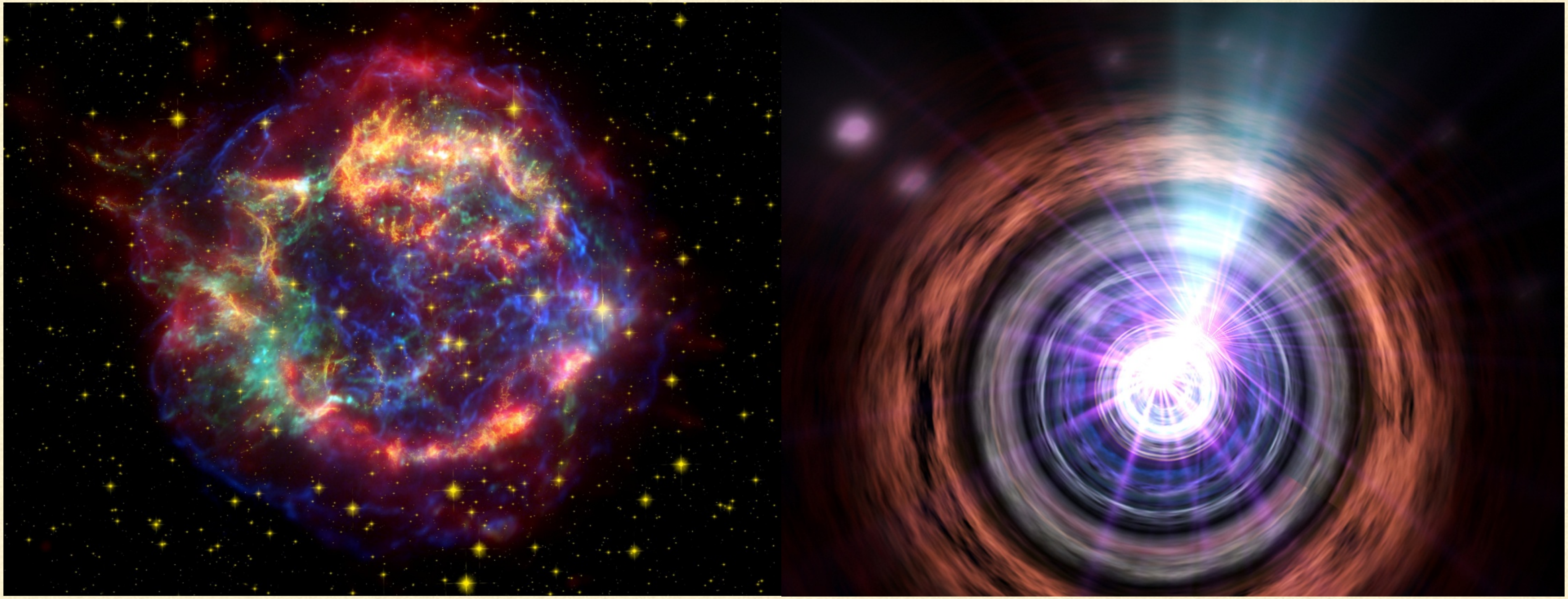
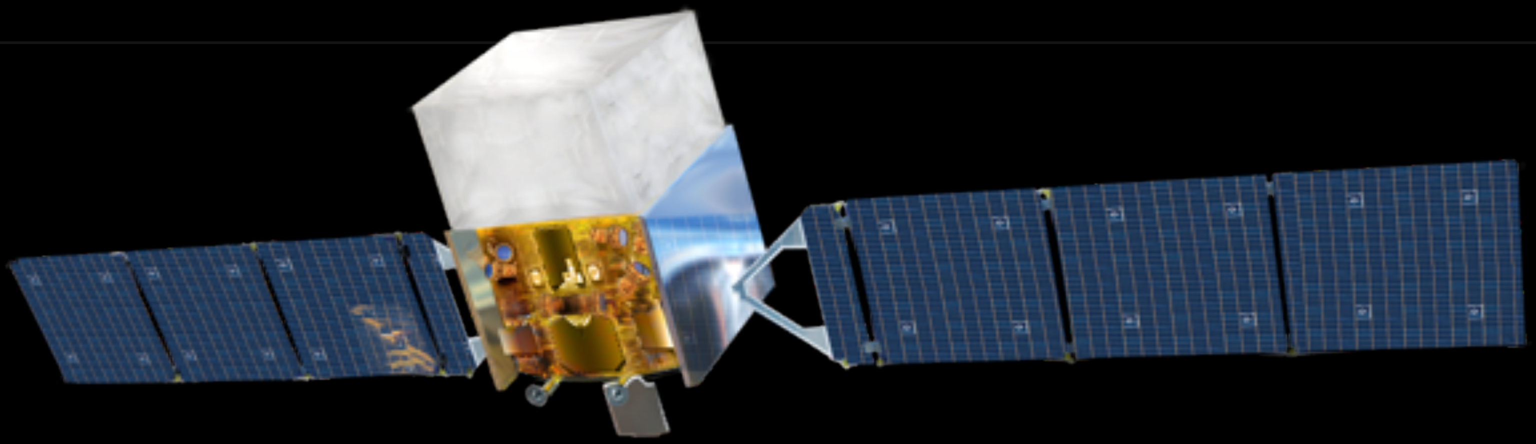


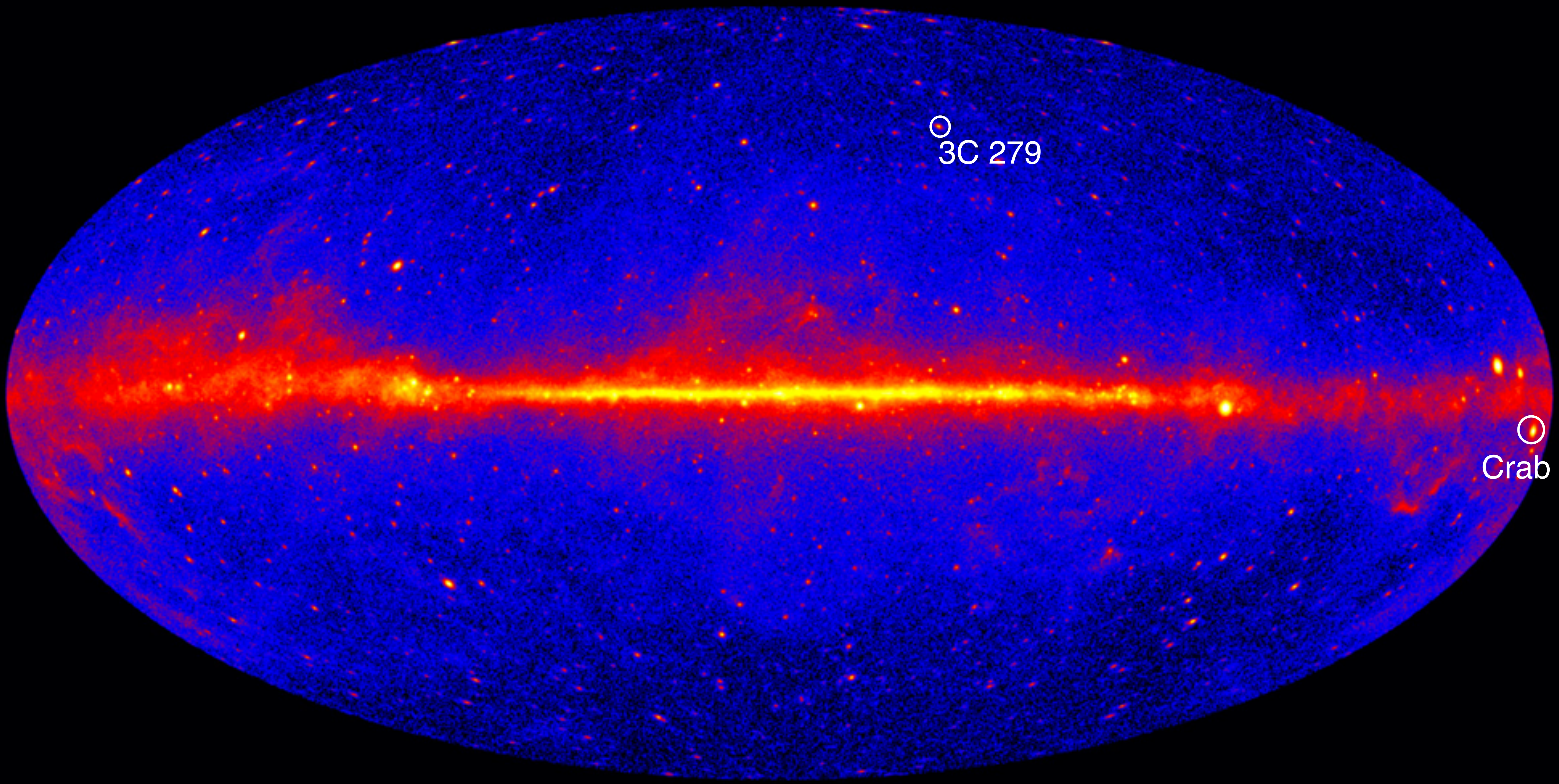
Particle Acceleration Mechanisms (II)

Yajie Yuan
Princeton University

Collaborators: R. Blandford, W. East, K. Nalewajko, J. Zrake, A. Spitkovsky

New challenges: fast variability of gamma-ray emission

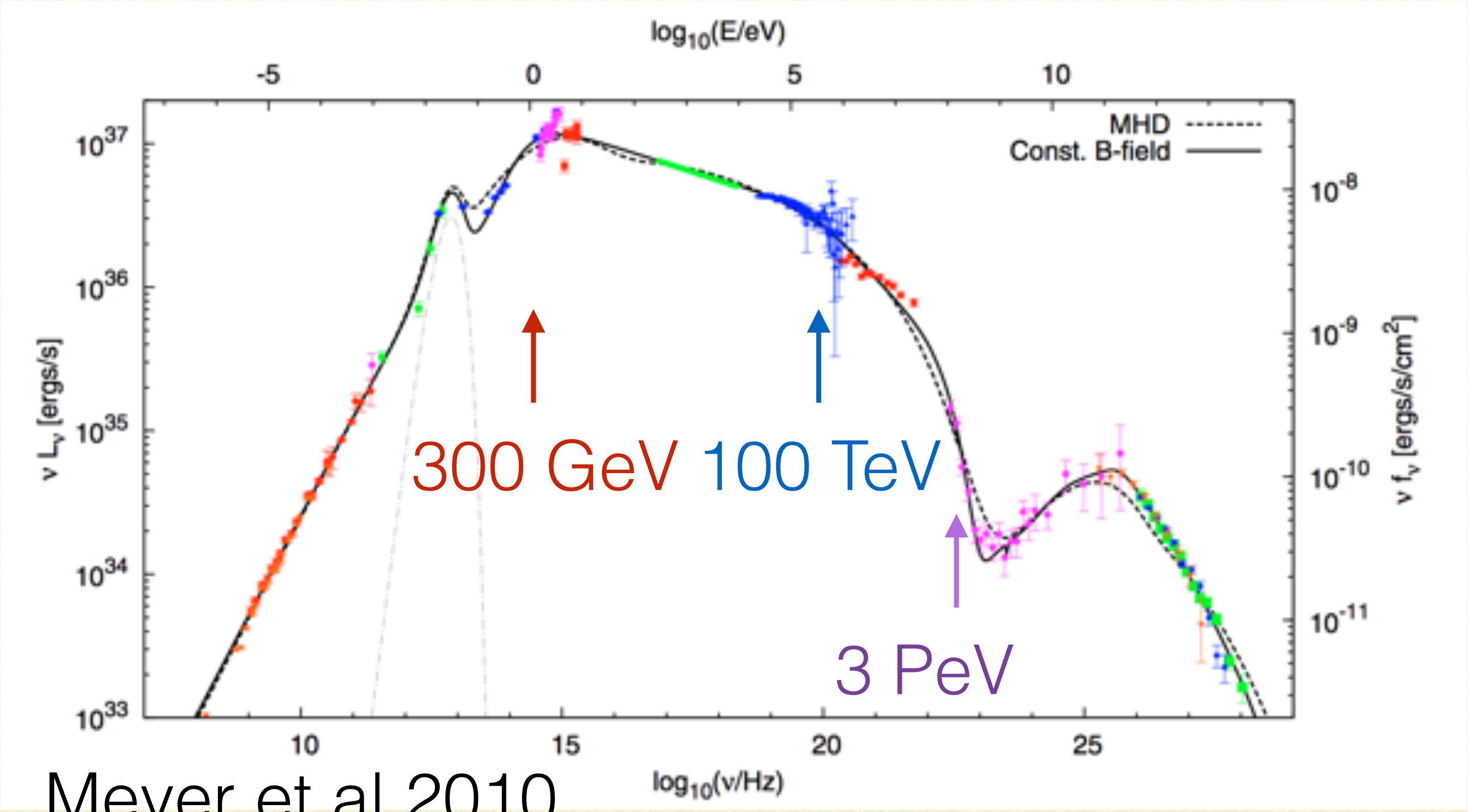




Fermi 5 year sky map.   Credit: NASA/DOE/Fermi LAT Collaboration

Crab Nebula as we know


Hubble and Chandra



Meyer et al 2010

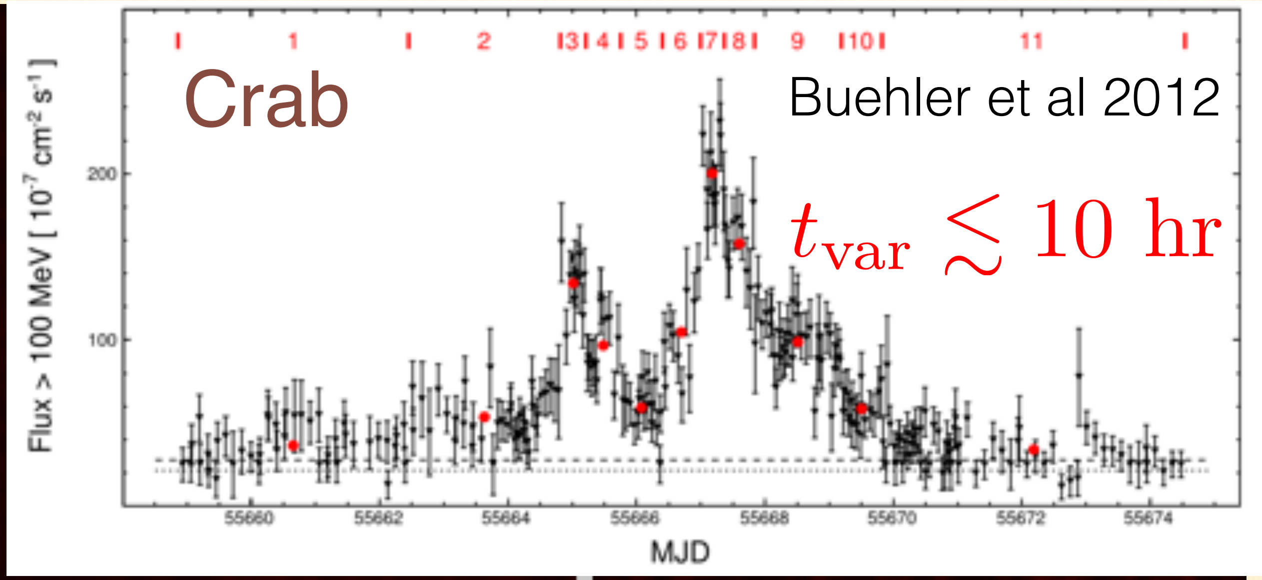
- Pulsar spin down power: 5e38 erg/s
- Synchrotron nebula luminosity: 1.3e38 erg/s
- Equipartition magnetic field: 0.3 mG

Puzzling flares

- $t_{\rm var} \lesssim 10$ hr.
- Isotropic equivalent L_γ ~ 1% pulsar spin down
- Above synchrotron radiation reaction limit

$$E_{\rm syn,lim} = \frac{m_e c^2}{\alpha_F} = 160\ {\rm MeV}$$

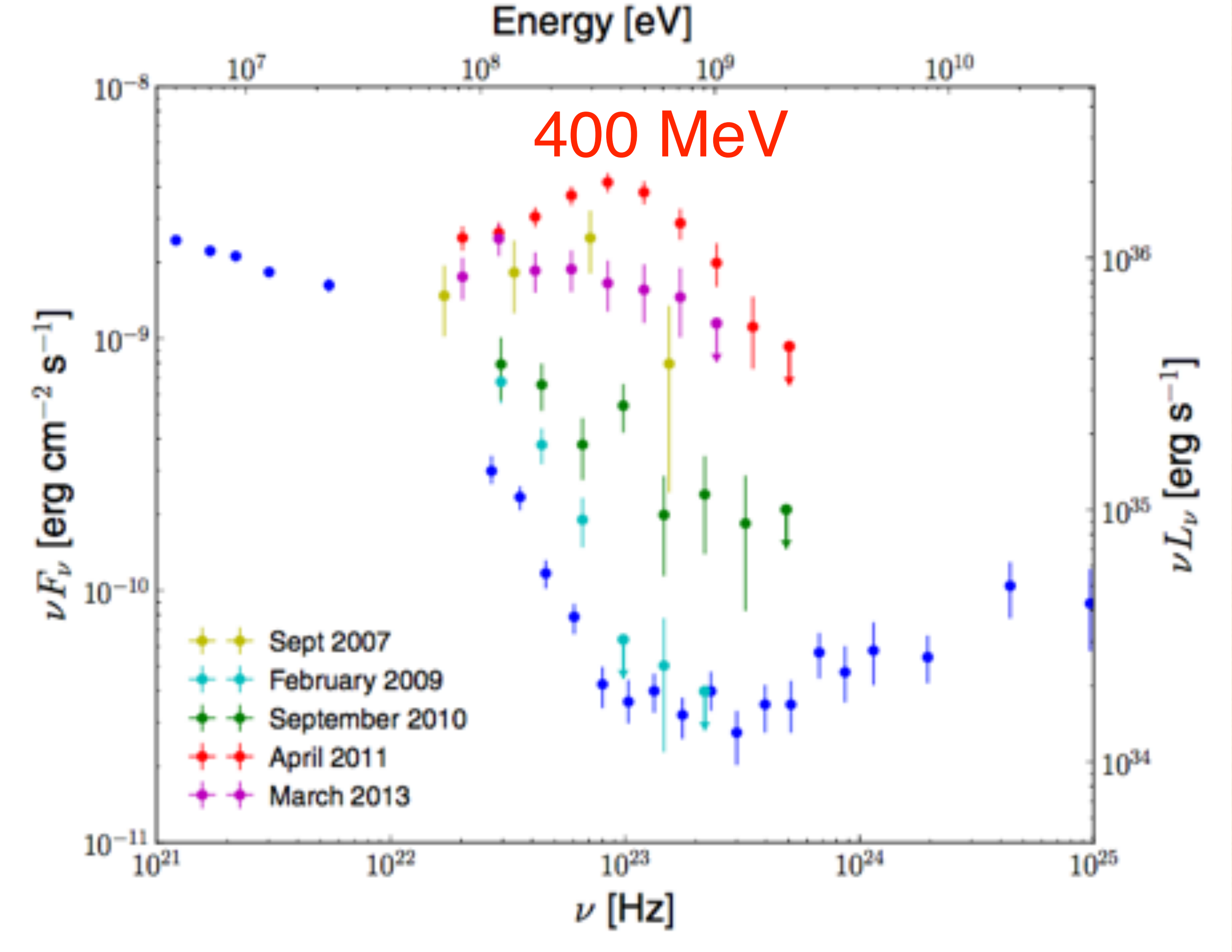
- No counterpart in other wavelengths so far



Crab

Buehler et al 2012

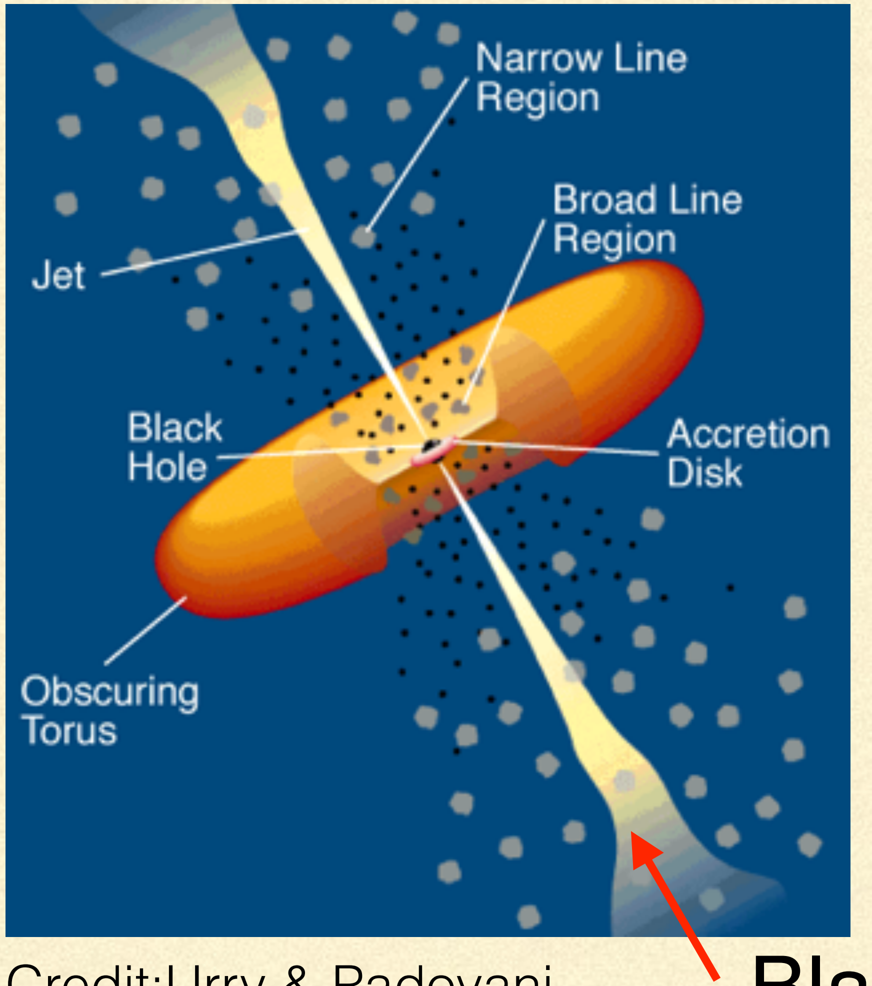
$t_{\rm var} \lesssim 10$ hr



400 MeV

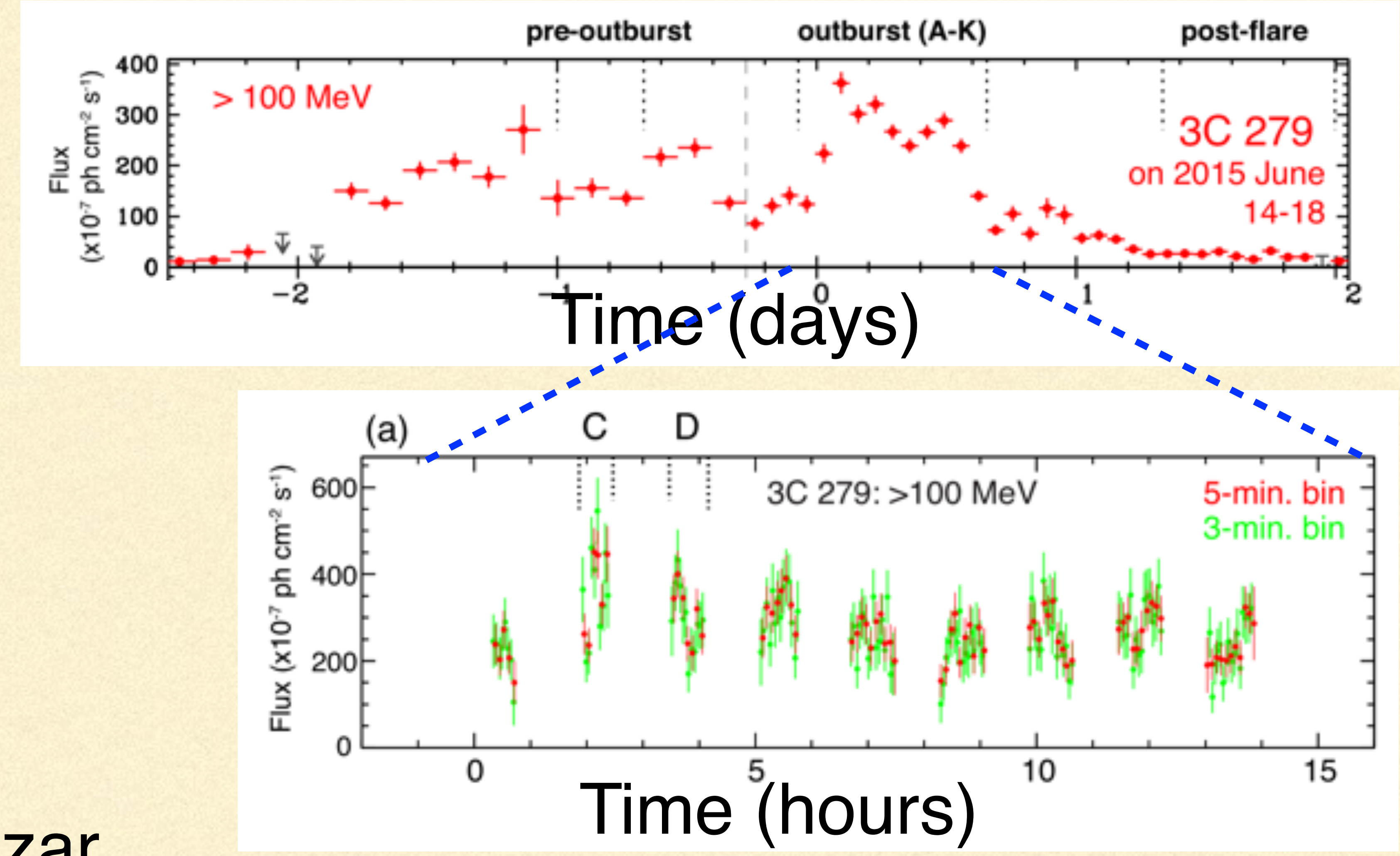
Buehler & Blandford 2014

3C 279 gamma-ray flares



Credit:Urry & Padovani

Blazar

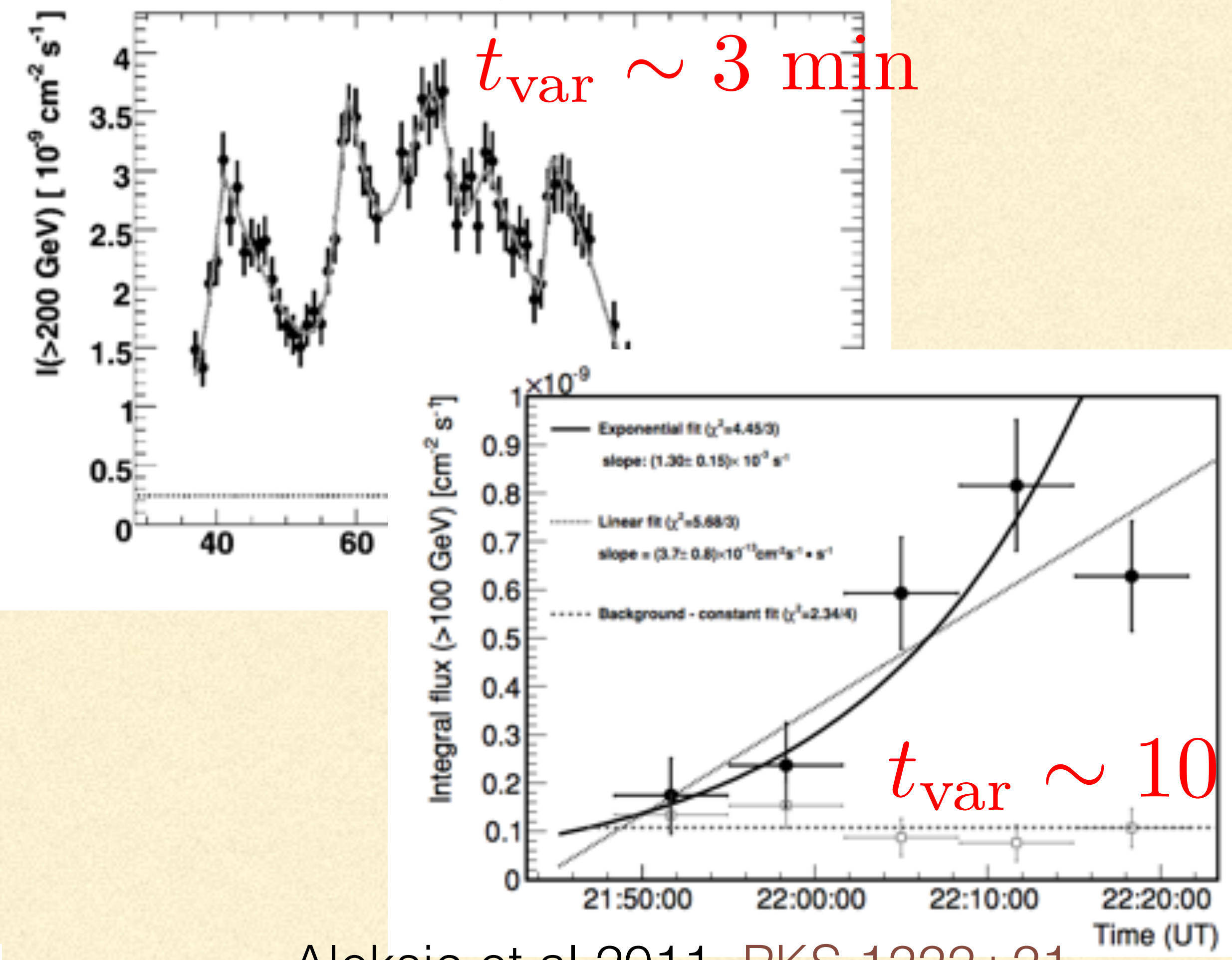


Ackermann et al 2016

- t_{var}~5 min v.s. r_g/c~1 hr
- Peak isotropic equivalent luminosity 10^{49} erg/s
- GeV flares might be synchrotron?

- Similar gamma-ray variability is seen in many other sources:
  - Other blazars
  - Non-blazar active galaxies
  - Gamma-ray bursts
  - Galactic superluminal sources/microquasars

Aharonian et al 2007, PKS 2155-304

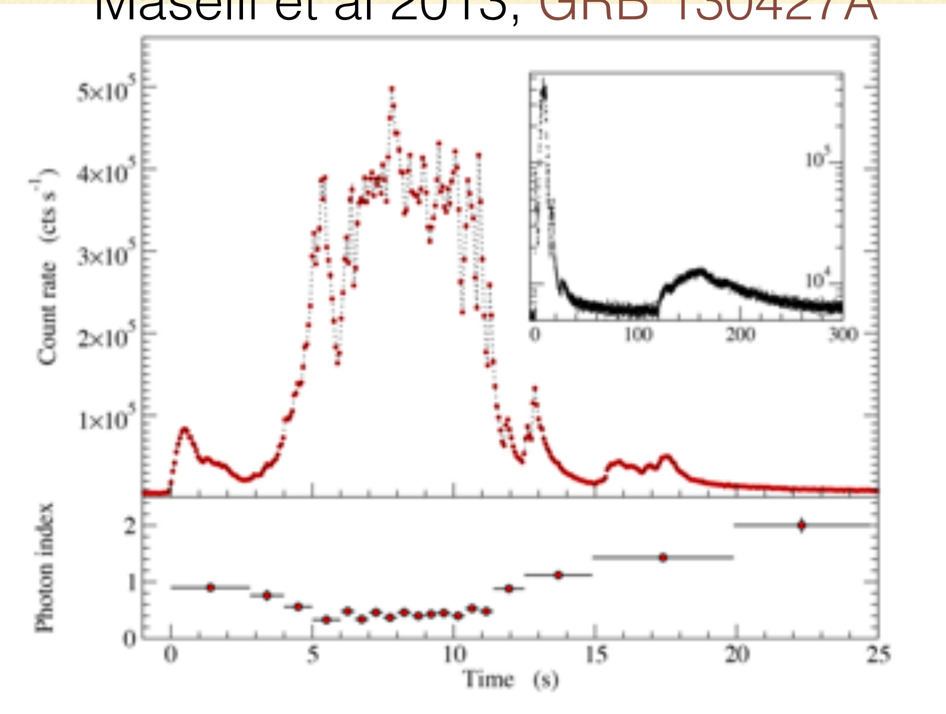


$t_{\rm var} \sim 3$ min

$t_{\rm var} \sim 10$ min

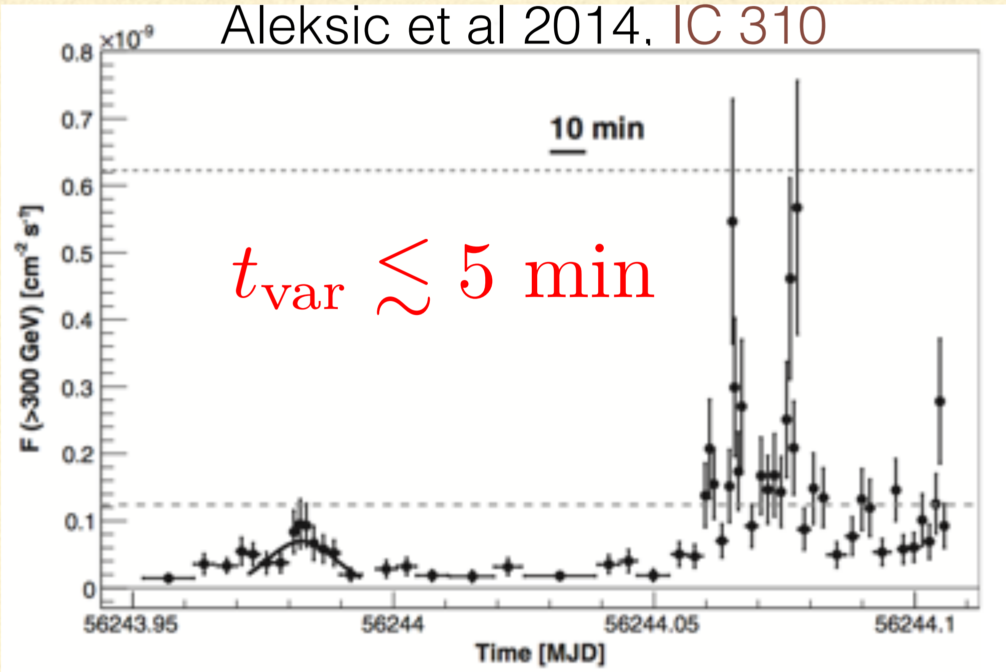
Aleksic et al 2011, PKS 1222+21

Maselli et al 2013, GRB 130427A



$t_{\rm var} \sim 10$ ms

Aleksic et al 2014, IC 310



$t_{\rm var} \lesssim 5$ min

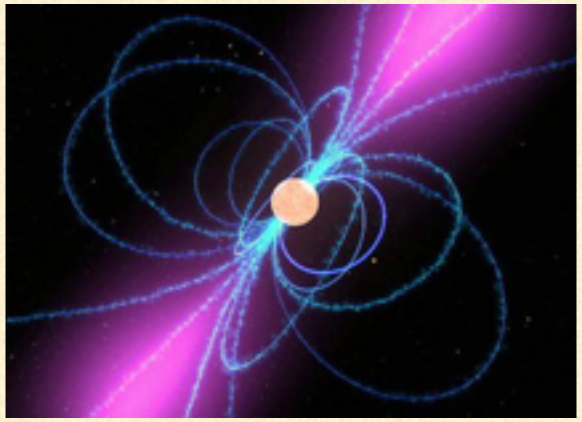
Common Challenges

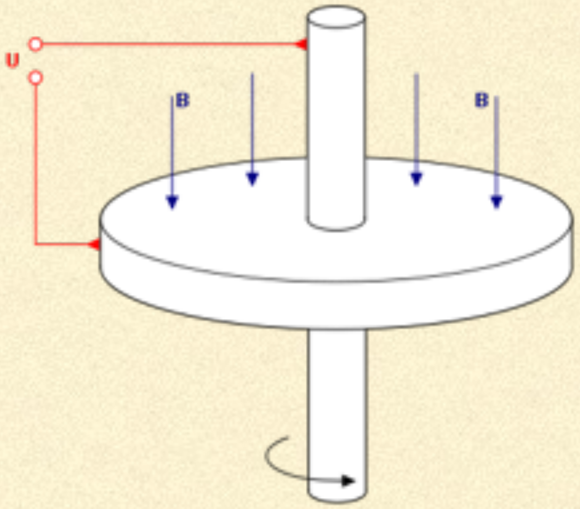
- Fast variability → small emitting region
- Apparently high radiation efficiency!
  - Concentration of magnetic energy into a very small volume and/or relativistic beaming
- Crab (and maybe others): Above radiation reaction limit

These might be results of efficient particle acceleration and electromagnetic dissipation in a highly magnetized outflow.

Follow the energy

Engine—Unipolar inductor

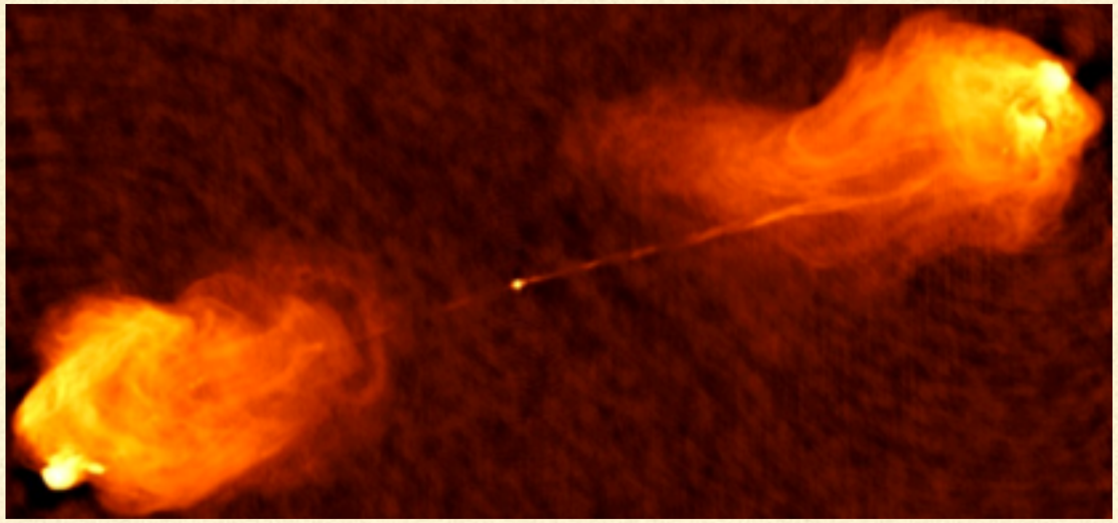




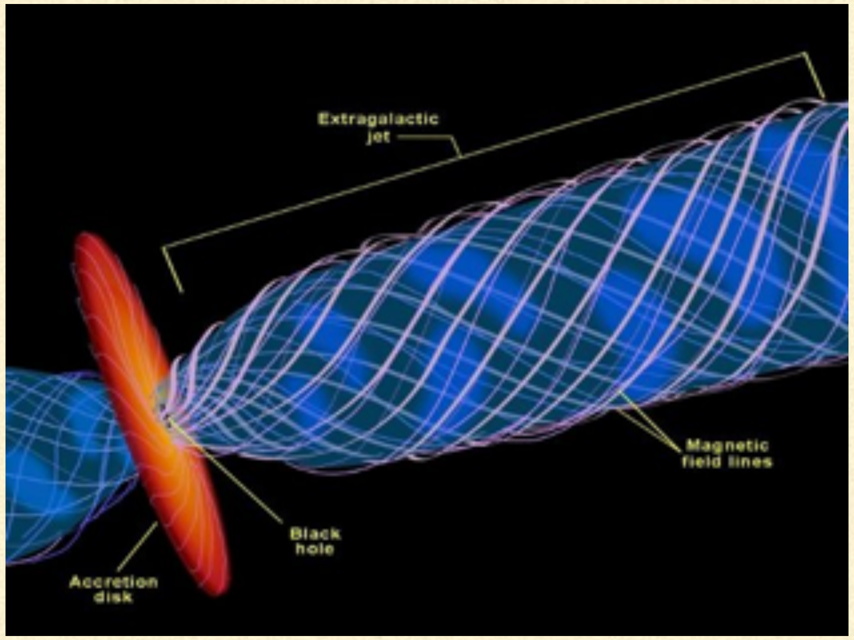
$$V = \omega\Phi,\ I = V/Z,\ P = VI$$

$$Z = \mu_0 c \approx 377\,\Omega$$

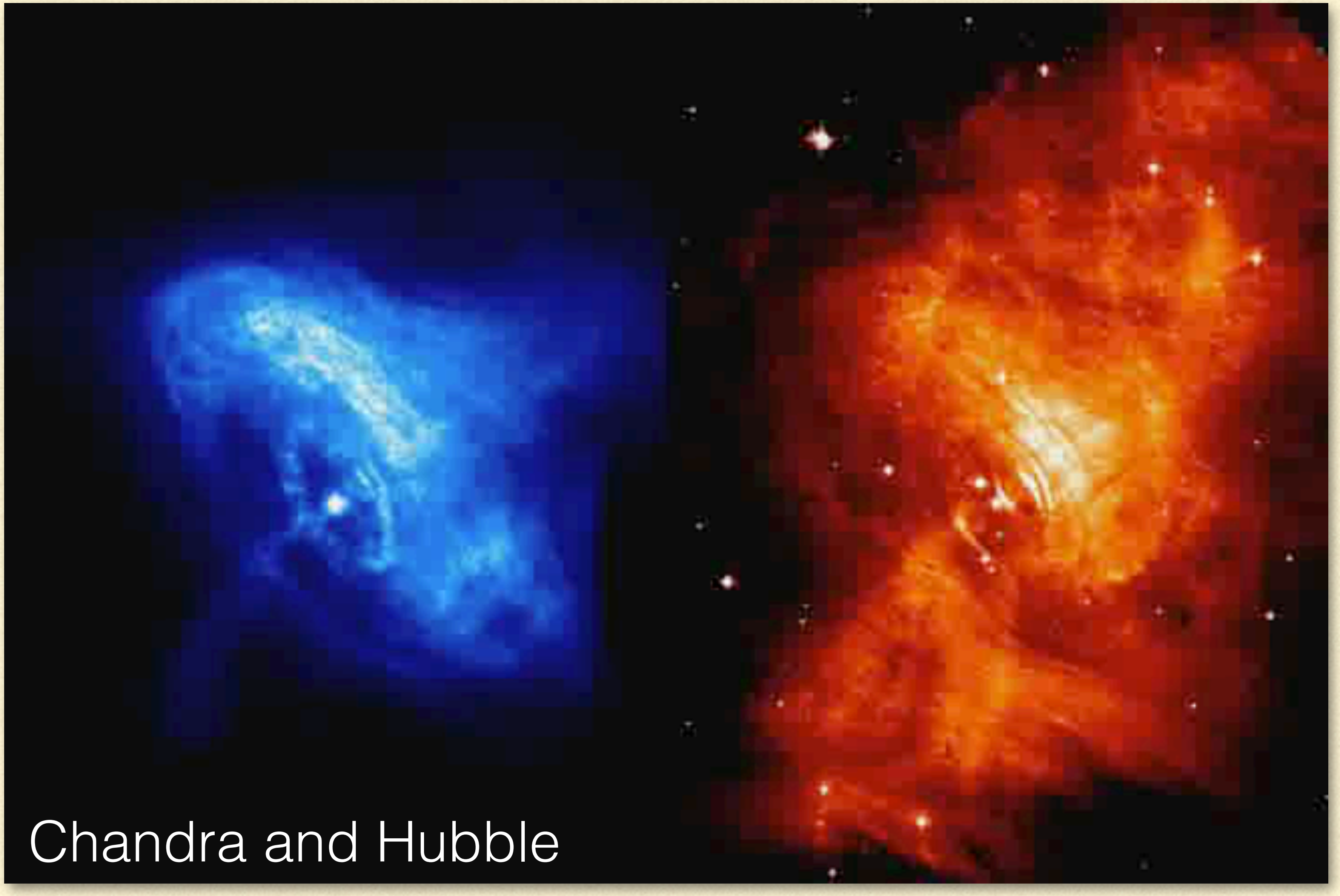
Crab pulsar: V~50 PV, P~5×10^{31} W
3C279: V~300 EV=3×10^{20} V, P~10^{39} W
GRB: V~100 ZV=10^{23} V, P~10^{44} W



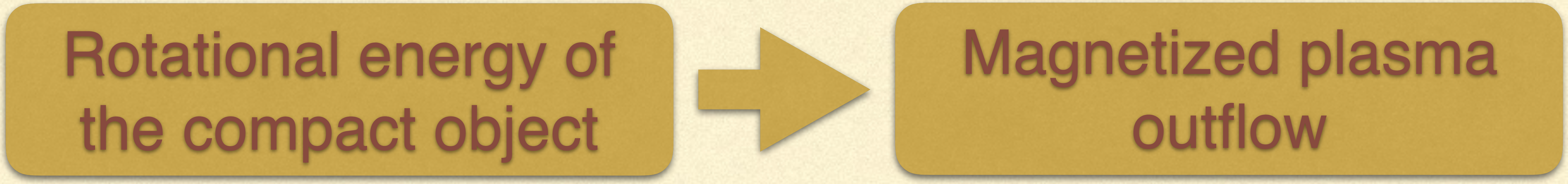
Cygnus A, NRAO



Follow the energy



Chandra and Hubble



Rotational energy of the compact object

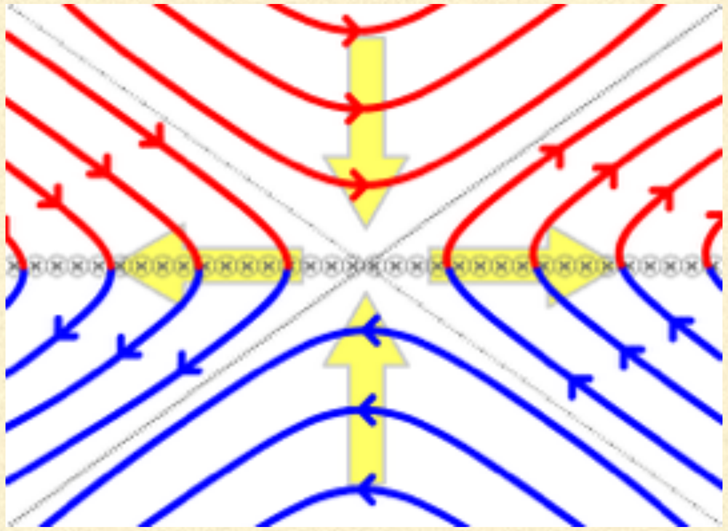
Magnetized plasma outflow

In many cases magnetic energy is the dominant free energy.

Shocks may not be good at dissipating magnetic energy.

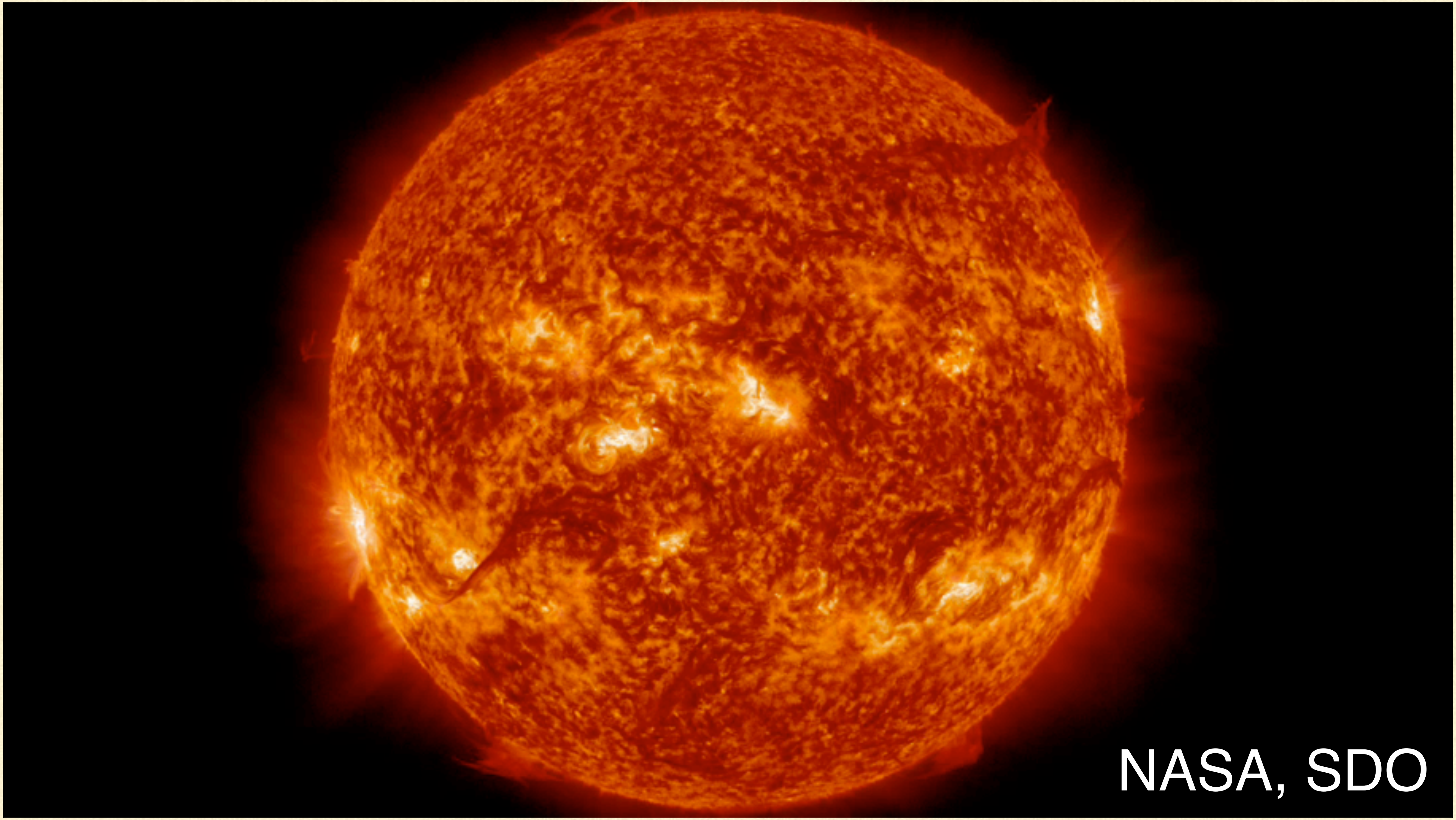
Diffusive shock acceleration may be slow, operating on many gyro-period time scales.

Magnetic reconnection



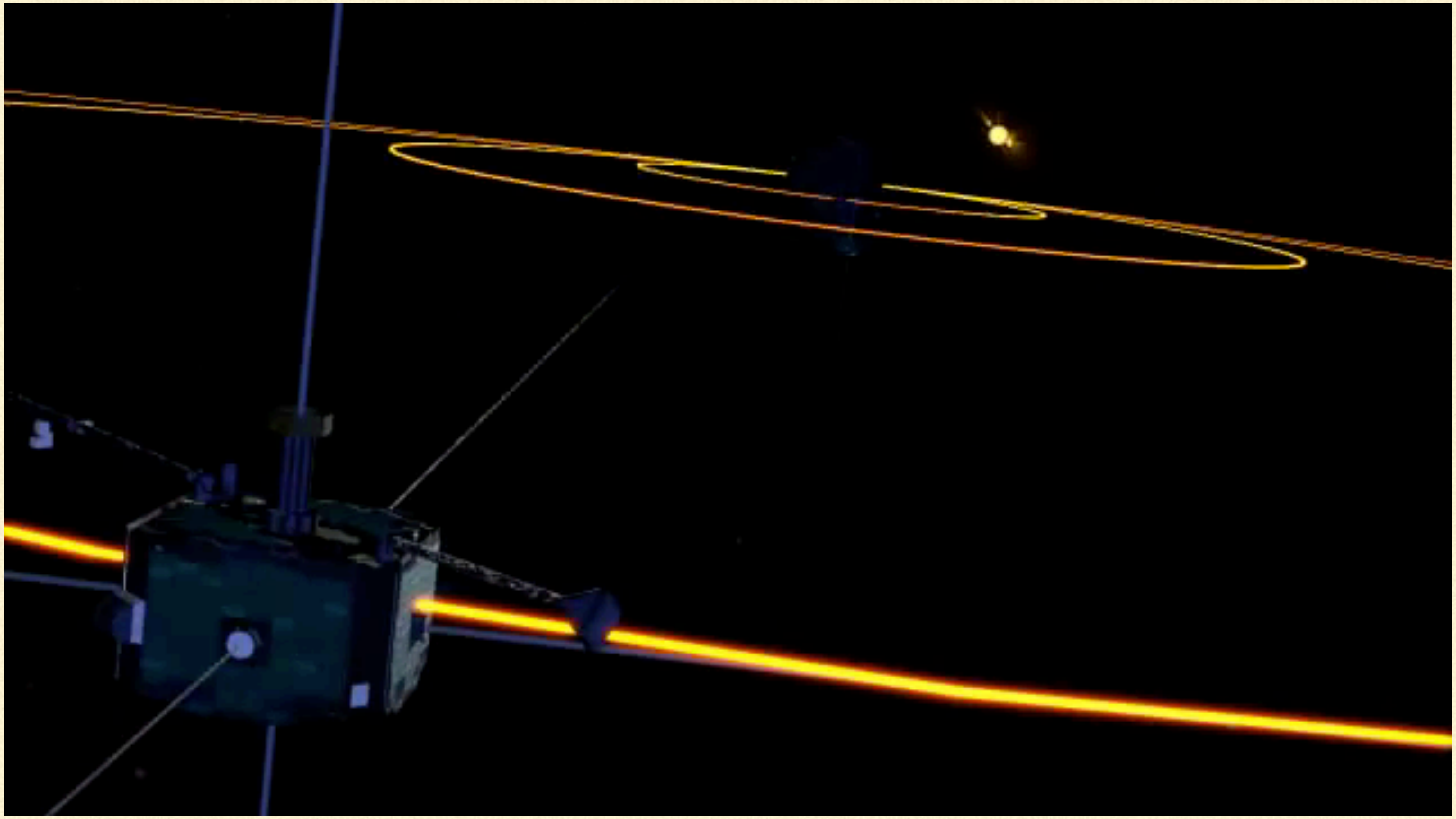
- Change of magnetic field topology, accompanied by release of magnetic energy
- Need resistivity or other non-ideal effect to break field lines

Non-relativistic reconnection near us



NASA, SDO

Non-relativistic reconnection near us



NASA, THEMIS

Historical notes

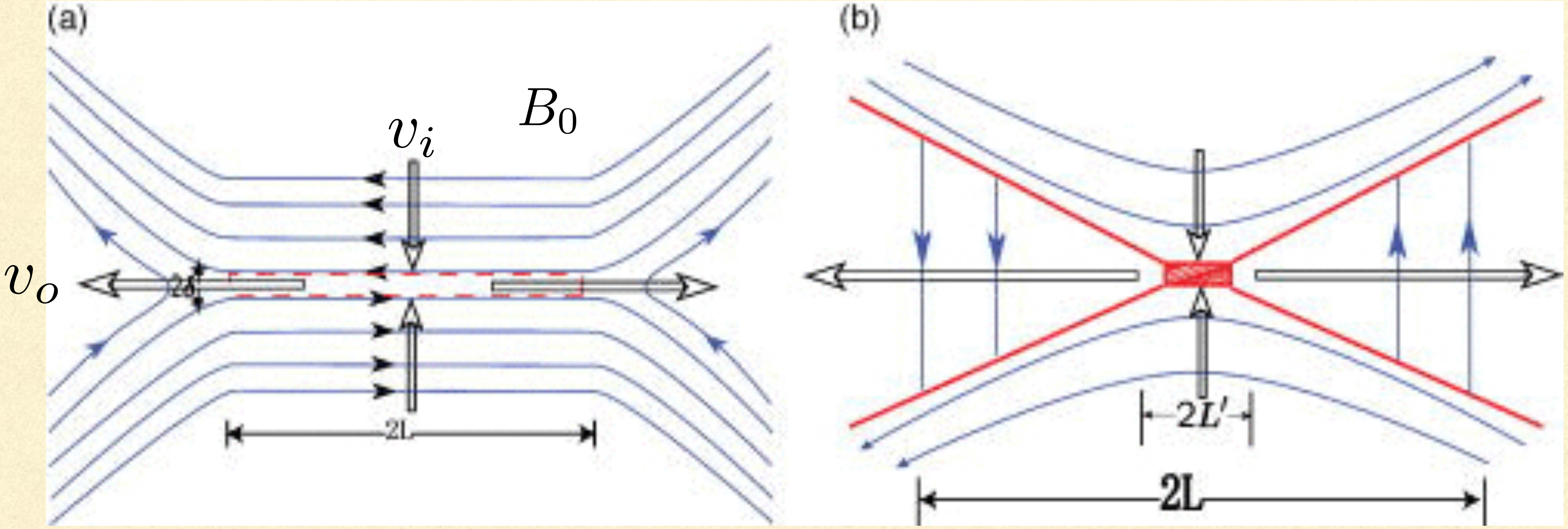
Resistive MHD $$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) + \eta \nabla^2 \boldsymbol{B}$$

- Sweet-Parker: $v_i = \eta/\delta,\ v_i L = v_o \delta,\ v_o \approx B_0/\surd$

$$\delta = L/\sqrt{S},\ v_{i,\mathrm{SP}} = v_{Ai}/\sqrt{S},\ \text{Lundquist number}$$

- Petschek: $v_{i,P} = v_{i,\mathrm{SP}}\sqrt{L/L'}$

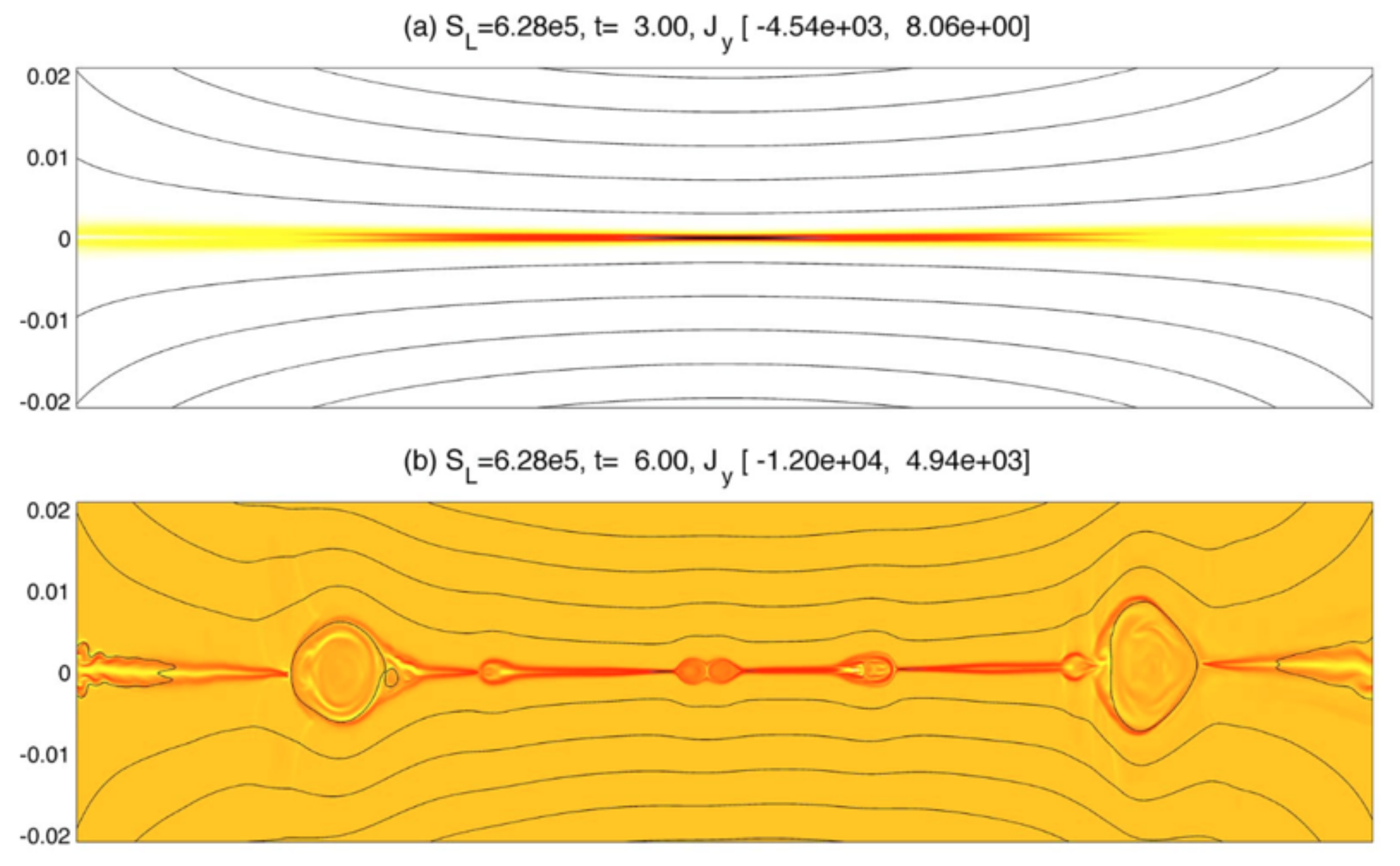
S is typically very large. Sweet-Parker reconnection is too slow!



Sweet-Parker reconnection

Petschek reconnection

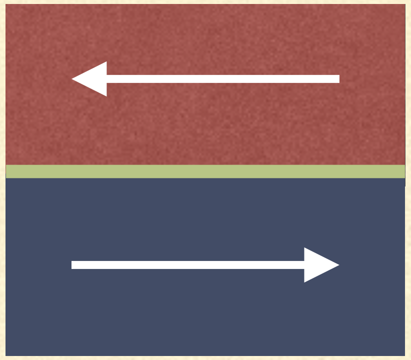
Fast reconnection due to plasmoid instability, $v_R \sim 0.01 v_A$

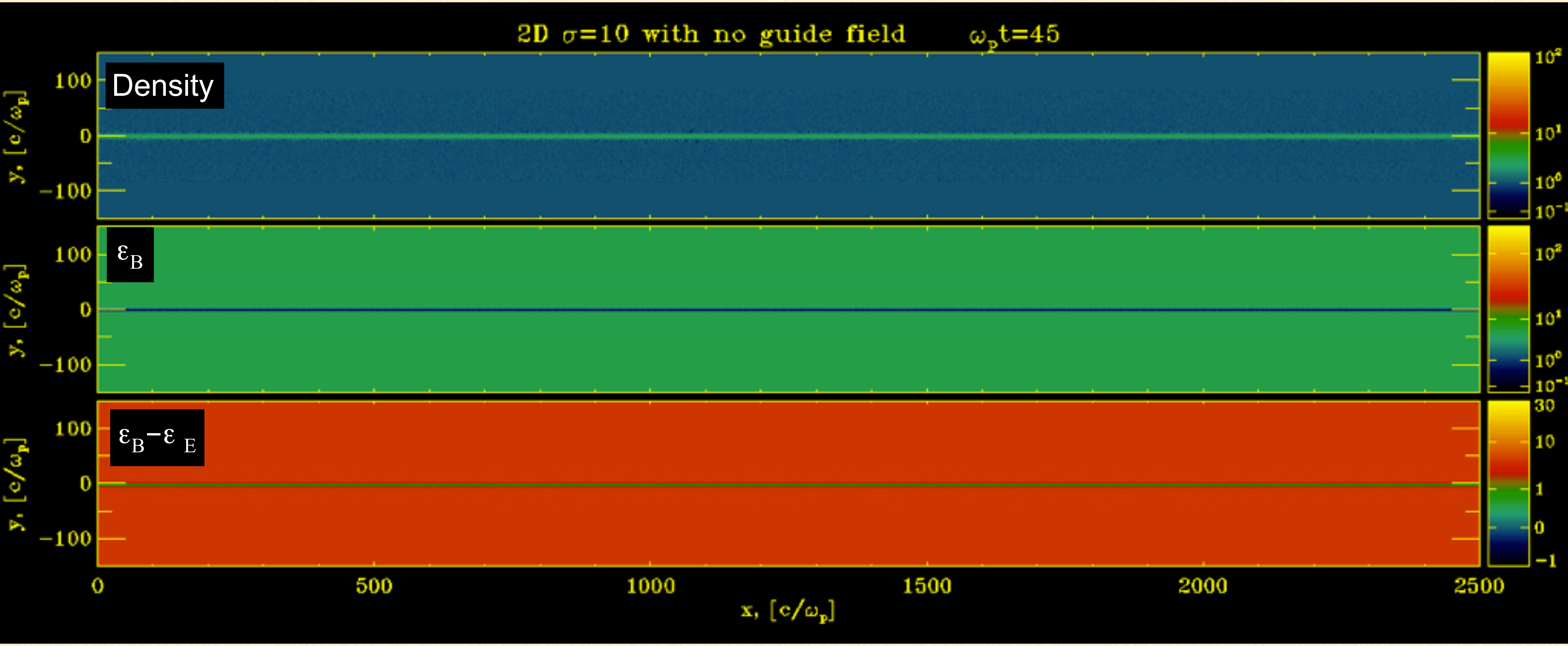


Bhattacharjee et al 2009

Relativistic reconnection in a collisionless plasma

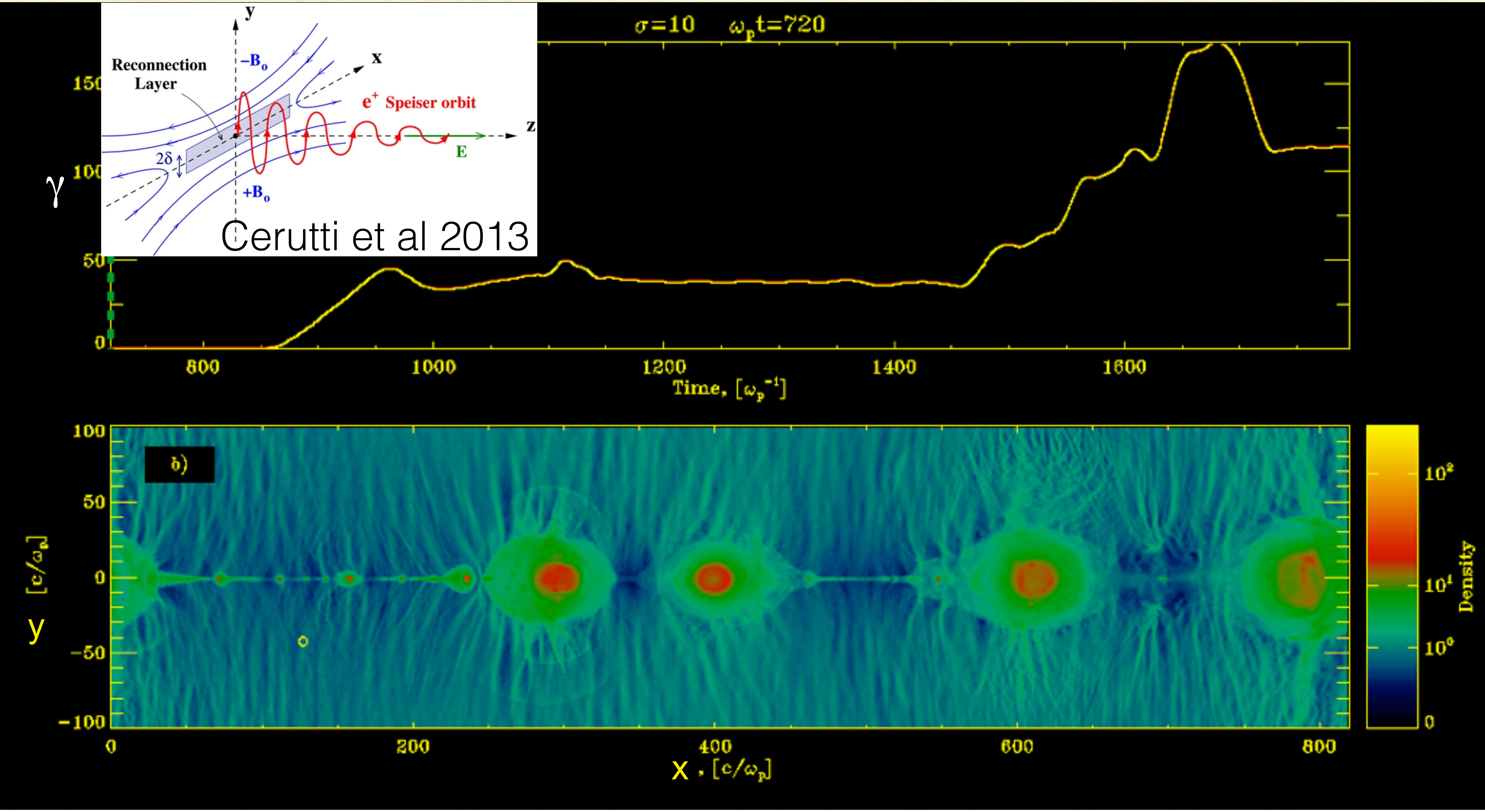
- Hierarchical process of plasmoid formation and merging
- Reconnection rate ~0.1 in highly magnetized plasmas (no guide field)





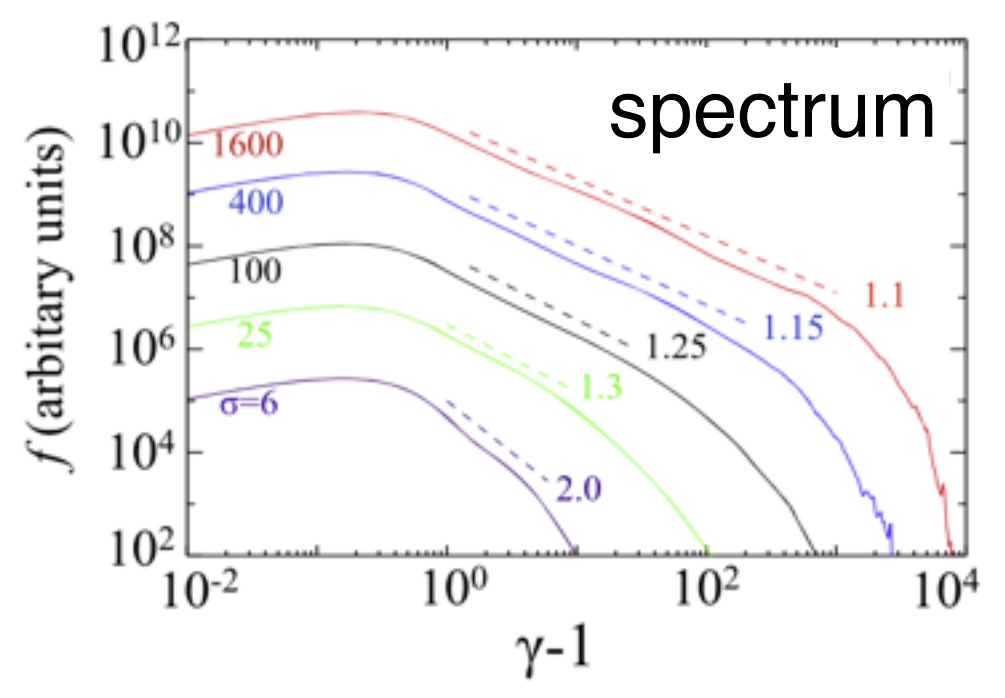
Sironi & Spitkovsky 2014

Particle acceleration in reconnection



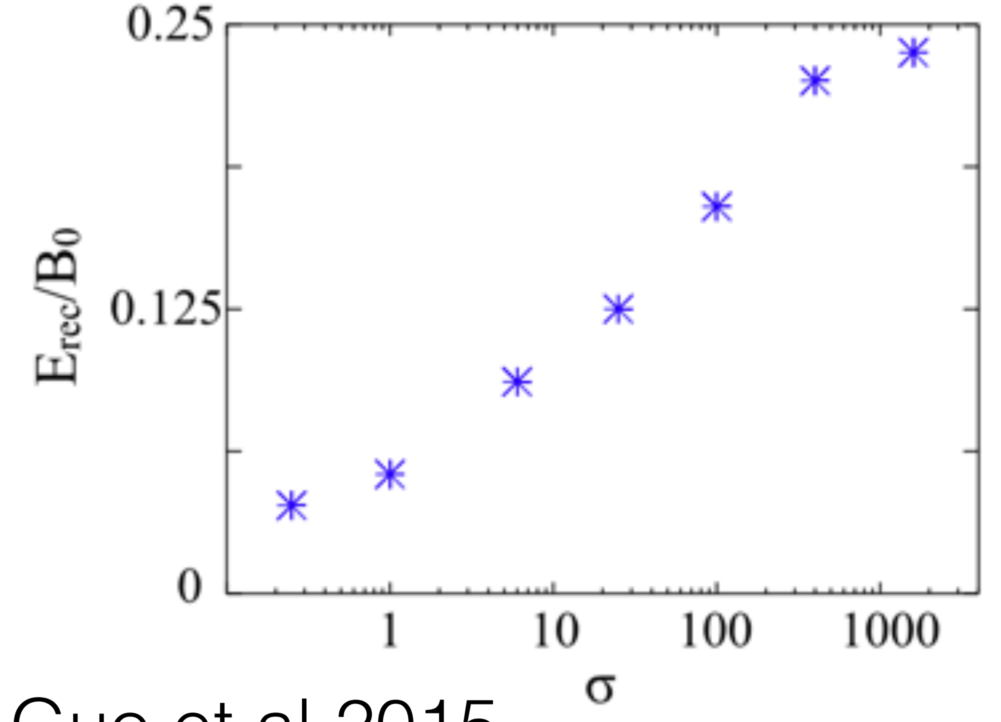
Sironi & Spitkovsky 2014

Dependence on σ



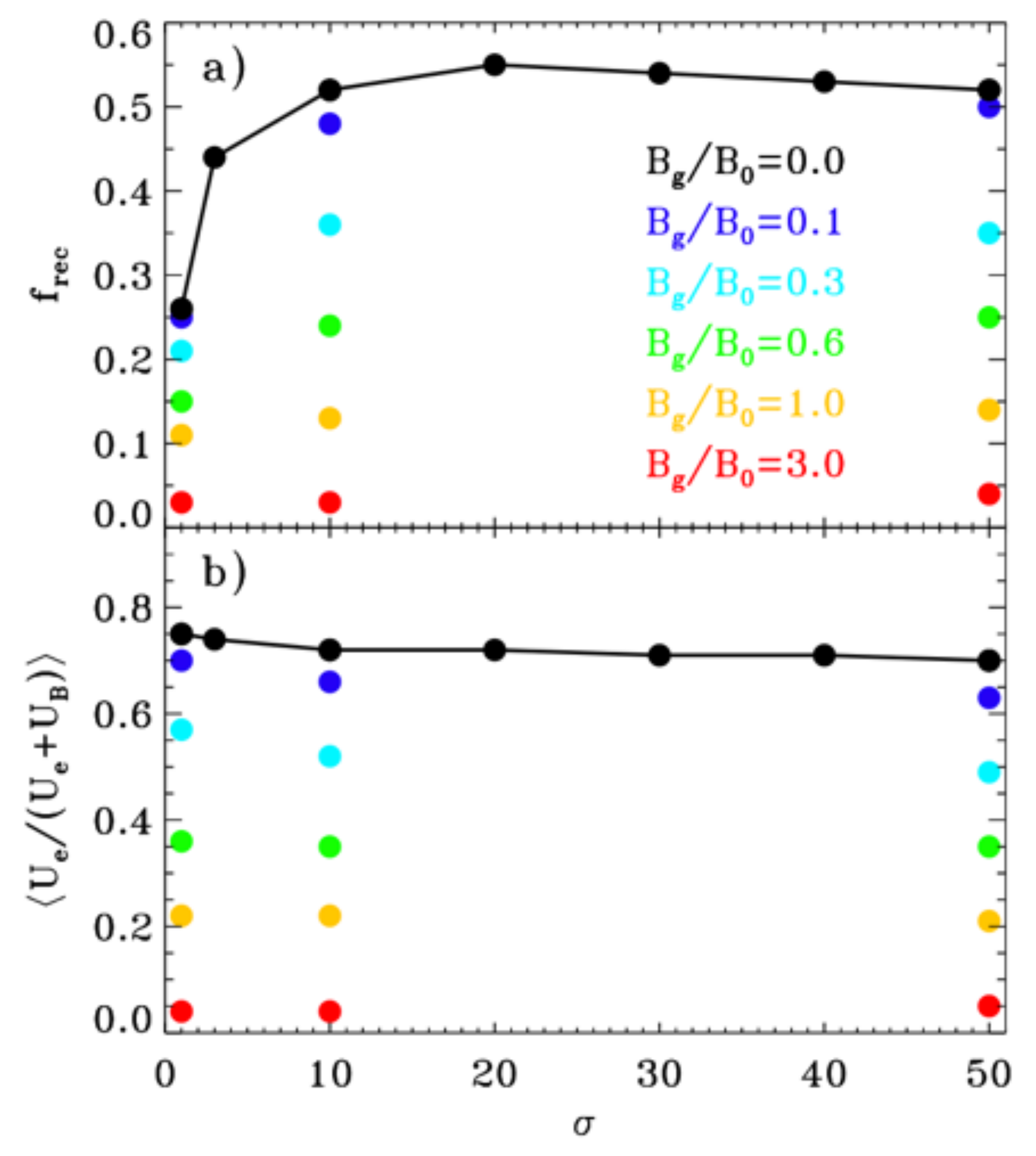
spectrum

reconnection rate



Guo et al 2015

Effect of guide field

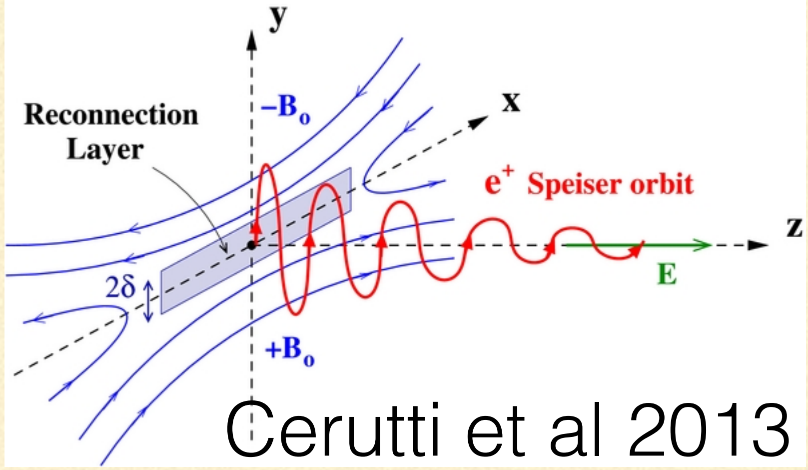


Sironi et al 2015

Main features of relativistic reconnection

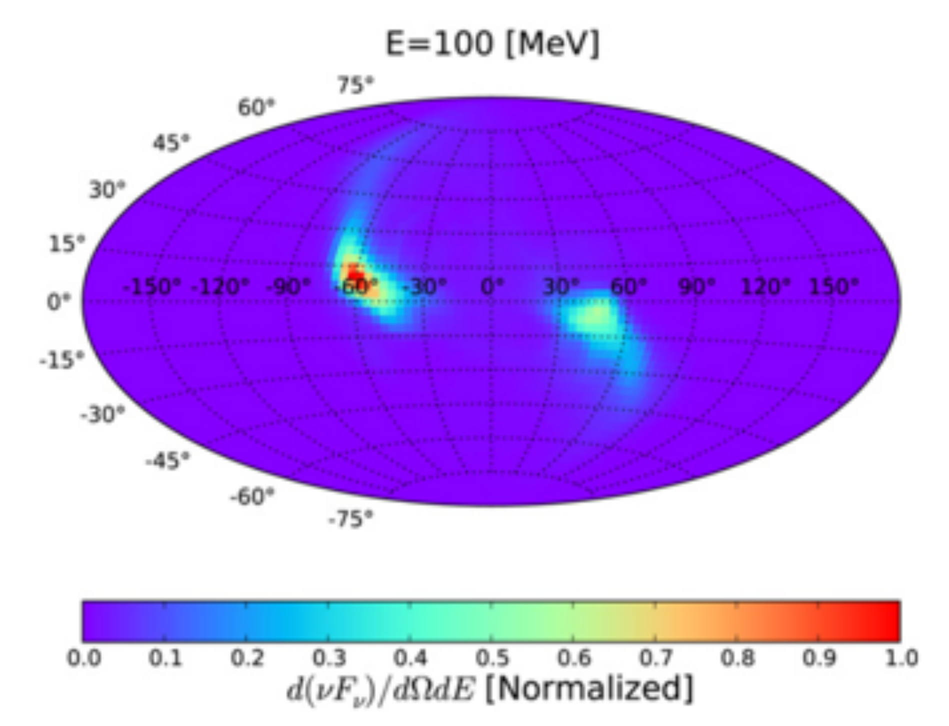
- Relativistic reconnection can be fast (inflow speed can reach 0.1c)
- Can generate robust nonthermal spectra, typically flatter than shock acceleration, reaching hard index -1 at large magnetizations
- Particle acceleration mechanisms include direct electric field acceleration at the X point, and Fermi-like acceleration during island mergers
- Some issues:
  - Is the total energy involved enough? The amount of magnetic free energy should be determined by the large scale configuration
  - Current sheet formation vs. onset of reconnection

Reconnection as an explanation for the Crab gamma-ray flares?

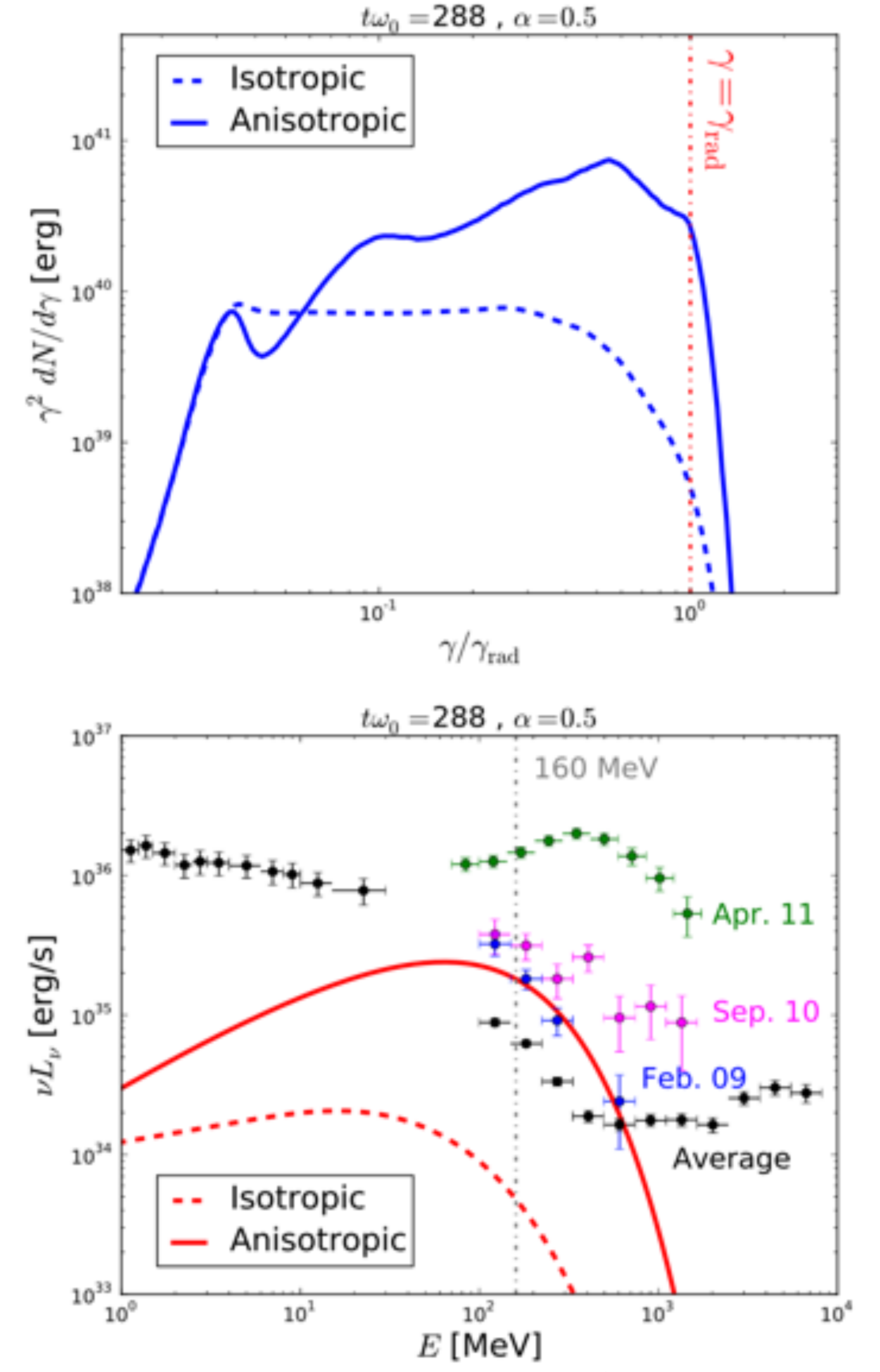


Cerutti et al 2013

Deep in current layer,
small radiative loss.



Kinetic beaming



Cerutti et al 2014

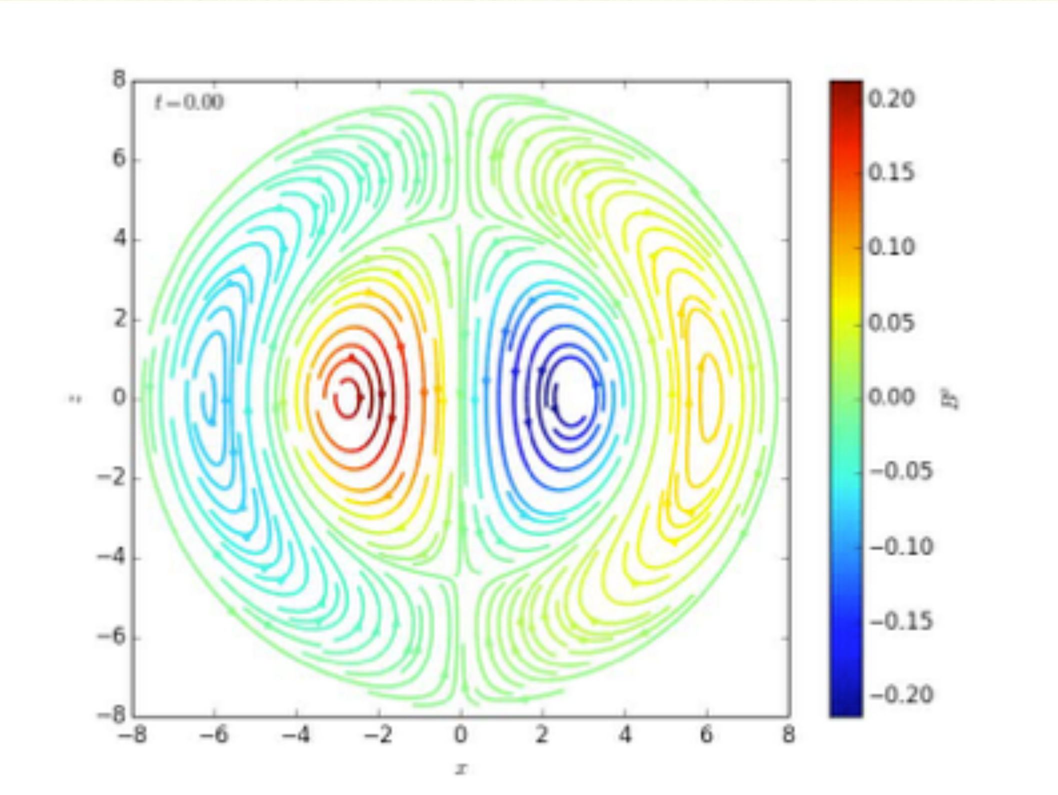
Magnetoluminescence

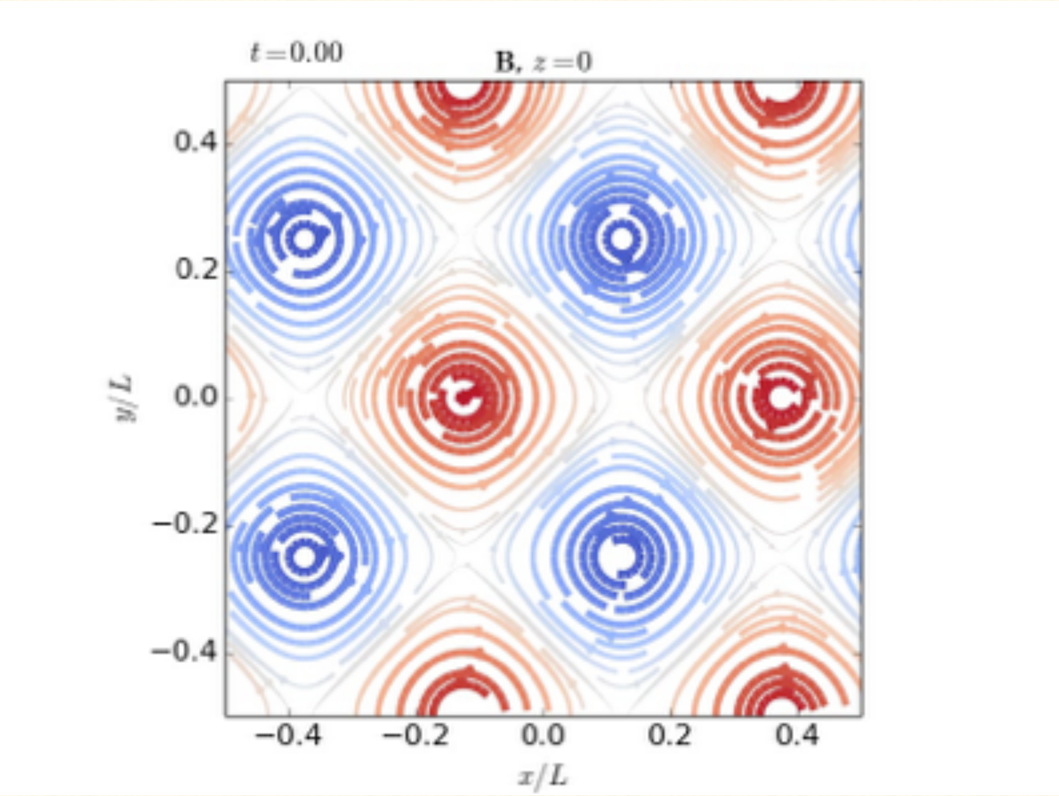
Large scale, catastrophic conversion of electromagnetic energy into high-energy, nonthermal radiation

Blandford et al 2014, 2015, 2017; East et al 2015; Nalewajko et al 2016; Yuan et al 2016; cf. Lyutikov et al 2016

An illustrative model problem: relaxation of relativistic magnetic equilibria

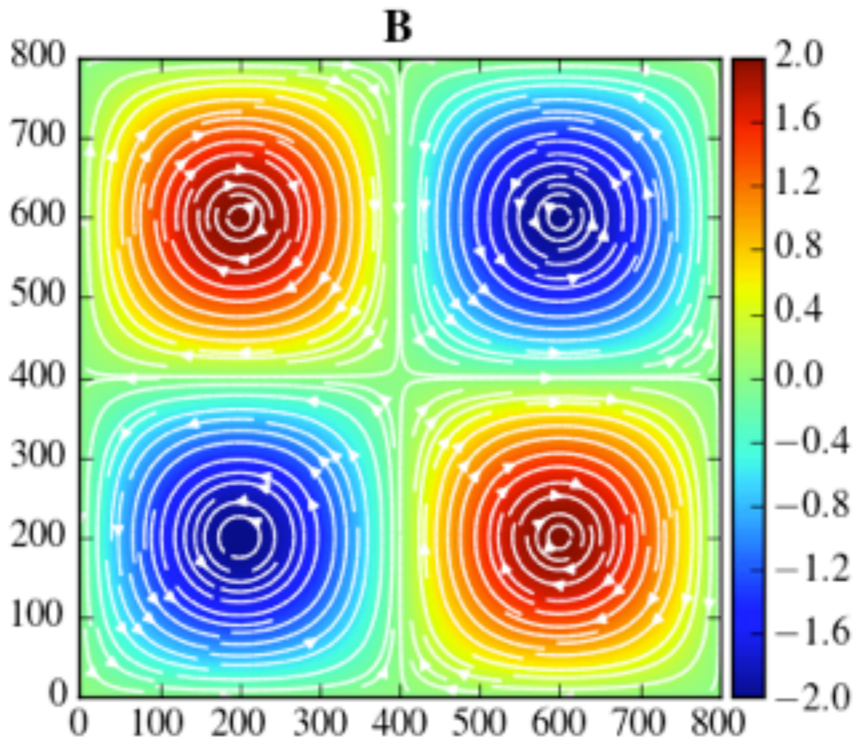
- Equilibria with free magnetic energy are unstable.
- Ideal instability grows on Alfven time scales.
- Efficient dissipation of magnetic energy upon saturation of the instability.

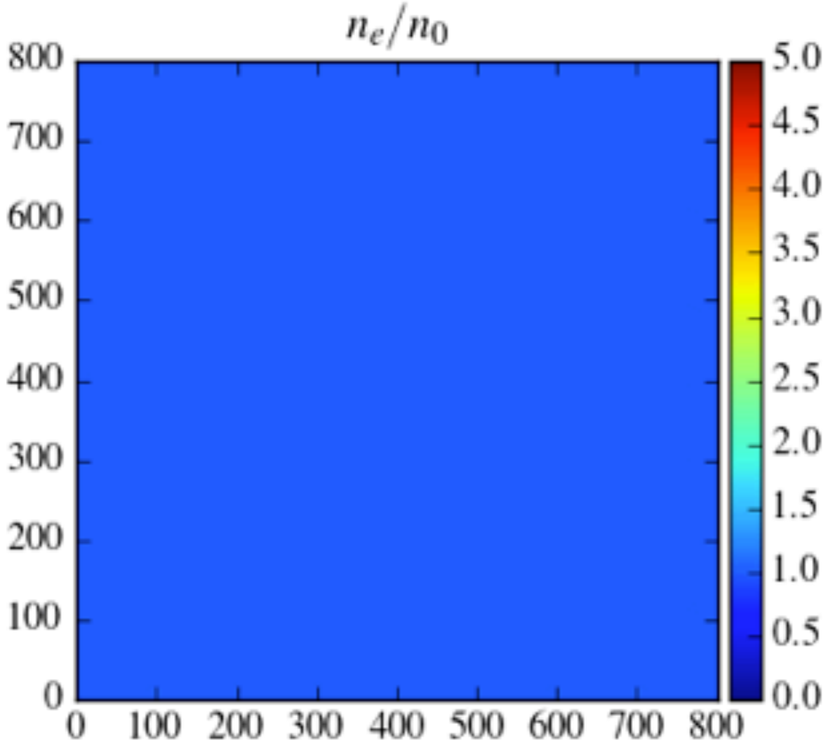


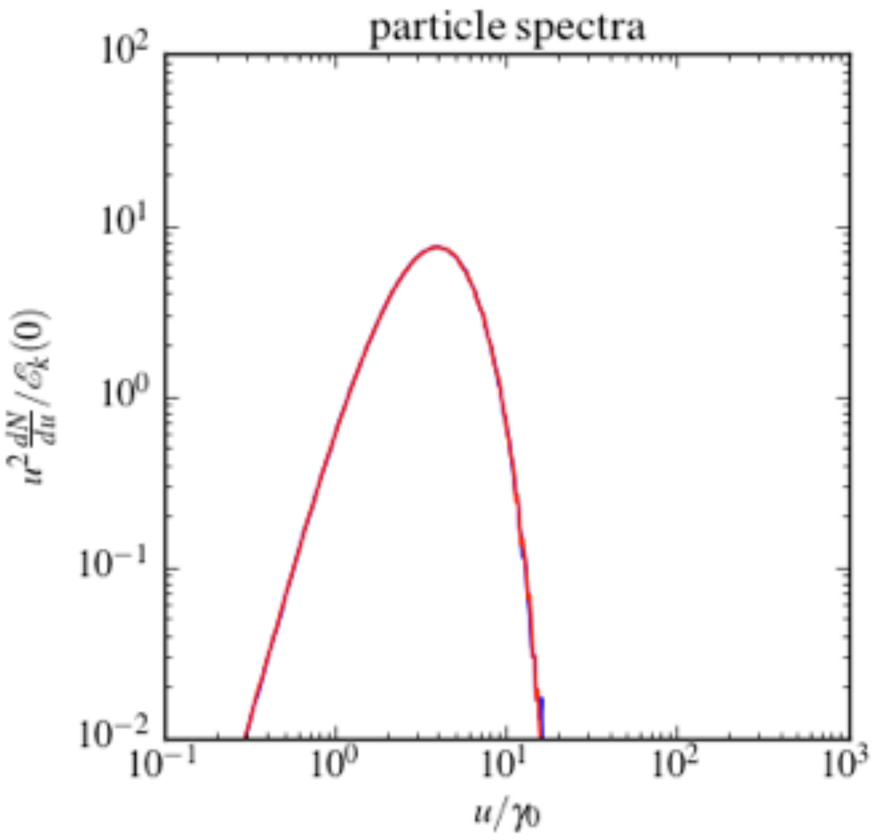


East, Zrake, Yuan & Blandford 2015

2D Particle-In-Cell simulation of a typical configuration



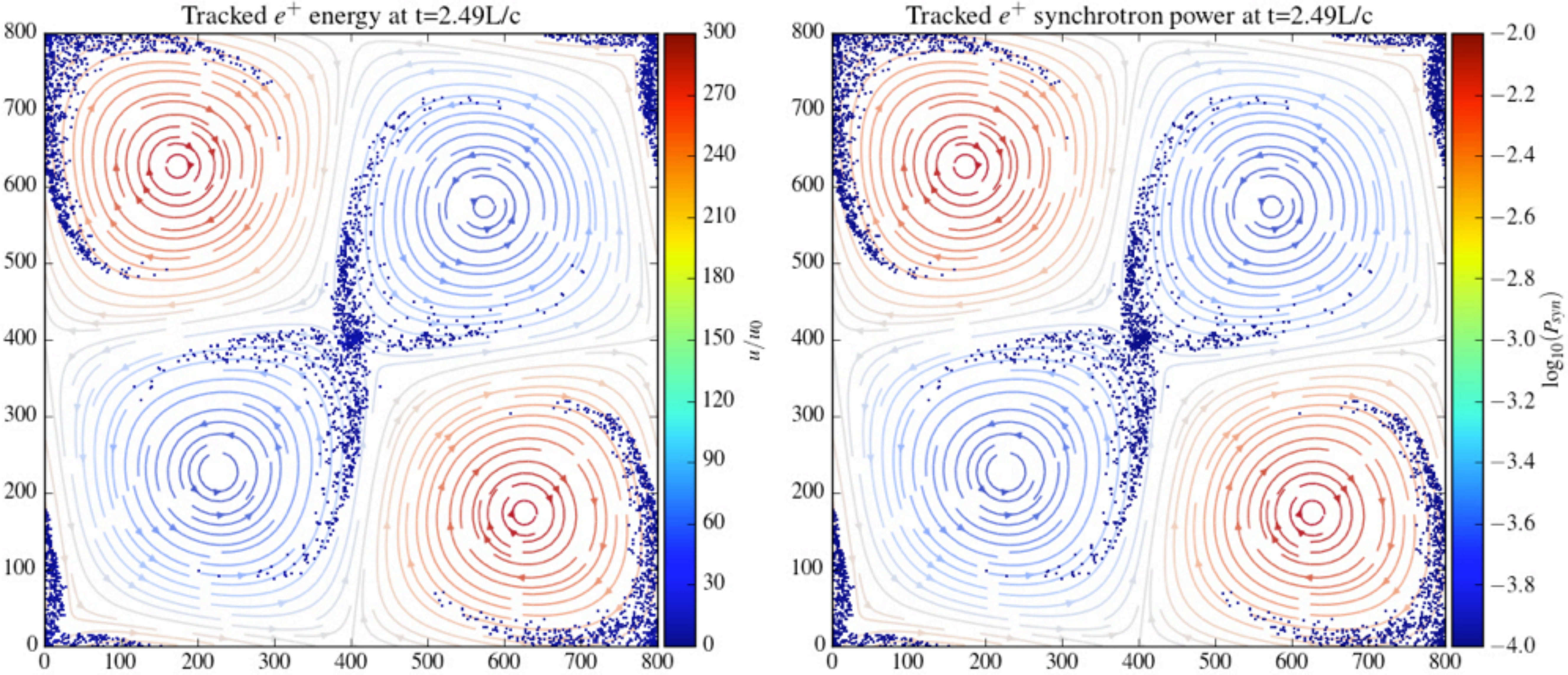




Example: σ=2.5, L/r_L=800, η=1.1e-8

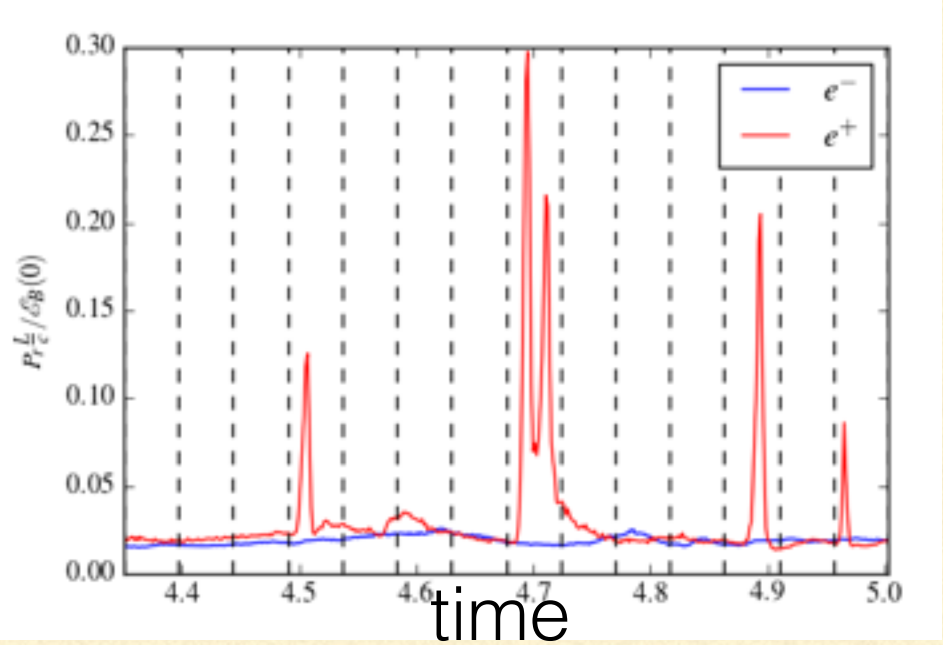
- Complex, small scale structures develop self-consistently from an initially smooth configuration!
- Magnetic reconnection happens at the current layer.
- Overall evolution is consistent with MHD results.

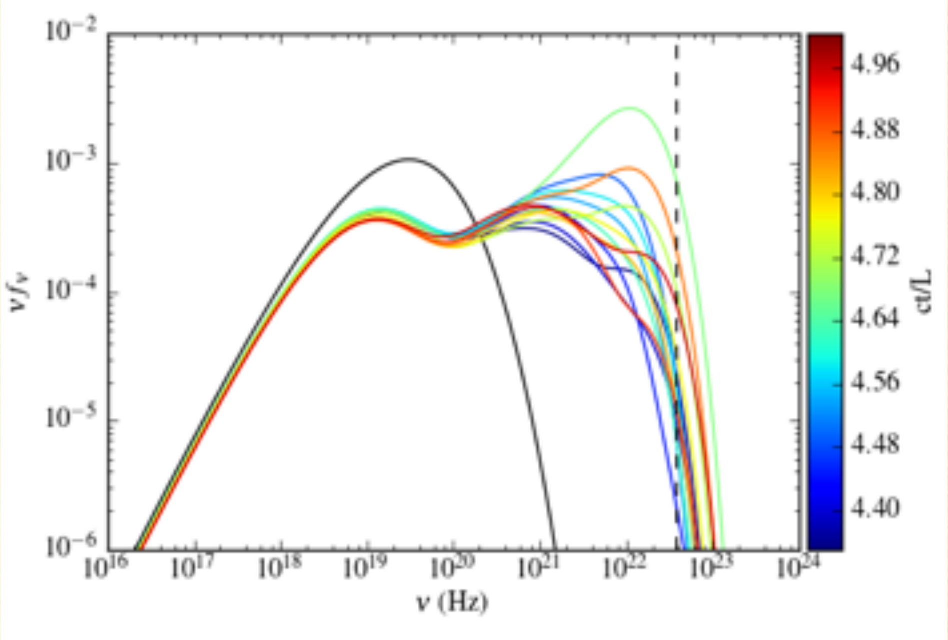
Where does most of the radiation come from?

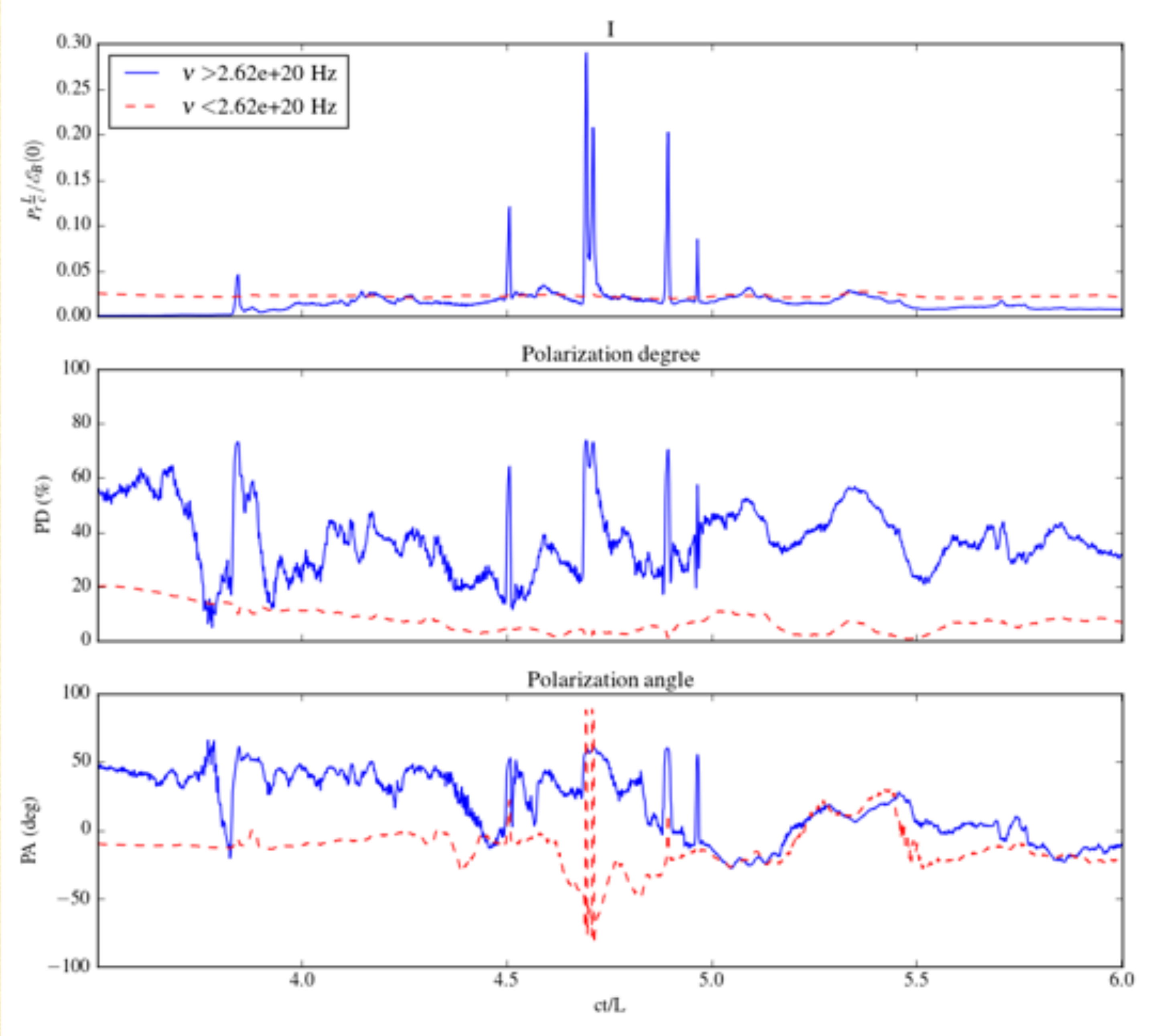


- Parallel electric field acceleration in the current layer, small synchrotron loss
- Compact, beamed synchrotron radiation is produced when particles are ejected from the current layers

Radiation signatures from simulations—a direct connection to the observations







Applications to astrophysical sources

- Rapid dynamic evolution + kinetic beaming + bunching of high energy particles due to tearing ==> Fast variability: emitting regions are smaller than the energy reservoir
- Impulsive acceleration during current layer formation may beat radiation reaction limit
- Modest radiation efficiency
- Caveats:
  - Scale separation in simulations vs. real systems
  - 2D vs. 3D
  - Need higher σ

Further reading

- Introductory text on magnetic reconnection:
  - Priest & Forbes (2000) Magnetic Reconnection: MHD Theory and Applications
  - Kulsrud (2005) Plasma Physics for Astrophysics
- Numerical simulations of relativistic reconnection
  - Cerutti, B., Uzdensky, D. A., & Begelman, M. C. 2012a, ApJ, 746, 148
  - Cerutti, B., Werner, G. R., Uzdensky, D. A., & Begelman, M. C. 2012b, ApJL, 754, L33
  - Cerutti, B., Werner, G. R., Uzdensky, D. A., & Begelman, M. C. 2013, ApJ, 770, 147
  - Cerutti, B., Werner, G. R., Uzdensky, D. A., & Begelman, M. C. 2014, ApJ, 782, 104
  - Guo, F., Li, H., Daughton, W., & Liu, Y.-H. 2014, PRL, 113, 155005
  - Guo, F., Liu, Y.-H., Daughton, W., & Li, H. 2015, ApJ, 806, 167
  - Sironi, L., Giannios, D., & Petropoulou, M. 2016, MNRAS, 462, 48
  - Sironi, L., & Spitkovsky, A. 2014, ApJL, 783, L21
  - Uzdensky, D. A., Cerutti, B., & Begelman, M. C. 2011, ApJL, 737, L40
  - Werner, G. R., Uzdensky, D. A., Cerutti, B., Nalewajko, K., & Begelman, M. C. 2016, ApJL, 816, L8
  - Zenitani, S., & Hoshino, M. 2001, ApJL, 562, L63
  - Zenitani, S., & Hoshino, M. 2007, ApJ, 670, 702