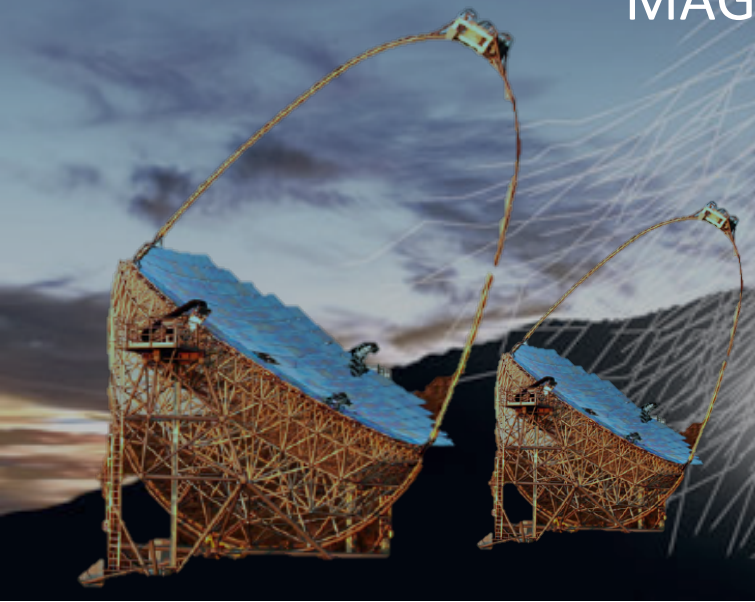
Unveiling VHE Emission from Pulsars with MAGIC

Marcos López
T. Schweizer, T. Saito, F. Dazzi, J. Rodriguez, G. Ceribella, D. Fidalgo, I. Snidaric, …
On behalf of the MAGIC collaboration

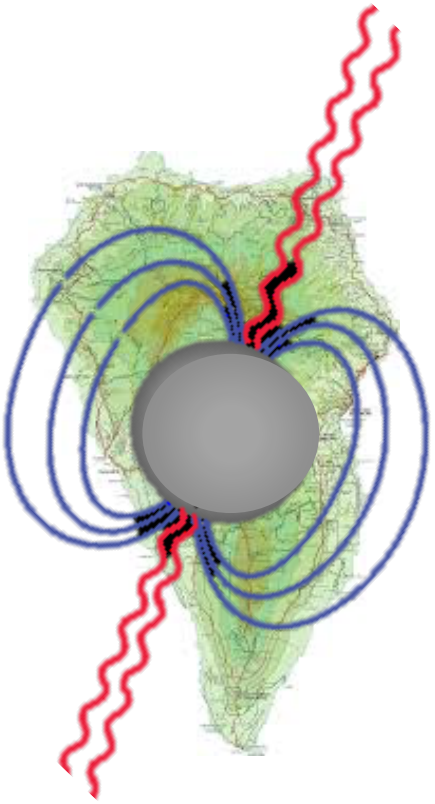
MAGIC 15th Anniversary Meeting



Outline

- Pulsars at VHE
- SumTrigger
- MAGIC Crab
- Geminga

Pulsars



Probes of extreme Physics

- Pulsars are highly magnetized and rapidly rotating neutron stars
  - Extreme density: M~1.4 $M_{\odot}$ & R~10 km
  - Huge magnetic fields: B~$10^{8\text{-}14}$G

➔ *Unique lab for nuclear and particle physics*

Pulsars

Probes of extreme Physics

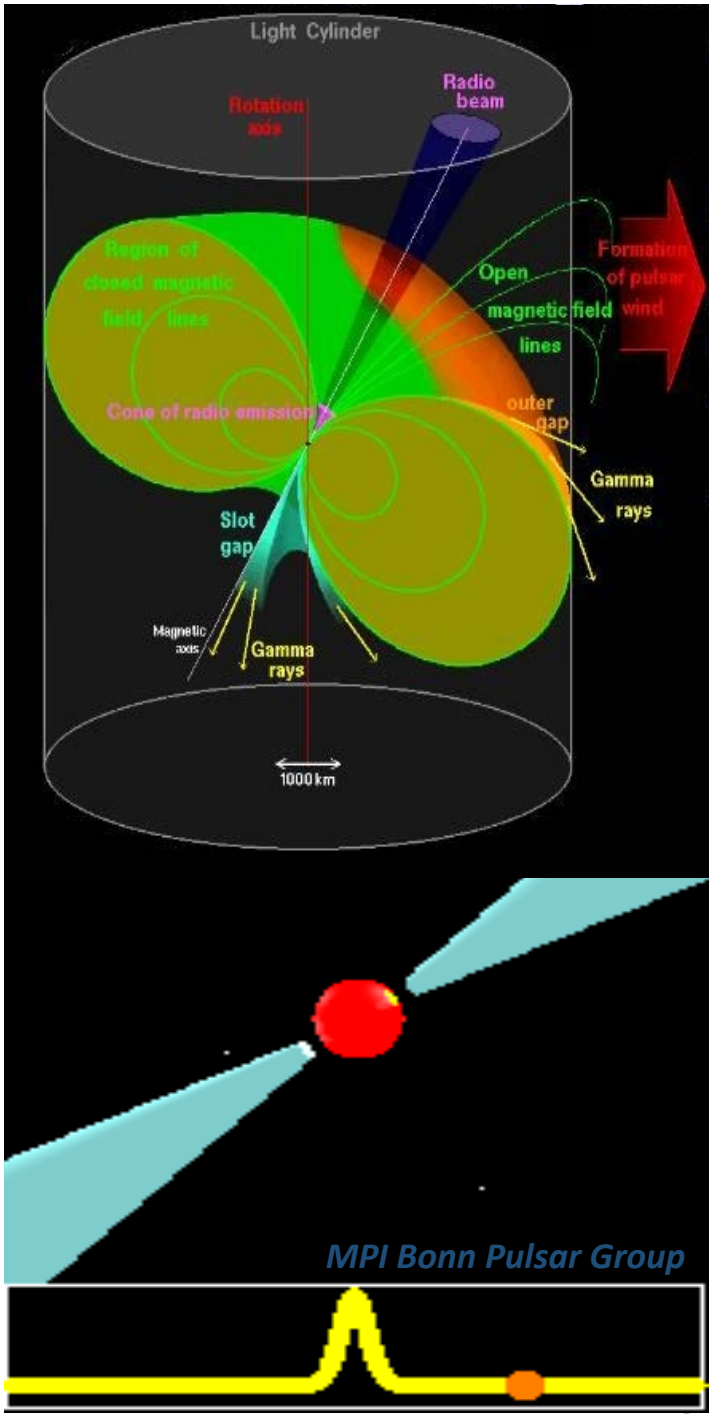
- Pulsars are highly magnetized and rapidly rotating neutron stars
  - Extreme density: M~1.4 $M_{\odot}$ & R~10 km
  - Huge magnetic fields: B~$10^{8\text{-}14}$G

➔ *Unique lab for nuclear and particle physics*

Magnetosphere

- Fast rotation + huge B field induces intense Electric field ➜ E so intense that pull particles out
- A dense plasma is co-rotating with the star:
  - Magnetosphere extends to the “light cylinder”
  - Non-thermal Emission (radio, optical, X-ray, γ-rays) produced in beams

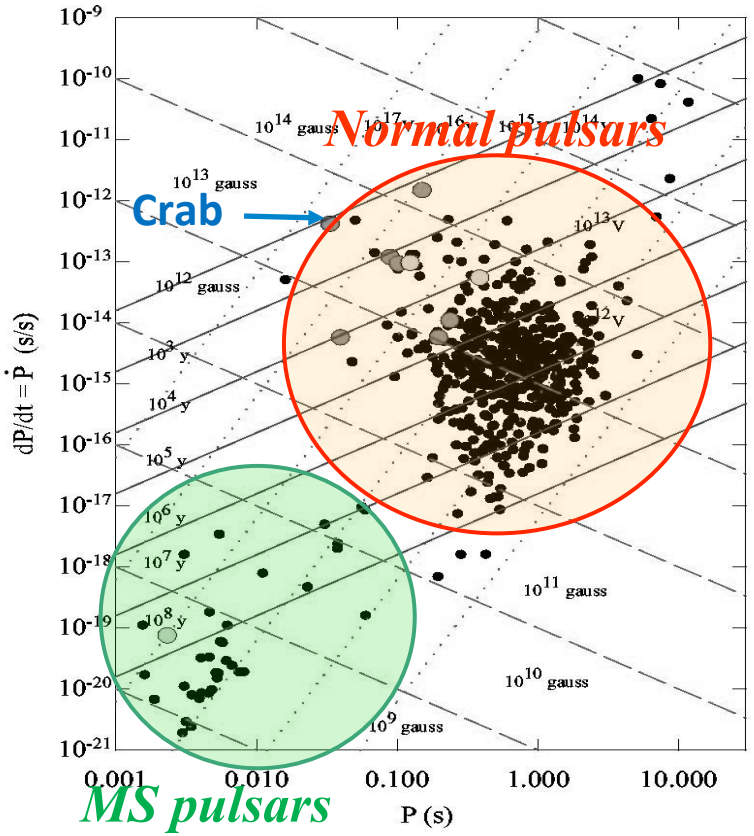
➔ *Acts like a cosmic light-house*



Pulsars at all wavelengths

Radio

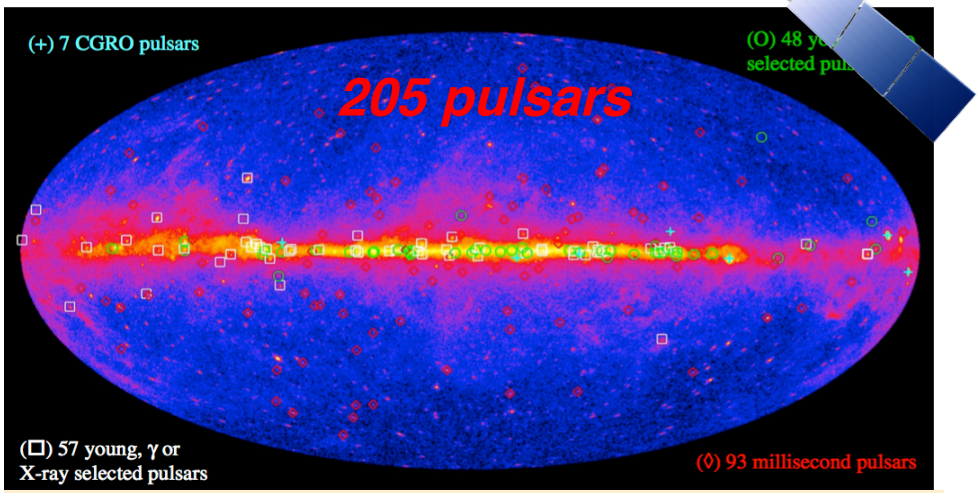
- First discovered in radio in 1967
- **+2600** radio pulsars known today
- Can an be grouped in:
  - **Normal** (young): B~10^{12}G
  - **Ms** (old): B~10^{8} G



Pulsars at all wavelengths

Radio

- First discovered in radio in 1967
- **+2600** radio pulsars known today
- Can an be grouped in:
  - **Normal** (young): B~10^{12}G
  - **Ms** (old): B~10^{8} G



Most of Fermi galactic sources are pulsars

γ-Rays

- Only **7** seen by EGRET in the 90's
- **+200** detected by Fermi-LAT:
  - Discovered new γ-ray pulsars in blind searches
  - Discovered a whole population of ms pulsars
  - Discovered many geminga-like pulsars

Light curve:

- Typically 2 peaks

Spectra:

- Well fitted by PL + sub-exp. cutoff

- Cutoff energies < 10 GeV

Pulsar models

Where do γ-rays come from?

Accelerated particles emit via synchro-curvature radiation

Emitting regions

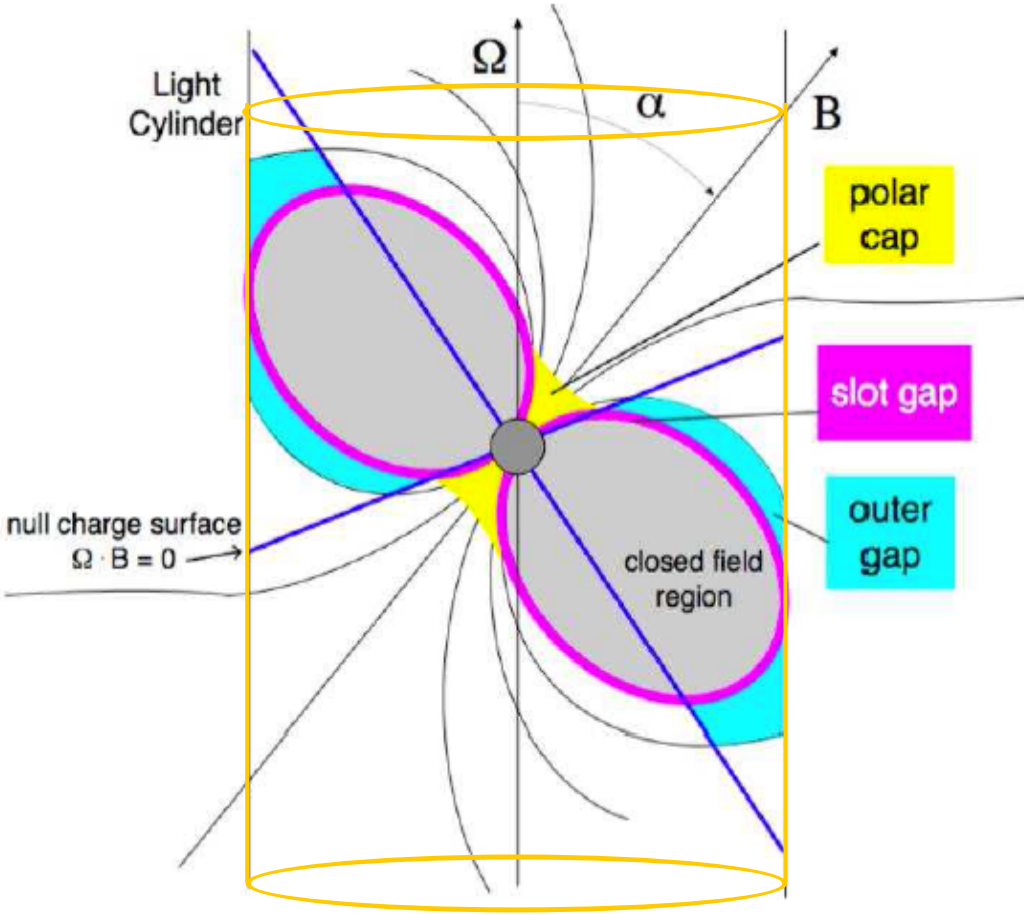
- Models try to explain observed γ-ray emission assuming different emitting regions:
  - Within magnetosphere: **PC**, **OG**, **SG**
  - Beyond magnetosphere

Light curves depends on geometry

- Depending on α, β different emission patterns expected (number of peaks, separation, radio/γ lag,…)

Spectrum depends on the physics of the emitting region

- Expected sharp exp. or sub-exp. cut-offs @ few GeV

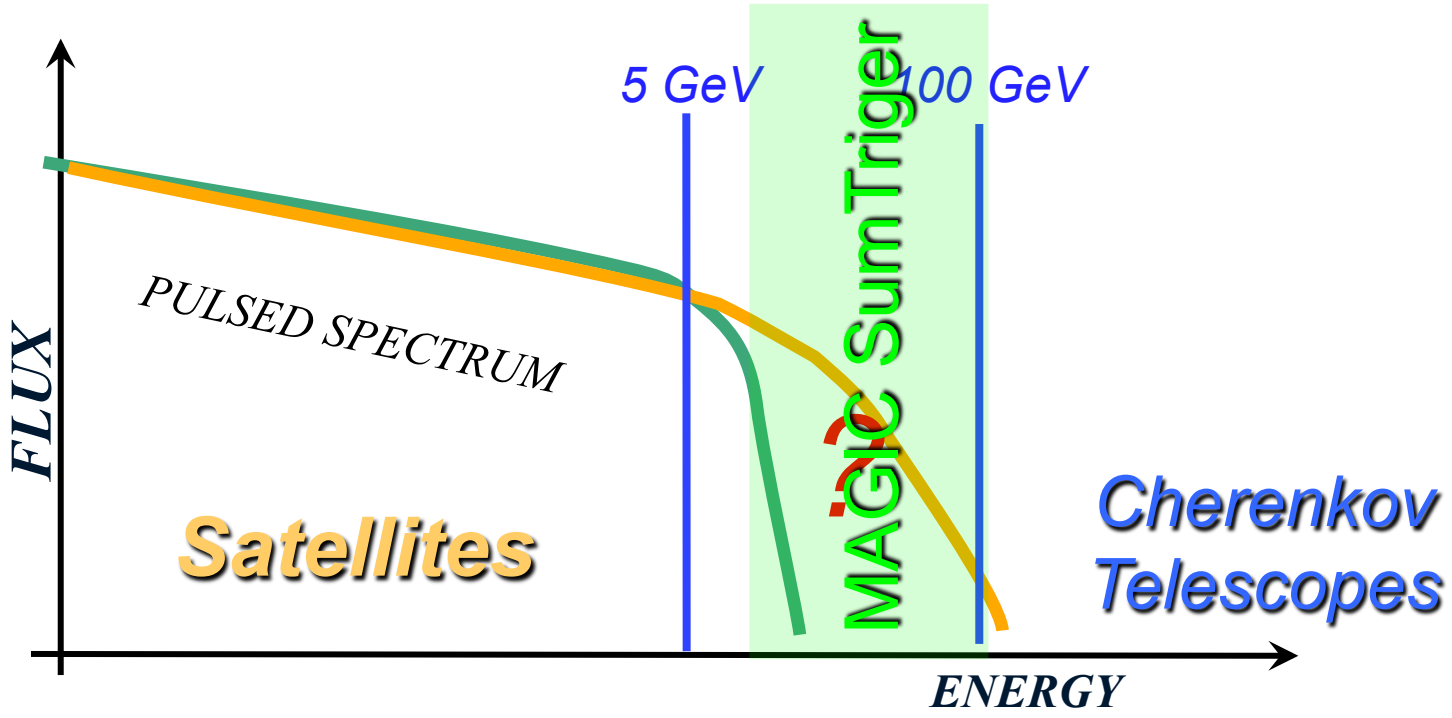


Credit: A.Harding

Pulsars at VHE?

Situation before MAGIC

- According to models and Fermi-LAT, pulsars are sources that intrinsically disappear at few GeV, so in principle they wouldn't be visible by CTs



Need for a detector at tens of GeV … The MAGIC SumTrigger

MAGIC developments for pulsars

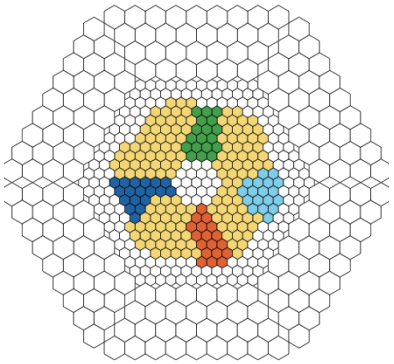
MAGIC SumTrigger-I (2007-2009): A new Trigger concept

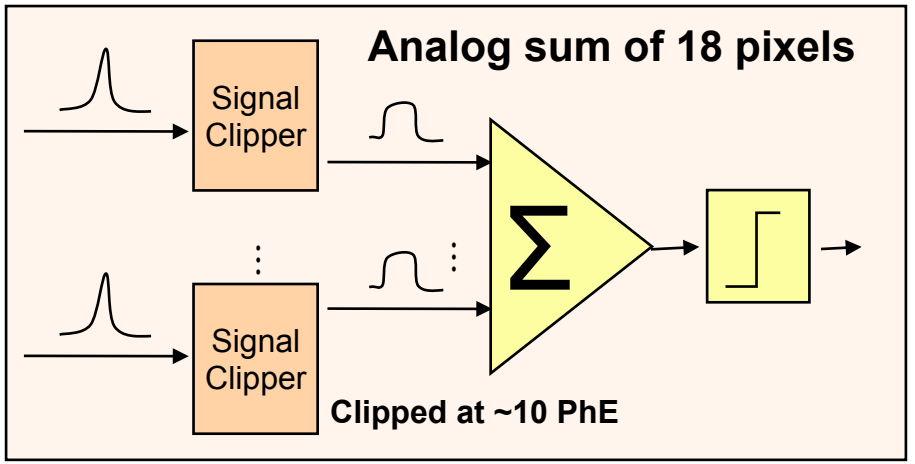
Okkie's idea: Add analog signals from a patch of PMTs & discriminate on summed signal

- Increased signal to noise ratio compared to a digital trigger

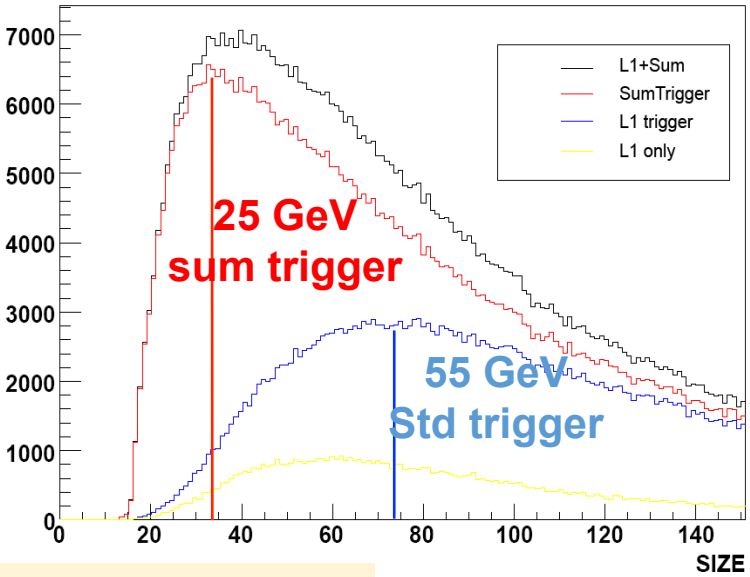
- Problem: Large amplitude from Afterpulses
  - Solution: Clipping signal

- Implemented in 2007: 24 clusters of 18 pixels in a ring area





Mono SumTrigger

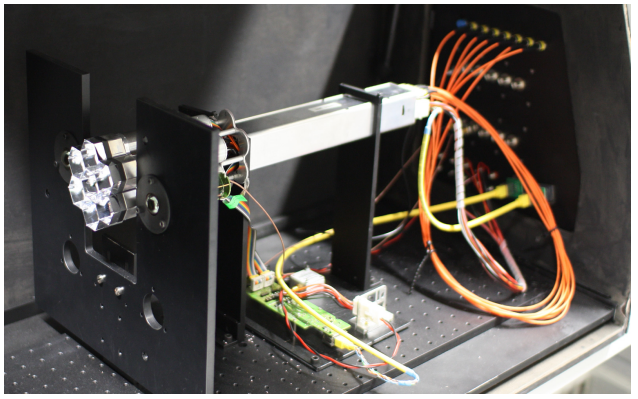


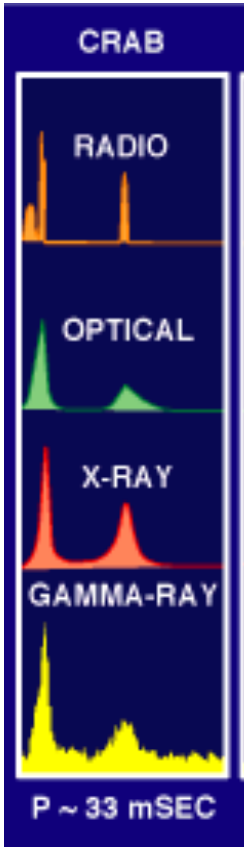
25 GeV trigger threshold:
a break-through for ground-based γ-ray astronomy

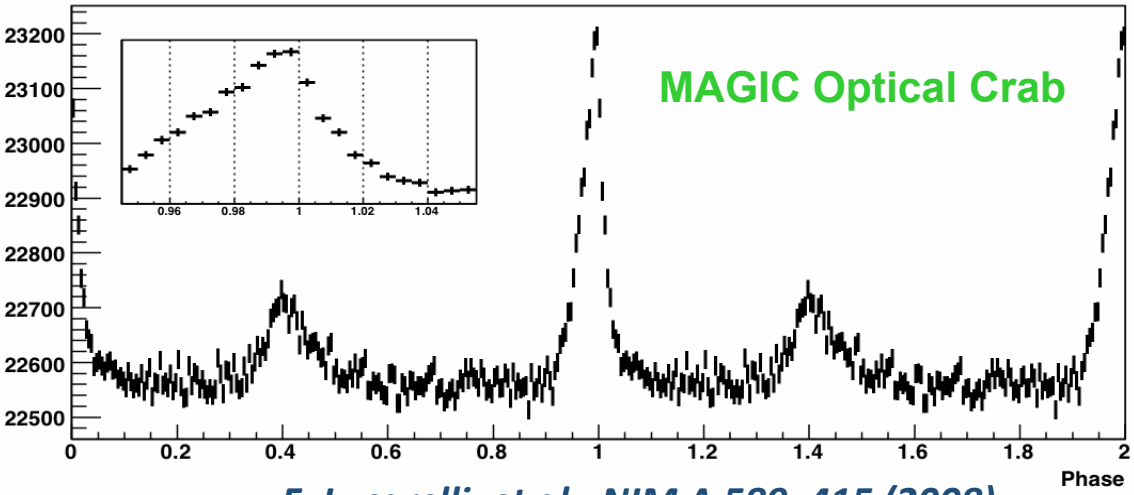
MAGIC developments for pulsars

MAGIC Central Pixel

- Modified Central pixel to detect fast optical pulses: 1 Hz to kHz
  - Digitalized by dedicated ADC @ 10 kHZ
  - Allows to check Timing System and Pulsar Software
  - Ideal for Crab: peaks aligned from optical to gamma-rays
- Crab pulsar sensitivity: 5σ in ~5 sec.







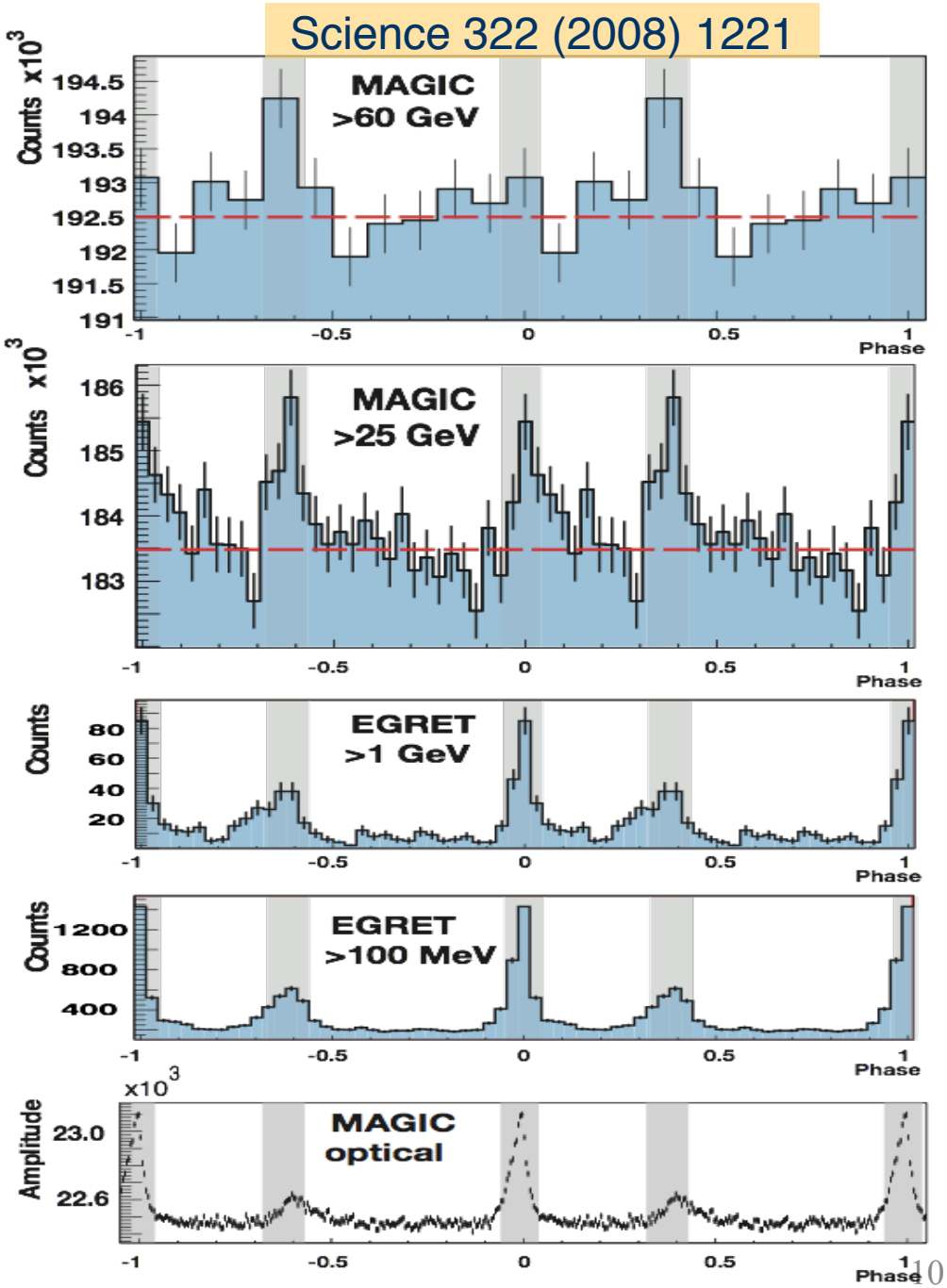
F. Lucarelli, et al., NIM A 589, 415 (2008)

First pulsar detected @ VHE: MAGIC (2008)

Detection above 25 GeV

- **22 h from** from Oct.07 to Feb. 08 with SumTrigger
- Clear detection: **6.4σ**
- Both, **P1** & **P2** seen !
- Pulses in phase with EGRET
- Hint of P2 > 60 GeV

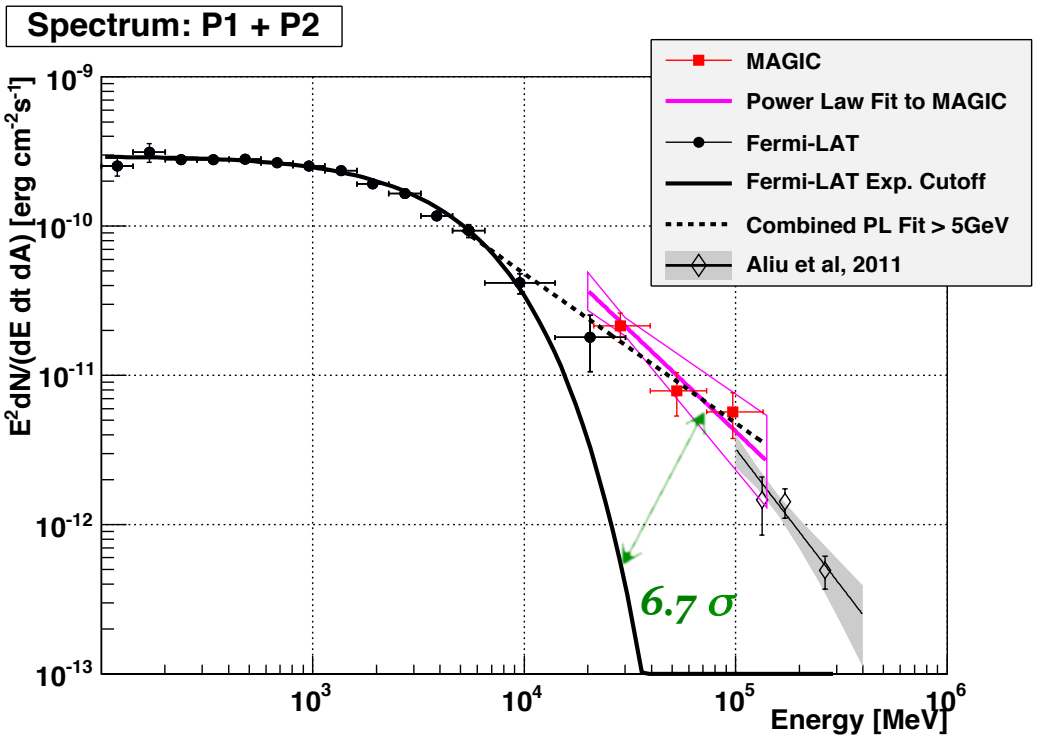
Polar Cap model excluded

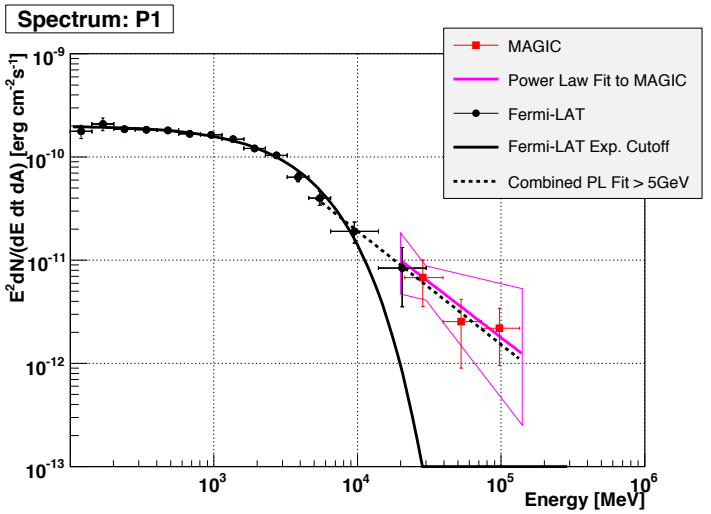


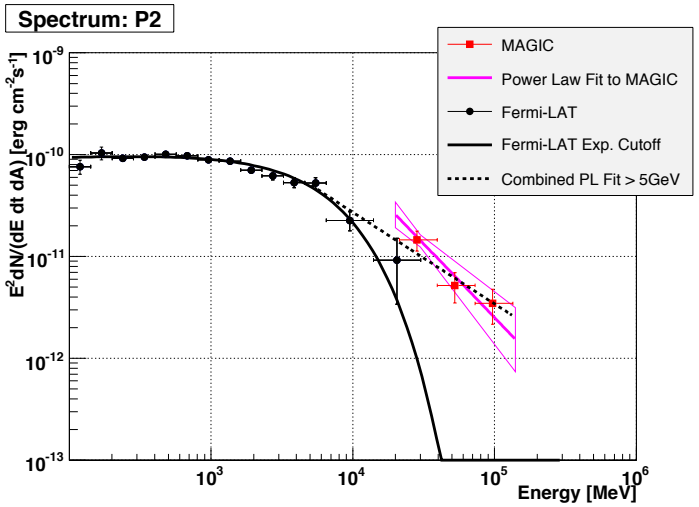
Crab SumT mono observations (2007-2009)

First phase-resolved spectra up to 100 GeV

- Further SumT observations, **~60h**, allowed to obtain first VHE first resolved spectra
- Each peak follows Power Laws
  - Exp. cutoff ruled out





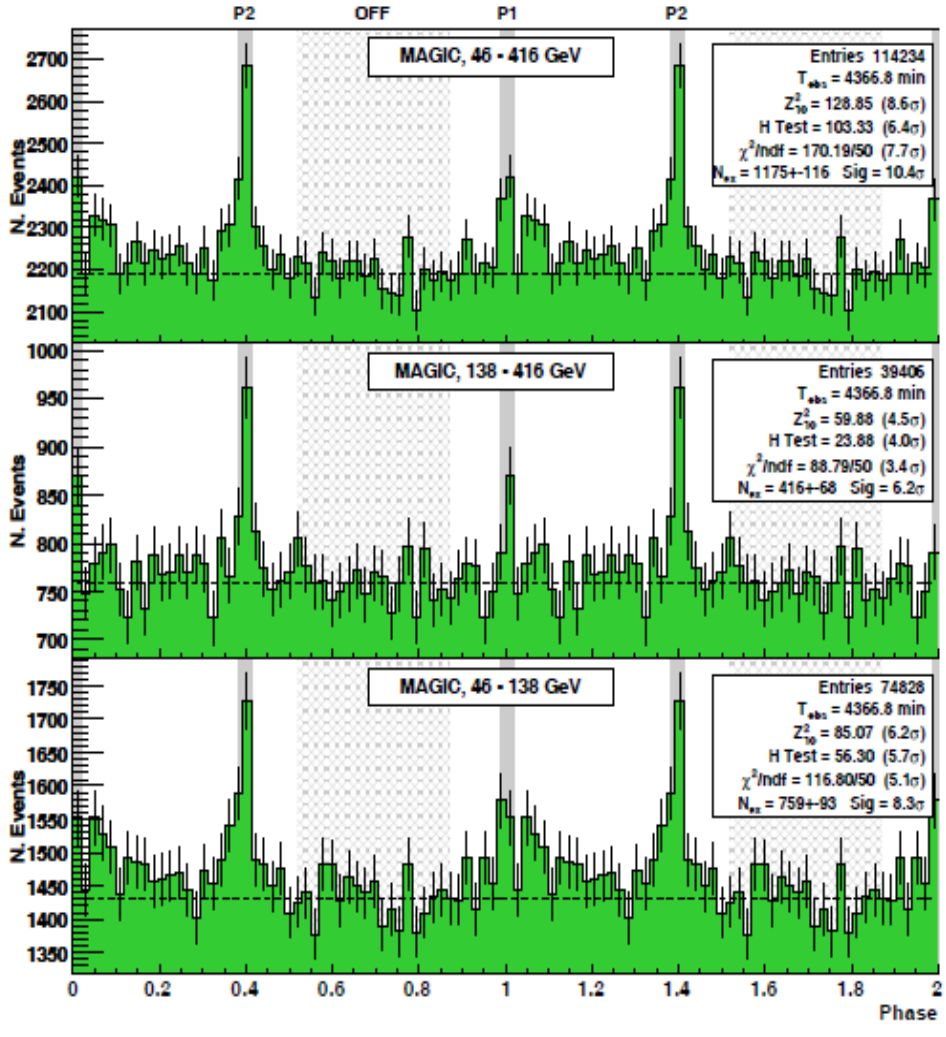


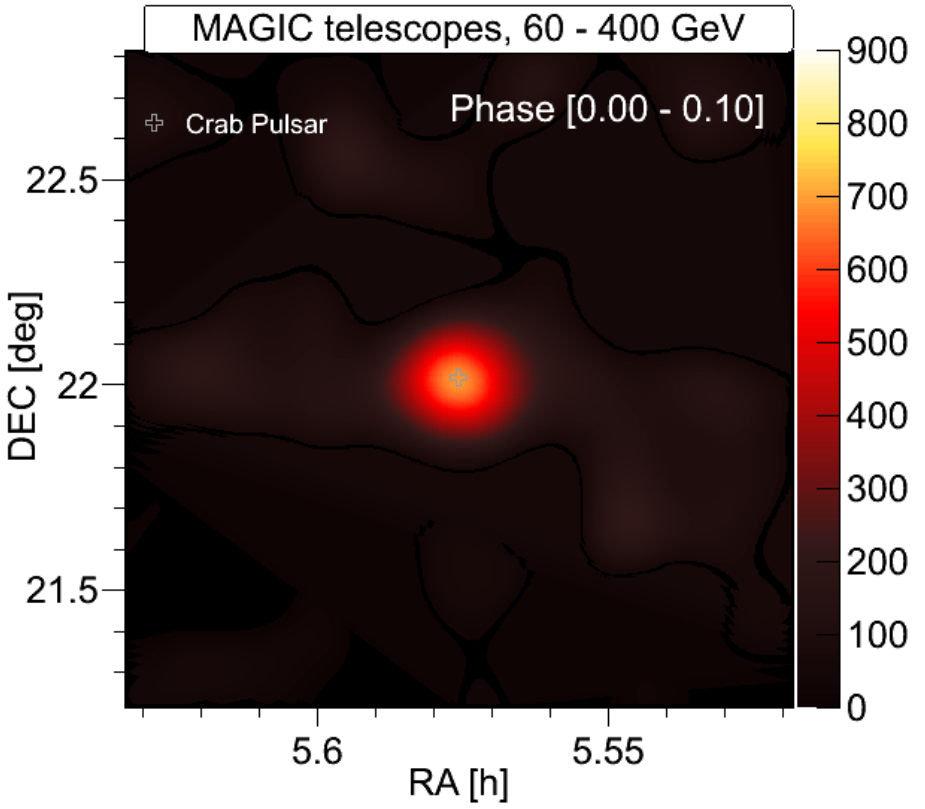
Aleksic et al., ApJ 742, 42, 2011

Crab Std. stereo observations (2009-2011)

Detection up to 400 GeV

- **73 h** from 2009-2011 with Standard trigger in Stereo mode
- Clear detection: P1: **5.2σ**, P2: **8.9 σ**



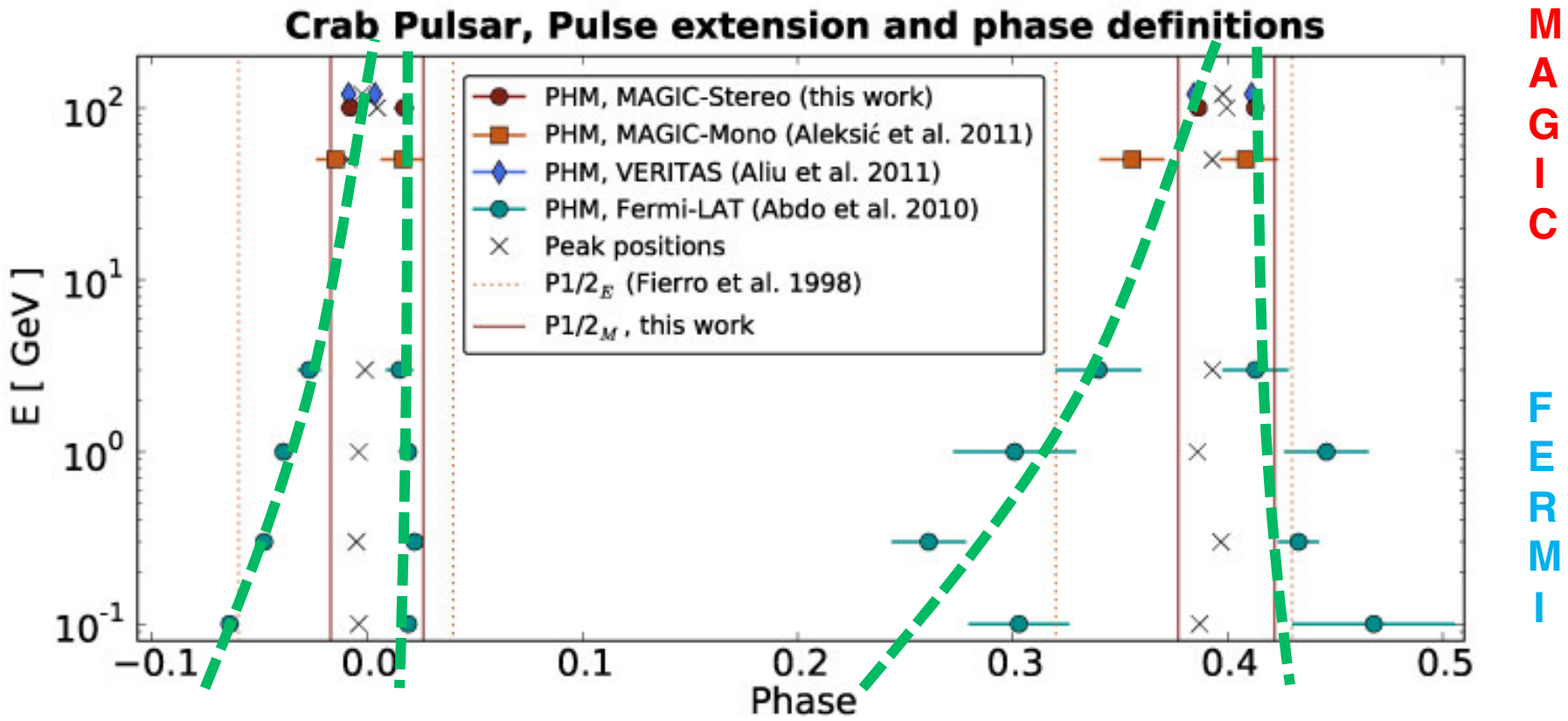


Aleksic et al, A&A 540, A69, 2012

Crab Std. stereo observations (2009-2011)

Light curve morphology

- Width of the peaks get narrower with energy



Crab Std. stereo observations (2009-2011)

First phase-resolved spectra up to 400 GeV

- Mono/Stereo spectra agree well
- Agreement also with VERITAS

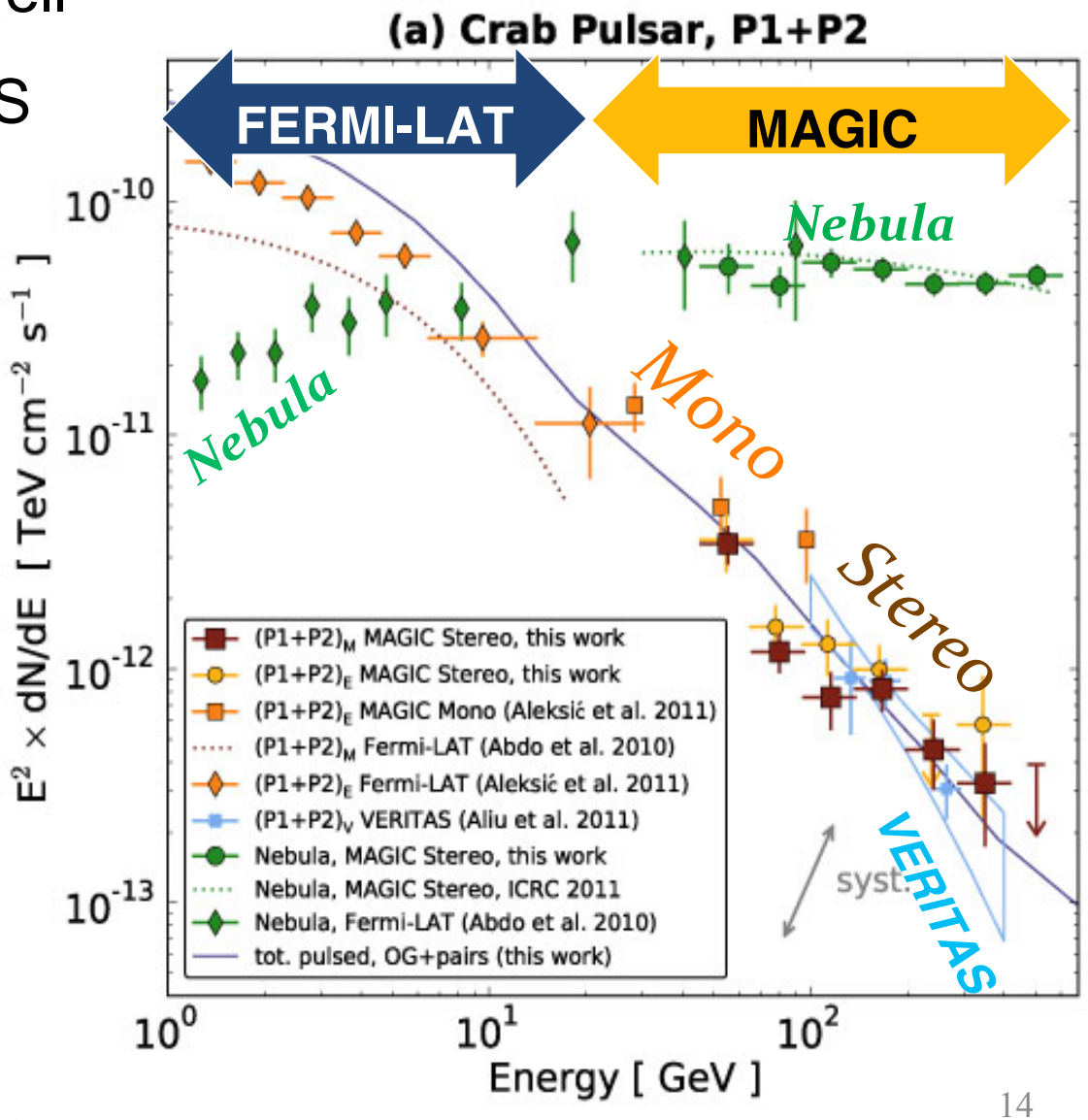
Spectral indexes

P1+P2 : Γ = -3.6 ± 0.3

P1 : Γ = -4.0 ±0.8

P2 : Γ = -3.4 ±0.3

Challenges Outer Gap model

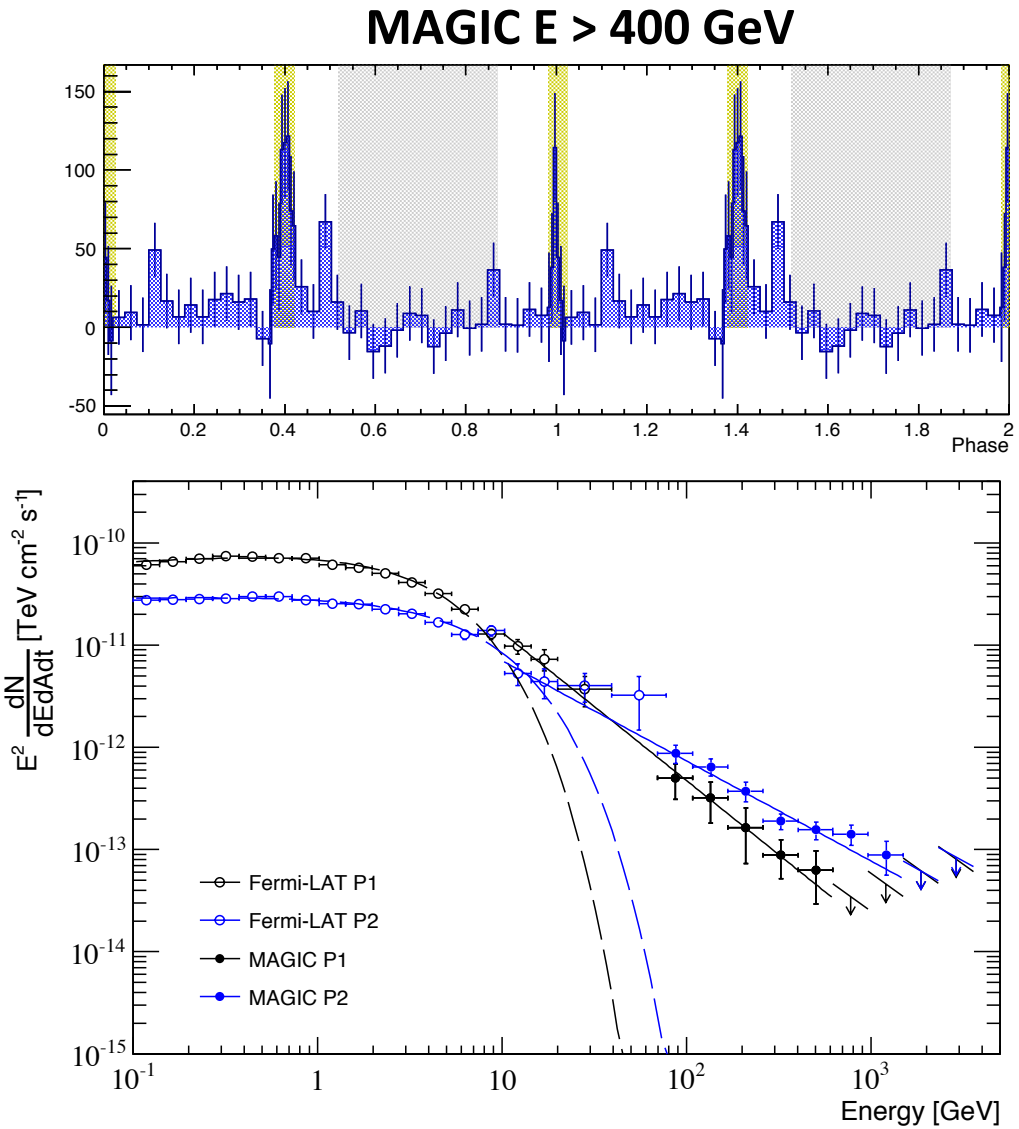


Pulsars at TeVs

Up to which energy does the Crab pulsate?

Detection up to 1.5 TeV

- Used **8 years** of Standard trigger data: **320** h
- Spectra of both peaks extending as power-laws far beyond the expected cutoffs:
  - **P1** detected up to **0.6 TeV** (*Γ*=3.5 ± 0.1)
  - **P2** detected up to **1.5 TeV** (*Γ*=3.0 ± 0.1)



Ansoldi et al., A&A 582 A133 (2016)

Implications of TeV emission

Constraining the emission site

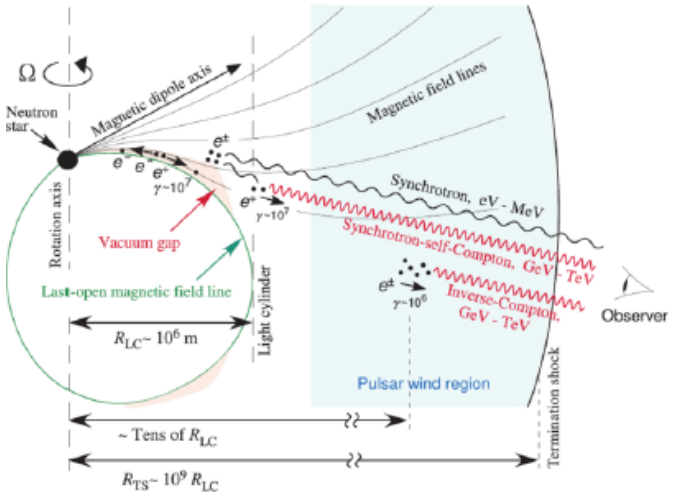
- Detection of TeV photons implies they are emitted by e^- with $\Gamma > 5 \times 10^6$
- Impossible to reach via synchro-curvature mechanism (would require unrealistic curvature radii, $R_c \sim 200\ R_{LC}$)

  → Synchrotron-curvature ruled out

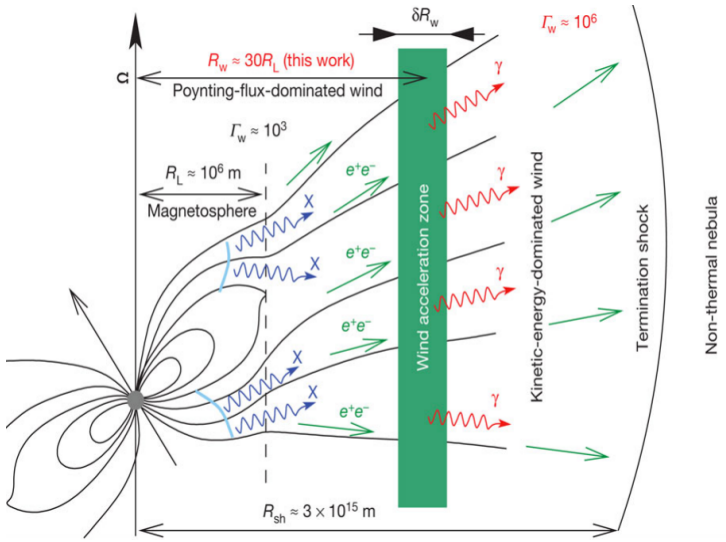
  → Only reasonable possibility is IC on soft photon fields

But Where ?

Within the magnetosphere?



Beyond the magnetosphere?



Implications of TeV emission

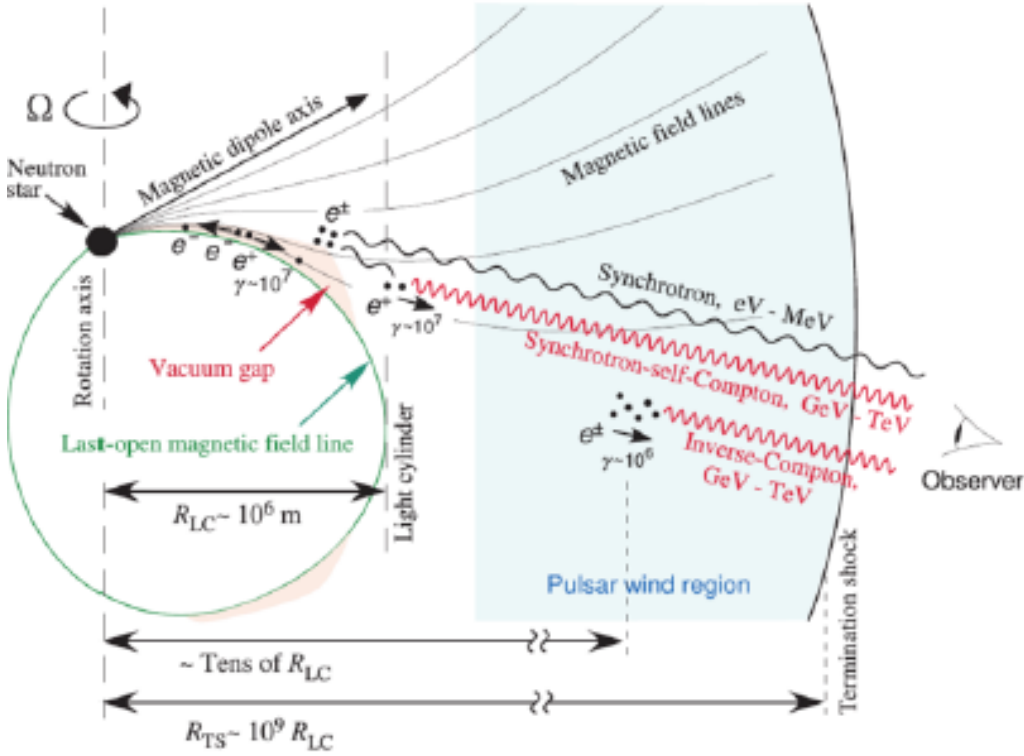
Constraining the emission site

Within the magnetosphere? Magnetospheric SSC model

- Primary e+ escaping the gap up-scatter synchrotron photons to TeV
- TeV photons quickly absorbed by ambient photons, producing e± pairs cascade
- Secondary photons created at a greater distance (tens of R_{LC}), can escape pair-production, produce GeV-TeV emission via SSC process

Problem:

Difficult to explain synchronization of pulse profile in the GeV and TeV, at least they are emitted in similar region



K. Hirotani, ApJ 766, 98 2013

Implications of TeV emission

Constraining the emission site

Beyond the magnetosphere?

- Pulsar wind up-scatter pulsed X-rays in a narrow zone (20-50 R_{LC})

Problems:

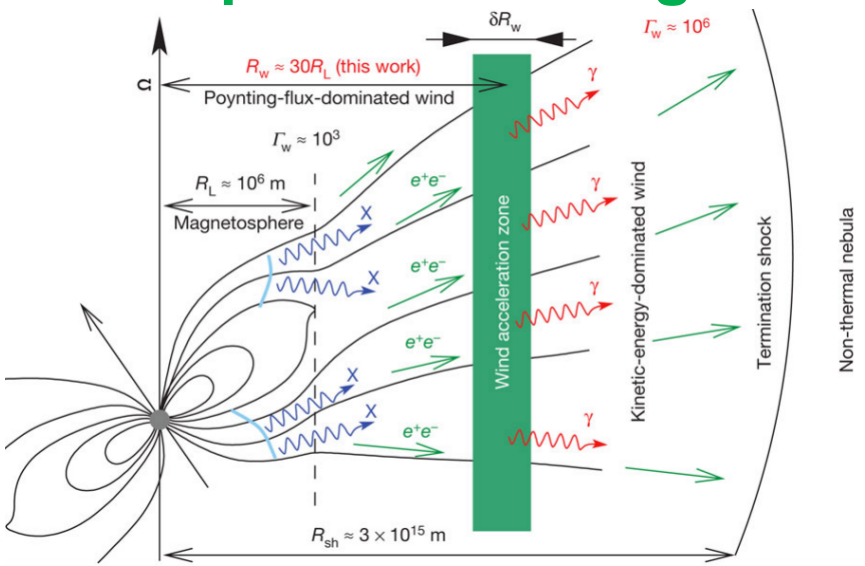
- Predict cutoff at ~500 GeV
  - ➜ Can not reproduce TeV emission.

Possible solution:

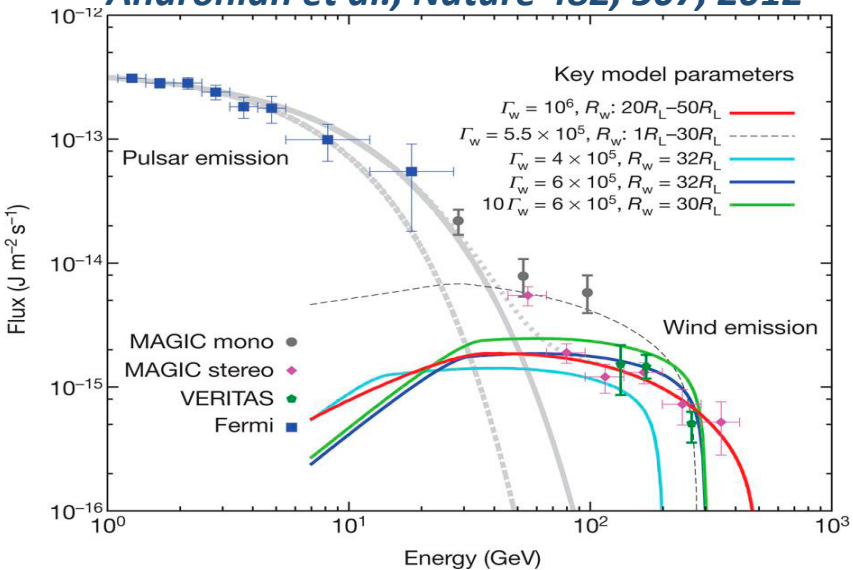
- Extend the acceleration region up to a much larger radius
- But at larger distances, broadening of peaks
  - ➜ Could not reproduce LC

Incompatible with MAGIC results. Would need to be revised

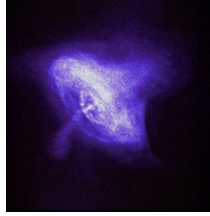
IC in the pulsar wind region



Aharonian et al., Nature 482, 507, 2012



Crab pulsar timeline



2008 MAGIC discovers Crab pulsar above 25 GeV → Polar Cap excluded
(Science 322, 1221, 2008)

2011 VERITAS measures spectrum in 100 - 400 GeV
(Science 334, 69, 2011)

2011 MAGIC phase resolved spectra 25 - 100 GeV
(ApJ 742, 42, 2011)

2012 MAGIC-Stereo spectra between 50 - 400 GeV → Outer gap questioned
(A&A 540, A69, 2012)

2014 MAGIC detects bridge emission above 50 GeV
(A&A, 565, L12, 2014)

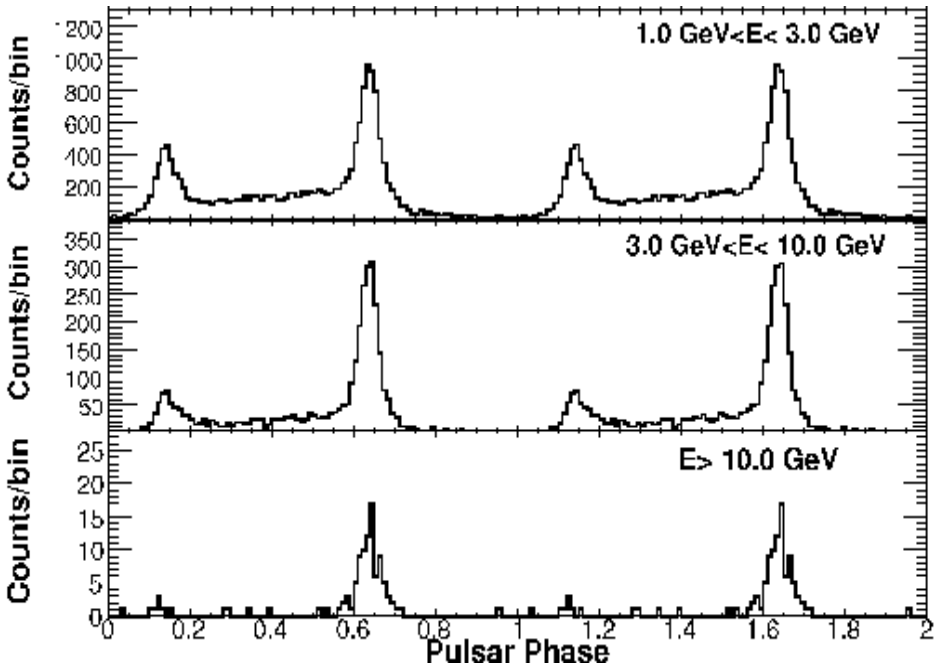
2016 MAGIC detects Crab pulsation up to TeV → Curvature Radiation questioned. Up to which energy spectrum continues?
(A&A, 585, A133, 2016)

2017 MAGIC sets stringent limits on Lorentz Invariance Violation from Crab Pulsar data
(ApJS 232(1) 2017)

Geminga

- Prototype of radio-quiet pulsar
- Very different from Crab:
  - Radio quiet Vs radio loud
  - Old (340 kyr) Vs Young (1 kyr)
  - Low Edot ($3 \cdot 10^{34}$ ergs/s) Vs High ($5 \cdot 10^{38}$ ergs/s)
  - Close (150 pc) Vs not so close (2000 pc)

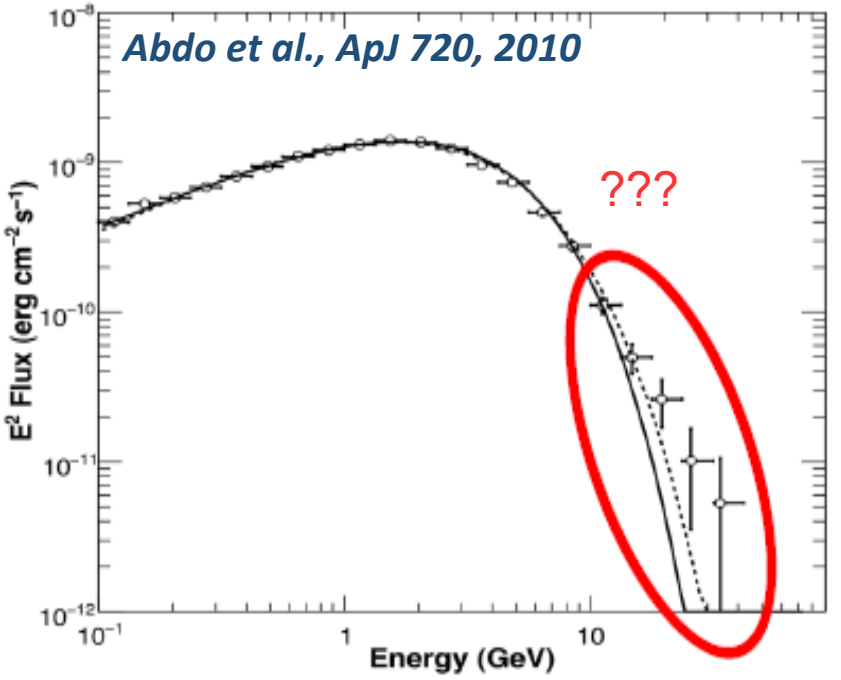
Different emission mechanism at VHE?



Fermi-LAT

- Pulsation seen above 10 GeV
- Sepectrum deviates from Exp. cutoff

  ➜ Motivated MAGIC observations)

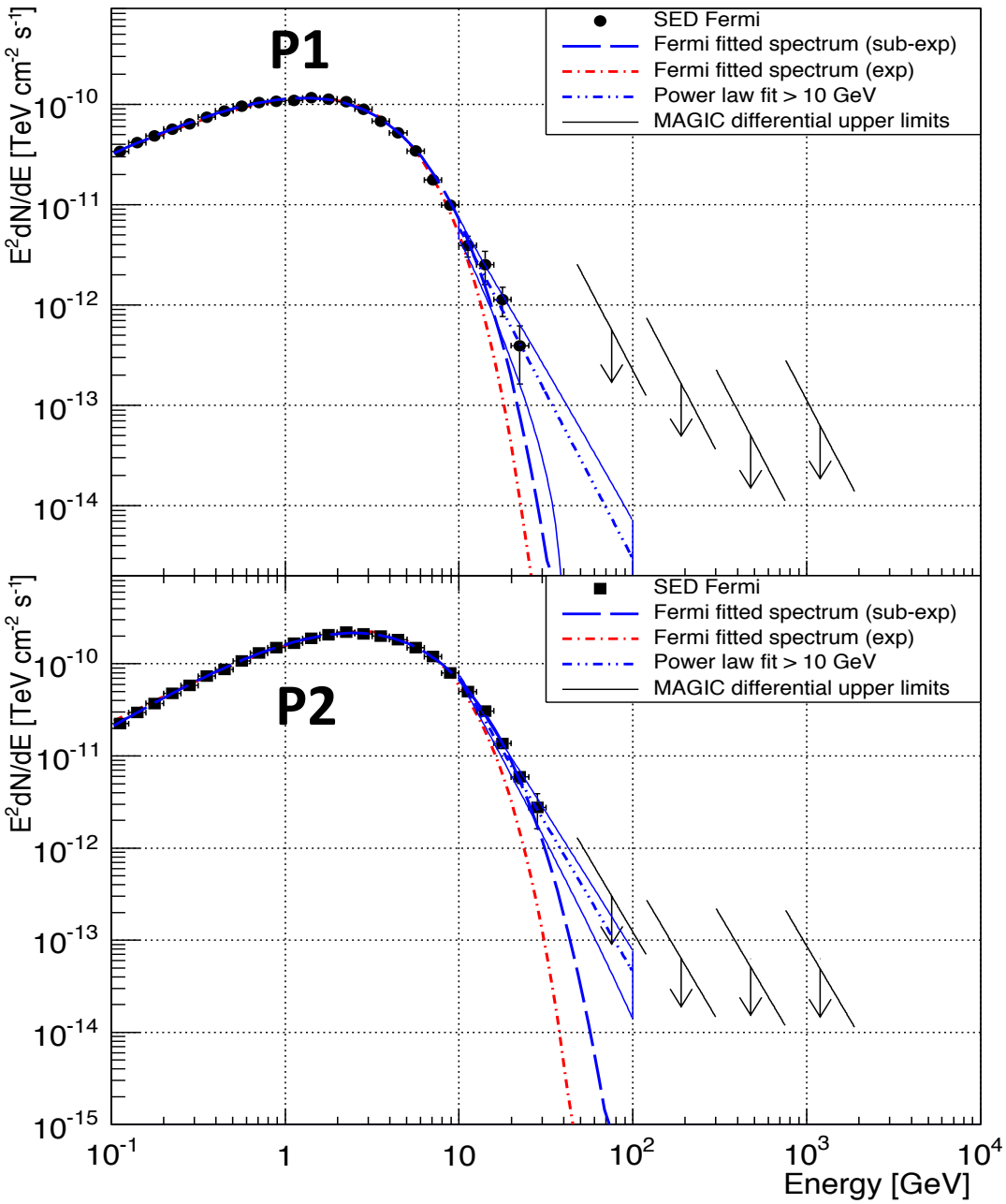


Geminga Stereo Std. Observations (2012-13)

Ahnen et al., A&A 591 A138 (2016)

- **63 h** in winter 2012/13 with Standard trigger
- Search for pulsations above 50 GeV
- No detection, but most constraining ULs so far

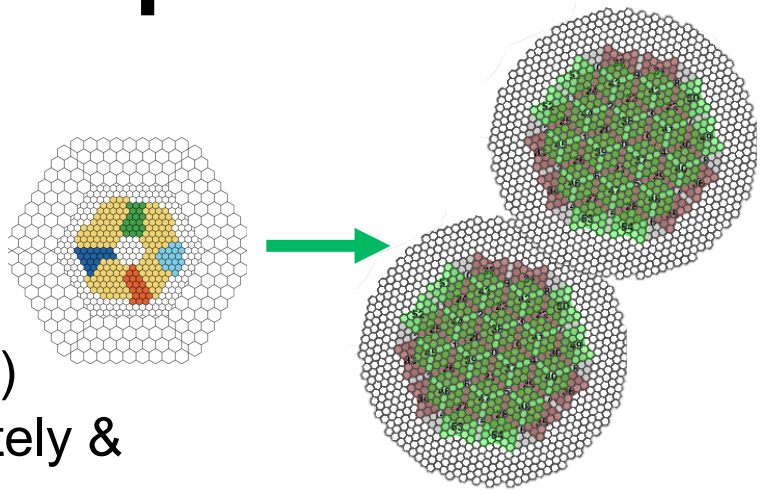
UL's don't allow to rule out existence of VHE power-law tail.

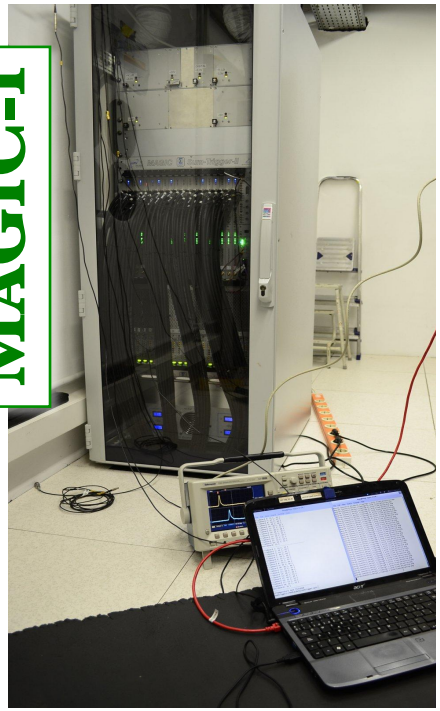


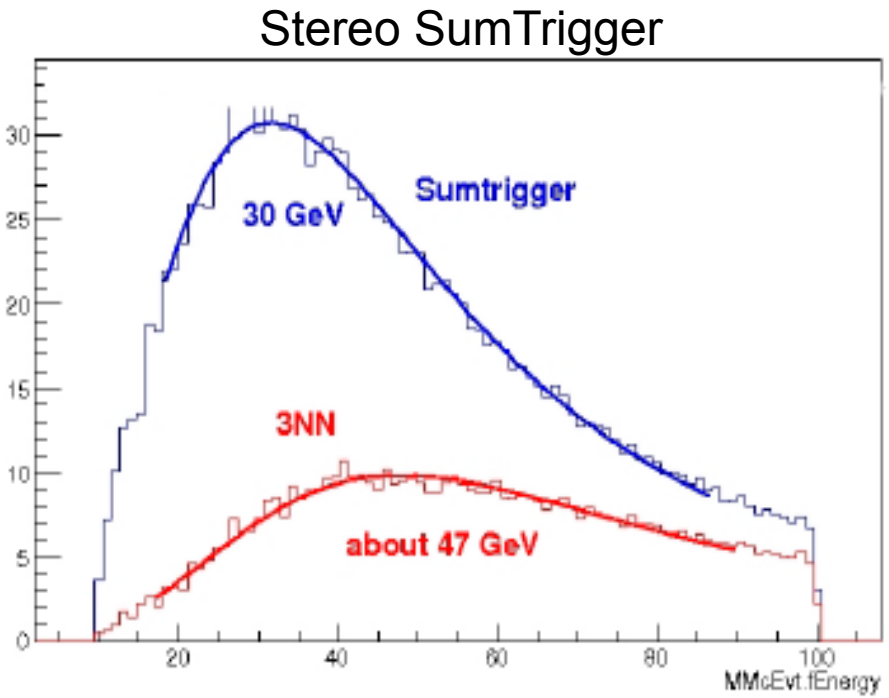
Latest development for pulsars

MAGIC (stereo) SumTrigger-II (2014+)

- Old system not suitable for Stereo
- Improved design:
  - Covers whole trigger area (and not only a ring)
  - Semi-automatic calibration. Settings set remotely & auto-adjustable (rate control)
  - Better reliability



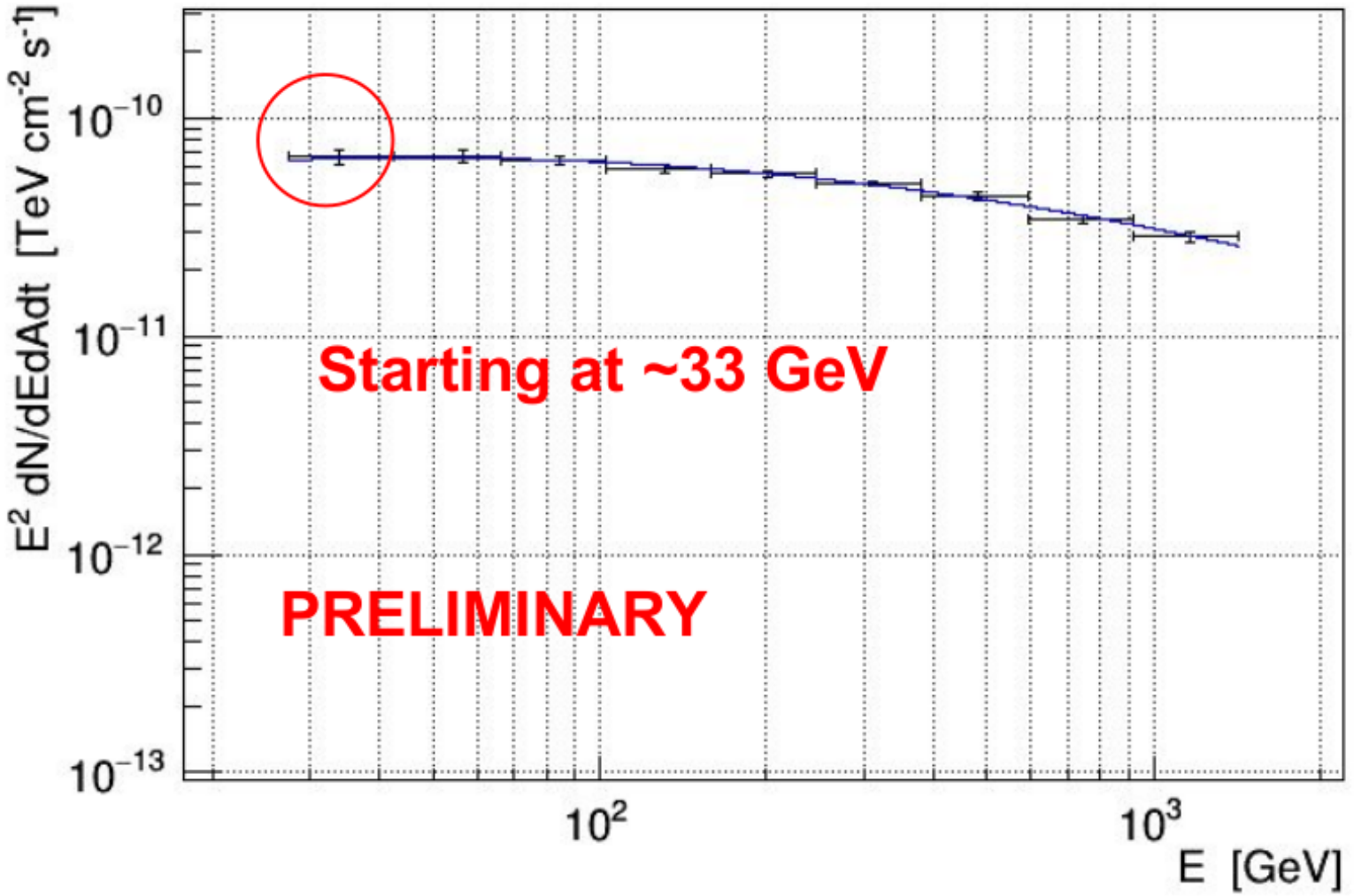




Crab SumTrigger-II (2014+)

First results with SumTrigger-II

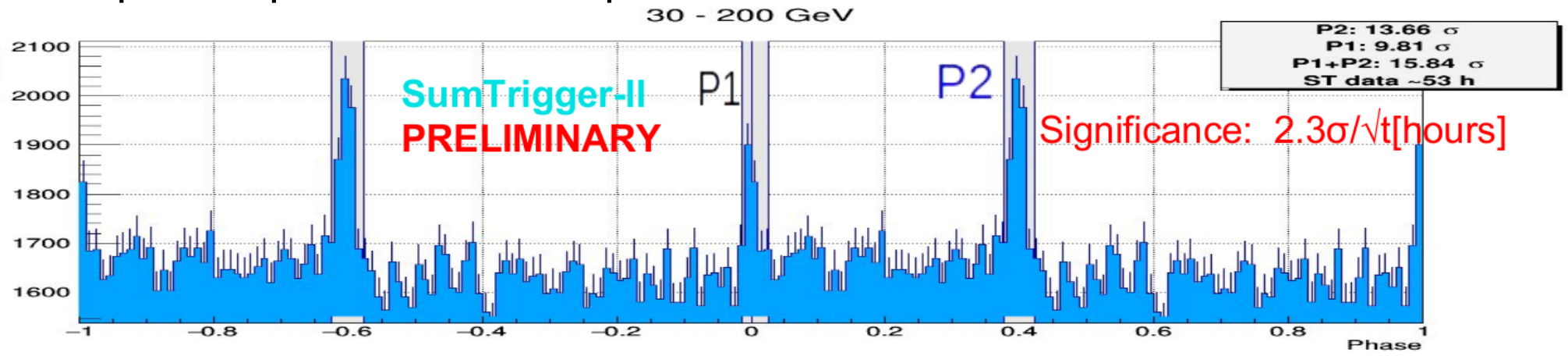
- First Stereo SumT data in 2014
- Nebula down to 30 GeV

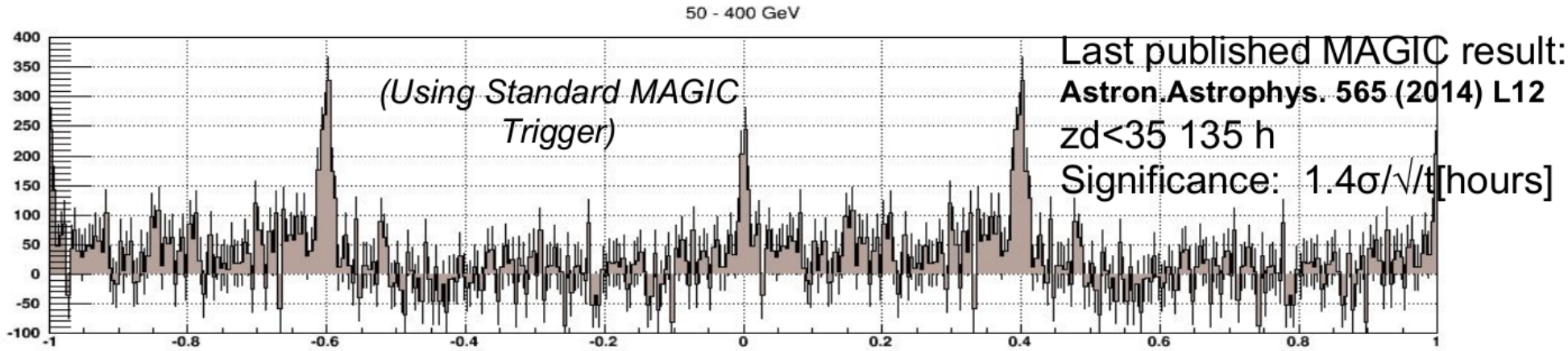


Crab SumTrigger-II (2014+)

First results with SumTrigger-II

- First Stereo SumT data in 2014
- Nebula down to 30 GeV
- Improved performance for pulsars



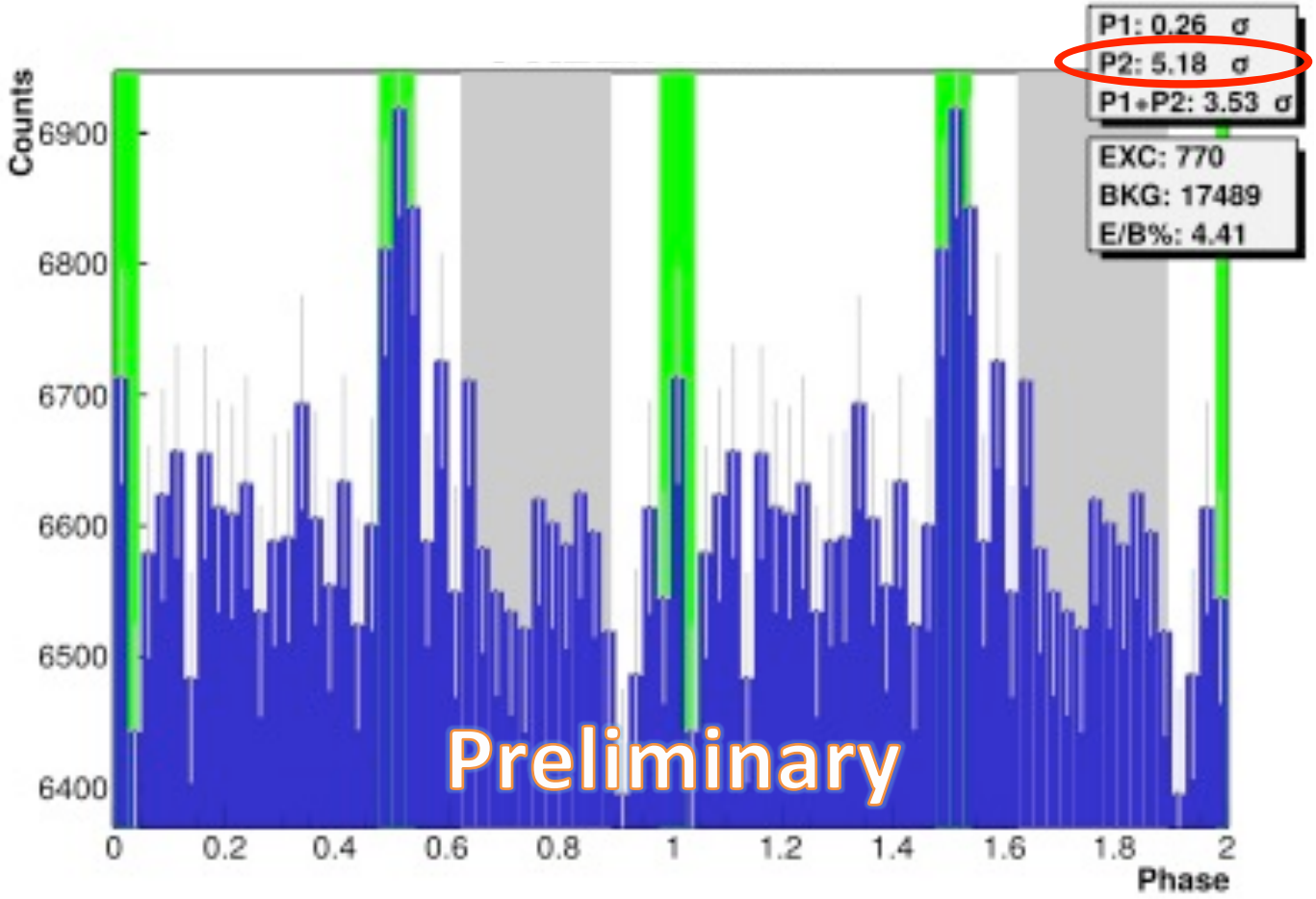


J. Rodriguez, TeVPa 2017

Highlight: Detection of Geminga pulsar

Observations with SumTrigger-II

- **~30** h in 2017
- Two independent analysis chains:
  - Std. cleaning
  - Special SumT cleaning
- Clear detection:
  - P2 detected at **5σ** level
  - P1 not visible



2nd VHE pulsar detected in the Northern Sky

Summary

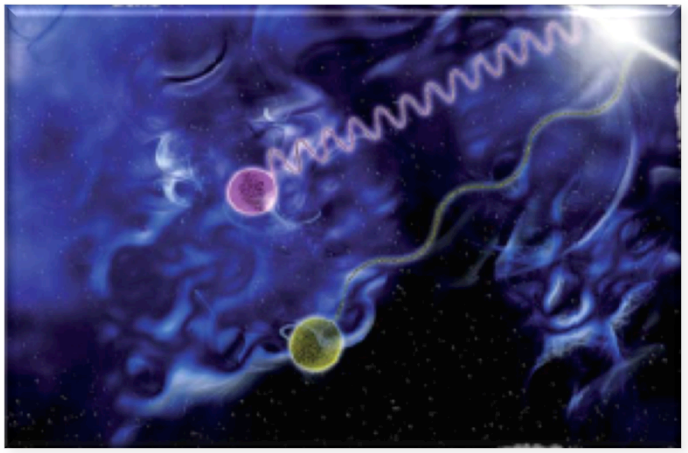
- MAGIC has pursuit pulsars since its very beginning
- Discovery of the first VHE pulsar, the Crab pulsar:
  - In 2008 above 25 GeV, and now up to TeVs
  - Polar cap ruled out, and other models questioned

    ➔ Led to rewriting of pulsar models
- Highlight 2018: **Detection of Geminga pulsar**
- Pulsars becoming a new class of VHE emitters
- Open questions:
  - Until which energy is Crab pulsating? Is the VHE emission created by a different component? Is there a cutoff somewhere?
  - Is Geminga showing also a Power-law?

Stay tuned ...

ВАХКУП

Lorentz Invariance

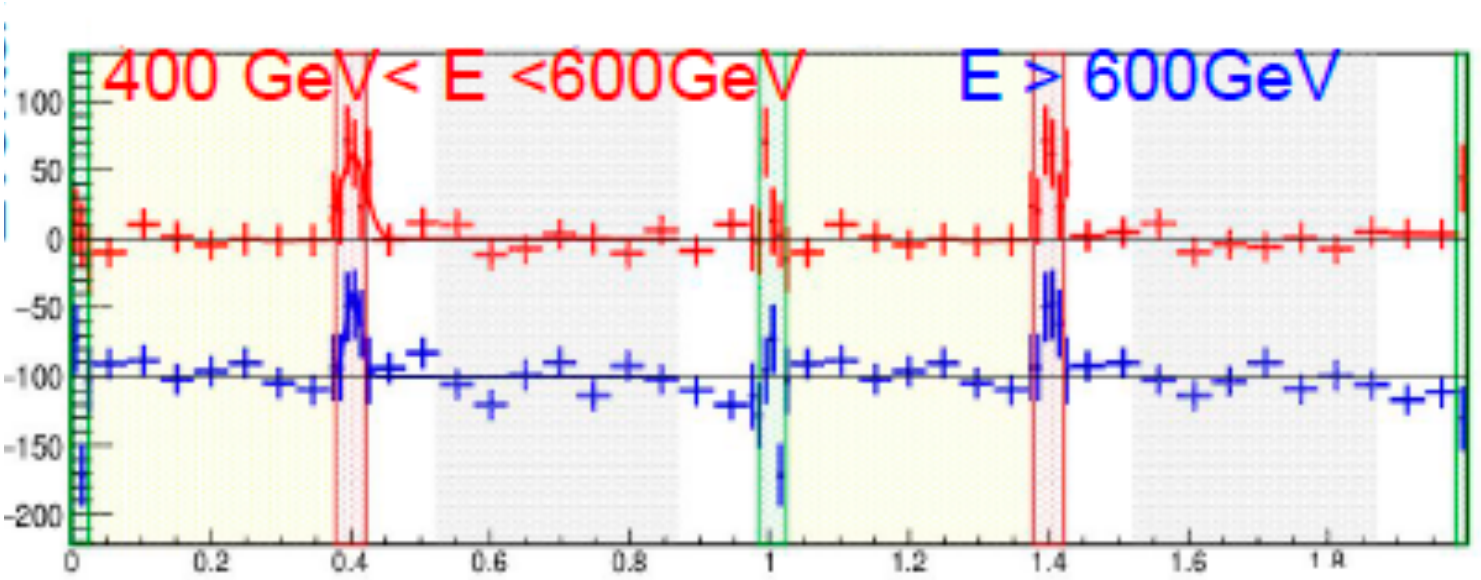


- Quantum Gravity theories predict foamy space-time structure at low scales

➔ Lorentz Invariance Violation: c = c(E**γ**)

LIV with Crab Pulsar @ TeV

- Search for energy dependent shift of the peak positions



ELIV (Linear)> 4.5-4.6 x 10^17 GeV

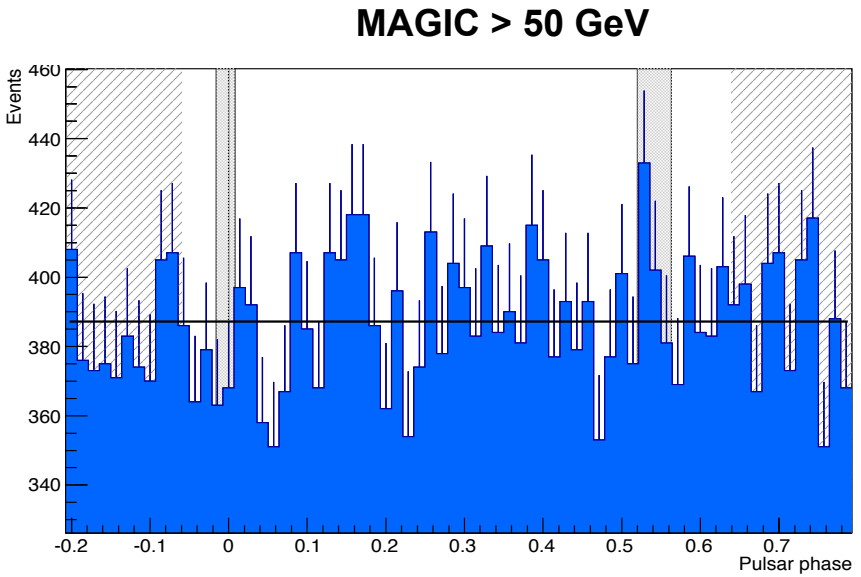
ELIV (Quadratic)> 5.3-5.9 x 10^10 GeV

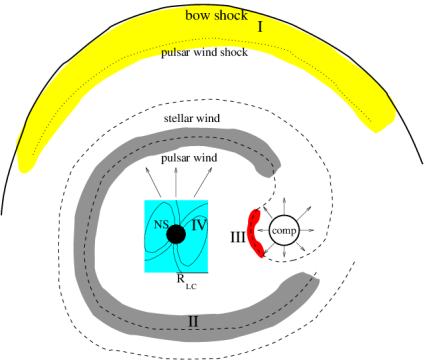
Ahnen et al., ApJ 232 (2017)

Pulsars in binary systems

Black widow B1957+20 ms pulsar

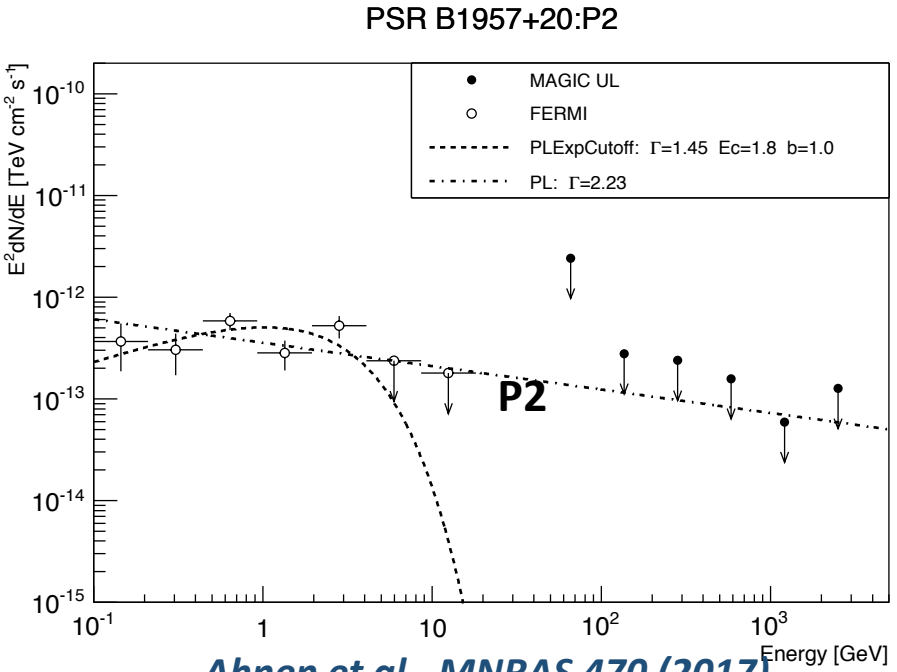
- MS pulsars orbiting low massive stars could produce VHE emission
  - But not (yet) detected
- MAGIC observed the system for 66 h
  - 4 possible regions in which γ-rays could be produced





Region	Expected emission
I. Bow shock	Extended / steady
II. Inner nebula	Point-like / steady
III. Binary system	Point-like / modulated
IV. Pulsar	Point-like / pulsed

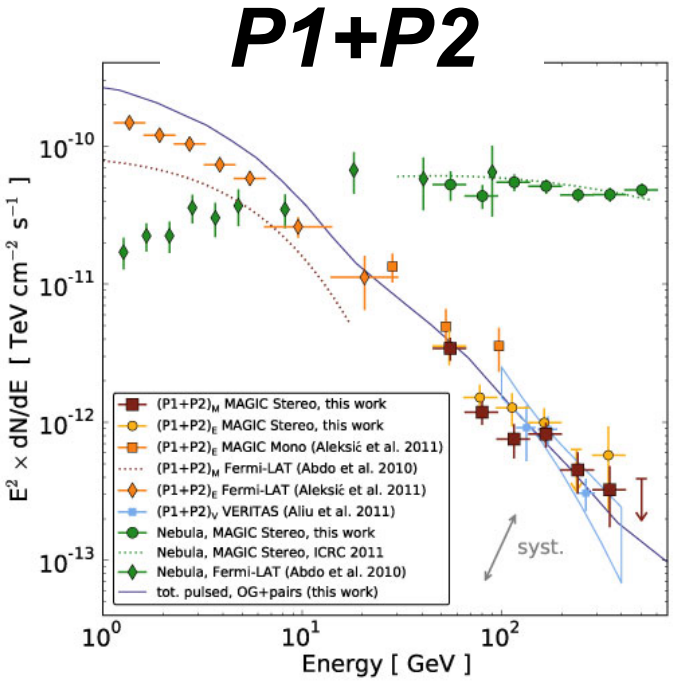
- No emission detected in any case:
  - Leptons not accelerated up to TeV? Not enough target?

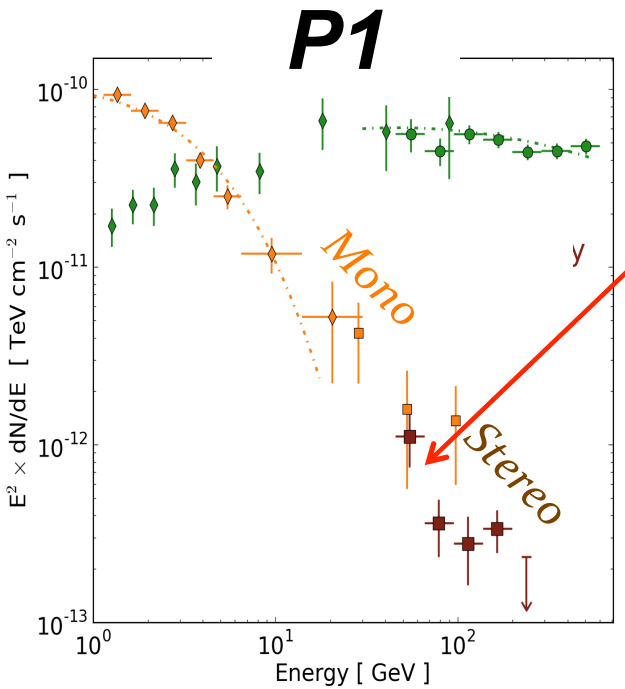


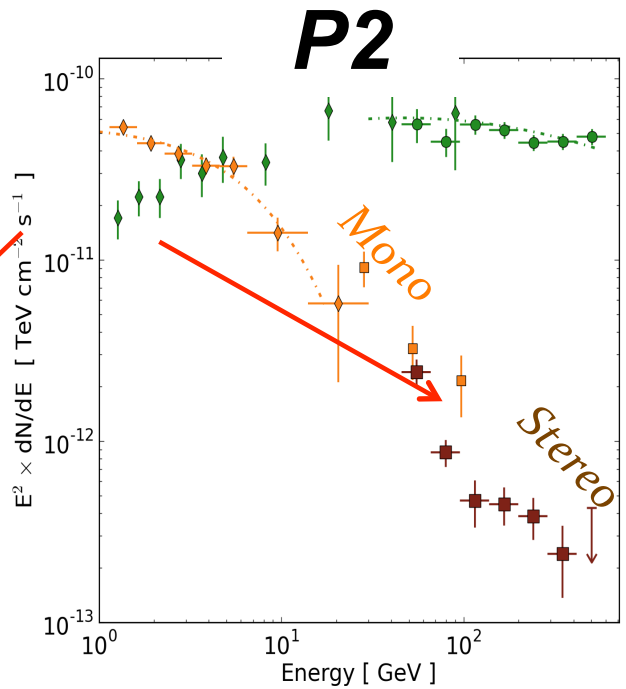
Ahnen et al., MNRAS 470 (2017)

Stereo observations (2009-2011)

First pulsar Phase-resolved spectrum @ hundreds GeV !







Phase-averaged index:

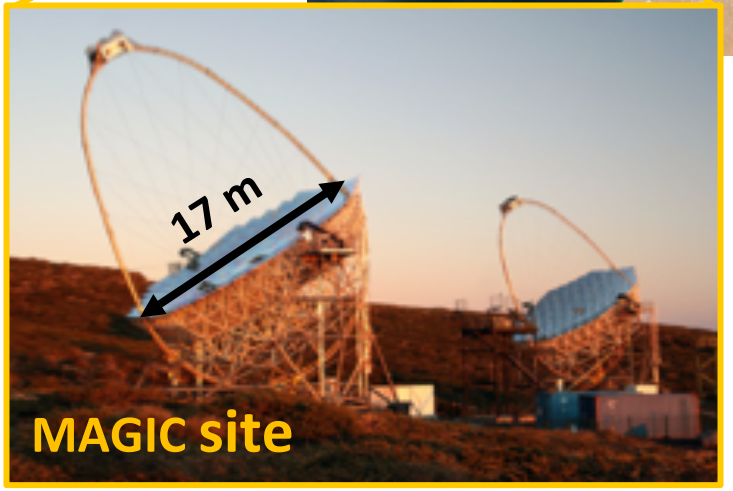
P1+P2 : Γ = -3.6 ± 0.3

P1 : Γ = -4.0 ±0.8

P2 : Γ = -3.4 ±0.3

P1/P2 ratio: ~0.4 ± 0.2 @ 100 GeV

The MAGIC telescopes



Characteristics

- 2 Imaging Atmospheric Cherenkov Telescopes
  - 17 m diameter with active mirror control
  - Fast readout ~2 GS/s
  - ~ 2TB per night

Performance

- Energy range: 50 GeV to 50 TeV
- Sensitivity: 10% Crab in 1 h above 100 GeV
- Energy resolution: 15 – 23%
- Angular resolution: ~0.1º

MAGIC continuous improvement

- 4x improvement sensitivity over last decade
- 10x at the lowest energies !