

Extended
**Observing Galactic Sources
with the HAWC Observatory**

Hao Zhou (LANL) for the HAWC Collaboration

- Transients

- TeV Binaries
- Flairs

- Highest energy accelerators

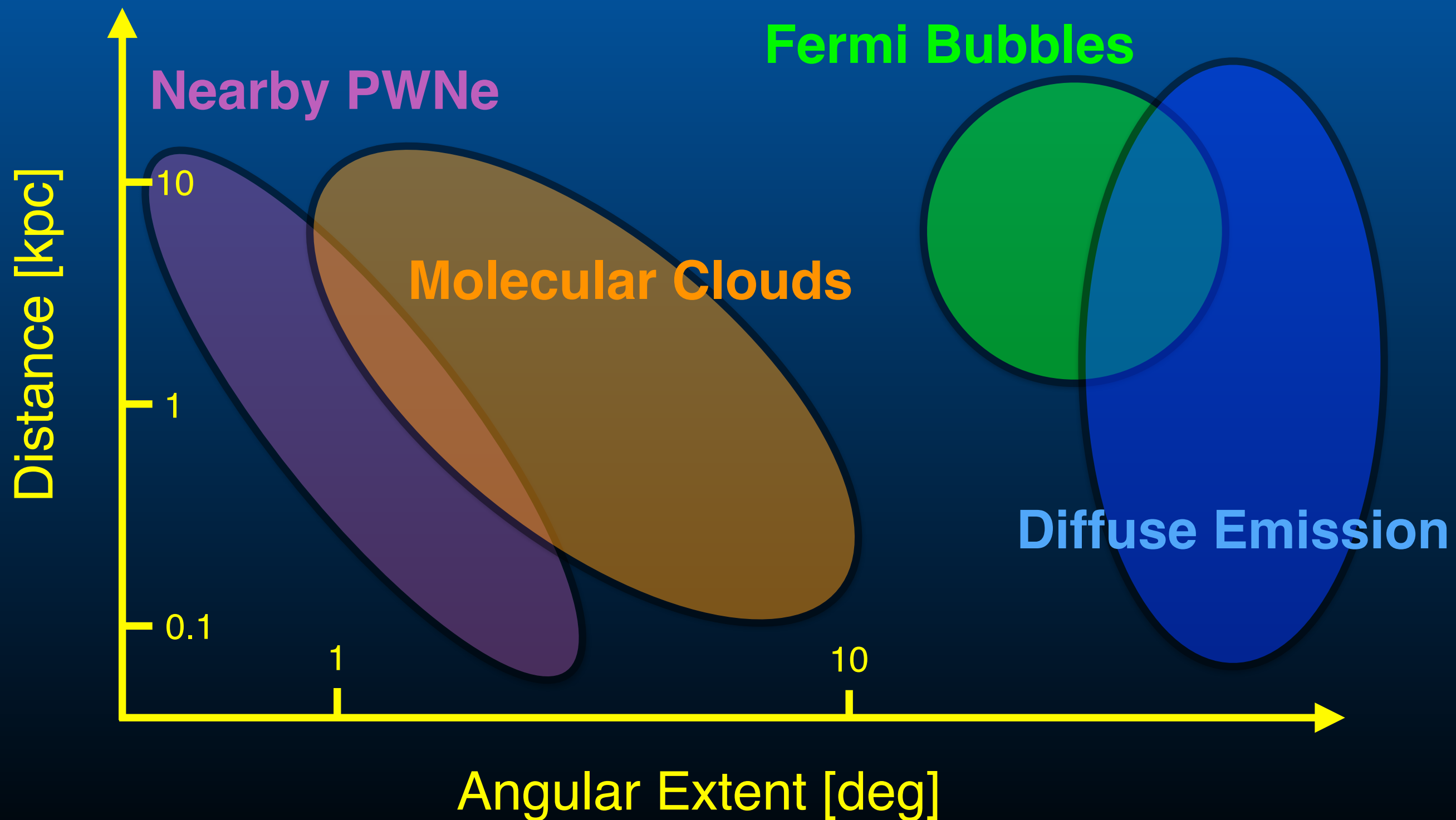
- Extended emission

- Diffuse emission
- Fermi bubbles
- Molecular clouds
- Nearby PWNe
- SNRs

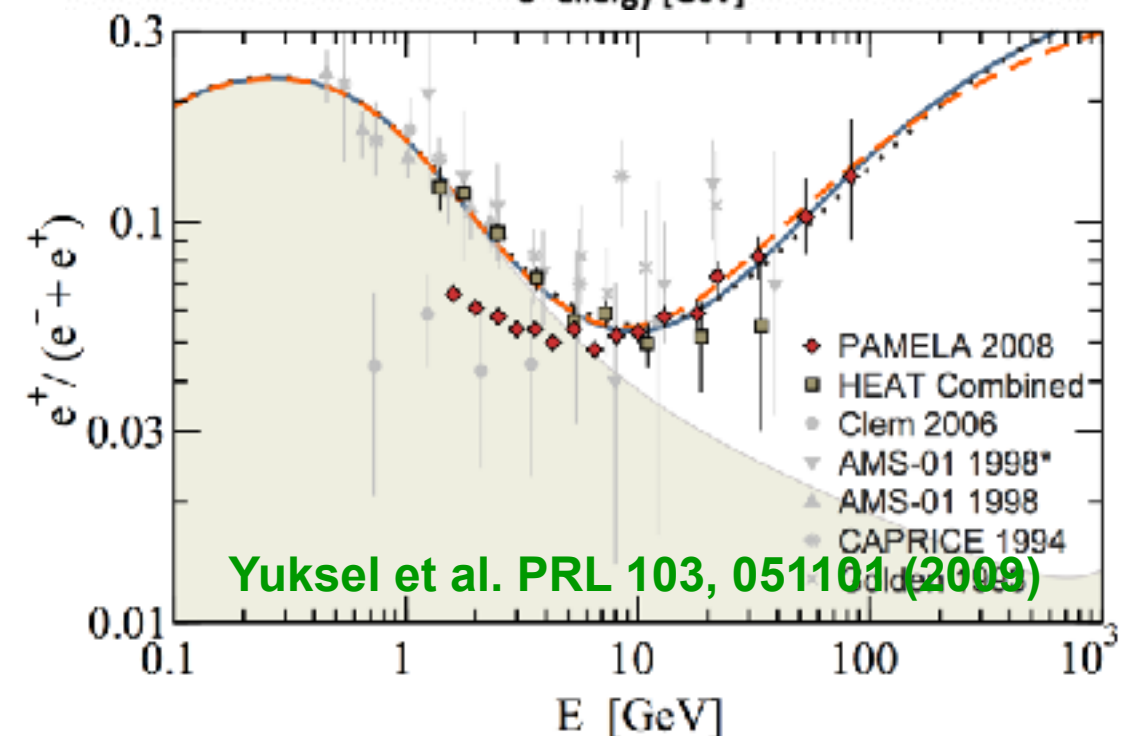
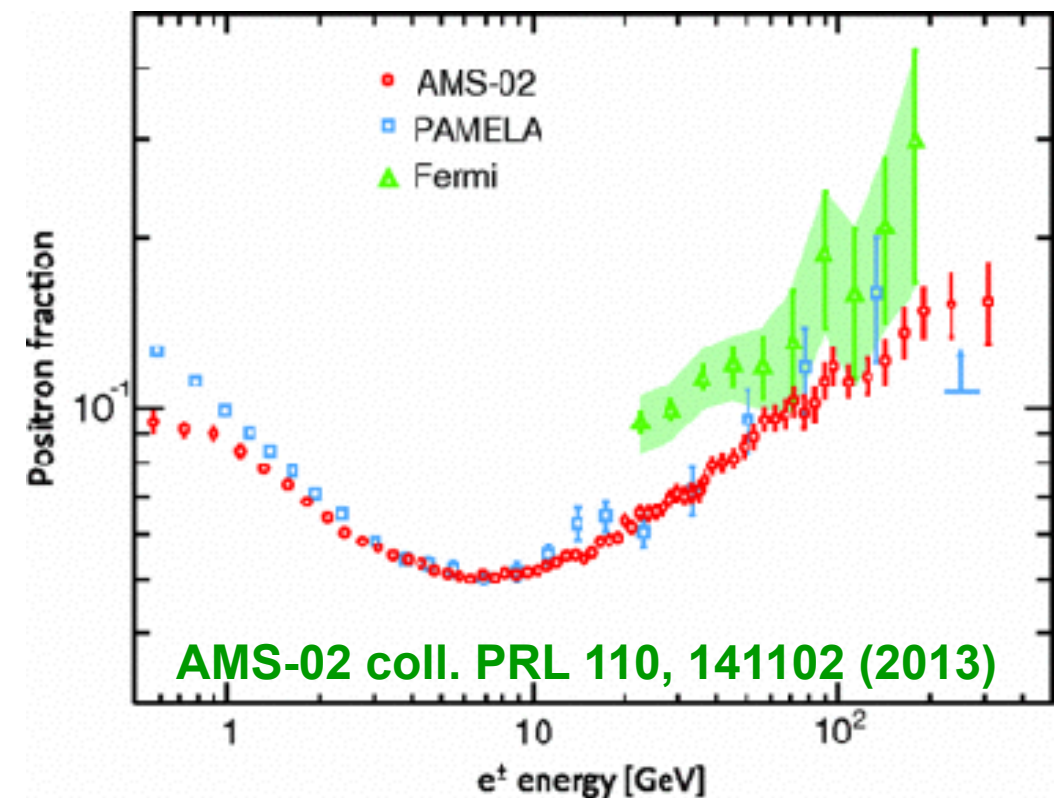
- High Duty Cycle

- High energy reach

- Wide field of view and angular resolution (1° - 0.2° , 68% cont.)



- Positron excess > 10 GeV indicates nearby source(s) of $e^\pm$
- **Nearby middle-aged pulsars**
 - old and close enough that $e^\pm$ could make to the earth
 - young enough that it is still energetic
- $e^\pm$ accelerated from these sources could contribute to the local $e^\pm$ flux.
 - **how many $e^\pm$ are accelerated?**
 - **how fast do they diffuse to the Earth?**



List of Nearby Middle-aged Pulsars

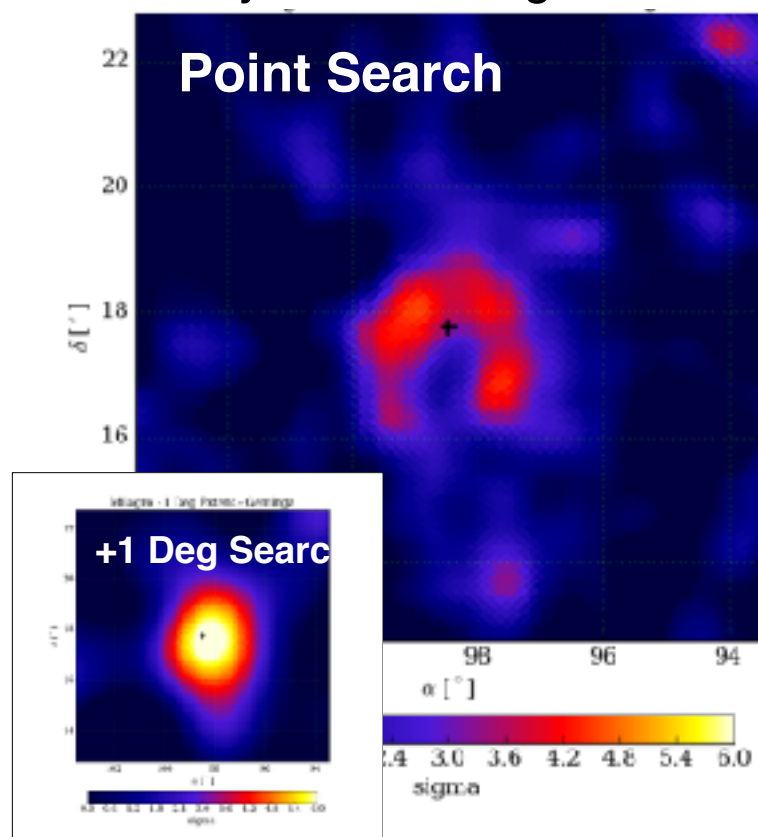
- A short list of candidates that meet the criteria of nearby and middle-aged.
- Two of them are in the sky region that HAWC has good sensitivity on.
 - Geminga and PSR B0656+14

#	NAME		G1 (deg)	Gb (deg)	RAJD (deg)	DECJD (deg)	DIST (kpc)	AGE (Yr)	EDOT (ergs/s)	C1 EDOT/DIST ²
1	B1055-52	v172	285.98	6.65	164.49569	-52.44896	0.09	5.35e+05	3.0e+34	3.7037e+36
2	J0633+1746	hh92	195.13	4.27	98.47564	17.77025	0.25	3.42e+05	3.2e+34	5.1200e+35
3	B0656+14	mlt+78	201.11	8.26	104.95056	14.23931	0.29	1.11e+05	3.8e+34	4.5184e+35
4	J1732-3131	aaa+09c	356.31	1.01	263.13975	-31.52306	0.64	1.11e+05	1.5e+35	3.6621e+35
5	B1001-47	mlt+78	276.04	6.12	150.83992	-47.78389	0.37	2.2e+05	3.0e+34	2.1914e+35
6	B1742-30	kac+73	358.55	-0.96	266.48460	-30.67319	0.20	5.46e+05	8.5e+33	2.1250e+35
7	J1000-5149	kbm+03	278.11	2.60	150.11725	-51.83281	0.13	4.22e+06	2.3e+33	1.3609e+35
8	J1741-2054	aaa+09c	6.43	4.91	265.48846	-20.89917	0.30	3.86e+05	9.5e+33	1.0556e+35
9	J0954-5430	mlc+01	279.00	-0.10	148.52517	-54.51486	0.43	1.71e+05	1.6e+34	8.6533e+34
10	J1755-0903	bbb+12	18.32	8.15	268.79318	-9.06433	0.23	3.87e+06	4.4e+33	8.3176e+34

ATNF Pulsar Catalog <http://www.atnf.csiro.au/people/>

Previous Observations

8 years of Milagro Data

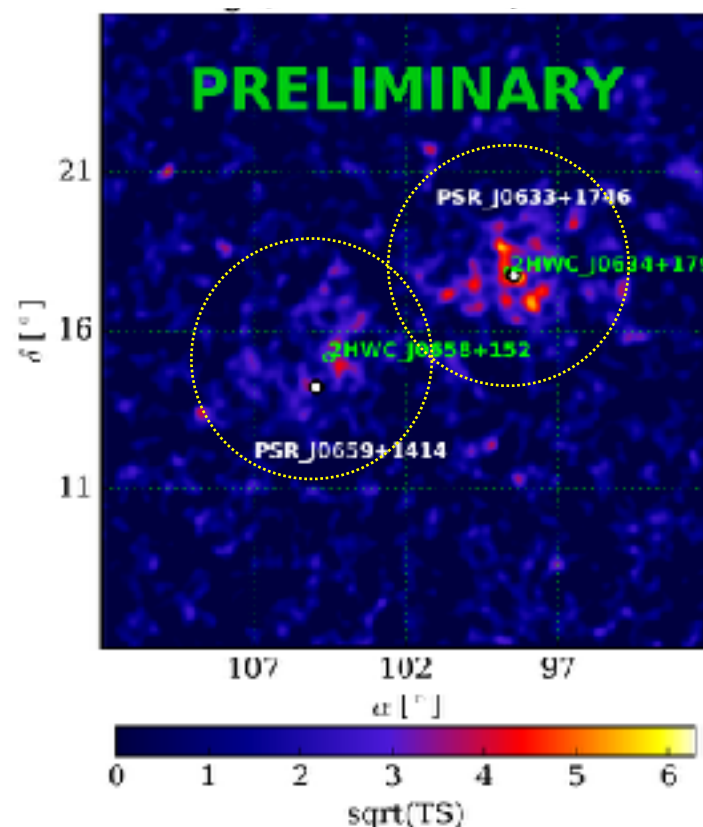


- **Geminga**
 - nearby middle-aged pulsar
 - significance: $\sim 6\sigma$ with $+1^\circ$ smoothing
 - size: $\sim 2.6^\circ$ in diameter
 - IACTs only set upper limits by far
- **PSR B0656+14 (Monogem)**
 - similar characteristics as Geminga pulsar
 - no TeV emission detected previously

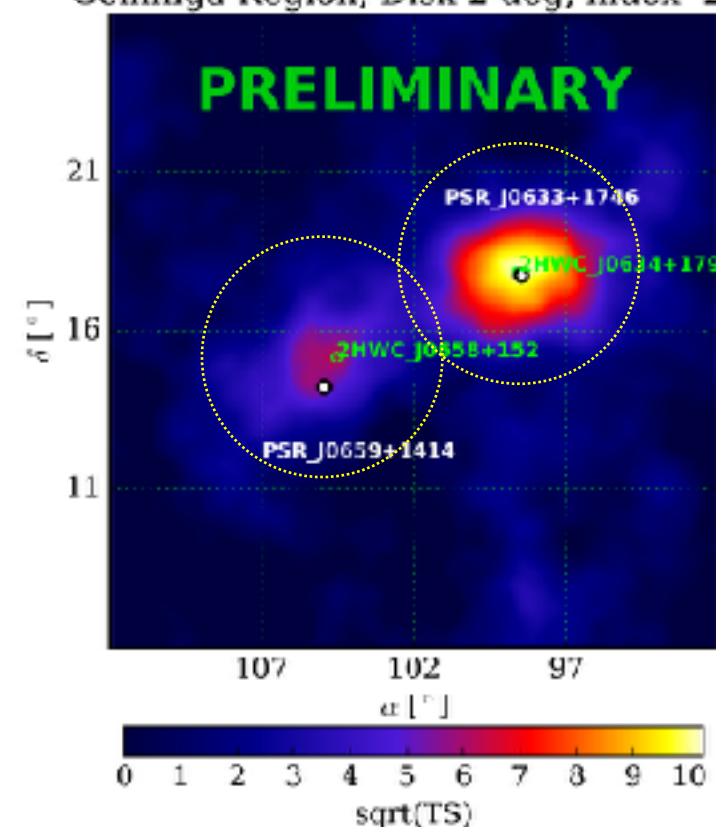
Two Extended TeV Sources

- Gamma-rays sources coincident with Geminga and B0656+14 pulsars were reported in the 2HWC catalog [[HAWC coll. ApJ 843:40 \(2017\)](#)].
- Extended TeV gamma-ray emission from PSR B0656+14 is a new discovery by HAWC.
- Both sources show an increase in significance for an extended morphology assumption.
- The gamma-ray measurement of both sources can constrain the positron flux from them.

Point source search



+2° Top-hat smoothing



Electron Diffusion Model

- We assume a model where e^+e^- pairs diffuse into the ISM around the pulsar.
- The **radial distribution of e^+e^-** , at a given time t , distance r from the source is:

[Atoyan et al. Phys. Rev. D52, 3265 (1995)]

Continuous injection of e^+e^-

$$f(t, r, E_e) = \frac{Q_0 E_e^{-\Gamma}}{4\pi D(E_e) r} \text{erfc}(r/r_d)$$

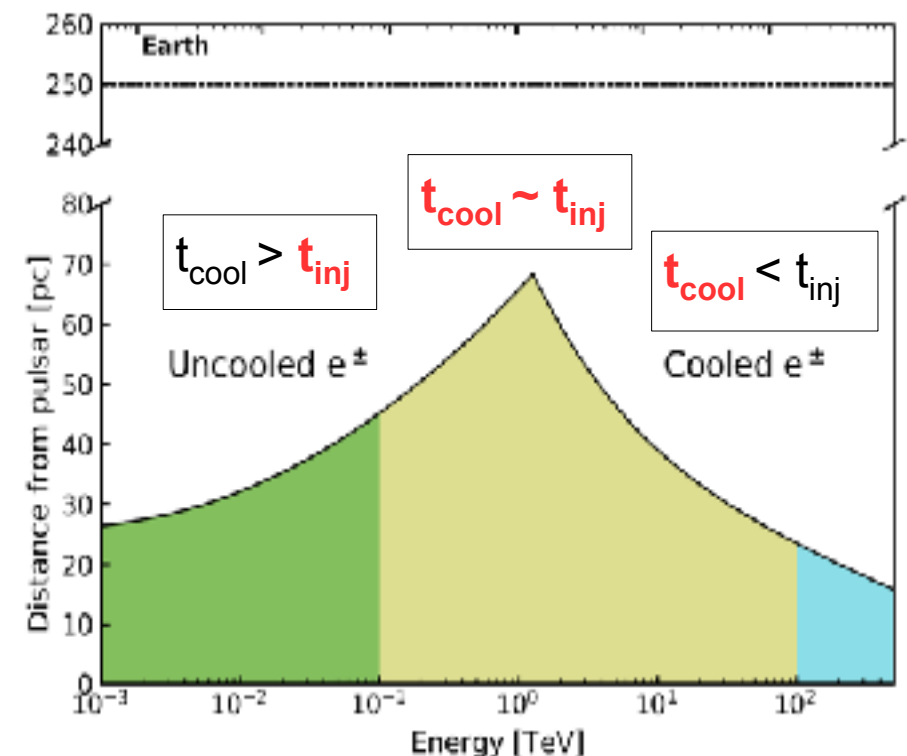
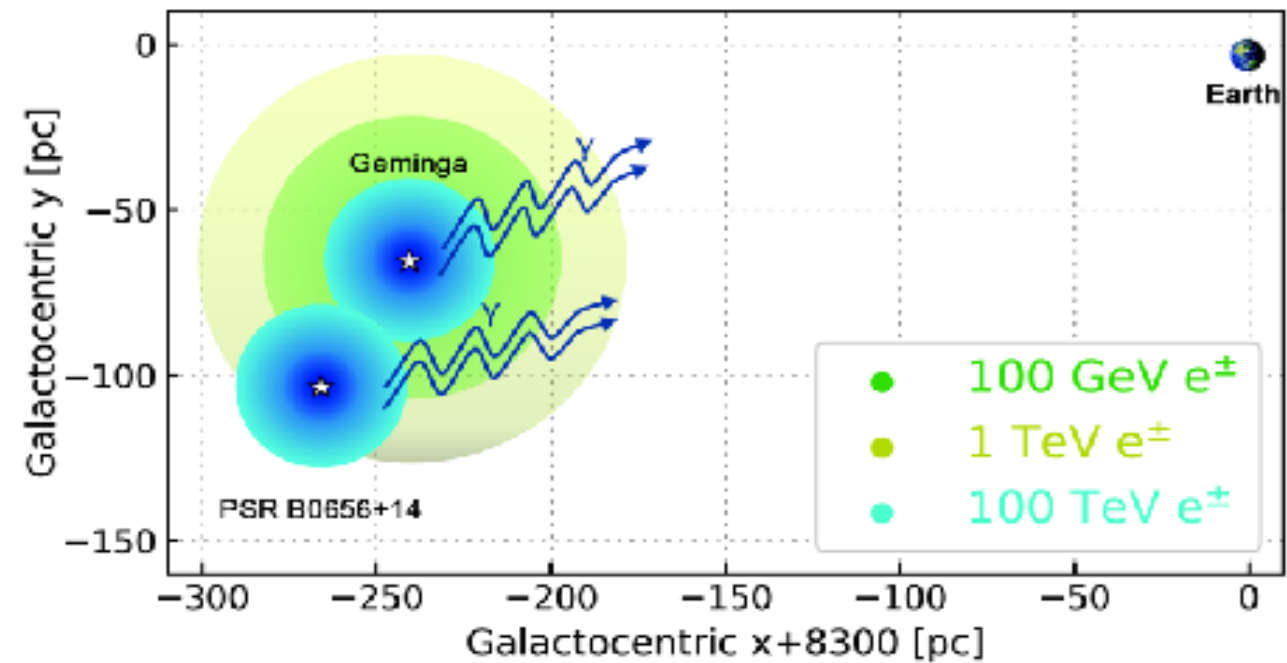
$$D(E_e) = D_0 (E_e/10 \text{ GeV})^\delta \quad \text{Diffusion coefficient}$$

$$r_d = 2\sqrt{D(E_e)t_E} \quad \text{Diffusion radius}$$

$$t_E = \min(t_{\text{cool}}, t_{\text{inj}}), \text{ where } t_{\text{inj}} = t_{\text{age}} \sim 3.4 \times 10^5 \text{ yr}$$

$$t_{\text{cool}} = f(E), \text{ for } E=100\text{TeV}, t_{\text{cool}} \sim 10^4 \text{ yr}$$

- We assume diffusion coefficient index (δ) fixed to 0.33



Gamma-Ray Profile

- We assume a model where e^+e^- pairs diffuse into the ISM around the pulsar.

- The **radial dist** time t , distance

[Atoyan et al. Ph

$$f(t, r, E_e) = \frac{Q}{4\pi r^2 D(E_e)}$$

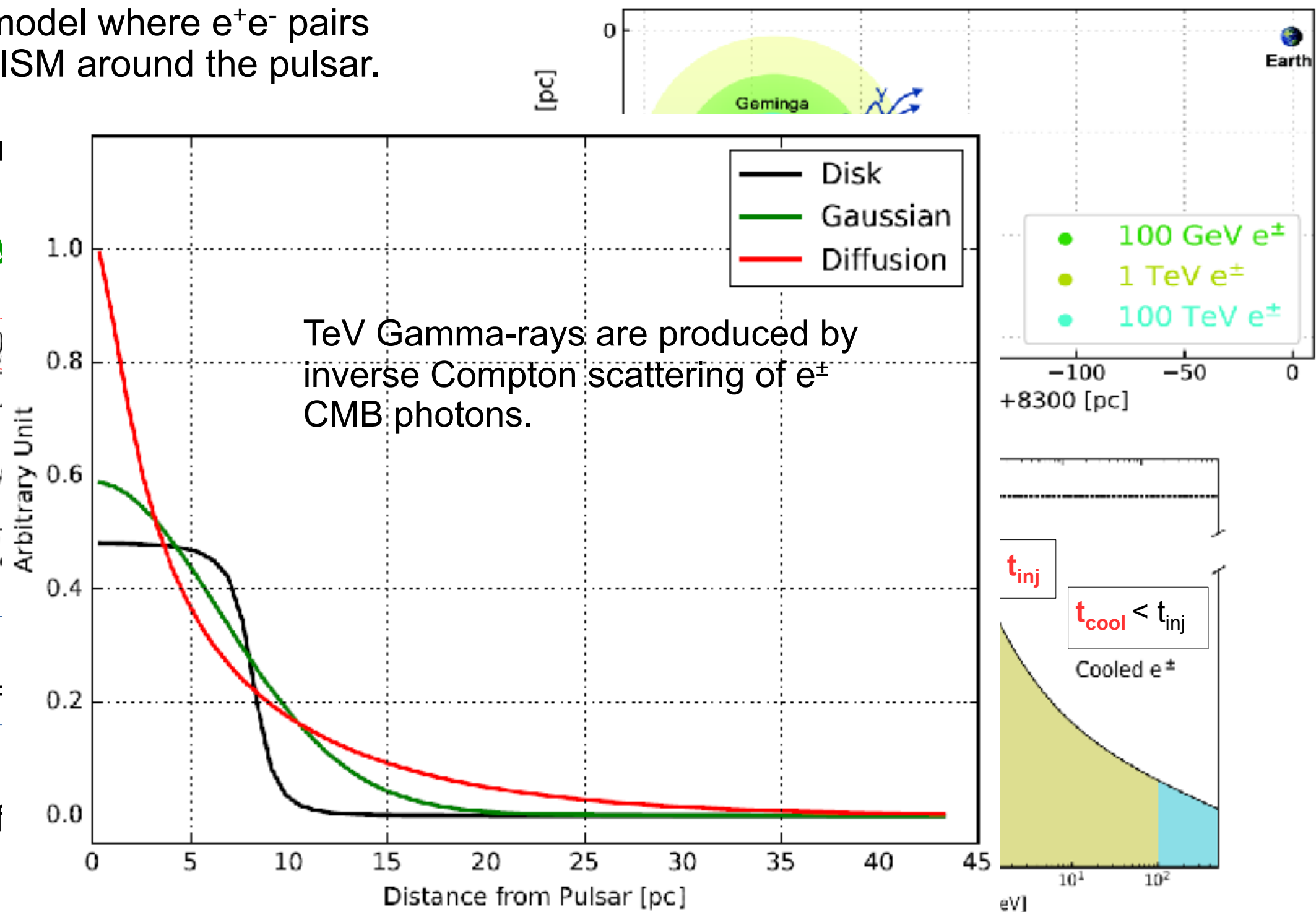
$$D(E_e) = D_0 (E_e / 100 \text{ GeV})^{-\alpha}$$

$$r_d = 2\sqrt{D(E_e) t}$$

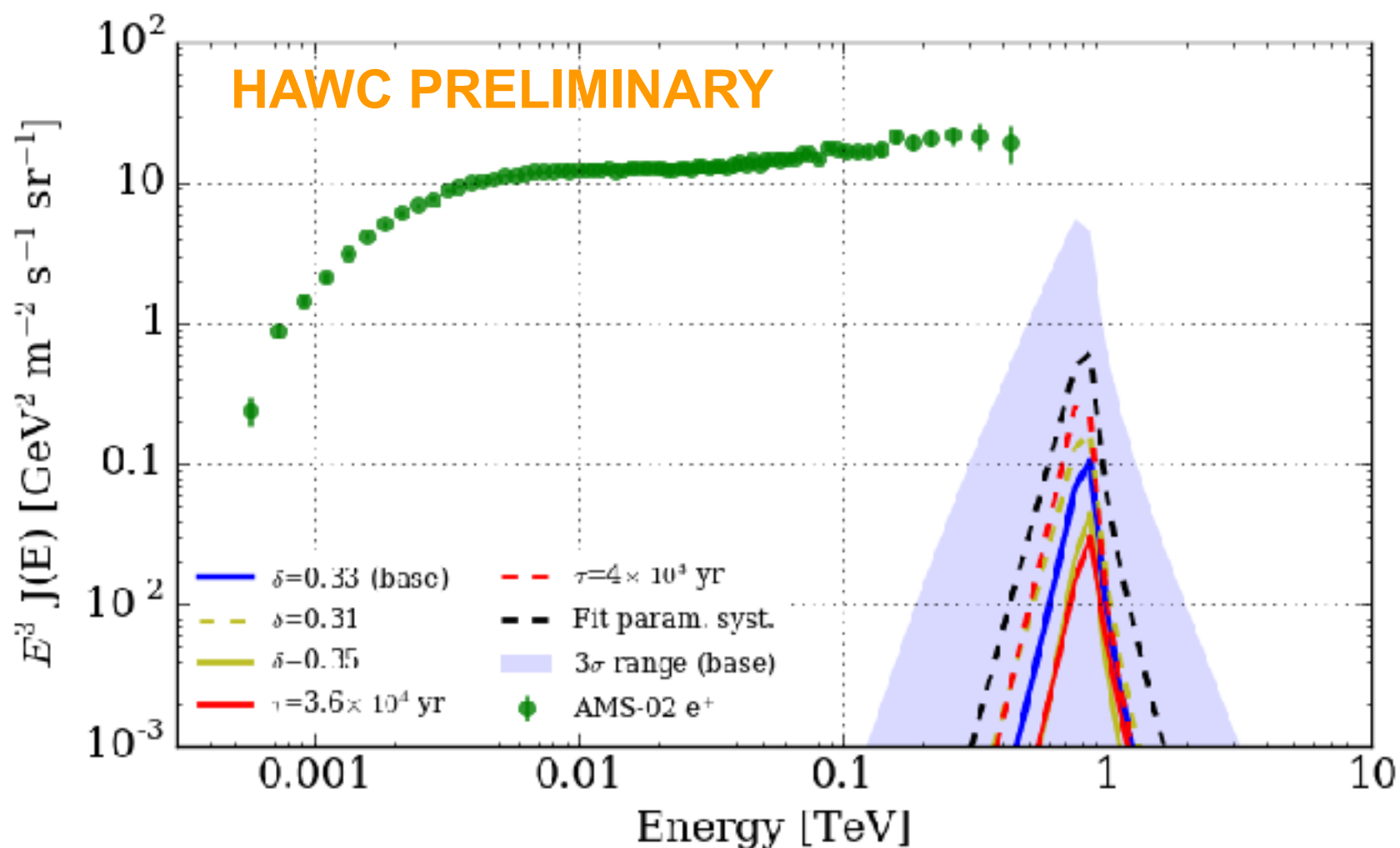
$$t_E = \min(t_{\text{cool}}, t_{\text{inj}})$$

$$t_{\text{cool}} = f(E), \text{ for } E =$$

- We assume dif



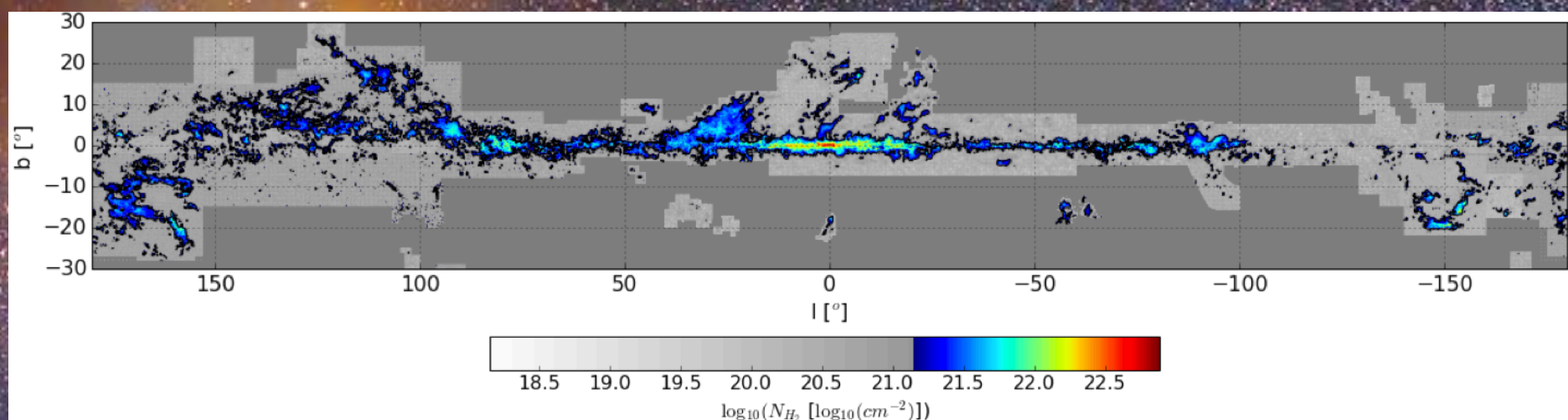
- Maximum likelihood fit to the data on the morphology and spectrum of the source.
- The fitted parameters using HAWC data are used as input to the EDGE code calculating the positron flux from both sources.



AMS-02 points from
PRL 113, 121102 (2014)

Giant Molecular Clouds

- Giant Molecular Clouds (GMCs) are dense concentrations of interstellar gas.
 - Composed mainly of cold, dark dust, and molecular gas.
 - Ideal places for the interaction of cosmic rays with the ambient gas that produces gamma rays.
 - Can probe the flux of cosmic rays in distant galactic regions and compare it with the local measurement



CfA-Chile survey mapping the CO distribution in the galaxy (Dame et al. 2001).

- Assuming that the cosmic-ray flux is the same as the locally measured cosmic-ray flux, the gamma-ray flux can be estimated as (Aharonian, 1990)

$$F_{\gamma} = \begin{cases} 1.45 \times 10^{-13} E_{\text{TeV}}^{-1.75} (M_5/d_{\text{kpc}}^2) \text{ cm}^{-2} \text{ s}^{-1} & 100 \text{ MeV} < E_{\gamma} < 1 \text{ TeV} \\ 2.85 \times 10^{-13} E_{\text{TeV}}^{-1.6} (M_5/d_{\text{kpc}}^2) \text{ cm}^{-2} \text{ s}^{-1} & E_{\gamma} > 1 \text{ TeV} \end{cases}$$

- We look at three GMCs: Aquila Rift, Taurus and Hercules.

GMC	Mass	Distance	Decl. Center	Extension
Aquila Rift	$1.5 \times 10^5 M_{\odot}$ ¹	$225 \pm 55 \text{ pc}$ ²	-7.6°	$< 0.068 \text{ sr}$
Taurus	$0.2 \times 10^5 M_{\odot}$ ³	$135 \pm 20 \text{ pc}$ ⁴	25.8°	$< 0.203 \text{ sr}$
Hercules	$0.5 \times 10^5 M_{\odot}$ *	$200 \pm 30 \text{ pc}$ ⁴	14.7°	$< 0.013 \text{ sr}$

¹Dame et al. ApJ 1987

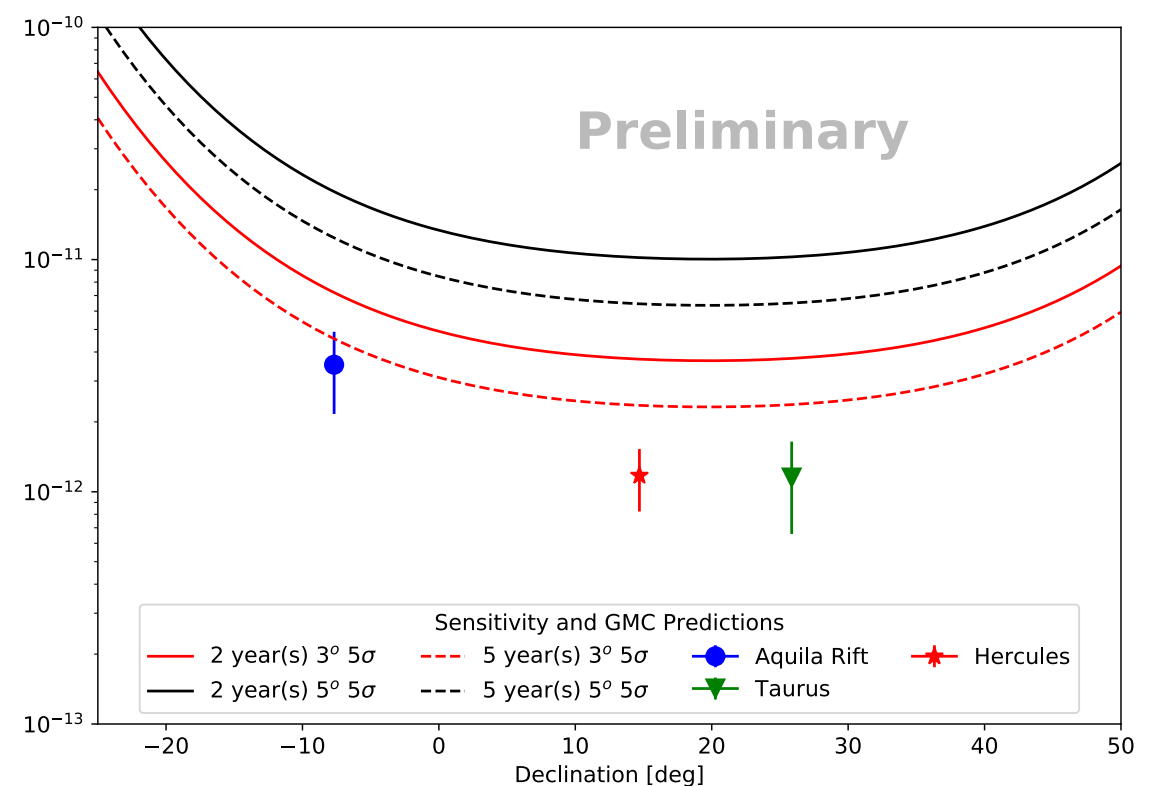
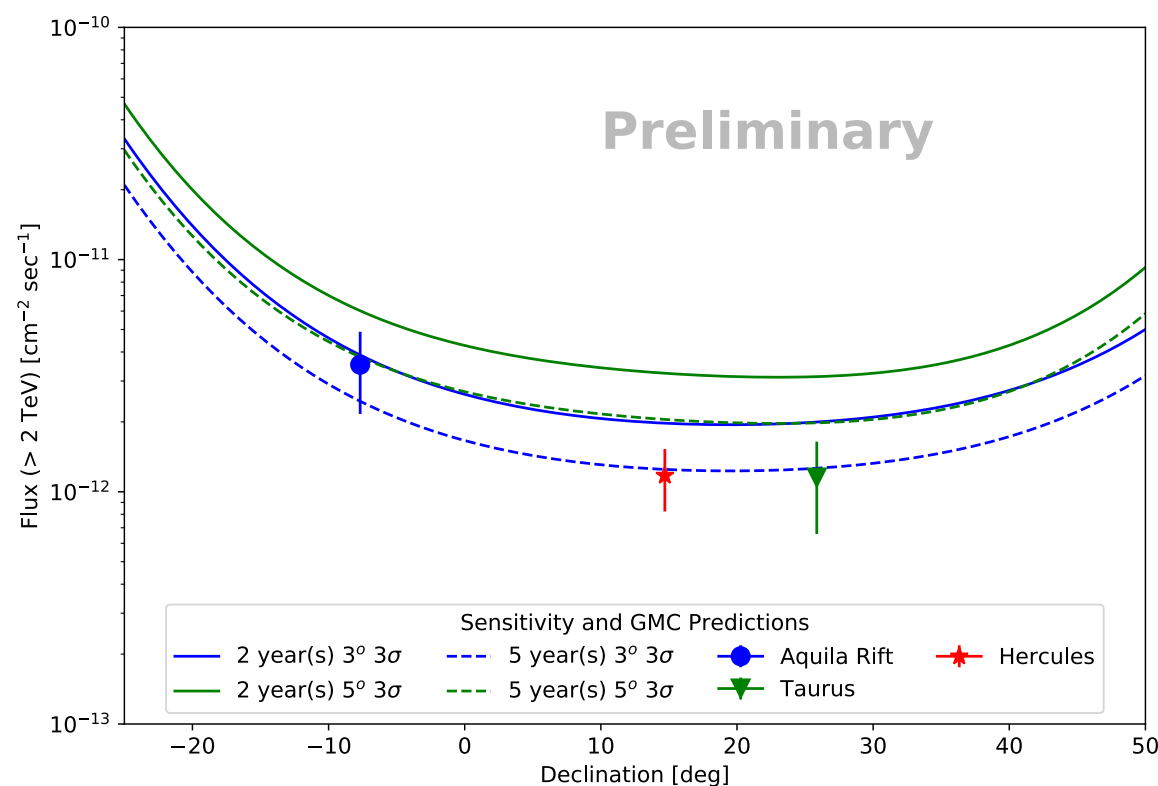
²Straizys, V., et al., A&A 2003

³Kenyon, S. J., et al., AJ 1994

⁴Schlaffly, E., et al. ApJ 2014

*Mass is assumed

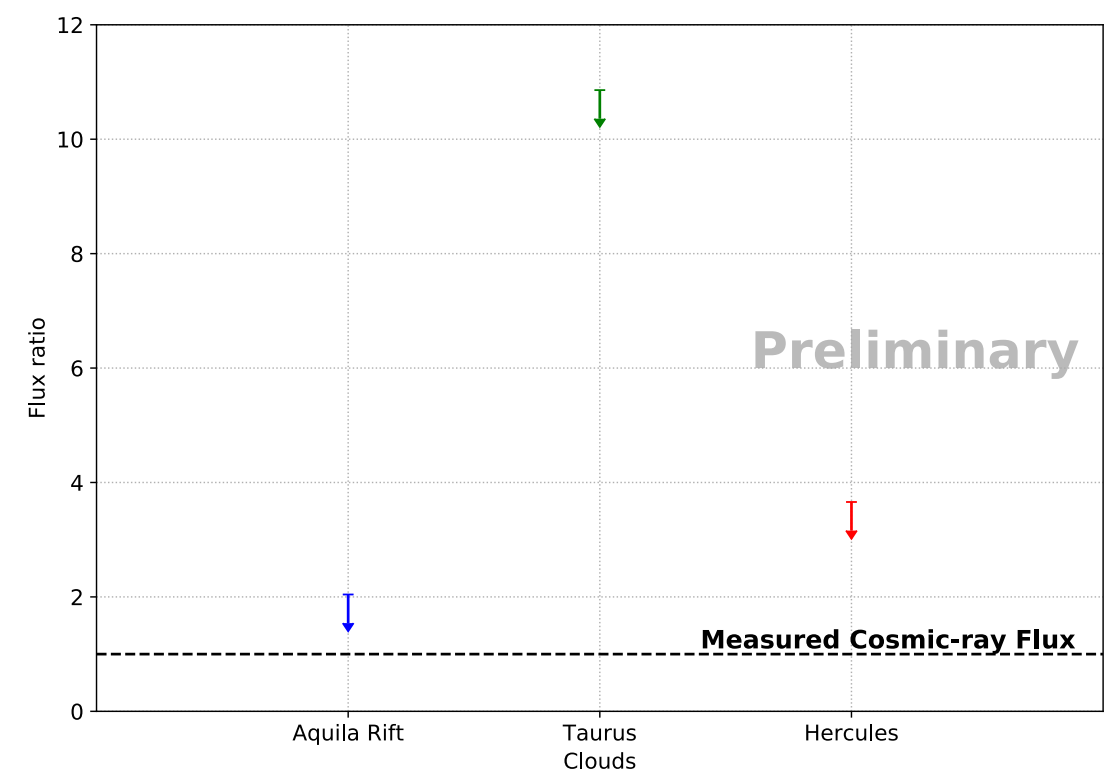
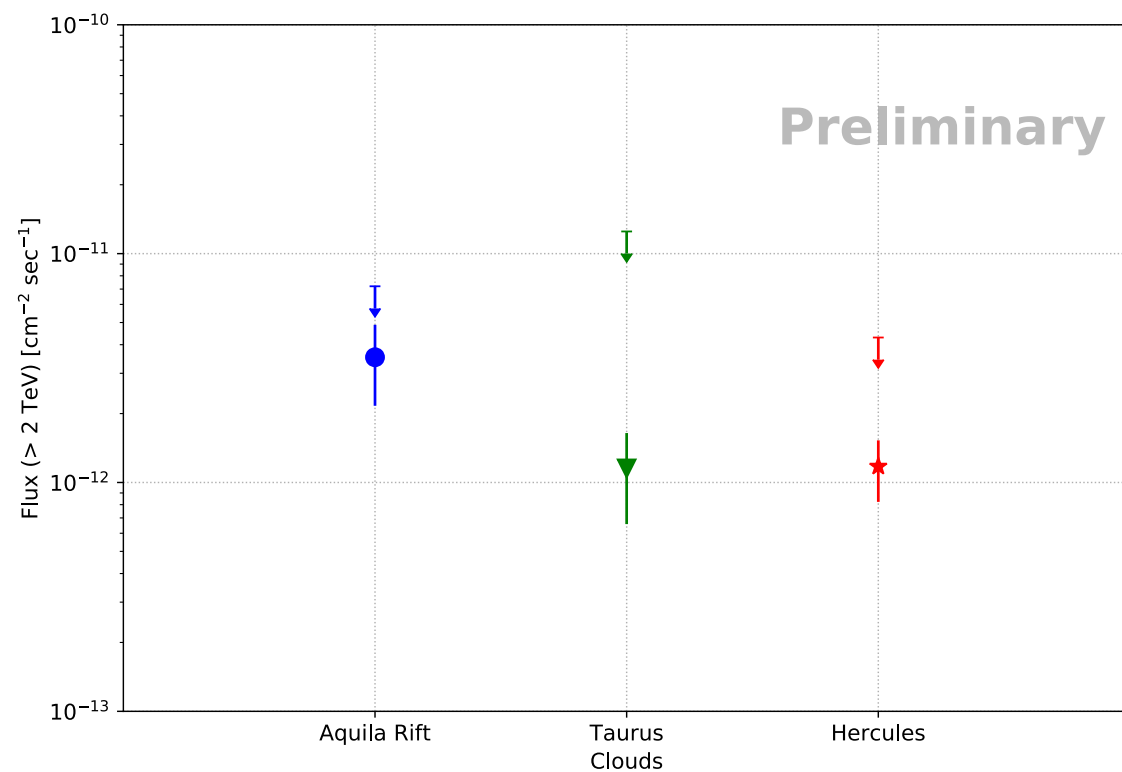
- Compare expected fluxes from previous equation to the HAWC sensitivity for 3σ and 5σ detection after 2 and 5 years of data for a circular source with 3° and 5° in radius.



HAWC sensitivity to extended sources and predicted integral fluxes of the GMCs in their respective declination. The error bars are calculated from the respective mass and distance errors.

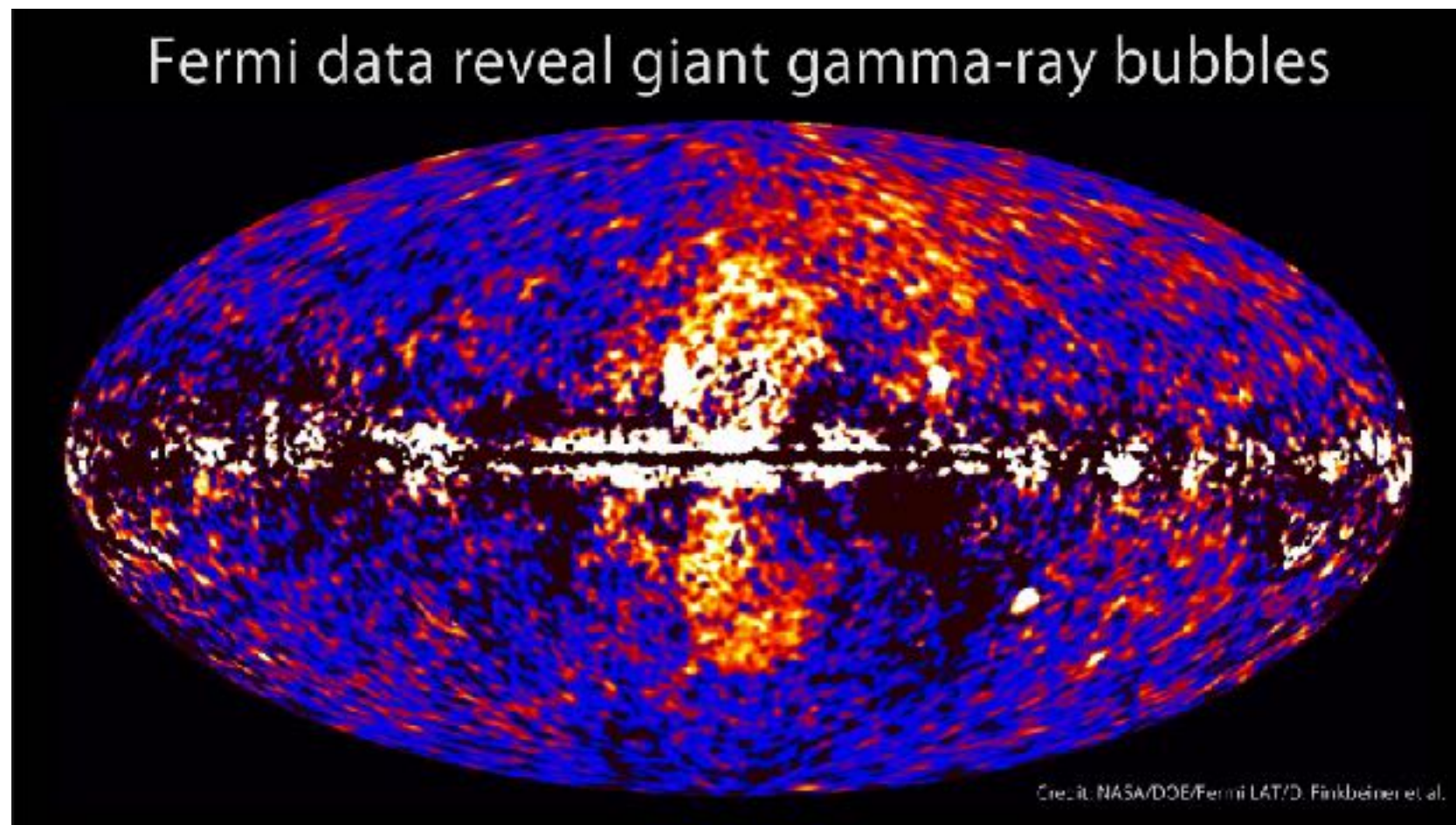
Current Upper Limits

- No significant excess was observed so 95% C. L. Upper limits are calculated.
- Also, the ratio of the upper limits to expected fluxes is calculated. The ratio is an upper limit on the cosmic-ray flux in the GMC region.



Fermi Bubbles

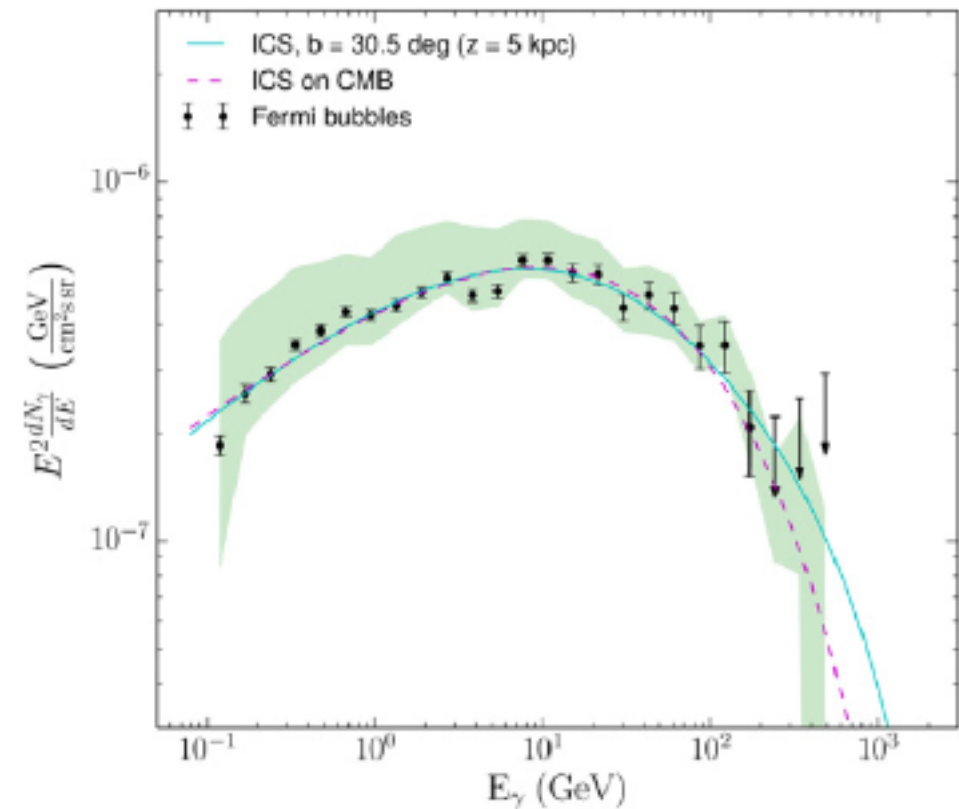
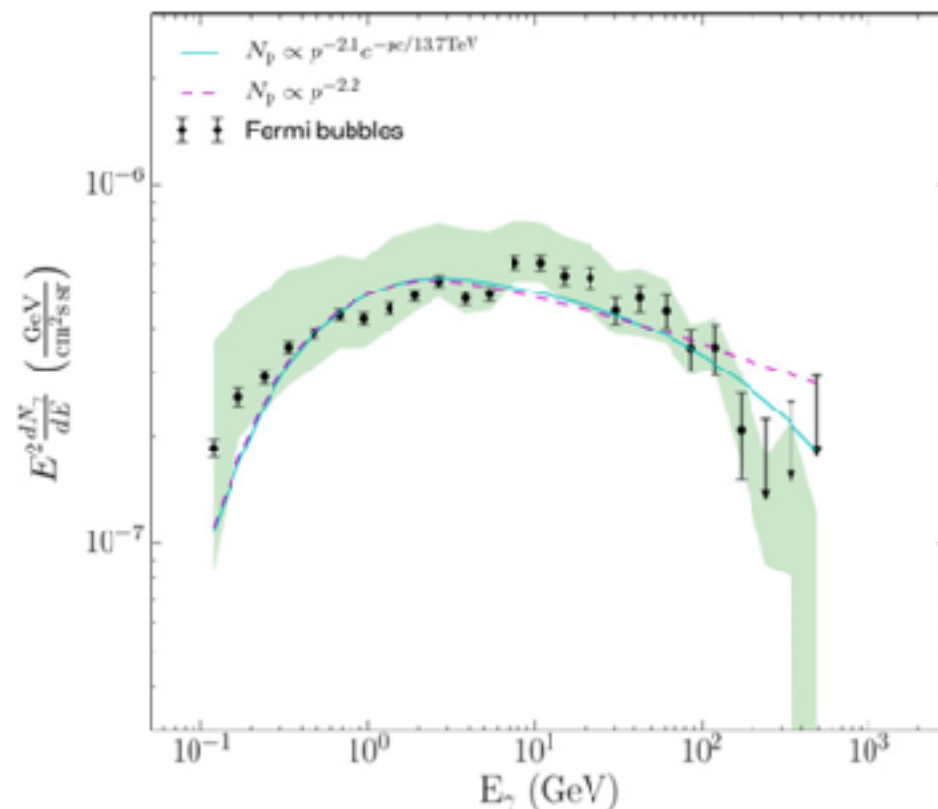
The Fermi bubbles are two large structures in gamma-rays above and below the Galactic center found in Fermi-LAT data.



Meng Su. et. al. *ApJ* 724, 1044 (2011)

Fermi Bubbles: Spectrum

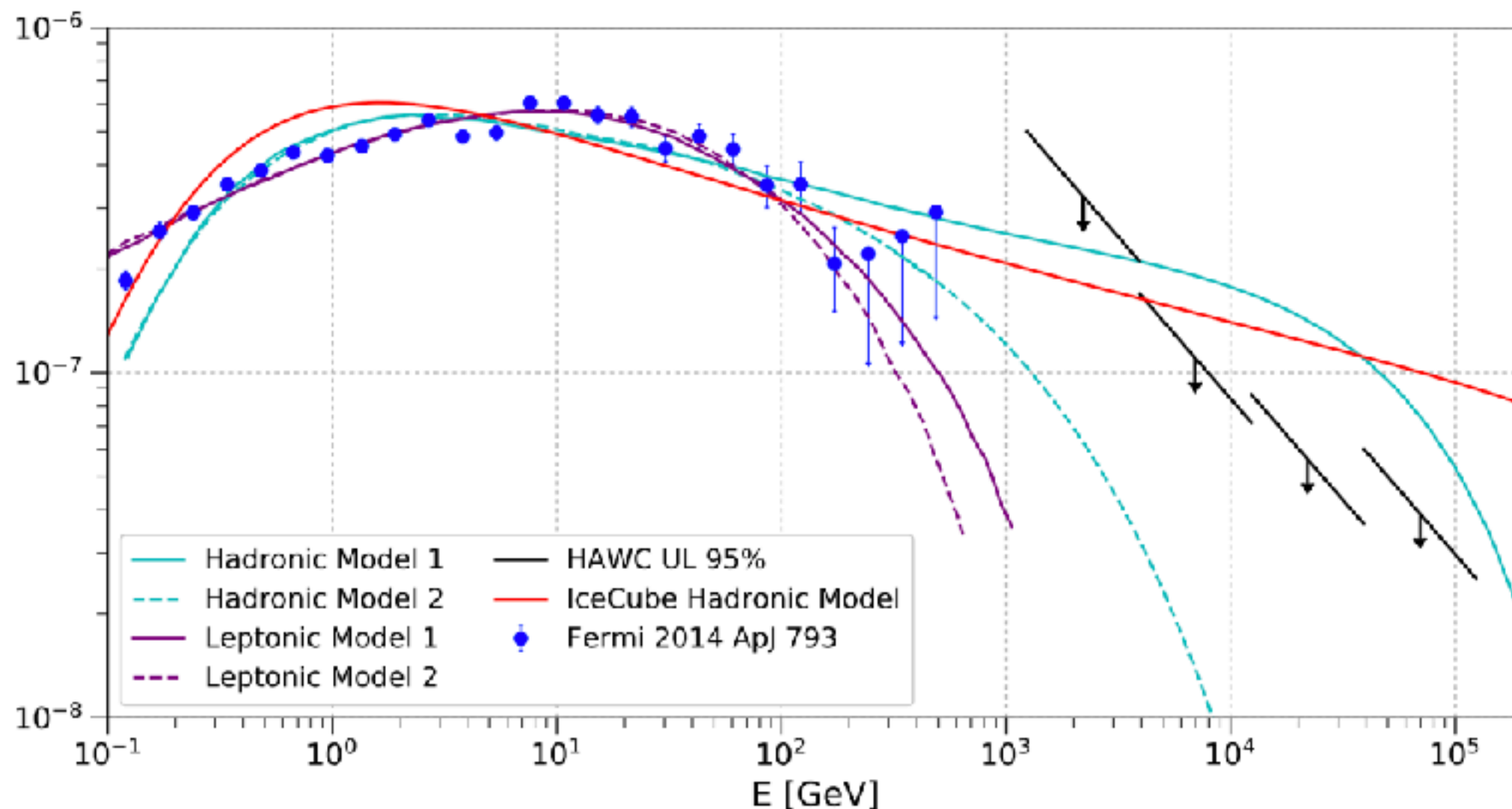
- Both, hadronic and leptonic mechanisms possible explanations for the measured spectrum ([Ackermann et al. 2014 ApJ 793 64](#))



- High energy gamma-ray data ($>500 \text{ GeV}$) desirable to constrain the spectrum and hence to shed more light on the origin of the Fermi bubbles.

Upper Limit on Fermi Bubbles

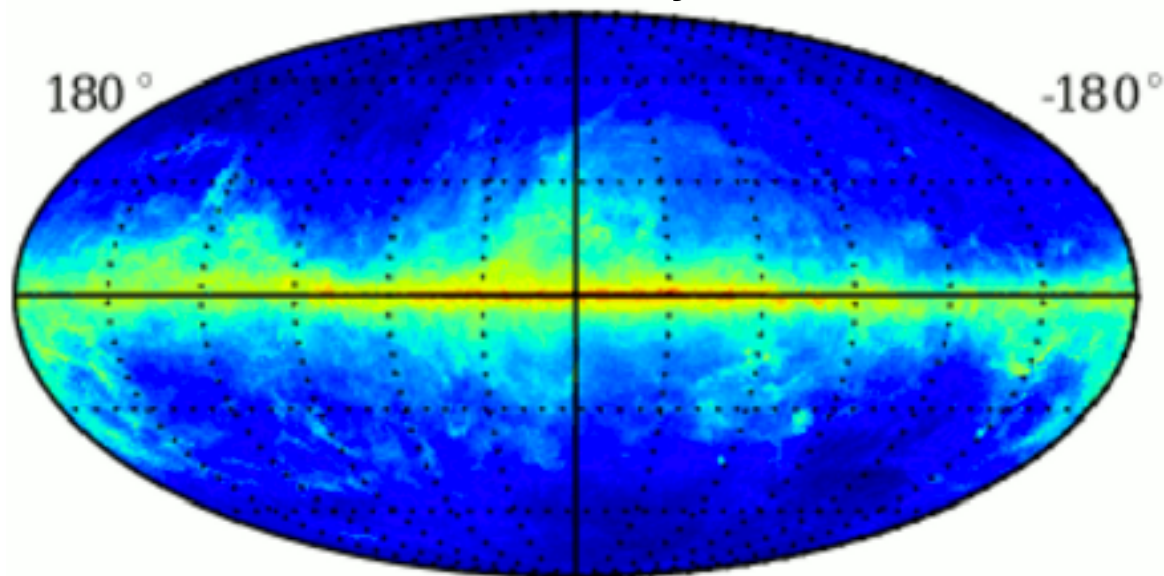
- No significant excess found after searching for gamma-ray emission in the Northern Fermi Bubble Region.
- Calculate 95% C. L. upper limits



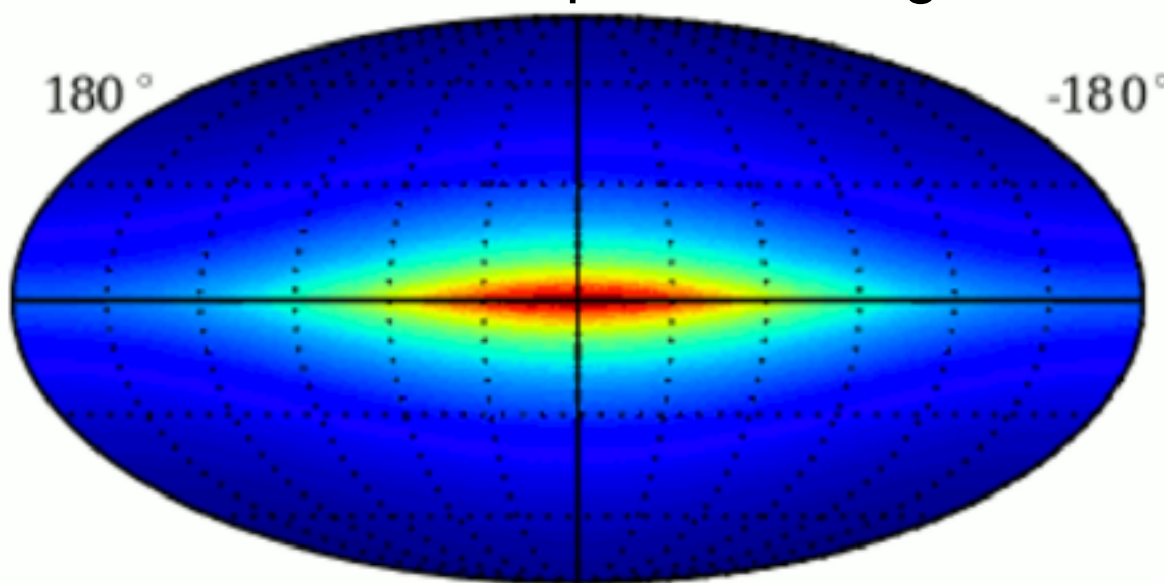
HAWC coll. ApJ 842, 85 (2017)

Galactic Diffuse Emission

π^0 decay



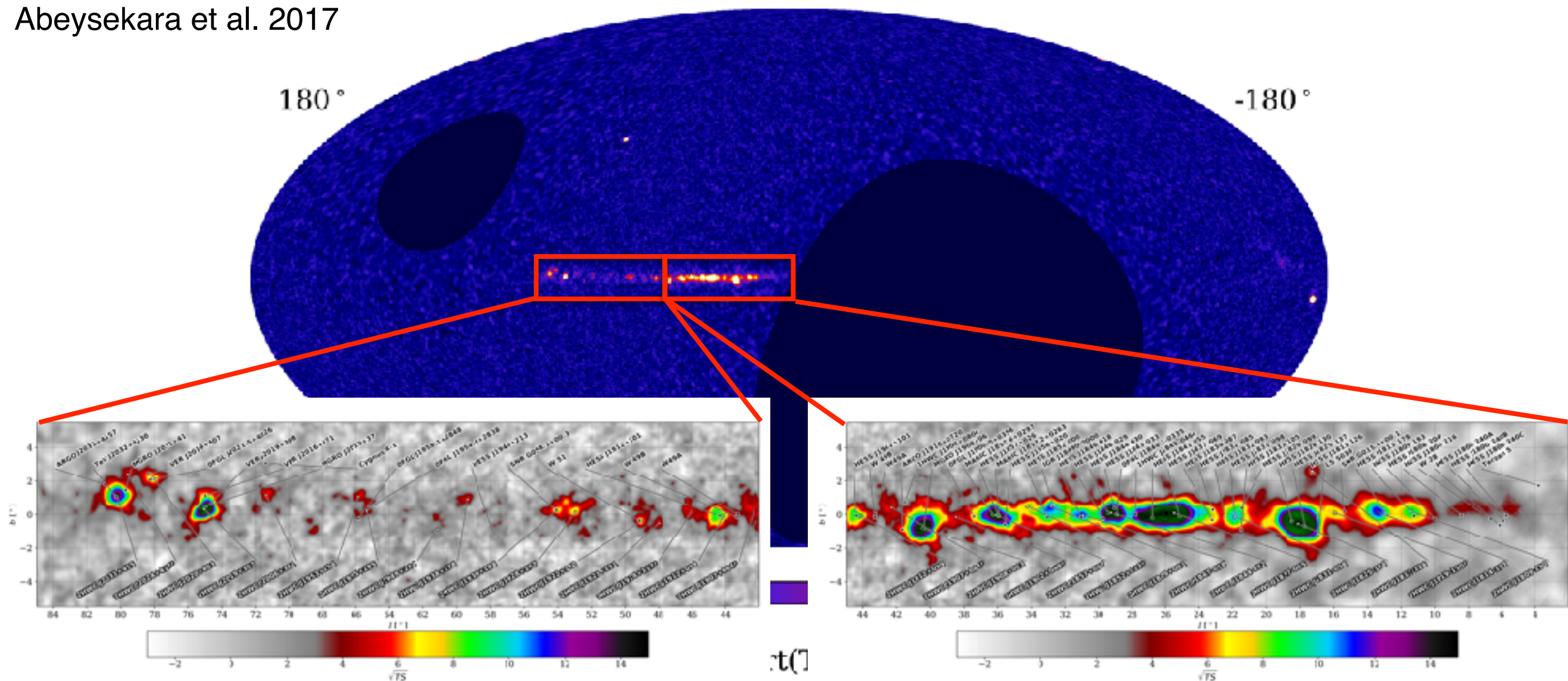
Inverse Compton Scattering



- Produced by cosmic rays interacting with the ISM and radiation fields
- At TeV energies:
 - π^0 decay: interaction between hadronic CRs and ISM
 - inverse Compton scattering: interaction between leptonic CRs and CMB
- By studying diffuse emission, we can learn about the acceleration and propagation of CRs in our Galaxy.

17 Months of HAWC Data

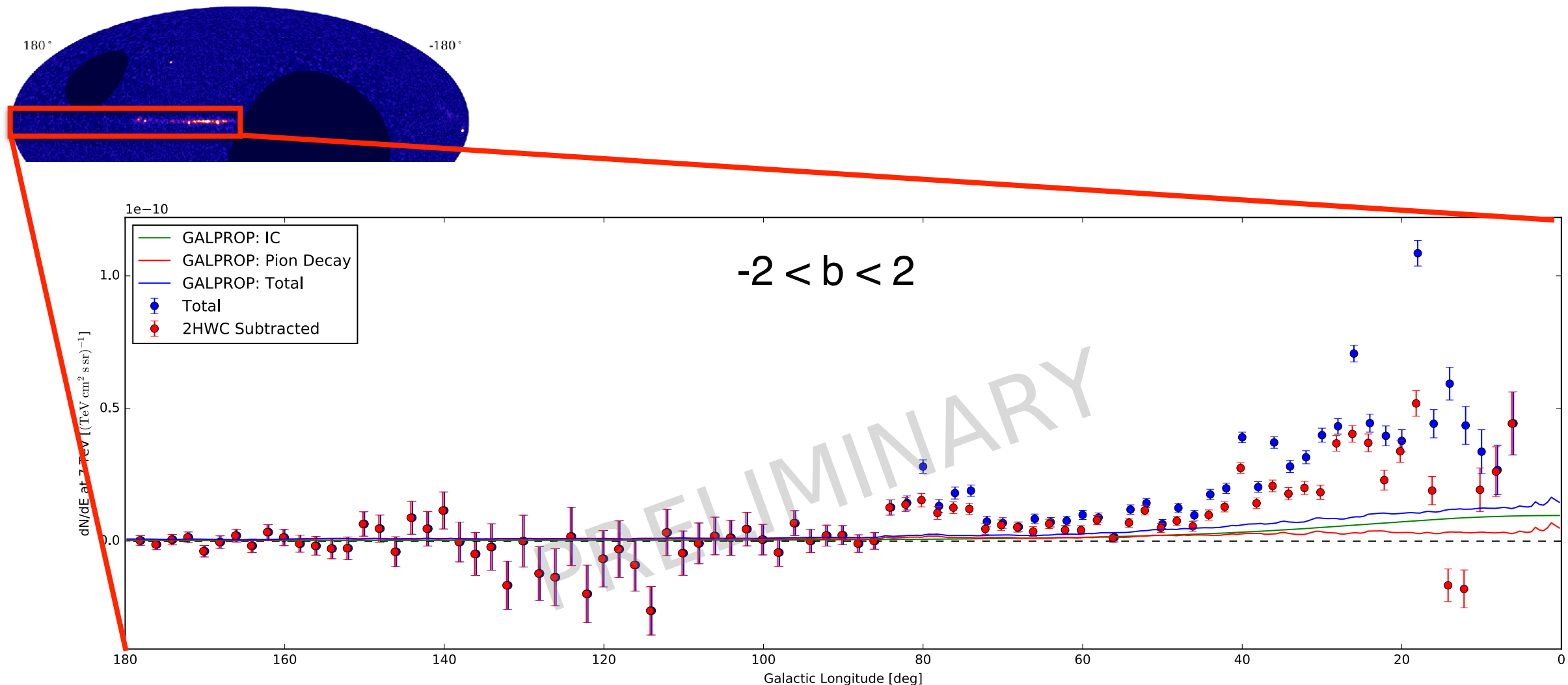
2HWC Catalog
Abeysekara et al. 2017



Challenge on the diffuse emission studies:

at TeV energies, gamma-ray emission from sources (resolved and unresolved) dominates over the diffuse emission.

Longitudinal Profile

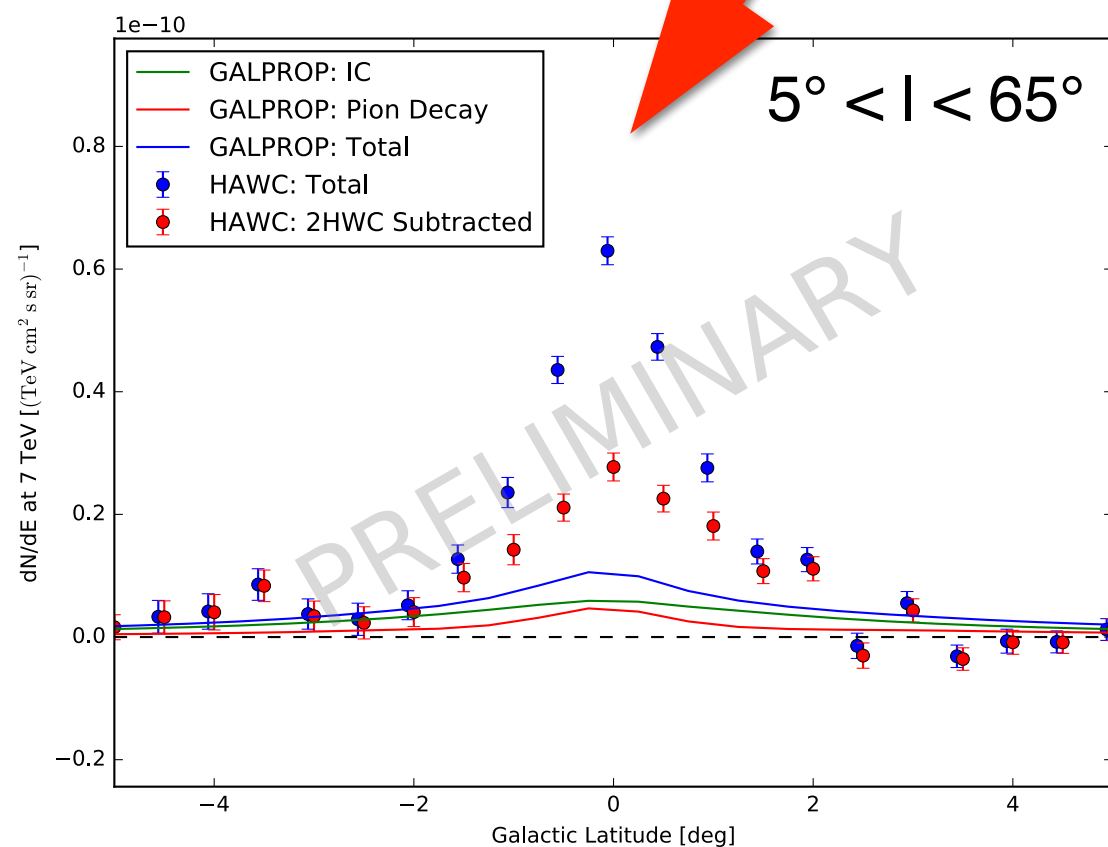
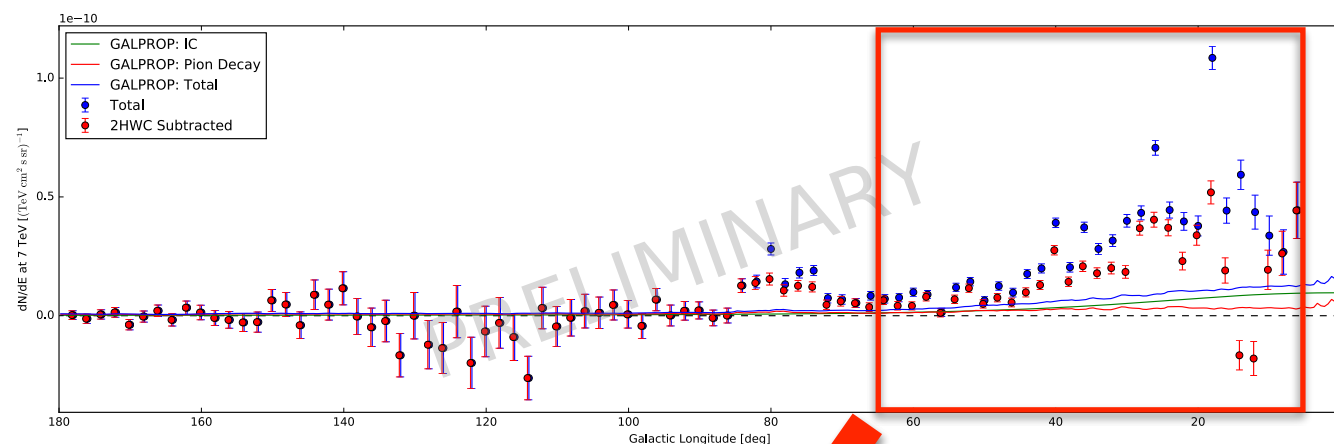


The resulting gamma-ray emission is a combination of

- extent of sources that 2HWC does not account for
- unresolved sources that are below the detection threshold
- Galactic diffuse emission

Latitudinal Profiles

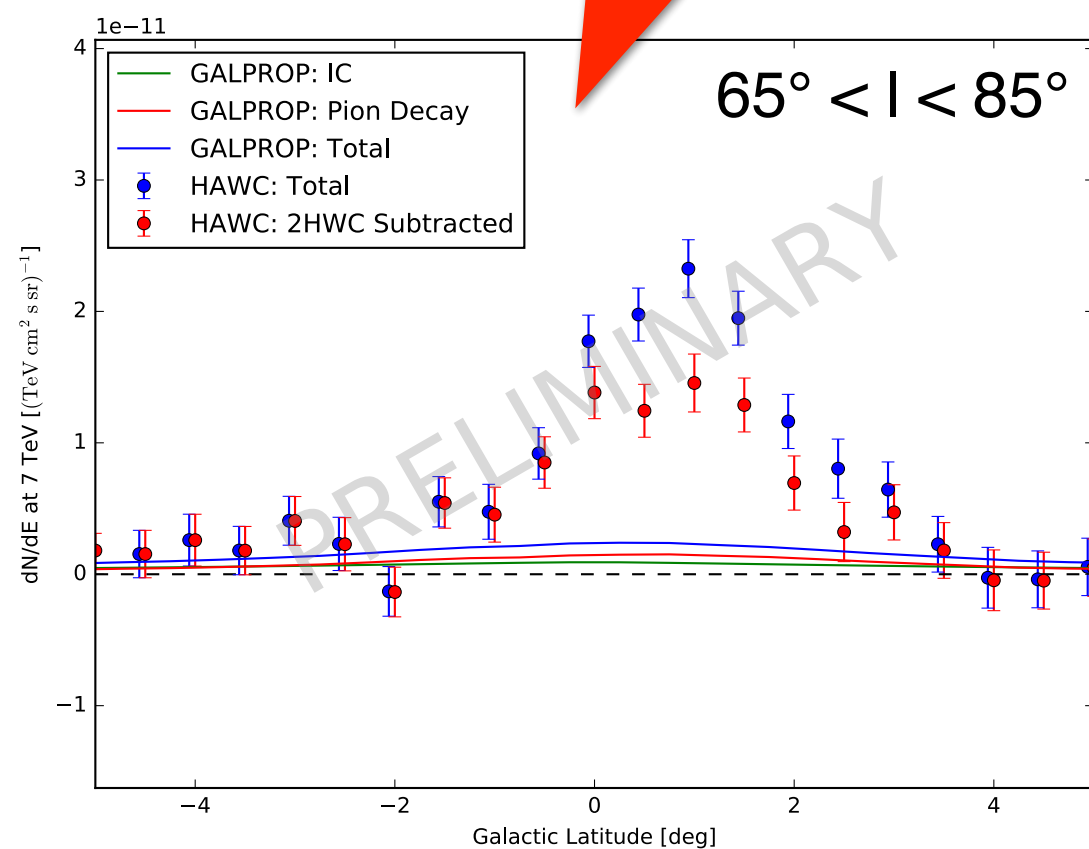
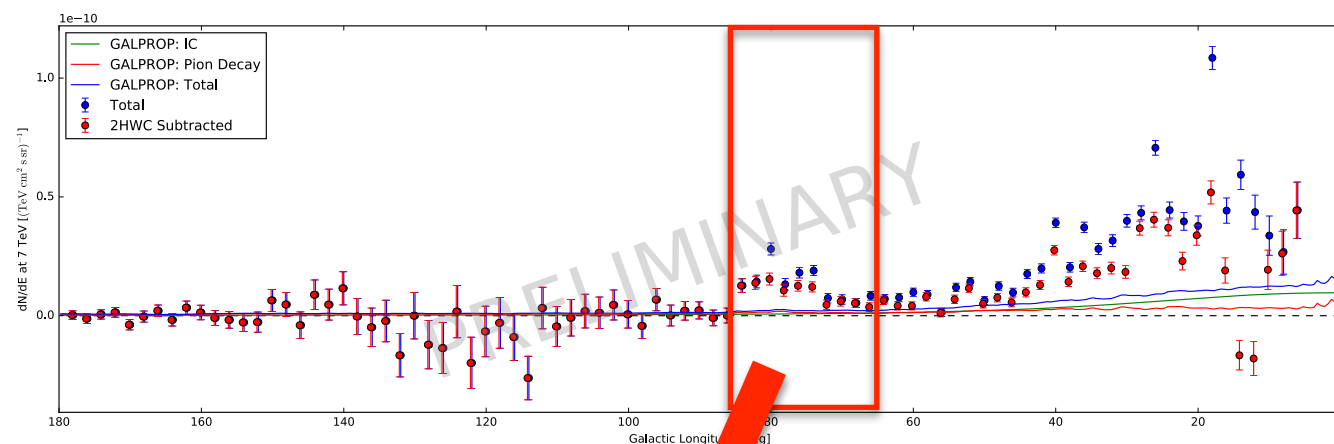
Inner Galaxy



- 24 sources identified in 2HWC
- Resolved sources account for about one third of the total emission
- Source-subtracted emission is 2-3 times of the emission predicted by GALPROP

Latitudinal Profiles

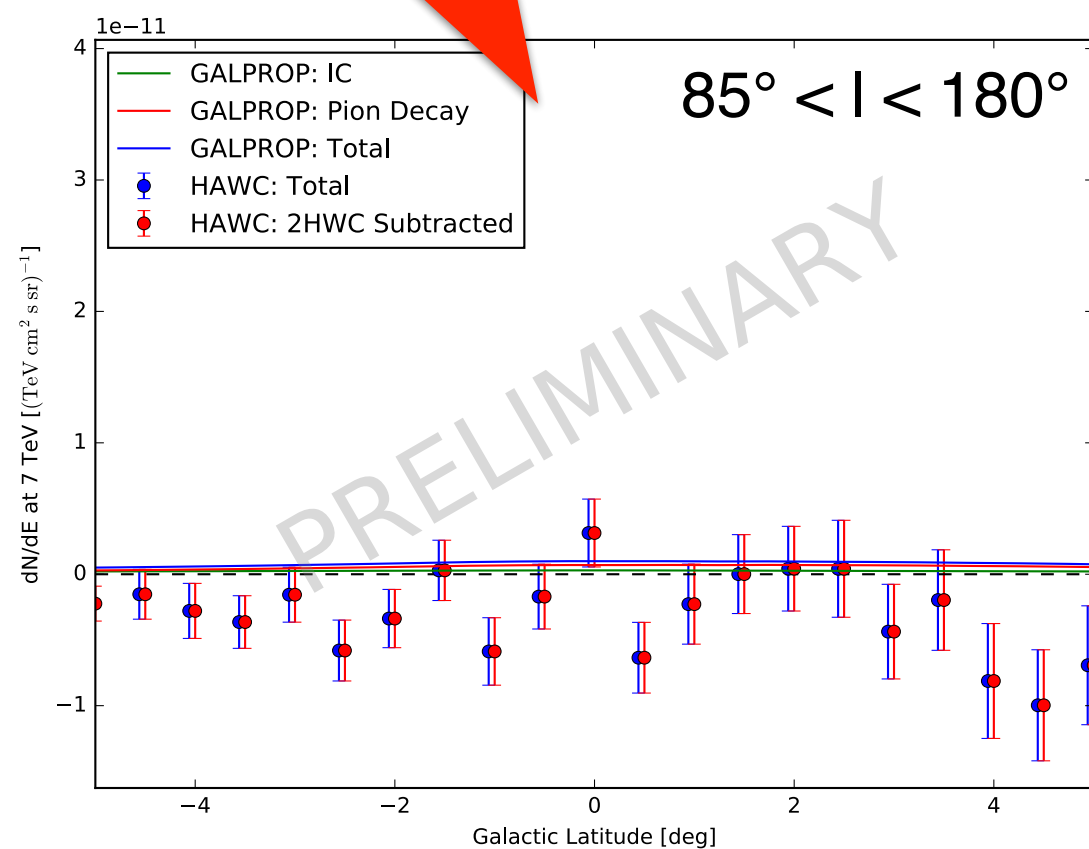
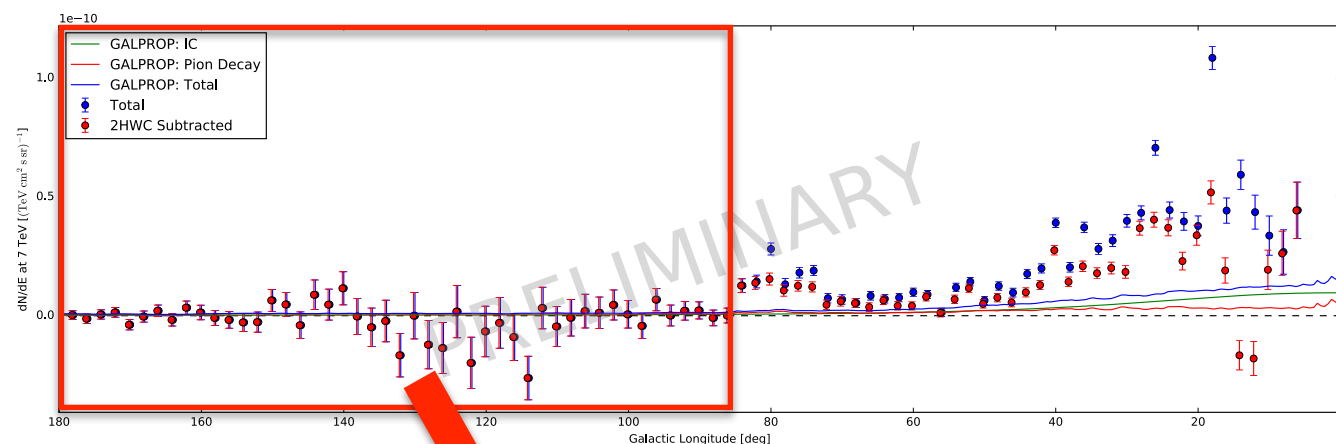
Cygnus region



- 7 sources identified in 2HWC
- Resolved sources account for about one fifth of the total emission
- Source-subtracted emission is an order of magnitude higher than the emission predicted by GALPROP

Latitudinal Profiles

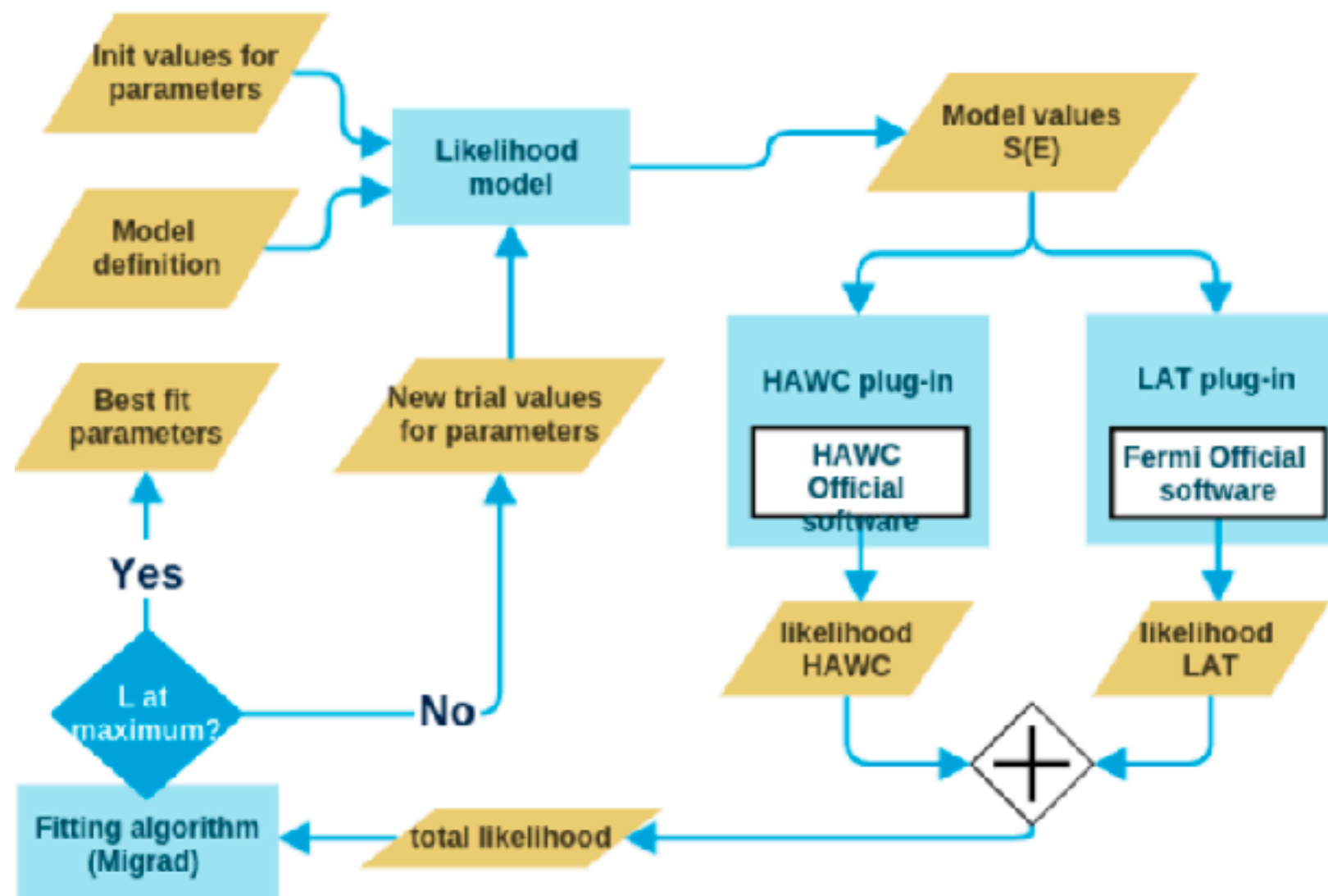
Outer Galaxy



- No source identified in 2HWC
- No significant gamma ray emission is found in this region

Software Tools - 3ML

- Multi-Mission Maximum Likelihood framework (3ML)
 - Contribution from people from Fermi, VERITAS and HAWC Collaborations
 - Joint likelihood fit with multiple/extended sources



Vianello, et. al. ICRC2015

Outlook

- **HAWC, as a wide-field-of-view detector, is sensitive to extended TeV gamma-ray emission.**
- With current dataset, we have measured
 - **Morphology of PWNe around Geminga and PSR B0656+14**
 - **Upper limit on GMCs and North Fermi bubble**
 - **Profile of Galactic diffuse emission (preliminary)**
- Looking forward to
 - **More data**
 - **Better analyses and systematic studies**
 - **More cross-observatory collaboration**
 - **More joint analyses**