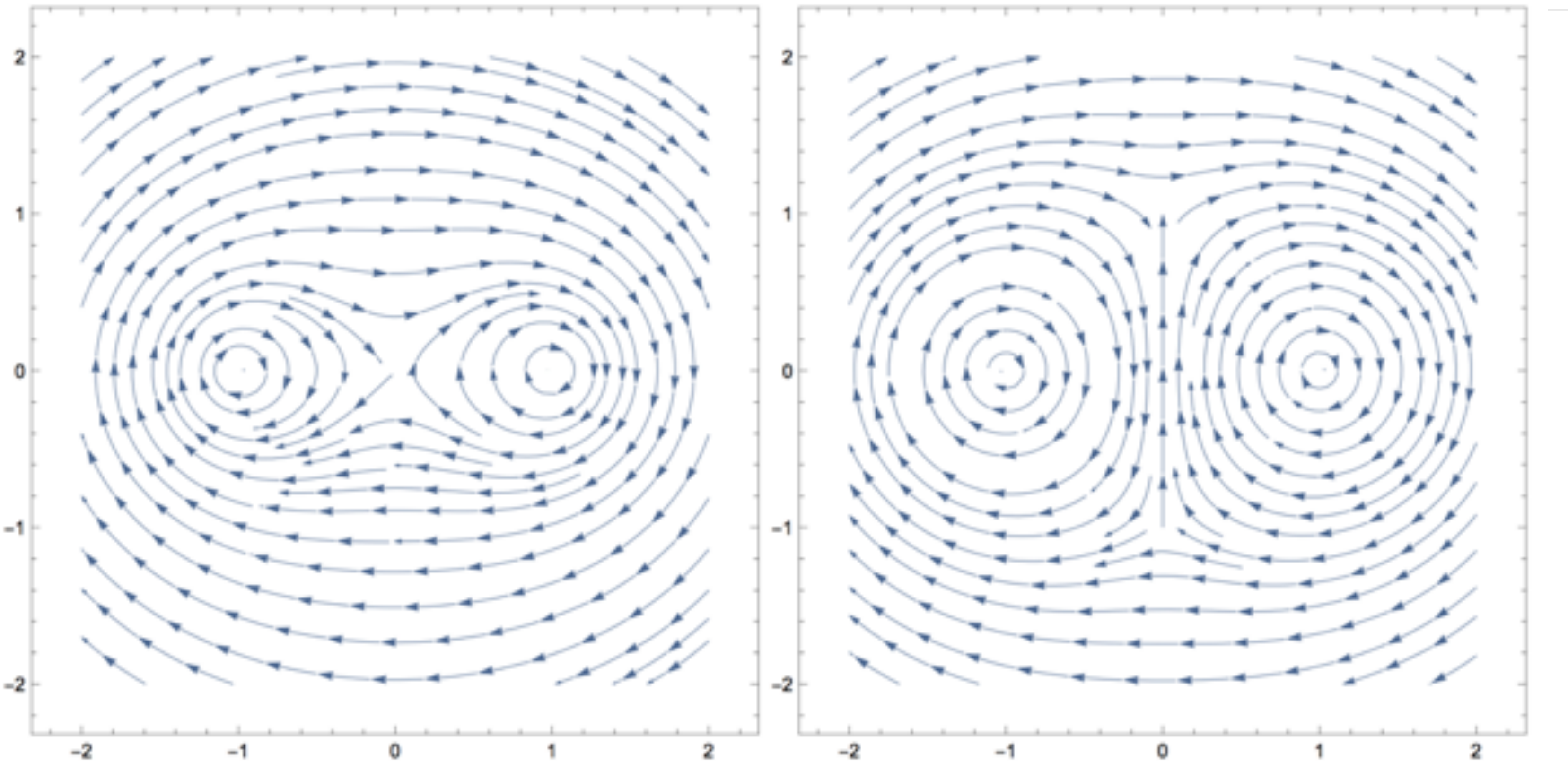








Current attraction: two stages: ``Free-fall'' and ``slow-resistive''

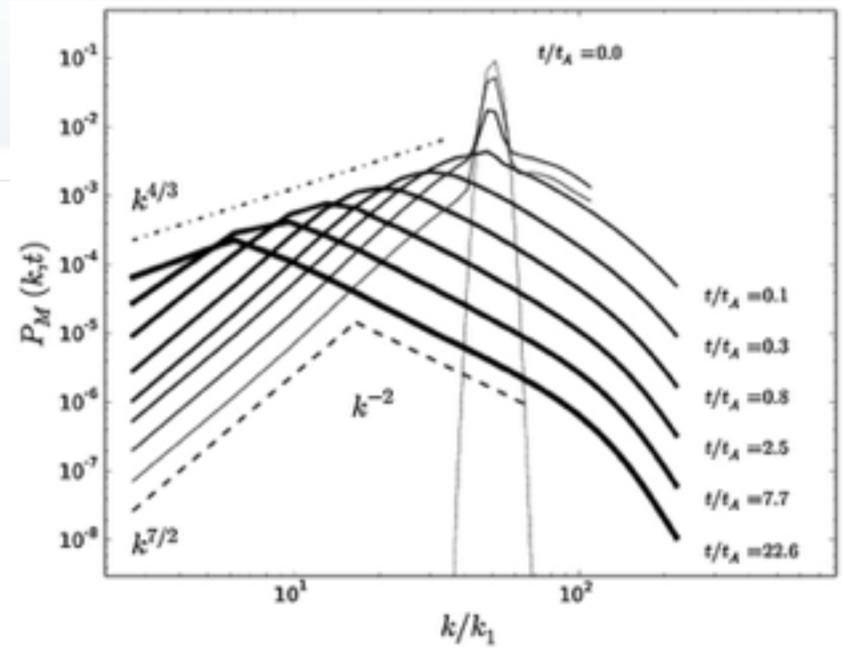


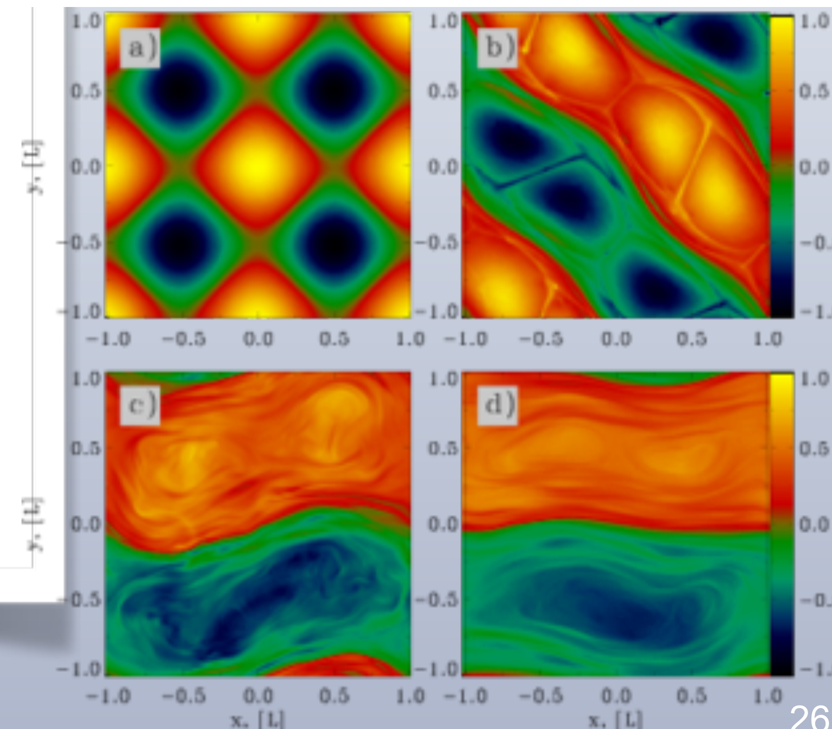
Initial attraction due to large-scale stresses
Quasi-steady (repulsion by the current sheet) - slow resistive reconnection
Two stages of particle acceleration: fast-impulsive and slow-resistive.

Inverse cascade

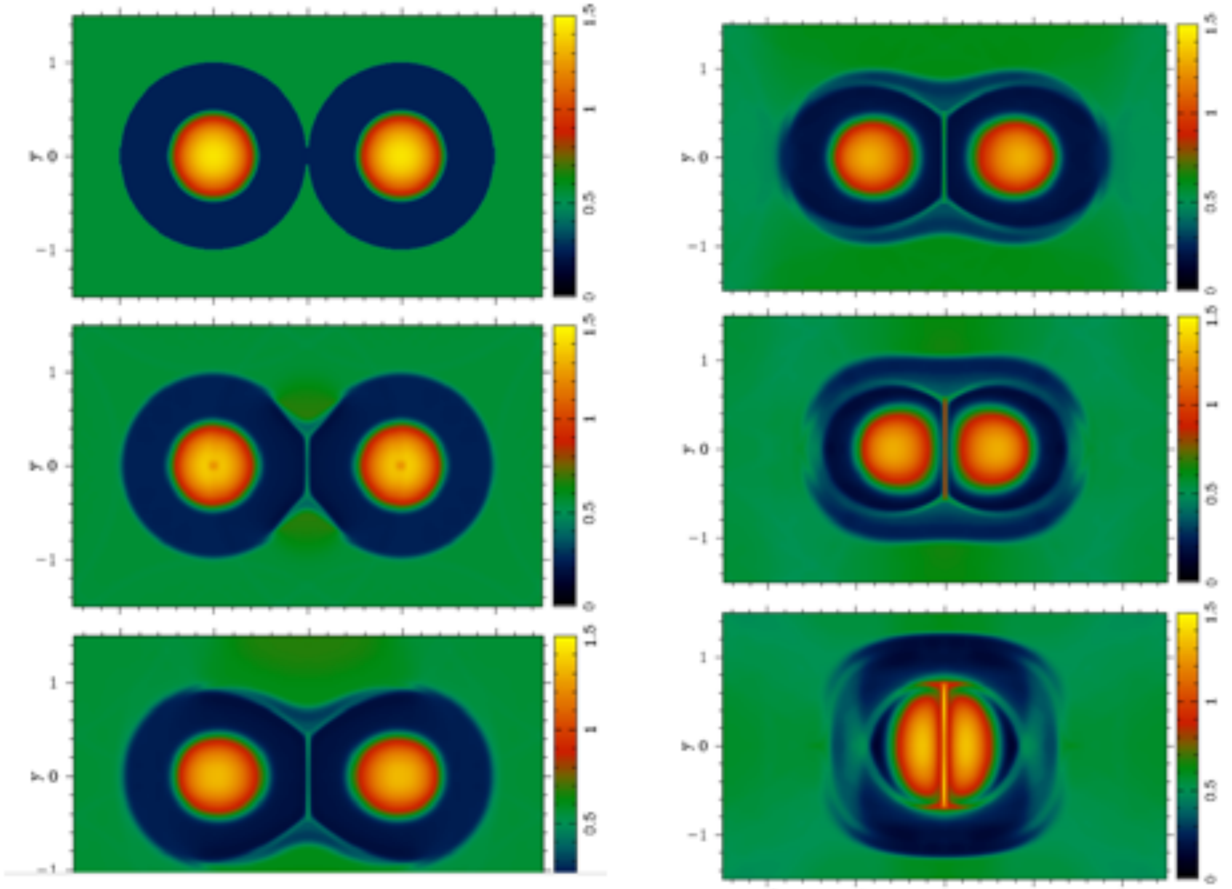
- Zrake '15 argued that island merger creates self-similar inverse cascade.
- Merger of islands into larger ones, up to box size
  - Conservation of area
  - Conservation of axial magnetic flux
  - Conservation of helicity
- $1 - 1/\sqrt{2} = 29\%$ fraction of magnetic energy is dissipated in each step

$$p = -\frac{\ln 2}{2\ln(1 - 1/\sqrt{2})} = 3.54 \approx 7/2$$





Merger of zero-current flux ropes

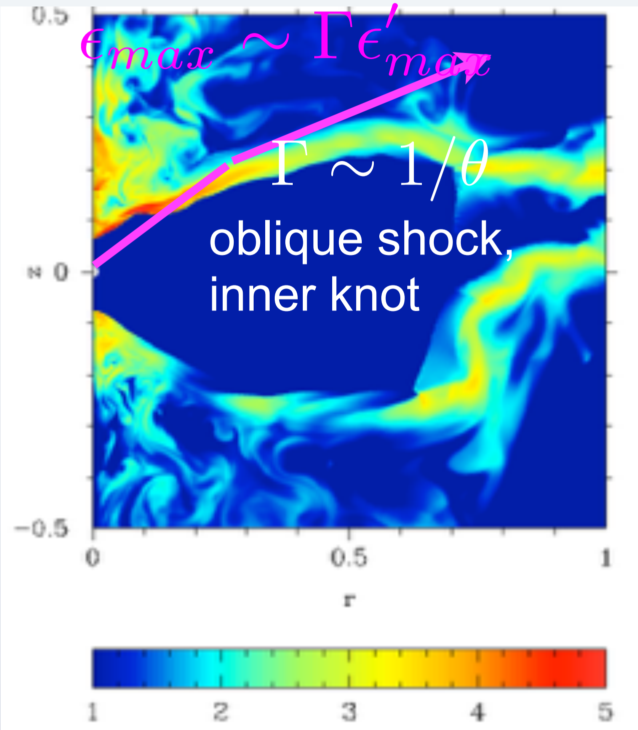


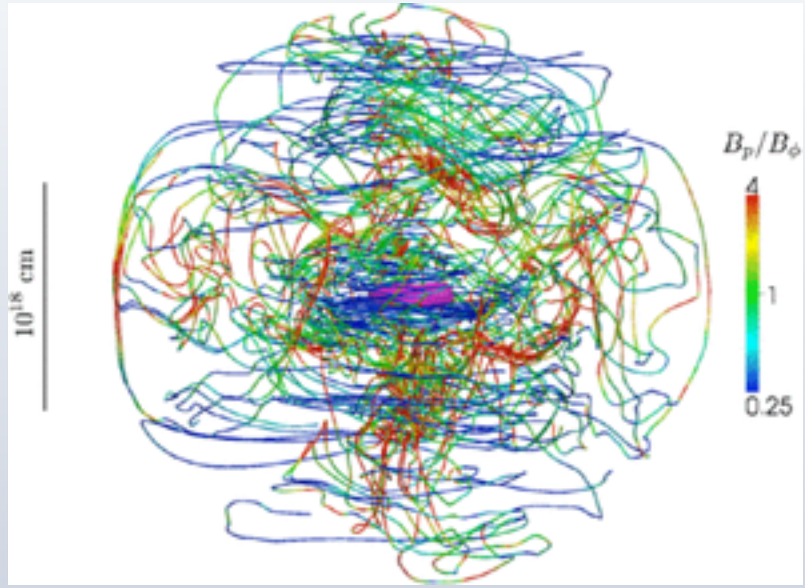
- No total current: no overall attraction force.
- First, resistive effects ``eat out" the envelopes (slow)
- After ||-current learn of each other - large scale attraction

Best case scenario

- High-sigma regions on the wind, but not too high: $\sigma_W \sim 10 - 100$.
- Post-shock $\gamma_T = \gamma_W / \sigma_W$
- Post-shock sigma amplification in decelerating flow: $\sigma_f \sim 100\text{-}500$
- Kink instability: formation of current tubes
- Initial stage of current tube merger: X-point collapse
- Particle acceleration to $\gamma_{max} \approx \gamma_T \sigma_f^2$
- Can easily reach $\gamma \sim 10^9 \gg \gamma_w \sigma_w^{5/2} \gg \gamma_w \sigma_w$

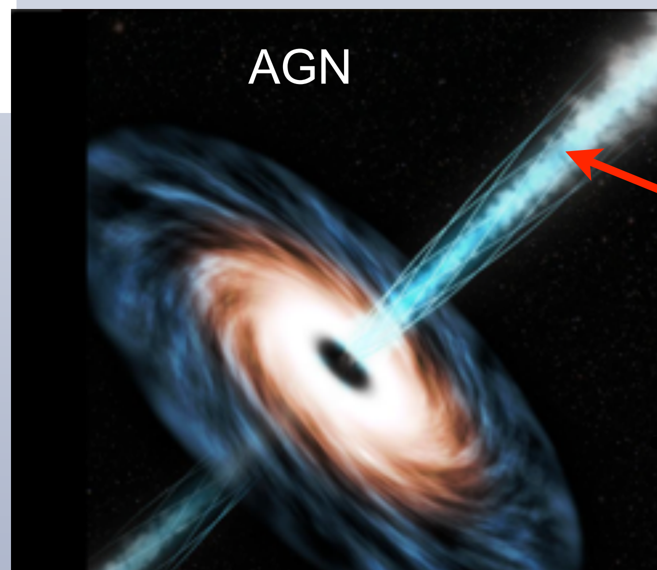
Where in Crab and AGNs?





Porth+ 2014

Komissarov & Lyutikov, 2011



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

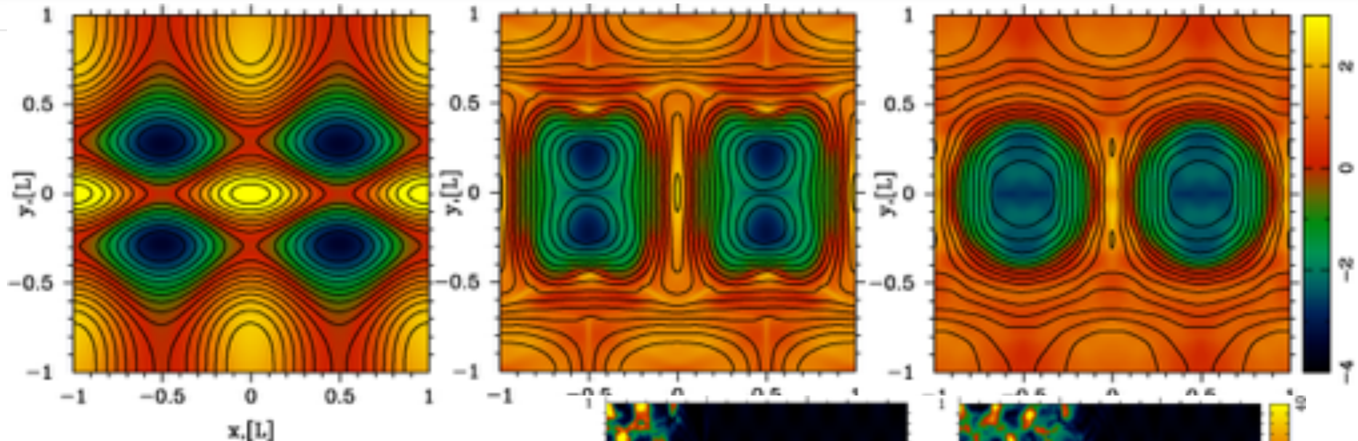
Conclusion

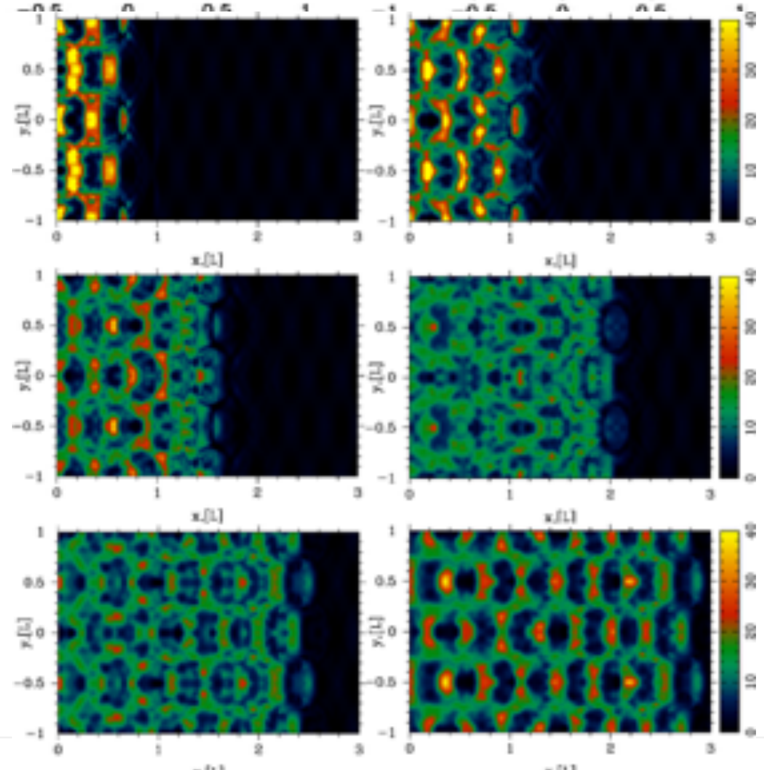
Reconnection in magnetically-dominated plasma

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

2.b island merger triggered by external perturbation

Stressed magnetic islands:

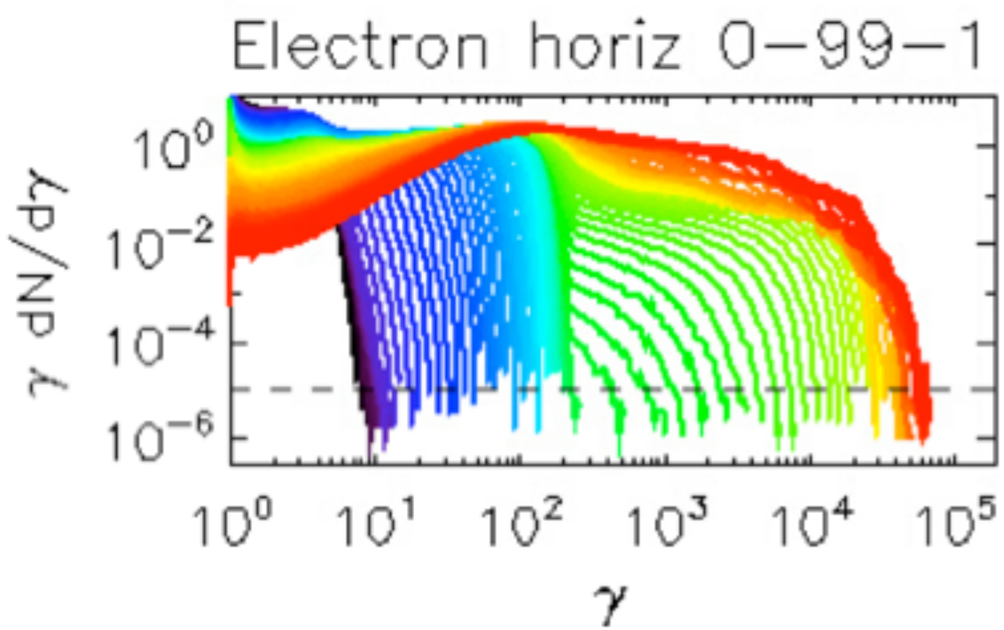


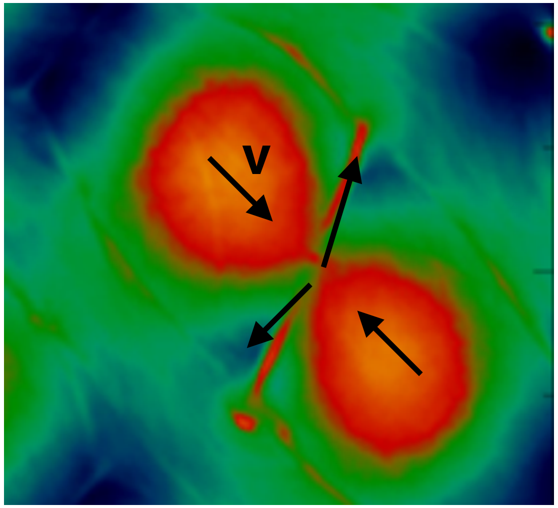


- Two ways to trigger fast reconnection:
  - development of tearing-like mode
  - external compression

Particle acceleration in island merger

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

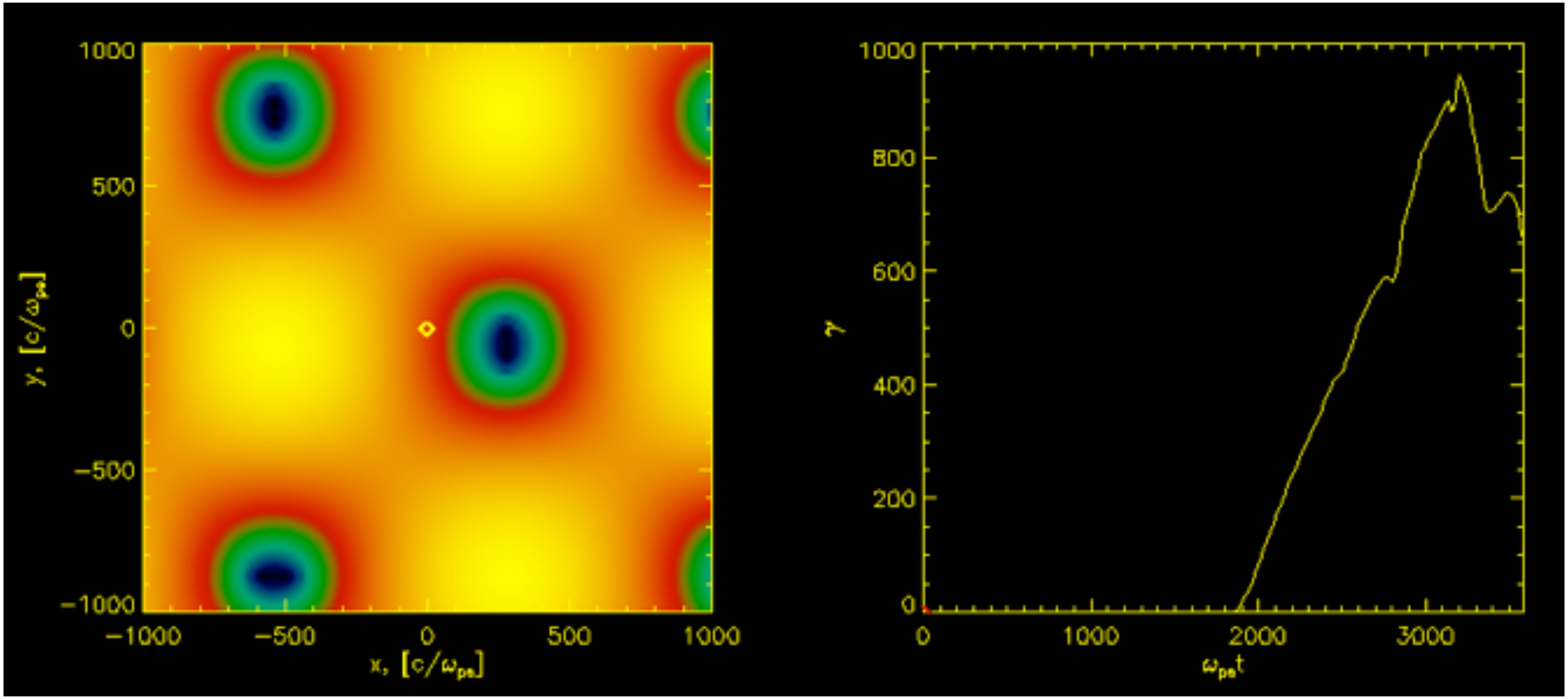




Sweet-Parker-like picture

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

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



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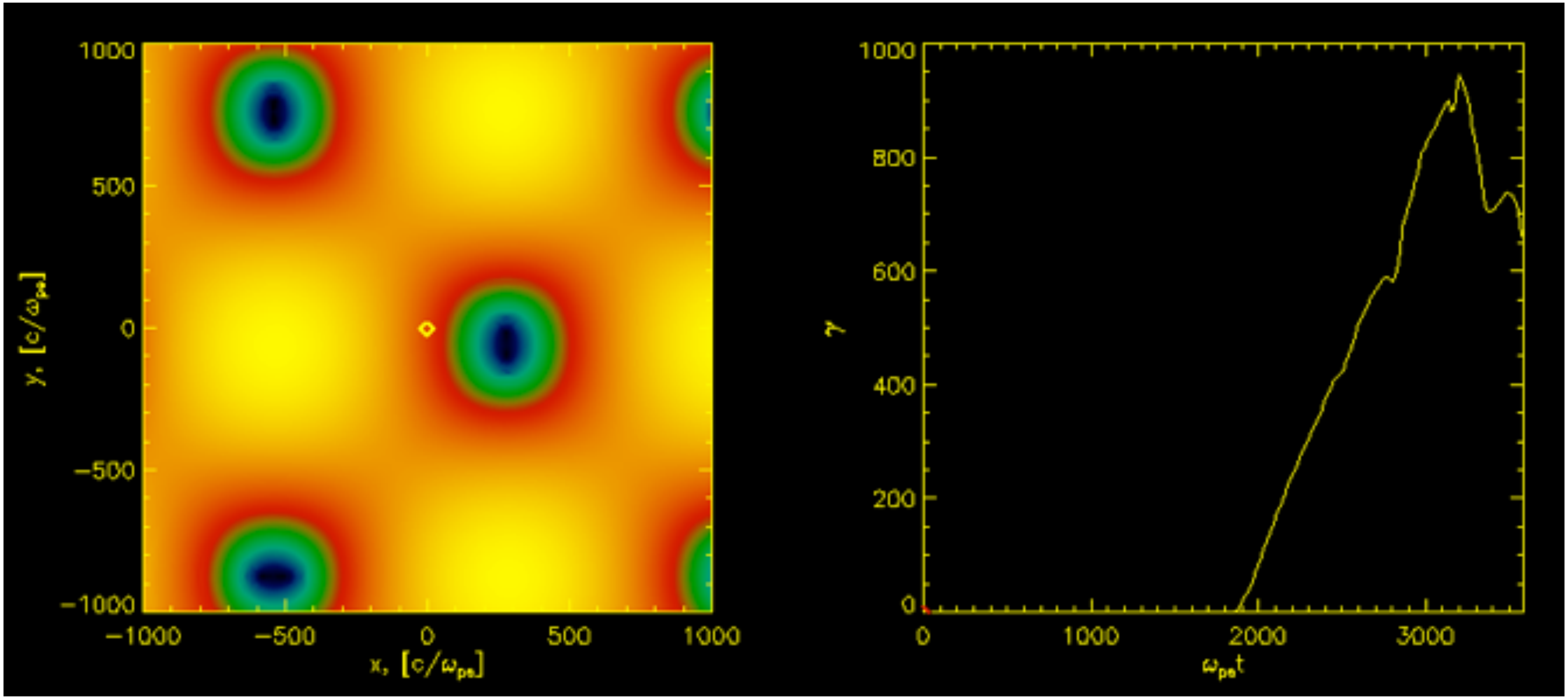

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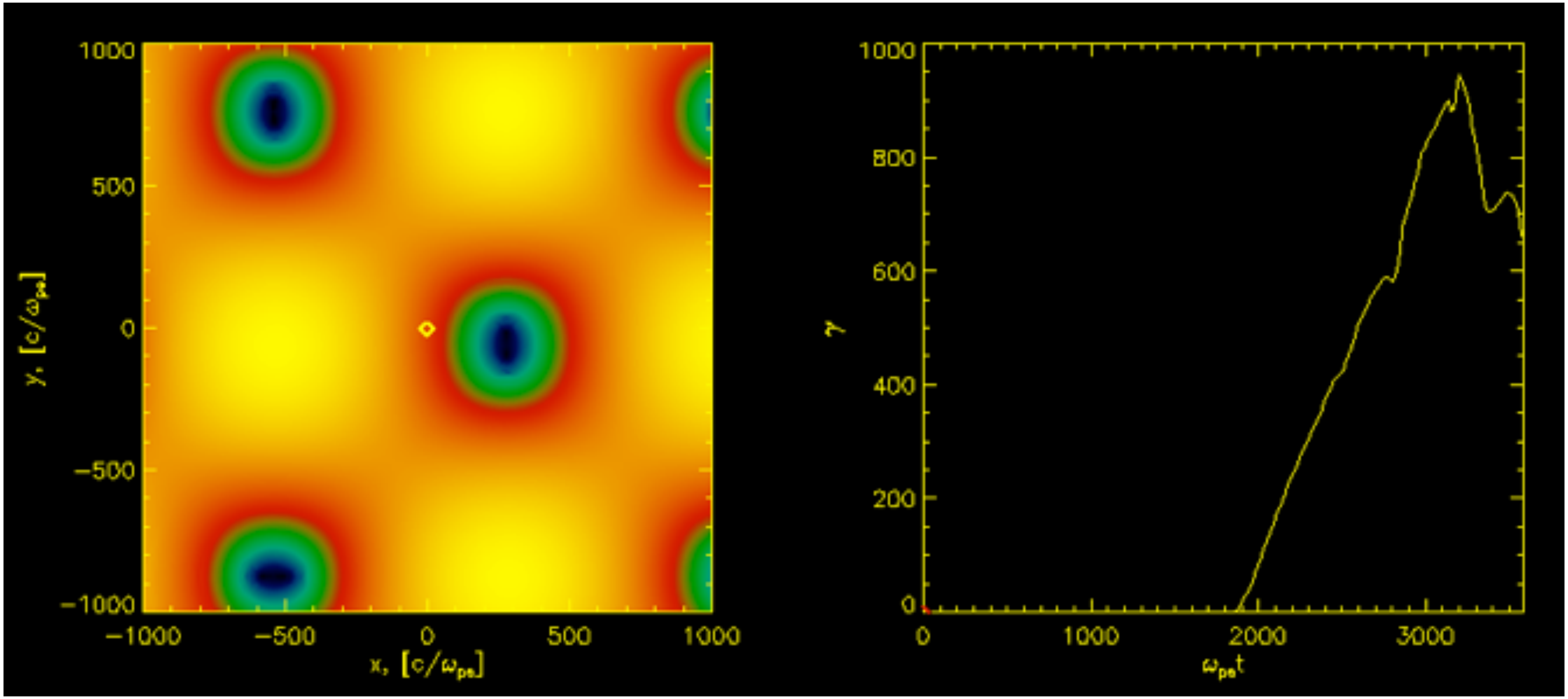
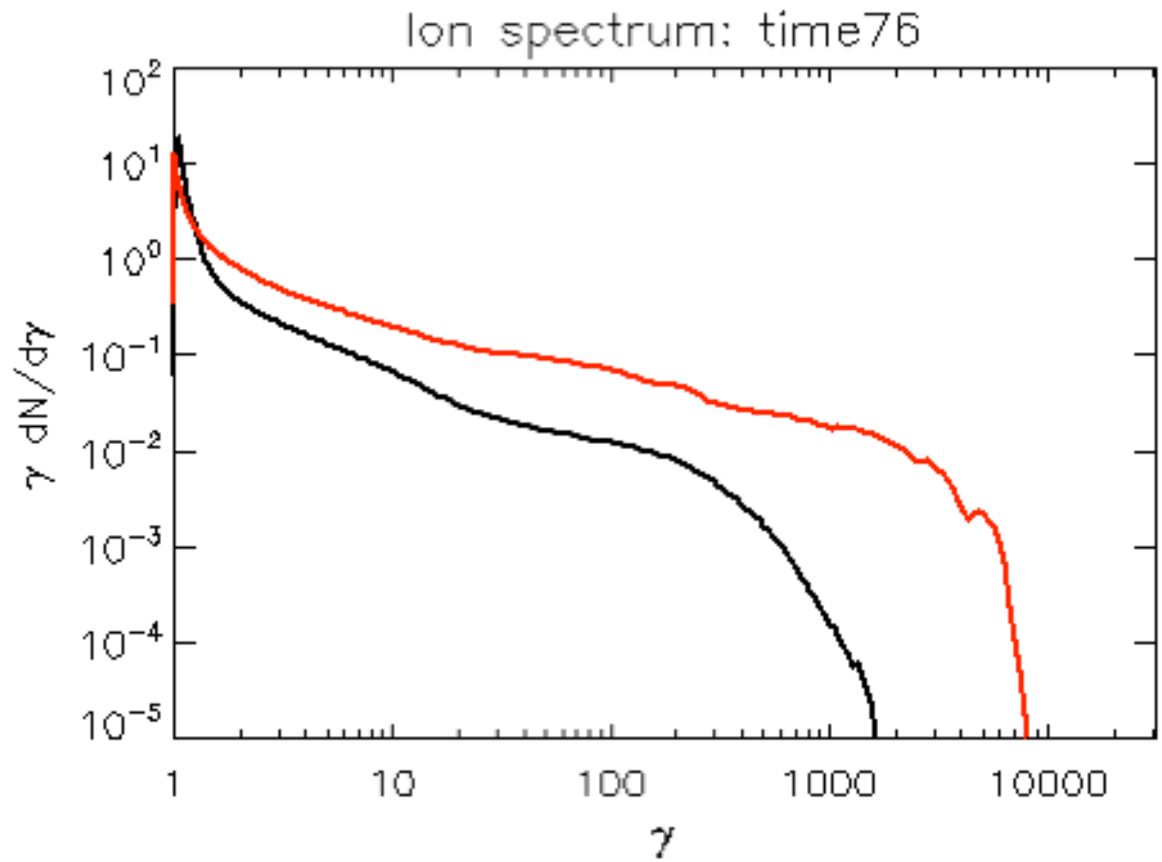


$$E \sim B \propto t$$

$$\epsilon \propto t^2$$

Spectra as functions of sigma

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



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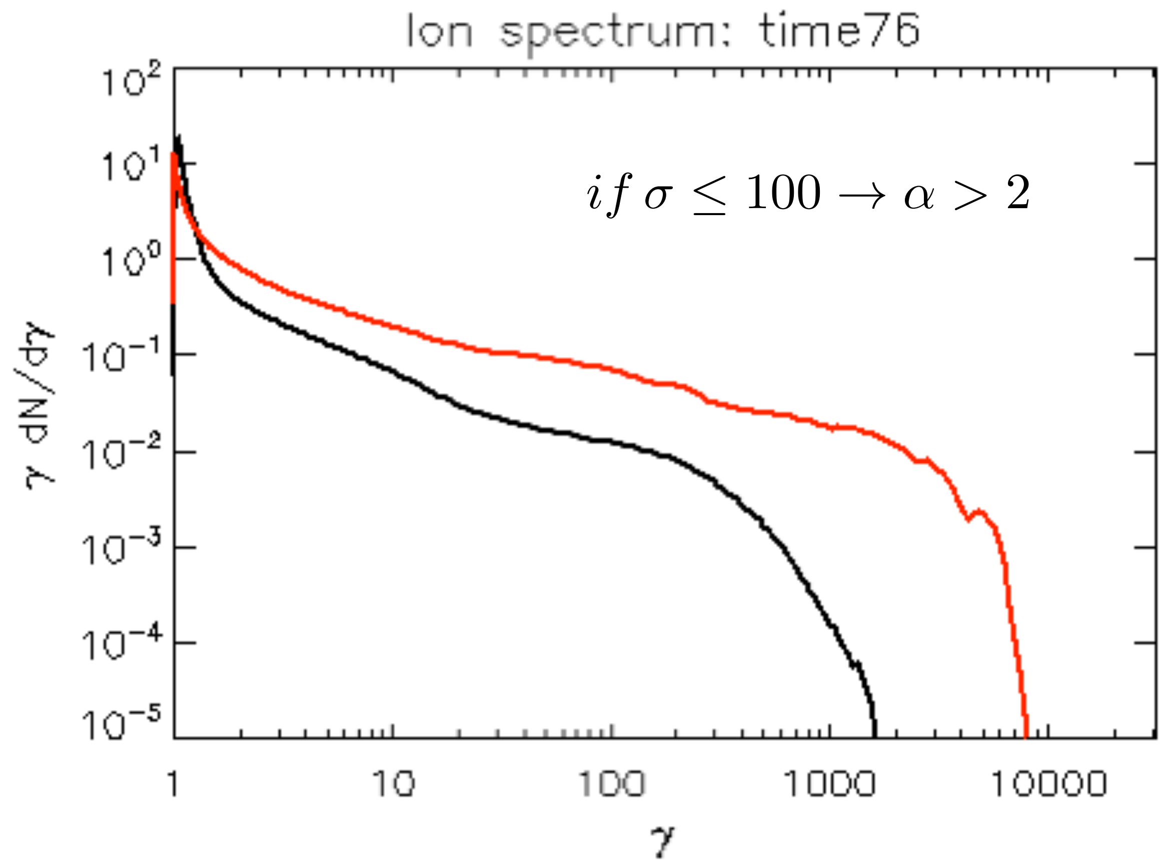

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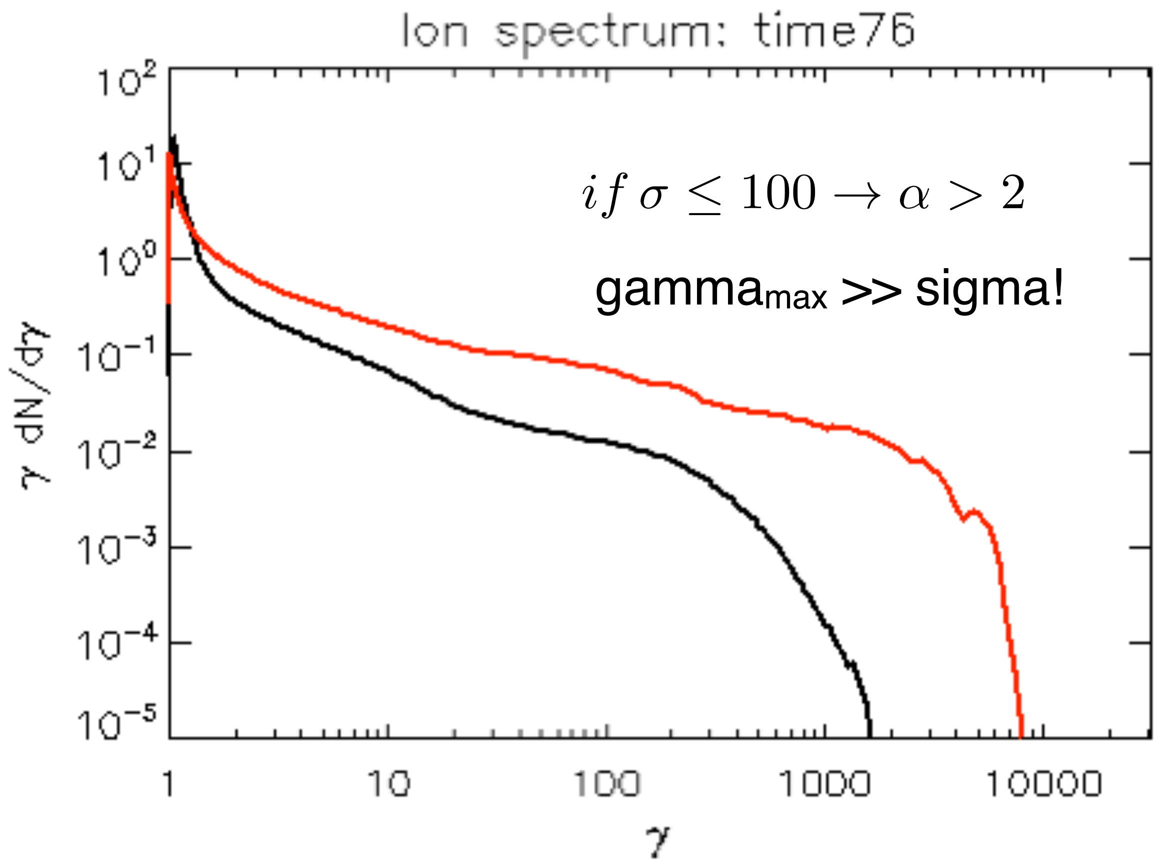
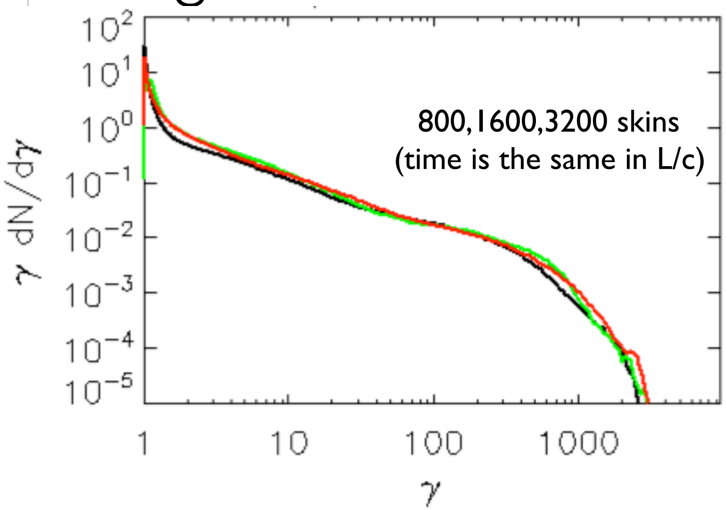
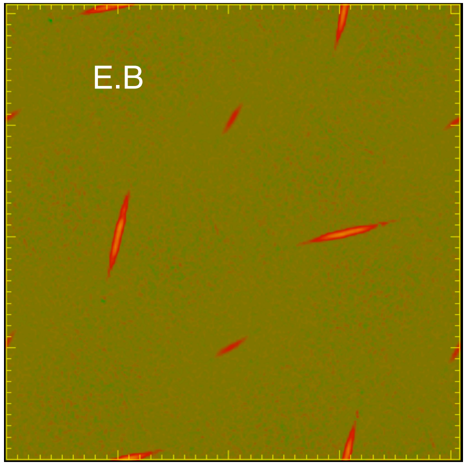


gamma ~ 10^9?

- 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 dominated





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- Optimal regime: sigma ~ 100, L/delta ~ 100-1000

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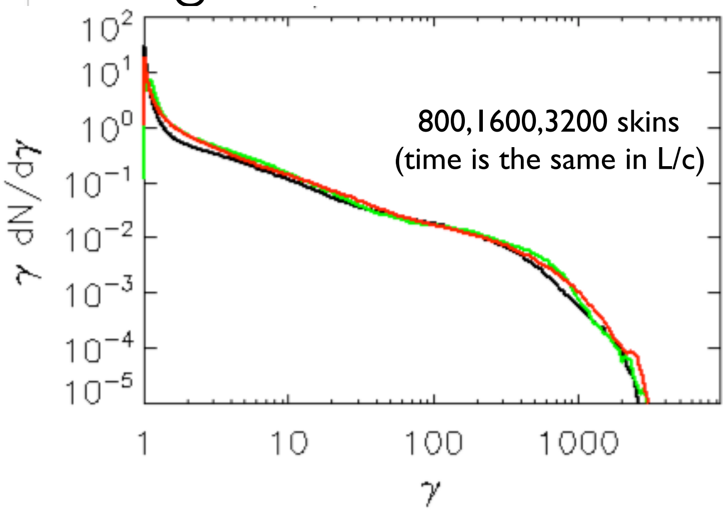
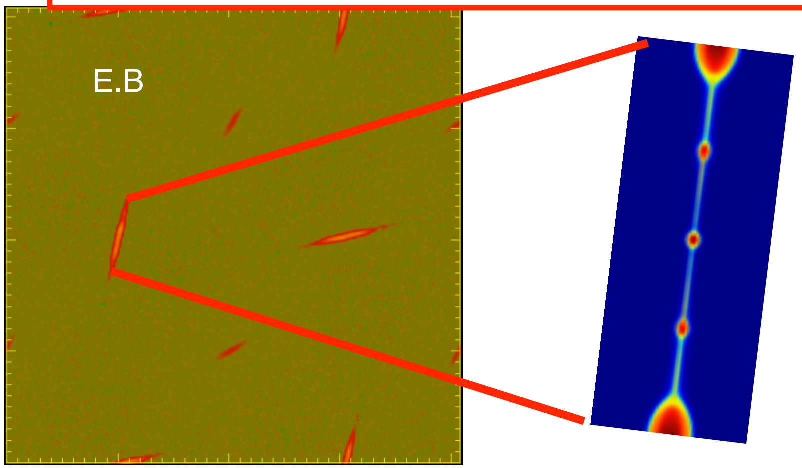


L>L$_{crit}$ - plasmoid instability of current sheet



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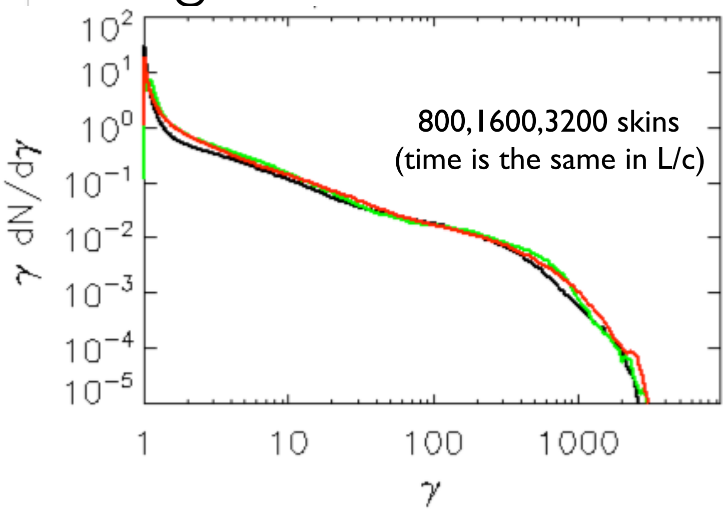

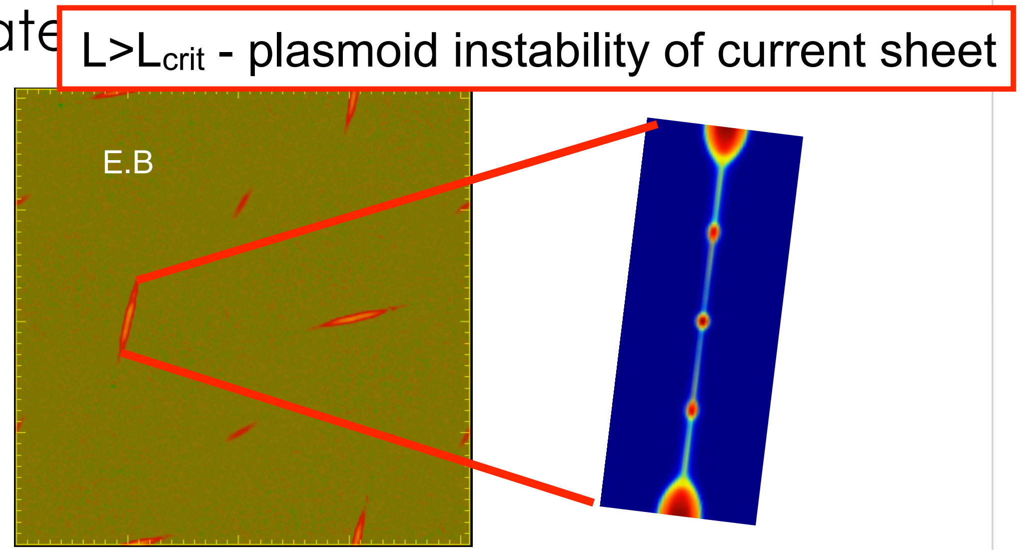

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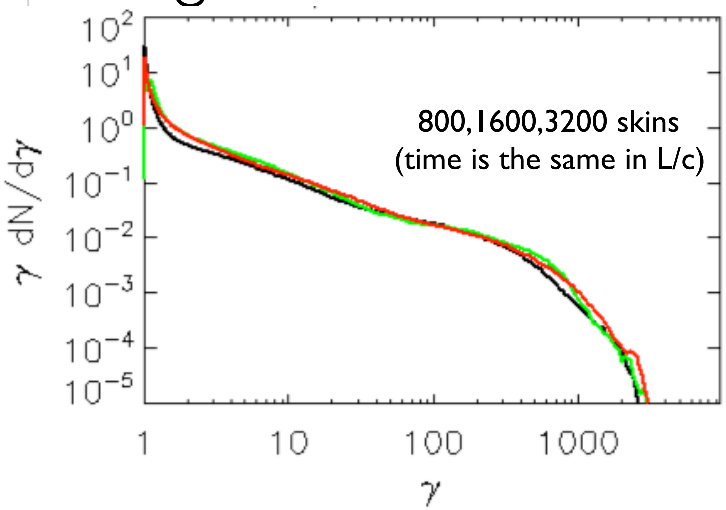

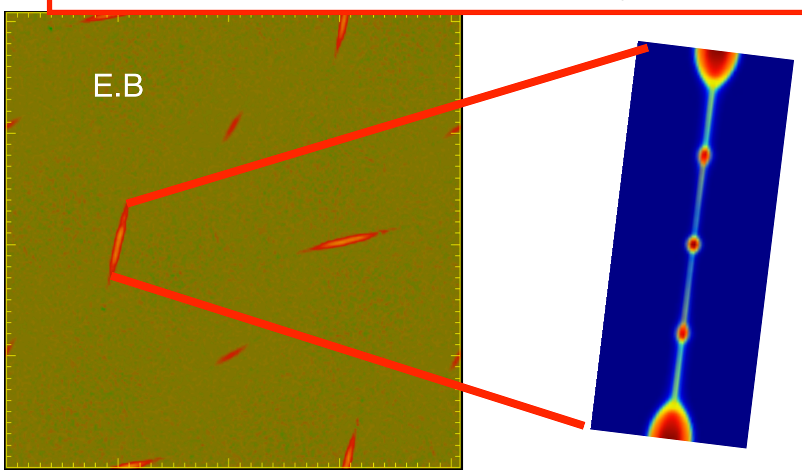

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$\alpha > 2$ E ~ B

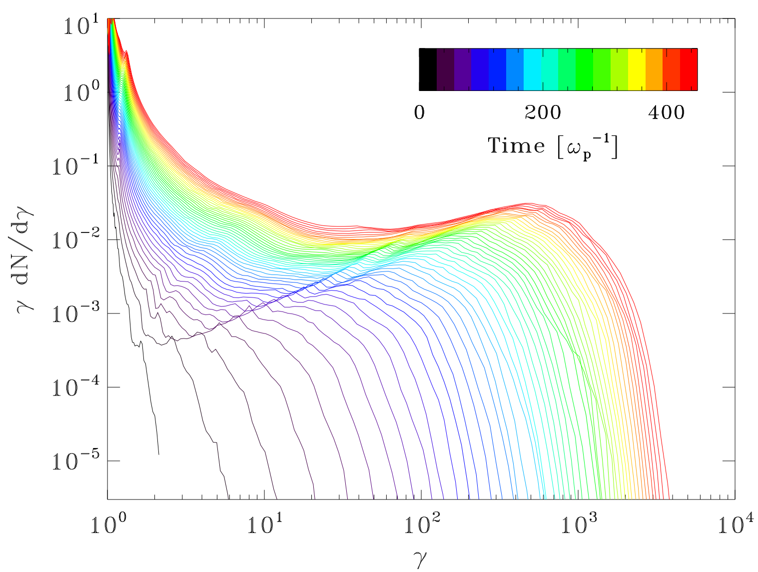
Acceleration in X-point collapse

- 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



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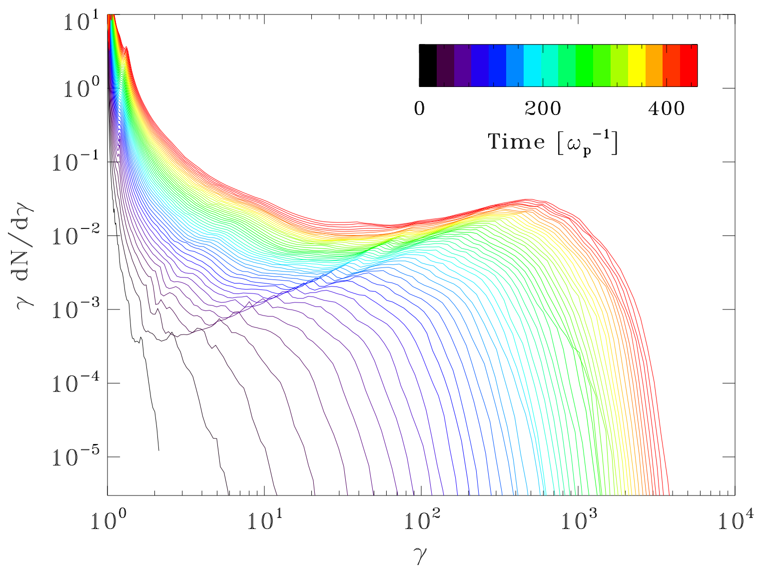
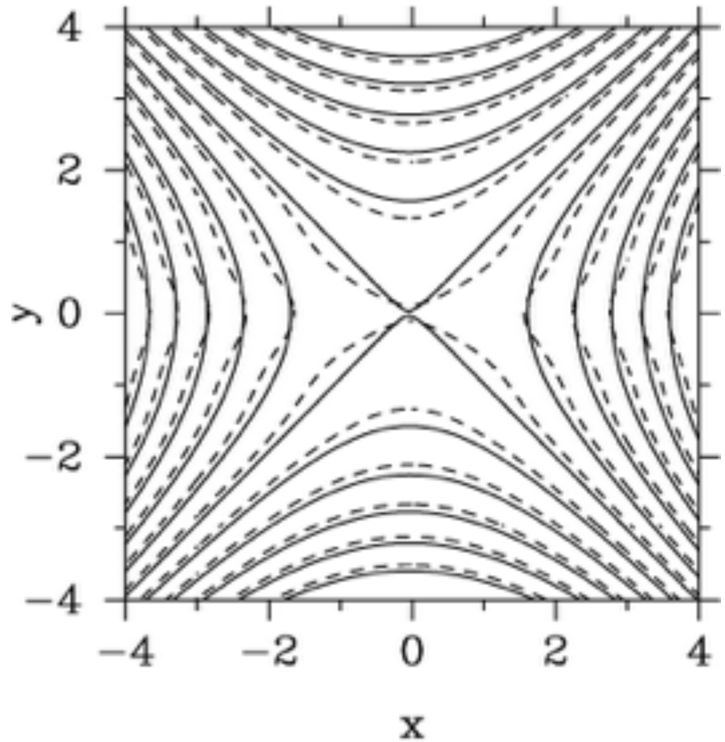
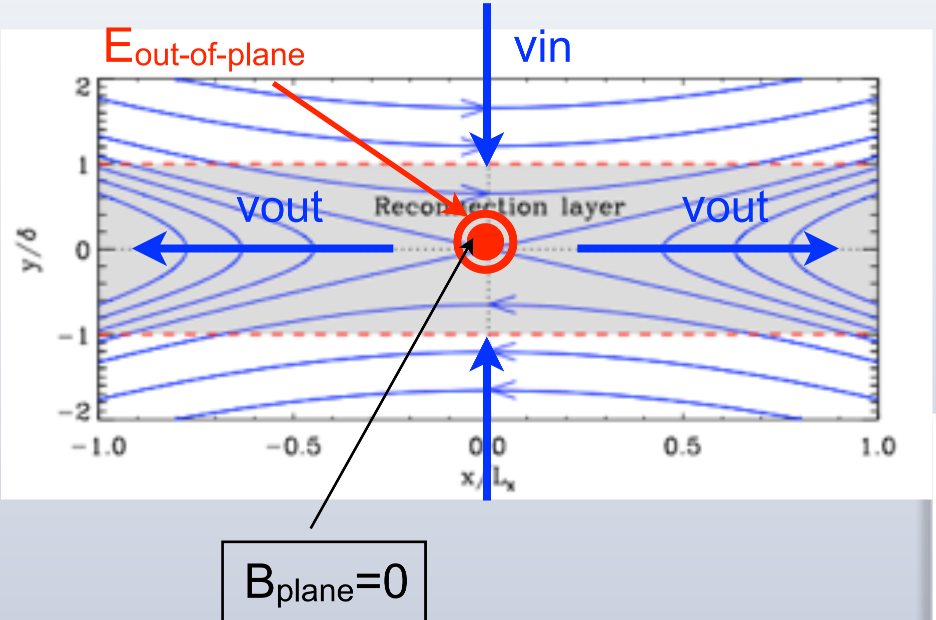


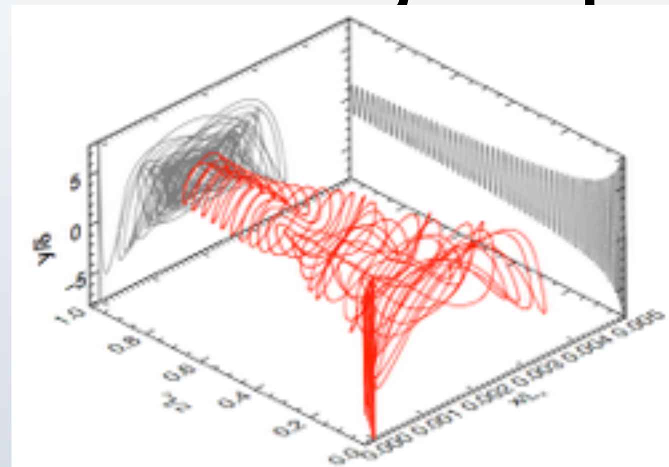
1.The X-point

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



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 (Hantao's talk)
- Large island merger: inflow velocities << c
- All particles accelerated (gamma < sigma)
- Typically tearing does not lead to global reconfiguration (sawtooth)