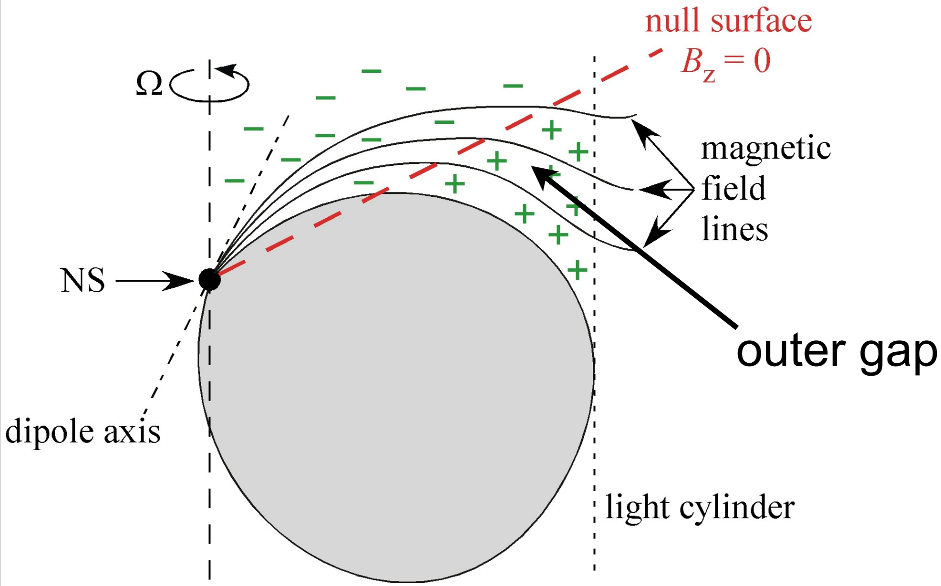
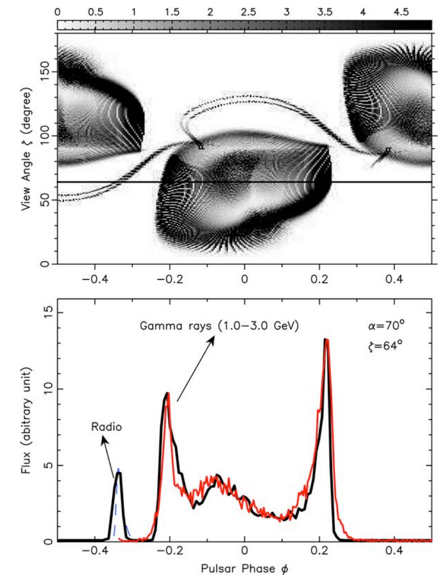
Spectra and emission mechanisms of gamma-ray pulsars

Maxim Lyutikov (Purdue U.)

Old story:

- Geometric model: good fits for outer/slot gaps

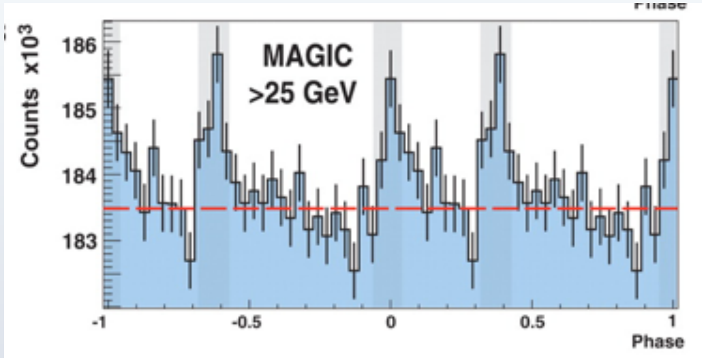




- Emit what? Curvature emission (Chen & Ruderman 1986)
- Hard to solve the full electrodynamic picture (eg. huge Lorentz factors needed, not screened by pair production)
- Clear prediction: above the break the spectrum must be exponentially suppressed

Bells and whistles

- The first whistle (2008): MAGIC sees Crab at 25 GeV
- Not enough by factor ~ few



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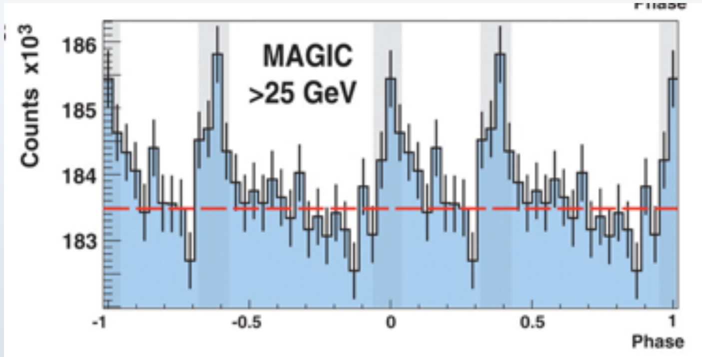
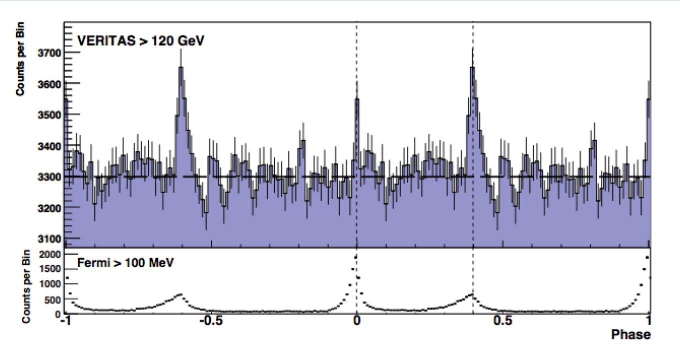
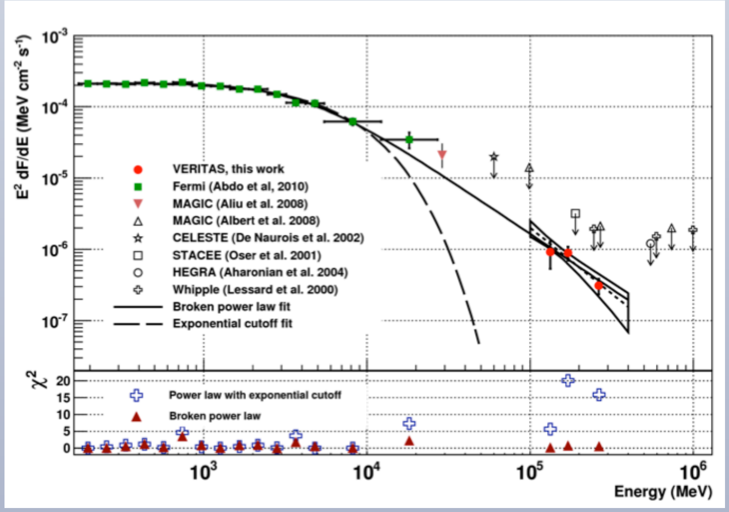


- The bell (2011): VERITAS sees Crab at > 100 GeV!
- Cut-off is non-exponential(!): Power-law
- IP is brighter than MP





Curvature emission near light cylinder is excluded

Lyutikov + 2012

- Astrophysical E-fields < B-field
- Equate acceleration by $E_{\|} = \eta\,(r/R_{LC})\,B$ 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 as the main emission mechanism (Lyutikov et al. 2011)

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models have E ~ 10^{-3} B

$\approx$ 150 GeV

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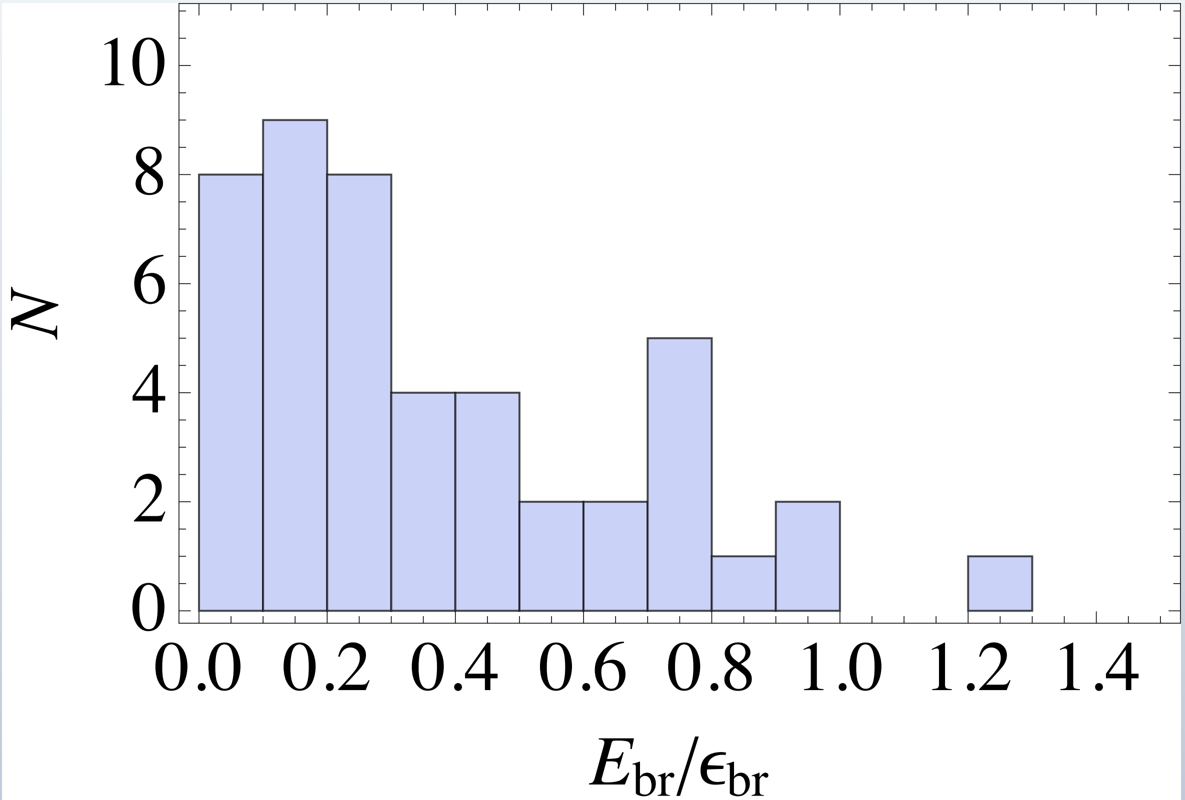
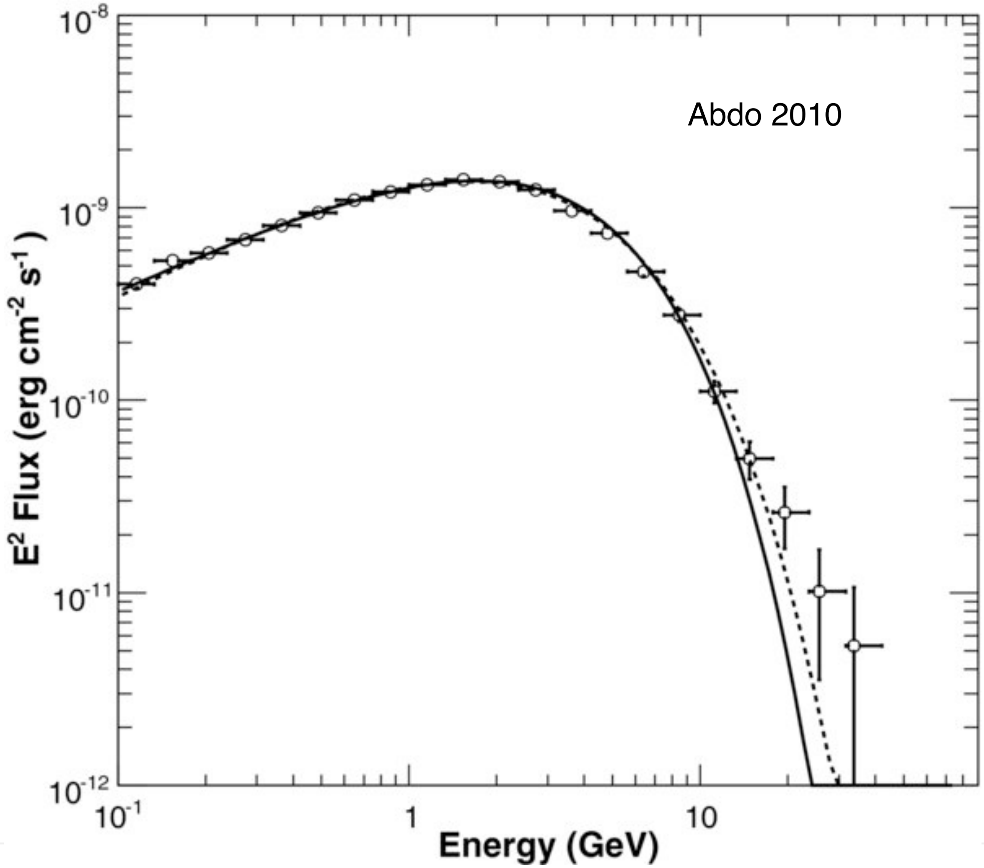
Other pulsar: maximal curvature energy at light cylinder



- 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

Physics is in the tail, not broadband

- curvature emission predicts exponential cut-off
- IC - most likely power-law



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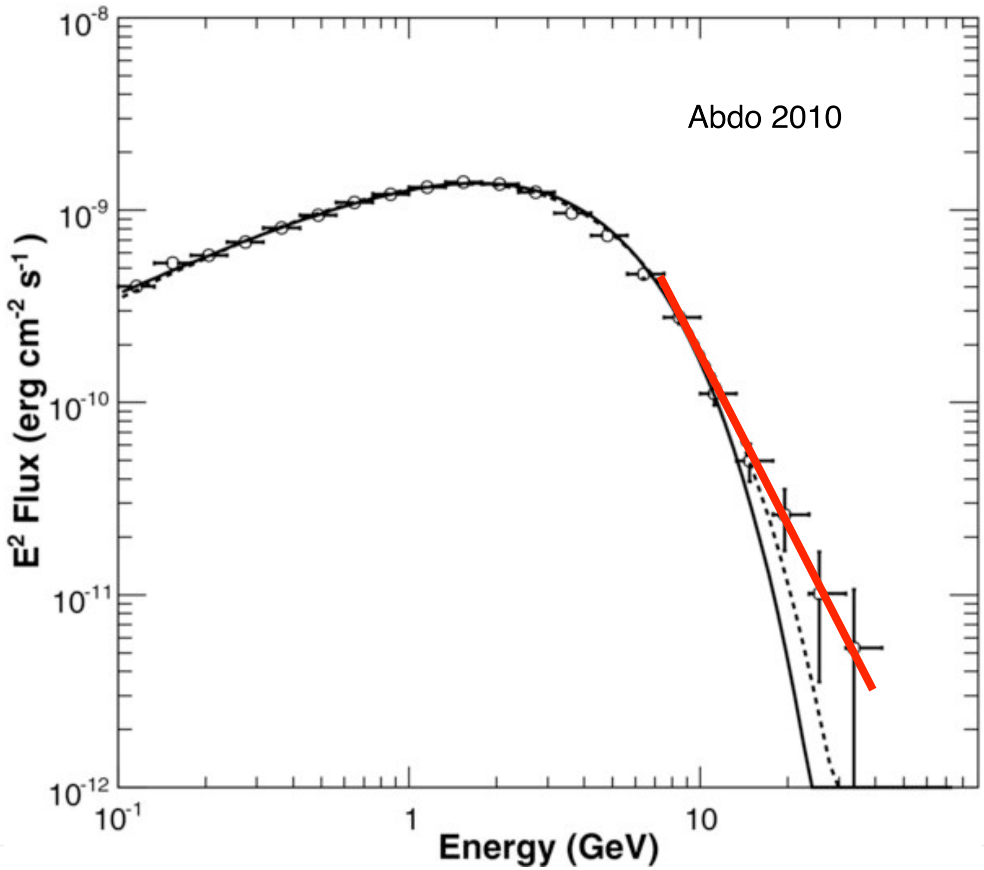
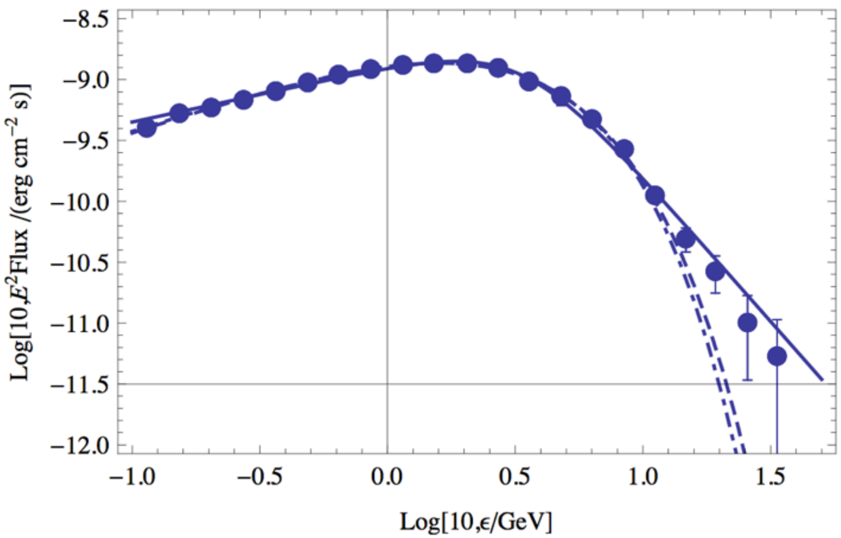
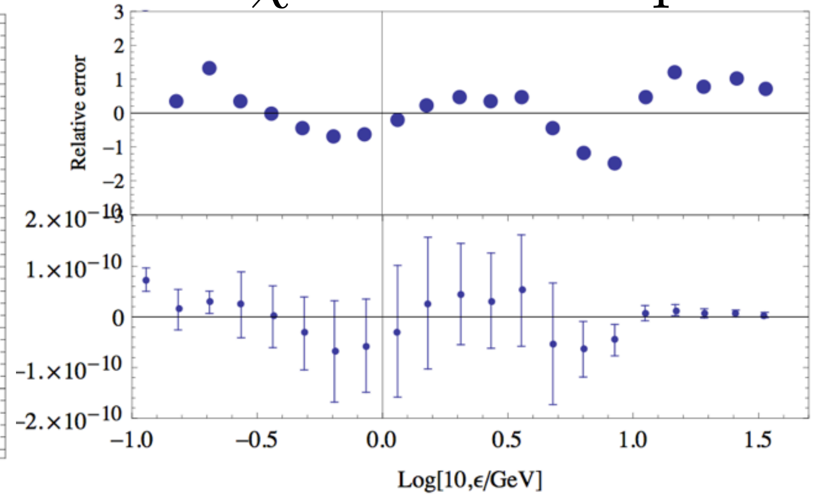


Lyutikov (2013)

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 chi^2 is accumulated near the break energy due to the ARBITRARY parametrization of the spectral roll-off**
- Similar results for phase-resolved spectra

Richards and Lyutikov (2018)

Pulsar	Power-law spectral index above 10 GeV	Power-law fit chi-square / ndf (probability)	Exponential cut-off fit chi-square / ndf (probability)	Notes
PSR J0007+7303	-3.69 ± 0.016	5.26 / 3 (0.15)	0.95 / 3 (0.81)	
PSR J0633+1746	-5.12 ± 0.16	5.54 / 2 (0.06)	4.87 / 2 (0.09)	Geminga
PSR J0835–4510	-4.54 ± 0.08	14.1 / 5 (0.02)	8.06 / 5 (0.15)	Vela
PSR J2021+3651	-4.73 ± 0.54	1.10 / 1 (0.29)	2.40 / 1 (0.12)	

Table 1: Spectral indices for the power-law fits, reduced chi-squares, and fit probabilities for the SED of each pulsar.

- Fits to > 10 GeV
- The fit results for all four of the pulsars analyzed in this study do not allow any firm claim to be made about the shape of the spectra above 10 GeV
- Four draws and one win for power-law (Crab)

Vela & Geminga (no published paper yet, just proceeding)

- Vela: Detected at 3 TeV (Djannati-Ataï 2017)
- Geminga above TeV (Lopez 2018)
- According to rumors, Geminga point is on the continuation of Fermi spectrum, Vela's above (extra component?)

Vela & Geminga
(no published paper yet, just proceeding)

- Vela:)
- Gem
- Acc ne continuation of Fe nponent?)

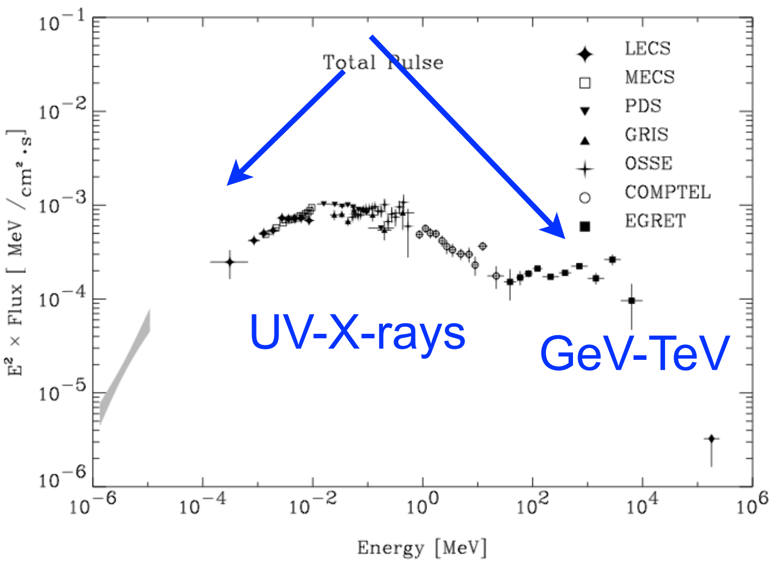
[Paul Ray](#)
Maxim Lyutikov and Alice Harding shake on a bet over whether the gamma-ray spectrum of the Vela Pulsar is power-law rather than exponentially cutoff above 10 GeV. — at Aspen Center for Physics.

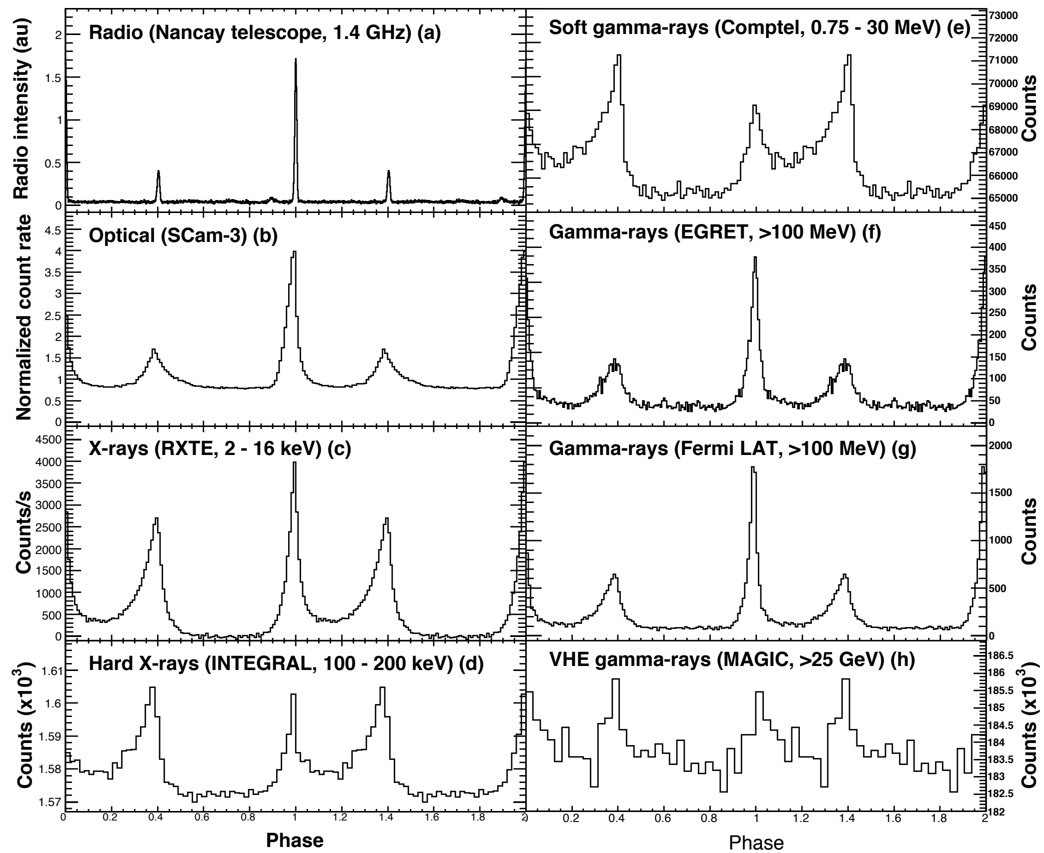
Detection of all the brightest gamma-ray pulsars above TeV excludes curvature emission.

Must be IC.

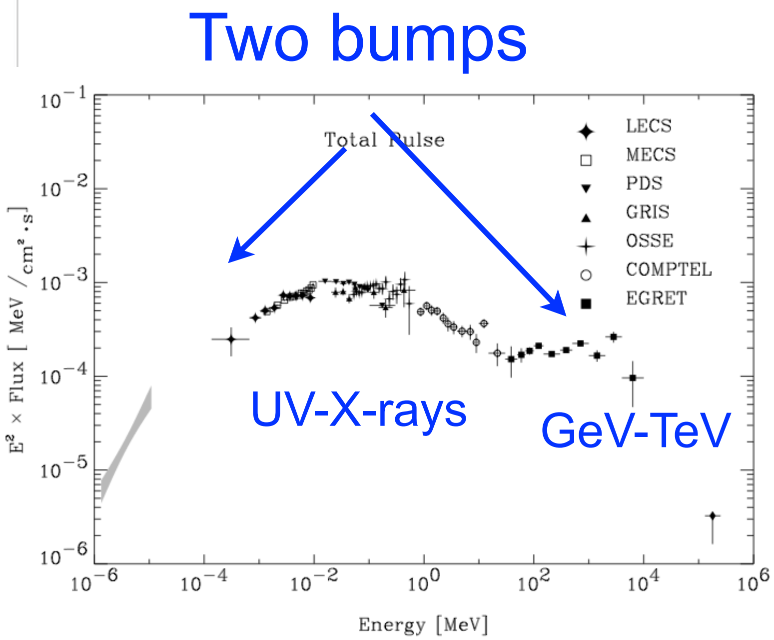
Crab spectrum & profiles

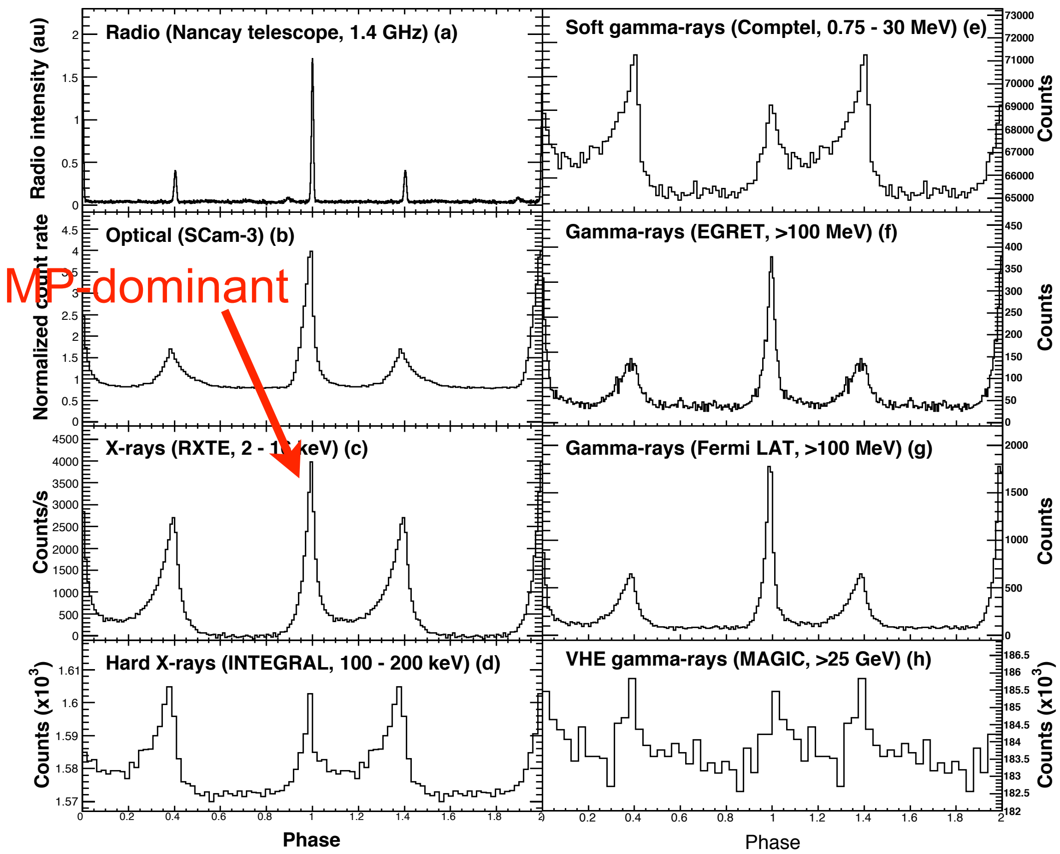
Two bumps





Crab spectrum & profiles





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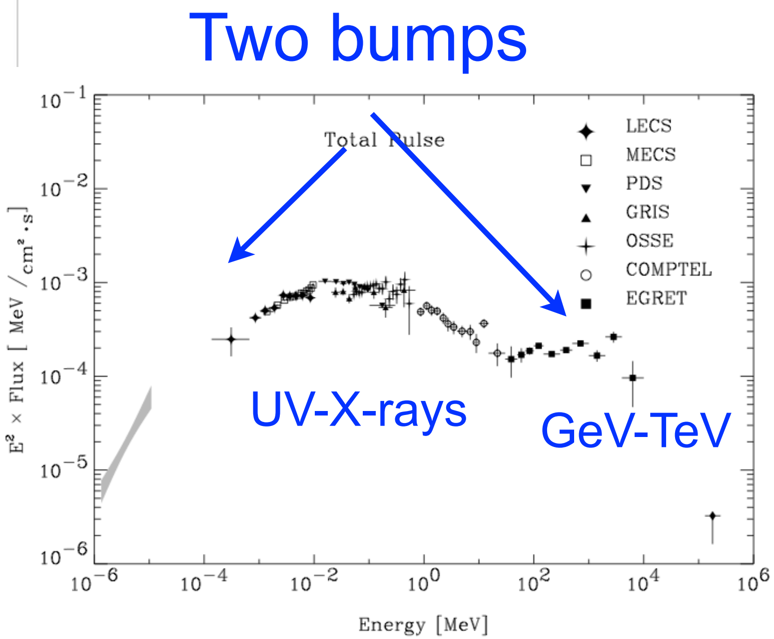

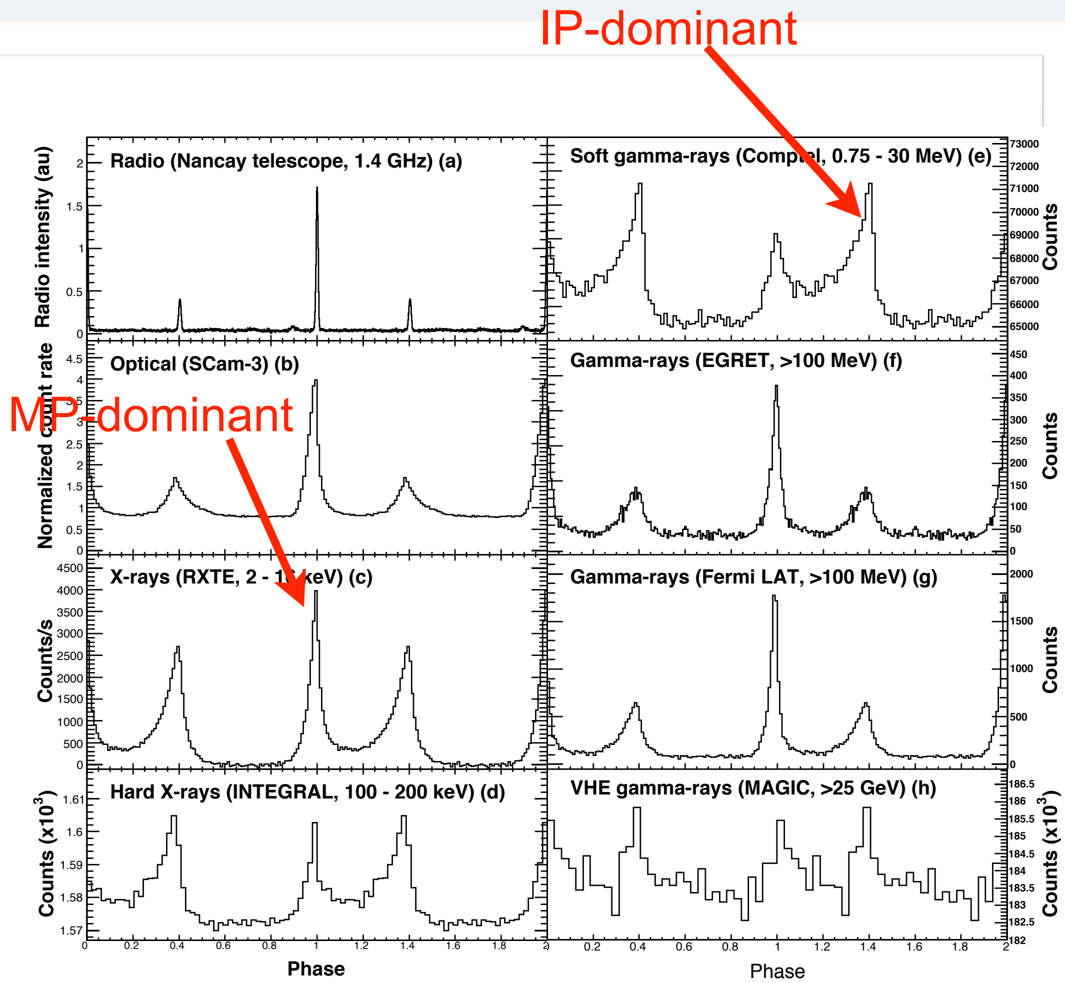

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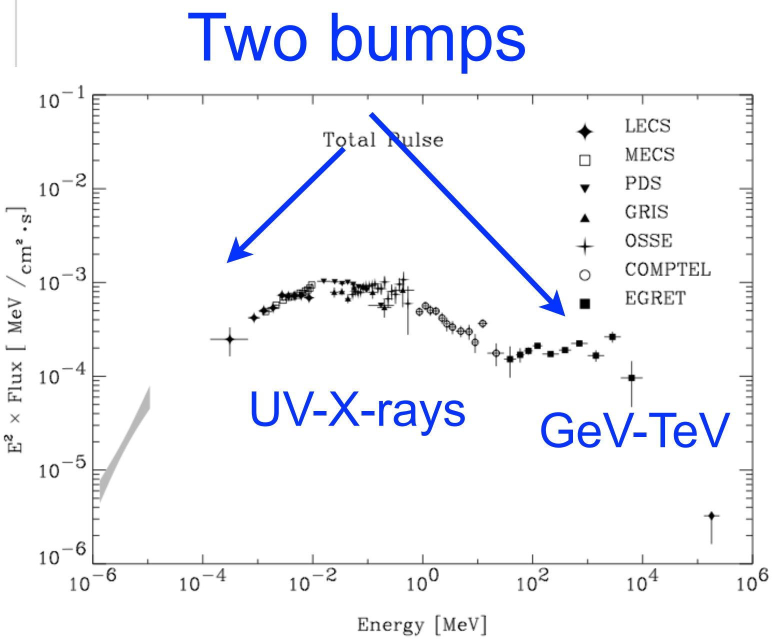

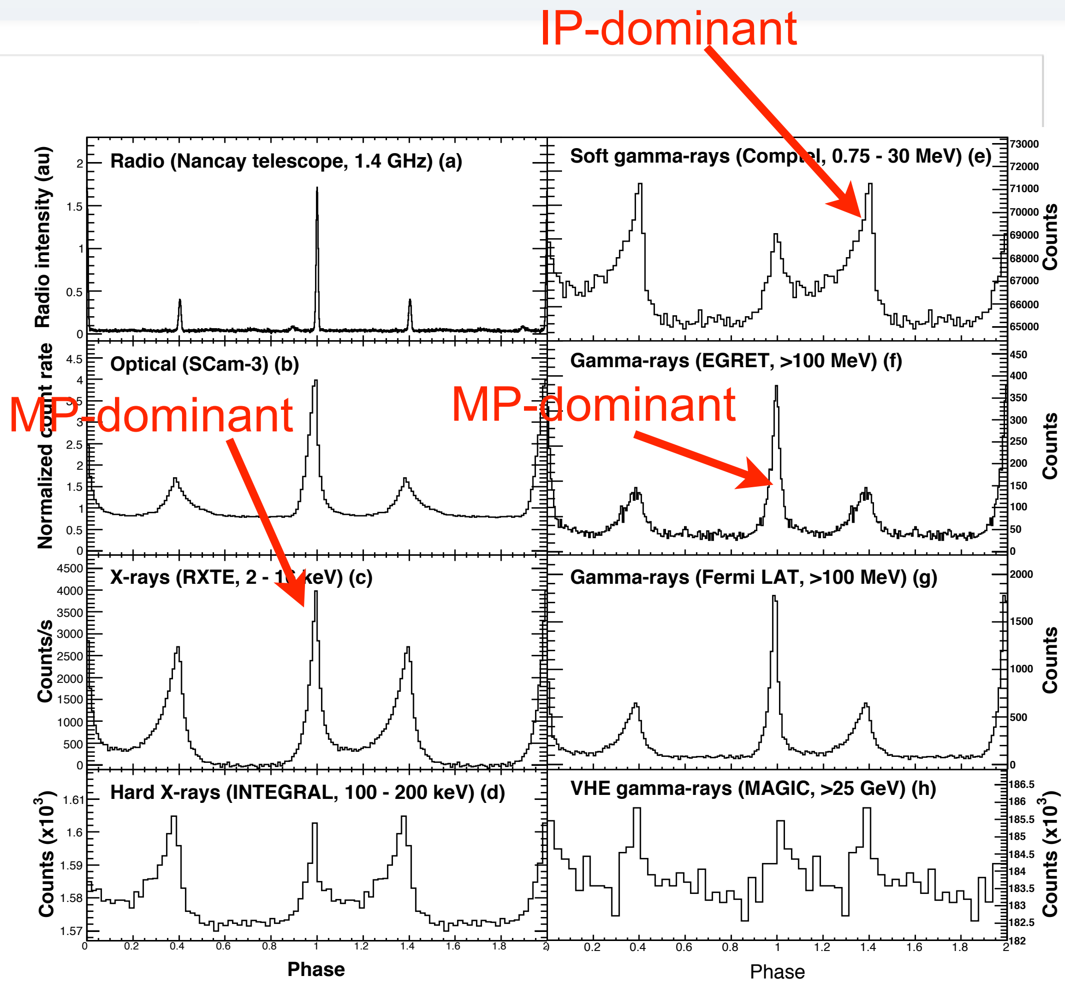

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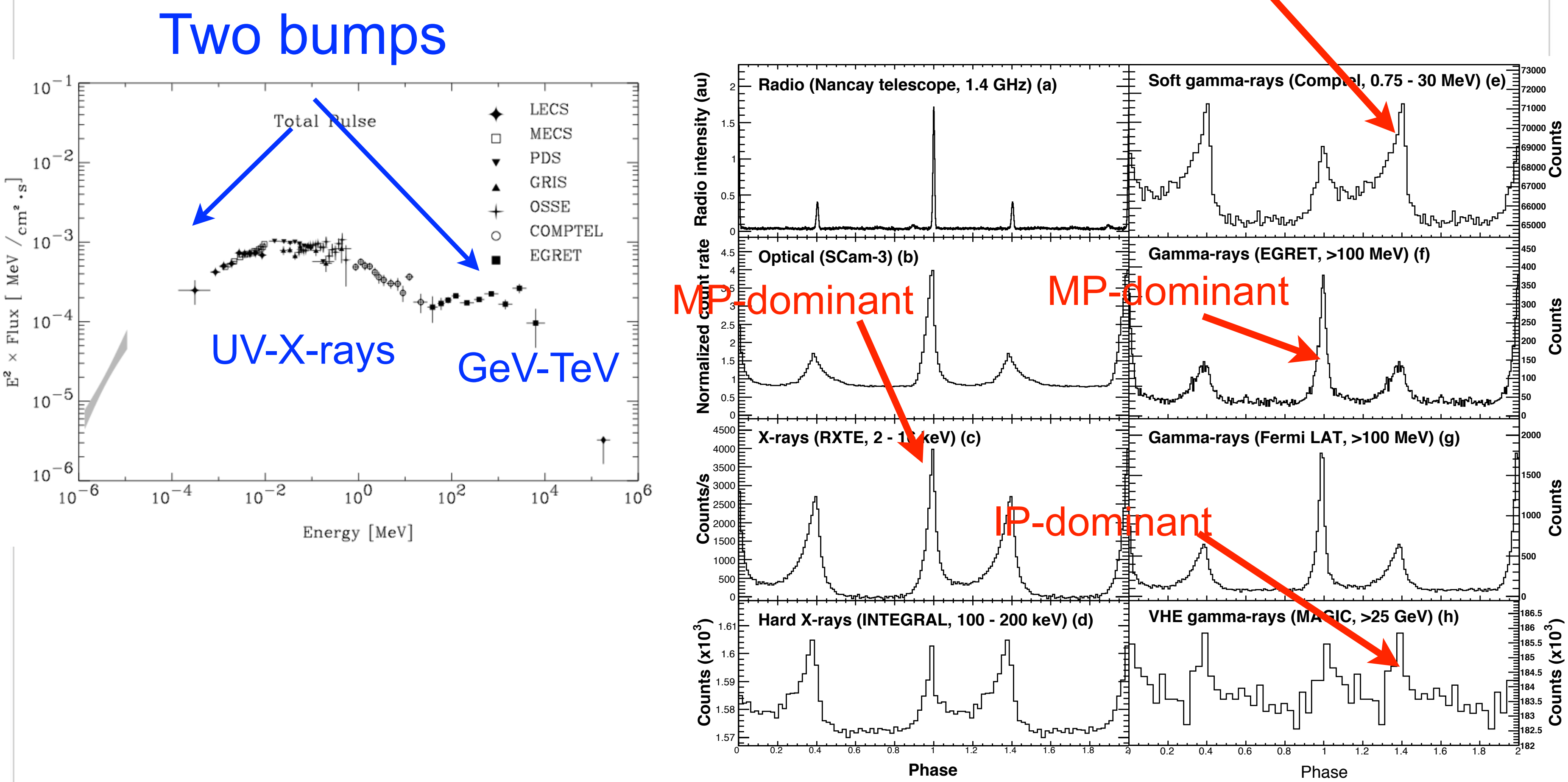

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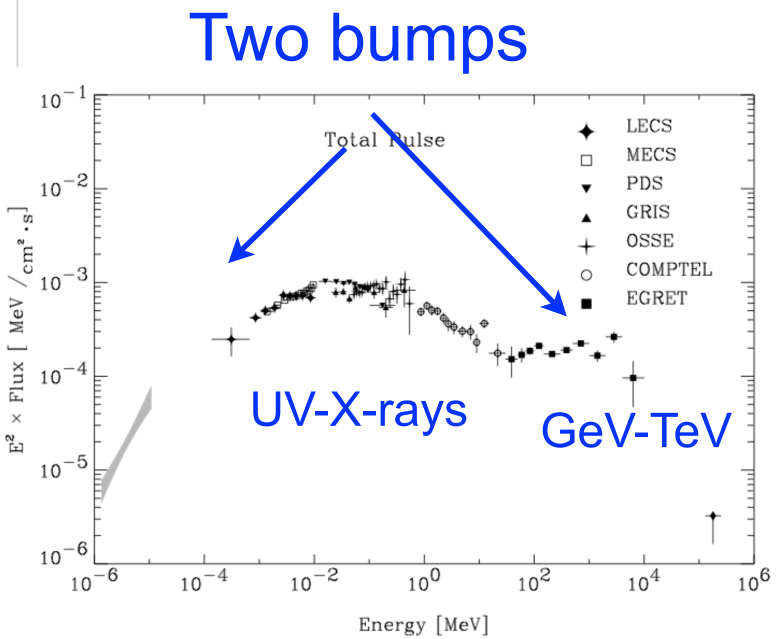
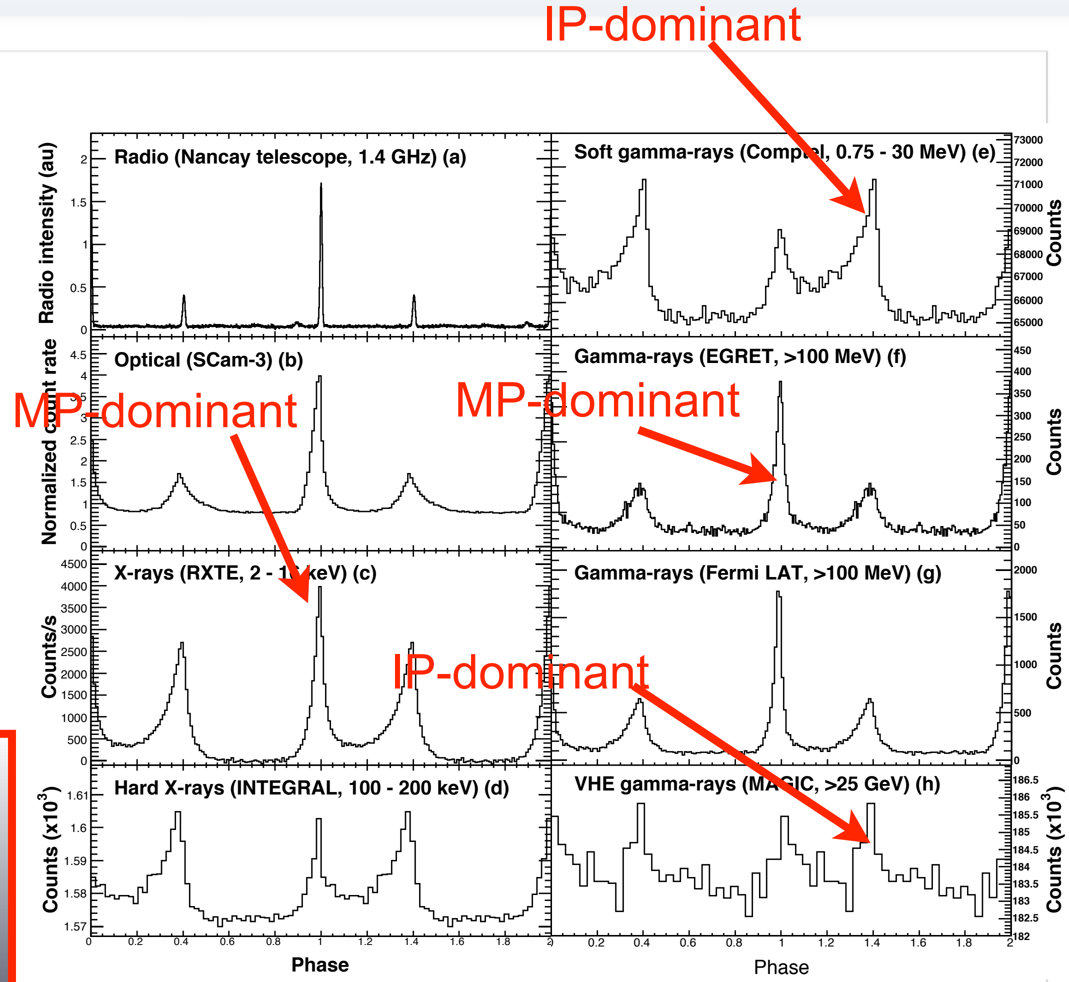
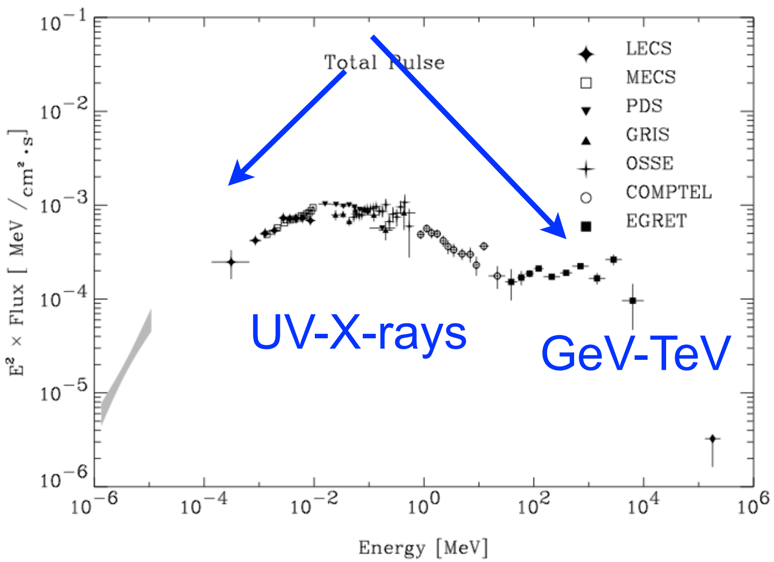


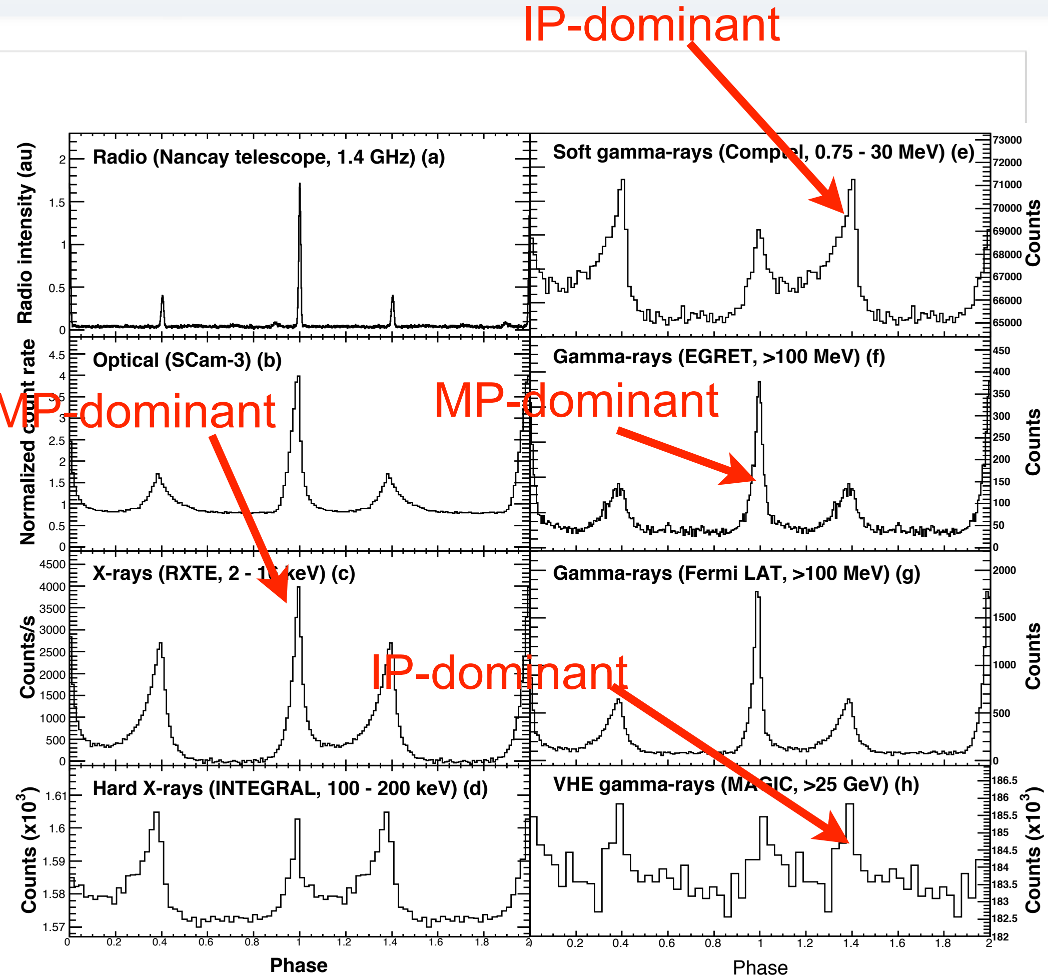


MP/IP patter is repeated in the two spectral bumps

Crab spectrum & profiles

Two bumps





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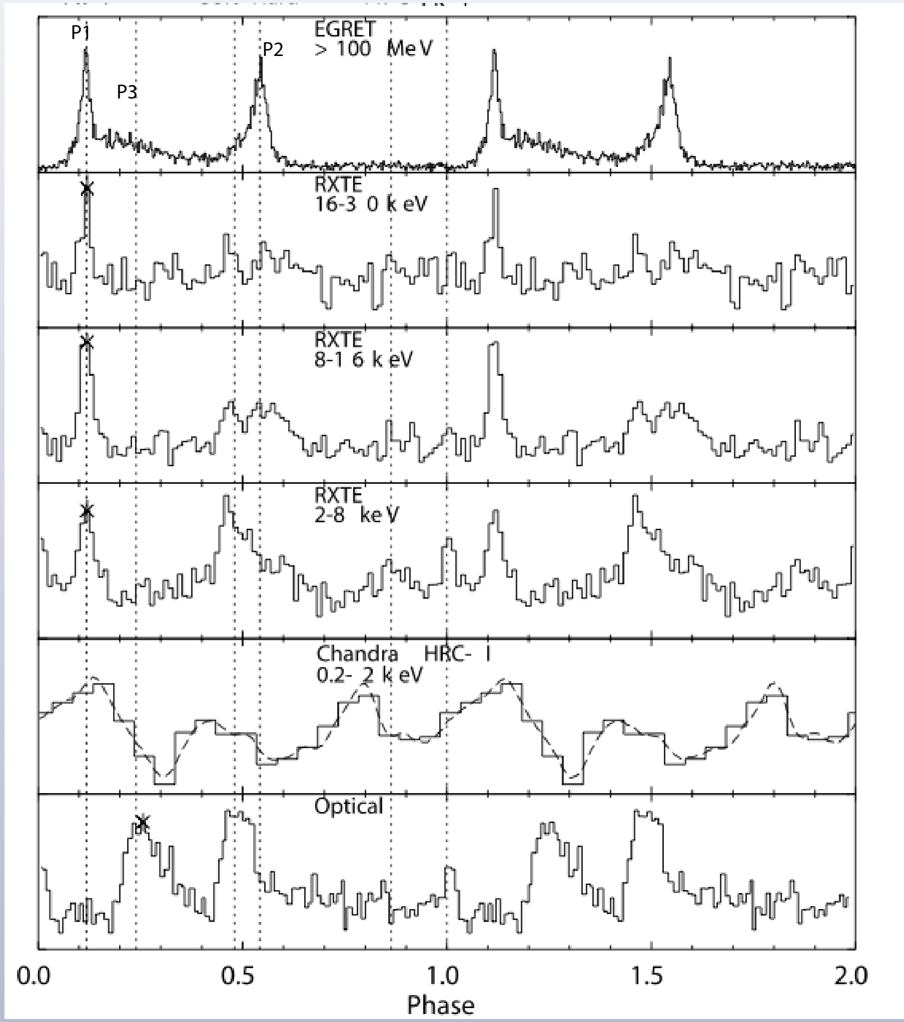
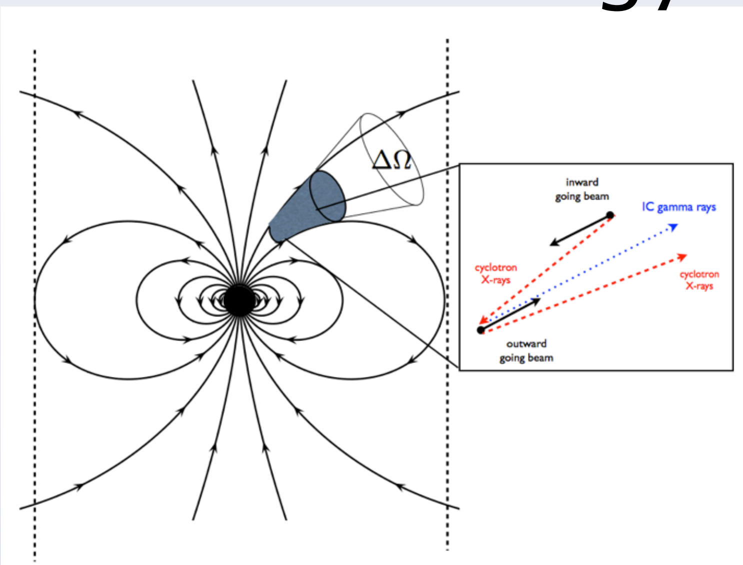
Consistent with IC model

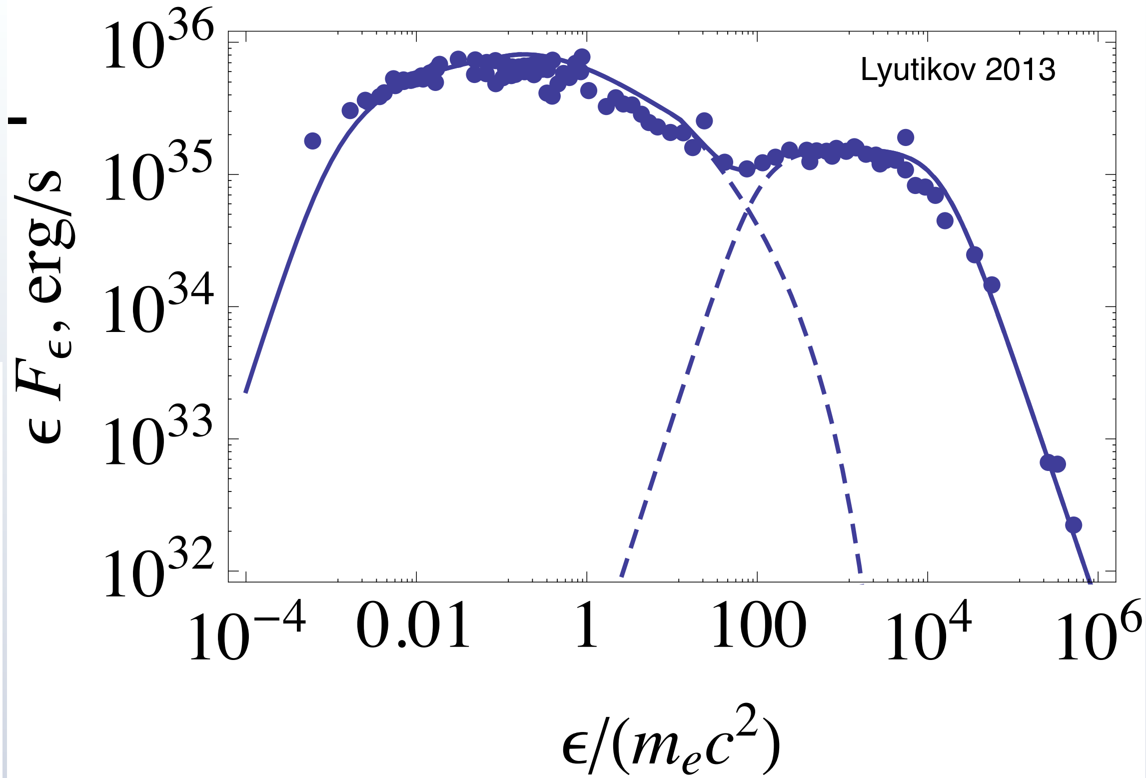
Vela profiles:



- All gamma-ray peaks have mirror images at lower energies

Data fit: cyclotron-self-Compton 10 orders in energy

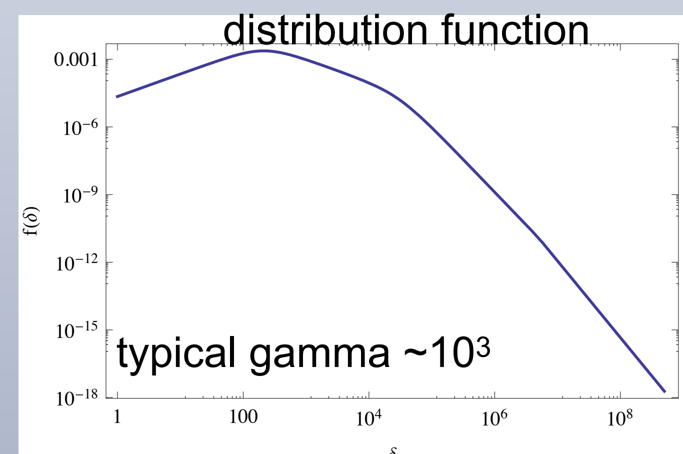




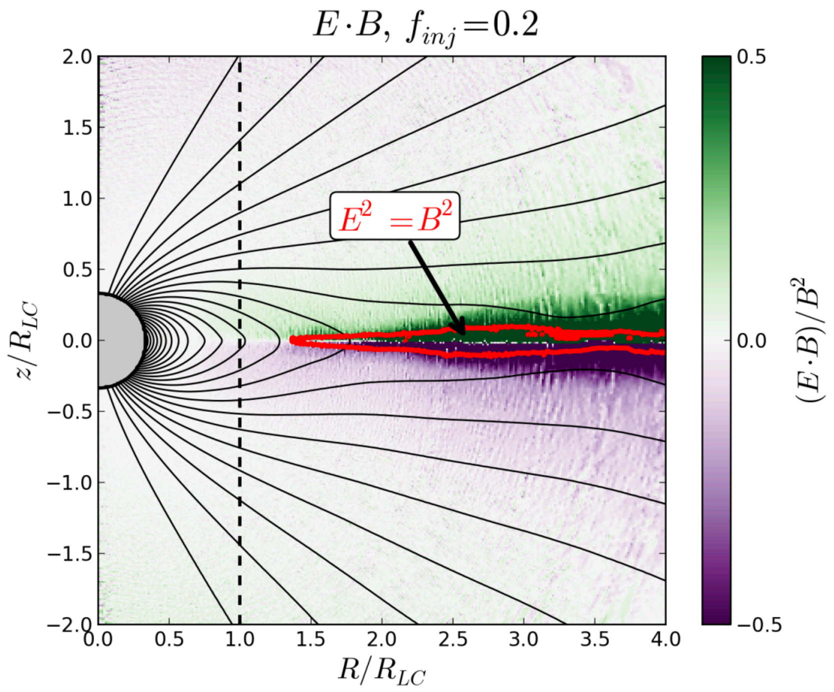
Highly constrained fit of ten orders in energy, 4 orders in flux with a few parameters

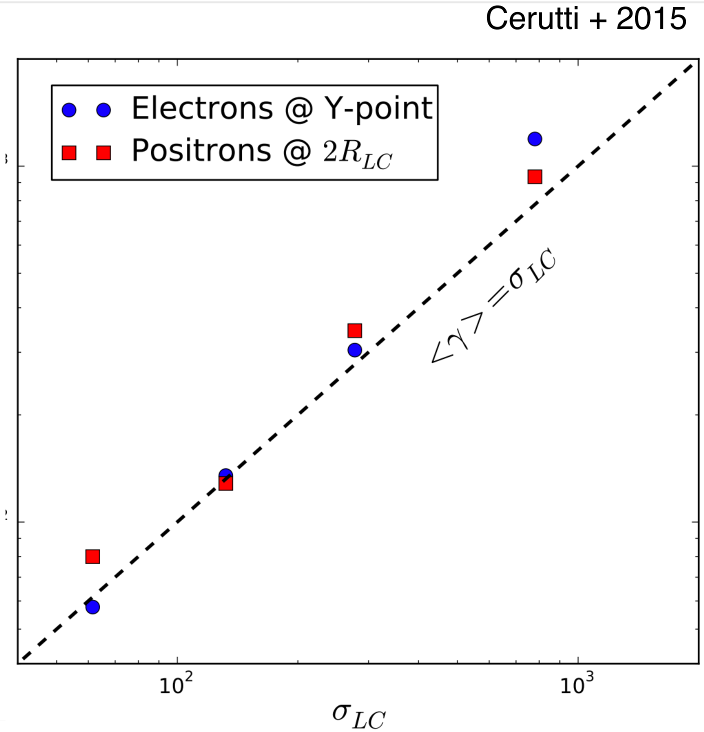
- Two counter-propagating flows
- Each cyclotron emission and IC by the other
- Scattering in the KN regime: **IC bump gives the distribution function**

- multiplicity: 10^6 -10^7
- $\beta_0 \propto (r - R_{NS})^3$
- $R_{min} \sim 20\ R_{NS}$



From outer gaps to Y-point





- Can 1D model of two counter-streaming plasma flows be applied at Y-point?
- Need large densities for IC - pair production.

Implications:

- **Spectral breaks are not due to curvature emission of the maximal energy particles**
- **Alternative possibility: IC scattering, break due to the details of particle distribution and scattering cross-section (in the KN regime)**
- **typical gamma ~ 10^3 - very reasonable**
- **high multiplicity, ~ 10^6 -10^7, but Crab nebula needs 10^6 on average.**
- **Pair production in the gaps**
- $\beta_0 \propto (r - R_{NS})^3$ **- follows from the theory of radio emission: radio and VHE gamma are related! (18 orders)**
- **Critique: where are soft photons in non-Crab pulsars? - IC scattering in KN is highly energy dependent, favors UV**