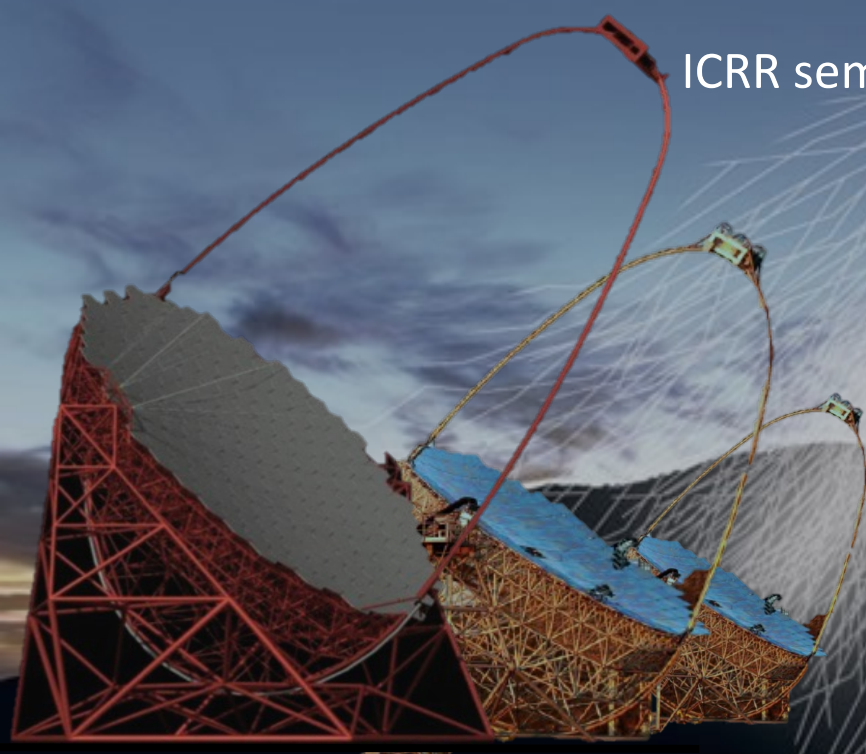
Unveiling VHE gamma-ray emission from Pulsars

Marcos López Moya

ICRR seminar, Japan, 27th July 2022



Outline

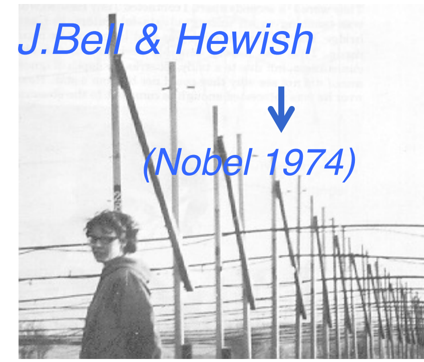
1. Basics on pulsars physics
   - Observational and inferred properties
   - Fermi-LAT pulsars
   - Emission models
2. Results from the observations of pulsars from ground
3. The CTA era

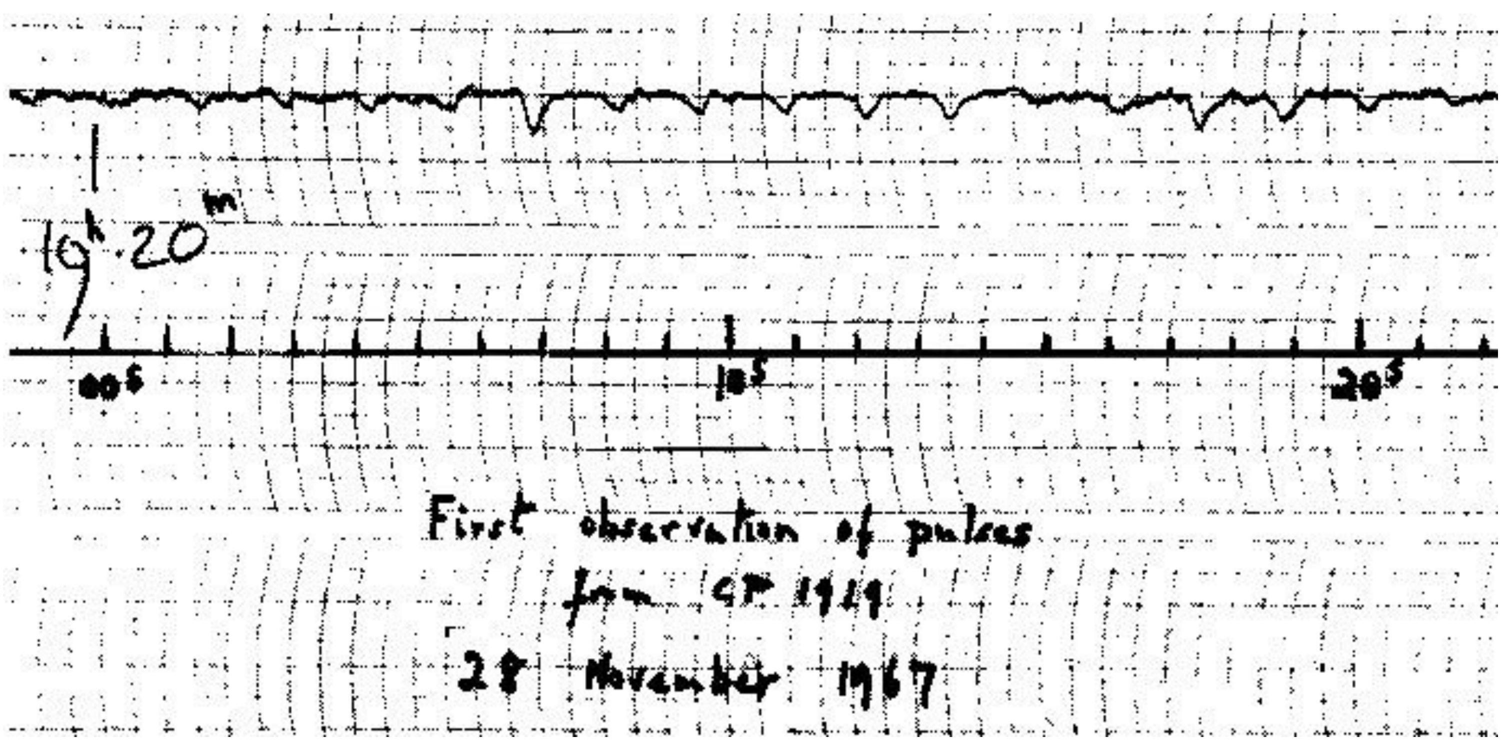
Basics on pulsars physics

Discovery

Radio

- First discovered in radio in 1967 by a PhD student (Jocelyn Bell):
  - Short pulses (10 ms) that were repeated every 1.3 s





Meticulous PhD work pays off

Discovery

Radio

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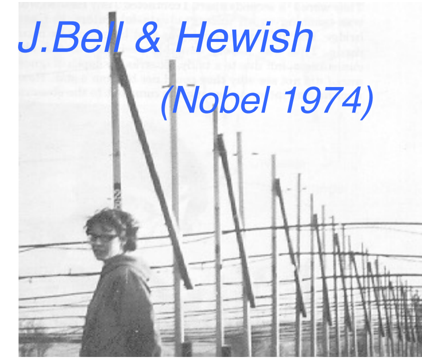
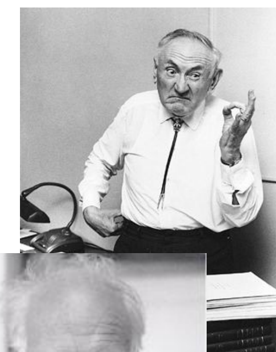
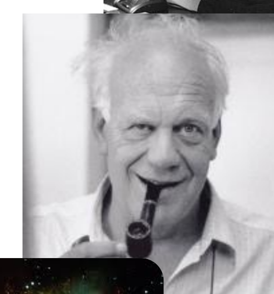


J.Bell & Hewish
(Nobel 1974)

Hypothesis

- **Aliens**. The source was called LGM1 (Little Green Man 1)
  - Discarded after similar signals at other sky positions.
- **White dwarf (R>100km)?**
  - No: The fat rotation would break the star.
- **Neutron Star (R~10km)?**
  - Until then only a theoretical hypothesis, proposed in 1933 by Zwicky & Baade
  - In 1968 Pacini discovered a neutron star at the center of the Crab Nebula





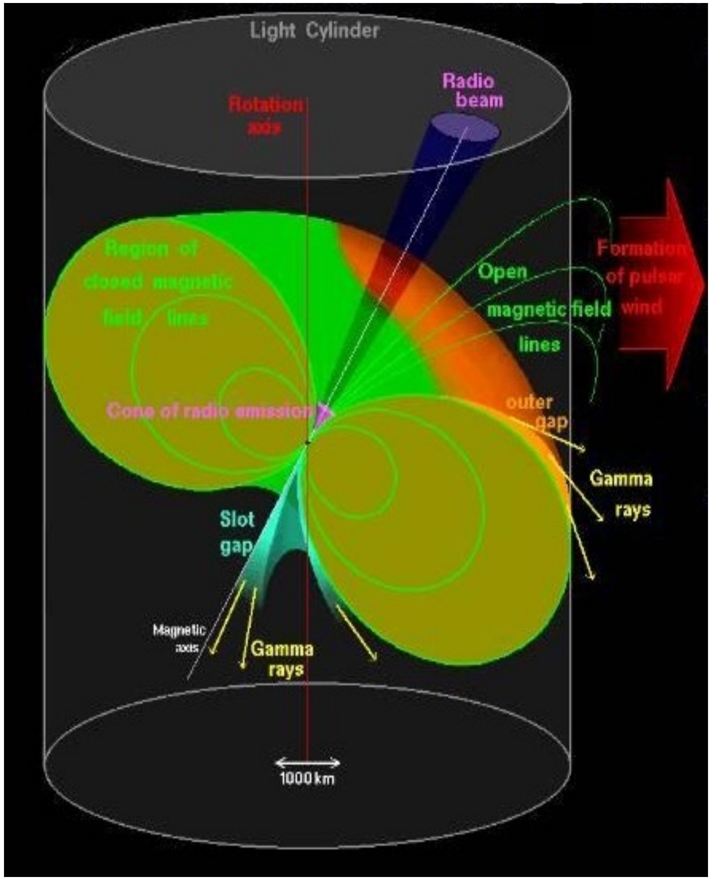
➔ *Pulsars = Neutron stars*

Pulsars

Probes of extreme Physics

- Pulsars are highly magnetized and rapidly rotating neutron stars
  - Extreme density: $M \sim 1.4\, M_{\odot}$ & $R \sim 10$ km
  - Huge magnetic fields: $B \sim 10^{8-14}$G
  - Fast rotators: up to hundreds of times / s

➔ *Unique labs for particle physics*



Pulsars

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➔ *Unique labs for particle physics*

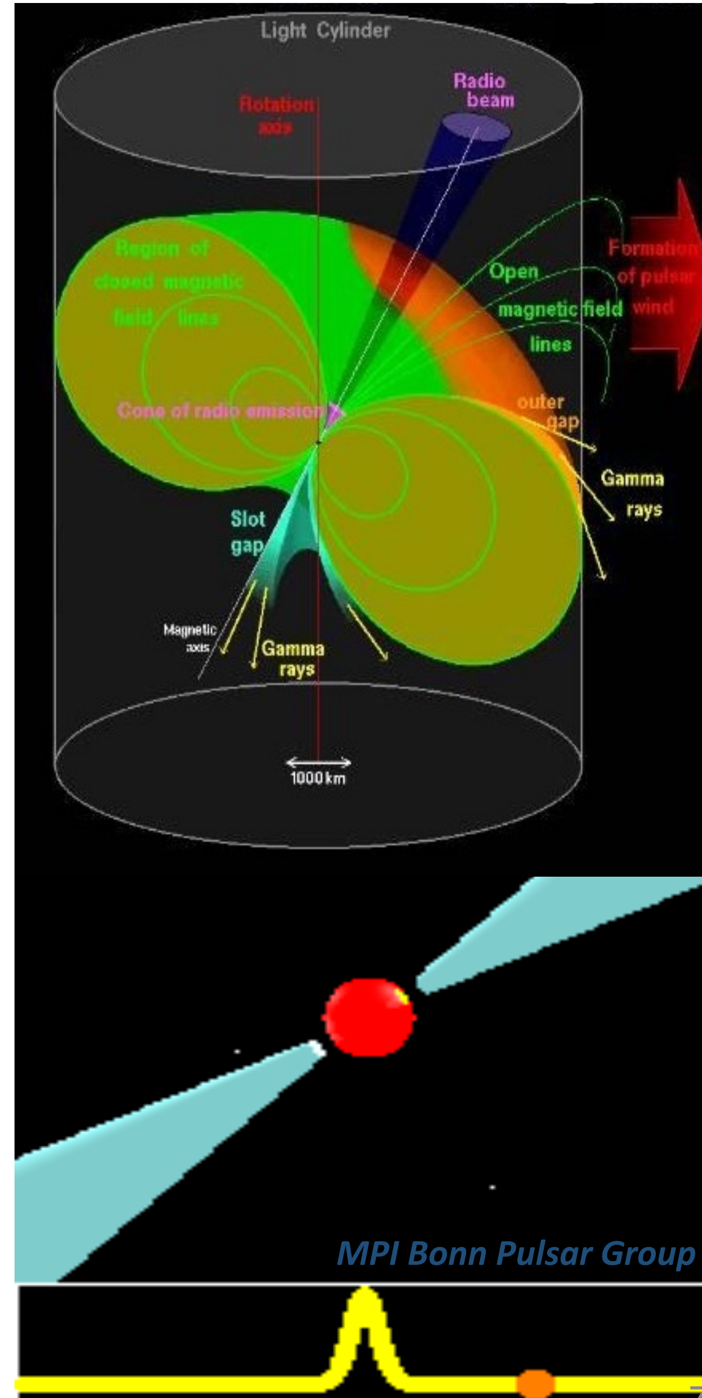
Magnetosphere

- 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”:

$$R_{LC} \equiv c / \Omega$$

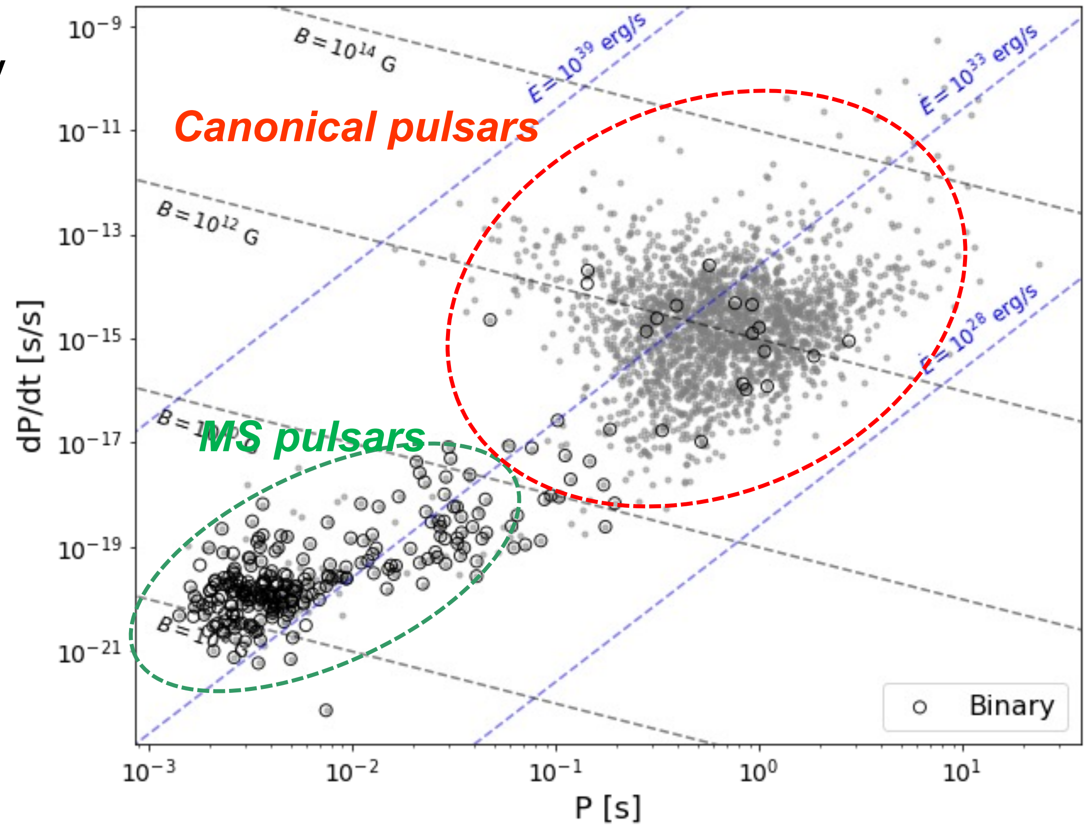
- Non-thermal Emission (radio, optical, X-ray, γ-rays) produced in beams

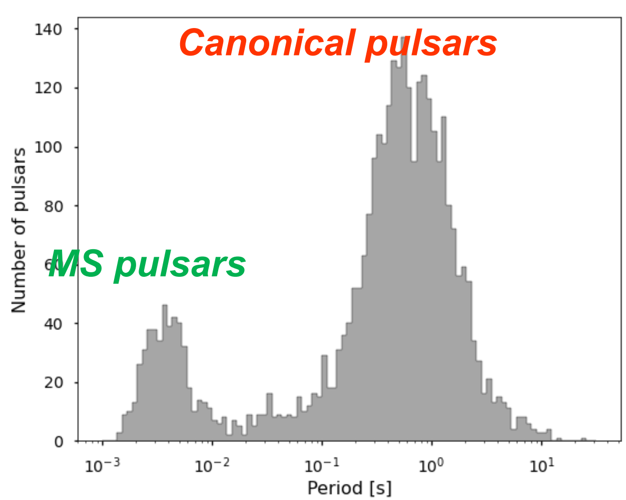
➔ *Acts like a cosmic light-house*

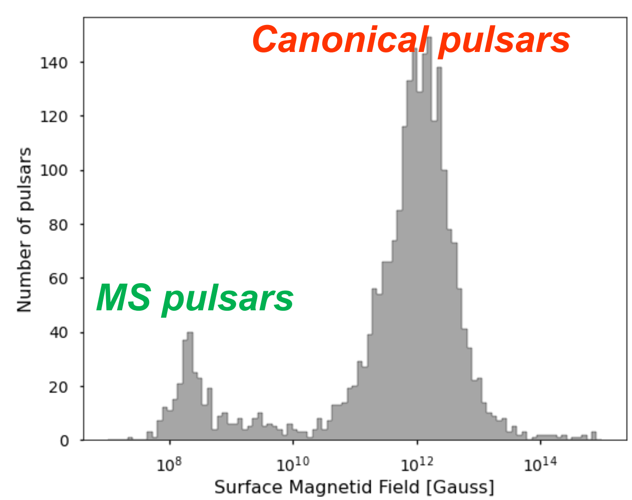


P – Pdot plot

- **~3000** radio pulsars known today
- Can an be grouped in:
  - **Normal** (young): B~10^{12}G
  - **MS** (old): B~10^{8} G



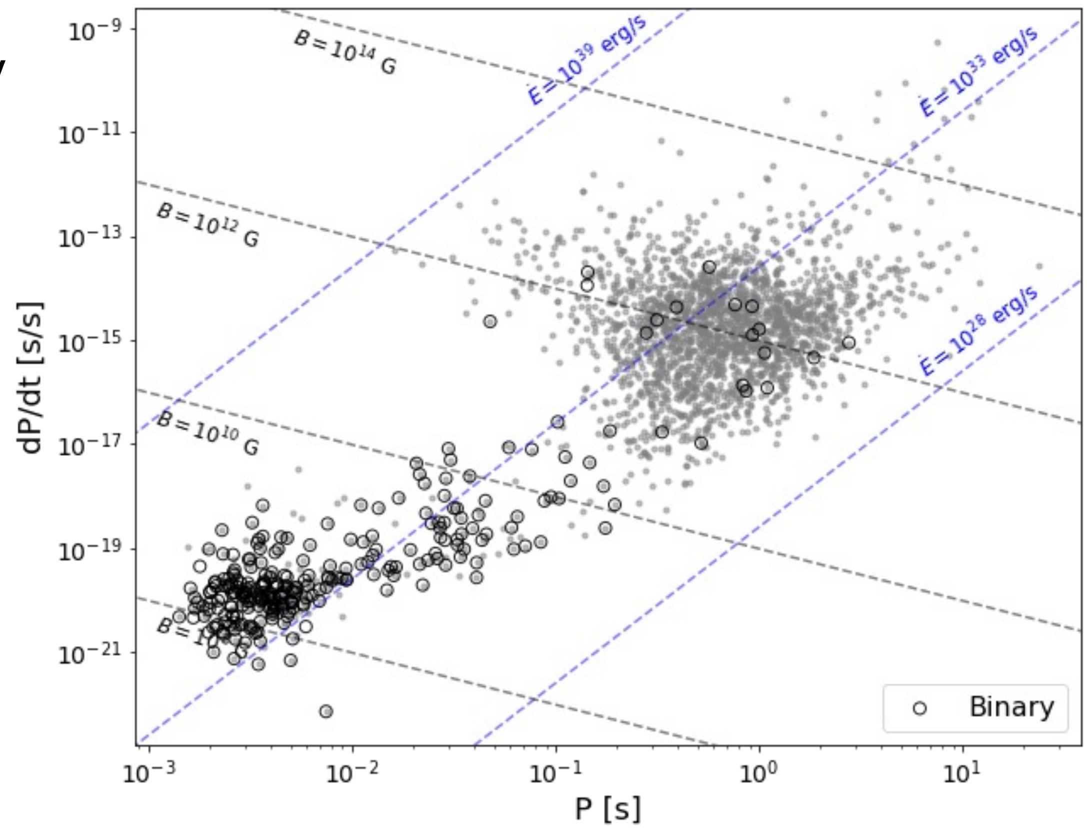


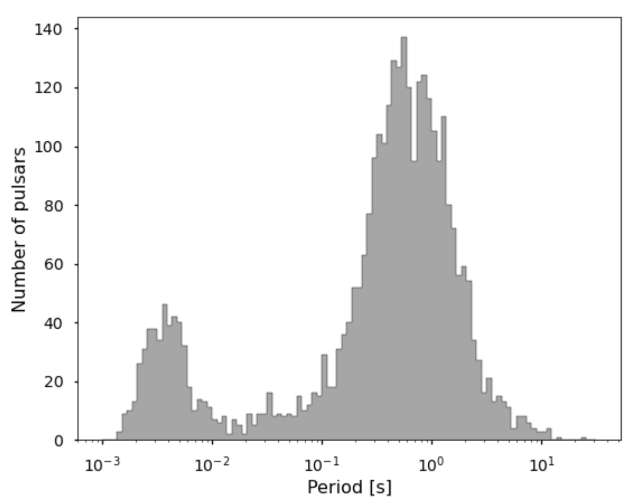


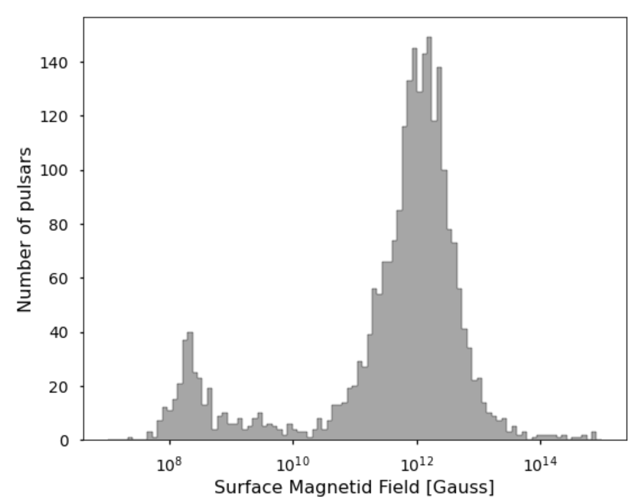
P – Pdot plot

- **~3000** radio pulsars known today
- Can an be grouped in:
  - **Normal** (young): B~10^{12}G
  - **MS** (old): B~10^8 G

- Just from P and Pdot we can estimate important quantities:
  - Spin-down power
  - Magnetic field
  - Age







Basic quantities inferred from P, Pdot

Spin-down power

- Initial parameters:
  - $M \approx 1.4\ M_{\odot}$
  - R ≈ 10 Km
  - Angular velocity: $\Omega = \frac{2\pi}{P}$
  - Moment of inertia for a sphere with radius R, mass M, and uniform density: $I = \frac{2MR^2}{5} \approx 10^{45}\ g \cdot cm^2$

- Rotational energy: $E_{rot} = \frac{1}{2} I\Omega^2 = \frac{2\pi^2 I}{P^2}$

- The rate at which the E_{rot} is changing is called **spin-down power:**

$$\boxed{\dot{E} \equiv -\frac{dE_{rot}}{dt} = \frac{4\pi^2 I\dot{P}}{P^3}} \quad (1)$$

- For Crab Pulsar, $P = 0.033\ s,\ \dot{P} = 10^{-12.4}$:

  E_{rot}(Crab) $\approx 2{\cdot}10^{49}\ erg$

  $\dot{E}$ (Crab) $\approx 4 \cdot 10^{38}\ erg/s$

Basic quantities inferred from P, Pdot

Magnetic field strength at stellar surface

- Initial parameters:
  - α: inclination angle. It is unknown.
- Power radiated by a rotating uniformly magnetized sphere with radius R and surface magnetic field strength B:

$$P_{rad} = \frac{2}{3c^3}(BR^3 \sin\alpha)^2 \left(\frac{2\pi}{P}\right)^2$$

- Magnetic dipole radiation extracts rotational kinetic energy from the neutron star and causes the pulsar period to increase with time.
- Assuming that the pulsar spin down is solely due to the magnetic dipole radiation: $P_{rad} = -\dot{E}$, and using (1)

$$\boxed{B = \sqrt{\frac{3c^3 I}{8\pi^2 R^6}} \cdot \sqrt{P\dot{P}} \approx 3.2 \cdot 10^{19} \sqrt{P\dot{P}} \ \ (gauss, P\ in\ seconds)} \quad (2)$$

- For Crab Pulsar, $P = 0.033\ s,\ \ \dot{P} = 10^{-12.4}:\ \ B \approx 4 \cdot 10^{12}\ gauss$

Basic quantities inferred from P, Pdot

Pulsar age

- Can be obtain it by integrating $P\dot{P}$, from pulsar's birth t=0, to today:

$$\int_0^\tau (P\dot{P})dt = \int_0^\tau \left(P\frac{dP}{dt}\right)dt = \int_{P_0}^{P} PdP = \frac{P^2 - P_0^2}{2}$$

  - Inverting (2): $P\dot{P} \approx \frac{B^2}{3.2 \cdot 10^{19}}$

  Assuming B $\approx cte$ with time, then $P\dot{P} \approx cte$. This allows to calculate the left side of the integral:

$$\int_0^\tau (P\dot{P})dt = \tau\, P\dot{P}$$

  - Assuming that the initial period P_0 at $t = 0$ was much smaller than the current one, then, we can calculate the right side: $\frac{P^2 - P_0^2}{2} \approx \frac{P^2}{2}$

- So, we obtain:

$$\boxed{\tau = \frac{P}{2\dot{P}}}$$

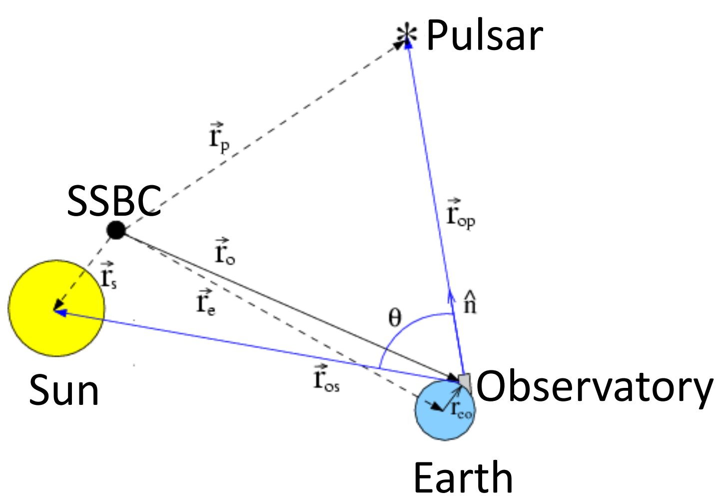
- For Crab Pulsar, $P = 0.033\ s,\ \dot{P} = 10^{-12.4}$: $\tau \approx 1300\ yr$ (similar to real one)

Pulsar timing

Barycenter correction

- **Goal**: Remove the effect on the arrival times t_{UTC}, of the relative movement pulsar-observatory

- **How:** Transforming measured arrival times to Solar System Barycenter (SSBC):



$$t_{bary} = t_{UTC} + \Delta_{prop} + \Delta_{Shapiro} + \Delta_{TDB-UTC}$$

$$\Delta_{prop} = \frac{\Delta r}{c} \approx \frac{\hat{n} \cdot \overrightarrow{r_0}}{c}$$

$$\Delta_{Shapiro} = \frac{2GM_{\odot}}{c^3} \ln(1 + \cos\theta)$$

$$\Delta_{TDB-UTC} = leapsec + 32.184s + \Delta_{TDB\_TDT}$$

Pulsar timing

Light curve (phaseogram)

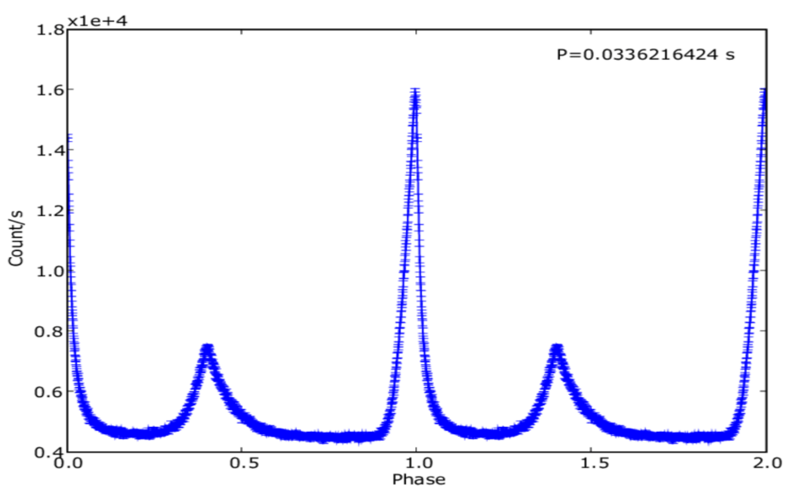
- Pulsar rotational frequency, F, is not constant but changes with time.
- Knowing the frequency at a reference time T_0 (epoch), F_0, and its derivatives (F_1, F_2,…), we can calculate F at any time t by a Taylor expansion:

$$F(t) = F_0 + F_1(t - T_0) + \frac{1}{2}F_2(t - T_0)^2 + \cdots$$

where t is the barycenter time.

- Integrating, and taking the fractional part, we get the rotational phase ϕ:

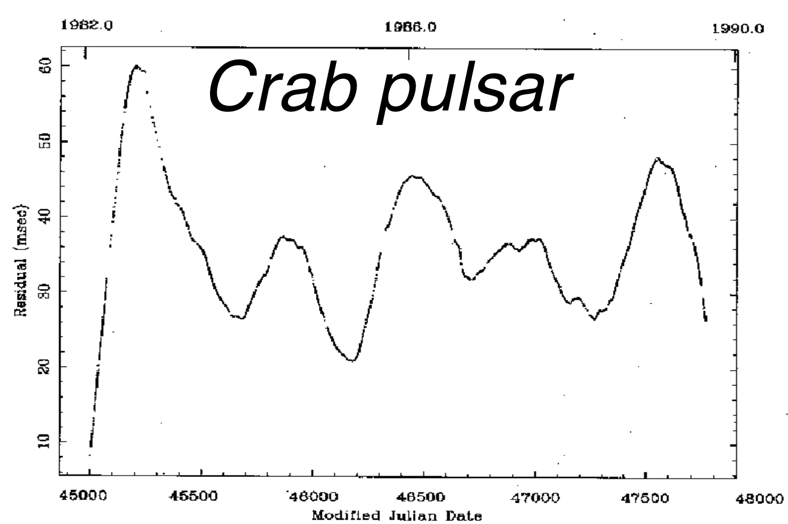
$$\boxed{\phi(t) = \phi_0 + F_1(t - T_0) + \frac{1}{2}F_2(t - T_0)^2 + \cdots}$$



Pulsar timing

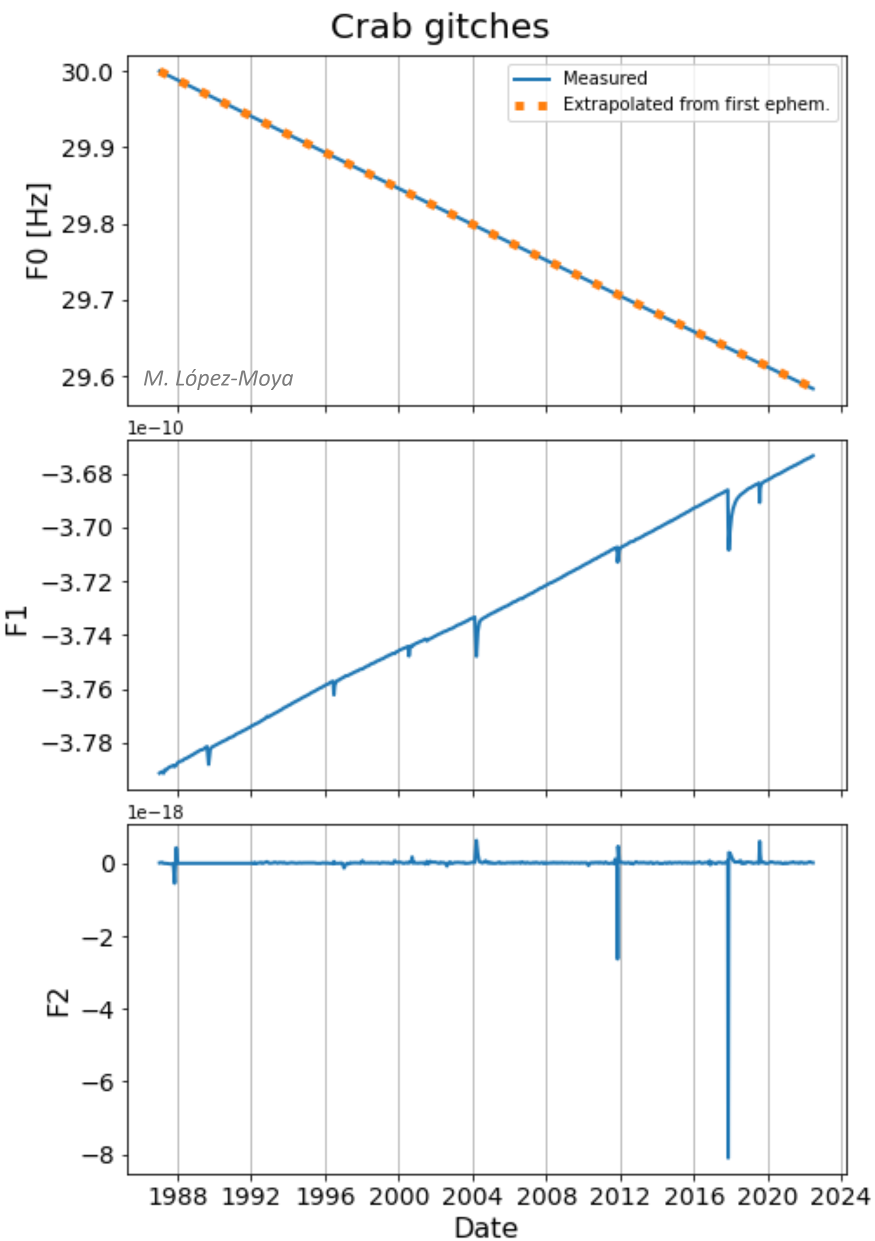
Pulsar ephemeris

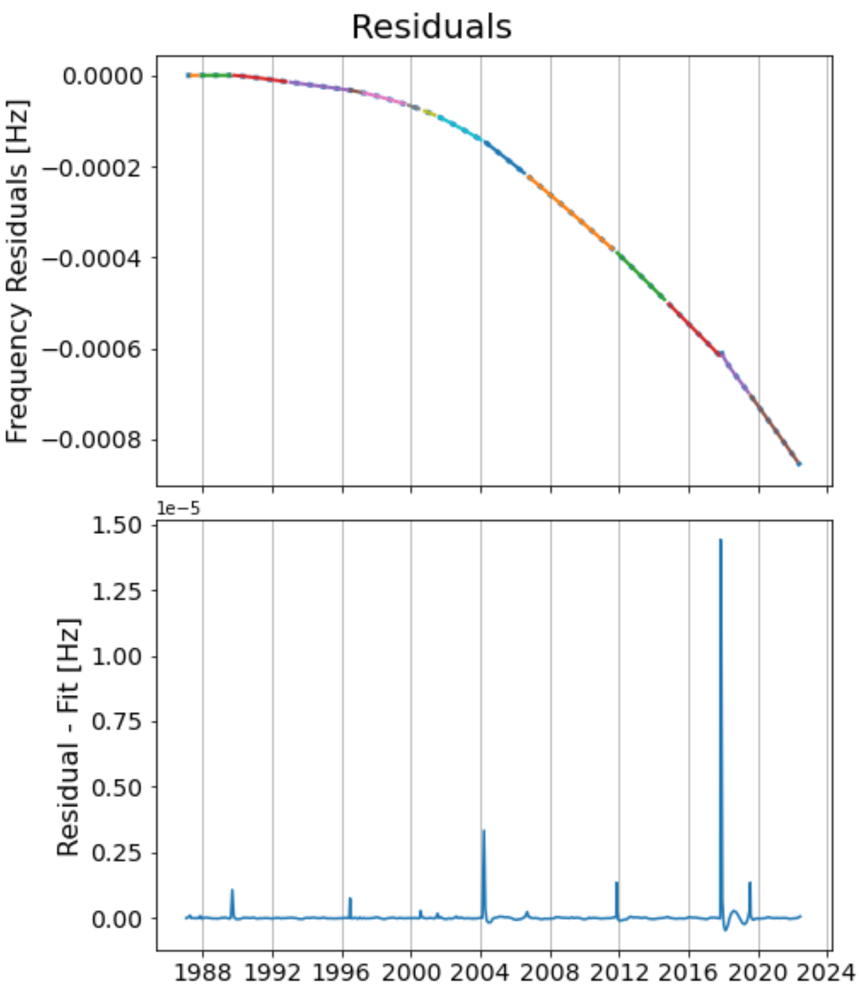
- For obtaining the LC we need to know first the pulsar ephemeris (F_0, F_1, F_2,…), or to get them by ourselves making a frequency scan.
  - Scans are computationally costly and requires high signal/noise ratio, so unpractical for Cherenkov telescopes.
- Ephemeris are taken from radio observations (e.g. Jodrell Bank observatory for Crab) or for strong pulsars from Fermi-LAT or X-ray data.
- Contemporaneous ephemeris are mandatory to avoid the effect of the irregularities in pulsar rotation: Timing noise & Glitches



Crab pulsar glitches

Data from Jodrell Bank Observatory





Pulsars at all wavelengths

Radio

- First discovered in radio in 1967
- **~3000** radio pulsars known today
- Can an be grouped in:
  - **Normal** (young): B~10^{12}G
  - **MS** (old): B~10^8 G

Optical and X-ray bands

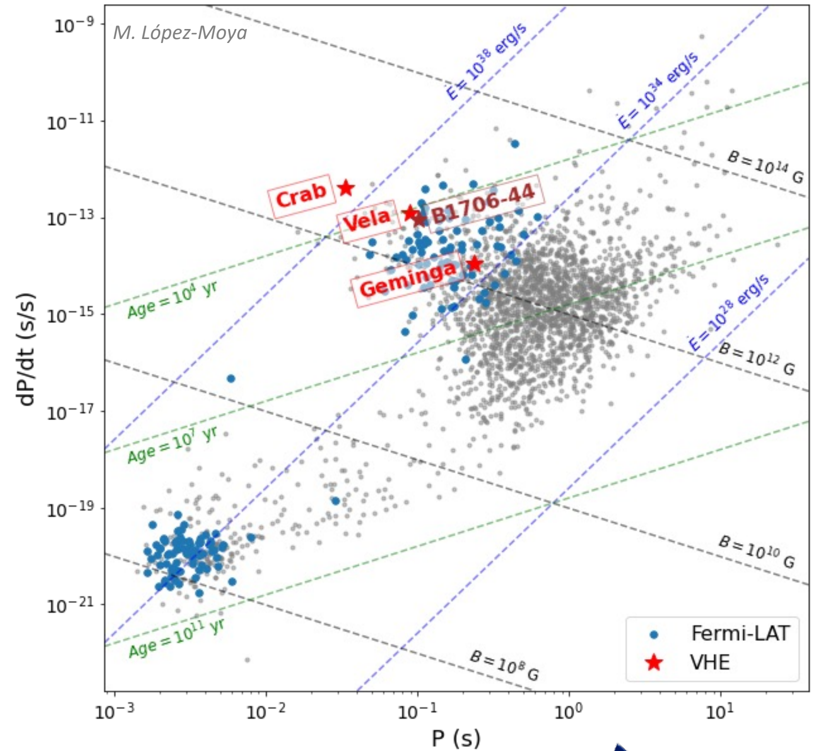
- Only ~**10** (Crab, Vela, Geminga,…) in the optical and **~100** at X-rays

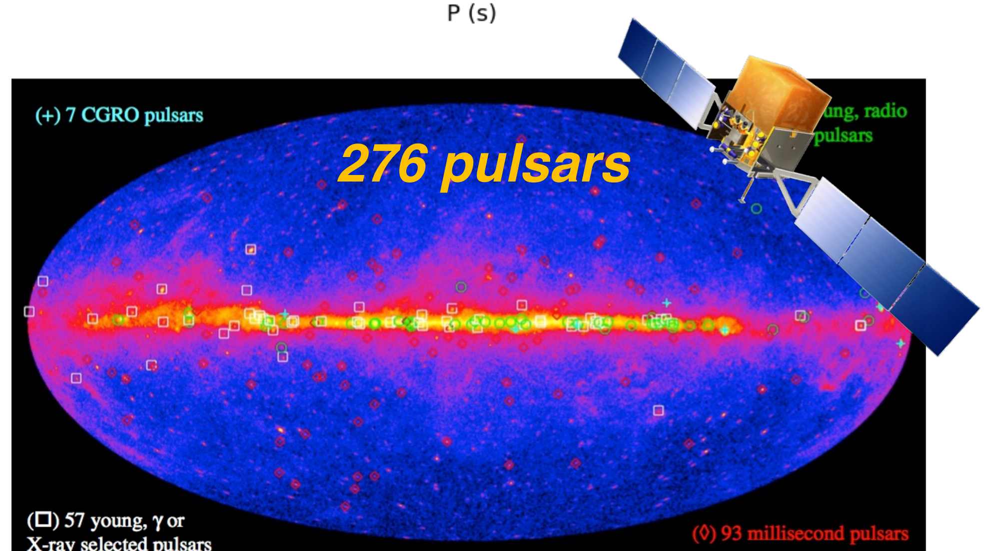
γ-Rays

- Only **7** seen by EGRET in the 90's
- **~280** detected by Fermi-LAT

VHE γ-Rays

- **3 (+1)** detected by MAGIC, HESS, VERITAS



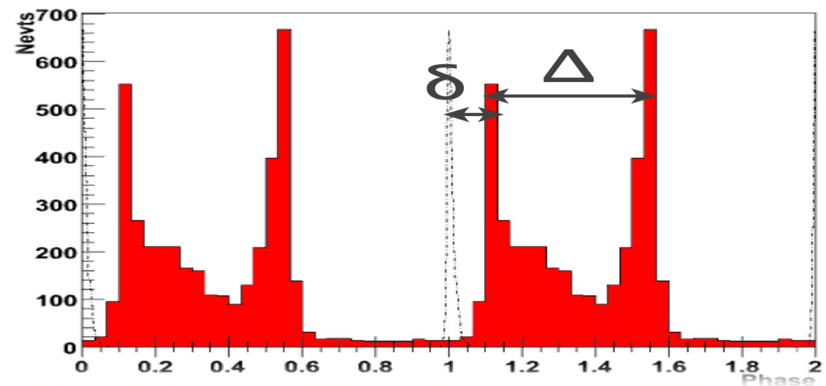


Most of Fermi galactic sources are pulsars

Fermi Pulsar Highlights

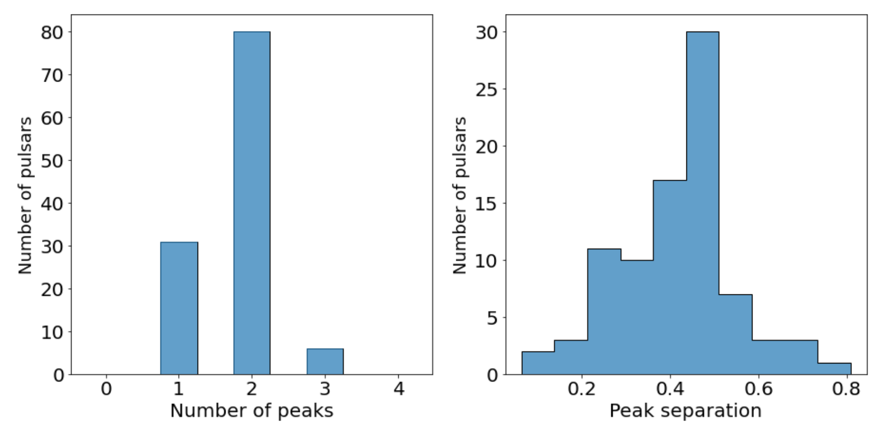
Discoveries

- **~280** pulsars
- Many in blind searches
- A whole population of MS pulsars
- Many Geminga-like pulsars



Light curve

- Typically **2 peaks**
- Separated by ~0.4-0.5 rotations



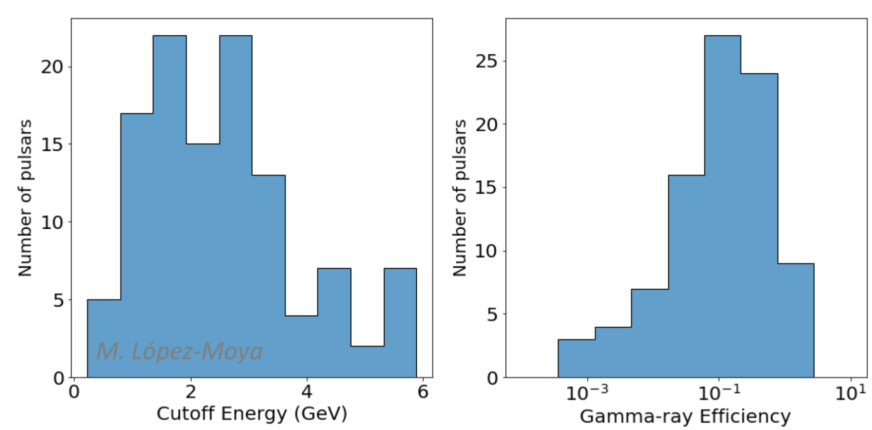
Data from Fermi-LAT 2nd Pulsar Catalog

Spectra

- Well fitted by PL + **sub-exp. Cutoff**
- **Cut-off energies < 10 GeV**

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

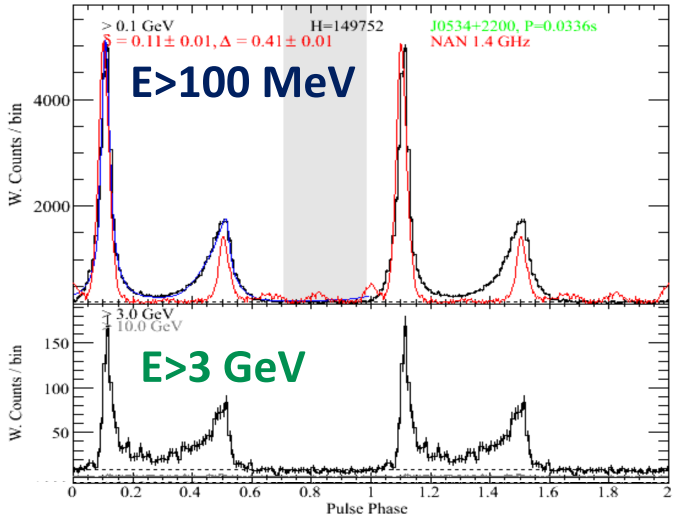
b=1: exp.
b<1: sub-exp.
b>1: super-exp.

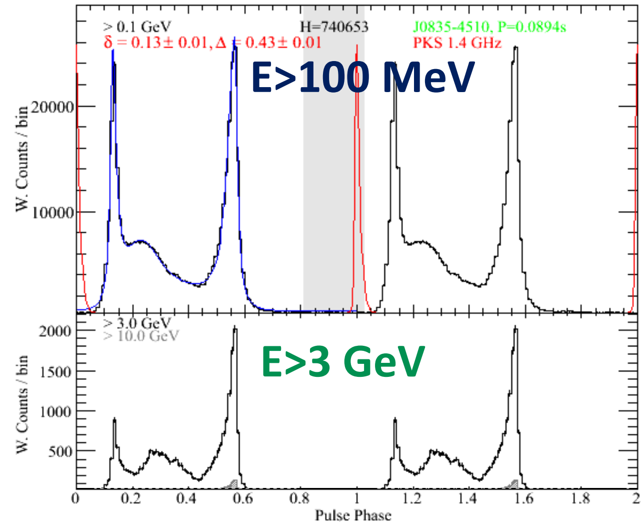


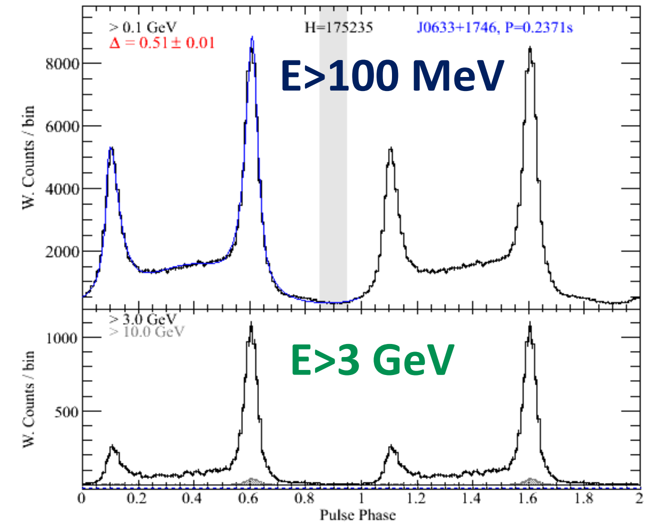
Favours Outer Gap model

The brightest Fermi pulsars (2PC)

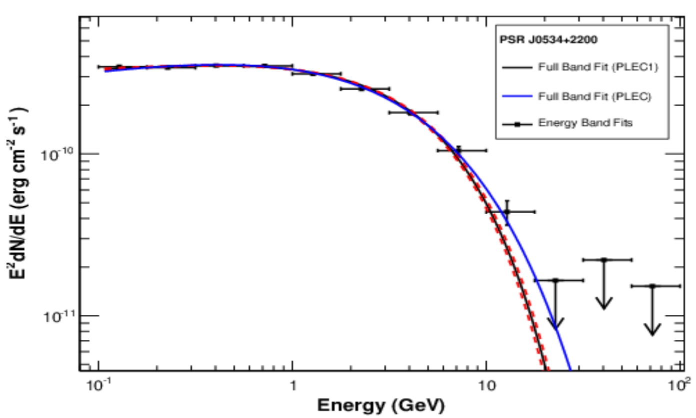
Crab | Vela | Geminga

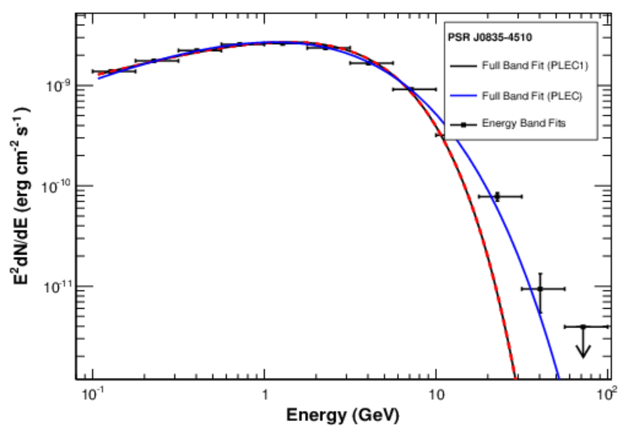


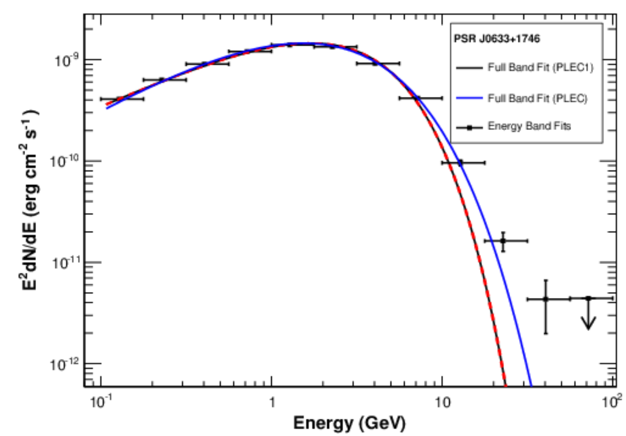




Two peaks per rotation ➜ But at HE 1st peak starts to dissapear







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

How do we explain light curves & pulsar cutoffs?

Pulsar models

Where do γ-rays come from?

Accelerated particles emit via synchro-curvature radiation

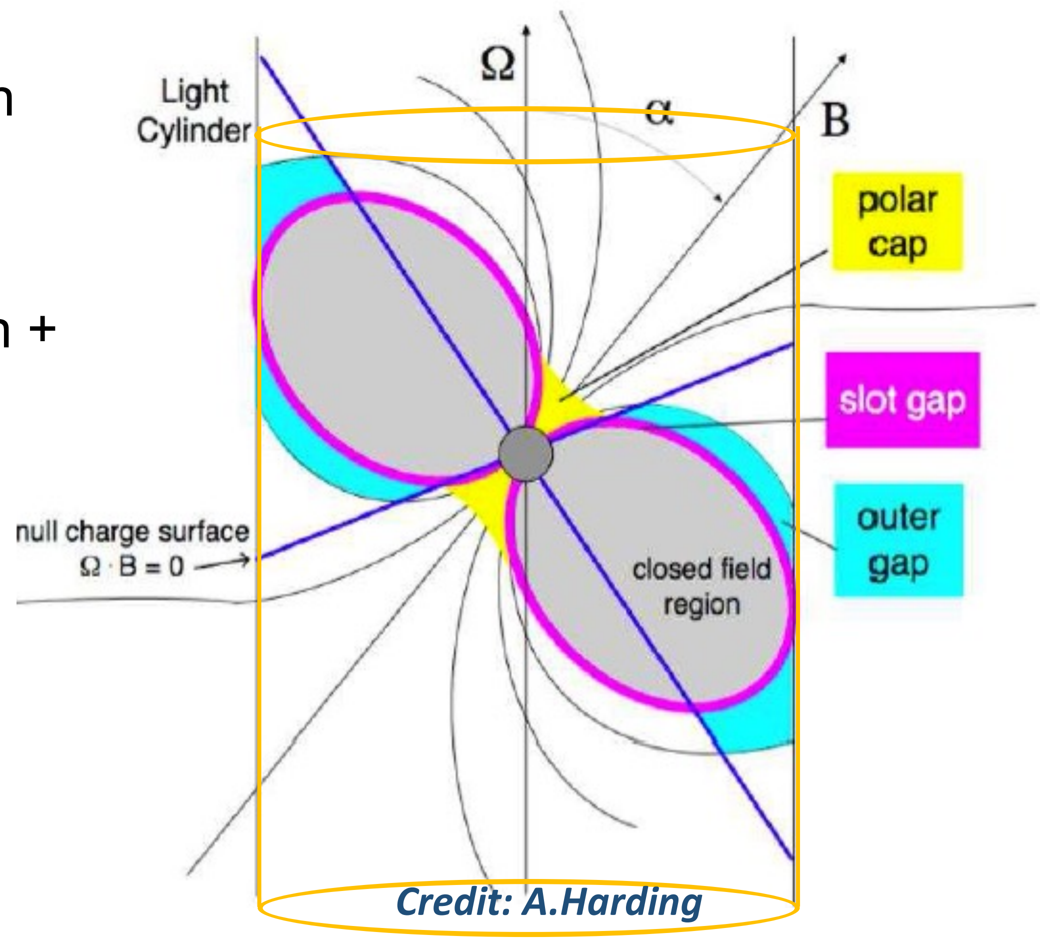
Emitting regions

- Models explain observed γ-ray emission assuming different emitting regions:
  - Within magnetosphere: **PC**, **OG**, **SG**
  - Outside magnetosphere: acceleration + radiation in Wind zone

Light curves depends on **geometry**:

- Rotational - magnetic axes angle α and viewing angle
- Explains number peaks & separation

Spectrum depends on the **physics** of emitting region

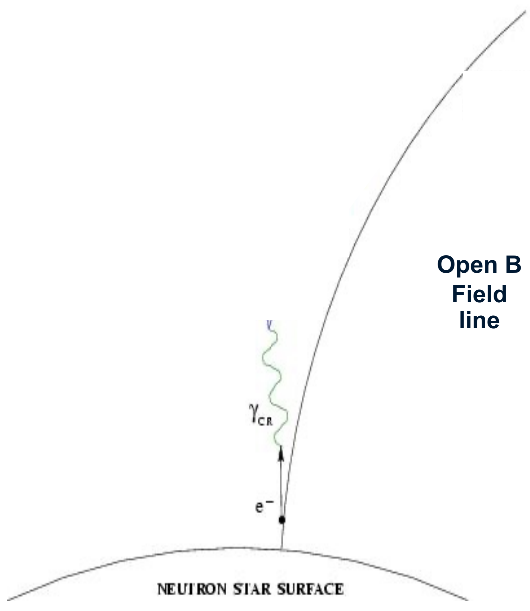


Credit: A.Harding

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

Understanding γ-ray emission

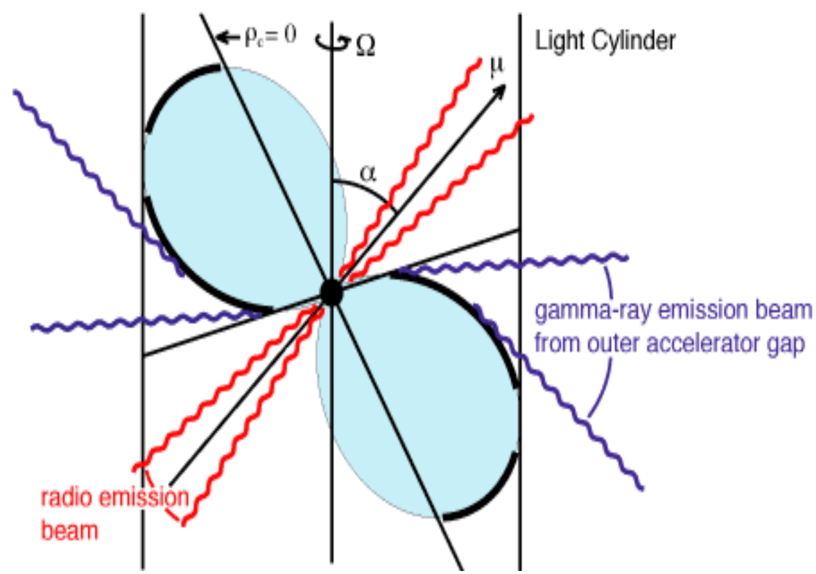
Polar Cap Model



- Particles accelerated along B-field lines emit γ-rays via Curvature radiation
- γ-rays interact with B-field, via Magnetic pair production: $\boxed{\gamma + B \rightarrow e^+ + e^-}$
- X-section: $\sigma_{pp} \propto B_\perp \cdot \exp\left(-\frac{1}{E_\gamma B_\perp}\right)$
- Electromagnetic cascade develops. Only γ's surviving pair-production escape

Predicts super-exp. cutoff @ few GeV

Outer Gap model



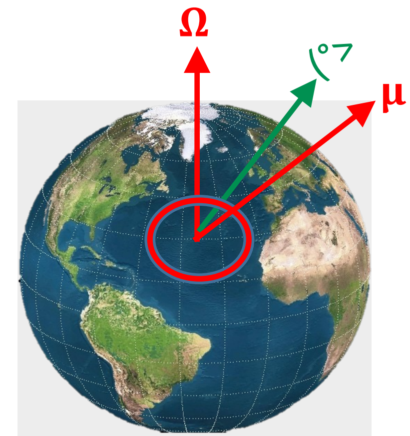
- Particles accelerated along B-field lines emit γ-rays via Curvature radiation
- B not strong enough for pair-production
- But γ-rays can interact with ambient X-rays or IR photons: $\boxed{\gamma + \gamma \rightarrow e^+ + e^-}$
- Electromagnetic cascade develops. Only γ's surviving pair-production escape

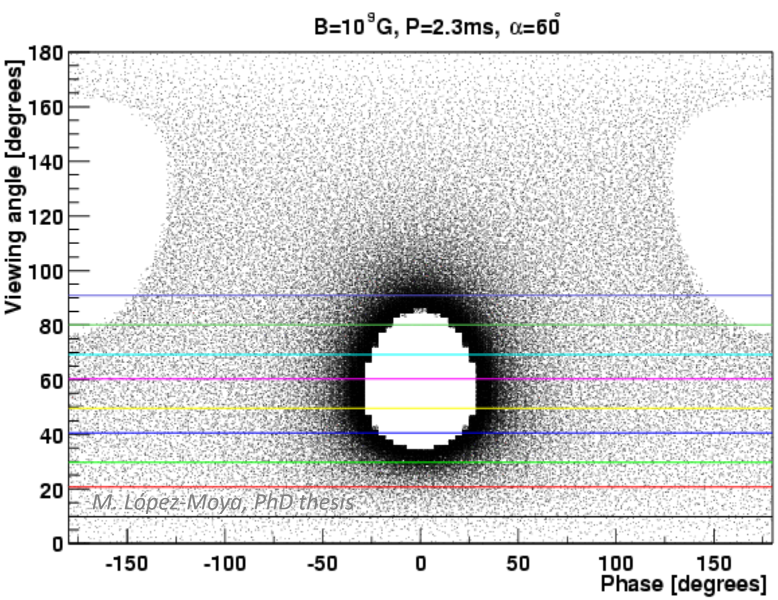
Predicts softer exp. cutoff @ few GeV

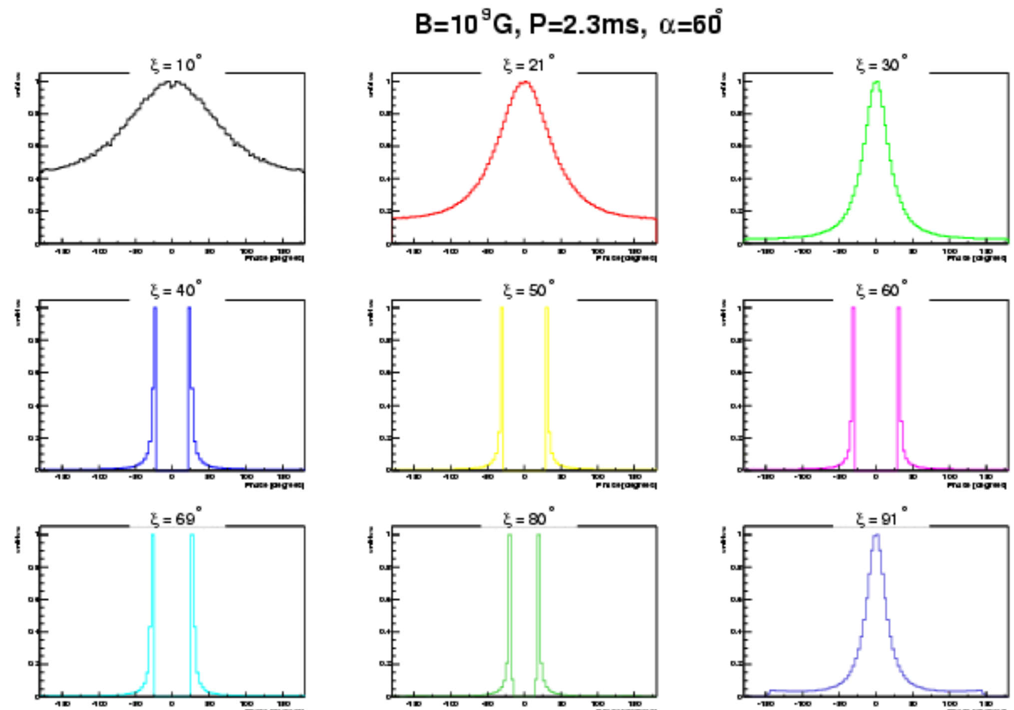
Understanding light curves

Light curves depends on:

- Pulsar geometry: Rotational - magnetic axes angle α, emitting region size, …
- Observer's viewing angle



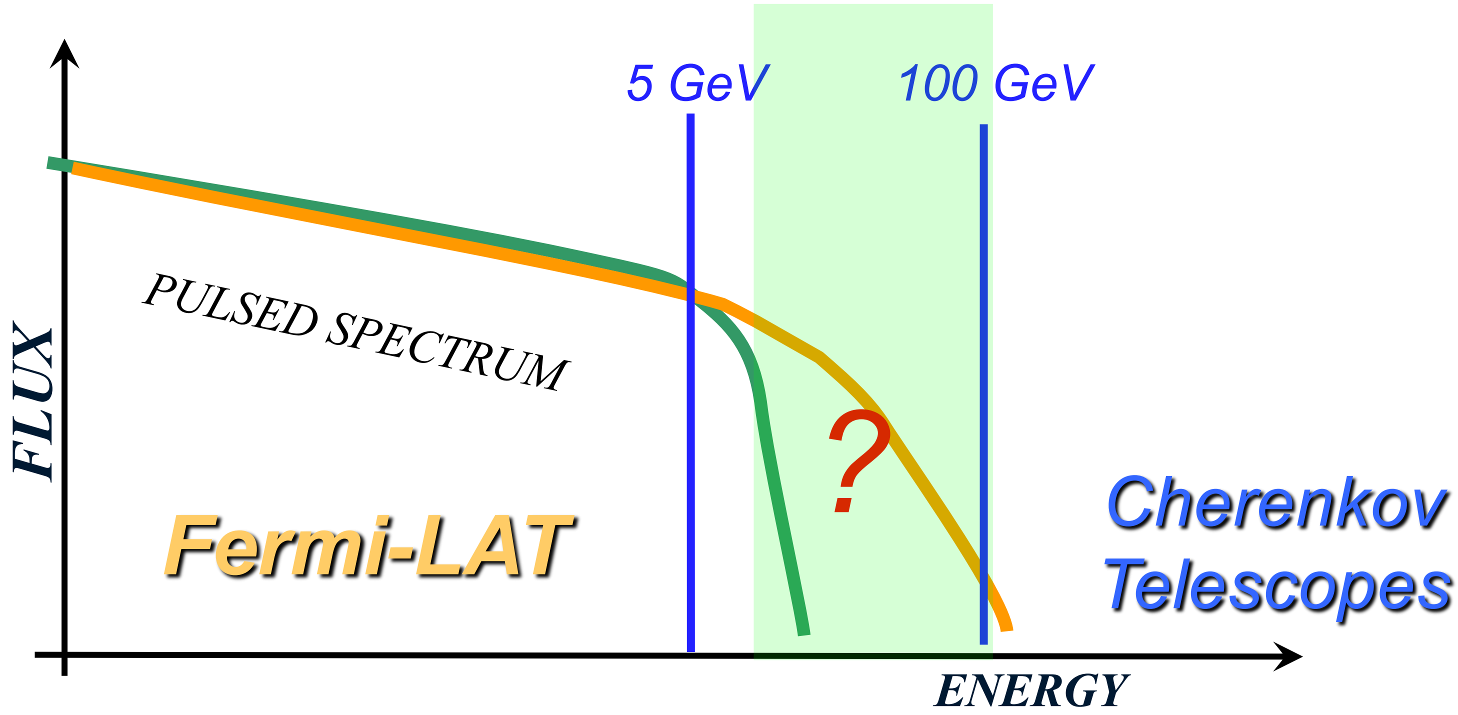




Different observers would see completely different light curves for the same pulsar

Pulsars at VHE?

- According to theoretical models and space observations, most pulsars disappear at few GeV, so very challenging for CTs.



In fact, it took many years to achieve the first detection…

Results from the observations of pulsars from ground

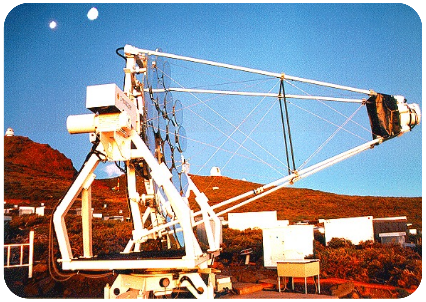
First attempts

Solar plants: 90's

- No signal found

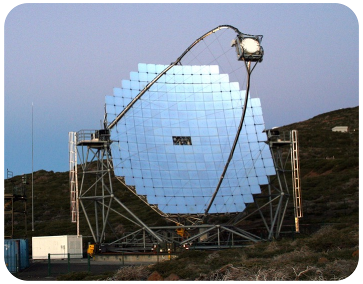
HEGRA: 90's

- No signal found



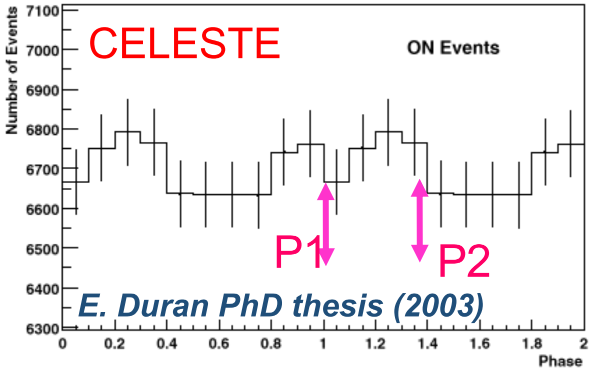
MAGIC, H.E.S.S., VERITAS

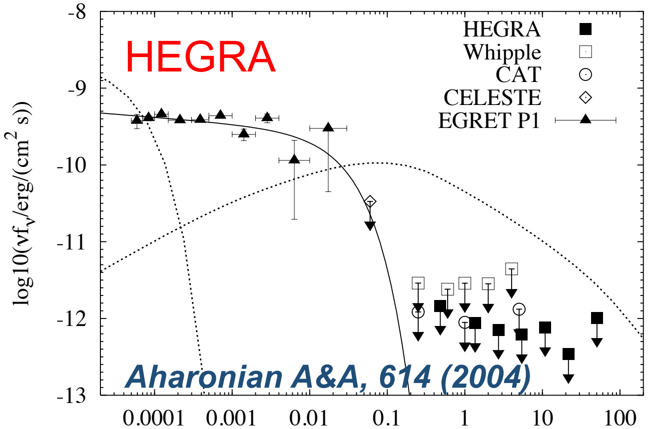
- They tried from the beginning of their operations. First attempts unsuccessful

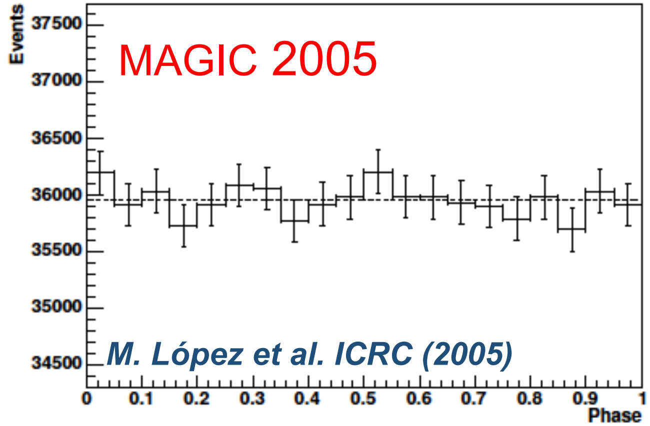


Energy threshold still not low enough
→ New hardware developments needed

Crab pulsar







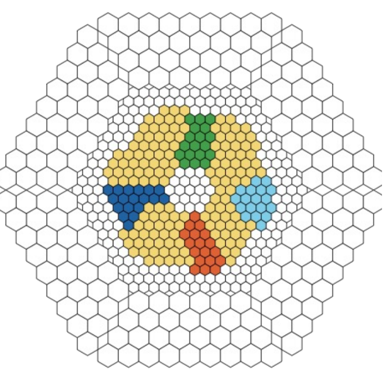
SumTrigger-I (2007-2009)

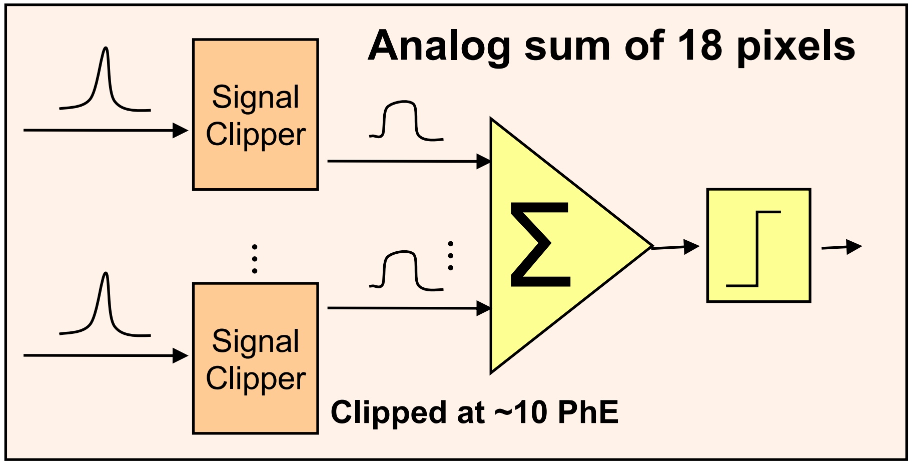
A new Trigger concept

Idea: Add analog signals from a patch of PMTs & discriminate on summed signal

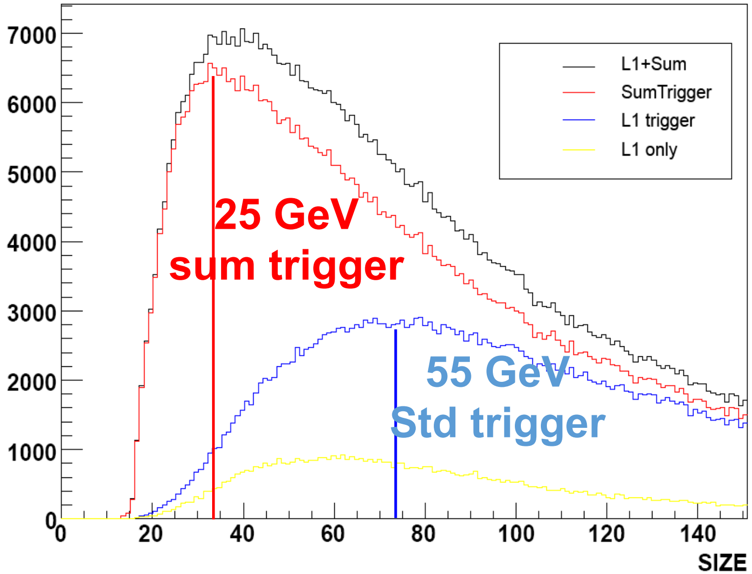
- Increased signal to noise ratio compared to a digital trigger

- Problem: Large amplitude from Afterpulses
  - Solution: Clipping signal
- Implemented in 2007





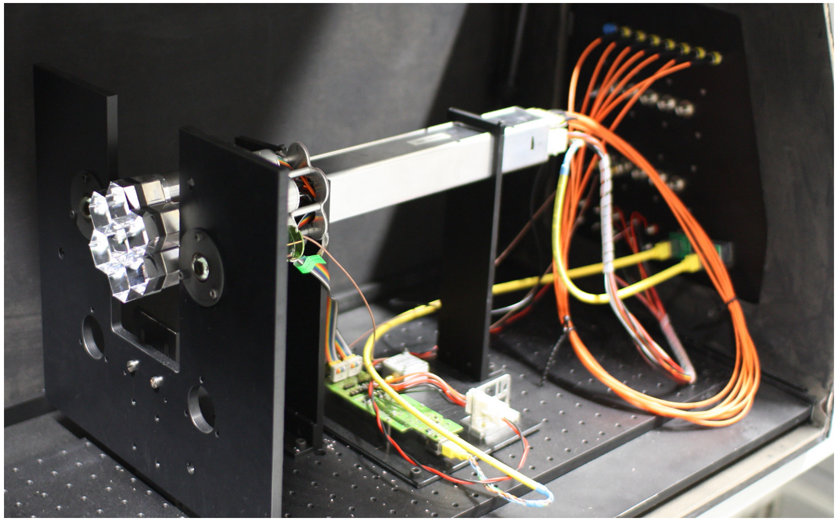
Mono SumTrigger

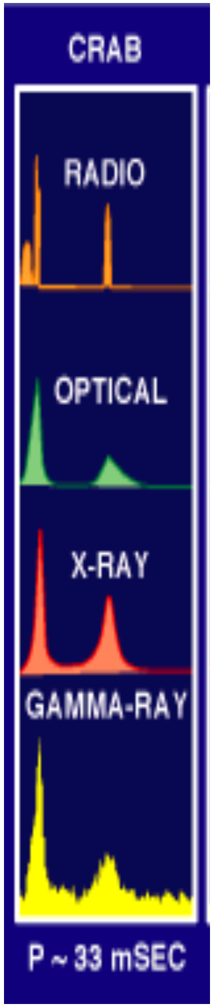


25 GeV trigger threshold:
a break-through for ground-based γ-ray astronomy

MAGIC Central Pixels

- Modified central pixel of the cameras 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
- Since 2020, both telescopes has its own central pixel
- Crab pulsar sensitivity: **5σ in ~5 sec.**





Allows simultaneous γ and optical observations

MAGIC Central Pixels

- Modified central pixel of the cameras to detect fast optical pulses: 1 Hz to kHz
  - Digitalized by dedicated ADC @ 10 kHZ
  - Allows to check Timing System and Pulsar Software
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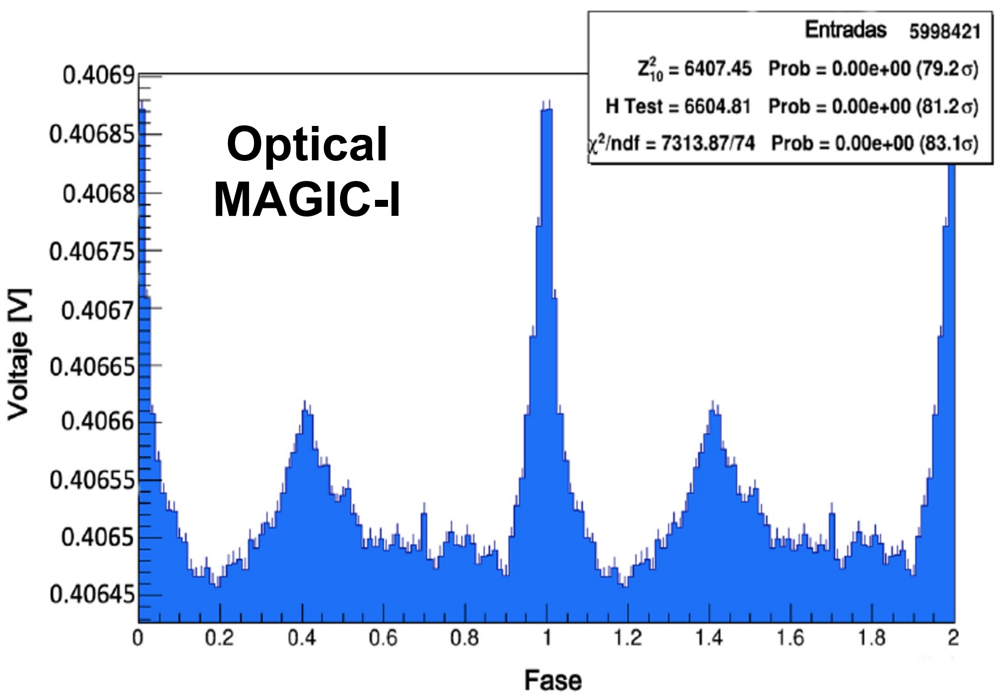
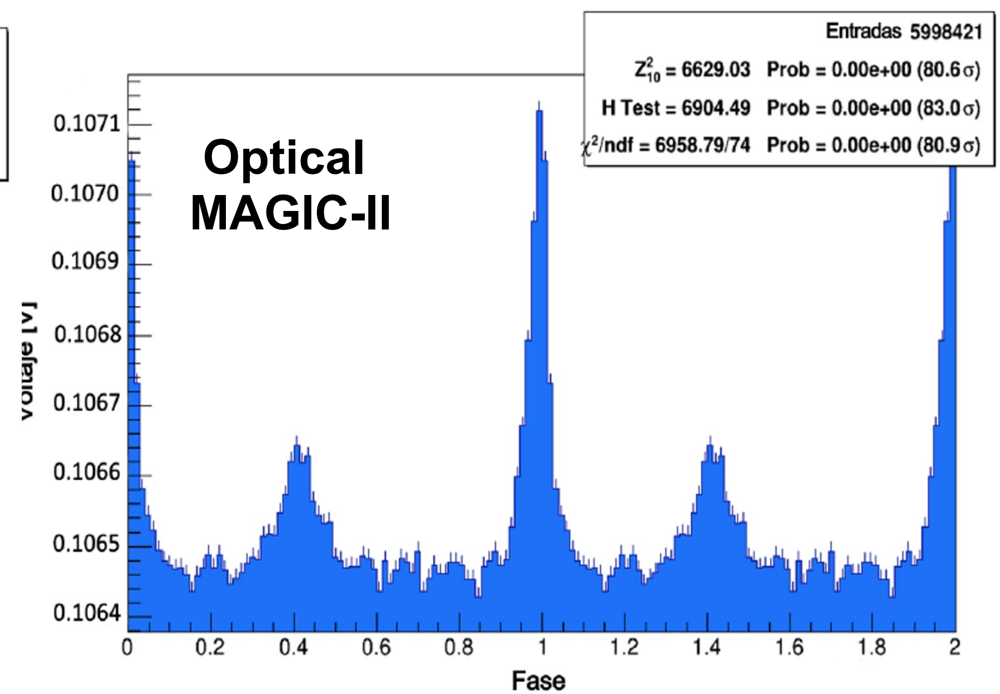




Crab: The first pulsar detected @ VHE

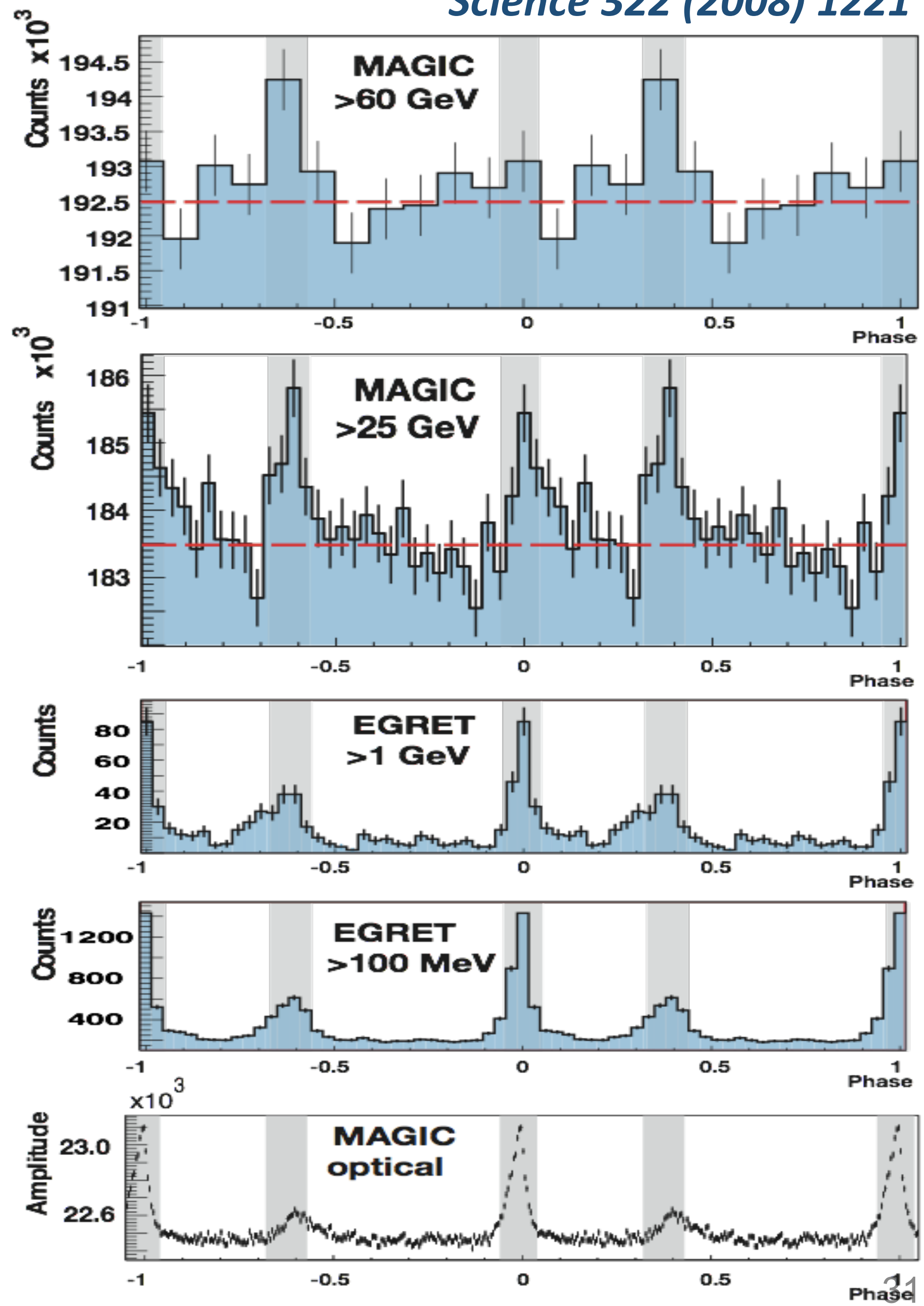
First pulsar detected @ VHE: MAGIC (2008)

Science 322 (2008) 1221

Detection above 25 GeV

- **22 h** with mono MAGIC SumTrigger
- Clear detection: **6.4σ**
- Both, **P1** & **P2** seen !
- Pulses in phase with EGRET
- Hint of P2 > 60 GeV

Polar Cap model excluded

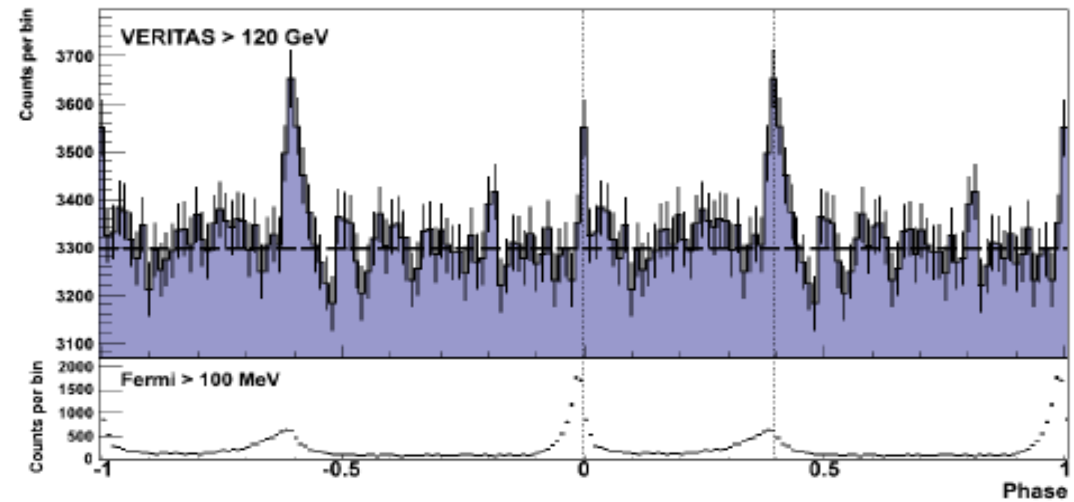


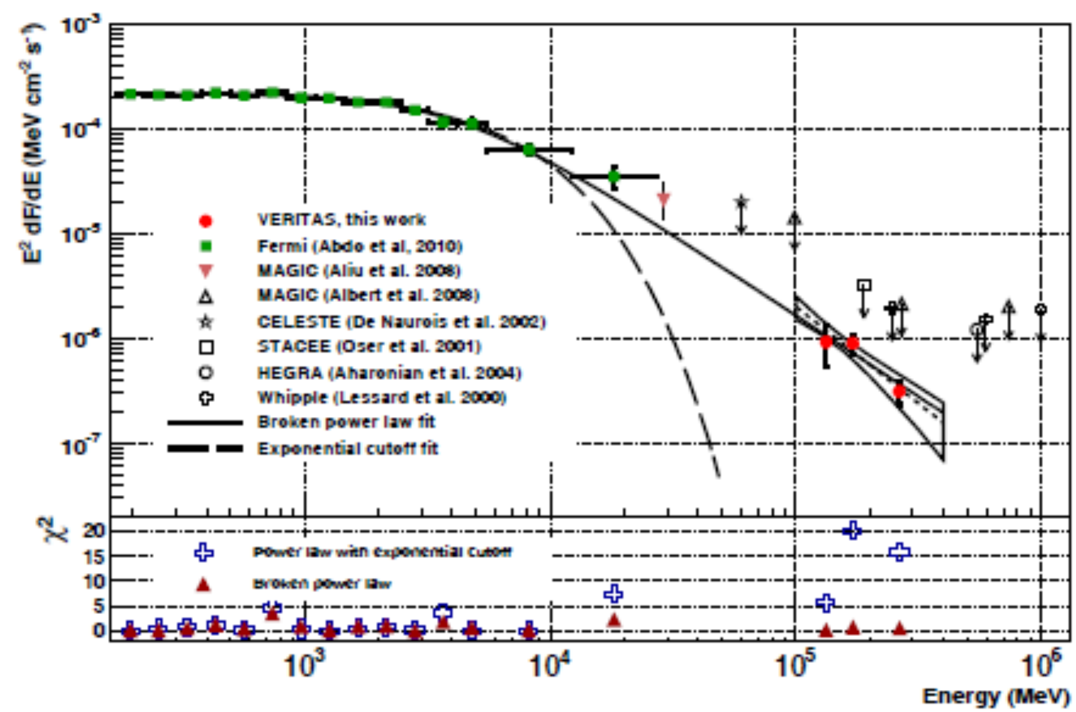
Crab: VERITAS detection and first spectrum

Science 334, 69, 2011

Spectra measured beyond 100 GeV

- **~100 h** between **2007 – 2011**
- Spectra extending as power-law from 100 to 400 GeV, far beyond the expected cutoff



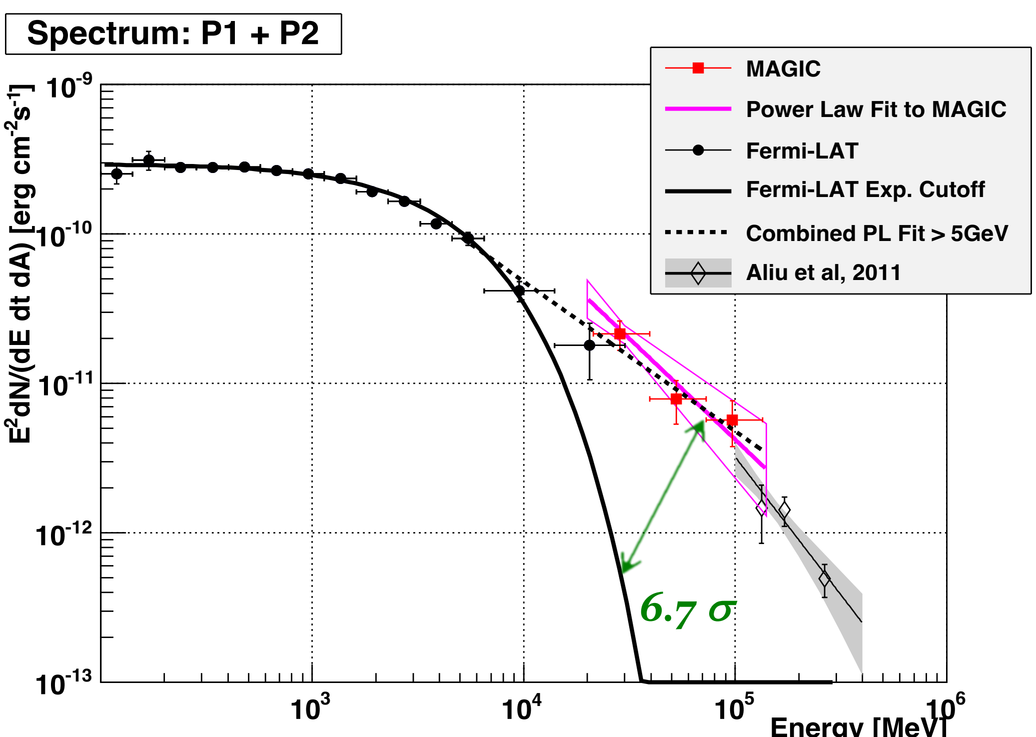


Crab: MAGIC mono observations

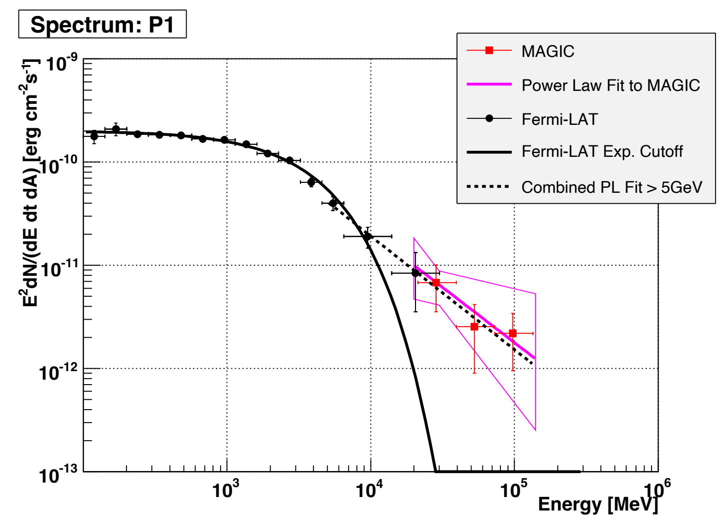
Phase-resolved spectra up to 100 GeV

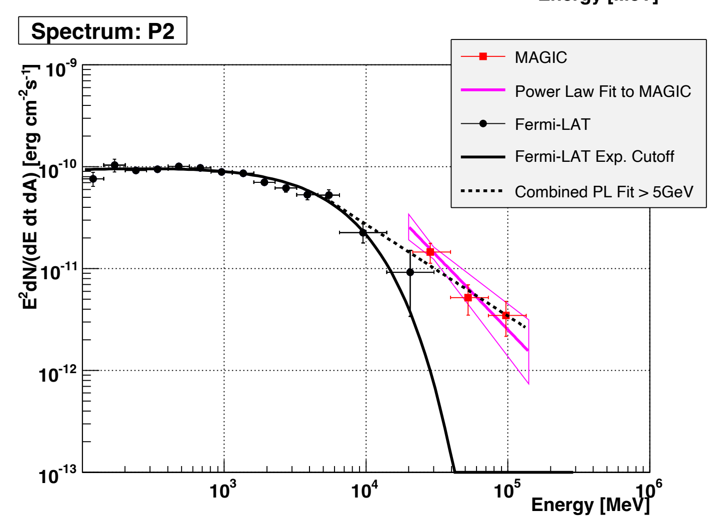
- **~60h** of SumTrigger observations between **2007 - 2009**
- Obtained first VHE resolved Crab pulsar spectra
- Each peak follows Power Laws

Spectral cutoff excluded



Aleksic et al., ApJ 742, 42, 2011



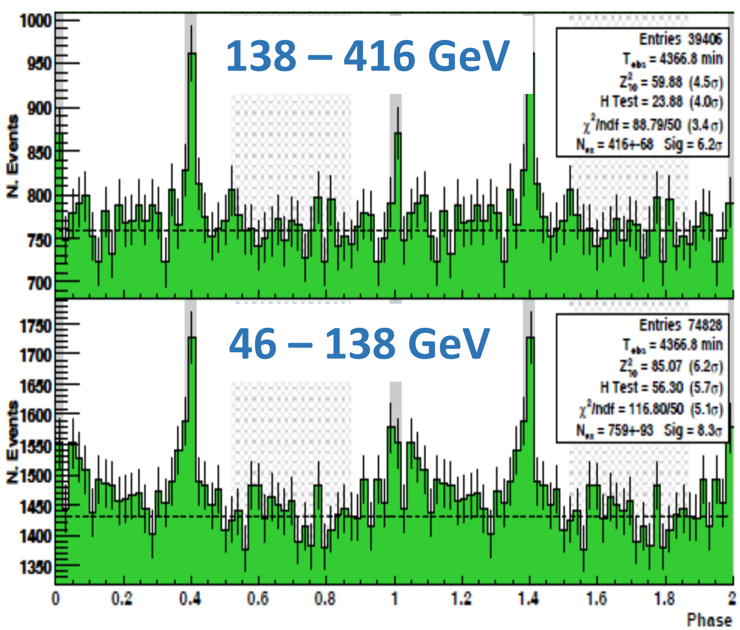


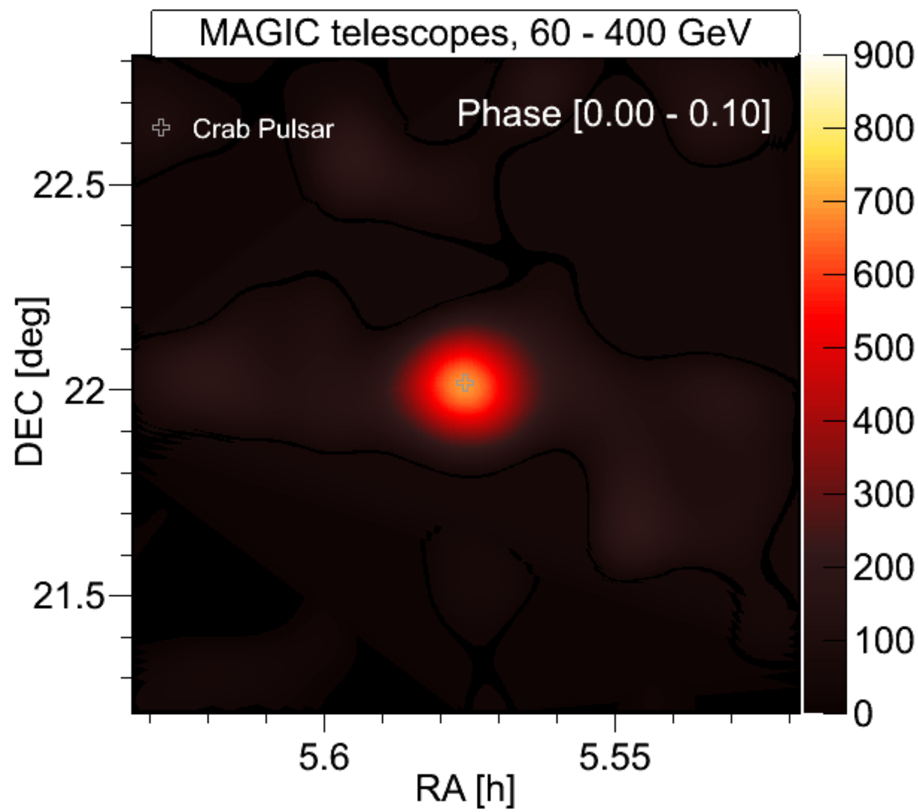
Crab: MAGIC stereo observations

Light curve morphology up to 400 GeV

- **~70 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





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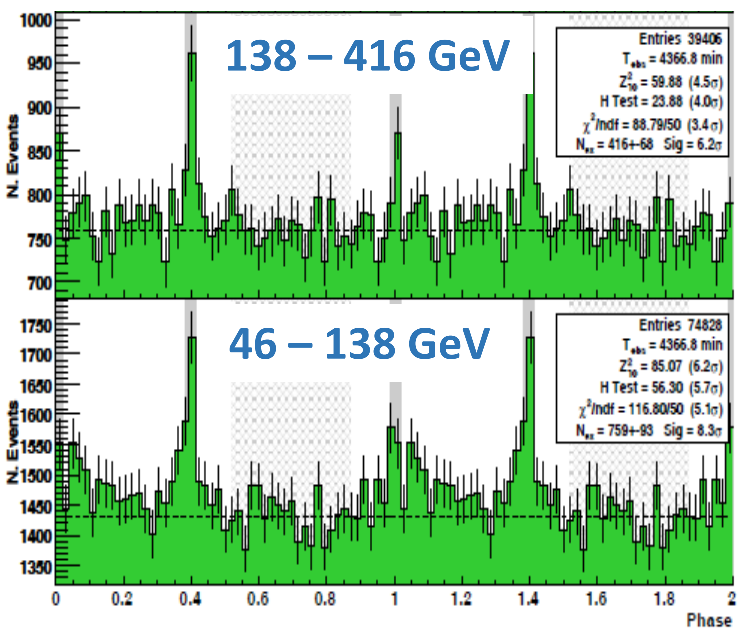
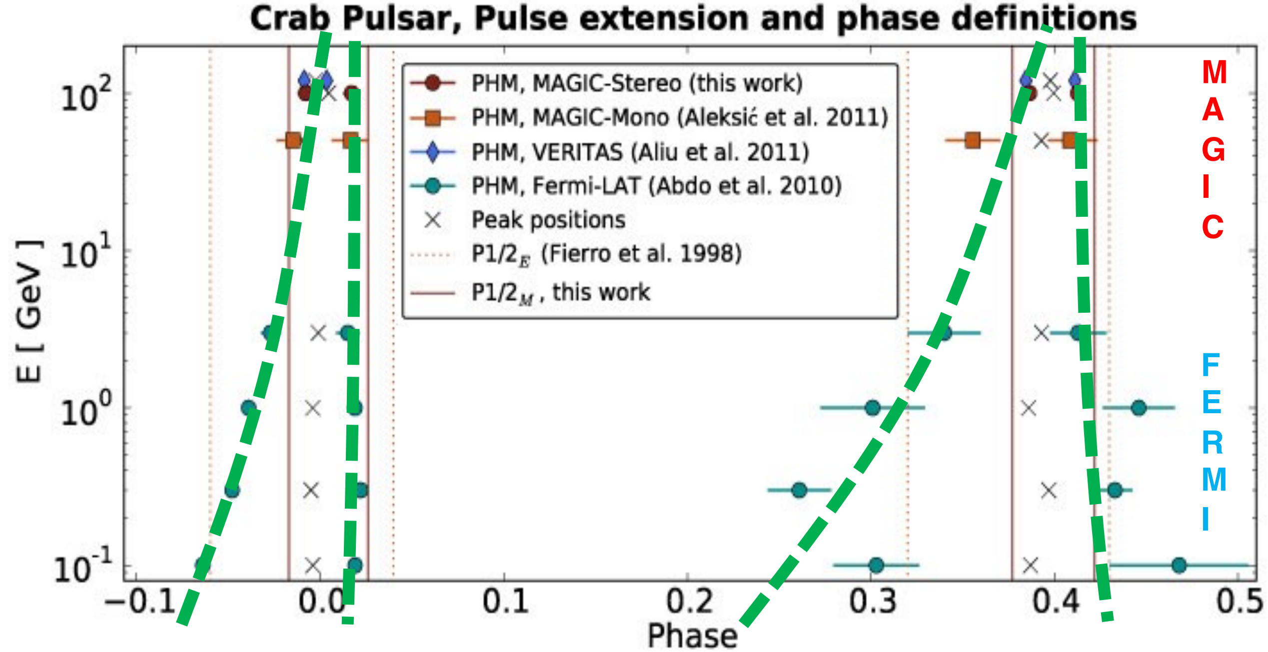




MAGIC TeV Crab pulsations

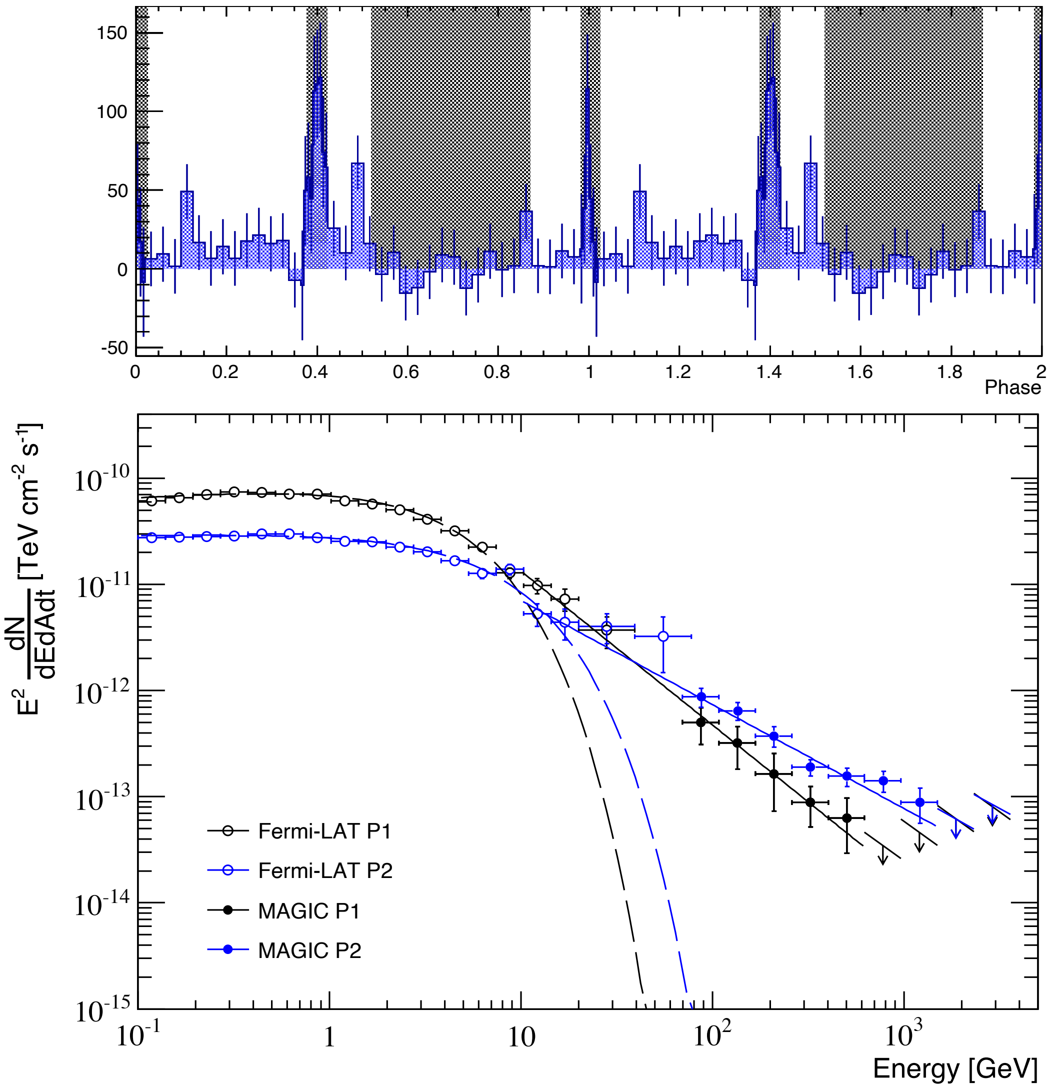
Up to which energy does the Crab pulsate?

Detection up to 1.5 TeV

- **320 h**: Used **8 years** (**2007-2014**) of MAGIC archive data
- Pulsation detected above 400 GeV
  - **P1** detected up to **0.6 TeV**
  - **P2** detected up to **1.5 TeV**
- Spectra of both peaks extending as power-laws:

Spectral indexes
P1: Γ = -3.5 ±0.8
P2: Γ = -3.0 ±0.3

MAGIC, E > 400 GeV



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

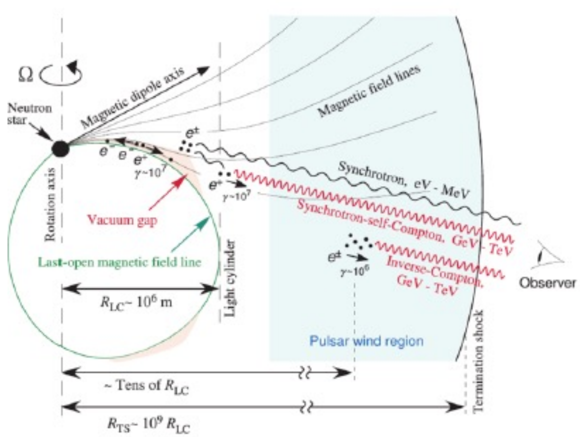
Crab: Implications of TeV emission

Constraining the emission site

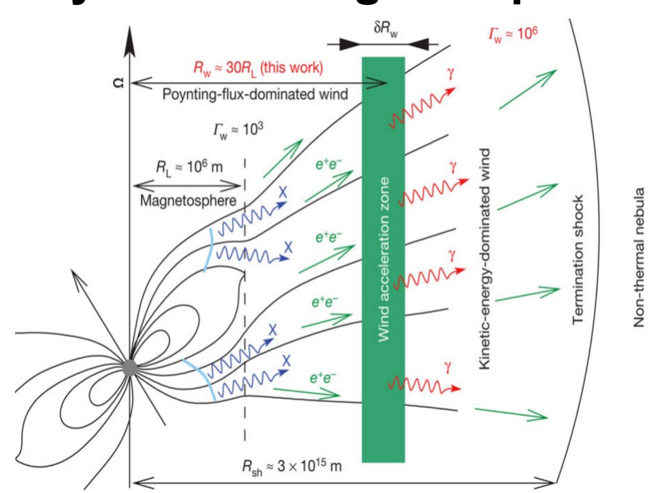
- Detection of TeV photons implies they are emitted by e^- with $\Gamma > 5 \times 10^6$
- Impossible to reach via synchro-curvature mechanism (would require unrealistic curvature radii, $R_C \sim 200\ R_{LC}$)
  → **Synchrotron-curvature ruled out**
  → Only reasonable possibility is **IC** on soft photon fields

But Where ?

Within the magnetosphere?



Beyond the magnetosphere?



➔ **Most likely inside, in the outer gap via IC**

But no model can fully explain TeV pulsations

Crab: 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.

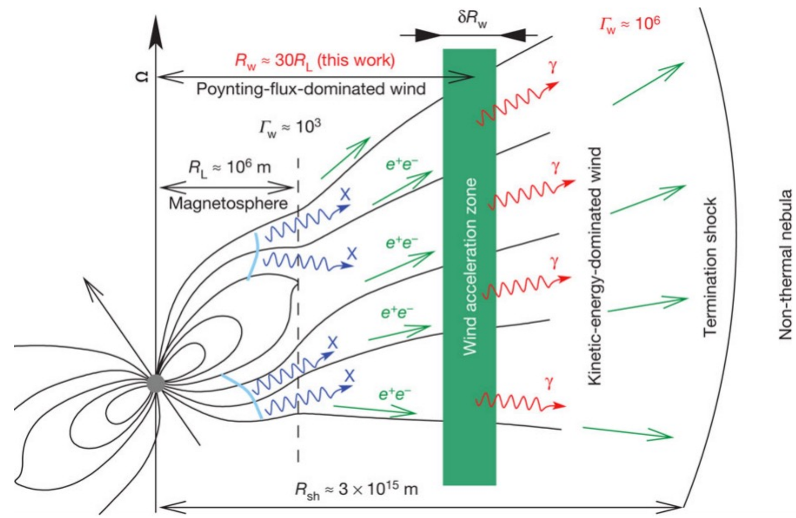
Possible solution

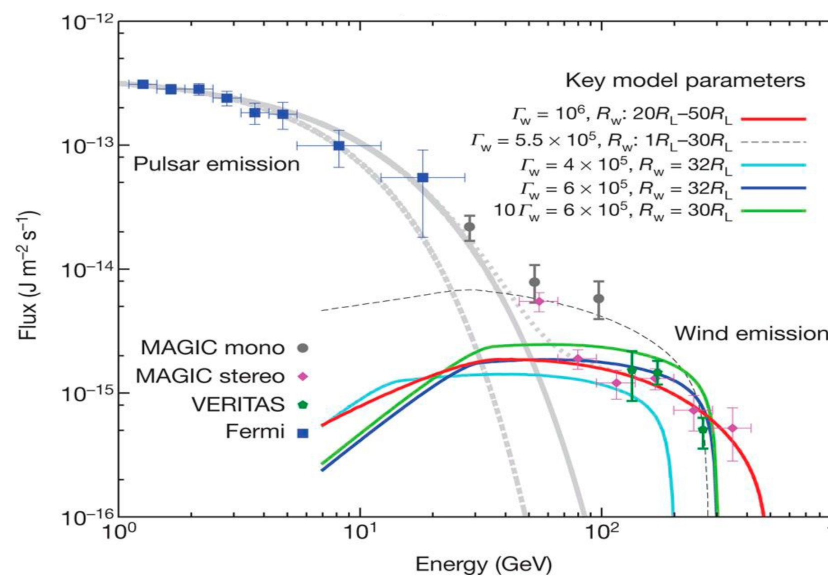
- Extend the acceleration region up to a much larger radius
- But at larger distances, broadening of peaks
  - ➜ Could not reproduce LC

Incompatible with MAGIC results

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)

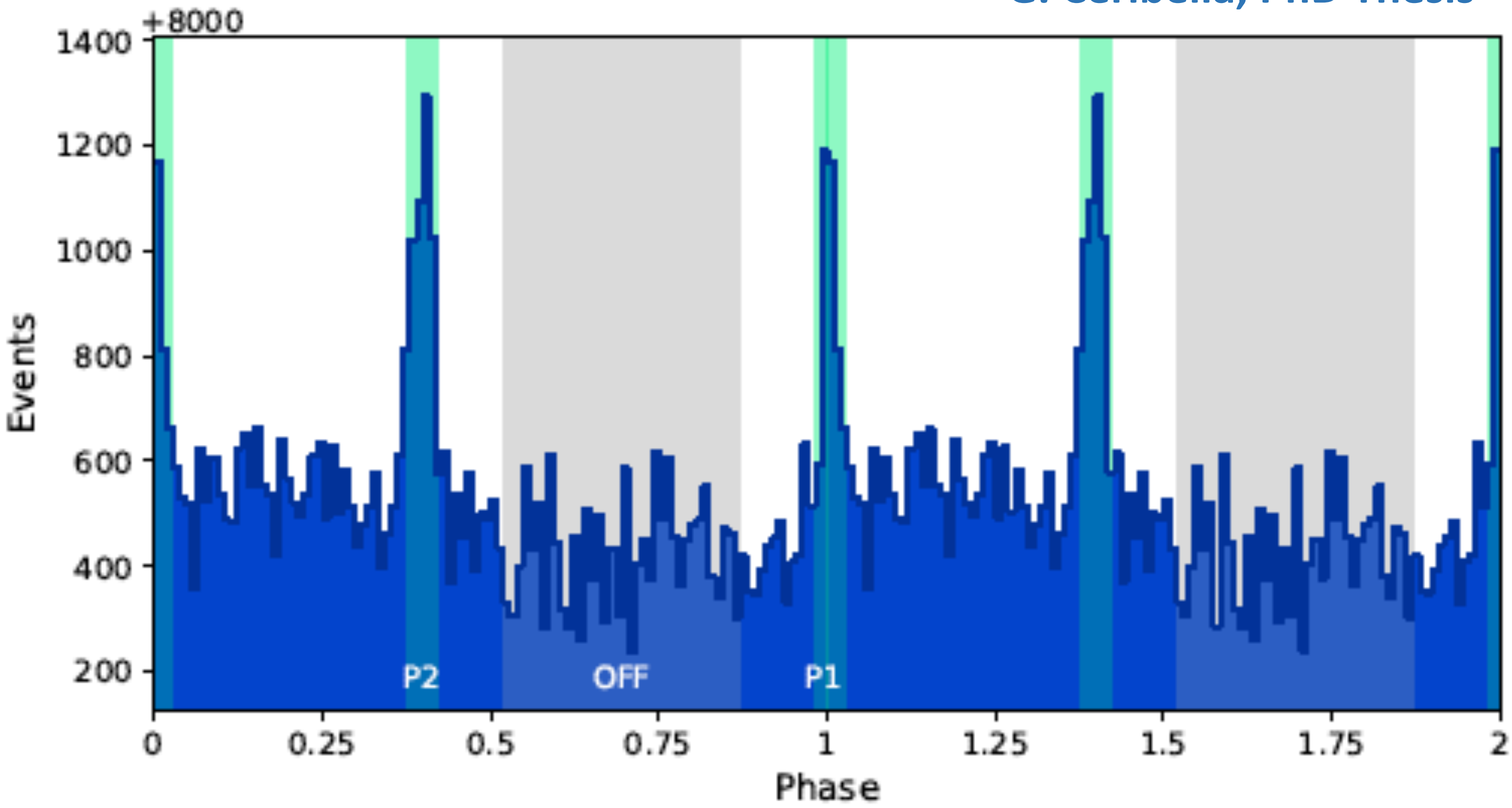
Observations with the MAGIC Sum-Trigger-II
in preparation

Crab latest results with SumTrigger-II

Light curve

- SumTrigger-II data: ~110 h
- P1+P2 @ **16 σ**
- Narrow peaks & clear bridge emission

G. Ceribella, PhD Thesis



Vela: the 2nd pulsar detected at VHE

Due to its proximity (d=287 pc), Vela is the brightest persistent γ-ray source

→ Good target for telescopes placed in Southern hemisphere

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

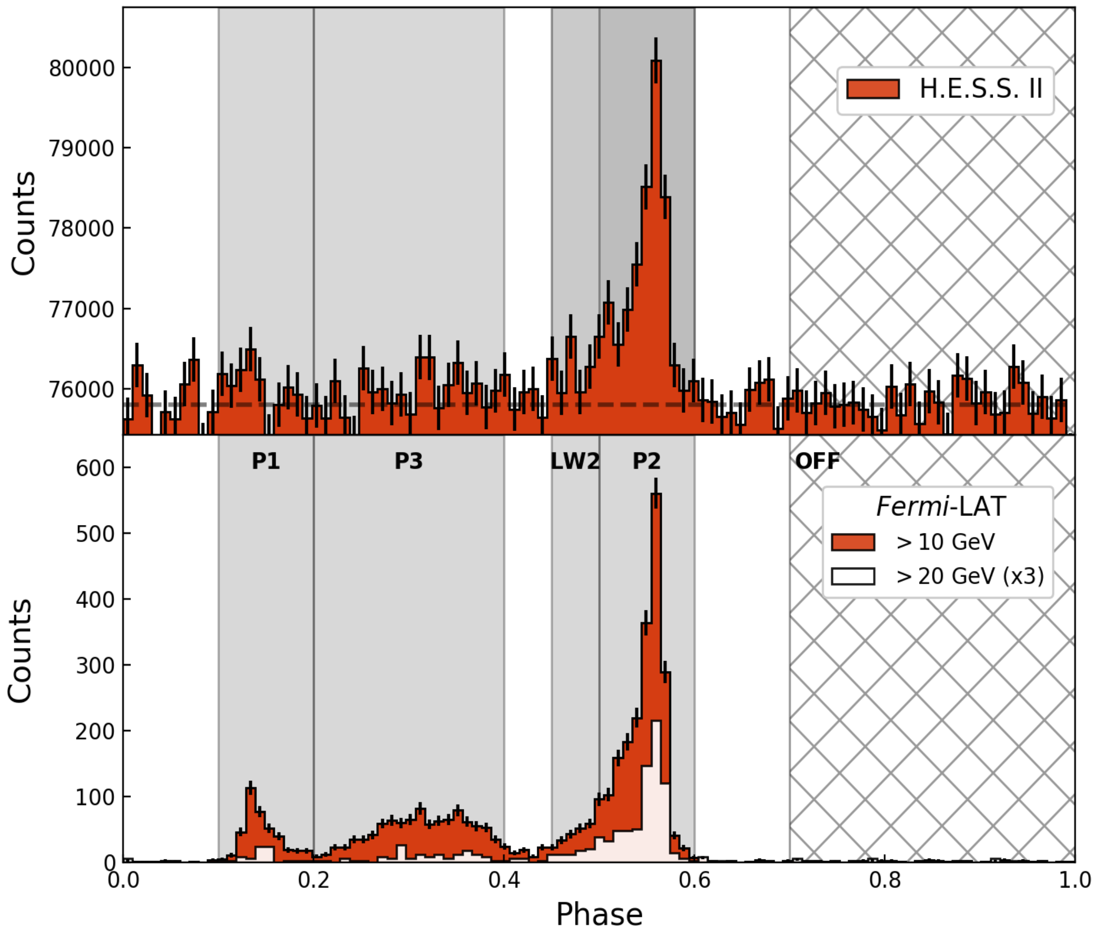
Observations

- **~40 h** collected from 2013 to 2015 with **CT5** (27 m)
- Energy range: 20 – 100 GeV

Light curve

- P2 detected at 15 σ

arXiv:1807.01302v1



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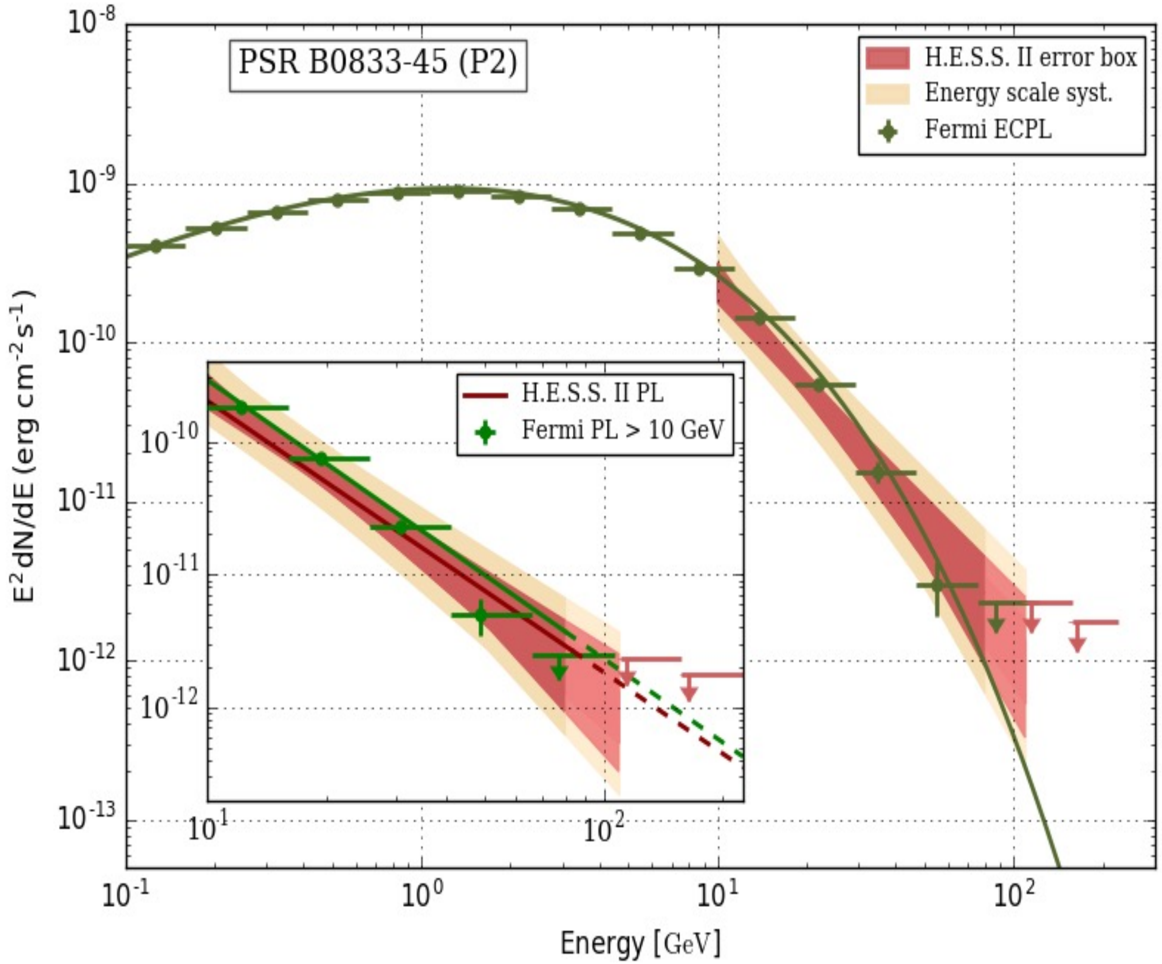


Light curve

- P2 detected at 15 σ

Spectrum

- Power-Law fits of **Fermi-LAT** and **H.E.S.S. II** (10-100 GeV) in agreement: Γ = -4.1+/- 0.2

Power-law tail or curved spectrum?

- Sub-exponential cutoff favoured at 3σ level

Vela: TeV emission

H.E.S.S. detection > 3 TeV

- **60 h** in stereo mode (2004 – 2016)
- Detection of P2:

  > 3 TeV: 5.3σ

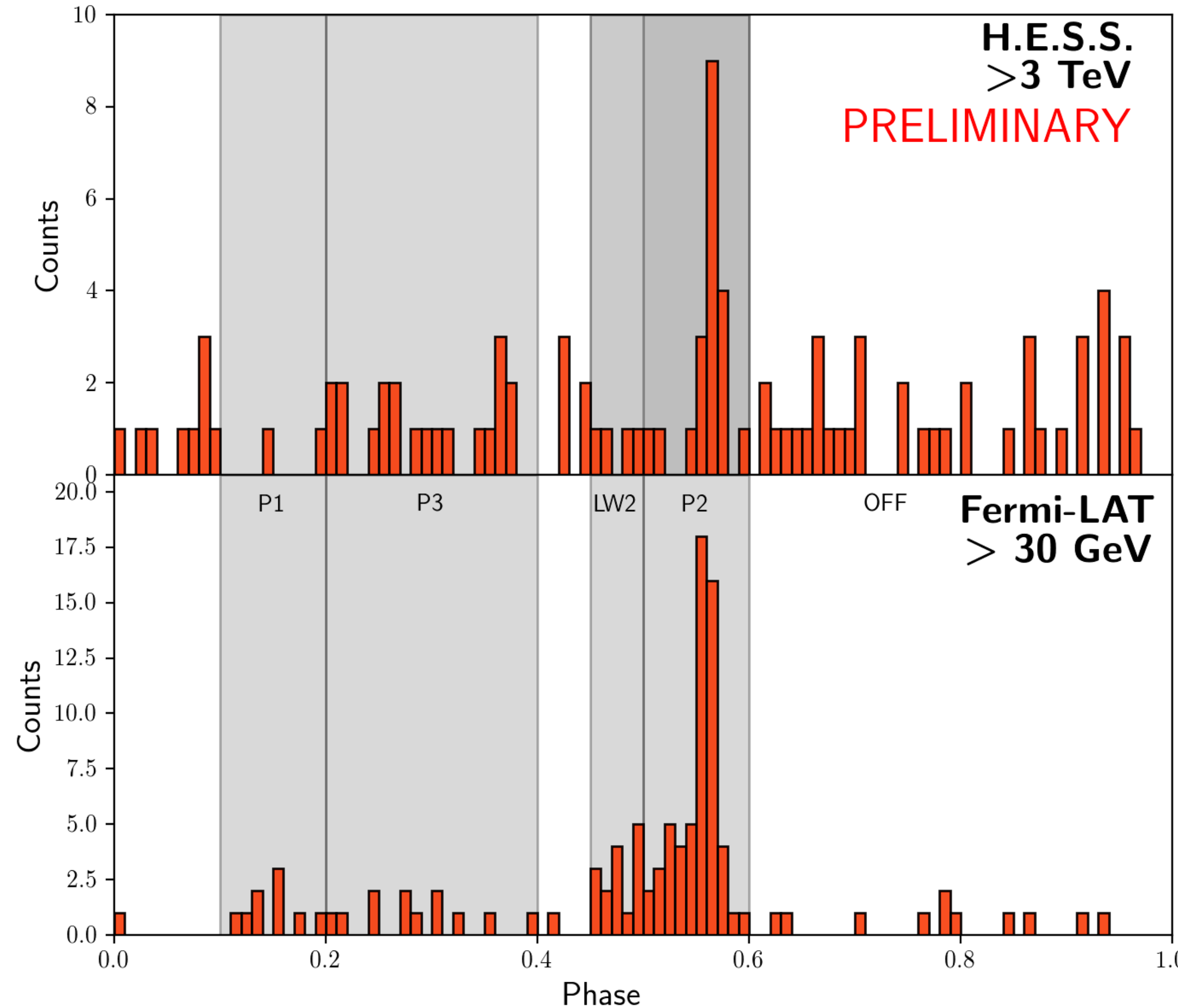
  > 7 TeV: 5.6σ

Most energetic pulsation ever detected

Spectrum: IC?

Paper still not published

A. Djannati-Ataï, Texas Symp. 2017

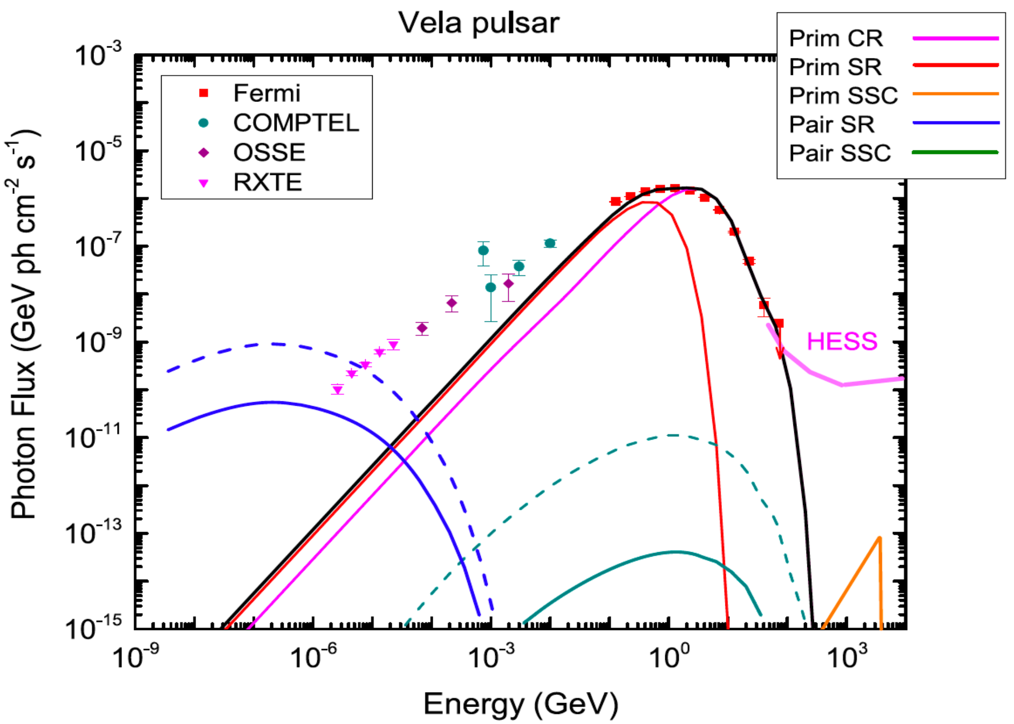


Vela: TeV emission

A distinct TeV component?

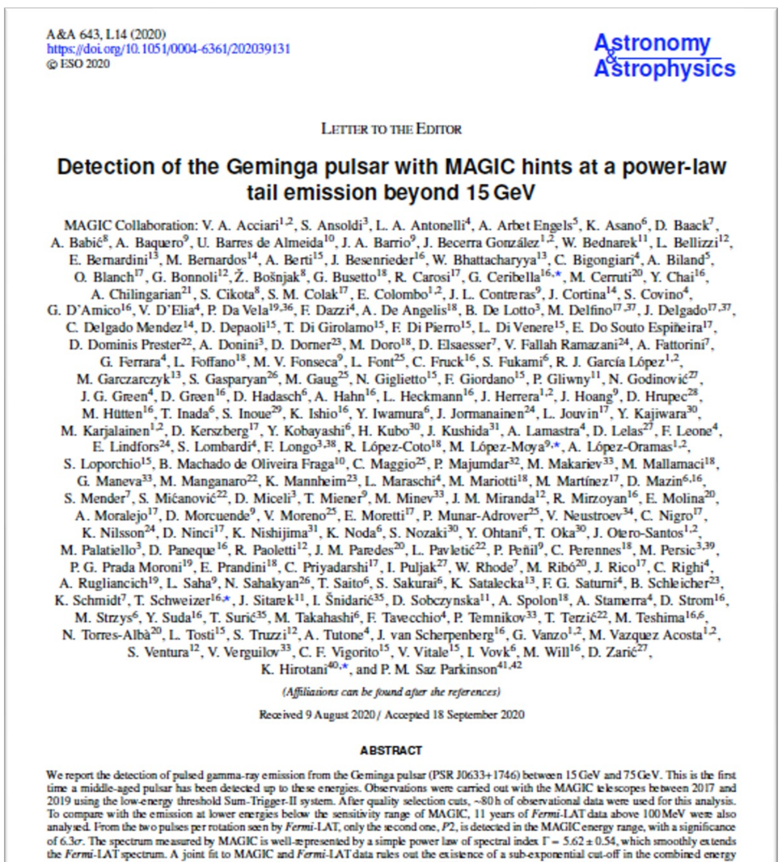
- Possibility of a second component (IC) for Vela already proposed +20 years ago in OG models.
  - E.g: Rudak & Dyks (2017): IC of primary e- with optical photons in the outer gap region.
- However, other SSC models don't expect a detectable 2nd component
  - E.g: Harding & Kalapathorakos (2015): SSC from primaries and pairs inside/outside LC

Harding & Kalapathorakos (2015)



Geminga: 2nd pulsar detected by MAGIC

Published as a 2020 A&A highlight



A&A 643, L14 (2020)
https://doi.org/10.1051/0004-6361/202039131

Astronomy & Astrophysics

Letter to the Editor

Detection of the Geminga pulsar with MAGIC hints at a power-law tail emission beyond 15 GeV

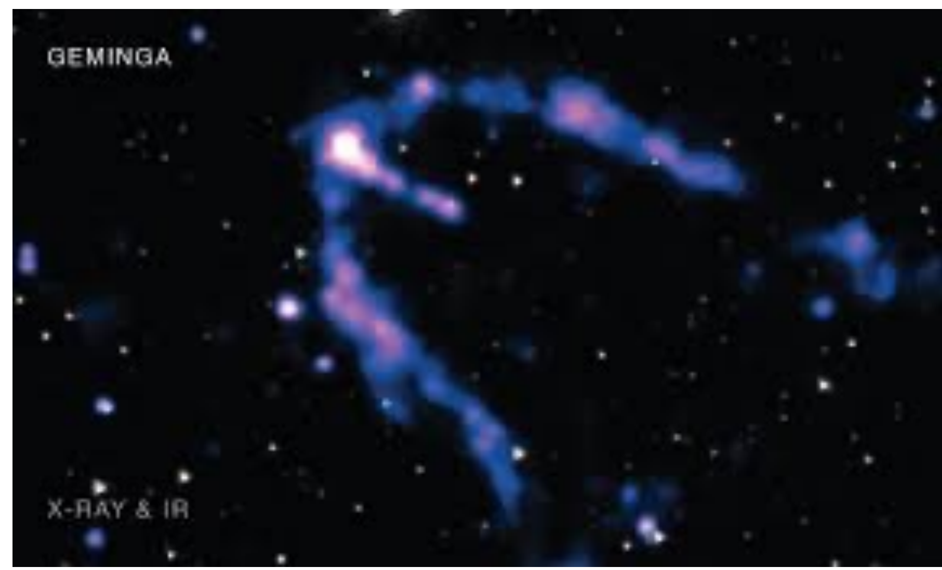
MAGIC Collaboration: V. A. Acciari[1,2], S. Ansoldi[3], L. A. Antonelli[4], A. Arbet Engels[5], K. Asano[6], D. Baack[7], A. Babić[8], A. Baquero[9], U. Barres de Almeida[10], J. A. Barrio[9], J. Becerra González[1,2], W. Bednarek[11], L. Bellizzi[12], E. Bernardini[13], M. Bernardos[14], A. Berti[15], J. Besenrieder[16], W. Bhattacharyya[13], C. Bigongiari[4], A. Biland[5], O. Blanch[17], G. Bonnoli[12], Ž. Bošnjak[8], G. Busetto[18], R. Carosi[17], G. Ceribella[16,*], M. Cerruti[20], Y. Chai[16], A. Chilingarian[21], S. Cikota[8], S. M. Colak[17], E. Colombo[1,2], J. L. Contreras[9], J. Cortina[14], S. Covino[4], G. D'Amico[16], V. D'Elia[4], P. Da Vela[19,36], F. Dazzi[4], A. De Angelis[18], B. De Lotto[3], M. Delfino[17,37], J. Delgado[17,37], C. Delgado Mendez[14], D. Depaoli[15], T. Di Girolamo[15], F. Di Pierro[15], L. Di Venere[15], E. Do Souto Espiñeira[17], D. Dominis Prester[22], A. Donini[3], D. Dorner[23], M. Doro[18], D. Elsaesser[7], V. Fallah Ramazani[24], A. Fattorini[7], G. Ferrara[4], L. Foffano[18], M. V. Fonseca[9], L. Font[25], C. Fruck[16], S. Fukami[6], R. J. García López[1,2], M. Garczarczyk[13], S. Gasparyan[26], M. Gaug[25], N. Giglietto[15], F. Giordano[15], P. Gliwny[11], N. Godinović[27], J. G. Green[4], D. Green[16], D. Hadasch[6], A. Hahn[16], L. Heckmann[16], J. Herrera[1,2], J. Hoang[9], D. Hrupec[28], M. Hütten[16], T. Inada[6], S. Inoue[29], K. Ishio[16], Y. Iwamura[6], J. Jormanainen[24], L. Jouvin[17], Y. Kajiwara[30], M. Karjalainen[1,2], D. Kerszberg[17], Y. Kobayashi[6], H. Kubo[30], J. Kushida[31], A. Lamastra[4], D. Lelas[27], F. Leone[4], E. Lindfors[24], S. Lombardi[4], F. Longo[3,38], R. López-Coto[18], M. López-Moya[9,*], A. López-Oramas[1,2], S. Loporchio[15], B. Machado de Oliveira Fraga[10], C. Maggio[25], P. Majumdar[32], M. Makariev[33], M. Mallamaci[18], G. Maneva[33], M. Manganaro[22], K. Mannheim[23], L. Maraschi[4], M. Mariotti[18], M. Martínez[17], D. Mazin[6,16], S. Mender[7], S. Mićanović[22], D. Miceli[3], T. Miener[9], M. Minev[33], J. M. Miranda[12], R. Mirzoyan[16], E. Molina[20], A. Moralejo[17], D. Morcuende[9], V. Moreno[25], E. Moretti[17], P. Munar-Adrover[25], V. Neustroev[34], C. Nigro[17], K. Nilsson[24], D. Ninci[17], K. Nishijima[31], K. Noda[6], S. Nozaki[30], Y. Ohtani[6], T. Oka[30], J. Otero-Santos[1,2], M. Palatiello[3], D. Paneque[16], R. Paoletti[12], J. M. Paredes[20], L. Pavletić[22], P. Peñil[9], C. Perennes[18], M. Persic[3,39], P. G. Prada Moroni[19], E. Prandini[18], C. Priyadarshi[17], I. Puljak[27], W. Rhode[7], M. Ribó[20], J. Rico[17], C. Righi[4], A. Rugliancich[19], L. Saha[9], N. Sahakyan[26], T. Saito[6], S. Sakurai[6], K. Satalecka[13], F. G. Saturni[4], B. Schleicher[23], K. Schmidt[7], T. Schweizer[16,*], J. Sitarek[11], I. Šnidarić[35], D. Sobczynska[11], A. Spolon[18], A. Stamerra[4], D. Strom[16], M. Strzys[6], Y. Suda[16], T. Surić[35], M. Takahashi[6], F. Tavecchio[4], P. Temnikov[33], T. Terzić[22], M. Teshima[16,6], N. Torres-Albà[20], L. Tosti[15], S. Truzzi[12], A. Tutone[4], J. van Scherpenberg[16], G. Vanzo[1,2], M. Vazquez Acosta[1,2], S. Ventura[12], V. Verguilov[33], C. F. Vigorito[15], V. Vitale[15], I. Vovk[6], M. Will[16], D. Zarić[27], K. Hirotani[40,*], and P. M. Saz Parkinson[41,42]

(Affiliations can be found after the references)

Received 9 August 2020 / Accepted 18 September 2020

ABSTRACT

We report the detection of pulsed gamma-ray emission from the Geminga pulsar (PSR J0633+1746) between 15 GeV and 75 GeV. This is the first time a middle-aged pulsar has been detected up to these energies. Observations were carried out with the MAGIC telescopes between 2017 and 2019 using the low-energy threshold Sum-Trigger-II system. After quality selection cuts, ~80 h of observational data were used for this analysis. To compare with the emission at lower energies below the sensitivity range of MAGIC, 11 years of *Fermi*-LAT data above 100 MeV were also analysed. From the two pulses per rotation seen by *Fermi*-LAT, only the second one, *P*2, is detected in the MAGIC energy range, with a significance of 6.3σ. The spectrum measured by MAGIC is well-represented by a simple power law of spectral index $\Gamma = 5.62 \pm 0.54$, which smoothly extends the *Fermi*-LAT spectrum. A joint fit to MAGIC and *Fermi*-LAT data rules out the existence of a sub-exponential cut-off in the combined energy range at the 3.6σ significance level. The power-law tail emission detected by MAGIC is interpreted as the transition from curvature radiation to



Geminga

One of the 3 strongest GeV pulsars, along Crab and Vela

Pulsar

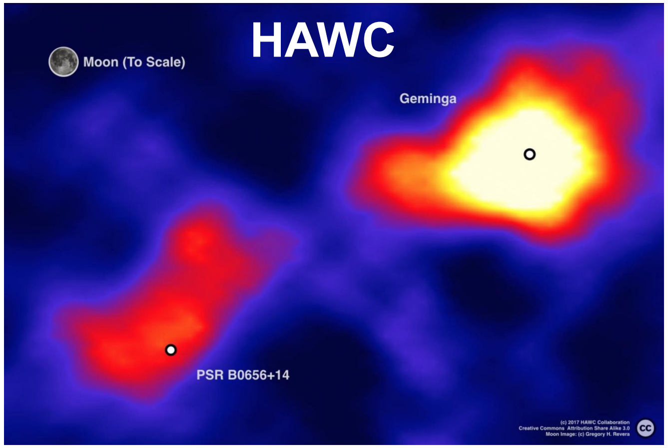
- Prototype of radio-quiet pulsar
- Very different from Crab

	Geminga	Crab
Radio	Quiet	Loud
Period (ms)	237	30
Age (kyr)	340	1
Distance (pc)	150	2000
Edot (erg/s)	$3 \cdot 10^{34}$	$5 \cdot 10^{38}$

Different emission properties @ VHE?

Nebula

- Extended emission detected by MILAGRO (~2.6º) and HAWC unfeasible for current CTs
- May account for up to 20% of e^+ excess



Science 6365 (2017)

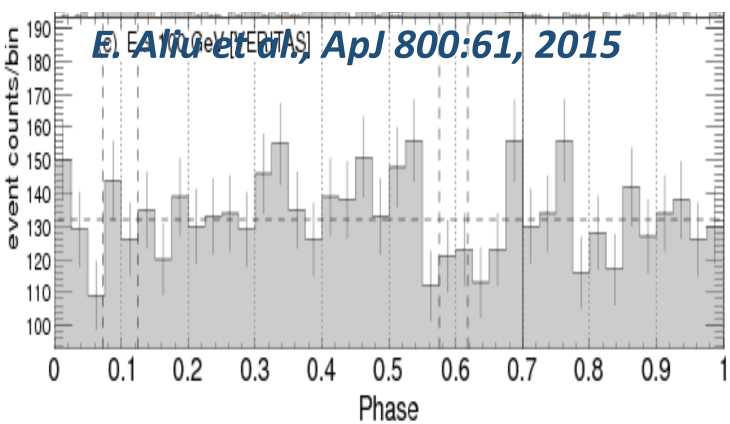
Geminga observations before SumTrigger-II

MAGIC Std.Trigger (2012-13)

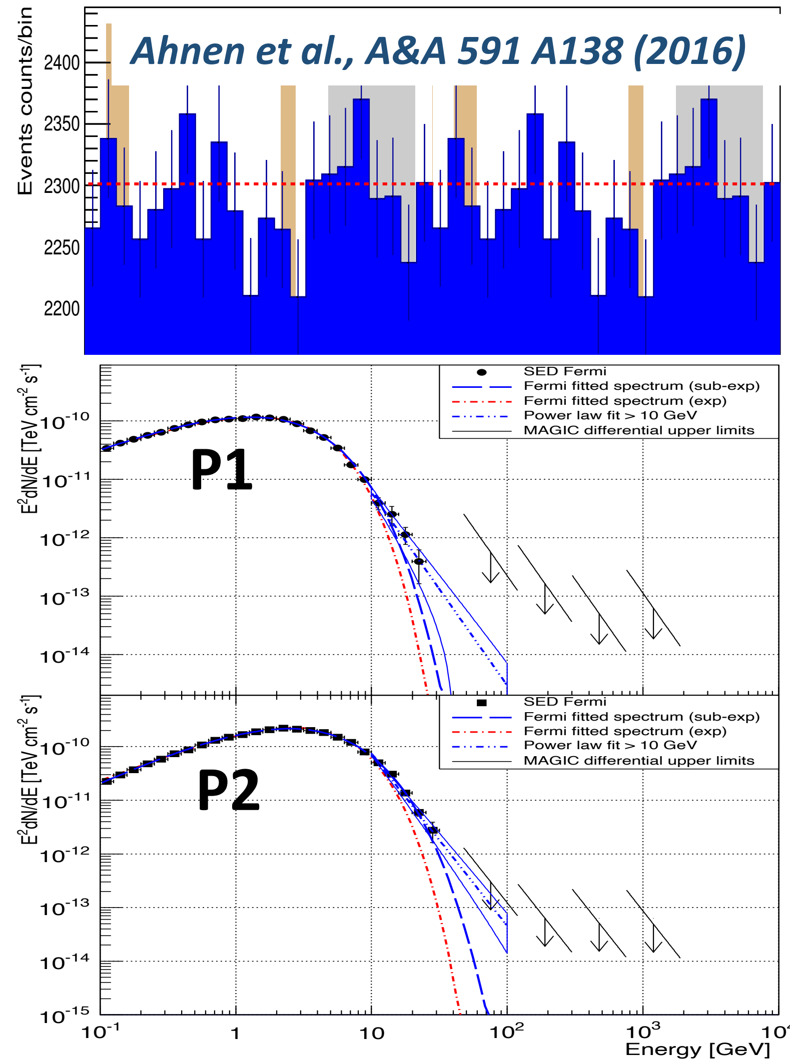
- **63 h** in with Std. trigger
- Search above **50 GeV**
- No detection, but constraining ULs

VERITAS (2007-2013)

- **72 h**
- Search above **100 GeV**
- No detection



MAGIC



Needed a lower threshold → MAGIC SumTrigger-II

Geminga detection with SumTrigger-II

Data: 2017-19

- **~80** h before cuts with SumT-II
- Low z.a.

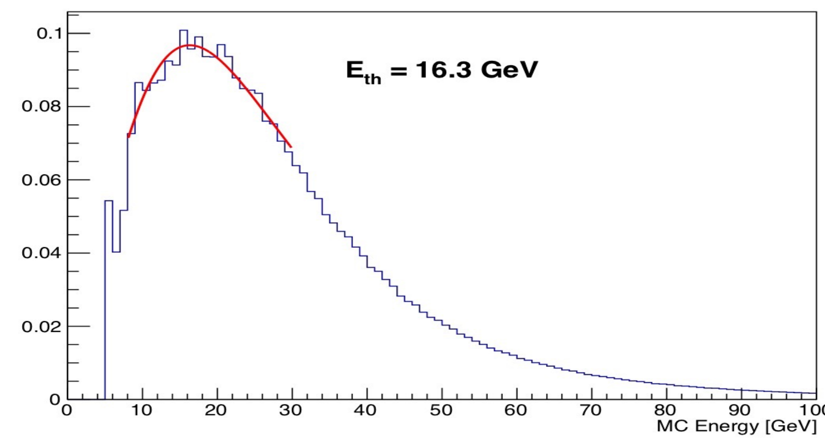
Analysis

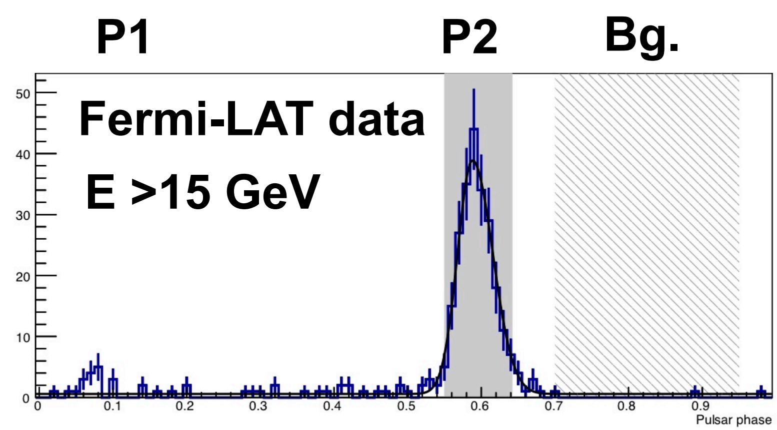
- Dedicated analysis and MC
- Expected Eth ~16 GeV for a source with spectral index of -5

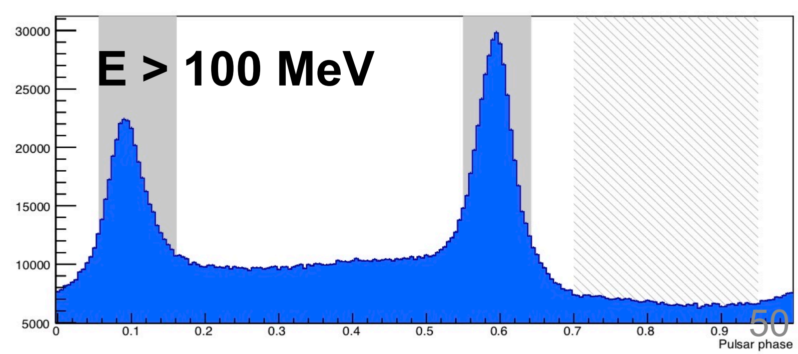
Fermi-LAT dedicated analysis

- Fermi Light curves at its highest energies fitted to define MAGIC phase signal regions

MC SumTrigger-II for Geminga





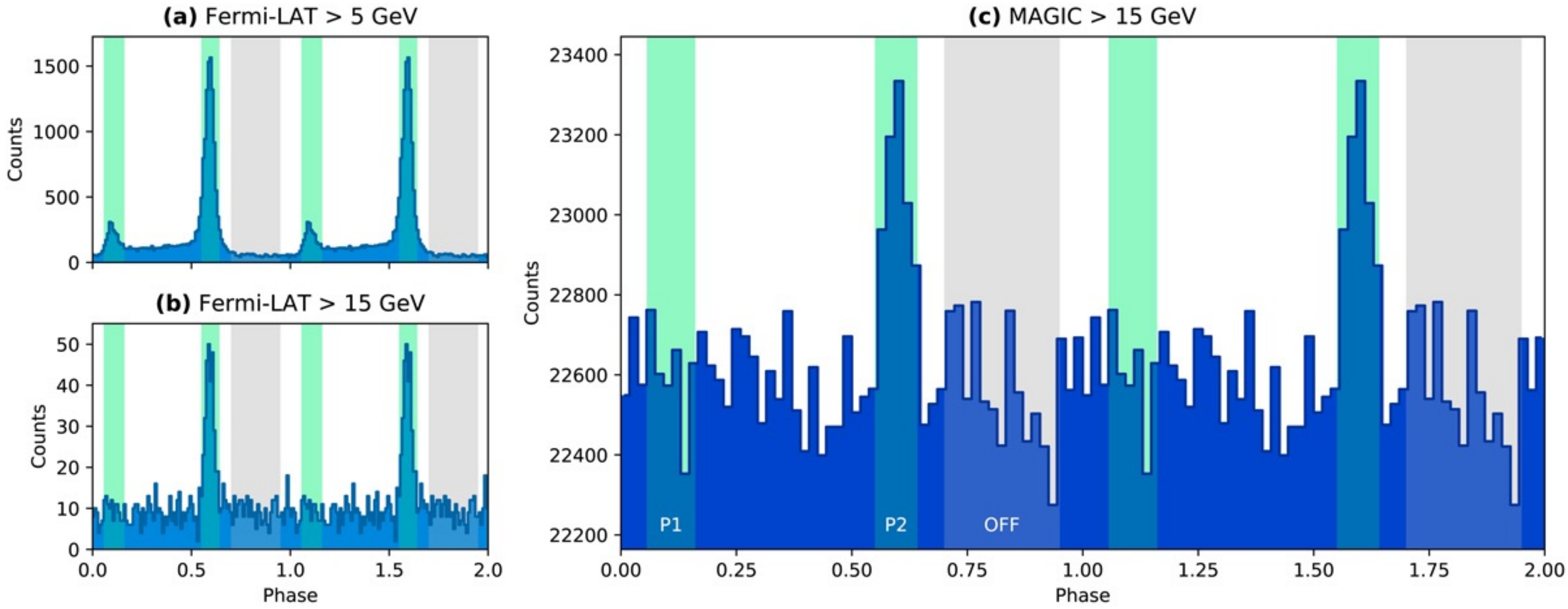


Geminga Light curve

Light curve

- P2 detected at **6σ** level
  - Energy range: **15 – 75** GeV
  - Pulse width similar to the one seen by Fermi-LAT
- P1 not visible

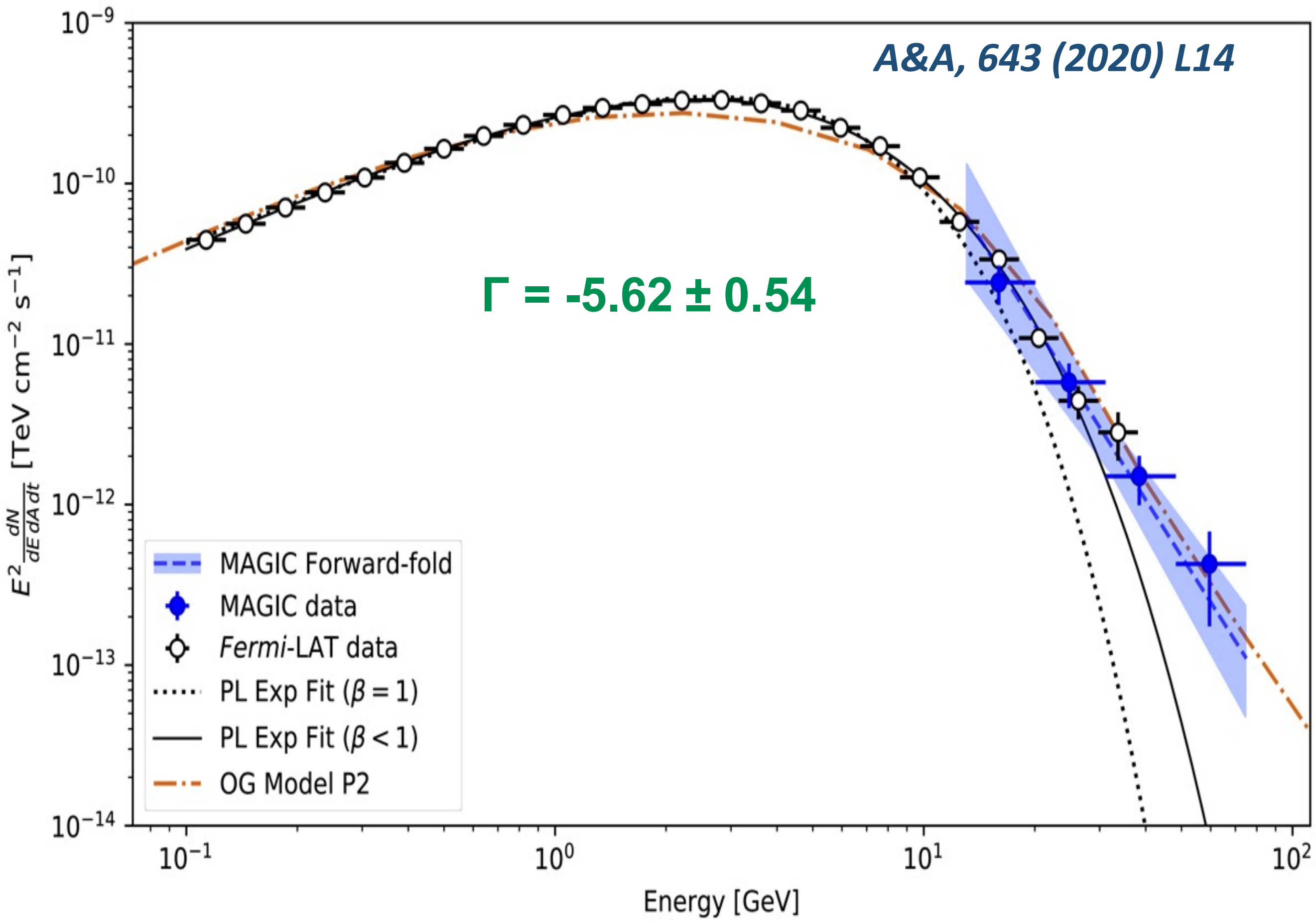
A&A, 643 (2020) L14



Spectral Energy Distribution of P2

Spectrum

- SED follows a step Power Law with index: Γ = 5.62 ± 0.54
- Sub-exponential cutoff disfavored at **3.6σ**



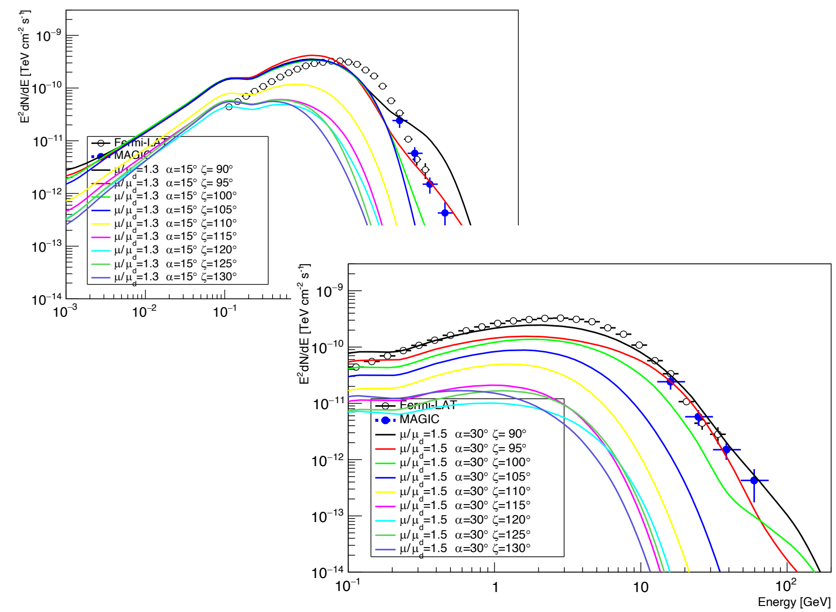
Implications of MAGIC results

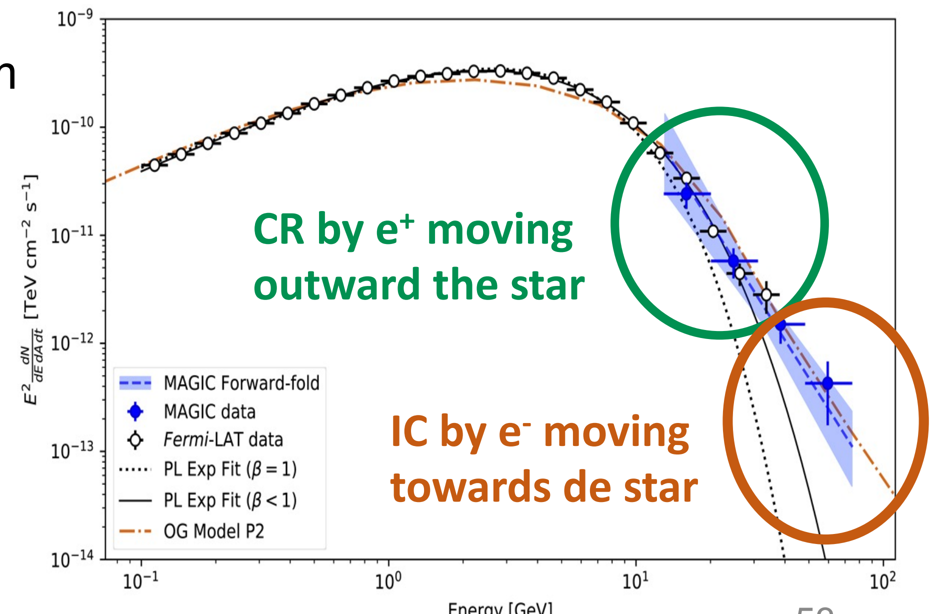
Outer gap model simulations

- Simulations were run for months to try to reproduce MAGIC spectra.
- Best model-fit to MAGIC data implies:
  - We observe Geminga nearly **perpendicularly** to its rotation axis (agrees with other authors).
  - Emission originates in the **northern outer gap**.
  - MAGIC data correspond to the transition from curvature radiation (CR) emitted by outward accelerated positrons to **IC** by electrons accelerated towards the star.
  - The IC component is predicted to extend above the energies detected by MAGIC

    → Good target for the LST1

Example of different simulations





Detection of PSR B1706-44 by HESS

The 4th VHE pulsar

PSR B1706-44 by HESS

Announced at ICRC19 but no paper yet

Pulsar

- One of the brightest Fermi-LAT pulsars
- Parameters similar to Vela, but 10x more distance

  P = 102 ms, age = 20 ky, d = 2 kpc

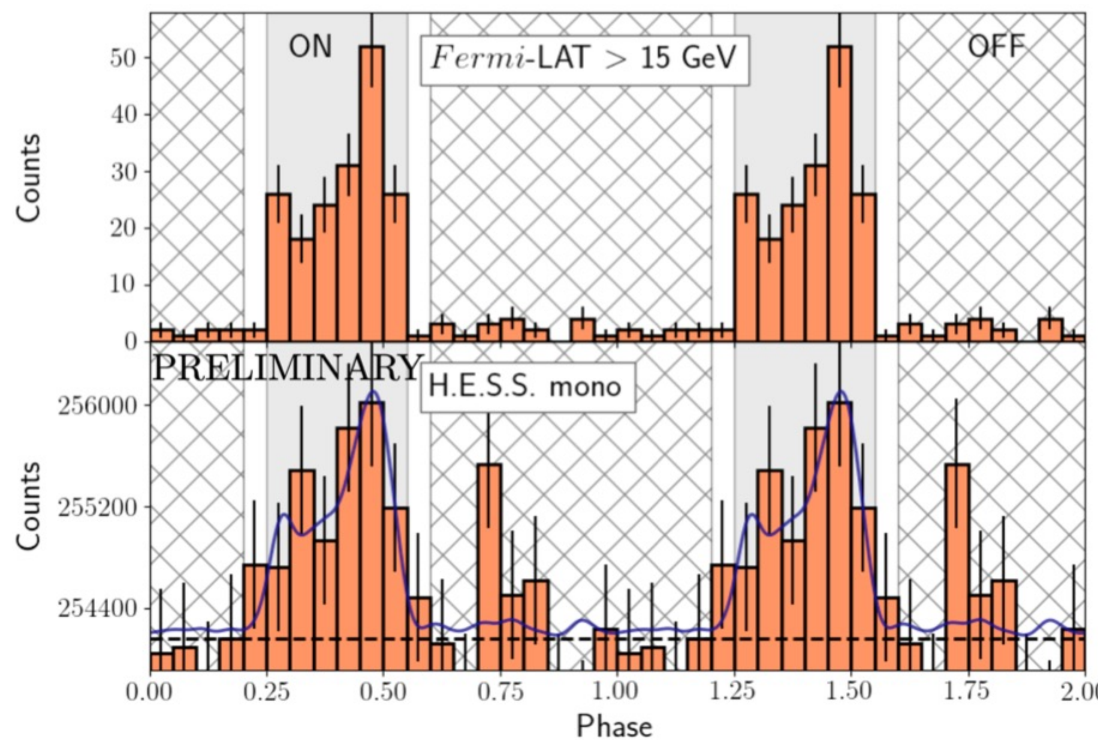
Observations

- 28 h after cuts, 2013 - 2015, taken with **CT5**

Results

- Detection at **4.7 σ**
- LC similar to Fermi-LAT

M. Spir-Jacob et al. Proc. ICRC19M. Spir-Jacob



PSR B1706-44 by HESS

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Pulsar

- One of the brightest Fermi-LAT pulsars
- Parameters similar to Vela, but 10x more distance

  P = 102 ms, age = 20 ky, d = 2 kpc

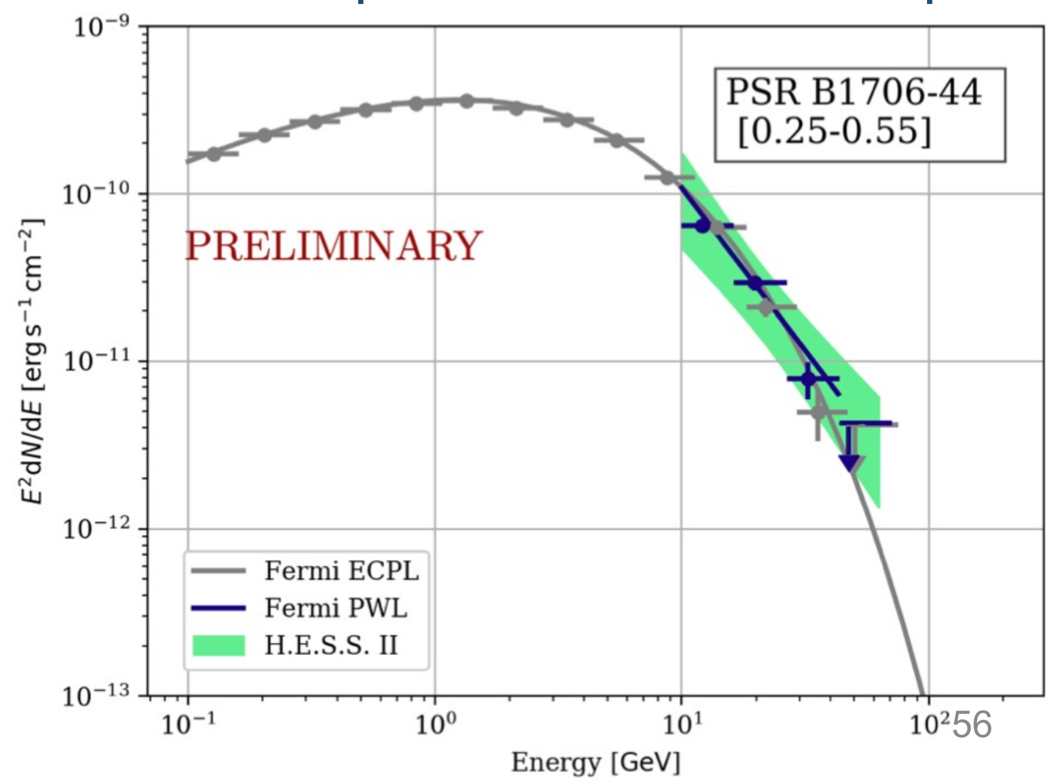
Observations

- 28 h after cuts, 2013 - 2015, taken with **CT5**

Results

- Detection at **4.7 σ**
- LC similar to Fermi-LAT
- Spectrum between **10 – 70** GeV
  - Spectral index: −3.8
- Statistic not enough to confirm or rule out power-law

M. Spir-Jacob et al. Proc. ICRC19M. Spir-Jacob



Pulsars in the CTA era

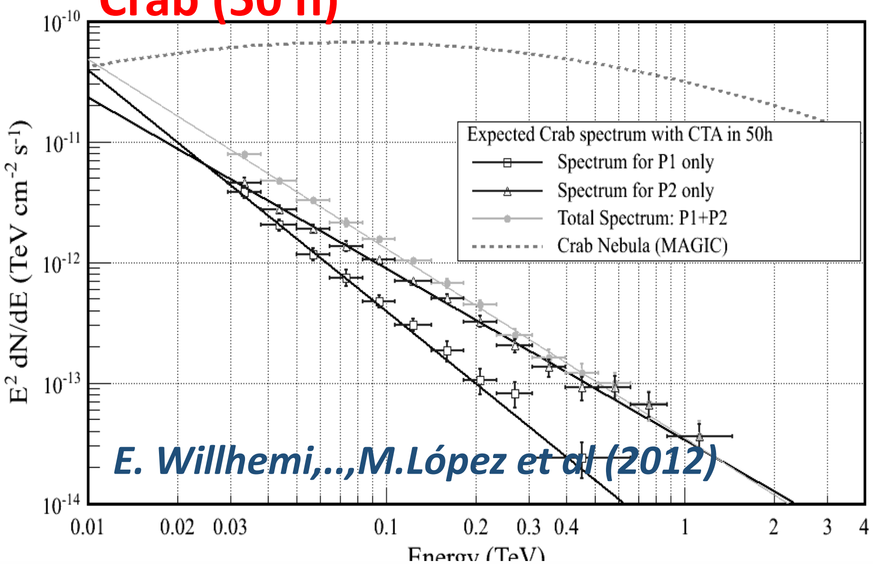
Needed higher sensitivity at GeV and TeV for pulsars

- Pulsars with sub exp-cutoff at GeVs (i.e., w/o VHE tail) almost impossible to catch with current CTs
- Crab pulsar spectrum at TeV already limited by statistics
- Geminga above 100 GeV difficult for MAGIC

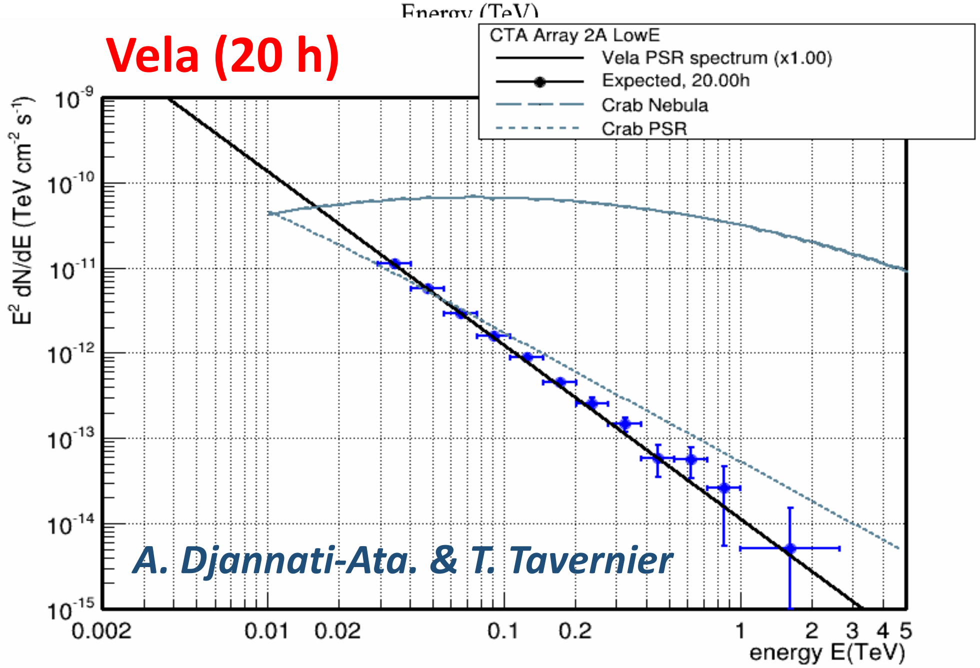
Discovery potential for CTA

Expected sensitivity in 50 h with CTA

Crab (50 h)

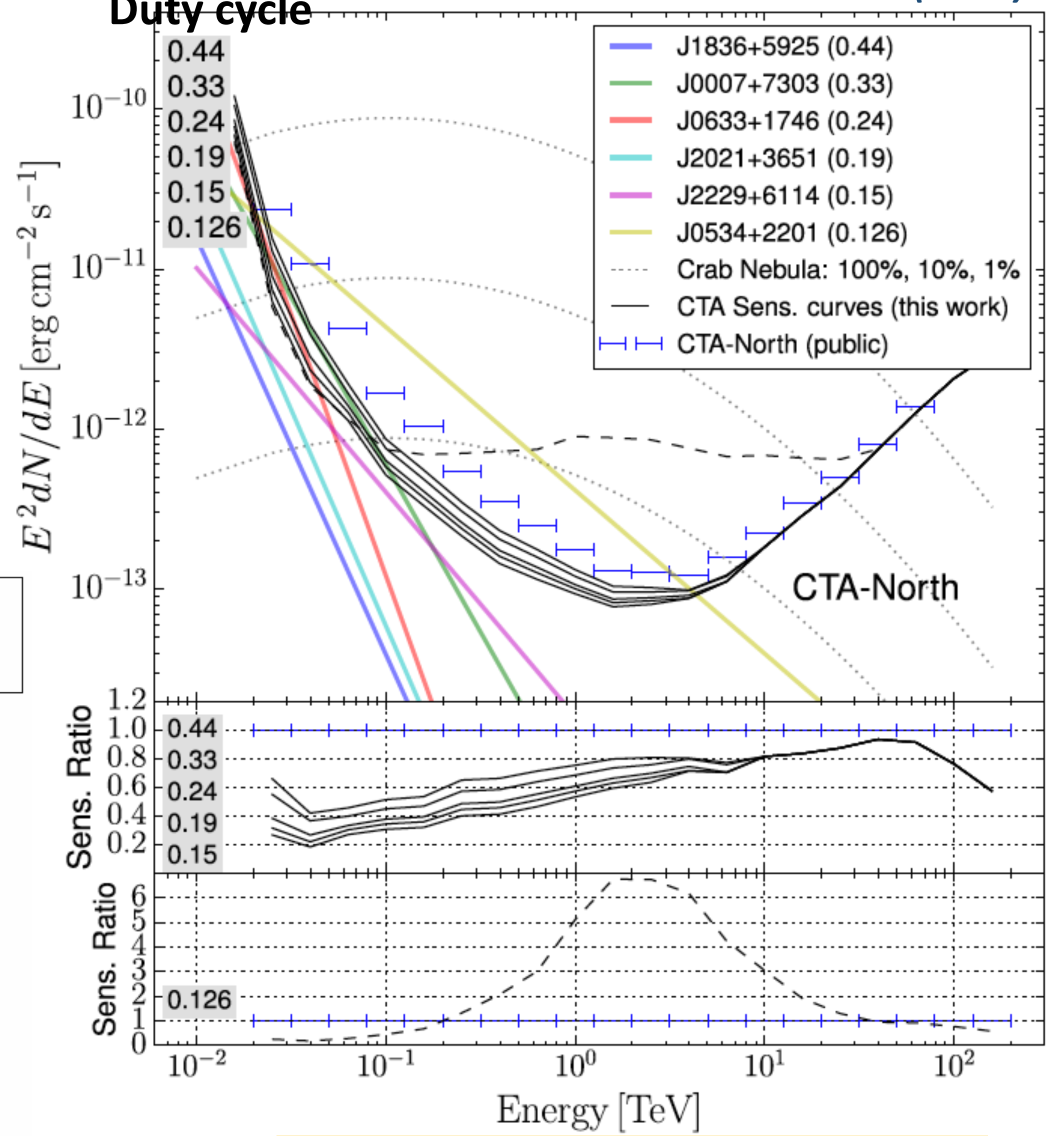


Vela (20 h)



A. Burtovoi et al. MNRAS 471 (2017)

Duty cycle



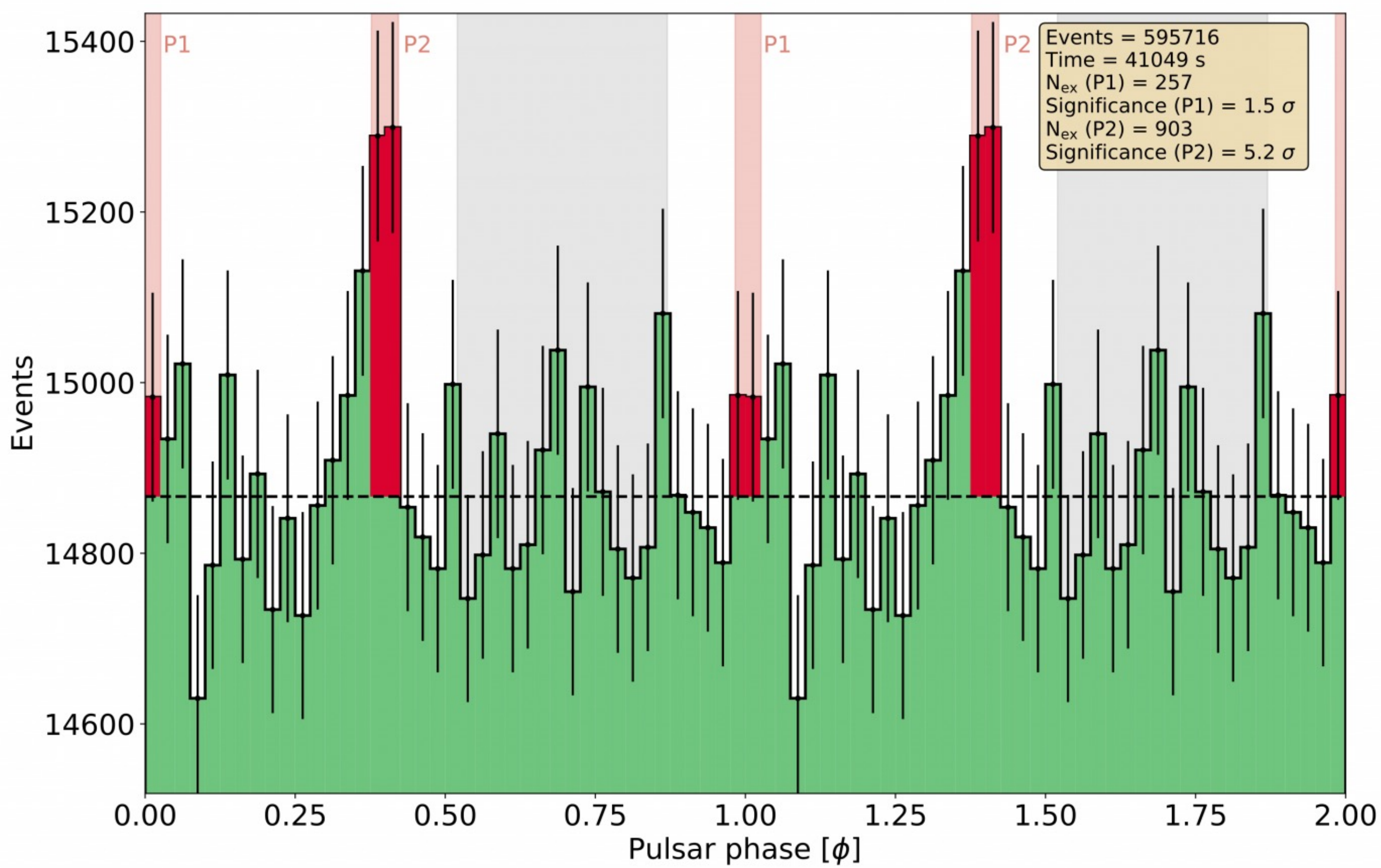
Several pulsars expected

Pulsars in the CTA era

LST-1 has already detected if first pulsar

- Crab already detected at 5σ in 11 h in 2020.

LST1 Collaboration



Summary

- Almost **300** pulsars detected in the GeV band by Fermi-LAT
  - Their spectra typically exhibit sub-exp cutoff at few GeV
- VHE emission from pulsars is challenging, both for theoretical and observational reasons:
  - **Crab** and **Vela** pulsars detected up to **TeV** with CTs
  - **Geminga** and **PSR B1706-44** detected up to **70 GeV**
- Opens questions:
  - Until which energy is the Crab pulsating? Is there a cutoff somewhere? Which is the mechanism producing the PL tail?
  - Is the Vela VHE spectrum formed by 2 different components?
  - Does Geminga also have a spectral tail?
- CTA will help to answer these and new questions