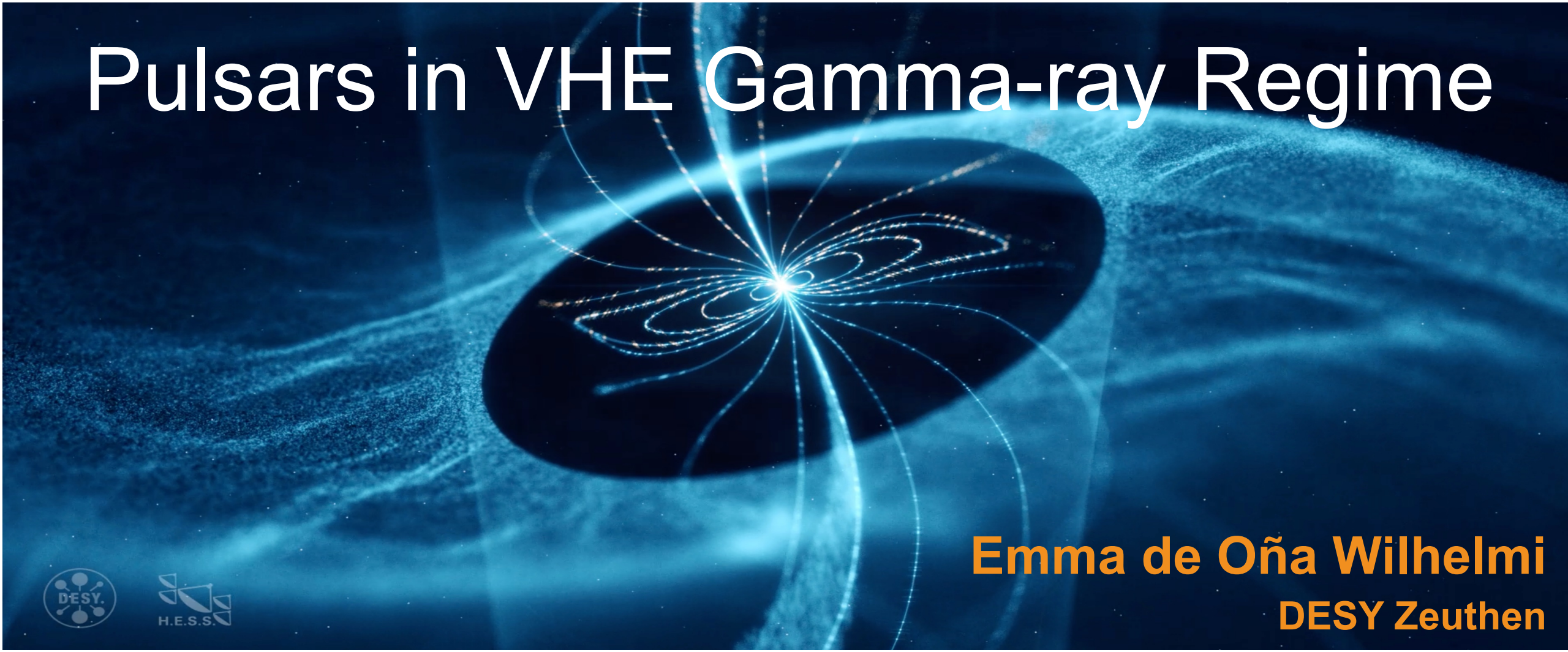
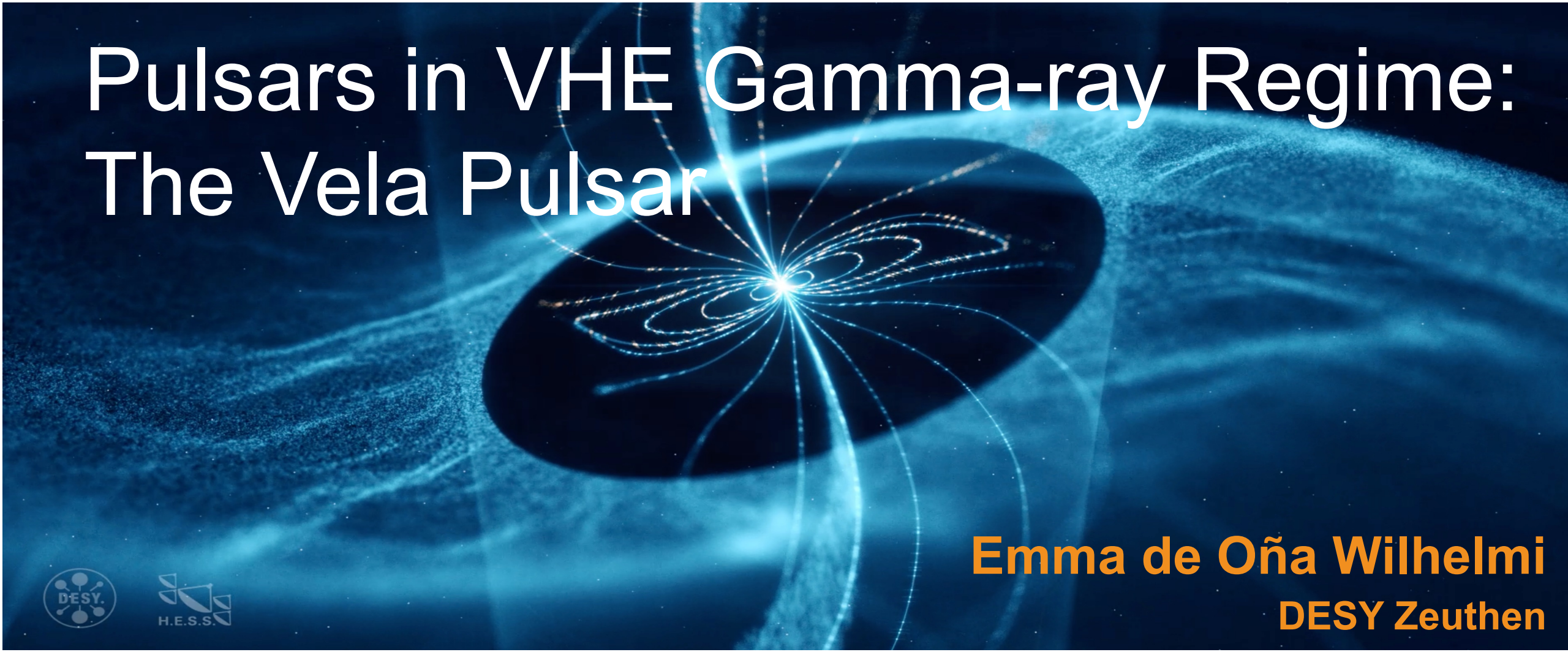
Pulsars in VHE Gamma-ray Regime



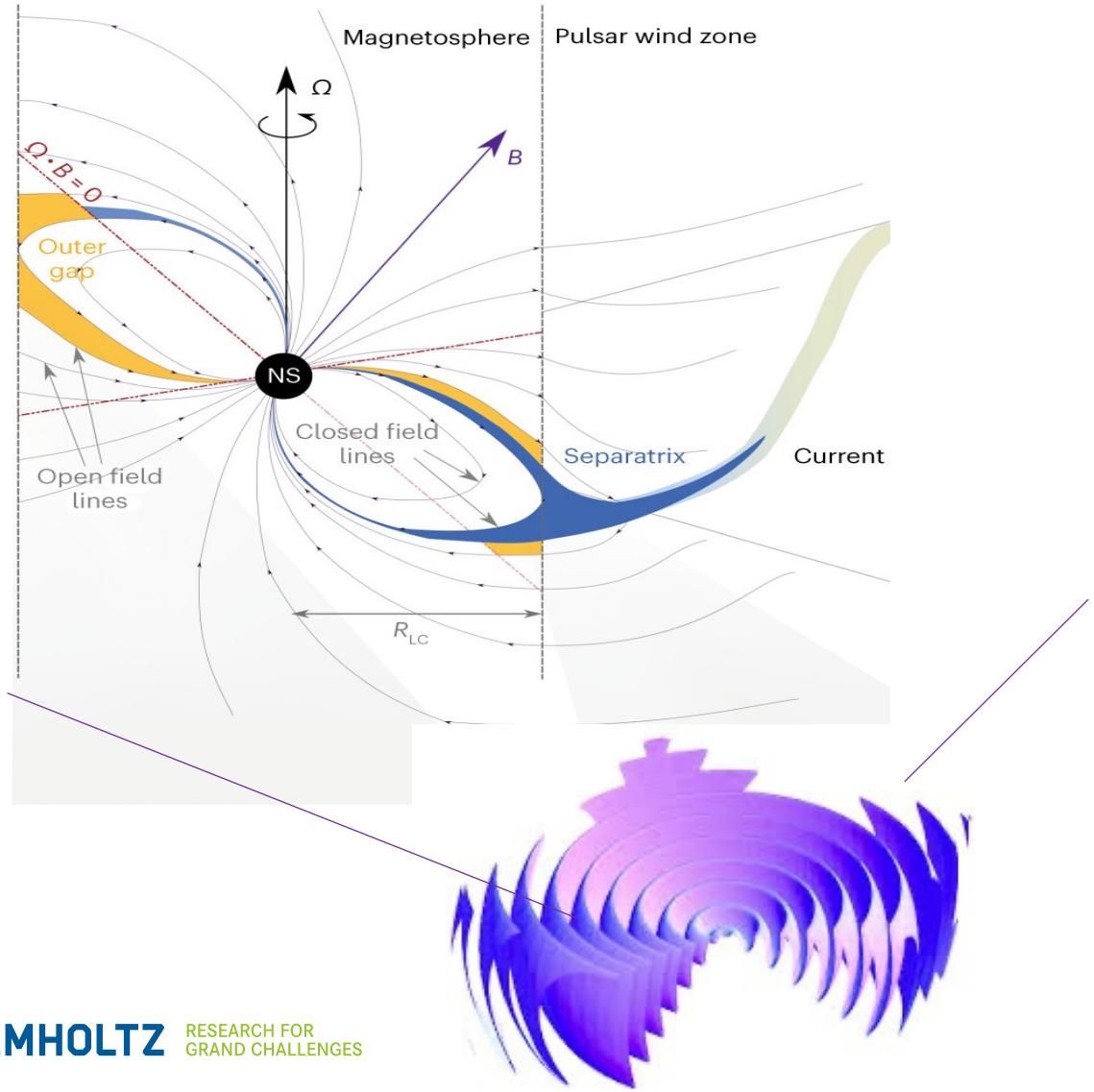
Emma de Oña Wilhelmi
DESY Zeuthen

Pulsars in VHE Gamma-ray Regime: The Vela Pulsar



Emma de Oña Wilhelmi
DESY Zeuthen

Pulsars as extreme accelerators and non-thermal sources



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

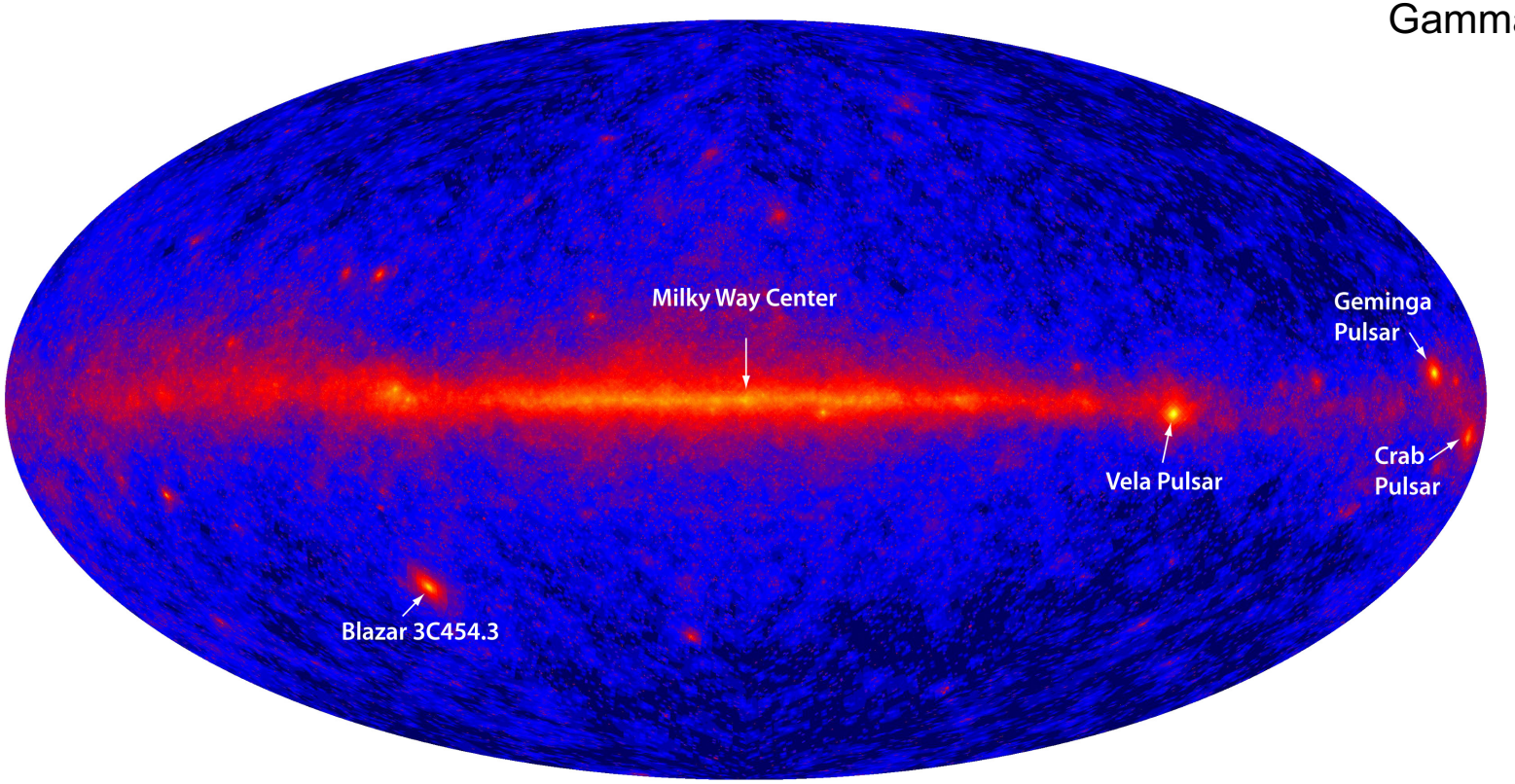
Fill the magnetosphere with dense plasma ρ_{GJ}
=> Enough e± pairs to achieve force-free condition

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

Image credit: the International Fermi LAT Collaboration.

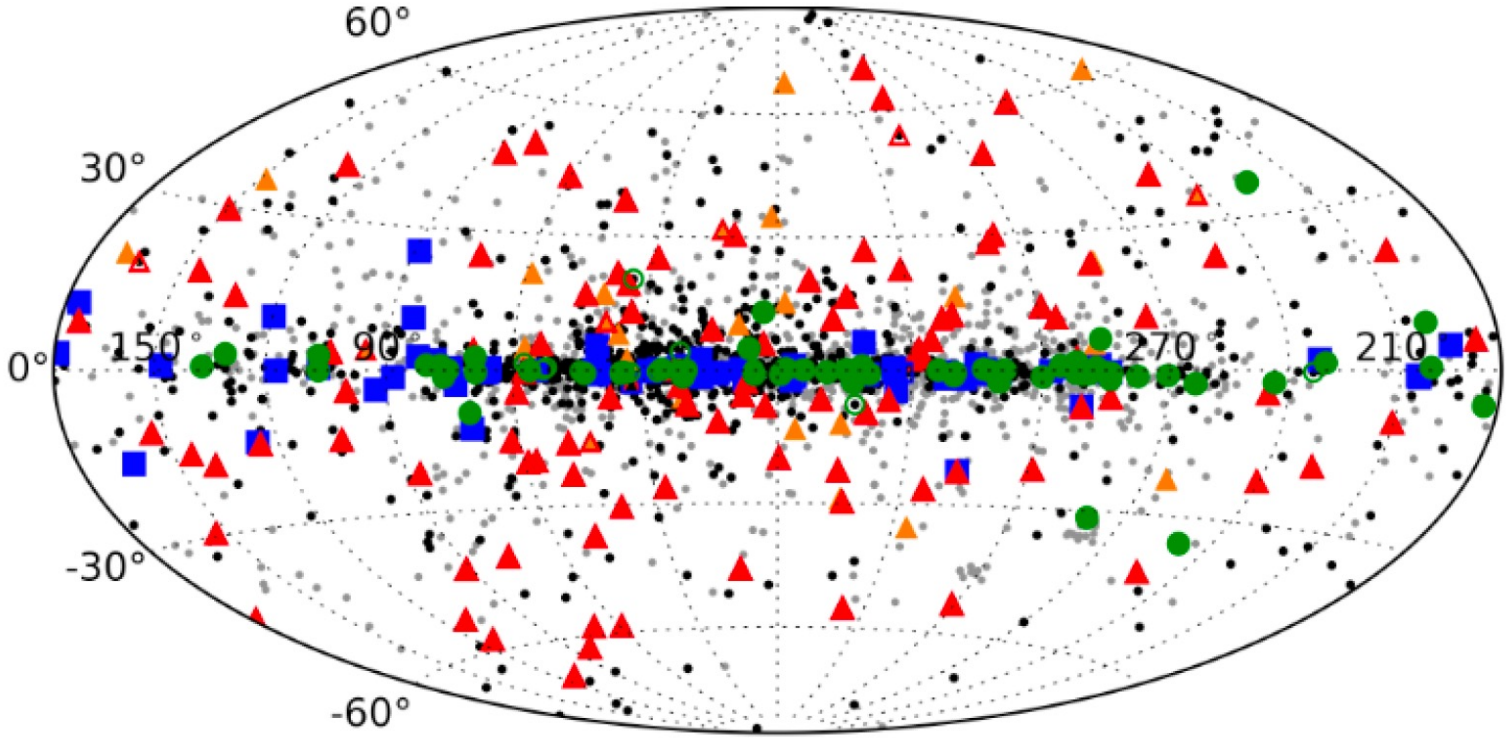
Gamma-ray sky at 1 GeV



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

Image credit: the International Fermi LAT Collaboration.

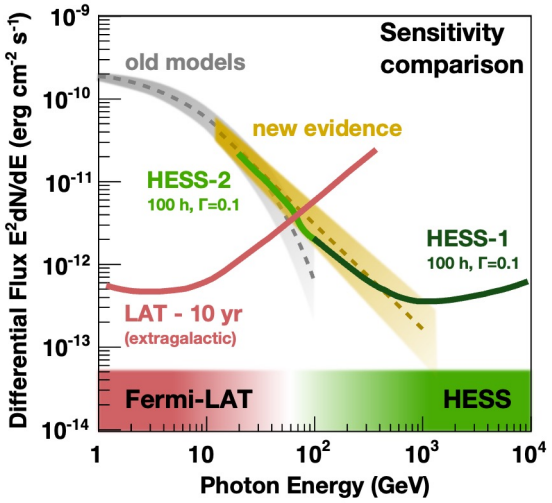
Gamma-ray sky at 1 GeV

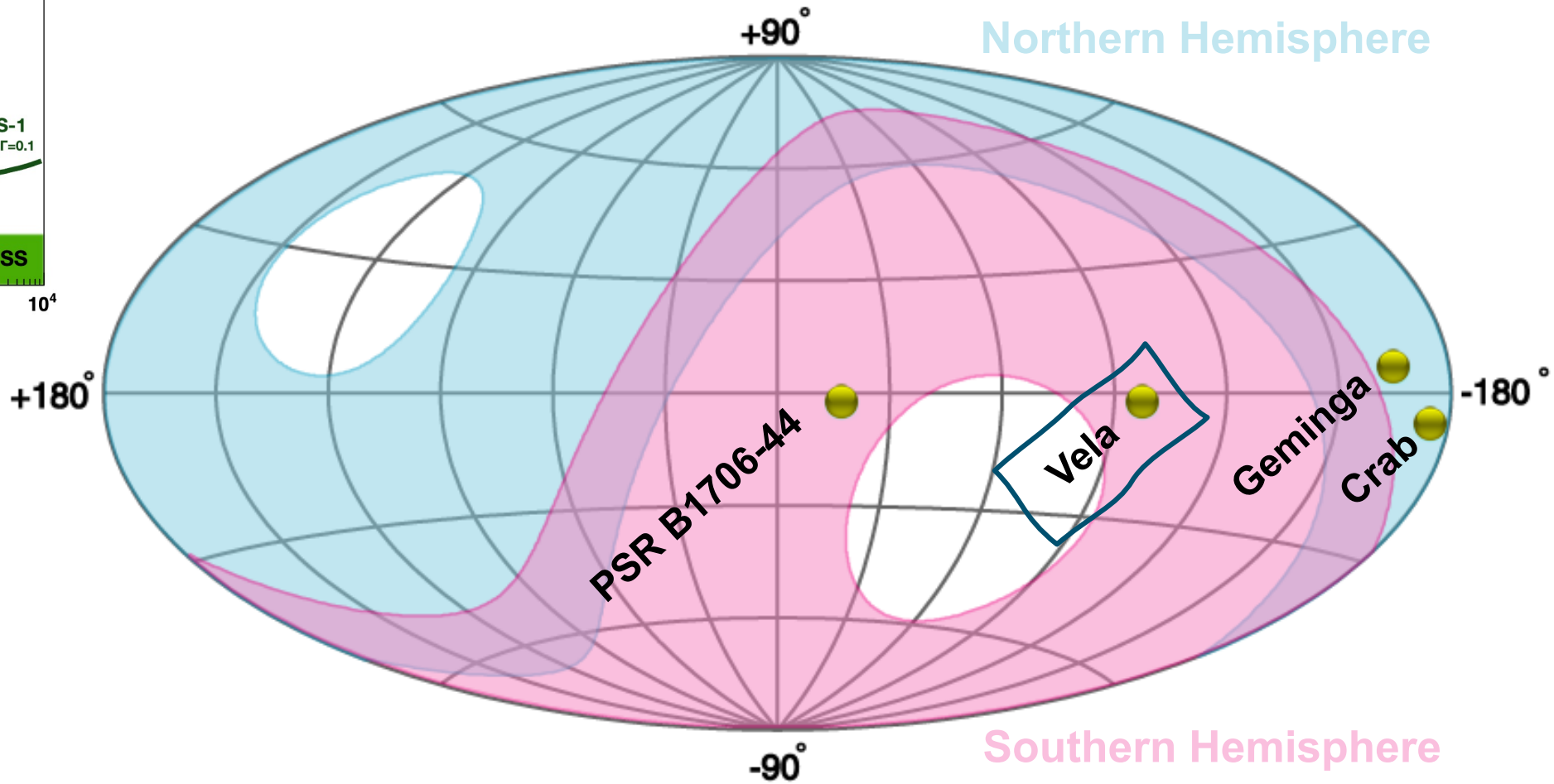


Pulsars are brightest Galactic sources at 1 GeV and the most numerous Galactic source population

VHE gamma-ray pulsars

https://www.tevcat.org/



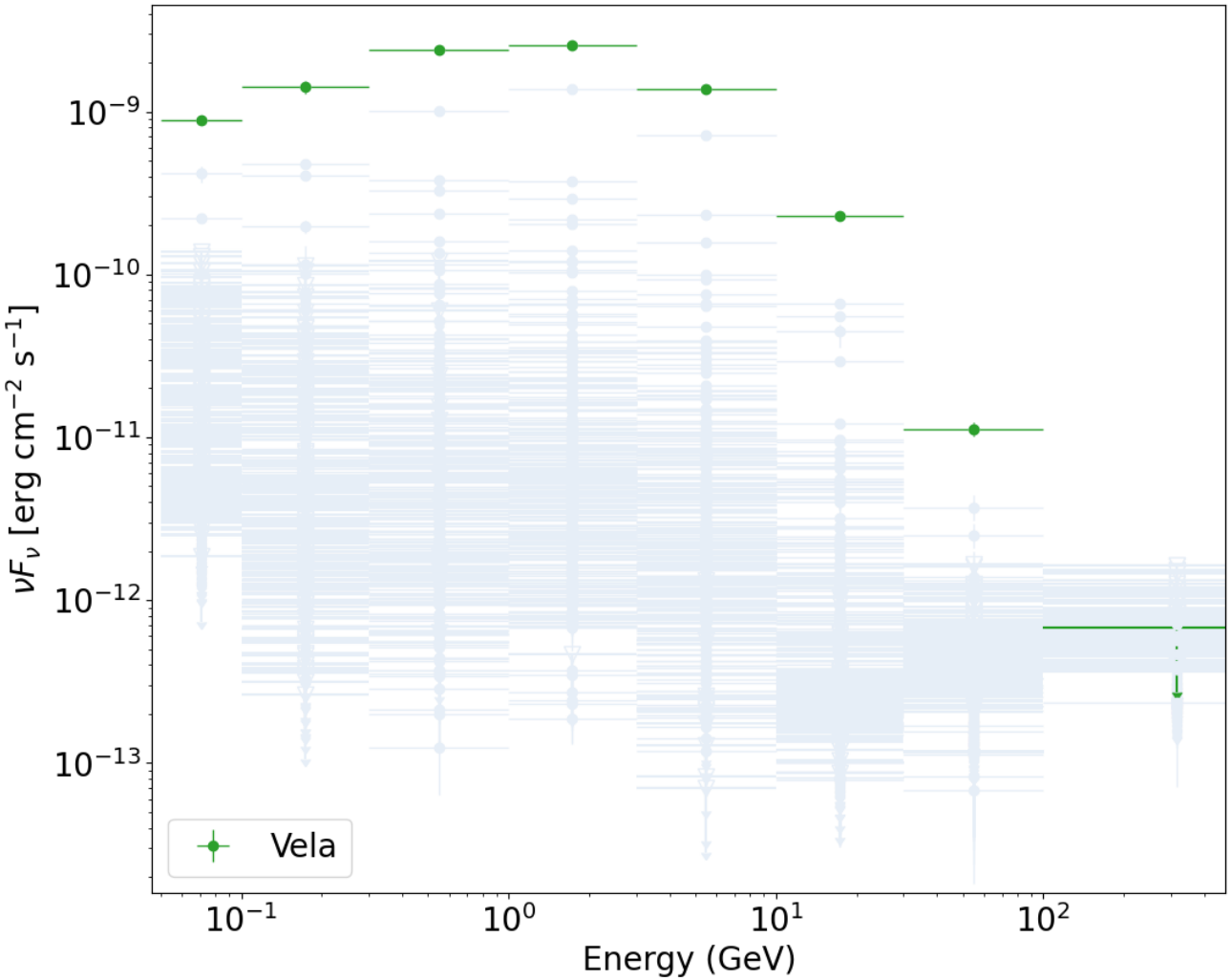


The Vela pulsar

Vela in the sub-100 GeV regime

Nearby d=287 pc
Young pulsar 11 kyr and period of 89 ms
$\dot{E} \sim 10^{37}$ erg/s

Spectra of LAT Pulsars in the 3PC



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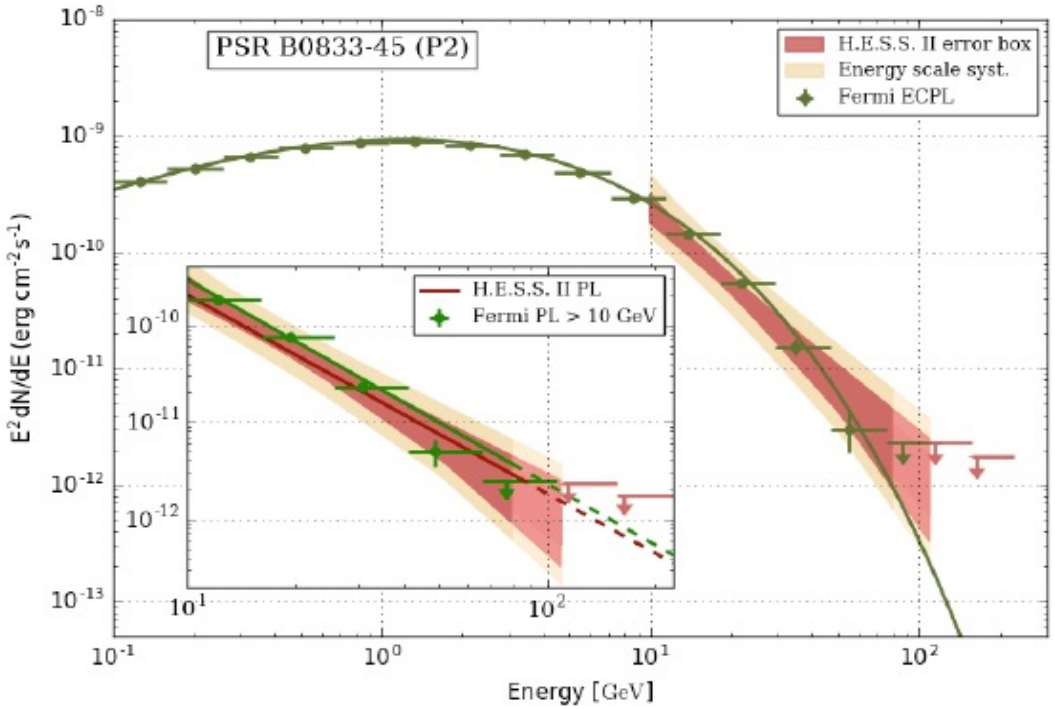
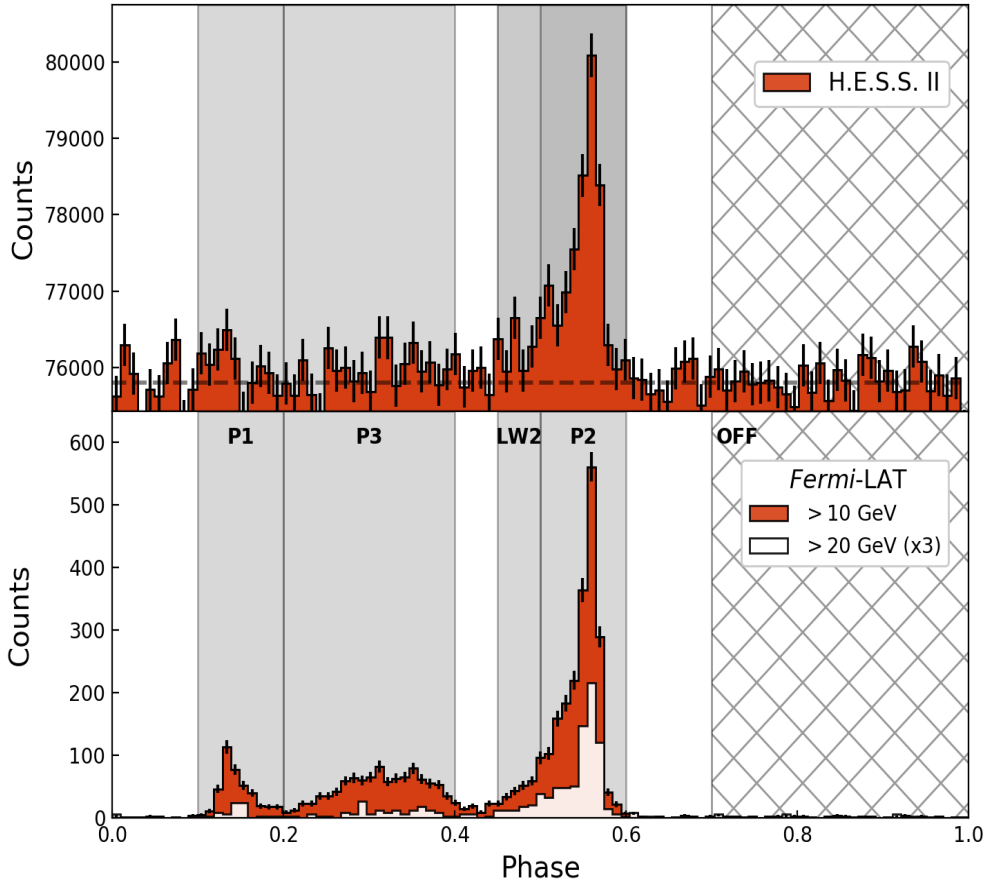


Vela Pulsar, HESS Collaboration 2018

Peak evolves with energy



Vela Pulsar, HESS Collaboration 2018

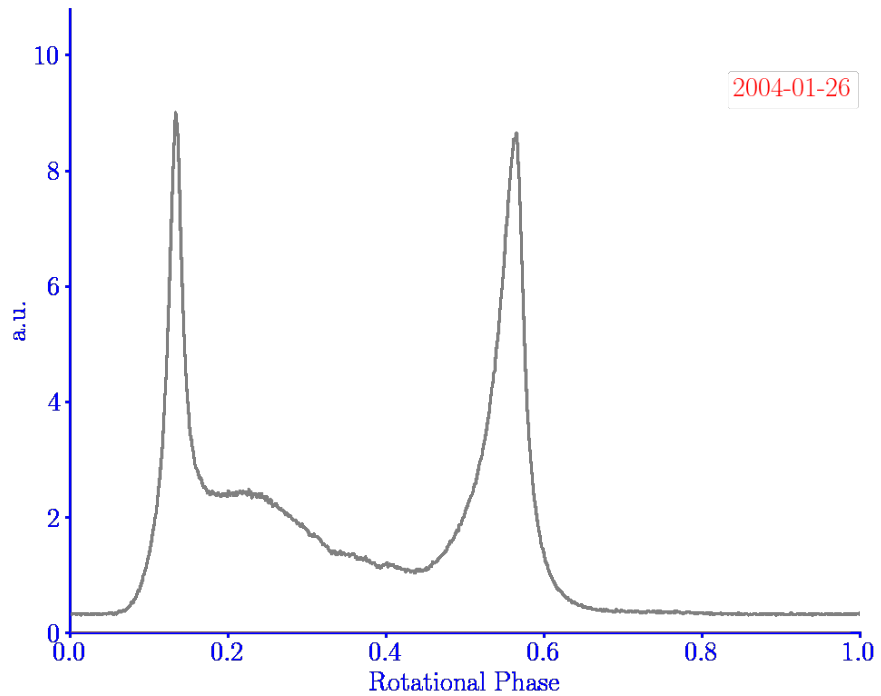
Detected in 40.3 h with HESS CT5

Light curve with 3 peaks, with P2 becoming prominent at high energies:

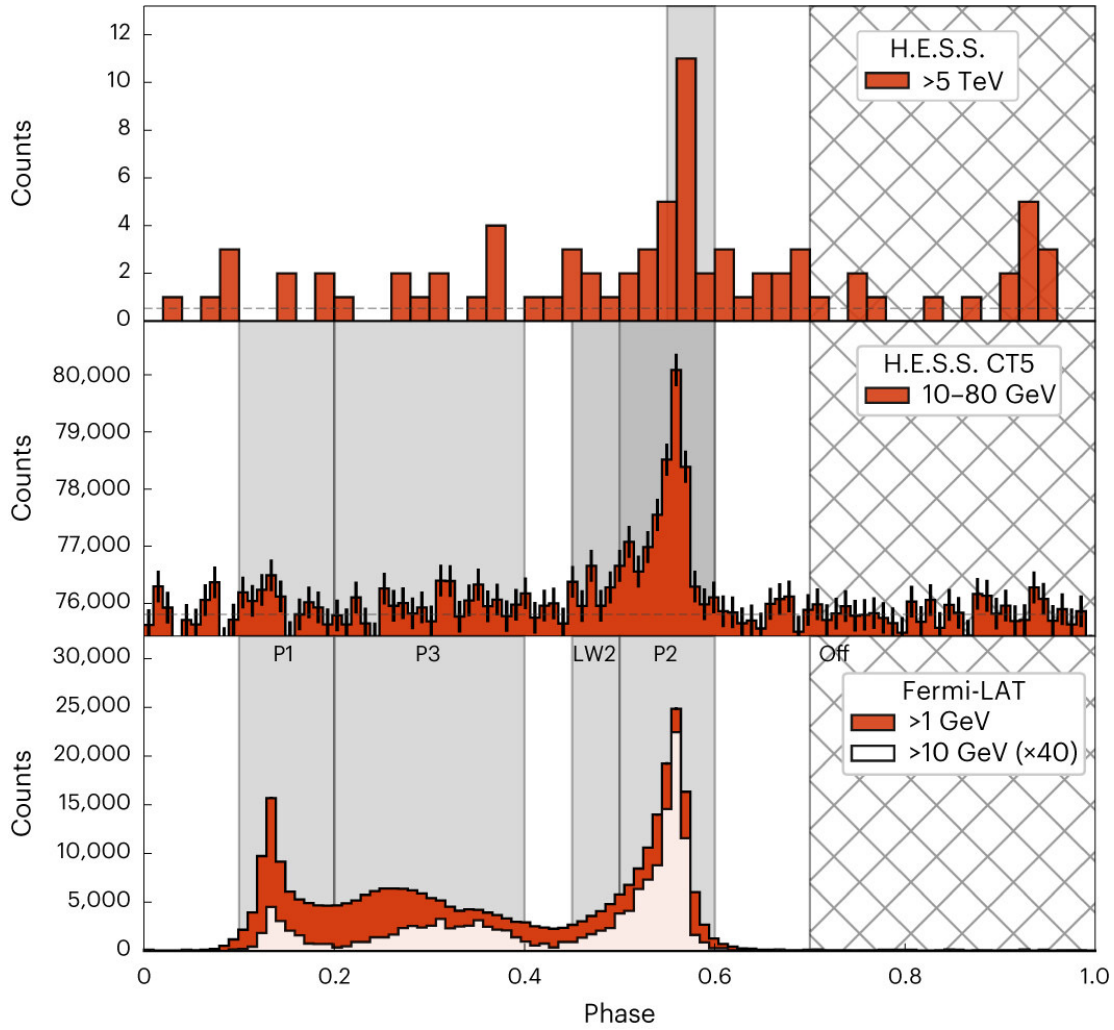
The Vela Pulsar in the TeV regime

Detection of Vela above 1 TeV

- **Data from 2004-2016 observations (80 h)**
- Phase-folding : ephemeris from LAT+ Parkes



HESS Collaboration et al 2023



The Vela Pulsar in the TeV regime

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HESS Collaboration et al 2023

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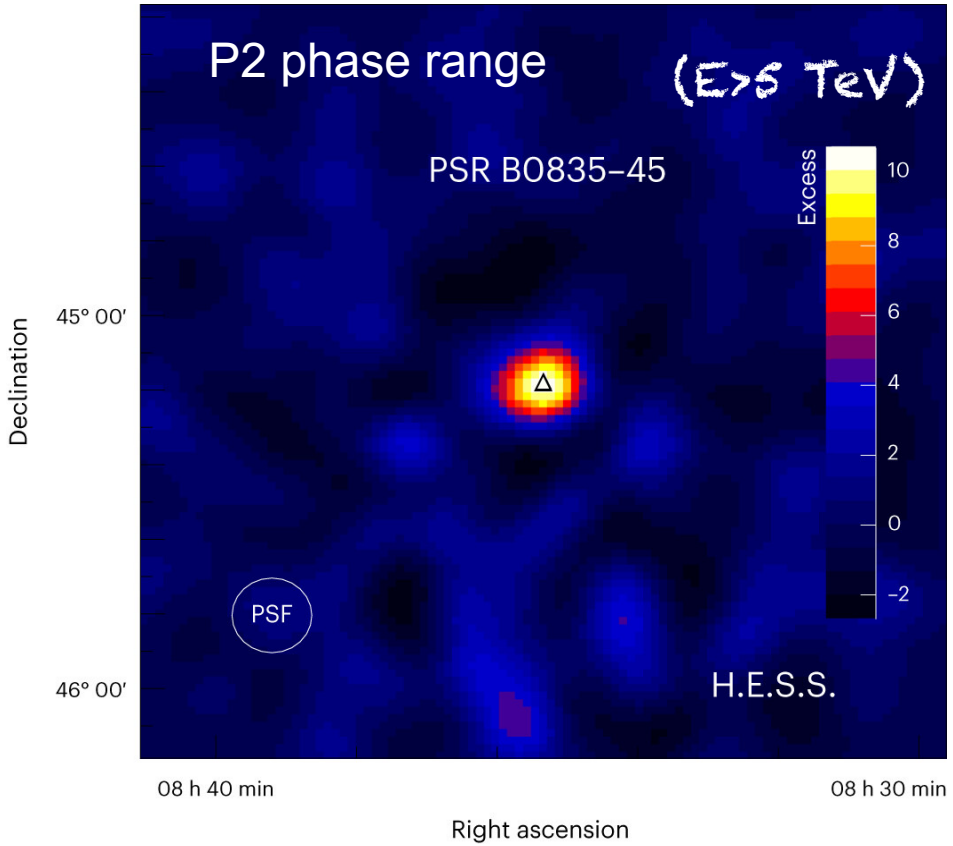
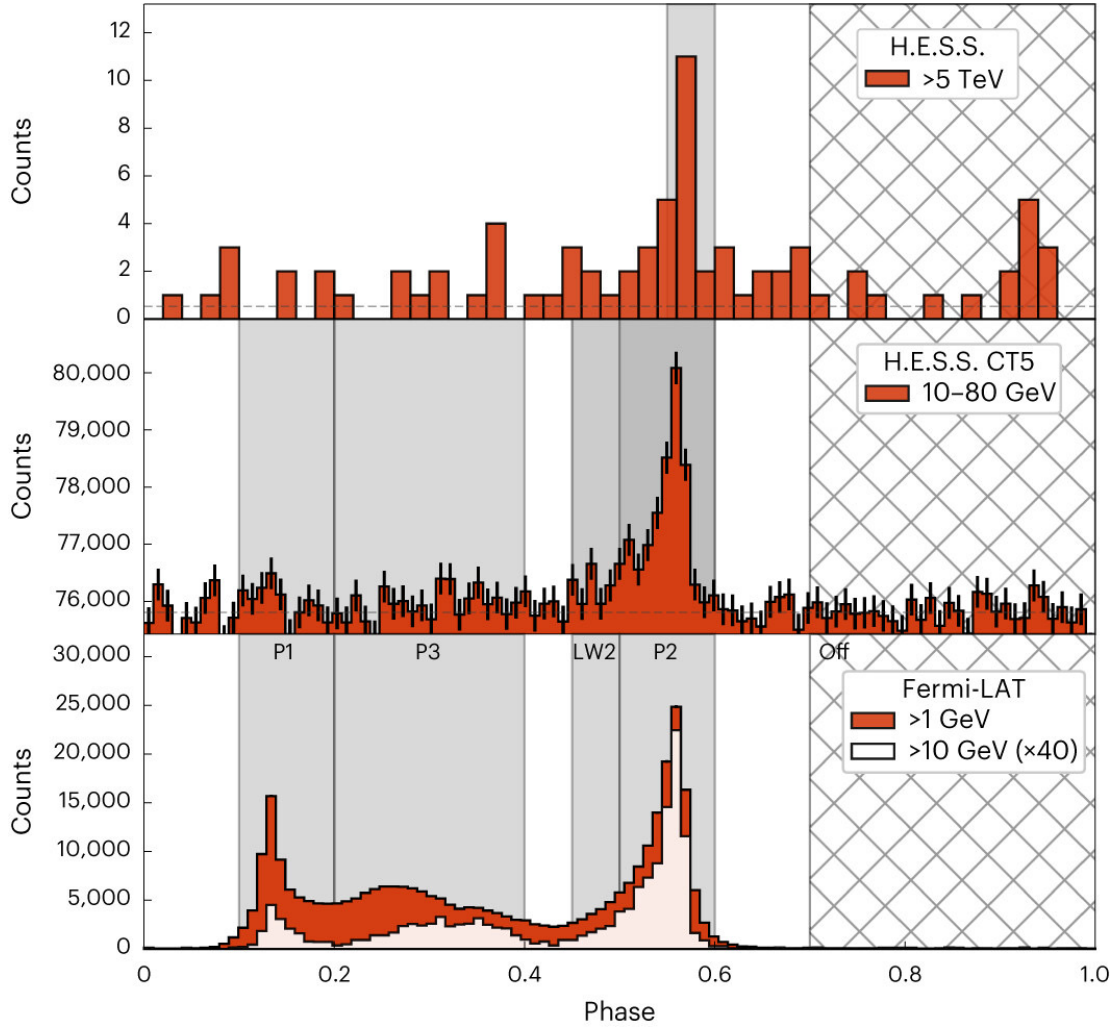
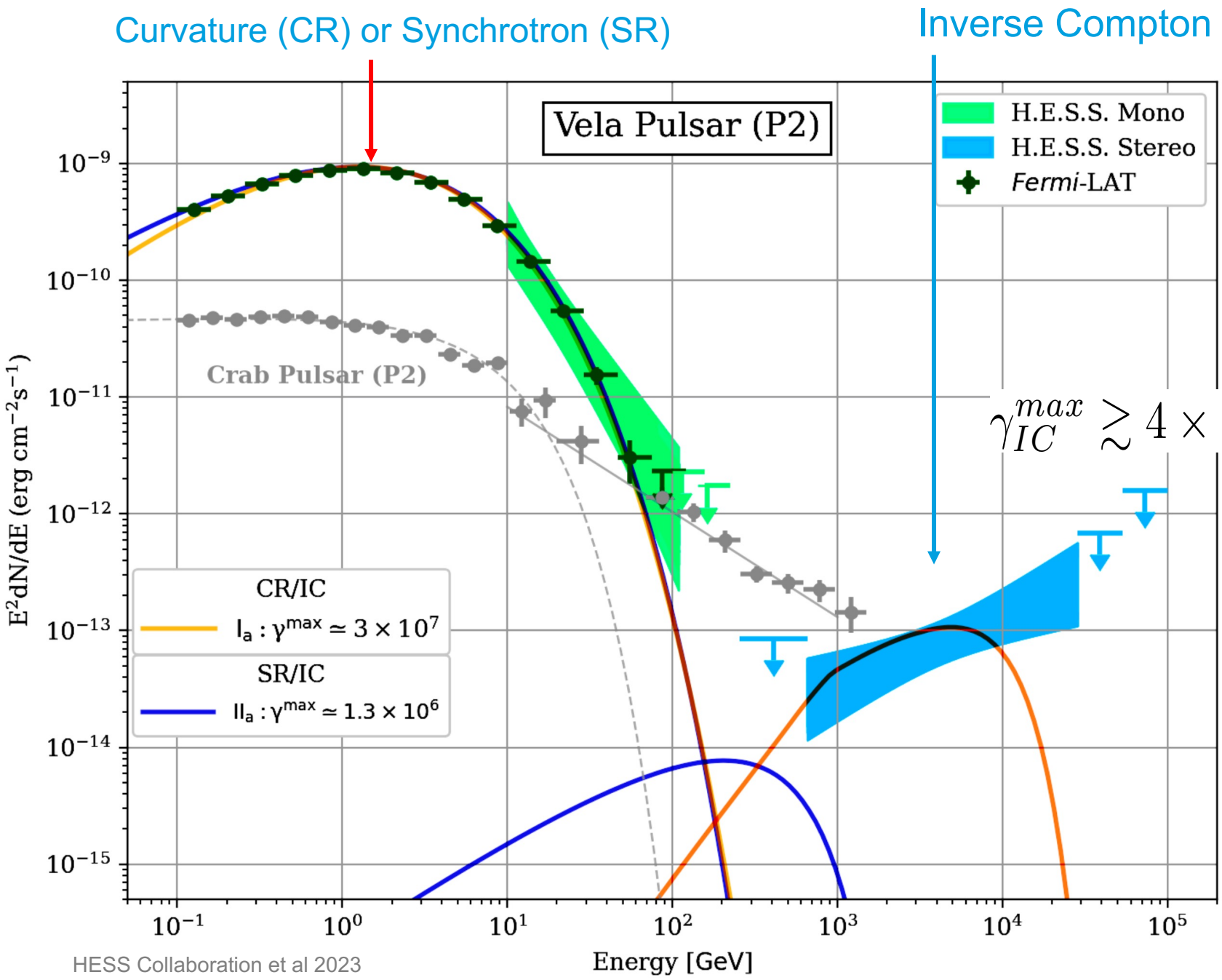




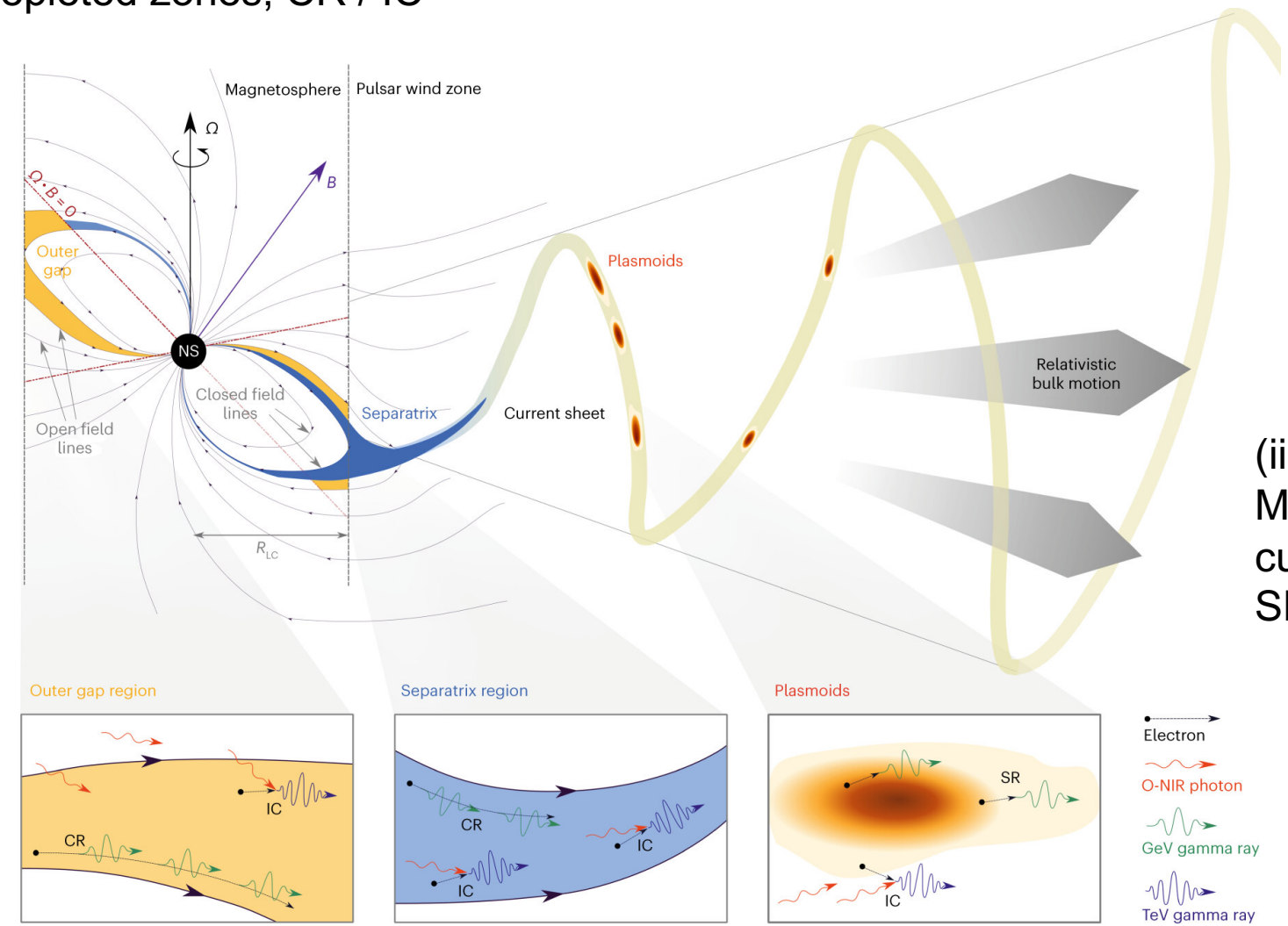


$$\gamma_{IC}^{max} \gtrsim 4 \times 10^7 (E_{\rm TeV}/20\ {\rm TeV})$$

HESS Collaboration et al 2023

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

HESS Collaboration et al 2023



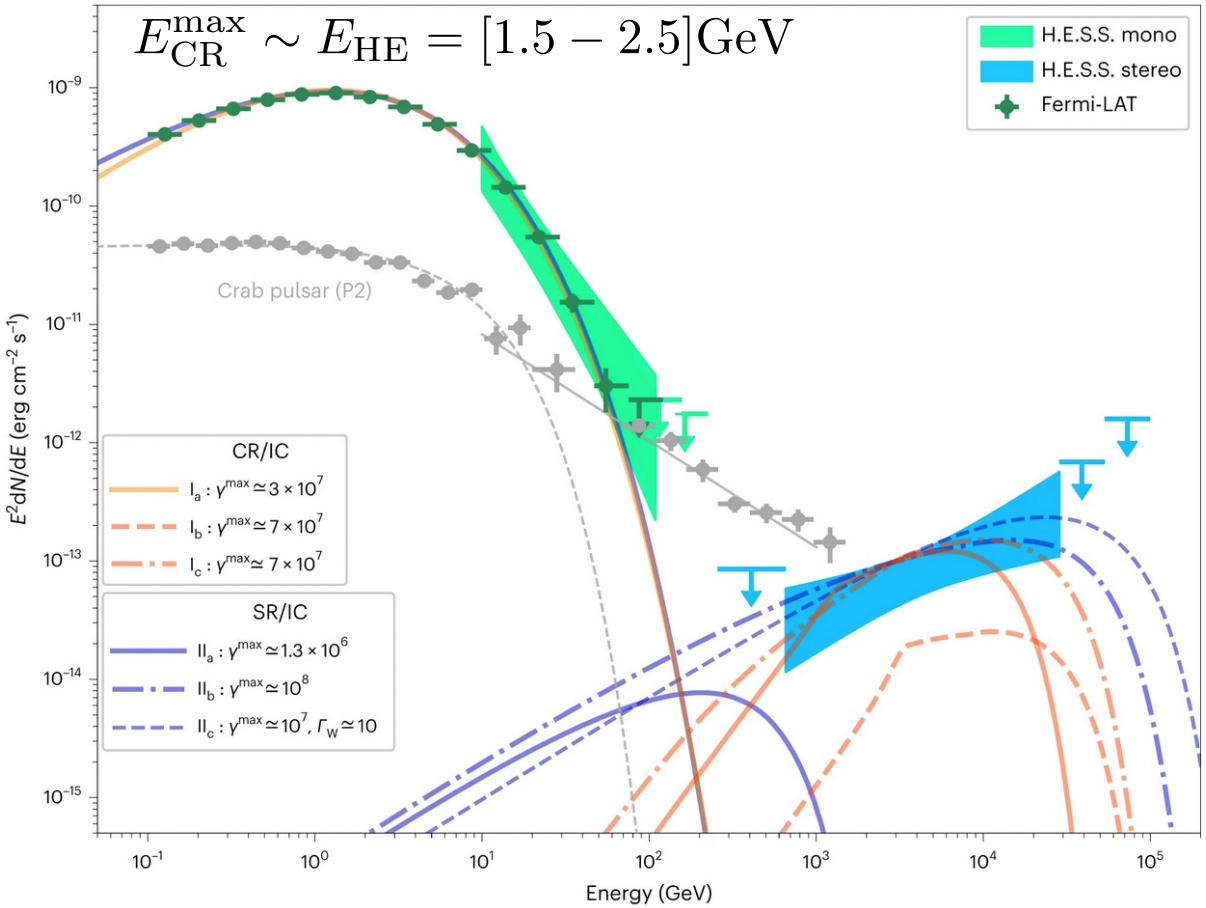
HESS Collaboration et al 2023

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

Using Vela+ to constrain theory

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

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



We fit HE and VHE to constrain emission region*

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

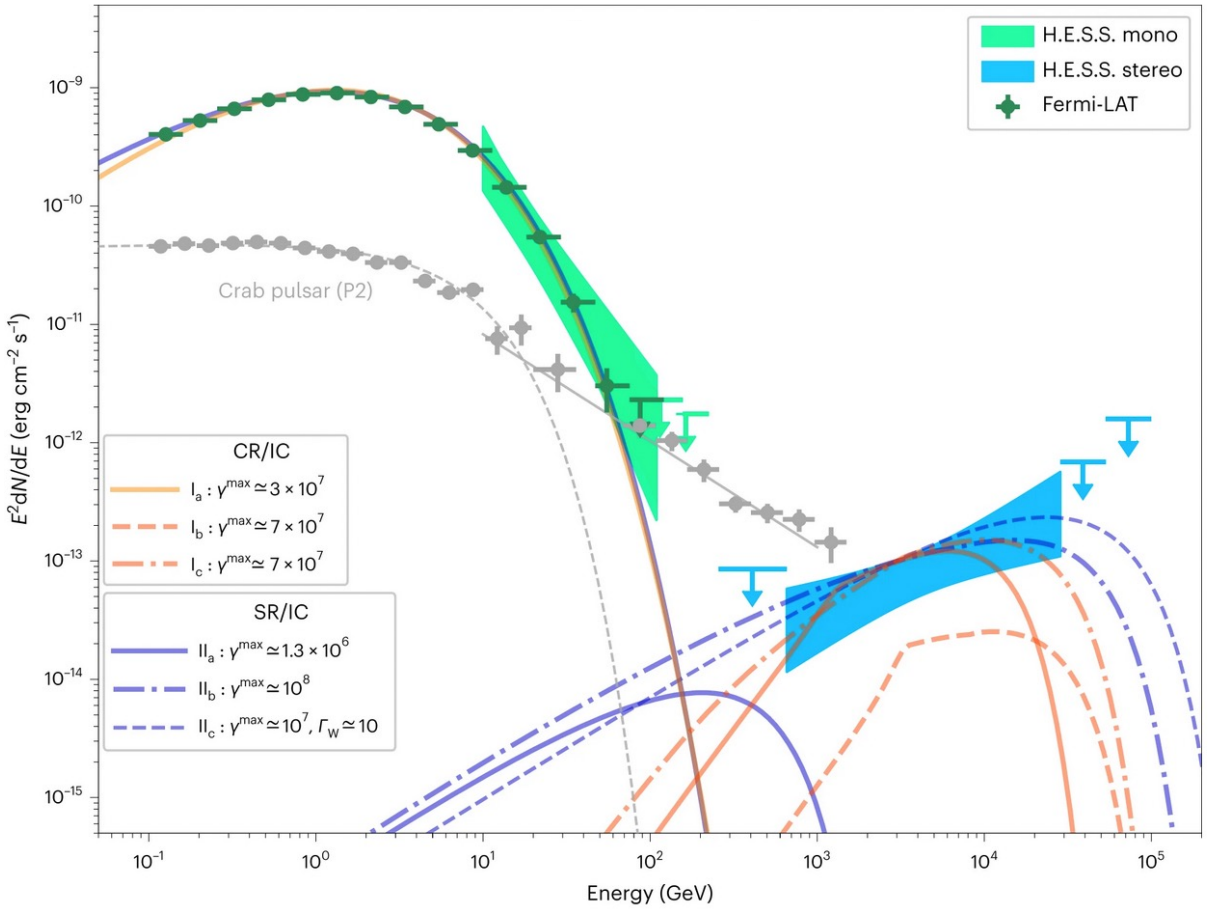
Curvature radius

Magnetic conversion efficiency

HESS Collaboration et al 2023

Using Vela+ to constrain theory

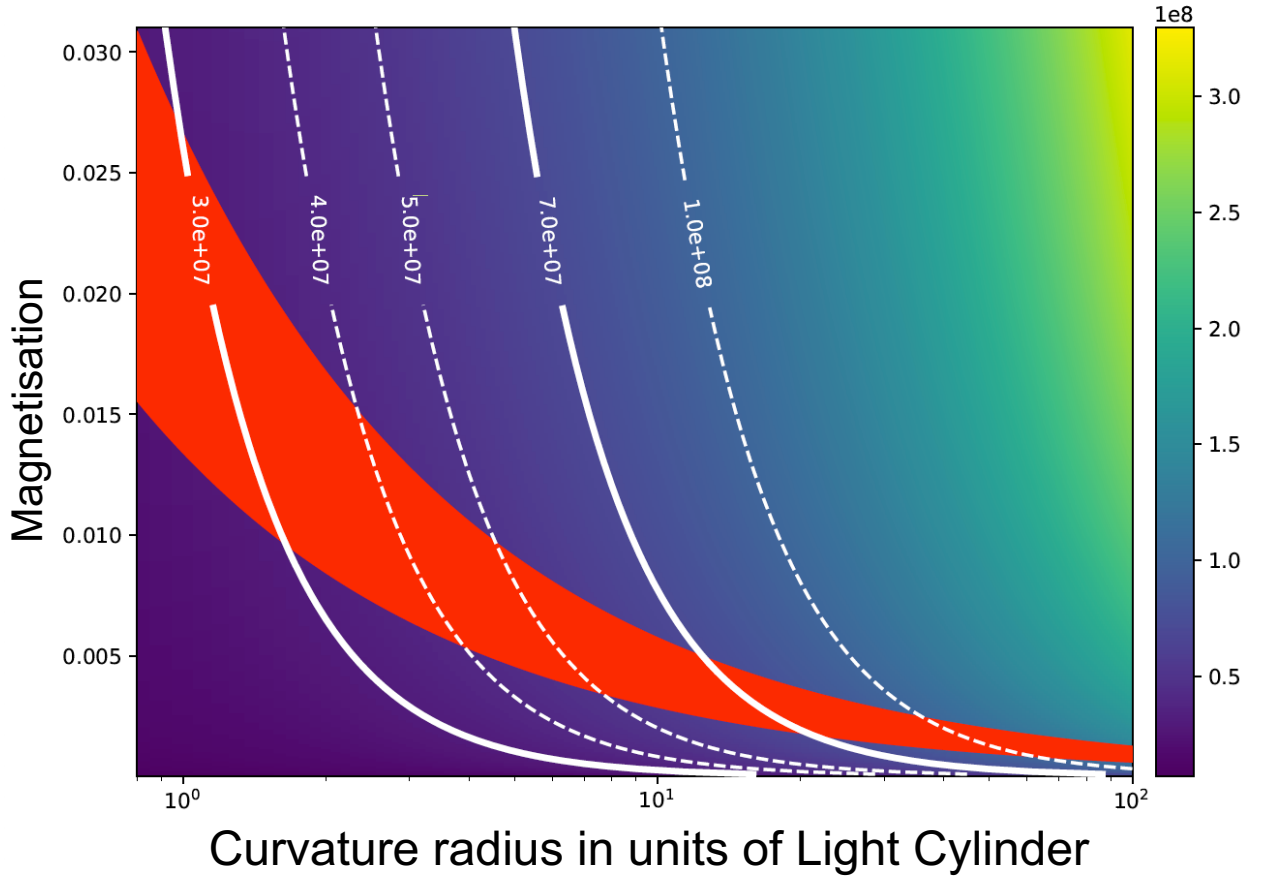
Curvature in gaps (outer gaps or separatrix/current sheets).



HESS Collaboration et al 2023

HESS data:

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



Using Vela+ to constrain theory

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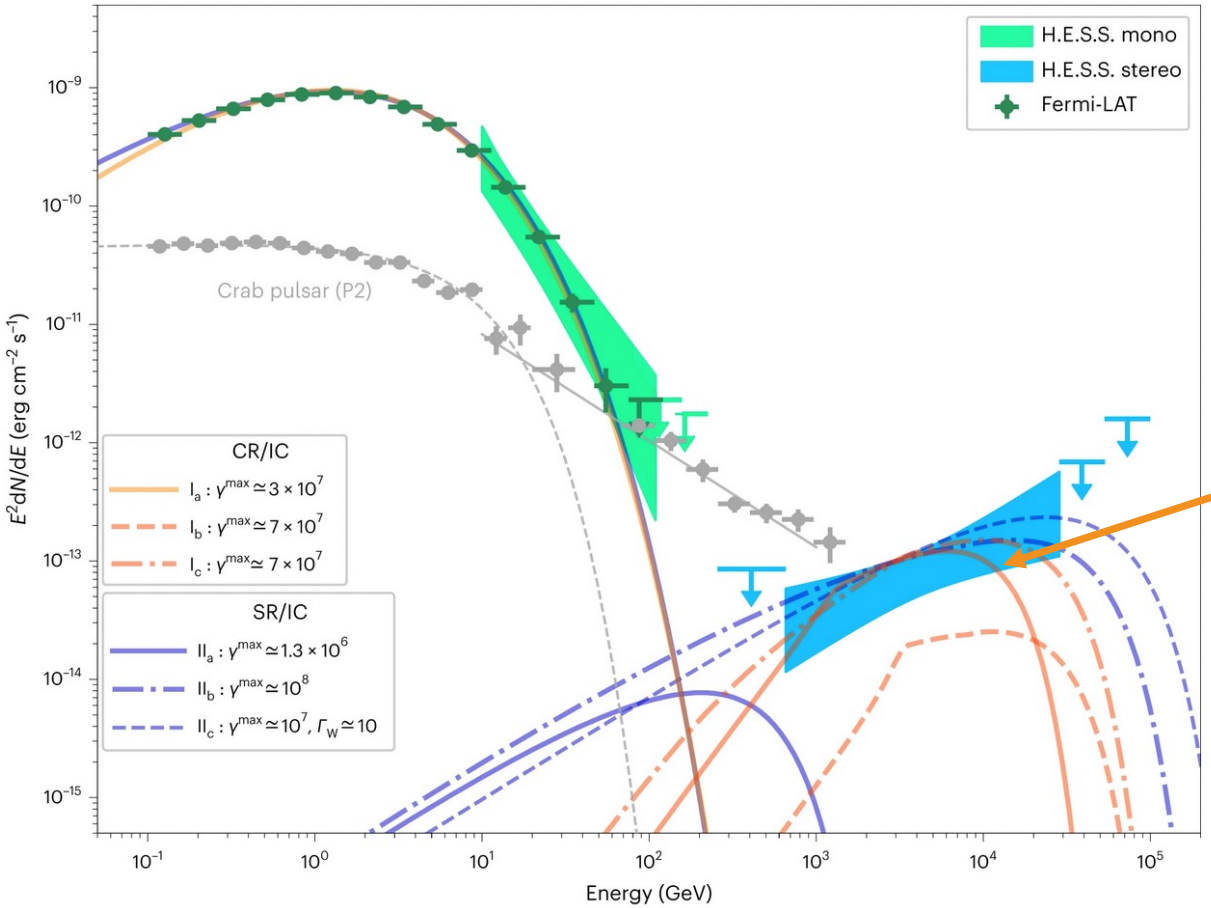

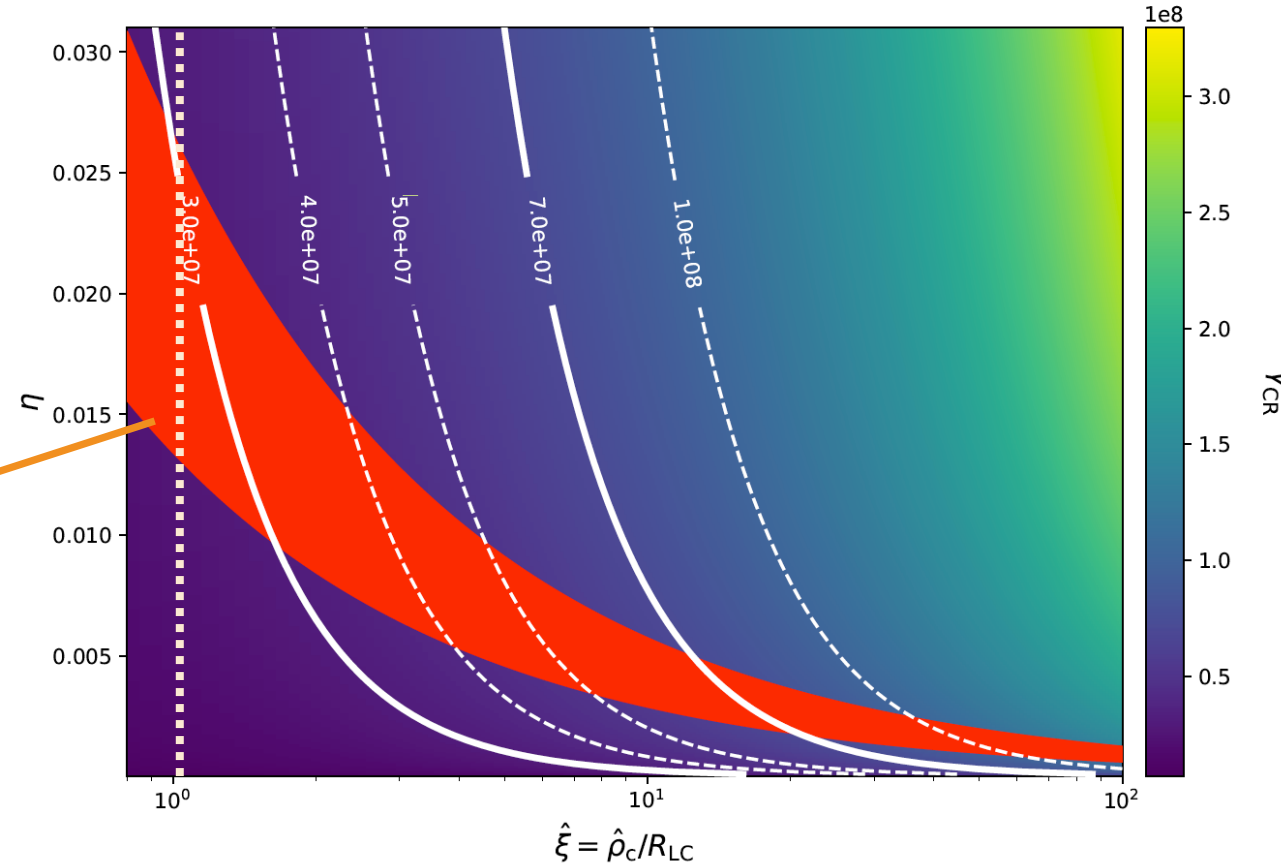

HESS Collaboration et al 2023

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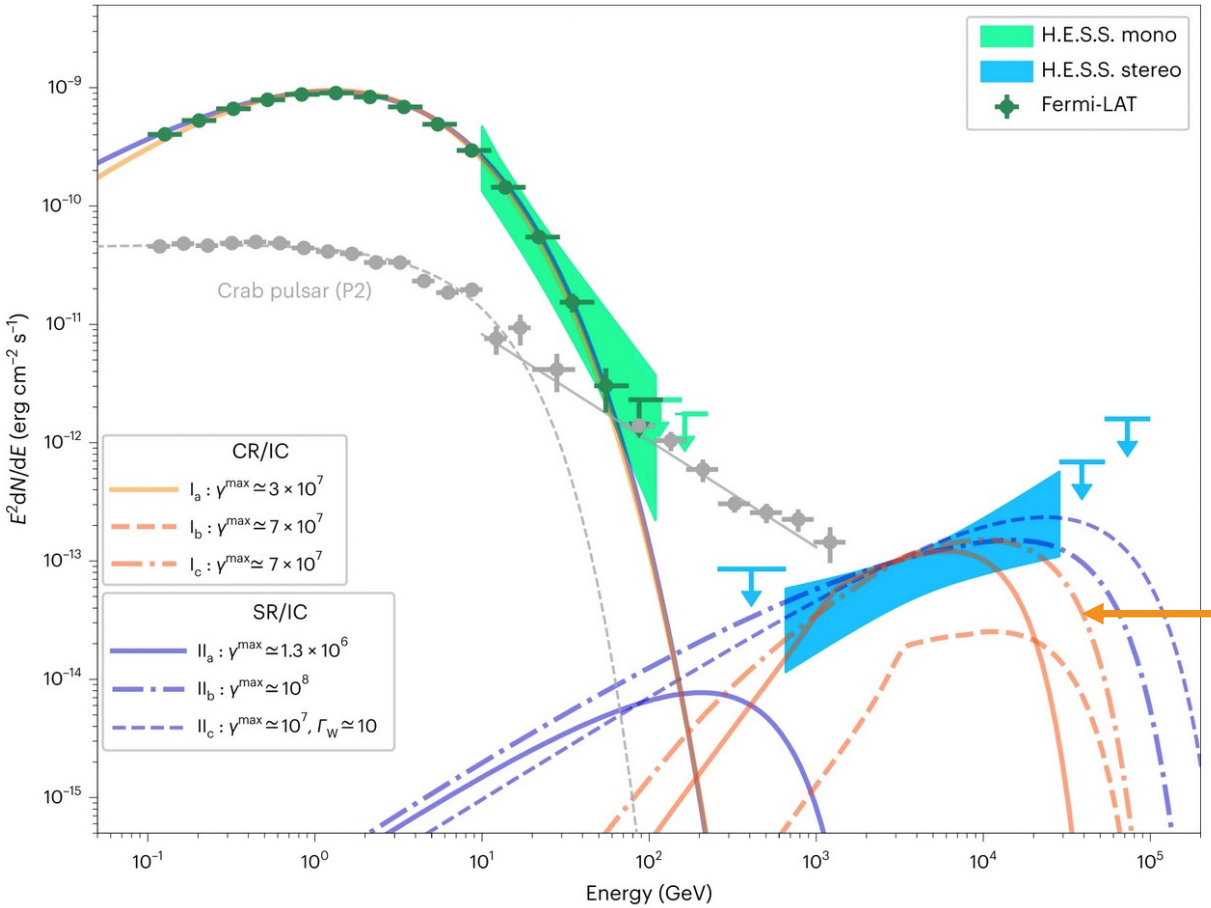

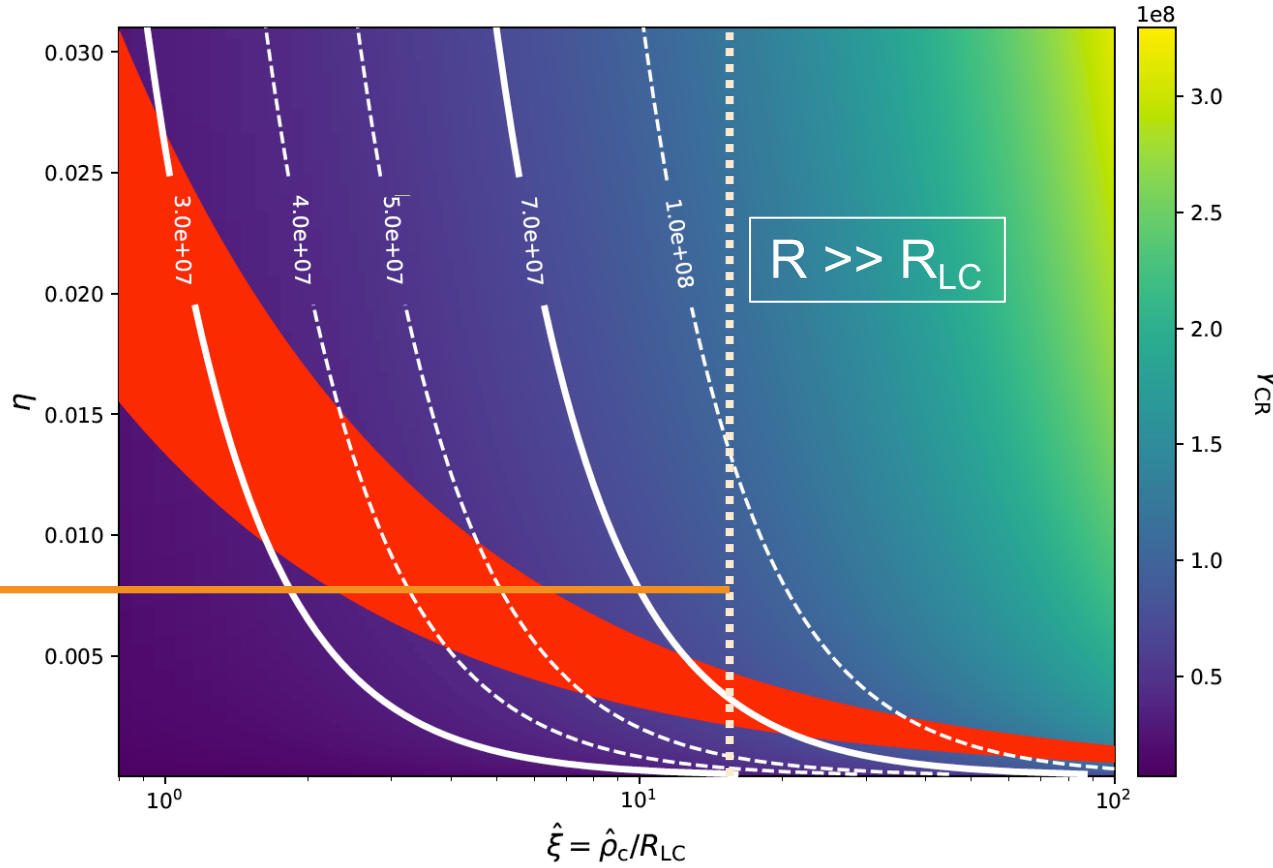

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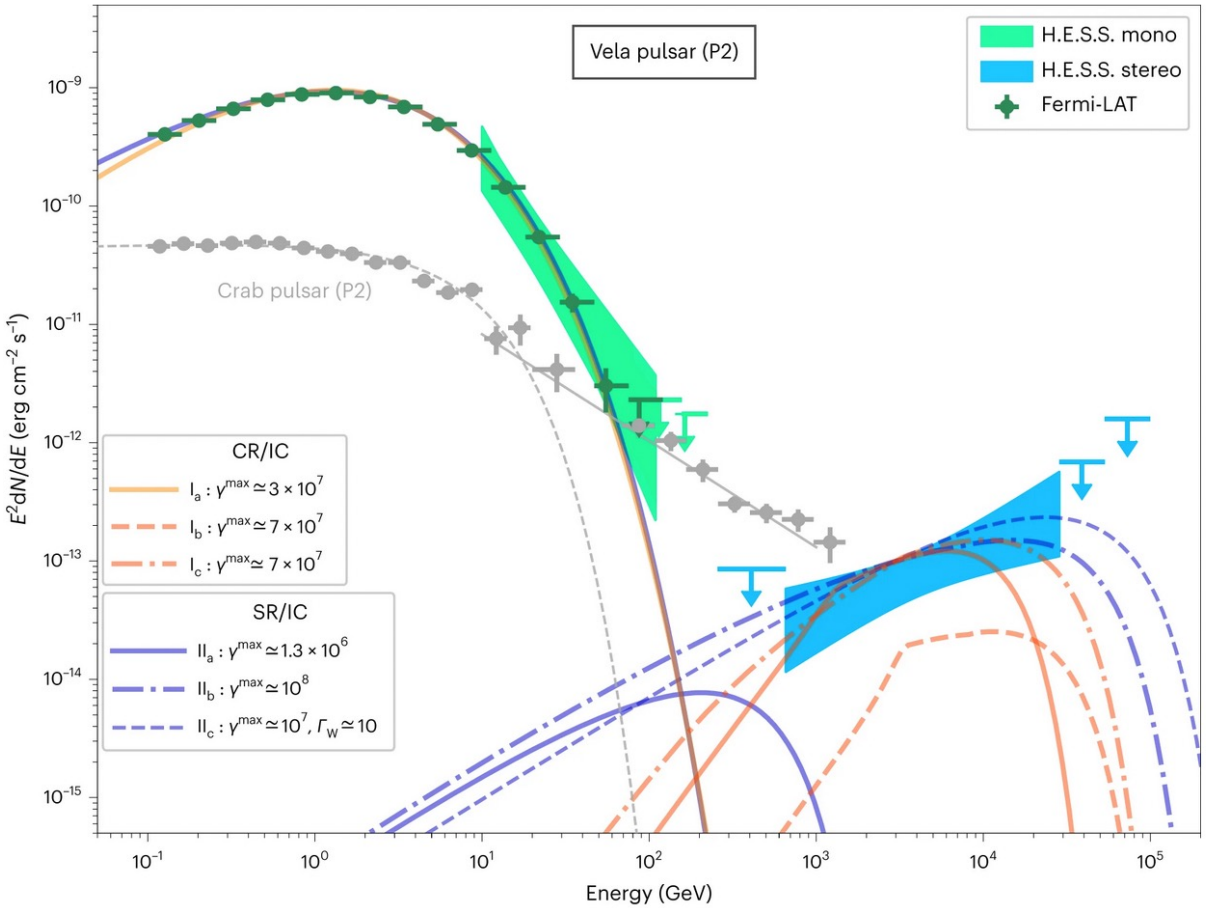
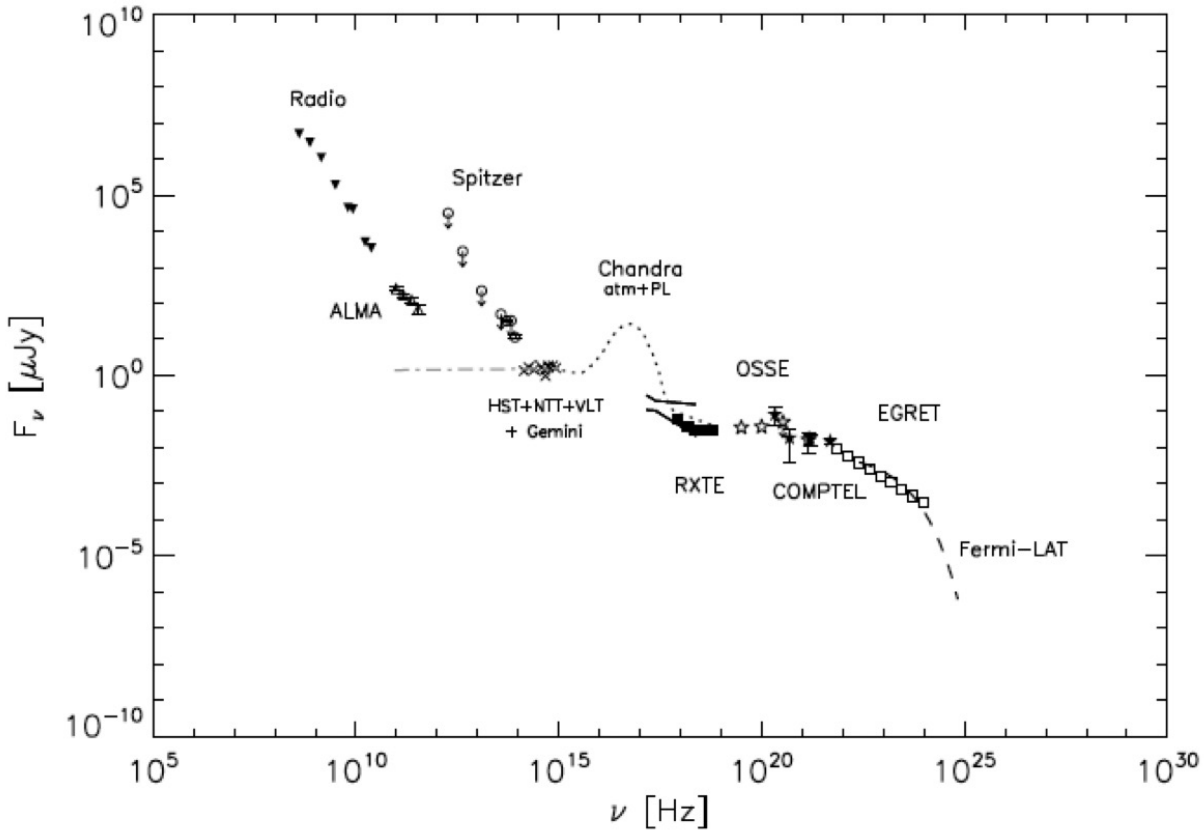
Curvature and IC Cooling

Dissipation region should happen beyond the LC



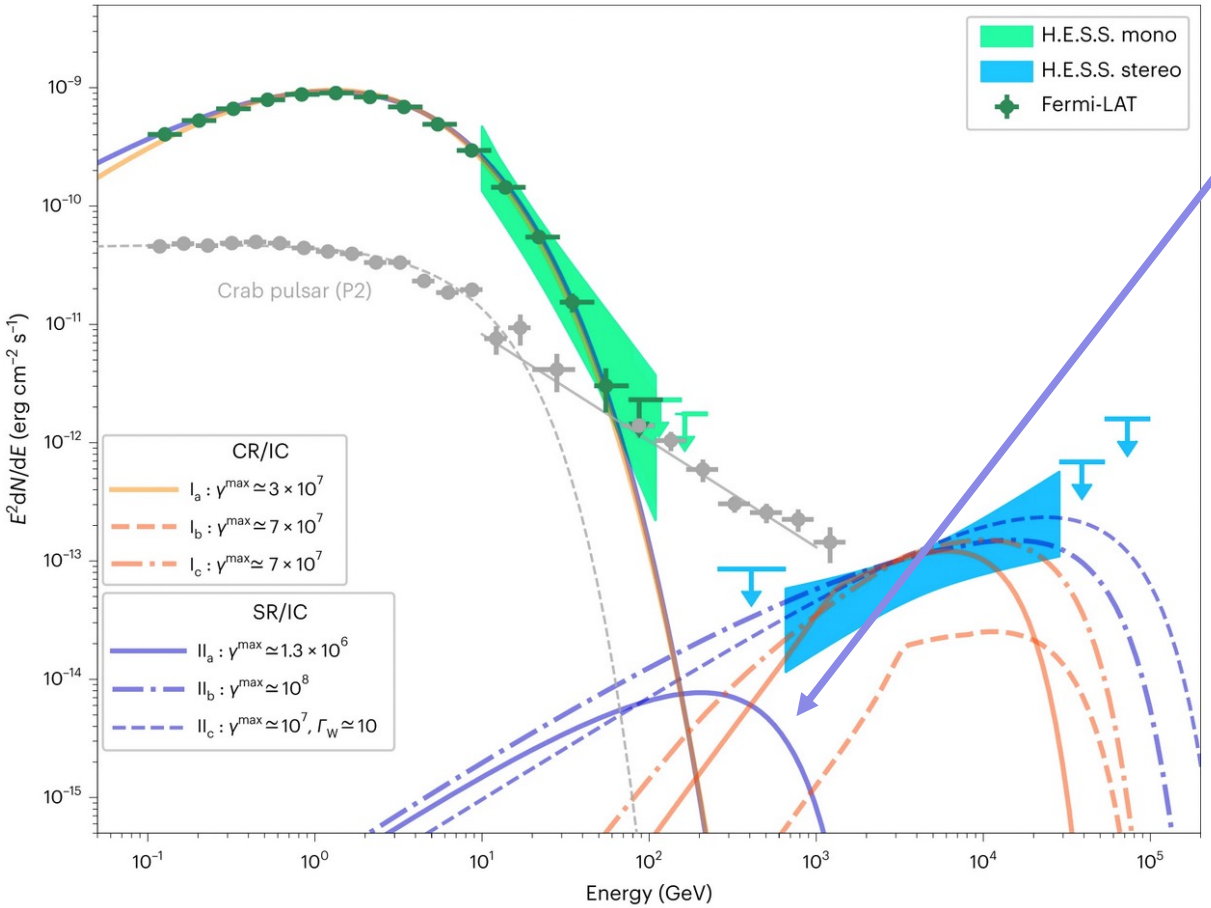


To reach the TeV level, we need to extrapolate the photon field to the FIR:

OP-NIR **OP-FIR**

Using Vela+ to constrain theory

Synchrotron in wind plasmoids



$B_{LC} = 5.53 \times 10^4$G

$$\gamma_{\rm SR}^{\rm max} \simeq 1.3 \times 10^6 (B_\perp/B_{\rm LC})^{-1/2} \, (E_{\rm SR}^{\rm max}/1.5\,{\rm GeV})^{1/2}$$

HESS data:

$$\gamma_{\rm IC}^{\rm max} \gtrsim 7 \times 10^7$$

Some alternatives:

* Escape of the highest particles
* Doppler-boosted emission

$$\simeq 5 R_{LC}$$

$$\Gamma_w \gtrsim 5$$

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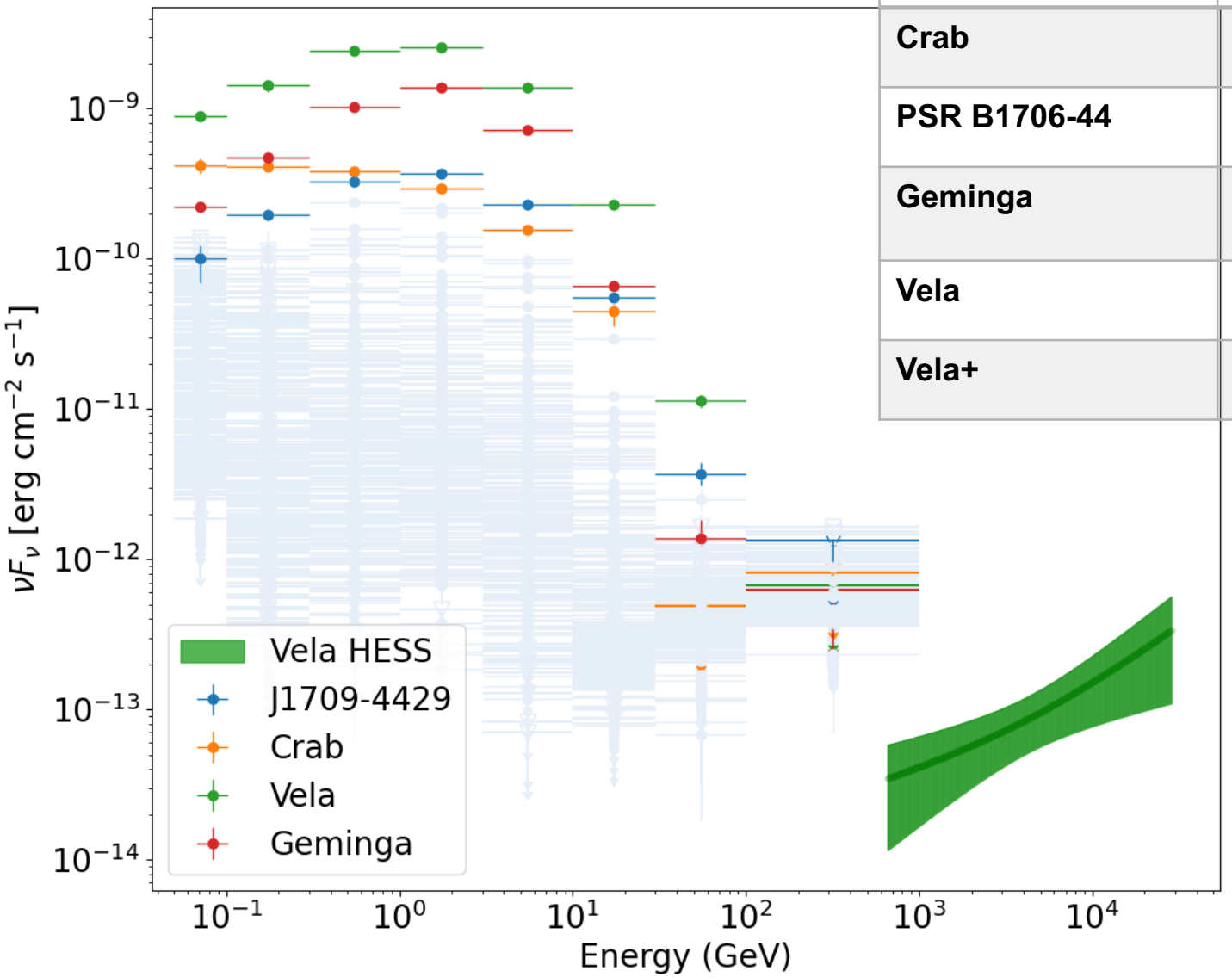
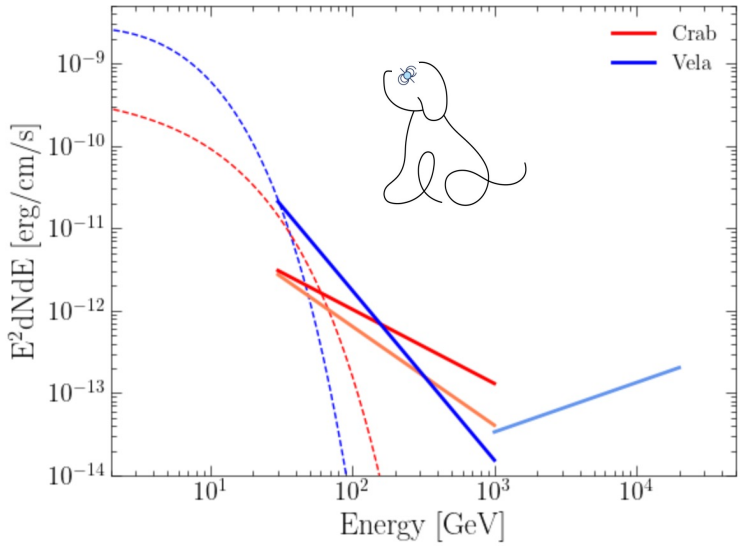
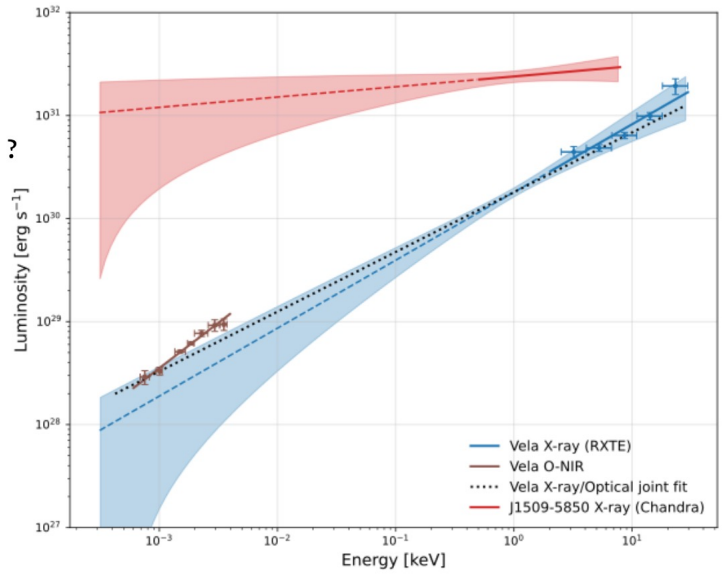


	Age [kyr]	D [kpc]	$\dot{E}/d^2$ [erg/s/kpc^2]	~E_{max} [TeV]	Γ_{VHE}
Crab	1.2	2	5×10^{38}	1.5	3. – 3.5
PSR B1706-44	18	2.6	6×10^{35}	0.075	3.76
Geminga	340	0.2	7×10^{35}	0.070	5.62
Vela	11	0.3	1×10^{38}	0.1	4.1
Vela+				20	1.4

Open Questions



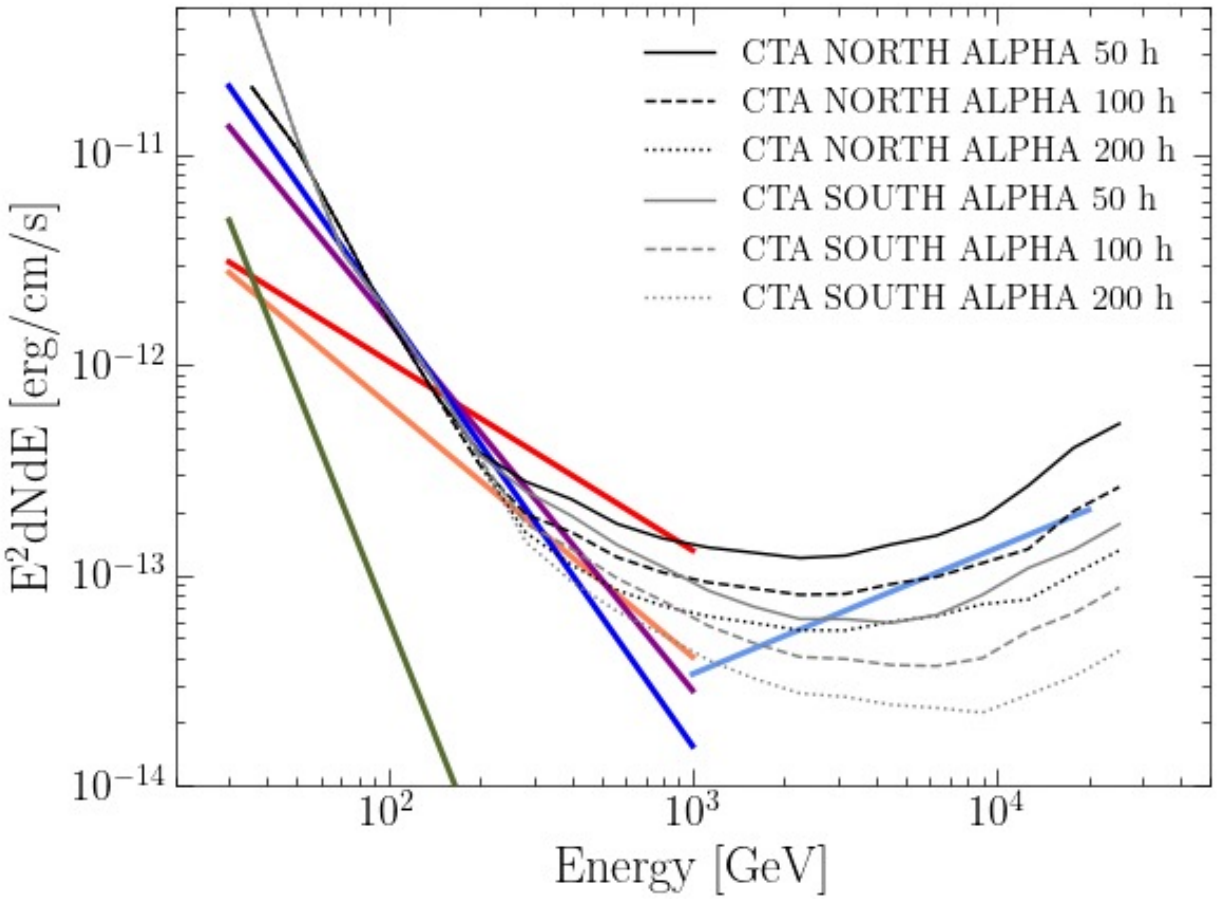


Maxime Regeard 2025

Inverse Compton targets: IR-O

- **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 (see ICRC 2025 HESS Results!)
- **What about Crab?**
  Is the target the most relevant parameter?
- **What can we learn?**
  Is the density of the electrons ~ ρ_{GJ}
  Maximum Lorentz factor / Energy
  Constraints on the Op/IR photon field

Major science case for CTAO



- Continuing Pulsar observations with IACTs, **Goal: probe the >20 TeV spectrum**
- Search on the database: 20 years of data available
- Probing other promising pulsars for VHE emission using the first CTAO prototypes
- CTAO will need ephemeris

Summary

Opening the pulsed TeV emission

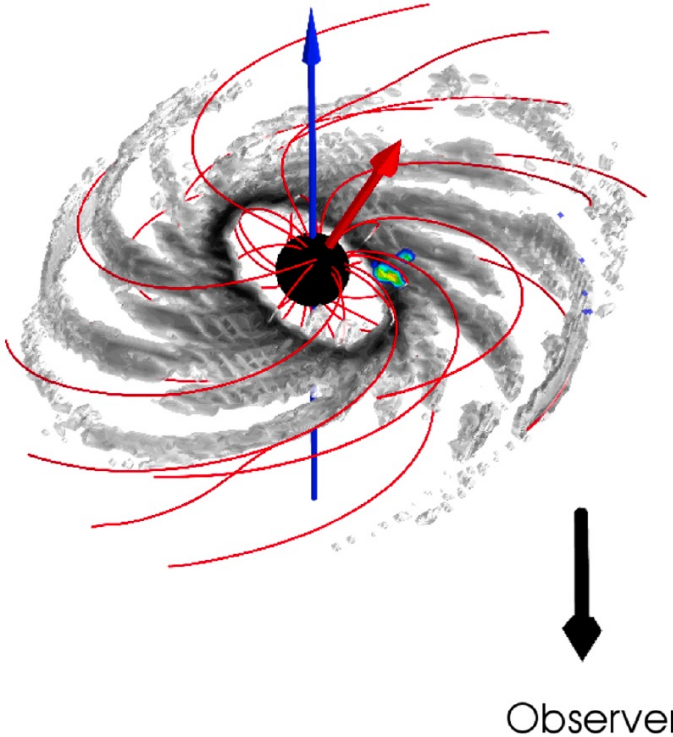
- **Four (five) pulsars have been detected with IACTs**
- **Despite the long observation times used for the first ones, the new discoveries are reachable in moderated time (Tobs < 100 h)**
- **These detections open more questions and boost the field of pulsars**
  - An unambiguous handle on Lorentz factors > 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!

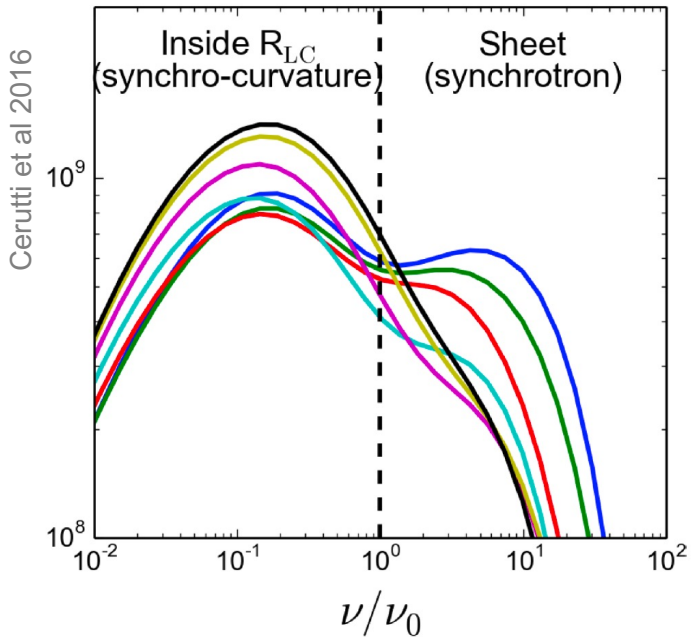
Backups

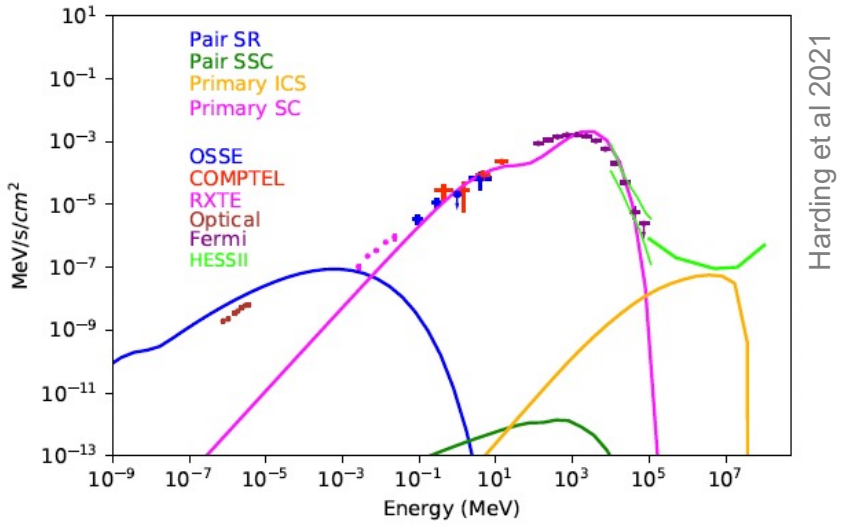
Meanwhile in the theory side…

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







The Vela Pulsar in the TeV regime

Detection of Vela above 1 TeV

- Data from 2004-2016 observations (80 h)
- Phase-folding : ephemeris from LAT+ Parkes
- Tests for periodicity @ predefined energies of 0.5, 1, 3 & 7 TeV => 4.3, 4.9, 5.6 σ post-trials

  Pulsed emission detected up **to 20 TeV**
  Phase & width compatible with <100 GeV pulses

HESS Collaboration et al 2023