Pulsar physics from VHE γ-ray observations

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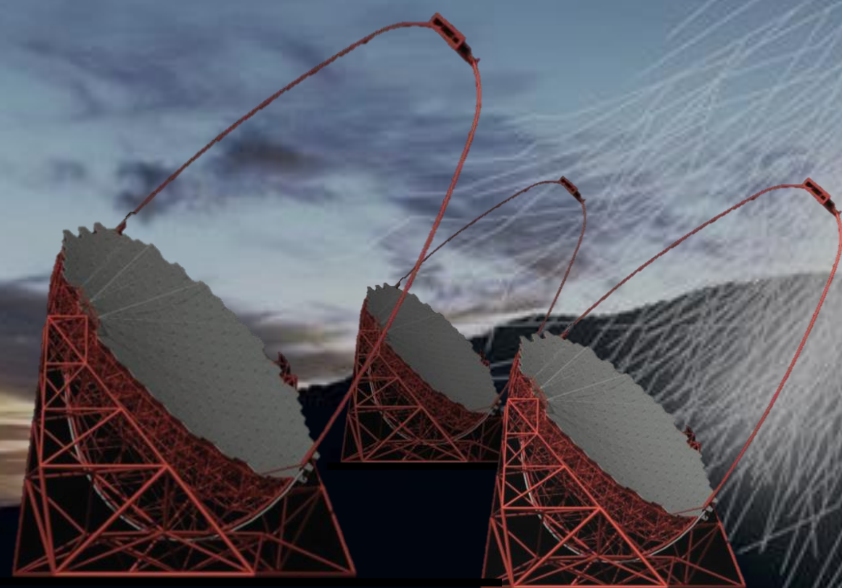
TevPA, CERN, 2016

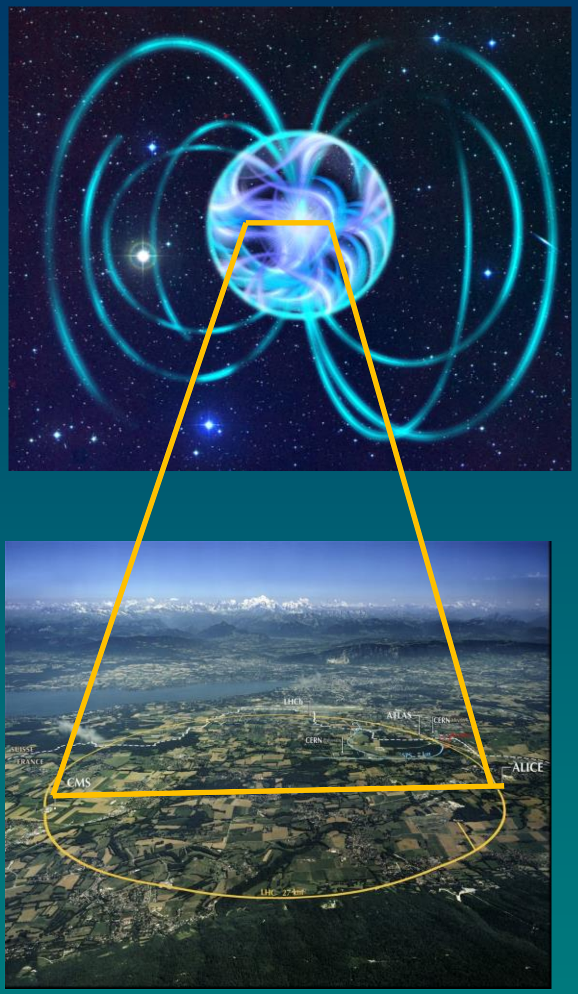


Outline

1. Pulsars at GeV in the Fermi era
2. Observations of Crab, Vela, Geminga at TeV with CTs
3. Outlook: the CTA era

Pulsar models

- Pulsars are highly magnetized and fast rotating neutron stars, born after SN explosions:
  - Extreme density: $M \sim 1.4 M_{sun}$, $R \sim 10$ km
  - Huge magnetic fields: $B \sim 10^{8-14}$G



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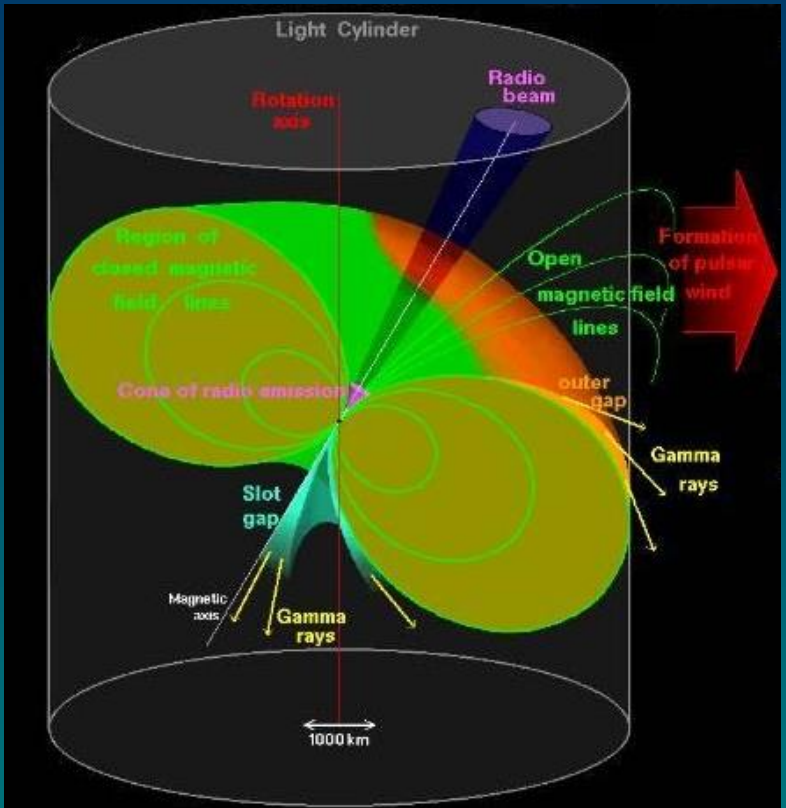
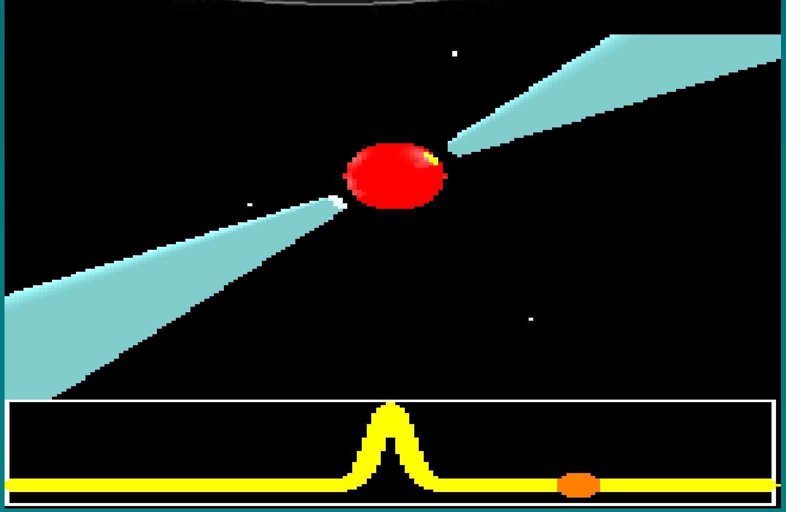


Magnetosphere

- Fast rotation + huge B field induces intense Electric field

➜ E so intense that pull particles out

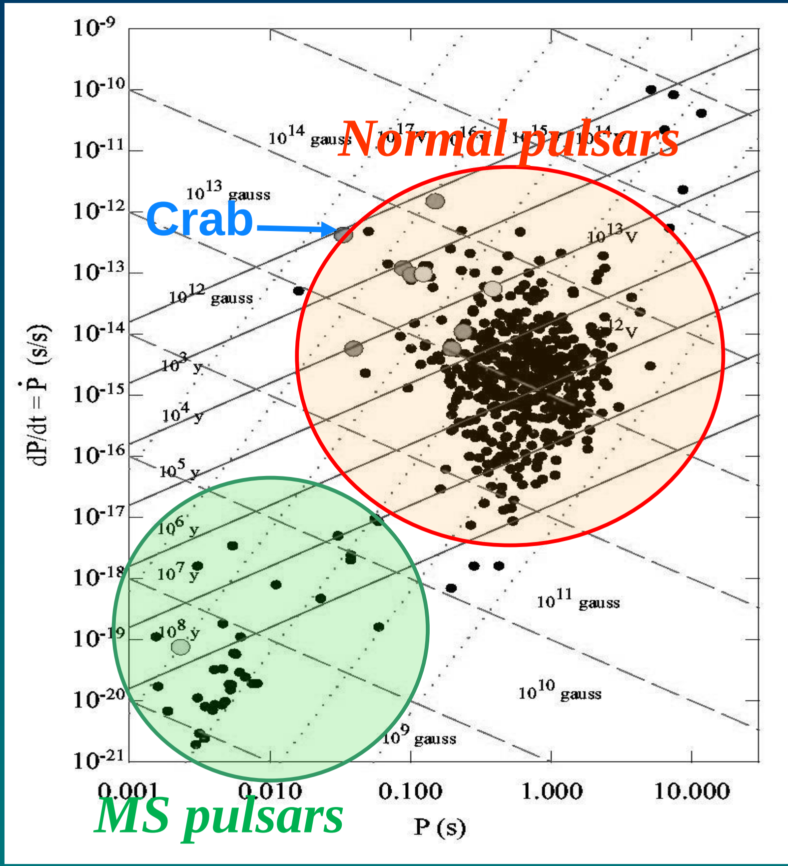
- A dense plasma co-rotates with the star:
  - Magnetosphere extends to the "light cylinder"
  - Non-thermal Emission (radio, optical, X-ray, γ-rays) produced in beams



➔ *Acts like a cosmic light-house*

Pulsar at all wavelengths

- First discovered in radio in 1967
- Radio: ~ 2000. Can be grouped in:
  - Normal (young): B~10^{12}G
  - MS (old): B~10^8 G
- Optical: Just 7 (Crab,Vela,Geminga,…)



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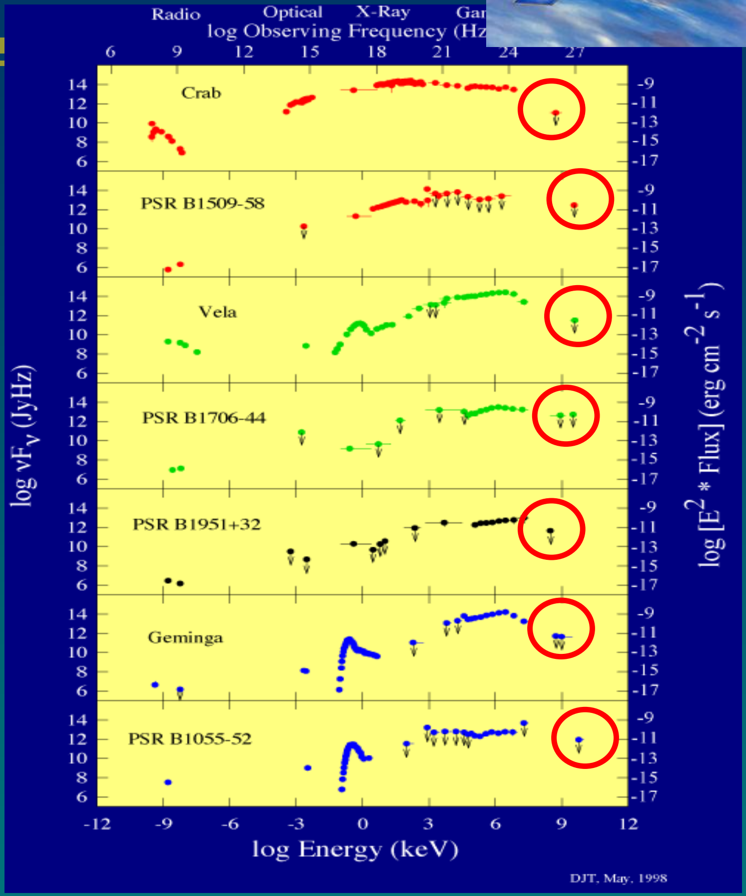
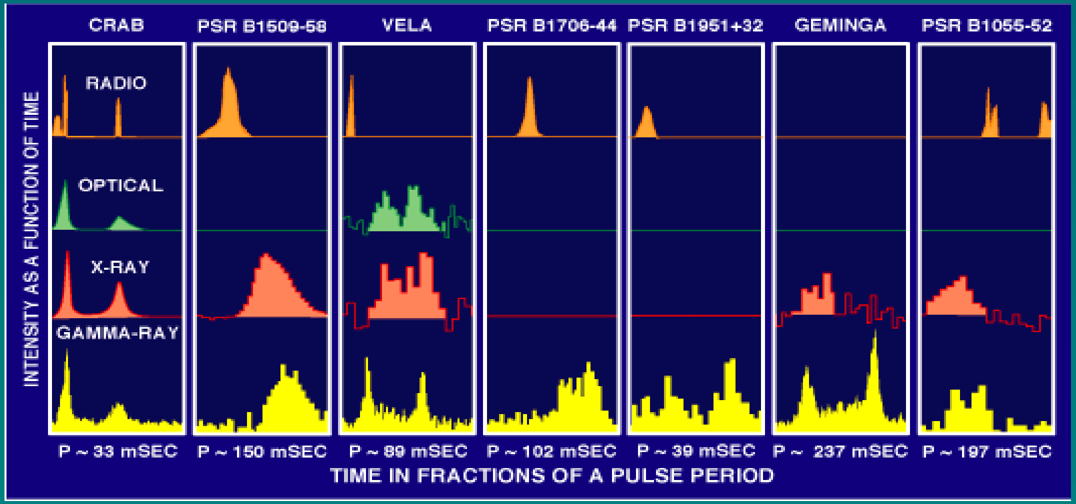
- γ-rays:
  - 90's: Only 7 seen by EGRET





Light curve:

- Typically 2 peaks

- All young radio emitters, but Geminga

Spectra:

- Maximum of emission at X- and γ-ray

- U.Ls at HE

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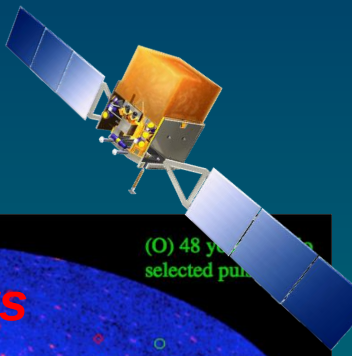
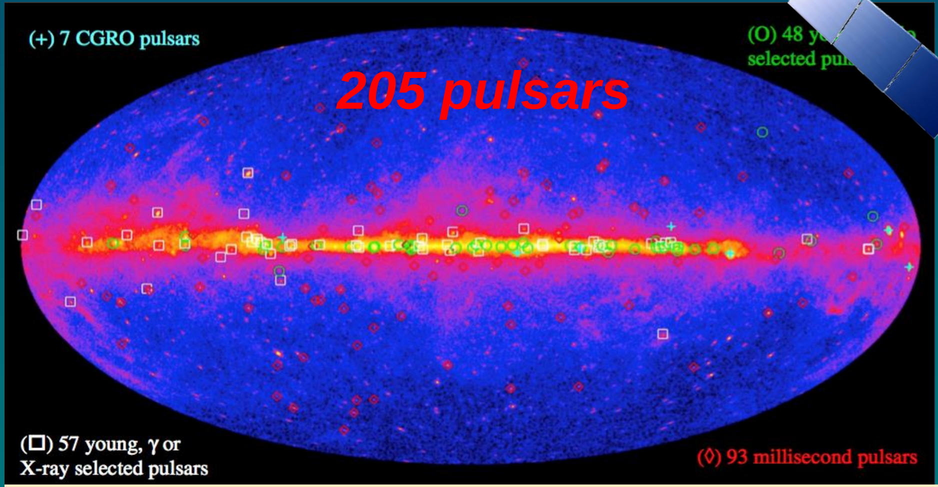




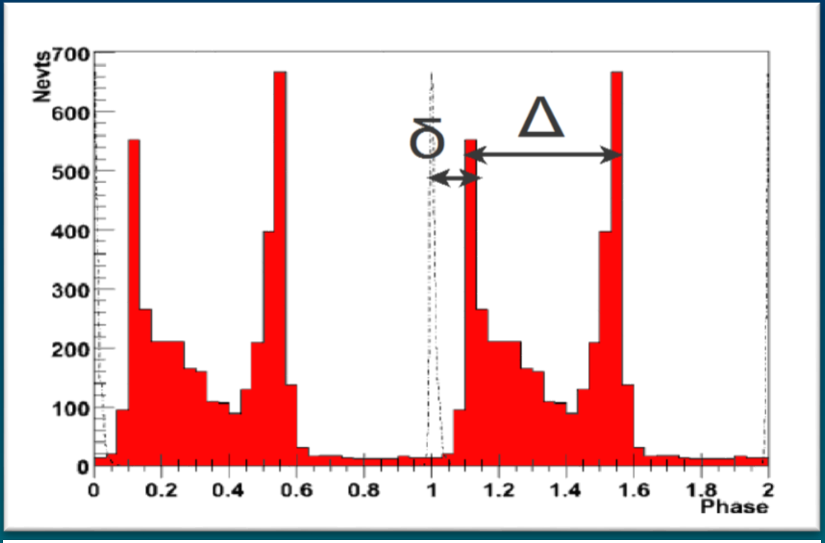
Most of Fermi galactic sources are pulsars

- γ-rays:
  - 90's: Only 7 seen by EGRET
  - 205 detected by Fermi

Fermi Pulsar Highlights:

- Confirmed all EGRET pulsars and candidate ones in many Unid. Sources)
- Discovered new γ-ray pulsars in blind searches
- Discovered many geminga-like pulsars
- Discovered a whole population of ms pulsars

What do we learnt from Fermi-LAT?



Light curves

Typically 2 sharp peaks:

- Separated by ~0.4-0.5 rotations

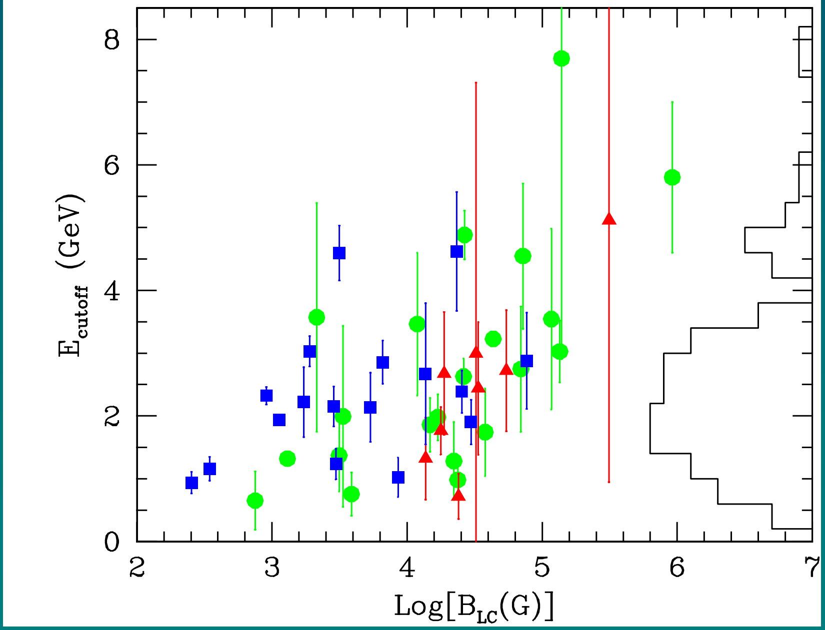
Spectra

- Well fitted by power-laws + sub-exponential cutoff

$$\frac{dN}{dE} = N_0 \cdot E^{-\Gamma} \cdot \exp\left(\frac{E}{E_c}\right)^{-b}$$

b=1: exp.
b<1: sub-exp.
b>1: super-exp.

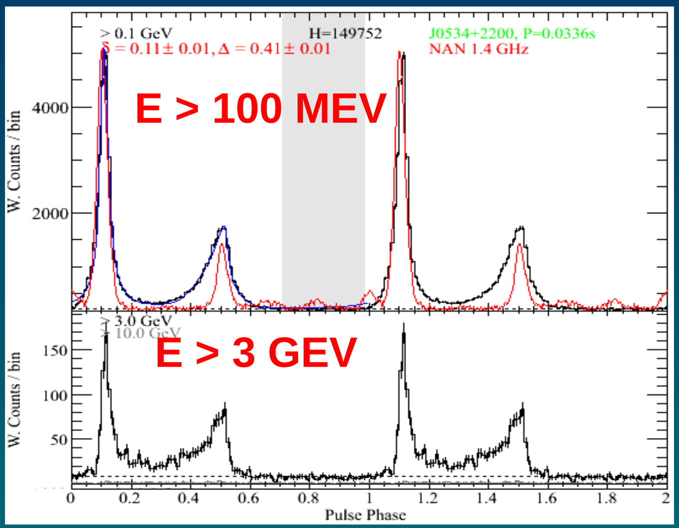
- Cutoff energies < 10 GeV
  - Most in narrow band: 1 - 4 GeV

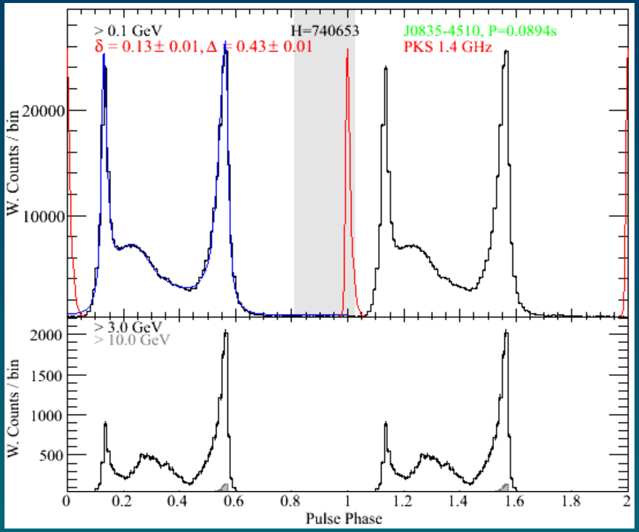


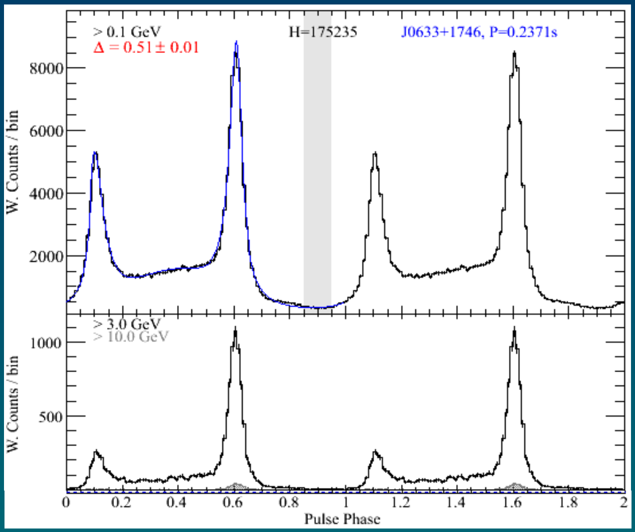
Disfavored low-altitude polar cap (PC) model ➜ HE emission originates most probably in the outer magnetosphere

The brightest Fermi pulsars in the 2PC

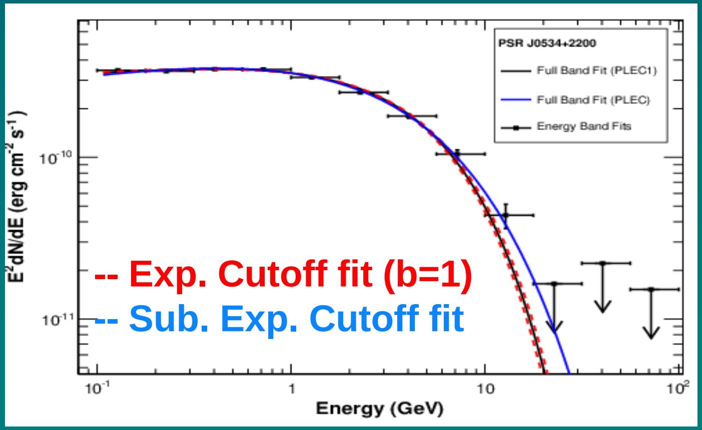
Crab | Vela | Geminga

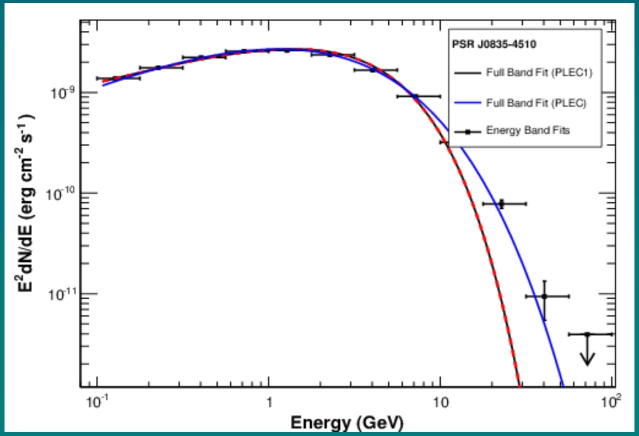


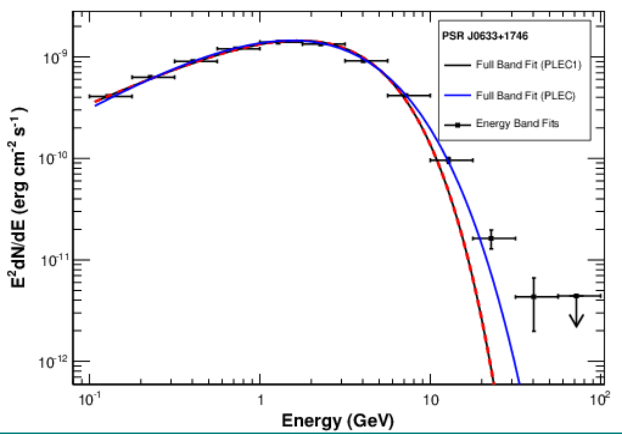




Two peaks per rotation → But at HE one peak starts to dominate





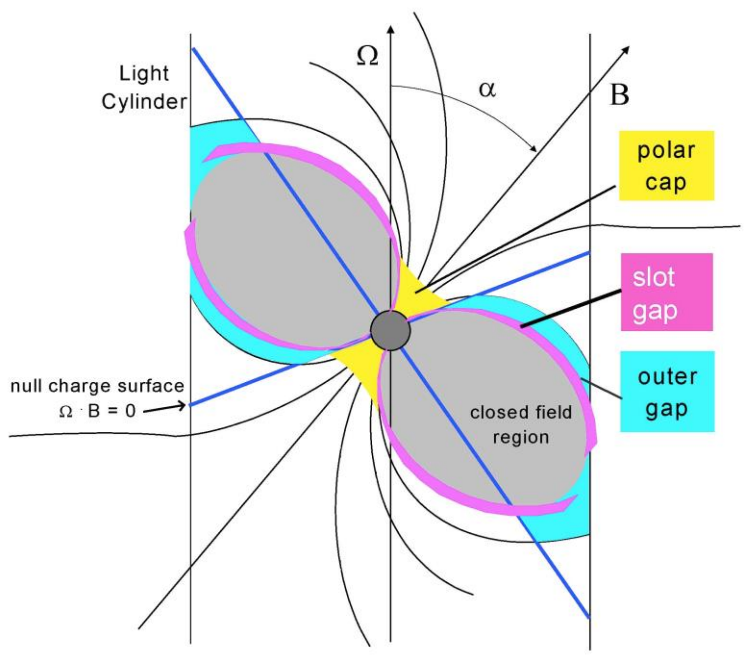


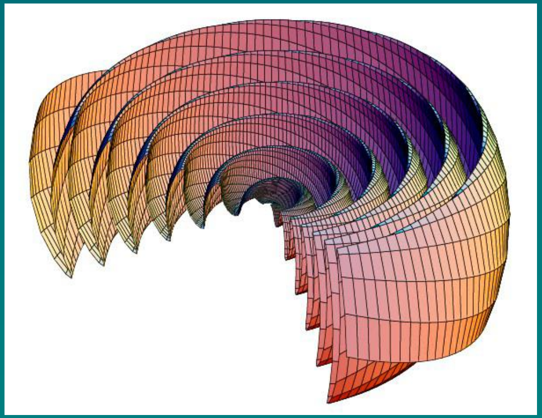
Sub-exp cutoff fit the data. Some deviation appear in Geminga

How do we explain the pulsar cutoffs?

Pulsar models: Origin of γ-rays

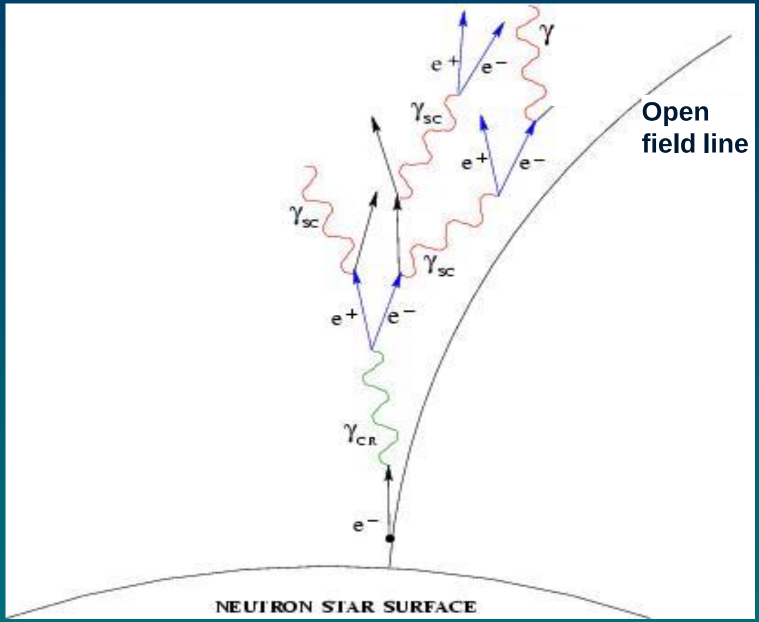
- Spectrum depends on the physics of the emitting region and Light curves on its geometry
- Different models assume different emitting regions:
  - Within the magnetosphere
    - Polar cap:
      acceleration + radiation near NS surface
    - Outer gap:
      acceleration + radiation near LC
    - Slot gap/TPC:
      acceleration + radiation from NS surf up to LC
  - Outside the magnetosphere
    - Striped wind:
      acceleration + radiation in Wind zone





Classical Pulsar models

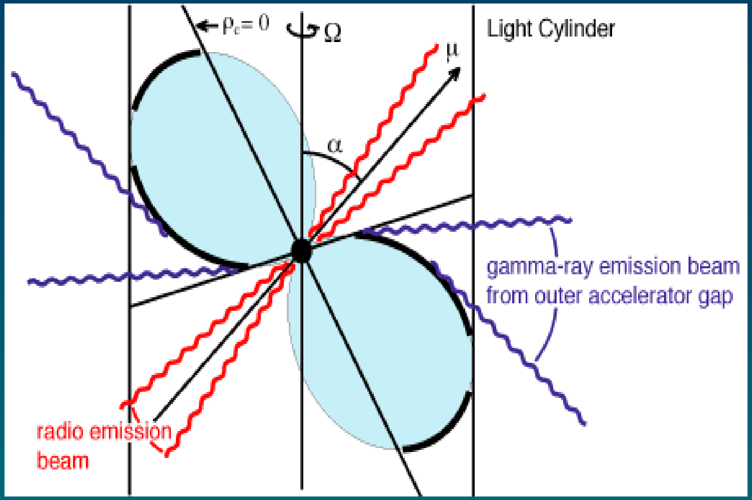
Polar Cap Model



- Particles accelerated along B-field lines emit γ-rays via Curvature radiation
- γ-rays interact with B-field, via *Magnetic pair production* $\gamma + \vec{B} \rightarrow e^{+} + e^{-}$
- An electromagnetic cascade develops, and only γ's surviving pair-production escape to the observer

Predicts super-exponential cutoff at few GeV

Outer Gap model

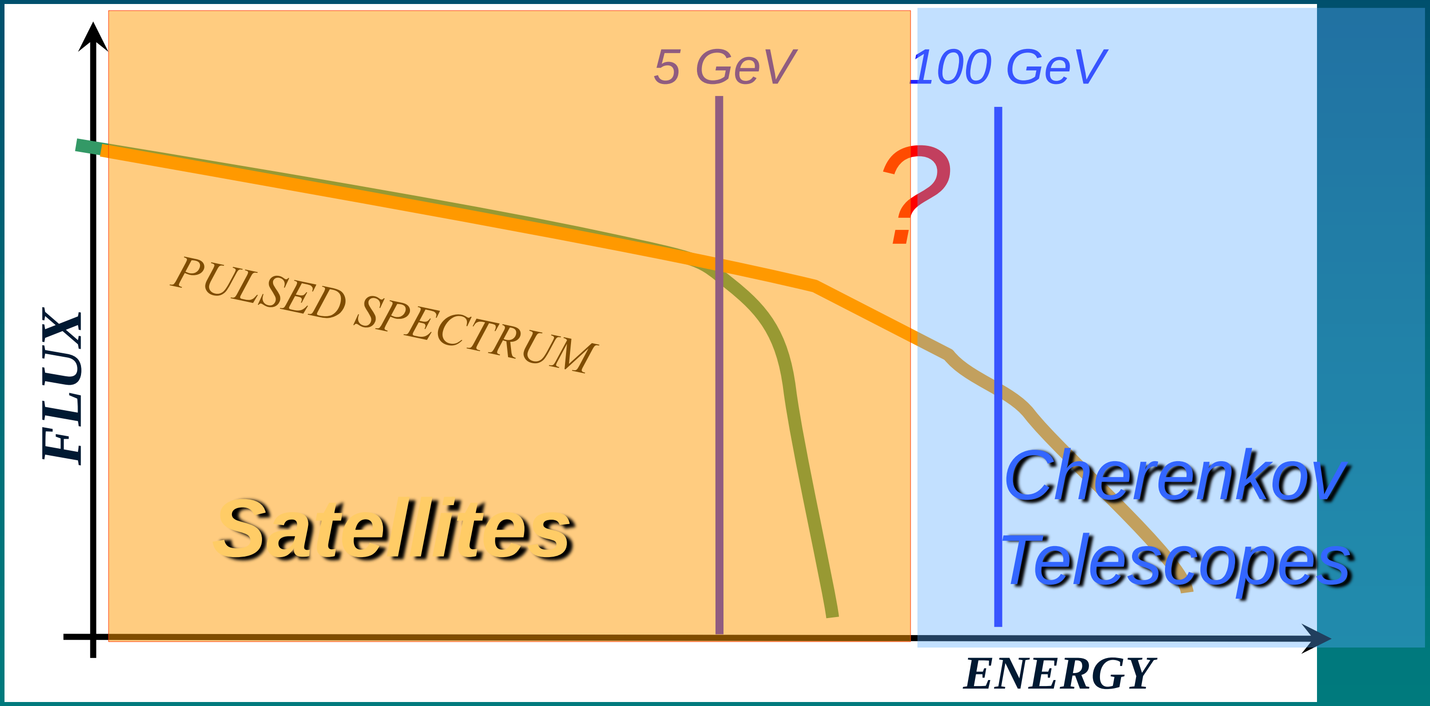


- γ-ray emission occurs near LC
- Charges accelerated close LC emitting *γ-rays via Curv. rad.*
- **B** not strong enough for pair-production.
- But *γ-rays* can interact with ambient X-rays or IR photons

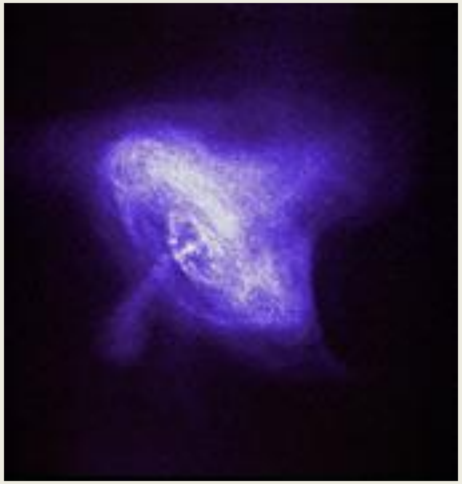
Predicts exponential cutoff at few GeV

Pulsars visible @ VHE ??

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



And this has been thought like this until few years ago …



Crab: First pulsar detected @ VHE

Crab timeline

Breakthrough of γ–ray astronomy from ground

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

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
(A&A 540, A69, 2012)
→ Outer gap questioned

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

2106 MAGIC detects Crab pulsation up to TeV
(A&A, 585, A133, 2016)
→ Curvature Radiation questioned. Up to which energy spectrum continues?

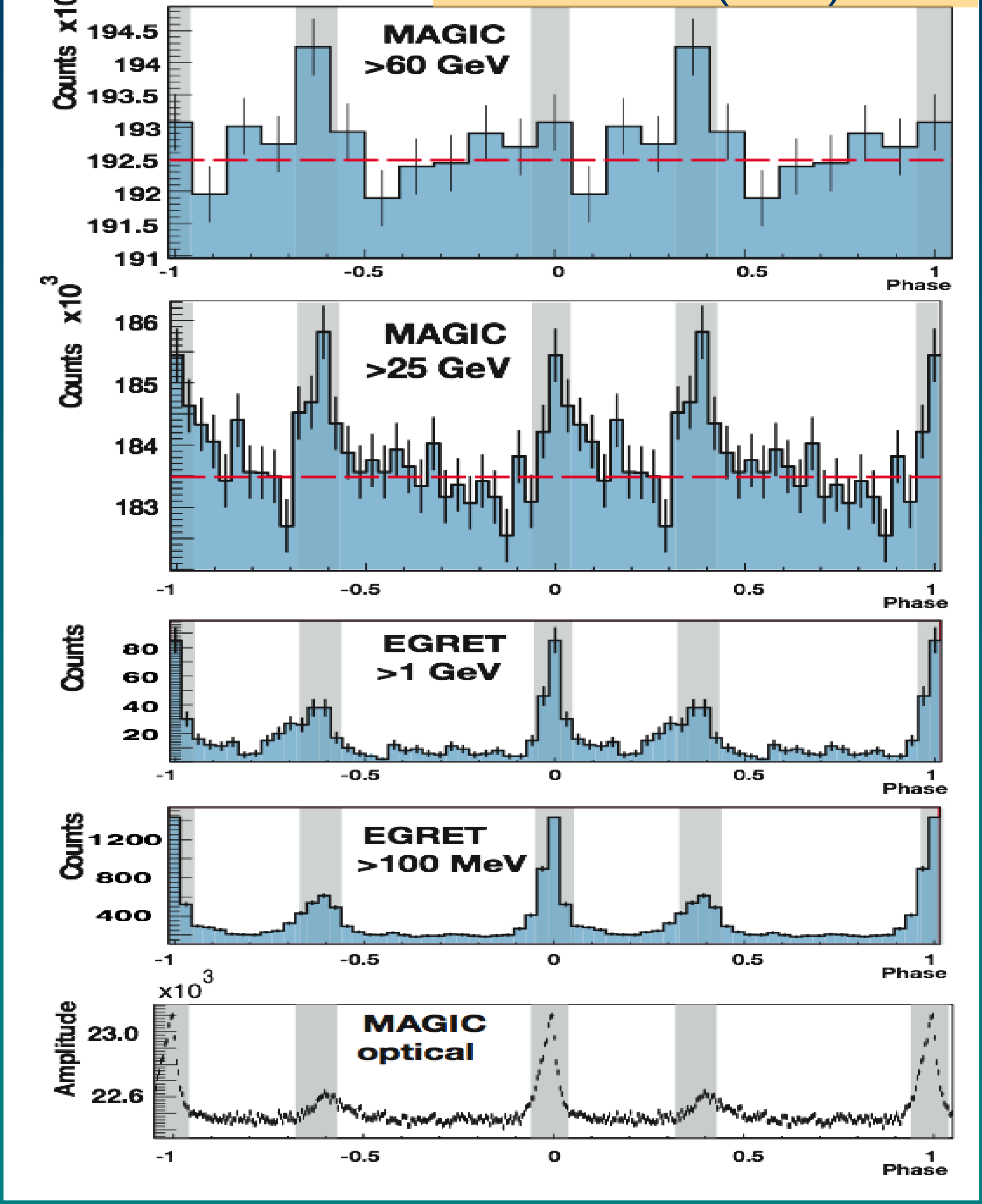
First pulsar detected @ VHE: MAGIC (2008)

- The development of the MAGIC SumTrigger allowed to detect Crab pulsar above 25 GeV
- 22 h in winter 2007/08

- Surprising discoveries:
  - P1 clearly still visible > 25 GeV
  - Hint of P2 > 60 GeV

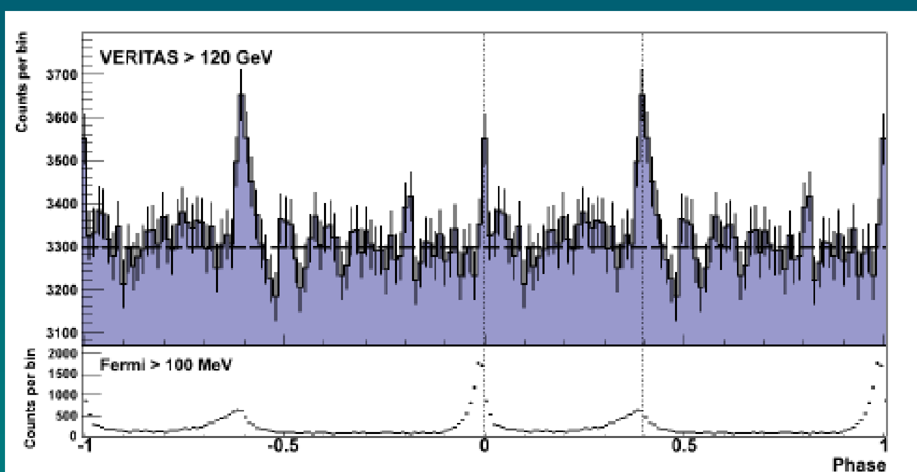
Polar Cap model excluded

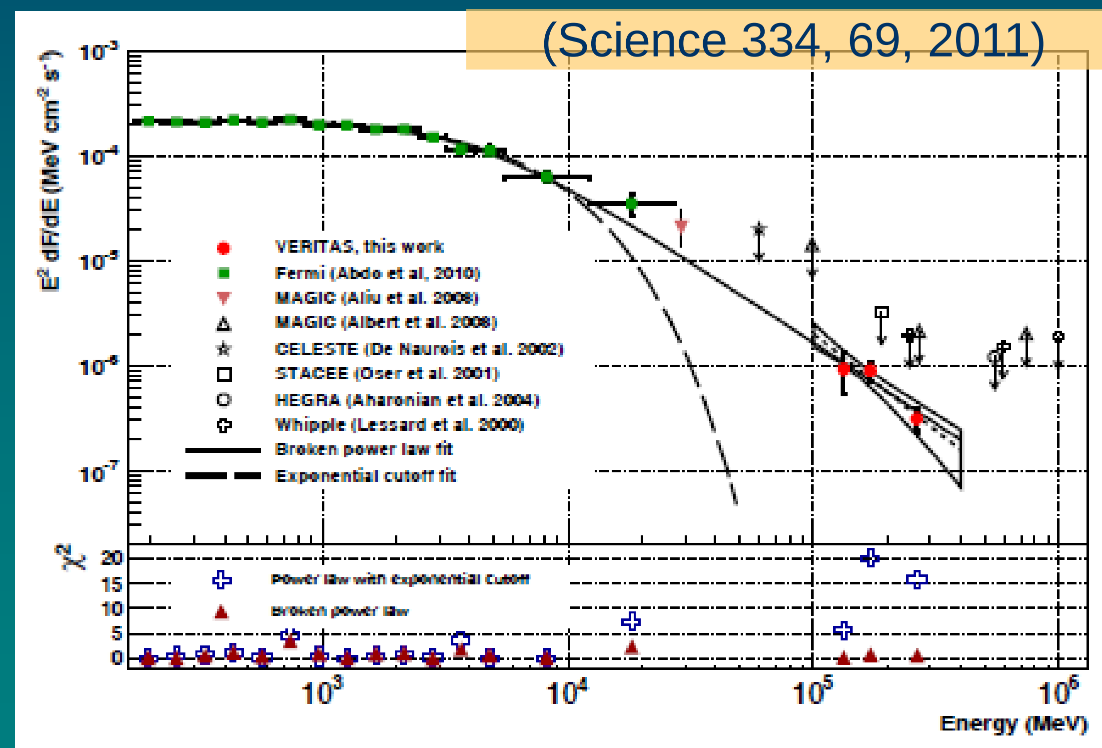
Science 322 (2008) 1221



VERITAS detection and first spectrum (2011)

- 107 h between 2007-2011
- Spectrum follows power-law from 100 to 400 GeV

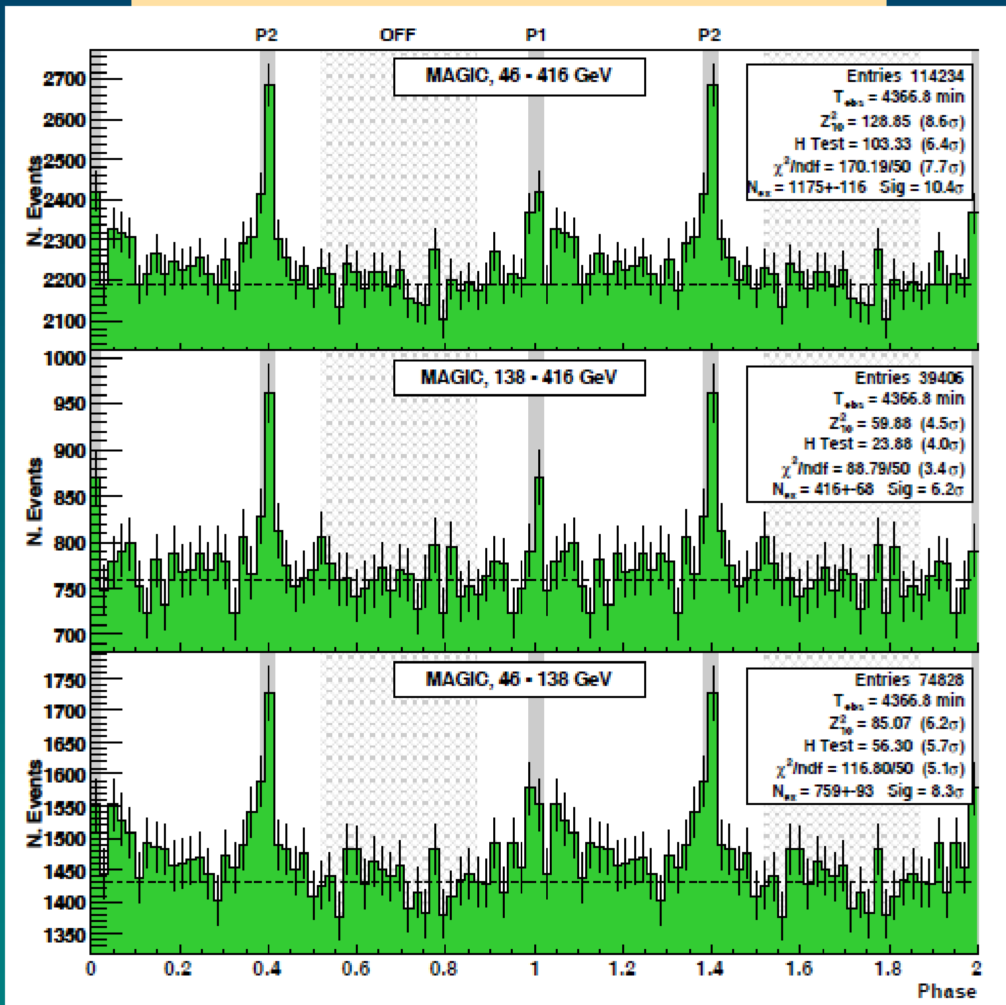


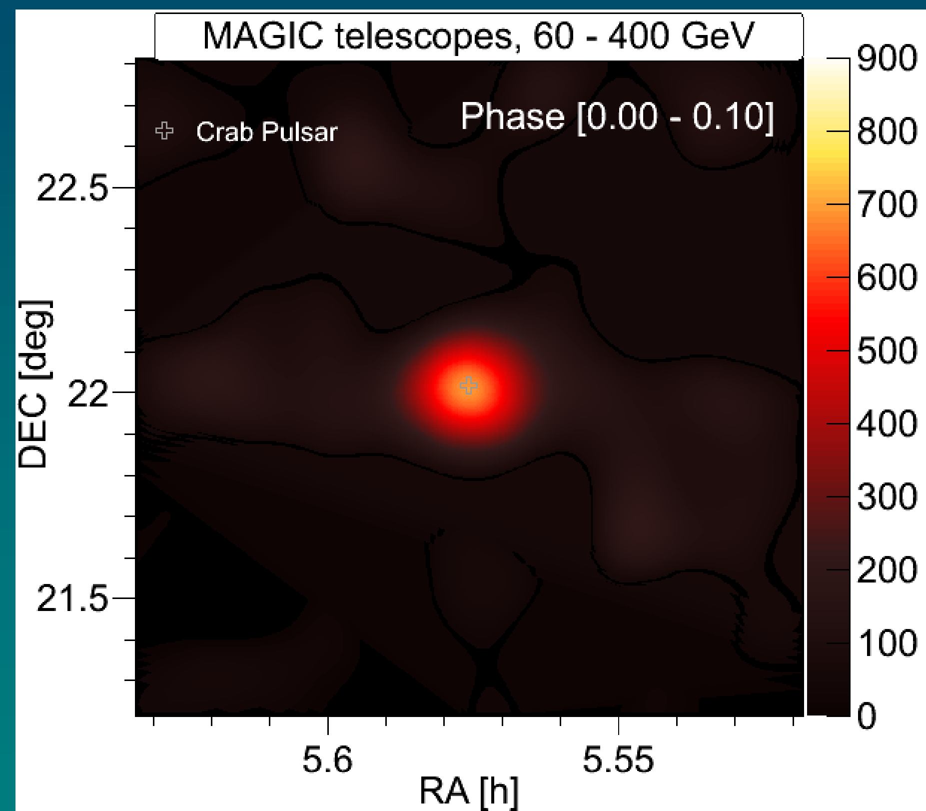


MAGIC stereo observations (2009-2011)

- MAGIC 73 h of stereo observations from 2009-2011

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

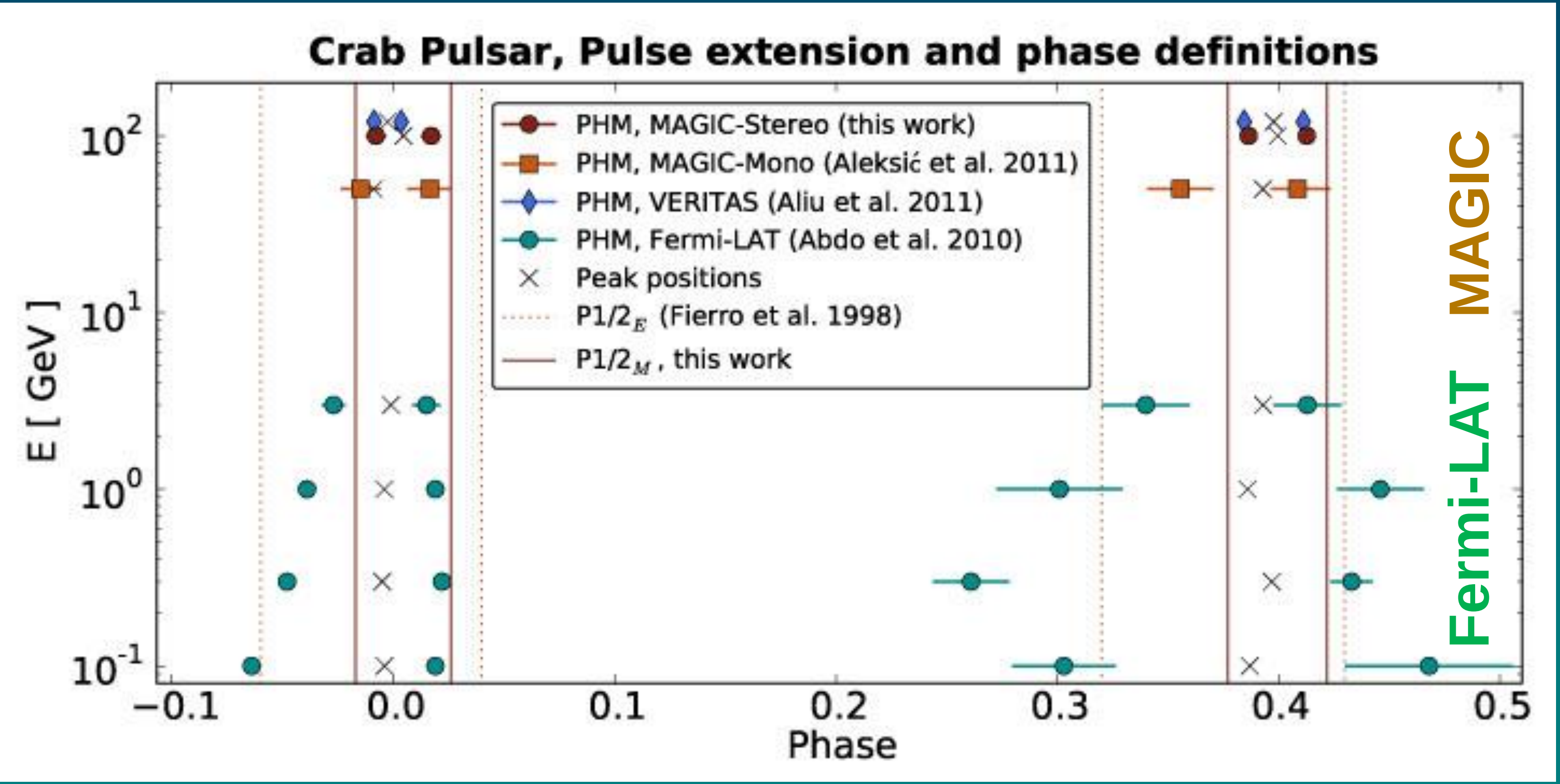




MAGIC stereo observations (2009-2011)

Light curve morphology

- Peaks width get narrower with energy

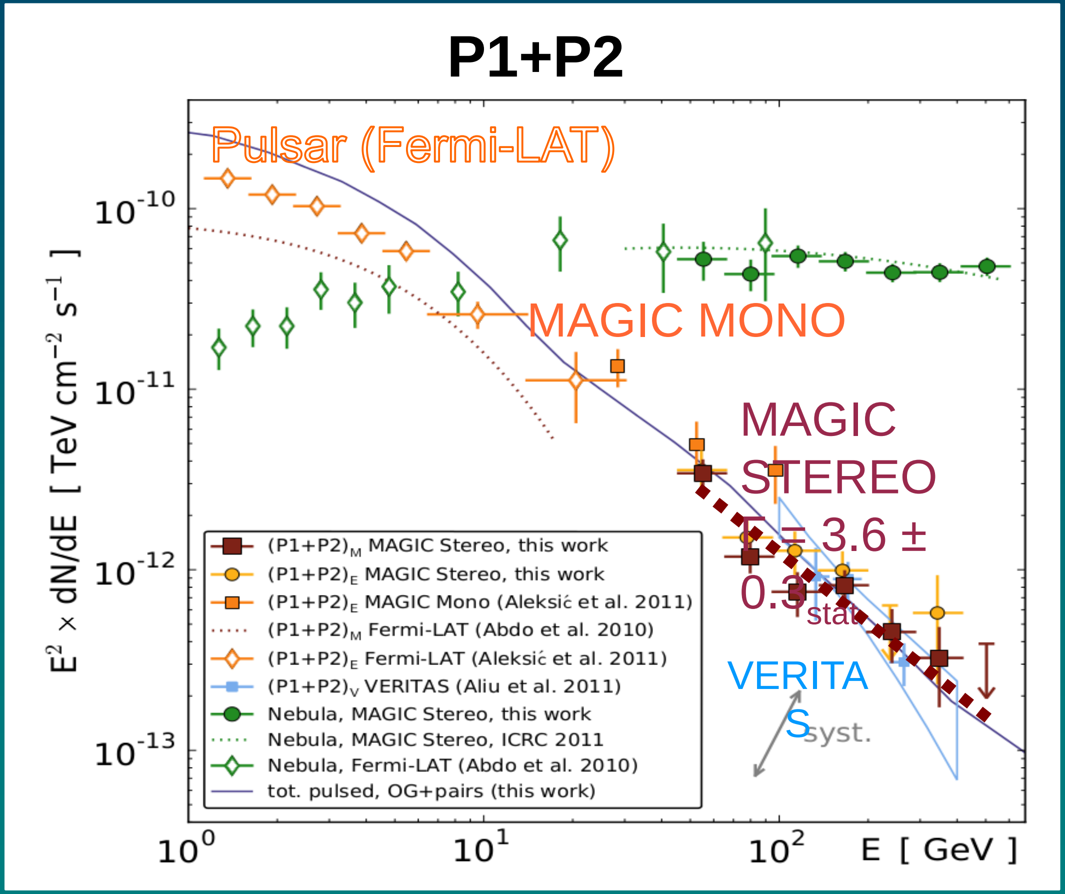


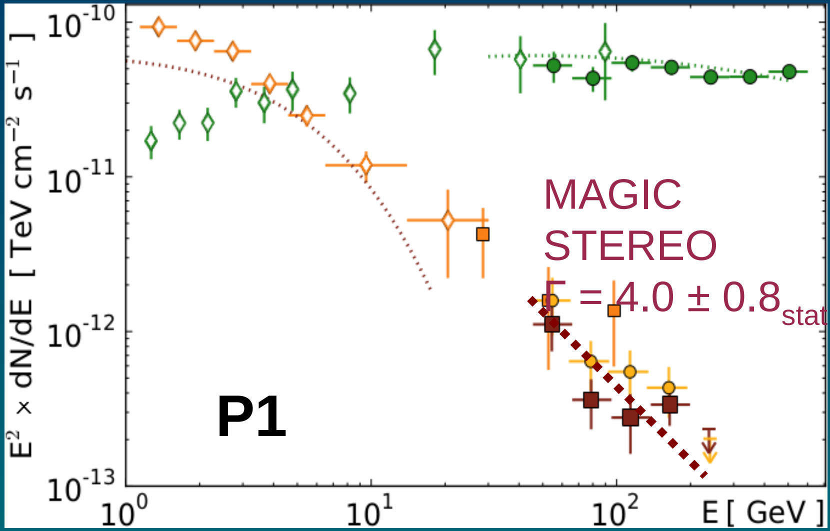
The pulses are aligned, becoming very narrow @ VHE

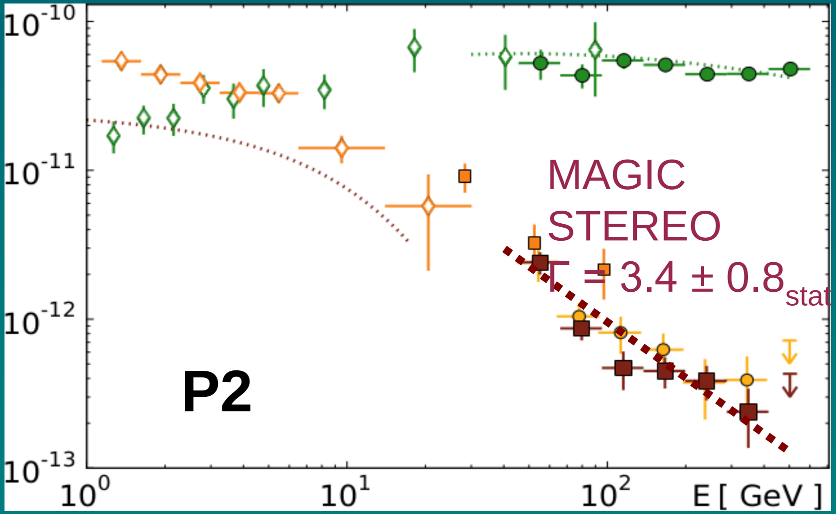
MAGIC stereo observations (2009-2011)

Phase-resolved spectrum up to 400 GeV

- Power law, joins Fermi-LAT, MAGIC and VERITAS





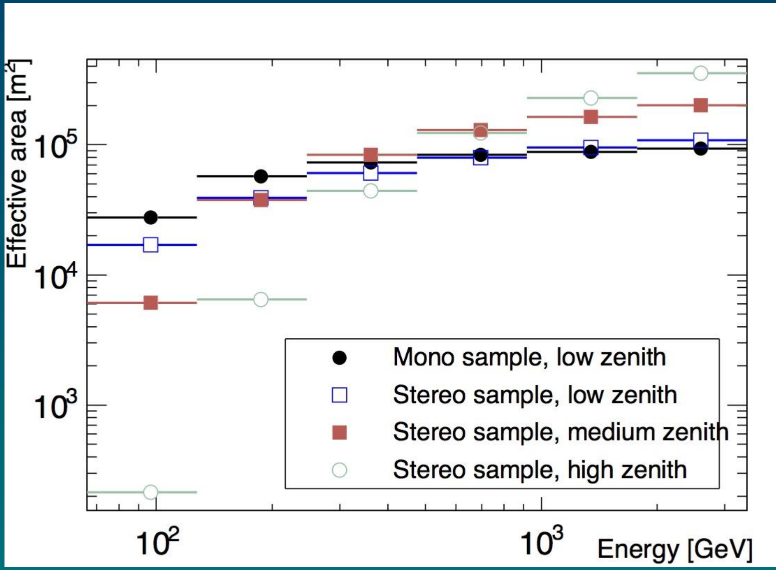


Challenges Outer Gap model

Latest MAGIC results: TeV Crab pulsations

Goal: Investigate maximum E at which Crab is still visible,

- 320 h of MAGIC archive data, 2007 – 2014, were re-analyzed
- Titanic effort:
  - Different instrument performance: Mono (1/3) and Stereo (2/3) data
  - Whole data sample subdivided into 19 sub-samples to account also for different Z.A. and instrument performances
  - Spectra combined when unfolded



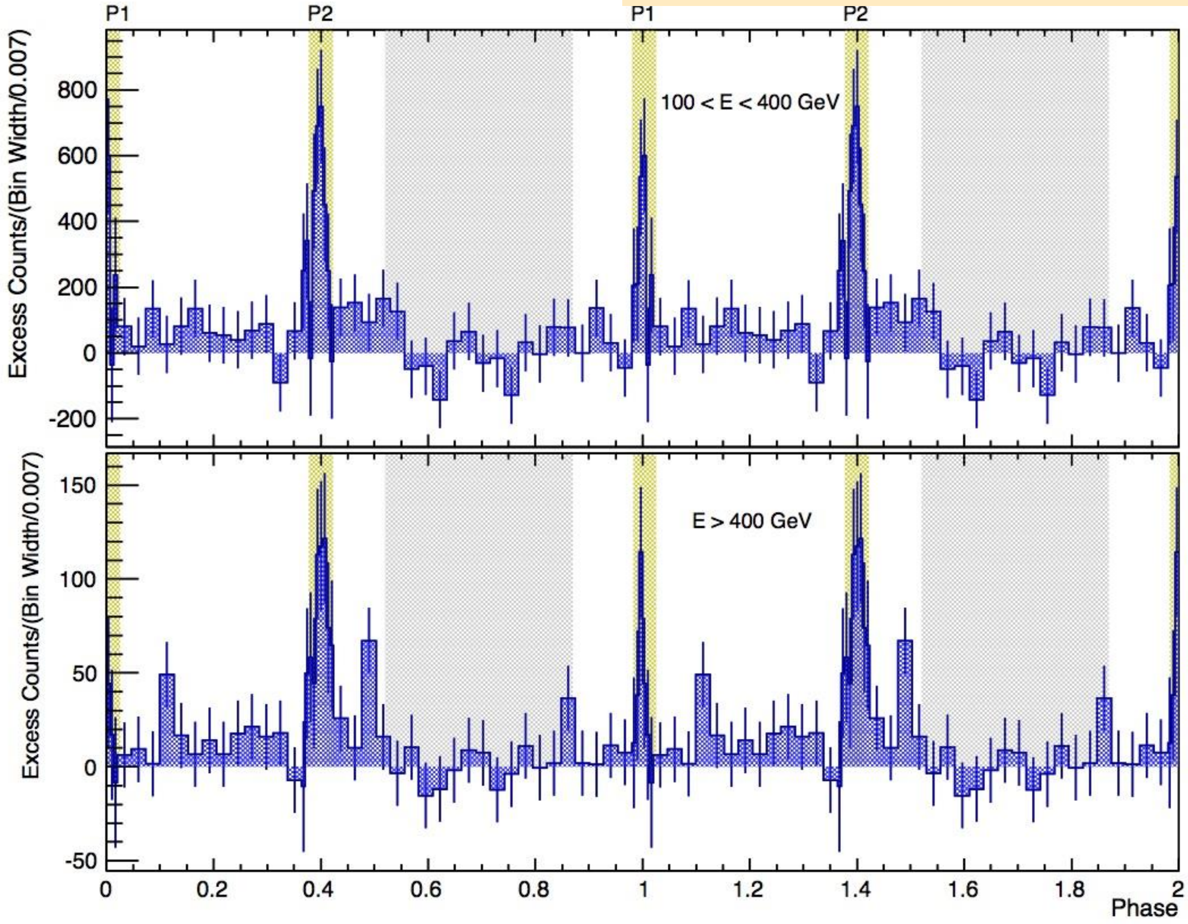
MONO data: 2007 - 2009

STEREO data: 2009 - 2014

MAGIC TeV Crab pulsations

- Pulsation detected above 400 GeV.
  - Emission mainly from P2 (6.0σ)
  - P1 only marginally seen (2.2σ)

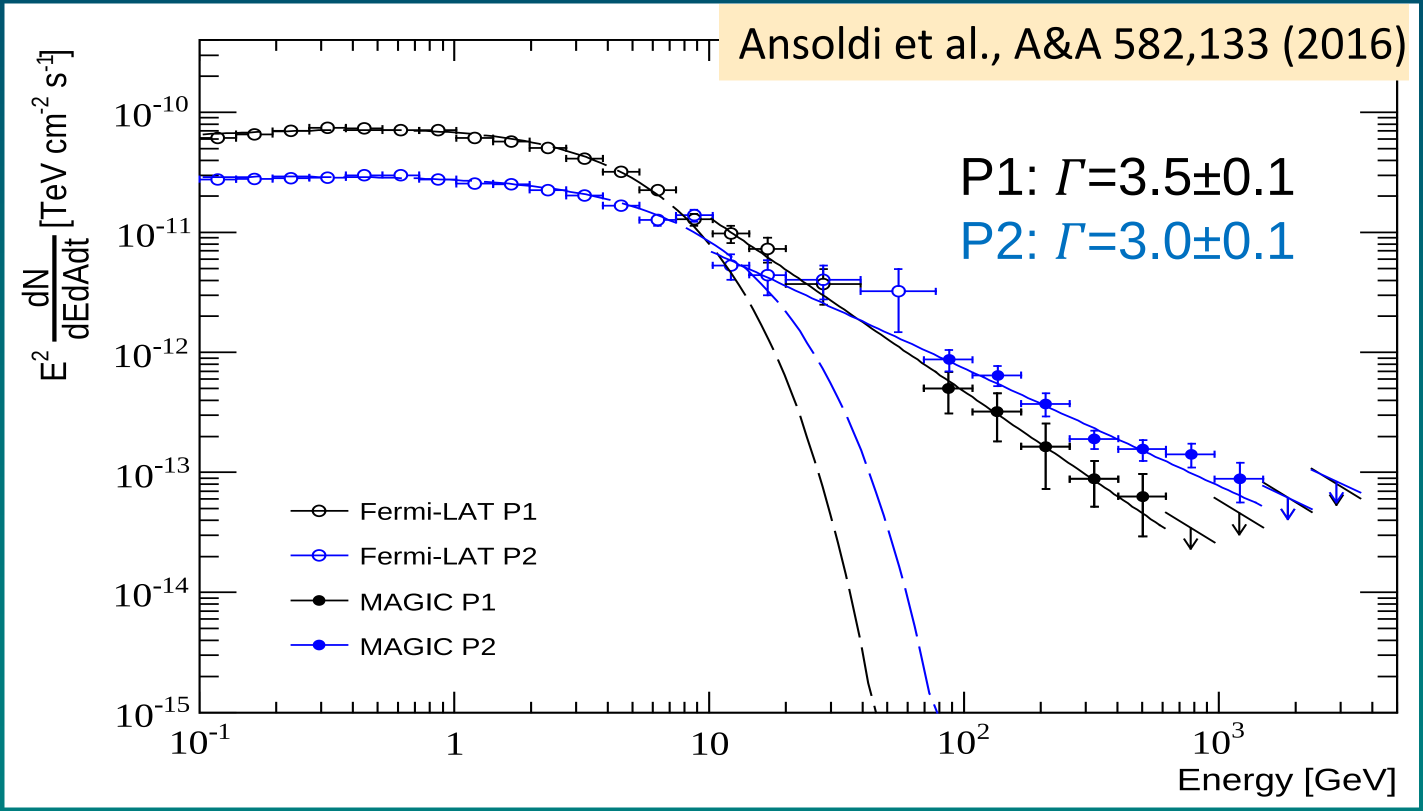
Ansoldi et al., A&A 582,133 (2016)



Energy Range [GeV]	P1		P2	
	N_{ex}	N_σ	N_{ex}	N_σ
100-400	1252±422	2.8	2537±454	5.6
>400	188±88	2.2	544±92	6.0
>680	130±66	2.0	293±69	4.3
>950	119±54	2.2	190±56	3.5

MAGIC TeV Crab pulsations

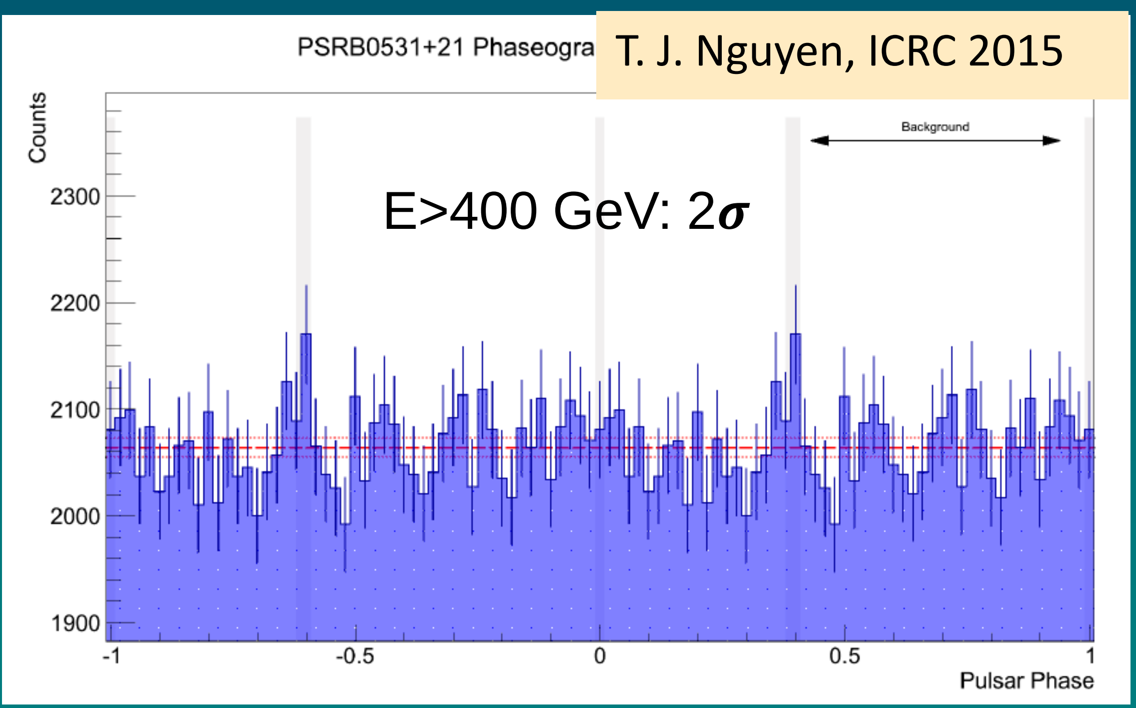
- Both peaks follow a power-law like spectrum:
  - Up to 600 GeV for P1
  - Up to 1.5 TeV for P2
- A joint Fermi-MAGIC fit reveals a softer spectrum for P1 w.r.t. P2

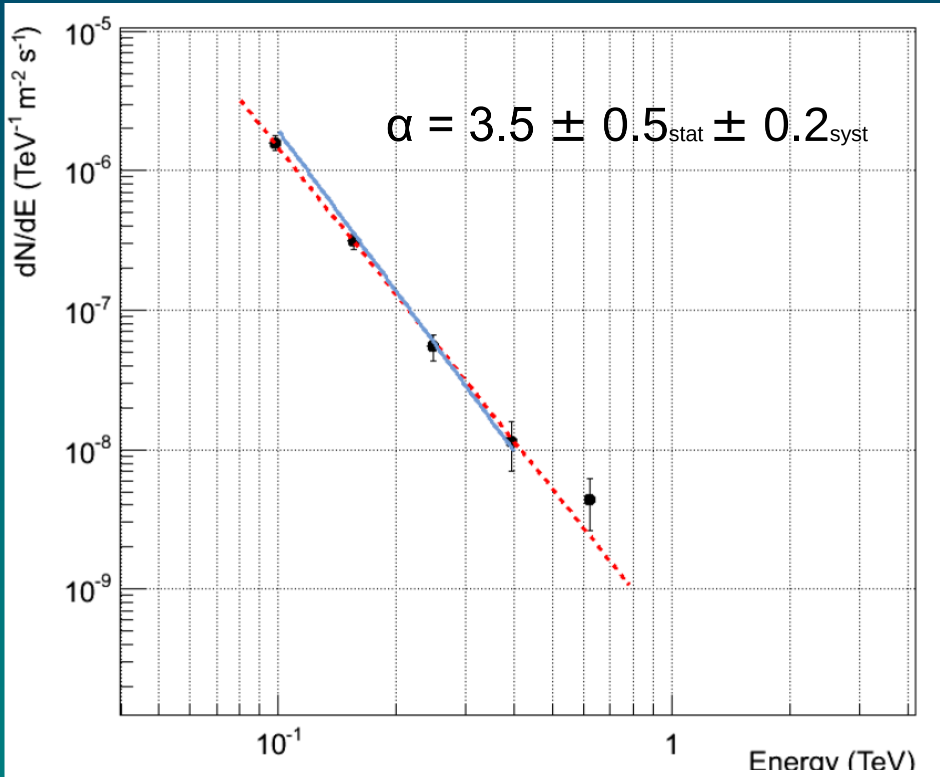


None classical model can explain TeV emission

Latest VERITAS results

- 194 h used, most after camera upgrade in summer 2012
- A hint of emission from P2 above 400 GeV (2.2σ)
- Spectrum fit to a power law from 100 to 600 GeV, agrees with MAGIC





Red: new spectrum with 194h
Blue: published VERITAS spectrum up to 400 GeV (Science 334, 69, 2011)

What does pulsed TeV tell us?

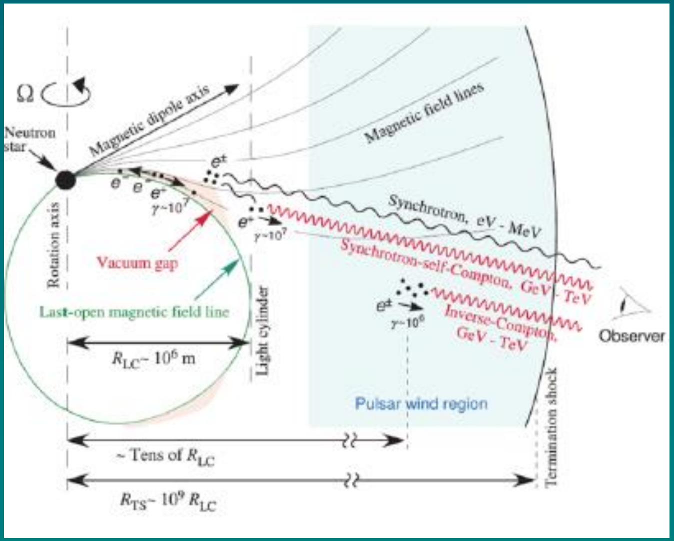
- Detection of TeV photons implies they are emitted by e- with $\Gamma > 5\cdot10^6$
  - Impossible to reach via synchro-curvature mechanism (would require unrealistic curvature radii, $R_c \sim 200\ R_{LC}$)

    → Synchrotron-curvature ruled out

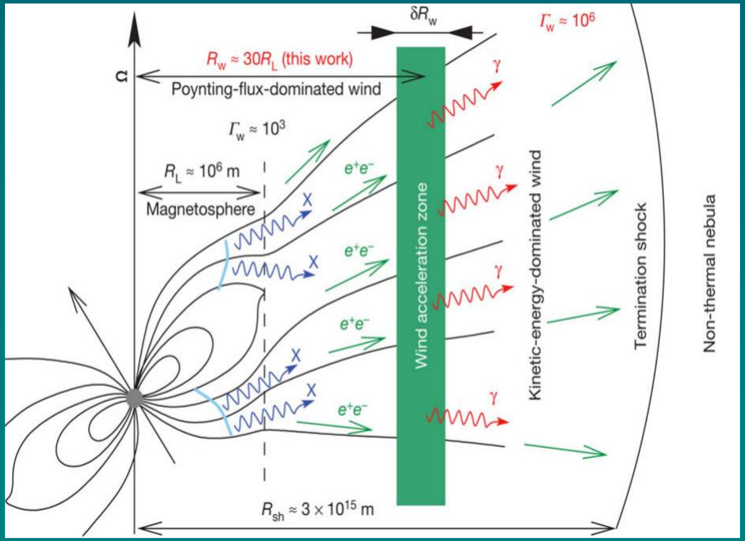
    → Only reasonable possibility is IC on soft photon fields

But Where ?

Within the magnetosphere?



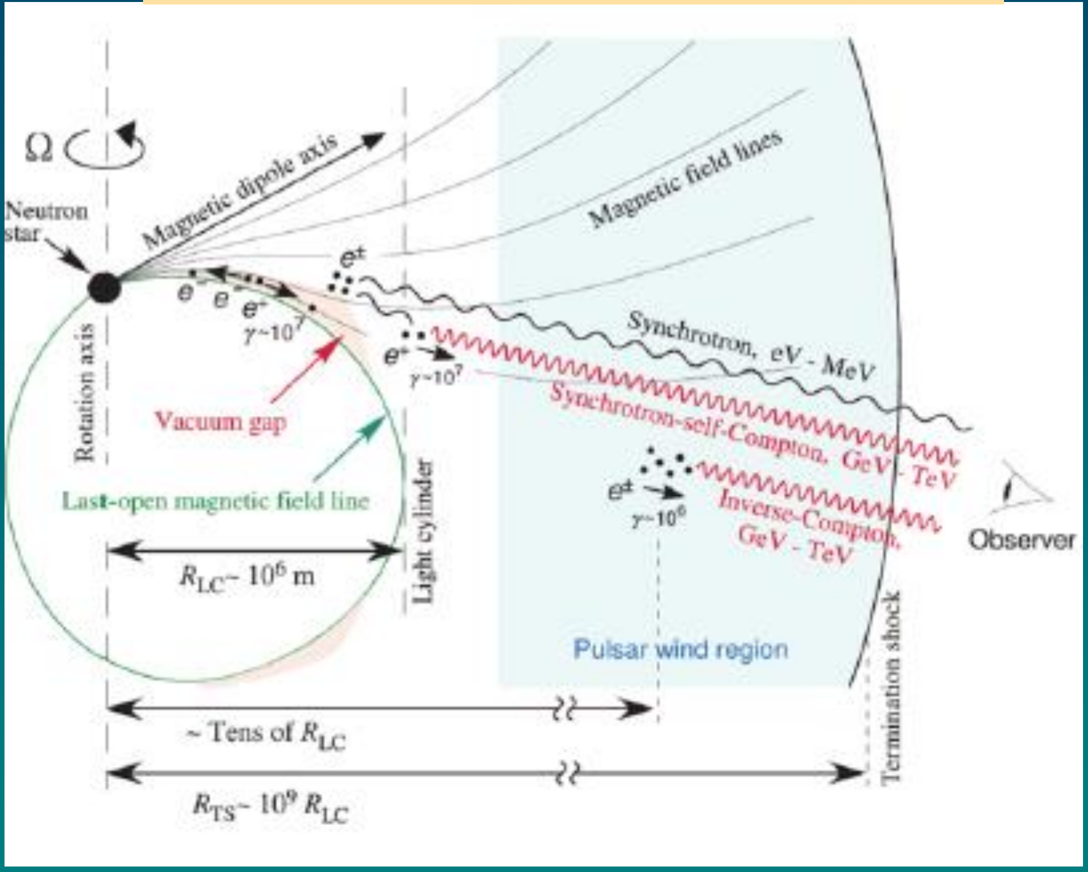
Beyond the magnetosphere?



Constraining the emission site

Within the magnetosphere? Magnetospheric SSC model

Hirotani & MAGIC, ApJ 766, 98 2013



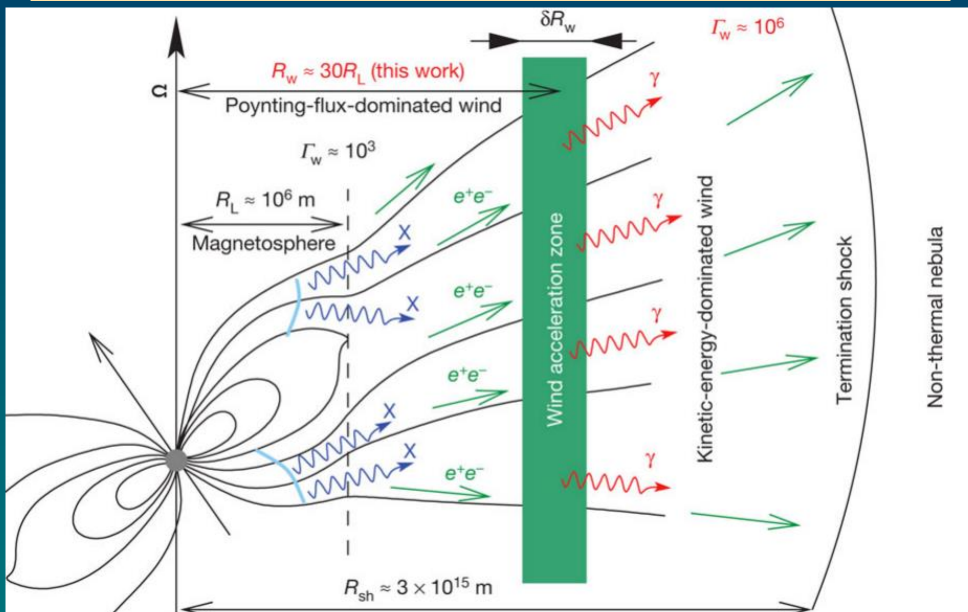
- Primary e^+ escaping the gap up-scatter synchrotron photons to TeV
- TeV photons quickly absorbed by ambient photons, producing $e^{\pm}$ pairs cascade
- Secondary photons created at a greater distance (tens of R_{LC}), can escape pair-production, produce GeV-TeV emission via SSC process

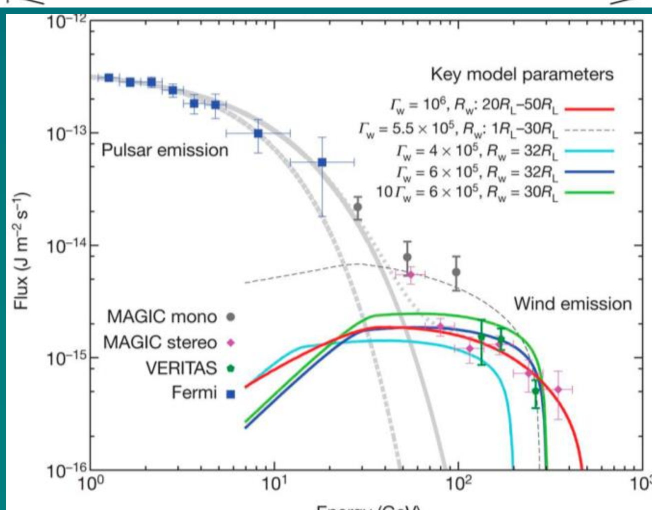
Problem: Difficult to explain synchronization of pulse profile in the GeV and TeV, at least they are emitted in similar region

Constraining the emission site

Beyond the magnetosphere? IC in the pulsar wind region model

Aharonian et al., Nature 482, 507, 2012





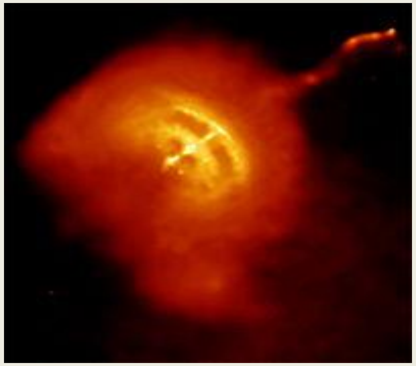
- Pulsar wind up-scatter pulsed X-rays, in a narrow zone (20-50 R_{LC})

Problems:

- Predict cutoff at ~500 GeV
  ➜ Can not reproduce TeV emission. The acceleration region should extend up to a much larger radius
- At larger distances, broadening of peaks
  ➜ Can not reproduce LC

Ruled out! (need to be revised)

Vela: the second pulsar detected at VHE



Due to its proximity (d = 287 pc), Vela is exceptionally bright in radio and in HE γ rays

➜ Good target for Chrenkov telescopes placed in South hemisphere

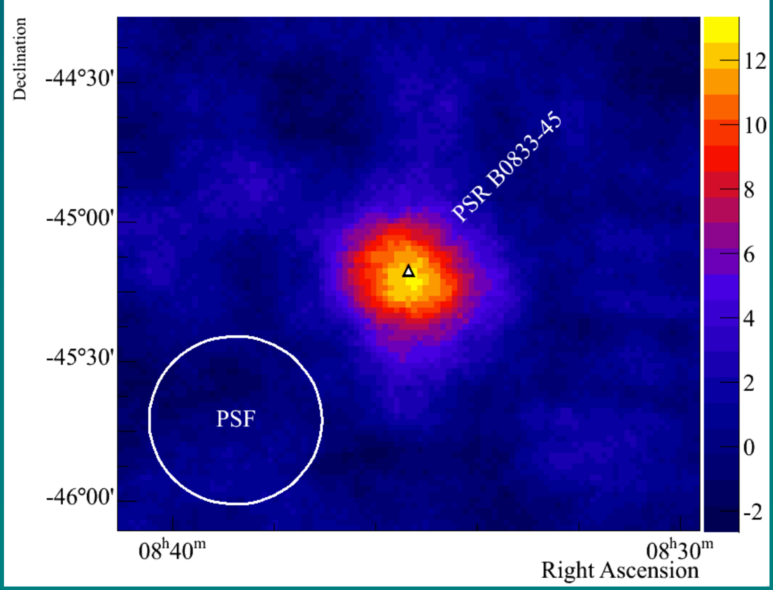
Vela detection by H.E.S.S.-II

Observations

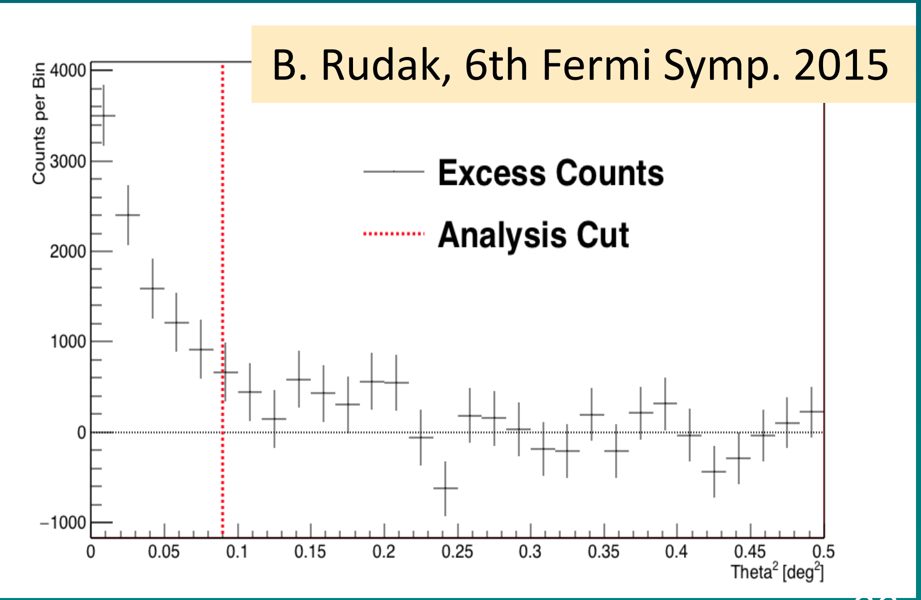
- 24 h collected in 2013/14, using only CT5 (28 m)
  - Energy range: 20 – 120 GeV, <E>~ 45 GeV
  - Effective area @ 20 GeV & 20º Z.A.: 1900 m^2

Sky map

- Signal compatible with a point source located at Vela pulsar position



Number of pulsed events as a

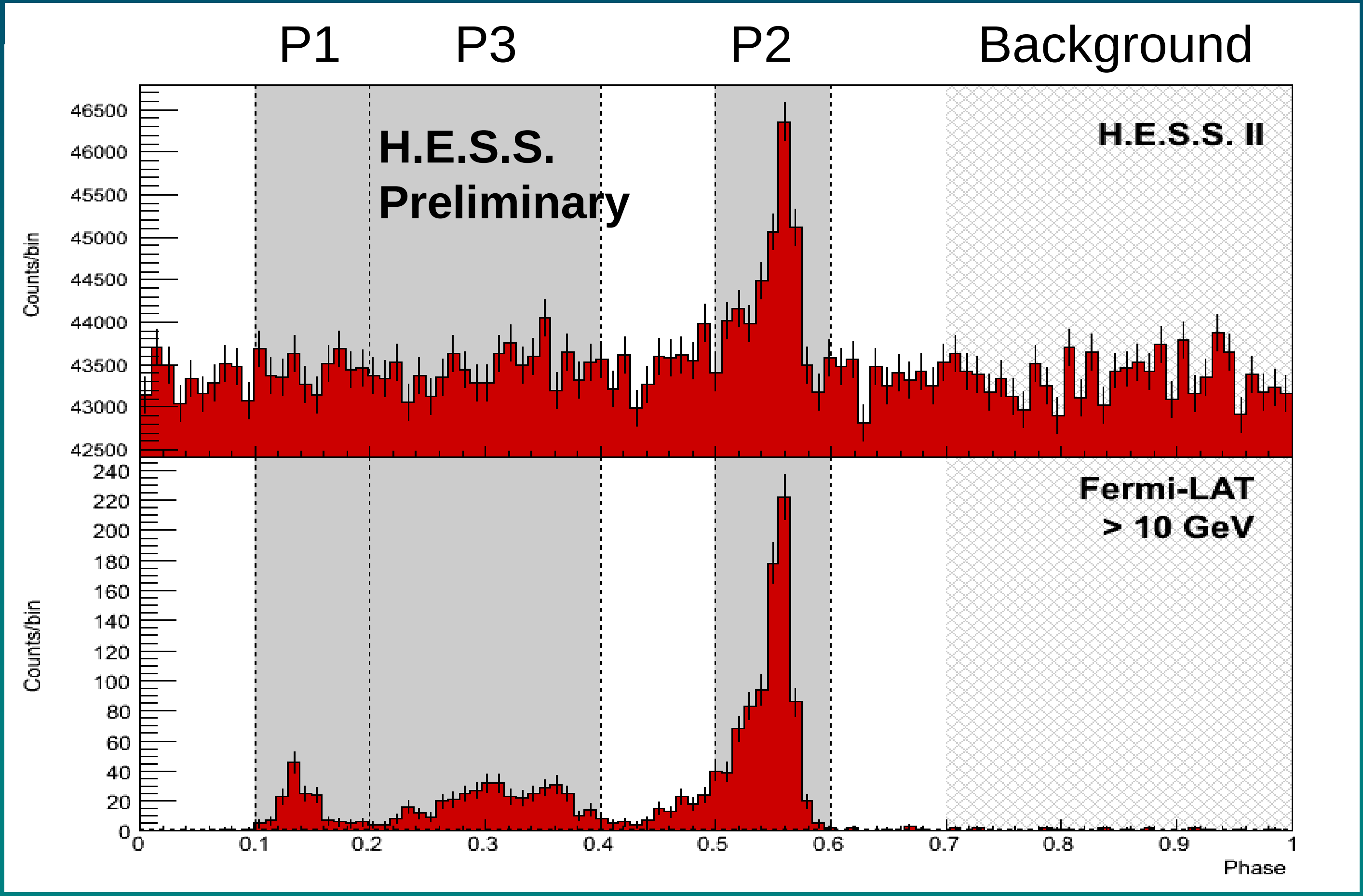


Vela: Pulse Profile

- Ephemeris provided by Fermi coll.
  - Two glitches during observation period
- Emission clearly detected from P2
  - No detection of P1 nor P3 (in agreement with Fermi-LAT > 10 GeV LC)

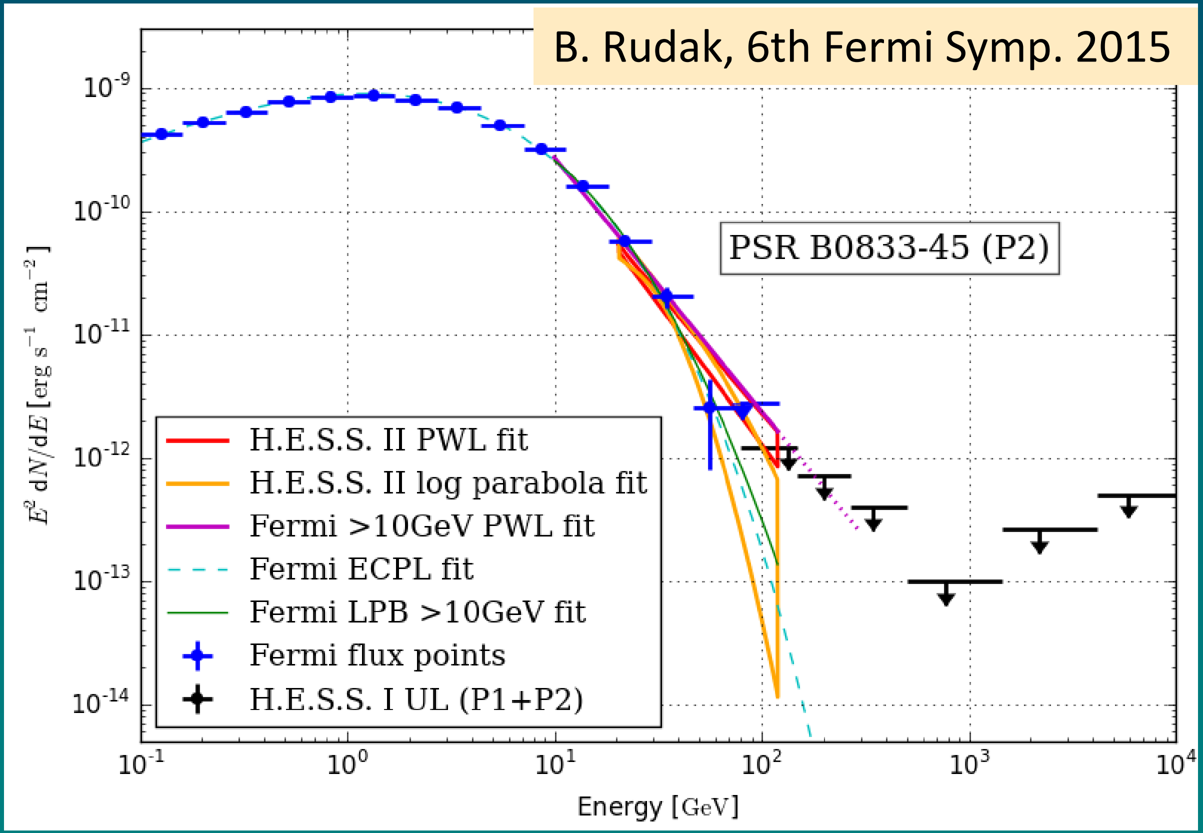
B. Rudak, 6th Fermi Symp. 2015

9838 excess events
H test significance: 14.6σ
Li-Ma significance: 12.8σ

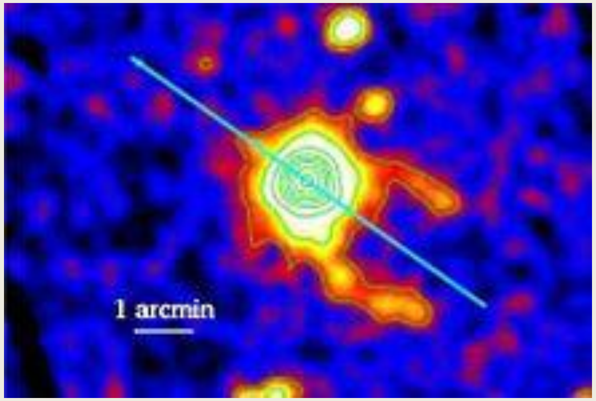


Vela: Spectral Energy Distribution of P2

- Vela P2 peak spectrum measured up to 120 GeV
- Excellent agreement between H.E.S.S. II and Fermi-LAT
- Power-law tail or curved spectrum???
  - Statistics above 10 GeV limit distinction between them



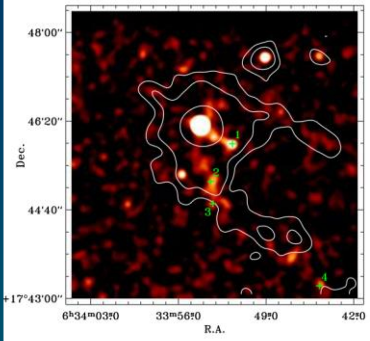
More statistics needed around 100 GeV to confirm or exclude PWL



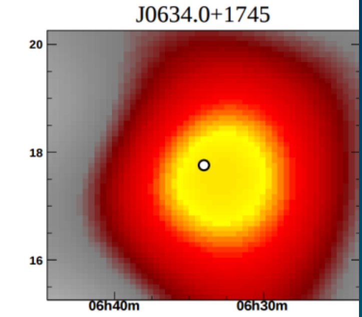
Search for Geminga VHE pulsations

Geminga as seen by Fermi

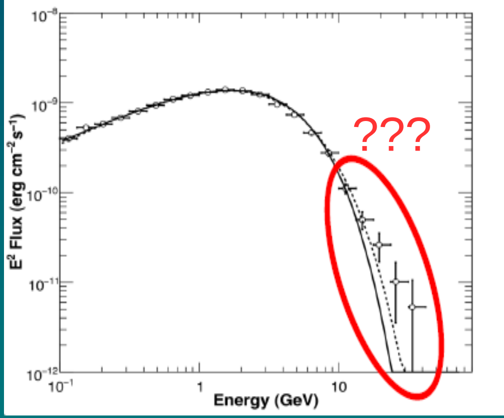
- Prototype of radio-quiet pulsar population
- Surrounded by challenging nebula, seen in X-ray and TeV scale, but not in GeV
- Deviation from exp cutoff seen in Fermi-LAT data ➜ Motivated VERITAS and MAGIC observations



X-ray Chandra



VHE Milagro



- Geminga very different from Crab in many aspects
  - Radio quiet Vs radio lout
  - Old Vs Young
  - Low Edot Vs. Hight Edot
  - Closeby Vs not_so_close

Different emission mechanism?

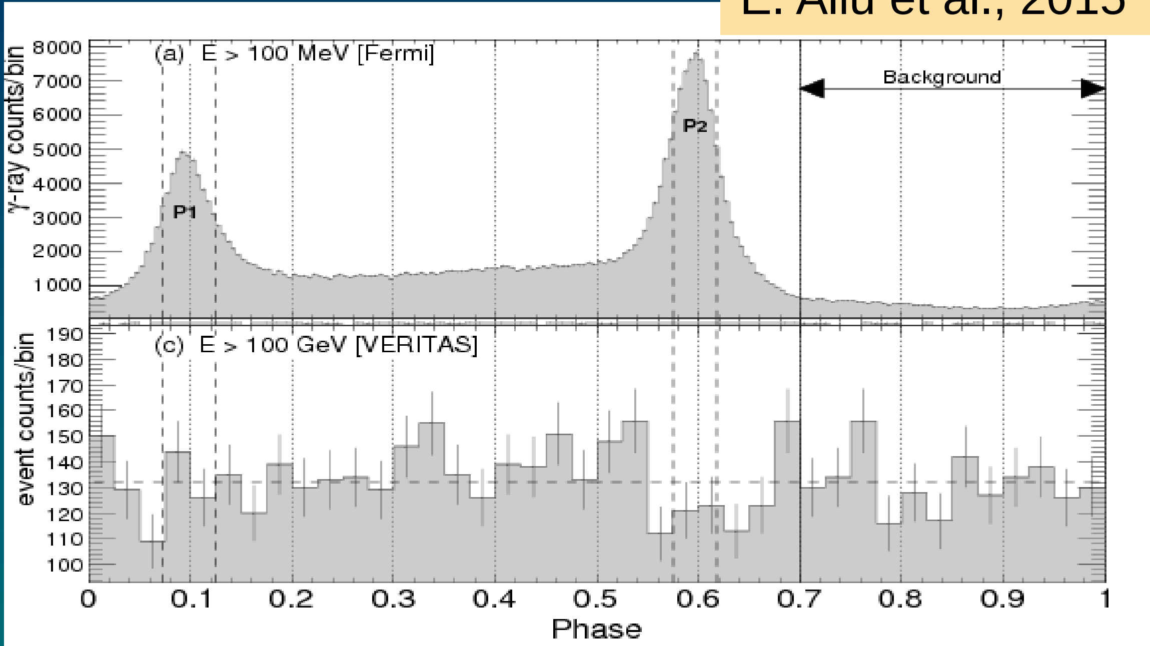
	Geminga	Crab
Period	237 ms	33ms
Estimated age	$340 \cdot 10^3$ yr	961 yr
$L_{SpinDown}$	$3 \cdot 10^{34}$ ergs/s	$5 \cdot 10^{38}$ ergs/s
Distance	150 pc	2000 pc

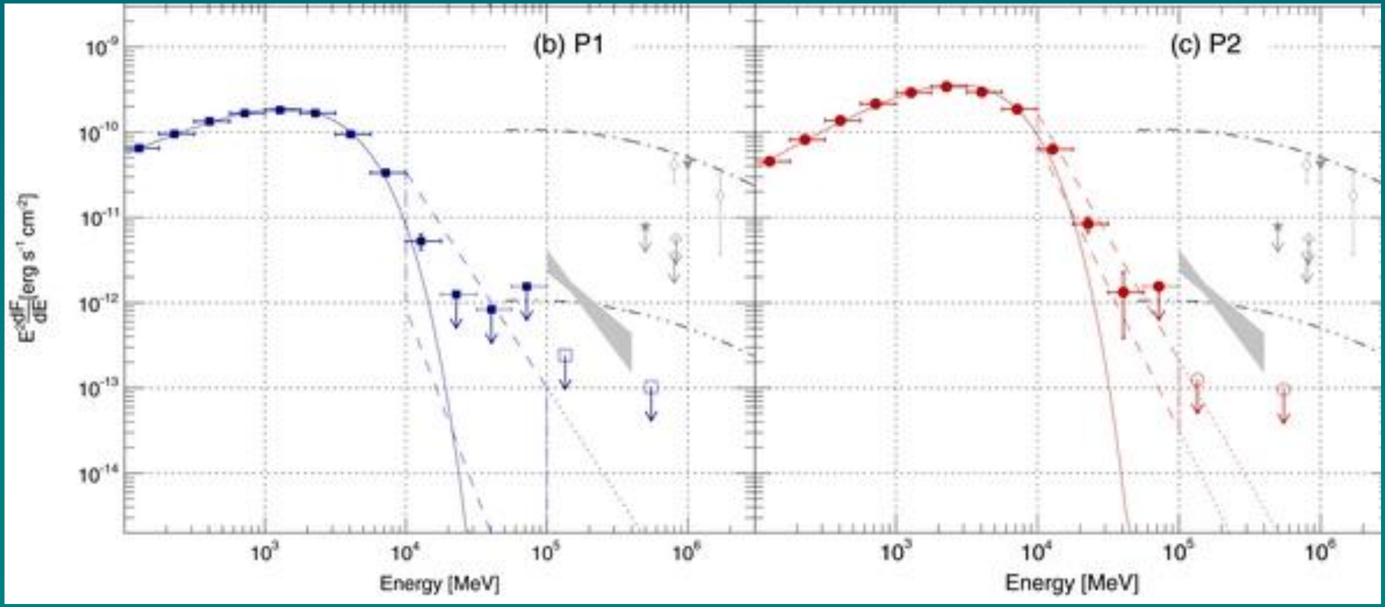
Geminga: VERITAS

- 72 h taken between 2007 and 2013
- Definition of P1 and P2 derived from the LAT light curve

No detection

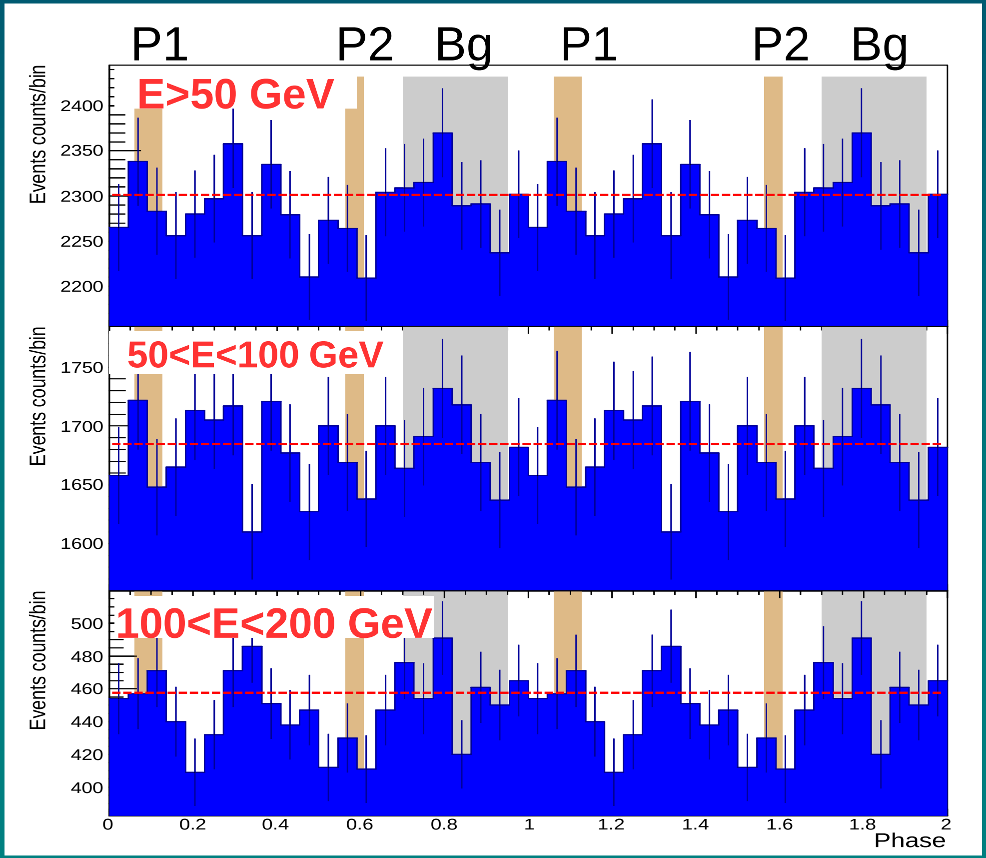
E. Aliu et al., 2015



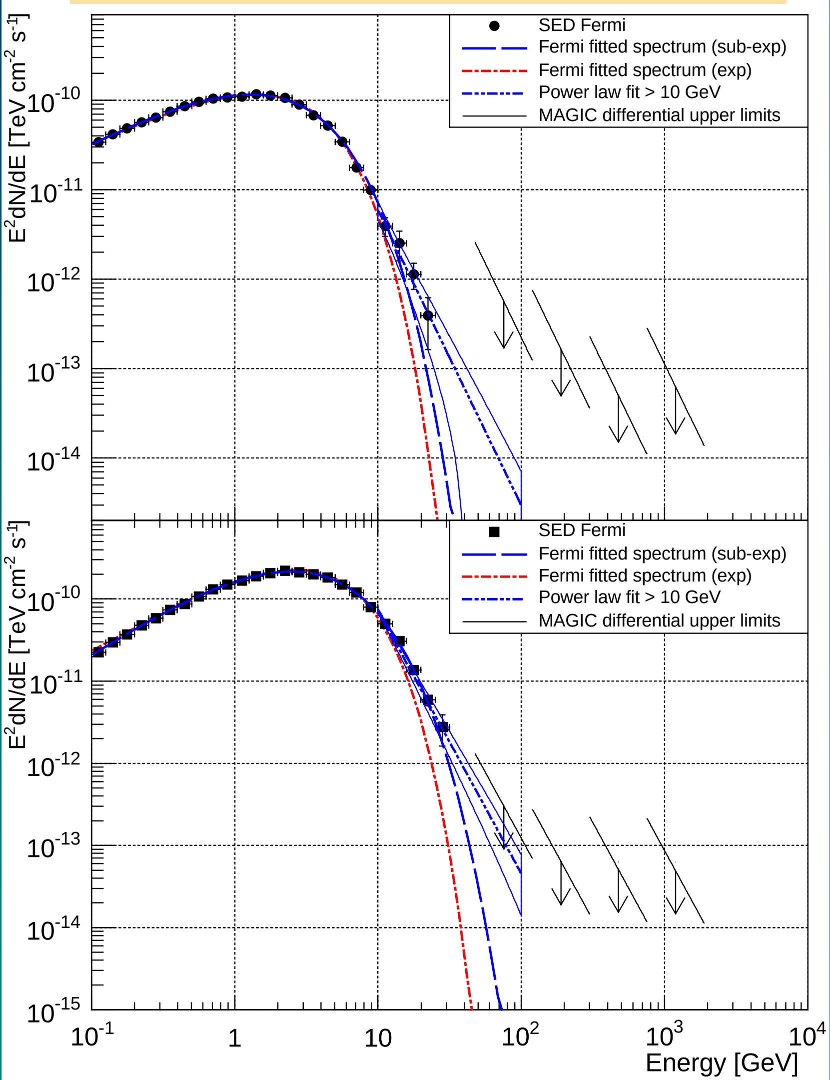


Geminga: MAGIC

- 63 h in winter 2012/13
- Search for pulsations in 3 different ranges 50 and 200 GeV
- No detection, but most constraining UL's so far

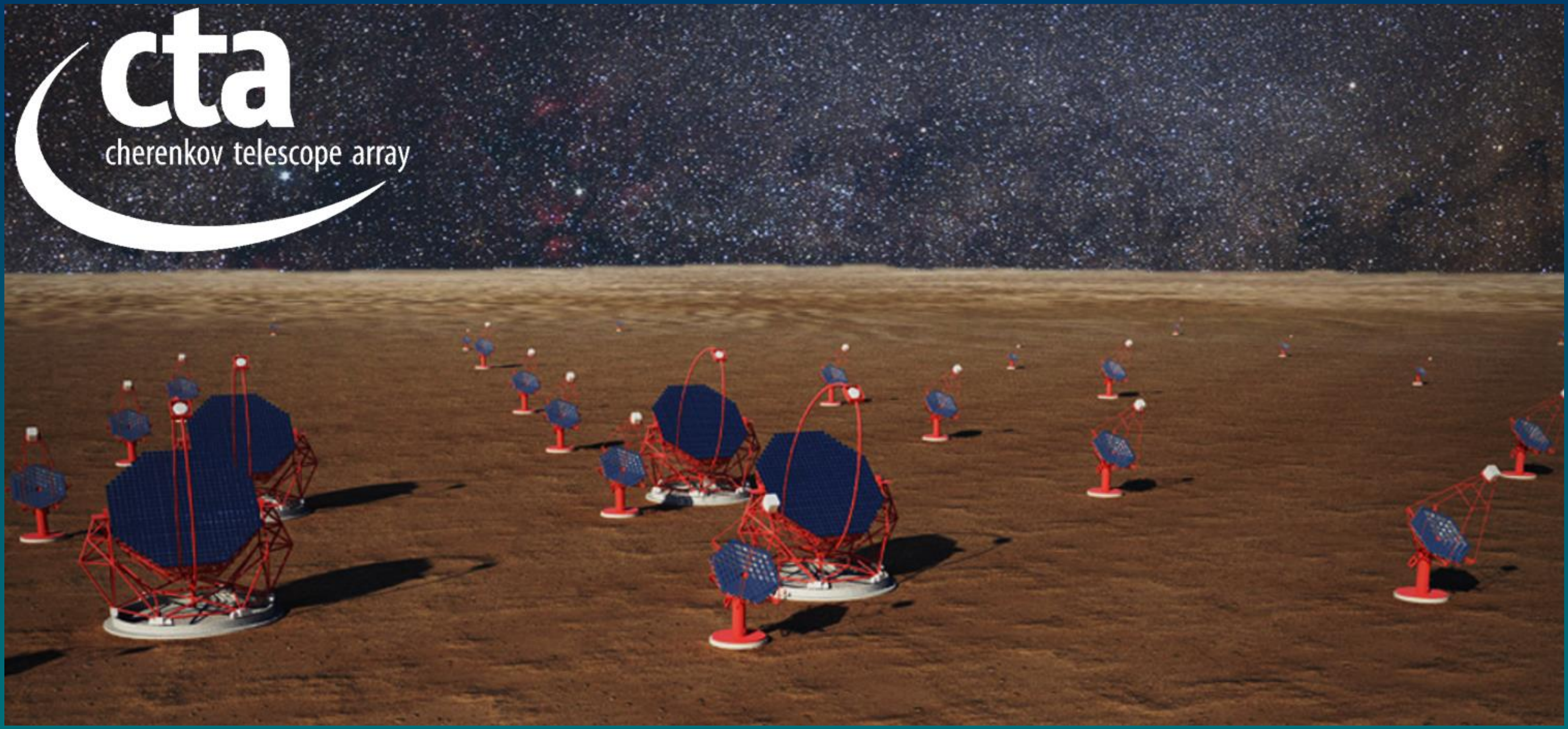


Ahnen et al., A&A 591 A138 (2016)



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

The CTA Era

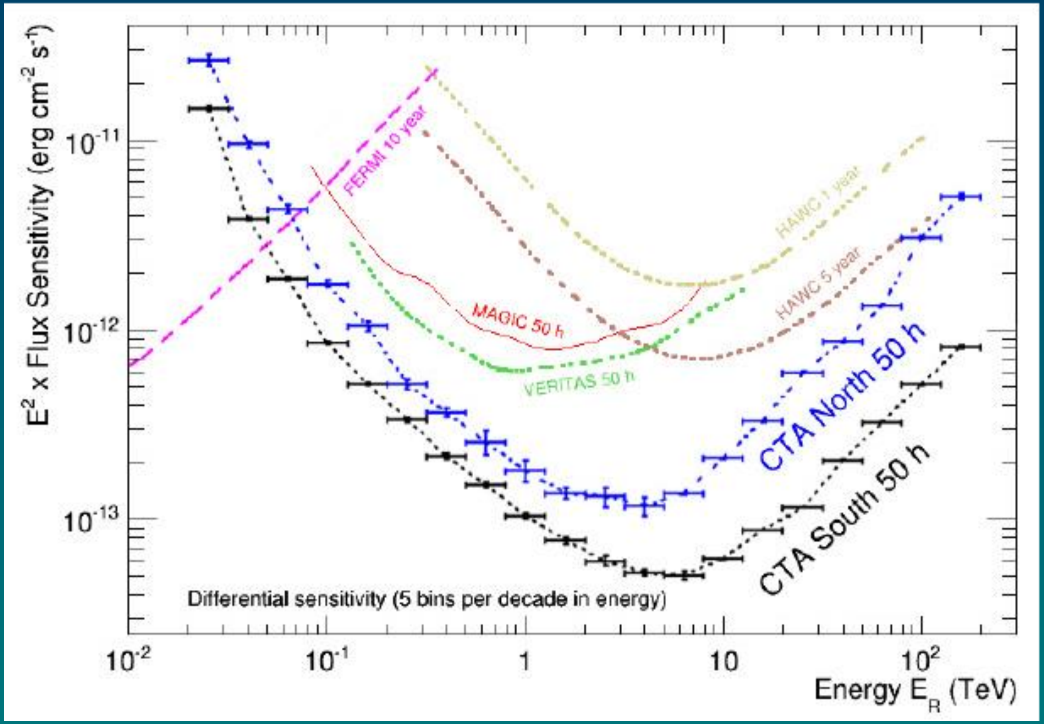


- CTA is the next generation of a Cherenkov gamma-ray observatory
  - A join effort of: HESS + MAGIC + VERITAS + new people
- Two observatories: North & South
- About 100 telescopes of 3 different sizes, for covering different energies ranges

Why do we need CTA for pulsars

Needed higher sensitivity at TeV:

- Crab pulsar spectrum at TeV already limited by statistics:
  - Really hard for current CTs to get another spectral point at TeV
  - This limits detection or exclusion of a spectral cut-off in the TeV range



Needed higher sensitivity at GeV:

- Pulsars with just sub exp-cutoff at GeVs (i.e. w/o VHE tail) almost impossible to catch with current CTs

Discovery Potential for CTA

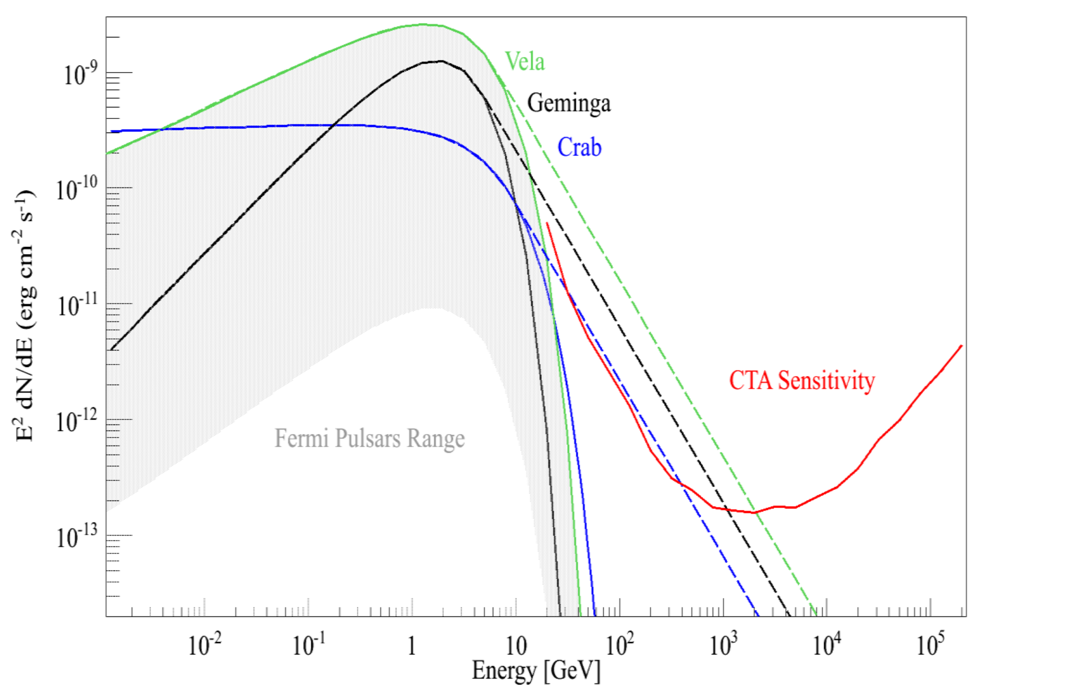
Extrapolating Fermi-LAT (exponential cutoff) from the 2FPC

- Detectability with CTA will depends on performance estimates and on the spectral shapes expected at CTA energies

- If the exponential cutoff is the only component, few pulsars would be observable in 50h

- But VHE tails (Crab-like) could be easily detectable from bright pulsars

E. Willhemi,..M.López et al 2012

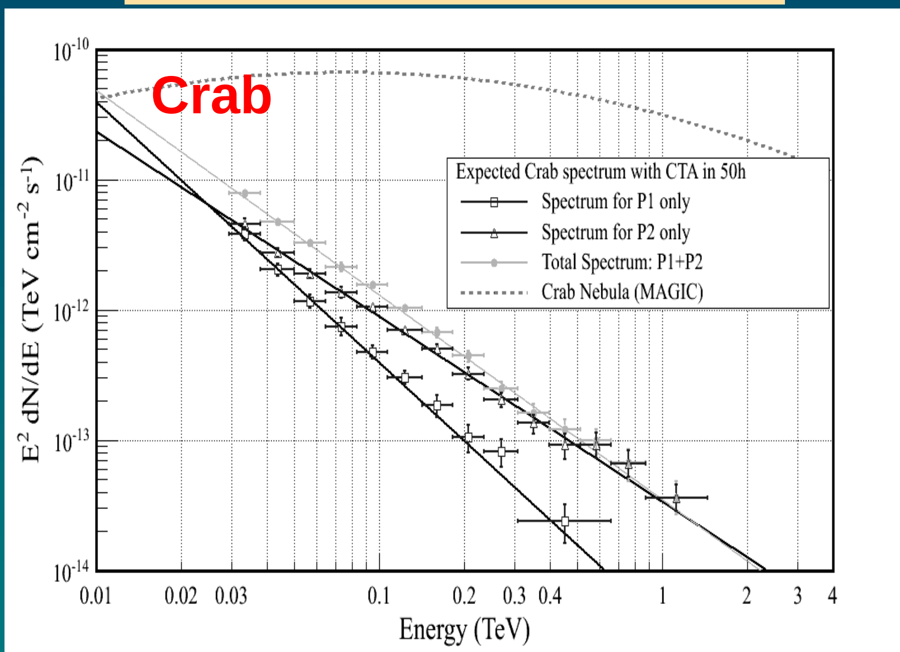


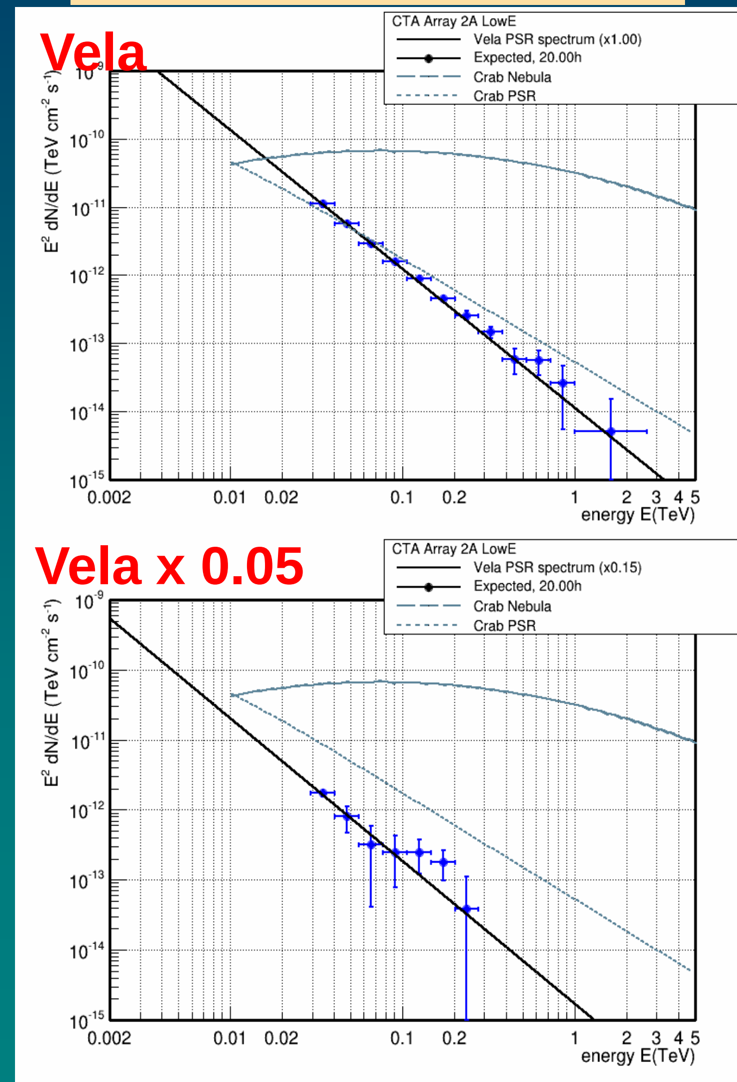
Discovery Potential for CTA

- Simulated spectra for Crab (50 h) and Vela (20 h) with CTA

A. Djannati-Ata. & T. Tavernier

E. Willhemi,..M.López et al 2012





Good potential for measuring >TeV pulsations in few hours

Conclusions

- More than 200 pulsars detected in the GeV band by Fermi-LAT
  - Their spectra typically exhibit sub-exp cutoff at few GeV
- But 2 pulsars, Crab and Vela, detected from ground at much higher energies than the measured Fermi cutoffs
- This opens new questions:
  - Until which energy is Crab pulsating? Which mechanism is producing its Power-law tail? Is there a cutoff somewhere?
  - Is Vela also showing a Power-law tail?
  - Are there others VHE pulsars?
- Difficult to detect new pulsars with current instruments:
  - Crab and Vela detected in ~25 h but not Geminga in 70 h
- We need to continue searching for VHE pulsars with better instruments, as CTA