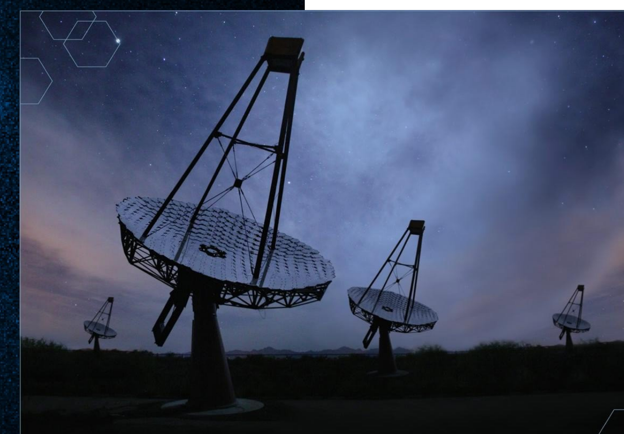
Pulsars @ VHE:
towards H.E.S.S.-II era

R. de los Reyes (MPIK) and B. Rudak (CAMK)

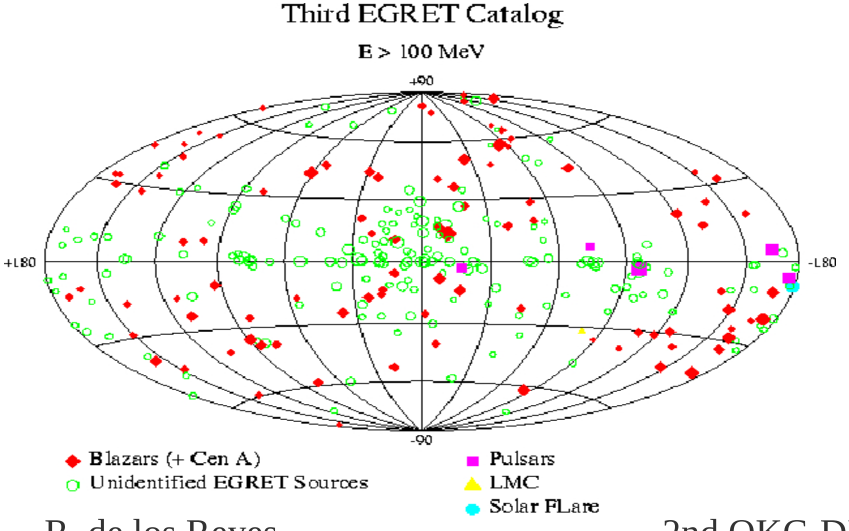
What we DO know?

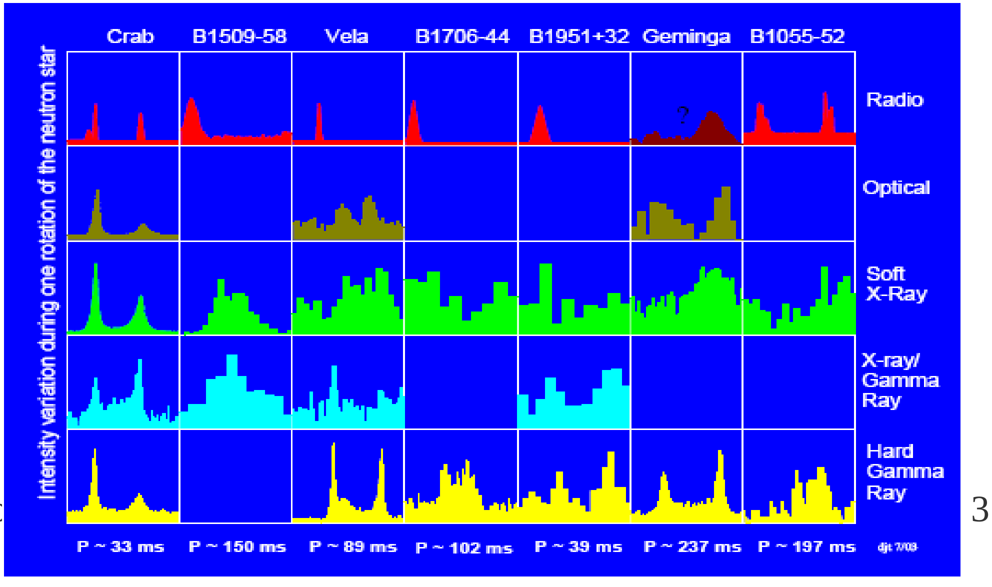


Credits: Chandra

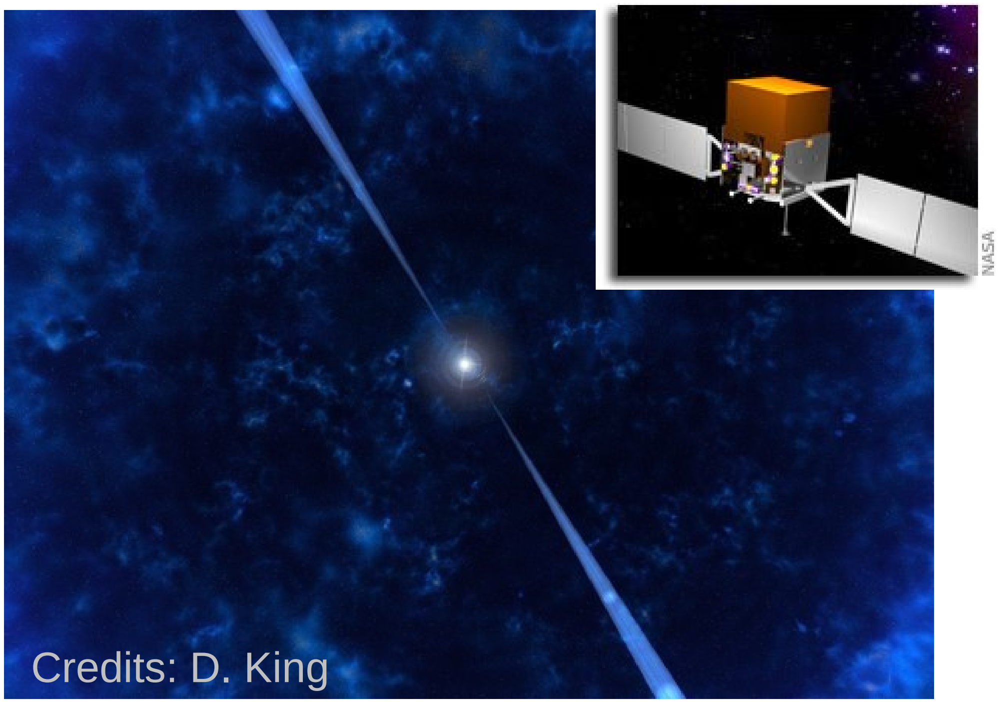
First pulsed detections in HE γ-rays: EGRET (30MeV-30GeV)

- Life time: 1991 - 2000
- 7 pulsars + 3 candidates
- 5 PSRs with photons>25 GeV.



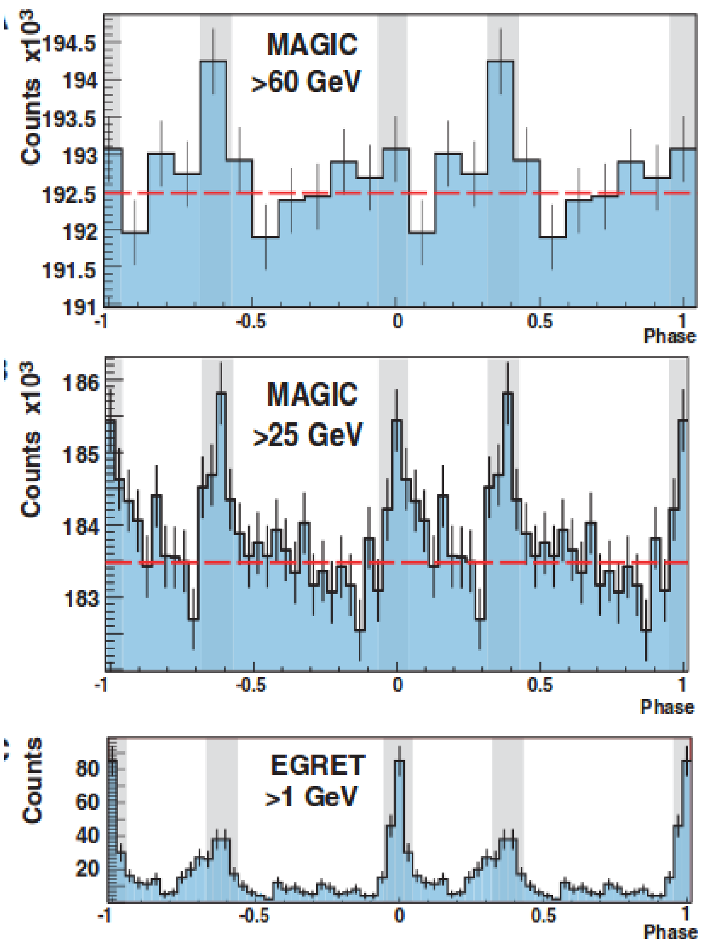


Increasing the HE γ-ray population: Fermi/LAT



- Launched: June 11, 2008
- 1^{st} catalogue: 46 pulsars
- 2^{nd} catalogue: 117 pulsars
- Current statistics (Fermi, 7 August) $\rightarrow$ 132 PSRs :
  - 81 young pulsars:
    - 42 radio selected
    - 3 X-ray selected
    - 36 γ-ray selected
  - 51 ms pulsars:
    - 50 radio selected
    - 1 γ-ray selected
- 25 PSRs found in radio searches of LAT detections

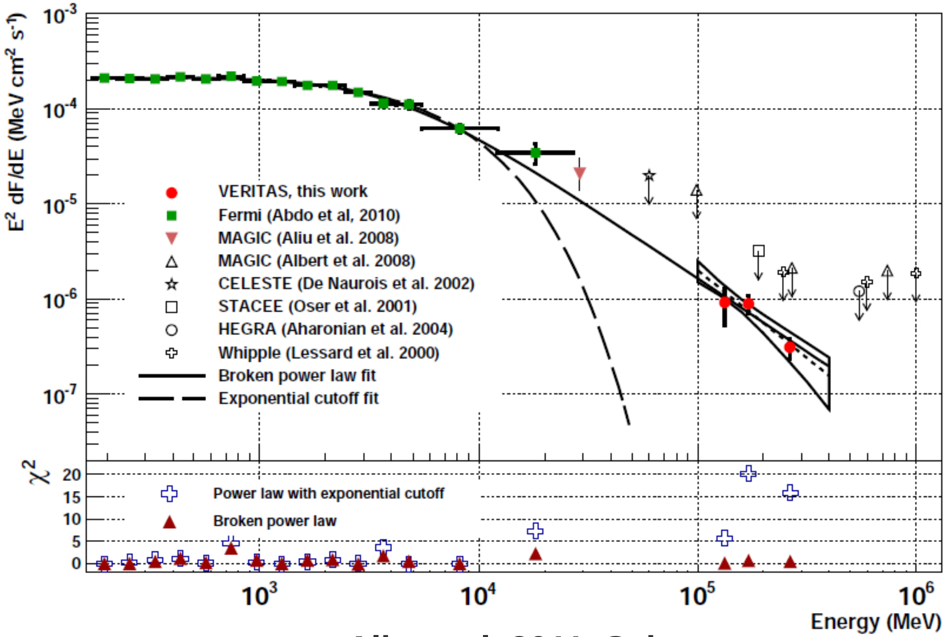
First pulsed detection in HE-VHE γ-rays: Crab by MAGIC (>25 GeV)



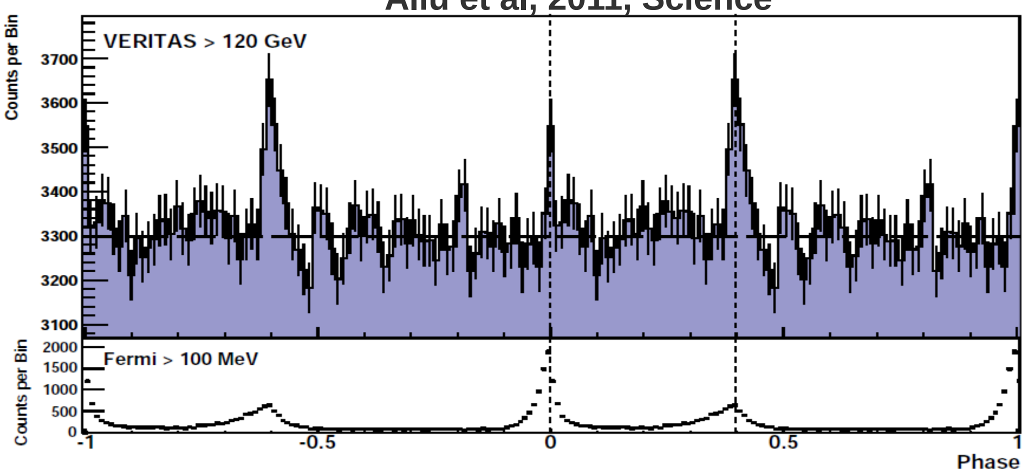
Aliu et al, 2008, Science

- First detection beyond EGRET energies.
- Observations:
  - Detection using a special trigger (SUM-trigger) at low energies.
  - E_{th} = 25 GeV
  - t_{obs} = 22.3^h.
  - θ ~ 20º
  - 6.4 σ
- E_{cutoff} ~ 17.7 – 23.2 GeV (model dependent: β=1-2).
- Pulses aligned with HE.
- Indication of P1/P2 decrease.

VHE pulsed emission above 120 GeV: Crab by VERITAS

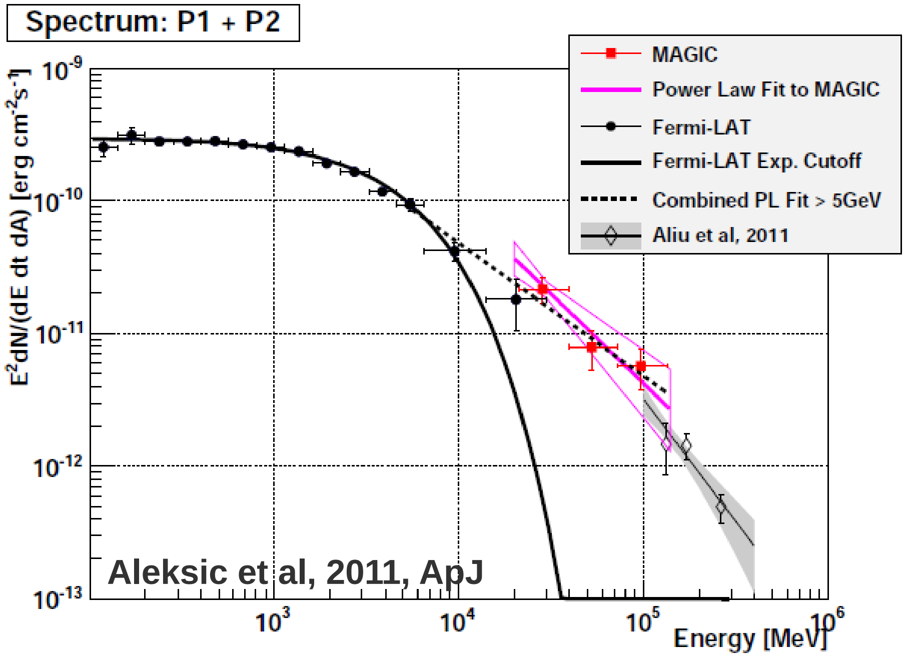


Aliu et al, 2011, Science

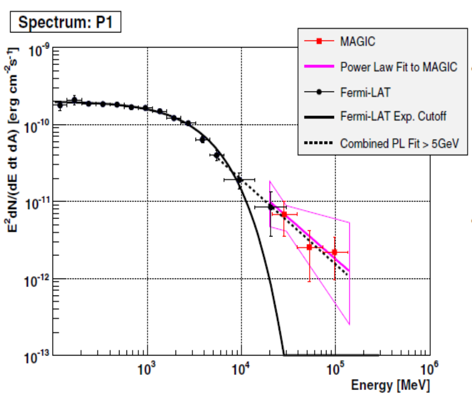


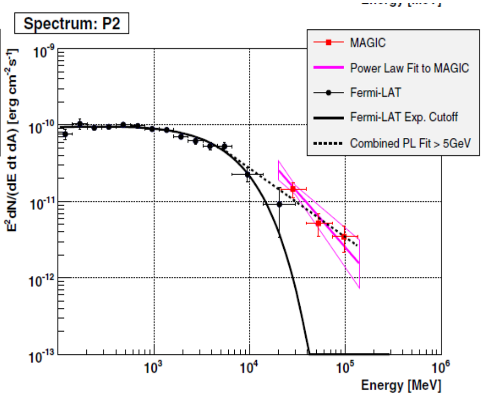
- First VHE emission >100 GeV detected.
- Observations:
  - t_{obs} = 107^h (77.7^h improved sensitivity)
  - E_{th} = 100 GeV (trigger)
  - 6.0 σ
- Spectrum template of power-law + exponential cutoff ruled out.
- Fermi + VERITAS fit to a broken power-law spectrum template.
- Light curve pulses aligned with Fermi light curve (Φ_1=-0.0026, Φ_2= 0.3978).
- P1/P2 decrease while increasing E.

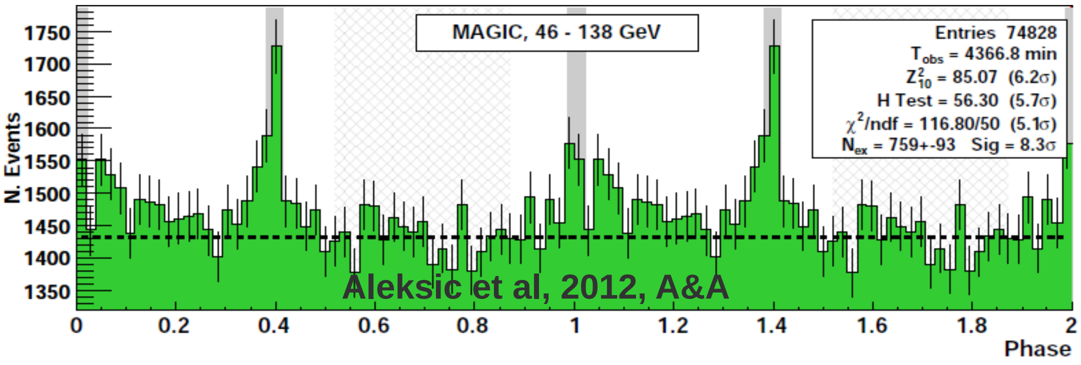
VHE pulsed emission between 25-400 GeV: Crab by MAGIC



- Gap between 25-120 GeV filled.
- Observations:
  - θ~20º
  - SUM-trigger **mono** (E_{th} =25 GeV):
    - t_{obs} = 59^h, 7.5 σ
  - MAGIC-II **stereo** (E_{th} =50 GeV):
    - t_{obs} = 73^h, 6.4 σ
- Broken power-law template confirmed.
- Spectrum fit for each light curve peak:
  - F_{P2}/F_{P1} (E>25GeV) ~ 2

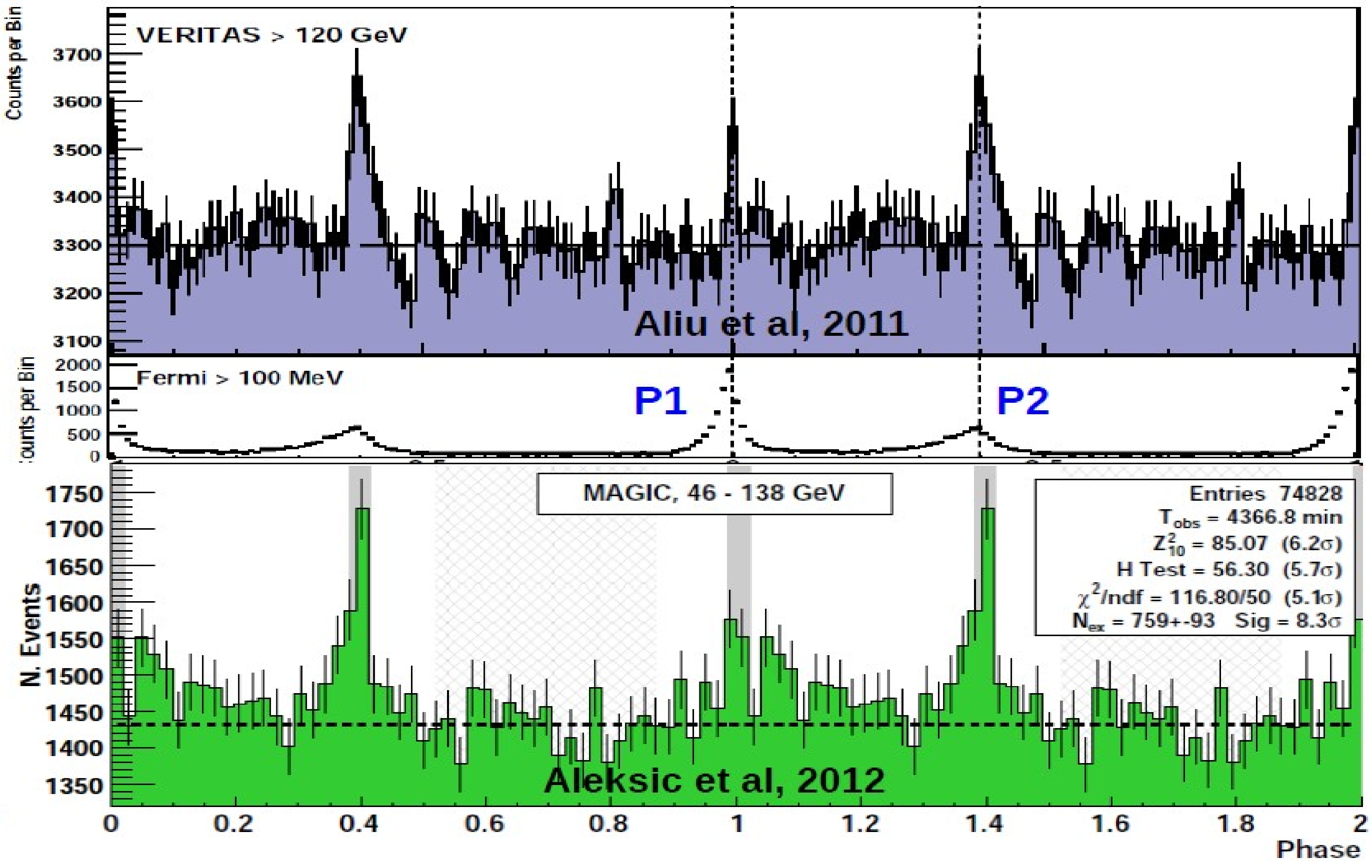






HE vs VHE light curve

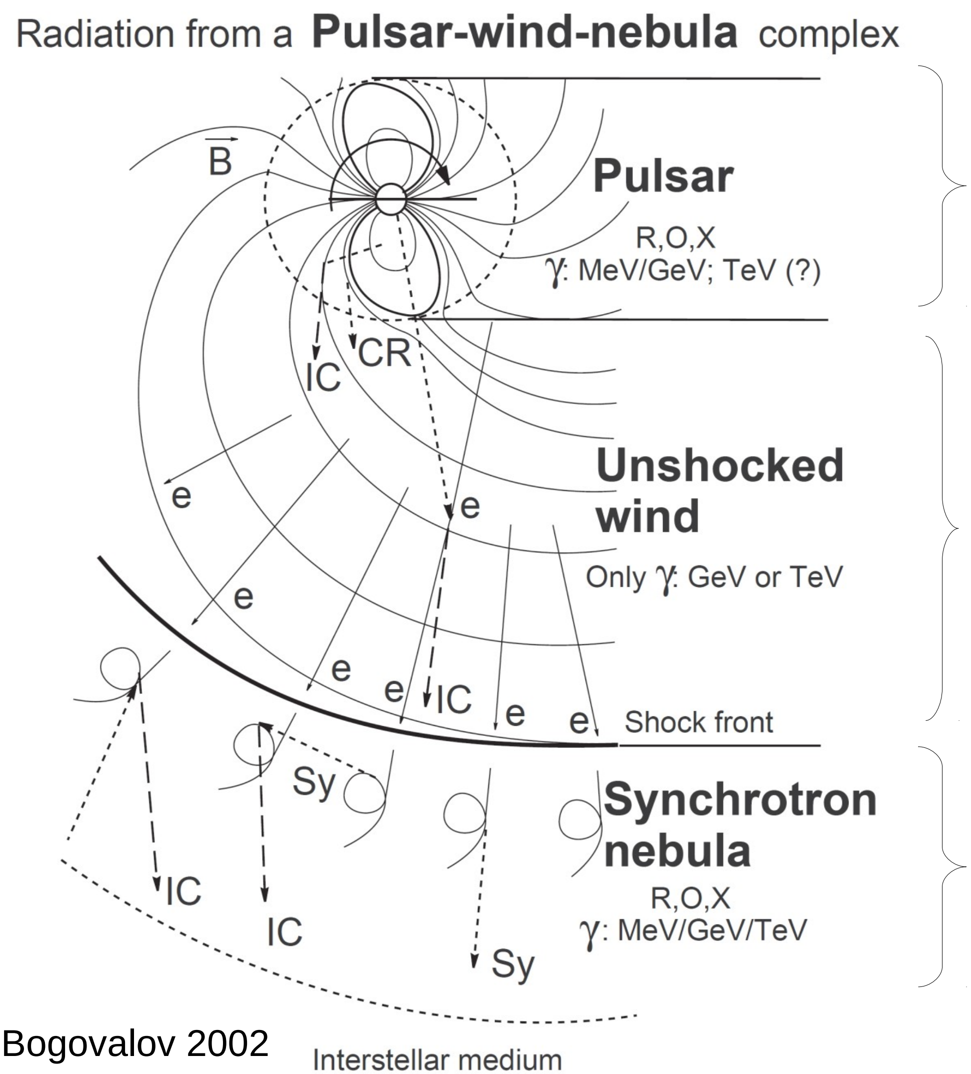
- P1/P2 decrease while E increases
- ¼ pulsed duty cycle (0.40 → 0.10).
- ~2 times the Off phase (0.36 → 0.9)



Origin of the HE-VHE γ-ray pulsed emission

- Pulsar energy spectra and light curves depend on:
  - Location and spatial extent of accelerators
  - Specific radiative processes
  - Geometry (i.e. Inclination and viewing angles)

Origin of the HE-VHE γ-ray pulsed emission



Pulsed inside LC

Pulsed outside LC

Unpulsed

Aharonian, Bogovalov 2002

Modeling young energetic pulsars @ VHE

TPC-slot gap models & outer gap models in the domain of VHE:

Synchro-Curvature Radiation and Inverse Compton Scattering components
can essentially reach ~10 GeV up to 10 TeV.

But
the level of escaping radiation is governed by intrinsic attenuation due to ambient fields of soft photons and magnetic field.

TPC Slot Gap vs Outer Gap example for the Crab pulsar parameters

Full electrostatic potential drop

ΔV (SG) ~ 10^{13} V

ΔV (OG) ~ 10^{15} V

Gap width:

$h_{SG} \cong 0.04$

$h_{OG} \cong 0.14$

Outer Gaps more powerful than Slot Gaps in terms of gamma-ray luminosity

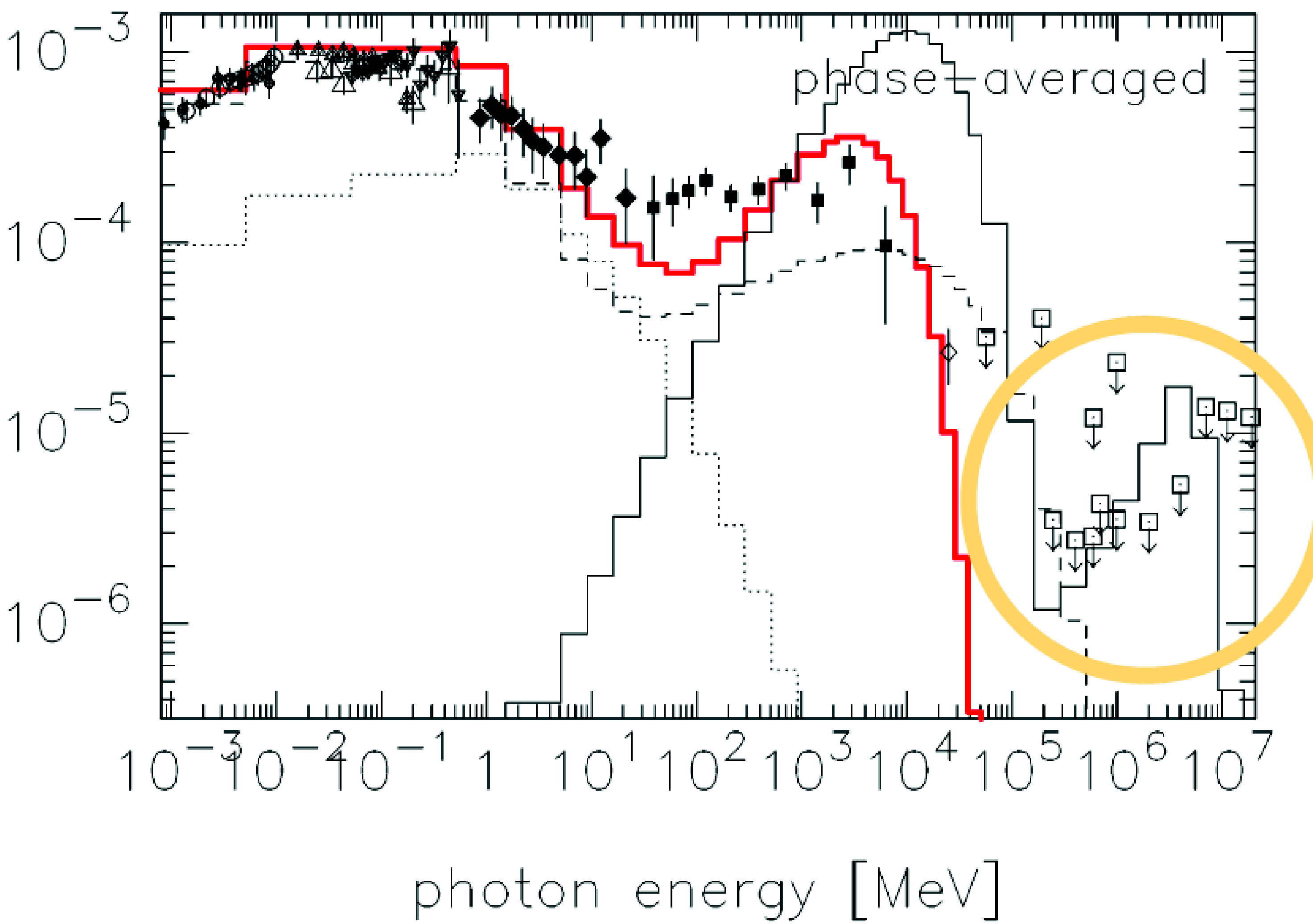
Harding, Stern, Dyks & Frackowiak 2008 (Slot Gaps)
Hirotani 2009 (Outer Gaps)

The Crab pulsar and 3D Outer Gap model
(before MAGIC&VERITAS results)

Synchro-curvature + ICS ($e^{\pm}$ pairs with IR-photons)

Intrinsic photons: black lines

Escaping photons: red line



α = 60 deg
ζ = 113 deg

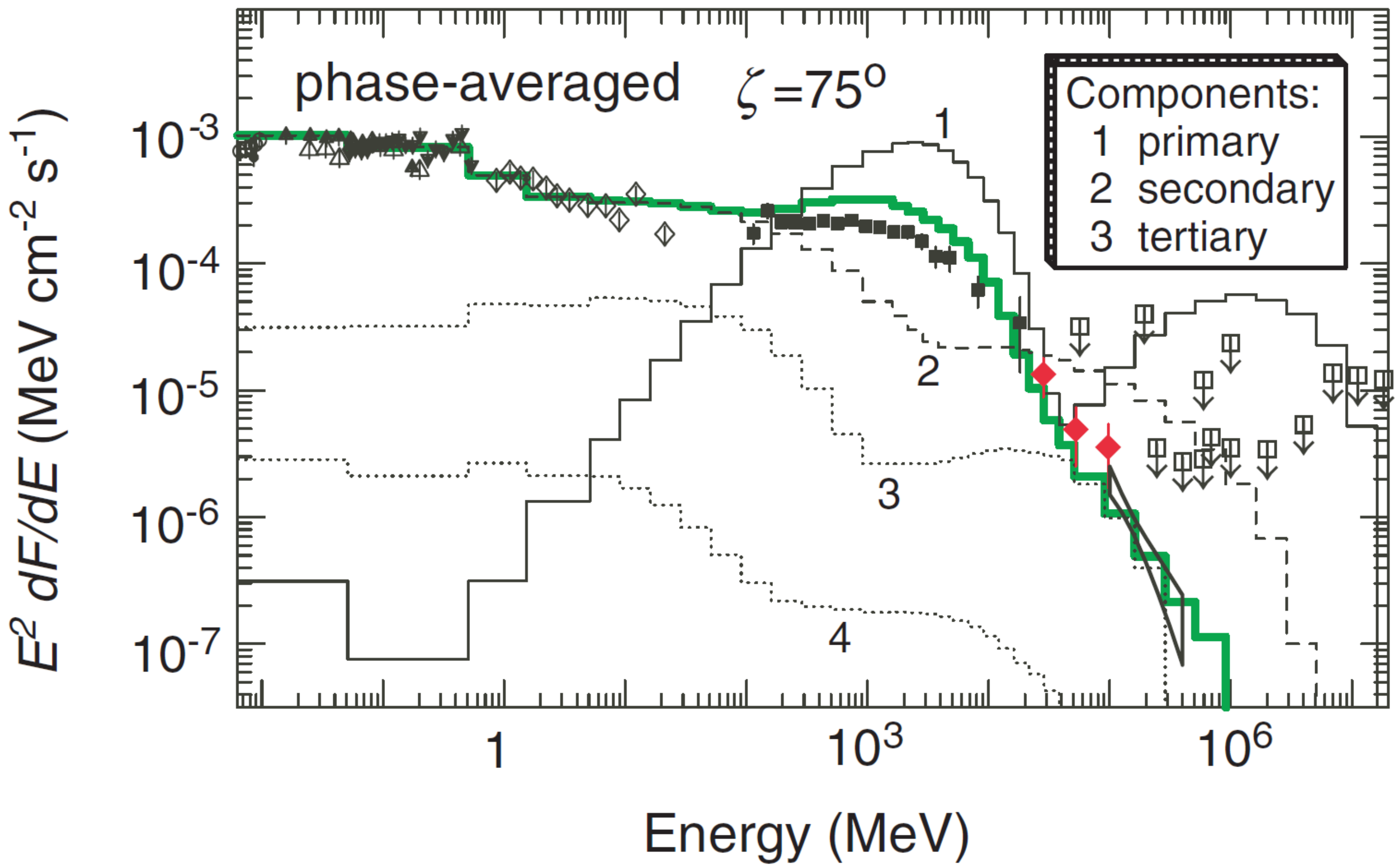
Attenuated by IR (Hirotani, 2009)

Allowed to escape after modifications of the model (the MAGIC-mono paper, 2011) – next slide ->

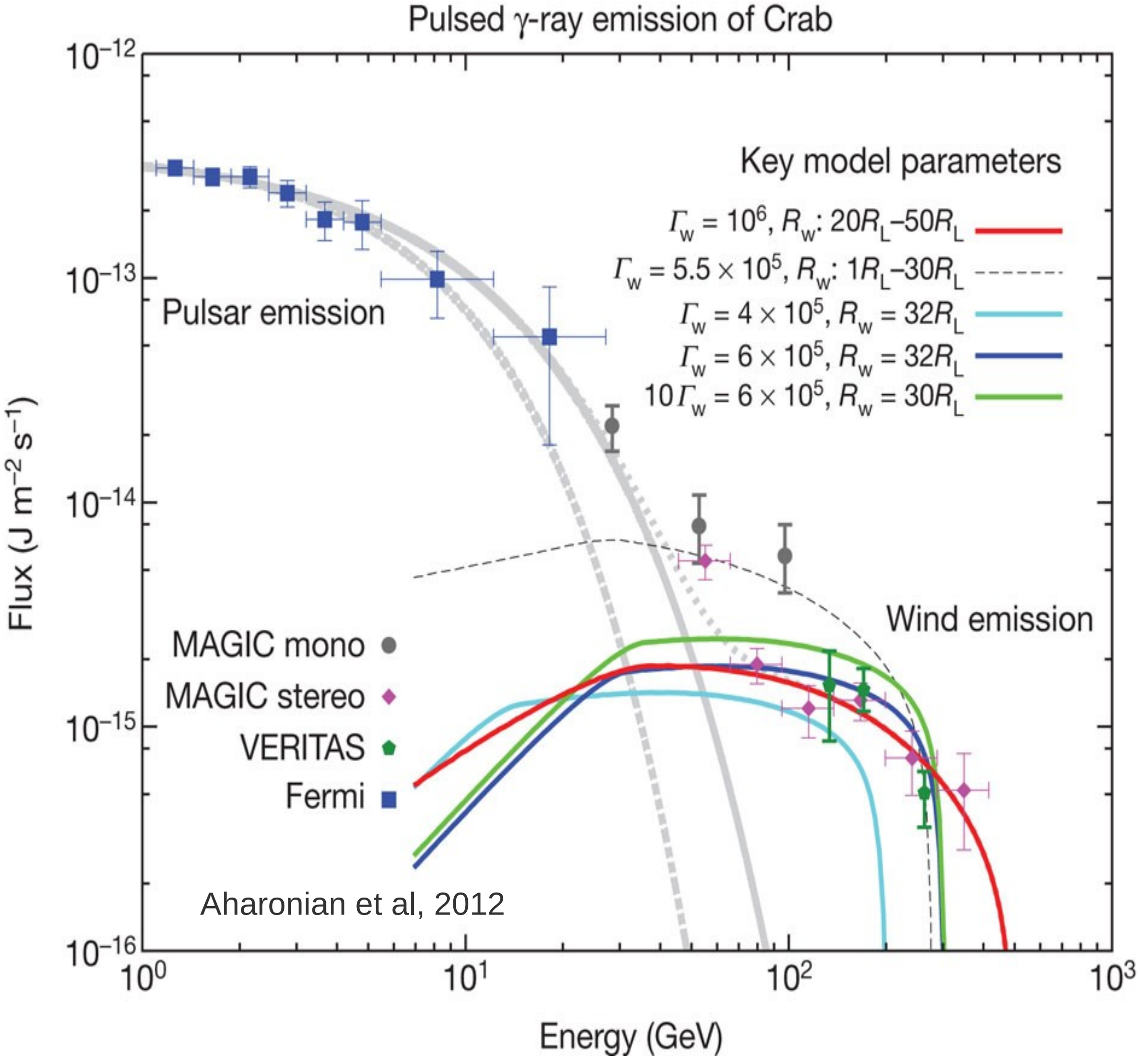
The Crab pulsar and 3D Outer Gap model

(MAGIC coll. + K. Hirotani → Aleksic, et al, 2011)

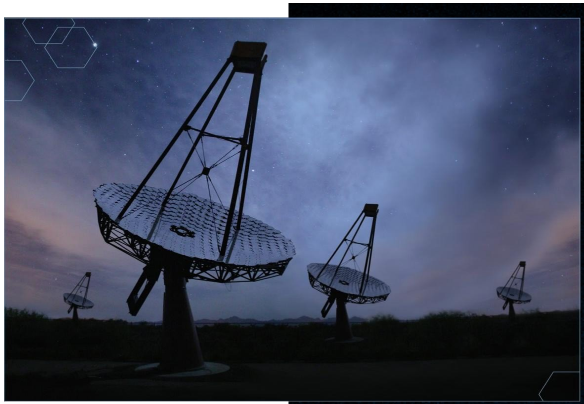
The Astrophysical Journal, 742:43 (14pp), 2011 November 20



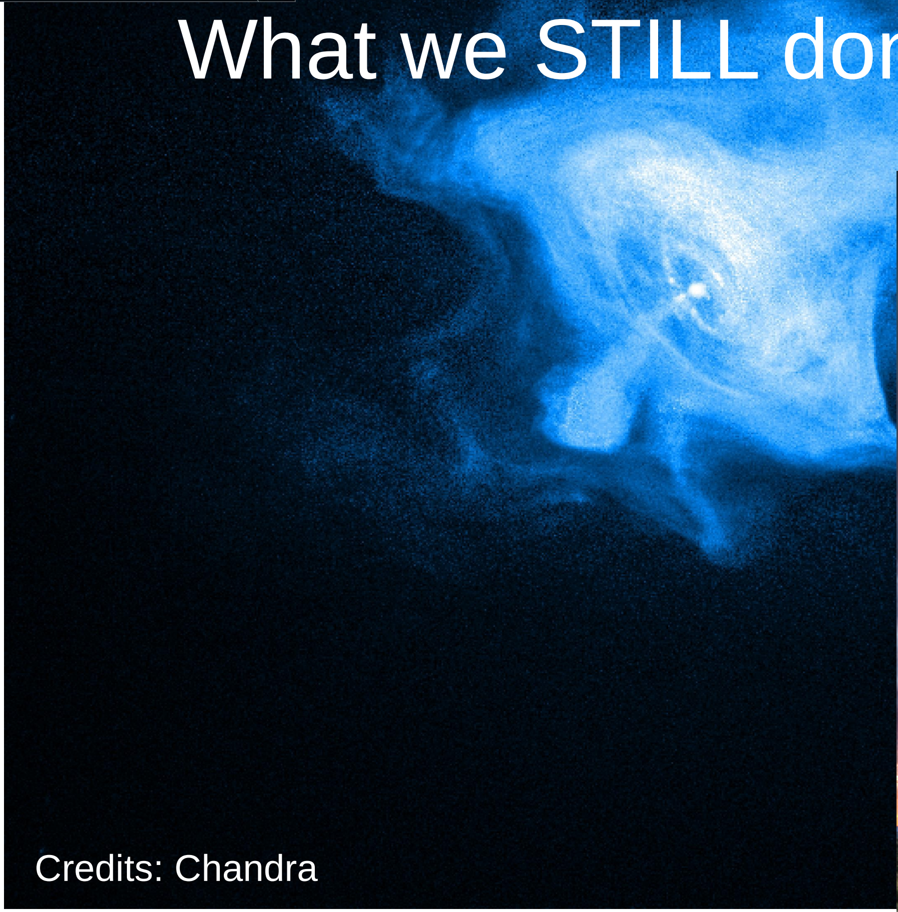
Generating pulsed VHE within the wind zone



- Magnetospheric winds as carriers of spin-down power.
- Cold ultra-relativistic wind at $r>20\ r_{Lc}$ (Aharonian et al, 2012).



What we STILL don't know?



Credits: Chandra

Pulsar population @ VHE

- Score: 132 HE pulsars vs 1 VHE pulsar.
- Is Crab the only pulsar with a power-law spectrum at VHE?
- If there are more pulsars like Crab, how many?

→ VHE observatories with E_{th} < 100 GeV:

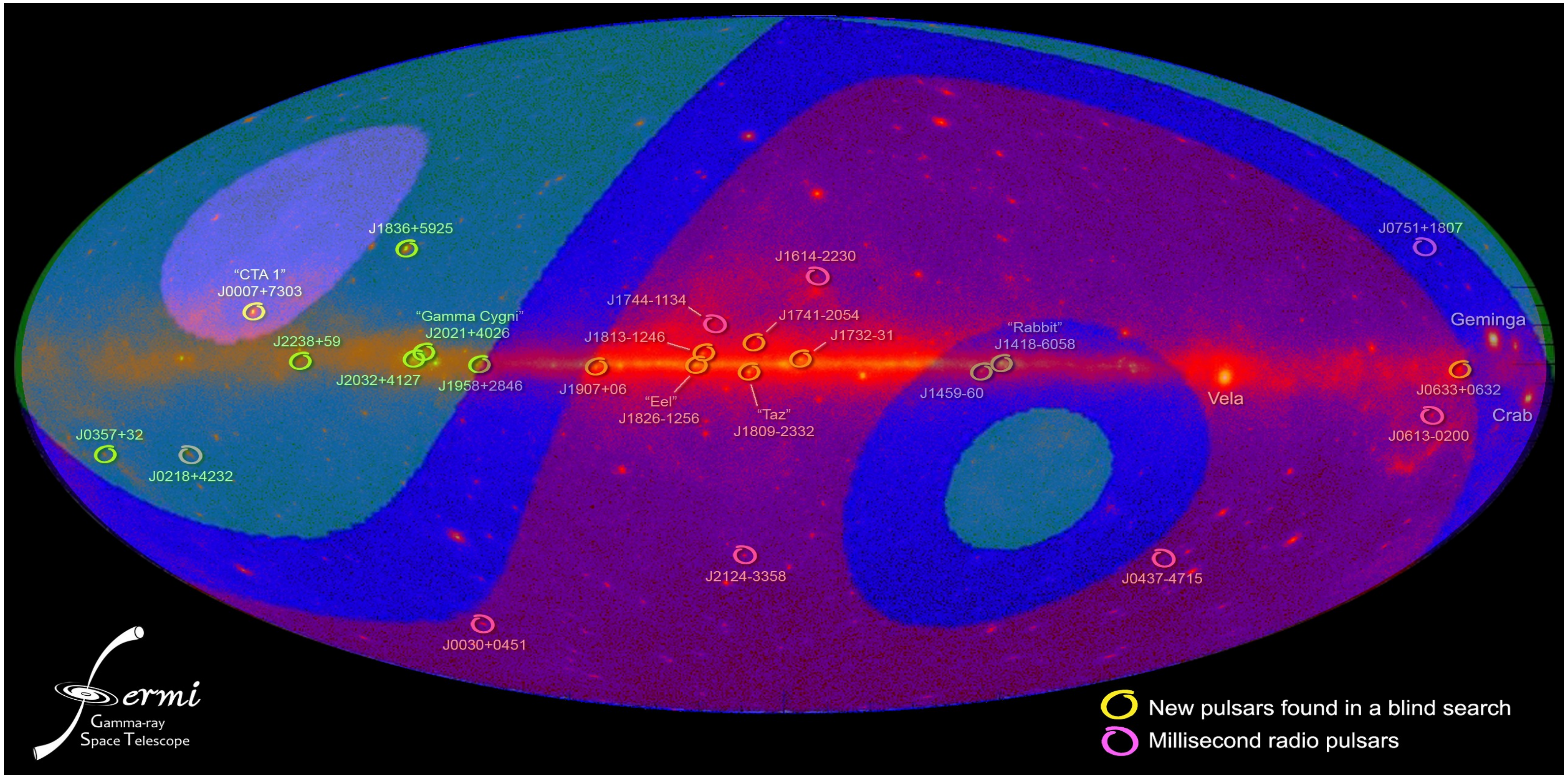
- **HESSII** (Southern hemisphere)
- MAGICII, VERITAS (Northern hemisphere)
- CTA: the near future (both hemispheres).

Pulsar population @ VHE

- If there are more pulsars like Crab, how many?

→ VHE observatories with E_{th} < 100 GeV:

- **HESSII** (Southern hemisphere)

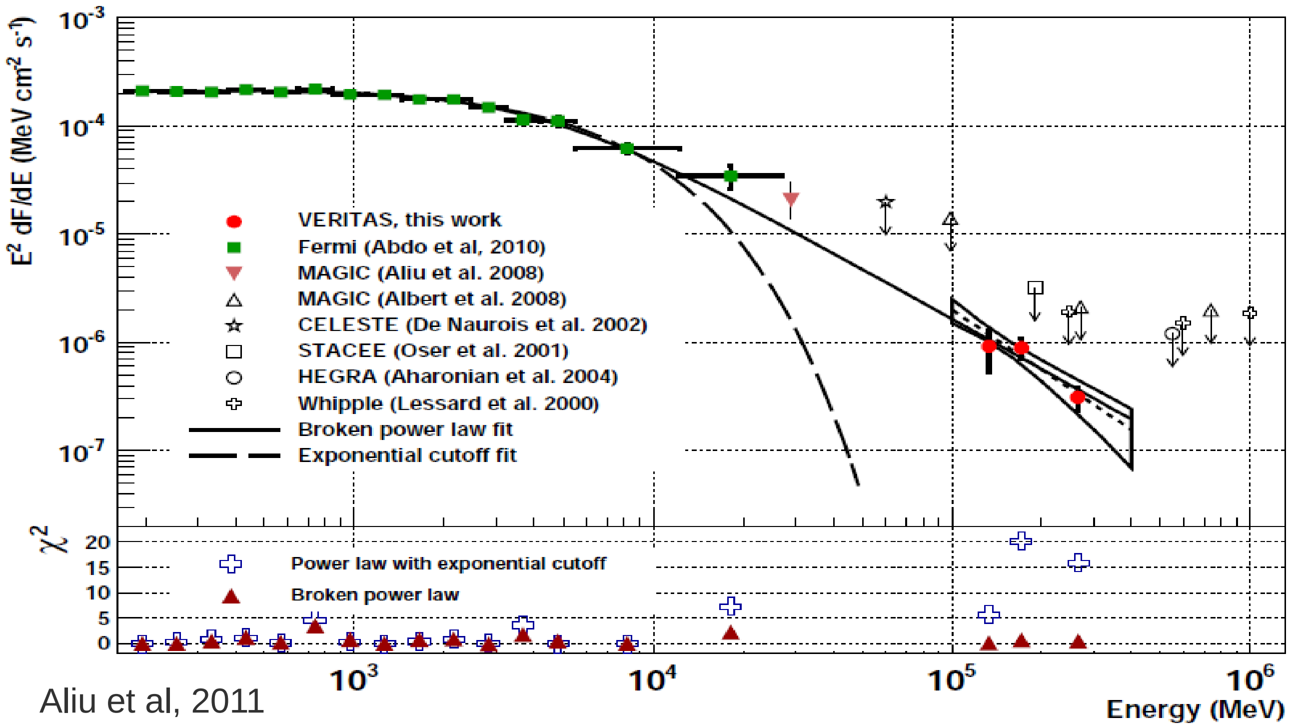


Pulsar population for H.E.S.S.-II

- Best candidates from the pulsar population @ HE:
  - 2nd Fermi pulsar catalog (2PC): 117 PSR
  - Fermi high energy catalog (>10 GeV) (1FHL):
    - 27 PSRs associated to Fermi-LAT pulsars.
    - 12 PSRs (> 25 GeV) → 5 PSRs with TeV PWN.

Pulsar population @ VHE:
Crab (PSR J0534+2200)

- Fermi 1-yr catalog (2010): Exponential cut-off
- VERITAS Crab pulsar (2011): broken-power law



Aliu et al, 2011

green:

$$\left(E/E_0\right)^{-\alpha} e^{-E/E_0}$$

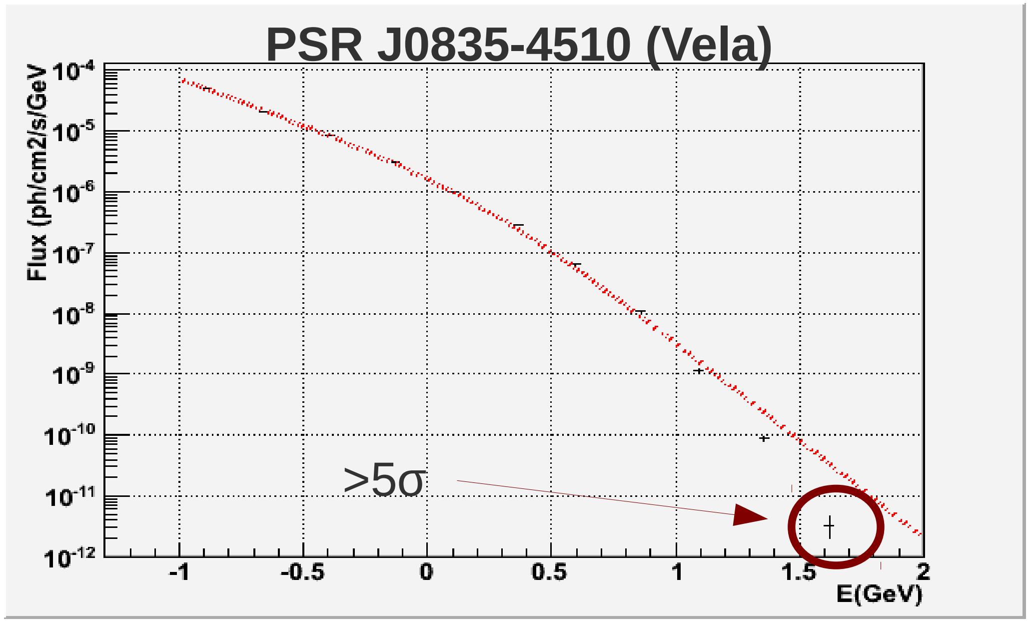
green + **red**:

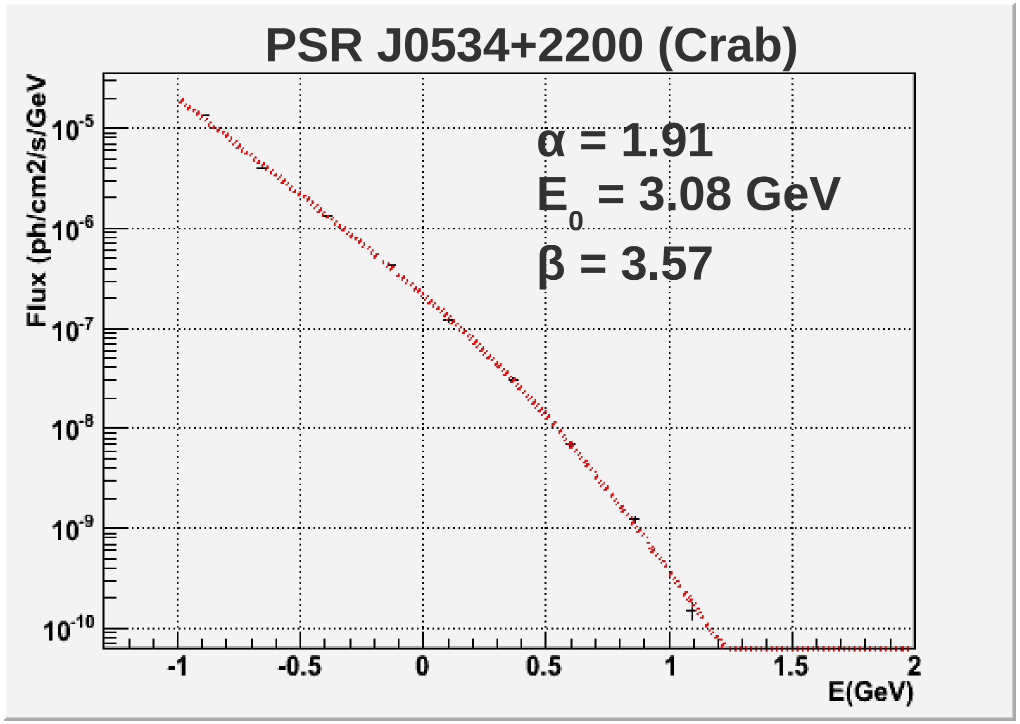
$$\frac{\left(E/E_0\right)^{-\alpha}}{1+\left(E/E_0\right)^{-(\alpha-\beta)}}$$

2nd Fermi Pulsar Catalog

- 117 pulsars fitted to power-law + Exponential cut-off.
- How well they fit to a BPL?.

$$f(E) = A \cdot \frac{(E/E_0)^{-\alpha}}{1+(E/E_0)^{-(\alpha-\beta)}} \quad cm^{-2} s^{-1} TeV^{-1}$$

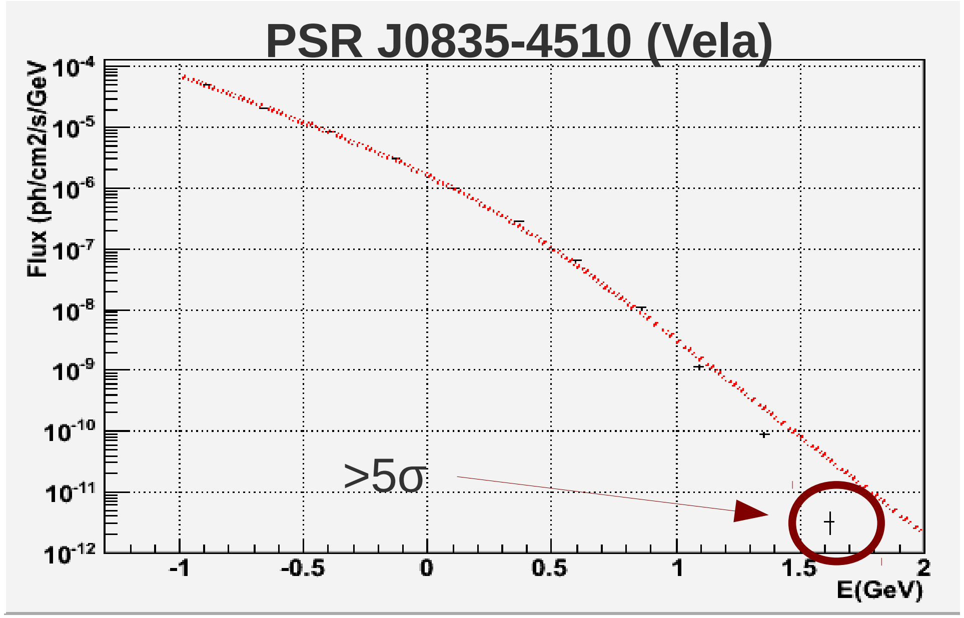


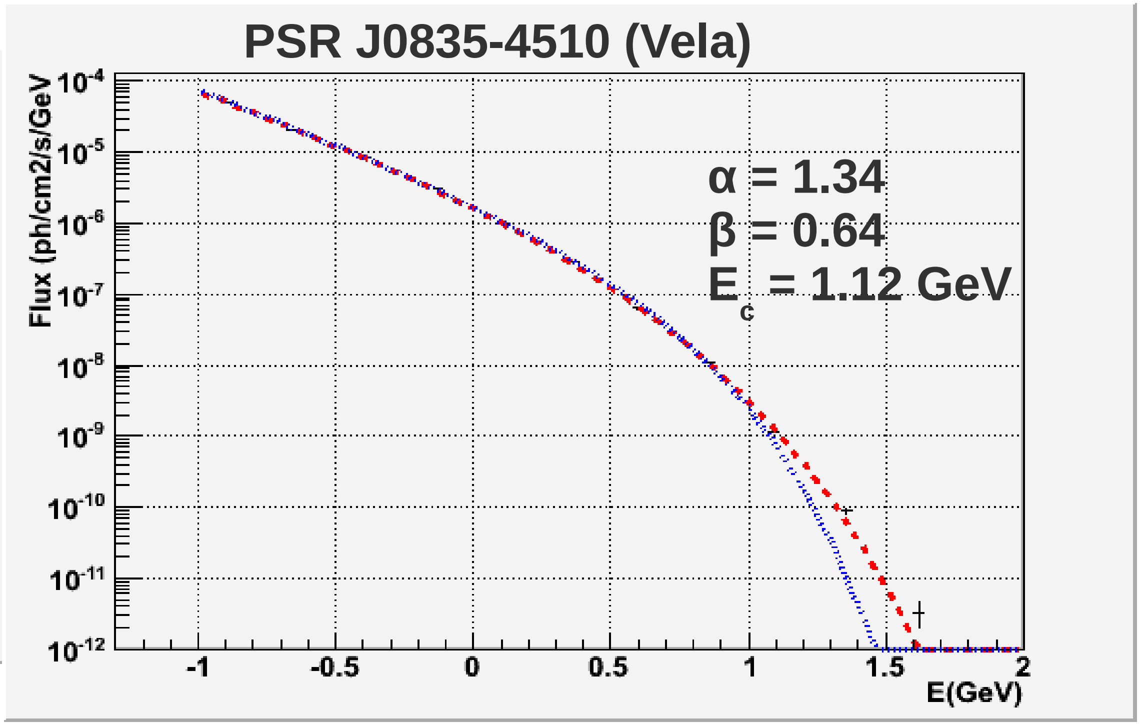


2^{nd} Fermi Pulsar Catalog

- 117 pulsars fitted to power-law + Exponential cut-off.
- How well they fit to a BPL or SubExpPL?.

$$f(E) = A \cdot (E/1\mathrm{GeV})^{-\alpha} \exp(-(E/E_c)^{\beta}) \quad cm^{-2} s^{-1} TeV^{-1}$$





2nd Fermi Pulsar Catalogue

- 117 pulsars fitted to power-law + Exponential cut-off.
- How well they fit to a BPL or SubExpCutoff?
  - 84/117 fit to a BPL
  - 89/117 fit to a SubExpCutoff

→ different populations with different emission models... possibly operating at different locations -like outer-gap variants and pulsar wind zones?

- Analysis cuts: timing. *Extrapolate* timing information from Fermi pulsar catalog comparing Fermi-VERITAS crab.
  - ¼ pulsed duty cycle (0.40 → 0.10).
  - ~2 times the Off phase (0.36 → 0.9).

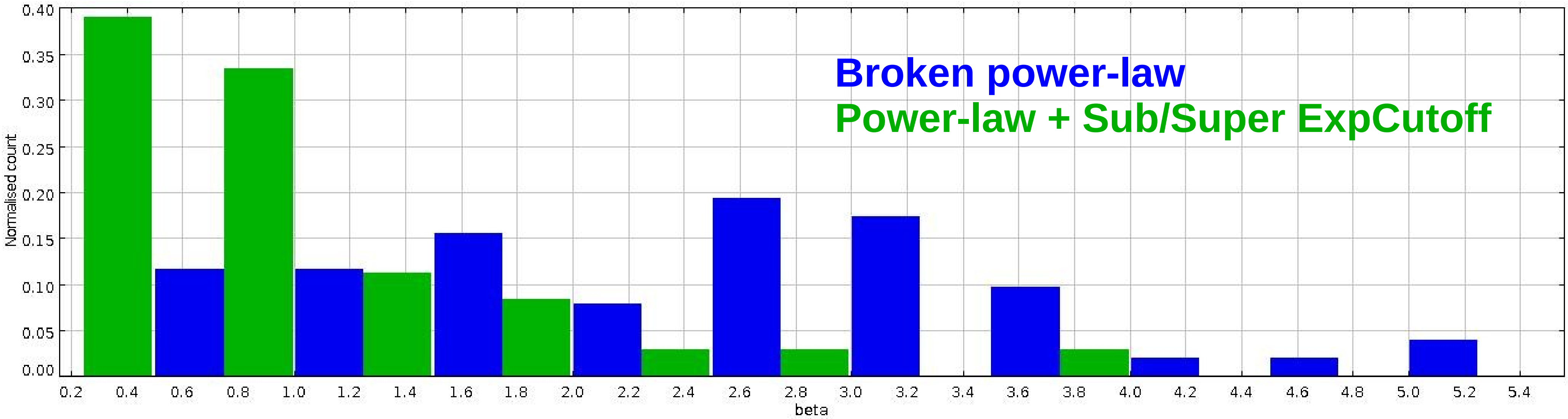
H.E.S.S. Fermi 2PC population target

Power-law + Sub/Super Exponential Cutoff

$$f(E) = A \cdot (E/1\mathrm{GeV})^{-\alpha} \exp(-(E/E_c)^{\beta}) \quad cm^{-2} s^{-1} TeV^{-1}$$

Broken Power-law

$$f(E) = A \cdot \frac{(E/E_0)^{-\alpha}}{1+(E/E_0)^{-\alpha+\beta}} \quad cm^{-2} s^{-1} TeV^{-1}$$

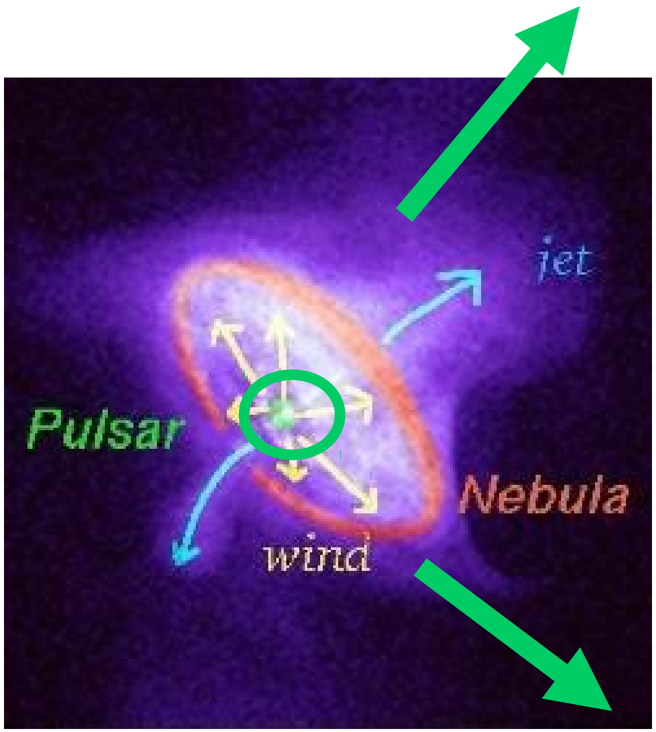


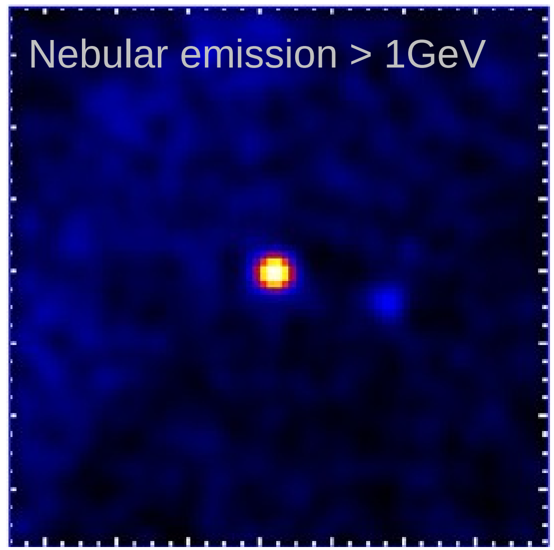
Challenges

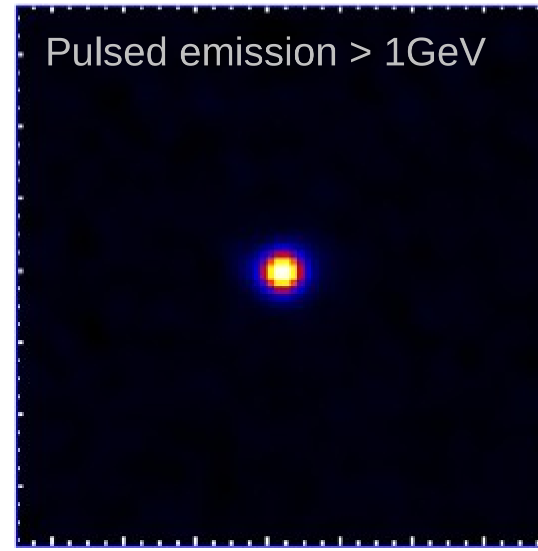
- Possible constrains:
    - Host PWN: additional background

Pulsar analysis

Steady analysis: signal = nebula + pulsar

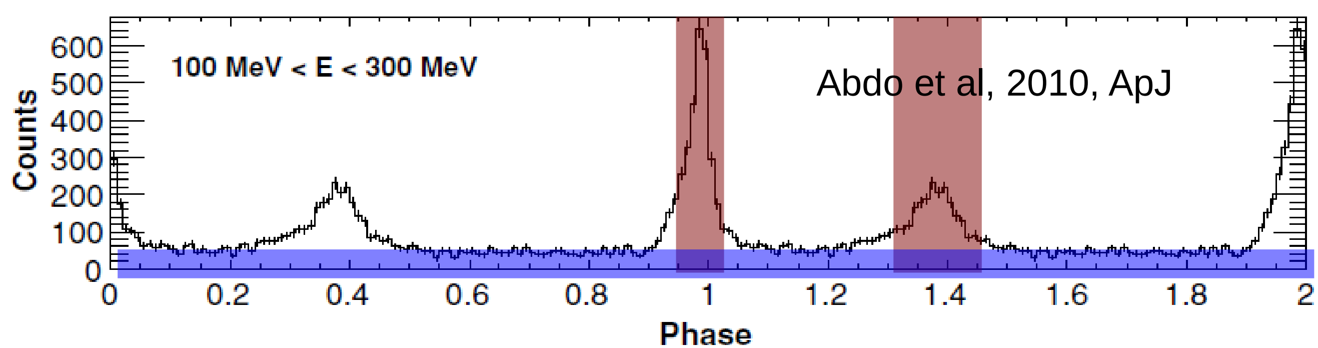






Abdo et al, 2010, ApJ

Timing analysis: signal = pulsar, bg = nebula



R. de los Reyes

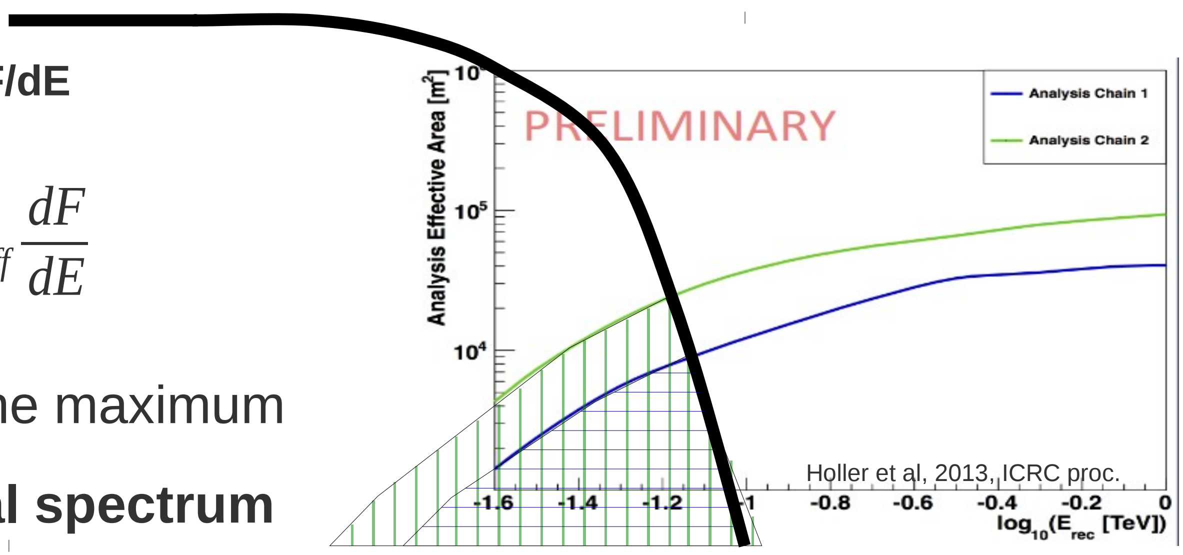
Challenges

- Possible constrains:
  - Host PWN: additional background
  - Energy threshold increase: limitation on the population source
    - Zenith angle (first candidates θ<30º)

Source flux dF/dE

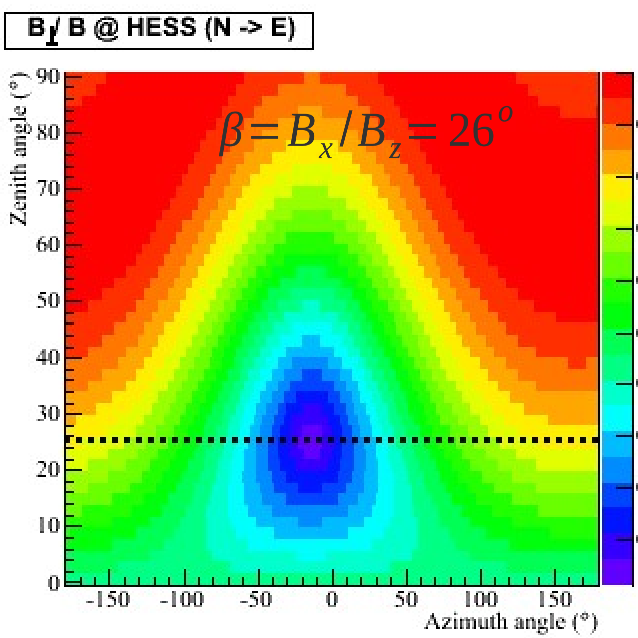
$$\frac{dRate}{dE} = A_{eff} \frac{dF}{dE}$$

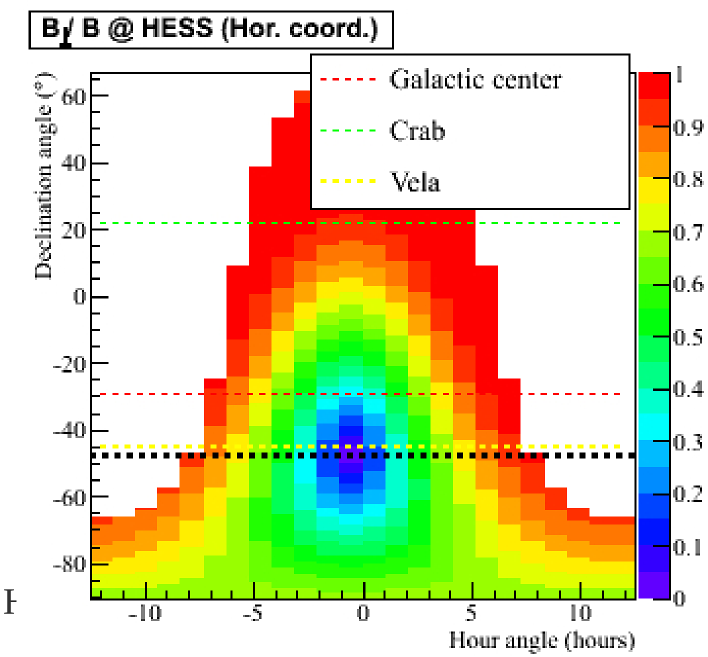
E_{th} ≡ Energy of the maximum of the **differential spectrum**



Challenges

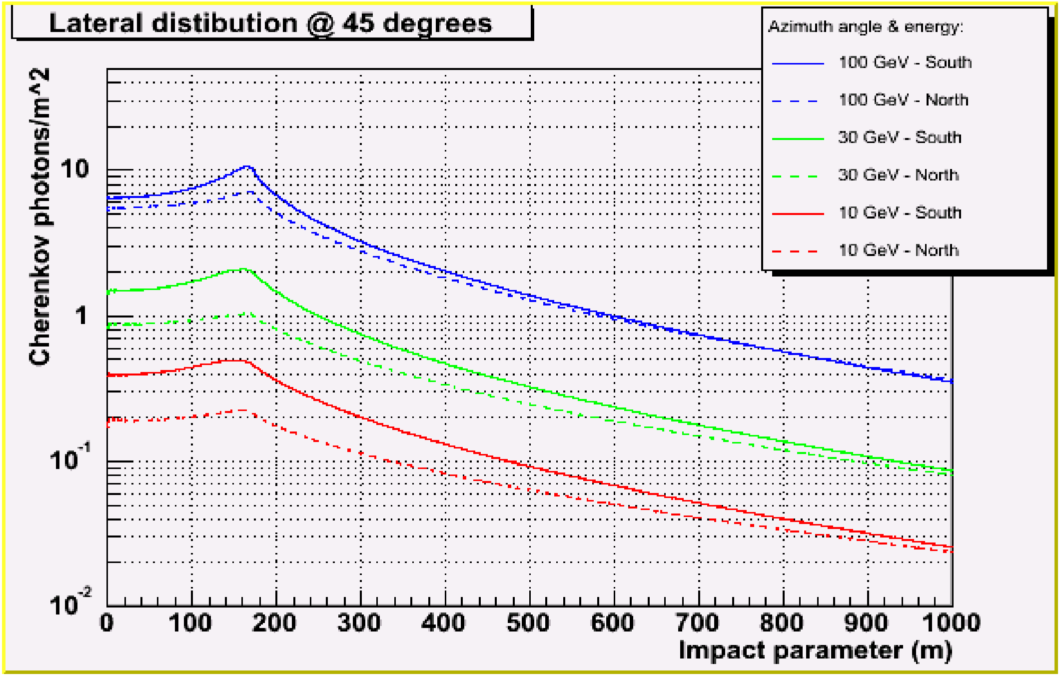
- Possible constrains:
  - Host PWN: additional background
  - Energy threshold increase: limitation on the population source
    - Zenith angle (first candidates θ<30º)
    - B field (sources with δ<10º)

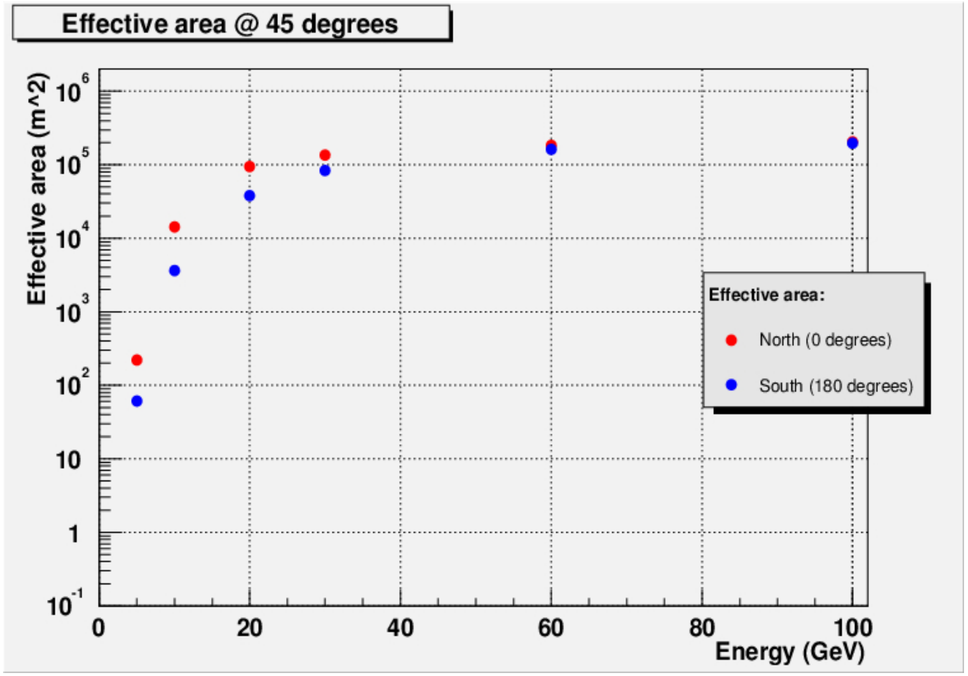




B field

- Magnetic field effects on H.E.S.S.-II sensitivity:
  - Increase of the E_{th}.
  - Decrease of the shower amplitude ($\rightarrow A_{eff}$)





de los Reyes, 2008, PhD thesis

B field

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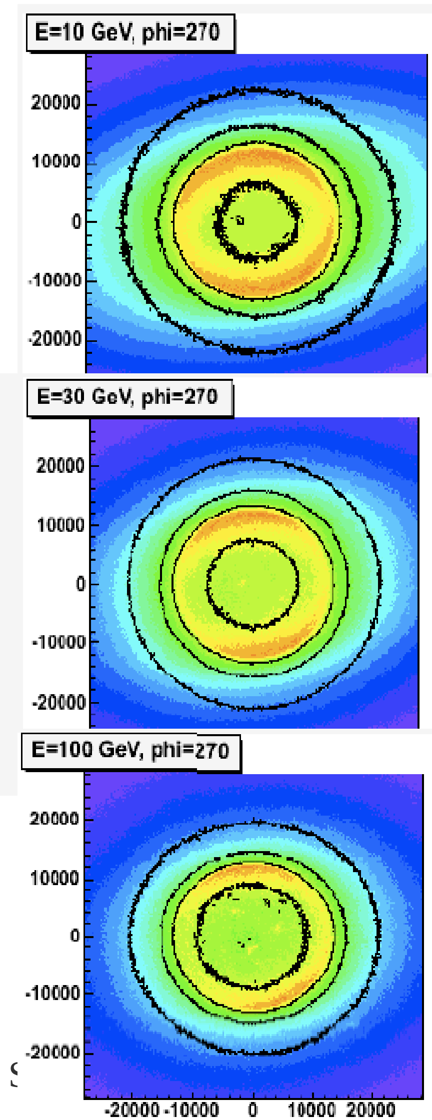
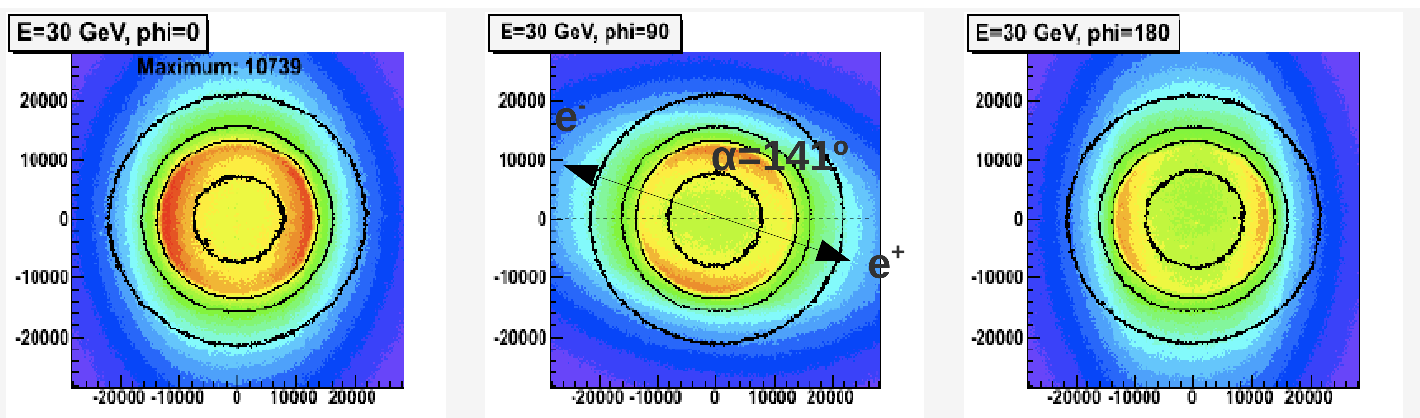
de los Reyes, 2008, PhD thesis



θ=15º



- "Twisting" of the air-shower image: Lorentz force direction

B field

- Magnetic field effects on H.E.S.S.-II sensitivity:
  - Increase of the E_{th}.
  - Decrease of the shower amplitude ($\rightarrow A_{eff}$)
  - "Twisting" of the air-shower image: MC simulations in azimuth for equivalent $B_{\perp}$ module for each zenith angle.

Theta (deg):	Azimuth bins (deg)
0.0	0 , 180
10.0	0 , 180
20.0	0 , 77 , 180
30.0	0 , 62 , 180
40.0	0 , 76 , 180
50.0	0 , 86 , 180

Preliminary
(extrapolating from MAGIC):
$\Delta B_{\perp} = 11\ \mu T \rightarrow$ 5-30% ΔA_{eff}

Conclusions

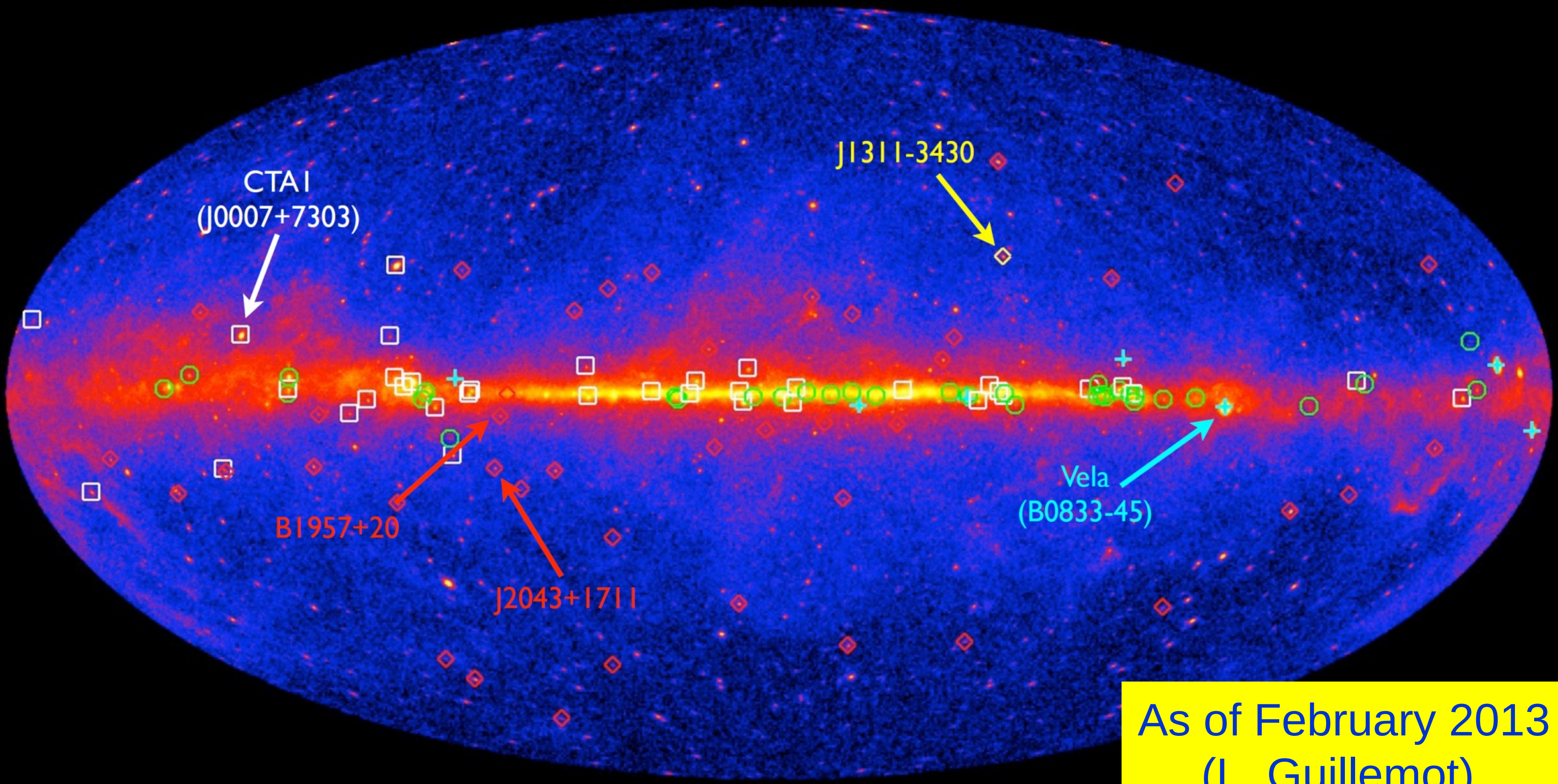
- Number of γ-ray pulsars increases rapidly.
- Fermi 2PC and 1 FHL do not rule out emission at VHE → Crab might not be alone.
- Fits to SubExponential cutoff and BPL template spectrum of Fermi 2PC data point to a population of high β values.
- H.E.S.S.-II is the only Cherenkov telescope with E_{th}<100 GeV in the Southern hemisphere.
- Pulsar light curve will improve the γ/hadron separation (limited at low energies).
- Background contribution from a putative PWN might complicate the analysis.
- Earth's magnetic field may have a strong effect at low energies.

Backup slides

Fermi LAT, E > 100MeV

121 γ-ray pulsars!

Cf. https://confluence.slac.stanford.edu/display/GLAMCOG/Public+List+of+LAT-Detected+Gamma-Ray+Pulsars



As of February 2013
(L. Guillemot)

41 young radio- and X-ray-selected (green circles, cyan crosses)

36 young γ-ray-selected (white squares)

43 radio-selected MSPs (red diamonds) + 1 γ-ray-selected MSP (yellow diamond)

from B. Rudak, Rencontres de Moriond, La Thuile, March 9-16 2013

2nd Fermi Pulsar Catalogue

- 117 pulsars with LC and spectral points.
- How well they fit to a BPL?.

$$f(E) = A \cdot \frac{(E/E_0)^{-\alpha}}{1 + (E/E_0)^{-\alpha+\beta}} \quad cm^{-2} s^{-1} TeV^{-1}$$

- 11 pulsars (PSR) excluded from the study:
  - 3 have F100="nan" (J0729-1448, J0940-5428, J1019-5749)
  - 7 have $\alpha = E_c$="nan" (J1024-0719, J1410-6132, J1513-5908, J1531-5610, J1741+1351, J1835-1106, J1939+2134)
  - J0835-4510 (Vela) can not be properly fitted by a BPL.

Conclusions (BPL scenario)

- Broken power-law (BPL) spectrum template seems to be possible for a large population of 2PC Fermi pulsars → includes 3 of the HESS2-Mono proposal candidates (except Vela pulsar).
- 2nd Fermi pulsar catalogue (117 pulsars):
  - 84 fitted to BPL with ranges:
    - $0.5 < \alpha < 6.7$
    - $0.5 < \beta < 9.0$
    - $0.13 < E_0 < 8.1$ GeV

HESS-II Mono Proposal

Fermi pulsars at VHE with H.E.S.S. II

P.I.: R. de los Reyes
Co-Authors: J. Bolmont, M. Chretien, M. Fuessling, M. Gajdus, G. Giavitto, M.-H. Grondin, M. Grudzinska, E. de Ona-Wilhelmi, B. Rudak, U. Schwanke, C. Venter, A. Zajczyk

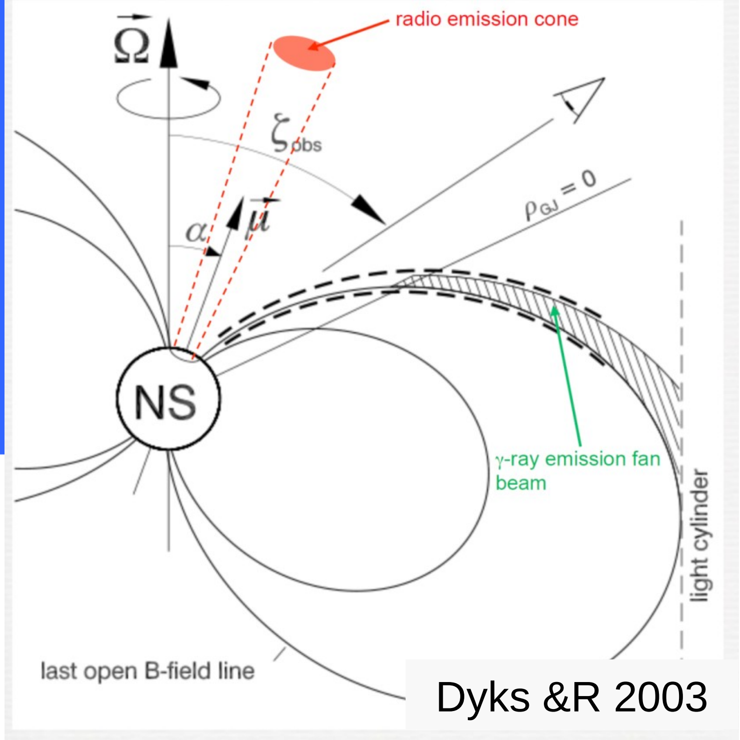
March 18, 2013

1 Abstract

During the last 4 years, *Fermi*-LAT has significantly increased the population of γ-ray pulsars. Recent results at Very High Energies (VHE) from VERITAS (>100 GeV) and MAGIC (>25 GeV) demonstrated the possibility of detecting pulsars at these energies. With an expected threshold below 100 GeV and being the only Cherenkov observatory in the Southern Hemisphere operating above these energies, H.E.S.S. II (mono) is in a unique position to observe the pulsar population visible from the Southern Hemisphere. In this proposal we request observation time for the first four of a top ten list of candidates based on the first year Fermi catalog and ordered by an energetic criteria and observation zenith angle. Their spectra at VHE (> 10 GeV) have been extrapolated taking

Why do pulsars radiate

in high energy domain?



Dyks &R 2003

1) Rotating, strongly
magnetized neutron stars ->
unipolar inductors

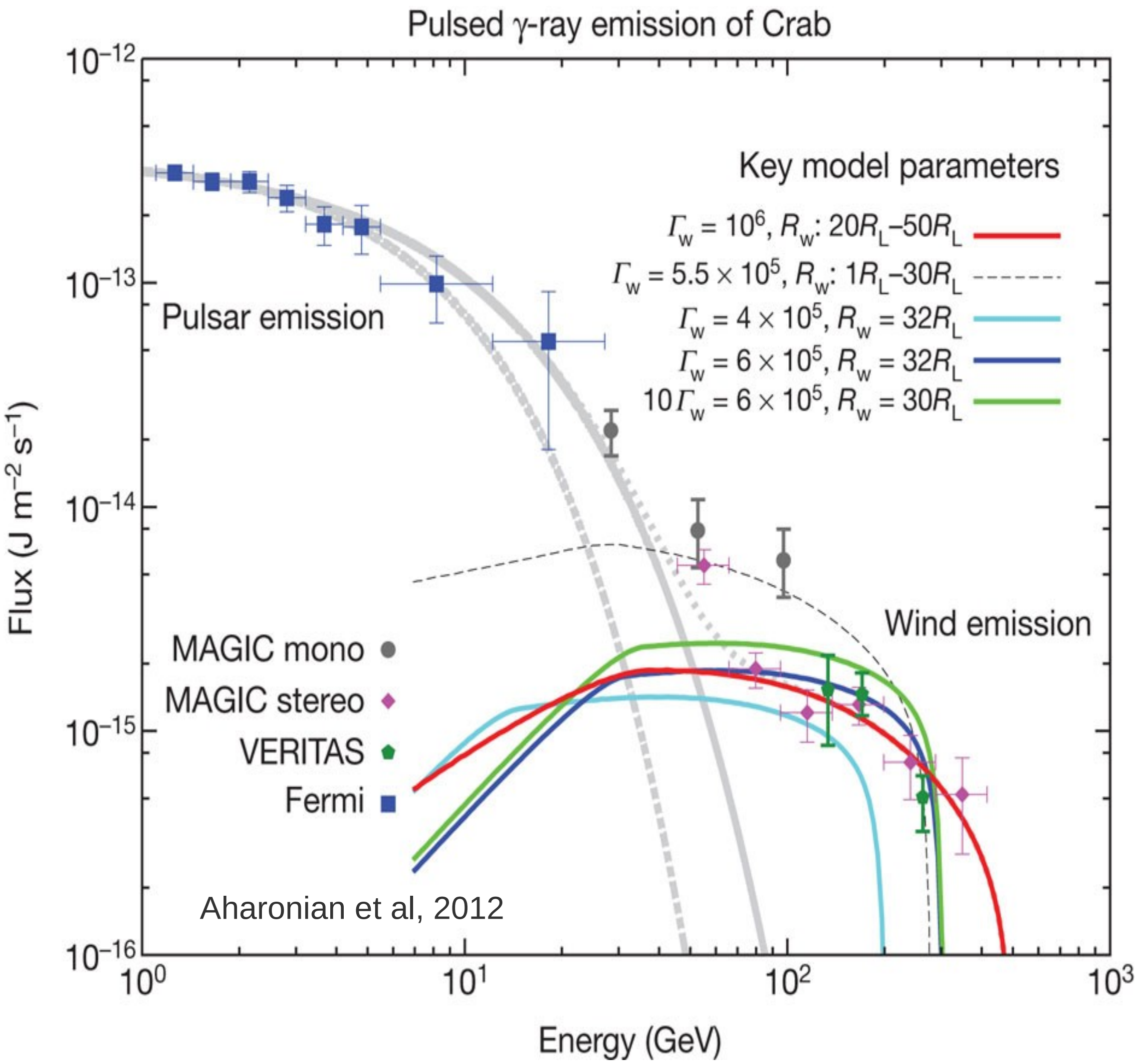
2) Maximum potential drop (for vacuum rotator)

Vmax ≈ 6 × 1012 B12 P-2 Volts,

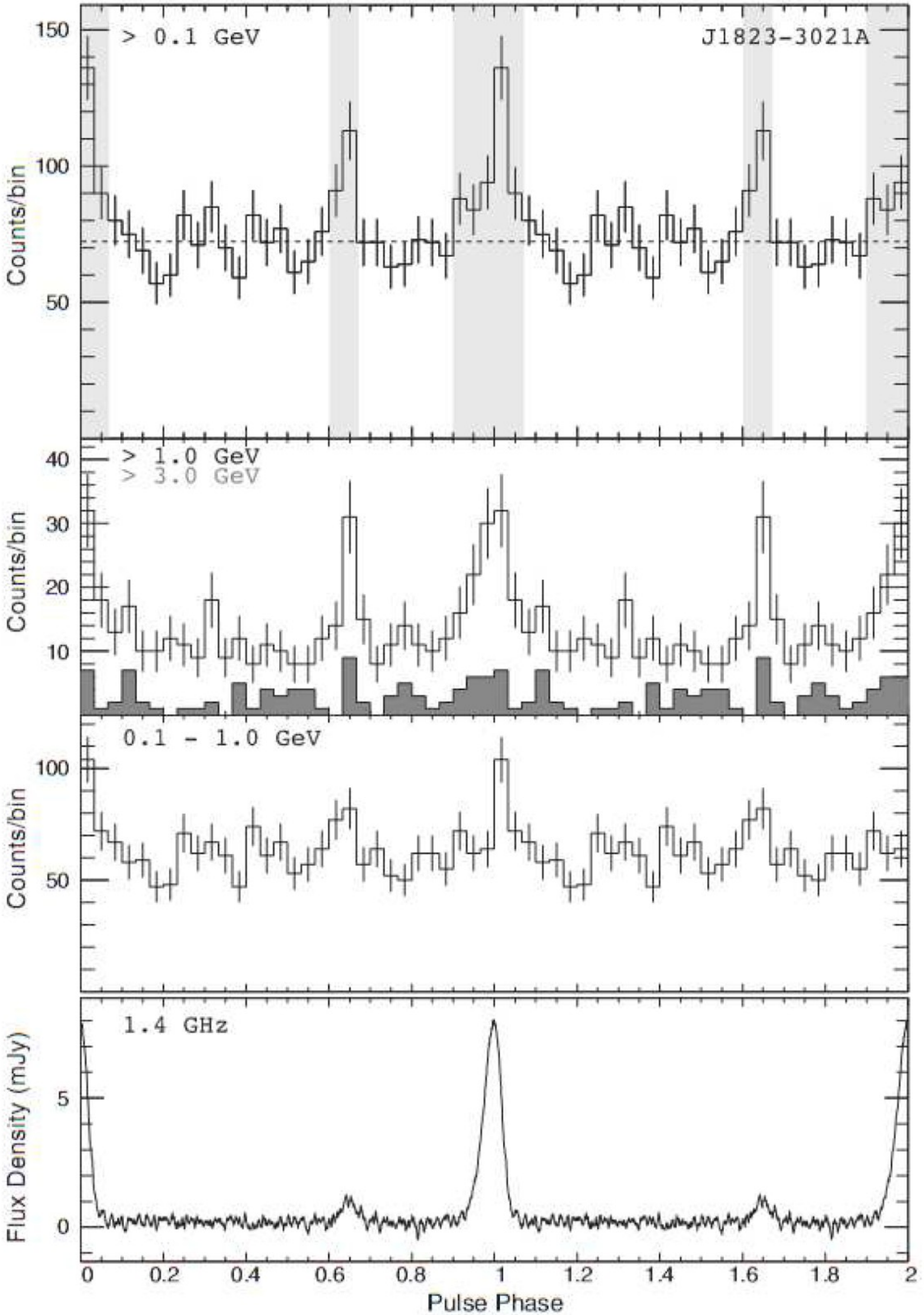
i.e. for young pulsars Vmax can exceed 1016 Volts.

Realistic potential drops are much smaller,
but high enough
to accelerate particles to ultrarelativistic energies.

Generating pulsed VHE within the wind zone



- Magnetospheric winds as carriers of spin-down power.
- After HE+VHE results:
  - Pulsar magnetosphere at tens of stellar radii (preferred outer gap models).
  - Generating pulsed VHE within the wind zone.
  - Cold ultra-relativistic wind at $r>20\ r_{Lc}$ (Aharonian et al, 2012).



Fermi LAT Collab., 2011

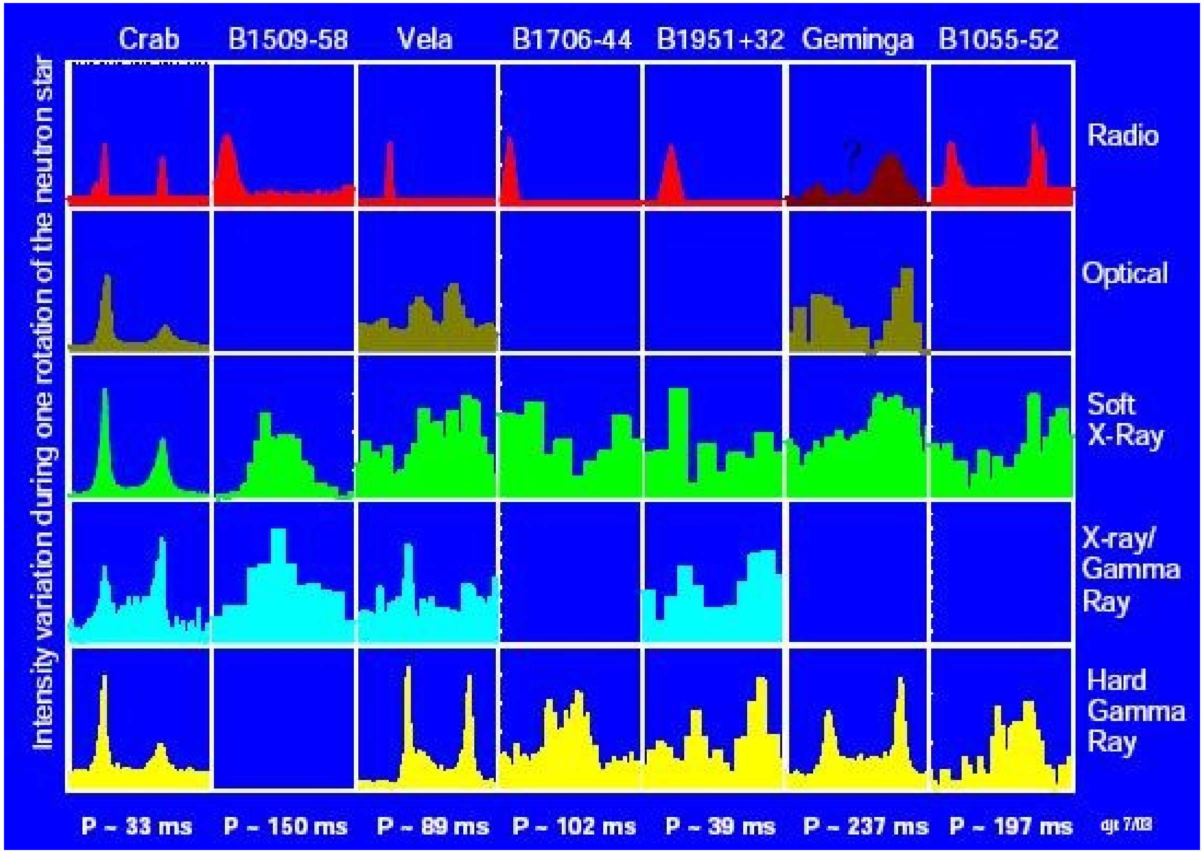
The first gamma-ray pulsar found in a globular cluster

PSR J1823-3021A

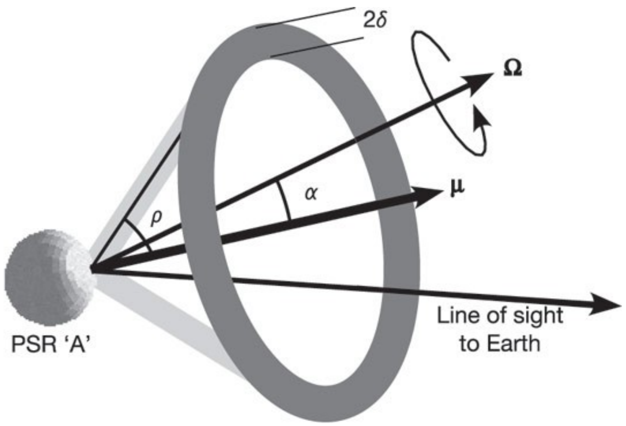
in NGC 6624

(P = 5 ms)

Origin of the γ-ray pulsed emission



Thompson D.J., 2004, ASSL



Light pulse profile probably related with the cone geometry

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Leading-trailing peaks asymmetry