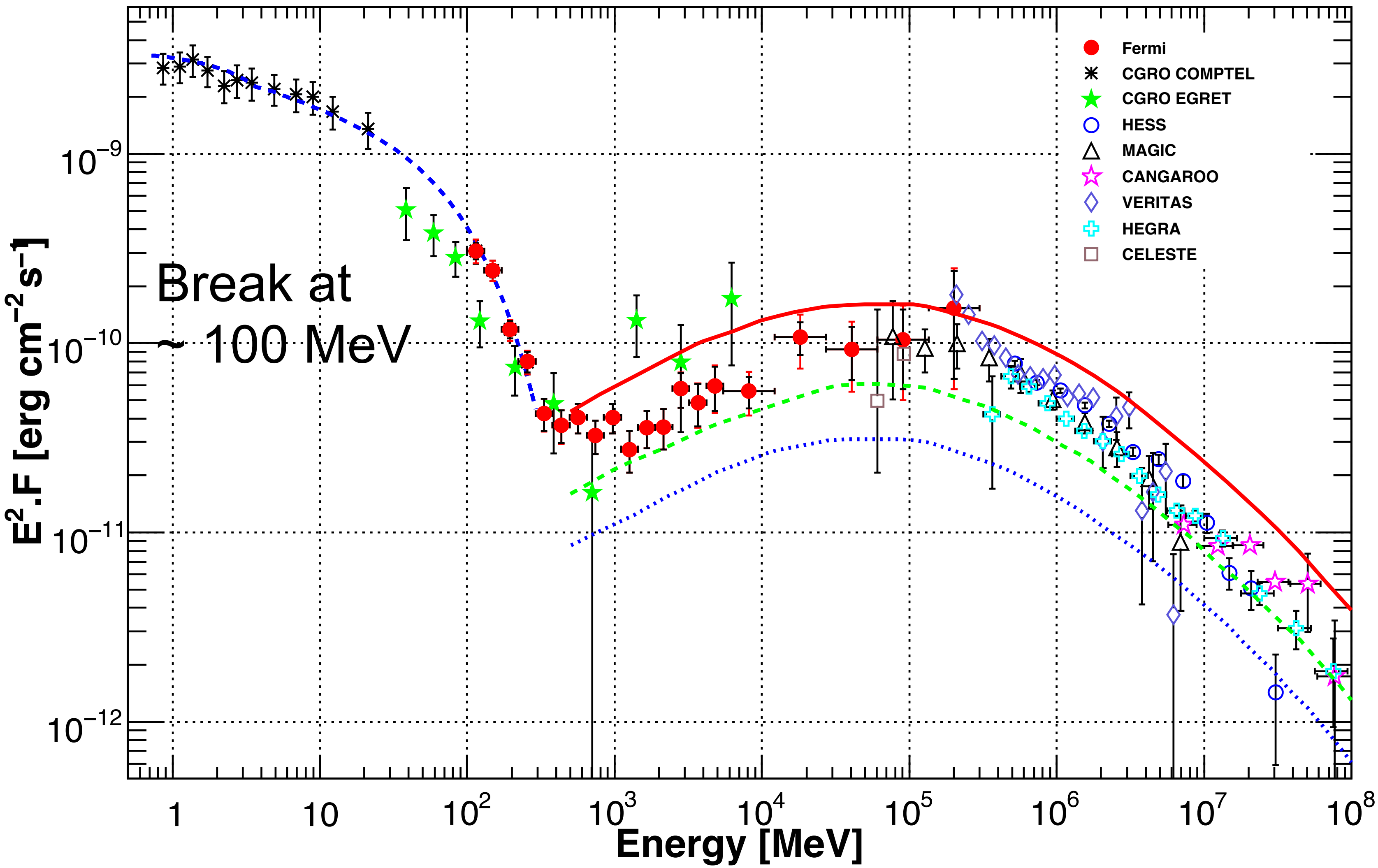
# Explosive X-point reconnection & Crab flares

Maxim Lyutikov (Purdue U.)

# Spectra of Crab nebula & flares

Tavani et al. 2010
Beuhler et al., 2011



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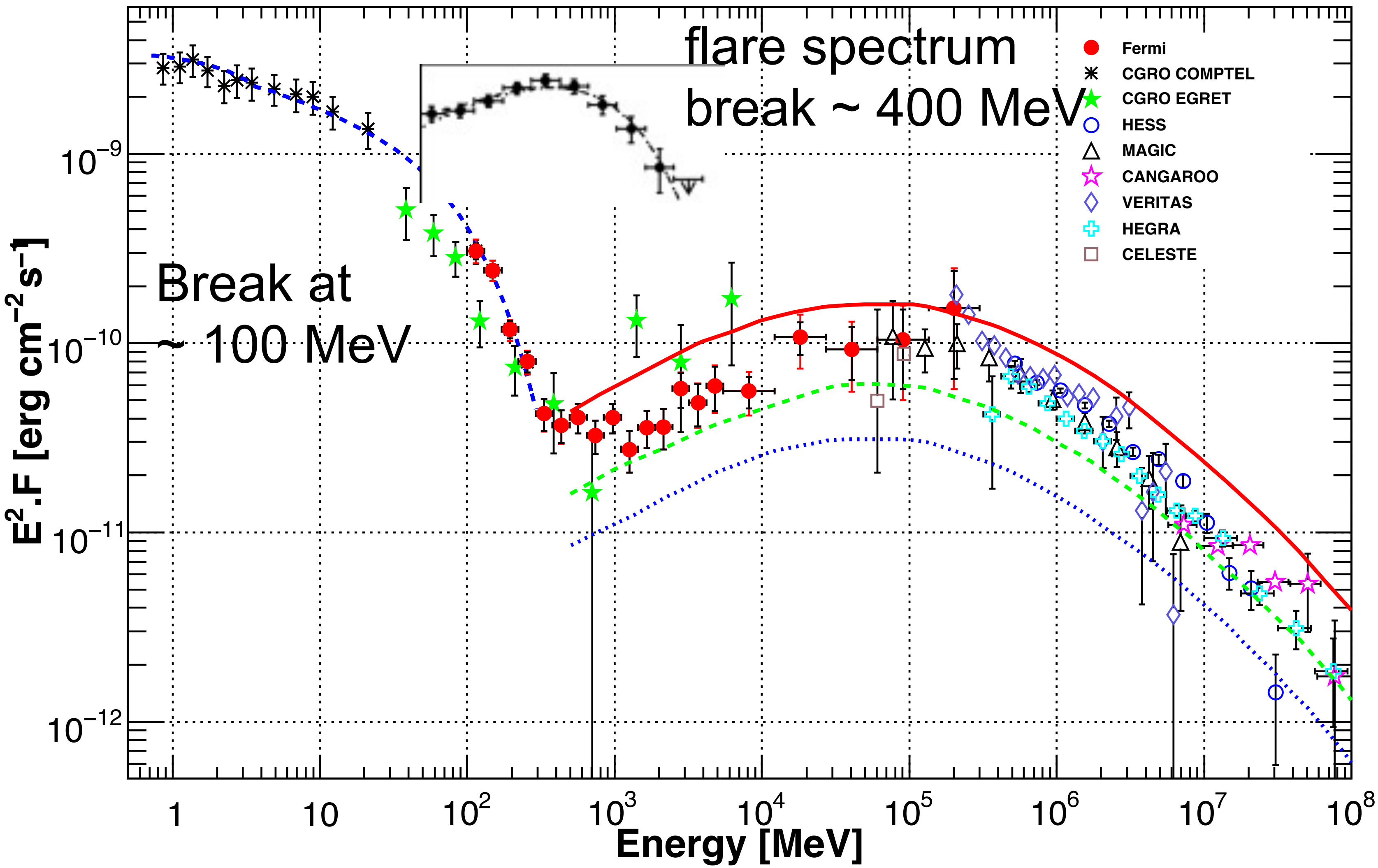


# *Upper limit to synchrotron frequency*

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
- **Typically eta < $10^{-2}$ for stochastic shock acceleration: this excludes stochastic acceleration schemes even for "normal" PWN emission**

Need E ~ B & more:
- relativistic motion AND/OR
- multi-zone

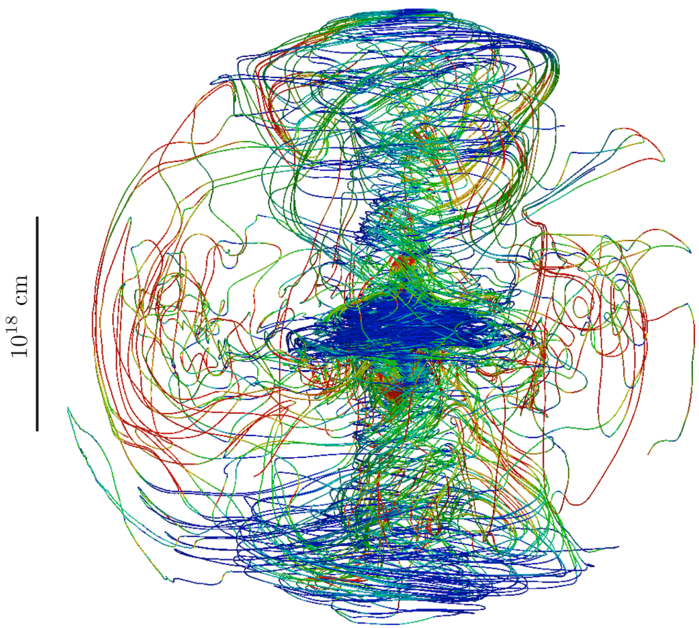
**E ~ B -> reconnection**

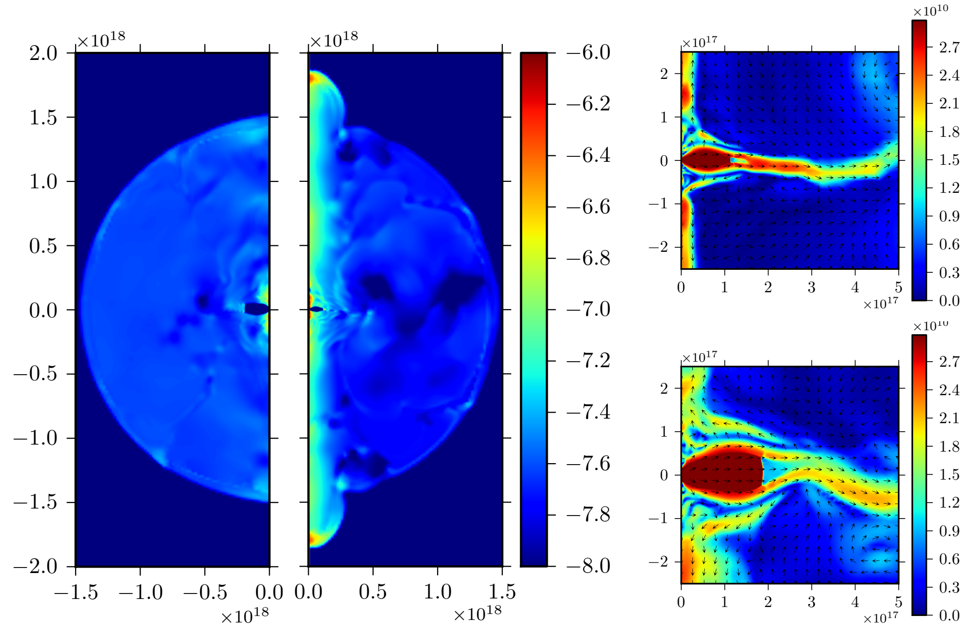
For sigma ~ 1, vA ~ c, E ~ B

# *Wind with varying magnetization*

Porth+2013, Komissarov+ 2013;
Lyubarsky 2012

- First 3D simulations




- Magnetic flux is destroyed in reconnection events near the axis
- The model can keep the morphology of small-sigma models and allow for reconnection in sigma ~ 1 regions

# Size and location of emission region

$$\epsilon_{\rm ph} \sim 500{\rm MeV},\ \tau_s \sim 1{\rm day} \to \gamma \sim 5 \times 10^9,\ B \sim 10^{-3} G$$

$$\gamma_{\rm max} \sim \frac{e}{m_e c^2}\sqrt{\frac{\dot{E}}{c}} \sim 10^{11} \to \Delta\theta \sim 0.05,\ r_{\rm em} \sim 10^{16}{\rm cm}$$

$$B_{\rm wind} \sim 3\frac{B_{\rm NS} R_{\rm NS}^3 \Omega^2}{c^2 r} \to r \sim 10^{17}{\rm cm}$$

- Emission occurs at r ~ few $10^{16}$ cm in a region occupying ~ few degrees

(Lyutikov, in prep)

# Not enough B-energy and particles

- Total energy $E_B \sim \frac{B^2}{8\pi}(c\tau)^3 \sim 10^{39}\mathrm{erg} - \mathrm{not\, enough}$
- How many particles needed? $N \sim \frac{L_\gamma \tau_d}{\gamma m_e c^2} \sim 10^{37}$
- Pulsar production rate $\dot{N} = \lambda \times 6 \times 10^{33} s^{-1}$ (in about a second)
- Total number of particles in the emitting volume

$$N = \frac{\dot{N}}{4\pi r^2 c}(c\tau)^3 \sim \lambda \times 10^{33}$$

- Almost all need to be accelerated - no way, will run into Alfven current limitation

$$I \sim \sqrt{L_\gamma c} \gg I_A = \gamma \frac{m_e c^3}{e}$$

- (Need background plasma to provide the return current)

# Relativistic bulk motion

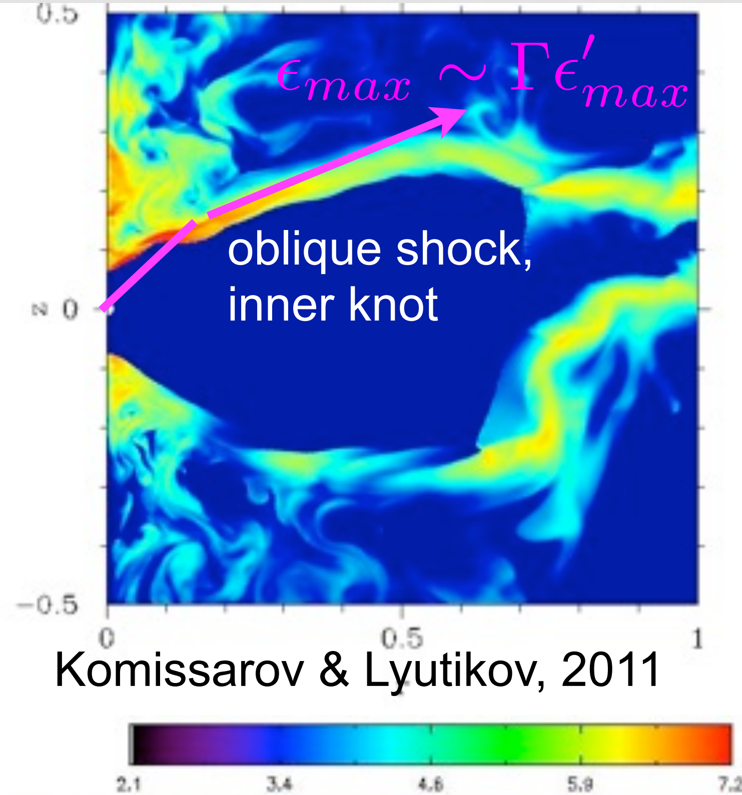
- Relativistic bulk motion with Doppler factor ~ few resolves all the problems:

$$\epsilon_{\rm ph} \to \delta\epsilon_{\rm ph}$$

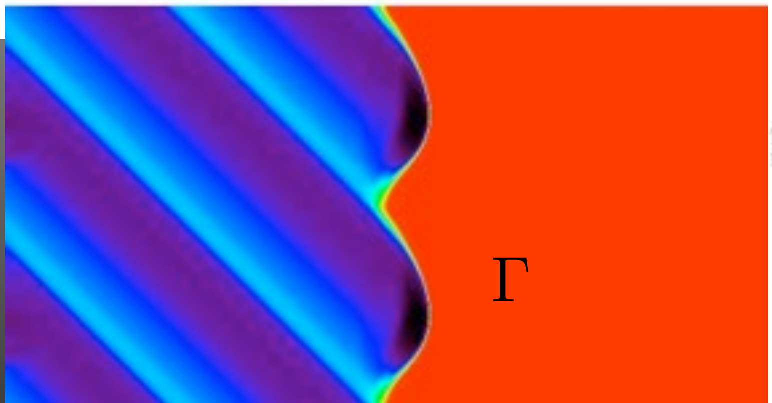
$$L_\gamma \to \delta^3 L_\gamma$$

$$\tau \to \tau/\delta^2$$

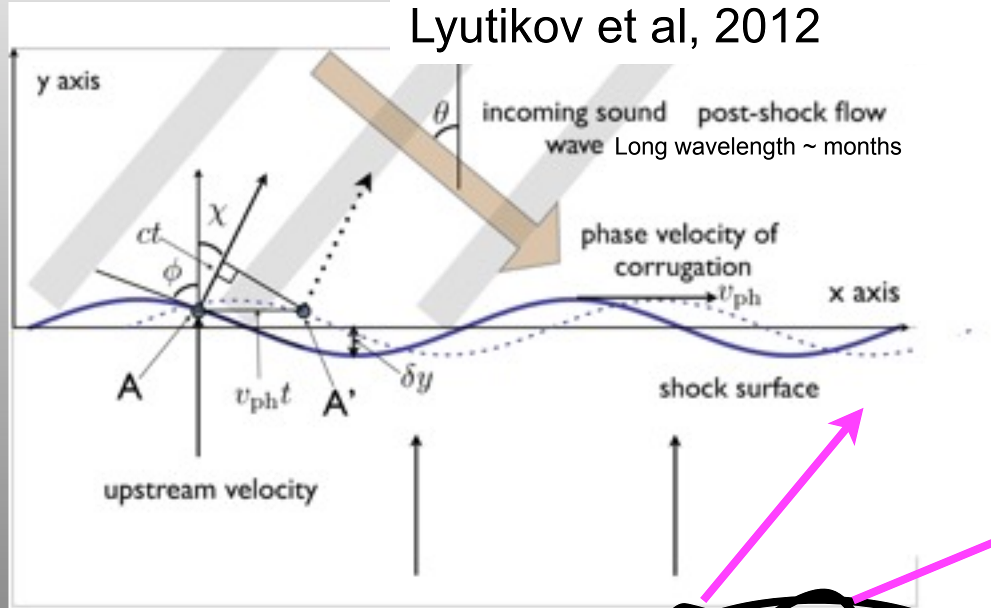
# *Bulk Gamma, shock corrugation*

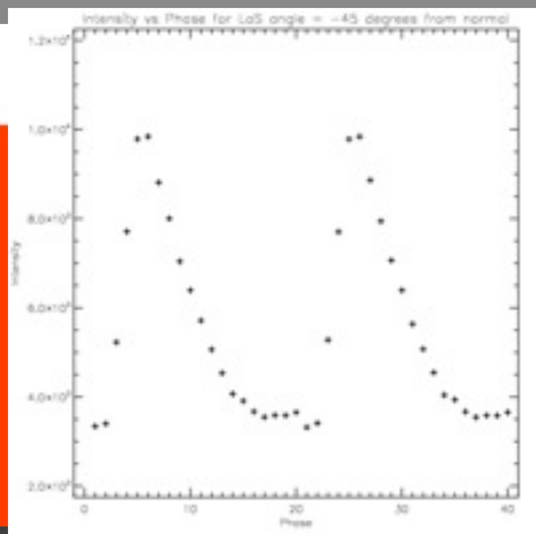


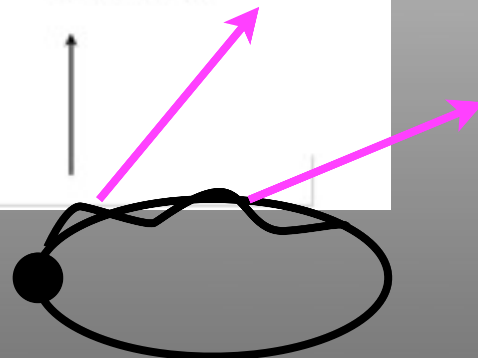

Komissarov & Lyutikov, 2011




Lyutikov et al, 2012





Short intensity variations
(No time of flight effects)



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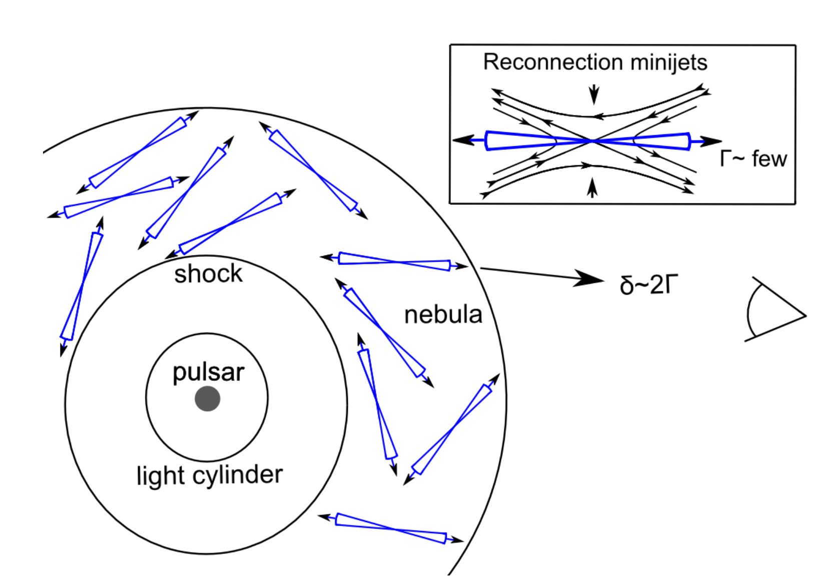
# Flare statistics: isotropic flares

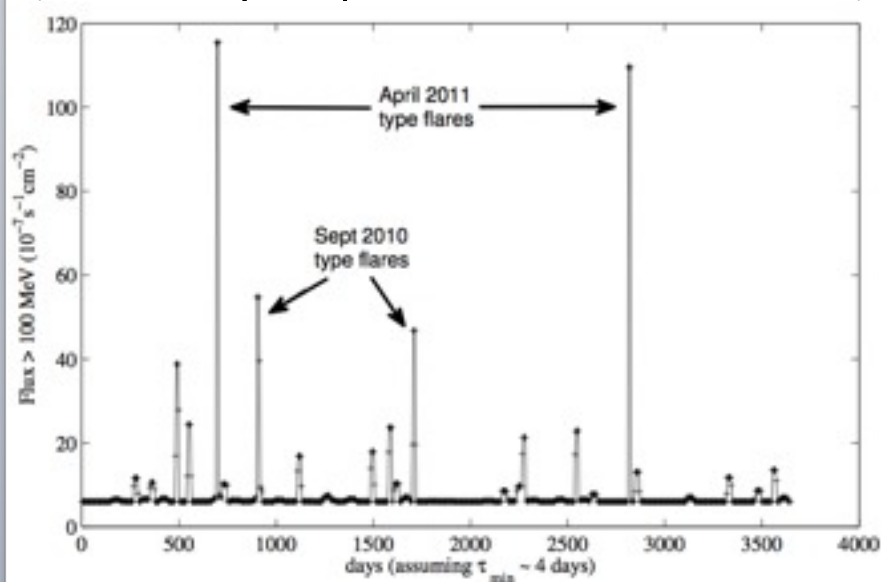



- Flares can be on top of persistent emission, OR
- all emission are flares – small ones average out

•probability of flare flux

$$\rho(F)dF \propto F^{-\frac{q+1}{q}}dF \approx \frac{1}{F}dF$$

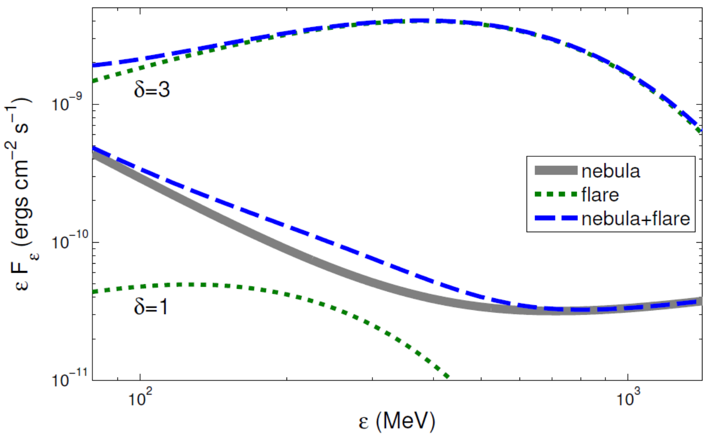
•average flare flux is dominated by bright rare flares.



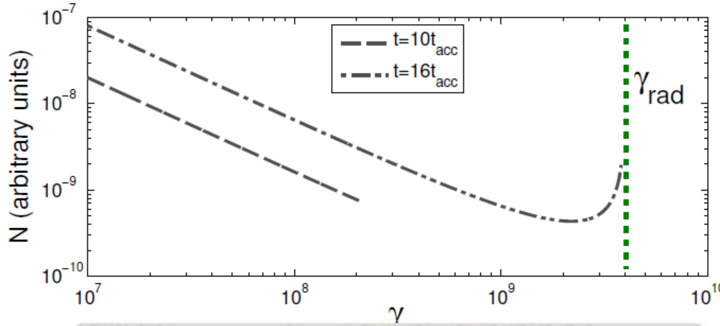

Power-law from shot noise!

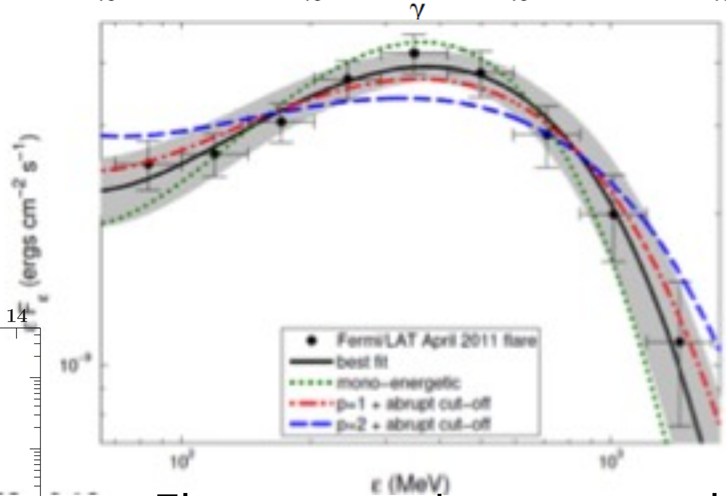
***Clausen-Brown, Lyutikov 2012***

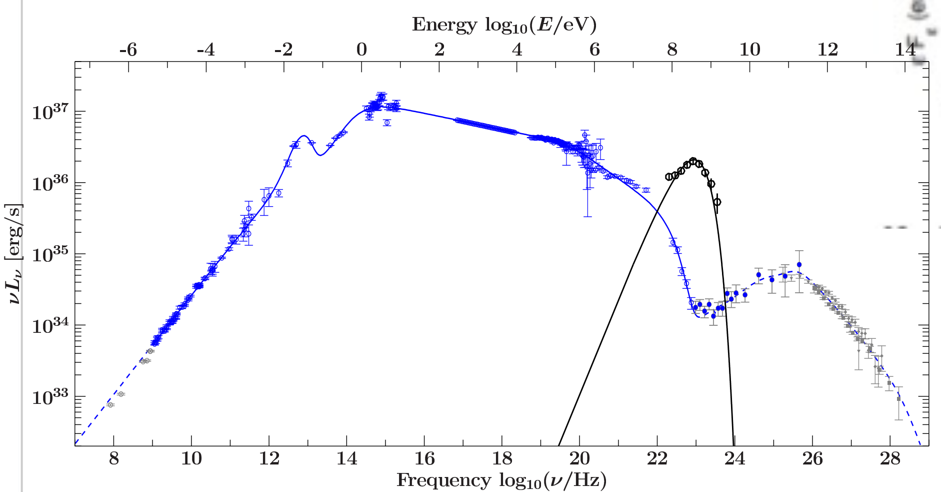
# Γ ~ few increases flux and peak energy, **nearly mono-energetic spectrum**




mild boost - huge increase in flux



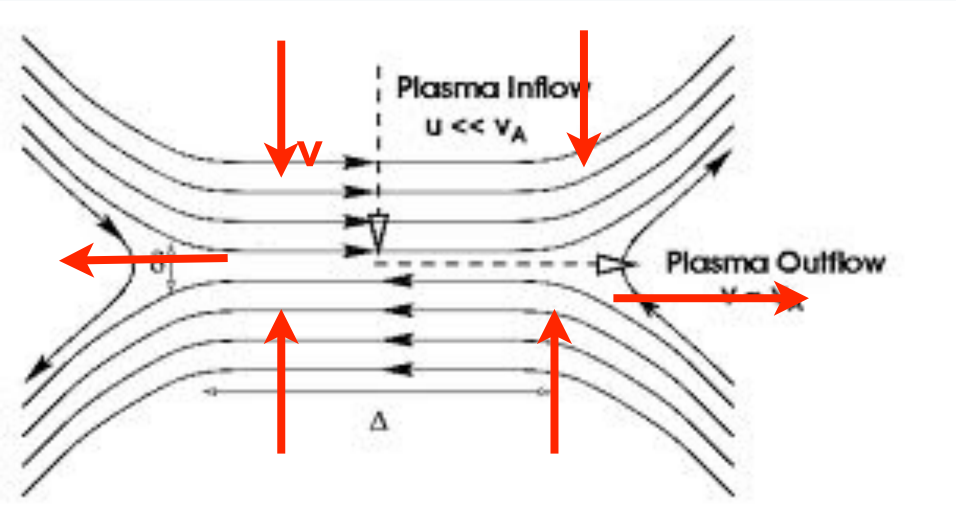






- Flare spectrum: nearly mono-energetic
- Flares are not seen at lower energies

Consistent with observations (Clausen-Brown & Lyutikov 2012)

# Acceleration by reconnection: efficient, non-stationary




- E ~ (vin/c) B - need relativistic inflow to have E ~ B
- + bulk motion with Gamma ~ few
- and/or acceleration in B < E, emission on exit

- E-field created by bulk particles, kinetic motion of high energy particles ~ along neutral line

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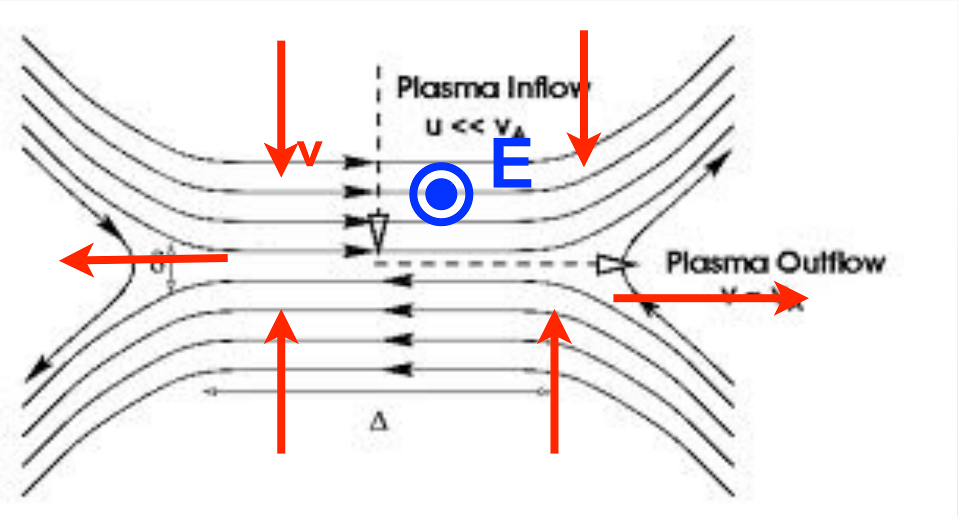


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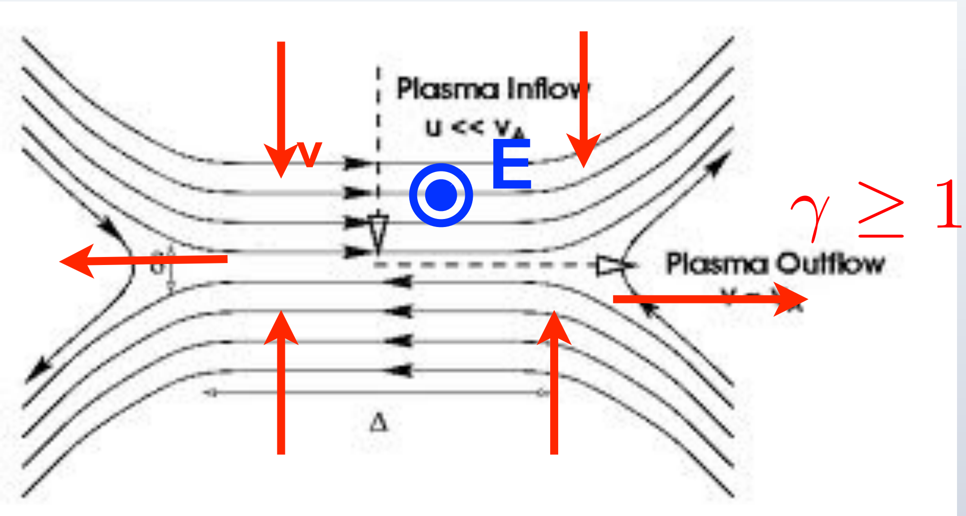


Reconnection in sigma >> 1 plasma: inflow & outflow can be relativistic (Lyutikov & Uzdensky 2002, others)

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# Physical model: collapse of magnetic X-point in force-free plasma (formation of current sheet)

- Current sheet can be unstable to tearing
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Lyutikov 2003, Komissarov+ 2007

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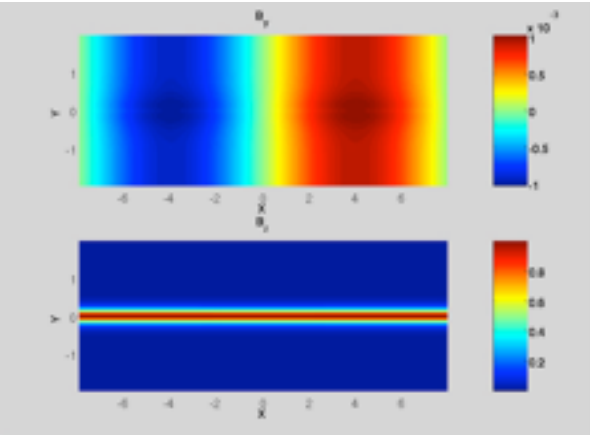

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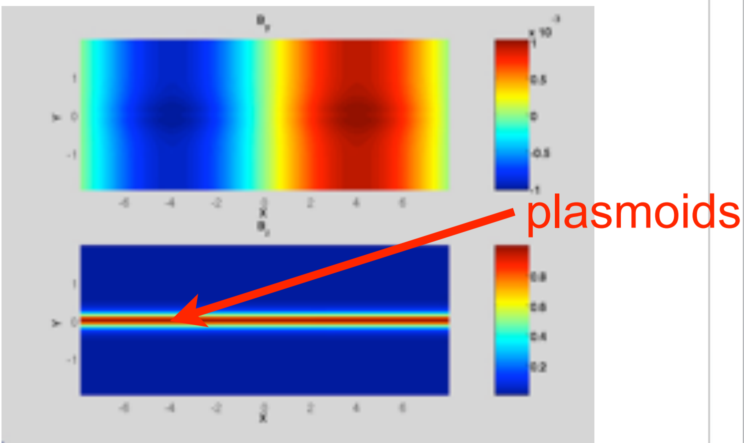


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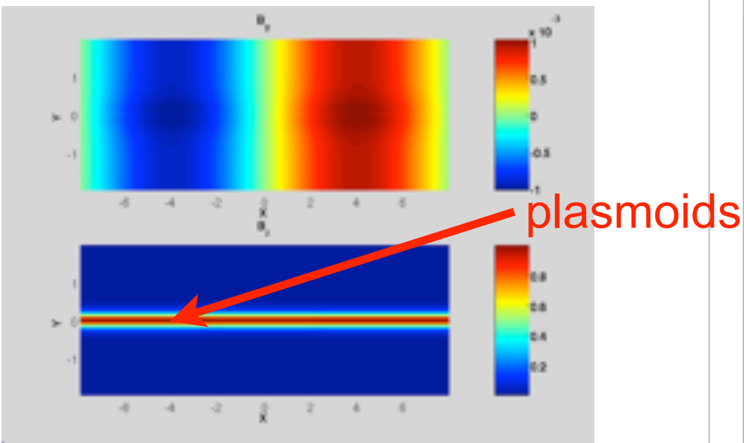


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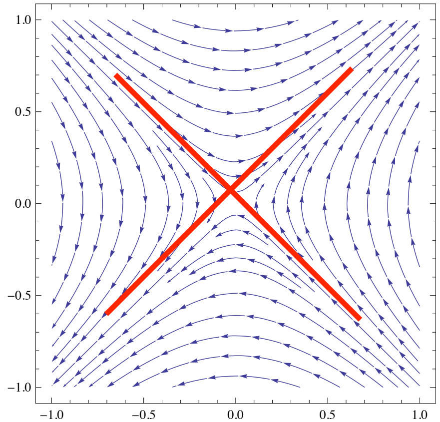
X-point collapse:



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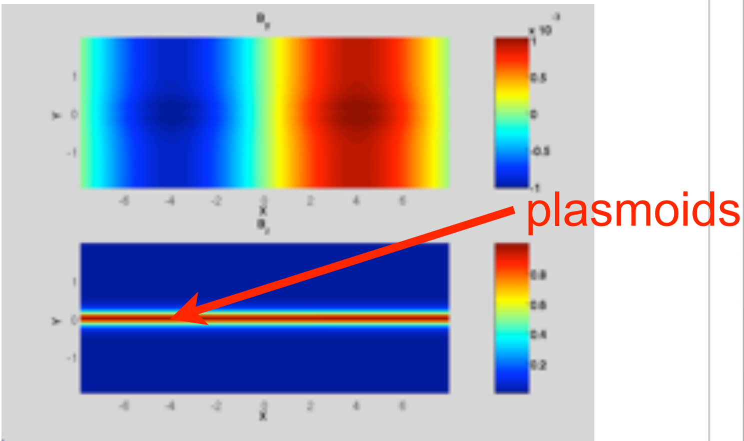


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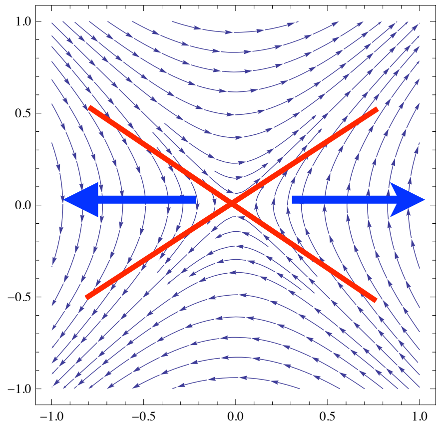

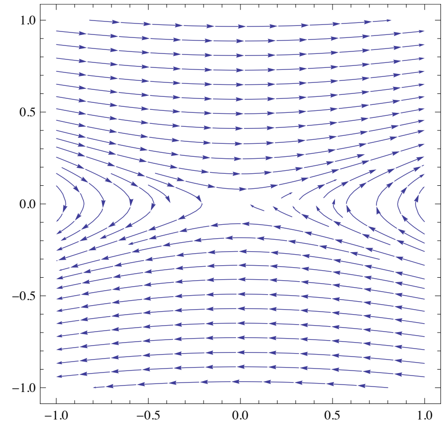

- **explosive** dynamics on Alfven (light) time
- Starting with smooth conditions
- E ~ $B_0$ (field outside), E>B with resistivity
- Particles drift towards null line



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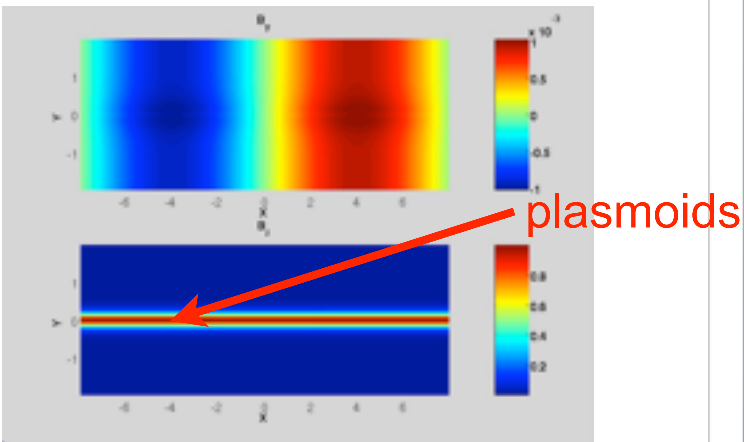


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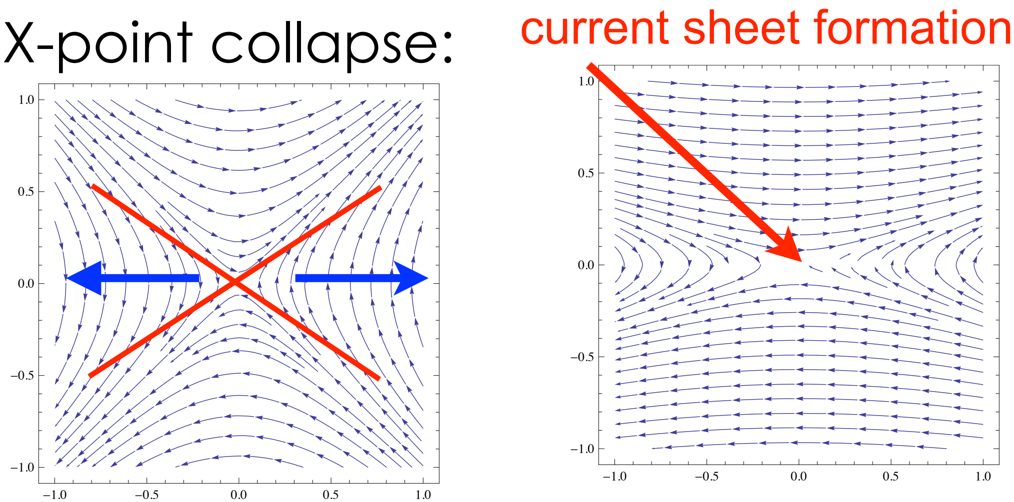


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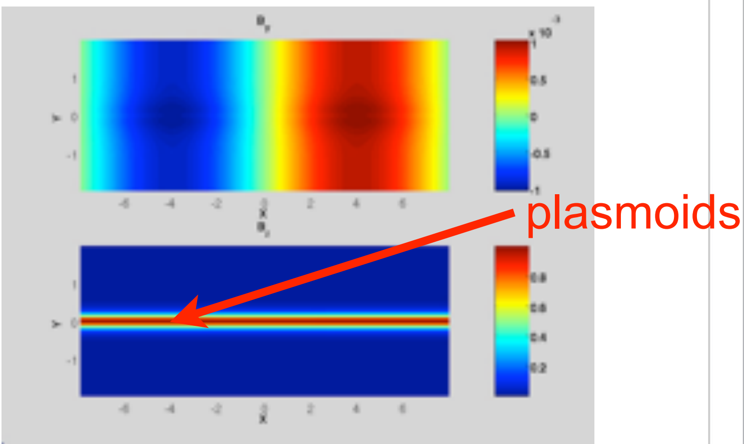


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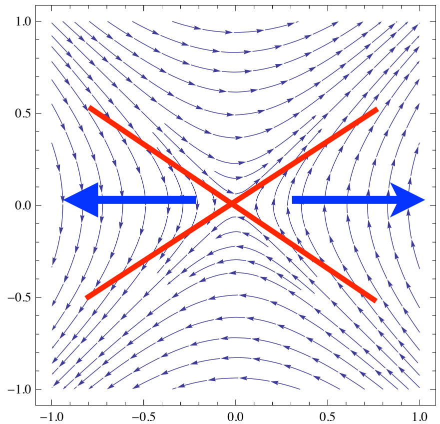

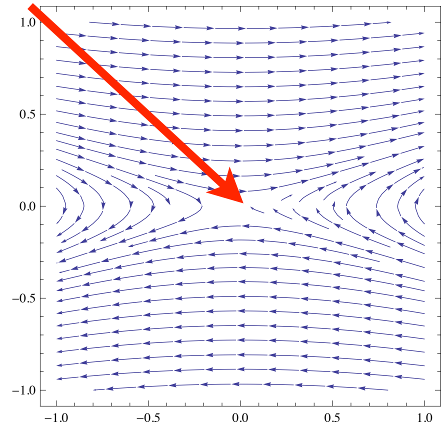


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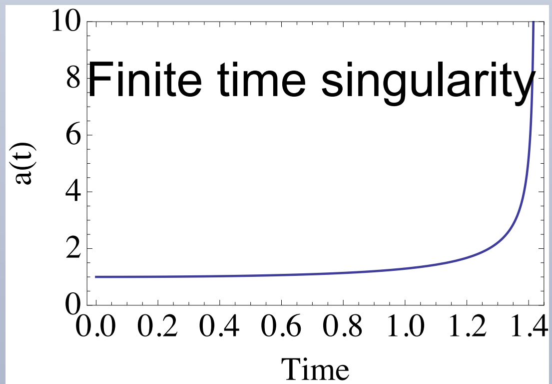

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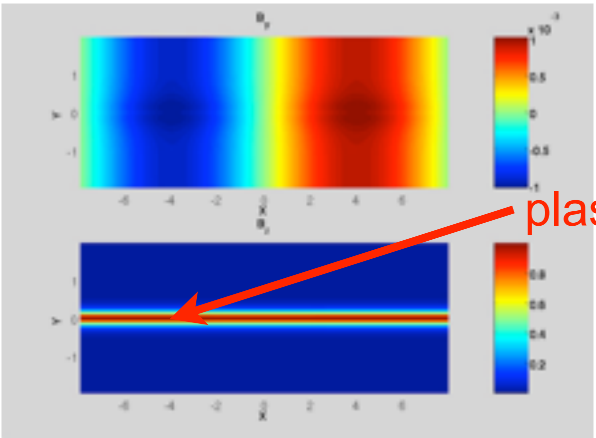


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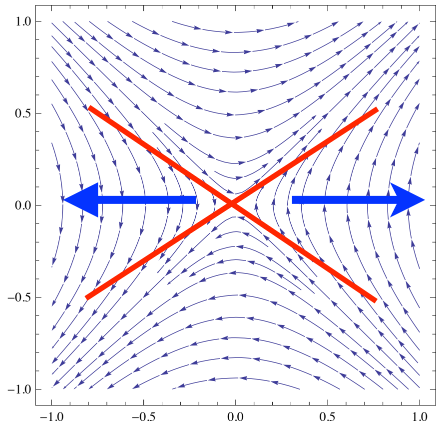


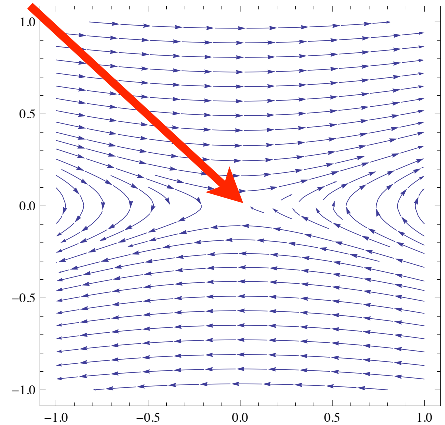


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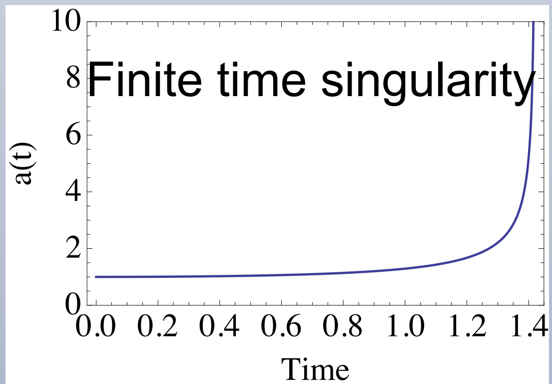
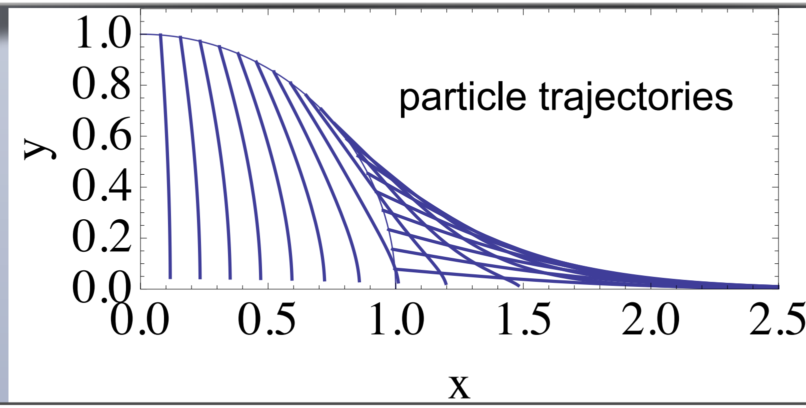
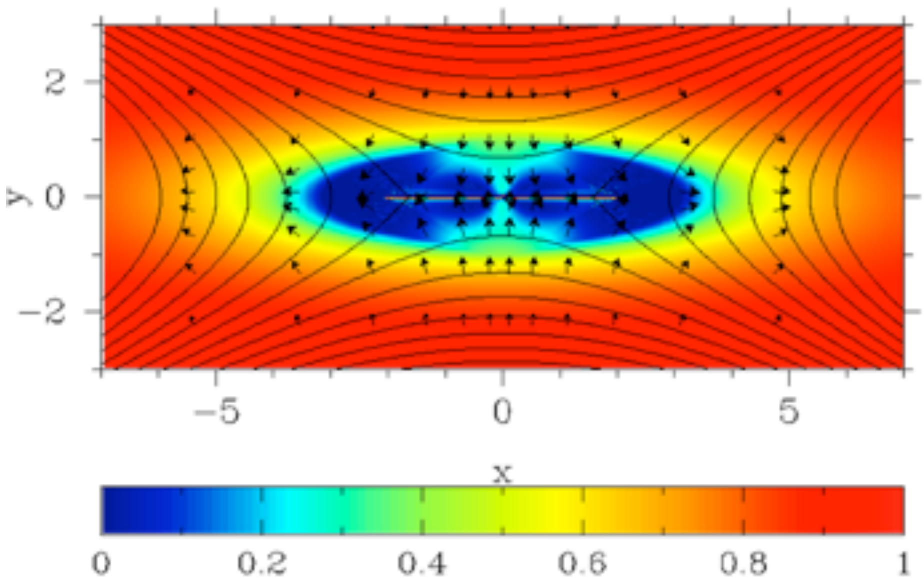


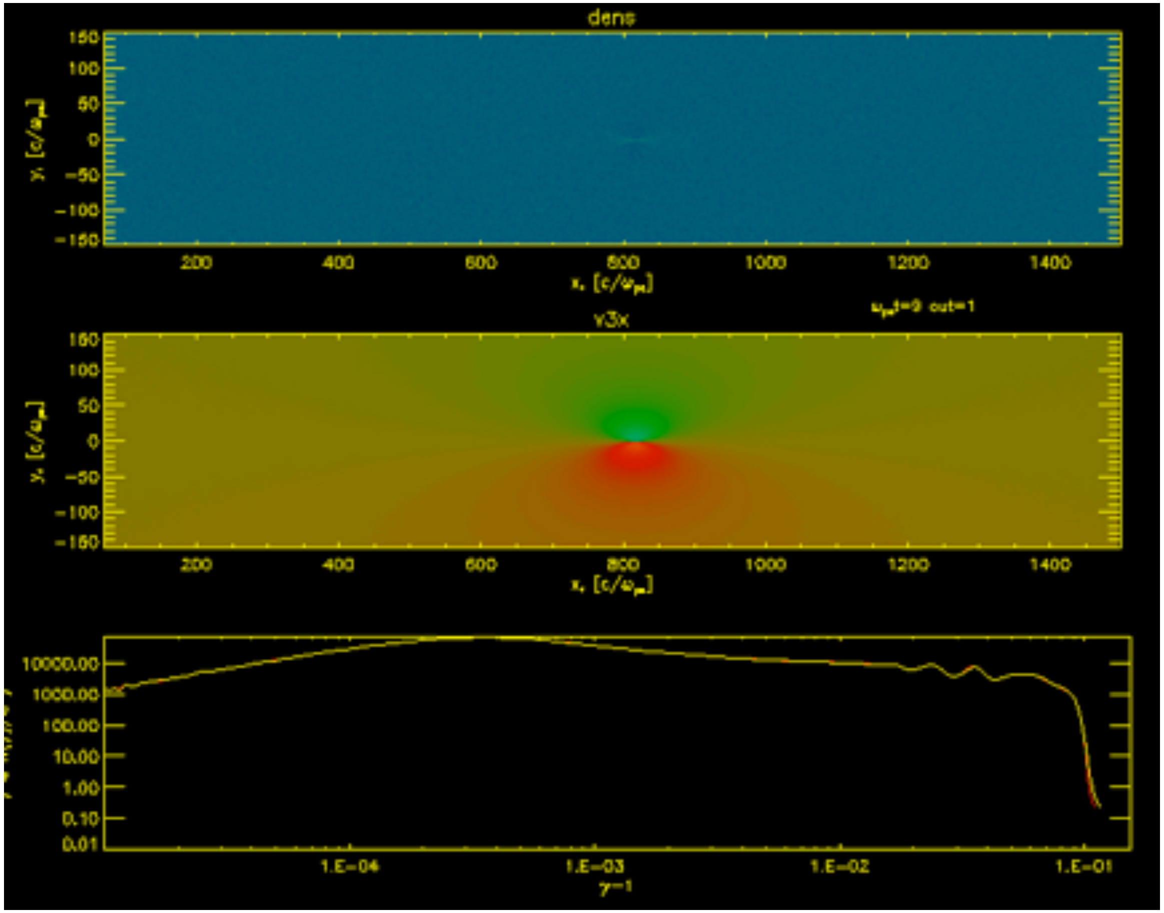
# Volumetric break-down

- Force-free X-point collapse predicts $E_z/B \sim y$
- Simulations do show volumetric break-down




Komissarov & Lyutikov, in prep

# Can produce power-laws




PIC simulations by Sironi

# The plasma regimes

$$\text{Relativistic skin depth}(n \rightarrow \gamma_w n) : \; \delta_{\rm rel} \sim \frac{r}{\lambda}$$

$$\lambda \sim 10^4 - 10^6$$

- Needed L ~ 0.01 r, $S = L^2/\delta^2 \sim 10^{4-6}$

- **Problem:** Need DC-type acceleration on sub-skin depth scales (gamma ~ $10^{4-8}$ over ~ 100 skins)?
- In relativistic plasma waves on sub-skin scales will be Landau-damped.

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$$\boxed{\begin{aligned} &\dot{E} \sim 4\pi r^2 \gamma_w n m_e c^3 \\ &n = \lambda n_{GJ} \end{aligned}}$$

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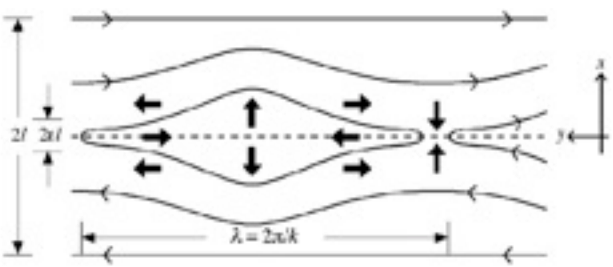
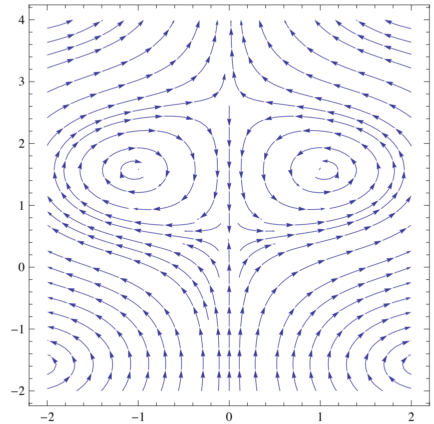
# What causes flares? - How to create the X-point?

- Tearing mode on Alfven (light crossing time along the sheet)
- $\Gamma_{\mathrm{tearing}} = v_A/L$ for $\frac{a}{L} \sim \left(\frac{\delta}{L}\right)^{1/3}$ ~ 1/few (Pucci & Velli 2013)



- Collision of two fast waves
- Collision of two shear flows
- Collision of two Alfven CD



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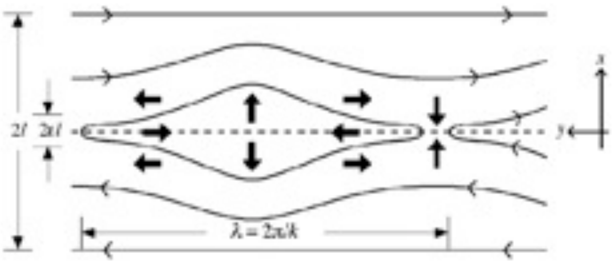

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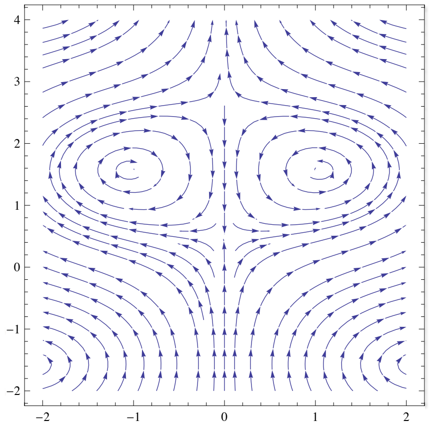
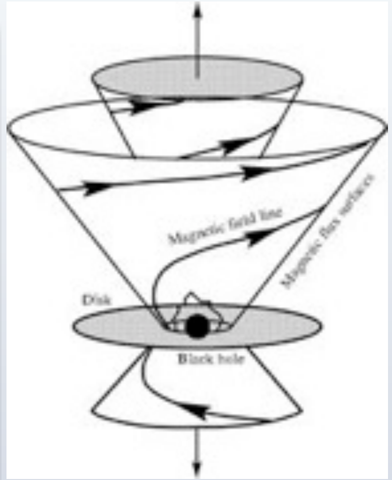


# Relevance to other sources: AGNs, GRBs




- BHs in AGNs and GRBs work similar to pulsar: rotating, magnetized central object produces relativistic magnetized wind
- ***Paradigm change (?): some (most?) particles are accelerated by magnetic reconnection (and not shocks)***