Joint Analysis of Geminga with WCDA and KM2A

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1. Introduction

- Leptons released by pulsars propagate through diffusion, emitting γ rays through IC-scattering, and form a large scale pulsar halo.
- Geminga, as the closest and clearest pulsar halo, offers an opportunity for detailed study of particle diffusion.
- This work conducted a joint analysis of Geminga.

2. Methods

- Multi-Mission Maximum Likelihood framework(3ML)
- Data sets from both WCDA and KM2A are consistent with 1LHAASO catalog paper.

Source	Morphology	Spectrum
Geminga	Diffusion Model	Exponential Cutoff Power-Law
PSR B0656	Diffusion Model	Exponential Cutoff Power-Law
Galactic Diffuse Emission	Planck's gas template	Smoothly Broken Power-Law
Other Sources	Gaussian Model	Power-Law

Table 1: Model set

- Equation (1) shows surface brightness distribution of diffusion model.

$$f_\theta = \frac{A}{\theta_d\,(\theta + 0.06\theta_d)} \exp\left(-\theta^2/\theta_d^2\right) \qquad (1)$$

$$\frac{dN}{dE} = K\left(\frac{E}{3TeV}\right)^{\alpha} \exp\left(-\frac{E}{E_b}\right) \qquad (2)$$

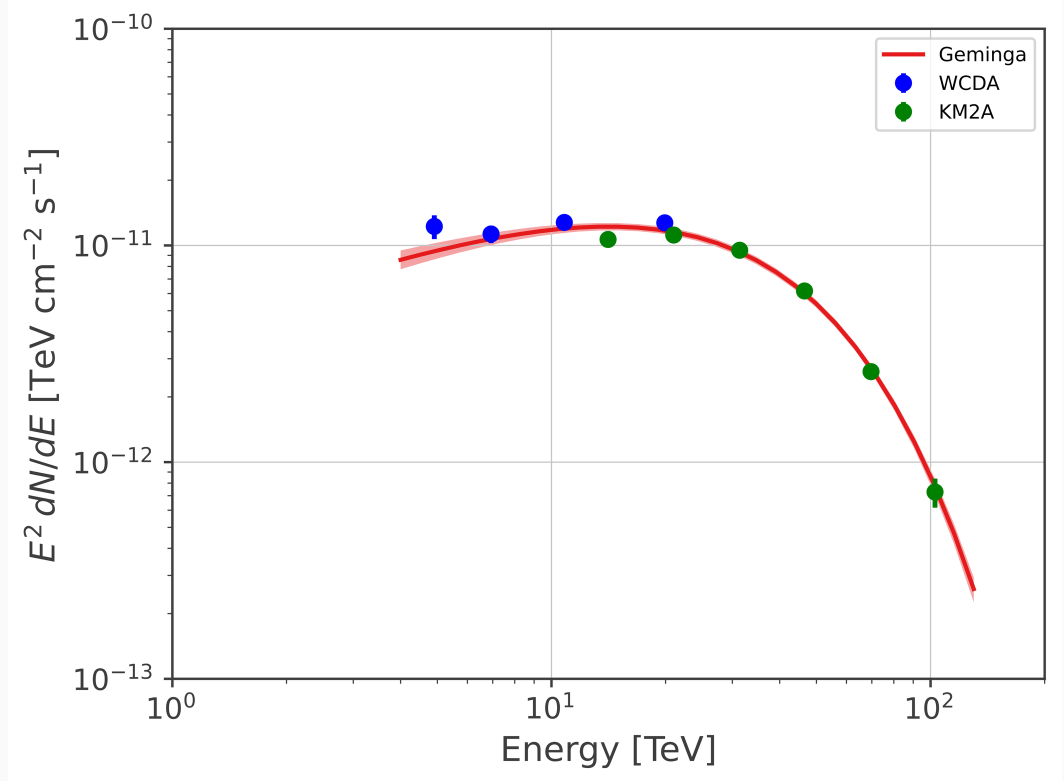


Figure 1: Energy spectrum of Geminga which can be described by Power-Law with an Exponential Cutoff (ECPL) (Equation (2)) Parameters are shown in Table 2.

Parameters	K/cm^2sTeV	α	E_b/TeV
Values	$(9.5 \pm 1.0) * 10^{-13}$	-1.35 ± 0.09	21.9 ± 1.2

Table 2: Spectral parameters of Geminga

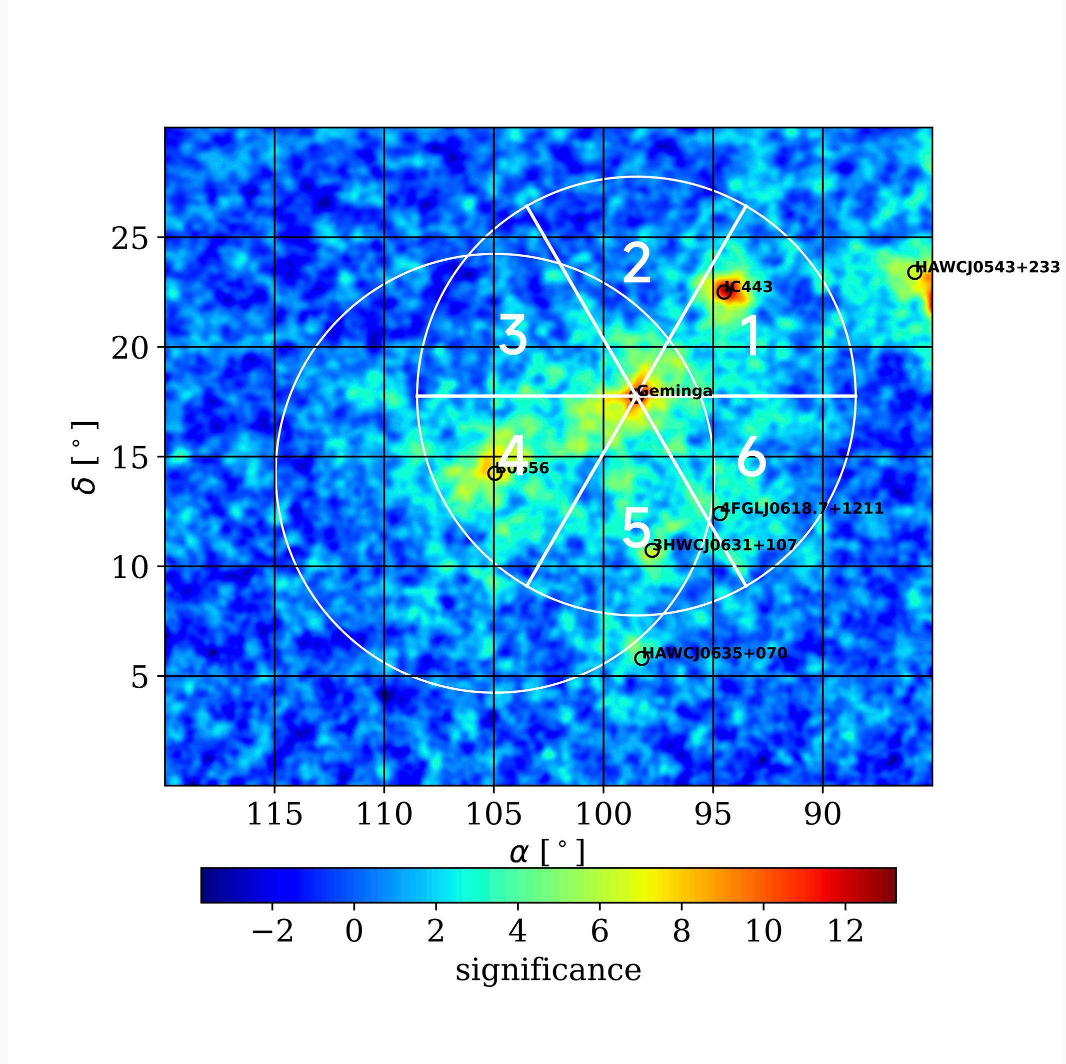


Figure 2: Significance map of Geminga observed by WCDA
Six sectors represent the different regions used to study anisotropic morphology

3. Anisotropic Diffusion

This work used two ways to study the anisotropic diffusion of Geminga:

1. The ROI is divided into 6 sectors. Within each sector, the diffusion radius is fitted, and these six data points are fitted using Equation (3) (referred to as the Pizza Slices method).
2. Diffusion radius is fitted directly using Equation (3) within entire ROI(referred to as the Forward Folding method)

$$\begin{aligned} f(\theta) &= \frac{A(\phi)}{\theta_d(\phi)\,(\theta + 0.06\theta_d(\phi))} \exp\left(-\theta^2/\theta_d^2(\phi)\right) \\ \theta_d(\phi) &= \theta_{d0}\,(1 + a_1\cos(\phi - \phi_0)) \\ A(\phi) &= A_0\,(1 + a_2\cos(\phi - \phi_0)) \end{aligned} \qquad (3)$$

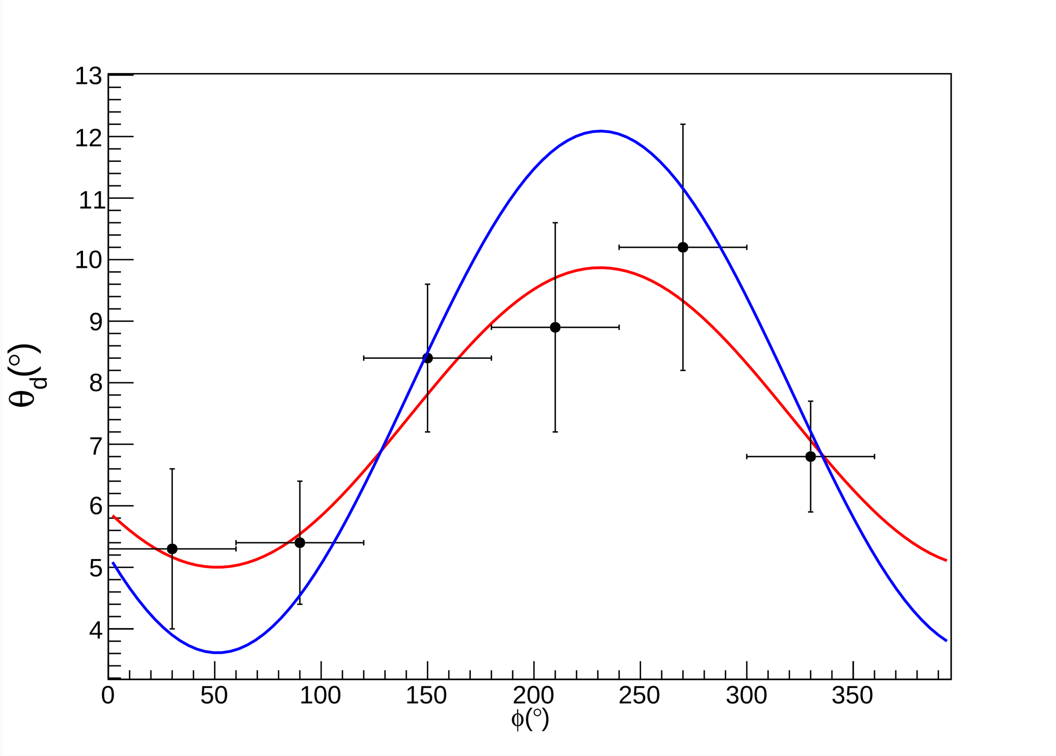


Figure 3: Anisotropic diffusion radius observed by WCDA
Red line is the result by fitting six data points
Blue line is direct fit result of Equation (3)

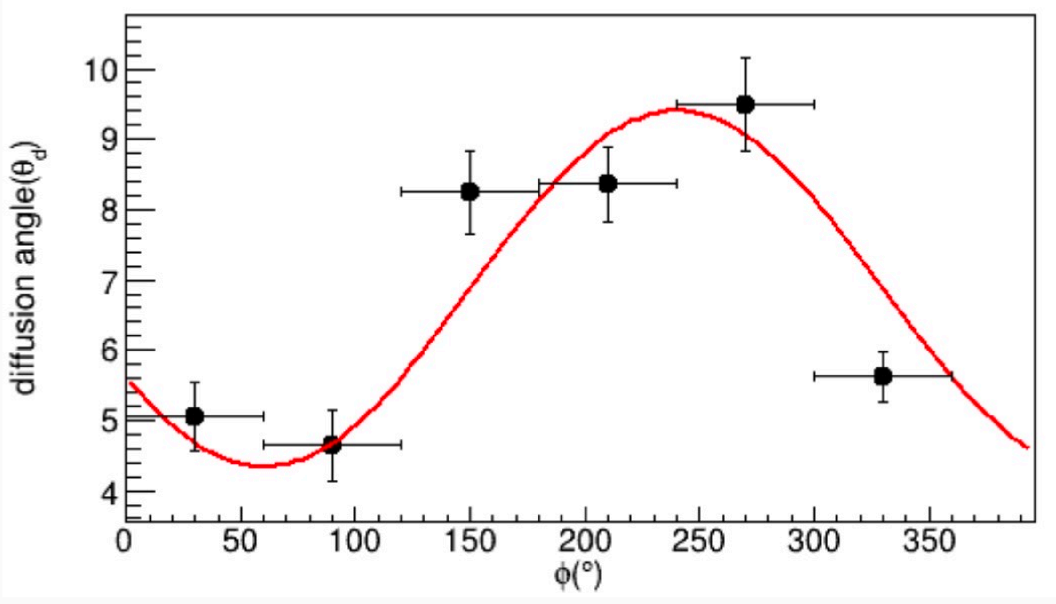


Figure 4: Anisotropic diffusion radius observed by KM2A
Courtesy of Yingying Guo

Methods	WCDA(Pizza Slices)	WCDA(Forward Folding)	KM2A
θ_{d0}(°)	7.43 ± 0.67	7.85 ± 1.44	7.09 ± 0.38
Amplitude a_1	0.33 ± 0.12	0.54 ± 0.23	0.39 ± 0.05
Phase Angle ϕ_0(°)	231.10 ± 23.06	231.26 ± 9.43	238.00 ± 4.50

Table 3: Parameters Comparison

The anisotropic variation trends of the diffusion radius observed in WCDA and KM2A are consistent.

4. Energy Dependent Diffusion

By fitting each energy bin from WCDA and KM2A individually, the evolution of the diffusion radius with energy was obtained.
Diffusion radii measured by WCDA, KM2A and HAWC are consistent with each other within errorbar.

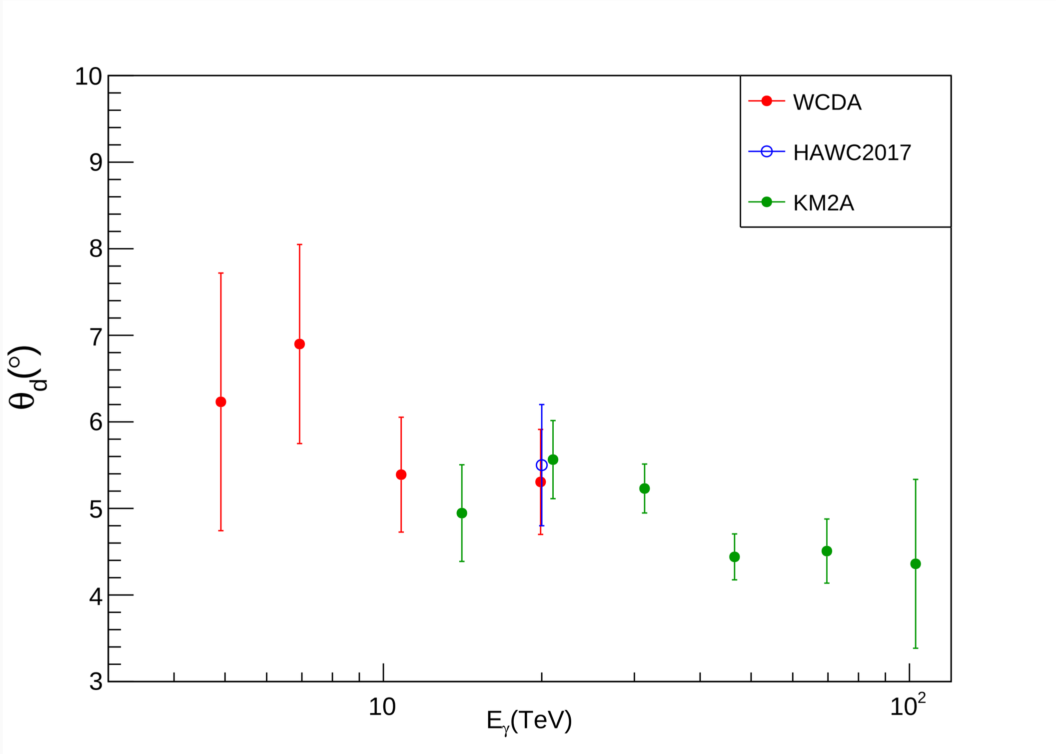
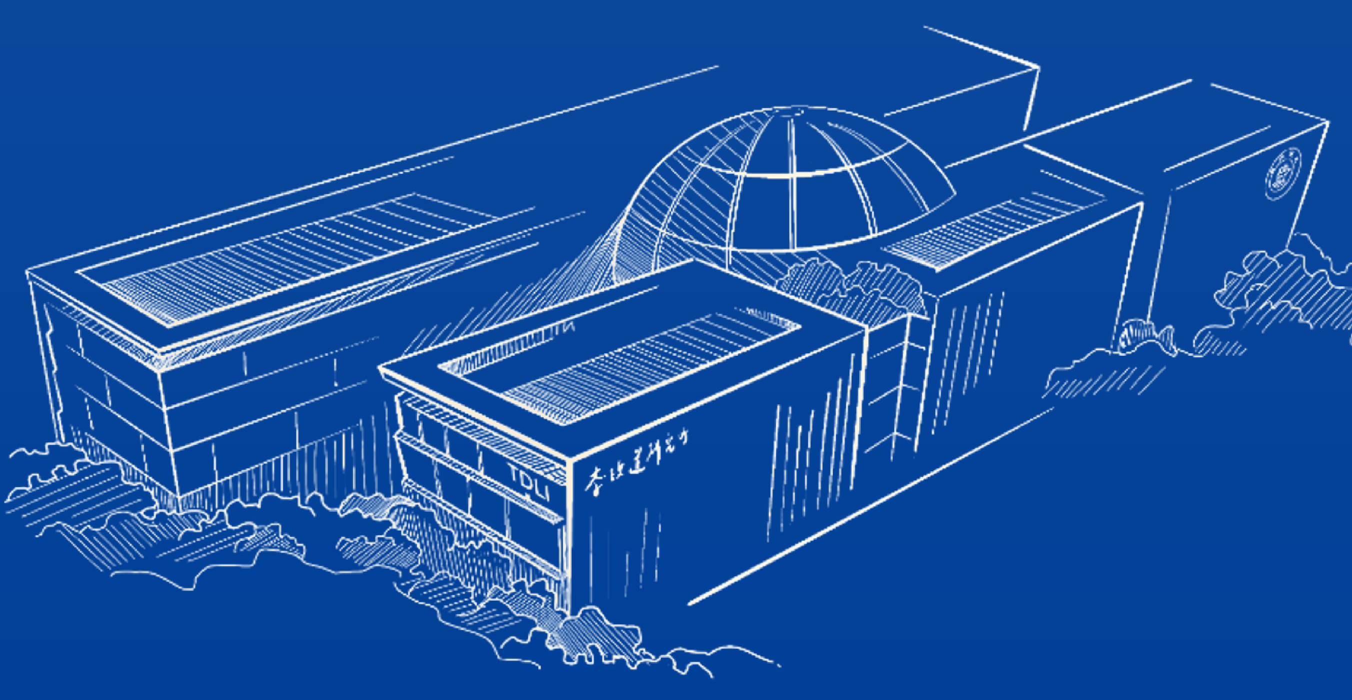


Figure 5: Energy Dependent Diffusion Radius



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