Recent VHE Results on Pulsars and Pulsar Wind Nebulae

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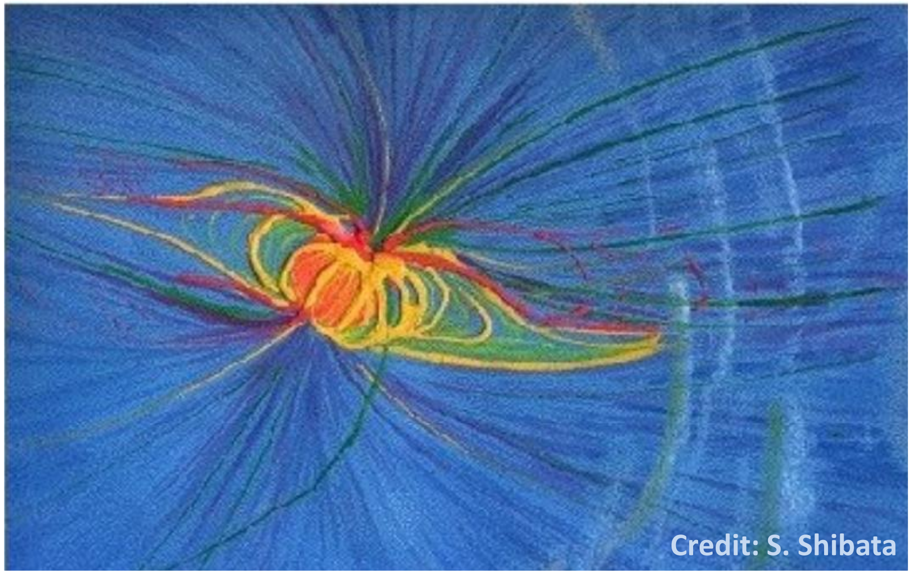
XXVII Cracow Epiphany Conference,
10 – 14 January 2022



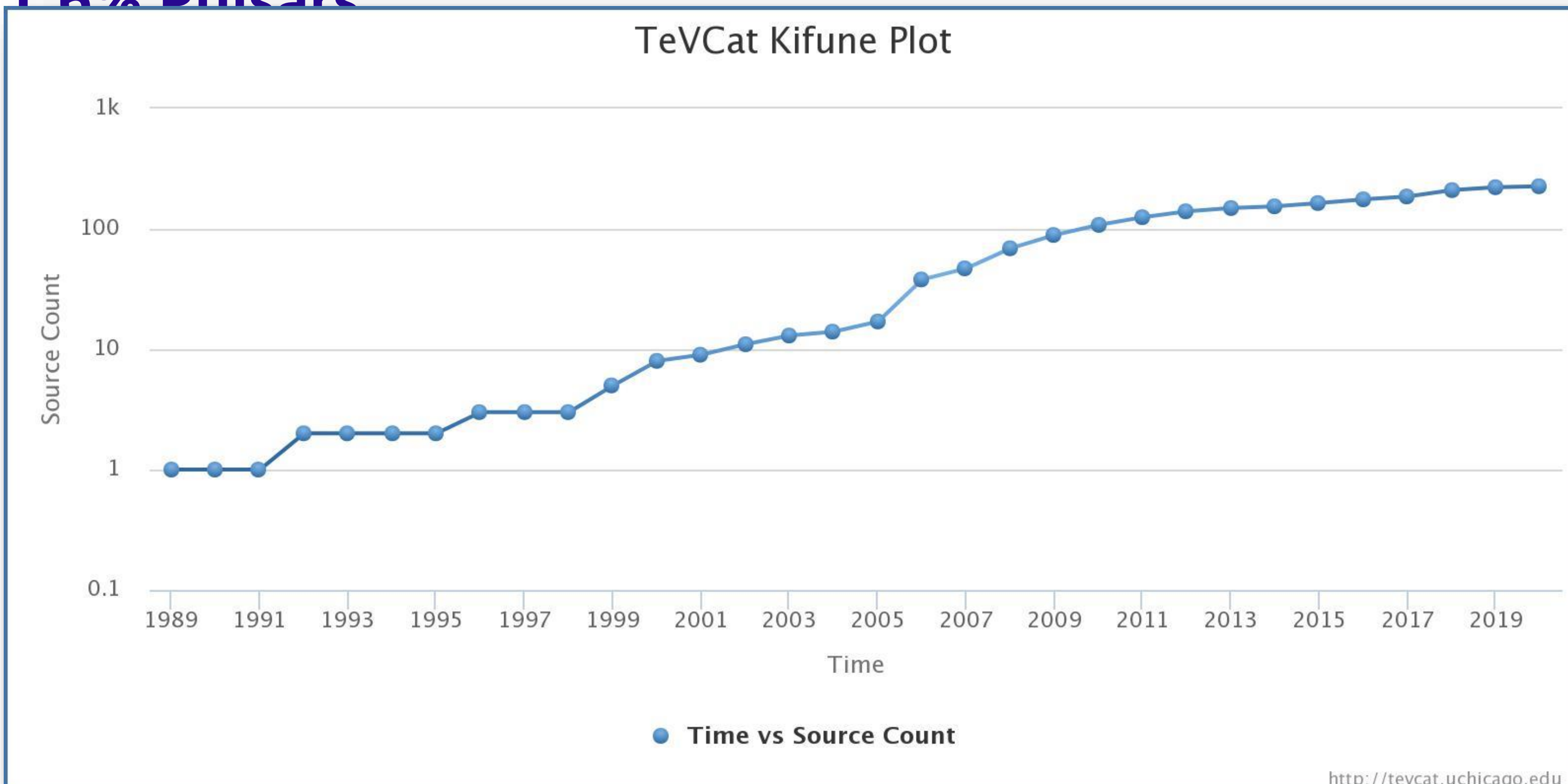
VHE Source Classes

- **TeVCAT lists 248 sources**

Cf. talks by W. Hofmann, R. Zanin

TeVCat Source Types (248 total)

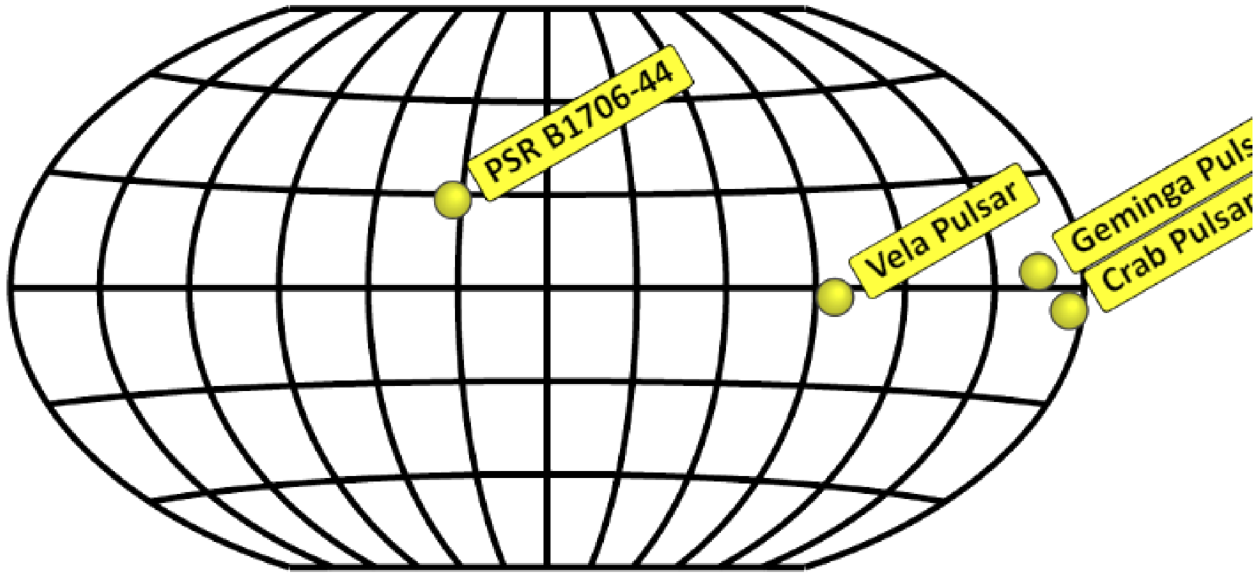
- **1.6% Pulsars**
-



http://tevcat2.uchicago.edu

VHE Pulsars

- **TeVCAT lists 4 pulsars:**
  - Crab
  - Vela
  - Geminga
  - PSR B1706-44
- <d> ~ 1 kpc
- <|b|> ~ 10º (4º)
- <age> ~ 1 kyr – 300 kyr
- ULs on 13 by VERITAS
  (Archer et al. 2019)



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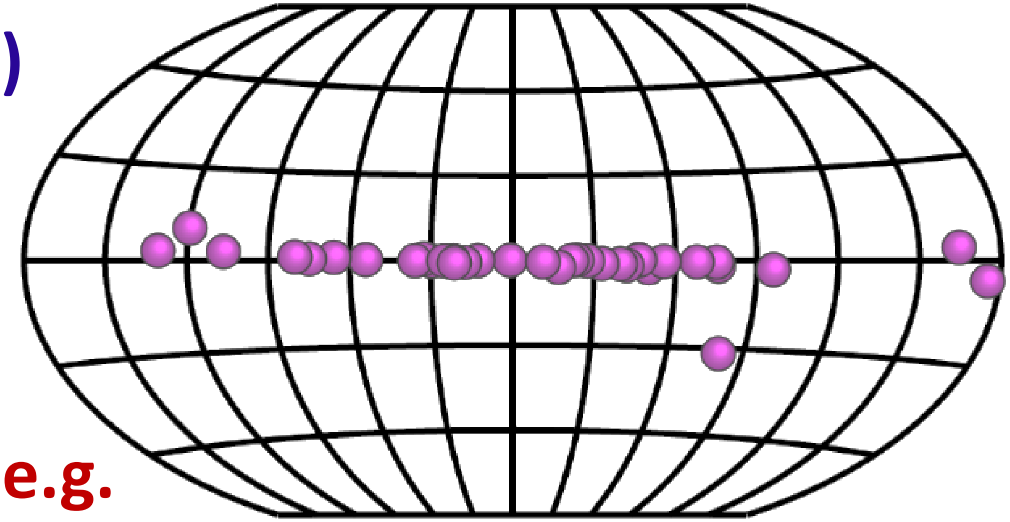
VHE Pulsar Wind Nebulae

- **TeVCAT lists 35 PWNe, e.g.**
  - Crab, Vela, MSH15-52, 3C 58, CTA 1, G0.9+0.1
- <d> ~ <1 – 10 kpc (50 kpc)
- <|b|> ~ 1.5^{o}
- <age> ~ 1 – 50 kyr



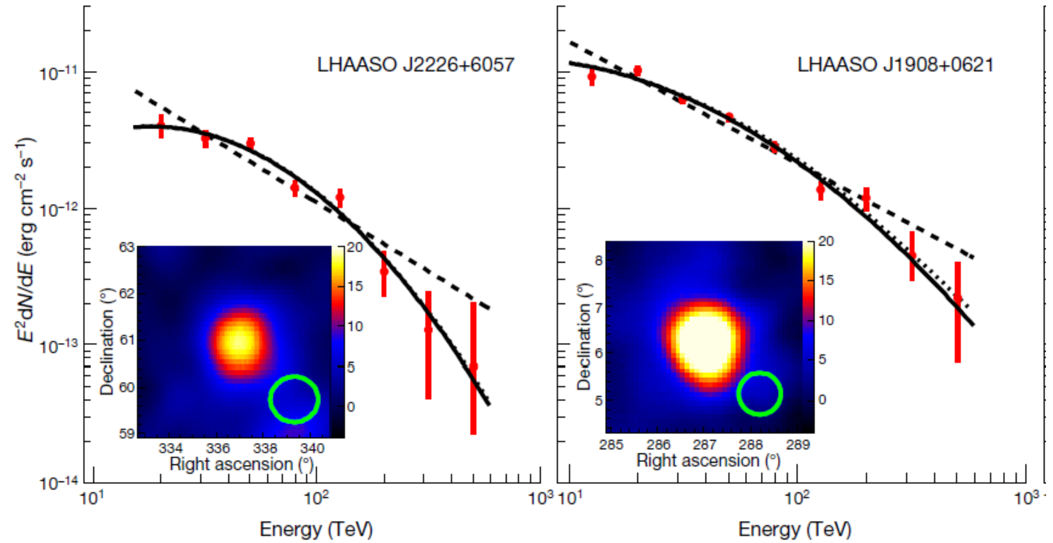
http://tevcat2.uchicago.edu

- **TeVCAT lists 6 TeV Halos, e.g.**
  - Vela X, Geminga, HESS J1825-137, Monogem
- <d> ~ 1 kpc
- <|b|> ~ 3^{o}

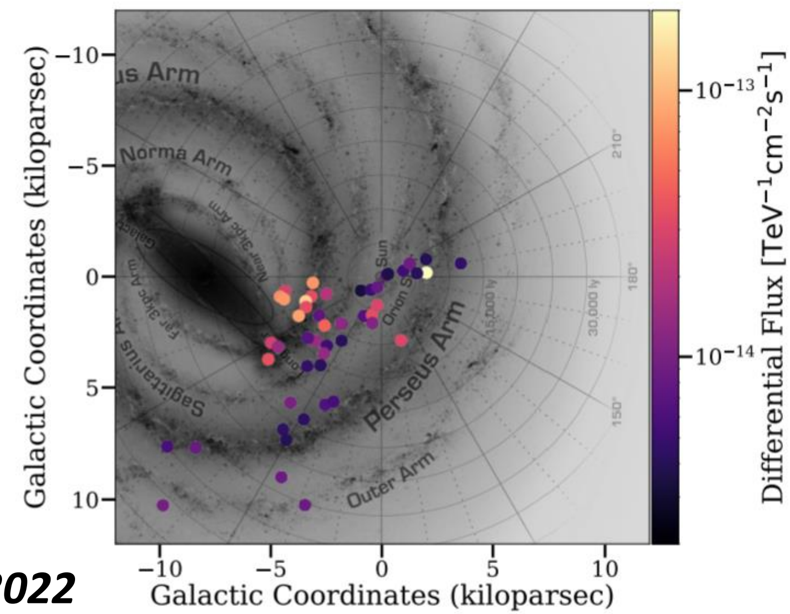
UHE Sources

Cao et al. (2021)

- **LHAASO**
  - 12 Galactic sources (including Crab Nebula)
  - 100 TeV – 1 PeV
  - Potentially PWNe, PSRs, SNRs, young massive stellar clusters
  - Protons / leptons?

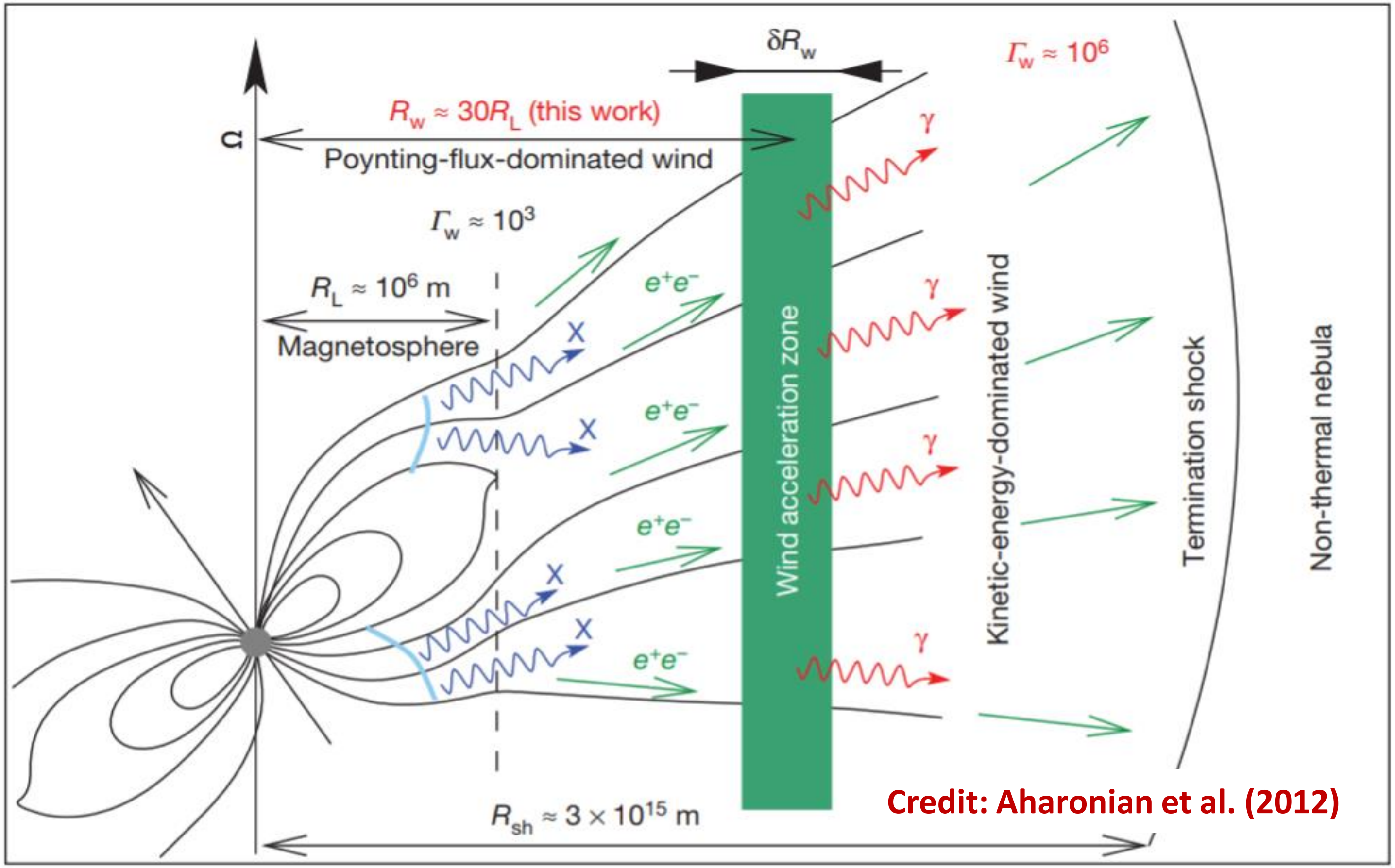


- **HAWC Third Catalog**
  - 65 sources
  - Majority: SNRs / (ATNF) PSRs / PWN halos



Albert et al. (2021); Abdalla et al. (2021)

Pulsars and PWNe: γ / CRs



Pulsars:

- Pulsed emission
- Pulsar wind

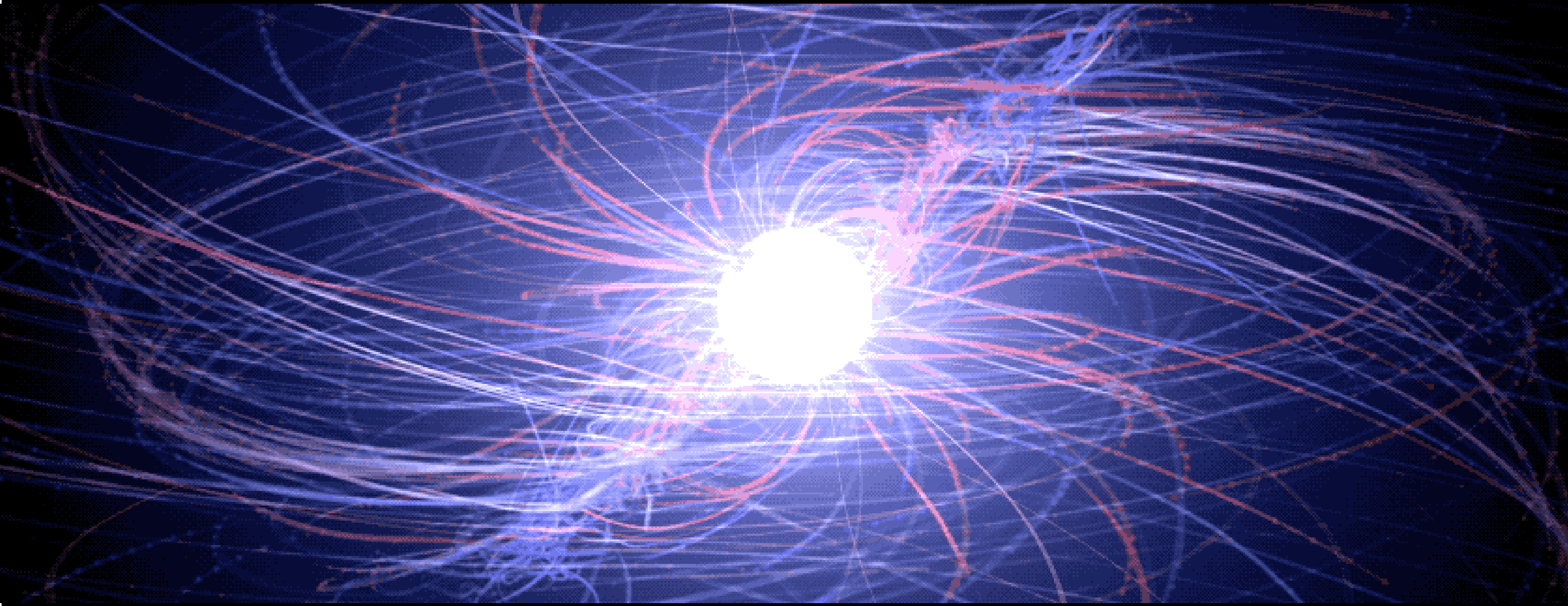
PWNe:

- Steady IC emission
- Escaping wind / halos

Pulsar Binaries:

- Modulated emission
- Binary wind / shock

VHE Pulsars



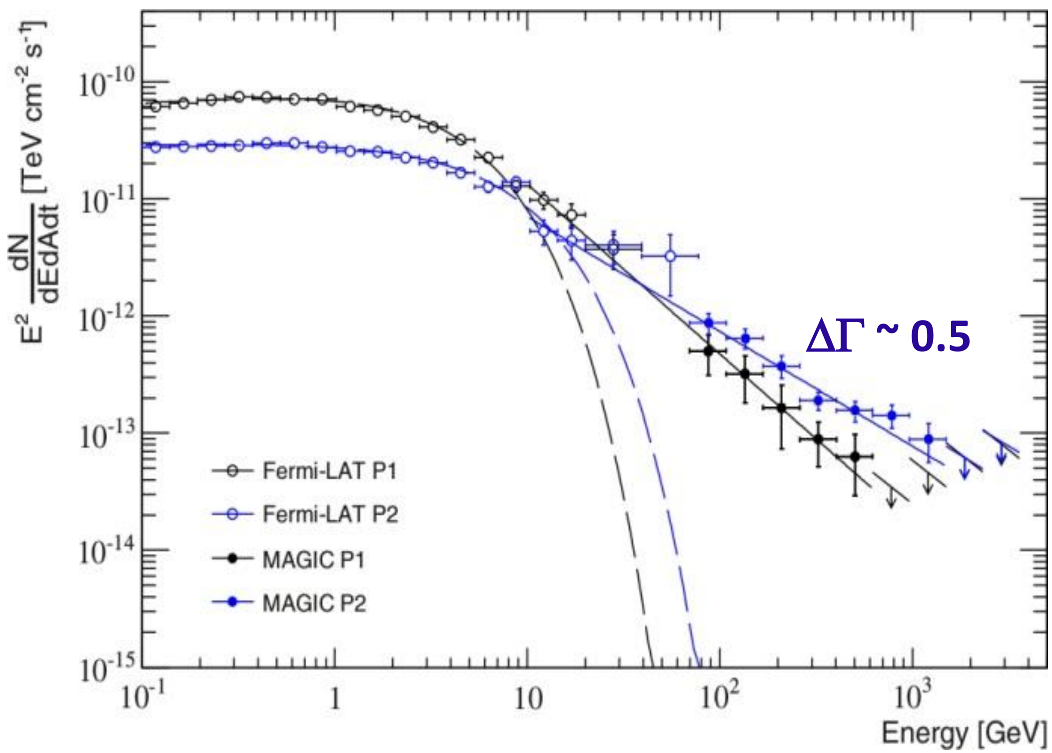
Credit:
C. Kalapotharakos
(NASA)

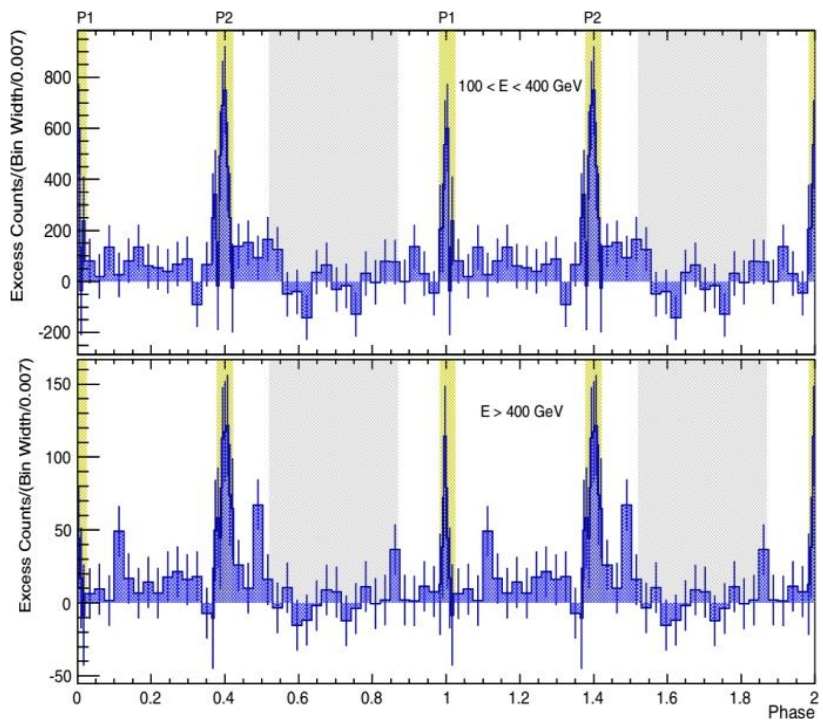
XXVII Cracow Epiphany Conference, 10 – 14 January 2022

Pulsed Emission from the Crab PSR @ 70 GeV to 1.5 TeV with MAGIC

Ansoldi et al. (2016)

- **Detection up to 1.5 TeV**
- **Both P1 and P2 still visible, in phase with *Fermi* ones**
- **IC near light cylinder, $\gamma > 5e6$**



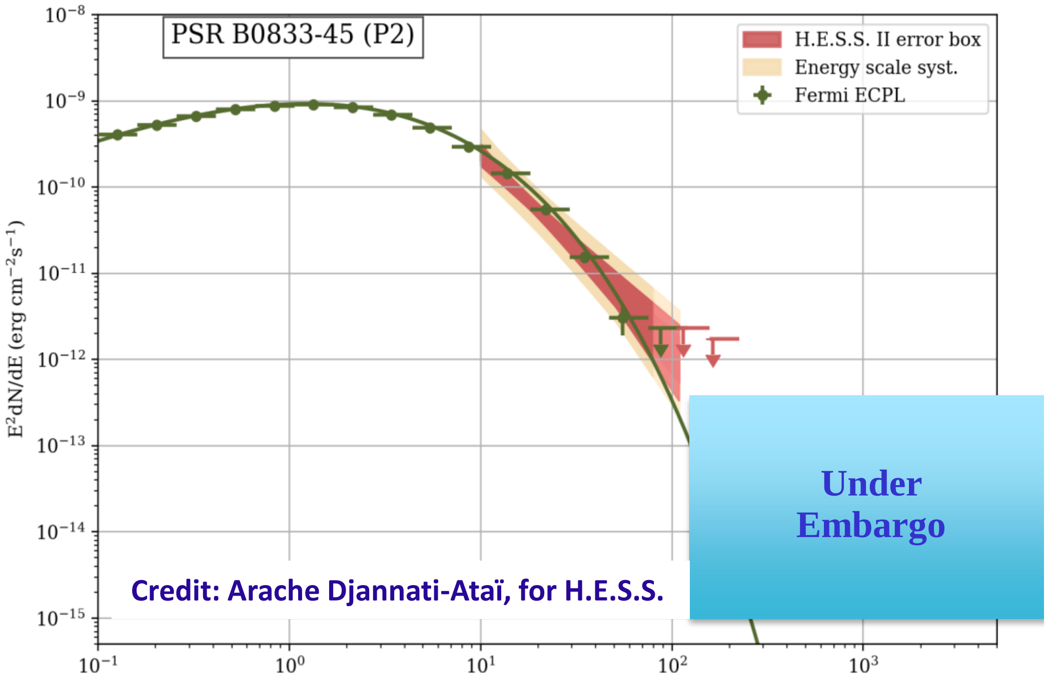


Pulsed TeV Emission from *Vela* PSR with H.E.S.S. @ 3 to >7 TeV

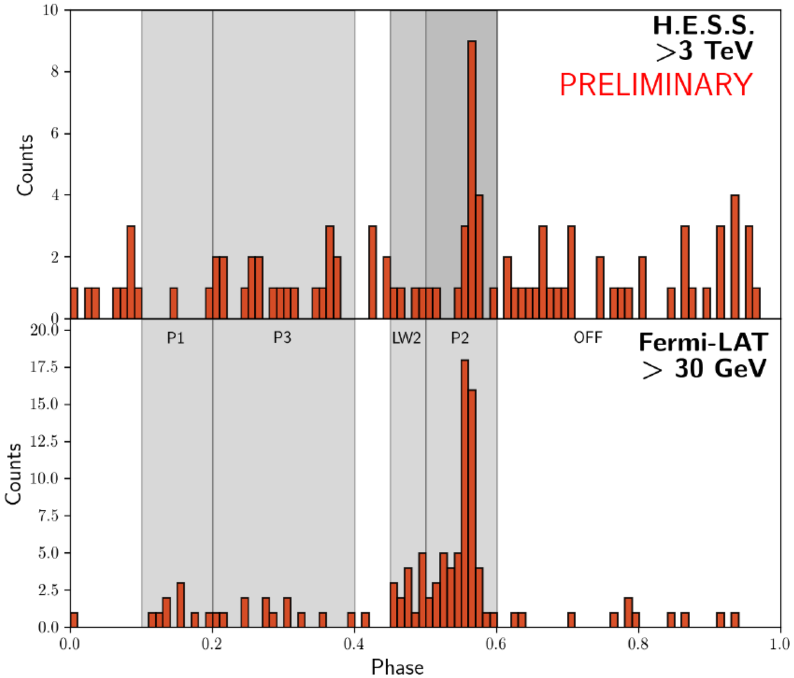
Djannati-Ataï et al. (2017)

- P = 89 ms; Edot ~ 7e36 erg/s; d = 0.29 kpc
- P2 detected at 5.6σ level; P1 not visible
- CR tail or a different spectral component?

Cf. Talk by R. Moderski on CT5 detection



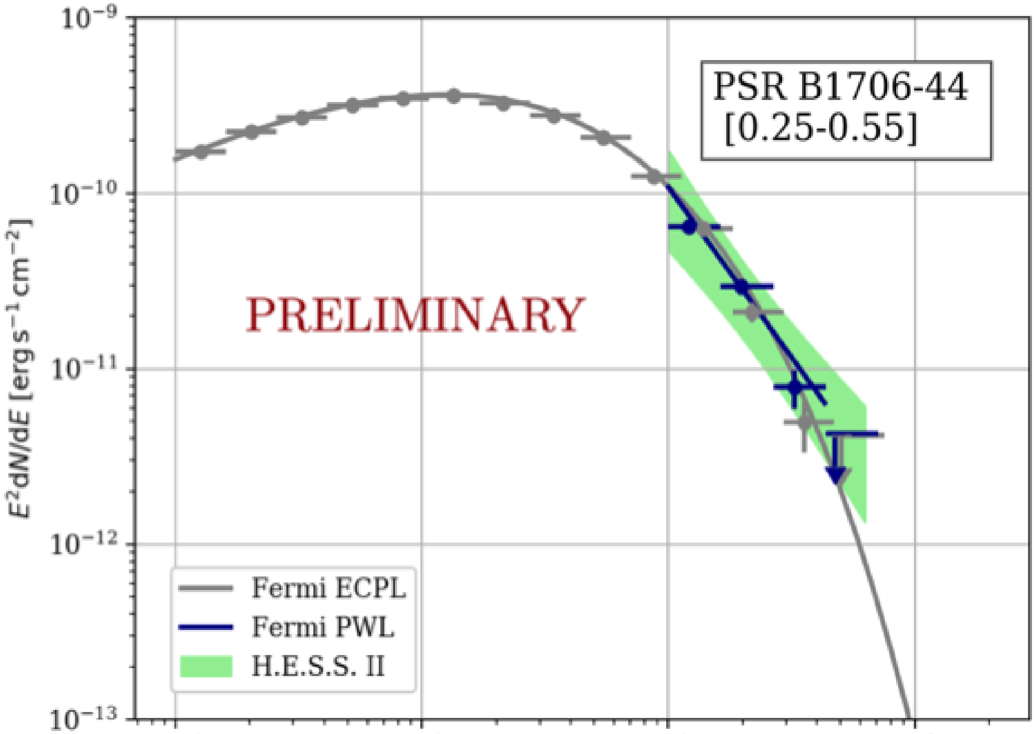
Credit: Arache Djannati-Ataï, for H.E.S.S.

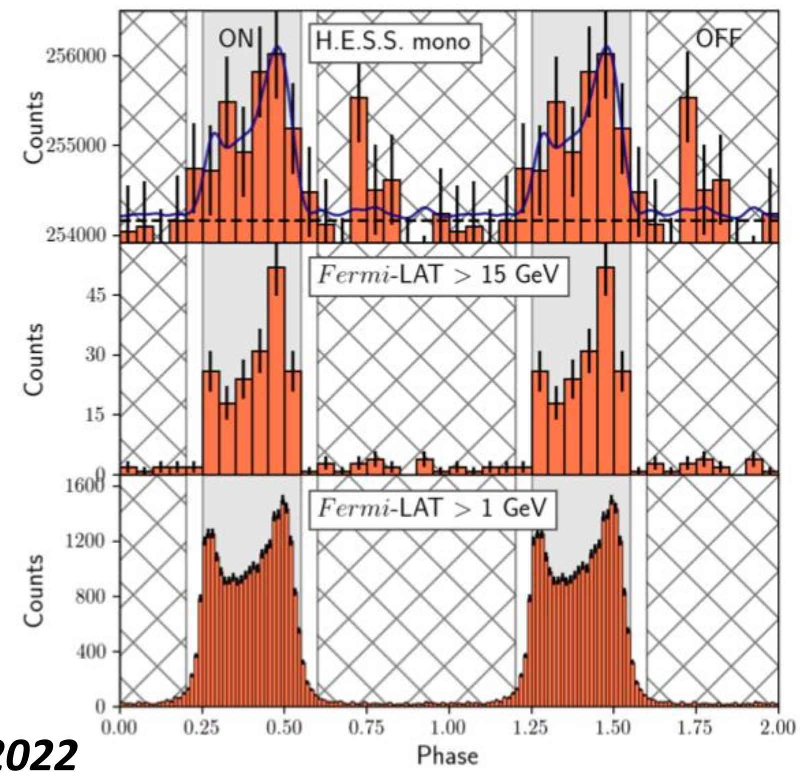


Detection of PSR B1706-44 with H.E.S.S. @ 10 – 80 GeV

Spir-Jacob, Djannati-Ataï et al. (2019)

- P = 102 ms; Edot ~ 3e36 erg/s; d = 2.3 kpc
- Detected at ~4.6σ
- Power-law fit to *Fermi* / H.E.S.S. data: Γ ~ 3.6; curved?

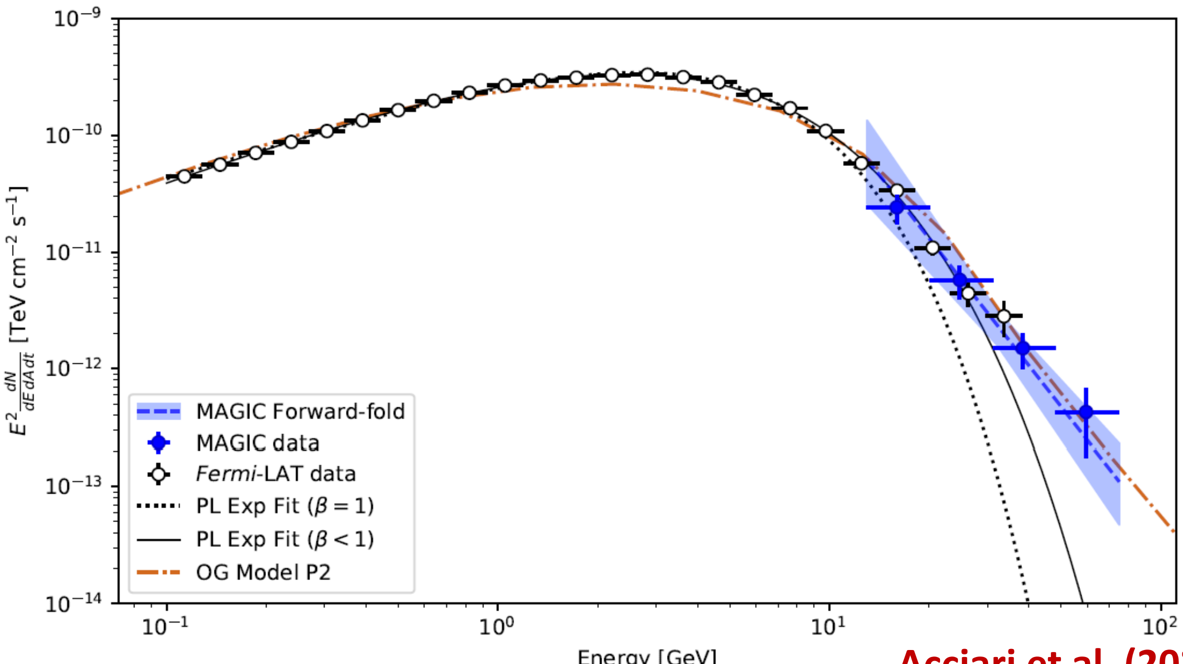


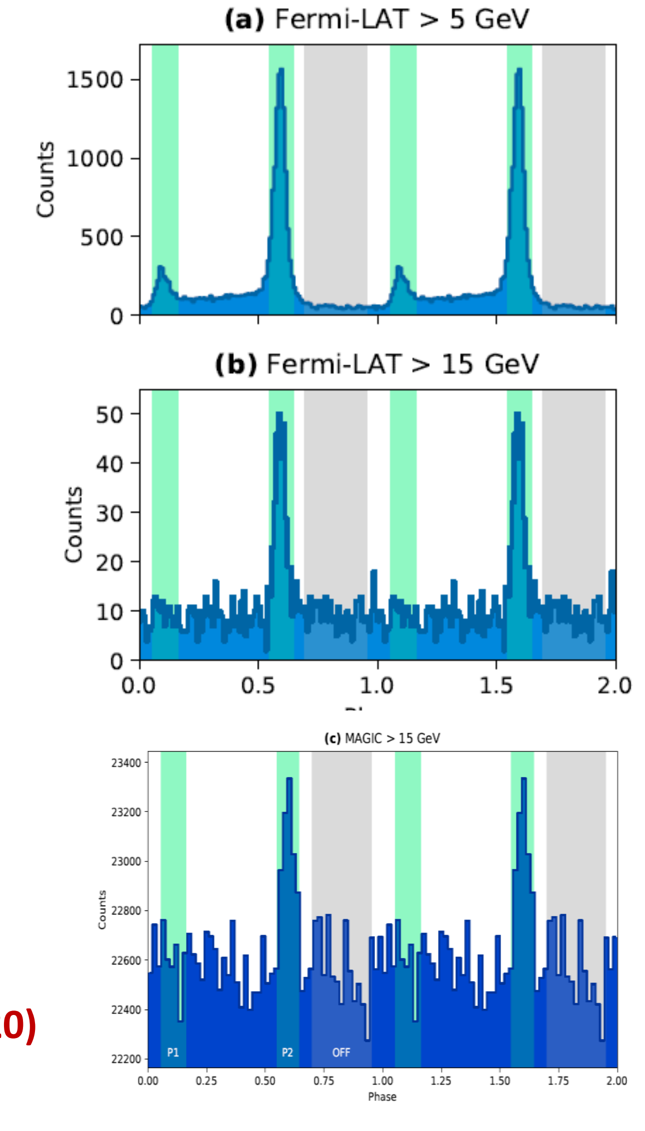


Pulsed (Sub) TeV emission from Geminga @ 15 – 75 GeV by MAGIC

- **Only P2 detected at significance of 6σ**
- **PL with Γ ~ 5.6 (softest ever measured by MAGIC) joining *Fermi* spectrum**
- **Special trigger: E_{low} = 15 GeV**

Cf. Talk by J. Sitarek





Acciari et al. (2020)

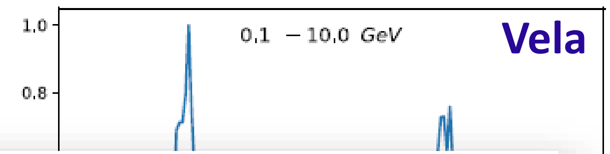
Some Open Questions

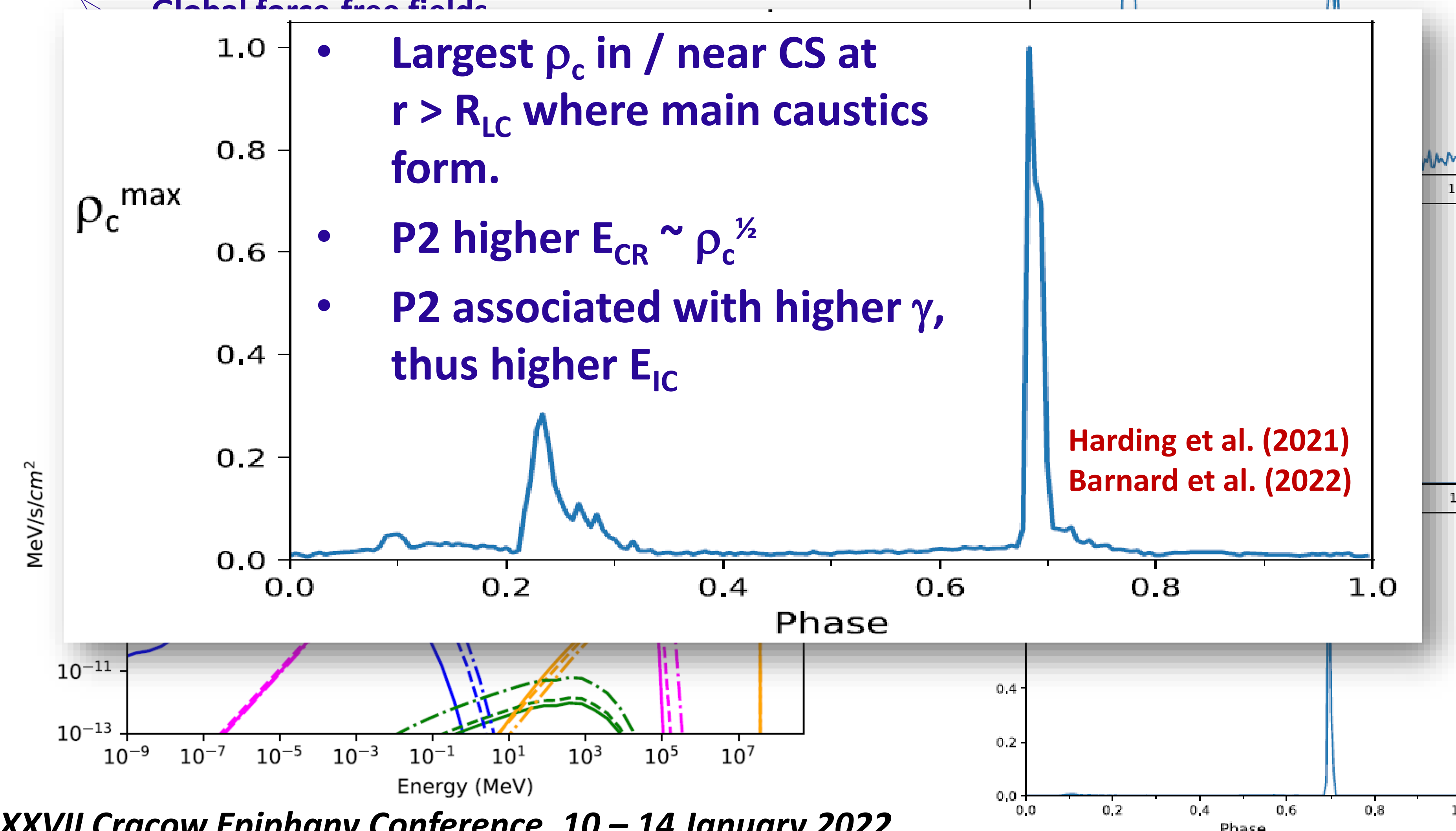
- Extension of SR / CR GeV component or new spectral component?
- Spatial origin of photons?
- Spectral shape of emitting particles (primaries / pairs)?
- Local and global electrodynamical properties?
- Pulsar (magnetosphere) geometry?

Spectral and energy-dependent light curve modelling

Models: Pulsed TeV Emission

- **Separatrix/CS**
  (Harding et al. 2021)
  - Global force-free fields



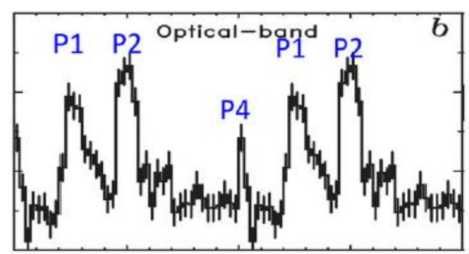


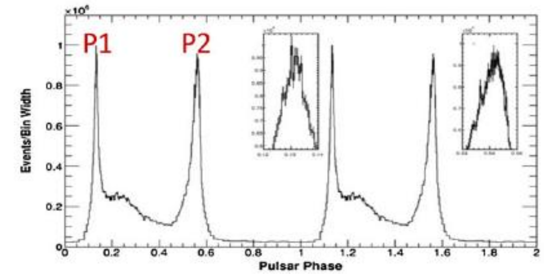
- Largest ρ_c in / near CS at $r > R_{LC}$ where main caustics form.
- P2 higher $E_{CR} \sim \rho_c^{1/2}$
- P2 associated with higher γ, thus higher E_{IC}

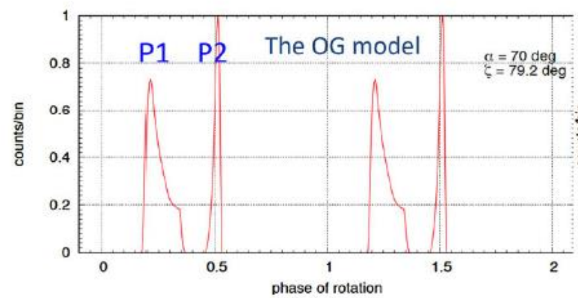
Harding et al. (2021)
Barnard et al. (2022)

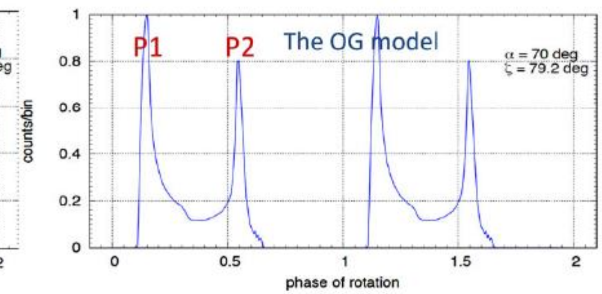
Models: Pulsed TeV Emission

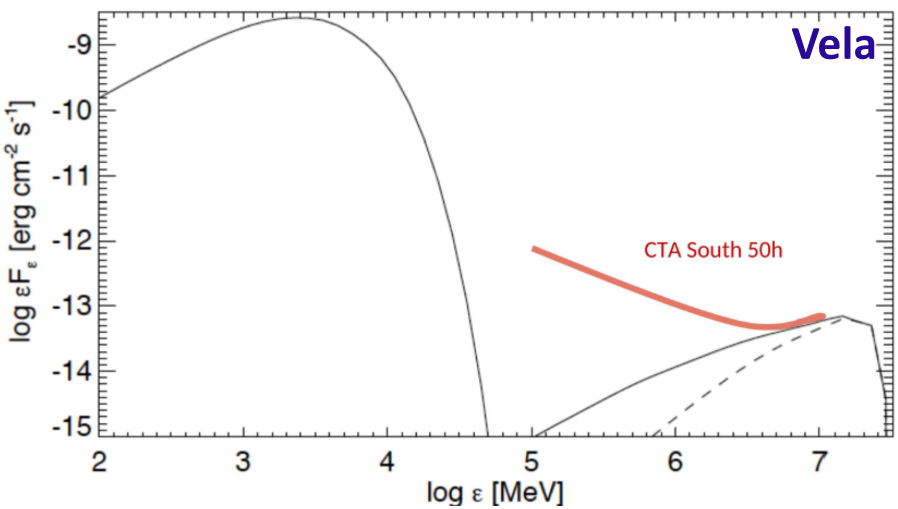
- **OG**
  (Rudak & Dyks 2017)
  - 3D gap (primaries) with inner layer (pairs)
  - Prim CR in gap, prim IC on pair SR
  - E_{low} of target photons: 0.1 eV vs. 0.001 eV
  - TeV component; P1/P2

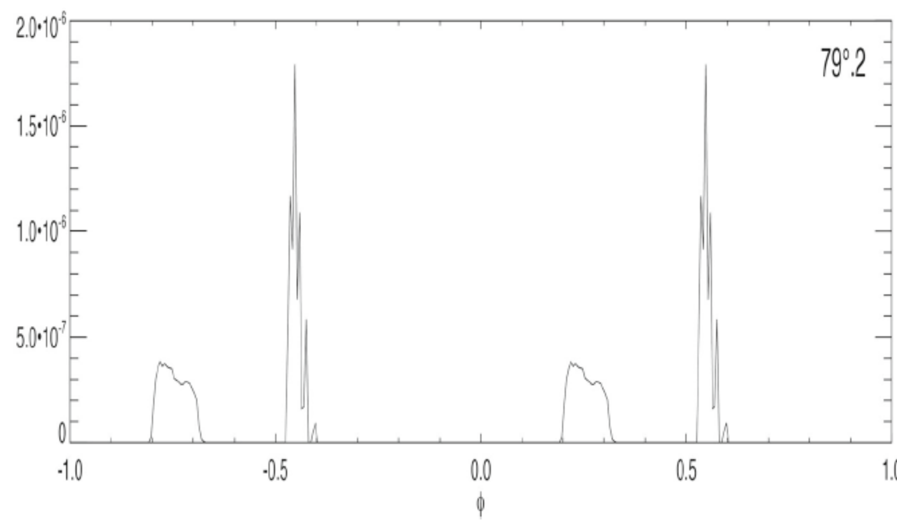








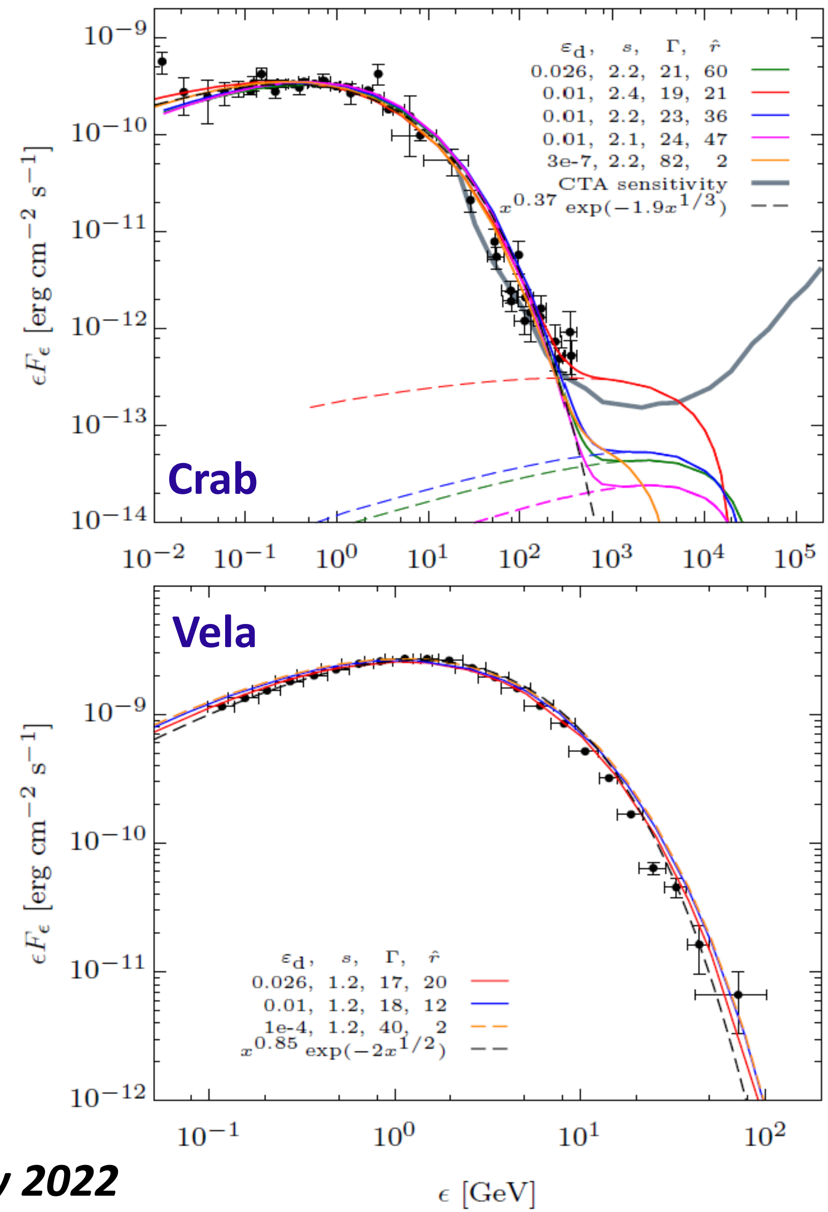




Models: Pulsed TeV Emission

- **Striped Wind**
  (Mochol & Petri 2015)
  - GeV component: Doppler-boosted SR from CS
  - TeV component: SSC
  - Constraining wind properties and magnetic reconnection: Γ (50–100), dissipation distance r, particle index s, dissipation efficiency ε
  - Vela: much harder particle spectrum, low SSC due to low SR flux; smaller r, lower particle number density, higher reconnection rate

- **Other**
  - Cold, low-σ Crab wind; ICS on magneto-spheric X-rays (Aharonian et al. 2012).
  - Magneto-centrifugal acceleration (Osmanov & Rieger 2019).



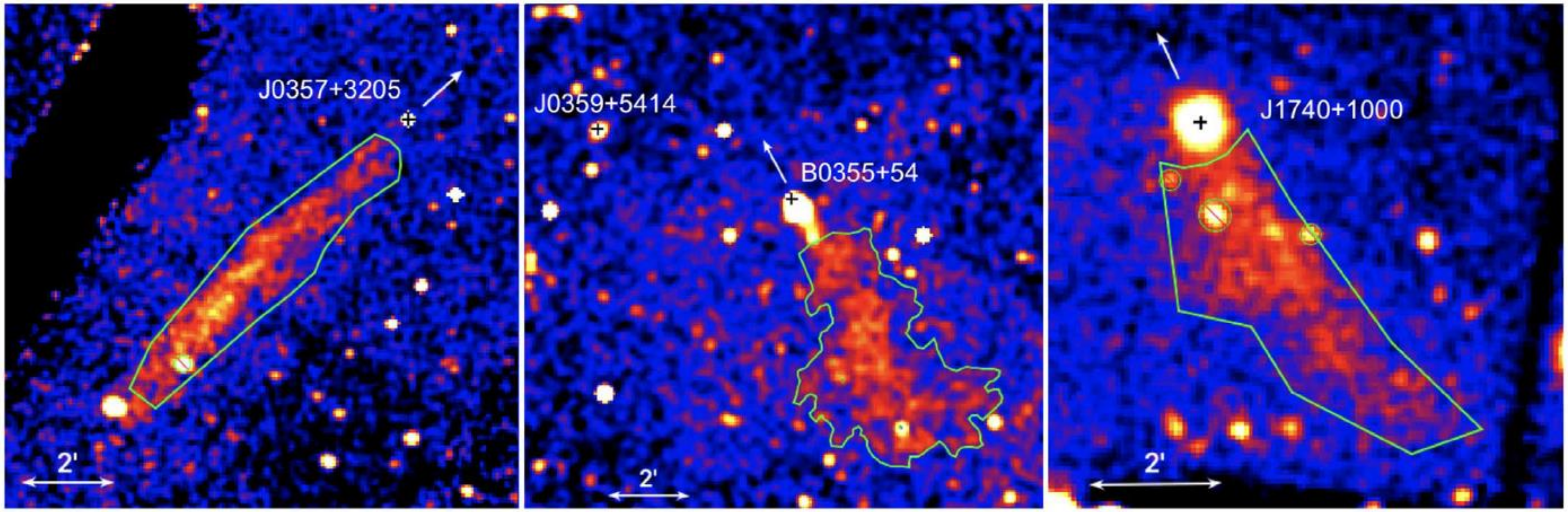
Other TeV Pulsar Results

- **ULs for VHE emission from the regions around three nearby supersonic pulsars (PSR B0355+54, PSR J0357+3205, and PSR J1740+1000) that exhibit long X-ray tails.**
- **Pulsar/Be system J2032+4127 with P = 50 yr: point source, flux peaking at periastron, sharply dropping 7 days after (γ–γ absorption). Spectrum for high and low states (spectral cutoff in low state)**

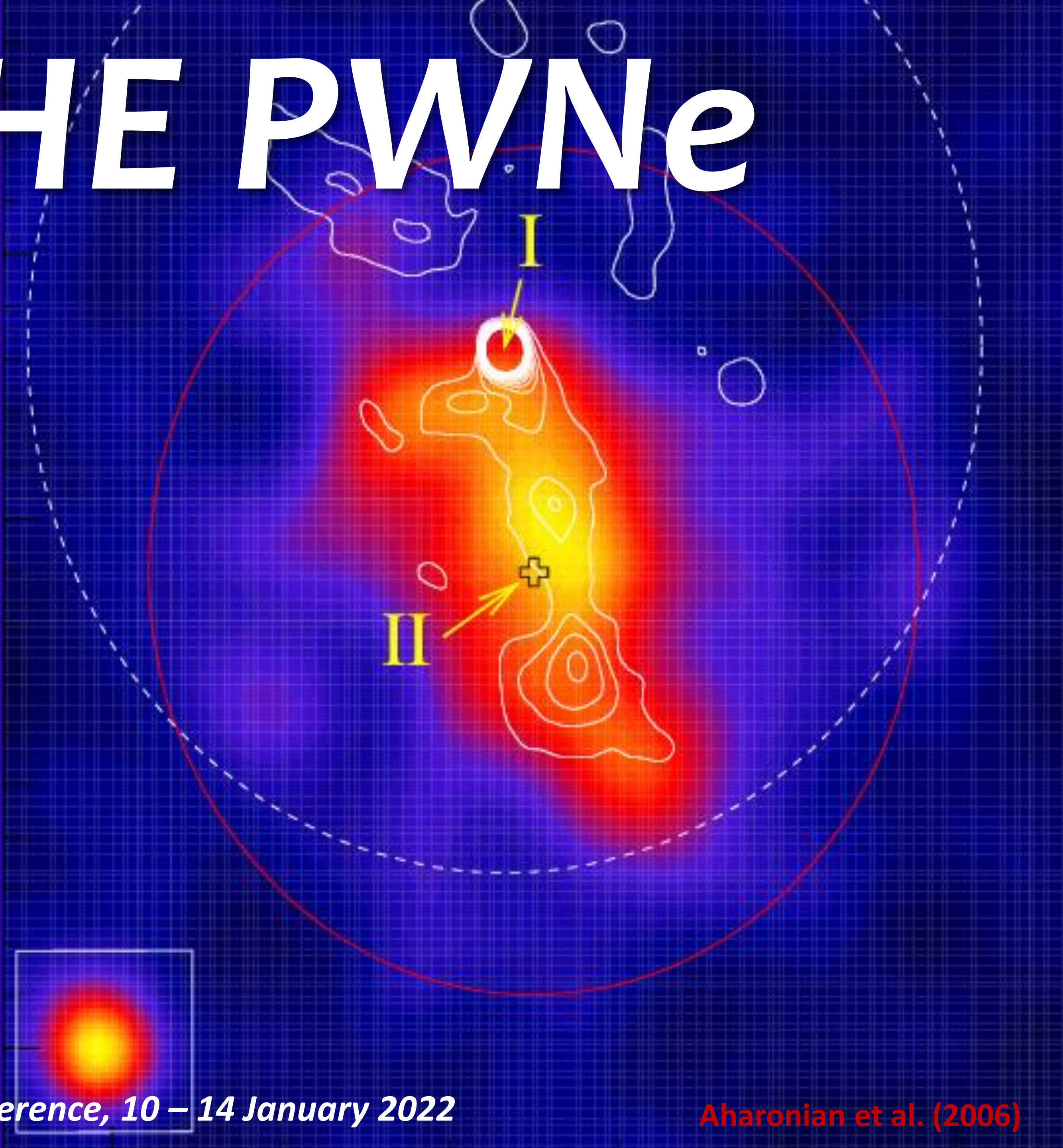
Cf. Talk by B. Hona

Benbow et al. (2021)

Abeysekara et al. (2018)



VHE PWNe

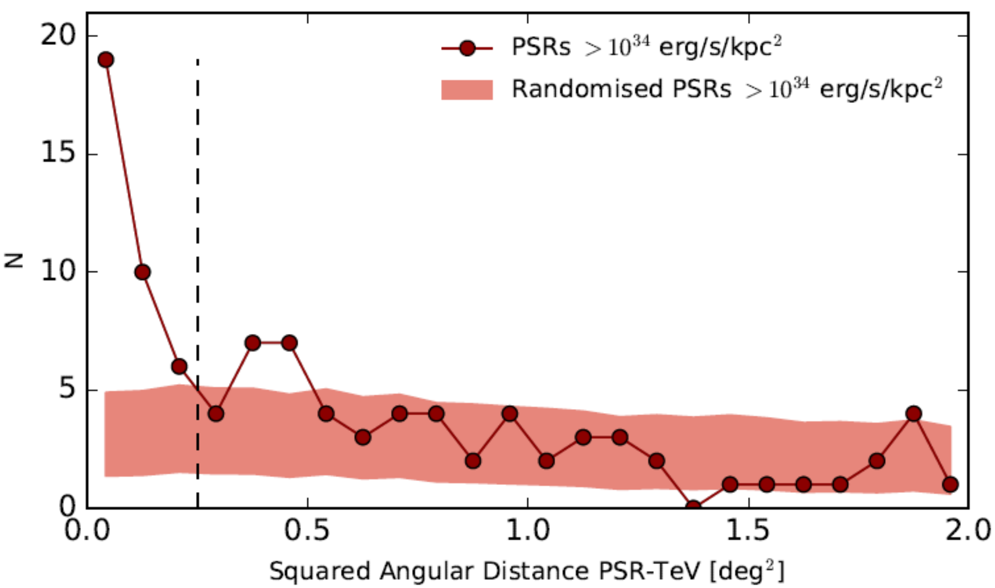


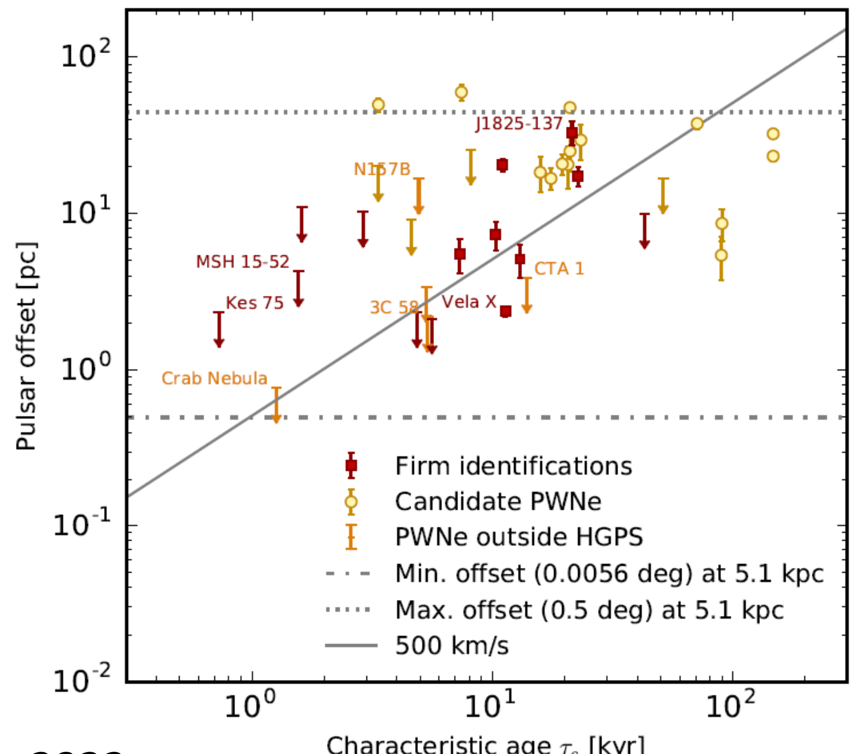
Aharonian et al. (2006)

TeV PWN Population

- **Based on the 9-year H.E.S.S. Galactic Plane Survey (HGPS): 3000 h of data!** **Abdalla et al. (2018)**
- **14 firm identifications + 5 external + 18 candidates + ULs**

1a. Spatial correlation: PWNe with energetic PSRs
1b. Increasing offset between PSR and PWN with age





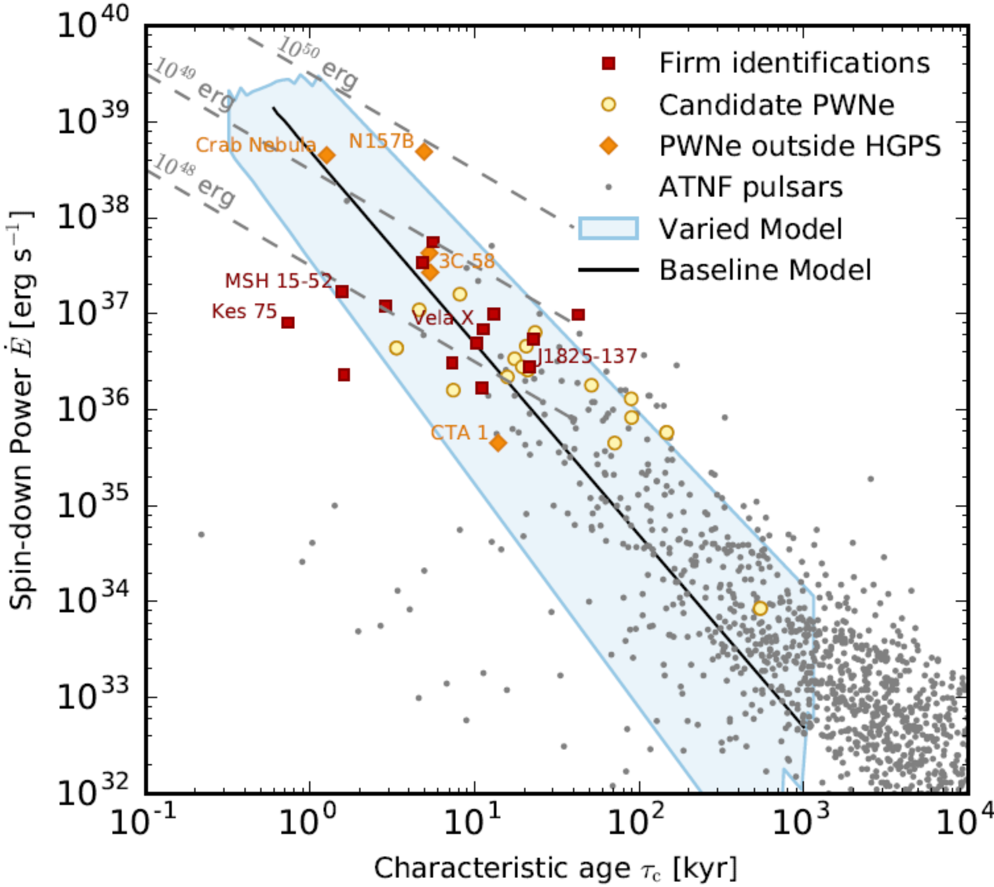
TeV PWN Population

Abdalla et al. (2018)

- Based on the 9-year H.E.S.S. Galactic Plane Survey (HGPS): 3000 h of data!
- 14 firm identifications + 5 external + 18 candidates + ULs

2. Younger, more energetic PSRs associated with TeV PWNe

- Edot/d^2 a good estimator for detectability



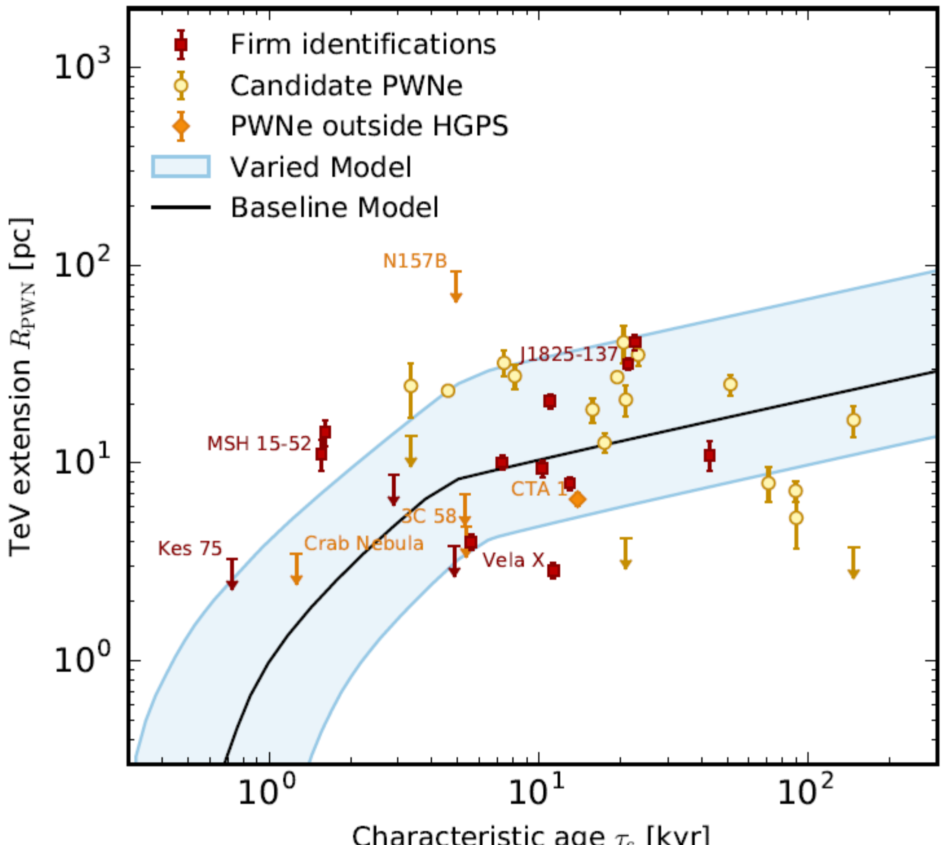
TeV PWN Population

Abdalla et al. (2018)

- Based on the 9-year H.E.S.S. Galactic Plane Survey (HGPS): 3000 h of data!
- 14 firm identifications + 5 external + 18 candidates + ULs

3. Older PWNe are more extended:

$R_{early} \sim t^{1.2}$
$R_{late} \sim t^{0.3}$



TeV PWN Population

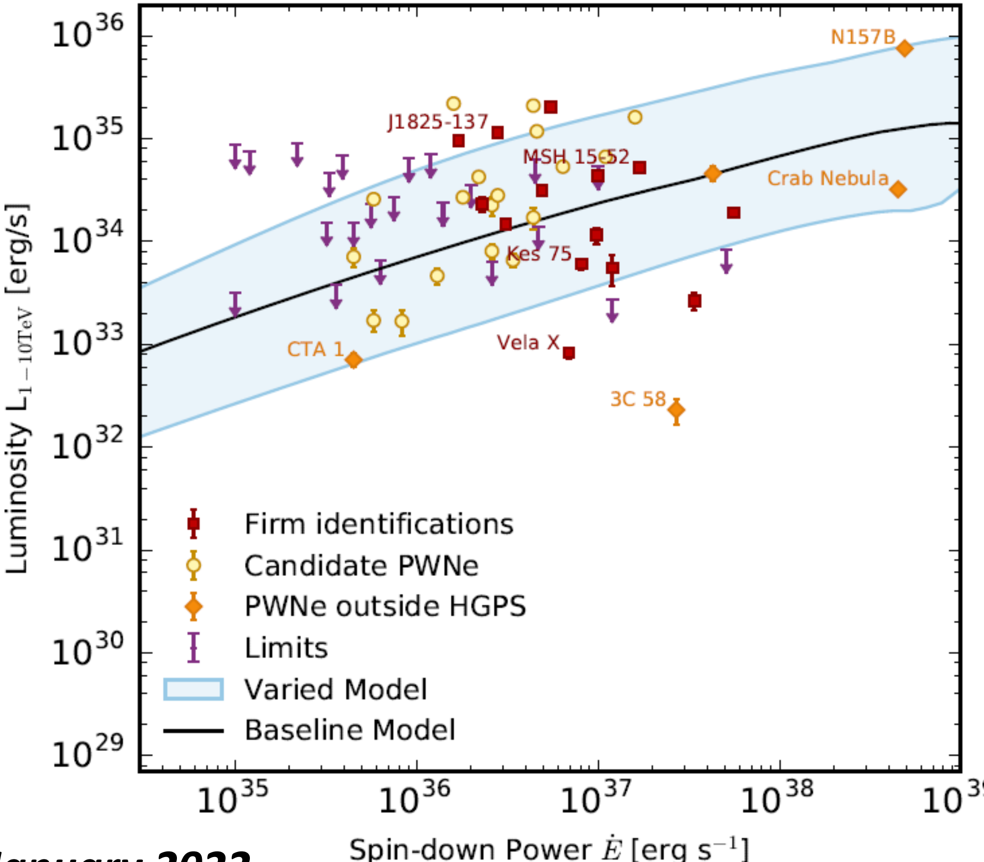
Abdalla et al. (2018)

- Based on the 9-year H.E.S.S. Galactic Plane Survey (HGPS): 3000 h of data!
- 14 firm identifications + 5 external + 18 candidates + ULs

4. Edot a proxy for evolutionary stage

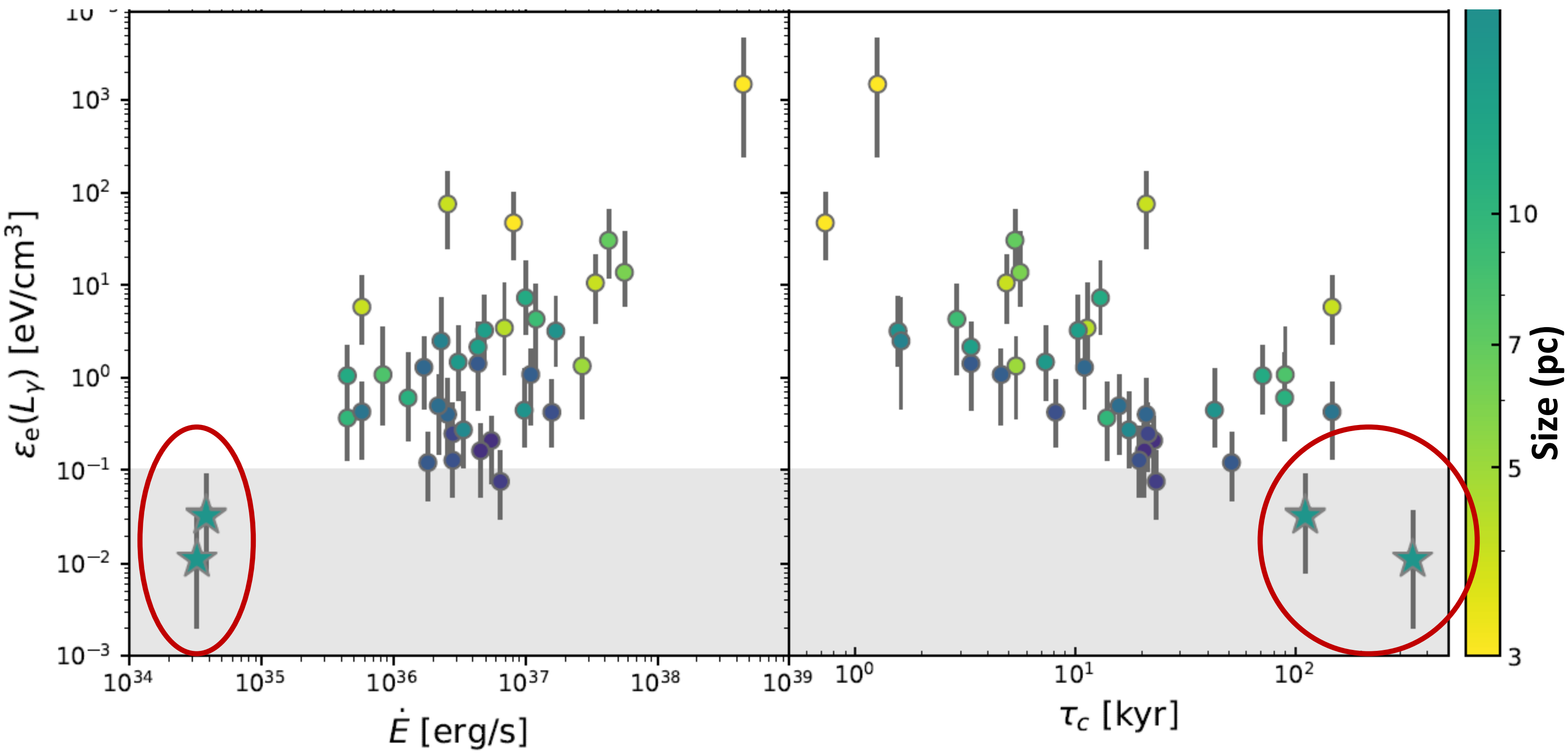
$L_{VHE} \sim Edot^{0.6}$

(High initial injection rate; accumulation; spinning down)



TeV PWN Population

- In young PWN, the local energy density ε_{PWN} dominates ε_{ISM}
- Different estimates for ε_{PWN} correlates: current Edot important for gamma-ray PWNe

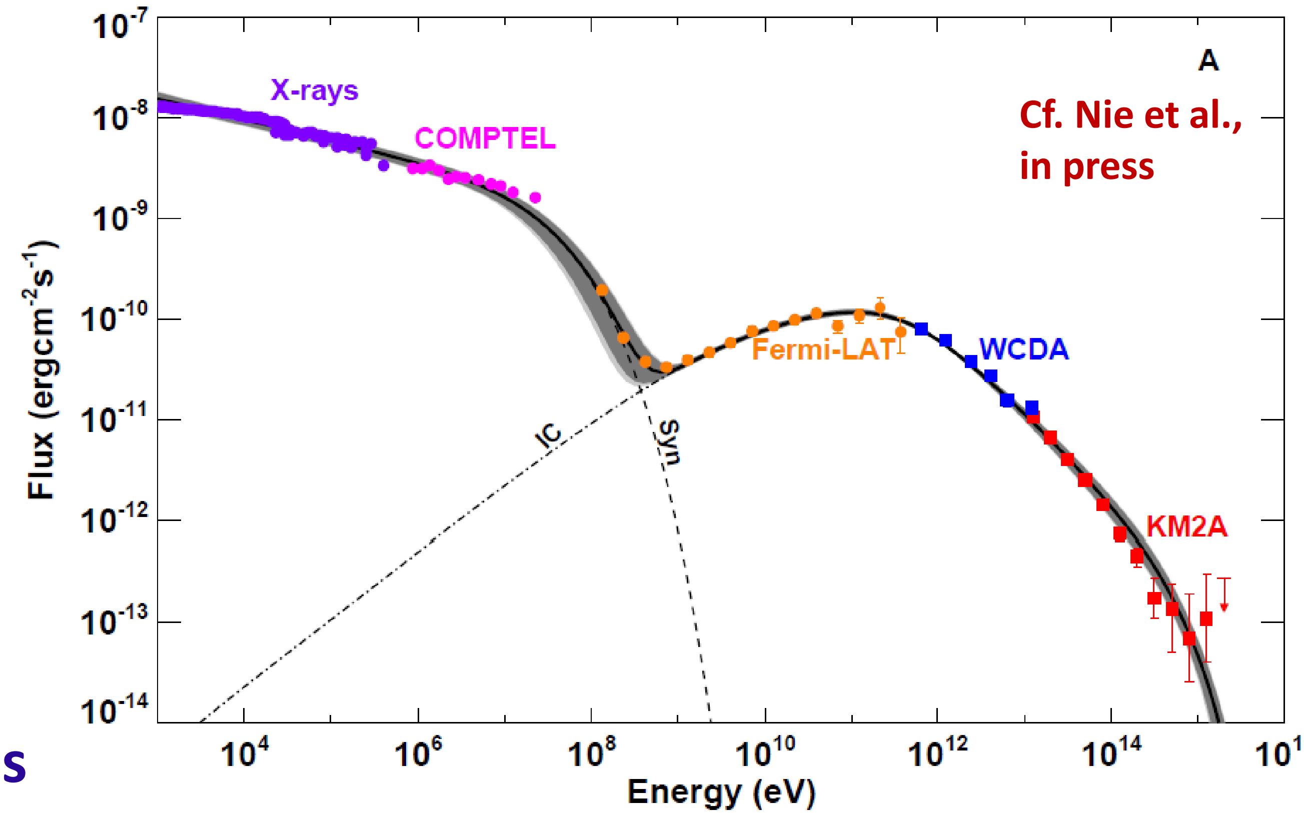


Giacinti et al. (2020)

PeV photons from Crab Nebula!

LHAASO, Cao et al. (2021)

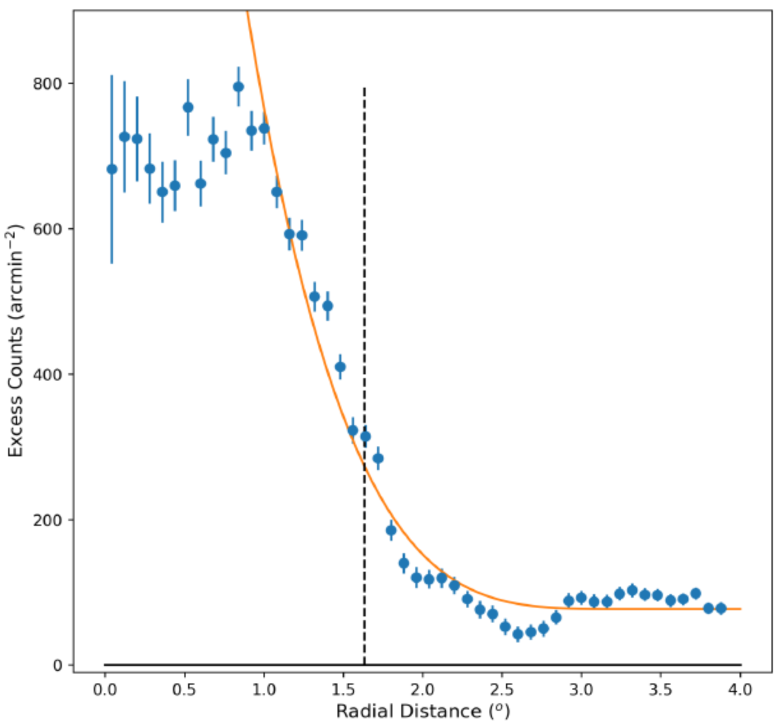
- Gradual steepening of spectrum (Γ ~2.5 @ 1 TeV; Γ ~ 3.7 @ 1 PeV)
- E^{γ}_{max} ~ 1 PeV (E^{KN}_{e} ~ 2 PeV)
- 0.5% of spindown
- Accelerator size ~ 0.1 pc
- B ~ 110 μG
- High acc. efficiency η – extra hadronic component?
- Not enough statistics to search for pulsations

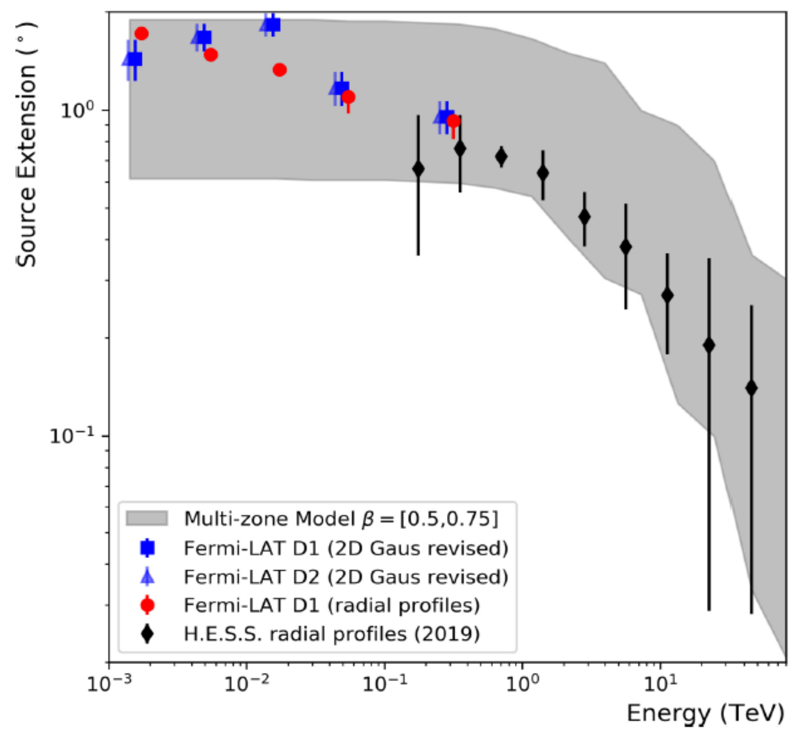


Cf. Nie et al., in press

Extended PWN HESS J1825-137

- **Analysis of 11.6 years of *Fermi* LAT (1 GeV and 1 TeV)**
- **Energy-dependent morphology, change in centroid opposite to PSR proper motion (older PWN or variable extension)**
- **Roughly constant size below cooling break, but cooling and proper motion influences size at higher energies; constrain velocity profile**

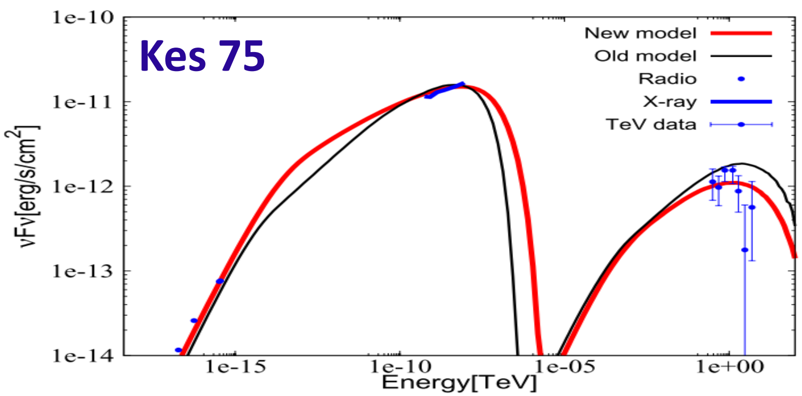


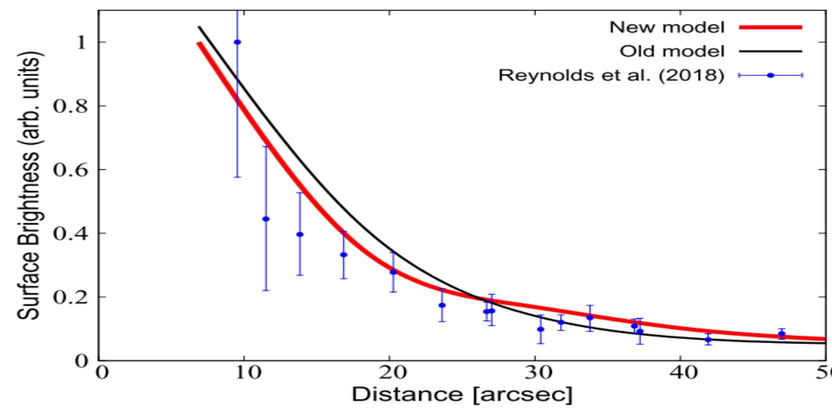


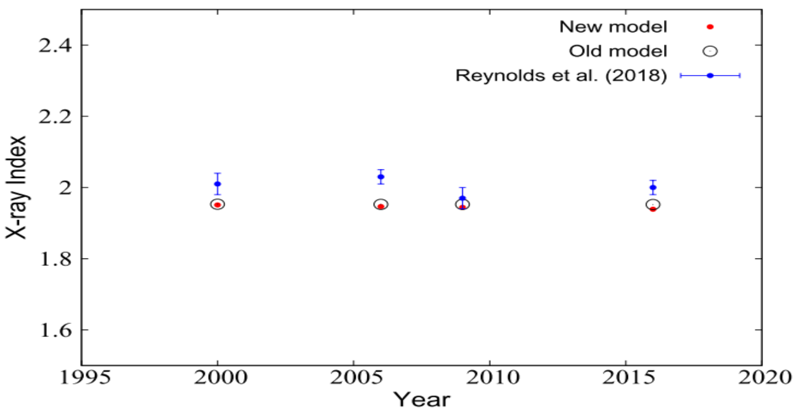
Principe et al. (2020)

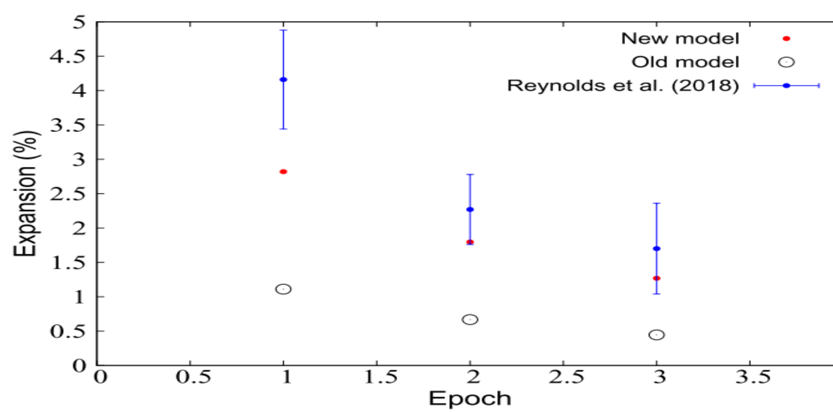
Spectro-morphological Studies

- **One of youngest composite SNRs, glitching PSR J1846–0258, which exhibited magnetar-like outbursts in 2006.**
- **Spatio-temporal leptonic emission code. Simulate the energy release from magnetar-like bursts: increase bulk speed for the last 50 years.**



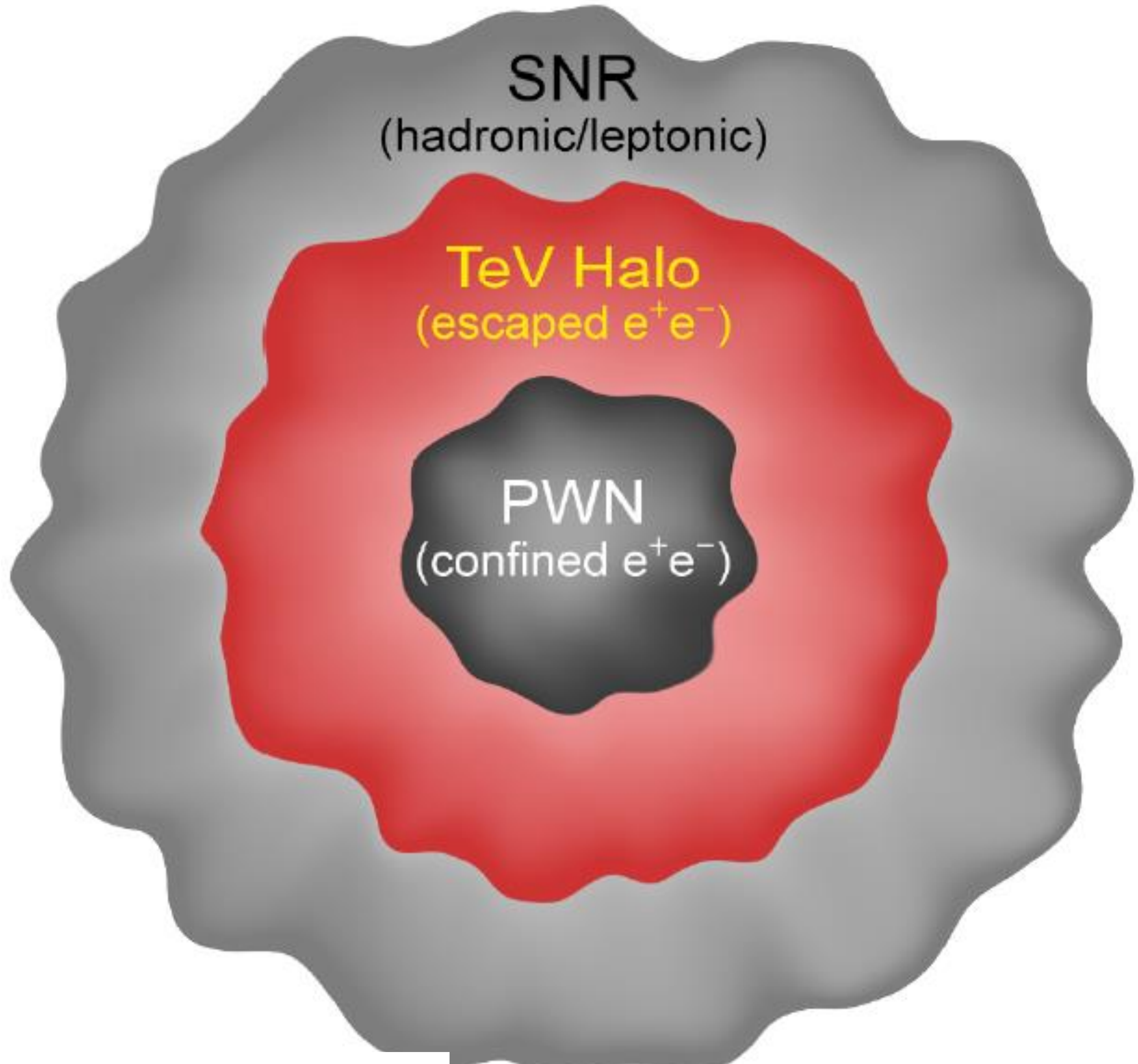






Kundu et al., in prep.

VHE PWN Halos

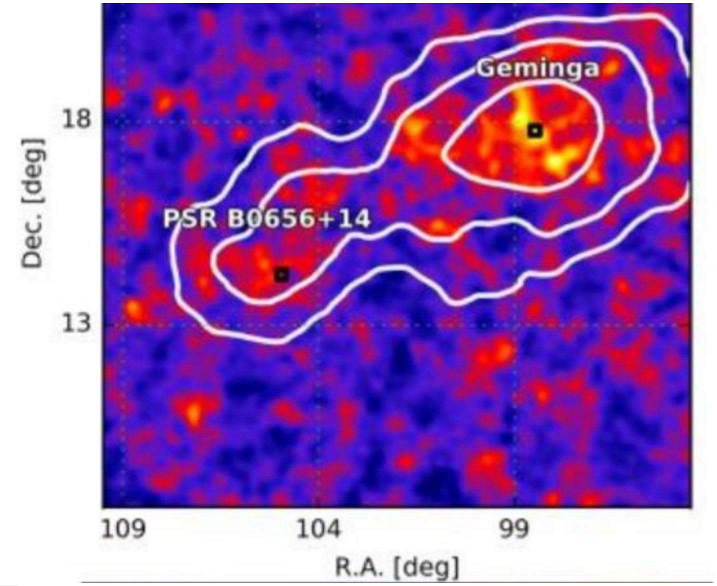


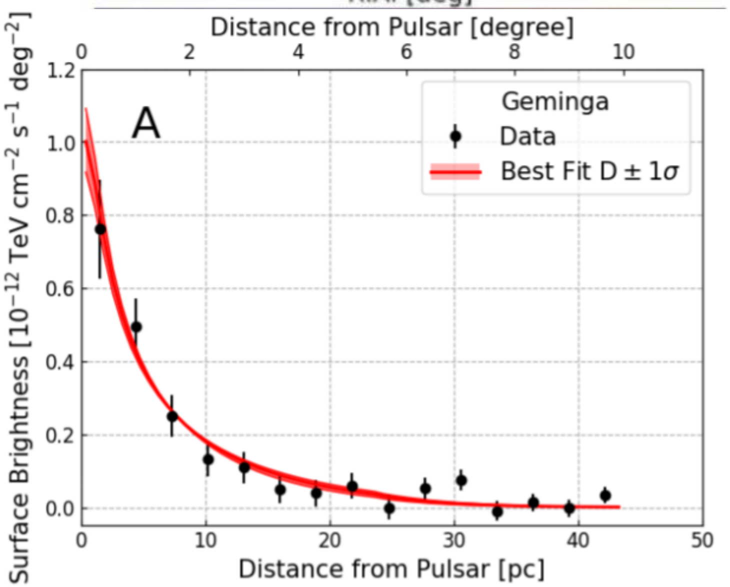
Sudoh et al. (2019)

Geminga, PSR B0656+14…

Cf. Talk by P. Huentemeyer; Abeysekara et al. (2017)

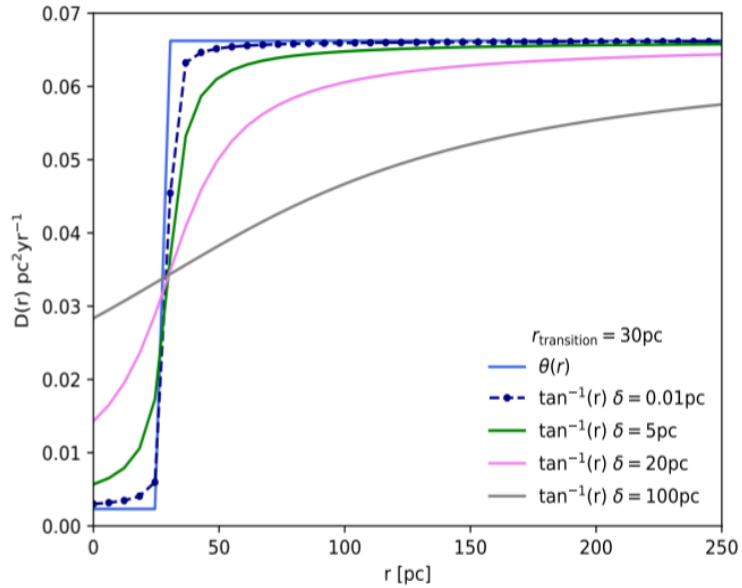
- HAWC detected extended TeV emission from Geminga and PSR B0656+14 (13σ and 8σ).
- Geminga previously seen by Milagro.
- E_{ph} ~ 20 TeV, E_e ~ 100 TeV. IC on CMB.
- Proton origin discounted (low matter densities required power exceeds spin-down).
- $D_{100} \sim E_e^{0.33} \sim 0.01 D_{ISM}$ (isotropic, homogeneous diffusion).
- Suppressing contribution to local positron flux?

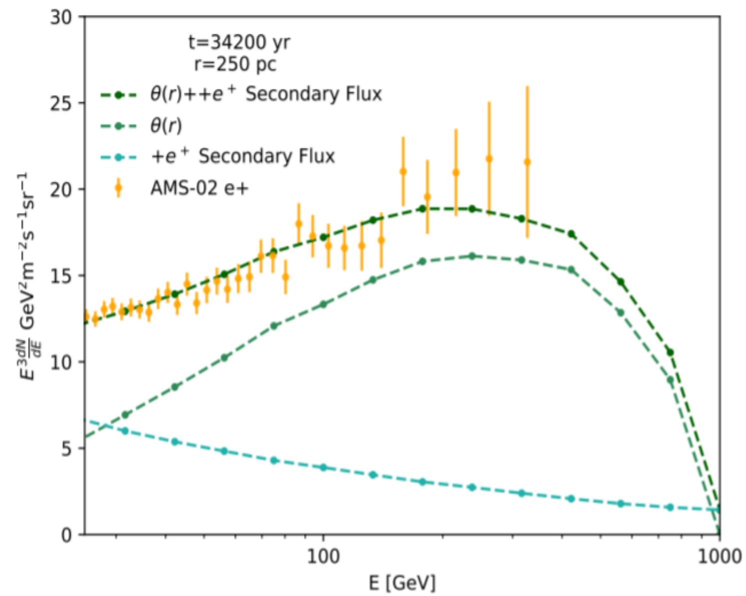




Geminga, PSR B0656+14…

- **Non-homogeneous D; 20 TeV e⁻ seen by H.E.S.S. imply larger local D.** — **Hooper & Linden (2018)**
- **Diffusion constant not constant (spatially non-homogeneous; pockets of inefficient diffusion?** — **Profumo et al. (2018)**
- **2-step D** — **Fang et al. (2018)**
- **MSP Halos (young PSRs)? GeV excess…** — **Hooper & Linden (2018)**
- **Constraints on magnetic turbulence** — **López-Coto & Giacinti (2018)**
- **Ballistic regime** — **Recchia et al. (2021)**
- **Halo fraction: generic for > 1e5 yr but low surface brightness** — **Giacinti et al. (2020)**



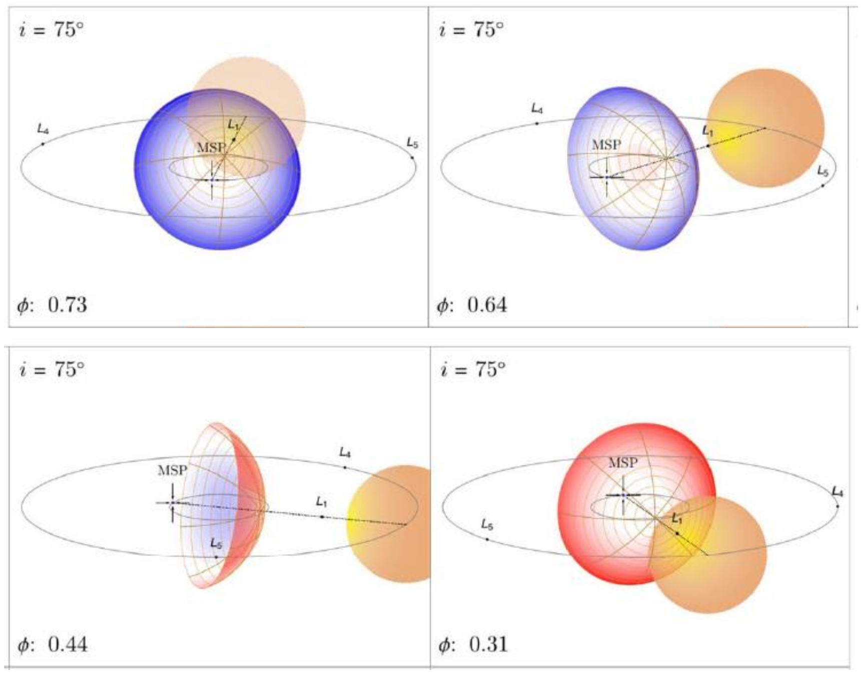


VHE Millisecond Pulsar Binaries

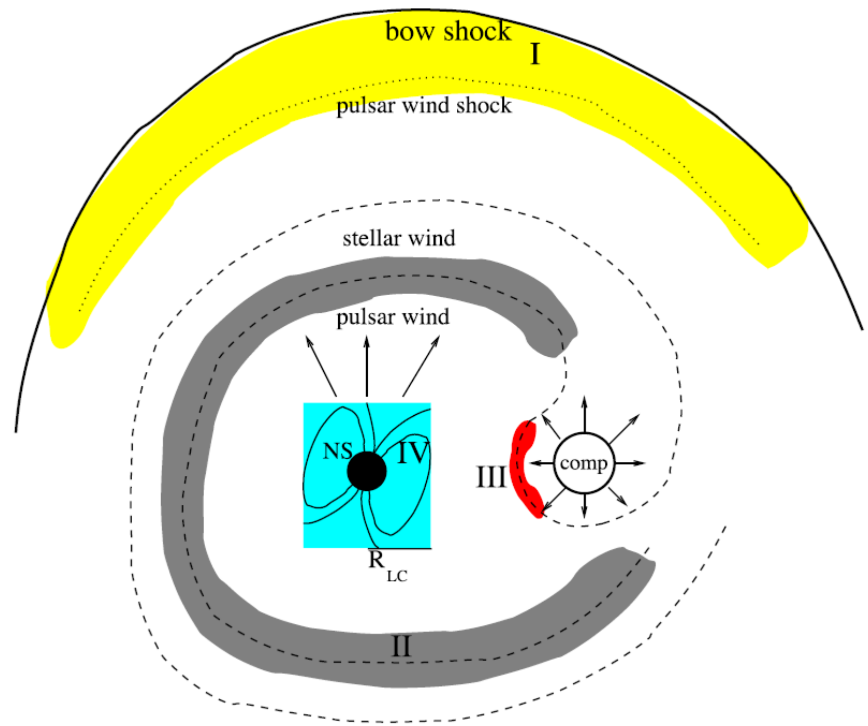
https://phys.org

Spider Binaries

- **Black widows and redbacks: MSP + tidally locked companion being ablated by pulsar wind**
- **P_b < 24h; flares on companion due to variable heating**
- **Intrabinary shock, mixing zone, bow shock are locations for particle acceleration**



Van der Merwe et al. (2020)

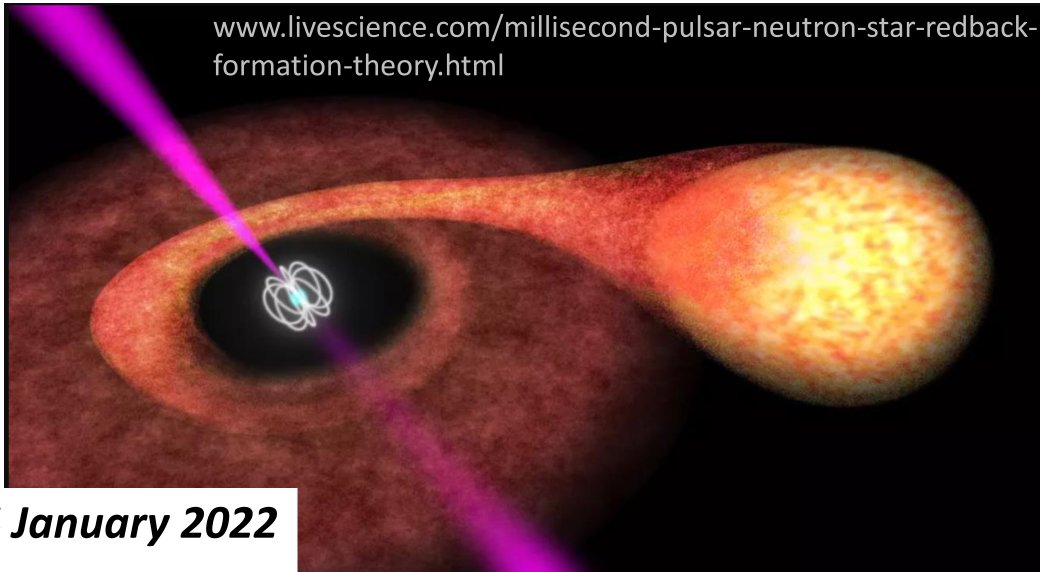


Ahnen et al. (2017)

Promising TeV Sources

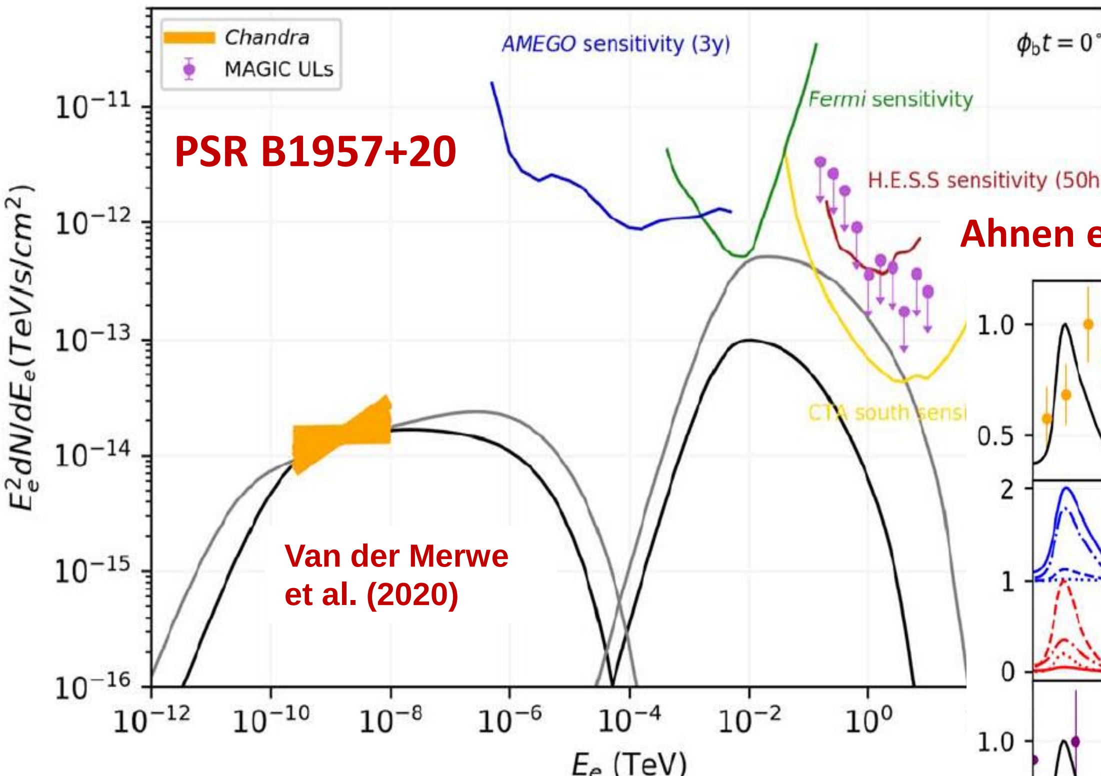
- Pulsar γ-ray binaries have eccentric orbits (often with long intervals between periastrons) while spiders have short, nearly circular orbits and probably stable shock geometry
- Pulsar radio timing and optical data from companion lead to well-constrained masses and orbital geometry
- Energetics: Edot ~ 1e35 erg/s permit multi-TeV electrons
- Nearby companion implies high energy density of target photons
- X-ray observations anchor particle spectrum, making TeV predictions more robust
- Contribution to positron fraction?

Wadiasingh et al. (2017, 2018, 2021); An et al. (2018); Kandel et al. (2019); Romani & Sanchez (2016); Linares & Kachelreiss (2021)

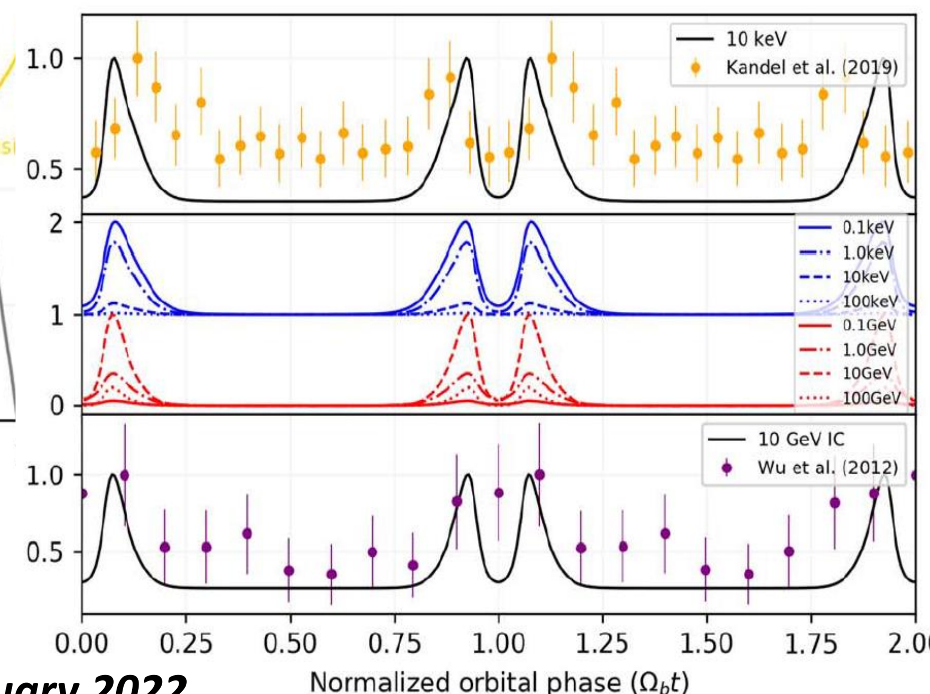


Modelling of Spider Binaries

- **Nearby MSP binaries with hot and flaring companions are promising candidates for orbitally-modulated TeV emission!**



Ahnen et al. (2017)

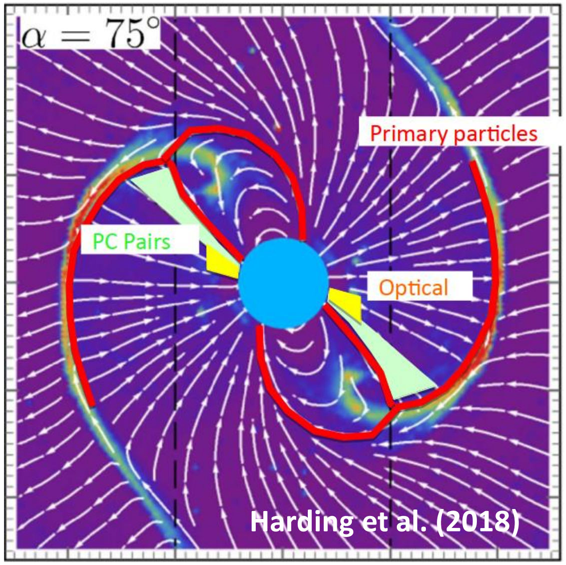


XXVII Cracow Epiphany Conference, 10 – 14 January 2022

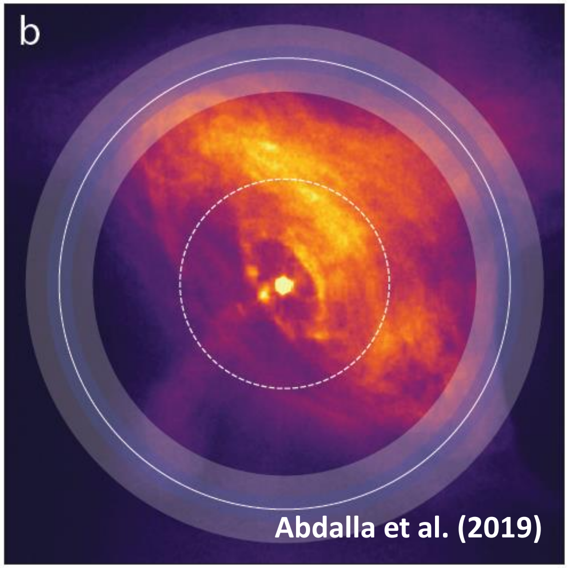
Role of CTA: PSR/PWN Science

Cf. Talk by R. Zanin

- **Pulsars**
  - ➢ Pulsed TeV emission from more sources; new spectral components (constrain shapes), improved TeV LCs (ΔE/E)
  - ➢ Electrodynamics (current structure, B-field geometry)
  - ➢ Acceleration mode, location
- **PWNe**
  - ➢ Population studies (sensitivity)
  - ➢ Constraint on spectral shape (wider energy range)
  - ➢ Energy-dependent, extended morphologies (FoV, res.)
  - ➢ Constraints on wind content and nebular geometry
- **PWN Halos**
  - ➢ Multi-step diffusion coefficient, mixing, particle acceleration and escape; evolutionary stages
  - ➢ Contribution to positron fraction (particle transport)
- **Pulsar Binaries**
  - ➢ TeV orbitally-modulated light curves; TeV variability?
  - ➢ Constraining IC spectrum
  - ➢ Particle acceleration and wind content



Harding et al. (2018)



Abdalla et al. (2019)

Conclusions

- Four pulsars detected by ground-based telescopes band so far: challenging models to consider new physics / geometries
- New pulsed SED component, or extension of GeV one?
- Growing population of PWNe: trends becoming clear
- Surprising PWN halo population with implications for terrestrial cosmic rays
- Exciting prospects for orbitally-modulated TeV signals from spider binaries that are bright and have flaring companions
- Continued measurements by current-generation Cherenkov telescopes + future CTA & multi-wavelength observations will continue to push the boundaries of our understanding of pulsar-related systems (and other sources)

“Who has measured the waters in the hollow of his hand, or with the breadth of his hand marked off the heavens? Who has held the dust of the earth in a basket, or weighed the mountains on the scales and the hills in a balance?” (Is. 40:12).