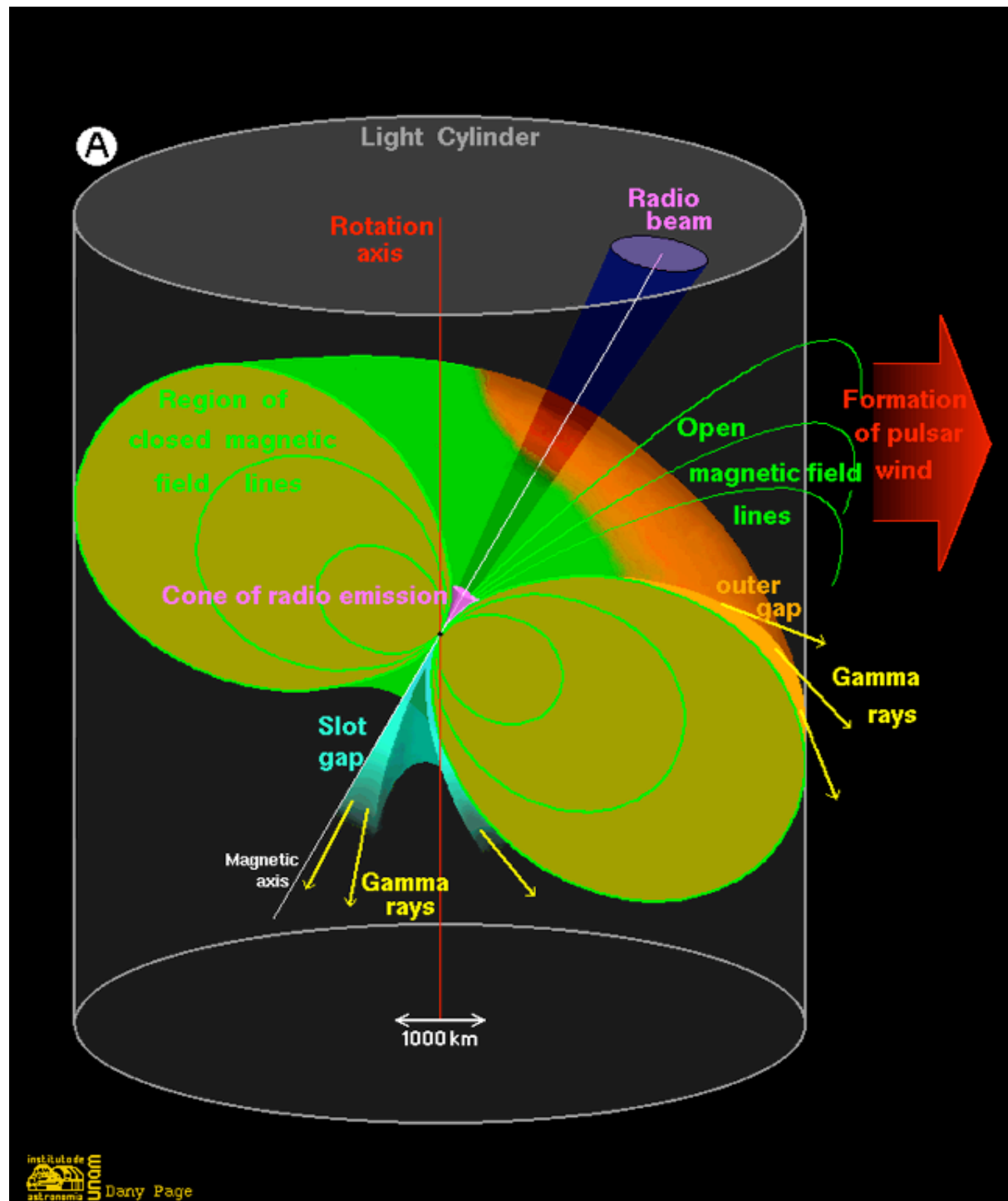


Observations of pulsars in high energy gamma-rays

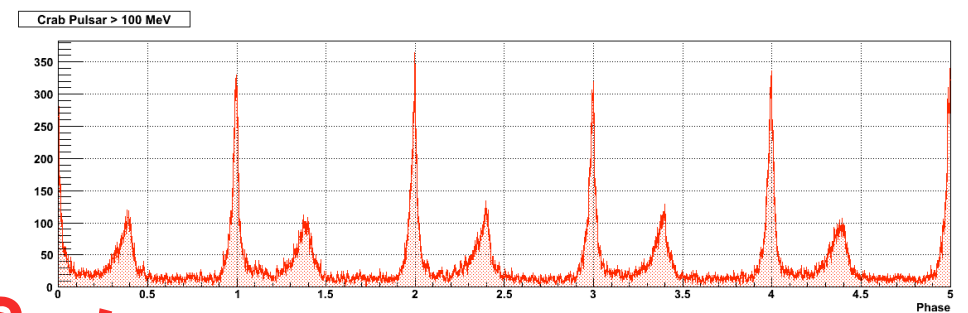
Takayuki Saito

Max-Planck-Institut fuer Physik

Pulsars



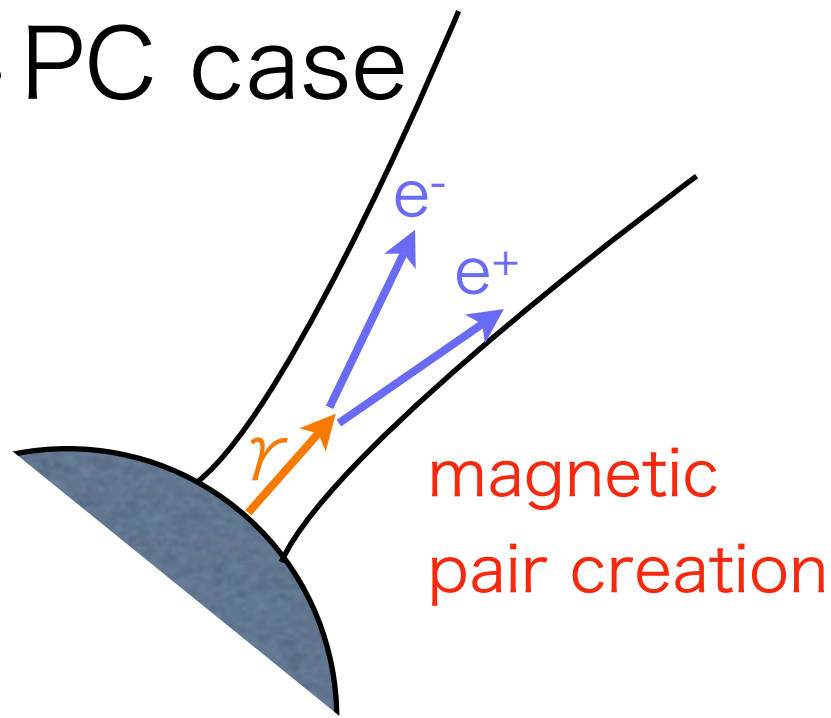
- Neutron star with strong B field
- Surrounded by dense plasma co-rotating with NS
- non-perpendicular-to-B E field **only** in **Polar Cap** and **Outer Gap**
- electrons accelerated along B field in **PC** and **OG**
- high energy gamma-rays produced via curvature radiation in **PC** and **OG**.



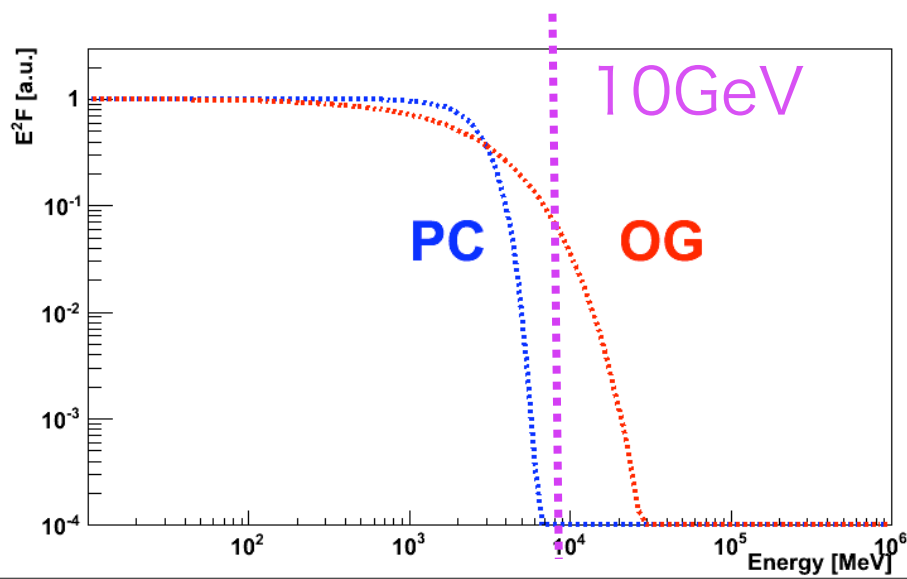
Are observed pulsations from PC or OG?

How to distinguish PC/OG?

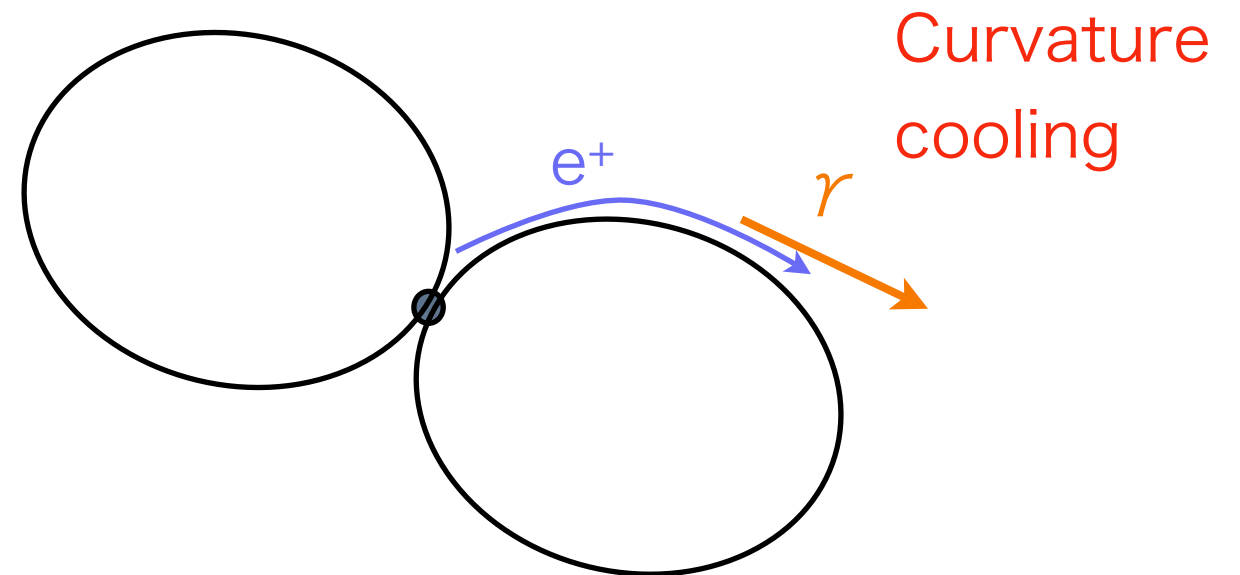
• PC case



- High energy gamma-ray interacts with strong B field creating a pair
- Very sharp (super-exponential) cutoff
- For Crab, no emission above 10 GeV



• OG case

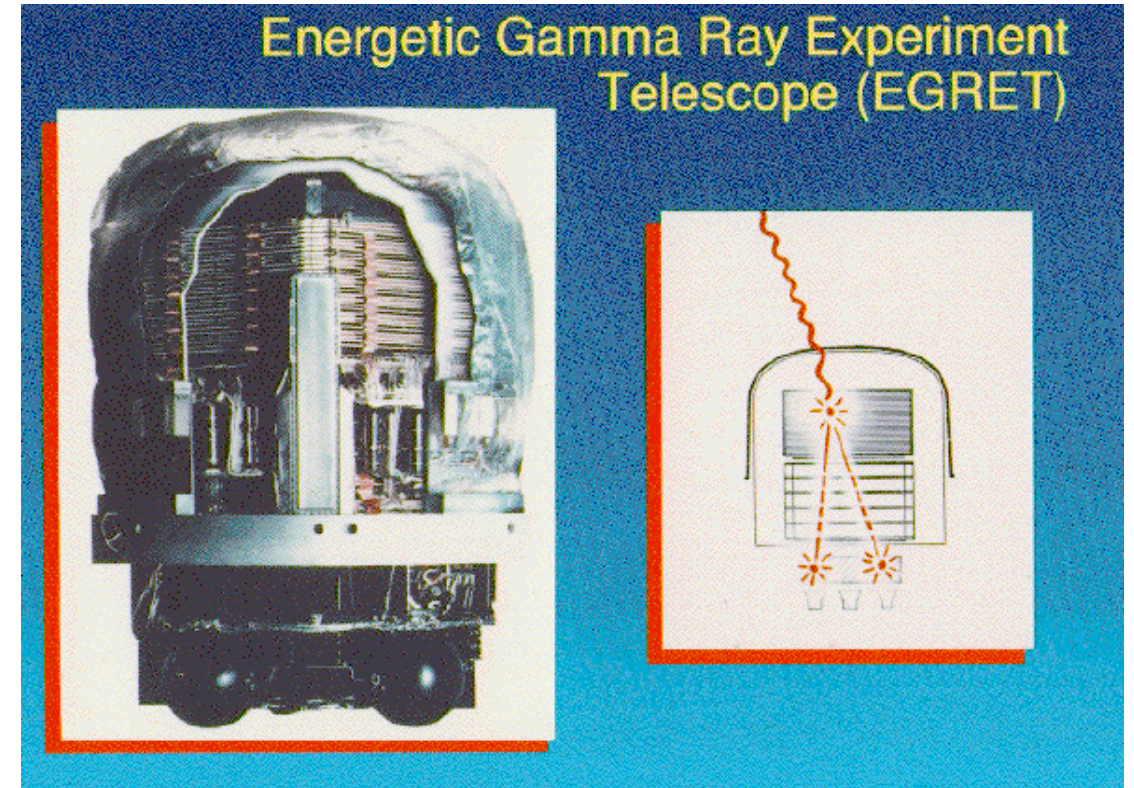
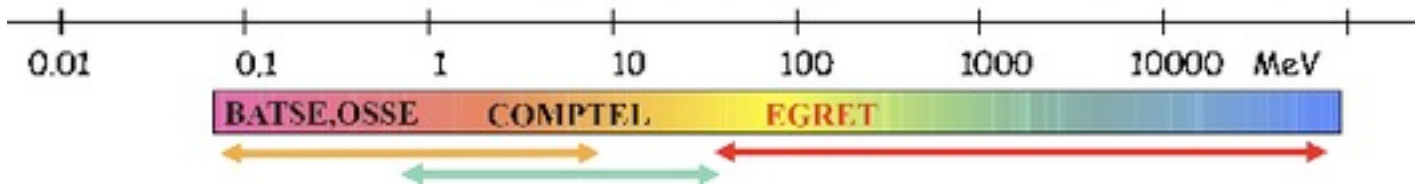
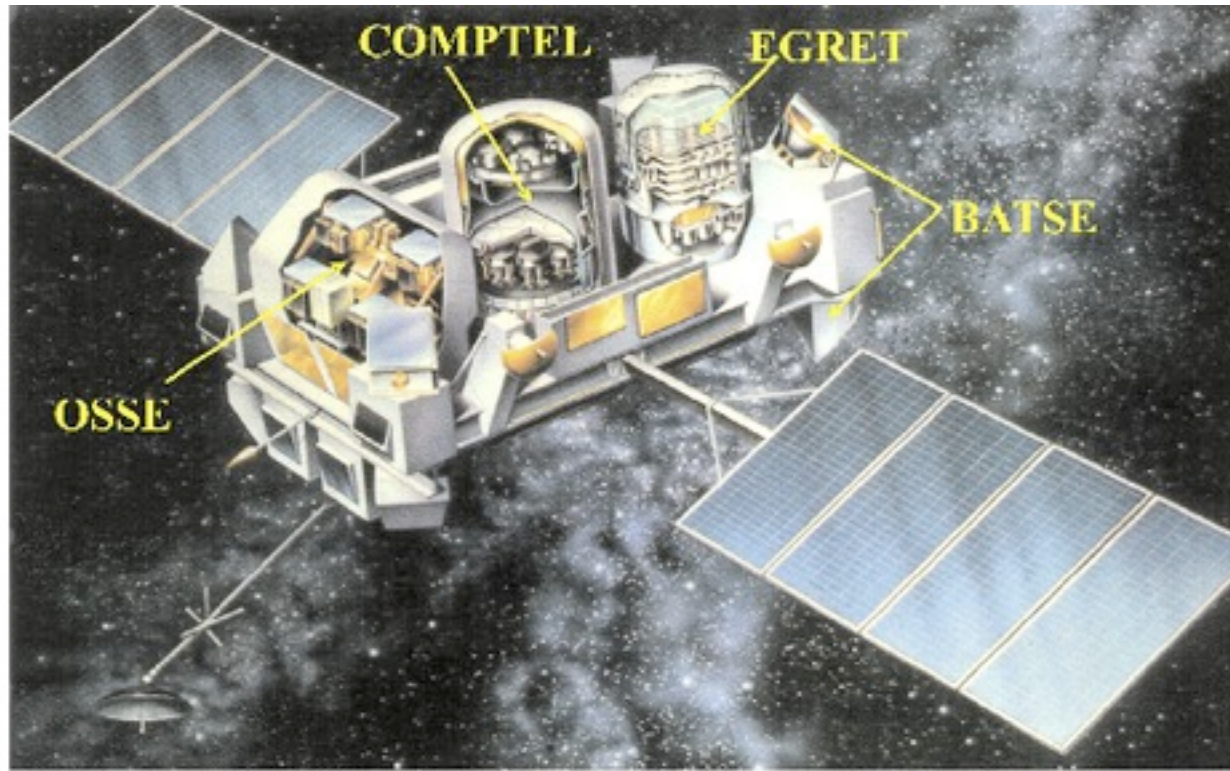


- Acceleration by E-field and cooling by curvature radiation balance
- Mono-energetic electron ($\Gamma \sim 10^7$)
- Exponential Cutoff at

$$E_{cut} = \frac{3\hbar c}{2R_{curv}} \Gamma^3$$

High energy end is the key!

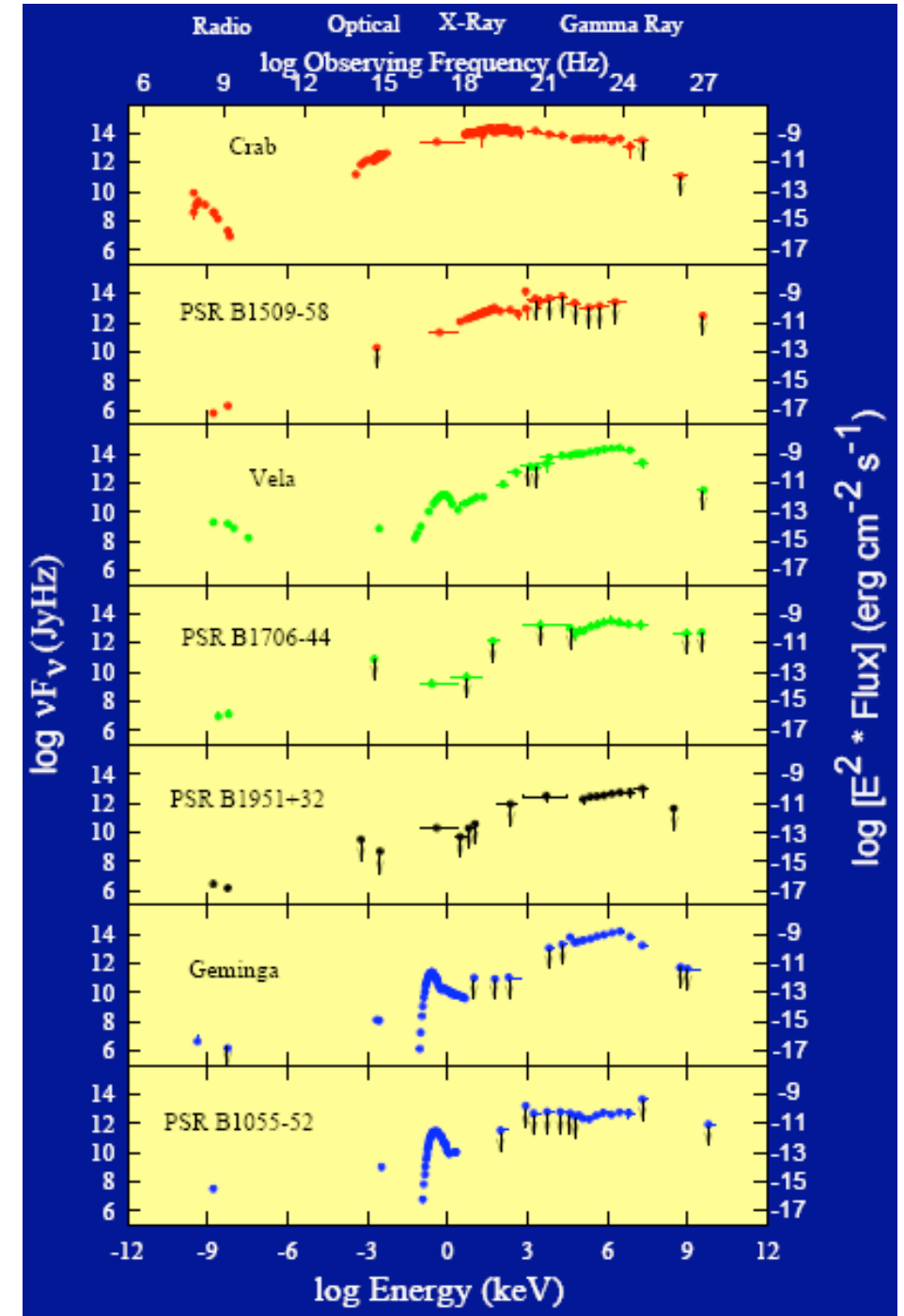
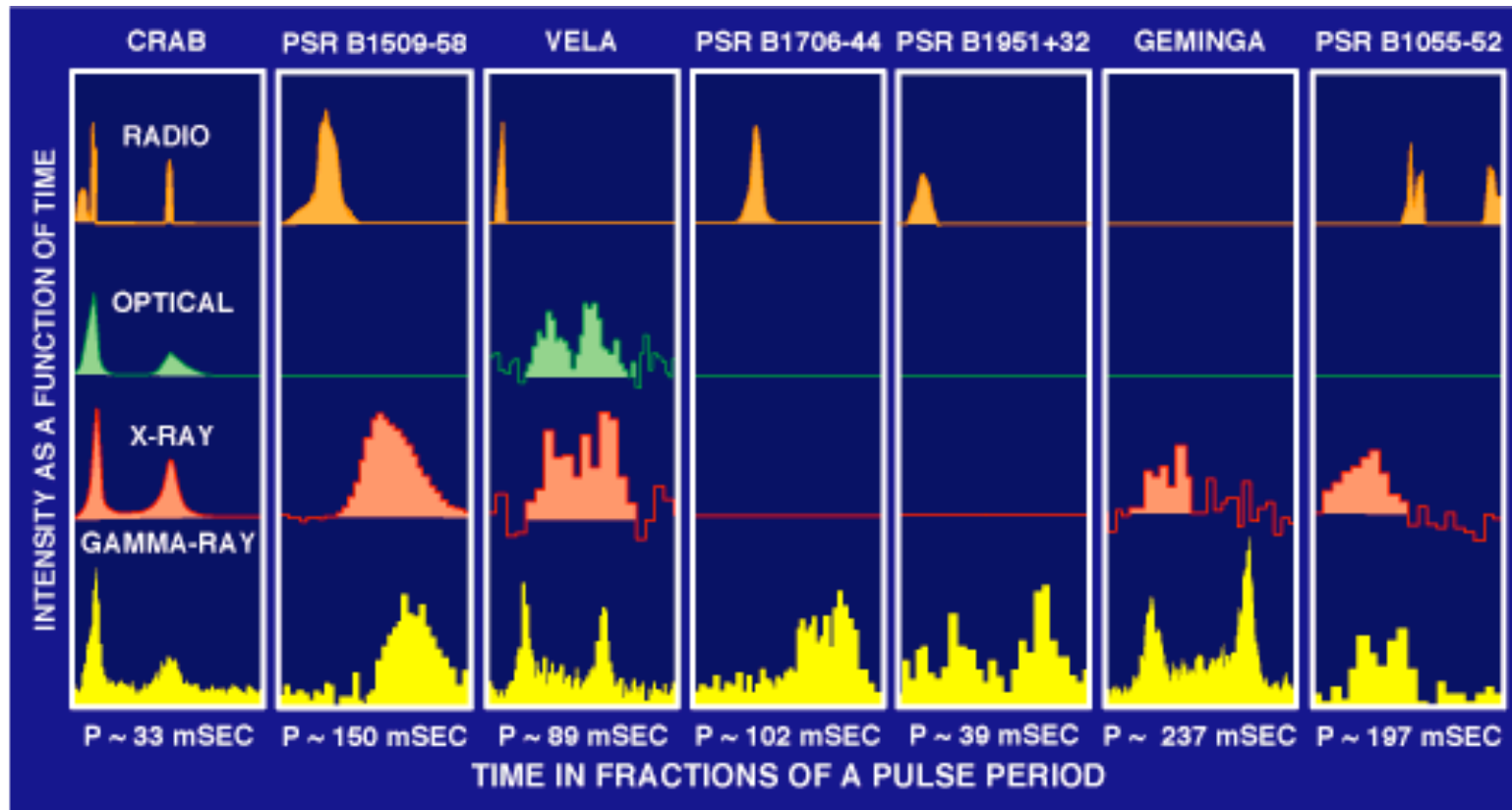
EGRET (1991-2000)



• on Compton Gamma-Ray Observatory

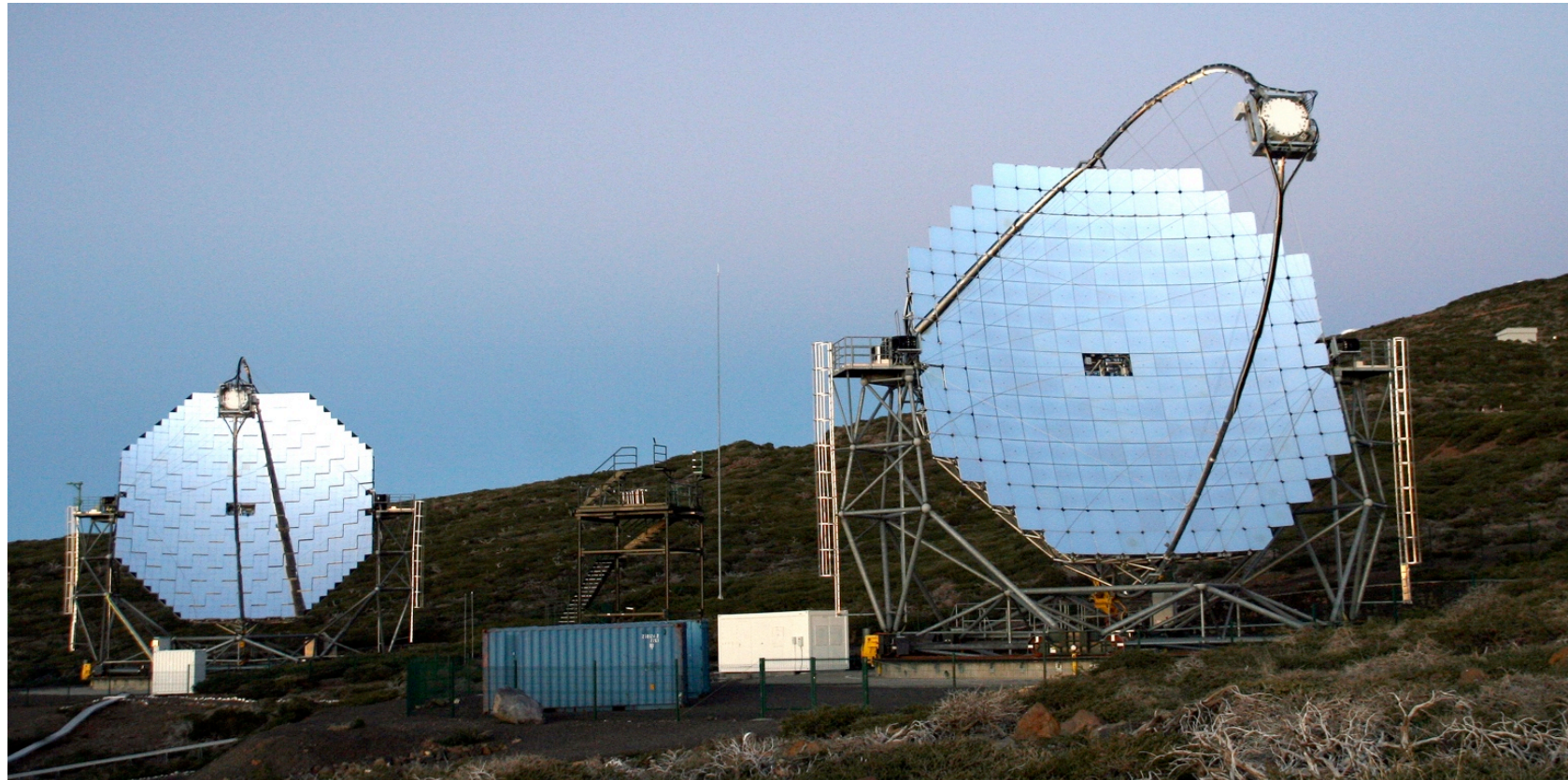
- 20 MeV- 30 GeV
- Operational 1991- 2000
- Anti-coincidence counter + Spark chamber + Calorimeter
- effective $\sim 0.15 \text{ m}^2$
- Detected first 7 gamma-ray pulsars

EGRET measurement (1991-2000)



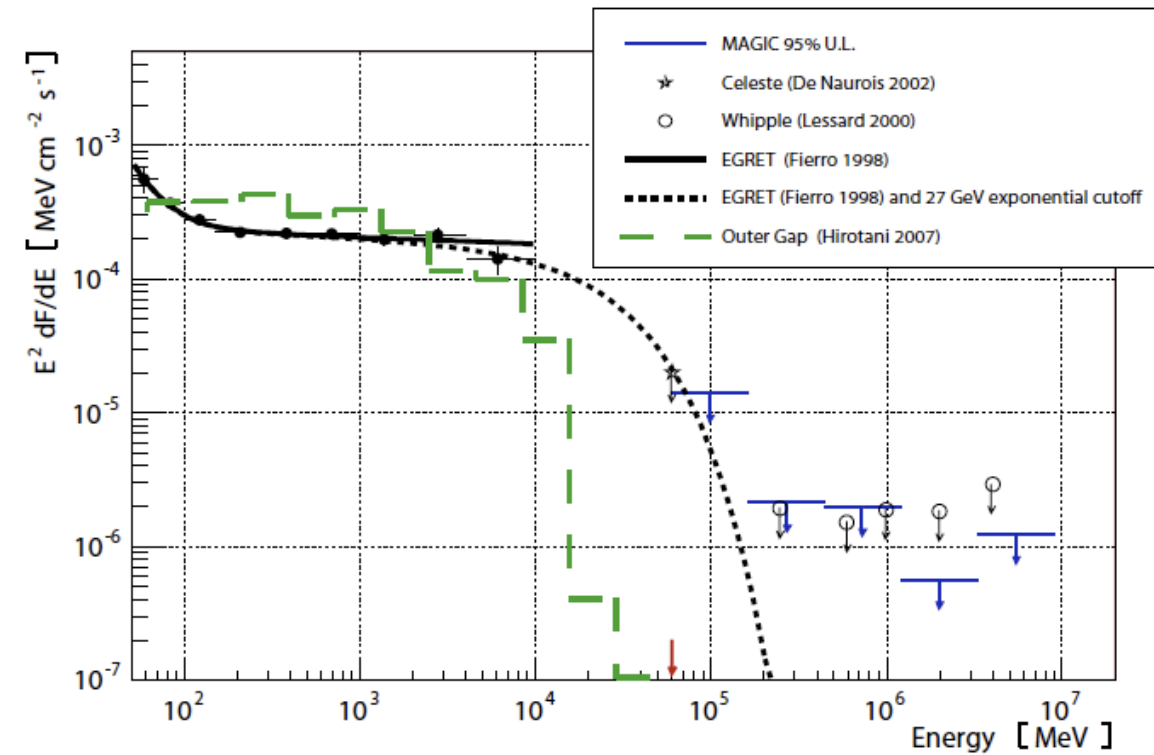
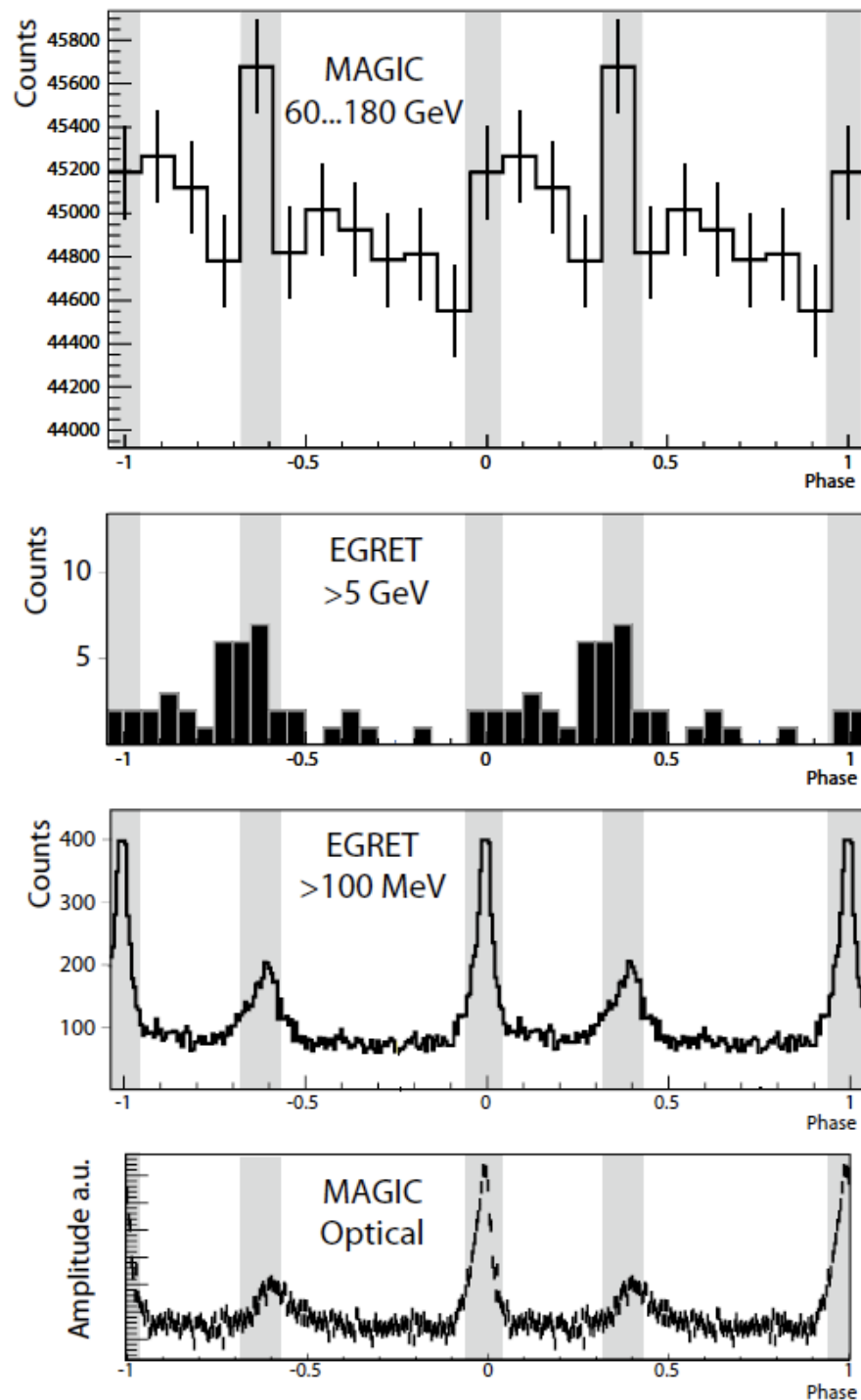
- 7 gamma-ray pulsars discovered
- Spectra up to a few GeV
- Cutoff shape not clear.....
- Both PC and OG possible.....

MAGIC telescope(s)



- Imaging Atmospheric Cherenkov Telescope
- Located at Canary Islands, LaPalma, 2200m a.s.l.
- World largest reflector, 17 m in diameter
- Operational since 2004
- Energy threshold 60 GeV (2004-2007)
- **World lowest energy threshold** among IACTs.
- Stereo since 2009

1st MAGIC Observations (Crab)



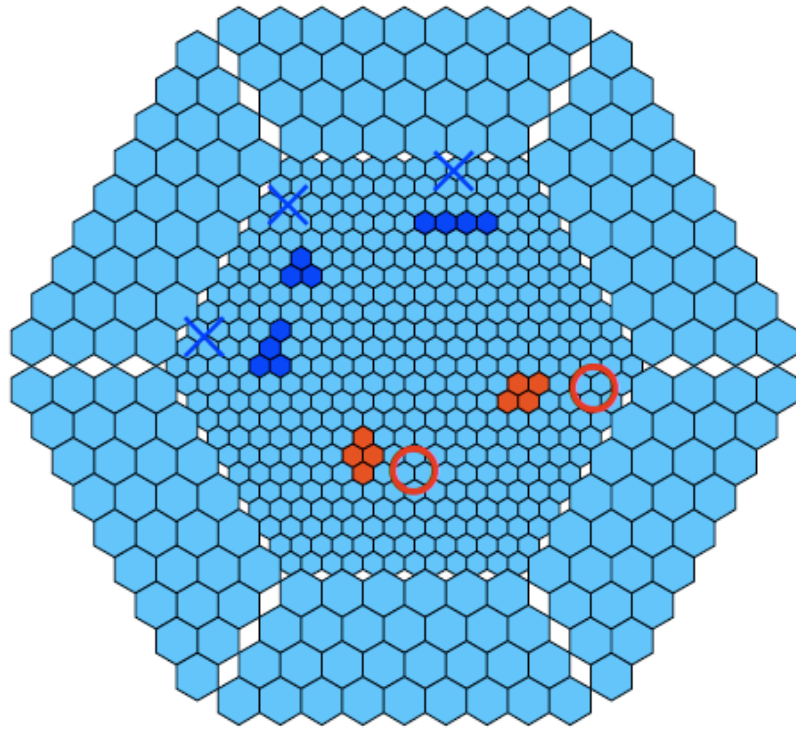
- Observations in 2005-2006
- A hint of pulsation above 60 GeV (2.6 sigma)
- Only from second pulse
- Catching the exponential tail? or just a fluctuation?

60GeV is not low enough!
Let's reduce further!!

New Trigger System (2007)

- Standard Trigger

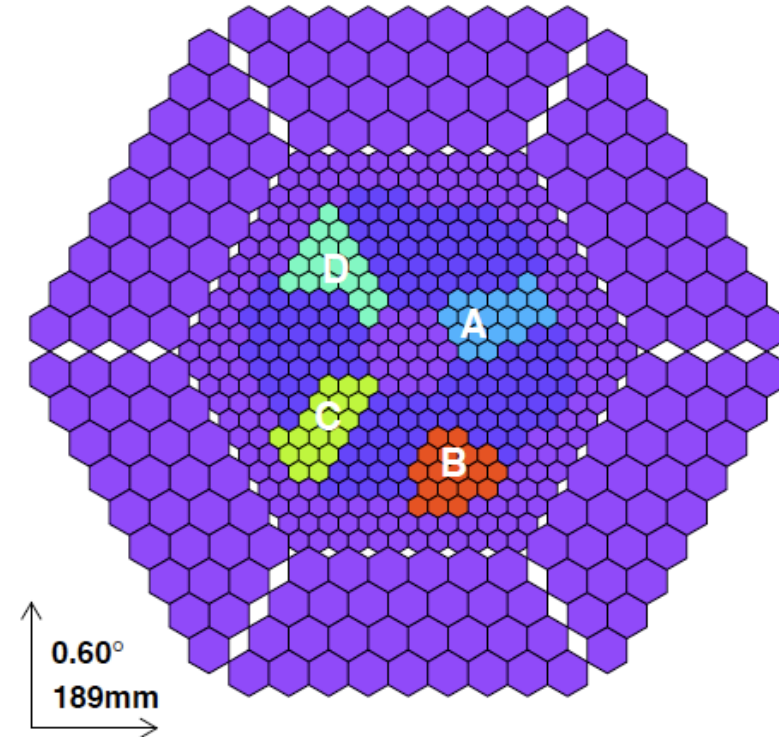
MAGIC Camera



- Pixel Threshold at ~6 phe
- 4NN Topology

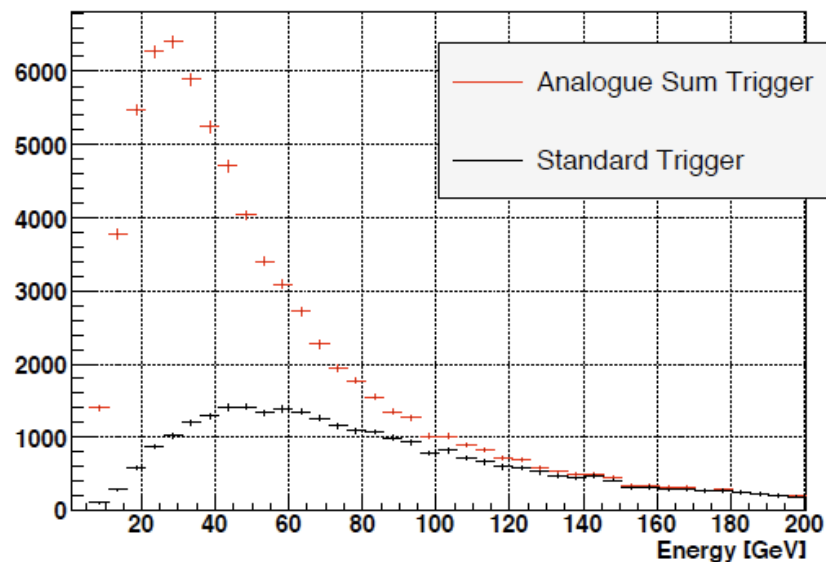
- New Analogue Sum Trigger

Sum Trigger Patches

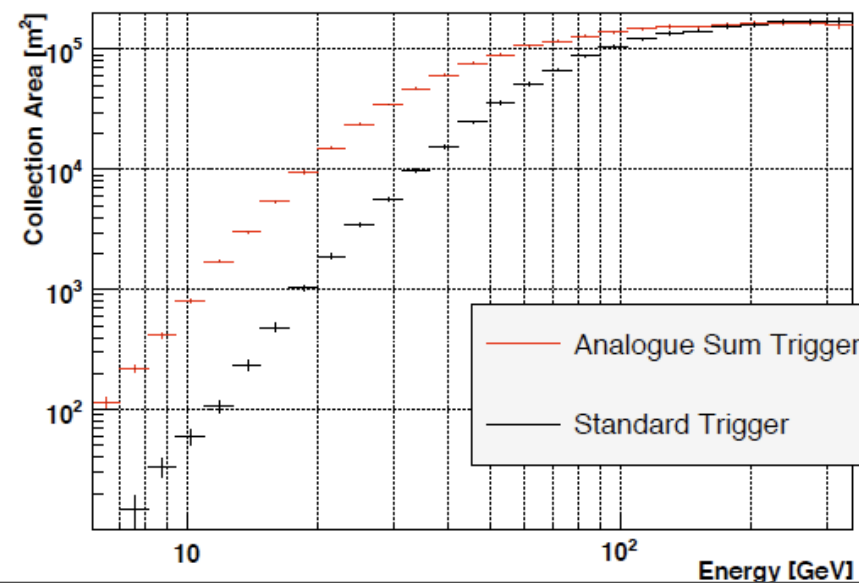


- Summing 18 analog signals
- Threshold for summed signal at 27 phe

Energy Distribution of the Sum Trigger

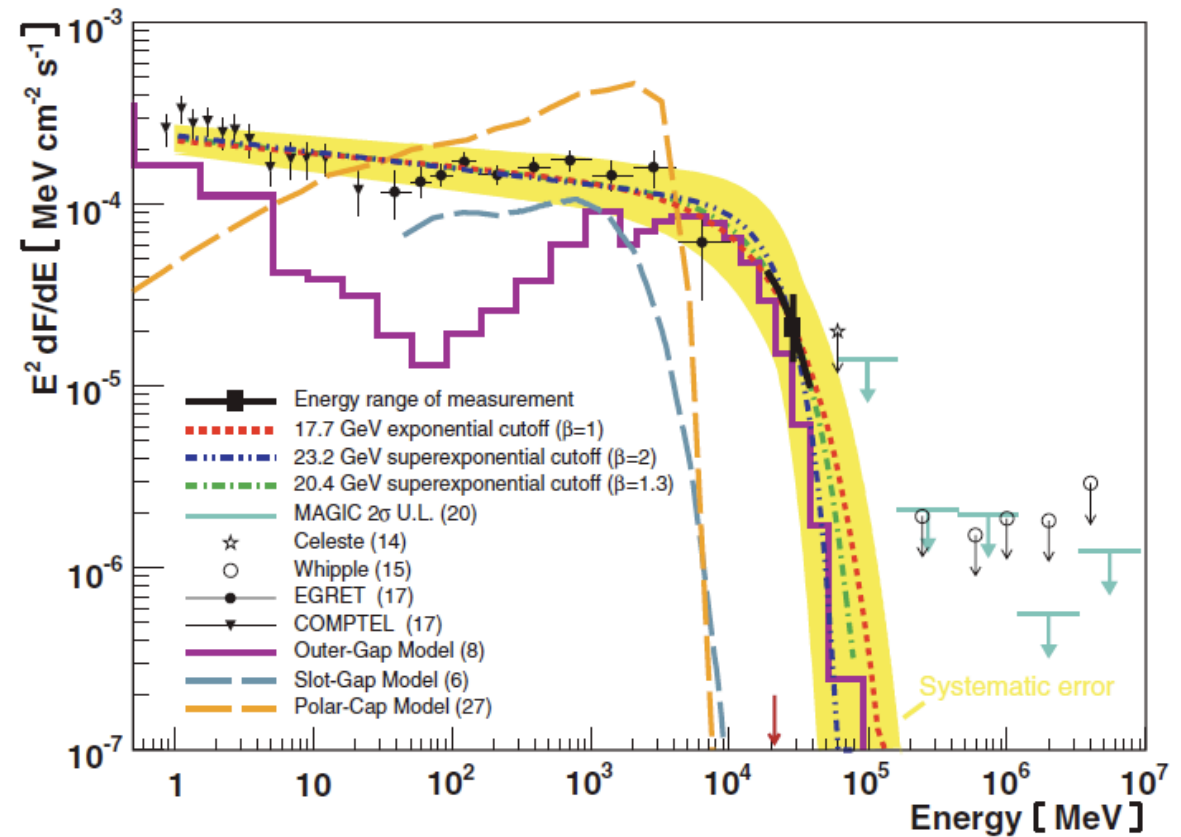
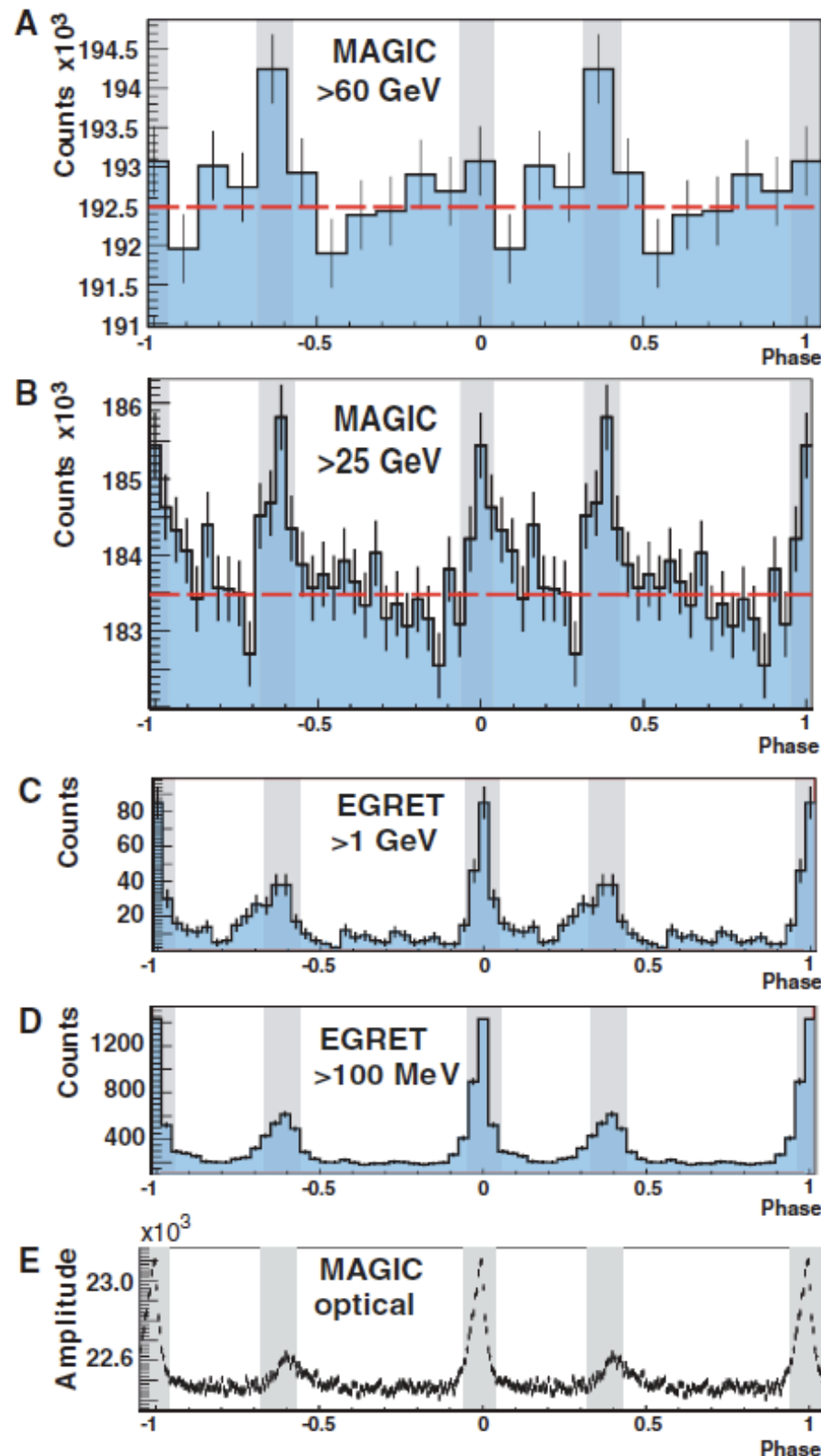


Collection Area



**Energy threshold
25 GeV!**

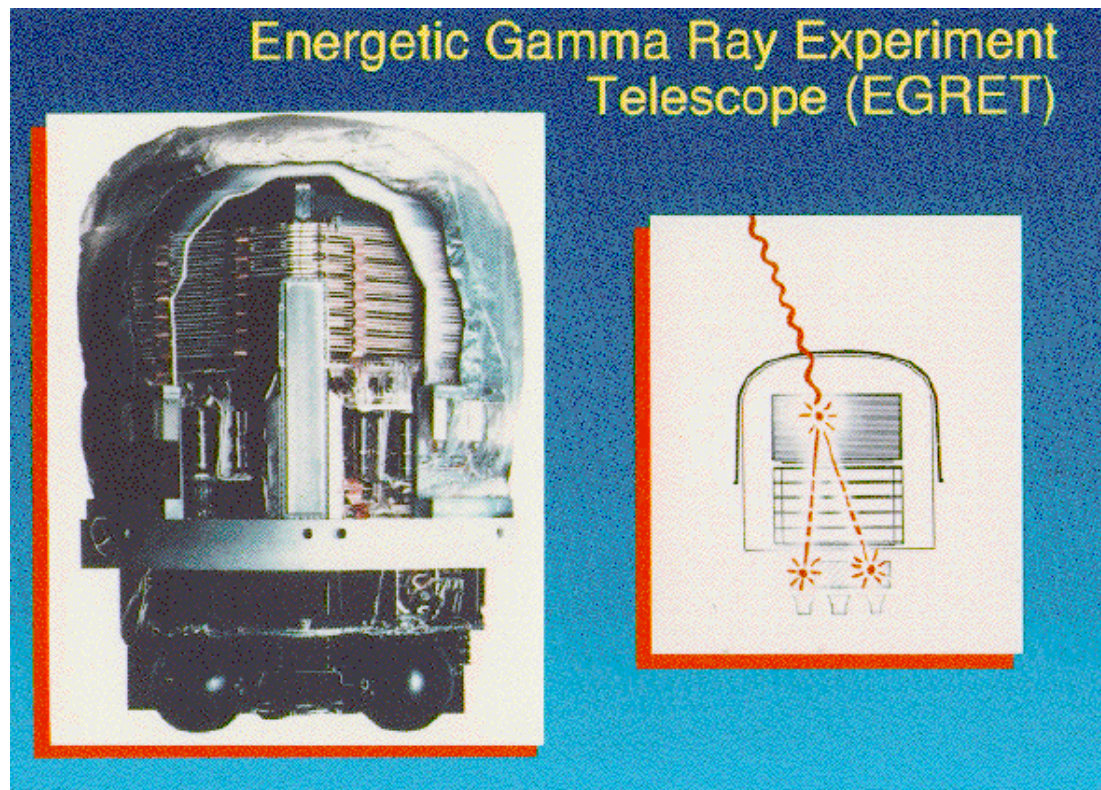
2nd MAGIC Observations (Crab)



- Observation in 2007-2008
- First pulsar detection by IACT
- Discovery of 25 GeV pulsation
- **PC rejected!**
- Spectral shape not clear...
- Combined with EGRET, 17.7 GeV exponential cutoff explains the results

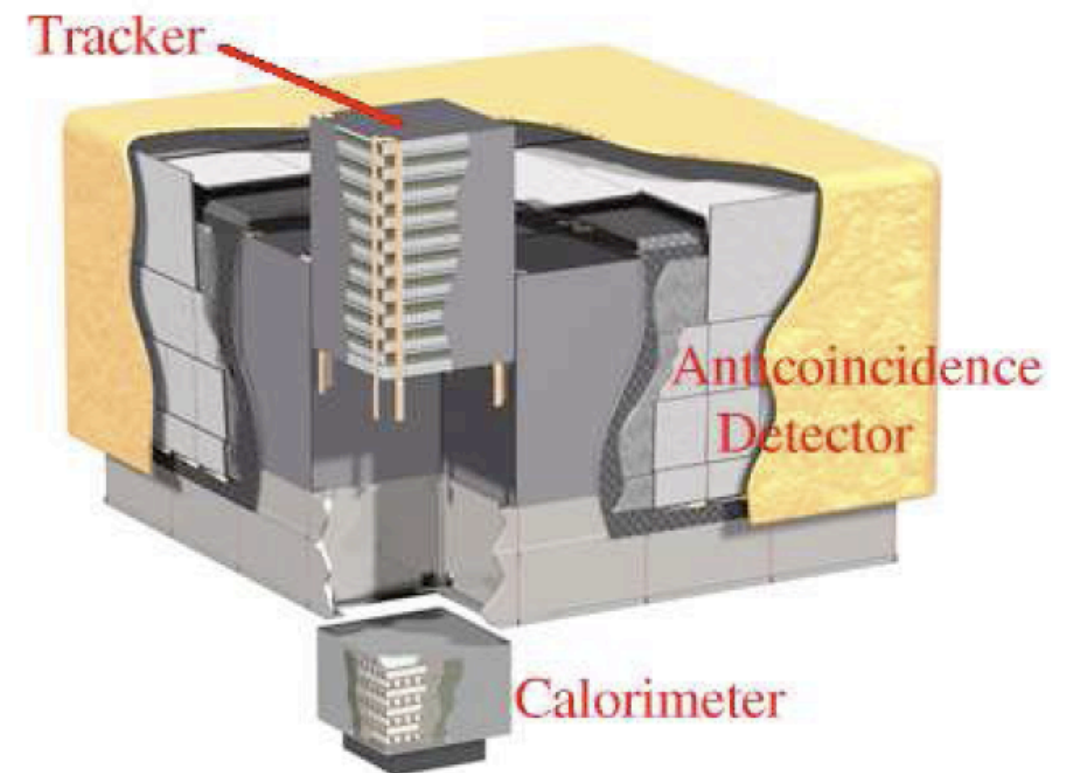
Fermi-LAT (2008-)

• EGRET



- 20MeV- 30 GeV
- Operational 1991- 2000
- Anti-coincidence counter + Spark chamber + Calorimeter
- effective $\sim 0.15 \text{ m}^2$
- Detected first 7 gamma-ray pulsars

• Fermi-LAT



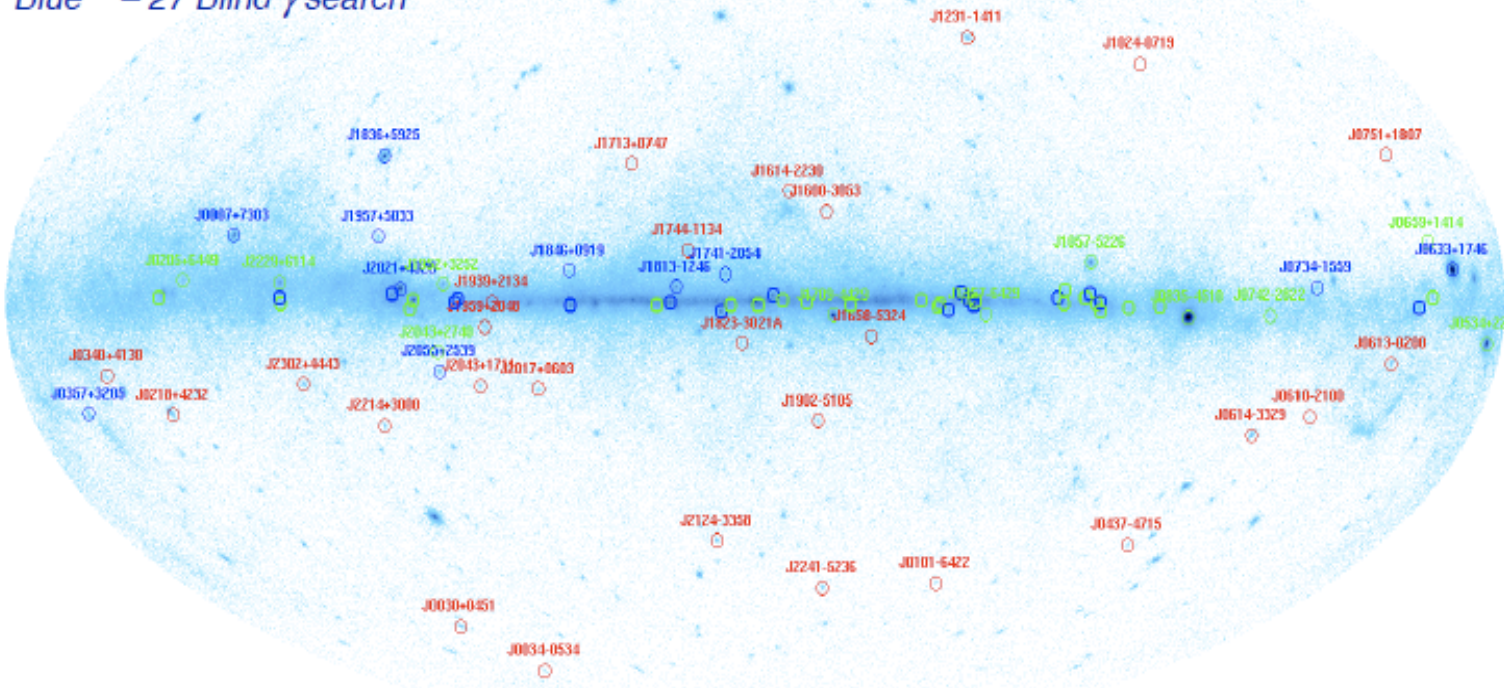
- 100MeV- 300 GeV
- Operational 2008 -
- Anti-coincidence counter + Silicon strip + Calorimeter
- effective $\sim 1 \text{ m}^2$
- 10 times higher sensitivity than EGRET
- Detected > 100 gamma-ray pulsars

Fermi-LAT observations (2008)

Green -- 34 radio ephemeris (young, and not-so-young)

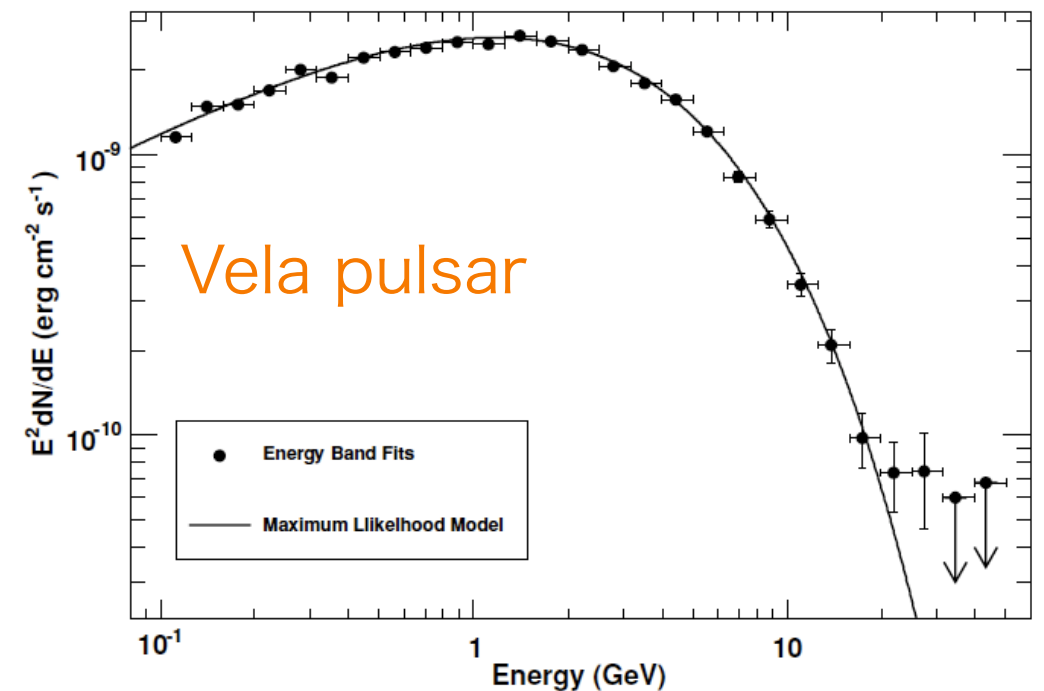
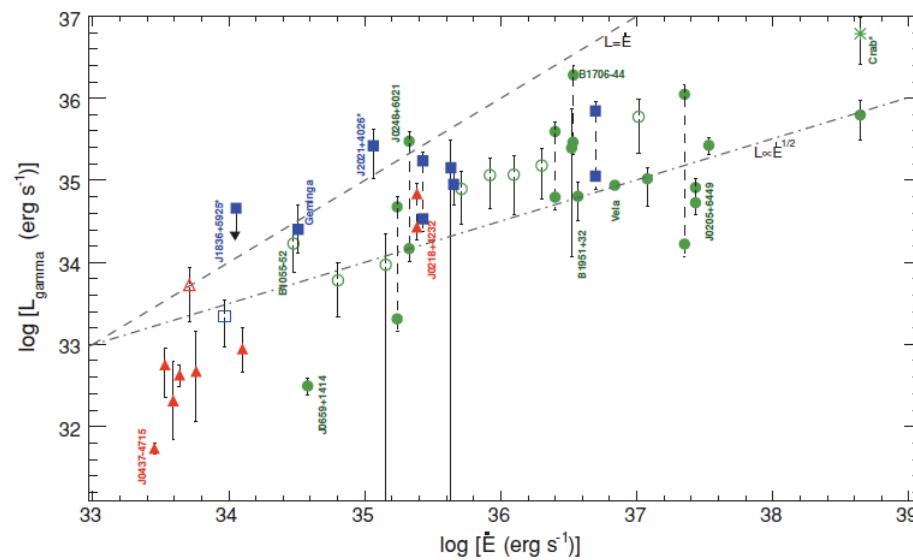
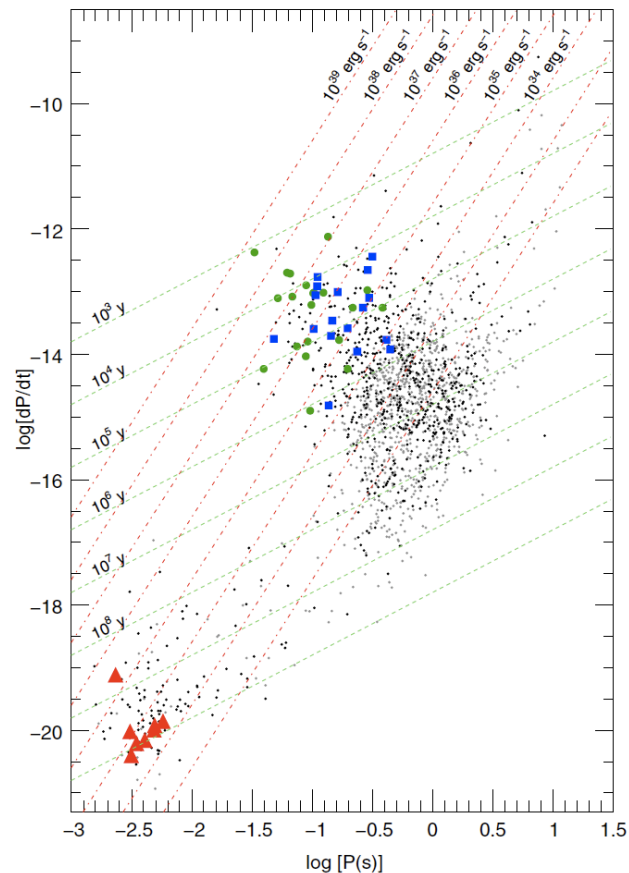
Red -- 27 radio MSP

Blue -- 27 Blind γ search

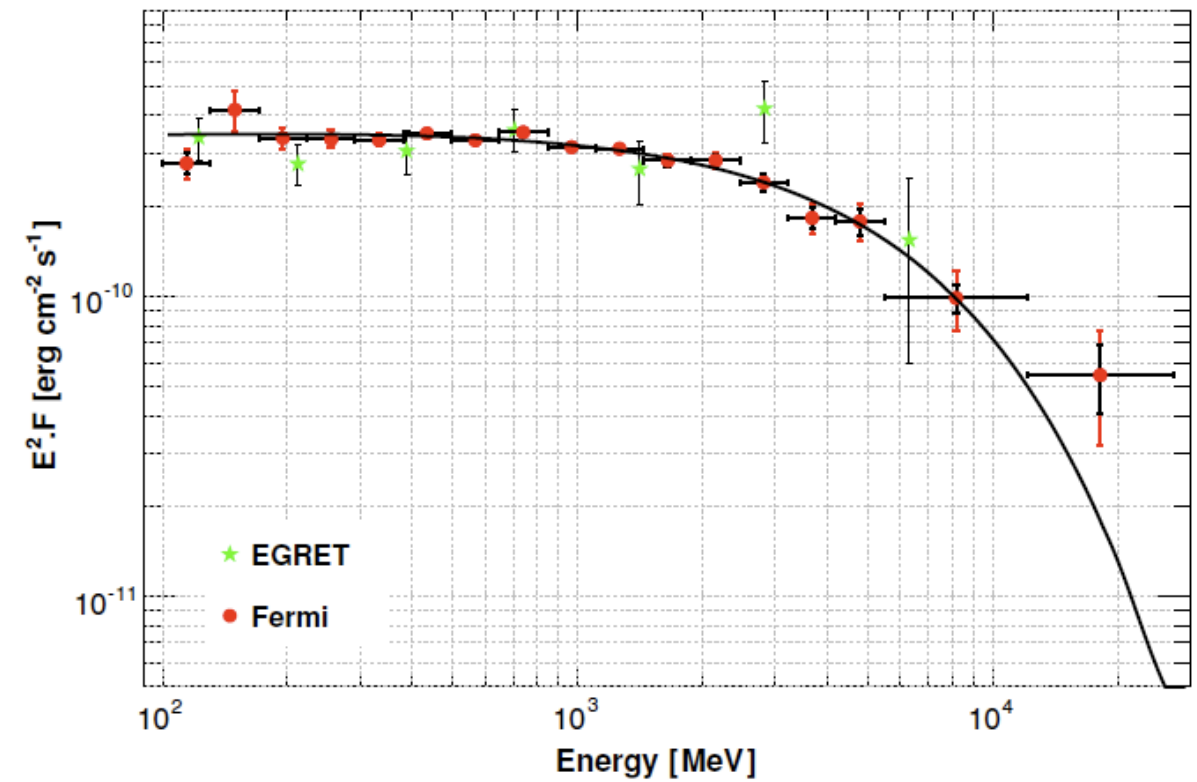
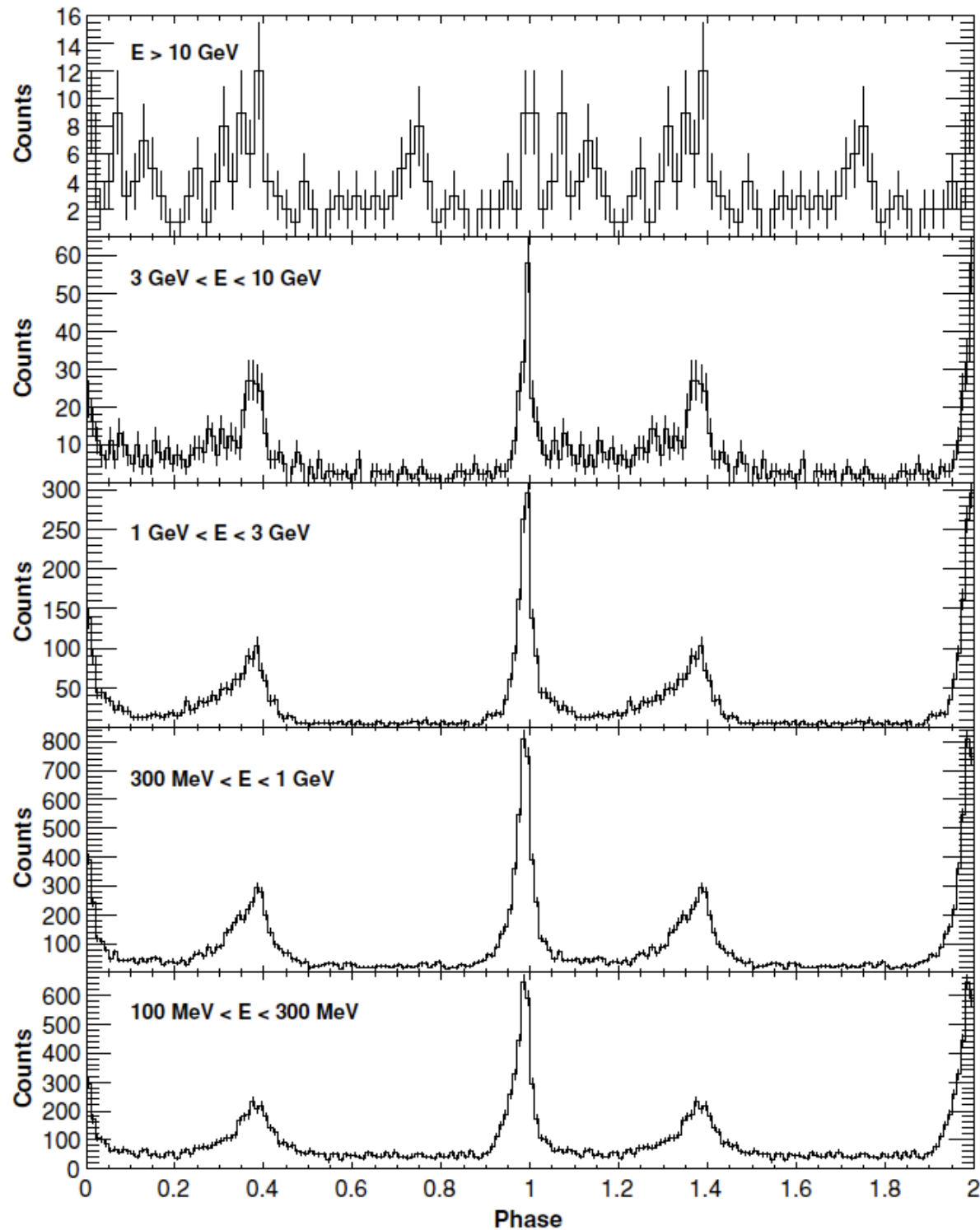


- Detected 46 gamma-ray pulsars in the first year
- Now more than 100 detected
- Population study

• All spectra basically consistent with exponential cutoff, supporting the OG model.



Fermi-LAT observations (Crab)

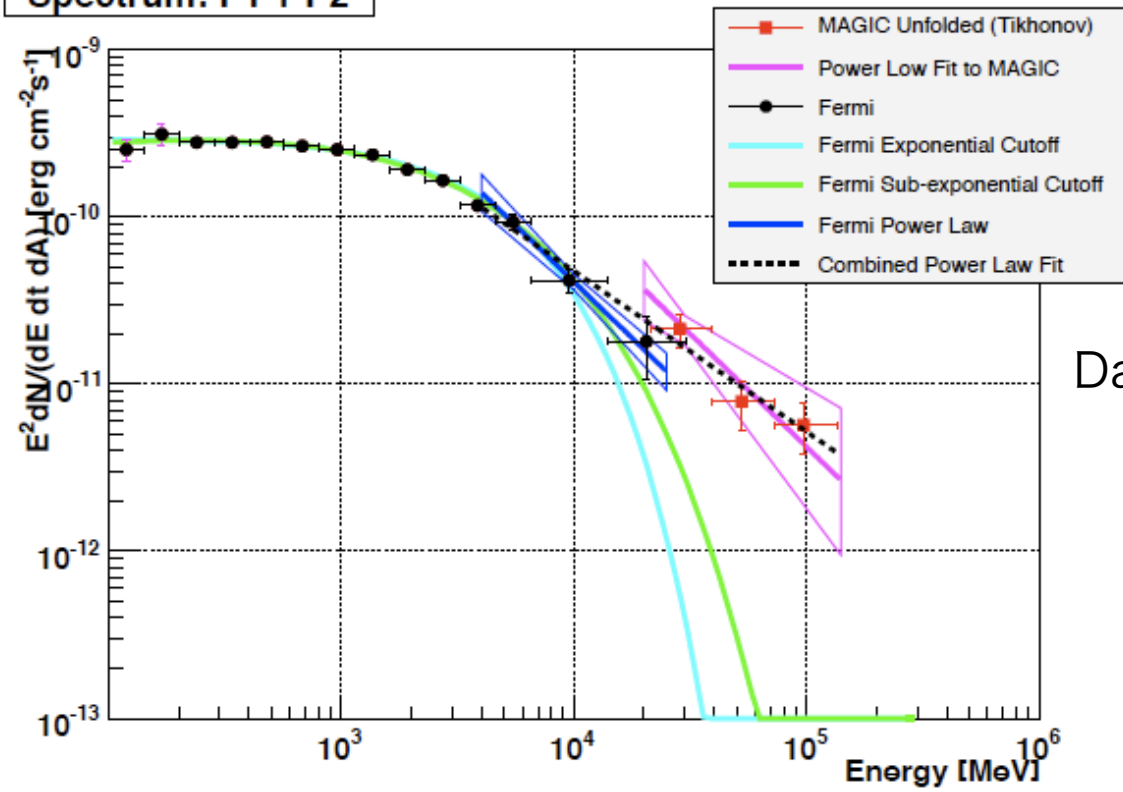


Exponential cutoff at 5.8 GeV?!

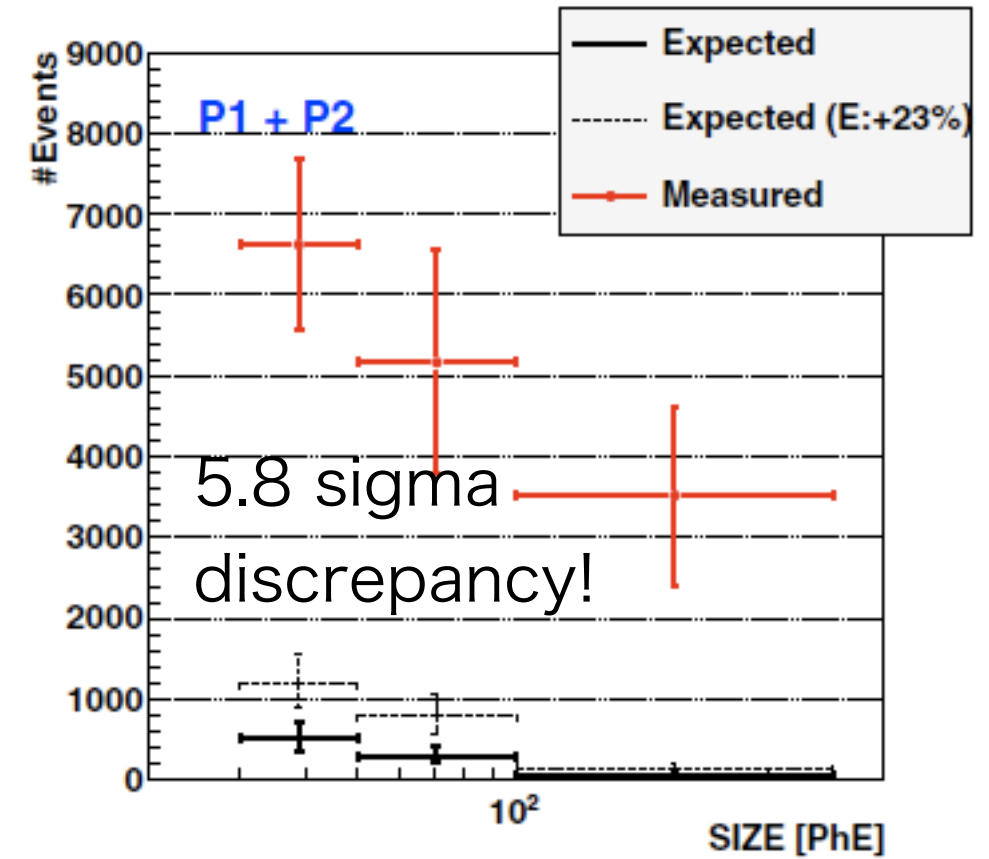
that the cut-off energy derived by the MAGIC Collaboration for a simple exponential cut-off ($17.7 \pm 2.8 \pm 5.0$) GeV is higher than the one obtained with the *Fermi*-LAT data, $E_c = (5.8 \pm 0.5 \pm 1.5)$ GeV. However, the cut-off energy obtained with the LAT using the softer EGRET spectrum ($\gamma = 2.022$) as done by MAGIC is within the uncertainties of the MAGIC value.

MAGIC/Fermi comparison

Spectrum: P1 + P2

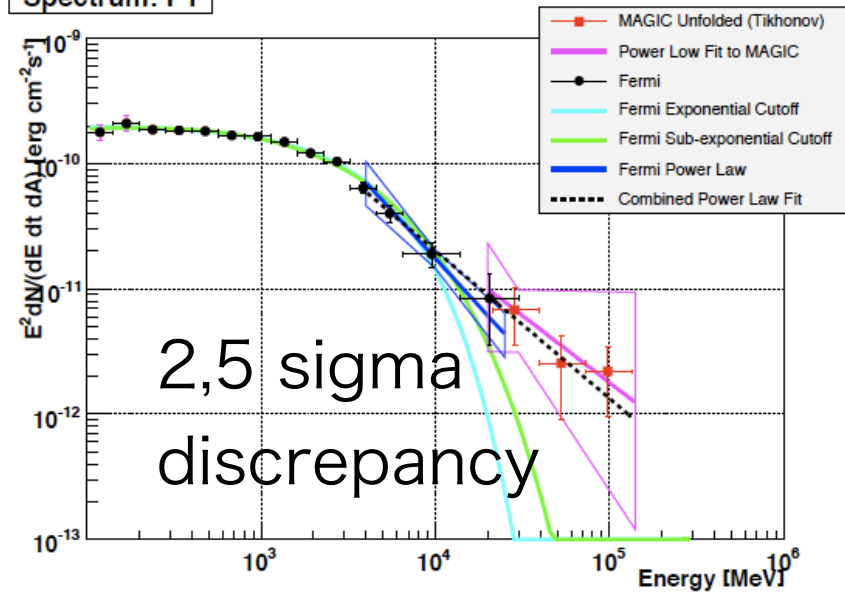


Data 2007-2009

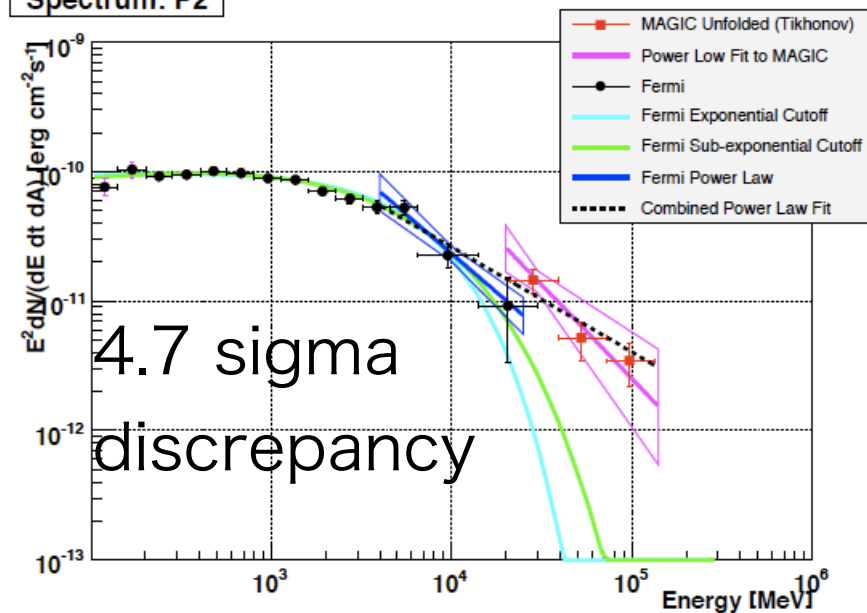


Event "SIZE" distribution

Spectrum: P1

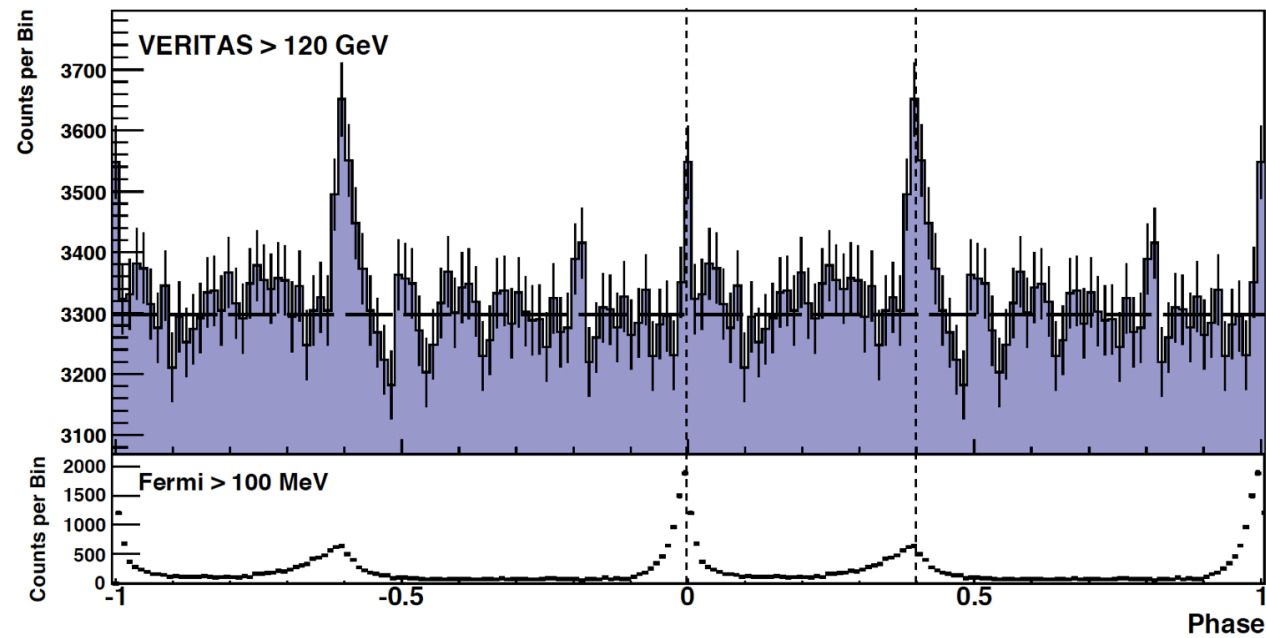


Spectrum: P2

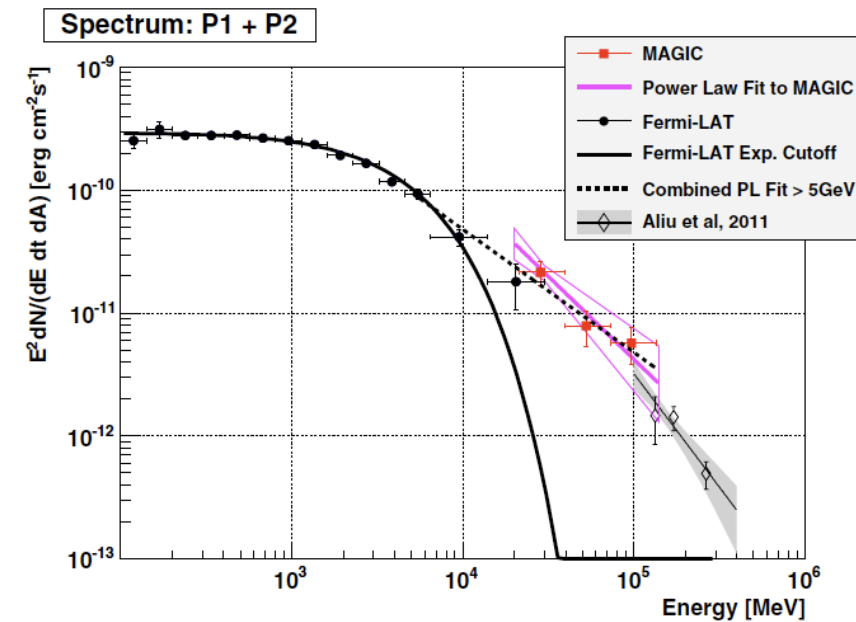
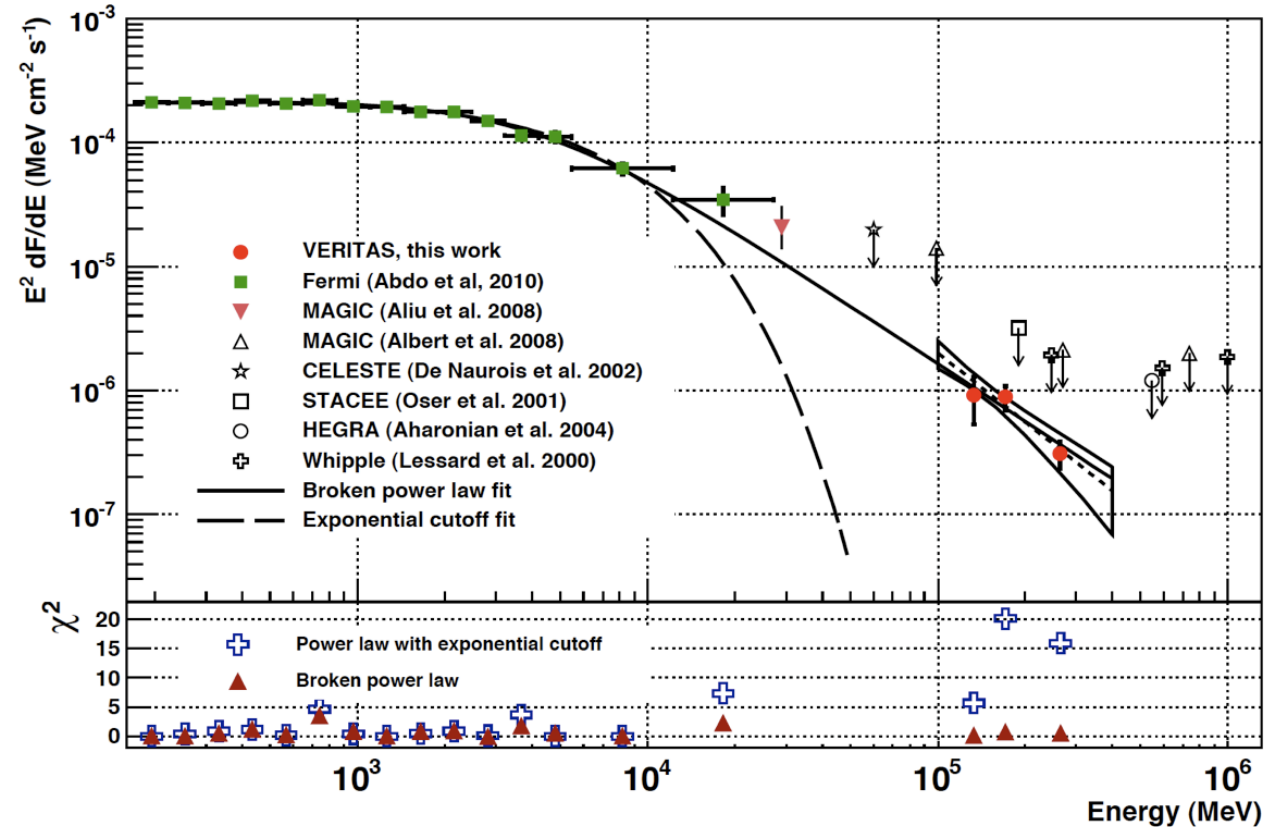


Spectrum doesn't follow exponential cutoff!
 Power-law-like tail!
 Conventional OG models questioned.

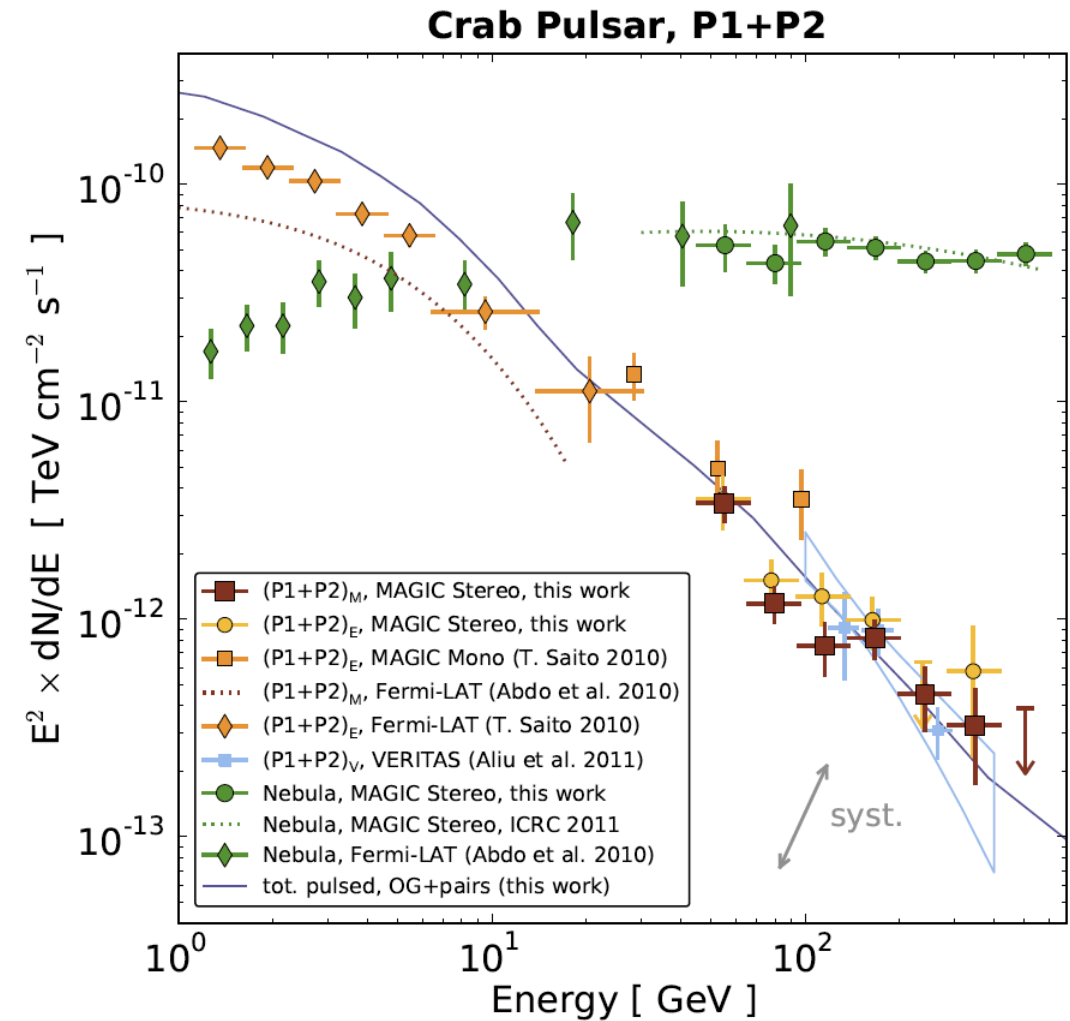
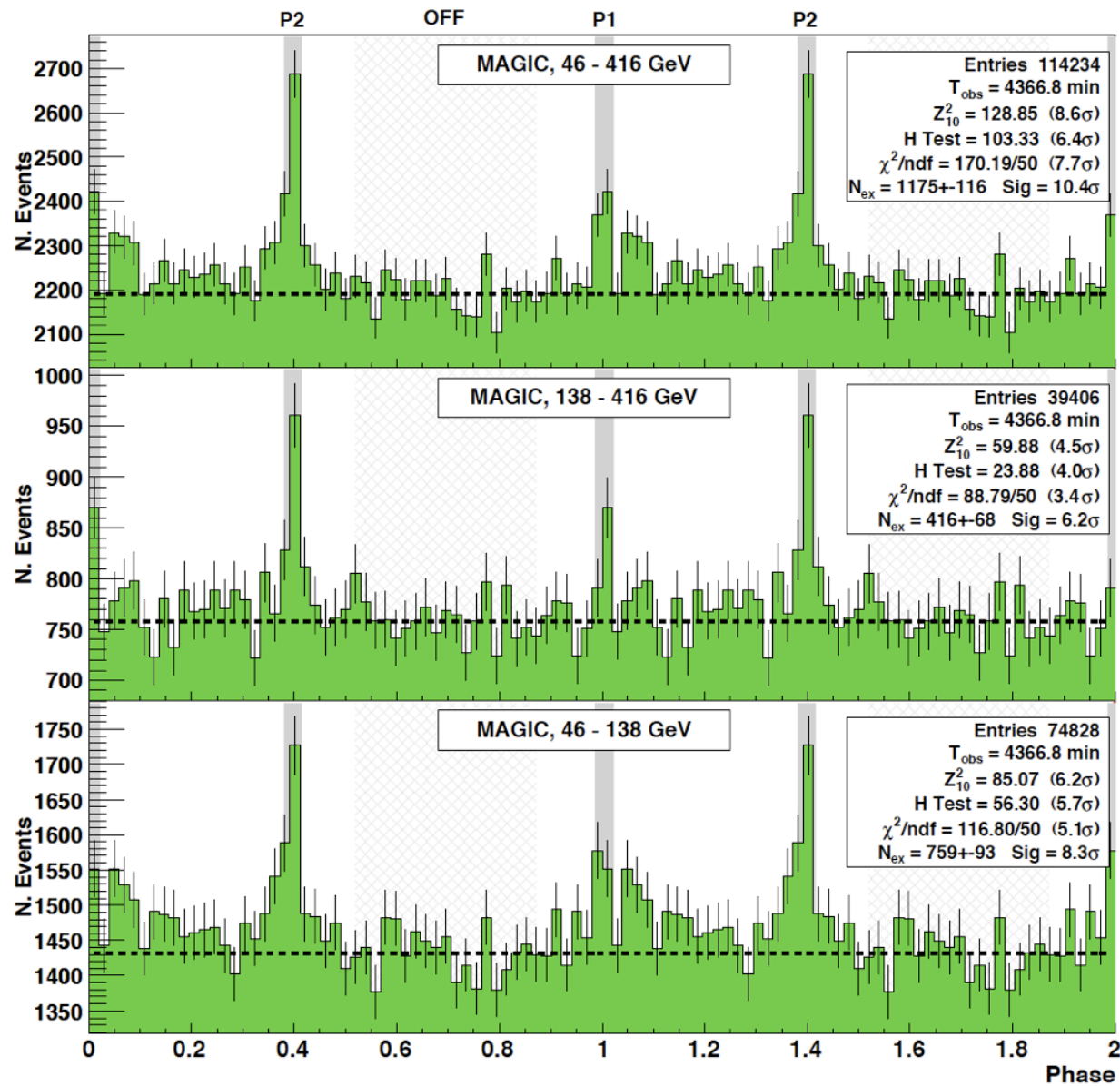
VERITAS observations (Crab)



- Observations 2009-2011
- Detect pulsation above 100 GeV
- Broken power law

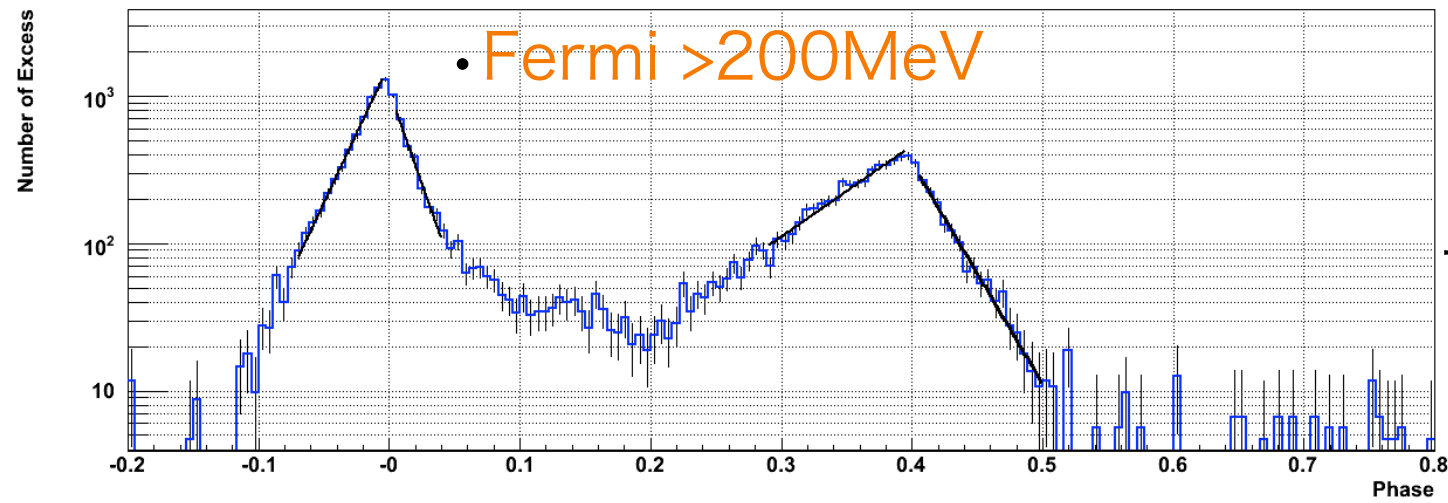


Stereo MAGIC observations (Crab)

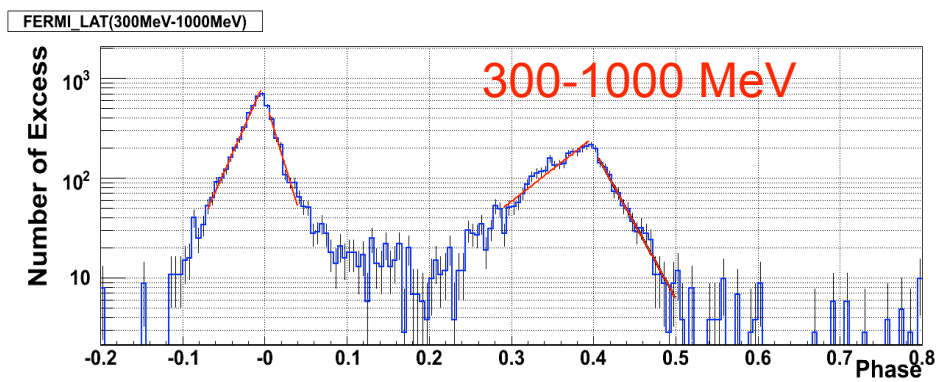
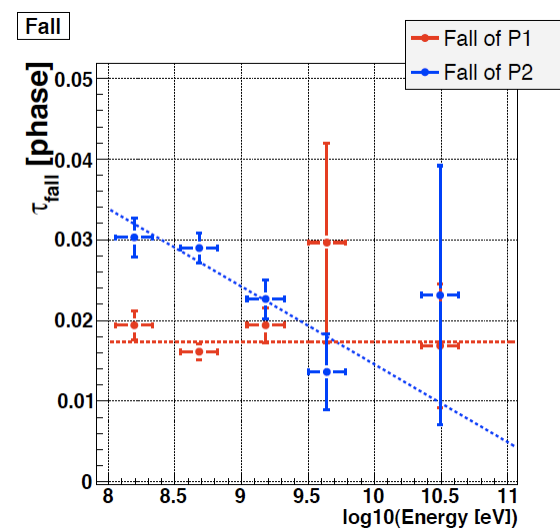
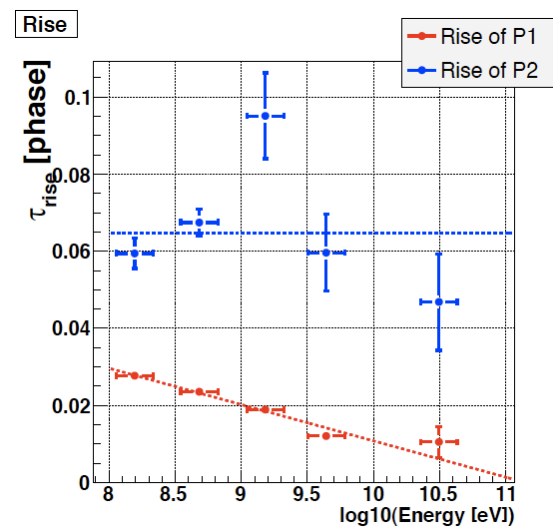
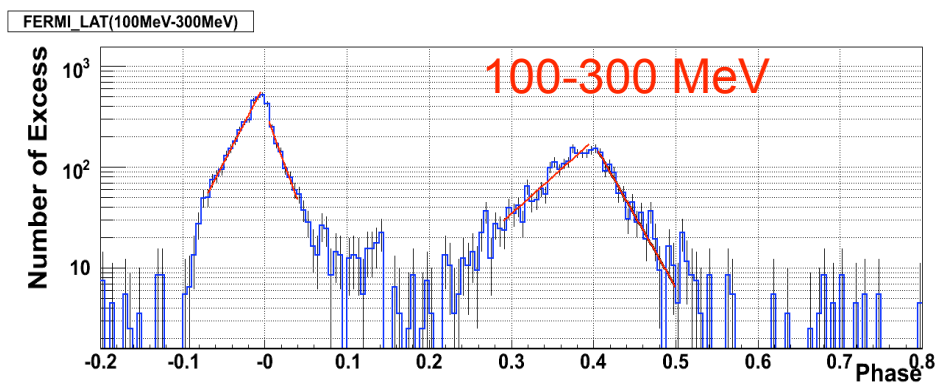


- No doubt that there is a power-law-like tail
- How to explain this? -> next three talks

Light Curve in log

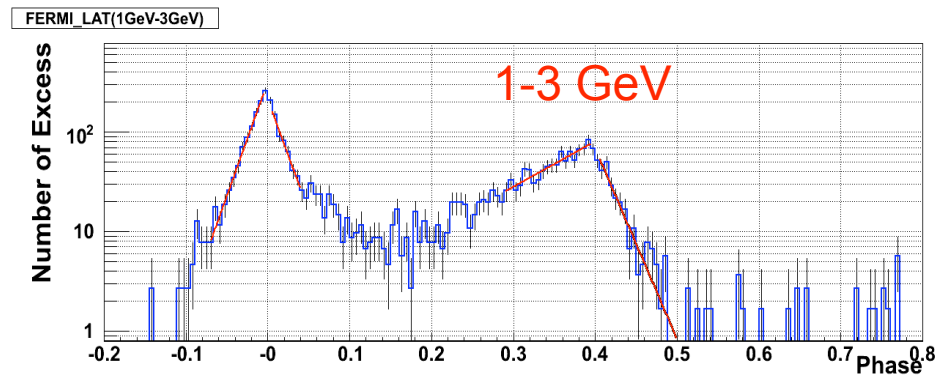


- In log scale, two triangles appear
- Slopes decrease with energy except for falling edge of P1



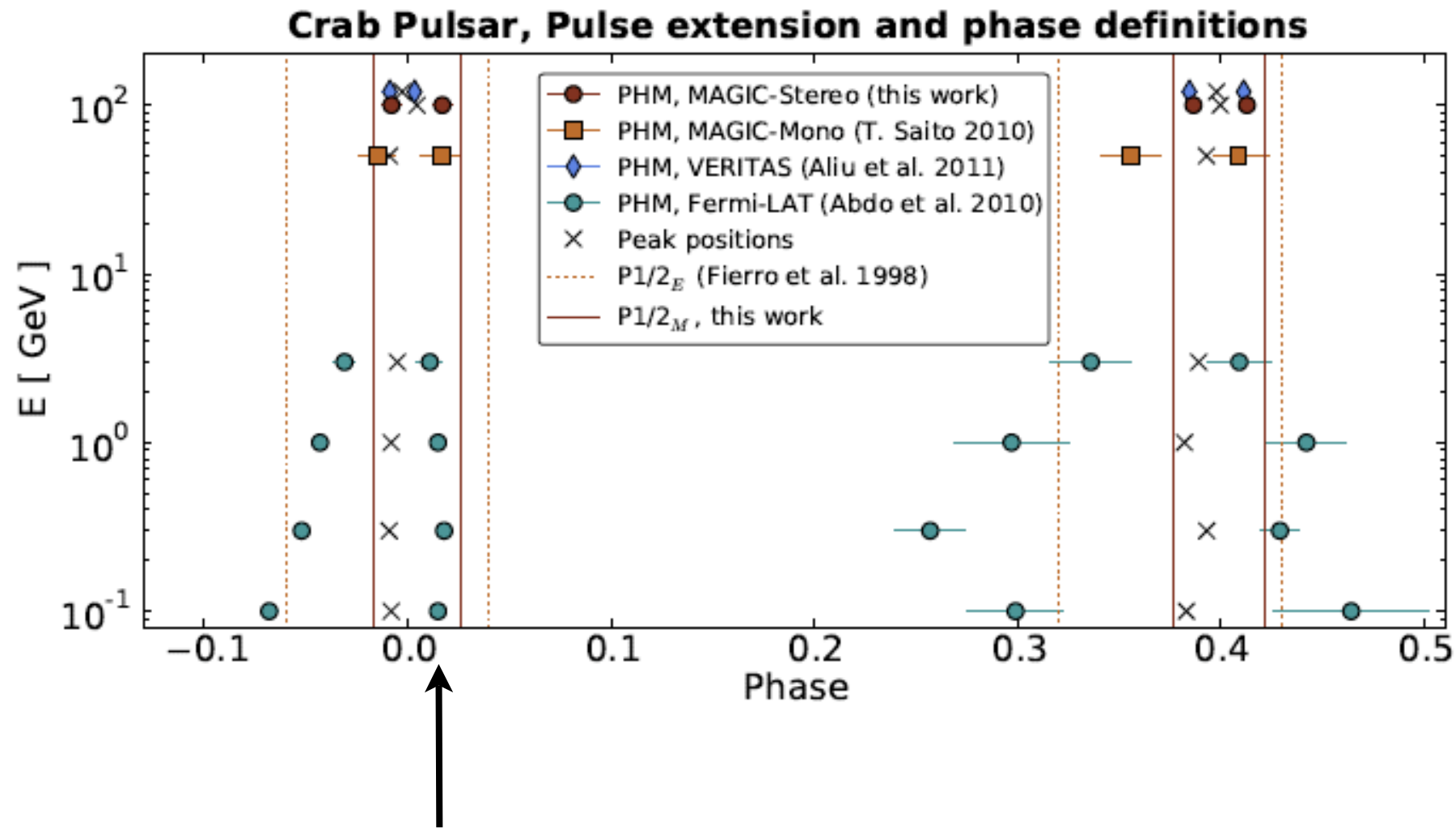
• Rise vs Energy

• Fall vs Energy



- Currently no explanation
- Hope this helps to construct better pulsar models

Pulse Width



- Width decreases with energy, consistent with previous slide
- See more in Kisaka san's talk

Conclusion and Prospect

- In the last 5 years, pulsar physics made **rapid progress** thanks to consecutive important measurements by MAGIC, Fermi and VERITAS
 - **PC model rejected** (for gamma-ray emission)
 - conventional **OG model forced to modify** (for Crab)
- However, in-depth study could be done **only with Crab**, which is unique/special in many senses. To understand pulsars further, more observations/detections in VHE are necessary
- **CTA** will make another “revolution” in pulsar physics :)