The Crab Nebula, pulsar winds and explosive reconnection in relativistic plasmas

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in collaboration with

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- ApJ 2017;

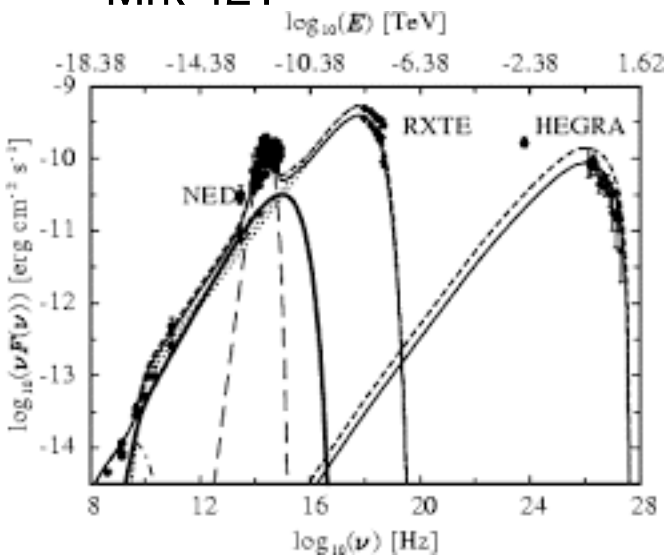
- JPP, submitted

Two related topics

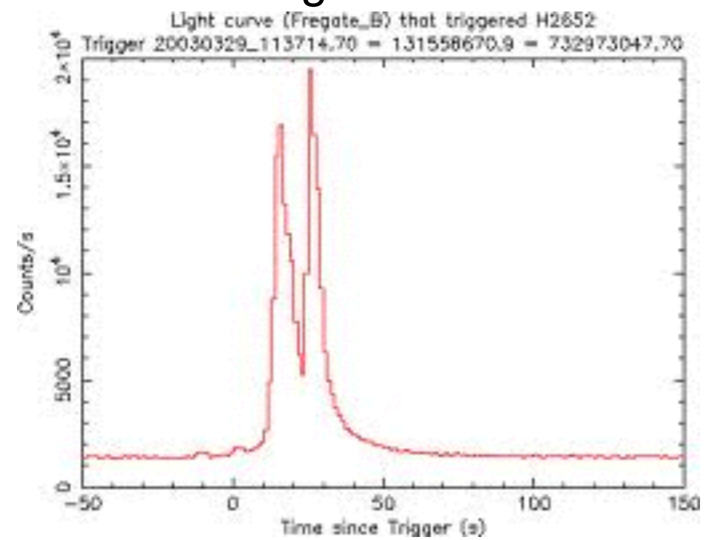
- Particle acceleration in relativistic astrophysical plasmas
- Structure of pulsar winds (Crab Nebula)

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

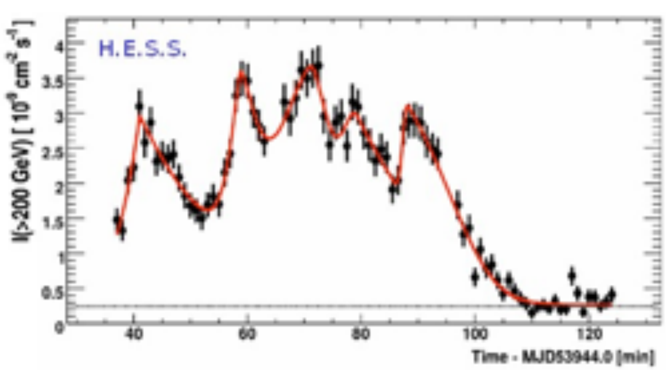
Mrk 421

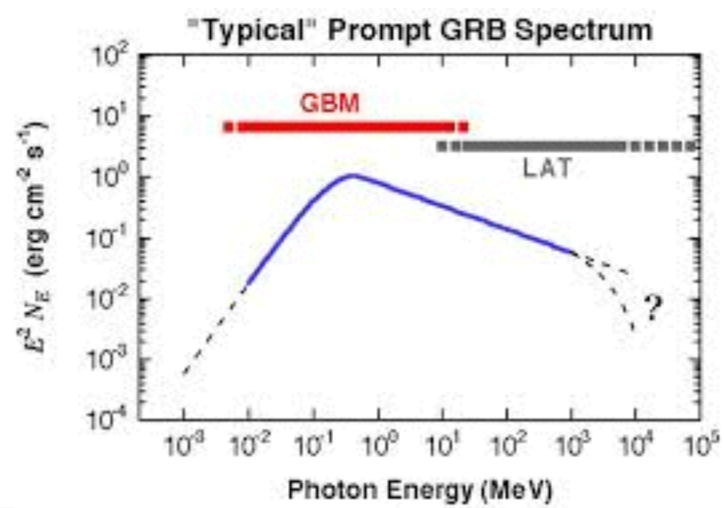


GRB light curve

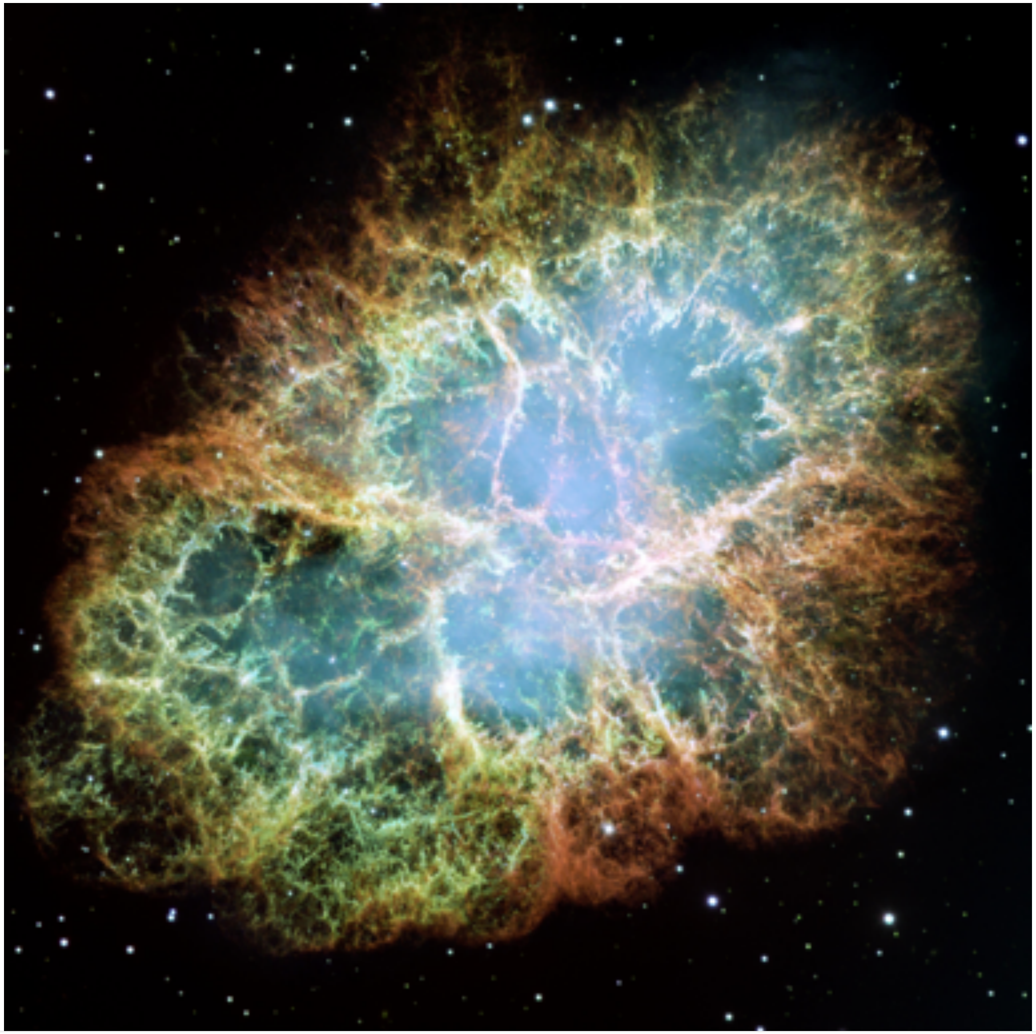


blazar PKS 2155-304





Crab Nebula: the paragon of high energy sources



Part I: The Crab Nebula we understand

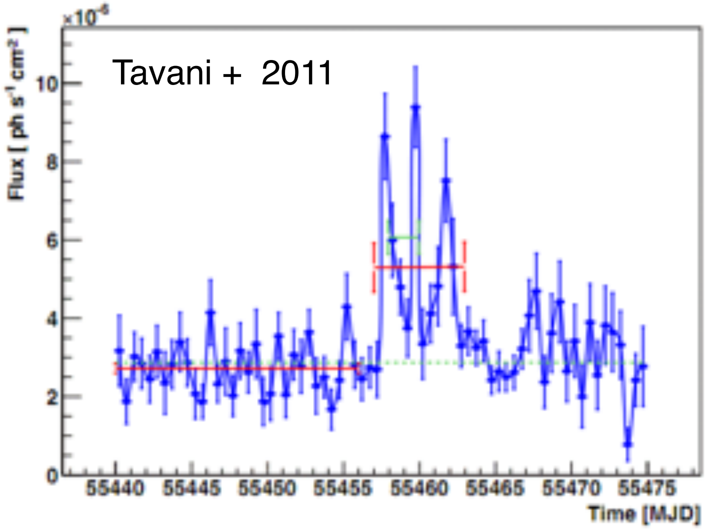
Crab flares

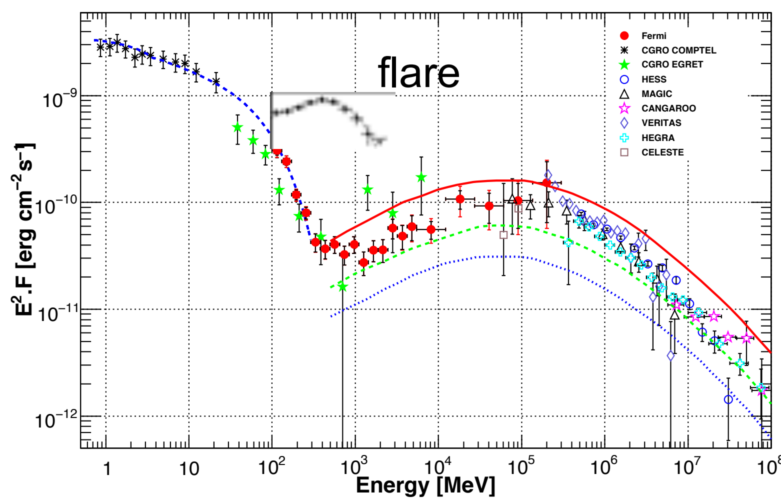
- Few times per year
- Random
- Flux increase by 40
- 100 MeV - 1GeV
- lasts for a day (<< dynamical time)

The synchrotron limit

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

$$\hbar\omega_s \approx \hbar\gamma^2\frac{eB}{m_ec} = \eta\frac{m_e\hbar c^3}{e^2} \approx 200\,\eta\,\mathrm{MeV}$$



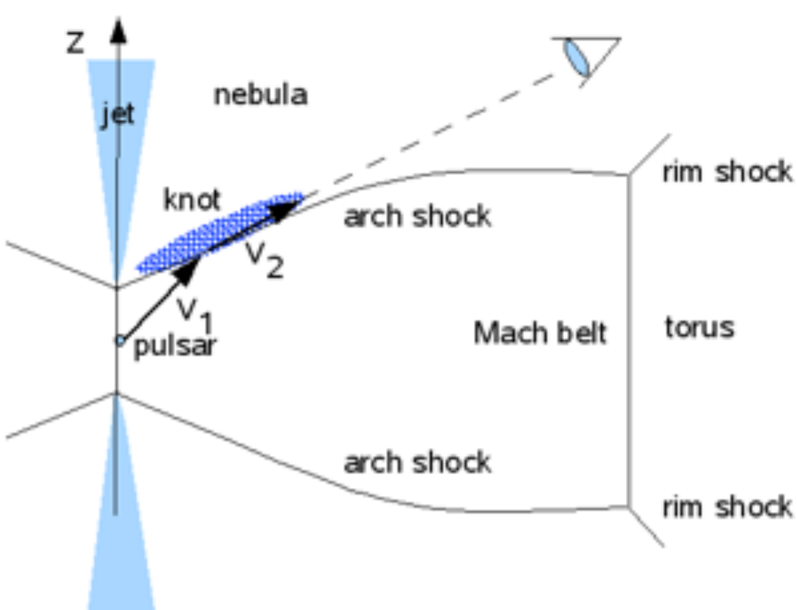


- **Shock acceleration is excluded**

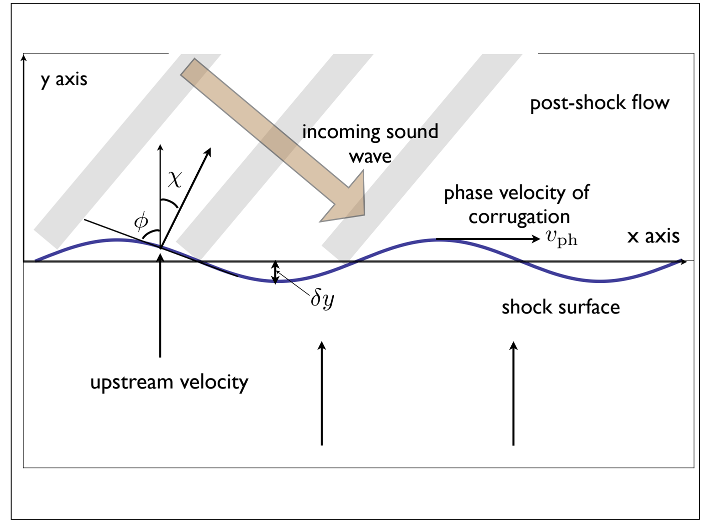
Nearly monoenergetic!

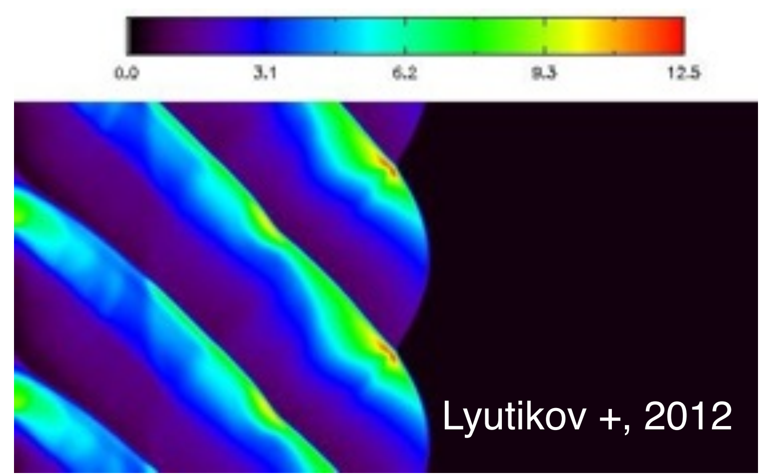
Flares from Crab Inner Knot?

$$L_w \propto \sin^2 \theta$$



Komissarov & Lyutikov 2011

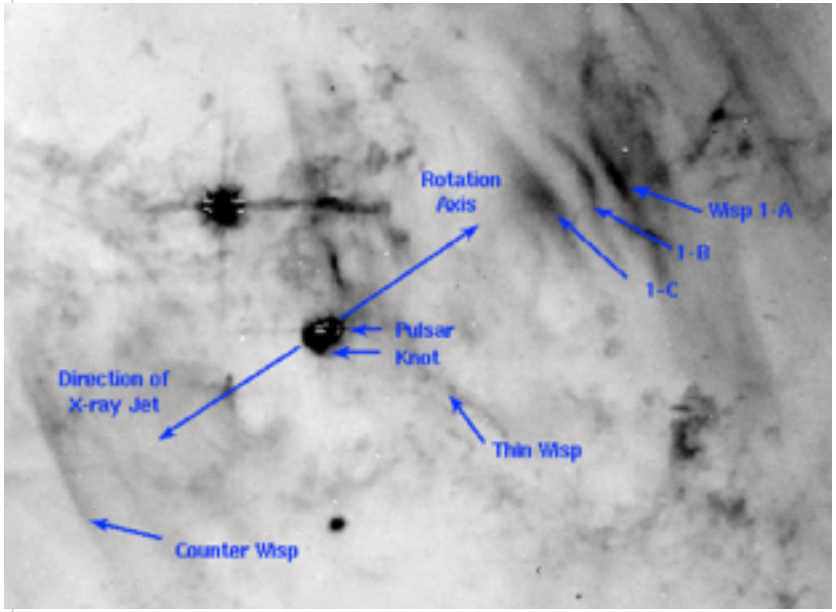


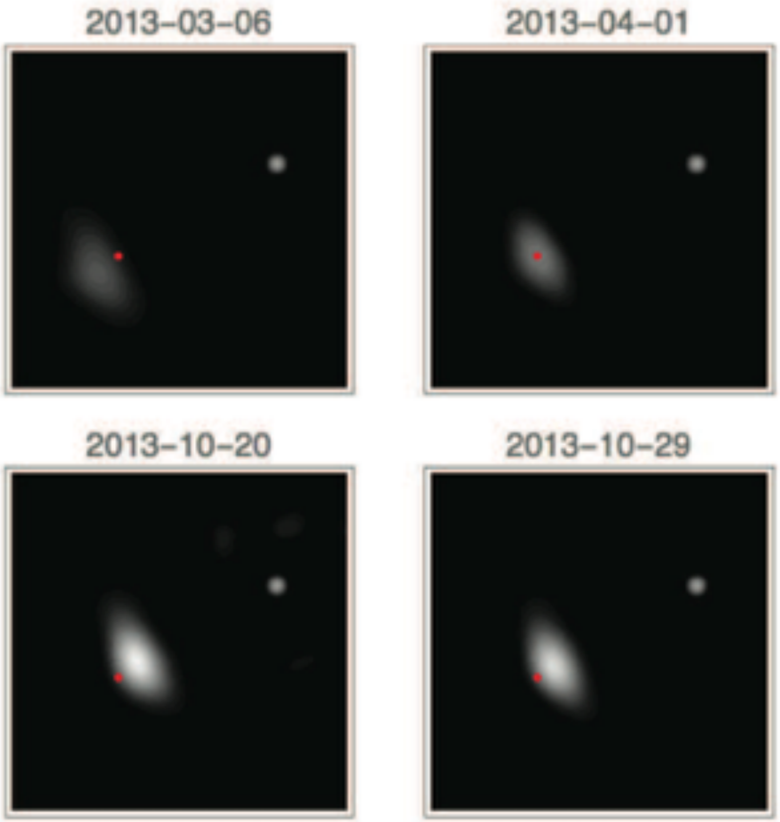


Lyutikov +, 2012

Crab Inner knot

Scales ~ 0.5'' (light day)

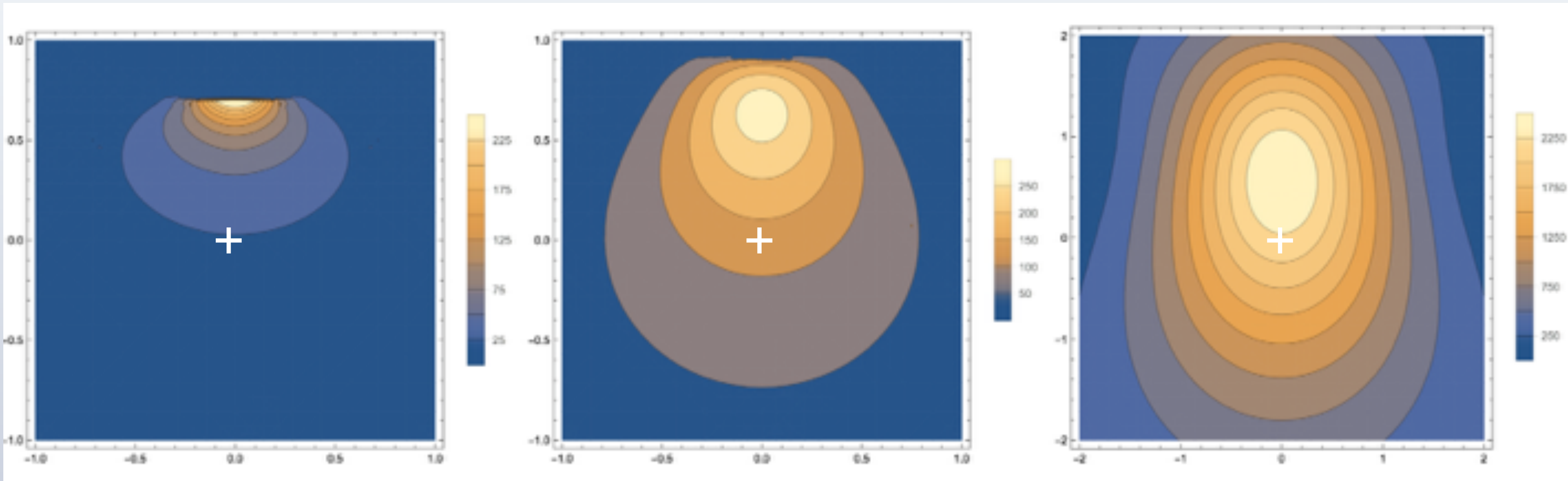


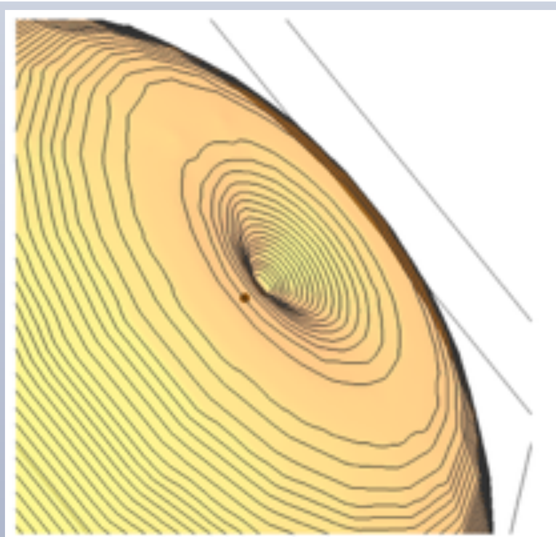


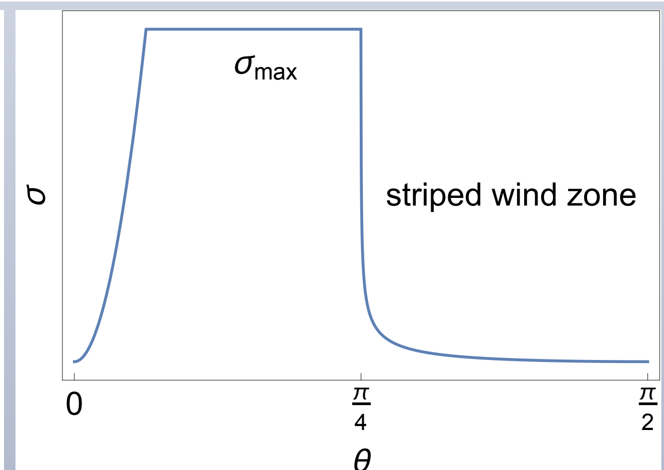
Rudy +, 2015

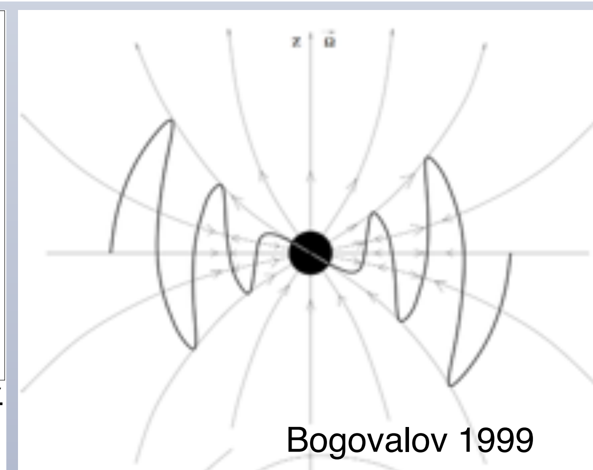
In the knot sigma is small!

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

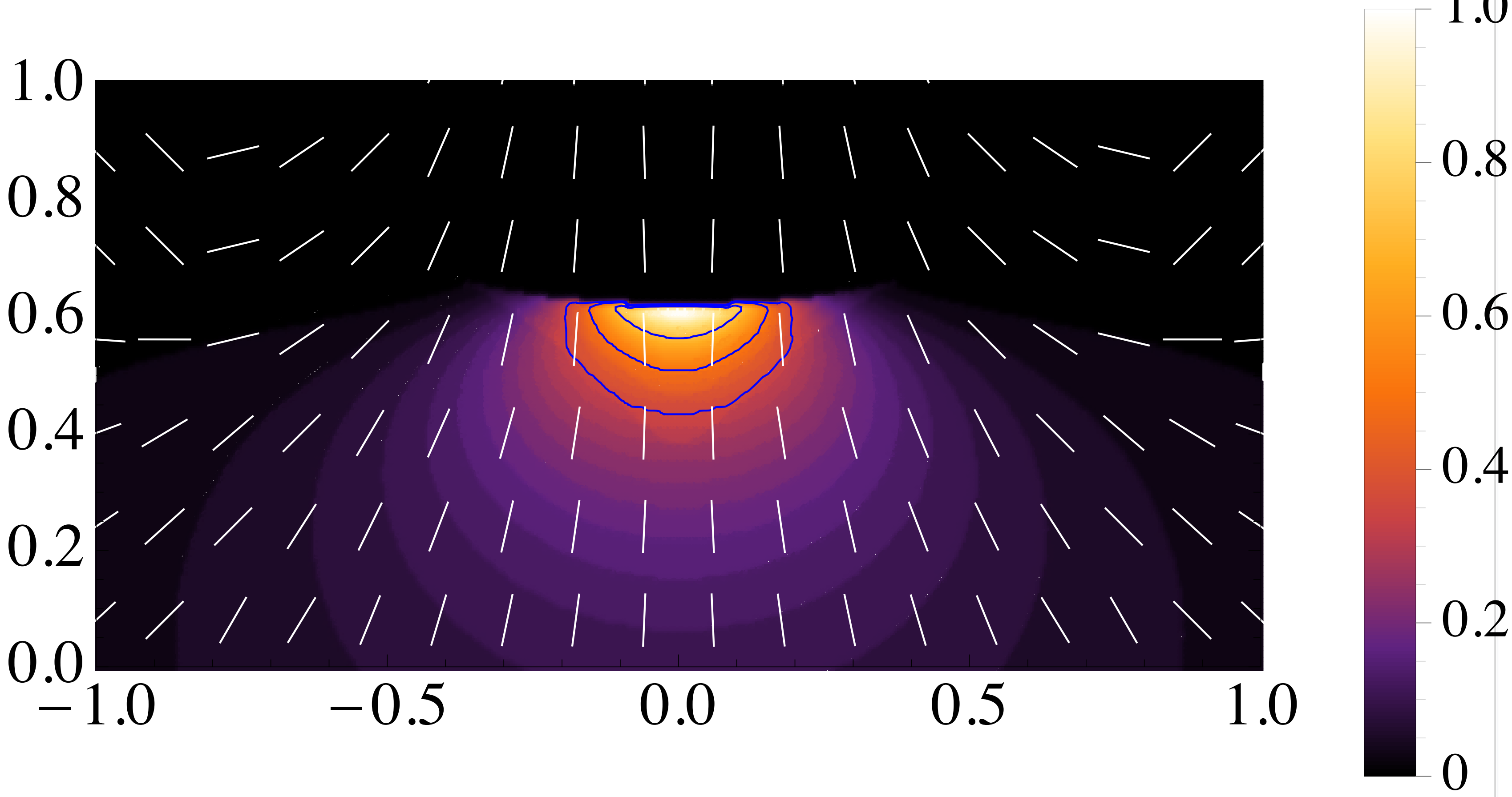








Polarization



Inner knot: surface of relativistic shock

• **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 $\ll 1\%$.

• **Variability**: The knot flux is anticorrelated with its separation from the pulsar.

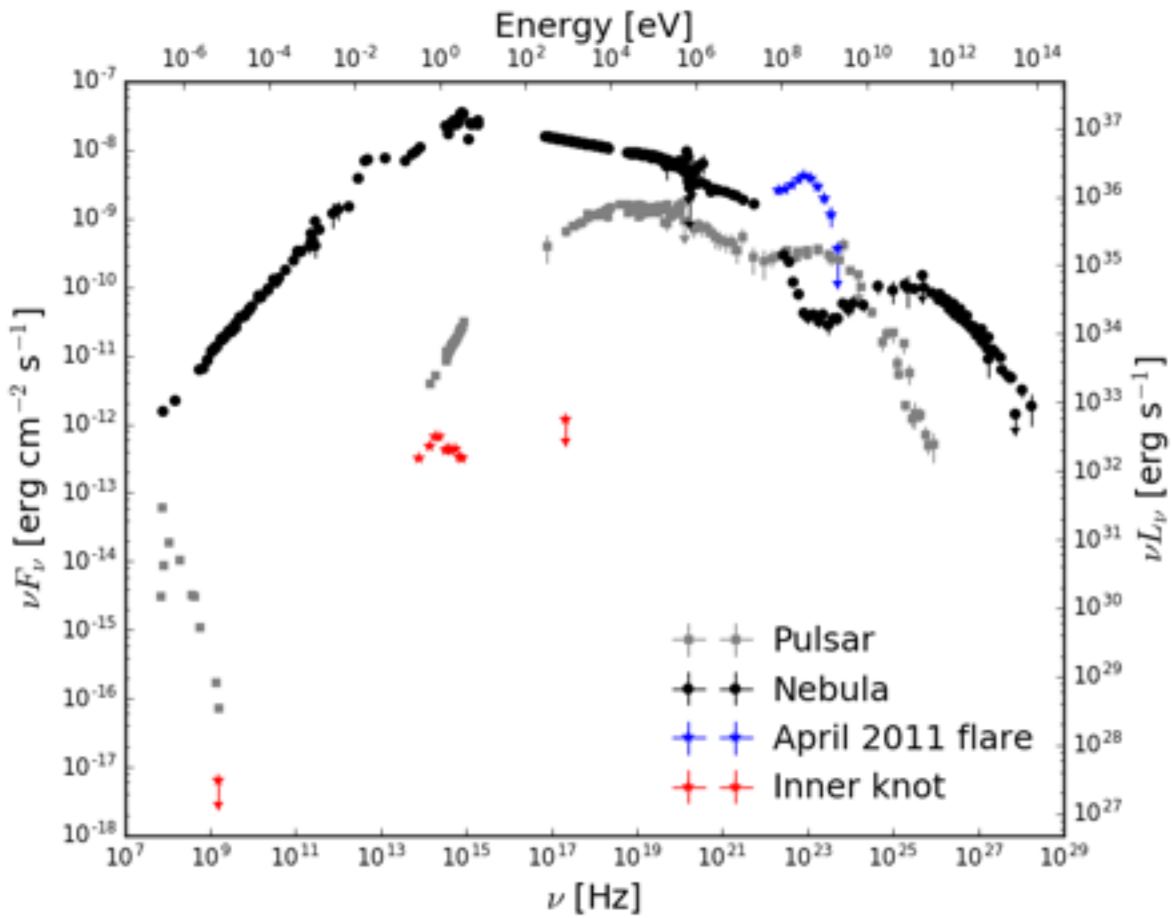
Not a sight of gamma-ray flares.

Pulsar winds: coming together of theory, simulations and observations

Wind properties

- Knot: **Thermal** (!) spectrum, $\gamma_w = 3 \times 10^4$

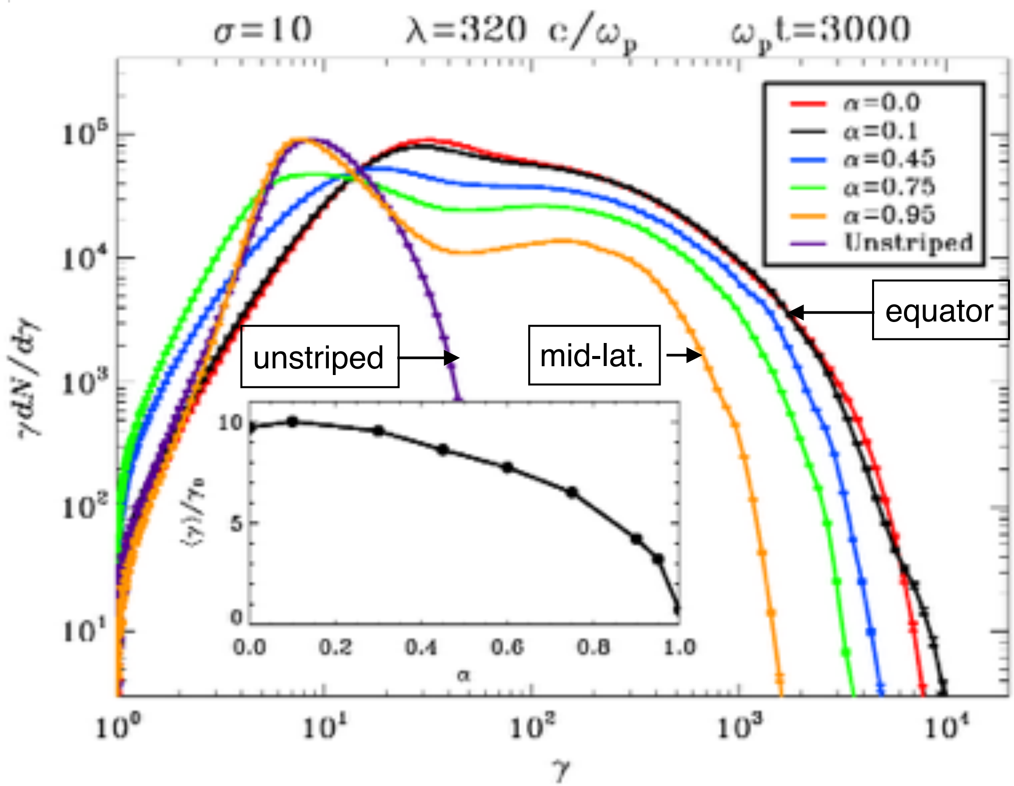
Porth +, 2017

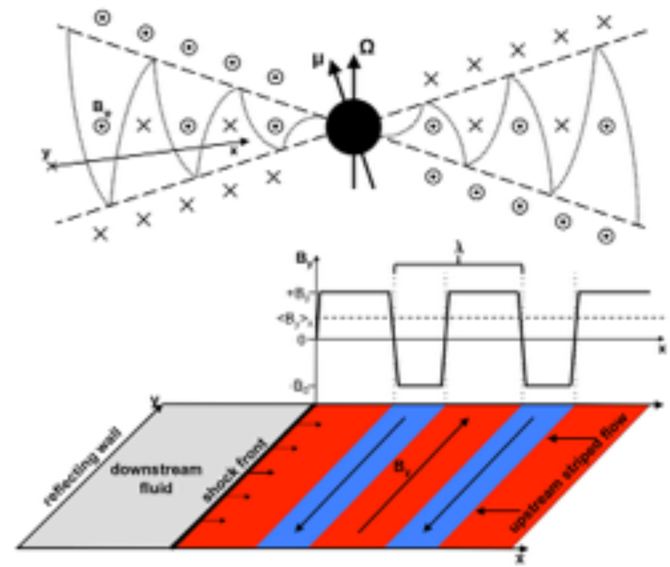


PIC simulations of termination shock in striped wind

Sironi & Spitkovsky 2011

- Reconnection-mediated shock

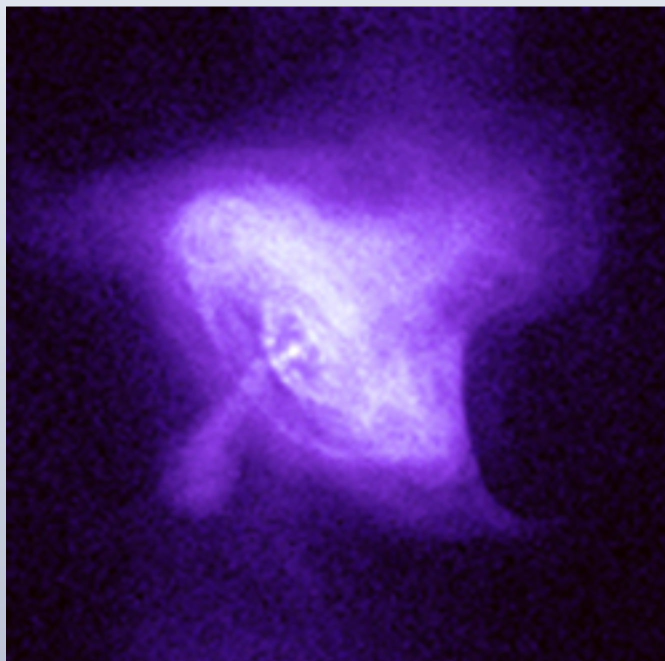




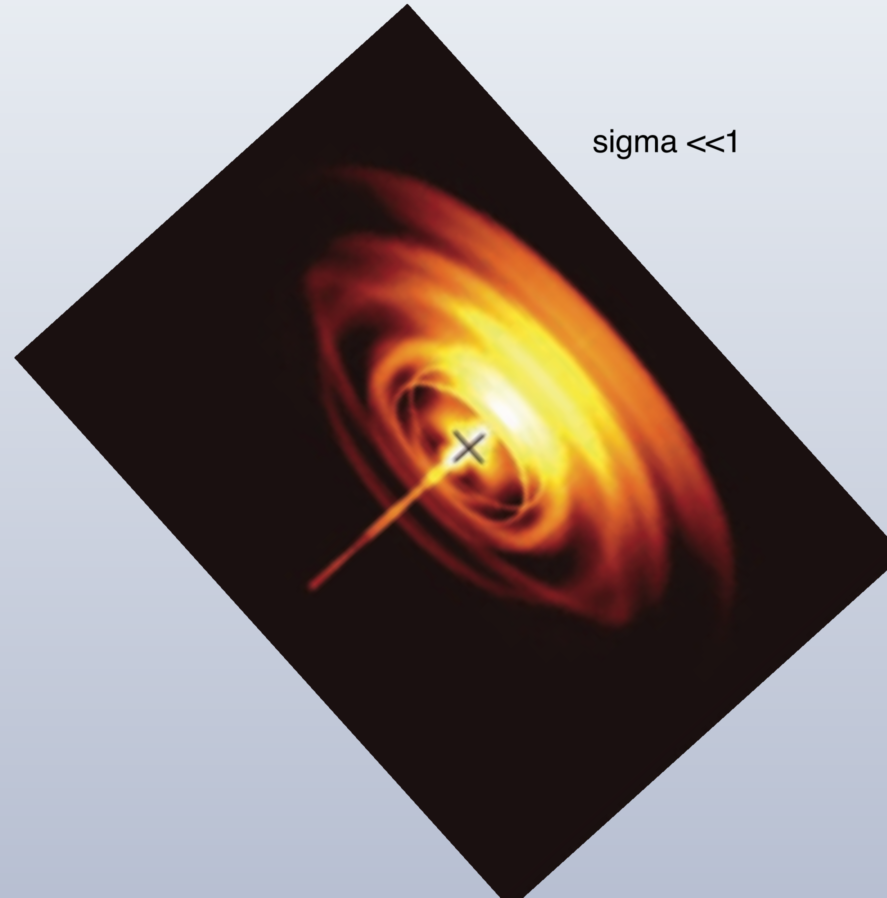
Only relativistic shocks with sigma < 10^{-2} can accelerate non-thermal particles

Large-scale torus structure

Komissarov & Lyutbarksy 2003

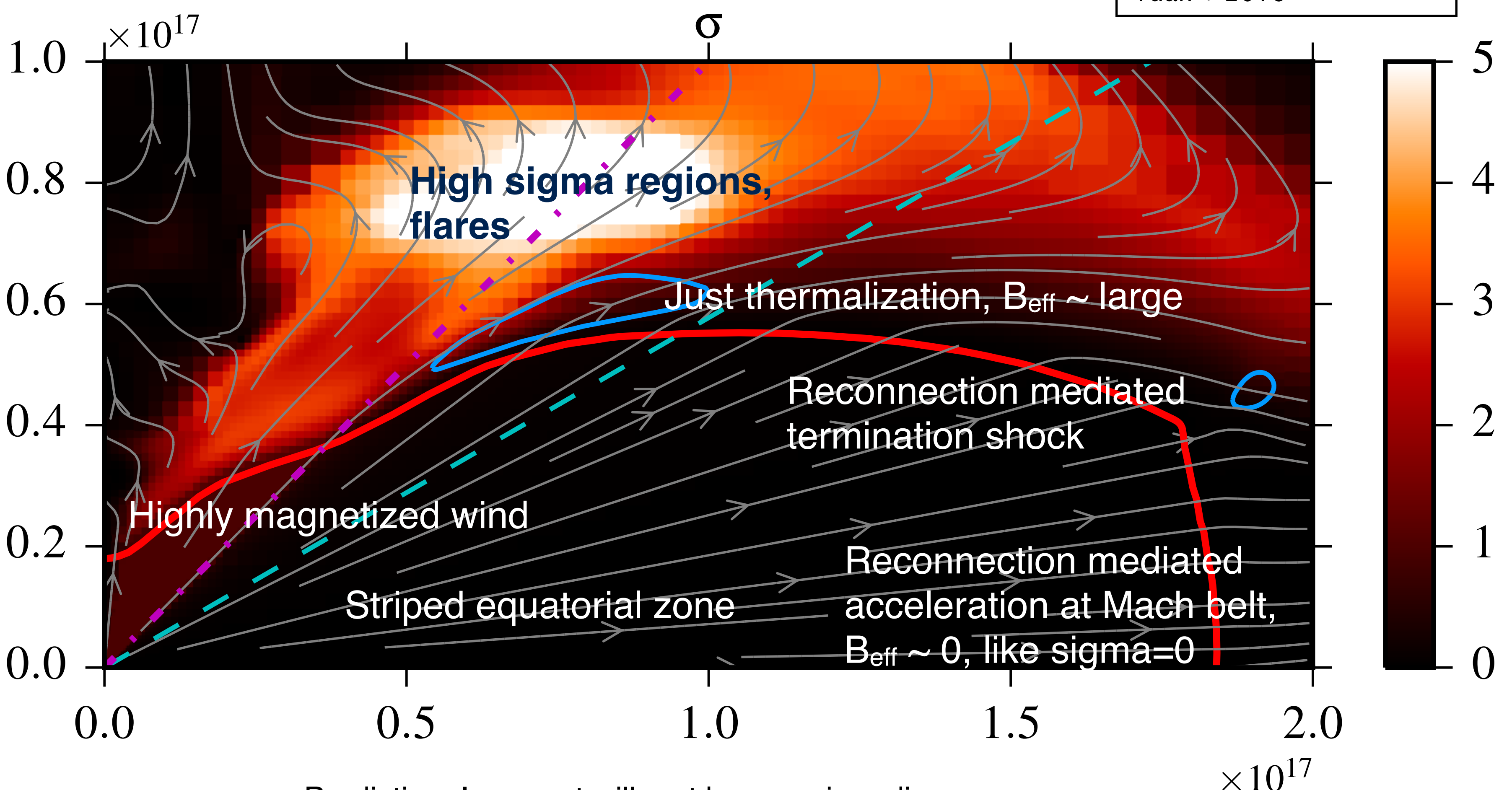


sigma <<1



Pulsar winds: coming together of theory, simulations and observations

Bogovalov 1999
Komissarov+ 2003
Porth+ 2014
Sironi +, 2011
Lyutikov+, 2016
Yuan + 2016



Prediction: Inner not will not be seen in radio

Conclusion 1

Ok, OK: We made an important progress in understanding pulsar winds

What about flares?

- Explosive reconnection and particle acceleration in relativistic plasmas

Crab flares: 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)

Explosive Reconnection in relativistic plasmas

Dissipation in relativistic force-free plasma: resistive tearing mode

- No shocks in $\sigma = \infty$ plasma
- Energy in B-field -> reconnection
- Resistive force-free

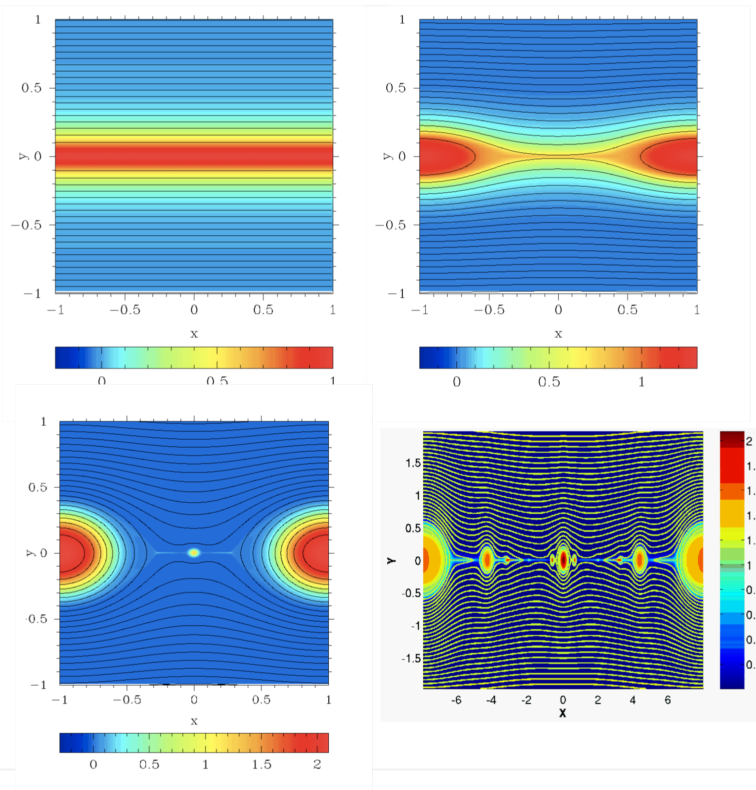
$$\mathbf{j}_{||} = \mathbf{E}_{||}/\eta$$

- Formation of magnetic islands, just like in non-relativistic case
- Growth like in non-relat.:

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

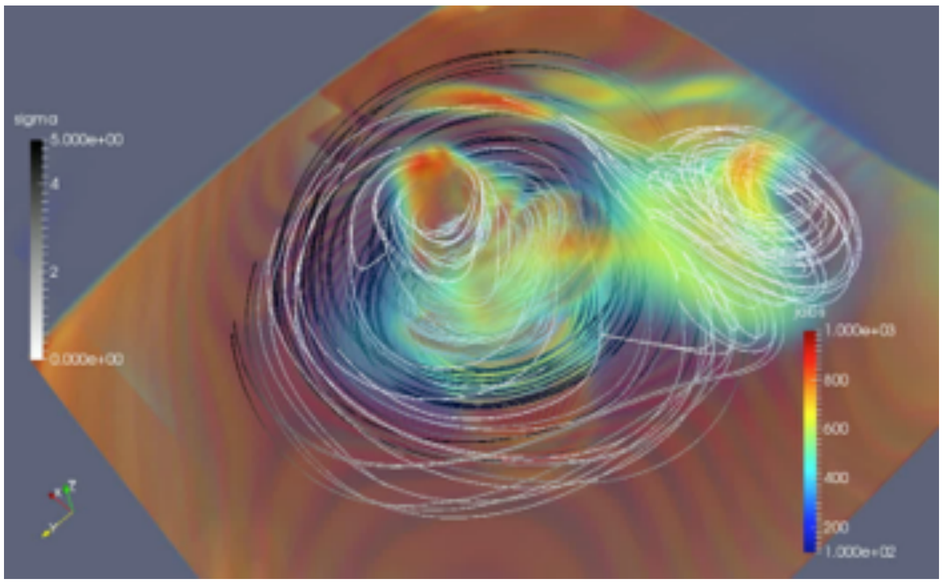
- **Fast, but not fast enough!**
- **Collisionless - fast on skin, slow on macroscopic scales**

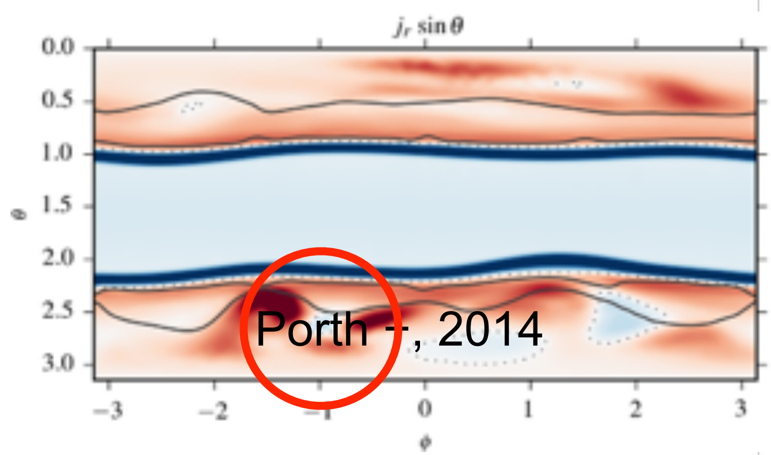
Lyutikov 2003
Komissarov +, 2006



Large scale simulations

- Toroidally-dominated B-fields are unstable to large-scale kinks
- Formation of current-tubes

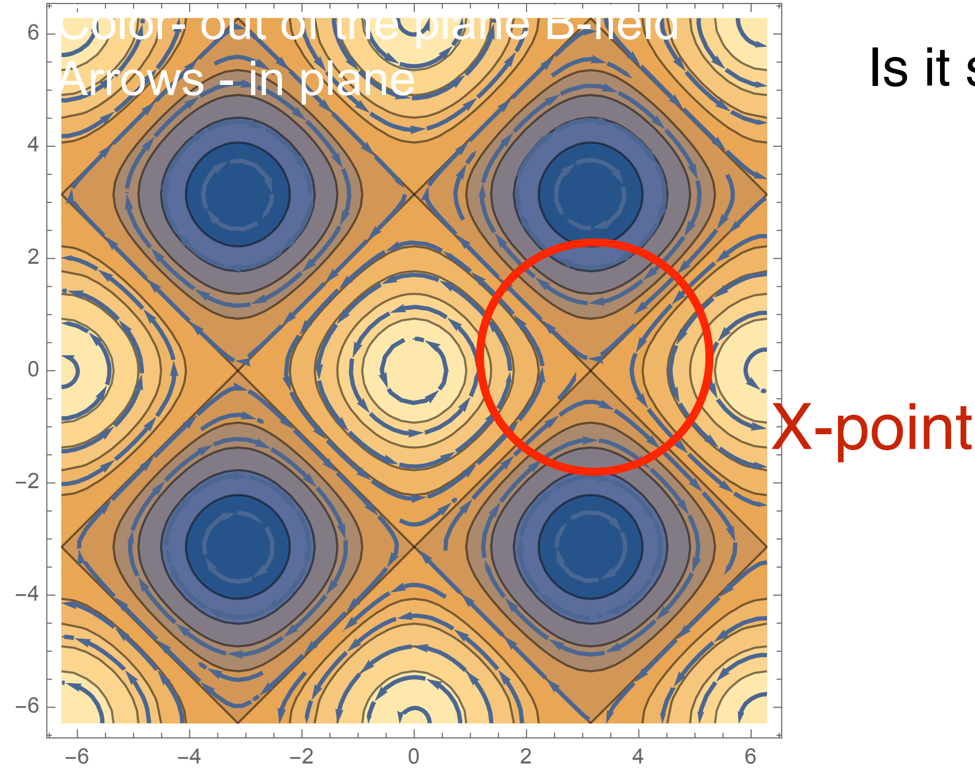




- Parallel currents attract. Can flux merger be the source of Crab flares?

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)



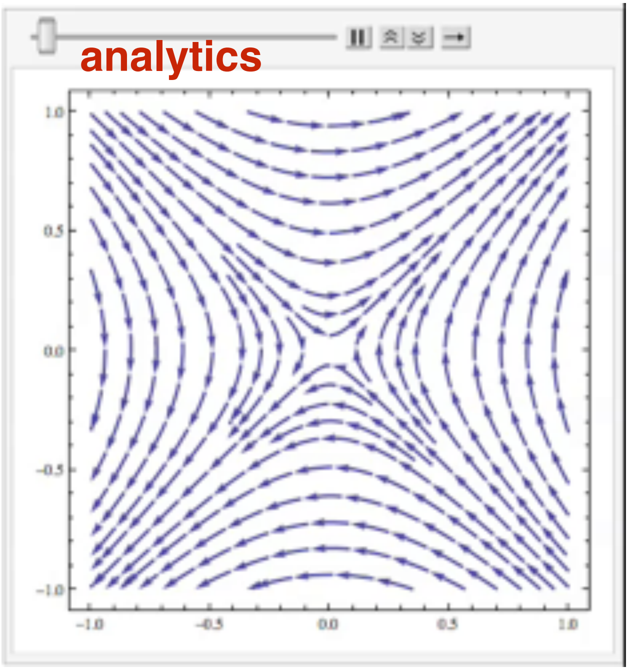
Is it stable?

- Detailed investigation of stability using analytical, relativistic fluid-type and PIC simulations (Lyutikov, + 2016)

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

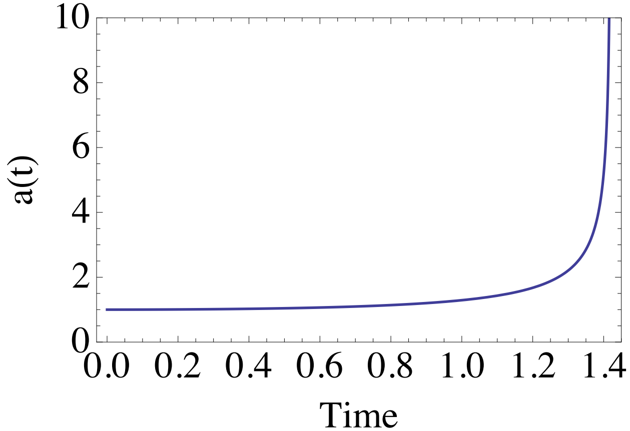
$$\sigma = \frac{B^2}{4\pi\rho c^2} \gg 1$$



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

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

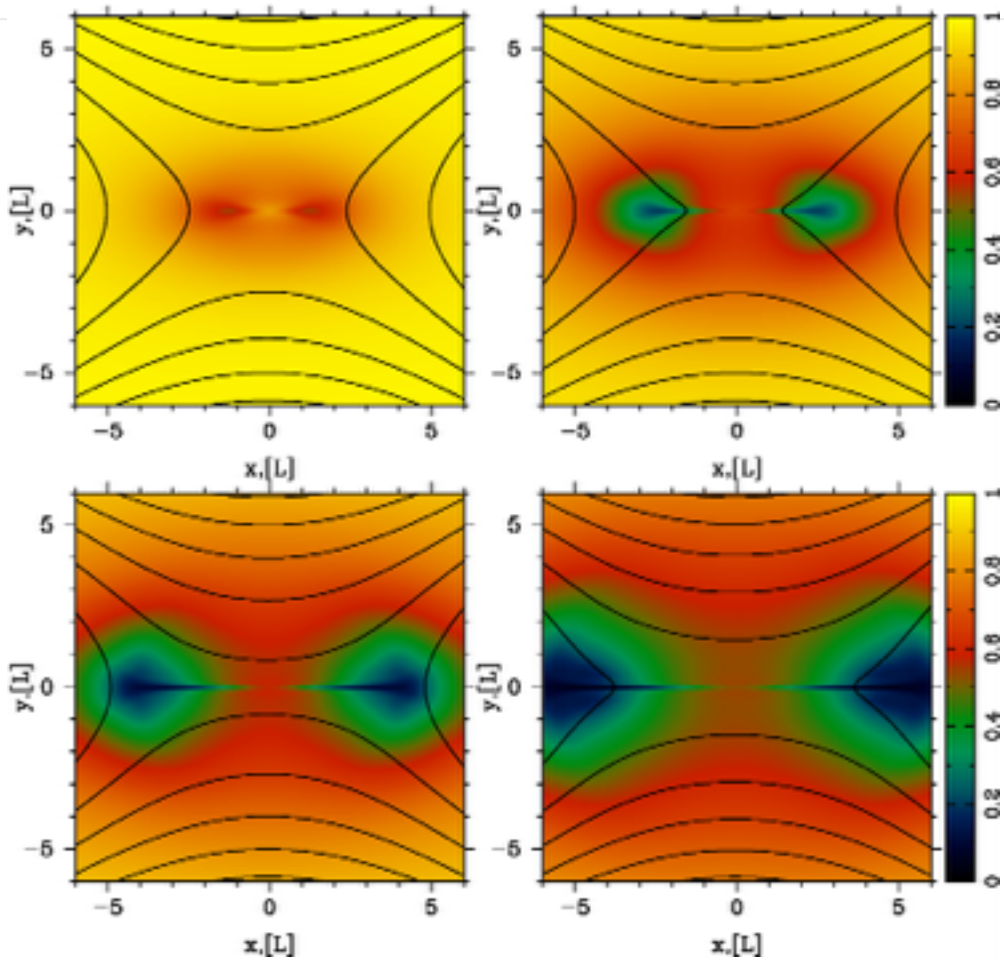
$$\partial_t^2 \ln a = \mathcal{A}\left(\frac{a^4-\lambda^2}{\lambda^4}\right), \mathcal{A} = \frac{c^2}{L^2}\frac{B_\perp^2}{B_0^2}$$



- **explosive** dynamics on Alfven time
- slow initial evolution
- Starting with smooth conditions
- Finite time singularity
- **Driven by large-scale stresses**

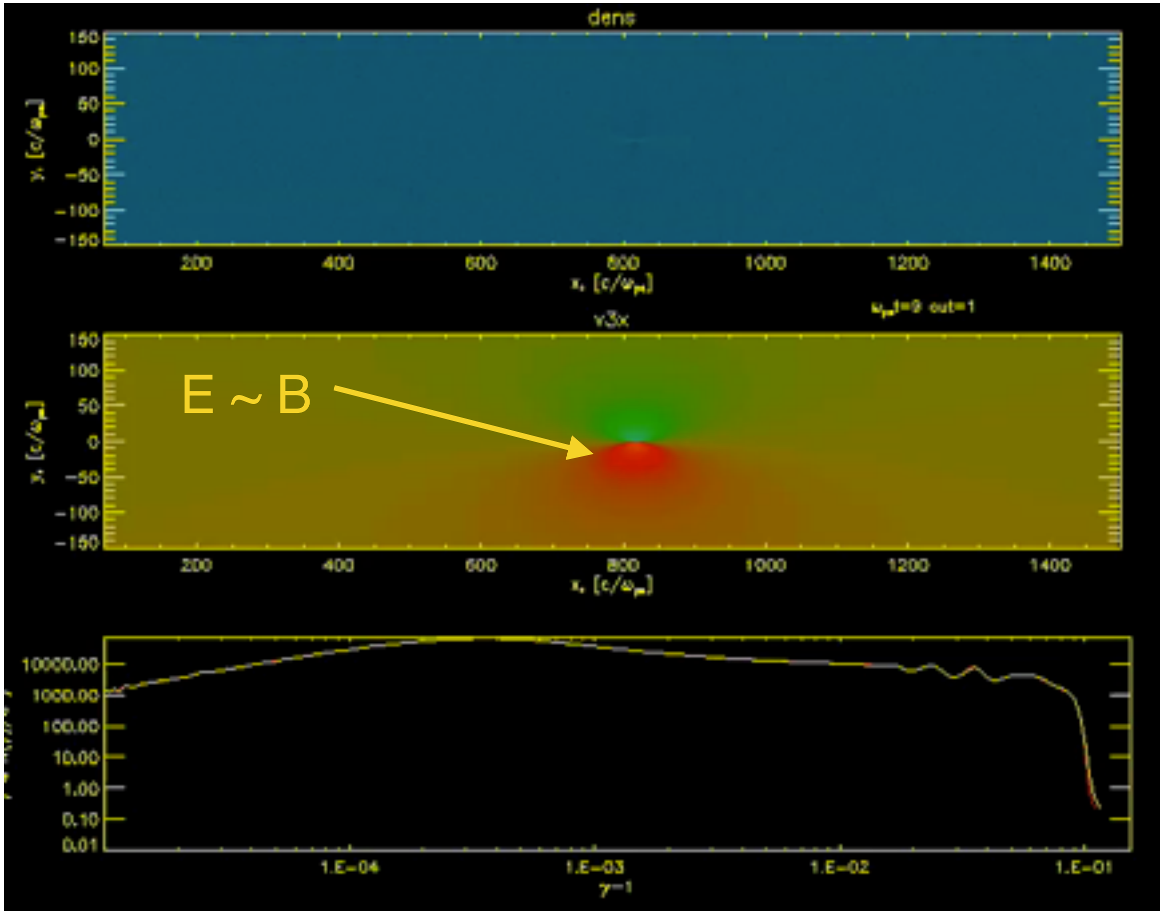
Theory, fluid and PIC simulations

Lyutikov +, 2017 JPP, submitted



1-E^2/B^2 in force-free simulations

Can produce power-laws



PIC simulations by Sironi

Acceleration in X-point collapse: charge starvation

- Highly efficient acceleration by E ~ B
- Driven by large scale magnetic stresses - **wide-open X-point** (not like in tearing mode - flat X-point)
- Acceleration starts abruptly, when reaching **charge starvation.**
  - During collapse current density grows

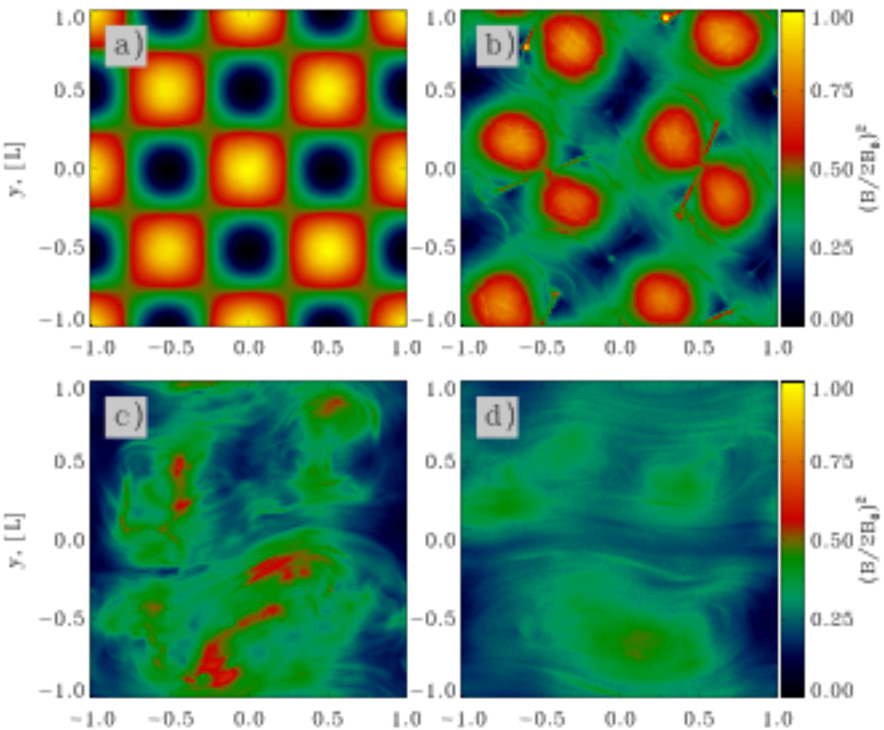
$$J_z \approx \frac{c}{4\pi}\frac{B_\perp}{L}a(t)^2$$

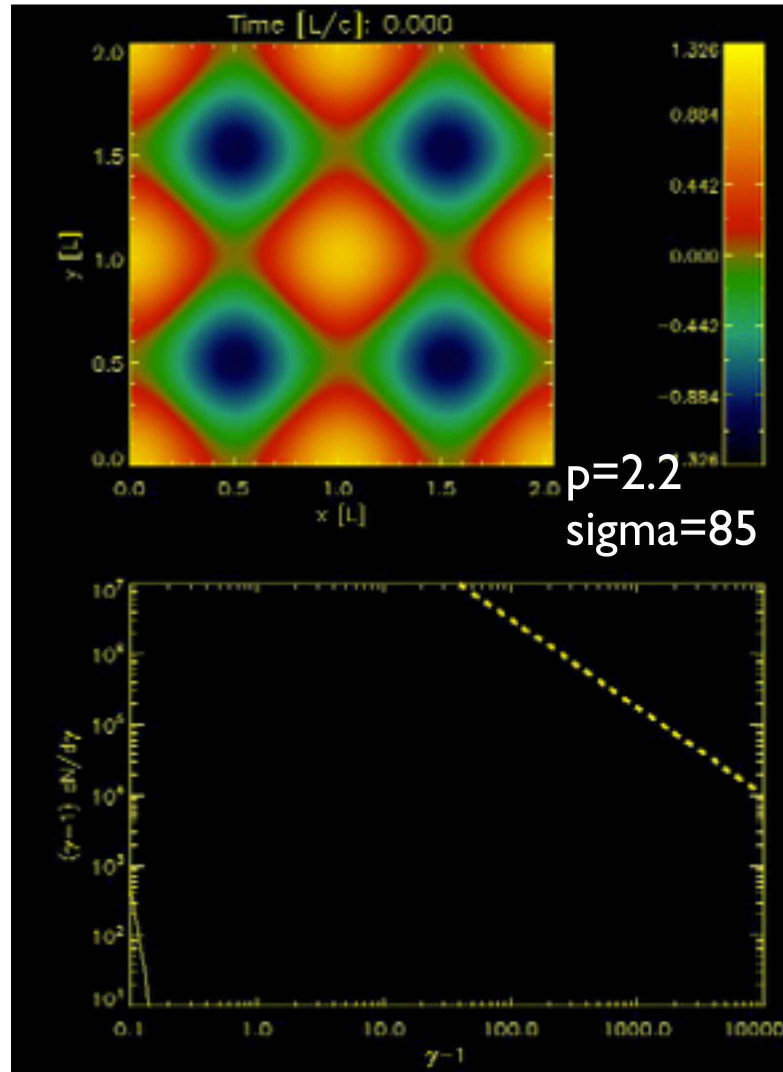
  - But J< 2 n e c - not enough particles to carry the current

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

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

Collapse of an ABC system of magnetic islands

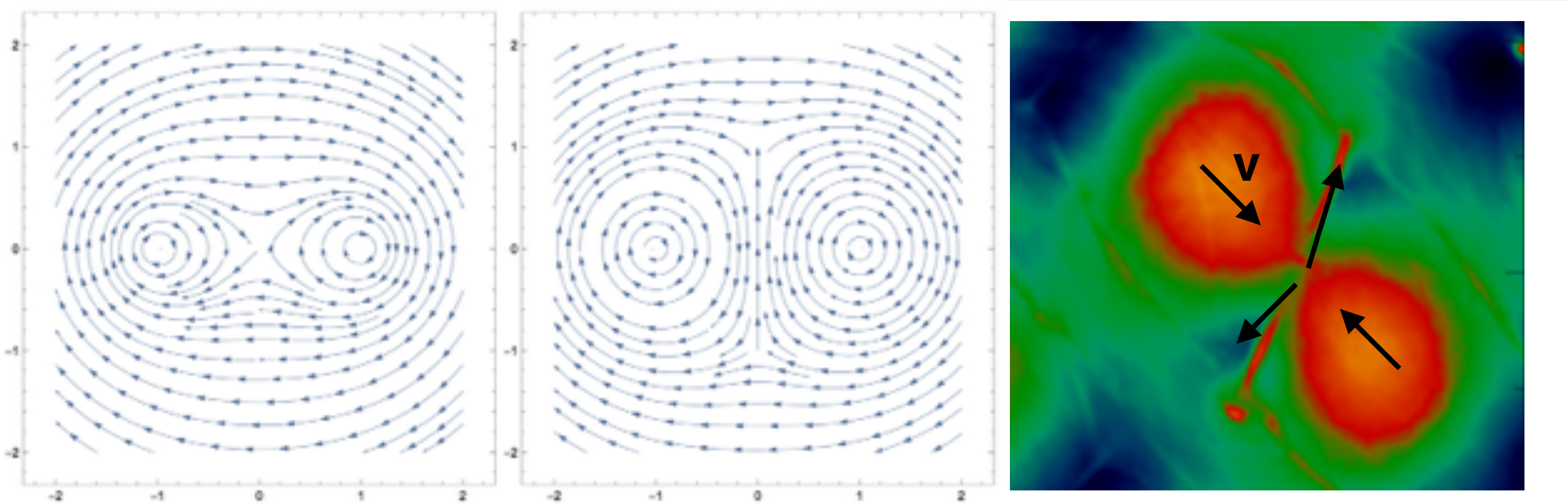




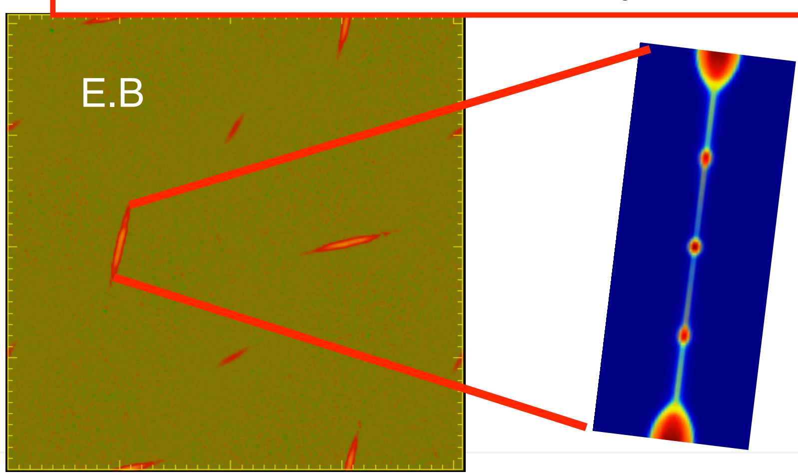
Two stages:

- Fast acceleration, not much B-field dissipated (X-point collapse)
- Slower acceleration, dissipation (island merger)

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

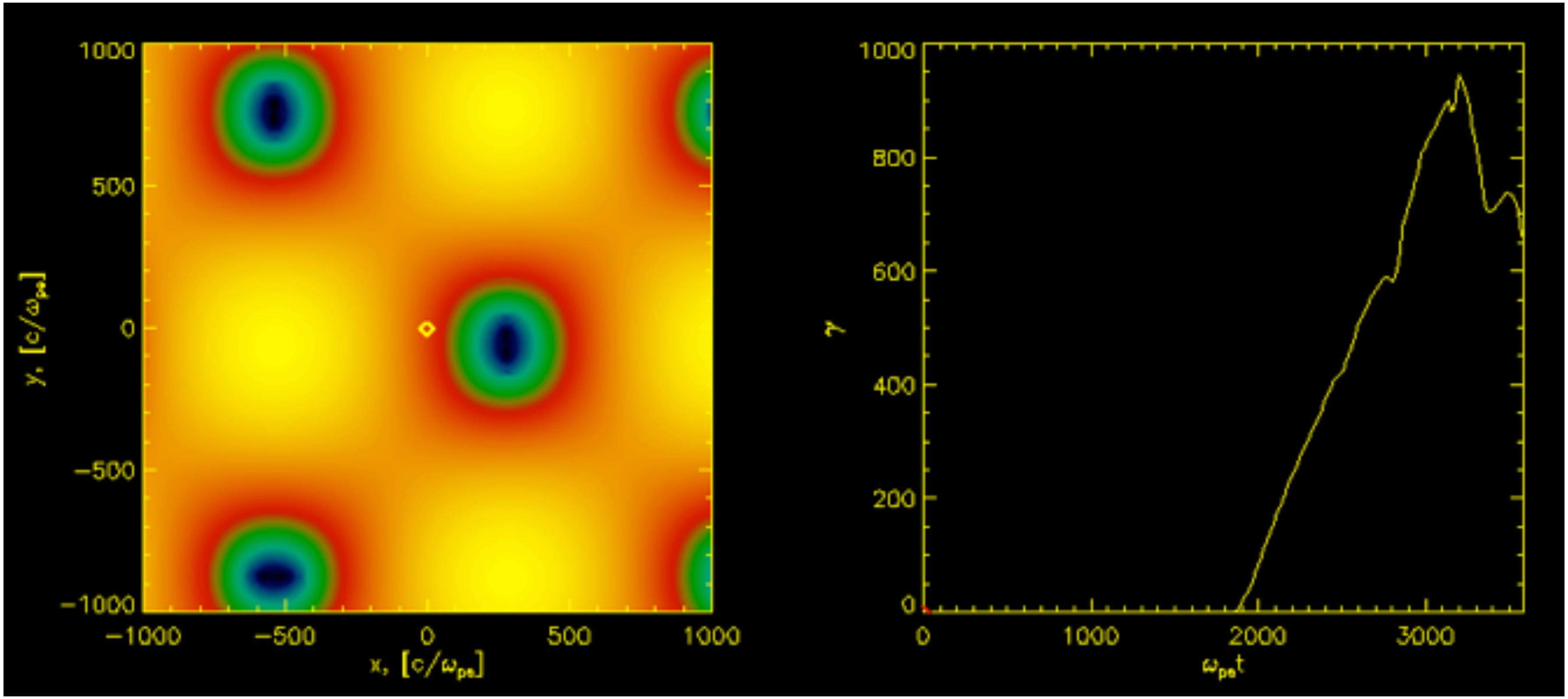


L>L_{crit} - plasmoid instability of current sheet



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.

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

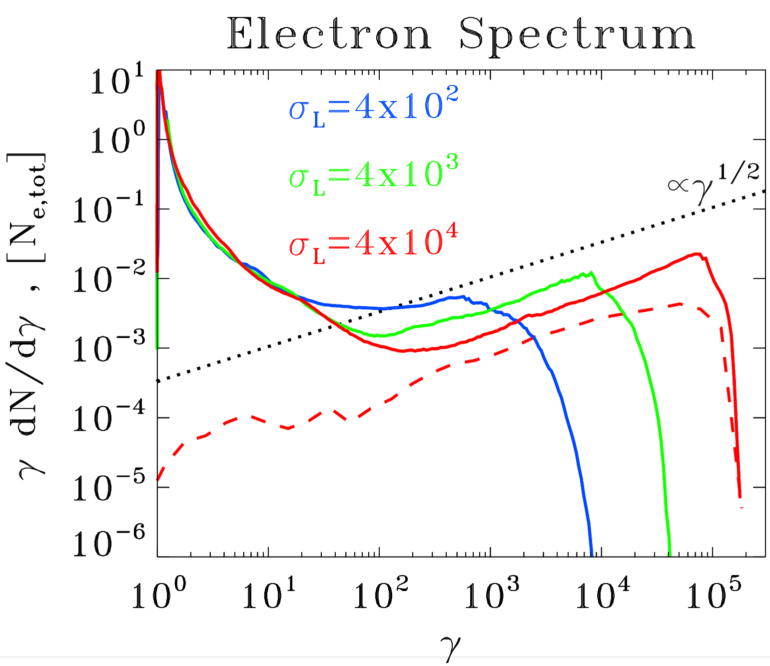


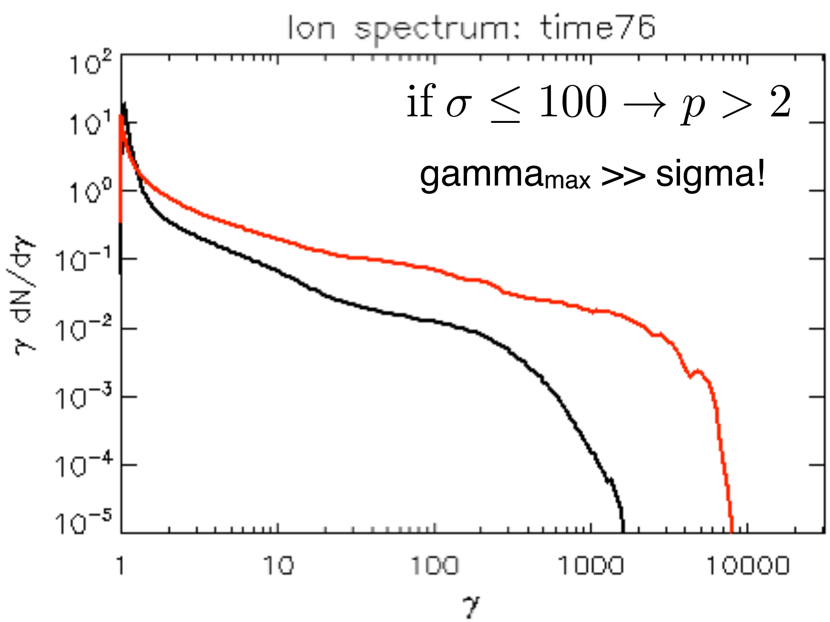
$$E \sim B \propto t$$

$$\epsilon \propto t^2$$

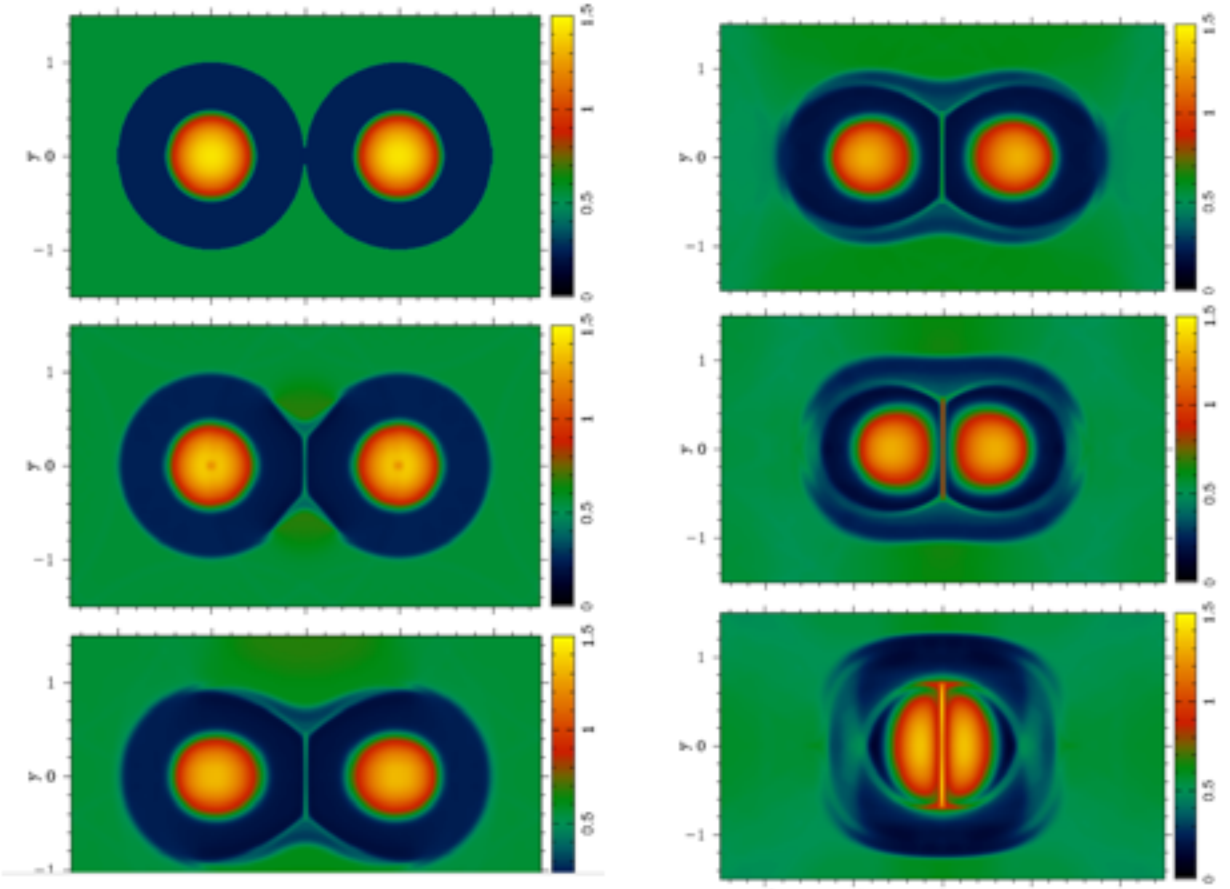
The problem with gamma_{max}

- Average magnetic energy gamma ~ sigma
- Need 10^9 - cannot accelerate all
- **Evidence for high energy bump, presumably generated at the X-point collapse**
- Even for sigma ~ 100s, p ~ 1.5 can reach 10^9



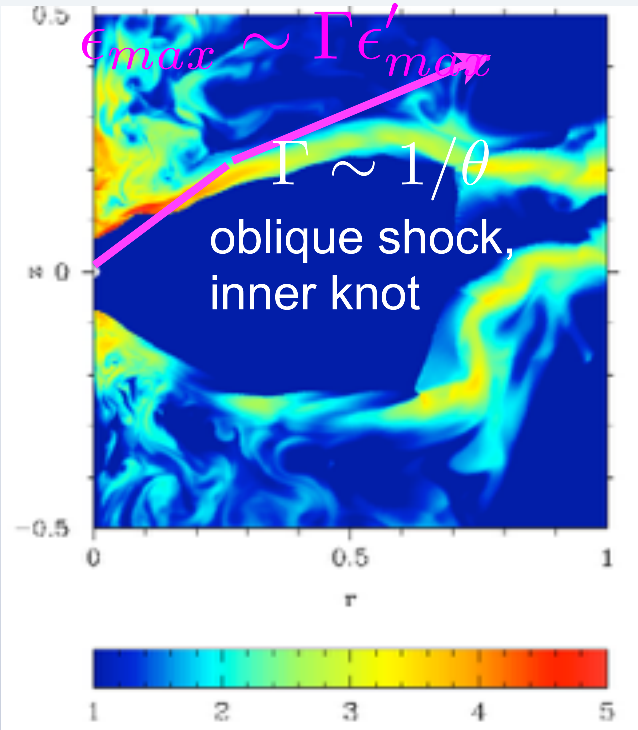


Merger of zero-current flux ropes

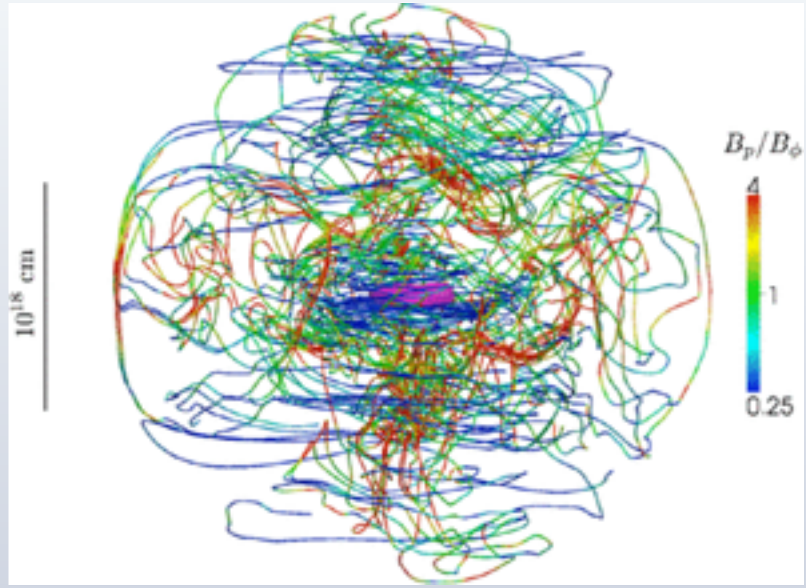


- No total current: no overall attraction force.
- First, resistive effects ``eat out'' the envelopes (slow)
- After ||-current learn of each other - large scale attraction

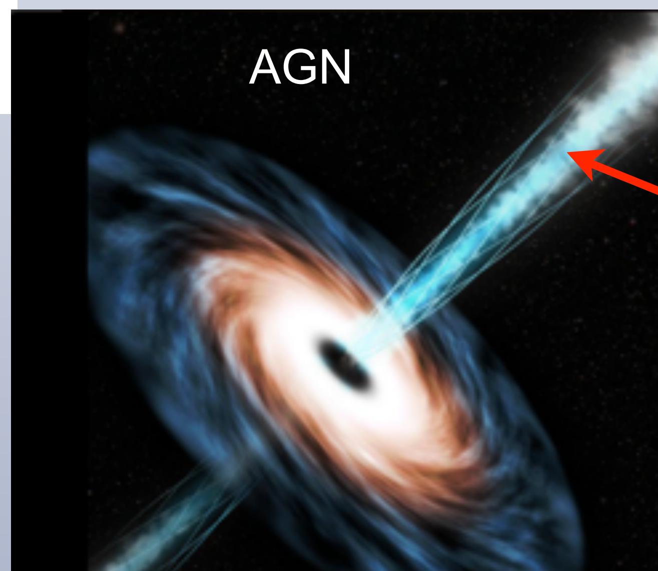
Where in Crab and AGNs?



Komissarov & Lyutikov, 2011



Porth+ 2014



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

Conclusion 2

Reconnection in magnetically-dominated plasma

- **can proceed explosively**
- **efficient particle acceleration**
- **reconnection can give p =1, alpha =0**
- **the explosive stage - X-point collapse - produces a separate accelerated component**
- **is an important, perhaps dominant for some phenomena, mechanism of particle acceleration in high energy astrophysical sources.**