Radiative Magnetic Reconnection in Astrophysical Plasmas

Dmitri Uzdensky

(University of Colorado, Boulder)

collaborators:

- B. Cerutti*, G. Werner, K. Nalewajko, M. Begelman (Univ. Colorado)
- A. Spitkovsky (Princeton)
- J. McKinney (Univ. Maryland)

*now @ Princeton

Workshop on Relativistic Plasma Astrophysics
Purdue, March 13, 2014

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- **Introduction:** ***Radiative*** magnetic reconnection in astrophysics.
- **Astrophysical examples** of radiative reconnection:
  - Strong **synchrotron cooling** in **pulsar magnetosphere** reconnection.
  - Relativistic pair plasma reconnection and **Crab Nebula γ-flares**.
  - Other examples: Magnetar Flares; Blazar TeV flares; GRBs; black-hole accretion-disk coronae, etc.
- **Sweet-Parker** model for resistive reconnection with strong radiative cooling.
- **Summary**

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- ***News Flash!! New Results on Particle Acceleration in Relativistic Pair Reconnection!***
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Particle Acceleration in Relativistic Pair Reconnection (*Werner et al. 2014*)

- 2D simulations using Vorpal (and Zeltron) PIC codes.
- Simplest setup: no radiation, no guide field, $L_x = L_y = L$.
- Focus on ***relativistic*** ($\sigma^{\mathrm{upstream}} \gg 1$), ***large-system*** ($L/\rho_0 \gg \sigma \gg 1$) regime ($\rho_0 = m_e c^2/eB_0$).

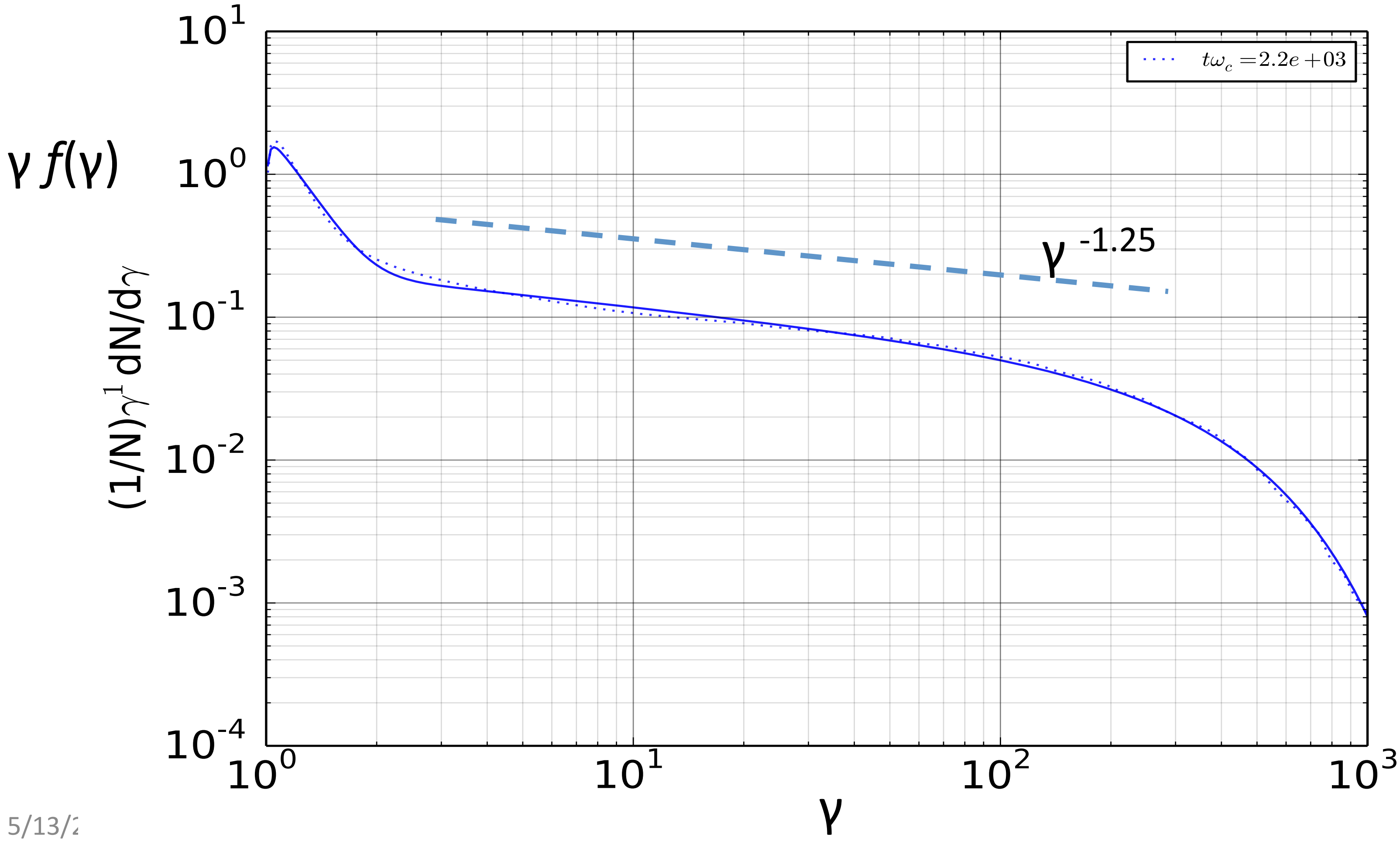
General Goal:

- completely characterize the resulting final particle energy distribution function in terms of ***L*** and **σ**.
- Is there a nonthermal power law tail and to what energies does it extend (how far beyond $\langle\gamma\rangle$)? What determines the high-energy cutoff?

Particle Acceleration in Relativistic Pair Reconnection (*Werner et al. 2014*)

Main Findings:

σ=100; L/ρ_0= 100 σ



Particle Acceleration in Relativistic Pair Reconnection (*Werner et al. 2014*)

Main Findings:

- (Low-energy) power law:

  $f(\gamma) \sim \gamma^{-\alpha}$

  $\alpha \rightarrow$ const ≈ 1.3 ± 0.2

for large enough *L* and σ>10.

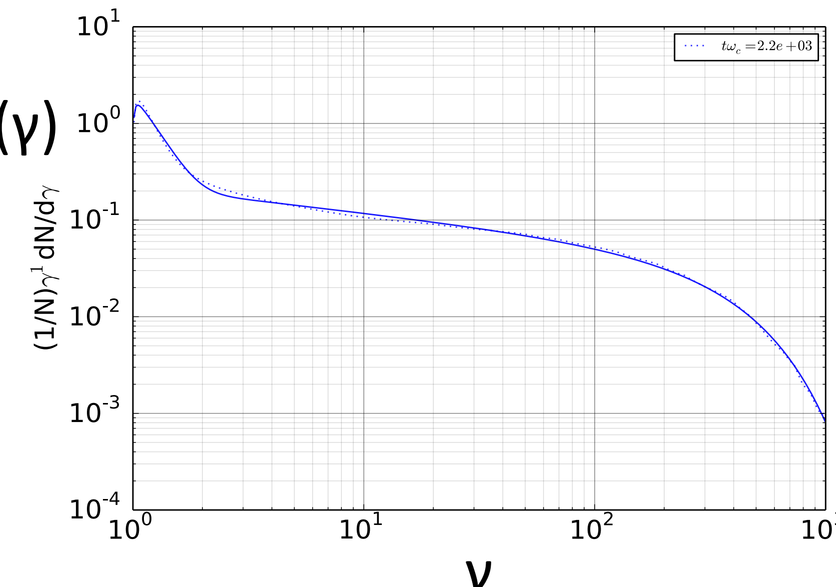
- Two high-energy cutoffs:

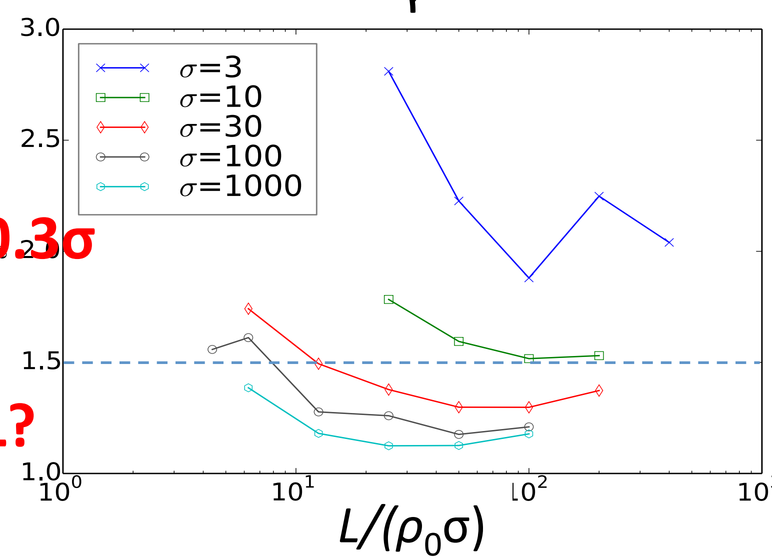
- exp $(-\gamma/\gamma_{c1})$; $\gamma_{c1} \sim 3\sigma$, weak L-dependence;

heating: $\varepsilon_{max} \approx \langle\varepsilon\rangle \sim 0.3\sigma$

- exp $(-\gamma/\gamma_{c2})^2$; $\gamma_{c1} \sim L$; weak σ-dependence

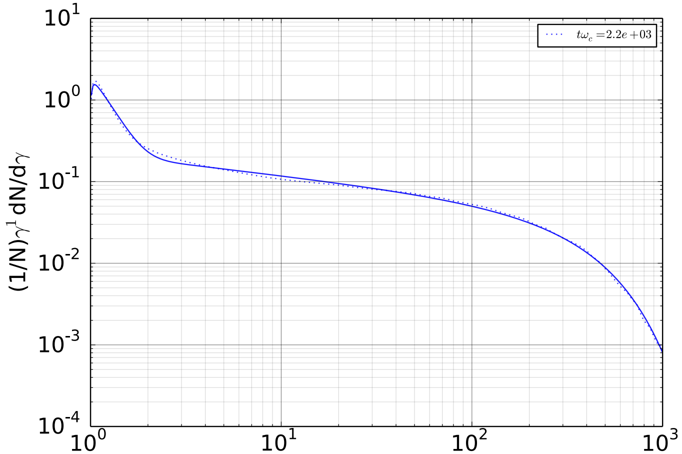
$\gamma_{max} \approx (L/\rho_0)/2$ **"extreme" accel.: $\varepsilon_{max} = eE_{rec}L$?**





Particle Acceleration in Relativistic Pair Reconnection (*Werner et al. 2014*)

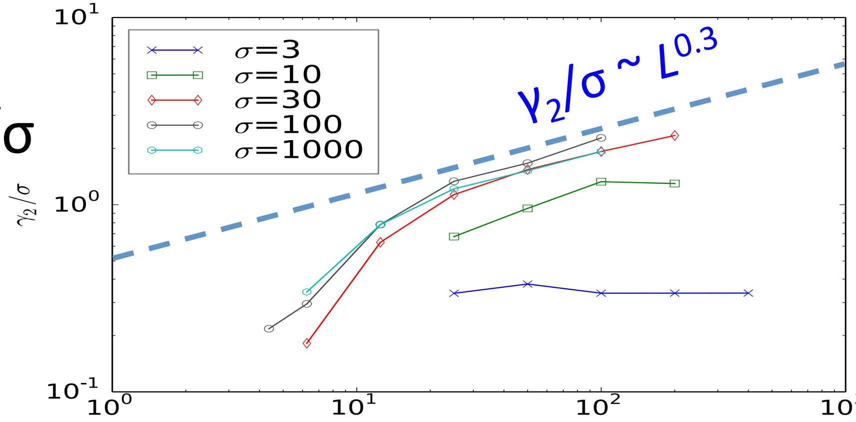
$\gamma f(\gamma)$



γ

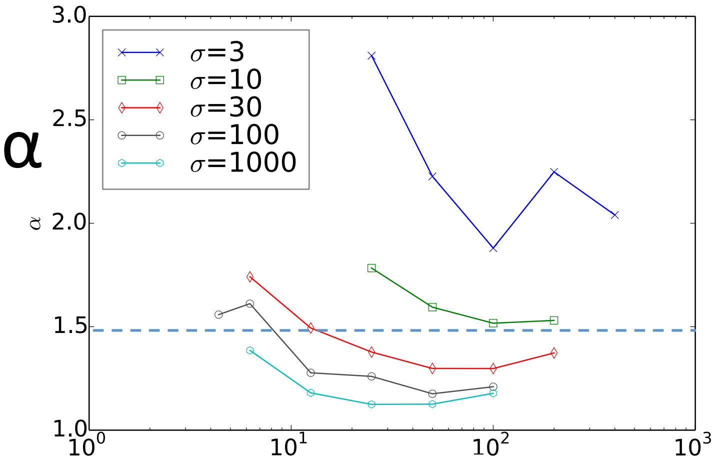
Energy-dominating scale γ_2: max of $\gamma^2 f(\gamma)$

γ_2/σ



$L/(\rho_0\sigma)$

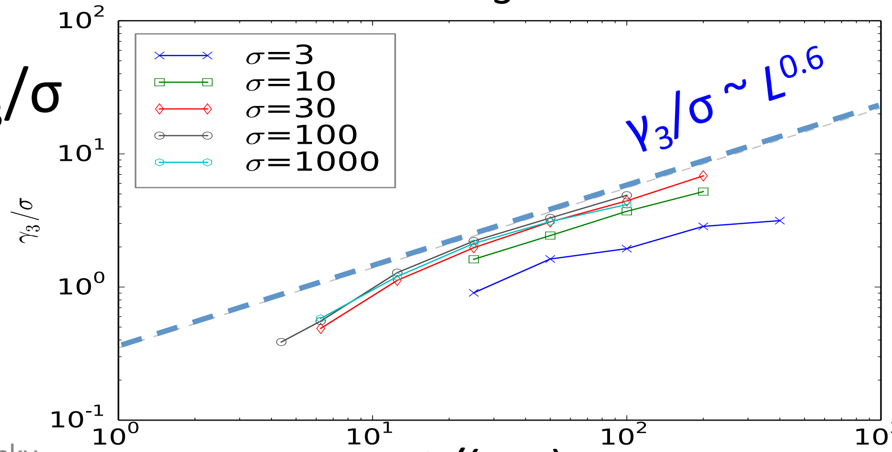
α



$L/(\rho_0\sigma)$

Radiation-dominating scale γ_3: max of $\gamma^3 f(\gamma)$

γ_3/σ



$L/(\rho_0\sigma)$

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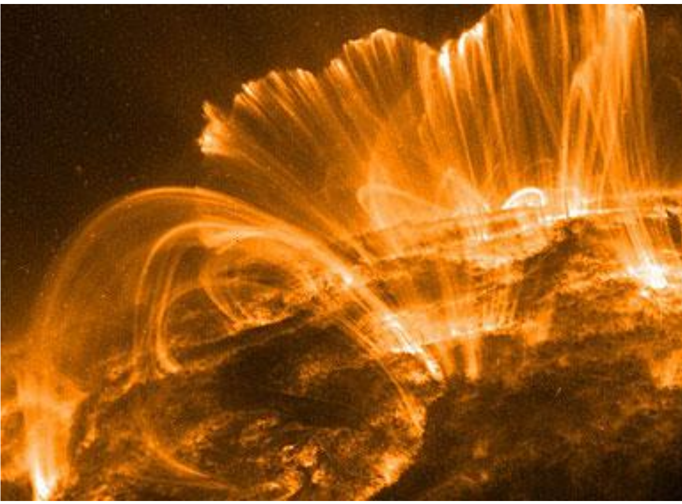
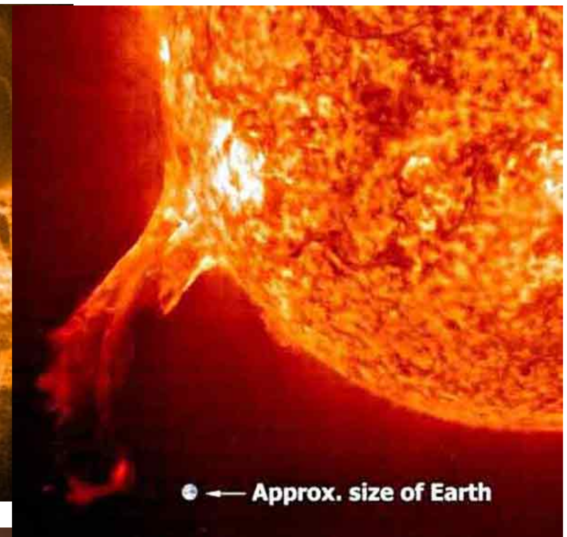
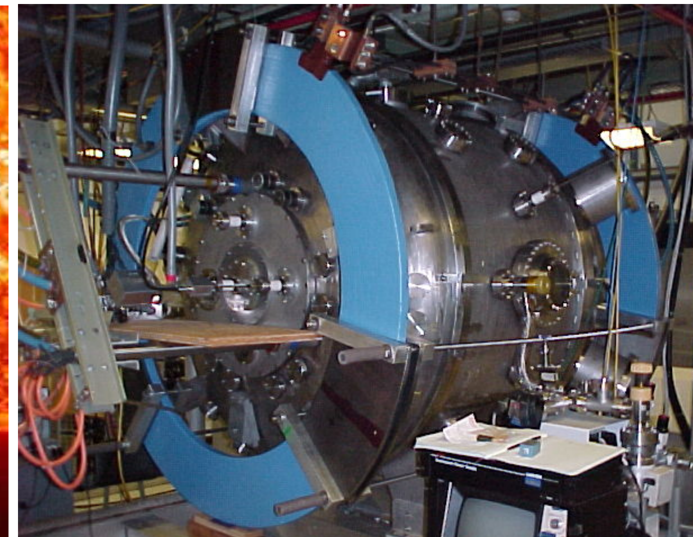
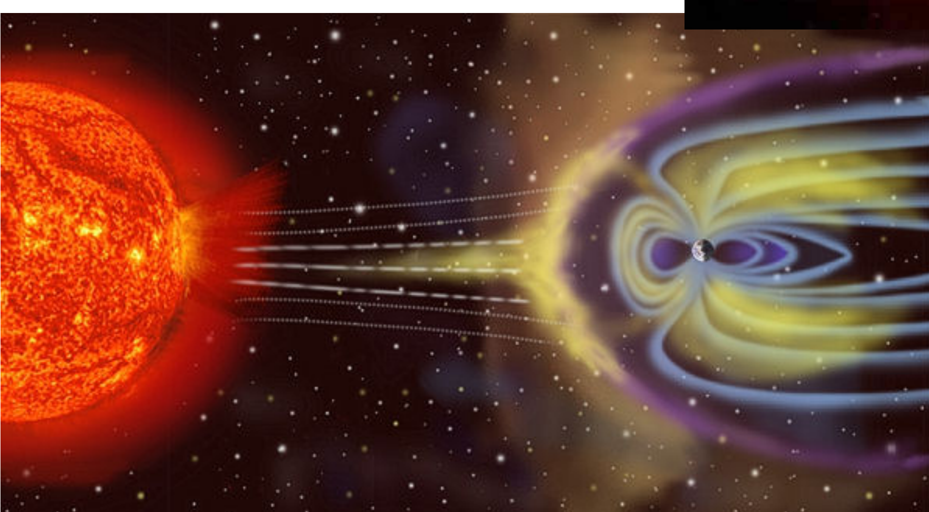
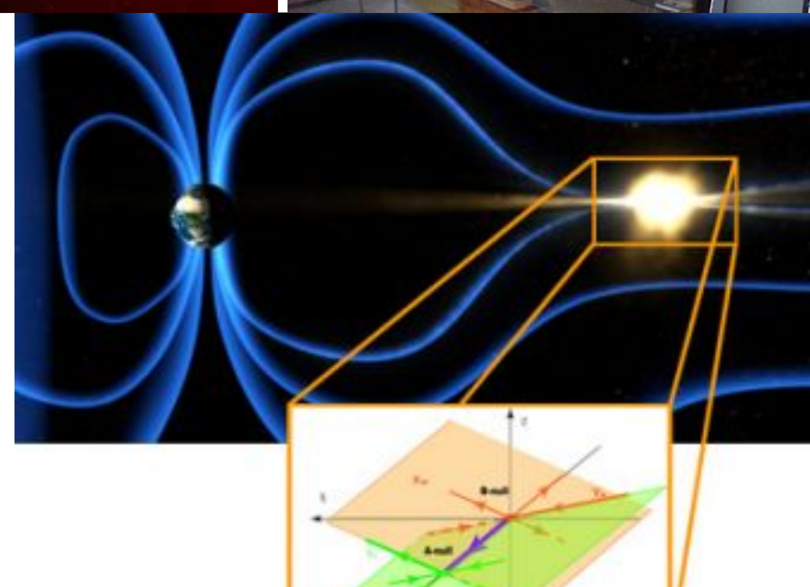
Traditional Magnetic Reconnection in the Solar System





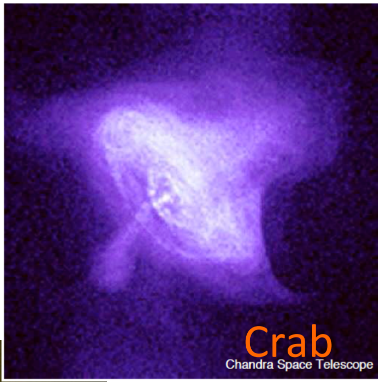


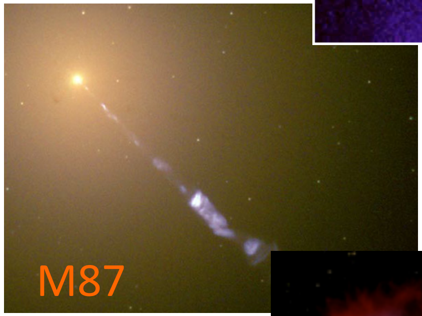


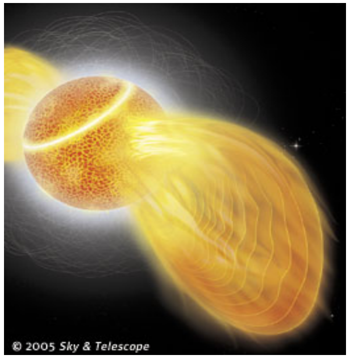


Reconnection in Astrophysics

- Pulsar magnetospheres, winds, PWNe
- AGN (e.g., blazar) jets, radio-lobes
- Gamma-Ray Bursts (GRBs)
- Magnetar (SGR) flares







Radiative Reconnection in Astrophysics

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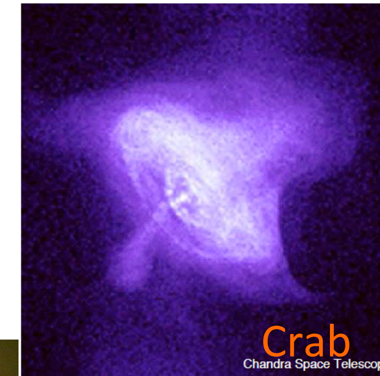
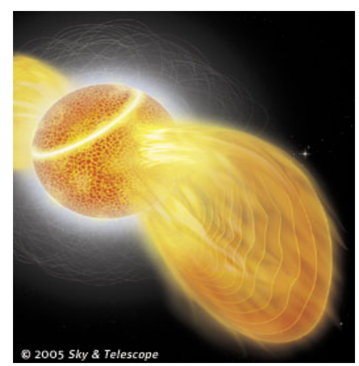




Radiation in Astrophysical Reconnection

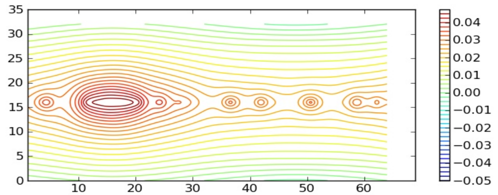
- In conventional reconnection studies (space/solar/lab), plasma consists of electrons and ions --- **no photons!**
- In contrast, in many high-energy ***astrophysical*** situations **radiation** is important --- strongly affects reconnection:

  - Radiative cooling;
  - Radiative drag on recn. outflow;
  - Radiation pressure;
  - Compton-drag resistivity.

- In addition, radiation is our only ***observational diagnostic*** into astrophysical reconnection.

  How does a reconnection layer look like, literally?

  – what are (prompt) **radiative signatures** (spectra, light curves) of reconnection seen by an outside observer



***Radiative magnetic reconnection* is a new frontier in plasma astrophysics!!**

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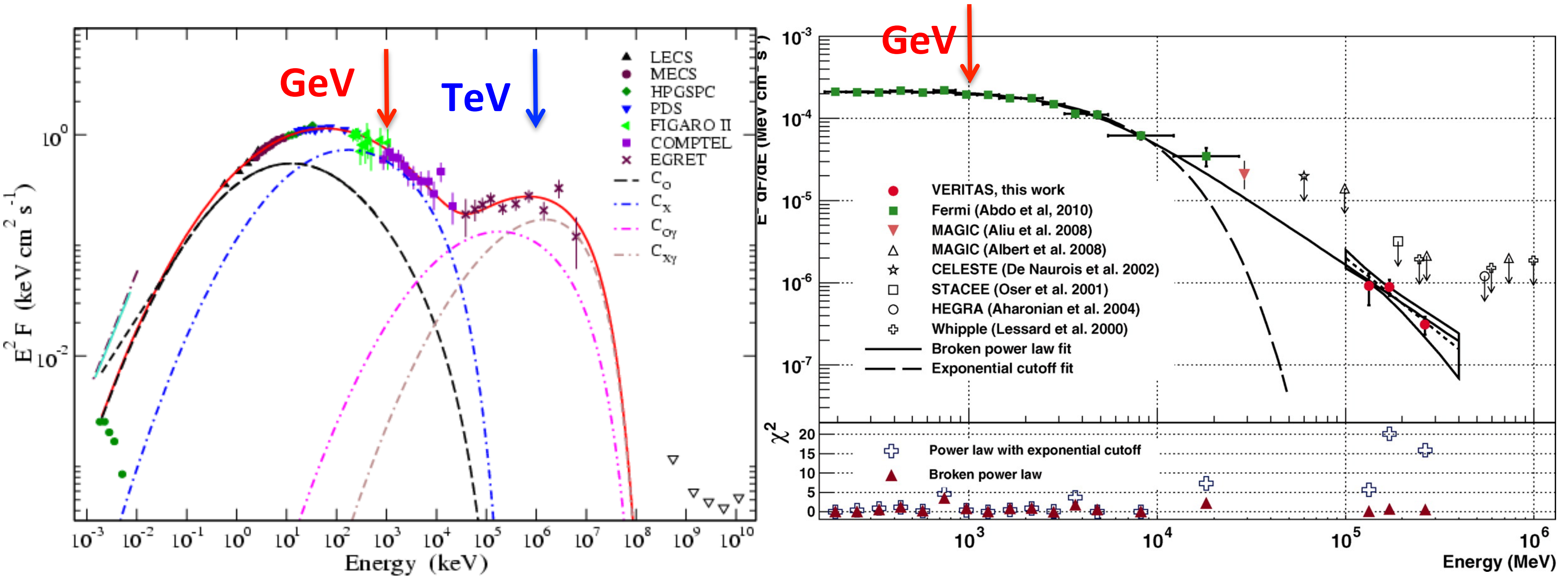
Astrophysical Example of Reconnection with Strong Radiative Cooling: Pulsar Magnetosphere

(Uzdensky & Spitkovsky ApJ 2014)

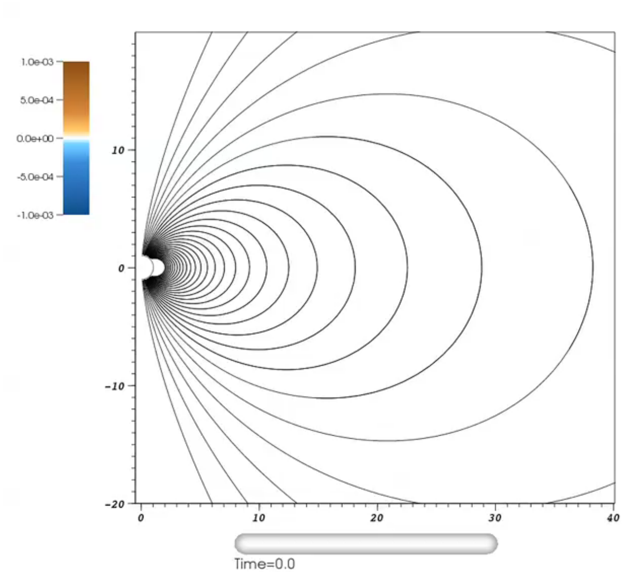
CRAB PULSED SPECTRUM



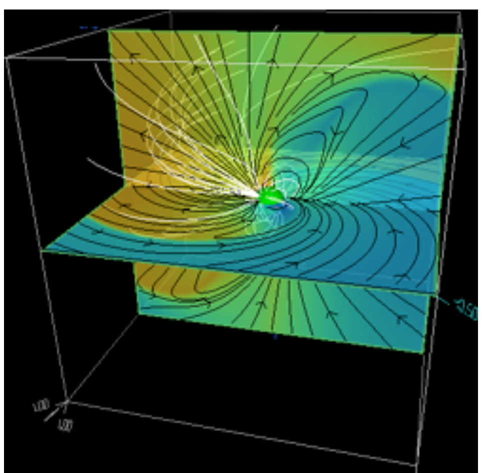
Detailed modeling of pulsed emission is affected by realistic geometry (oblique rotator), relativistic kinematics, etc. (Bai & Spitkovsky 2010).

But what are the basic plasma parameters in the emitting region?

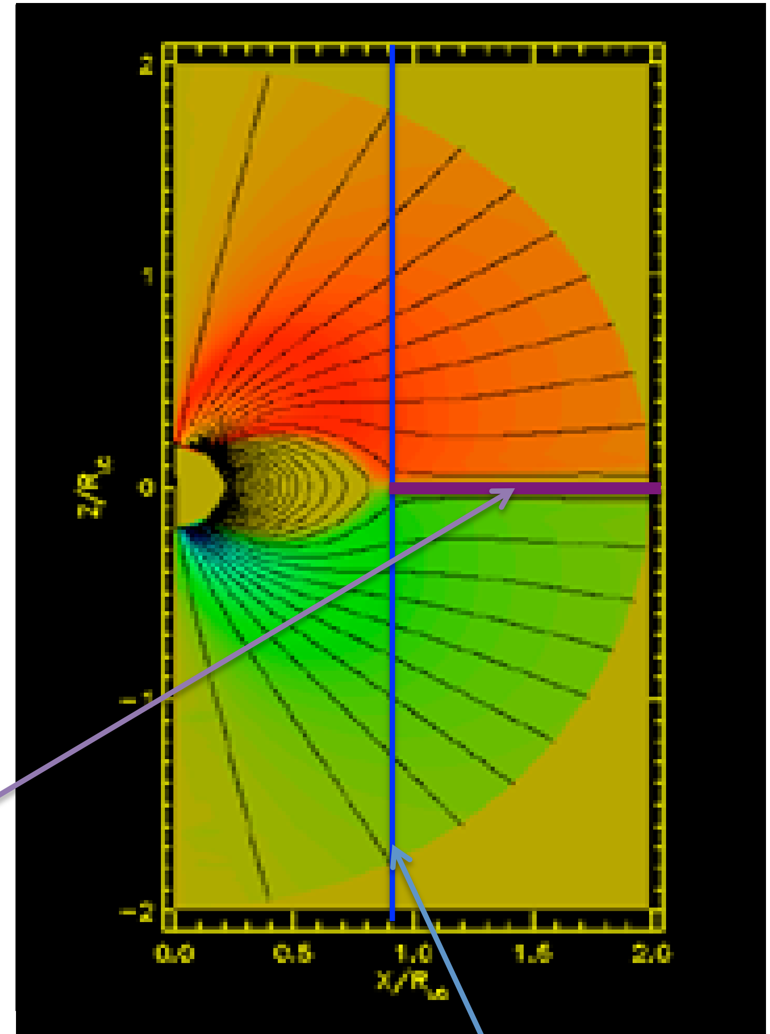
Pulsar Magnetosphere: General Structure



Parfrey & Beloborodov 2012



Spitkovsky 2006



Spitkovsky'06

equatorial
current sheet

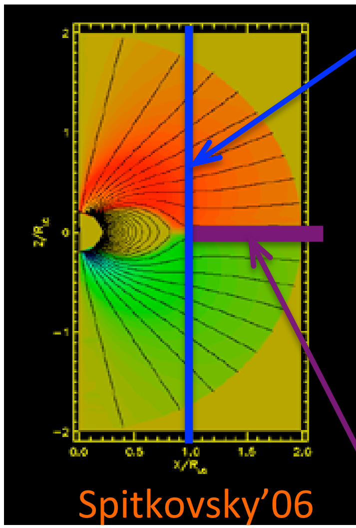
Light Cylinder

$R_{NS} \approx 10$ km

$R_{LC} = c/\Omega \approx 1000$ km

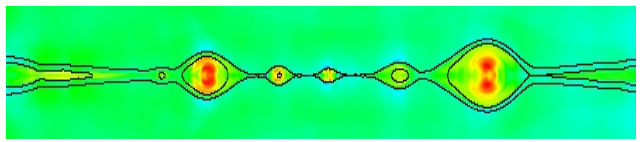
Reconnecting Pulsar Magnetosphere

- Equatorial current sheet should be tearing-unstable (*Lyubarsky' 96*), leading to a hierarchical chain of (merging) plasmoids/flux ropes.

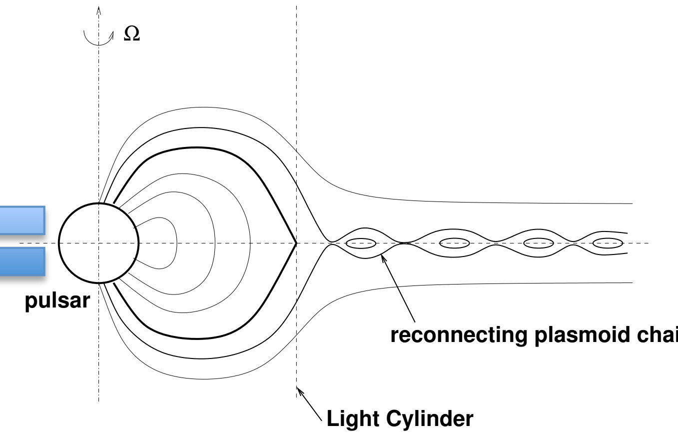


Light Cylinder

equatorial current sheet



(Loureiro et al. '07, '12)

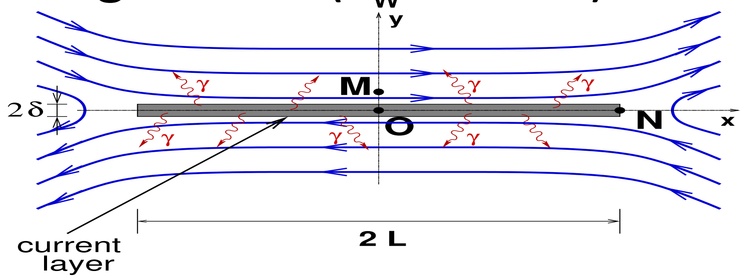


(Bucciantini et al. 2006; Contopoulos & Spitkovsky 2007)

- **Questions:**
  - What are the basic plasma conditions inside inter-plasmoid current sheets (actual sites of energy dissipation) ?
  - What are the observational consequences ?

Reconnection with strong synchrotron cooling near pulsar Light Cylinder

- What are *T, n,* and δ in pulsar-wind comoving frame ($\Gamma_w \approx 100$)?



- Three equations:
  - Pressure Balance: $B_0^2/8\pi = 2\,n\,T$
  - Energy balance with strong synchrotron cooling (*c.f. Lyubarsky' 96*):

$$S_{in} = \frac{c}{4\pi} E B_0 \sim 2n\,\Lambda(B,\gamma_T)\,\delta \quad \text{where} \quad \Lambda(B,\gamma) = 2\,\sigma_T c\,\frac{B_\perp^2}{8\pi}\,\gamma^2$$

  - Ampere's Law: $j_z = 2\,n\,e\,v_{dr} = 2\,n\,e\,c\,\beta_{dr} \sim (c/4\pi)\,B_0/\delta$

- Dimensionless parameters:
  - dimensioness rec. rate: $\beta_{rec} = E/B_0 \sim 0.1$ (PIC simulations)
  - e^+/e^- drift velocity: $\beta_{dr} = v_{dr}/c \approx 1 \Leftrightarrow \delta \approx \rho$

RESULTS

Obtain 3 comoving plasma parameters (T, n, δ) in terms of B_0 (~4 MG):

- **Temperature:**

$$\gamma_T = T / m_e c^2 \sim (\beta_{dr}\,\beta_{rec})^{1/2}\, b^{-1/2} \sim 4 \times 10^4\ (\beta_{dr}\,\beta_{rec})^{1/2}$$

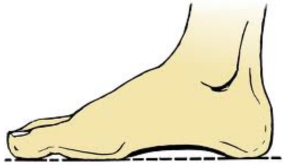
-- at synchrotron radiation-reaction limit: $e\,E_{rec}\,c = \Lambda_{synch}(\gamma, B_0)$

- **Density:**

$$n \sim (\beta_{dr}\,\beta_{rec})^{-1/2}\,(B_0^2/8\pi\, m_e c^2)\, b^{1/2} \sim 2 \times 10^{13}\ \mathrm{cm}^{-3}\ (\beta_{dr}\,\beta_{rec})^{-1/2}$$

-- rad. cooling → strong plasma compression >> ambient density *(Uzdensky & McKinney 2011)*

- **Layer thickness:**



$$\delta \sim (\beta_{rec}/\beta_{dr})^{1/2}\, r_e\, b^{-3/2} \sim 30\ \mathrm{cm}\ (\beta_{rec}/\beta_{dr})^{1/2}$$

normalized magnetic field: $b = B_0/B_{cl} = r_e/\rho_c \ll 1$; $B_{cl} = e/r_e^2 \approx 6\times10^{15}$ G.

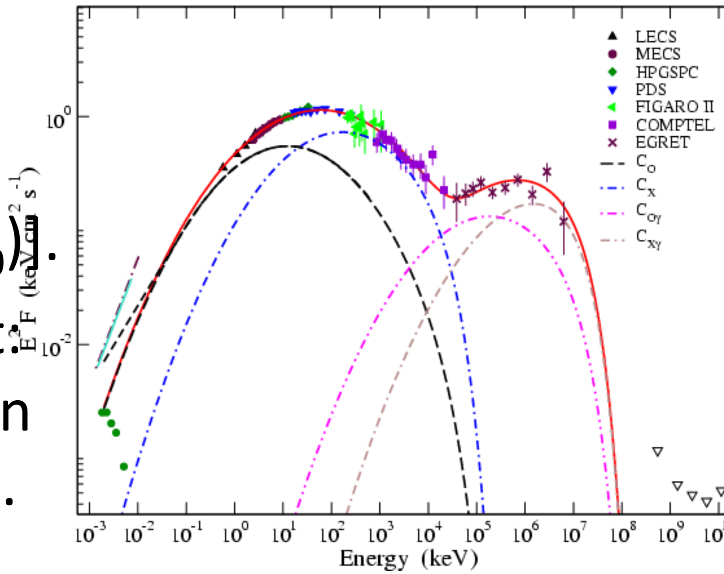
Astrophysical Implications (for Crab, etc.):

- Pulsed GeV FERMI γ-ray emission:

(c.f. Lyubarsky '96, Petri '12, Arka & Dubus '13)

Comoving temperature T ≈ 10 GeV at the radiation-reaction limit $[e\, E_{rec}\, c = \Lambda_{synch}(\gamma, B_0)]$.

Synchrotron radiation at standard max. limit: $\varepsilon_{ph} \sim \beta_{rec}\, m_e\, c^2 / \alpha \approx 20$ MeV → GeV emission after Doppler boost (due to rel. pulsar wind).



- Pulsed VHE (> 100 GeV) MAGIC/VERITAS γ-ray emission:

Inverse Compton scattering on hot pairs (ε = Γ T≈1 TeV) in the layer.

- Pulsed radio emission:

dynamic reconnecting plasmoid chain with *cm*-scales…

SUMMARY

- (σ,L) parameter-space PIC study of relativistic pair reconnection:
  - power law $f(\gamma) \sim \gamma^{-\alpha}$ with $\alpha \approx 1.3$ and $[\exp(-\gamma/\gamma_{c1}) \times \exp(-\gamma/\gamma_{c2})^2]$ cutoff;
  - $\gamma_{c1} \sim \sigma L^{0.3} \leq 10 \langle\gamma\rangle$; $\gamma_{c2} \sim L$ – total voltage drop.
- Radiation is often important in high-energy astro reconnection!
- Radiation is our only direct diagnostic of astrophysical reconnection.
- Reconnection with strong synchrotron cooling in pulsar (e.g., Crab) magnetosphere outside LC:
  - Reconnection layer parameters (comoving T, n, δ) depend only on B_0.
  - Can potentially explain FERMI observations of pulsed gamma-ray (GeV) emission for Crab and other pulsars.
- Sweet-Parker resistive MHD reconnection with strong rad. cooling:
  - heating/cooling balance determines layer temperature;
  - cooling leads to plasma compression and faster reconnection.