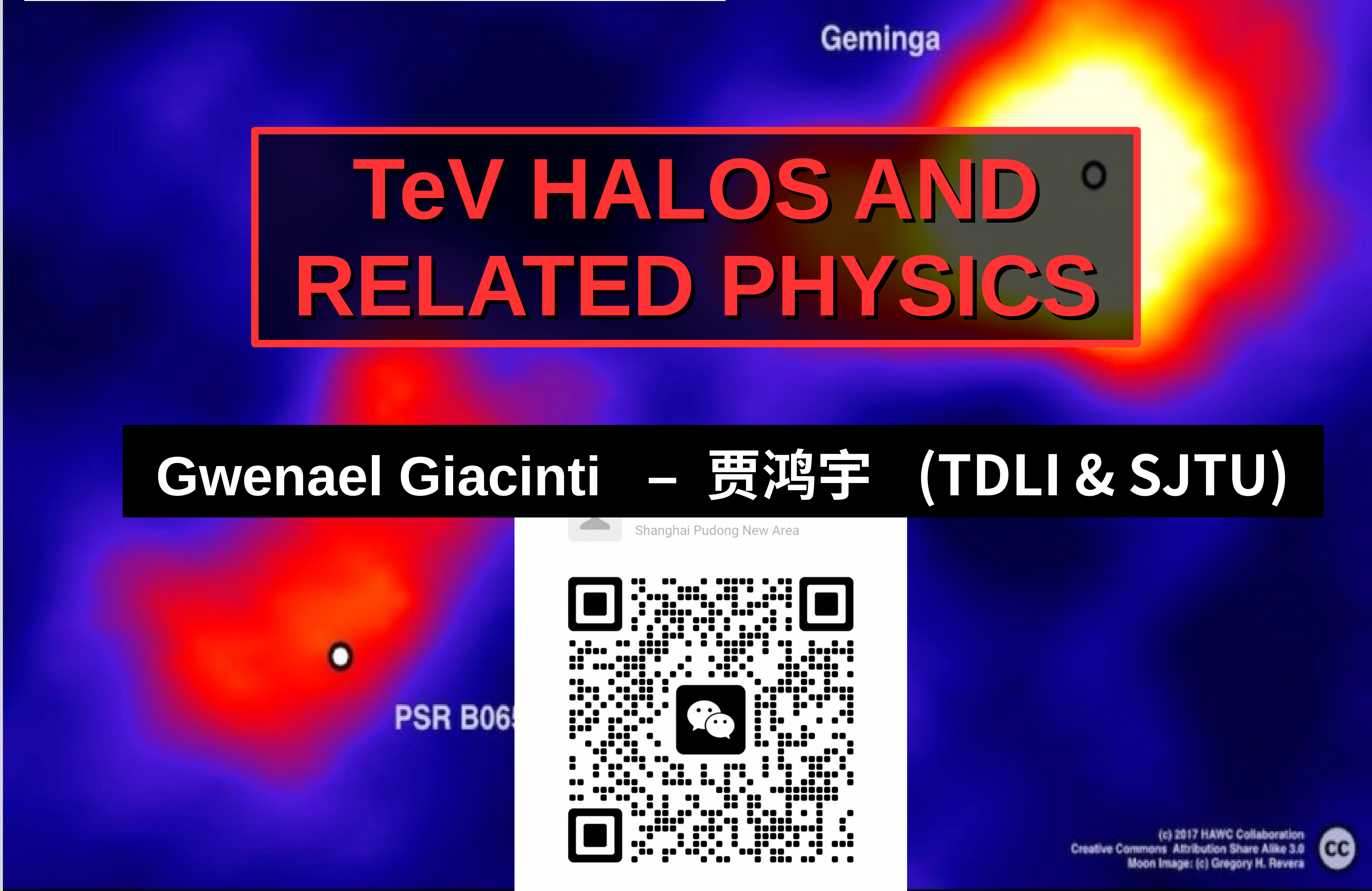
上海交通大學 SHANGHAI JIAO TONG UNIVERSITY | 李政道研究所 Tsung-Dao Lee Institute

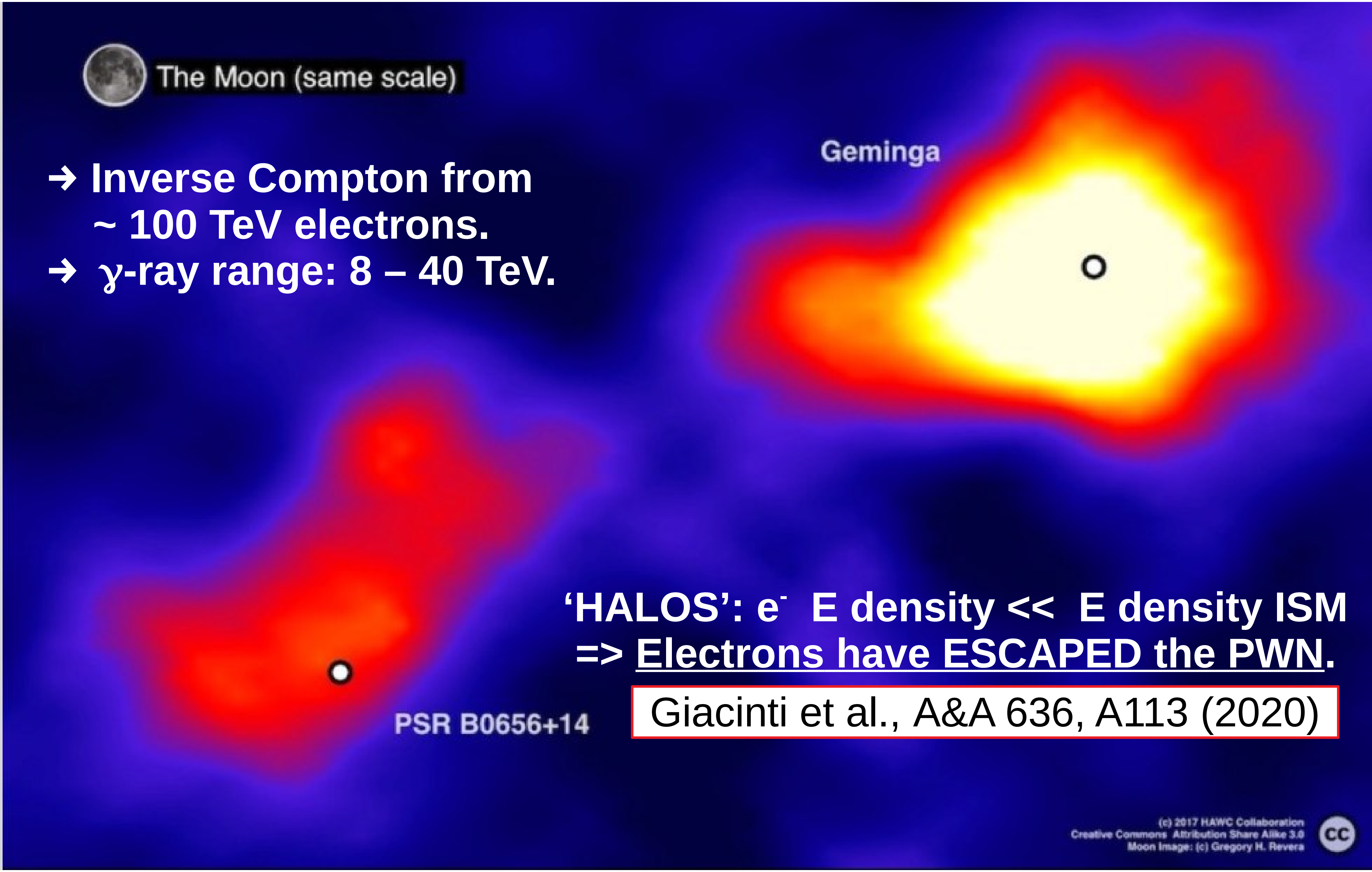
TeV HALOS AND RELATED PHYSICS

Gwenael Giacinti – 贾鸿宇 （TDLI & SJTU)



Shanghai Pudong New Area

HAWC observ. of Geminga & Monogem



➜ **Inverse Compton from ~ 100 TeV electrons.**

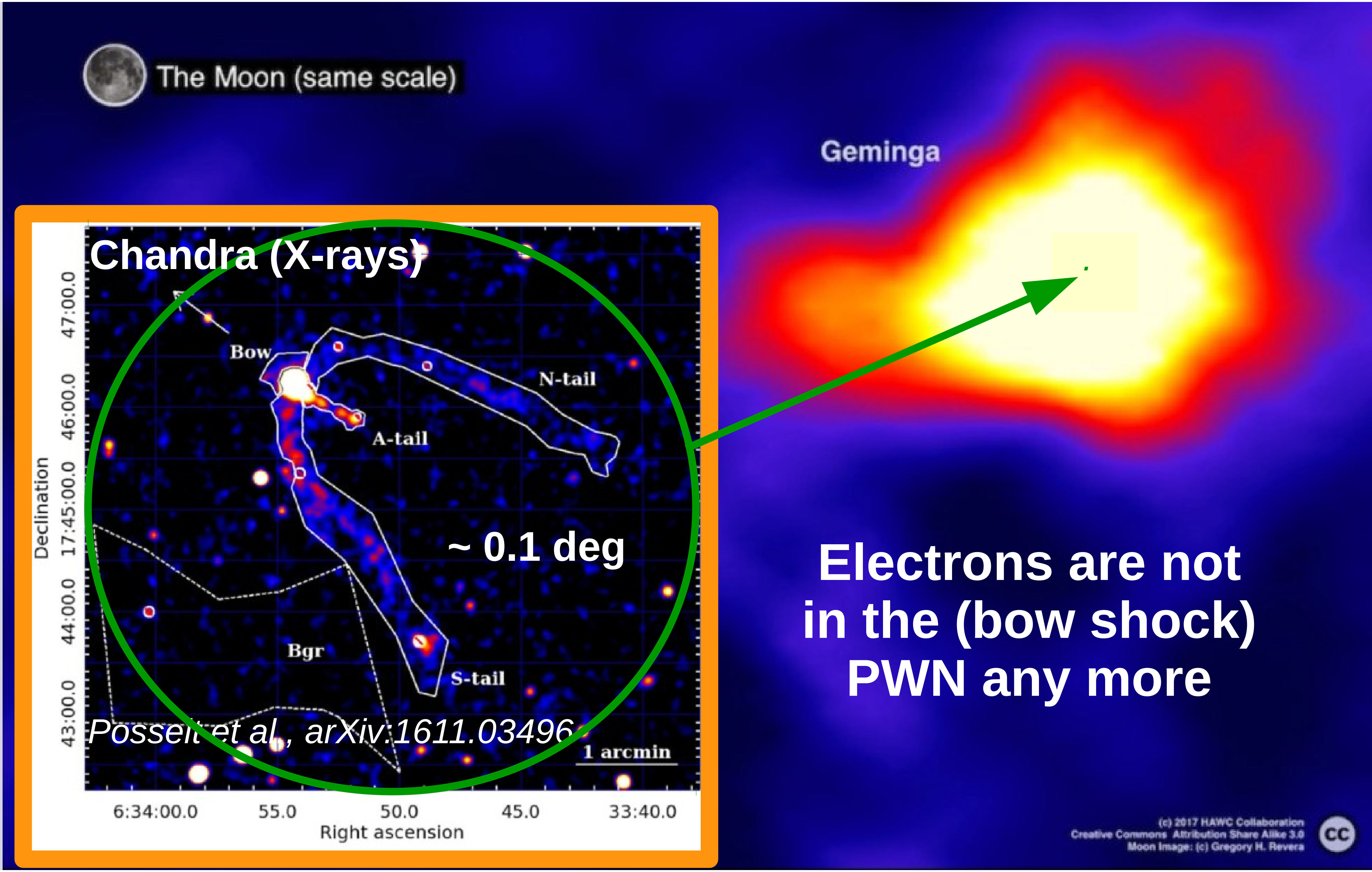
➜ **γ-ray range: 8 – 40 TeV.**

'HALOS': e^- E density << E density ISM

=> <u>Electrons have ESCAPED the PWN</u>.

Giacinti et al., A&A 636, A113 (2020)

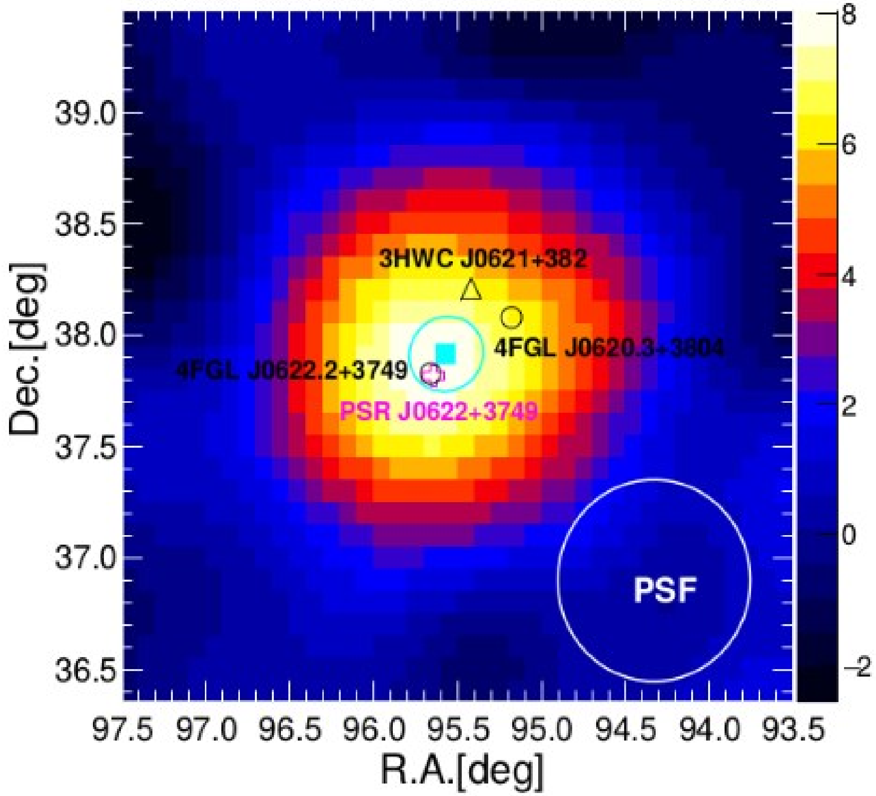
HAWC observ. of Geminga & Monogem

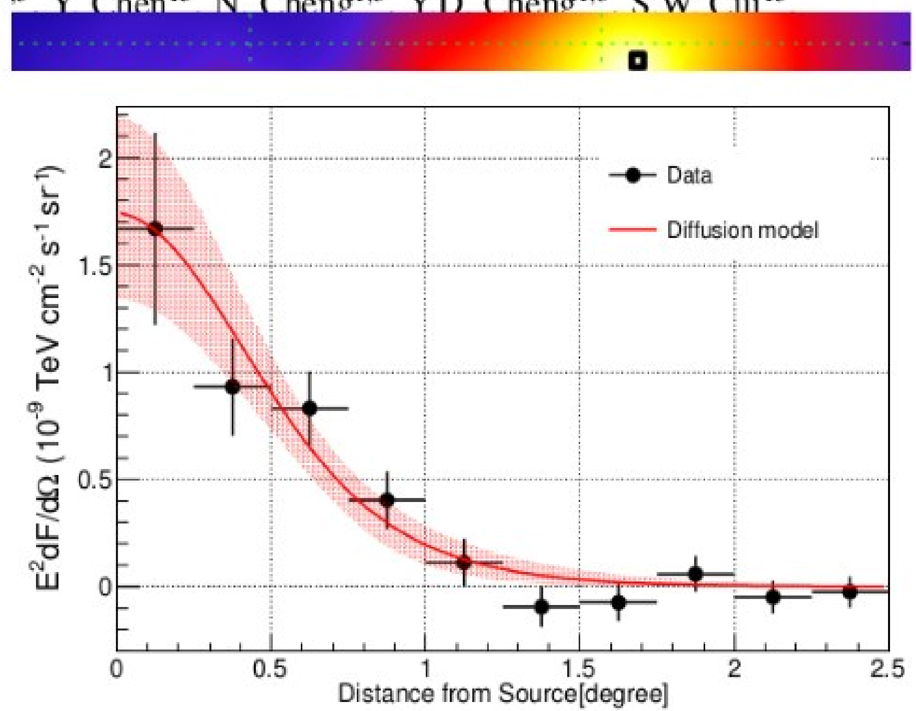


TeV Halo detected by LHAASO

Extended Very-High-Energy Gamma-ray Emission Surrounding PSR J0622 + 3749 Observed by LHAASO-KM2A

F. Aharonian[26,27], Q. An[4,5], Axikegu[20], L.X. Bai[21], Y.X. Bai[1,3], Y.W. Bao[15], D. Bastieri[10], X.J. Bi[1,2,3], Y.J. Bi[1,3], H. Cai[23], J.T. Cai[10], Z. Cao[1,2,3], Z. Cao[4,5], J. Chang[16], J.F. Chang[1,3,4], X.C. Chang[1,3],
Chen[20], M.J. Chen[1,3], M.L. Chen[1,3,4], Q.H. Chen[20],
[,3], Y. Chen[15], N. Cheng[1,3], Y.D. Cheng[1,3], S.W. Cui[13]



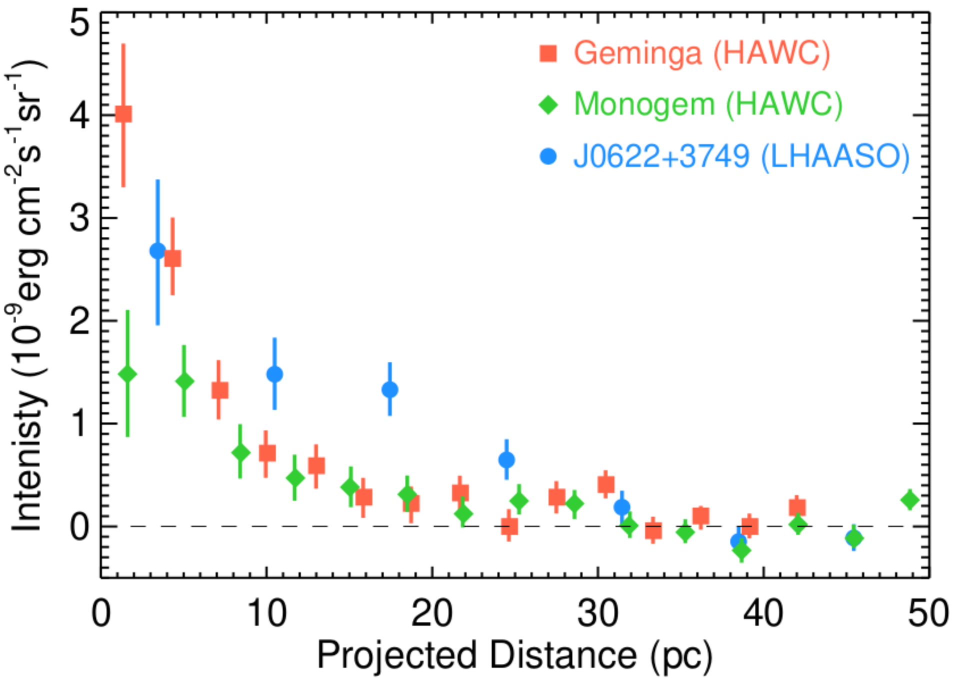


LHAASO Collaboration, PRL (2021)

Summary of firmly detected TeV Halos

Liu, IJMPA (2022)

Pulsar	P (s)	$\dot{P}$ (10^{-14})	τ_c (kyr)	d (kpc)	L_s (10^{34}erg/s)	$L_s/4\pi d^2$ (10^{-10}erg/cm^{2}s)
PSR J0633+1746[a]	0.237	1.097	342	0.25[c]	3.2	43
PSR B0656+14[b]	0.385	5.494	111	0.29	3.8	38
PSR J0622+3749	0.333	2.542	208	1.6[d]	2.7	0.88



PWNe & Potential TeV Halos in LHAASO Catalogue

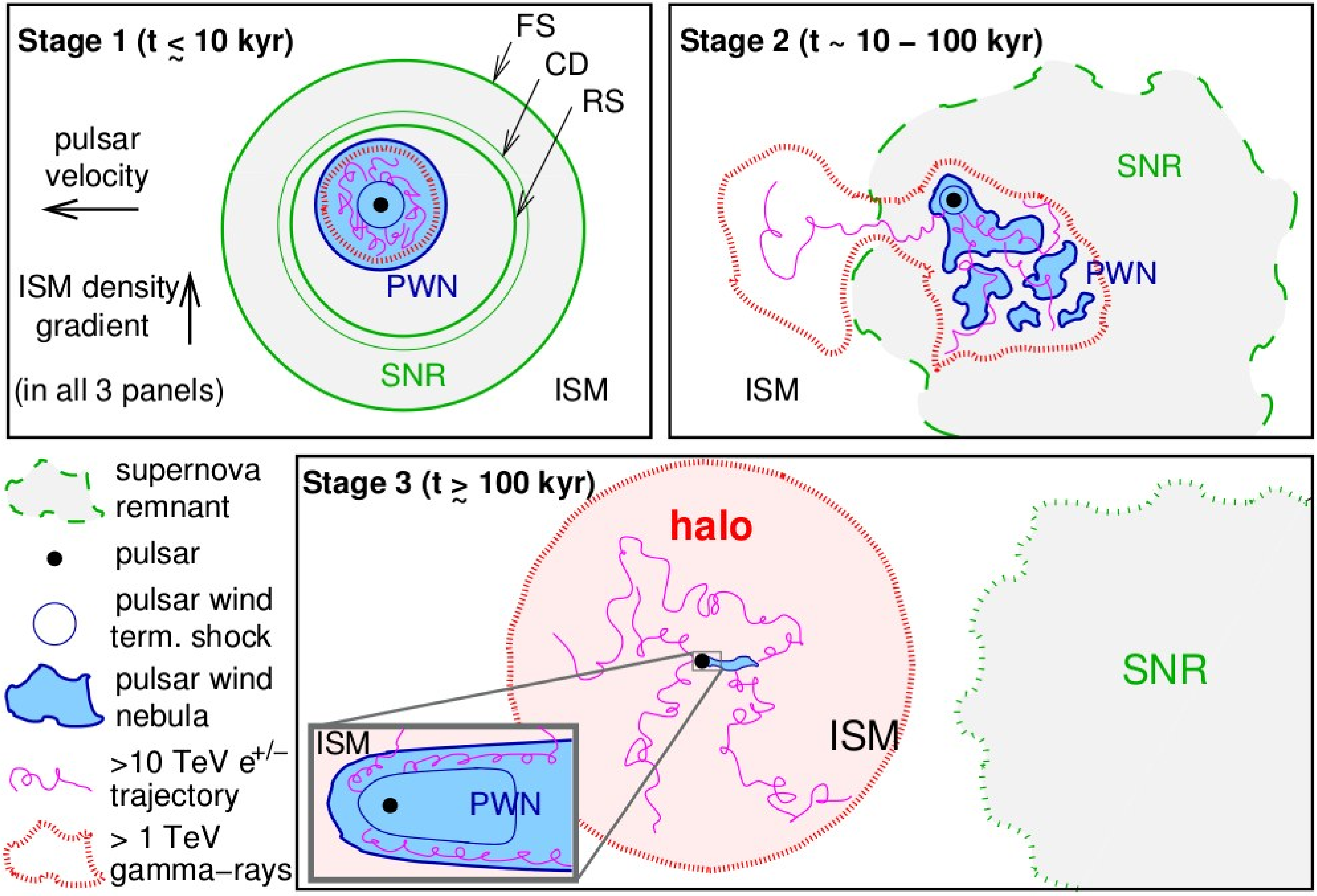
Table 4. 1LHAASO sources associated pulsars

Source name	PSR name	Sep.(°)	d (kpc)	τ_c (kyr)	$\dot{E}$ (erg s^{-1})	P_c	Identified type in TeVCat
1LHAASO J0007+7303u	PSR J0007+7303	0.05	1.40	14	4.5e+35	7.3e-05	PWN
1LHAASO J0216+4237u	PSR J0218+4232	0.33	3.15	476000	2.4e+35	3.6e-03	
1LHAASO J0249+6022	PSR J0248+6021	0.16	2.00	62	2.1e+35	1.5e-03	
1LHAASO J0359+5406	PSR J0359+5414	0.15	-	75	1.3e+36	7.2e-04	
1LHAASO J0534+2200u	PSR J0534+2200	0.01	2.00	1	4.5e+38	3.2e-06	PWN
1LHAASO J0542+2311u	PSR J0543+2329	0.30	1.56	253	4.1e+34	8.3e-03	
1LHAASO J0622+3754	PSR J0622+3749	0.09	-	208	2.7e+34	2.5e-04	PWN/TeV Halo
1LHAASO J0631+1040	PSR J0631+1037	0.11	2.10	44	1.7e+35	3.5e-04	PWN
1LHAASO J0634+1741u	PSR J0633+1746	0.12	0.19	342	3.3e+34	1.3e-03	PWN/TeV Halo
1LHAASO J0635+0619	PSR J0633+0632	0.39	1.35	59	1.2e+35	9.4e-03	
1LHAASO J1740+0948u	PSR J1740+1000	0.21	1.23	114	2.3e+35	1.4e-03	
1LHAASO J1809-1918u	PSR J1809-1917	0.05	3.27	51	1.8e+36	6.2e-04	
1LHAASO J1813-1245	PSR J1813-1245	0.01	2.63	43	6.2e+36	6.3e-06	
1LHAASO J1825-1256u	PSR J1826-1256	0.09	1.55	14	3.6e+36	1.6e-03	
1LHAASO J1825-1337u	PSR J1826-1334	0.11	3.61	21	2.8e+36	2.8e-03	PWN/TeV Halo
1LHAASO J1837-0654u	PSR J1838-0655	0.12	6.60	23	5.6e+36	2.2e-03	PWN
1LHAASO J1839-0548u	PSR J1838-0537	0.20	-	5	6.0e+36	6.1e-03	
1LHAASO J1848-0001u	PSR J1849-0001	0.06	-	43	9.8e+36	1.2e-04	PWN
1LHAASO J1857+0245	PSR J1856+0245	0.16	6.32	21	4.6e+36	3.1e-03	PWN
1LHAASO J1906+0712	PSR J1906+0722	0.19	-	49	1.0e+36	5.9e-03	
1LHAASO J1908+0615u	PSR J1907+0602	0.23	2.37	20	2.8e+36	6.8e-03	
1LHAASO J1912+1014u	PSR J1913+1011	0.13	4.61	169	2.9e+36	1.5e-03	
1LHAASO J1914+1150u	PSR J1915+1150	0.09	14.01	116	5.4e+35	1.8e-03	
1LHAASO J1928+1746u	PSR J1928+1746	0.04	4.34	83	1.6e+36	1.6e-04	
1LHAASO J1929+1846u	PSR J1930+1852	0.29	7.00	3	1.2e+37	2.6e-03	PWN
1LHAASO J1954+2836u	PSR J1954+2836	0.01	1.96	69	1.1e+36	1.6e-05	PWN
1LHAASO J1954+3253	PSR J1952+3252	0.33	3.00	107	3.7e+36	6.7e-03	
1LHAASO J1959+2846u	PSR J1958+2845	0.10	1.95	22	3.4e+35	2.8e-03	PWN
1LHAASO J2005+3415	PSR J2004+3429	0.25	10.78	18	5.8e+35	9.9e-03	
1LHAASO J2005+3050	PSR J2006+3102	0.20	6.04	104	2.2e+35	9.2e-03	
1LHAASO J2020+3649u	PSR J2021+3651	0.05	1.80	17	3.4e+36	1.5e-04	PWN
1LHAASO J2028+3352	PSR J2028+3332	0.36	-	576	3.5e+34	8.0e-03	
1LHAASO J2031+4127u	PSR J2032+4127	0.08	1.33	201	1.5e+35	1.0e-03	PWN
1LHAASO J2228+6100u	PSR J2229+6114	0.27	3.00	10	2.2e+37	2.2e-03	PWN
1LHAASO J2238+5900	PSR J2238+5903	0.07	2.83	27	8.9e+35	3.0e-04	

LHAASO Collaboration, ApJS 271, 25 (2024)

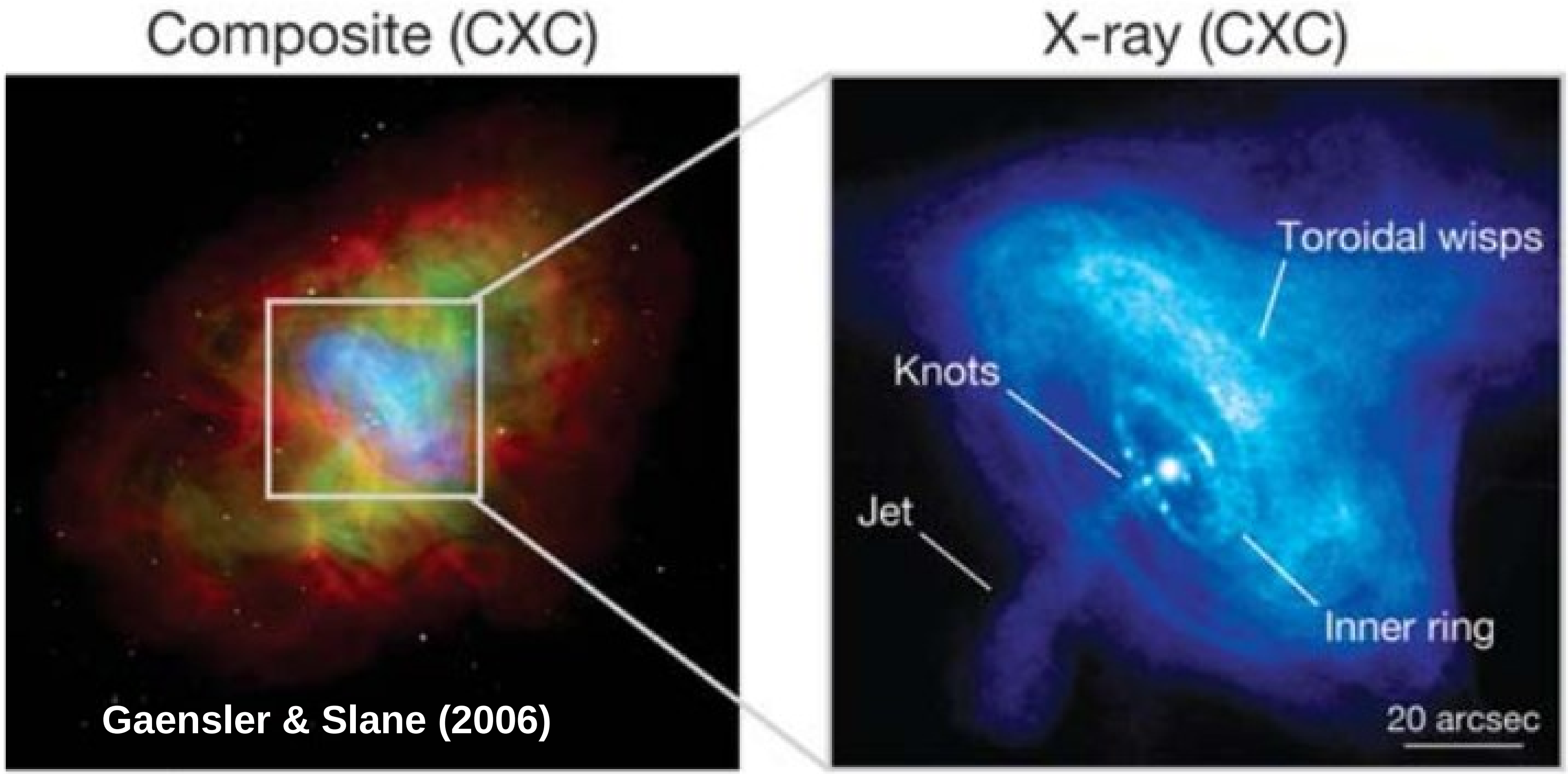
Evolutionary stages of a PWN :

Giacinti, Mitchell, Lopez-Coto, Joshi, Parsons & Hinton, A&A 636, A113 (2020), arXiv:1907.12121:



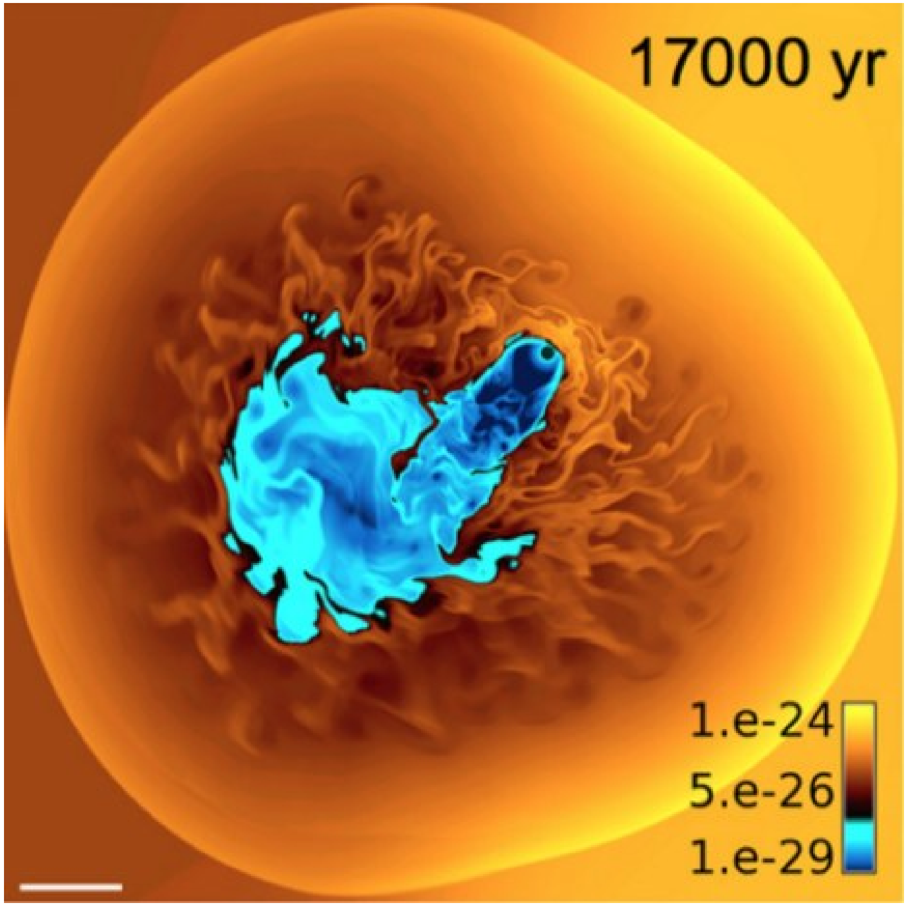
Evolutionary stages of a PWN :

Stage 1 : e.g. Crab Nebula (0.94 kyr)



Evolutionary stages of a PWN :

Stage 2 : e.g. G327.1-1.1 (17 kyr)

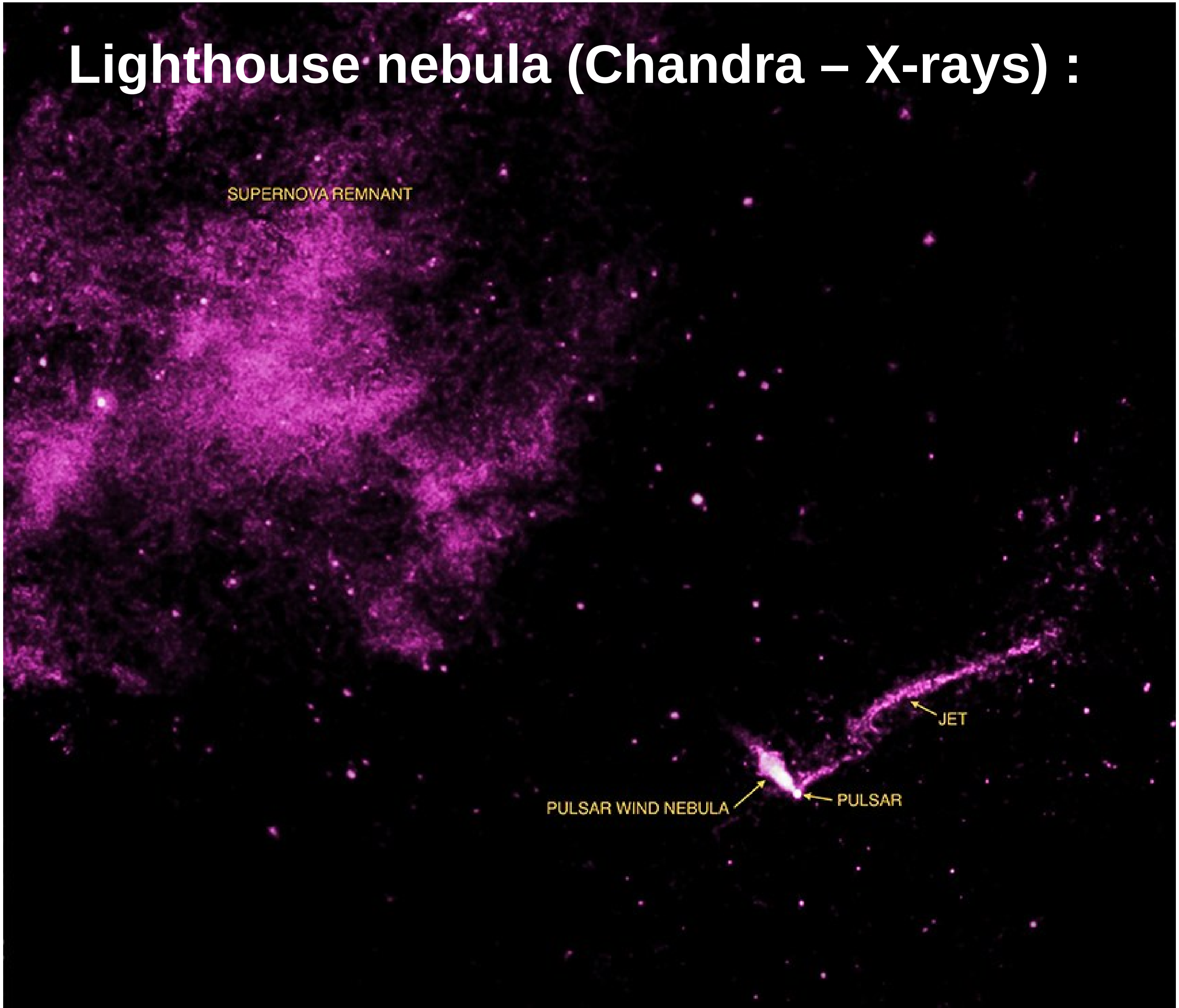


Simulation -Temim et al. (2015)

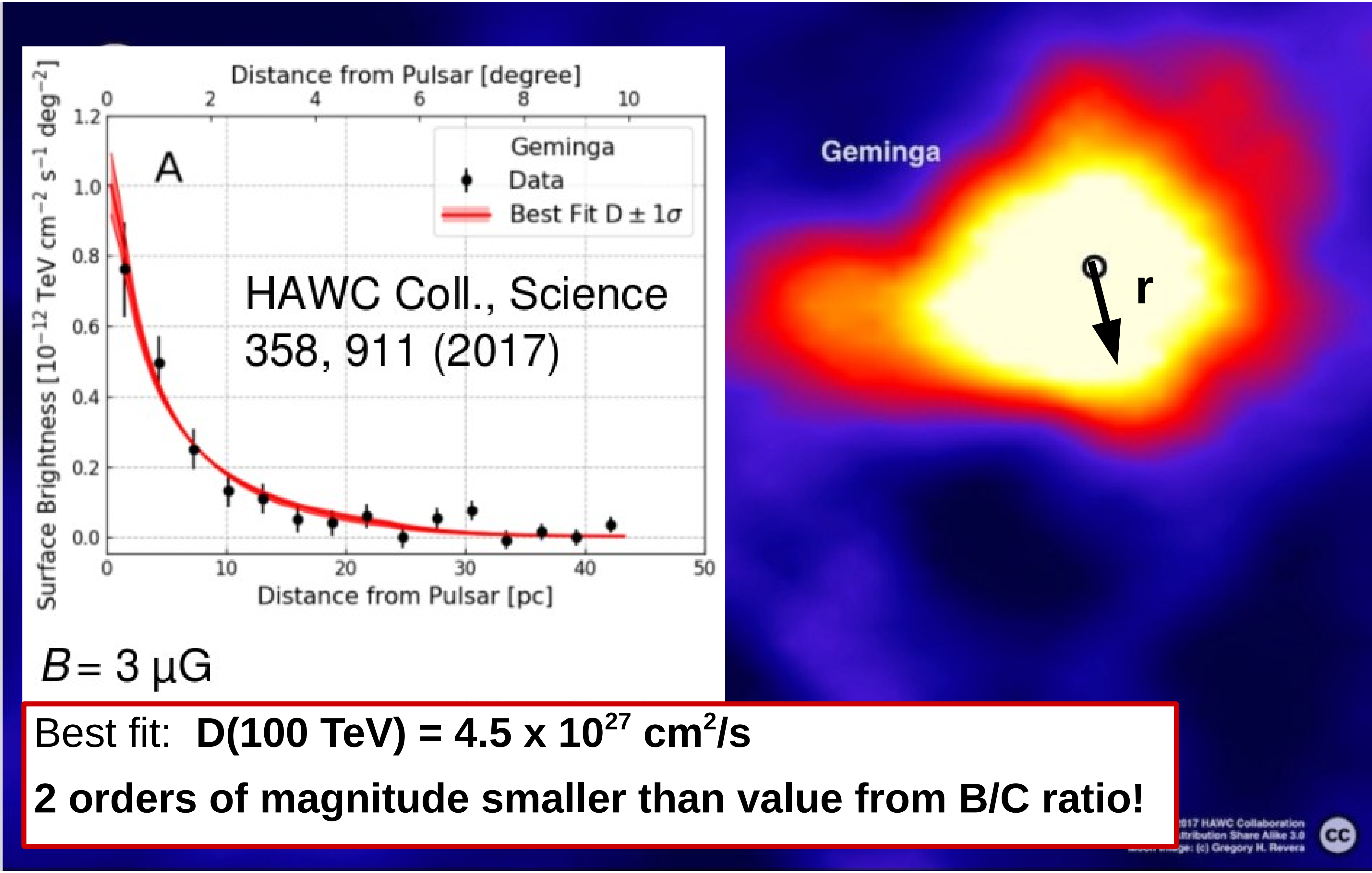
Evolutionary stages of a PWN :

Stage 3

Lighthouse nebula (Chandra – X-rays) :



TeV Halos as probes of ISMF properties

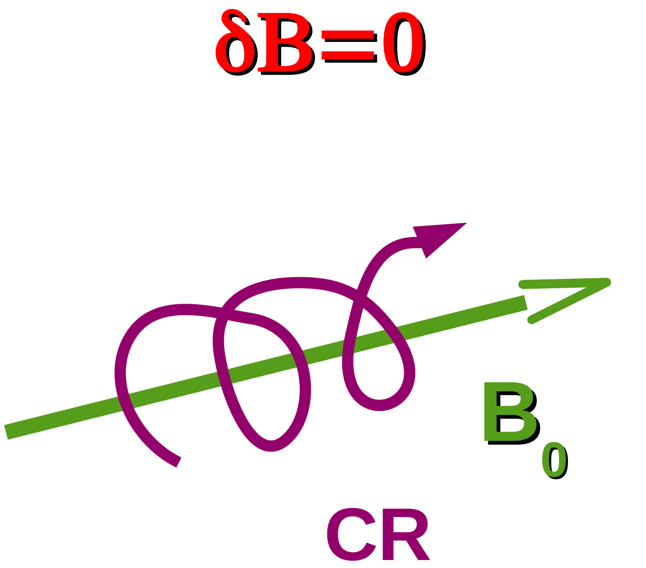


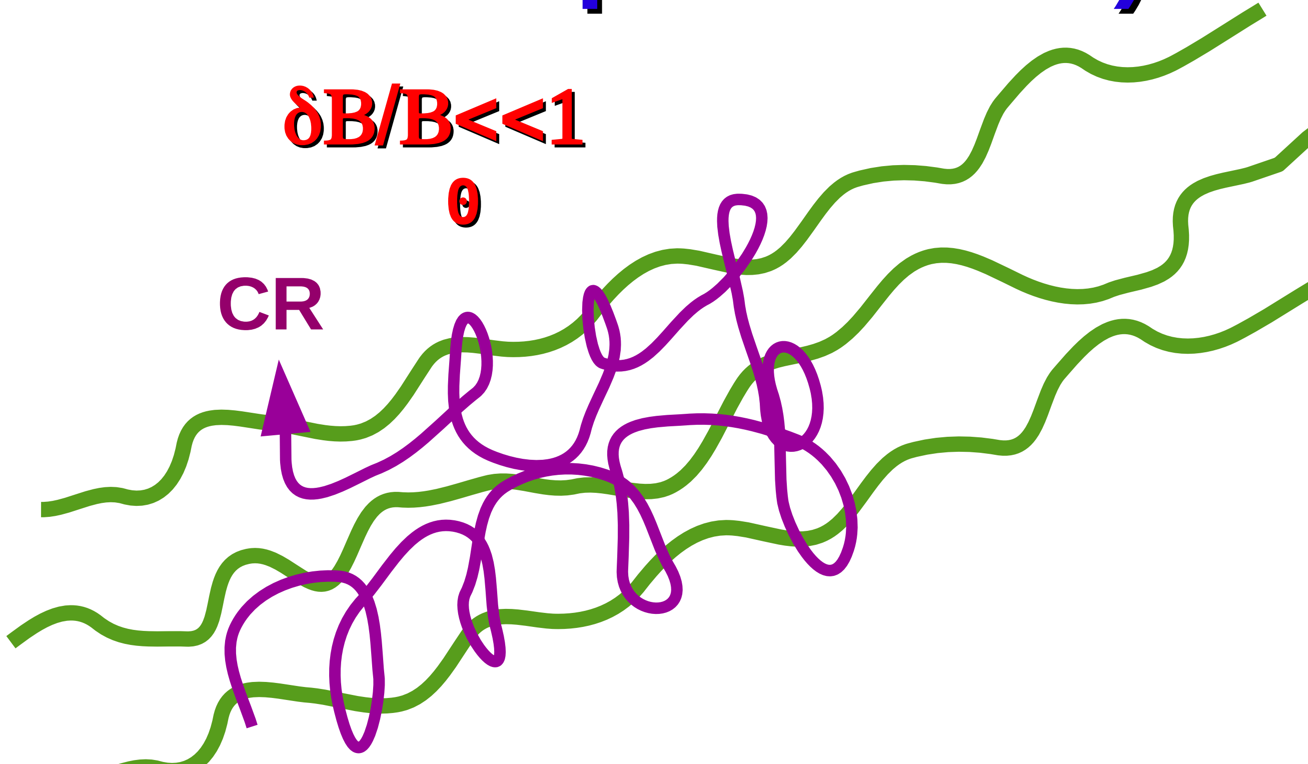
$B = 3\ \mu G$

Best fit: **D(100 TeV) = 4.5 x 10^{27} cm^2/s**

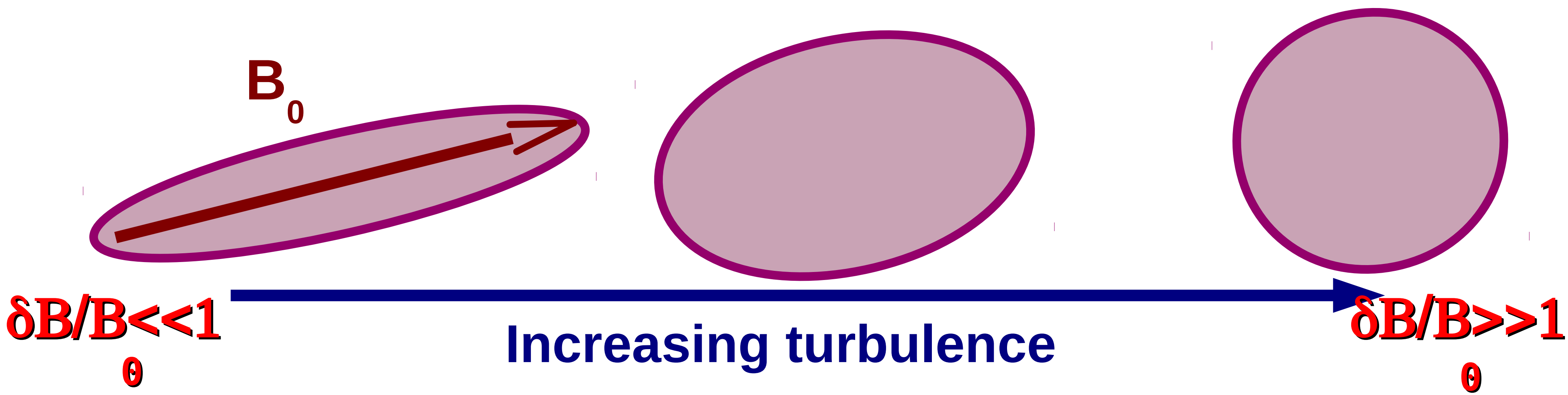
2 orders of magnitude smaller than value from B/C ratio!

CR diffusion (Parallel/Perpendicular)

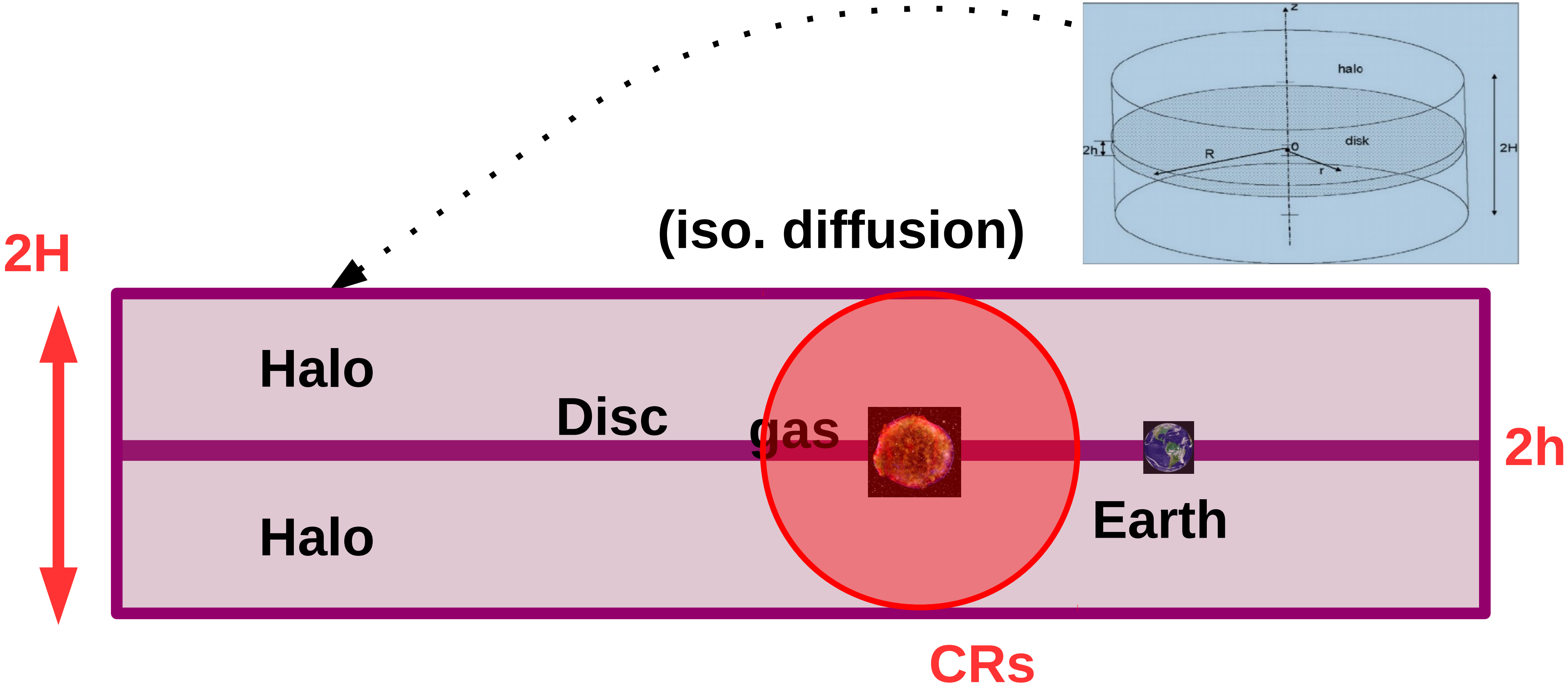




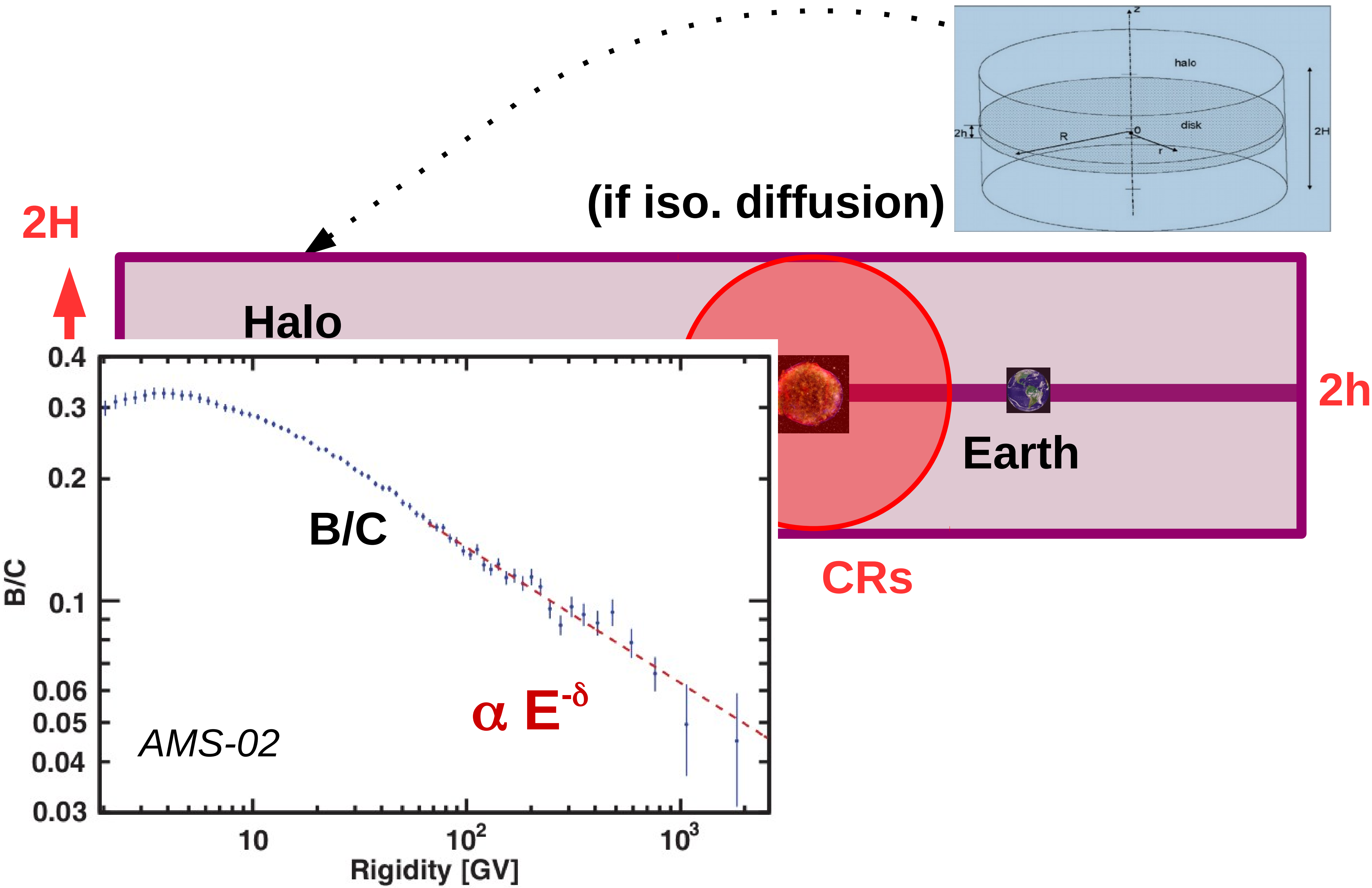
Iso turbulence with power-law spectrum → D(E) α E$^{\delta}$



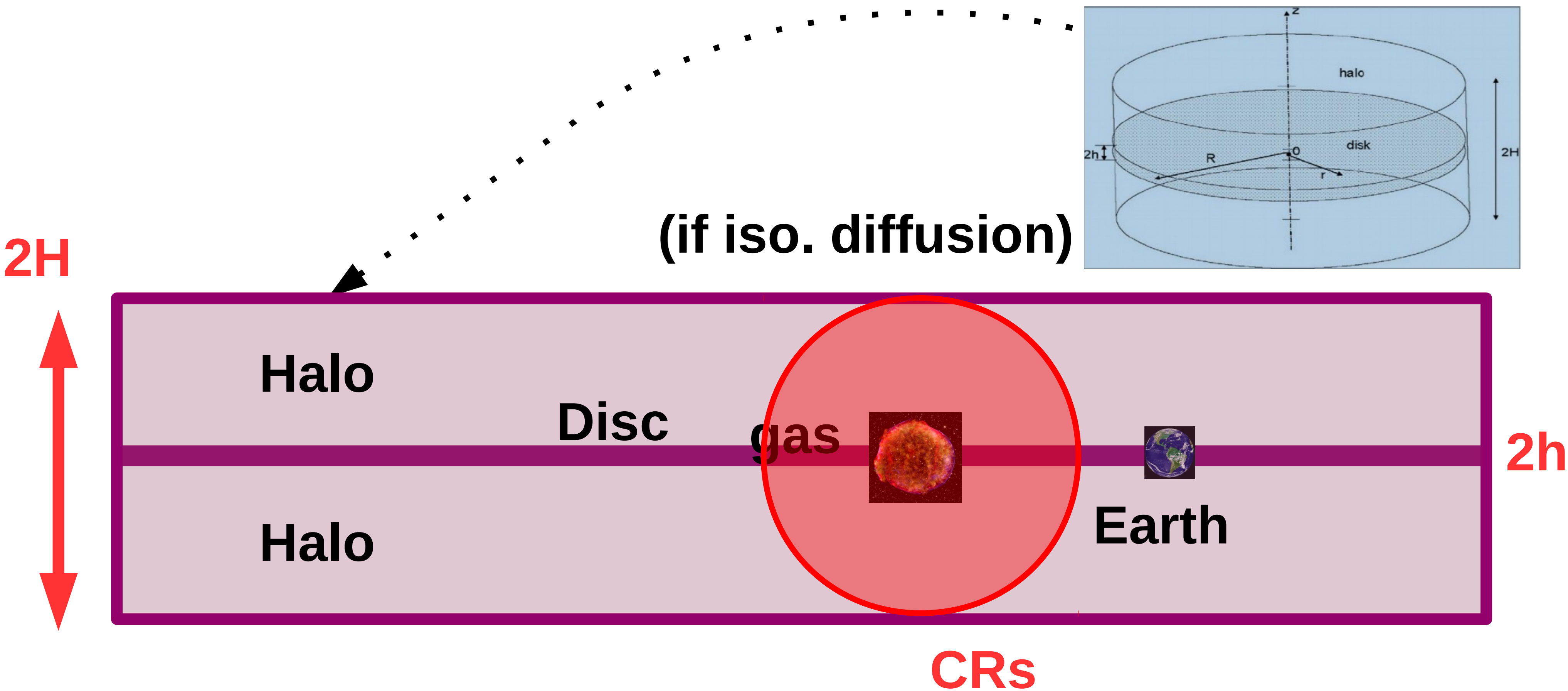
Simplified Milky Way seen edge-on :



Simplified Milky Way seen edge-on :



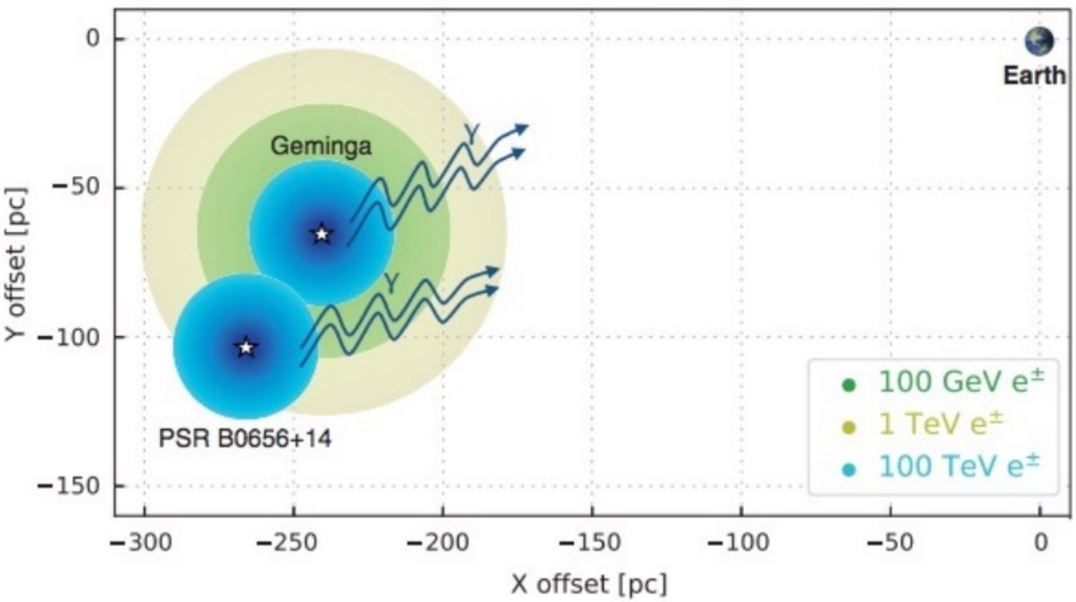
Simplified Milky Way seen edge-on :

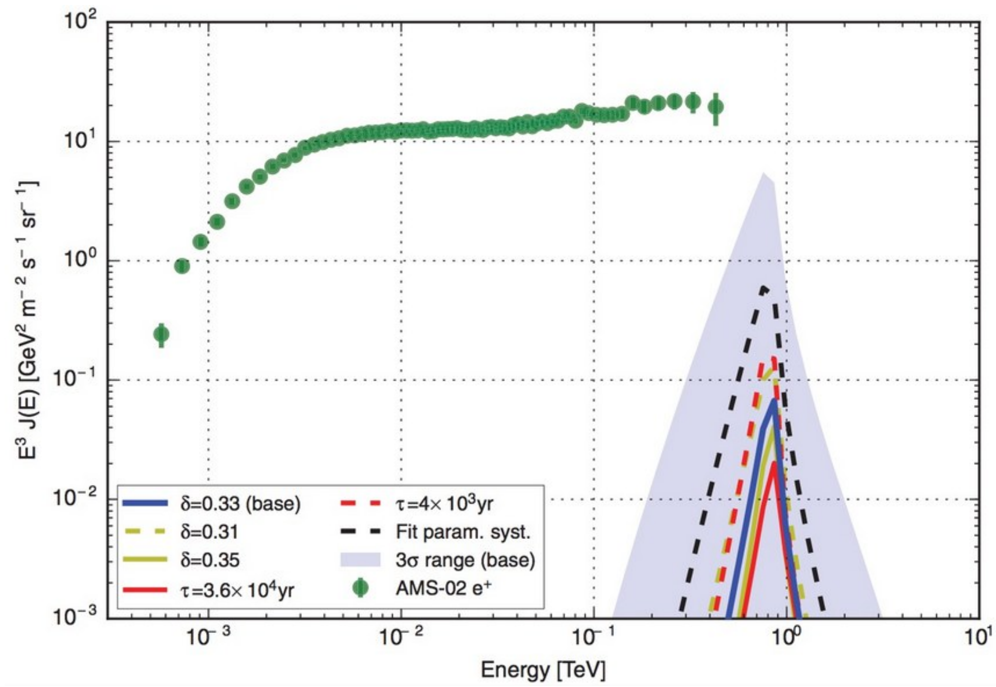


Grammage : $X = c\rho h H / D_z$ ~ several g/cm² at GeV

D ~ 10^{28} cm²/s at GeV **for H ~ several kpc**

HAWC Coll., Science 358, 911 (2017)





Assuming the same D in our local environment, Geminga and Monogem cannot explain the local positron flux.

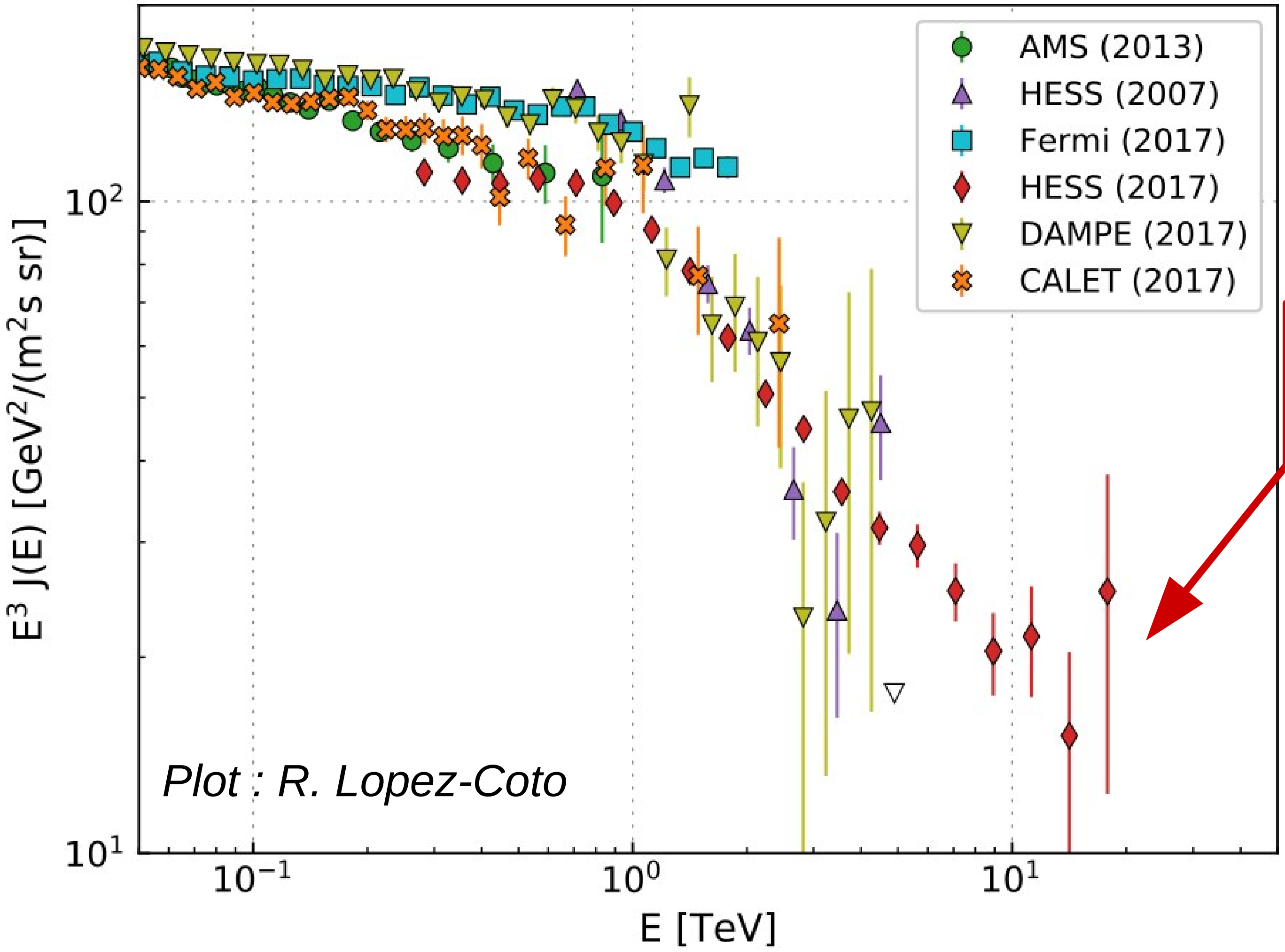
Di Mauro et al.(2019): GeV halo around Geminga (Fermi) → <20% e^+ flux.

Problems to solve :

→ How can we now explain the B/C ratio ?
→ How can we now explain electron and positron spectra at Earth ?

H.E.S.S. (2017) all-electron spectrum

Power-law between 1 and 20 TeV. Index ~ 3.8

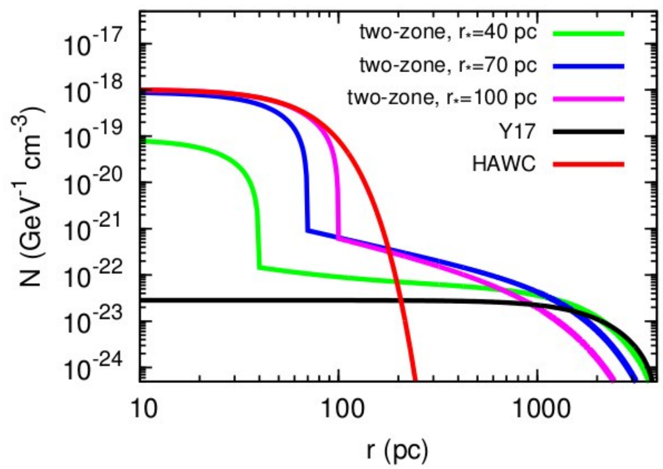


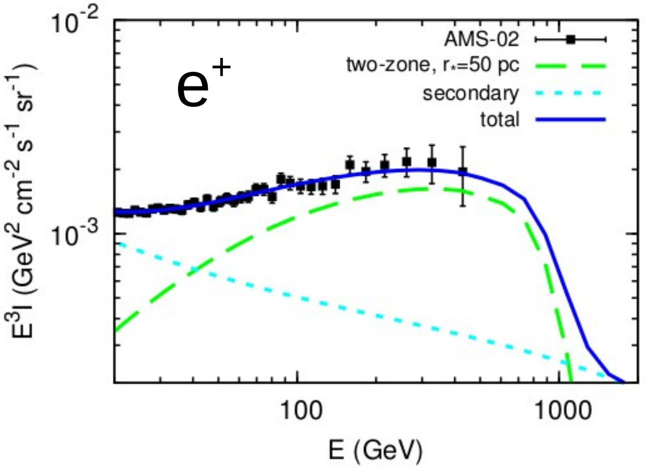
cooling time
~ 10 kyr !

Hooper & Linden (2018): **Cannot be explained with known pulsars** and HAWC's D coeff. => Slow diffusion regions must be small.

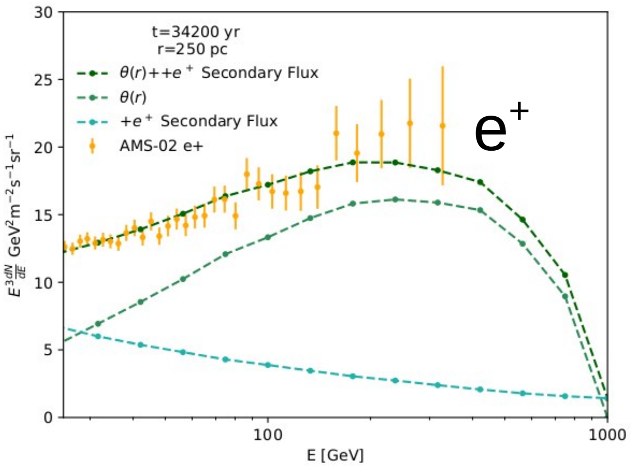
Possible solutions :

→ **Two-zone models**: - *Fang et al. (2018)* :





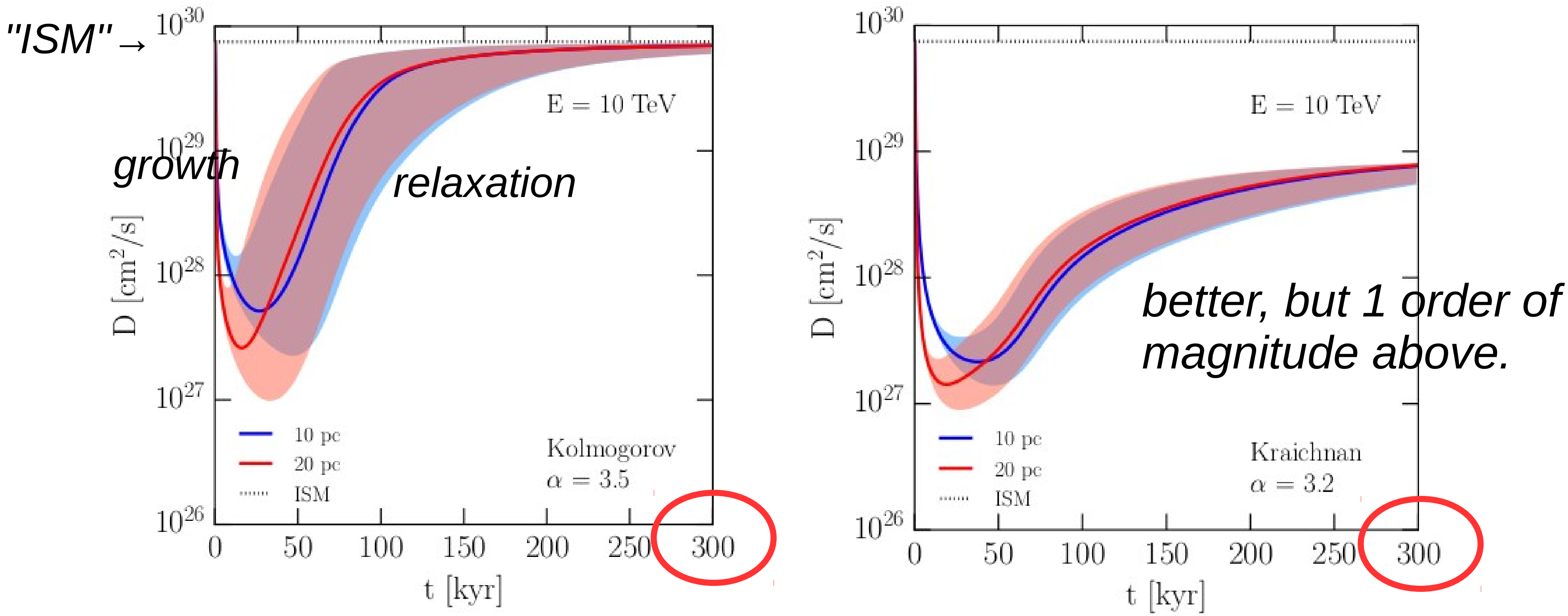
- *Profumo et al. (2018)* :



→ Small pocket of reduced D, then larger D outside

→ "likely still within the PWN." ???

Evoli, Linden & Morlino (2018): Alfven waves from escaping **e**$^{+/-}$ generate a region of low D around pulsars

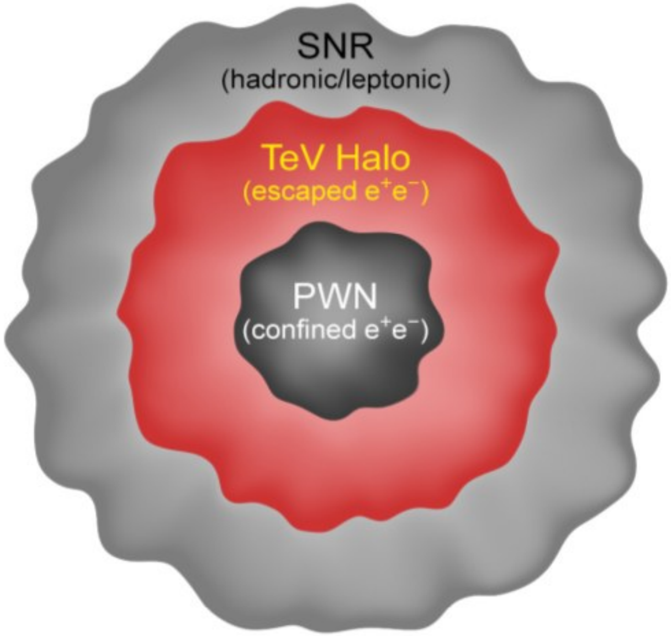


=> Relaxes too rapidly to confine e^{-} around Geminga.

→ ***Fang, Bi & Yin (2019) :*** No, Geminga is too weak to generate enough e$^{+/-}$ to generate turbulence. May be downstream of the SNR shock.

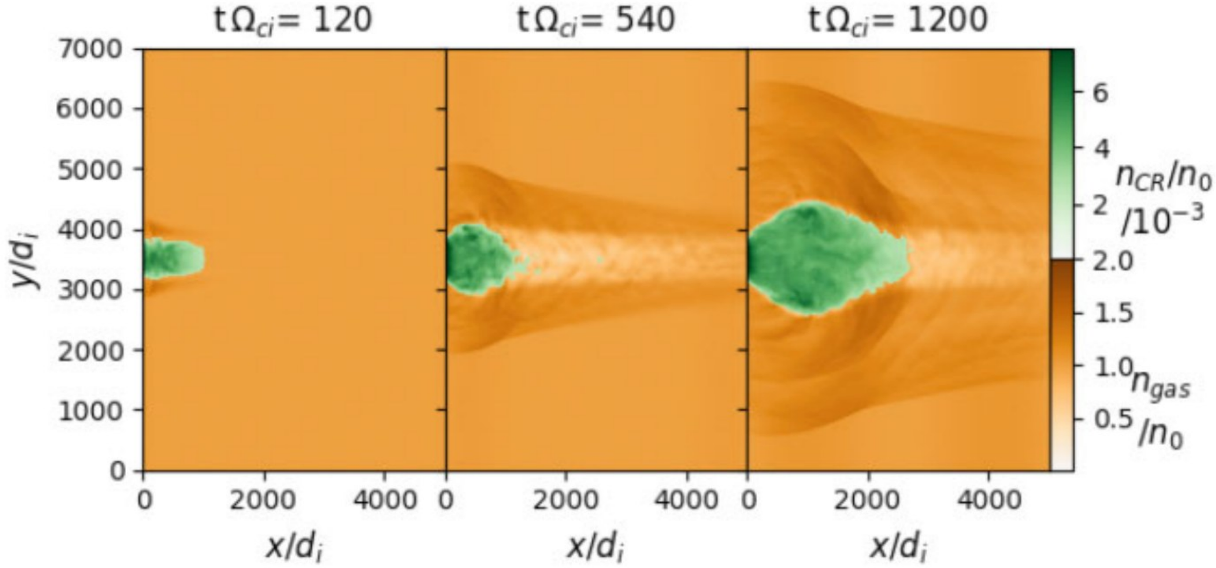
=> STILL INSIDE SNR (?)

… Similar to definition of Sudoh et al., arXiv:1902.08203 :



More likely explanation:

Outside the SNR, but CR-proton-driven instabilities

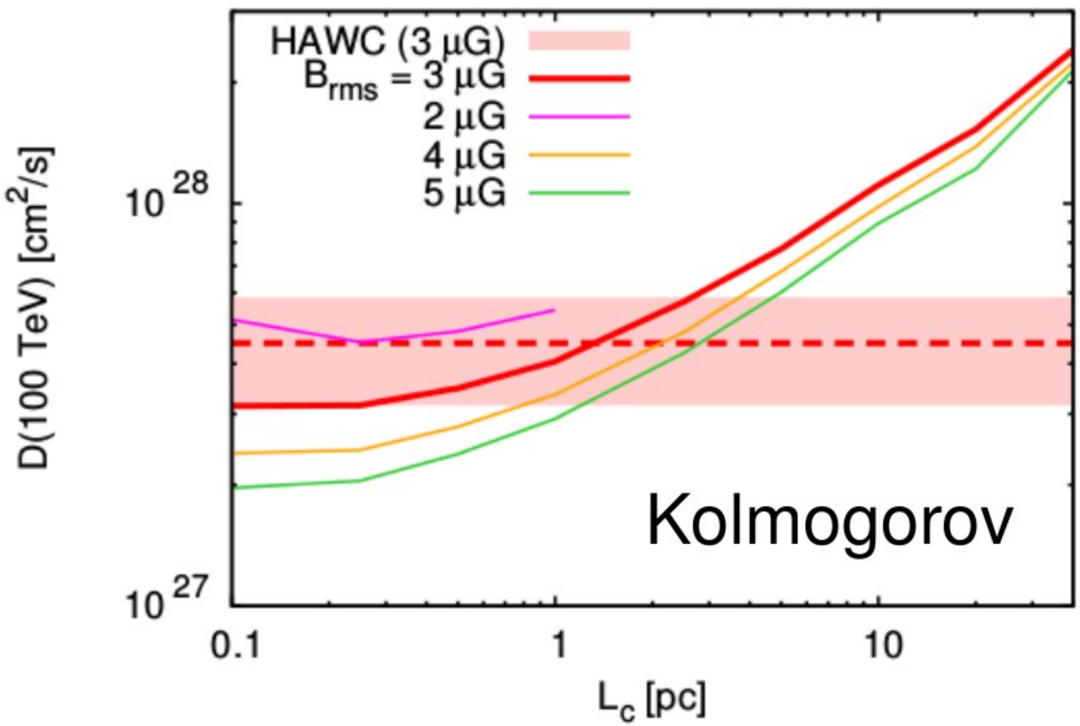


Schroer et al. (2023): PIC simulations

Or D_{HAWC} = Theoretical D ?

Lopez-Coto & Giacinti, MNRAS (2018):

Individual particles propagated numerically in 3D synthetic turbulence.

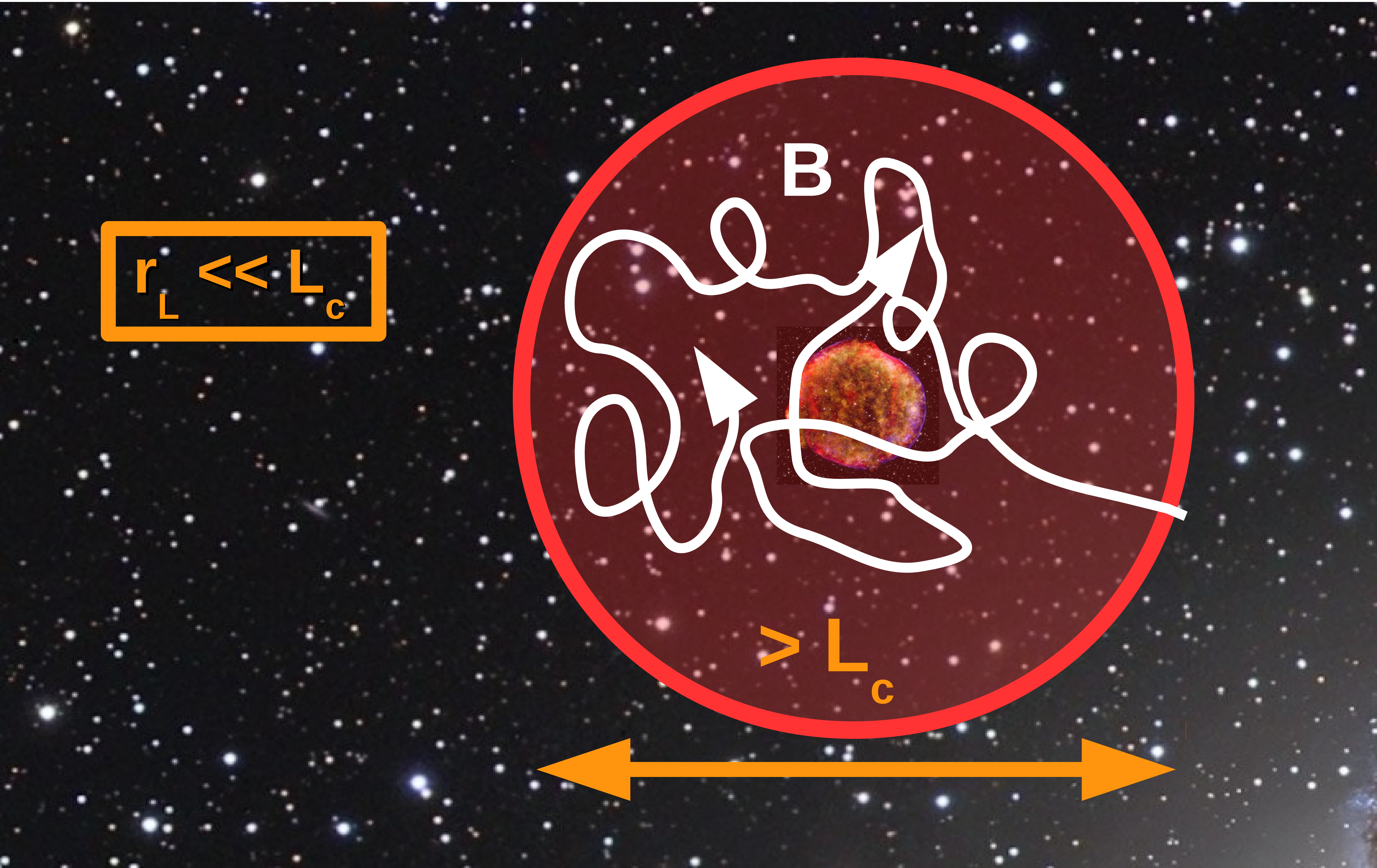


=> HAWC findings agree with theoretical expectations :

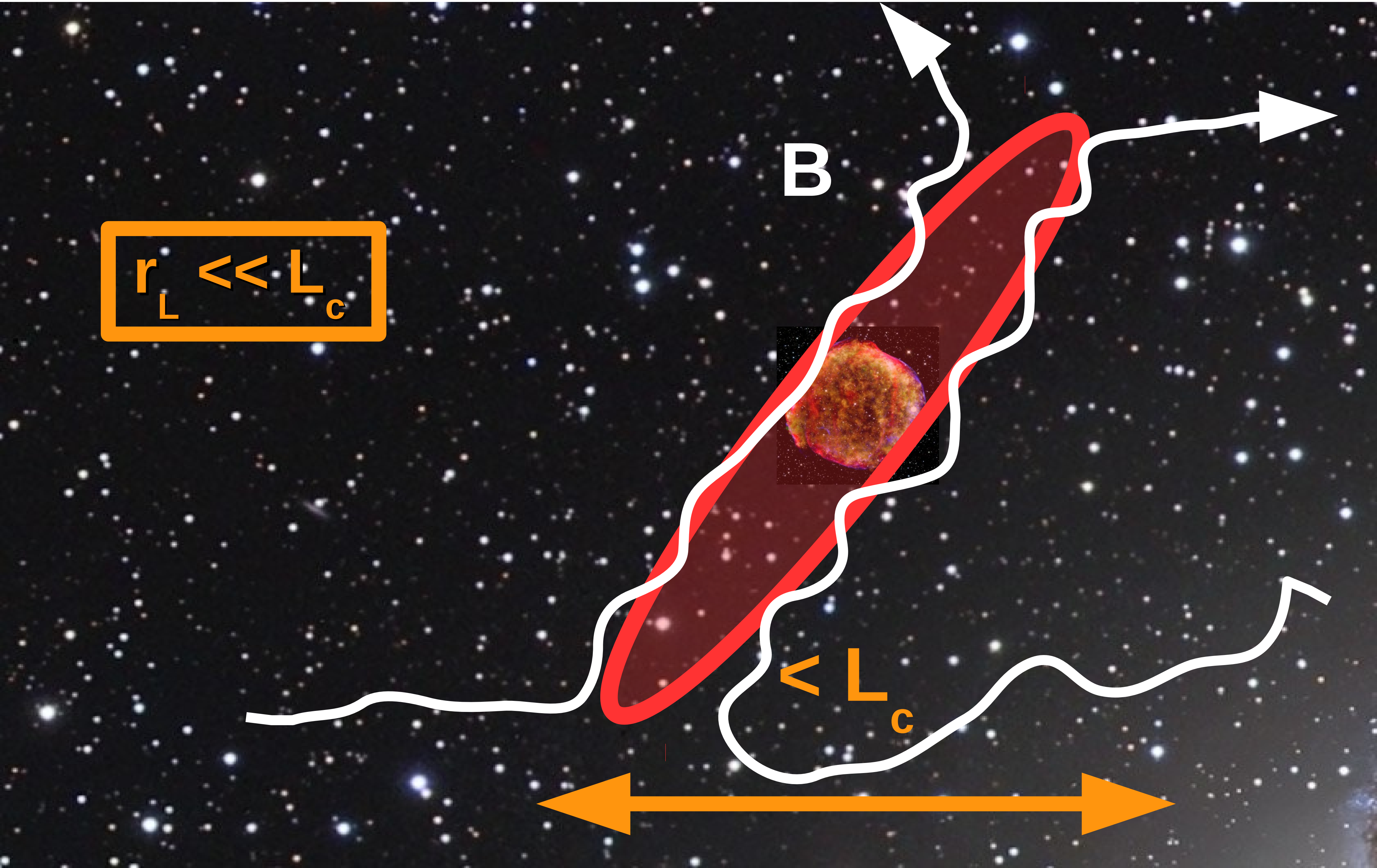
(a) For a **strongly turbulent** magnetic field (i.e. regular B negl.),

(b) For coherence lengths ~ a few pc.

But is CR diffusion (ever) isotropic ?



But is CR diffusion (ever) isotropic ?



Predicted γ-ray surface brightness

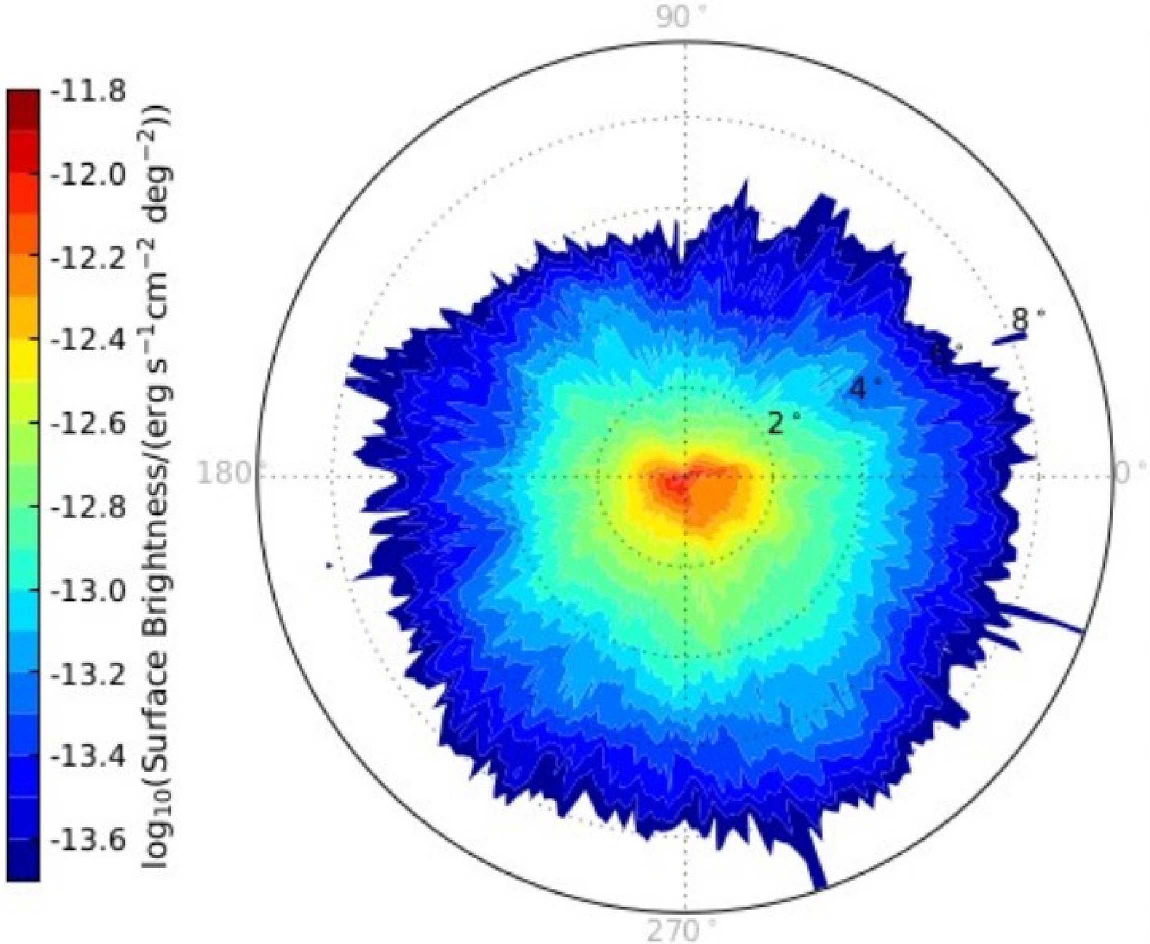
Lopez-Coto & Giacinti, MNRAS (2018) [arXiv:1712.04373]

→ Propagate individual e^- in 3D synthetic turbulence, taking into account synchrotron + IC losses

→ Calculate γ-ray emission, Compare with HAWC.

Kolmogorov,
B_{rms}=3 μG,
L_c = 5 pc

OK



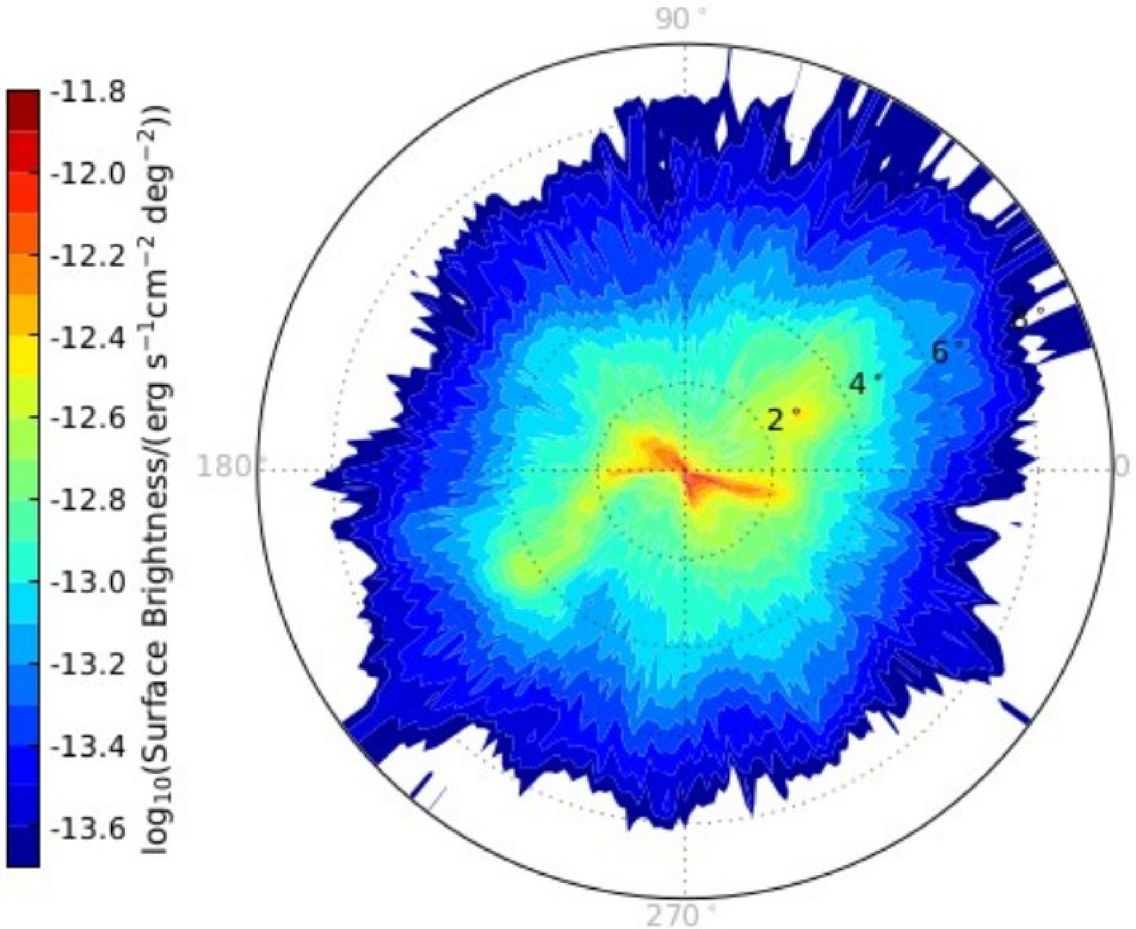
Predicted γ-ray surface brightness

Lopez-Coto & Giacinti, MNRAS (2018) [arXiv:1712.04373]

Large coherence lengths (> 10 pc) ruled out (Too asymmetric):

Kolmogorov,
B_{rms}=3 μG,
L_c = 10 pc

ALMOST INCOMPATIBLE WITH HAWC MEASUREMENTS



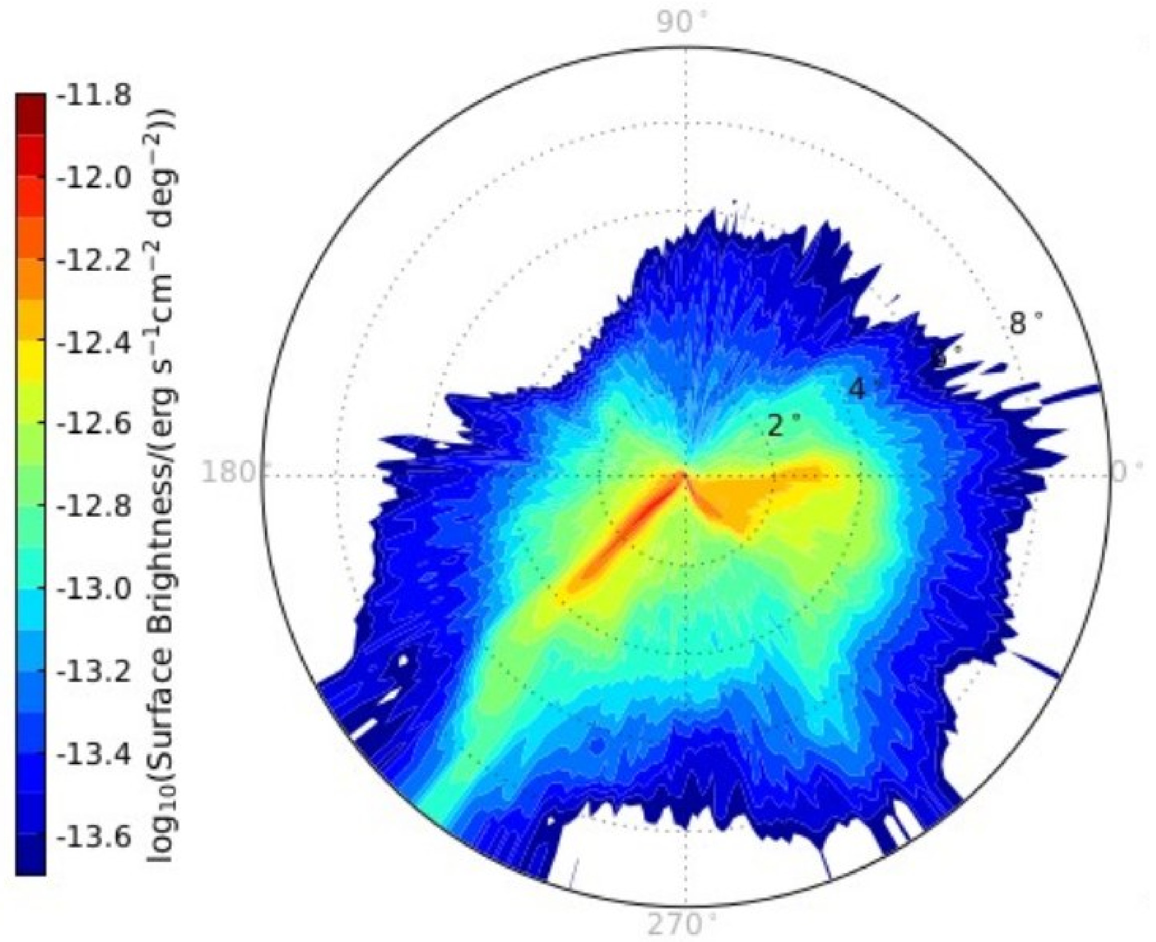
Predicted γ-ray surface brightness

Lopez-Coto & Giacinti, MNRAS (2018) [arXiv:1712.04373]

Large coherence lengths (> 10 pc) ruled out (Too asymmetric):

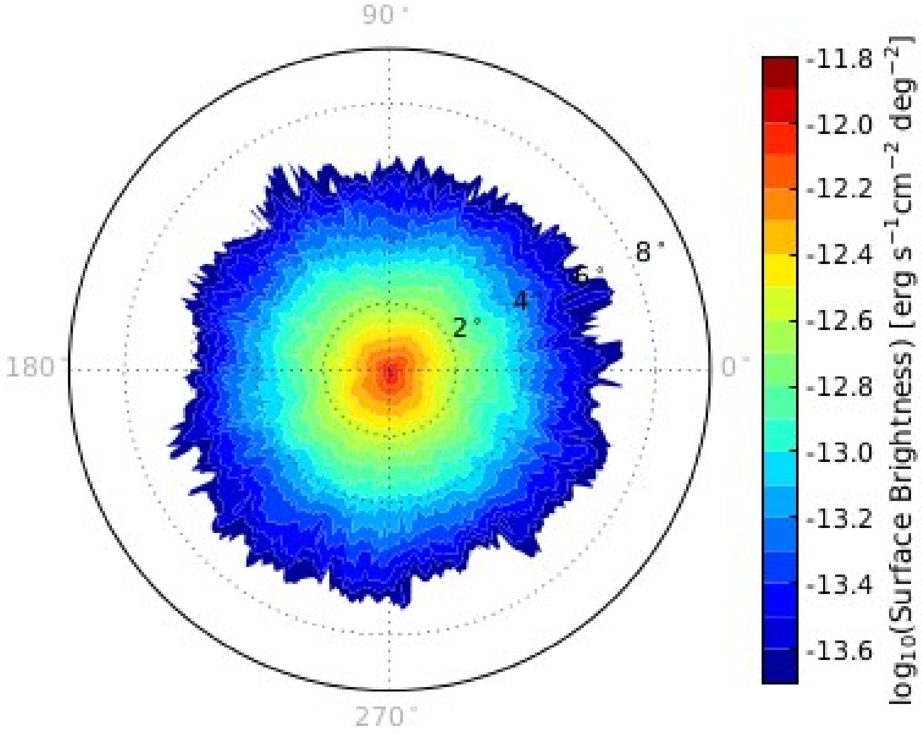
Kolmogorov,
B_{rms}=3 μG,
L_c = 40 pc

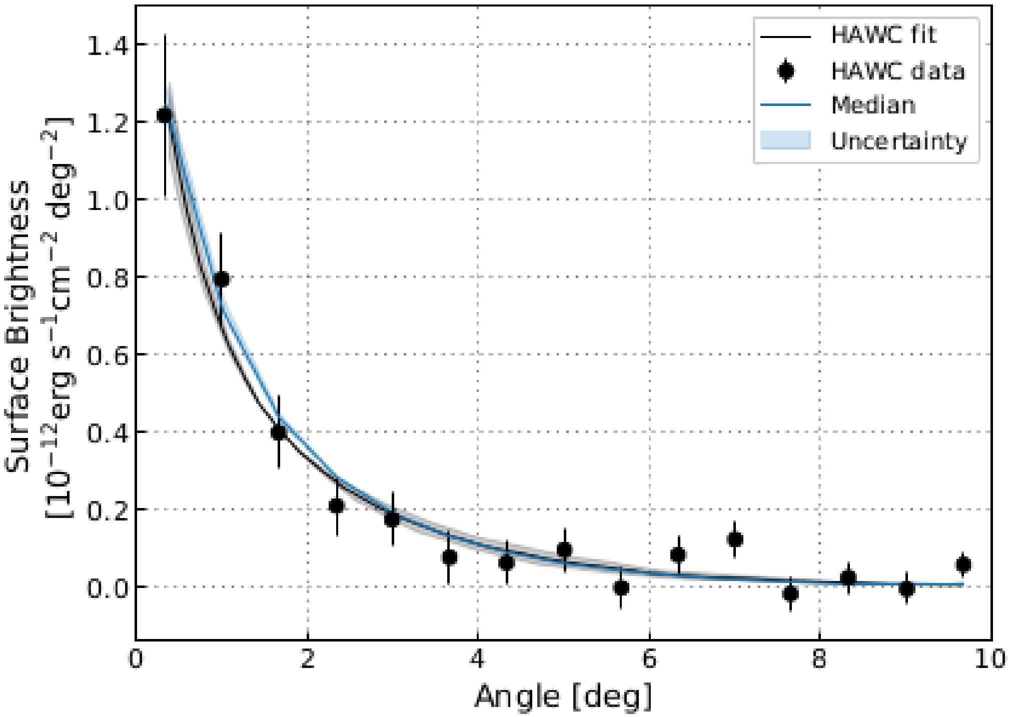
INCOMPATIBLE WITH HAWC MEASUREMENTS



Best fit to HAWC measurements (χ^2/ndf<1)

Kolmogorov / Kraichnan, B = 3 μG, L_c = 1 pc

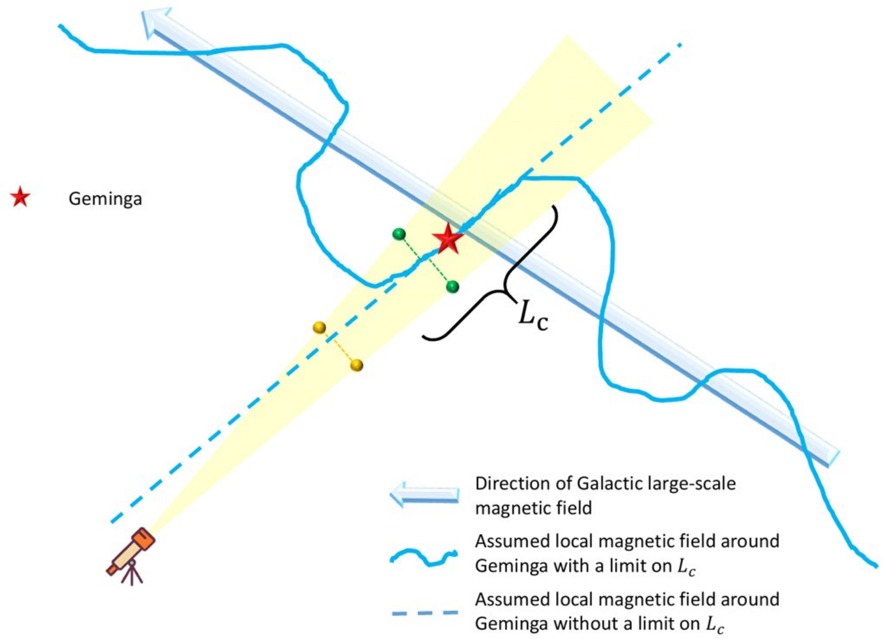


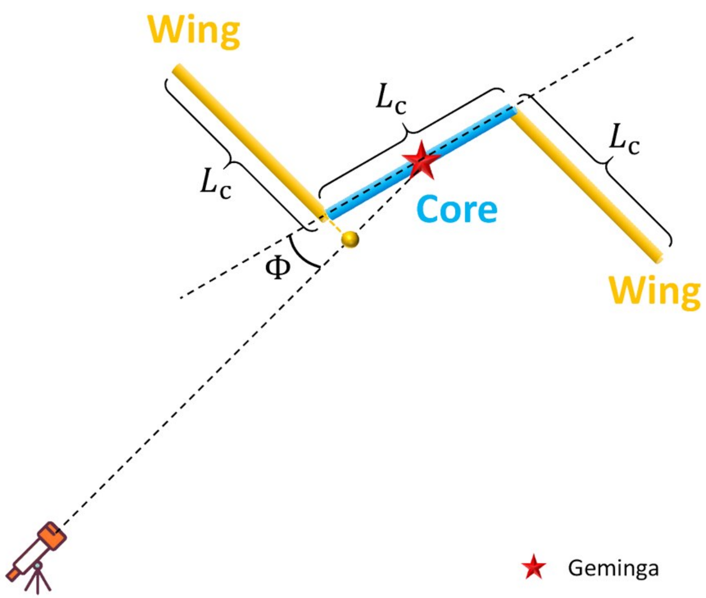


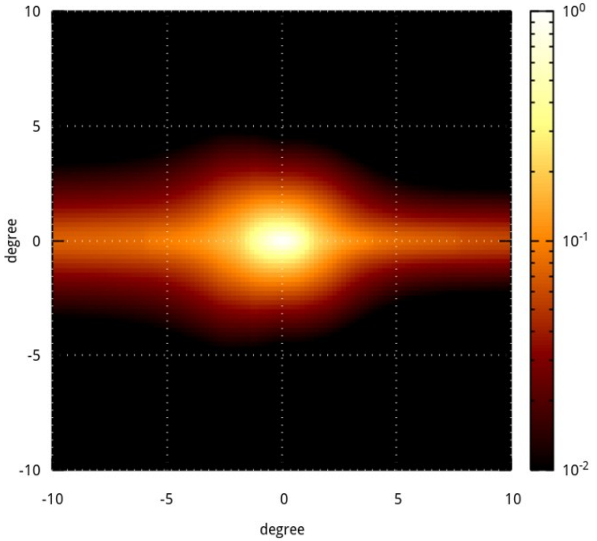
Lopez-Coto & Giacinti, MNRAS (2018) [arXiv:1712.04373]

USE OF γ-RAY DATA TO PROBE ISMFs !

Or could the local L_c be >> 40 pc ?







Fang et al., PRD (2023)

And the electon spectrum, and B/C constraints ?

An undiscovered pulsar in the Local Bubble as an explanation of the local high energy cosmic ray electron spectrum

R. López-Coto,[1,2,*] R.D. Parsons,[2] J.A. Hinton,[2] and G. Giacinti[2]

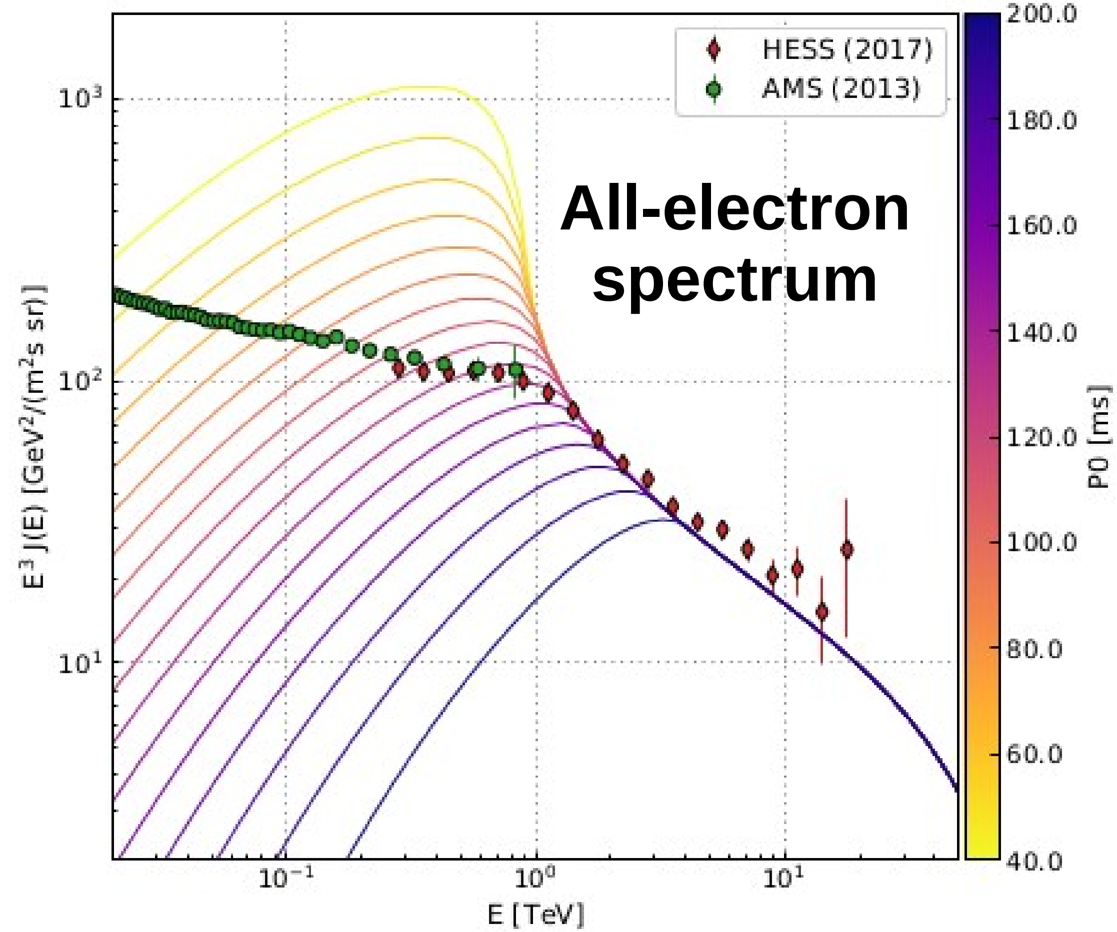
Phys. Rev. Lett. **121**, 251106 (2018)

– Required characteristics :
→ Age > 300 kyr,
→ Distance < 90 pc,
→ Spin-down power ~10^{33} – 10^{34} erg/s.

Consistent with known population.

Breitschwerdt+, Nature (2016): SN 2.2 Myr ago at 60 – 130 pc.

Fang+, arXiv:1906.08542: PSR B1055-52, if d ~ 90 pc (??)



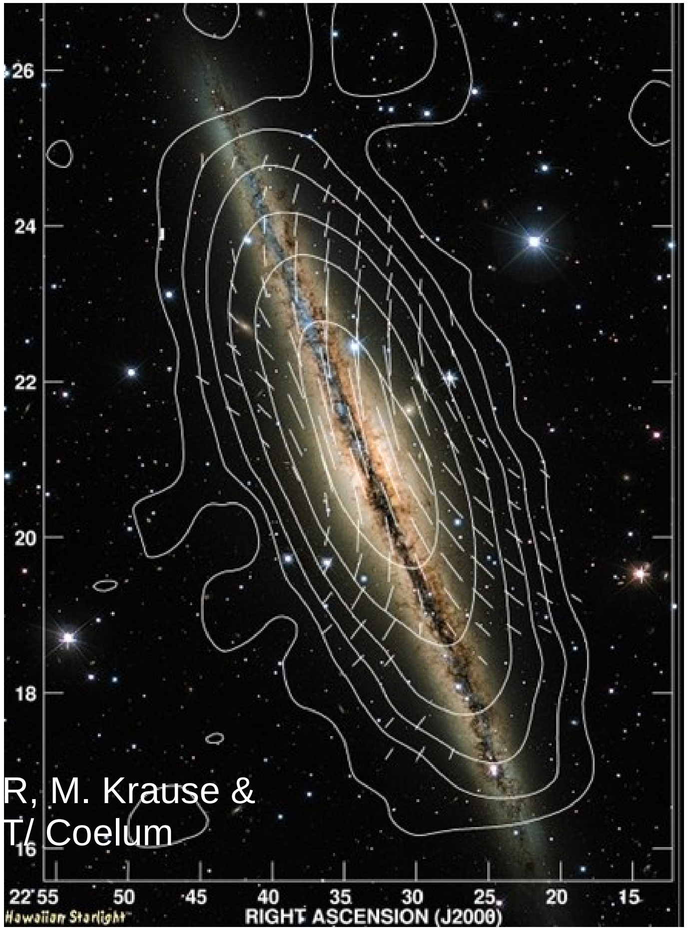
d=50 pc, $\dot{E} = 1.3 \times 10^{33}$ erg/s, $\alpha = 2.4$, $B = 3$ μG.

B/C ratio

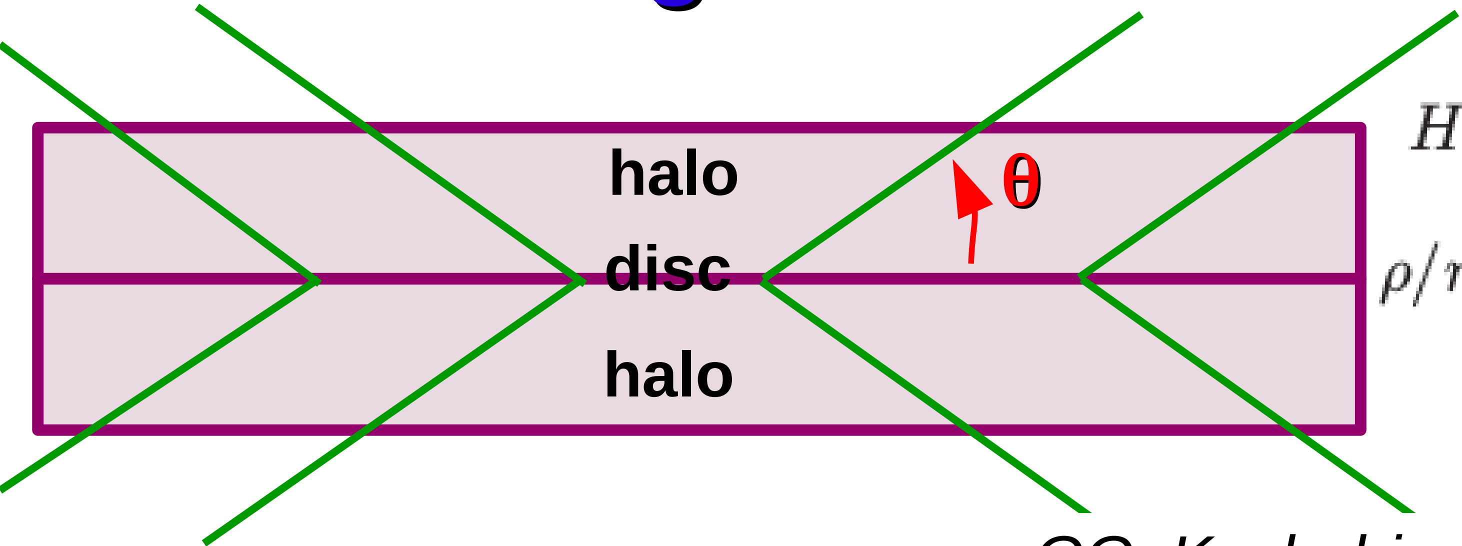
→ Probes CR propagation on **kpc scales.**

=> Small D in the disc viable if CRs escape the Galaxy quickly, with **faster diffusion in the halo (or advection)**.

=> Quick escape by parallel diffusion
along a large-scale field ?



Grammage with an out-of-plane B

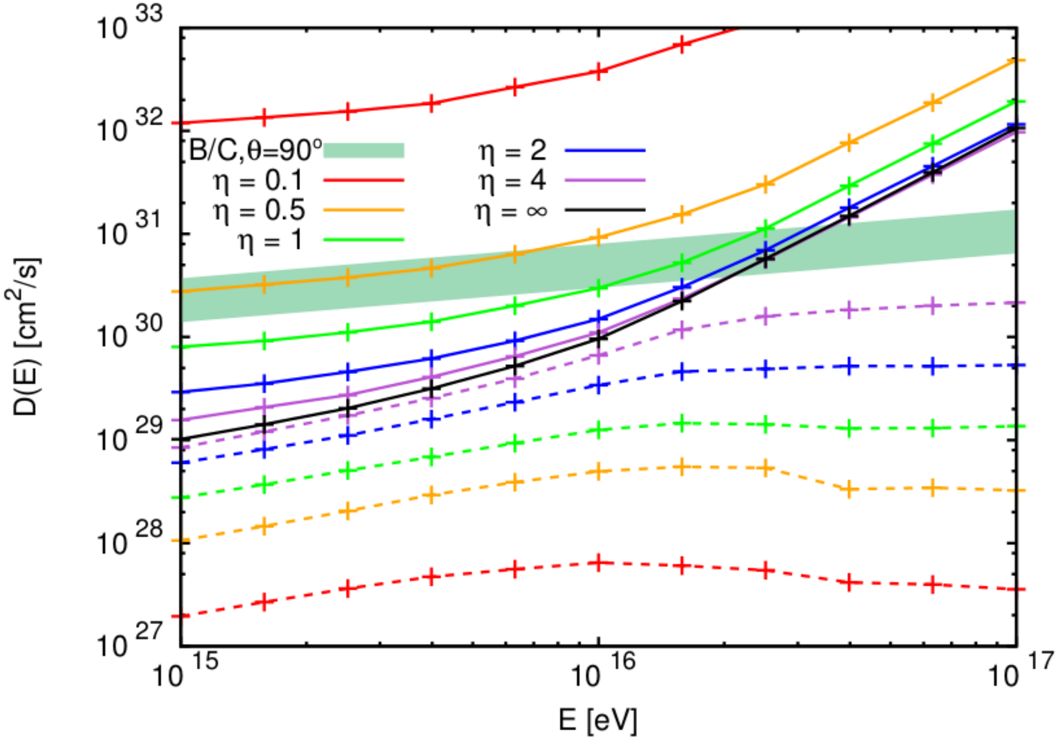


$H = 5\,\mathrm{kpc}$

$\rho/m_\mathrm{p} \simeq 1/\mathrm{cm}^3$ $h = 150\,\mathrm{pc}$

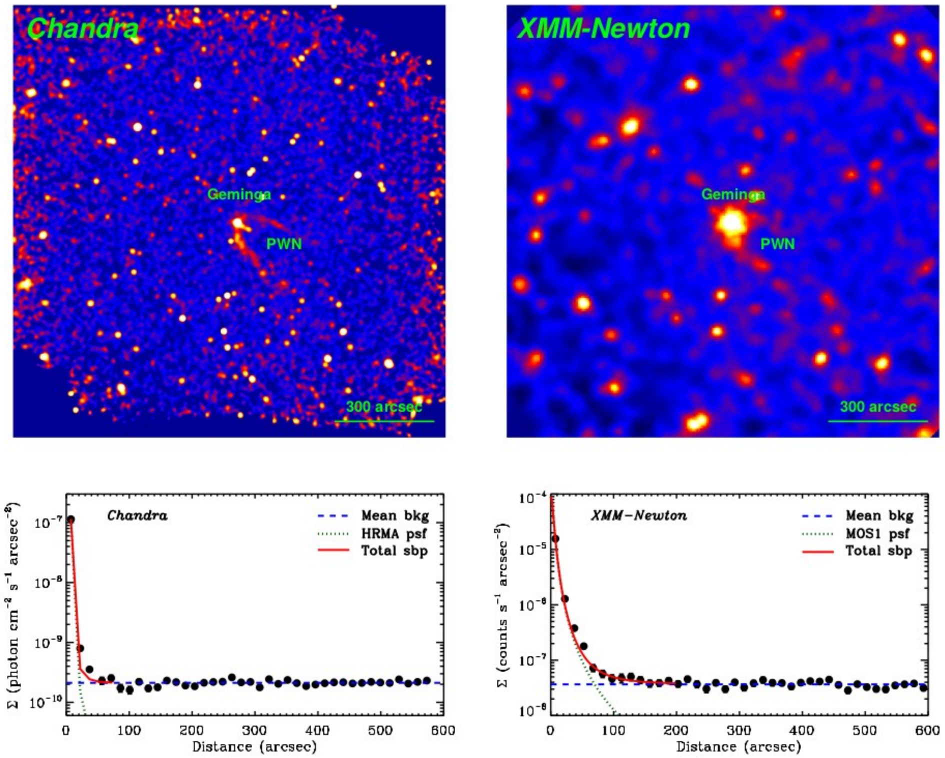
GG, Kachelriess & Semikoz (2018)

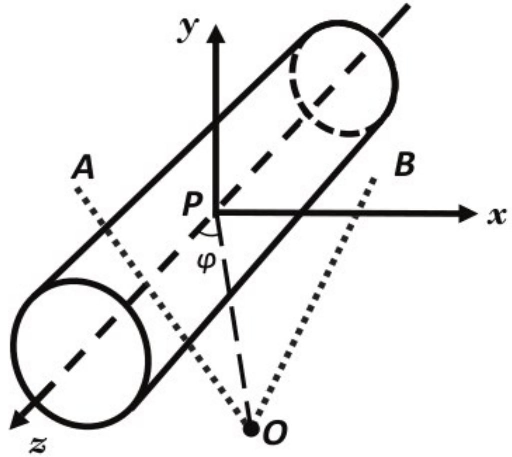
$\eta = B_\mathrm{rms}/B_0$



Or Impact of a regular B field ?

→ *Liu, Ge, Sun & Wang (2019)* : Discrepancy between IC γ-rays and X-ray synchrotron (Chandra/XMM) in a small region around Geminga.
=> B field aligned towards us?



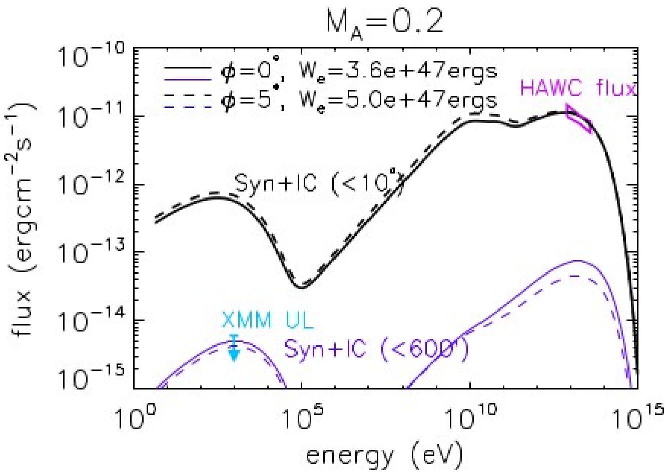


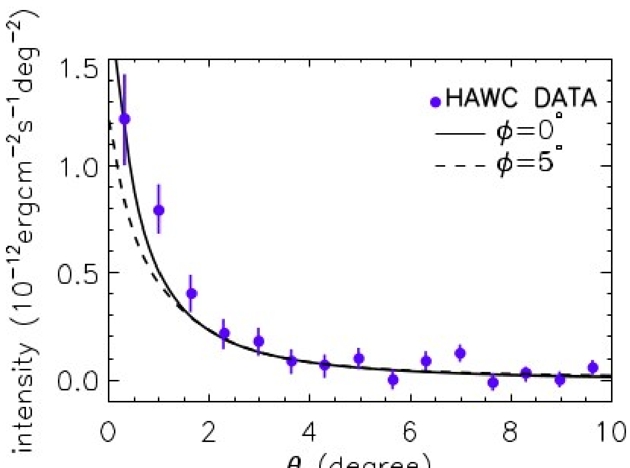
$$P = \frac{2q^4 B^2 \gamma^2 \beta^2 \sin^2\alpha}{3m^2c^3}$$

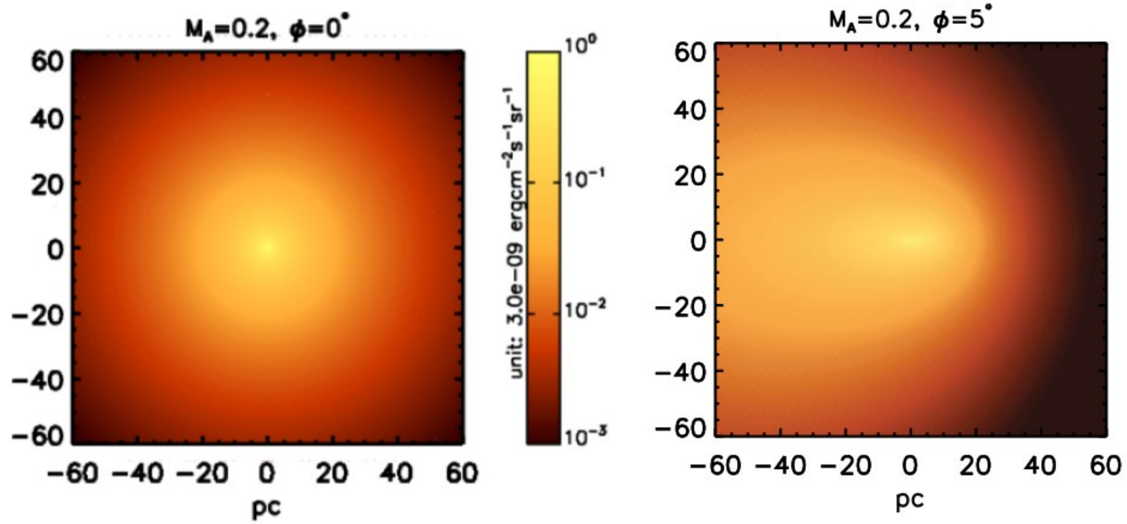
$$B \lesssim 0.8\mu\mathrm{G}$$

Or Impact of a regular B field ?

→ *Liu, Yan & Zhang (2019)* : sub-Alfvenic turbulence, with such a large-scale B field → Find no need for a small D.





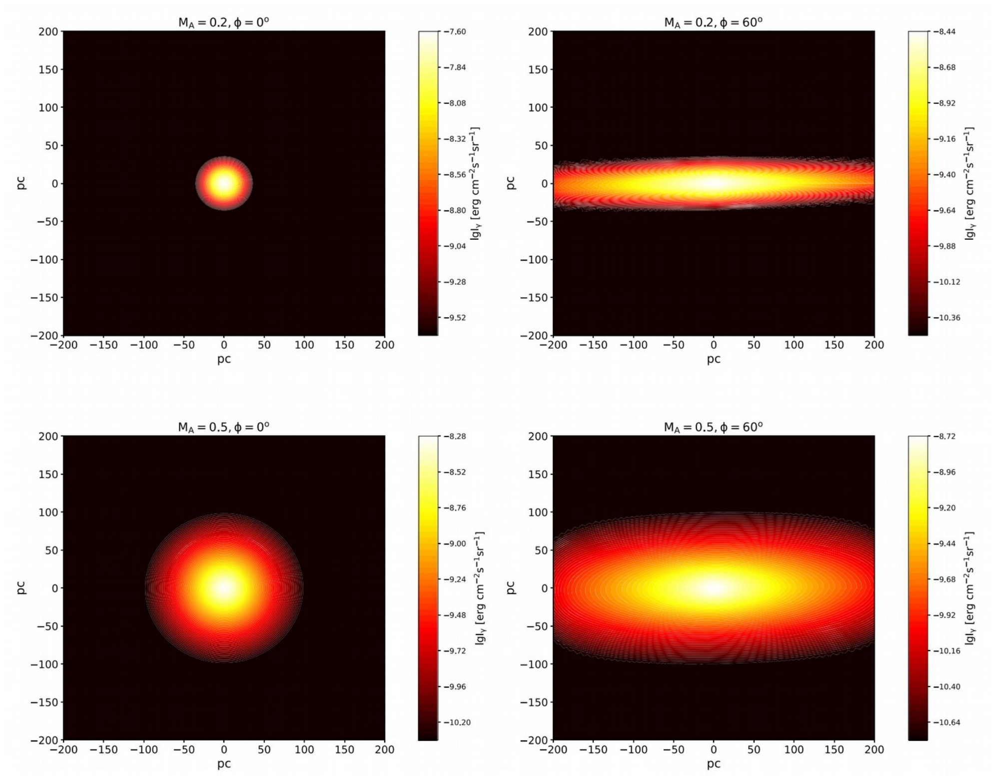


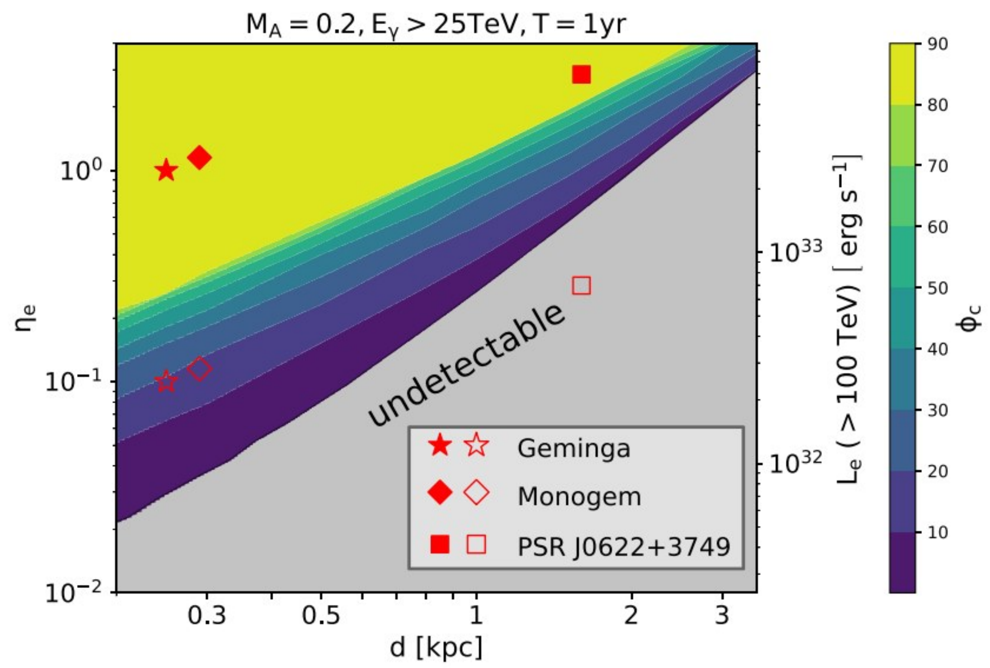
→Impact field line wandering=> Ruled out for *Lopez-Coto& GG (2018)*'s turbulence. Does it work for another? Need to check in this model.

Yan, Liu et al. 2022

Mean B field around other pulsar halos cannot be always aligned with LOS.
Then why elongated halo is not observed?

Larger inclination angle -> more diffuse

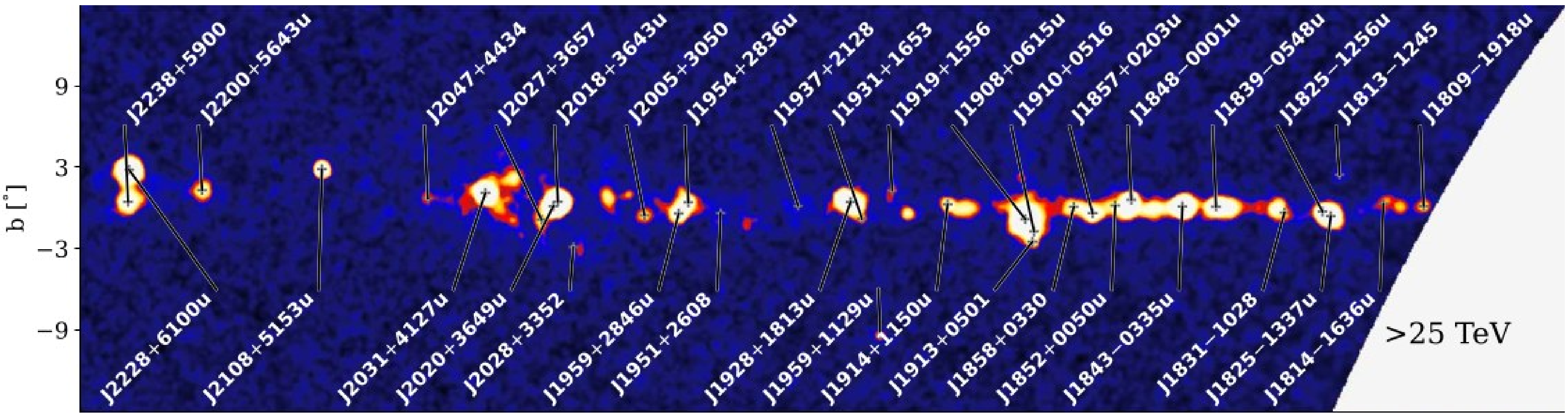




Sky at 25 TeV – 1 PeV with LHAASO

LHAASO Collaboration, ApJS 271, 25 (2024)

Many **extended sources** w/ **irregular shapes:**

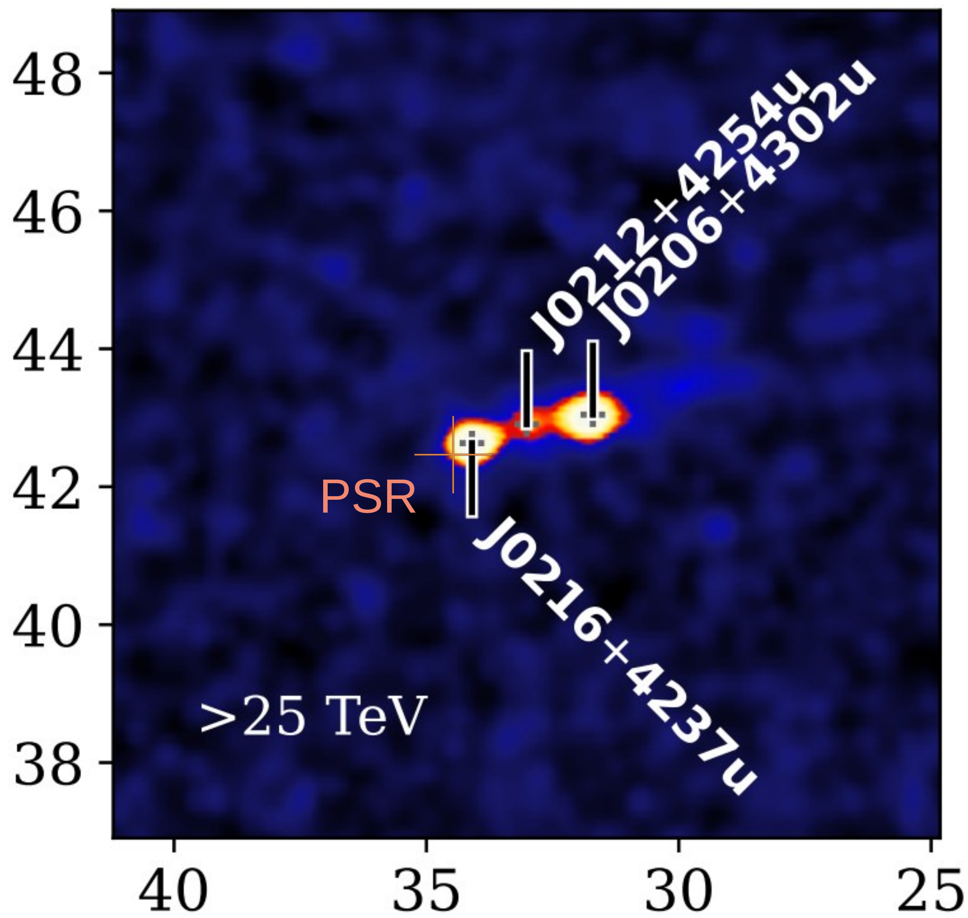


Large offsets between sources & center emission:

Table 4. 1LHAASO sources associated pulsars

Source name	PSR name	Sep.(°)	d (kpc)	τ_c (kyr)	$\dot{E}$ (erg s^{-1})	P_c	Identified type in TeVCat
1LHAASO J0007+7303u	PSR J0007+7303	0.05	1.40	14	4.5e+35	7.3e-05	PWN
1LHAASO J0216+4237u	PSR J0218+4232	0.33	3.15	476000	2.4e+35	3.6e-03	
1LHAASO J0249+6022	PSR J0248+6021	0.16	2.00	62	2.1e+35	1.5e-03	
1LHAASO J0359+5406	PSR J0359+5414	0.15	-	75	1.3e+36	7.2e-04	
1LHAASO J0534+2200u	PSR J0534+2200	0.01	2.00	1	4.5e+38	3.2e-06	PWN
1LHAASO J0542+2311u	PSR J0543+2329	0.30	1.56	253	4.1e+34	8.3e-03	
1LHAASO J0622+3754	PSR J0622+3749	0.09	-	208	2.7e+34	2.5e-04	PWN/TeV Halo
1LHAASO J0631+1040	PSR J0631+1037	0.11	2.10	44	1.7e+35	3.5e-04	PWN
1LHAASO J0634+1741u	PSR J0633+1746	0.12	0.19	342	3.3e+34	1.3e-03	PWN/TeV Halo
1LHAASO J0635+0619	PSR J0633+0632	0.39	1.35	59	1.2e+35	9.4e-03	
1LHAASO J1740+0948u	PSR J1740+1000	0.21	1.23	114	2.3e+35	1.4e-03	
1LHAASO J1809-1918u	PSR J1809-1917	0.05	3.27	51	1.8e+36	6.2e-04	
1LHAASO J1813-1245	PSR J1813-1245	0.01	2.63	43	6.2e+36	6.3e-06	
1LHAASO J1825-1256u	PSR J1826-1256	0.09	1.55	14	3.6e+36	1.6e-03	
1LHAASO J1825-1337u	PSR J1826-1334	0.11	3.61	21	2.8e+36	2.8e-03	PWN/TeV Halo
1LHAASO J1837-0654u	PSR J1838-0655	0.12	6.60	23	5.6e+36	2.2e-03	PWN
1LHAASO J1839-0548u	PSR J1838-0537	0.20	-	5	6.0e+36	6.1e-03	
1LHAASO J1848-0001u	PSR J1849-0001	0.06	-	43	9.8e+36	1.2e-04	PWN
1LHAASO J1857+0245	PSR J1856+0245	0.16	6.32	21	4.6e+36	3.1e-03	PWN
1LHAASO J1906+0712	PSR J1906+0722	0.19	-	49	1.0e+36	5.9e-03	
1LHAASO J1908+0615u	PSR J1907+0602	0.23	2.37	20	2.8e+36	6.8e-03	
1LHAASO J1912+1014u	PSR J1913+1011	0.13	4.61	169	2.9e+36	1.5e-03	

Peculiar source/halo: Aligned sources? No counterpart?



LHAASO Collaboration (arxiv:2305.17030)

"Mirage" sources and large offsets: Asymmetric CR diffusion around sources

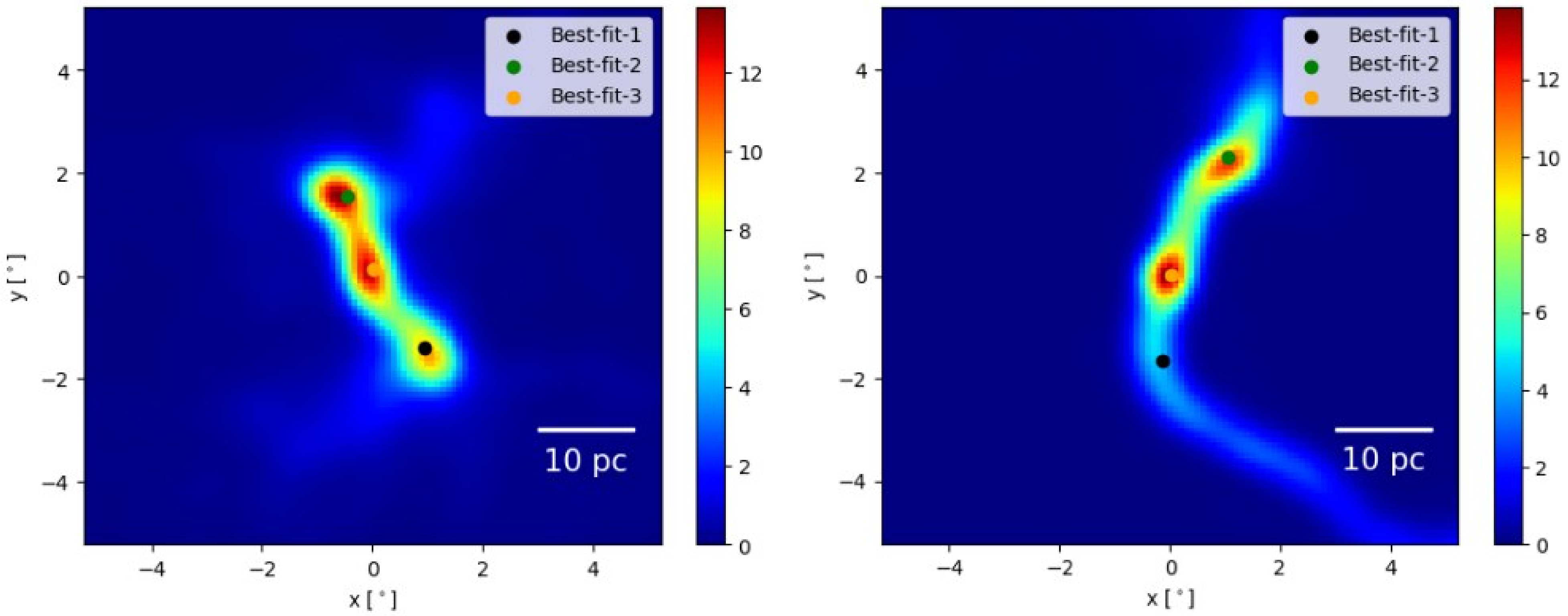
Works from Yiwei Bao

References:

Bao, Giacinti, Liu, Zhang & Chen, arXiv:2407.02478 (Submitted to PRL)
Bao, Liu, Giacinti, Zhang & Chen, arXiv:2407.02829 (Submitted to PRD)
Bao et al., In prep.

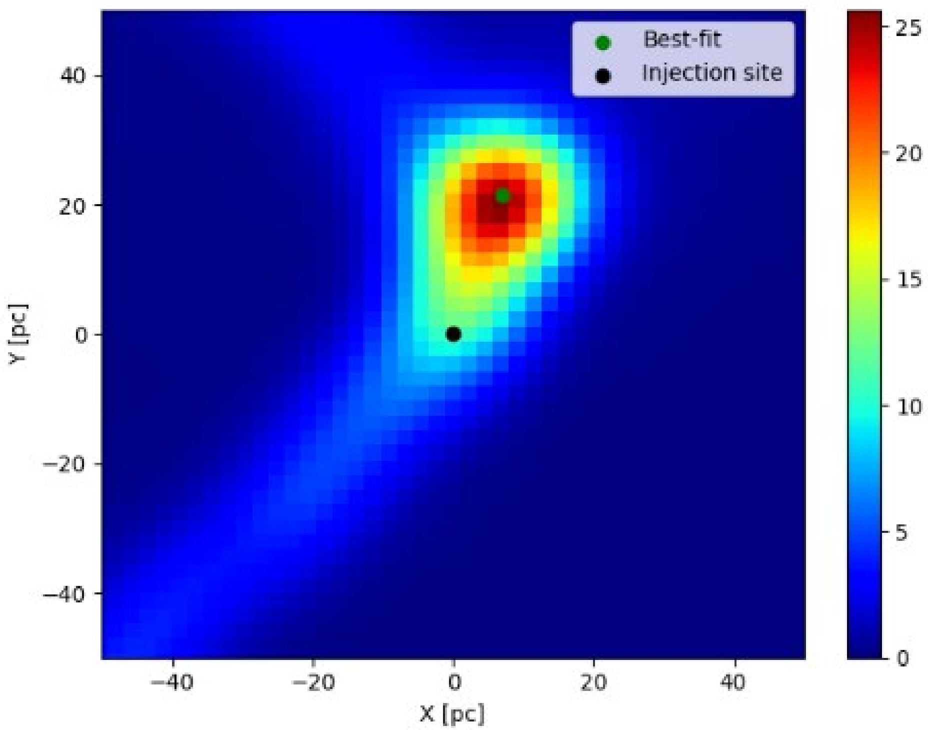
Appearance of “mirage” sources:

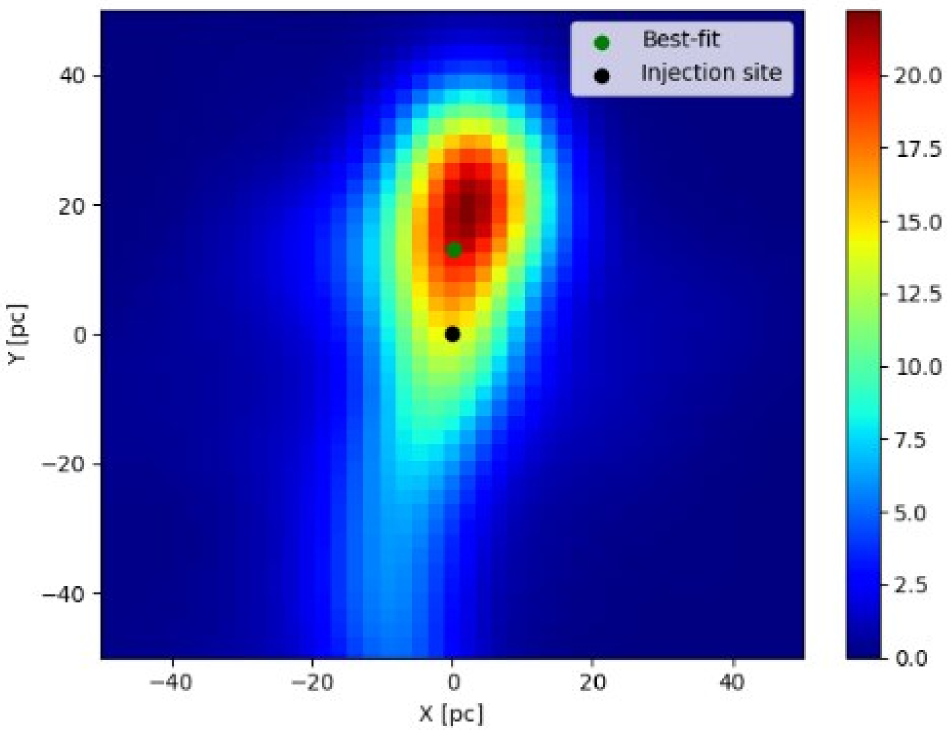
→ Convolve the simulation results with LHAASO PSF
→ Try to identify the source by calculating the TS value
(as done w/ LHAASO data)



L_c = 40pc ; B_{turb} = 3 μG ; B_{reg} = 0 μG; Kolmogorov turbulence ; (8192 particles)

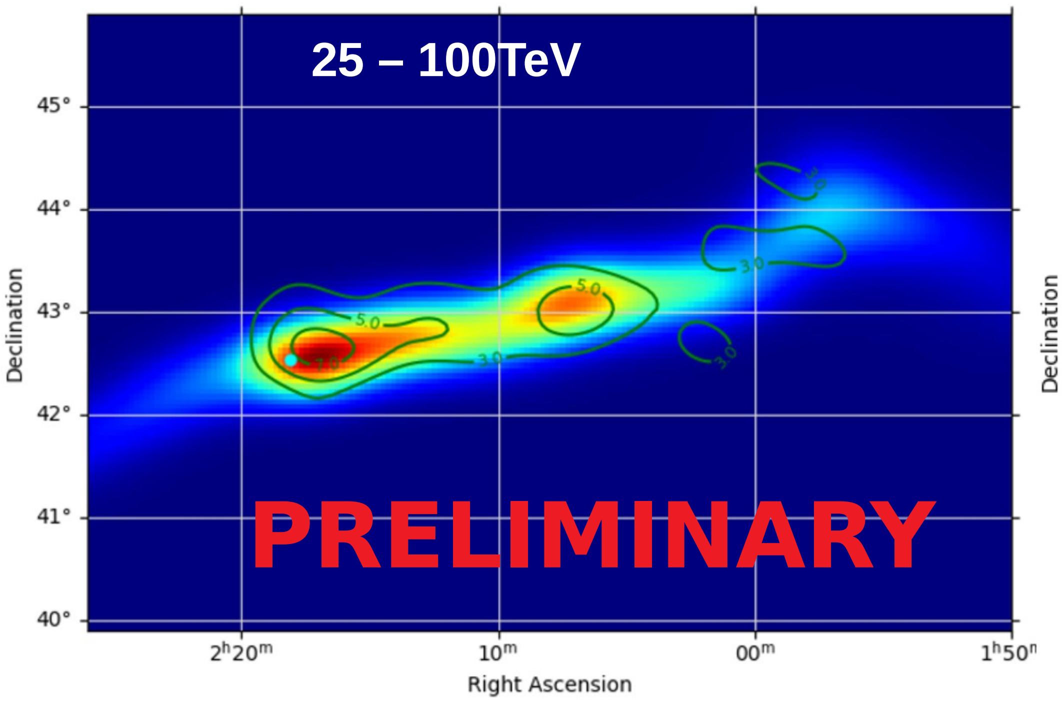
Large offsets:

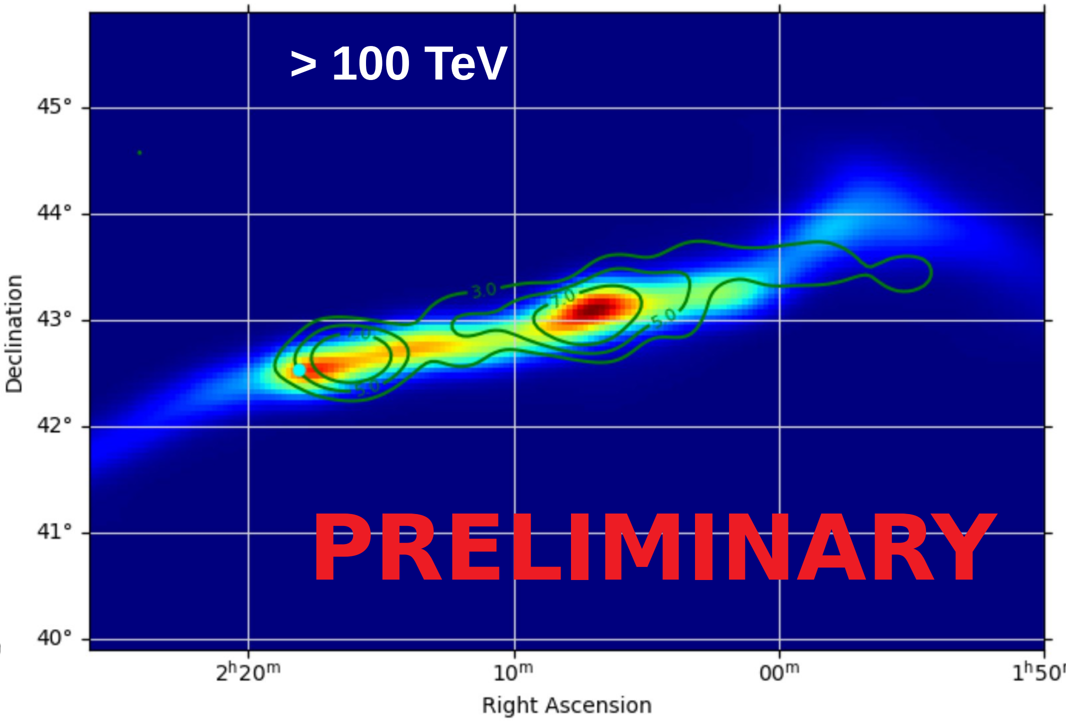




B_{turb} ~ 1 μG ; B_{reg} = 0 μG ; L_c = 200 pc ; Kolmogorov turbulence ; (8192 particles)

Our simulations vs LHAASO source





Our fitting parameters:

L_c = 267 pc

B_{reg} = 1.16 μG

B_{turb} = 0.95 μG

Kolmogorov

α = 2.2

E_{cut} = 1 PeV

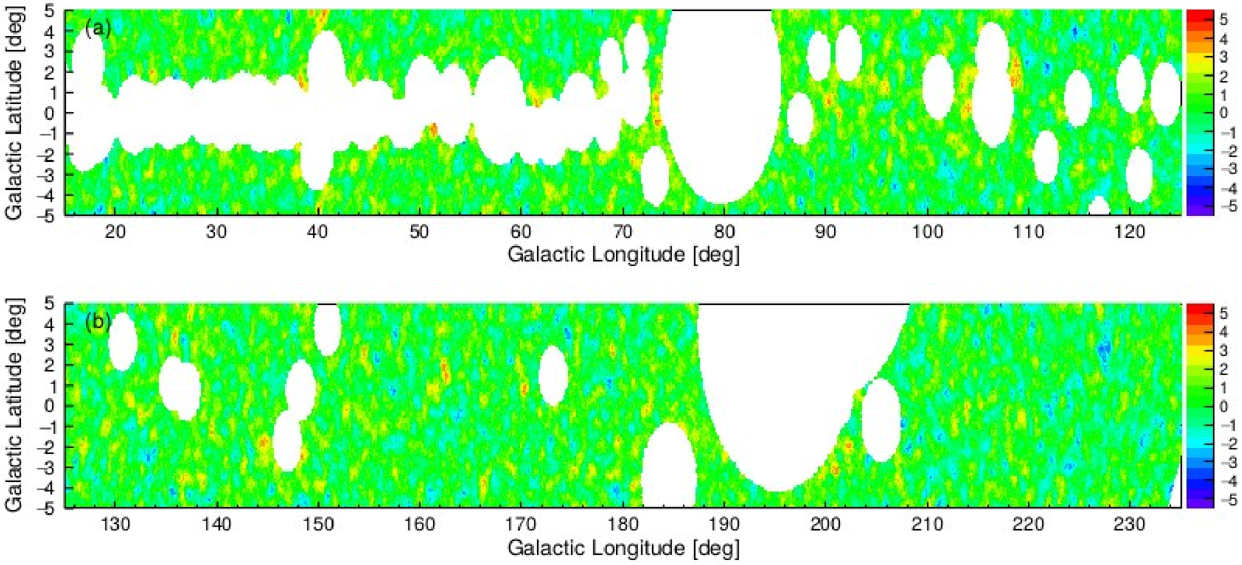
Assumptions here: BSPWN, injection from 180 degree

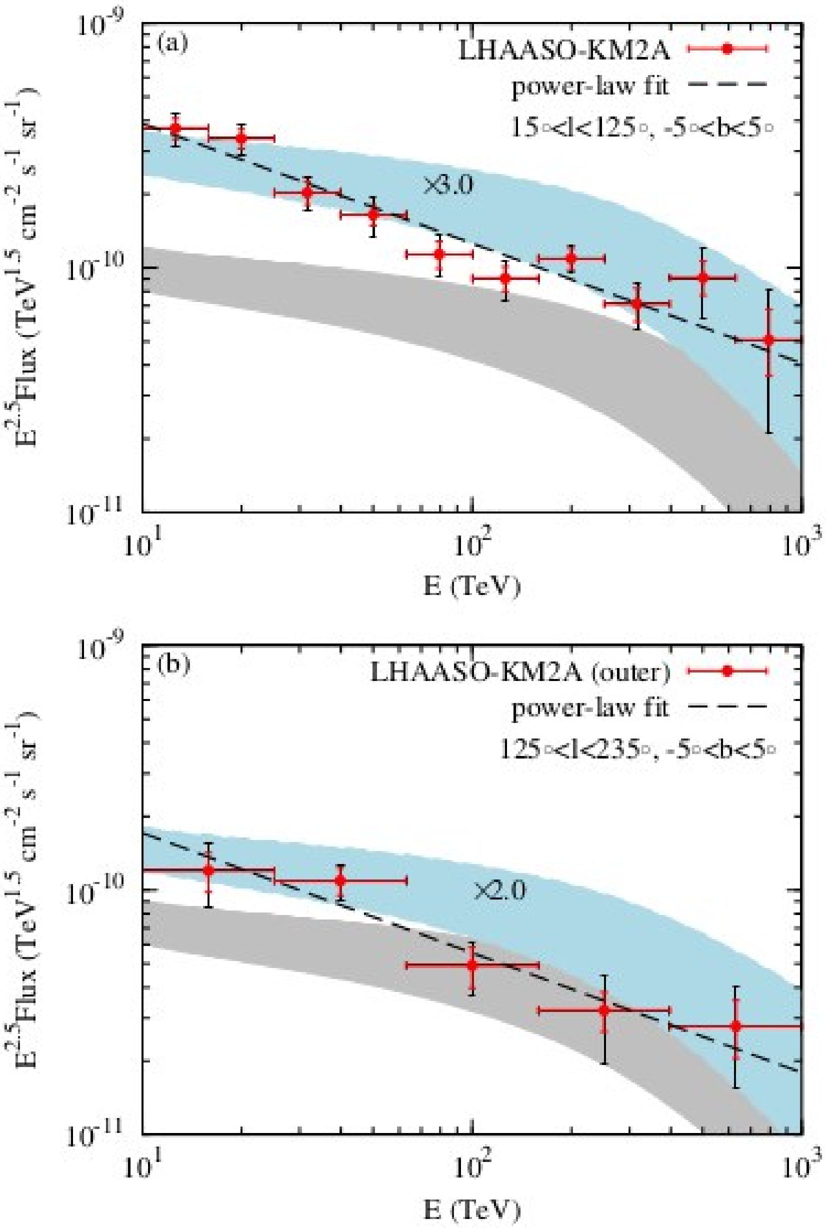
The additional source is a "**mirage**", where the magnetic field bends inwards/outwards

Contribution of TeV Halos to the diffuse Galactic UHE gamma-ray background ?

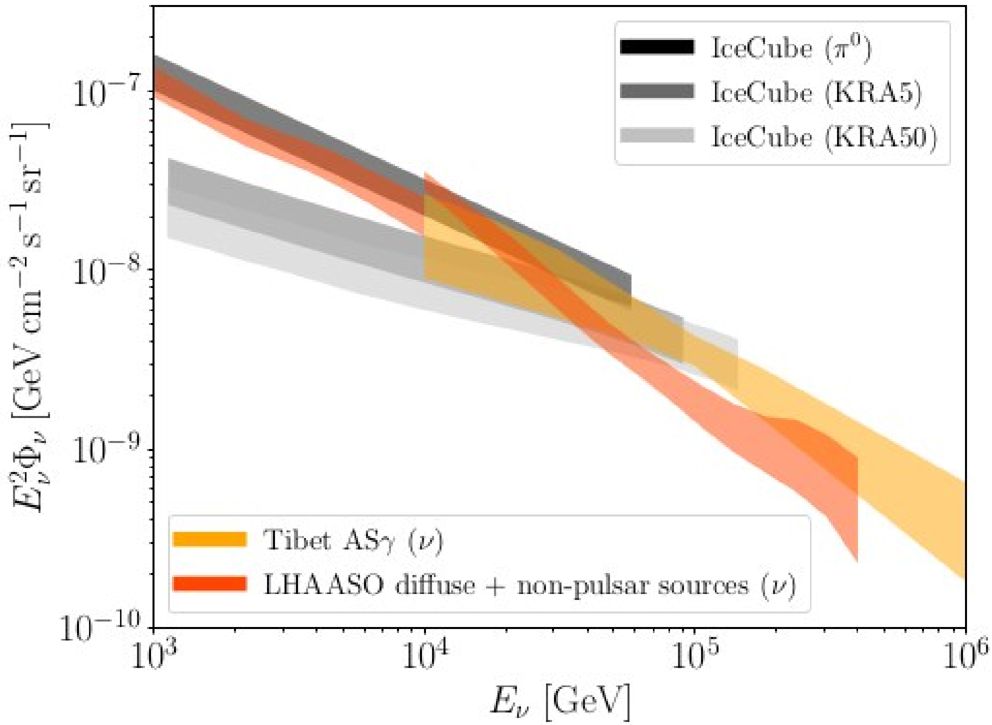
The sky at ~ 10 TeV – 1 PeV: Diffuse Galactic emission from LHAASO

LHAASO Collaboration, arXiv:2305.05372





Comparing ν and γ observations



- The flux sum of LHAASO diffuse and 1LHAASO sources excluding pulsars, PWNe, TeV halos is comparable to IceCube flux above ~30 TeV —> **LHAASO diffuse emission mainly comes from hadronic interactions at these energies**

KF & Murase ApJL *2307.02905*

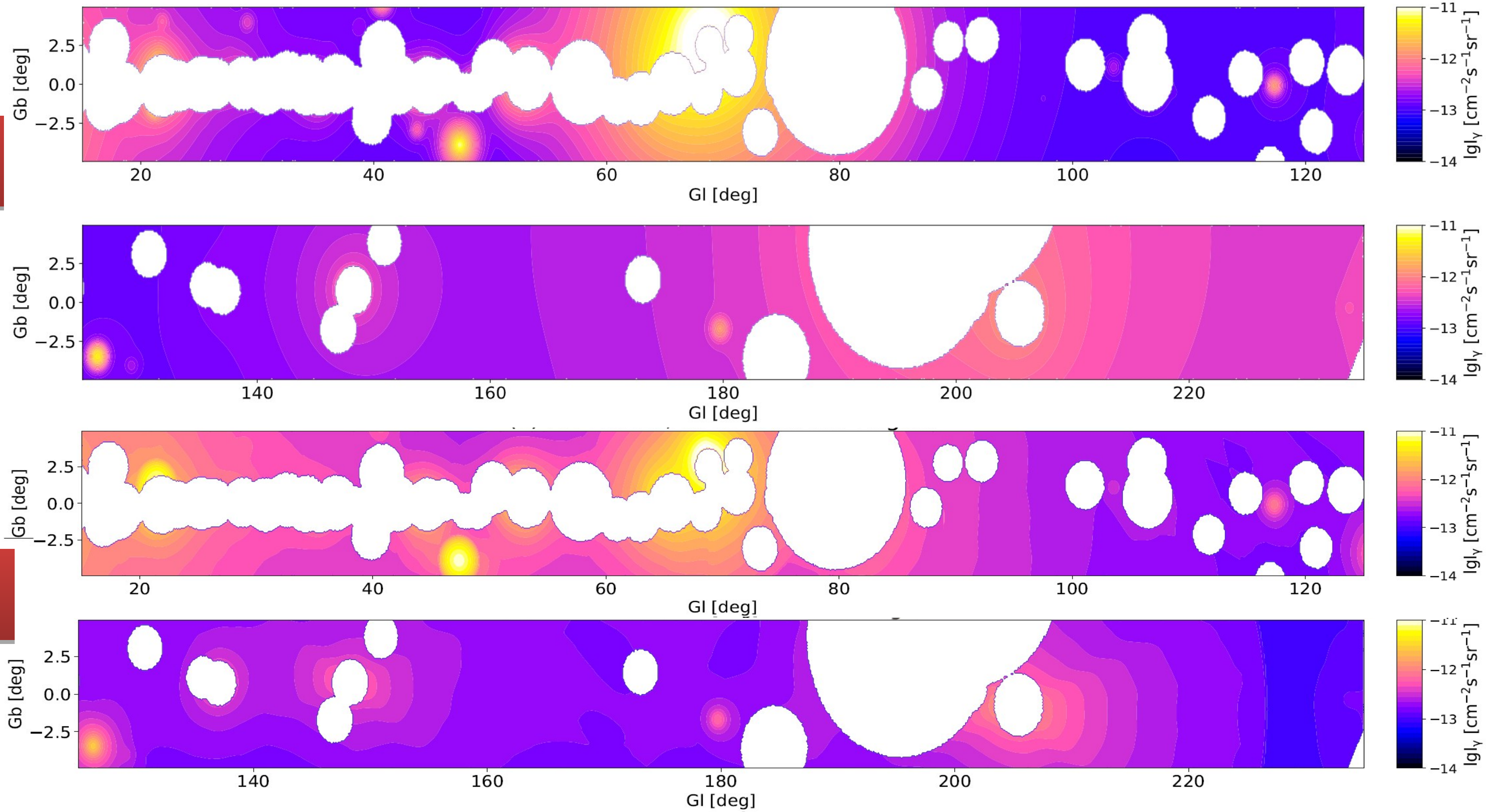
Slide from Ke Fang

2D Intensity Map

Yan, Liu, et al., Nature Astronomy (2024)

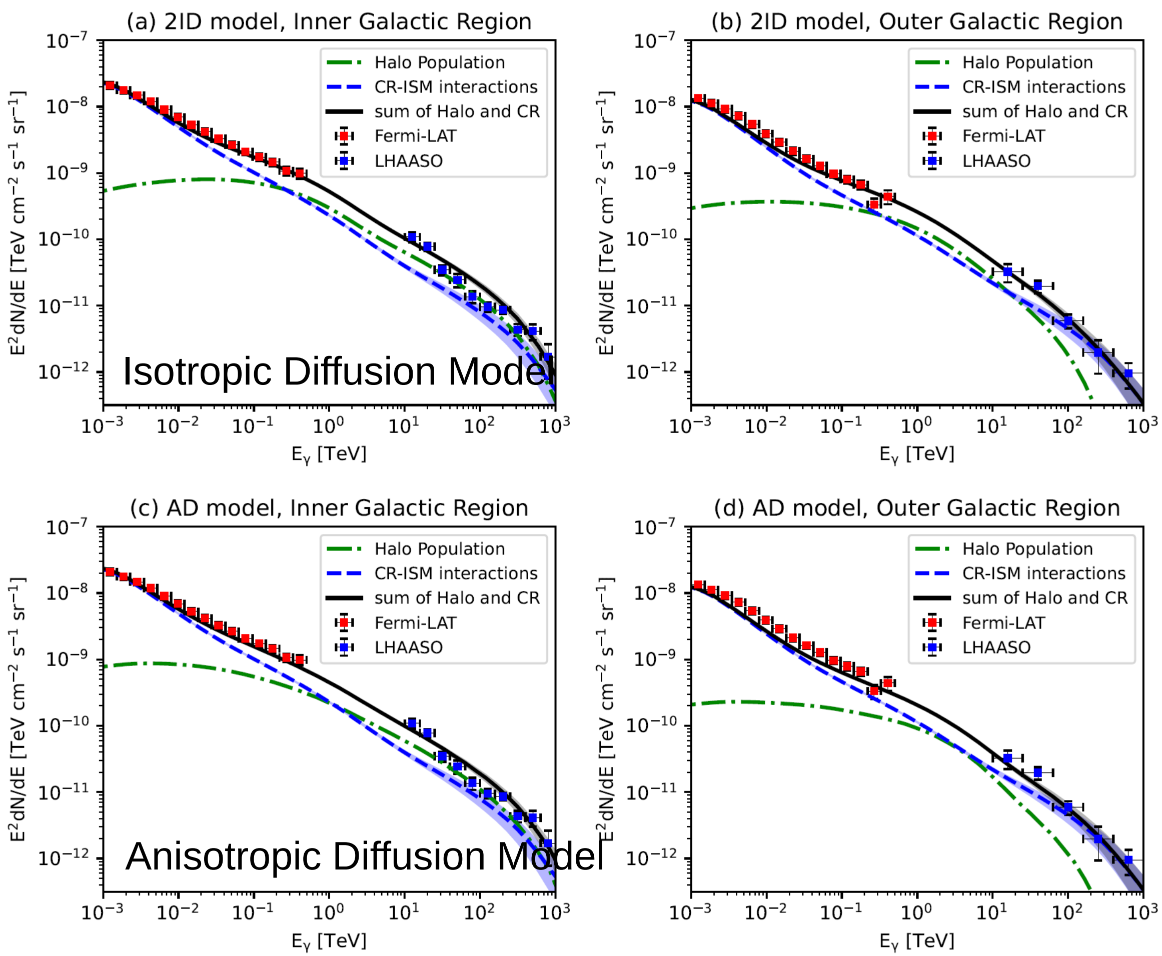
Isotropic Diffusion

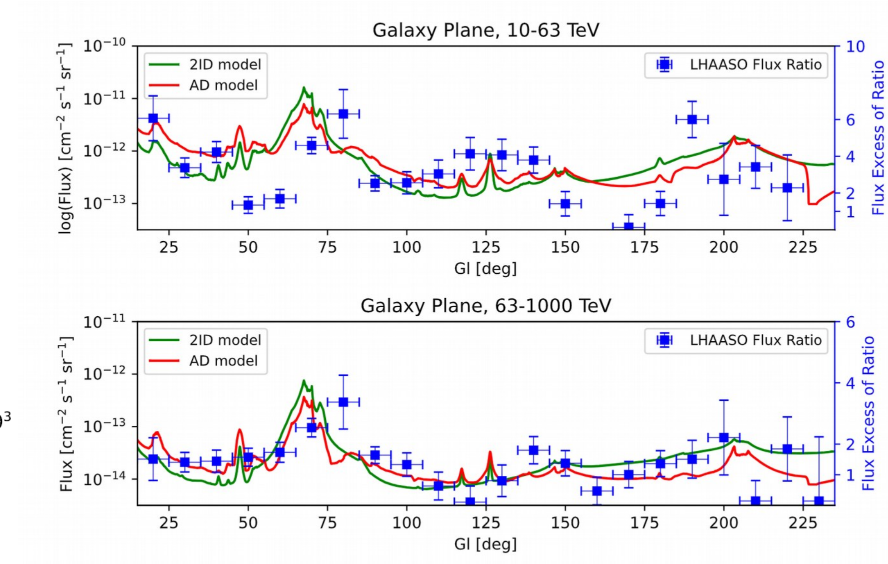
Anisotropic Diffusion



Pulsars in ATNF catalogue that may produce a TeV halo

Flux and longitudinal profile   Yan, Liu, et al., Nature Astronomy (2024)





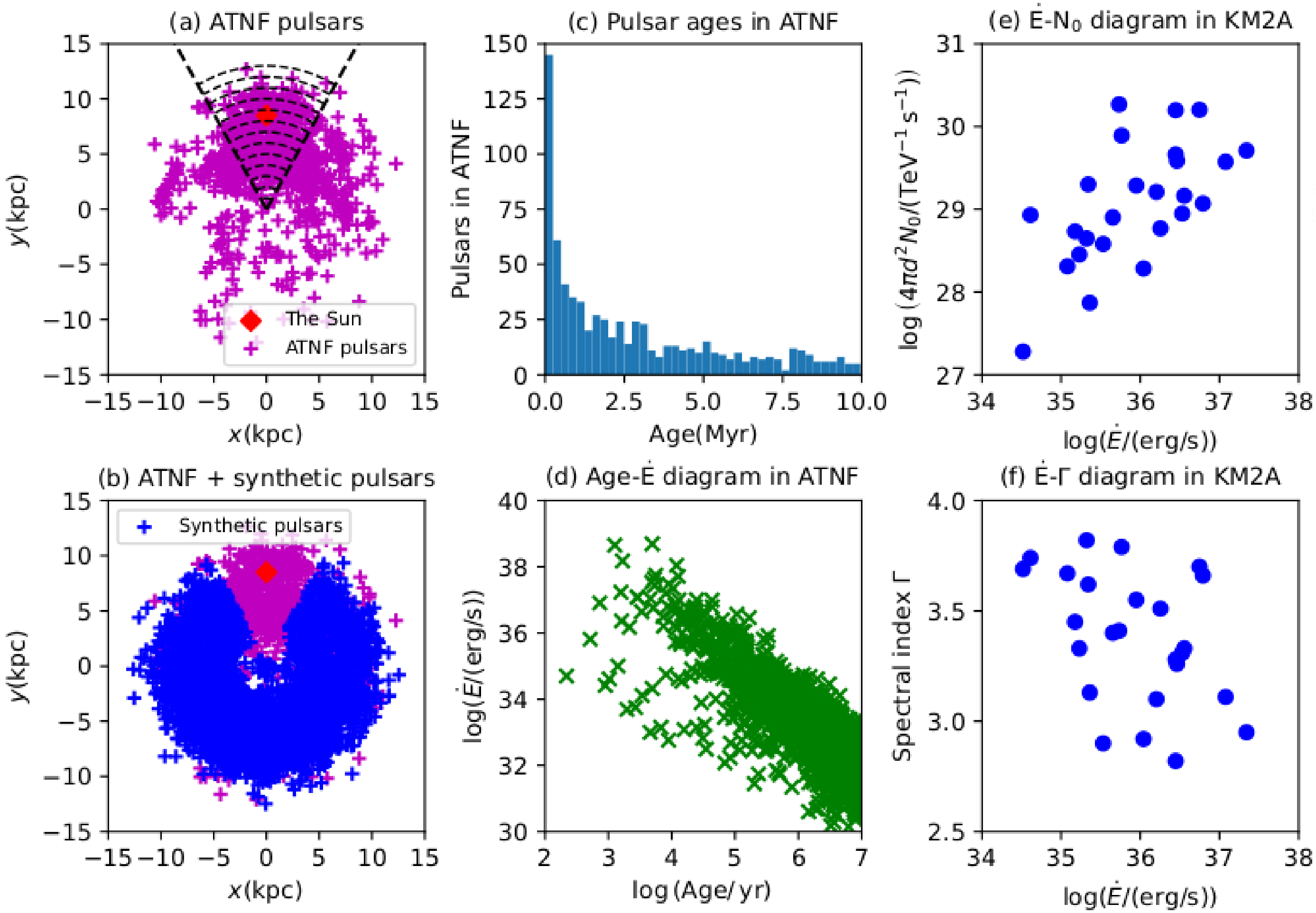
$$Q\left(E_{\mathrm{e}}, t\right)=Q_0(t)\, E_{\mathrm{e}}^{-s} e^{-E_{\mathrm{e}} / E_{\max }}$$

$$L_{\mathrm{s}}(t)=\eta_e L_{\mathrm{s}, 0} /\left(1+t / \tau_0\right)^2$$

$s=2.2$, $\eta_e \sim 0.1$ for both models

Leptonic contribution to the diffuse γ-ray background

Samy Kaci, Giacinti & Semikoz, arXiv:2407.20186



$$\log\left(\frac{\dot{E}}{\mathrm{erg/s}}\right) = \begin{cases} 38.59 - 0.69\log\left(\frac{\tau}{\mathrm{yr}}\right), & \tau \leq 10^5\,\mathrm{yr} \\ 42.23 - 1.48\log\left(\frac{\tau}{\mathrm{yr}}\right), & \tau > 10^5\,\mathrm{yr} \end{cases}$$

$$dN/dE \equiv N_0\,(E/E_0)^{-\Gamma}$$

$$\log\left(\frac{4\pi d^2 N_0}{\mathrm{TeV}^{-1}\,\mathrm{s}^{-1}}\right) = 7.19 + 0.61\log\left(\frac{\dot{E}}{\mathrm{erg/s}}\right)$$

$$\Gamma = 9.59 - 0.17\log\left(\frac{\dot{E}}{\mathrm{erg/s}}\right)$$

Figure 1. Summary of the source generation procedure. Panel (a) shows the ATNF pulsars with age from 0 to 10 Myr in the region (between the two dashed lines) used to extract their statistical properties. Panel (b) shows the ATNF and the synthetic pulsars generated with the same statistical properties. Histogram (c) shows the age distribution of the ATNF pulsars in the sampling region shown in panel (a). Panel (d) shows the relationship between the age of pulsars and their spindown power. Panels (e) and (f) respectively show the relationship between the spindown power and the reference flux and the spindown power and the spectral index reported by KM2A in Cao et al. (2024).

Leptonic contribution to the diffuse γ-ray background

Samy Kaci, Giacinti & Semikoz, arXiv:2407.20186

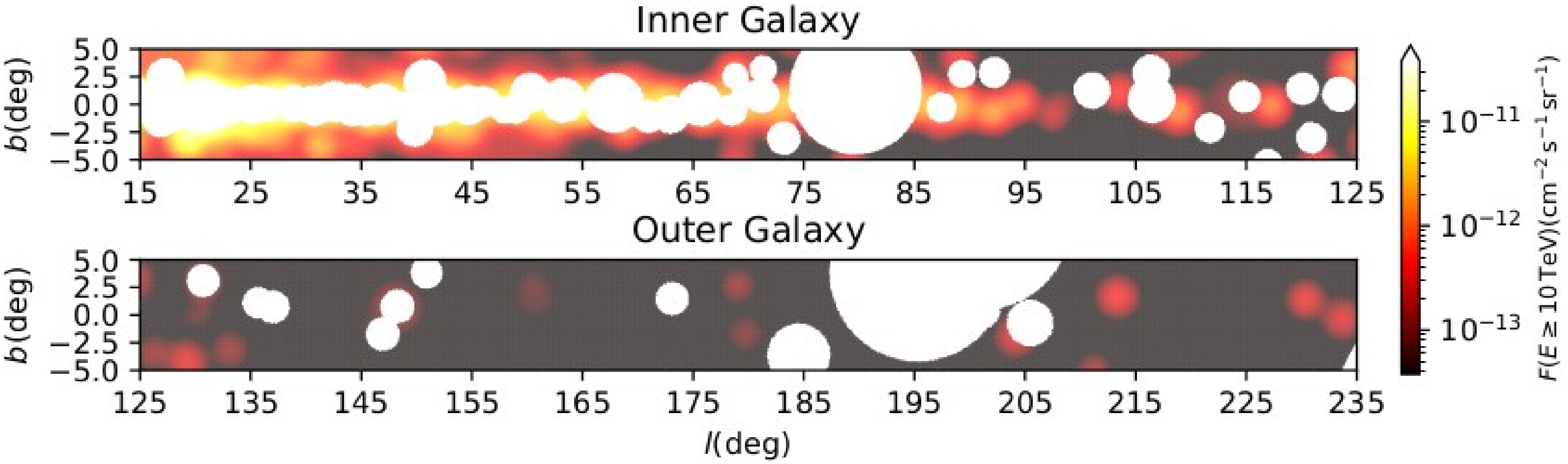


Figure 2. Gamma-ray flux of unresolved sources (without cut in spindown power) above 10 TeV in the (l, b) plane for the inner Galaxy (upper panel) and outer Galaxy (lower panel). The white regions represent the masks of LHAASO from Cao et al. (2023). The upper bound of the color-bar represents the sensitivity of LHAASO to a point source located at a declination of -10° and the lower bound of the color-bar represents 0.1% of its upper bound.

Leptonic contribution to the diffuse γ-ray background

Samy Kaci, Giacinti & Semikoz, arXiv:2407.20186

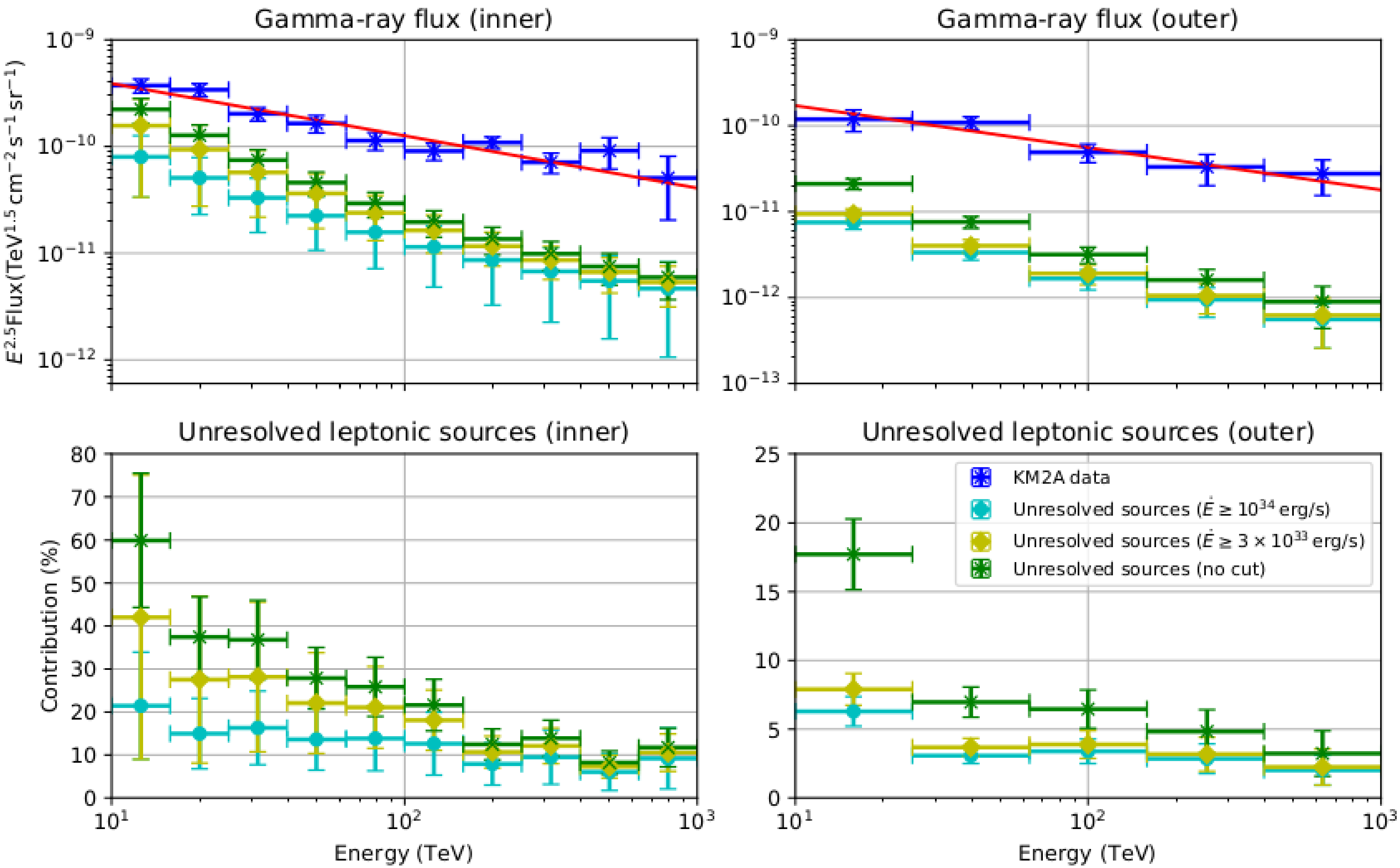


Figure 3. Contribution of unresolved sources to the diffuse gamma-ray background measured by LHAASO. The upper left (right) panel shows the diffuse flux measured by KM2A and the flux of unresolved sources in the inner (outer) Galaxy. The lower left (right) panel shows the relative contribution of unresolved sources to the diffuse flux measured by LHAASO in the inner (outer) Galaxy.

Conclusions and perspectives

- Halos: **Relativistic e^- energy density subdominant (test particles in the ISM).**

- **HAWC measurements compatible with e^- in ISM turb. :**

  $B_{rms} \sim 3\ \mu G$ $L_c <\sim 5$ pc

- Or impact of a regular B field to match lack of X-ray synchrotron ?

- **TeV halos as a probes of** :
  → **Turbulent interstellar magnetic fields**
  → CR-driven instabilities around hadronic sources?

- Contribution to UHE diffuse background unclear – Might be small

Analyses w/ LHAASO: → **2D on sky,**
→ **function of E_γ ?**