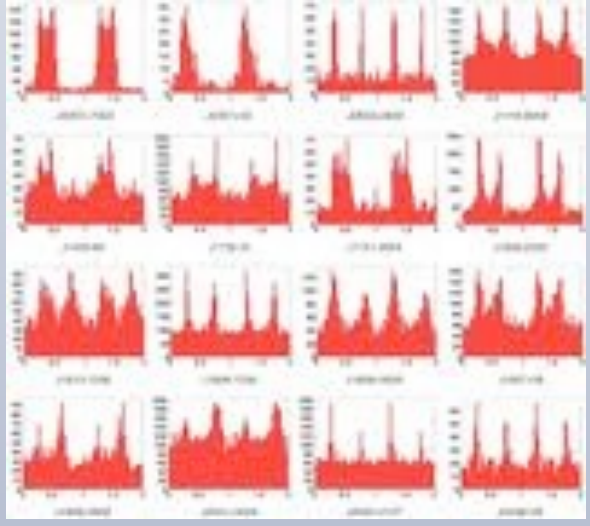
Gamma-ray emission from Crab pulsar and the nebula: paradigm shifts?

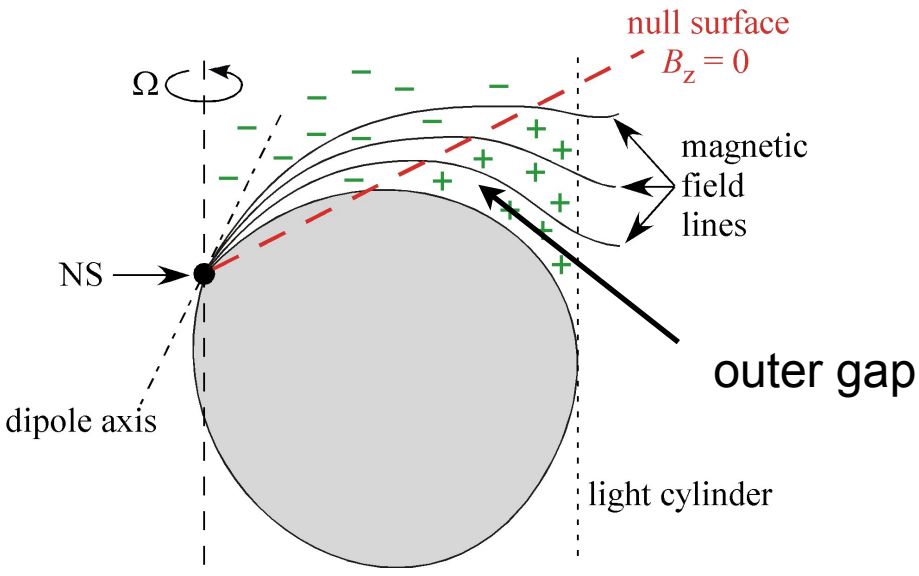
Maxim Lyutikov (Purdue U., Osservatorio Arcetri)

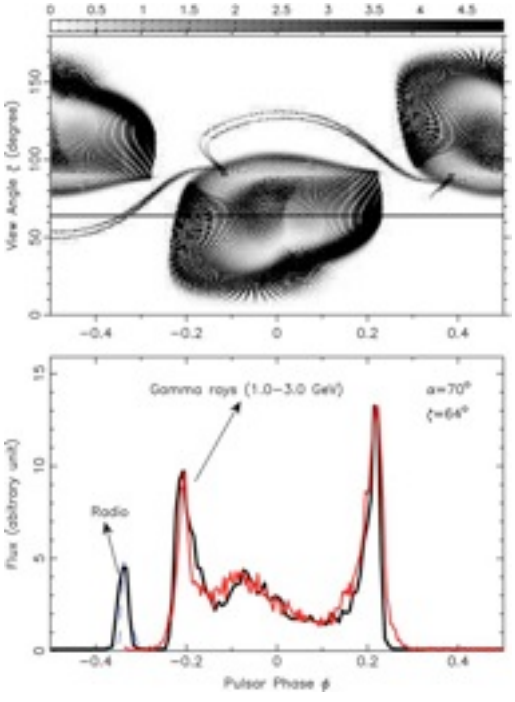
1. Pulsar Gamma-ray emission



Outer/slot gaps: messy physics, good fits geometrical

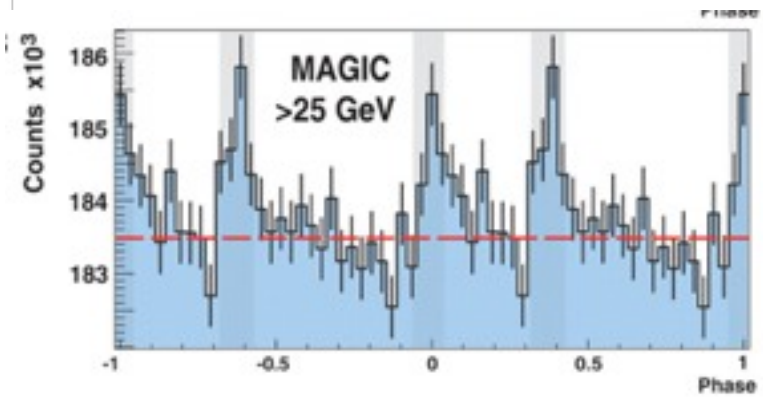
- $E_{\parallel} \sim 10^{-2}$-$10^{-1}$ B accelerates particles which emit curvature emission (Cheng & Ruderman 1986)
- **Above the break the spectrum must be exponentially suppressed**





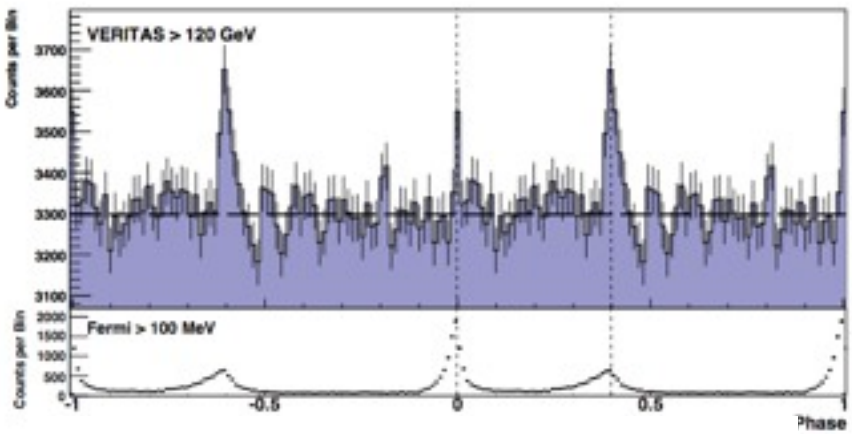
New results

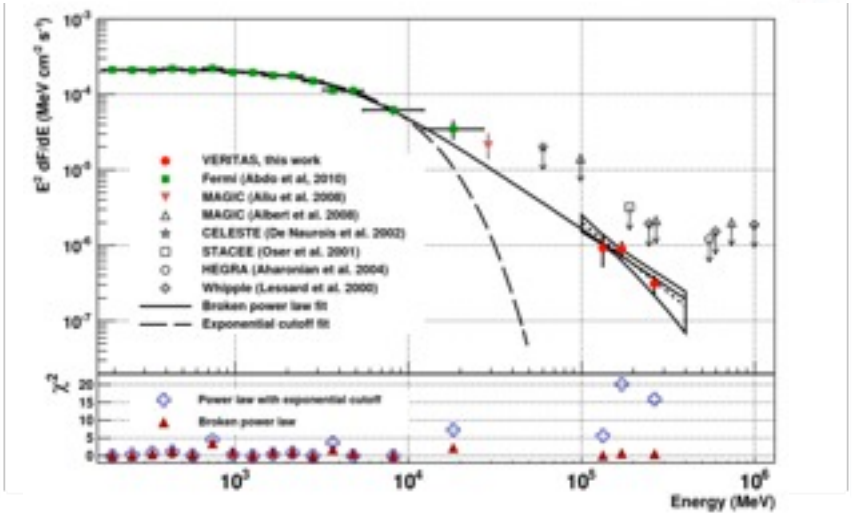
- MAGIC sees Crab at ~ 25 GeV



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

- VERITAS sees Crab at > 150 GeV!





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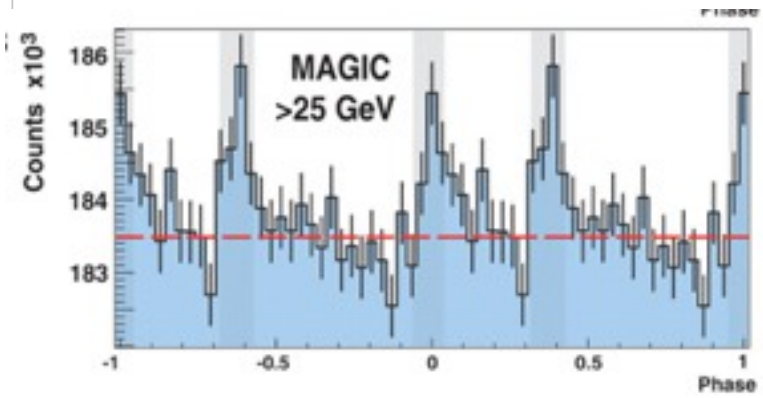

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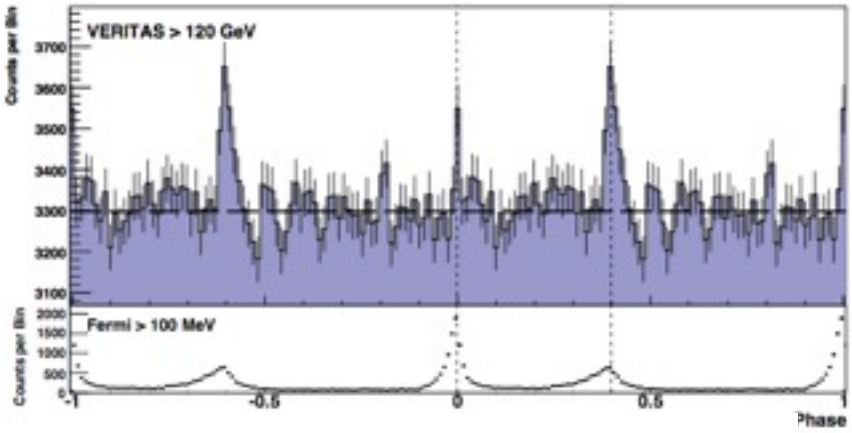
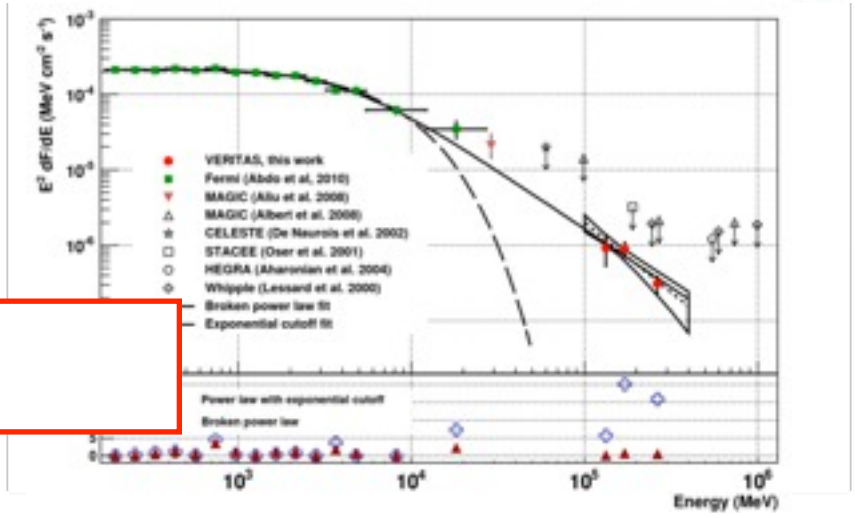




- Cut-off is non-exponential!

Curvature emission near light cylinder is excluded

- Astrophysical E-fields < B-field
- Equate acceleration by $E_{\parallel} = \eta\,(r/R_{LC})\,B$ to curvature losses in $R_C = \xi R_{LC}$

Maximum possible energy break due to curvature emission

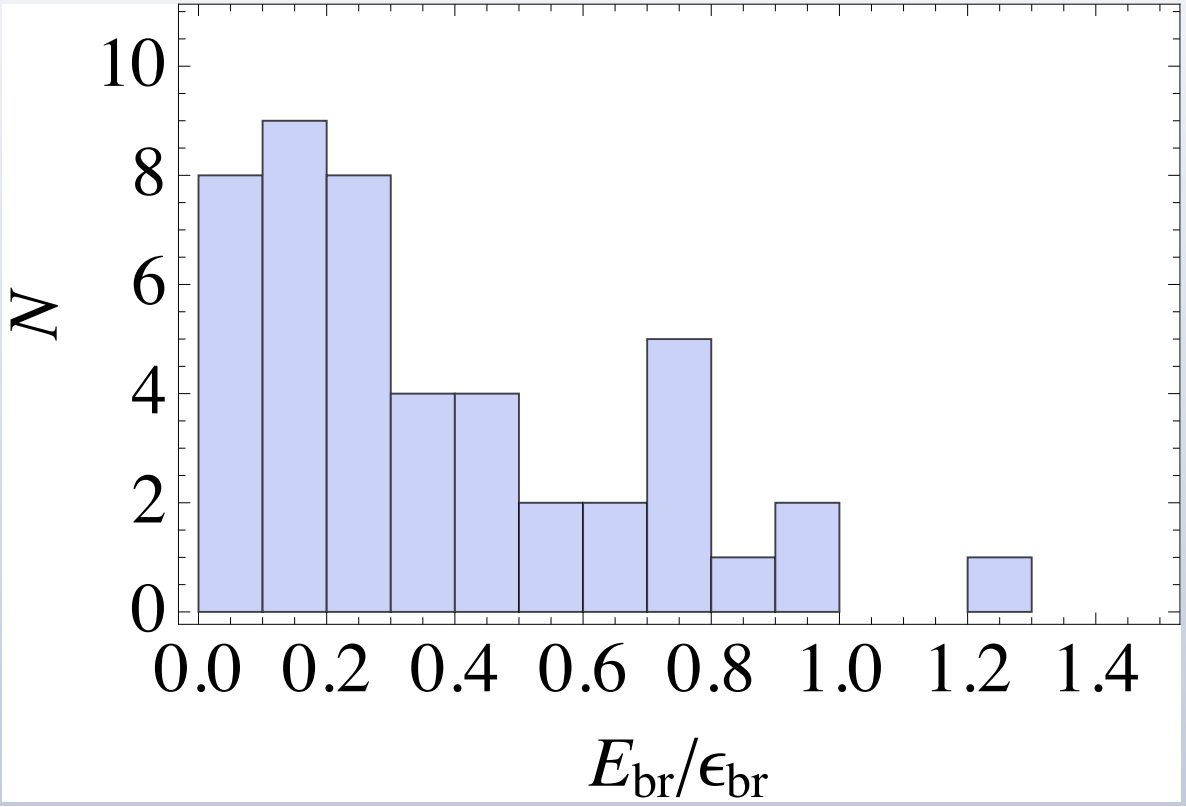
$$\epsilon_{br} = (3\pi)^{7/4} \frac{\hbar}{(ce)^{3/4}} \eta^{3/4} \sqrt{\xi}\, \frac{B_{NS}^{3/4} R_{NS}^{9/4}}{P^{7/4}} \left(\frac{r_{em}}{R_{LC}}\right)^{-1}$$

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)

Other pulsar: maximal curvature energy at light cylinder



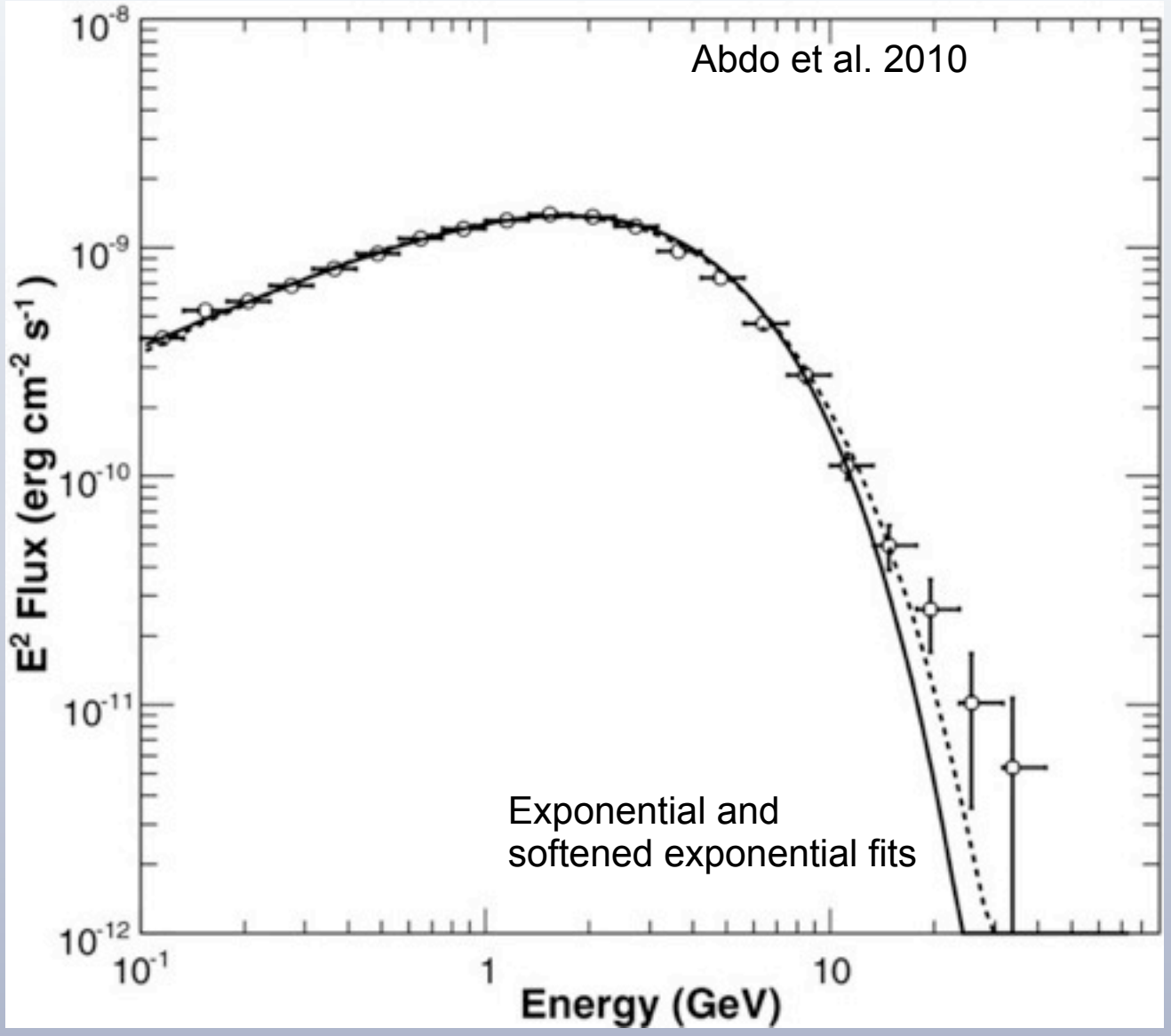
- Ratio of the observed break energies E_{br} for 46 pulsars to the maximum predicted for curvature radiation ε_{br}
- For Crab $E_{br}/\varepsilon_{br} \sim 0.05$ seemed OK, but not OK -> Lower limits

Implications of Crab detection by VERITAS:

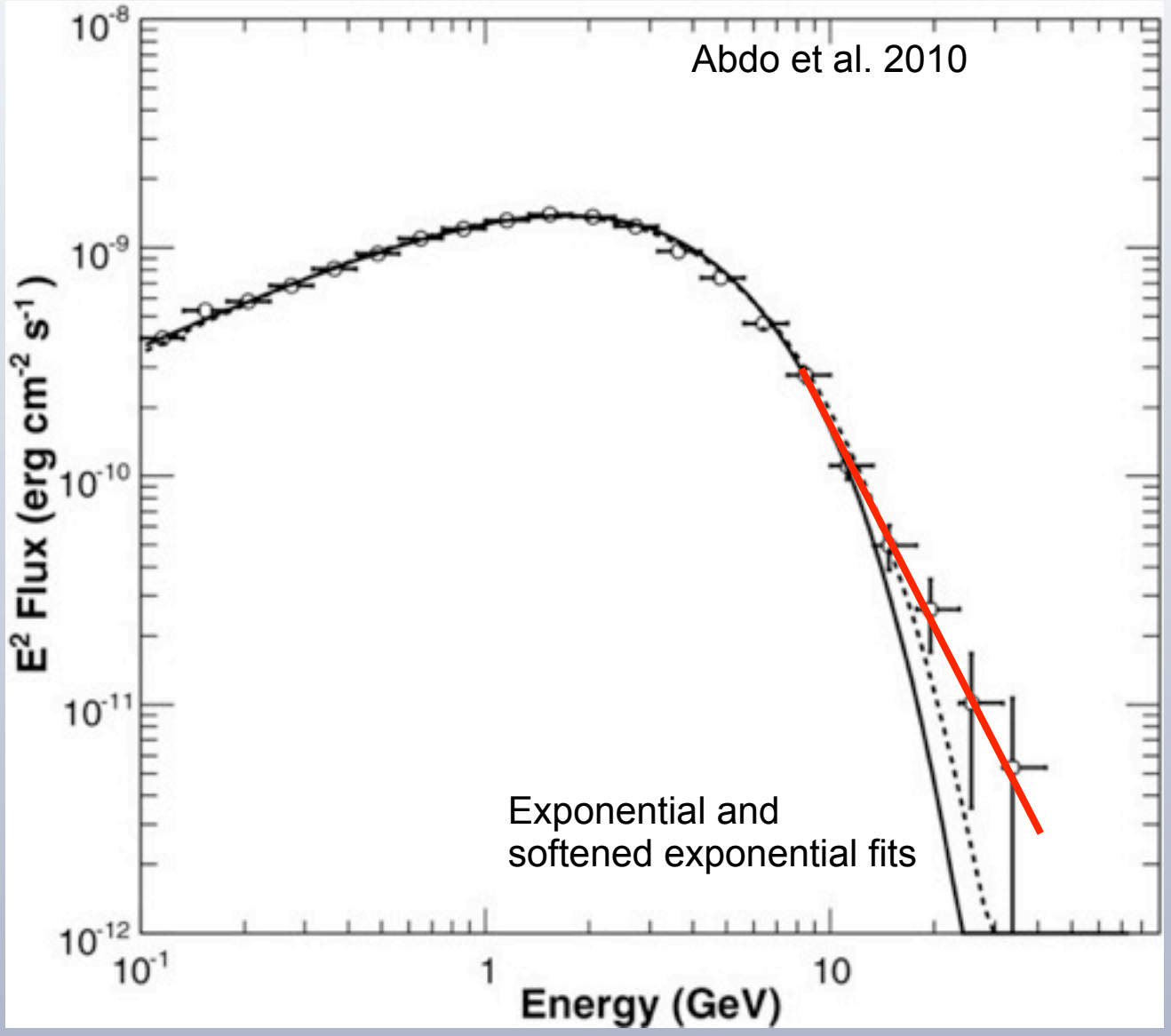
- **Spectral break in Crab is not due to curvature emission of the maximal energy of particles**
- **Alternative possibility: IC scattering**
- **Break due to the details of particle distribution and scattering cross-section (in the KN regime)**

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

Fermi spectrum of Geminga



Fermi spectrum of Geminga



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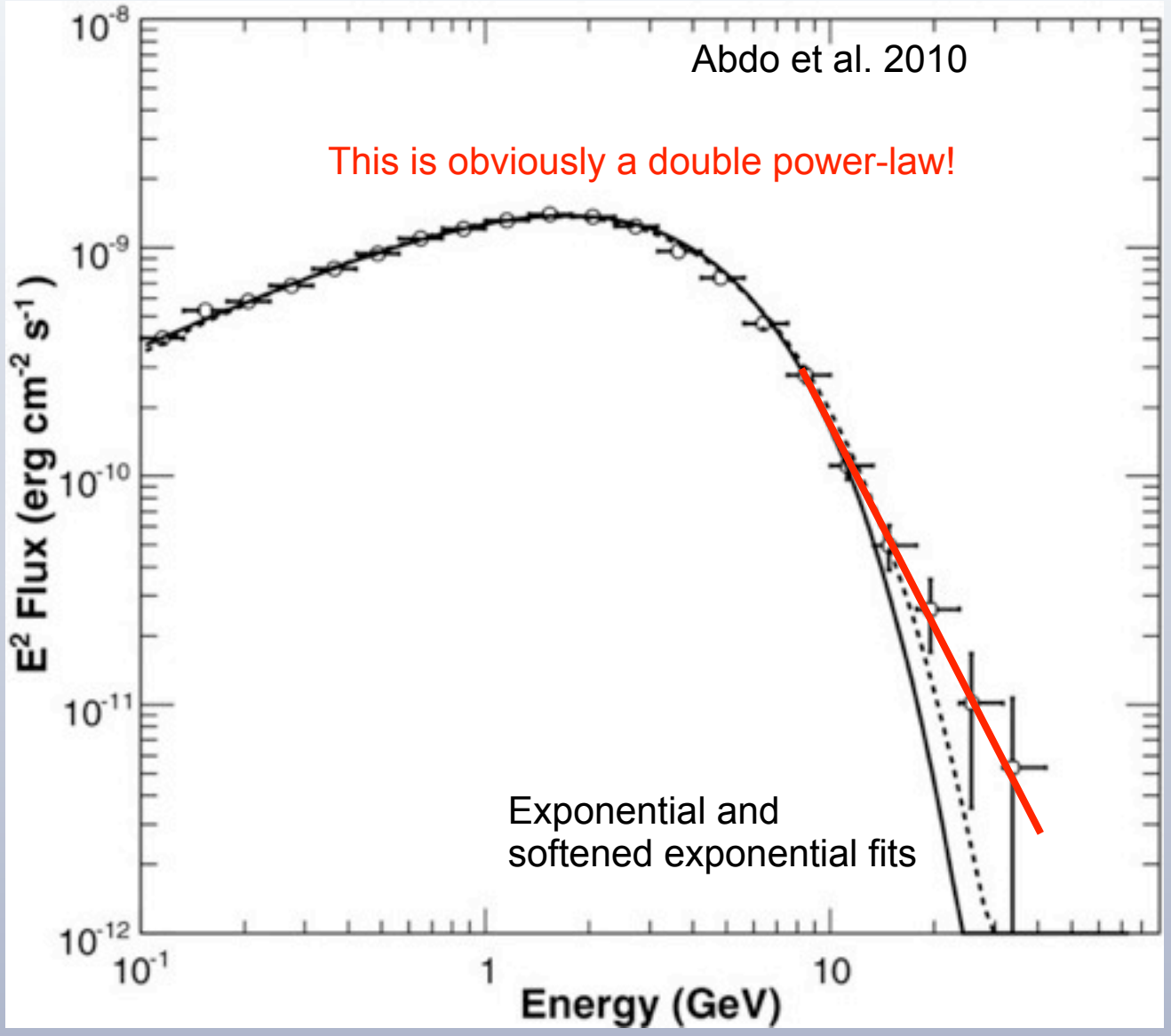
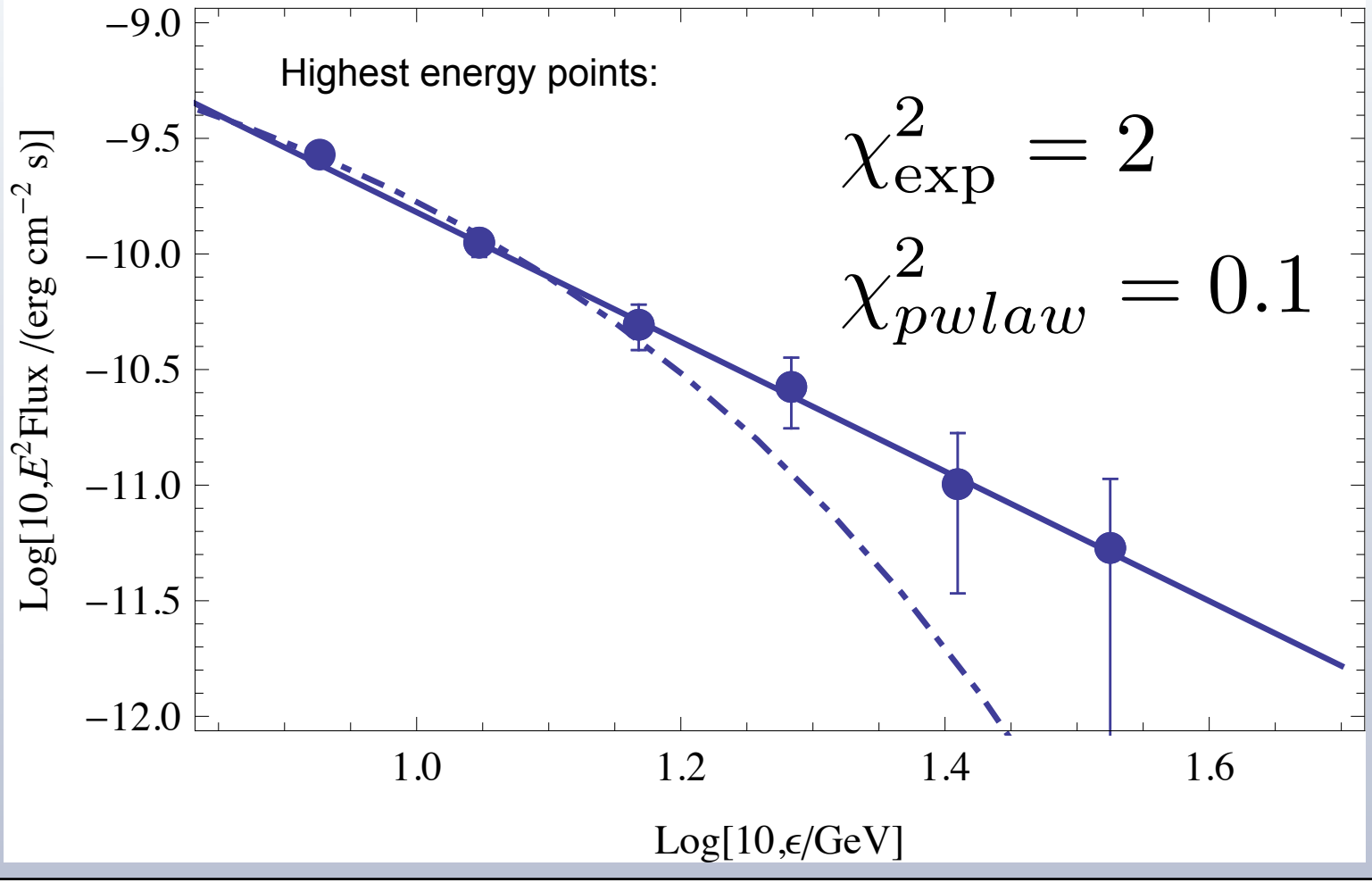


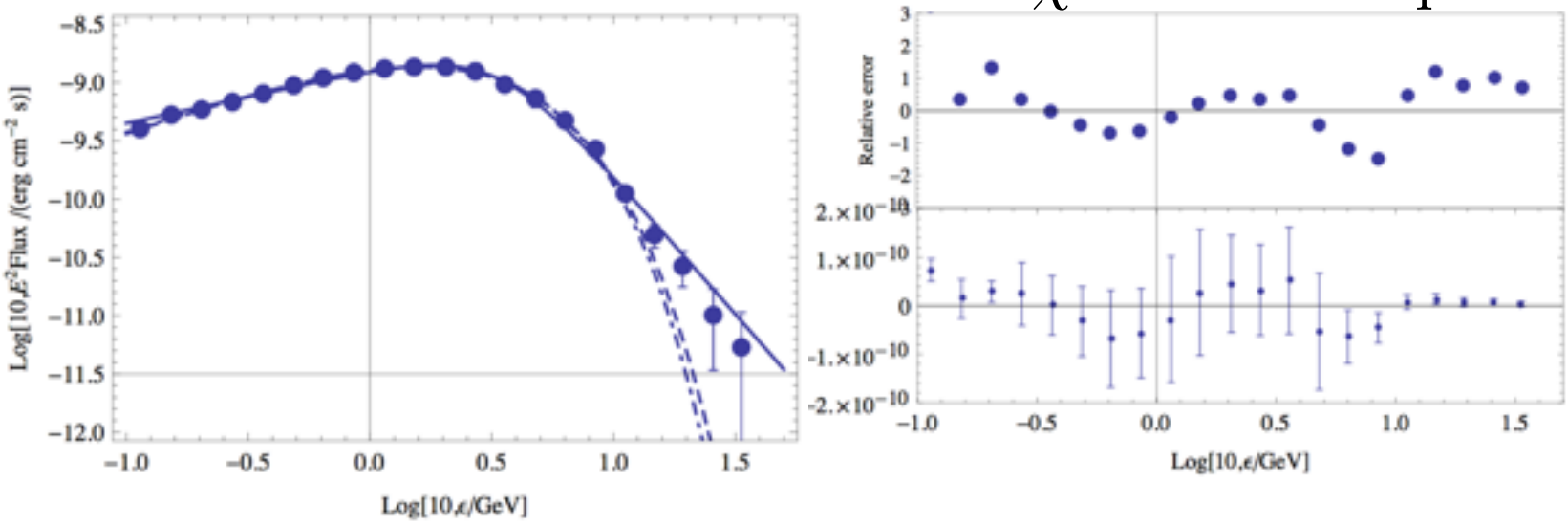
Geminga: fits



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

Geminga: broad band fits

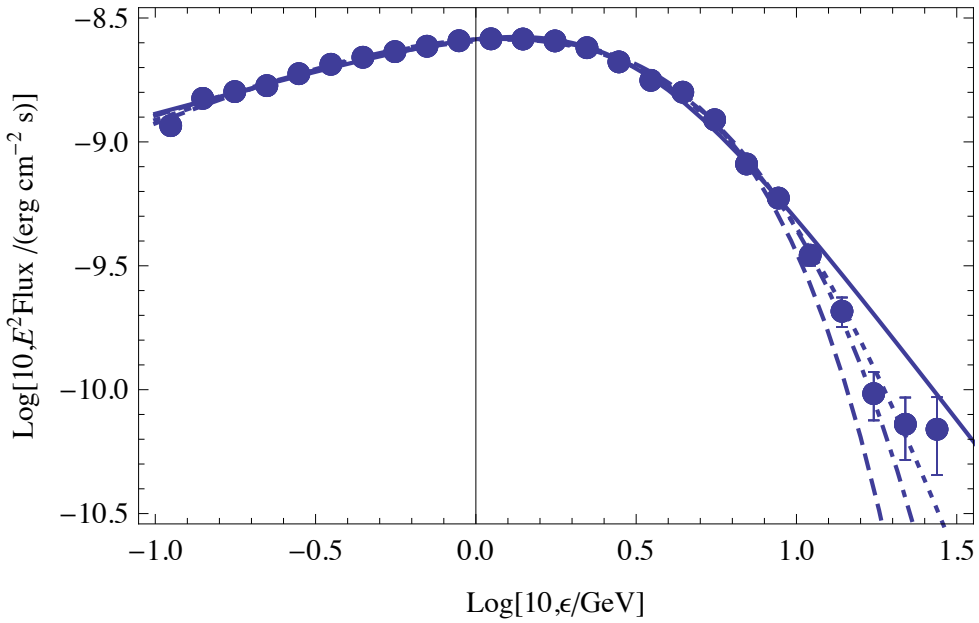
errors χ^2 for double pwlaw



model	Fit function	α	β	ϵ_{br}	reduced, unweighted χ^2	b	dof
a	$\left(\left(\frac{\epsilon}{\epsilon_{br}}\right)^{\alpha}+\left(\frac{\epsilon}{\epsilon_{br}}\right)^{-\beta}\right)^{-1}$	2.38	0.45	3.32	1.26	–	17
b	$\epsilon^{\beta}e^{-\frac{\epsilon}{\epsilon_{br}}}$	–	.70	2.35	1.13	–	18
c	$\epsilon^{\beta}e^{-\left(\frac{\epsilon}{\epsilon_{br}}\right)^{b}}$	–	0.75	1.98	0.83	0.91	17

- The errors are not random
- **Most of the chi² is accumulated near the break energy due to the ARBITRARY parametrization of the spectral roll-off**
- Similar results for phase-resolved spectra

Vela



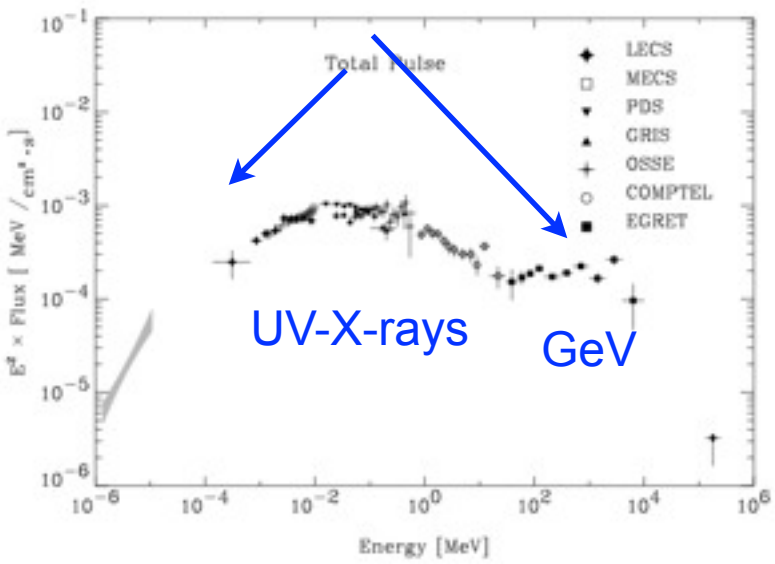
- Double power-law are as good as exp.

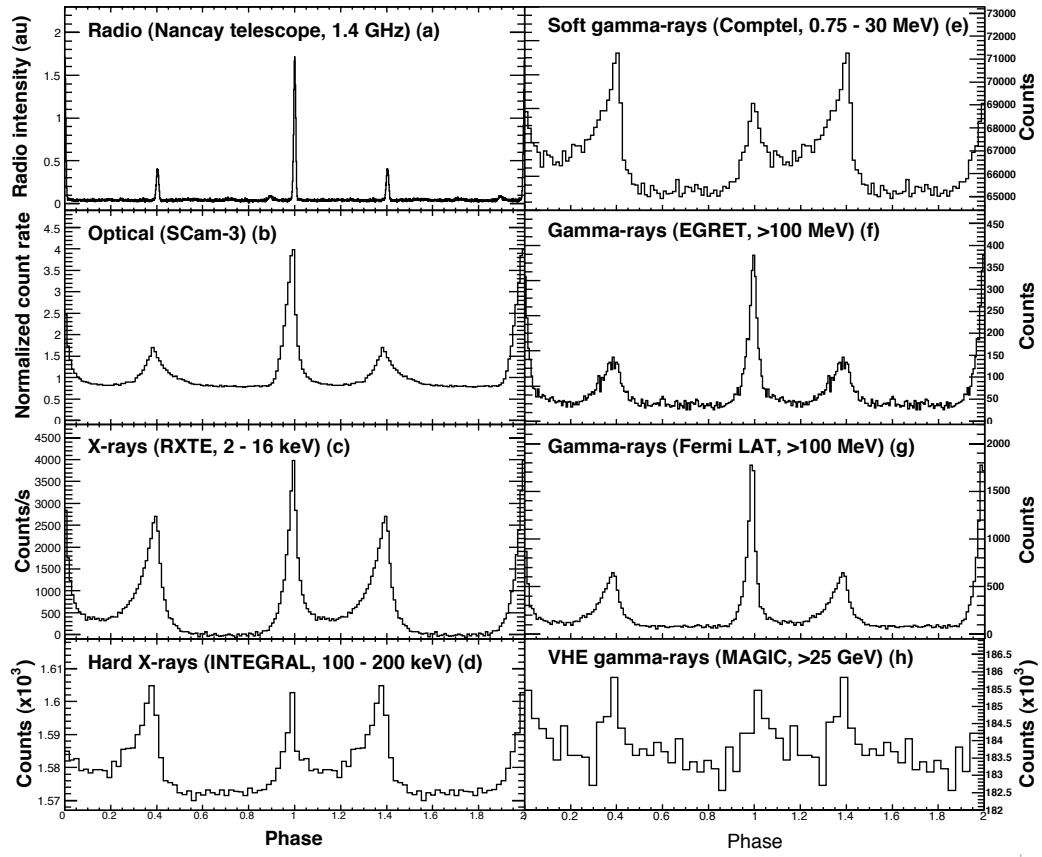
- Various parametrizations of roll-offs reduce chi^2

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

Crab spectrum & profiles

Two bumps





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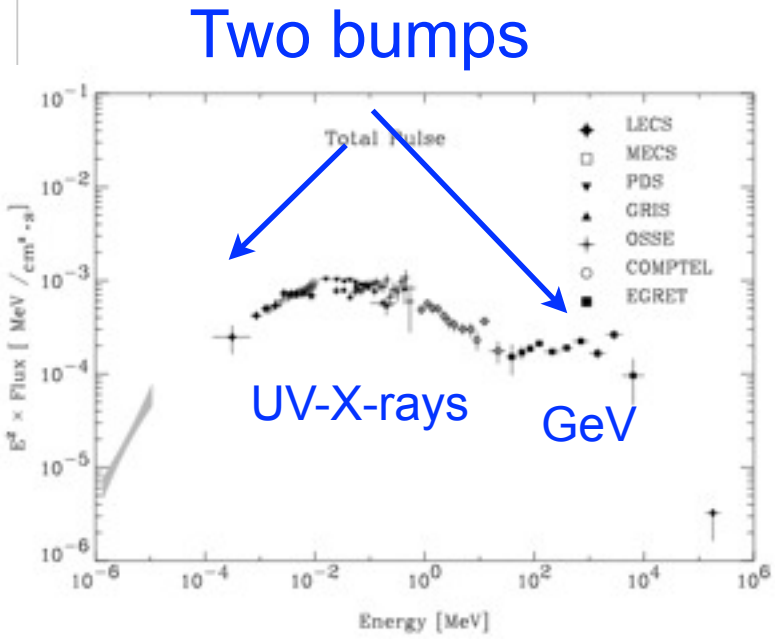

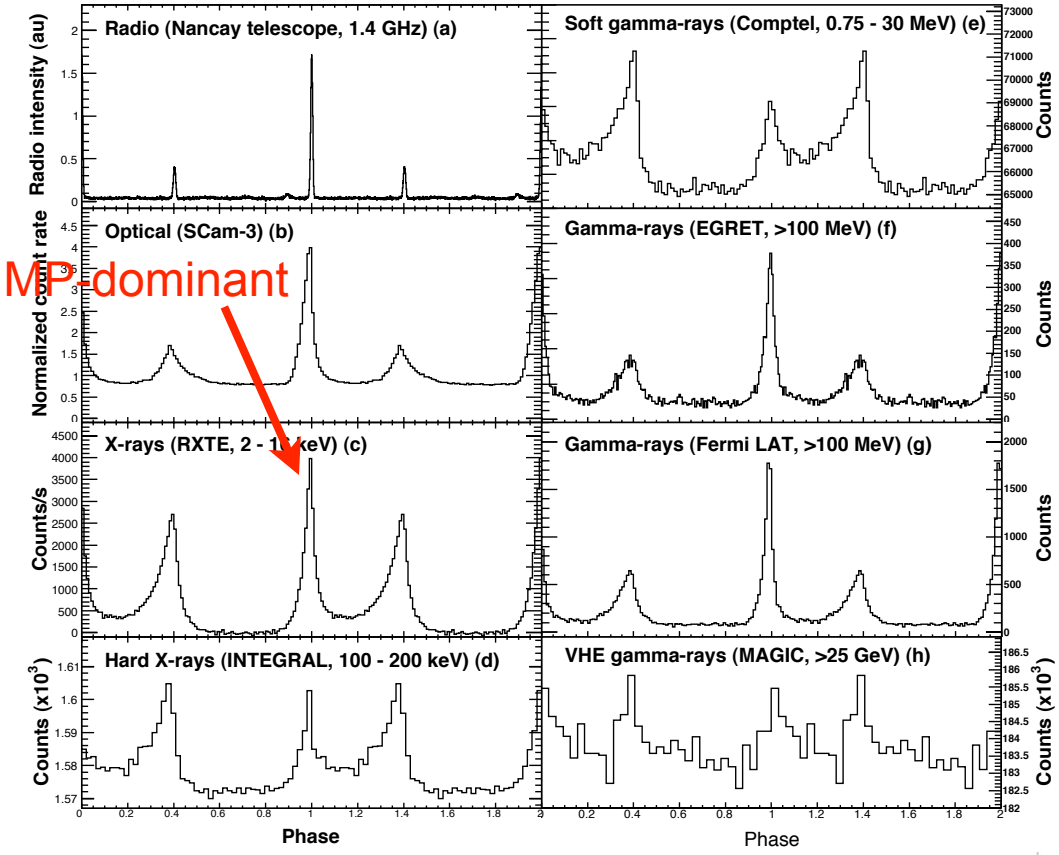

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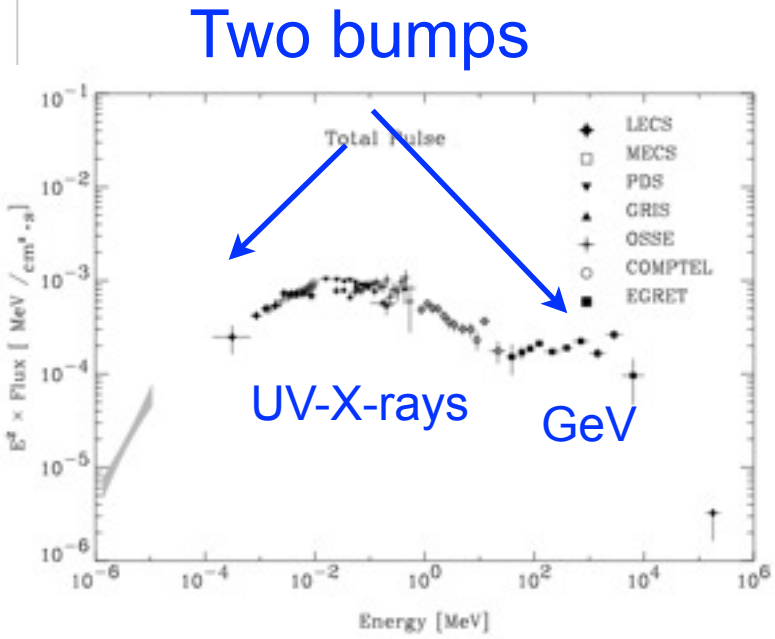

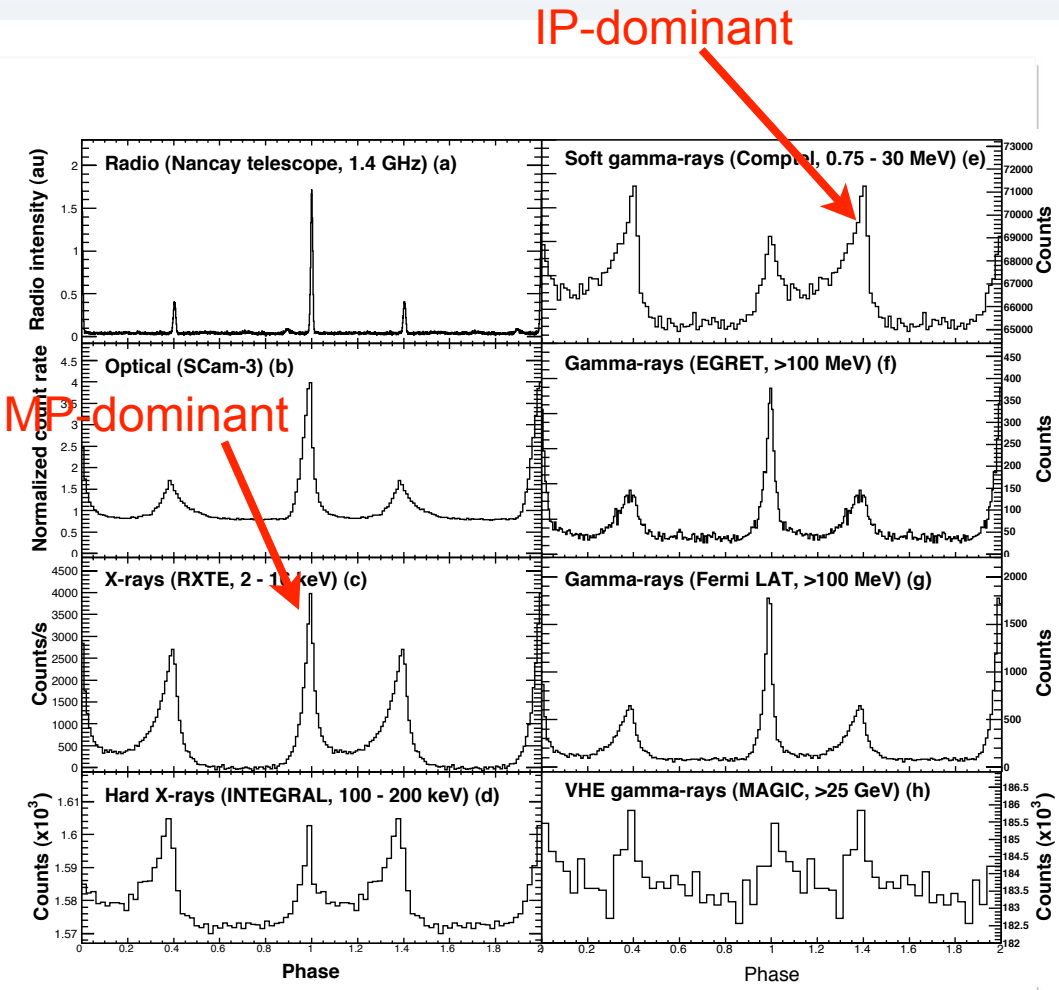

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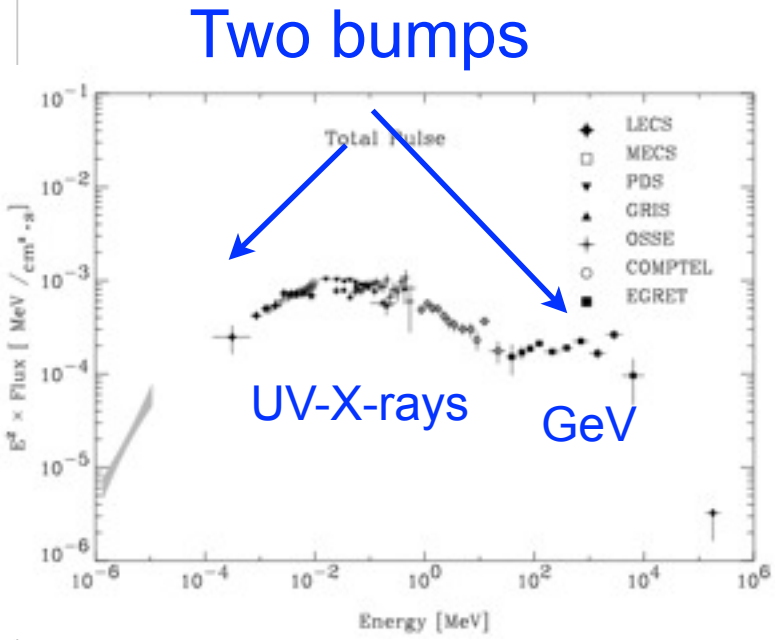

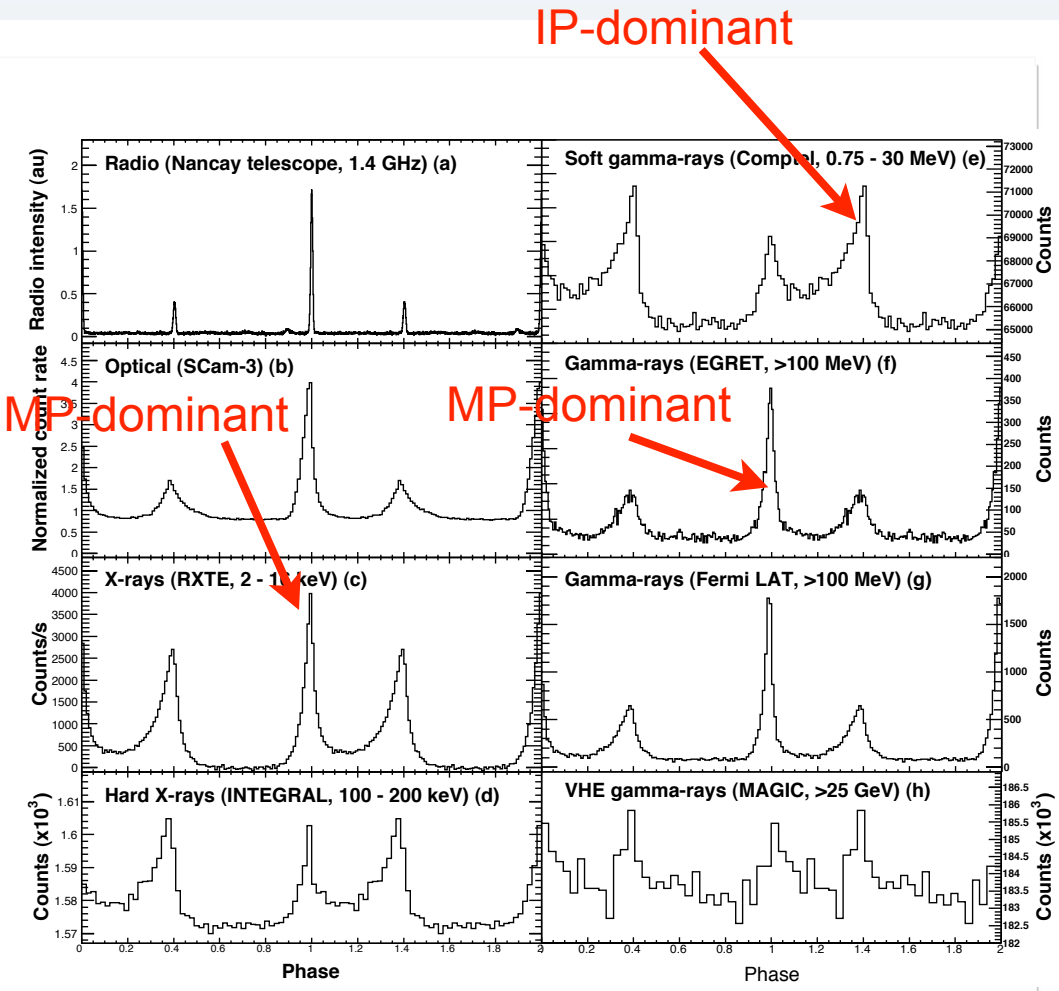

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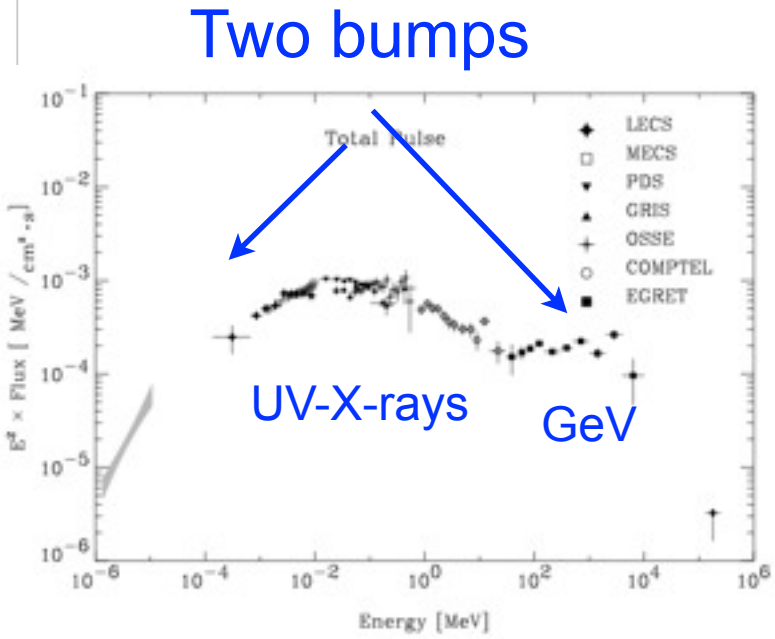

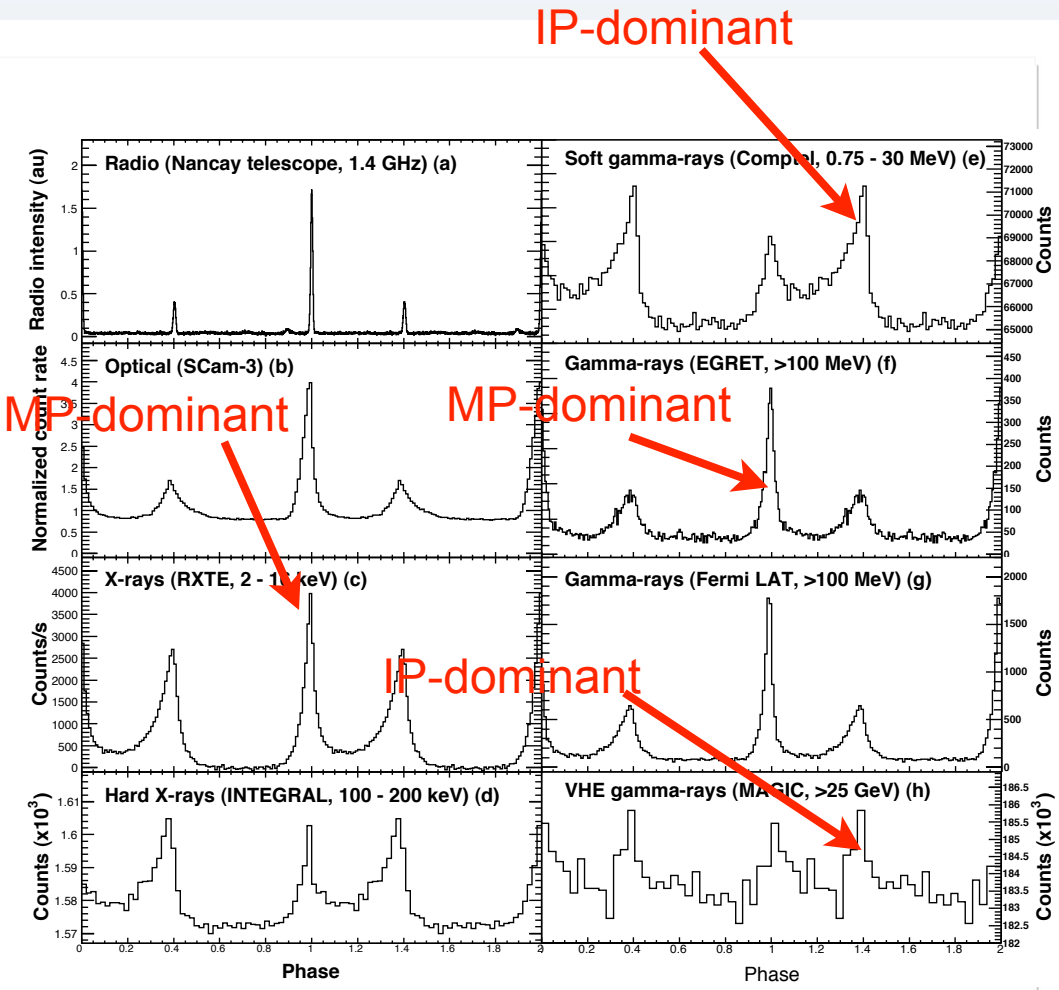

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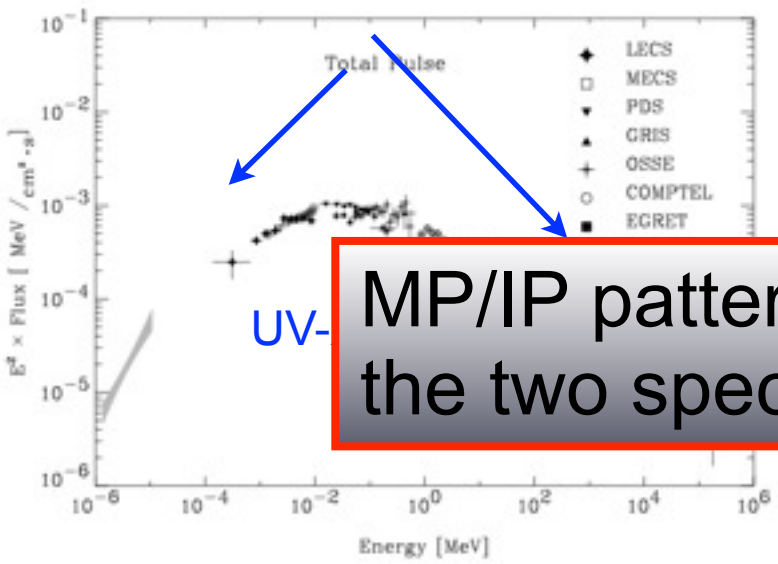
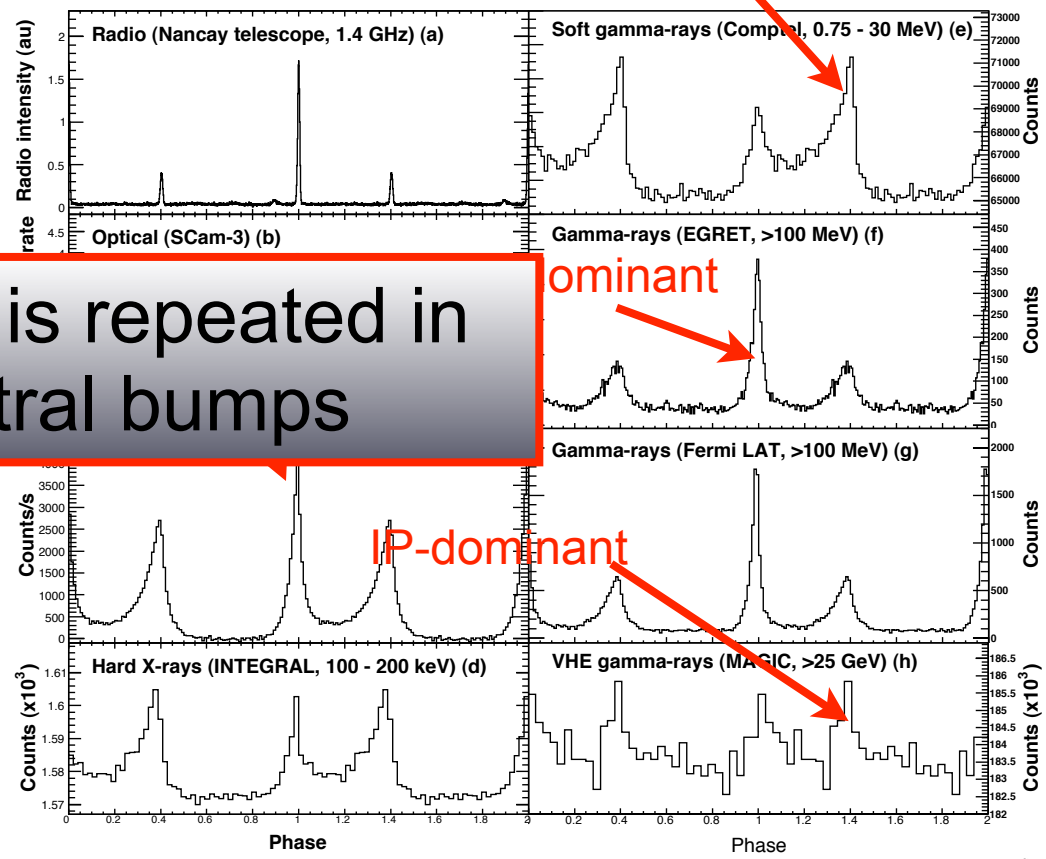


UV-

MP/IP patter is repeated in the two spectral bumps

IP-dominant



ominant

IP-dominant

Scaling of L_γ with E_{sd}

- Acceleration by $E_{||}$ = radiation losses

$$L_\gamma = ec \times \eta B \times \lambda n_{GJ} \times \frac{V_{em}}{R_{LC}^3} \times R_{LC}^3$$

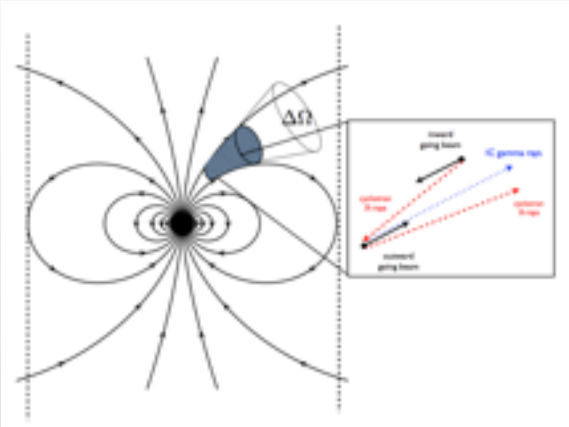
$$L_\gamma = \lambda \eta \eta_V \dot{E}_{SD}$$

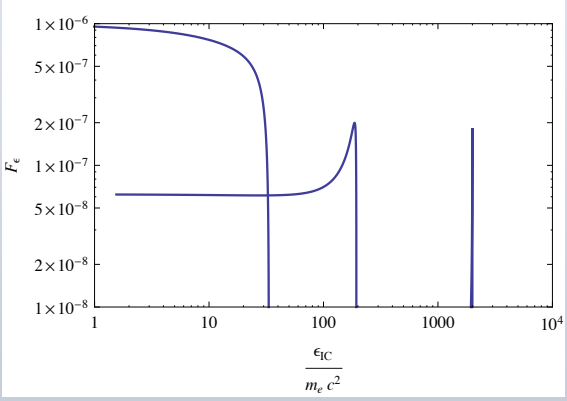
- **Linear!**
- (Everyone uses $L_\gamma \propto \sqrt{\dot{E}_{SD}}$ - potential-limited, from polar caps)
- Known problem of too many observed pulsars
- uncertainty of the geometrical parameter η_G and accelerating E-field η

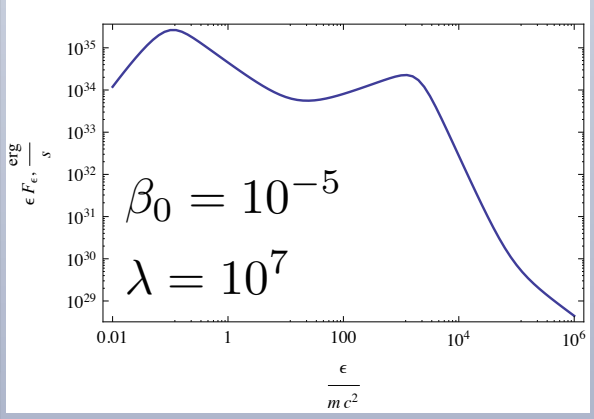
IC model (in progress)

- ``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 $v_{\parallel}$

- Two counter-streaming components:
- optical-X-ray: boosted cyclotron-synchrotron
- gamma rays: IC scattering of the ``first'' cyclotron photons by the ``second'' particles
- Deep in KN regime

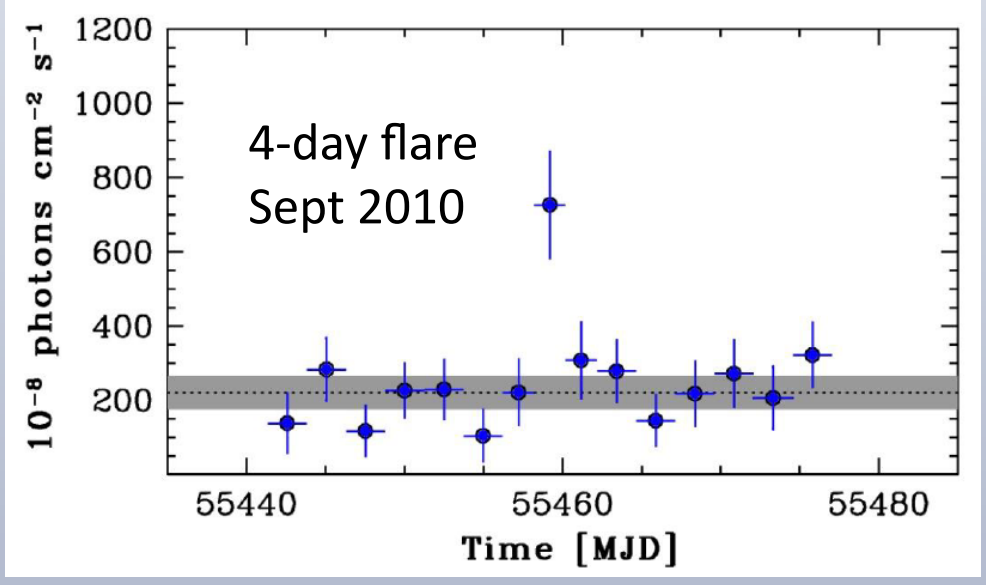






2. Crab nebula flares seem inconsistent with the stochastic shock acceleration

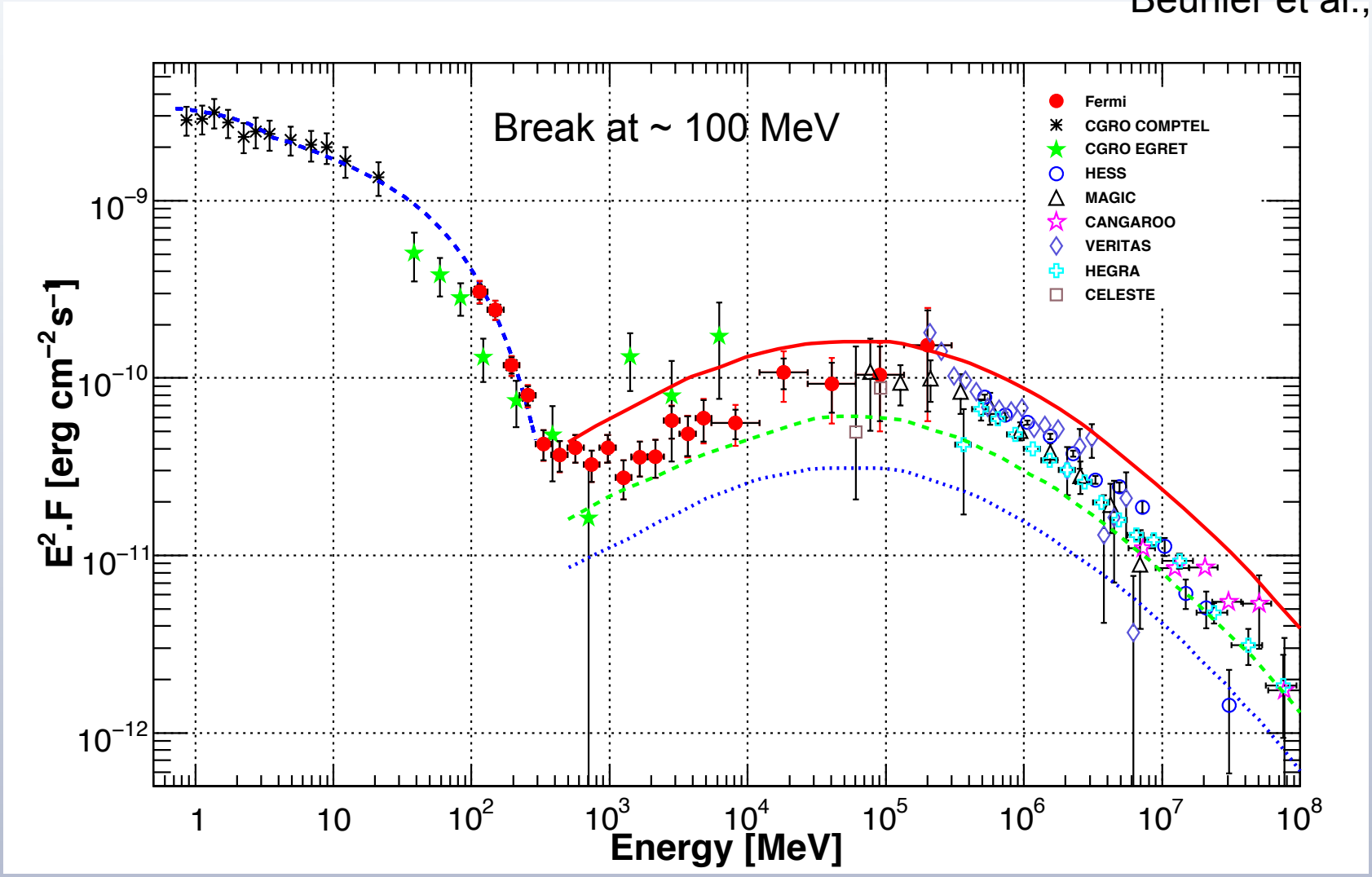
(with Eric Clausen-Brown)



Tavani et al. 2011

Crab nebula

Tavani et al. 2010
Beuhler et al., 2011



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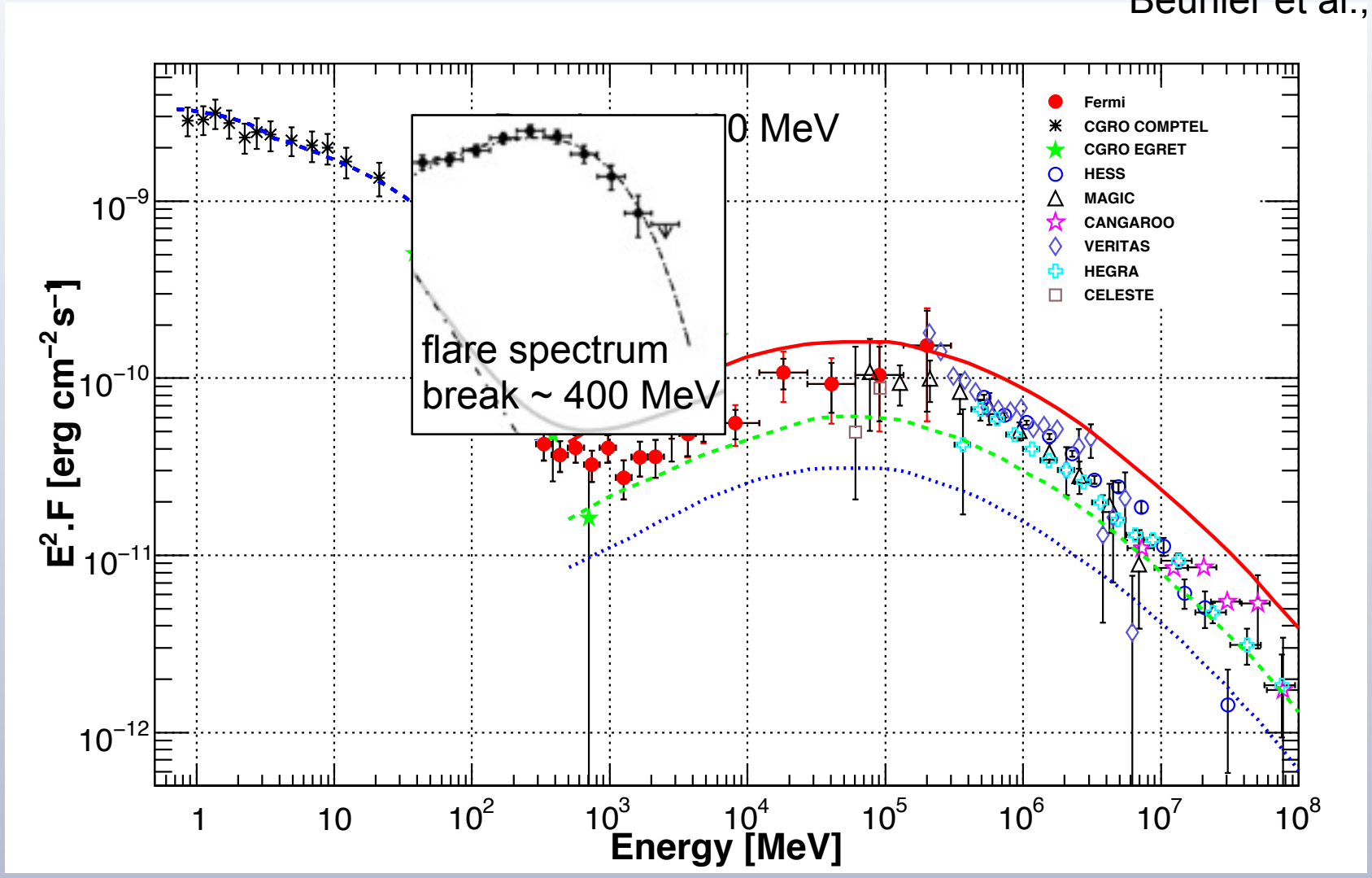

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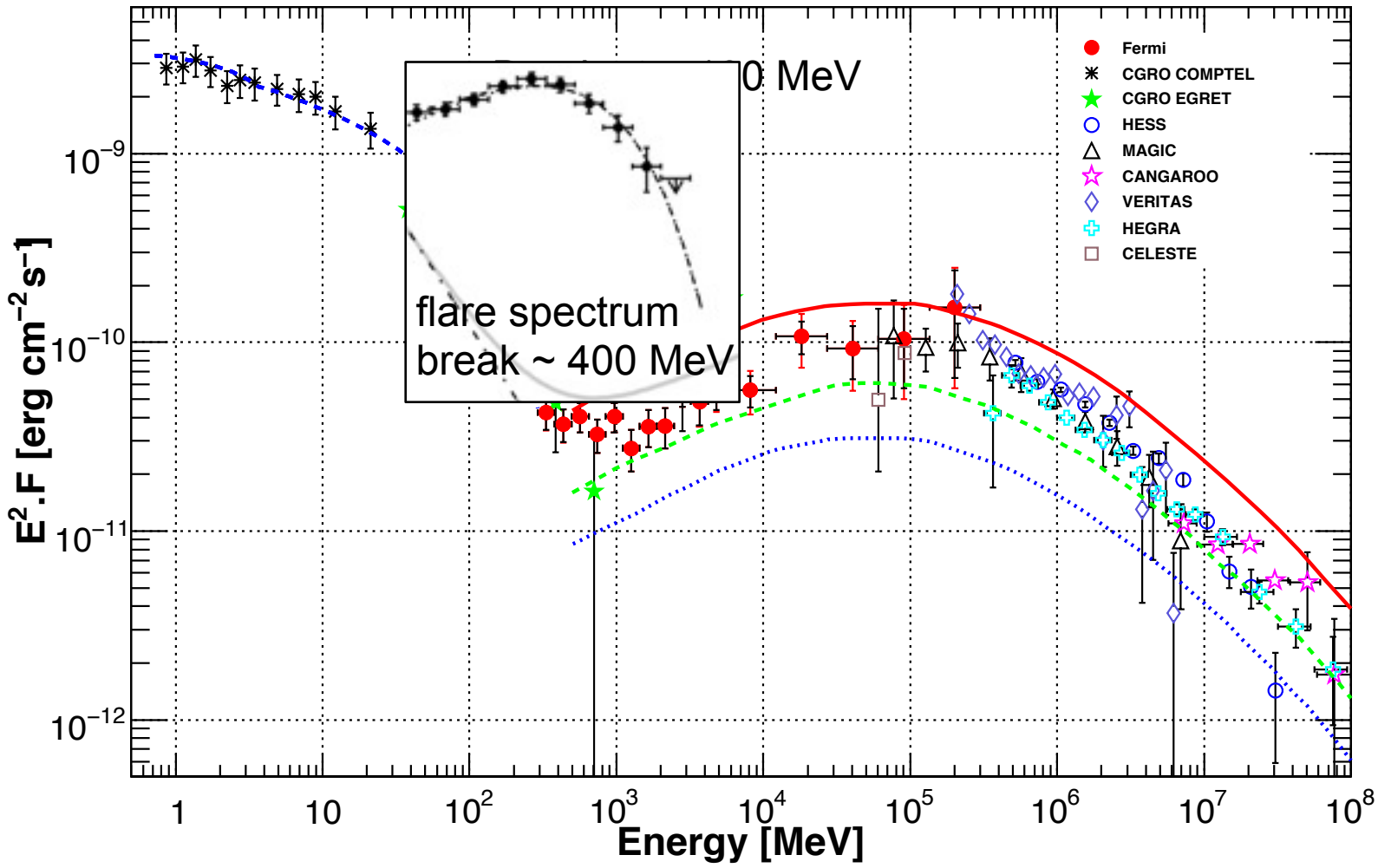

Flare time scales << nebular dynamical time, termination shock size

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)
- Typically eta < 10^{-2} for stochastic shock acceleration: this excludes stochastic acceleration schemes.

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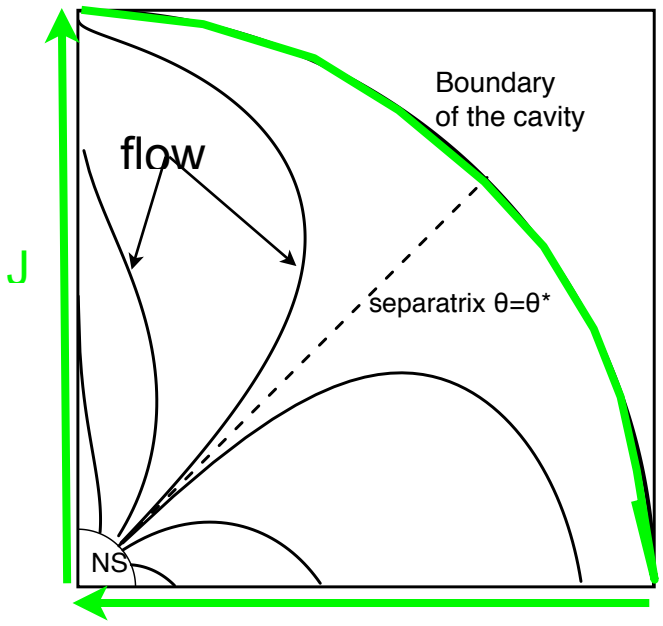
Doppler boosting:

$$\omega \to \delta\omega$$
$$I \propto \delta^{2+\alpha}, \delta^{3+\alpha} \to \delta^{3-4}$$
$$\delta = \frac{1}{\Gamma(1-\beta\cos\theta)}$$

Even delta ~ 2 can increase the flux by 10-20 times
And short time scales - aka GRBs

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

High sigma model of pulsar wind nebulae *(Lyutikov 2010)*

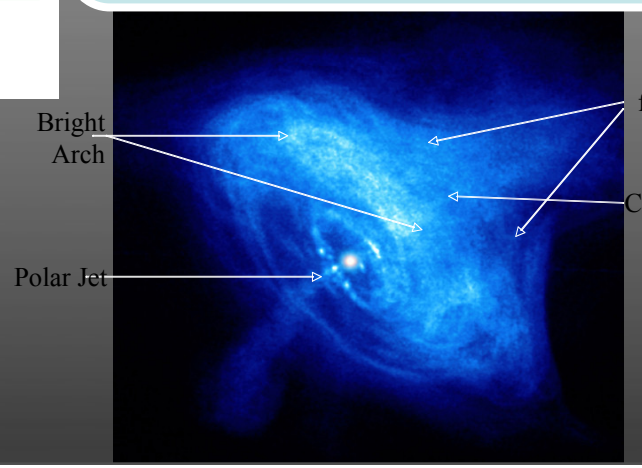


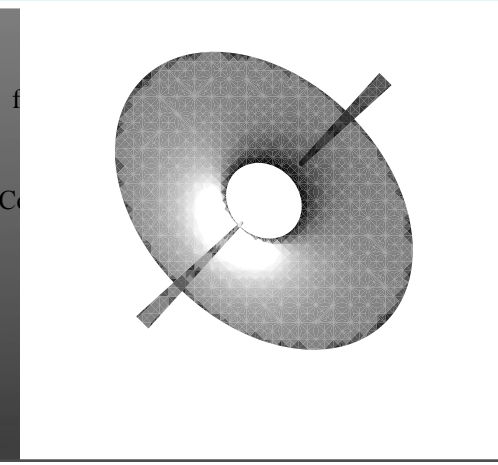
On the axis: toothpaste tube

- *Lyutikov (2010): 100 MeV is still too much.*
- *Ideal flow in the bulk, dissipation on boundary*
- "We propose that [...] the excessive magnetic flux is destroyed in a reconnection-like process"

High sigma model of PWNe

- No shocks! (Acceleration in reconnection)
- Relativistic bulk motion of emitting plasma



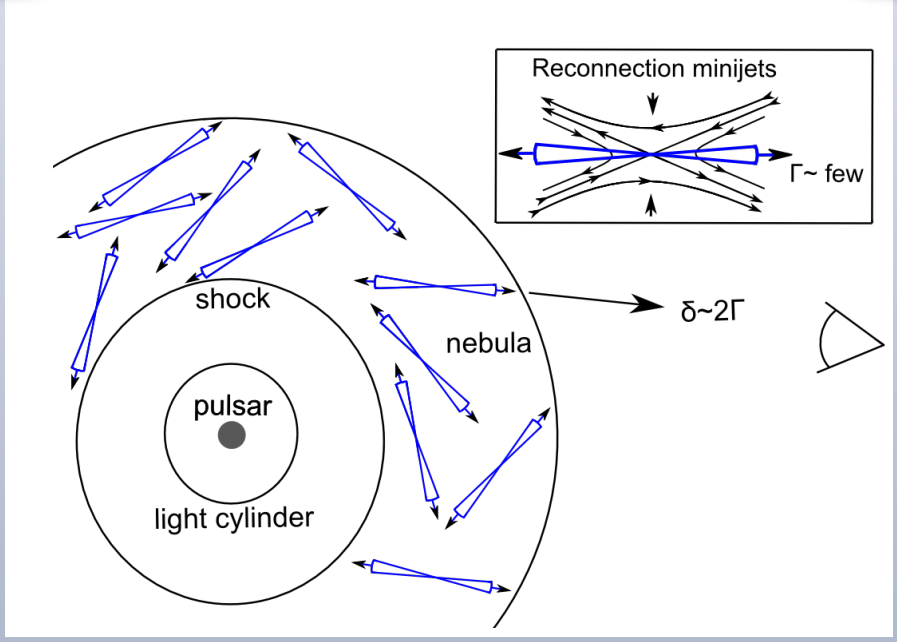


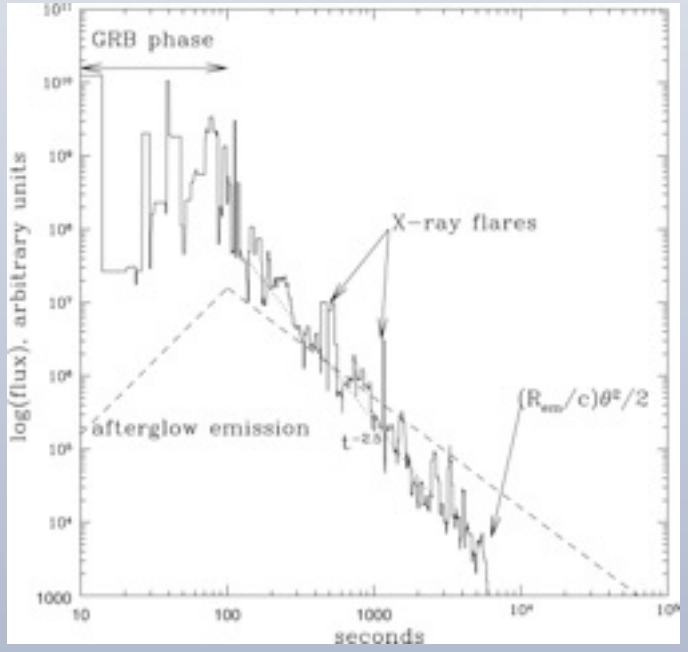
Nebula emission originates in spontaneous relativistic reconnection outflows

Clausen-Brown, Lyutikov 2012, MNRAS, accepted

- Relativistic reconnection: Lyutikov & Uzdensky, Lyubarsky, Hoshino
- $E \sim (v_{in}/c)\ B \sim B$
- outflow gamma >> 1

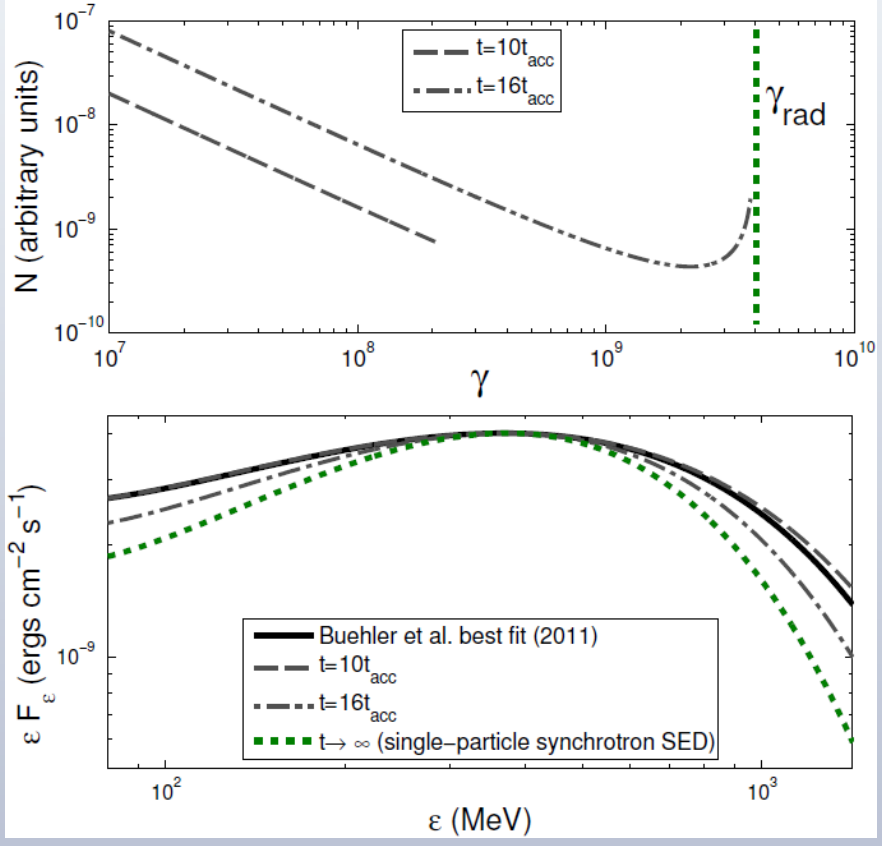
GRBs: Prompt emission produced by emitters moving randomly in the bulk frame (Lyutikov 2006).





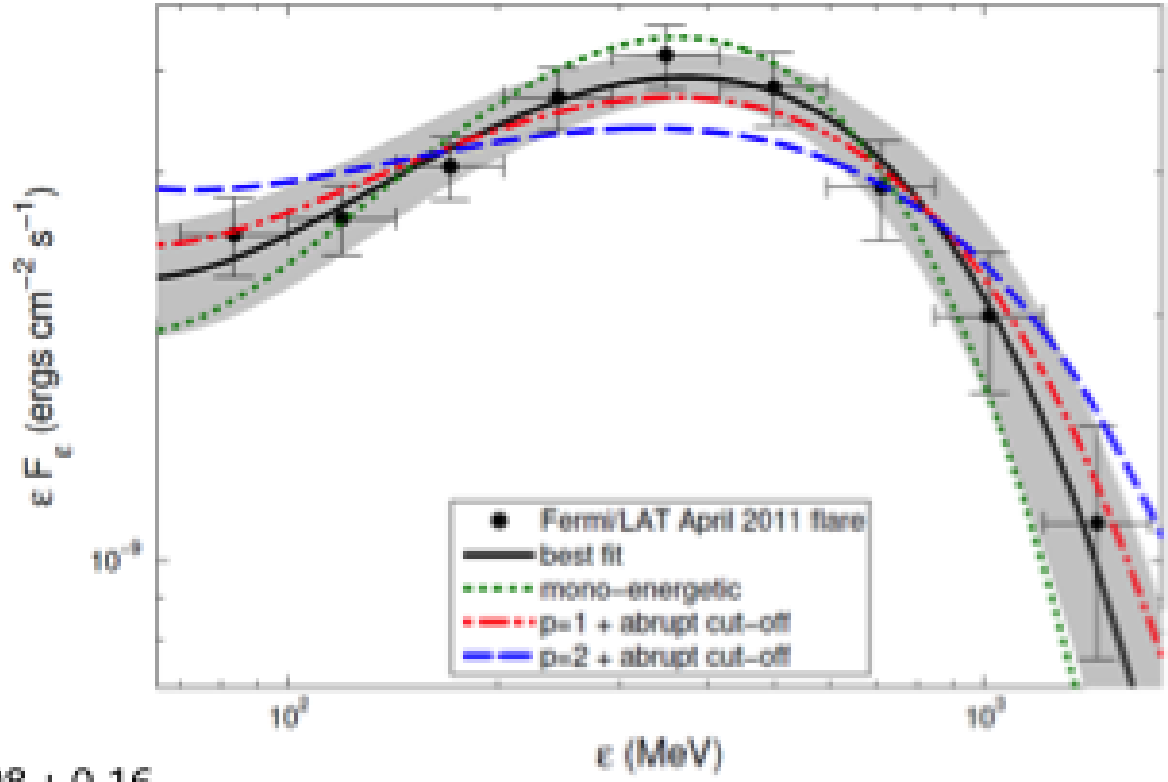
Radiation reaction-limited acceleration: pile-up

- Many reconnection models predict a particle spectrum of power-law p=1 (escape ~ r_L)
- 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

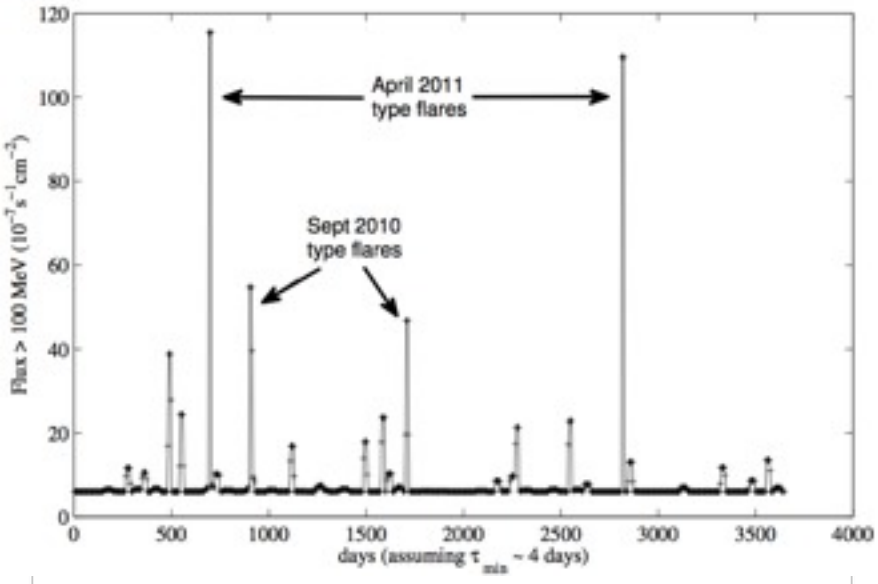
- Observed SED inconsistent with shocks, but is in line with reconnection particle spectrum + pile-up

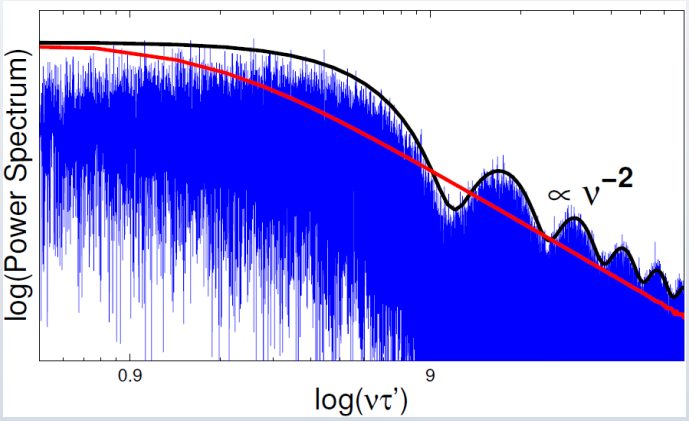
Flare statistics: isotropic flares

- probability of flare flux

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

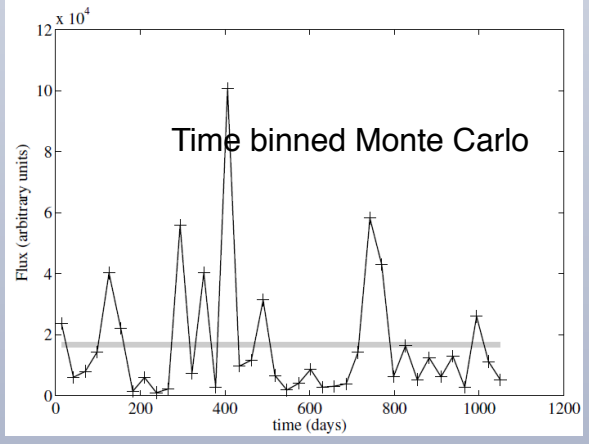
- average flare flux is dominated by bright rare flares.





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

std. dev. → $\dfrac{\sigma}{\langle F(t)\rangle} \approx \gamma_1 \approx \dfrac{\Gamma^{3/2}}{(n\tau')^{1/2}}$



Conclusion

- **Inverse Compton emission may be the dominant high energy emission mechanism in the majority of pulsars**

- **Reconnection is an important, perhaps dominant, mechanism of particle acceleration in PWNs.**