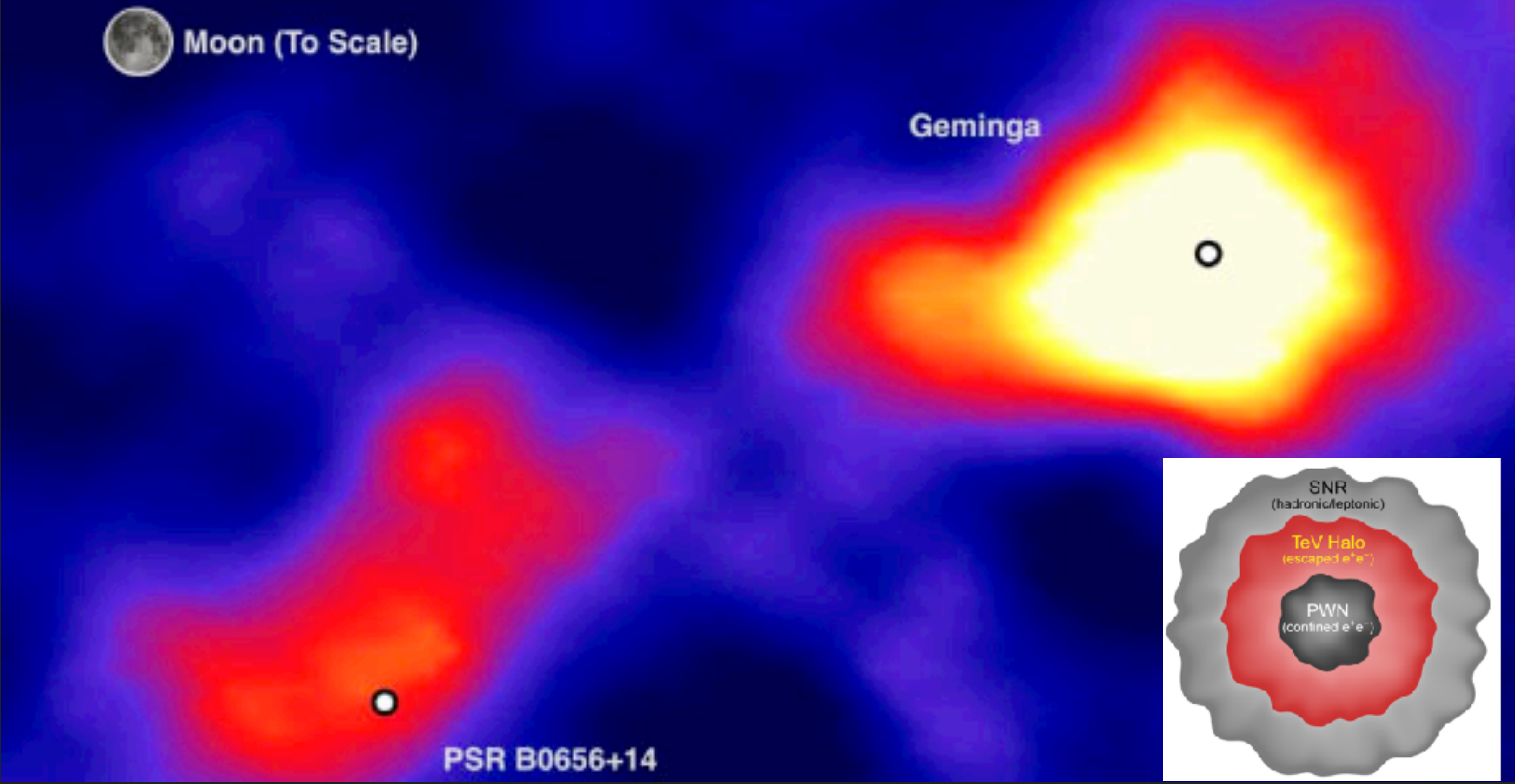


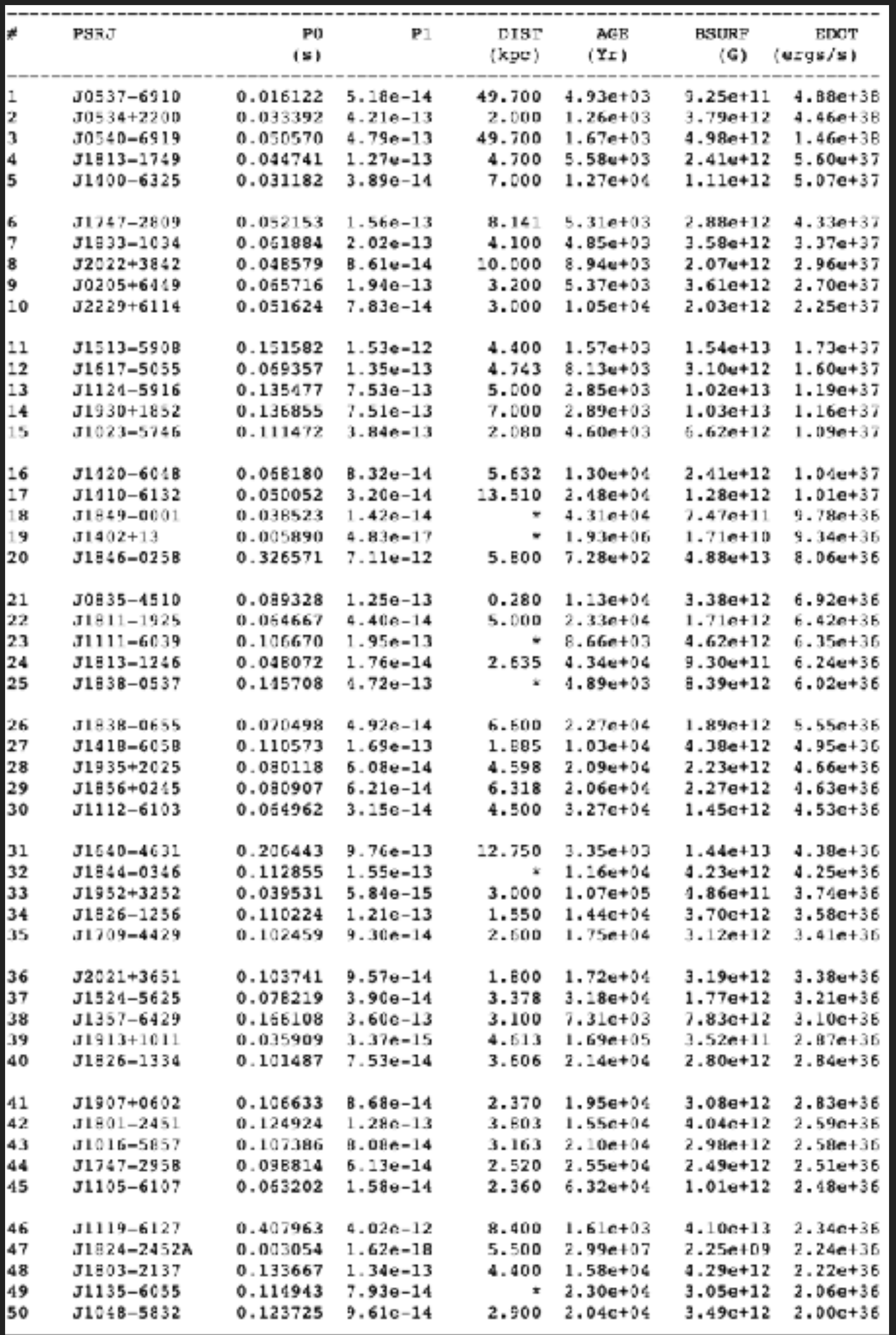
TeV Gamma-Rays From PWNe and TeV Halos

TIM LINDEN

Stockholm University

PULSARS AS A BATTERY

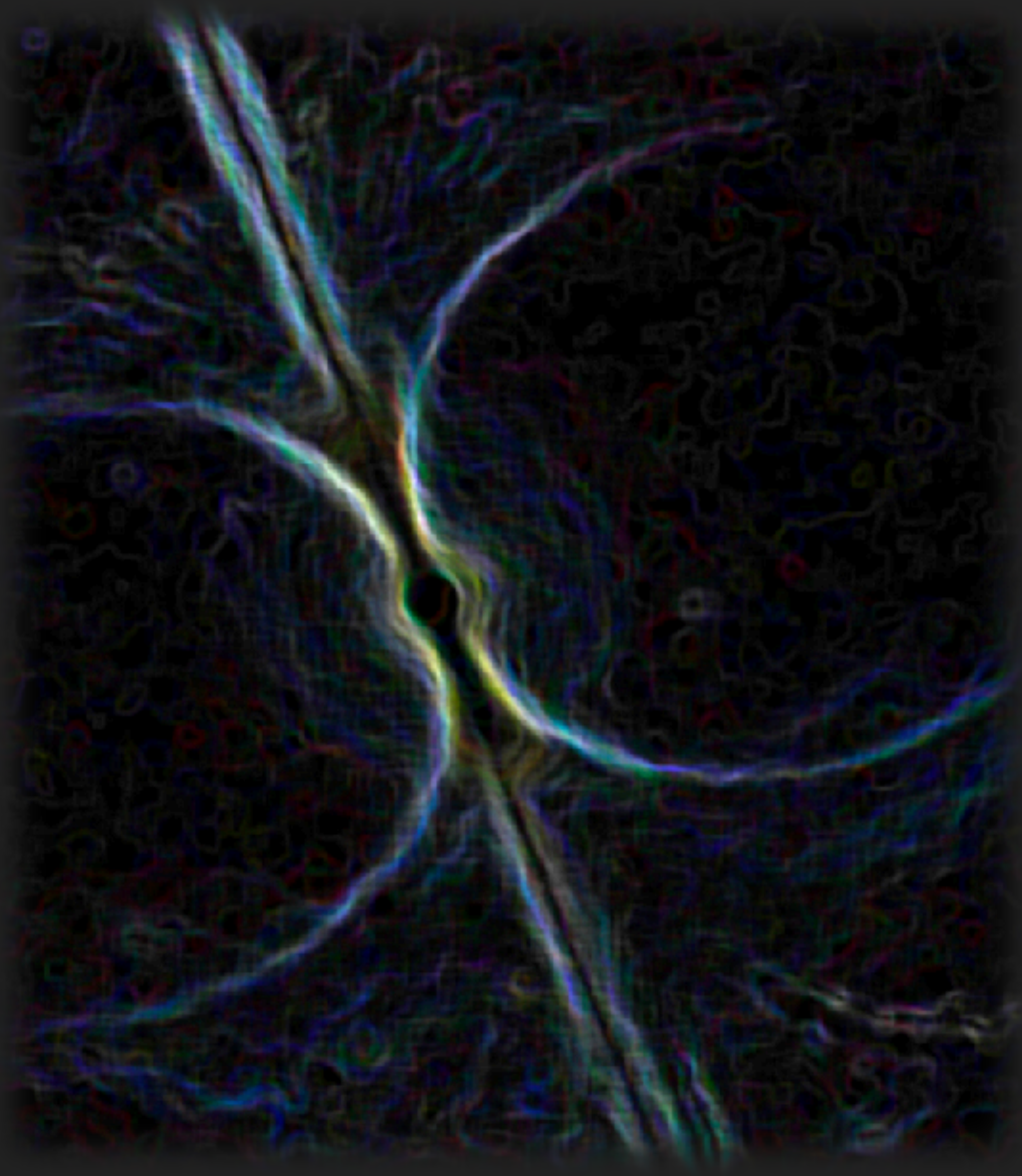
- Emission that is (at least primarily) powered by the rotational power of the pulsar.
- Precision studies are possible because that quantity is well-known.
- Also provides evidence of pulsar age, magnetic field, distance.
- Energetics of very young pulsars not known.
- Selection effects due to pulsar beaming are uncertain.



```
------------------------------------------------------------------------------------------
#     PSRJ                  P0         P1          DIST       AGE       BSURF       EDOT
                            (s)                    (kpc)      (Yr)        (G)   (ergs/s)
------------------------------------------------------------------------------------------
1     J0537-6910      0.016122  5.18e-14         49.700  4.93e+03   9.25e+11  4.88e+38
2     J0534+2200      0.033392  4.21e-13          2.000  1.26e+03   3.79e+12  4.46e+38
3     J0540-6919      0.050570  4.79e-13         49.700  1.67e+03   4.98e+12  1.46e+38
4     J1813-1749      0.044741  1.27e-13          4.700  5.58e+03   2.41e+12  5.60e+37
5     J1400-6325      0.031182  3.89e-14          7.000  1.27e+04   1.11e+12  5.07e+37

6     J1747-2809      0.052153  1.56e-13          8.141  5.31e+03   2.88e+12  4.33e+37
7     J1833-1034      0.061884  2.02e-13          4.100  4.85e+03   3.58e+12  3.37e+37
8     J2022+3842      0.048579  8.61e-14         10.000  8.94e+03   2.07e+12  2.96e+37
9     J0205+6449      0.065716  1.94e-13          3.200  5.37e+03   3.61e+12  2.70e+37
10    J2229+6114      0.051624  7.83e-14          3.000  1.05e+04   2.03e+12  2.25e+37

11    J1513-5908      0.151582  1.53e-12          4.400  1.57e+03   1.54e+13  1.73e+37
12    J1617-5055      0.069357  1.35e-13          4.743  8.13e+03   3.10e+12  1.60e+37
13    J1124-5916      0.135477  7.53e-13          5.000  2.85e+03   1.02e+13  1.19e+37
14    J1930+1852      0.136855  7.51e-13          7.000  2.89e+03   1.03e+13  1.16e+37
15    J1023-5746      0.111472  3.84e-13          2.080  4.60e+03   6.62e+12  1.09e+37

16    J1420-6048      0.068180  8.32e-14          5.632  1.30e+04   2.41e+12  1.04e+37
17    J1410-6132      0.050052  3.20e-14         13.510  2.48e+04   1.28e+12  1.01e+37
18    J1849-0001      0.038523  1.42e-14              *  4.31e+04   7.47e+11  9.78e+36
19    J1402+13        0.005890  4.83e-17              *  1.93e+06   1.71e+10  9.34e+36
20    J1846-0258      0.326571  7.11e-12          5.800  7.28e+02   4.88e+13  8.06e+36

21    J0835-4510      0.089328  1.25e-13          0.280  1.13e+04   3.38e+12  6.92e+36
22    J1811-1925      0.064667  4.40e-14          5.000  2.33e+04   1.71e+12  6.42e+36
23    J1111-6039      0.106670  1.95e-13              *  8.66e+03   4.62e+12  6.35e+36
24    J1813-1246      0.048072  1.76e-14          2.635  4.34e+04   9.30e+11  6.24e+36
25    J1838-0537      0.145708  4.72e-13              *  4.89e+03   8.39e+12  6.02e+36

26    J1838-0655      0.070498  4.92e-14          6.600  2.27e+04   1.89e+12  5.55e+36
27    J1418-6058      0.110573  1.69e-13          1.885  1.03e+04   4.38e+12  4.95e+36
28    J1935+2025      0.080118  6.08e-14          4.598  2.09e+04   2.23e+12  4.66e+36
29    J1856+0245      0.080907  6.21e-14          6.318  2.06e+04   2.27e+12  4.63e+36
30    J1112-6103      0.064962  3.15e-14          4.500  3.27e+04   1.45e+12  4.53e+36

31    J1640-4631      0.206443  9.76e-13         12.750  3.35e+03   1.44e+13  4.38e+36
32    J1844-0346      0.112855  1.55e-13              *  1.16e+04   4.23e+12  4.25e+36
33    J1952+3252      0.039531  5.84e-15          3.000  1.07e+05   4.86e+11  3.74e+36
34    J1826-1256      0.110224  1.21e-13          1.550  1.44e+04   3.70e+12  3.58e+36
35    J1709-4429      0.102459  9.30e-14          2.600  1.75e+04   3.12e+12  3.41e+36

36    J2021+3651      0.103741  9.57e-14          1.800  1.72e+04   3.19e+12  3.38e+36
37    J1524-5625      0.078219  3.90e-14          3.378  3.18e+04   1.77e+12  3.21e+36
38    J1357-6429      0.166108  3.60e-13          3.100  7.31e+03   7.83e+12  3.10e+36
39    J1913+1011      0.035909  3.37e-15          4.613  1.69e+05   3.52e+11  2.87e+36
40    J1826-1334      0.101487  7.53e-14          3.606  2.14e+04   2.80e+12  2.84e+36

41    J1907+0602      0.106633  8.68e-14          2.370  1.95e+04   3.08e+12  2.83e+36
42    J1801-2451      0.124924  1.28e-13          3.803  1.55e+04   4.04e+12  2.59e+36
43    J1016-5857      0.107386  8.08e-14          3.163  2.10e+04   2.98e+12  2.58e+36
44    J1747-2958      0.098814  6.13e-14          2.520  2.55e+04   2.49e+12  2.51e+36
45    J1105-6107      0.063202  1.58e-14          2.360  6.32e+04   1.01e+12  2.48e+36

46    J1119-6127      0.407963  4.02e-12          8.400  1.61e+03   4.10e+13  2.34e+36
47    J1824-2452A     0.003054  1.62e-18          5.500  2.99e+07   2.25e+09  2.24e+36
48    J1803-2137      0.133667  1.34e-13          4.400  1.58e+04   4.29e+12  2.22e+36
49    J1135-6055      0.114943  7.93e-14              *  2.30e+04   3.05e+12  2.06e+36
50    J1048-5832      0.123725  9.61e-14          2.900  2.04e+04   3.49e+12  2.00e+36
```

MULTIPLE MECHANISMS FOR GAMMA-RAY PRODUCTION: PULSAR MAGNETOSPHERE

- Critical e^+e^- creation point is the pulsar magnetosphere.
  - 1.) Electrons “boiled” off the pulsar surface, and accelerated to TeV-PeV energies.
  - 2.) Synchrotron emission produces e^+e^- pairs which then cascade to produce a high e^+e^- multiplicity.
  - 3.) Ratio of e^+ to e^- leaving pulsar may not be 1:1.



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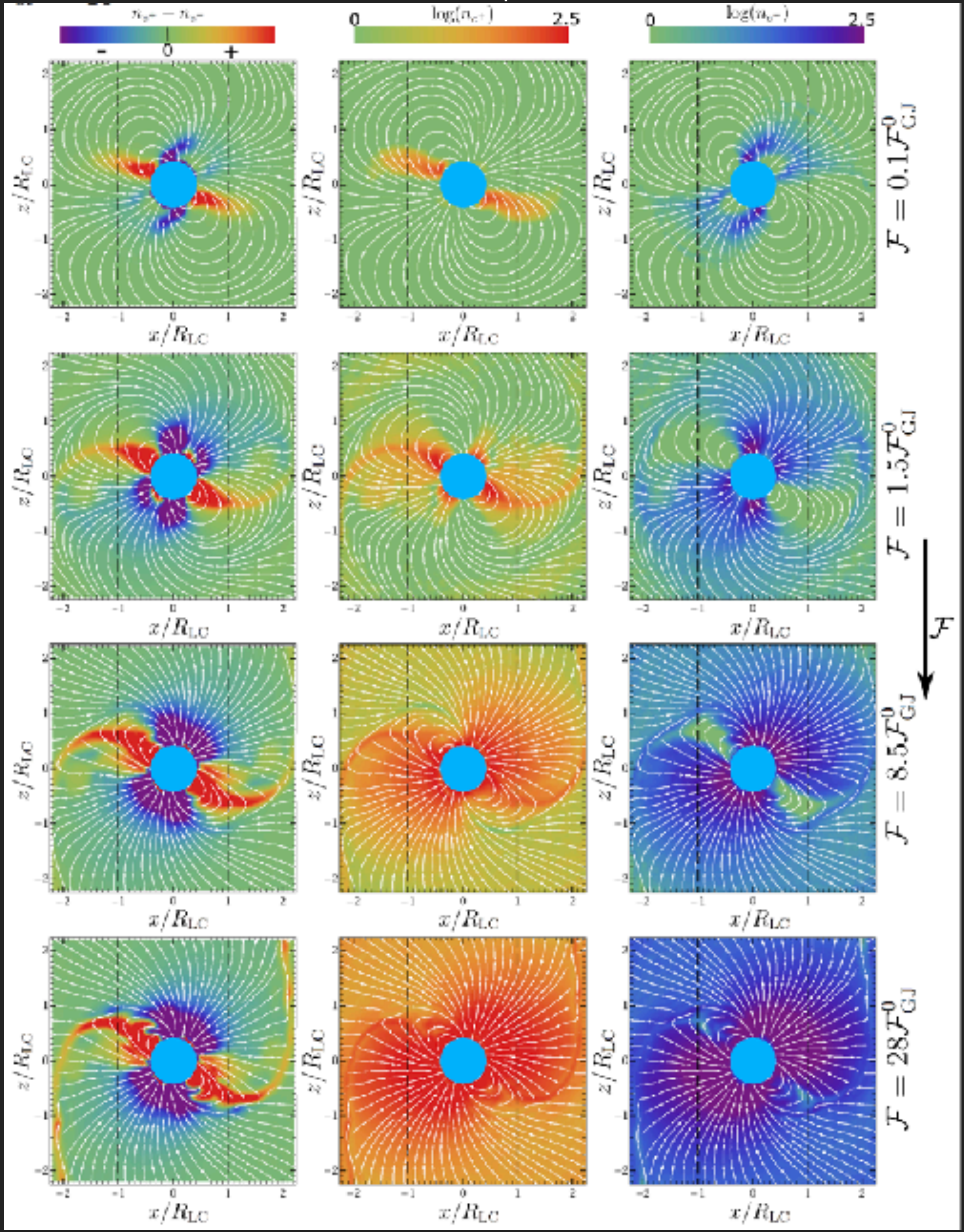
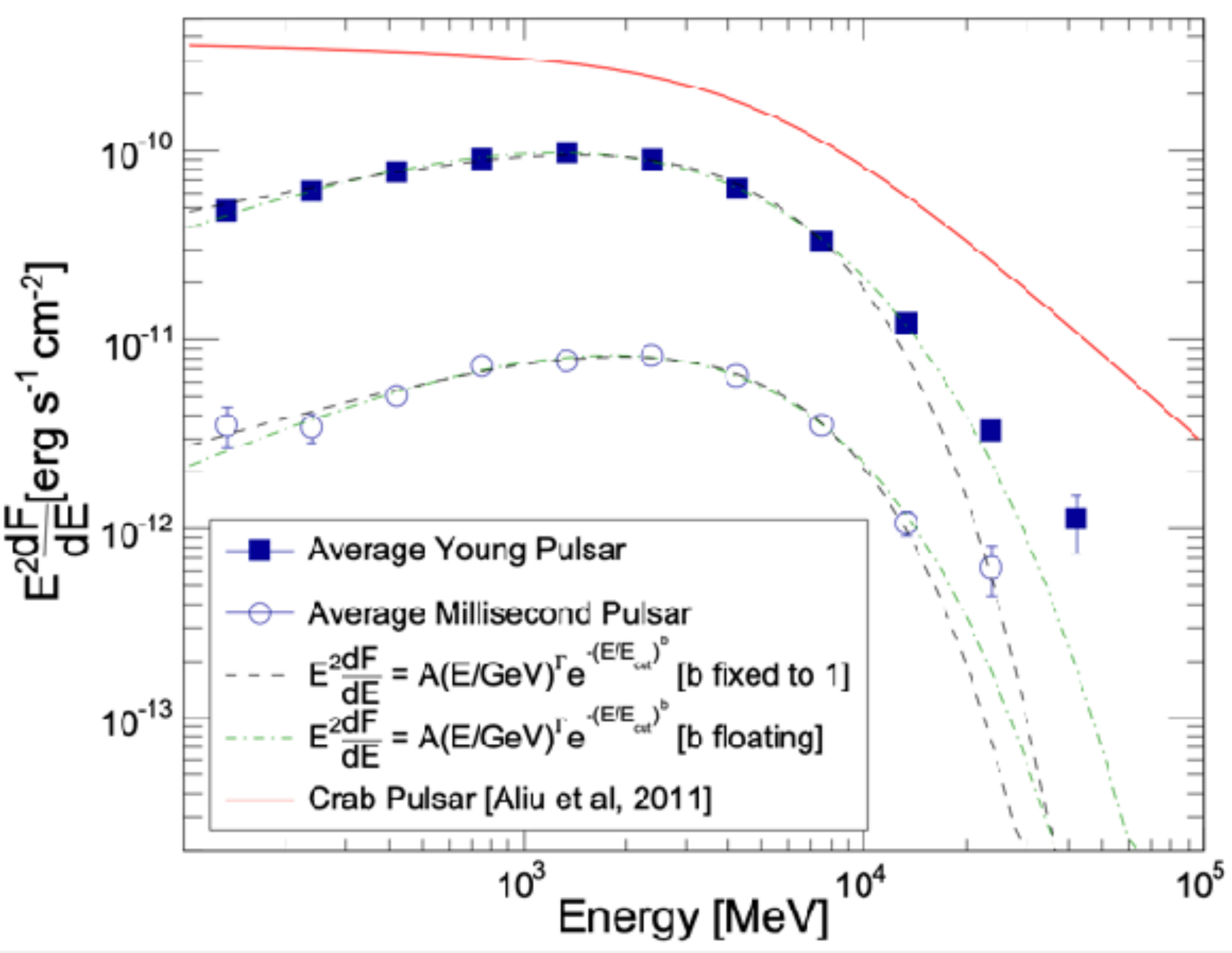


Kalapotharakos et al. (2017; 1710.03170)

MULTIPLE MECHANISMS FOR GAMMA-RAY PRODUCTION: PULSAR MAGNETOSPHERE



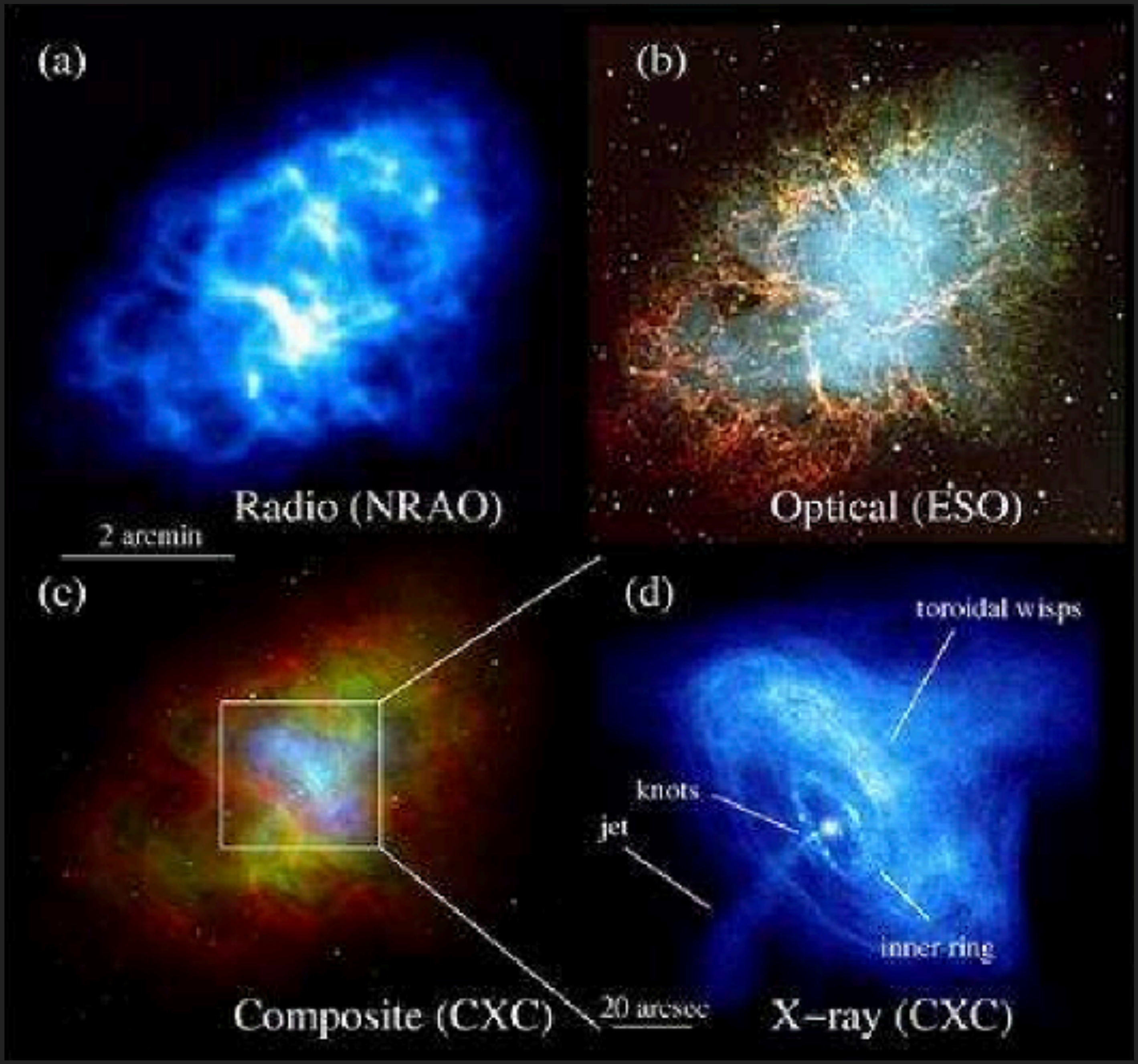
McCann (2014; 1412.2422)

- Critical e^+e^- creation point is the pulsar magnetosphere.
    - Interestingly - many pulsars have similar gamma-ray spectra.

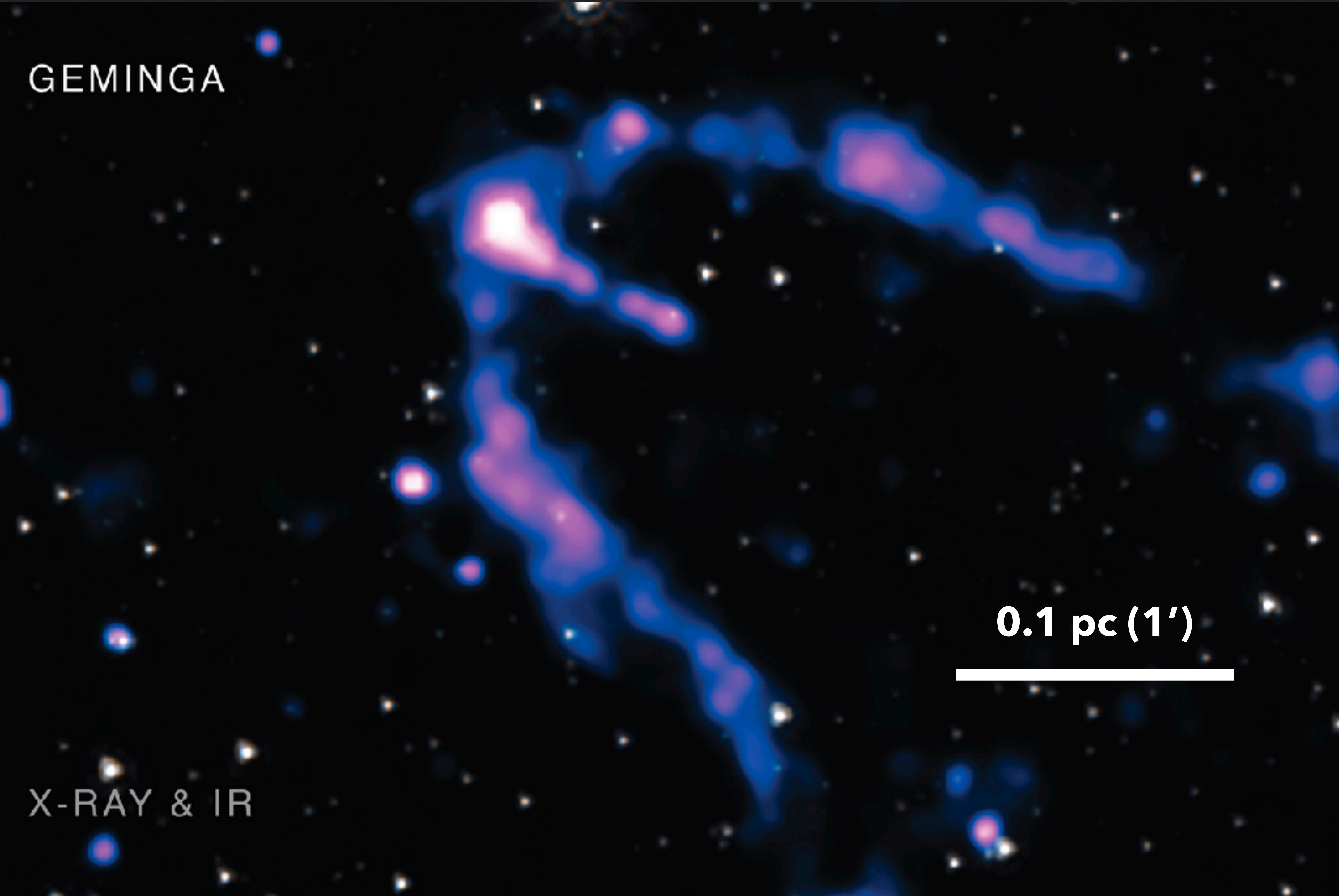
MULTIPLE MECHANISMS FOR GAMMA-RAY PRODUCTION: PULSAR WIND NEBULA

- These e+e- are then propelled outward in a wind
- Complex interplay between PWN and SNR
  - Free Expansion Phase
  - Sedov Phase
  - ISM Phase
- Reacceleration of e+e- and final electron spectrum not well understood.

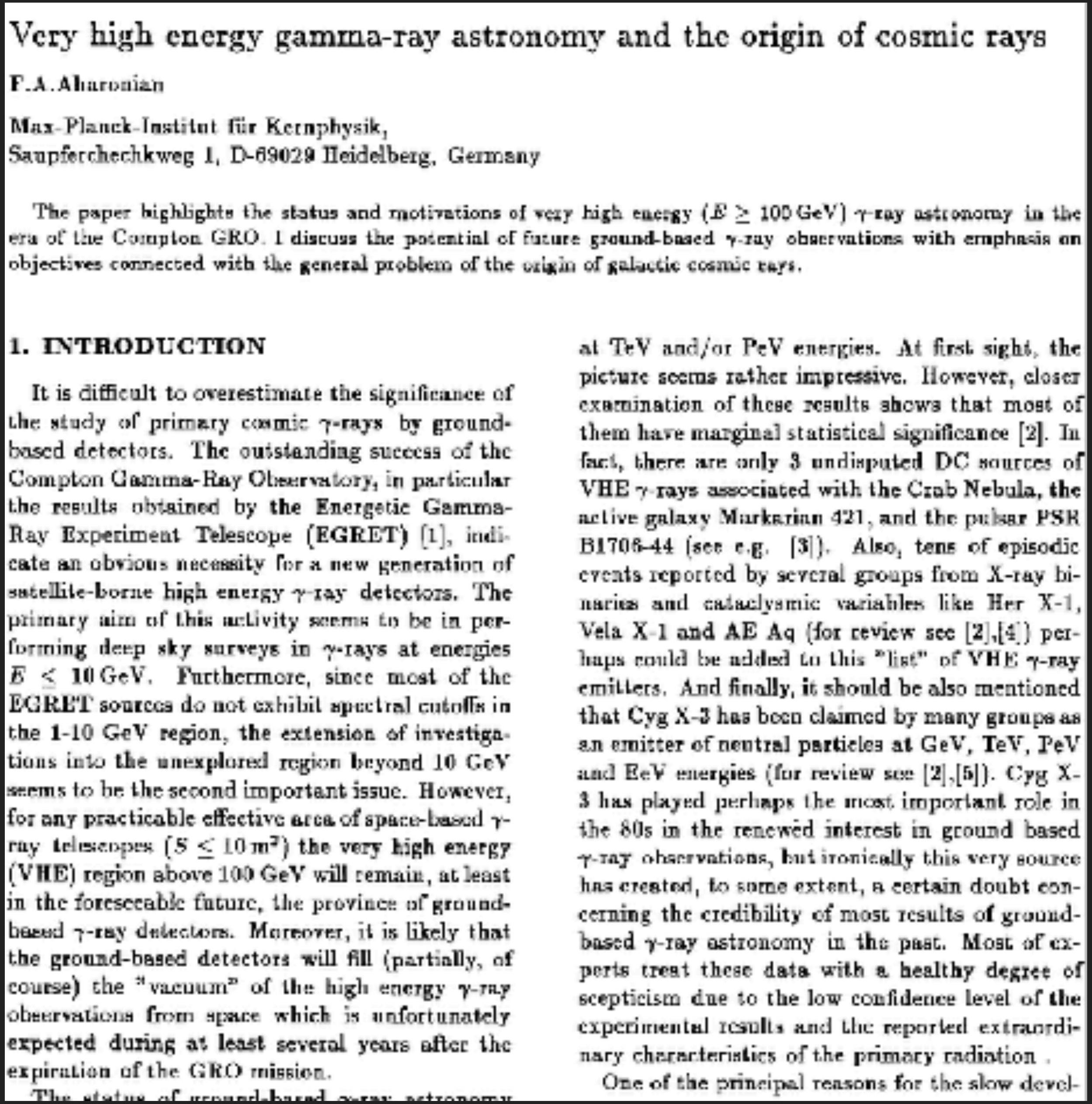
Gaensler & Slane (2006; astro-ph/0601081)



MULTIPLE MECHANISMS FOR GAMMA-RAY PRODUCTION: PULSAR WIND NEBULA



WHAT HAPPENS WHEN THESE ELECTRONS EVENTUALLY ESCAPE?



Very high energy gamma-ray astronomy and the origin of cosmic rays

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The paper highlights the status and motivations of very high energy ($E \geq 100$ GeV) γ-ray astronomy in the era of the Compton GRO. I discuss the potential of future ground-based γ-ray observations with emphasis on objectives connected with the general problem of the origin of galactic cosmic rays.

1. INTRODUCTION

It is difficult to overestimate the significance of the study of primary cosmic γ-rays by ground-based detectors. The outstanding success of the Compton Gamma-Ray Observatory, in particular the results obtained by the Energetic Gamma-Ray Experiment Telescope (EGRET) [1], indicate an obvious necessity for a new generation of satellite-borne high energy γ-ray detectors. The primary aim of this activity seems to be in performing deep sky surveys in γ-rays at energies $E \leq 10$ GeV. Furthermore, since most of the EGRET sources do not exhibit spectral cutoffs in the 1-10 GeV region, the extension of investigations into the unexplored region beyond 10 GeV seems to be the second important issue. However, for any practicable effective area of space-based γ-ray telescopes ($S \leq 10\ \mathrm{m}^2$) the very high energy (VHE) region above 100 GeV will remain, at least in the foreseeable future, the province of ground-based γ-ray detectors. Moreover, it is likely that the ground-based detectors will fill (partially, of course) the "vacuum" of the high energy γ-ray observations from space which is unfortunately expected during at least several years after the expiration of the GRO mission.

The status of ground-based γ-ray astronomy

at TeV and/or PeV energies. At first sight, the picture seems rather impressive. However, closer examination of these results shows that most of them have marginal statistical significance [2]. In fact, there are only 3 undisputed DC sources of VHE γ-rays associated with the Crab Nebula, the active galaxy Markarian 421, and the pulsar PSR B1706-44 (see e.g. [3]). Also, tens of episodic events reported by several groups from X-ray binaries and cataclysmic variables like Her X-1, Vela X-1 and AE Aq (for review see [2],[4]) perhaps could be added to this "list" of VHE γ-ray emitters. And finally, it should be also mentioned that Cyg X-3 has been claimed by many groups as an emitter of neutral particles at GeV, TeV, PeV and EeV energies (for review see [2],[5]). Cyg X-3 has played perhaps the most important role in the 80s in the renewed interest in ground based γ-ray observations, but ironically this very source has created, to some extent, a certain doubt concerning the credibility of most results of ground-based γ-ray astronomy in the past. Most of experts treat these data with a healthy degree of scepticism due to the low confidence level of the experimental results and the reported extraordinary characteristics of the primary radiation .

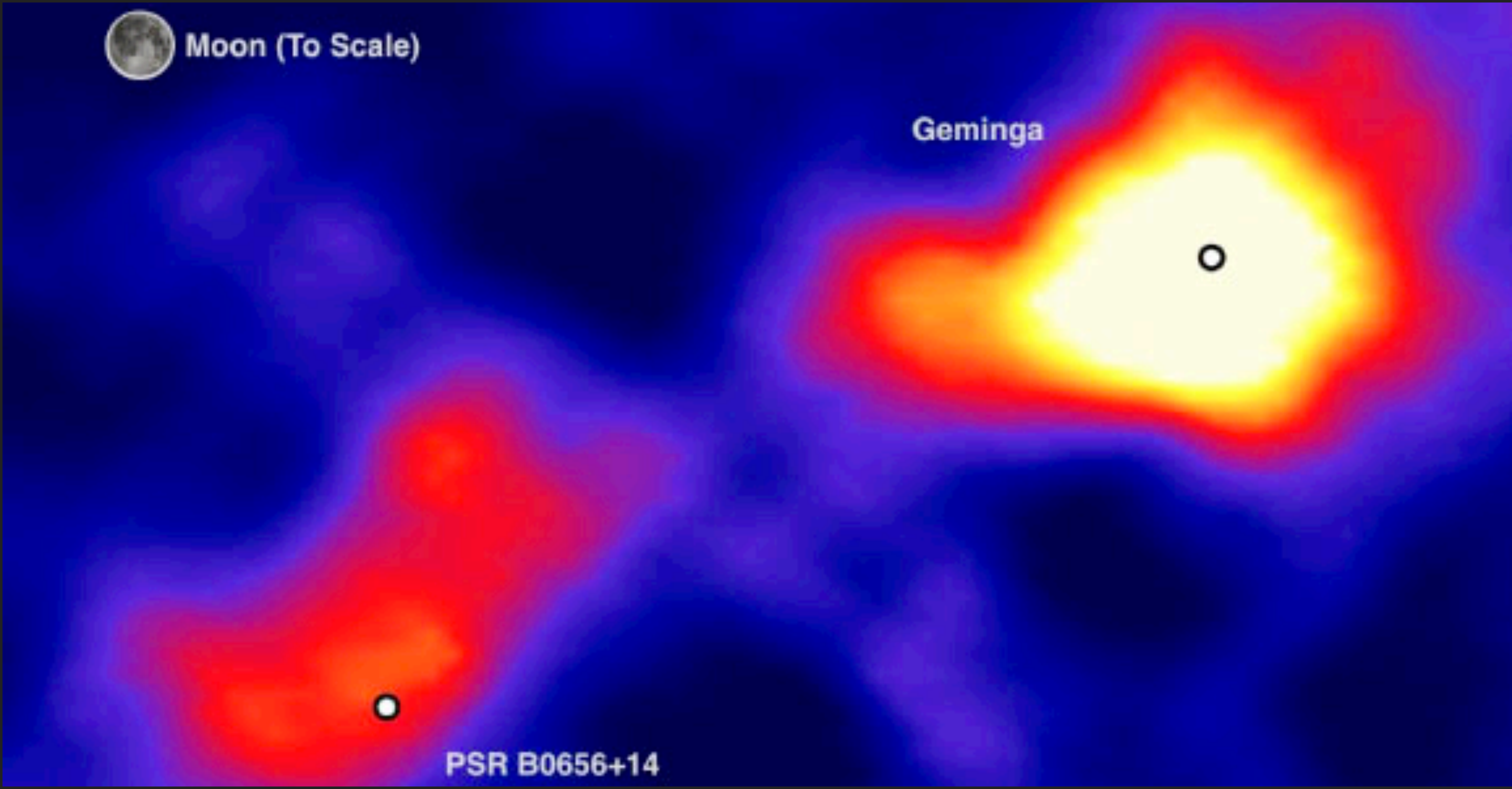
One of the principal reasons for the slow devel-

- Lifetime of TeV electrons is longer than lifetime of PWN:

$$\tau_{e+e-} = 130 \left(\frac{1\ \mathrm{TeV}}{E}\right) \left(\frac{10\ \mu\mathrm{G}}{B}\right)^2\ \mathrm{kyr}$$

- These electrons must escape - and propagate through the ISM.
- Propagation through ISM is very efficient.

MULTIPLE MECHANISMS FOR GAMMA-RAY PRODUCTION: TEV HALO



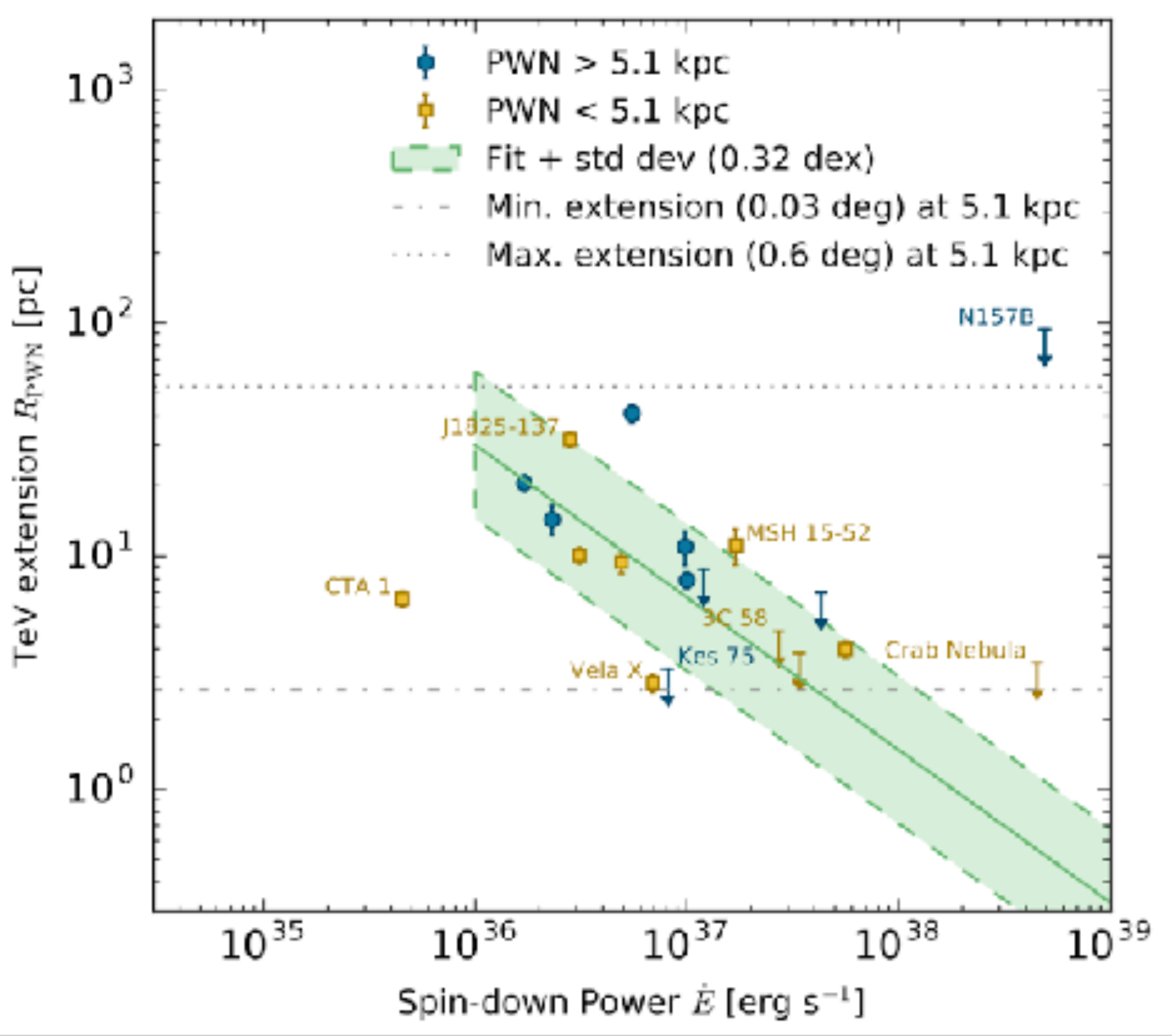
- Emission Region is much larger – but not <u>too</u> large.

MULTIPLE MECHANISMS FOR GAMMA-RAY PRODUCTION: TEV HALO

- In addition to being much larger – the evolution of the morphology is very different

PWN in the ISM have a radius that is proportional to spindown power.

$$R_{\rm PWN} \simeq 1.5 \left(\frac{\dot{E}}{10^{35}\,{\rm erg/s}}\right)^{1/2} \times \left(\frac{n_{\rm gas}}{1\,{\rm cm}^{-3}}\right)^{-1/2} \left(\frac{v}{100\,{\rm km/s}}\right)^{-3/2} {\rm pc}$$



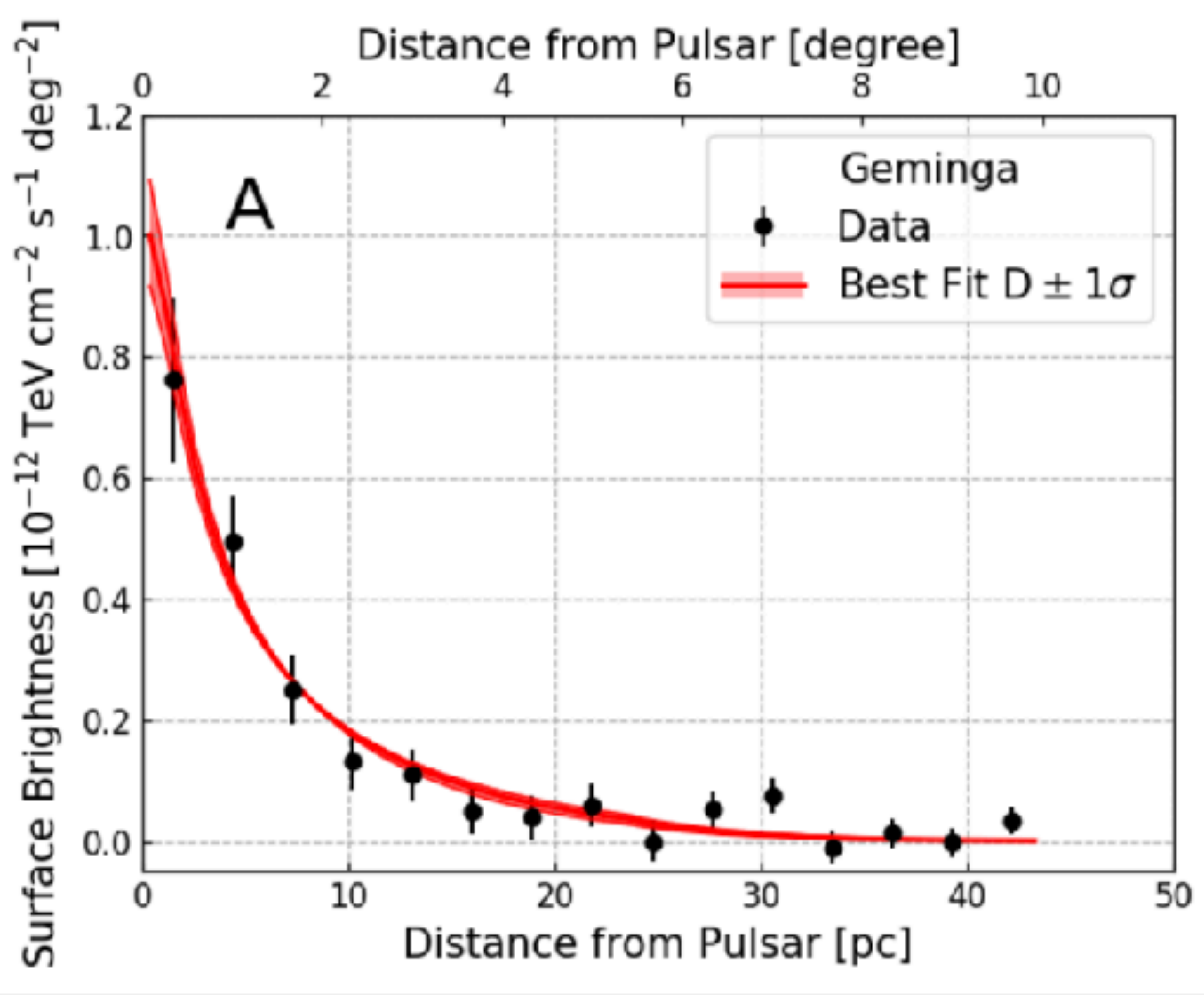
TeV Halos have an extension that is inversely proportional to spindown power (perhaps, proportional to age).

THE DIVIDING LINE BETWEEN THE PWN AND THE TEV HALO

- Emission Profile is consistent with particle diffusion

- Strong evidence that particles are propagating through turbulent magnetic fields.

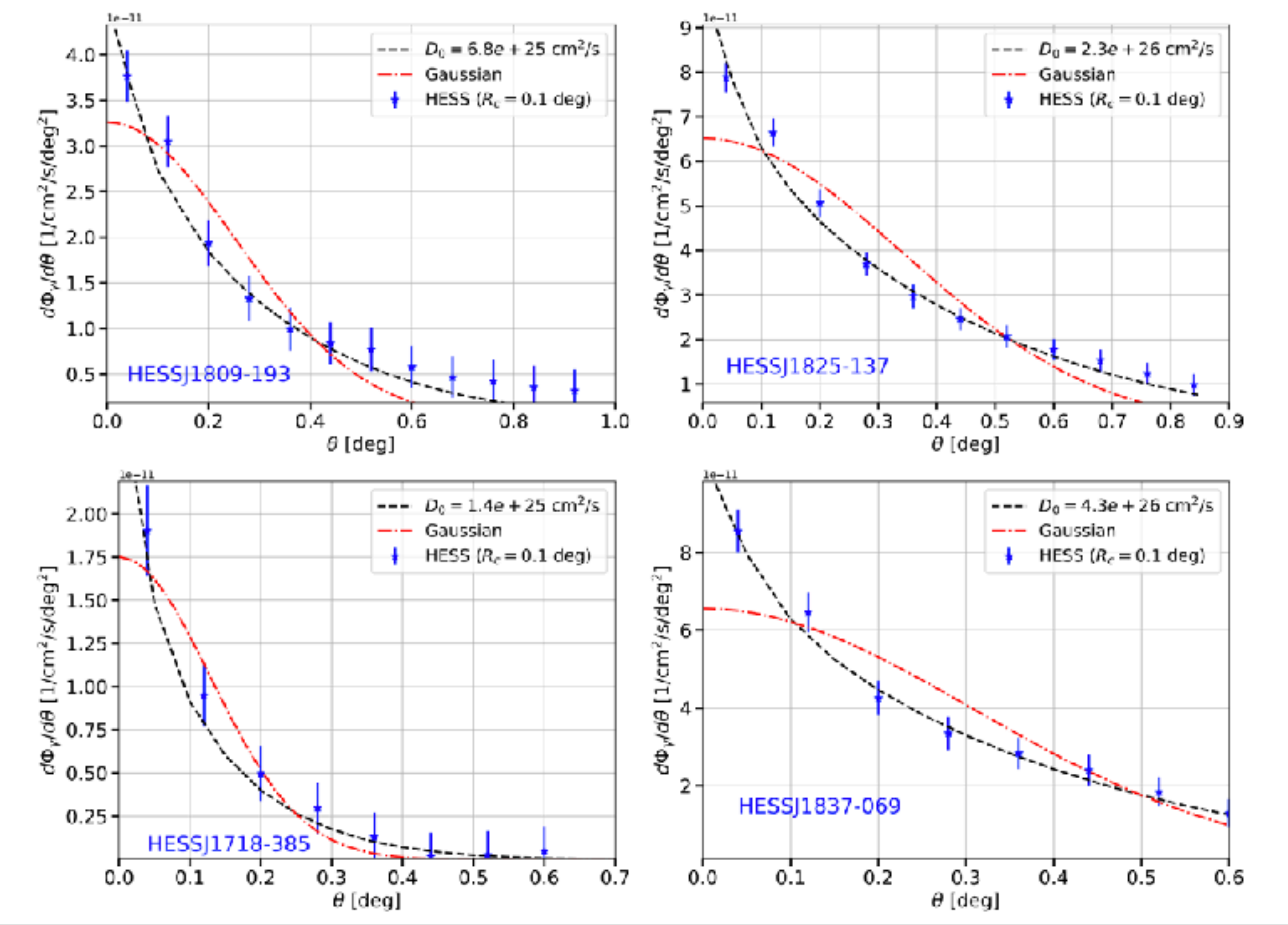
Abeysekara et al. (2017; 1711.06223)



- But diffusion coefficient 2-orders of magnitude smaller than ISM!

THE DIVIDING LINE BETWEEN THE PWN AND THE TEV HALO

Di Mauro, Manconi, Donato (2019; 1908.03216)

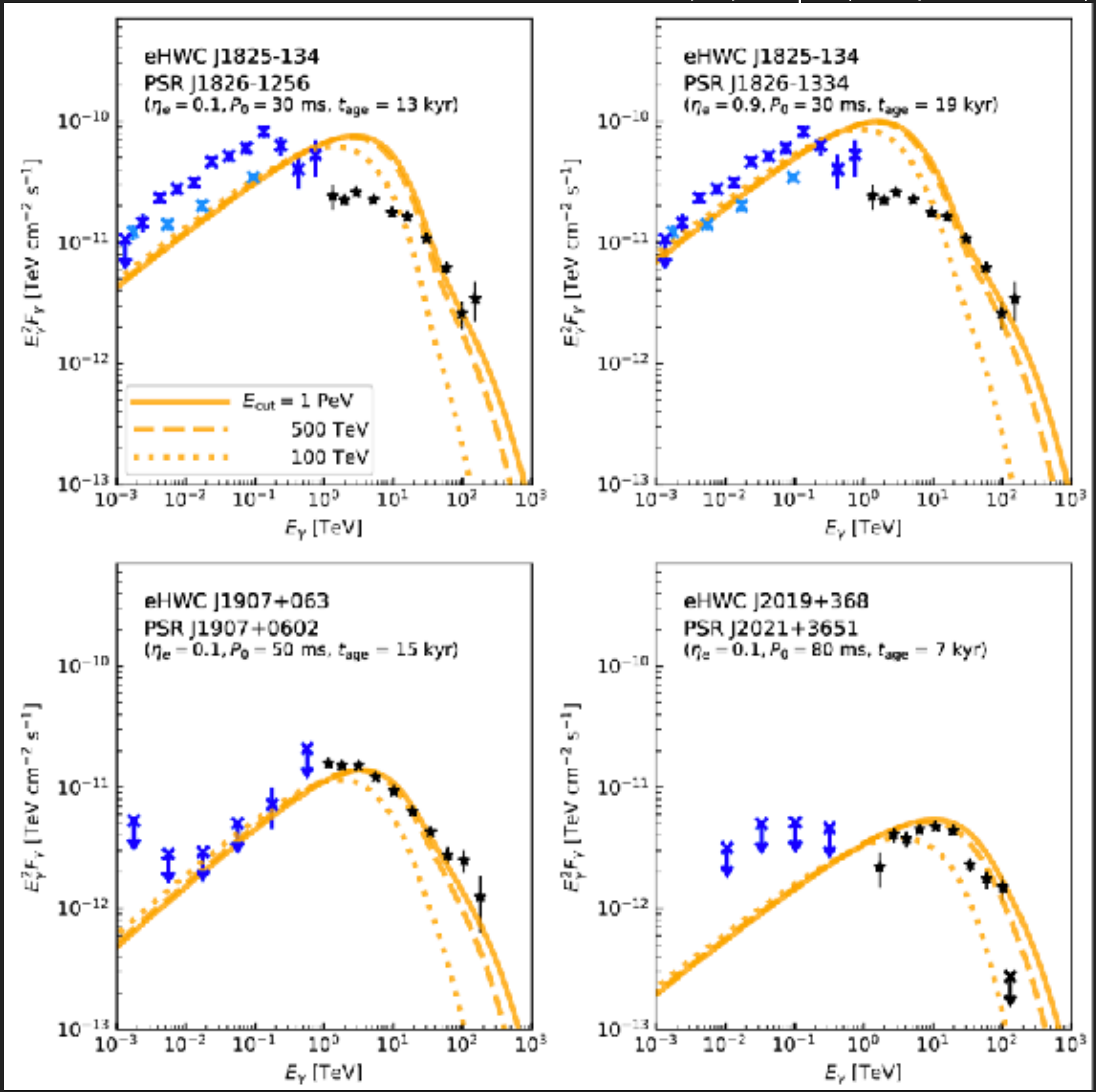


- This is <u>not</u> unique to Geminga and Monogem

THE DIVIDING LINE BETWEEN THE PWN AND THE TEV HALO

- 8 out of 9 HAWC sources above 56 TeV are consistent with pulsars.
- Most have spectra more consistent with leptonic, rather than hadronic, emission.

Sudoh, TL, Hooper (2021; 2101.11026)



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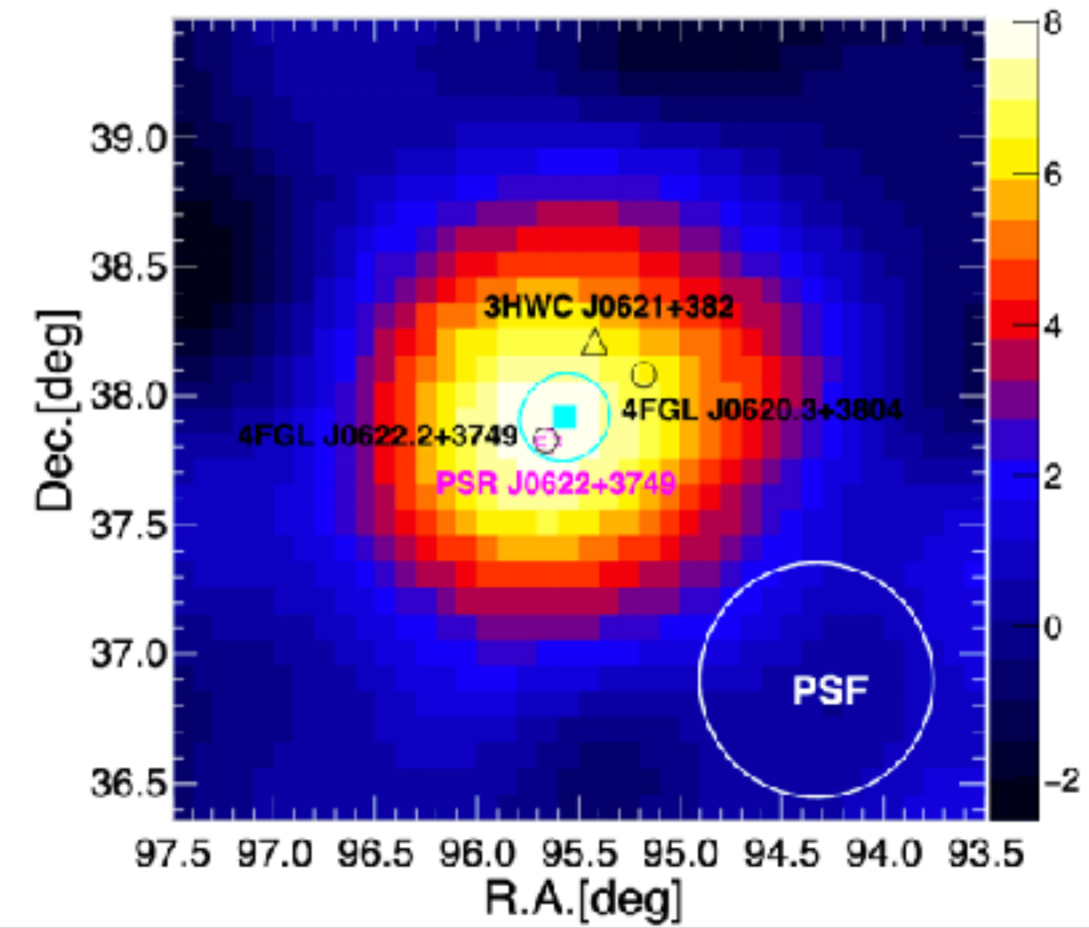
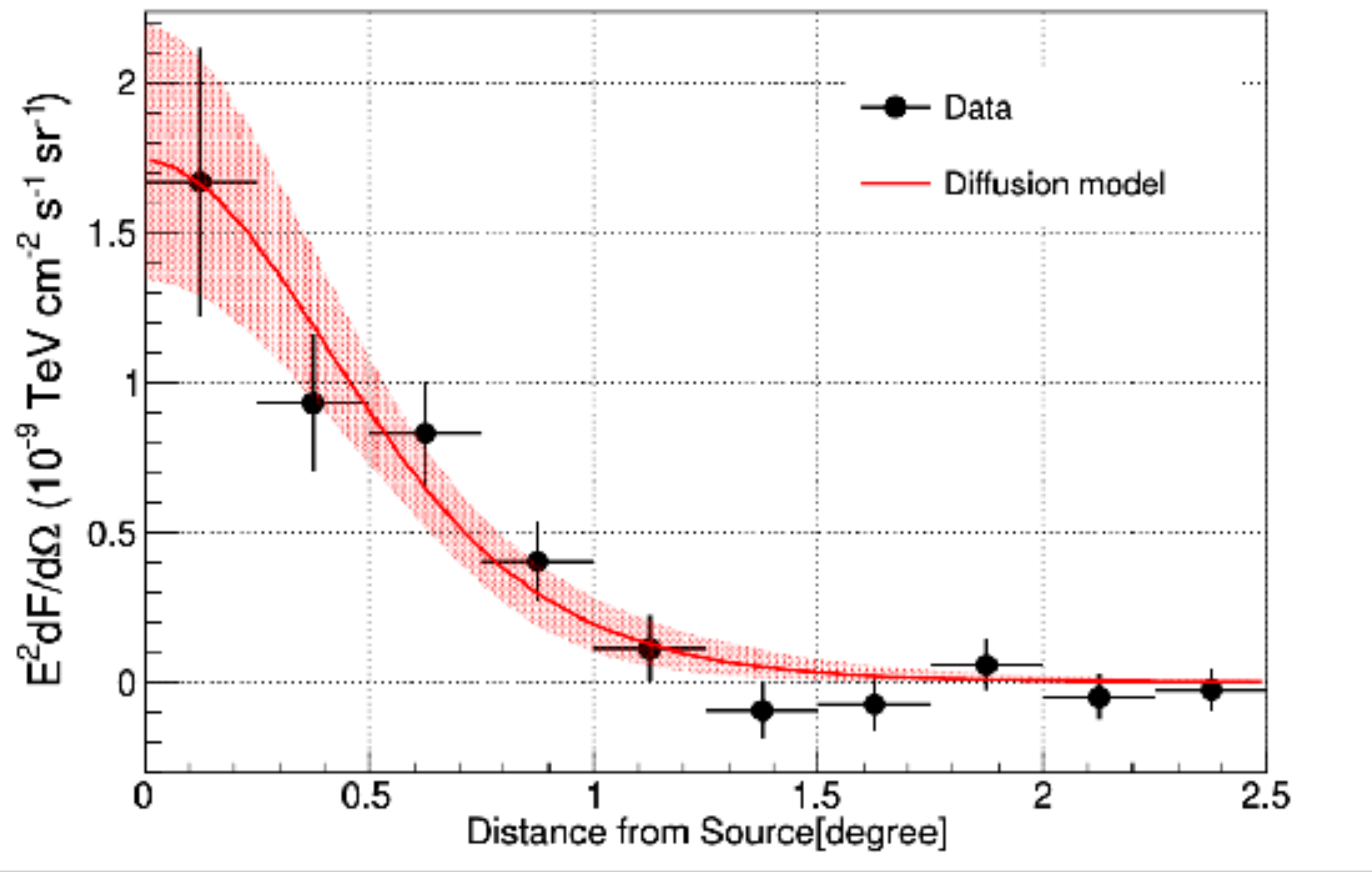
THE DIVIDING LINE BETWEEN THE PWN AND THE TEV HALO

LHAASO Collaboration (2021; 2106.09396)





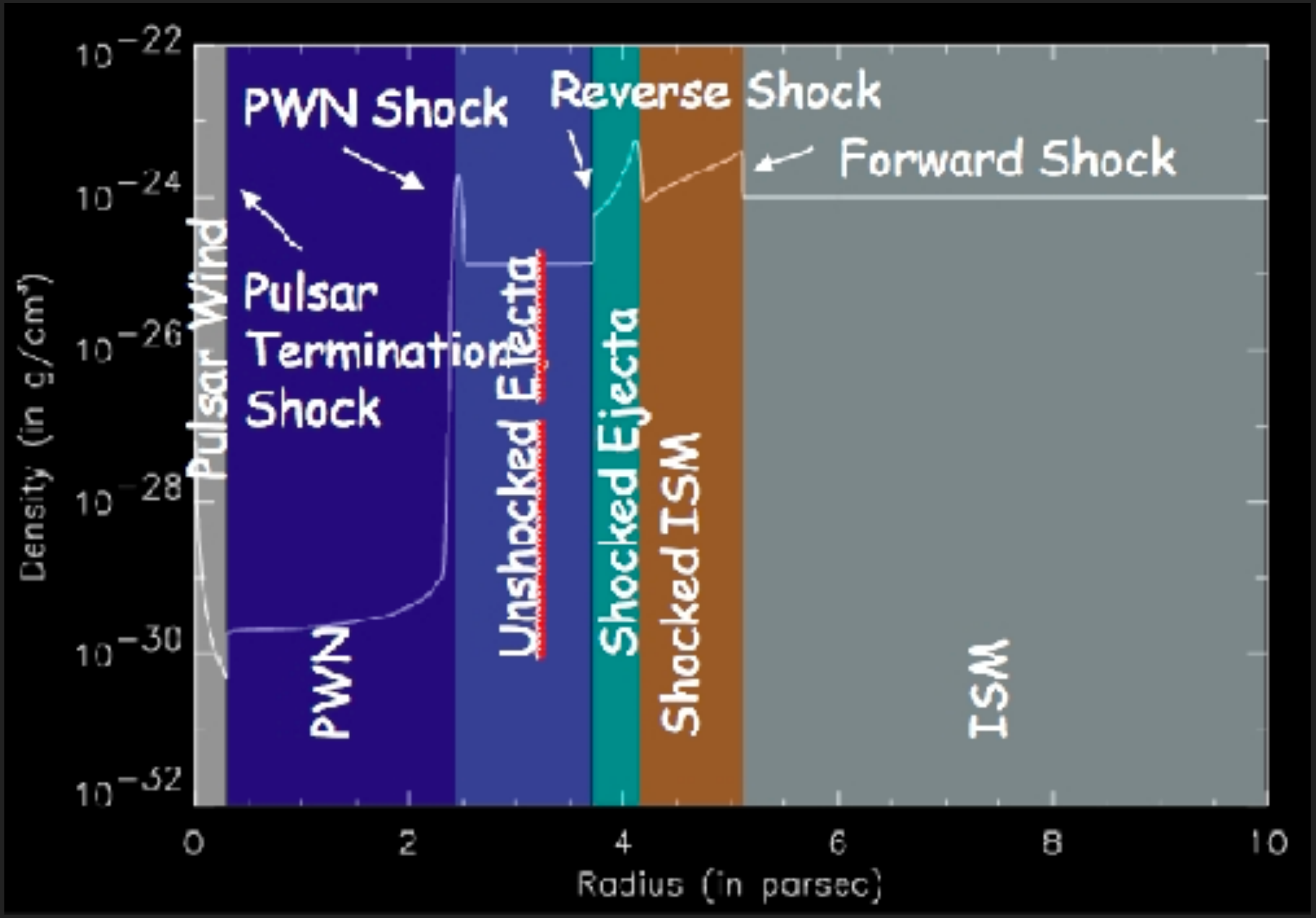
- This is not unique to Geminga and Monogem.
- Moreover - a similar inhibition of diffusion and spatial extent are observed in pulsars spanning from 20-300 kyr.

CONCLUSION 1: TEV HALOS ARE A NEW FEATURE

- TeV halos are a new feature
    - 3 orders of magnitude larger than PWN in volume
    - Opposite energy dependence

- PWN are morphologically connected to the physics of the termination shock

- TeV halos need a similar morphological description.



DIFFERENCES IN DEFINITION

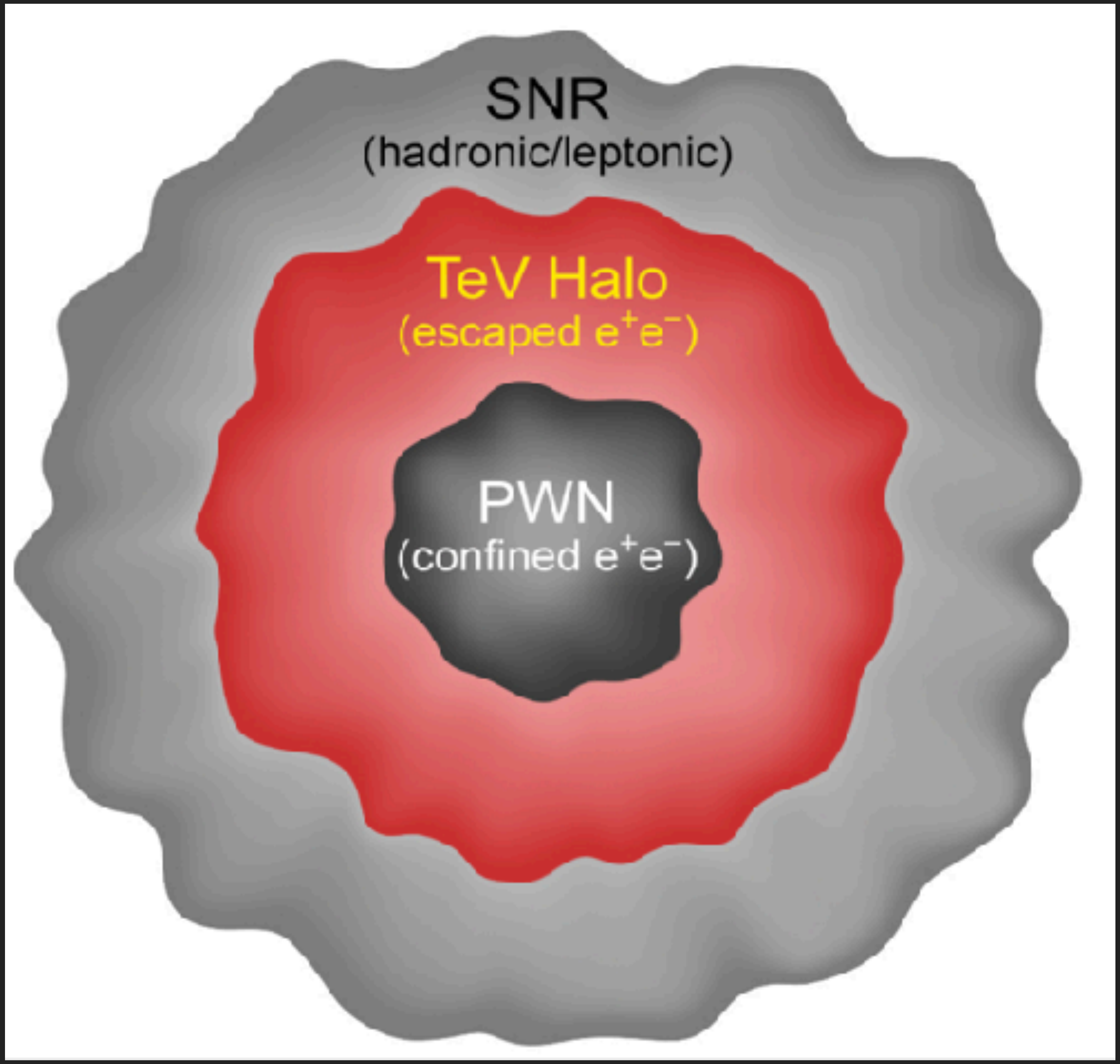
- An alternative definition of a “TeV halo” has been used by Giacinti et al. 2019 (1907.12121)

- Linden et al. (2017) - A TeV halo is a leptonic gamma-ray source surrounding a pulsar, where the electrons are diffusing through the medium (rather than being driven by convective pulsar winds).

- Giacinti et al. (2019) - A TeV halo is a leptonic gamma-ray source surrounding a pulsar, where the emission stems from a region where the electron density falls below the ambient ISM electron density.

DOES IT MATTER?

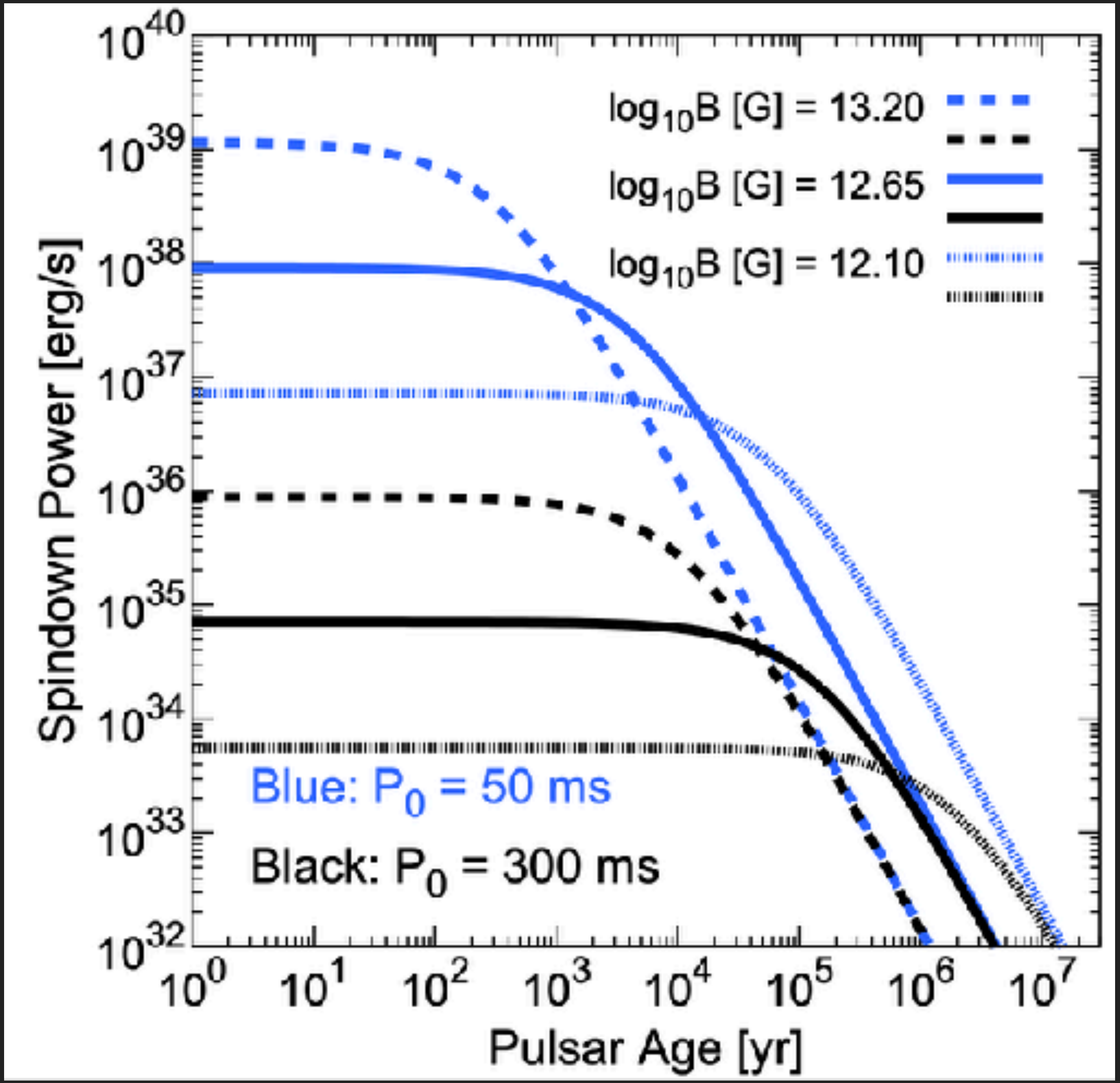
- Physics is invariant under a change in definition.
- ICS Halos, Gamma-Ray Halos – Same physical objects and may use either definition.



ONE ASSUMPTION

- Observations of Geminga and Monogem indicate that they convert ~10% of their spindown power to e+e- pairs that escape the PWN.
- We assume this is generic for all pulsars, but examine significant changes in pulsar parameters.

Sudoh, TL, Beacom (2019; 1902.08203)



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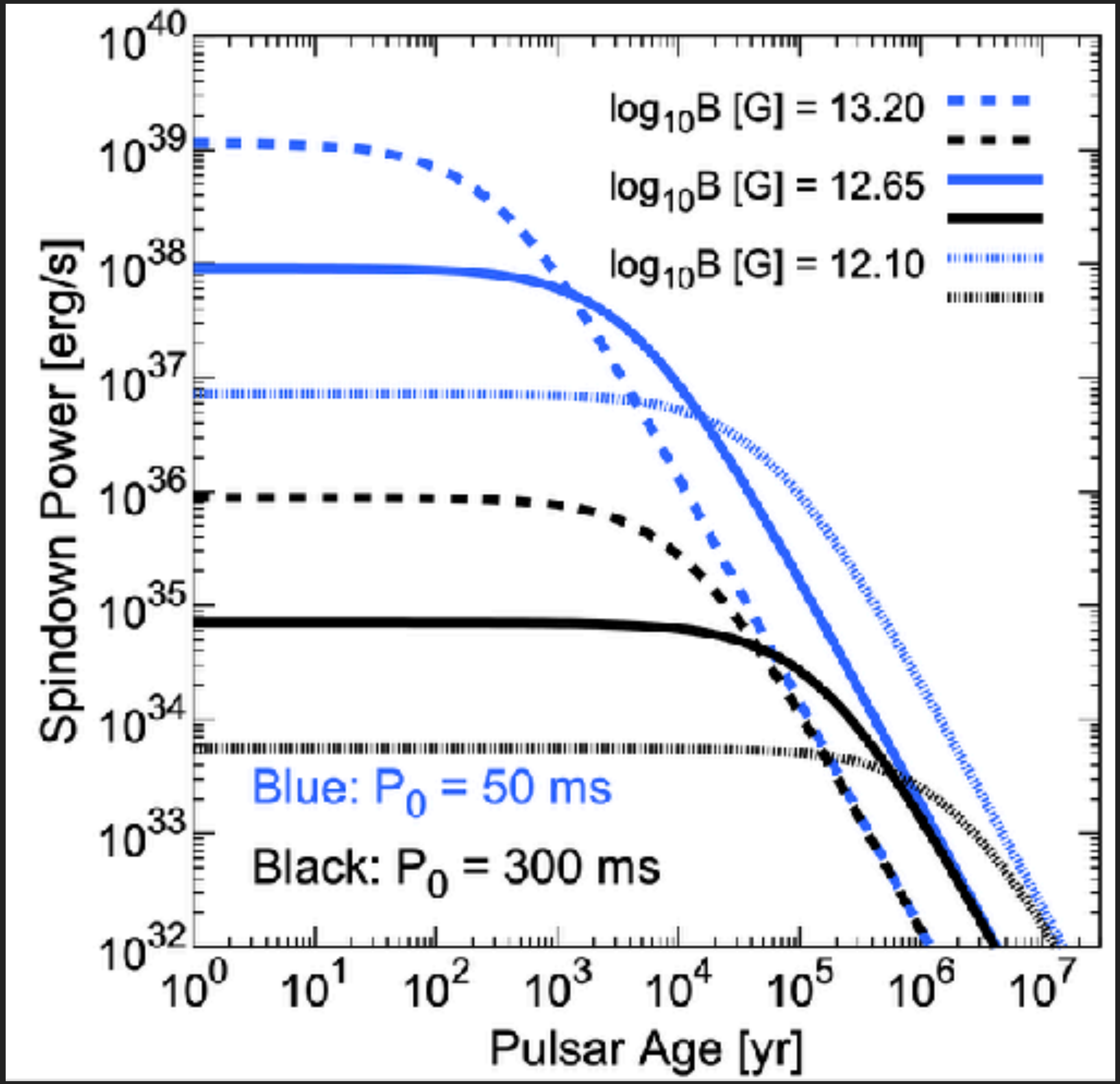
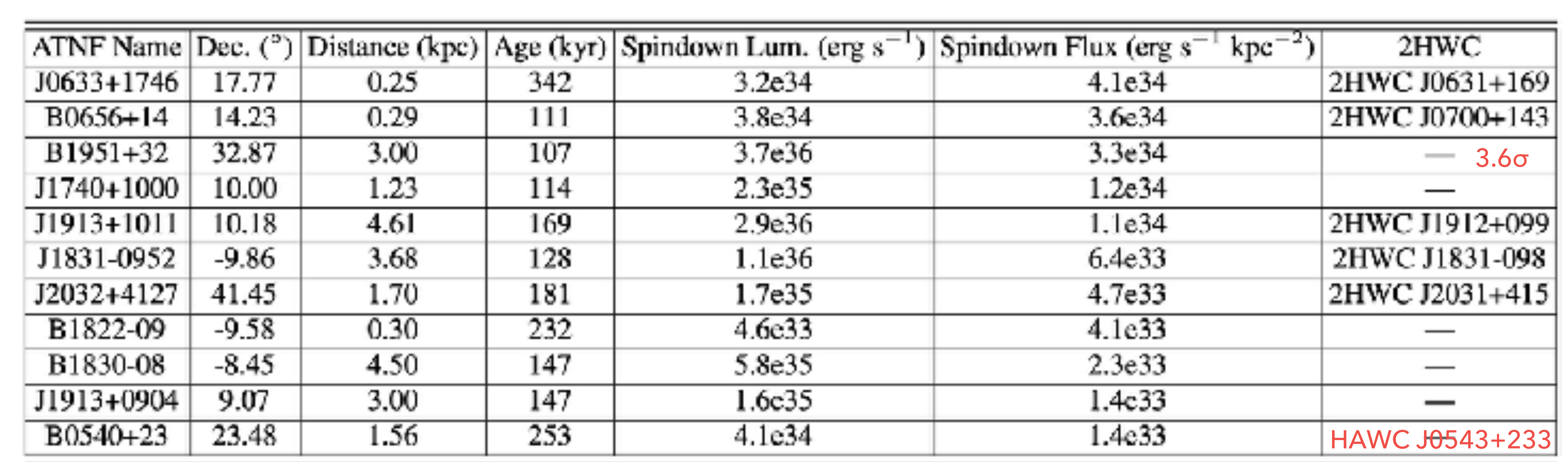


Linden et al. (2017; 1703.09704)



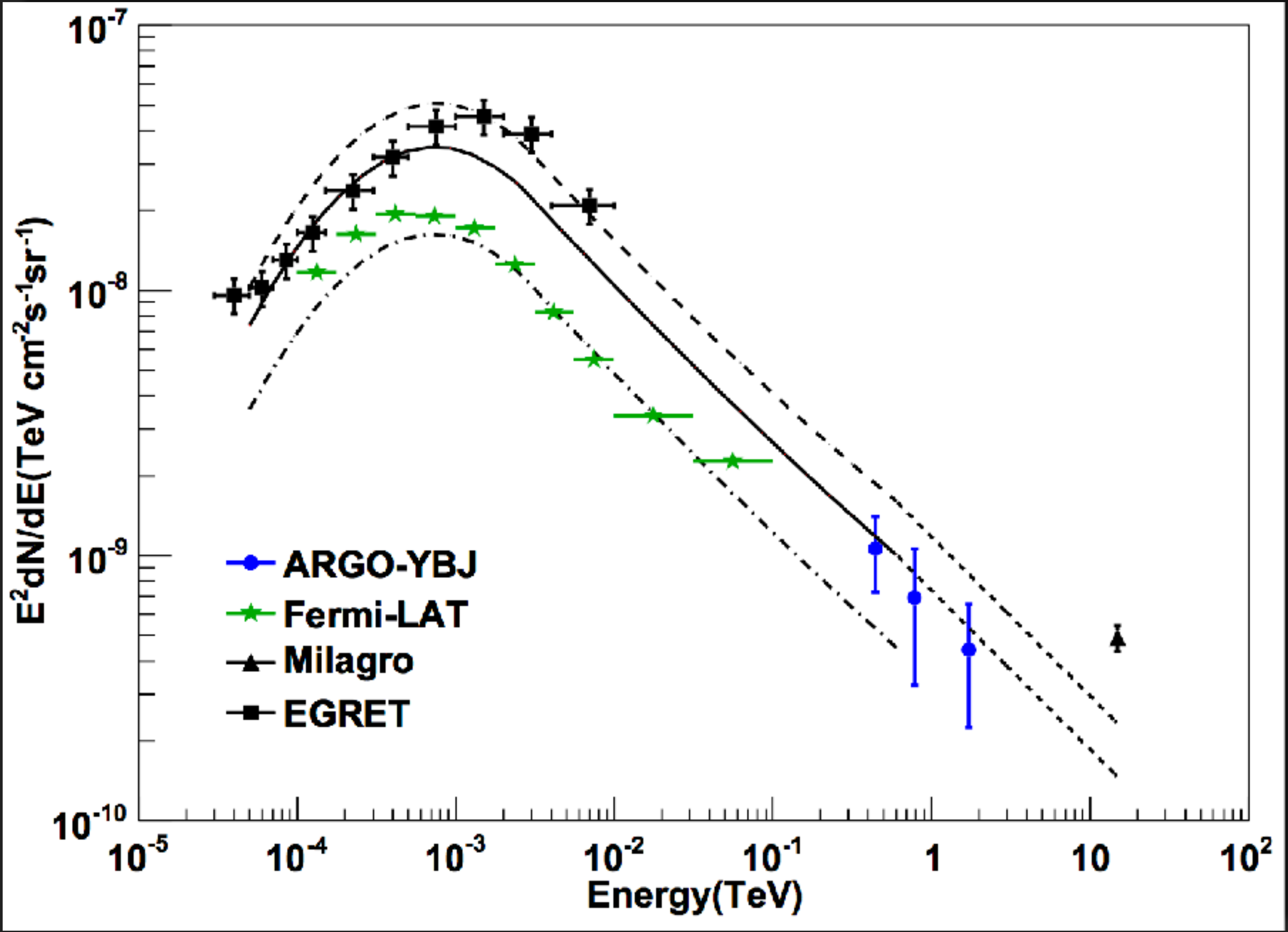
ATNF Name	Dec. (°)	Distance (kpc)	Age (kyr)	Spindown Lum. (erg s^{-1})	Spindown Flux (erg s^{-1} kpc^{-2})	2HWC
J0633+1746	17.77	0.25	342	3.2e34	4.1e34	2HWC J0631+169
B0656+14	14.23	0.29	111	3.8e34	3.6e34	2HWC J0700+143
B1951+32	32.87	3.00	107	3.7e36	3.3e34	— 3.6σ
J1740+1000	10.00	1.23	114	2.3e35	1.2e34	—
J1913+1011	10.18	4.61	169	2.9e36	1.1e34	2HWC J1912+099
J1831-0952	-9.86	3.68	128	1.1e36	6.4e33	2HWC J1831-098
J2032+4127	41.45	1.70	181	1.7e35	4.7e33	2HWC J2031+415
B1822-09	-9.58	0.30	232	4.6e33	4.1e33	—
B1830-08	-8.45	4.50	147	5.8e35	2.3e33	—
J1913+0904	9.07	3.00	147	1.6e35	1.4e33	—
B0540+23	23.48	1.56	253	4.1e34	1.4e33	HAWC J0543+233

IMPLICATION 1: DIFFUSE TEV GAMMA-RAYS

- There is bright diffuse gamma-ray emission across the galactic plane.

- Ratio of point source emission to diffuse emission is a powerful marker of emission mechanisms and local propagation.

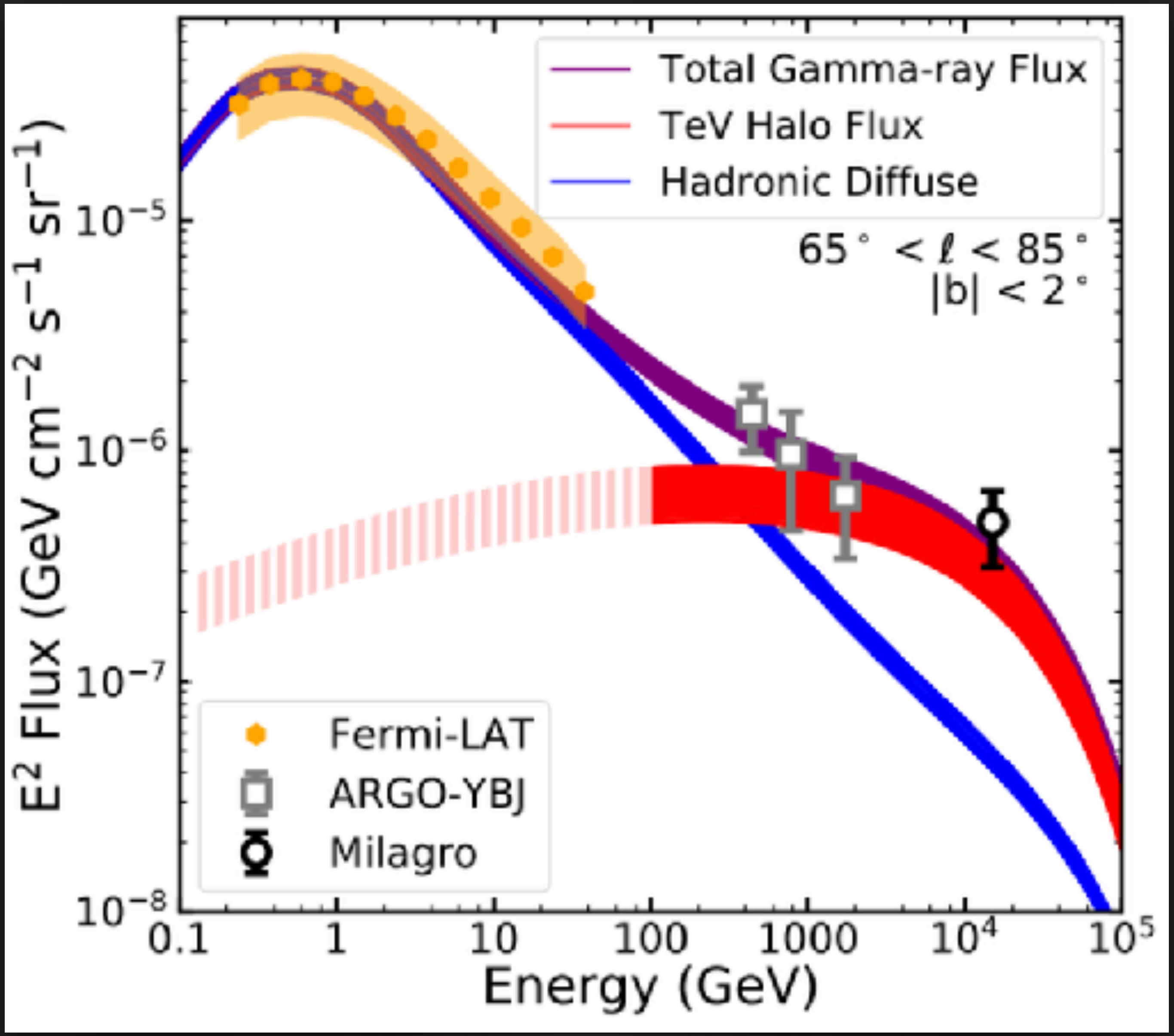
IMPLICATION 1: DIFFUSE TEV GAMMA-RAYS



IMPLICATION 1: DIFFUSE TEV GAMMA-RAYS

- TeV halos naturally explain the spectrum and intensity of this emission.
- Multiple halos observed with $E^{-2.0}$ spectra.
- Note - "Halo" is not needed
  - Pulsar efficiency ~10%
  - Power must escape PWN

Linden & Buckman (2017; 1707.01905)



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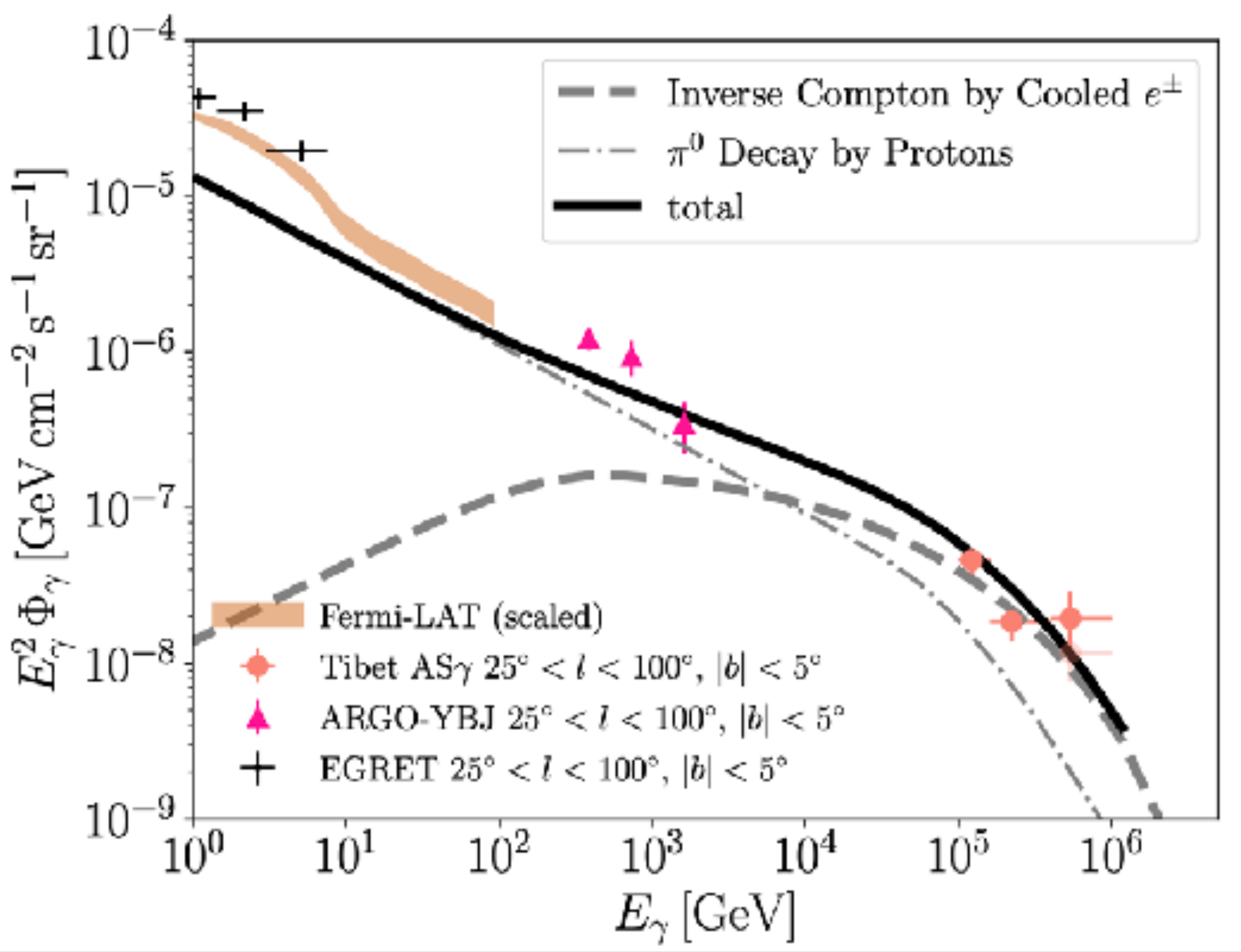
- Note - “Halo” is not needed
    - Pulsar efficiency ~10%
    - Power must escape PWN
    - Recently extend to 100 TeV energies.

Fang & Murase (2021; 2104.09491)



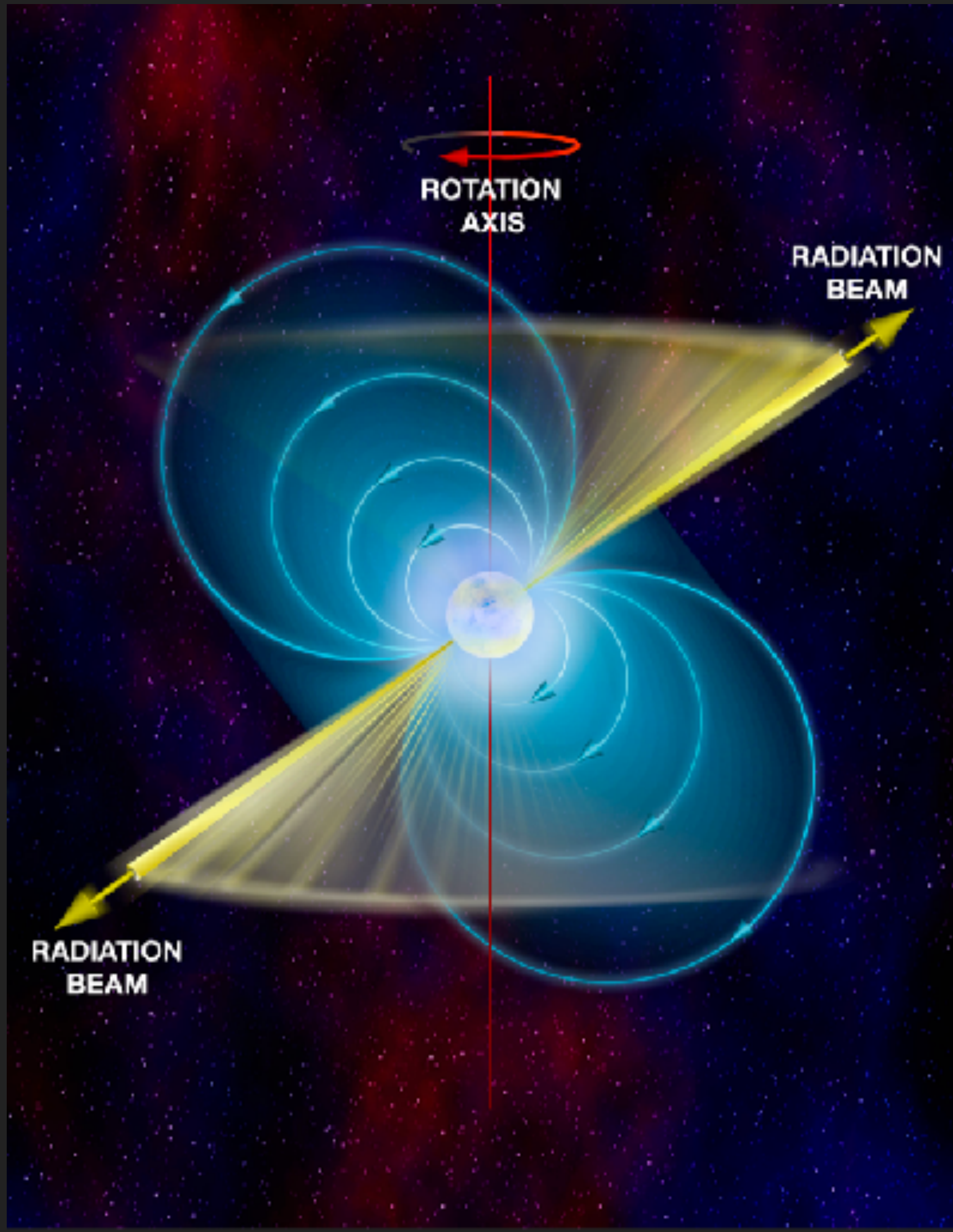
IMPLICATION 2: SOURCES

- Radio pulsars are beamed!
- Beaming fraction is small

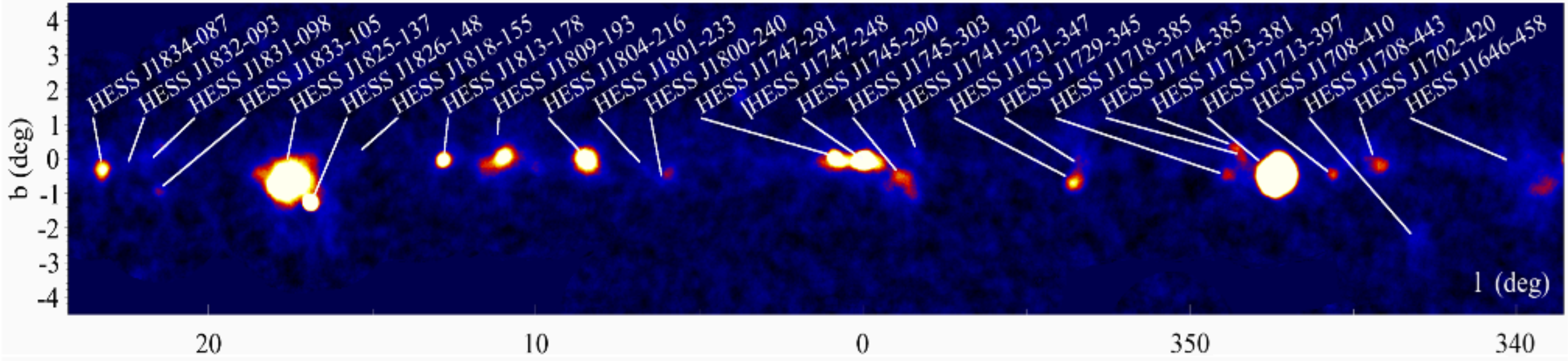
$$f = \left[1.1\ \left(\log_{10}\left(\frac{\tau}{100\ \mathrm{Myr}}\right)\right)^2 + 15\right]\ \%$$

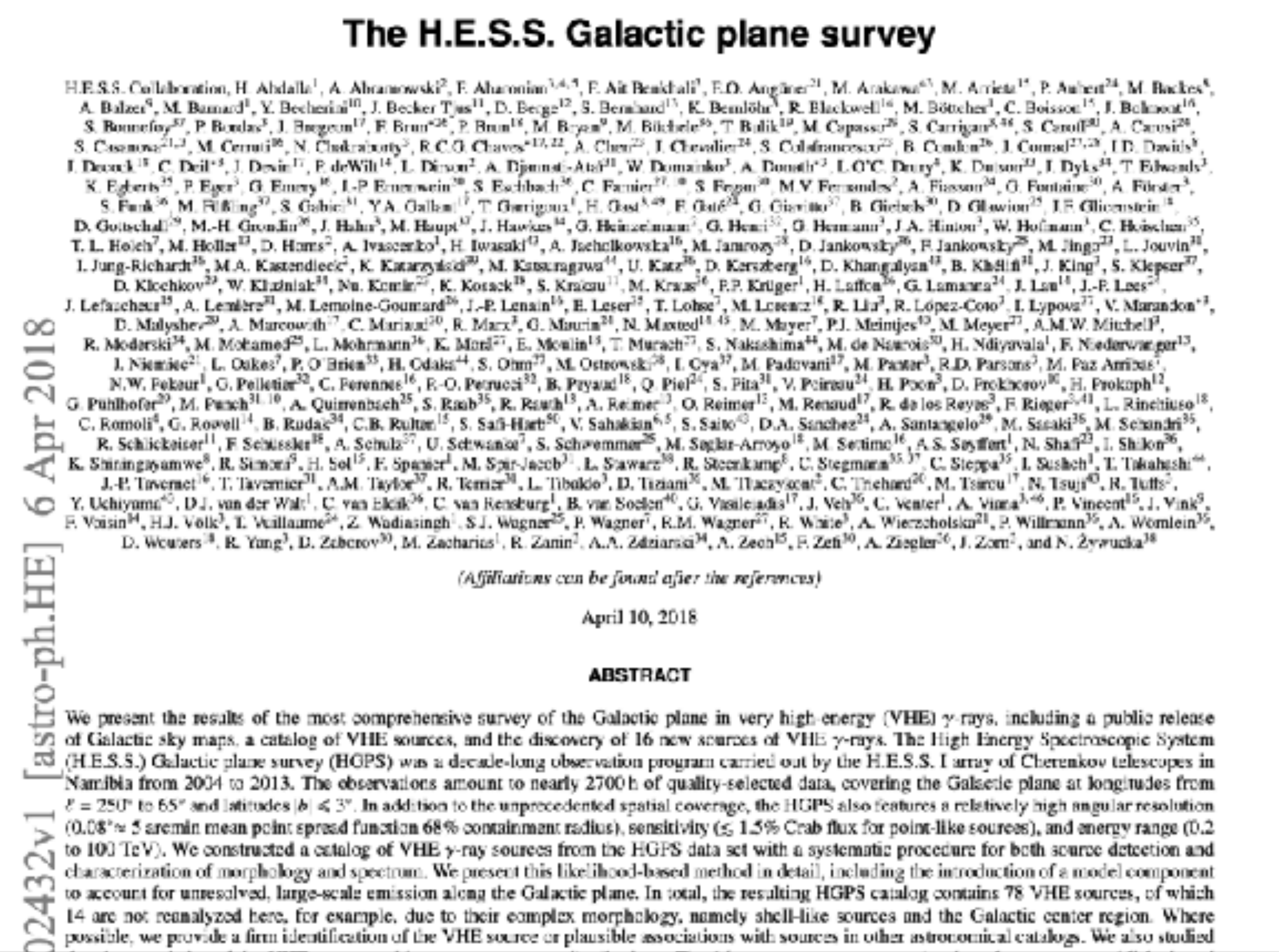
Tauris & Manchester (1998)

- This varies between 15-30%.
- Most pulsars are unseen in radio!



IMPLICATION 2: SOURCES





The H.E.S.S. Galactic plane survey

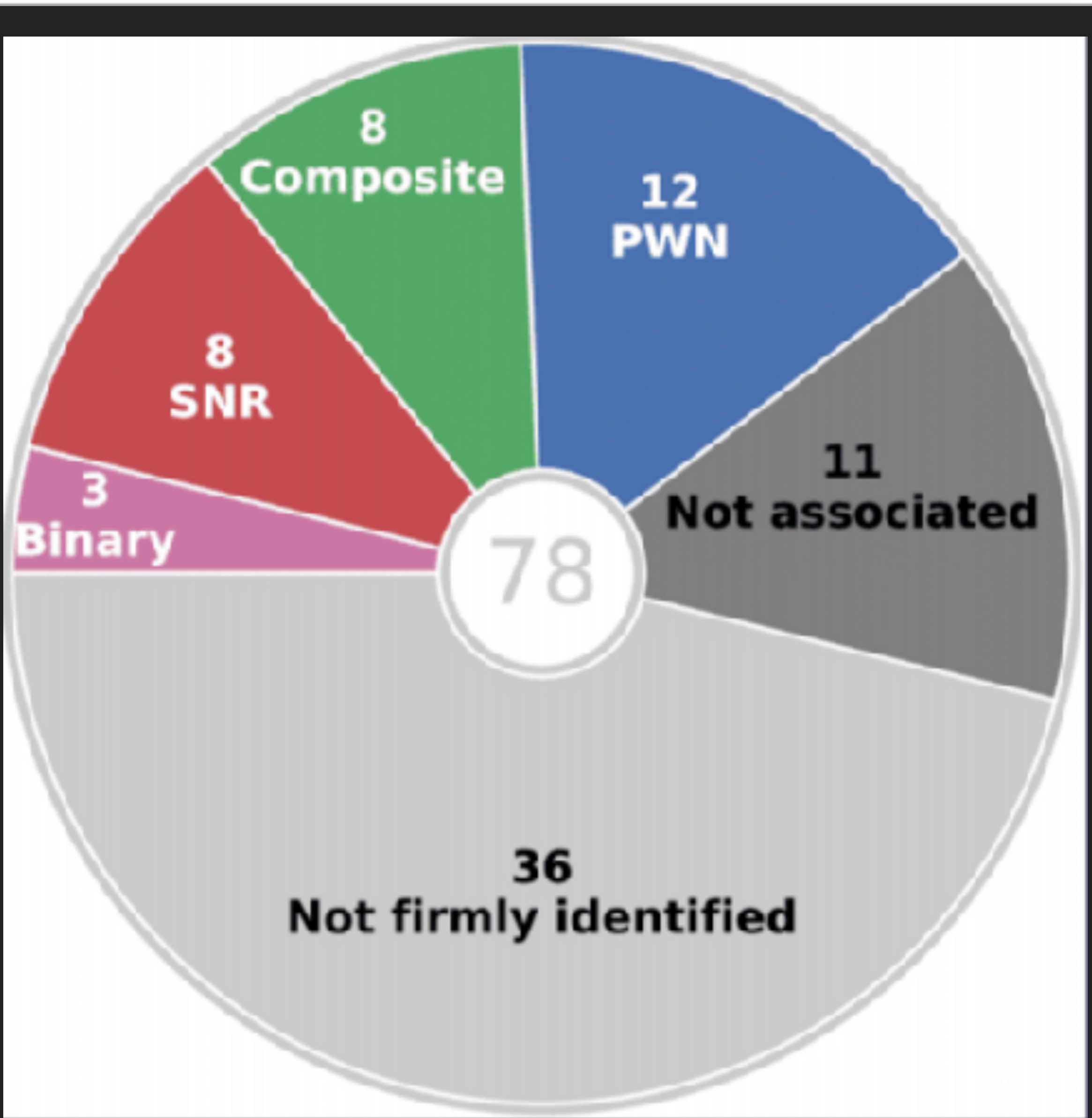
(Affiliations can be found after the references)

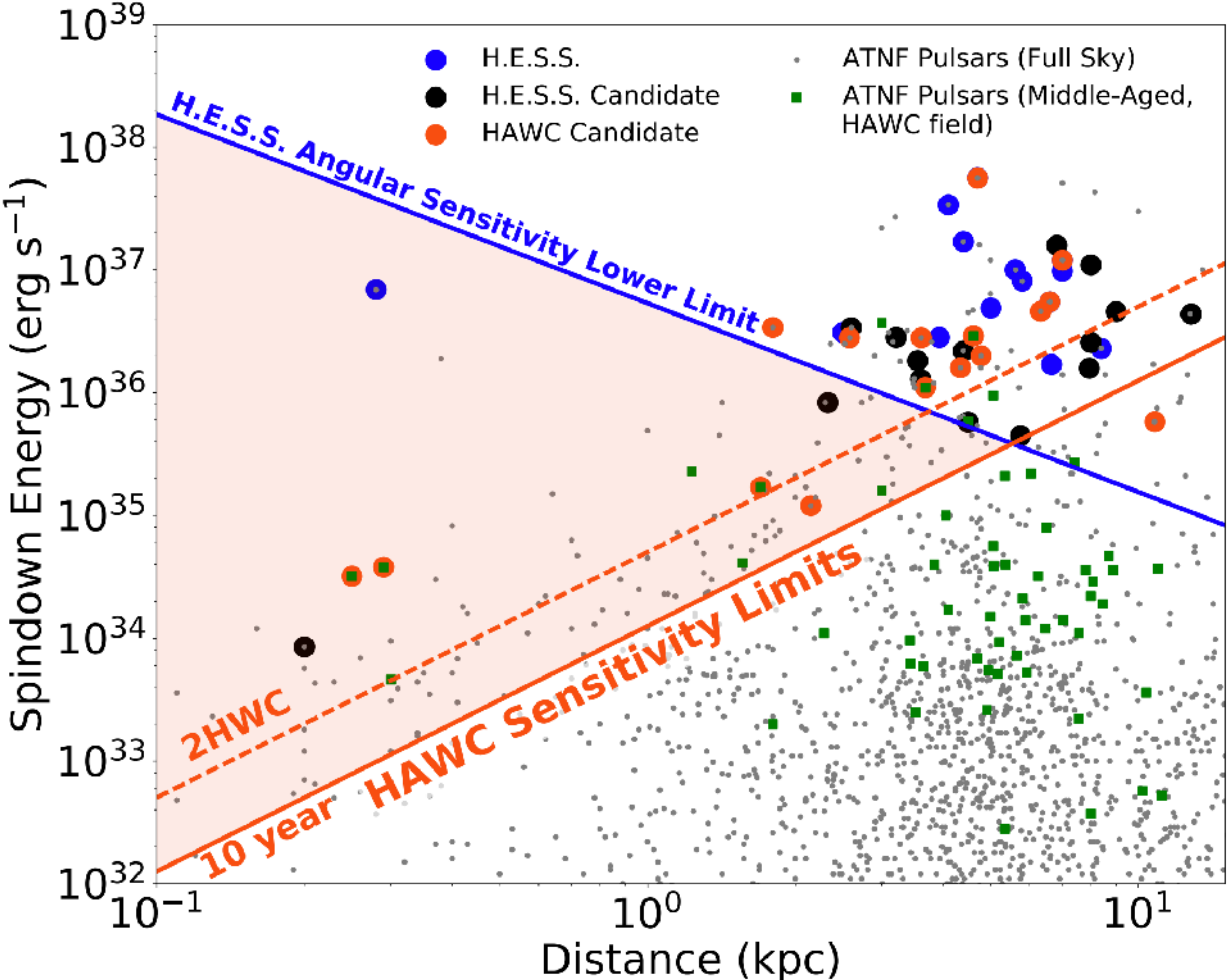
April 10, 2018

02432v1 [astro-ph.HE] 6 Apr 2018

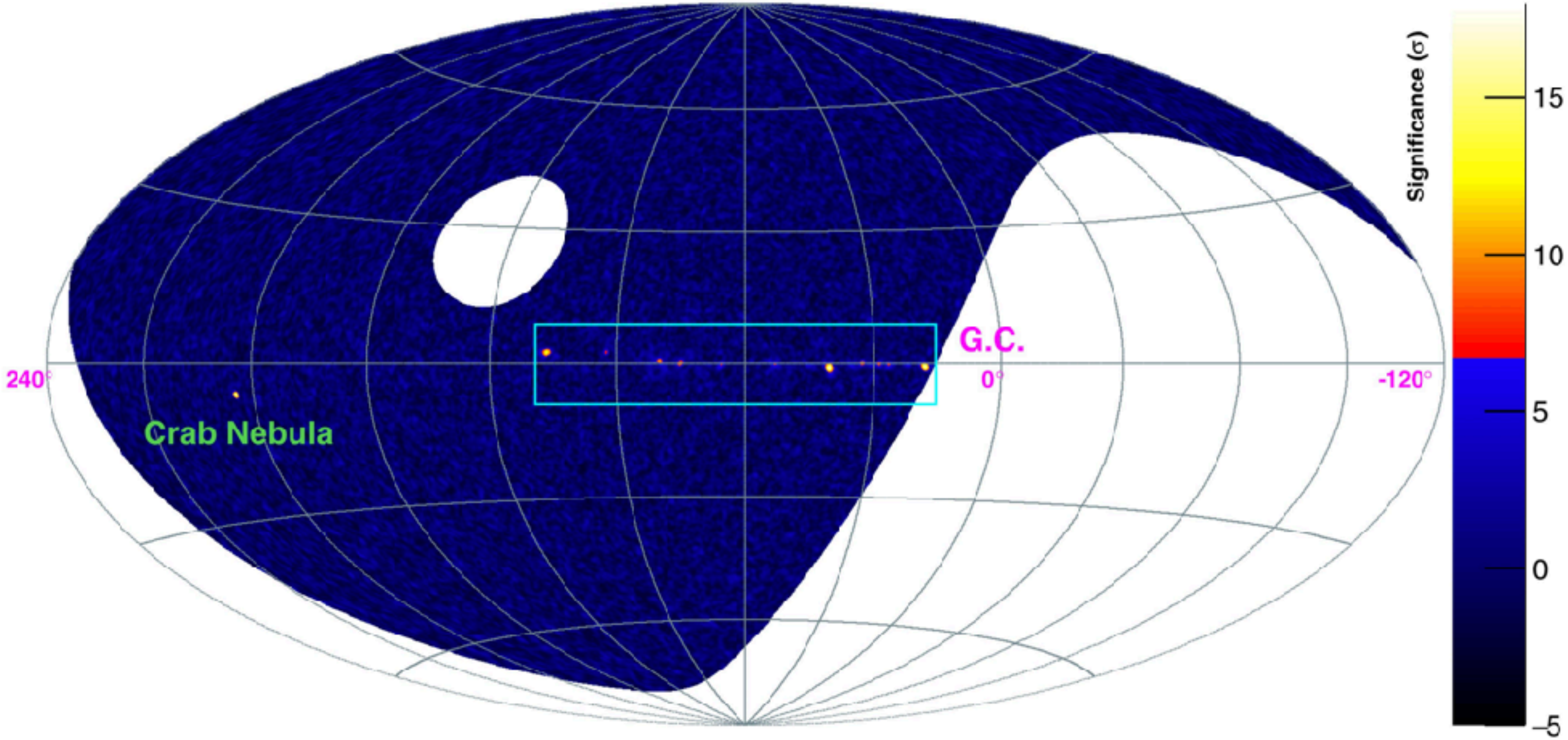
ABSTRACT

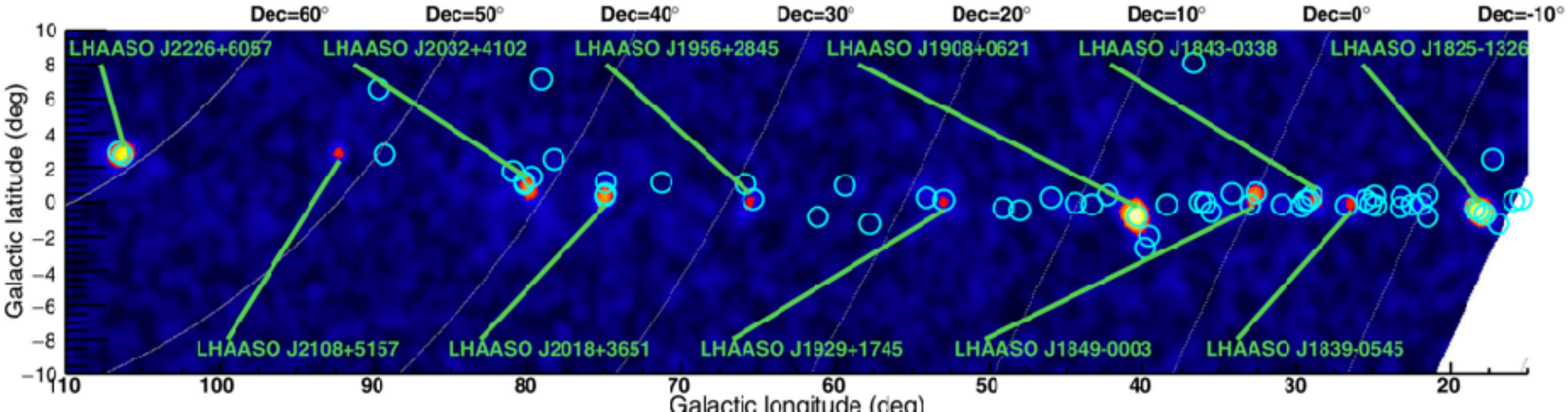
We present the results of the most comprehensive survey of the Galactic plane in very high-energy (VHE) γ-rays, including a public release of Galactic sky maps, a catalog of VHE sources, and the discovery of 16 new sources of VHE γ-rays. The High Energy Spectroscopic System (H.E.S.S.) Galactic plane survey (HGPS) was a decade-long observation program carried out by the H.E.S.S. I array of Cherenkov telescopes in Namibia from 2004 to 2013. The observations amount to nearly 2700 h of quality-selected data, covering the Galactic plane at longitudes from $\ell = 250°$ to $65°$ and latitudes $|b| \lesssim 3°$. In addition to the unprecedented spatial coverage, the HGPS also features a relatively high angular resolution ($0.08° \approx 5$ arcmin mean point spread function 68% containment radius), sensitivity ($\lesssim 1.5\%$ Crab flux for point-like sources), and energy range (0.2 to 100 TeV). We constructed a catalog of VHE γ-ray sources from the HGPS data set with a systematic procedure for both source detection and characterization of morphology and spectrum. We present this likelihood-based method in detail, including the introduction of a model component to account for unresolved, large-scale emission along the Galactic plane. In total, the resulting HGPS catalog contains 78 VHE sources, of which 14 are not reanalyzed here, for example, due to their complex morphology, namely shell-like sources and the Galactic center region. Where possible, we provide a firm identification of the VHE source or plausible associations with sources in other astronomical catalogs. We also studied




H.E.S.S.
H.E.S.S. Candidate
HAWC Candidate
ATNF Pulsars (Full Sky)
ATNF Pulsars (Middle-Aged, HAWC field)
H.E.S.S. Angular Sensitivity Lower Limit
2HWC
10 year HAWC Sensitivity Limits
Spindown Energy (erg s^{-1})
Distance (kpc)
10^{39}
10^{38}
10^{37}
10^{36}
10^{35}
10^{34}
10^{33}
10^{32}
10^{-1}
10^{0}
10^{1}

LHAASO Sky @ >100 TeV





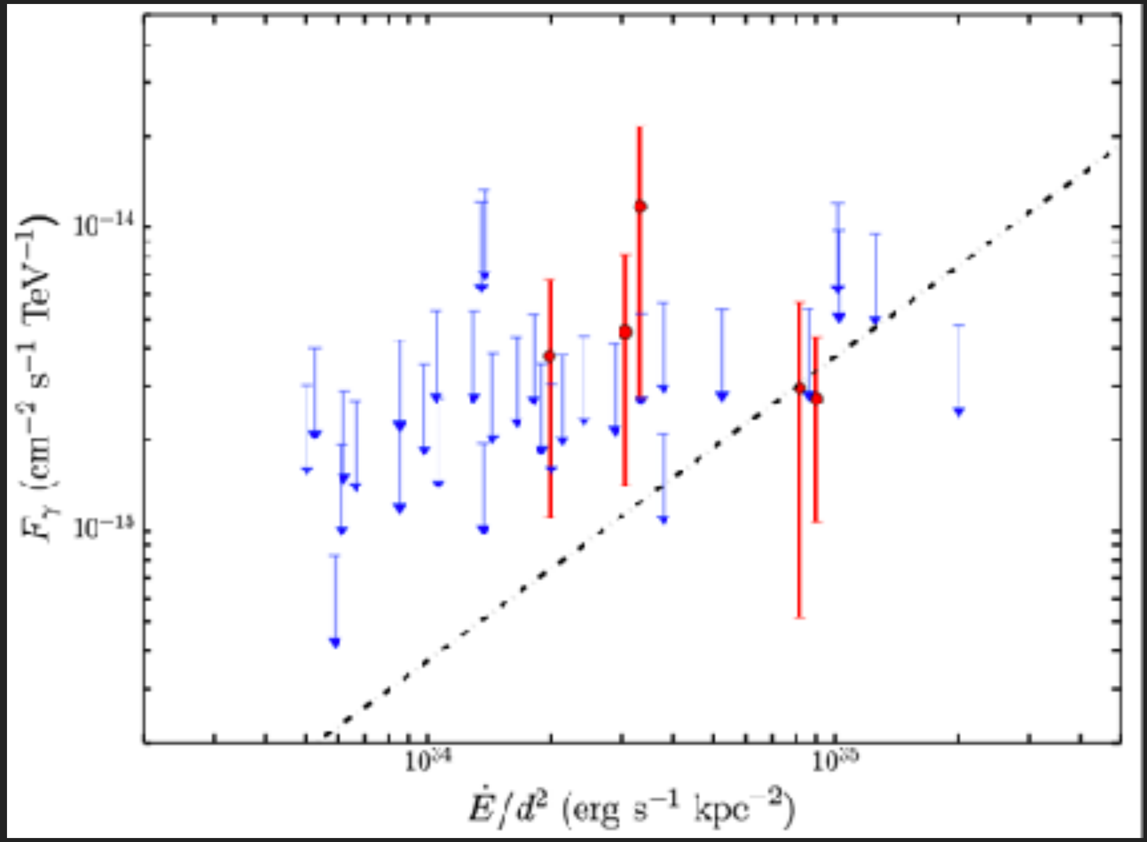
IMPLICATION 2: SOURCES

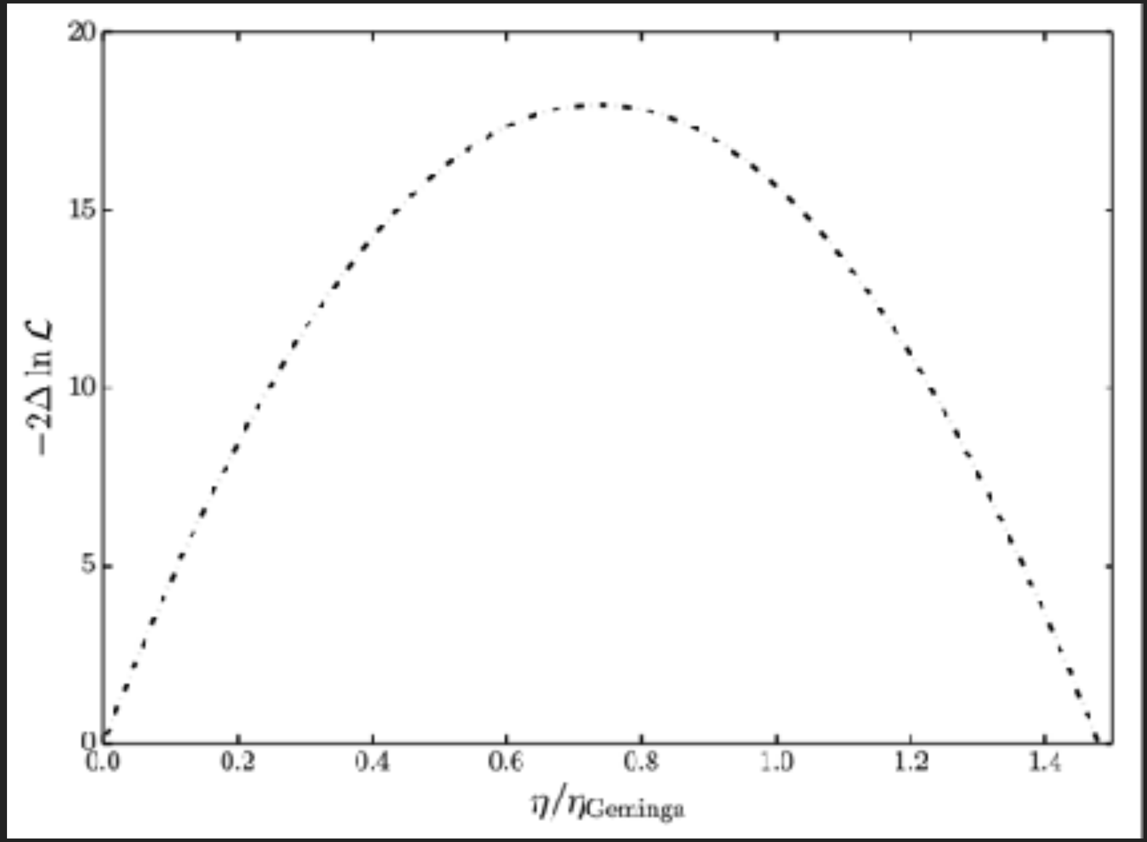
Hooper, TL (2021; 2104.00014)

- Do MSPs Have TeV Halos?

- Tentative: **4.24σ** evidence from a HAWC stacking analysis.

- Important theoretical implications:
  - Cosmic-Ray confinement near pulsars?
  - Cosmic-Ray diffusion at high latitudes
  - PWN/Magnetospheric acceleration models.

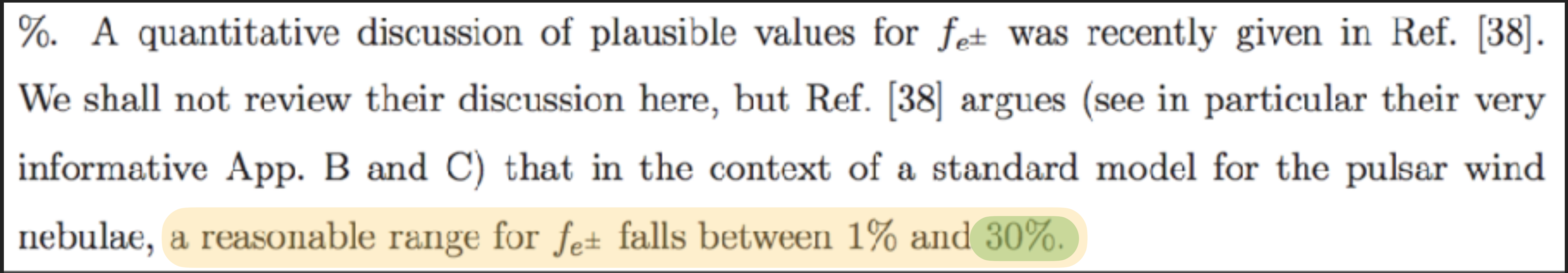




IMPLICATION 3: POSITRON EXCESS

- What were the uncertainties in pulsar models?
  - I: The e^+e^- production efficiency?

Profumo (0812.4457); Malyshev et al. (0903.1310)



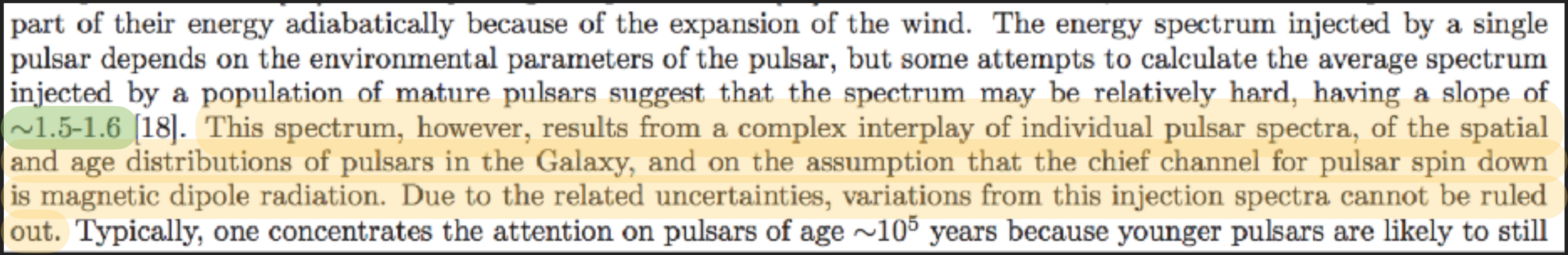
%. A quantitative discussion of plausible values for $f_{e^\pm}$ was recently given in Ref. [38]. We shall not review their discussion here, but Ref. [38] argues (see in particular their very informative App. B and C) that in the context of a standard model for the pulsar wind nebulae, a reasonable range for $f_{e^\pm}$ falls between 1% and 30%.

  - II: The e^+e^- spectrum.
  - III: The propagation of e^+e^- to Earth.

IMPLICATION 3: POSITRON EXCESS

- What were the uncertainties in pulsar models?
  - I: The e^+e^- production efficiency?
  - II: The e^+e^- spectrum.

Hooper et al. (2008; 0810.1527)



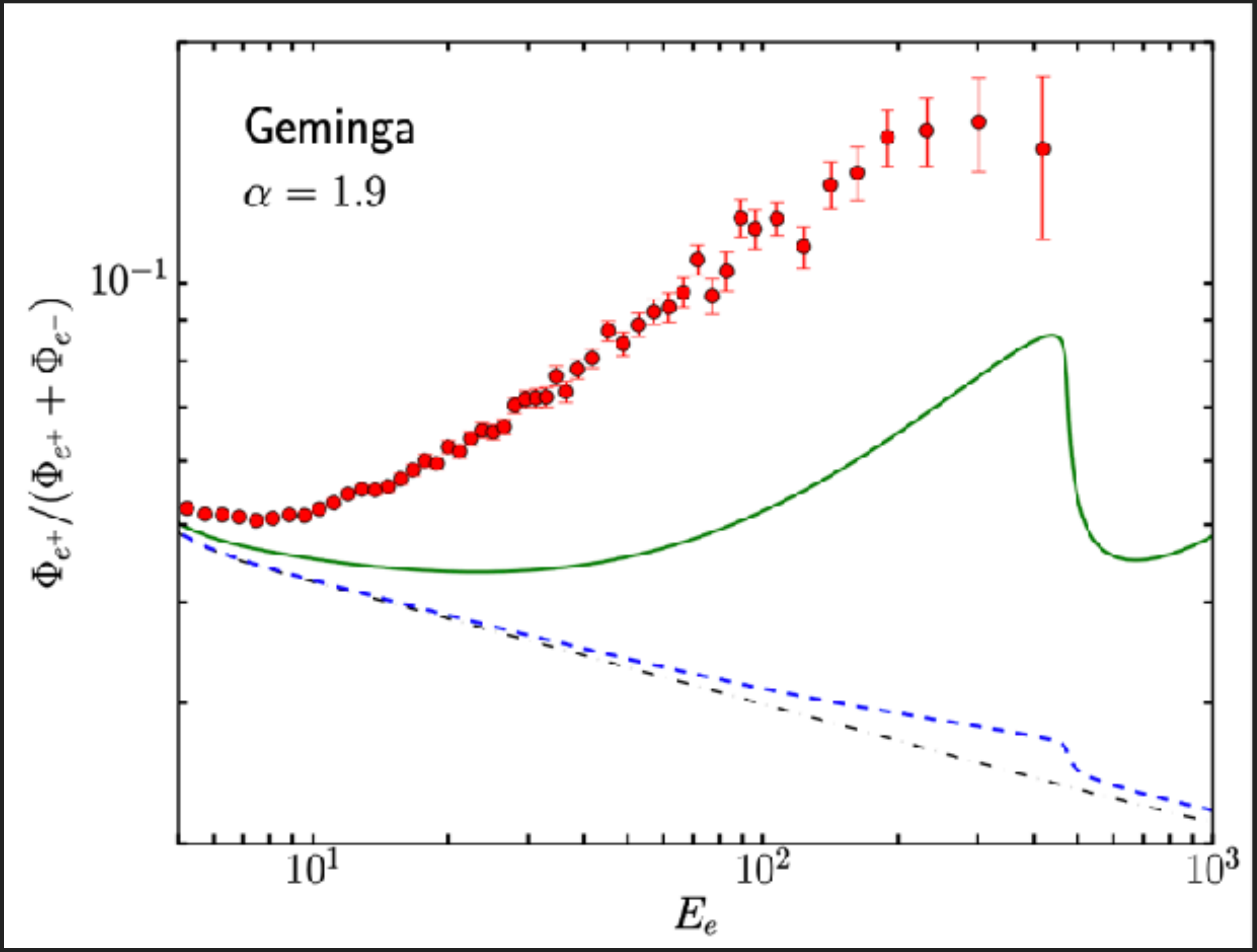
part of their energy adiabatically because of the expansion of the wind. The energy spectrum injected by a single pulsar depends on the environmental parameters of the pulsar, but some attempts to calculate the average spectrum injected by a population of mature pulsars suggest that the spectrum may be relatively hard, having a slope of $\sim$1.5-1.6 [18]. This spectrum, however, results from a complex interplay of individual pulsar spectra, of the spatial and age distributions of pulsars in the Galaxy, and on the assumption that the chief channel for pulsar spin down is magnetic dipole radiation. Due to the related uncertainties, variations from this injection spectra cannot be ruled out. Typically, one concentrates the attention on pulsars of age $\sim 10^5$ years because younger pulsars are likely to still

- III: The propagation of e^+e^- to Earth.

IMPLICATION 3: POSITRON EXCESS

- TeV Halos answer both of these questions!

Hooper, Cholis, TL, Fang (2017; 1702.08436)



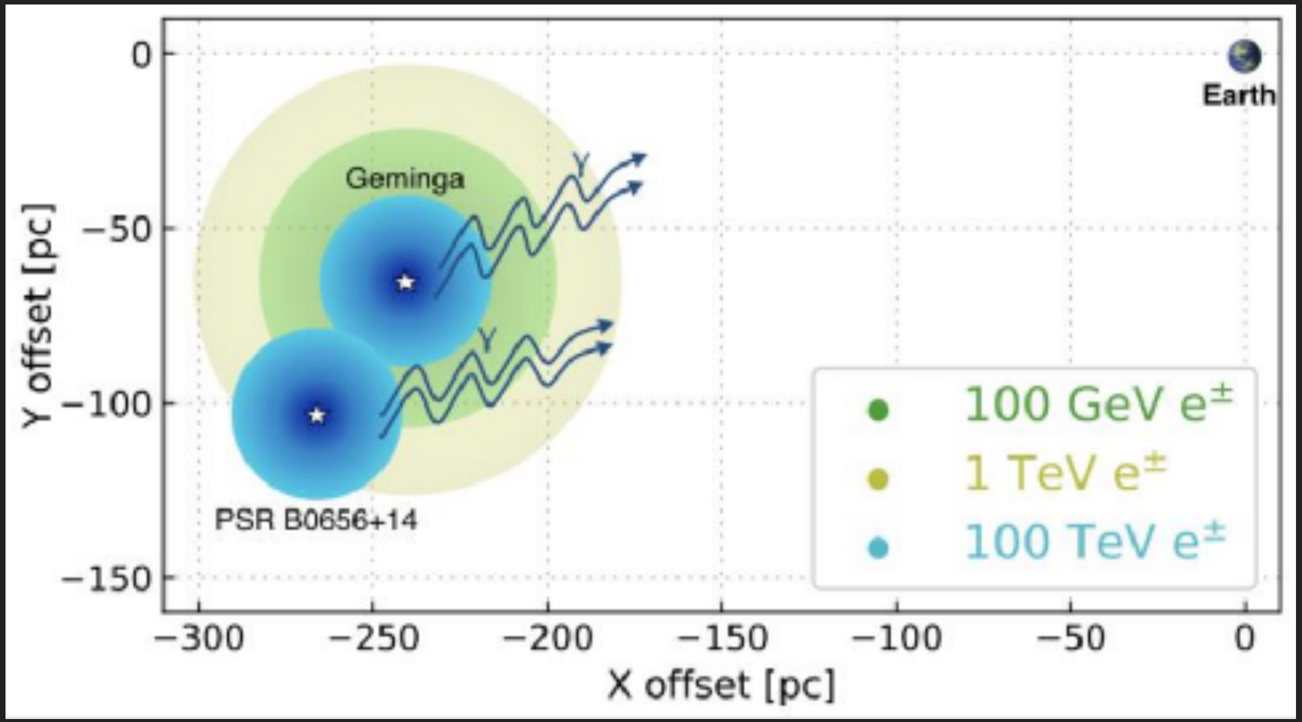
- Can use gamma-ray flux at the source to determine the total e^+e^- energy!

- In agreement with models of the positron excess!

IMPLICATION 3: POSITRON EXCESS

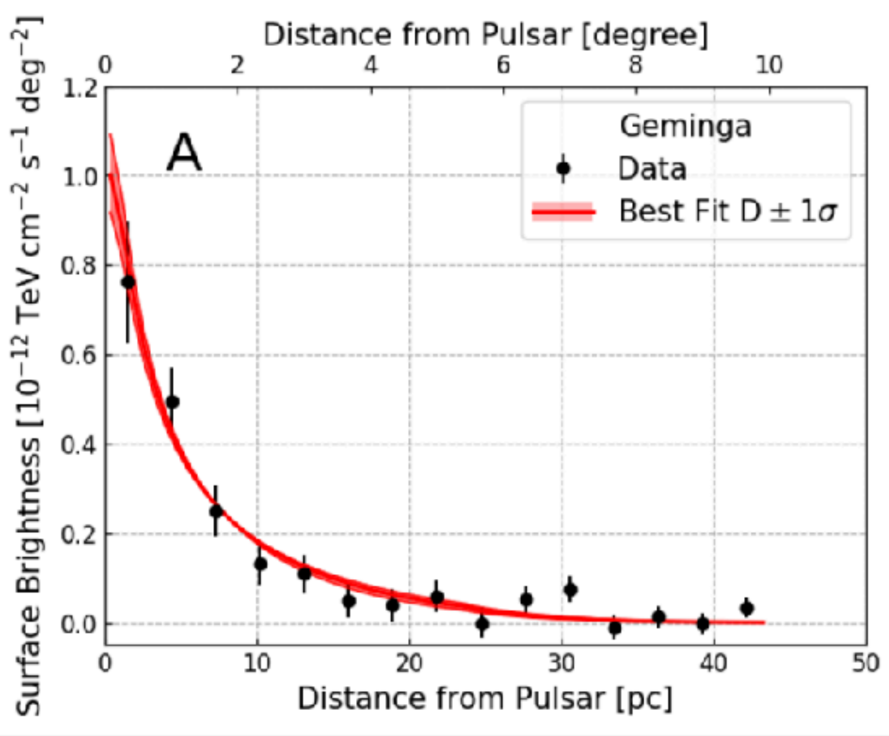
- What were the uncertainties in pulsar models?
  - I: The e^+e^- production efficiency?
  - II: The e^+e^- spectrum.
  - III: The propagation of e^+e^- to Earth.

Abeysekara et al. (2017; 1711.06223)

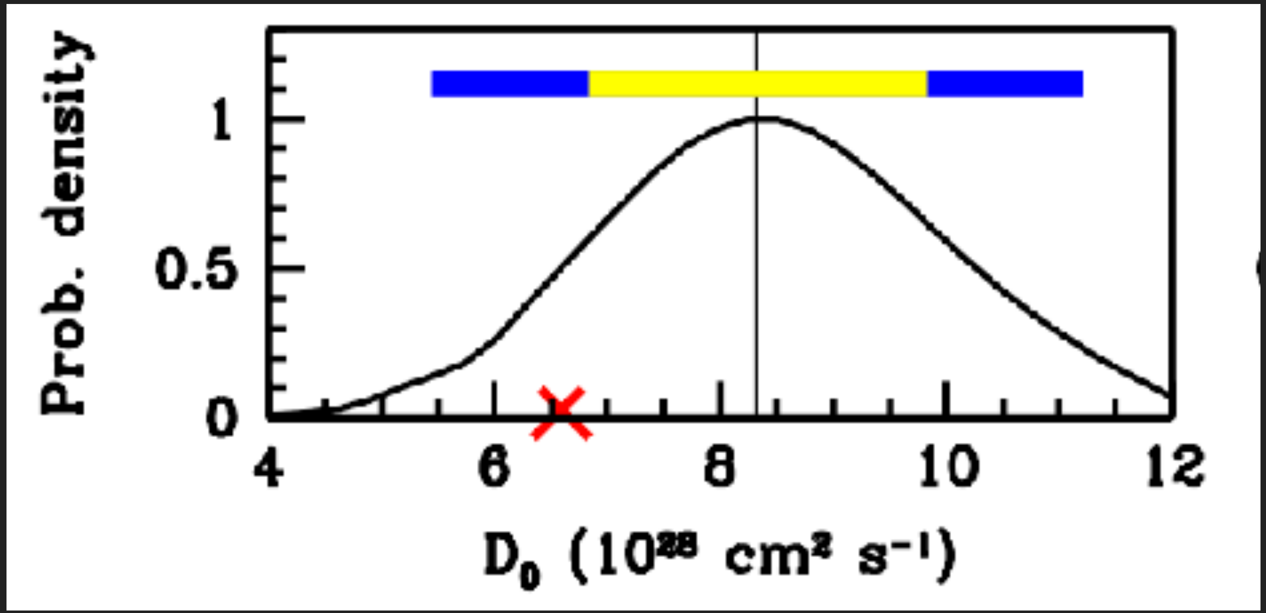


WHAT IS THE PHYSICS OF TEV HALOS?

- Models to Explain Inhibited Diffusion:
  - Diffusion Coefficient in TeV halos: ~10^{28} cm^2 s^{-1} at 10 TeV
  - Average diffusion coefficient in Milky Way: ~10^{30} cm^{2}s^{-1} at 10 TeV



Abeysekara et al. (2017; 1711.06223)

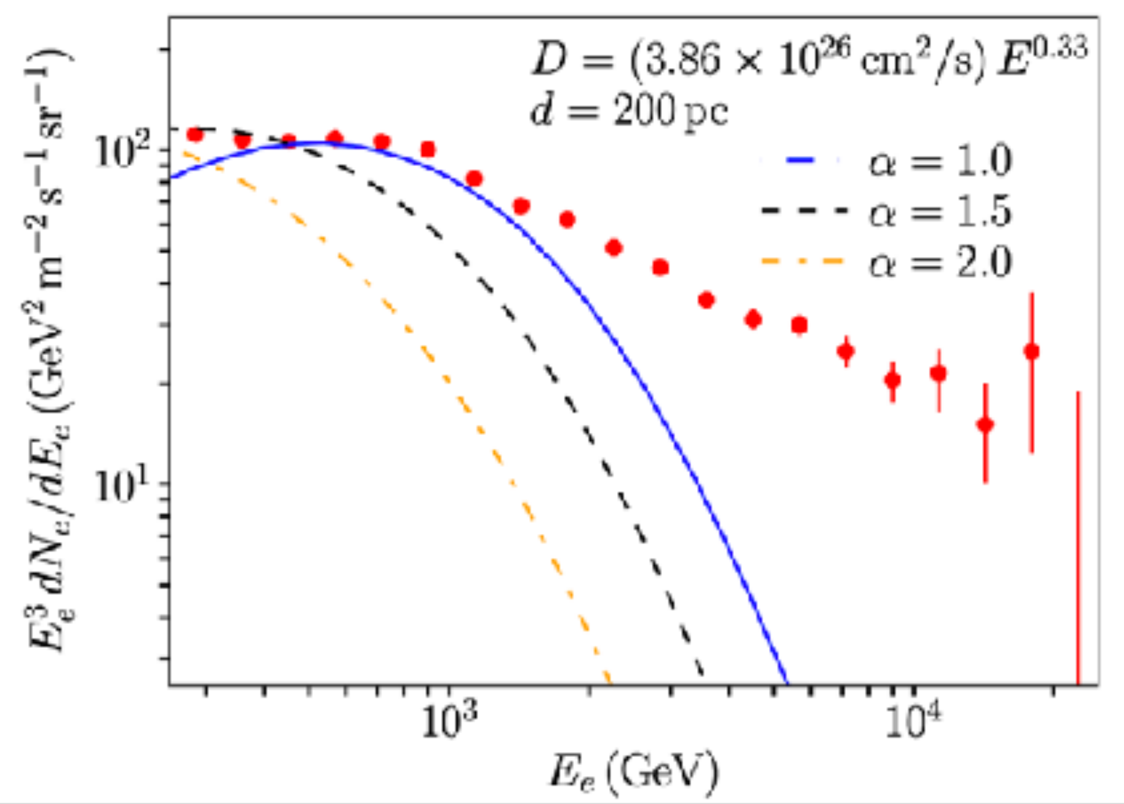


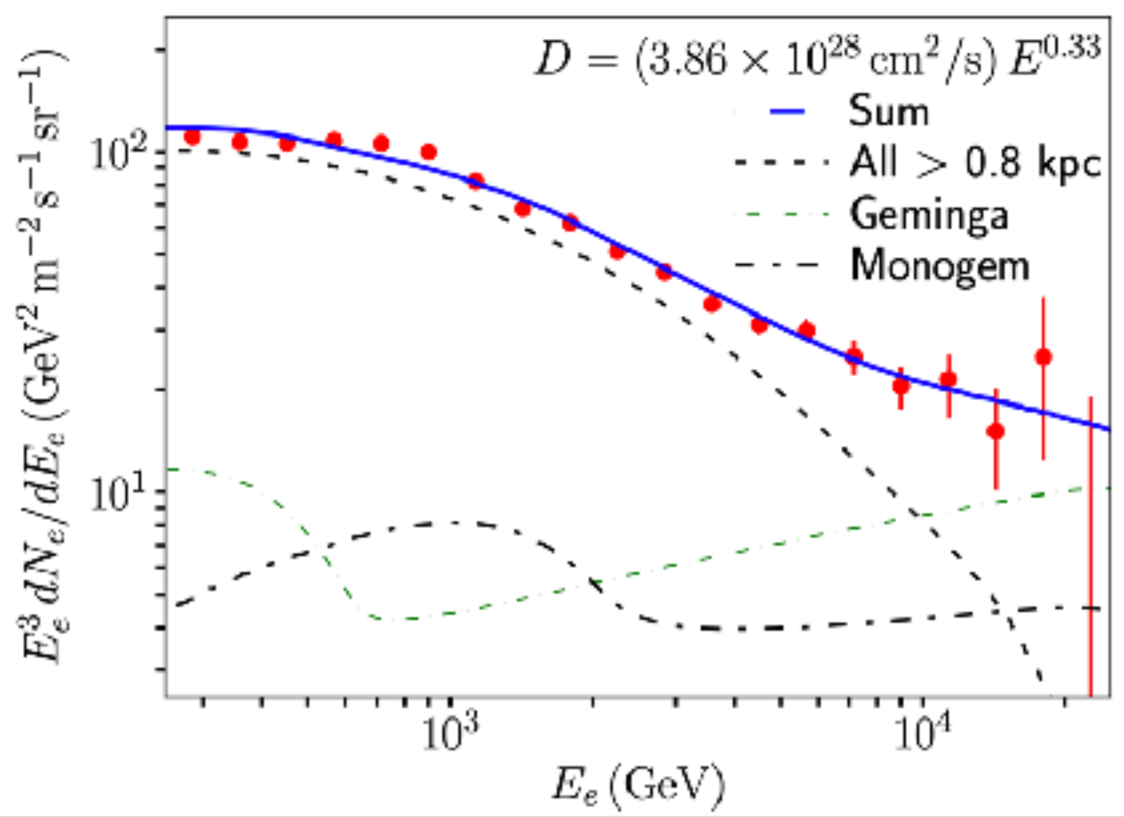
Trotta et al. (2010, 1011.0037)

WHAT IS THE PHYSICS OF TEV HALOS?

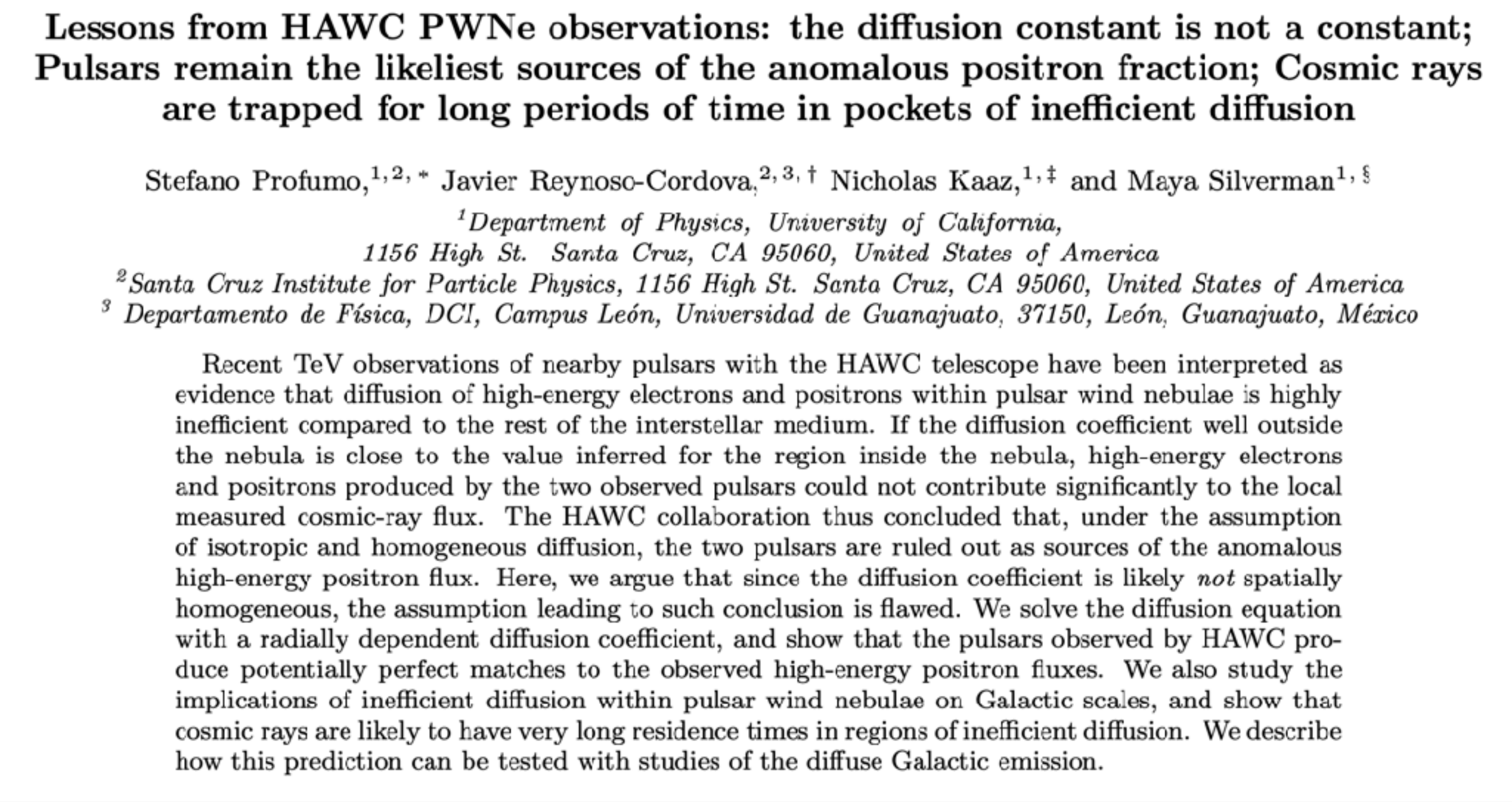
- Models to Explain Inhibited Diffusion:
  - Diffusion Coefficient in TeV halos: ~10^{28} cm^2 s^{-1} at 10 TeV
  - Local diffusion coefficient is much higher.

Hooper & TL (2017; 1711.07482)





WHAT IS THE PHYSICS OF TEV HALOS?



Lessons from HAWC PWNe observations: the diffusion constant is not a constant; Pulsars remain the likeliest sources of the anomalous positron fraction; Cosmic rays are trapped for long periods of time in pockets of inefficient diffusion

Stefano Profumo,[1,2,*] Javier Reynoso-Cordova,[2,3,†] Nicholas Kaaz,[1,‡] and Maya Silverman[1,§]

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1156 High St. Santa Cruz, CA 95060, United States of America
[2]*Santa Cruz Institute for Particle Physics, 1156 High St. Santa Cruz, CA 95060, United States of America*
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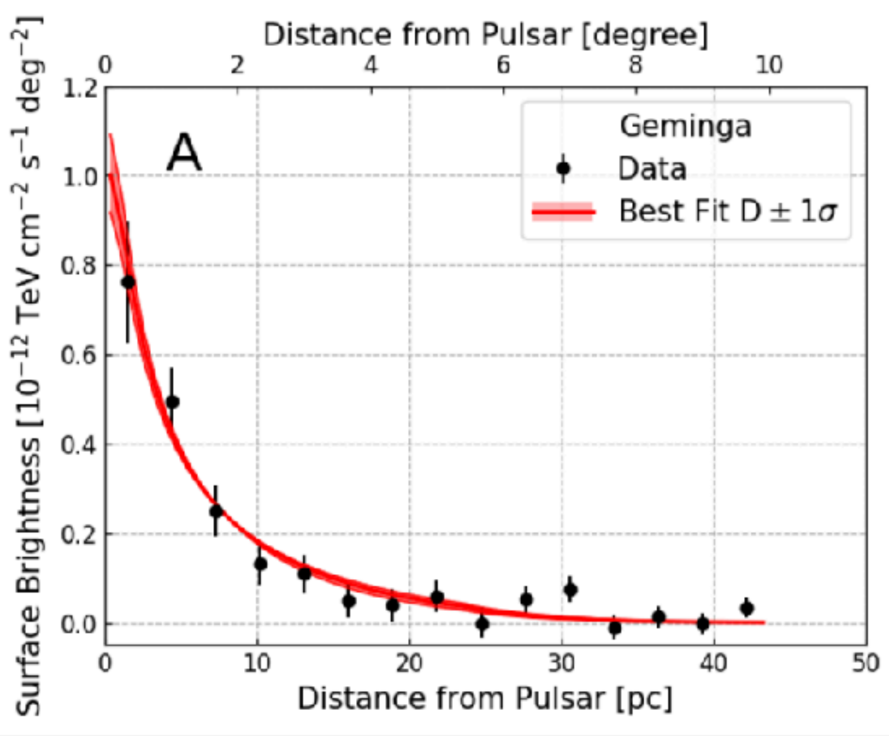
Recent TeV observations of nearby pulsars with the HAWC telescope have been interpreted as evidence that diffusion of high-energy electrons and positrons within pulsar wind nebulae is highly inefficient compared to the rest of the interstellar medium. If the diffusion coefficient well outside the nebula is close to the value inferred for the region inside the nebula, high-energy electrons and positrons produced by the two observed pulsars could not contribute significantly to the local measured cosmic-ray flux. The HAWC collaboration thus concluded that, under the assumption of isotropic and homogeneous diffusion, the two pulsars are ruled out as sources of the anomalous high-energy positron flux. Here, we argue that since the diffusion coefficient is likely *not* spatially homogeneous, the assumption leading to such conclusion is flawed. We solve the diffusion equation with a radially dependent diffusion coefficient, and show that the pulsars observed by HAWC produce potentially perfect matches to the observed high-energy positron fluxes. We also study the implications of inefficient diffusion within pulsar wind nebulae on Galactic scales, and show that cosmic rays are likely to have very long residence times in regions of inefficient diffusion. We describe how this prediction can be tested with studies of the diffuse Galactic emission.

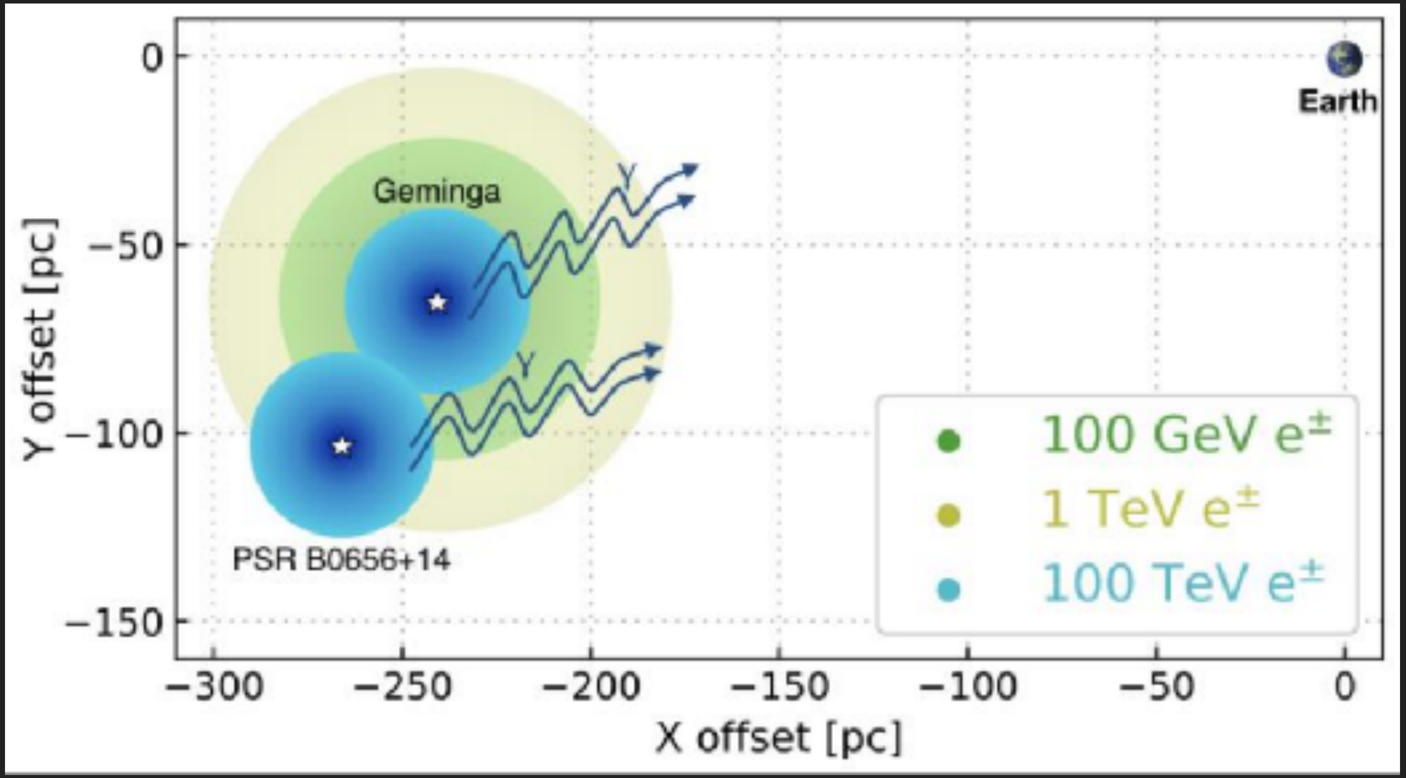
WHAT IS THE PHYSICS OF TEV HALOS?

Abeysekara et al. (2017; 1711.06223)



- Models to Explain Inhibited Diffusion:

- Pre-Existing Regions of Low Diffusion
  - Reasonable when only Geminga and Monogem were detected - but not now.

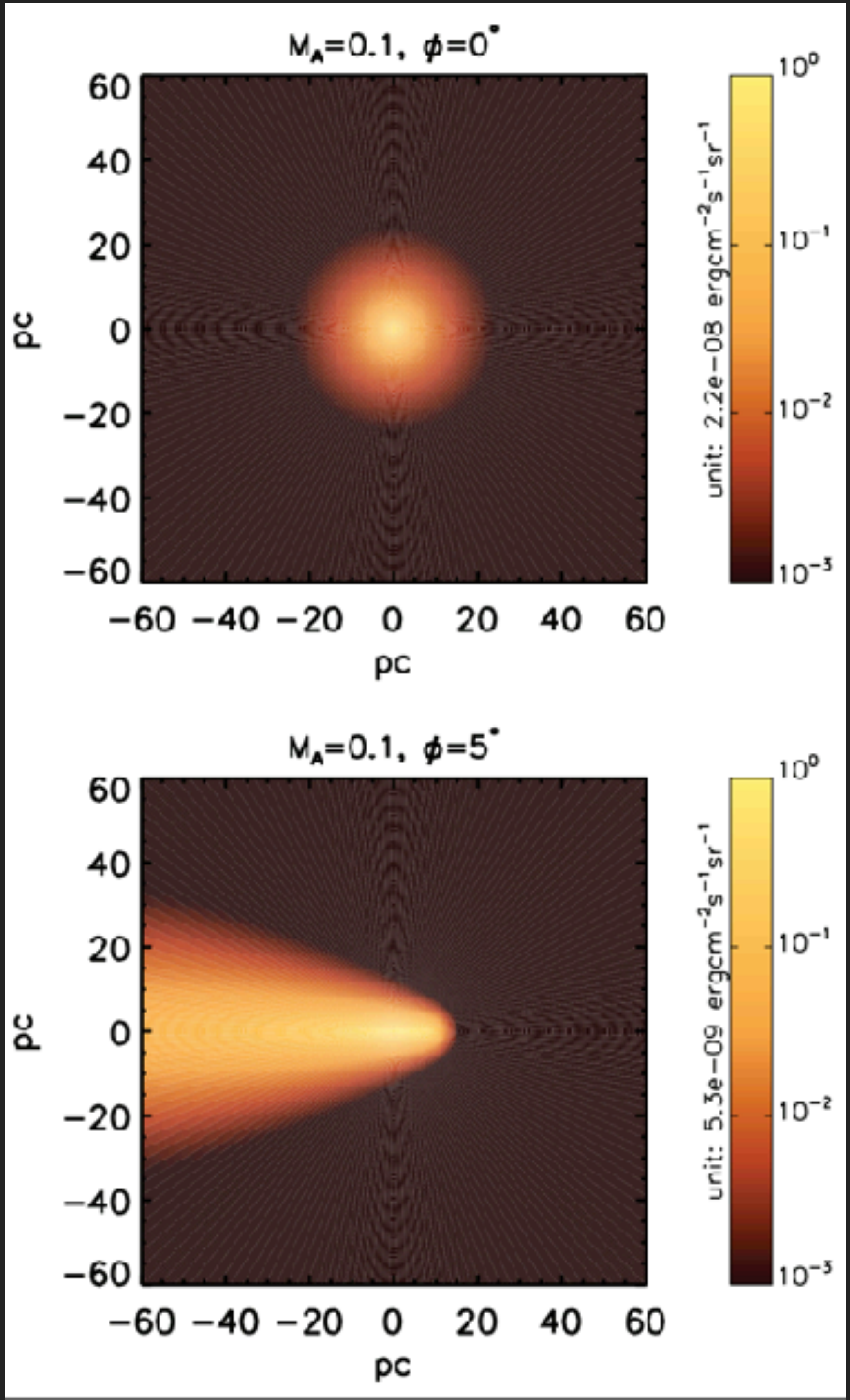


Abeysekara et al. (2017; 1711.06223)

WHAT IS THE PHYSICS OF TEV HALOS?

- Models to Explain Inhibited Diffusion:

- One-Dimensional Diffusion
  - Magnetic fields must be pointed along line of sight - unlikely if many halos detected.



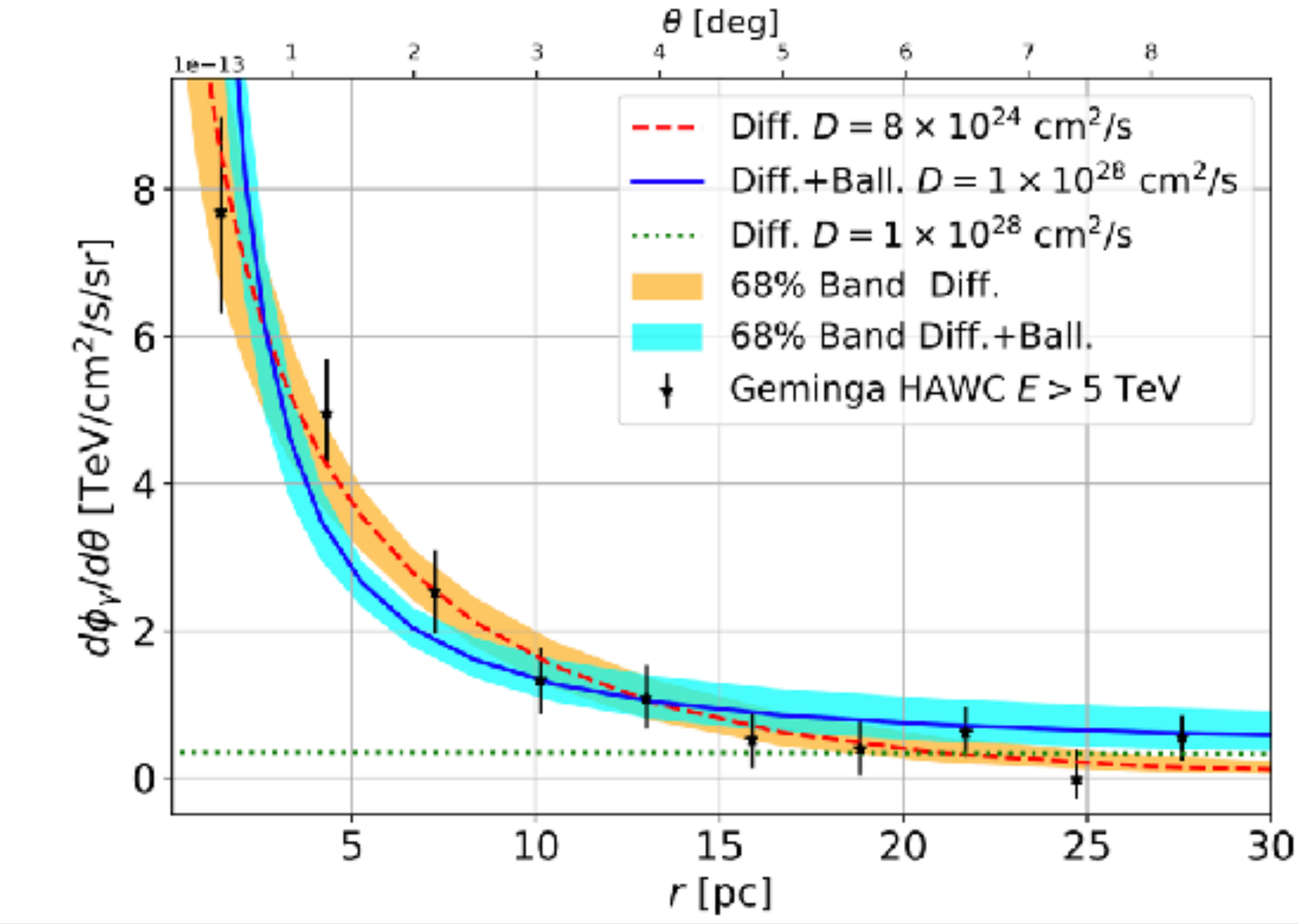
Liu, Yan, Zhang (2019; 1904.11536)

WHAT IS THE PHYSICS OF TEV HALOS?

- Models to Explain Inhibited Diffusion:

- Transition from Ballistic Propagation
  - However, necessary efficiency for conversion of spin down power to e+e- is much higher than 100%.

Recchia et al. (2021; 2106.02275)



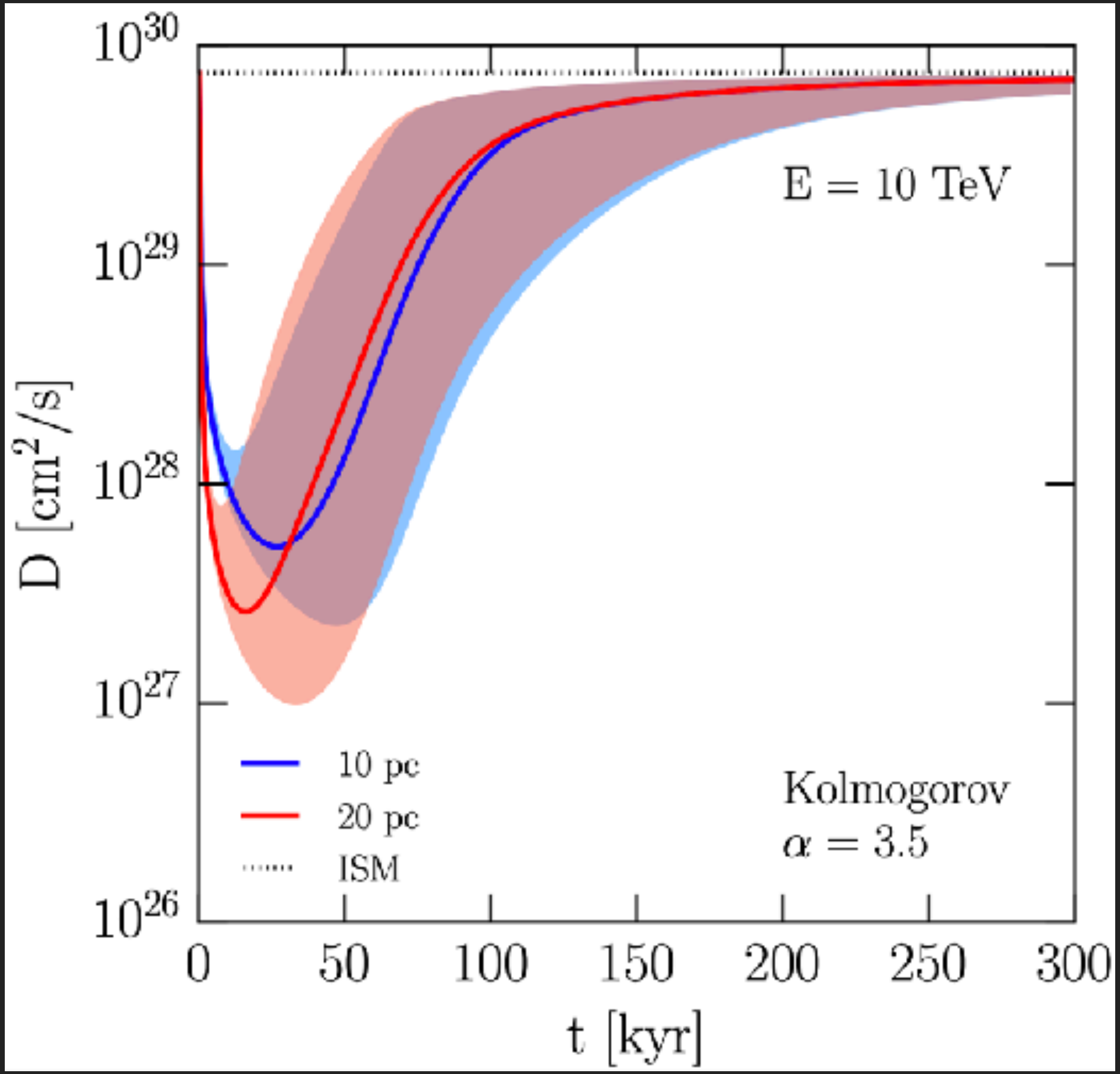
Bao, Fang & Bi (2021; 2107.07395)

WHAT IS THE PHYSICS OF TEV HALOS?

- Models to Explain Inhibited Diffusion:

- The Pulsar/SNR could lower the surrounding diffusion coefficient
  - Pulsar may not be powerful enough to change diffusion over 20 pc scales.

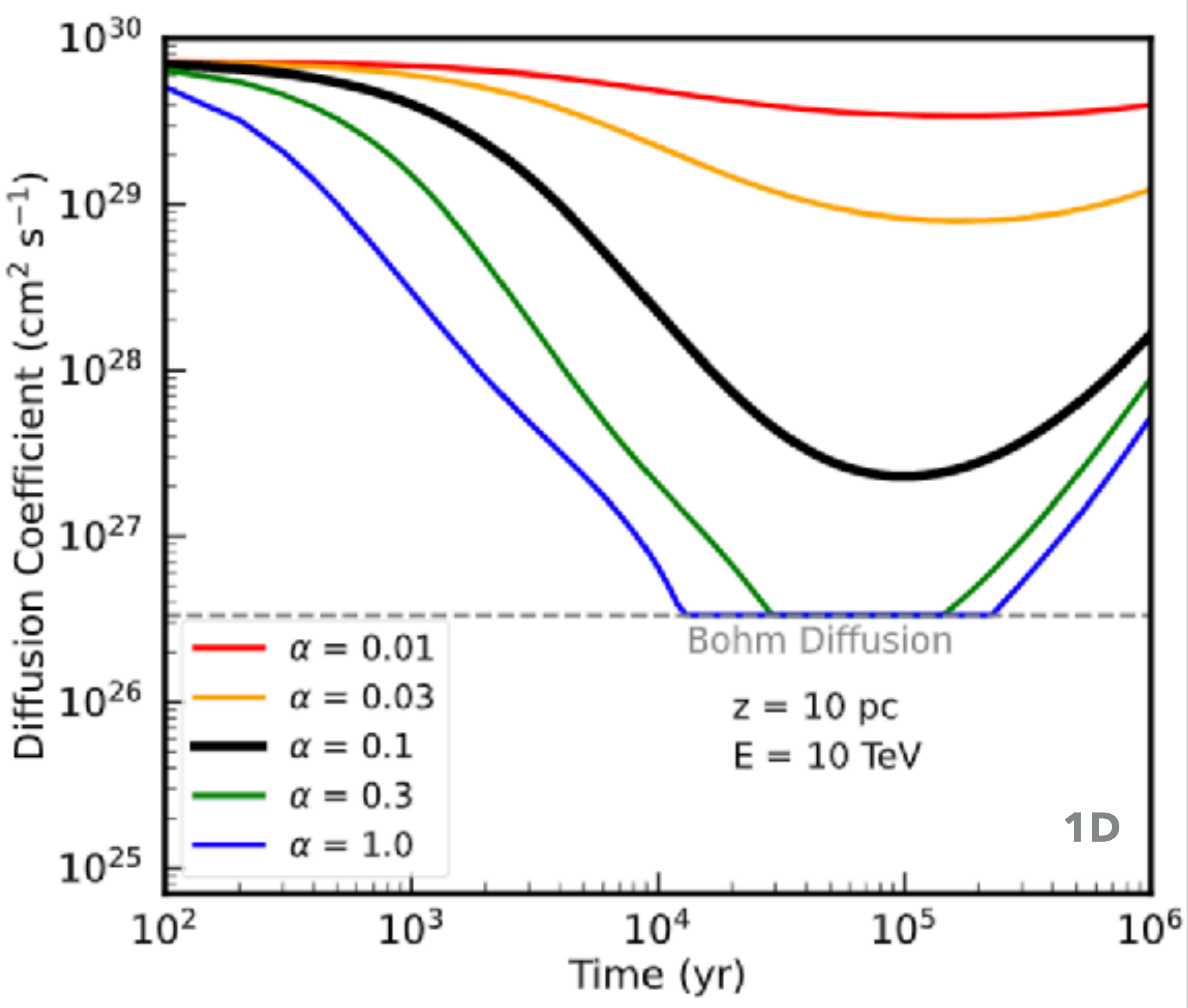
Evoli, TL, Morlino (2018; 1807.09263)



WHAT IS THE PHYSICS OF TEV HALOS?

Mukhopadhyay & TL (2021; TBS)

- Models to Explain Inhibited Diffusion:
- The Pulsar/SNR could lower the surrounding diffusion coefficient

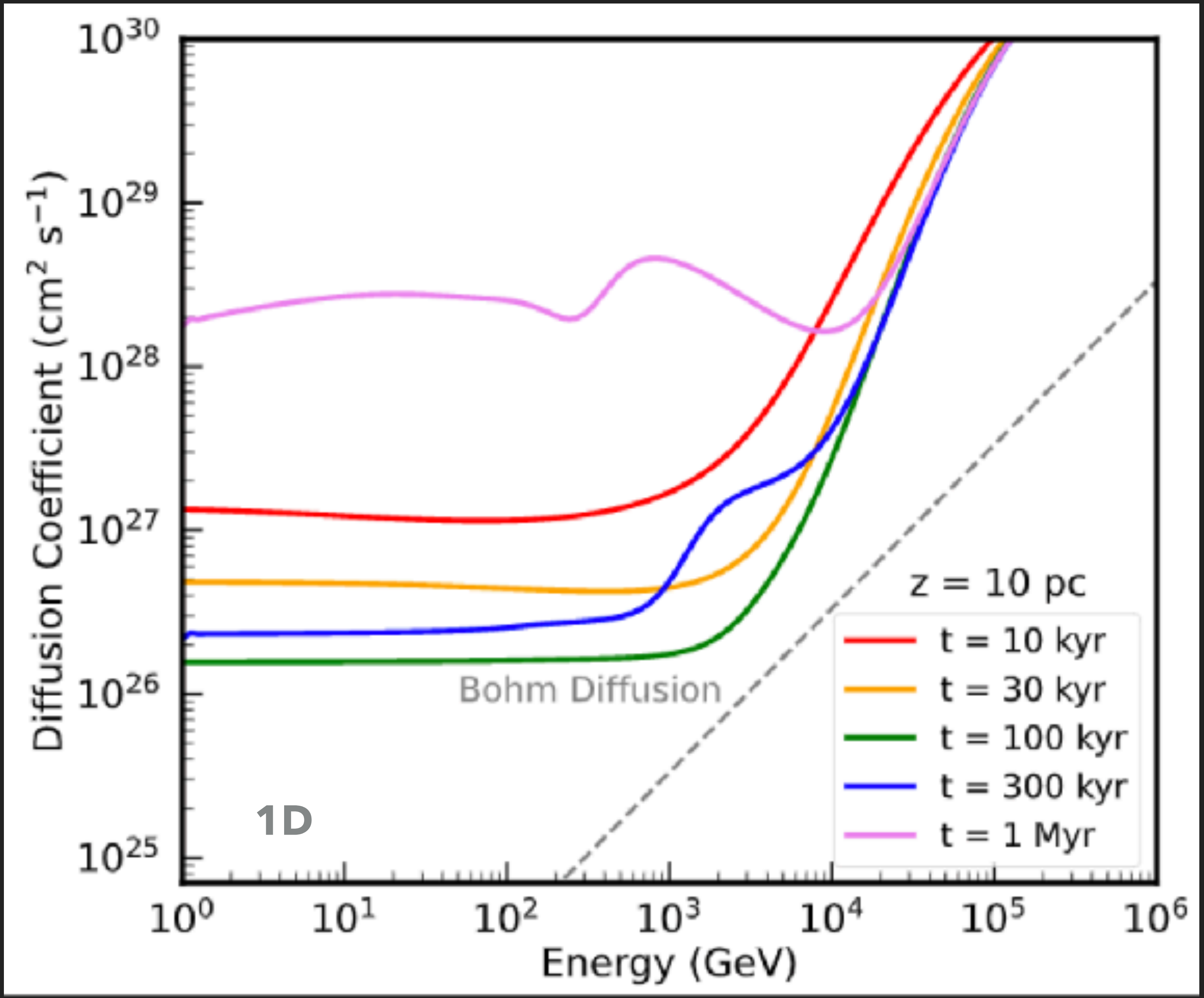


- The diffusion coefficient returns to its default value much slower than previously thought!

WHAT IS THE PHYSICS OF TEV HALOS?

Mukhopadhyay & TL (2021; TBS)

- Models to Explain Inhibited Diffusion:



- The Pulsar/SNR could lower the surrounding diffusion coefficient

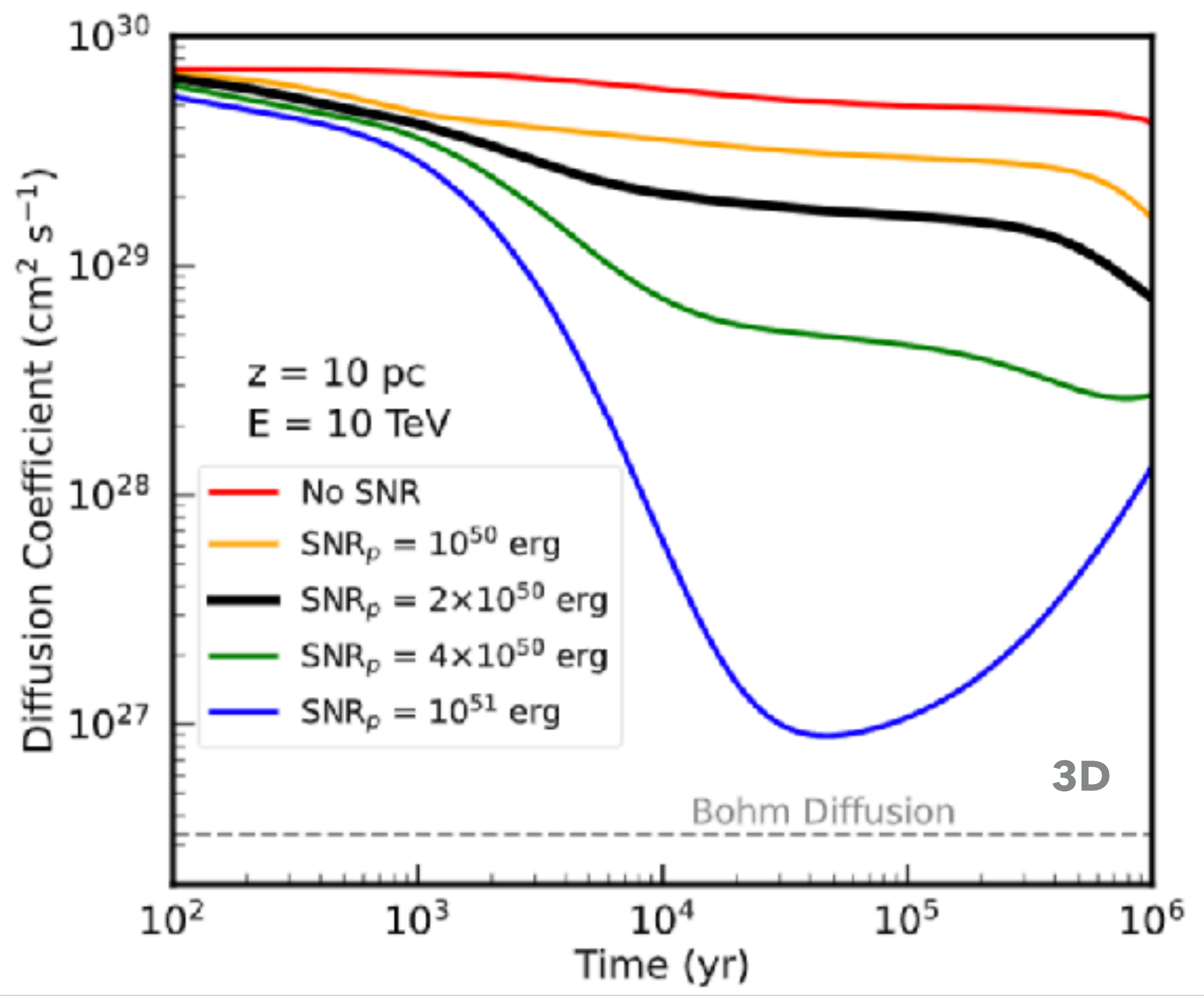
- There are specific spectral features of this inhibited diffusion - testable predictions in the GeV and 10s of TeV range.

WHAT IS THE PHYSICS OF TEV HALOS?

Mukhopadhyay & TL (2021; TBS)

- Models to Explain Inhibited Diffusion:

- The Pulsar/SNR could lower the surrounding diffusion coefficient

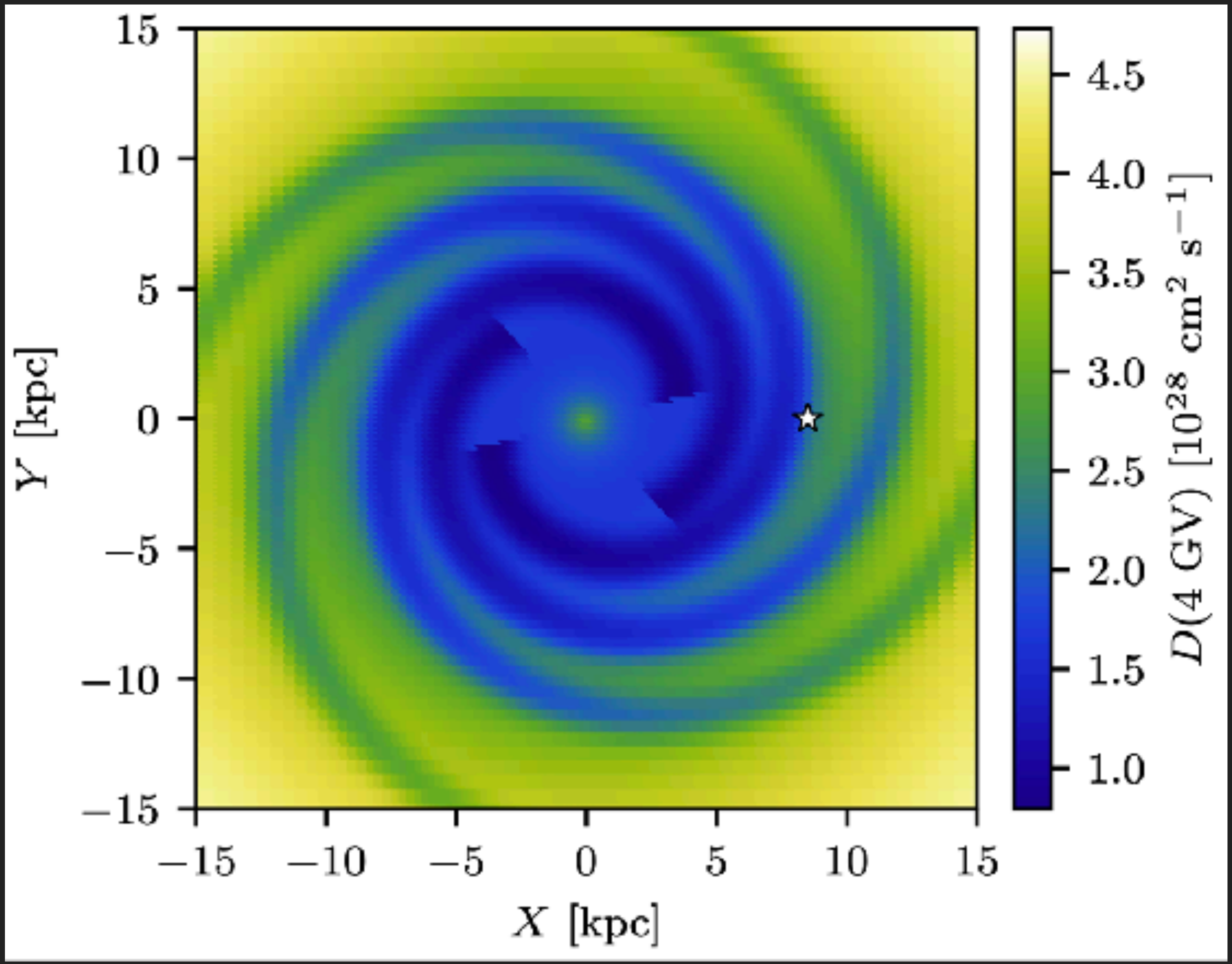


- For full 3D models, need more energy to inhibit diffusion on 10 pc scales – SNR contributions may be important.

BROADER IMPLICATIONS

- The cause of decreased diffusion within TeV halos could have significant implications for cosmic-ray physics.

Jóhannesson et al. (2019.1903.05509)



- Potentially testable with high-energy observations from HAWC and LHAASO.

CONCLUSIONS

- Pulsars contribute gamma-ray emission in three regimes:
    - Pulsar Magnetosphere: Pulsed
    - Pulsar Wind Nebula: Dominated by shock physics, includes significant radio/X-Ray signal.
    - TeV Halo: Gamma-Ray Dominant and Diffusive
- TeV Halos appear to be generic features around pulsars with ages ~20-500 kyr.
- Pulsars likely dominate the diffuse and point source emission in the Milky Way. They also likely produce the positron excess.
- It is important to understand the underlying physical mechanism that causes diffusion near halos to be suppressed.