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A Brief Overview, and Recent Developments in the Theory of High-Energy Emission from the Crab Nebula

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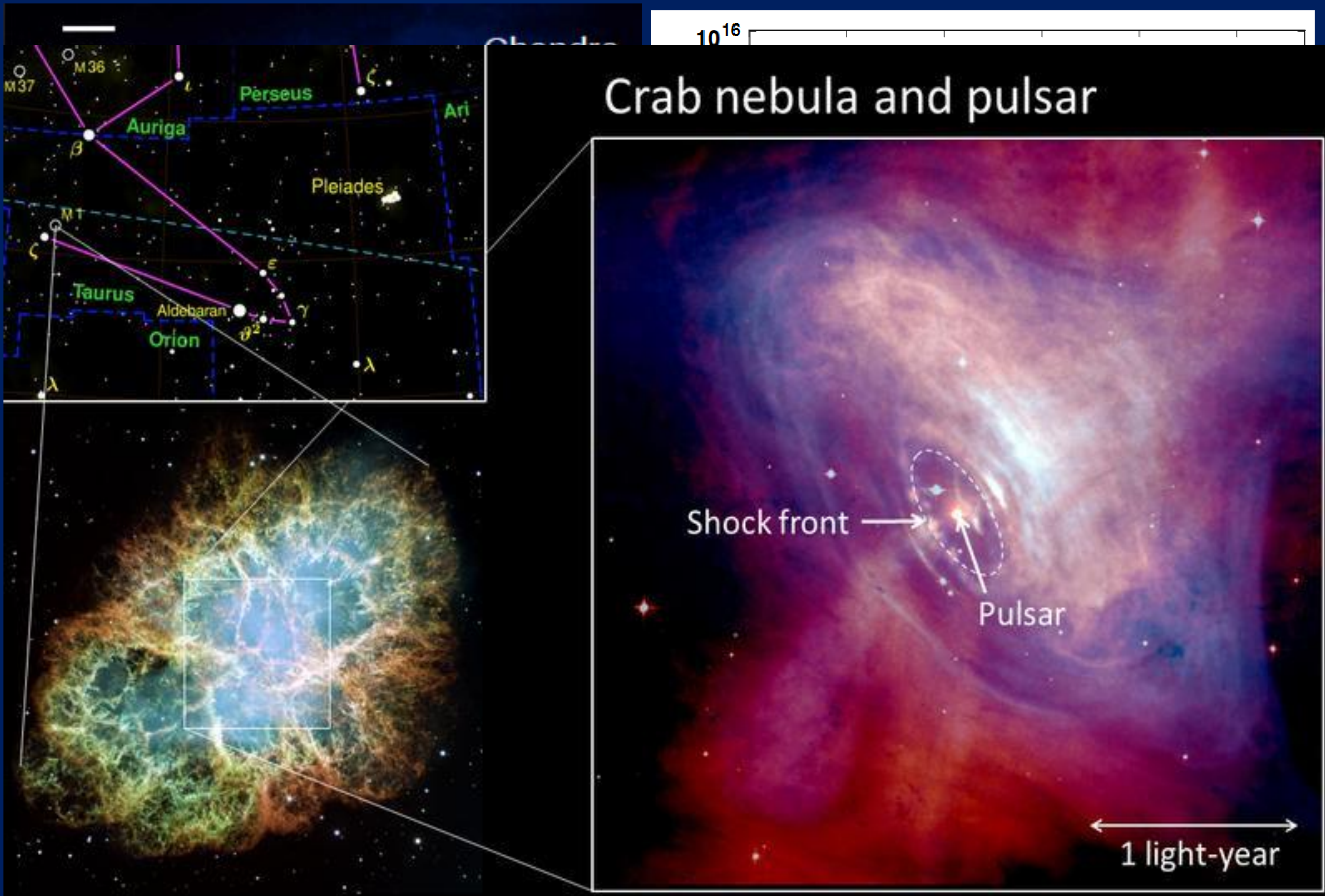
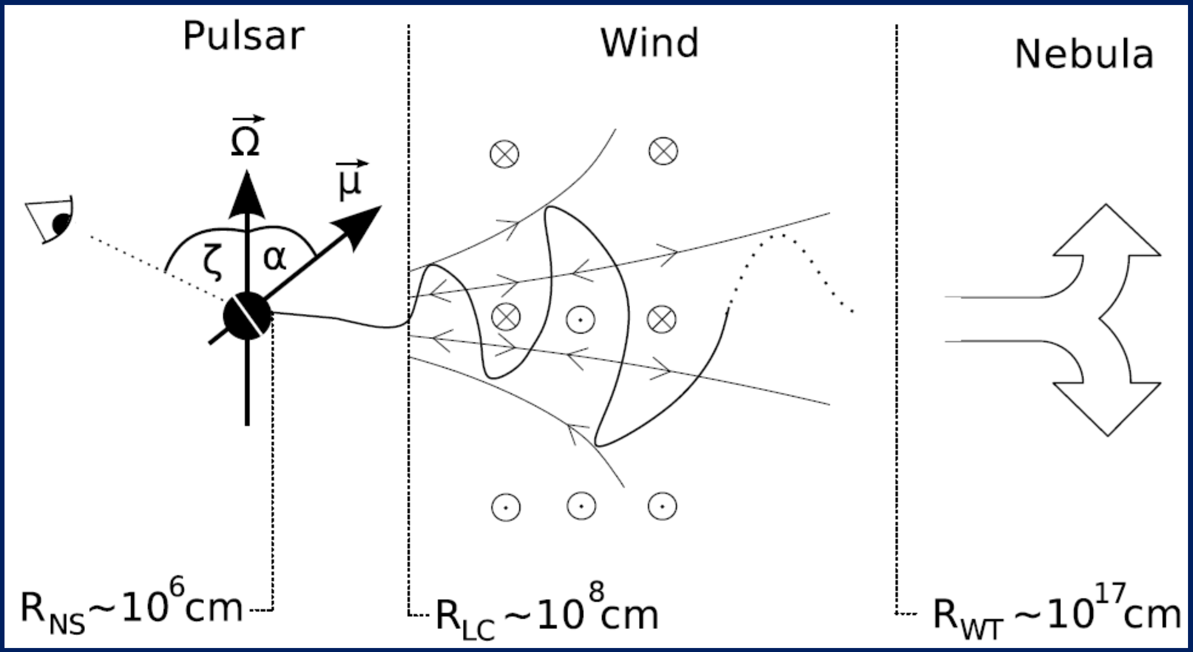
The Crab Nebula



Pulsar Wind Nebula



Buehler & Blandford (2014)

Rees & Gunn (1974)

Wind pressure=Nebula pressure

$$\frac{\dot{L}}{4\pi R_{\mathrm{S}}^2} \approx \frac{\tau \dot{L}}{\frac{4}{3}\pi R_{\mathrm{N}}^3}$$

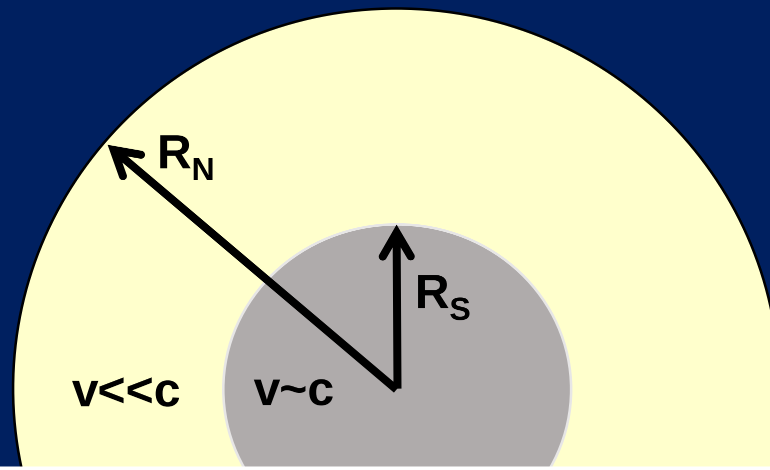
τ=963 yrs

R_N=2 pc

→ $R_s \approx 3*10^{17}$ cm

Pulsar Wind Nebula

MHD model of pulsar wind (Kennel & Coroniti 1984)

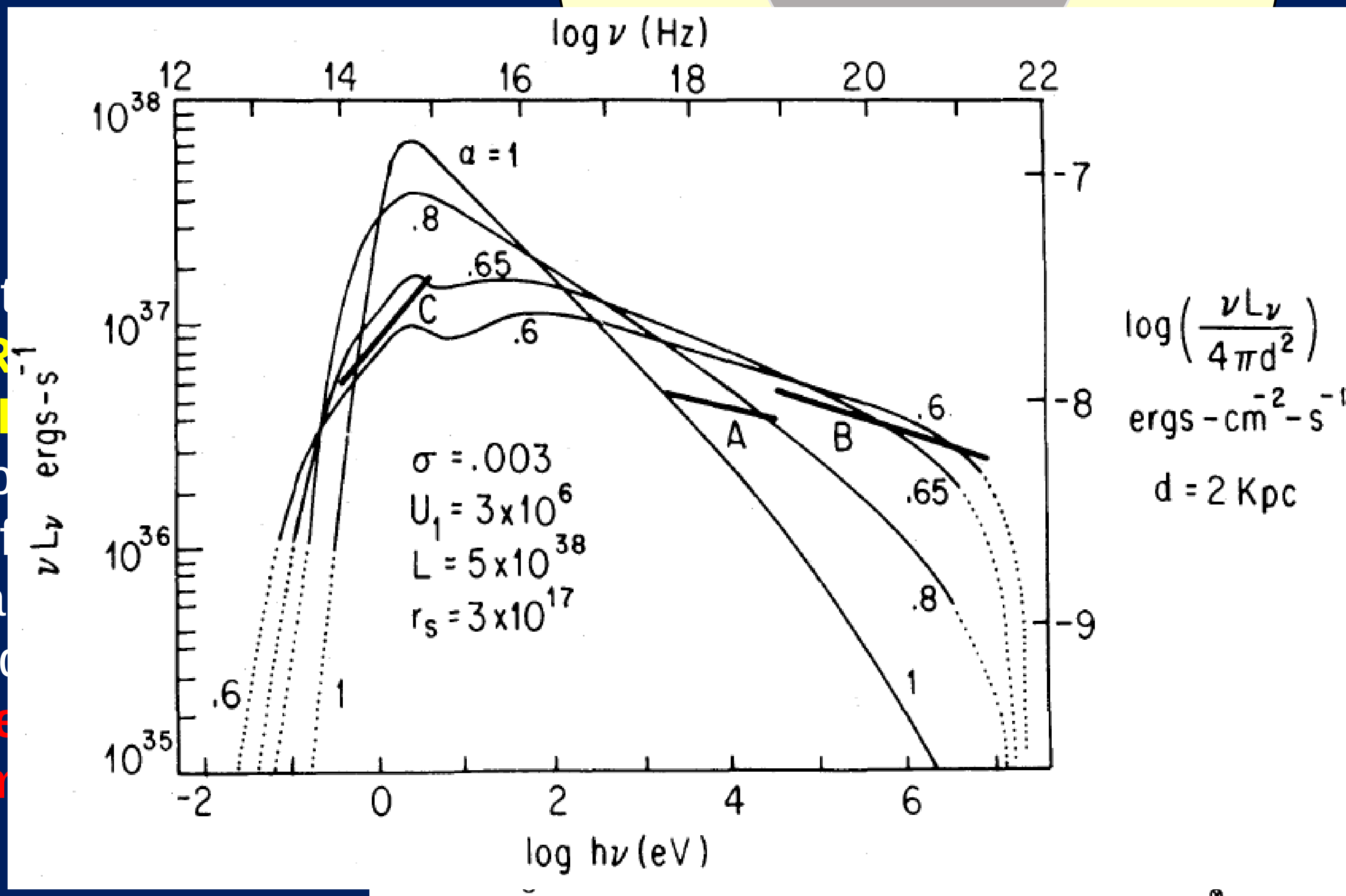


$$\sigma \equiv \frac{\text{Magnetic energy density}}{\text{Particle energy density}} = \frac{B_1^2}{4\pi n_1 u_1 \gamma_1 m c^2}$$

$$L = 4\pi n_1 \gamma_1 u_1 m c^3 r_S^2 (1+\sigma)$$

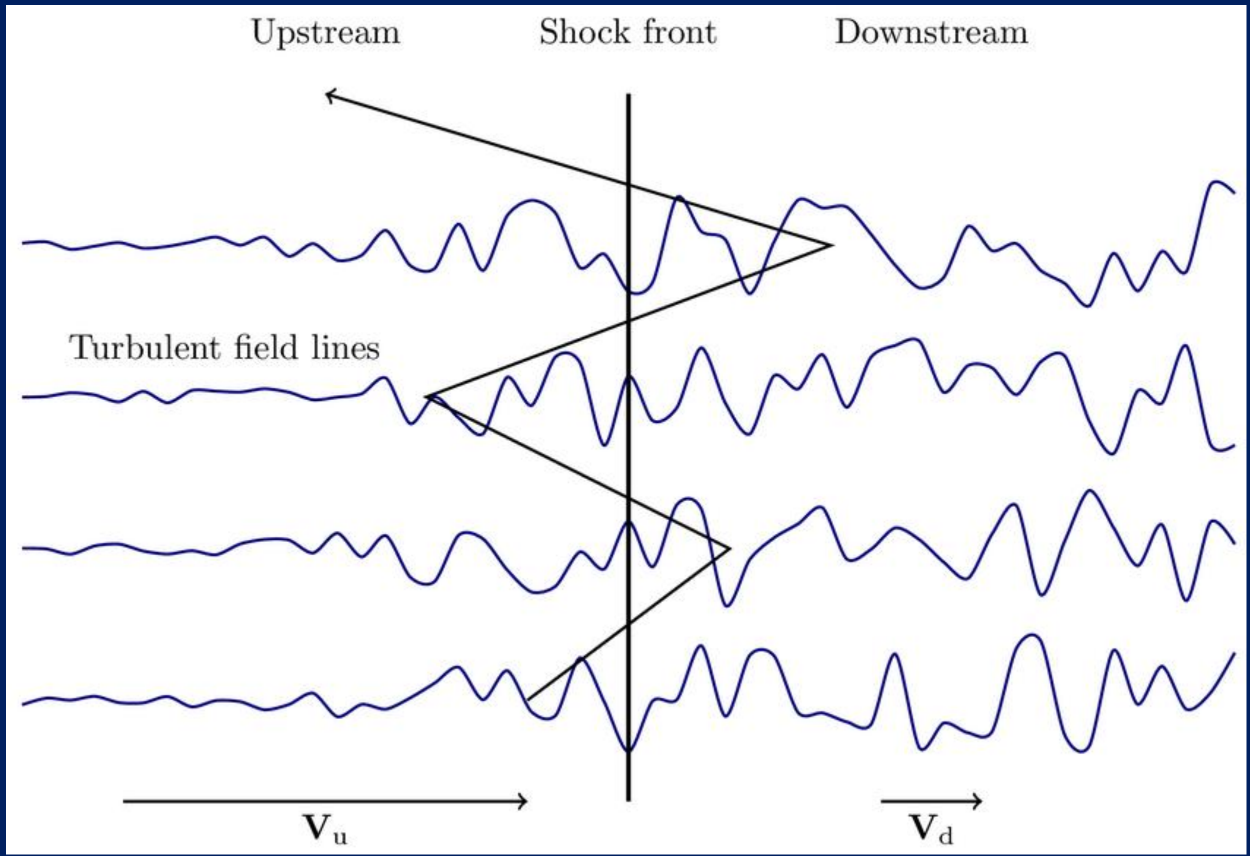
$$B_1 = \left[\frac{L}{c r_S^2}\frac{\sigma}{(1+\sigma)}\right]^{1/2}$$

- Model parameters:
  1. Pulsar luminosit
  2. Shock radius, R
  3. Nebula radius, I
  4. Magnetization p
  5. Preshock wind f
  6. Particle spectra
     - ➢ Power-law (**shock acce Order Ferm**

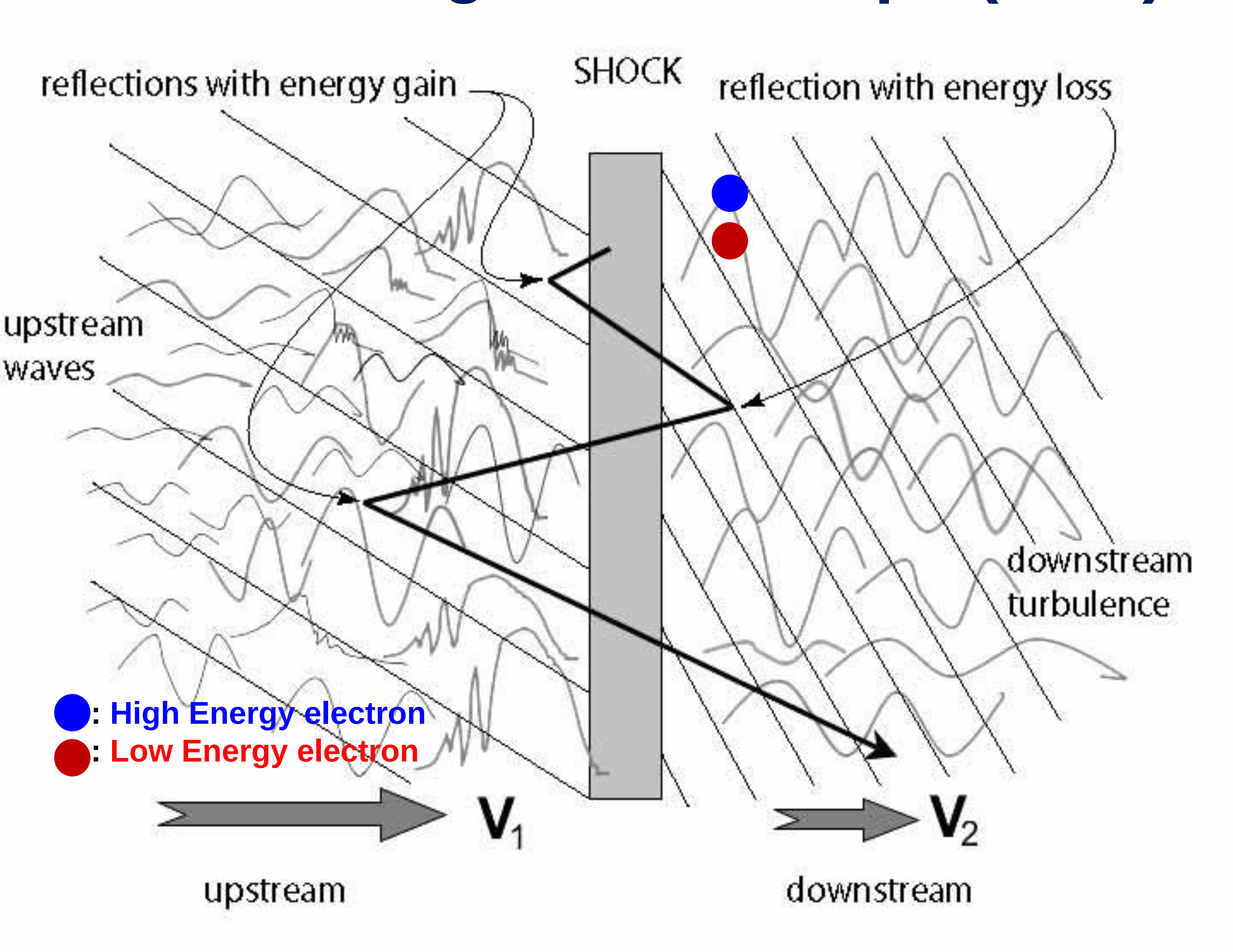


Shock Acceleration

- Shock acceleration (Fermi 1949, Blandford & Ostriker 1978) at termination shock→quiescent spectrum.
  - Mediated by MHD scattering centers.
  - Toroidal magnetic field (parallel to TS), reduces likelihood of particles being recycled back upstream.
  - “Shock-regulated escape”: lowest energy particles are more likely to advect downstream.

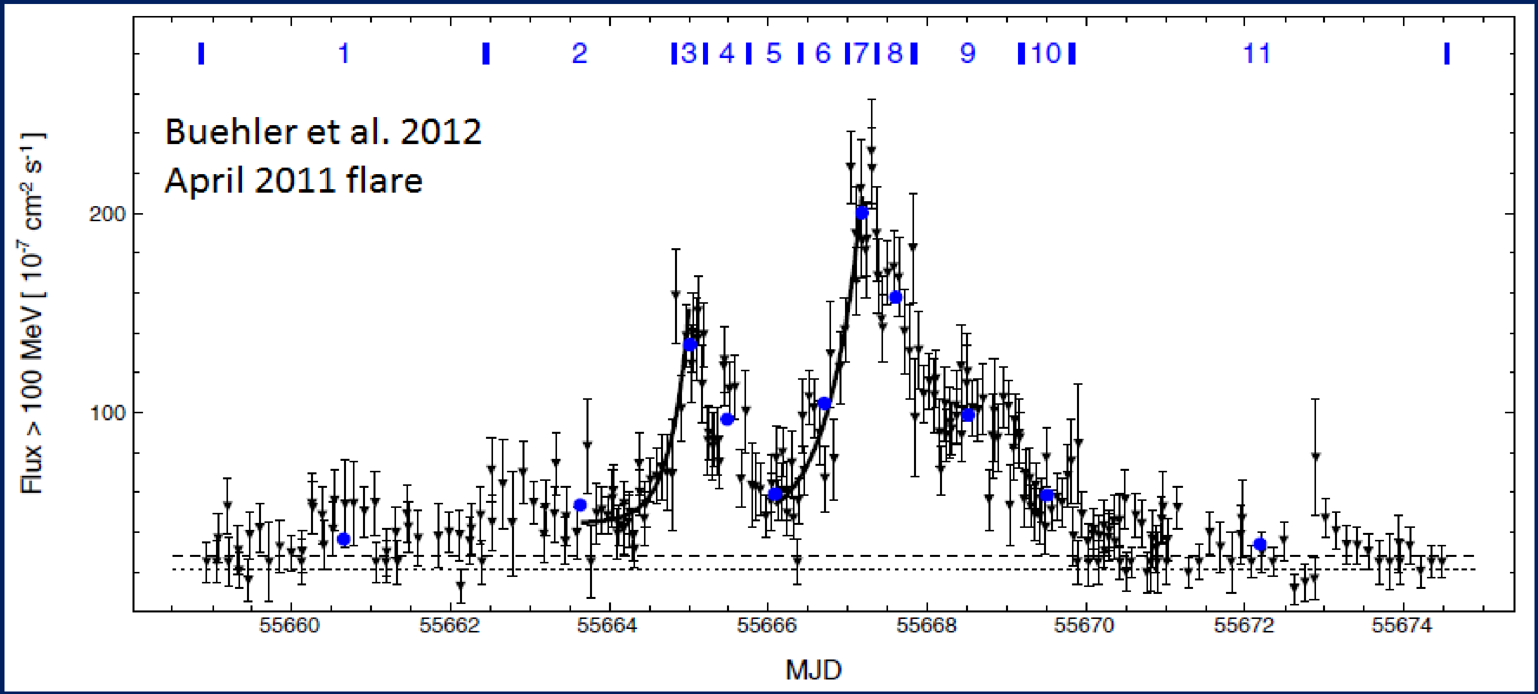


Shock-Regulated Escape (SRE)



Gamma-Ray Flares from Crab Nebula

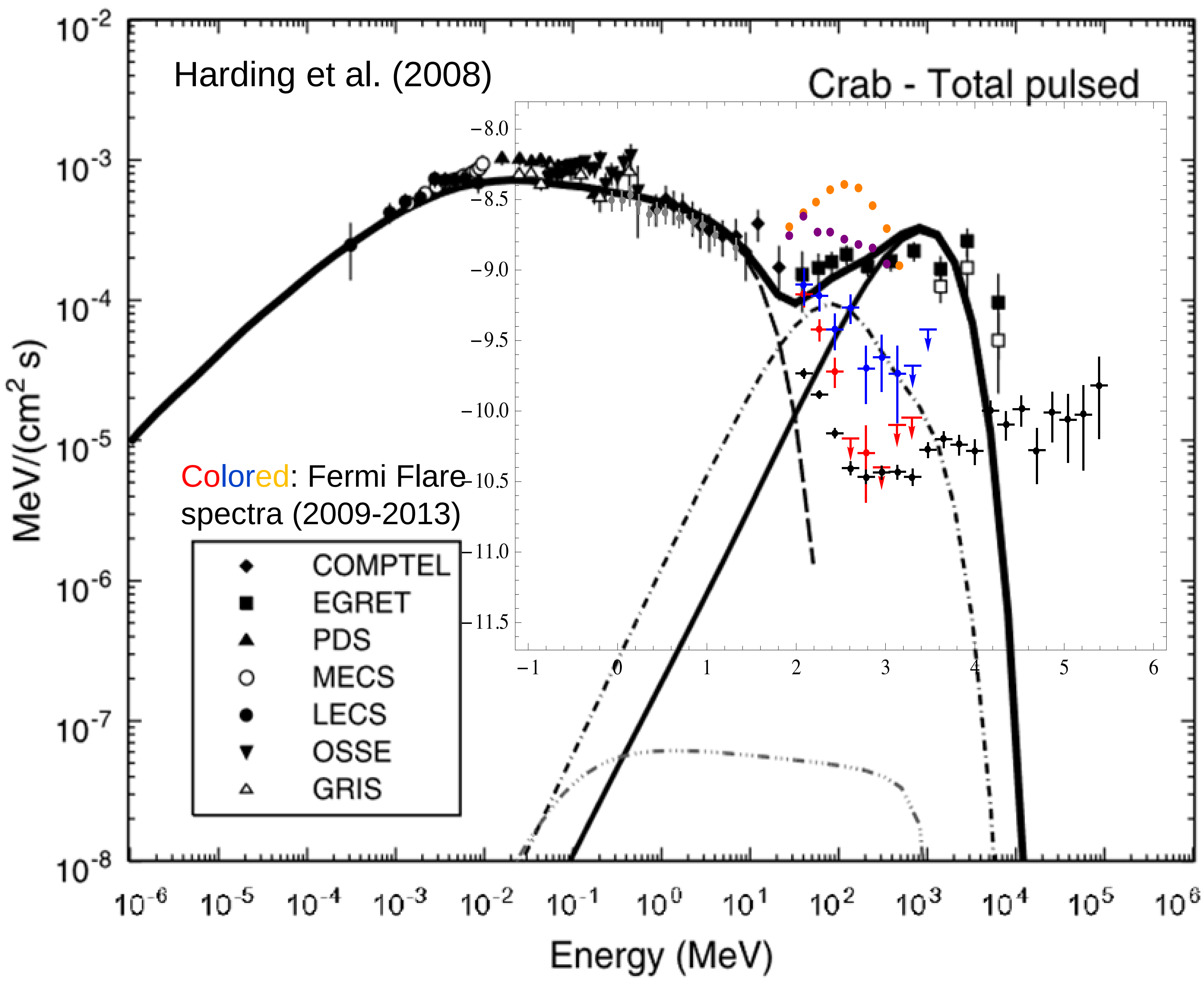
- **Rapid variability** observed in Fermi-LAT gamma-ray flares.
- Gamma-ray flares observed in **2007**, **2009**, **2010**, **2011**, **2013**.



Flares were unexpected!

Peak L=4*10^{36} ergs/s
Spin L=5*10^{38} ergs/s
Total E=3*10^{42} ergs

Broadband SED and Flare Spectra



Challenges of Theory

- How do the particles end up with most of the magnetic energy downstream of the TS?

At $r<R_S$: $\sigma \sim 10^3$-10^4

At $r \geq R_S$: $\sigma \ll 1$

"σ problem"

- Synchrotron "burn-off" limit? (radiation reaction limited emission)

$$\epsilon_{\rm pk}(\gamma) = \xi \frac{B}{B_{\rm crit}} \gamma^2 m_e c^2$$

$$\gamma_{\rm MHD} = \sqrt{\frac{6\pi q}{B\,\zeta\,\sigma_{\rm T}}} = 8.25 \times 10^9 \left(\frac{B}{200\,\mu{\rm G}}\right)^{-1/2} \zeta^{-1/2}$$

- γ_{MHD} found by equating maximum MHD acceleration rate with synchrotron loss rate.

$$\epsilon_{\rm MHD} \equiv \epsilon_{\rm pk}(\gamma_{\rm MHD}) = \frac{6\pi\,\xi q\, m_e c^2}{B_{\rm crit}\zeta\,\sigma_{\rm T}} = 158\ {\rm MeV}\,\xi\,\zeta^{-1}$$

>3 GeV photons observed in flares!

****ς and ξ are order unity model parameters from Kroon et al. (2016)****

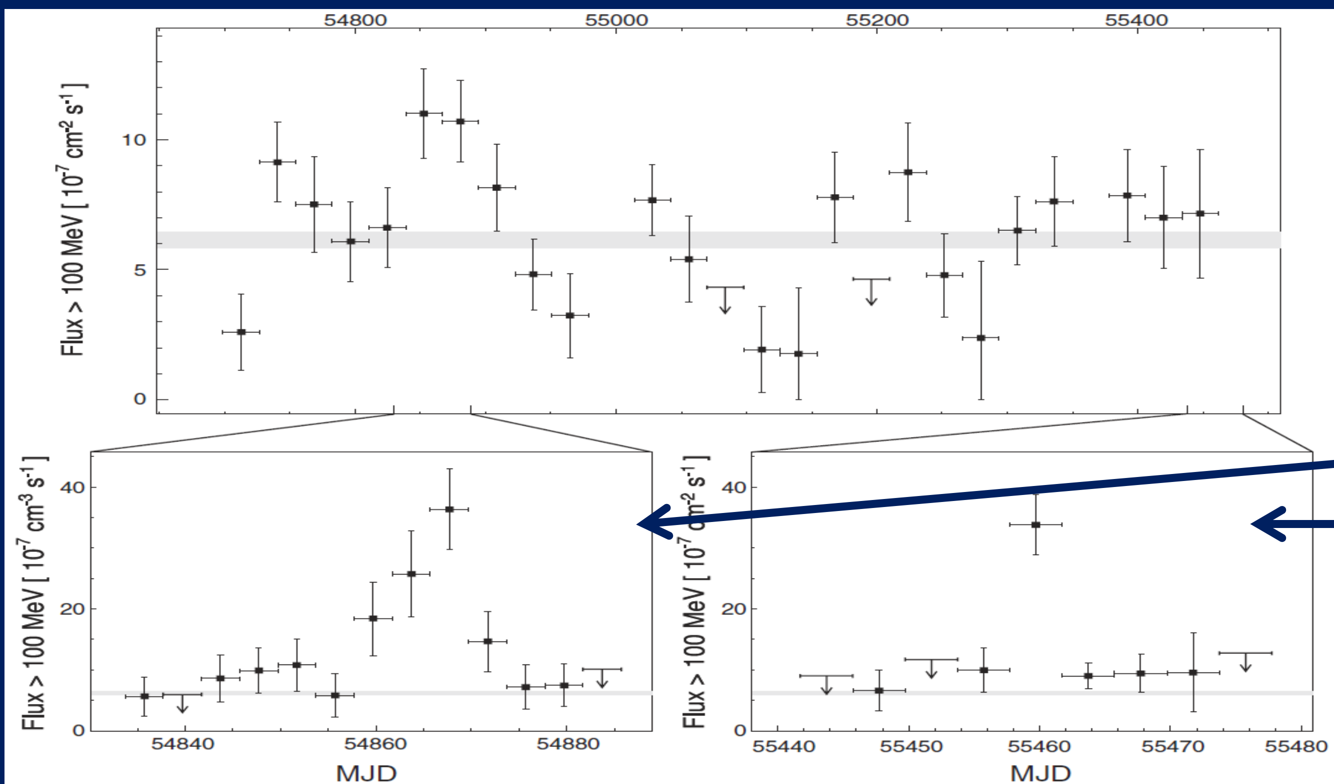
The Fermi Era: Powerful γ-ray Flares

- Classical Diffusive Shock Acceleration (DSA) can't explain the energetic/temporal features of the flares, but works well for long term quiescent state emission.
- Magnetic reconnection can explain it (non-ideal MHD).

$$\epsilon_{\max} = 158\ \mathrm{MeV}\left(\xi + \frac{E}{B} + \frac{D_0}{D_0^{\max}}\right)$$

E/B>1, boosts E_{max} above burnoff limit.

- Fermi observed >3 GeV emission from some of the flares.



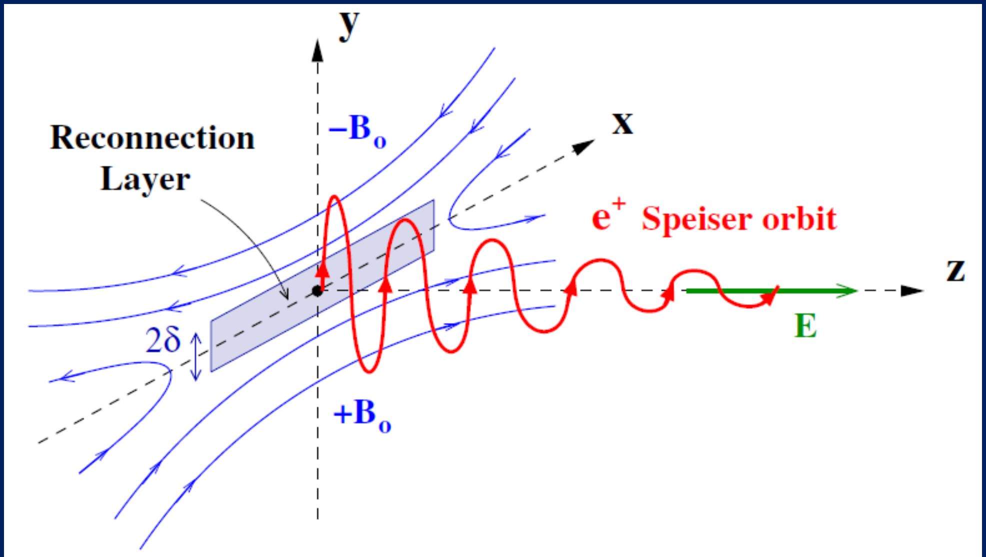
(Peak around 400 MeV)

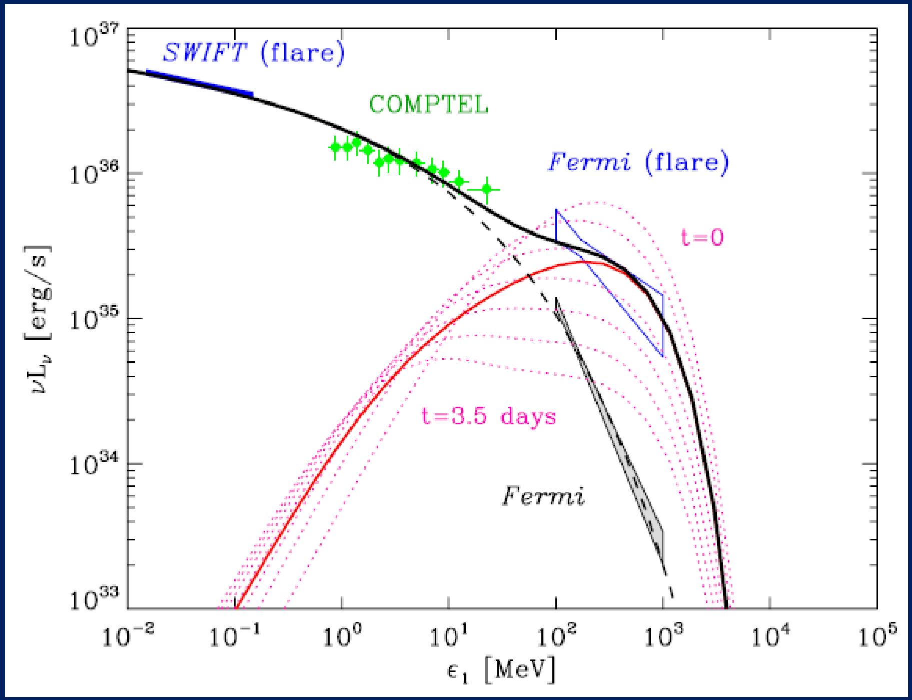
Abdo et al. (2011)

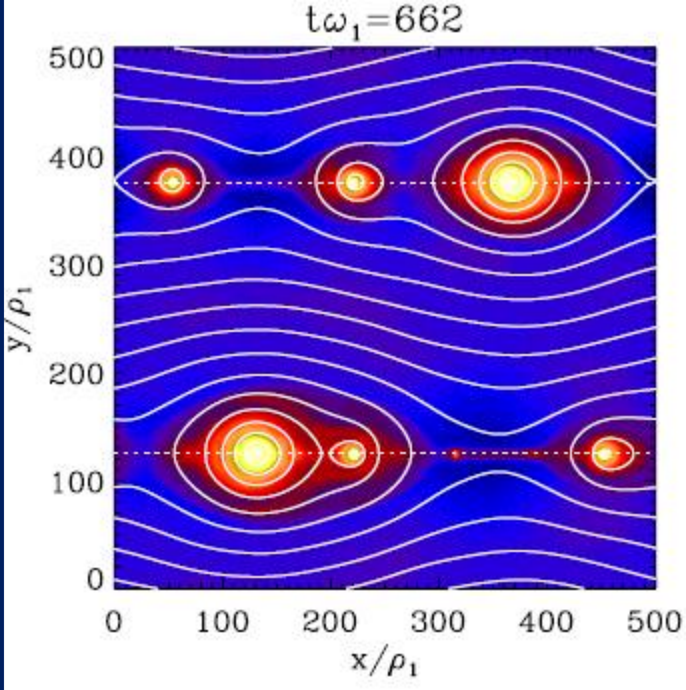
Feb. 2009
Sept. 2010

Reconnection Simulations

- PIC simulations of shock-driven reconnection, Cerutti et al. (2013).



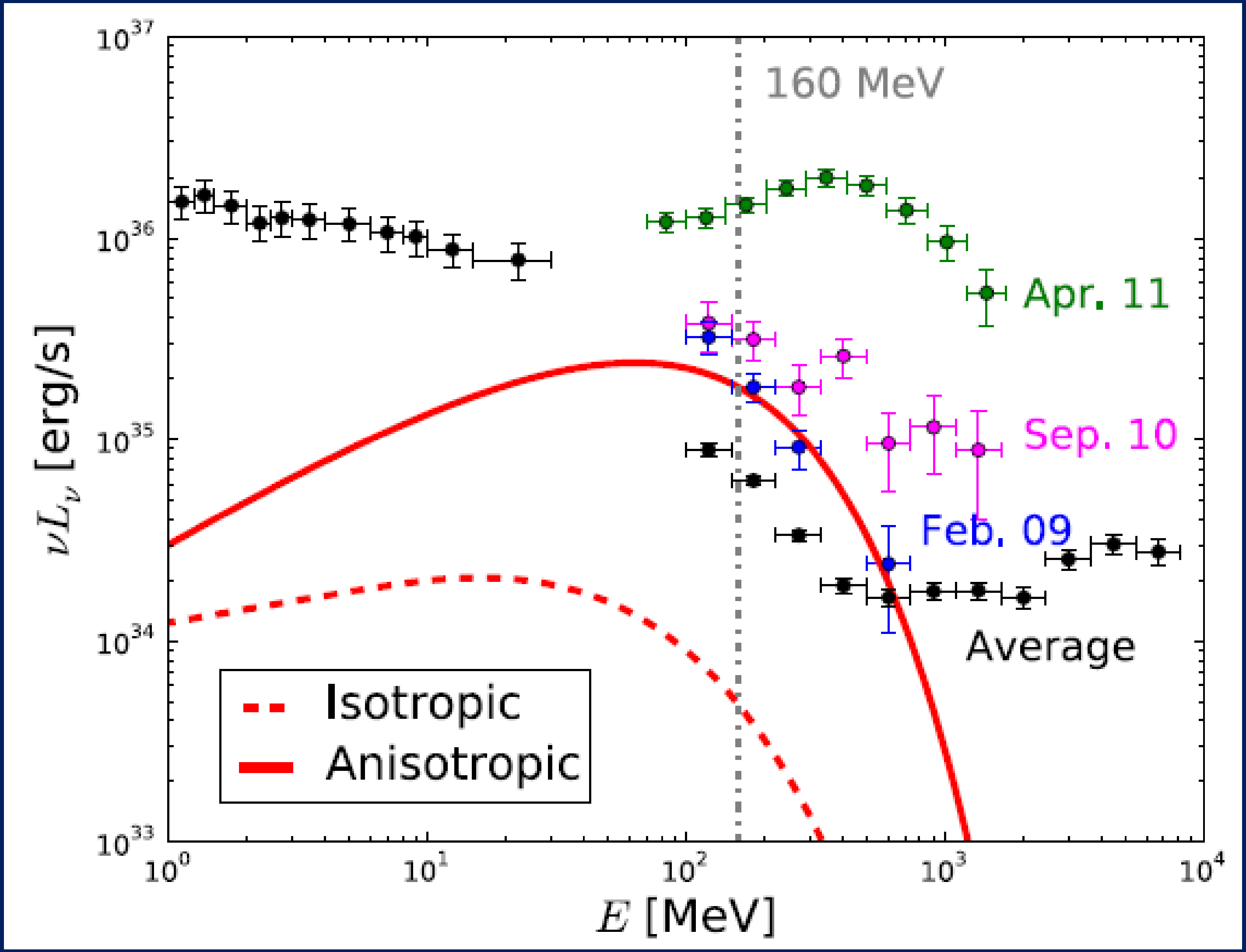


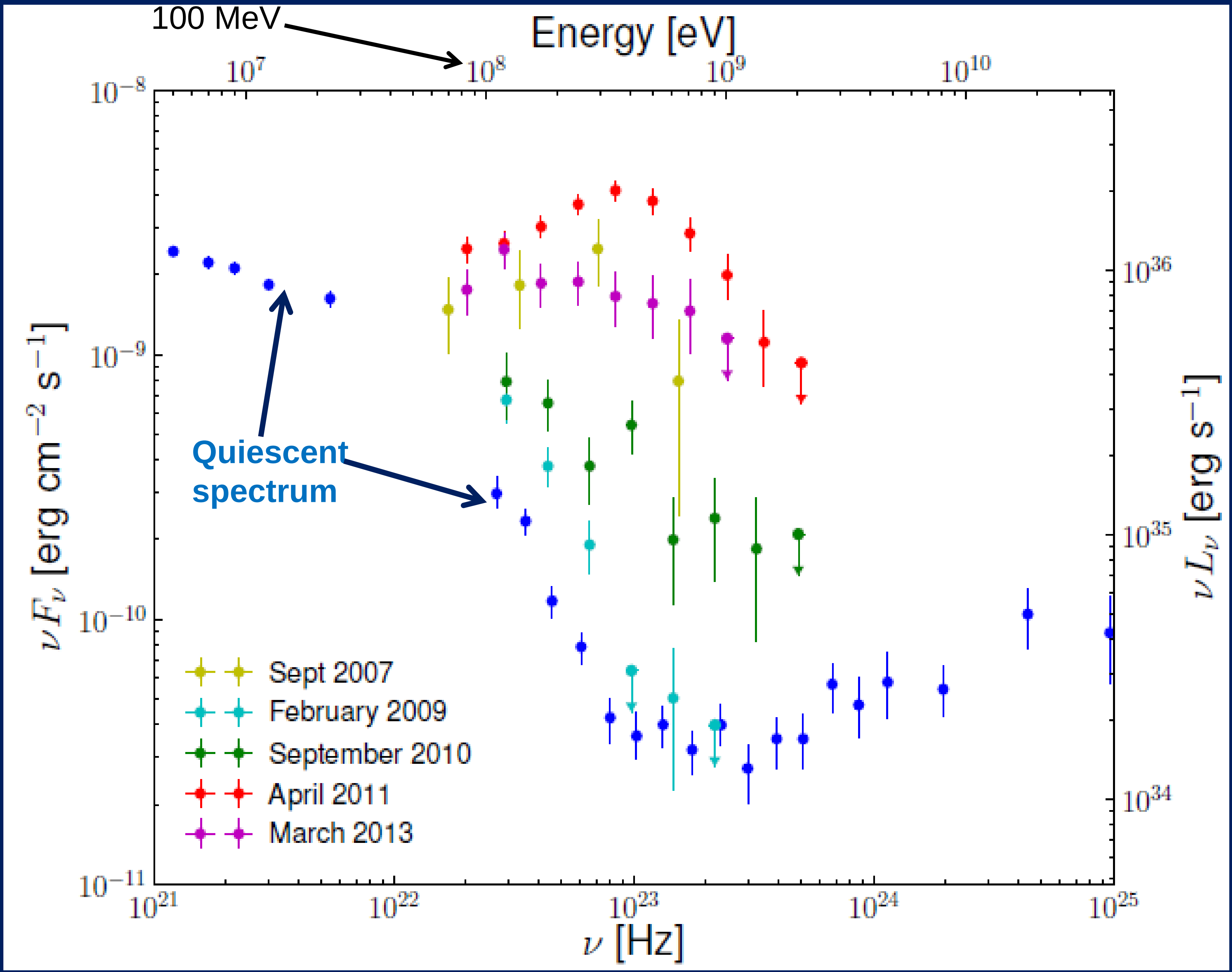


- Shock-driven magnetic reconnection provides a powerful mechanism to explain the flares.
- BUT simulation generated spectra don't reproduce the observed spectra…

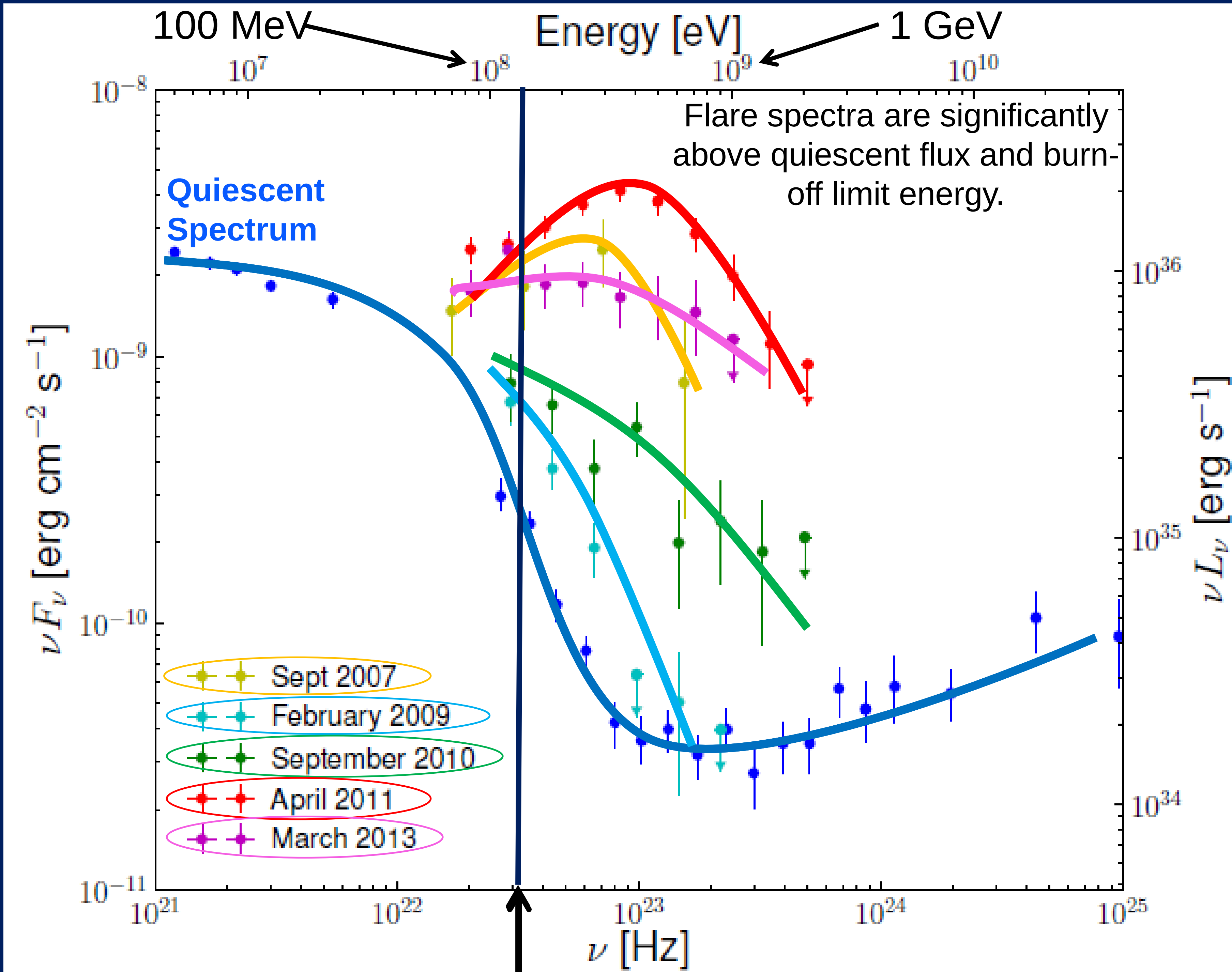
Cerutti, Werner, Uzdensky, & Begelman (2014)

- Reconnection simulations demonstrate **efficient electrostatic acceleration**, but the resulting spectra **do not fit** the observational data very well.





Buehler & Blandford (2014)



Synchrotron Burnoff Buehler & Blandford (2014)

New Theoretical Model (Kroon et al. 2016)

$$<\dot{p}>_{\rm gain} = qE + qB\rho\zeta^{-1} = A_0\, m_e c$$

1st Order processes

Momentum diffusion

$$D(p) = D_0 m_e c\, p$$

$$<\dot{p}>_{\rm loss} = -\frac{B_0}{m_e c} p^2$$

Synch. losses

$$\frac{\partial f}{\partial t} = -\frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2\left(-D(p)\frac{\partial f}{\partial p} + <\dot{p}>_{\rm gain} f + <\dot{p}>_{\rm loss} f\right)\right] - \frac{f}{t_{\rm esc}(p)} + \dot{f}_{\rm source}$$

2nd Order Stochastic Acceleration

Electrostatic + Shock Acceleration

Synchrotron Losses

SRE+Bohm Diffusive Escape

Injection Spectrum

$$\frac{\partial f}{\partial t} = -\frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2\left(-D_0 m_e c\, p\frac{\partial f}{\partial p} + A_0 m_e c f - \frac{B_0 p^2}{m_e c} f\right)\right] - \left(\frac{C_0 m_e c}{p} + \frac{F_0 p}{m_e c}\right) f + \frac{\dot{N}_0\, \delta(p - p_0)}{4\pi p_0^2} = 0$$

- Analytic models are more useful than simulations for fitting data→computational time, variation of parameters.

Analytical Solution

- **Steady-state solution** for the electron number distribution:

$$N_{\rm G}(x,x_0)=\frac{\dot{N}_0\Gamma(\mu-\kappa+1/2)}{\tilde{B}D_0\Gamma(1+2\mu)\,x_0^2}\left(\frac{x}{x_0}\right)^{\tilde{A}/2}e^{-\tilde{B}(x^2-x_0^2)/4}M_{\kappa,\mu}\left(\frac{\tilde{B}x_{\rm min}^2}{2}\right)W_{\kappa,\mu}\left(\frac{\tilde{B}x_{\rm max}^2}{2}\right)$$

- With the analytic solution, we can perform an **integral convolution** with the **synchrotron emissivity** function. The synchrotron **flux at the detector** is given by

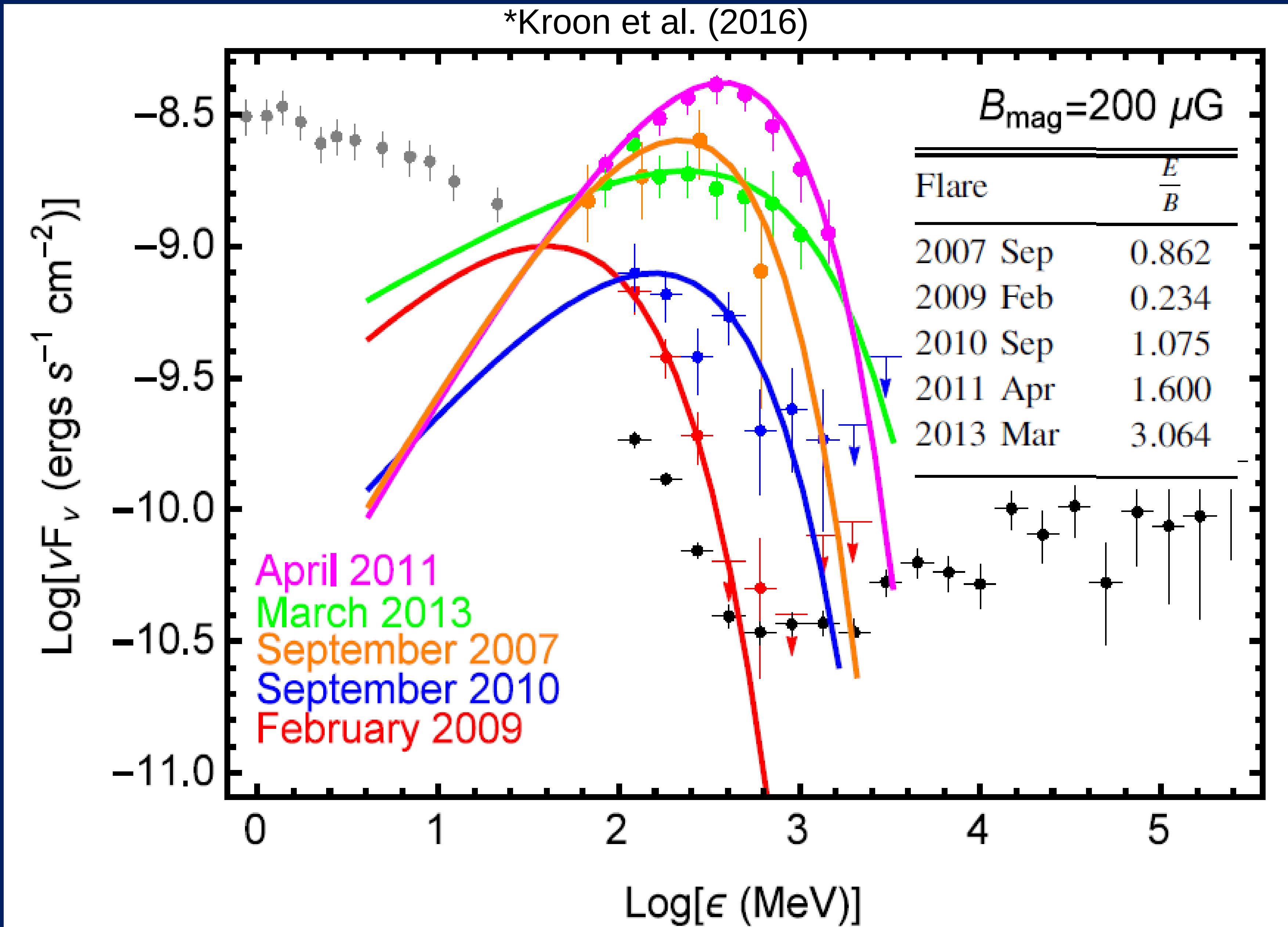
$$\mathscr{F}_\nu(\nu)=\frac{1}{4\pi D^2}\int_1^\infty N_{\rm G}(\gamma,\gamma_0)P_\nu(\nu,\gamma)d\gamma\ \propto\ {\rm erg\ s^{-1}\ cm^{-2}\ Hz^{-1}}$$

where *D* is the distance to the source.

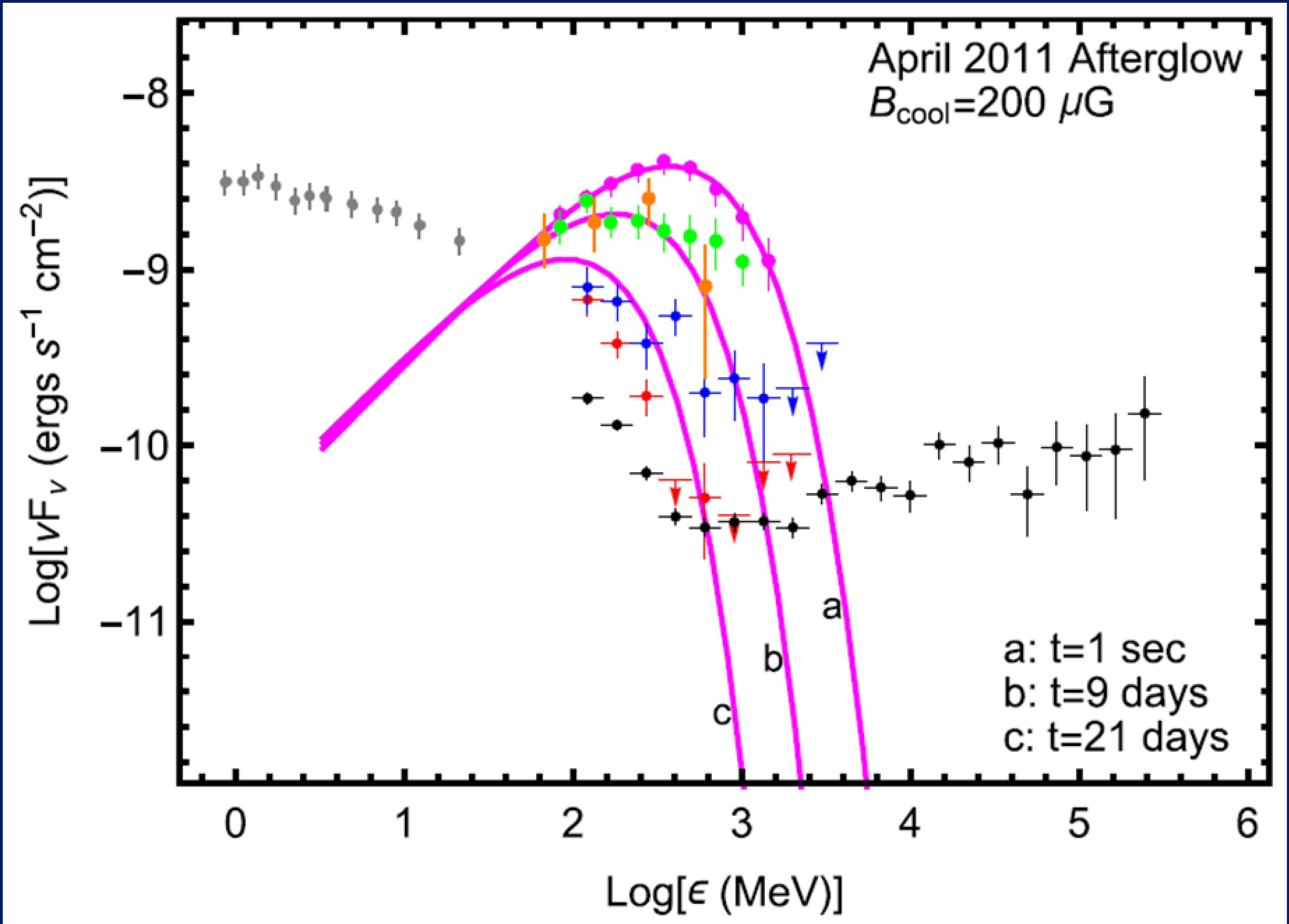
- **How does this analytic model compare with the observed flare spectra?...**

Flare Spectral Fits (Kroon et al. 2016)

- These are the **most successful theoretical calculations** of the Crab nebula flare spectra to date!



Afterglow Spectra for April 2011 Flare



Conclusions

- **Prior Models**
  - DSA dominates acceleration during quiescence.
  - MHD flow transport is more efficient than spatial diffusion.

- **Kroon et al. (2016) Model**
  - **Electrostatic acceleration** via shock-driven reconnection provides most of the power for the flares.
  - **Shock acceleration** and **stochastic MHD acceleration** are also important for determining the spectral shapes.
  - The NRL/GMU collaboration is currently developing a **time-dependent model for the gamma-ray flares**, and the preliminary results are very interesting!

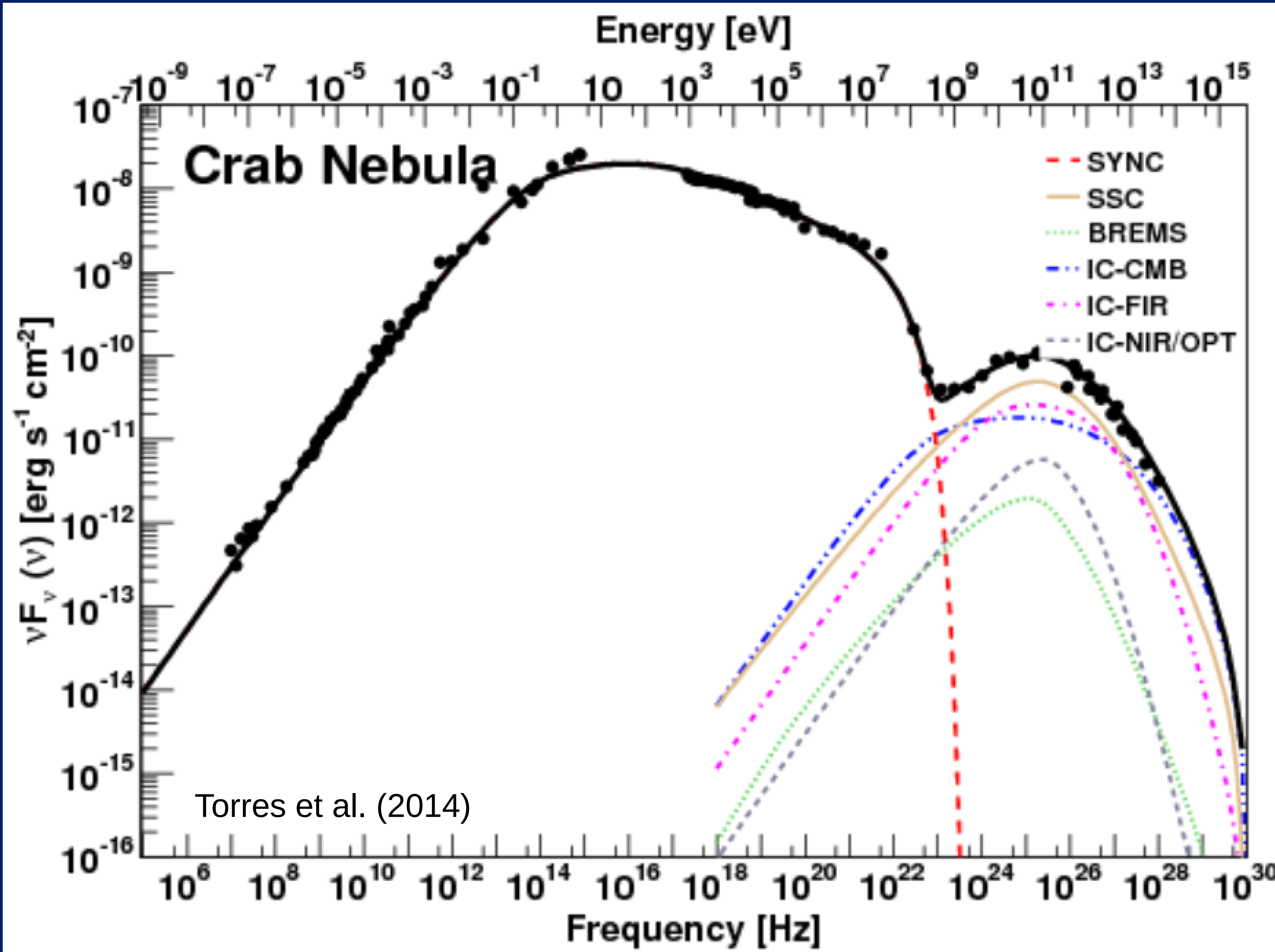
- **Fermi** has discovered new mysterious acceleration processes that have **challenged** our understanding of HE astrophysics and led to **new insights**!

Additional slide(s) follow.

Data Table

Flare	σ_{mag}	$\tilde{A}_{sh}$	$\tilde{A}_{elec}$	$\tilde{B}$	$\tilde{C}$	m_-	$D_0\,(s^{-1})$	$\frac{E}{B}$
2007 Sep	0.0802	3.740	32.26	5.50×10^{-19}	10.0	−0.261	94.00	0.862
2009 Feb	0.0401	7.480	17.52	1.10×10^{-18}	45.0	−1.575	47.00	0.234
2010 Sep	0.0980	3.060	32.94	4.50×10^{-19}	53.0	−1.347	114.9	1.075
2011 Apr	0.1026	2.925	46.80	4.30×10^{-19}	15.0	−0.288	120.2	1.600
2013 Mar	0.6784	0.440	13.56	6.50×10^{-20}	40.0	−2.198	795.4	3.064

- Significant electrostatic acceleration in April 2011 and March 2013 flares, E/B~2-3.
- The sigma parameter, σ<1, shows that model is consistent with MHD physics.
- This process efficiently converts Poynting flux into relativistic particle energy, and then into gamma-rays.



Energy [eV]
Crab Nebula
SYNC
SSC
BREMS
IC-CMB
IC-FIR
IC-NIR/OPT
Torres et al. (2014)
$\nu F_\nu(\nu)$ [erg s^{-1} cm^{-2}]
Frequency [Hz]