Pulsars in Gamma-ray Astronomy with H.E.S.S.

Maxime Regeard
JRJC 2024

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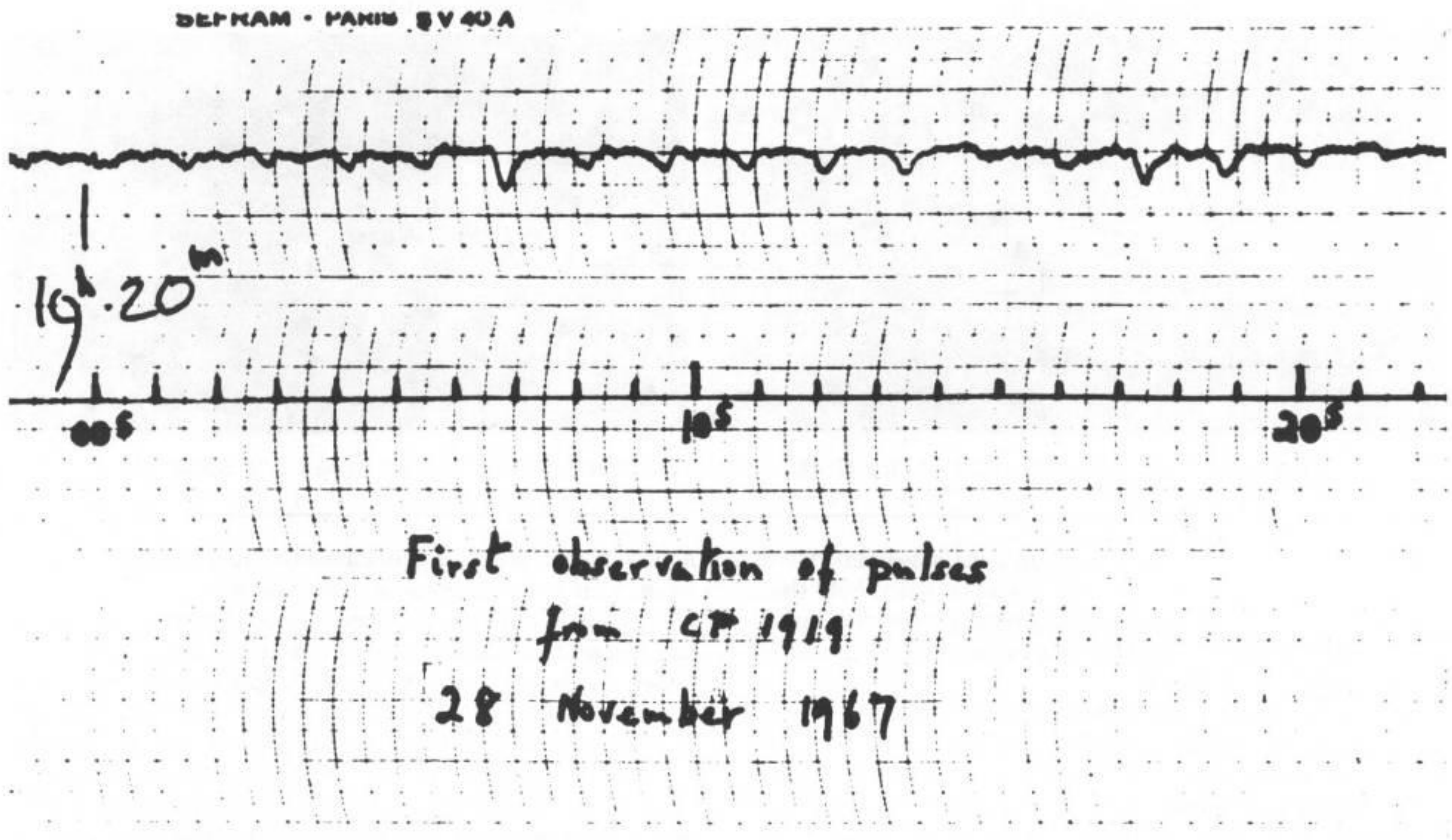
- Pulsars
- Gamma-ray astronomy
- Pulsars in Gamma-ray astronomy
- Pulsars in Gamma-ray astronomy with H.E.S.S.

Pulsars

Pulsars: Discovery by Jocelyn Bell



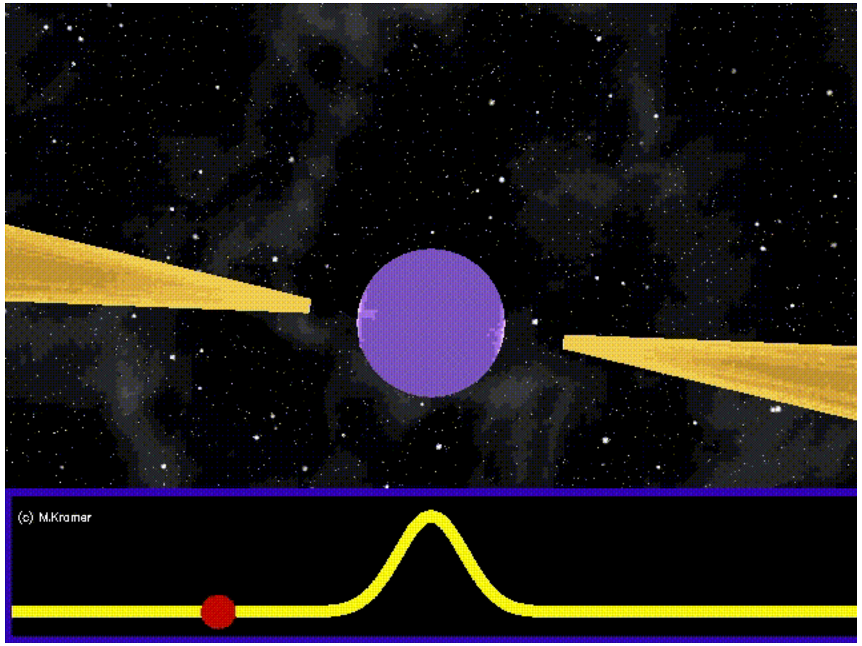
"I got it on a fast recording. As the chart flowed under the pen I could see that the signal was a series of pulses . . . 1⅓ seconds apart." (Deflections are down).

Pulsars: Discovery by Jocelyn Bell

- **PhD thesis with Antony Hewish on a radio telescope**
- **August 1967, hint of pulsation**
- **On 28 November 1967, they record the first signal from a pulsar repeating every 1.337 second**
- **Nicknamed the signal *LGM-1*: *Little Green Men 1***
- **December 21, second puslar detected confirmed the astrophysical source origin**
- **Hewish received the Nobel Price for the discovery, BUT NOT BELL !**

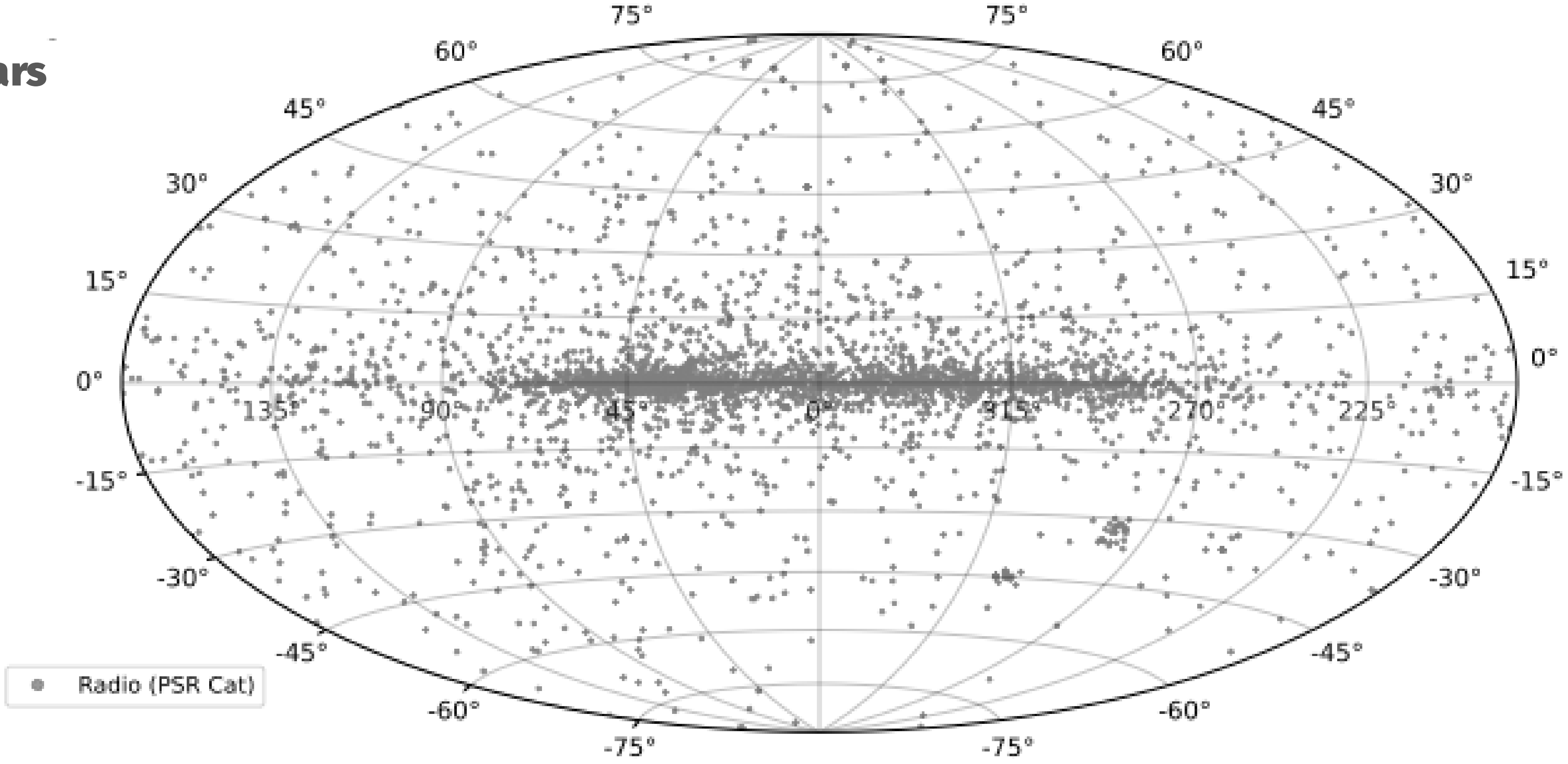
Pulsars: What is it ?

- Understood as a highly magnetised spining neutron star
- Originates from the collapse of a star
- Pulsar (Neutron star):
  - Mass ~1.4 Solar mass
  - Radius of 10-12 km
  - Spin period: few milisecondes to secondes
  - High Magnetic field: 10^7 to 10^{13} G $\rightarrow$ 10^3 to 10^9 T (interstellar magnetic field: few μG)
- Electromagnetic radiation at the magnetic poles
- Pulsar are spining NOT pulsating ! Analogous to a lighthouse
- Pulsar Geometry: The light beam has to cross Earth's line of sight



Pulsar: Where is it ?

~3000 pulsars



Pulsars: Where is it ?

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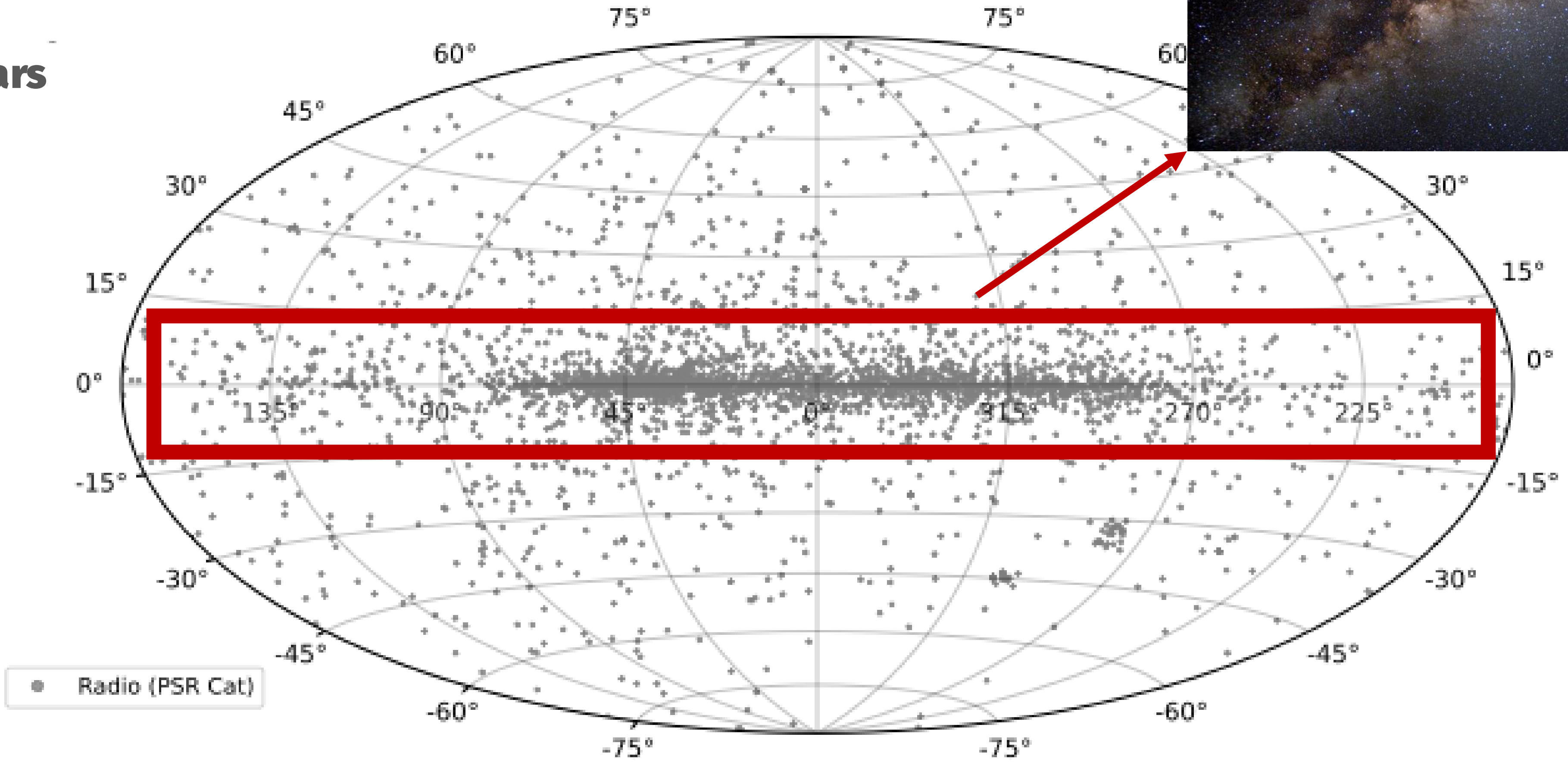

Pulsars: Where is it ?

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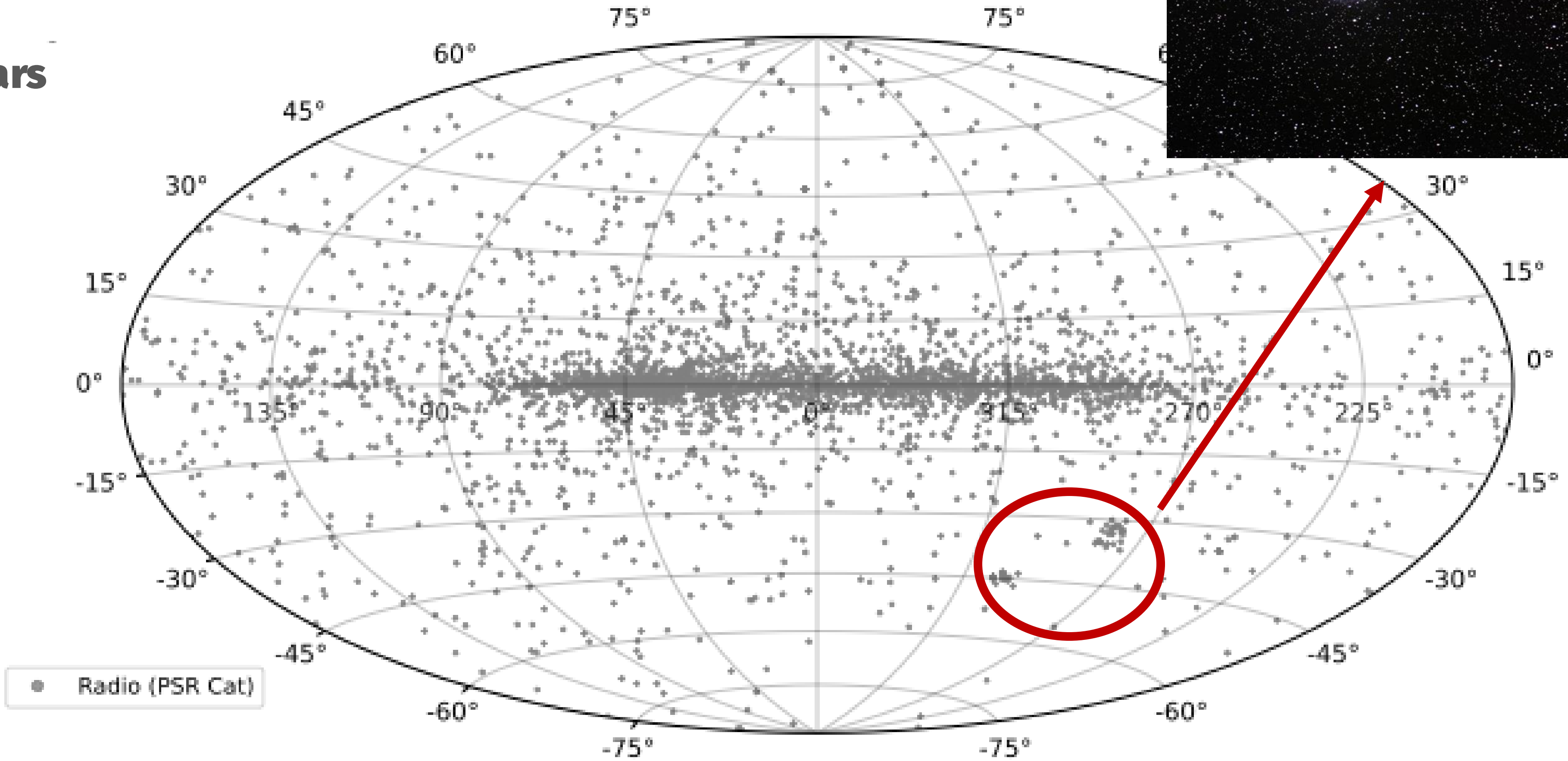
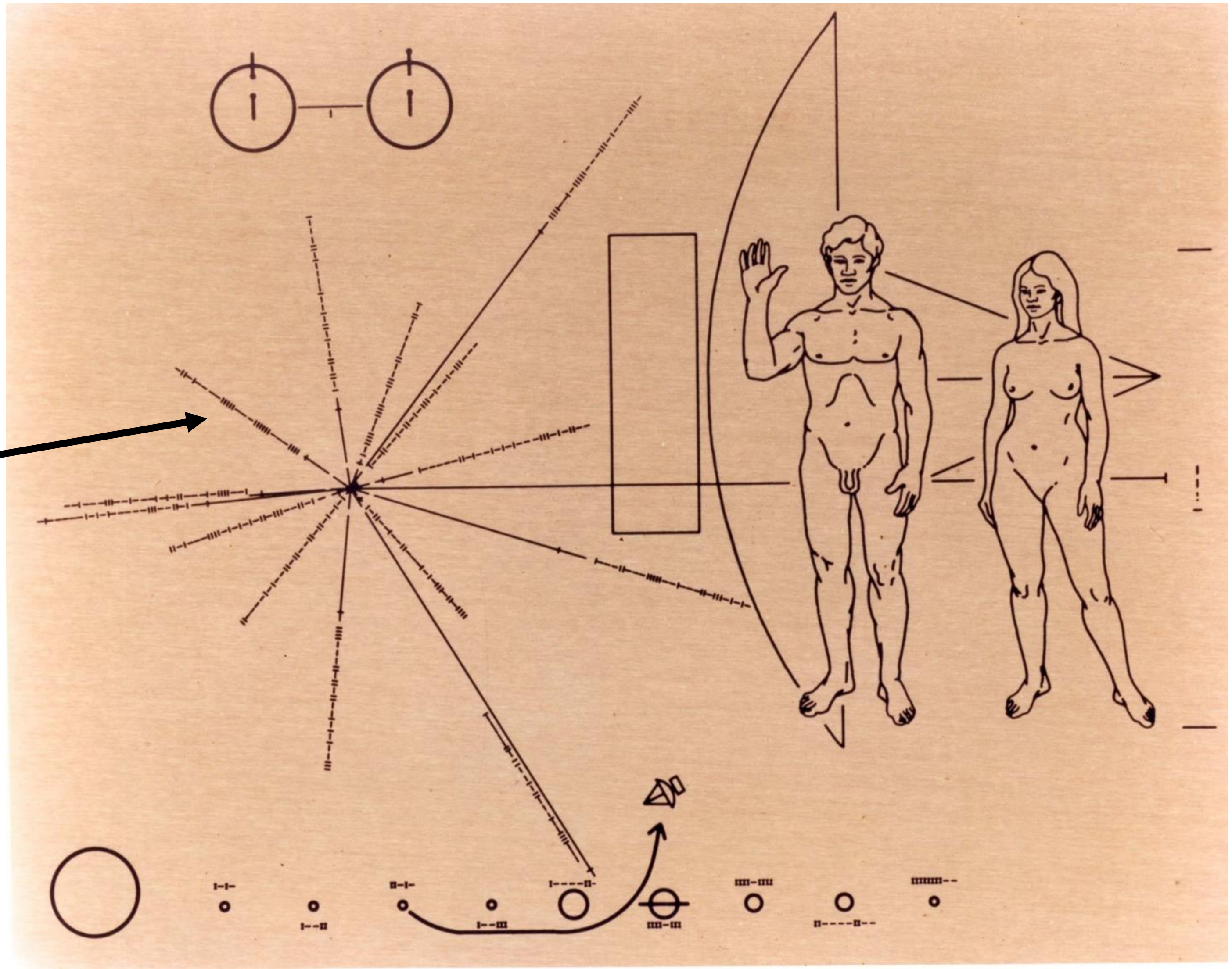


Pulsars: fun facts

Pionner's plaque

Map using pulsar

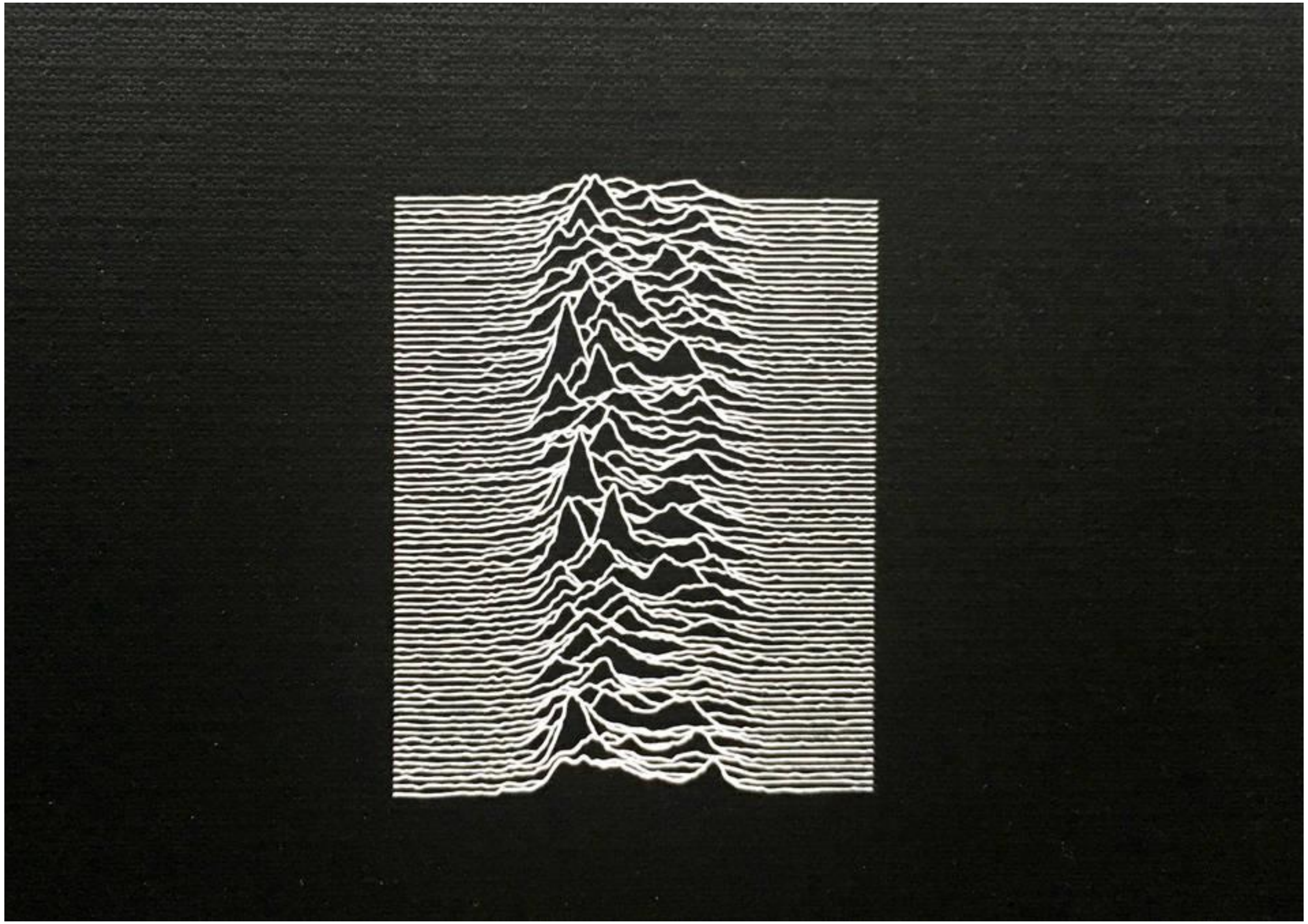


Pulsars: fun facts

Unknown pleasures – Joy Division

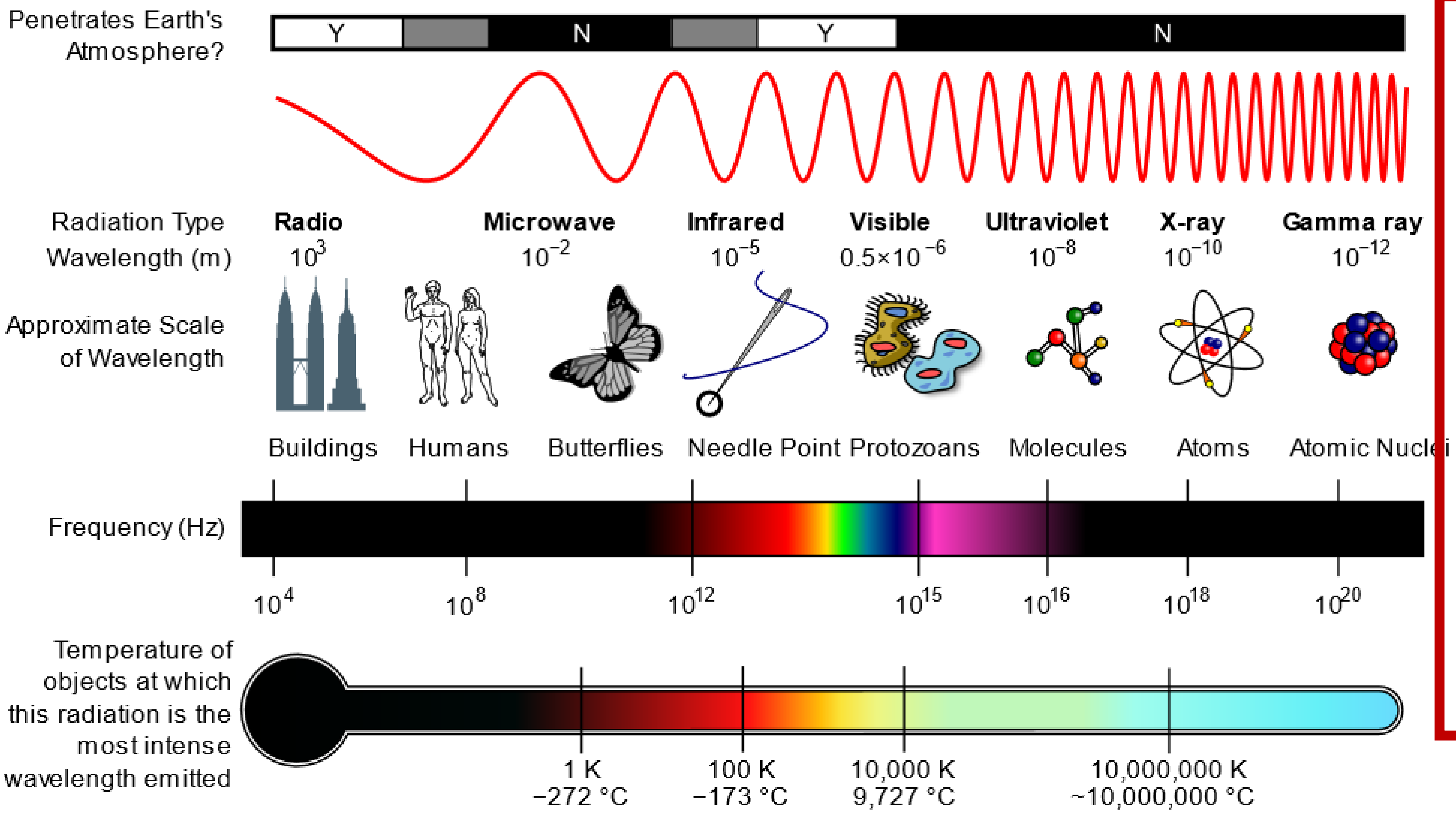
Pulsation of CP 1919 first pulsar discover by Jocelyn Bell

That's cool !



Gamma-ray astronomy

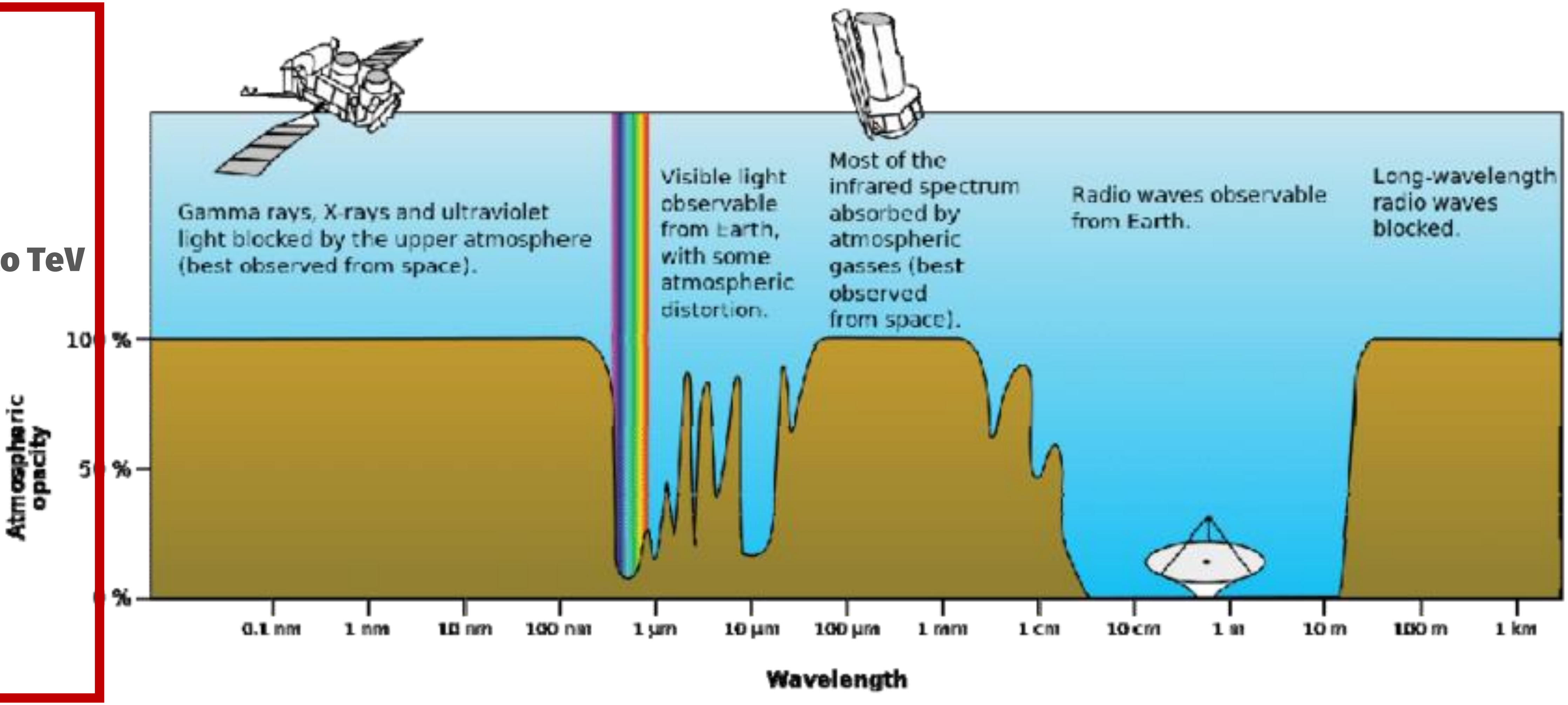
Gamma-ray astronomy



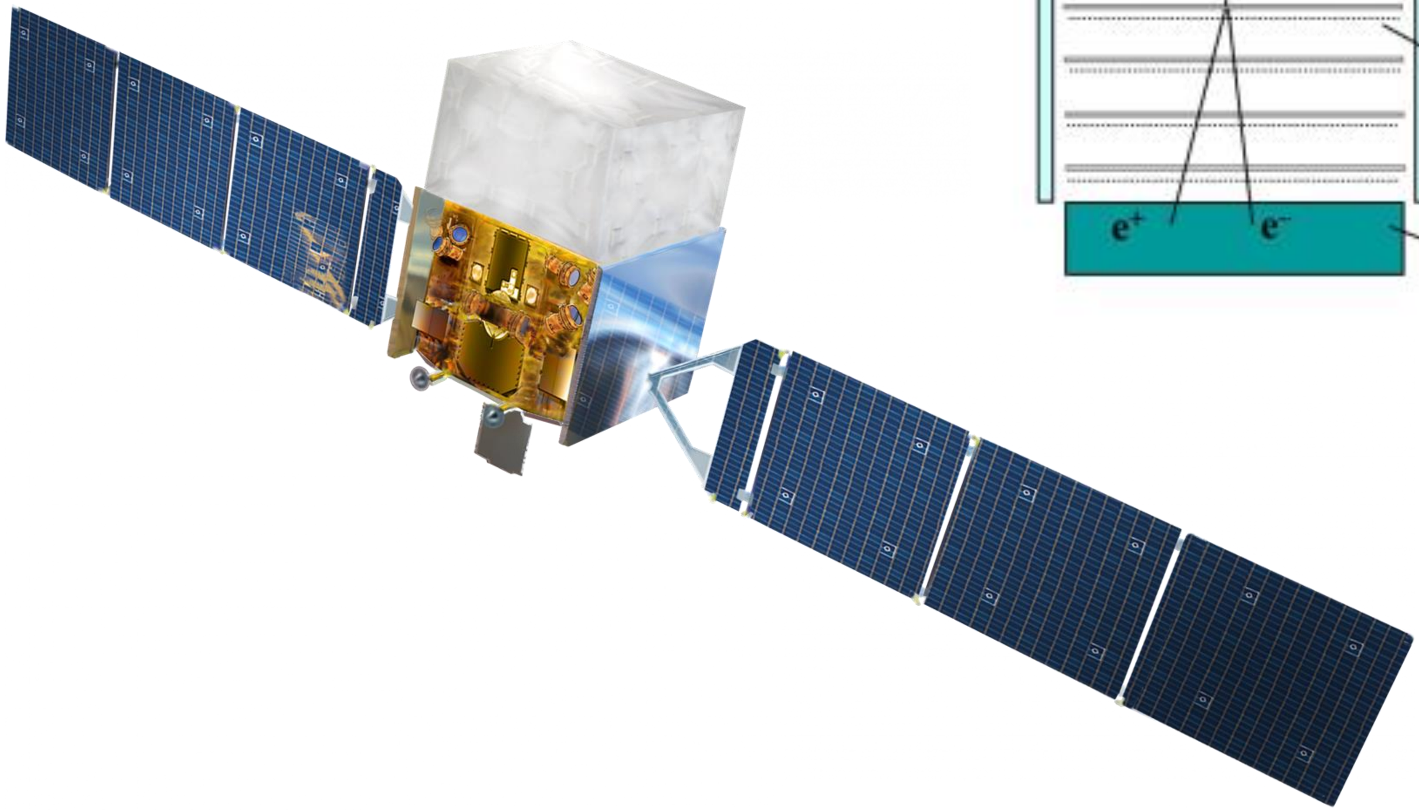
(MeV) GeV to TeV

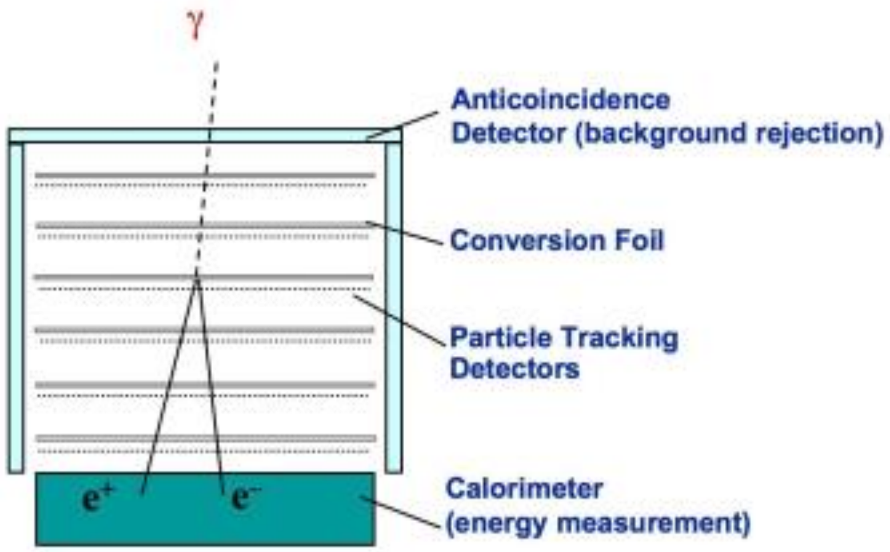
Gamma-ray astronomy

(MeV) GeV to TeV



Fermi-LAT

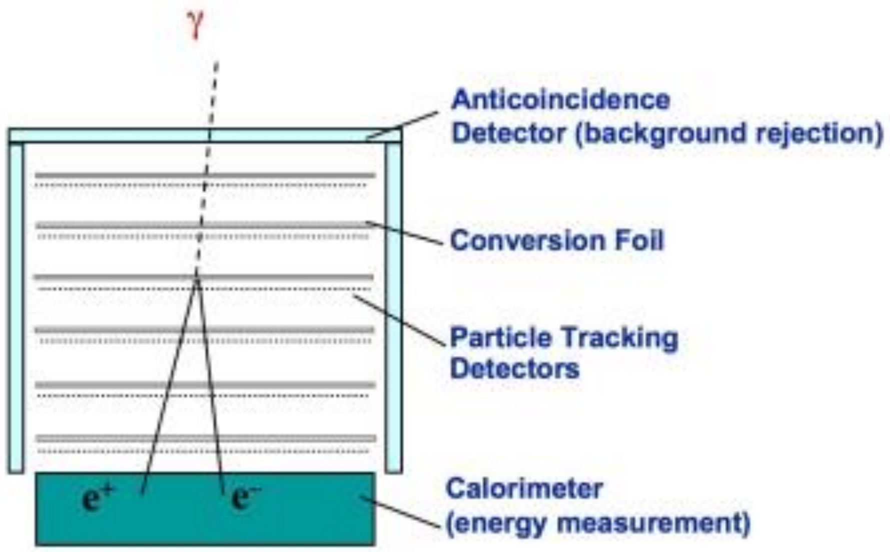




- Survey telescope (see all sky every ~3h)
- Energy range: 20 MeV – 300 GeV
- # of photons decrease with energy
- → limited by the area of detection (1 m²)

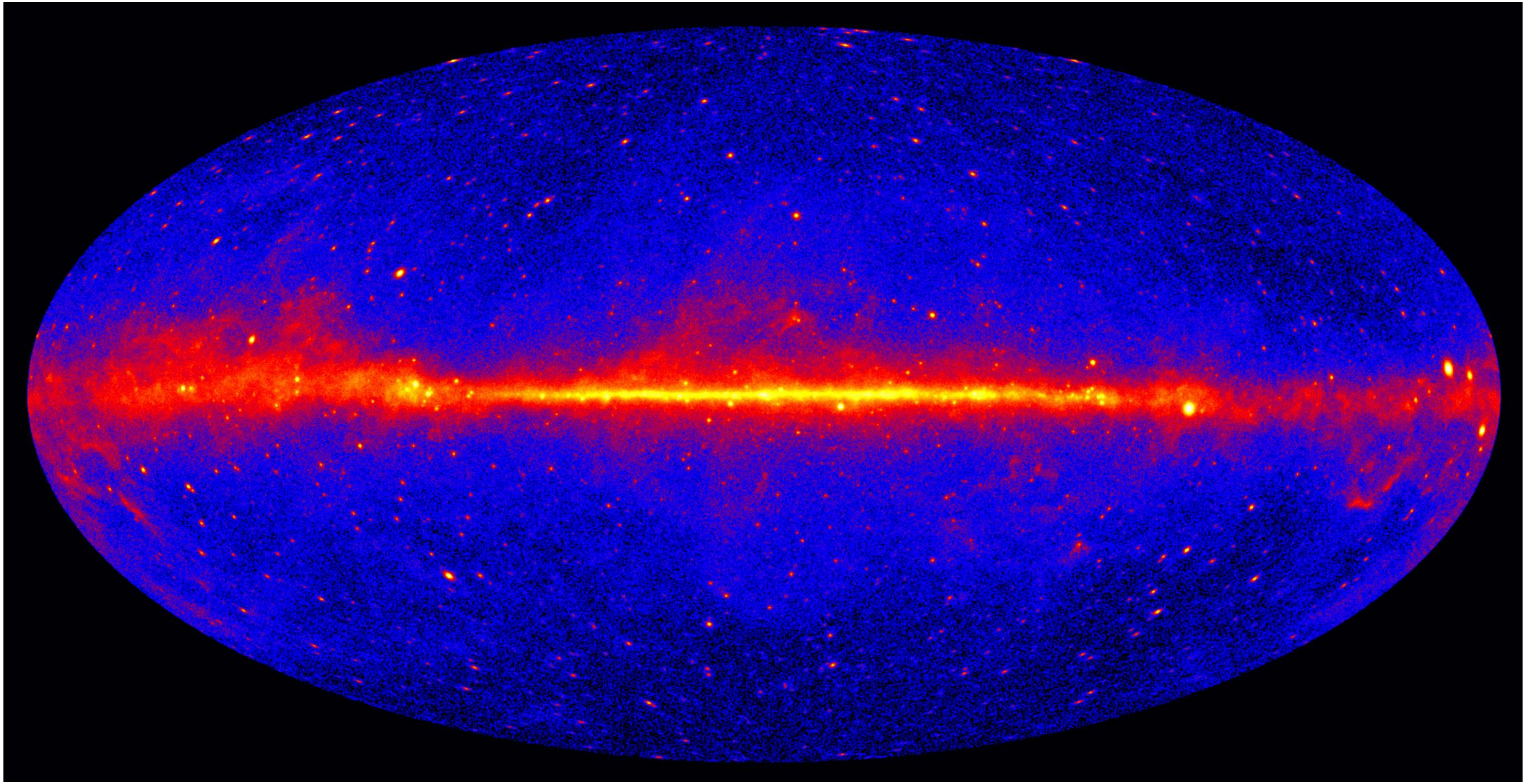
Fermi-LAT

Krampouz-LAT

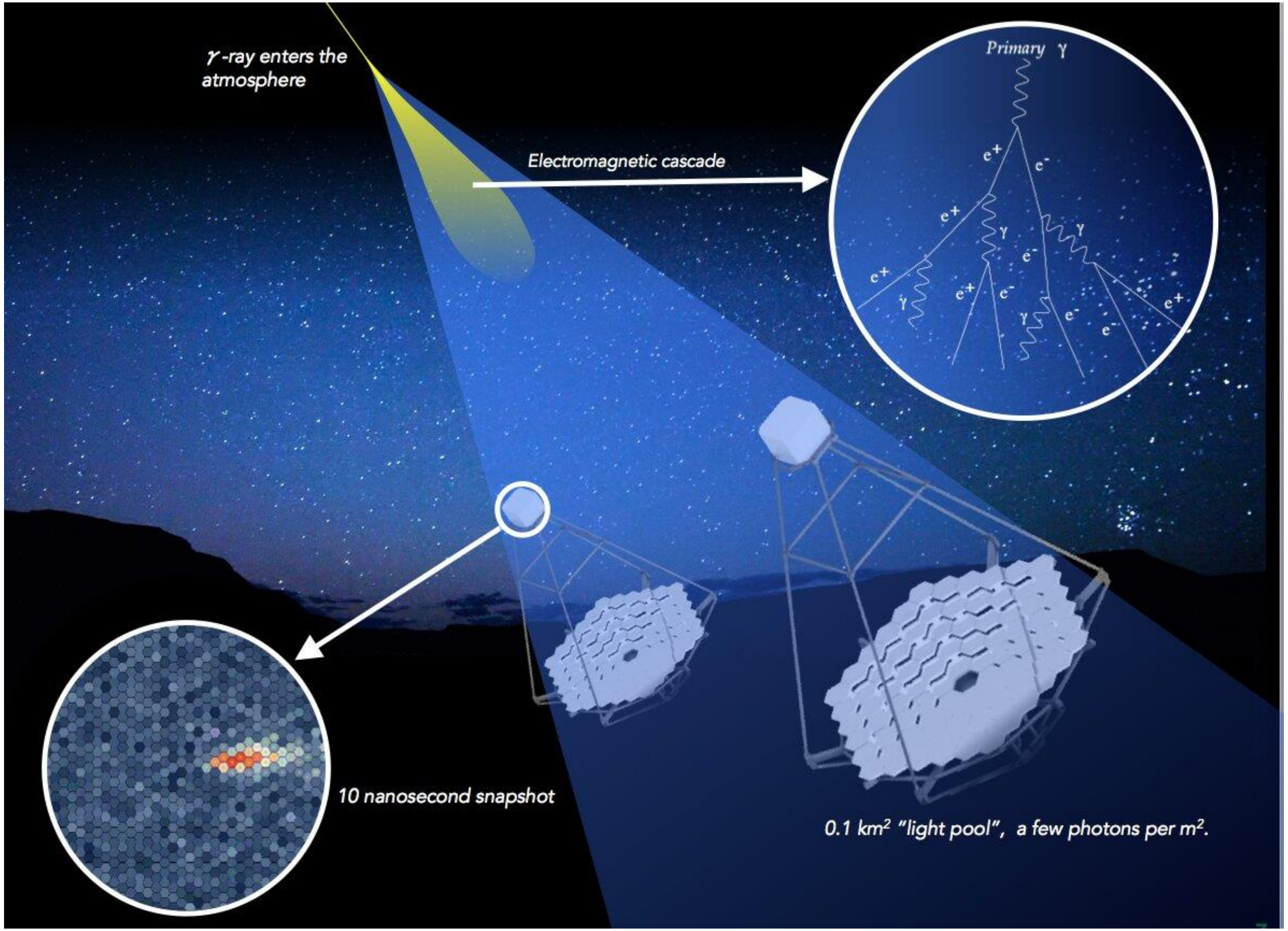


- **Survey telescope (see all sky every ~3h)**
- **Energy range: 20 MeV – 300 GeV**
- **# of photon decreases with energy**
- **→ limited by the area of detection (1 m²)**

Fermi-LAT



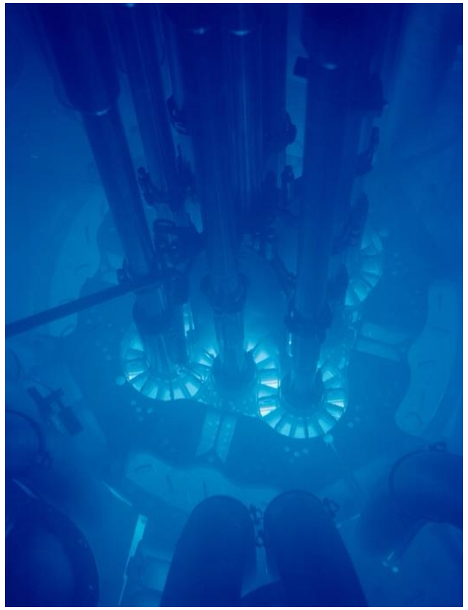
Imaging Atmospheric Cherenkov Telescope (IACTs)



Particles from the cascade traveling faster light in the atmosphere (not in vaccum !) emit light

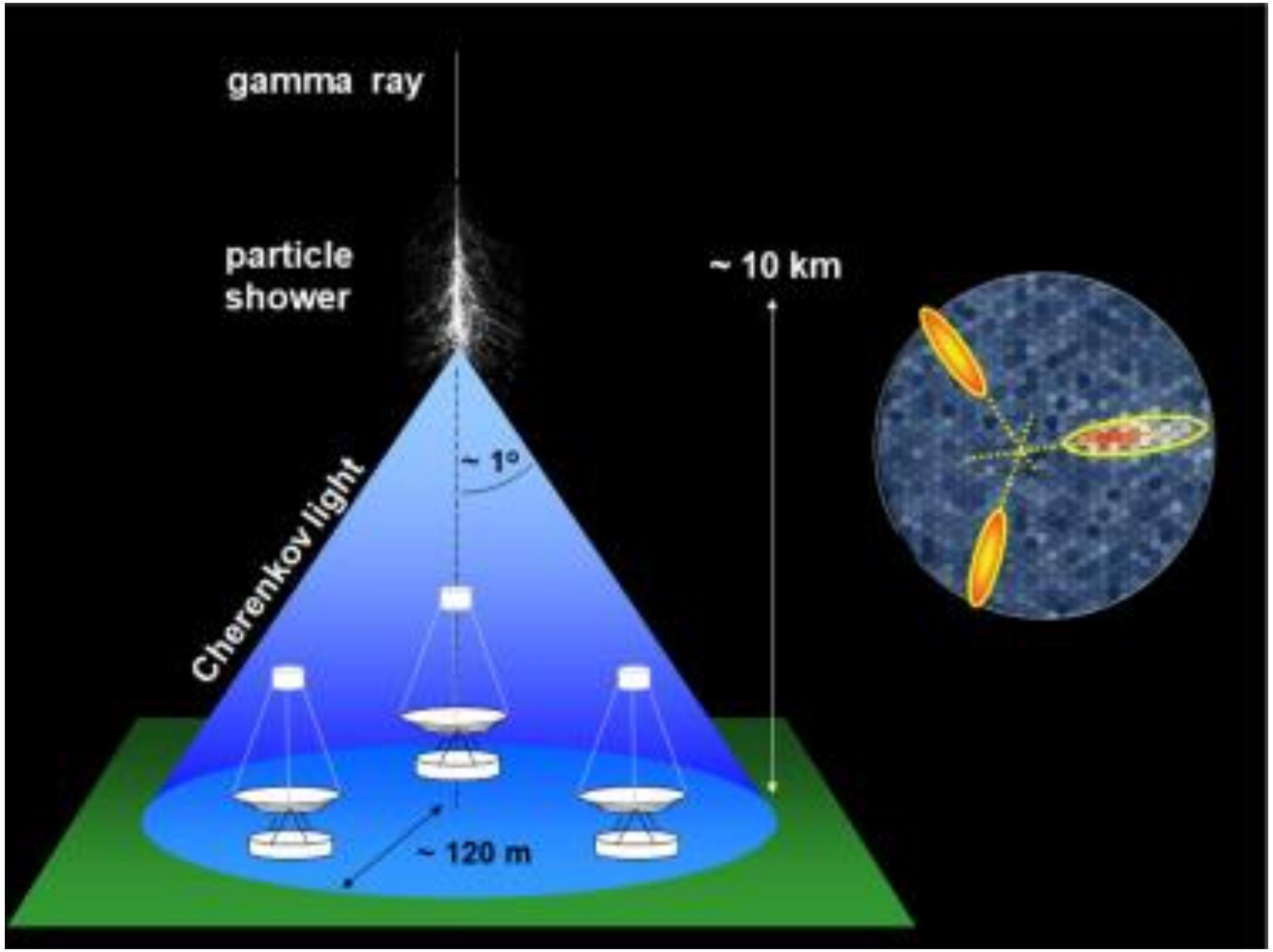
Cherenkov light

Analogous to sonic boom



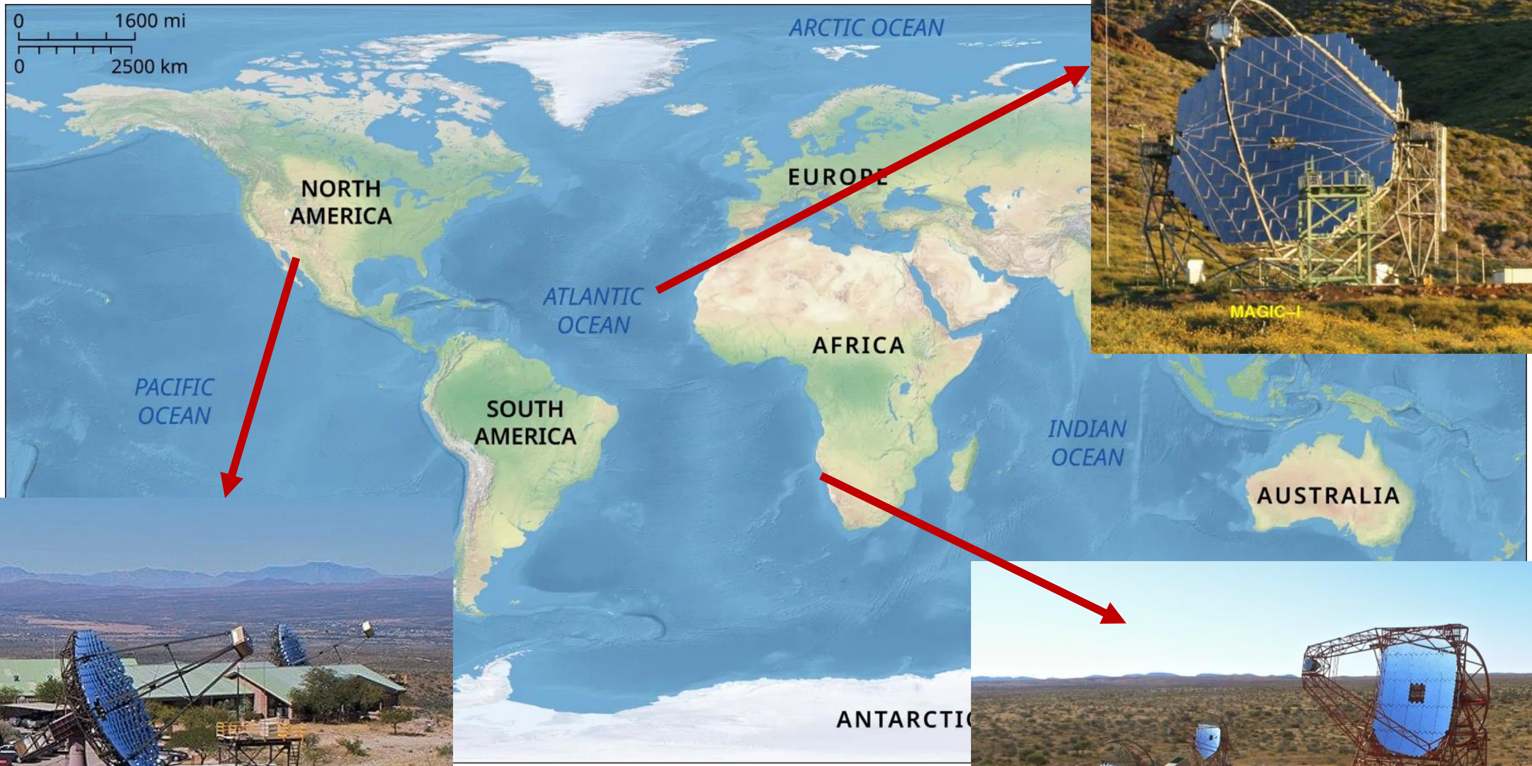
Imaging Atmospheric Cherenkov Telescope (IACTs)

- Imaging Cherenkov light gives information on the incident gamma-ray photon
- Direction from the shape and triangulation (when several telescope)
- Shower depth, linked to # of Cherenkov photons → energy
- Energy range: 10 GeV to 100 TeV
- Pointing telescope with FoV of 2-8 deg^2



IACTs on Earth

MAGIC, Canary Island

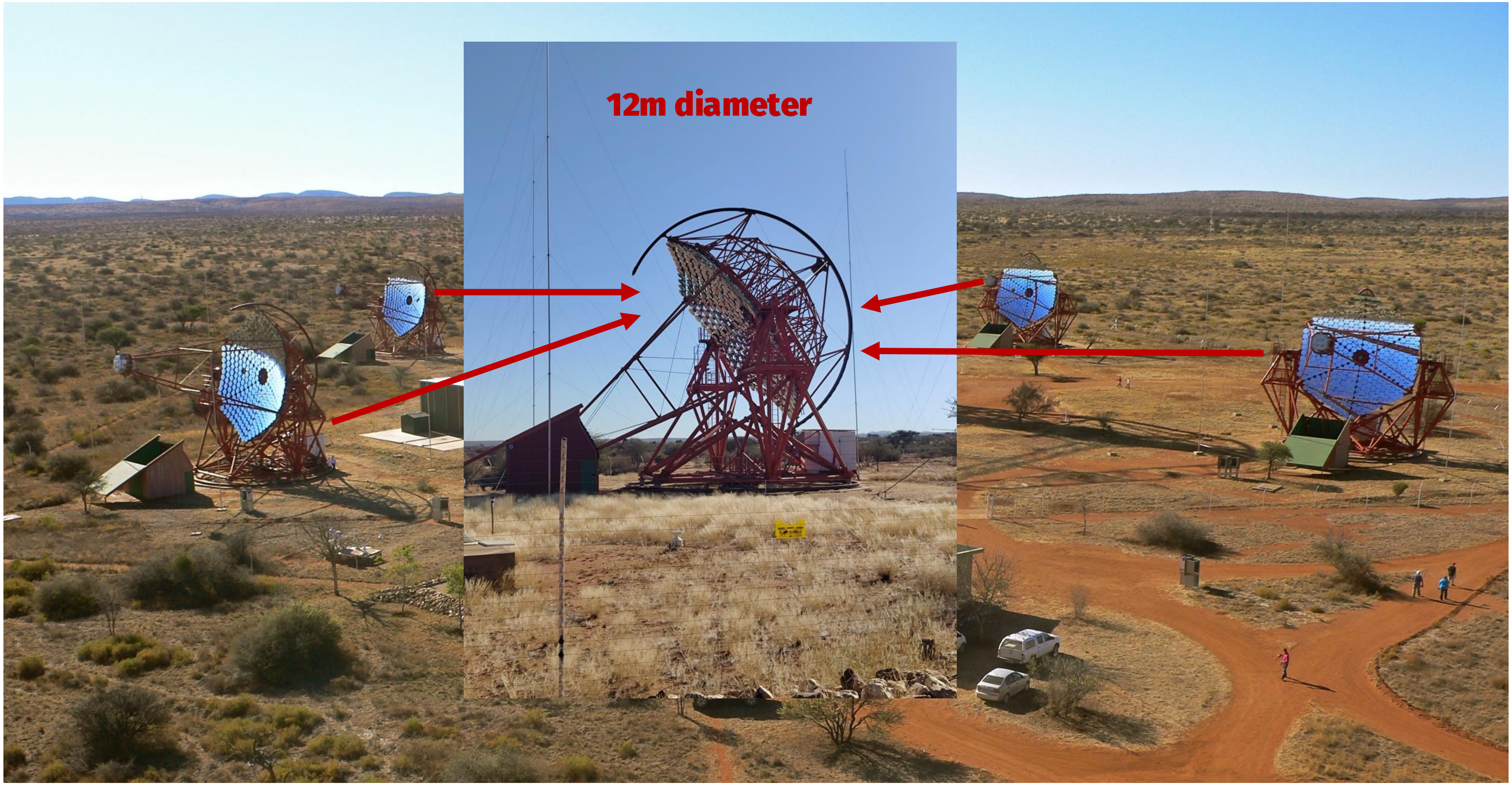


VERITAS, USA

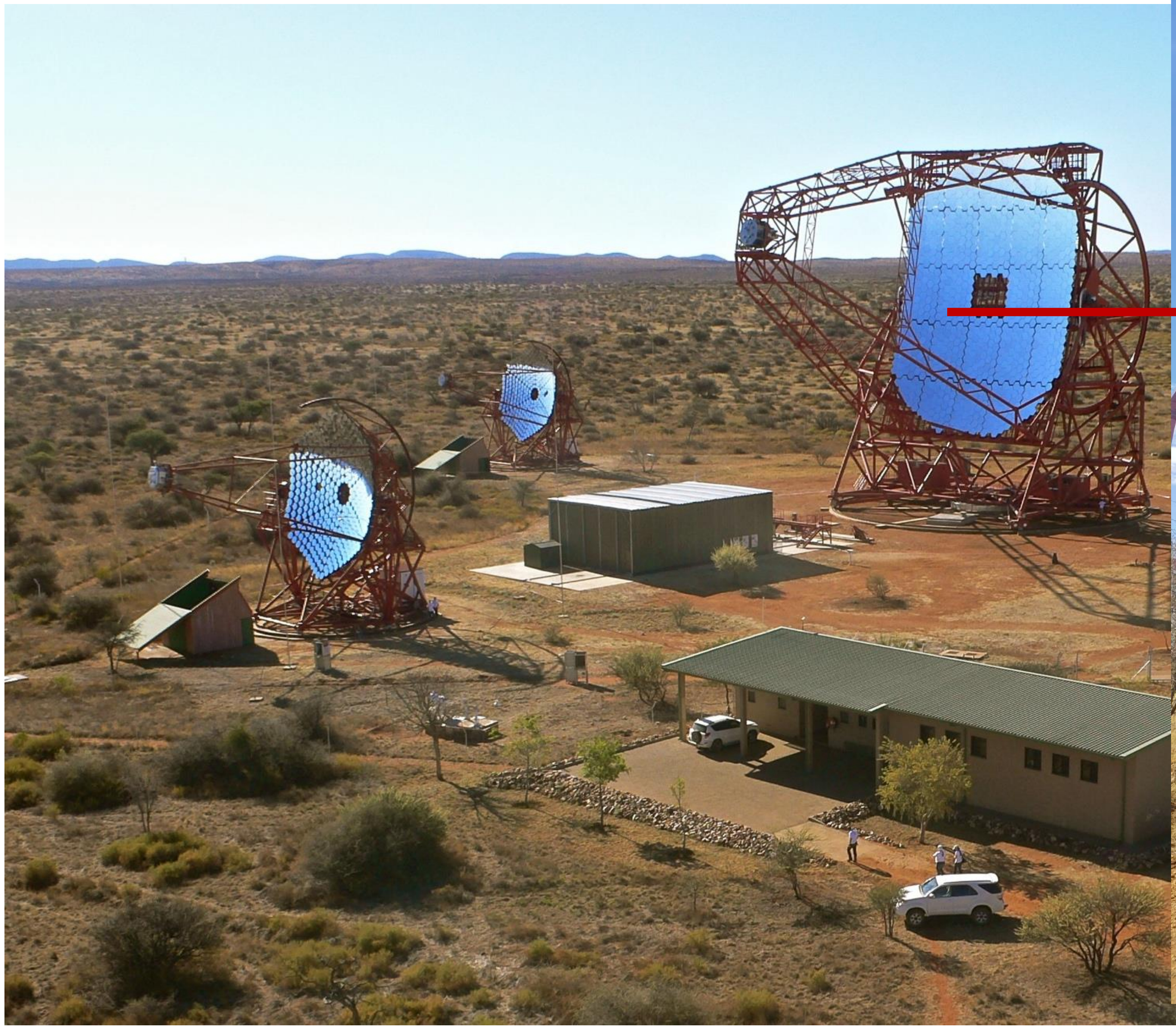
H.E.S.S., Namibia

H.E.S.S.

H.E.S.S.



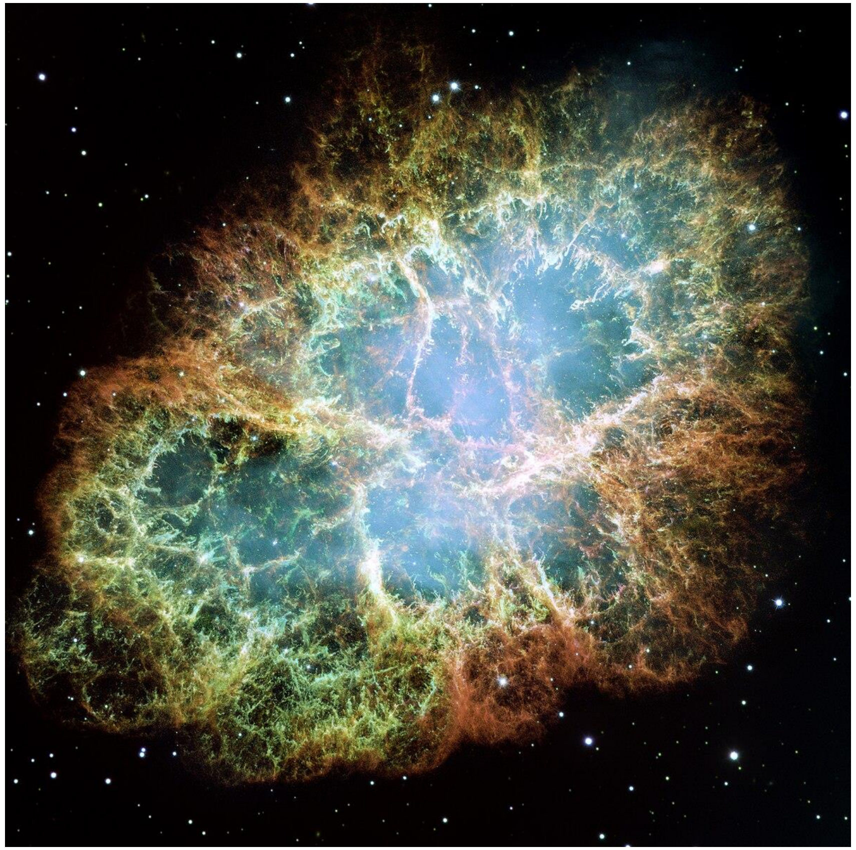
H.E.S.S.



Pulsar in gamma-ray astronomy

Why pulsars and gamma-ray

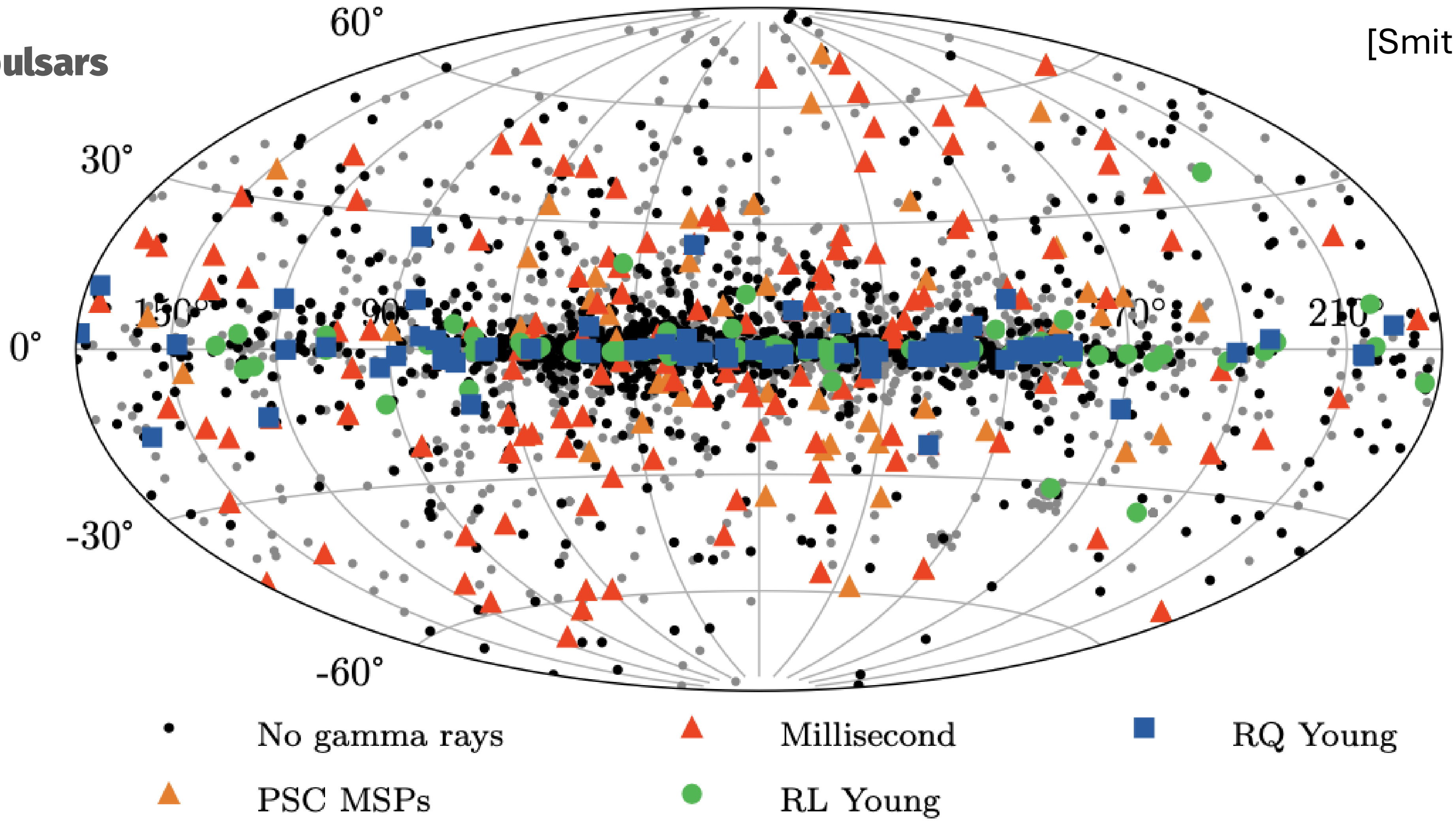
- To produce gamma-ray at GeV and TeV energies → accelerate particles
- Strong magnetic field is a great « tool » to accelerate particles
- Pulsars are amongst the most highly magnetised astrophysical sources
- Needs for huge energy pool
- Spin down energy loss through rotation can be as high as 10^{37} erg . s^{-1}
- Pulsar Wind Nebula (PWN) observed at GeV and TeV.



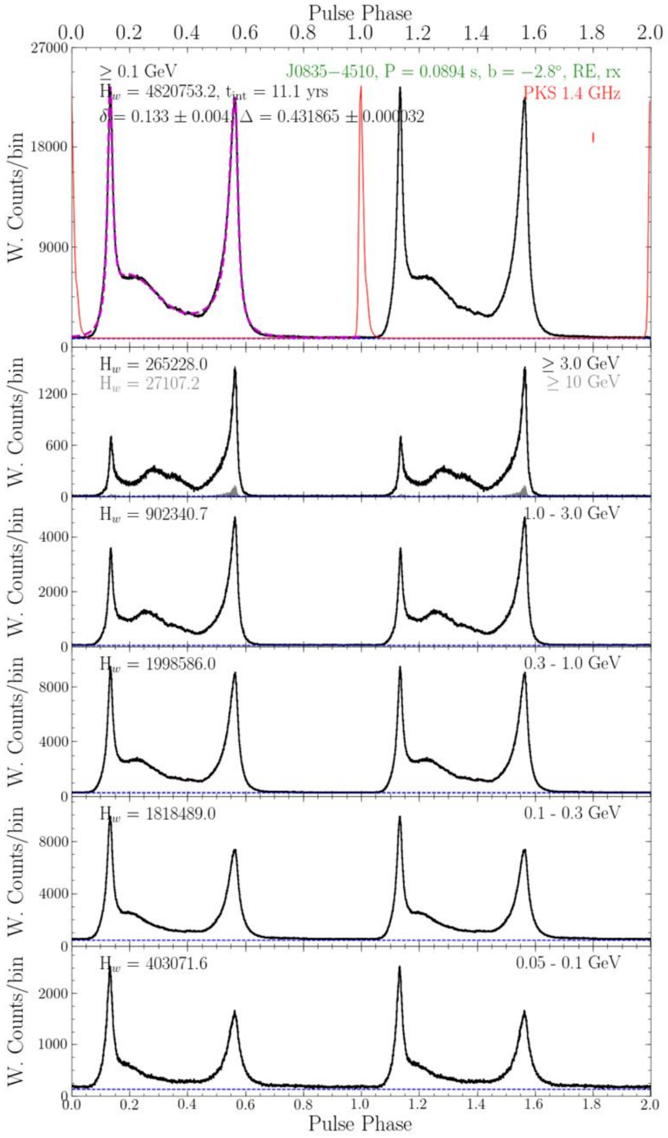
Pulsars in Gamma-ray: Fermi-LAT 3PC

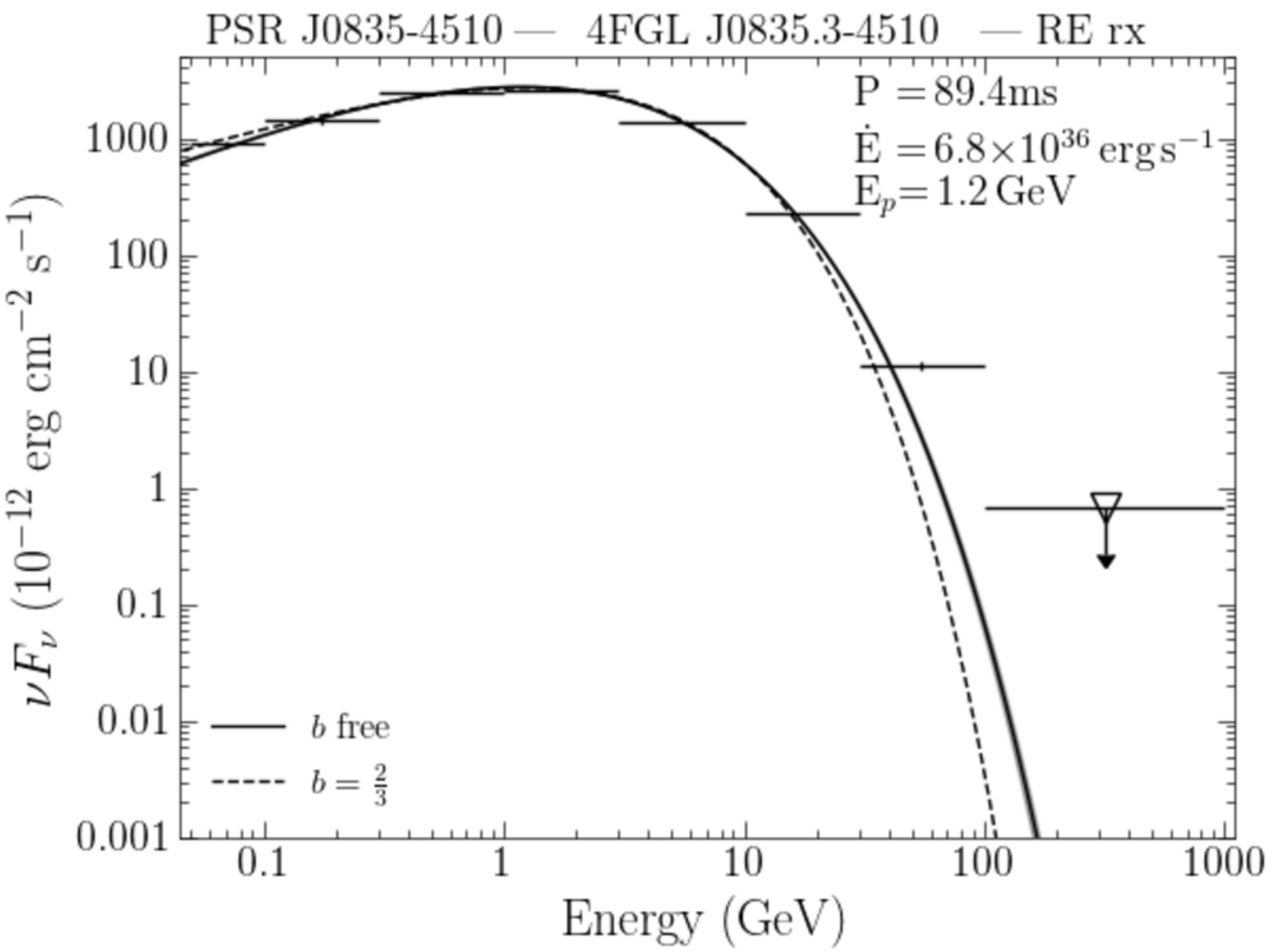
~ 300 pulsars

[Smith D. et al., 2023]



Pulsars in Gamma-ray: Fermi-LAT 3PC



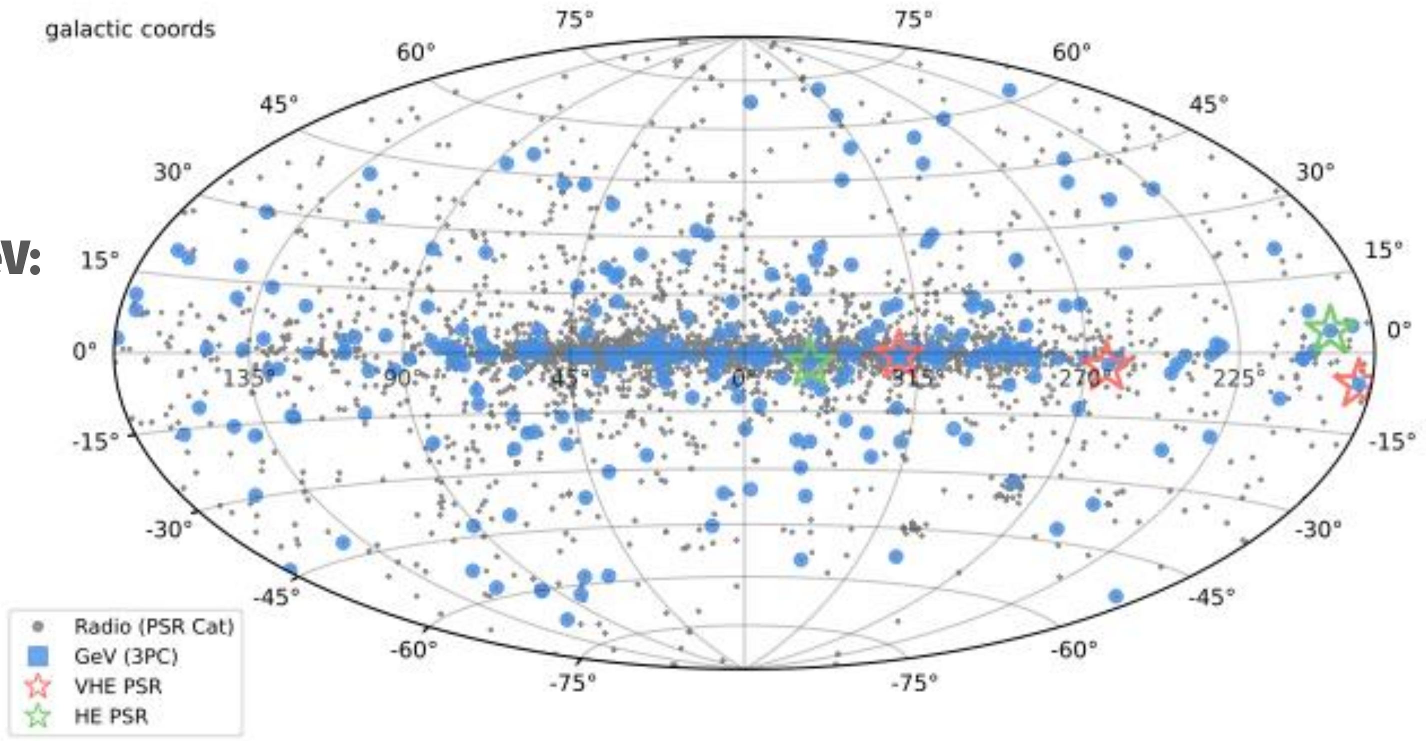


Pulsars in Gamma-ray: IACTs

5 pulsars detected by IACTs

2 in the high energy range only < 100 GeV:
- **PSR B1706-44**
- **Geminga**

3 beyond 100 GeV:
- **Crab (up to 1.5 TeV)**
- **Vela (beyond 20 TeV)**
- **PSR J1509-5850**



HE pulsars:
- **We detect the tail of the GeV emission as seen in Fermi-LAT data.**

VHE pulsars:
- **It's another story …**

Two different pulsars at TeV

Crab pulsar

A power-law tail that extend from GeV to ~ 1 TeV

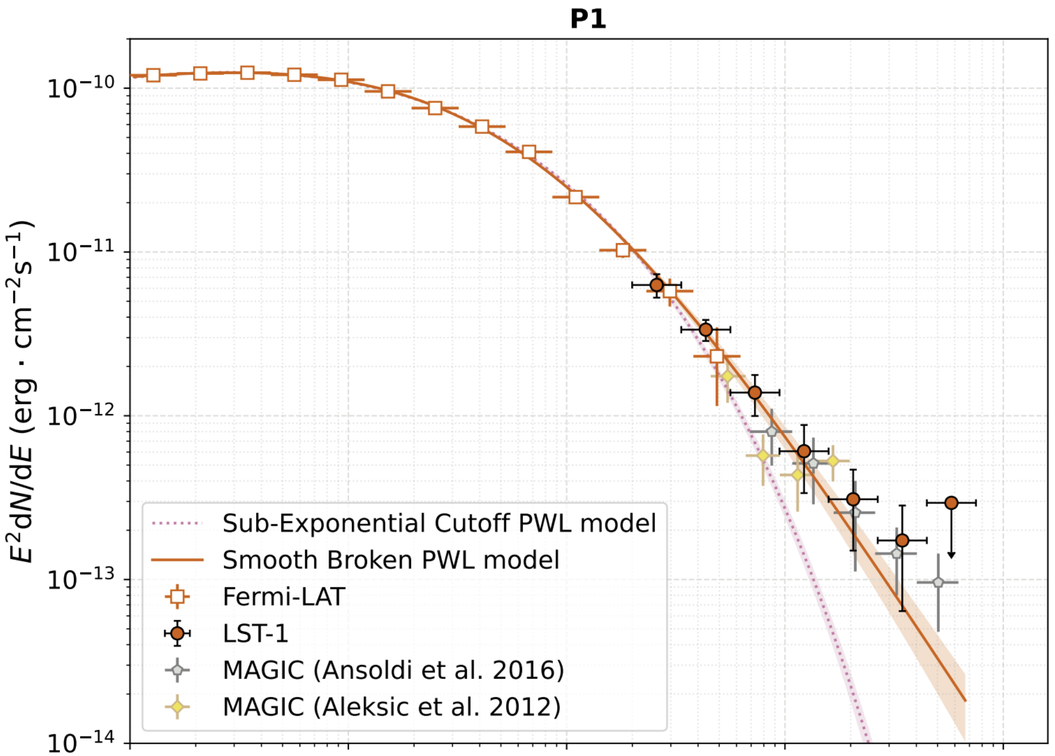


Figure 8 from [Abe, K., et al. 2024]

Vela pulsar

A second component, distinct from the GeV one

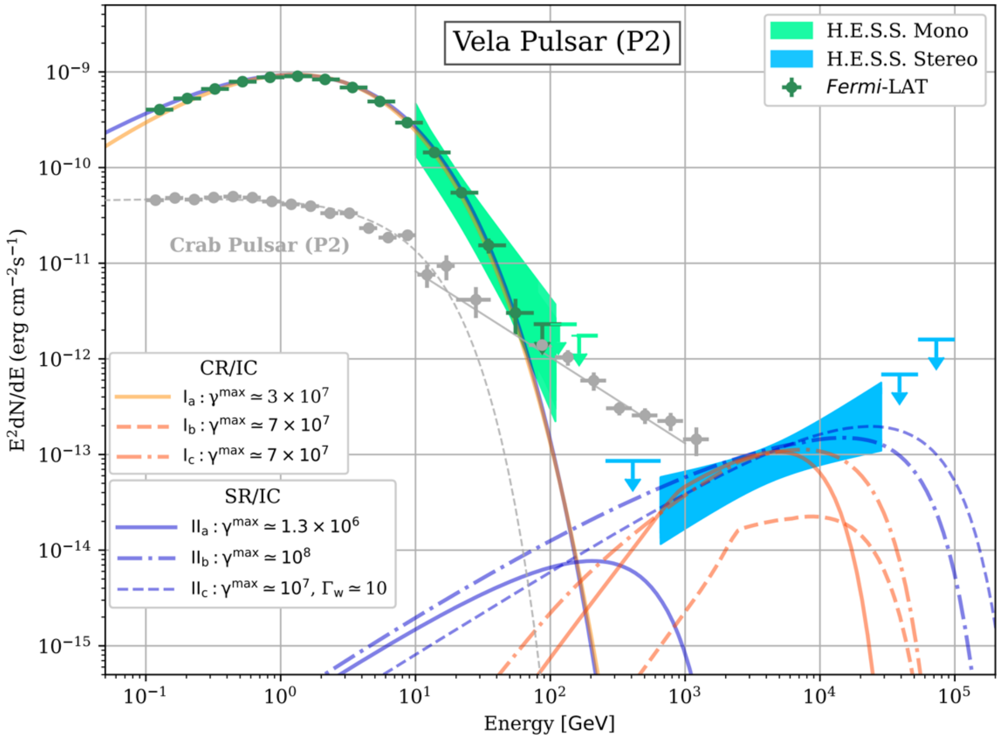


Figure 3 from [Aharonian, F., et al. 2023]

Pulsar in gamma-ray astronomy with H.E.S.S.

Curvature study

The Crab pulsar displays a power-law tail that deviate from the spectral shape seen by Fermi-LAT

H.E.S.S. detects 2 pulsars in the HE range:

- Vela
- PSR B1706-44

Is the spectral shape of these pulsars similar to Crab or not ?

Important because the Crab challenges the traditional emission mechanisms:

- Synchrotron Radiation (SR)
- Curvature Radiation (CR)

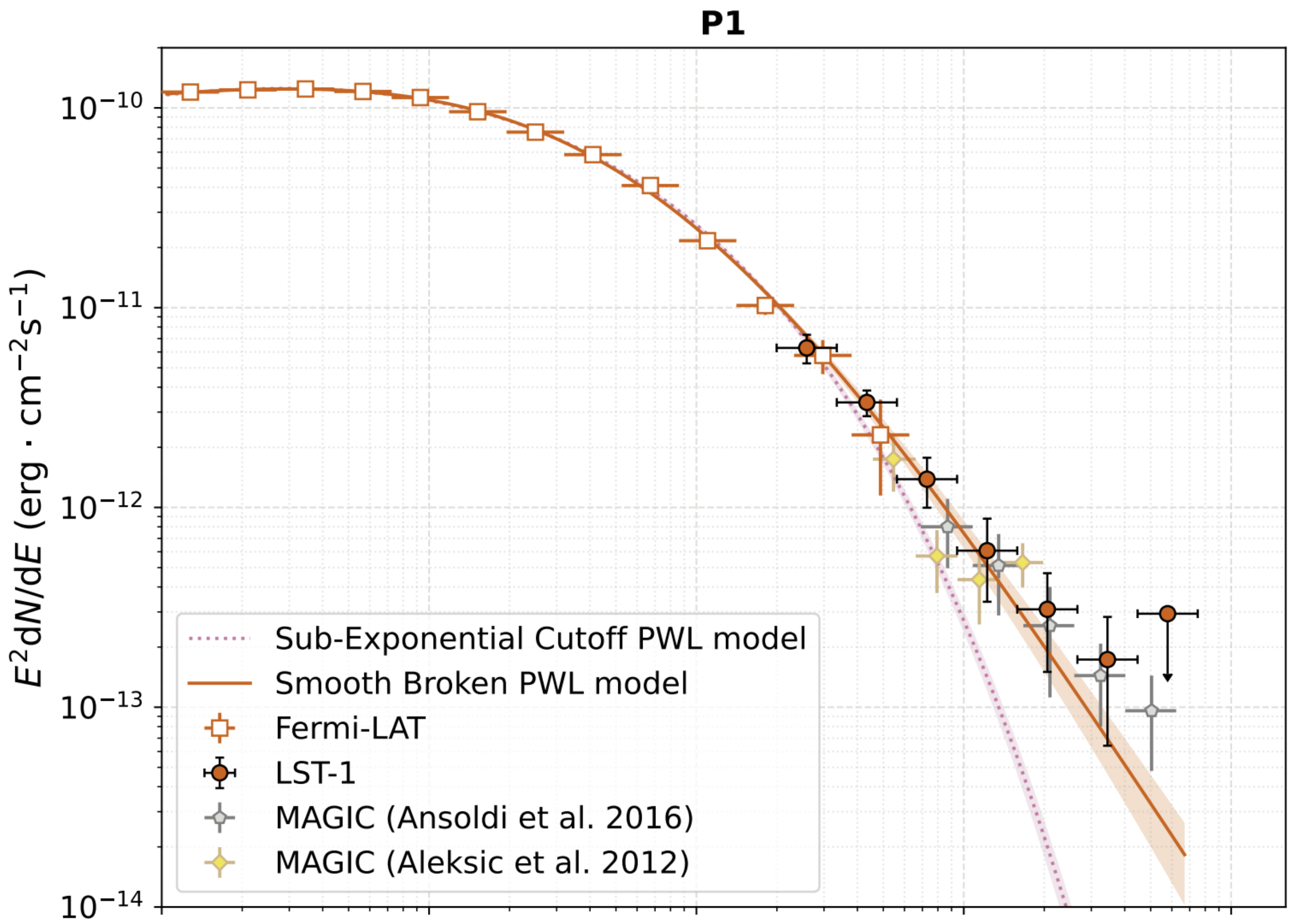


Figure 8 from [Abe, K., et al. 2024]

Analysis method

What we want to do ?

- Determine wether there is curvature or not in the tail of the GeV bump of pulsars

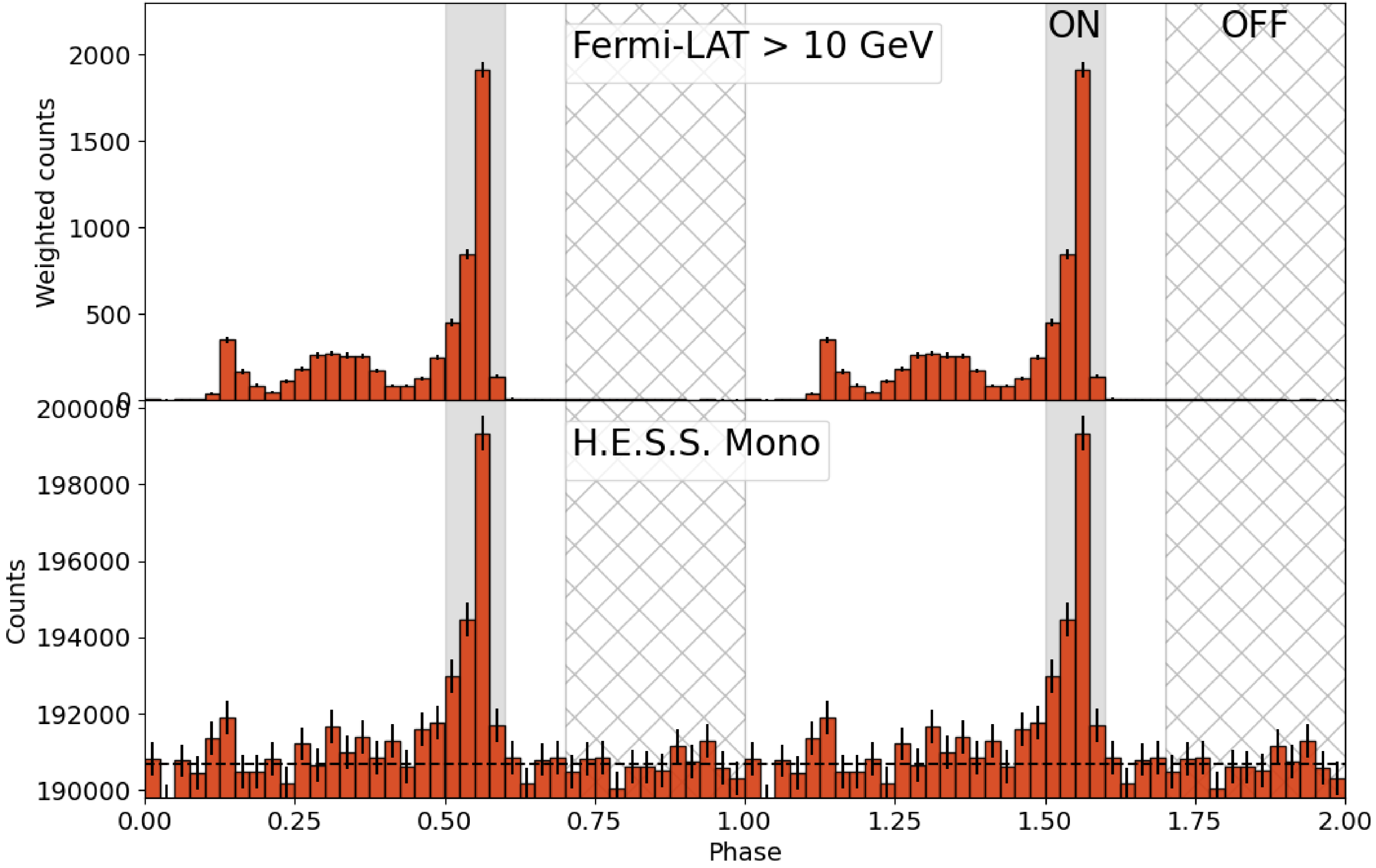
How to do it ?

- Perform a likelihood ratio between a power-law and a log-parabola above different energy thresholds through a joint analysis of Fermi-LAT and H.E.S.S. Mono data
- First energy threshold is defined as 10 GeV → begining of the Crab power-law tail
- Increase this energy threshold as far as the statistics allow it → 15 GeV, 20 GeV, etc.

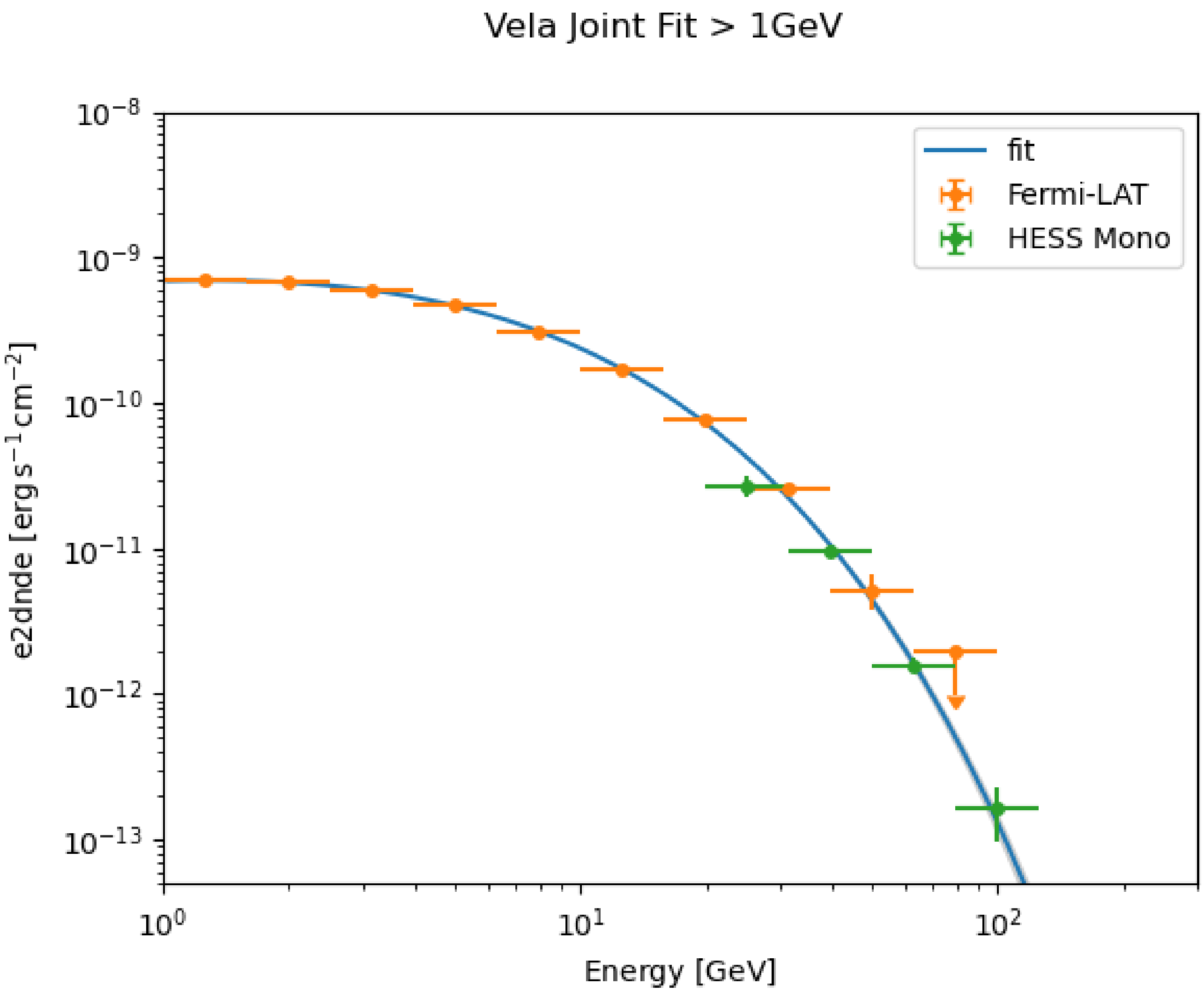
However

- We are not trying to prove that a log-parabola better described the data in this energy range.
- We are using this model because it is the simplest model to describe curvature.
- Power-law and Log-parabola are nested models → assessment of statistics is straight forward.

Vela: Phasograms



Vela: Fermi-LAT – H.E.S.S. Joint-fit



Power-law with exponential cutoff:

$$\phi(E) = \phi_0 \cdot \left(\frac{E}{E_0}\right)^{-\Gamma} \exp(-(\lambda E)^{\alpha})$$

$\phi(1.8\ GeV)$
$= 5.2 \times 10^{-10} \pm 0.6\ MeV^{-1}s^{-1}cm^{-2}$
$\Gamma = 1.4\ \pm 0.04$
$\lambda = 9.2 \times 10^{-4} \pm 1.5\ MeV^{-1}$
$\alpha = 5.6 \times 10^{-1}\ \pm 0.2$

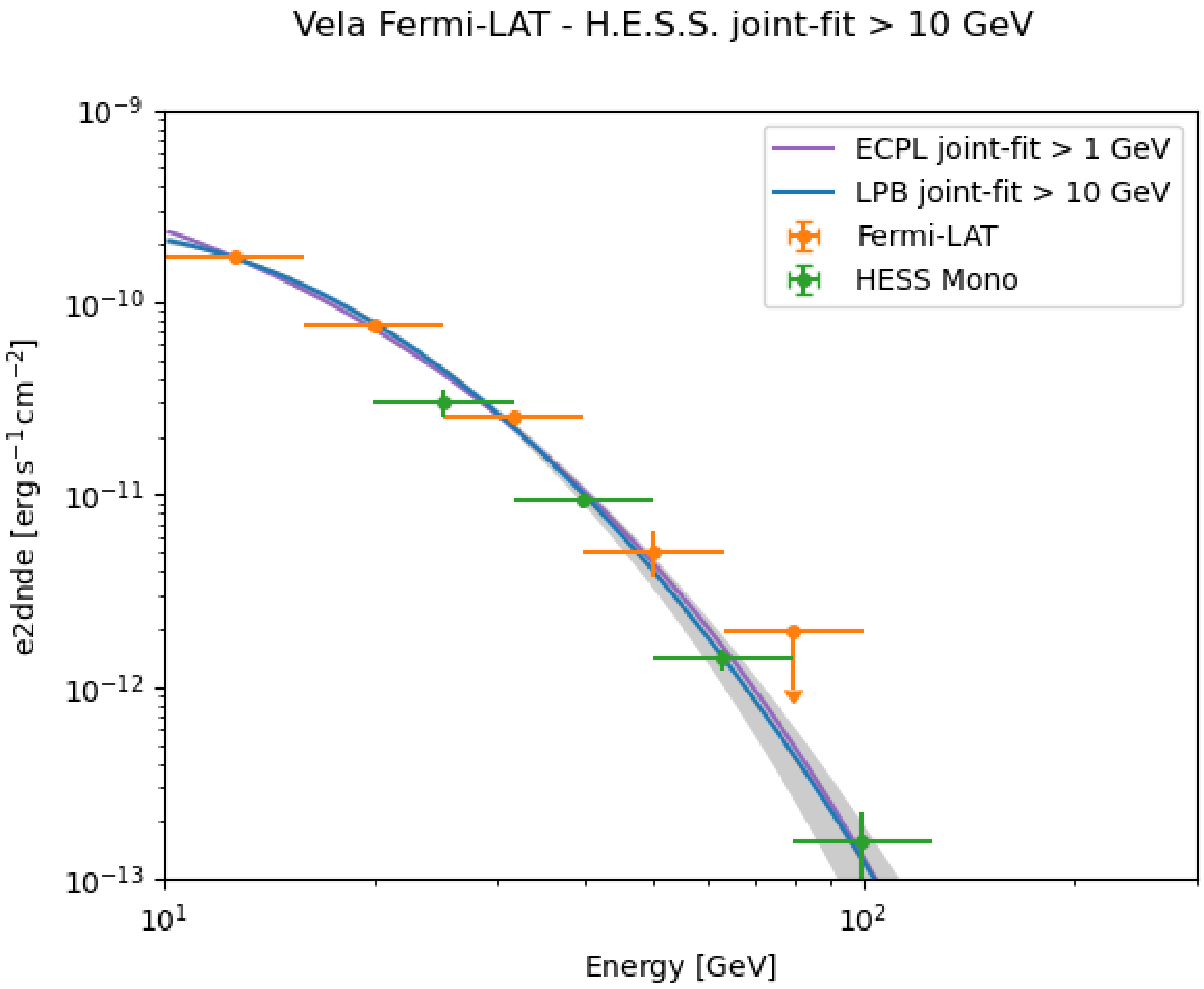
Vela: Curvature study

Log-parabola:

$$\phi(E) = \phi_0 \left(\frac{E}{E_0}\right)^{-\alpha-\beta\cdot log\left(\frac{E}{E_0}\right)}$$

$\phi(20\ GeV) = 1.2 \times 10^{-7} \pm 0.06\ TeV^{-1}s^{-1}cm^{-2}$
$\alpha = 4.2\ \pm 0.08$
$\beta = 1.1\ \pm 0.2$

Likelihood ratio:
7.3 σ in favour of the Log-parabola



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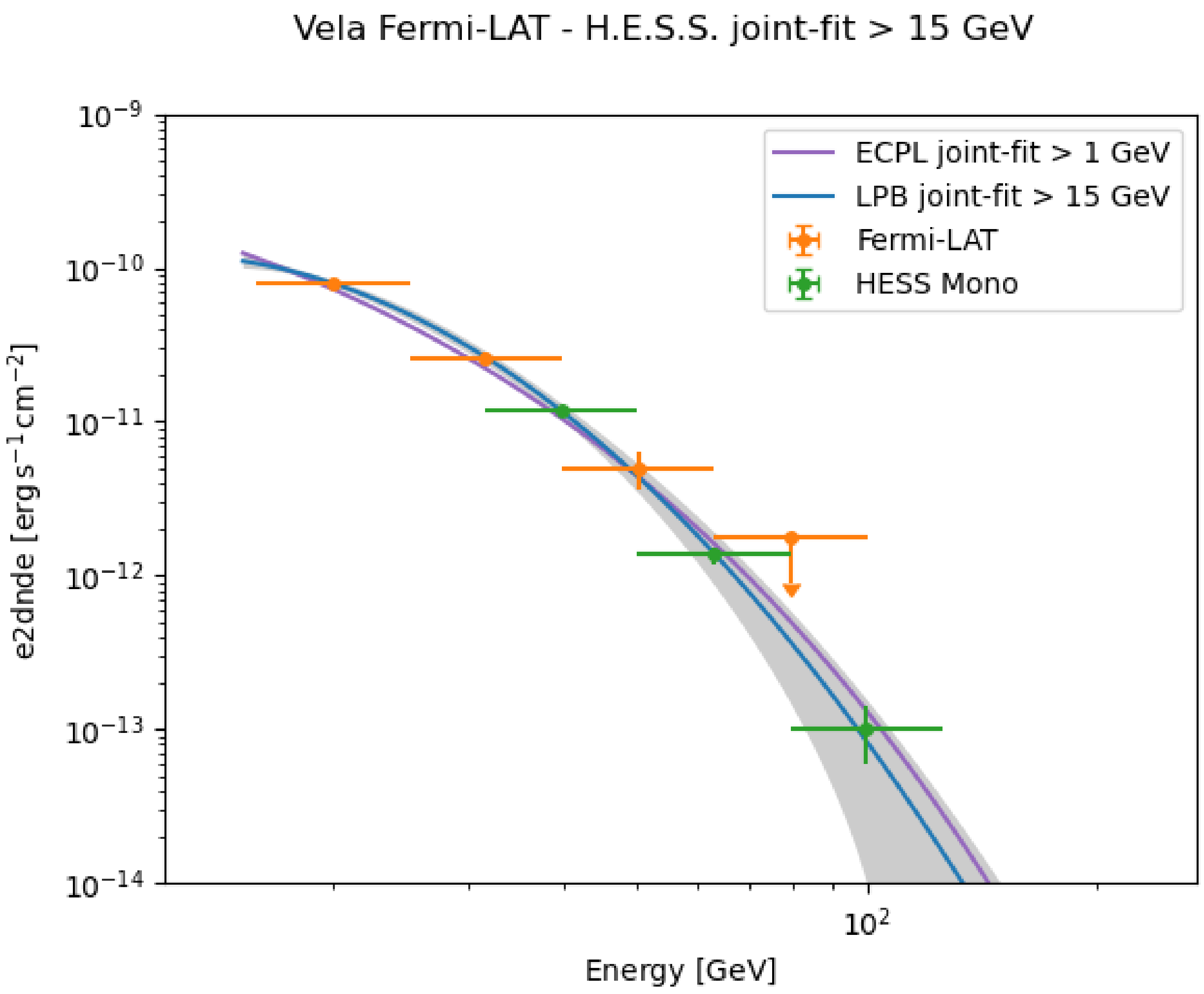
$\phi(20\ GeV) = 1.2 \times 10^{-7} \pm 0.06\ TeV^{-1}s^{-1}cm^{-2}$
$\alpha = 3.7\ \pm 0.3$
$\beta = 1.6\ \pm 0.5$

Likelihood ratio:
5.7 σ in favour of the Log-parabola



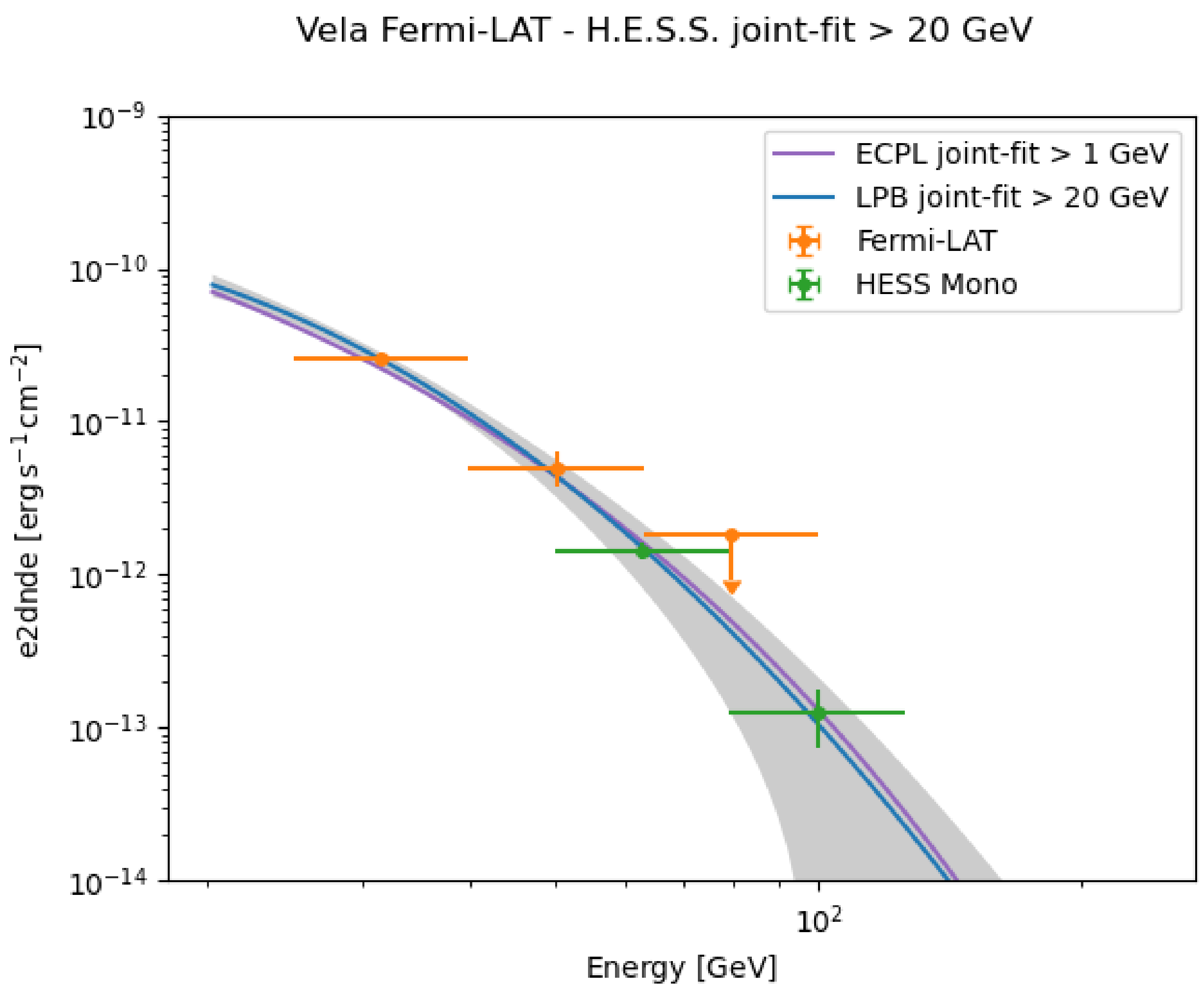
Vela: Curvature study

Log-parabola:

$$\phi(E) = \phi_0 \left(\frac{E}{E_0}\right)^{-\alpha-\beta\cdot log\left(\frac{E}{E_0}\right)}$$

$\phi(20\ GeV) = 2.0 \times 10^{-7} \pm 0.02\ TeV^{-1}s^{-1}cm^{-2}$
$\alpha = 5\ \pm 0.4$
$\beta = 1.4\ \pm 0.6$

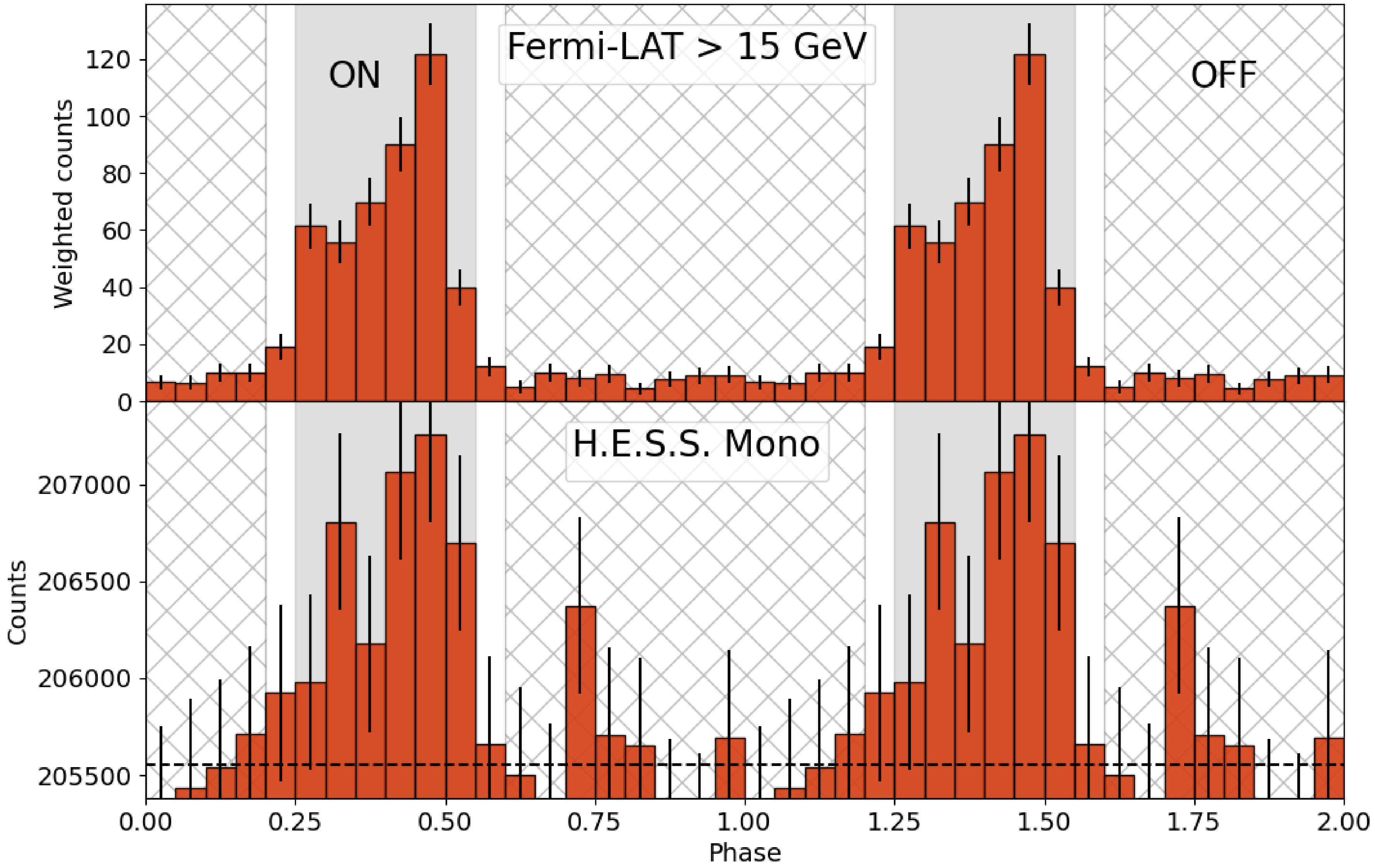
Likelihood ratio:
3.1 σ in favour of the Log-parabola



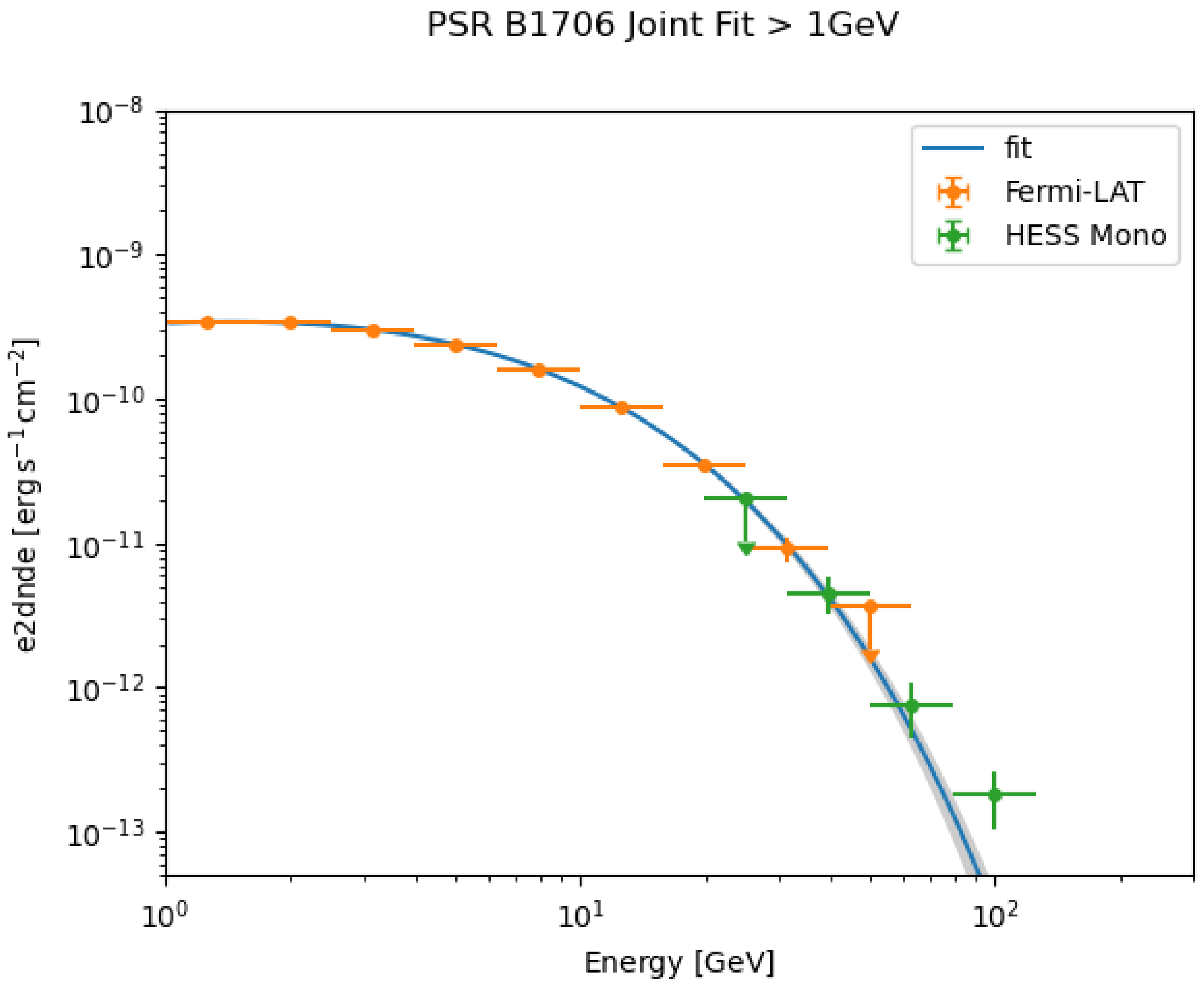
Vela: Curvature study

Dataset	Significance	PowerLaw	LogParabola
H.E.S.S.	X	$\alpha = 4.1 \pm 0.2$	X
Fermi-LAT (>10 GeV)	5.6σ	$\alpha = 4.0 \pm 0.07$	$\alpha = 4.1 \pm 0.1$ $\beta = 1.0 \pm 0.2$
Fermi-LAT (>15 GeV)	3σ	$\alpha = 4.6 \pm 0.2$	$\alpha = 3.6 \pm 0.4$ $\beta = 1.6 \pm 0.7$
Joint (>10 GeV)	7.3σ	$\alpha = 4.1 \pm 0.05$	$\alpha = 4.2 \pm 0.08$ $\beta = 1.1 \pm 0.2$
Joint (>15 GeV)	5.7σ	$\alpha = 4.4 \pm 0.1$	$\alpha = 3.7 \pm 0.3$ $\beta = 1.6 \pm 0.5$
Joint (>20 GeV)	3.1σ	$\alpha = 4.8 \pm 0.2$	$\alpha = 5.0 \pm 0.4$ $\beta = 1.4 \pm 0.6$

PSR B1706-44: Phasograms



PSR B1706-44: Fermi-LAT – H.E.S.S. Joint-fit



Power-law with exponential cutoff:

$$\phi(E) = \phi_0 \cdot \left(\frac{E}{E_0}\right)^{-\Gamma} \exp(-(\lambda E)^{\alpha})$$

$\phi(1.8\ GeV) = 1.9 \times 10^{-10} \pm 0.3\ MeV^{-1}s^{-1}cm^{-2}$
$\Gamma = 1.4 \pm 0.07$
$\lambda = 6.0 \times 10^{-4} \pm 1.6\ MeV^{-1}$
$\alpha = 6.2 \times 10^{-1} \pm 0.4$

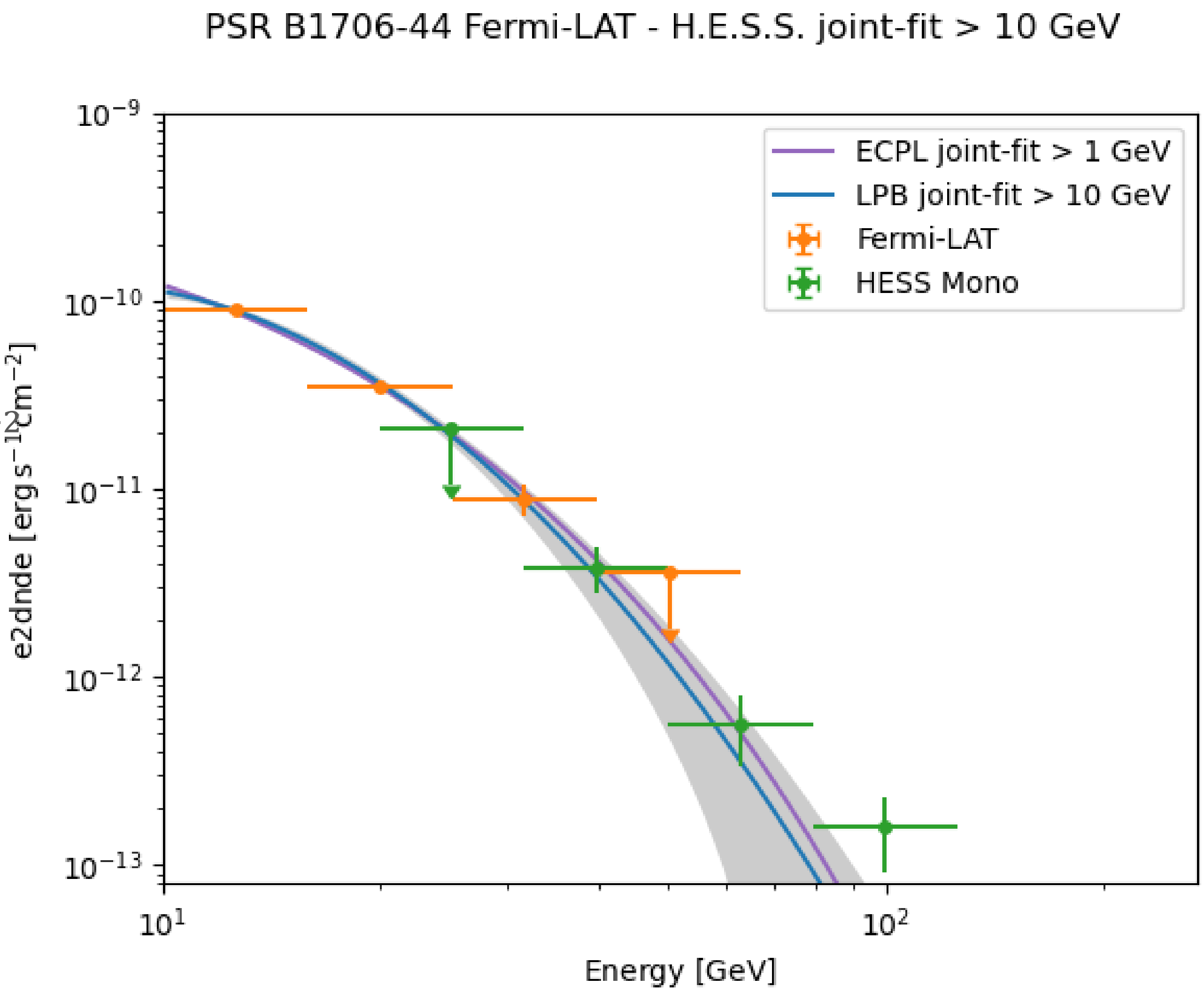
PSR B1706-44: Curvature study

Log-parabola:

$$\phi(E) = \phi_0 \left(\frac{E}{E_0}\right)^{-\alpha-\beta\cdot log\left(\frac{E}{E_0}\right)}$$

$\phi(20\ GeV) = 5.6 \times 10^{-8} \pm 0.4\ TeV^{-1}s^{-1}cm^{-2}$
$\alpha = 4.5\ \pm 0.2$
$\beta = 1.3\ \pm 0.5$

Likelihood ratio:
3.8 σ in favour of the Log-parabola



PSR B1706-44: Curvature study

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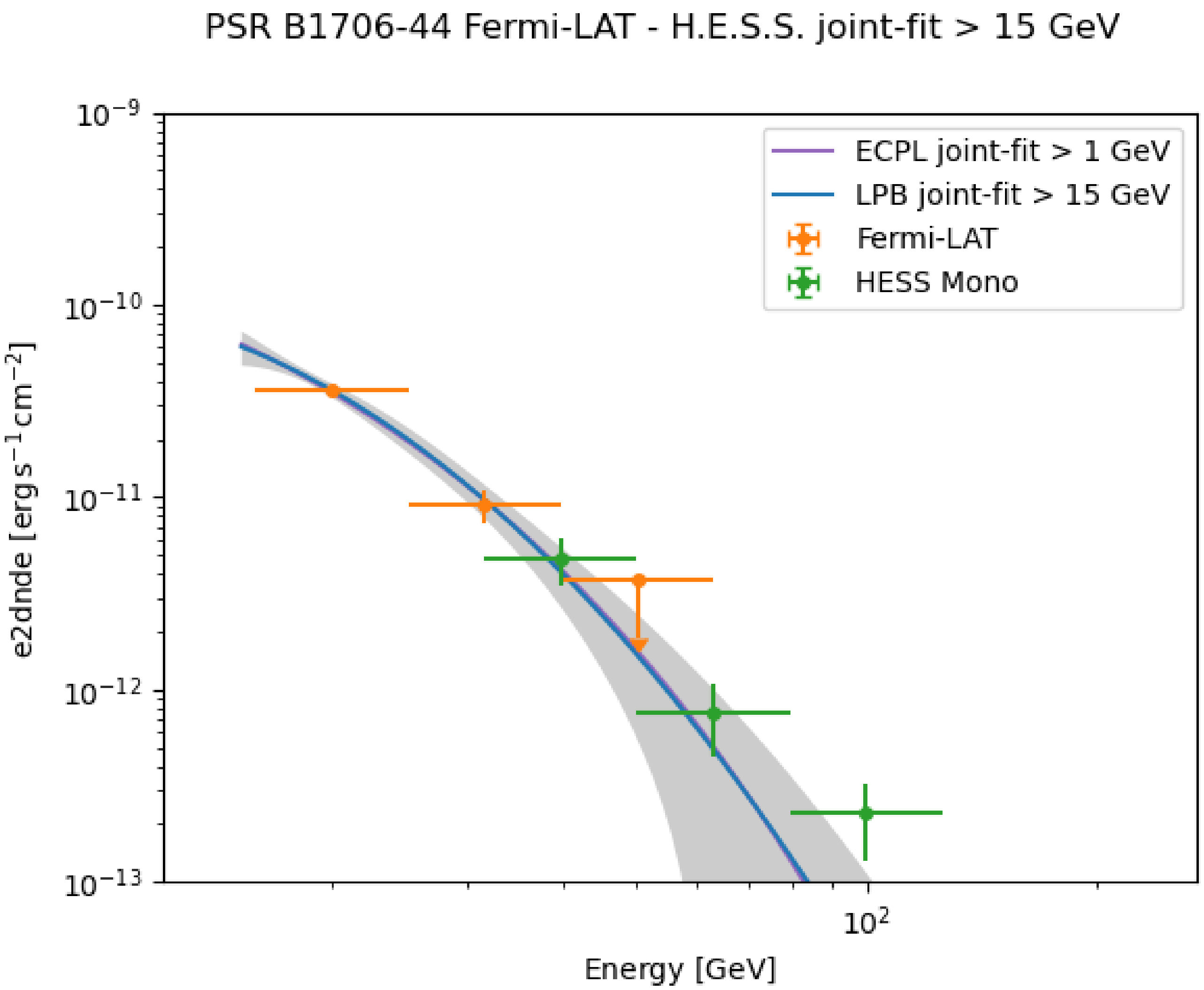
$\alpha = 4.3\ \pm 0.6$
$\beta = 1.3\ \pm 1.1$

Likelihood ratio:
1.8 σ in favour of the Log-parabola



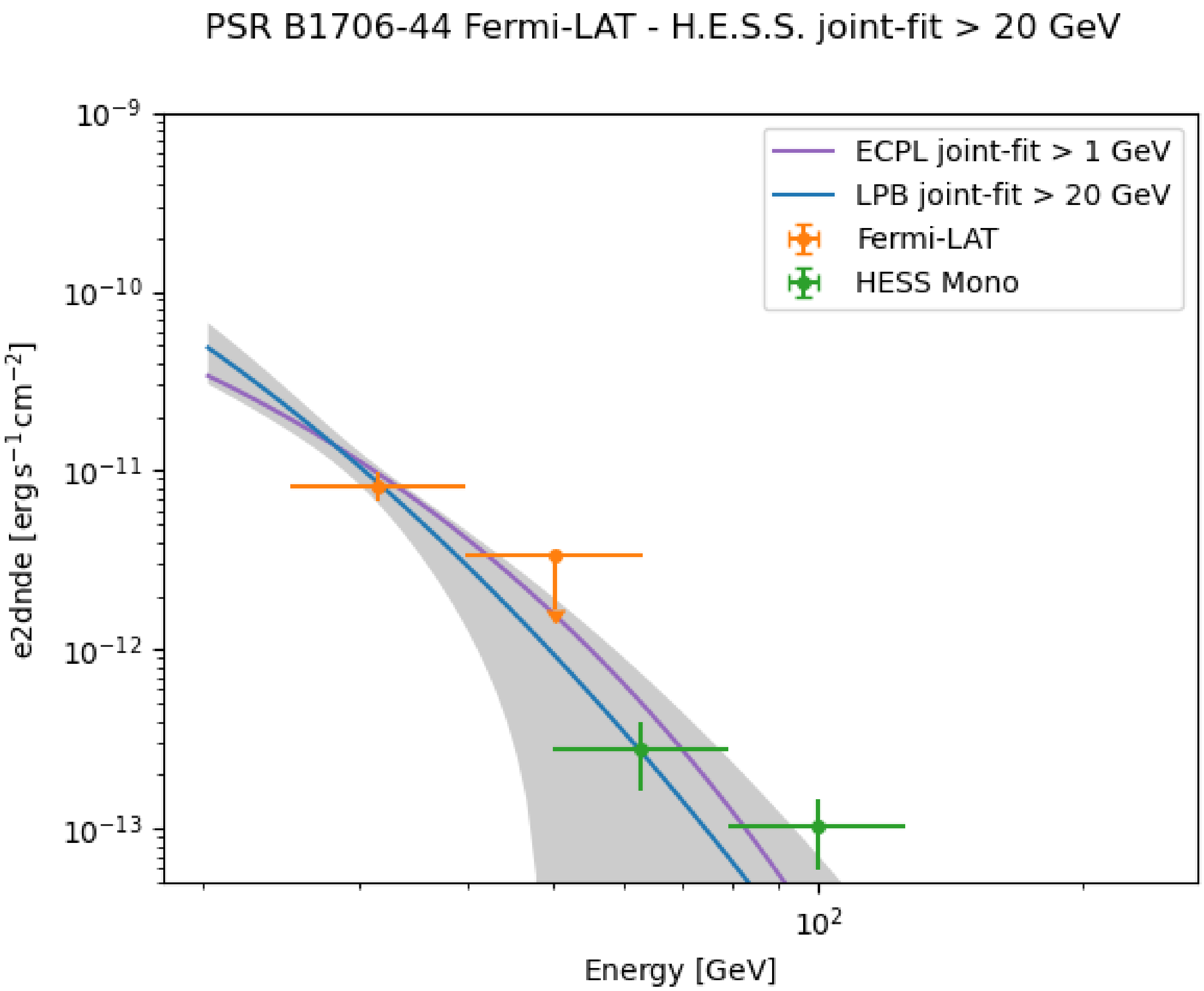
PSR B1706-44: Curvature study

Log-parabola:

$$\phi(E) = \phi_0 \left(\frac{E}{E_0}\right)^{-\alpha-\beta\cdot log\left(\frac{E}{E_0}\right)}$$

$\phi(20\ GeV) = 7.9 \times 10^{-8} \pm 3.0\ TeV^{-1}s^{-1}cm^{-2}$
$\alpha = 5.4\ \pm 0.9$
$\beta = 0.9\ \pm 1.5$

Likelihood ratio:
0.8 σ in favour of the Log-parabola



PSR B1706-44: Curvature study

Dataset	Significativity	PowerLaw	LogParabola
H.E.S.S.	X	$\alpha = 3.3 \pm 0.3$	X
Fermi-LAT (>10 GeV)	3.9σ	$\alpha = 4.3 \pm 0.1$	$\alpha = 4.6 \pm 0.04$ $\beta = 1.4 \pm 0.3$
Fermi-LAT (>15 GeV)	X	$\alpha = 5.1 \pm 0.4$	X
Joint (>10 GeV)	3.8σ	$\alpha = 4.2 \pm 0.1$	$\alpha = 4.5 \pm 0.6$ $\beta = 1.3 \pm 0.1$
Joint (>15 GeV)	1.8σ	$\alpha = 4.8 \pm 0.3$	$\alpha = 4.3 \pm 0.6$ $\beta = 1.3 \pm 1.1$
Joint (>20 GeV)	0.8σ	$\alpha = 5.6 \pm 0.6$	$\alpha = 5.4 \pm 0.9$ $\beta = 1 \pm 1.5$

Curvature study: Conclusion and summary

- Qualifying the behaviour of the high energy end of pulsar spectra in the tens of GeV range is of prime importance for constraining emission models
  - As seen in the case of the Crab pulsar the extension of its emission challenged dramatically the standard CR picture

- Methods : we elaborated on a quantitative method ([Abdalla, H. et al., 2018]) to test for curvature for two pulsars detected with HESS : Vela and B1706-44

- We are able to detect a curvature and exclude the onset of a power-law, up to 20 GeV for Vela and up to 10 GeV for B1706-44

Conclusions and Summary

- Pulsars are fun !

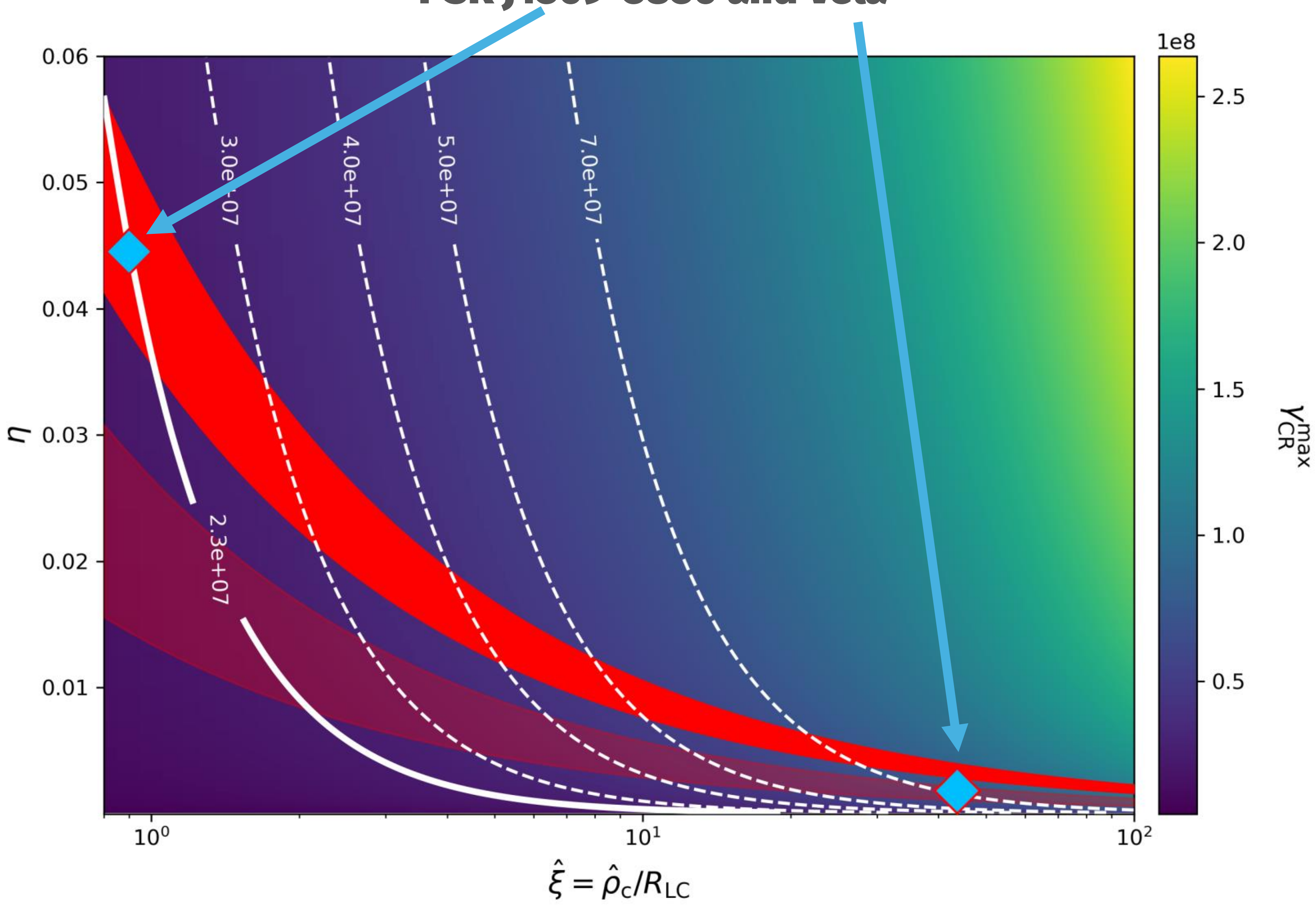
- With H.E.S.S. we are still looking for new pulsars

- But CTAO will be the real game changer for pulsar astronomy at TeV

Backup

Curvature radiation

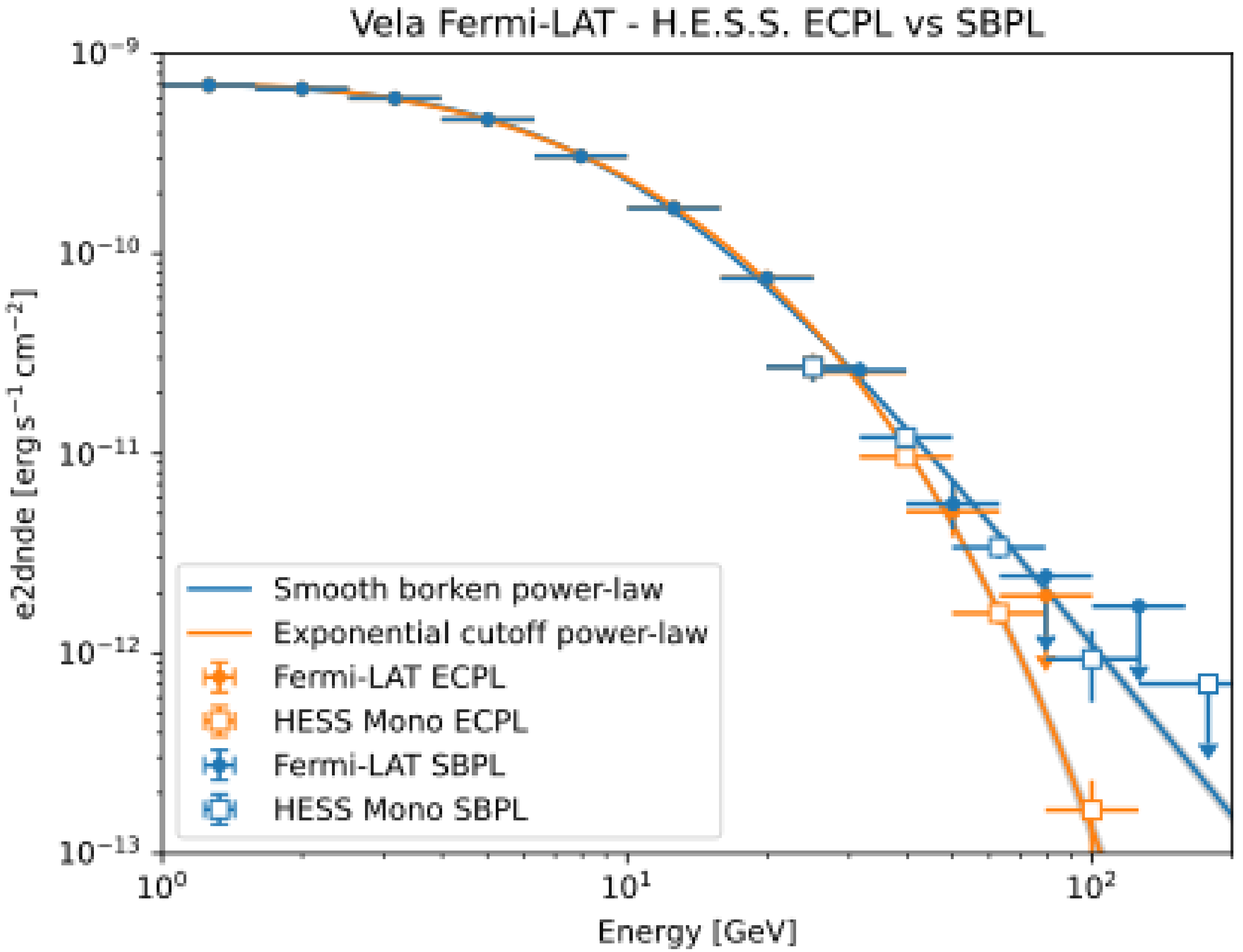
PSR J1509-5850 and Vela



ECPL vs SBPL: Vela

ECPL vs SBPL :

- **SBPL fit gives an E_{break} of 38 GeV but not statistically favoured**
- **Further tests favour ECPL, e.g.: Fixing E_{break} to 10 GeV**
  $\Delta TS(AIC) = 8.2,$
  $\Delta TS(BIC) = 8.2$

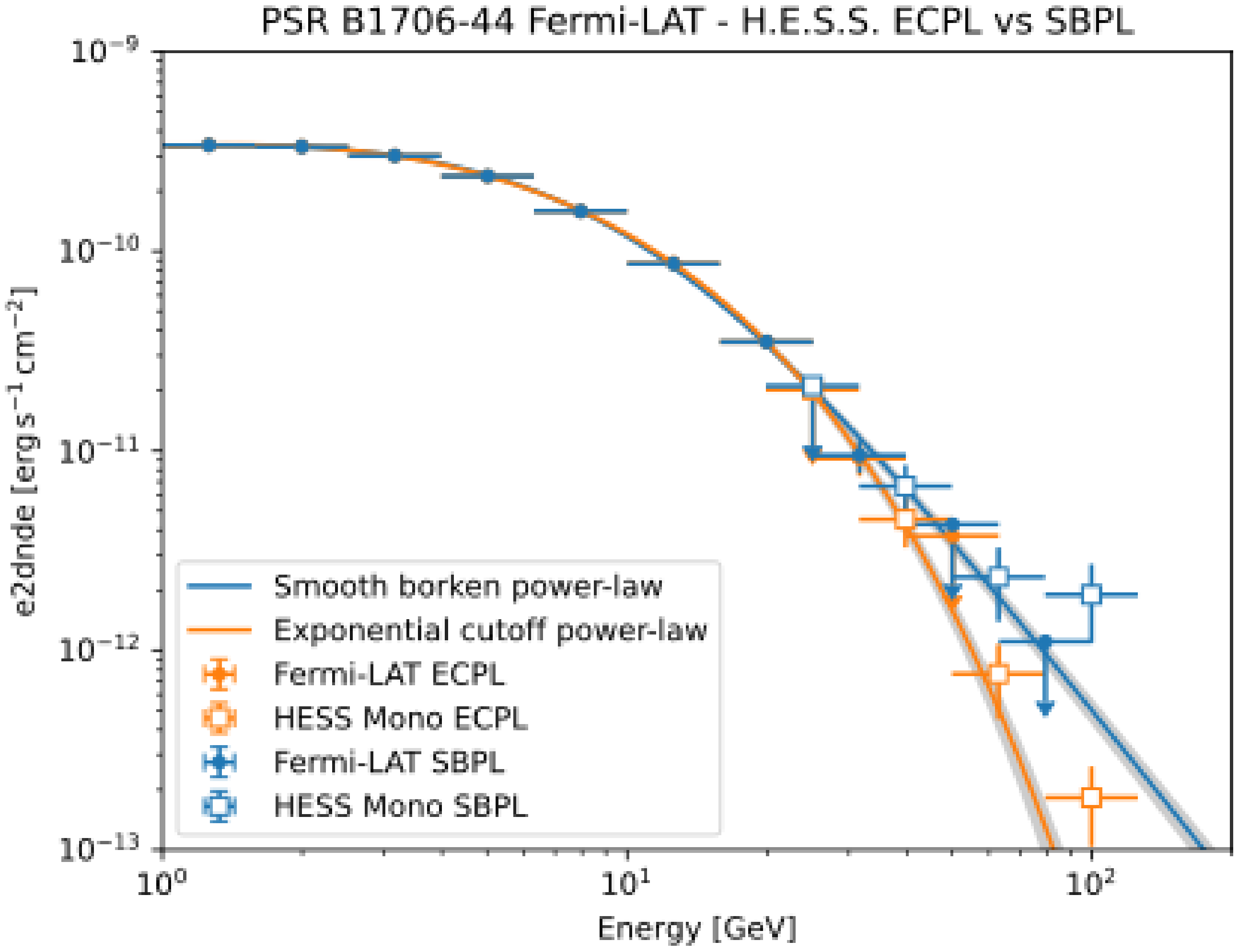


ECPL vs SBPL: PSR B1706-44

ECPL vs SBPL:

- **SBPL fit gives an E_{break} of 22.6 GeV but not statistically favoured**

- **Further tests favour ECPL, e.g.: Fixing E_{break} to 10 GeV**
  $\Delta TS(AIC) = 7.7,$
  $\Delta TS(BIC) = 7.7$



Crab pulsar: Veritas 2011

Detection of a signal in the up to 400 GeV

SED → First case of discrepancy with power-law exponentially cutoff as seen by Fermi-LAT

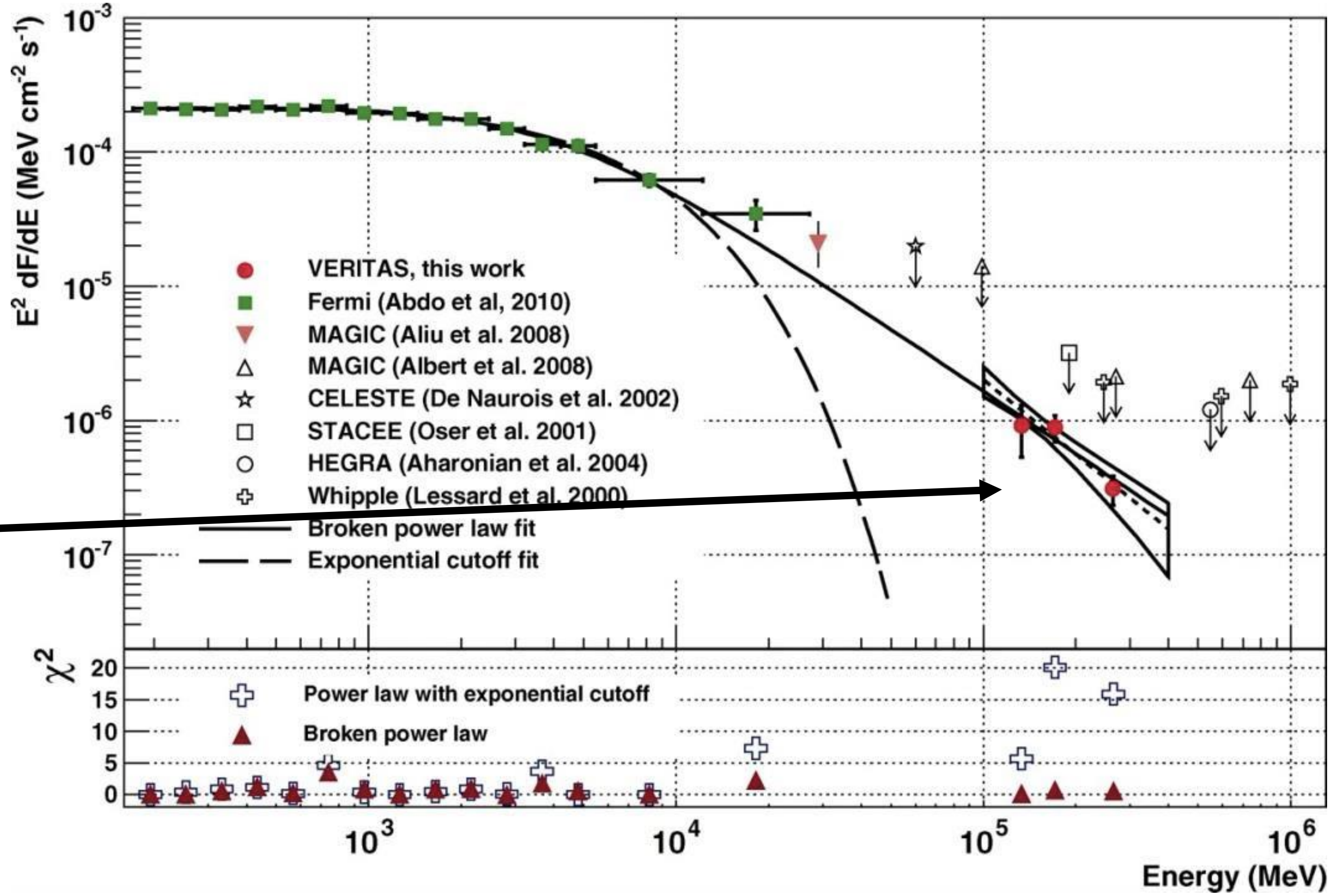


Figure 2 from [Aliu et al., 2011]

Crab pulsar: MAGIC 2016

Confirmed by MAGIC: detection of signal up to ~ 1 TeV

« Traditional » Curvature Radiation scenarii seriously challenged !

Is it the same emission component ?

What about other pulsars :
Is the high energy end of the gamma-ray pulsars' emission a power-law tail?

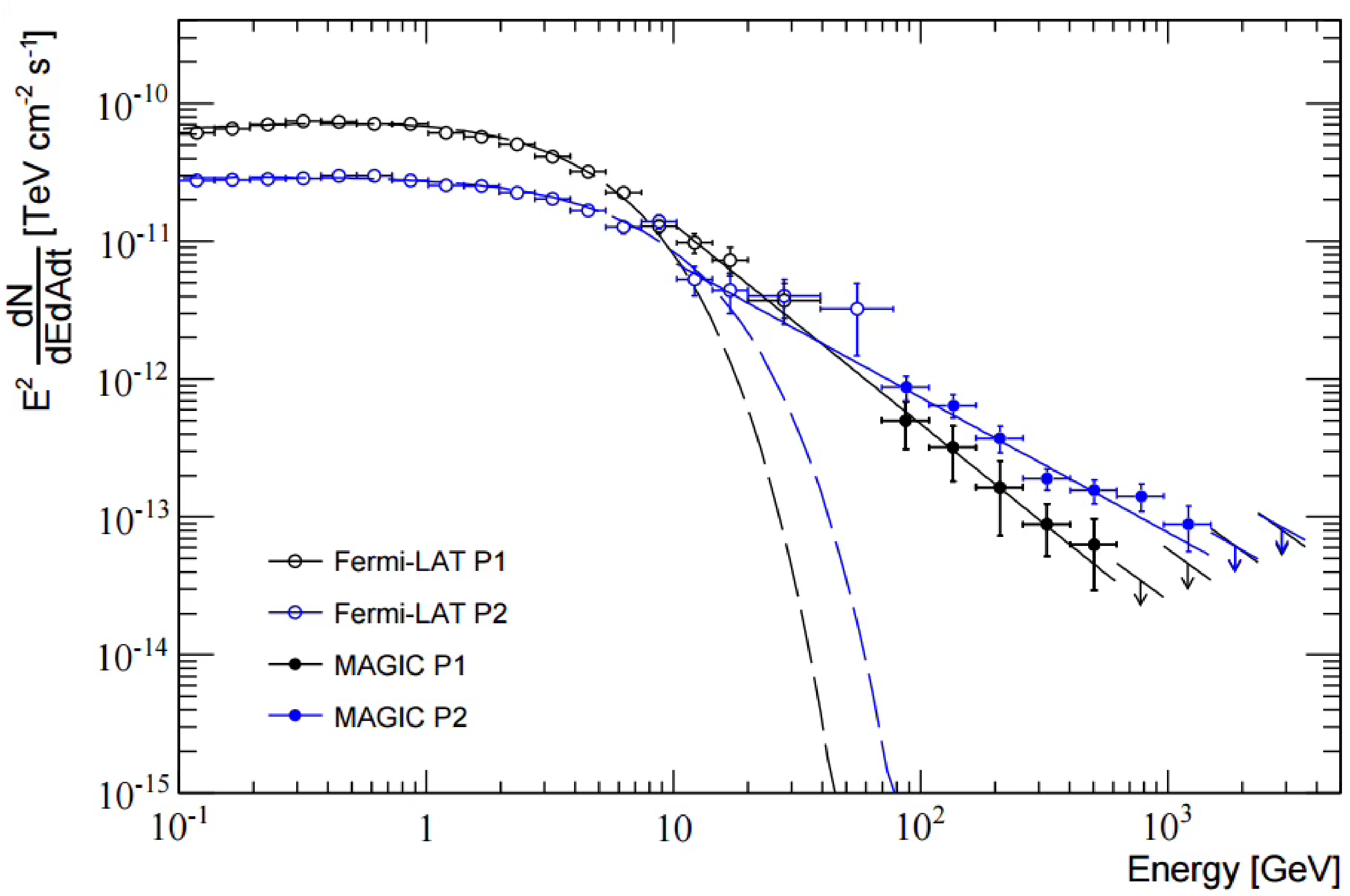


Figure 4 from [Ansoldi et al. 2016]

Vela pulsar: H.E.S.S. 2018

Detection of pulsation from the Vela pulsar by H.E.S.S. up to ~100 GeV

Propose to use a likelihood ration between a power-law and a log-parabola to probe curvature

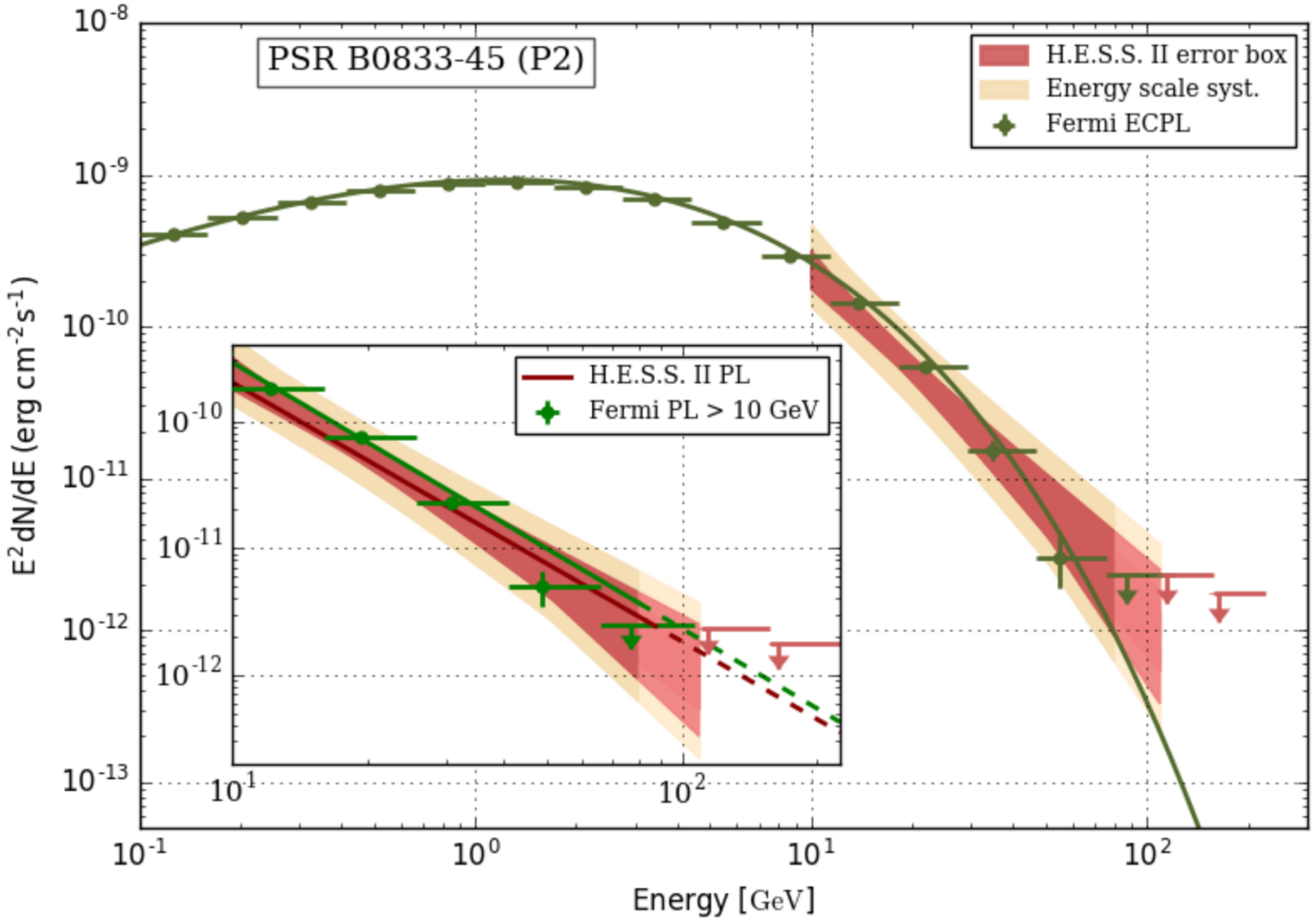


Figure 5 from [Abdalla, H. et al., 2018]

PSR B1706-44: H.E.S.S. 2019

Detection of PSR B1706-44 in the HE range by H.E.S.S.

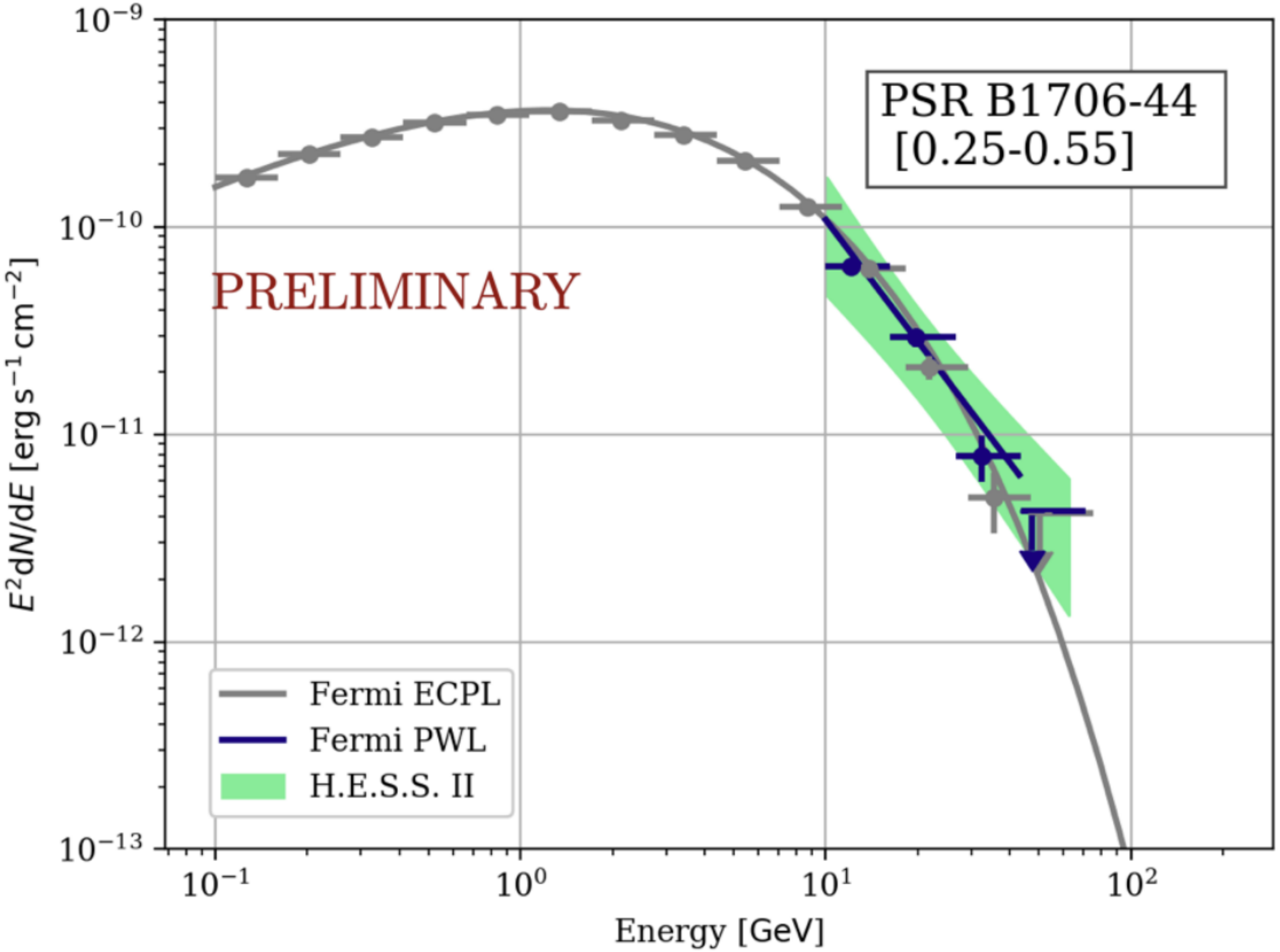


Figure 2 from [Spir-Jacob, M., et al. 2019]

Vela pulsar: H.E.S.S. 2023

Detection of pulsation from the Vela pulsar by H.E.S.S. beyond 20 TeV

TeV emission is interpreted as Inverse Compton scattering.

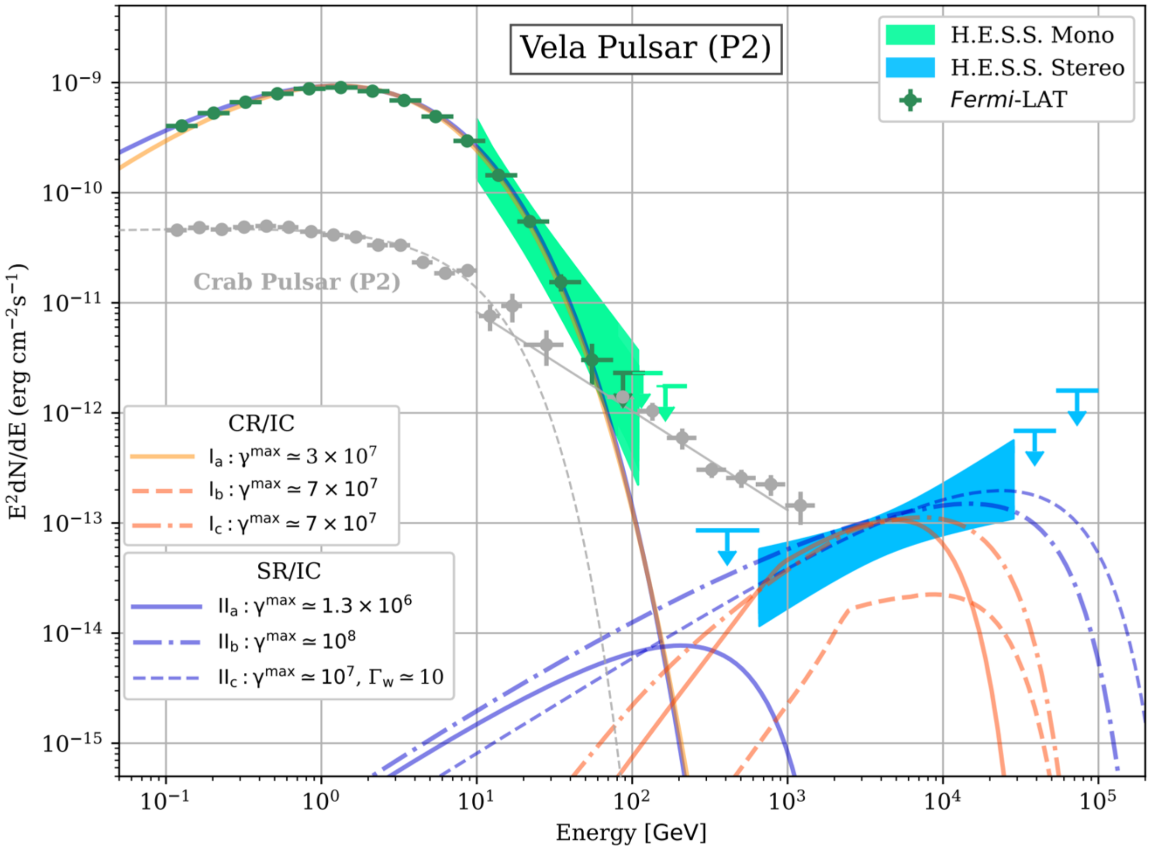


Figure 3 from [Aharonian, F., et al. 2023]