Pulsar Observations with the MAGIC telescopes

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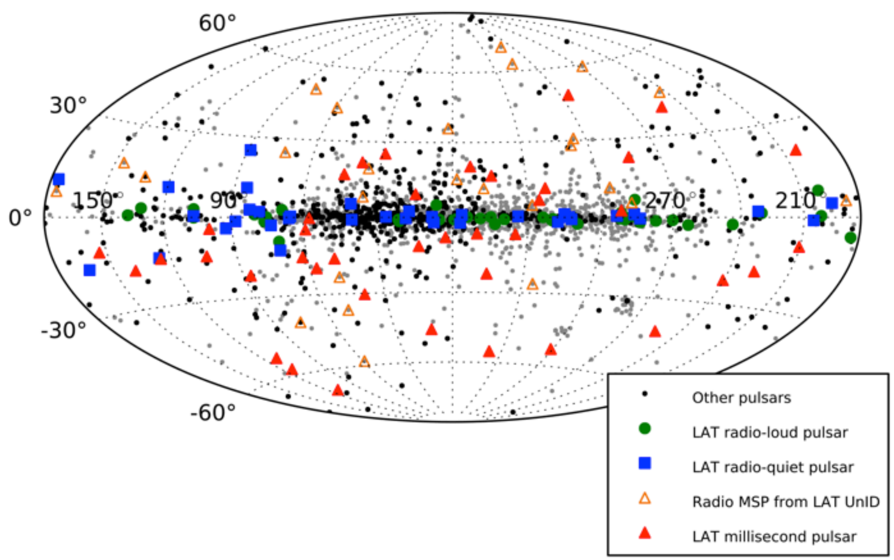
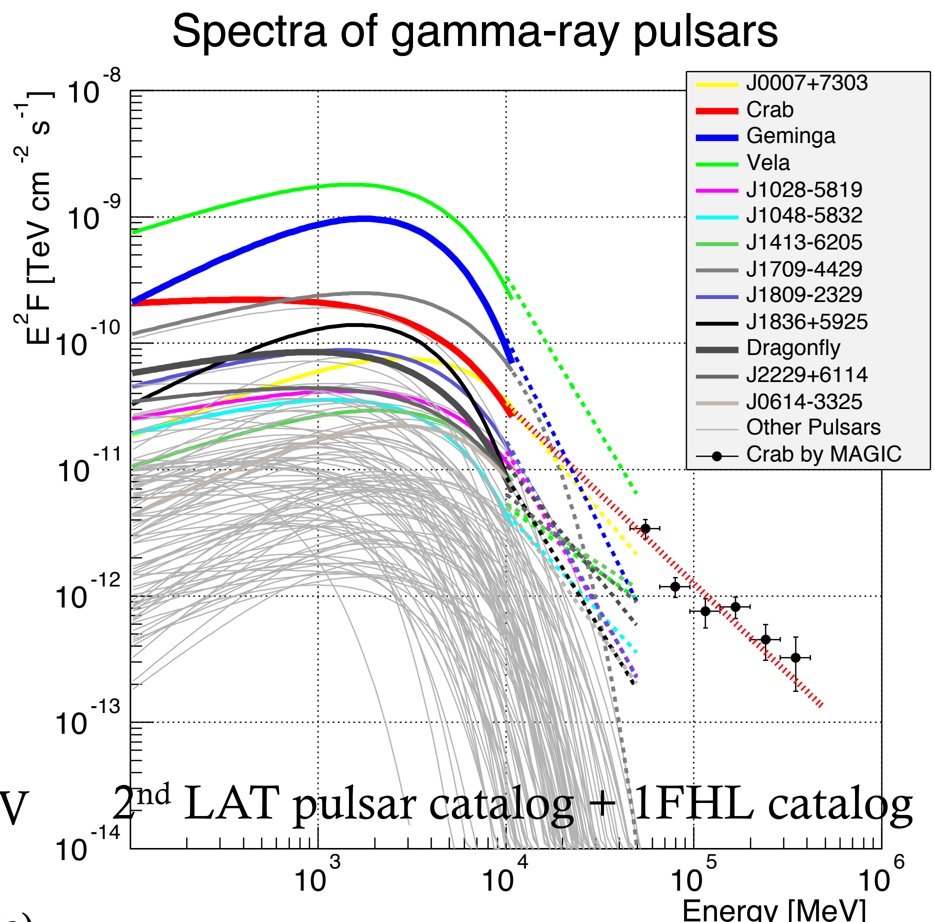
Outline

- Introduction
  - Gamma-ray Pulsars and emission mechanism
  - MAGIC telescopes
- Detection of TeV pulses from the Crab pulsar
- Observation of the Geminga pulsar

Gamma ray pulsars



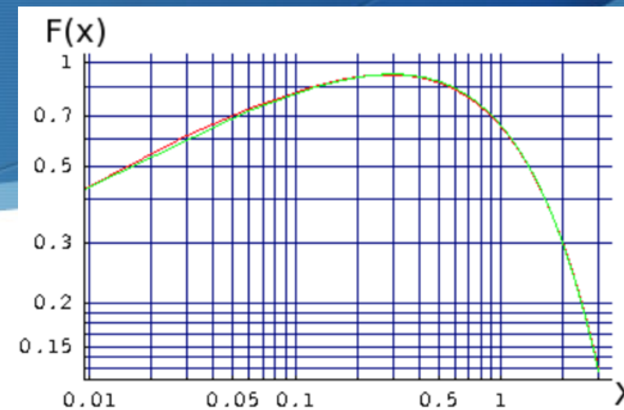


- ~150 Pulsars detected by LAT > 100 MeV
- 12 pulsars by LAT > 25 GeV
- Only 2 are detected by IACTs (Crab and Vela)

- In general, spectra show cutoff at a few GeV

Gamma-ray Emission mechanism

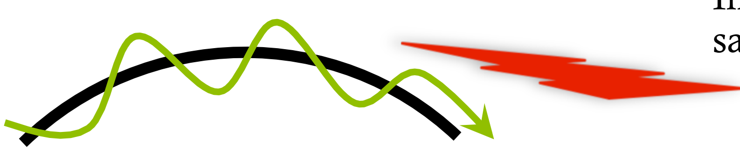
Why cutoff at GeV?



Curvature Radiation

Curvature Radiation spectrum from an electron with energy Γmc^2 shows a power law with exponential cutoff at

$$E_c = \frac{3}{2}\Gamma^2 \hbar \frac{eB'}{mc} = \frac{3}{2}\Gamma^3 \frac{\hbar c}{R_{curv}} \quad \sim \text{GeV} \ (\Gamma \sim 10^7)$$



Synchro-Curvature Radiation

In the case of Synchro-Curvature radiation, spectral shape is basically the same with a cutoff at

$$E_c = \frac{3}{2}\Gamma^3 \frac{\hbar c}{R_{curv}} Q$$

$$Q = \cos^2\alpha \left(1 + 3\xi + \xi^2 + \frac{R_{gyr}}{R_{curv}}\right)$$

$$\xi = \frac{R_{curv}}{R_{gyr}} \frac{\sin^2\alpha}{\cos^2\alpha}$$

(Vigano et al MNRAS 2015)

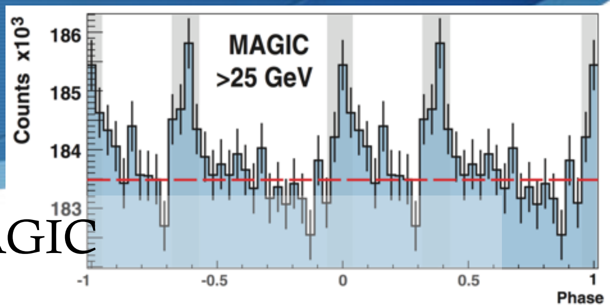
<u>If electrons are mono energetic and field curvature is the same,</u> pure exponential cutoff is expected from outer gap emission.

The MAGIC telescopes

- At LaPalma, Canary, Spain at 2250 m a.s.l.
- 2 Imaging atmospheric Cherenkov Telescopes (IACT) with a 17 m dish
    - 1st Telescope operational since 2004
    - Stereo observation since 2009
- Stereo performance:
    - Energy range: 50 GeV - a few tens of TeV
    - Integral sensitivity above 220 GeV: 0.66% C.U.
    - Angular resolution: 0.1 – 0.05 degrees
    - Energy resolution: 15-24%

All performance parameters available in Aleksic et al., Aph 72 76, 2016

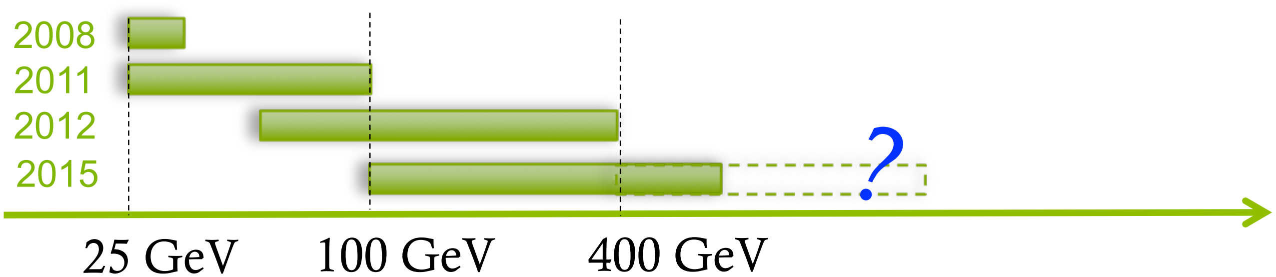
Crab Pulsar and MAGIC

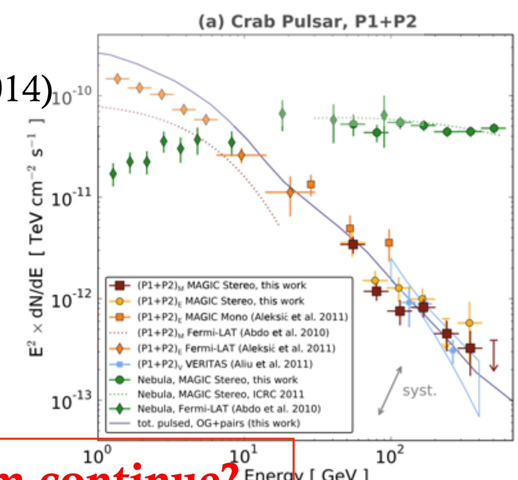


- In 2008, first detection of a pulsar at 25 GeV with mono-MAGIC
  - Polar Cap excluded (Science 322, 1221, 2008)

- In 2011, VERITAS detected pulsation above 100 GeV. (Science 334, 69, 2011)
- In 2011, spectral measurement at 25 - 100 GeV with mono-MAGIC (ApJ 742, 42, 2011)
- In 2012, spectral measurement at 50 - 400 GeV with stereo-MAGIC
  - Curvature Radiation questioned (A&A 540, A69, 2012)

- In 2014, bridge emission detected above 50 GeV. (A&A, 565, L12, 2014)





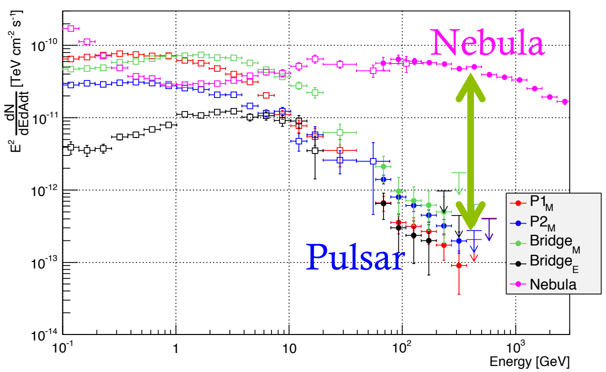
Exponential cutoff ruled out. **Up to which does the spectrum continue?**

Search for TeV pulses

Normally,

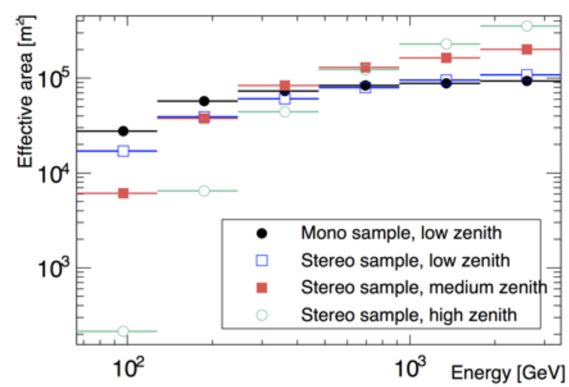
$$\text{Sensitivity} \sim \frac{1}{\sqrt{Area*Time}}\frac{\sqrt{\varepsilon_{BG}}}{\varepsilon_\gamma}$$

Stereo sensitivity is better than Mono because ε_{BG} can be largely reduced by better hadron/gamma separation and angular resolution.



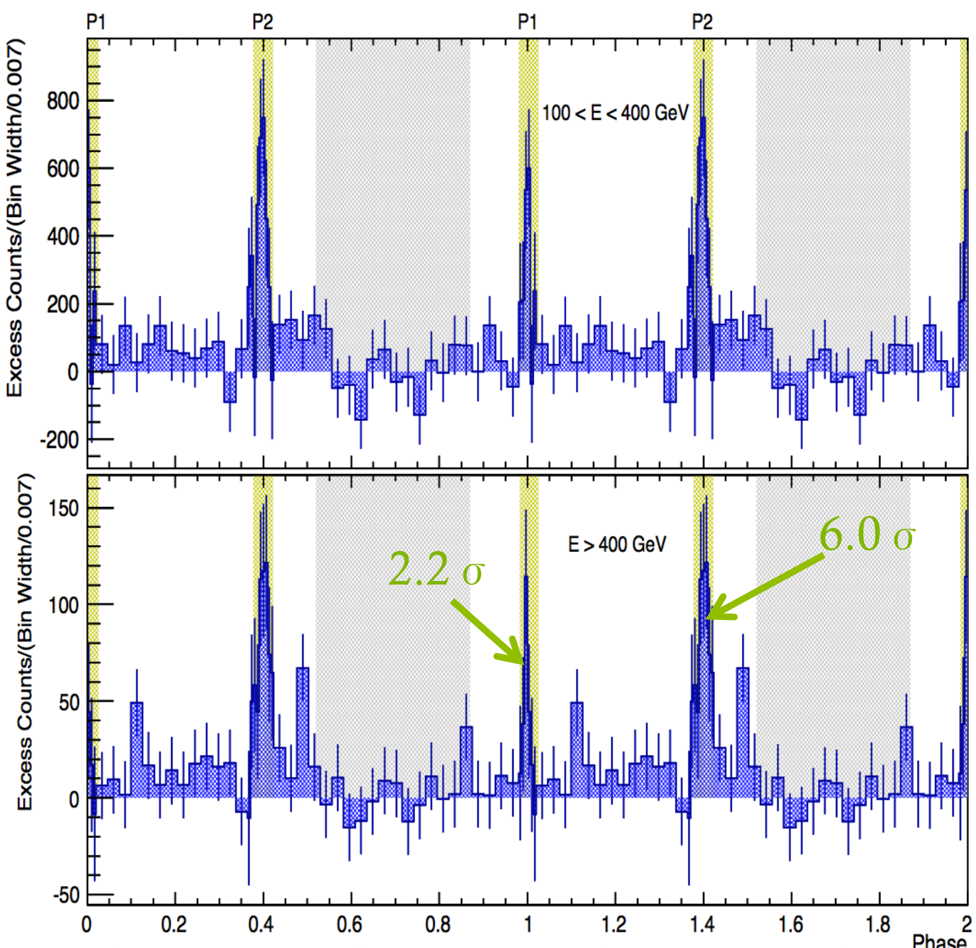
But for the Crab pulsar above ~300 GeV, BG is fully dominated by gamma-rays from Crab nebula. Therefore,

$$\text{Sensitivity} \sim \frac{1}{\sqrt{Area*Time*\varepsilon_\gamma}}$$



Therefore, mono observations are equally important as stereo observations.

Detection of TeV Pulses!



P1	P2	OFF
-0.017 – 0.026	0.377 – 0.422	0.52 – 0.87

- Mono 97 hours
- Stereo 221 hours
- Cuts are optimized for nebula BG

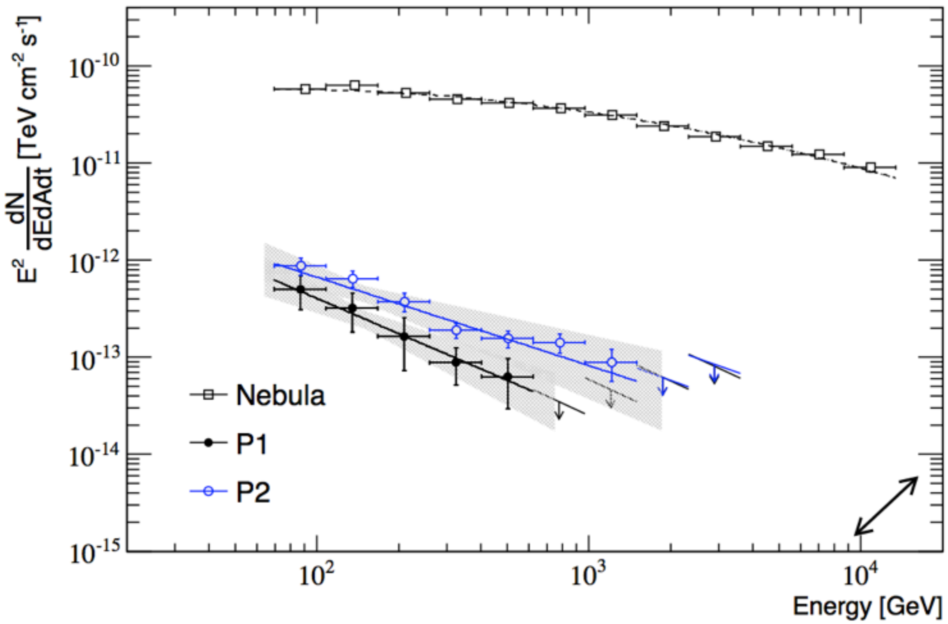
Table 1. Number of excess events and corresponding significance of P1 and P2 for different energy ranges in ~320 hours of data.

energy range	P1		P2	
[GeV]	N_{ex}	Significance	N_{ex}	Significance
100–400	1252±442	2.8 σ	2537±454	5.6 σ
> 400	188±88	2.2 σ	544 ± 92	6.0 σ
> 680	130±66	2.0 σ	293±69	4.3 σ
> 950	119±54	2.2 σ	190±56	3.5 σ

Profile above 400 GeV

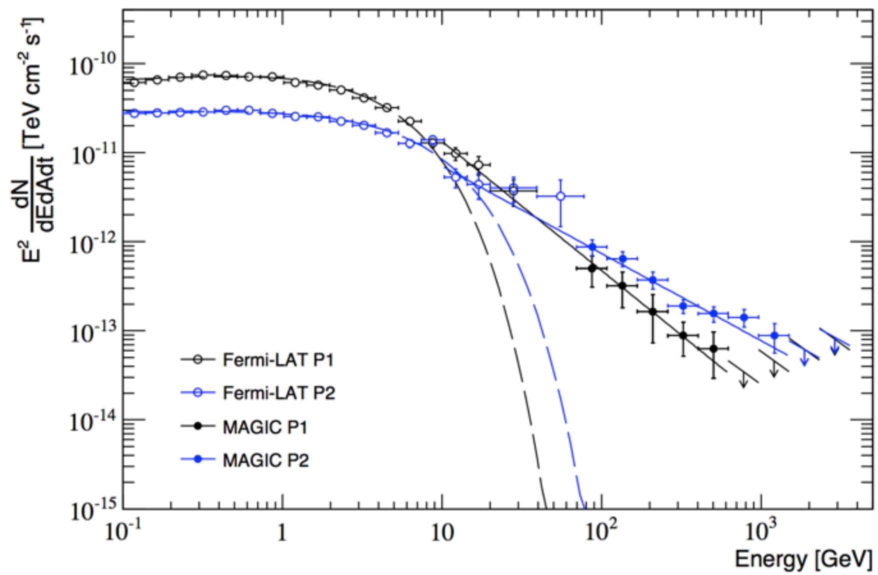
P1 Peak Phase	$0.9968 +\text{-} 0.0020_{stat} +\text{-} 0.005_{sys}$
P2 Peak Phase	$0.4046 +\text{-} 0.0035_{stat} +\text{-} 0.006_{sys}$
P1 FWHM	$0.010 +\text{-} 0.003_{stat} +\text{-} 0.002_{sys}$
P2 FWHM	$0.040 +\text{-} 0.009_{stat} +\text{-} 0.007_{sys}$

Energy Spectrum



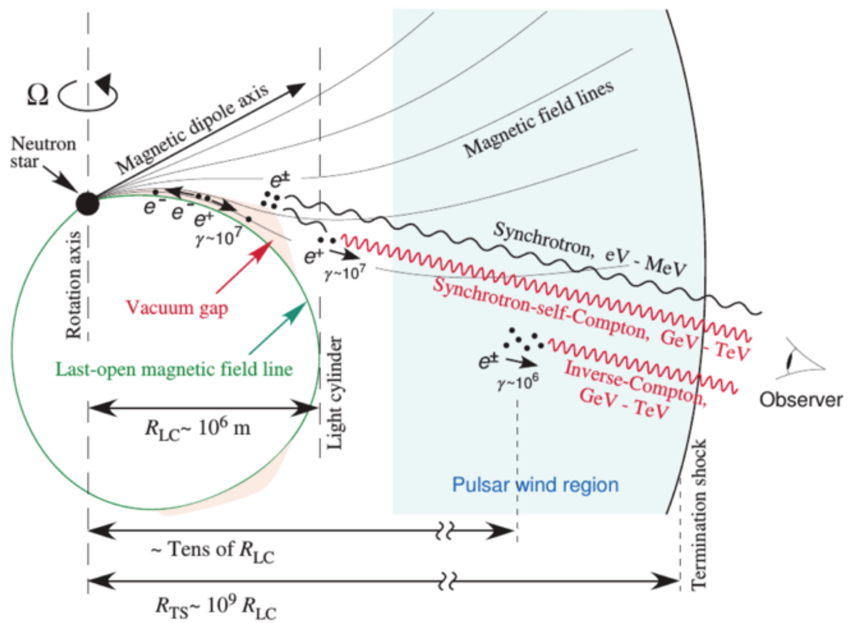
		E_0 [GeV]	f_{E_0} [TeV^{-1} cm^{-2} s^{-1}]	α	χ^2/dof
MAGIC	P1	150	$(1.1\pm0.3)\times10^{-11}$	3.2±0.4	0.3/3
	P2	150	$(2.0\pm0.3)\times10^{-11}$	2.9±0.2	5.4/5
Fermi-LAT & MAGIC	P1	50	$(5.3\pm0.8)\times10^{-10}$	3.5±0.1	1.5/6
	P2	50	$(5.7\pm0.6)\times10^{-10}$	3.0±0.1	8.4/9

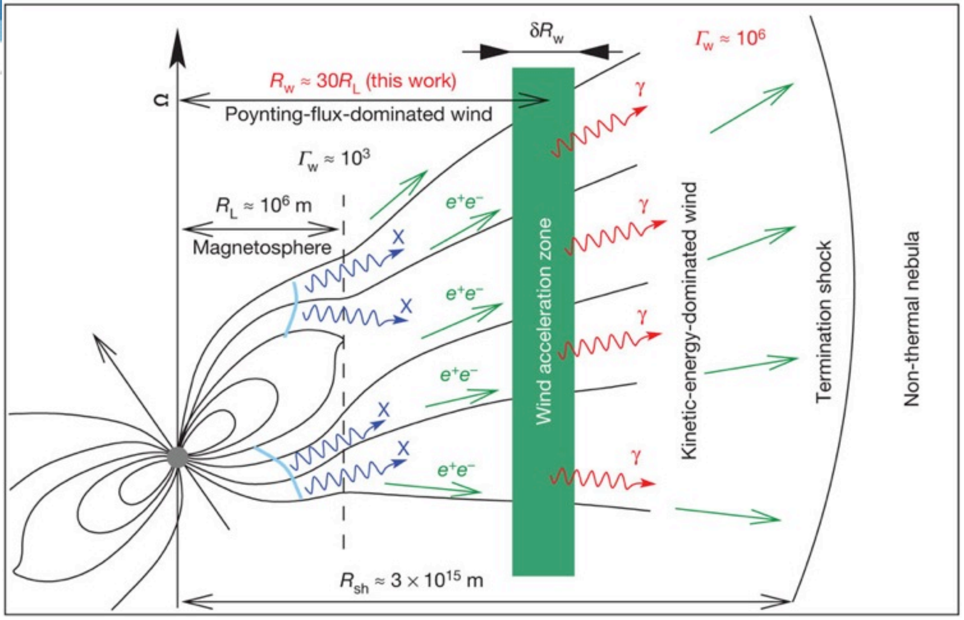
- Broken Power law between 100 MeV and 1 TeV.
- Fermi+MAGIC combined fit suggests softer spectrum of P1 than P2.



Physics Interpretation

The only possibility is Inverse Compton scattering.





Magnetospheric Cascade model

(Hirotani, ApJ 766, 98 2013)

multi TeV electrons -> IC on ambient IR photons
-> multi TeV photons -> absorbed by IR photons
-> cascade

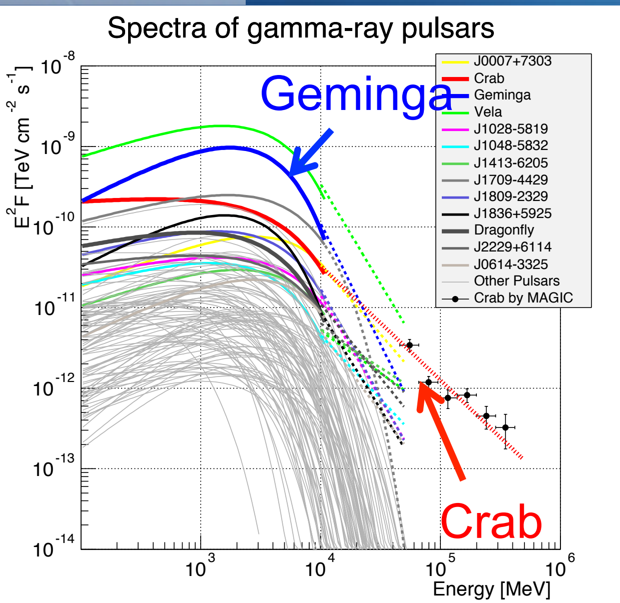
Wind scattering model

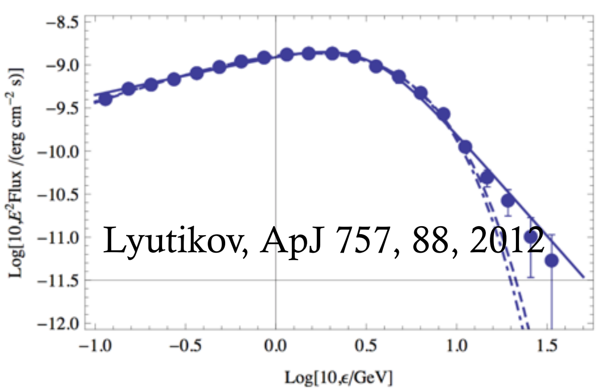
(Aharonian et al., Nature 482, 507, 2012)

Pointing Flux->plasma wind -> IC pulsed X-ray photon

But none of the models can explain the narrow peaks and simultaneous LC…..

Geminga Pulsar

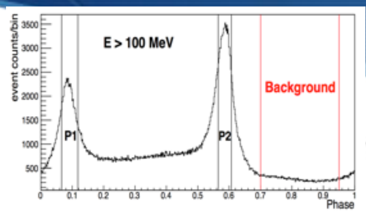


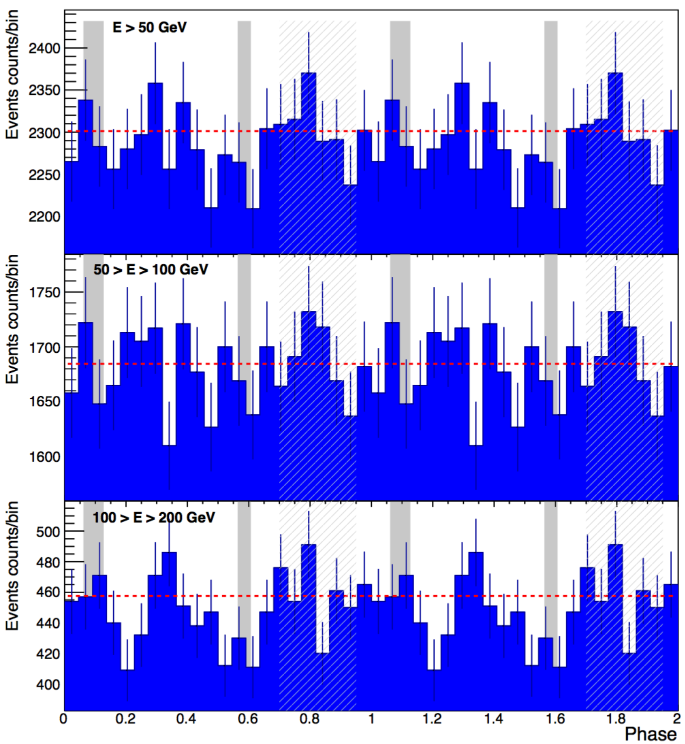


	Crab	Geminga
P	34 ms	237 ms
dP/dt	4.2e-13 s/s	1.1e-14 s/s
R_{LC}	1600 km	11300 km
Age	1000 years	3e5 years
B_0	4e12 G	1.6e12 G
B_{LC}	950 kG	1.1 kG
L_{sp}	5e38 erg/s	3e34 erg/s
Distance	2 kpc	250 pc

- Totally different property than Crab.
- At 3 GeV, 5 times brighter than Crab
  - Due to short distance?
- Power-law-like extension after the break is reported based on Fermi data
- 25 GeV pulsation is also detected

Geminga Observation





P1	P2	OFF
0.066 ~ 0.118	0.565 – 0.607	0.7 – 0.95

- Observation between Dec. 2012 and March 2013
- 63 hours after selection

- Definition of P1 (P2) phase was derived by fitting Asymmetric Gaussian to the LAT light curve above 5 (10) GeV (+- 1 σ).

- **No signal found**

Energy range (GeV)	P1	P2	P1 + P2
≥ 50	0.2σ	-0.1σ	0.1σ
50-100	-0.2σ	0.2σ	0.0σ
100-200	0.7σ	-1.4σ	-0.3σ

Flux Upper Limits

- Cutoff power law fit to LAT data above 0.1 GeV

$$\frac{dF}{dE} = N_0 \left(\frac{E}{E_0}\right)^{-\alpha} exp(-(E/E_c)^b),$$

	N_0	α	E_c [GeV]	b
P1	3.0 ± 0.3	1.12 ± 0.04	1.2 ± 0.1	0.81 ± 0.04
P2	4.3 ± 0.4	0.78 ± 0.03	1.1 ± 0.1	0.70 ± 0.03
PA	28.3 ± 1.8	0.94 ± 0.02	0.8 ± 0.1	0.67 ± 0.02

< 1

- Power law fit to LAT data above 10 GeV

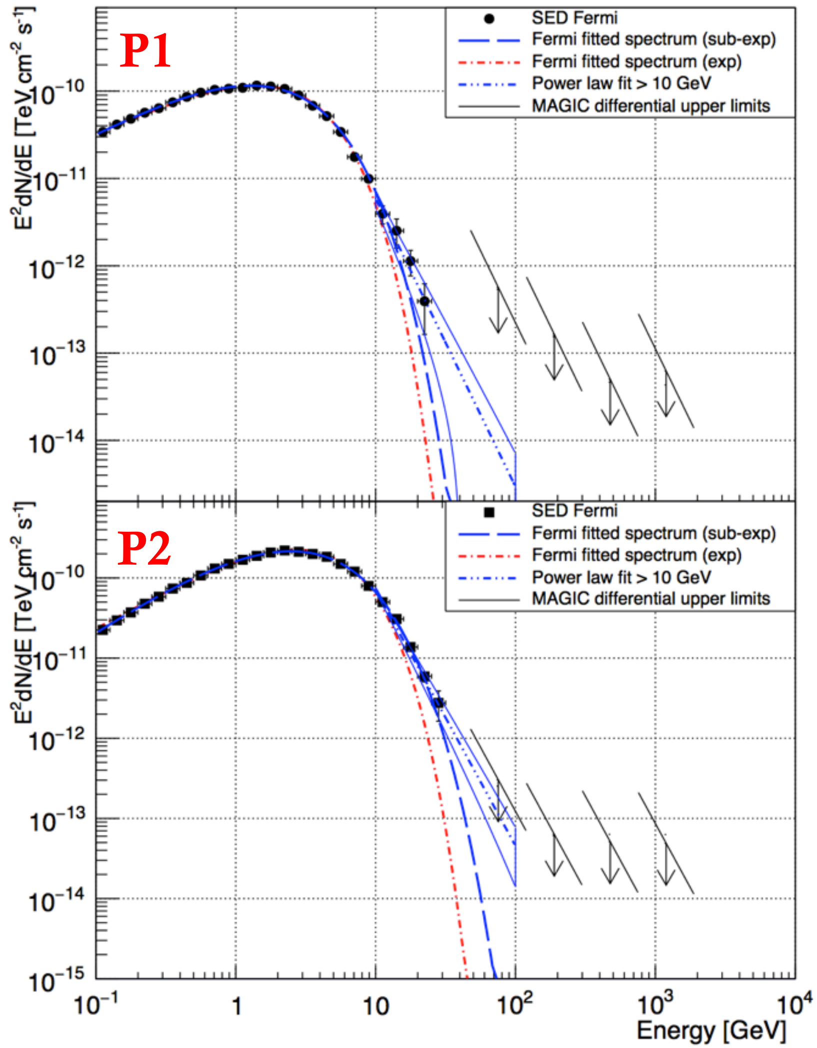
$$\frac{dF}{dE} = N_0 (E/10GeV)^{-\alpha}$$

	N_0	α
P1	$(5.9 \pm 1.4) \times 10^{-5}$	5.3 ± 0.7
P2	$(7.2 \pm 0.1) \times 10^{-4}$	5.2 ± 0.3

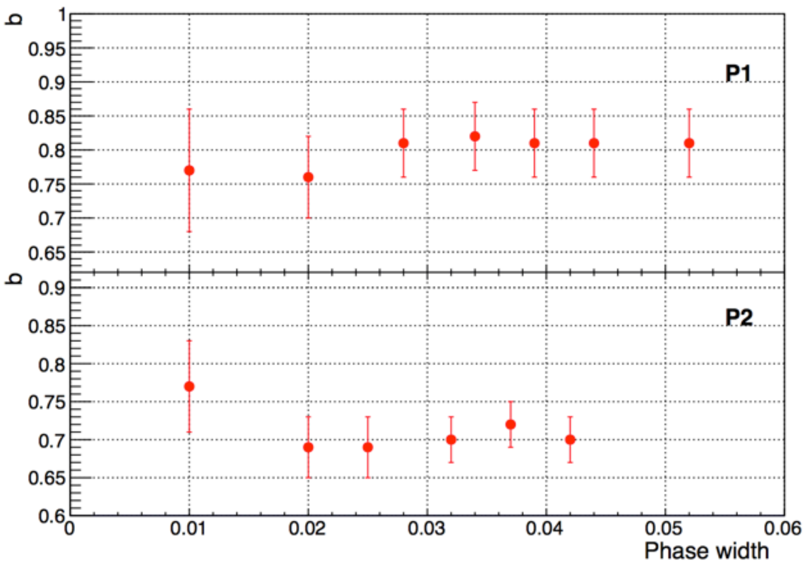
N_0 [10^{-10}MeV^{-1}s^{-1}cm^{-2}]

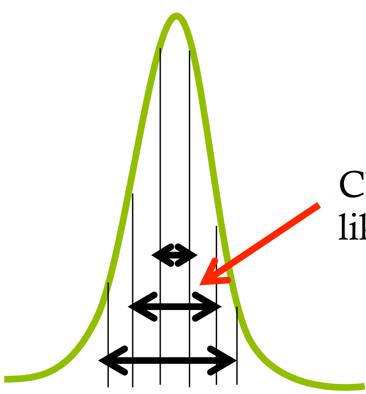
- P2 limits are close to but slightly above the power law extension.

- <u>Lowering the energy threshold is important.</u>



More Fermi-LAT data analysis





Changing phase width like this

$$\frac{dF}{dE} = N_0 \left(\frac{E}{E_0}\right)^{-\alpha} exp(-(E/E_c)^b),$$

"**b**" should be 1, if emission comes from mono-energetic electrons at the same place.

Smaller **b** could be explained as the sum of different cutoff energies from different phases.

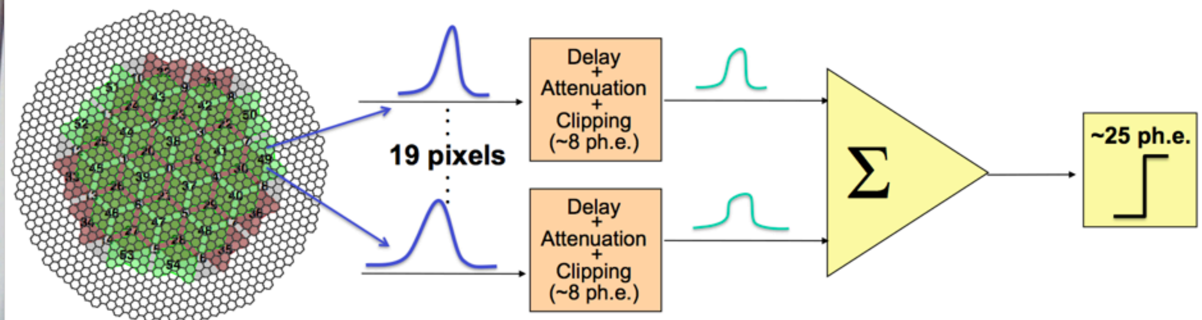
But **b** is significantly smaller than 1 even with phase width 0.01.

This may constrain the 3D modeling of the pulsar magnetosphere.

Lowering MAGIC threshold

The sum trigger-II

To detect Geminga, lowering the energy threshold is needed.



In order to lower the energy thresholds,

- new trigger system have been installed
- new analysis technique is being studied right now

Conclusion

- By analyzing archival data, MAGIC detected pulsation up to TeV energies from the Crab pulsar.
  - Gamma-ray spectrum from 100 MeV to 1 TeV can be described as a broken power law.
  - The only possible emission mechanism is Inverse Compton scattering.
  - However, no model can explain both the spectrum and pulse shape simultaneously.
- MAGIC observed the Geminga pulsar for 63 hours.
  - No signal has been found.
  - Fermi-LAT data suggest a power law like extension after the break at a few GeV. Index is ~ -5
  - Flux upper limit set by MAGIC is close to the extension.
  - Lowering the energy threshold is the key to detect Geminga and we are working on that.