Gamma-ray emission from Crab pulsar and the nebula: paradigm shifts?

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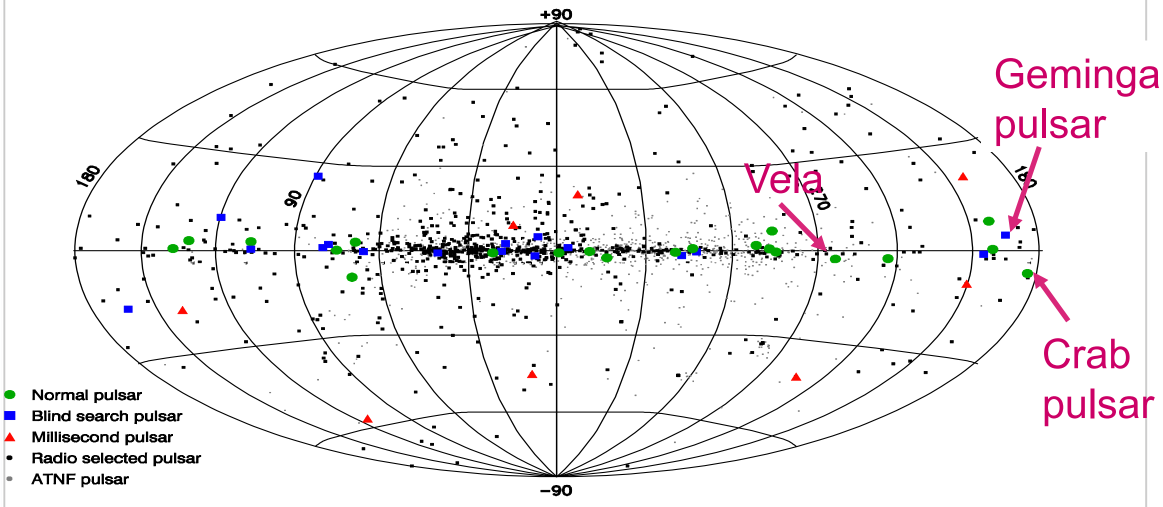
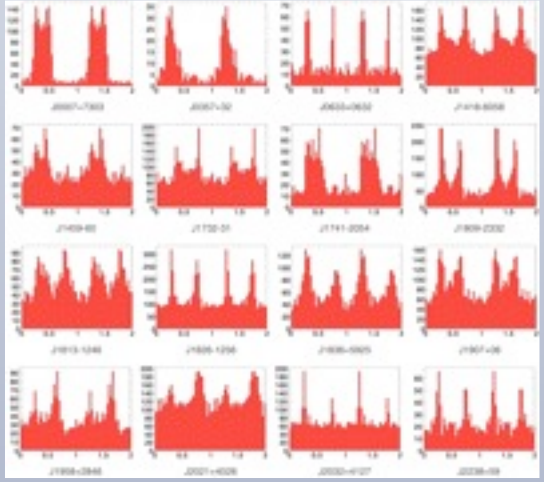
1. Gamma-ray emission of pulsars

Lively time in high energy astrophysics and pulsar astrophysics

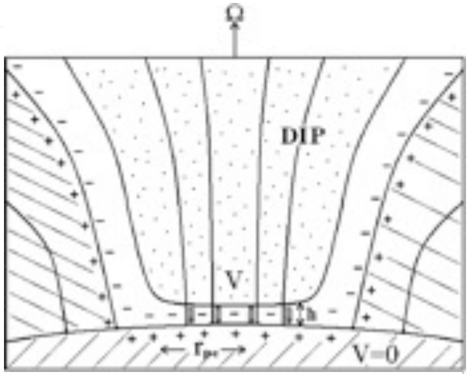
- *Fermi*: *LAT* has detected > 100 pulsars above 100 MeV



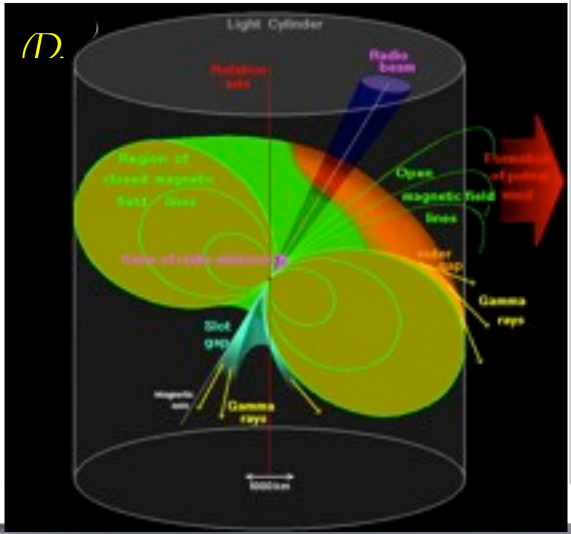


Models of pulsar gamma-ray emission

- Polar caps (Arons, Harding, Daugherty +)
  - well defined physics
  - does not fit the profiles
  - super-exponential spectral cut-off - not observed
  - **excluded**



- Slot/outer gaps (Ruderman, Cheng, Romani +)
  - messy physics
  - good geometrical fits
    - vacuum dipole (Romani +)
    - force-free models (Spitkovsky)
    - caustics: dipole + sweep-back + magnetospheric currents + abberation + time of flight



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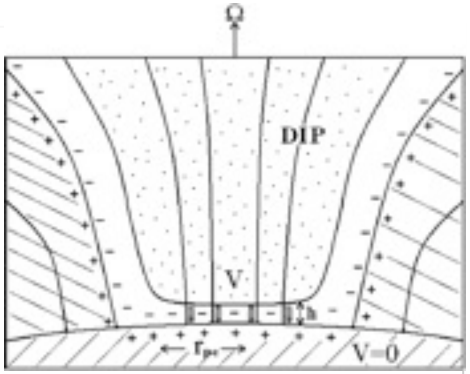

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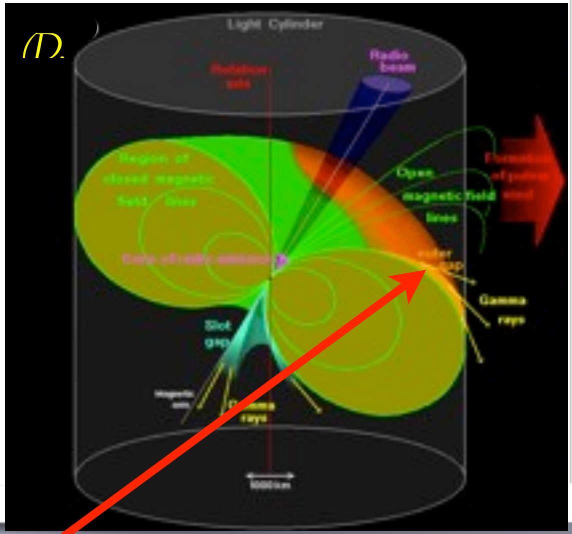
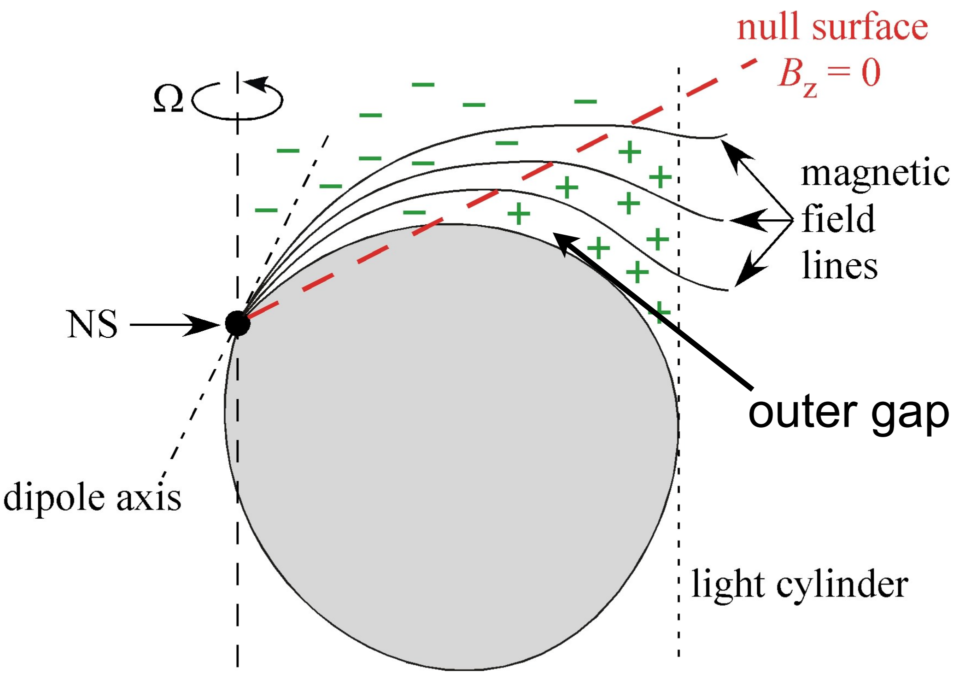
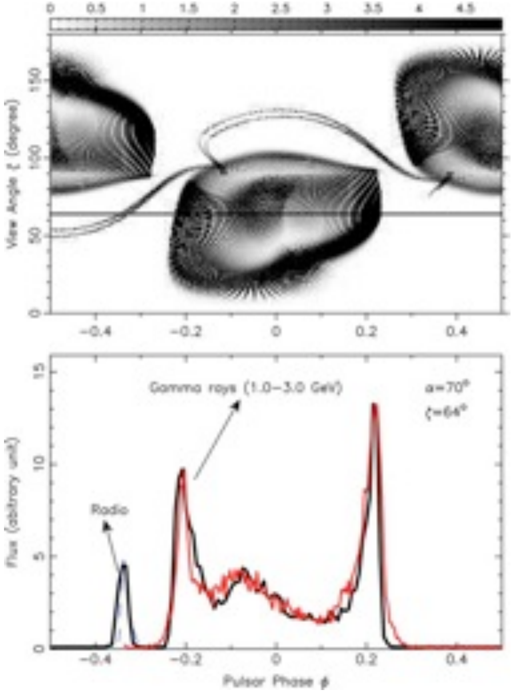


production of gamma-rays
(Cheng & Ruderman 1986)

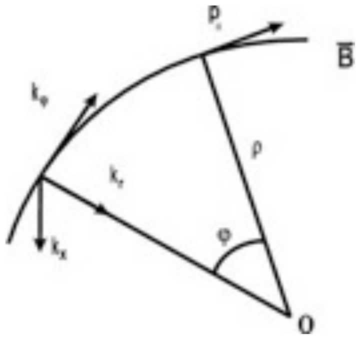
Outer gap models: geometrical - good fits

- Rotation induces charge density in the magnetosphere
- null line: outer gap
- $E_{||}$ accelerates particles which emit





Emit what?

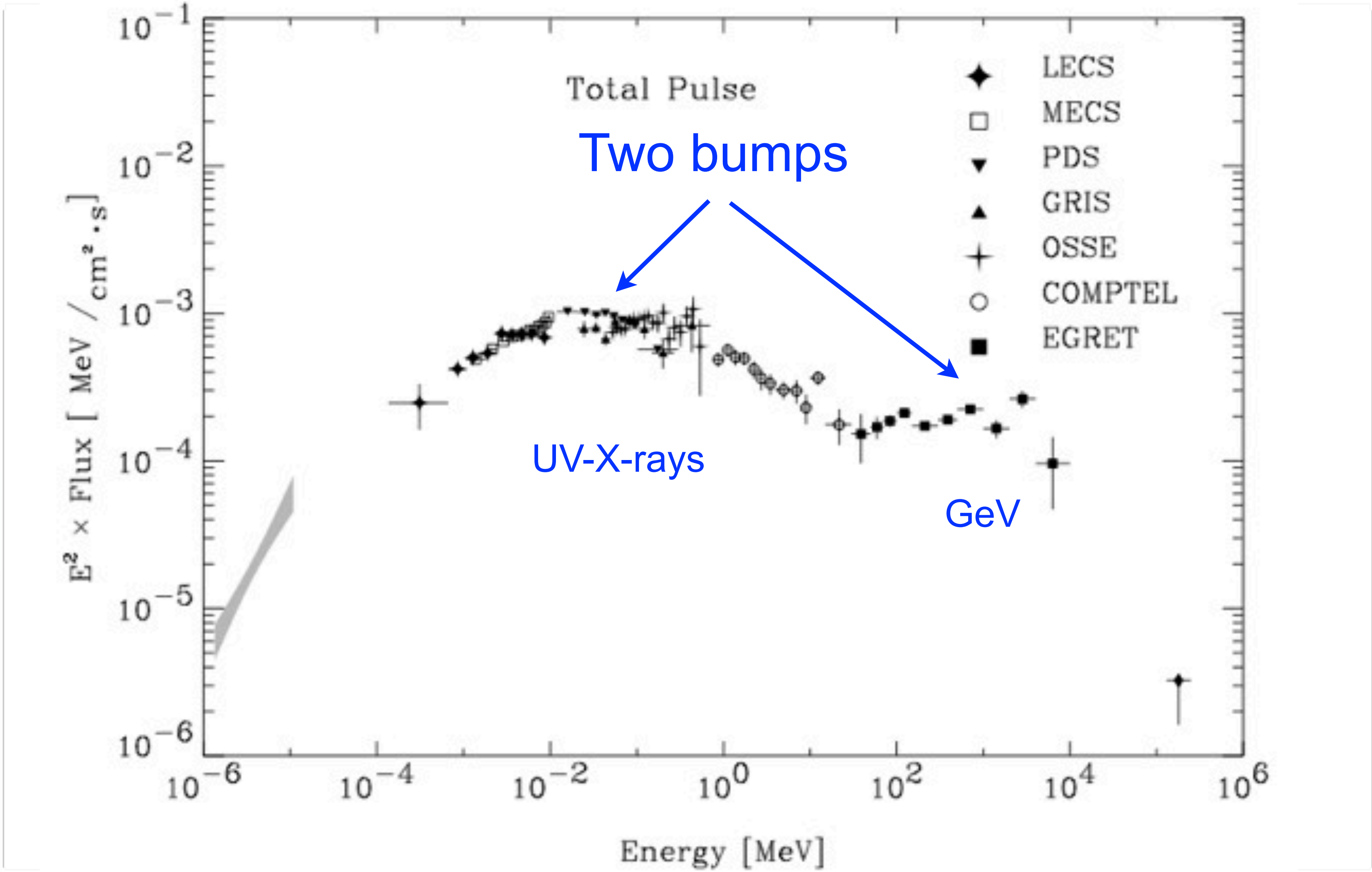


- Curvature emission (Chen & Ruderman 1986)

$$\epsilon_{ph} = \frac{\hbar\gamma^3 c}{R_C}$$

- Hard to solve the full electrodynamic picture:
- $E_{||}$ accelerates particles, produce pairs and currents, pairs screen $E_{||}$, currents distort B-field, changing $E_{||}$, non-local radiative transfer.
- Typically $E_{||} \sim 10^{-2}$-10^{-1} B (Hirotani)
- **Above the break the spectrum must be exponentially suppressed**

Crab pulsar spectrum: two bumps

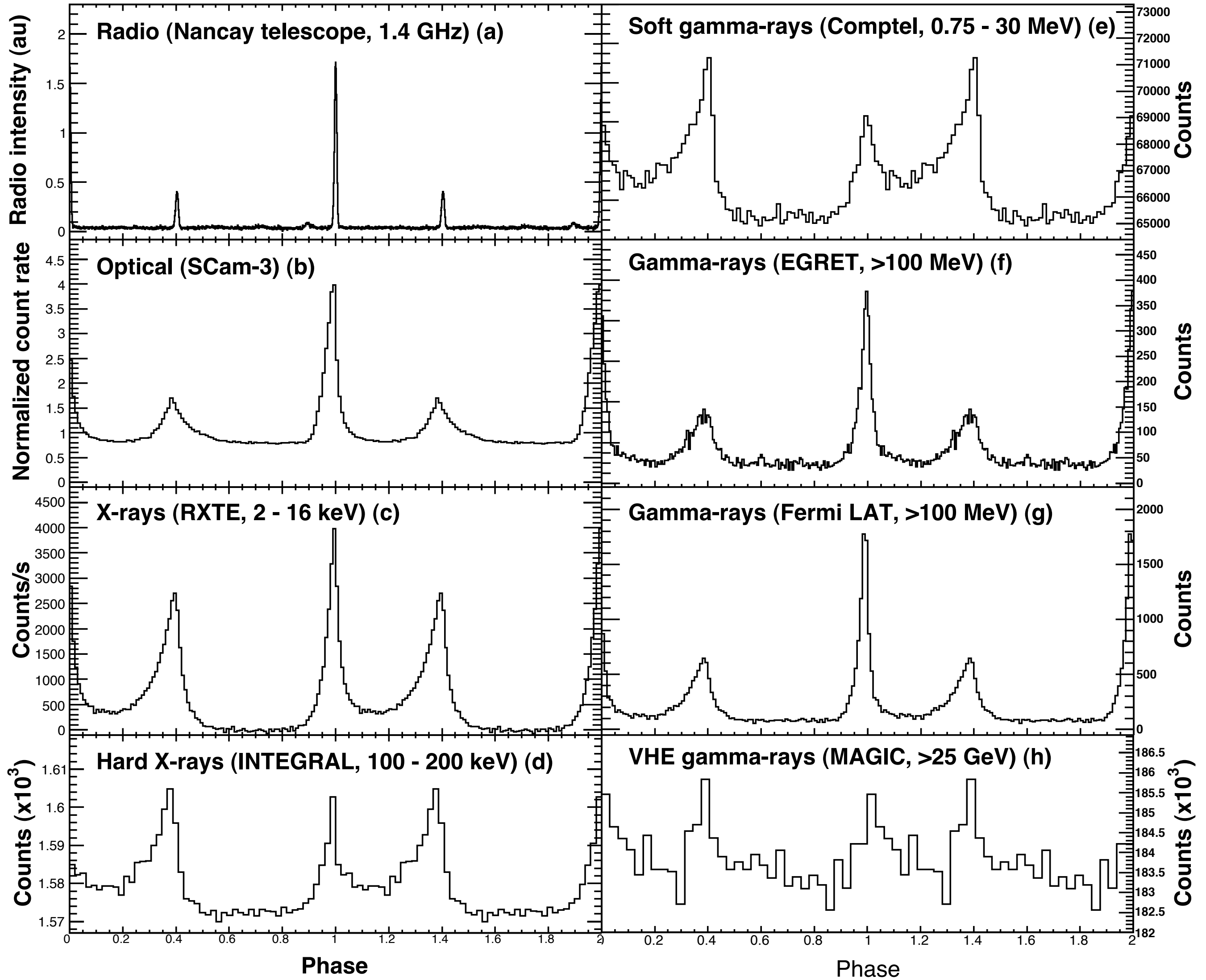


Two bumps

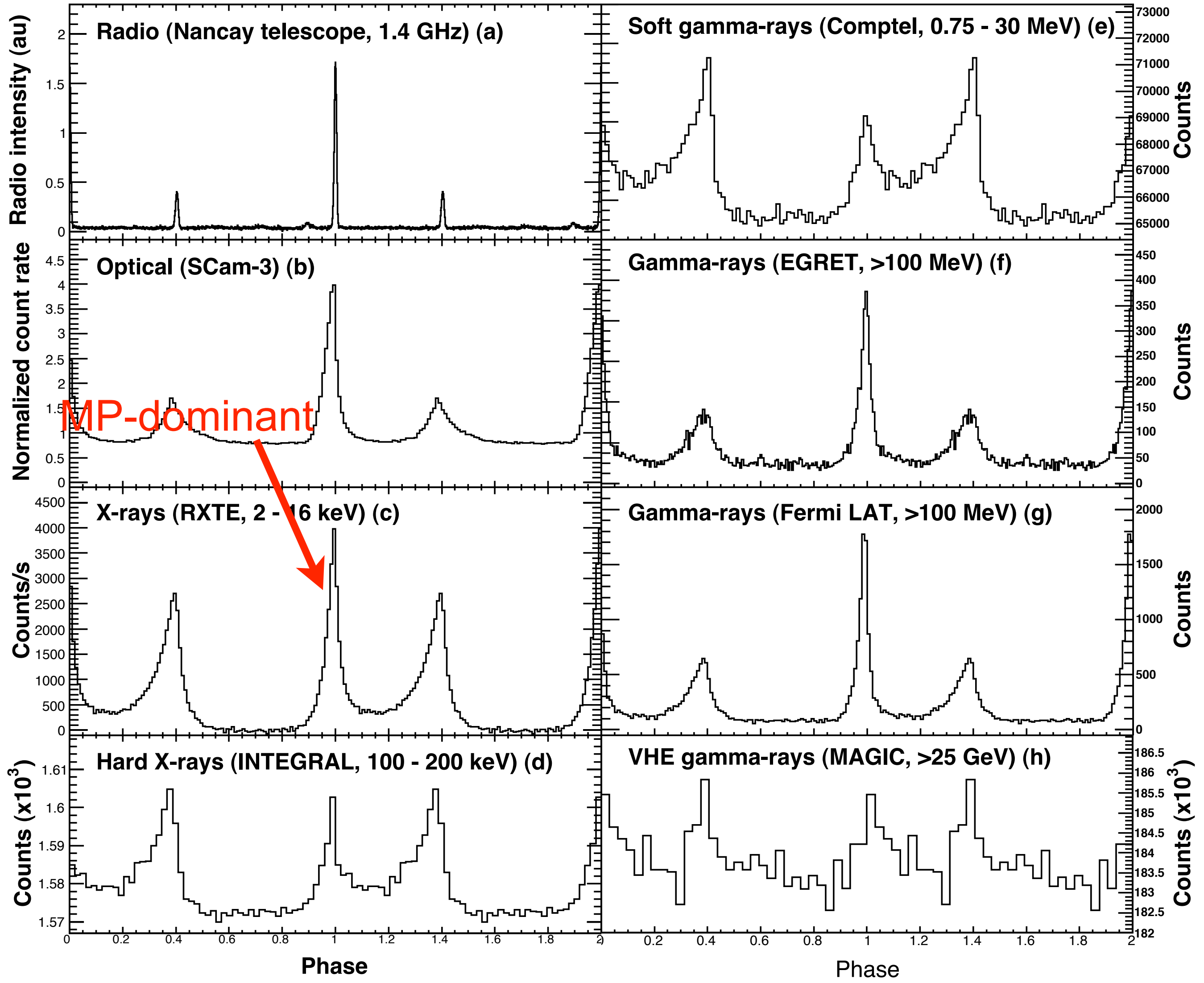
UV-X-rays

GeV

Crab profiles

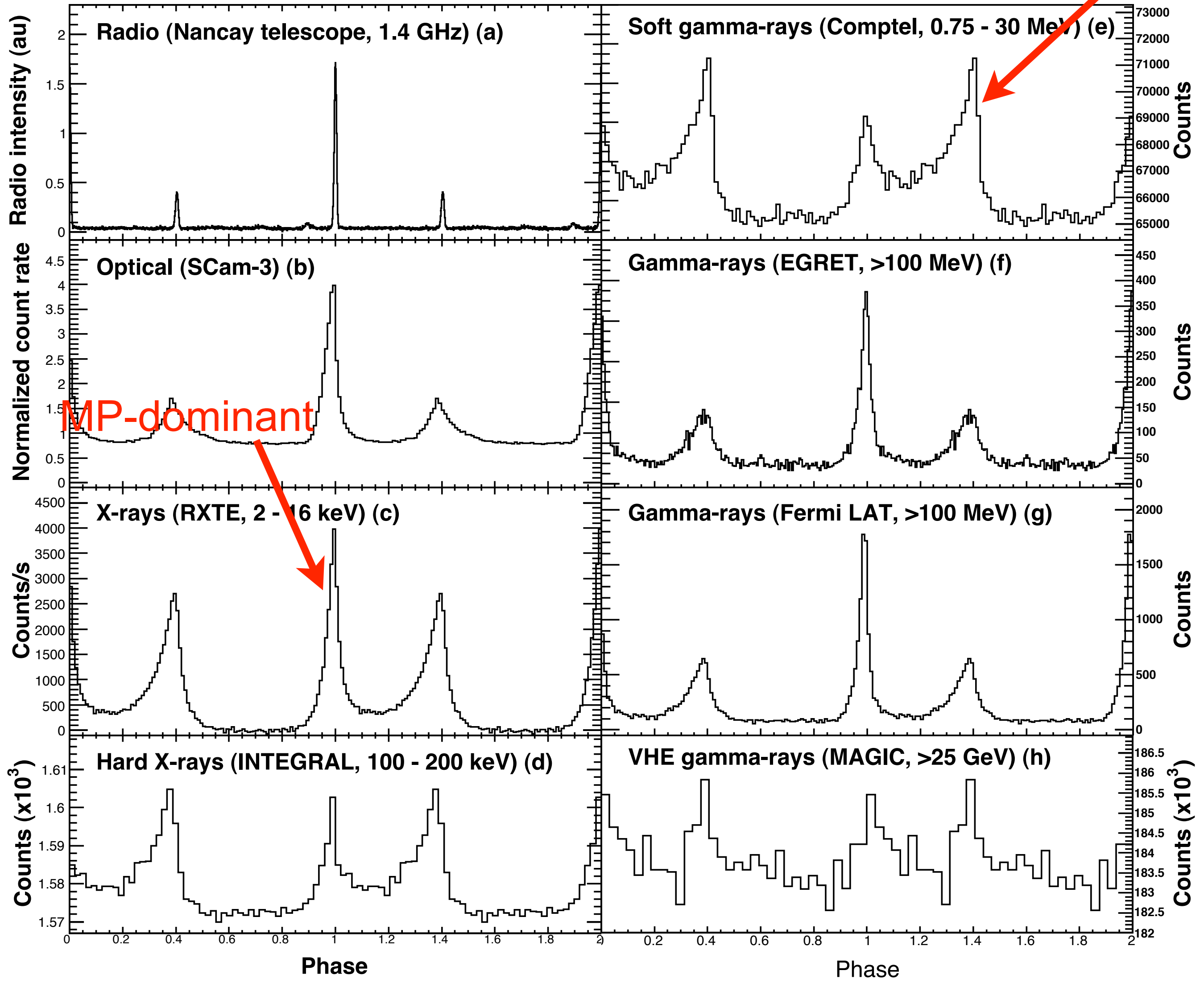


Crab profiles



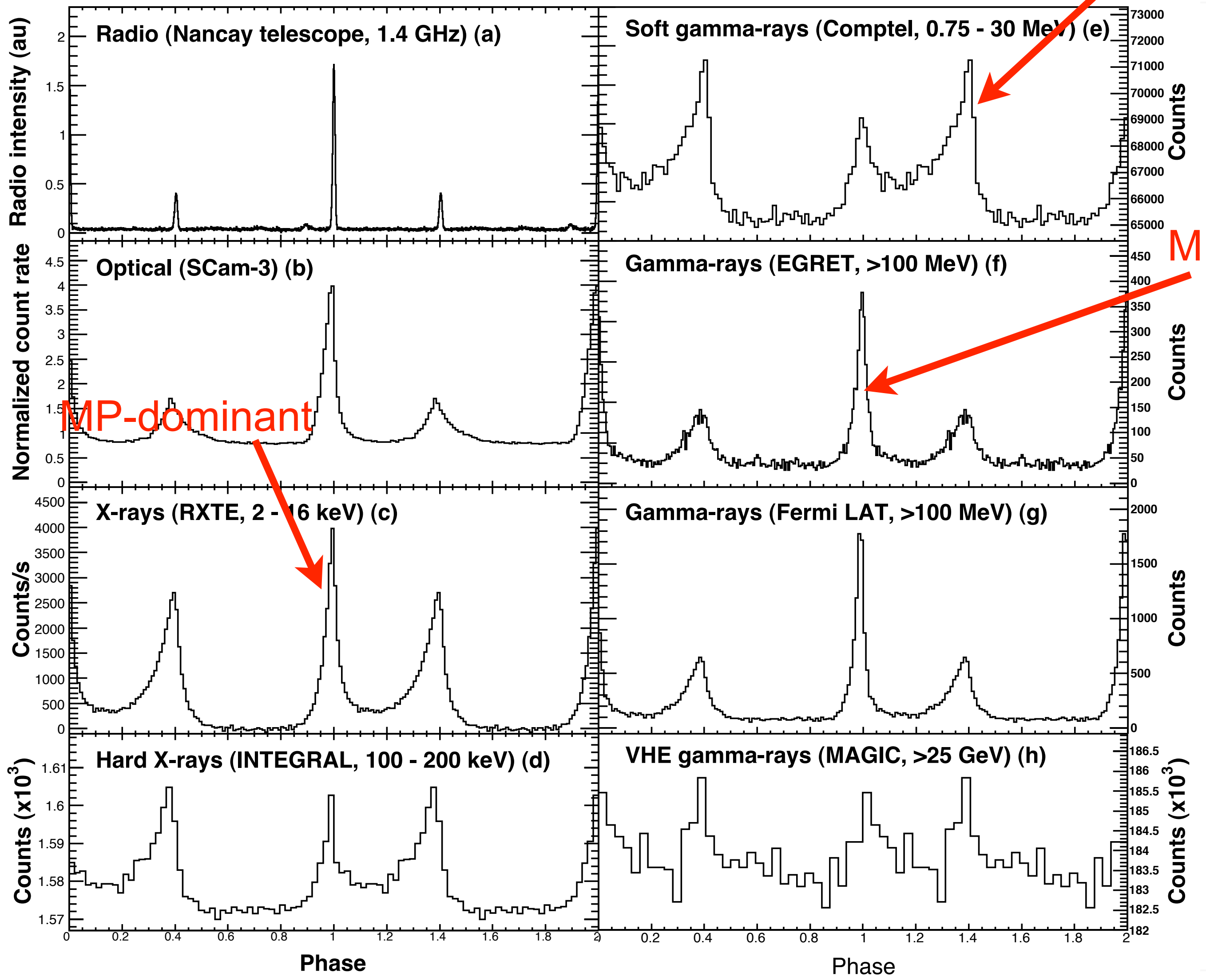
Crab profiles

IP-dominant



MP-dominant

Crab profiles



IP-dominant

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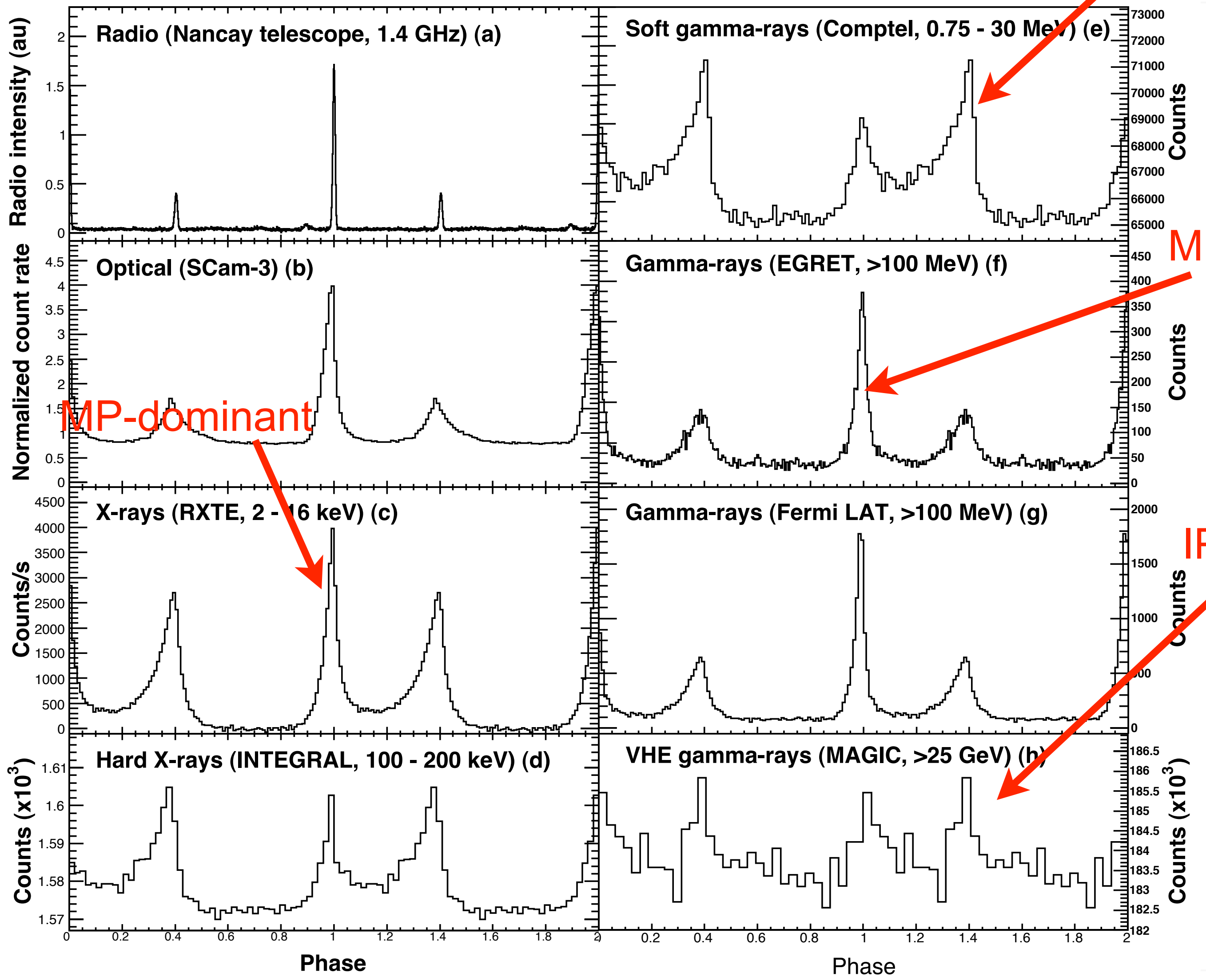
Crab profiles



IP-dominant

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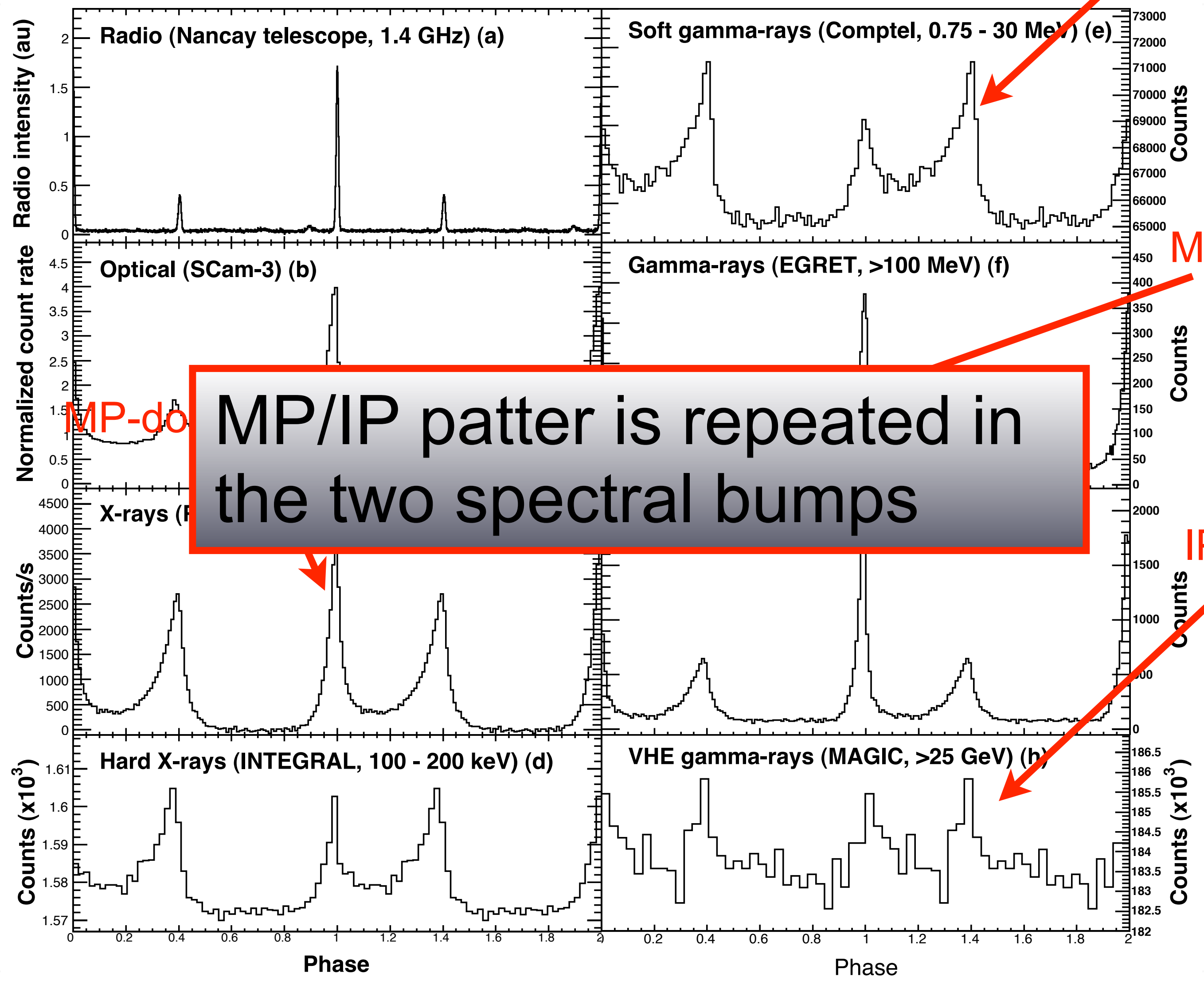
Crab profiles



IP-dominant

MP-dominant

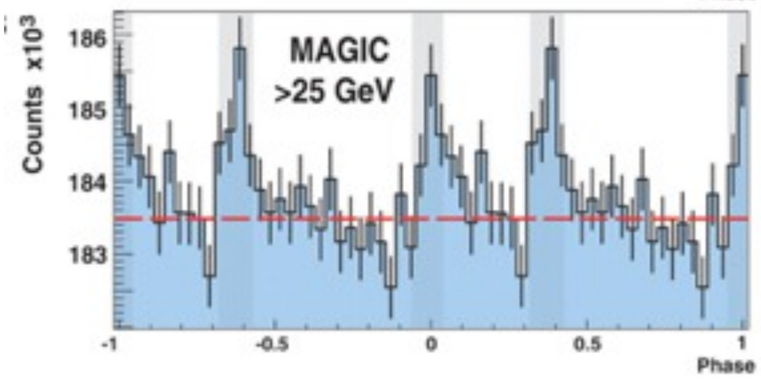
MP-do

IP-dominant

MP/IP patter is repeated in the two spectral bumps

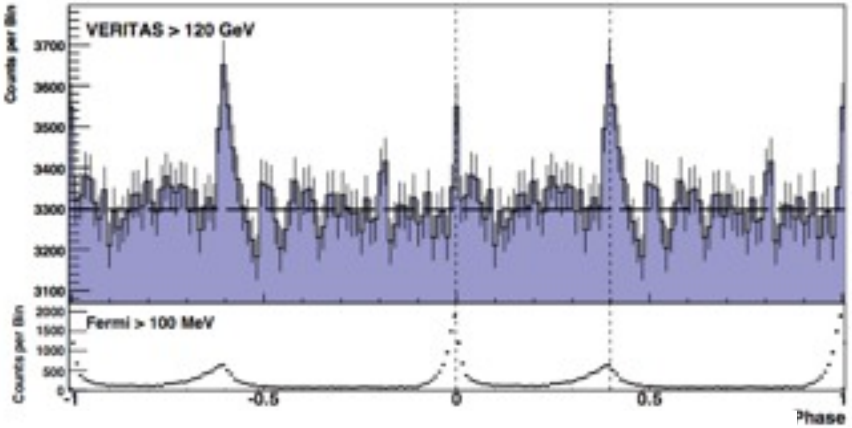
New results

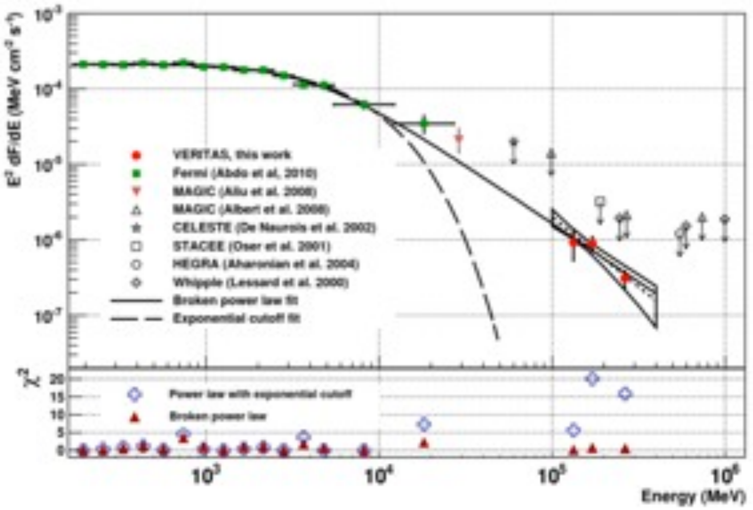
- MAGIC sees Crab at ~ 25 GeV



- With indication of non-exponential cut-off (2011)

- VERITAS sees Crab at > 150 GeV!





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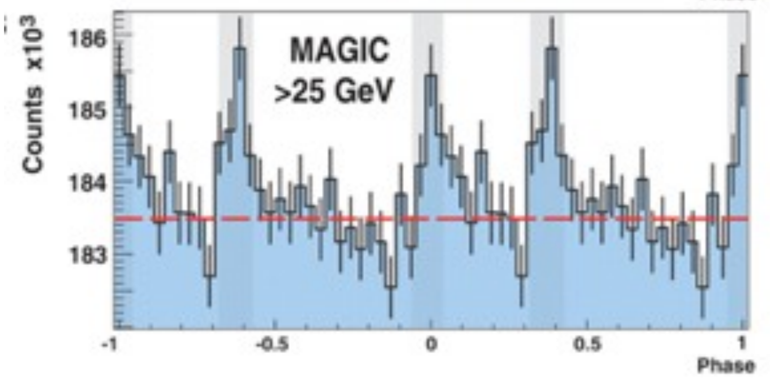

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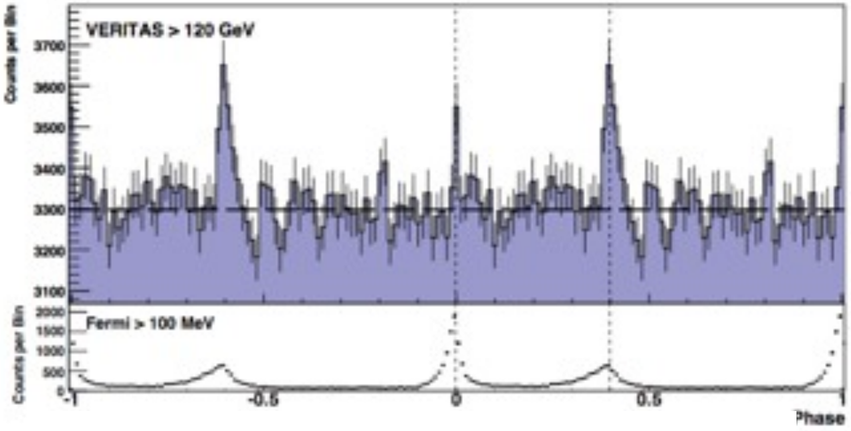
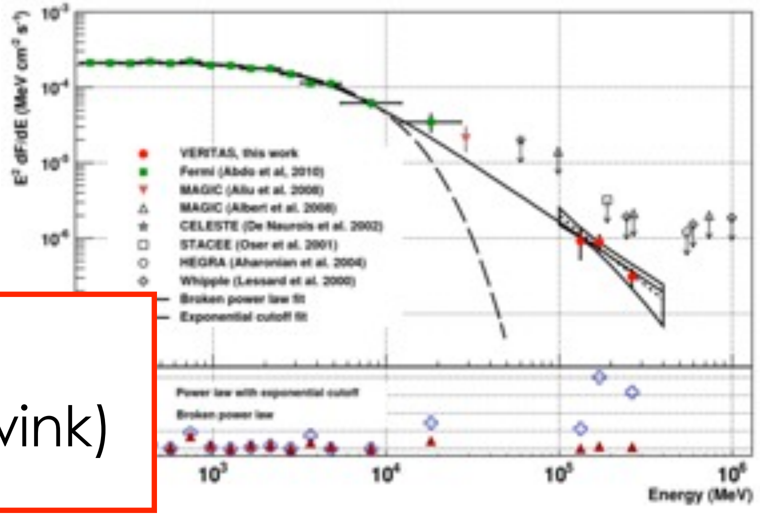




- Cut-off is non-exponential!
- IP is brighter than MP (wink, wink)

Curvature emission near light cylinder is excluded

- Astrophysical E-fields < B-field
- Equate acceleration by $E_{\|} = \eta B$ to curvature losses in $R_C = \xi R_{LC}$

Maximum possible energy break due to curvature emission

$$\epsilon_{br} = (3\pi)^{7/4} \frac{\hbar}{(ce)^{3/4}} \eta^{3/4} \sqrt{\xi} \frac{B_{NS}^{3/4} R_{NS}^{9/4}}{P^{7/4}} \left(\frac{r_{em}}{R_{LC}} \right)^{-9/4}$$

For Crab, assuming E=B

$\approx$ 150 GeV

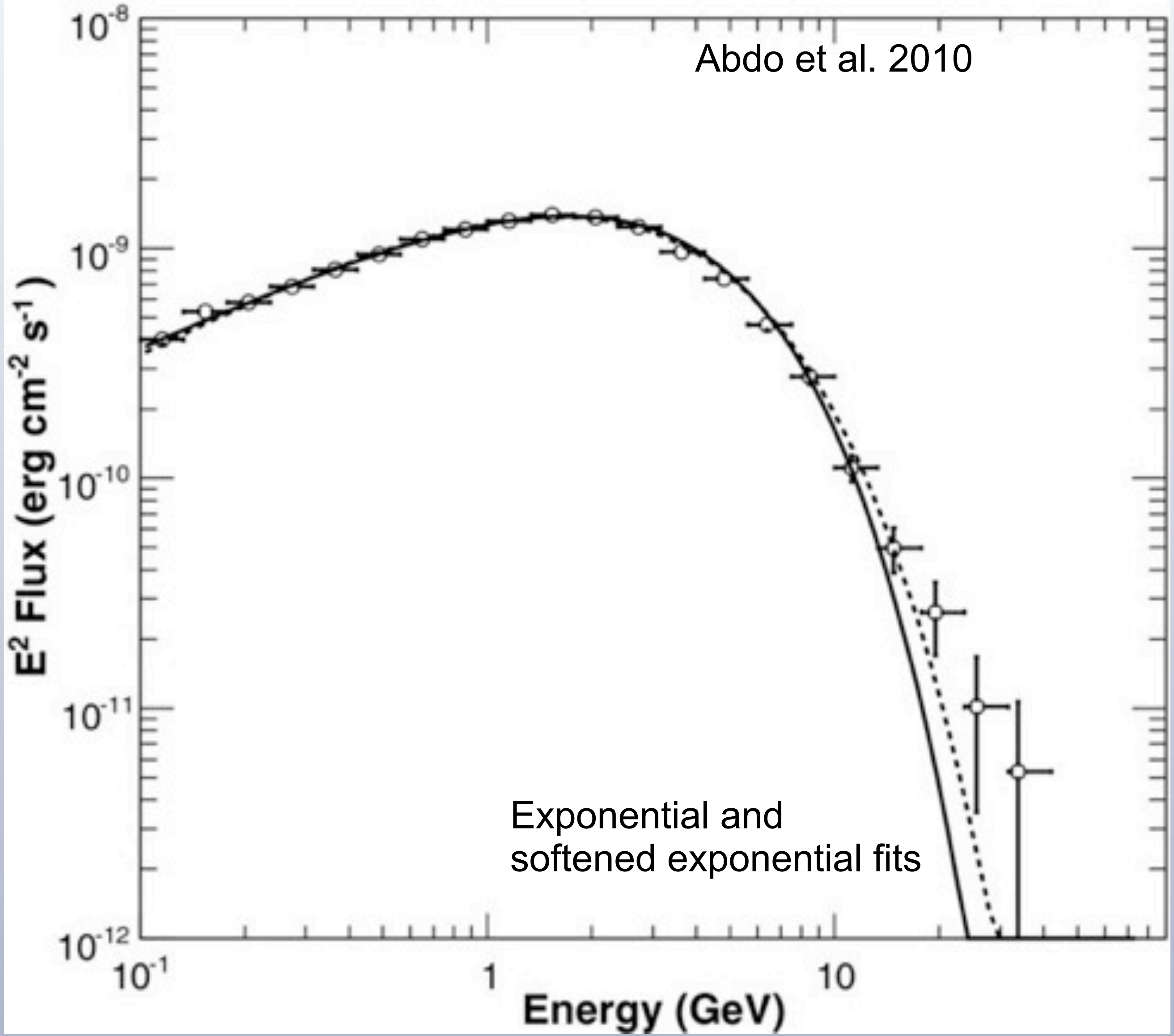
- Detection of Crab above 150 GeV (with non-exponential cut-off) exclude curvature emission from near the light cylinder (Lyutikov et al. 2011)
- E.g. Bai & Spitkovsky: emission within 5% of LC

Implications of Crab detection by VERITAS:

- Spectral break in Crab is not due to curvature emission of the maximal energy of particles
- Alternative possibility: IC scattering
- Break due to the details of particle distribution and scattering cross-section (in the KN regime)

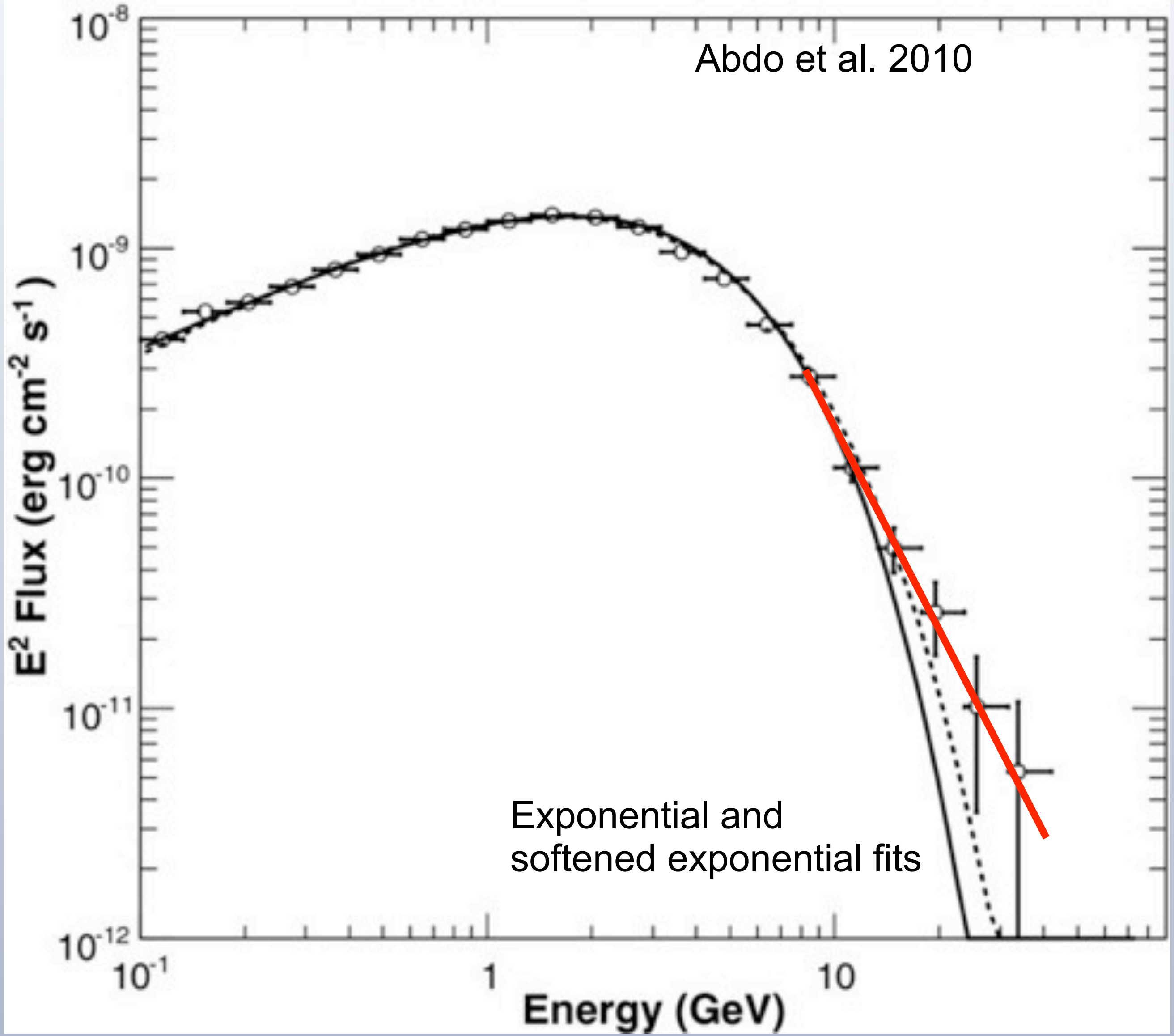
- Is Crab special (e.g. high level of soft photons)?
- What about other pulsars?
    - Vela
    - Geminga

Fermi spectrum of Geminga



Exponential and
softened exponential fits

Fermi spectrum of Geminga



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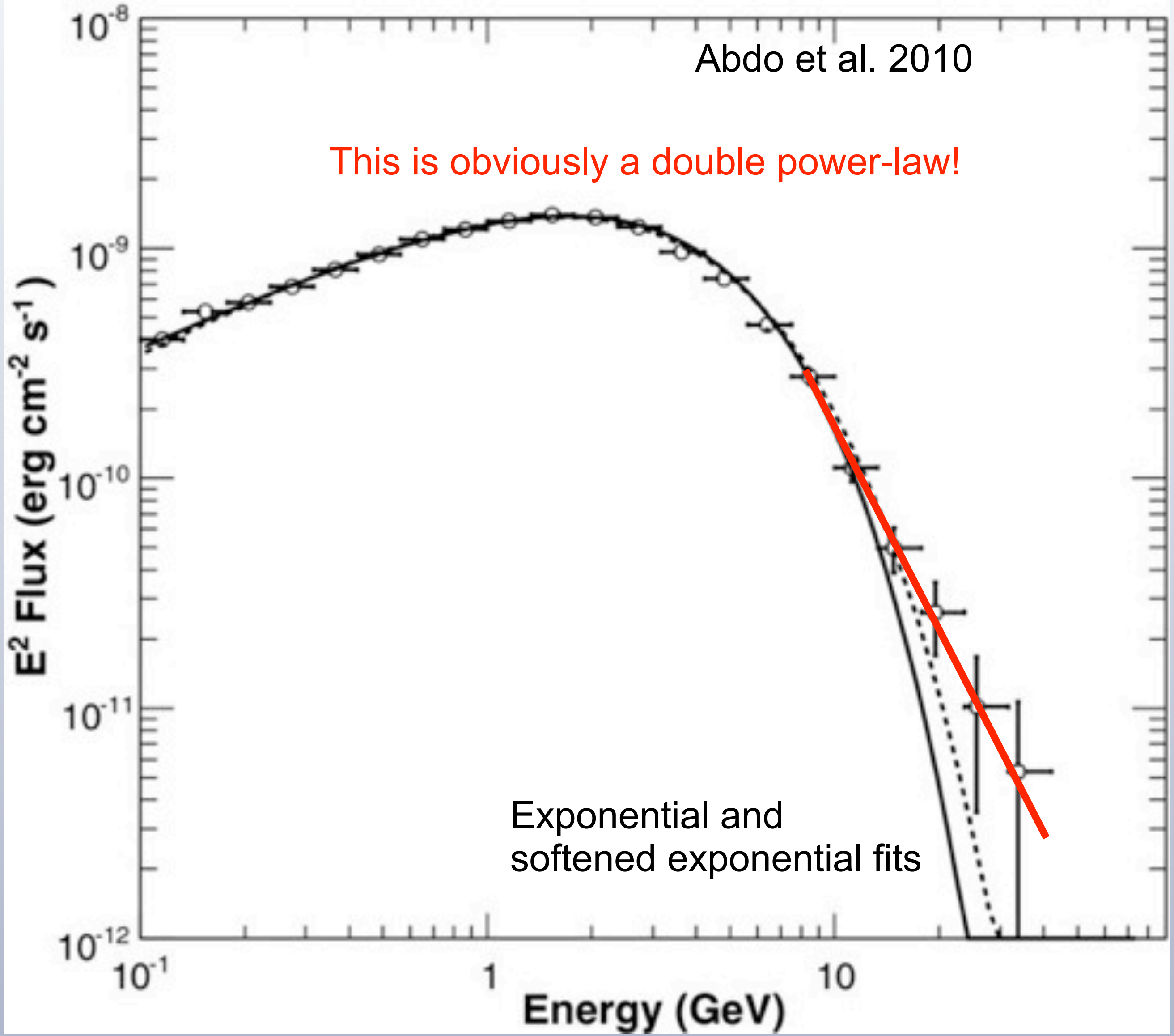
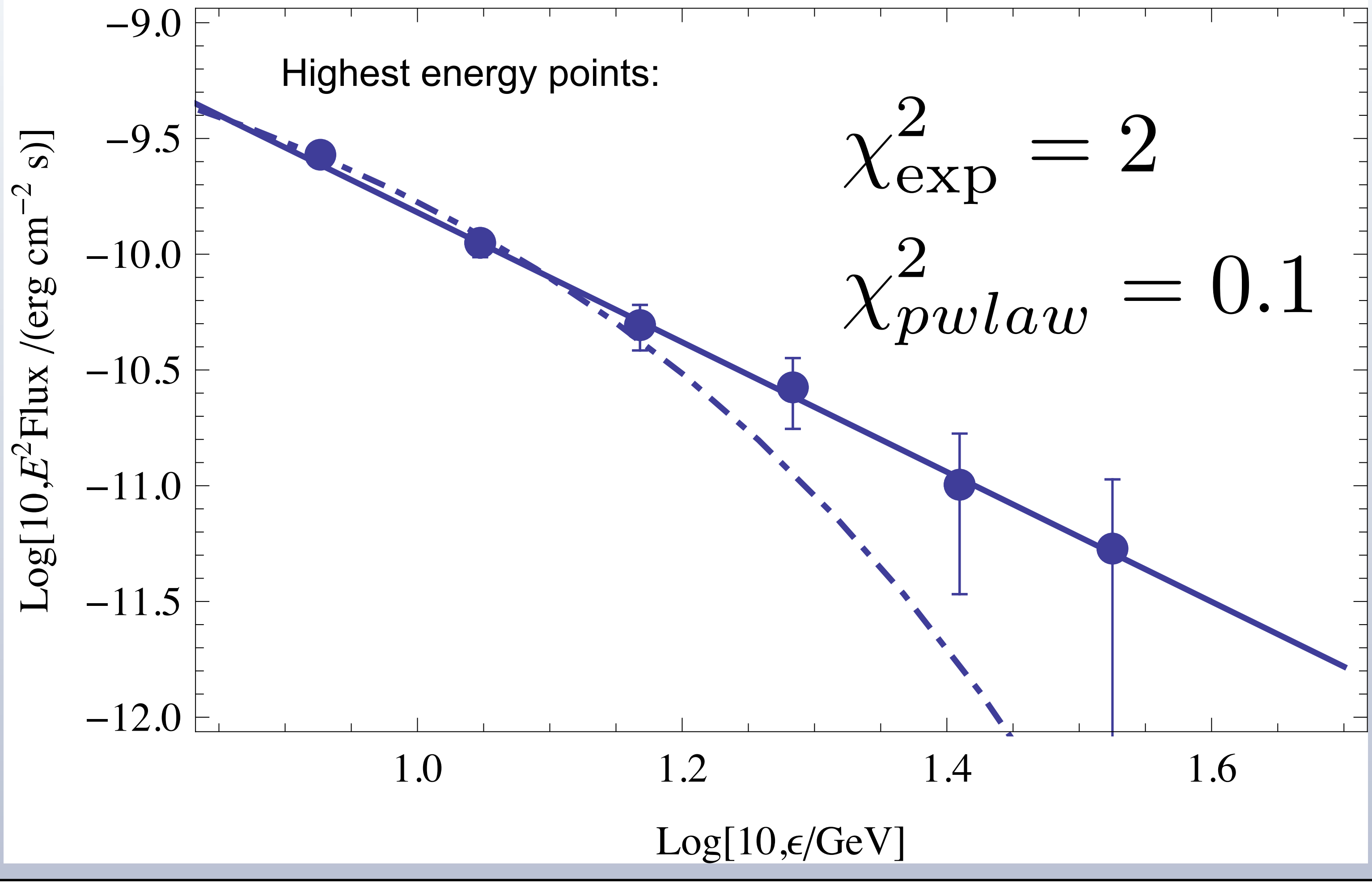


Abdo et al. 2010

This is obviously a double power-law!

Exponential and
softened exponential fits

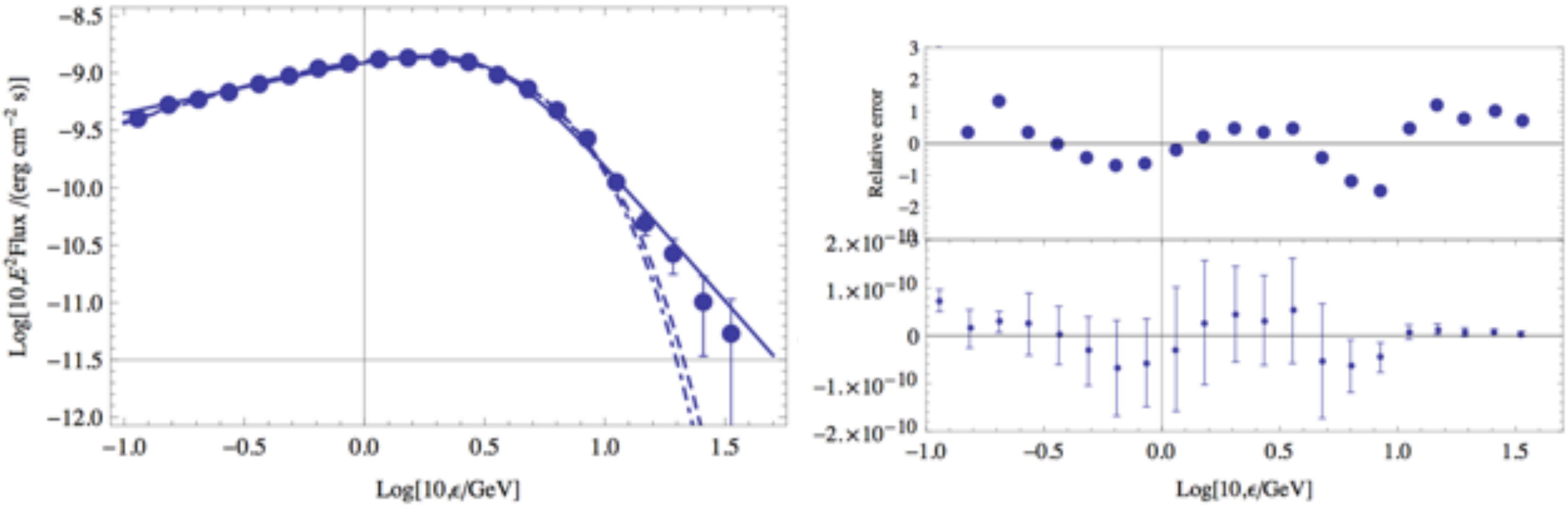
Geminga: fits



- The highest energy data points actually have the **smallest** error bars.
- Too broad energy bins?

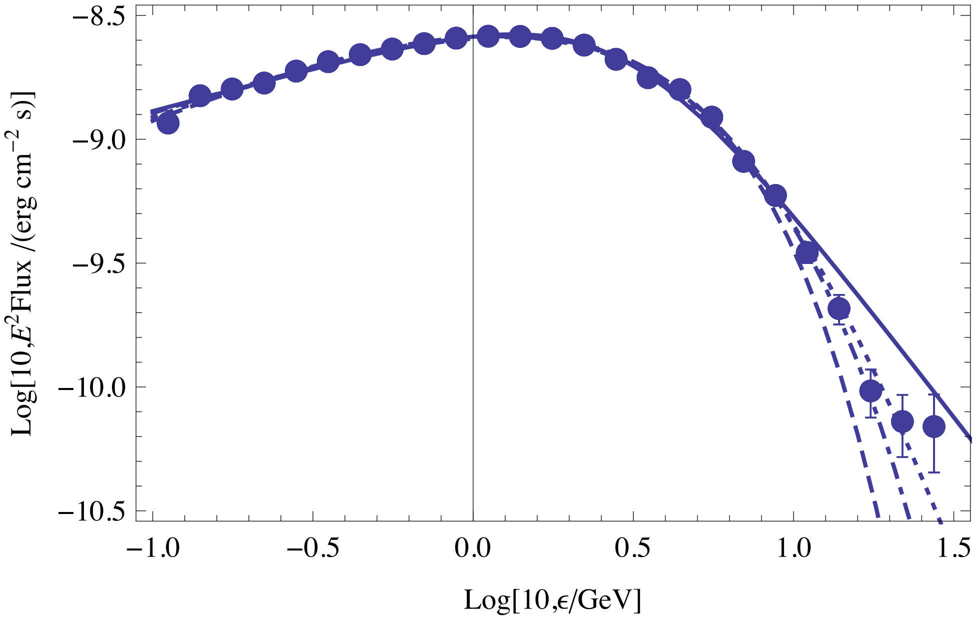
Geminga: broad band fits

errors χ^2 for double pwlaw



- The errors are not random
- **Most of the chi^2 is accumulated near the break energy due to the ARBITRARY parametrization of the spectral roll-off**
- Similar results for phase-resolved spectra

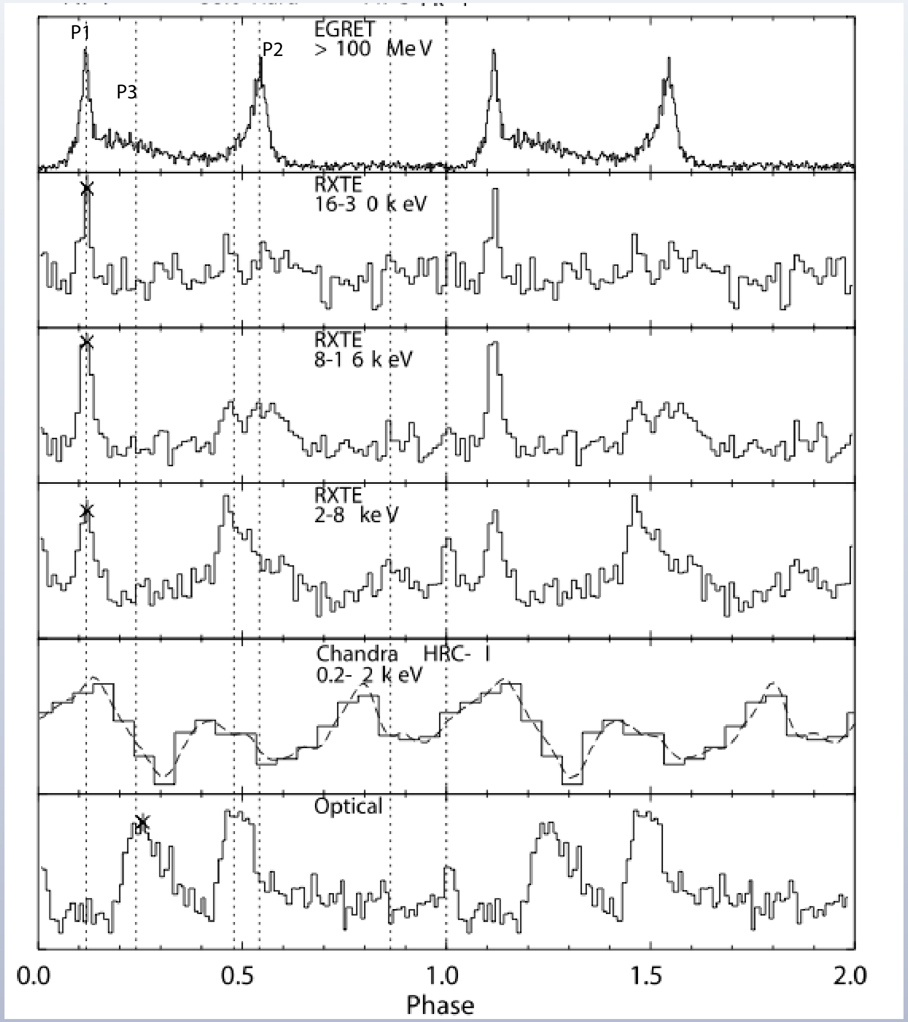
Vela



- Double power-law are as good as exp.
- Various parametrizations of roll-offs reduce chi^2

model	Fit function	α	β	ϵ_{br}	reduced χ^2	b	dof
a	$\left(\left(\frac{\epsilon}{\epsilon_{br}}\right)^{\alpha}+\left(\frac{\epsilon}{\epsilon_{br}}\right)^{-\beta}\right)^{-1}$	1.68	0.34	2.91	2.2	–	21
b	$\left(\left(\frac{\epsilon}{\epsilon_{br}}\right)+\left(\frac{\epsilon}{\epsilon_{br}}\right)^{-\beta}\right)^{-\alpha}$	4.11	0.11	8.8	1.3	–	21
c	$\epsilon^{\beta}e^{-\frac{\epsilon}{\epsilon_{br}}}$	–	.42	3.1	2.0	–	22
d	$\epsilon^{\beta}e^{-\left(\frac{\epsilon}{\epsilon_{br}}\right)^{b}}$	–	0.59	1.58	1.4	0.73	21

Vela profiles:



- All gamma-ray peaks have mirror images at lower energies
- No simple 1:1 correspondence: anisotropy and KN effects

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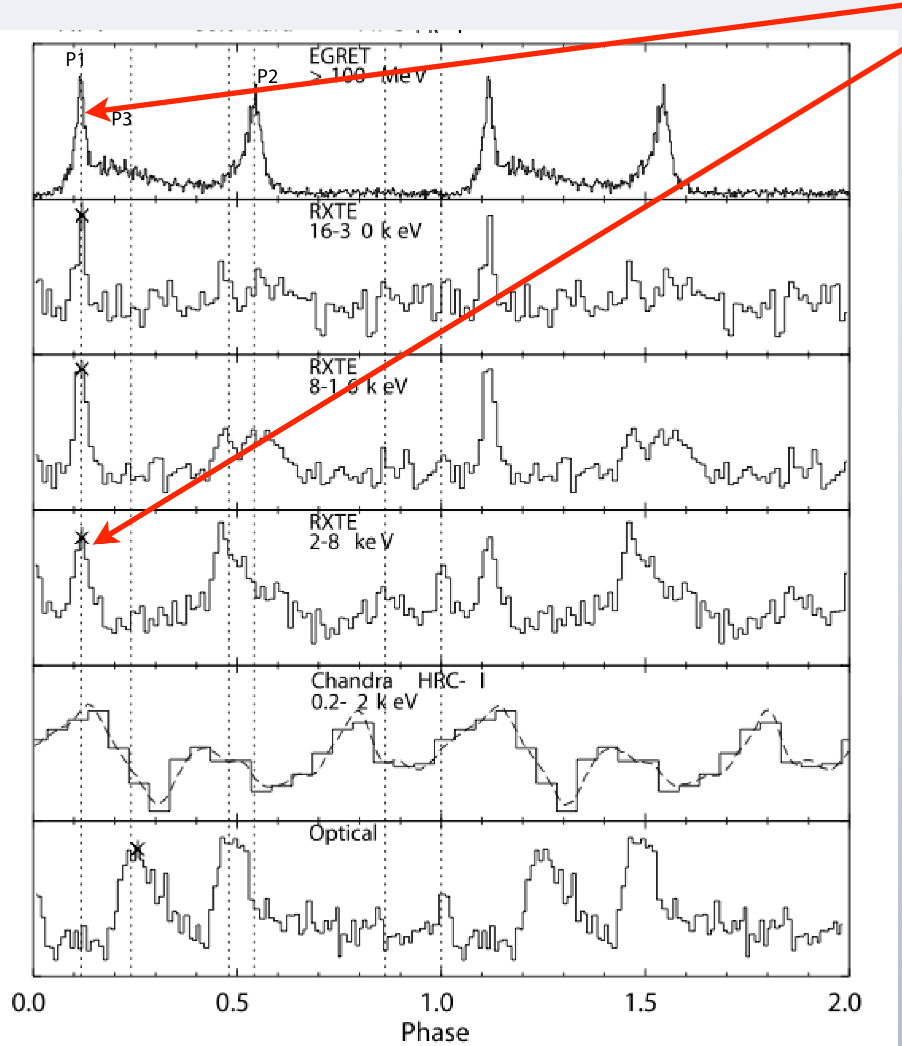

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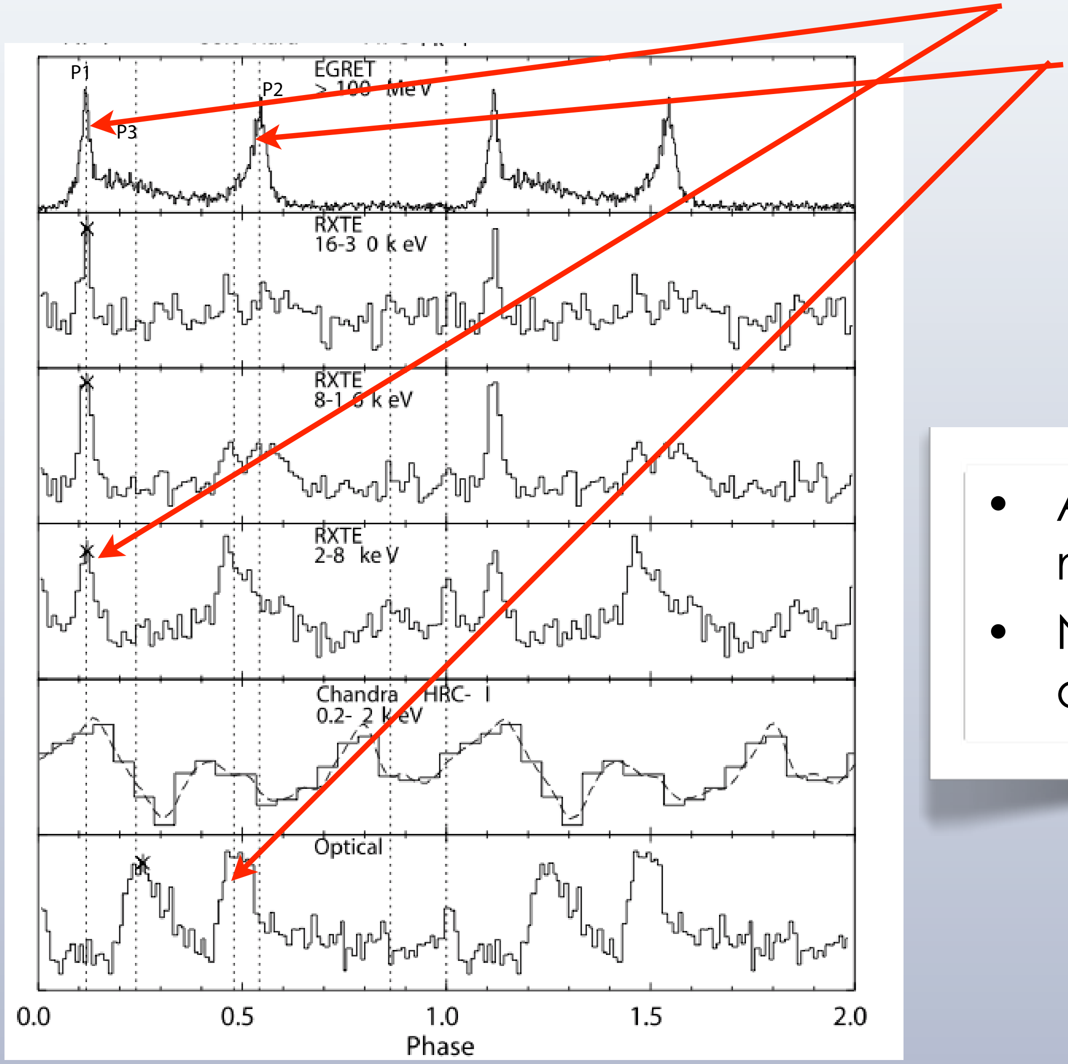

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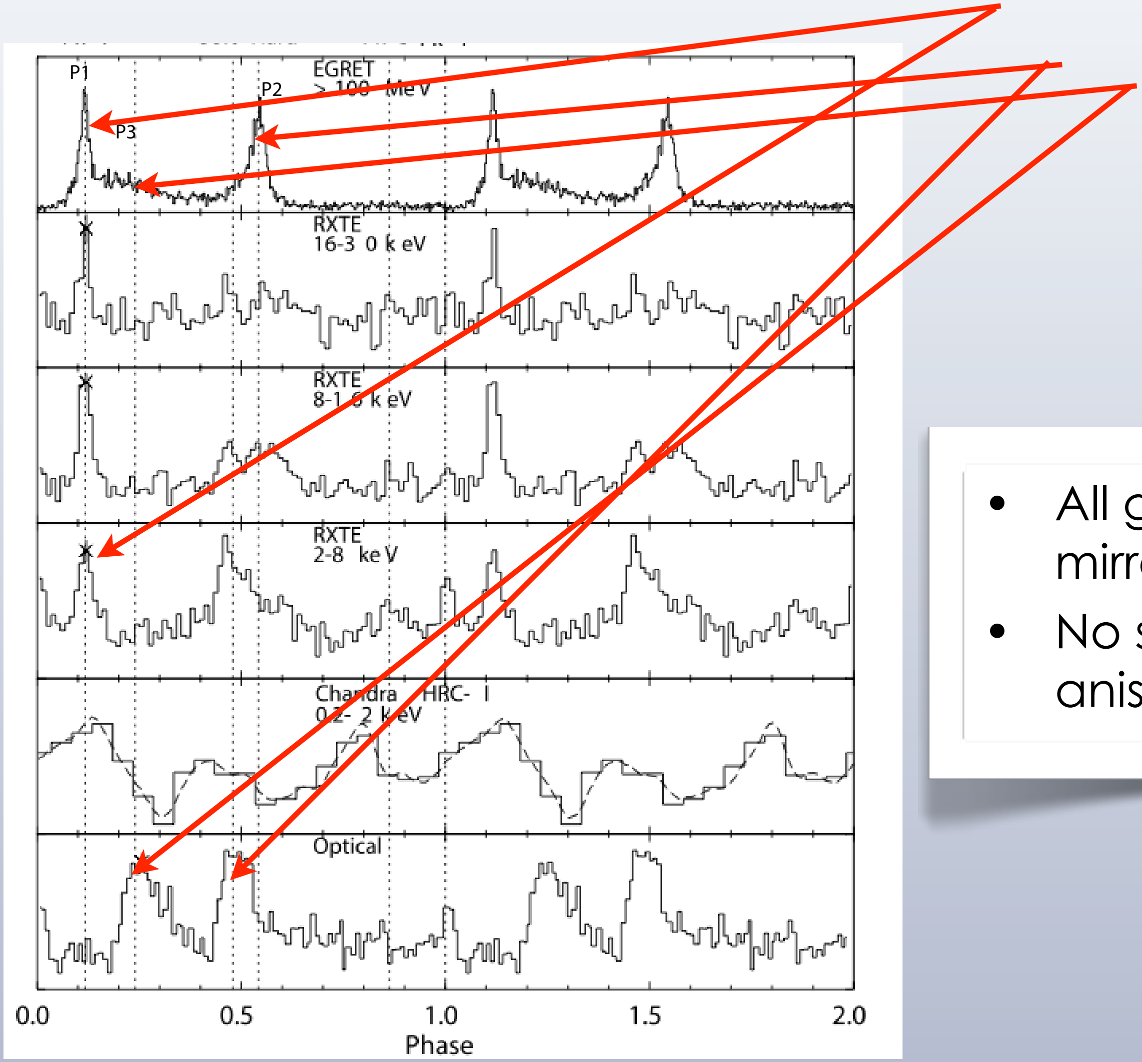

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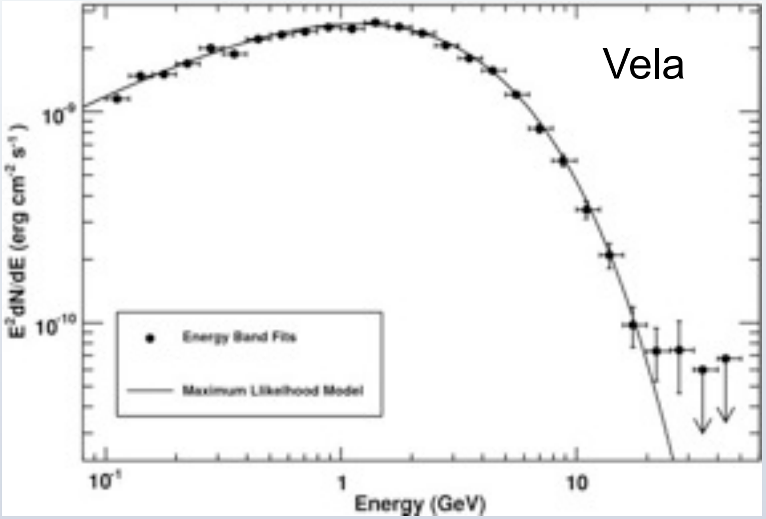
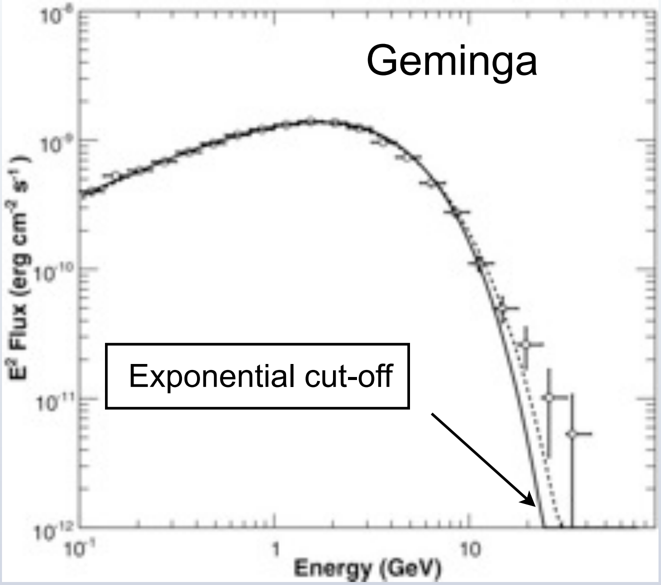
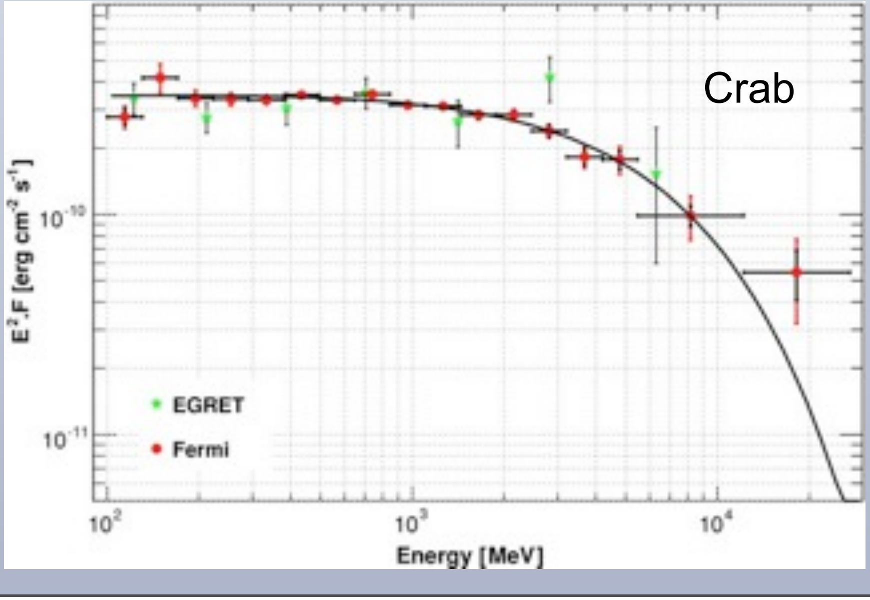
Looking back at Fermi spectra:





Exponential cut-off



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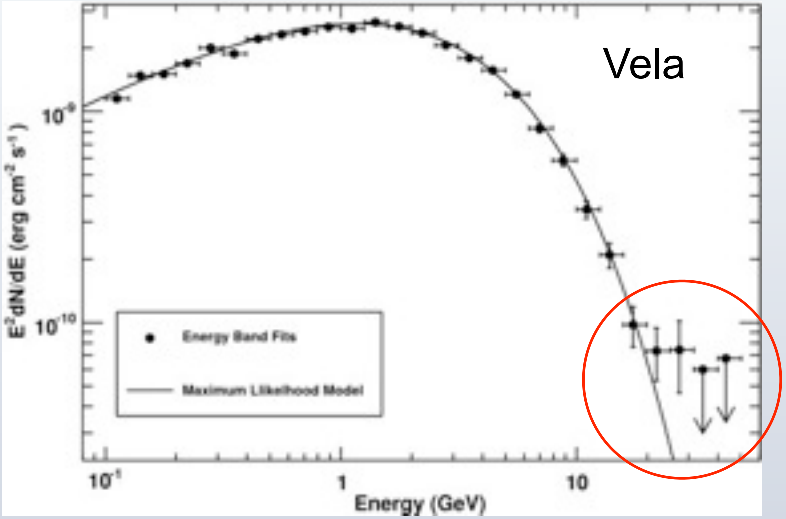

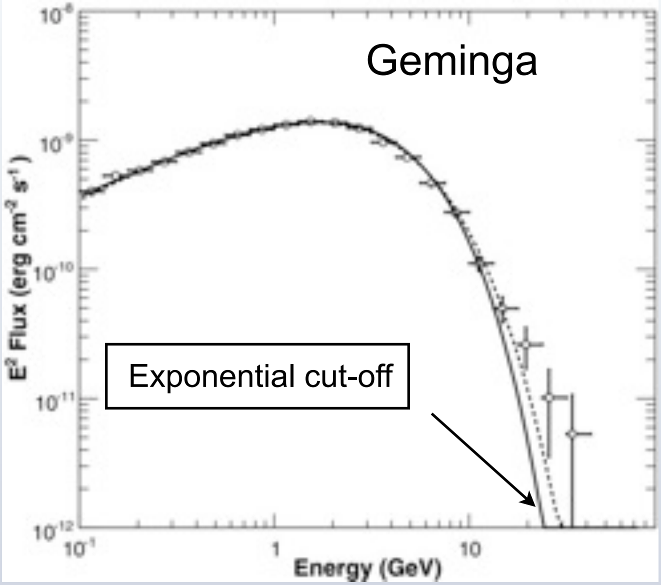

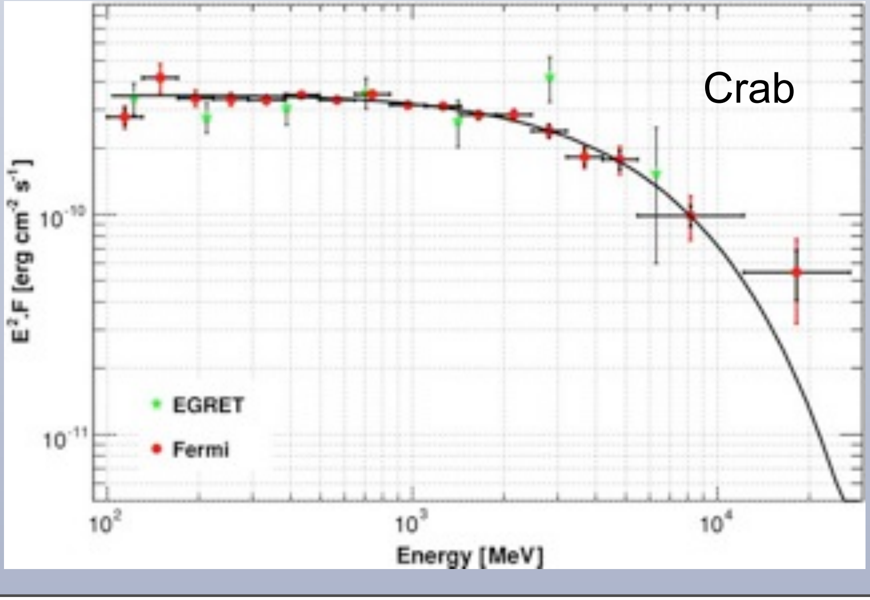

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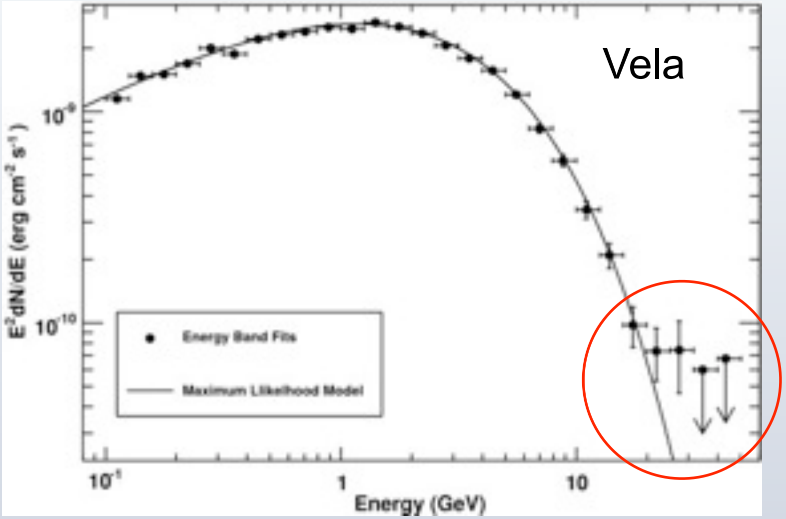

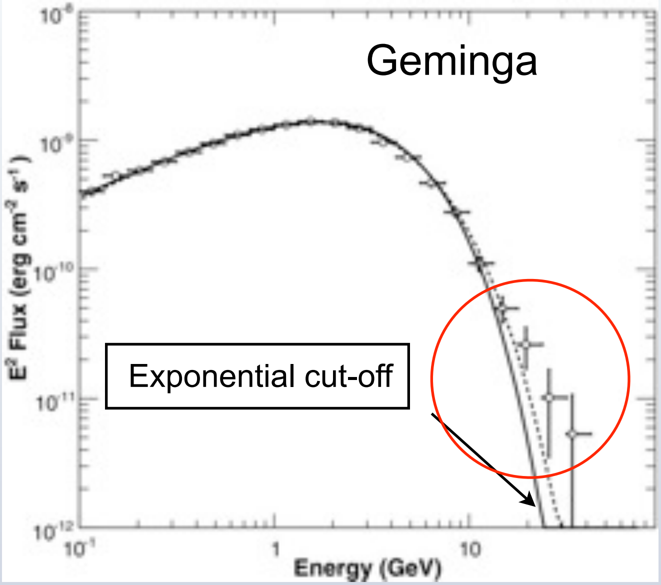

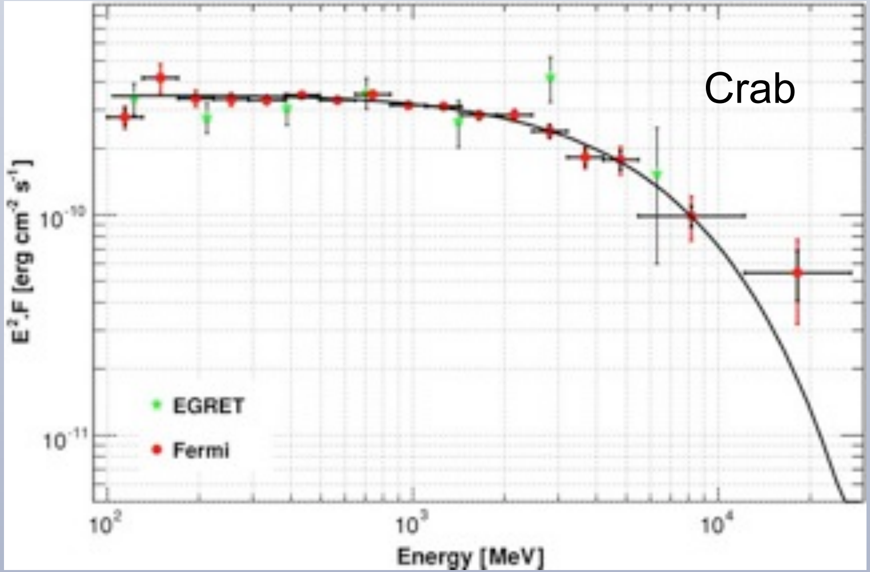

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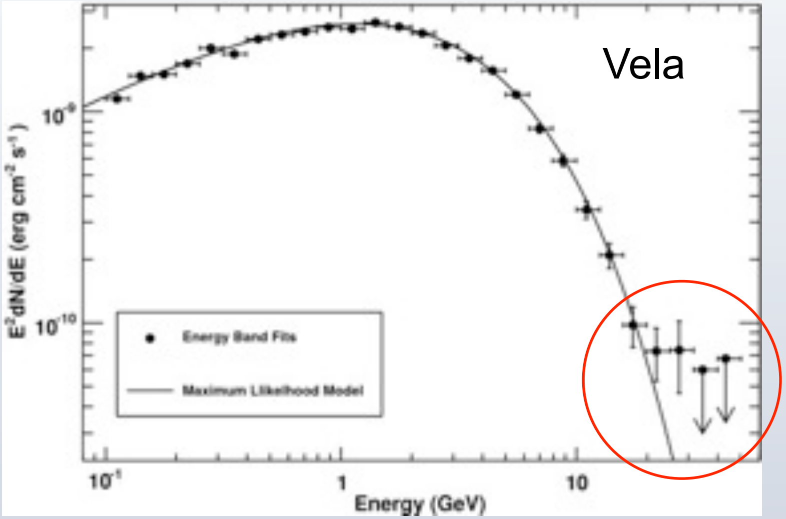
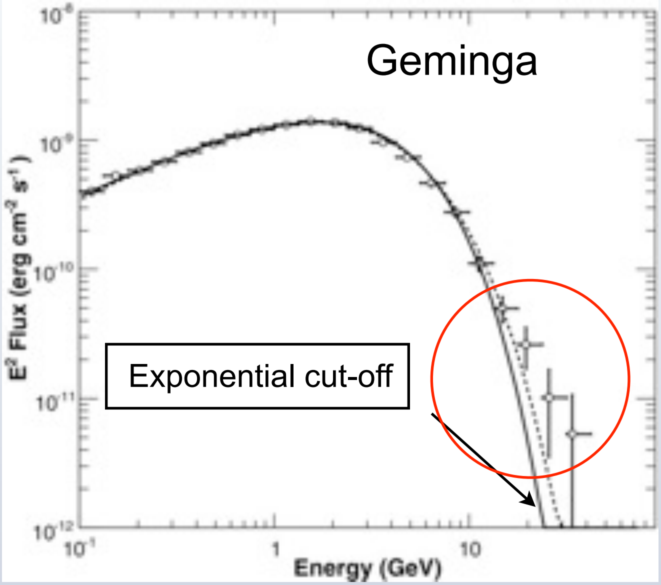
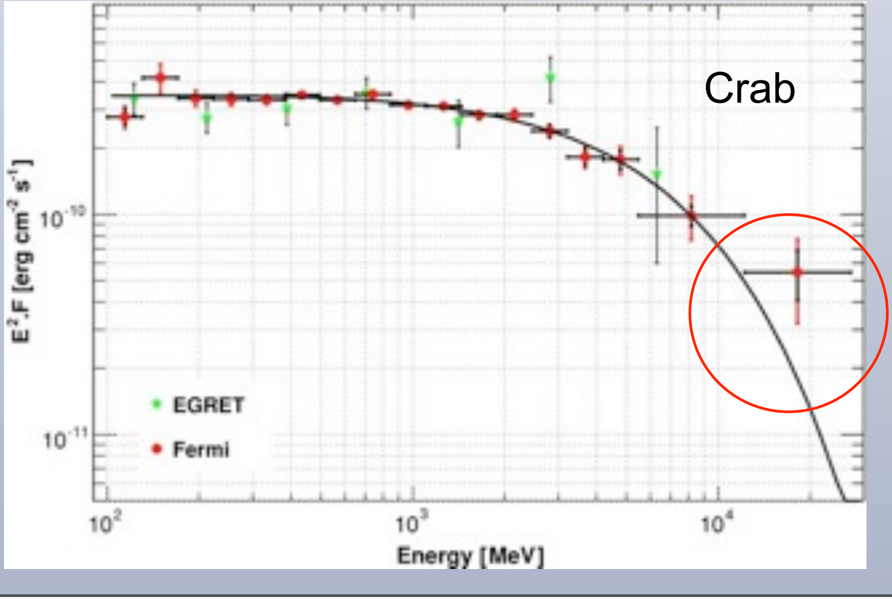


Vela



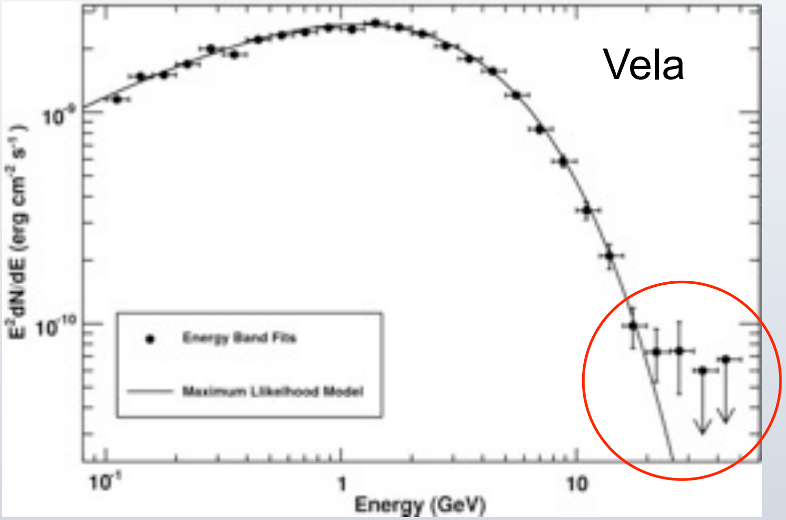
Geminga

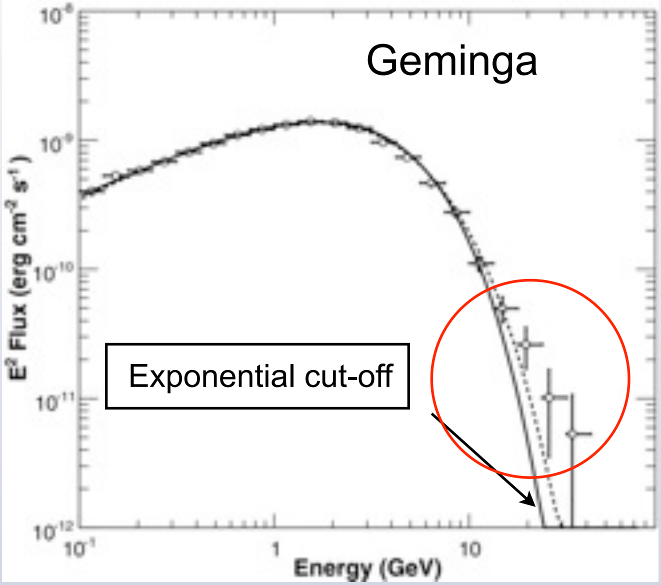
Exponential cut-off

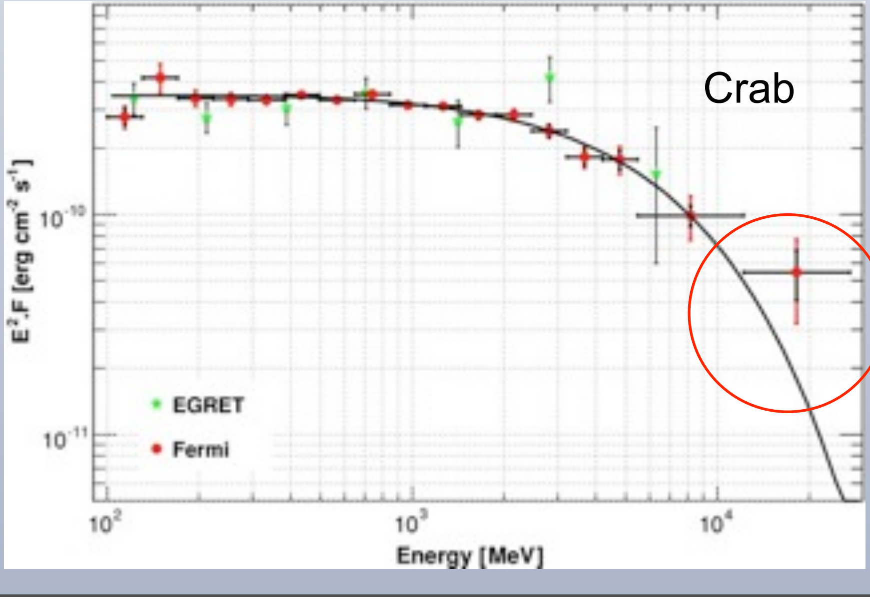


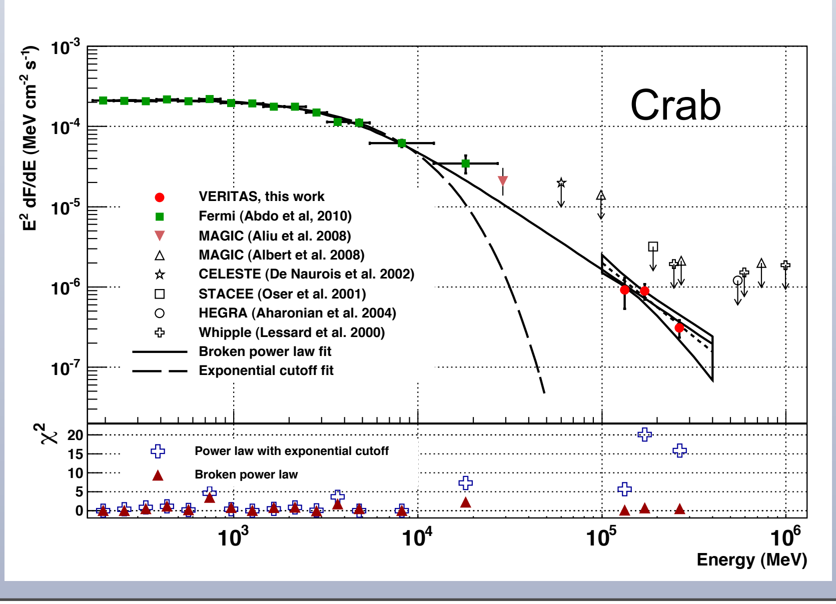
Crab

Looking back at Fermi spectra:

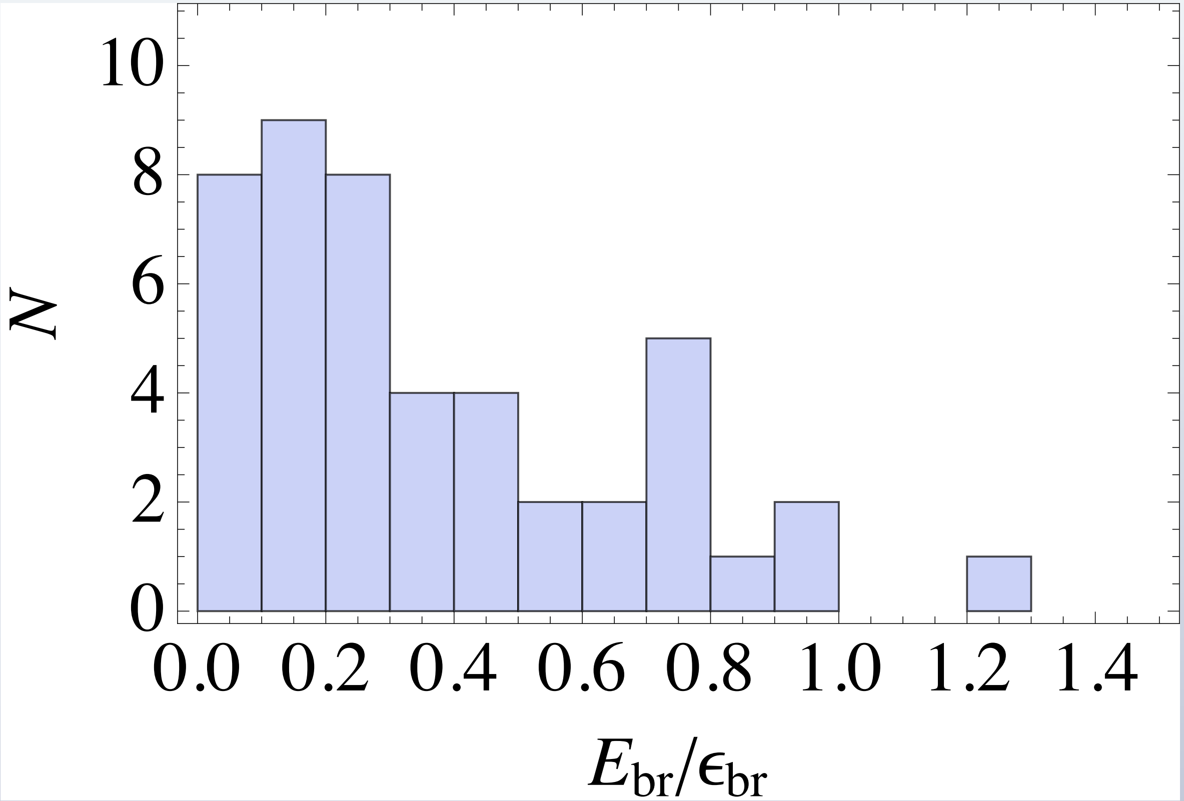








Other pulsar: maximal curvature energy at light cylinder



- Ratio of the observed break energies E_{br} for 46 pulsars to the maximum predicted for curvature radiation ε_{br}
- For Crab E_{br}/ε_{br} ~ 0.05 seemed OK, but not OK -> Lower limits

Scaling of Lγ with E$_{sd}$

- Acceleration by E$_{||}$ = radiation losses

$$L_\gamma = ec \times \eta B \times n_{GJ} \times \eta_G R_{LC}^3$$

$$L_\gamma \approx \eta \eta_G \dot{E}_{SD}$$

- **Linear!**
- (Everyone uses $L_\gamma \propto \sqrt{\dot{E}_{SD}}$ - potential-limited, from polar caps)
- Known problem of too many observed pulsars
- uncertainty of the geometrical parameter η_G and accelerating E-field η

Upshot: pulsar spectral modeling

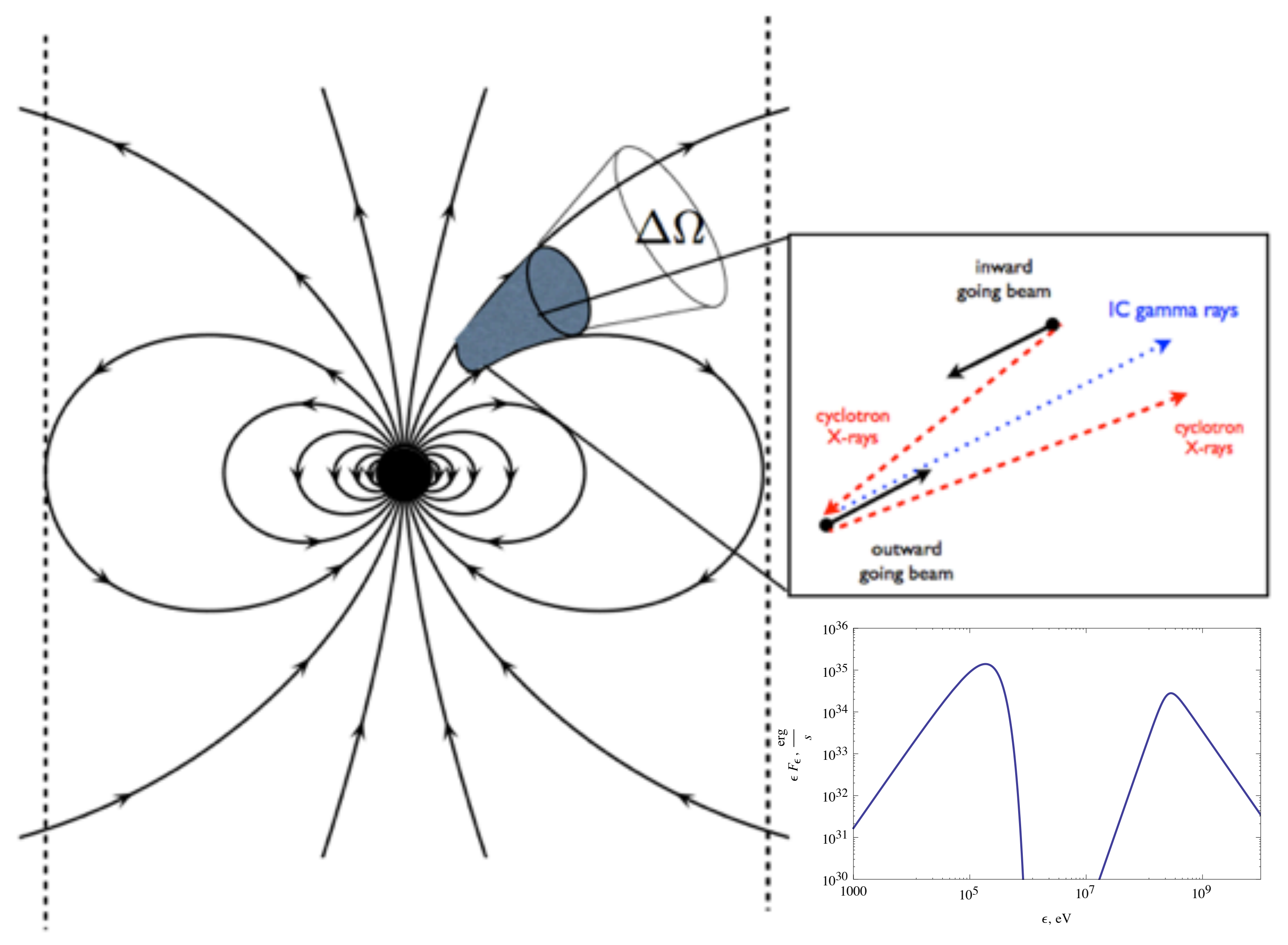
- Broadband pulsar high energy spectra of the brightest gamma-ray pulsars are generally consistent with the double power law shapes.
  - Crab and Geminga are inconsistent with exp. cut-off
  - Vela is consistent with double power law
- In Geminga most errors in the broadband double power law fit are accumulated due to the **arbitrary** parametrization of the spectral roll-off between the two asymptotic power laws
  - Due to low background above ~ few GeV Fermi is especially sensitive there
- **This favors the inverse Compton (IC) scattering for the production of gamma-ray photons**

IC model (in progress)

- ``Off-the shelf'' SSC models not applicable
  - Random B-field of given value
  - Isotropic particle distribution
  - single value for bulk motion
- Regular B-field, changing sharply in the emission region
- Strong radiative damping: non-isotropic distribution
- Continuous $v_{||}$

- Need two distinct components:
- optical-X-ray: boosted cyclotron-synchrotron
- gamma rays: IC scattering of the ``first'' cyclotron photons by the ``second'' particles

IC model (in progress)

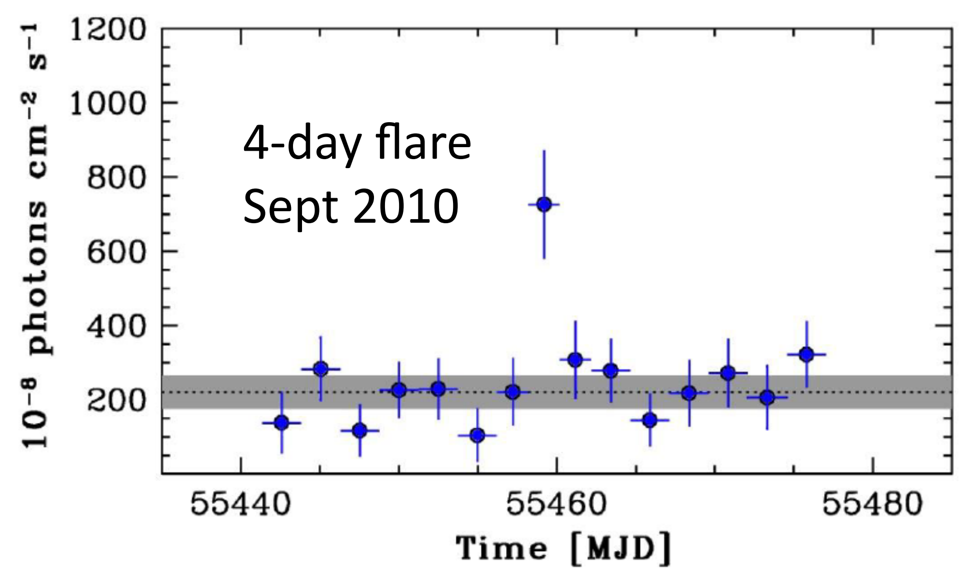


$\beta_0 = 3\ 10^{-6}$

$\lambda = 5\ \ 10^6$

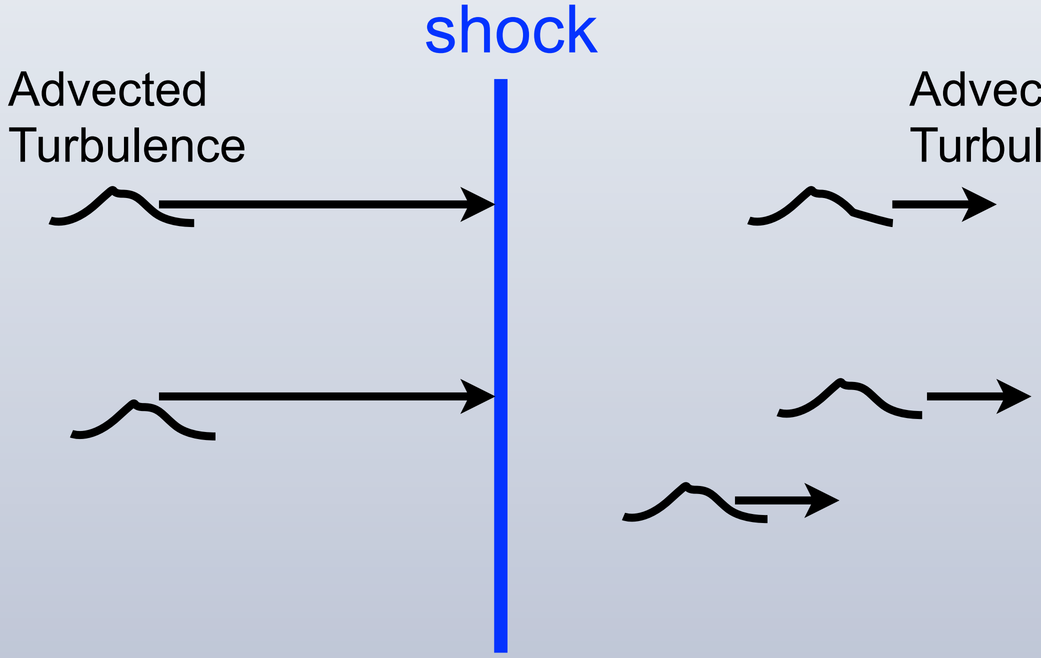
2. Crab nebula flares seem inconsistent with the stochastic shock acceleration

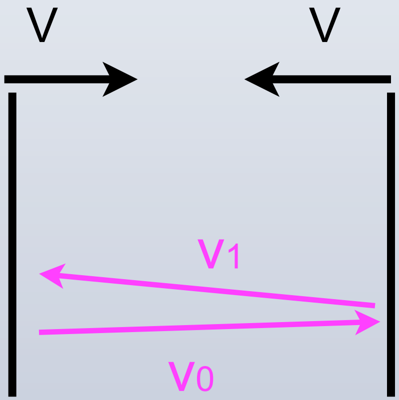
(with Eric Clausen-Brown)



Tavani et al. 2011

The accepted model of Cosmic Ray acceleration: Fermi-I at shocks



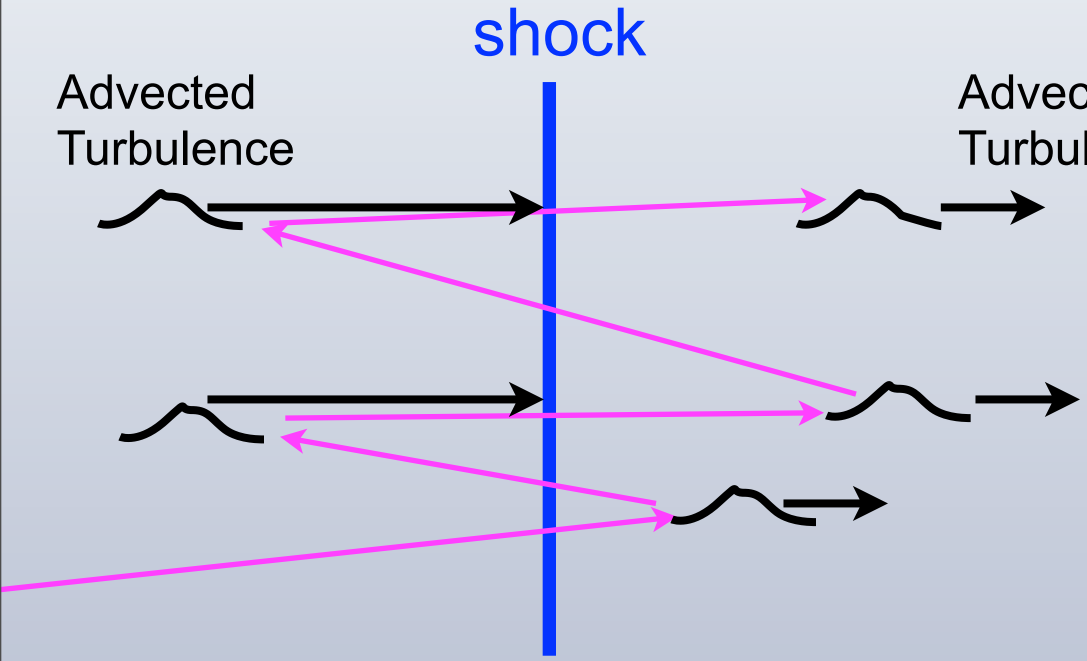


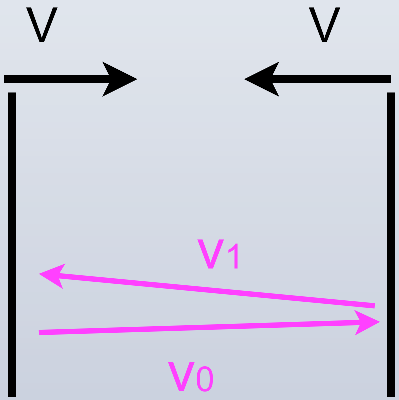
$$v_0 + V = v_1 - V$$

$$v_1 = v_0 + 2V$$

$$\frac{\delta\epsilon}{\epsilon} \sim \frac{v}{c}$$

The accepted model of Cosmic Ray acceleration: Fermi-I at shocks





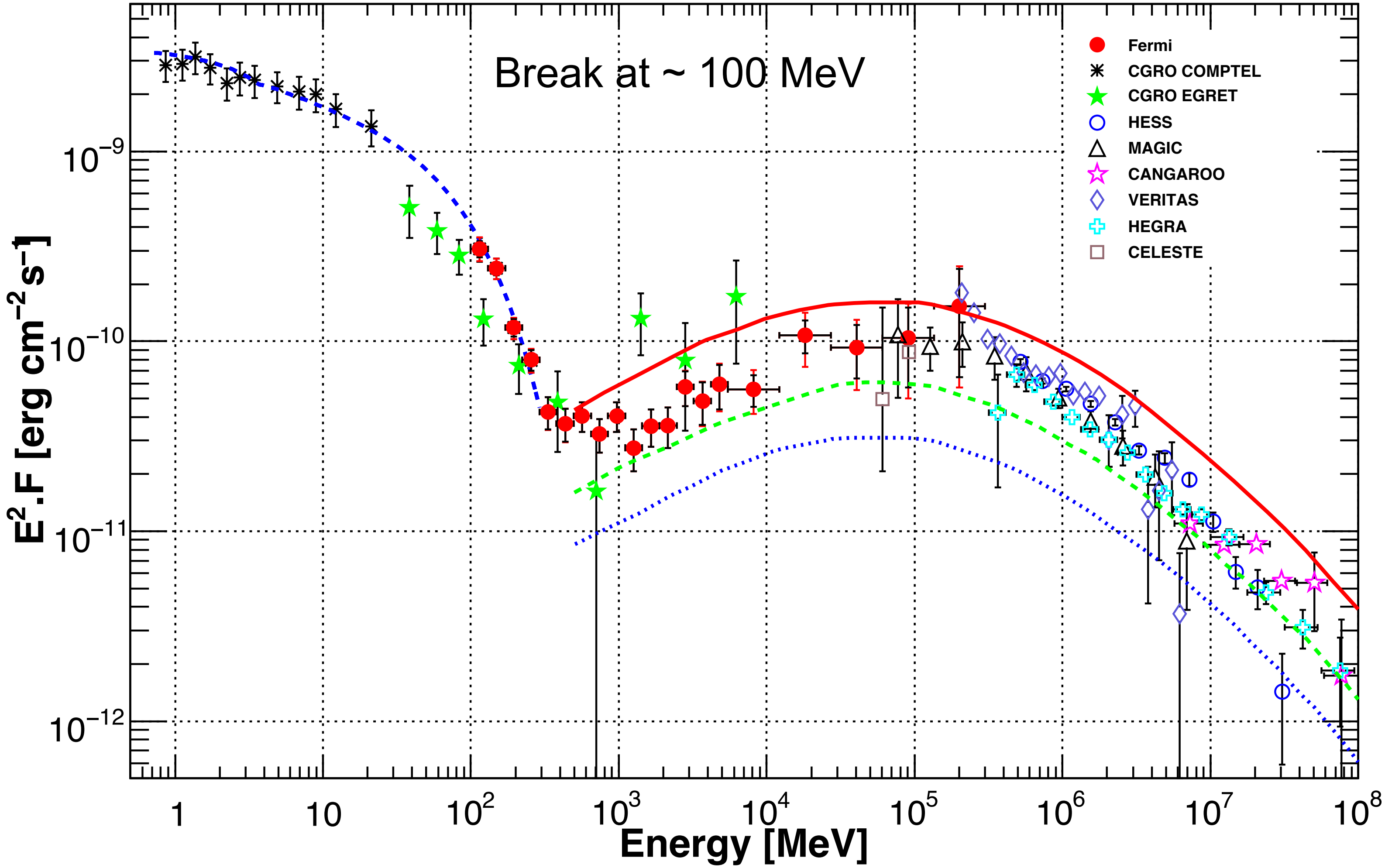
$$v_0 + V = v_1 - V$$

$$v_1 = v_0 + 2V$$

$$\frac{\delta\epsilon}{\epsilon} \sim \frac{v}{c}$$

Crab nebula

Tavani et al. 2010
Beuhler et al., 2011



Crab nebula

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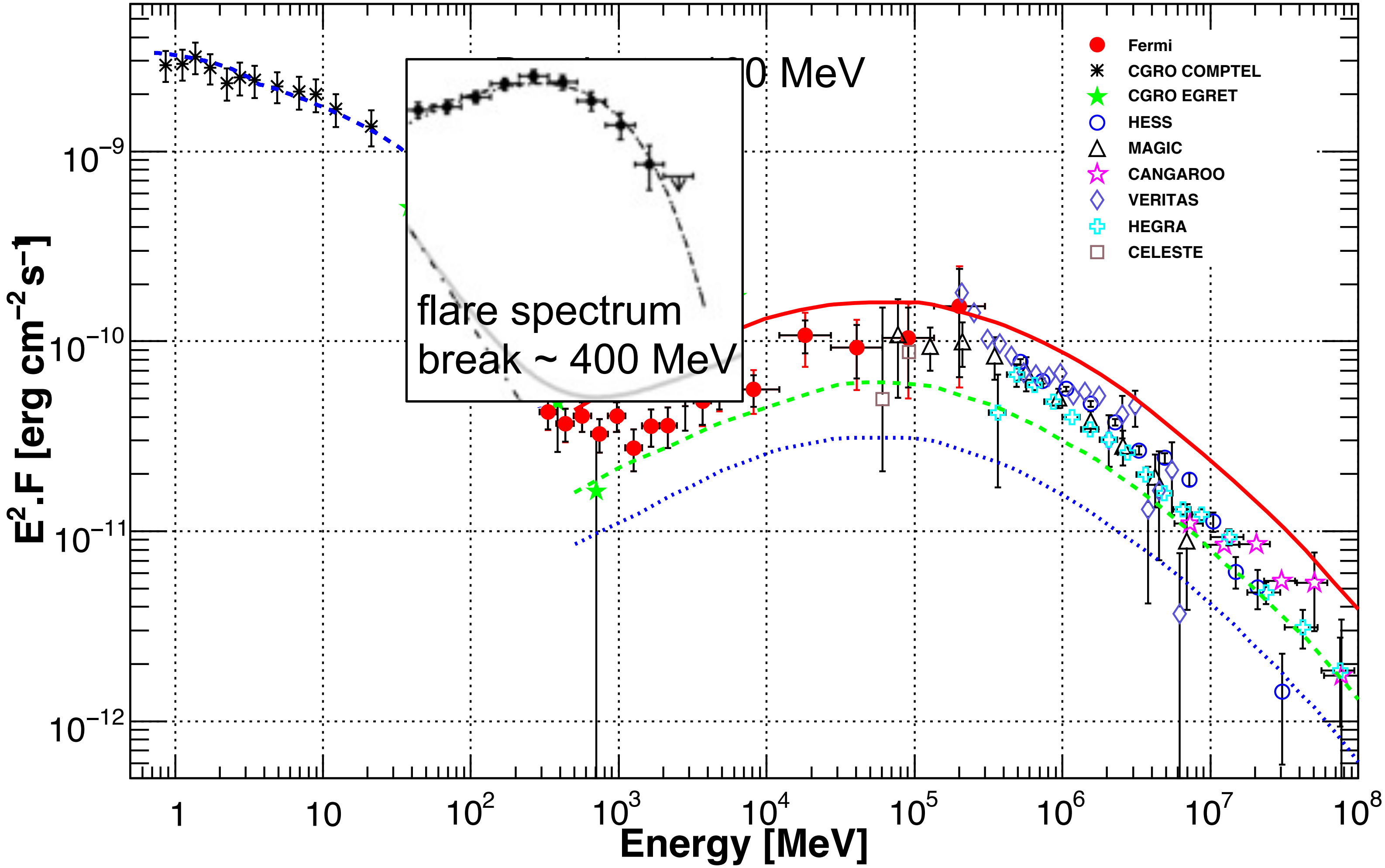

flare spectrum
break ~ 400 MeV

Crab nebula

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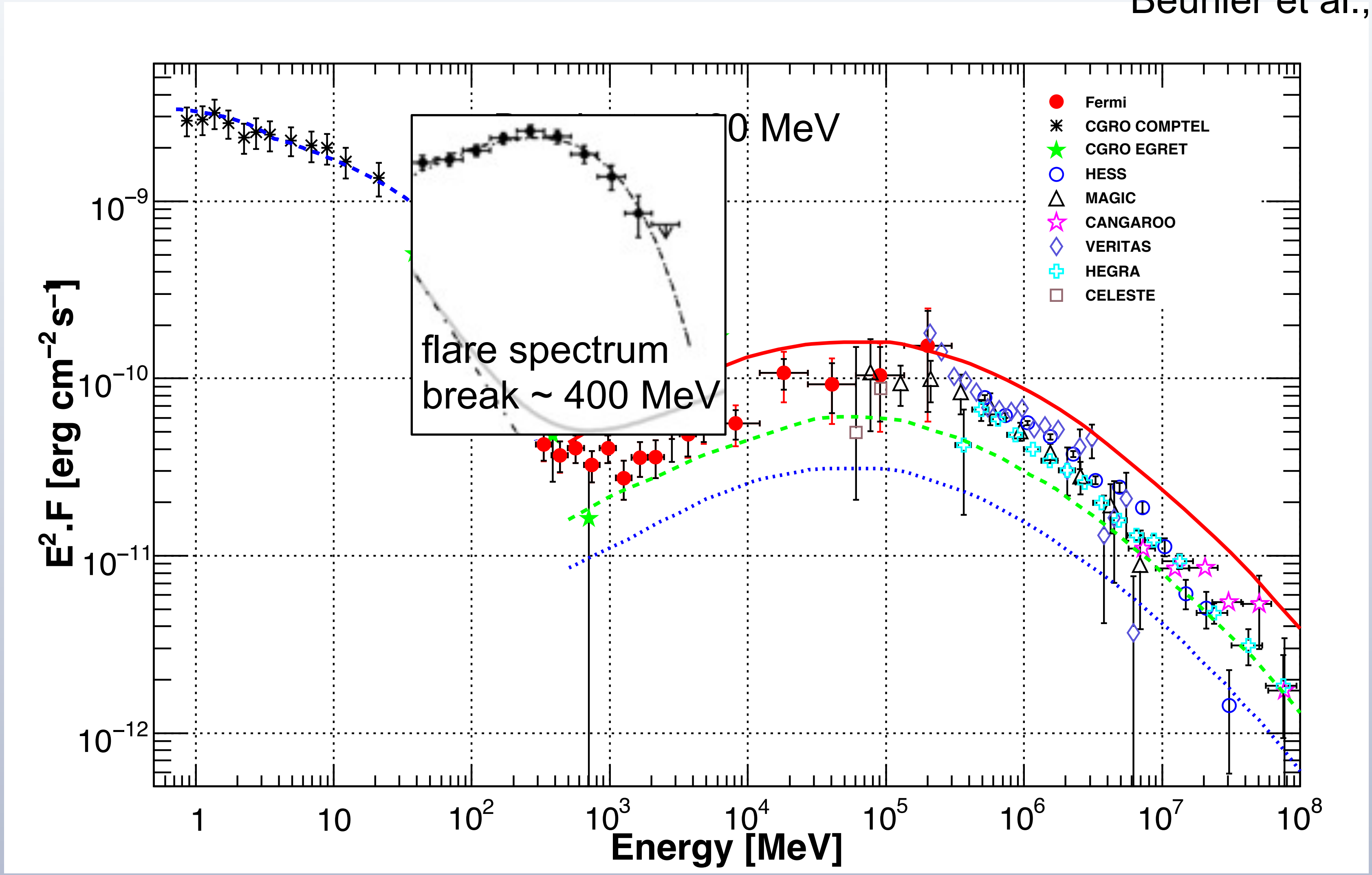

flare spectrum
break ~ 400 MeV

Flare time scales << nebular dynamical time, termination shock size

Upper limit to synchrotron frequency

Accelerating E-field < B-field

$$eEc = \eta eBc = \frac{4e^4}{9m^2c^3}B^2\gamma^2$$

$$E_p = \frac{27}{16\pi}\eta\,\frac{mhc^3}{e^2} = 236\,\eta\,\mathrm{MeV}.$$

Lyutikov ‘10,
Komissarov & Lyutikov ’11
de Jager ‘98 (for shocks)

- Same as Fermi acceleration on inverse gyroscale (requires very efficient scattering, stochastic acceleration: eta << 1)

I am not aware of any stochastic acceleration model that gives eta ~ 1. Typically eta ~ 10^{-2}.

Possible resolutions.

Doppler boosting

$$\omega \to \delta\omega$$

$$I \propto \delta^{2+\alpha}, \delta^{3+\alpha} \to \delta^{3-4}$$

$$\delta = \frac{1}{\Gamma(1-\beta\cos\theta)}$$

Even delta ~ 2 can increase the flux by 10-20 times

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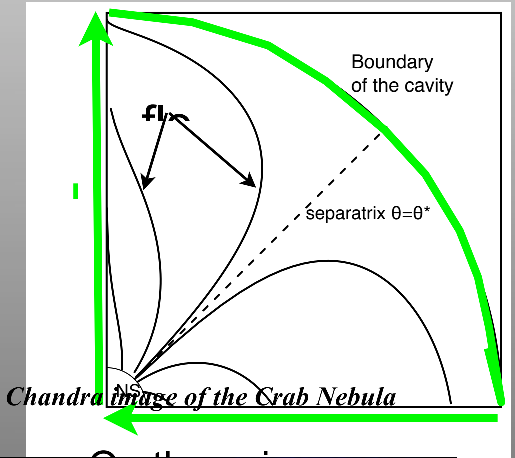
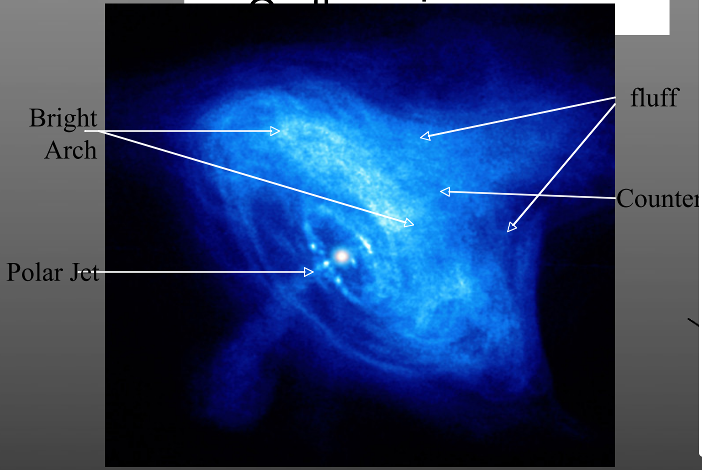
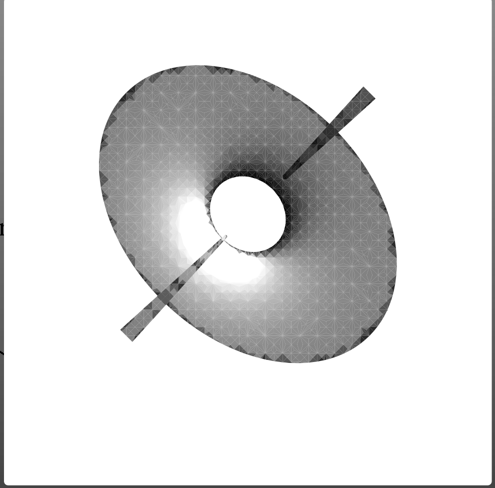
Lyutikov (2010): Ideal flow in the bulk, dissipation on boundary

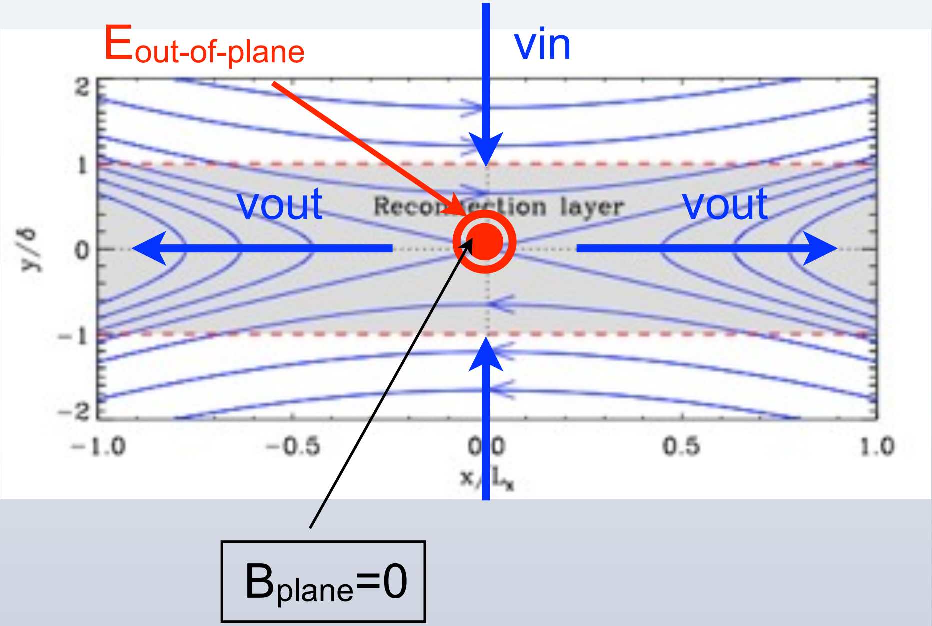






Paradigm shift: some (most?) particles are accelerated by magnetic reconnection (and not shocks)

Reconnection: E ~ B

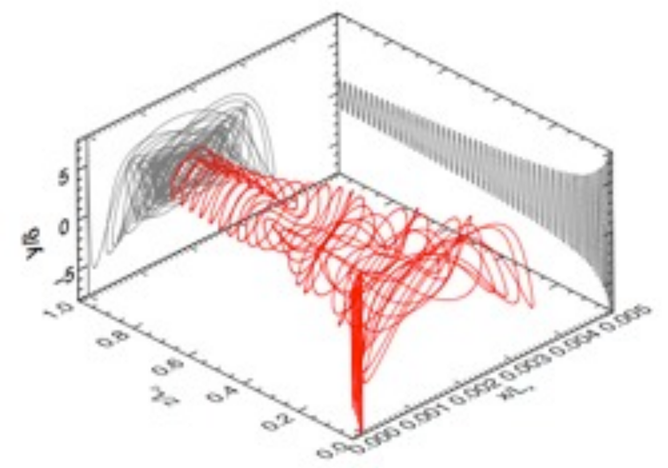


- Relativistic reconnection: Lyutikov & Uzdensky,Lyubarsky, Hoshino
- E ~ (v_{in}/c) B.
- Inflow velocity v ~ c, E ~ B

$$\beta_{in} \sim \sqrt{\frac{\sigma}{S}}$$

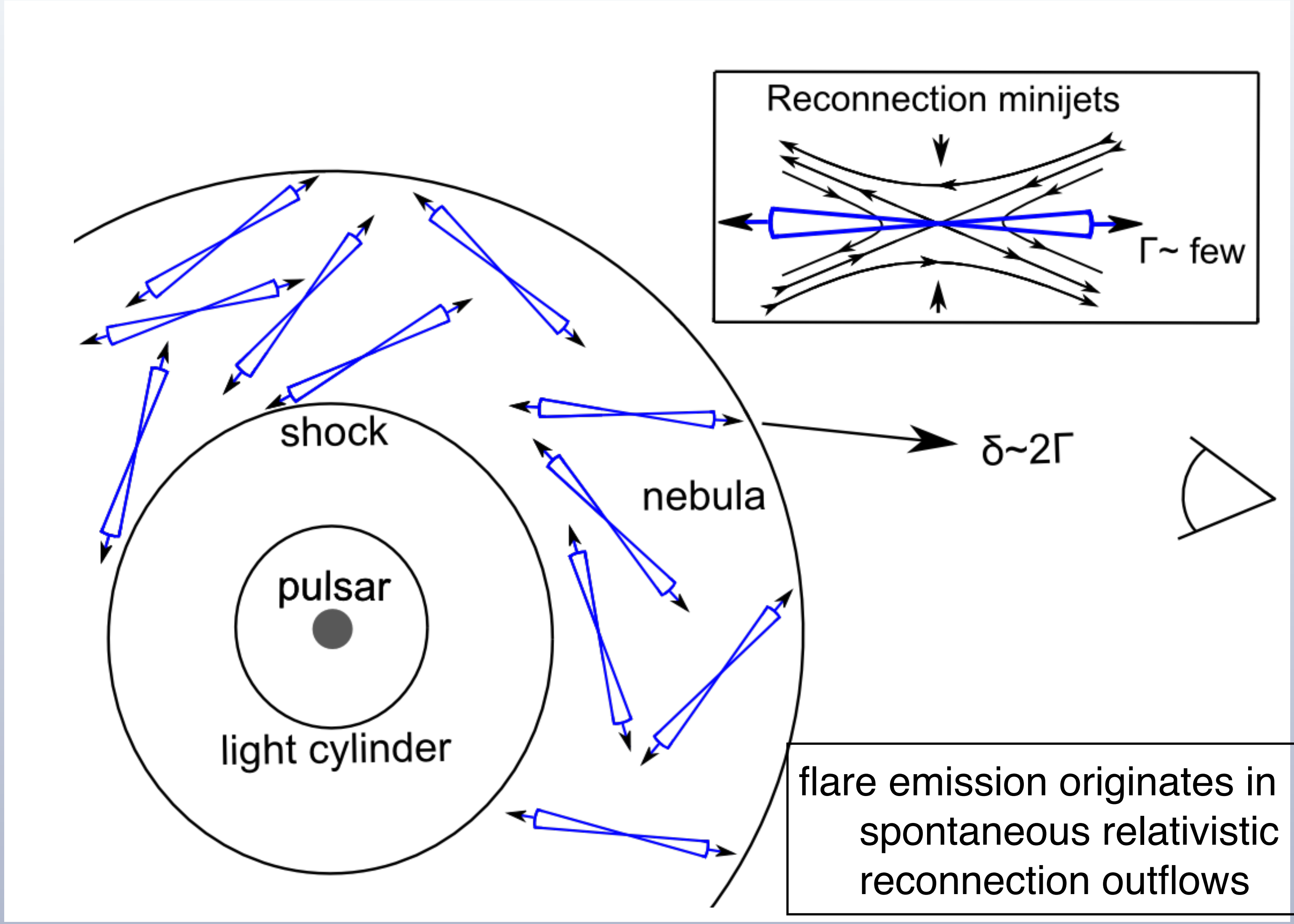
$$\gamma_{\rm out} = \gamma_{\rm in}(1+\sigma)$$

Uzdensky et al.: Accelerate in a region where B is small, with E >B, emit where B is large.



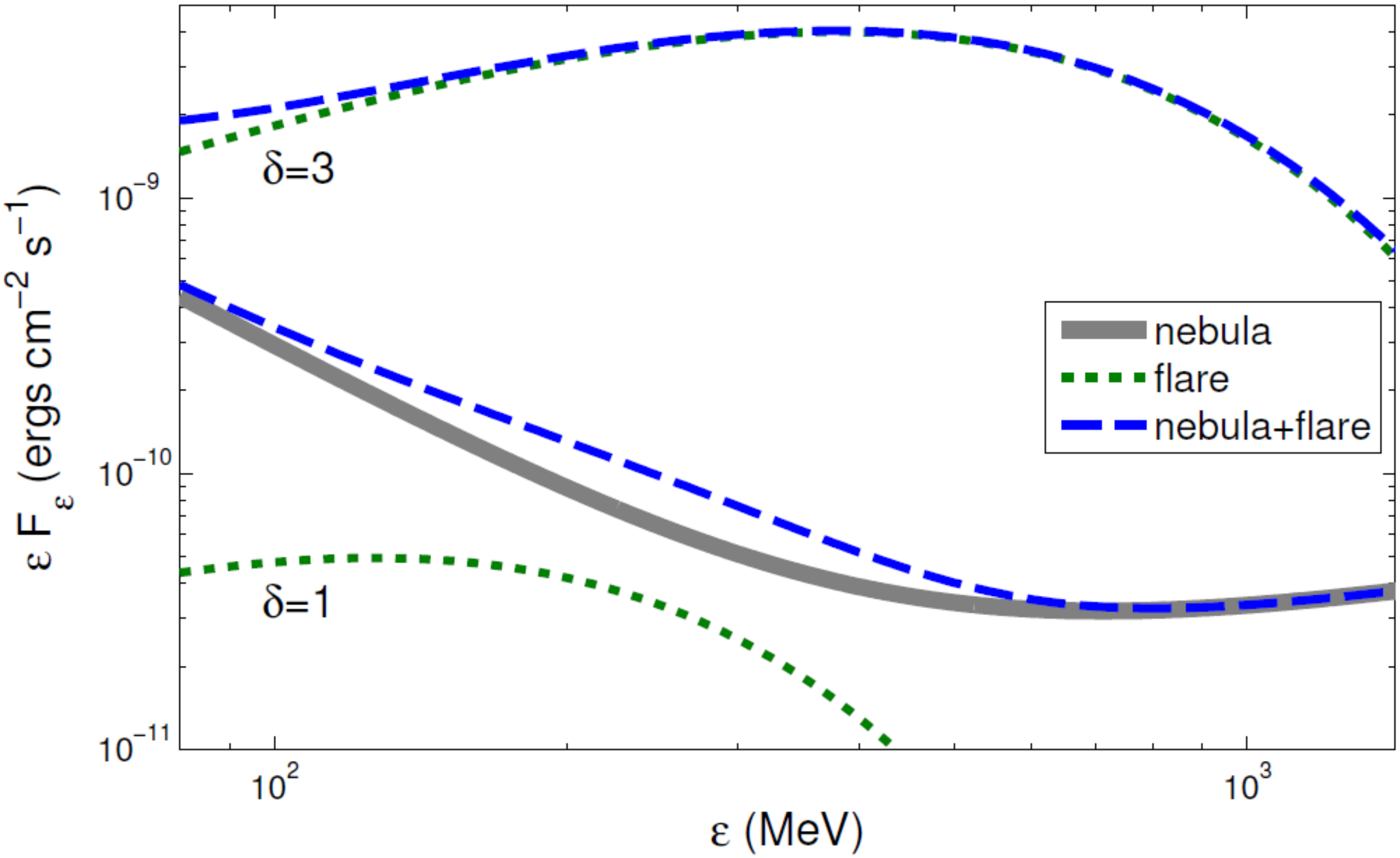
Reconnection + bulk motion

Clausen-Brown & Lyutikov 2012



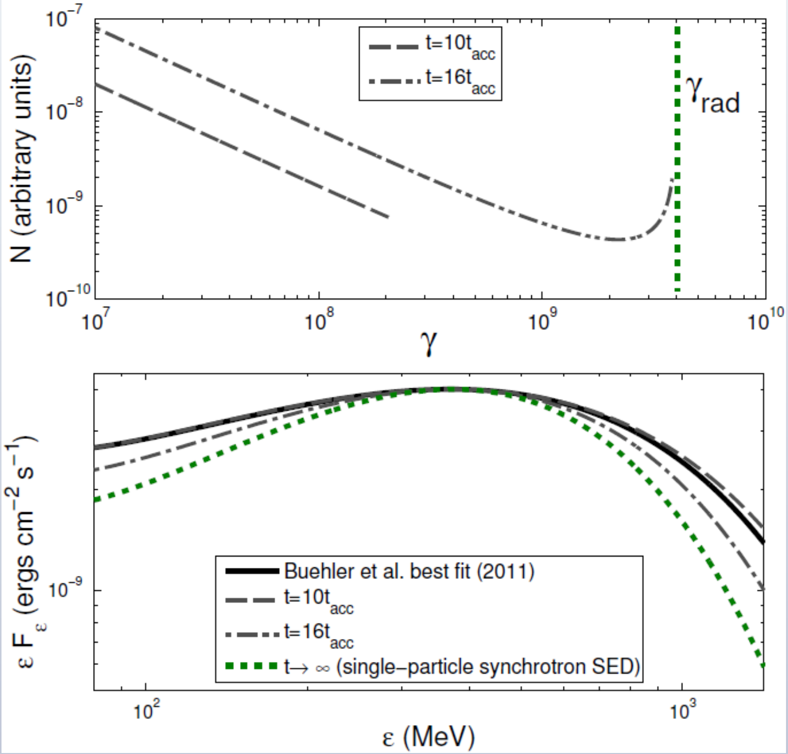
flare emission originates in spontaneous relativistic reconnection outflows

Γ ~ few increases flux and peak energy



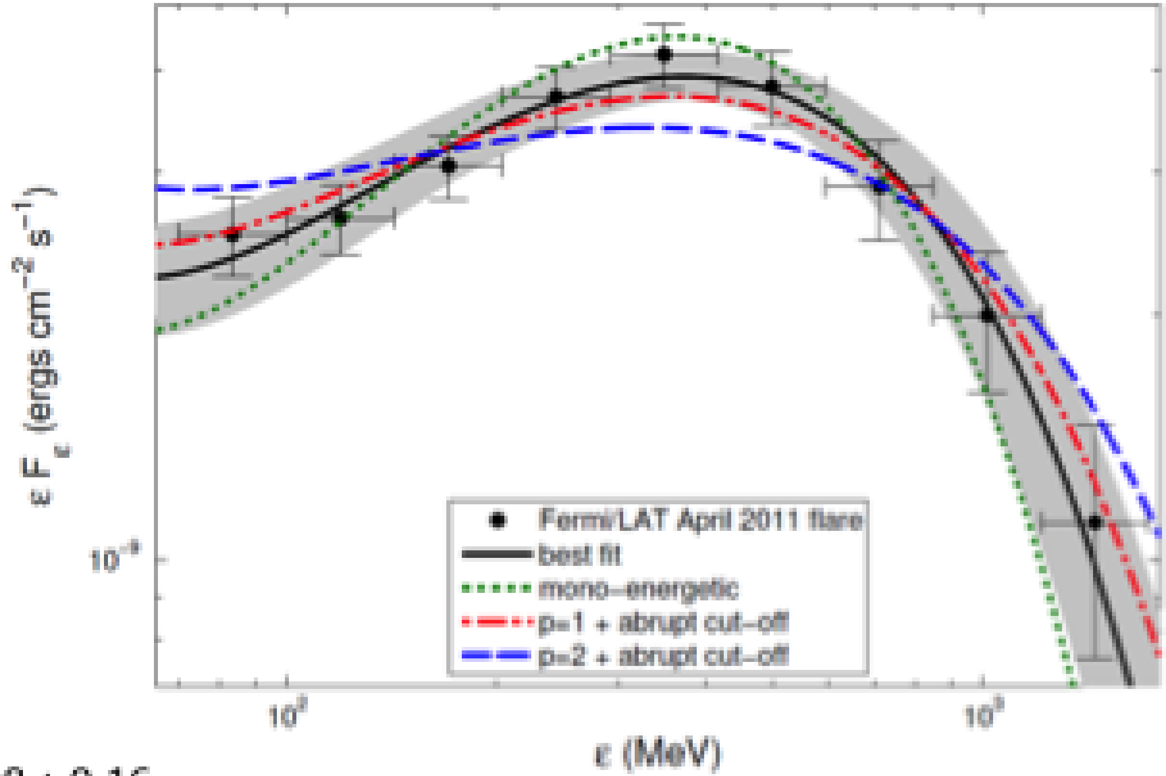
Radiation reaction-limited acceleration: pile-up

- Many reconnection models predict a particle spectrum of power-law p=1
- When this particle spectrum approaches radiation limit, a "pile-up" distribution is produced
- As pile-up grows, the SED approaches that of a single-particle synchrotron SED



Gray area is one-sigma error region from fitting data to:

$$\Phi = A\varepsilon^{-\gamma_F} \exp\left(-\frac{\varepsilon}{\varepsilon_{cut}}\right)$$



- Best fit for this SED is $\gamma_F = 1.08 \pm 0.16$
  - $\gamma_F = 0.7$ approximates single-particle synchrotron SED
  - $\gamma_F = 1.3$ approximates p=1 particle distribution
  - $\gamma_F = 1.56$ approximates p=2 particle distribution (shock acceleration)

- This is consistent with power-law of index p = 1 with pile-up (previous slide), or with distribution of power law index p = -0.2

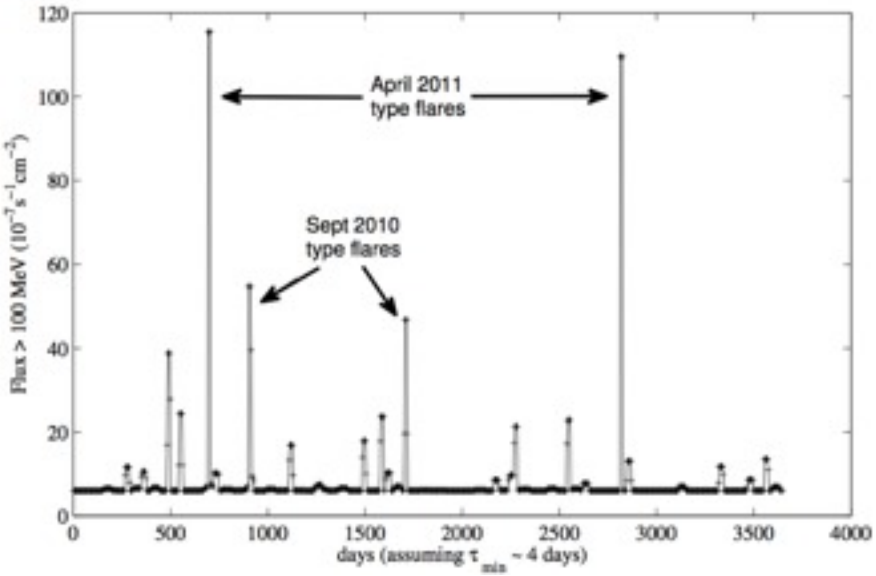
- Observed SED inconsistent with shocks, but is in line with reconnection particle spectrum + pile-up

Flare statistics

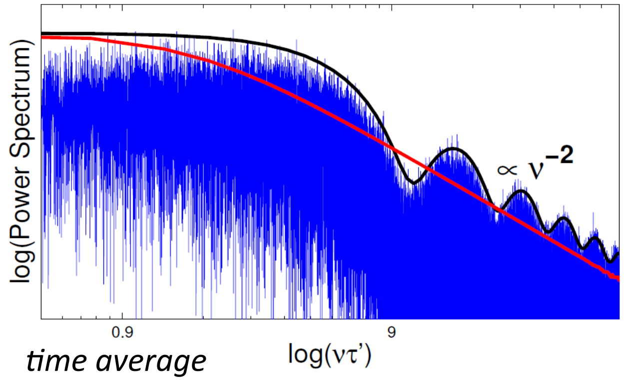
- **Model A:**
  - •shock gives average emission
  - •rare reconnection events
  - •probability of flare flux

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

  - •average flare flux is dominated by bright rare flares.



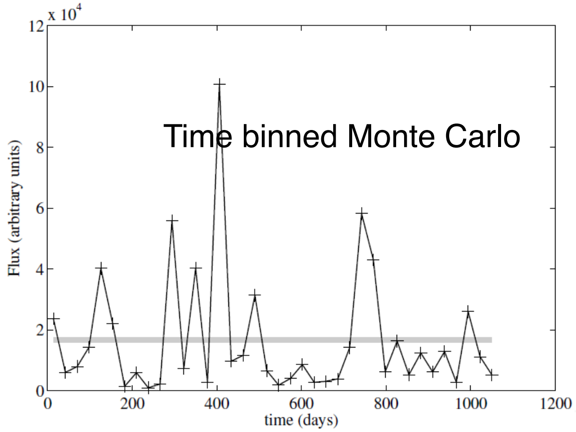
- **Model B: overlapping flares**



time average $\rightarrow$ $\langle F(t)\rangle \approx n\tau'(2\Gamma)^{2+\alpha}F'$

std. dev. $\rightarrow$

$$\frac{\sigma}{\langle F(t)\rangle} \approx \gamma_1 \approx \frac{\Gamma^{3/2}}{(n\tau')^{1/2}}$$



Conclusion

- **Reconnection is an important, perhaps dominant, mechanism of particle acceleration in PWNs.**
- Observed SED implies hard electron spectrum as predicted by reconnection models.
- Can reproduce intermittency