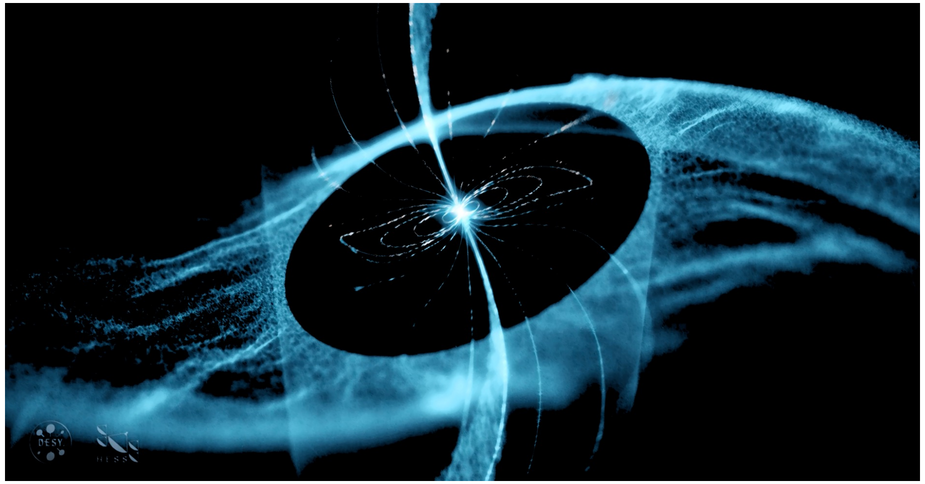
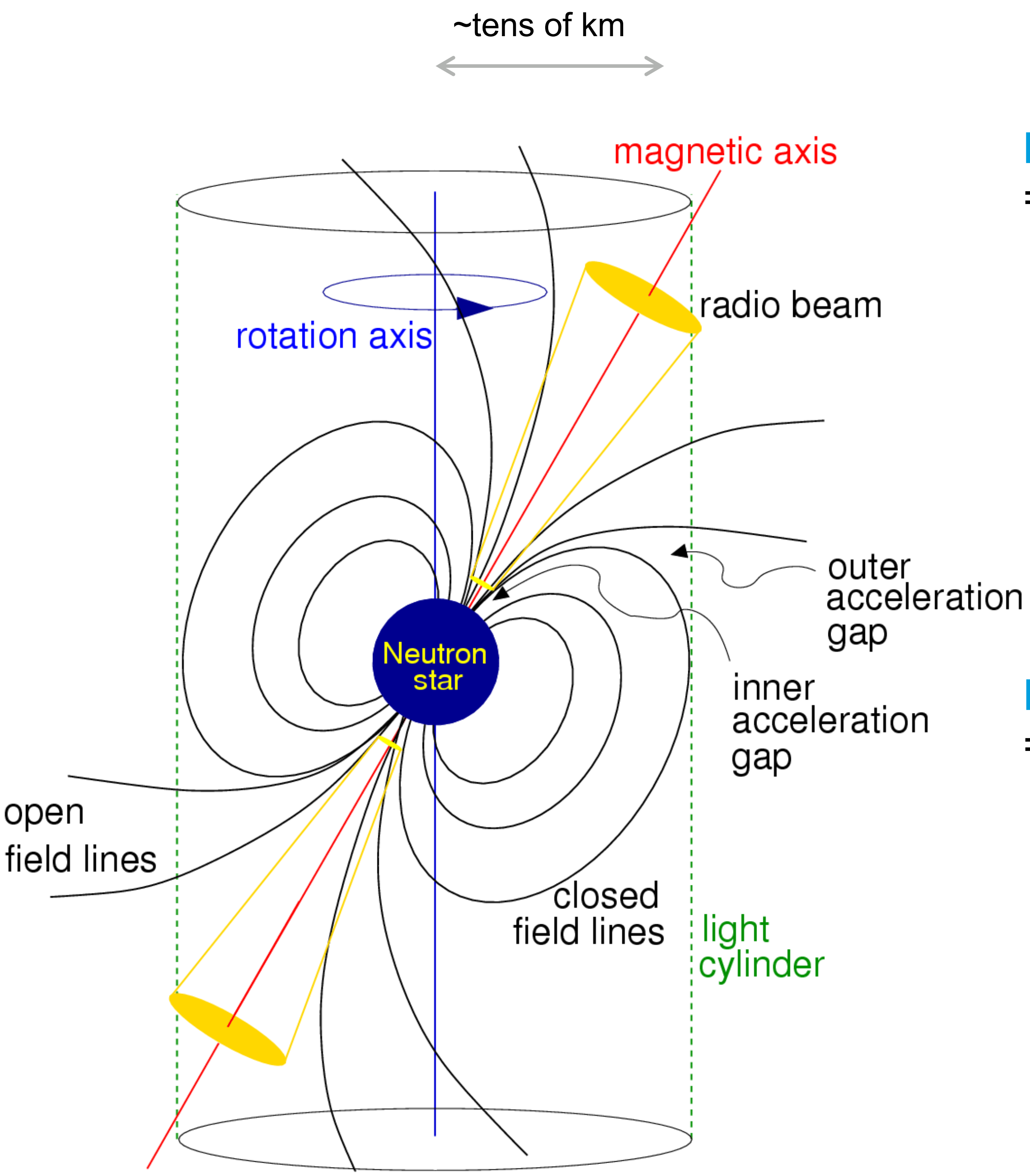
Pulsars in VHE gamma rays

Emma de Oña Wilhelmi
DESY Zeuthen





Lorimer and Kramer 2012

Large rotational power $\dot{E}$ with EMF ~10^7 V
=> Extract charged particles from neutron star surface

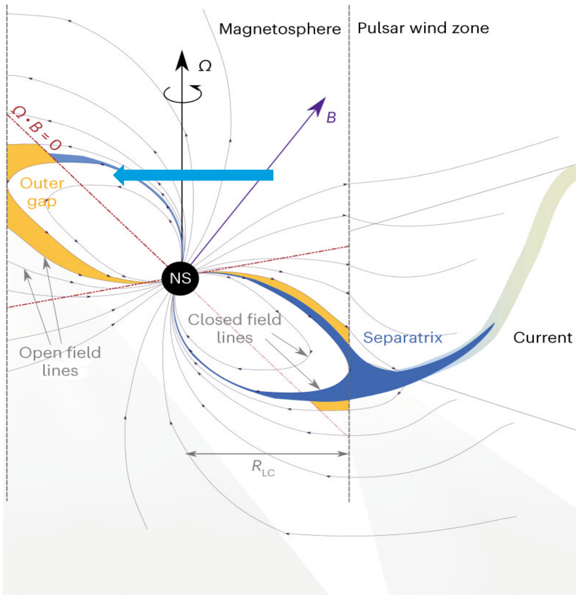
Fill the magnetosphere with dense plasma ρ_{GJ}
=> Enough e± pairs to achieve force-free condition

Particle accelerations only possible in regions with $\rho < \rho_{GJ}$
=> Gaps around open magnetic lines

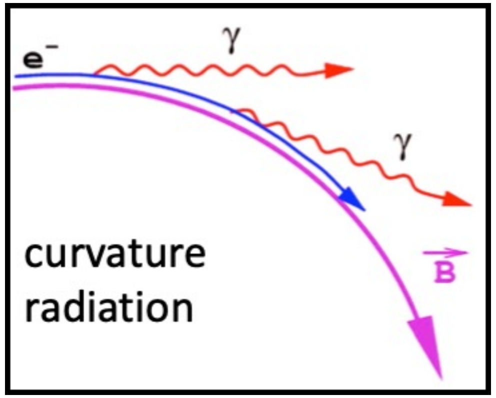
Radio, X-ray and Gamma-ray pulses
=> rotating light beams sweeping past the Earth

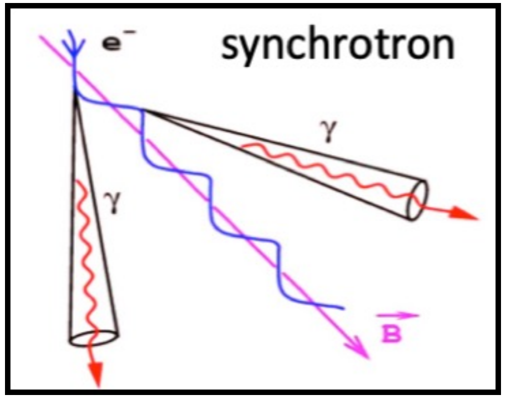
Pulsars as extreme accelerators and non-thermal sources

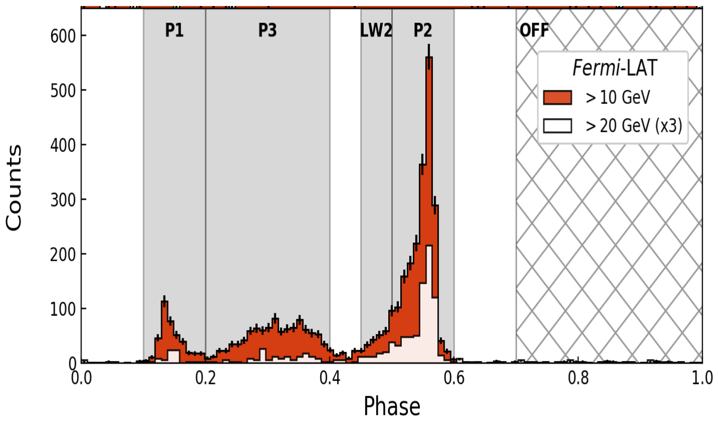
Radiation B~[1e4, 1e12] G



Acceleration



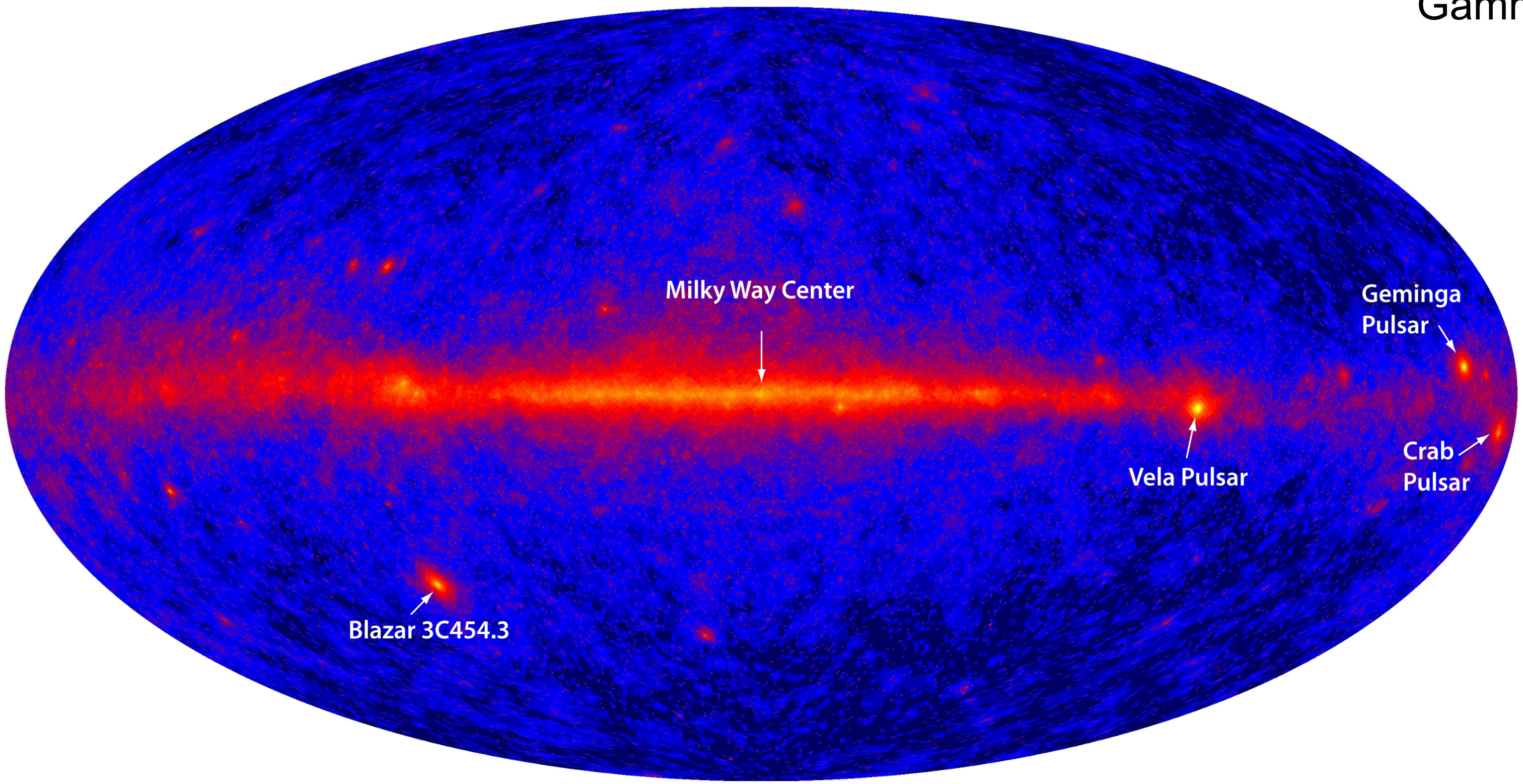




Pulsed radiation

Image credit: the International Fermi LAT Collaboration.

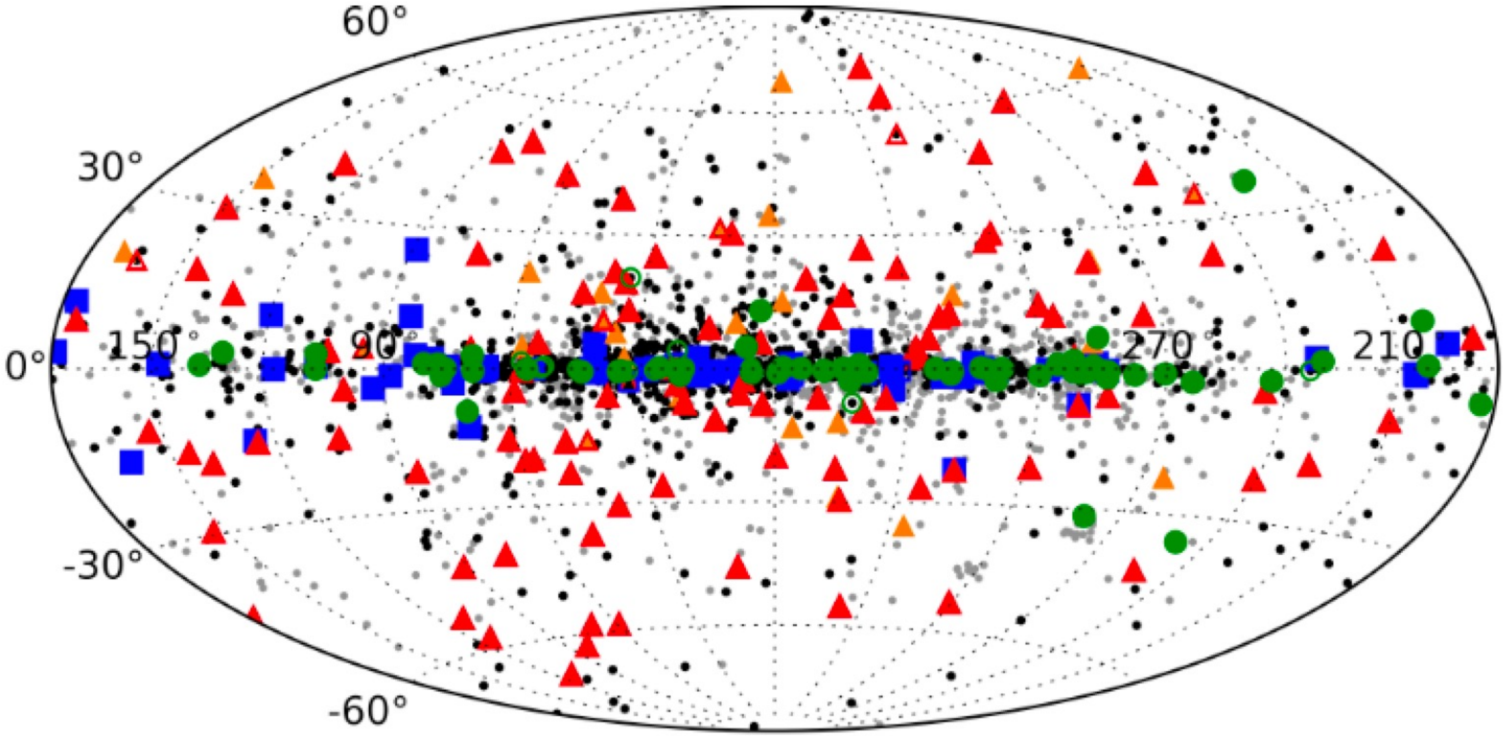
Gamma-ray sky at 1 GeV



Pulsars are brightest Galactic sources at 1 GeV and the most numerous Galactic source population

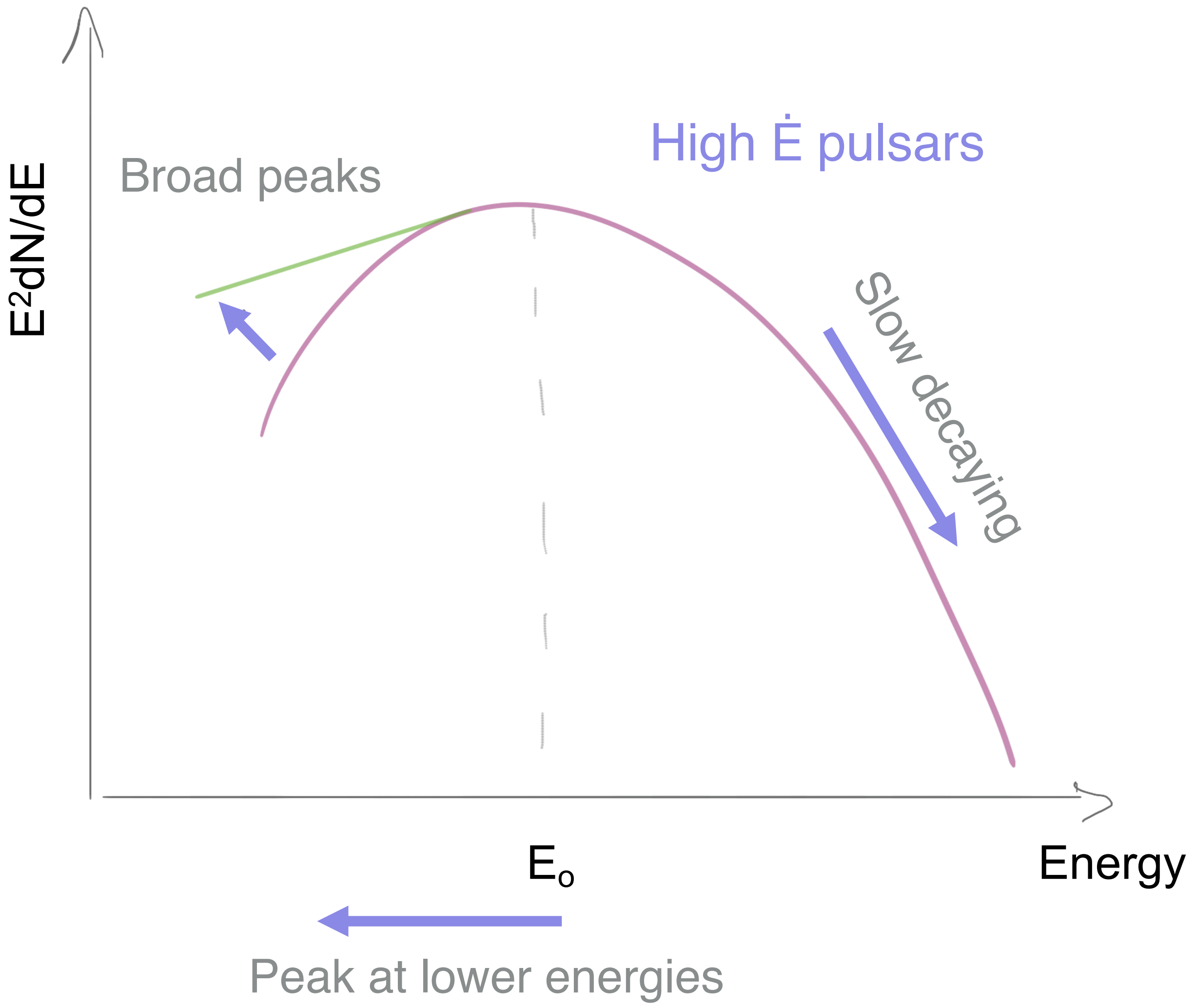
Image credit: the International Fermi LAT Collaboration.

Gamma-ray sky at 1 GeV



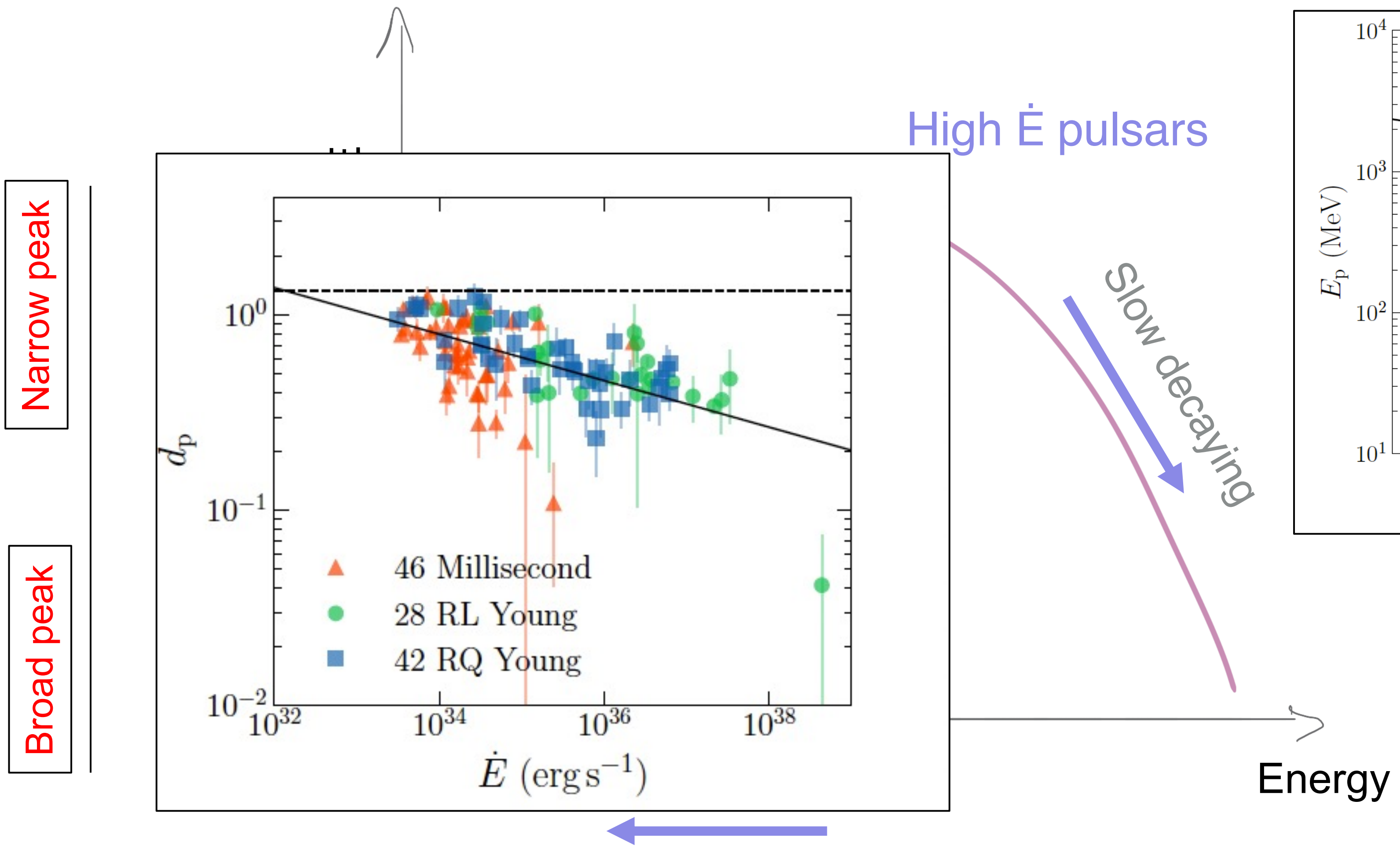
Pulsars are brightest Galactic sources at 1 GeV and the most numerous Galactic source population

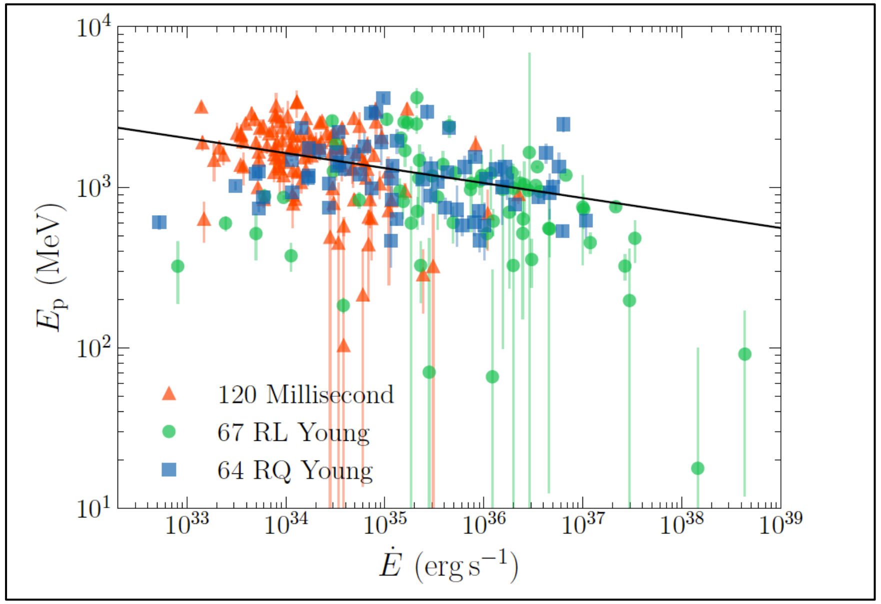
The LAT spectra in the GeV regime



The Spectrum in the GeV regime

3PC, LAT Collaboration 2023

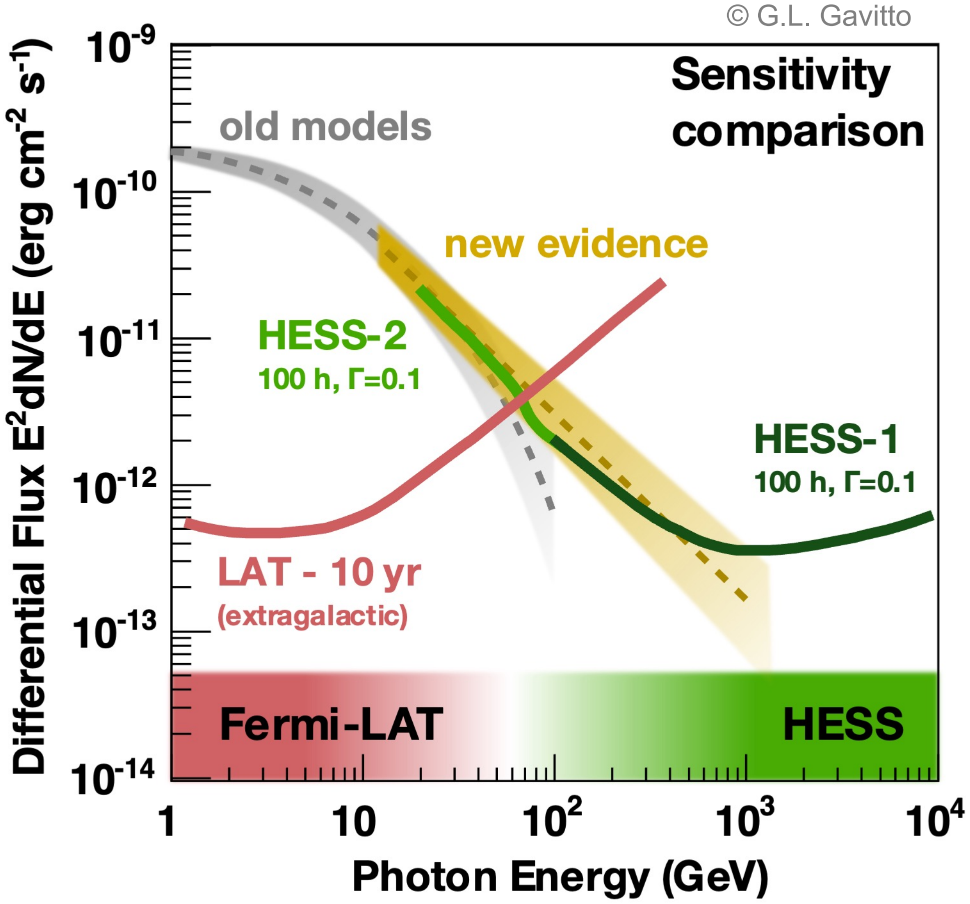




Peak at lower energies

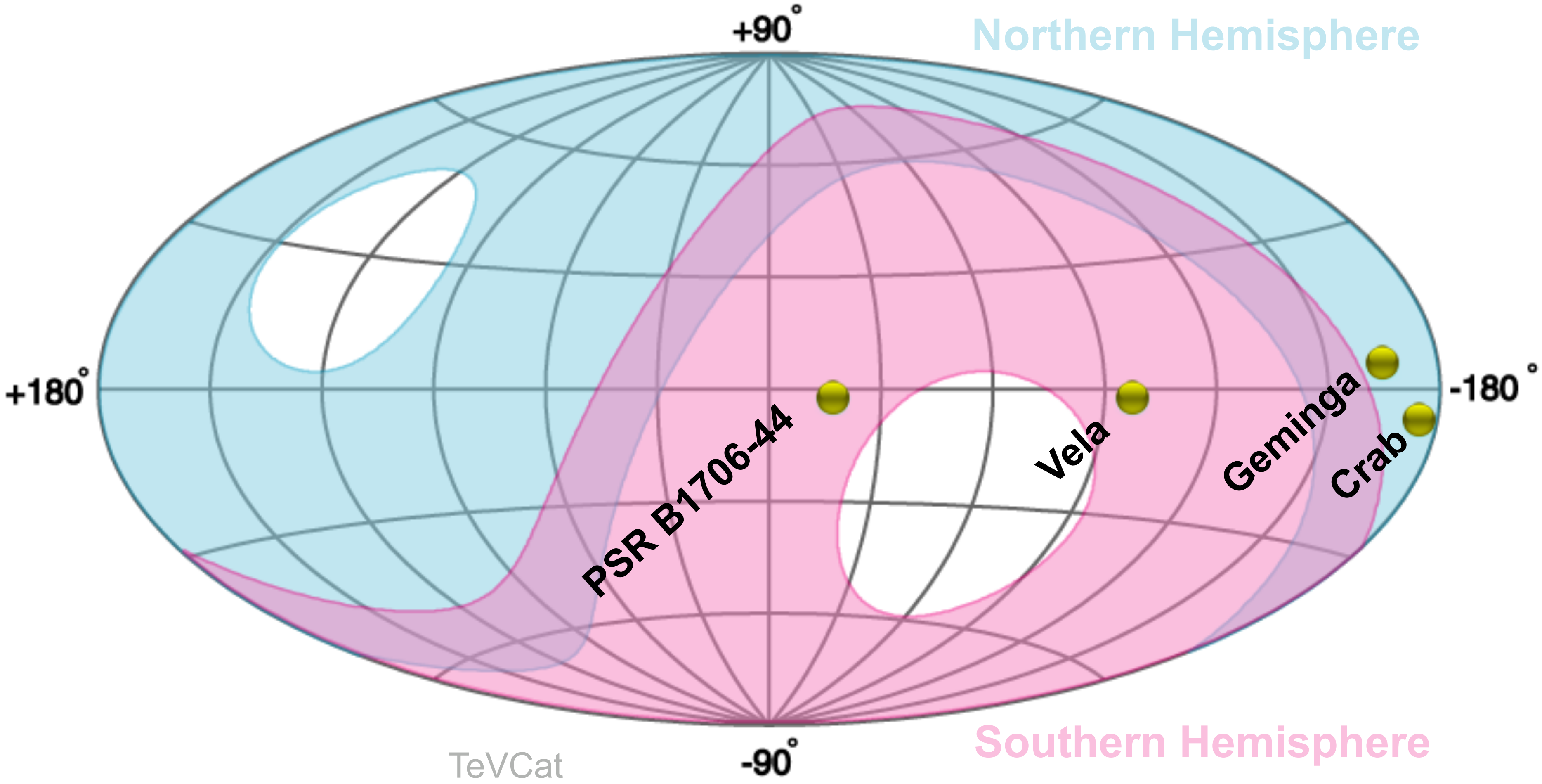
© Francisco Salgado based on images by M. SubbaRao, S. Criswell, B. Humensky, and J.F. Salgado

The Very-high Energy Regime

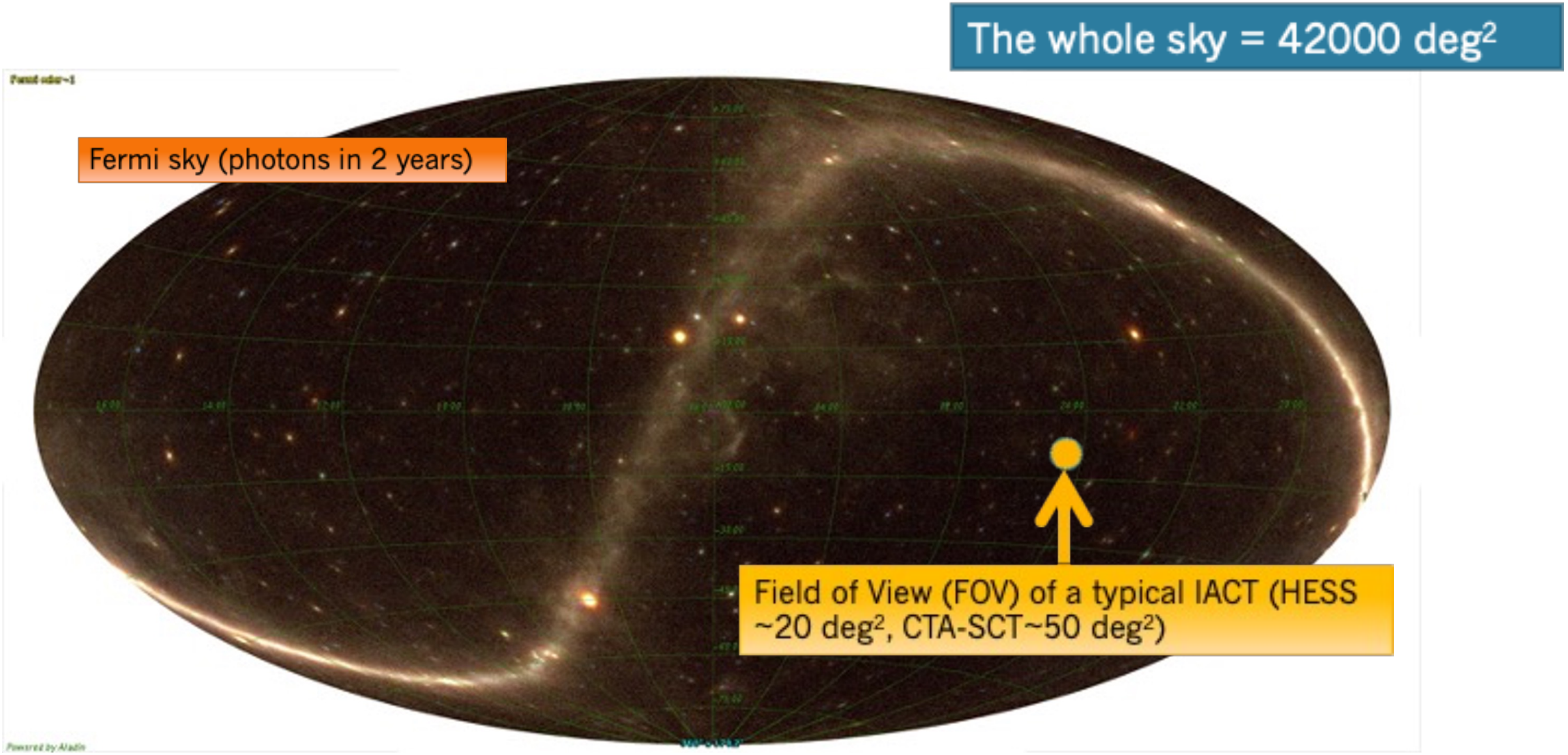


IACTs gamma-ray pulsars

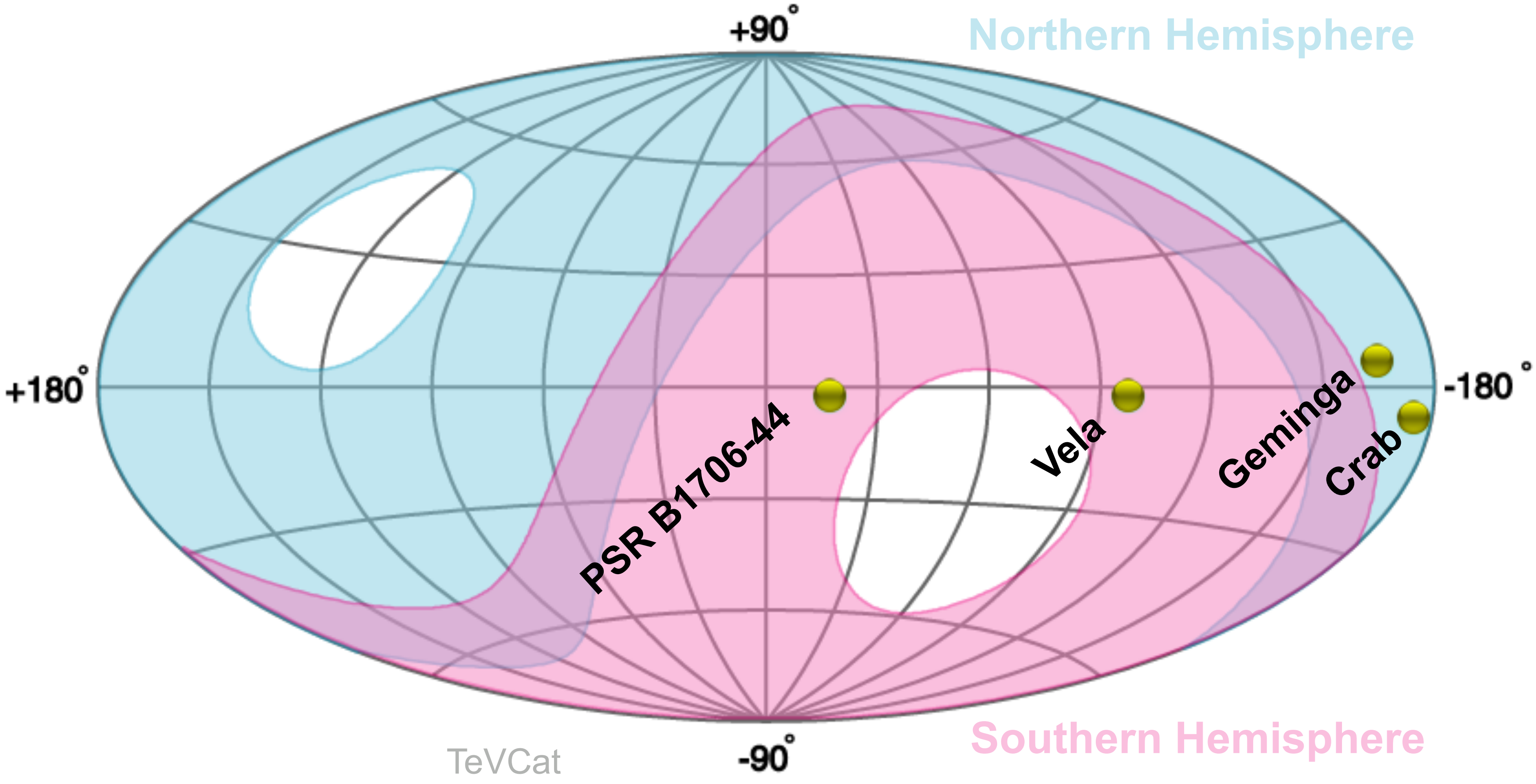
IACTs gamma-ray pulsars

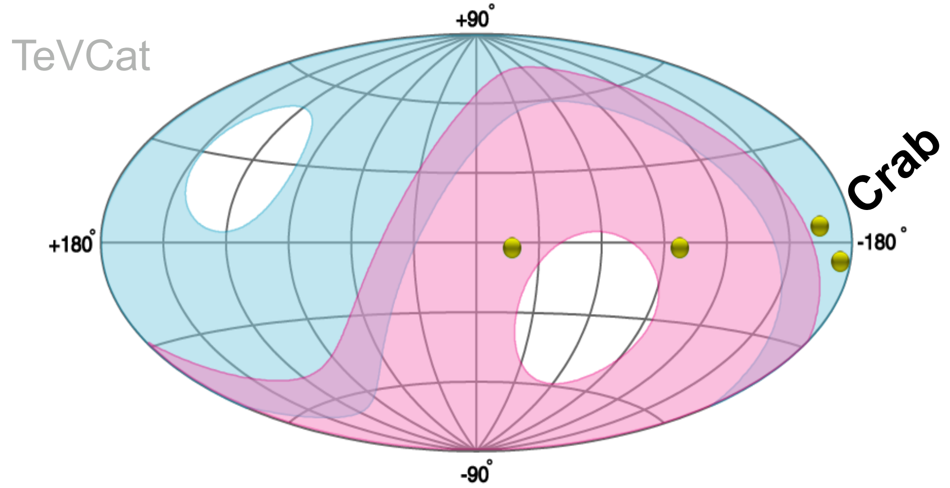


IACTs gamma-ray pulsars



IACTs gamma-ray pulsars

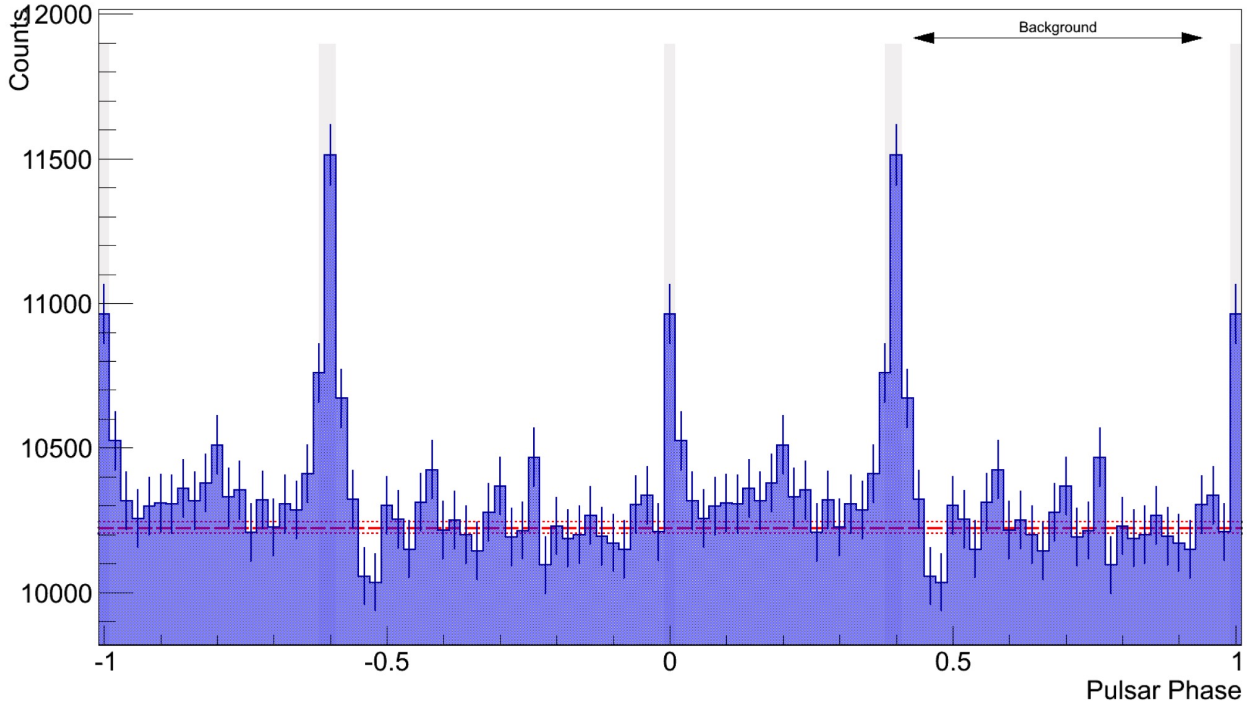




	Age [kyr]	D [kpc]	$\dot{E}/d^2$ [erg/s]	~E_{max} [TeV]	Γ_{VHE}
Crab	1.2	2	5×10^{38}	1.5	3. – 3.5

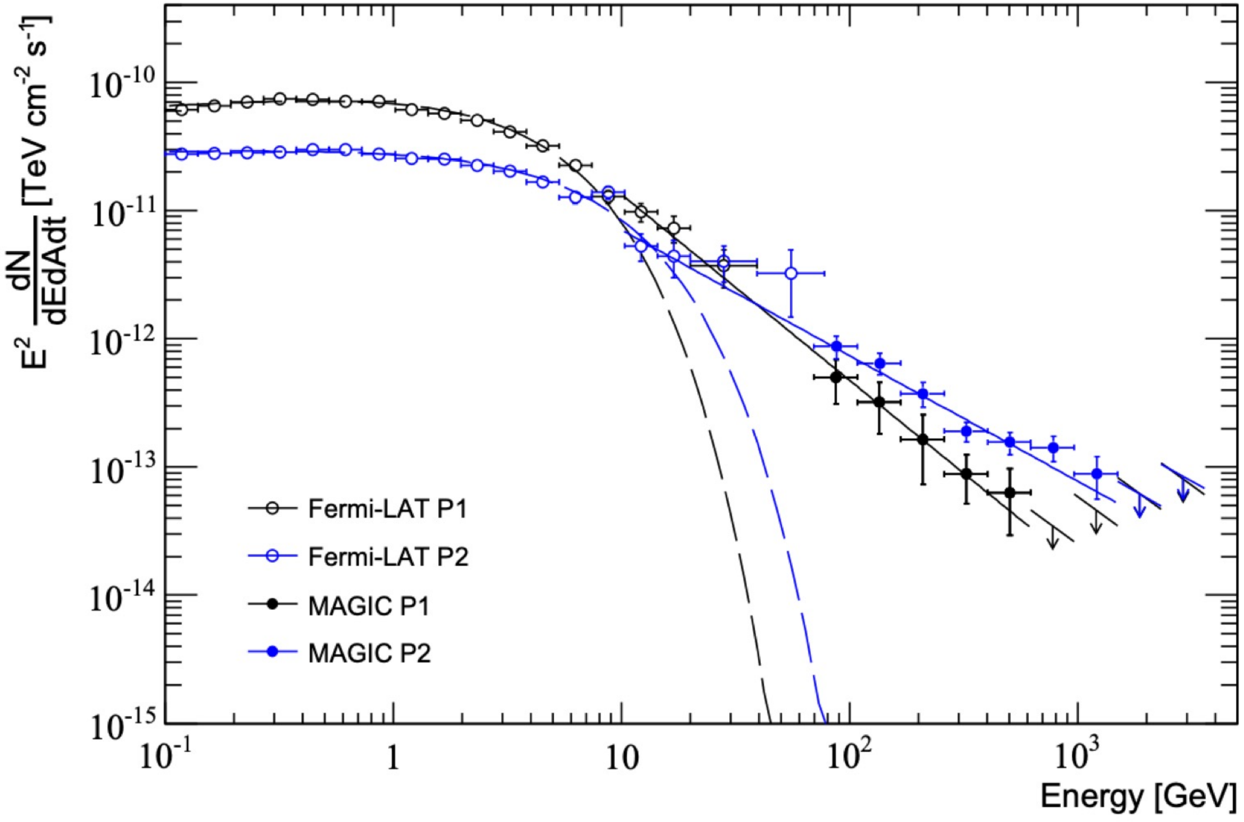
Crab:
detected by MAGIC/VERITAS 2015, after 320/107 hours of observation

Crab Pulsar, VERITAS Collaboration 2015



IACTs Pulsars: the Crab pulsar

Crab Pulsar, MAGIC Collaboration 2017



=> First case of departure from exp-cutoff

=> One or two components?

=> Inverse Compton (but absorption)

First IACT pulsar

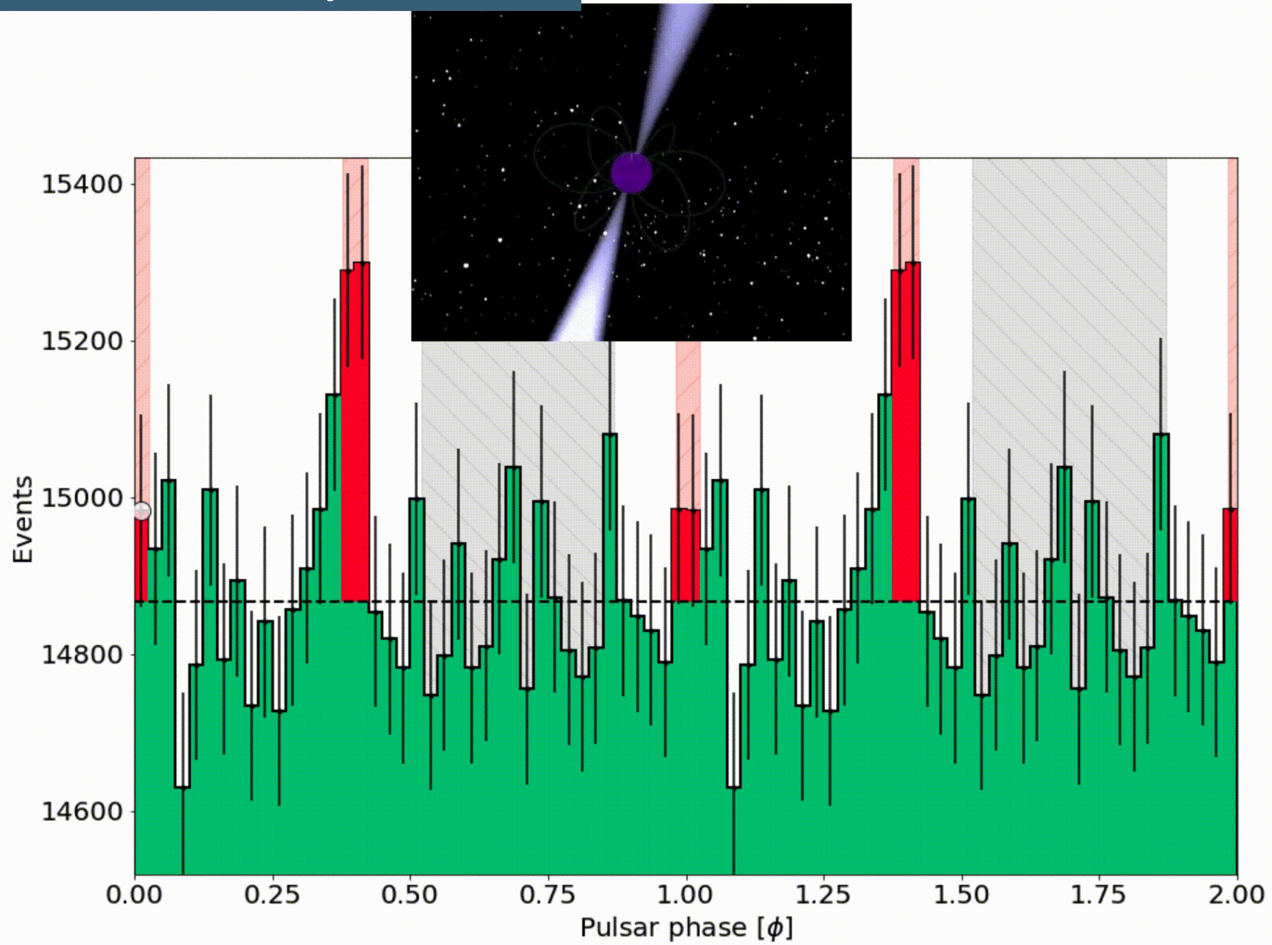
First TeV pulsar

First CTA pulsar

Don’t miss poster by G. Brunelli et al.

Don’t miss talk by D. Green

IACTs Pulsars: the Crab pulsar



Phasogram of Crab Pulsar as measured by the LST-1. Credit: LST Collaboration

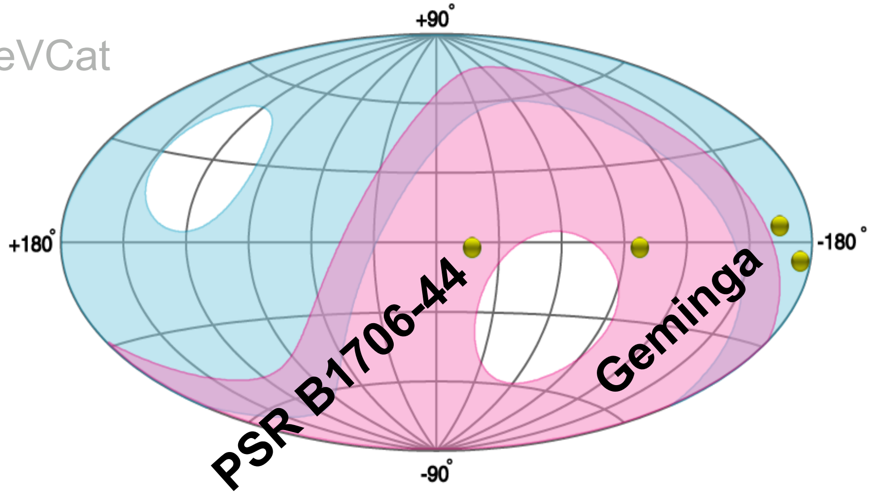
First IACT pulsar

First TeV pulsar

First CTA pulsar

LST-1 detected the pulsation ~1 σ $hour^{-1/2}$

Comparable to MAGIC with two telescopes
=> detected above 5 σ in 25h



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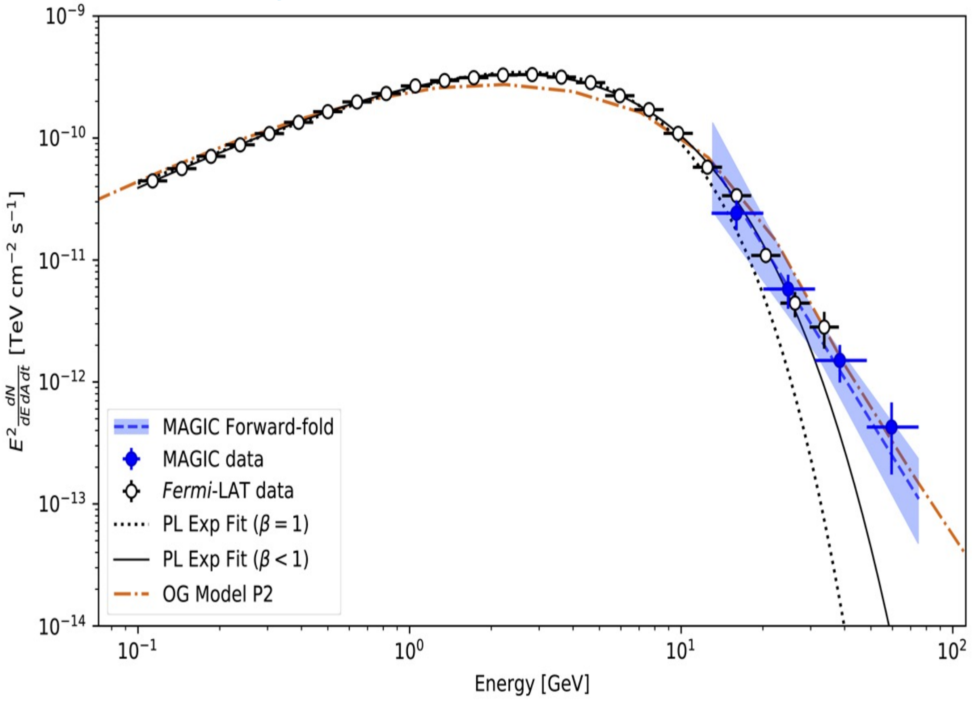
Crab	1.2	2	5x10^{38}	1.5	3. – 3.5
PSR B1706-44	18	2.6	6x10^{35}	0.075	3.76
Geminga	340	0.2	7x10^{35}	0.070	3.8

Geminga

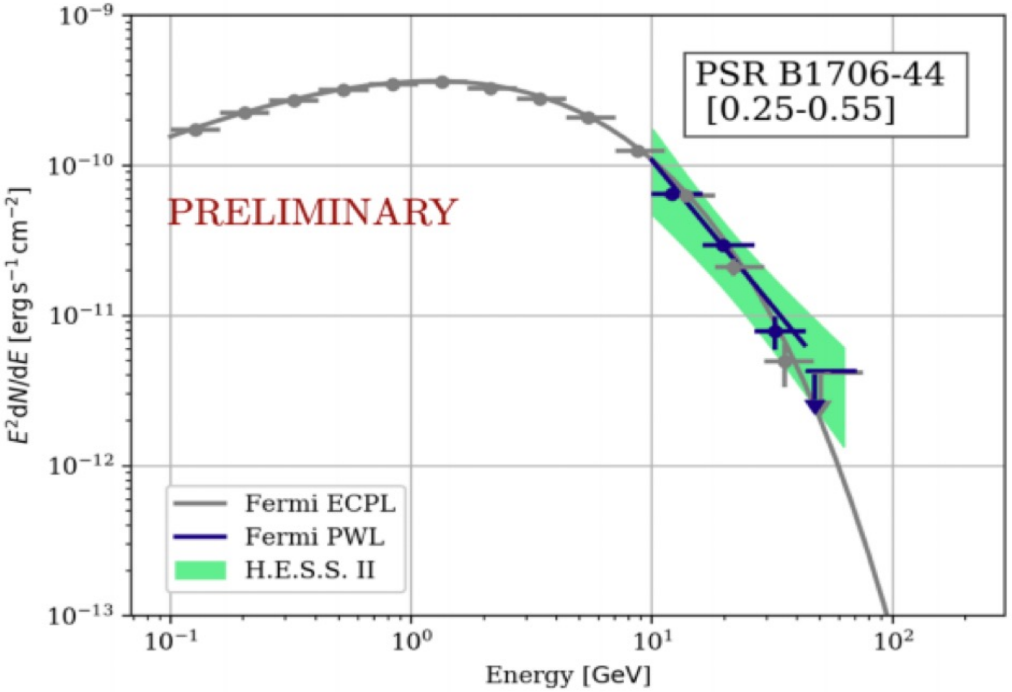
80 hours



Geminga, MAGIC Collaboration 2020

PSR B1706-44

28.3 hours

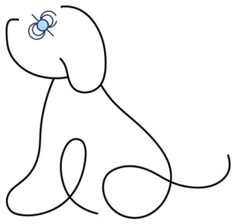


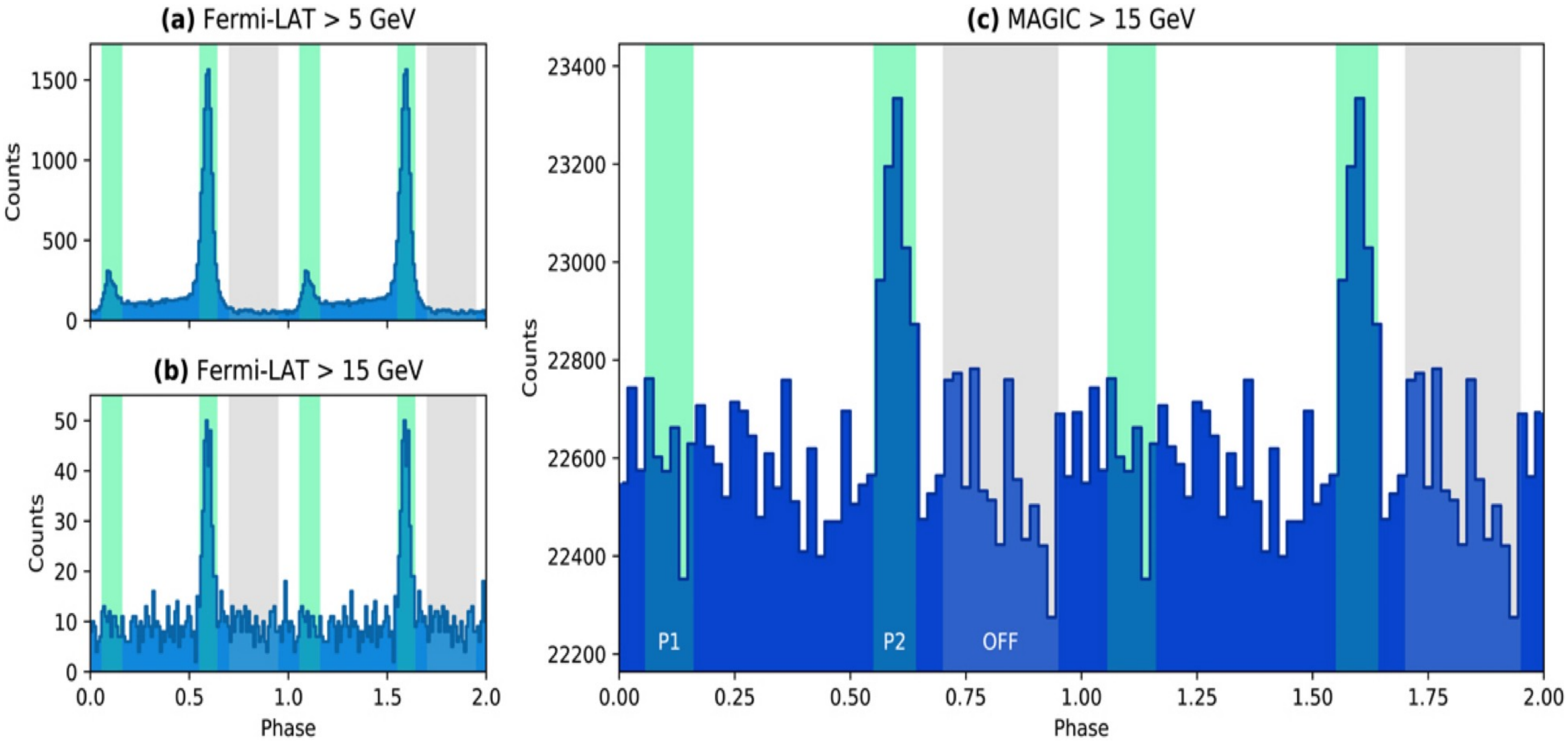
PSR B1706-44, Spir-Jacob et al, 2019

Similar trends:

Departs from an exponential cutoff => **Pulsars with tails**

Coherence in light curve (evolution with energy)

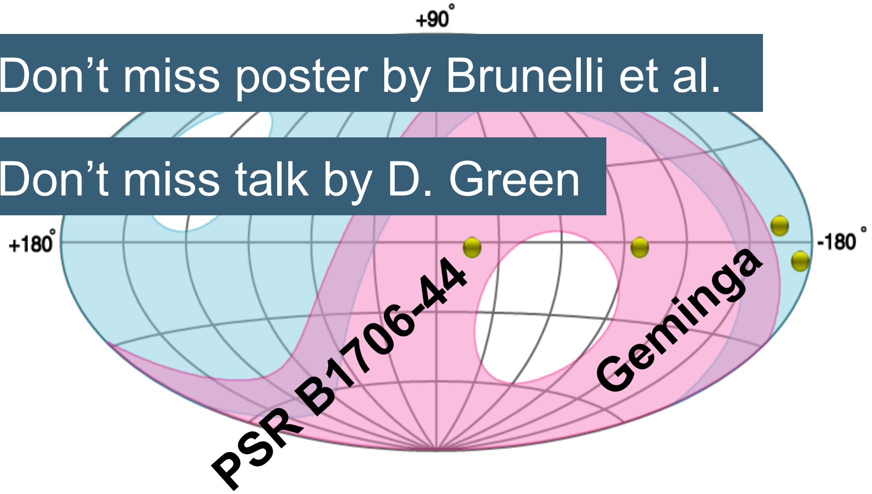




Geminga Pulsar, MAGIC Collaboration 2020

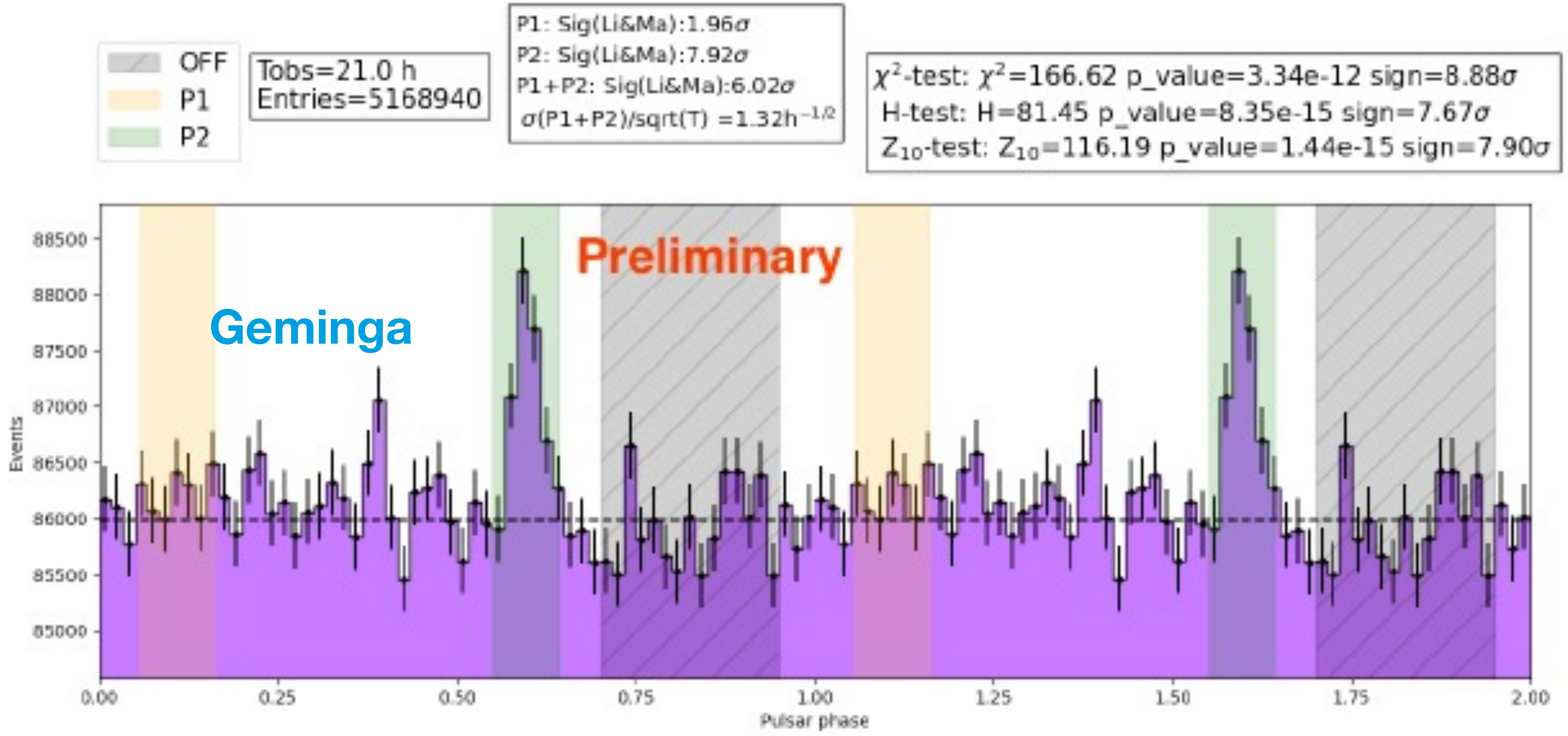
Don’t miss poster by Brunelli et al.

Don’t miss talk by D. Green



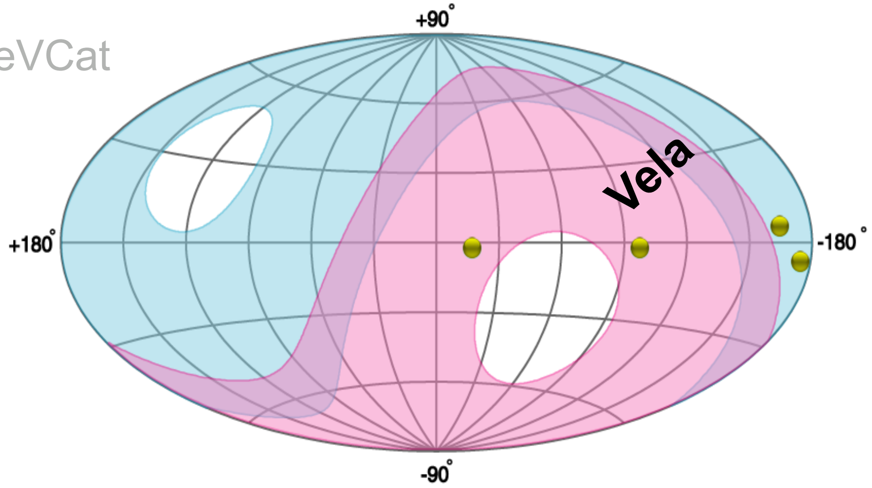
LST-1 detected the pulsation ~0.5 – 1.7 σ $hour^{-1/2}$

=> detected above 5 σ in 25h (80 with MAGIC)



Phasogram of Geminga Pulsar as measured by the LST-1. Credit: LST Collaboration / Mas-Aguilar et al 2023

TeVCat



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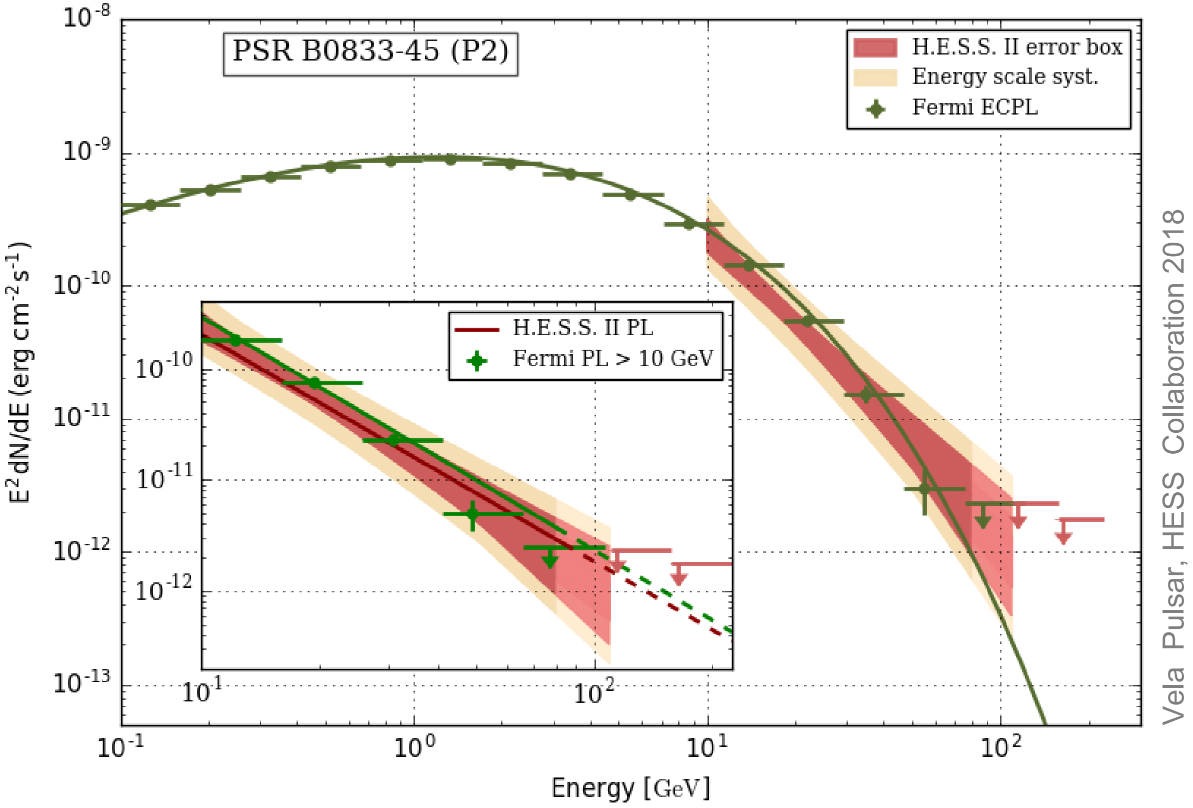
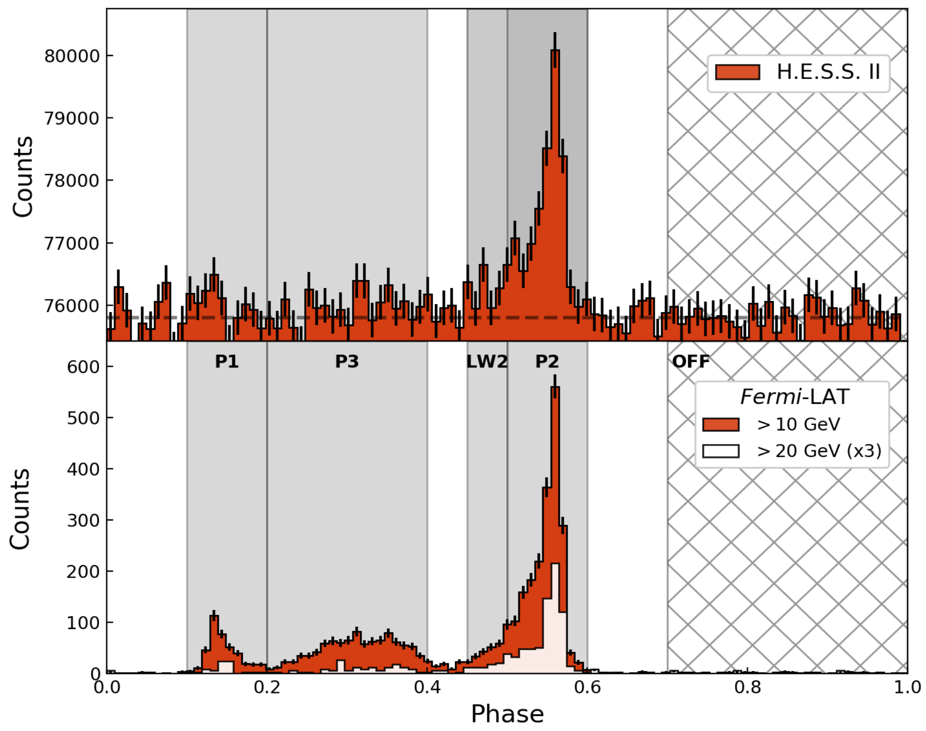
PSR B1706-44	18	2.6	6x10^{35}	0.075	3.76
Geminga	340	0.2	7x10^{35}	0.070	5.62
Vela	11	0.3	1x10^{38}	0.1	4.1

Vela

40.3 h

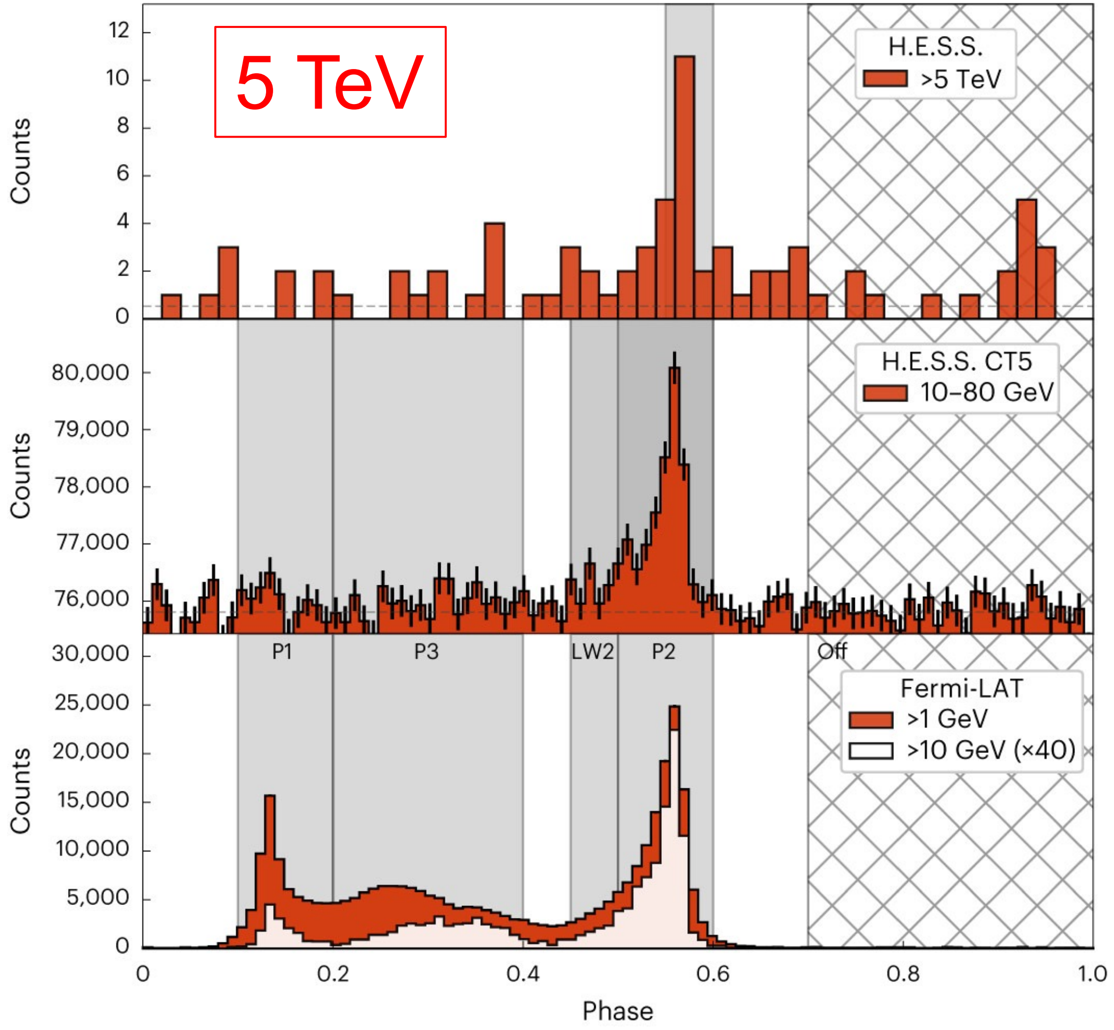


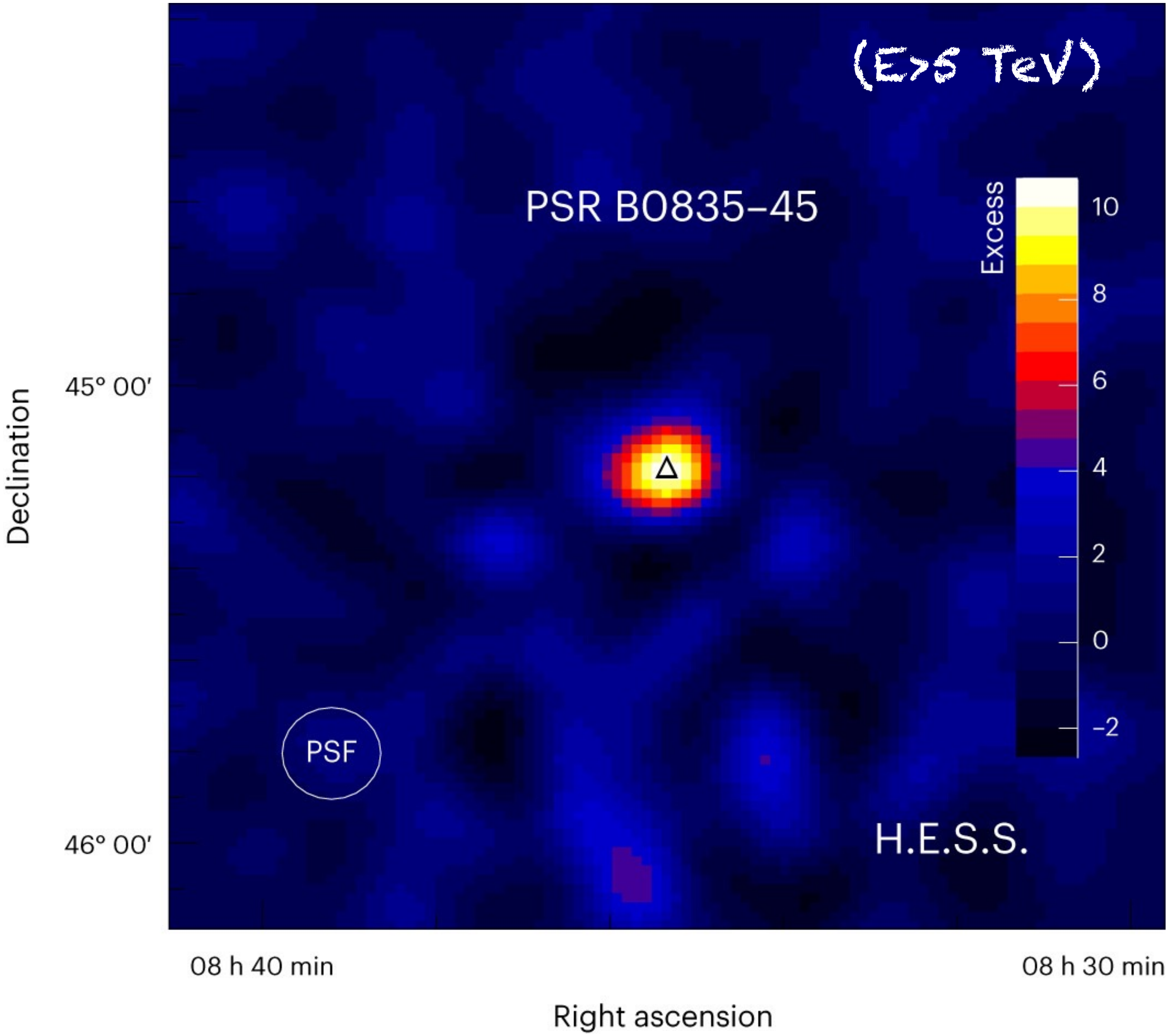
Peak evolves with energy



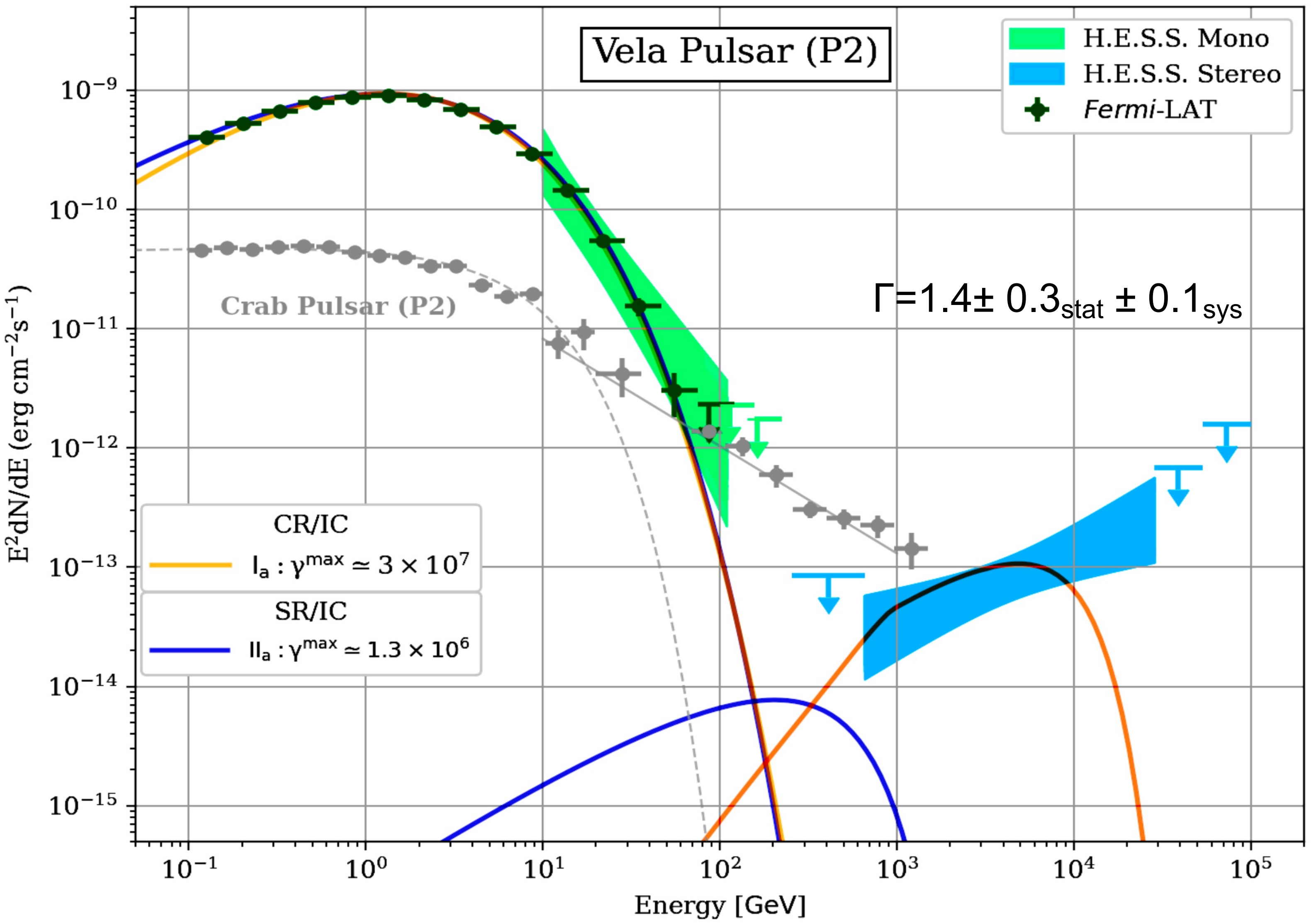
Vela Pulsar, HESS Collaboration 2018

HESS deep observations observations (80 h)





HESS Collaboration et al 2023



HESS Collaboration et al 2023

One of the hardest TeV sources

In the K-N regime:

$$\gamma_{IC}^{max} \gtrsim 4 \times 10^{7} (E_{\rm TeV}/20 \text{ TeV})$$

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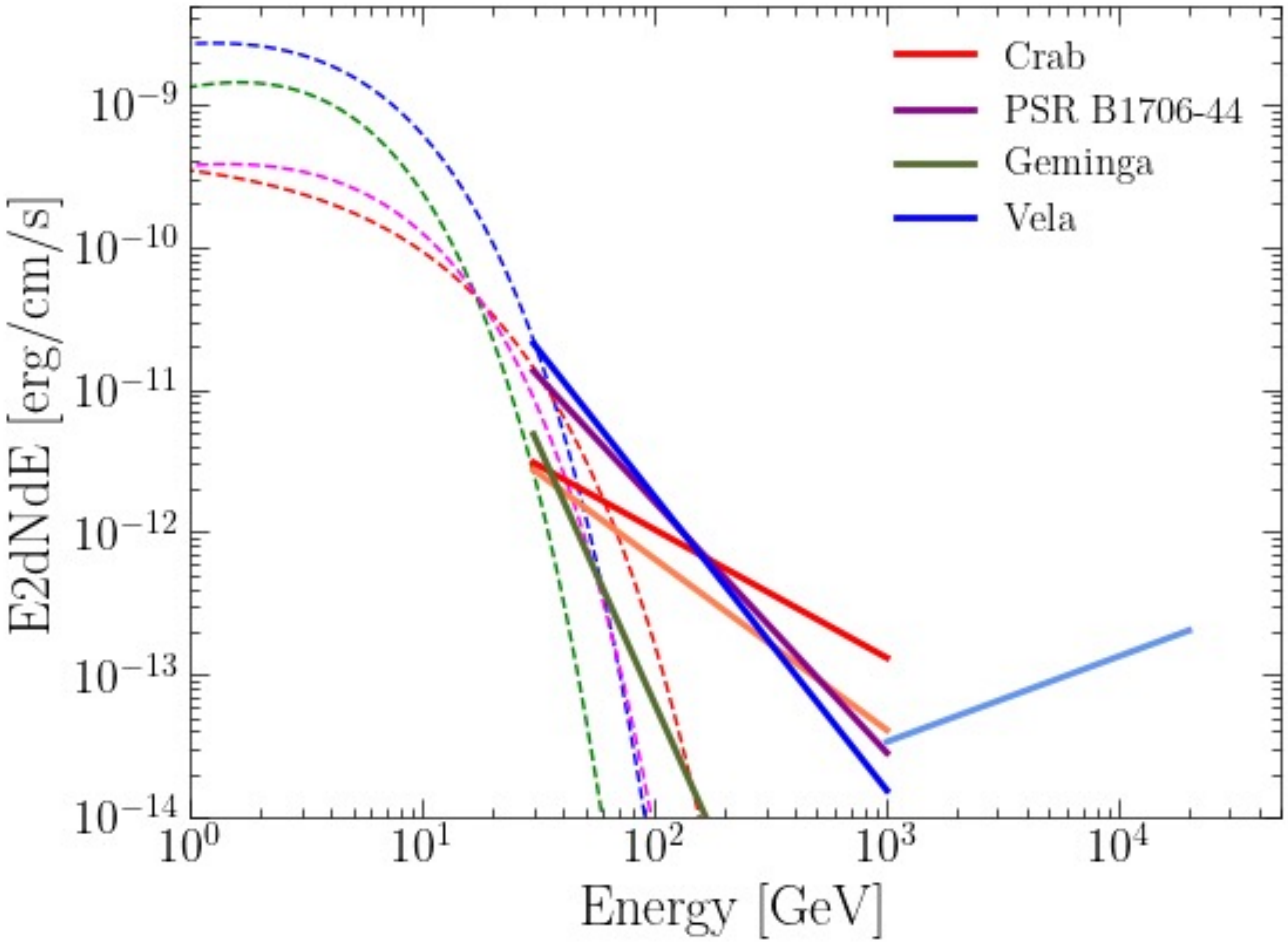
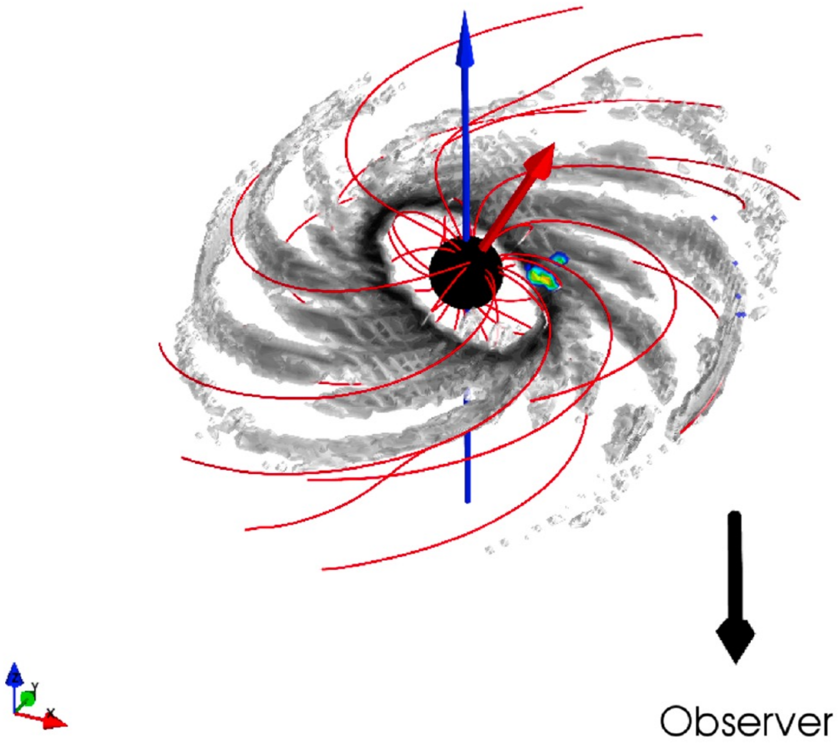
Vela+				20	1.4


Crab
PSR B1706-44
Geminga
Vela
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
E2dNdE [erg/cm/s]
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
Energy [GeV]

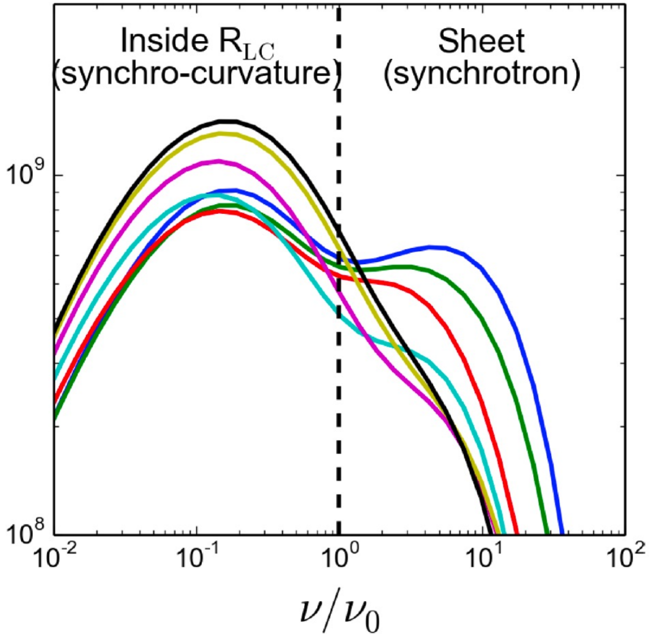
Meanwhile in the theory side…

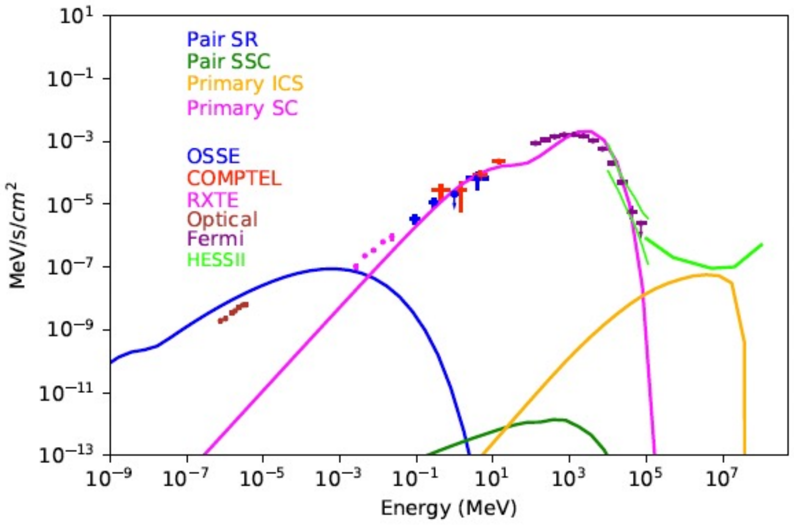
New theoretical ideas and simulations based on Particle-in-Cell have been developed to understand more complex dissipative magnetosphere

Systematic modeling of pulsar light curves and spectra
=> Most particle acceleration occurs high in the magnetosphere and/or beyond
=> Multiple acceleration regions/components - Gaps vs Stripped winds

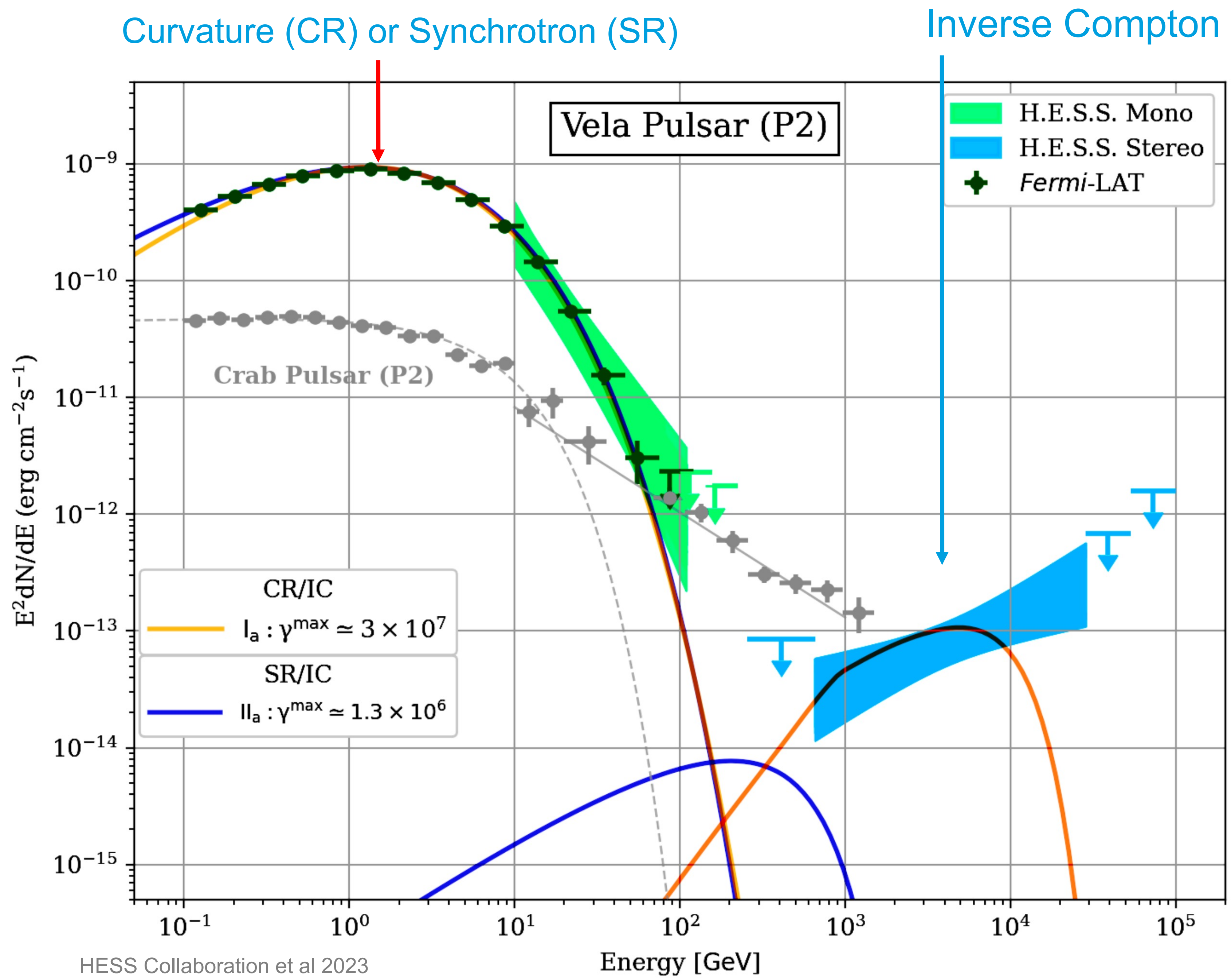


Cerutti et al 2016





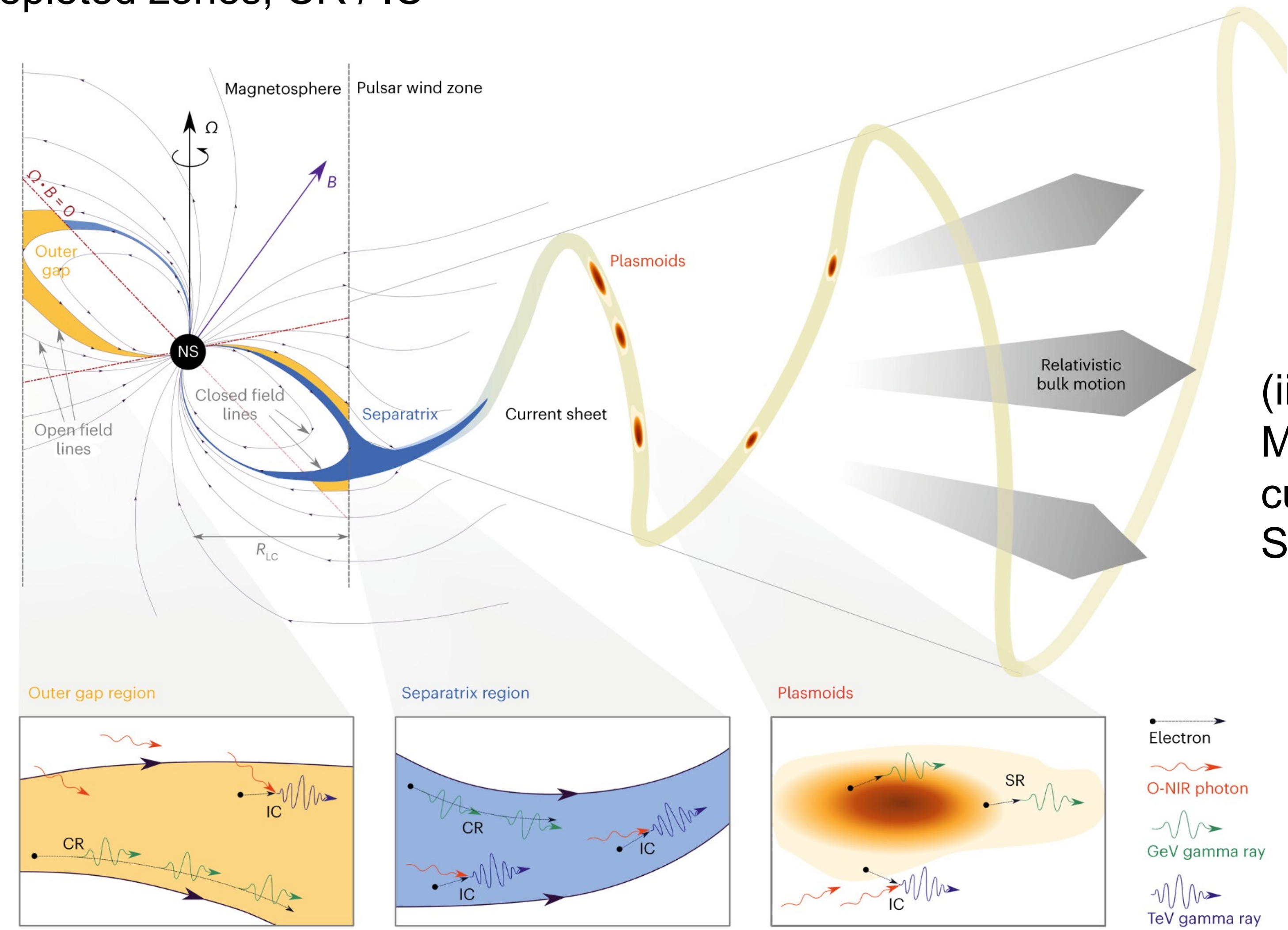
Harding et al 2021



HESS Collaboration et al 2023

HESS Collaboration et al 2023

(i) **Magnetospheric models**
accelerating E||, charge
depleted zones; CR / IC



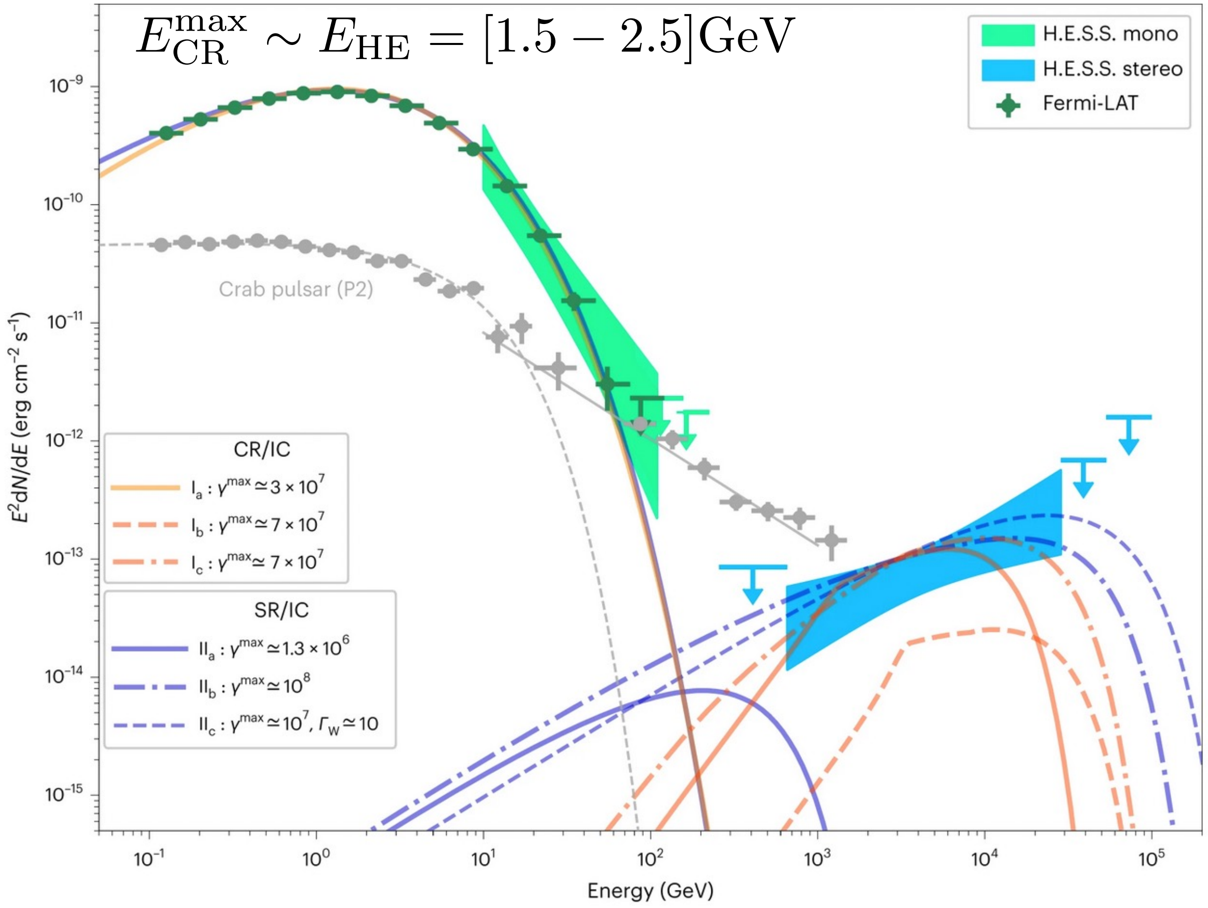
(ii) **Wind models:**
Magnetic reconnection
current sheet; non-ideal MHD;
SR / IC

HESS Collaboration et al 2023

Using Vela+ to constrain theory

* **CAVEAT**: Same particle population emitting at HE and VHE!

Curvature in gaps (outer gaps or separatrix/current sheets).



HESS Collaboration et al 2023

We fit HE and VHE to constrain emission region*

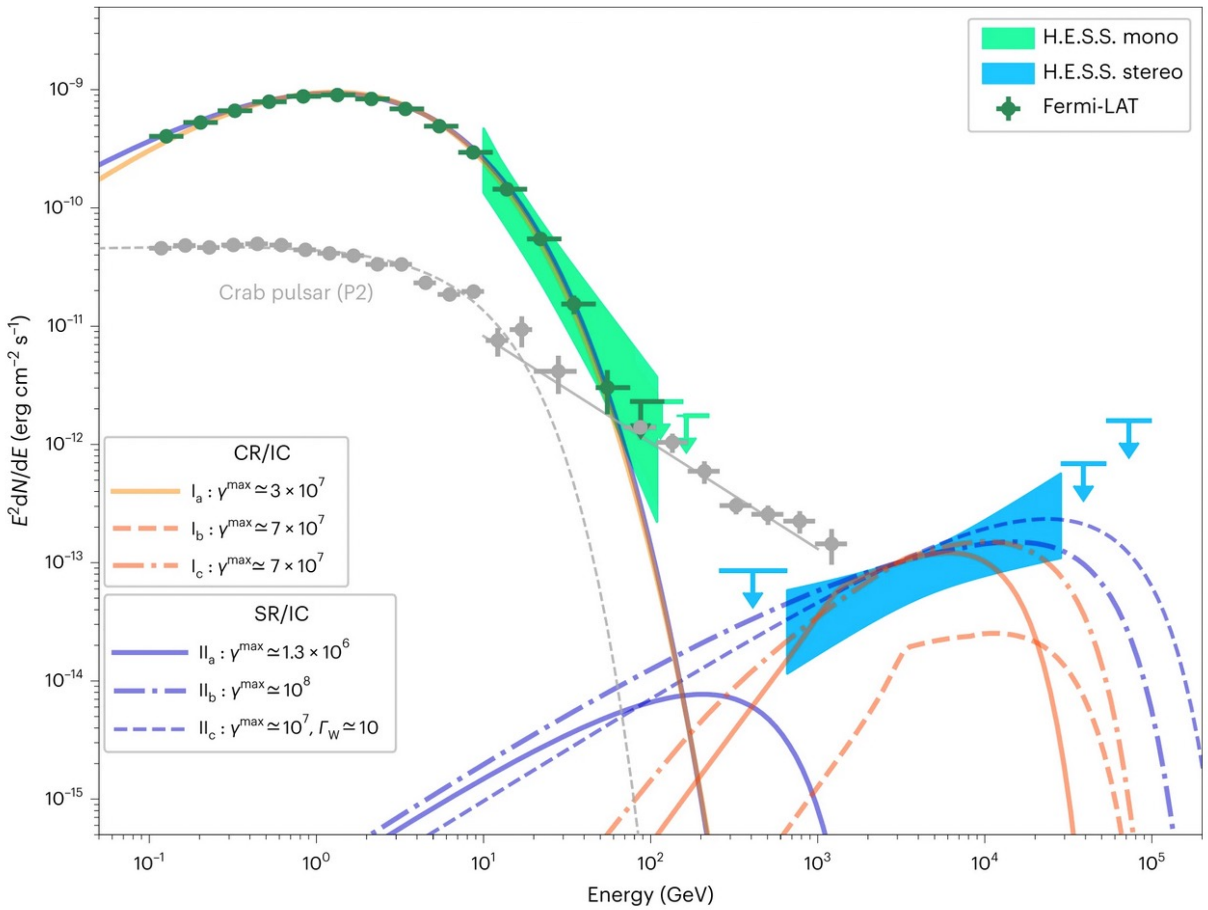
$$E_{\rm CR}^{\rm max} \simeq 5\,{\rm GeV}\,\xi^{1/2}\eta_{-1}^{3/4}$$

Curvature radius

Magnetic conversion efficiency

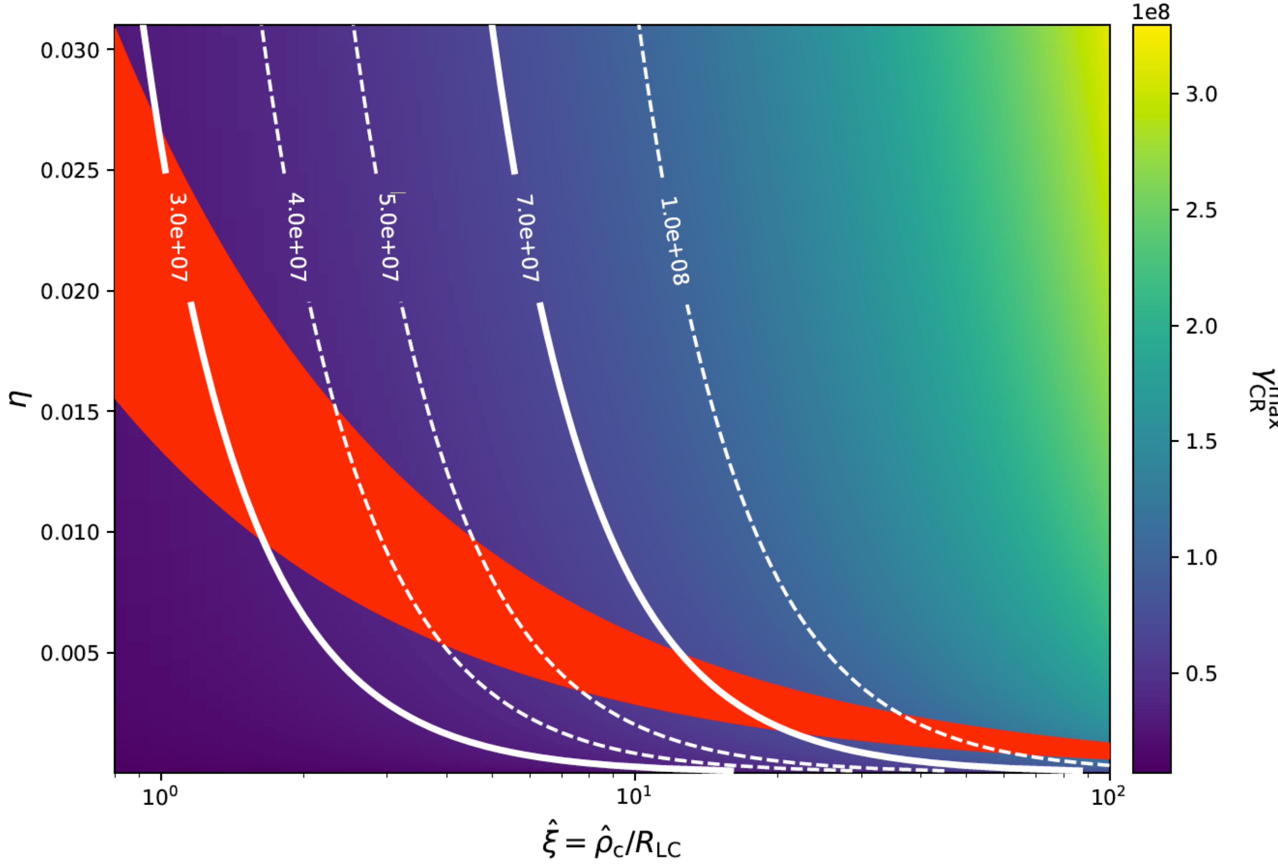
Using Vela+ to constrain theory

Curvature in gaps (outer gaps or separatrix/current sheets).



HESS data:

The red band results from GeV-peak fit $\gamma_{IC}^{max} \gtrsim 7 \times 10^7$



HESS Collaboration et al 2023

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HESS data:

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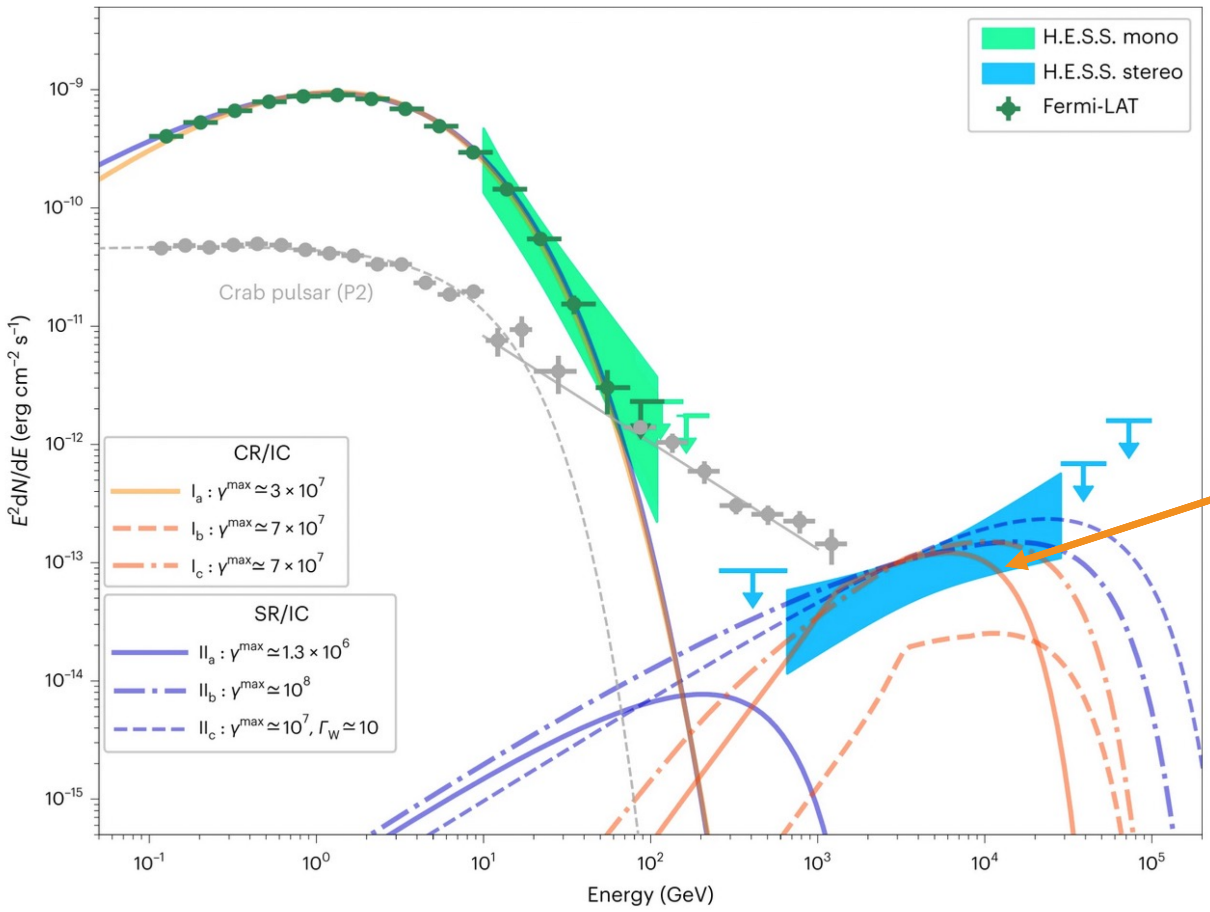
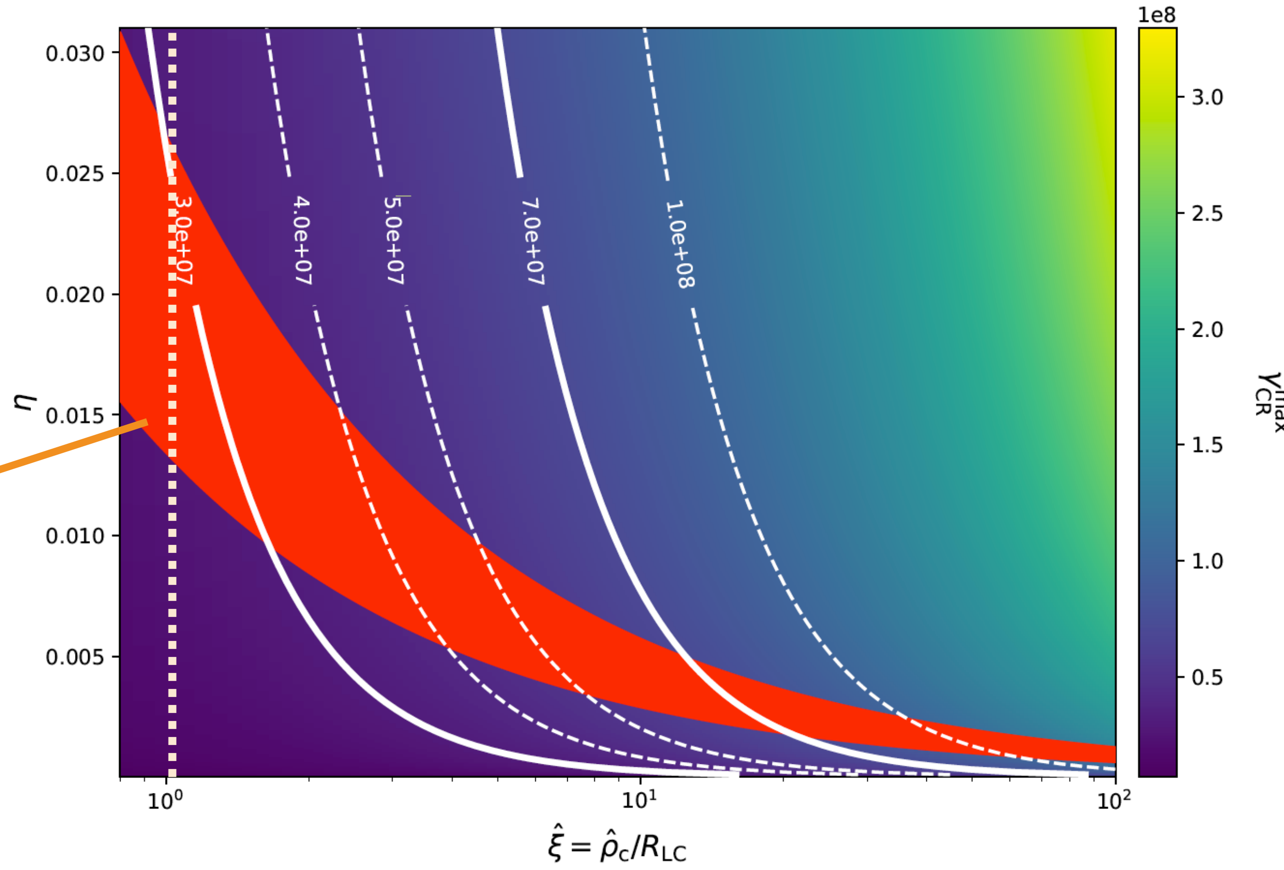


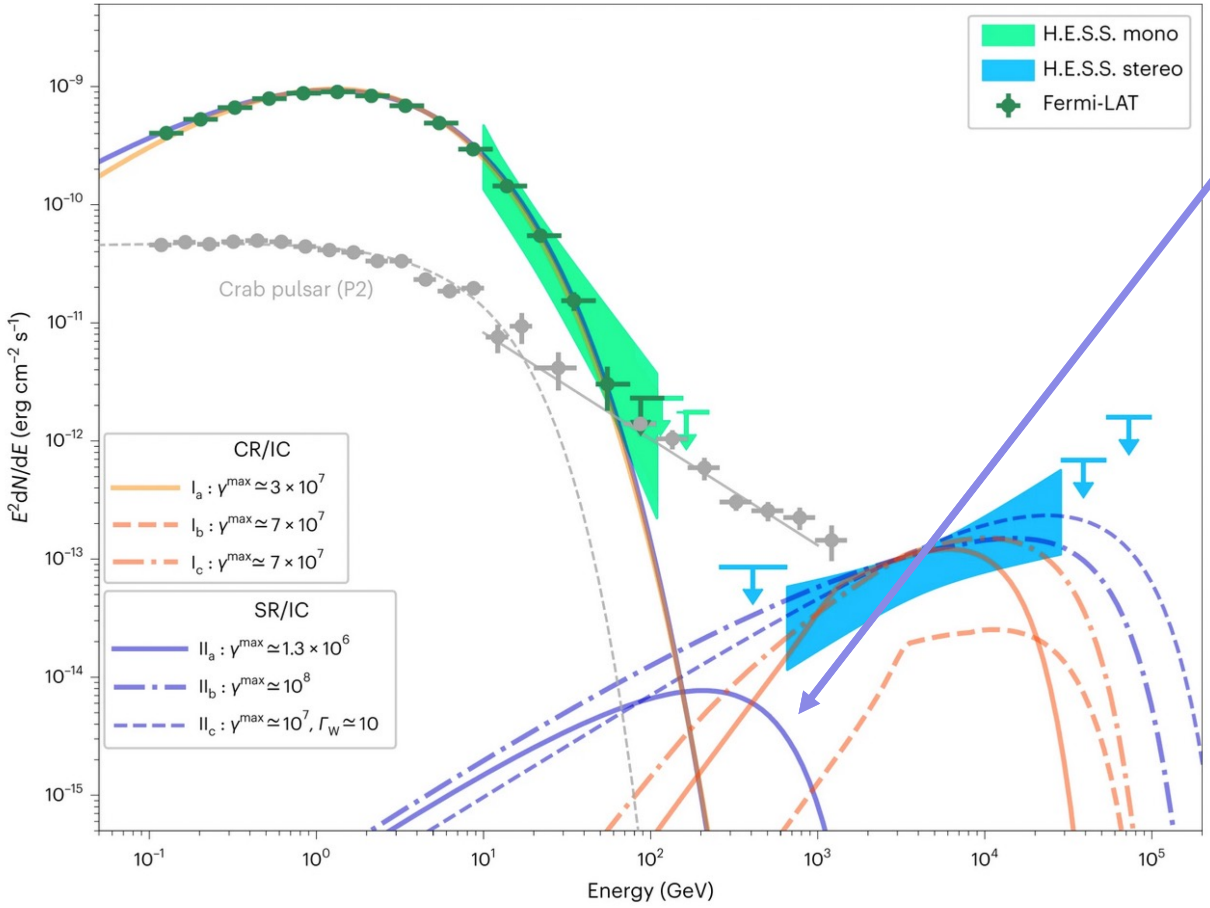
The red band results from GeV-peak fit



HESS Collaboration et al 2023

Using Vela+ to constrain theory

Synchrotron in wind plasmoids



$$\gamma_{\rm SR}^{\rm max} \simeq 1.3\times10^6 (B_\perp/B_{\rm LC})^{-1/2} (E_{\rm SR}^{\rm max}/1.5\,{\rm GeV})^{1/2}$$

HESS data:

$$\gamma_{\rm IC}^{\rm max} \gtrsim 7\times10^7$$

Some alternatives:

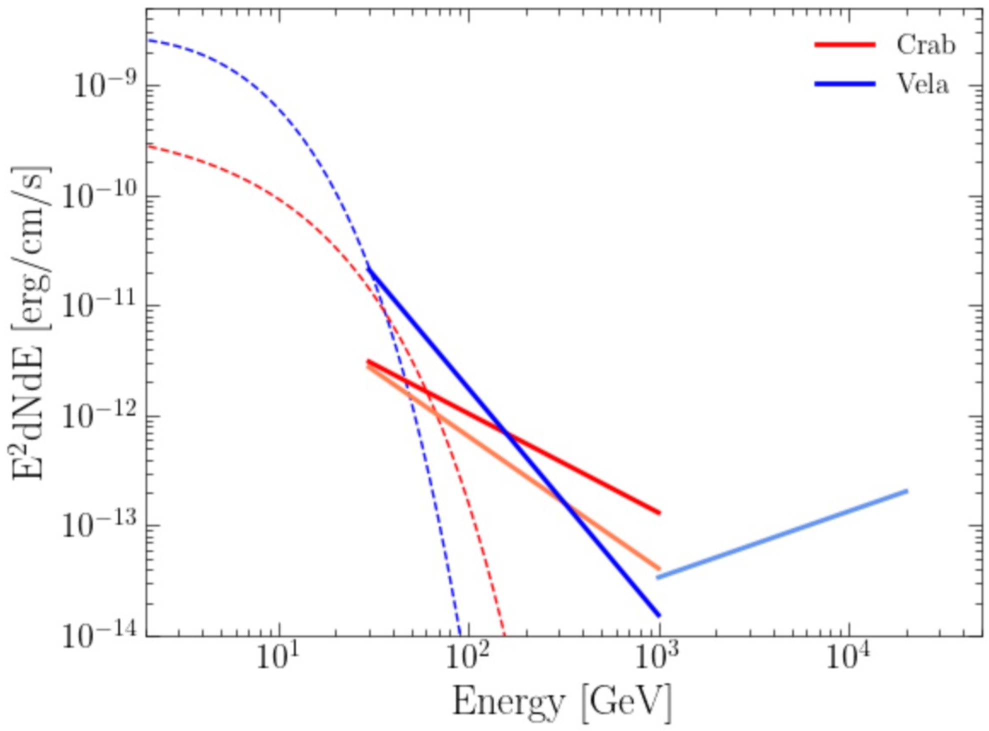
* Escape of the highest particles
* Doppler-boosted emission

$$\simeq 5R_{LC}$$

$$\Gamma_w \gtrsim 5$$

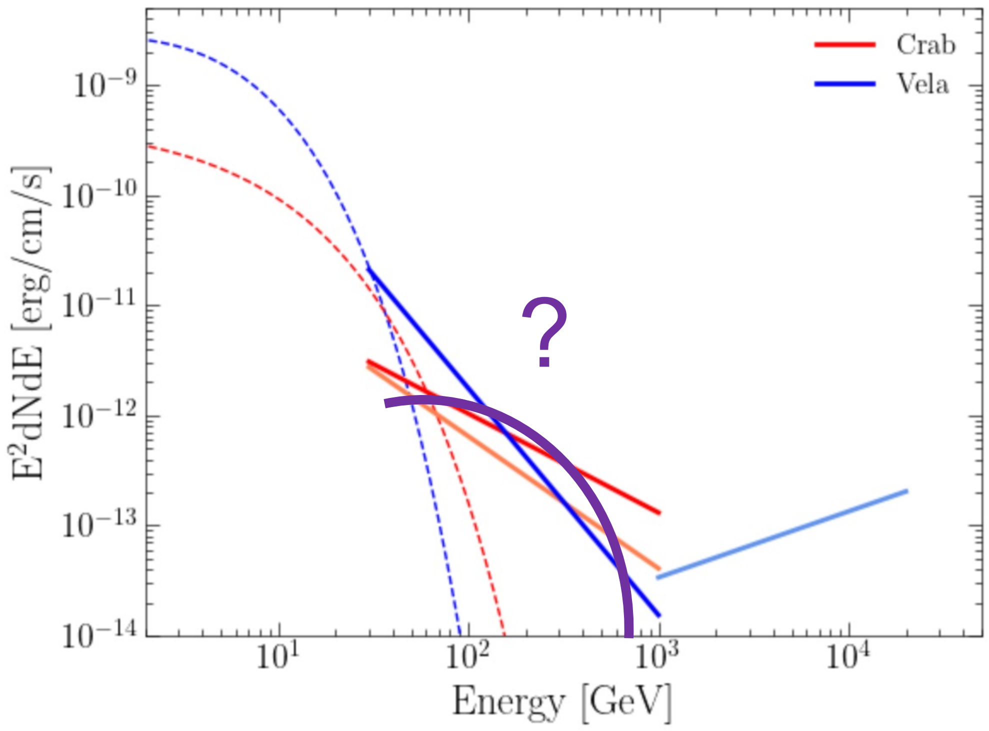
HESS Collaboration et al 2023

Open Questions and ongoing activities



- What's the nature of the tails? Inverse Compton? Where is the radiation produced?
- What's the nature of the multi-TeV component? Are there more pulsars like Vela? Surely there are!
- What about Crab?
- What can we learn?
  Is the density of the electrons ~ ρ_{GJ}
  Maximum Lorentz factor / Energy
  Constrains on the Op/IR photon fields
- Extreme e^{+-} accelerators => Cosmic ray electrons

Open Questions and ongoing activities



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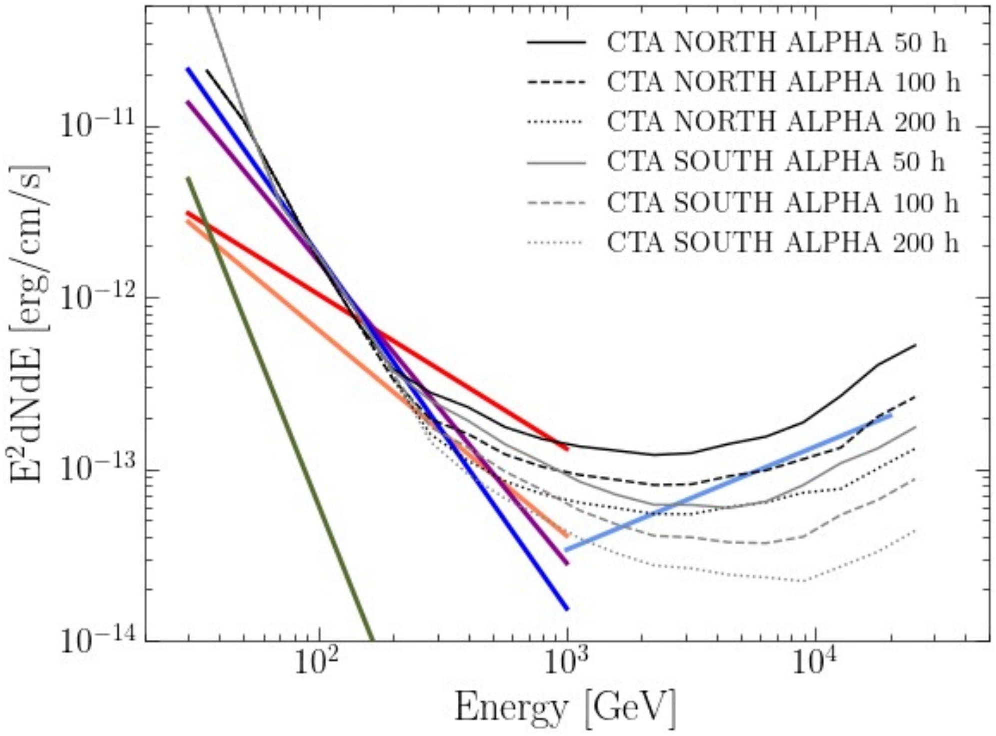
Open Questions and ongoing activities



- Continuing Pulsar observations with IACTs,
  Goal: probe the >20 TeV spectrum

  => Techniques to improve Effective Area > 10 TeV

- Search on the database: 20 years of data available

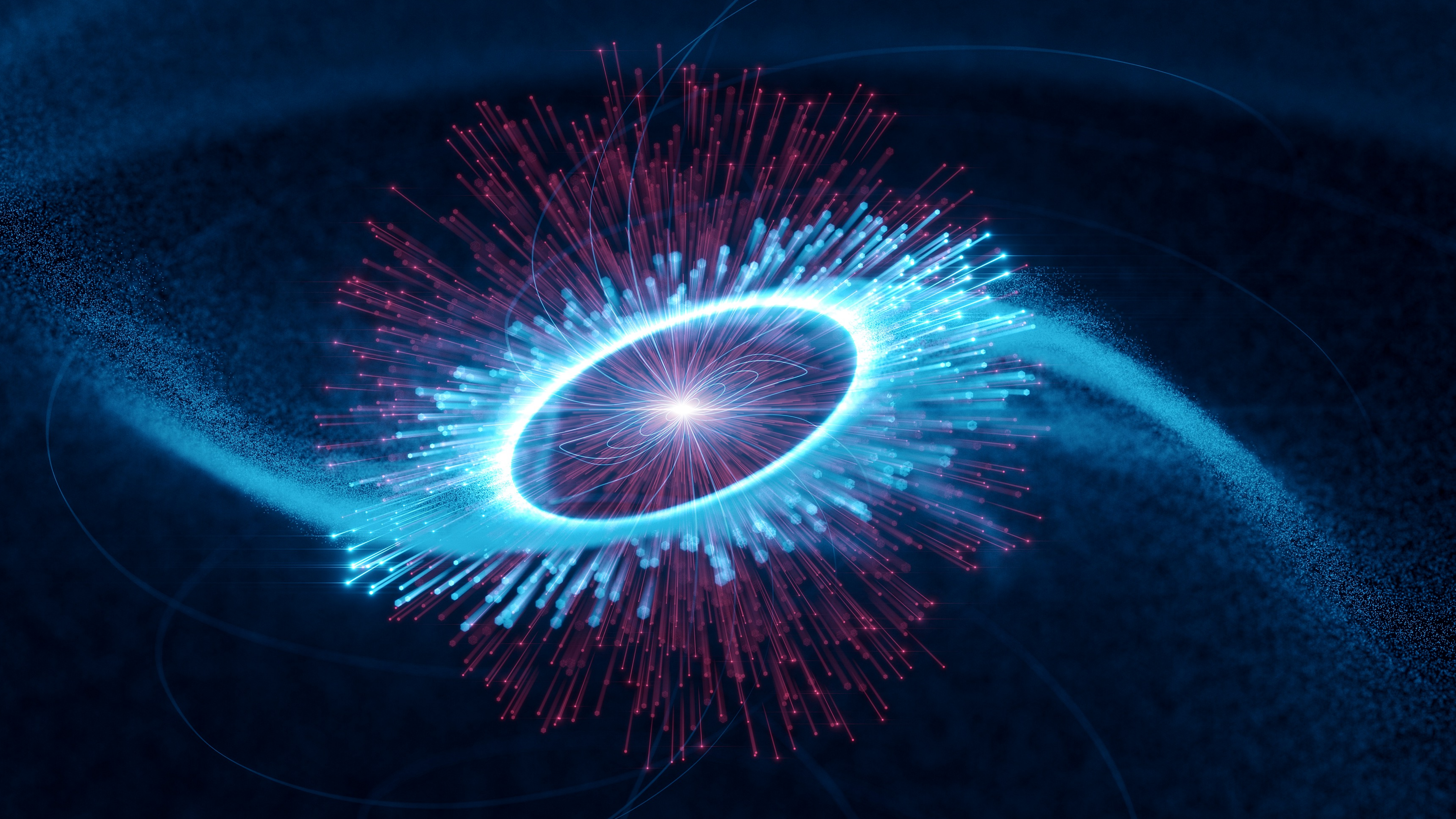
- Probing other promising pulsars for VHE emission using the first CTA prototypes

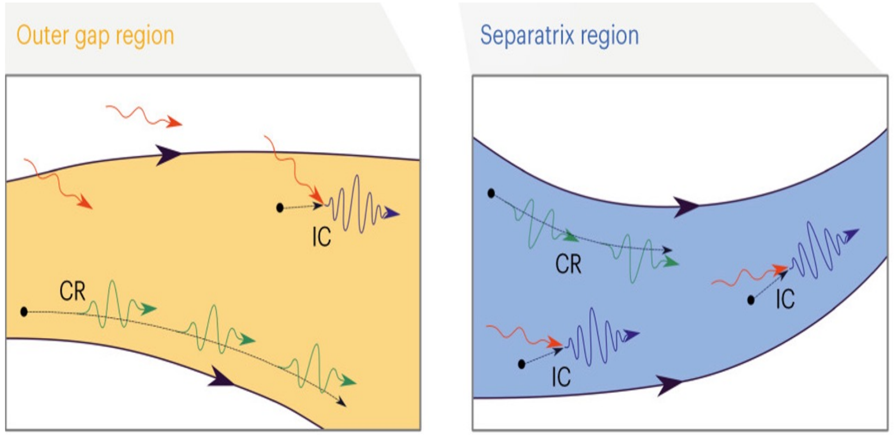
Major science case for CTA

Summary

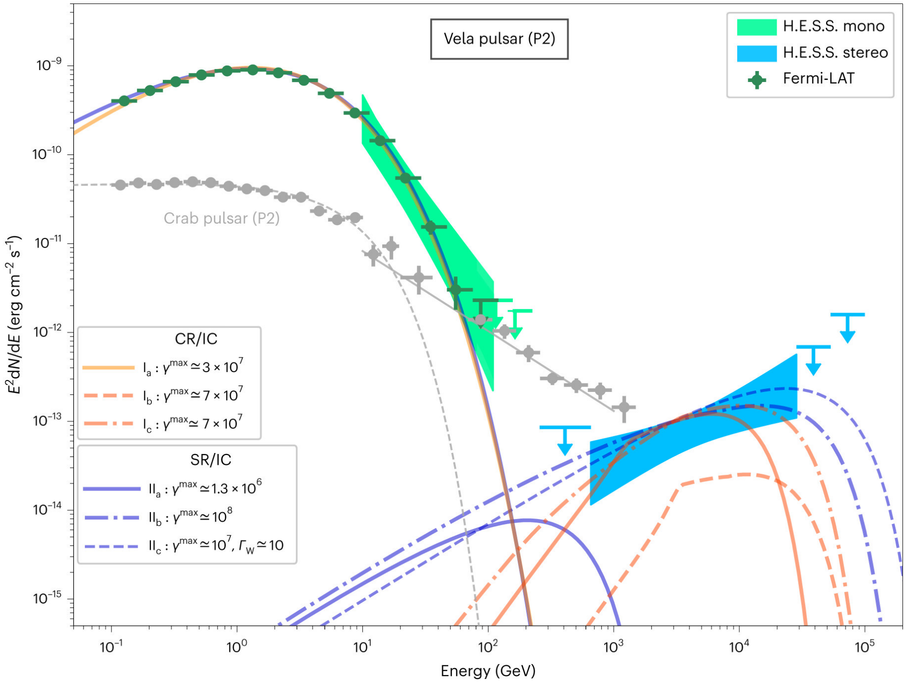
Opening the pulsed TeV emission

- **Four pulsars have been detected with IACTs**
- **Despite the long observation times used for the first ones, the new discoveries are reachable in moderated time (Tobs < 100 h)**
- **These detections open more questions and boost the field of pulsars**
    - An unambiguous handle on Lorentz factors > 4×10^7
    - VHE emission, i.e. dissipation region beyond but close to LC (even in the Doppler-boosted scenario)
    - Challenges for both CR/IC and SR/IC scenarios => to be continued!





$E_{\rm HE}^{\rm peak} \sim 1.5$ GeV



Target: OP-NIR Target: OP-FIR

- **To reach the TeV level, we need to extrapolate the photon field o the FIR:**