Magnetic Reconnection and Radiation in Astrophysics

Dmitri Uzdensky

(University of Colorado, Boulder)

In collaboration with: B. Cerutti, G. Werner, M. Begelman (Colorado)

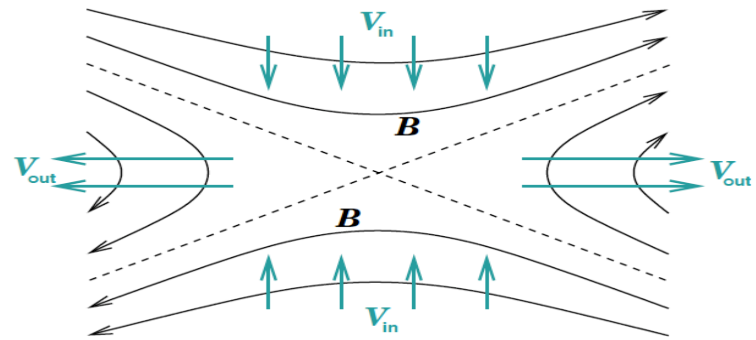
Ginzburg Conference on Physics
Lebedev Physics Inst., Moscow, June 1, 2012.

OUTLINE

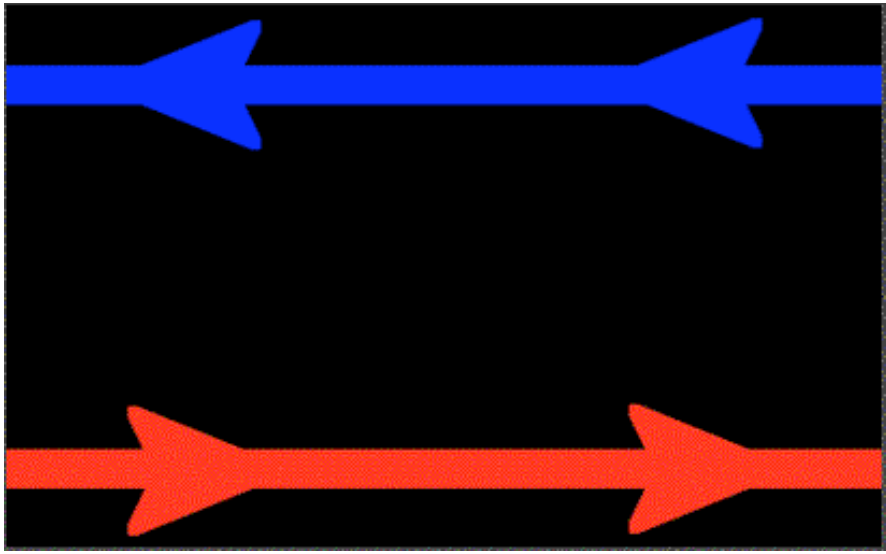
- Introduction to reconnection
- ***Radiative*** magnetic reconnection in astrophysics.
- Astrophysical illustrations:
  - Extreme particle acceleration and **Crab Nebula γ-flares**.
  - Strong ***anisotropy*** of particle acceleration and focusing and rapid variability of radiation in relativistic pair reconnection.
  - Strong **synchrotron cooling** in pulsar magnetosphere recn.
  - (Giant flares in **magnetar** [SGR] magnetospheres)
  - (**GRB** prompt emission)
- Summary

Introduction: Magnetic Reconnection

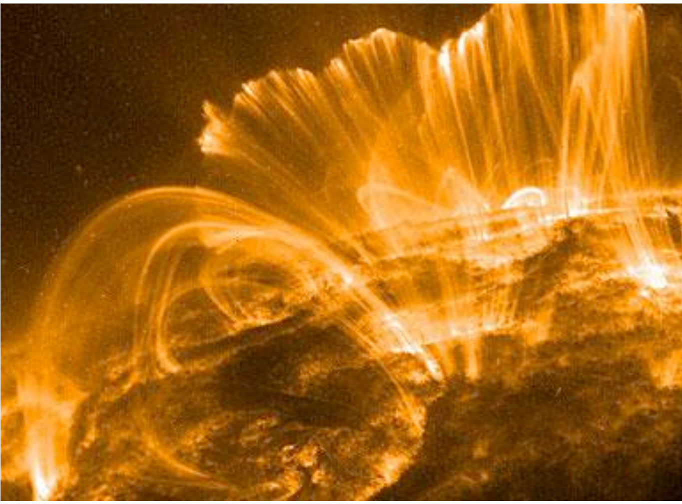
- **Magnetic reconnection** is a rapid rearrangement of magnetic field topology

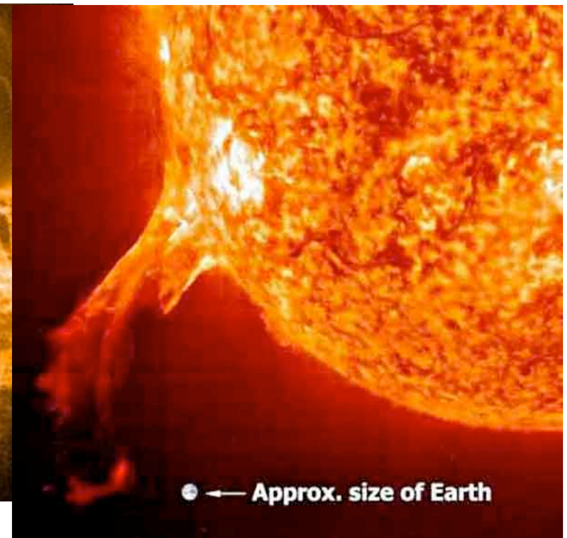


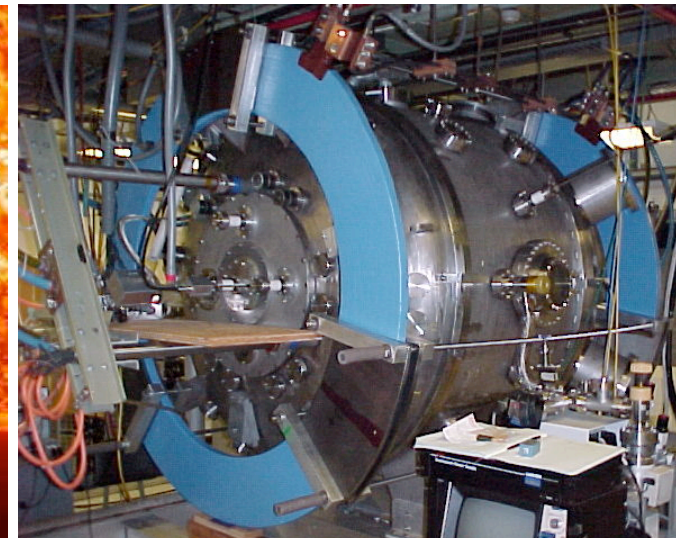
- Reconnection often results in violent release of magnetic energy and its conversion to:
  - electron and ion heating
  - bulk kinetic energy
  - non-thermal particle acceleration

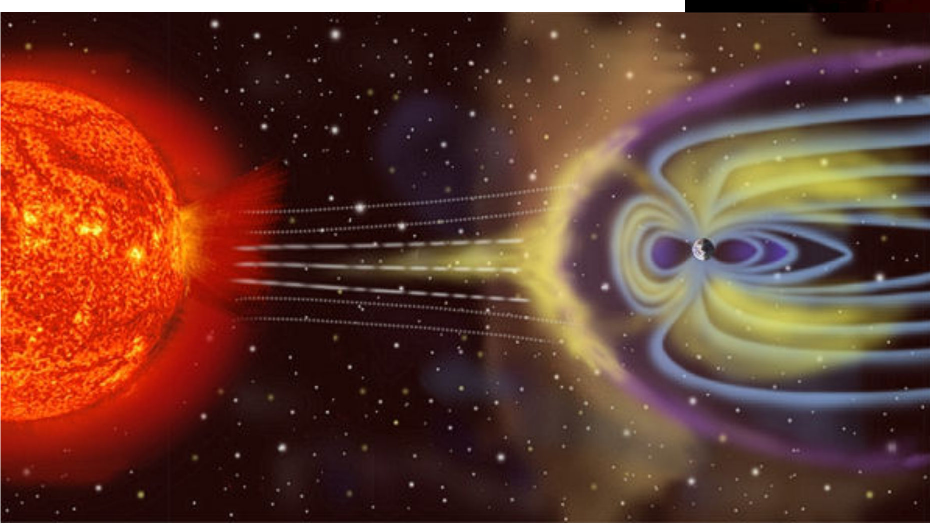


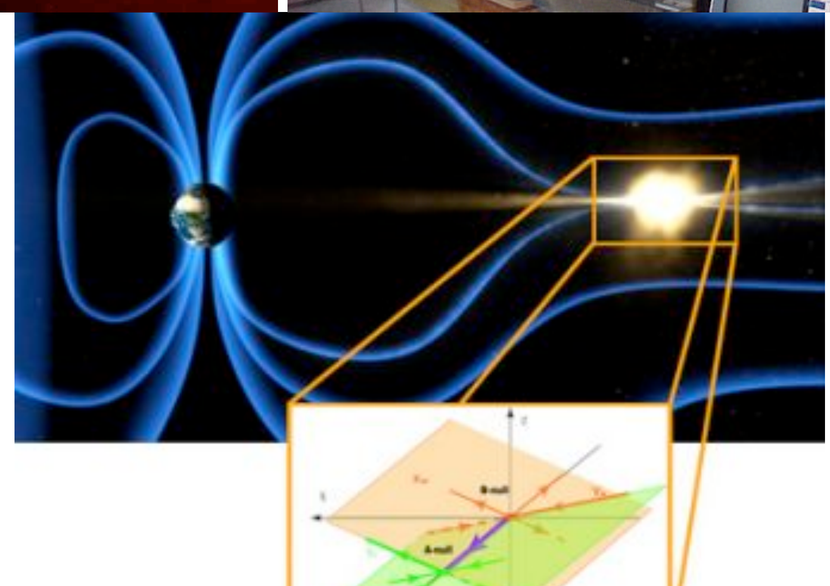
Traditional Magnetic Reconnection in the Solar System











Radiation in Astrophysical Reconnection

- In conventional reconnection studies (space/solar/laboratory), the plasma consists charged particles (*e*-ns & ions) --- **no photons!**

- In contrast, in many ***astrophysical*** situations energy density is so high that **radiation** strongly affects reconnection:

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

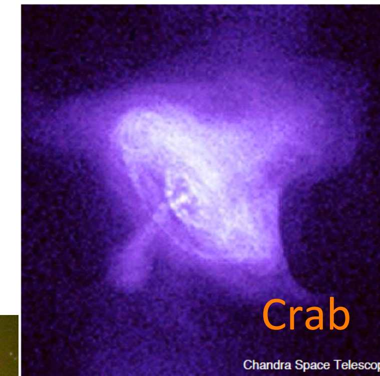
- In addition, radiation is our only ***observational diagnostic*** into astrophysical reconnection.

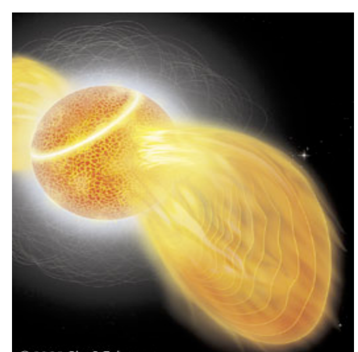
- Radiative magnetic reconnection is a young subject:

(Dorman & Kulsrud 1995; Lyubarsky 1996; Jaroschek & Hoshino 2009; Giannios et al. 2009; McKinney & Uzdensky 2010; Medvedev 2010; Uzdensky & McKinney 2011; Uzdensky 2011; Nalewajko et al. 2011; Cerutti et al. 2012ab; Takahashi et al. 2012)

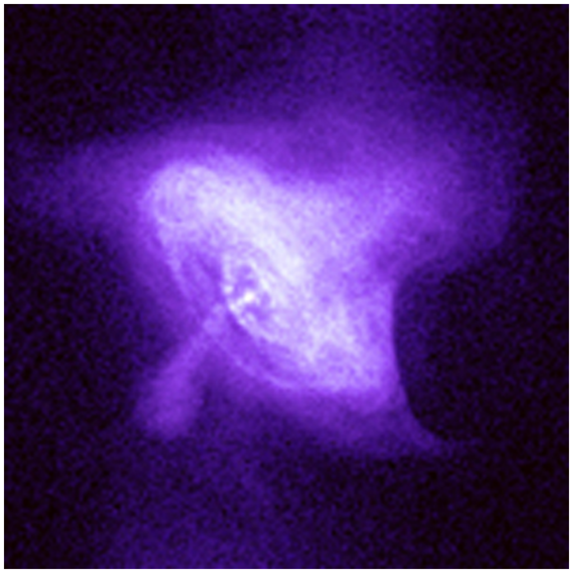
Reconnection in Astrophysics

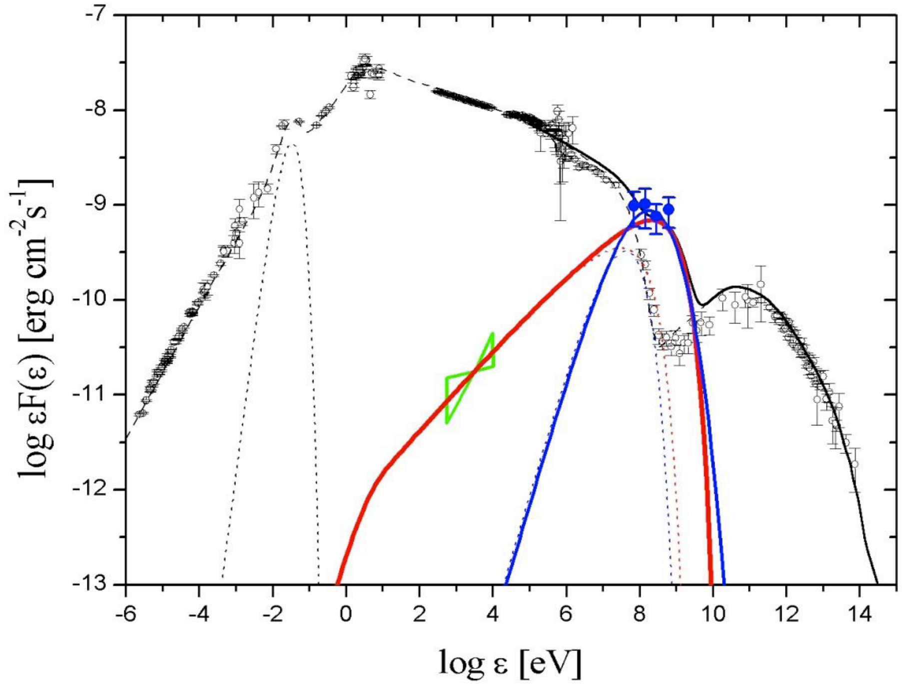
- Pulsar magnetospheres, winds, PWNe
- AGN (e.g., blazar) jets, radio-lobes
- Gamma-Ray Bursts (GRBs)
- Magnetar flares





Gamma-Ray Flares in the Crab





September 2010 AGILE/FERMI γ-flare

Observational constraints:

- Flare duration: τ = 1 day --> $l \sim 3 \times 10^{15}$ cm
- Photon energy: > 100 MeV --> $\gamma_9 \sim 3\ B_{-3}^{-1/2}$ -- PeV !!
- Isotropic flare energy: $\mathcal{E} \sim 4 \times 10^{40}$ erg

Main Problem: synchrotron emission > 100 MeV challenges classical models of acceleration

➢ **Maximum electron energy is limited by radiative losses:**

- Accelerating electric force: $\mathbf{f_{acc} = eE}$
- Radiation reaction force: $\mathbf{f_{rad} = 2/3\ r_e^2\ \gamma^2\ B^2}$

$\Big\}$ $\mathbf{f_{acc} = f_{rad} \rightarrow \gamma_{max}}$

- Synchrotron photon energy: $\mathbf{\varepsilon_{max} = 3/2\ \gamma^2_{max}\ \hbar\ \omega_c}$ = **160×(E/B) MeV**

In classical acceleration mechanisms: E < B ➔ ε_{max} < 160 MeV

(e.g., de Jager et al. 1996; Lyutikov 2010)

> the flares challenge classical acceleration theories !

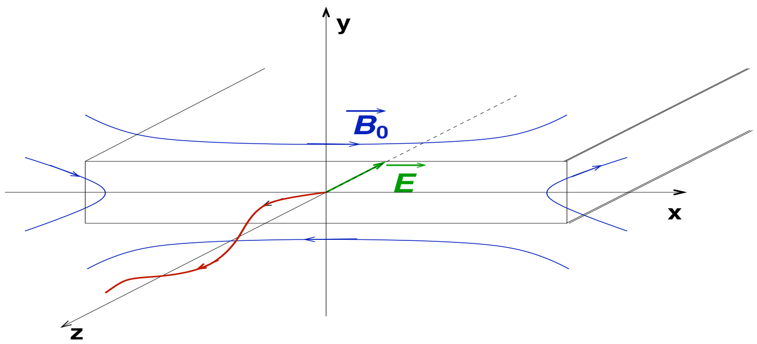
Our solution: *(Uzdensky, Cerutti, & Begelman 2011; Cerutti et al 2012a)*

- Relax $E < B_{perp}$ assumption !
- Impossible in ideal MHD $(E + v \times B/c = 0)$
- **Reconnection layers** are a natural place for this to happen.

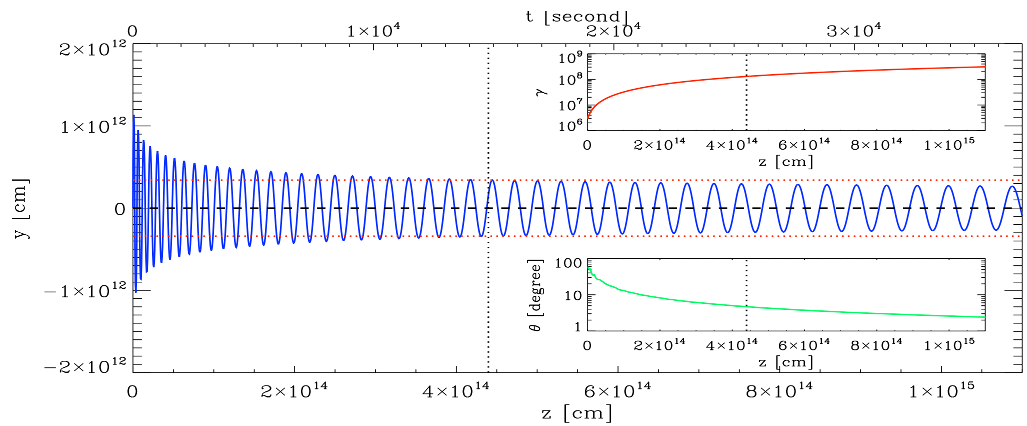
MAIN IDEA

(Uzdensky, Cerutti, & Begelman 2011; Cerutti et al. 2012; also Kirk 2004)

- Energetic (PeV) particles on relativistic Speiser orbits:
  - accelerated by reconnection E_z in z-direction;
  - confined to reconnection midplane by reversing reconnection magnetic field B_x.



- Test-particle calculations: ultra-relativistic particles focus deep into a thin fan beam along the layer.

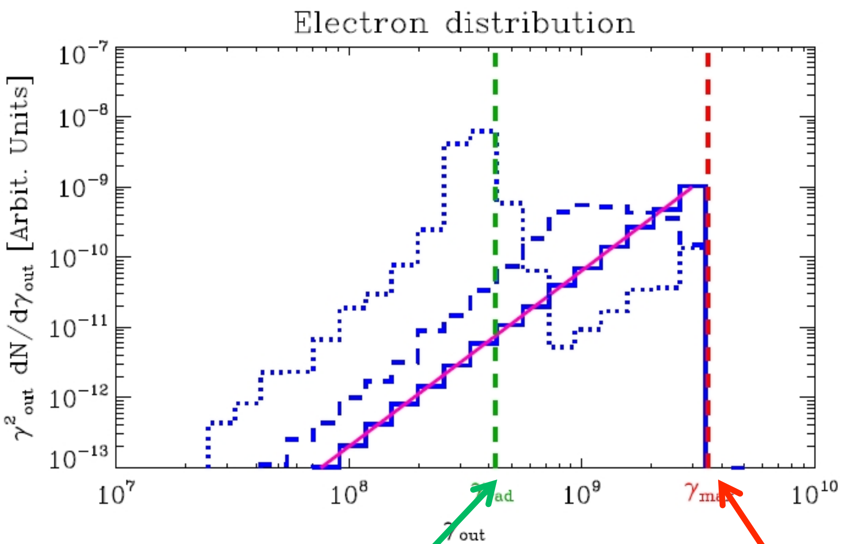


- Deep in the layer, B is small and synchrotron radiation reaction is reduced.

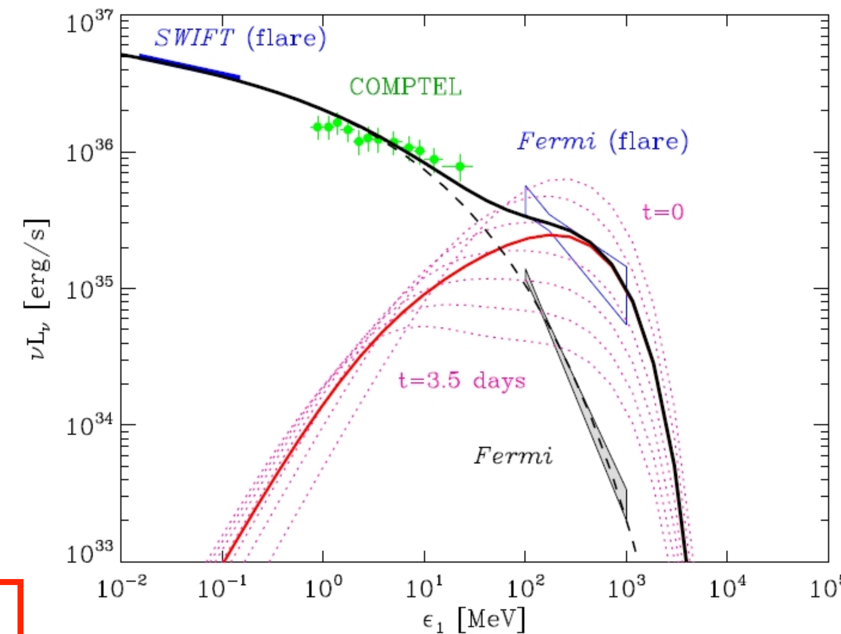
- Particles can reach higher energies and emit photons with $\varepsilon > \varepsilon_{sync,*} = 160$ MeV

Test particle population study:
Application to Crab Nebula flares *(Cerutti et al. 2012)*

- **Continuous particle injection + synchrotron cooling during flare.**



Spectral Energy Distribution (photons)



$\gamma_{rad} = (3c\beta_{rec}/2r_e\omega_0)^{1/2} \approx 4\times10^8$

$\gamma_{max} = eEL_z/m_ec^2 \approx 3.5\times10^9$

The particles pile up at the maximum energy available ≈ monoenergetic

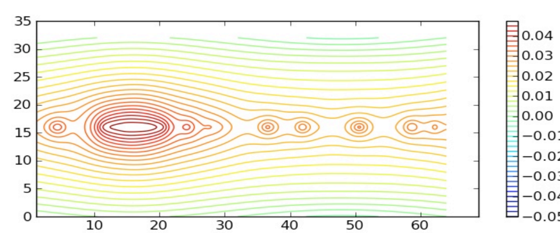
Energetics modest: **$E_{pairs} < 10^{-3}\, E_{mag}$** (>10% w/out beaming).

Negligible Inverse Compton emission

Anisotropy of Particle Acceleration and Radiation in Relativistic Pair Reconnection

(Cerutti, Werner, Uzdensky, & Begelman 2012)

- How do we describe accelerated particle population?
  - Previous numerical studies focused only on *energy* distribution…
  - New **Q**: what is the ***angular distribution*** of accelerated particles?
  - This is important because relativistic particle anisotropy → anisotropy of observable radiation...
- How does a reconnection look like, literally?
  - what are (prompt) **radiative signatures** of reconnection, as seen by an outside observer:
    - observable photon spectrum;
    - light curve

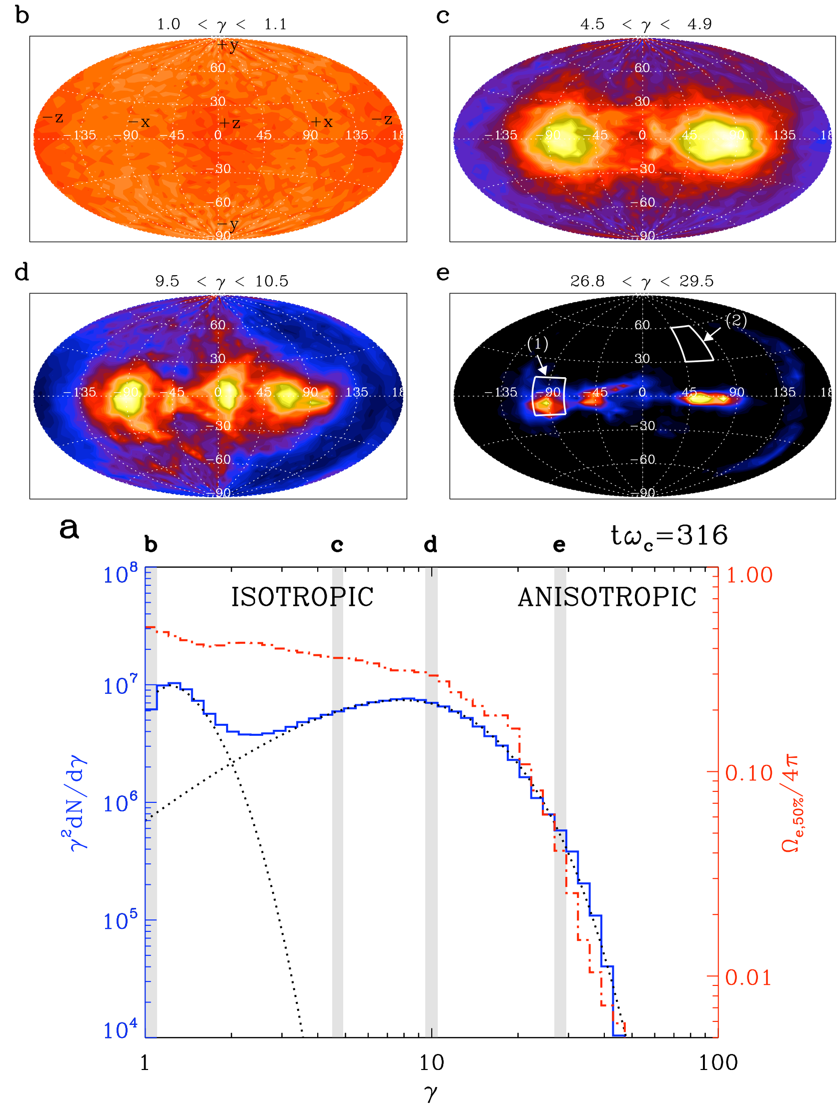


Particle anisotropy in PIC simulations of relativistic pair reconnection *(Cerutti et al. 2012)*

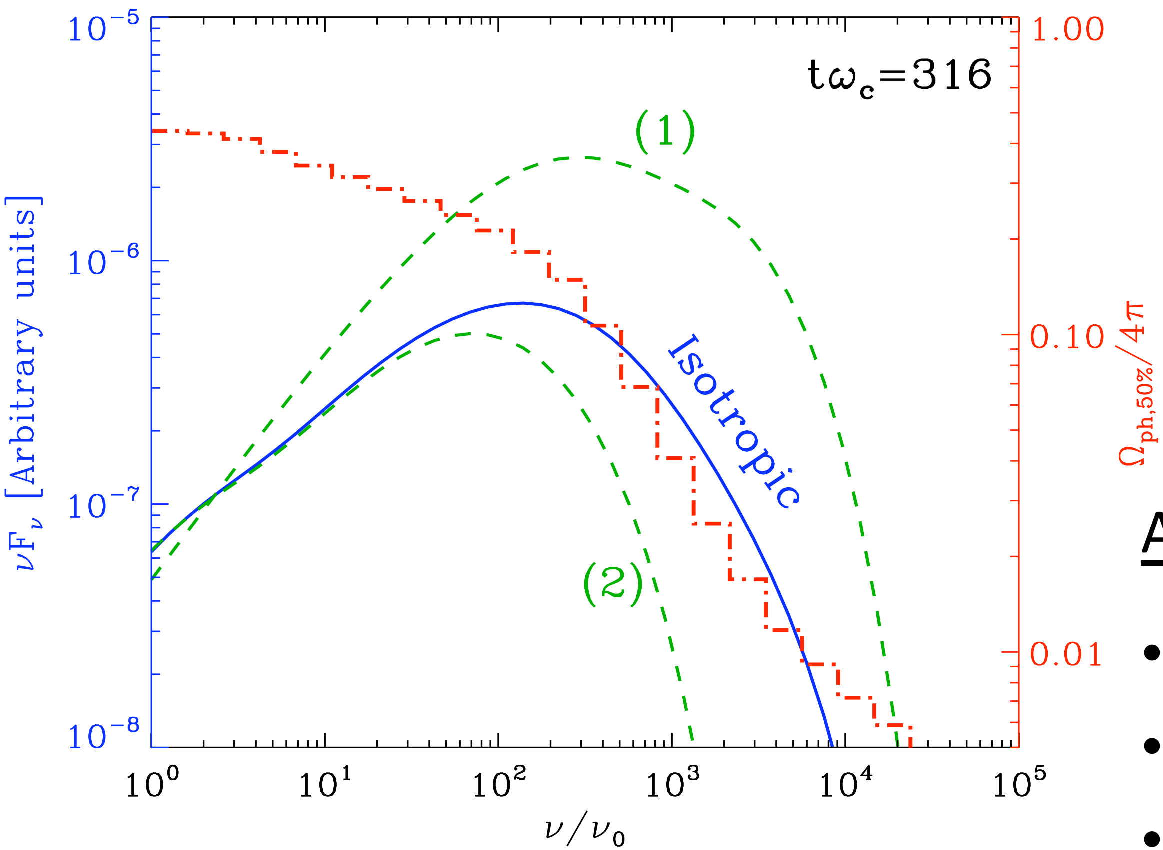
- **Main result:**

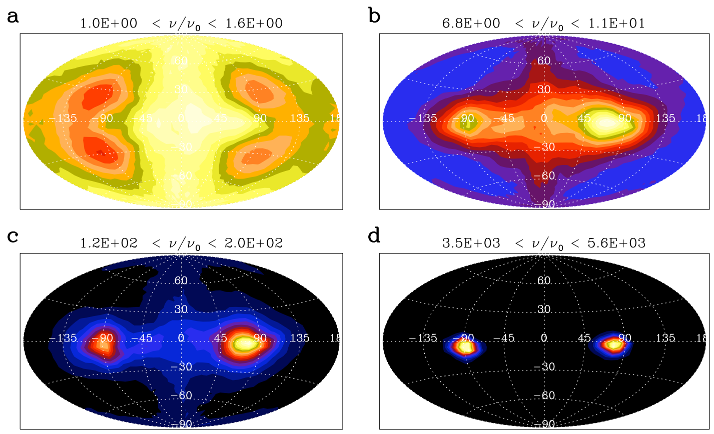
energetic particle population is highly anisotropic!

- Particle anisotropy is energy-dependent: ***stronger focusing for highest energy particles***.



Synchrotron emission anisotropy in relativistic pair reconnection *(Cerutti et al. 2012)*

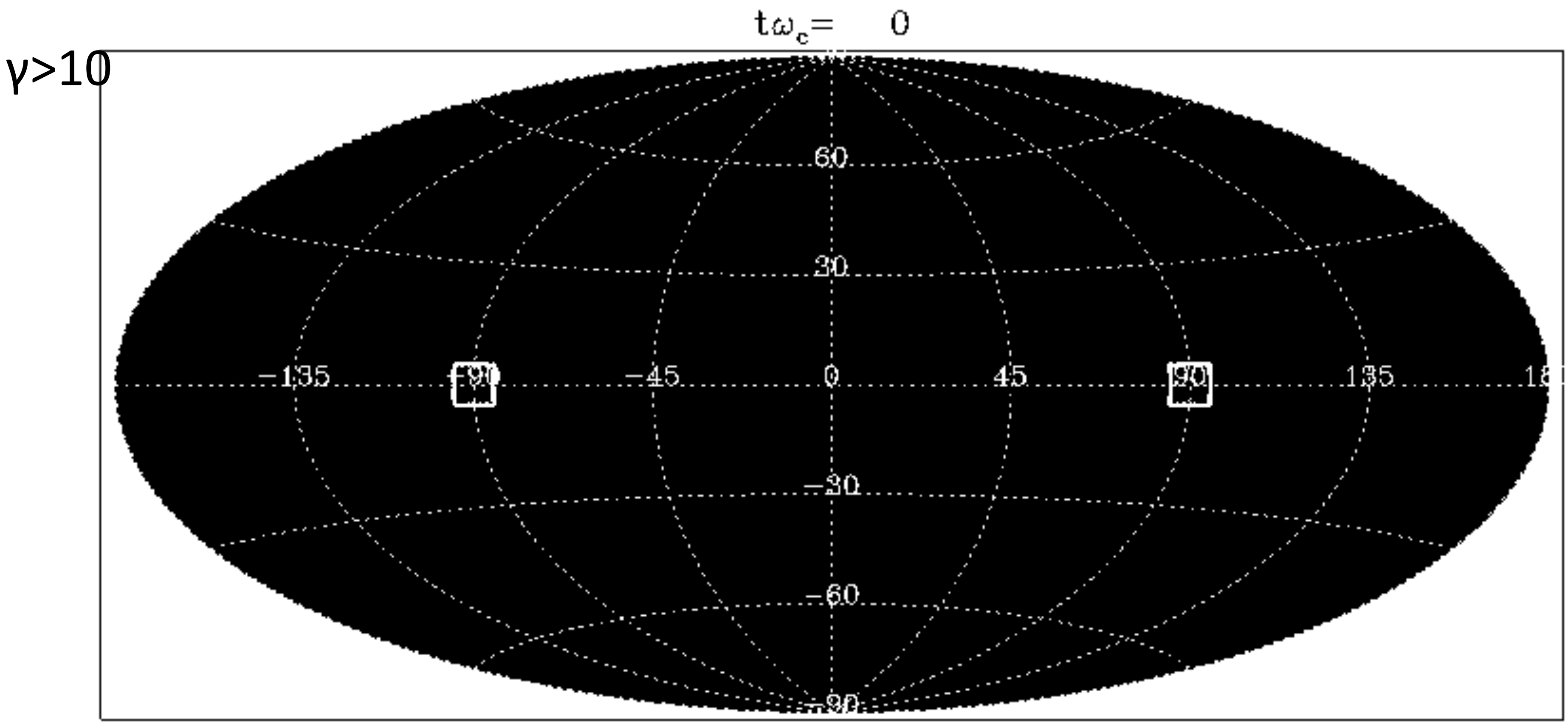




Astrophysical implications:

- flare energetics;
- flare statistics;
- different from traditional achromatic Doppler.

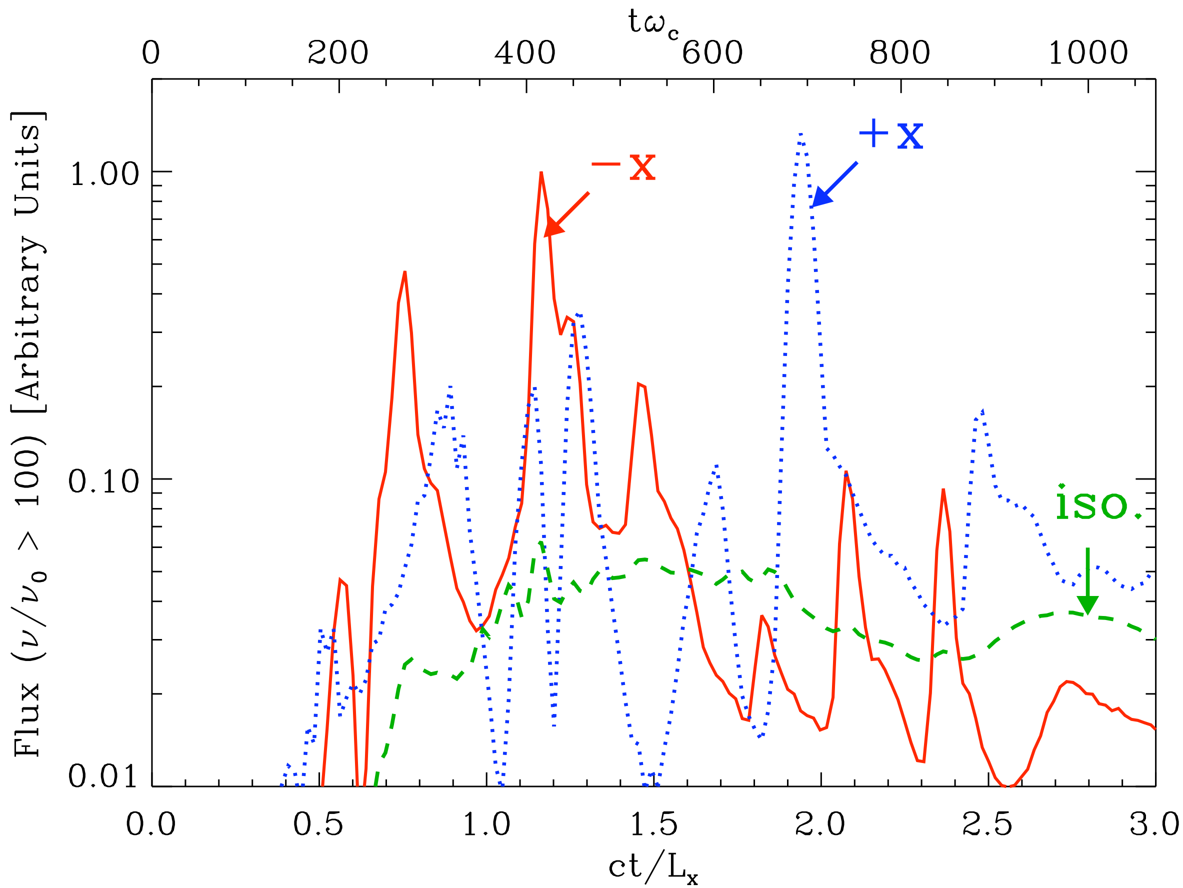
Rapid emission variability in relativistic pair reconnection *(Cerutti et al. 2012)*



Energetic particles form highly focused beams that sway from side to side in the reconnection layer midplane.

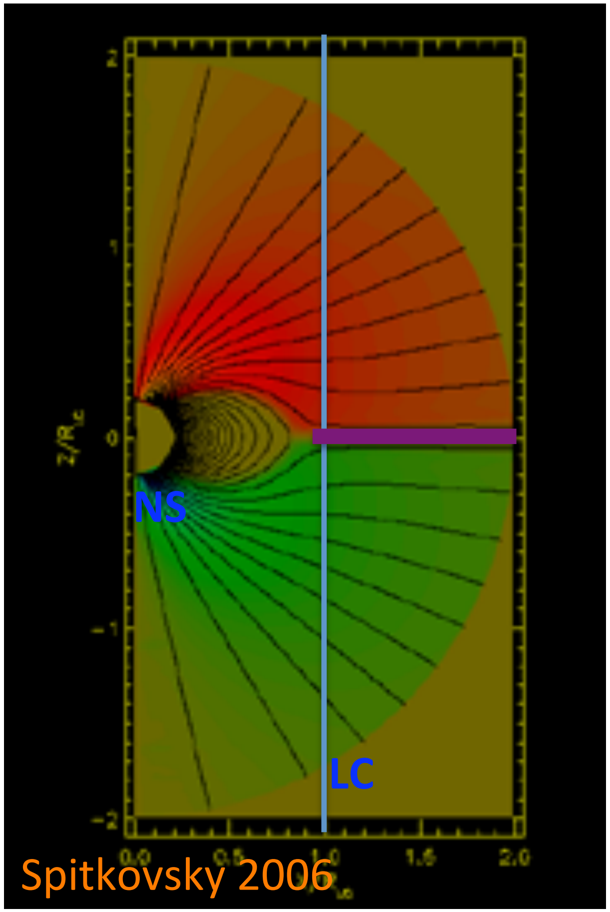
Rapid emission variability in relativistic pair reconnection *(Cerutti et al. 2012)*

Swaying beams create rapid variability of radiation seen by external observer.



Simulated high-energy emission light curve

Radiative reconnection in pulsar magnetosphere (at r ~ R_{LC}):

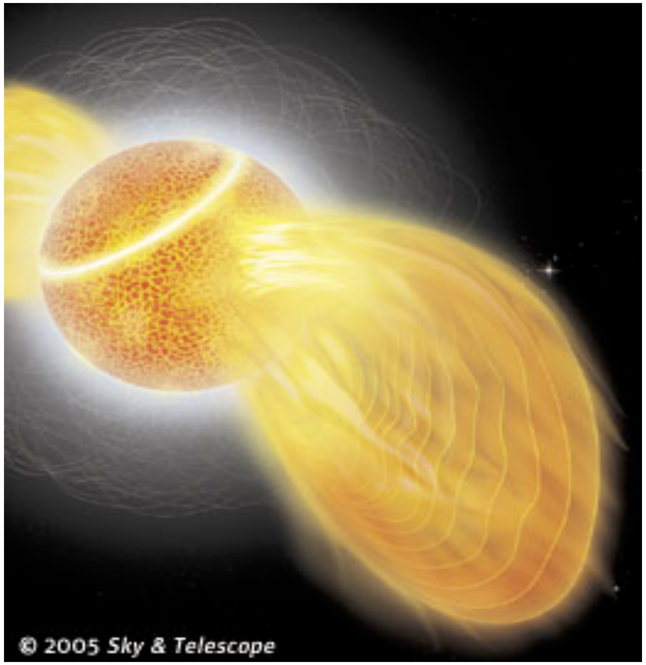


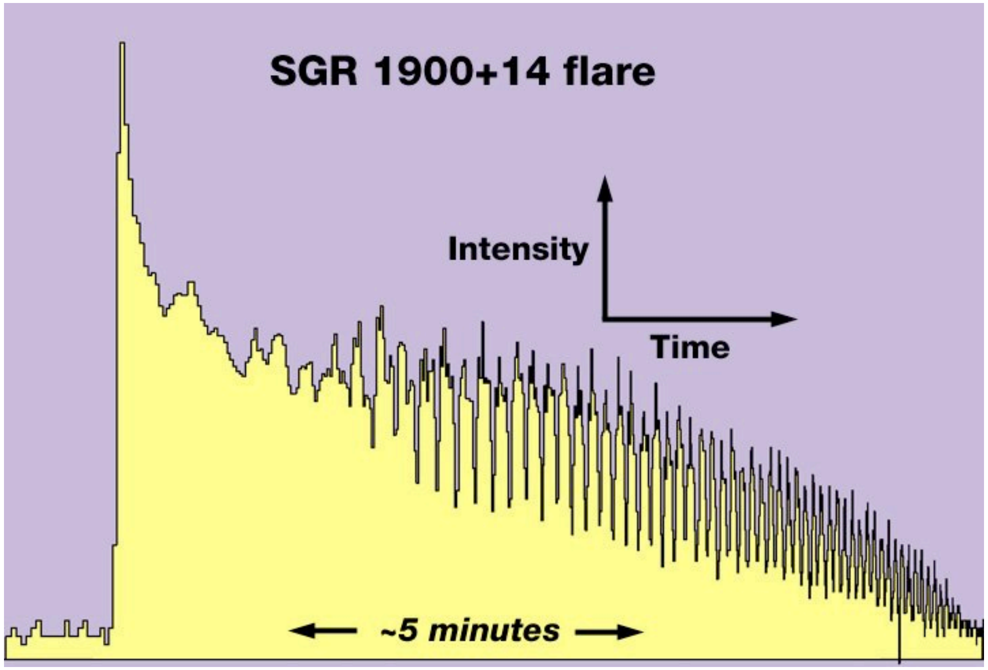
- Strong prompt ***synchrotron cooling*** should dominate reconnection energetics in pulsar (e.g., Crab) magnetosphere near Light Cylinder (LC).
- Pressure balance + heating/cooling balance + Ampere's law yield:
  - $T \approx$ rad. reaction limit: $\gamma_{rad} \sim 3 \times 10^4$, $T \approx 10$ GeV;
  - $n = B^2/(16\,\pi\, T) \sim 10^{11} - 10^{12}$ cm^{-3};
  - $\delta \approx \rho_c(\gamma_{rad}) \approx 10 - 100$ cm.

(for $B_{LC} \approx 10^6$ G)

Reconnection in magnetar magnetosphere and SGR Flares

- Magnetars: isolated neutron stars with Peta-Gauss fields.
- Soft Gamma Repeaters (SGRs): magnetars exhibiting powerful (up to 10^{44} – 10^{46} ergs in ~ 0.3 sec) γ-ray flares.





Reconnection interpretation: *Thompson & Duncan 2001; Lyutikov 2003, 2006*

Physics of Ultra-strong Field Reconnection

(Uzdensky 2011)

- Critical Quantum Magnetic Field:

$$\hbar\Omega_e = m_e c^2 \;\Rightarrow\; B_* \equiv \frac{m_e^2 c^3}{e\hbar} \simeq 4.4\times 10^{13}\,\mathrm{G}\,.$$

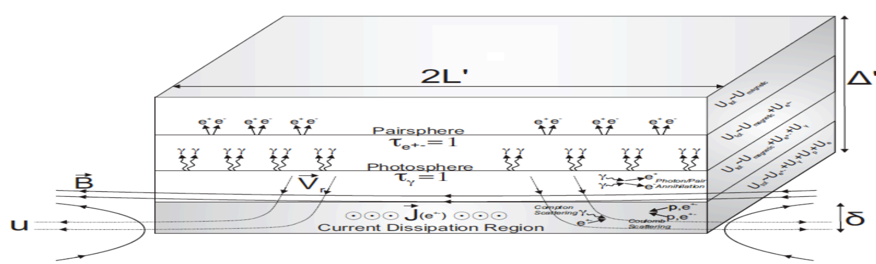
- Pressure balance/energy conservation determine layer temperature, T_0:

$$P_{\rm magn} = \frac{B_0^2}{8\pi} = P_{\rm rad} = \frac{a}{3}T_0^4 \quad \Rightarrow \theta_e \equiv \frac{T}{m_e c^2} \simeq 2.2\, b^{1/2}$$

$\rightarrow$ **relativistically-hot plasma:** $T \sim m_e c^2$ **!**

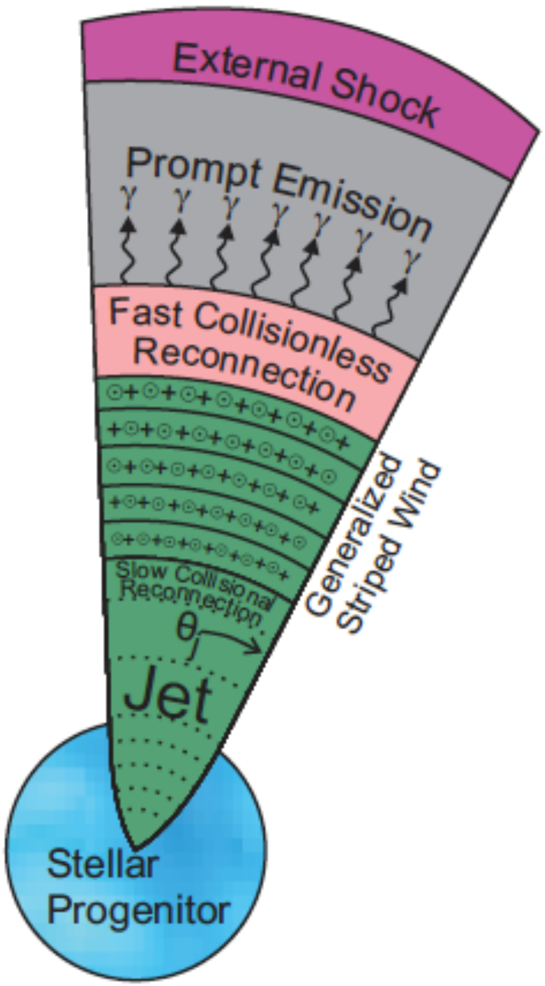
$(b \equiv B_0/B_*.)$

- Huge pair production: $n(\theta_e \gg 1) \simeq 0.1827\, \bar{\lambda}_C^{-3}\, \theta_e^3 \simeq 3.2\times 10^{30}\, \theta_e^3\, \mathrm{cm}^{-3}\,.$
- Current layer is dressed in **optically-thick pair coat**!
- Reconnection becomes a **radiative transfer** problem! (c.f., accretion disks)



Reconnection Switch for GRB Jet Dissipation

(McKinney & Uzdensky 2012)



- Near central engine, pair density huge, plasma is collisional, reconnection is relatively slow.
- At larger distances, B drops, T drops, pairs recombine, density drops.
- Then, reconnection layers become collisionless → switches to faster energy dissipation

Summary

- In contrast to traditional solar-system plasmas, in many high-energy astrophysical systems magnetic reconnection and particle acceleration are often affected by **radiation**.
- Radiation is our only direct diagnostic of astrophysical reconnection.
- Radiative reconnection is a **new frontier** in reconnection research.
- <u>Examples:</u>
  - **Crab PWN** γ-ray flares: radiatiation reaction presents strong, but not insurmountable, difficulties for extreme particle acceleration powering ~ 1 GeV synchrotron radiation.
  - **Blazar** gamma-ray flares: reconnection minijets may give short time-scales, prompt rad. cooling may be important on global transit time-scale;
  - Strong synchrotron cooling in **pulsar** magnetosphere reconnection (LC);
  - **Magnetar** reconnection: highly collisional, optically thick "dressed" layer;
  - **GRB jets**: pairs annihilate, photons escape → transition to fast collisionless reconnection.