Study of Pulsars at VHE

Where/How are gamma-rays produced in pulsars?

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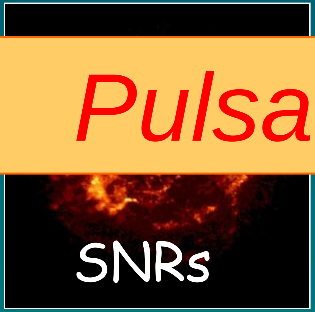
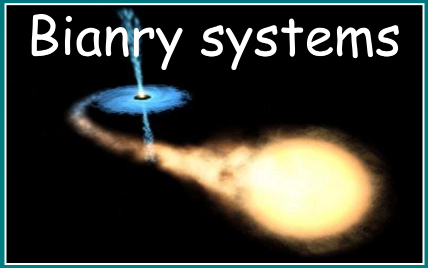
Outline

- Introduction to gamma-ray pulsars, first observation and models
- Recent 0bservations from the sky
- (Timing analysis)
- First observations from ground
- First discovery from ground
- Outlook: pulsars in the CTA era

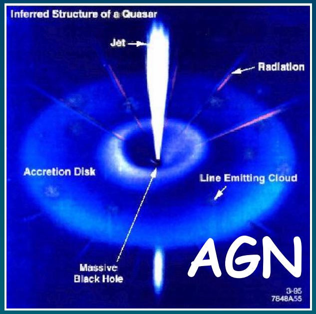
γ-ray Physics Targets

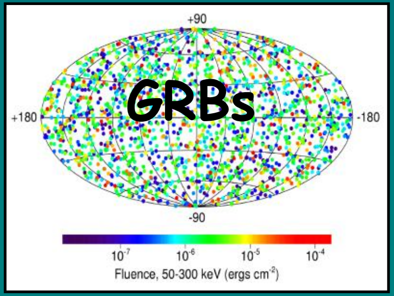
Galactic



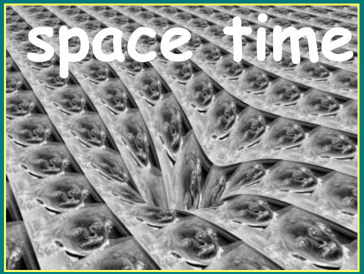


Extragalactic





Fundamental Physics



Pulsars one of the hottest topics

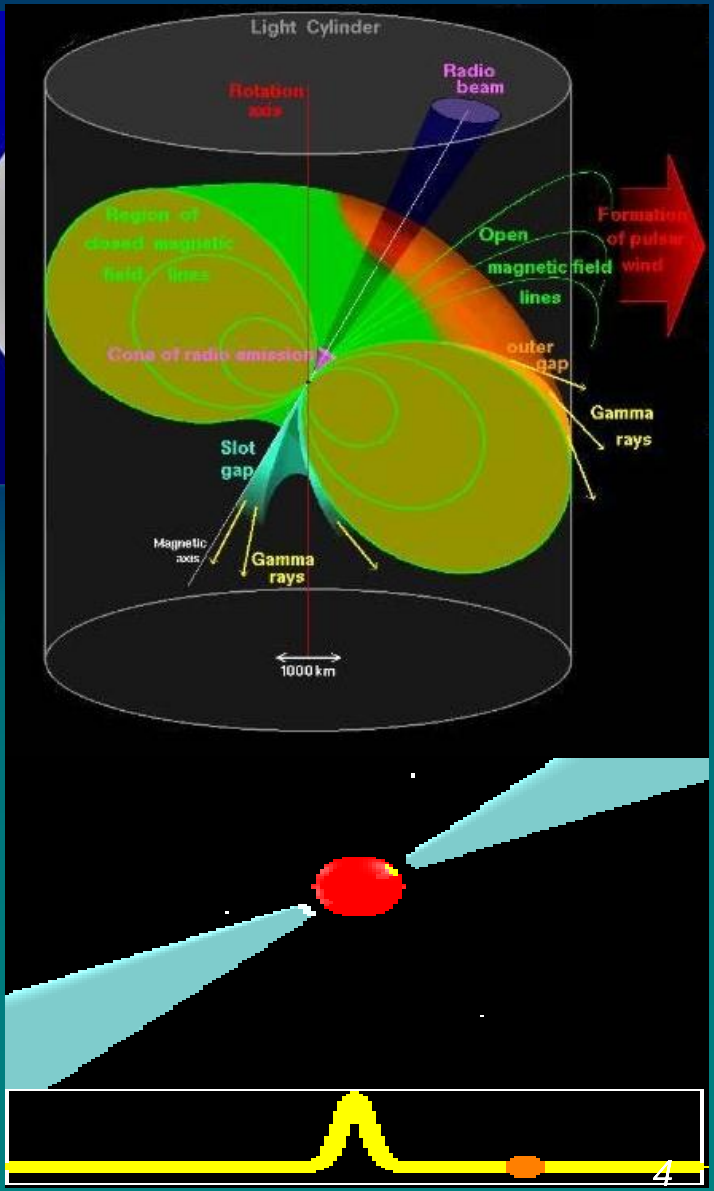
Pulsars

- Pulsars are highly magnetized and rapidly rotating neutron stars
  - Typical mass 1.4 M_{sun}, R~10 km
  - Extreme internal density and huge magnetic fields

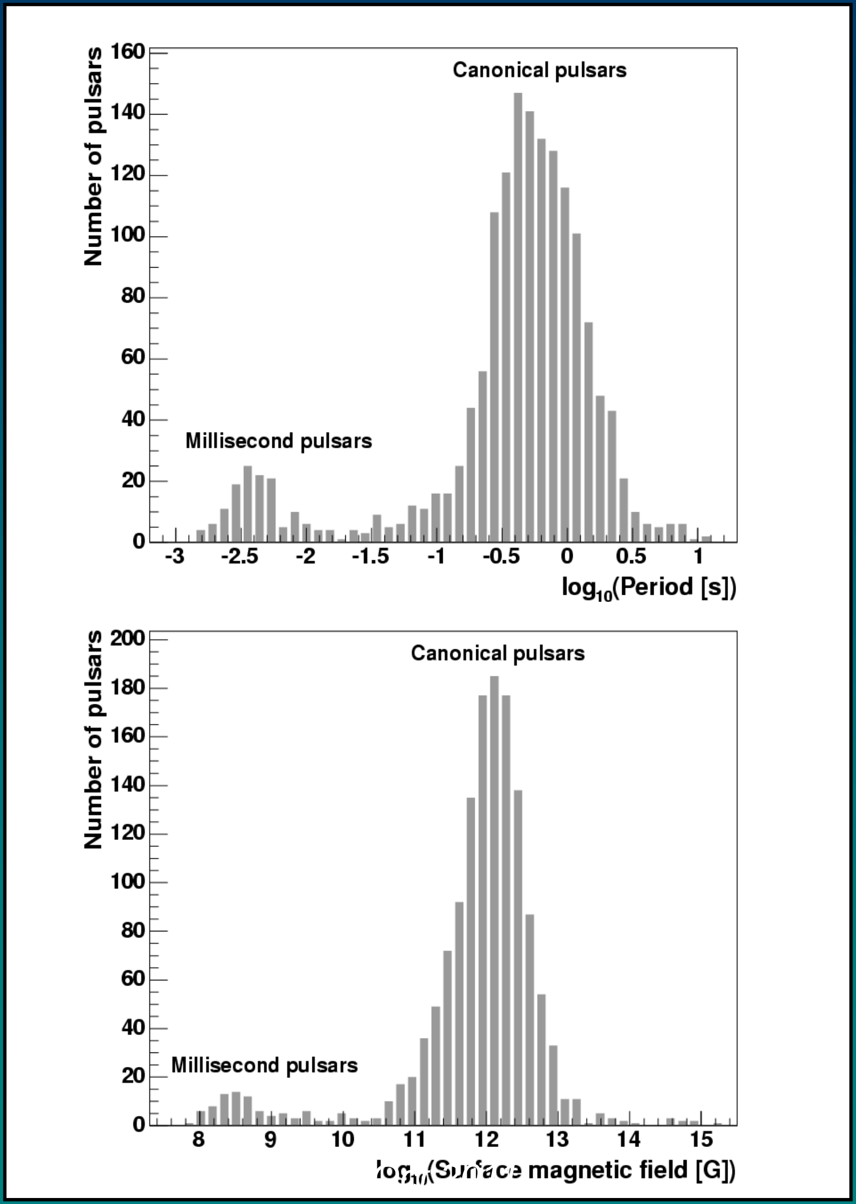
➔ Unique lab for nuclear and particle physics

- 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

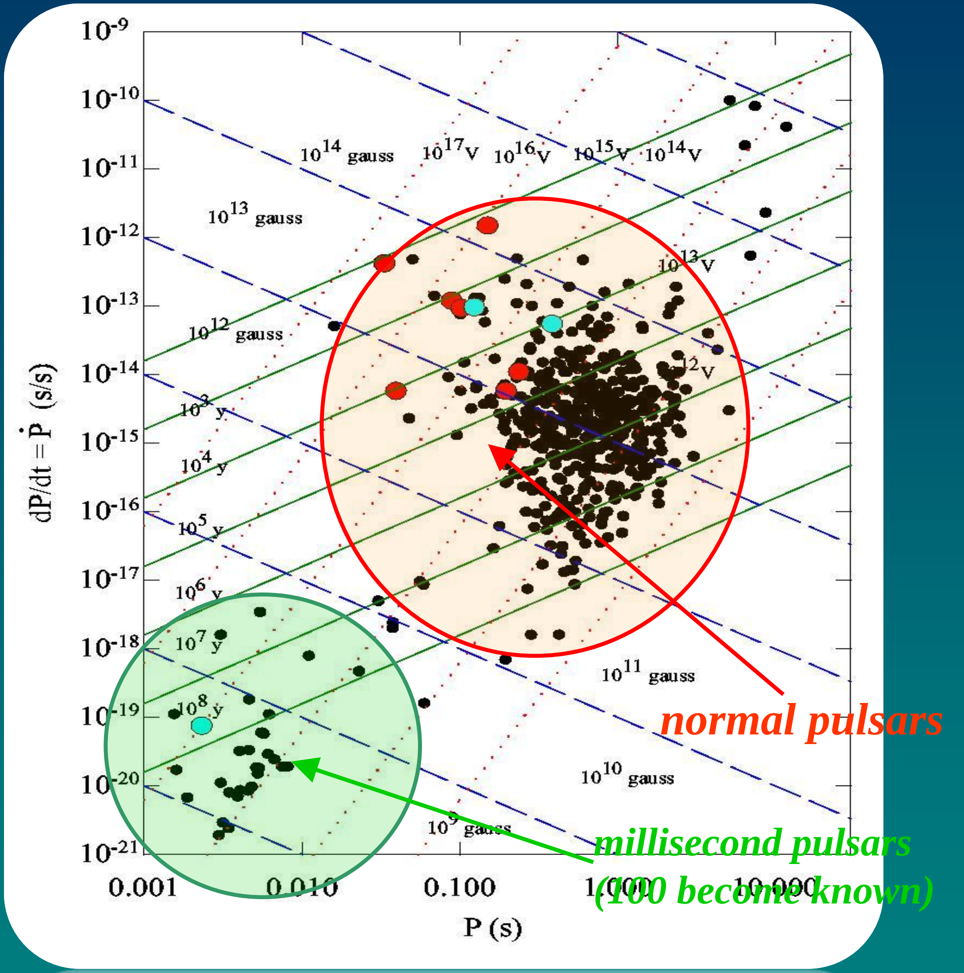
➔ Acts like a cosmic light-house



Pulsars



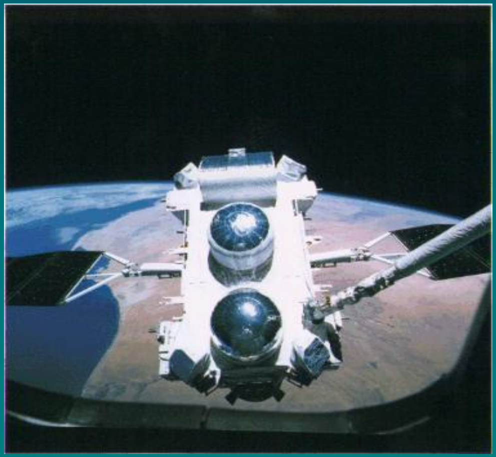
Number of pulsars
Canonical pulsars
Millisecond pulsars
log10(Period [s])
Number of pulsars
Canonical pulsars
Millisecond pulsars
log10(Surface magnetic field [G])



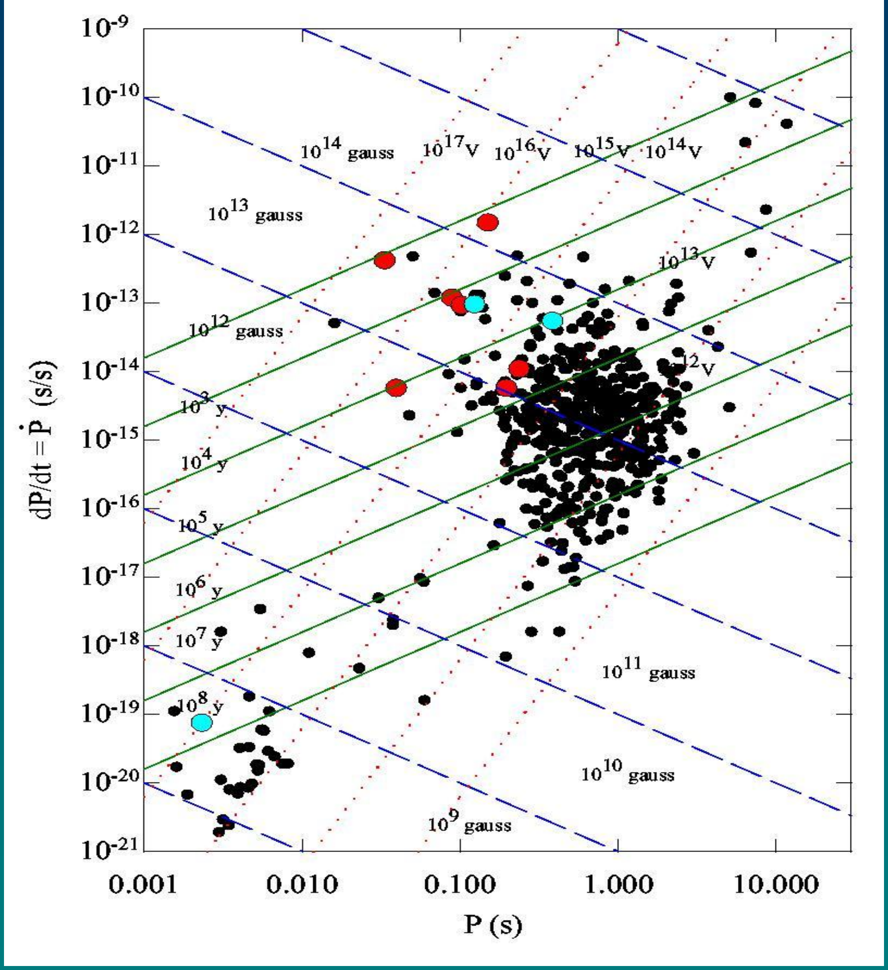
dP/dt = Ṗ (s/s)
P (s)
normal pulsars
millisecond pulsars
(100 become known)

Pulsars

- More than 1700 radio pulsars are known today.
- They can be grouped in canonical and ms
- *Only 7 (+3) detected in γ-rays, with EGRET*

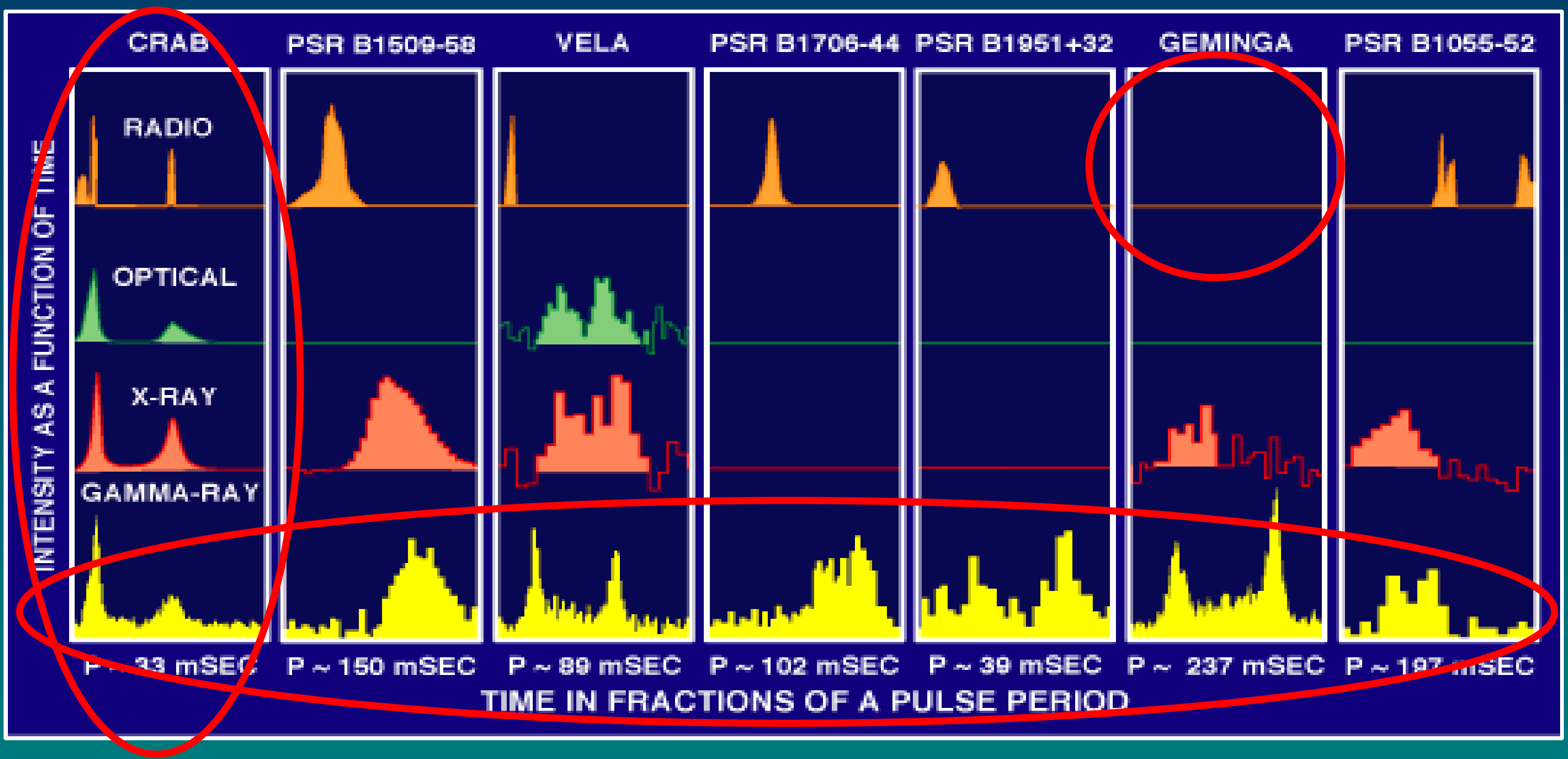


- *About 100 seen by Fermi*



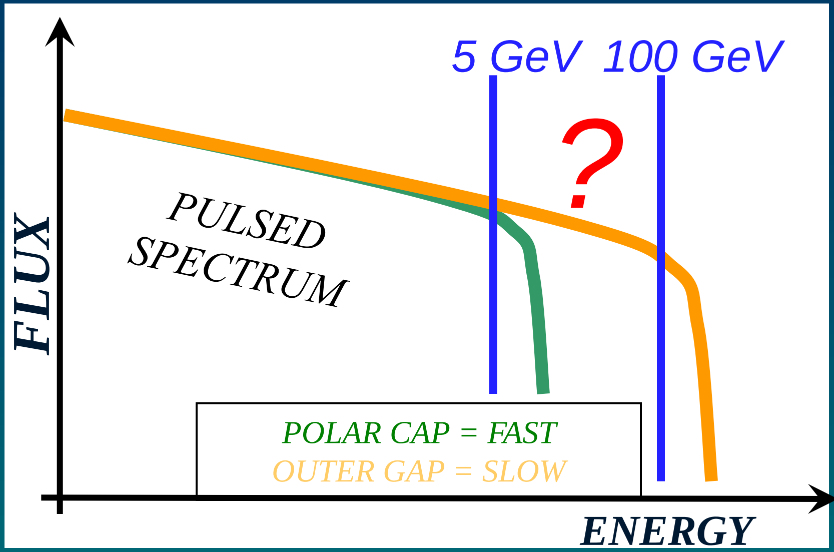
- *7 γ-ray pulsars*
- *+3 candiates*

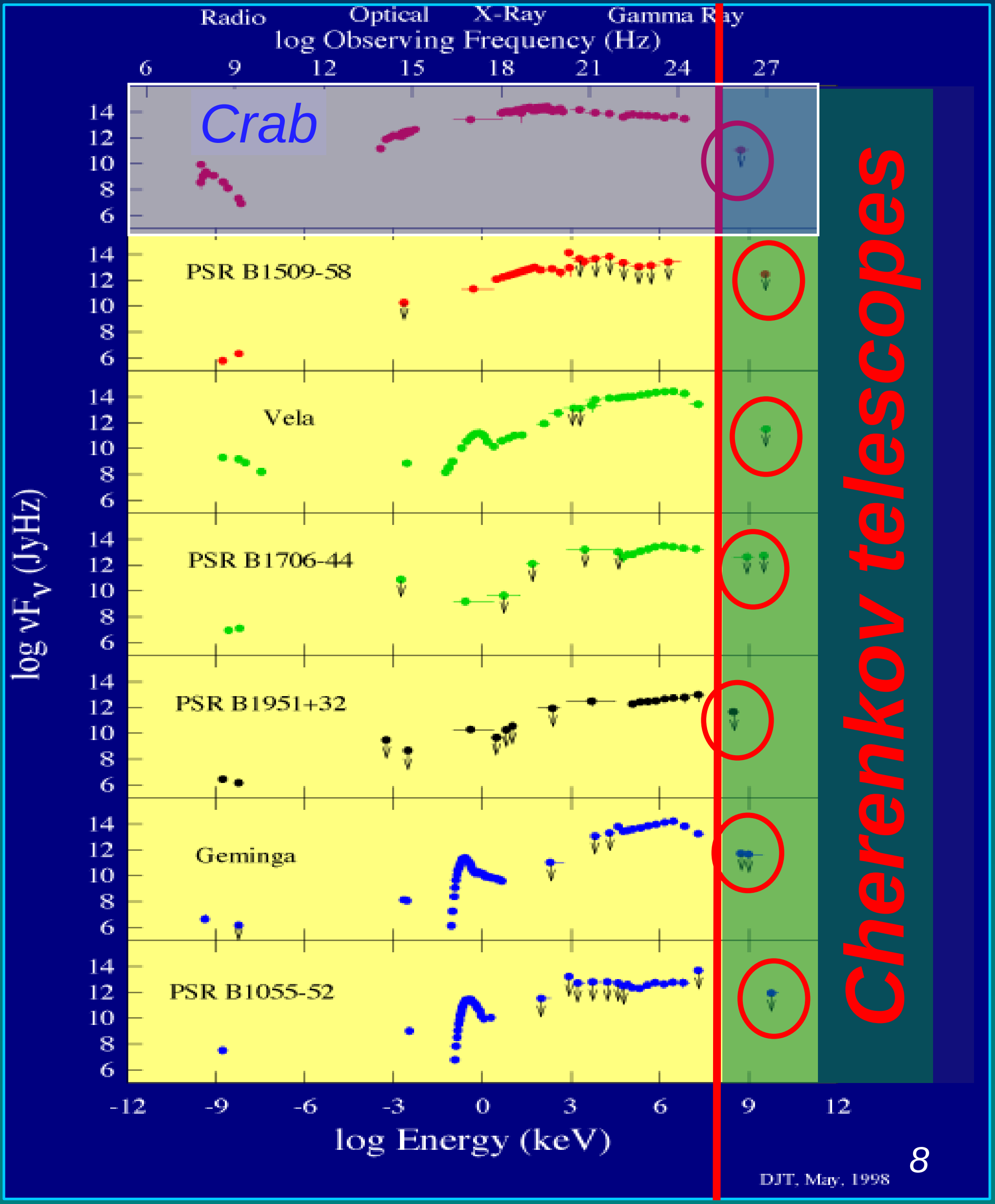
What we learnt from EGRET



- Typically 2 peaks with phase separation 0.2-0.5, and interpulse emission.
- All, but Geminga, radio emitters
- Crab only pulsar which same behaviour at all wavelengths !

EGRET pulsars: Multi-wavelength spectra



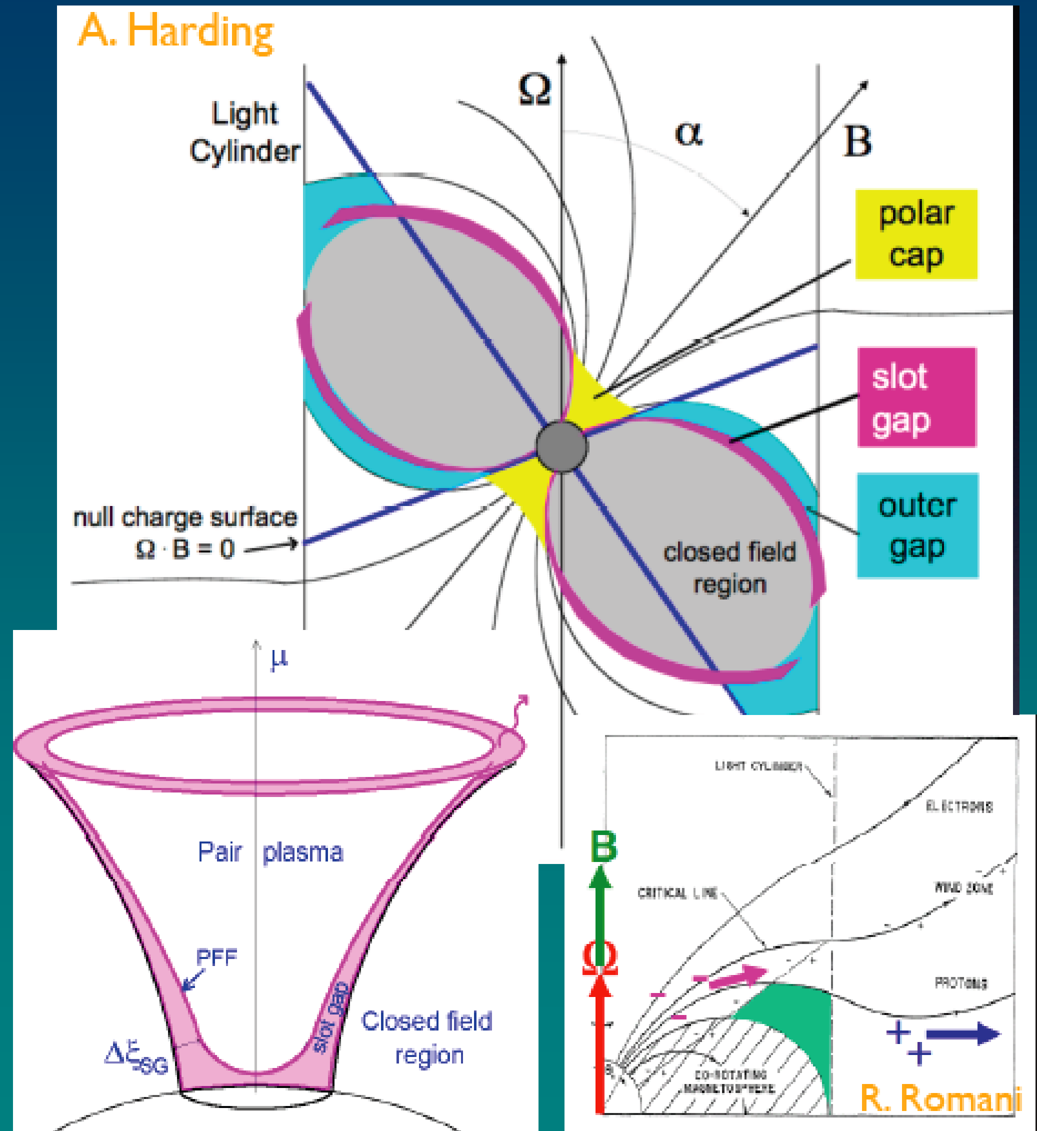


- Observational challenge since 20 years
- Instrument with sensitivity well below 100 GeV needed

Pulsar models of γ–ray emission

Pulsar models: overview

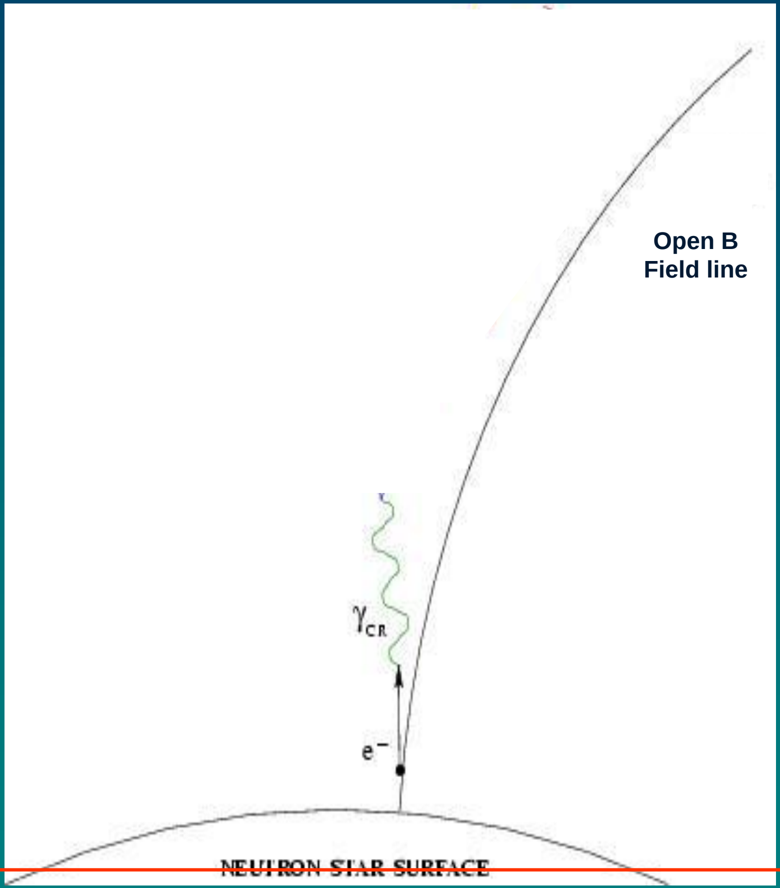
- Different models try to explain observed γ-ray emission.
  - Assume different emitting region in magnetosphere ➔ different emission geometry: PC, OG, TPC, SG
- Spectrum depends on the physics of the emitting region
- Light curves depend on geometry



Pulsar models: Polar Cap

Polar Cap Model

Sturrock (1971); Ruderman & Sutherland (1975); Harding (1981); Daugherty & Harding (1982)



- Acceleration of electrons
- Cooling mechanisms
  - a) Curvature radiation
  - b) Synchrotron, I.C. of X-rays
- γ-rays interact with magnetic field, via *Magnetic pair production*

$$\gamma + \vec{B} \rightarrow e^+ + e^-$$

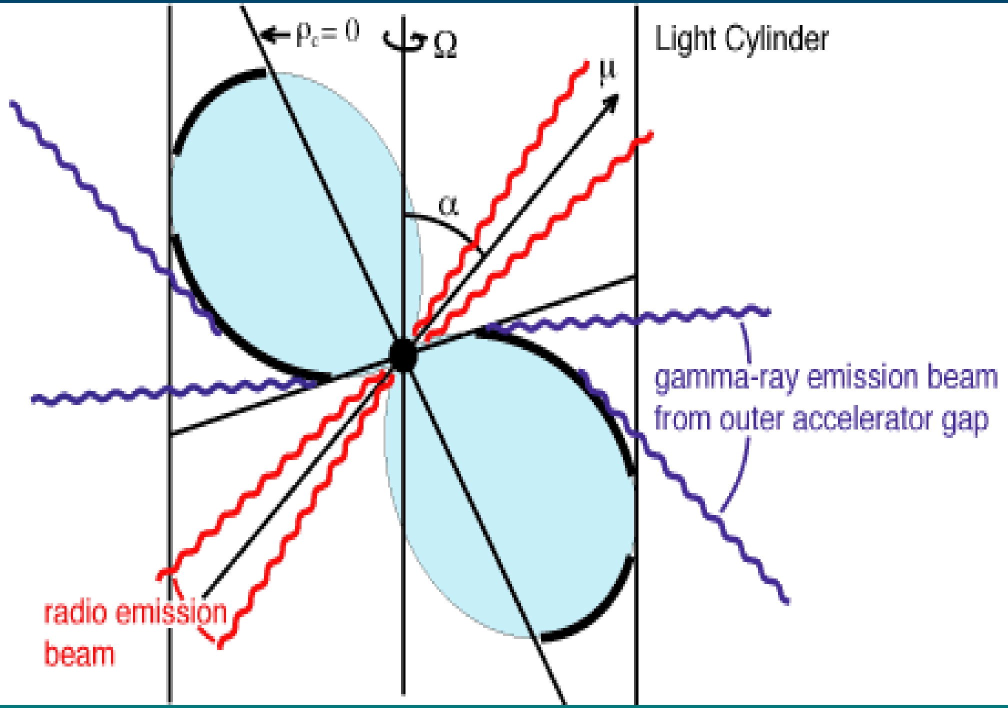
$$\kappa \propto B_p \cdot \exp(-1/E_\gamma B_p)$$

Polar Cap model predicts ***super-exponential cutoff*** in high energy γ-ray spectra

Pulsar models: Outer Gap

Outer Gap model

Cheng, Ho & Ruderman (1986); Romani (1996)



- γ-ray emission occurs near LC
- Charges accelerated in vacuum gap

  → *γ-rays via Curv. rad.*
- **B** not strong enough for pair-production. But:

  *γ-rays i*nteract with non-thermal X-rays

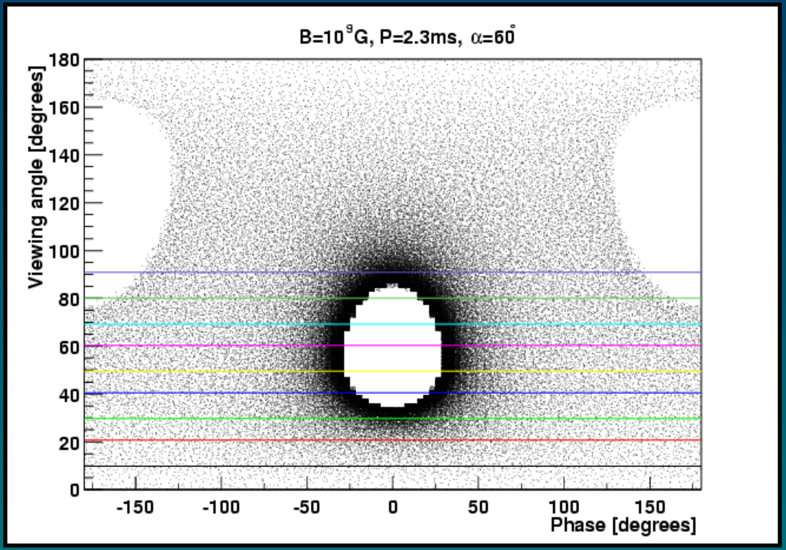
$$\gamma\gamma \rightarrow e^{+}e^{-}$$

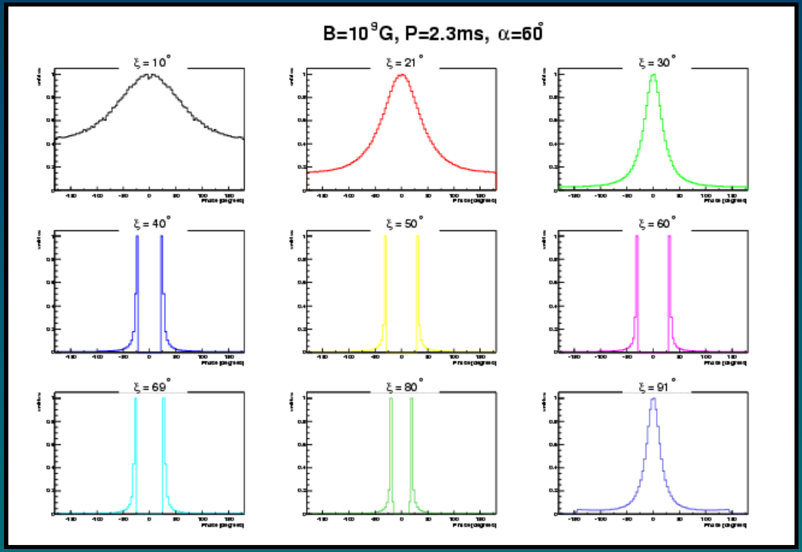
Softer ***exponential cutoff*** in the high energy γ-ray spectra

Electrons may up scatter IR photons to TeV Gamma-rays

Lightcurves zoo (in polar cap model)

Understanding light curves





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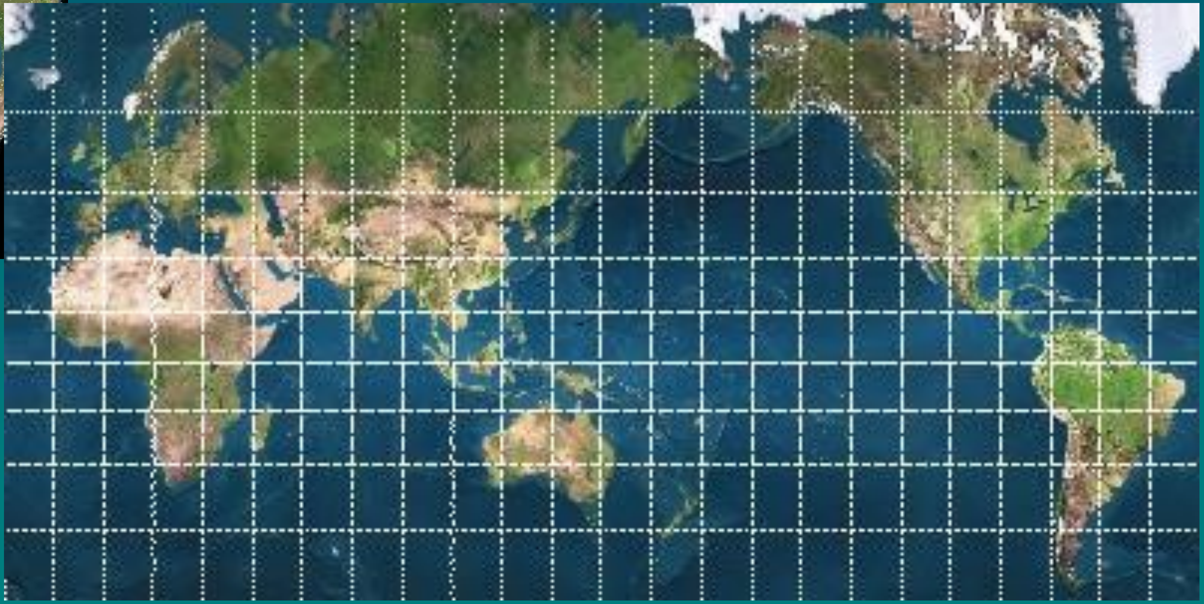
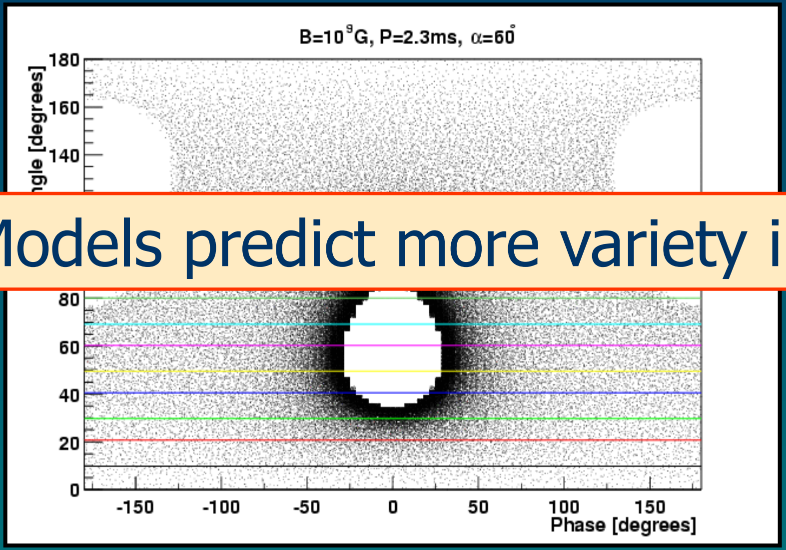
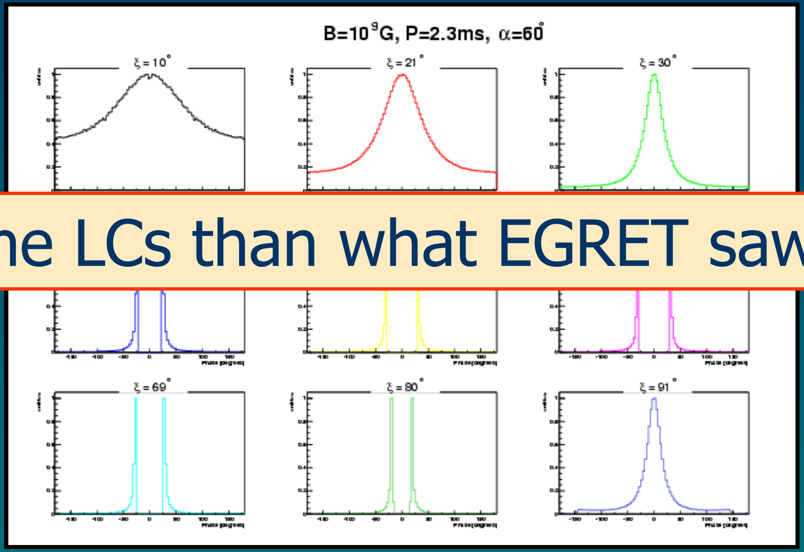
Understanding light curves



Lightcurves zoo (in polar cap model)

Understanding light curves





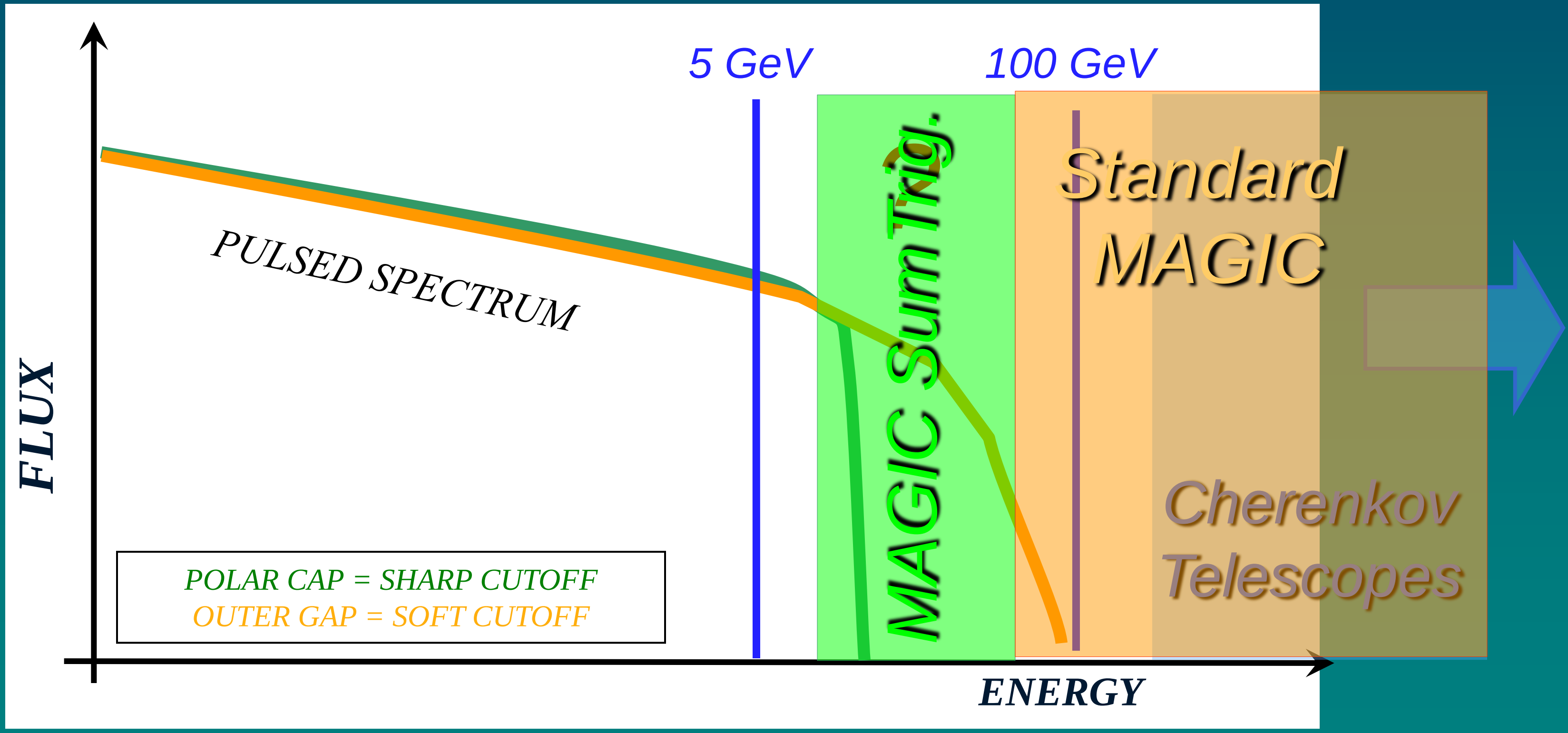
Models predict more variety in the LCs than what EGRET saw

- *Light curves depends on:*
  - *pulsar geometry, hence on P (polar cap size ~ $P^{-1/2}$)*
  - *Observer*
- *Different observers can see completely different light curves for the same pulsars*
  - *2 and 1 peak light curves are explained in this scenario*

Where do γ-rays come from? Outer/slot gap,polar cap?

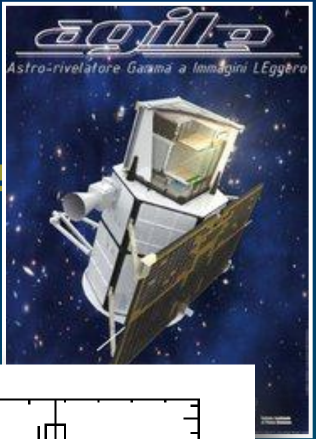
Discrimination between models

- Different models predict different spectral cutoff.
- Measuring the spectral tail is possible to distinguish between models.



Recent Space observations of gamma-ray pulsars

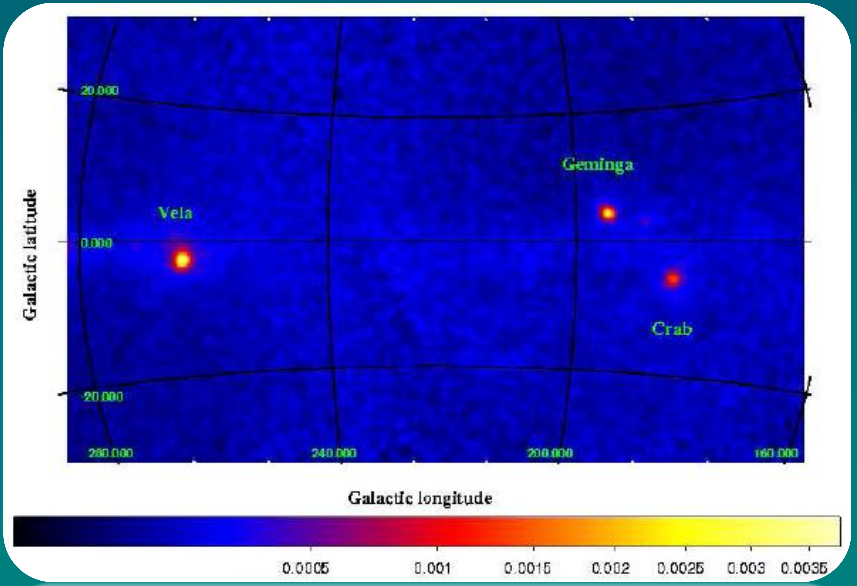
AGILE

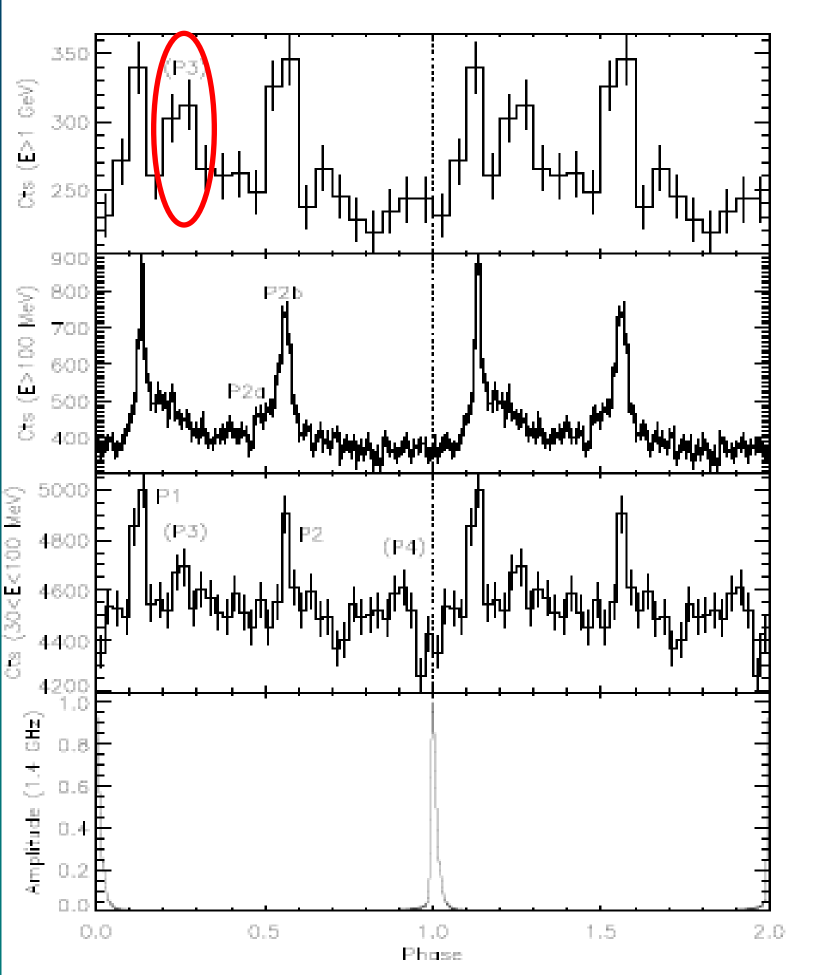


- Almost more statistics than EGRET, but with better timing

Example: Vela

- *The see new features in the light curve > 1 GeV:*
  - *3rd peak*



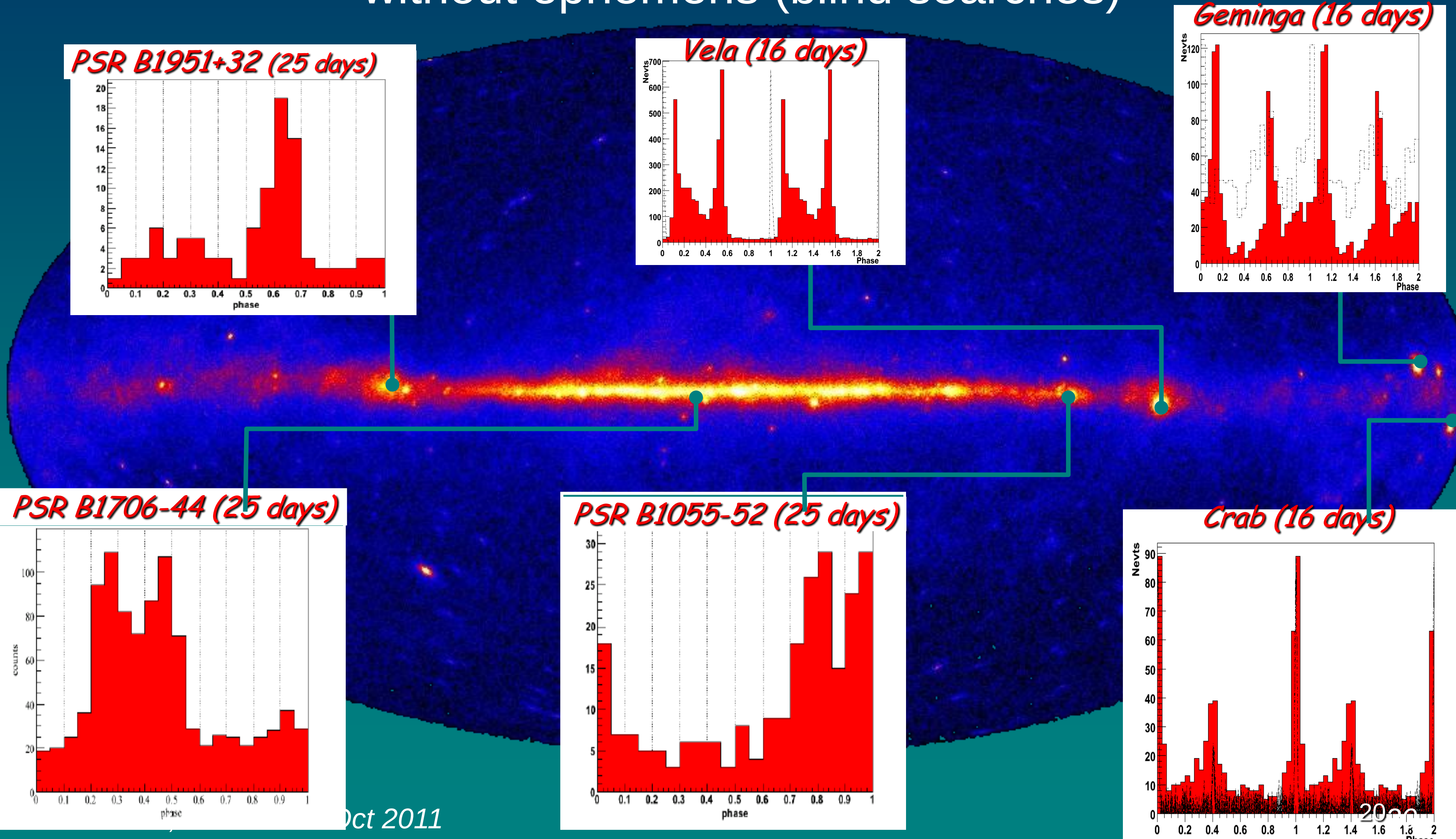


Fermi

- Fermi working very successfully
  - 4 days Fermi = 1 year EGRET!
    - due to 25 x higher sensitivity, and overall, to larger FOV (Fermi map the whole sky every 3 hours)
    - From vela they collect ~10 phs above 10 GeV every day
- Pulsar Highlights:
  - Confirmed all EGRET pulsars and candidate ones
  - Discovered many geminga-like pulsars
  - Discovered new γ-ray pulsars associated with Unid. EGRET sources
  - Discovered a population of ms pulsars

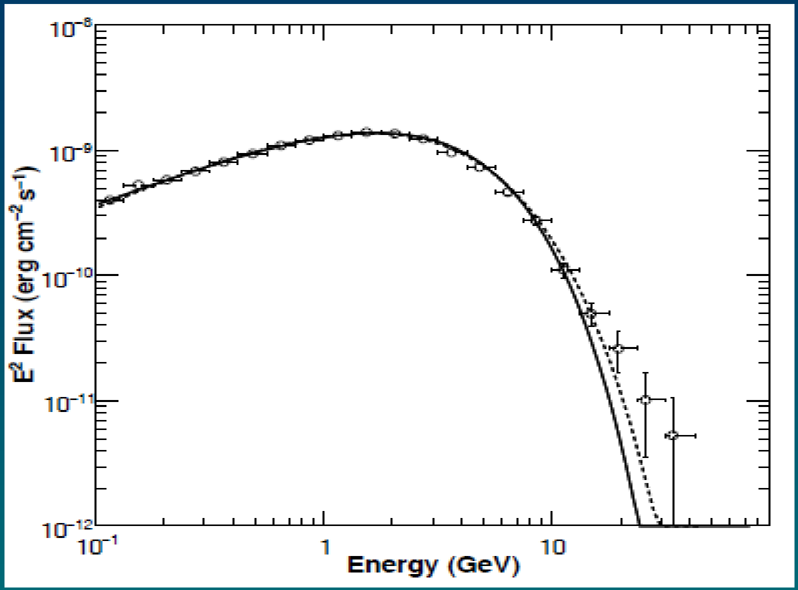
Fermi: EGRET pulsars

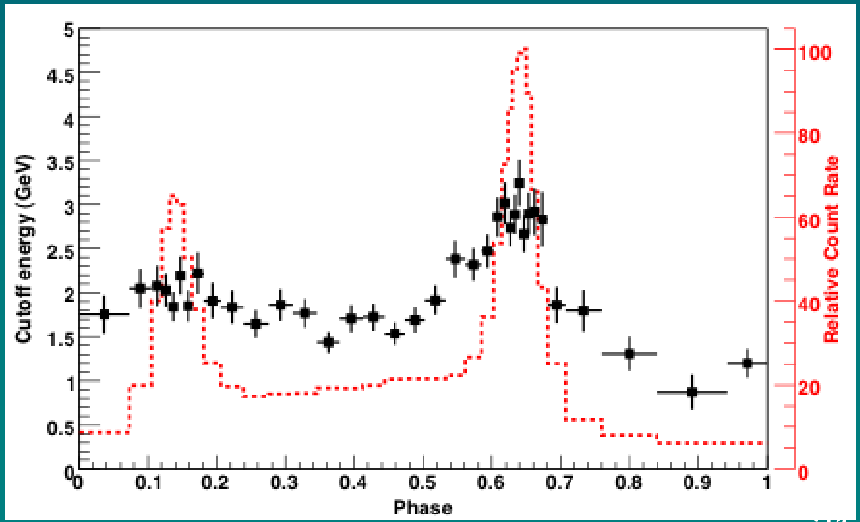
After 2 months, signal strong enough to see EGRET pulsars without ephemeris (blind searches)



Fermi: Geminga

- Spectral index and cutoff energy variations thought to to emission altitude changes with energy (see e.g. Geminga).
- In general, pulsar spectra are consistent with simple-exponential cutoffs, indicative of absence of magnetic pair attenuation.

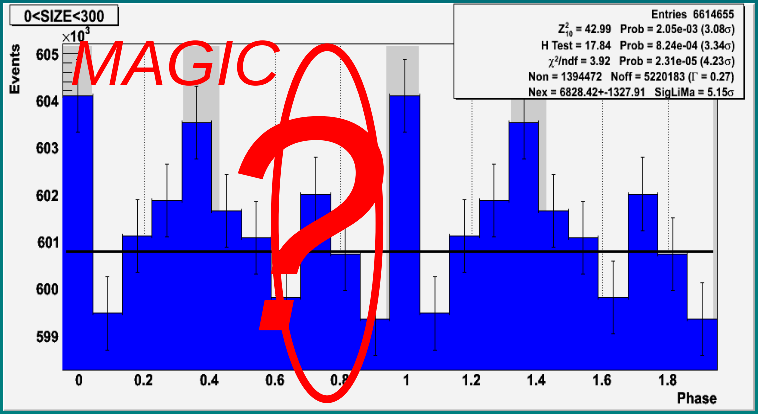


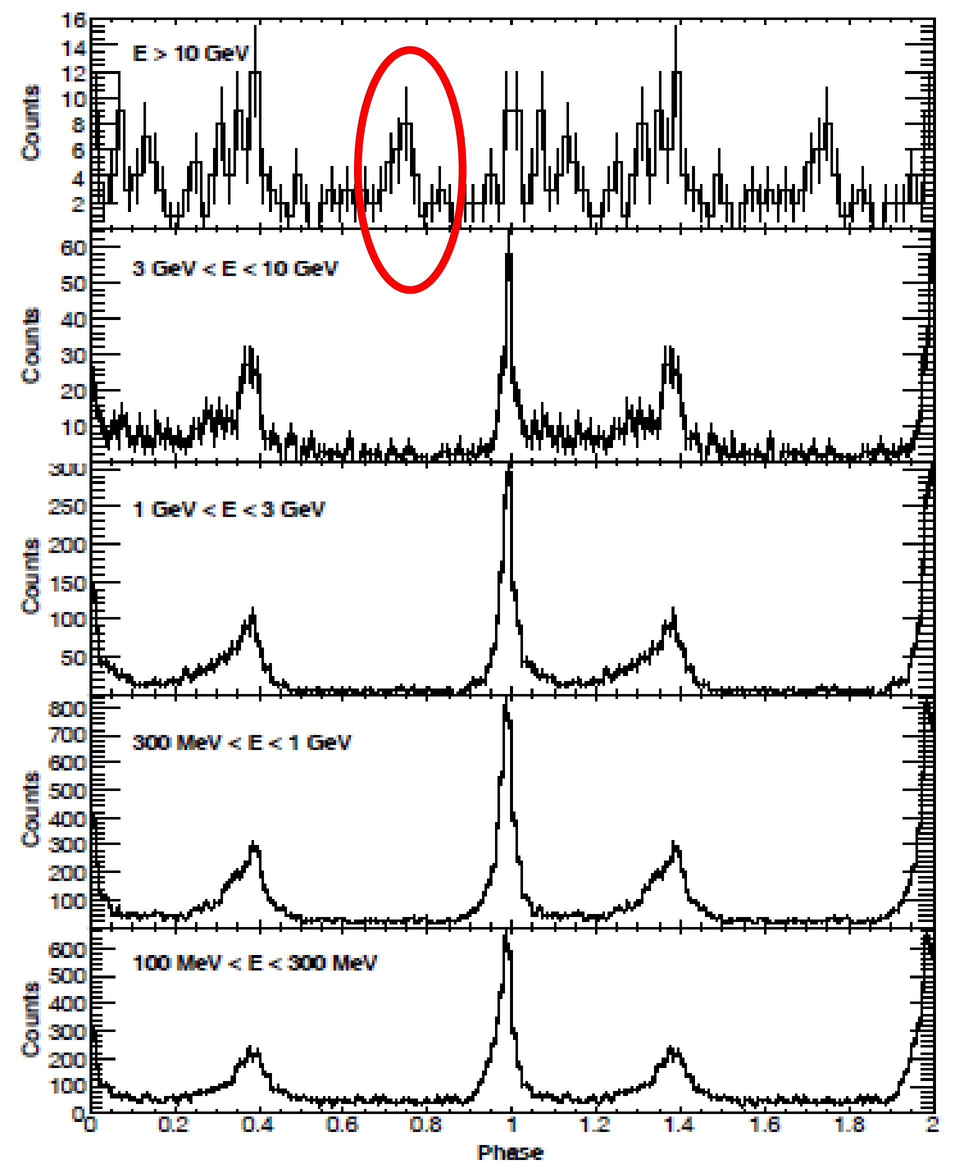


Cutoff energy vs. pulse phase, for the Geminga pulsar

Fermi: Crab

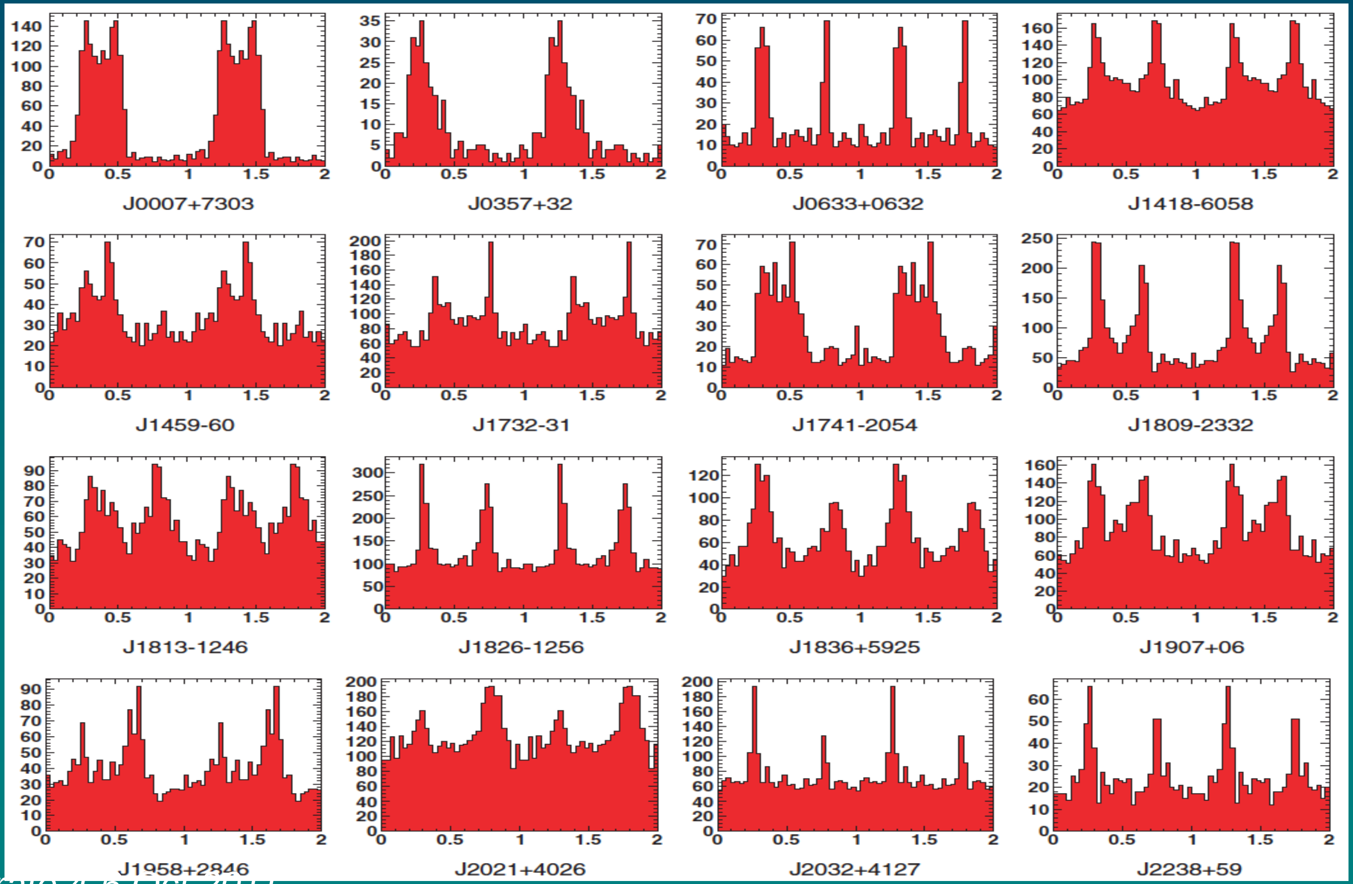
- Peaks are asymmetric
  - Peak positions stable with energy
  - P1/P2 ratio decrease with energy
- A third peak (2.3□) observed above 10 GeV at phase ~0.74, coincident with a radio feature (HFC2)





Fermi: Discoveries in blind searches

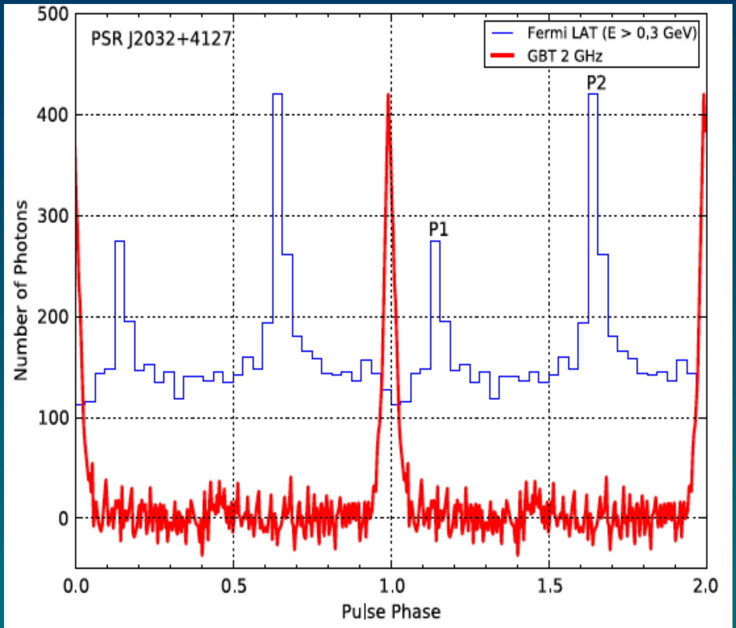
- Higher statistic of Fermi compared to EGRET allows blind searches
- After 4 months of data → 16 pulsars found



Fermi: Discoveries in blind searches

Some Not radio-quiet any more

- Fermi provides precise pulsar positions → sensitive pulse searches in (archival or new) radio or X-ray data
  – PSRs J1741-2054, J1907+0602 & J2032+4127 are nor radio-quiet pulsars any more.
- Unknown pulsars must be powering many Fermi unidentified sources
  – Counterpart searches are underway

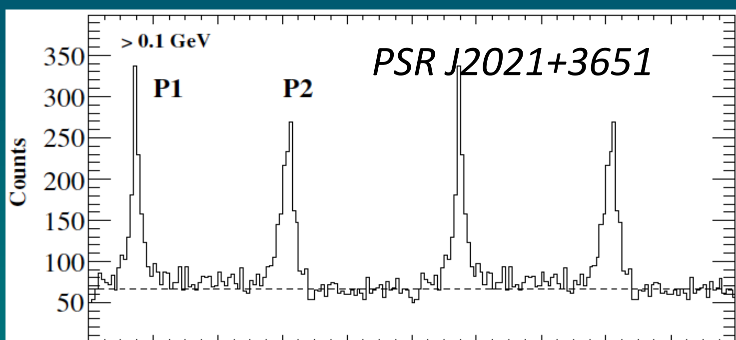


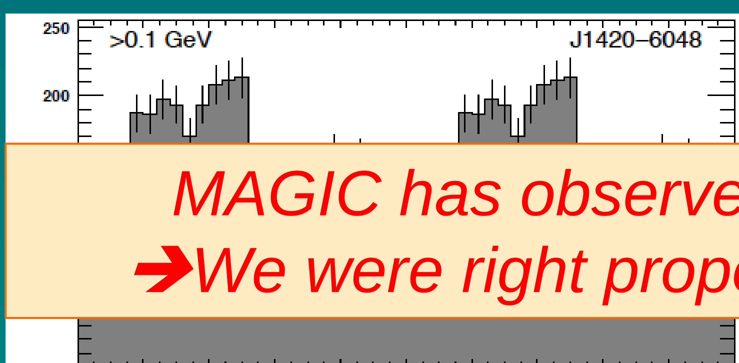
No longer just gamma-ray pulsars!

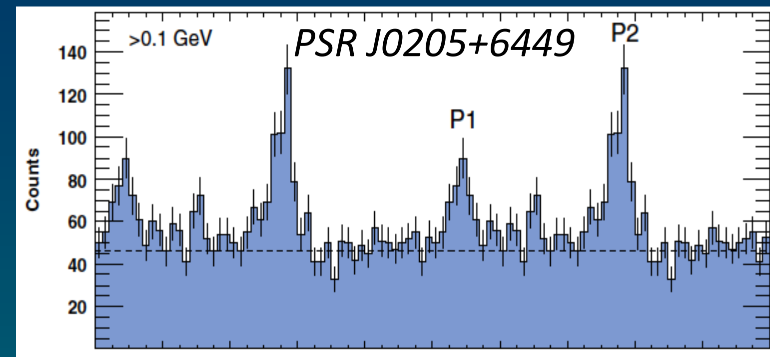
(Camilo et al., ApJ 705, 1, 2009)

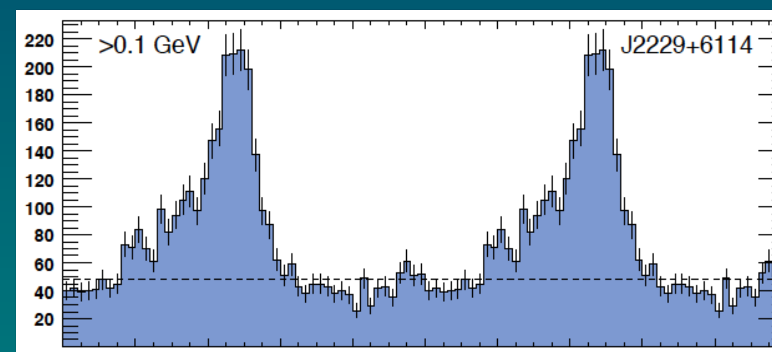
Fermi: Young radio-loud pulsars

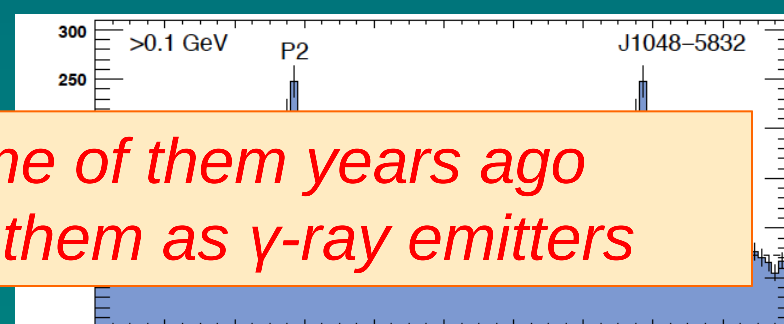
- Fermi detected young radio-loud γ-ray pulsars, all highly energetic ($\dot{E} > 3\ 10^{33}$ erg/s).
- Many coincident with Unid. EGRET sources:









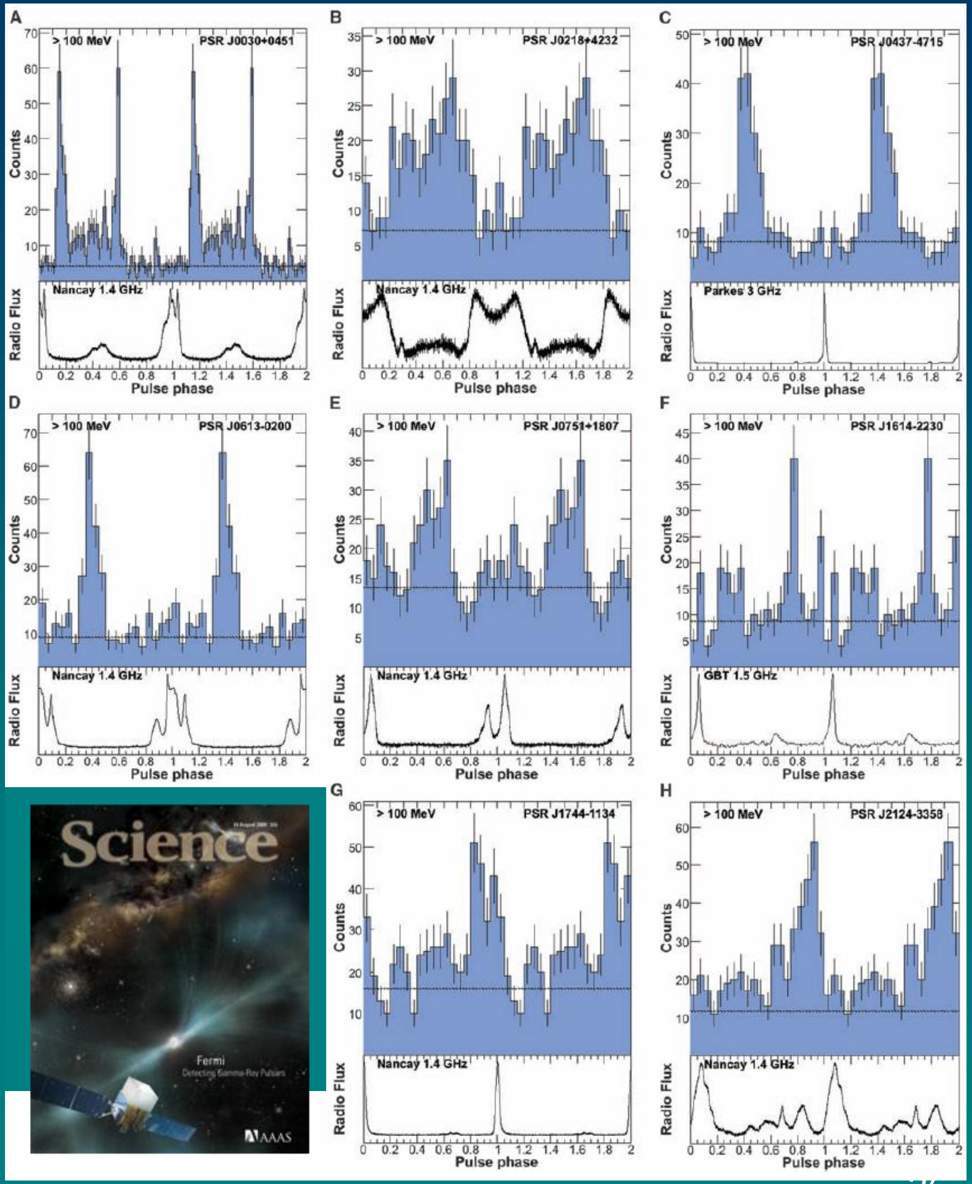


MAGIC has observed some of them years ago
➔We were right proposing them as γ-ray emitters

Fermi: Radio-loud millisecond pulsars

- First ms ever detected in γ-rays: PSR J0030+0451

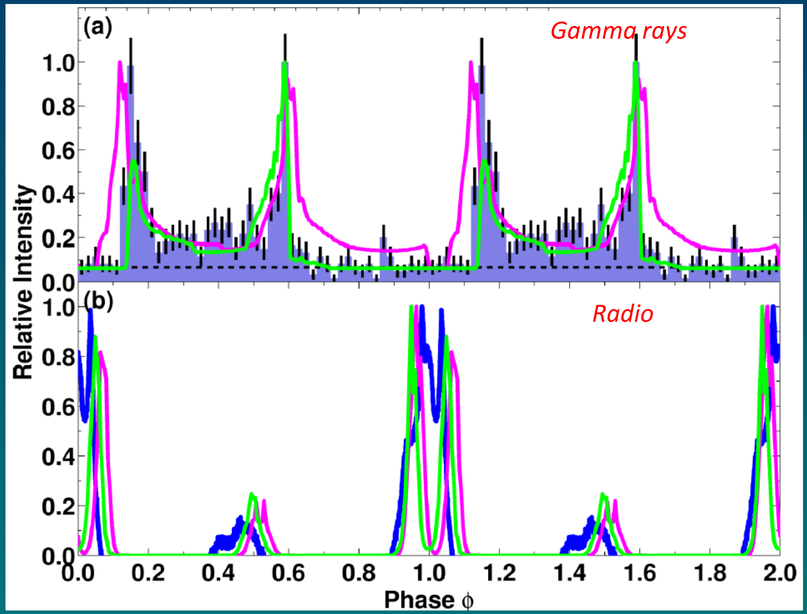
- After 9 months of data taking, 8 γ-ray MSPs (Abdo et al. Science 325, 848, 2009).



What do we learnt from Fermi?

Light curves

- Typically 2 peaks
  - the first one lagging the radio by 0.1 to 0.2 (with a few exceptions, e.g. J2229+6114).
- Two-Pole Caustic (TPC) or the Outer Gap (OG) models generally provide good fits to the observed profiles.
  - Polar Cap emission remains plausible for some pulsars.

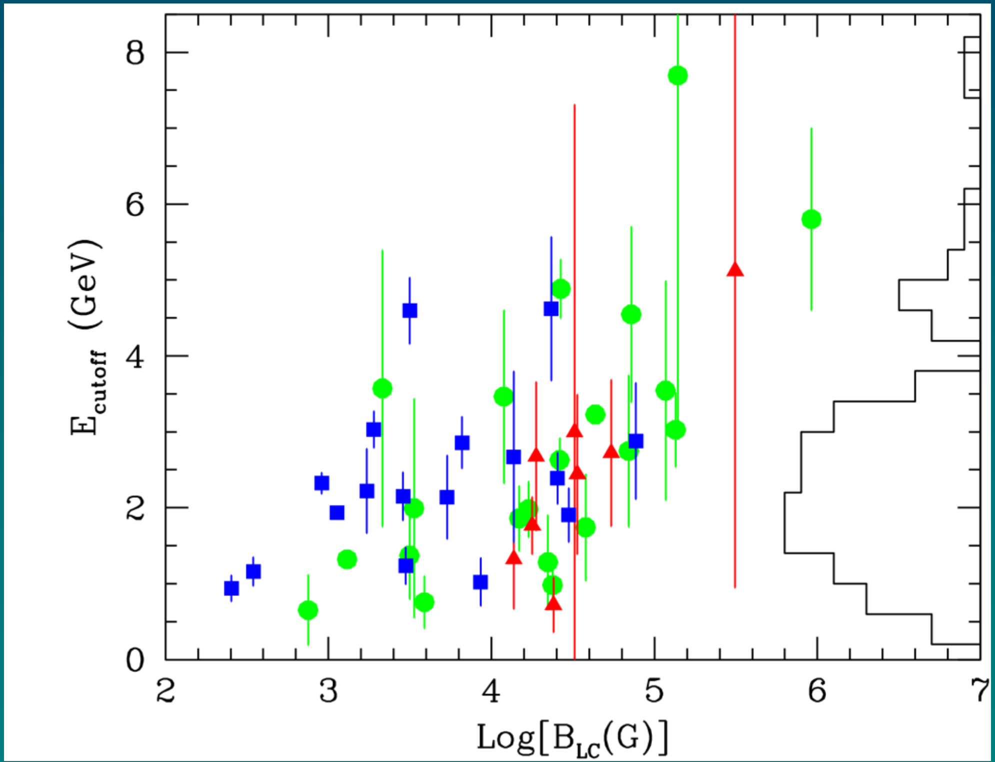


OG (green) and TPC (magenta) fits to J0030+0451's light curve (Venter, Harding & Guillemot, ApJ 2009)

What do we learnt Fermi?

Spectra

- Spectra are consistent with exponentially cutoff power-laws
- cutoff energies below 10 GeV.



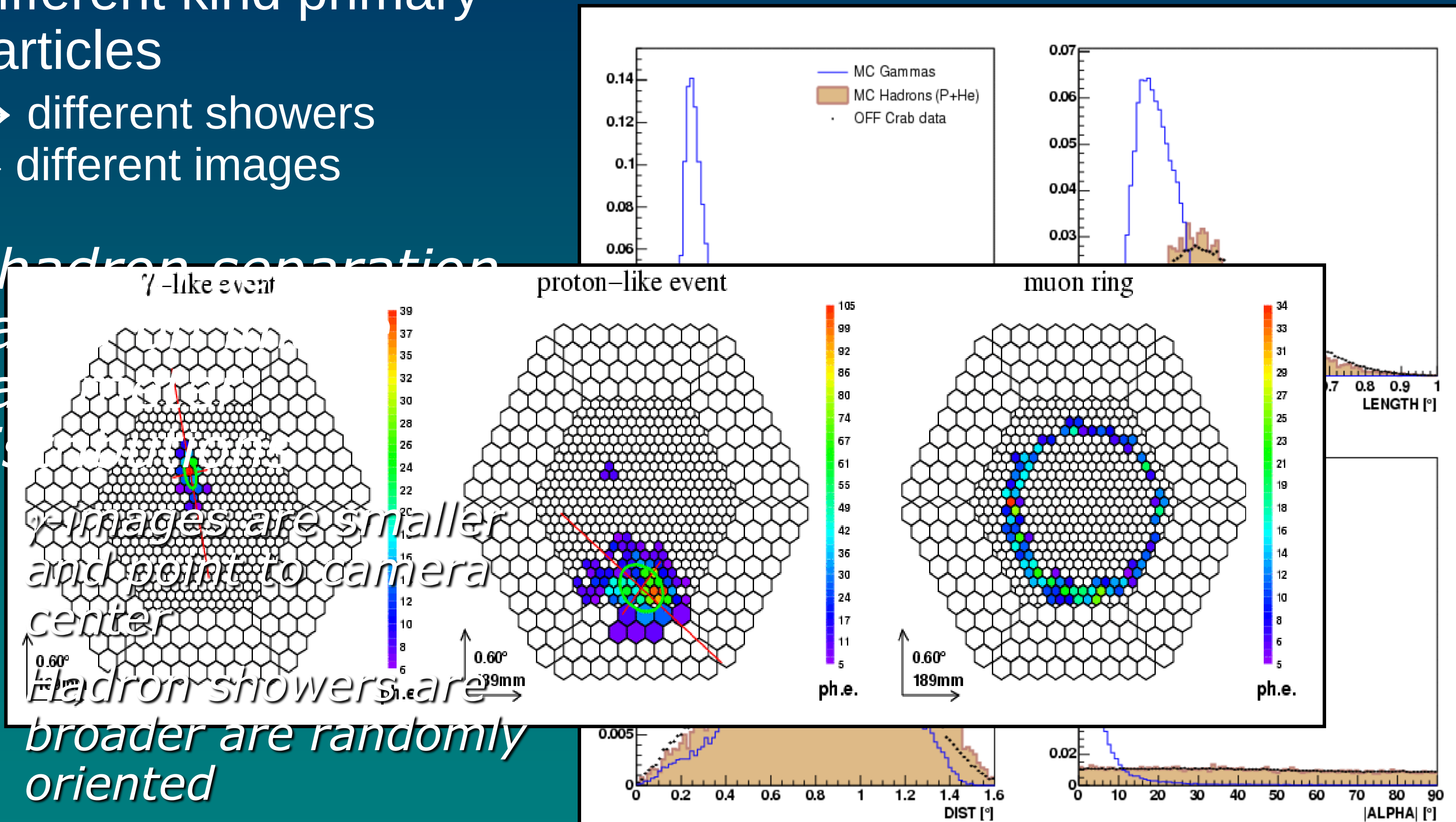
Cutoff energy vs. B_{LC} for the 46 catalog PSRs

Pulsar Timing Analysis

γ/hadron separation (I)

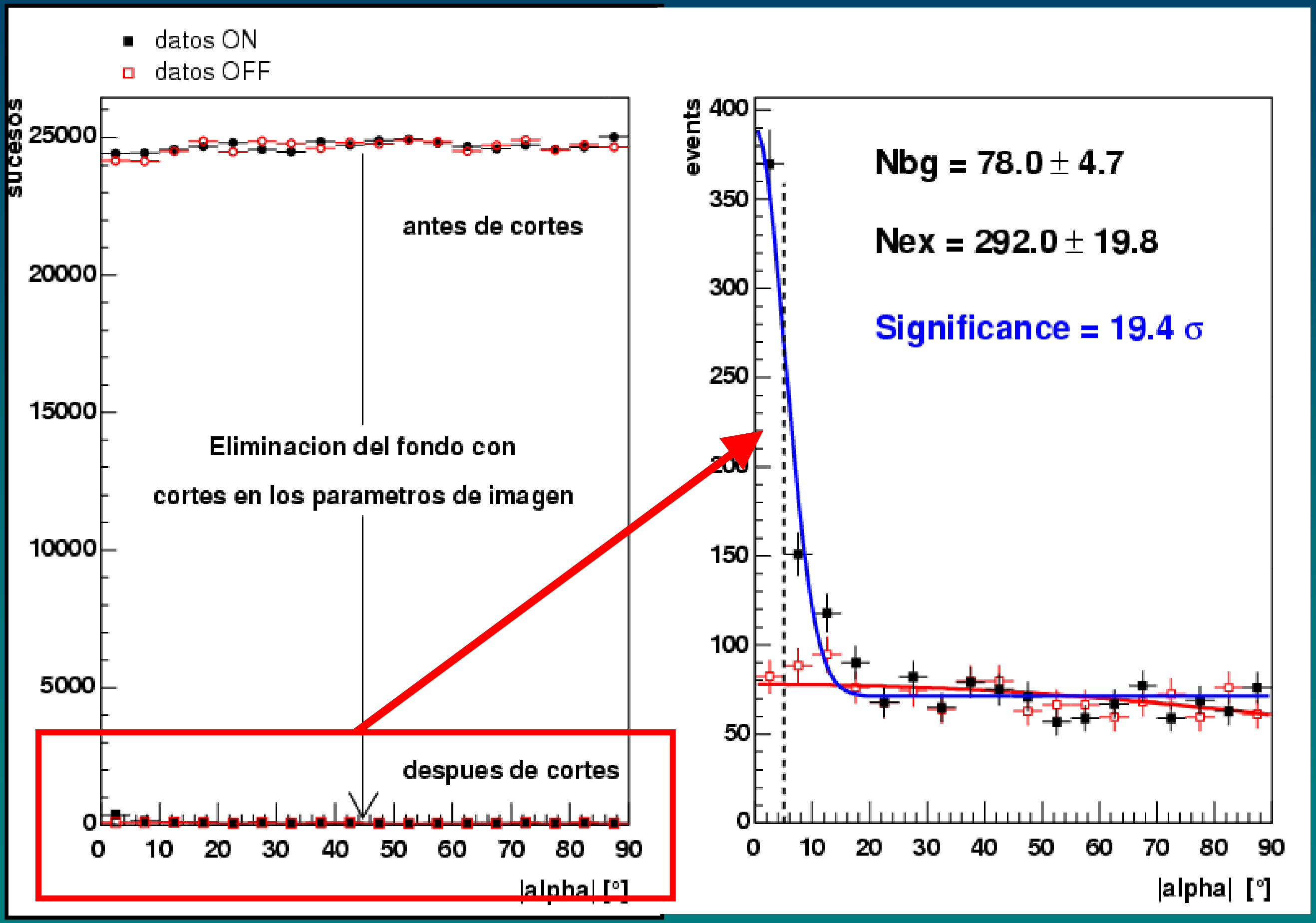
- Different kind primary particles
  → different showers
  → different images

- γ/hadron separation based on ... parameter distributions
  - γ-images are smaller and point to camera center
  - Hadron showers are broader are randomly oriented



γ/hadron separation (II)

- After applying γ/hadron cuts based on image shape, exploit shower direction



Timing analysis

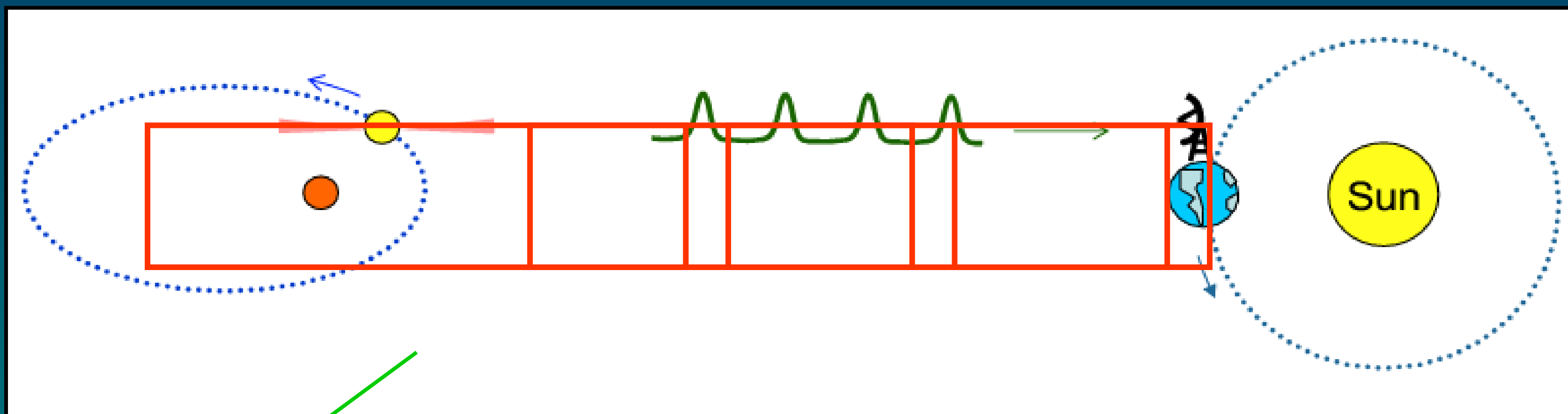
Goal: *Find the periodic signal of the pulsar, hidden in the arrival times of the atmospheric showers*

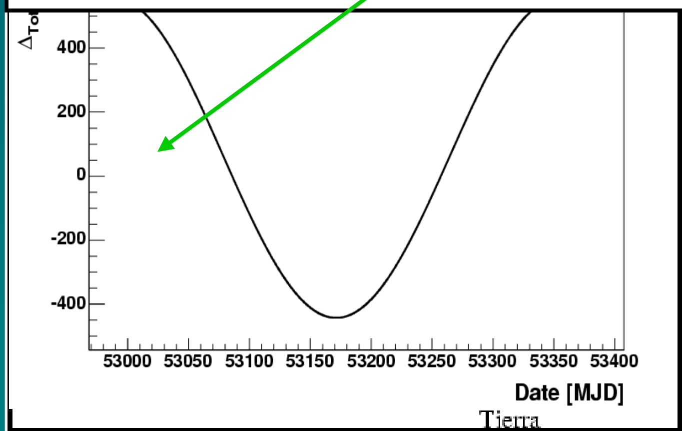
- *The timing analysis involves 4 steps:*
  - *Barycenter correction*
  - *Obtain the Light curve*
  - *Application of Uniformity test*
  - *Upper limits calculation*

All these steps have been implemented in a dedicated software, for the pulsar Analysis in MAGIC

Timing analysis (I)

Barycenter correction

- Remove the effect of the earth movement on the arrival times $t_{UTC.}$
- 



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

$$\Delta_{TDB-UTC} = leap\sec + 32.184 + \Delta_{TDB\_TDT}$$

Timing analysis (II)

Ligth curve

- If *F* is the known rotational frequency of the pulsar at time T_0, the number of revolutions in $dt=t-T_0$ is:

$$dN = F(t)\cdot dt \quad \xrightarrow{\text{Taylor}} \quad F(t) = F(T_0) + \dot{F}(T_0)(t-T_0) + \frac{1}{2}\ddot{F}(T_0)(t-T_0)^2 + \cdots$$

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

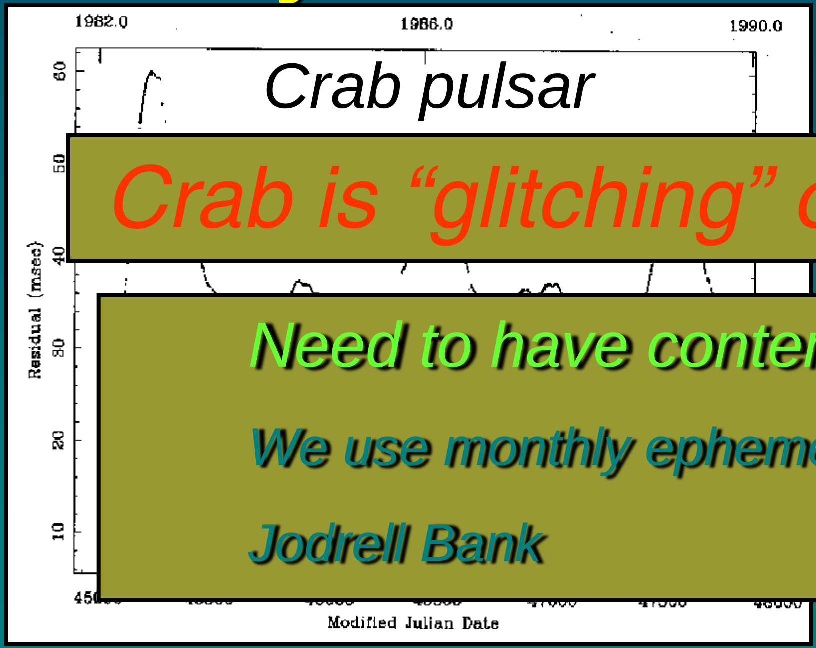
$$\phi(t) = \phi(T_0) + (t-T_0)F + \frac{1}{2}(t-T_0)^2\dot{F} + \frac{1}{6}(t-T_0)^3\ddot{F} + \cdots$$

where *t* is the barycenter time

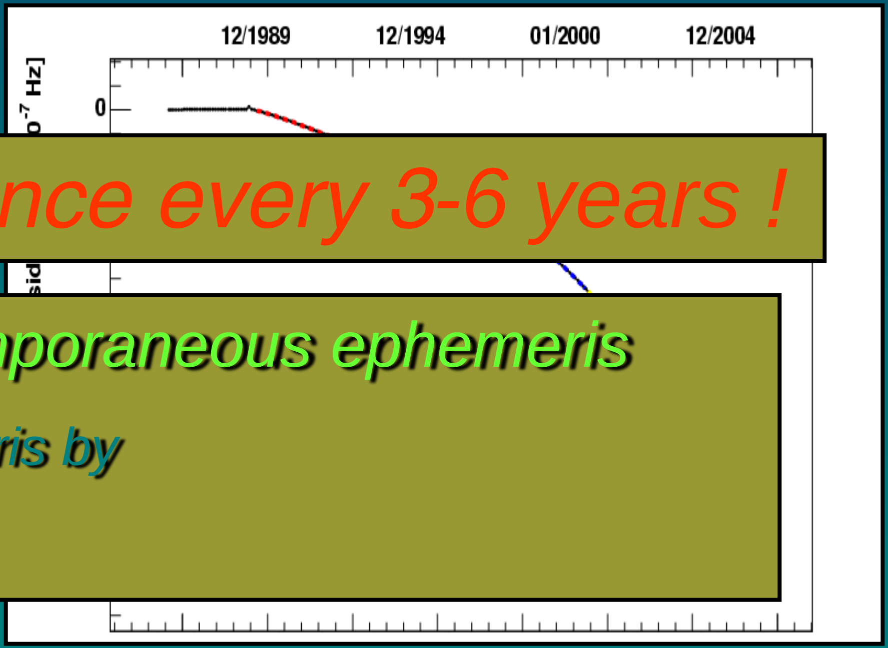
Timing analysis (III)

- Ephemeris are usually taken from radio observations but affected by irregularities in pulsar rotation*:*

Timing noise



Glitches



Crab is "glitching" once every 3-6 years !

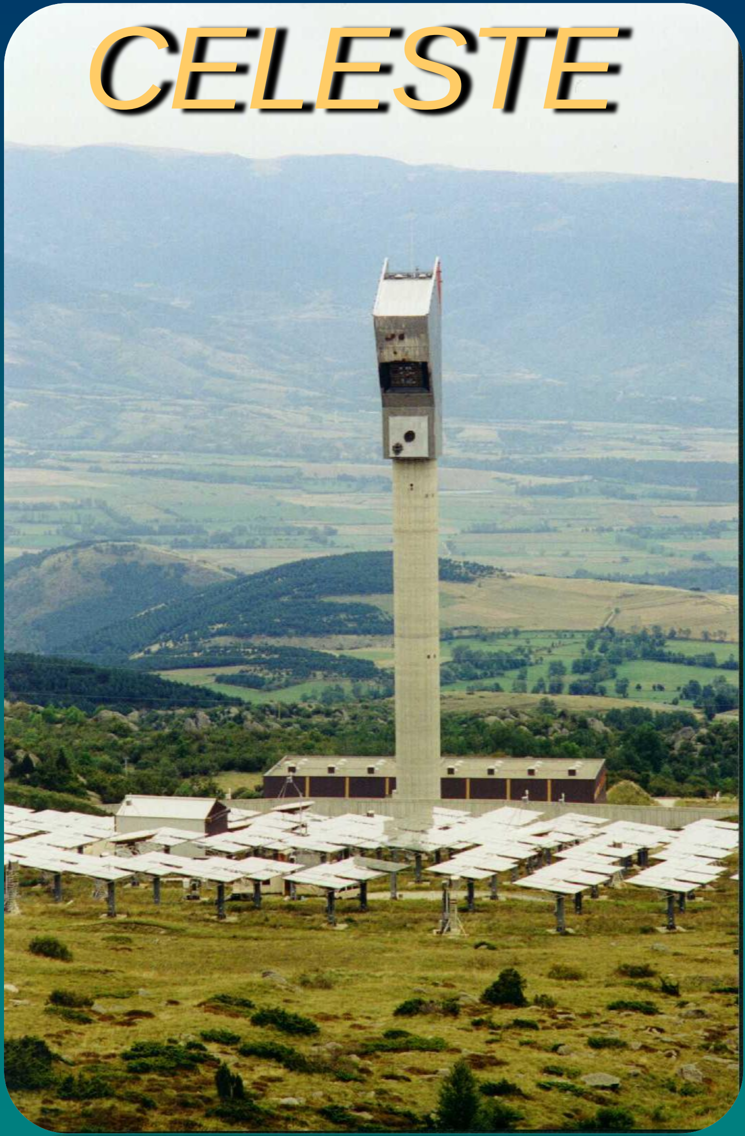
Need to have contemporaneous ephemeris

We use monthly ephemeris by

Jodrell Bank

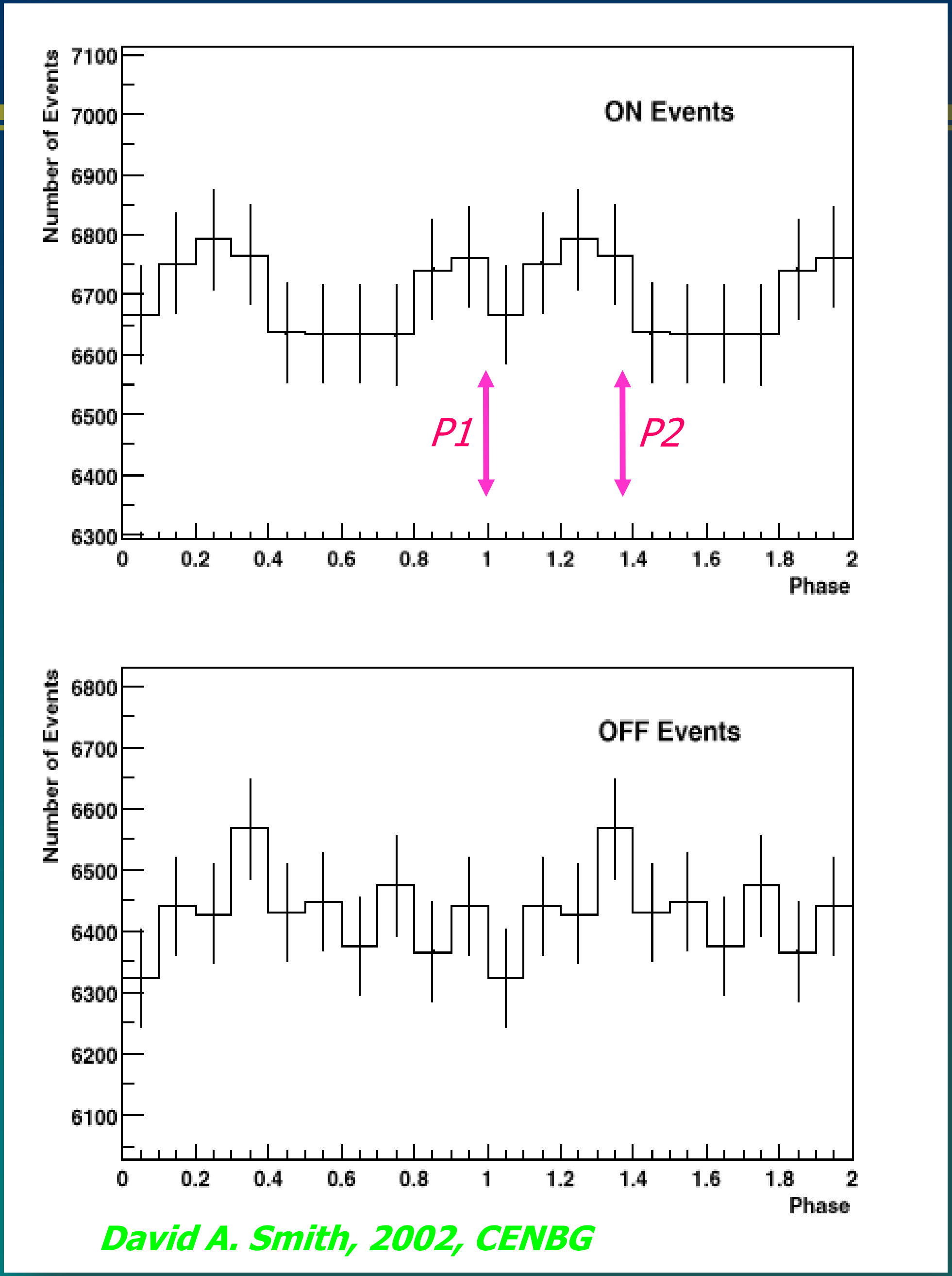
First attempts to see gamma-ray pulsars from ground

Results from Solar Plants

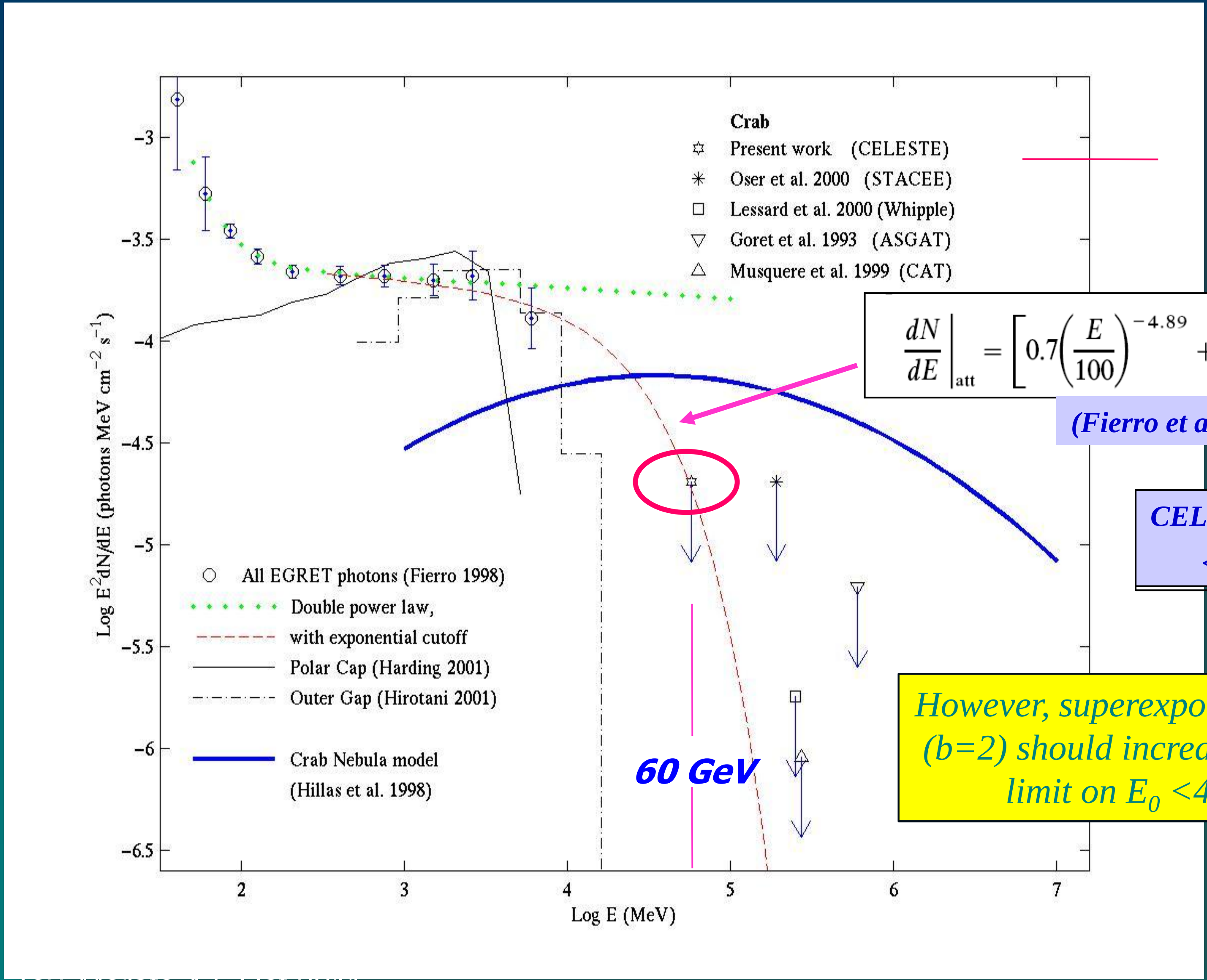


CELESTE: Crab observations

- No significance pulsed signal found.
- Obtained conservative upper limits



CELESTE: Crab pulsar limit



$$\left.\frac{dN}{dE}\right|_{att} = \left[0.7\left(\frac{E}{100}\right)^{-4.89} + 2.3\left(\frac{E}{100}\right)^{-2.05}\right]e^{-E/E_0}$$

(Fierro et al)

CELESTE: Eo<26 GeV

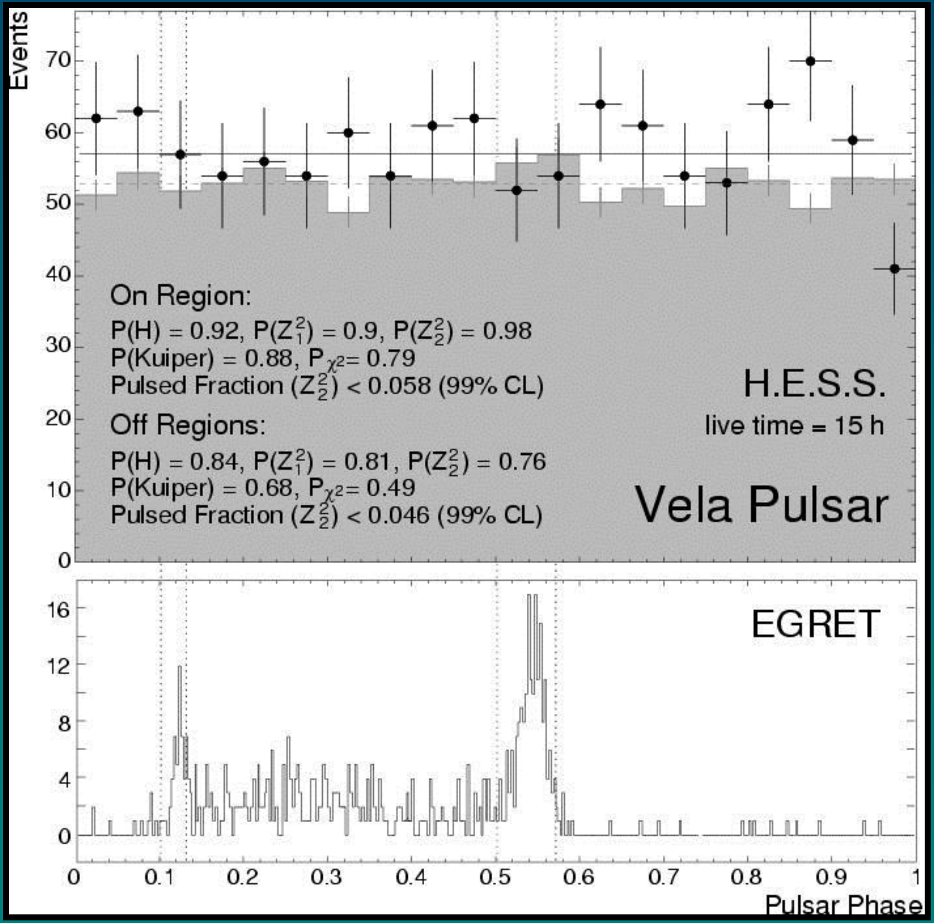
<0.5 γ/minute

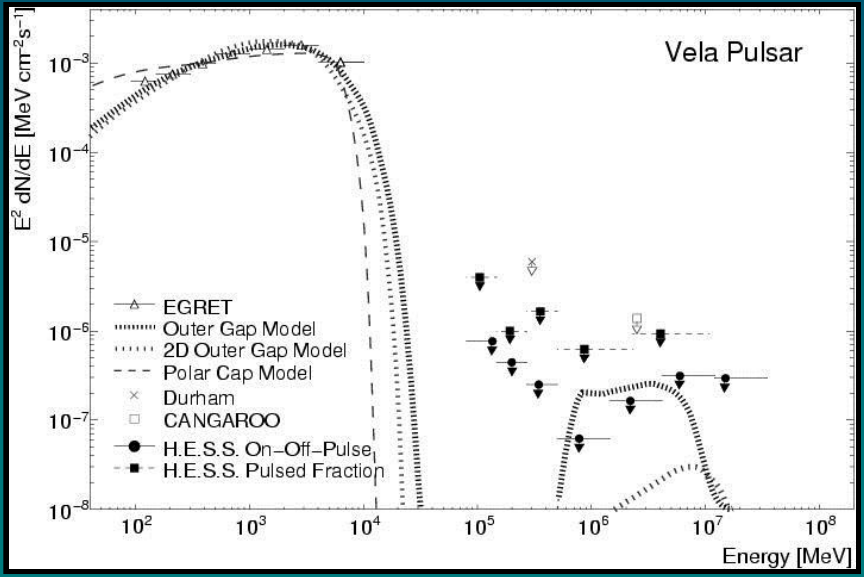
However, superexponential cutoff (b=2) should increase the upper limit on E_0 <40 GeV.

Results from HESS

HESS results

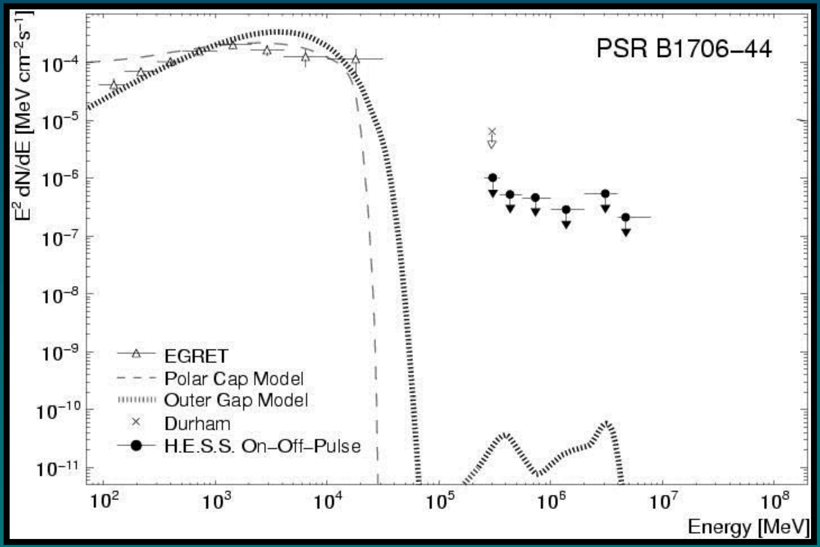
- HESS searched for emission >100 GeV from 7 young pulsars (4 were seen by EGRET)
- No pulsed signal found → Upper limits

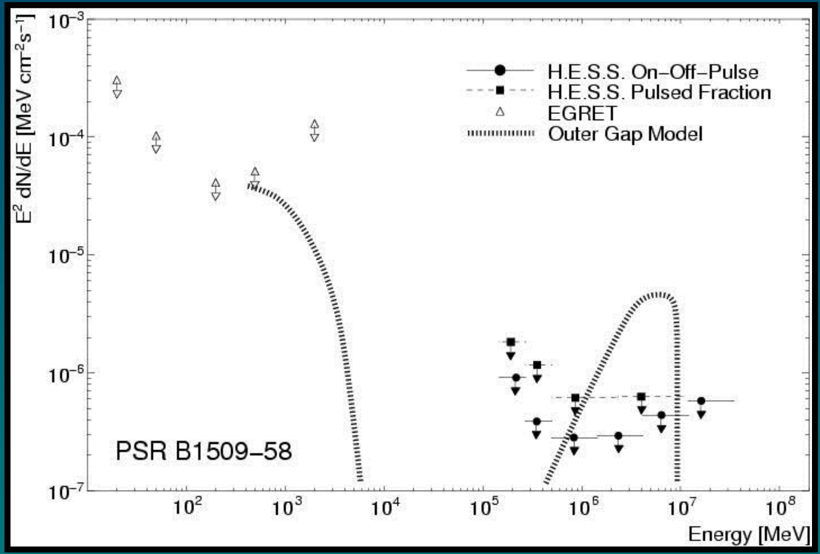




HESS results

- HESS searched for emission >100 GeV from 7 young pulsars (4 were seen by EGRET)
- No pulsed signal found → Upper limits

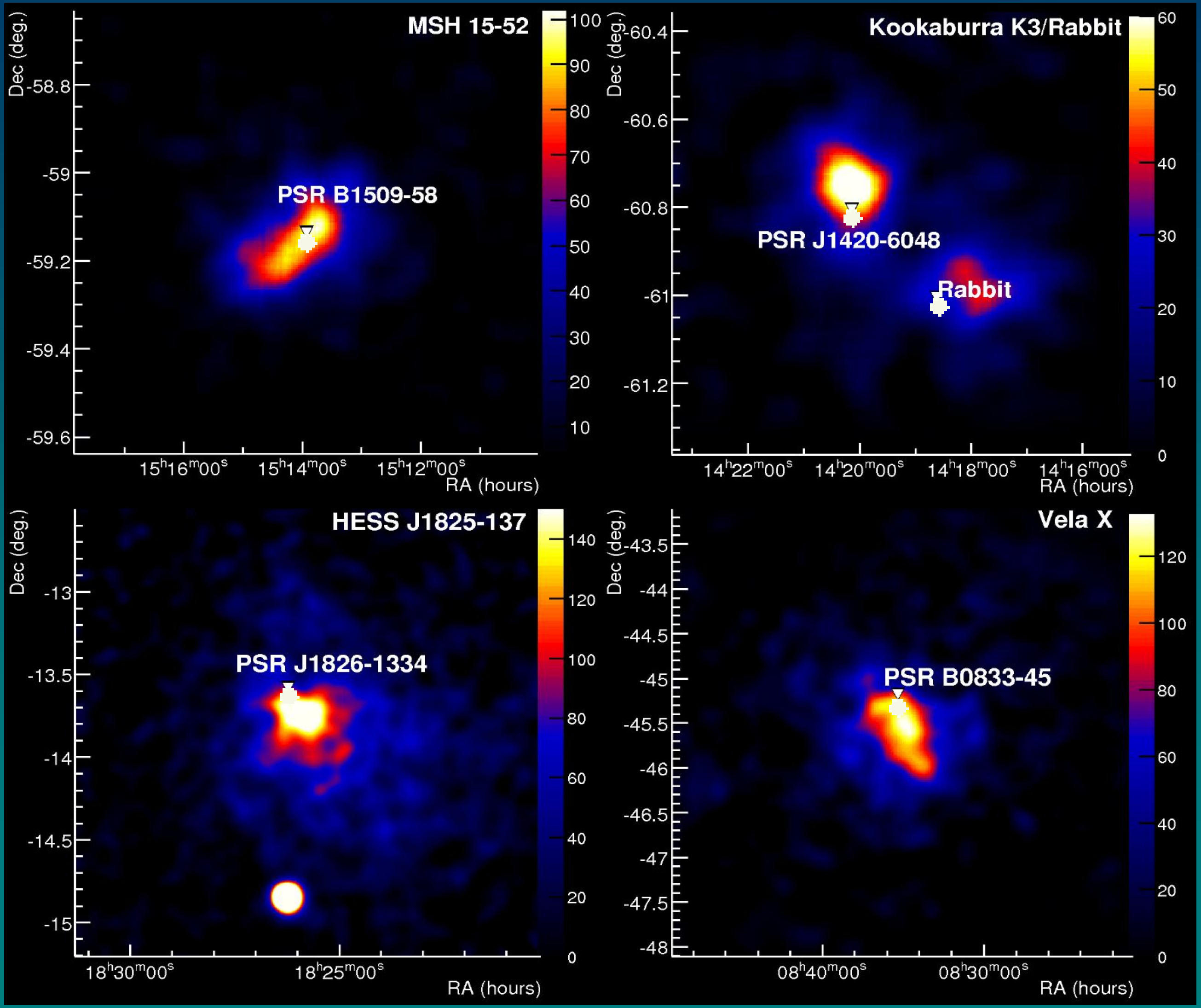




- *U.l. implies that* $\eta = \frac{L_\gamma}{\dot{E}} < 10^{-4}$
- *constrain IC component predicted by outer gaps*

HESS results

- Only the Pulsar Wind Nebulae are visible at TeV



MAGIC observations

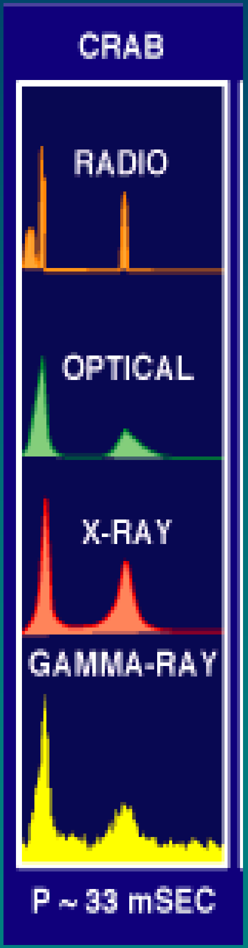
MAGIC & Pulsars

- MAGIC tried from the very beginning to detect pulsars
  - Developed dedicated hardware to help to the pulsar program (central pixel, sumtrigger,…)
- Main targets: Crab and other EGRET pulsars observed since 2005
- Other observed targets:
  - PSR J0205+6449, PSR J2229+6114/ 3C 58, PSR J0218+4232
  - ms pulsars in M13

MAGIC optical observations of Crab

***Motivation:* Check that MAGIC electronic+software are reliable for γ-ray pulsar searches**

- *MAGIC PMTs designed to detect fast Cherenkov pulses ~2ns*
  → Need to be adapted to low frequency observations
- A PMT was modified to be set at the camera center for optical observations



Electronic Chain

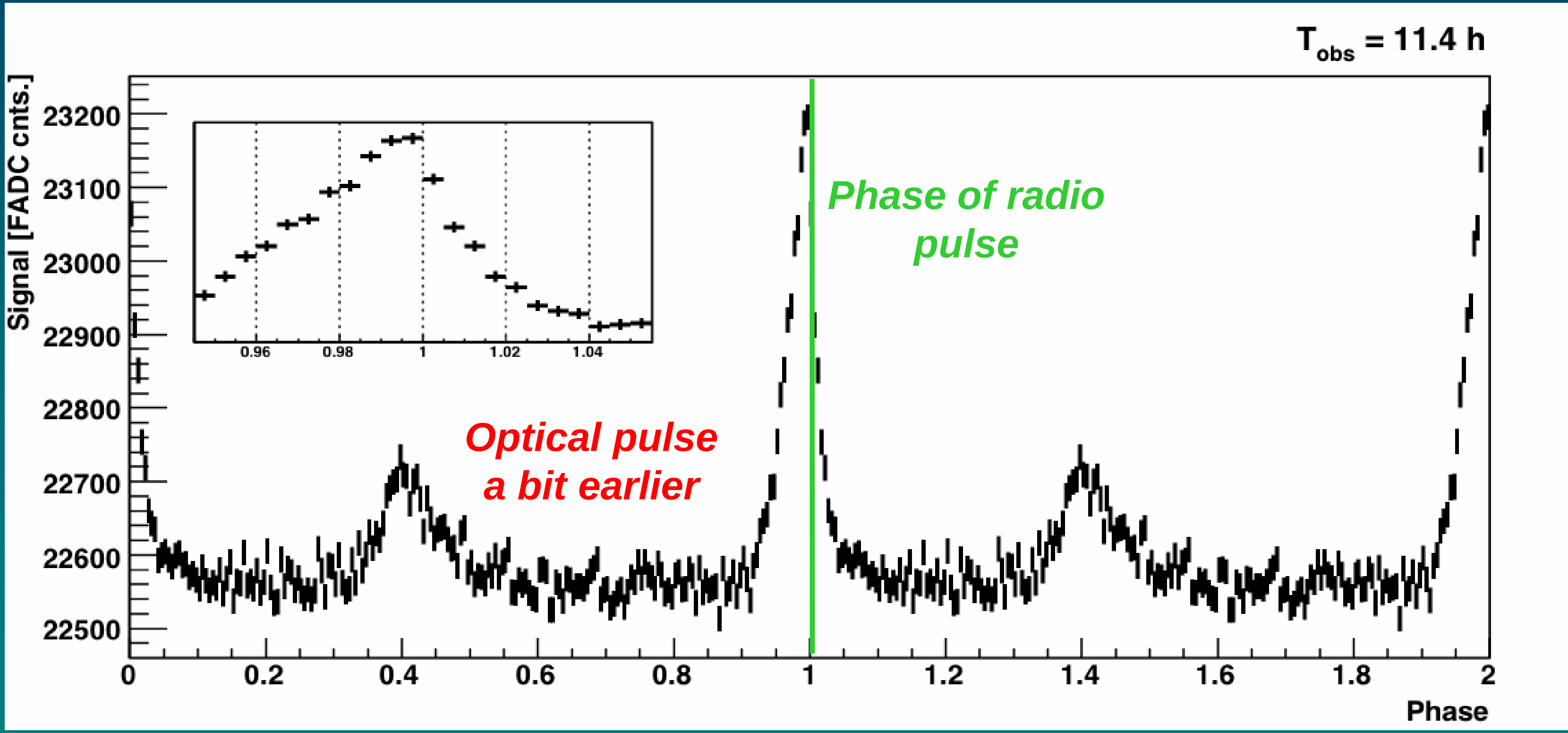
- Cpix signal is split in 2:
  → To 16 bits ADC, rate 20 kHz
  → MAGIC FADC

Allows γ and optical simultaneous observations

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

MAGIC optical observations of Crab

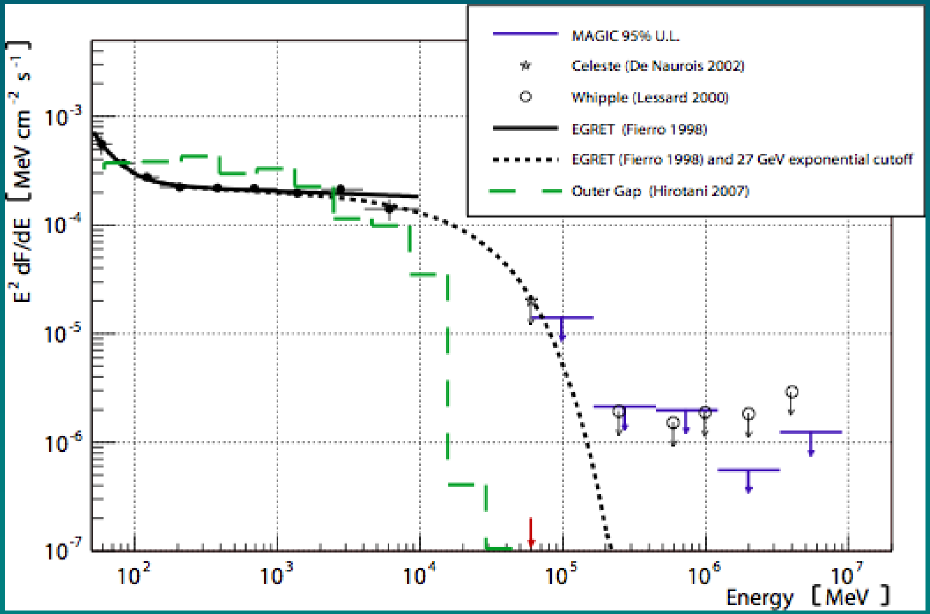
- MAGIC Crab campaign observed in optical and γ simultaneously $\rightarrow$ *Made Crab result robust*

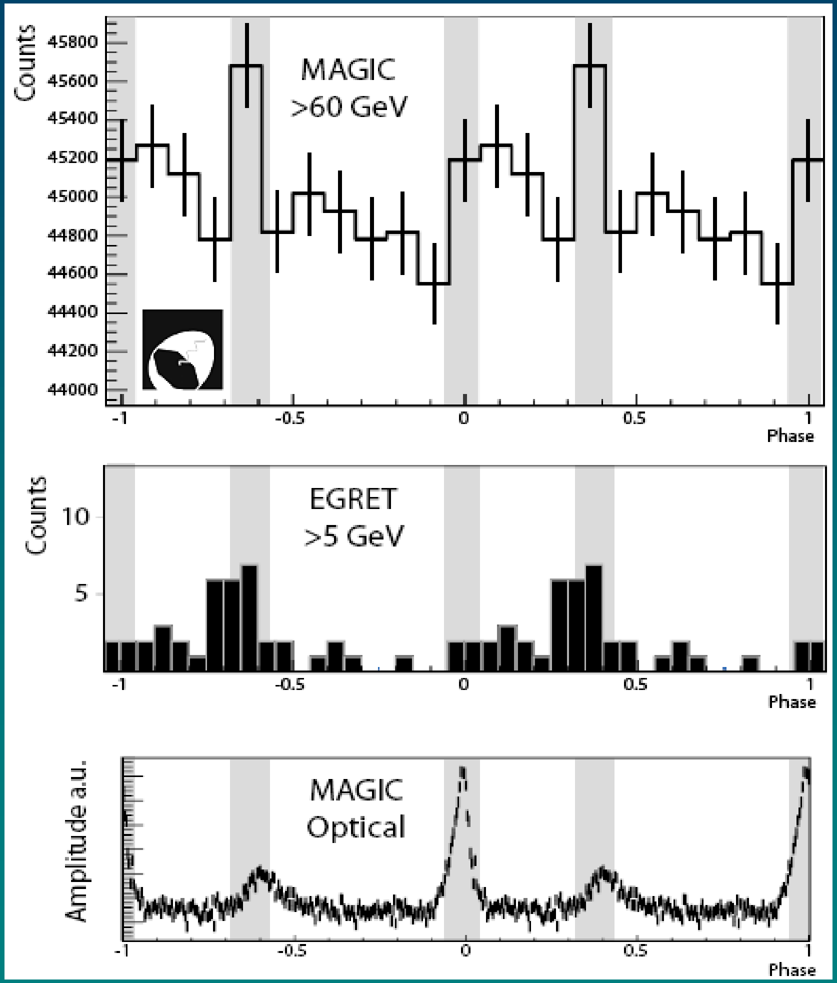


First Crab observations with MAGIC

- Data taken in Oct-Dec 2005.
  16 hours of optimal quality
- A hint of a signal found from P2
  - 2.9σ in phase with EGRET
- Derived upper limits
  - Eo<27 GeV (exp. case)
  - Eo<60 GeV (super-exp case)

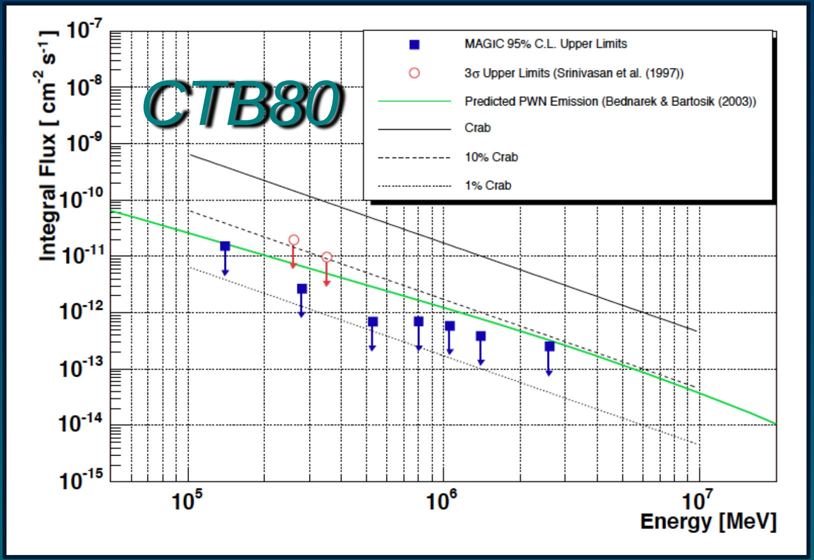
J. Albert et al., Astrophys. J. 674,1037 (2008)

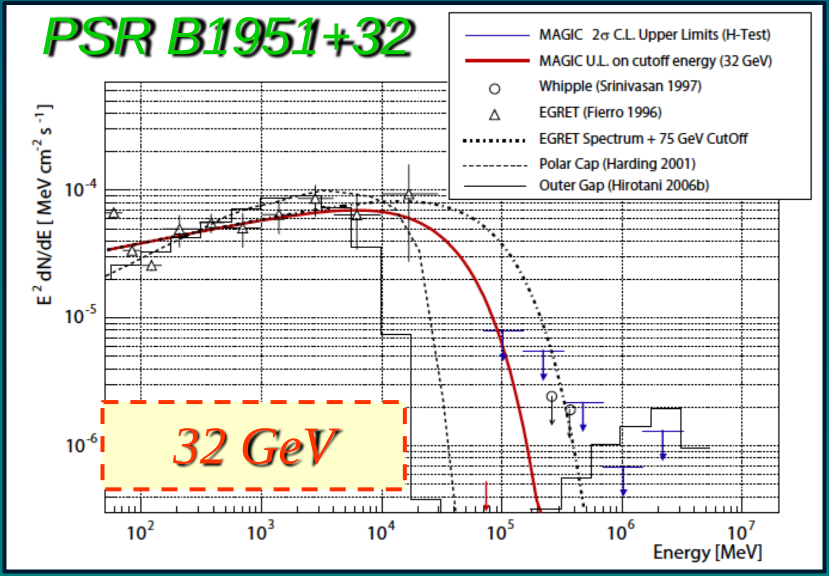




Search for VHE emission from PSRB1951+32

- *Was prime γ-ray pulsar candidate to be detected from ground*
  - *31 hours of data taken in 2006*
- *Results steady emission:*
  - *Our u.l. rule out the predicted steady emission from the associated nebula CTB80*
- *Results pulsed emission:*
  - *Polar cap models predicts cutoff within allowed region derived from our results.*
  - *pulsed TeV emission from outer gap models excluded.*





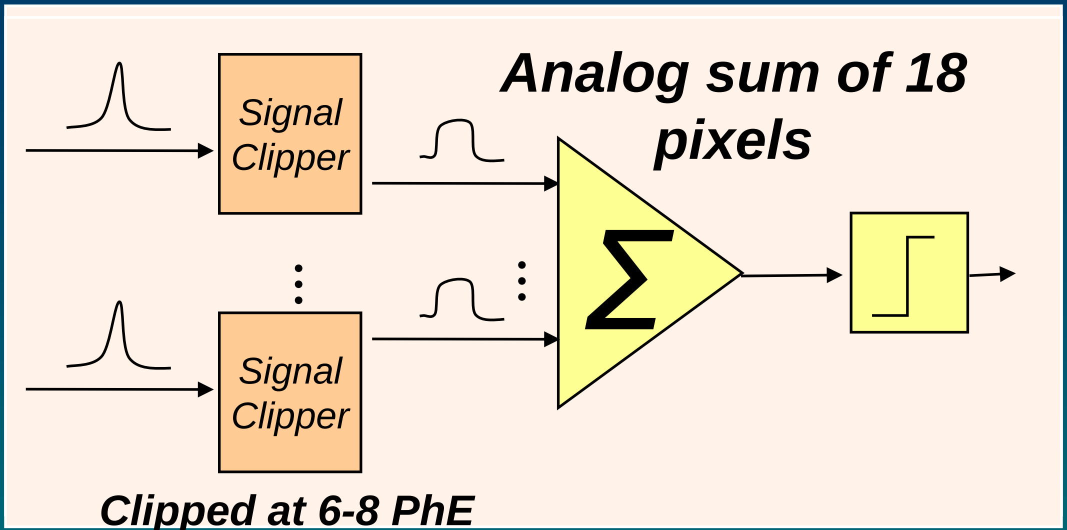
J. Albert et al., Astrophys. J. 669,1143 (2007)

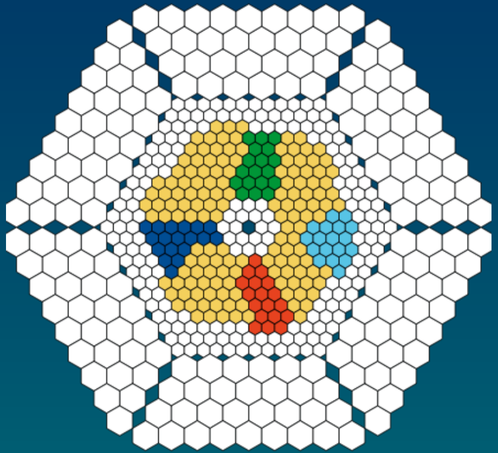
Summary first MAGIC pulsar campaign

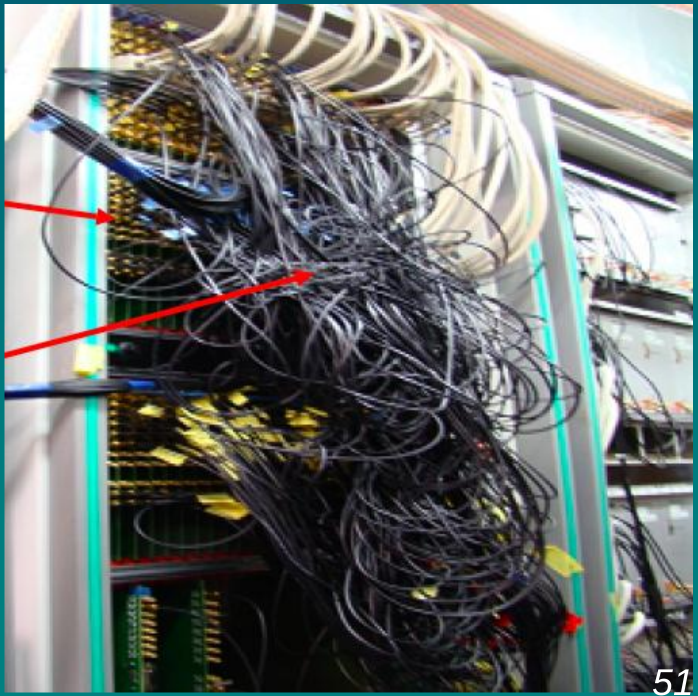
- No pulsed signal detected but obtained a hint of pulsed emission from P2 and the lowest upper limit so far
- Conclusion:
  – Even the low energy threshold of MAGIC (55 GeV) was not enough for catching pulsars
  – Next winter campaign in 2006 we tried again with different trigger topology, but still no success
  – Solution: Develop a new trigger concept

→ The MAGIC SumTrigger

A new trigger concept







MAGIC SumTrigger

- 24 Clusters of 18 pixels in a ring area
- *Add analog signals from a cluster &* discriminate on summed signal
- Problem: Large amplitude from Afterpulses
  - Solution: Clipping signal
- Built at MPI (Munich) in summer 2007

A new trigger concept

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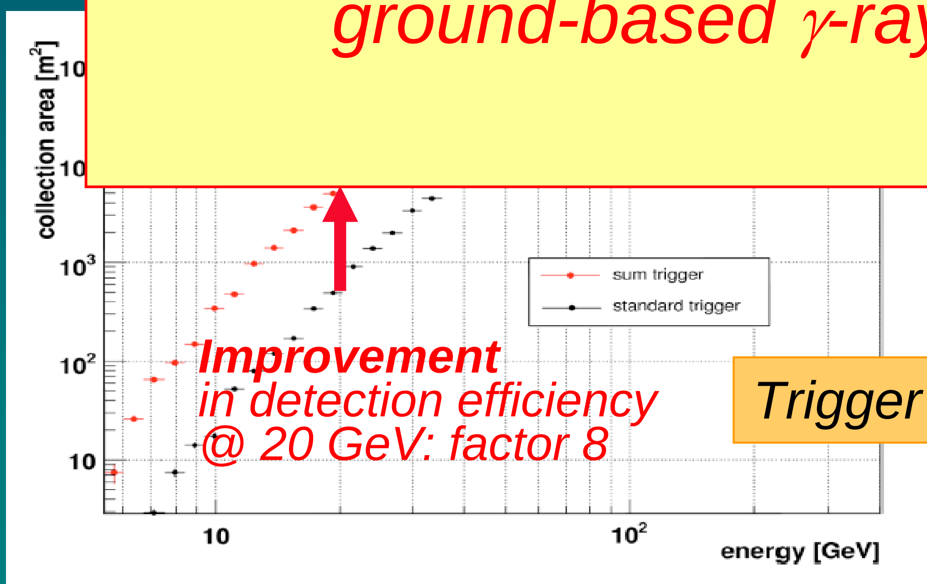
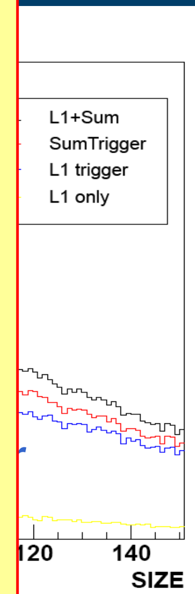


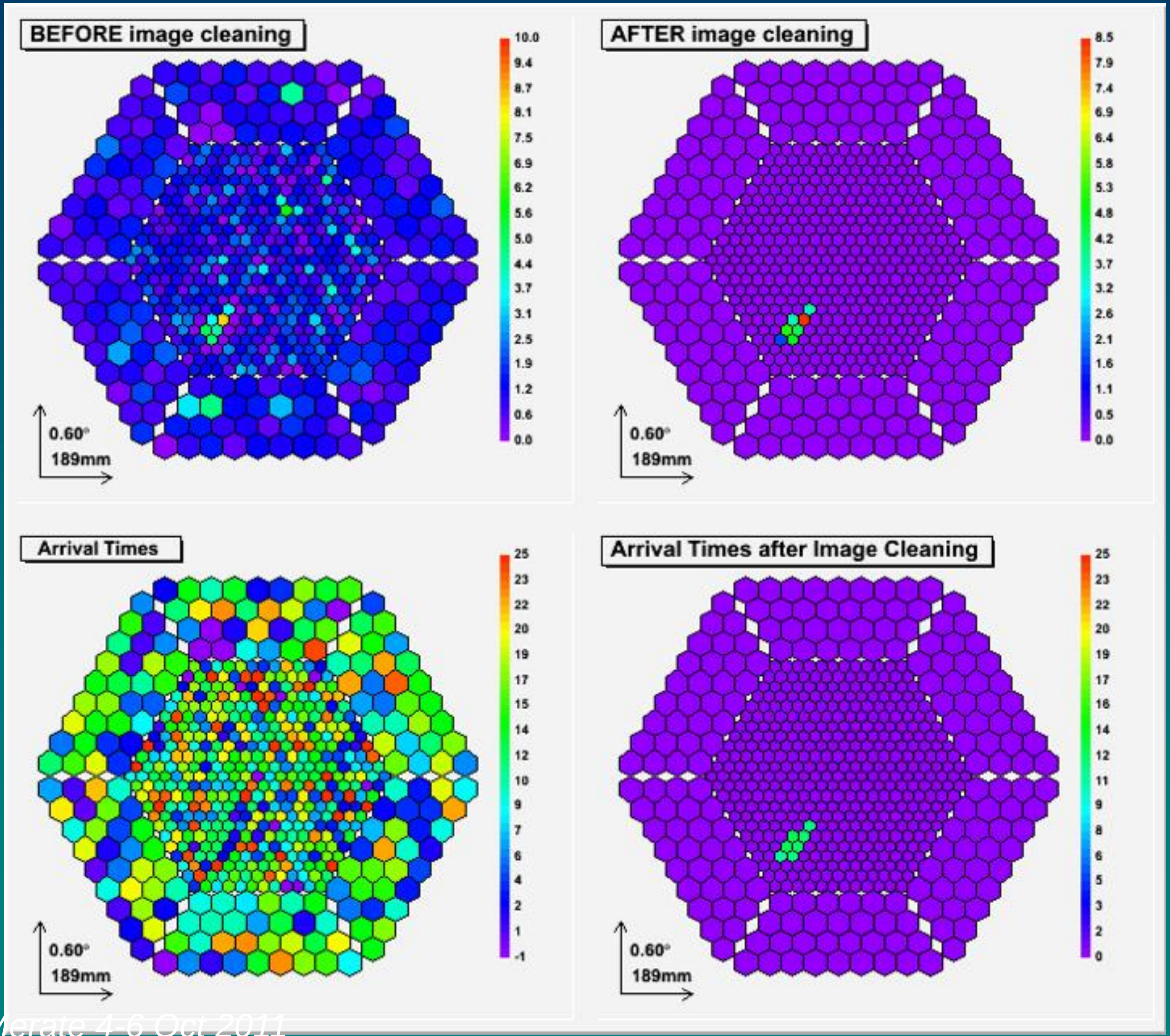
Low trigger threshold of 25 GeV:

a break-through for ground-based γ-ray astronomy

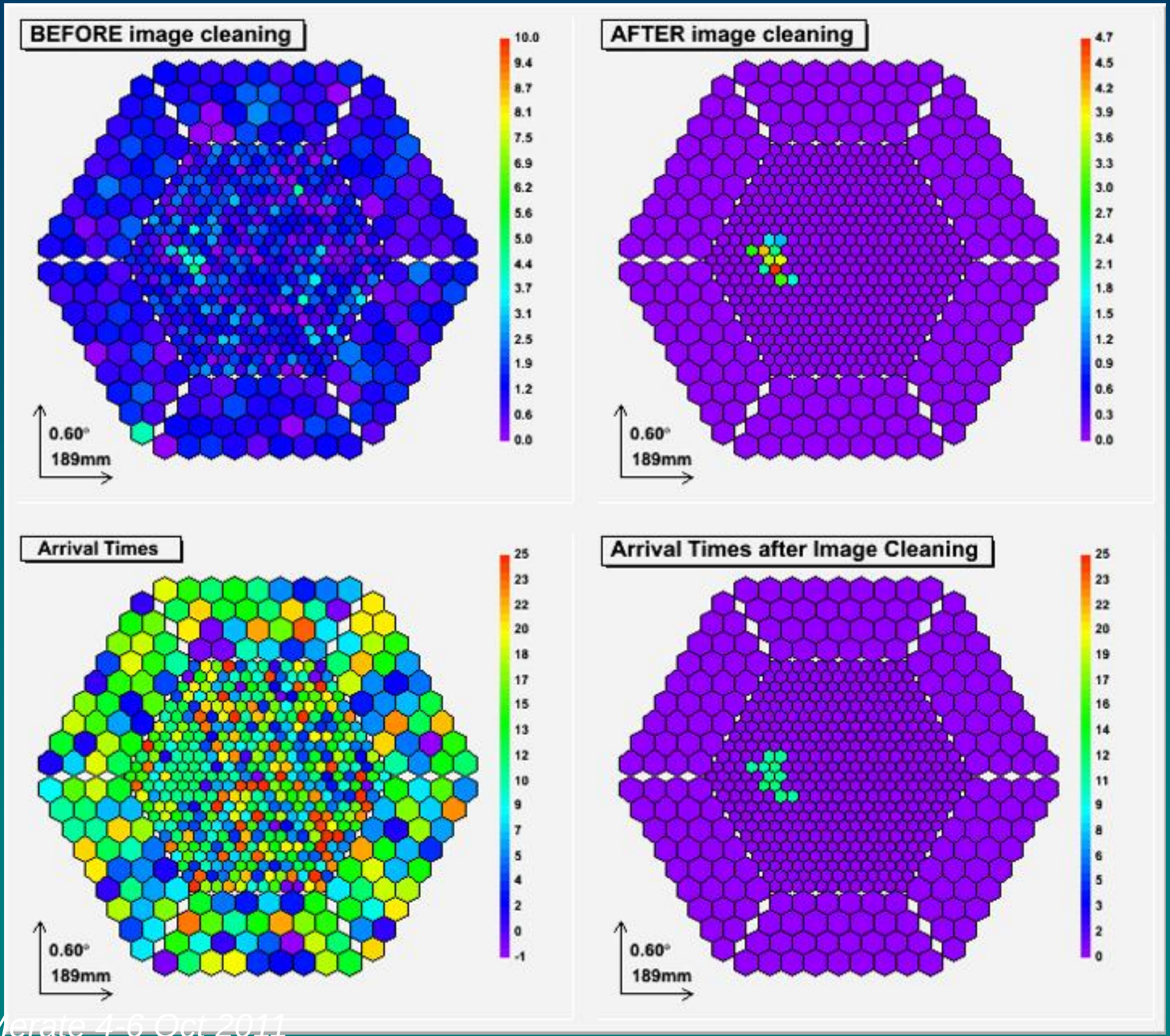


Trigger threshold decreased in a factor ~2

Low energy events: 20-40 PhE



Low energy events: 20-40 PhE



First Detection ever of Crab pulsar with MAGIC mono (above 25 GeV)

Mono Observations with sumtrigger

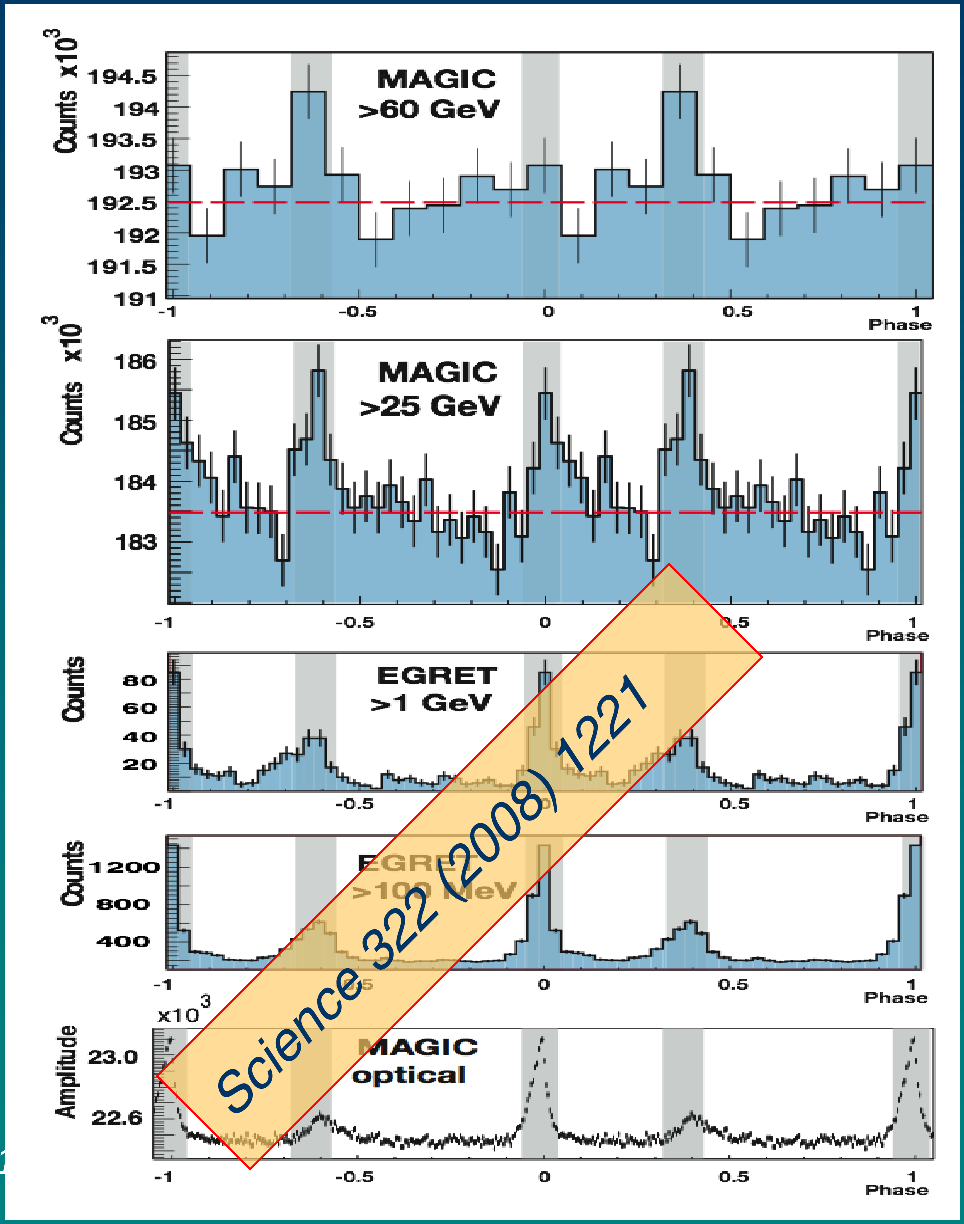
- Oct.07 to Feb.08: 22.3 h

Clear detection: 6.4σ

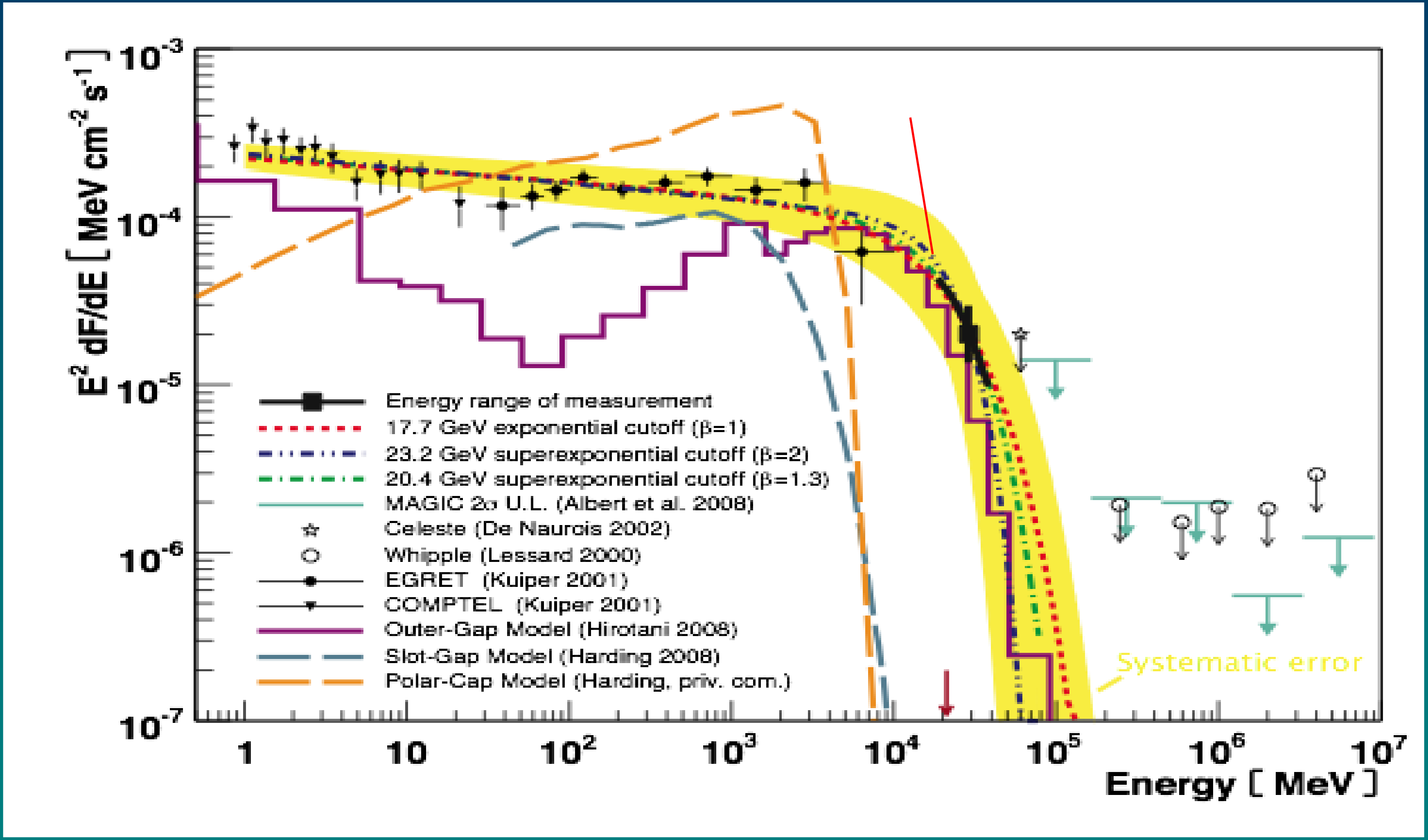
Pulses in phase with EGRET

P1 clearly visible at 25 GeV →First Surprise

Pulsed emission still visible > 60 GeV ! P2 became dominant



Total spectrum (P1+P2) of cutoff



Relatively high cutoff >20 GeV !
Comparison with pulsar models

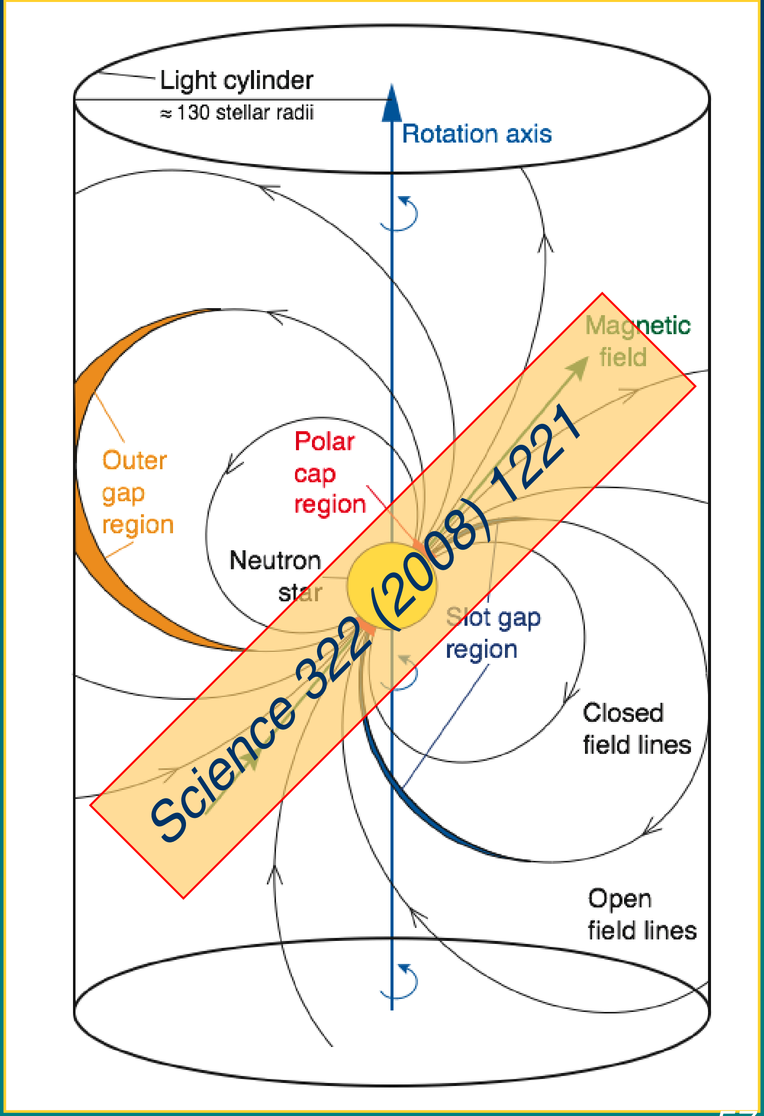
- Our superexponential cutoff:
  23.2 GeV+-2.9_{stat} GeV+-6.6_{syst} GeV
- We can calculate the absorption of gamma-rays in the magnetic field

$$\varepsilon_{\max} \approx 0.4\sqrt{P\frac{r}{R_0}}\max\left\{1,\frac{0.1B_{crit}}{B_0}\left(\frac{r}{R_0}\right)^3\right\}GeV$$

Baring et al., 2001

- From which we can put a lower limit on the distance of the emitting region:
  6.2 +- 0.2_{stat} +- 0.4_{syst} neutron star radii

- **The high location of the emission region excludes the *classical* polar cap model (emission distance < 1 stellar radius) and challenges the slot gap model**

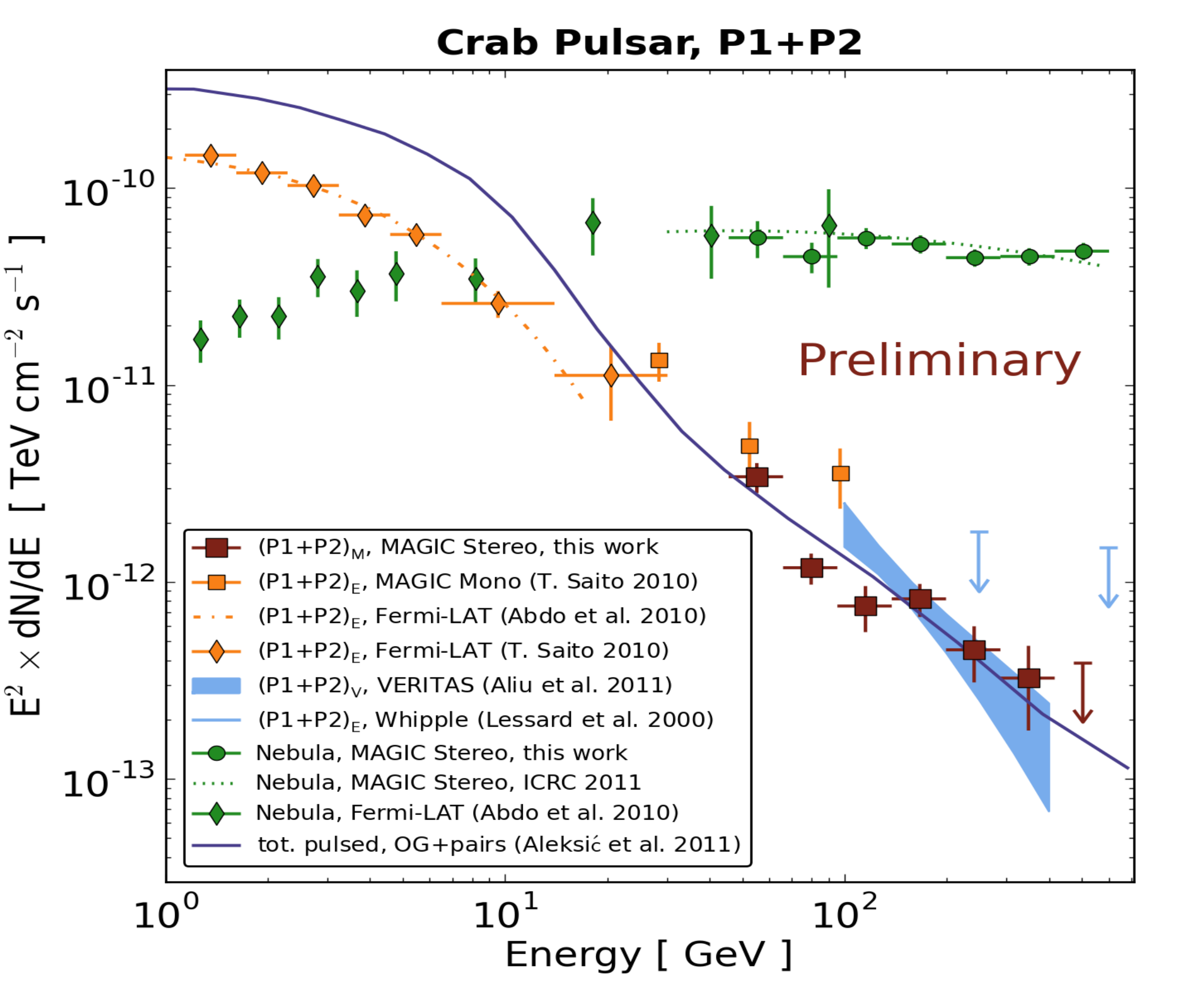


MAGIC stereo

- In 2009 the MAGIC telescope came into operation

Recent Detection with MAGIC stereo

- Used 73 h of stereo data from 2009/10

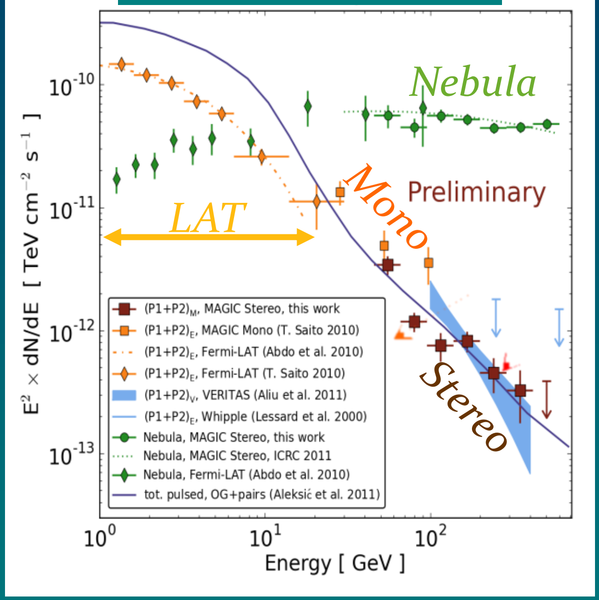


- *MAGIC Stereo provides spectra up to 400 GeV.*
- *Mono/stereo spectra agree… and go well beyond a cutoff at few GeV!*

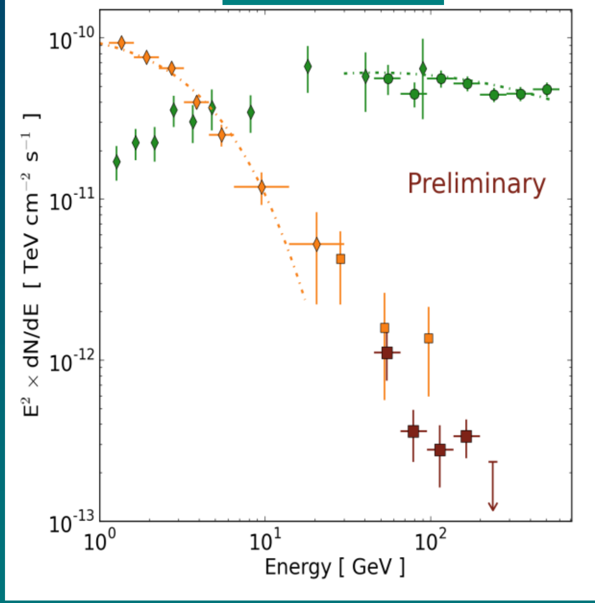
Recent Detection with MAGIC stereo

- Used 73 h of stereo data from 2009/10

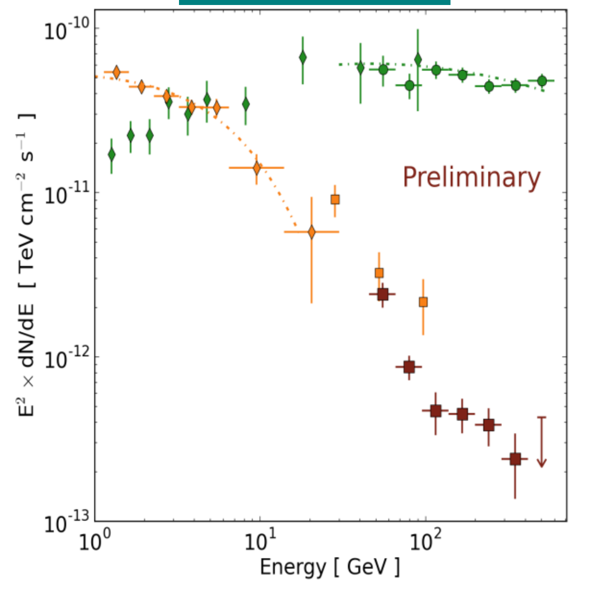
Sum of Both Peaks



First Peak



Second Peak



MAGIC measurements rule out extrapolation of Fermi exponential fit.

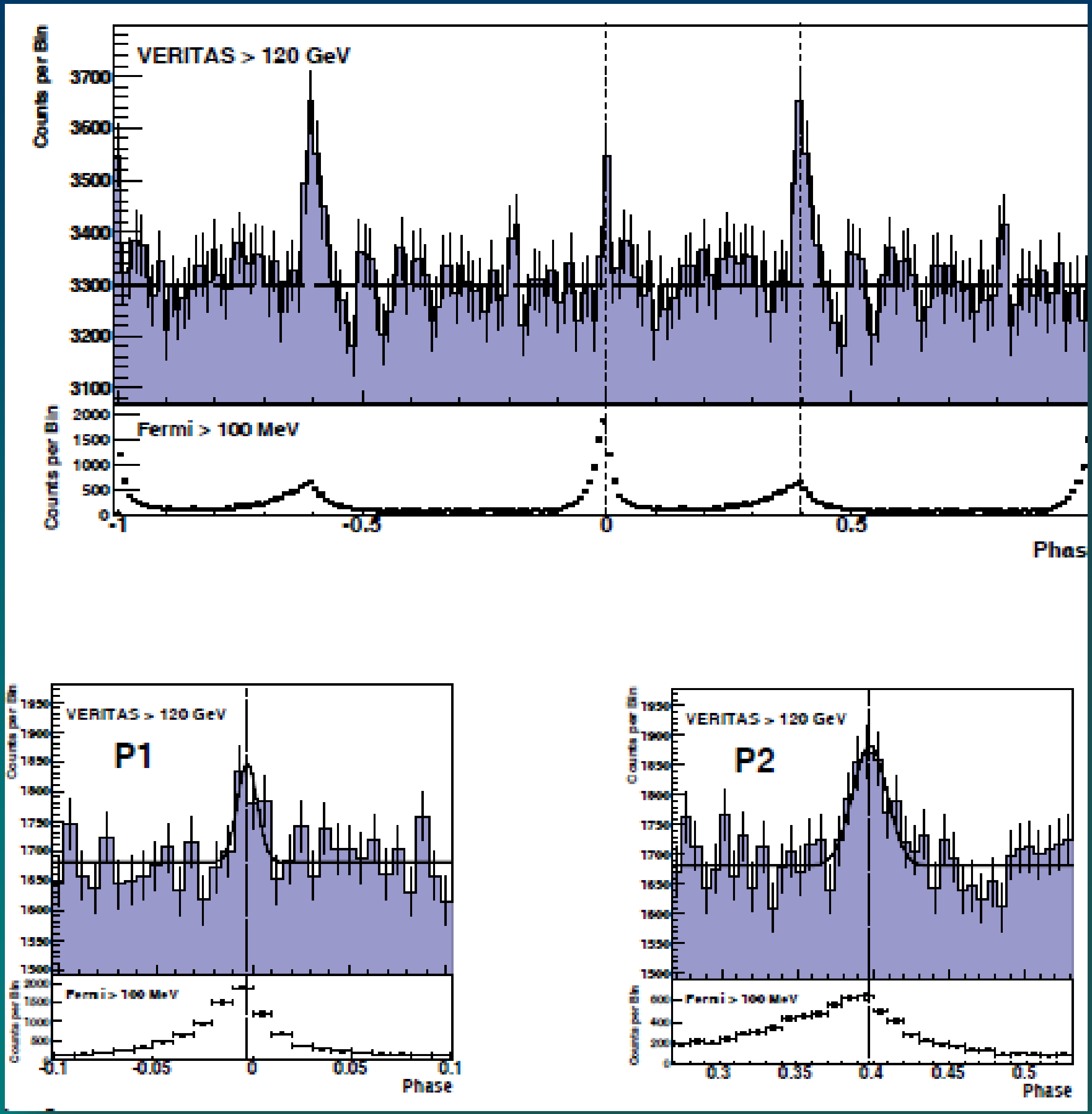
No current pulsar model can explain the observations!
Do other pulsars also have a VHE tail?

Veritas Crab detection

- Veritas has recently report the detection of the Crab pulsar
  - Confirmation of MAGIC first detection
  - Latest MAGIC result in agreement with Veritas spectrum
- They used 107 h of data taken between 2007 and 2011

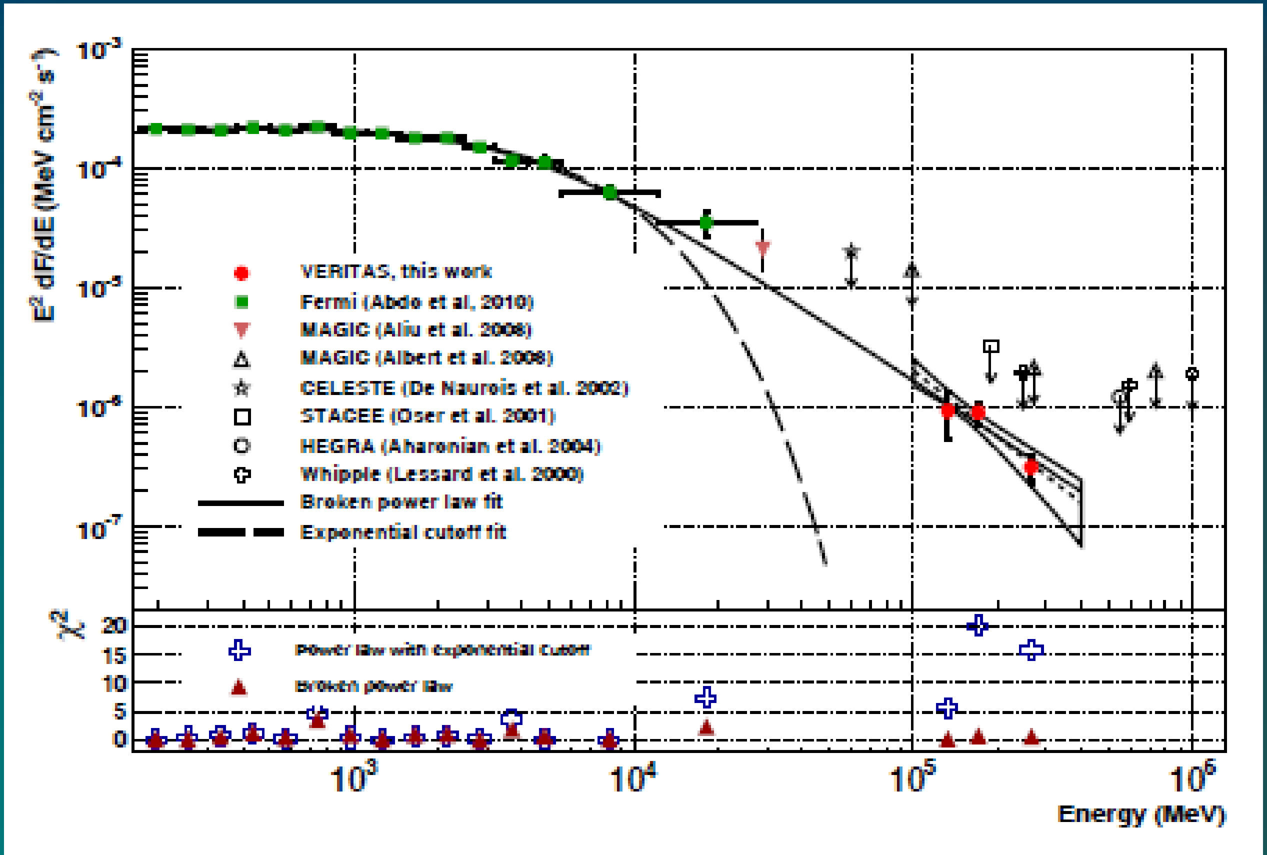
Veritas Crab detection

- Light curves



Veritas Crab detection

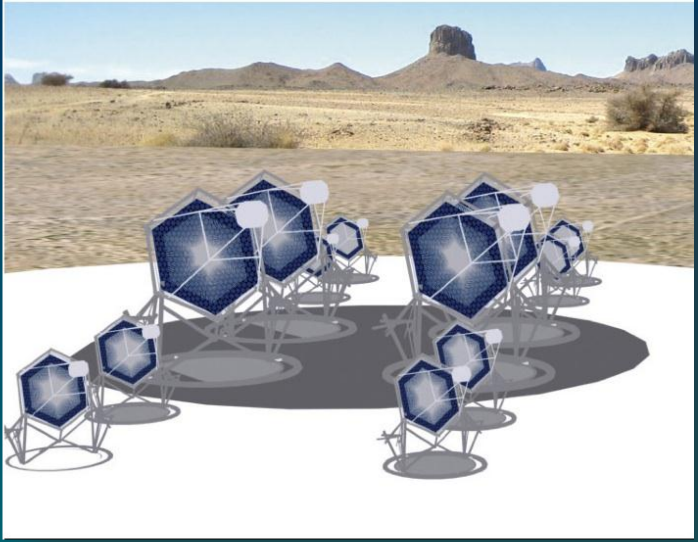
- Spectrum

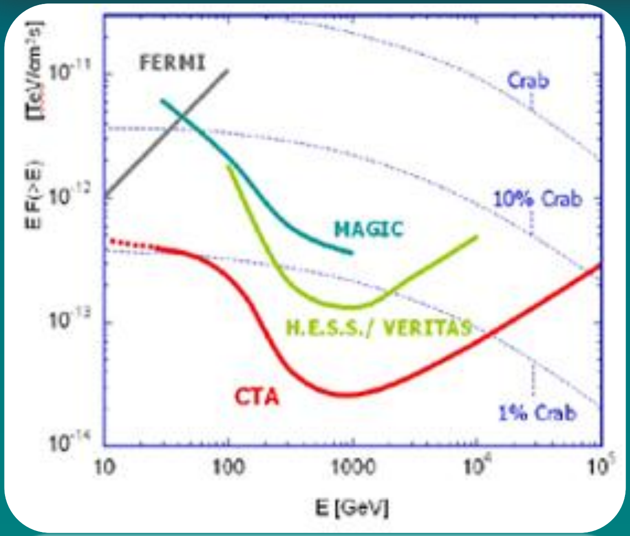


Pulsars in the CTA era

Pulsars in CTA era

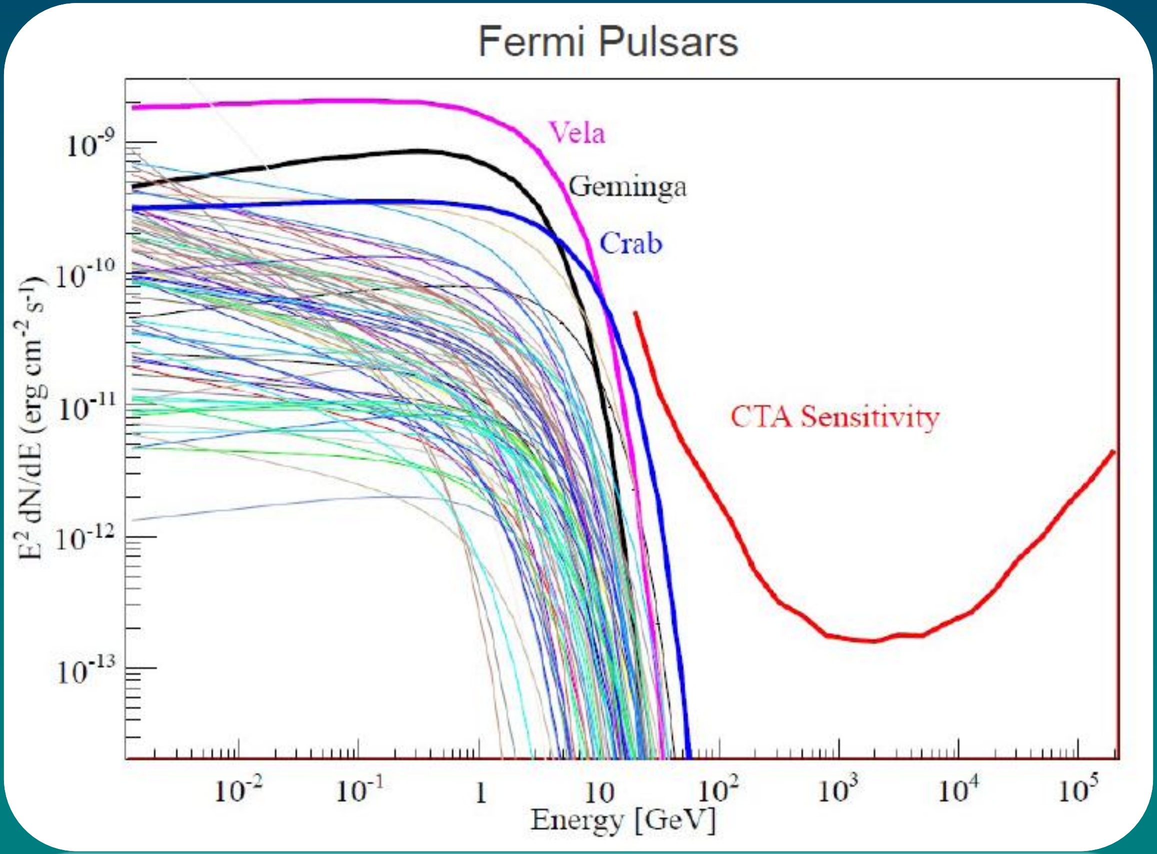
- CTA represents the next generation of CTs
- About 100 telescopes of 3 different sizes, for covering different energies ranges
- A big improvement in sensitivity is expected
- So, what about pulsars studies with CTA?





Pulsars in CTA era

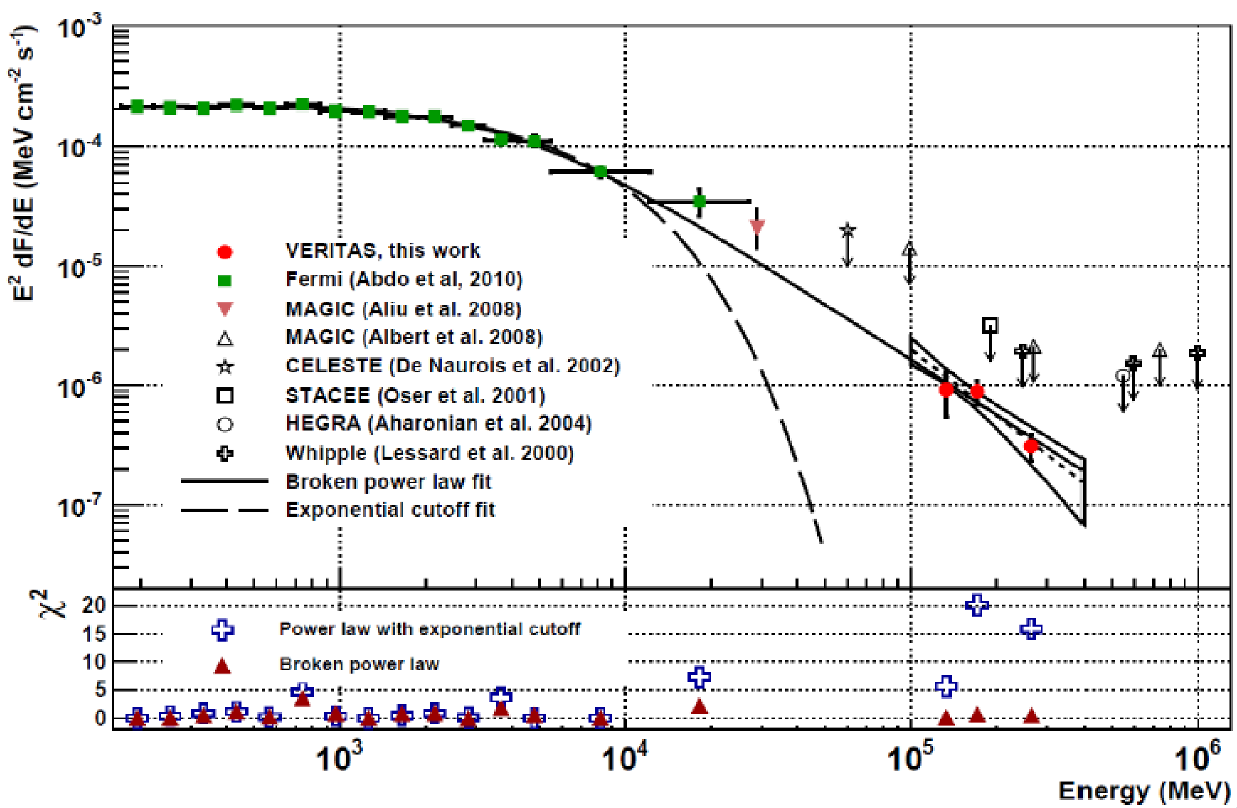
- If FERMI spectral fits are used, no any single pulsar would be detected by CTA!



Pulsars in CTA era

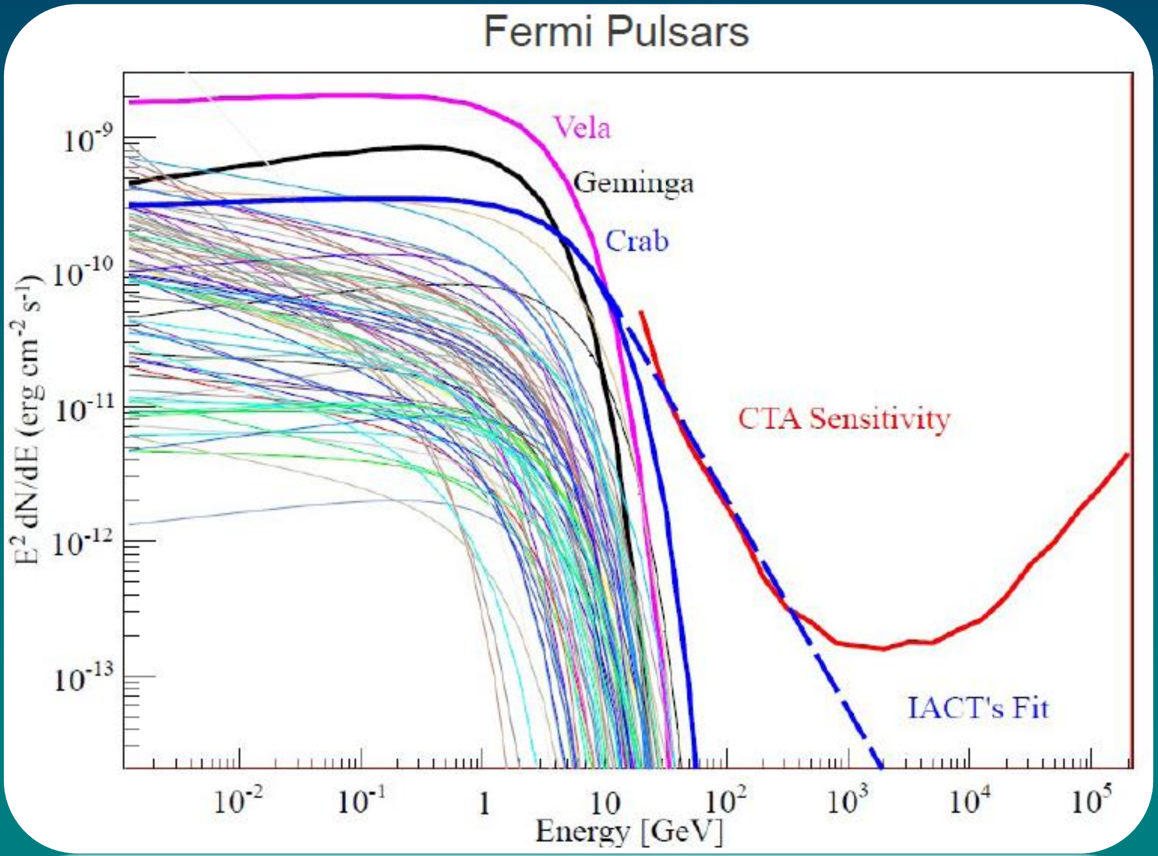
- But, we have discovered that pulsed emission continue up to hundreds of GeV, like a power law

VHE Crab Pulsar Emission



Pulsars in CTA era

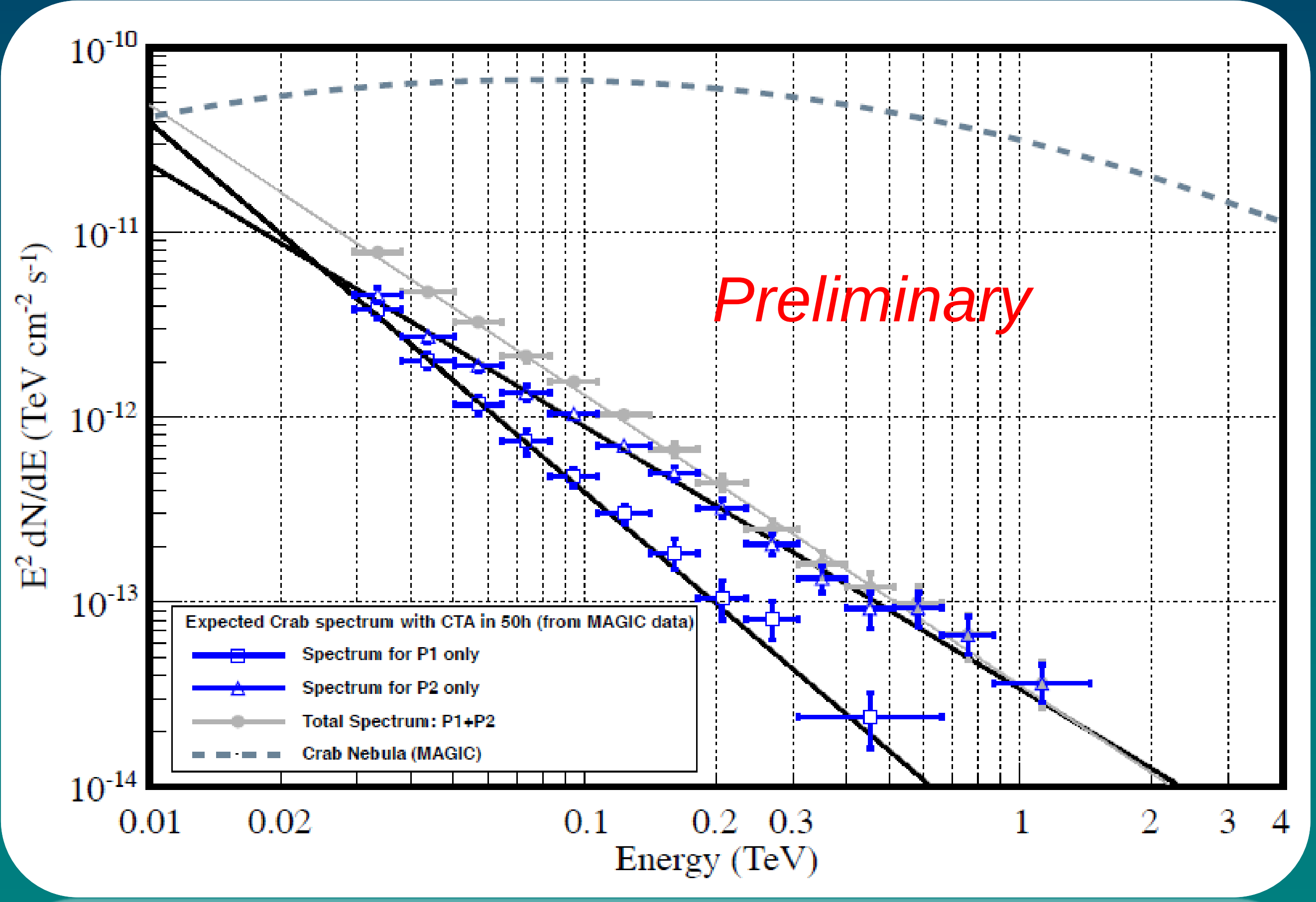
- But, we have discovered that pulsed emission continue up to hundreds of GeV, like a power law



Pulsars in CTA era

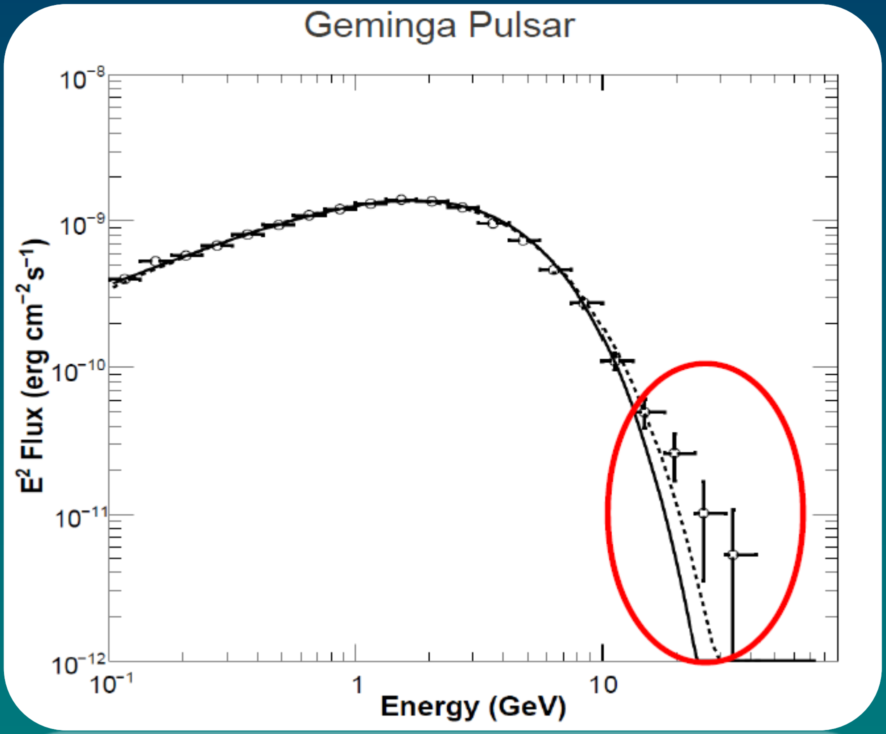
Crab pulsar

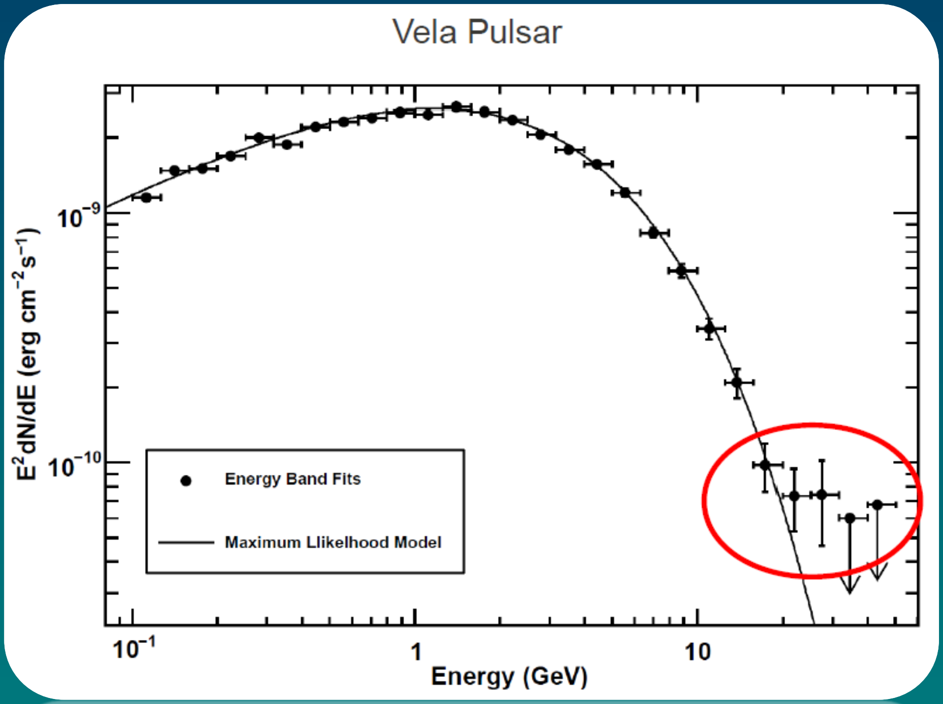
- Expectations for CRAB pulsars using MAGIC measurements



Pulsars in CTA era

What about other pulsars?





Other pulsars seems to have a VHE tail→Good targets for CTs

Summary

- Fermi has increased in more than a factor 10 the number of gamma-ray pulsars. But still, they are much less than in radio
- Pulsars seemed impossible to detect with current CTs, due to low spectral cutoffs, but... *we insisted…*
- MAGIC First detection of Crab pulsar after chasing it with CTs for more than 20 years:
  - Both peaks visible & Cutoff higher than expected

Excludes polar cap model

- *Veritas recently also detected the Crab pulsar, measuring power law spectrum up to 200 GeV*

Excludes also outer gap

- *Later MAGIC stereo observation allowed to made for the first time phase resolved spectroscopy at VHE*

Our old pulsar theories doesn’t seem to work at VHE.

Needed new models/ideas

That’s all.
Thanks for your attention