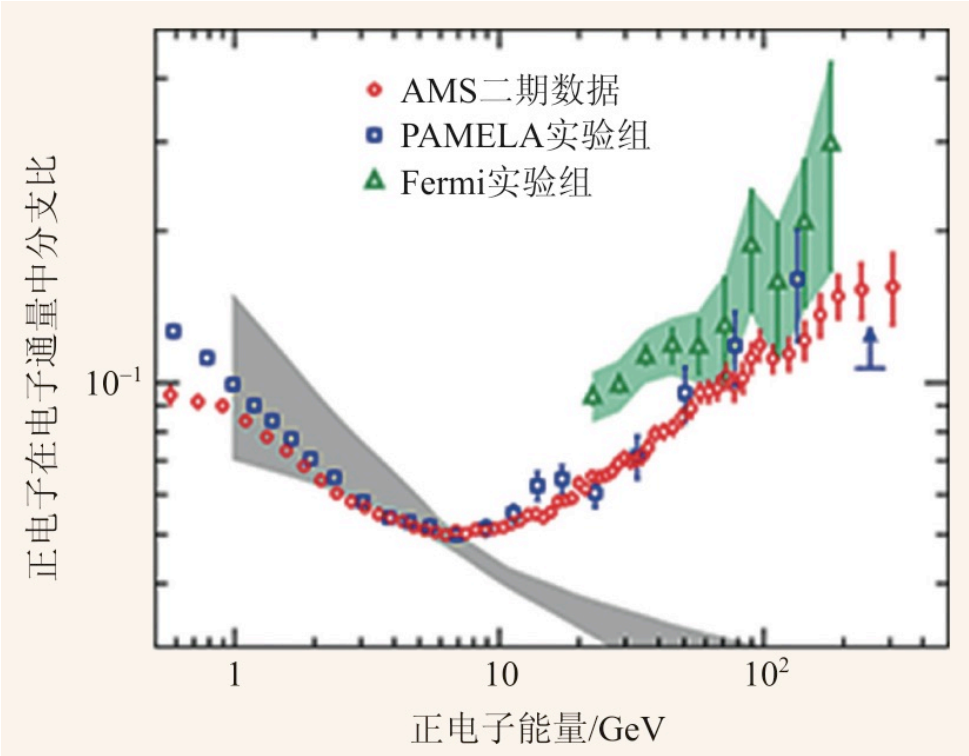
Positron excess, **TeV gamma ray halo**, cosmic ray propagation

Xiao-Jun Bi/IHEP, CAS

Jan. 7-10, 2020

The 10th International Workshop on Air Shower Detection at High Altitudes
Nanjing University, P.R. China

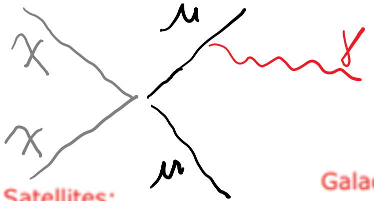
Positron excess and extra e+ sources



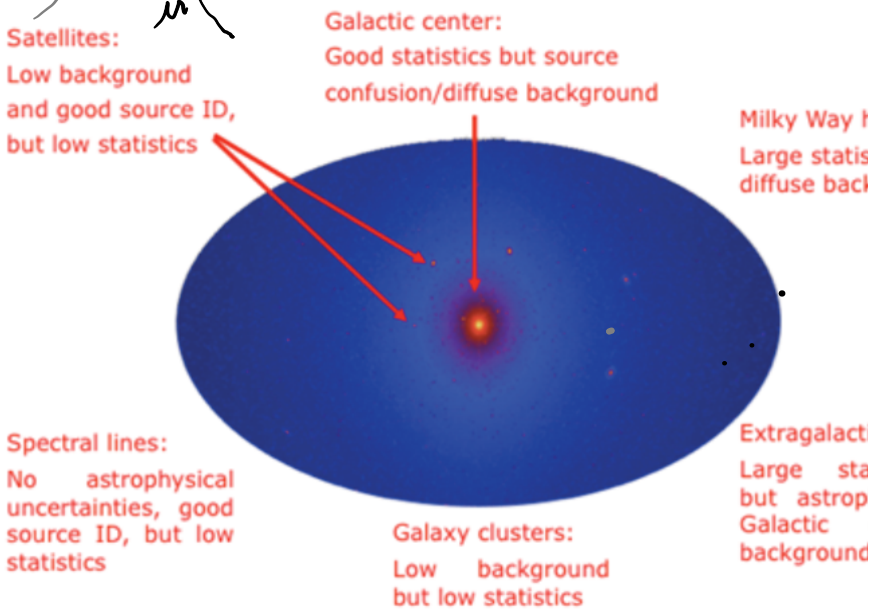
Positron excess detected by PAMLEA is confirmed by AMS-02 with higher precision.

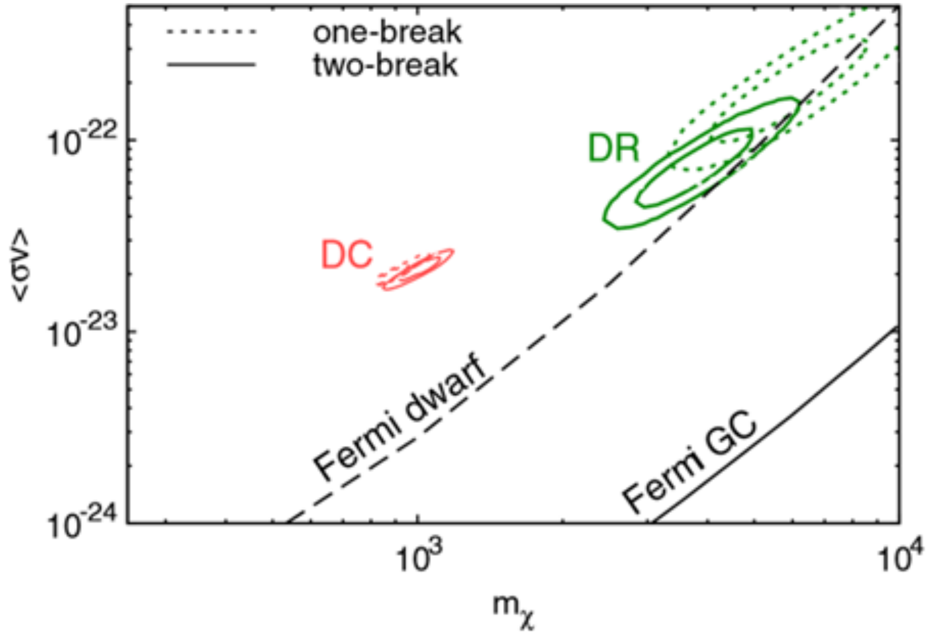
Extra positron sources:

- Dark matter X X ⟶ 。 。 。 ⟶ e^-e^+
- Astrophysical sources – pulsars ⟶ e^-e^+



Constraints on the DM models





Channels	m_χ(TeV)	AMS-02 (2σ)	Fermi limits	Planck limits
$\mu^+\mu^-$	0.89	$3.79 \times 10^{-24} < \langle \sigma_{\rm ann} v \rangle < 6.49 \times 10^{-24}$	2.95×10^{-24}	2.58×10^{-24}
$\tau^+\tau-$	3.89	$5.29 \times 10^{-23} < \langle \sigma_{\rm ann} v \rangle < 1.06 \times 10^{-22}$	1.25×10^{-23}	1.06×10^{-23}

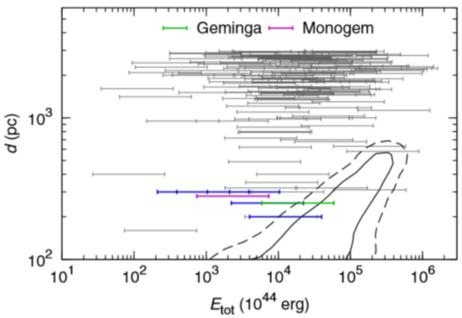
Excluded!?

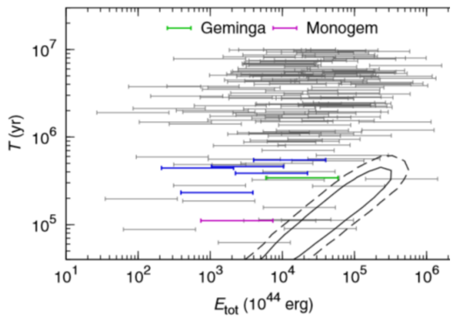
Fermi PRD2014

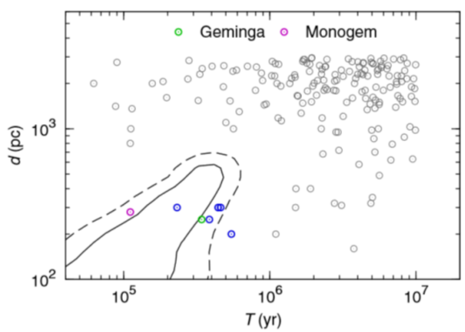
Q. Xiang, X. Bi, S. Lin, P. Yin 2017

DM needs very large annihilation cross, but severely constrained by Fermi and Planck observations.

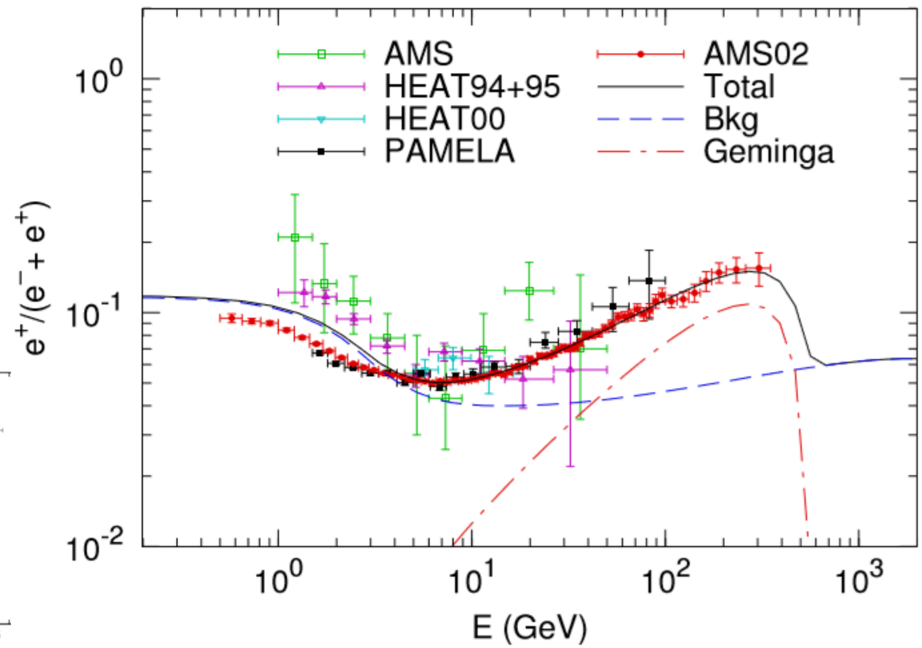
Geminga and Monogem are the most possible candidates

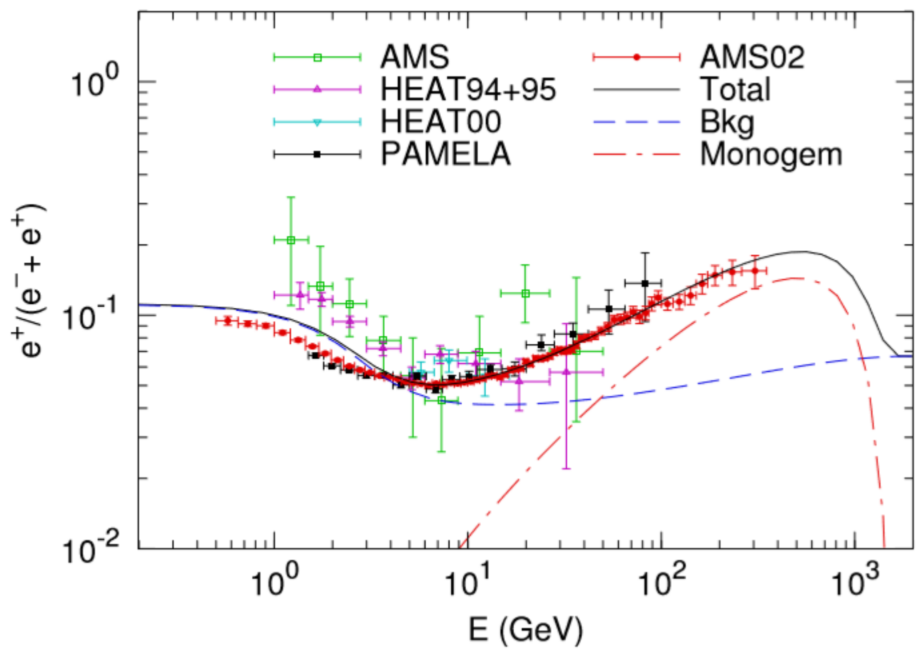






Pulsars can explain the positron excess, but requires a very high conversion efficiency, that is, we have to assume nearly 100% spin-down energy converted to e+-.





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REPORT

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

A. U. Abeysekara[1], A. Albert[2], R. Alfaro[3], C. Alvarez[4], J. D. Álvarez[5], R. Arceo[4], J. C. Arteaga-Velázquez[5], D. Avila Rojas[3], H...
+ See all authors and affiliations

Science 17 Nov 2017:
Vol. 358, Issue 6365, pp. 911-914
DOI: 10.1126/science.aan4880

Figures

▼ Tables ▼ Supplementary Materials ▼ Additional Files

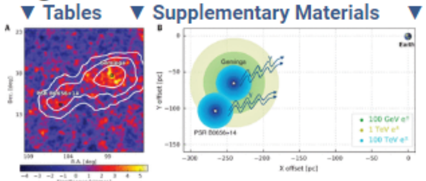
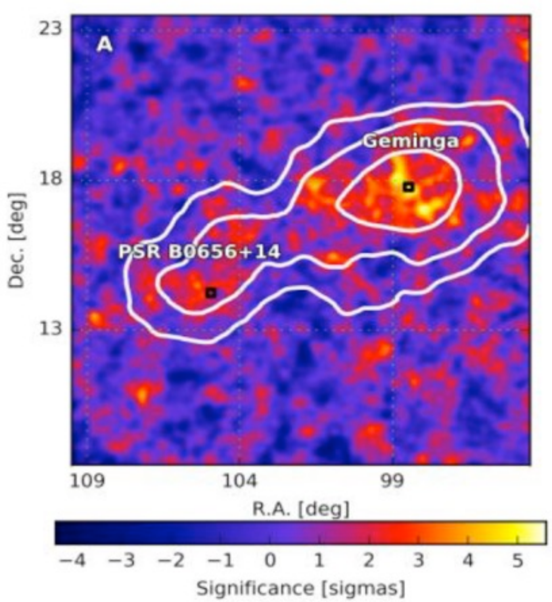
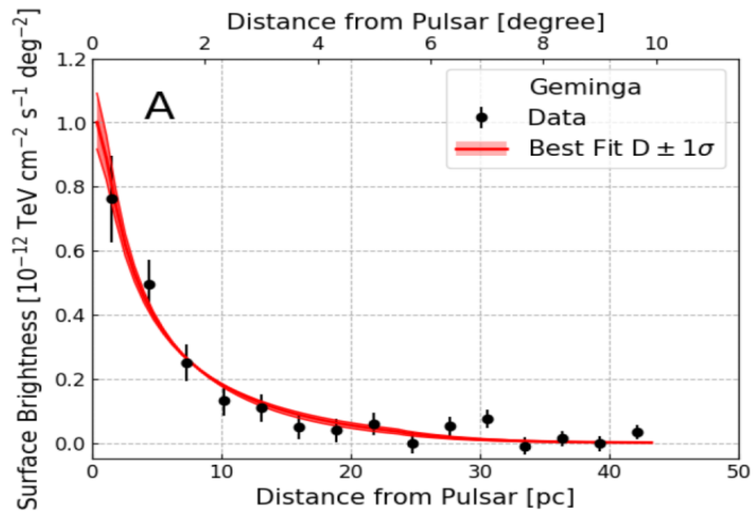


Fig. 1 Spatial morphology of Geminga and PSR B0656+14.

(**A**) HAWC significance map (between 1 and 50 TeV) for the region around Geminga and PSR B0656+14, convolved with the HAWC point spread function and with contours of 5σ, 7σ, and 10σ for a fit to the diffusion model. R.A., right ascension; dec., declination. (**B**) Schematic illustration of the observed region and Earth, shown projected onto the Galactic plane. The colored circles correspond to the diffusion distance of leptons with three different energies from Geminga; for clarity, only the highest energy (blue) is shown for PSR B0656+14. The balance between diffusion rate and cooling effects means that tera−electron volt particles diffuse the farthest (fig. S1).

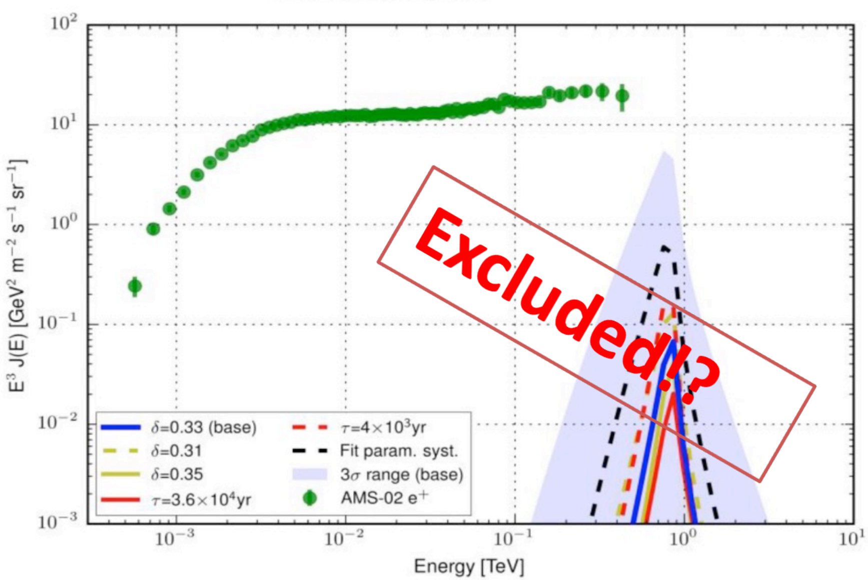
New development --TeV gamma-ray halo of Geminga/Monogem



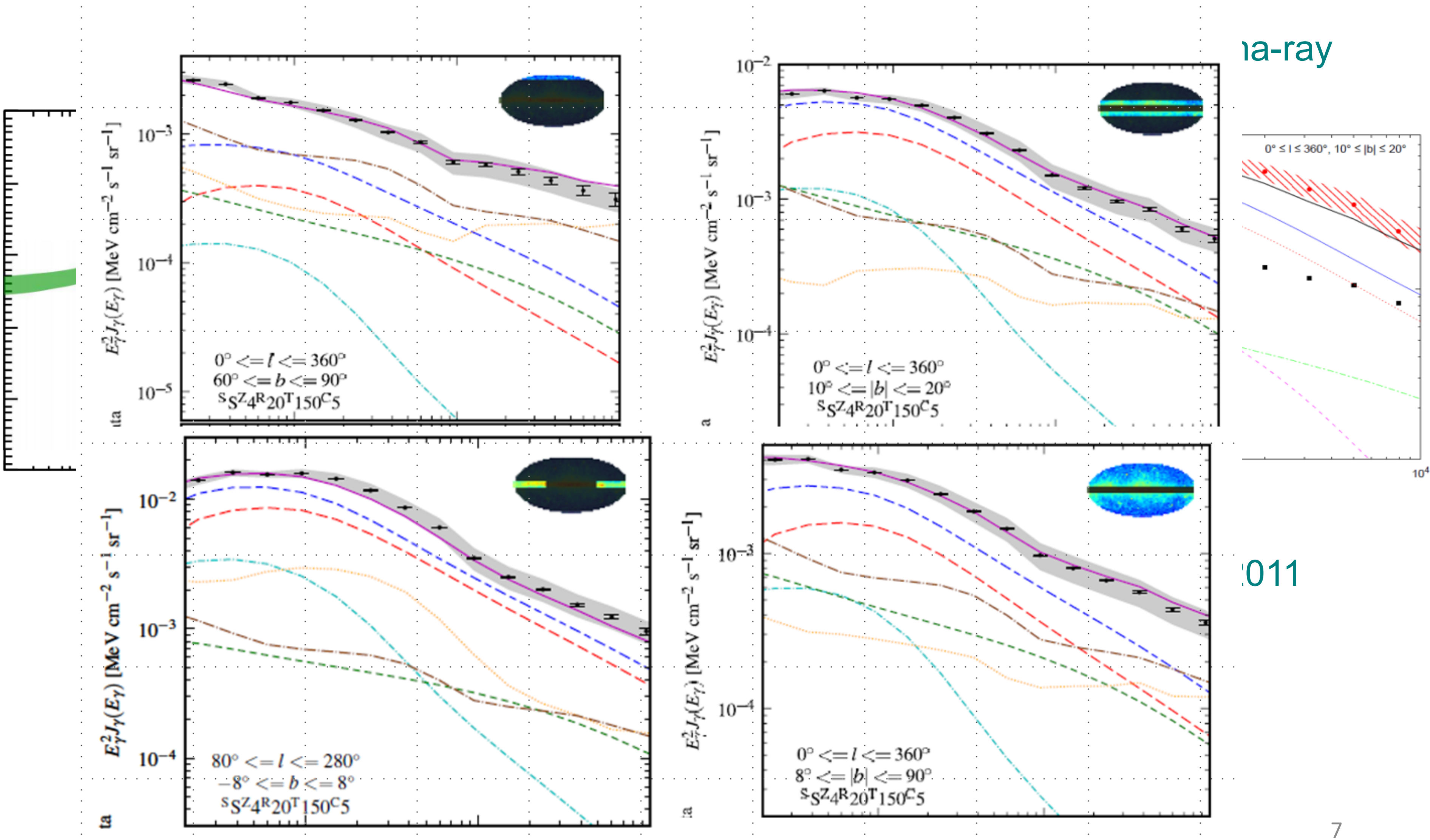


A.U. Abeysekara et al. HAWC collaboration, Science 2017

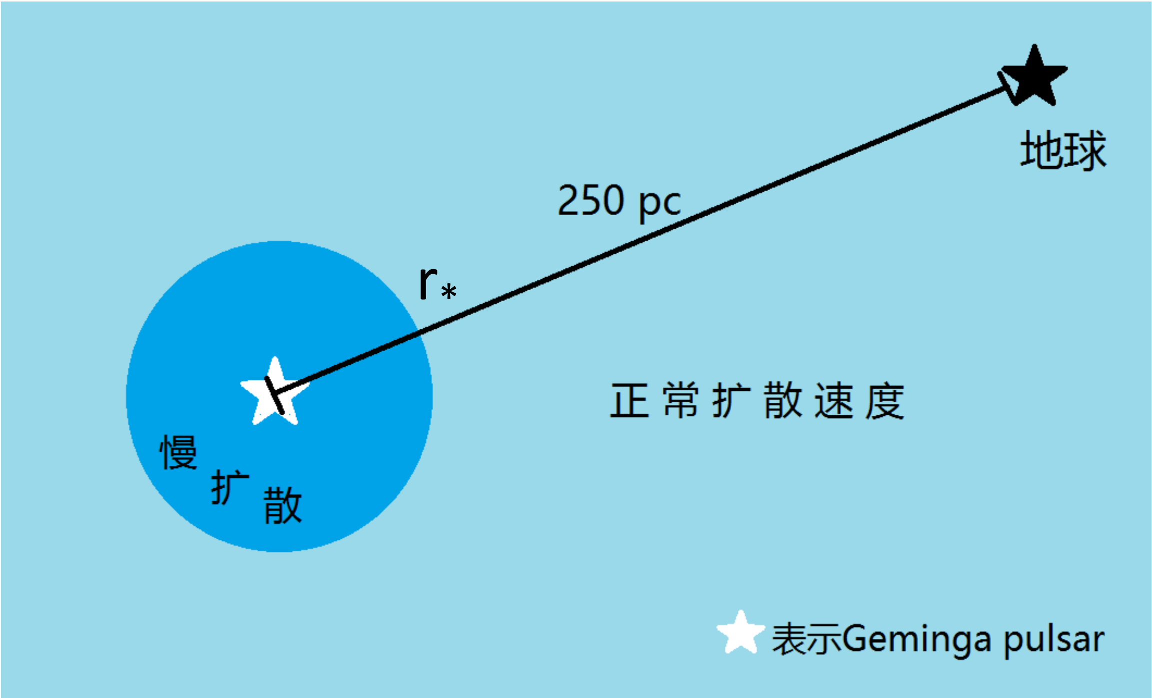
- PWN accelerate high energy e+- !
- The diffusion coefficient is hundreds times **smaller** than the conventional value at the ISM derived by B/C !
- In slow diffusion, the positron flux from the pulsar is negligible to AMS-02 data! Need exotic sources!



But, the conventional propagation model has been very successful!



How to solve the contradiction: slow diffusion(2 orders) by HAWC and conventional fast diffusion by B/C?



Two-zone diffusion for Geminga

Fang, BI, Yin, Yuan
APJ863(2018) 30

- The slow diffusion region is near the source; while the diffusion is still fast in most interstellar space.
- All the previous predictions are not changed! We need to check the positron flux in this scenario.

Two-zone diffusion for Geminga

Propagation equation: $$\frac{\partial N}{\partial t} - \nabla(D\nabla N) - \frac{\partial}{\partial E}(bN) = Q\,,$$

Diffusion coefficient: $$D(E,r) = \begin{cases} D_1(E), & r < r_\star \\ D_2(E), & r \geq r_\star \end{cases}\,,$$

D1 is derived by HAWC, D2 is the normal value

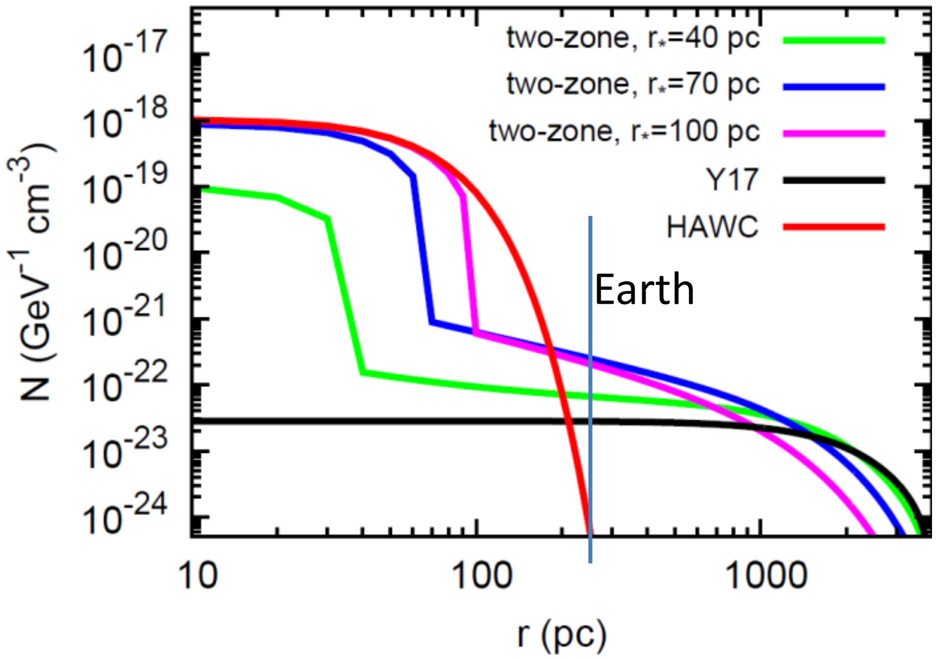
Numerical solution is required!

Operator splitting:
$$\mathcal{L}_r = \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 D(r)\frac{\partial}{\partial r}\right]\,,$$
$$\mathcal{L}_E = b\frac{\partial}{\partial E} + \frac{\partial b}{\partial E}\,.$$

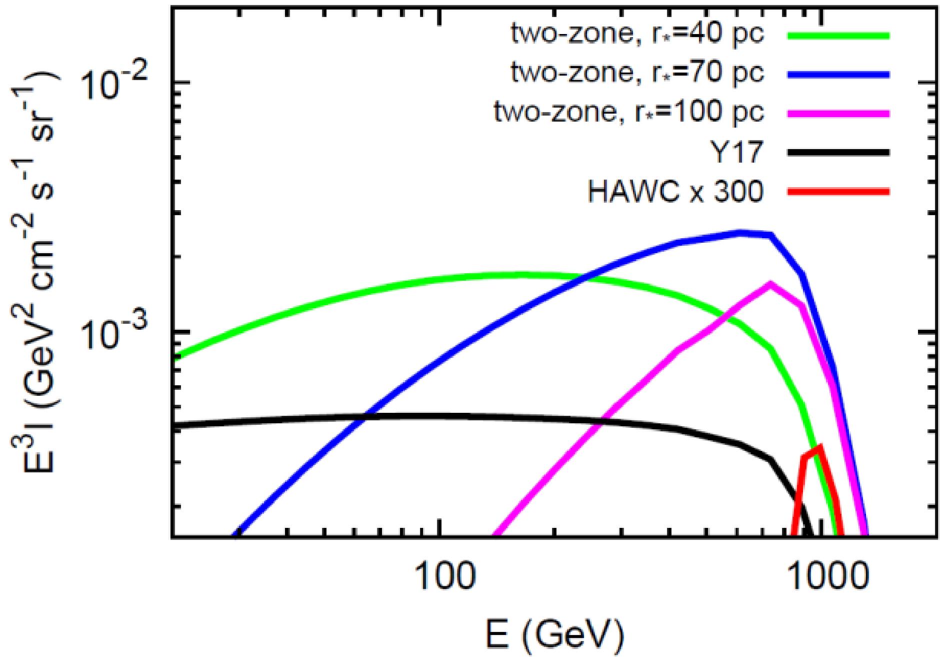
- The finite volume method is adopted for the diffusion operator
- GALPROP and DRAGON only apply to cases of smooth varying of D
- **We may expect the scenario be between the normal case (~1) and HAWC case (<1%)**

Unexpected result of positron flux!

Spatial distribution of e-/e+



Spectrum at the earth

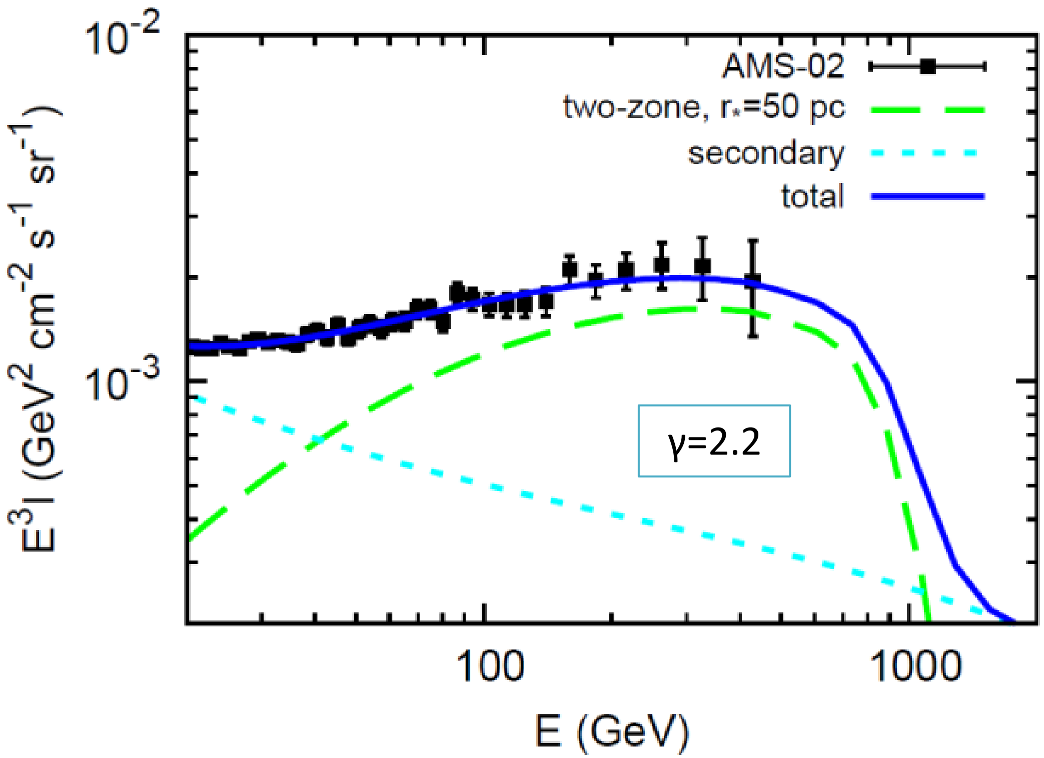


K. Fang, X. Bi, P. Yin, Q. Yuan 2018

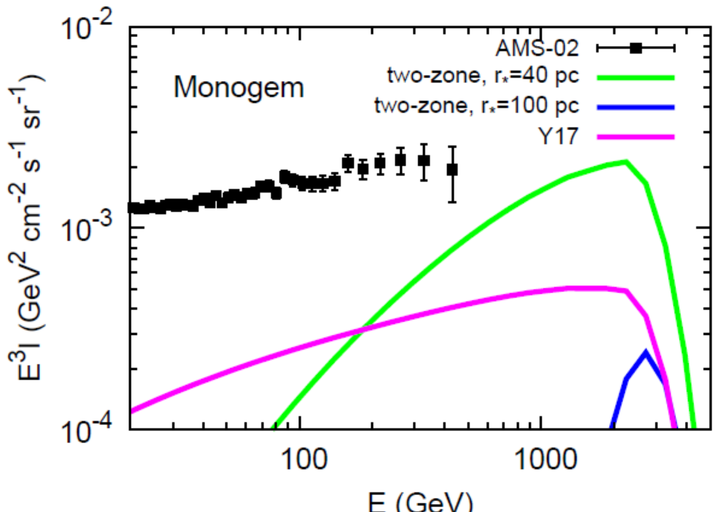
- Black line: fast diffusion with normal speed
- Red line: slow diffusion given by HAWC
- Other lines: two-zone diffusion with r*=40 pc, 70 pc, 100 pc; the CR are confined in the slow diffusion region for a long time.

Geminga (considering the HAWC new observation) solves the positron excess

Compare with AMS-02 e+



Fang, BI, Yin, Yuan APJ2018

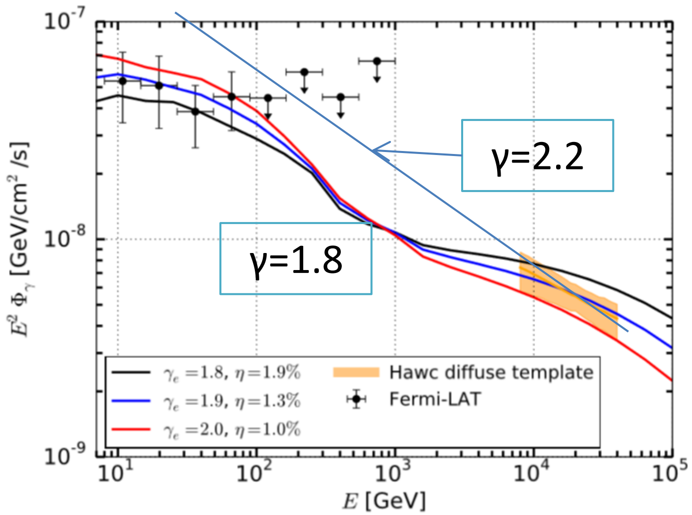


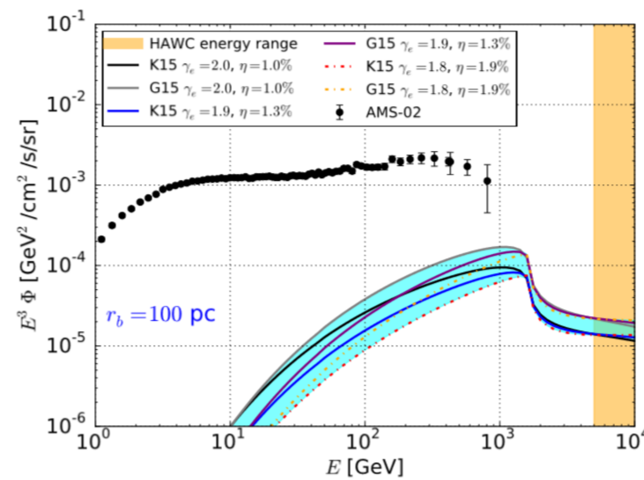
- The best-fit r_star is 50 pc
- The conversion efficiency of Geminga is ~50-70%
- many papers studied in the two-zone model

Profumo et al.
Evola et al.
Tang et al.
Johnnaesson et al.
Fleischhack et al.
Liu et al.
Bao et al.
Blasi
……..

Constraints from Fermi

- Gamma rays from the halo at low energy constrain the electron spectrum harder and less electrons/positrons at low energy.

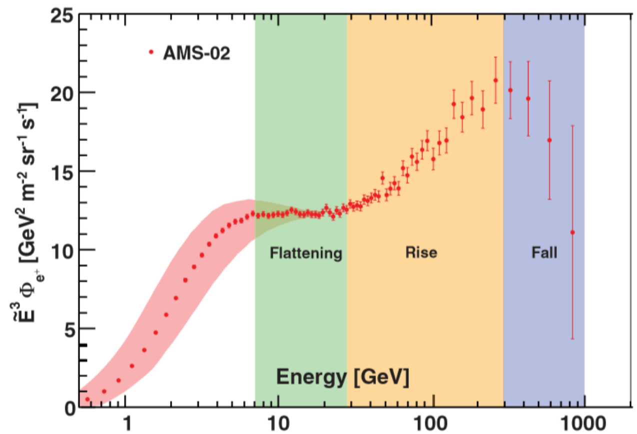


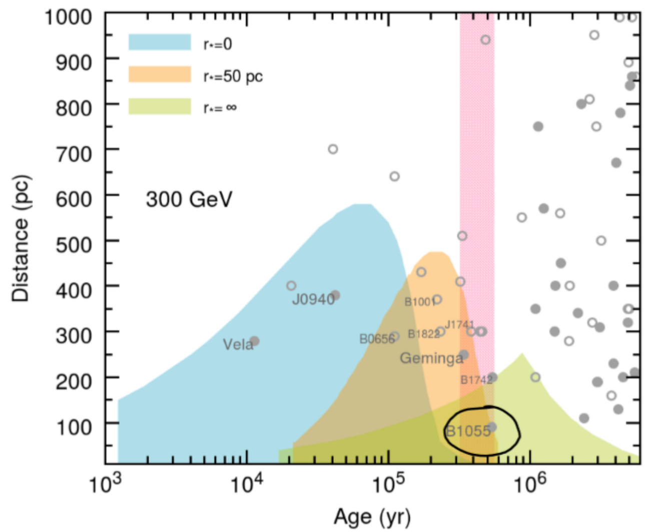


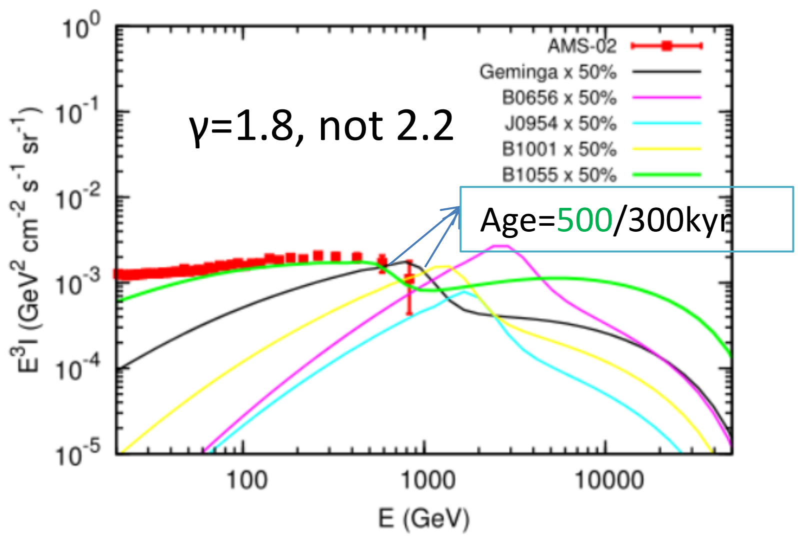
SQ Xi et al. 1810.10928, GeV observations of the extended pwn constrain the pulsar interpretations of the cosmic-ray positron excess

Di Mauro et al. 1903.05647

Our new analysis







- Most pulsars are hard with indices smaller than 2.
- Reanalyzed the pulsars contribution in a two-zone diffusion model.
- A older and closer pulsar is an ideal source to account for AMS-02. B1055 is the best one.

Distance of B1055

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

Lopez-Coto, Parsons, Hinton & GG , Phys. Rev. Lett. **121**, 251106 (2018)

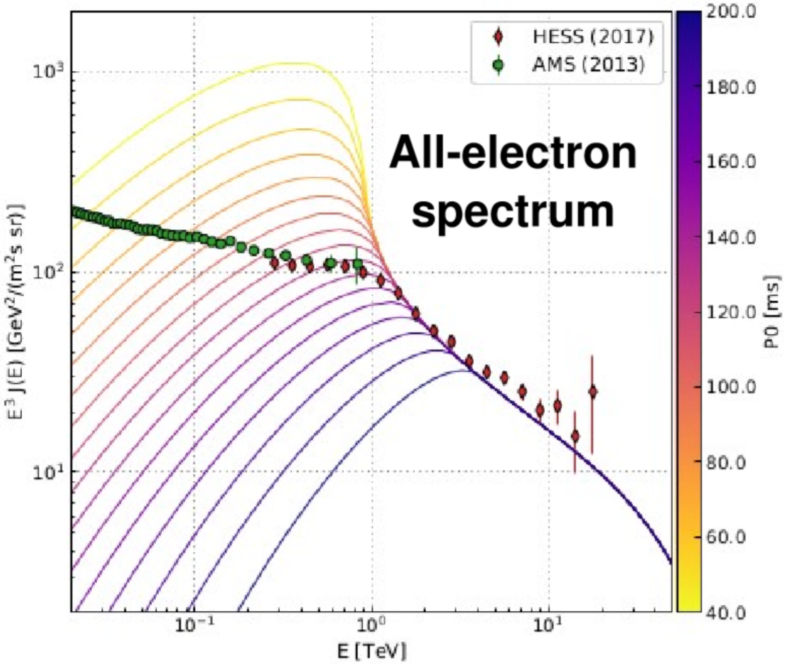
Can a nearby, old, undiscovered pulsar reproduce the HE $e^{-/+}$ spectra, with a HAWC-like diff. coeff. in the entire local ISM ? **YES !**

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

Consistent with known population.

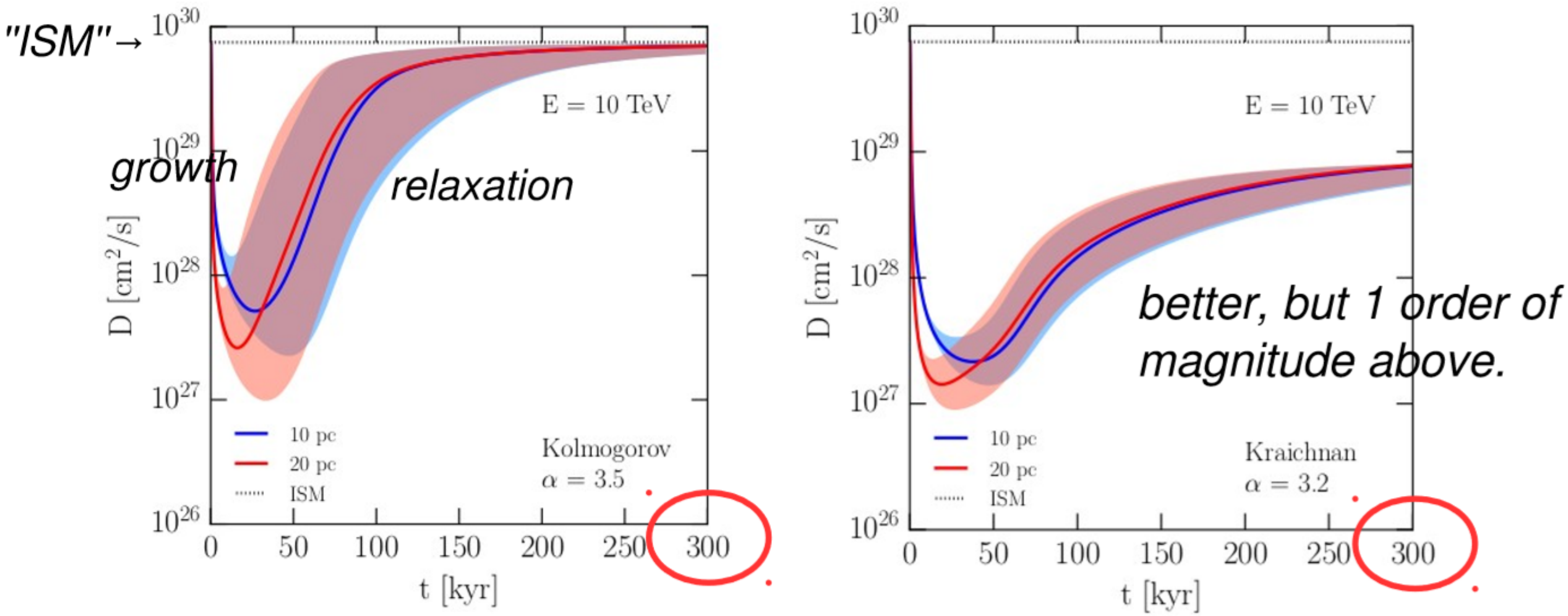
Breitschwerdt+, Nature (2016): SN 2.2 Myr ago at 60 – 130 pc.

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



d=50 pc, E = 1.3 × 10^{33} erg/s, α = 2.4, B = 3 μG.

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



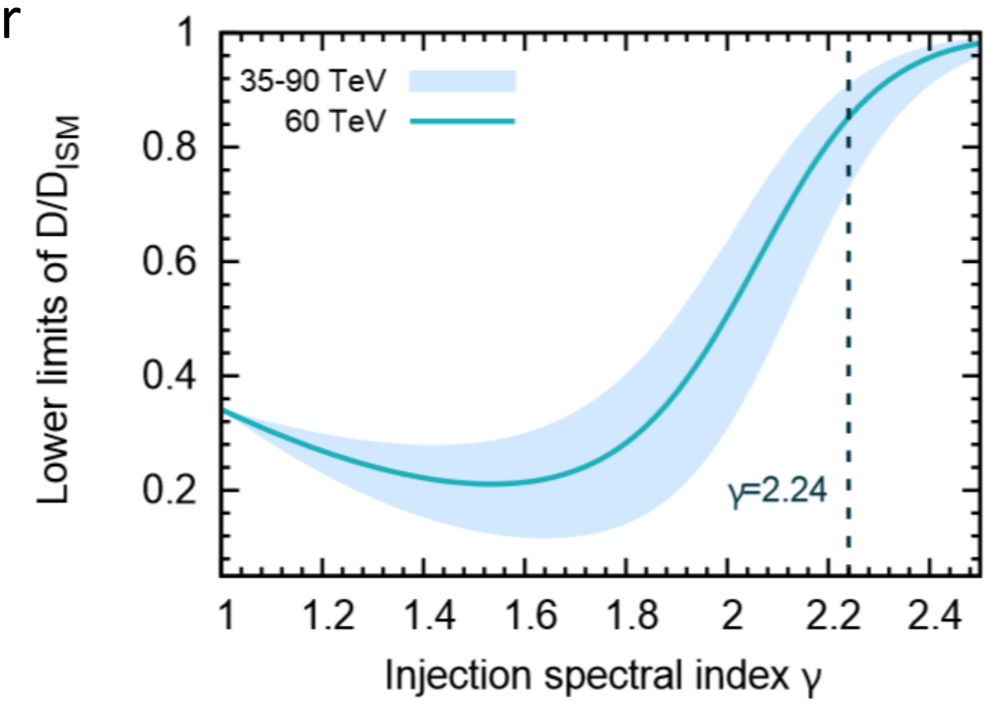
Relaxes too rapidly to confine e⁻ around Geminga.

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

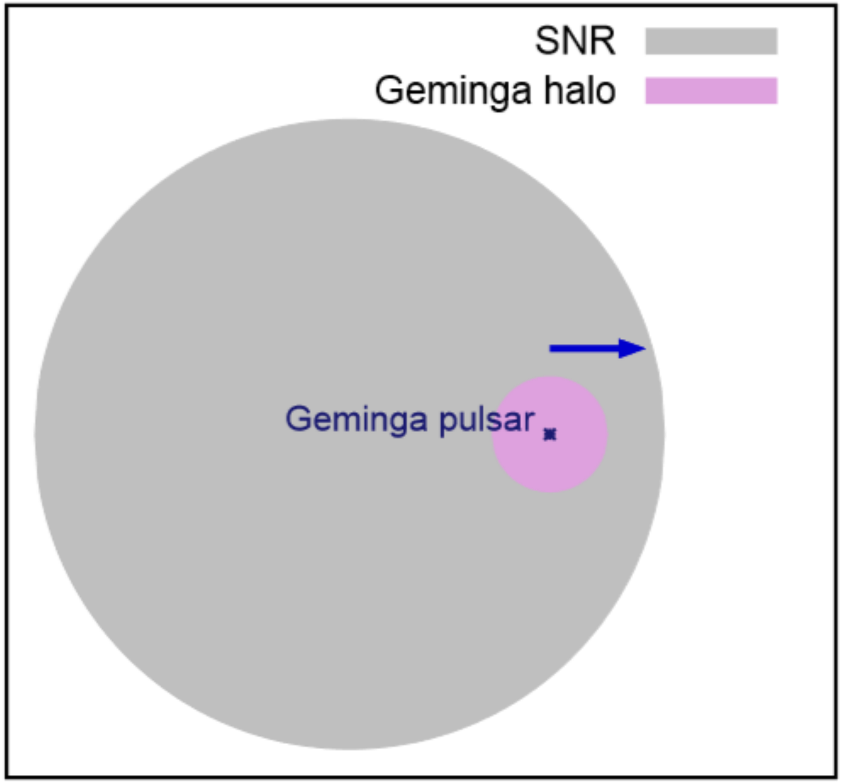
Review talk at ICRC2019

Lower limit by e^{+-} streaming instability

- We derive a lower limit on the diffusion coefficient by assuming: no energy loss of electrons; no wave dissipation; we get an analytic solution $D(x) = D_{\rm ISM} \exp\left(-\frac{4\pi e v_A E}{B_0 c}\int_x^\infty N dx'\right)$
- Considering the proper motion of Geminga at 200km/s, Geminga has left 70pc from its original place. We take electrons for the late 1/3 life time (230 – 340 kyr)
- Lifetime of e (50TeV) < 10kyr
- We then get the lower limit
- Observed is 1/1000 $D_{\rm ISM}$



Slow diffusion may be an environment effect



If:

low density

ISM density is 0.08 atom/cm^3

initial energy is 2 x 10^51 erg

high energy

the scale of SNR can reach **~90 pc** at 342 kyr

Leahy & Williams 2017

In the shock frame:

kinetic energy loss

⇩

thermal energy + turbulent energy

⇨

avaiable for turbulence:
6 x 10^-12 erg/cm^3

magnetic energy:
4 x 10^-13 erg/cm^3

Mechanism to generate the slow diffusion

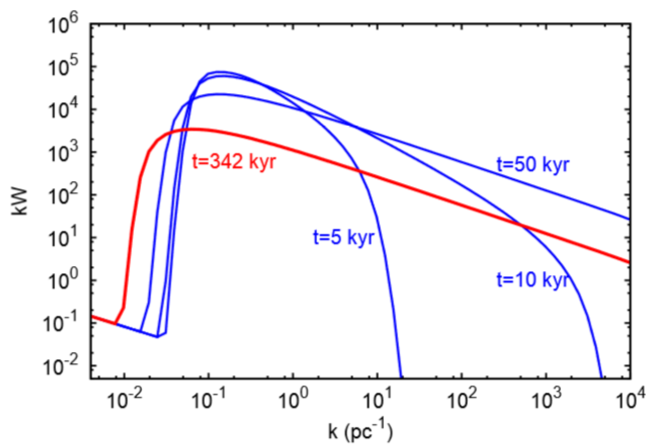
- The diffusion coefficient is determined by the plasma turbulence $D(E_{\rm res}) = \frac{1}{3} r_g c \cdot \frac{1}{kW(k)}$

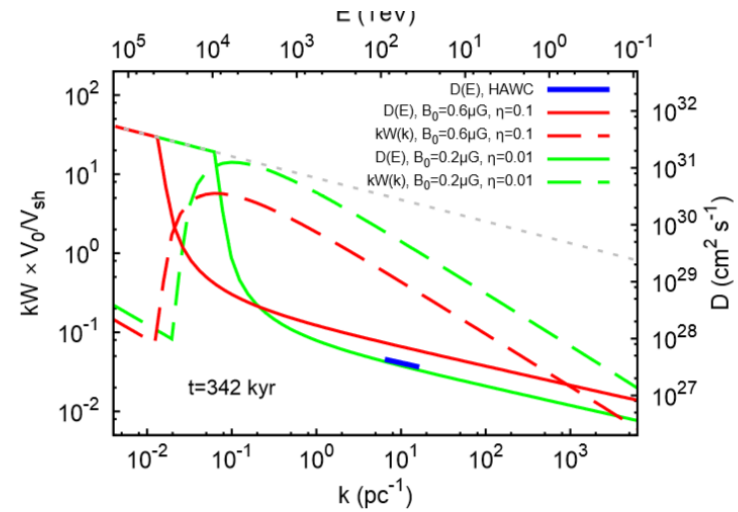
  where $\int W(k)dk = \delta B^2/B_0^2$
- We proposed that the explosion of SN and following SNR will form a turbulent region within the SNR by shock waves, where the diffusion is highly suppressed.

Fang, BI, Yin, MNRAS488(2019) 4074

Mechanism to generate the slow diffusion

- We calculate the evolution of the wave spectrum W with time and the diffusion coefficient today
- In some parameters the diffusion coefficient is consistent with HAWC value





Fang, BI, Yin, MNRAS488(2019) 4074

TeV gamma ray halos

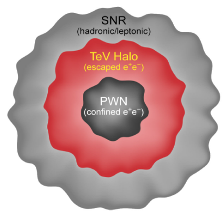
- According the mechanism proposed above the slow diffusion of a PWN within a SNR should be a quite general scenario, since pulsars are always associated with its SNR unless they are too old.

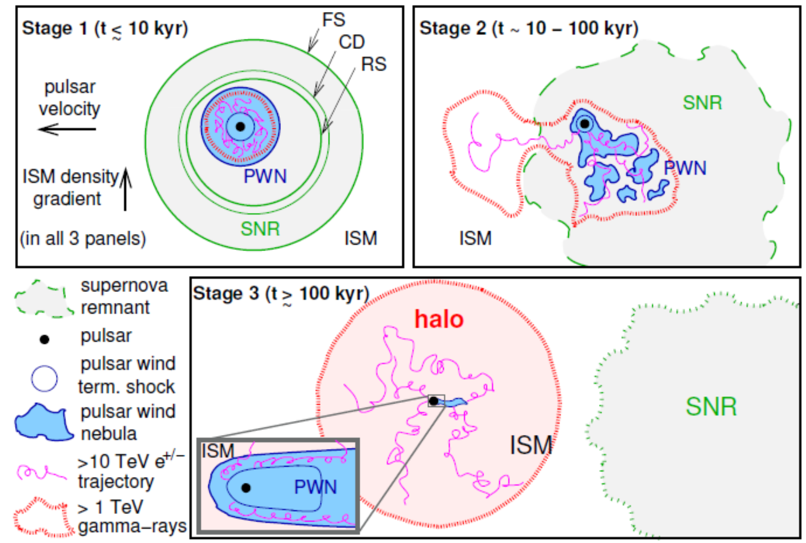
- We should expect to observe many such TeV gamma ray halos corresponding to pulsars if the detector is sensitive enough.

Slow Diffusion vs Confinement
Halo vs PWN

On the TeV Halo Fraction in gamma-ray bright Pulsar Wind Nebulae

G. Giacinti[1], A.M.W. Mitchell[2], R. López-Coto[3], V. Joshi[4], R.D. Parsons[1], J.A. Hinton[1]





PHYSICAL REVIEW D **100,** 043016 (2019)

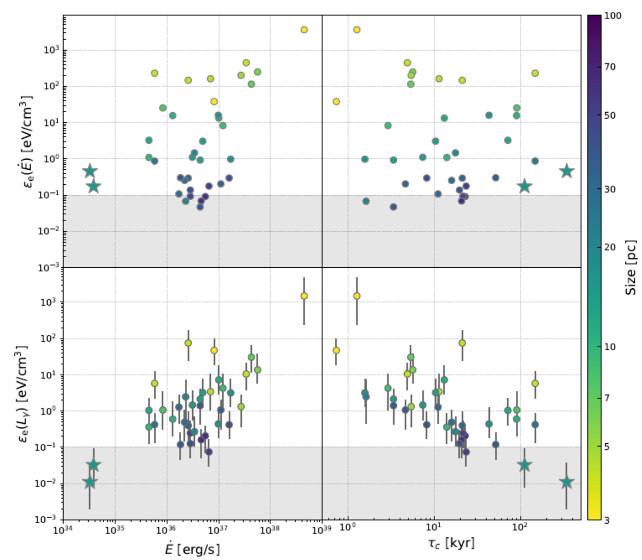
TeV halos are everywhere: Prospects for new discoveries

Takahiro Sudoh,[1,2,*] Tim Linden,[2,3,†] and John F. Beacom[2,3,4,‡]

PHYSICAL REVIEW D **98,** 063017 (2018)

Self-generated cosmic-ray confinement in TeV halos: Implications for TeV γ-ray emission and the positron excess

Carmelo Evoli,[1,2,*] Tim Linden,[3,†] and Giovanni Morlino[1,2,4,‡]



MNRAS **488,** 4074–4080 (2019)
Advance Access publication 2019 July 26
doi:10.1093/mnras/stz1974

Possible origin of the slow-diffusion region around Geminga

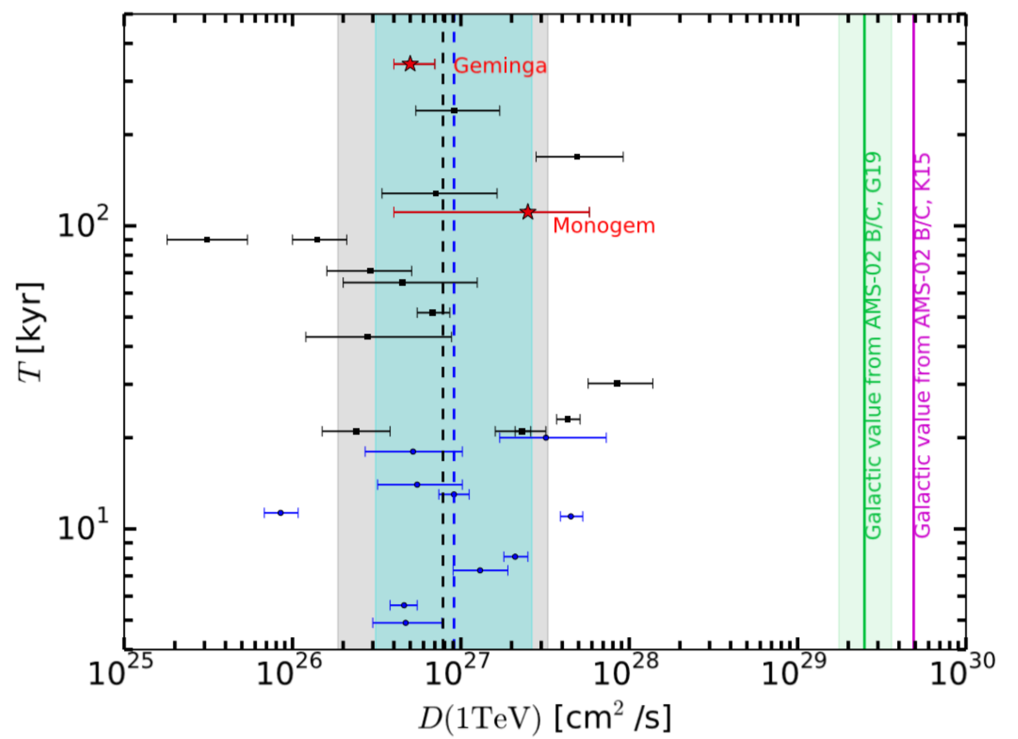
Kun Fang,[1] Xiao-Jun Bi[1,2★] and Peng-Fei Yin[1]

Slow diffusion is universal

- A large group of TeV sources are analyzed and the diffusion coefficients are derived.
- All the D are much smaller than ISM value.

PSR	l	b	d	T	$\dot{E}$	Name
	[deg]	[deg]	[kpc]	[kyr]	[erg/s]	
J1016-5857	284.08	-1.88	3.16	21	$2.6\cdot10^{36}$	HESS J1018-589 B
J1028-5819	285.06	-0.50	1.42	90	$8.3\cdot10^{35}$	HESS J1026-582
J1459-6053	317.89	-1.79	1.84	65	$9.1\cdot10^{35}$	HESS J1458-608
J1632-4757	. 336.30	0.08	4.84	240	$5.0\cdot10^{34}$	HESS J1632-478
J1718-3825	348.95	-0.43	3.49	90	$1.3\cdot10^{36}$	HESS J1718-385
J1809-1917	11.18	-0.35	3.27	51.7	$1.8\cdot10^{36}$	HESS J1809-193(2HWC J1809-190)
J1813-1246	17.24	2.44	2.63	43	$6.2\cdot10^{36}$	HESS J1813-126(2HWC J1812-126)
B1823-13	18.00	-0.69	3.61	21	$2.8\cdot10^{36}$	HESS J1825-137(2HWC J1825-134)
J1831-952	21.90	-0.13	3.68	128	$1.1\cdot10^{36}$	HESS J1831-098(2HWC J1831-098)
J1838-0655	25.25	-0.20	6.60	23	$5.6\cdot10^{36}$	HESS J1837-069(2HWC J1837-065)
J1841-0524	27.02	-0.33	4.12	30.2	$1.0\cdot10^{36}$	HESS J1841-055
J1856+0245	36.01	0.06	6.32	21	$4.6\cdot10^{36}$	HESS J1857+026(2HWC J1857+027)
J1857+0143	35.17	-0.57	4.57	71	$4.5\cdot10^{35}$	HESS J1858+020
J1907+0602	40.18	-0.89	2.37	20	$2.8\cdot10^{36}$	HESS J1908+063(2HWC J1908+063)
J1913+1011	44.48	-0.17	4.61	169	$2.9\cdot10^{36}$	HESS J1912+101(2HWC J1912+099)
B0833-45	263.55	-2.79	0.28	11.3	$6.9\cdot10^{36}$	HESS J0835-455(Vela X)
J1301-6305	304.10	-0.24	10.72	11	$1.7\cdot10^{36}$	HESS J1303-631
J1357-6429	309.92	-2.51	3.10	7.3	$3.1\cdot10^{36}$	HESS J1356-645
J1420-6048	313.54	0.23	5.63	13	$1.0\cdot10^{37}$	HESS J1420-607
J1617-5055	332.50	-0.28	4.74	8.1	$1.6\cdot10^{36}$	HESS J1616-508
J1640-4631	338.32	-0.02	12.75	3.4	$4.4\cdot10^{36}$	HESS J1640-465
B1706-44	343.10	-2.69	2.60	18	$3.4\cdot10^{36}$	HESS J1708-443
J1813-1749	12.82	-0.02	4.70	5.6	$5.6\cdot10^{37}$	HESS J1813-178(2HWC J1814-173)
J1826-1256	18.56	-0.38	1.55	14	$3.6\cdot10^{36}$	HESS J1826-130(2HWC J1825-134)
J1833-1034	21.50	-0.89	4.10	4.9	$3.4\cdot10^{37}$	HESS J1833-105
J0633+1746	195.13	4.27	0.19	342	$3.3\cdot10^{34}$	GEMINGA(2HWC J0635+180)
B0656+14	201.11	8.26	0.29	111	$3.8\cdot10^{34}$	MONOGEM(2HWC J0700+143)

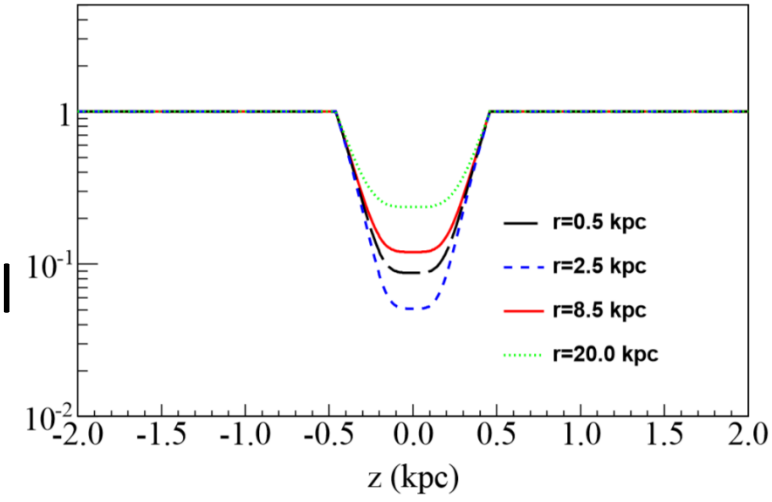
Di Mauro et al., 1908.03216



Non-uniform propagation

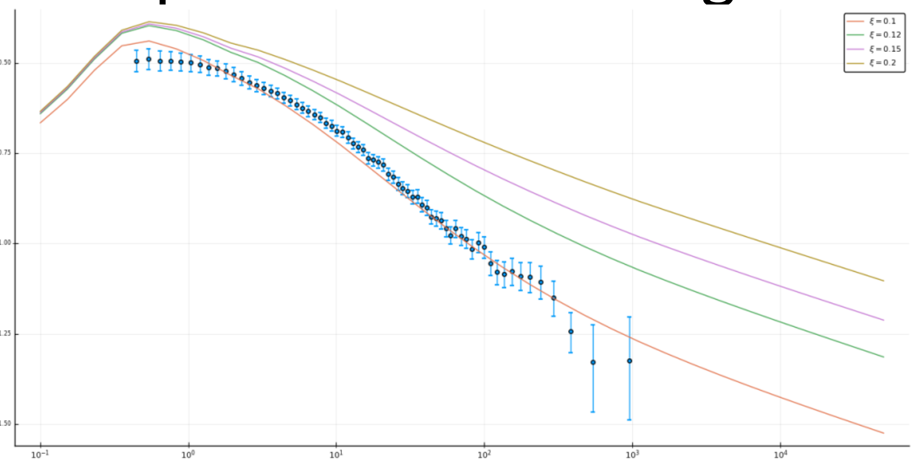
- Considering that 1-3 SNs are generated each 100 years with a pulsar lifetime ~10^6 years, there are about ~10^4 such slow diffusion regions (r*~50pc), which take significant fraction at the Galactic disk. Therefore we expect the disk diffusion on average is slower than that outside of the disk. We call it a non-uniform CR propagation in the Galaxy.

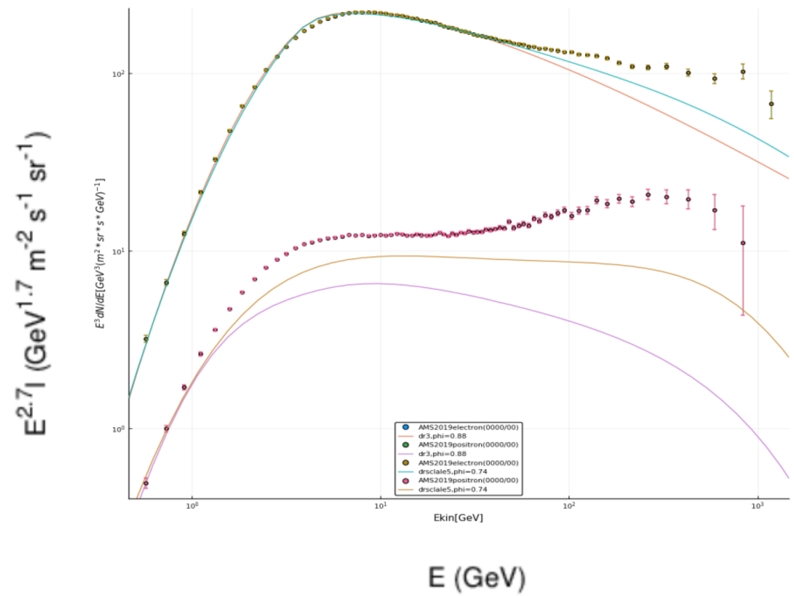
- Such a picture is different from the conventional one may lead to different bkg and dark matter signal



Preliminary results for the nonuniform propagation

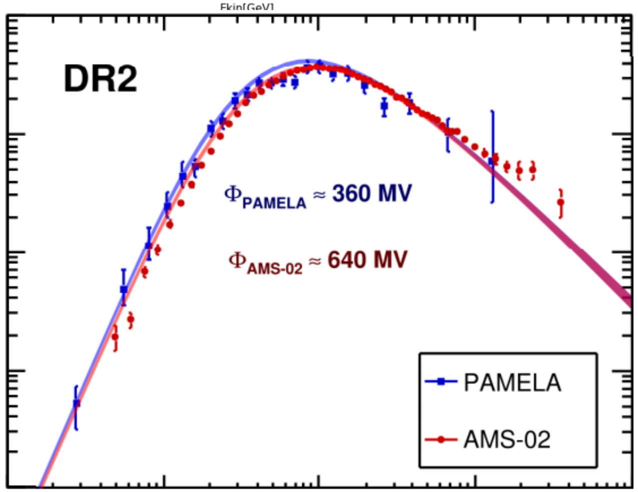
- Need some special treatment of diff operators now. program is ready now.
- Spectrum hardening

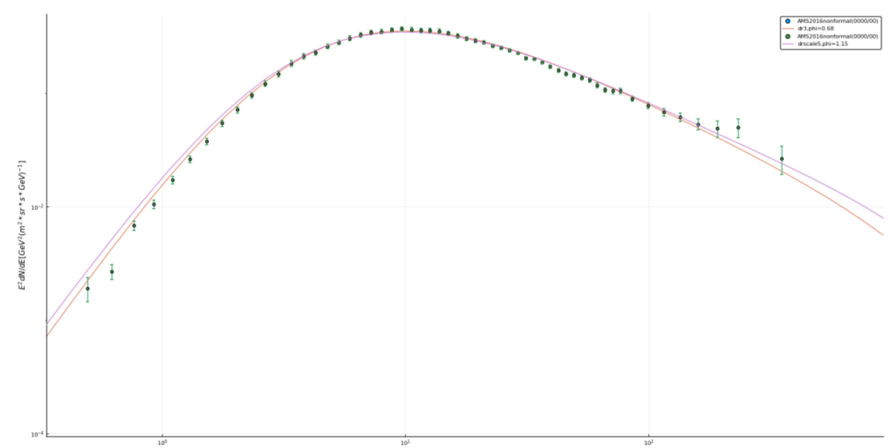




B/C

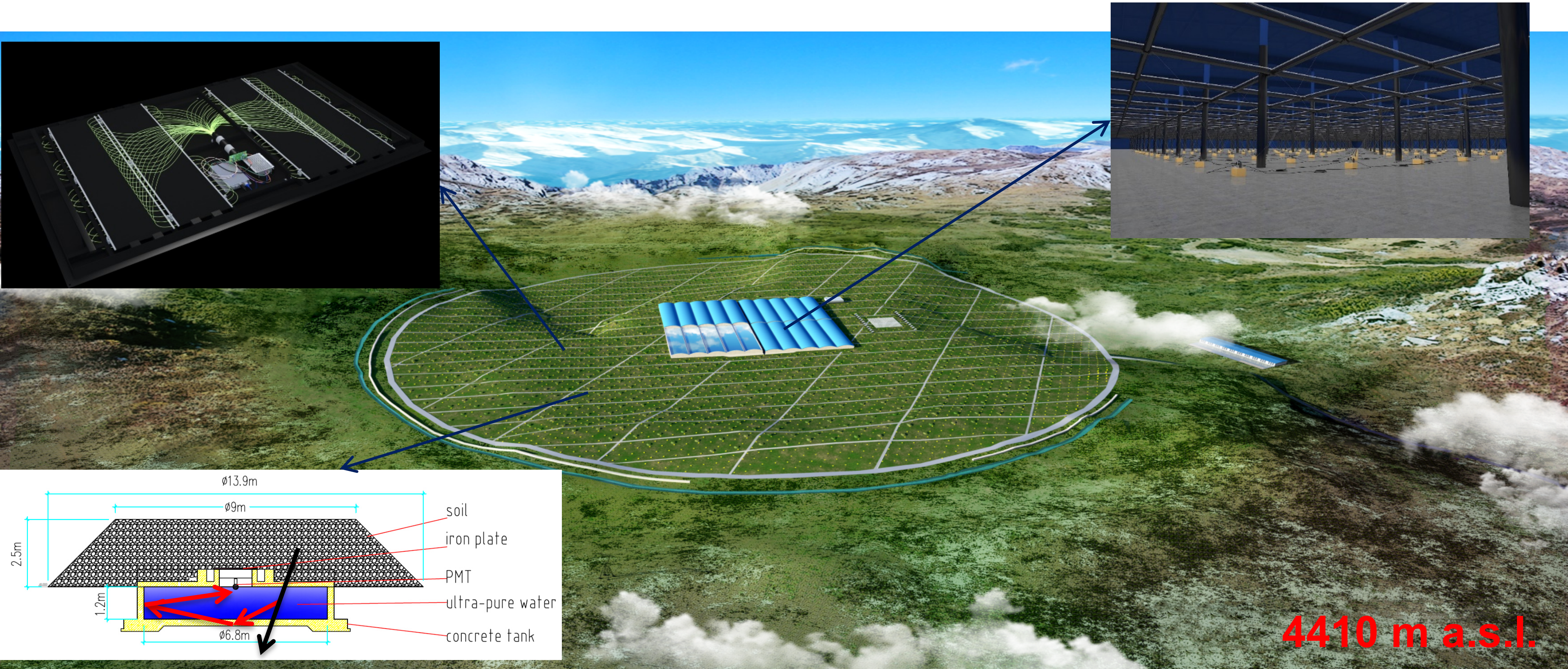
antiproton





LHAASO

Large High Altitude Air Shower Observatory



Possible TeV gamma ray halos in the FoV of LHAASO

NAME	RA (°)	Dec (°)	l (°)	b (°)	r (kpc)	t (100 kyr)	$\dot{E}$ (10^{34}erg s^{-1})	$\dot{E}/r^2$ (10^{34}erg s^{-1}kpc^{-2})	Comments[a]
J0633+1746	98.5	17.8	195.1	4.3	0.19	3.42	3.25	90.03	Geminga, detected by HAWC
B0656+14	105.0	14.2	201.1	8.3	0.29	1.11	3.80	45.18	detected by HAWC
B1951+32	298.2	32.9	68.8	2.8	3.00	1.07	374	41.56	with X-ray PWN, missed in TeV
J1954+2836	298.6	28.6	65.2	0.4	1.96	0.69	105	27.33	detected by Milagro
J1740+1000	265.1	10.0	34.0	20.3	1.23	1.14	23.2	15.33	with X-ray PWN, missed by HAWC
J1913+1011	288.3	10.2	44.5	-0.2	4.61	1.69	287	13.50	detected by HESS,YBJ,HAWC
J1836+5925	279.1	59.4	88.9	25.0	0.30	18.3	1.14	12.67	missed in TeV
J2032+4127	308.1	41.5	80.2	1.0	1.33	2.01	15.2	8.59	detected in X-ray,TeV
J1928+1746	292.2	17.8	52.9	0.1	4.34	0.83	160	8.49	detected by HAWC?
J1831-0952	277.9	-9.9	21.9	-0.1	3.68	1.28	108	7.97	detected by HESS,HAWC
B0114+58	19.4	59.2	126.3	-3.5	1.77	2.75	22.1	7.05	
J0633+0632	98.4	6.5	205.1	-0.9	1.35	0.59	11.9	6.53	detected by HAWC
J0248+6021	42.1	60.4	136.9	0.7	2.00	0.62	21.3	5.33	
B0355+54	59.7	54.2	148.2	0.8	1.00	5.64	4.54	4.54	the Mushroom X-ray PWN
J1938+2213	294.6	22.2	57.9	0.3	3.42	0.62	36.6	3.13	
J0538+2817	84.6	28.3	179.7	-1.7	1.30	6.18	4.94	2.92	with X-ray PWN, missed by HAWC?
B1830-08	278.4	-8.5	23.4	0.1	4.50	1.47	58.4	2.88	with X-ray PWN
J2043+2740	310.9	27.7	70.6	-9.2	1.48	12.0	5.64	2.57	
J2021+4026	305.4	40.4	78.2	2.1	2.15	0.77	11.6	2.51	detected in X-ray,TeV
J1857+0143	284.4	1.7	35.2	-0.6	4.57	0.71	45.1	2.16	detected by HESS,HAWC
B0611+22	93.6	22.5	188.8	2.4	1.74	0.89	6.24	2.06	
J1841-0345	280.4	-3.8	28.4	0.4	3.78	0.56	26.9	1.88	
J1913+0904	288.3	9.1	43.5	-0.7	3.00	1.47	16.0	1.78	
B0540+23	85.8	23.5	184.4	-3.3	1.56	2.53	4.09	1.68	detected by HAWC
J1846+0919	281.6	9.3	40.7	5.3	1.53	3.60	3.41	1.46	
J0611+1436	92.8	14.6	195.4	-2.0	0.89	10.7	0.80	1.01	
J0357+3205	59.5	32.1	162.8	-16.0	0.83	5.40	0.59	0.85	missed by ASgamma
J1838-0549	279.7	-5.8	26.3	0.2	4.06	1.12	10.1	0.61	
B0919+06	140.6	6.6	225.4	36.4	1.10	4.97	0.68	0.56	
J1835-0944	278.9	-9.7	22.5	-1.0	4.22	5.25	5.64	0.32	

[a] Part of the information is collected from http://snrcat.physics.umanitoba.ca/.

TABLE I. The top 30 bright middle-aged pulsars within the field of view of LHAASO. The parameters of the pulsars are given by the ATNF catalog[b].

[b] https://www.atnf.csiro.au/research/pulsar/psrcat/

Summary

- TeV gamma ray halos are detected by HAWC, which indicate a slow diffusion region around the pulsar.
- Pulsars are still the likeliest source of the anomalous positrons in PAMELA and AMS-02 in two zone model.

- It is very likely that the slow diffusion is induced by the shock wave of its SRN. Slow diffusion region is universal to each pulsar and form a slow diffusion disk.
- Such a nonuniform diffusion may change both the background and dark matter signal.
- LHAASO has great potential to discover more TeV gamma halos.