Tim Linden

“TeV Halos” - Extended Sources Surrounding Pulsars

Stockholms universitet

Two Early Papers

NUCLEAR PHYSICS B
PROCEEDINGS
SUPPLEMENTS

ELSEVIER

Nuclear Physics B (Proc. Suppl.) 39A (1995) 193–206

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

F.A.Aharonian

Max-Planck-Institut für Kernphysik,
Saupferchechkweg 1, D-69029 Heidelberg, Germany

Whether or not the spectra of γ-ray pulsars continue to the VHE region is a question which remains one of the interesting issues of ground-based γ-ray observations. Besides the pulsed radiation produced in the magnetosphere, one may expect γ-rays from much more extended regions surrounding the pulsars. The pulsars are undisputed sources of relativistic electrons accelerating particles directly in the magnetospheres as well as through the pulsar wind termination shocks (see e.g. [45],[62]). The last mechanism seems likely to be responsible for the injection of electrons up to energies 10^{15} eV into the Crab Nebula [47]. The interaction of these electrons with the photon fields in the nebula results in the production of observable VHE γ-radiation (see Sec.6).

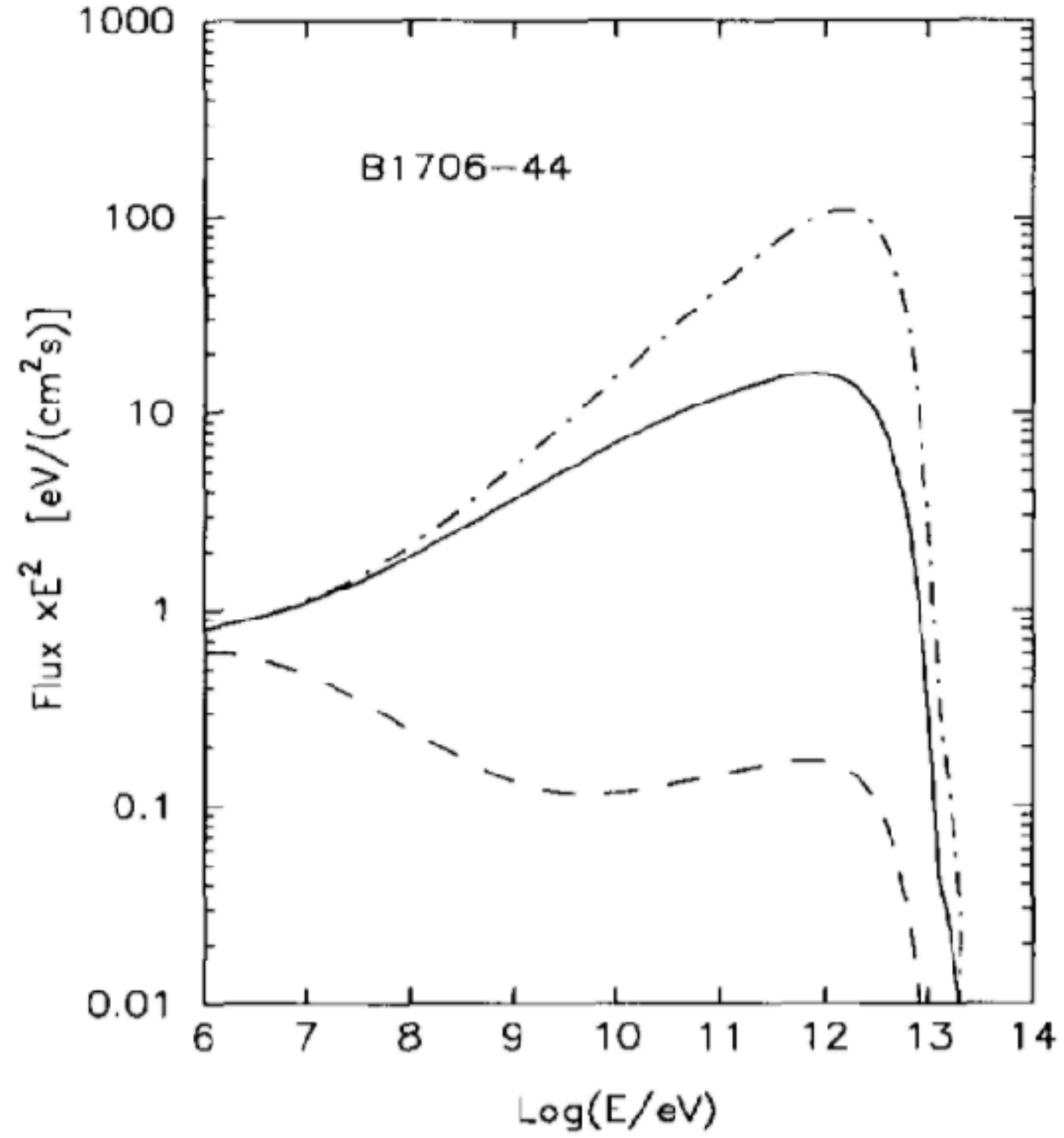
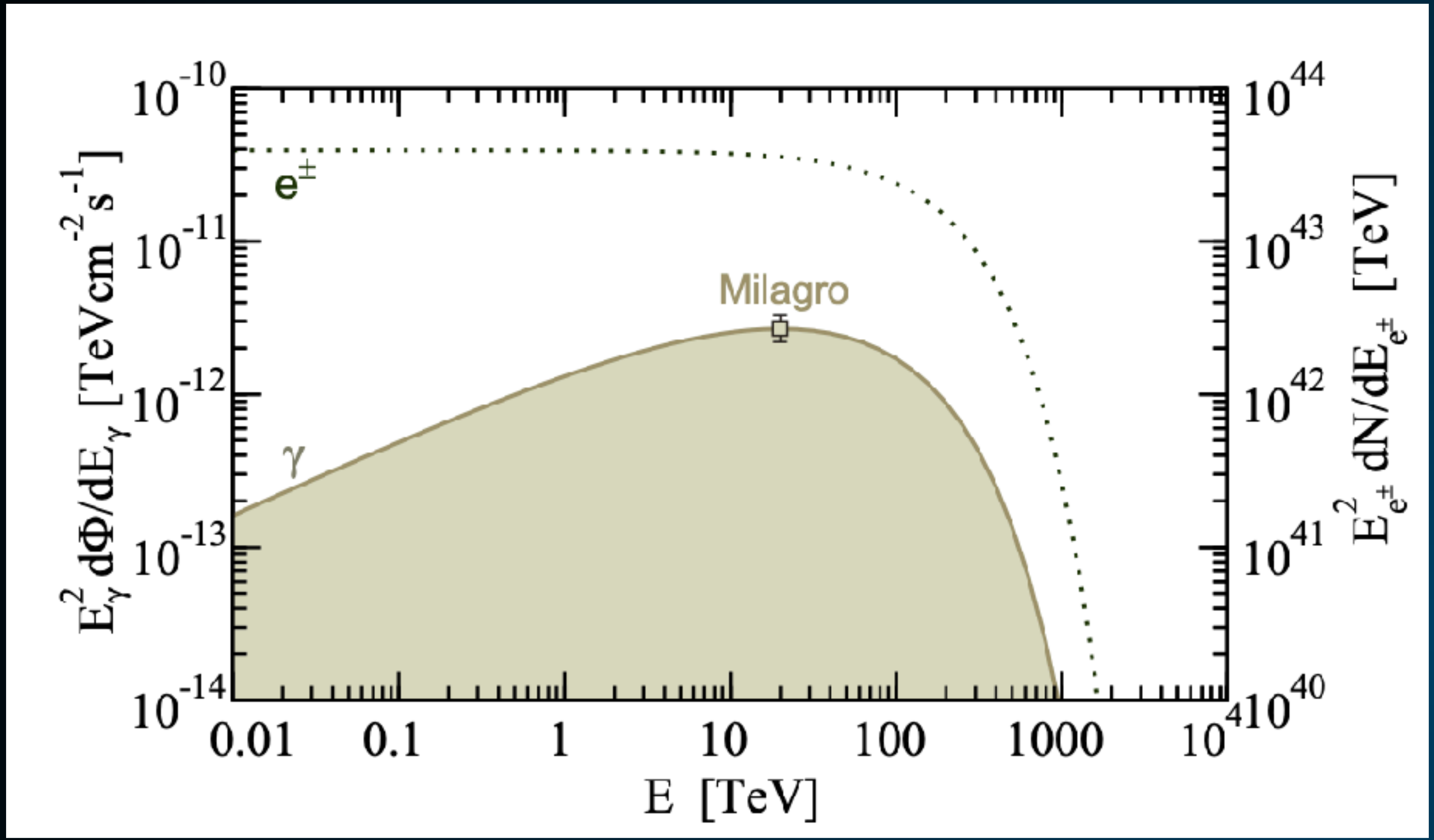
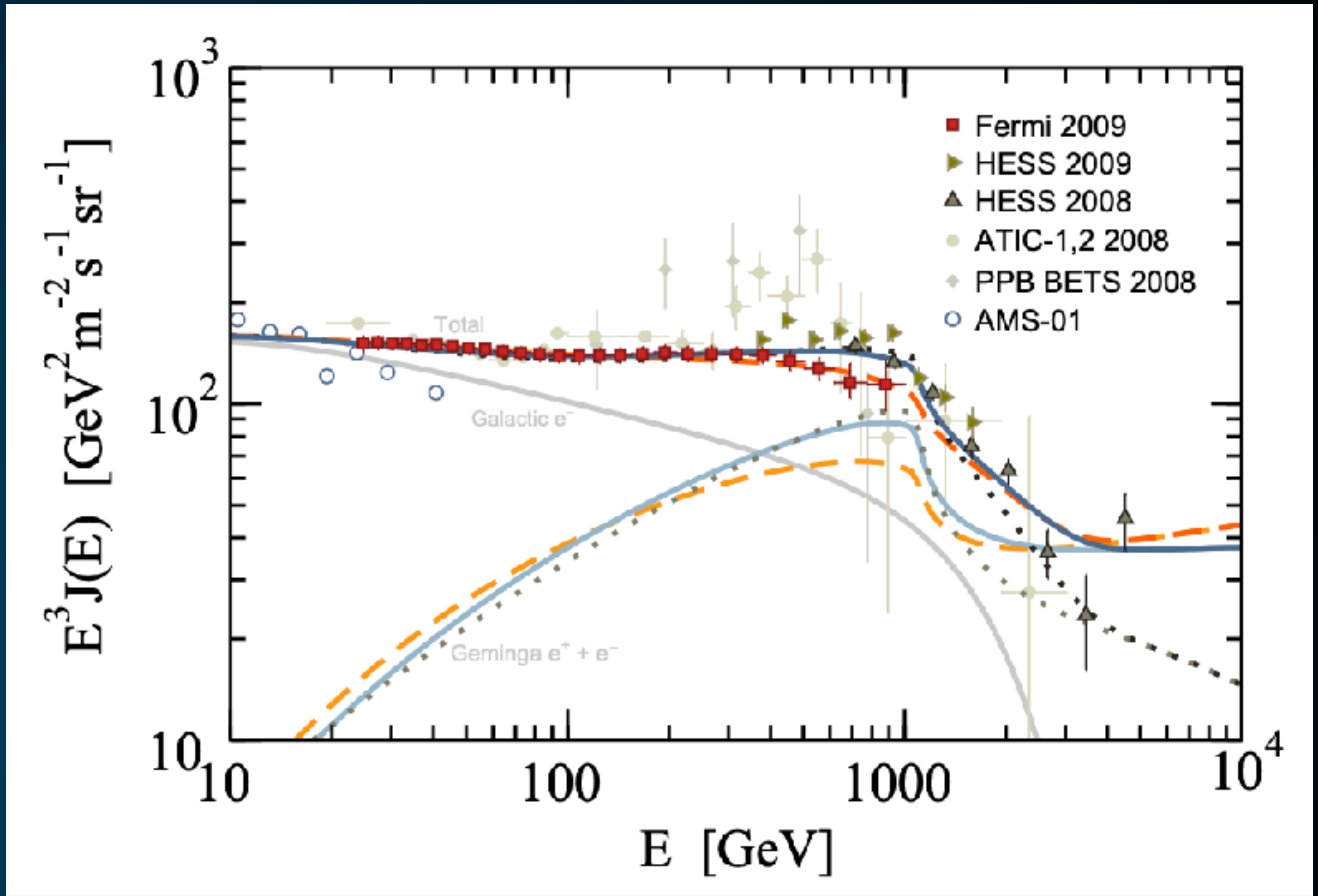


Figure 8. Gamma-ray fluxes expected within different angles from the pulsar PSR B1706-44: 0.1° (dashed line), 1° (solid line), 10° (dash-dotted line). It is assumed that total $W_e = 10^{49}$ erg energy has been released in the power-law distributed electrons with $\alpha = 2$ at the first stages of the pulsar; the distance to the source $d = 1.8$ kpc. The power-law diffusion coefficient and parameters characterizing the ISM are the same as those used in Figures 5 and 6.

Two Early Papers

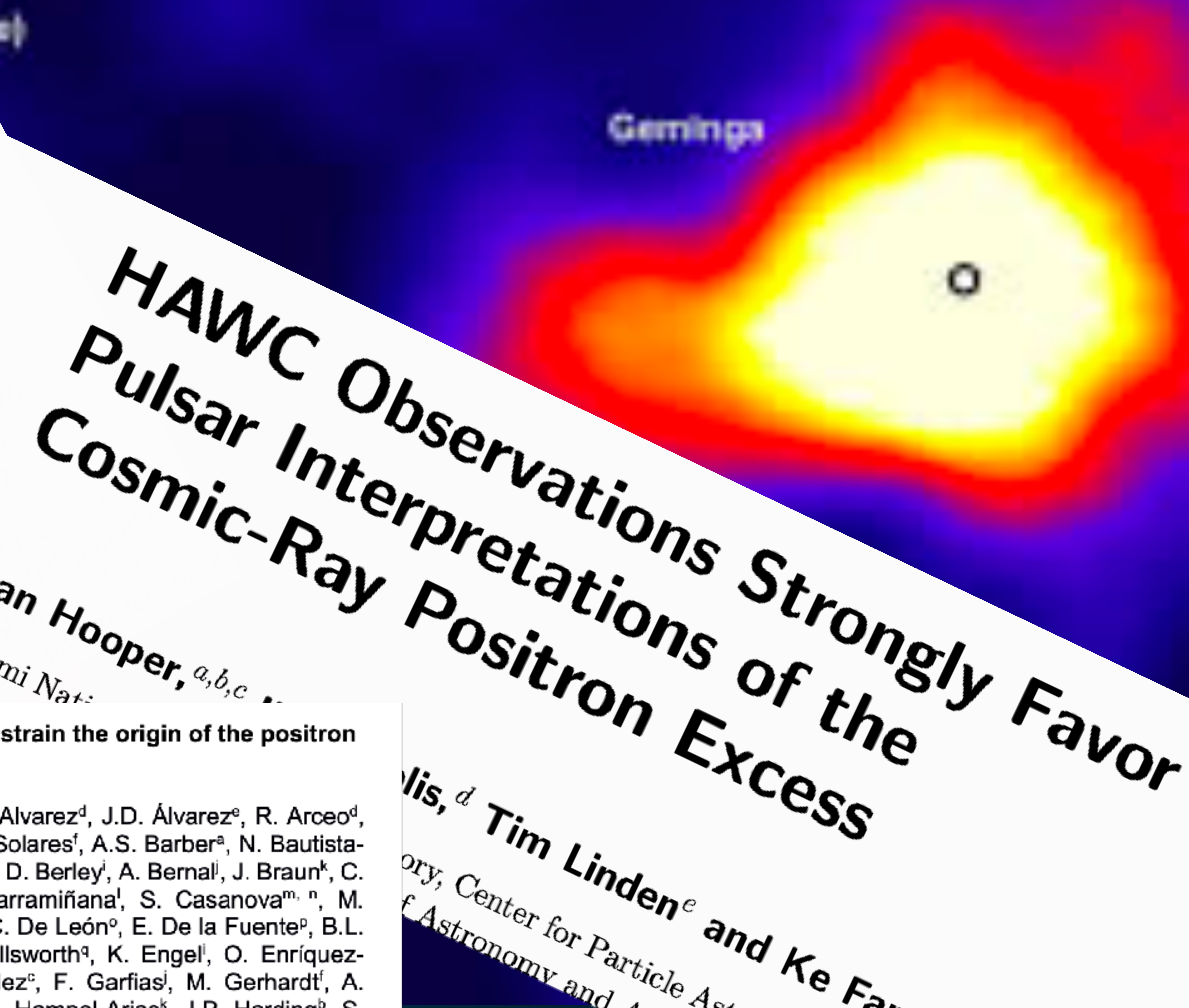
Yüksel, Kistler, Stanev (2008; 0810.2784)





Yüksel et al noted the importance of TeV gamma-ray observations (in particular Milagro observations of Geminga) for understanding the positron excess.

The Field Explodes



Using HAWC to Discover Invisible Pulsars

Tim Linden,[1,*] Katie Auchettl,[1,†] Joseph Bramante,[2,‡] Ilias Cholis,[3,§] Ke Fang,[4,5,¶] Dan Hooper,[6,7,8,**] Tanvi Karwal,[3,††] and Shirley Weishi Li[1,‡‡]

[1] Center for Cosmology and AstroParticle Physics (CCAPP), and Department of Physics, The Ohio State University Columbus, OH, 43210

[2] Perimeter Institute for Theoretical Physics, Waterloo, Ontario, N2L 2Y5, Ca

[3] Department of Physics and Astronomy, The Johns Hopkins University, Baltimore

[4] University of Maryland, Department of Astronomy, College Park, MD, 20

[5] Joint Space-Science Institute, College Park,

Fermi National Accelerator Labor… Center for Particle Astro…

University of Chicago, Depar… Astronomy and Astroph…

of Chicago, Kav… Cosmological Physic…

27 Feb 2017

HAWC Observations Strongly Favor Pulsar Interpretations of the Cosmic-Ray Positron Excess

Dan Hooper,[a,b,c] …lis,[d] Tim Linden[e] and Ke Fang[f,g]

[a] Fermi Nati… …ory, Center for Particle Astrophysics,

[b] Uni… …f Astronomy and Astrophysics

Extended gamma-ray sources around pulsars constrain the origin of the positron flux at Earth

Authors: A.U. Abeysekara[a], A. Albert[b], R. Alfaro[c], C. Alvarez[d], J.D. Álvarez[e], R. Arceo[d], J.C. Arteaga-Velázquez[e], D. Avila Rojas[c], H.A. Ayala Solares[f], A.S. Barber[a], N. Bautista-Elivar[g], A. Becerril[c], E. Belmont-Moreno[c], S.Y. BenZvi[h], D. Berley[j], A. Bernal[l], J. Braun[k], C. Brisbois[f], K.S. Caballero-Mora[d], T. Capistrán[l], A. Carramiñana[l], S. Casanova[m, n], M. Castillo[e], U. Cotti[e], J. Cotzomi[o], S. Coutiño de León[l], C. De León[o], E. De la Fuente[p], B.L. … Díaz-Vélez[p], R.W. Ellsworth[q], K. Engel[j], O. Enríquez-… J.A. García-González[c], F. Garfias[j], M. Gerhardt[f], A. … J.A. Goodman[j], Z. Hampel-Arias[k], J.P. Harding[b], S. … J. Hinton[n], B. Hona[f], C.M. Hui[s], P. Hüntemeyer[f], A. … S. Kaufmann[d], D. Kieda[a], A. Lara[r], R.J. Lauer[t], W.H. … J.T. Linnemann[v], A.L. Long… K. Malone[x], S.S. Marinelli[v], O … H. Martínez-Huerta[y], J.A. … L. Nellen[aa], M. Newbold[a], … E.G. Pérez-Pérez[g], Z. Ren[t], C. … E. Ruiz-Velasco[c], H. Salazar[o], … Schoorlemmer[n], G. Sinnis[b], A.J. S… K. Tollefson[v], I. Torres[l], T.N. … G. Wisher[k], J. Wood[k], T. Yapici[v], … J. Hahn[n], H. Li[b], H. Zhang[b]

TWO-ZONE DIFFUSION OF ELECTRONS AND POSITRONS FROM GEMINGA EXPLAINS THE POSITRON ANOMALY

Kun Fang,[1,2] Xiao-Jun Bi,[1,2] Peng-Fei Yin,[1] and Qiang Yuan[3,4]

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[2] *School of Physics, University of Chinese Academy of Sciences, Beijing 100049, China*

[3] *Key Laboratory of Dark Matter and Space Astronomy, Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210008, China*

[4] *School of Astronomy and Space Science, University of Science and Technology of China, Hefei, Anhui 230026, China*

25 Jul 2018

(Dated: July 26, 2018)

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,§]

[1] *Department of Physics, University of California, 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*

[3] *Departamento de Física, DCI, Campus León, Universidad de Guanajuato, 37150, León, Guanajuato, México*

What's in a name? That which we call a rose by any other name would smell as sweet.

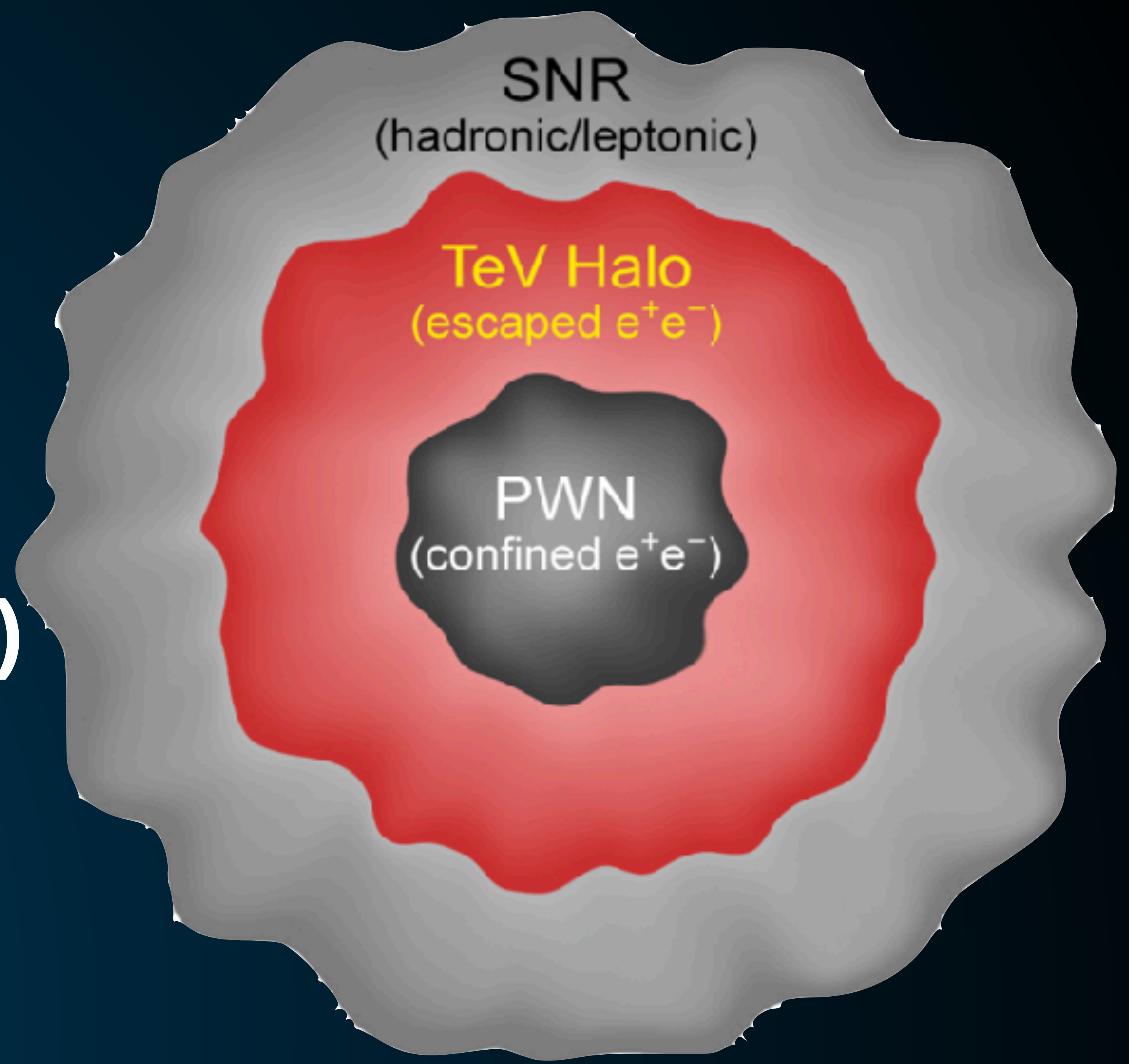
William Shakespeare

Personal Definition

Sudoh, TL, Beacom (2019; 1902.08203)

“TeV halos” are:

1.) Spatially Extended
2.) Leptonic (inverse-Compton scattering of CR electrons)
3.) Diffusive (not convective or advective) propagation
4.) Most prominent at TeV energies.



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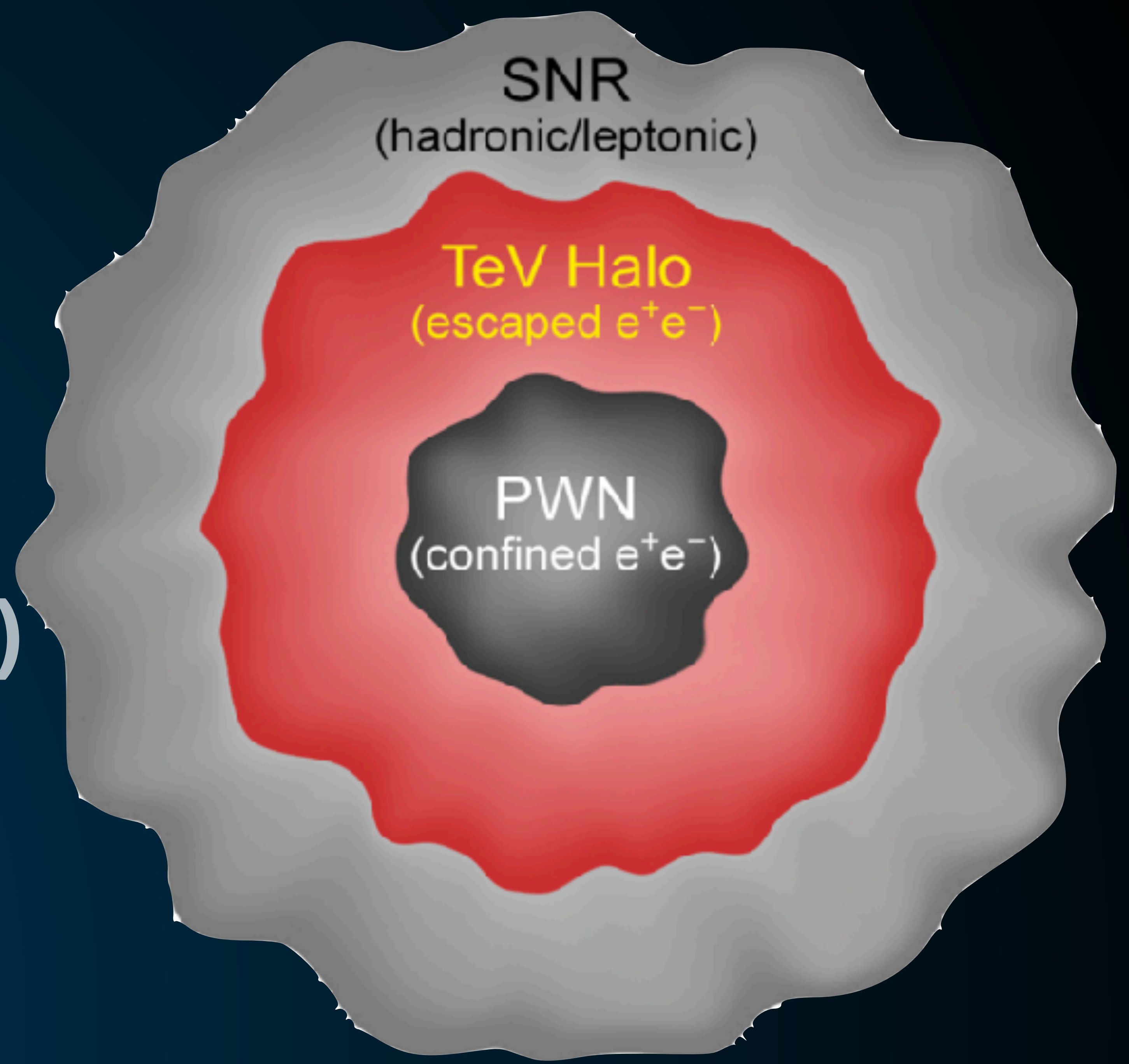


"TeV halos" are:

1.) Spatially Extended
2.) Leptonic (inverse-Compton scattering of CR electrons)
3.) Diffusive (not convective or advective) propagation
4.) Most prominent at TeV energies.

Why?

1.) Minimally distinct from PWN (convective), SNR (hadronic), Pulsar (PS).
2.) Maximally observational (energy range, morphology, ICS/synchrotron ratio).
+ Note: Ratio of Pulsar CR energy to interstellar electron density is derived.
3.) Maximally encapsulates the novel advances of TeV observations.

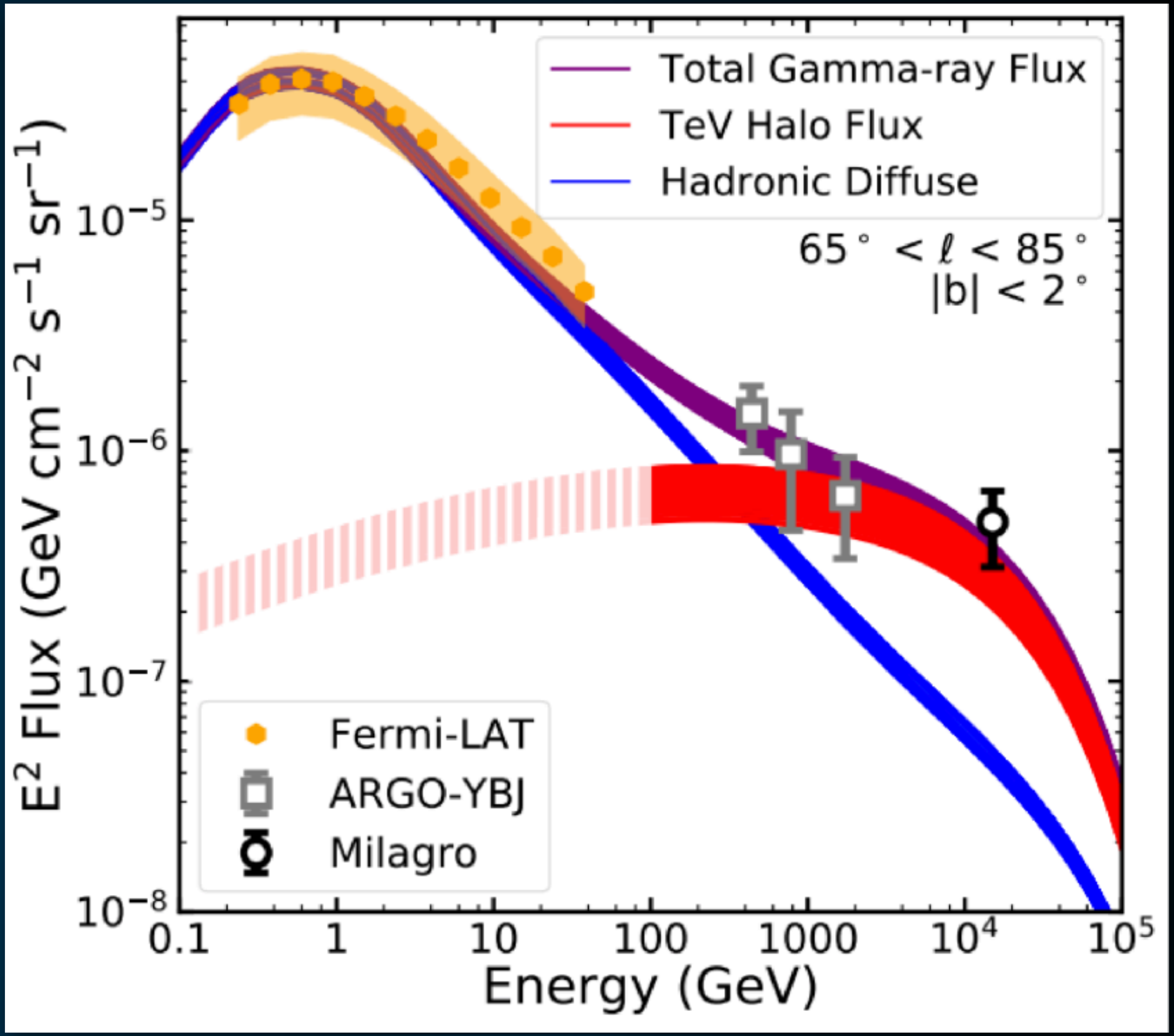
Does this Matter?

Generally, no.

a.) Young pulsars convert a reasonable fraction of their spindown power to e+e- (10%)

b.) The e+e- spectrum extends to high energies ($E^{-1.7}$ to $E^{-1.9}$)?

c.) These electrons lose a reasonable fraction of their energy to ICS (~50%)



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Hooper, Cholis, TL (2017; 1705.09293)

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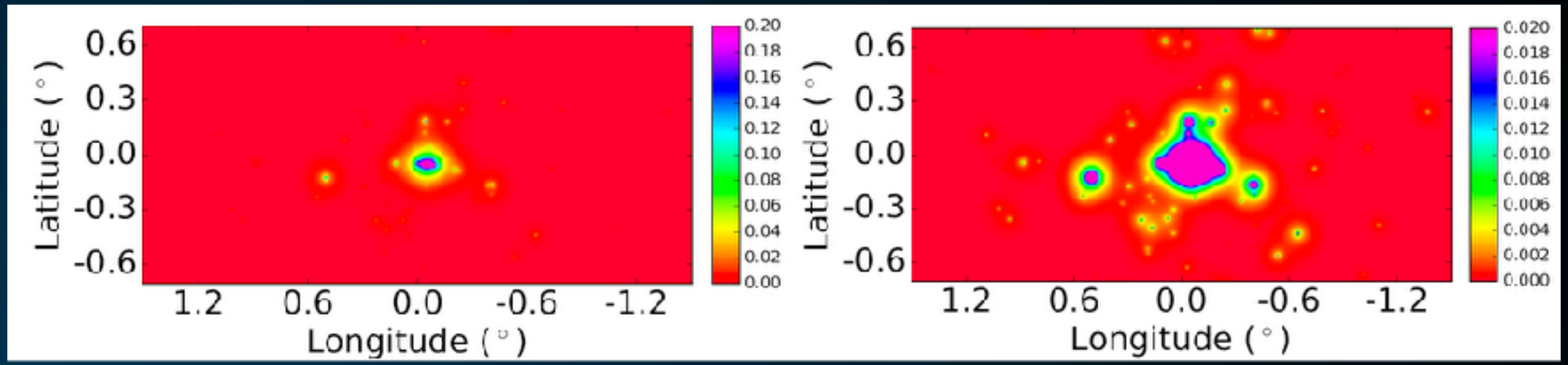
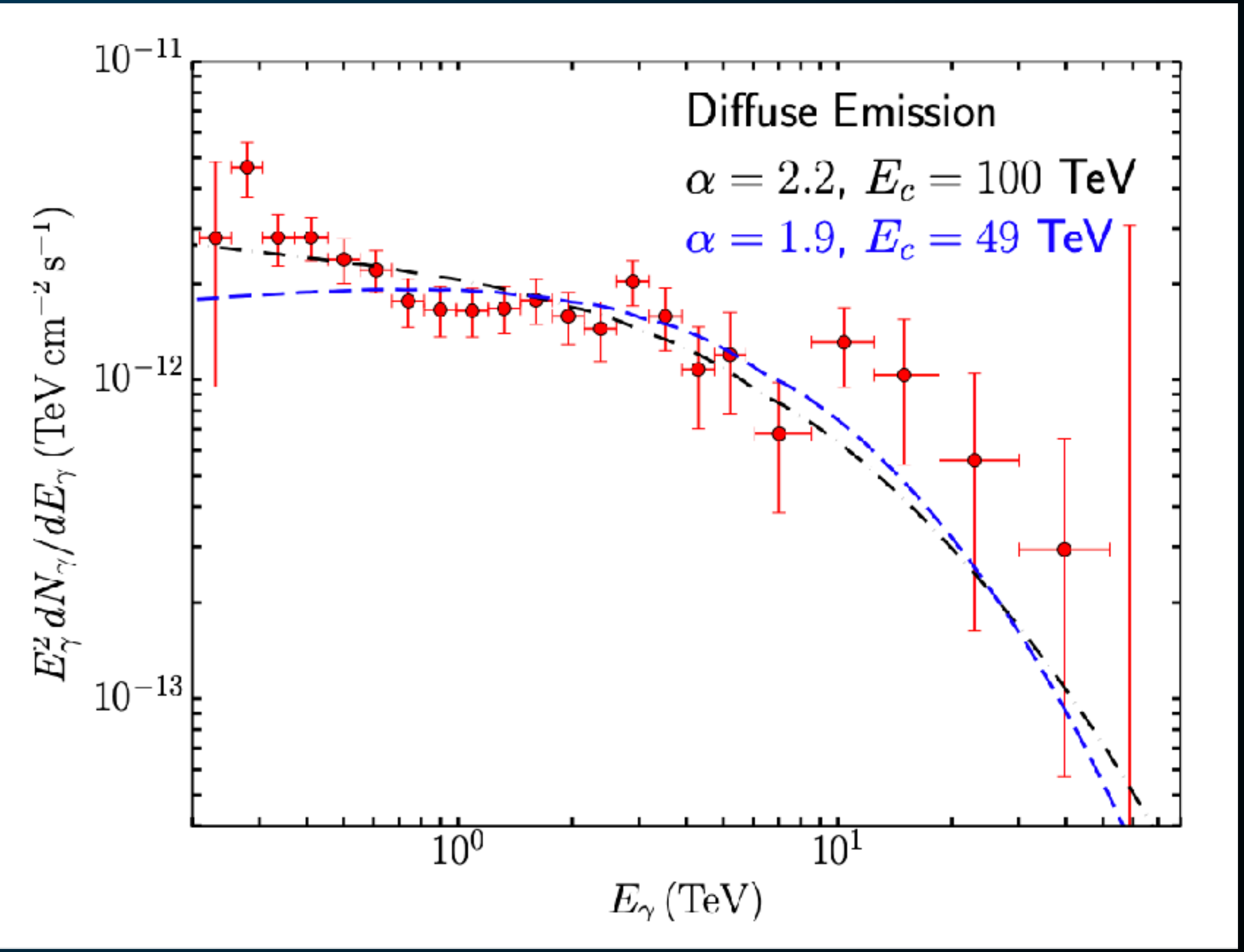
c.) These electrons lose a reasonable fraction of their energy to ICS (~50%) in the GC

d.) The GC star-formation rate is a good proxy for pulsar formation





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TL et al. (2017; 1703.09704)

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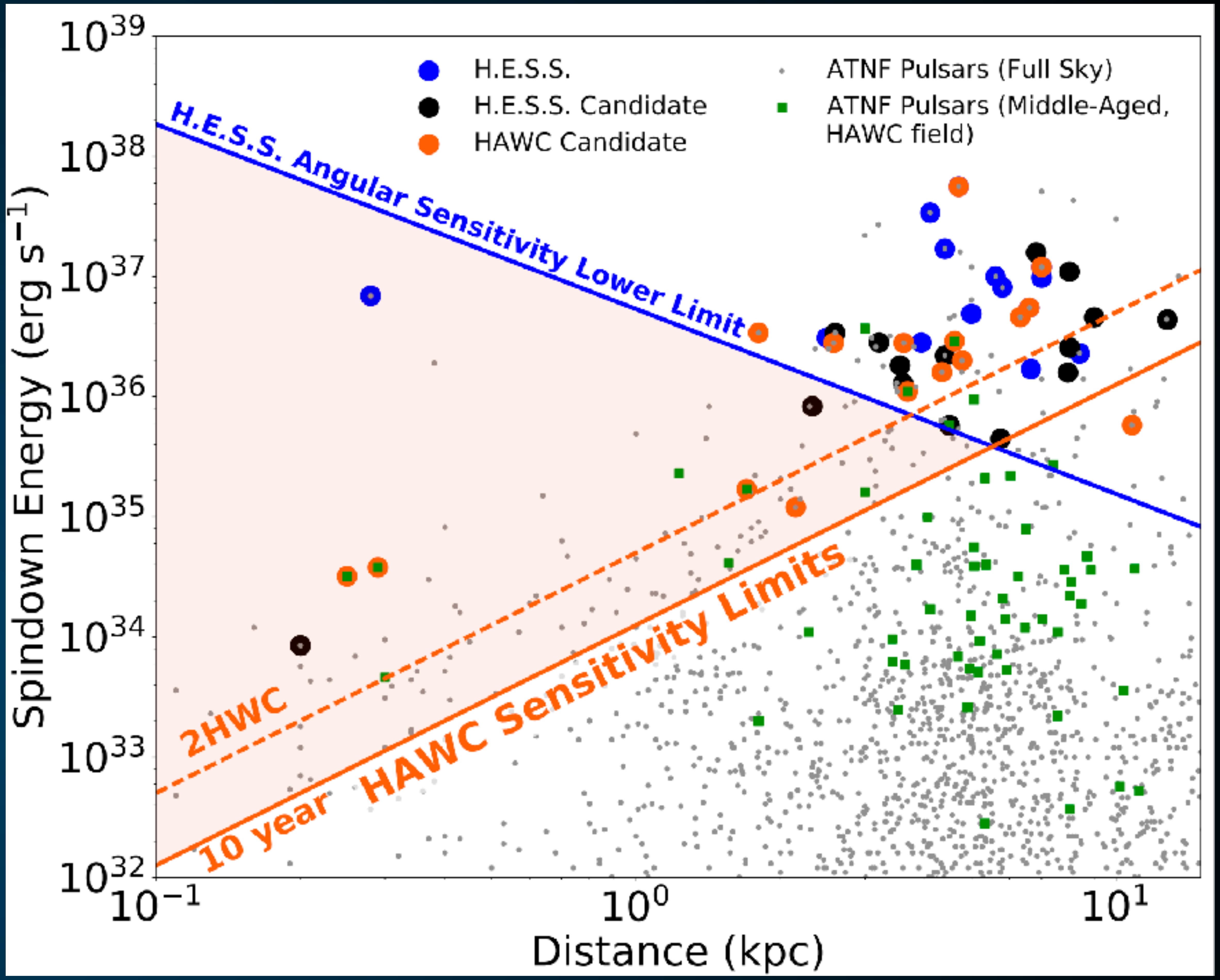

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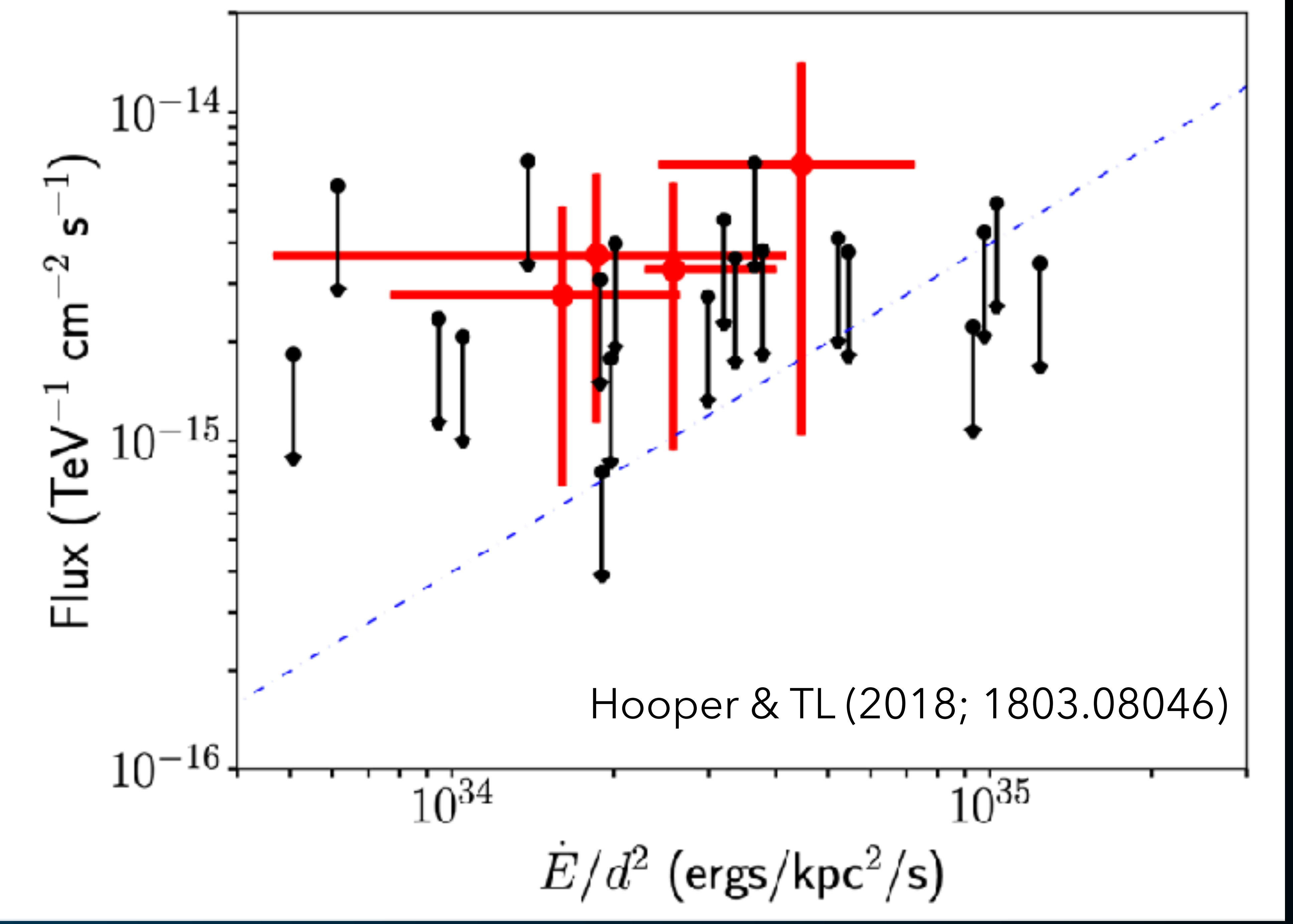
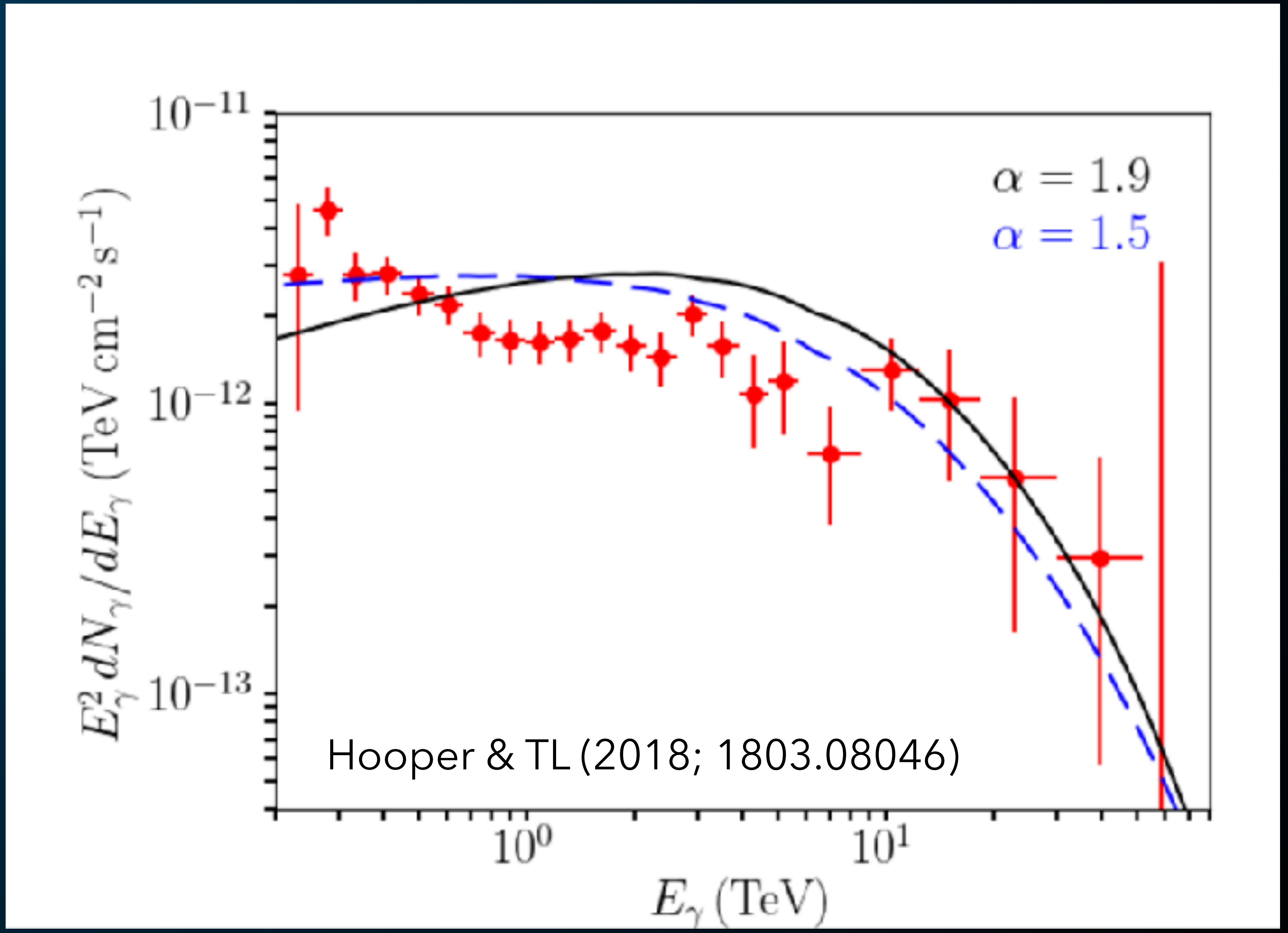
e.) e+e- Acceleration can occur in the pulsar magnetosphere





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Sudoh, TL, Beacom (2020; 2005.08982)

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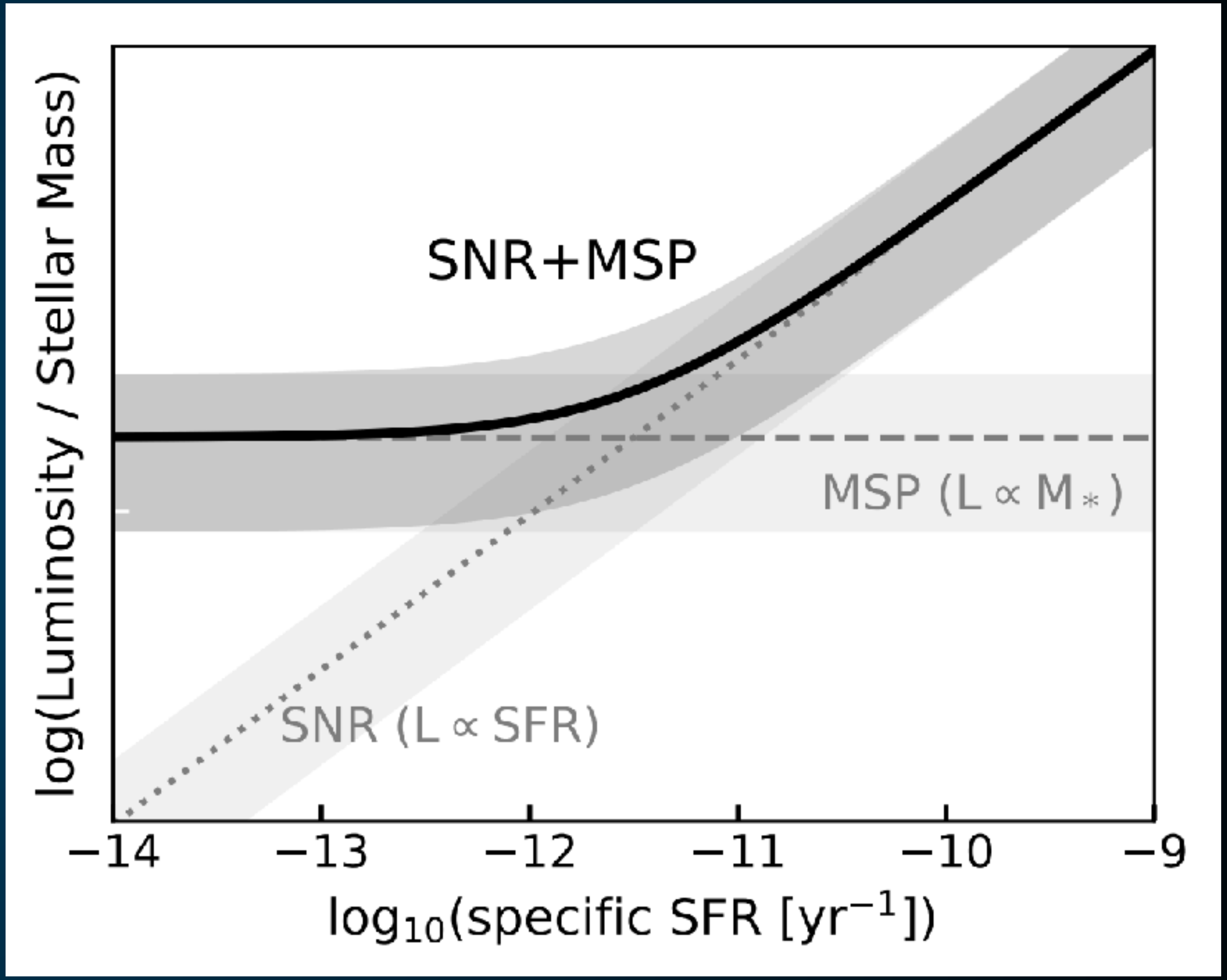

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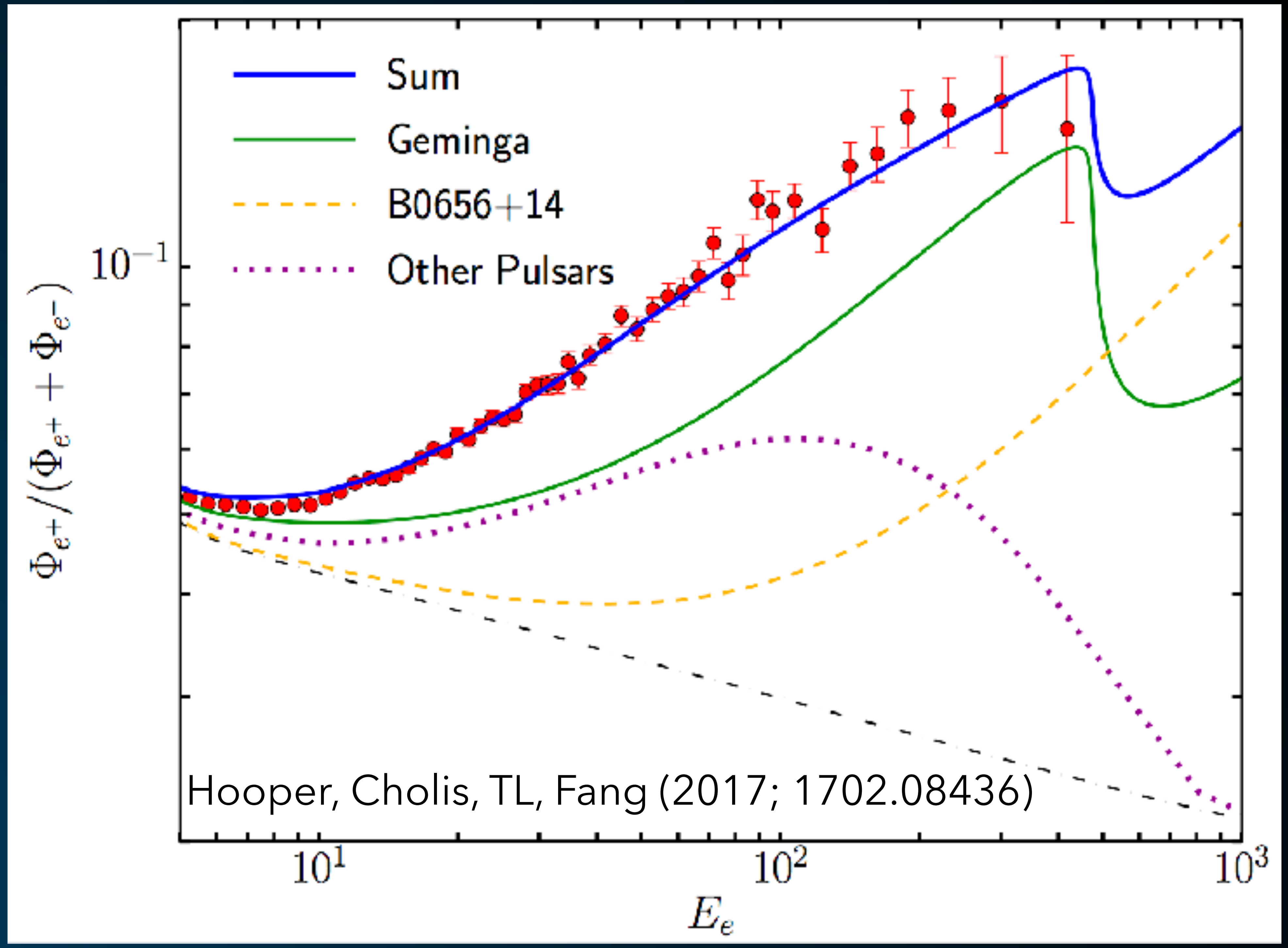
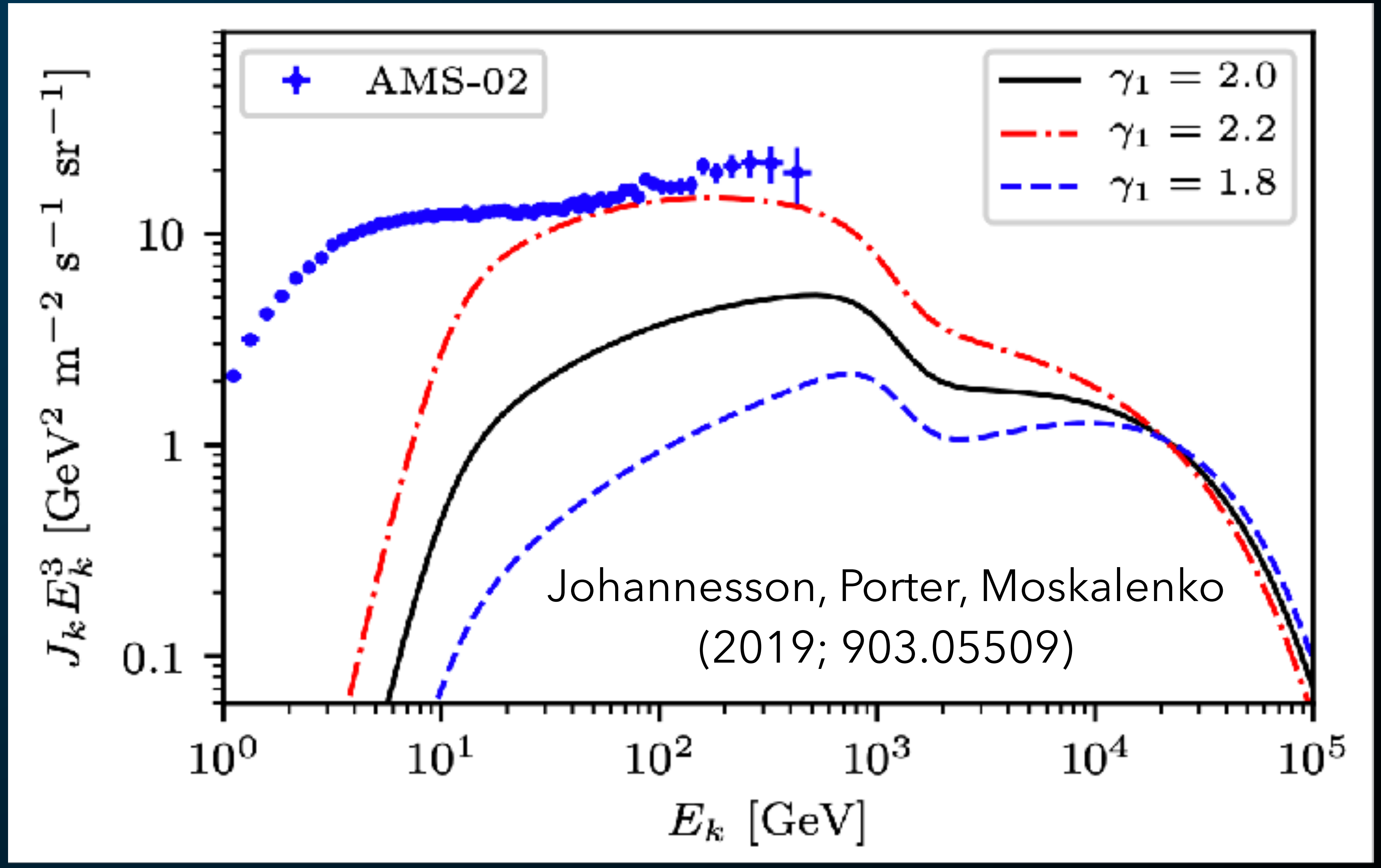
d.) Low energy electrons are not indefinitely trapped within halos





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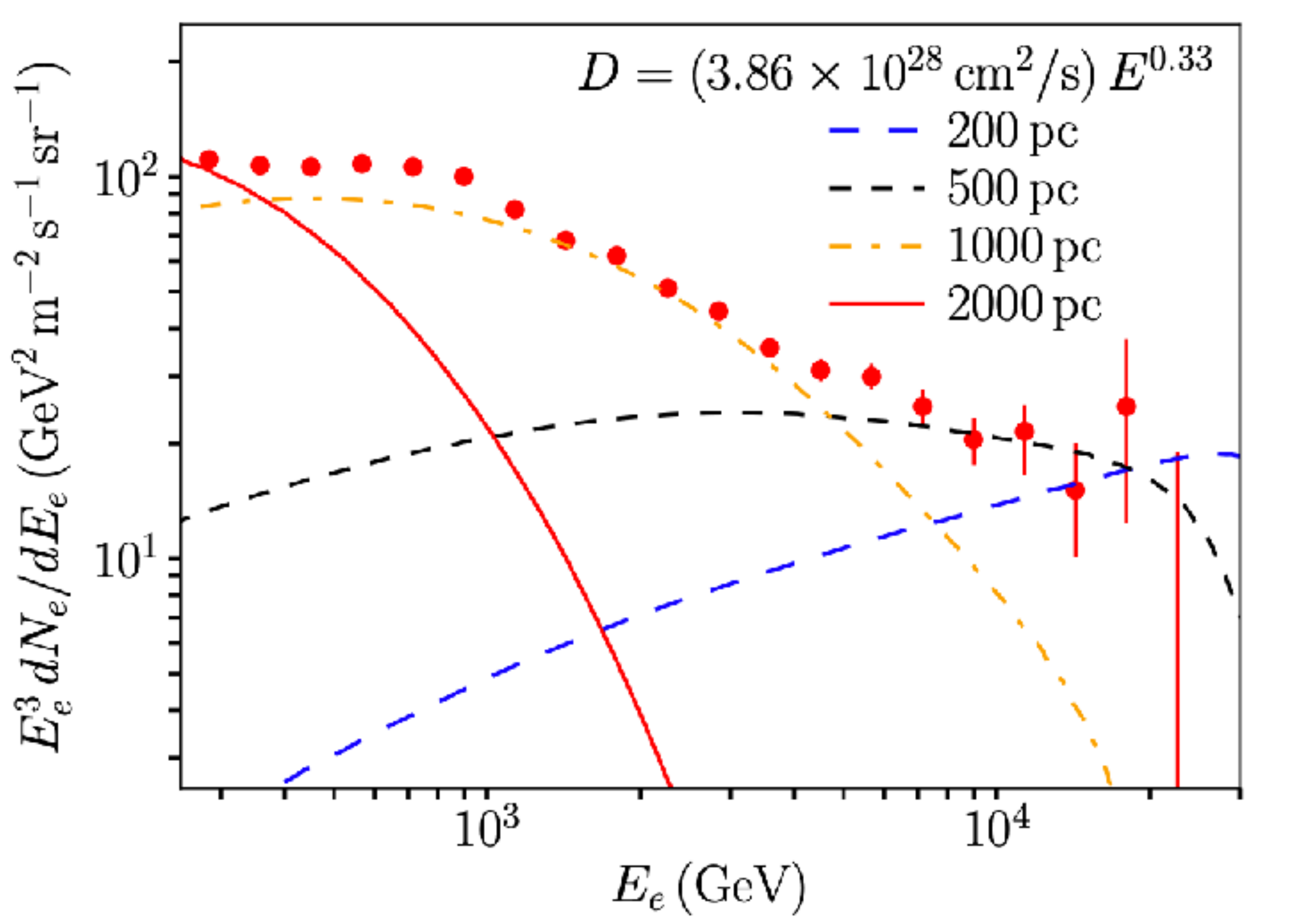
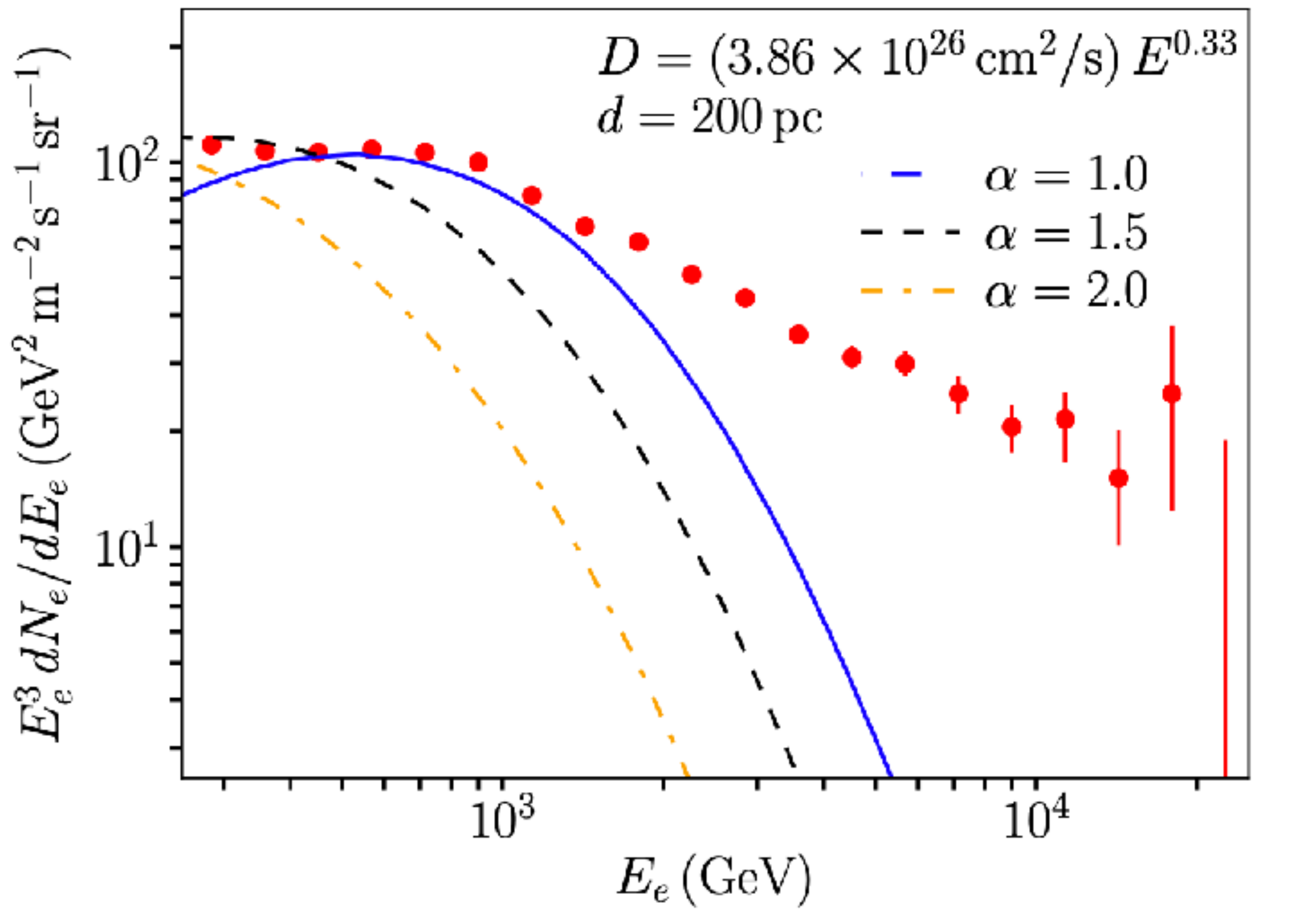


Hooper & TL (2017; 1711.07482)



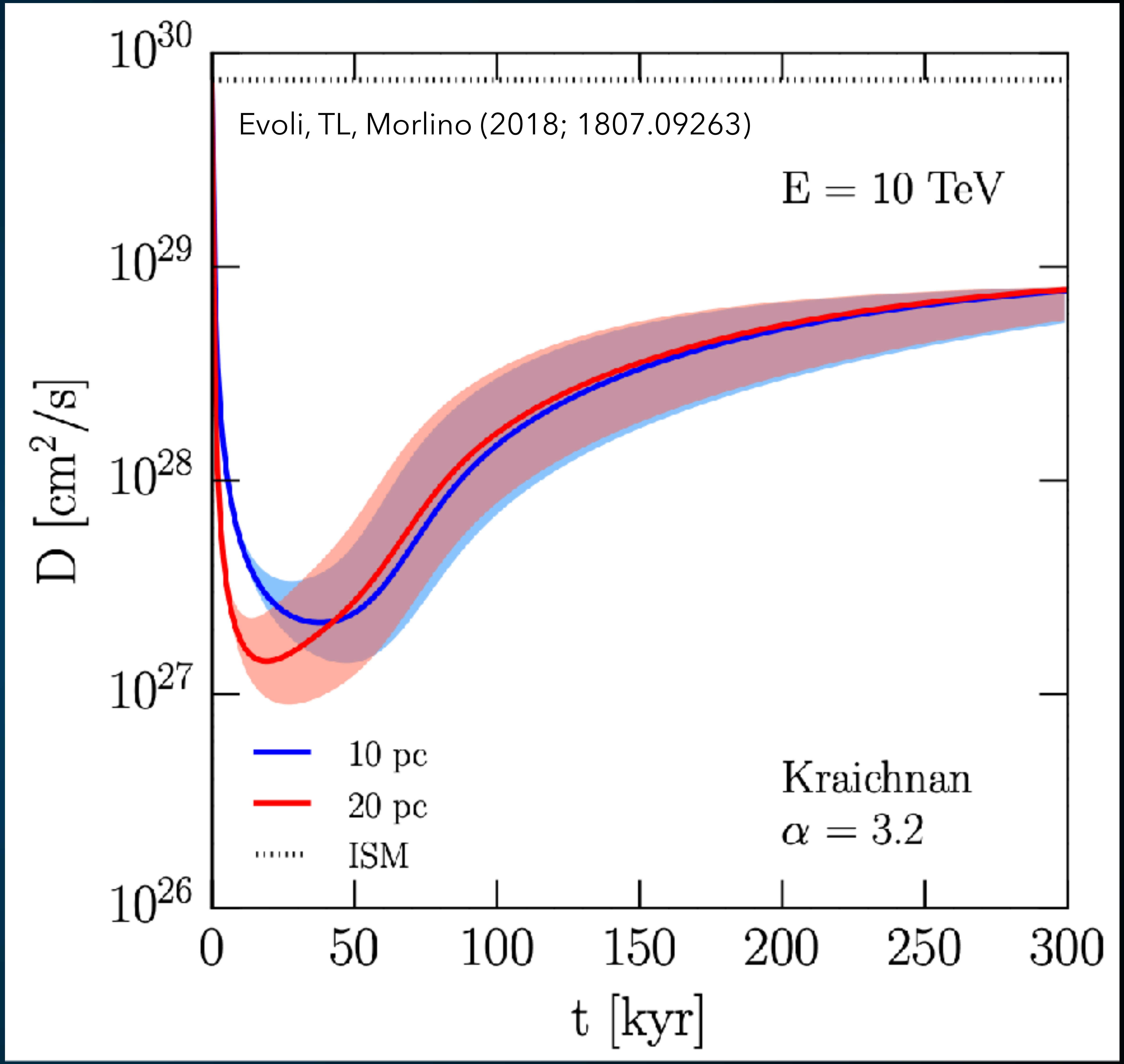
What does matter?

The electron acceleration efficiency as a function of time.

The location of the electron acceleration (PWN termination shock vs. pulsar magnetosphere).

The magnetic field strength in the region where electrons cool.

The physical propagation process (diffusion vs. convection).



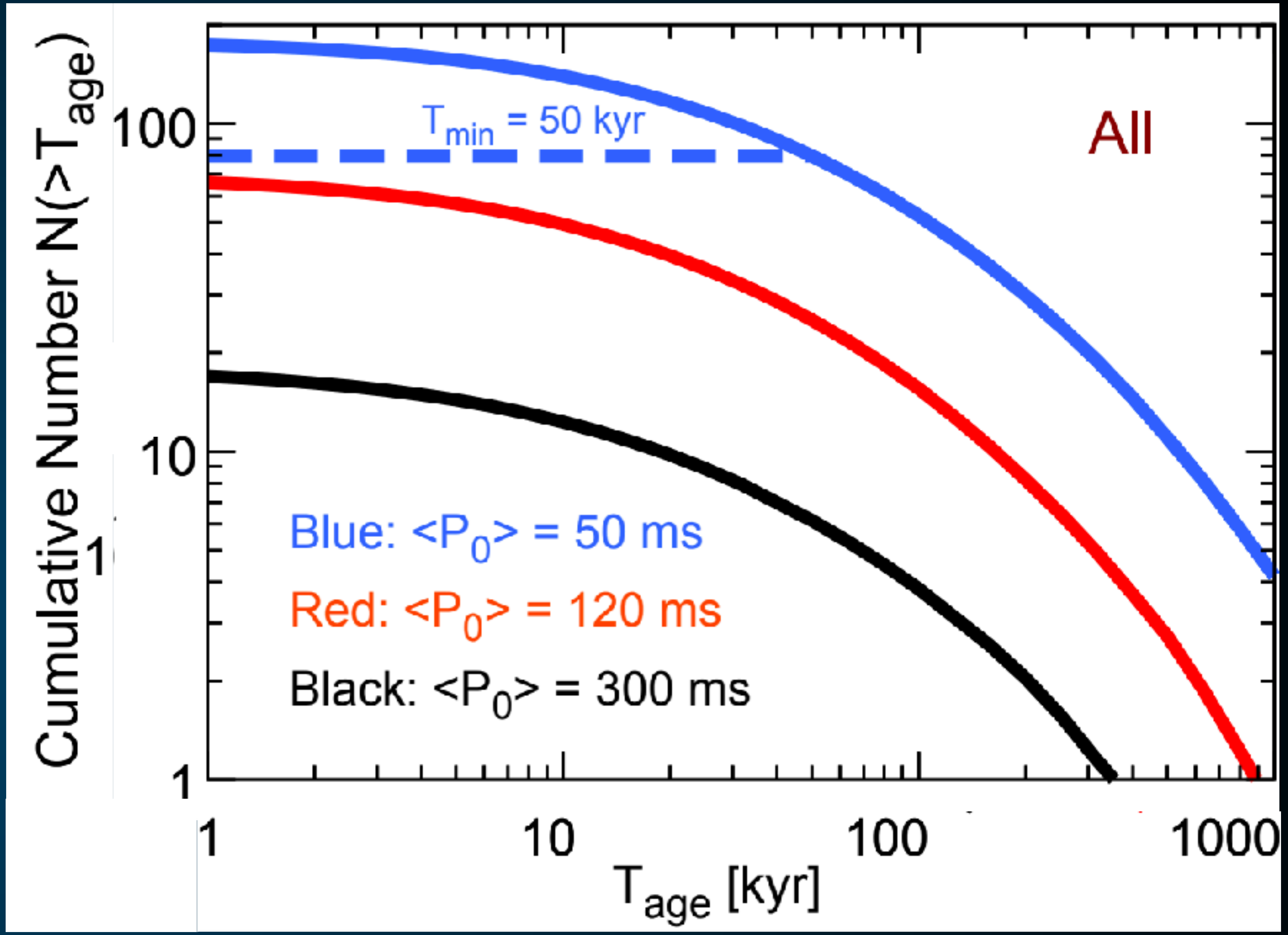
What does matter?

Sudoh, TL, Beacom (2019; 1902.08203)

Does particle propagation "return to normal" at the same location that our observations end? (Seems unlikely?)

Are pulsars efficient e+e- accelerators over their full lifetimes?

What fraction of young electrons are lost to PWN magnetic fields?



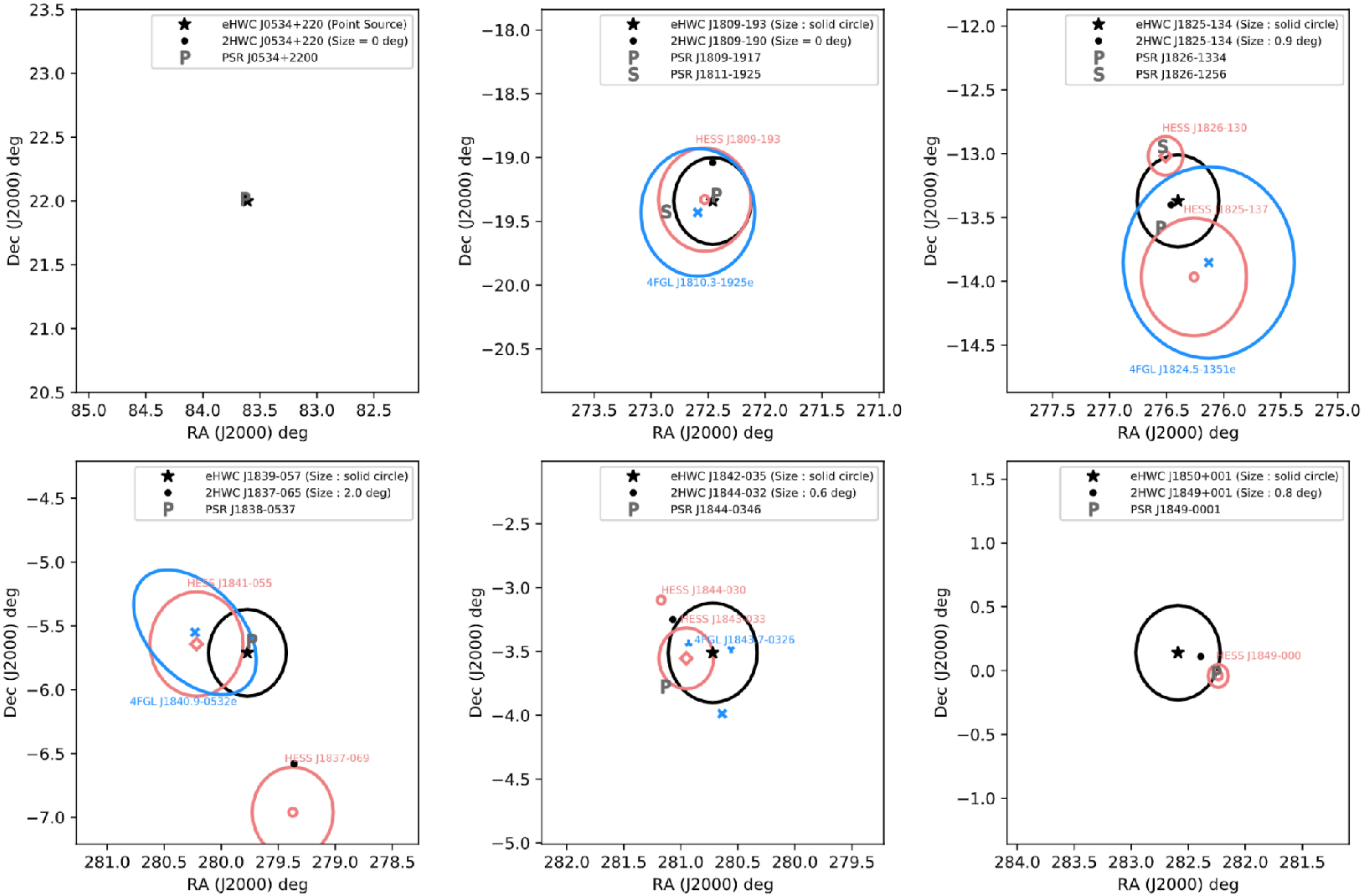
Is the Truth Even More Exciting?

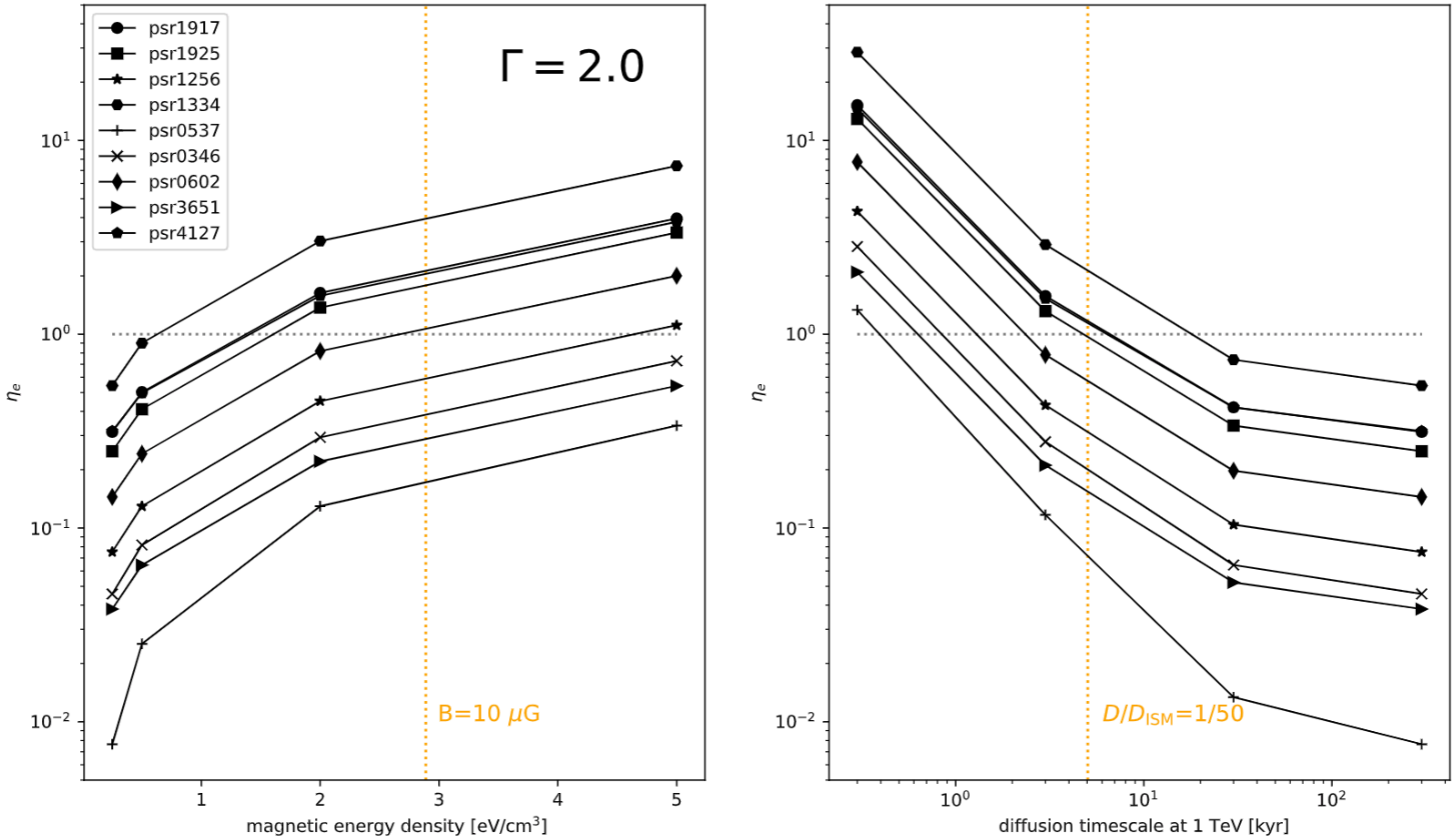
Sudoh, TL, Hooper (2020; TBS)

HAWC Source	Pulsar Candidate	Distance (kpc)	$\dot{E}$ (erg/s)	$\dot{E}/4\pi d^2$ (TeV/cm^2/s)	F_γ (TeV/cm^2/s)	P (s)	$\dot{P}$ $\times 10^{14}$	$t_c \equiv P/2\dot{P}$ (kyr)	Radio
eHWC J0534+220	PSR J0534+2200	2.00	4.5×10^{38}	5.9×10^{-7}	1.8×10^{-10}	0.033	42.1	1.26	Yes
eHWC J1809-193	PSR J1809-1917	3.27	1.8×10^{36}	8.8×10^{-10}	8.5×10^{-11}	0.083	2.55	51.4	Yes
–	PSR J1811-1925	5.00	6.4×10^{36}	1.3×10^{-9}	–	0.065	4.40	23.3	No
eHWC J1825-134	PSR J1826-1334	3.61	2.8×10^{36}	1.1×10^{-9}	2.3×10^{-10}	0.110	7.53	21.4	Yes
–	PSR J1826-1256	1.55	3.6×10^{36}	7.8×10^{-9}	–	0.101	12.1	14.4	No
eHWC J1839-057	PSR J1838-0537	2.0	6.0×10^{36}	7.8×10^{-9}	4.1×10^{-10}	0.146	47.2	4.89	No
eHWC J1842-035	PSR J1844-0346	2.4	4.2×10^{36}	3.8×10^{-9}	7.6×10^{-11}	0.113	1.55	11.6	No
eHWC J1850+001	PSR J1849-0001	7.00	9.8×10^{36}	1.0×10^{-9}	4.5×10^{-11}	0.039	1.42	43.1	No
eHWC J1907+063	PSR J1907+0602	2.37	2.8×10^{36}	2.6×10^{-9}	4.6×10^{-11}	0.107	8.68	19.5	Yes
eHWC J2019+368	PSR J2021+3651	1.80	3.4×10^{36}	5.5×10^{-9}	2.7×10^{-11}	0.104	9.57	17.2	Yes
eHWC J2030+412	PSR J2032+4127	1.33	1.5×10^{35}	4.4×10^{-10}	5.1×10^{-11}	0.143	1.13	201	Yes

Eight of the nine highest-energy HAWC sources are coincident with known pulsars.

The highest luminosities seem to be provided by systems with ages < 50 kyr.


eHWC J0534+220 (Point Source)
2HWC J0534+220 (Size = 0 deg)
PSR J0534+2200
eHWC J1809-193 (Size : solid circle)
2HWC J1809-190 (Size = 0 deg)
PSR J1809-1917
PSR J1811-1925
HESS J1809-193
4FGL J1810.3-1925e
eHWC J1825-134 (Size : solid circle)
2HWC J1825-134 (Size : 0.9 deg)
PSR J1826-1334
PSR J1826-1256
HESS J1826-130
HESS J1825-137
4FGL J1824.5-1351e
eHWC J1839-057 (Size : solid circle)
2HWC J1837-065 (Size : 2.0 deg)
PSR J1838-0537
HESS J1841-055
4FGL J1840.9-0532e
HESS J1837-069
eHWC J1842-035 (Size : solid circle)
2HWC J1844-032 (Size : 0.6 deg)
PSR J1844-0346
HESS J1844-030
HESS J1843-033
4FGL J1843.7-0326
eHWC J1850+001 (Size : solid circle)
2HWC J1849+001 (Size : 0.8 deg)
PSR J1849-0001
HESS J1849-000
RA (J2000) deg
Dec (J2000) deg



psr1917
psr1925
psr1256
psr1334
psr0537
psr0346
psr0602
psr3651
psr4127
$\Gamma = 2.0$
η_e
B=10 μG
magnetic energy density [eV/cm^3]
$D/D_{\rm ISM}$=1/50
diffusion timescale at 1 TeV [kyr]

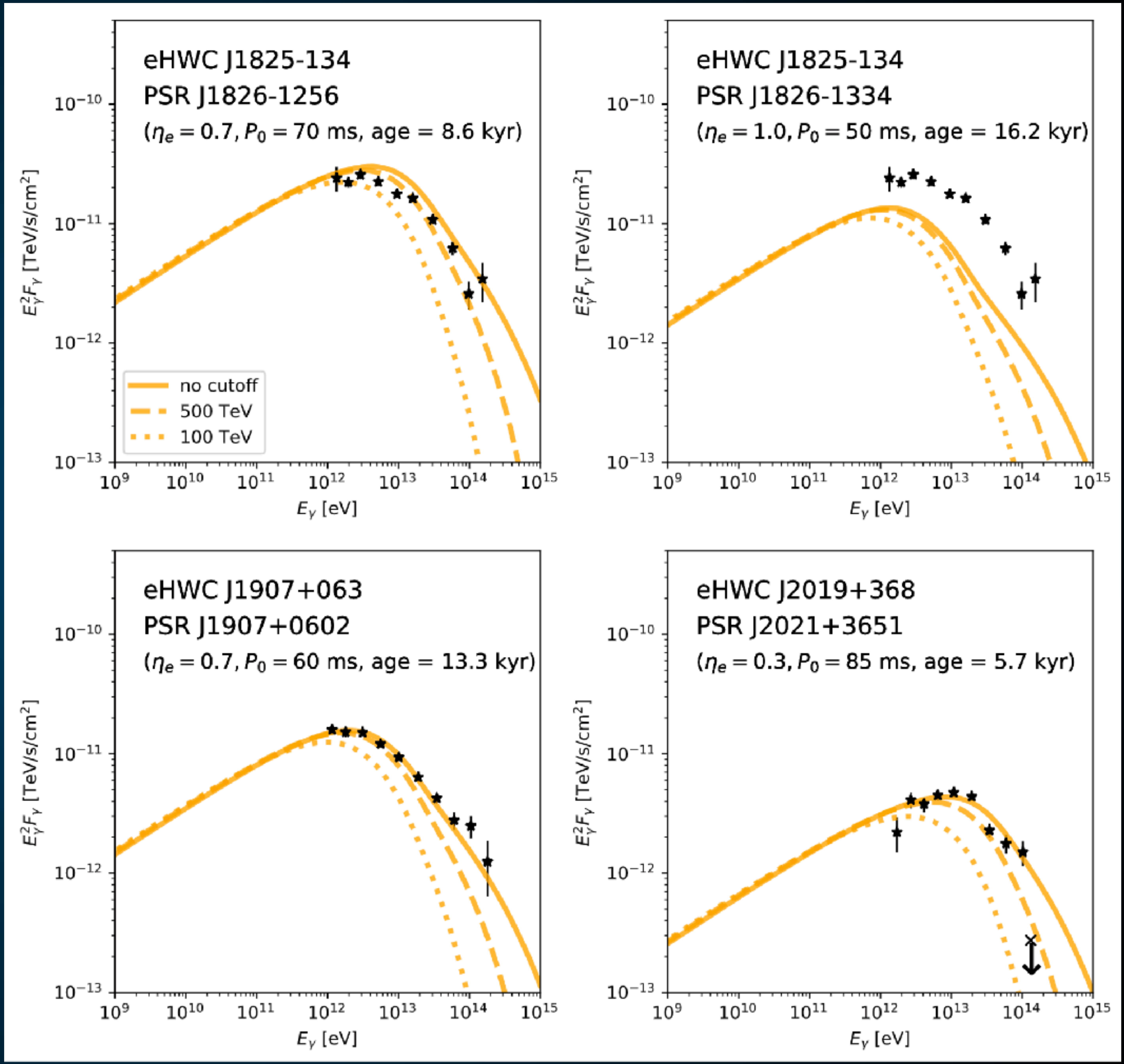
Pulsars Fit!

Can also fit the TeV gamma-ray emission spectrum with pulsars.

Pulsar fits are <u>more</u> constrained

1.) Spectral cut from Klein-Nishina
2.) Spindown power sets luminosity

While hadronic emission can fit the data, the spectral cuts must be added by hand.



Hidden Pulsars

At present - we are focusing on whether individual systems (with known pulsars) are TeV halos, PWNs, or SNRs

However, we already <u>know</u> that many of these sources must exist without known pulsars.

On the evolution of pulsar beams

T. M. Tauris[1,2★†] and R. N. Manchester[2]
[1]*Institute of Physics & Astronomy, Aarhus University, DK-8000 Aarhus C*
[2]*Australia Telescope National Facility, CSIRO, PO Box 76, Epping, NSW*

$$f = \left[1.1\left(\log_{10}\left(\frac{\tau}{100\ \mathrm{Myr}}\right)\right)^2 + 15\right]\% \qquad (5)$$

For middle-aged pulsars (100-400 kyr) this corresponds to beaming fractions between 21–25%. We note that these re-

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ABSTRACT
We have analysed polarization data for a large number of isolated pulsars to investigate the evolution of pulsar radio beams. Assuming that a circular beam is directed along the axis of a dipolar magnetic field, we demonstrate that the distribution of magnetic inclination angles for the parent population of all pulsars is not flat but highly concentrated towards small inclination angles and that, consequently, the average beaming fraction is only ~10 per cent. Furthermore, we find that there is a tendency for the beam axis to align with the rotational axis on a time-scale of $\sim 10^7$ yr. This has interesting consequences for statistical studies of the pulsar population. Finally, the luminosity of pulsars is shown to be independent of the impact parameter, which indicates that pulsar beams are sharp-edged and have a relatively flat integrated intensity distribution.

Key words: methods: statistical – stars: neutron – pulsars: general.

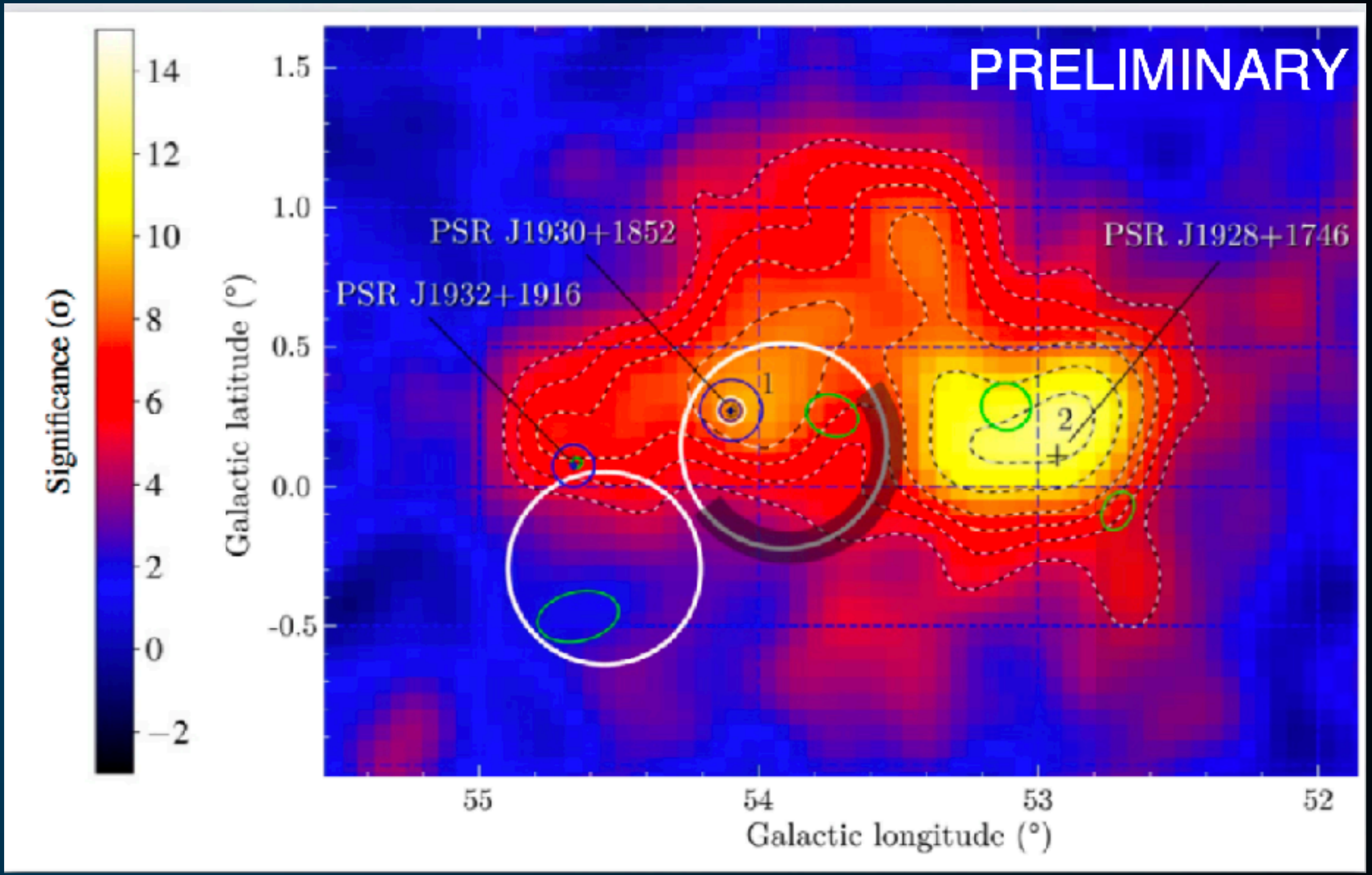
Models where the majority of HAWC sources <u>are not</u> TeV halos are inconsistent with data.

Hidden Pulsars

How do we deal with this in the case of individual systems?

Angular Resolution will be key:

- **HESS/VERITAS/CTA**
- **Correlation with Gas Density**
- **Synchrotron Polarization**



Plot from Kelly Malone's talk (yesterday)

What are the key questions to answer for individual systems?

- **Want to know leptonic/hadronic acceleration and escape**
- **Neutrino production?**

Conclusions

The state of TeV halo studies has progressed rapidly since 2017

- More than a half dozen systems
- Starting to understand the variety of the source class

Science Results have already been spectacular

- Pulsars are essentially verified as the source of the positron excess
- First evidence of inhomogeneous diffusion outside of “standard sources”

Future is extremely promising.