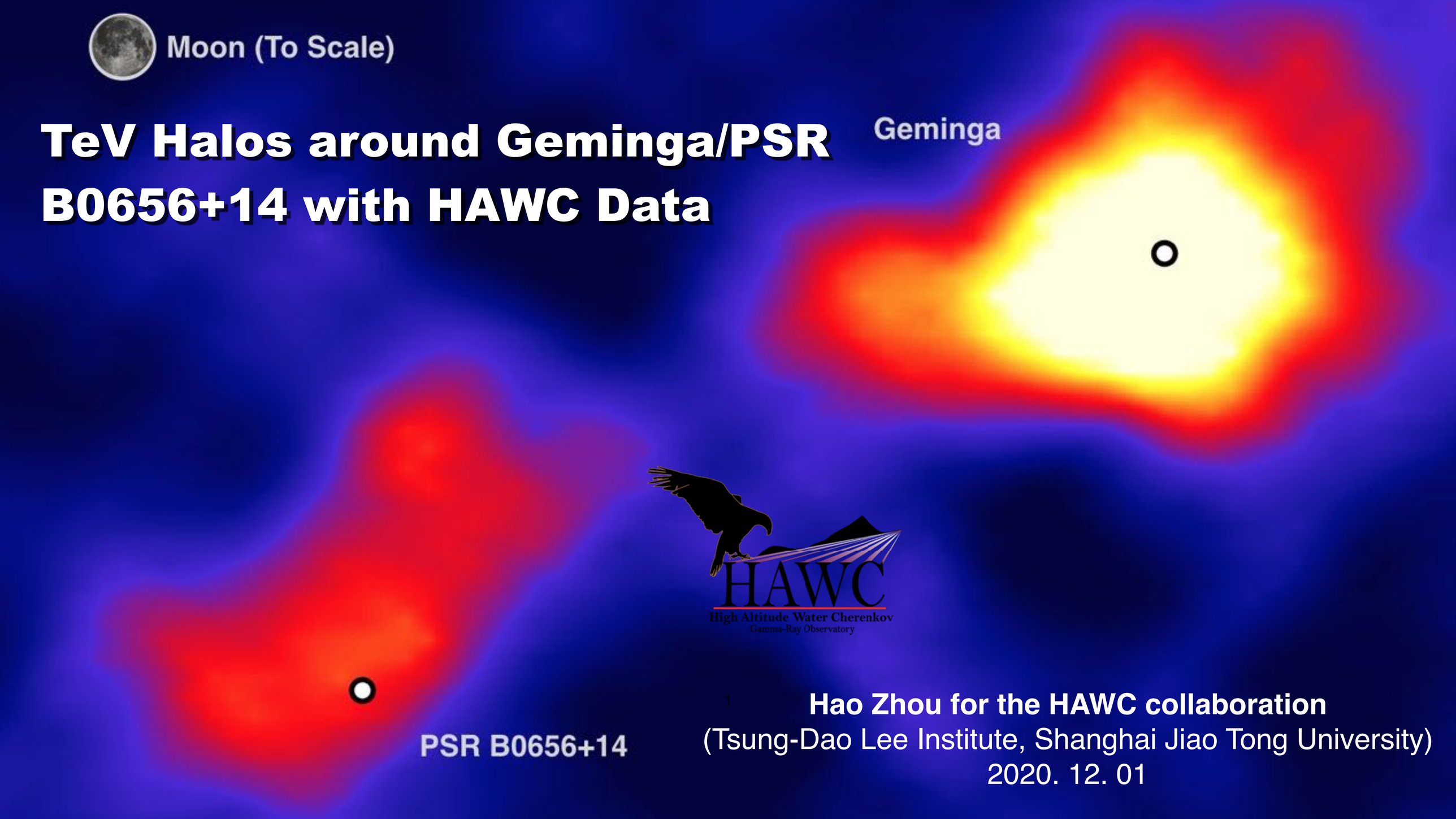


TeV Halos around Geminga/PSR B0656+14 with HAWC Data

Hao Zhou for the HAWC collaboration
(Tsung-Dao Lee Institute, Shanghai Jiao Tong University)
2020. 12. 01

Why is Geminga an interesting pulsar?

The first example of TeV halo class

- 2017 - HAWC revealed very extended gamma-ray emission around Geminga
- 2009 - Milagro published its gamma-ray catalog including Geminga

Why is Geminga an interesting pulsar?

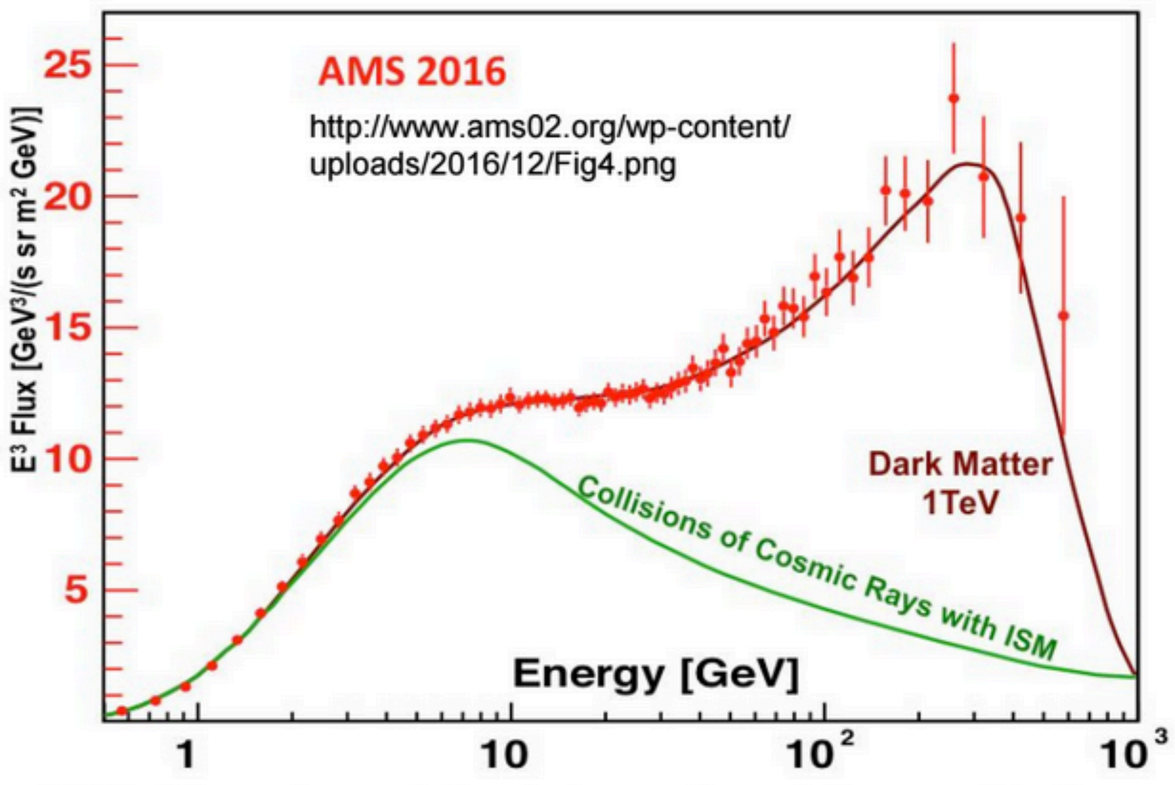
Not only a pulsar halo

- 2017 - HAWC revealed very extended gamma-ray emission around Geminga
- 2009 - Milagro published its gamma-ray catalog including Geminga
- 1991 - ROSAT observed pulsed emission in soft X-ray
- 1972 - SAS-2 discovered a gamma-ray source

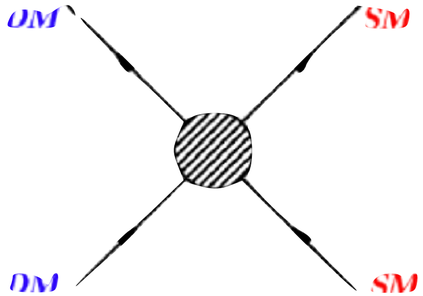
Geminga - Gemini gamma-ray source
- “It is not there”

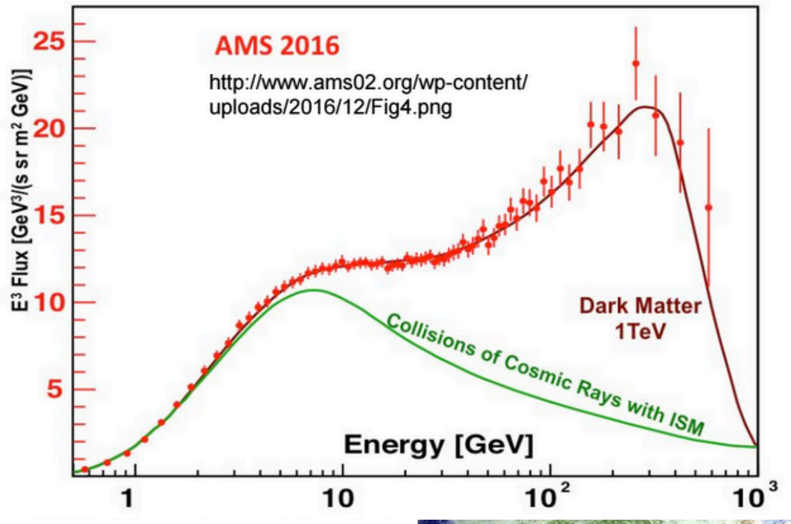
Why is Geminga an interesting pulsar?

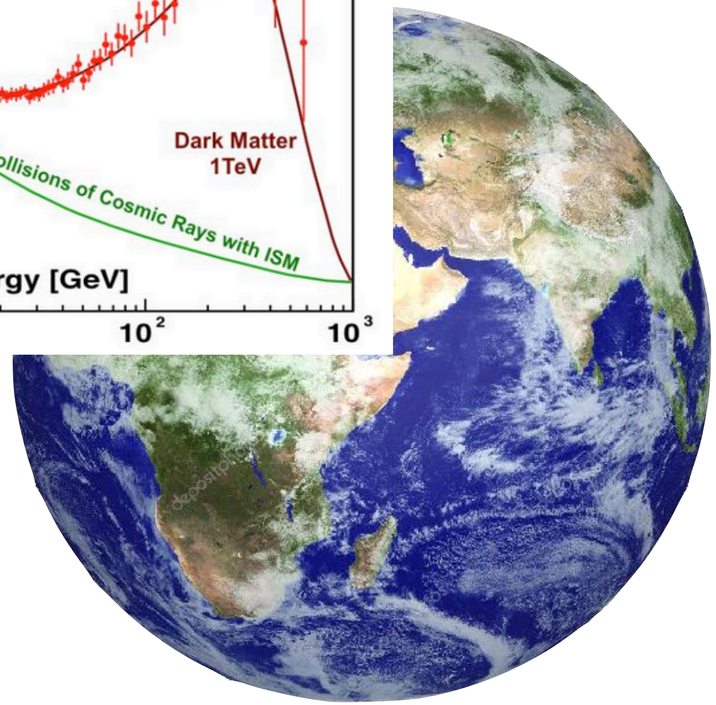
Local Cosmic Positron Excess



Local Cosmic Positron Excess







Are these positrons from?

- Dark matter decay or annihilation
- Nearby astrophysical sources

List of Nearby Middle-aged Pulsars

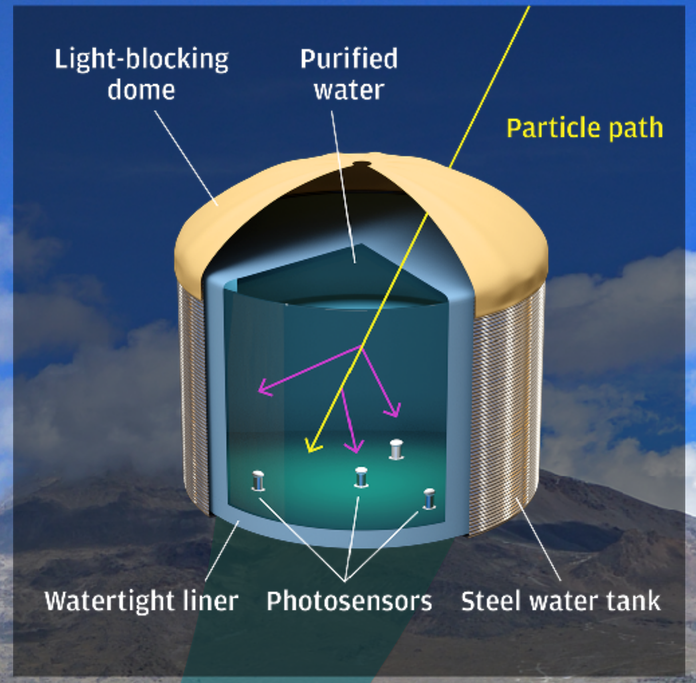
- A short list of candidates that meet the criteria of nearby and middle-aged.
- Two of them are good candidates in northern sky.
  - Geminga and PSR B0656+14 (Monogem)

#	NAME		Gl (deg)	Gb (deg)	RAJD (deg)	DECJD (deg)	DIST (kpc)	AGE (Yr)	EDOT (ergs/s)	C1 EDOT/DIST^2
1	J0633+1746	hh92	195.134	4.266	98.47564	17.77025	0.19	3.42e+05	3.2e+34	8.8643e+35
2	B0656+14	mlt+78	201.108	8.258	104.95082	14.23872	0.29	1.11e+05	3.8e+34	4.5184e+35
3	B1951+32	kcb+88	68.765	2.823	298.24252	32.87792	3.00	1.07e+05	3.7e+36	4.1111e+35
4	J1740+1000	mca00	34.011	20.268	265.10813	10.00175	1.23	1.14e+05	2.3e+35	1.5203e+35
5	J1913+1011	mh1+02	44.485	-0.167	288.33475	10.18971	4.61	1.69e+05	2.9e+36	1.3646e+35
6	J1836+5925	aaa+09c	88.875	24.999	279.05697	59.42504	0.30	1.83e+06	1.1e+34	1.2222e+35
7	J1741-2054	aaa+09c	6.422	4.907	265.48867	-20.90328	0.30	3.86e+05	9.5e+33	1.0556e+35
8	J2032+4127	aaa+09c	80.224	1.028	308.05466	41.45675	1.33	2.01e+05	1.5e+35	8.4798e+34
9	J1755-0903	bbb+12	18.324	8.150	268.79318	-9.06433	0.23	3.87e+06	4.4e+33	8.3176e+34
10	J1831-0952	lfl+06	21.897	-0.128	277.89293	-9.86714	3.68	1.28e+05	1.1e+36	8.1226e+34

ATNF Pulsar Catalog http://www.atnf.csiro.au/people/pulsar/psrcat/

The HAWC Observatory

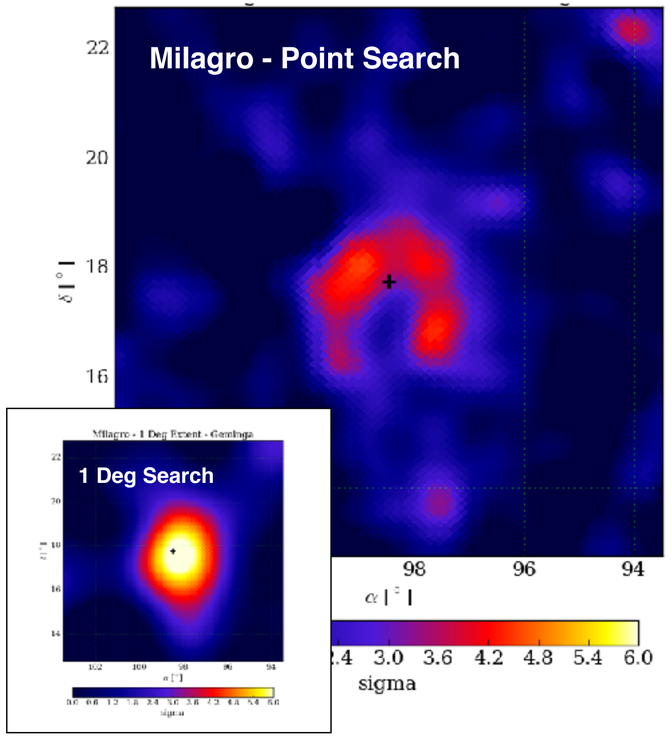
- 300 Water Cherenkov Detectors
- 22,000 m^2 detector area
- Sub TeV - >100 TeV Sensitivity
- Wide field of view: ~2 sr
- High duty cycle: >95%



Excellent detector for extended source observations

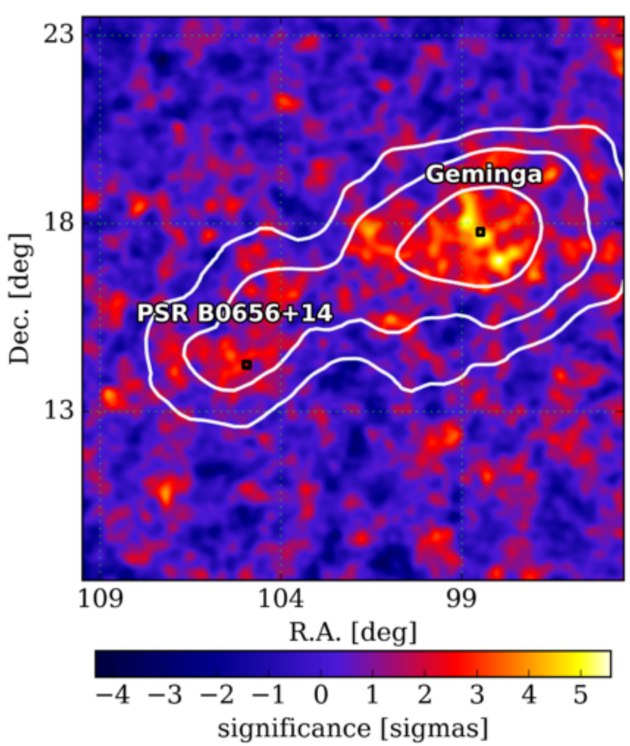
Full array inaugurated on March 20, 2015

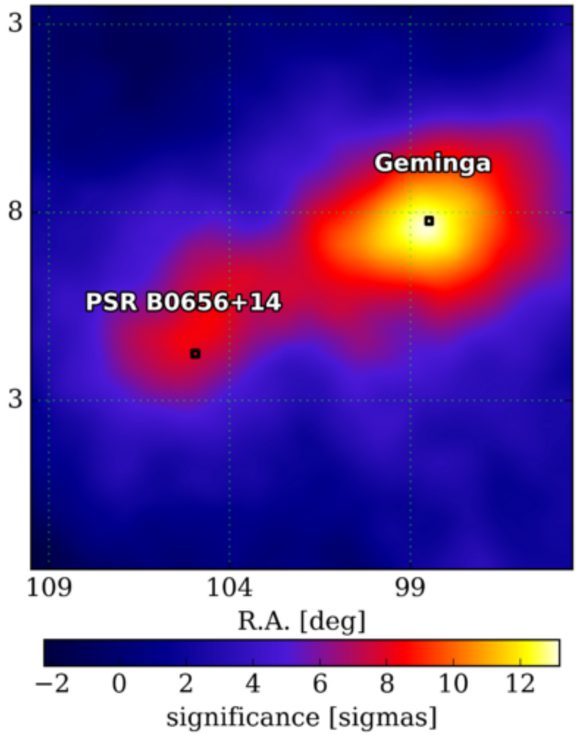
Source Candidate with 8y Milagro Data



HAWC Detects TeV Halos with 1.5y Data

The HAWC Collaboration, *Science* 358, 911 (2017)

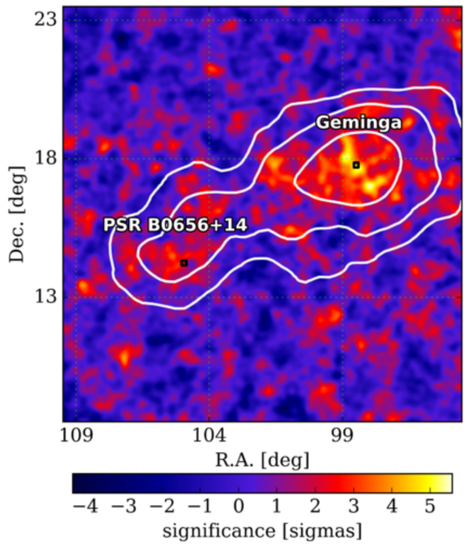


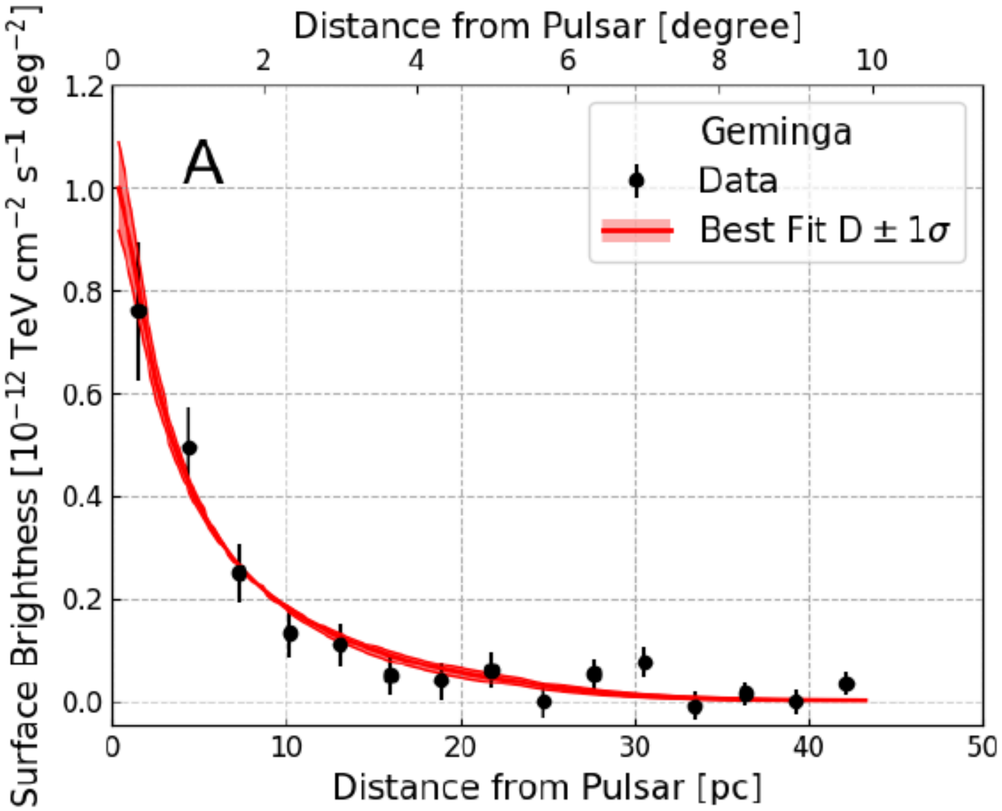


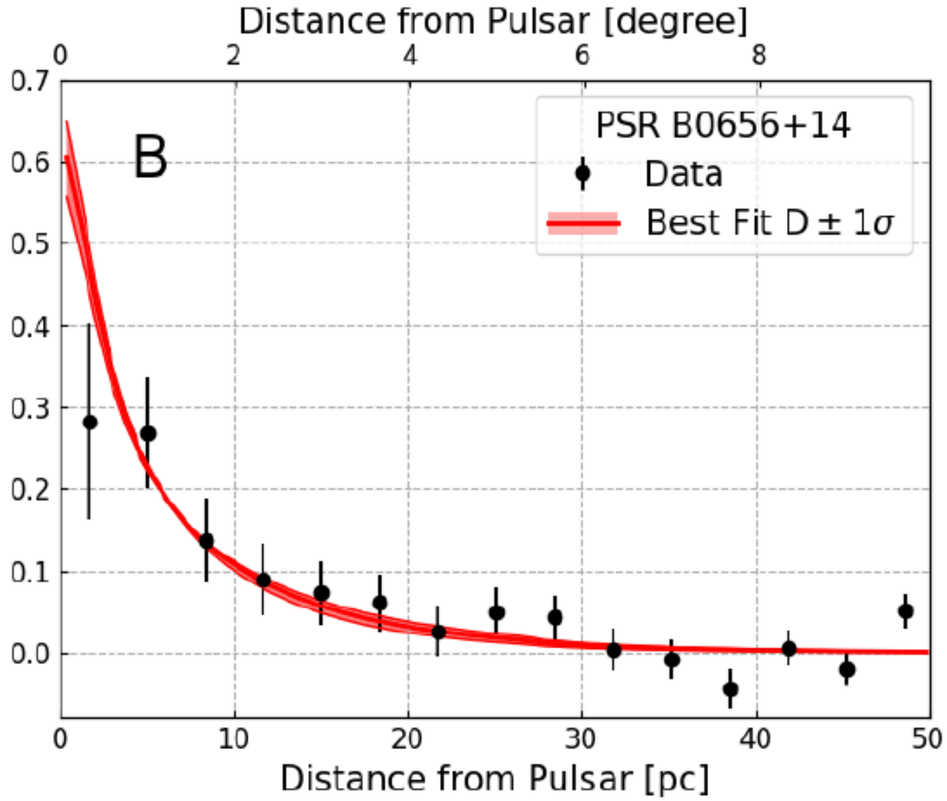
Very extended gamma-ray emission (tens of pc) is detected, much larger than typical PWNe.

HAWC Measures the Diffusion Profiles

The HAWC Collaboration, *Science* 358, 911 (2017)



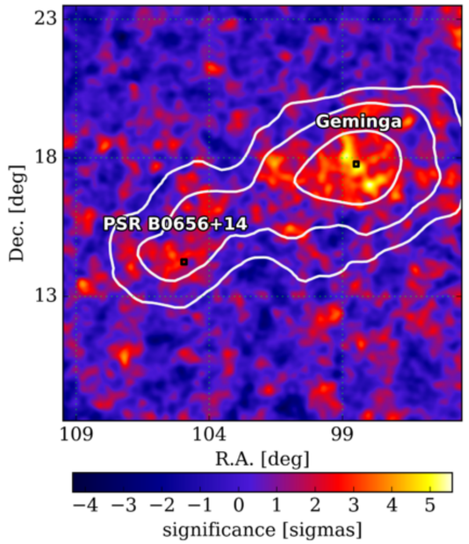


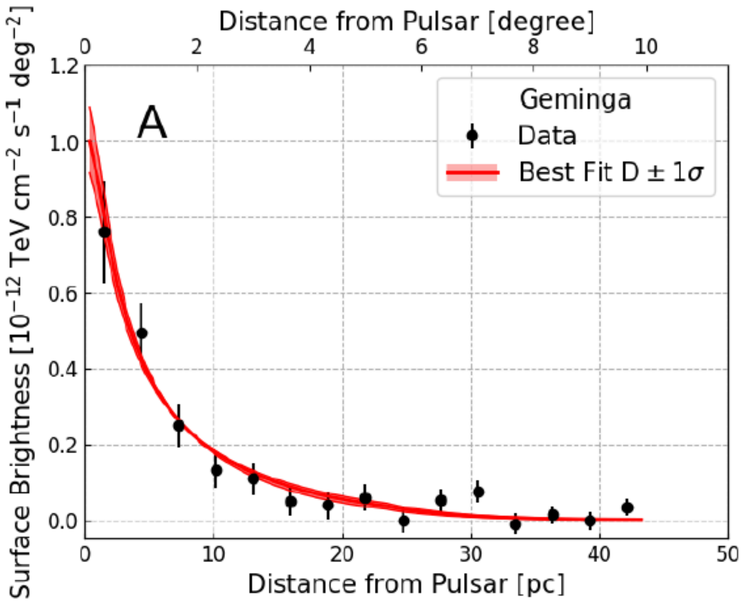


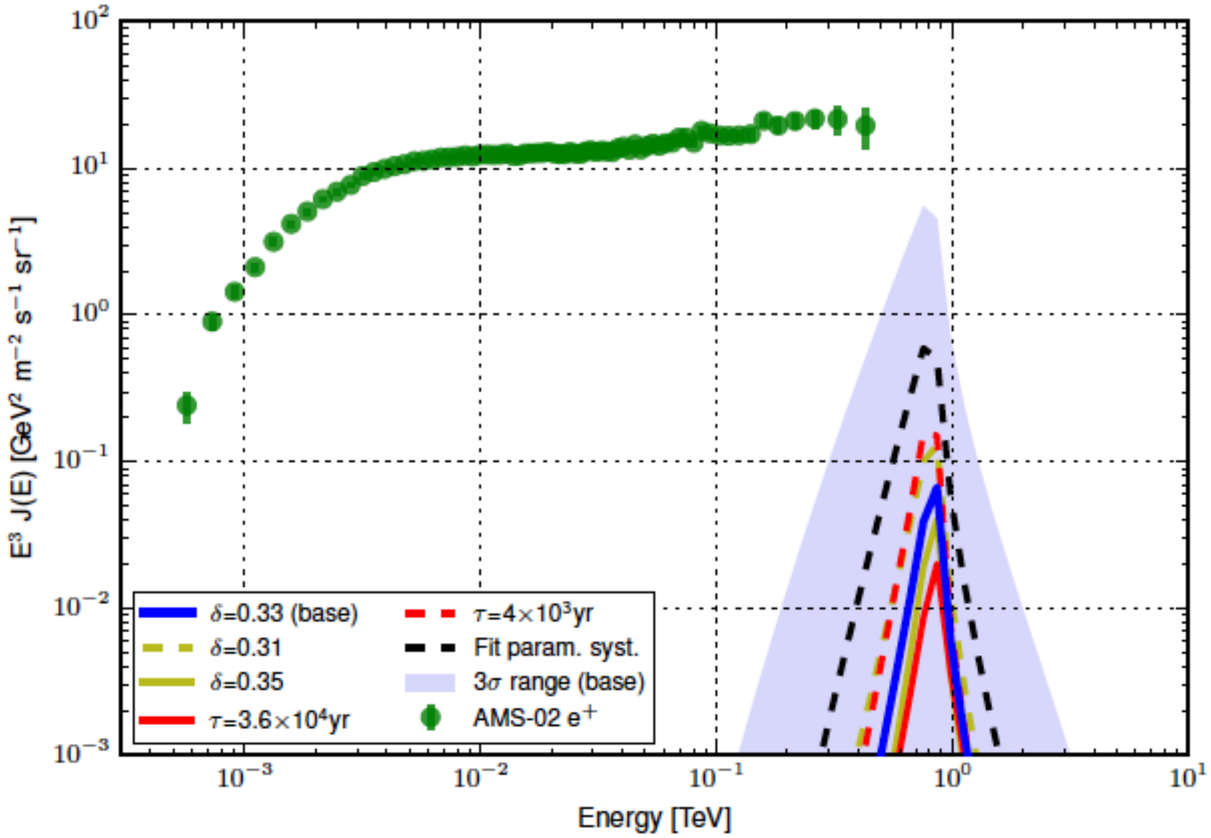
Diffusion coefficient, directly measured by HAWC, is two order of magnitude lower than that indirectly derived from cosmic ray primary/secondary ratio.

Implications on the Positron Excess

The HAWC Collaboration, *Science* 358, 911 (2017)







Assuming the HAWC measured diffusion coefficient, the positrons from Geminga or Monogem contribute negligibly to the positron flux measured by satellite detectors like AMS-02.

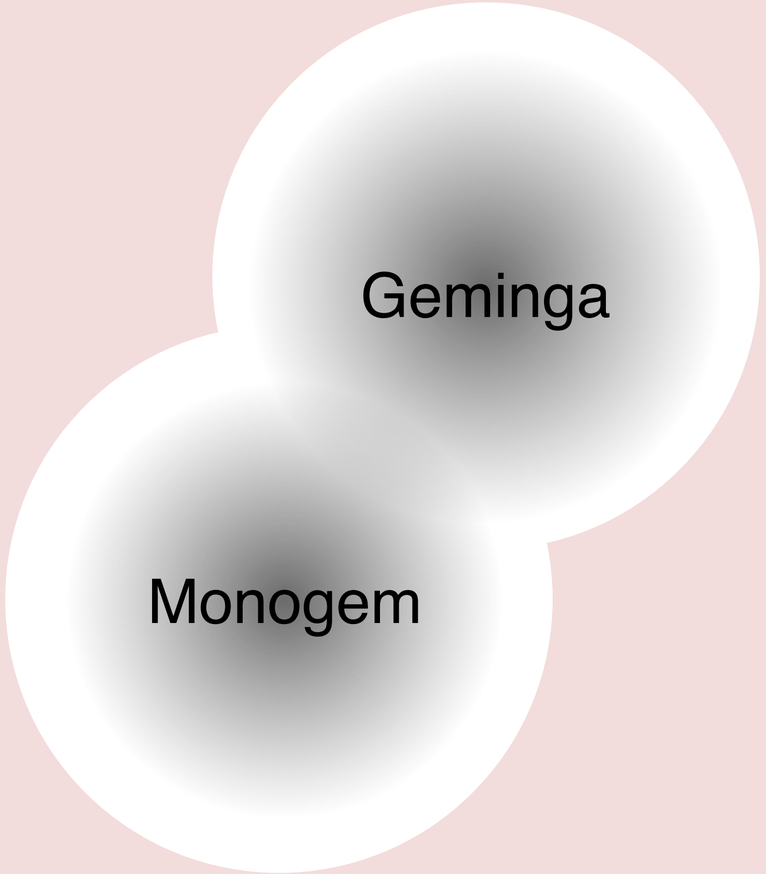
Questions about Diffusion Remain

Geminga

Monogem

- How does diffusion depend on energy?
- How big are the low-diffusion regions? Are they generated from the pulsars or property of ISM?

Questions about Diffusion Remain



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Questions about Diffusion Remain

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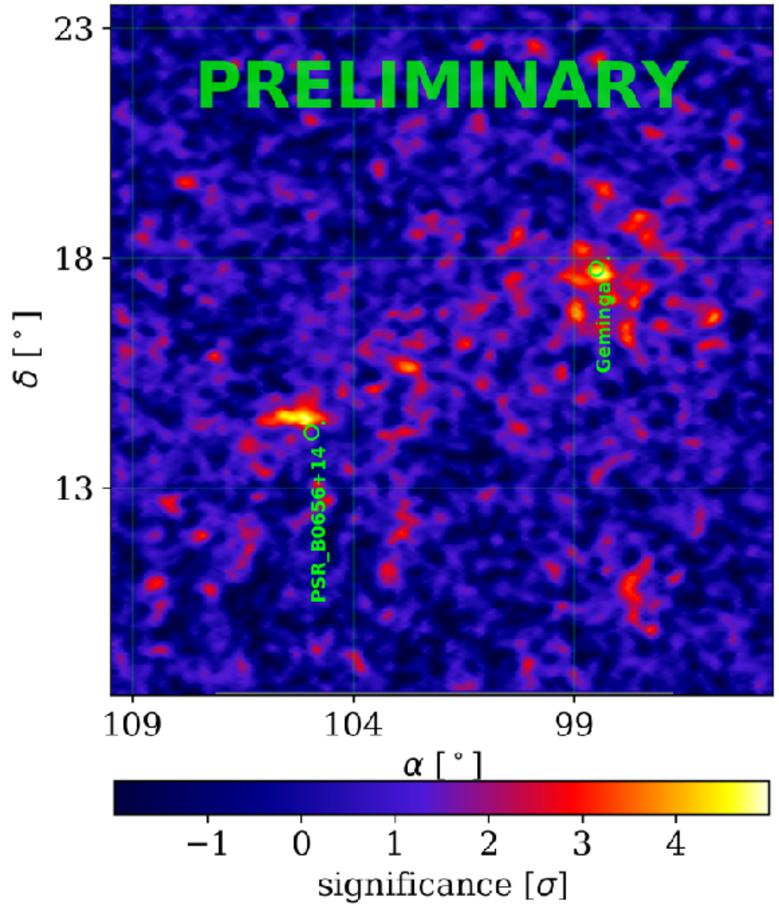
HAWC Observation with 3y Data

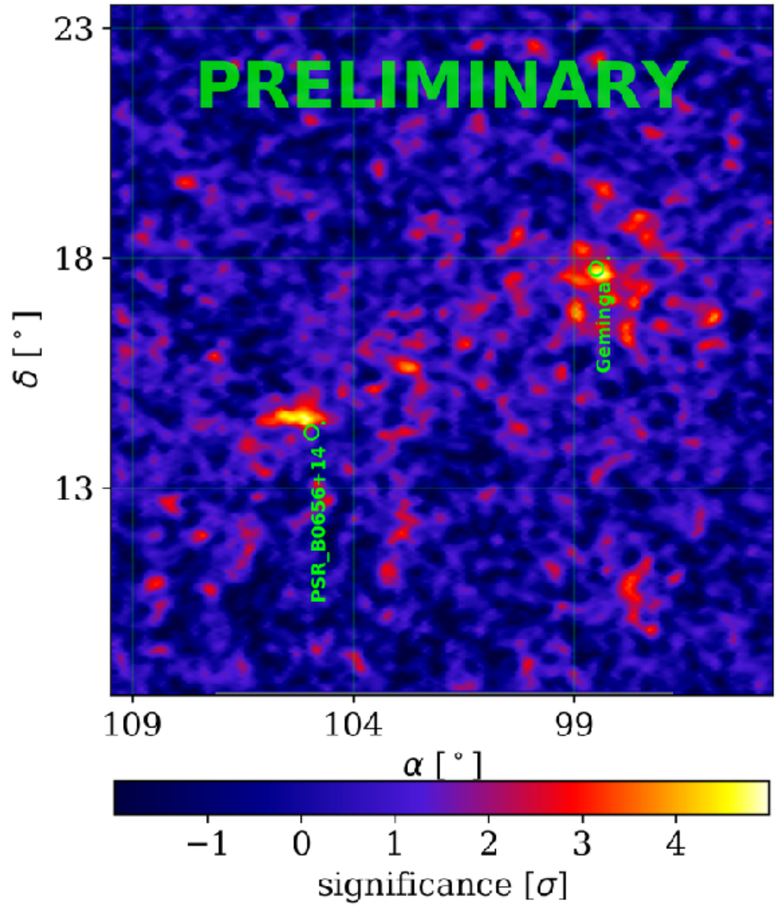
Reconstructed energy > 1 TeV



1039 days of HAWC data using new energy estimator

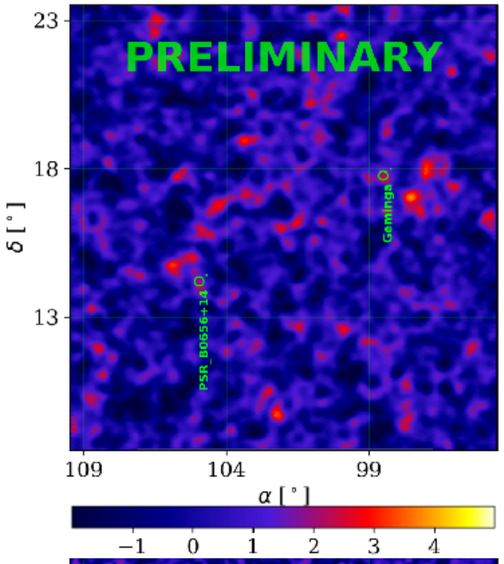
HAWC Observation with 3y Data

Reconstructed energy > 1 TeV

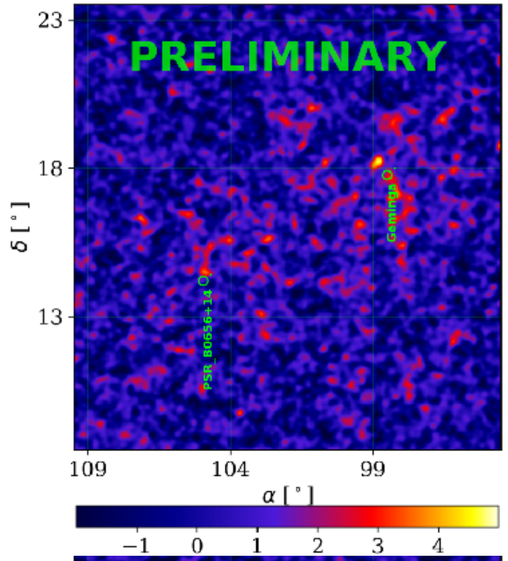


1039 days of HAWC data using new energy estimator

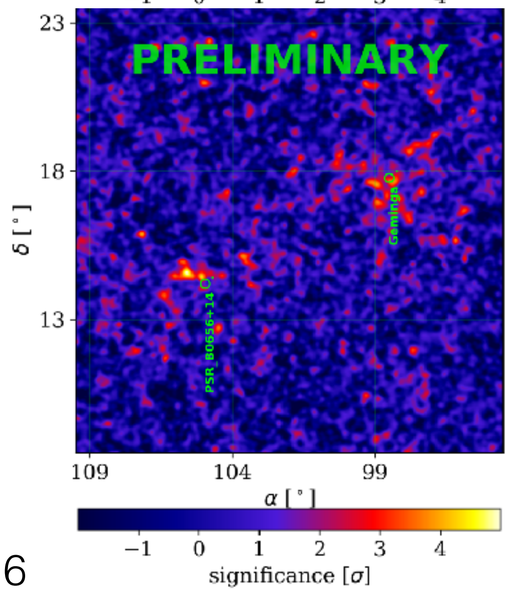
1 TeV < E < 5.6 TeV



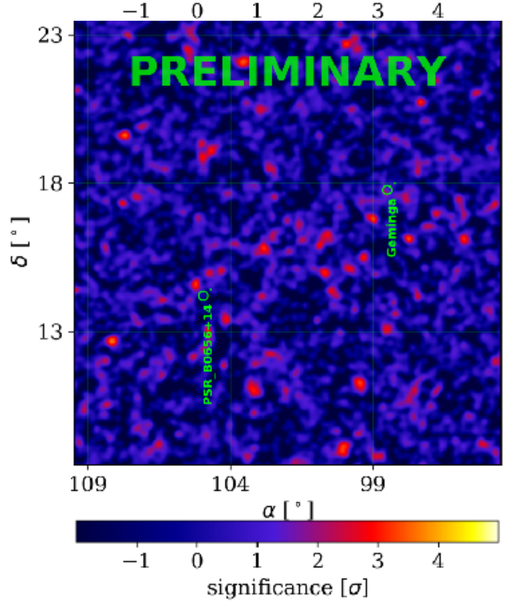
5.6 TeV < E < 17 TeV



17 TeV < E < 56 TeV

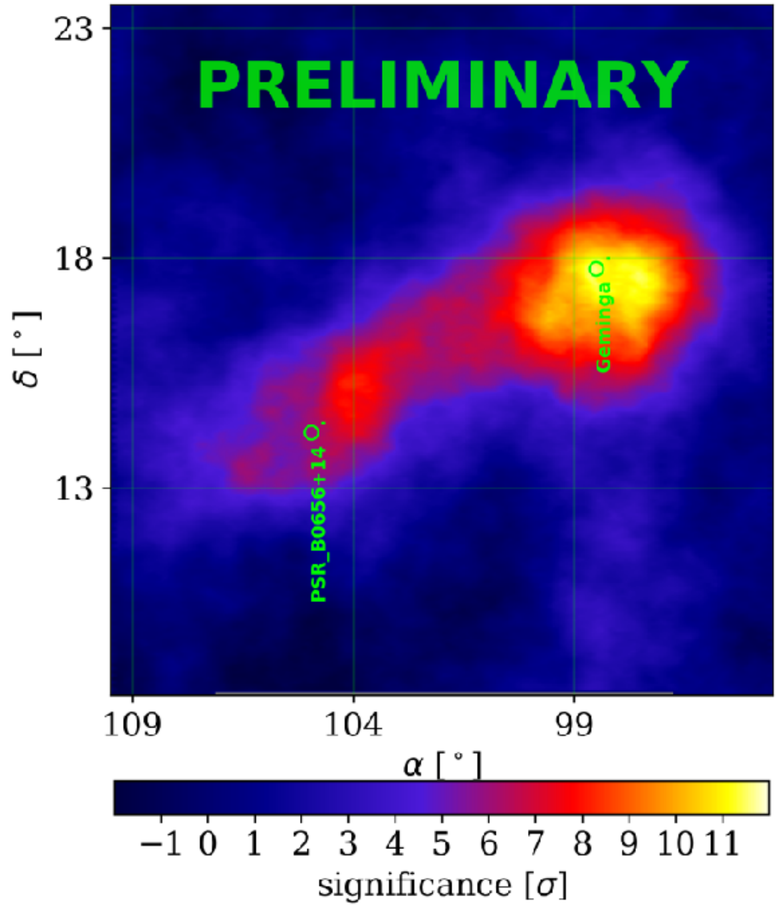


E > 56 TeV



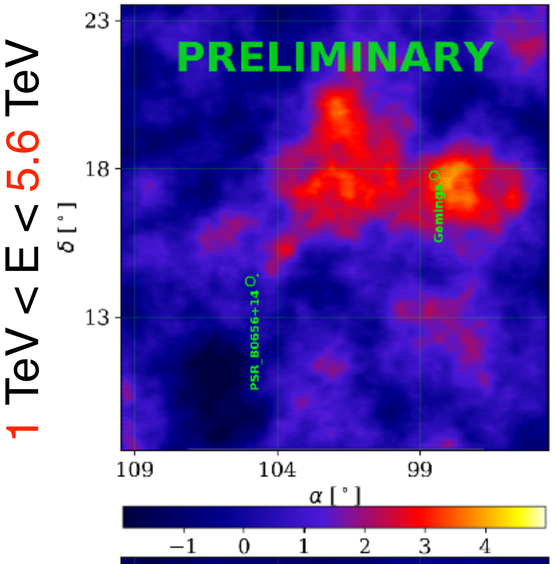
With Additional Smoothing

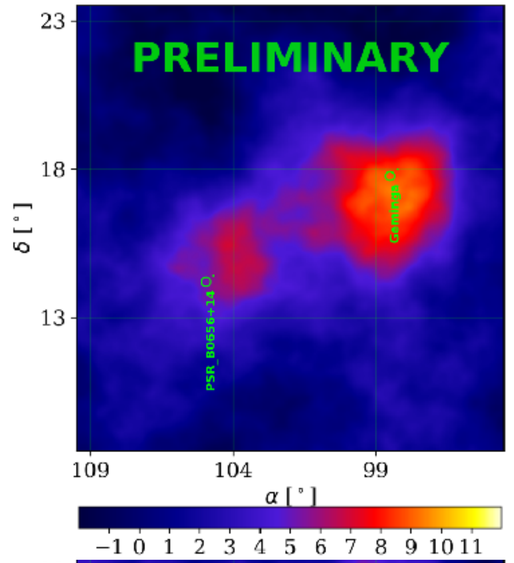
Reconstructed energy > 1 TeV



1039 days of HAWC data using new energy estimator

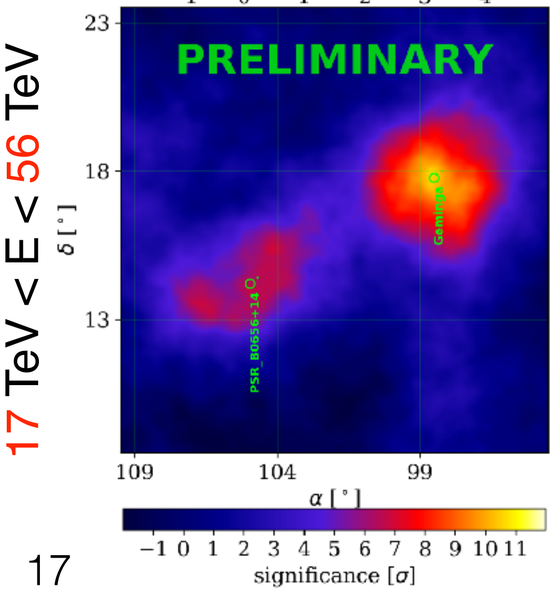
1 TeV < E < 5.6 TeV

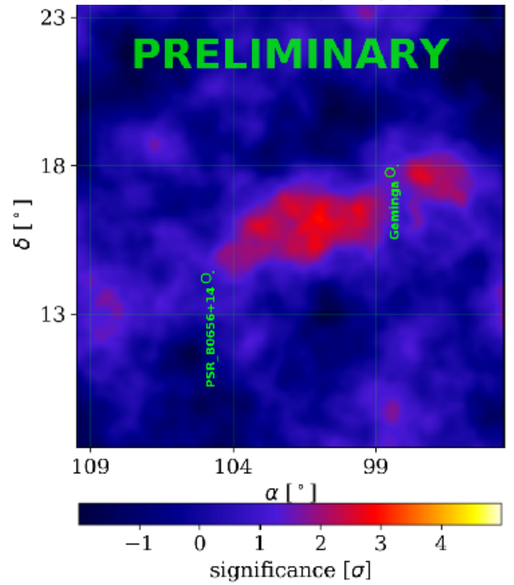




5.6 TeV < E < 17 TeV

17 TeV < E < 56 TeV

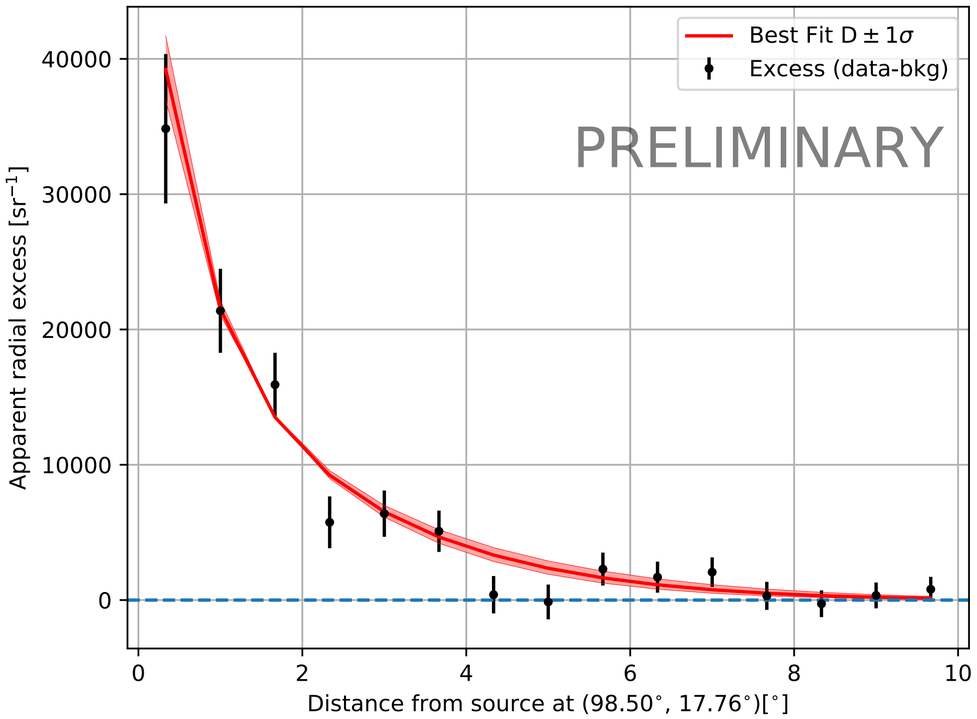


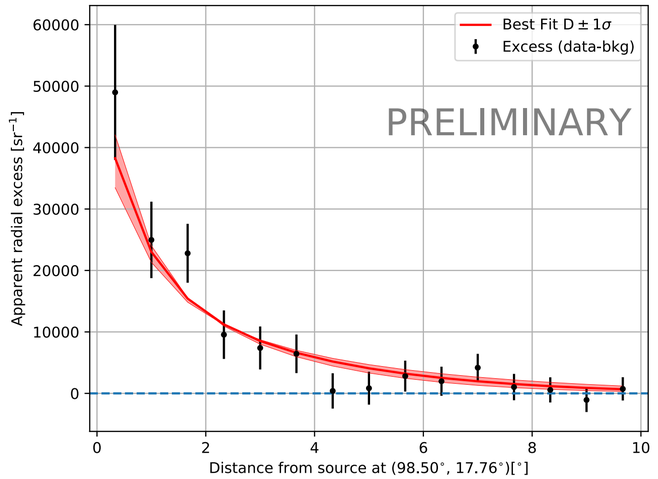


E > 56 TeV

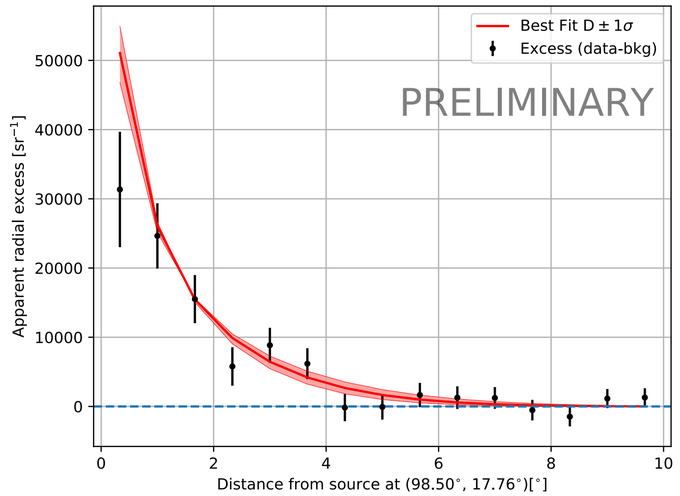
Radial Profiles of Geminga

Reconstructed energy > 1 TeV





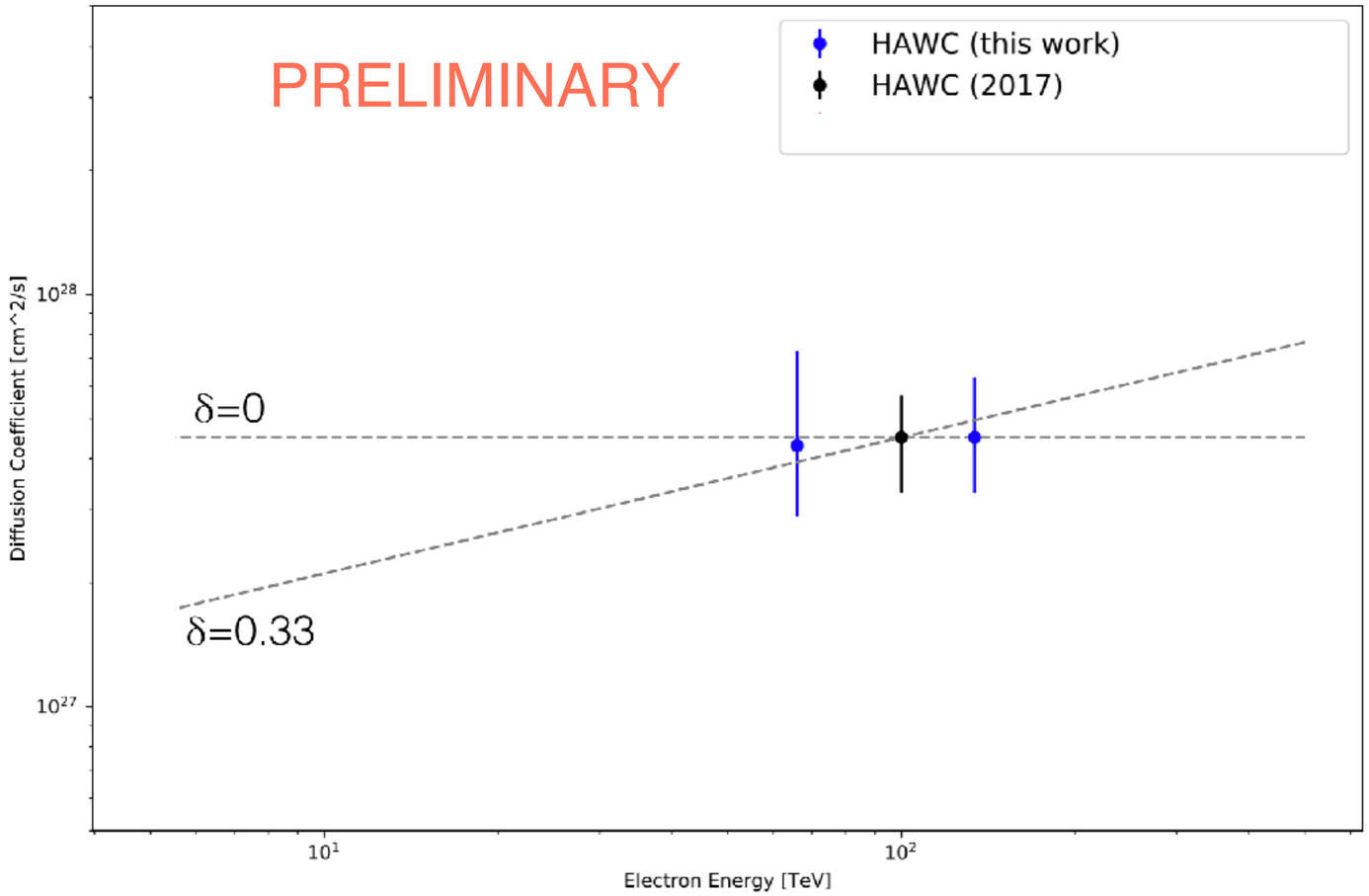
5.6 TeV < E < 17 TeV



17 TeV < E < 56 TeV

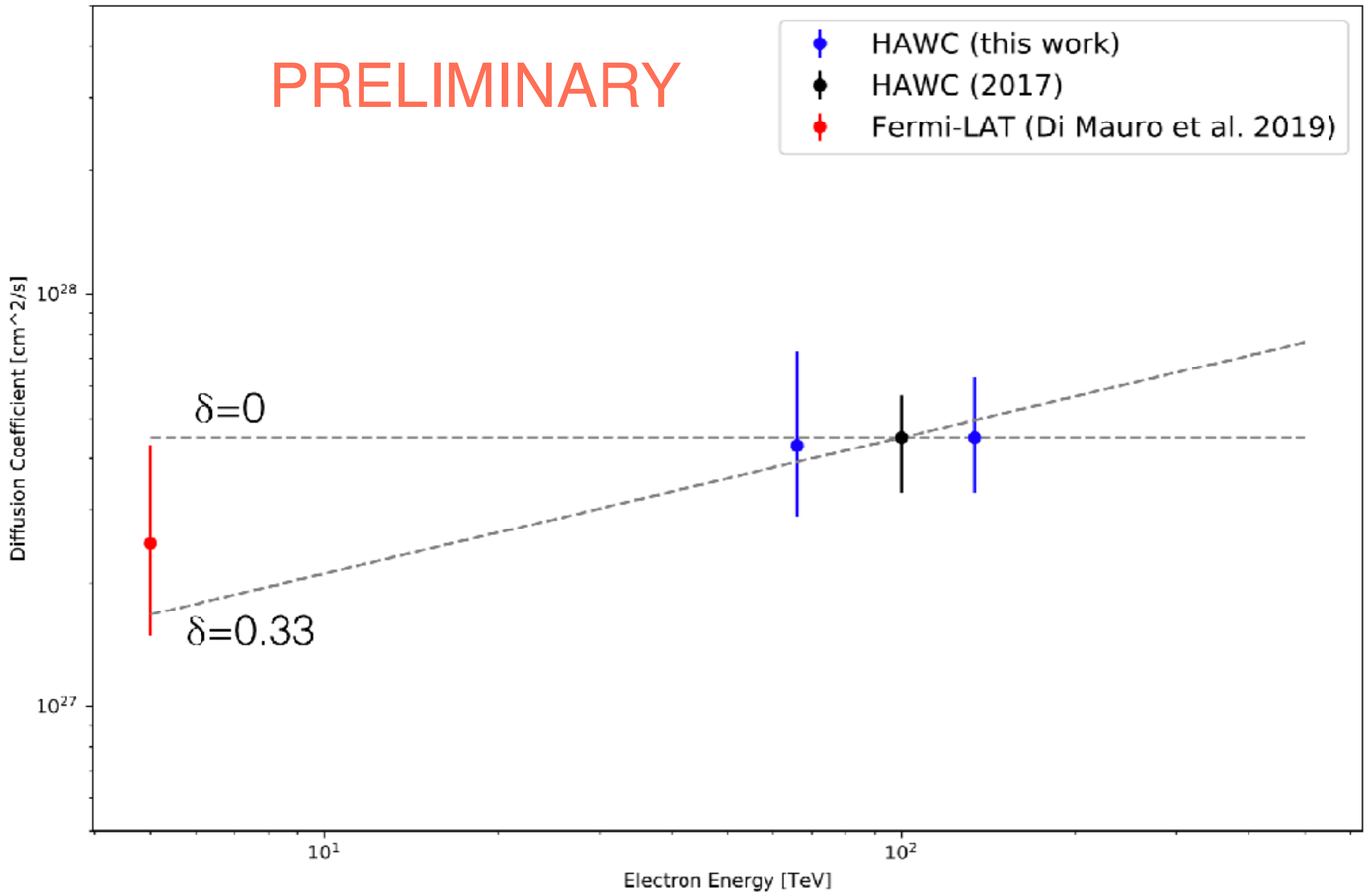
The gamma-ray emission around Geminga is significantly detected in two mid-energy bins.

Energy-Dependent Diffusion



- Current data yet provide good constraint on the diffusion index.

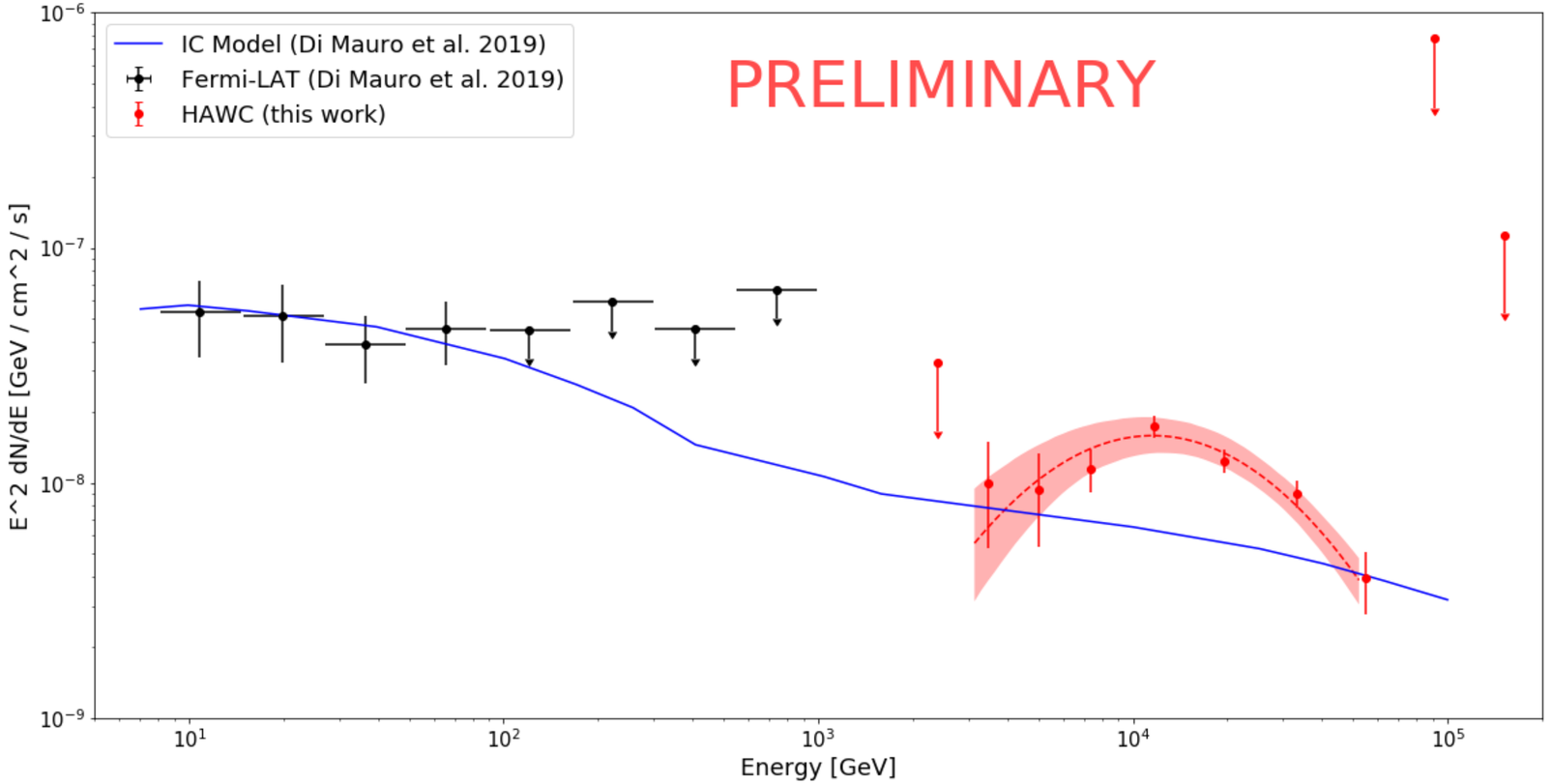
Energy-Dependent Diffusion



- Current data yet provide good constraint on the diffusion index.
- More data and multi-wavelength studies are the key.

Di Mauro et al. (2019) https://arxiv.org/pdf/1903.05647.pdf

Multi-Instrument Spectrum



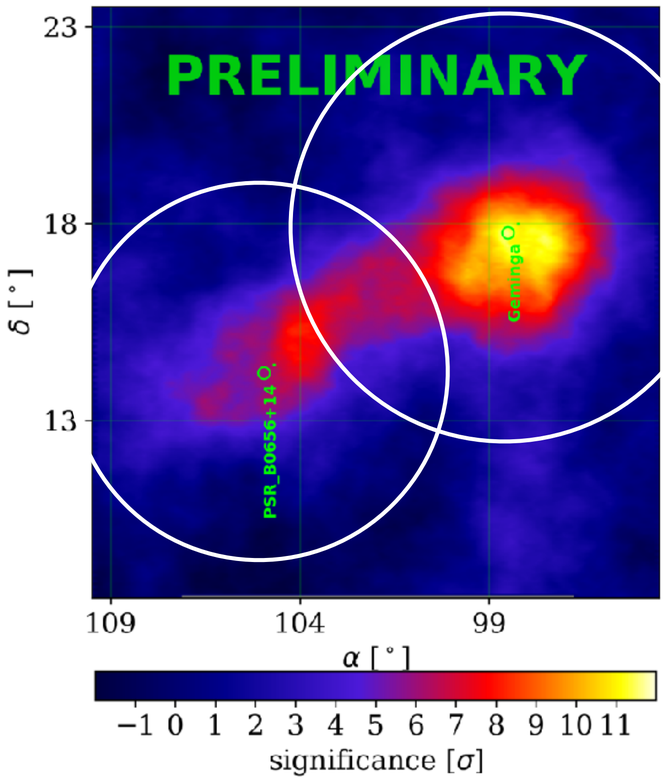
Possible explanations for the double-humped distribution

- Very hard electron spectrum?
- Target photon field?
- Time-dependent particle injection?
- Second population of electron/positron?

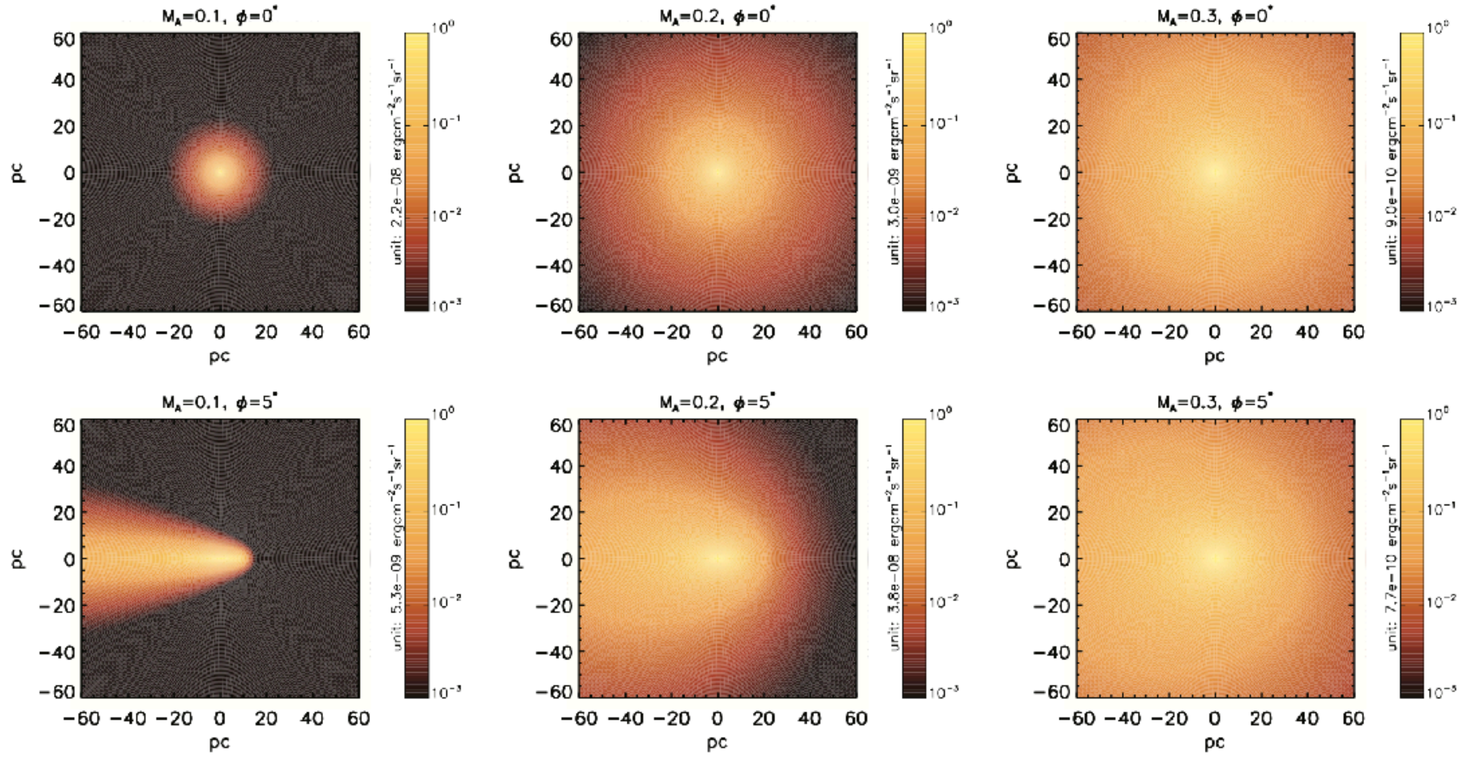
Di Mauro et al. (2019) https://arxiv.org/pdf/1903.05647.pdf

Anisotropic Diffusion?

Data



Simulations

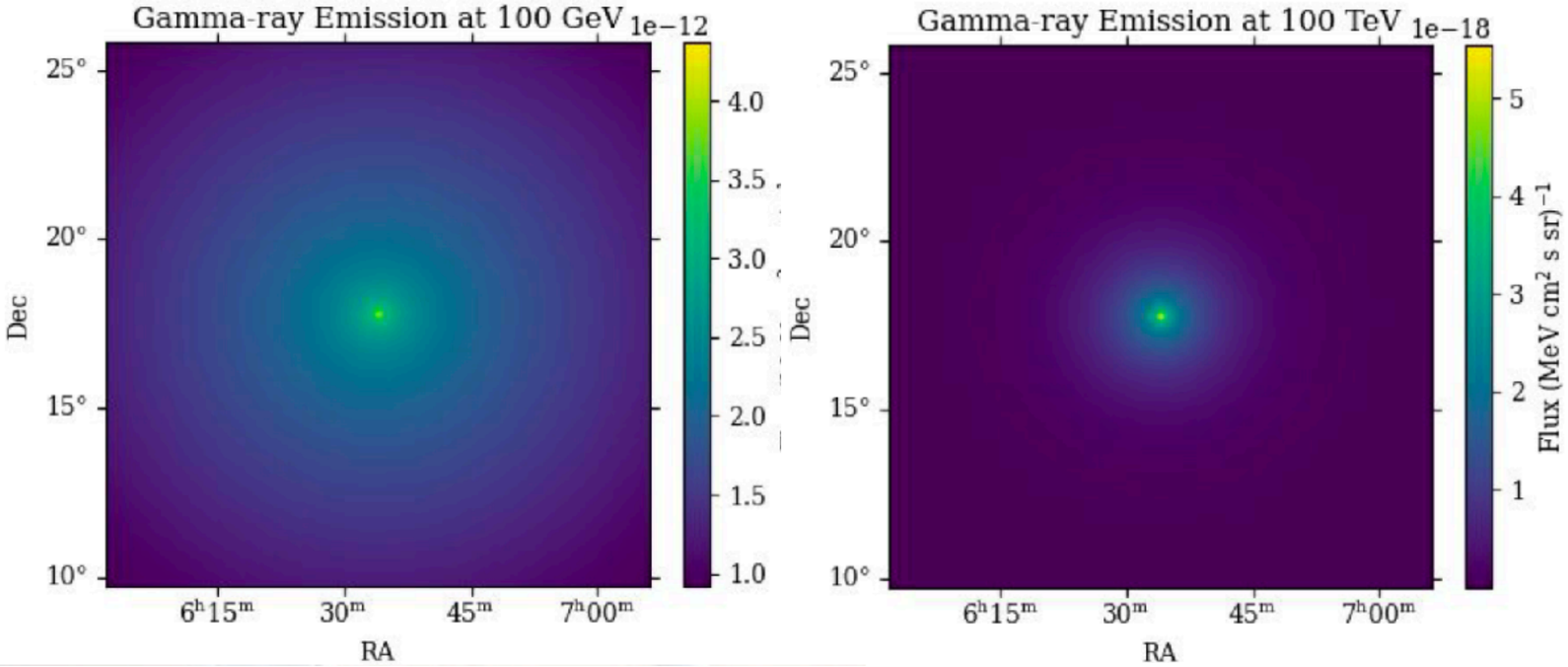


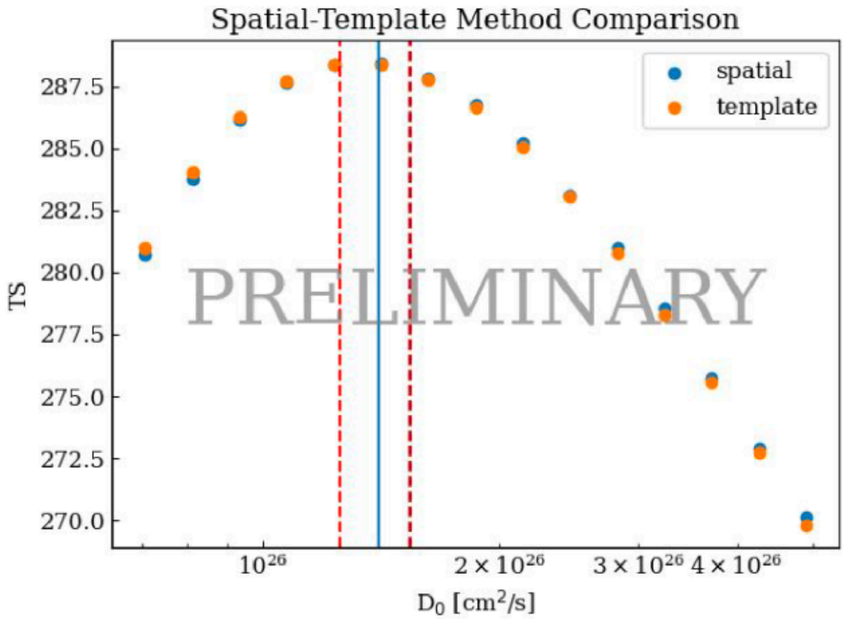
Gamma-ray morphologies with different viewing angle and M_A.

Liu, Yan & Zhang, Physical Review Letters 123 (22), 2019

Courtesy of Dr. Ruoyu Liu

Spatial Template Fit





- physical models used to estimate the gamma-ray emission from electron inverse Compton scatterings
- able to incorporate proper motion, asymmetric diffusion or other non-analytical templates
- interpolations used to fit physical parameters directly

For more details,
see Ramiro Torres' poster

Questions about Diffusion Remain

Geminga

Monogem

- How does diffusion depend on energy?
- How big are the low-diffusion regions? Are they generated from the pulsars or property of ISM?

Other TeV halos?
See Kelly Malone's talk

Why are TeV Halos interesting?

- Might contribute significantly to TeV source population and to Galactic diffuse emission.
- As probes into the cosmic ray propagation far away from the earth.
- More TeV halo detections are anticipated with future data from HAWC and LHAASO (and CTA and SWGO).

#	NAME		Gl (deg)	Gb (deg)	RAJD (deg)	DECJD (deg)	DIST (kpc)	AGE (Yr)	EDOT (ergs/s)	C1 EDOT/DIST^2
1	B1055-52	vl72	285.984	6.649	164.49602	-52.44898	0.09	5.35e+05	3.0e+34	3.7037e+36
2	J0633+1746	hh92	195.134	4.266	98.47564	17.77025	0.19	3.42e+05	3.2e+34	8.8643e+35
3	B0906-49	dmd+88	270.265	-1.019	137.14762	-49.21807	1.00	1.12e+05	4.9e+35	4.9000e+35
4	B0656+14	mlt+78	201.108	8.258	104.95082	14.23872	0.29	1.11e+05	3.8e+34	4.5184e+35
5	B1951+32	kcb+88	68.765	2.823	298.24252	32.87792	3.00	1.07e+05	3.7e+36	4.1111e+35
6	J1732-3131	aaa+09c	356.307	1.007	263.13975	-31.52306	0.64	1.11e+05	1.5e+35	3.6621e+35
7	B1742-30	kac+73	358.553	-0.963	266.48464	-30.67311	0.20	5.46e+05	8.5e+33	2.1250e+35
8	J1740+1000	mca00	34.011	20.268	265.10813	10.00175	1.23	1.14e+05	2.3e+35	1.5203e+35
9	J1913+1011	mhl+02	44.485	-0.167	288.33475	10.18971	4.61	1.69e+05	2.9e+36	1.3646e+35
10	J1000-5149	kbm+03	278.107	2.603	150.11725	-51.83281	0.13	4.22e+06	2.3e+33	1.3609e+35
11	J1105-4353	bbb+12	283.486	14.947	166.35350	-43.88472	0.13	2.23e+06	2.3e+33	1.3609e+35
12	J1836+5925	aaa+09c	88.875	24.999	279.05697	59.42504	0.30	1.83e+06	1.1e+34	1.2222e+35
13	B1259-63	jlm+92	304.184	-0.992	195.69849	-63.83573	2.63	3.32e+05	8.3e+35	1.2000e+35
14	J1741-2054	aaa+09c	6.422	4.907	265.48867	-20.90328	0.30	3.86e+05	9.5e+33	1.0556e+35
15	J0954-5430	mlc+01	278.999	-0.101	148.52517	-54.51486	0.43	1.71e+05	1.6e+34	8.6533e+34
16	J2032+4127	aaa+09c	80.224	1.028	308.05466	41.45675	1.33	2.01e+05	1.5e+35	8.4798e+34
17	J1755-0903	bbb+12	18.324	8.150	268.79318	-9.06433	0.23	3.87e+06	4.4e+33	8.3176e+34
18	J1831-0952	lfl+06	21.897	-0.128	277.89293	-9.86714	3.68	1.28e+05	1.1e+36	8.1226e+34
19	J1151-6108	ncb+15	295.814	0.909	177.98692	-61.13822	2.22	1.57e+05	3.9e+35	7.9133e+34
20	B1821-24A	lbm+87	7.797	-5.578	276.13337	-24.86968	5.50	2.99e+07	2.2e+36	7.2727e+34