Geminga pulsar contribution to the cosmic-ray positron excess according to the γ-ray observations

Zhao-Huan Yu（余钊焕）

School of Physics, Sun Yat-Sen University

https://yzhxxzxy.github.io

Based on Guang-Yao Zhou, Zhao-Huan Yu, Qiang Yuan, Hong-Hao Zhang, arXiv:2205.07038, Commun. Theor. Phys.

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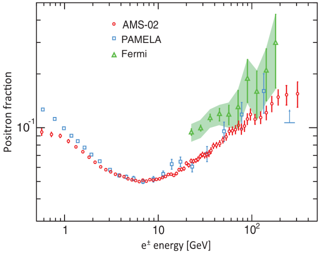
The Cosmic-ray Positron Excess

☯ Since 2008, measurements of **cosmic-ray (CR) positrons** by **PAMELA**, **Fermi-LAT**, and **AMS-02** show an **unexpected excess** at energies $\gtrsim 10$ GeV

🔮 Possible interpretations for this excess include **annihilating** or **decaying dark matter** as well as **astrophysical sources** like **nearby pulsars** within kpc



[AMS Coll., PRL 110, 141102 (2013)]

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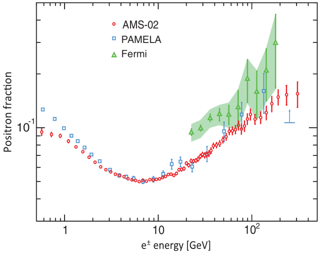
🌀 Particularly, the **middle-aged pulsar Geminga** with a distance of ~ 250 pc is widely assumed to produce **high energy positrons** that could **propagate to the Earth**



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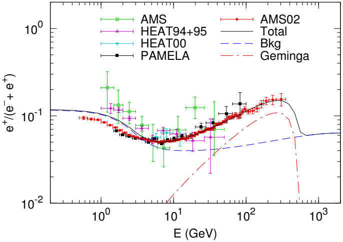
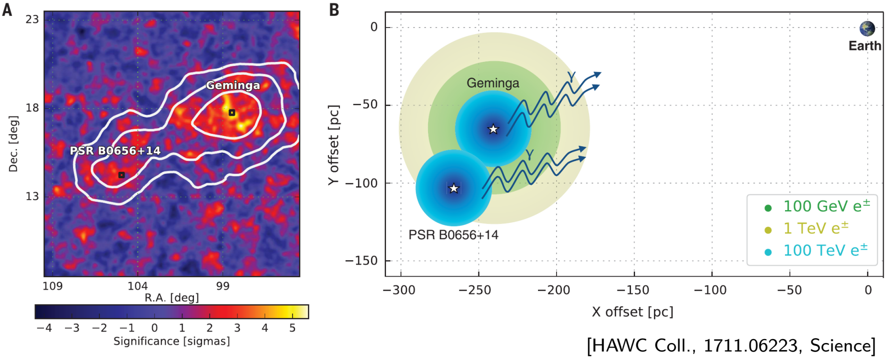


[PF Yin, **ZHY**, Q Yuan, XJ Bi, 1304.4128, PRD]

HAWC Observations of 10 TeV γ-rays

- In 2017, the **High-Altitude Water Cherenkov Observatory (HAWC)** observed ~ 10 TeV γ **rays spatially extended about 2 degrees** around **Geminga**, which would be produced by **positrons** and **electrons** of energies ~ 100 TeV via **inverse Compton scattering (ICS)** off low energy photons
- This confirms **Geminga** as a **source** of high energy positrons and electrons



[HAWC Coll., 1711.06223, Science]

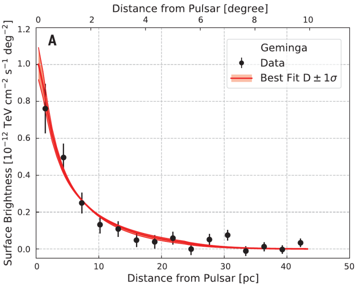
Slow Diffusion of Electrons and Positrons

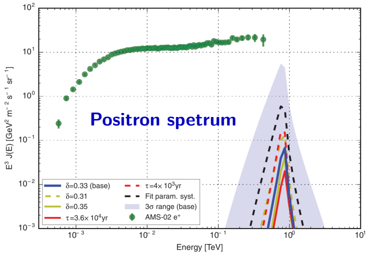
However, the γ-ray **surface brightness profile (SBP)** around **Geminga** measured by **HAWC** implies a **diffusion coefficient smaller** than the **normal value** by at least **2 orders of magnitude**

Diffusion coefficient $D(E) = D_{100}\left(\frac{E}{100\ \text{TeV}}\right)^{\delta}$

$$\delta = \frac{1}{3}, \quad D_{100} = 3.2^{+1.4}_{-1.0} \times 10^{27}\ \text{cm}^2/\text{s}$$

Such **slow diffusion** implies **much less CR positrons** arriving at the Earth, **unlikely** to explain the **positron excess**





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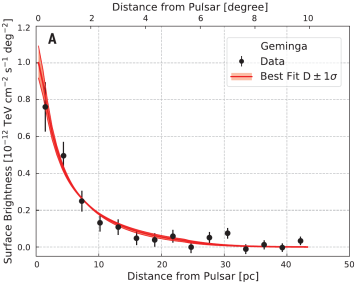

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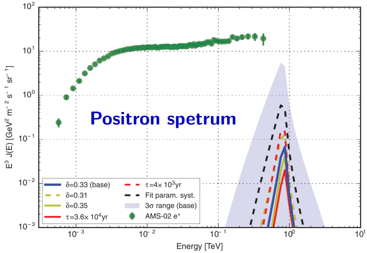
The observation of **another extended γ-ray halo** around the **pulsar J0621+3749** by **LHAASO** further established the general conclusion of **slow diffusion** around pulsars

[LHAASO Coll., 2106.09396, PRL]

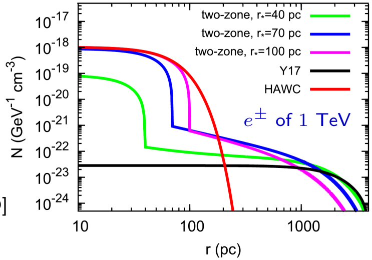


[HAWC Coll., 1711.06223, Science]

Two-zone Diffusion

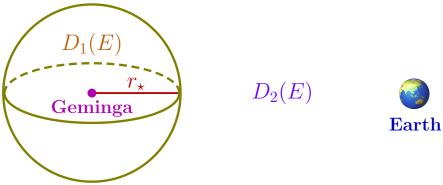
By assuming a **two-zone diffusion model** with **slow diffusion** in a small zone around the source but **normal diffusion** outside the zone, positrons from **Geminga** can still sufficiently contribute to the **positron excess**

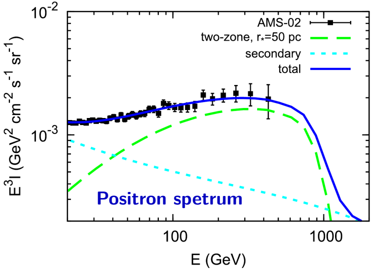
[K Fang, PF Yin, XJ Bi, Q Yuan, 1803.02640, ApJ;
Profumo, Reynoso-Cordova, Kaaz, Silverman, 1803.09731, PRD]



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

$$D_1(E) < D_2(E)$$





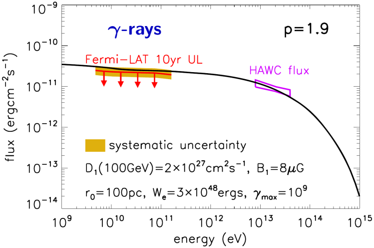
[1803.02640, ApJ]

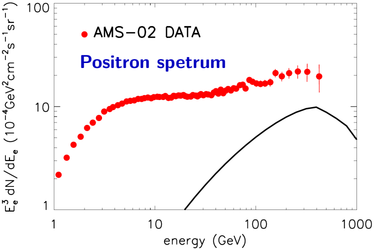
Fermi-LAT γ-rays: Analysis by Xi et al.

- **Positrons** and **electrons** from **Geminga** are also expected to induce **extended ICS γ rays** in the **Fermi-LAT** range $\mathcal{O}(1)$–$\mathcal{O}(100)$ GeV

- Based on **two-zone diffusion** templates, an analysis of **10-yr Fermi-LAT γ-ray data** by **Xi et al.** (denoted as **X19**) **did not find** such extended emission and derive 95% C.L. **upper limits** on the γ-ray flux in $\sim$ 5–100 GeV

- Combined with the **HAWC data**, $e^{\pm}$ from **Geminga** with a **single power-law injection spectrum** can only contribute a **small faction** to the **AMS-02 positron spectrum**





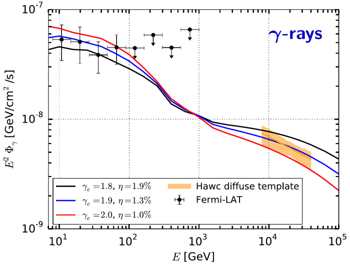
[SQ Xi, RY Liu, ZQ Huang, K Fang, XY Wang, 1810.10928, ApJ (2019)]

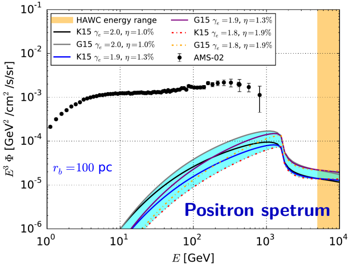
Fermi-LAT γ-rays: Analysis by Di Mauro et al.

Taking into account both a **larger region of interest** and the **proper motion** of the **Geminga pulsar**, another analysis of **Fermi-LAT data** by **Di Mauro et al.** (denoted as **D19**) claimed a **discovery** of **extended γ-ray emissions** around Geminga in the energy range of ~ 10–100 GeV

The derived **γ-ray flux** is **higher** than the **X19 upper limits** by a factor of ~ 3

Considering both the **D19 γ-ray flux** and the **HAWC data**, the Geminga contribution to the **position flux** they obtained is **not enough** for the **AMS-02 excess** assuming a **conversion efficiency** $\eta \sim 1$–2% for the pulsar spin-down energy converted to $e^{\pm}$ energies





[Di Mauro, Manconi, Donato, 1903.05647, PRD]

Low Energy Cutoff

🏛 Both the **X19** and **D19** analyses assumed a **single power-law Geminga** $e^{\pm}$ **injection spectrum** with a **spectral index** γ and a **high energy cutoff** $E_{\rm hc}$:

$$Q \propto E^{-\gamma} \exp\left(-\frac{E}{E_{\rm hc}}\right)$$

🧱 The inconsistency with the **AMS-02 data** may indicate that there are **less low energy positrons and electrons** producing GeV γ rays

🏢 In order to simultaneously explain the **HAWC**, **Fermi-LAT**, and **AMS-02 data**, we attempt to modify the injection spectrum by adding a **low energy cutoff** $E_{\rm lc}$:

$$Q \propto E^{-\gamma} \exp\left(-\frac{E}{E_{\rm hc}}\right) \exp\left(-\frac{E_{\rm lc}}{E}\right)$$

Propagation Equation for CR $e^{\pm}$

- The **diffusion-cooling propagation equation** for **CR** $e^{\pm}$:

$$\frac{\partial N}{\partial t} - \nabla \cdot (D \nabla N) - \frac{\partial}{\partial E}(bN) = Q$$

- N is the $e^{\pm}$ **differential number density**, and E is the $e^{\pm}$ energy
- D is the **diffusion coefficient** in the **two-zone diffusion** model
- The **energy loss rate** b is contributed by **synchrotron radiation** and **ICS**

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- The **energy loss rate** b is contributed by **synchrotron radiation** and **ICS**
- The **source term** for high energy $e^\pm$ **injected by Geminga** is

$$Q(t,E,r) = q(t,E)\delta(r), \quad q(t,E) = q_0 \left(1 + \frac{t}{\tau}\right)^{-2} E^{-\gamma} \exp\left(-\frac{E}{E_{\mathrm{hc}}}\right) \exp\left(-\frac{E_{\mathrm{lc}}}{E}\right)$$

- $\tau \simeq 12$ kyr is the characteristic initial **spin-down time scale** of Geminga
- q_0 is determined by $\int q(t_{\mathrm{s}}, E)\, E\, \mathrm{d}E = \eta \dot{E}_{\mathrm{s}}$, where η is the **conversion efficiency**
- **Geminga age** $t_{\mathrm{s}} \simeq 342$ kyr, **spin-down luminosity** $\dot{E}_{\mathrm{s}} \simeq 3.2 \times 10^{34}$ erg s^{-1}

Photon Emissivity

- The **photon emissivity** due to $e^\pm$ **ICS** based on the **Klein-Nishina cross section** is

$$Q_{\rm ICS}(t, E_\gamma, r) = 4\pi \sum_j \int_0^\infty d\epsilon\, n_j(\epsilon) \int_{E_{\rm min}}^{E_{\rm max}} dE\, J(t, E, r) F(\epsilon, E, E_\gamma)$$

- $n_j(\epsilon) = \frac{15U_j}{(\pi k T_j)^4} \frac{\epsilon^2}{\exp(\epsilon/kT_j) - 1}$ is the **photon number density** of a **background field** j with energy ϵ, temperature T_j, energy density U_j, and Boltzmann constant k

- $J(t, E, r) = \frac{v_e N(t, E, r)}{4\pi}$ is the $e^\pm$ **intensity** with $e^\pm$ speed v_e

$$F(\epsilon, E, E_\gamma) = \frac{3\sigma_{\rm T}}{4\gamma_e^2 \epsilon}\left[2q \ln q + (1 + 2q)(1 - q) + \frac{\Gamma^2 q^2 (1 - q)}{2(1 + \Gamma q)}\right]$$

$$\Gamma = \frac{4\epsilon\gamma_e}{m_e c^2}, \quad q = \frac{E_\gamma}{\Gamma(E_e - E_\gamma)}$$

- $\sigma_{\rm T}$ is the **Thomson cross section**, and $\gamma_e = \frac{E}{m_e c^2}$ is the Lorentz factor of $e^\pm$

🍔 We consider **three background photon components** for the **ICS processes**, including the **CMB**, the **IR background**, and the **optical background**

Component j	T_j (K)	U_j (eV/cm^3)
CMB	2.7	0.26
IR	20	0.3
Optical	5000	0.3

🥓 The **synchrotron energy loss rate** due to a **magnetic field** B in the **interstellar medium** is given by $b_{\rm syn} = \dfrac{\sigma_{\rm T}\gamma_e^2 B^2}{6\pi m_e c}$, while the **energy loss rate** due to **ICS** is estimated following XP Tang & Piran, 1808.02445, MNRAS

γ-ray Energy Spectrum and SBP

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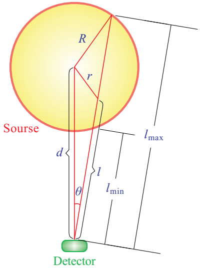
Integrating $Q_{\text{ICS}}(t_s, E_\gamma, r)$ along the **light of sight**, we obtain the **γ-ray flux** for specific energy E_γ and angular separation θ as

$$I(E_\gamma, \theta) = \frac{1}{4\pi}\int_{l_{\min}}^{l_{\max}} \mathrm{d}l\, Q_{\text{ICS}}(t_s, E_\gamma, r)$$

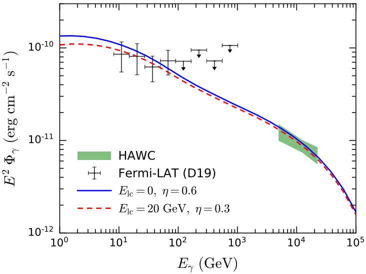


Integrate out θ → **γ-ray energy spectrum Φ_γ**

Integrate out E_γ → **SBP** as a function of θ

Numerical Result according to the D19 γ-ray Observation

- First, we try to interpret the **HAWC** and **AMS-02** data according to the **Fermi-LAT γ-ray observation** from the **D19 analysis**
- **Without the low energy cutoff $E_{\rm lc}$**, the data can be explained by a quite **unrealistic conversion efficiency $\eta = 60\%$**
- With $E_{\rm lc} = 20$ GeV, only $\eta = 30\%$ is needed



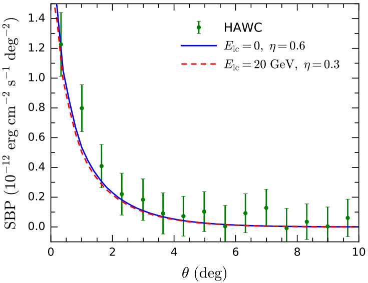
$r_\star = 50$ pc

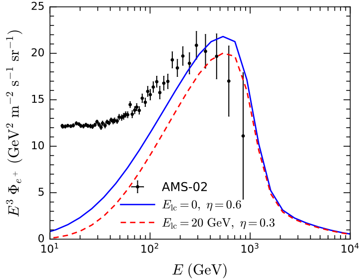
$D_{100}^{r<r_\star} = 3.5 \times 10^{27}$ cm^2 s^{-1}

$D_{100}^{r\geq r_\star} = 1.7 \times 10^{30}$ cm^2 s^{-1}

$B = 3\ \mu$G

$\gamma = 2.2$





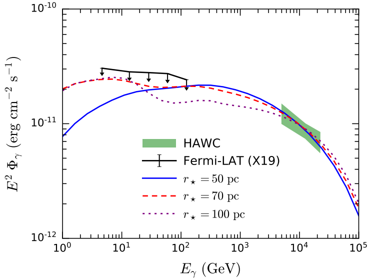
Parameter Scan according to the X19 γ-ray Constraint

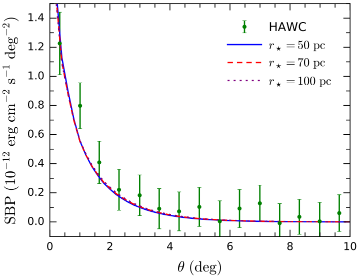
- Second, we attempt to explain the **HAWC** and **AMS-02** data according to the **Fermi-LAT γ-ray constraint** from the **X19 analysis**
- We treat γ, $E_{\rm hc}$, $E_{\rm lc}$, η, B, and $D_{100}^{r<r_\star}$ as **free parameters** and perform a scan in the parameter space with **fixed** $r_\star$ and $D_{100}^{r\geq r_\star} = 1.7 \times 10^{30}$ cm^2 s^{-1}
- The **MultiNest algorithm** is utilized to improve the fitting efficiency
- The **best results** are obtained as

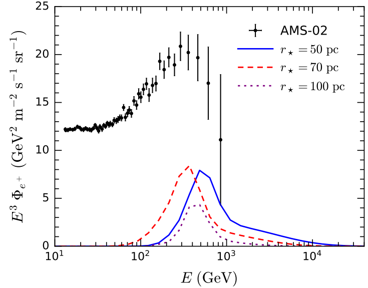
$r_\star$ (pc)	50	70	100
γ	2.10	1.93	1.70
$E_{\rm hc}$ (TeV)	520	537	463
$E_{\rm lc}$ (GeV)	870	302	547
η	15%	21%	16%
B (μG)	5.0	6.9	7.2
$D_{100}^{r<r_\star}$ (10^{27} cm^2 s^{-1})	4.8	7.8	8.5

Best Results according to the X19 γ-ray Constraint

While the **HAWC data** are properly fitted and the γ-ray flux in 5 GeV $\lesssim E_\gamma \lesssim 100$ GeV lies below the **X19 upper limits**, we find that **Geminga** can only supply **less than 50%** of the **AMS-02 positron flux** at $E \sim 400$ GeV







Summary

- We attempt to interpret the **AMS-02 CR positron excess** by injection from the **nearby pulsar Geminga**, assuming a **two-zone diffusion scenario** and an injection spectrum with a **low energy cutoff**
- Since the high energy positrons and electrons from Geminga can induce γ rays via ICS, we take into account the **extended γ-ray observations** around Geminga from **HAWC** for ~ 10 TeV and from **Fermi-LAT** for $\mathcal{O}(1)$–$\mathcal{O}(100)$ GeV
- According to the **extended γ-ray observation** claimed by the **D19 analysis** of Fermi-LAT data, we find that Geminga **could explain** the positron excess for a 30% **energy conversion efficiency** into positrons and electrons
- However, based on the **constraint** on extended γ rays from the **X19 analysis**, positrons from Geminga would be **insufficient** to account for the positron excess
- A **further robust analysis** of **Fermi-LAT data** for the extended γ rays would be crucial to determine whether Geminga can explain the positron excess or not

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Thanks for your attention!

Further Explanation

- Our results show that the **X19 constraint** favors $\gamma < 2$, $\eta \lesssim 21\%$, and E_{lc} of several hundred GeV, which **suppress** the γ**-ray flux** at $\sim \mathcal{O}(10)$ GeV

- According to an approximate relation

$$E_\gamma = 20 \left(\frac{E}{100\ \mathrm{TeV}} \right)^2 \mathrm{TeV}$$

for $e^\pm$ ICS off CMB photons, $\mathcal{O}(10)$ GeV γ **rays** are induced by $\mathcal{O}(\mathrm{TeV})$ $e^\pm$

- Thus, the **X19 constraint** implies less $\mathcal{O}(\mathrm{TeV})$ positrons and electrons from Geminga, resulting in a **lower CR positron flux** for $E \sim \mathcal{O}(100)$ GeV at the Earth, which is **insufficient** to explain the **AMS-02 excess**