Slow diffusion around Geminga and positron excess on the Earth

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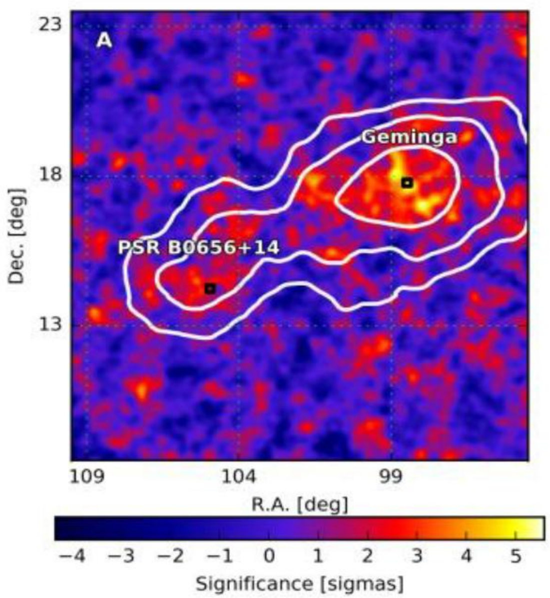
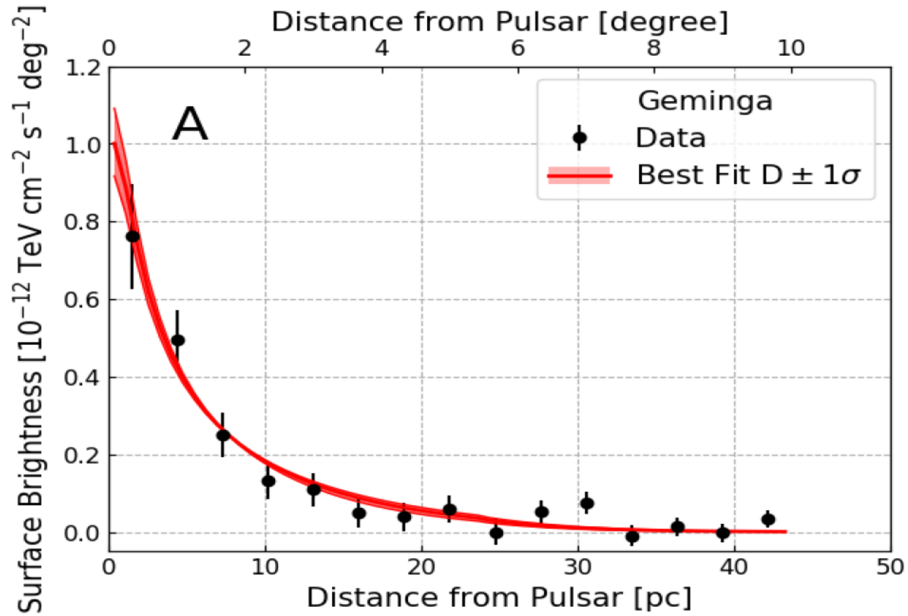
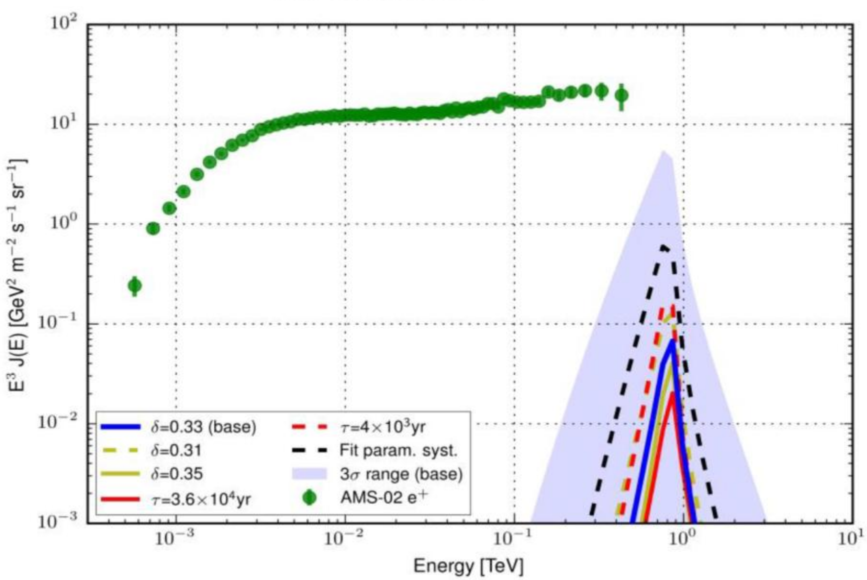
TeV gamma-ray halo of Geminga



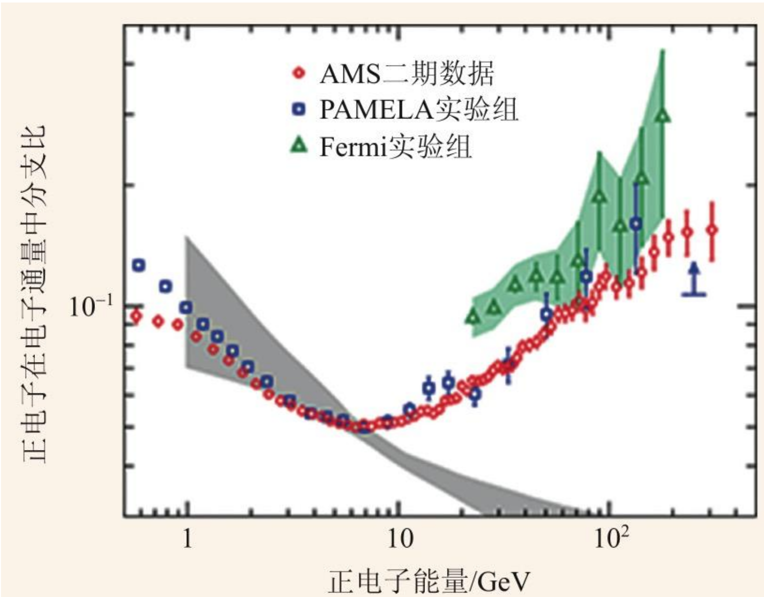




A.U. Abeysekara et al. HAWC collaboration, Science 2017

- The diffusion coefficient is hundreds times **slower** than that at the ISM derived by B/C !
- The pulsar contribution of e+ to AMS-02 data is negligible?

Positron excess and extra e+ sources



Positron excess is confirmed by different experiments.

Extra positron sources:

- ➢ Astrophysical sources - pulsars
- ➢ Dark matter

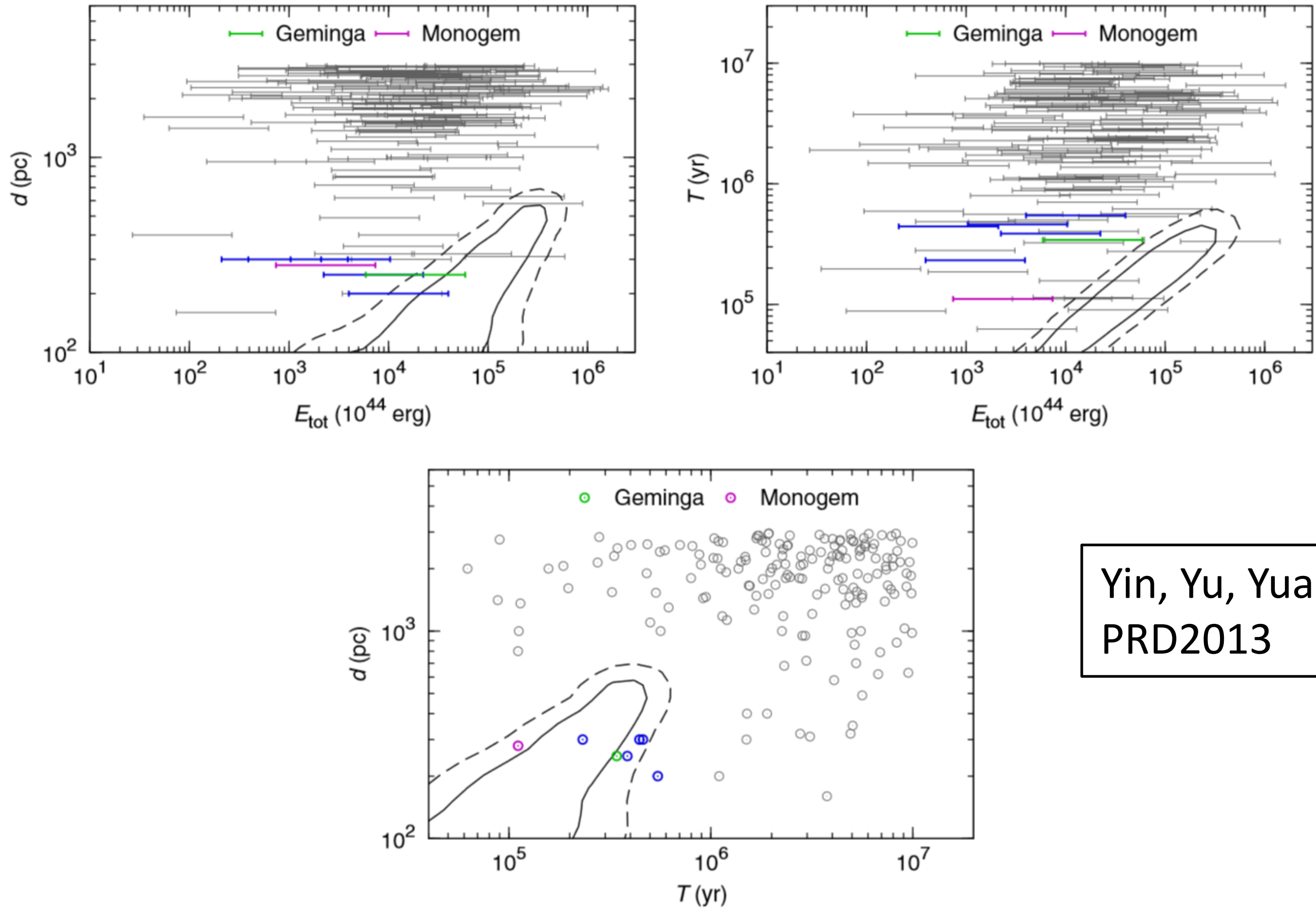
Channels	m_χ(TeV)	AMS-02 (2σ)	Fermi limits	Planck limits
$\mu^+\mu^-$	0.89	$3.79\times10^{-24} < \langle\sigma_{\rm ann}v\rangle < 6.48\times10^{-24}$	2.95×10^{-24}	2.58×10^{-24}
$\tau^+\tau-$	3.89	$5.29\times10^{-23} < \langle\sigma_{\rm ann}v\rangle < 1.06\times10^{-22}$	1.25×10^{-23}	1.06×10^{-23}

Excluded!?

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

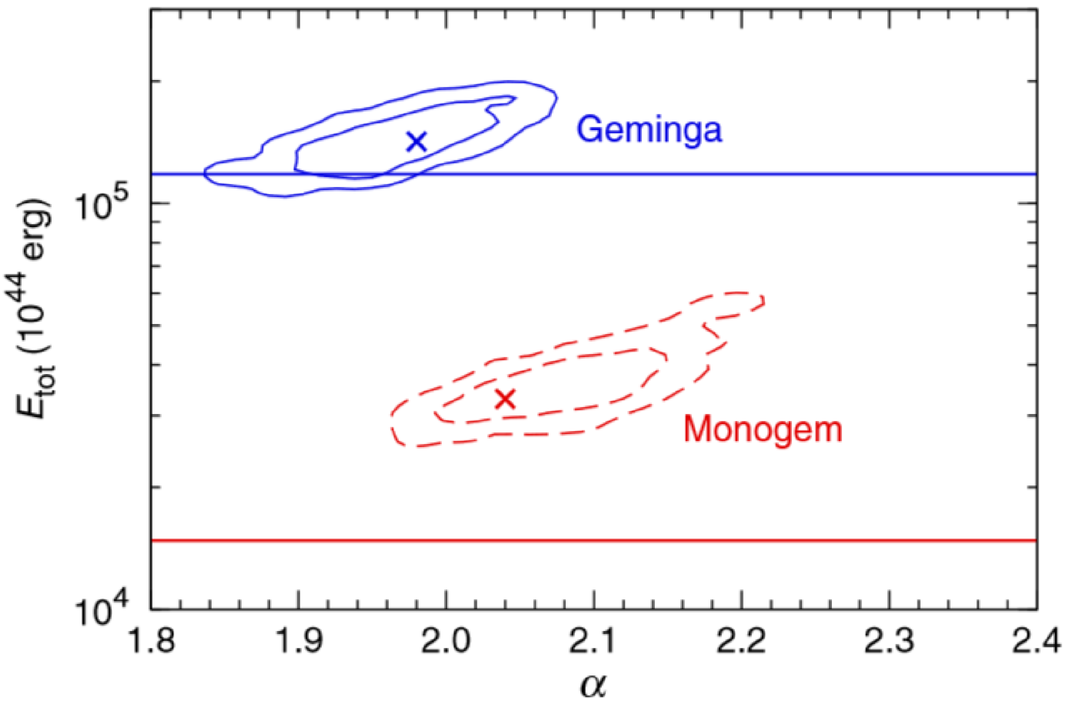
DM needs very large annihilation cross, but severely constrained by Fermi and Planck observations.

Can positrons come from nearby pulsars?



Yin, Yu, Yuan, Bi, PRD2013

Geminga and Monogem are most possible candidates



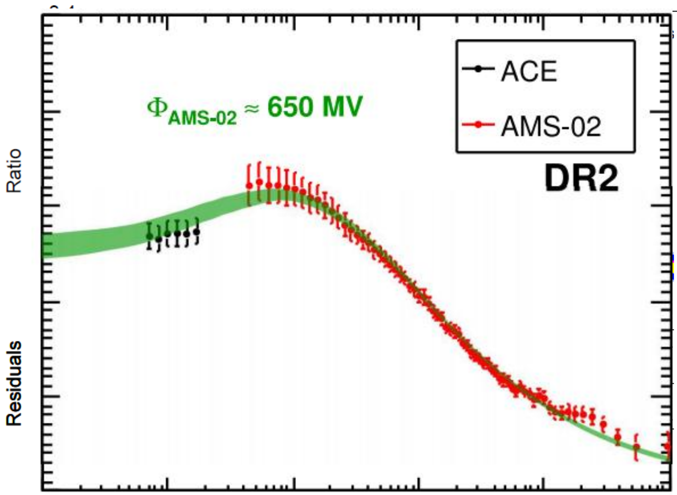
Considering all possible uncertainties, pulsars can explain the positron excess marginally assuming 100% spin-down energy transferred to e+-.

But, the HAWC result seems to indicate the pulsar scenario is excluded either, so that no proper extra positron sources available to account for positron excess! (DM not favor)

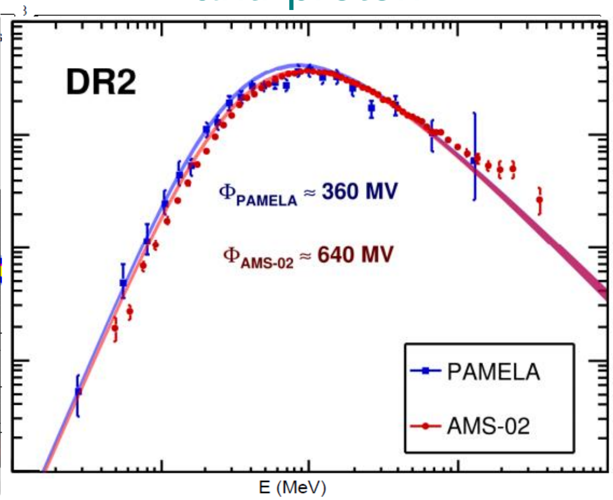
Diffusion in ISM must be large!

Contradiction#1

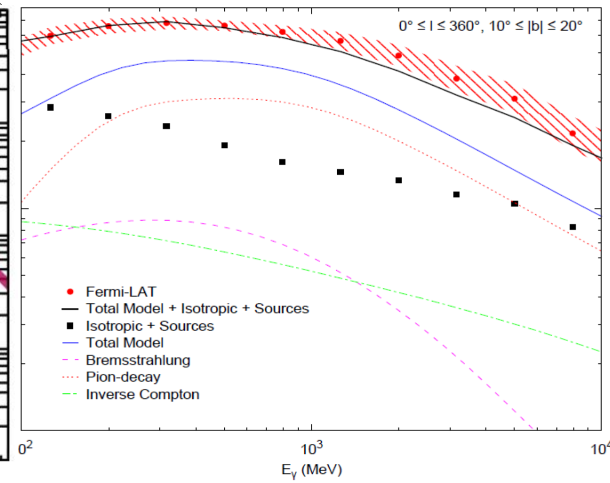
B/C



anti-proton



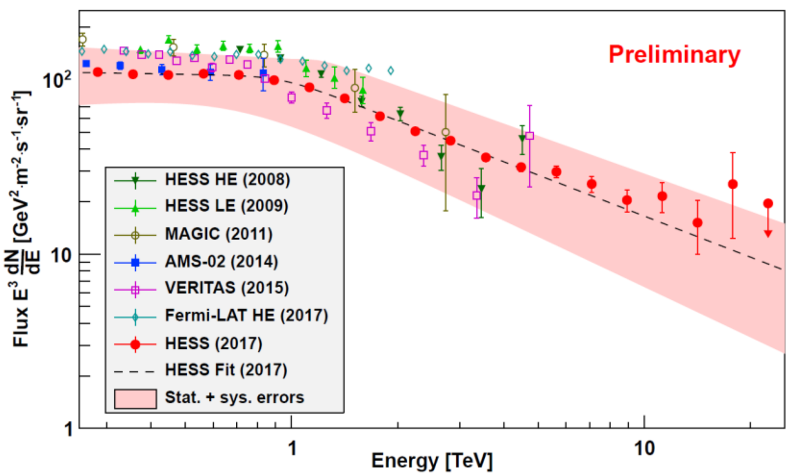
diffuse gamma-ray



Trotta *et al.* 2011

Yuan *et al.* 2017

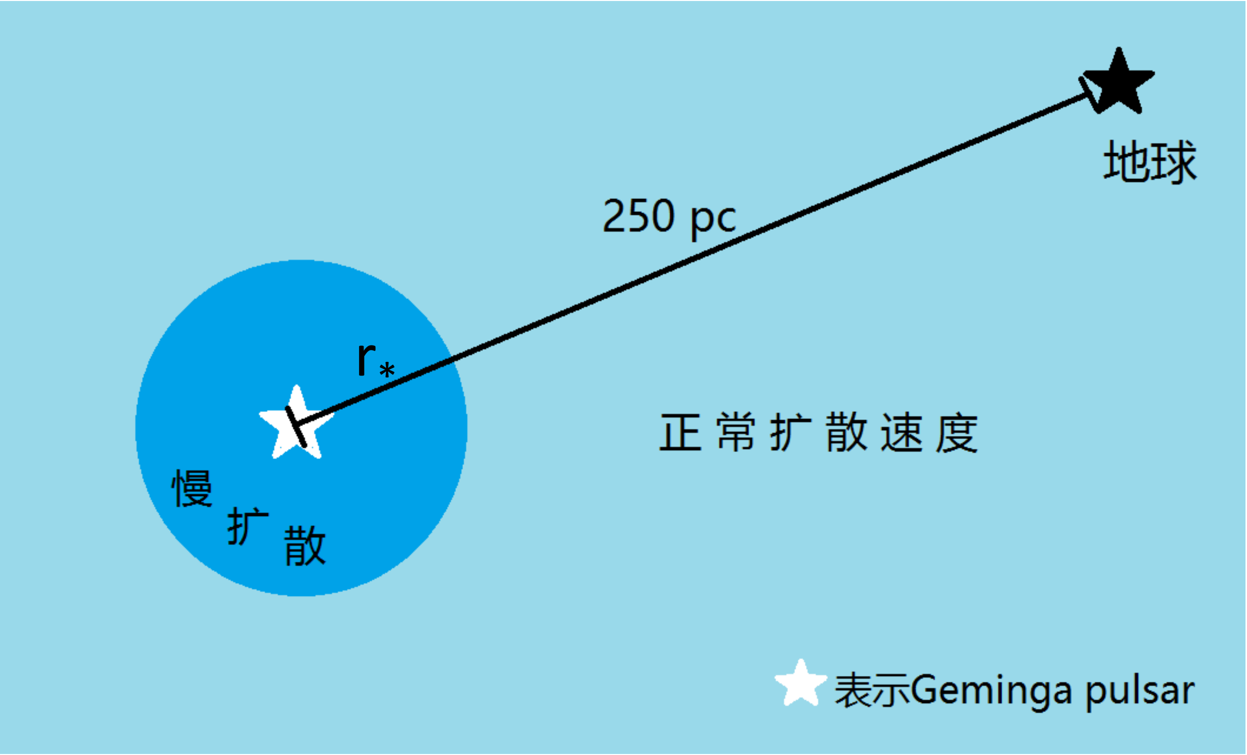
Contradiction#2



H.E.S.S has observed 20 TeV e-/e+ -> no source exist within few pc

The H.E.S.S Collaboration 2017

Two-zone diffusion for Geminga



- The slow diffusion region is near the source; while the diffusion is still fast in most interstellar space.

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

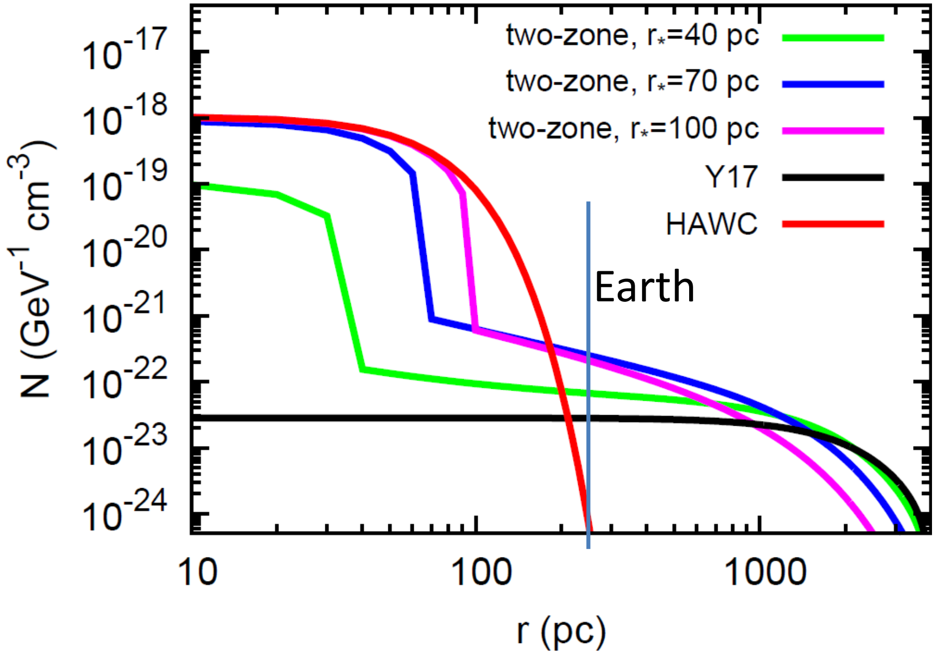
Numerical solution is required!

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

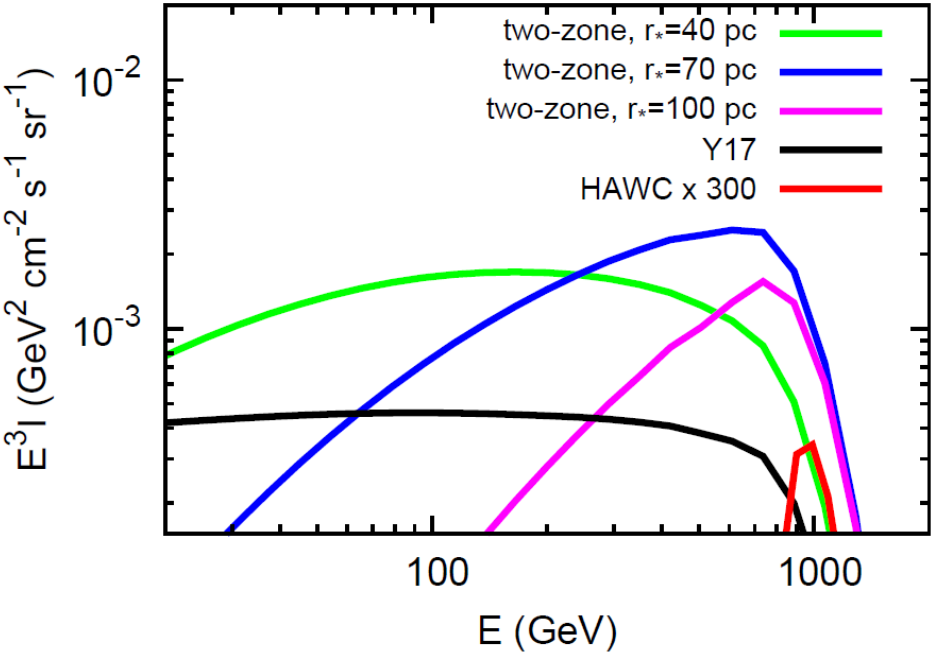
- The finite volume method is adopted for the diffusion operator
- GALPROP and DRAGON only apply to cases of smooth varying of D
- **We may expect the scenario be between the normal case and HAWC case**

Unexpected result of positron flux!

Spatial distribution of e-/e+



Spectrum at the earth

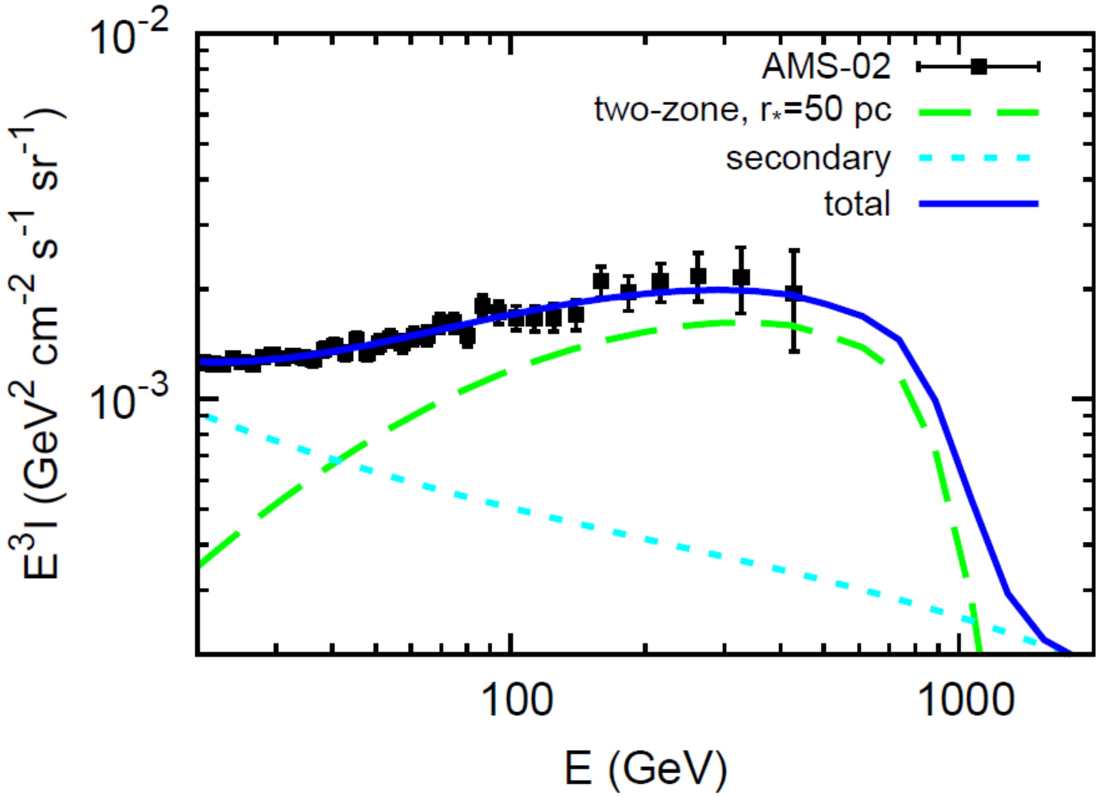


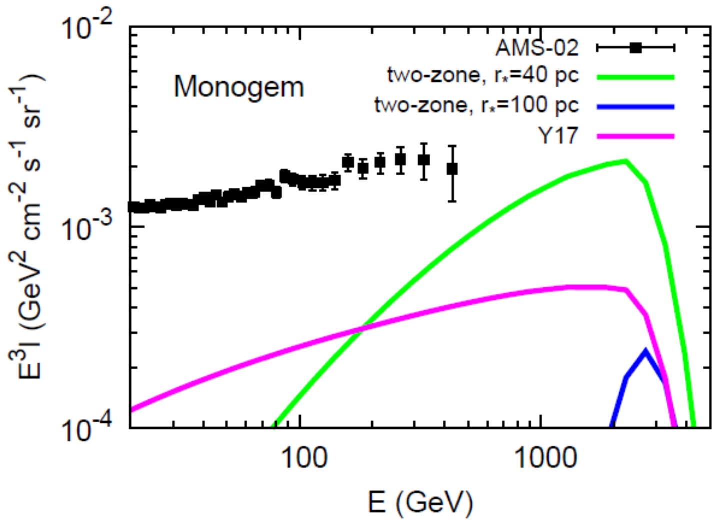
K. Fang, X. Bi, P. Yin, Q. Yuan 2018

- 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

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

Compare with AMS-02 e+



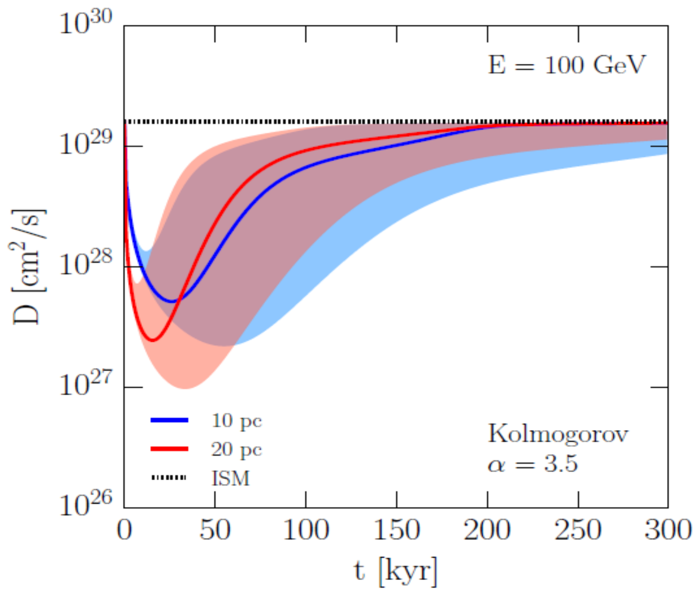


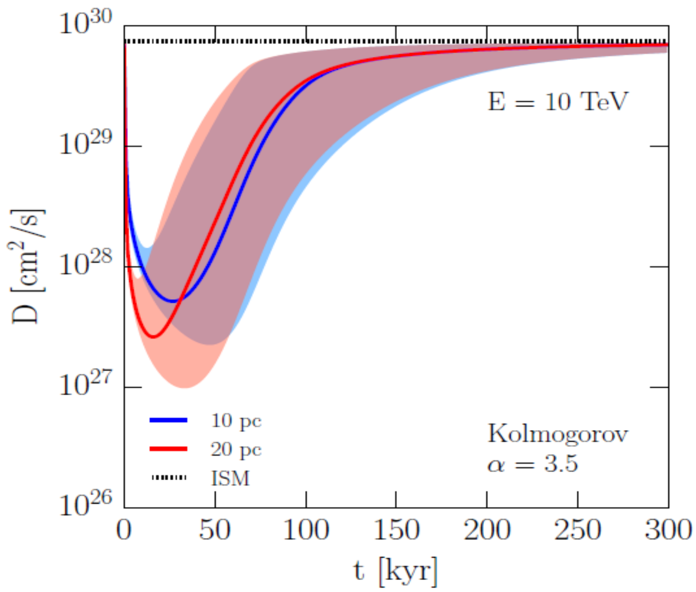
K. Fang, X. Bi, P. Yin, Q. Yuan 2018

- The best-fit r_star is 50 pc
- The conversion efficiency of Geminga is ~50-70%

What is mechanism to produce a slow diffusion?

- MHD waves can be amplifed by CRs streaming instabiltiy due to the large cosmic ray density gradient – a widely discussed mechanism necessary for DSA (see Ptuskin et al 2003)

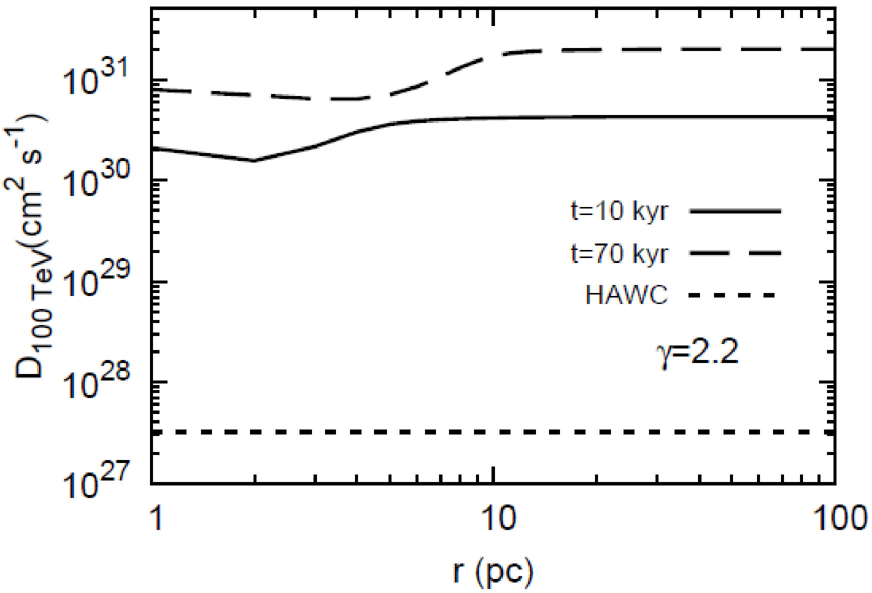


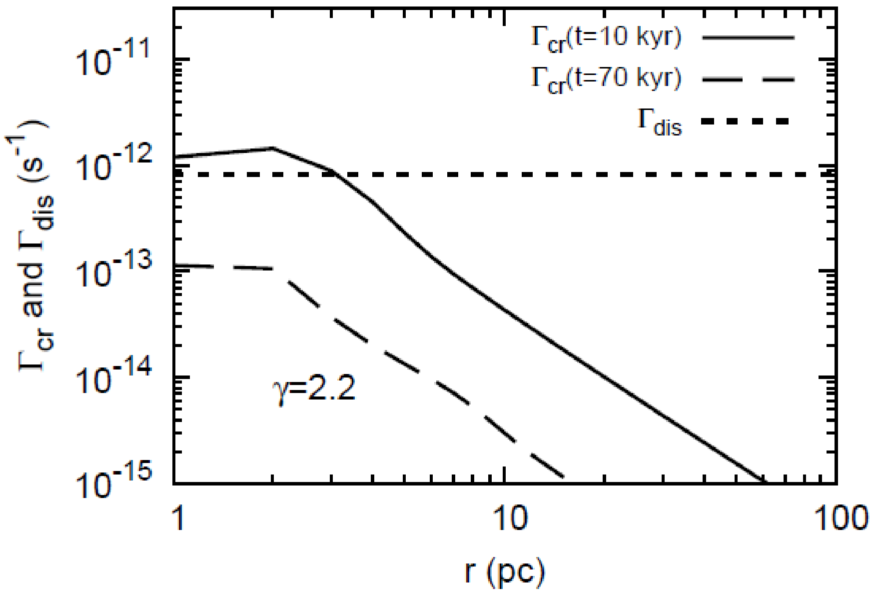


Evoli et al. 2018 has given a careful calculation of D based on the mechanism

Self-generated turbulence

- Evoli et al adopt a one-dimensional diffusion assuming the electrons transport within a 1pc tube flux
- We have done a 3D calculation for the self-generated turbulence and the D

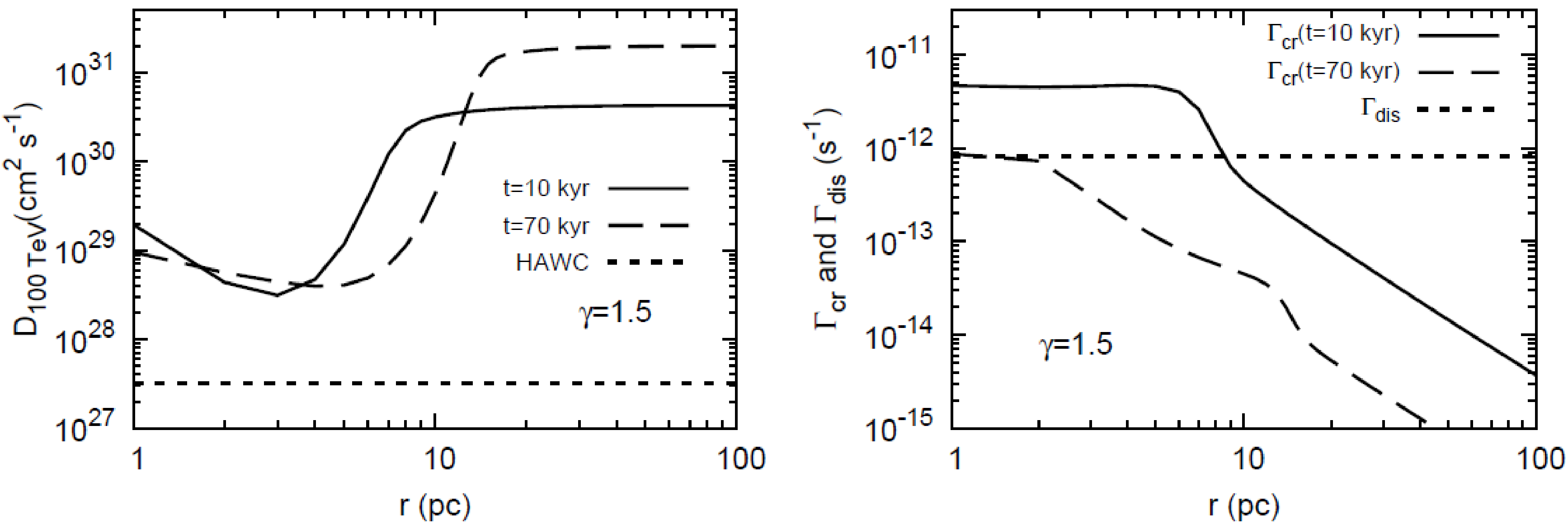




left：100 TeV diffusion coefficient at 100TeV near Geminga

right：growth and dissipation rate at different time

Self-generated waves



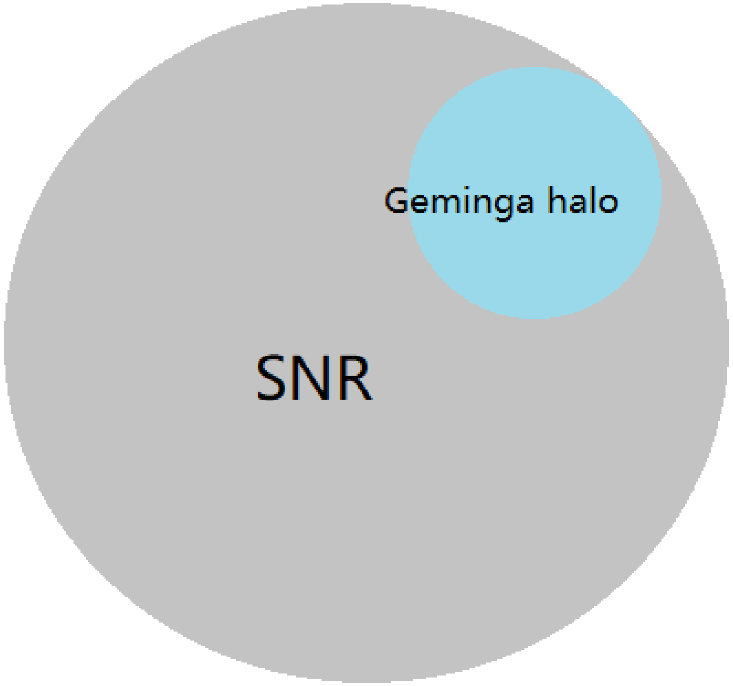
left：100 TeV diffusion coefficient at 100TeV near Geminga

right：growth and dissapiation rate at different time

So this mechanism does not work to generate such a small diffusion coefficient! (Similar to not work to accelerate CR up to the knee.)
Actually the reason is simple as the high energy electron (~100TeV) energy density is too small to amplify the MHD waves.
We suspect if this is an environment effect?

A possible mechanism

Just a guess: The slow diffusion may be an effect left by its prior SNR

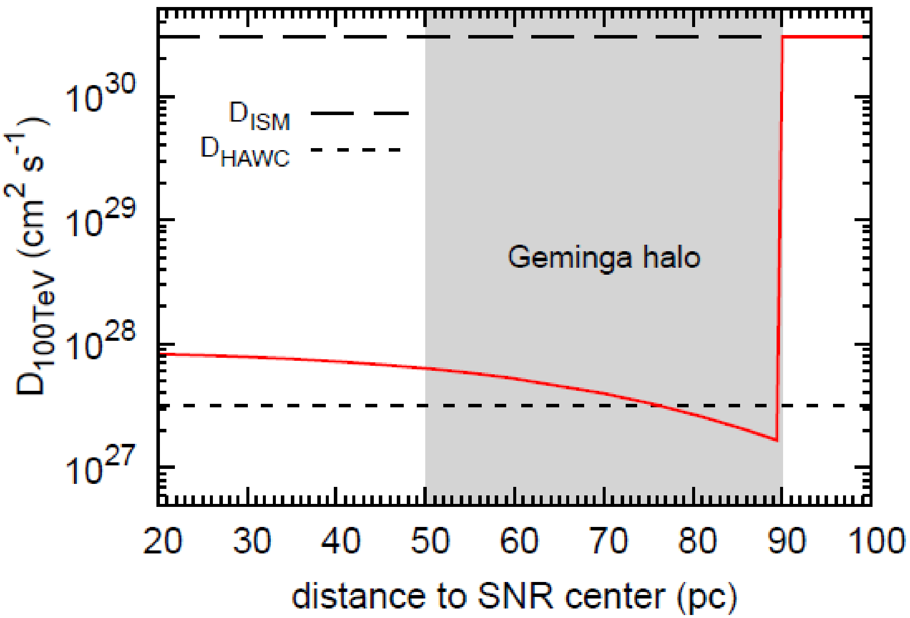


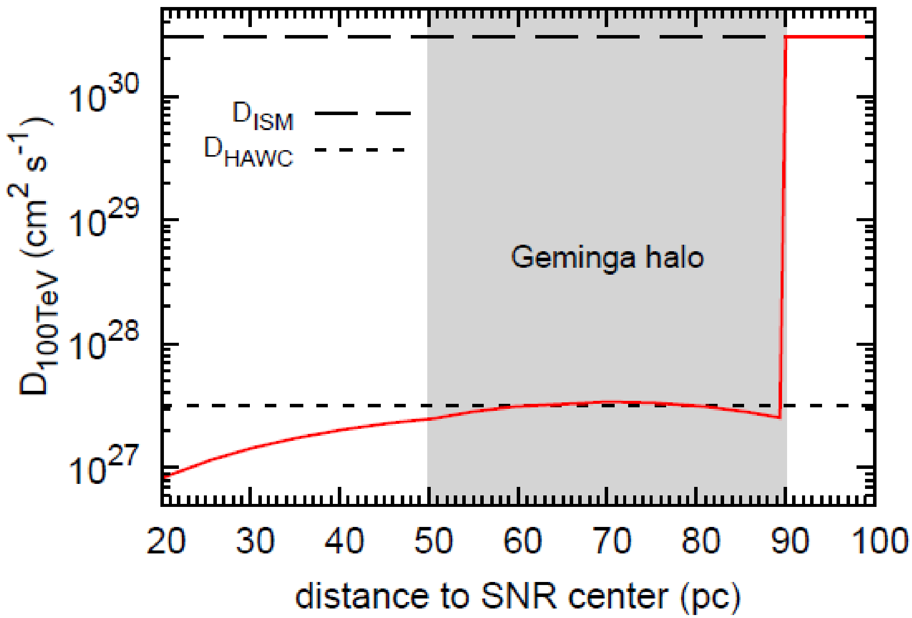
The fast motion of the pulsar has been ignored. Geminga has travelled ~70pc away from its origin positron.

According to a SNR evolution model SNR can expand to 90pc or large after 340 kyr evolution if ISM density is low, in such case the pulsar is still within the SNR as shown;

The medium in the downstream of the shock may have strong turbulence and have a very small diffusion coefficient

A possible mechanism





A very strong turbulence is generated after passing the shock wave; then we calculate its decay with time by dissipation

$$\mathcal{F}(R) = \begin{cases} \mathcal{F}_0 \exp\{-\Gamma_{\rm dis} \cdot [t_{\rm age} - t(R)]\}\,, & t(R) \le t_{\rm age} \\ \mathcal{F}_{\rm ISM}\,, & t(R) > t_{\rm age} \end{cases}$$

Different assumption of the initial condition:

Left：the turbulence is independent on the strength of shock waves

Right：f0 is proportional to the shock wave velocity;

Summary

- HAWC observation of the TeV gamma ray halos indicate a very slow diffusion around Geminga. Two zone diffusion model explains well the positron excess on the Earth.
- Self-generated waves by CR e-+ is not enough to amplify the MHD waves to such slow diffusion.
- We guess such slow diffusion is possibly related with the prior SNR, considering the fast motion of the pulsar and the TeV halo is generated quite late.

- Prospects： future observation of more such regions at different energies and ages can give us more clues to finally get the correct mechanism to produce the slow diffusion.

AMS-02的观测结果

- AMS-02测量了正负电子比例，电子、正电子和正负电子和等能谱。测量到宇宙线中正电子超出！
- 正电子还没有明确的测量到截断

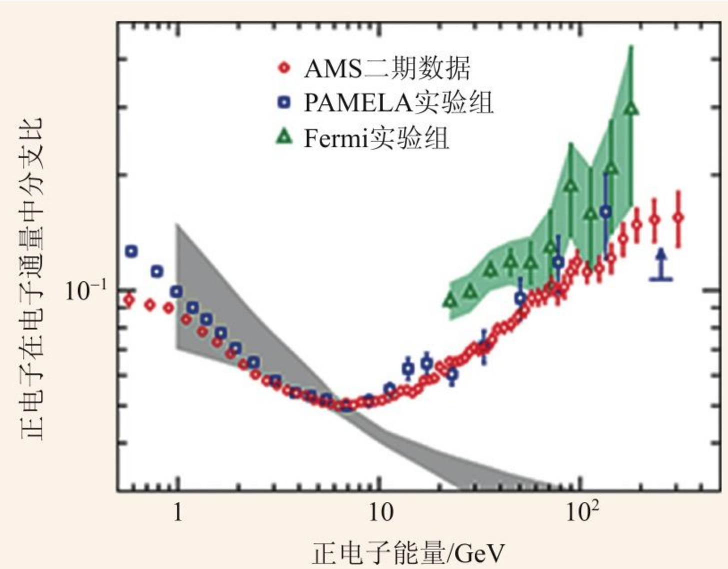
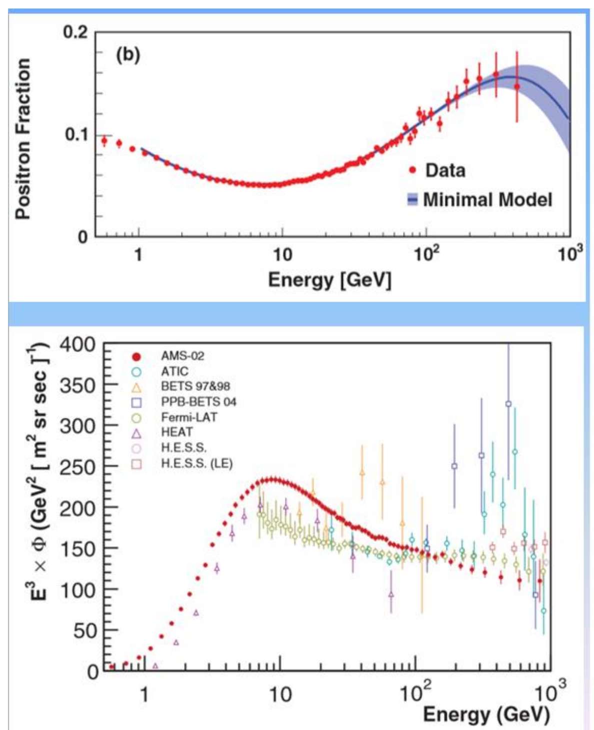
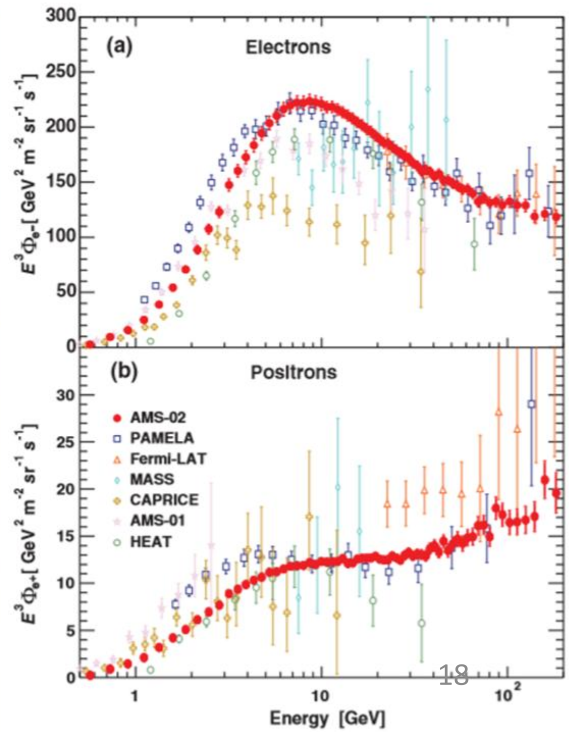


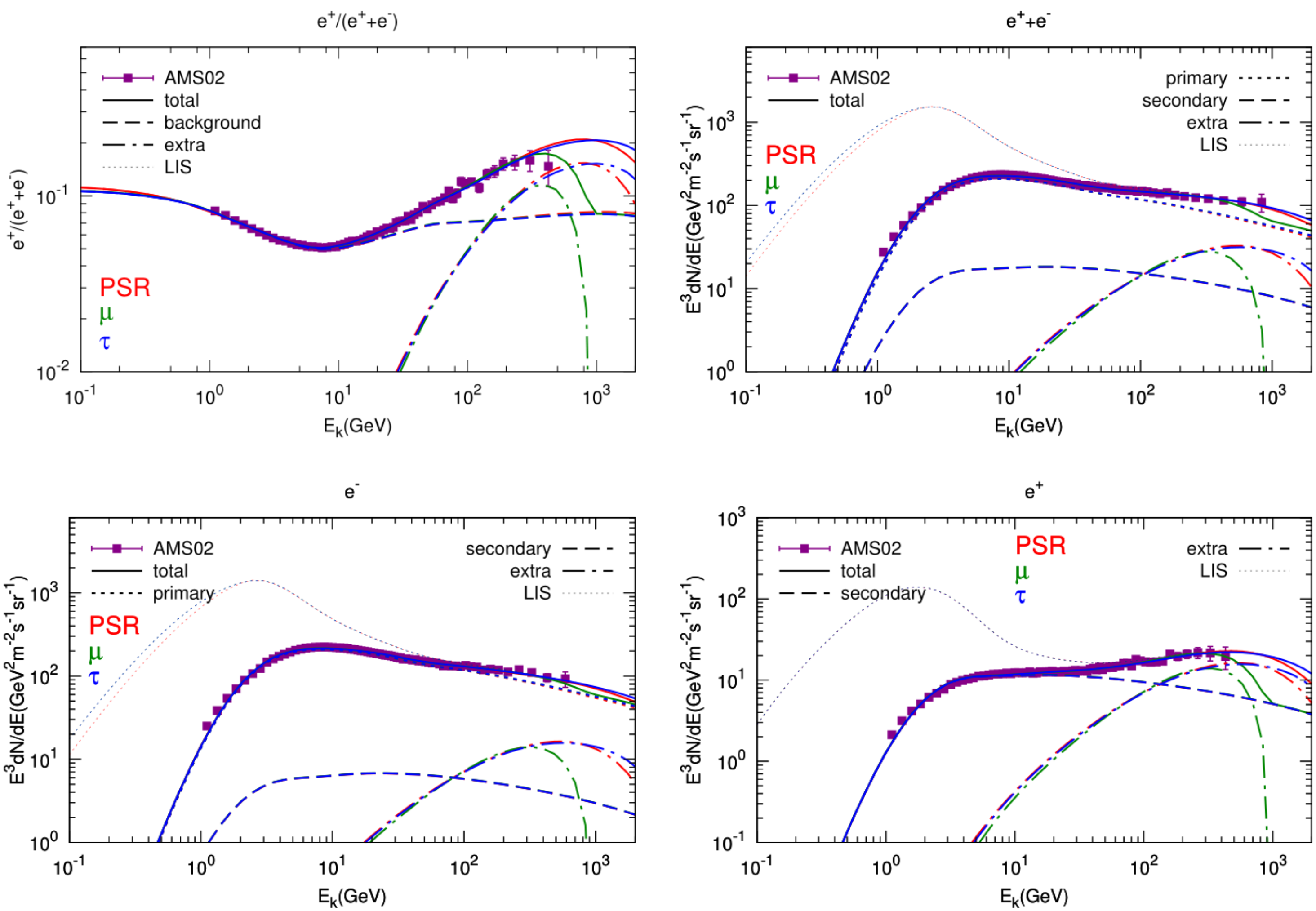
图6 实验上测量到的宇宙射线中正电子分数随着正电子能量的分布函数。从图中可以看出，10 GeV之后该分数呈单调增加趋势(图片引自文献[7])





第一步：能谱上是否可以区分两者的贡献

Lin SJ et al.
PRD91.063508, 2015

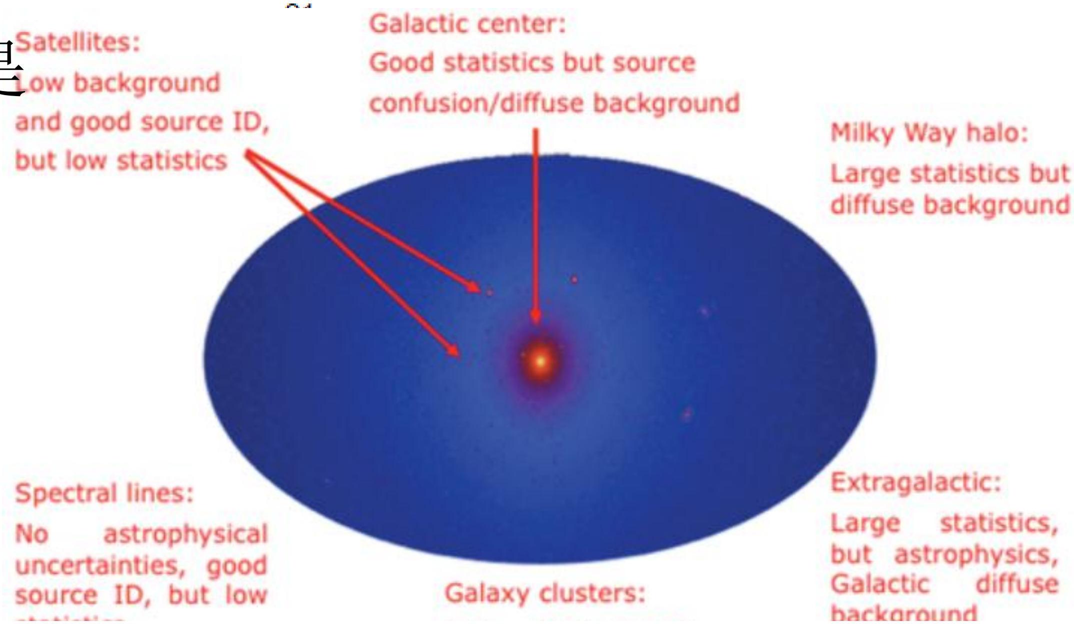


Conclusions of the quantitative study II

Both astrophysical sources, like pulsars, or dark matter can give good fit the AMS-02 data. AMS02 data can not distinguish the two scenarios.

		$\frac{\chi^2}{\text{d.o.f.}}$	χ^2	$\frac{e^+}{e^+ + e^-}$	e^-	e^+
DR	PSR	0.92	175.4	42.95	54.22	78.26
	μ	0.89	171.6	39.94	55.36	76.26
	τ	0.91	175.2	42.72	55.21	77.24
DC	PSR	0.47	88.99	51.87	14.77	22.35
	μ	1.16	223.1	88.7	46.95	87.45
	τ	0.62	118.0	59.5	21.52	37.02

第二步：定量检验两个模型是否可以解释数据



Yuan, Bi, Chen, Guo, Lin, Zhang, 1304.1482, 1409.6248

伽玛射线和反质子的限制

Channels	m_χ(TeV)	AMS-02 (2σ)	Fermi limits	Planck limits
$\mu^+\mu^-$	0.89	$3.79\times10^{-24} < \langle\sigma_{\rm ann}v\rangle < 6.48\times10^{-24}$	2.95×10^{-24}	2.58×10^{-24}
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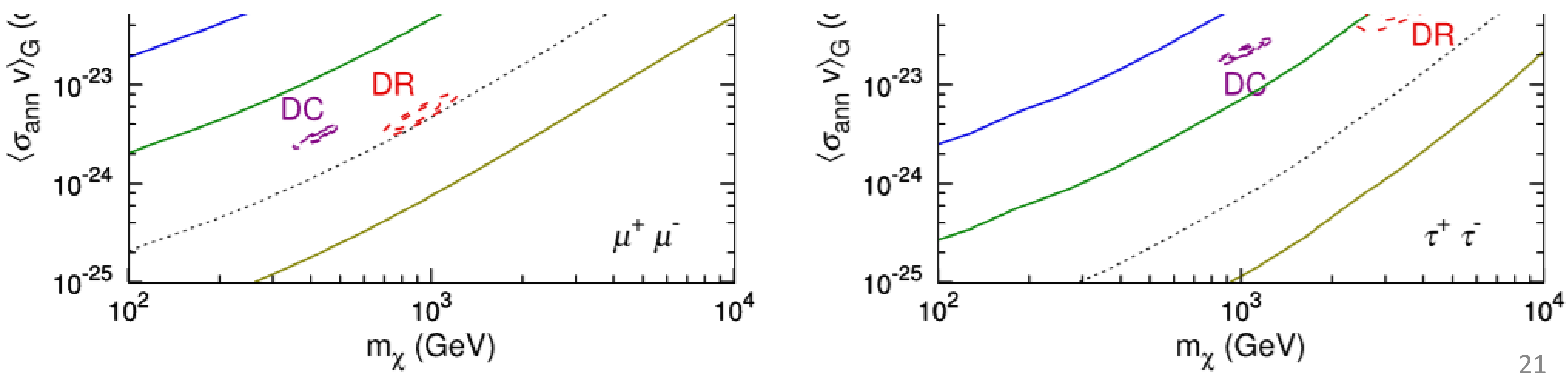
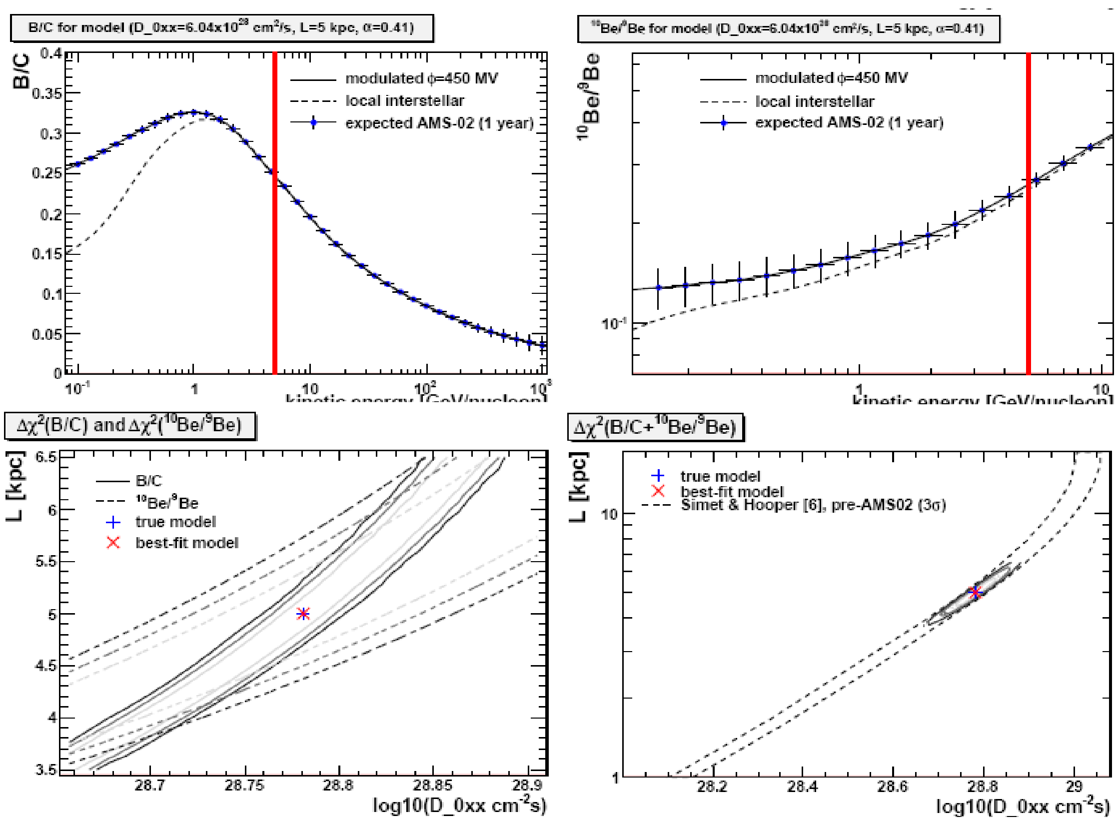


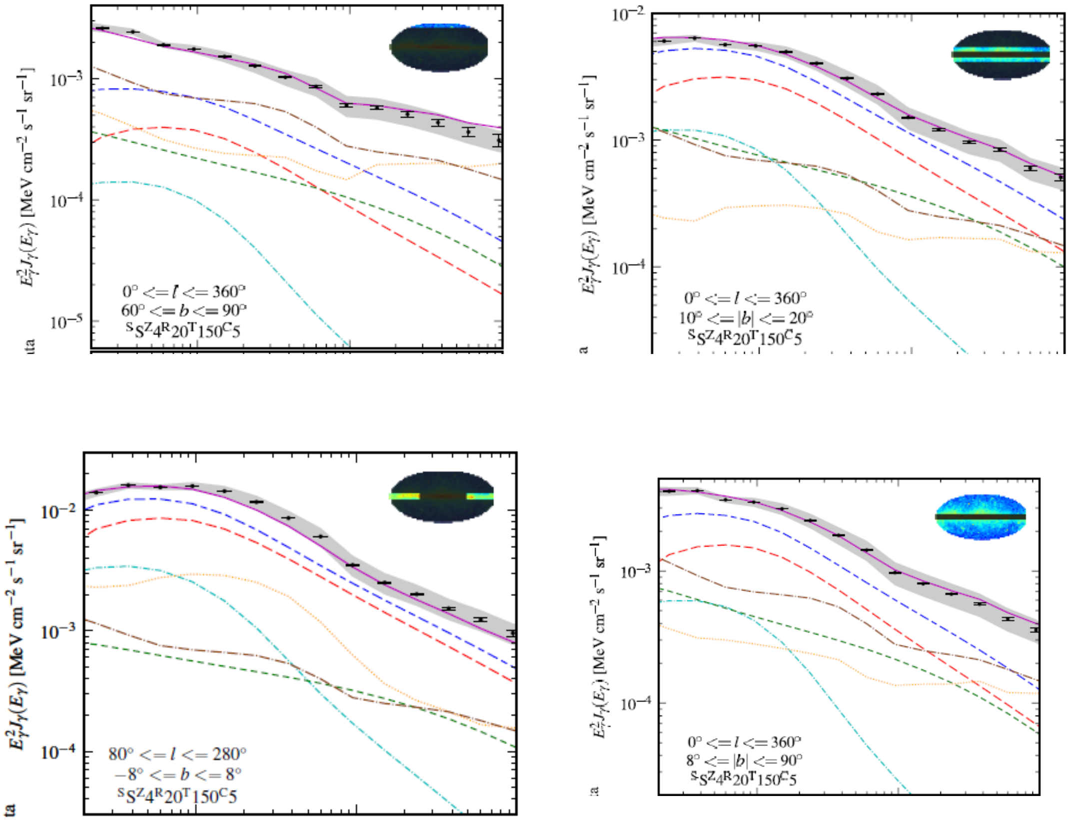
1. B/C, (Sc+Ti+V)/Fe, ^{10}Be/^{9}Be, ^{26}Al/^{27}Al

- 通常宇宙线中H,He,C,N,O,Fe等为原初元素；Li,Be,Be,Sc, Ti,V等为次级元素，由原初元素通过反应产生
- 通过次级元素和原初元素的比例研究宇宙线传播

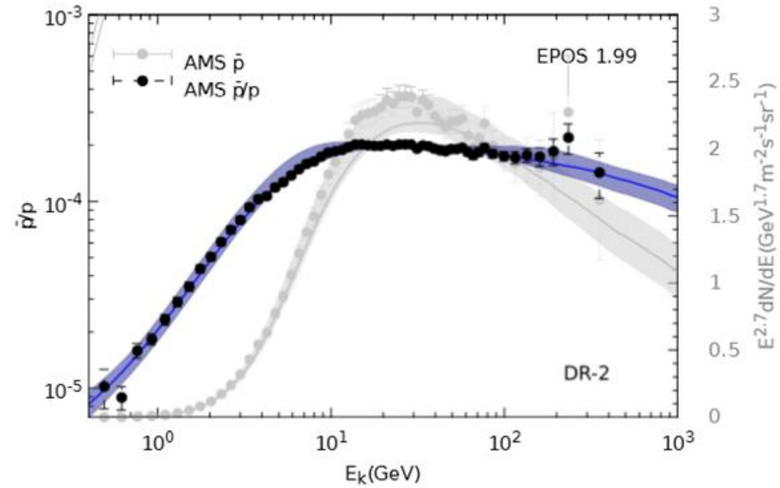


Pato et al. 2010, JCAP

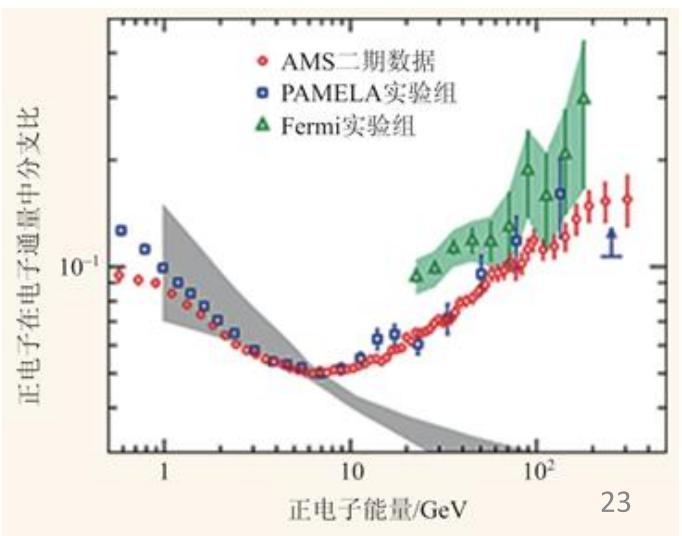
Galactic diffuse gamma-rays



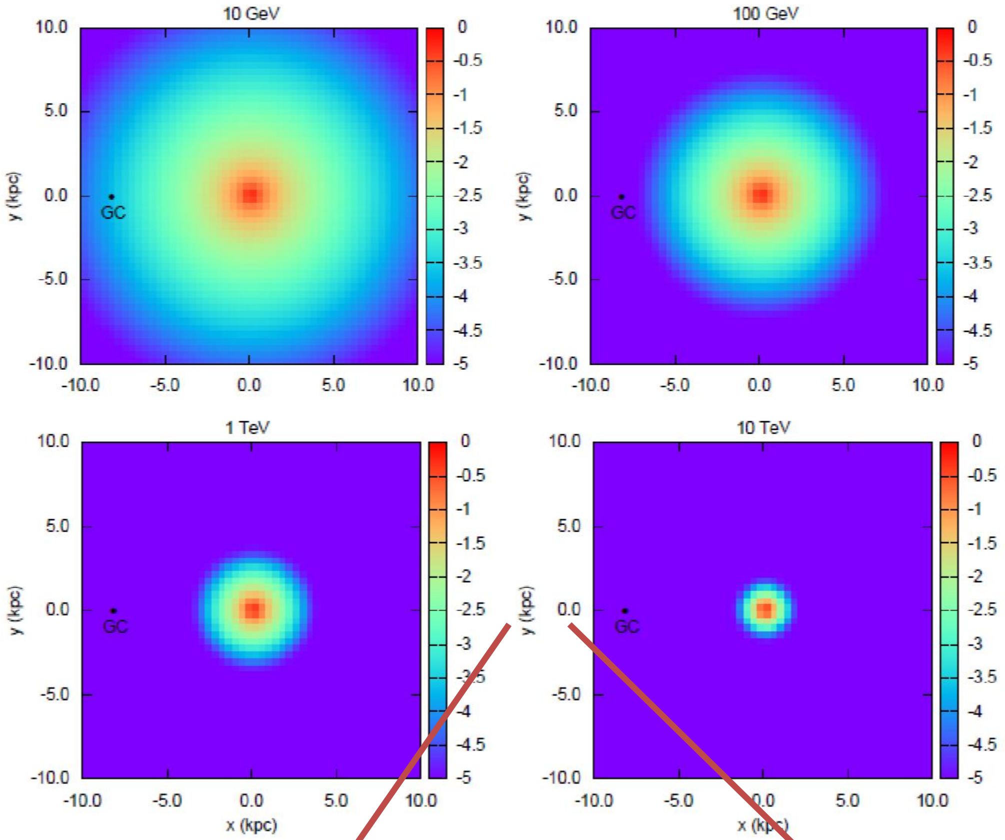
Antiproton flux



Positron flux



e^{+-} Propagation distance



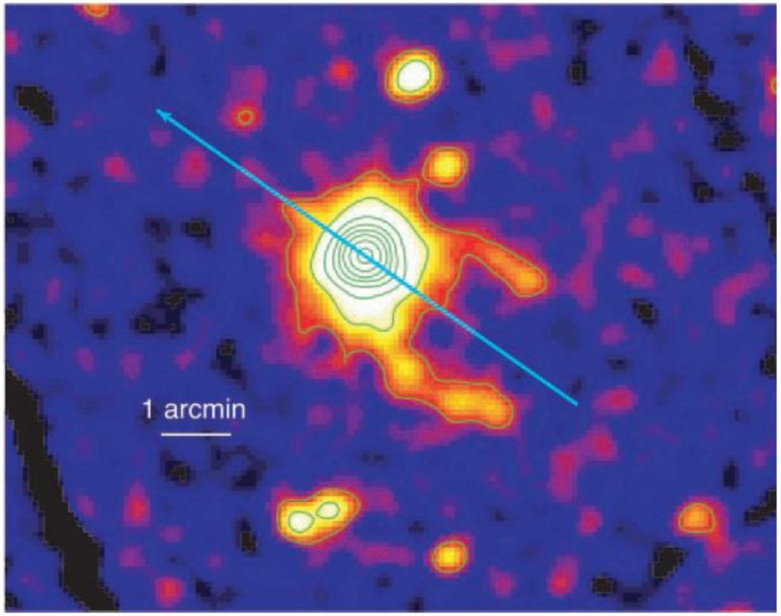
High energy e^{+-} can only come from nearby sources – the nearby SNR or pulsar induce <u>large anisotropy, DM not</u>

If coming from nearby pulsar or SNR they may have possible <u>features at higher energies, DM not</u>

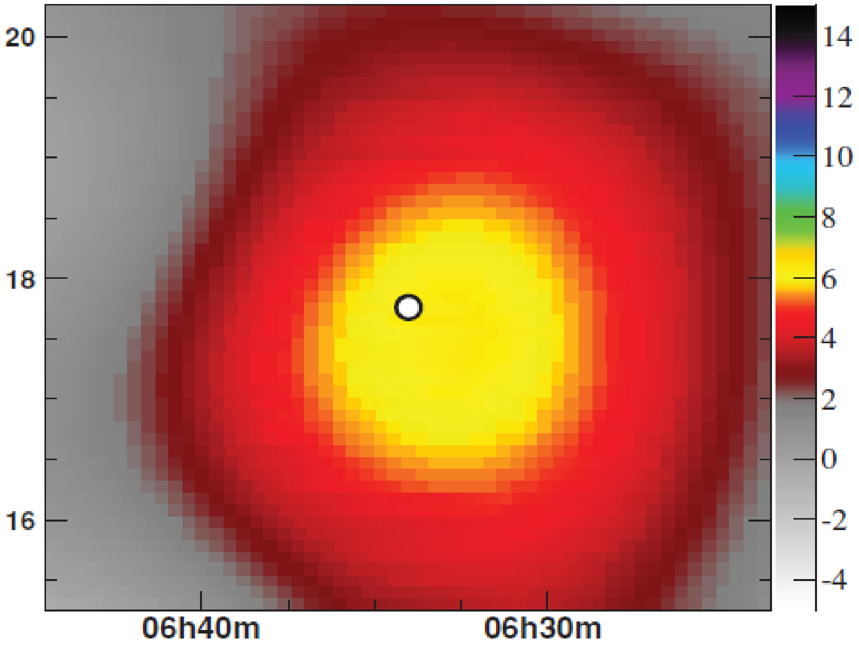
Two-zone diffusion for Geminga

Geminga: a plausible candidate of positron excess

- r = 250 pc,   t = 342 kyr,   W = 1.23e49 erg
- Observed multi-TeV halo (Milagro, HAWC)



0.3-5 keV, XMM-Newton
P.A.Caraveo *et al.* 2003



35 TeV, Milagro
A. A. Abdo et al. 2009