Gamma-ray Pulsar Halos

Based on Liu 2022, IJMPA, 37, 2230011, arXiv:2207.04011

See also
Lopez-Coto et al. 2022, NA, 6, 199, arXiv:2202.06899
Fang 2022, FrASS, 9, 1022100, arXiv:2209.13294

Ruoyu Liu
Nanjing University

08.03.2023, CDY talk (online)

Outline

What are pulsar halos?

- Observations

How are they formed?

- Theoretical Models

Why are they important?

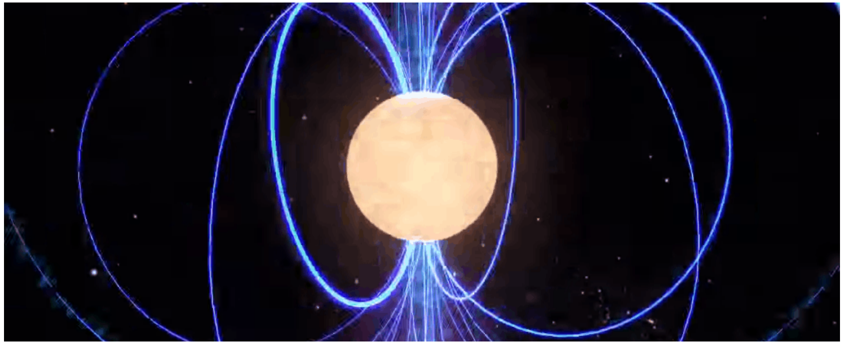
- Implications

How could we figure out their nature?

- Prospect

Pulsar and Pulsar Wind

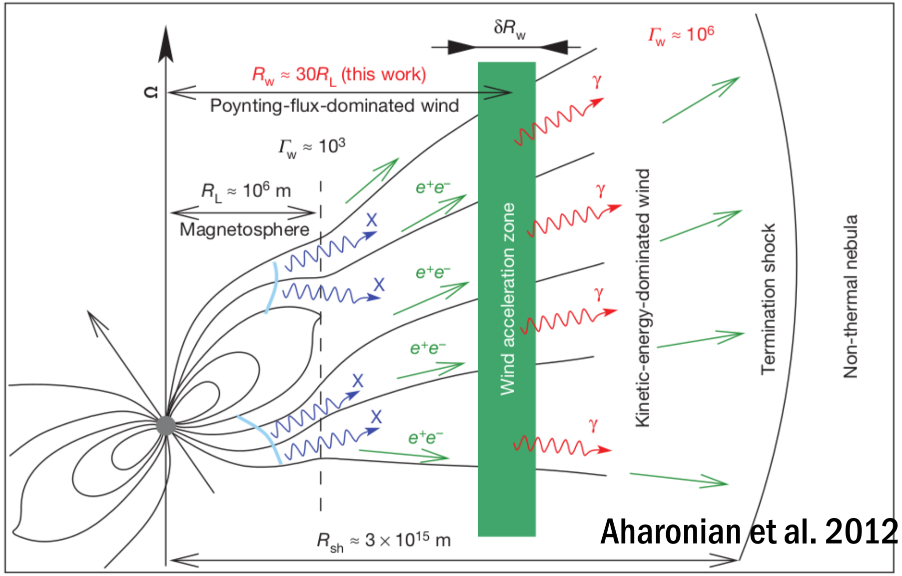
Pulsars: highly magnetized, fast-rotating neutron star



$$L \propto B^2 R^6 P^{-4}$$

$$\dot{\Omega} = -k\Omega^n \qquad L_s \equiv I\Omega\dot{\Omega} = \frac{L_{s,0}}{(1+t/\tau_0)^{\frac{n+1}{n-1}}}$$

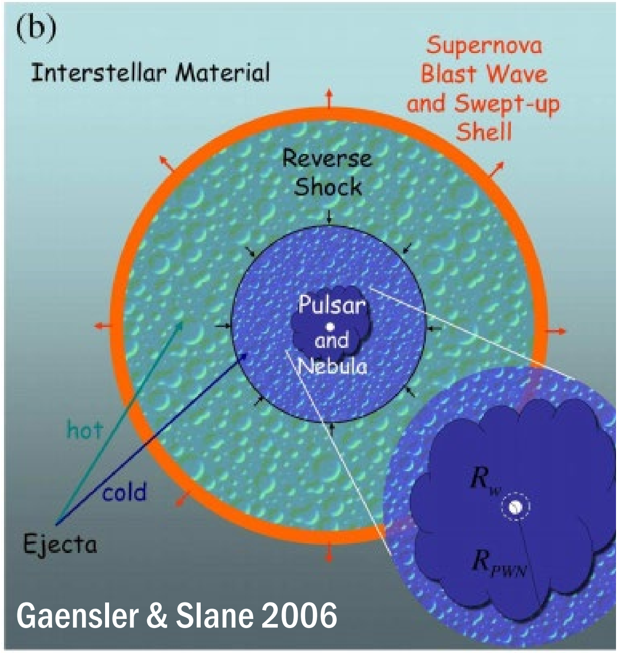
n: braking index (1<=n<=3)
τ_0: initial spin-down timescale
$L_{s,0}$: initial spin-down luminosity

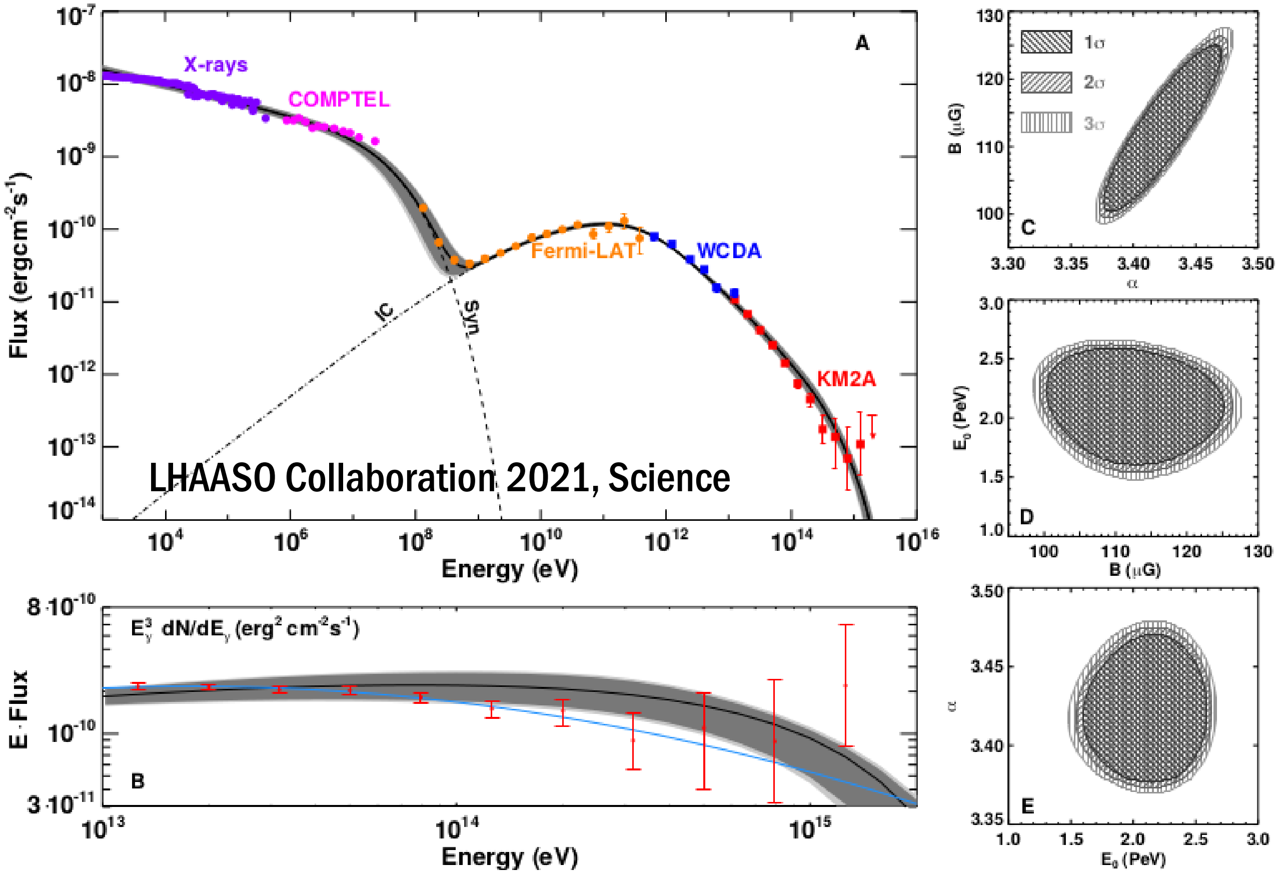


Aharonian et al. 2012

Rotational energy ⟶ electromagnetic energy ⟶ kinetic energy

Pulsar Wind Nebula: shocked pulsar wind

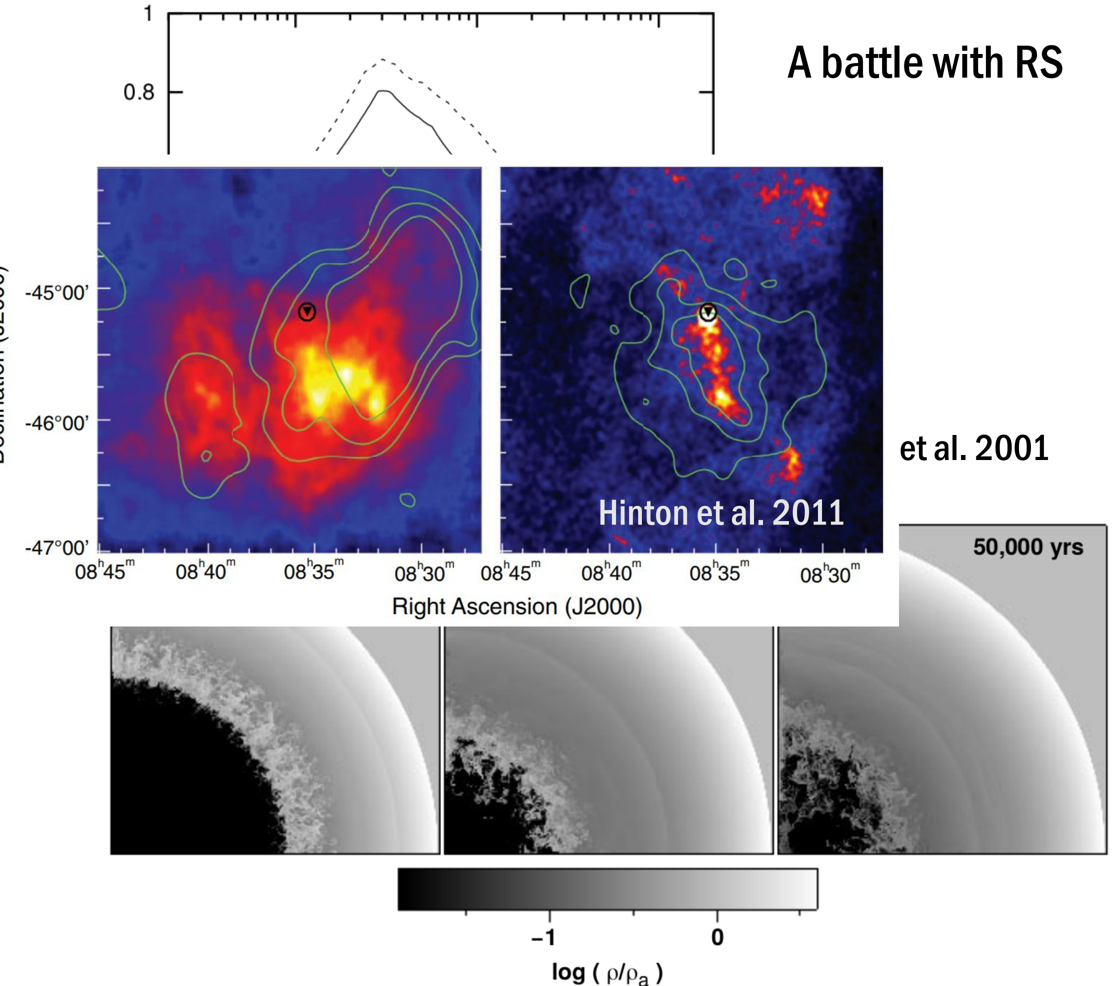




A guaranteed high-energy leptons accel

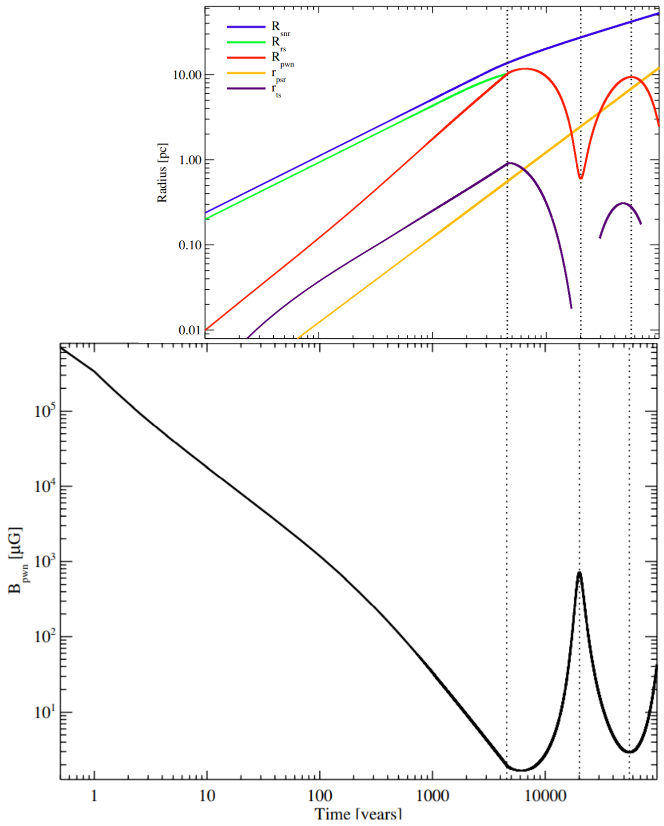
What's going on next?

A battle with RS



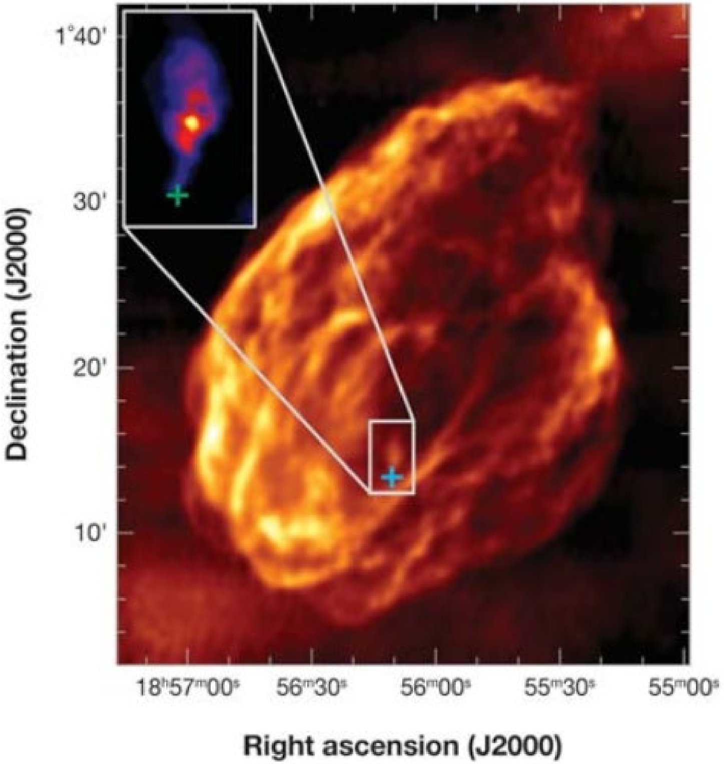
et al. 2001

Gelfand et al. 2009



Bow-Shock PWN

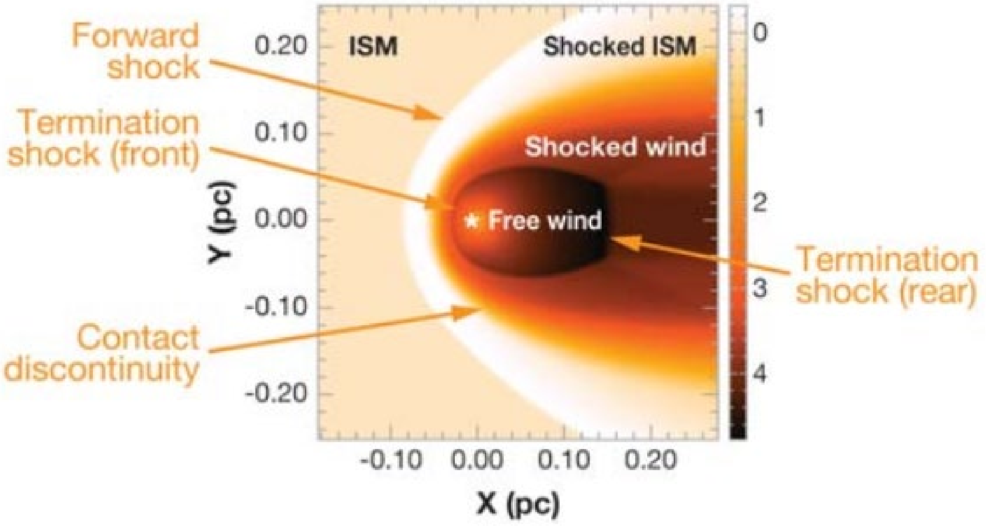
Conservation of Momentum: Natal kick velocity: 400-500 km/s



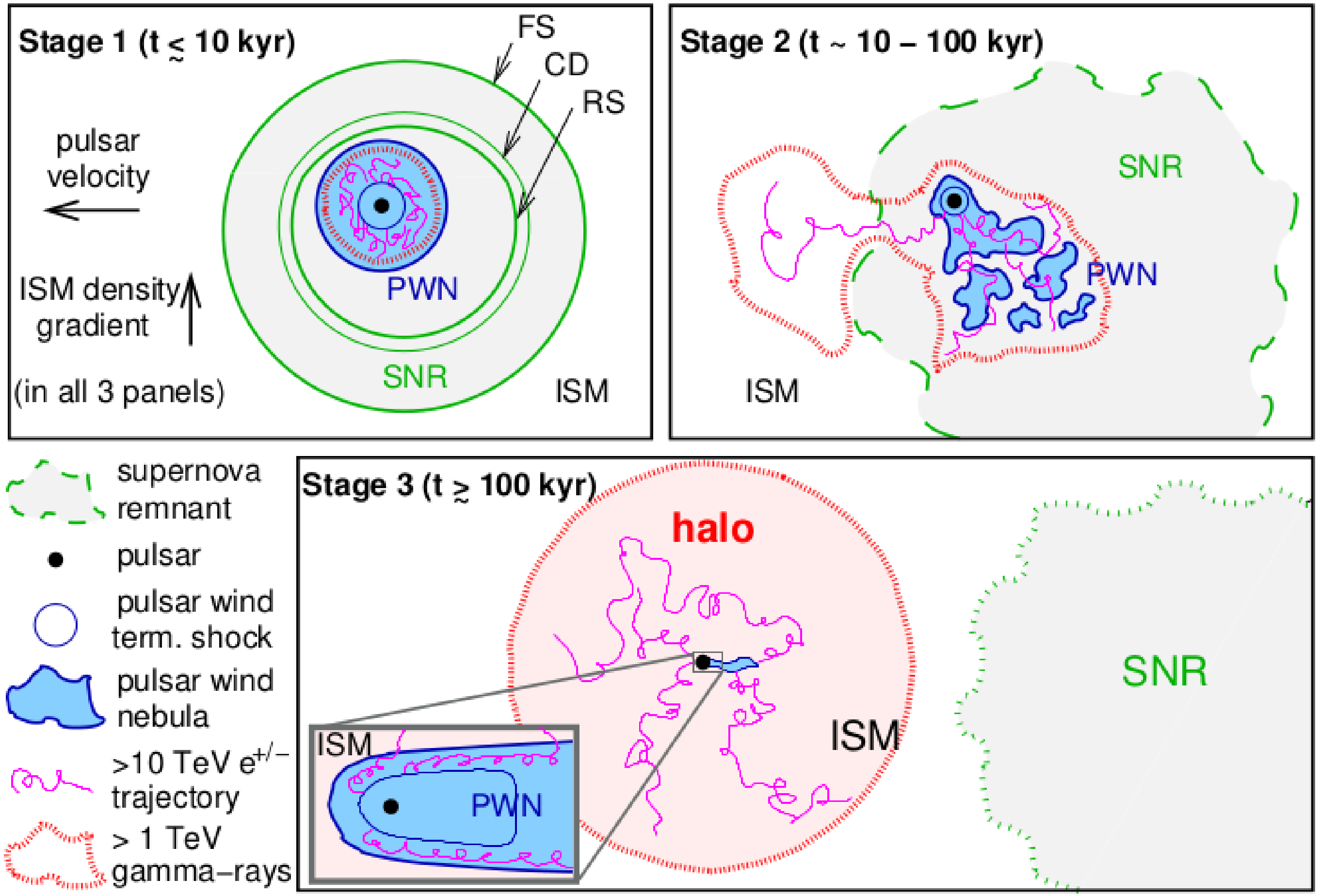
Giacani et al. 1997 Frail et al. 1996

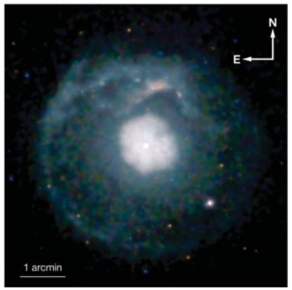
Pulsar will eventually leave the related SNR

$$t_{cross} = 44\left(\frac{E_{SN}}{10^{51}\mathrm{ergs}}\right)^{1/3}\left(\frac{n_0}{1\ \mathrm{cm}^{-3}}\right)^{-1/3}\left(\frac{V_{\rm PSR}}{500\ \mathrm{km\ s}^{-1}}\right)^{-5/3}\mathrm{kyr.}$$

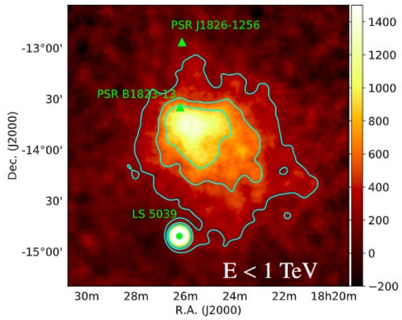


Gaensler et al. 2004

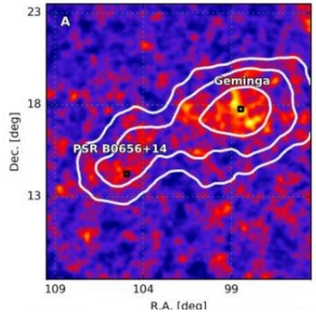




SNR G21.5-0.9
PSR J1833-1034



HESS J1825-137
PSR J1826-1334

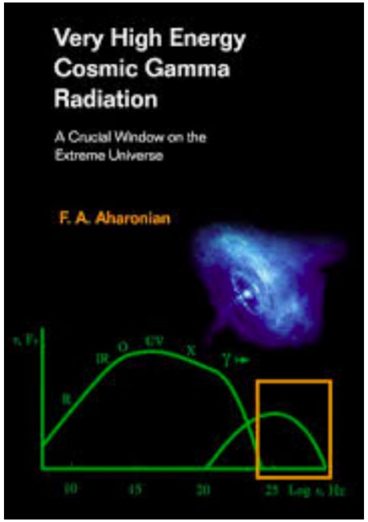


Geminga
Monogem

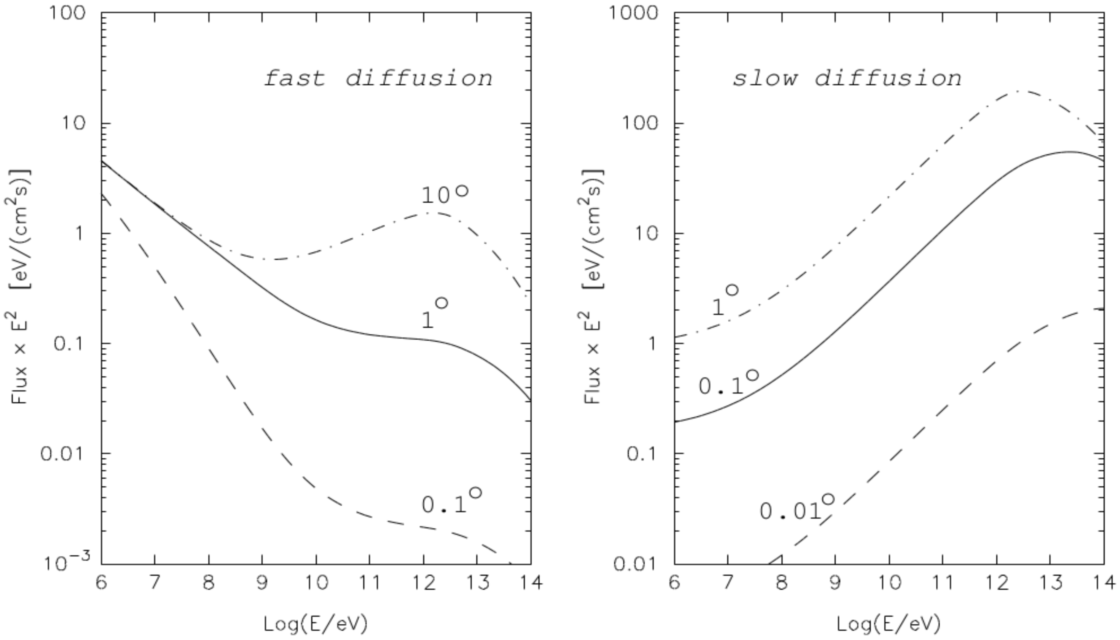
Prediction of halo around leptonic CR sources

Prediction of relativistic electron clouds expanding in the ISM around CRe sources

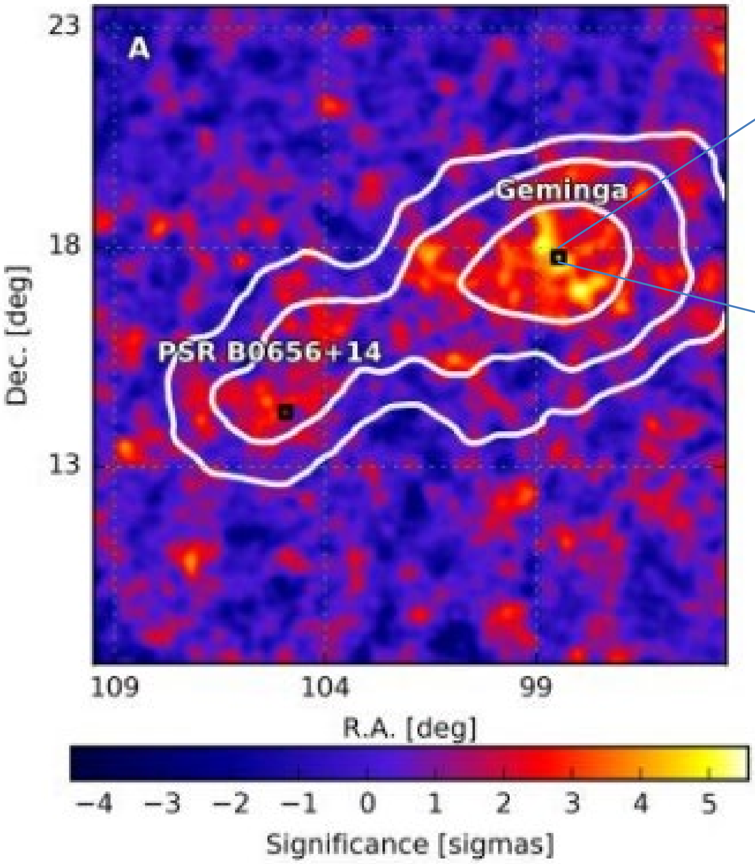
Inverse Compton of electrons on IR/CMB → gamma ray

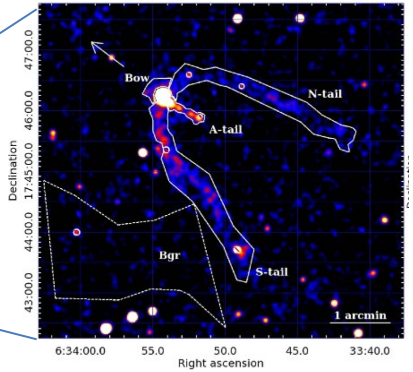


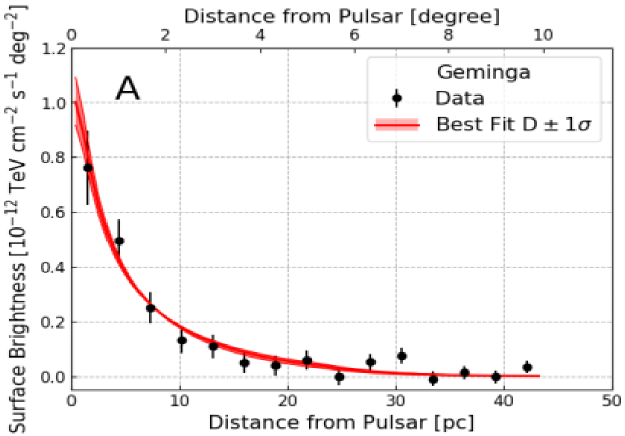
Aharonian 2004

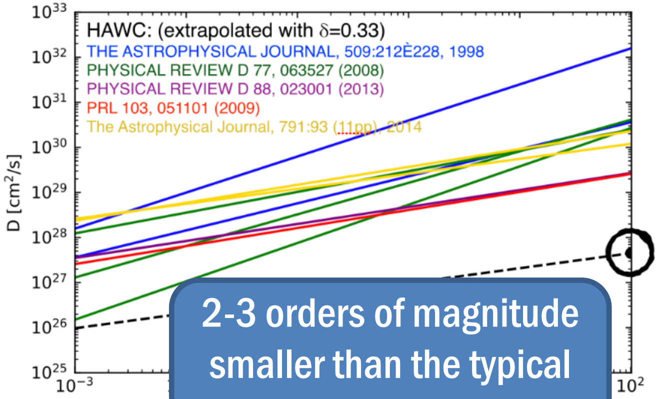


HAWC's measurement

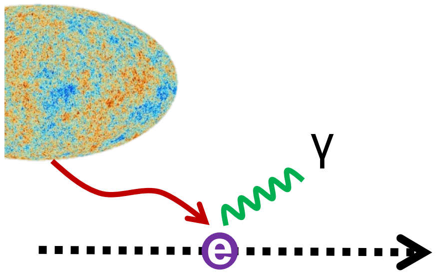






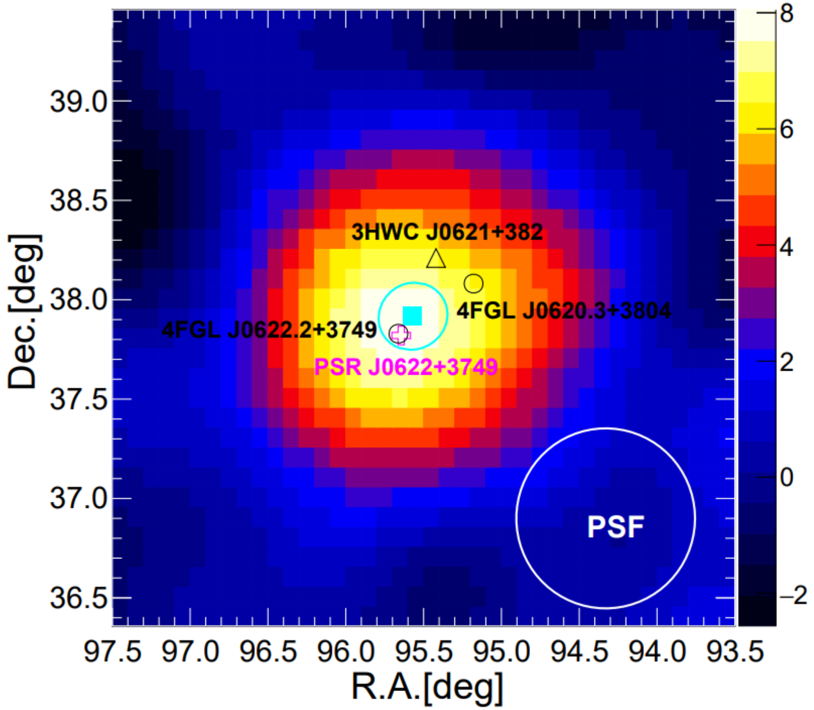


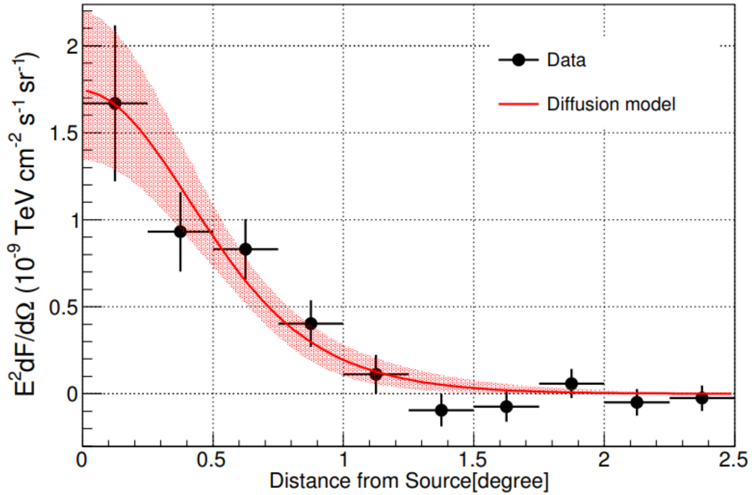
2-3 orders of magnitude smaller than the typical ISM diffusion coefficient

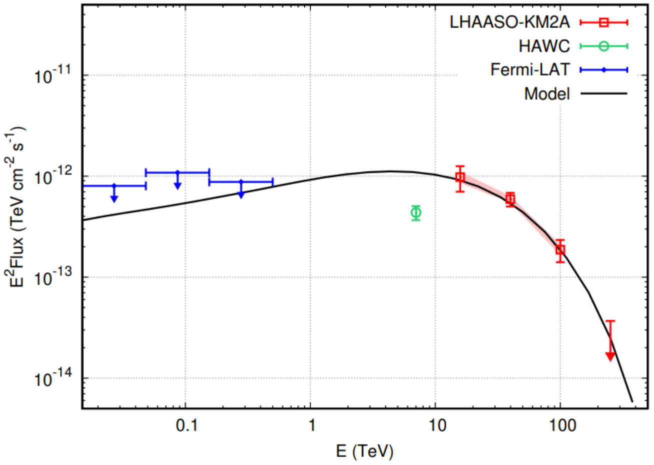


²/sec]	4.5 ± 1.2
two PWN	

LHAASO's measurement

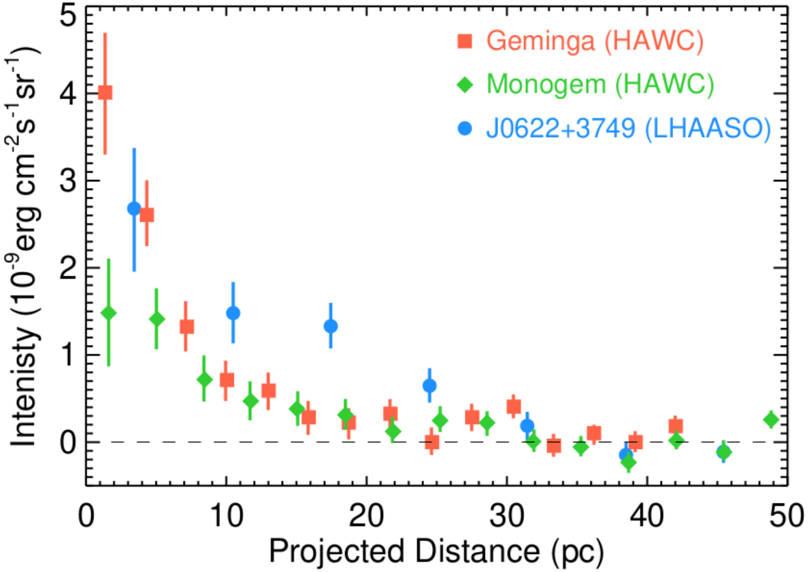






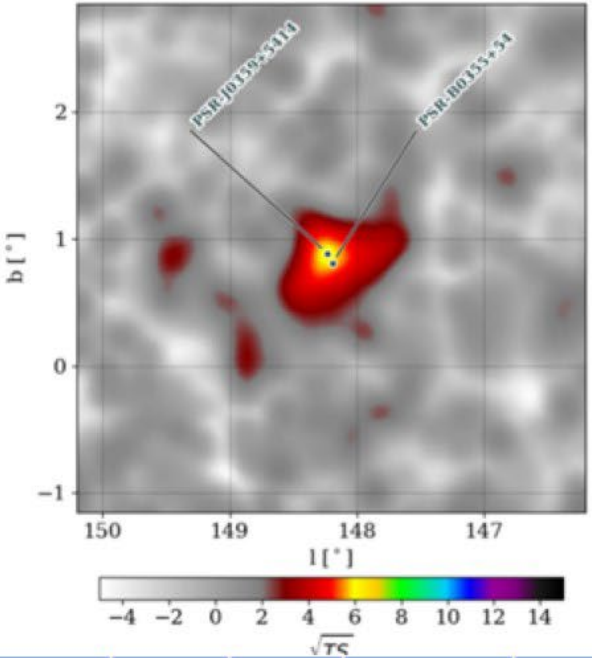
$D \approx (8.9\ ^{+4.5}\ _{-3.9})\ \mathrm{x}10^{27}(d/1.6\ \mathrm{kpc})^2\ \mathrm{cm}^2\mathrm{s}^{-1}$ for $E_e \sim 160$ TeV

LHAASO Collaboration 2021, PRL



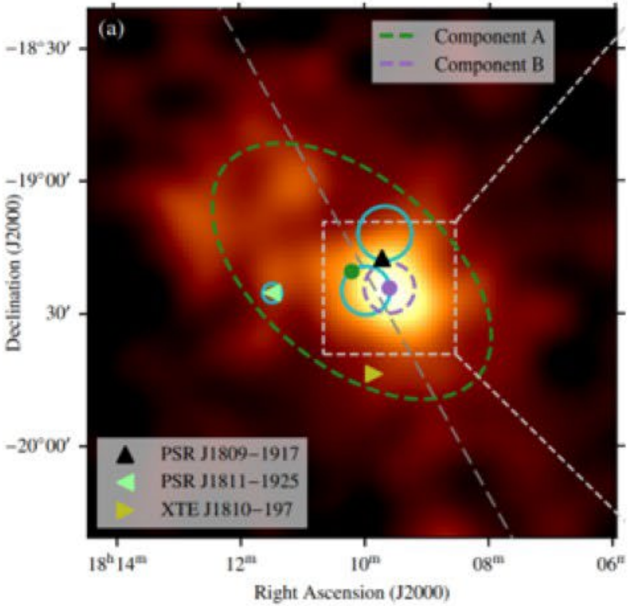
Pulsar	P (s)	$\dot{P}$ (10^{-14})	τ_c (kyr)	d (kpc)	L_s (10^{34}erg/s)	$L_s/4\pi d^2$ (10^{-10}erg/cm^{2}s)
PSR J0633+1746[a]	0.237	1.097	342	0.25[c]	3.2	43
PSR B0656+14[b]	0.385	5.494	111	0.29	3.8	38
PSR J0622+3749	0.333	2.542	208	1.6[d]	2.7	0.88

More Candidates



	T_c (kyr)	P_0 (s)	Dist. (kpc)	E_{dot} (erg/s)
J0359+5414	75.2	0.079	3.4	1.3e36
J0358+5413	564	0.156	1.6	4.5e34

HAWC Collaboration 2023, ApJ



	T_c (kyr)	P_0 (s)	Dist. (kpc)	E_{dot} (erg/s)
J1809-1917	51.4	0.082	3.3	1.8e36
J0358+5413	564	0.156	1.6	4.5e34

HESS Collaboration 2023

1. GeV gamma-ray Emission

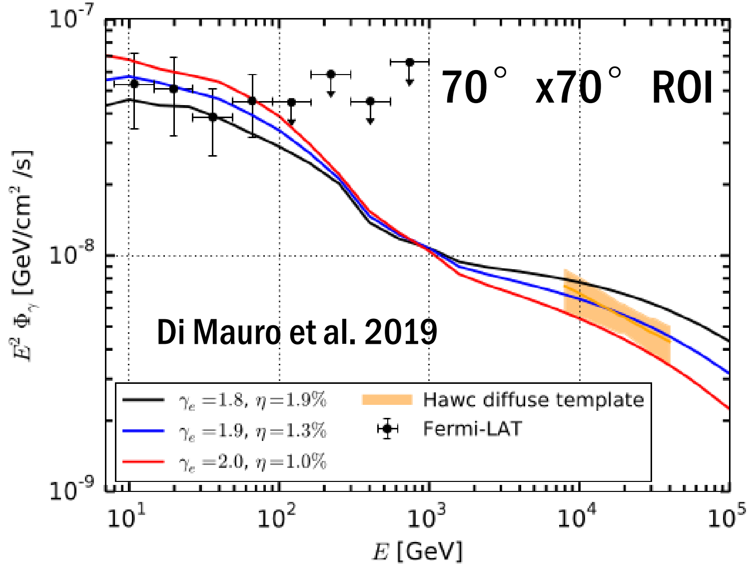
Depending on Low-energy spectrum

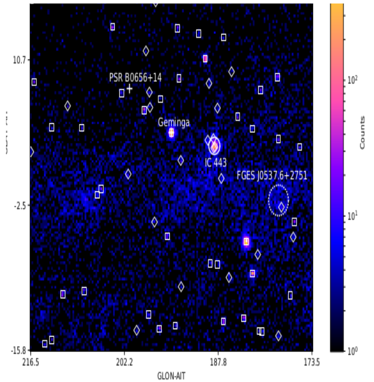
2. X-ray Emission

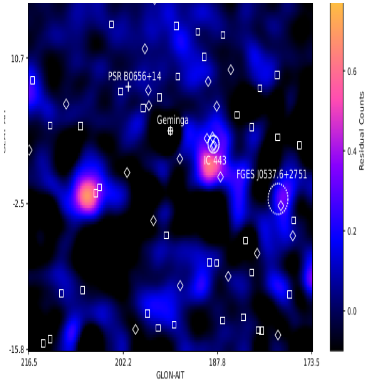
$$E_\gamma \approx (E_e/m_e c^2)^2 \epsilon = 25(E_e/100\mathrm{TeV})^2\ \mathrm{TeV}$$

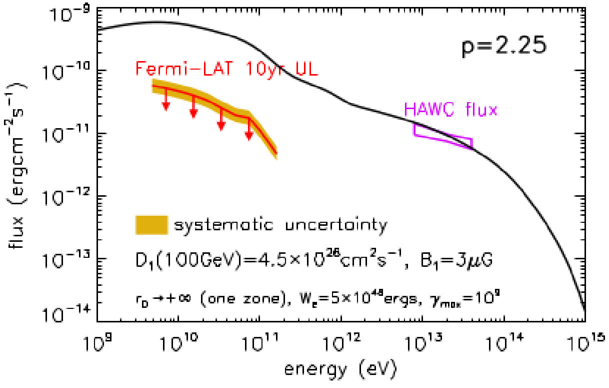
$$E_{\mathrm{syn}} \simeq 2(E_e/100\mathrm{TeV})^2 (B/3\mu\mathrm{G})\ \mathrm{keV},$$

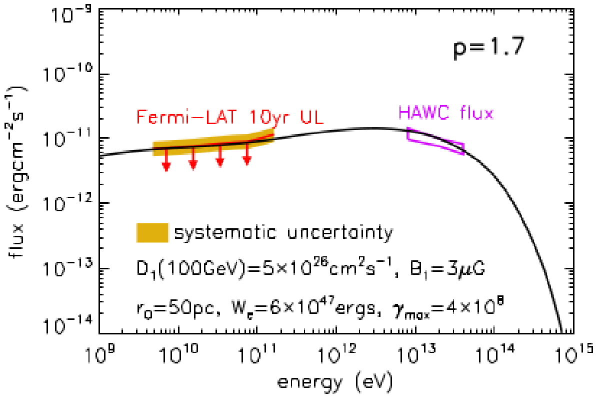
Searching for GeV halo

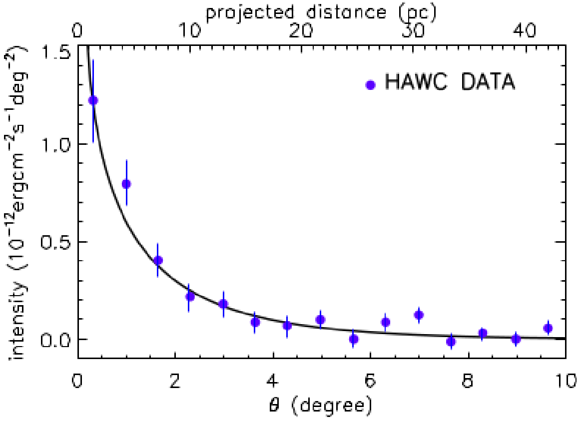


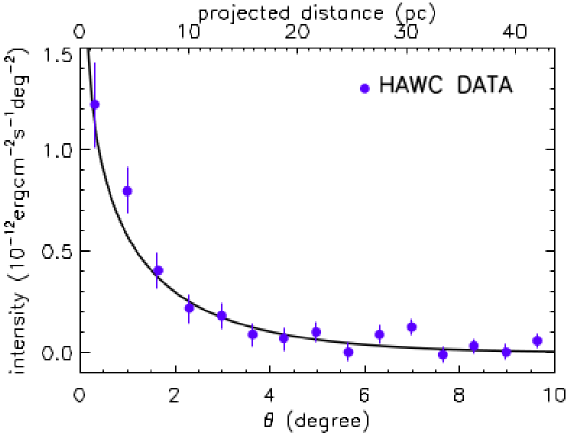








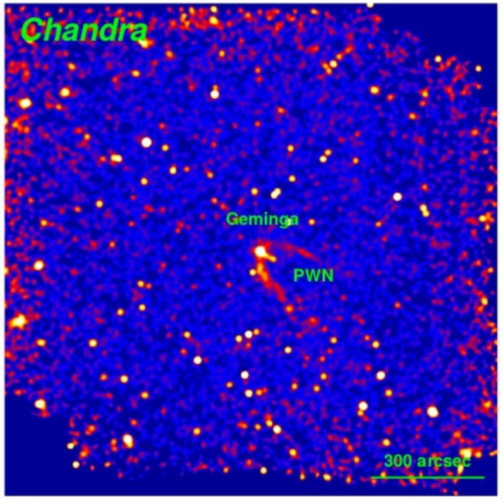


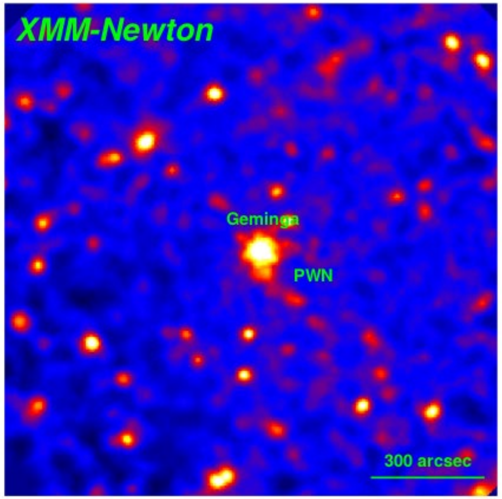


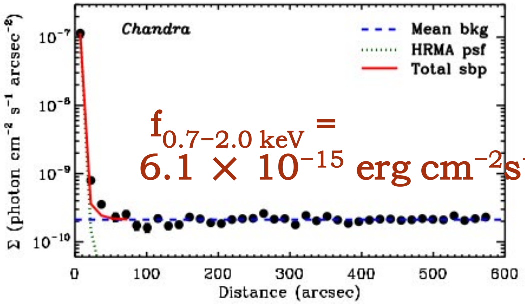
40° x40° ROI, 10-500GeV

Xi, RYL et al. 2019

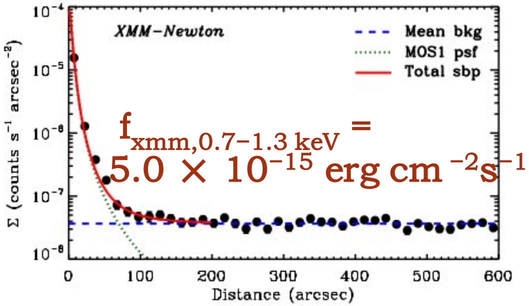
X-ray measurements







$f_{0.7-2.0\ \mathrm{keV}} = 6.1 \times 10^{-15}\ \mathrm{erg\ cm^{-2} s^{-1}}$

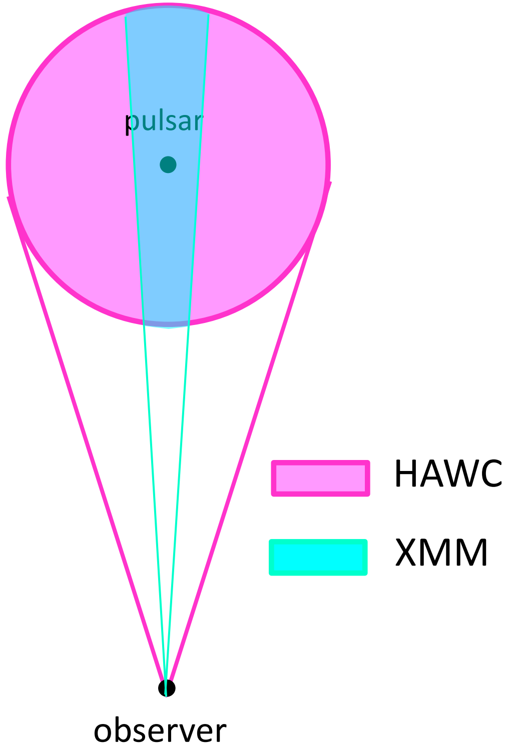


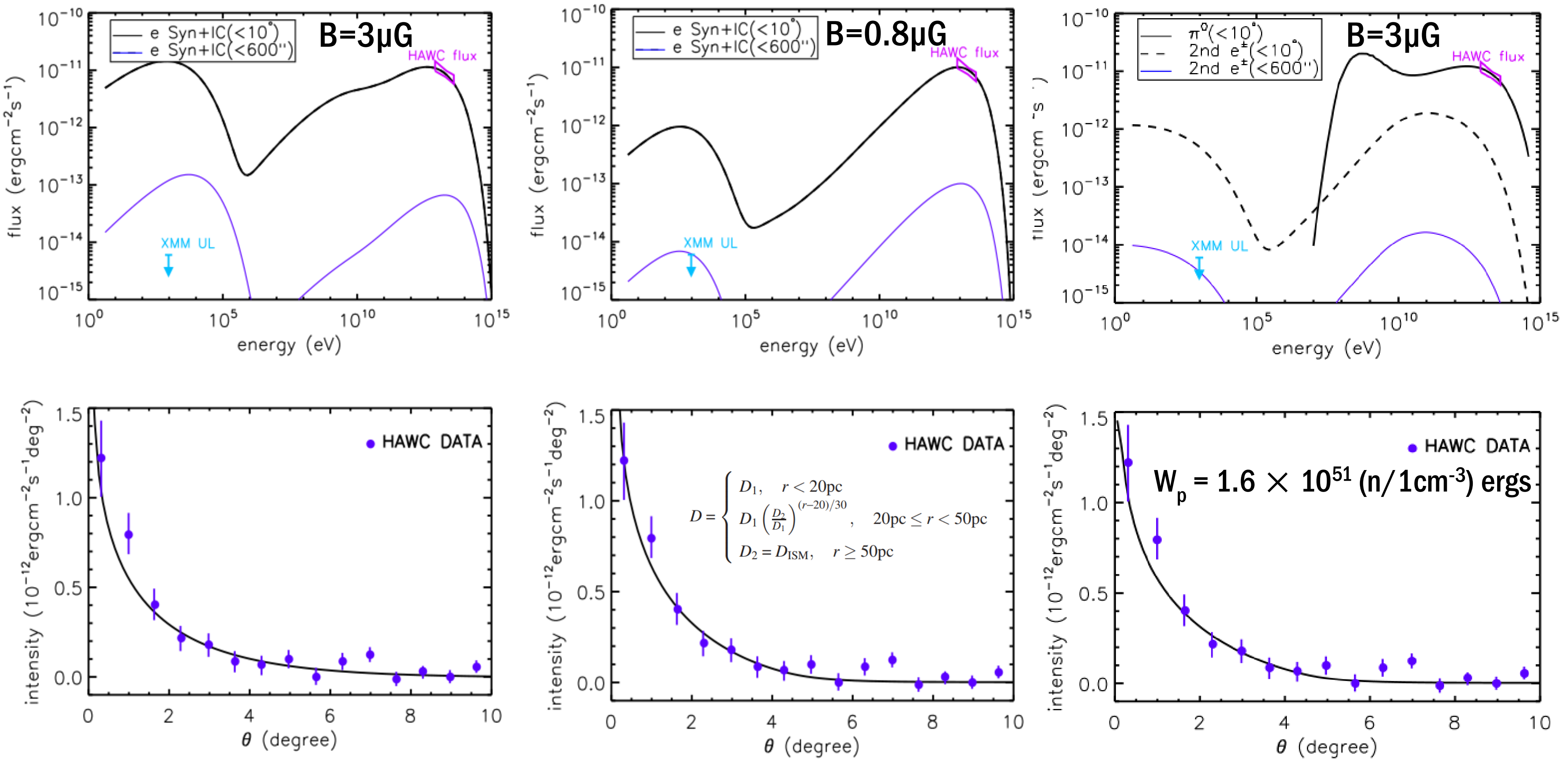
$f_{xmm,0.7-1.3\ \mathrm{keV}} = 5.0 \times 10^{-15}\ \mathrm{erg\ cm^{-2} s^{-1}}$

RYL et al. 2019a

Small FOV

Cannot determine background





B=3μG
e Syn+IC(<10°)
e Syn+IC(<600")
HAWC flux
XMM UL
flux (ergcm^{-2}s^{-1})
energy (eV)
B=0.8μG
e Syn+IC(<10°)
e Syn+IC(<600")
HAWC flux
XMM UL
B=3μG
π^0(<10°)
2nd $e^{\pm}$(<10°)
2nd $e^{\pm}$(<600")
HAWC flux
XMM UL
HAWC DATA
intensity (10^{-12}ergcm^{-2}s^{-1}deg^{-2})
θ (degree)
$D = \begin{cases} D_1, & r < 20\text{pc} \\ D_1\left(\frac{D_2}{D_1}\right)^{(r-20)/30}, & 20\text{pc} \le r < 50\text{pc} \\ D_2 = D_{\rm ISM}, & r \ge 50\text{pc} \end{cases}$
$W_p = 1.6 \times 10^{51}$ (n/1cm^{-3}) ergs

Model I: Isotropic, suppressed diffusion model

$$\frac{\partial N(E_e, r, t)}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 D(E_e, r)\frac{\partial N}{\partial r}\right) - \frac{\partial}{\partial E_e}\left(\dot{E}_e N\right) + Q(E_e, t)\delta(r)$$

$$D(E, r) = \begin{cases} D_0 (E/100\,\mathrm{TeV})^{\delta_0}, & r < r_0 \\ D_{\rm ISM} (E/100\,\mathrm{TeV})^{\delta}_{\rm ISM}, & r \geq r_0 \end{cases}$$

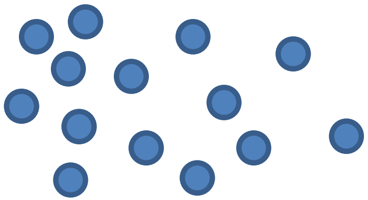
n ~(Q/4πDr) * exp($-r^2/L_{diff}$)

Key issue: Origin of the slow diffusion

CR self-regulation – Streaming Instability

Net flux v_D

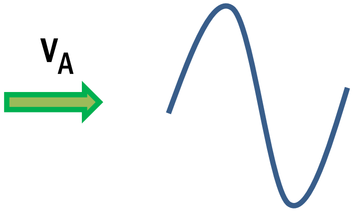
High-density



Low-density

Diffusion: wave-particle scattering

v_A



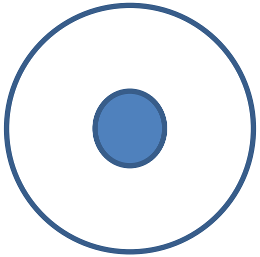
Isotropization in wave frame

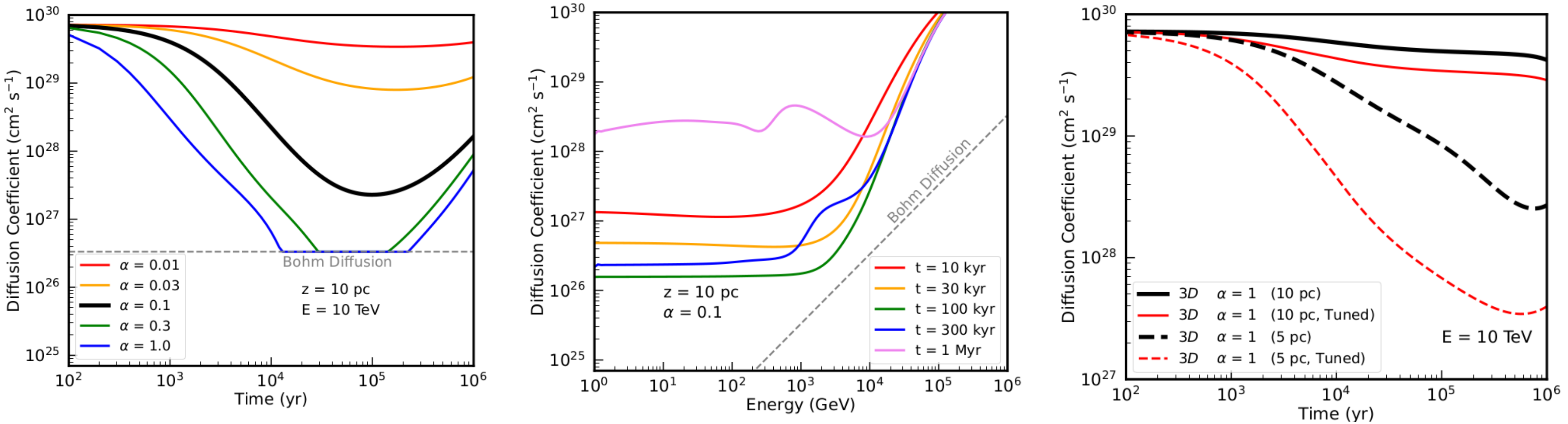
Momentum gain in wave : $nm(v_D - v_A)$

Kulsrud 1969

$$\frac{\partial W}{\partial t} + v_A \frac{\partial W}{\partial z} = (\Gamma_{CR} - \Gamma_D) W$$

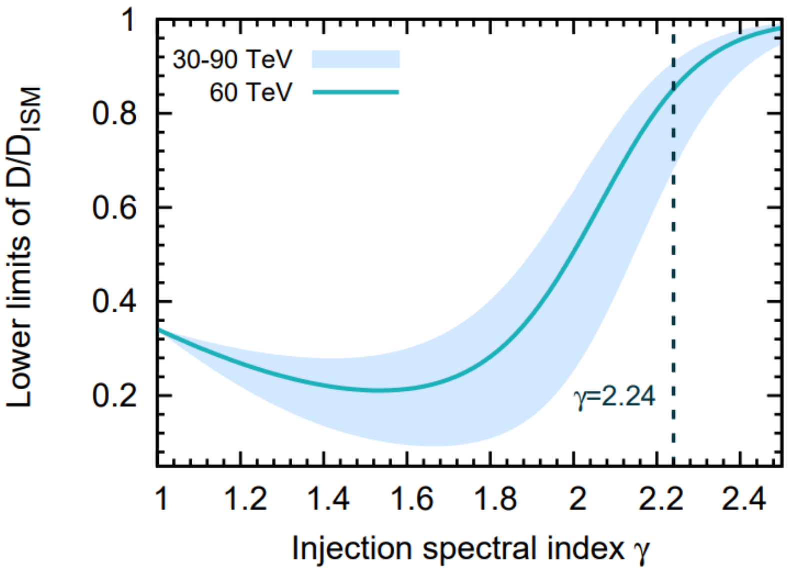
$$\frac{\partial f}{\partial t} = Q_e(p,z,t) - u_A \frac{\partial f}{\partial z} + \frac{\partial}{\partial z}\left(D(p,z,t) \frac{\partial f}{\partial z} \right) + \frac{\partial u}{\partial z}\frac{p}{3}\frac{\partial f}{\partial p} - \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 \frac{dp}{dt} f \right)$$

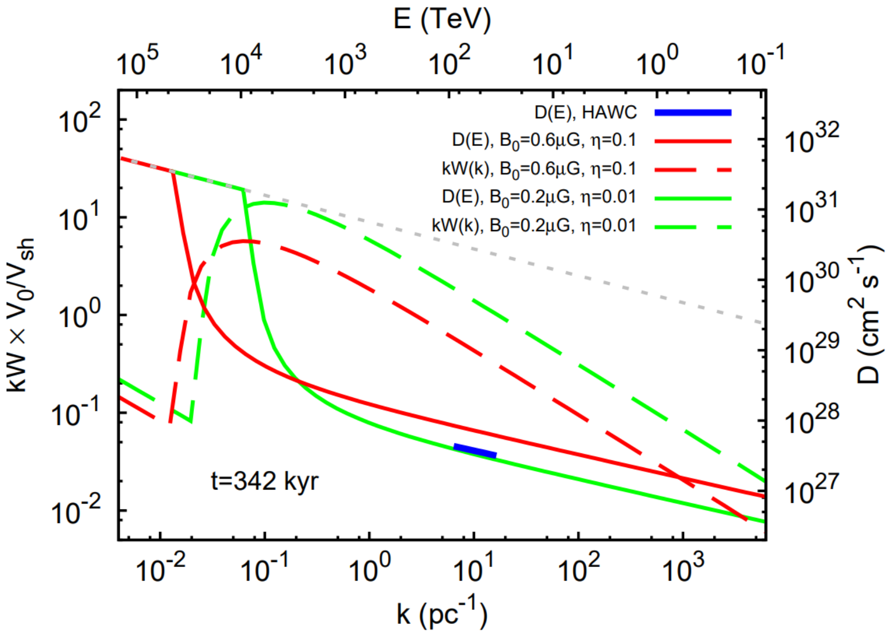




Mukhopadhyay & Linden 2022

See also Evoli et al. 2018





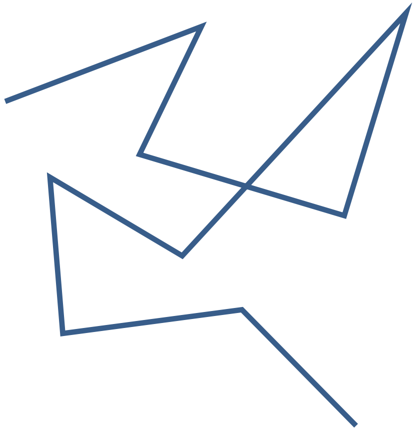
Without considering damping, cooling
$\longrightarrow$ most optimistic case

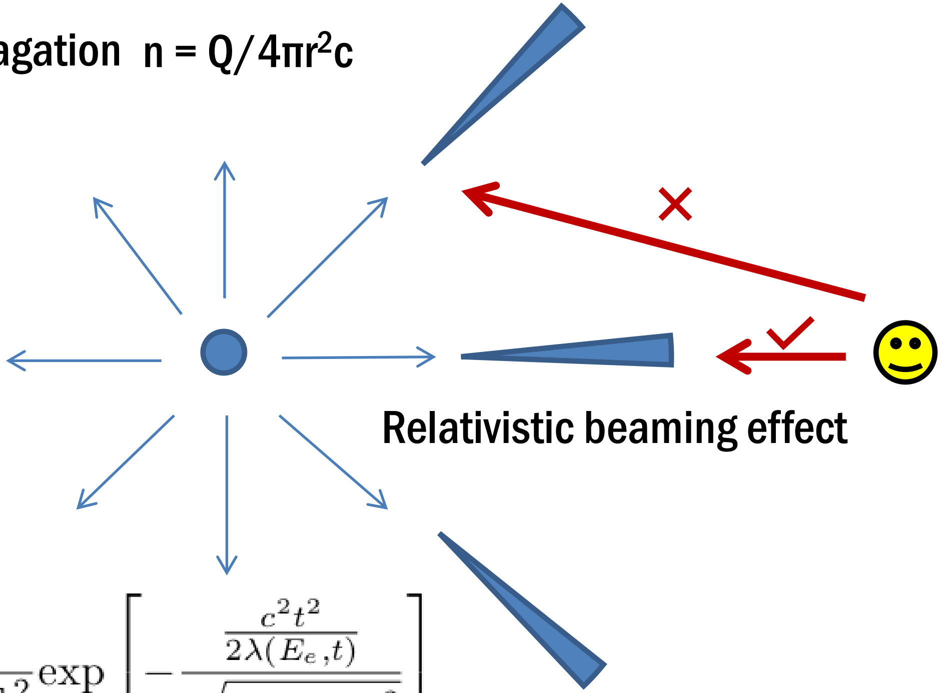
SNR-driven turbulence?

Fang et al. 2019

Model II: Transition from Ballistic Propagation to Diffusion

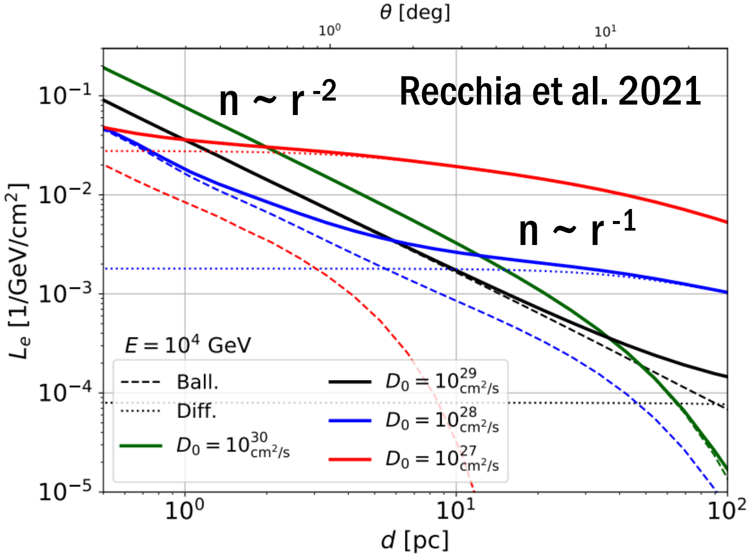
r < Mean free path $\lambda \sim 3D/c$: quasi-ballistic propagation $n = Q/4\pi r^2 c$

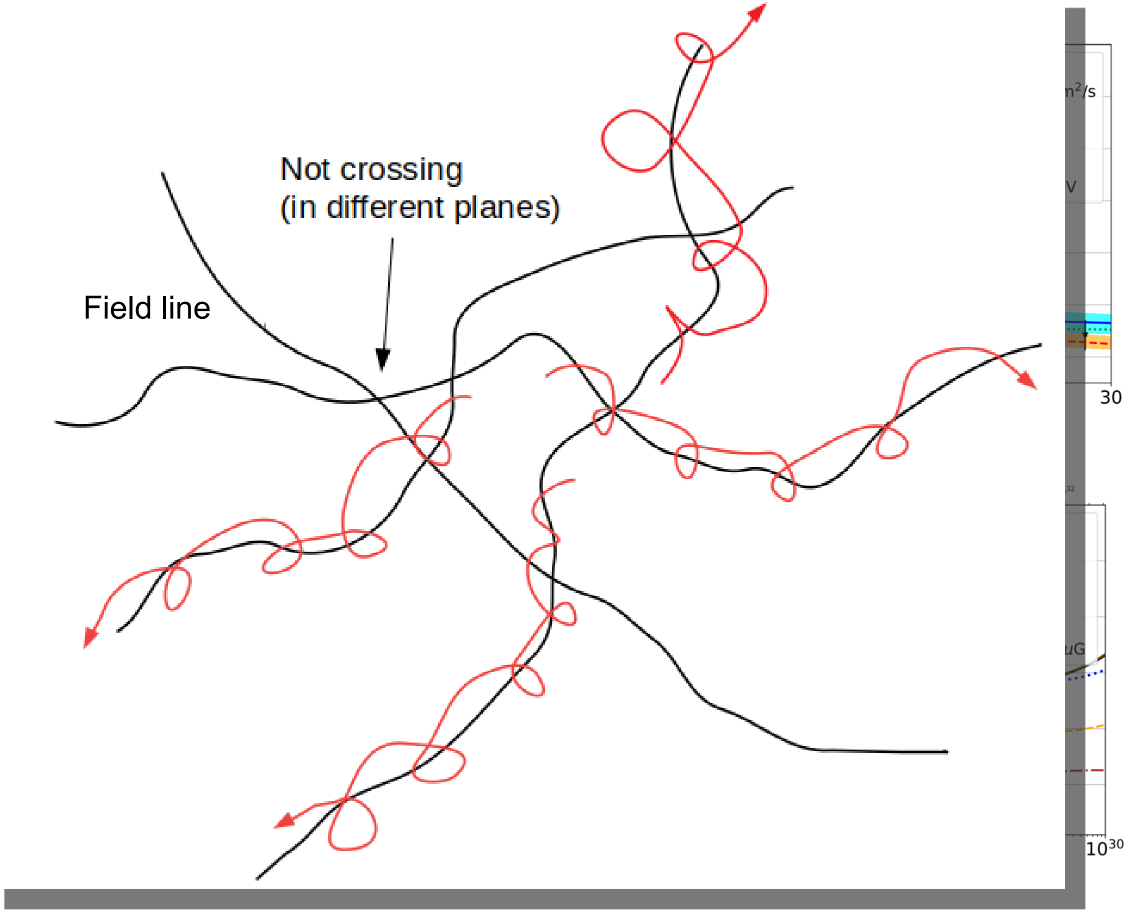




$$P(E_e, r, t) = \frac{\theta(ct - r)}{(ct)^3 Z\left(\frac{c^2t^2}{2\lambda(E_e,t)}\right)\left[1 - \left(\frac{r}{ct}\right)^2\right]^2} \exp\left[-\frac{\frac{c^2t^2}{2\lambda(E_e,t)}}{\sqrt{1 - \left(\frac{r}{ct}\right)^2}}\right]$$

Alosio & Berezinsky 2009; Prosekin et al. 2015

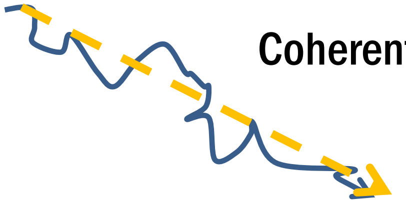




Energy crisis η_e>~1 (see also Bao et al. 2021)

$r_g << r < \lambda$, ballistic v.s. helical

r_g ~0.01-0.1 pc for 100TeV particles



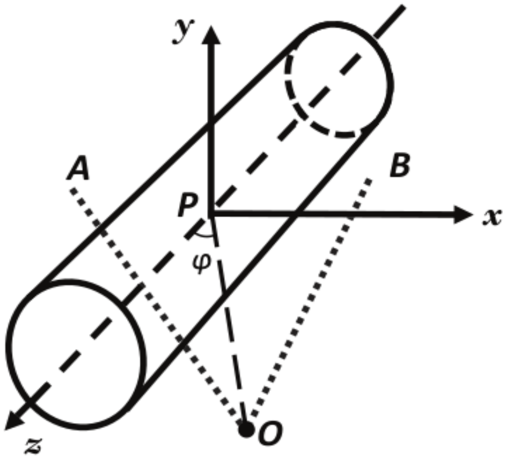
Coherent length 10-100pc

Model III: Anisotropic Diffusion

sub-Alfvenic ($M_A \sim \Delta B_{inj}/B_0 < 1$) turbulence, **anisotropic**

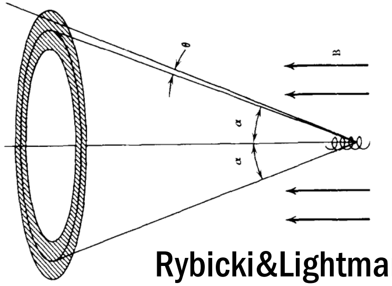
(in ISM, $0.1 \lesssim M_A \lesssim 1$)

$$D_{zz} = D_{\parallel} = D_0 (E_e/1\mathrm{GeV})^q$$
$$D_{rr} = D_{\perp} = D_{zz} M_A^4$$

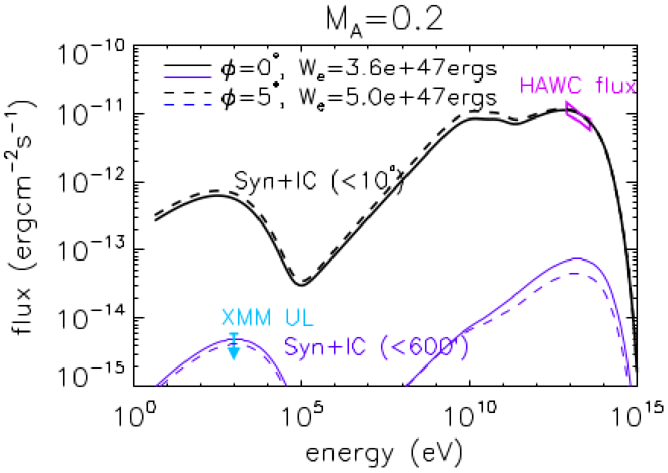


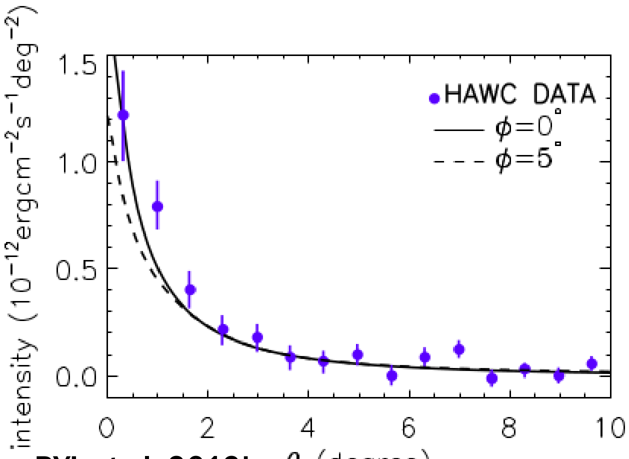
X-ray emission can be reduced significantly if the mean B field is roughly aligned with our line of sight

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



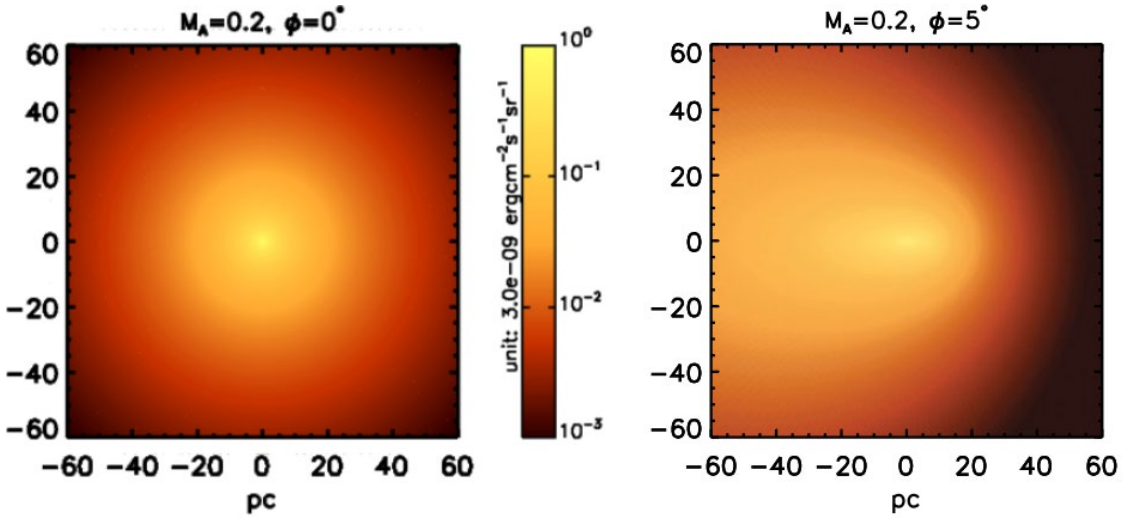
Rybicki&Lightman1979





RYL et al. 2019b

$$\frac{\partial N_e}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rD_\perp \frac{\partial N_e}{\partial r}\right) + D_\parallel \frac{\partial^2 N_e}{\partial z^2} - \frac{\partial}{\partial E_e}\left(\dot{E}_e N_e\right) + Q(E_e, t)\delta(r)\delta(z)$$

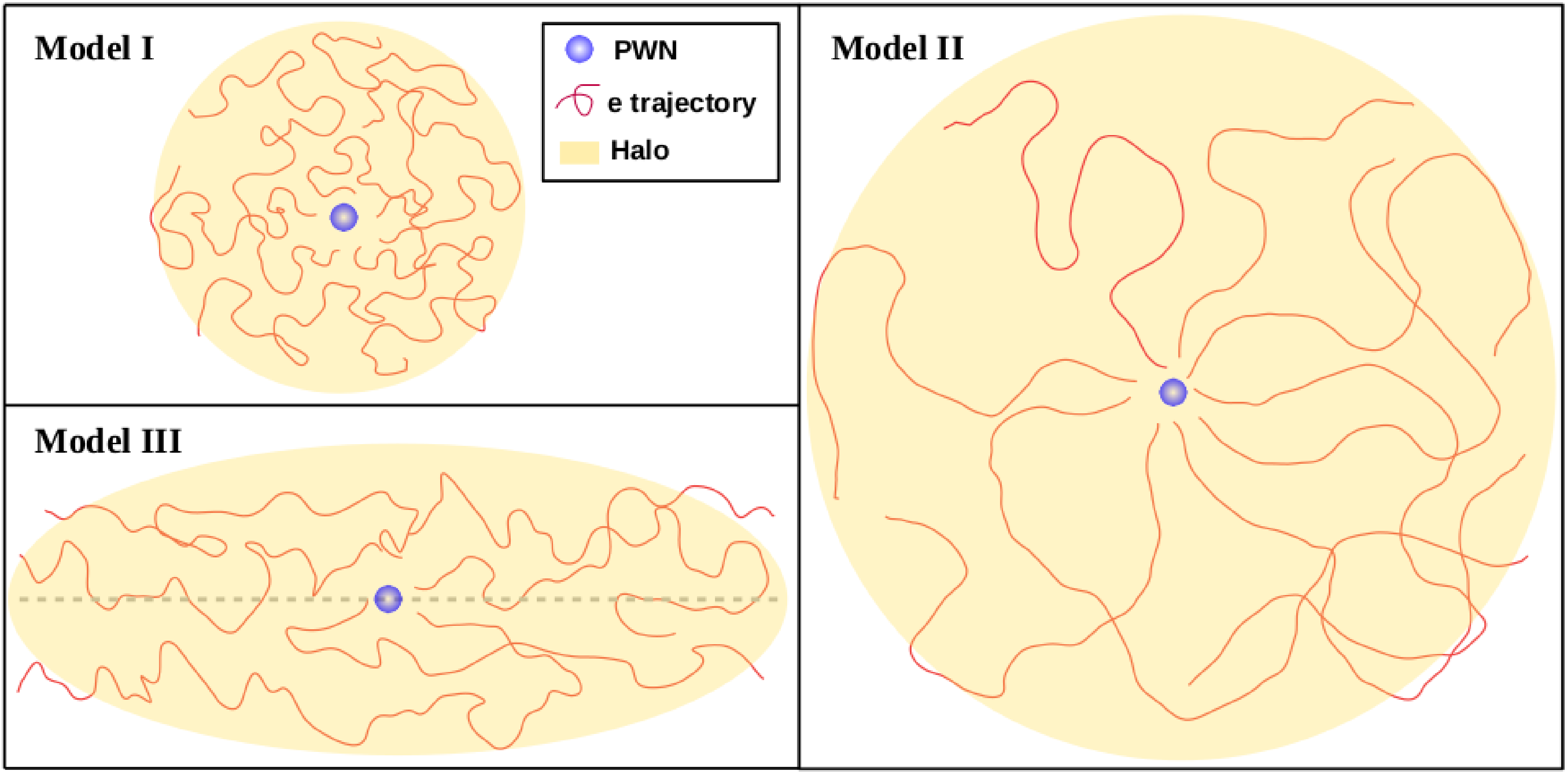


Mean B field around other pulsar halos cannot be always aligned with LOS.

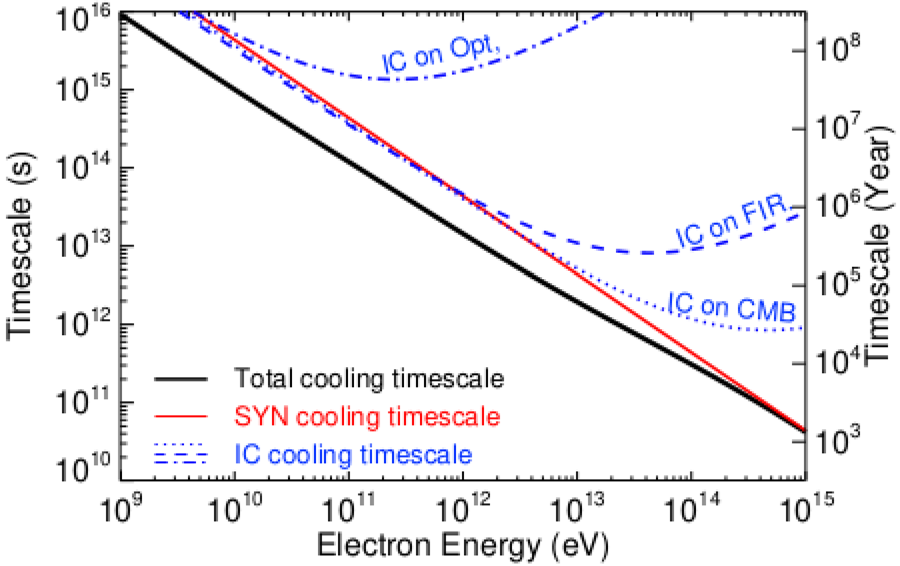
Then why elongated halo is not observed?

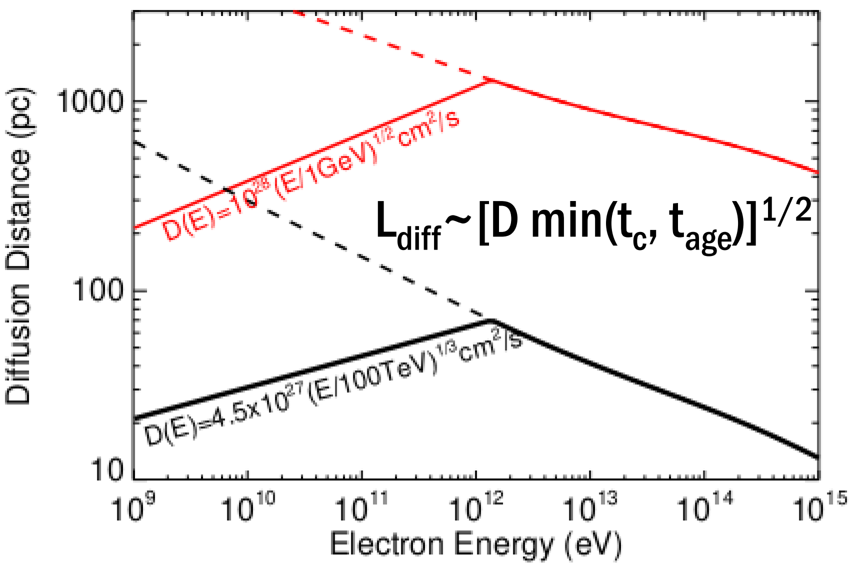
See also De La Torre Luque et al. 2022

Model	Diffusion Coefficient	Magnetic Field	Field Topology	Energy Budget
I	$\sim 0.01 D_{\rm ISM}$	$< 1\,\mu$G	Chaotic	$\sim 0.01 - 0.1 L_{\rm s}$
II	$\sim D_{\rm ISM}$	$< 1\,\mu$G	Chaotic[a]	$\sim L_{\rm s}$
III	$D_{\parallel} \sim D_{\rm ISM},\ D_{\perp} \sim 0.01 D_{\rm ISM}$	typical $B_{\rm ISM}$	Regular[b]	$\sim 0.01 - 0.1 L_{\rm s}$



Physical Implications – Diffuse Gamma-ray Emission

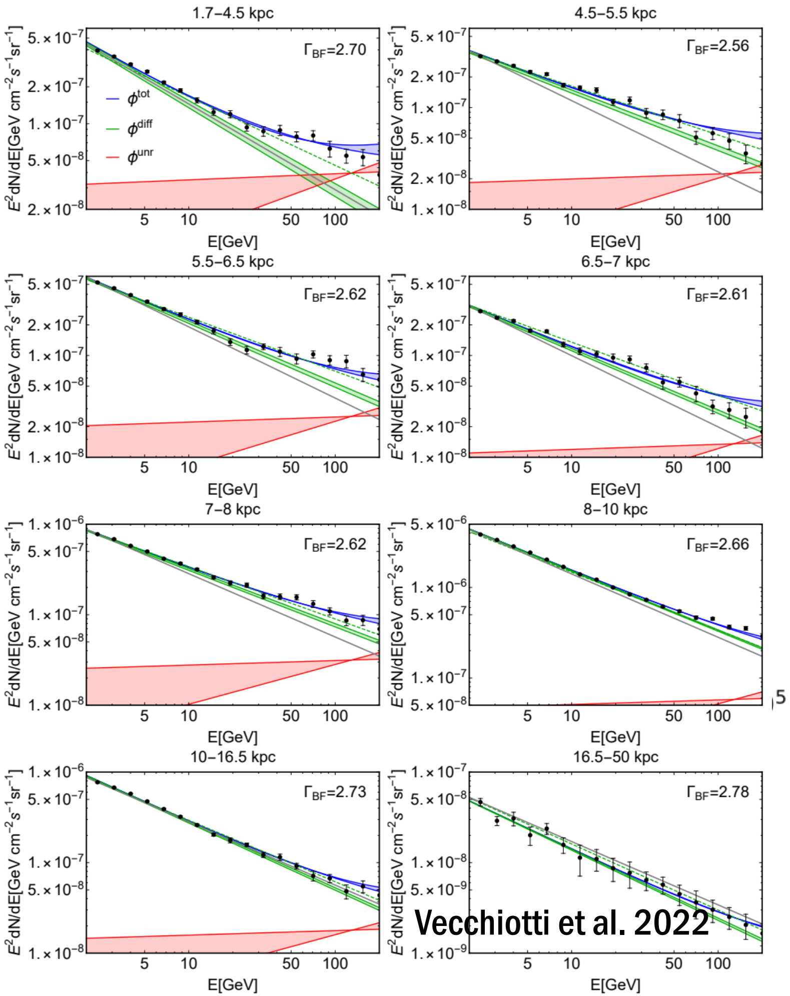




$L_{diff} \sim [D \min(t_c, t_{age})]^{1/2}$

TeV-emitting Electrons/positrons cool before leaving Galactic plane

Physical Implications – Diffuse Gamma-ray Emission



Vecchiotti et al. 2022

integrated Milky Way SN(=pulsar birth) rate of $\sim$0.015 yr^{-1}

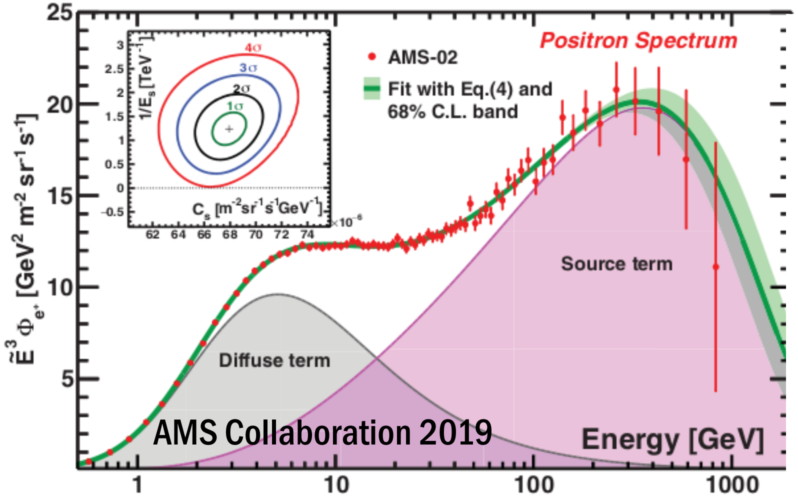
10% of the spin-down power e$^{\pm}$ pairs above 1 GeV

Injection: PL+exp.cutoff, p=1.7, E_c=100TeV

May form a Diffuse Gamma-ray Background influencing the significance of extended sources above 1TeV

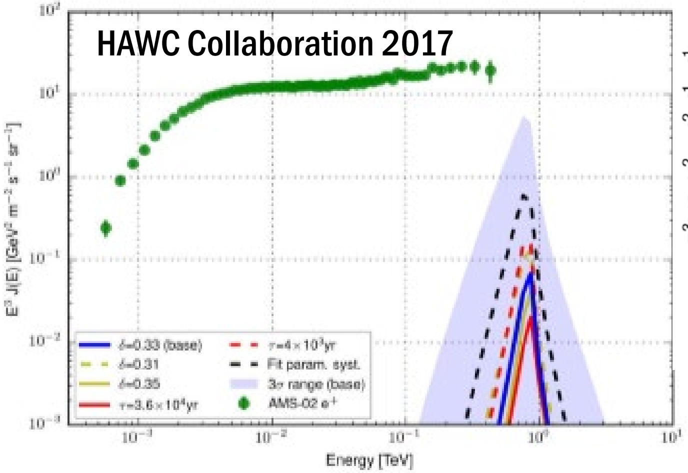
Physical Implications – Positron Excess

Dark Matter v.s. Astrophysical Objects

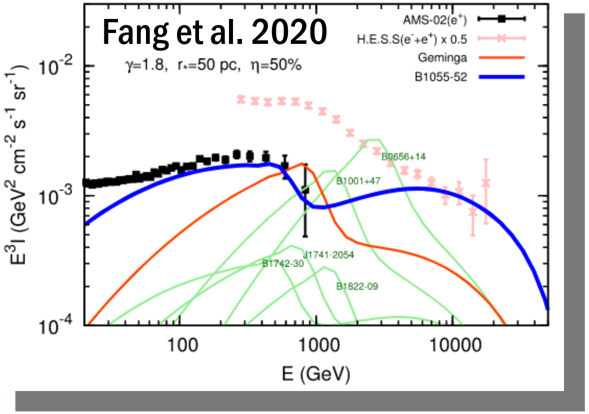


AMS Collaboration 2019

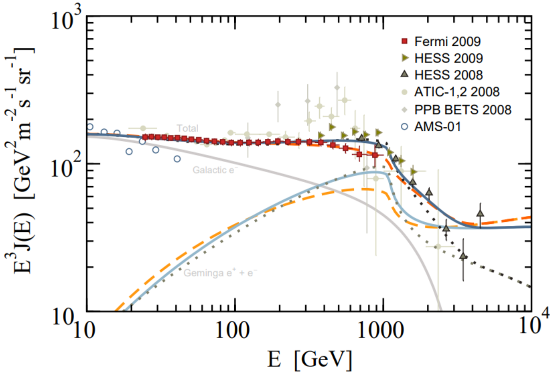
Model I



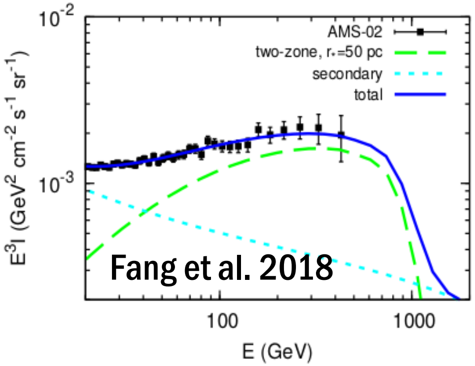
HAWC Collaboration 2017



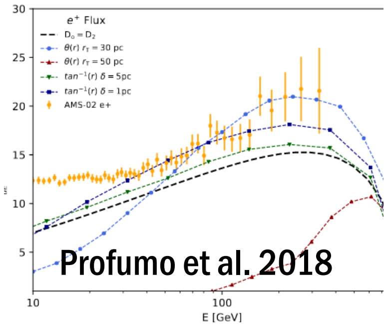
Fang et al. 2020



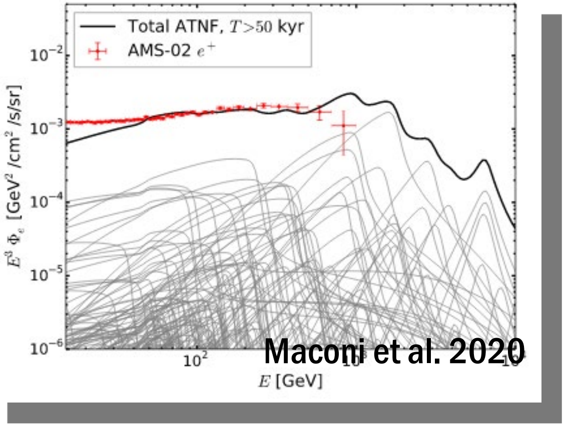
Yuksel et al. 2009



Fang et al. 2018

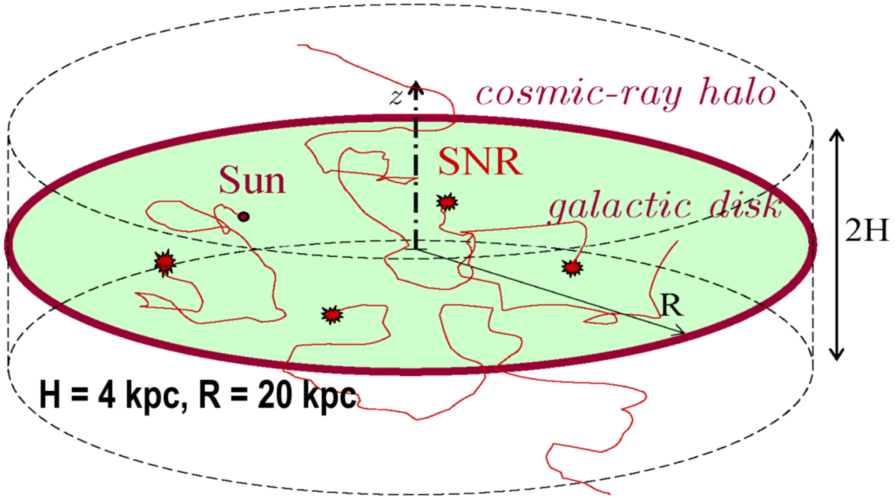


Profumo et al. 2018

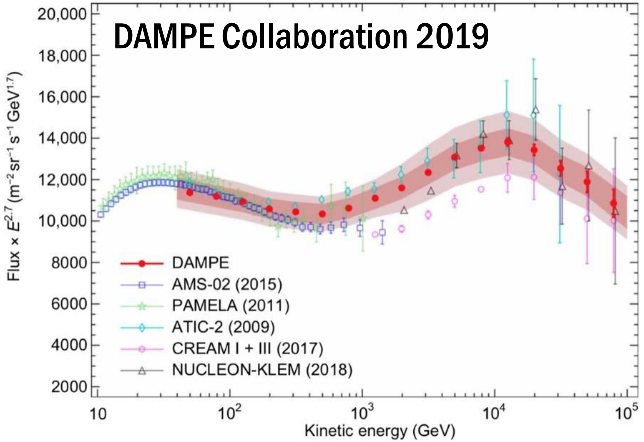


Maconi et al. 2020

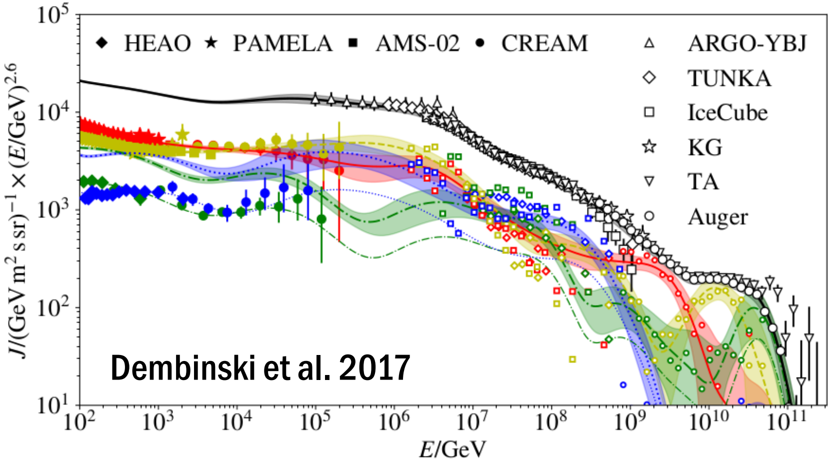
Physical Implications – CR transport & Interstellar B



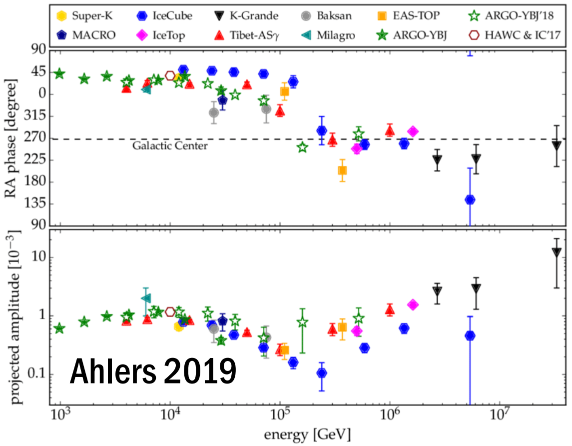
Ginzburg & Ptuskin 1976, Berezinsky et al. 1990, Strong & Moskalenko 1998 (GALPROP), Donato et al 2002, Shibata et al 2004, Ptuskin et al. 2006, Strong et al. 2007, Vladimirov et al. 2010, Bernardo et al. 2010, Maurin et al 2010, Putze et al 2010, Trotta et al 2011...



CR spectrum

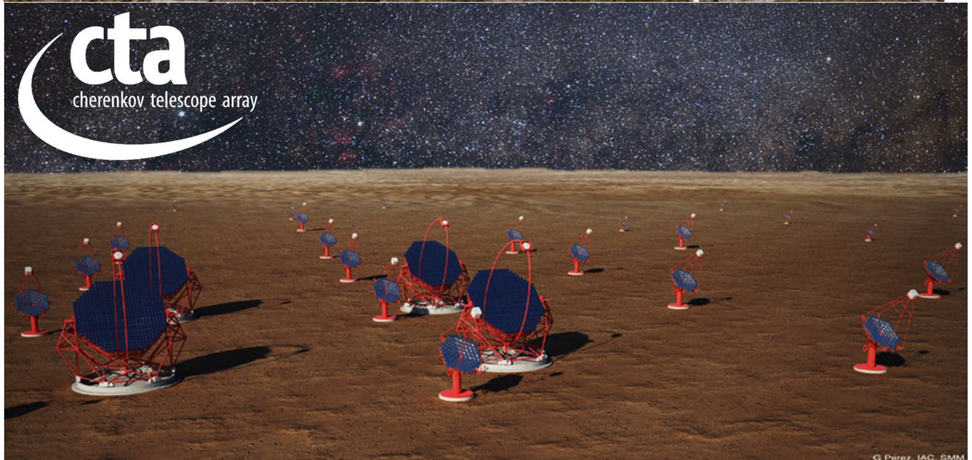


CR anisotropy

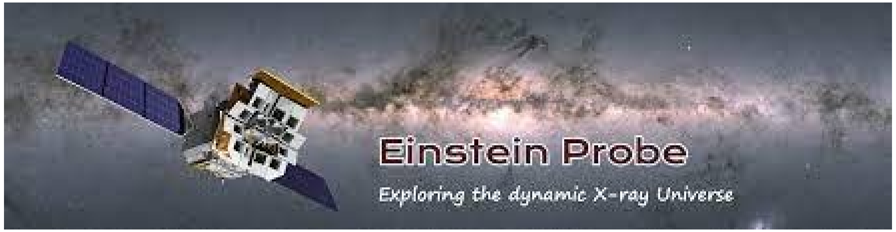


Prospect

discovery, spectrum, morphology

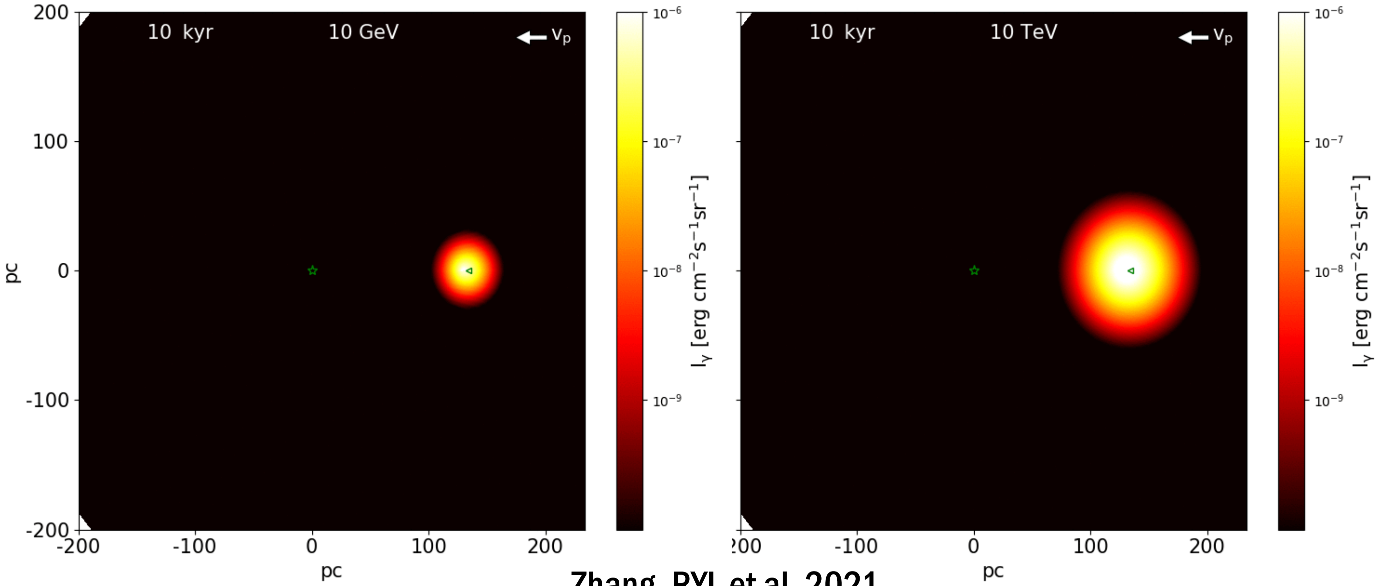


SWGO
The Southern Wide-field Gamma-ray Observatory

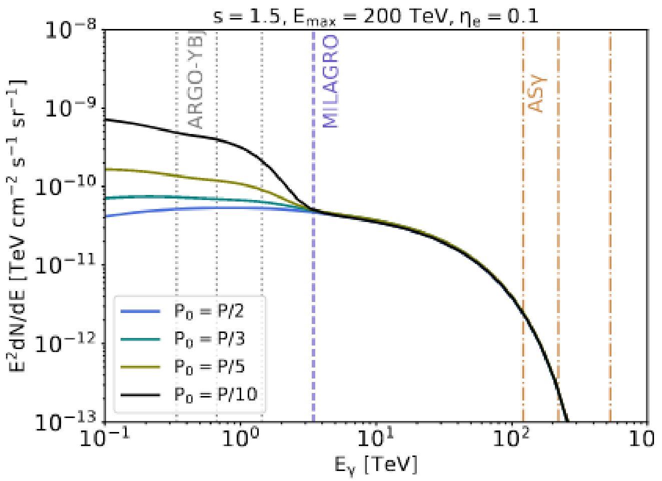


Why LHAASO/SWGO?

① Large FOV
② high sensitivity above 10TeV
③ >10 TeV, clean physics (unimportant streaming instability, irrelevant with early evolution, lower background...)

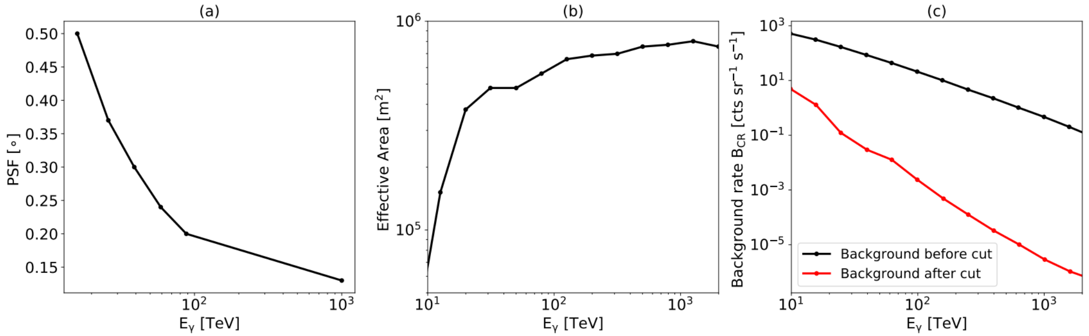


Zhang, RYL et al. 2021



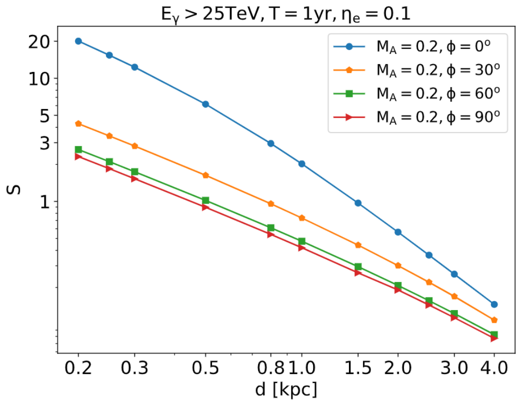
Yan & RYL 2023, under review

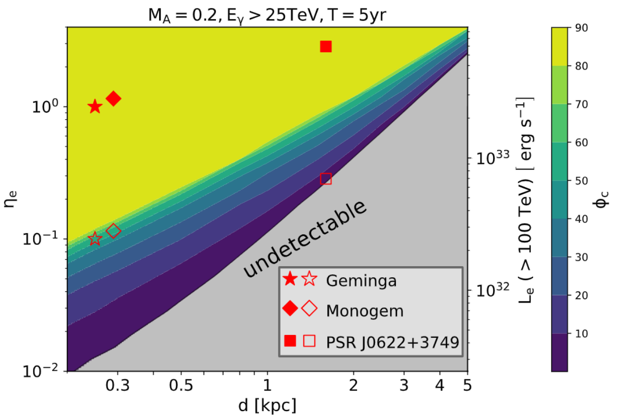
Distinguish different models – search for elongated halos

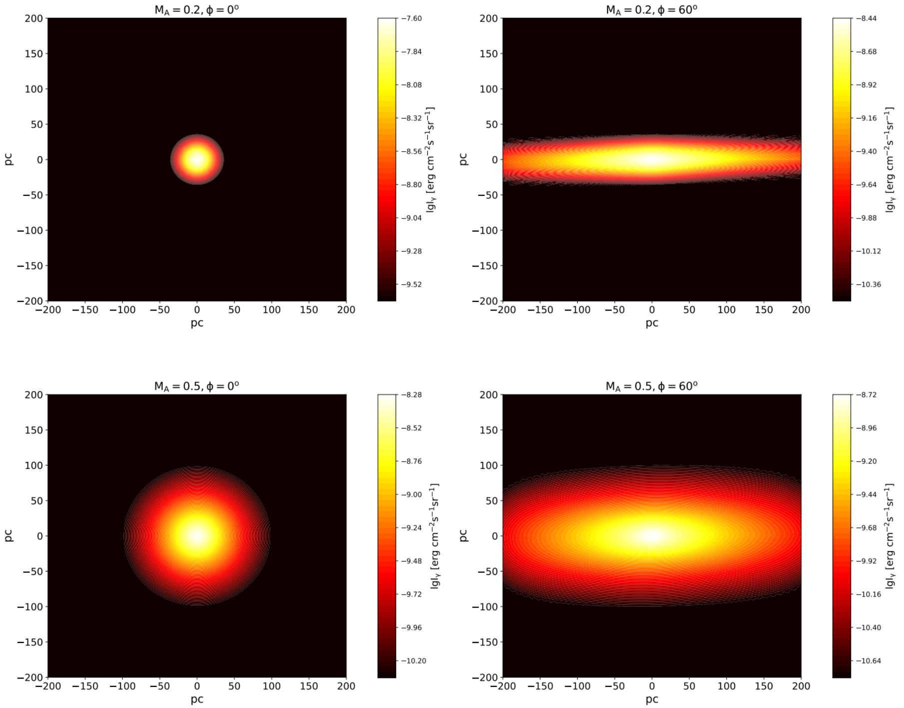


A Geminga-like halo

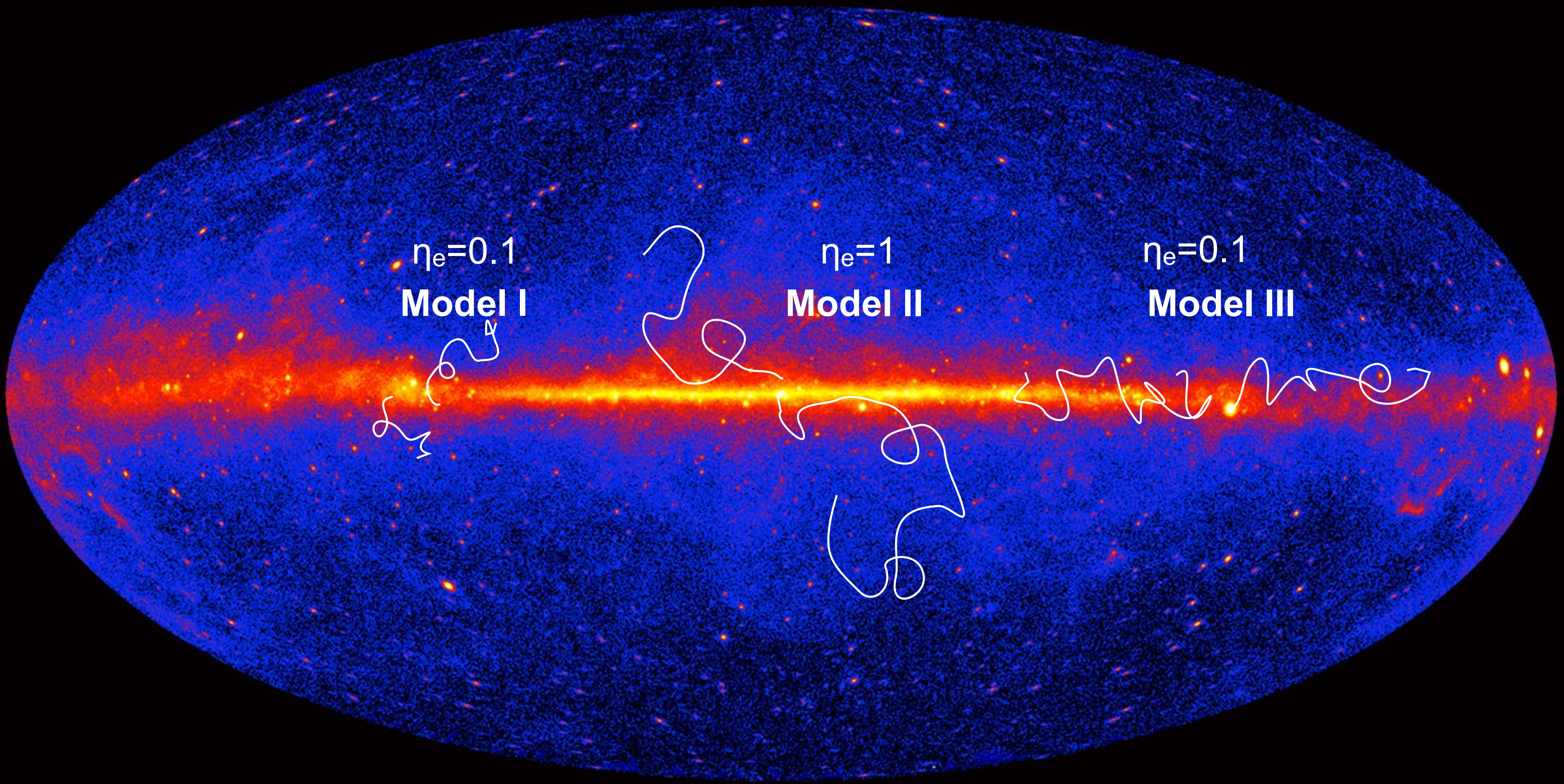
Injection spectrum $dN/dE = E^{-2}\exp(-E/200\mathrm{TeV})$





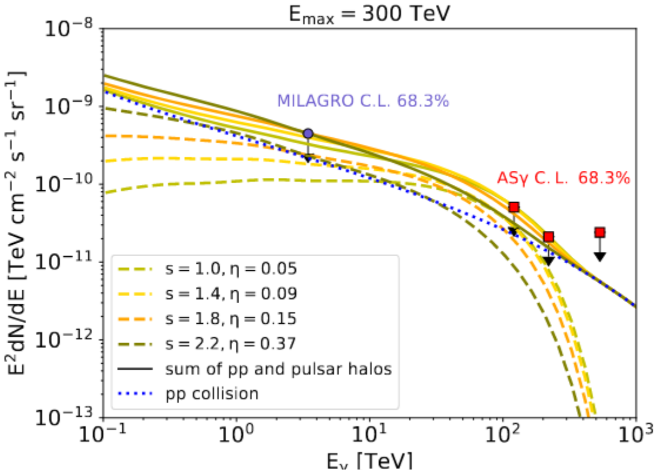


Yan, RYL et al. 2022

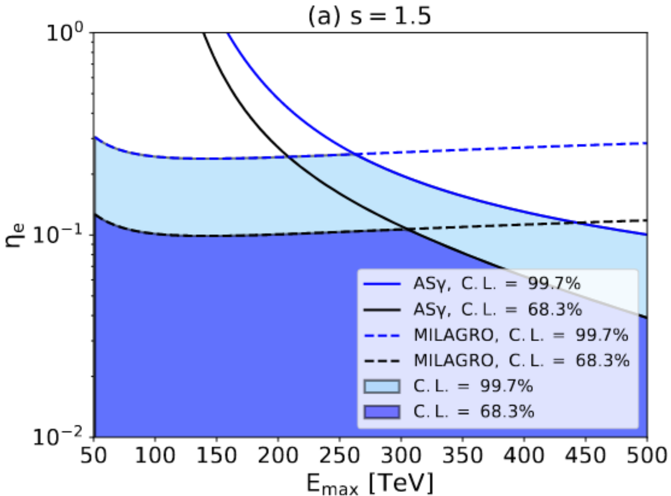


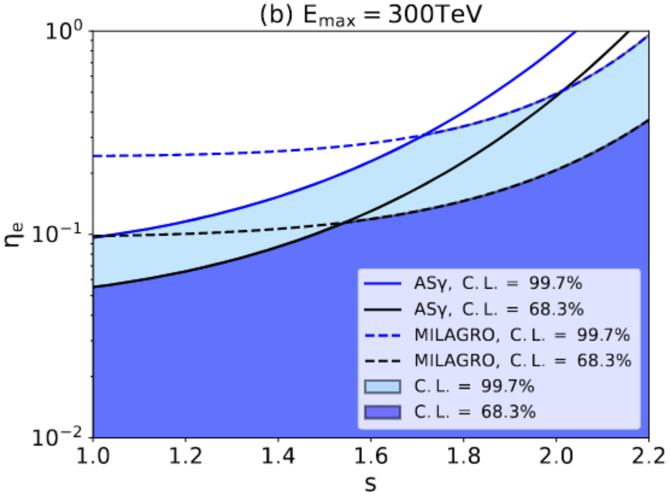
η_e=0.1
Model I
η_e=1
Model II
η_e=0.1
Model III

Distinguish different models - Constraints on the $e^{+/-}$ pair injection



- with characteristic age between 100 kyr and 10 Myr
- within the region of interests (ROI) for ASγ (i.e., 25° < l < 100°, | b |< 5°) and for MILAGRO (i.e., 40° < l < 100°, | b |< 5°)
- remove pulsars within 0.5 degree from the observed TeV sources in the TeVcat
- Correct for the beaming fraction





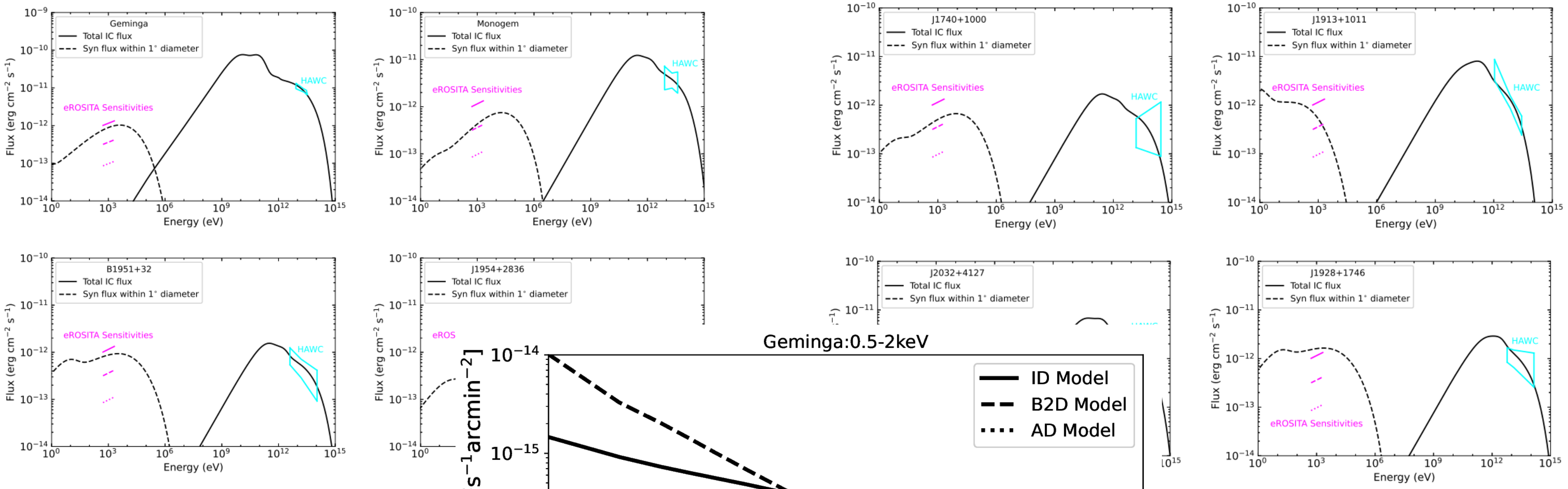
More accurate DGE

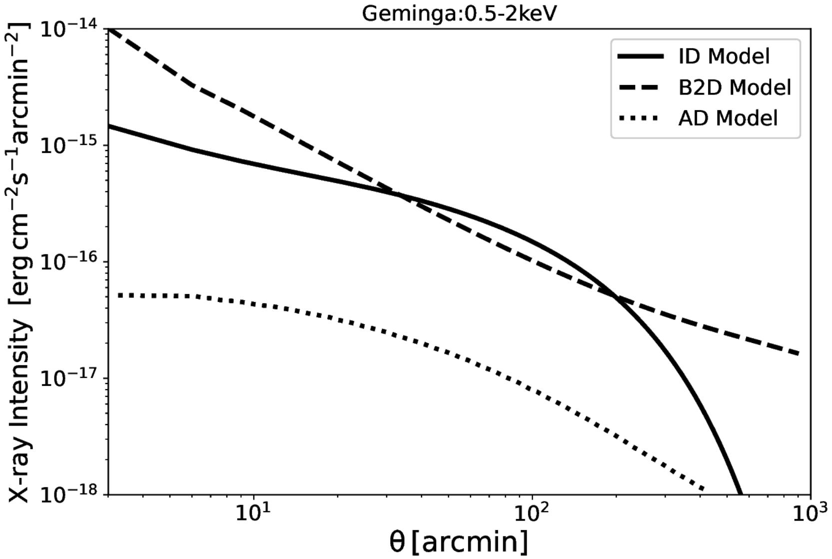
↓

stronger constraint

Yan & RYL 2023, under review

X-ray observations





Li, Zhang, RYL et al., 2022

Summary

- Pulsar halos are a new class of TeV gamma-ray sources, usually with extension of several tens parsecs. Gamma-ray emissions are produced via escaped $e^{\pm}$ pairs upscattering CMB
- Pulsar halos have not been detected (significantly) at GeV and X-ray band.
- Three models have been suggested and there are pros and cons:

  - Model I: isotropic, suppressed diffusion. Simple, consistent with observed morphology; origin of the slow diffusion and low B field

  - Model II: transition from ballistic to diffusive propagation. Work with standard ISM diffusion coefficients; energy crisis, unphysical assumption

  - Model III: anisotropic diffusion model. Work with standard ISM diffusion coefficients and B field. Predict many elongated halos which have not been detected.
- Important contribution to the CR positron excess, Galactic diffuse gamma-ray background...
- Unravel puzzles with new-generation instruments

Thanks for your attention!