Estimating the Diffusion around pulsars through gamma-ray observations

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SEZIONE DI TORINO

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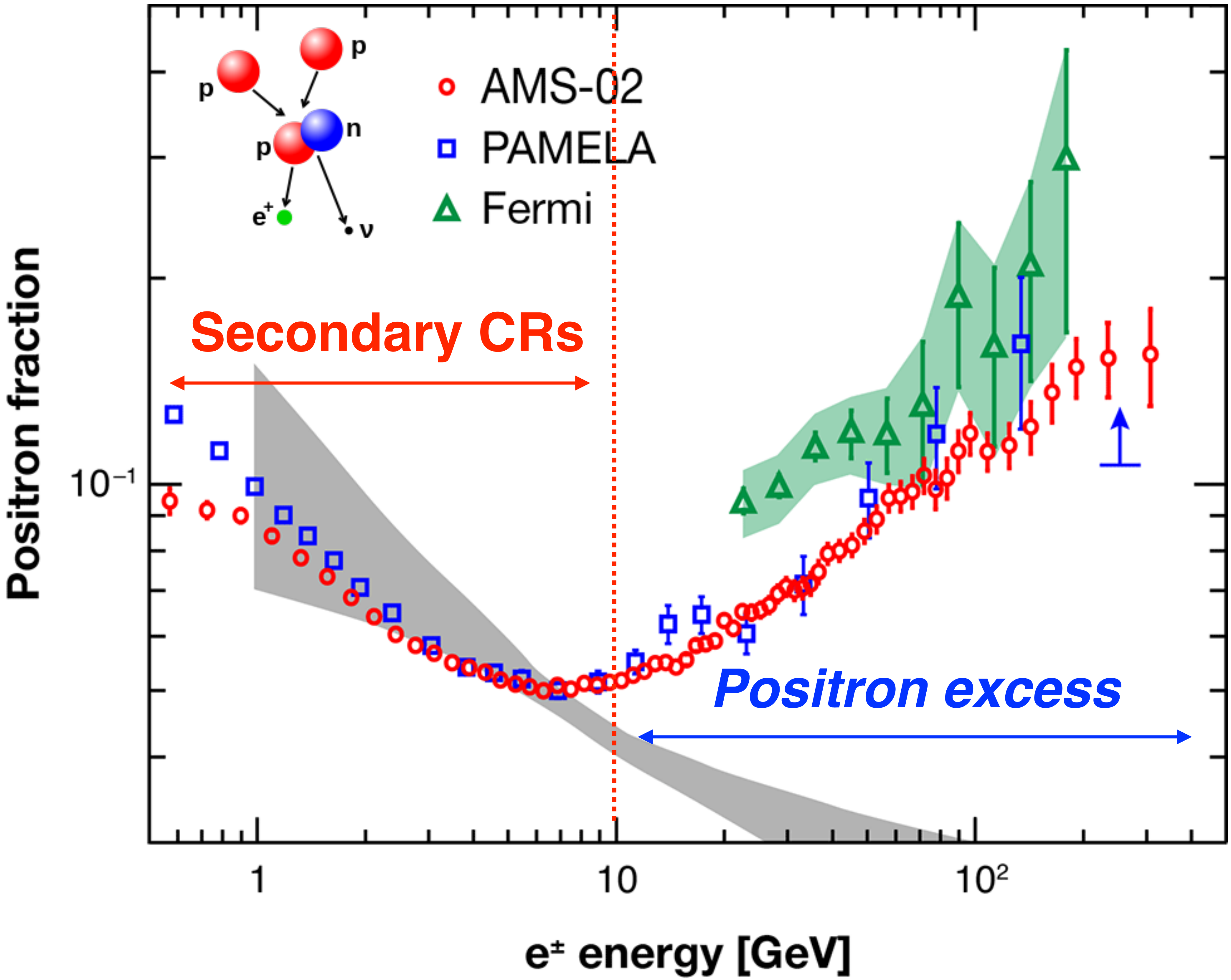
Talk based on the following papers:

1. *Detection of a γ-ray halo around Geminga with the Fermi-LAT data and implications for the positron flux,* MDM, S. Manconi, F. Donato, PRD 100, 123015 (2019)
2. *Evidences of low-diffusion bubbles around Galactic pulsars,* MDM, S. Manconi, F. Donato PRD 101, 103035 2020.
3. *Does the Geminga, Monogem and PSR J0622+3749 γ-ray halos imply slow diffusion around pulsars?*, S. Recchia, MDM, F.A. Aharonian, S. Gabici, F. Donato, S. Manconi *Phys.Rev.D* 104 (2021) 12, 123017.
4. *Constraining positron emission from pulsar populations with AMS-02 data*, L. Orusa, MDM, S. Manconi, F. Donato. JCAP 12 (2021) 12, 014.
5. Geminga's pulsar halo: an X-ray view, S. Manconi, F. Donato, MDM and others. ArXiv: 2403.10902

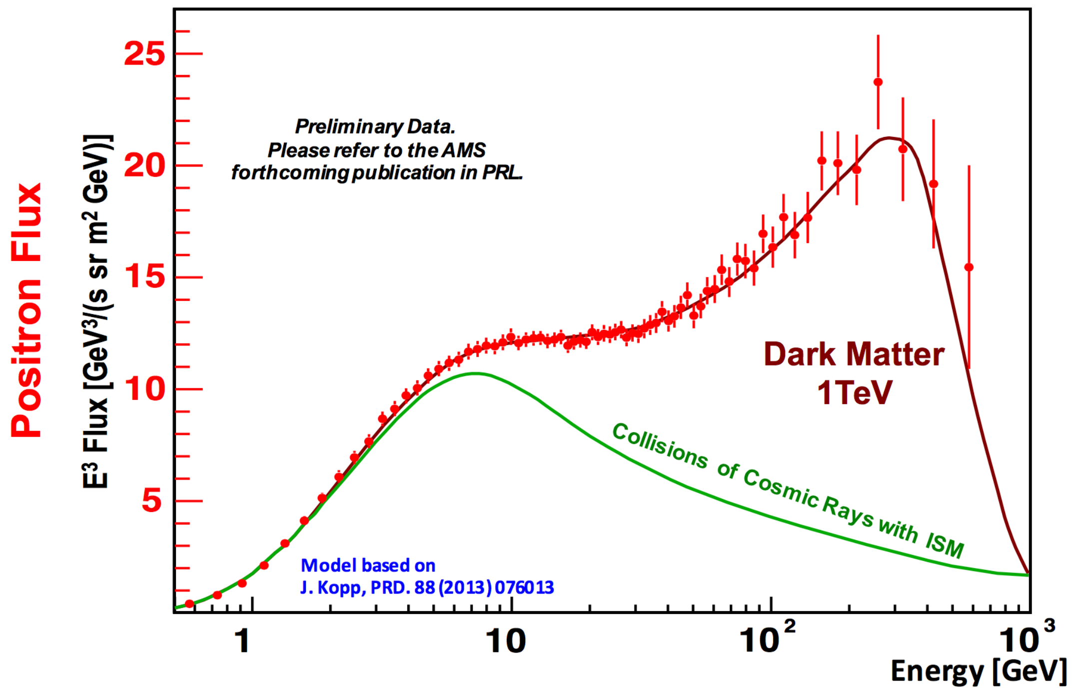
T. Linden, D. Hooper, P. Martin, T. Sudoh, E. Pinetti, C. Evoli, Morlino…

What is the positron excess?

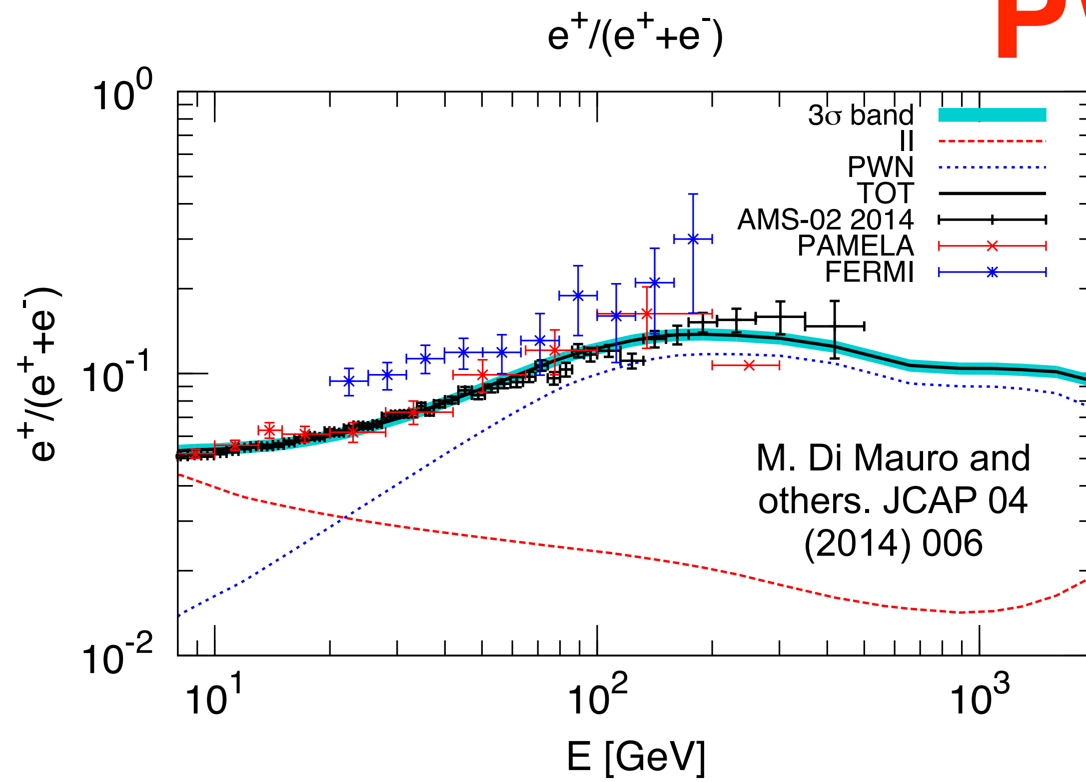


Possible Origin of Positron excess

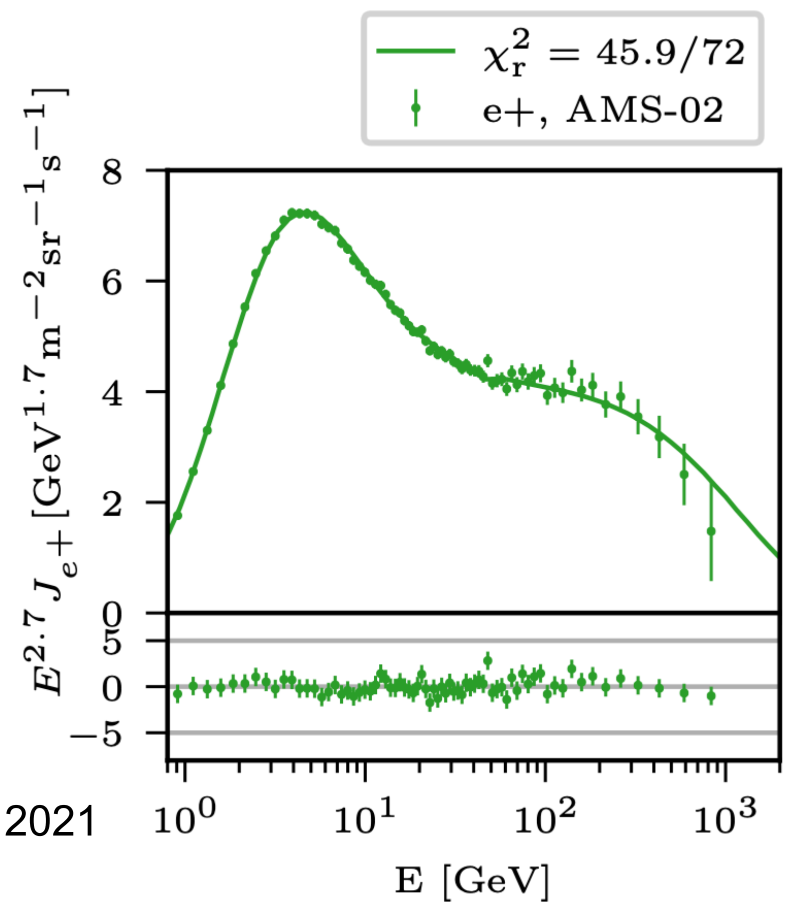
Dark matter



PWNe



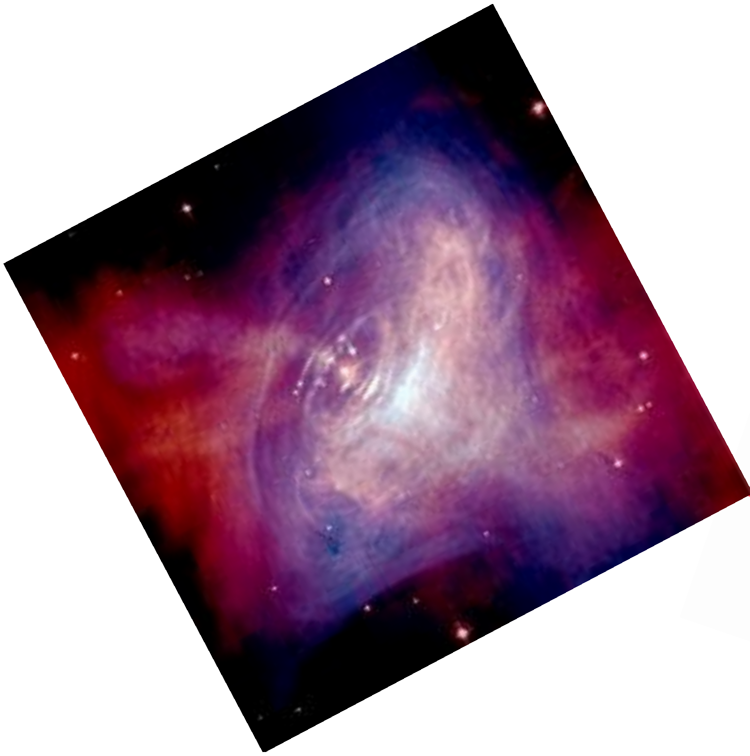
Supernova remnants

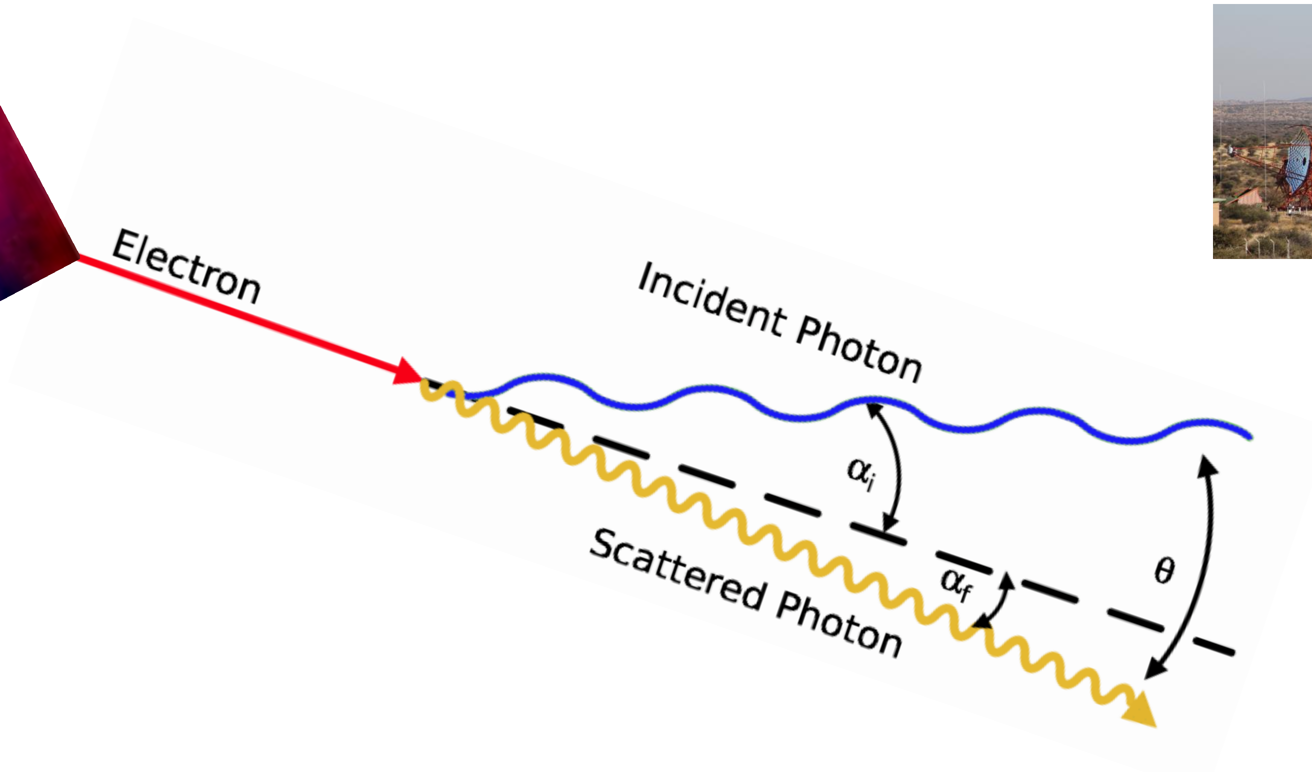


Mertsch, Vittino, Sarkar 2021

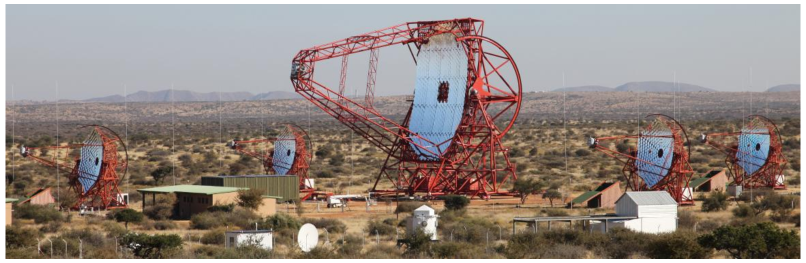
Exact origin of positron excess is still very debated!!

γ rays produced by inverse Compton scattering

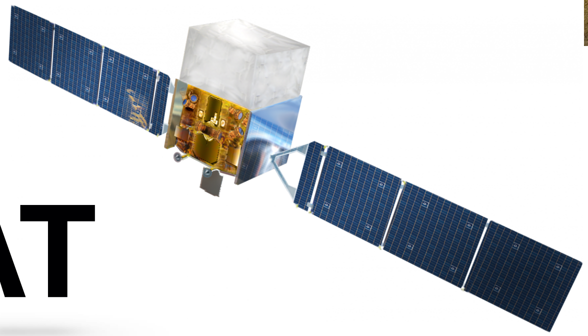




IACTs



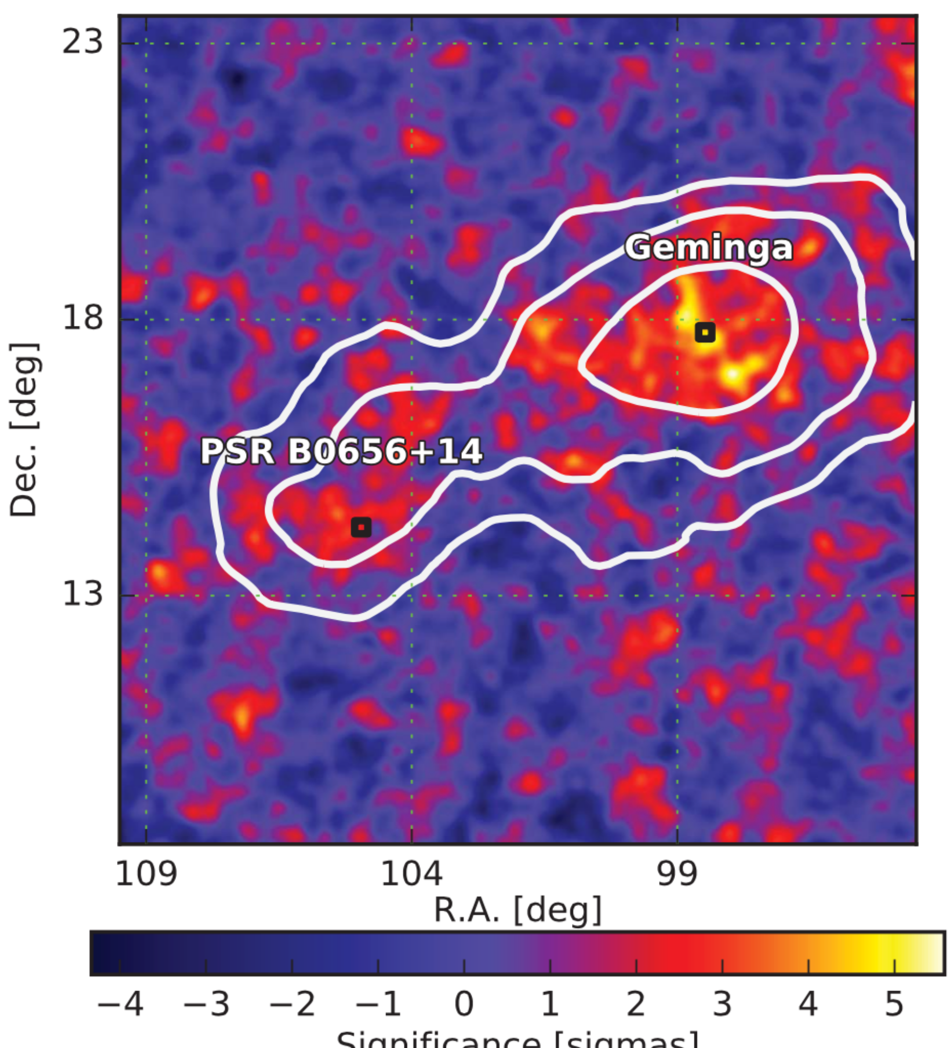
HAWC

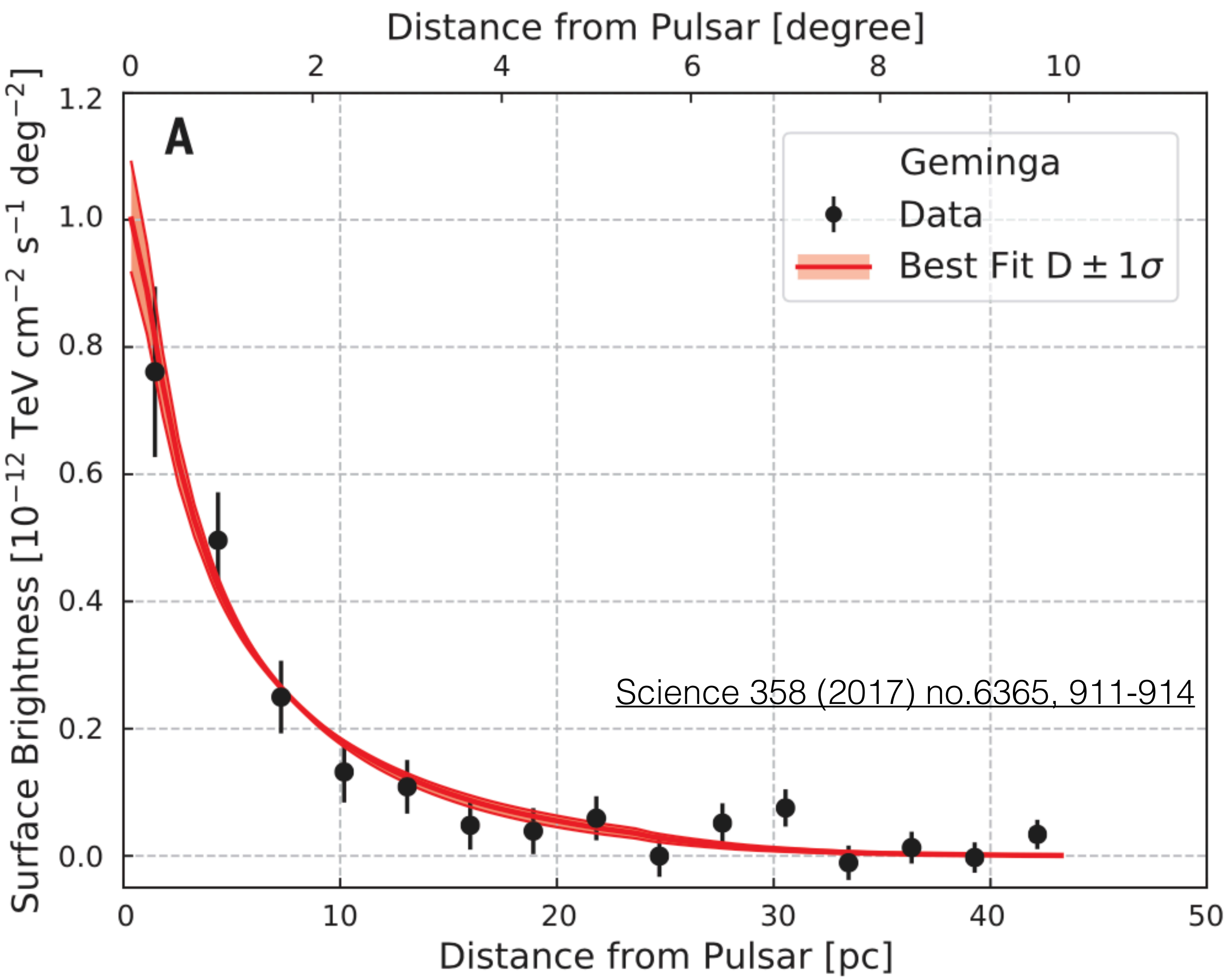


Fermi-LAT

HAWC results for Geminga and Monogem PWNe

- HAWC detected an extended emission from Geminga and Monogem PWNe for **E>5 TeV**.
- ***In the vicinity of the PWN, the diffusion coefficient D must be about 500 times smaller than the average in the Galaxy.***

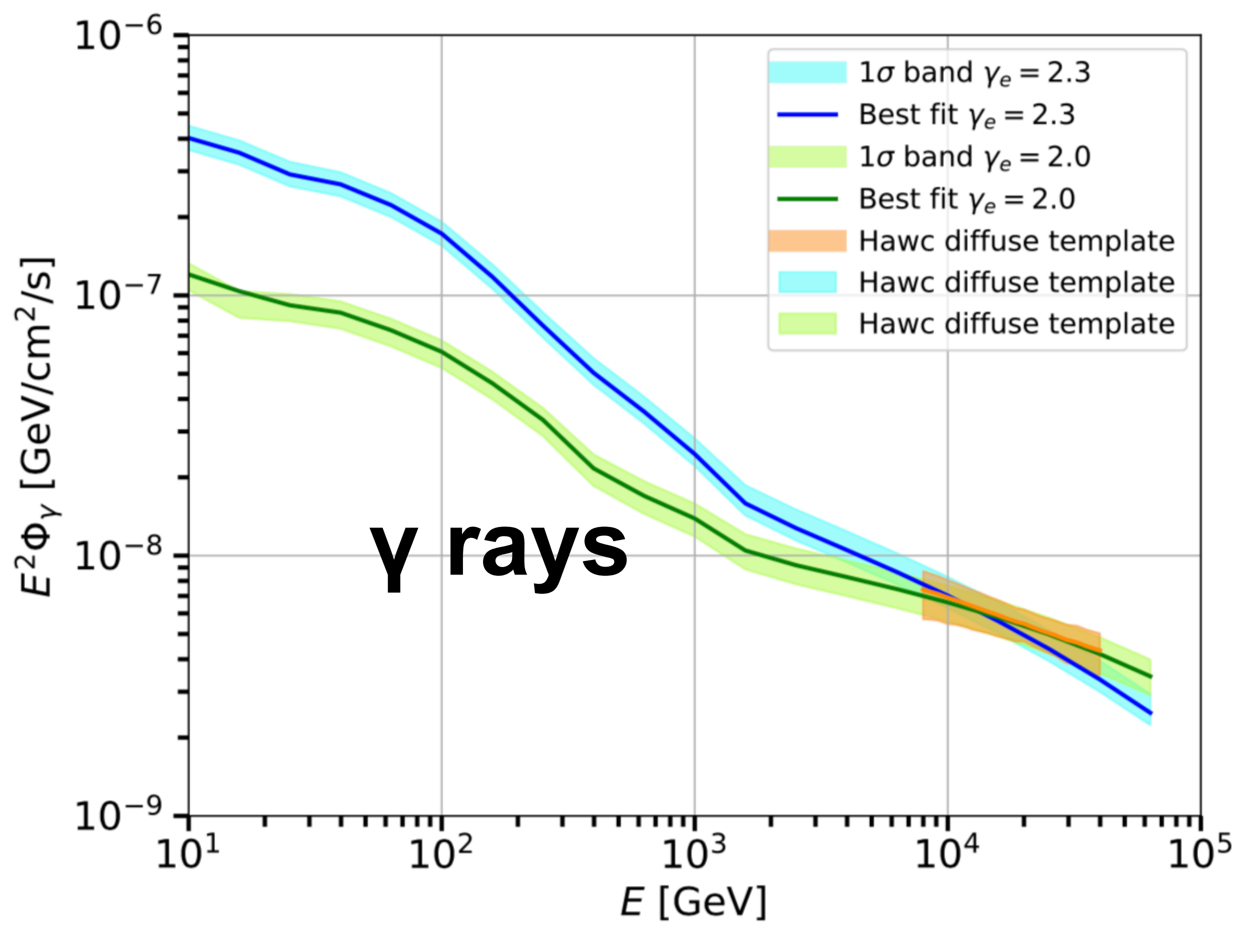


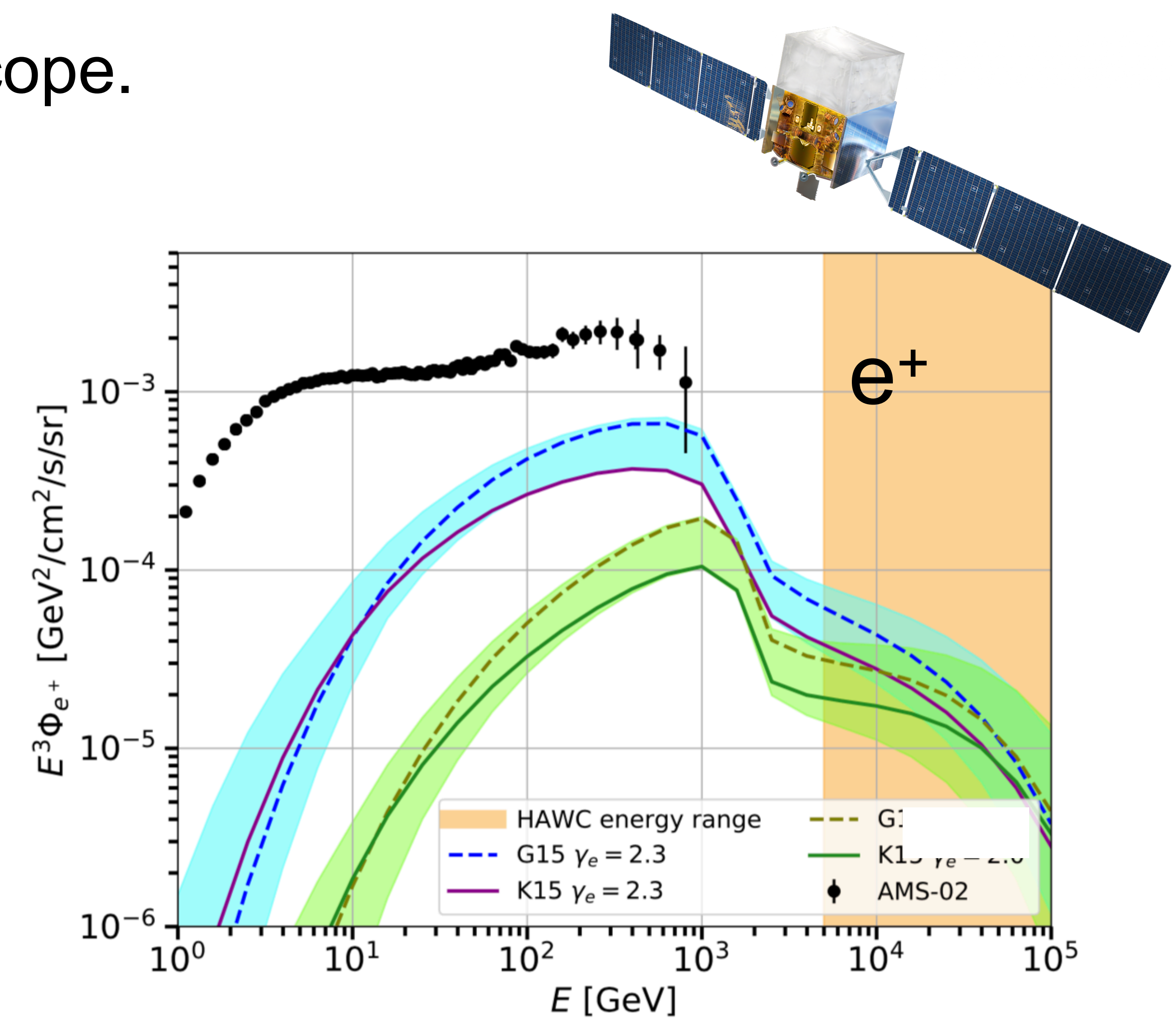


Science 358 (2017) no.6365, 911-914

Predictions for the e⁺ flux from Geminga using HAWC data

- Tuning the model with HAWC data (above 10 TeV) is not possible to have a precise prediction for the AMS-02 positron excess.
- We should use γ-ray data between 10 GeV to 1 TeV.
- Fermi-LAT is ideal for this scope.

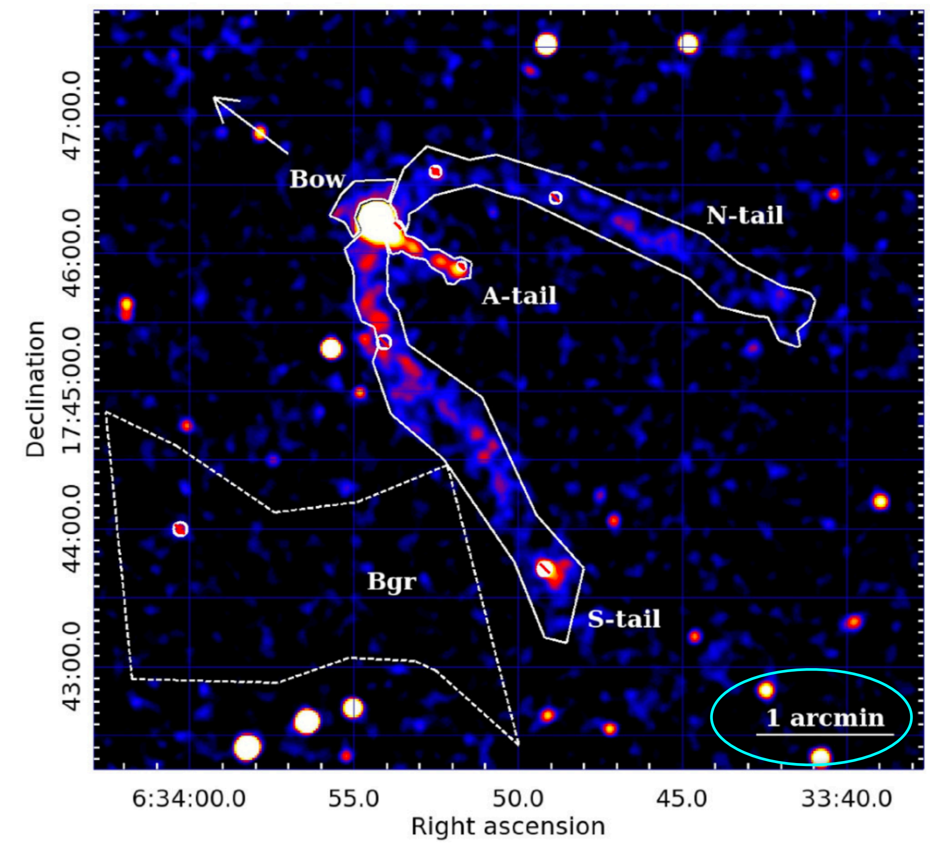




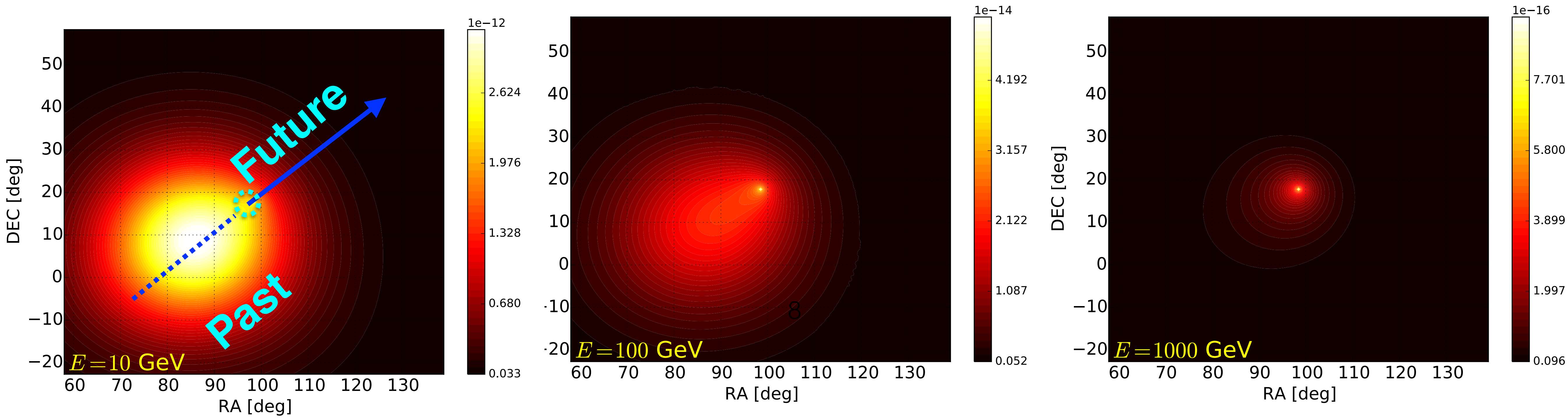
Di Mauro, Manconi, Donato PRD 100, 123015 (2019)

Geminga proper motion

- Geminga has a proper motion of **211 km/s** which implies this pulsar moved about **70 pc** across its age.
- Our analysis is unique in γ-ray astronomy because we search for a source that is moving across the sky in γ rays.



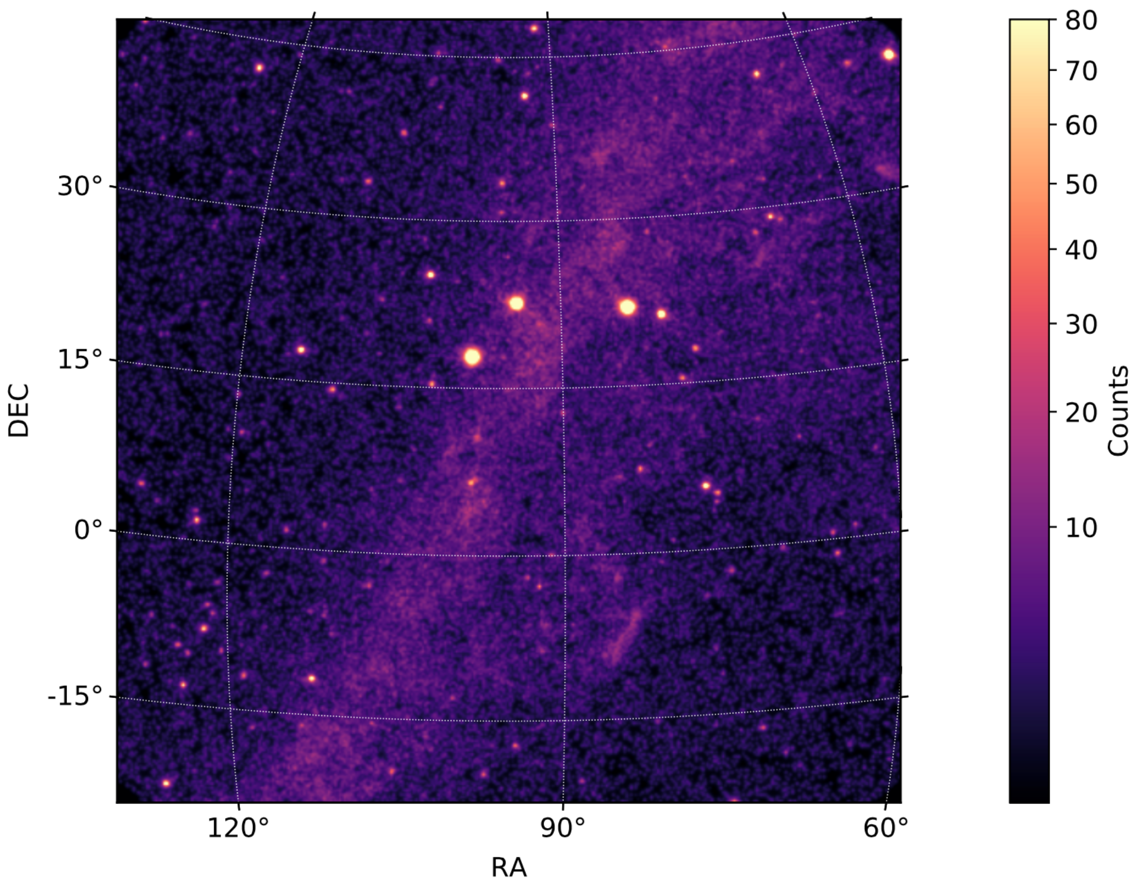
Posselt et al. 2008

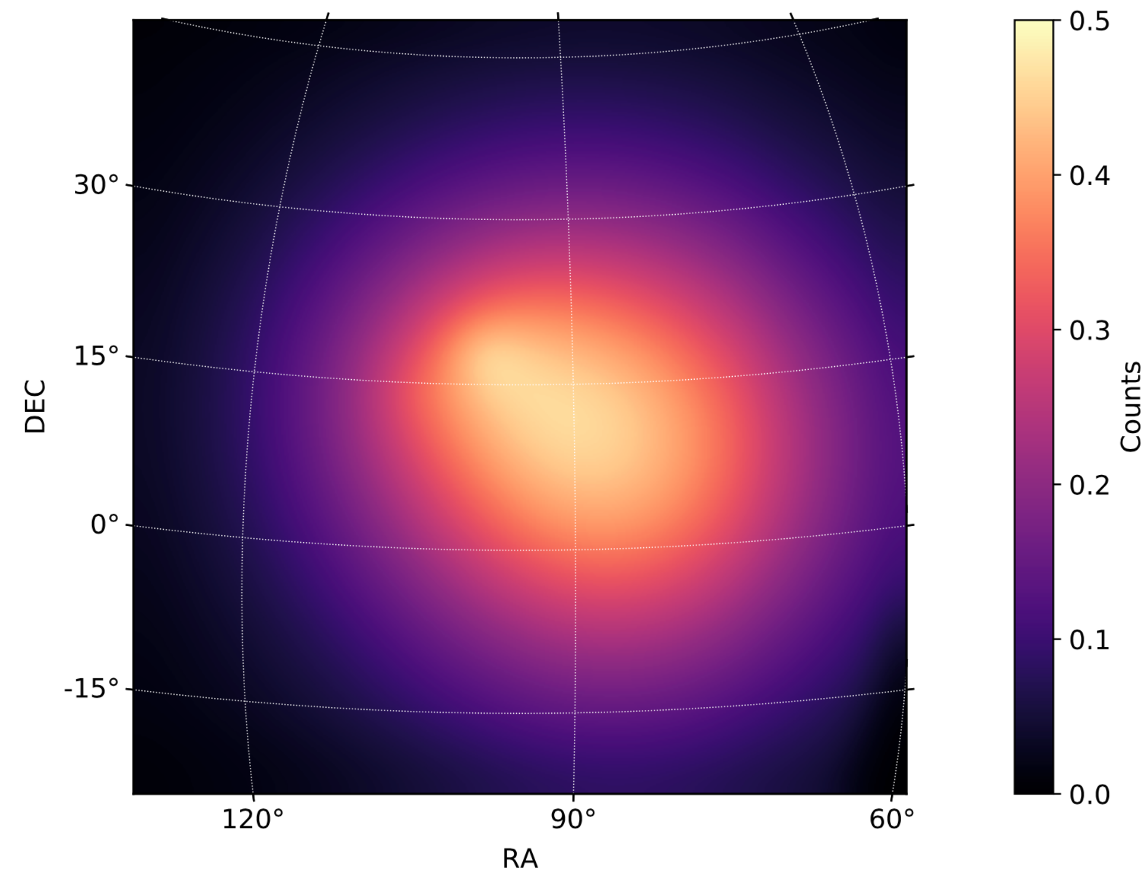


Di Mauro, Manconi, Donato PRD 100, 123015 (2019)

Analysis of Fermi-LAT data

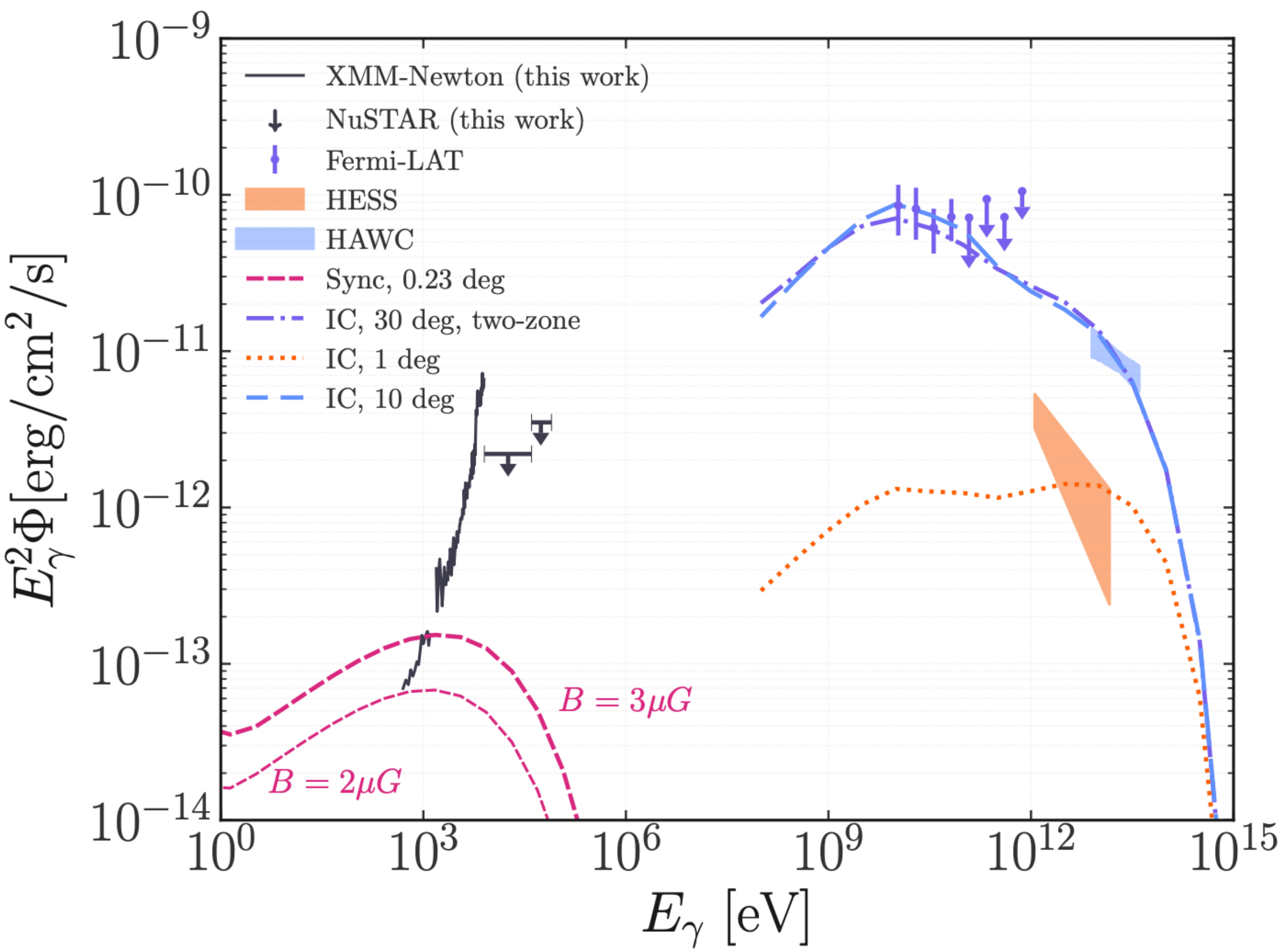
- We have performed an analysis of 115 months of Fermi-LAT data for **E>8 GeV**.
- Our model with the pulsar proper motion is preferred at least at **4σ significance**.
- We find a **7.8-11.8 σ significance emission from Geminga with a diffusion D(1 GeV)= 2.3 10^{26} cm^2/s with δ=0.33.**





Search of a Synchrotron halo

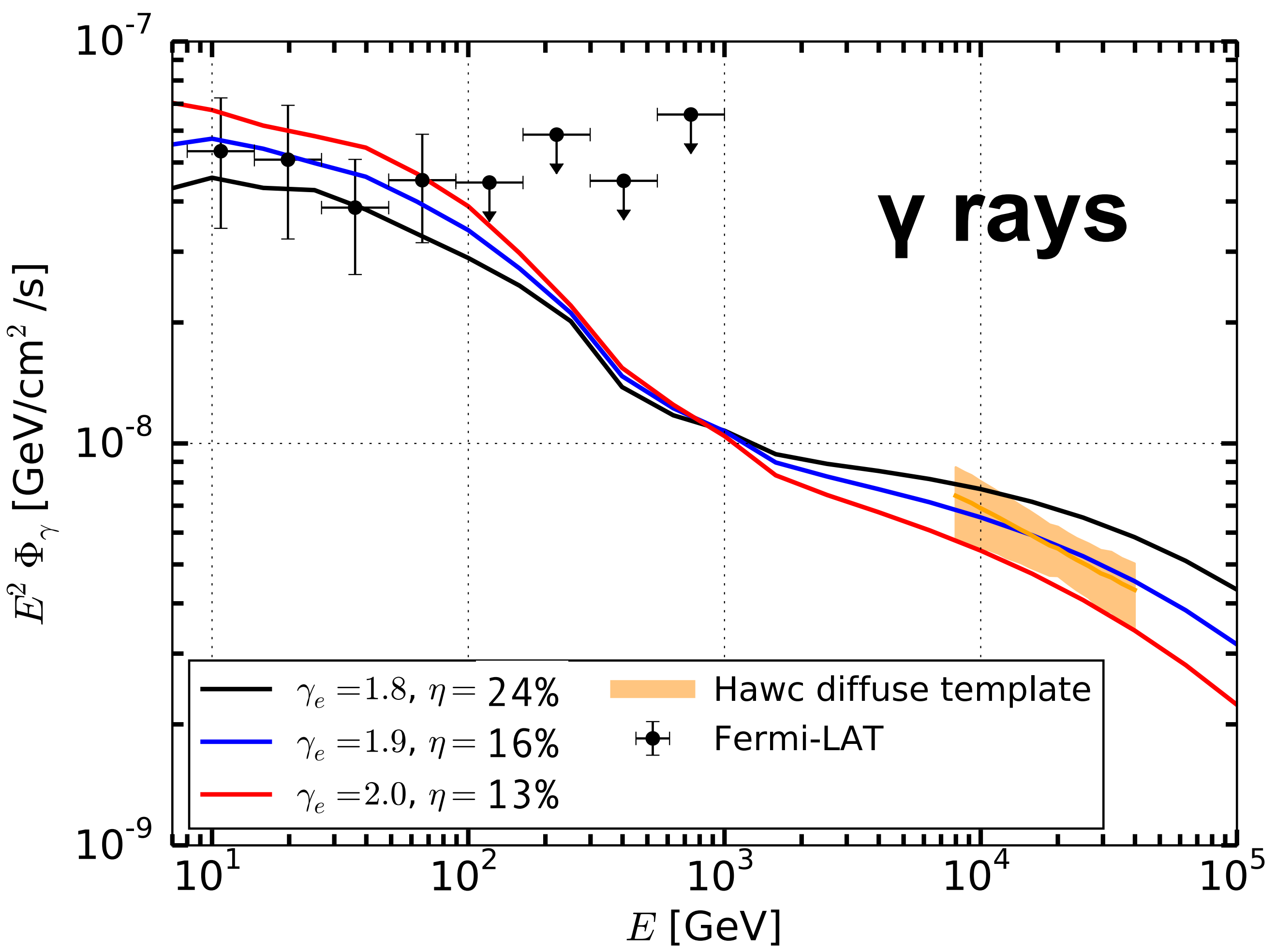
- We performed the most comprehensive X-ray study of the Geminga pulsar halo to date, utilising archival data from XMM–Newton and NuSTAR (0.5−79 keV).
- We find no significant emission and set robust constraints on the ambient magnetic field strength and the diffusion coefficient.

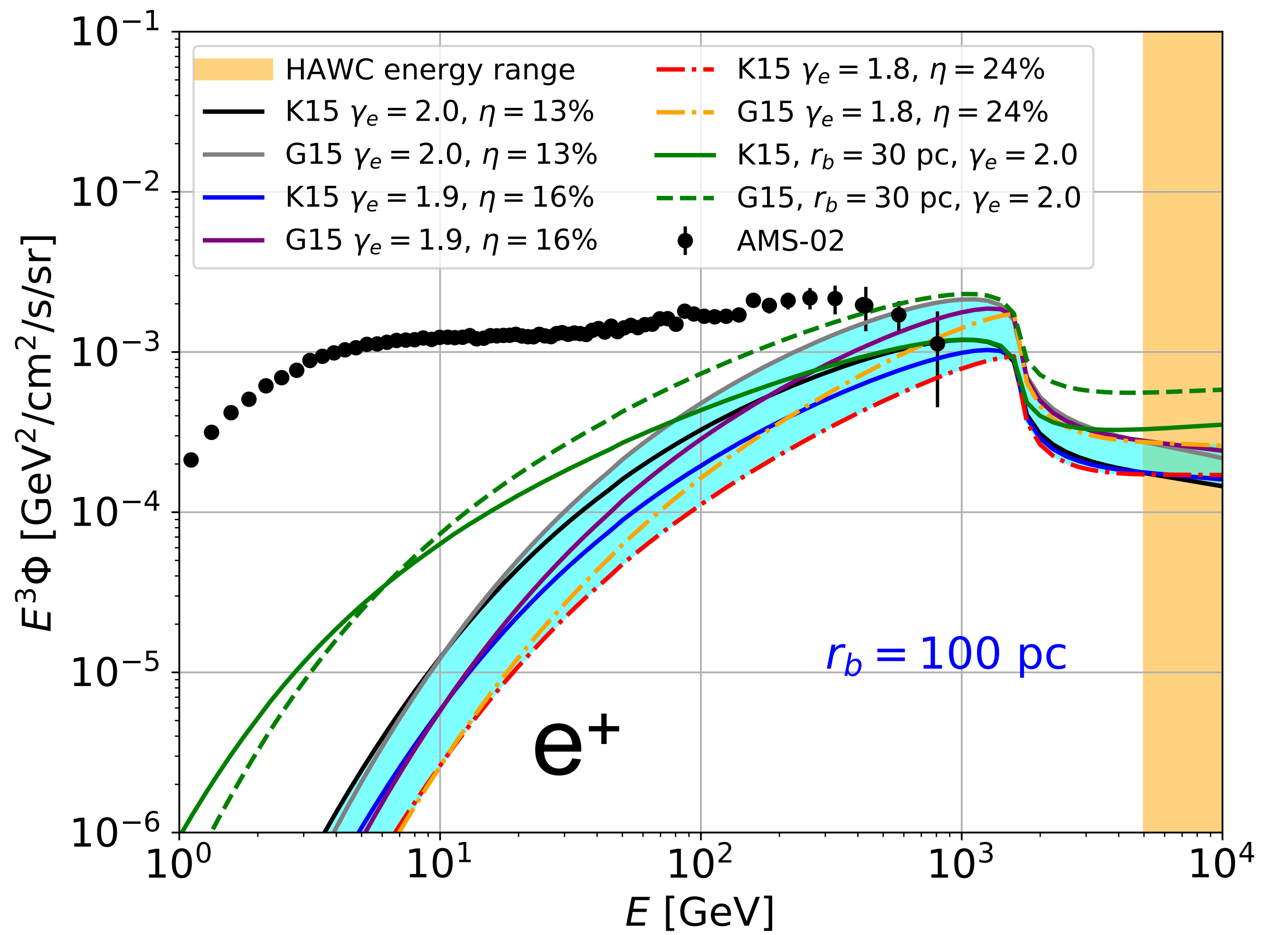


Manconi, Donato, MDM and others ArXiv: 2403.10902

Contribution of Geminga to the positron excess

- Geminga alone can contribute to the entire positron excess around 1 TeV.
- The exact contribution depends on the size of the low-diffusion halo.
- Several other pulsars will contribute as well.

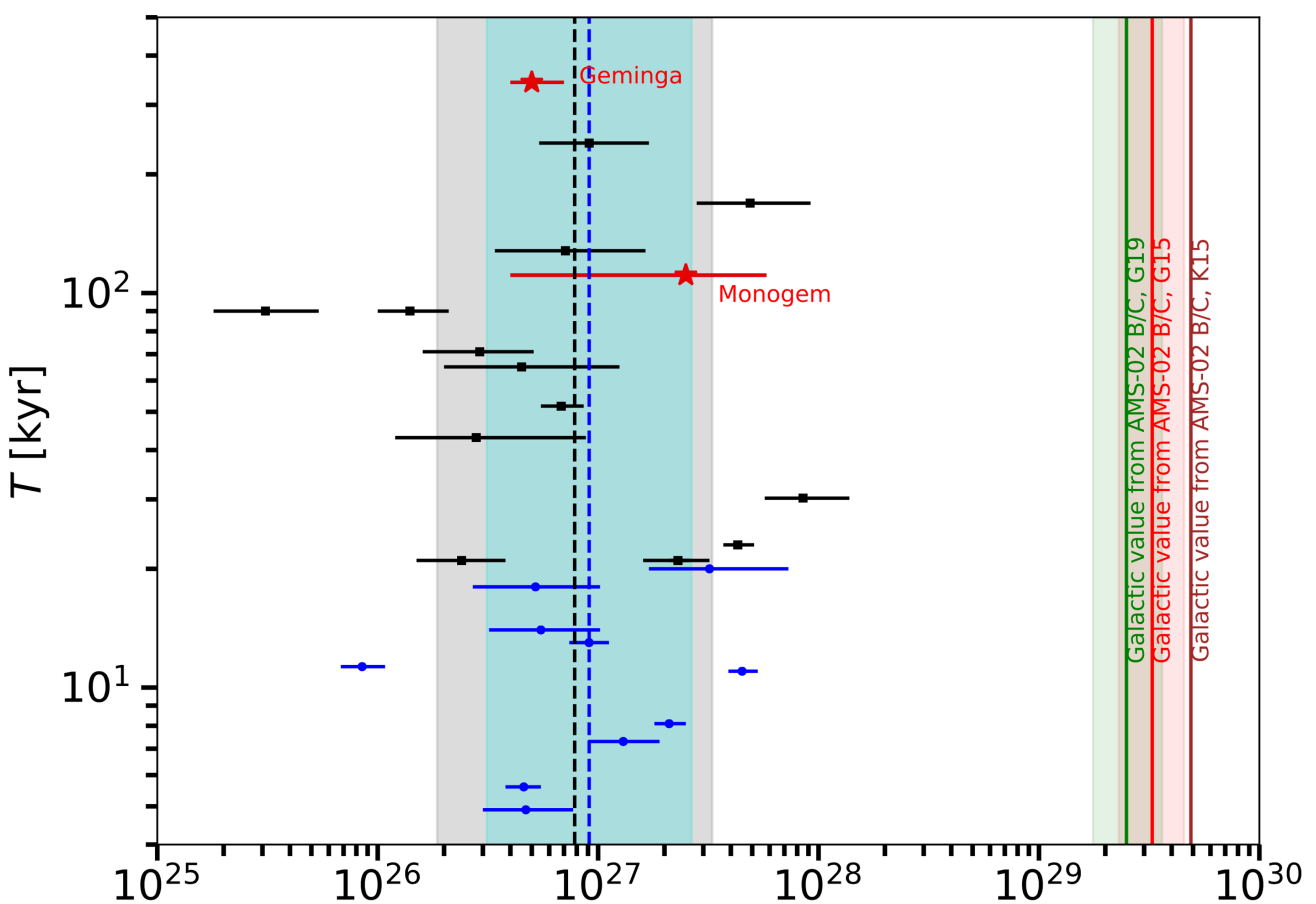




Di Mauro, Manconi, Donato PRD 100, 123015 (2019)

Results for the diffusion coefficient around PWNe

- 27 source detected by HESS and classified in TeVCat as PWN or Unid.
- We use HESS flux maps in HGPS.
- We find a diffusion coefficient around the PWNe of our sample of **8 10^{26} cm^2/s at 1 TeV**.
- We find that the size of the ICS halo is at least **35 pc**.

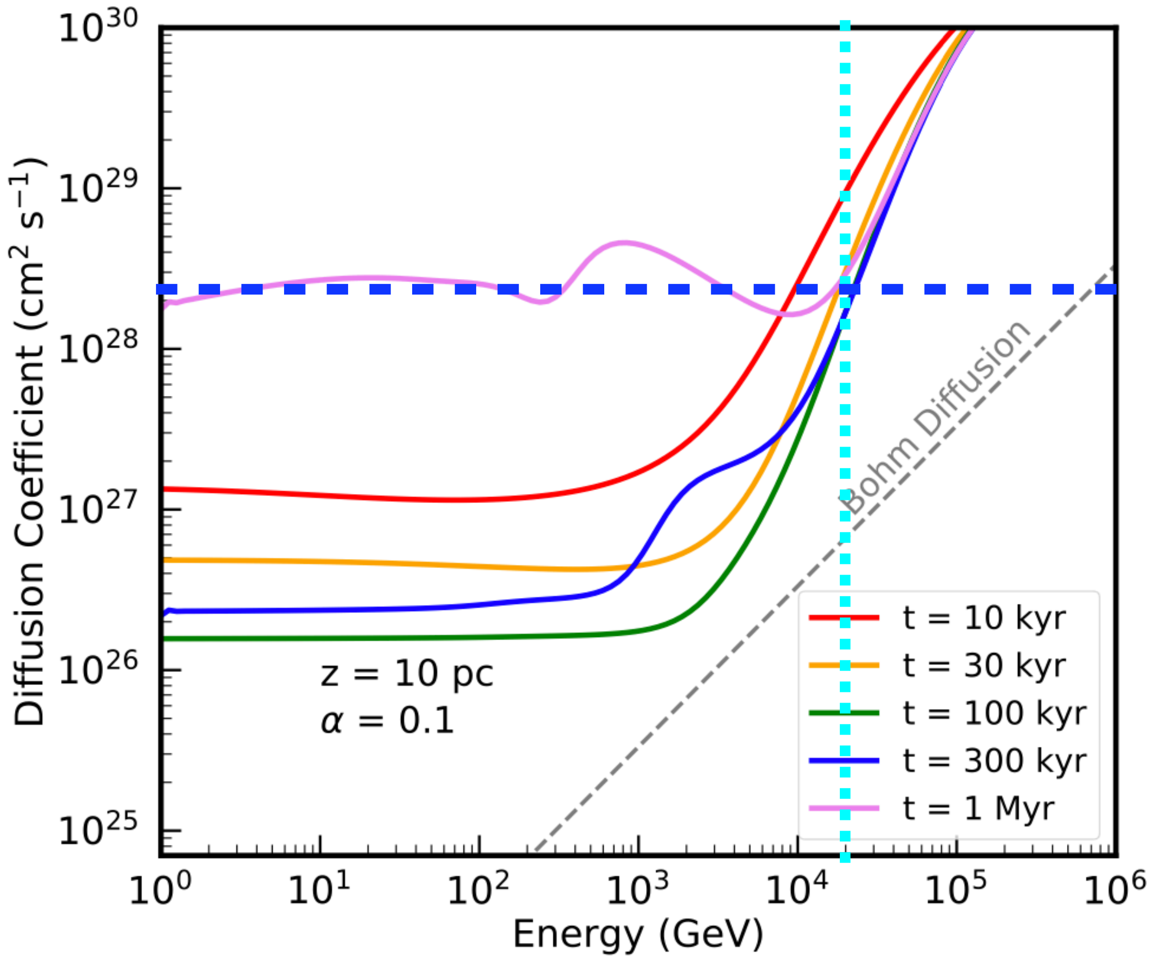


Inhibited diffusion around middle-age pulsars seems a common pattern!

Di Mauro, Manconi, Donato *PRD* 101 (2020) 10, 103035

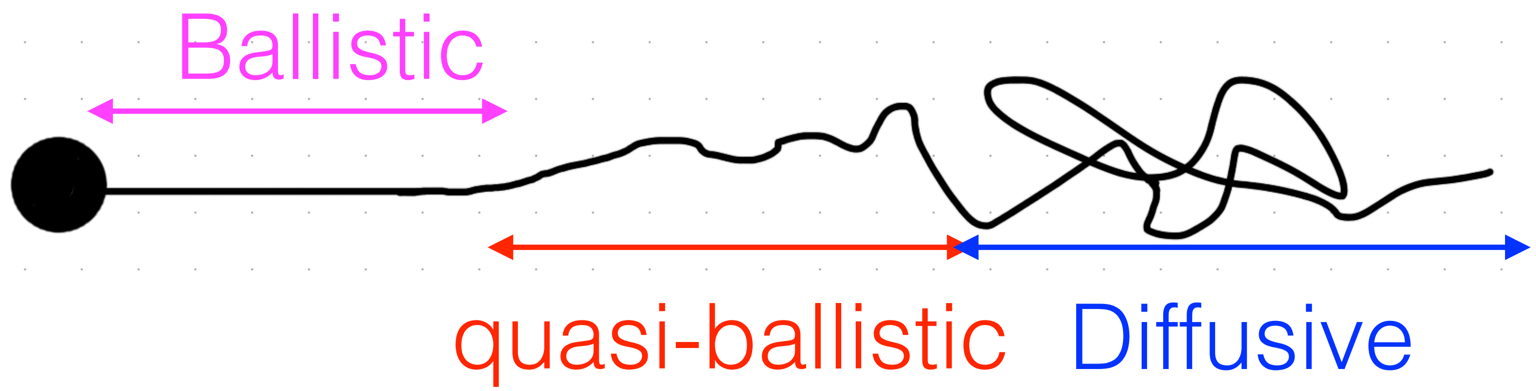
Possible theoretical interpretation

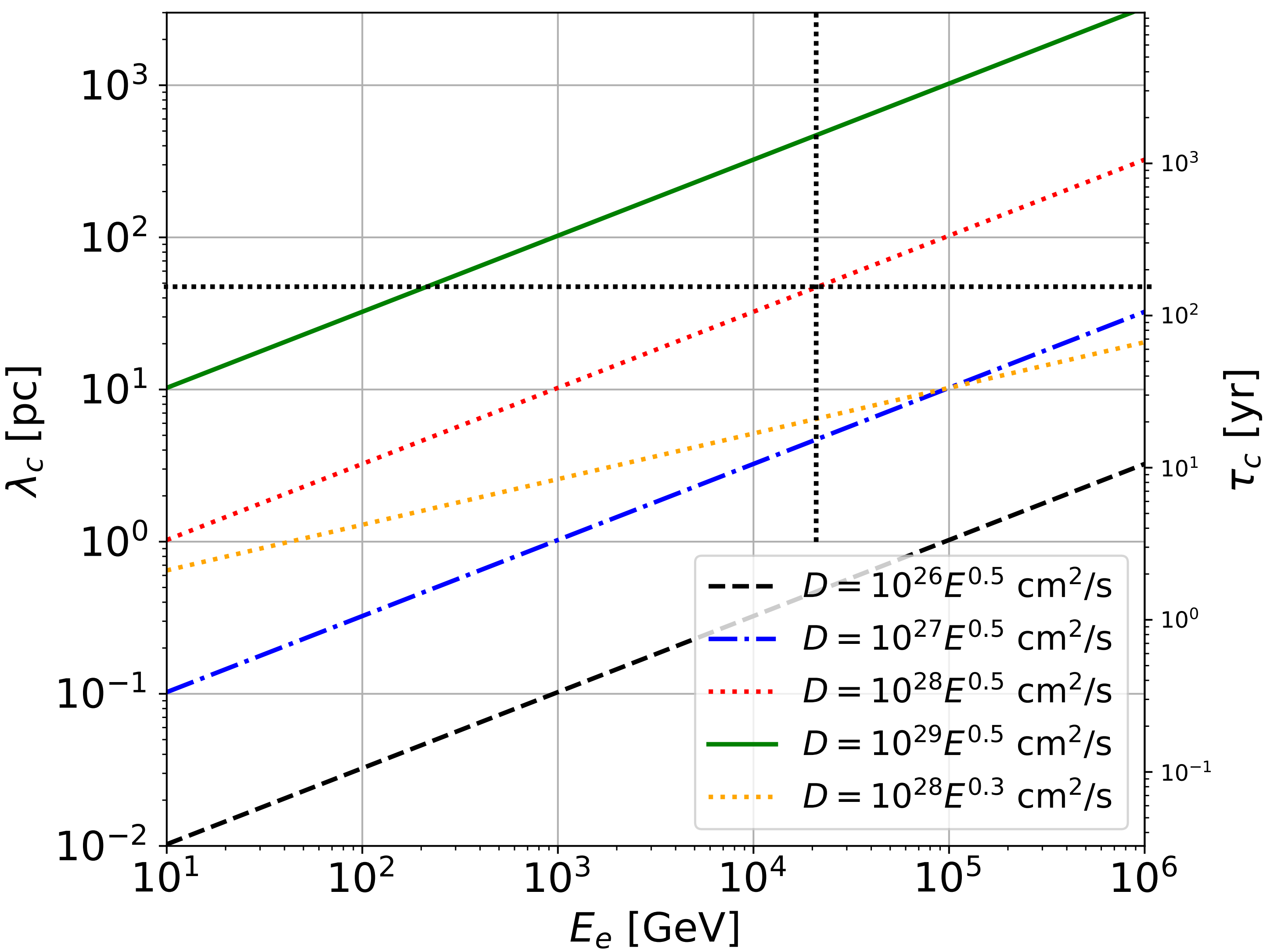
- Theoretical interpretation for inhibited diffusion is related to "*cosmic-ray gradient produced by the central source that induces a streaming stability that "self-confines" the cosmic-ray population*" (P. Mukhopadhyay, T. Linden 2022, C. Evoli, T. Linden, G. Morlino *PRD* 98 (2018) 6, 063017).
- ***The effect seems to be relevant for middle-age pulsars BUT not for TeV energies!!***



P. Mukhopadhyay, T. Linden 2022

Transition between ballistic and diffusive propagation





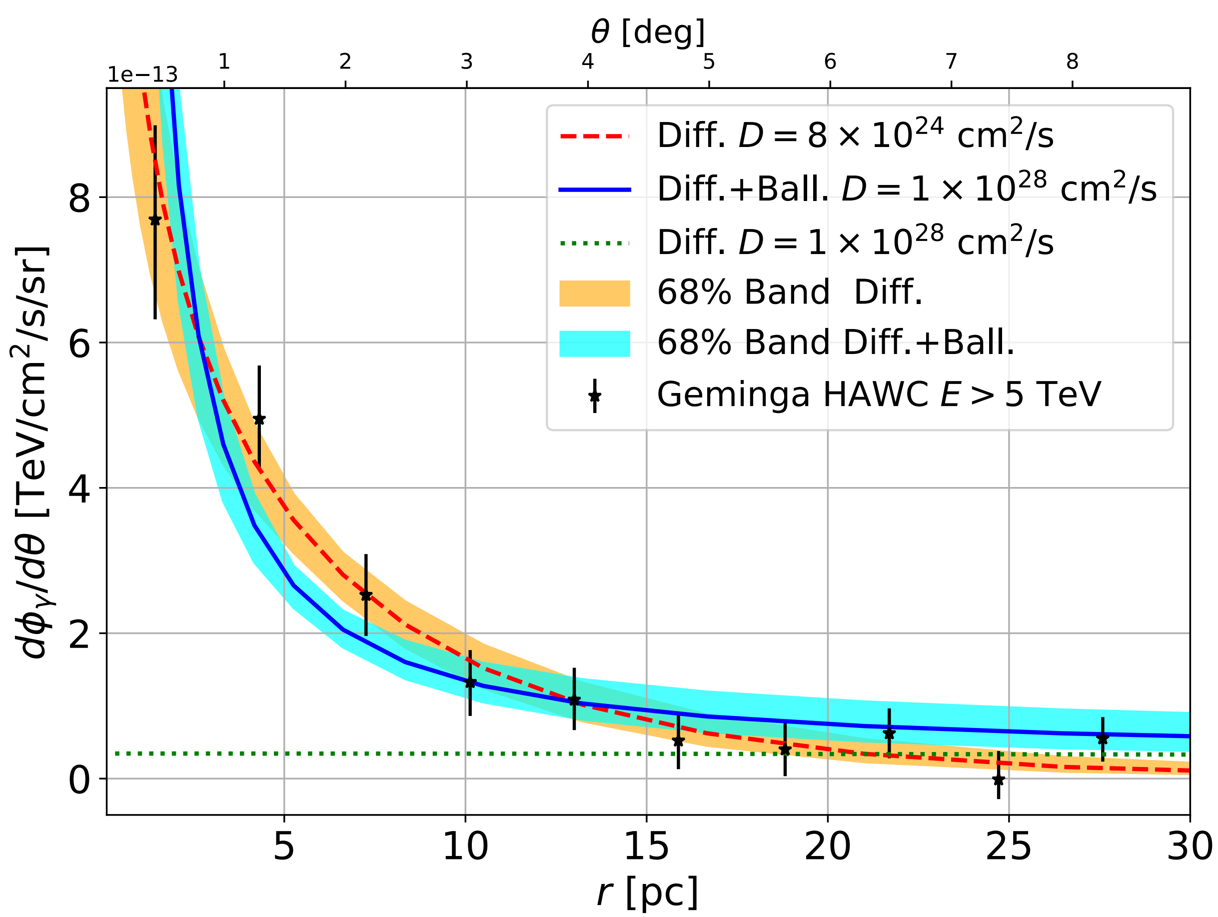
$$\tau_c = 3D(E)/c^2$$

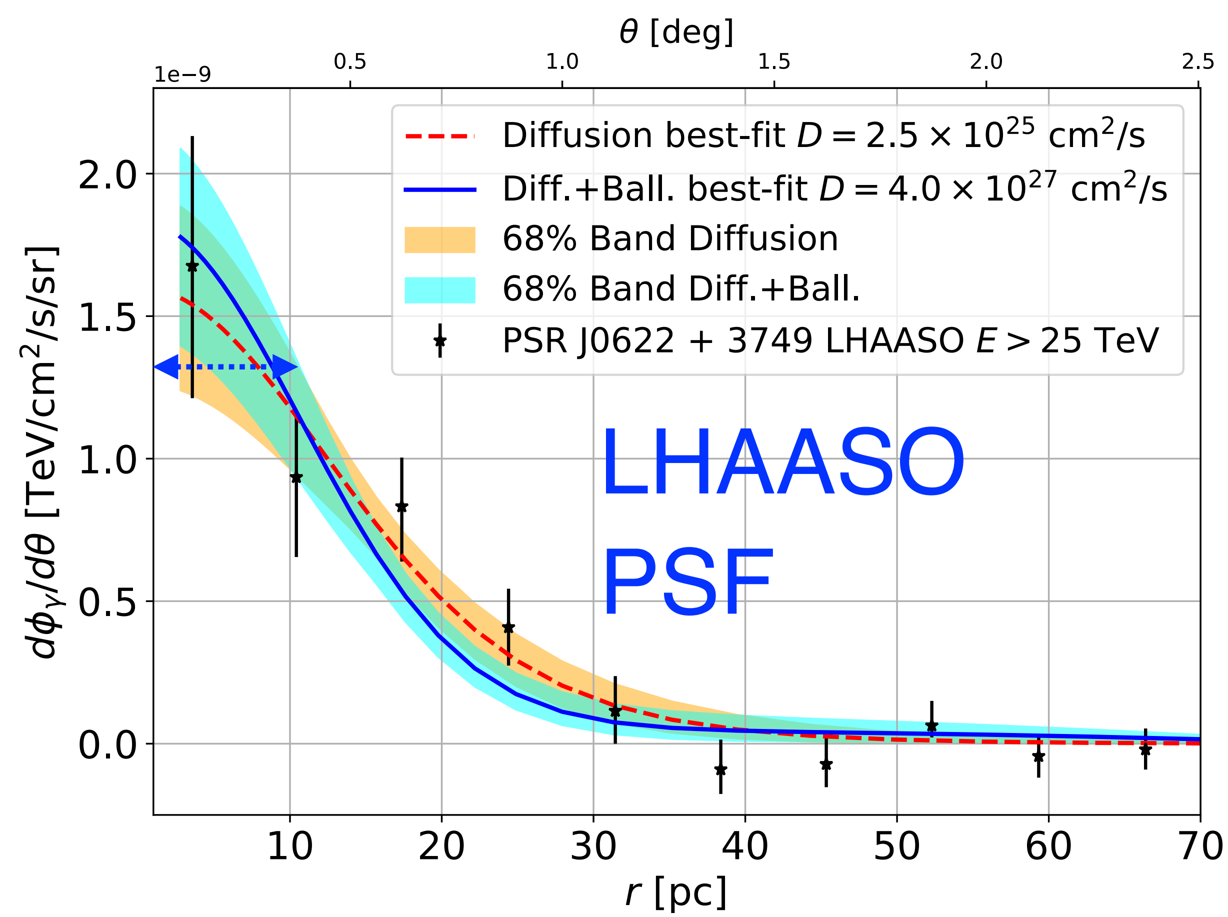
$$\lambda_c(E_{\rm GeV}) \approx 0.3\, D_{0,28} E_{\rm GeV}^{\delta}\ {\rm pc}$$

For D=10^{28} cm^2/s, λ_c is tens of pc, i.e. of the order of Geminga halo extension in HAWC.

Fit to Geminga, Monogem and PSR J0622+3749 data

- The model works well for the three pulsars.
- Best-fit of D is of the order of 10^{28} cm^2/s.
- *No new phenomenon or suppressed diffusion is needed.*
- *However, large efficiency (even larger than 100%) are required for Geminga.*

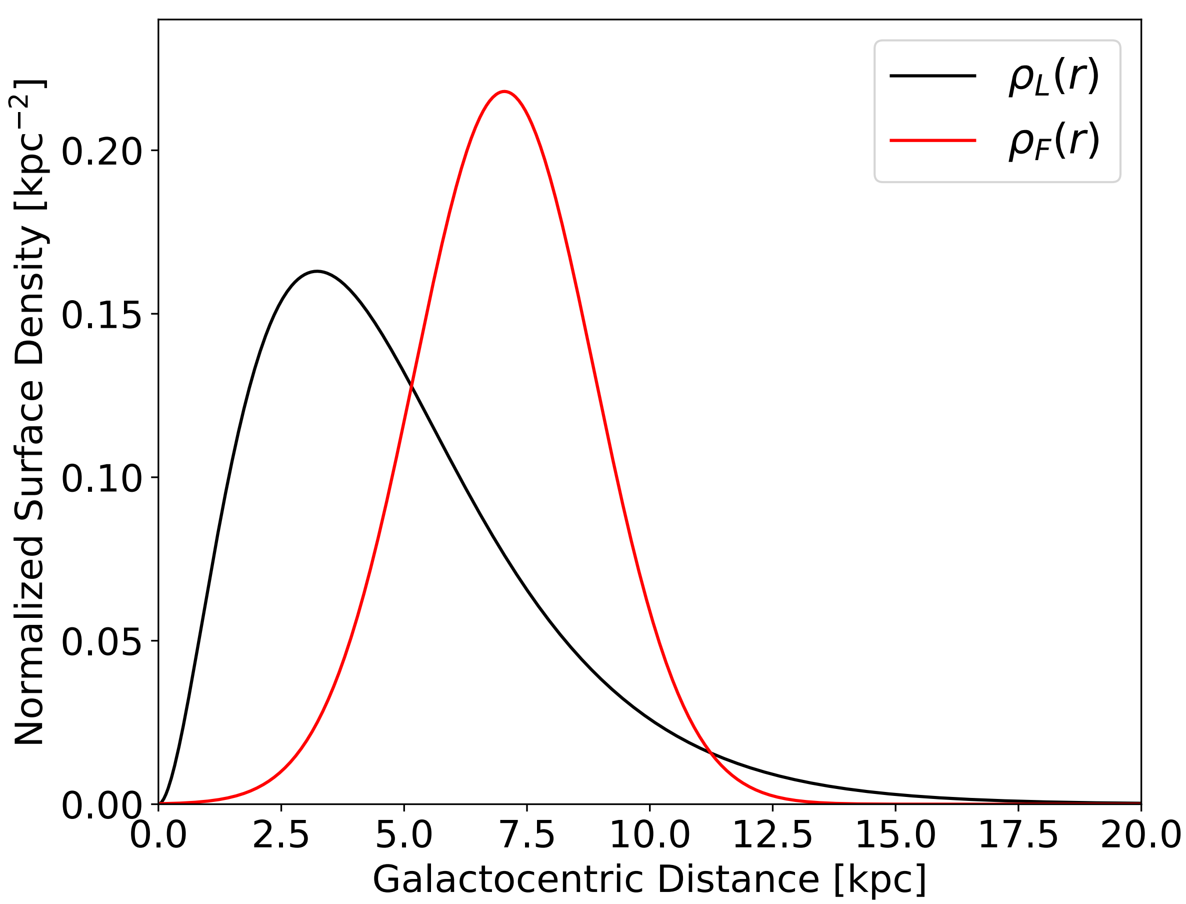


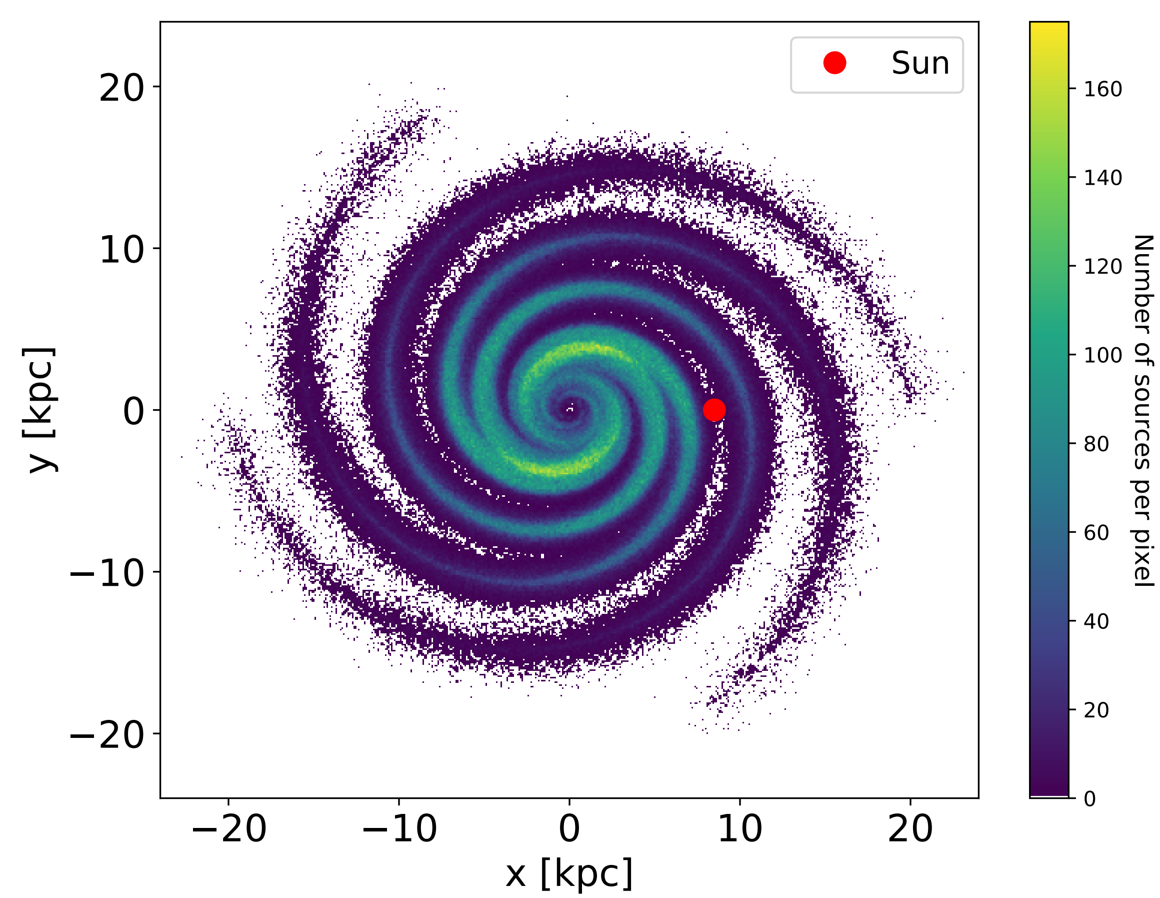


S. Recchia et al *Phys.Rev.D* 104 (2021) 12, 123017.

Contributions of pulsars to the positron excess

Pulsar property	Simulated quantity	Benchmark	Variations
Age	T	Uniform $[0, t_{max}]$	-
Spin-down		CB20[44]	FK06[65]
	P_0	Gaussian [0.3s; 0.15s]	-
	$\log_{10}(B)$	Gaussian [12.85G; 0.55G]	Gaussian [12.65G; 0.55G]
	n	Uniform [2.5-3]	Constant [3]
	$\cos\alpha$	Uniform [0-1]	Constant [0]
$e^{\pm}$ injection	γ_e	Uniform [1.4-2.2]	-
	η	Uniform [0.01-0.1]	-
Radial distribution	$\mathbf{r}$	$\rho_L(r)$ [43]	$\rho_F(r)$[65]
Kick velocity	v_k	-	FK06VB [65]



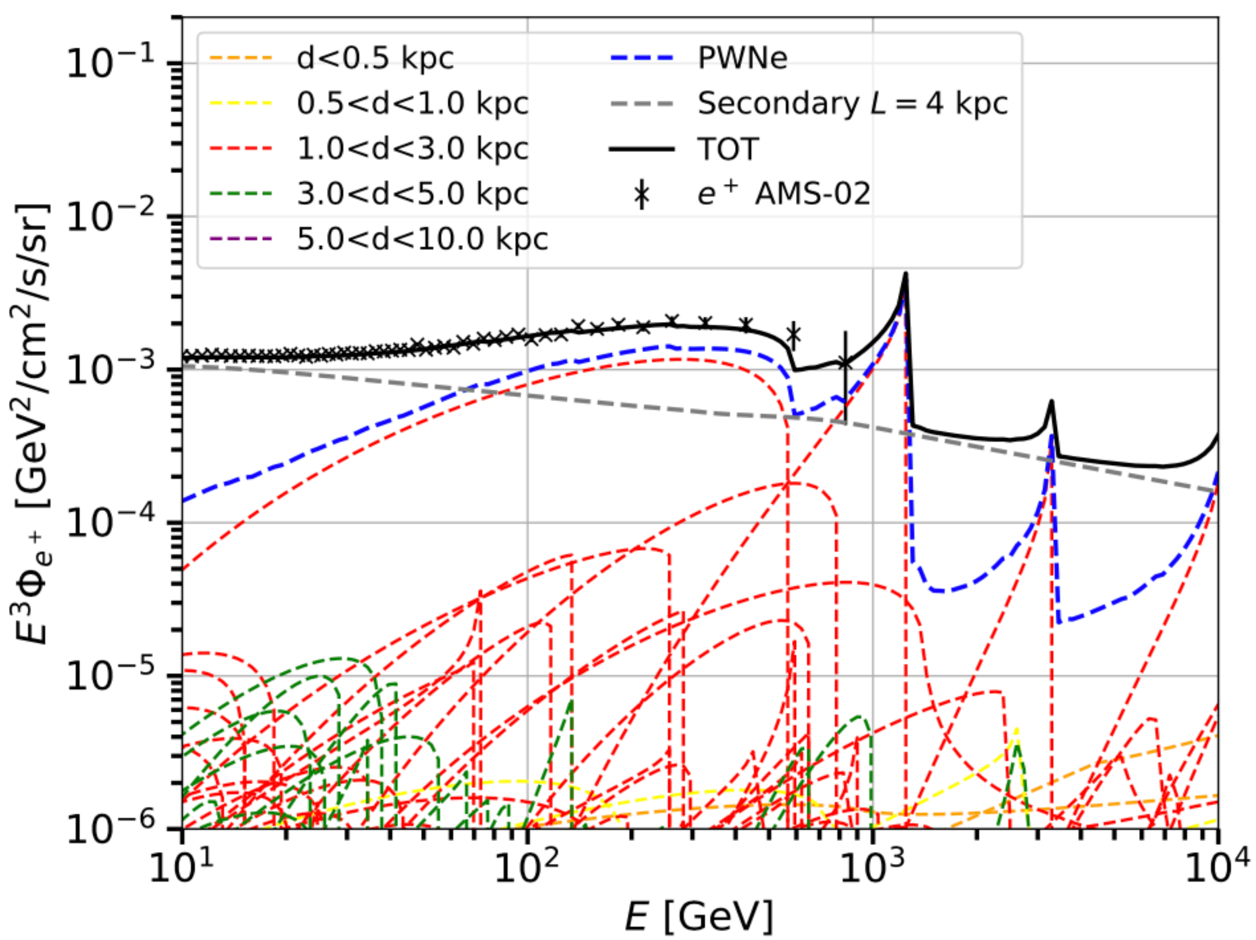


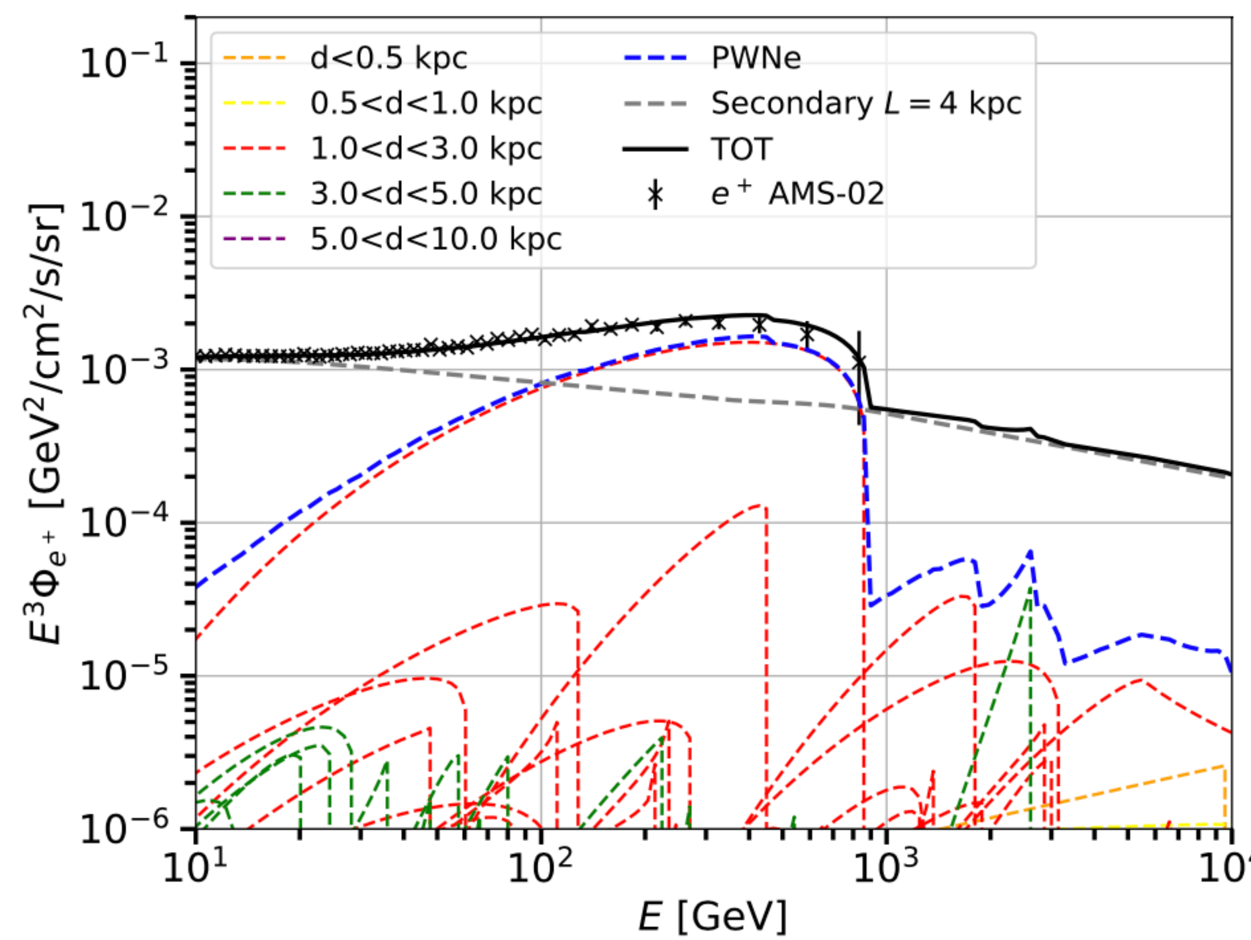
Orusa et al. JCAP 12 (2021) 12, 014.

A few pulsars dominate the positron flux

	AMS-02 errors	Total flux 1%
ModA	1.3/2.9/3.3	1.0/1.8/2.2
ModB	3.5	1.9
ModC	3.9	3.0
ModD	5.4	3.5
ModE	1.0	1.0

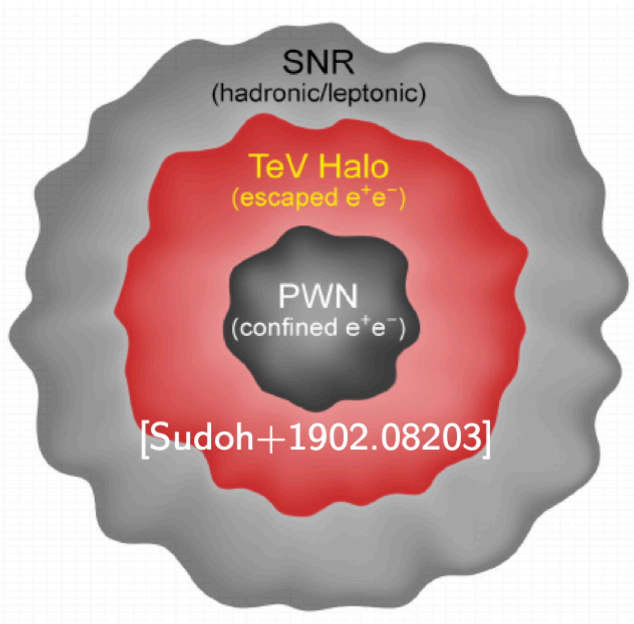
Efficiencies between 1-10% are sufficient to fit the data



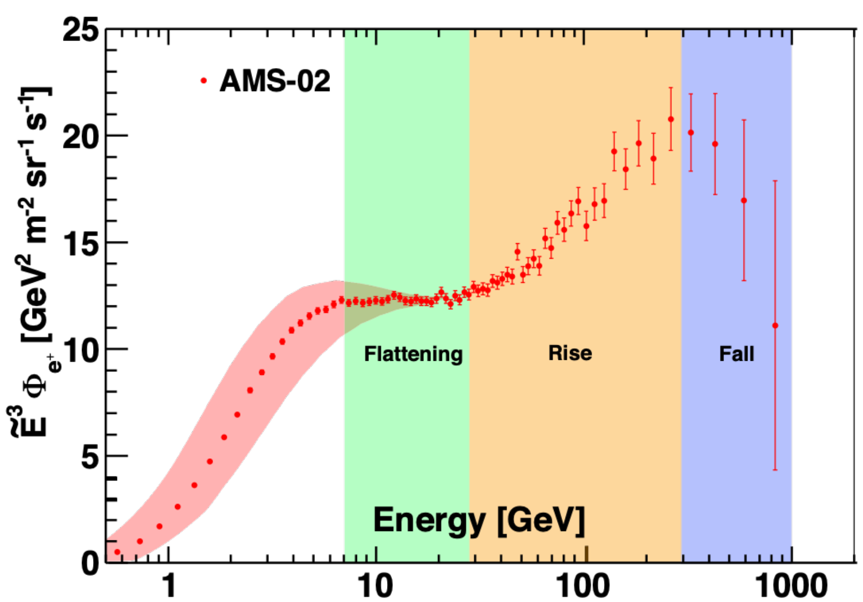


Orusa et al. JCAP 12 (2021) 12, 014.

Open problems



- **ICS halos:**
  - Are inhibited diffusion halos around pulsars really needed to fit gamma-ray halos?
  - If low-diffusion halos are presented, what's their size and are they a general feature?
  - What is the theoretical interpretation for low-diffusion halos?
    - Future observations (LHAASO-HAWC-SWGO-CTA)



- **Positron excess:**
  - Since a few pulsars contribute to most of the excess, what are these objects?
  - What is the physical process that produce positrons from pulsars (efficiency, injection of positrons)?

Backup slide

Gamma rays from ICS

ICS power

$$\mathcal{P}^{IC}(E, E_\gamma) = \frac{3\sigma_T c\, m_e^2 c^4}{4E^2} \int_{\frac{m_e c^2}{4E}}^{1} dq \frac{d\mathcal{N}}{d\epsilon}(\epsilon(q)) \times \quad (3$$

$$\times \left(1 - \frac{m_e^2 c^4}{4qE^2(1-\tilde{\epsilon})}\right) \left[2q \log q + q + 1 - 2q^2 + \frac{\tilde{\epsilon}(1-q)}{2-2\tilde{\epsilon}}\right]$$

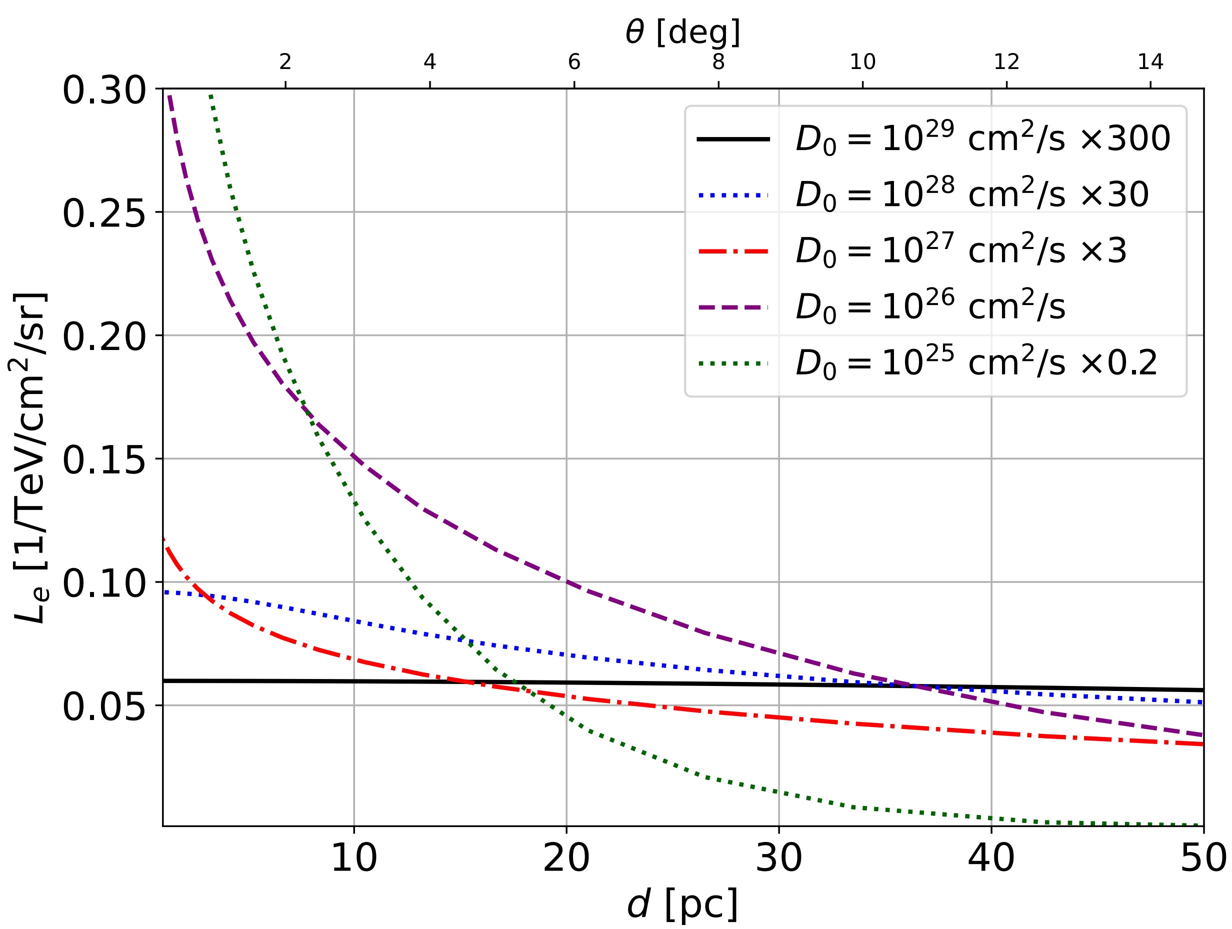
Flux of photons for Sync.

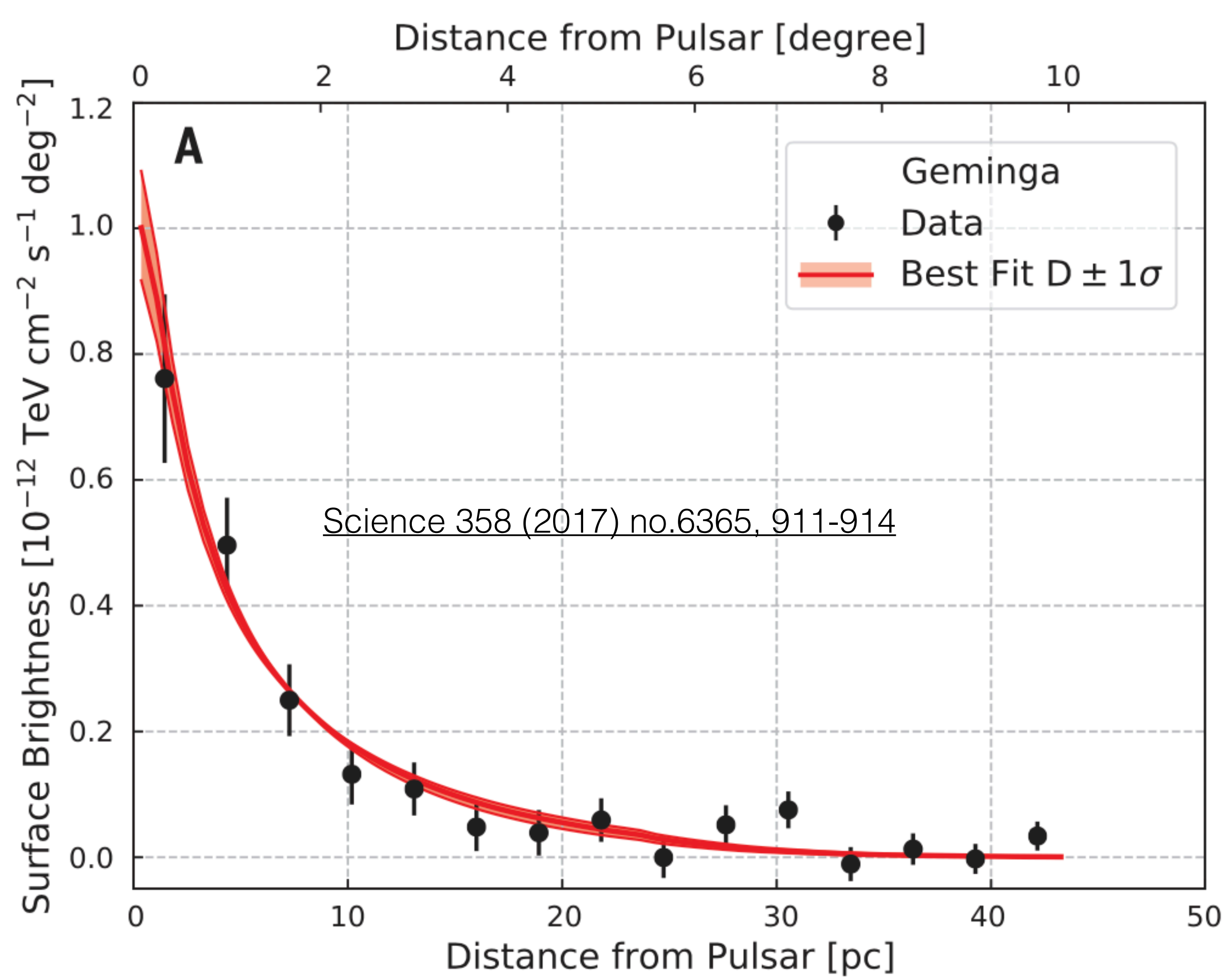
$$\mathcal{M}(E, \theta) = \int_{\Delta\Omega} d\Omega \int_0^\infty dr\, \mathcal{N}_e(E, r)$$

$$\phi^{\mathrm{IC,Sync}}(E_\gamma, \Delta\Omega) = \frac{1}{4\pi} \int_{m_e c^2}^{\infty} dE \mathcal{M}(E, \Delta\Omega) \mathcal{P}^{\mathrm{IC,Sync}}(E, E_\gamma)$$

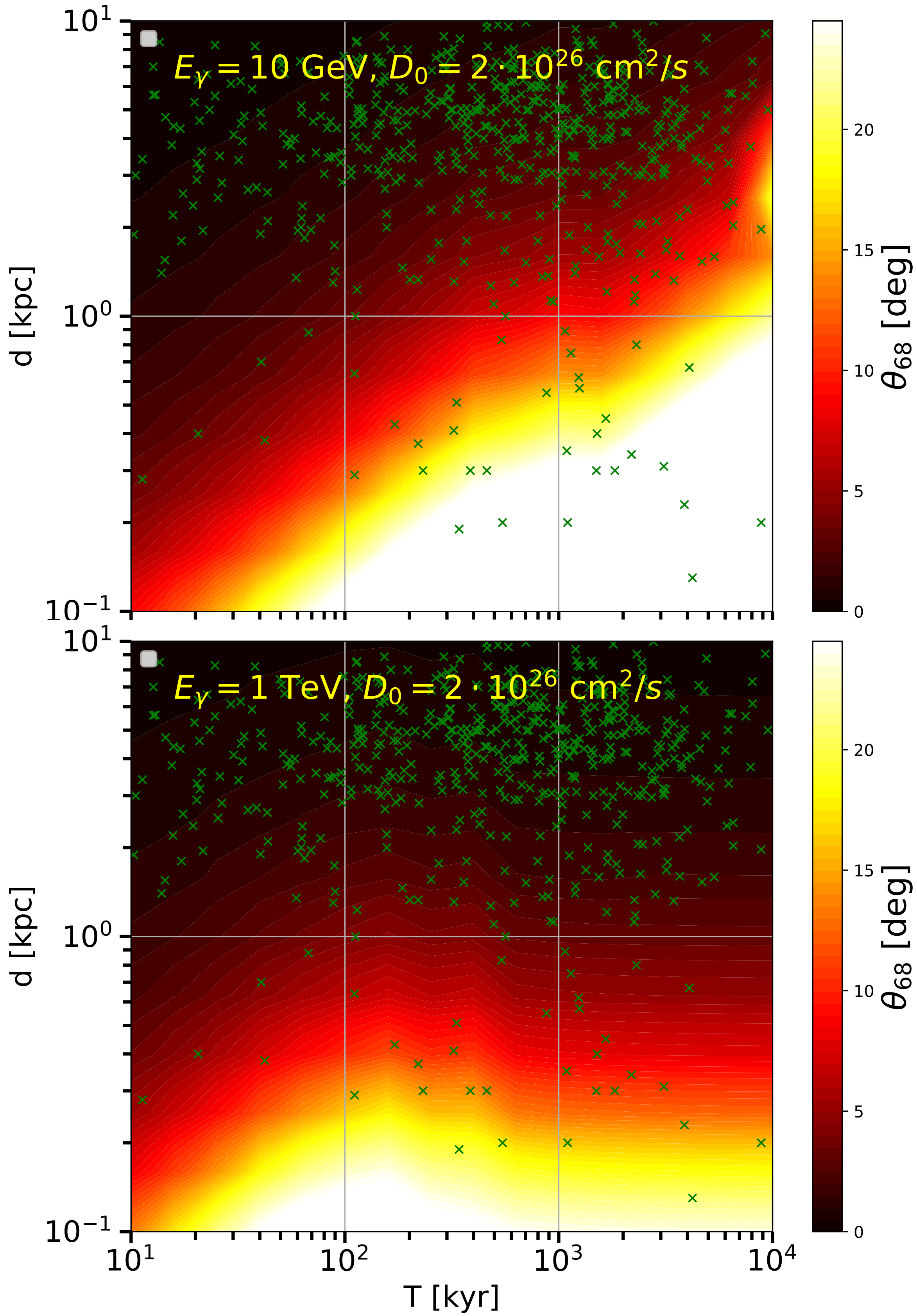
HAWC results for Geminga and Monogem PWNe

- HAWC detected an extended emission from Geminga and Monogem PWNe for **E>5 TeV**.
- ***In the vicinity of the PWN, the diffusion coefficient D must be about 500 times smaller than the average in the Galaxy.***





ICS halo extension



$$\Phi_\gamma^{68\%} = 2\pi \int_0^{\theta_{\rm EXT}} \frac{d\Phi_\gamma}{d\theta} \sin\theta d\theta$$

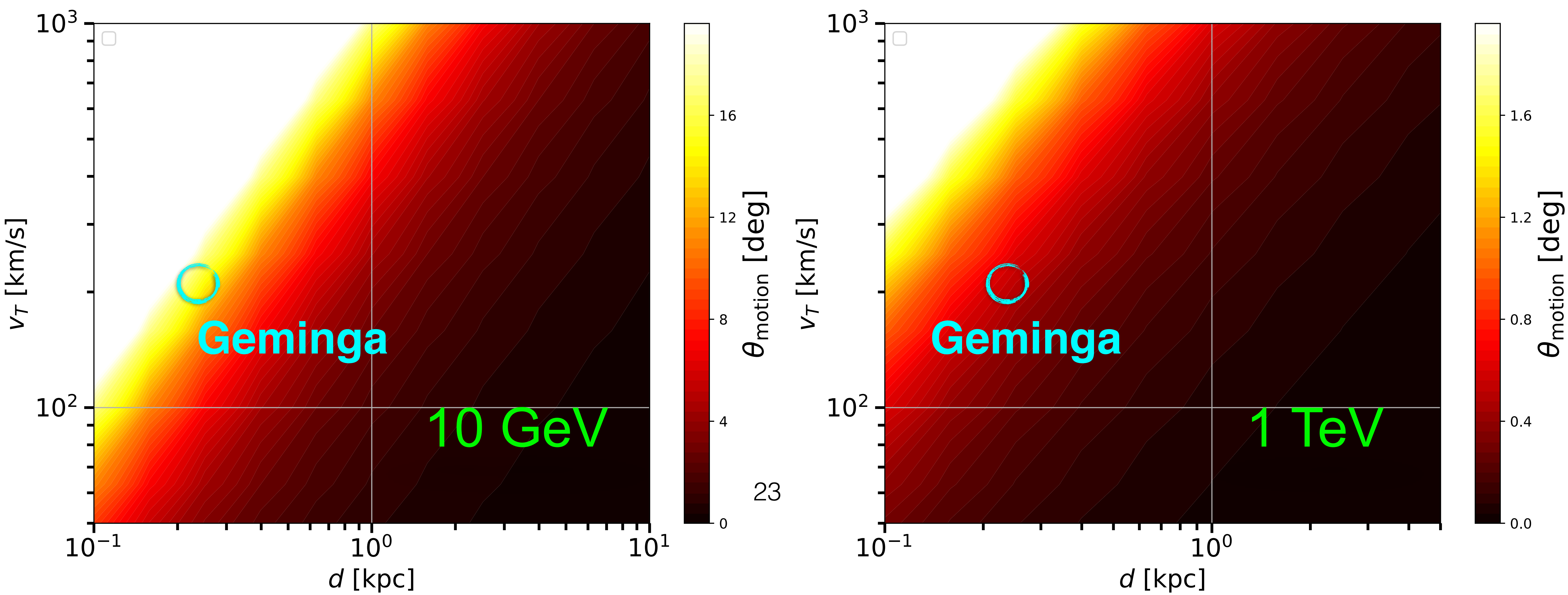
- $D=10^{26}$ cm^2/s —> Most of ICS halos at GeV energies would be several of degrees extended.
- If $D=10^{26}$ cm^2/s IACTs and HAWC-LHAASO should detect several halos.

x ATNF catalog pulsars

Di Mauro, Manconi, Donato *PRD* 101 (2020) 10, 103035

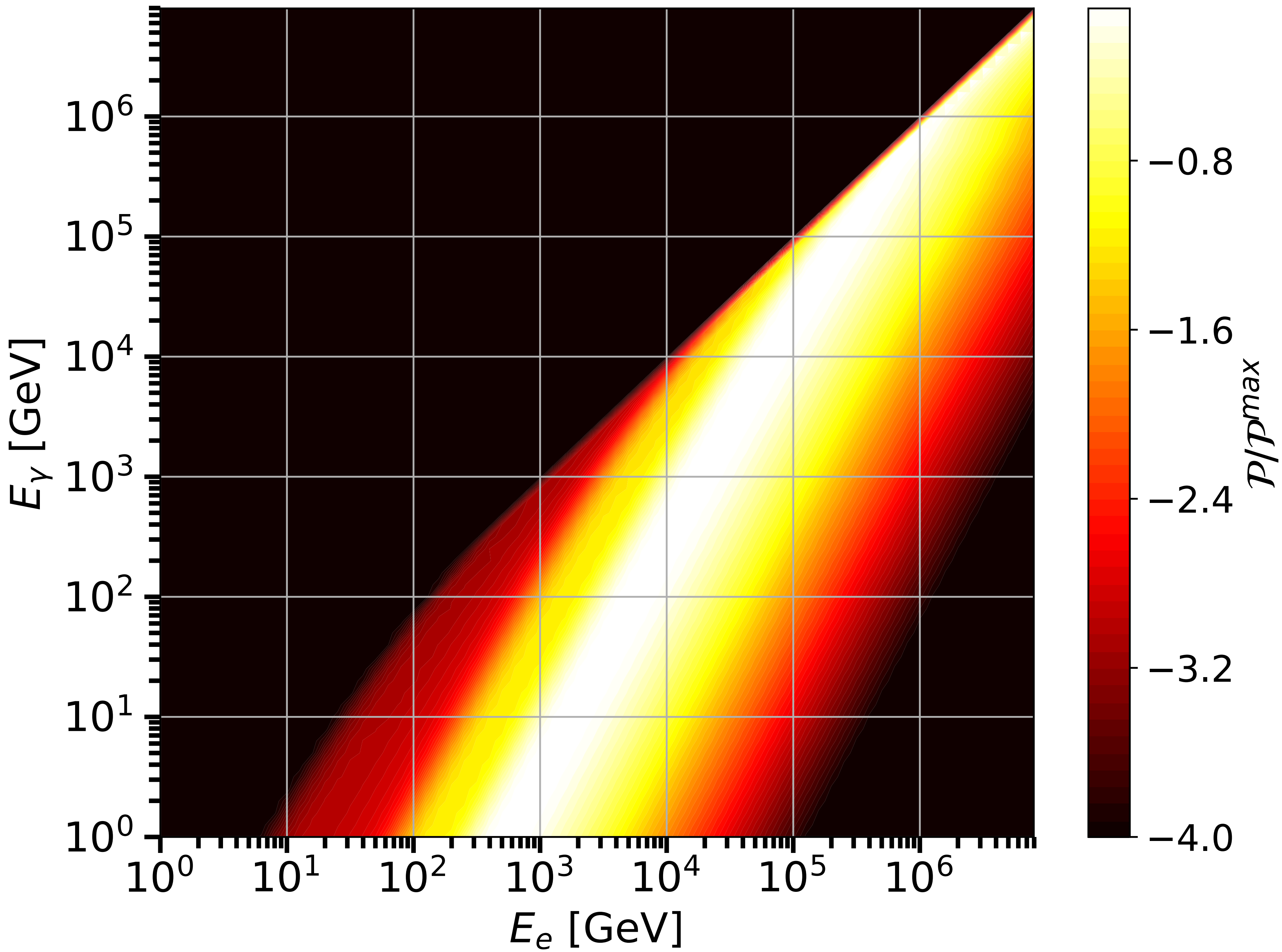
Pulsar proper motion

- The average pulsar proper motion is around 200 km/s (Faherty et al. 2007).
- At GeV the proper motion is not relevant for d>a few kpc and T< few hundreds kyr.
- At TeV the effect is much smaller.



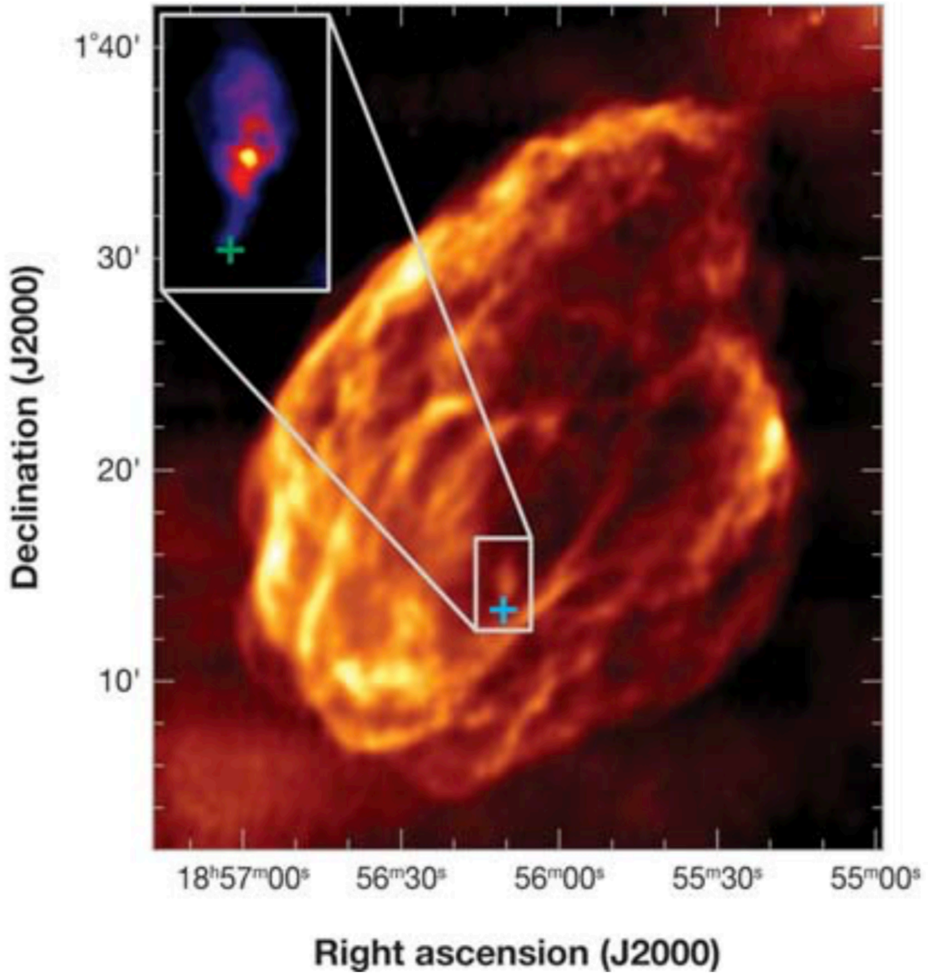
Di Mauro, Manconi, Donato *PRD* 101 (2020) 10, 103035

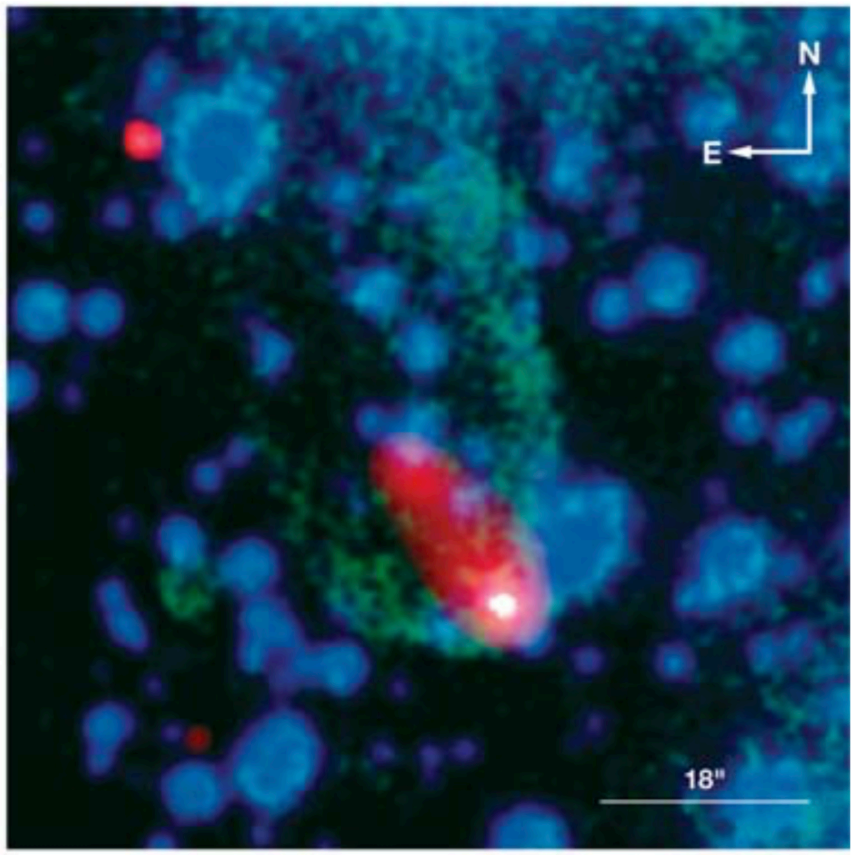
Are pulsars TeV Pevatron?



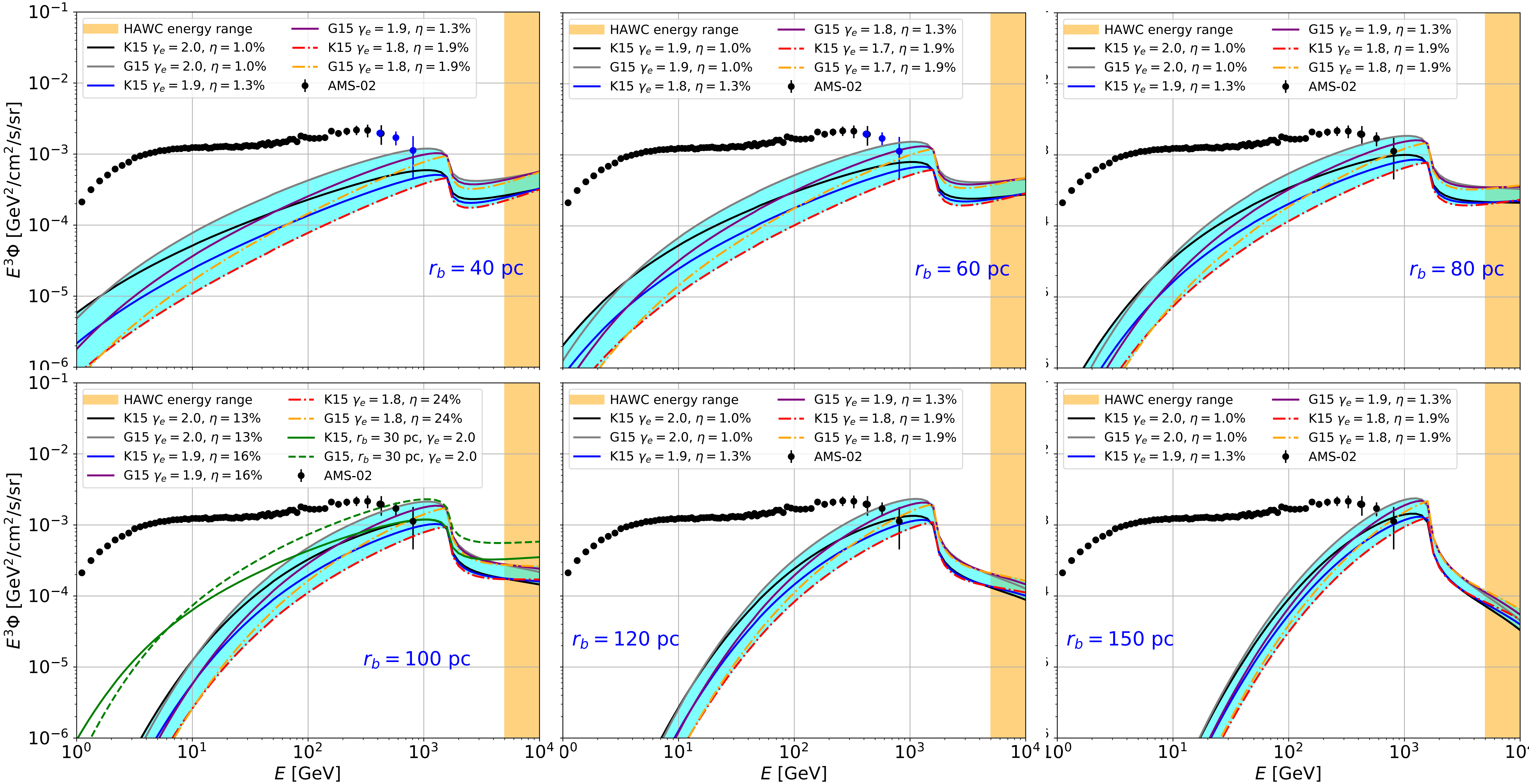
Cosmic-ray e± accelerated by PWNe

- The engine of a PWN is a pulsar, i.e. a rapidly spinning neutral star (NS).
- A NS has huge magnetic fields (10^9-10^{12} G) which produce wind of particles extracted from the NS surface.
- This wind shines from radio to gamma rays and after a few kyrs interact with the SNR reverse shock.
- The pulsar proper motion and the interaction with the SNR reverse shock generate a relic PWN and a bow shock.



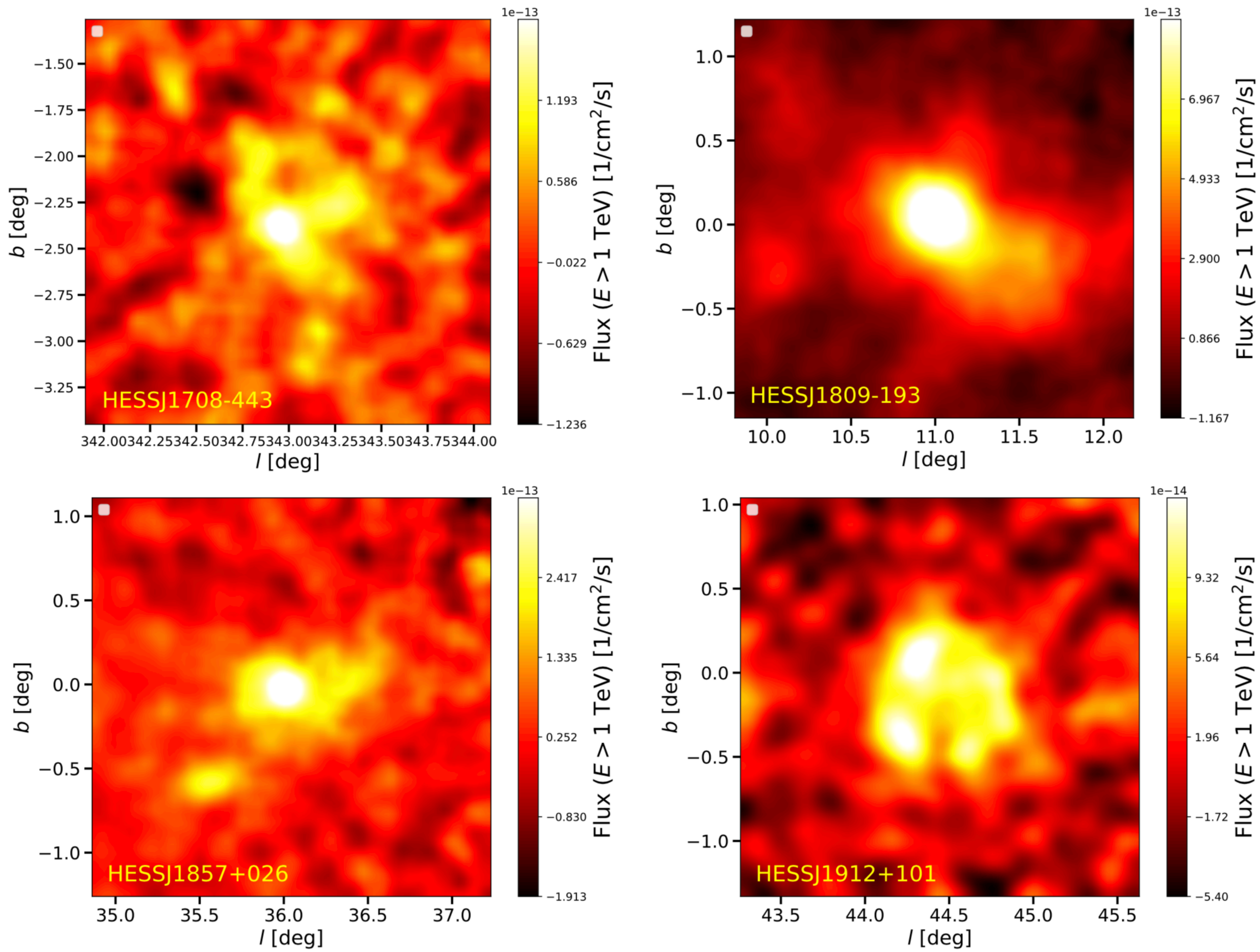


Contribution of Geminga to the positron excess



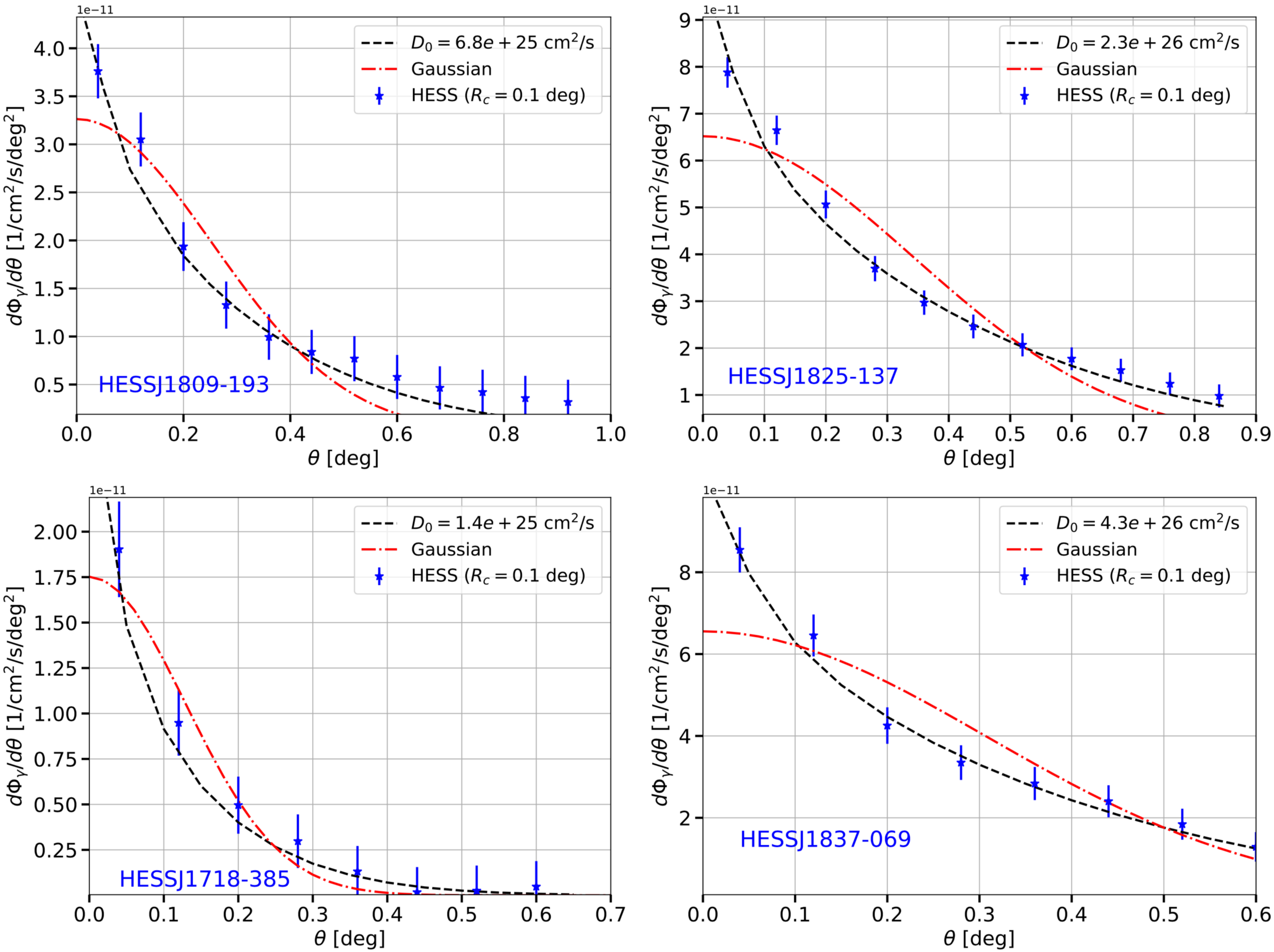
HESS flux maps

- We selected sources detected mainly by HESS because they released flux maps.
- The flux is provided for a correlation radius of 0.1 and 0.2 deg and in maps with a pixel size of 0.02 deg.
- We removed sources close to our sources of interests.



Di Mauro, Manconi, Donato *PRD* 101 (2020) 10, 103035

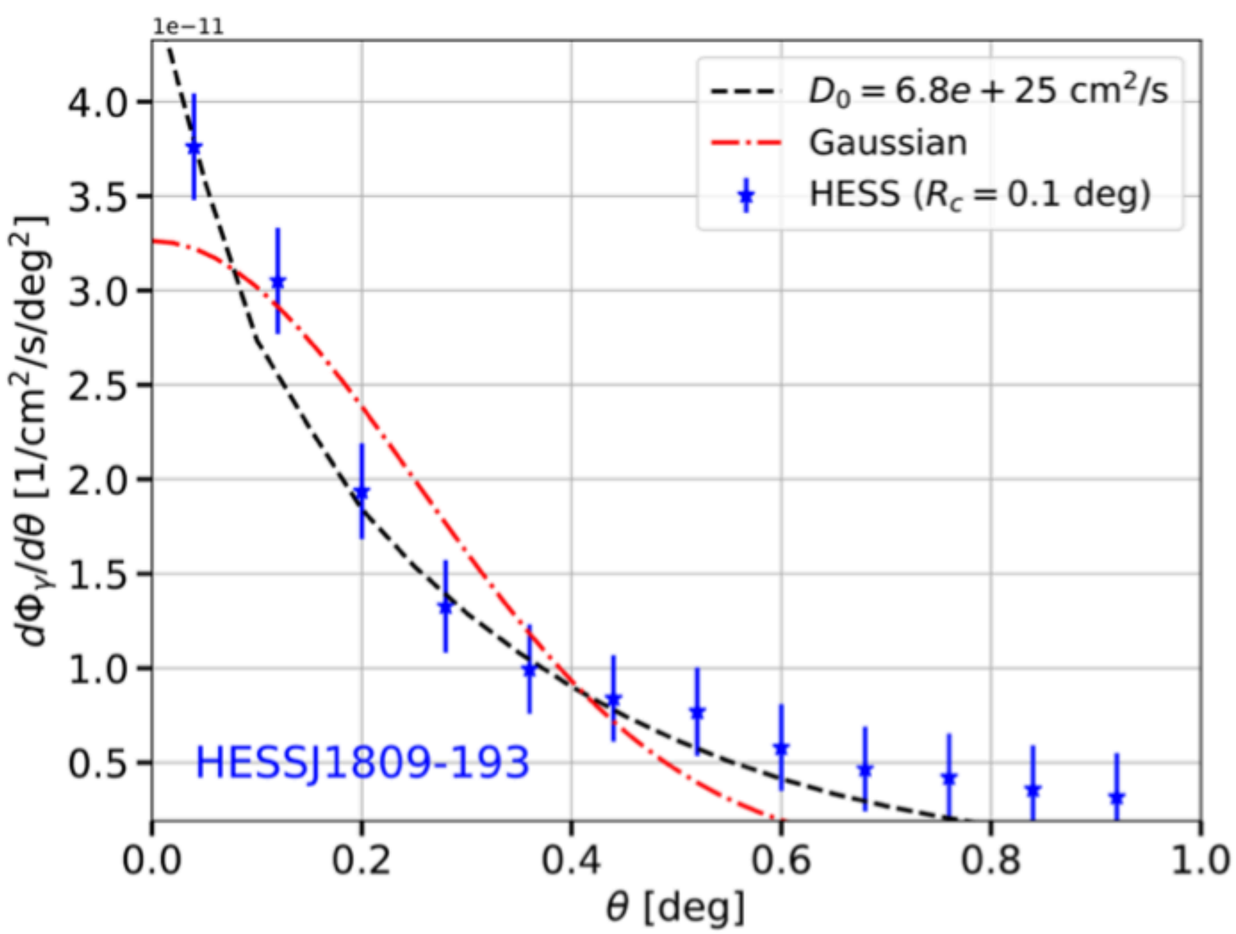
Surface brightness data

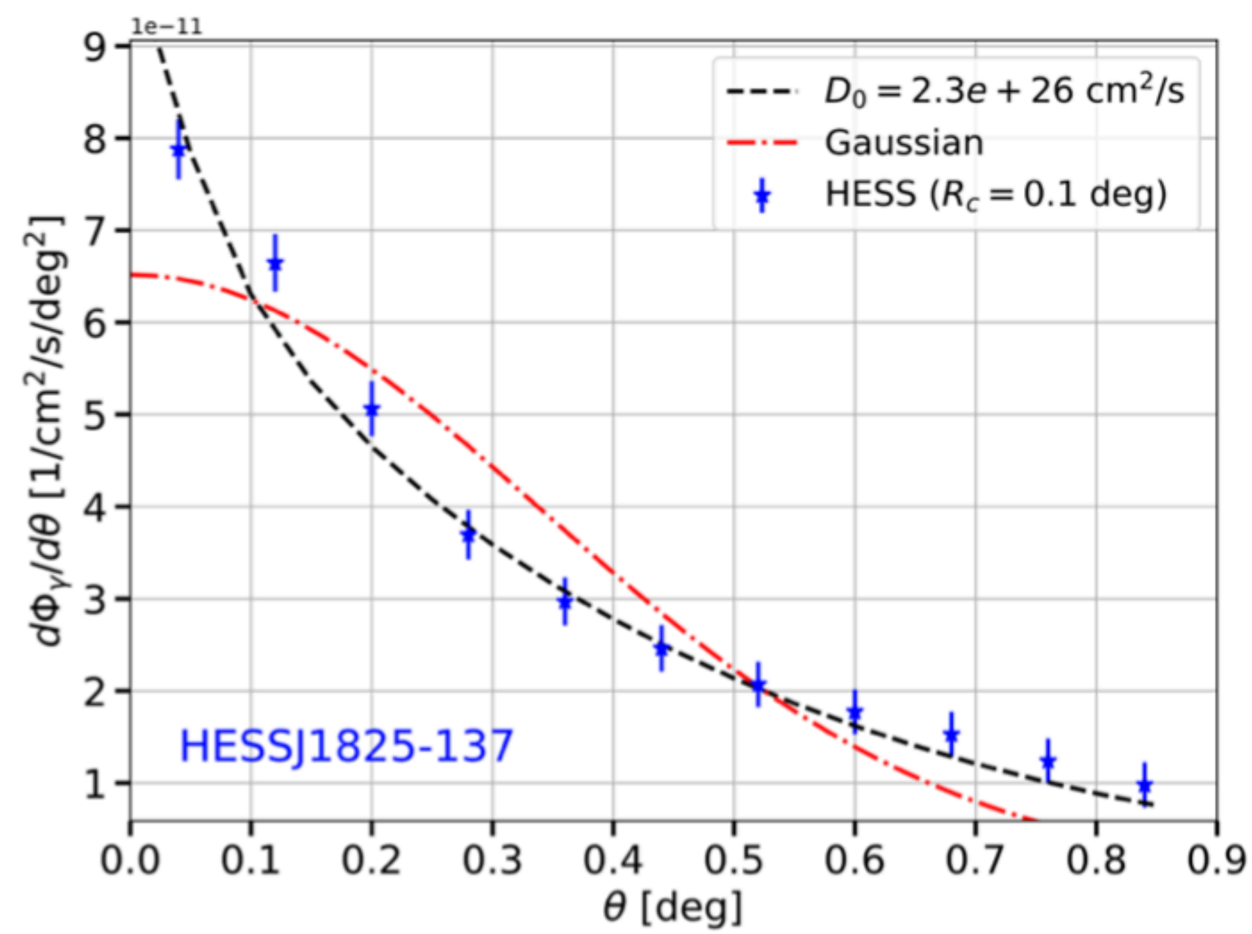


Di Mauro, Manconi, Donato *PRD* 101 (2020) 10, 103035

Is HESS detecting ICS halos?

- Source detected by HESS and classified in TeVCat as PWN or Unid.
  - We have a list of 27 sources.
- We use HESS flux maps in HGPS*.
- We extract the source surface brightness that we use to calculate D_0.



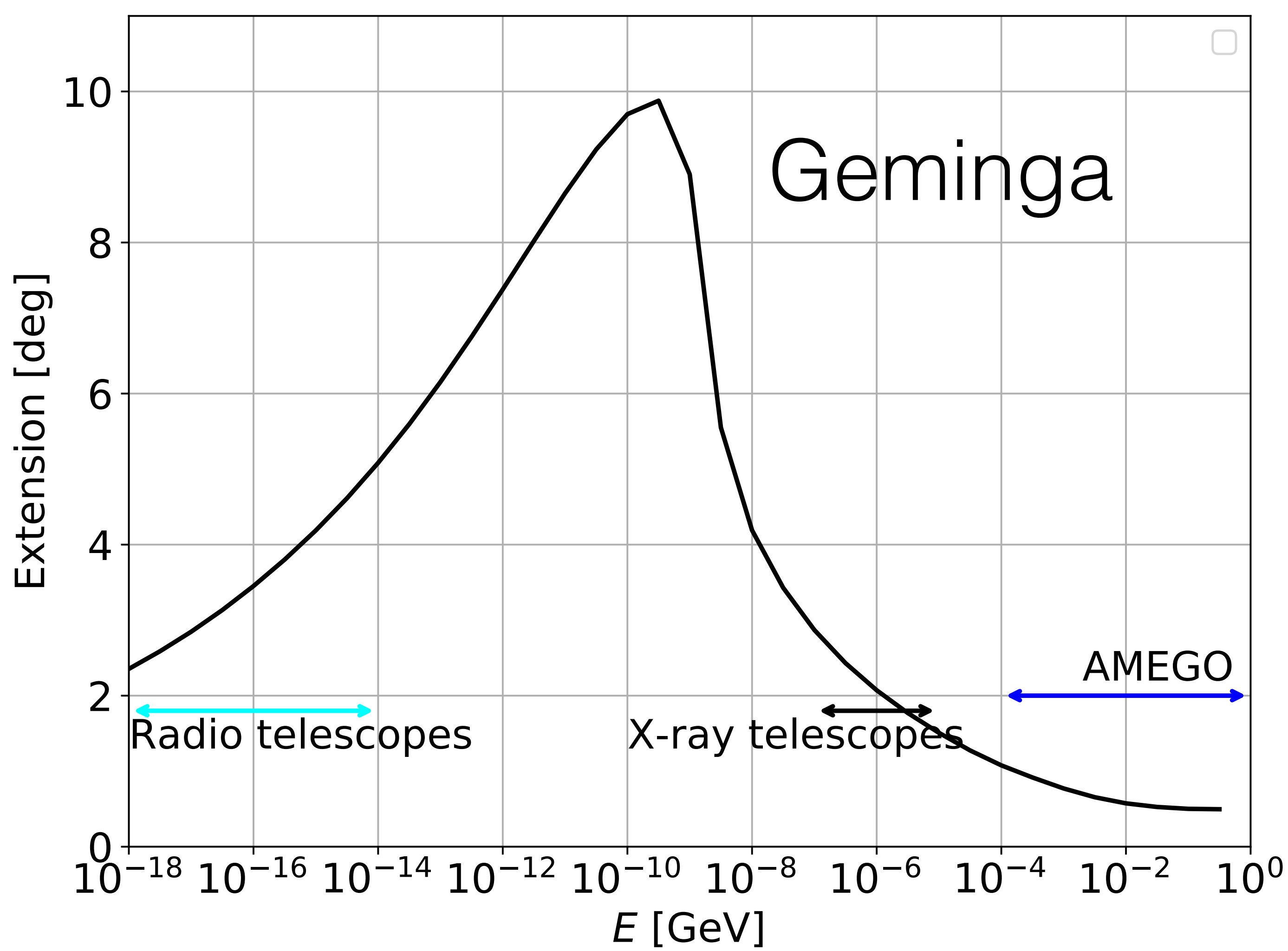


*correlation radius of 0.1 and 0.2 deg and maps with a pixel size of 0.02 deg.

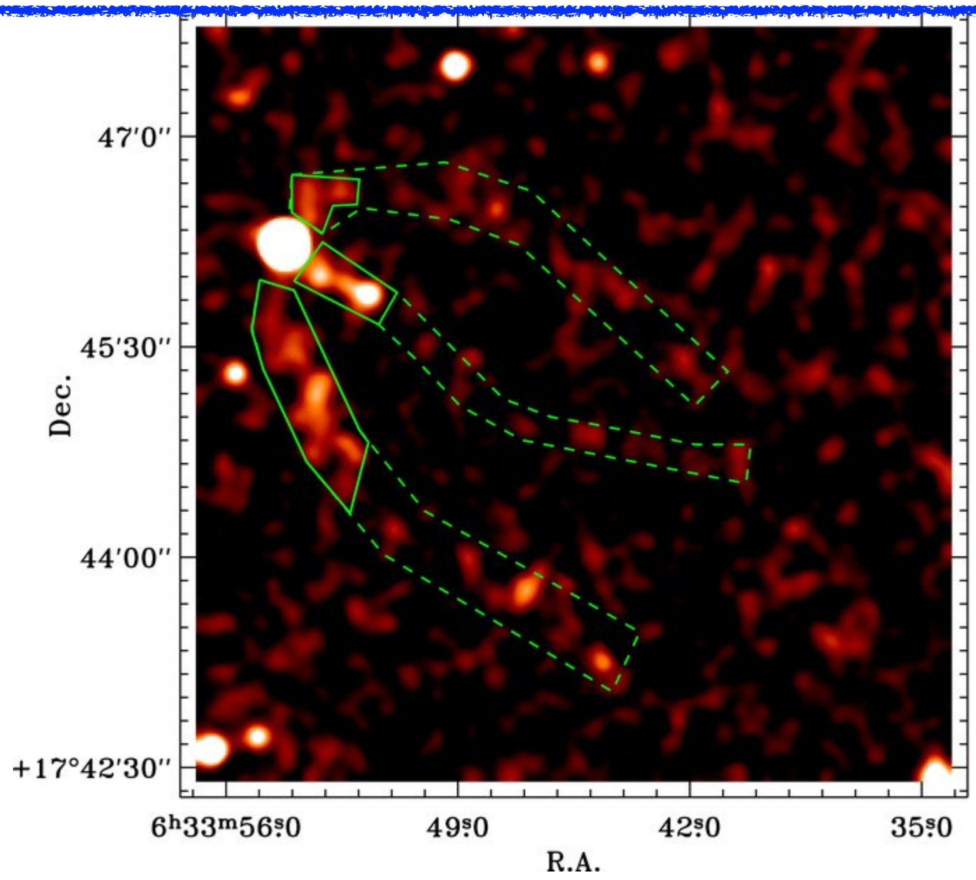
Di Mauro, Manconi, Donato PRD 101 (2020) 10, 103035

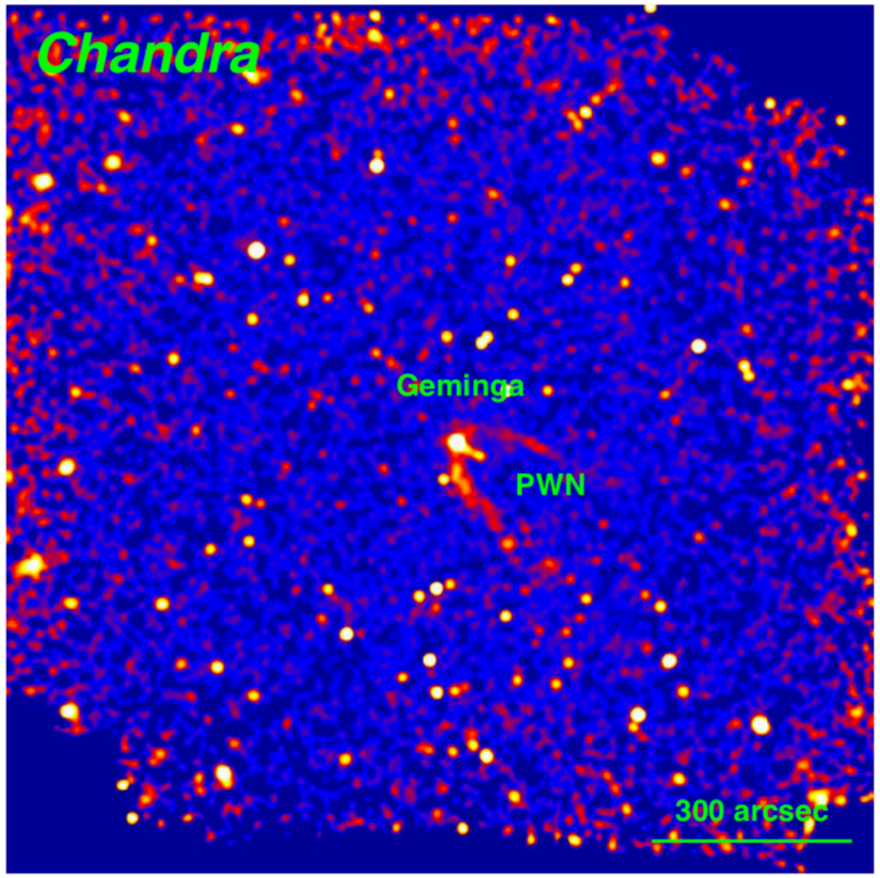
Extension of Geminga sync. halo

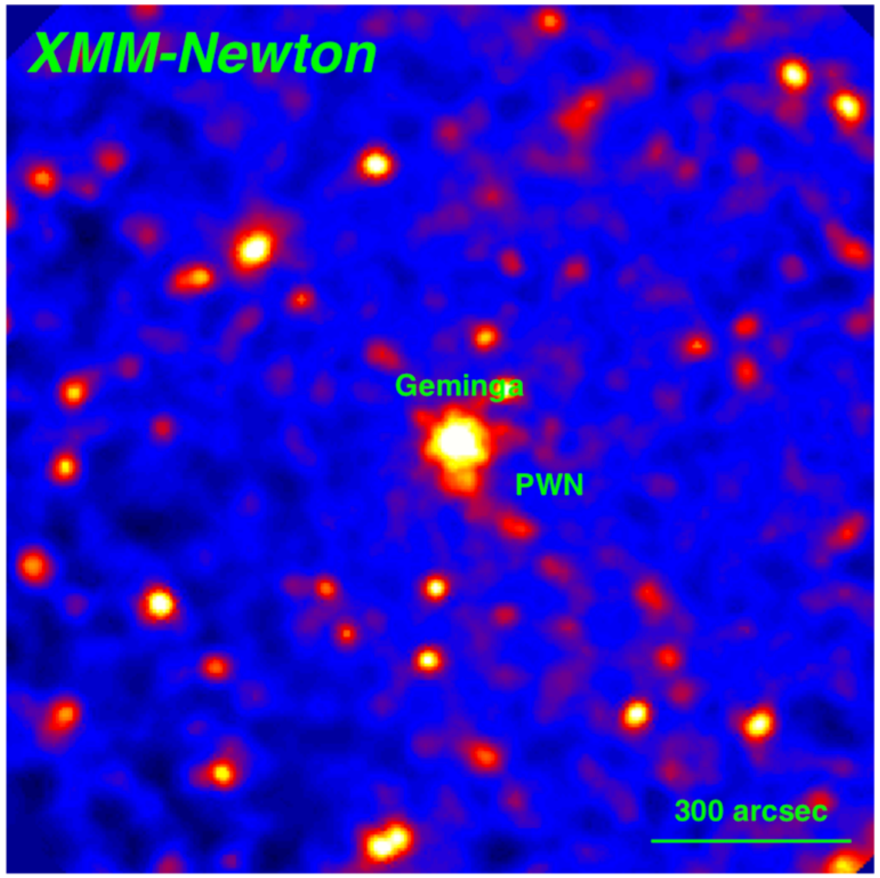
- For sources within a few kpc, sync. halos are at least of the size of one degree at radio and X-ray energies.
  - This makes the detection of these halos very challenging with current X-ray and radio telescopes.



Current observations of pulsars and PWNe in X rays



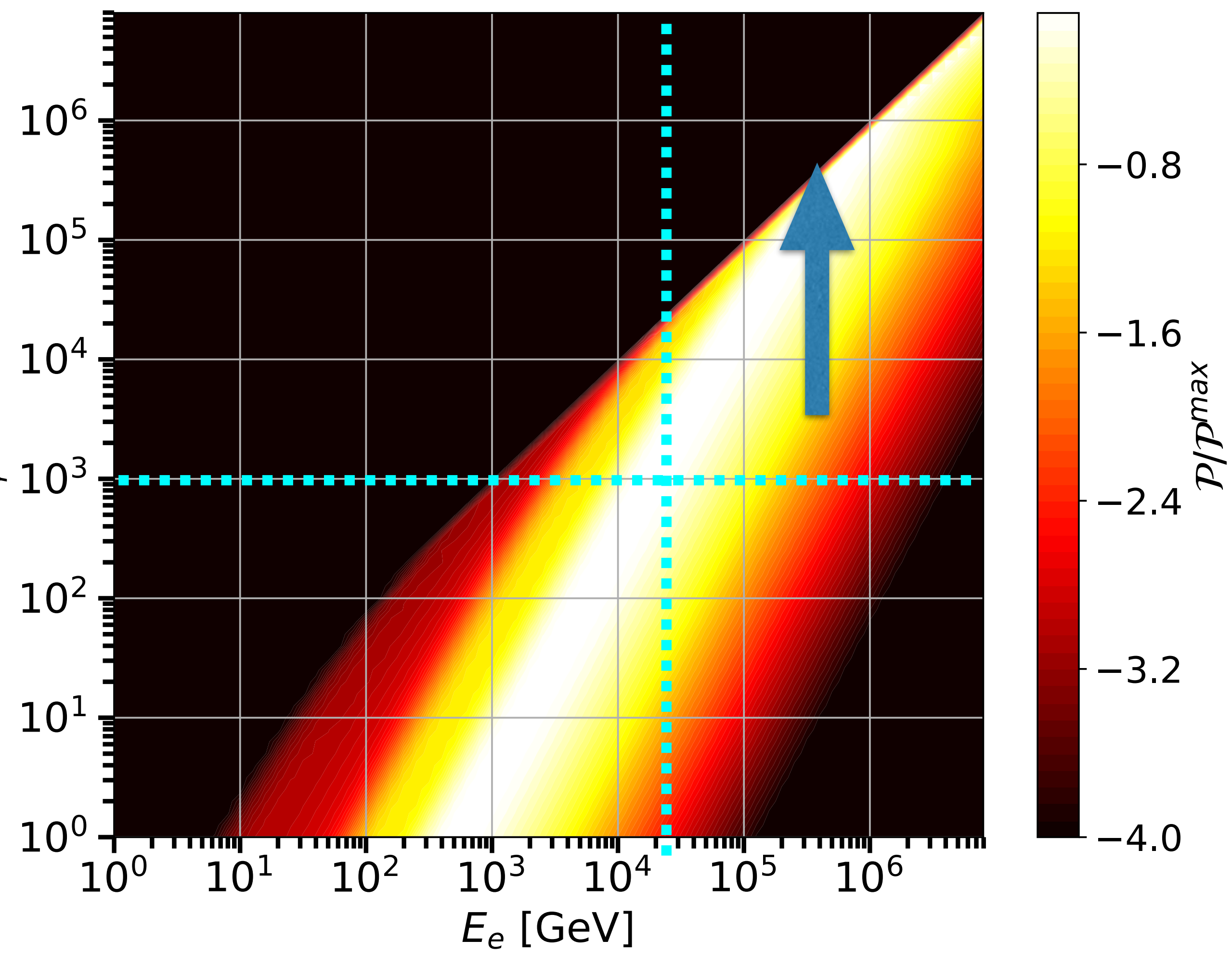


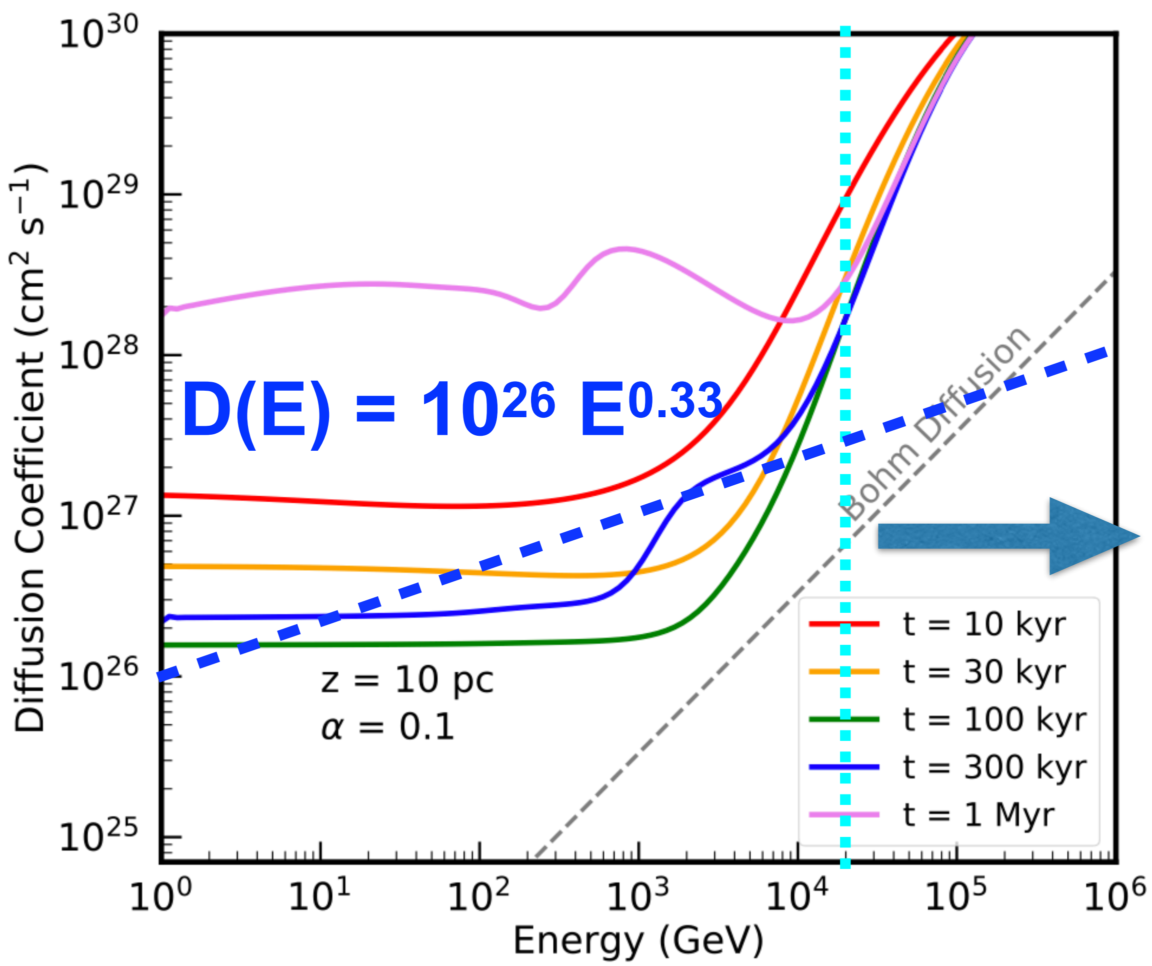


Ruo-Yu Liu et al. ApJ 875 (2019) no.2, 149

Possible theoretical interpretation

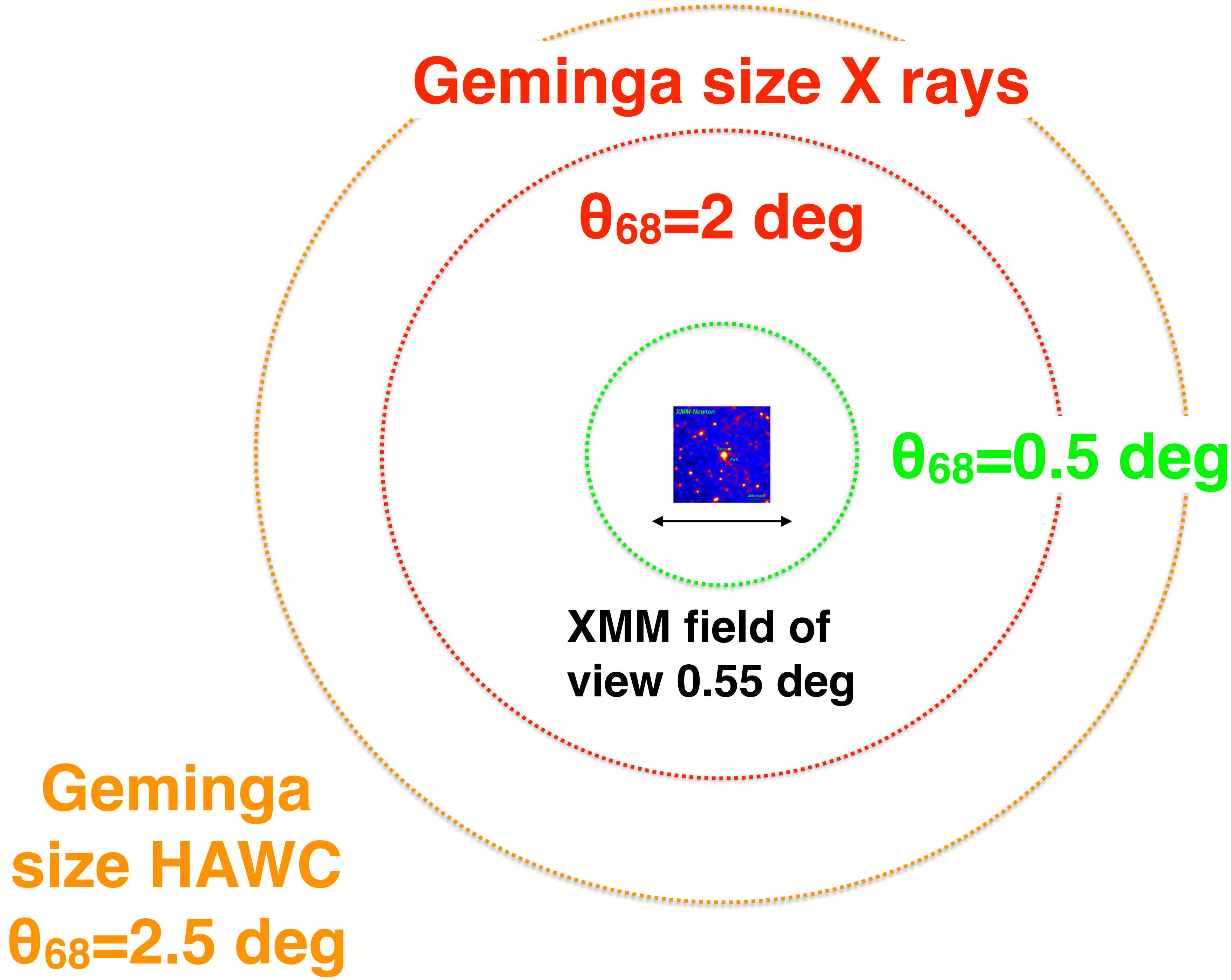
- Theoretical interpretation for inhibited diffusion is related to "*cosmic-ray gradient produced by the central source that induces a streaming stability that "self-confines" the cosmic-ray population*" (P. Mukhopadhyay, T. Linden 2022, C. Evoli, T. Linden, G. Morlino *PRD* 98 (2018) 6, 063017).
- ***The effect seems to be relevant for middle-age pulsars BUT not for TeV energies!!***





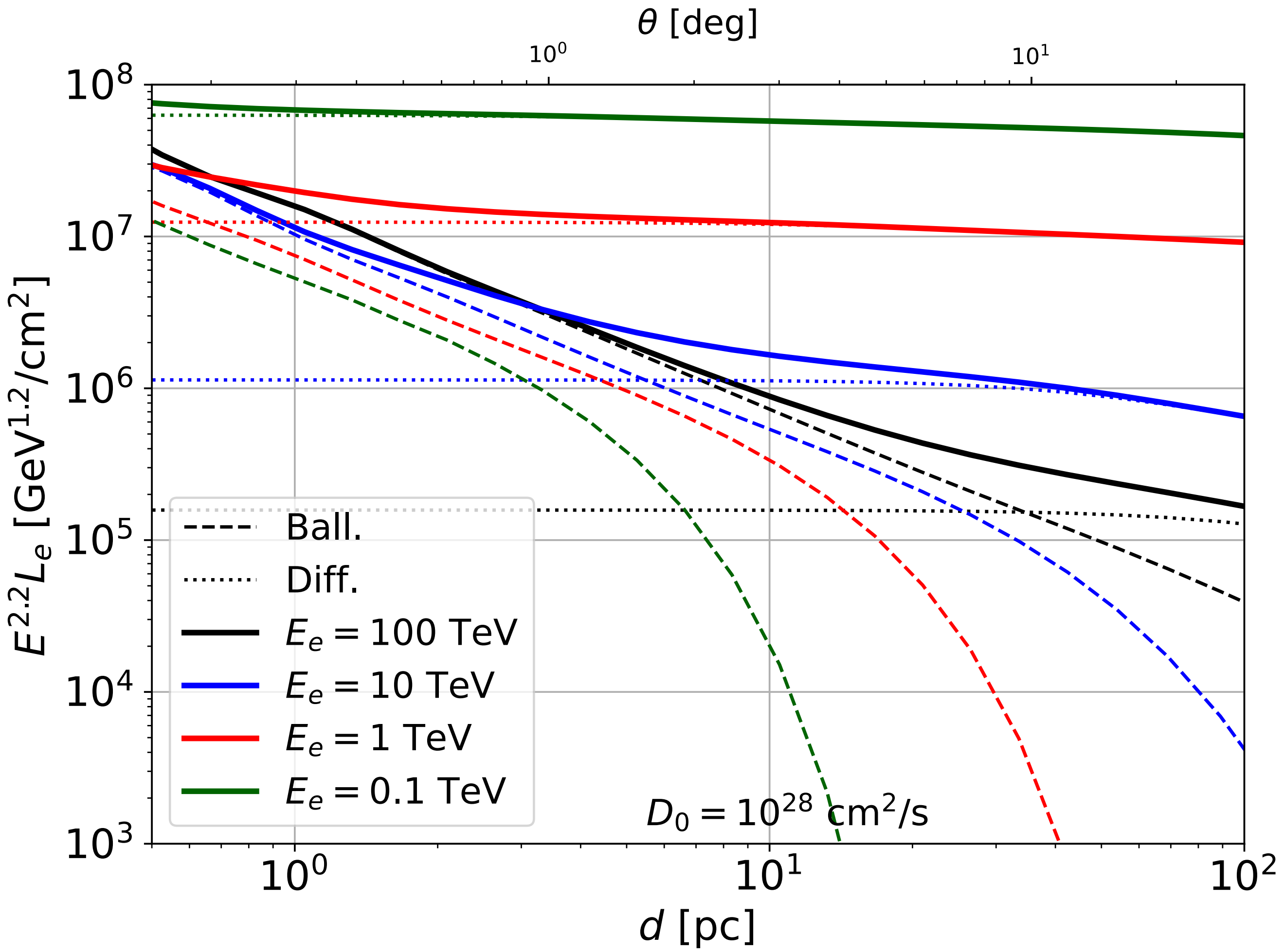
P. Mukhopadhyay, T. Linden

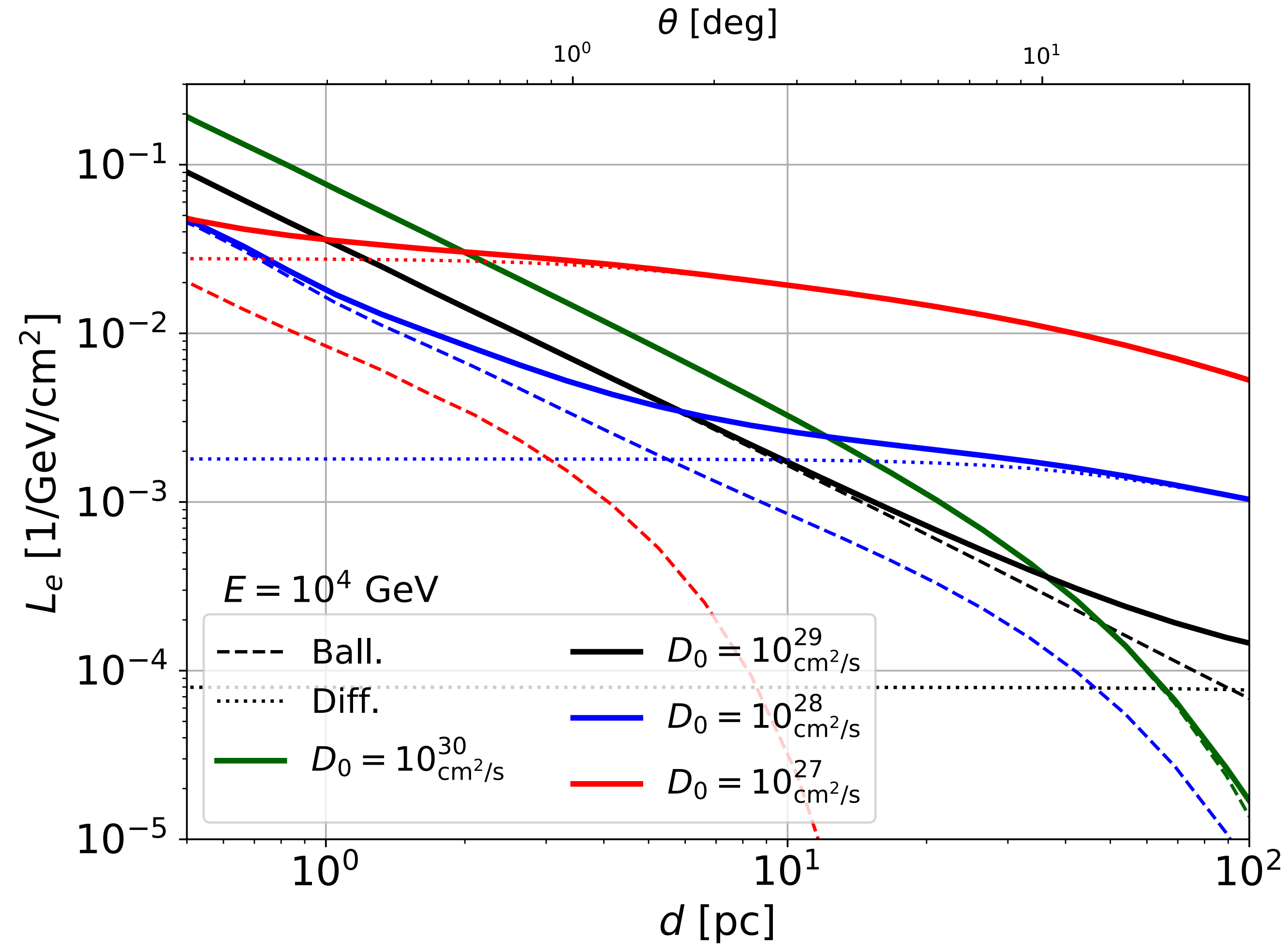
X-ray observations compared to halo size and HAWC data



Spatial distribution of propagated leptons

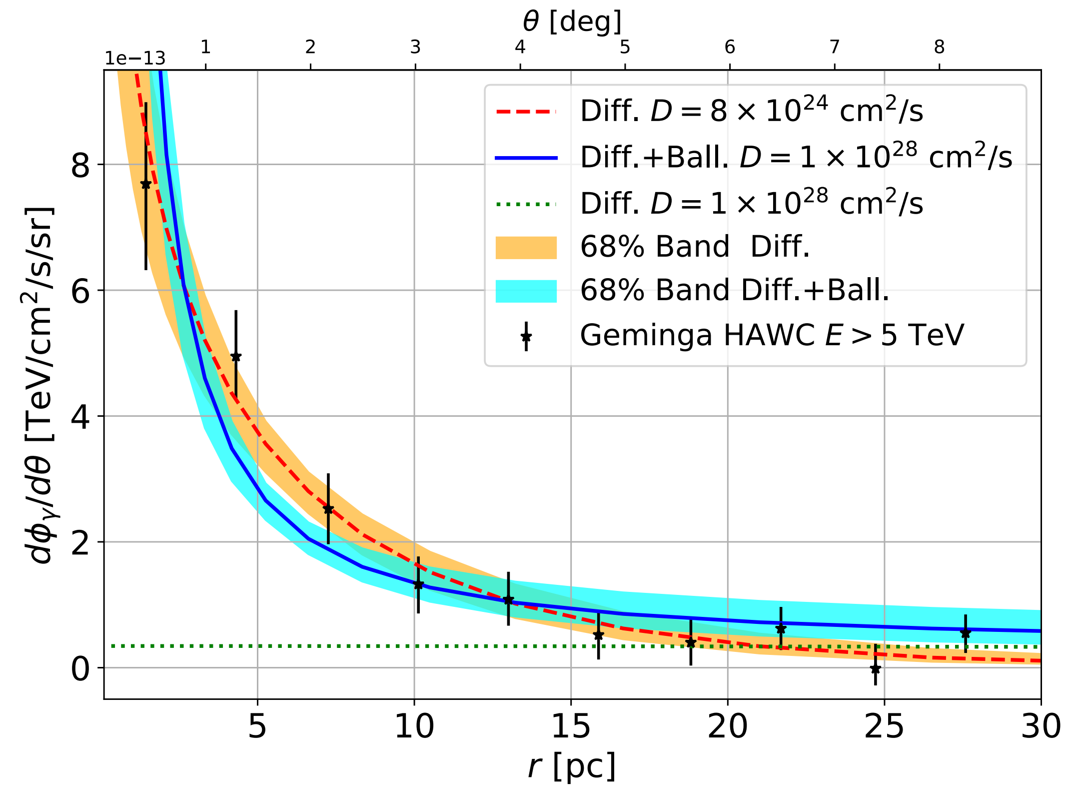
- Accounting properly for the transition between ballistic and diffusive propagation is important above TeV energies.
- For lower energies the diffusive propagation dominates the ballistic one.

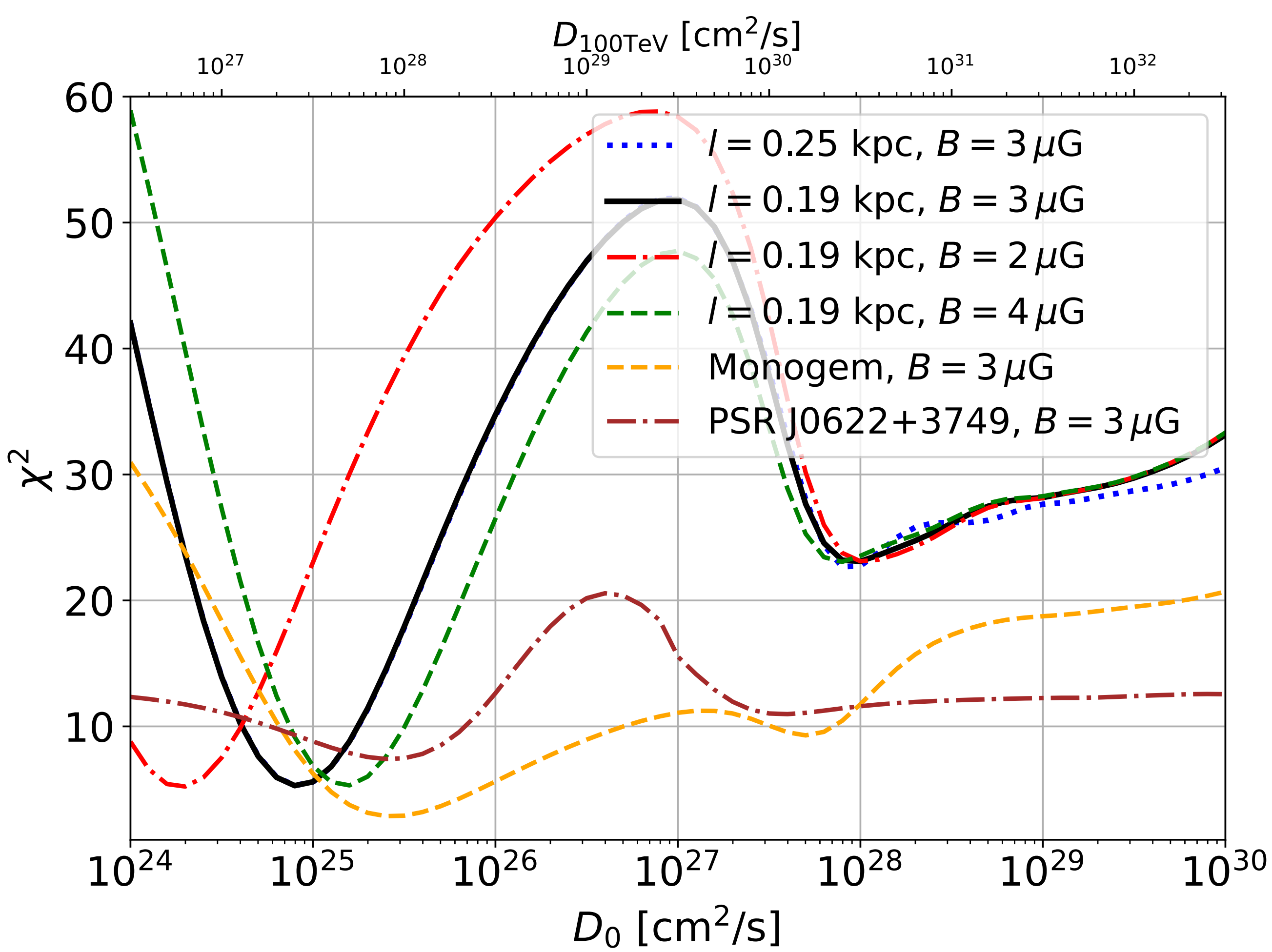


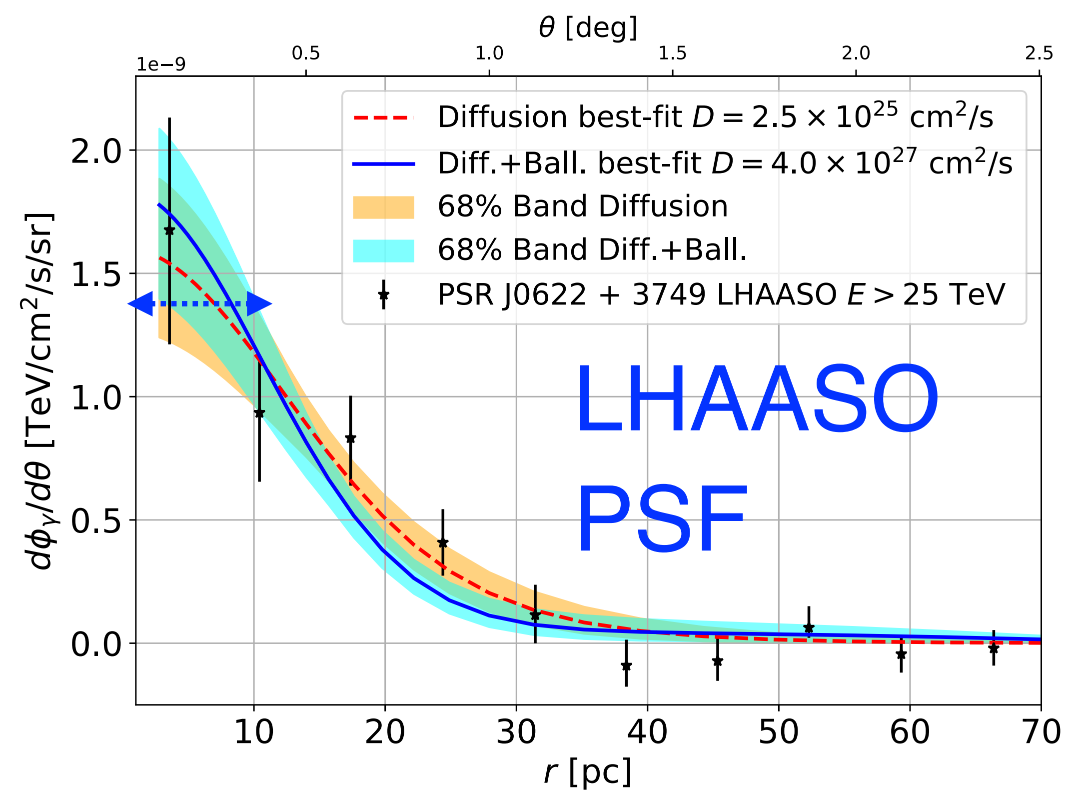


Fit to Geminga, Monogem and PSR J0622+3749 data

- The model works well for the three pulsars.
- Our model has the advantage of being very simple (Occam's Razor).
  - ***No new phenomenon or suppressed diffusion is needed.***







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Geminga SED from MeV to TeV