Pulsar gamma ray halos and implications on cosmic rays propagation

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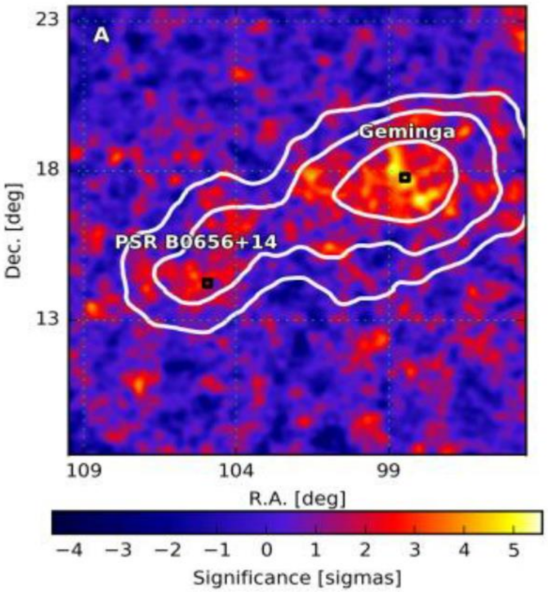
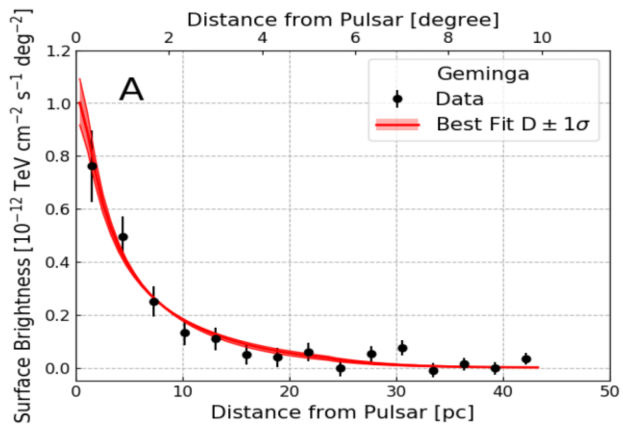
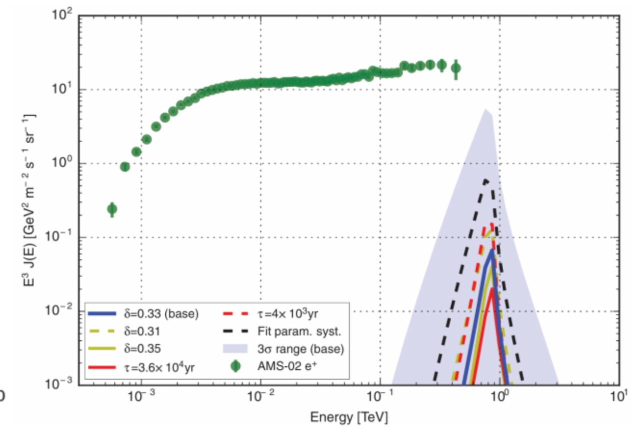
Slow diffusion around the γ-ray halos of Geminga/Monogem







A.U. Abeysekara et al. HAWC Coll.
Science 358, 911–914 (2017)

- In order to explain the halo 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 Geminga pulsar is negligible to AMS-02 positron data! Need exotic sources!

What mechanism leads to the gamma-ray halo profile?

- Slow diffusion

- Anisotropic diffusion

- Ballistic-diffusive propagation

What mechanism leads to the gamma-ray halo profile?

- Slow diffusion

- **Anisotropic diffusion**

- **Ballistic-diffusive propagation**

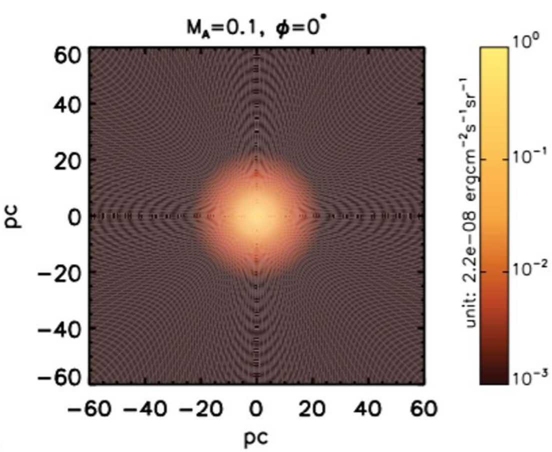
Anisotropic diffusion

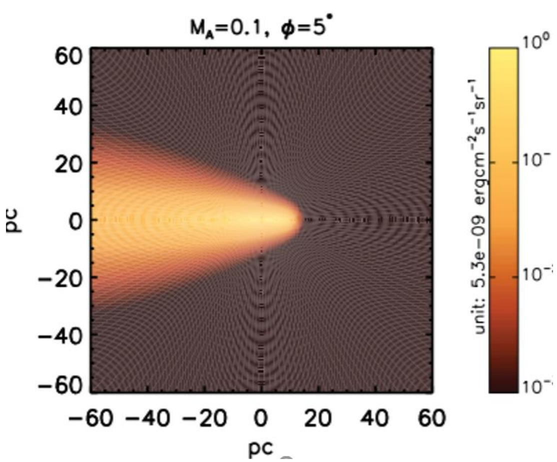
Liu, Yan, Zhang, PRL123, 22, 221103 (2019)

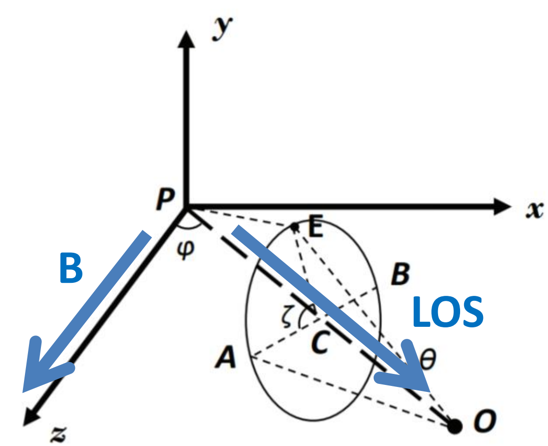
- In scale of coherent length diffusion is anisotropic

$$D_{zz} = D_{||} = D_0(E_e/1\mathrm{GeV})^q$$

- $$D_{rr} = D_{\perp} = D_{zz} M_A^4$$ M_A = 0.1, 0.2, 0.3
- Diffusion parallel to mean magnetic field is the typical Galactic value, that perpendicular to the direction is very small.
- If LOS happens to be alined with direction of B



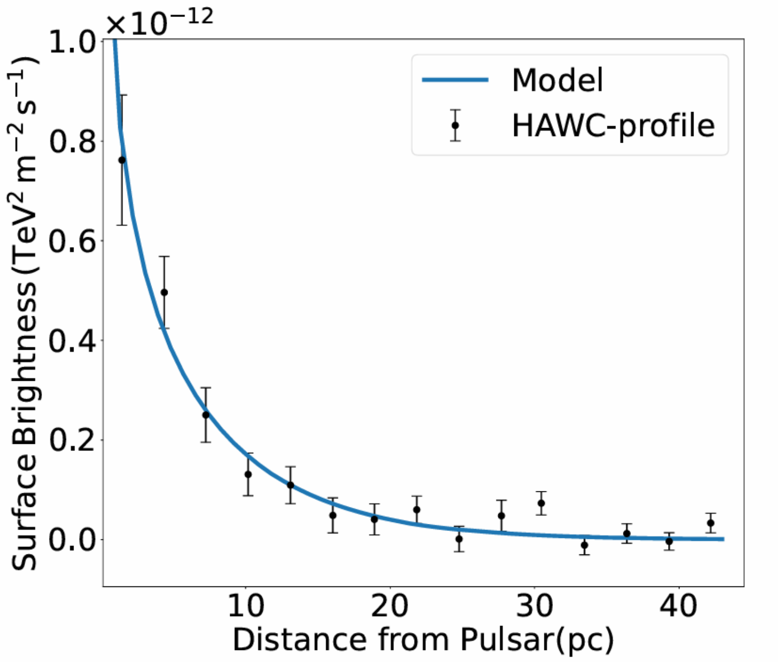


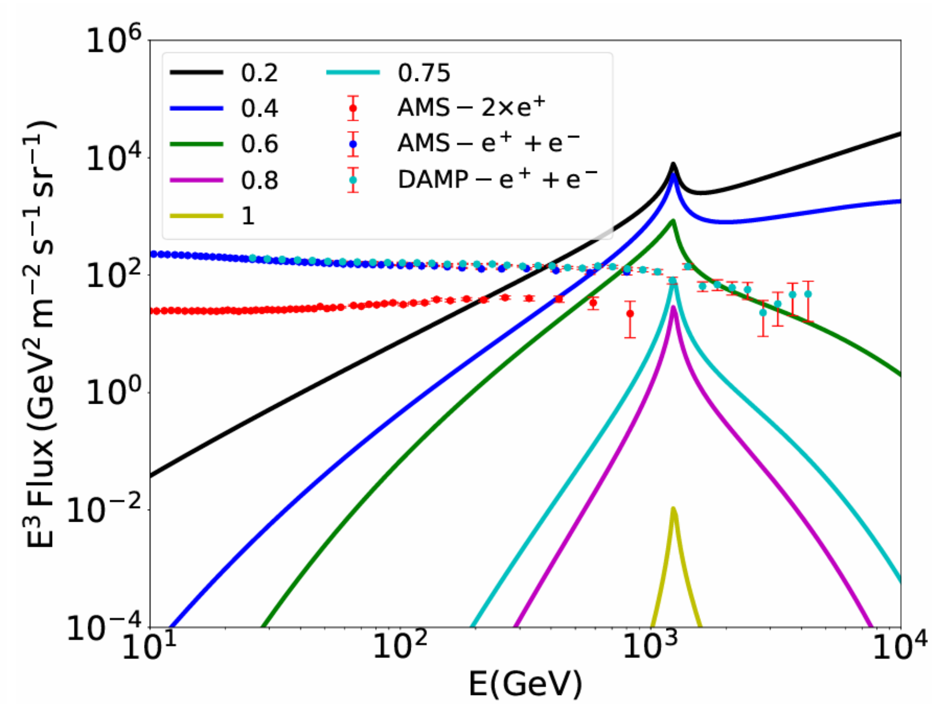


Constraints on anisotropic diffusion by positron fluxes

Xia, **BXJ**, Fang, Liu, arixv: 2024.XXXX

- e+- are confined in a narrow tube and propagate fast to the earth.
- Fit the HAWC profile and calculate the e^{+-} flux for different M_A
- M_A=1, the flux is negligible; M_A < 0.75, the flux exceeds the DAMPE measurement.

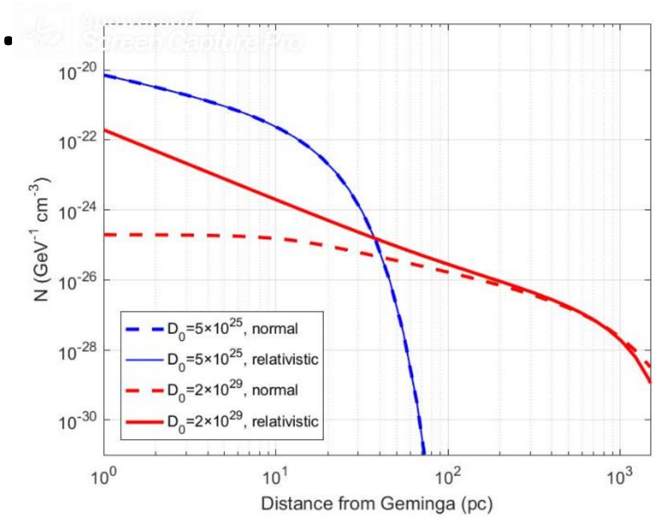




Ballistic-diffusive propagation

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

- The diffusion equation is non-relativistic. For $t<3D/c^2$, diffusion rate $d \sim \sqrt{Dt}$, is superluminal.
- Most recently injected particles propagate ballistically with speed of light. The BD propagation account for the Geminga γ-ray halo profile without a slow diffusion.

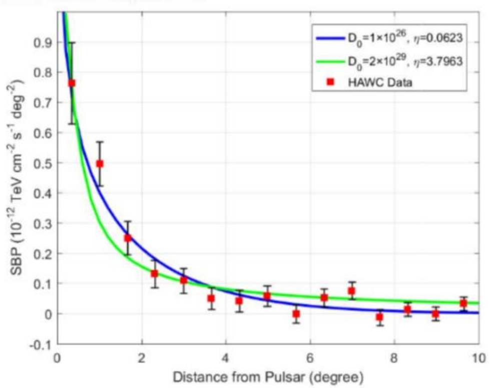


BD cann’t fit the halo profiles

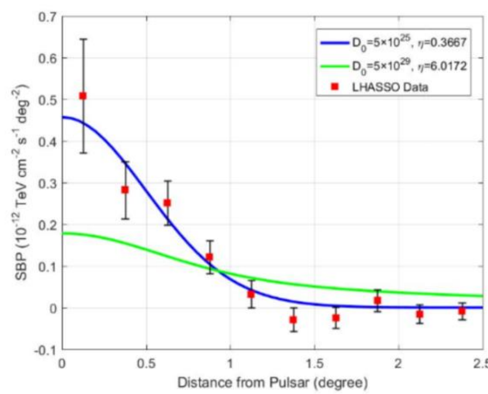
Bao, Fang, **BXJ**,
Astrophys.J. 936 (2022) 2, 183

- BD fits the profile much worse than the slow diffusion scenario. Especially for LHAASO J0621+3755 it can not account for the profile.

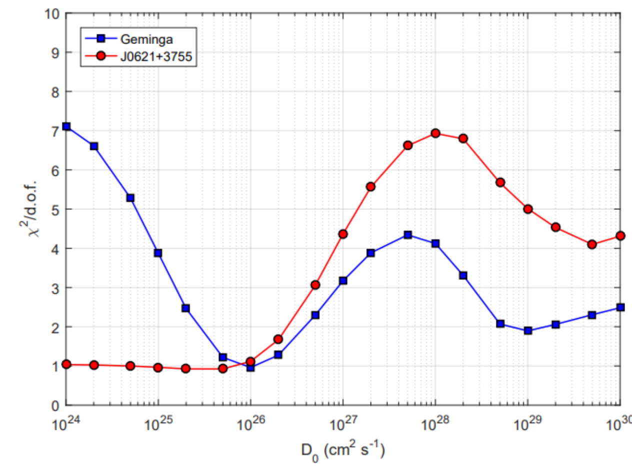
Geminga

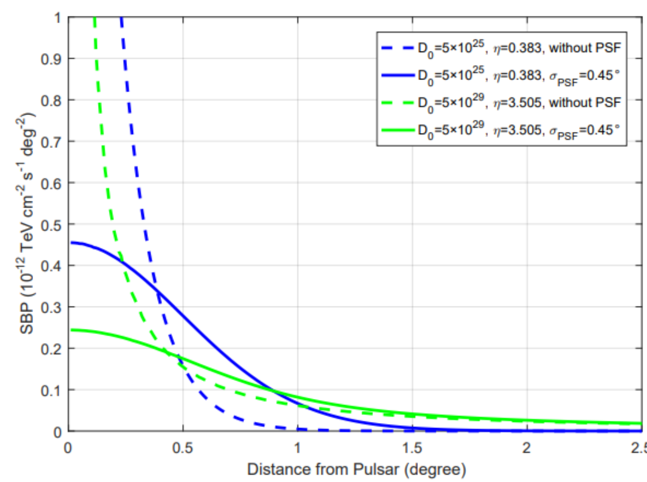


LHAASO J0621+3755



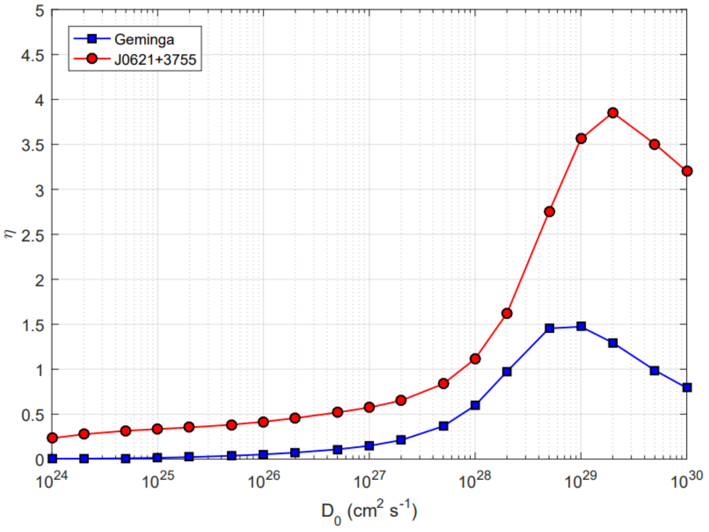
- BD propagate e^{-+} away from the PWN too fast.





BD requires too high efficiency

- As e^{+-} propagate very fast it requires very high transfer efficiency from spin-down energy to e^{+-} to account for the observed luminosity.



- **BD propagation doesn't work to account the pulsar γ-ray halos.**

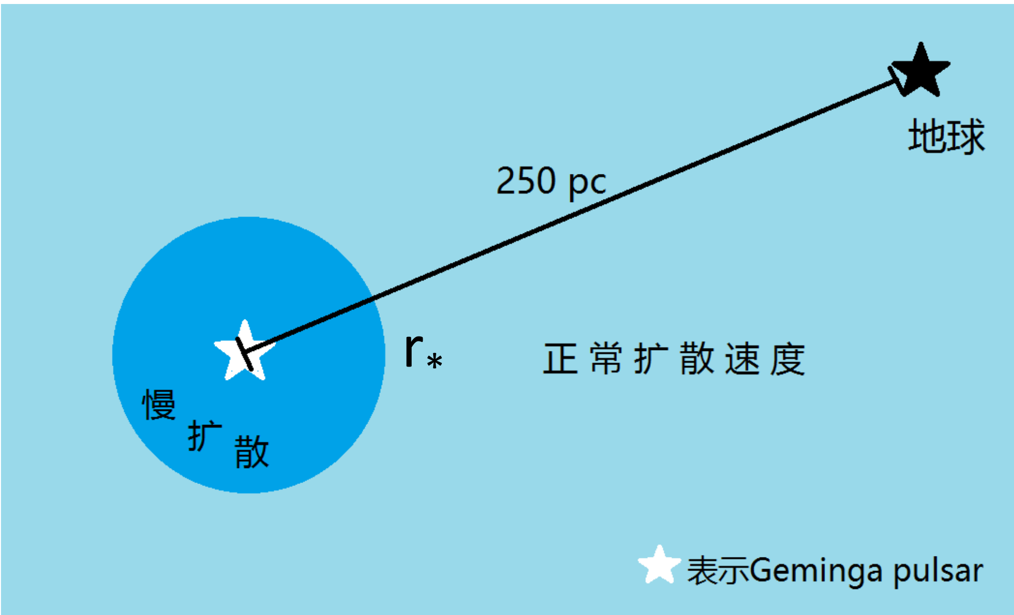
What mechanism leads to the gamma-ray halo profile?

- **Slow diffusion**
  - Contradiction between halo and B/C
  - AMS02 positron flux
  - Mechanism leads to slow diffusion

- Anisotropic diffusion

- Ballistic-diffusive propagation

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

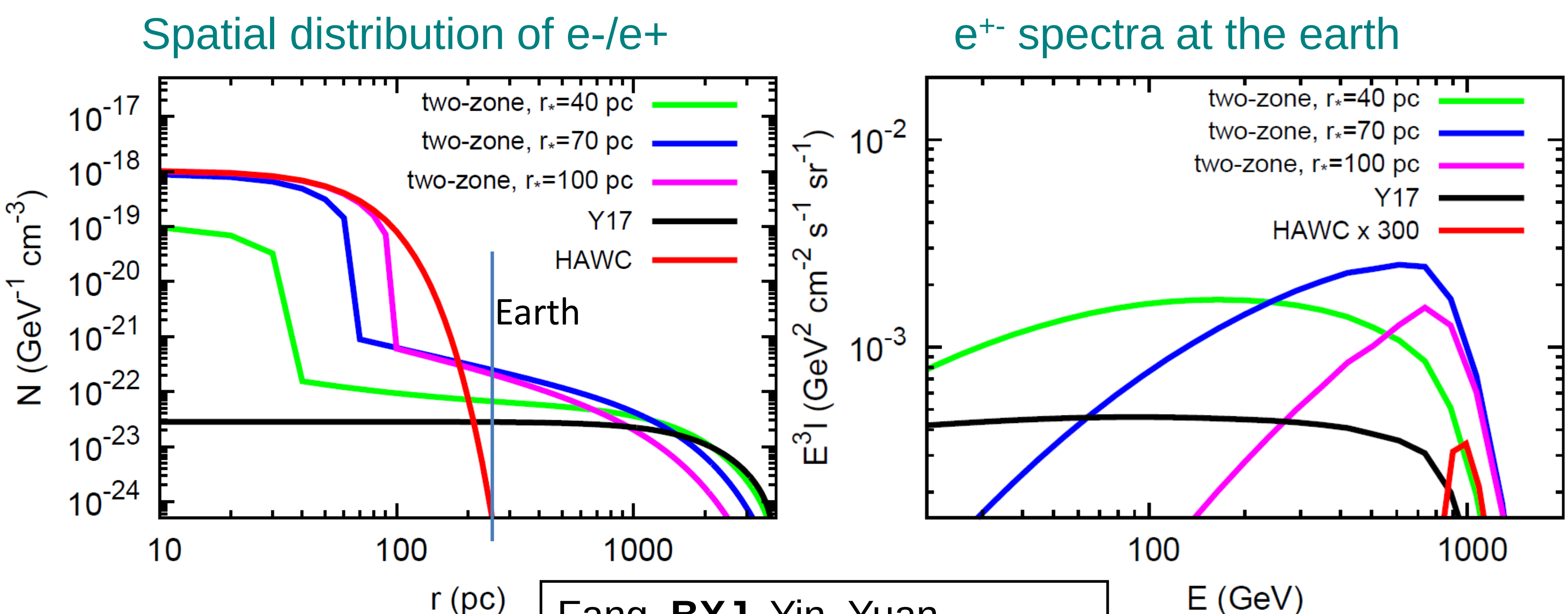


Two-zone diffusion for Geminga

Fang, **BXJ**, Yin, Yuan
APJ 863(2018) 30

- The slow diffusion region is near the source; while the diffusion is still fast in most interstellar space.
- All the previous predictions in CR physics are nearly not changed! Such as B/C, antiproton, diffuse gamma rays.
- We need to check the positron flux in this scenario.

Unexpected result of positron flux!

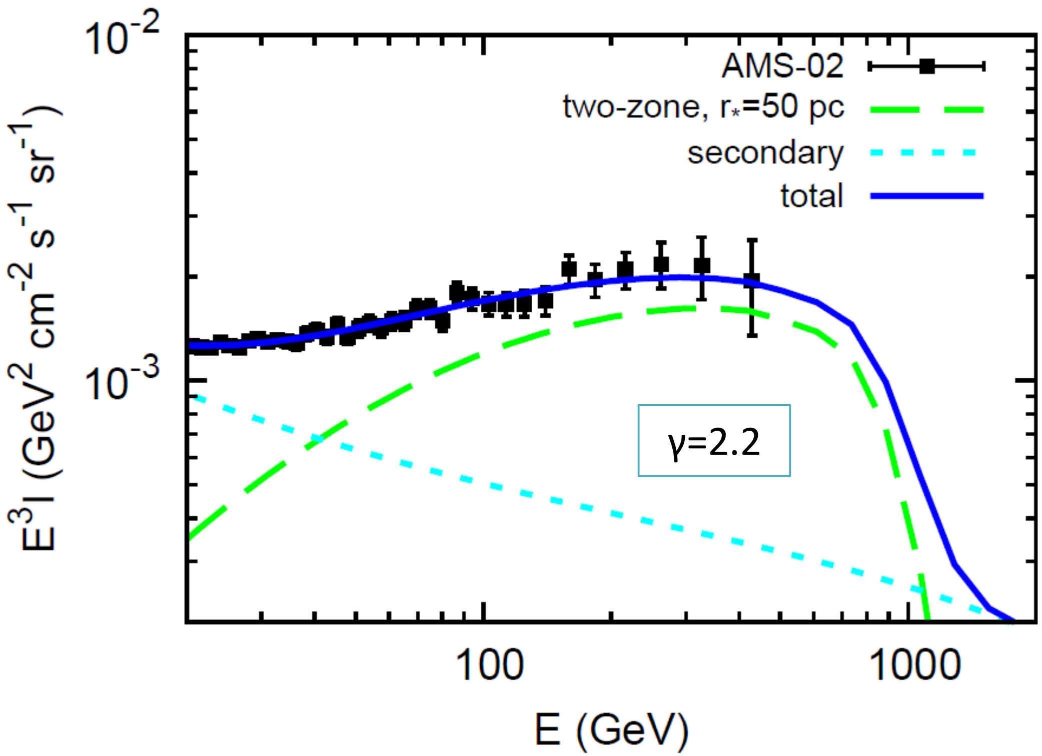


Fang, **BXJ**, Yin, Yuan
Astrophys.J. 863 (2018) 1, 30

- 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 solves the positron excess

Compare with AMS-02 e+



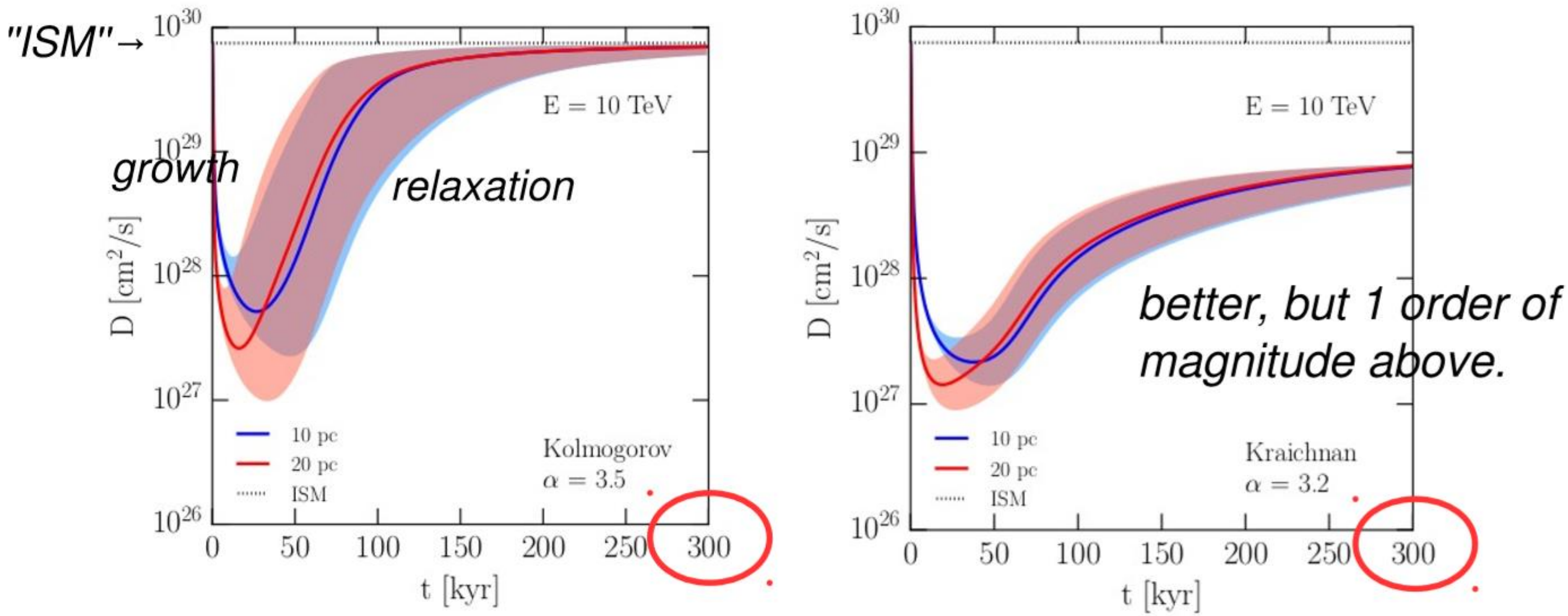
Fang, **BXJ**, Yin, Yuan
Astrophys.J. 863 (2018) 1, 30

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

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

Mechanism to suppress the diffusion?

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.

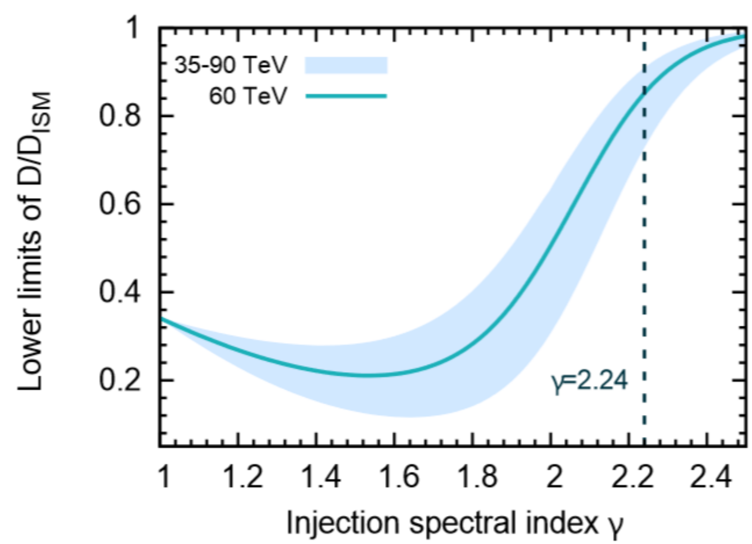
Streaming instability leads to slow diffusion around Geminga?

Fang, **BXJ**, Yin, MNRAS488(2019) 4074

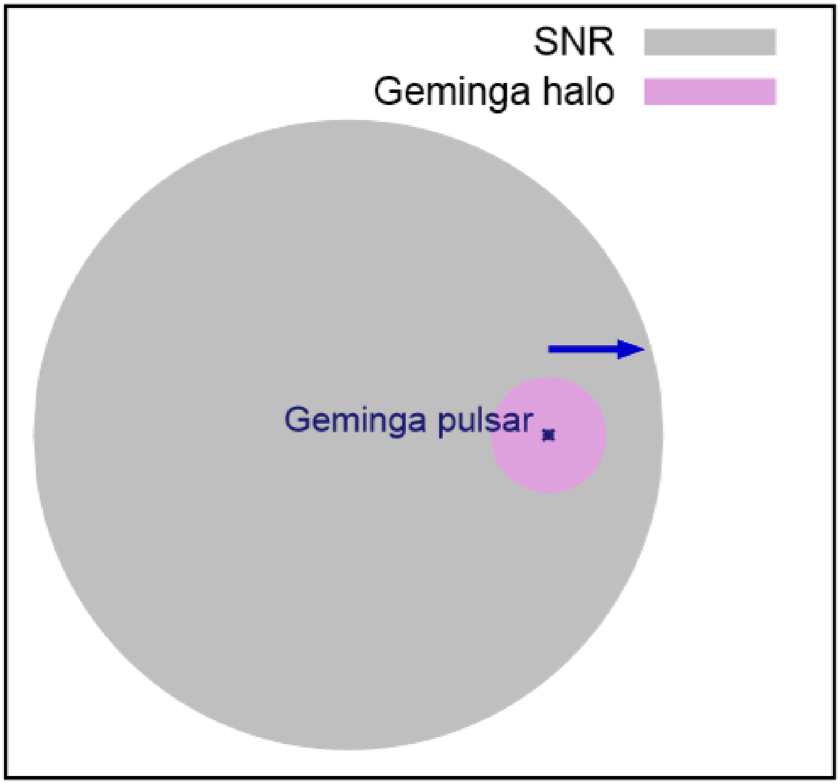
- A ***lower*** limit on the diffusion coefficient is derived by assuming: no energy loss of electrons; no wave dissipation; we get an analytic solution

$$D(x) = D_{\rm ISM} \exp\left(-\frac{4\pi e v_A E}{B_0 c}\int_x^\infty N dx'\right)$$

- 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 $D_{\rm ISM}$



Down-stream of SNR shock



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

Proper motion of Geminga at 200km/s, Geminga left **70pc** from its birth place.

In the shock frame:

kinetic energy loss

⇩

thermal energy + turbulent energy

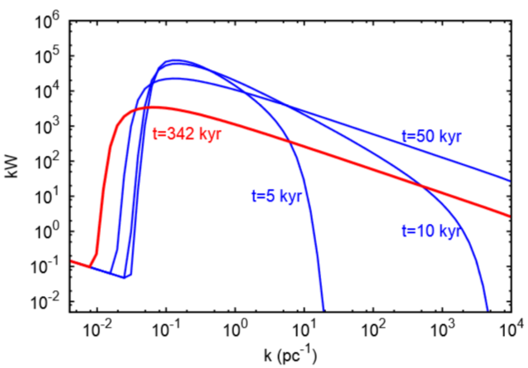
⇨ avaiable for turbulence: 6 x 10^-12 erg/cm^3

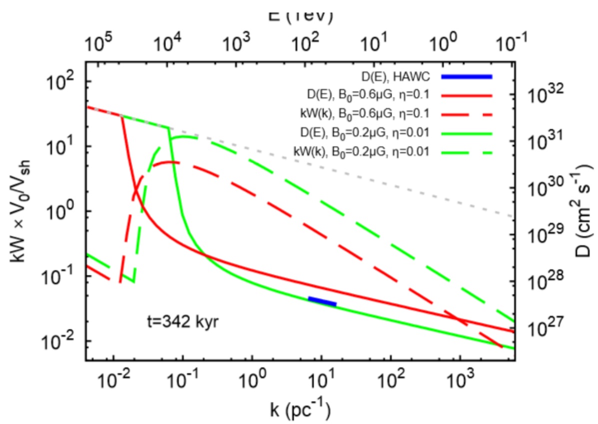
magnetic energy: 4 x 10^-13 erg/cm^3

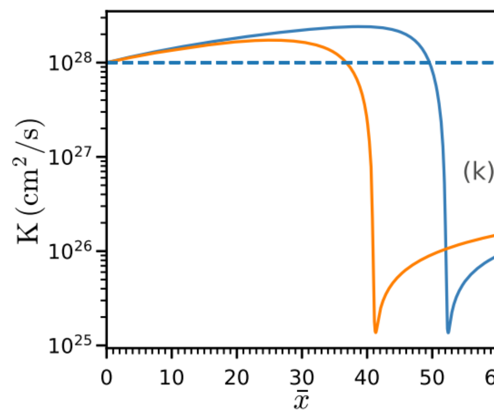
Mechanism to generate the slow diffusion

Fang, **BXJ**, Yin, MNRAS488(2019) 4074

- The evolution of the turbulence wave spectrum W with time and the diffusion coefficient were calculated; In some parameters the diffusion coefficient is consistent with HAWC value







- Coupled equations with gas dynamics, CR pressure, turbulence transport equations are solved. The CR diffusion coefficient is suppressed by more than three orders

Wang, Zank, et al, ApJ932:65, (2022)

Geminga observation in LHAASO

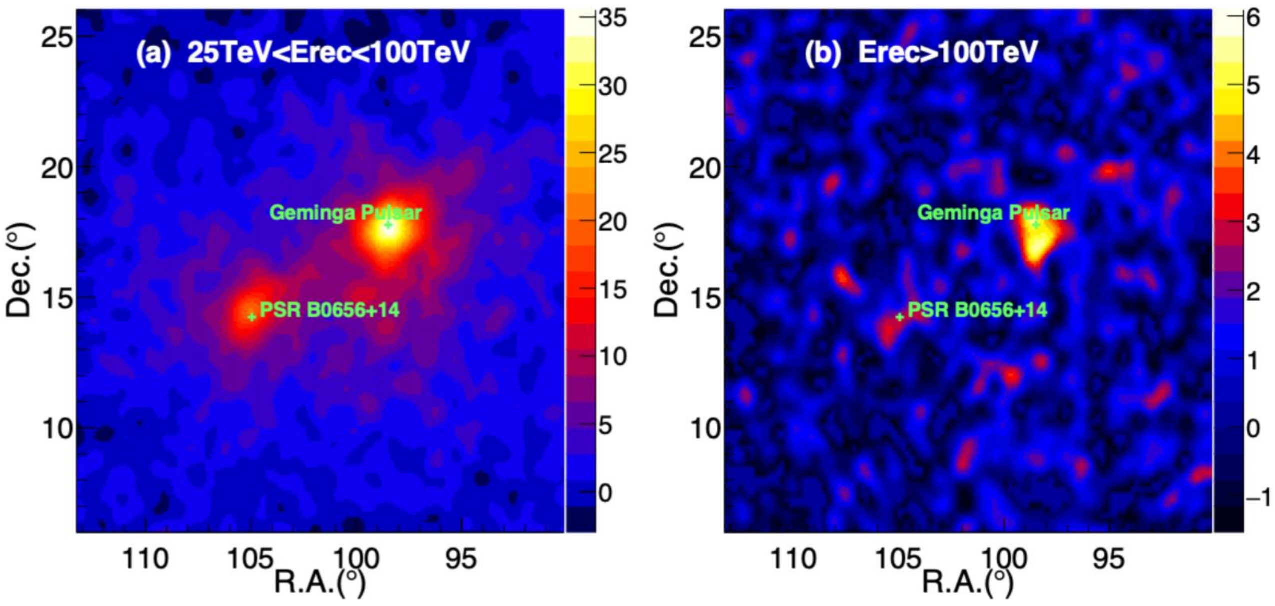
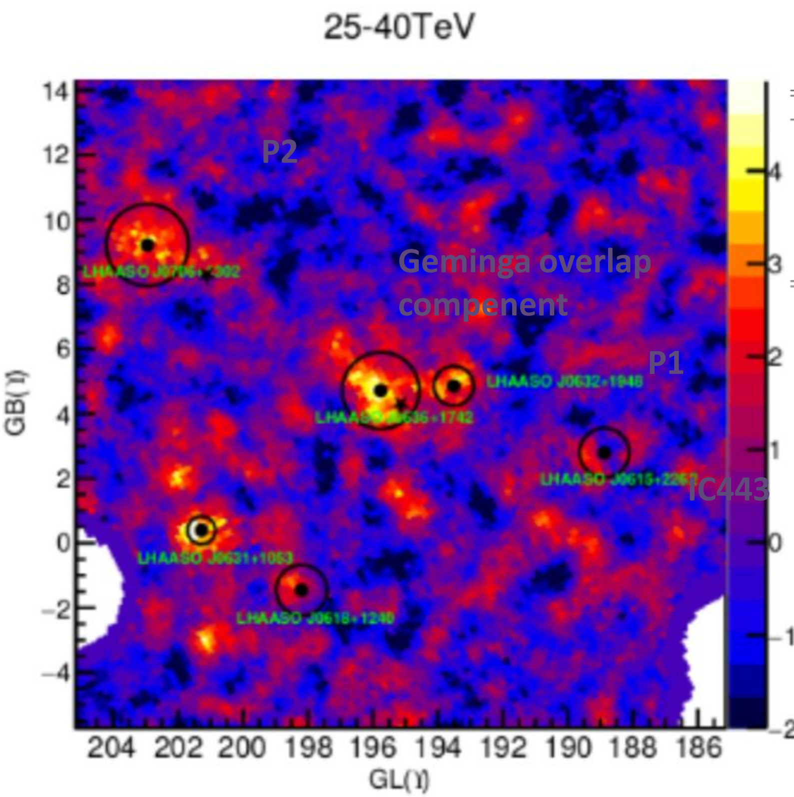


FIG. 1. The significance map for $25 < E_\gamma < 100$ TeV (left) and $E_\gamma > 100$TeV (right) in Galactic coordinate around Geminga and Monogem. Green crosses label the locations of the two pulsars, Geminga and PSR B0656+14. Both images are smoothed using a 0.3-degree Gaussian kernal.

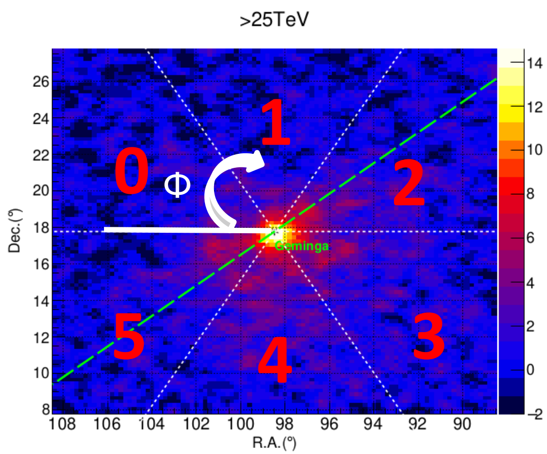
Individual sources

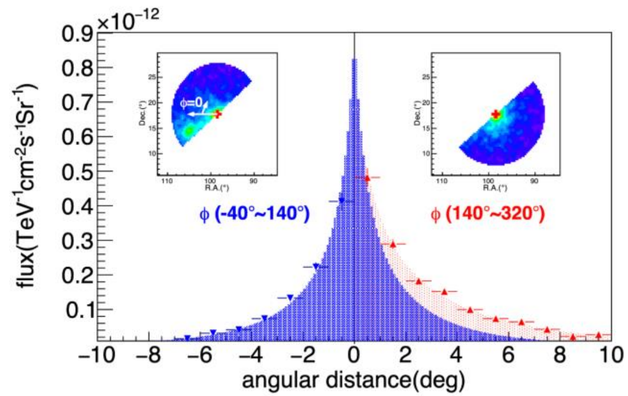


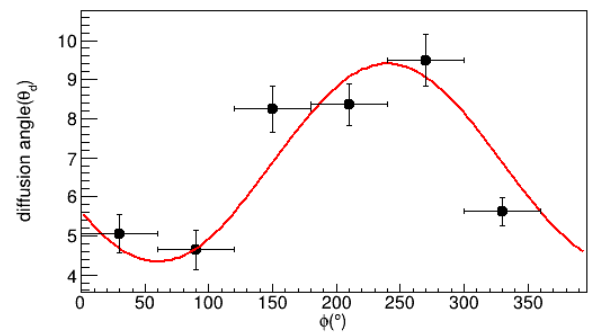
Name	R.A. (°)	Dec. (°)	R_{68} (°)	TS	Association
LHAASO J0615+2219	93.88 ± 0.17	22.33 ± 0.16	0.61 ± 0.15	29	IC443
LHAASO J0619+1228	94.81 ± 0.19	12.48 ± 0.14	0.88 ± 0.15	41	4FGL J0618.7+1211
LHAASO J0631+1037	97.81 ± 0.04	10.63 ± 0.04	0.39 ± 0.05	283	3HWC J0631+107
LHAASO J0632+1923	98.08 ± 0.11	19.40 ± 0.11	0.81 ± 0.15	86	PSR J0630+19
LHAASO J0633+1738	98.50 ± 0.06	17.64 ± 0.05	0.72 ± 0.05	224	-
LHAASO J0640+1710	100.2 ± 0.14	17.18 ± 0.11	1.31 ± 0.10	133	-
LHAASO J0708+1304	107.0 ± 0.23	13.08 ± 0.17	1.13 ± 0.19	32	-

#	NAME	RAJ (hms)	DECJ (dms)	DIST (kpc)	DIST_DM (kpc)	AGE (Yr)	BSURF (G)	EDOT (ergs/s)
1	J0630+19 dsm+16	06:30:04 119 dsm+16	+19:37 8 dsm+16	0.982	0.982 ymw17	*	*	*

Asymmetric halo





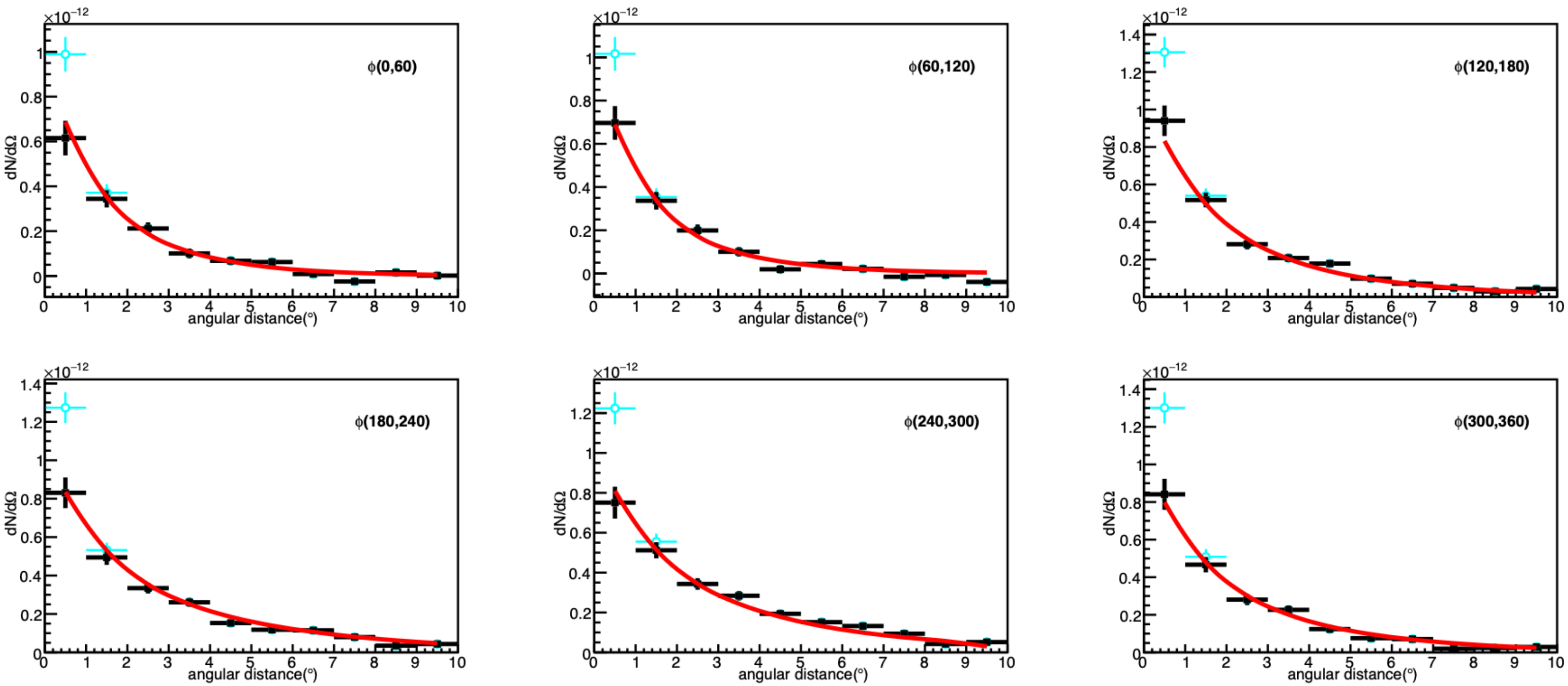


$$f(\theta,\phi,E_\gamma) = \frac{C(\phi,E_\gamma)}{\theta_d(\phi,E_\gamma)\left[\theta + 0.113\theta_d(\phi,E_\gamma)\right]} e^{-[\theta/\theta_d(\phi,E_\gamma)]^{1.52}}$$

$$\theta_d(\phi,E_\gamma) = \theta_0\left[1 + A_\theta\cos(\phi-\phi_\theta)\right]\left(E_\gamma/30\ \mathrm{TeV}\right)^{-\rho},$$

$$C(\phi,E_\gamma) = C_0\left[1 + A_c\cos(\phi-\phi_\theta)\right]\left(E_\gamma/30\ \mathrm{TeV}\right)^{\alpha+\beta\ln(E_\gamma/30\ \mathrm{TeV}}$$

Profiles of Geminga



Possible origin models for asymmetrical morphology:

1. Inhomogeneous diffusion (Two-zone diffusion)

$$\frac{\partial N}{\partial t} = \frac{\partial}{\partial x}\left[D(x,y,z)\frac{\partial N}{\partial x}\right] + \frac{\partial}{\partial y}\left[D(x,y,z)\frac{\partial N}{\partial y}\right] + \frac{\partial}{\partial z}\left[D(x,y,z)\frac{\partial N}{\partial z}\right] + \dots$$

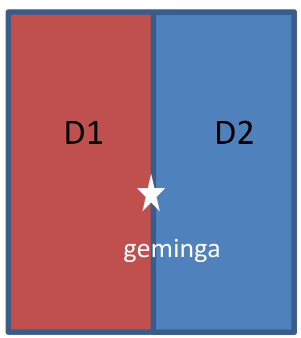
- The diffusion coefficient is not constant, but spatially dependent.
- The simpliest case is **two-zone** diffusion.

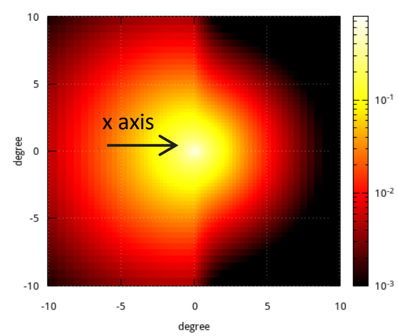
Two-zone diffusion:

D1 > D2

larger D means larger extent.

$$D(x,y,z) = \begin{cases} D_1, & x < 0 \\ D_2, & x > 0 \end{cases},$$





Possible origin models for asymmetrical morphology:

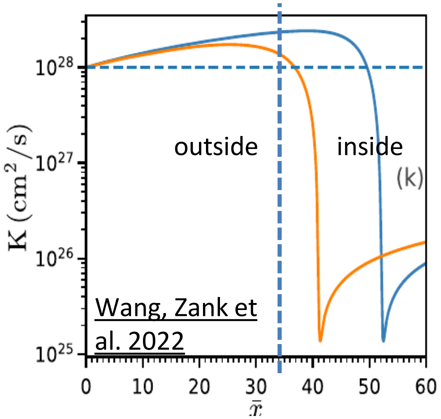
2.Inhomogeneous diffusion (SNR environment)

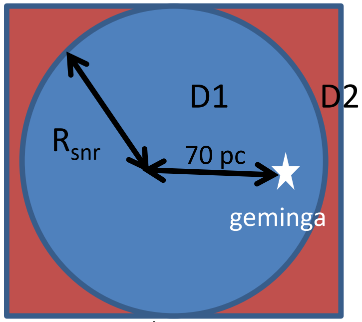
Diffusion inside the SNR could be much slower!

$$\frac{\partial N}{\partial t} = \frac{\partial}{\partial x}\left[D(x,y,z)\frac{\partial N}{\partial x}\right] + \frac{\partial}{\partial y}\left[D(x,y,z)\frac{\partial N}{\partial y}\right] + \frac{\partial}{\partial z}\left[D(x,y,z)\frac{\partial N}{\partial z}\right] + \ldots$$

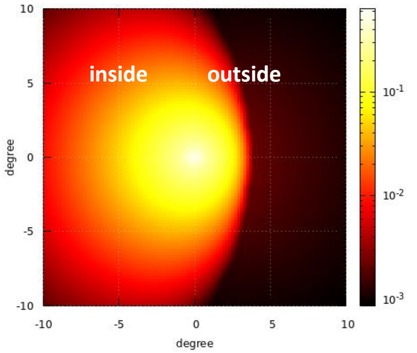
D1: inside D2: outside

D1 << D2





Fang, Bi et al. 2019



Possible origin models for asymmetrical morphology:

3. Anisotropic diffusion

$$\frac{\partial N}{\partial t} = \frac{D_{rr}}{r}\frac{\partial}{\partial r}\left(r\frac{\partial N}{\partial r}\right) + D_{zz}\frac{\partial^2 N}{\partial z^2} + ...$$

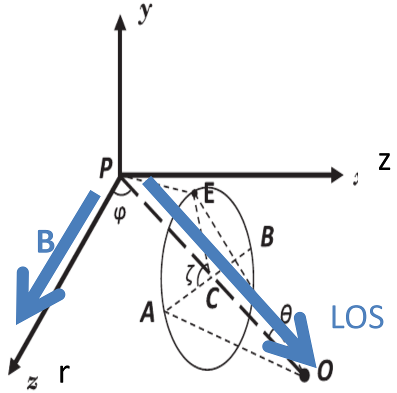
Drr: parallel to the mean field

Dzz: perpendicular to the mean field

Drr = Dzz * Ma^4 （Drr>>Dzz）

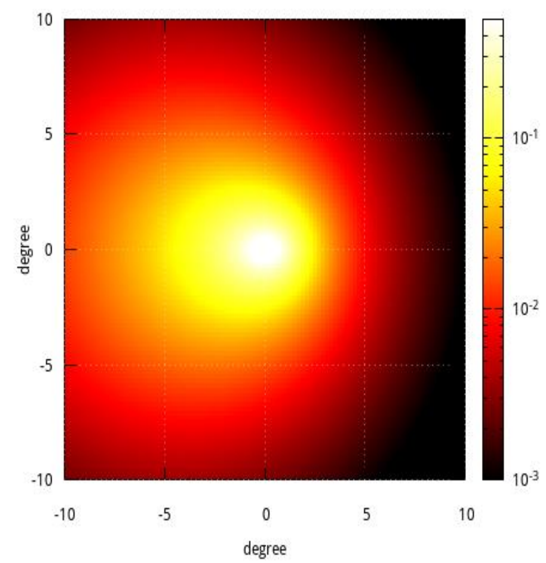
Ma is the Alfvenic Mach number.

ϕ is the angle between B and los.

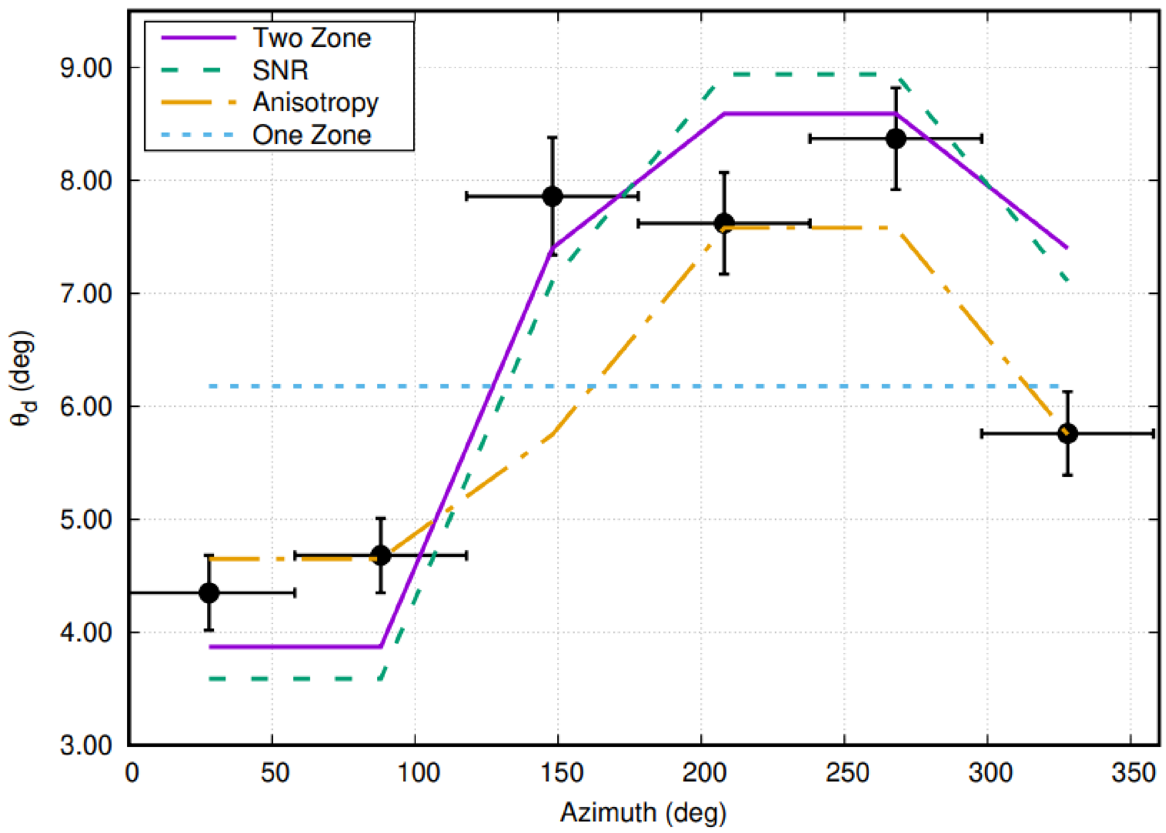


Liu, Yan et al. 2019

- The asymmetry of the halo is may be explained by **anisotropic diffusion**.
- Drr explains the small extent of the halo.



Possible origin models for asymmetrical morphology



Central excess at the position of Geminga

- An excess at the center of the halo. It should be part of the halo.
  - center coincide with the pulsar
  - spectrum consistent with halo
  - extension much larger than PWN.
- Inhomogeneity exists in multi-scales of the ISM, such as filaments, bubbles, or shells. The ISM exhibits a fractal-like feature.

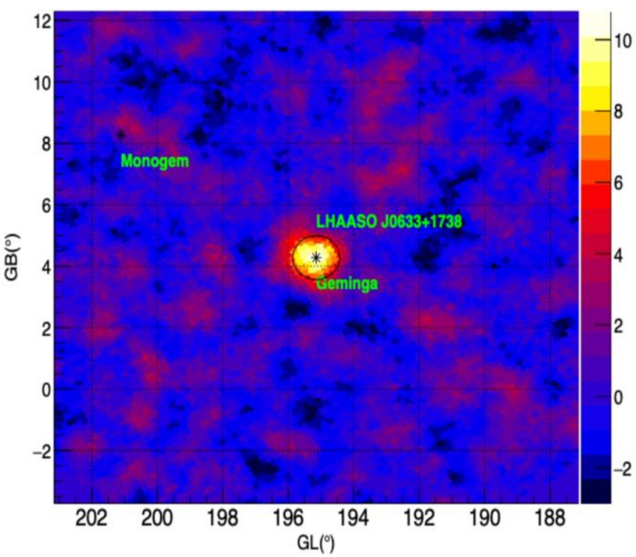


FIG. 4. The total profile of Geminga above 25TeV, corresponds to a median energy of 34TeV. The red dots represent the data after deducting the gaussian source coinciding with Geminga, while the black dots represent the data without deducting this source, and the red line represents the expectation of the diffusion model.

anomalous diffusion **?**

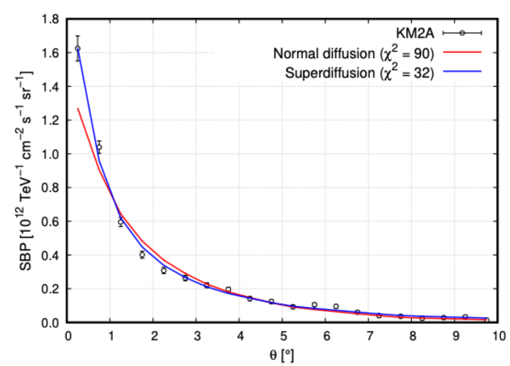


FIG. 6. Comparison of profile data fitting using the superdiffusion model (Lévy index α = 1.6) versus the normal diffusion model.

Summary

- Slow diffusion seems the best scenario to account for the gamma ray halos around pulsars.
- Geminga provides the excess positrons in the two-zone diffusion and slow diffusion may be due to SNR environment.
- LHAASO provides much more precise measurement on the halos and deeper view on the propagation process.