Extended Very-High-Energy Gamma-ray Emission Surrounding PSR J0622 + 3749 Observed by LHAASO-KM2A

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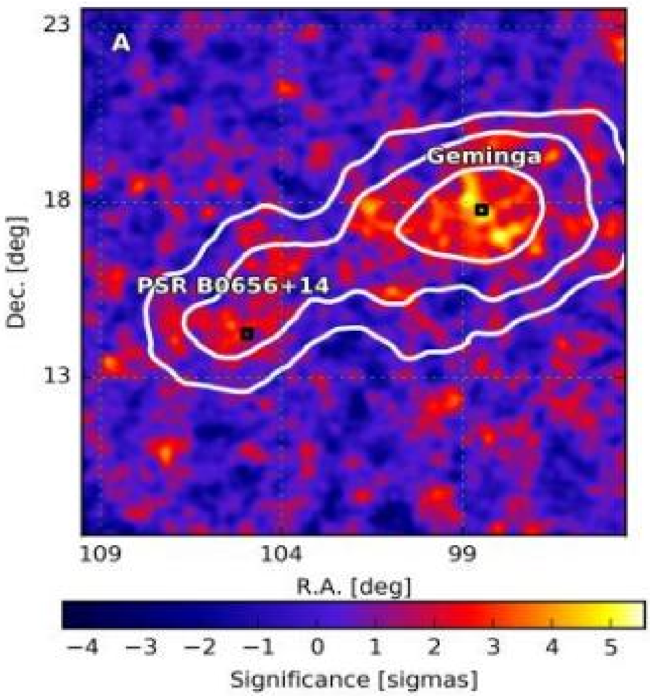
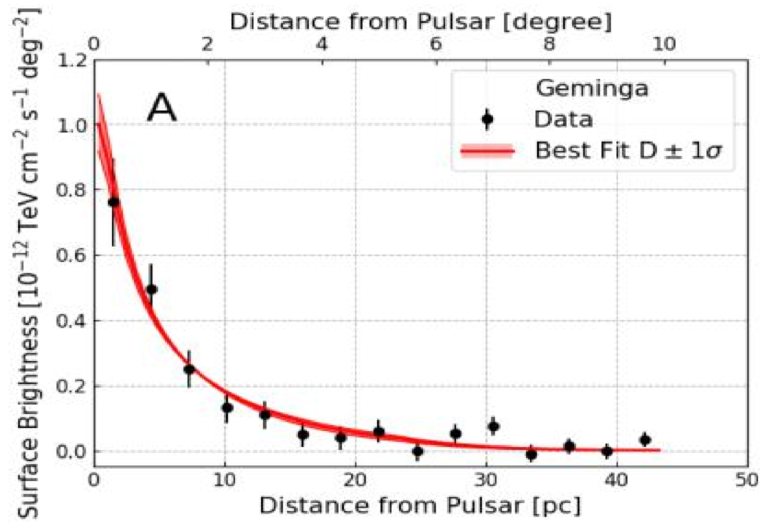
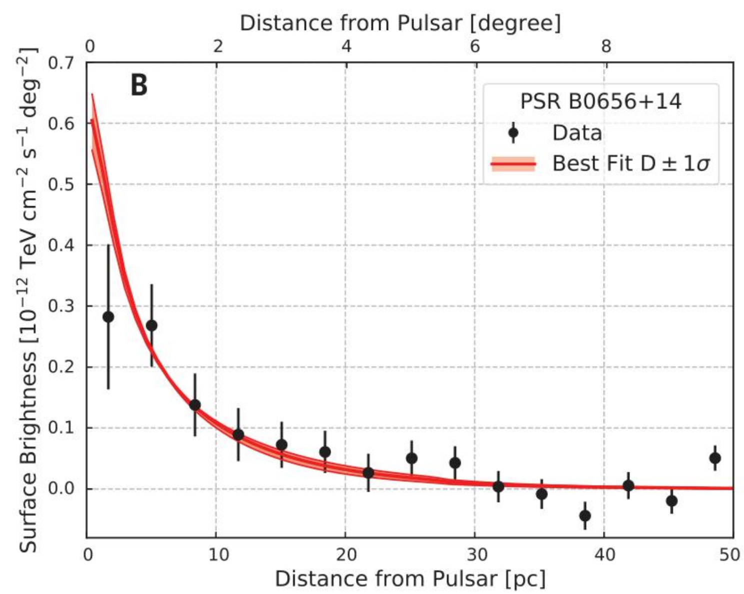
2021-08-24

TeV γ-ray halo of Geminga/Monogem







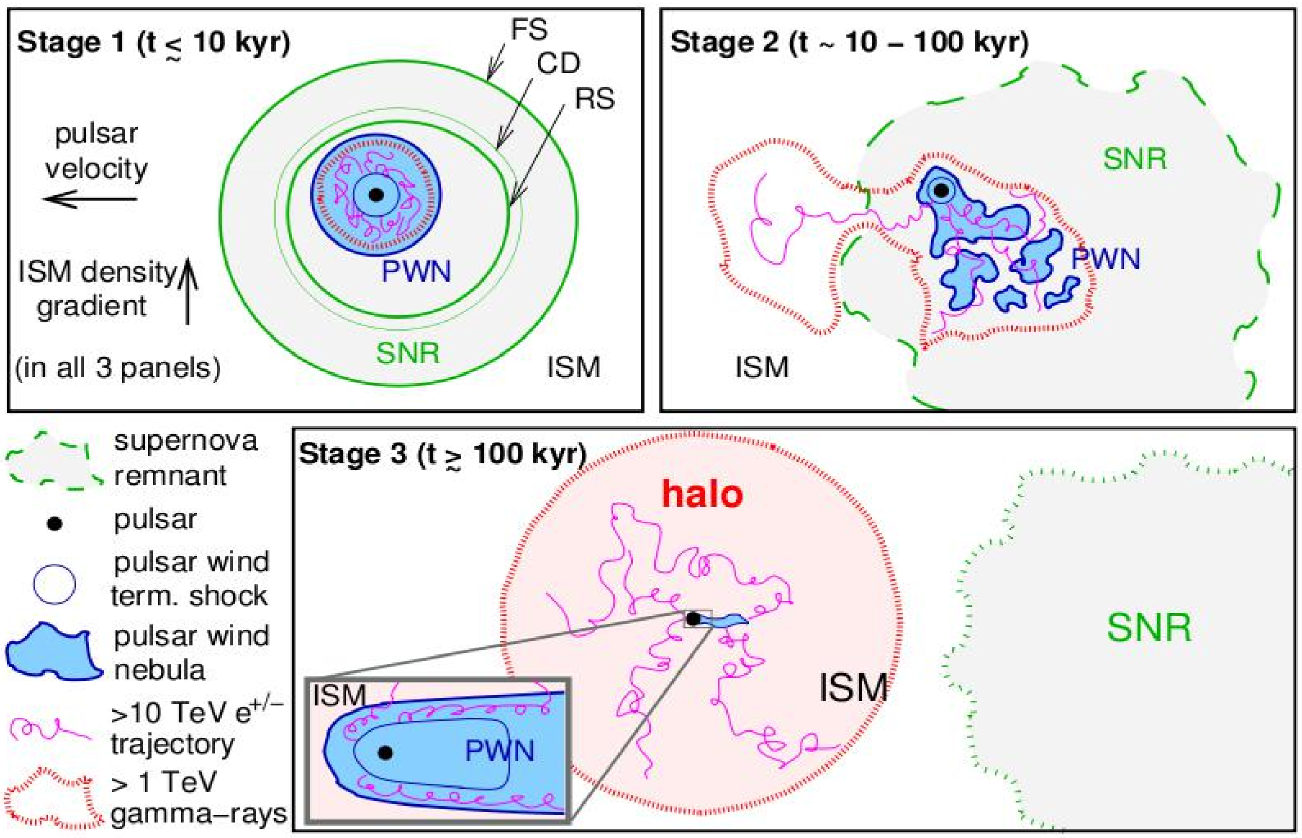
Two orders of magnitude smaller than the typical ISM diffusion coefficient

HAWC Collaboration 2017, Science, 2017, 358, 911

Pulsar halos: extended emission from particles (e+e-) diffuse/escape from pulsar wind nebula

Halo fraction in TeV-bright pulsar wind nebulae

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



Halo Model

- Overdensity of relativistic electrons around a source, but source itself is not dominating the dynamics of the ISM
- Halos only form when the pulsar is very old (> 100 kyr)
- Energy density in electrons/positrons significantly less than ISM energy density
- Halos do not significantly contribute to TeV gamma-ray flux; Geminga and Monogem are the only known halos. Some other systems may be starting to transition to halos

Some Key Projects

1. How do TeV Halos form and evolve?

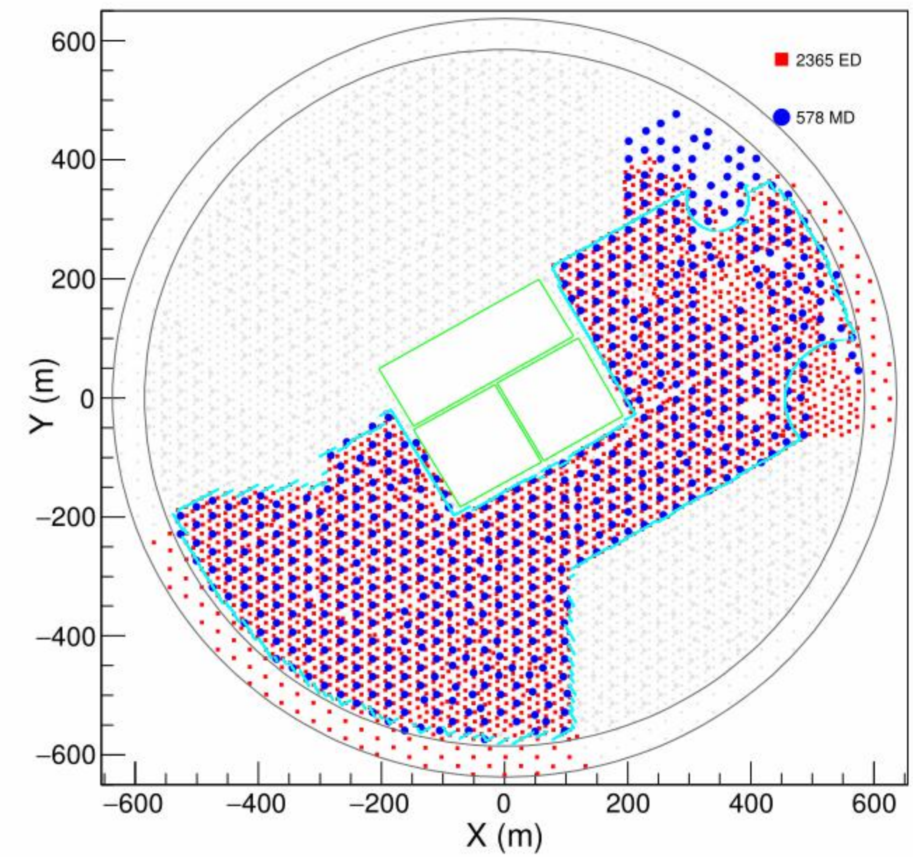
2. How do they affect electron diffusion in the Galaxy?

3. What can we learn about the Galactic pulsar population from studying TeV Halos?

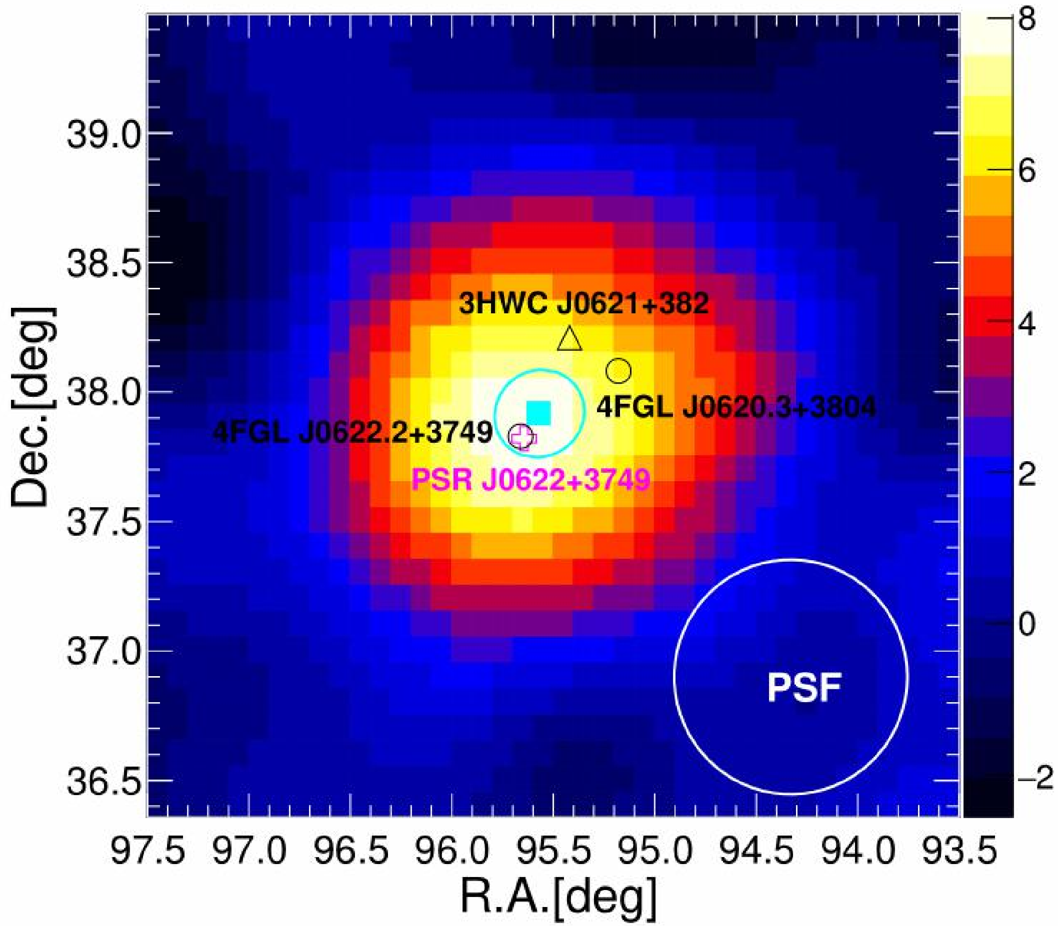
½ LHAASO-KM2A

2019年12月27日—2020年11月15日，

Fiducial area is ~0.4 km^2



LHAASO J0621+3755



Significance map with energy above 25 TeV

Extention

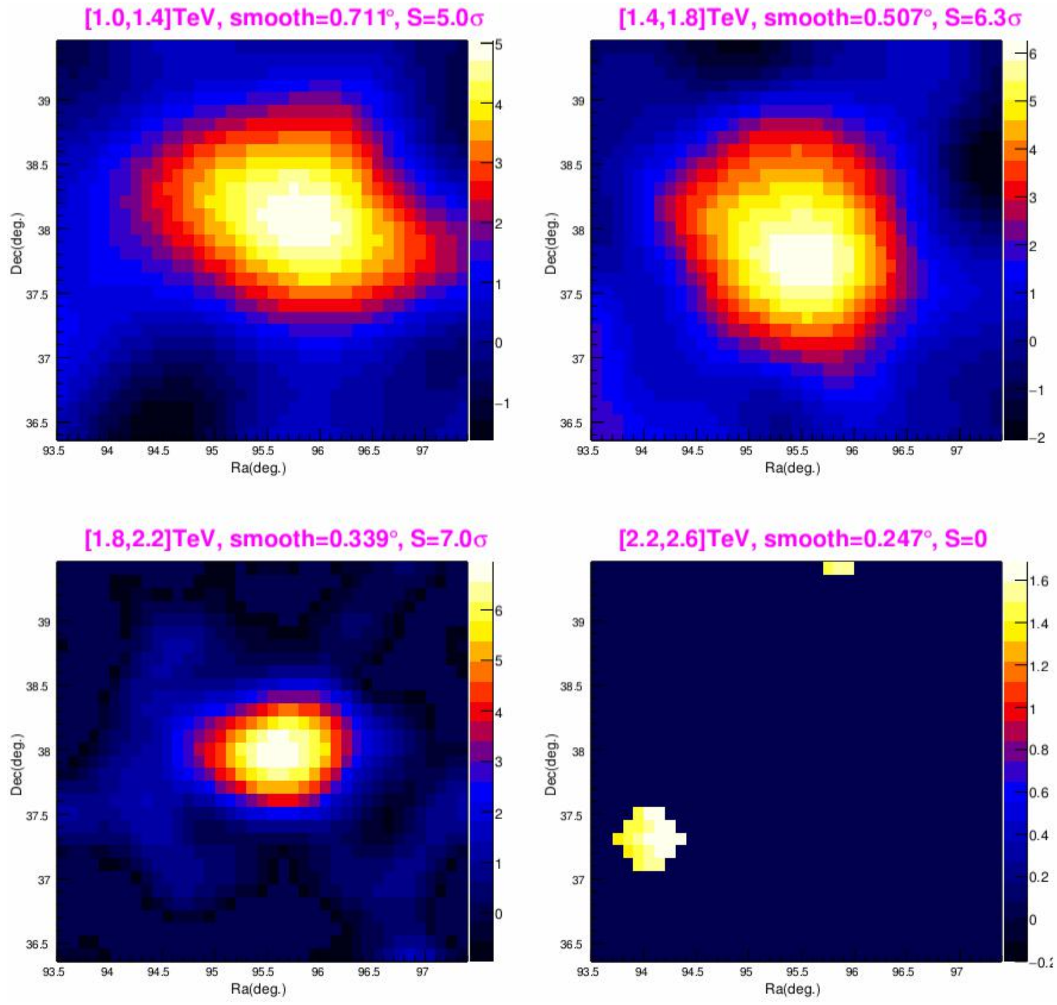
To define a source to be extended, TS_{ext} ≥ 16 is required (TSext =16 corresponds to a formal 4σ significance), where

$$\mathrm{TS}_{\mathrm{ext}} = 2\log(\mathcal{L}_{\mathrm{ext}}/\mathcal{L}_{\mathrm{ps}}).$$

Template	Extension[a] (°)	RA (°)	Dec (°)	TS	N_{p}^{b}
Point source	-	95.56 ± 0.10	37.85 ± 0.07	63.0	3
2D Gaussian	0.40 ± 0.07	95.47 ± 0.11	37.92 ± 0.09	79.5	4
Uniform disk	0.70 ± 0.10	95.44 ± 0.11	37.94 ± 0.09	80.2	4
Diffusion	0.91 ± 0.20	95.48 ± 0.10	37.90 ± 0.09	78.1	4

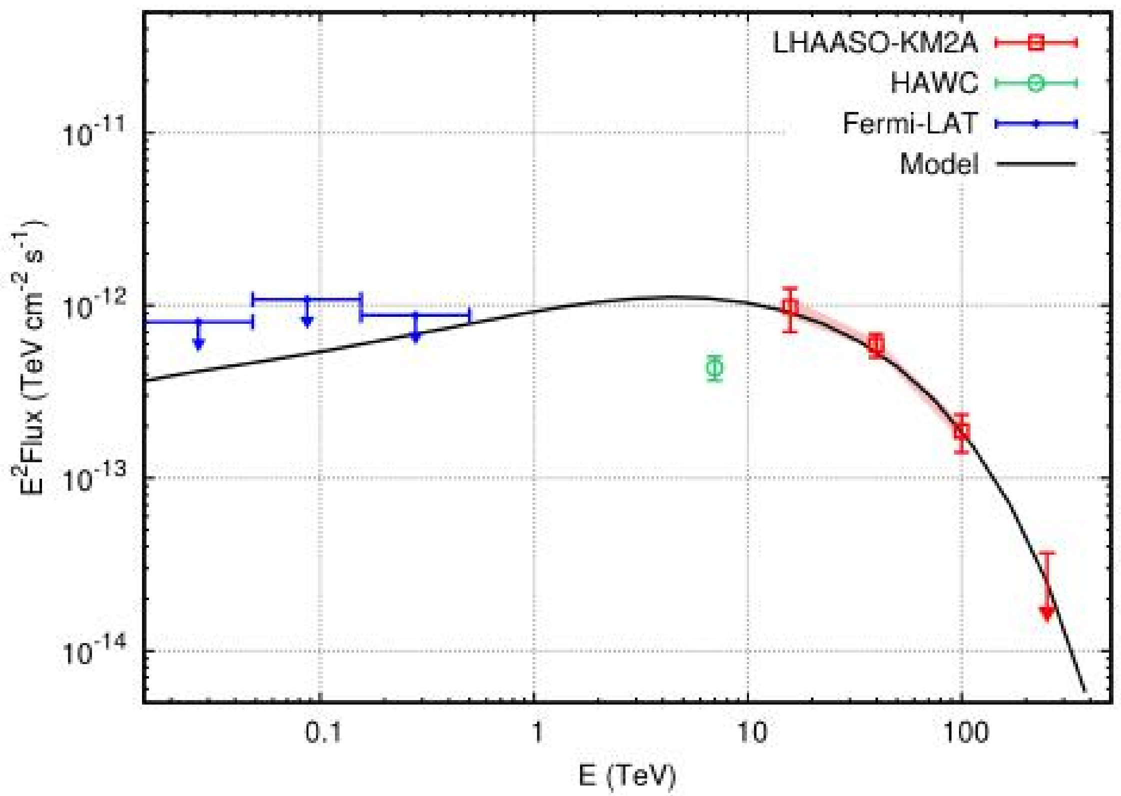
corresponds to a significance of ~4.1σ

Energy dependent morphology



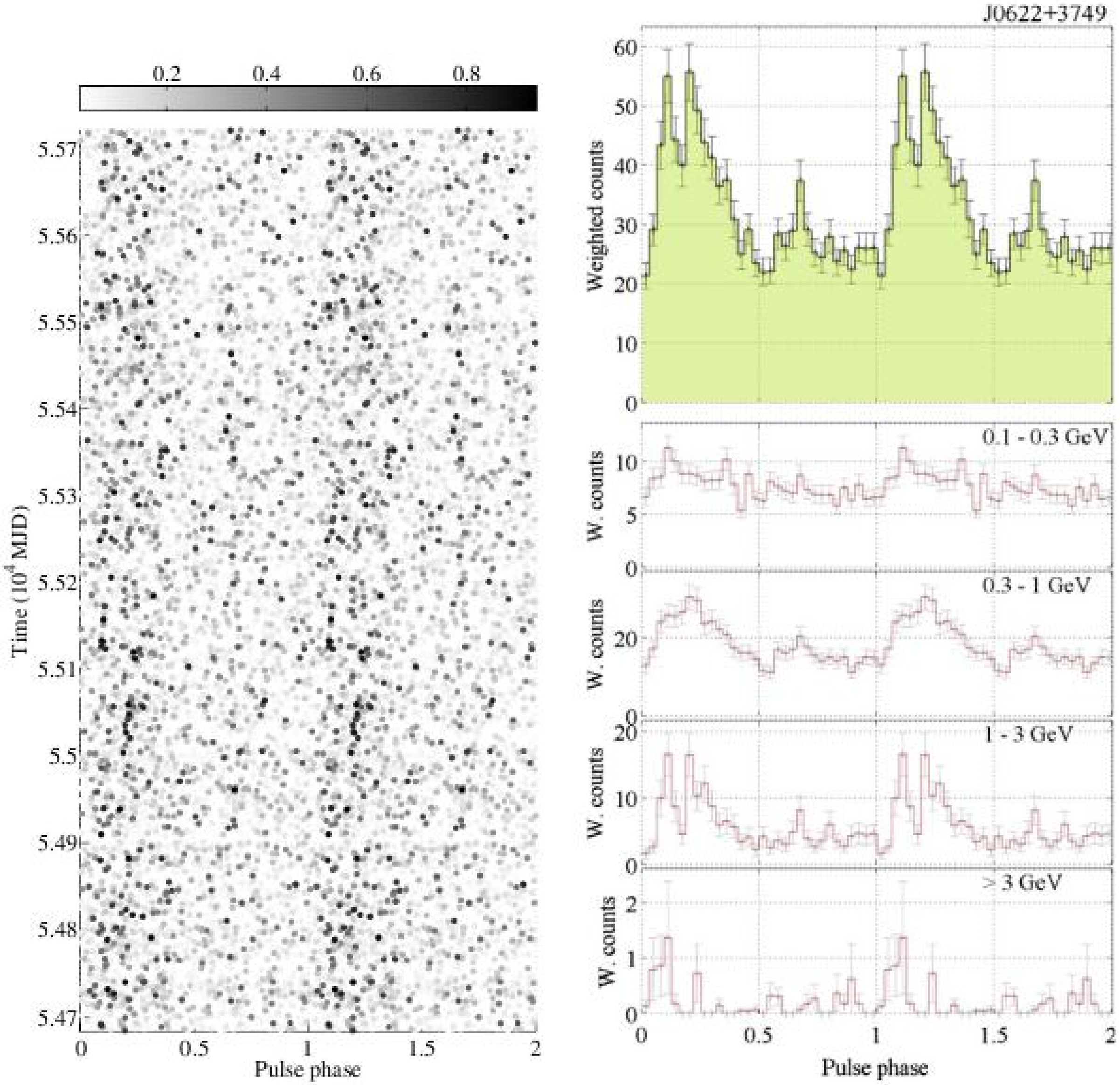
$log(E_{rec}/TeV)$	N_{obs}	N_{on}	N_{bkg}
1.0-1.4	646.0	33714	33068.00
1.4-1.8	166.5	664	497.49
1.8-2.2	33.8	70	36.18
2.2-2.6		0	2.04

SED



$$\frac{dN}{dE} = (3.11 \pm 0.38_{\rm stat} \pm 0.28_{\rm sys})\,(\mathrm{TeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}) \times 10^{-16}\,(E/40\ \mathrm{TeV})^{-2.92 \pm 0.17_{\rm stat} \pm 0.02_{\rm sys}}\,.$$

Fermi pulsar: PSR J0622+3749



P: 0.333 s
Age: 208 kyr
Edot: 2.7e34 erg/s

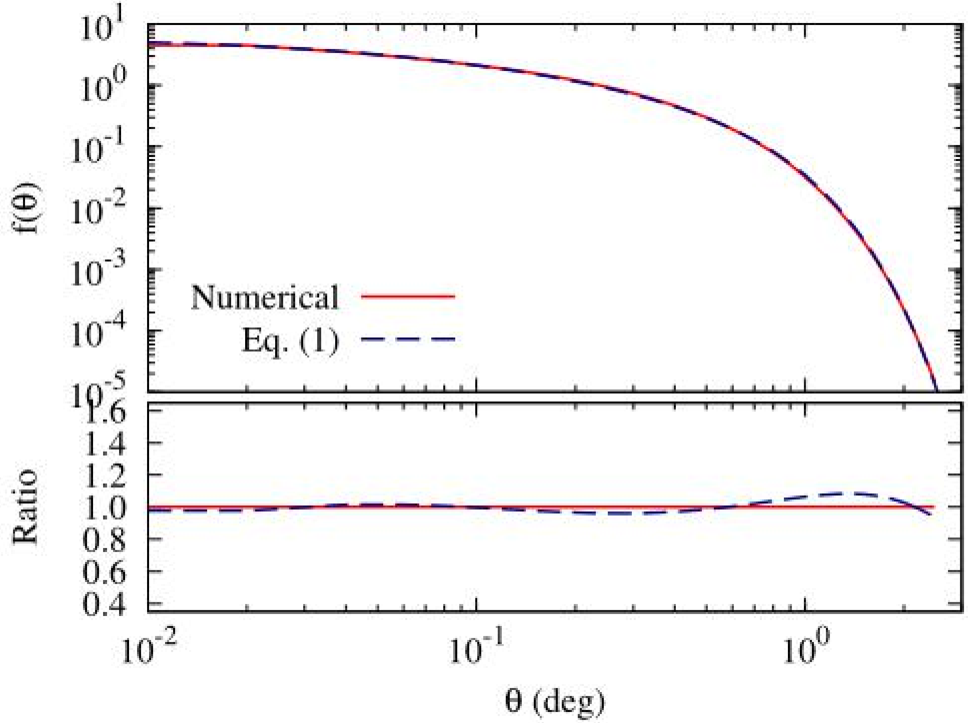
d: 1.6 kpc (very roughly estimated based on gamma luminosity)

Pletsch et al. (2012)

diffusion model

$$f(\theta) \propto \frac{1}{\theta_d(\theta + 0.085\theta_d)} \exp[-1.54(\theta/\theta_d)^{1.52}], \quad (1)$$

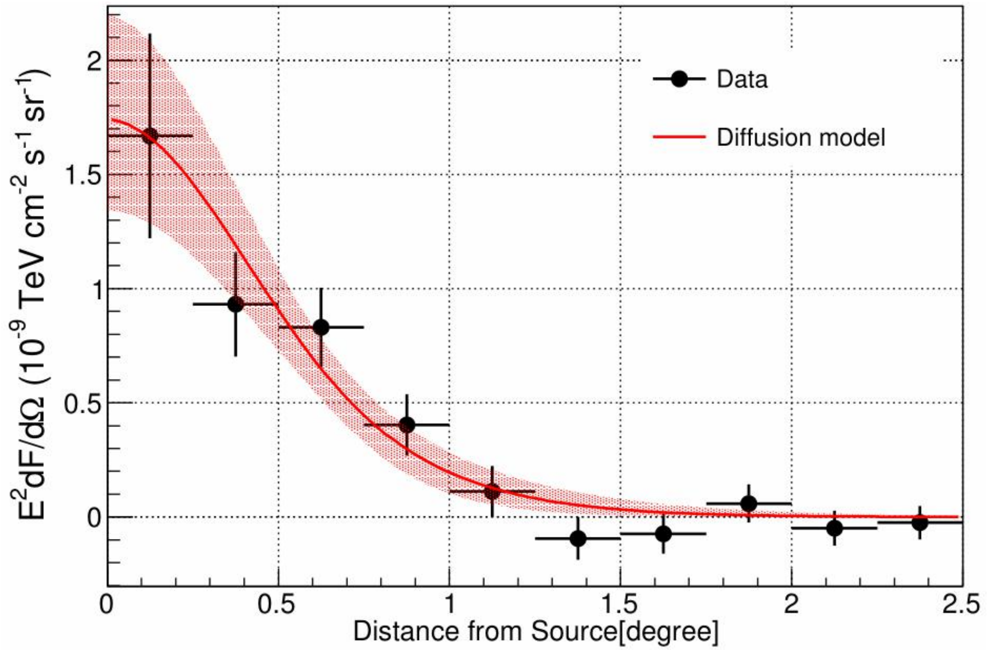
$$\theta_d = \frac{180^\circ}{\pi} \cdot \frac{2\sqrt{D(E_e)t_E}}{d}$$



θ: angular distance
$\theta_{d:}$ diffusion extension
D(Ee) :diffusion coefficient

t_E ~5.5 kyr cooling time of electrons and positrons with ~ 160 TeV

Radial Profiles

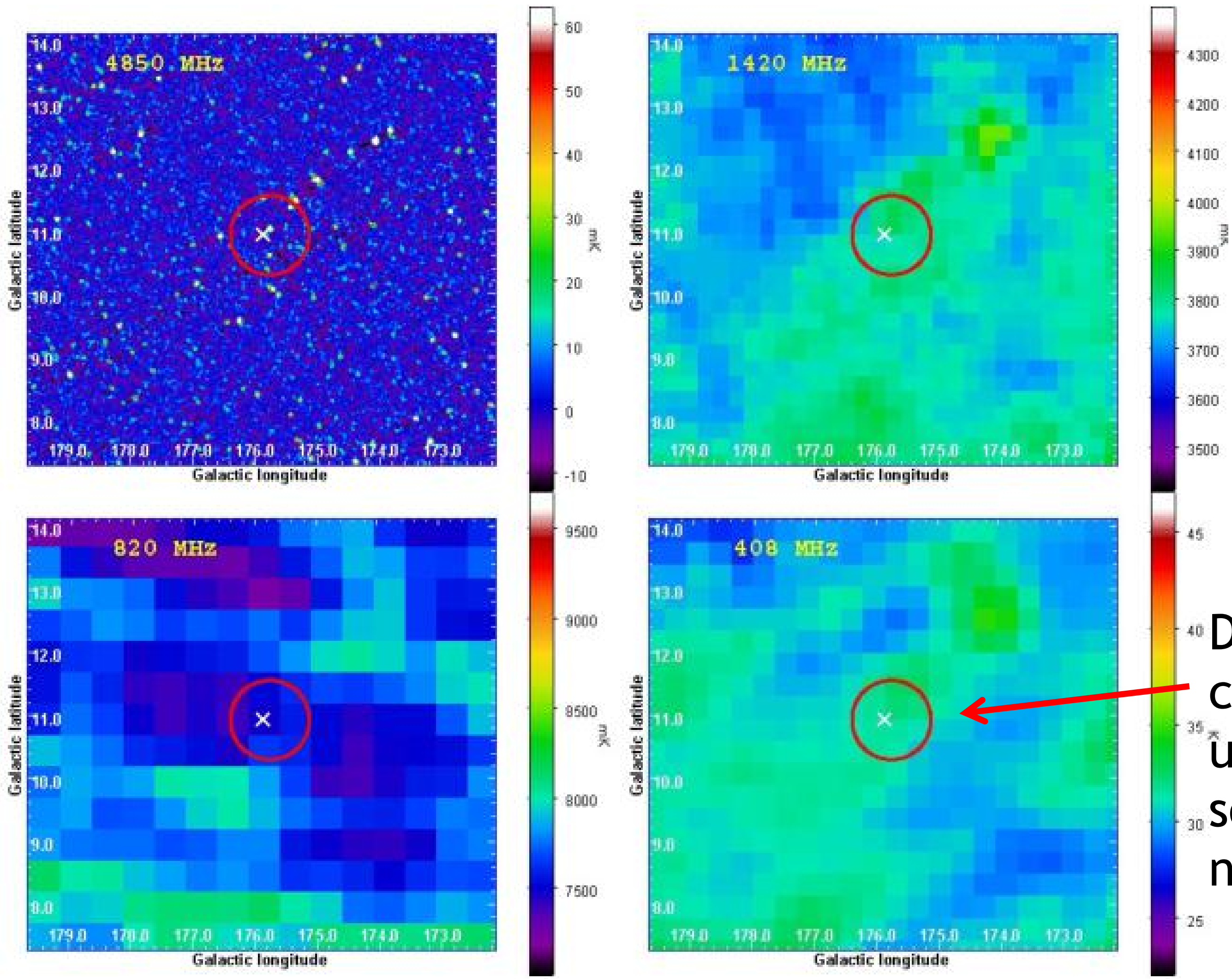


Gamma-ray energies as large as 40TeV--> e+e- as energetic as 160TeV

Inferred diffusion coefficients:

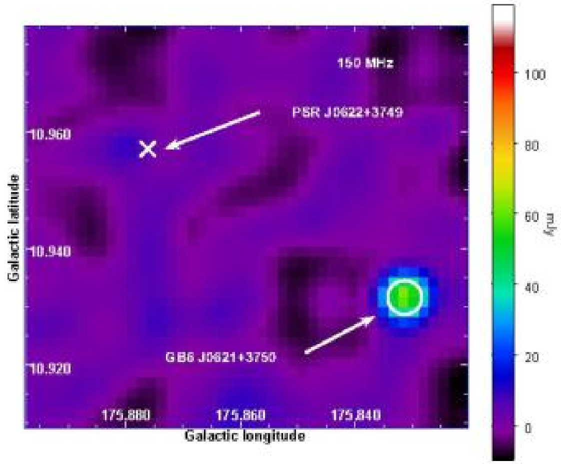
$$D(160\ \text{TeV}) \sim 8.9^{+4.5}_{-3.9} \times 10^{27} (d/1.6\ \text{kpc})^2\ \text{cm}^2\ \text{s}^{-1}.$$

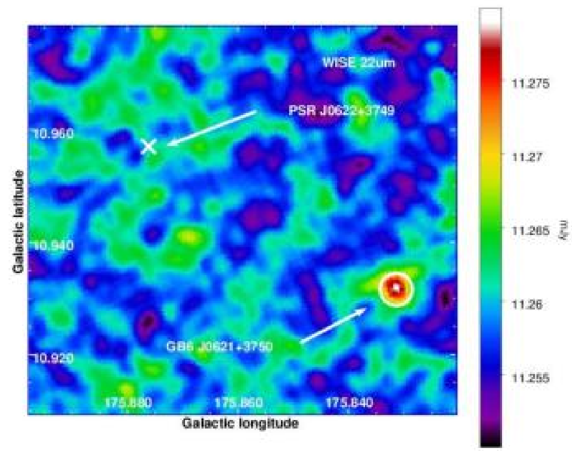
Multi-wavelength searches (H. Zhu)

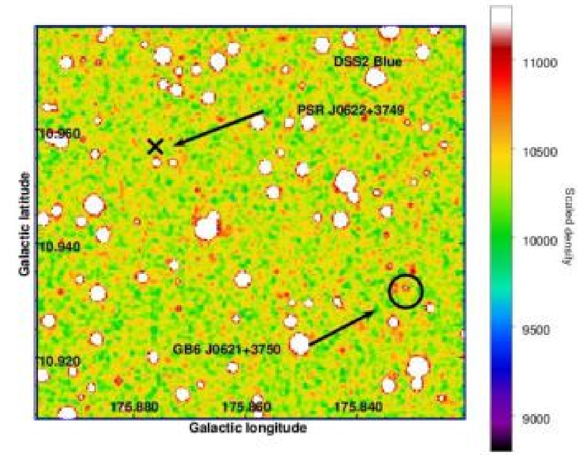


Diffuse emission could be unresolved sources, or stripe noise

Multi-wavelength searches (H. Zhu)

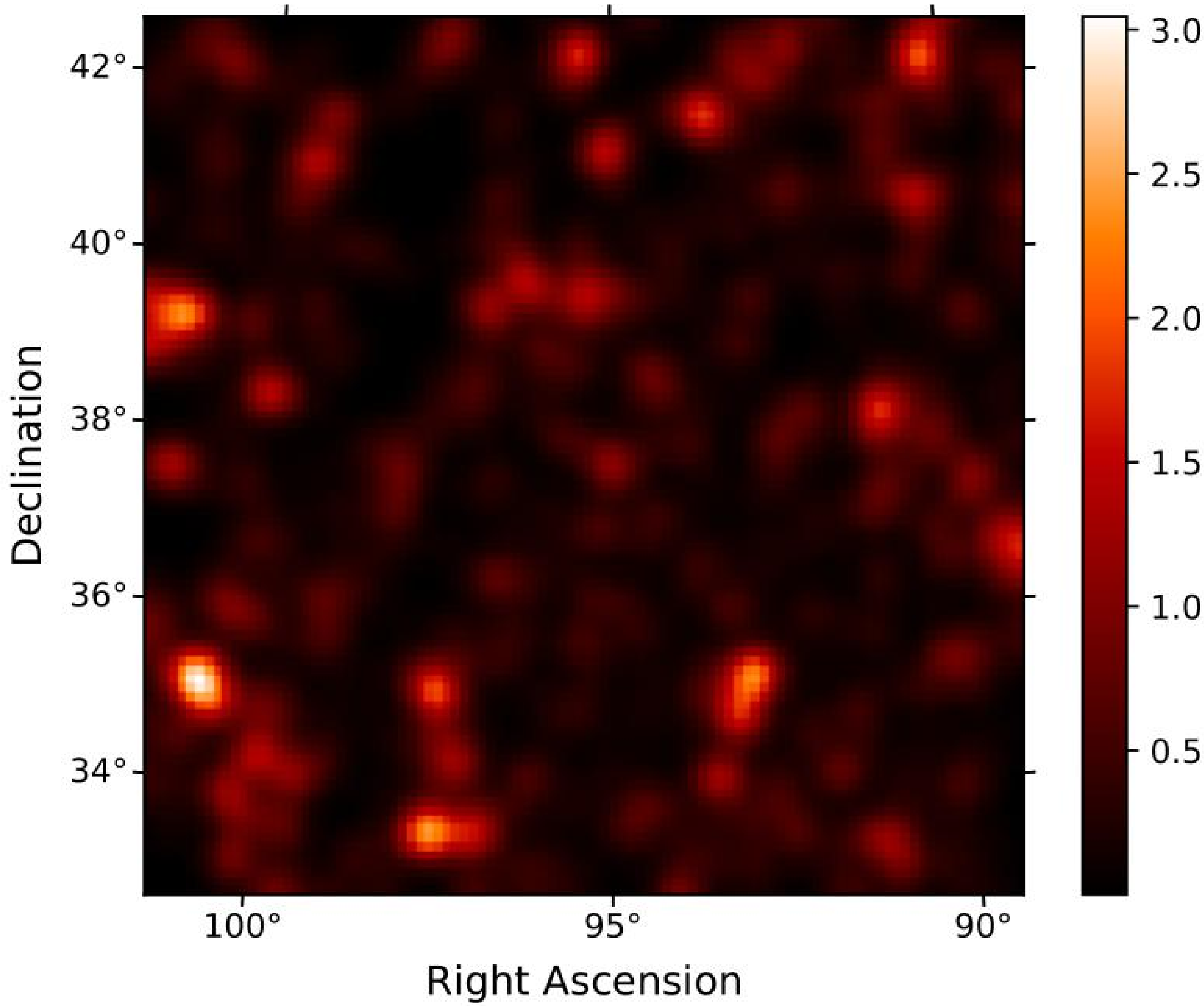






No radio, infrared, optical counterpart at the pulsar's location

Fermi-LAT analysis (X. Huang)



No significant excess > 15 GeV around the pulsar's location

SED Modeling (K. Fang)

$$q(E) \propto E^{-\alpha} \exp[-(E/E_c)^{\beta}]$$

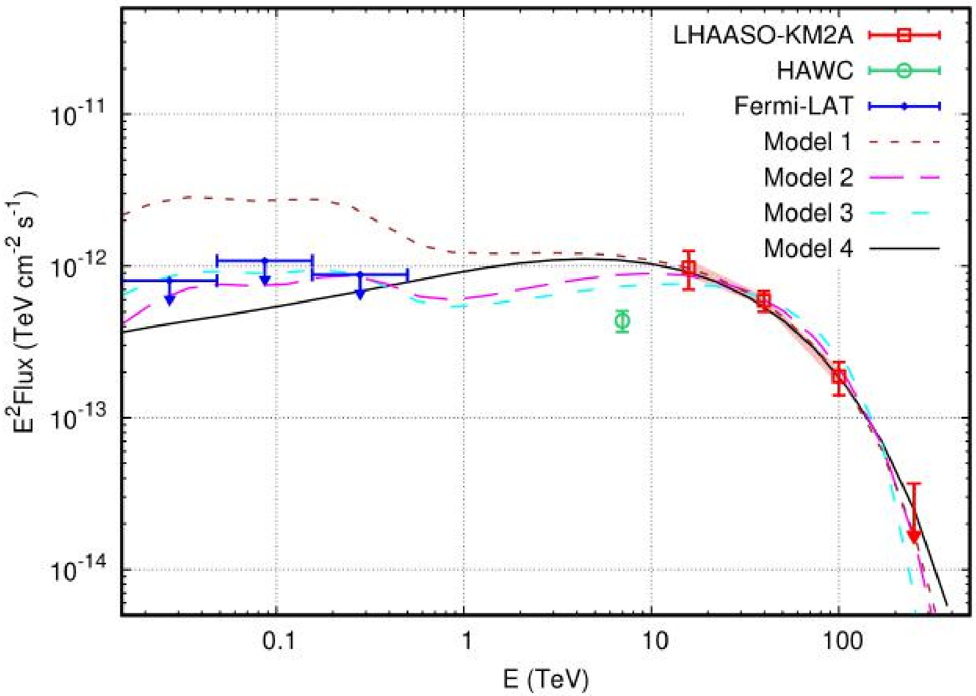


TABLE S1. Model parameters to fit the wide-band SED.

Model	α	β	E_c (TeV)	η
1	1.0	1.0	100	0.30
2	0.0	1.0	70	0.20
3	1.0	5.0	300	0.20
4[a]	1.5	1.0	150	0.40

[a] This is a two-zone diffusion model with a slow-diffusion zone size of 50 pc. See the text for details.

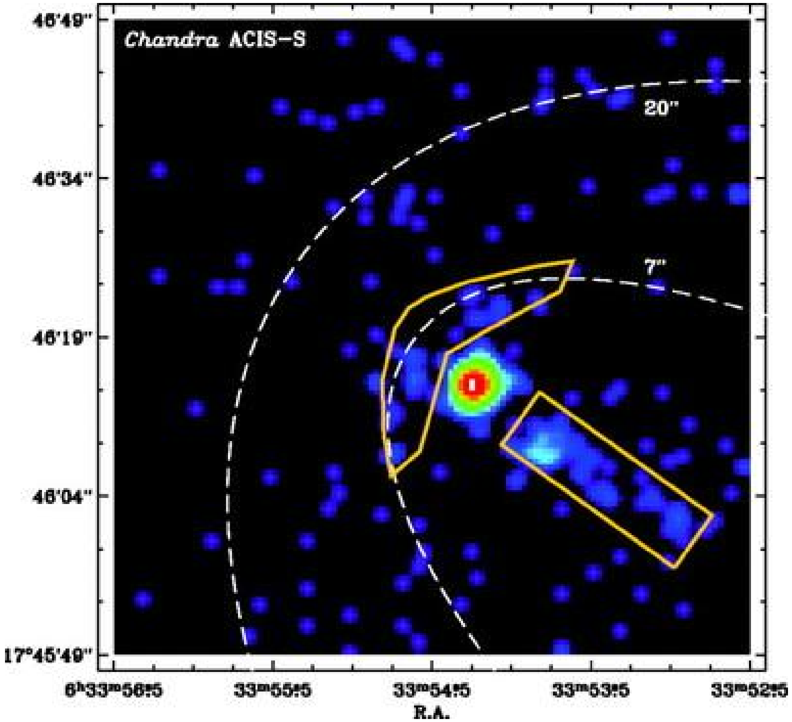
Comparison with Geminga and B0656+14

TABLE II: Comparison of the properties of pulsars J0622+3749, Geminga, and Monogem.

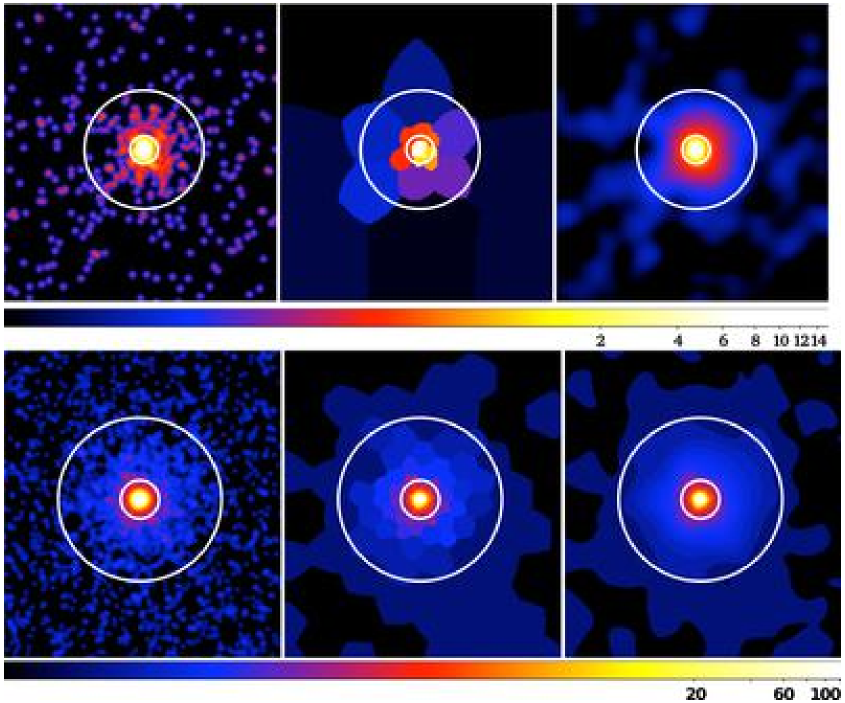
Name	P (s)	$\dot{P}$ (10^{-14} s s^{-1})	$\dot{E}$ (10^{34} erg s^{-1})	τ (kyr)	d (kpc)	Ref.
J0621+3755	0.333	2.542	2.7	207.8	1.60	[13]
Geminga	0.237	1.098	3.3	342.0	0.25	[38]
Monogem	0.385	5.499	3.8	110.0	0.29	[38]

- PSR J0622+3749 shares similar properties with the other two pulsar halos observed by HAWC (Geminga and Monogem)
- No other counterpart of PSR J0622+3749 has been found in radio, infrared, optical, X-ray, and GeV gamma-rays (different from Geminga and Monogem)

X-ray PWNe of Geminga and Monogem



Pavlov et al. (2006)



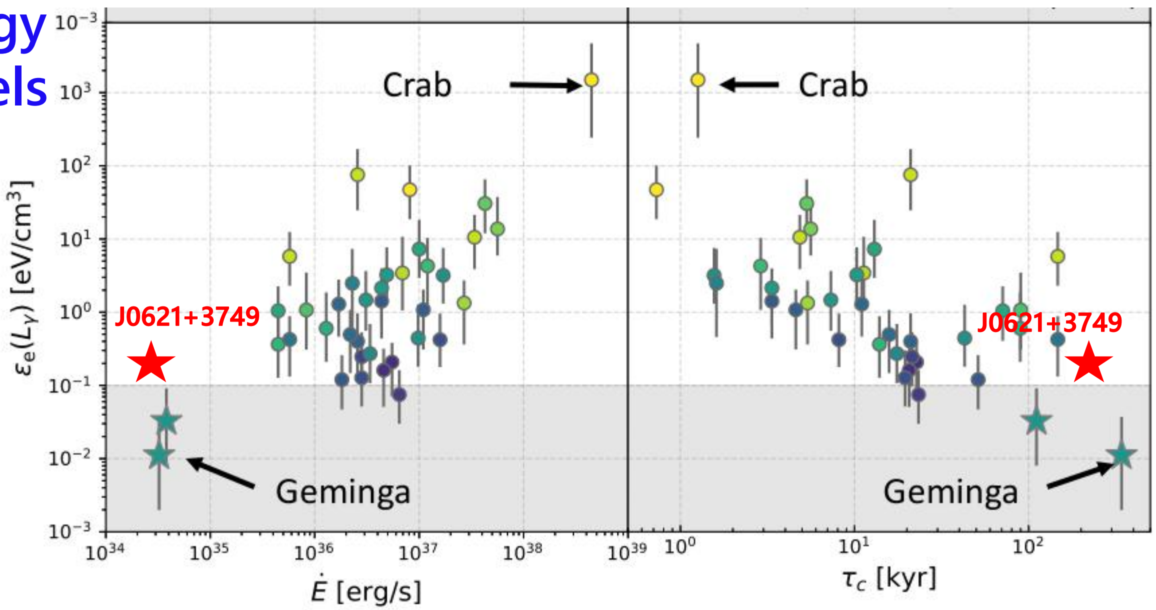
Birzan et al. (2016)

- The X-ray nebula of Monogem has an unabsorbed flux of 8.3×10^{-15} erg s^{-1} cm^{-2} in 0.5-8 keV
- For a distance of 5 times larger, the expected flux of that of J0622+3749 is probably too low (point source sensitivity of Chandra ACIS is 4×10^{-15} erg s^{-1} cm^{-2} for 10^4 s exposure)

Known PWN / halo population

- Halos as region with energy density far below ISM levels ~0.1 eV/cm^{-3}
- What about other halos?
- LHAASO J0621+3755 around PSR J0621+3749 (P=0.333s Age=208 kyr,Edot=2.7e34 erg/s)

Giacinti et al, A&A 636, A113 (2020)



The top 30 bright middle-aged pulsars within the field of view 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	

By Xiaojun Bi and Kun Fang

Potential pulsar halos by LHAASO-KM2A

Pulsar name	RA(°)	DEC(°)	Extension(°)	TS(>25TeV)	Age(Kyr)	Distance(Kpc)
Geminga	98.58	17.52	1.70±0.12	479.1	342	0.25
Monogem	105.12	14.57	0.85±0.24	118.3	111	0.29
J0622+3749	95.46	37.96	0.42±0.06	84.5	208	1.6
J1831-0952	277.79	-9.95	0.45±0.124	43.3	128	3.68
B0540+23	85.94	23.49	0.71±0.07	61	253	1.56
J2021+4026	305.67	40.57	0.36±0.10	49.1	77	2.15
J2229+6114	337.06	60.93	0.44±0.006	299.7	10.5	3
J2238+5903	339.36	59.10	0.69±0.12	106	26	2.83
J0633+0632	98.69	6.6	0.52±0.14	23	59	1.35
J0248+6021	42.59	60.62	0.58±0.17	24.1	62	2

LHAASO is a **Pulsar Halo Factory!**

Summary

- The LHAASO discovery of this source enriches the class of so-called pulsar halos and confirms that high-energy particles generally diffuse very slowly in the disturbed medium around pulsars.
- TeV halos serve as a tool to study the ISM turbulence, which is fundamentally important to understand the transport of CRs in our Galaxy
- There are potentially many more TeV halos in our Galaxy and LHAASO is a finding machine for TeV halos

谢谢！