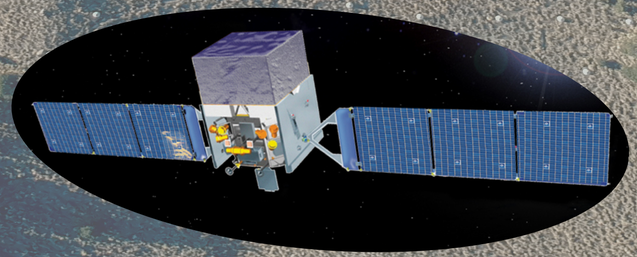
From MeV to TeV: Six Decades of γ-ray Astronomy

Fermi Gamma-ray Space Telescope

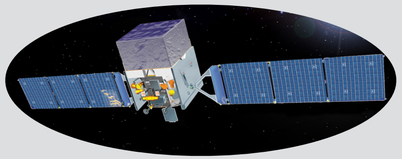
HAWC
High Altitude Water Cherenkov Gamma-Ray Observatory



Chad Brisbois

Michigan Technological University

Outline



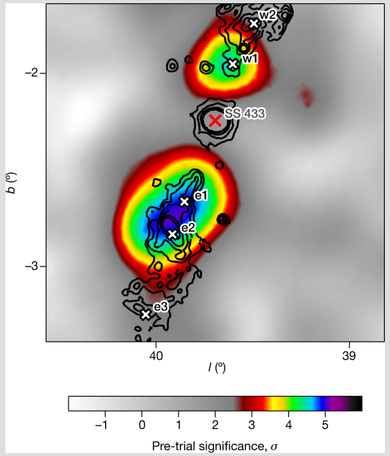
- Science Highlights
- Common Strengths
- Fermi-HAWC Synergies
- The Future

Some Fermi Highlights

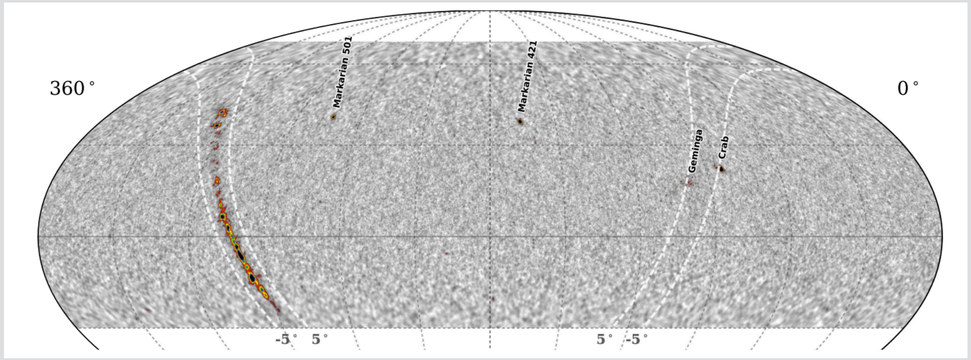
Graphic from Fermi Science Playoffs https://fermi.gsfc.nasa.gov/fermi10/brackets/

Some HAWC Highlights

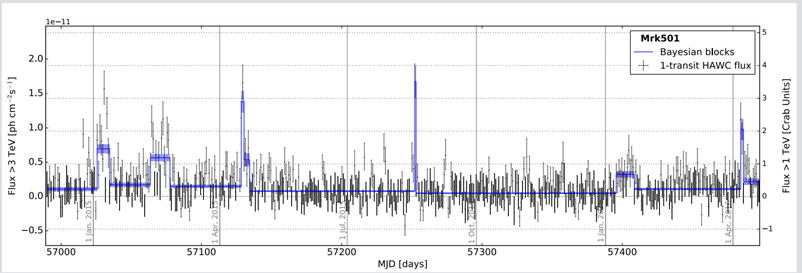
SS 433



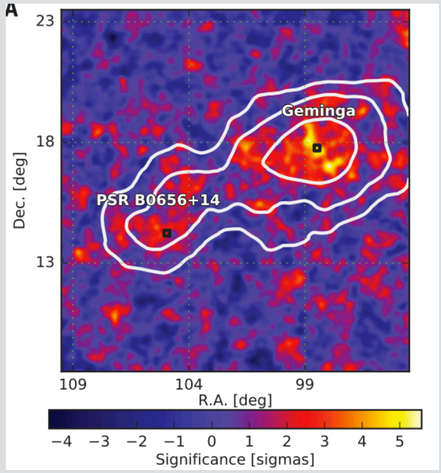
2HWC Catalog



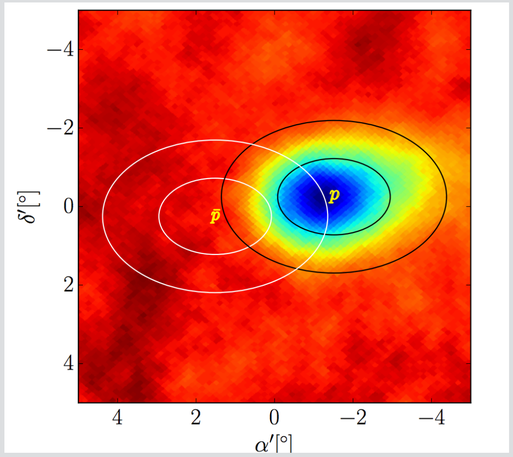
Monitoring of TeV sky



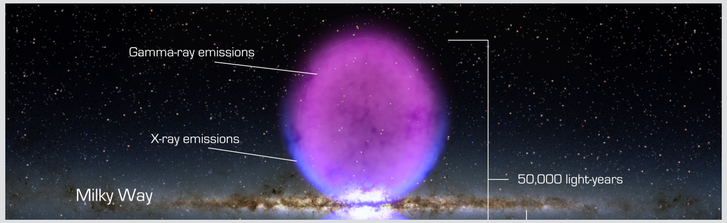
TeV Halos



Moon, Sun Shadow



(Northern) Fermi Bubble

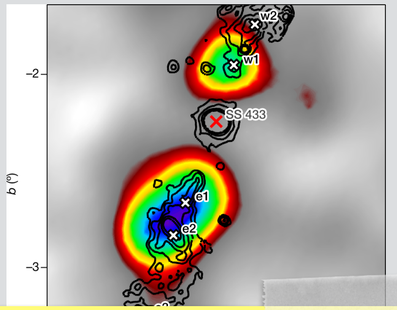


Coming Soon: >100 TeV sky

https://www.hawc-observatory.org/publications/

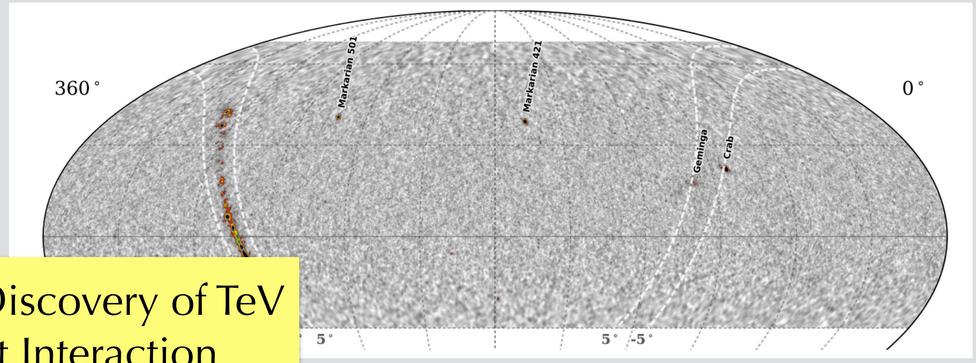
Some HAWC Highlights

SS 433

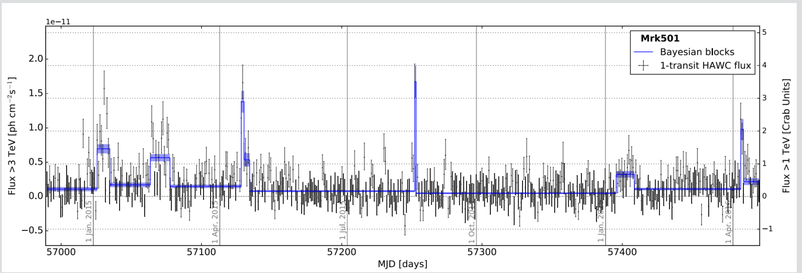


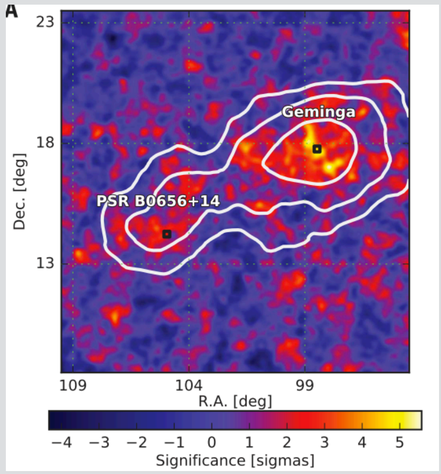
See Hao Zhou's talk from Monday "Discovery of TeV Gamma-Ray Emission from the Jet Interaction Regions of Microquasar SS 433 with HAWC"

2HWC Catalog

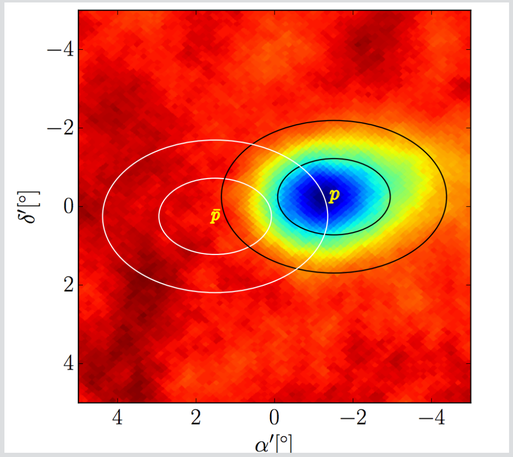


Monitoring of TeV sky





TeV Halos



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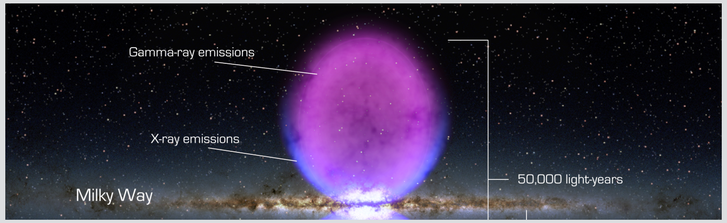


(Northern) Fermi Bubble

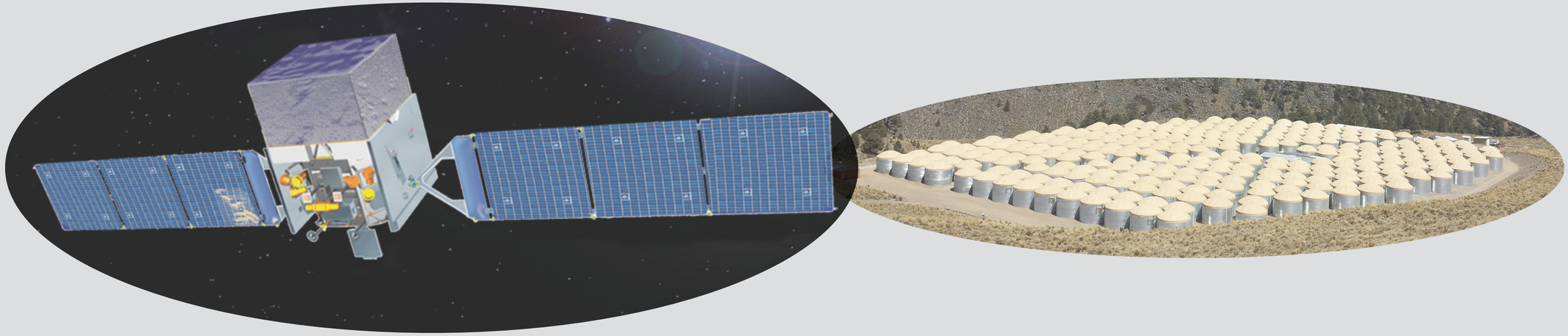
Coming Soon: >100 TeV sky

https://www.hawc-observatory.org/publications/

Common Strengths

Continuous Operations
Wide Field-of-View

MeV GeV TeV



100 MeV—100 TeV sky with nearly continuous coverage starting in 2014

Six Decades in Energy!

Giacomo Principe's talk from Monday "The First Catalog of Fermi-LAT sources below 100 MeV"

New Developments: LAT Low Energy Catalog, HAWC >100 TeV sky

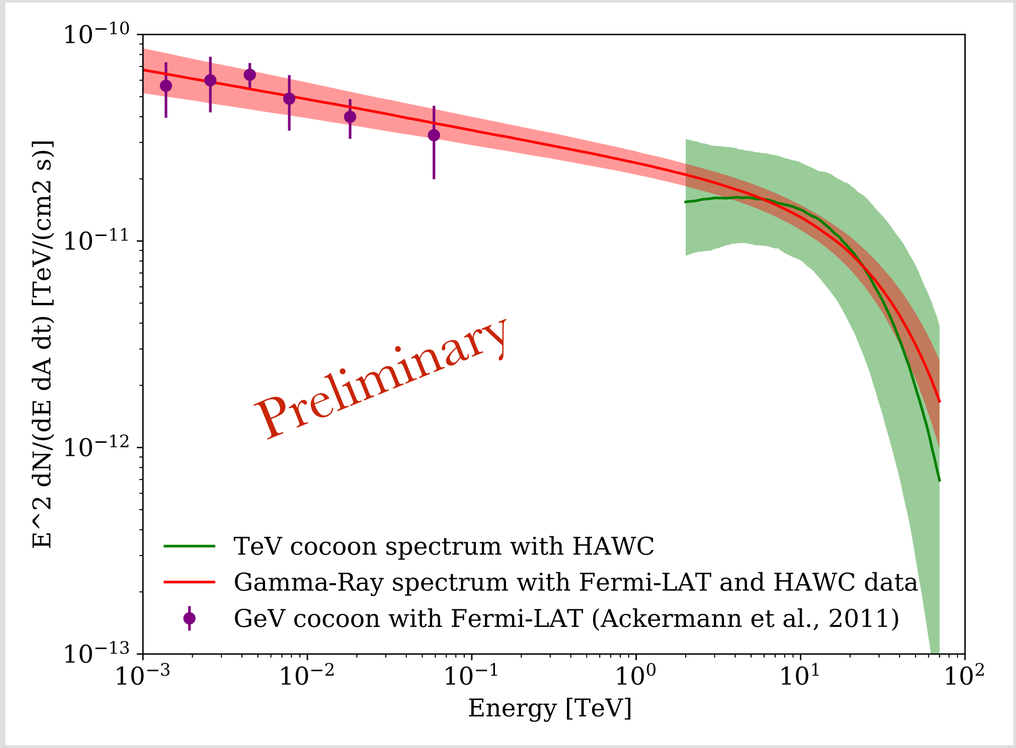
Fermi-HAWC Synergies

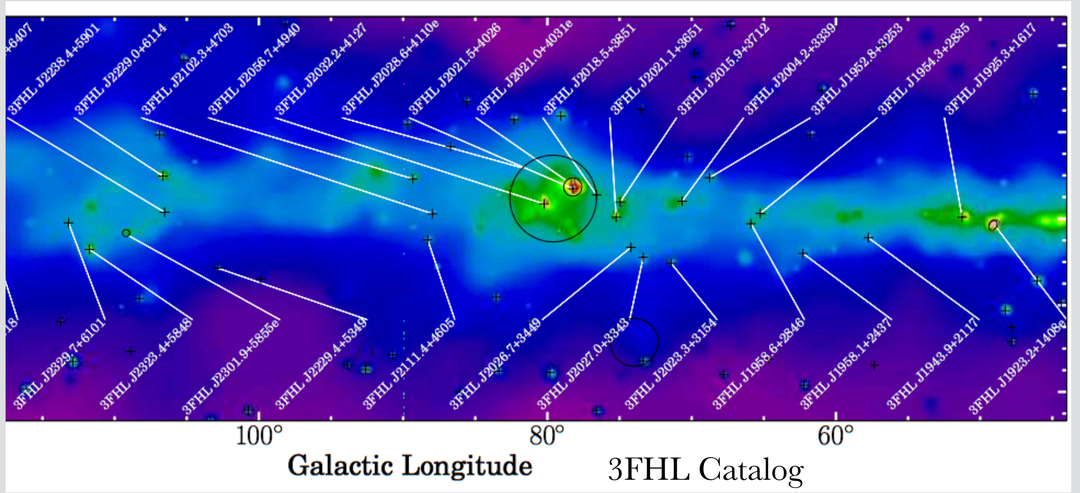
The Cygnus Region

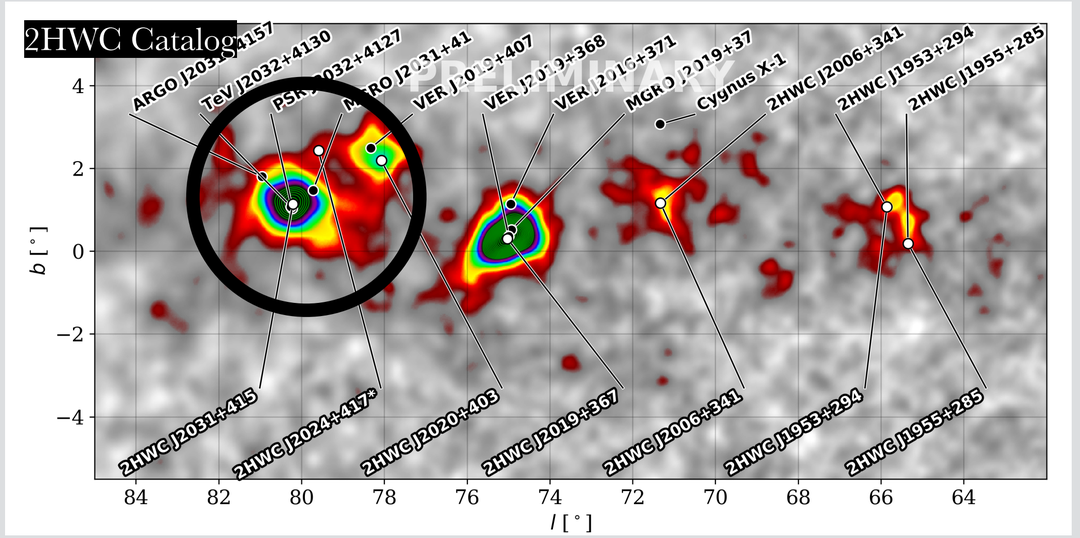
Cygnus Cocoon

Acceleration in Star-Forming Regions

Seems to be power law up to tens of TeV!







See Binita Hona's poster, "Particle Acceleration by a Star Forming Region in the Cygnus Constellation with HAWC and Fermi-LAT"

Fermi-HAWC Synergies

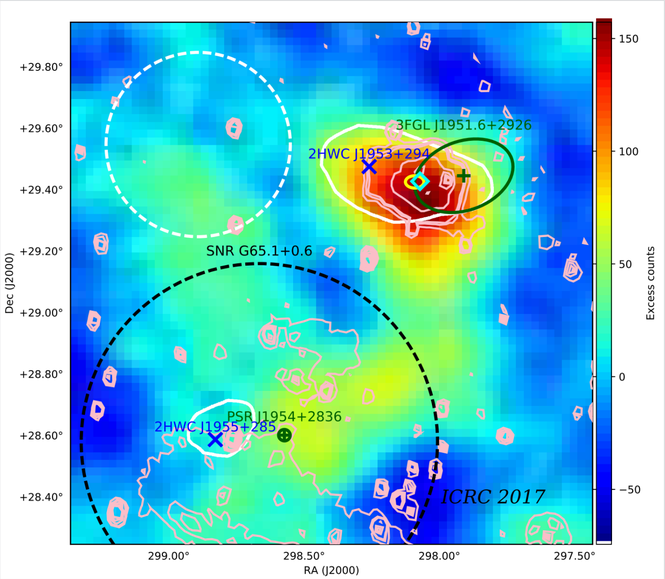
The Cygnus Region

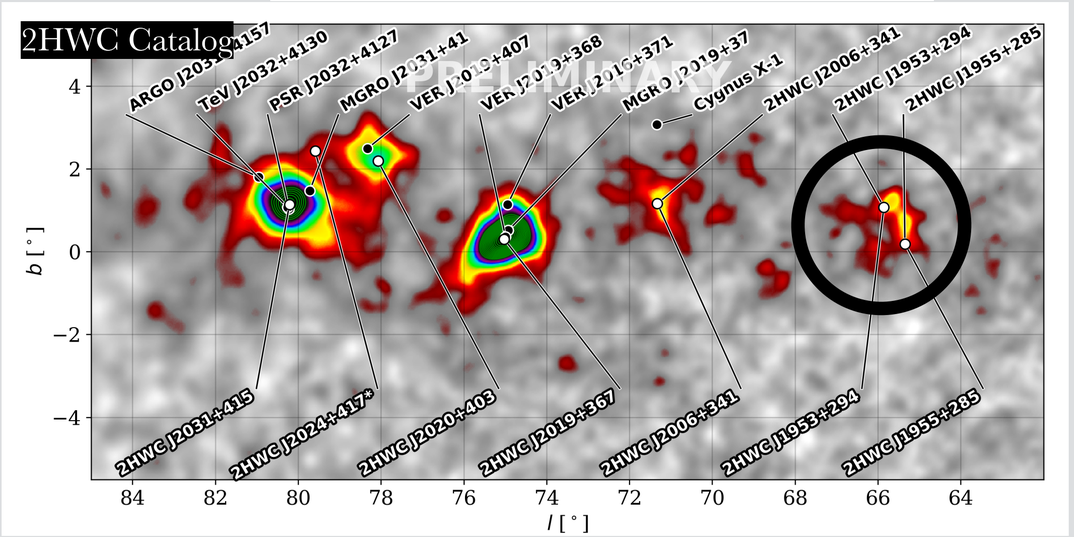
2HWC J1953+294 / DA 495

Discovered by HAWC at TeV
Followup by VERITAS & Fermi-LAT
Associated with 3FGL J1951.6+2926

Previously observed PWN at this location in Radio & X-ray
No pulsations detected from Radio→γ-rays!

Could this be an example of an misaligned pulsar?





Park, N., VERITAS Collaboration, Fermi-Lat Collaboration, HAWC Collaboration 2017, International Cosmic Ray Conference, 35, 696

Fermi-HAWC Synergies
Geminga & The Positron Excess

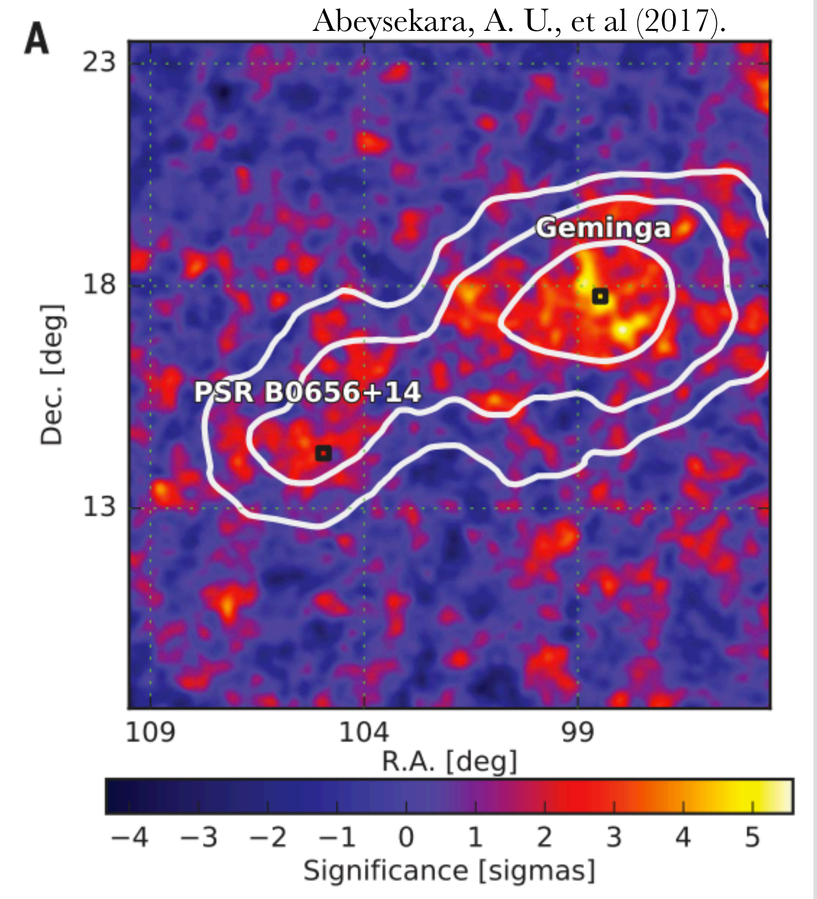
Geminga

Nearby Pulsars may explain positron excess
HAWC results called this into question

One/Two Zone model — More observations needed

"Can pulsars explain the observed positron excess?"
One: difficult
Two: maybe

Abeysekara, A. U., et al (2017).



See Andy Smiths talk from Tuesday
"Observation of Extended PWNe with HAWC"

Fermi-HAWC Synergies
Geminga & TeV Halos

TeV Halos

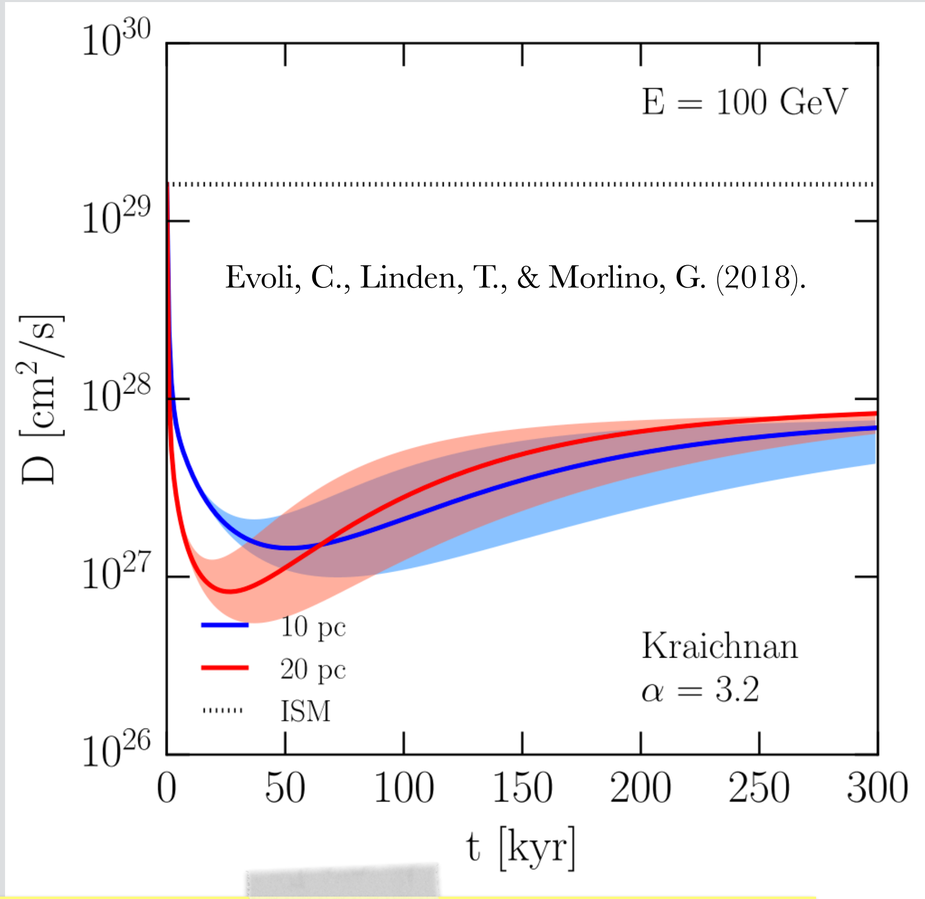
Extended Emission around Geminga and Monogem
Pulsars seem to be a prototype for a new class of objects

There seems to be more of these objects….
(ATels 10941, 12013), Linden et al 2017

HAWC result inspired new efforts using Fermi-LAT
Can we understand this together?

Wide FoV instruments can do this kind of analysis.
Radii of Geminga halo ~5°, too big for IACTs

If we can understand/define characteristics of this source class, we may be able to identify misaligned pulsars



See Andy Smiths talk from Tuesday
"Observation of Extended PWNe with HAWC"

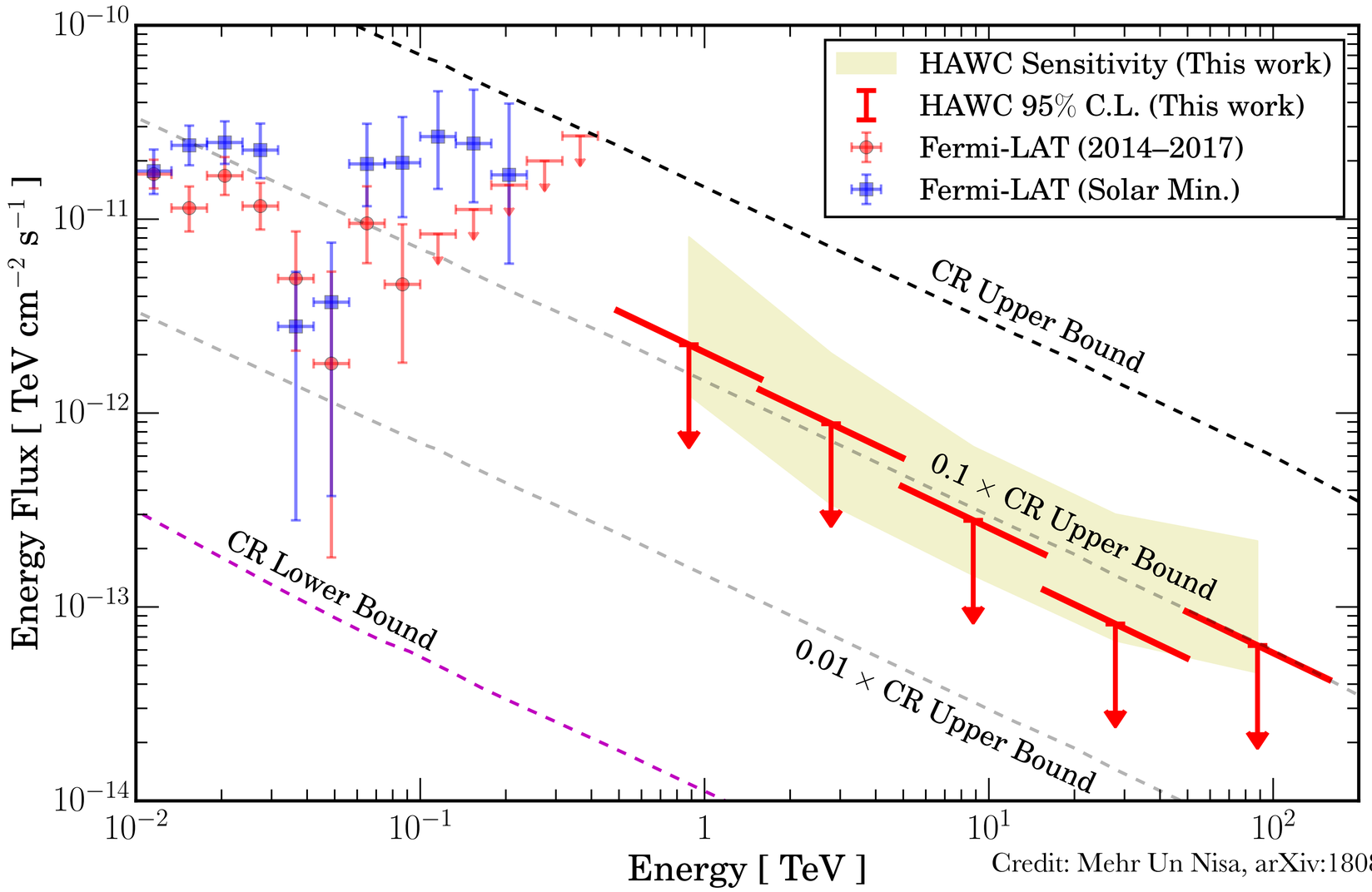
Requires two zone model interpretation

Fermi-HAWC Synergies

Sun Observations

How does the Sun's γ-ray emission vary with time?

Sun is most bright at high energies during solar minimum, HAWC observations agree with that (so far)



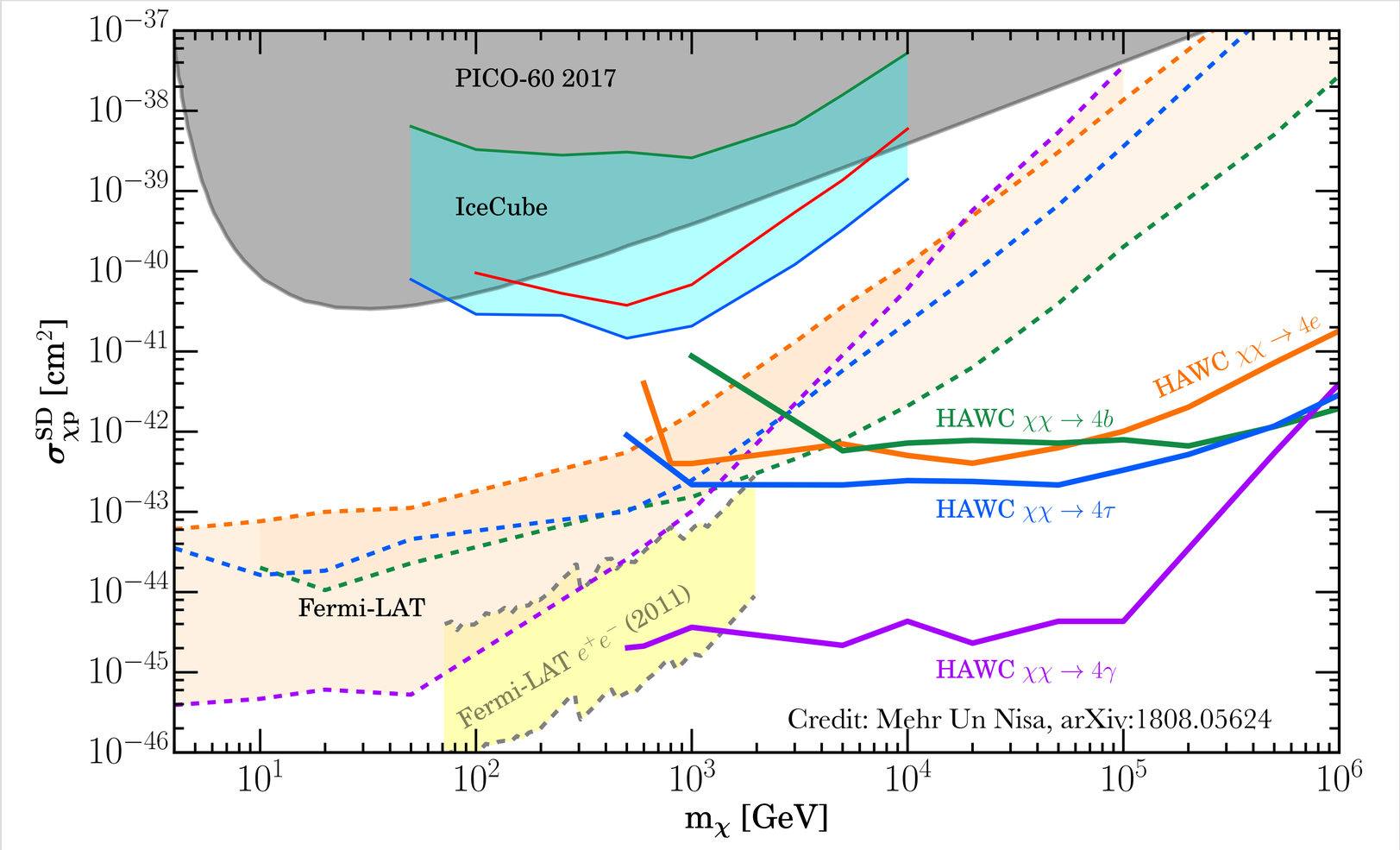
Credit: Mehr Un Nisa, arXiv:1808.05620

Fermi-HAWC Synergies

Dark Matter

Sun Observations

Fermi & HAWC constrains the spin-dependent dark matter-proton scattering cross section!
We can probe Dark Matter masses from 4 GeV to 1 PeV.



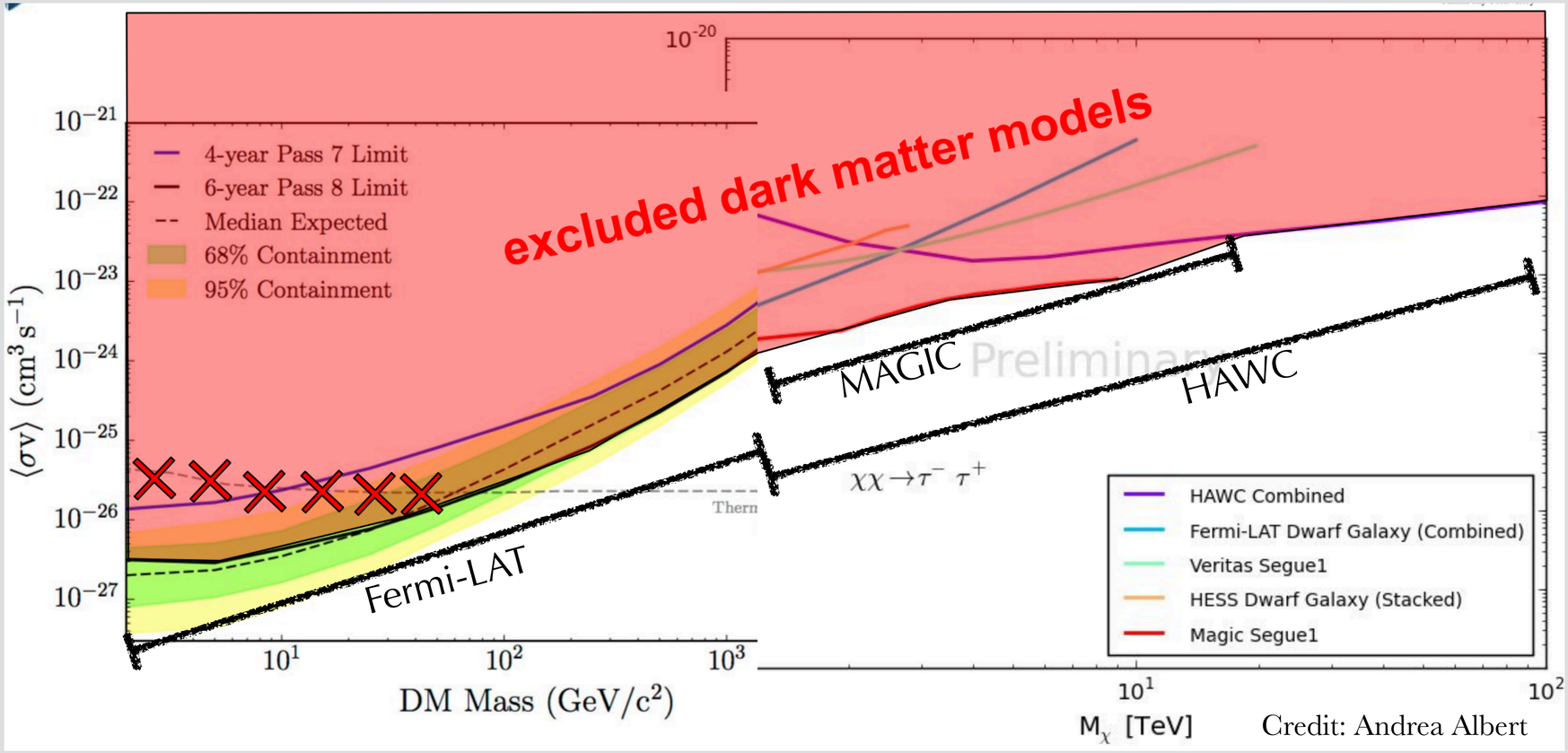
Fermi-HAWC Synergies

Dark Matter

Wide FoV enables Verification

If we see Dark Matter in X location, it should also be in location Y *at the same mass*.

Between HAWC and Fermi, we can probe Dark Matter masses from 2 GeV to >100 TeV.



Credit: Andrea Albert

Dwarf Galaxy Limits

Fermi-HAWC Synergies
Lorentz Invariance Violation

Many tests of many models

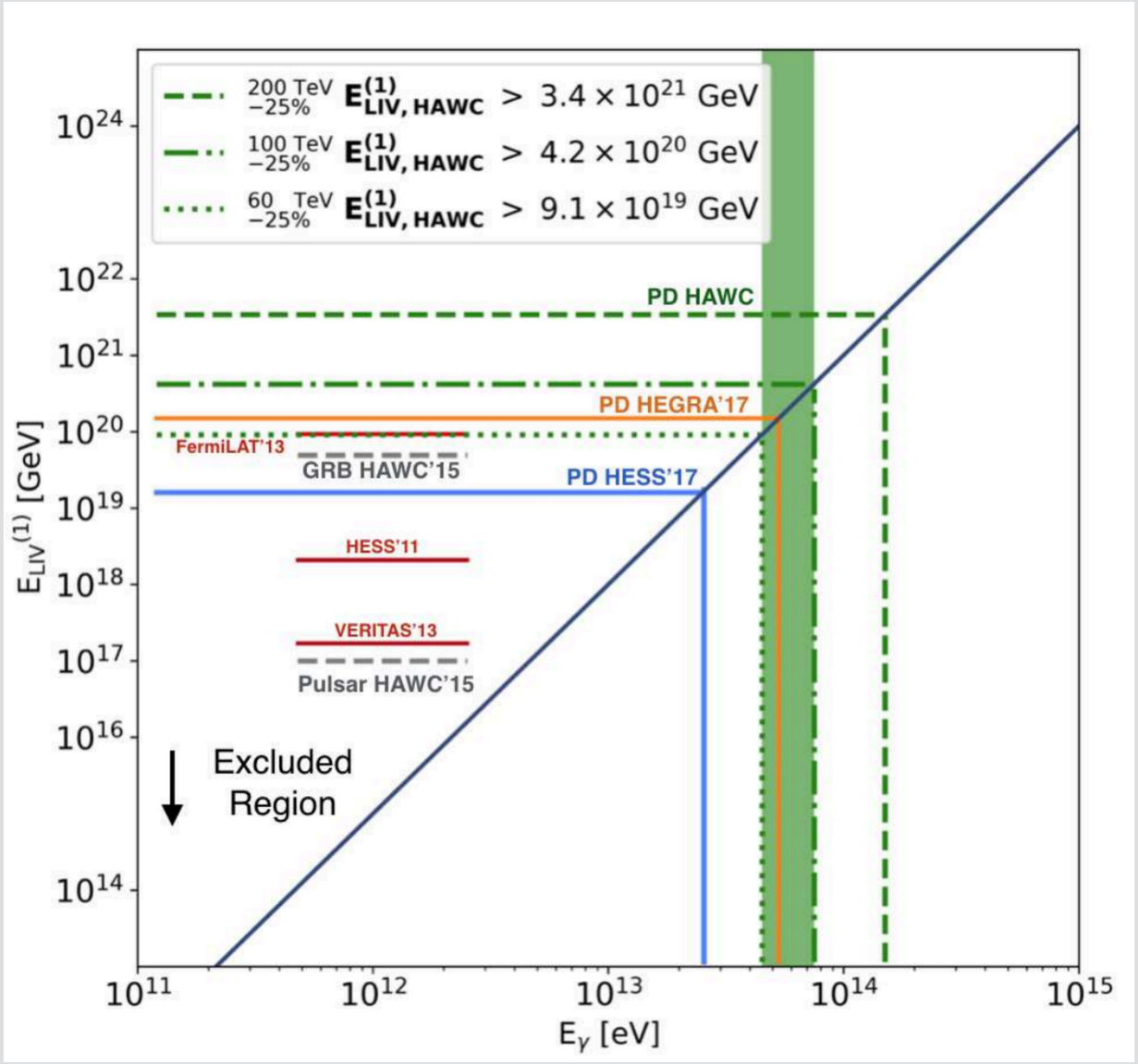
Vacuum Photon Decay -

Beyond an energy E_γ, decay into $e^\pm$ pairs is likely

$$E_{LIV}^{(n)} > E_\gamma \left[\frac{E_\gamma^2 - 4m_e^2}{4m_e^2} \right]^{1/n}$$

HAWC analysis can also investigate dispersion relations

$$\Delta t \propto \left(\frac{\Delta E}{E_{LIV}} \right)^n$$



Martìnez-Huerta, H., et al, 2017, ICRC, 35, 868

Brisbois C., Nemrioff R.J., LAT Pass 8 Constraints on Lorentz Invariance Violations with GRB090510A, Fermi Symposium 2015

Fermi-HAWC Synergies

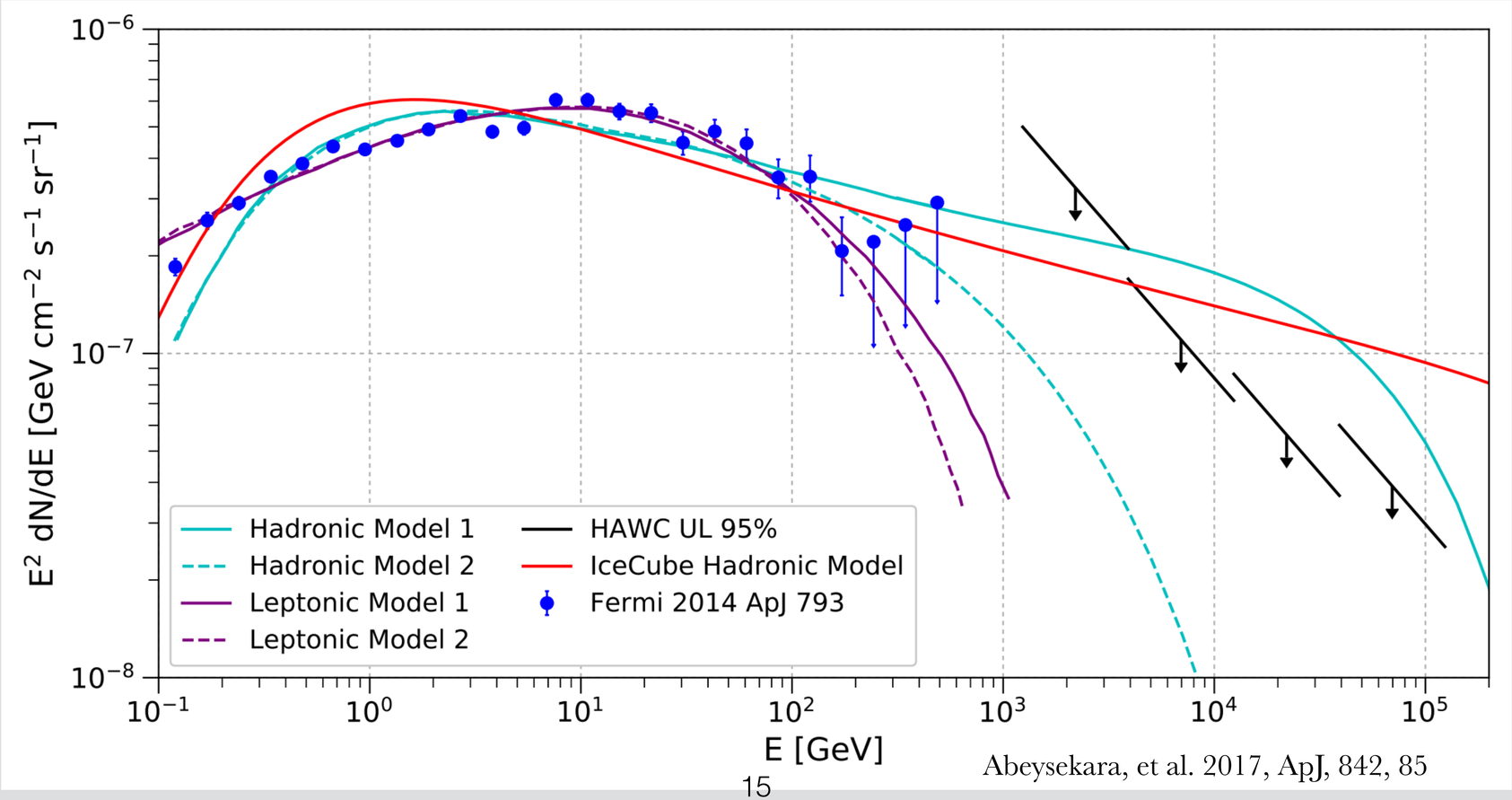
Very Extended Sources

Nearly unbiased exposure enables extended studies

Examinations of large fractions of the sky difficult with pointed instruments.

Characterizing large angular scale emission is a challenge

Unresolved sources, Galactic Diffuse Emission, Mismodeled emission from known sources



Abeysekara, et al. 2017, ApJ, 842, 85

Fermi-HAWC Synergies
Unified Software Framework

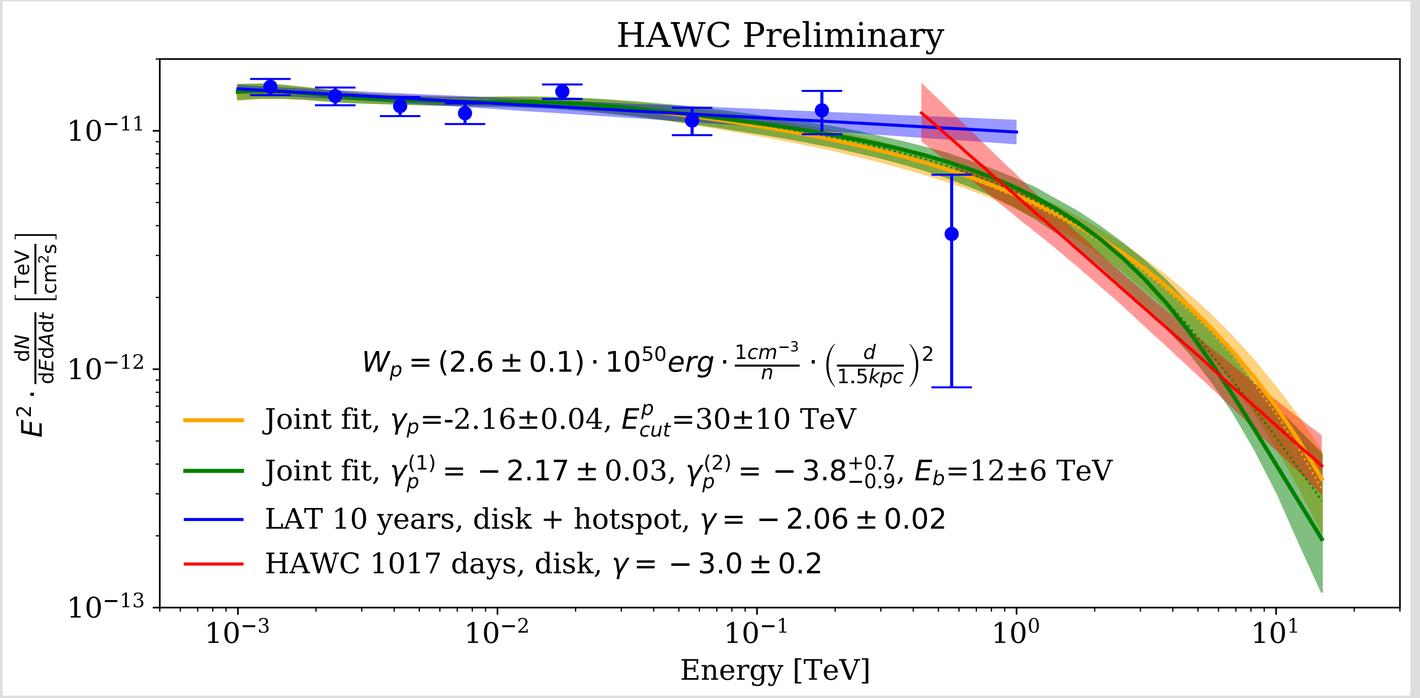
3ML: Multi-Mission Maximum Likelihood Framework

Single Framework in Python to unify analysis from different instruments.

Only a few analyses use both Fermi & HAWC data so far.

A Combined analysis gives greater insight! Currently quite a few plugins, but others are welcome!

`https://github.com/giacomov/3ML`



See Henrike Fleischhack's talk: "HAWC's View on Supernova Remnants"

Fermi-HAWC Synergies

Monitoring the γ-ray sky

Time-Domain Astronomy

Fermi & HAWC see most of the sky constantly

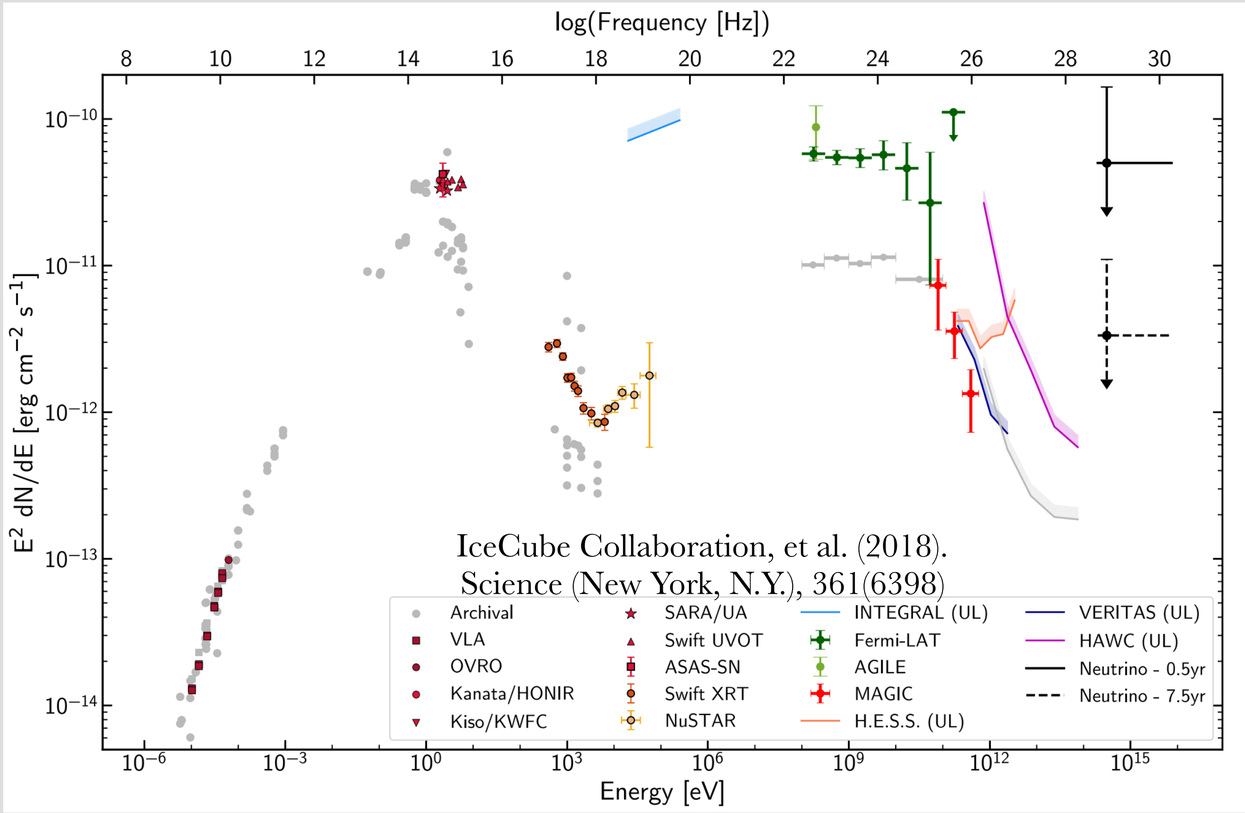
Periodicity? Other Time variation?

Multi-Messenger Astronomy

Coincidence between Neutrinos, Gravitational Waves, and γ-rays clarify physical models of extreme astrophysical environments

Transient γ-rays

Trigger from Fermi/HAWC will cause other instruments at other wavelengths to observe that region of the sky (9 ATels reporting Transients)

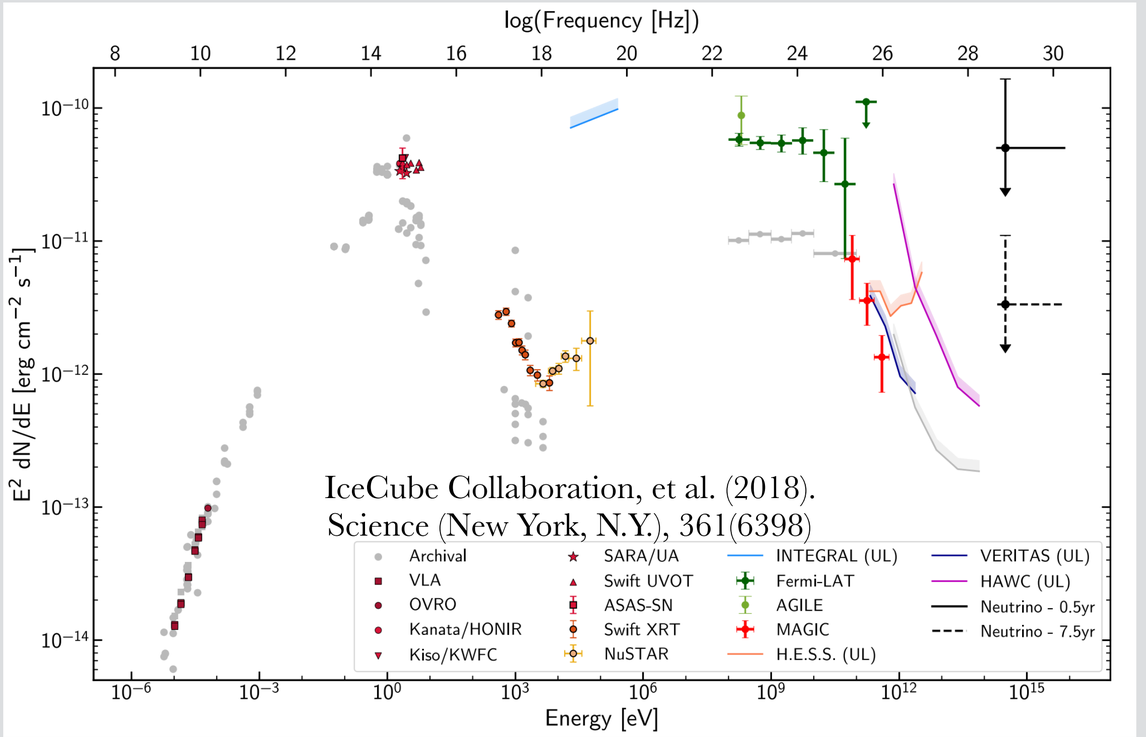


The Future

Fermi & HAWC are great instruments, ready to bring new insights from simultaneous observations of the whole γ-ray sky!

Tools such as 3ML will enable simultaneous fitting of sources across many instruments

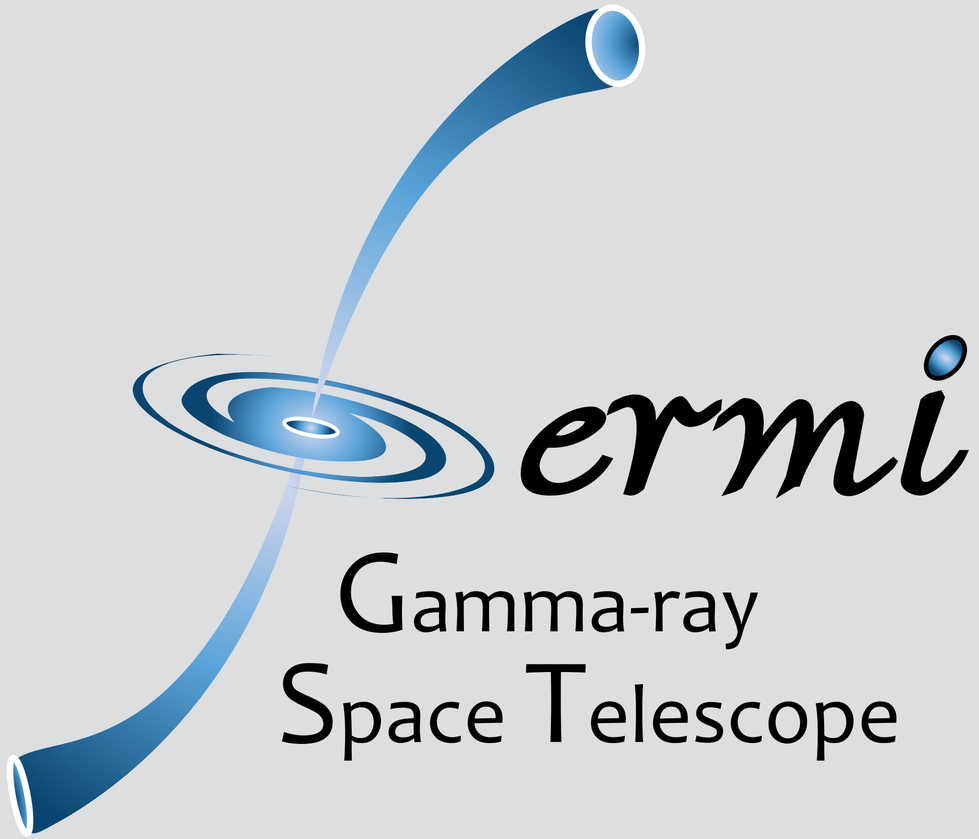
What if we could make this plot for the next Gravitational Wave/Neutrino detection?



Fermi/HAWC almost entirely bridges the gap between X-rays and neutrinos!

Thank you!

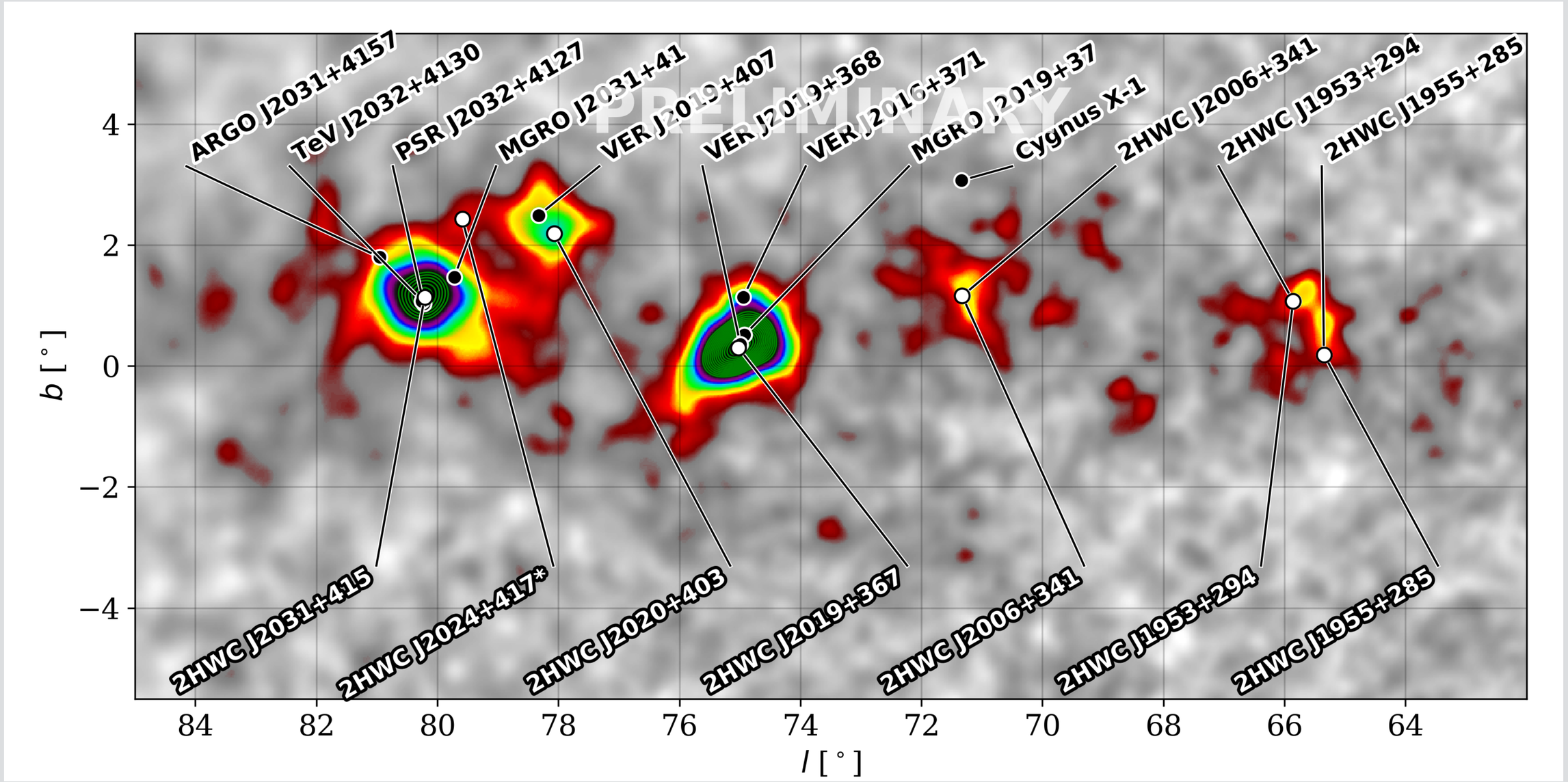

HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory


ermi
Gamma-ray
Space Telescope

Backup Slides

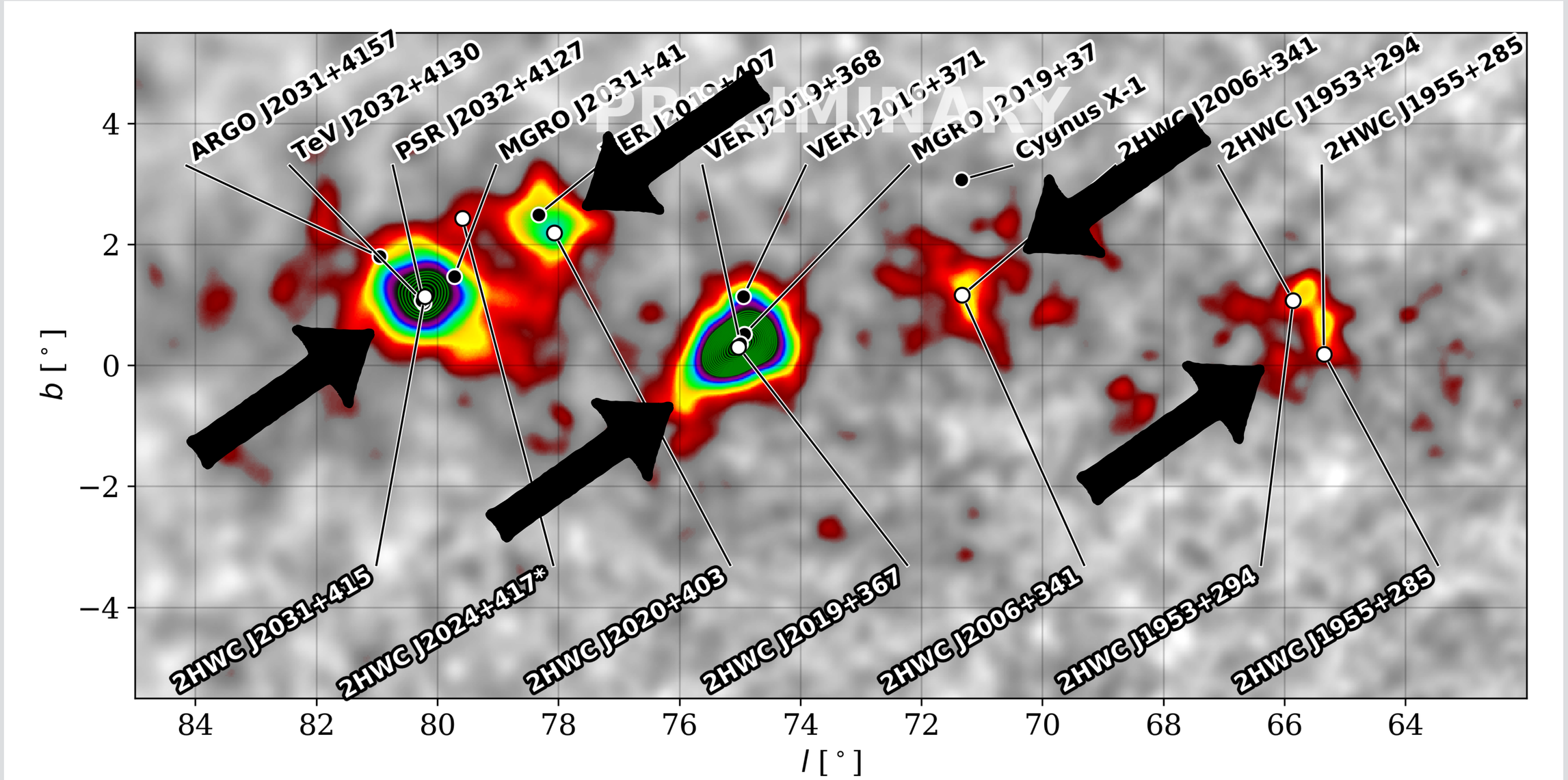
Fermi-HAWC Synergies

The Cygnus Region



Fermi-HAWC Synergies

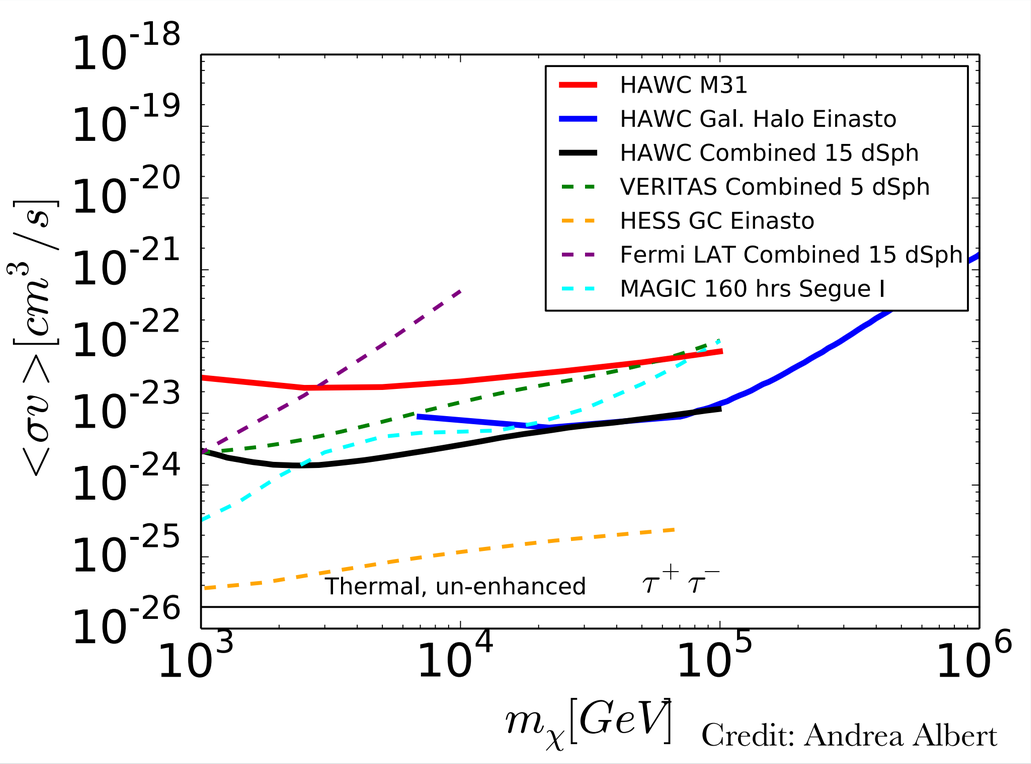
The Cygnus Region



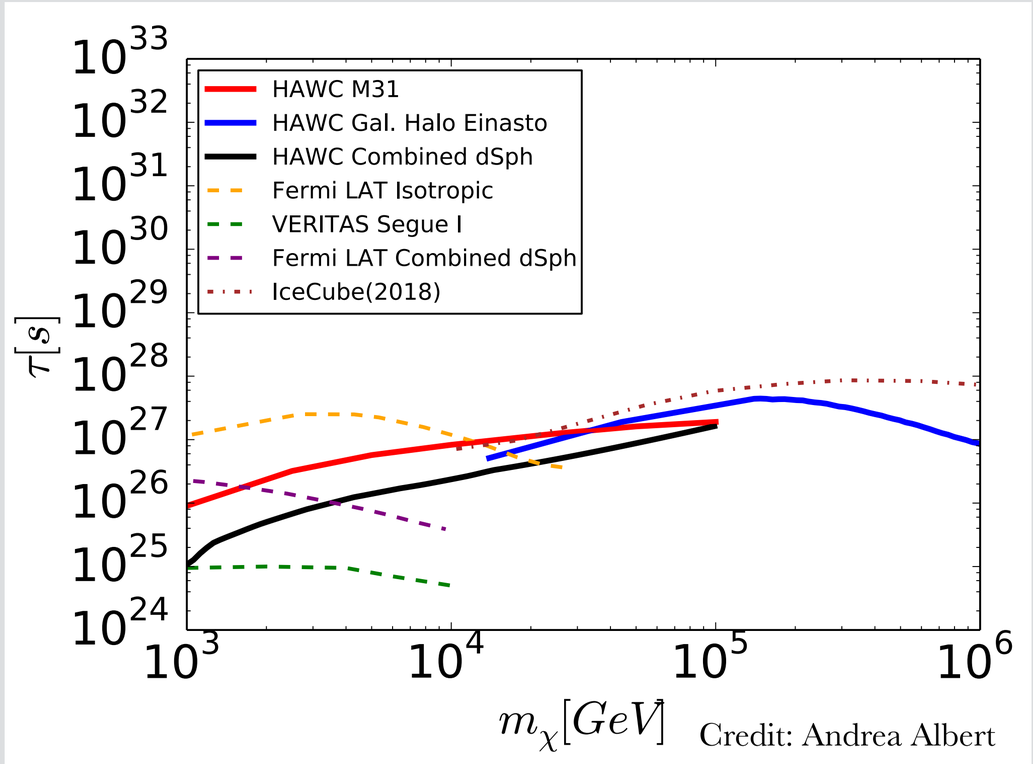
Fermi-HAWC Synergies
Dark Matter

Wide FoV, Continuous uptime enables trivial coincidence observations

If we see Dark Matter in annihilating/decaying somewhere, we should see it elsewhere. e.g. Galactic Center vs M31



$\tau\tau$ Annihilation upper limit



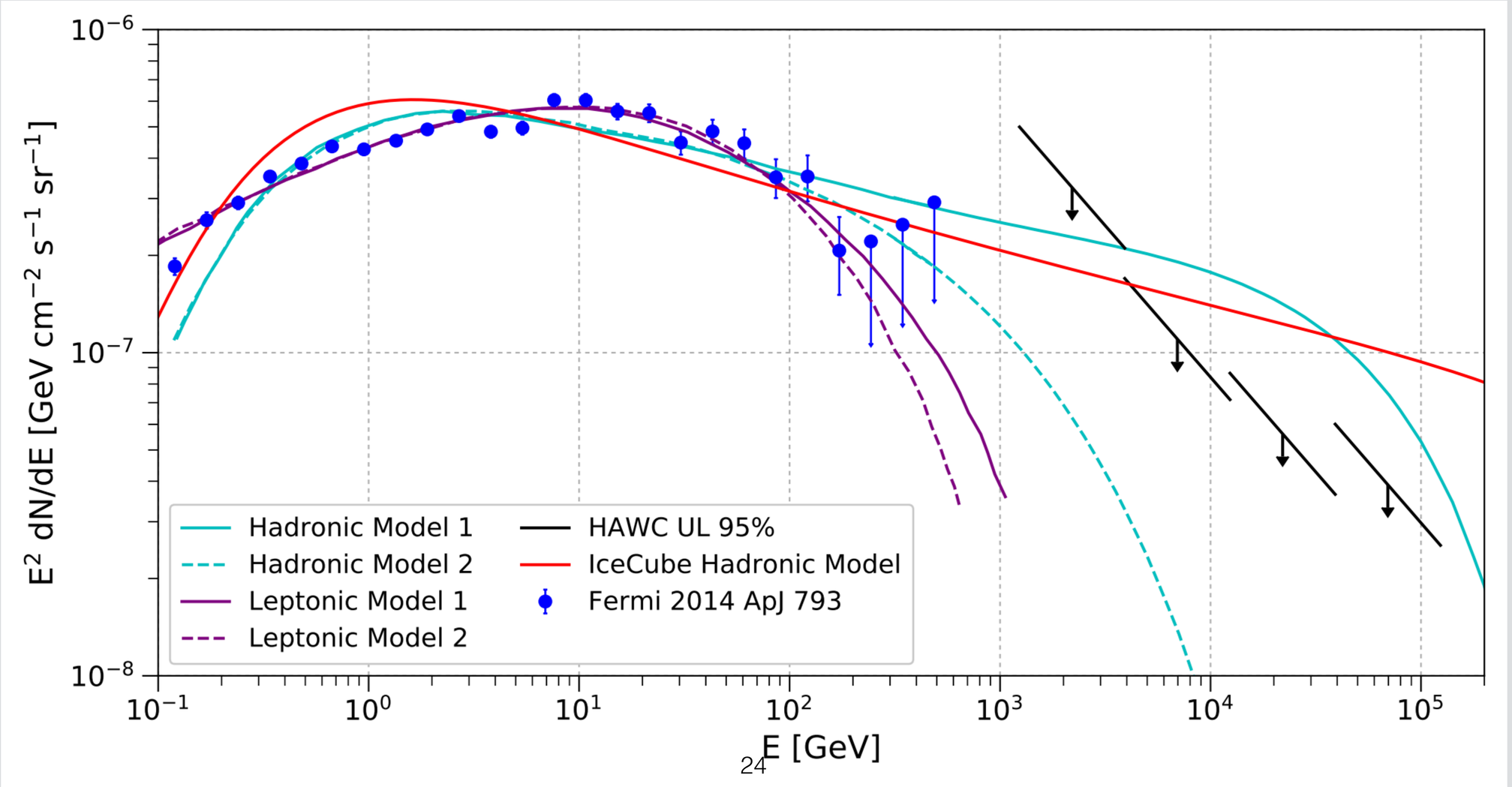
$\tau\tau$ Decay lifetime lower limit

Fermi-HAWC Synergies

Very Extended Sources

Nearly unbiased exposure enables extended studies

Mismodeled emission from known sources



Fermi-HAWC Synergies

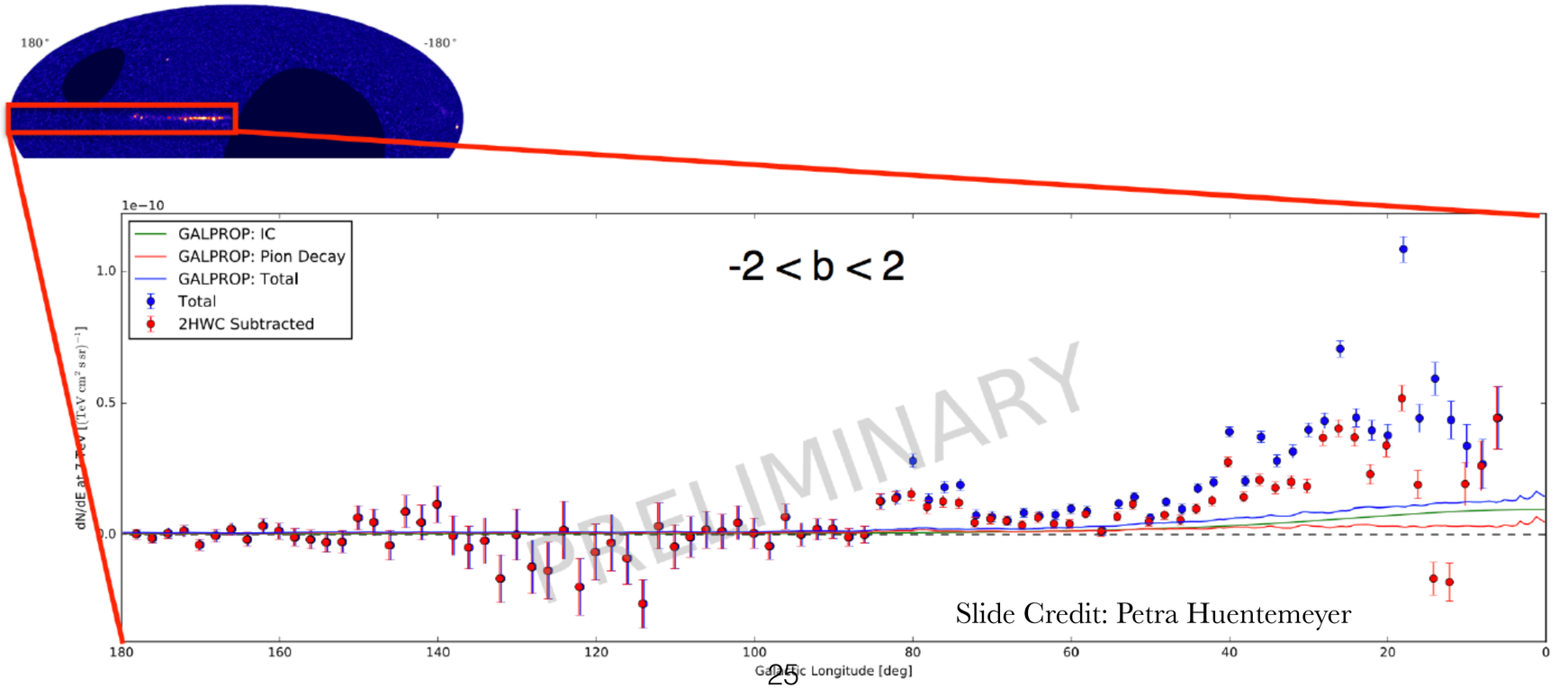
Very Extended Sources

Nearly unbiased exposure enables extended studies

Mismodeled emission from known sources

Extended Emission – Diffuse Emission

ICRC2017, Contrib. [436] [GA251] Probing Galactic Diffuse TeV Gamma-Ray Emission with the HAWC Observatory – **Hao Zhou, LANL**

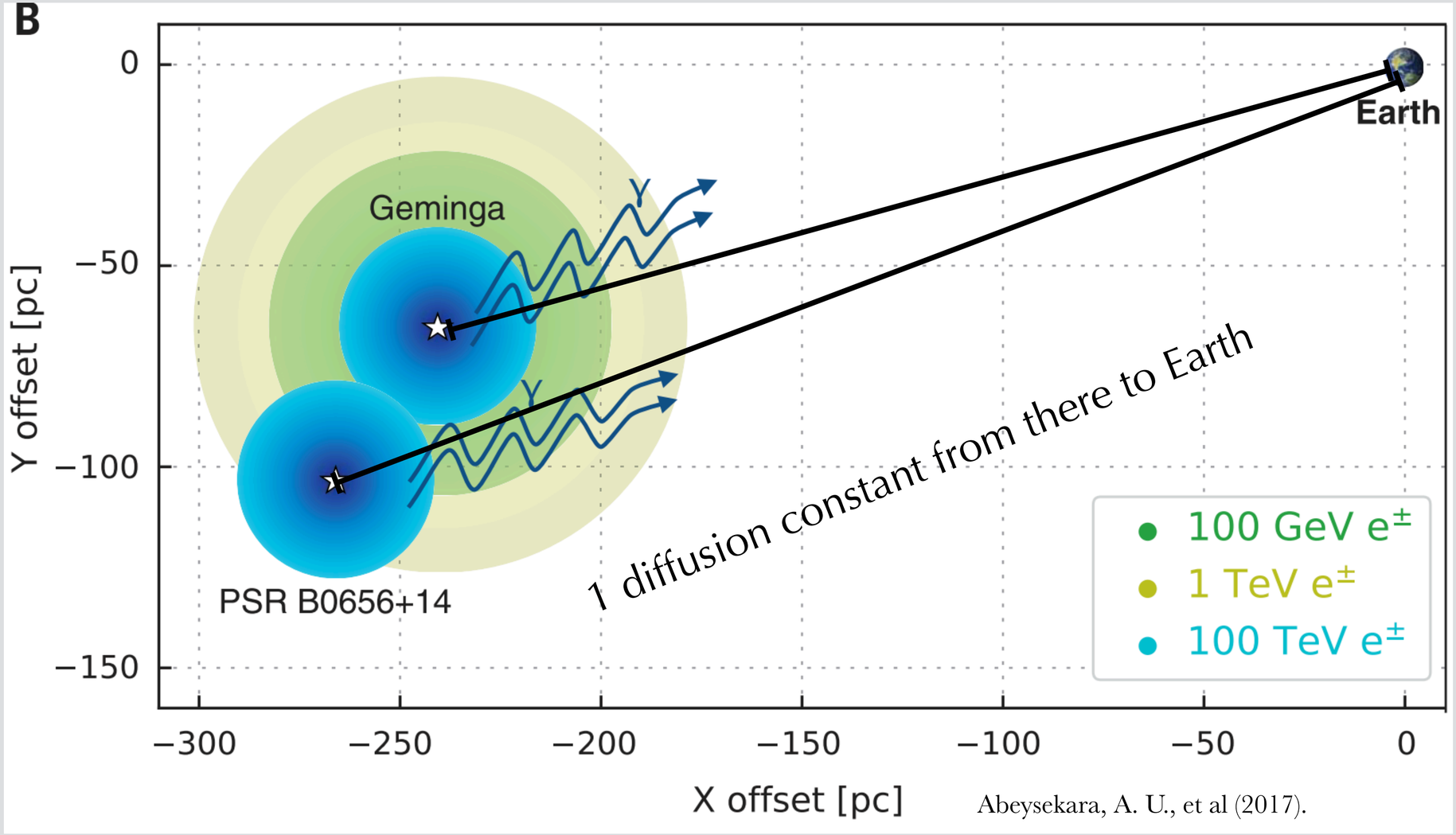


Slide Credit: Petra Huentemeyer

Fermi-HAWC Synergies

Geminga & The Positron Excess

1 Zone

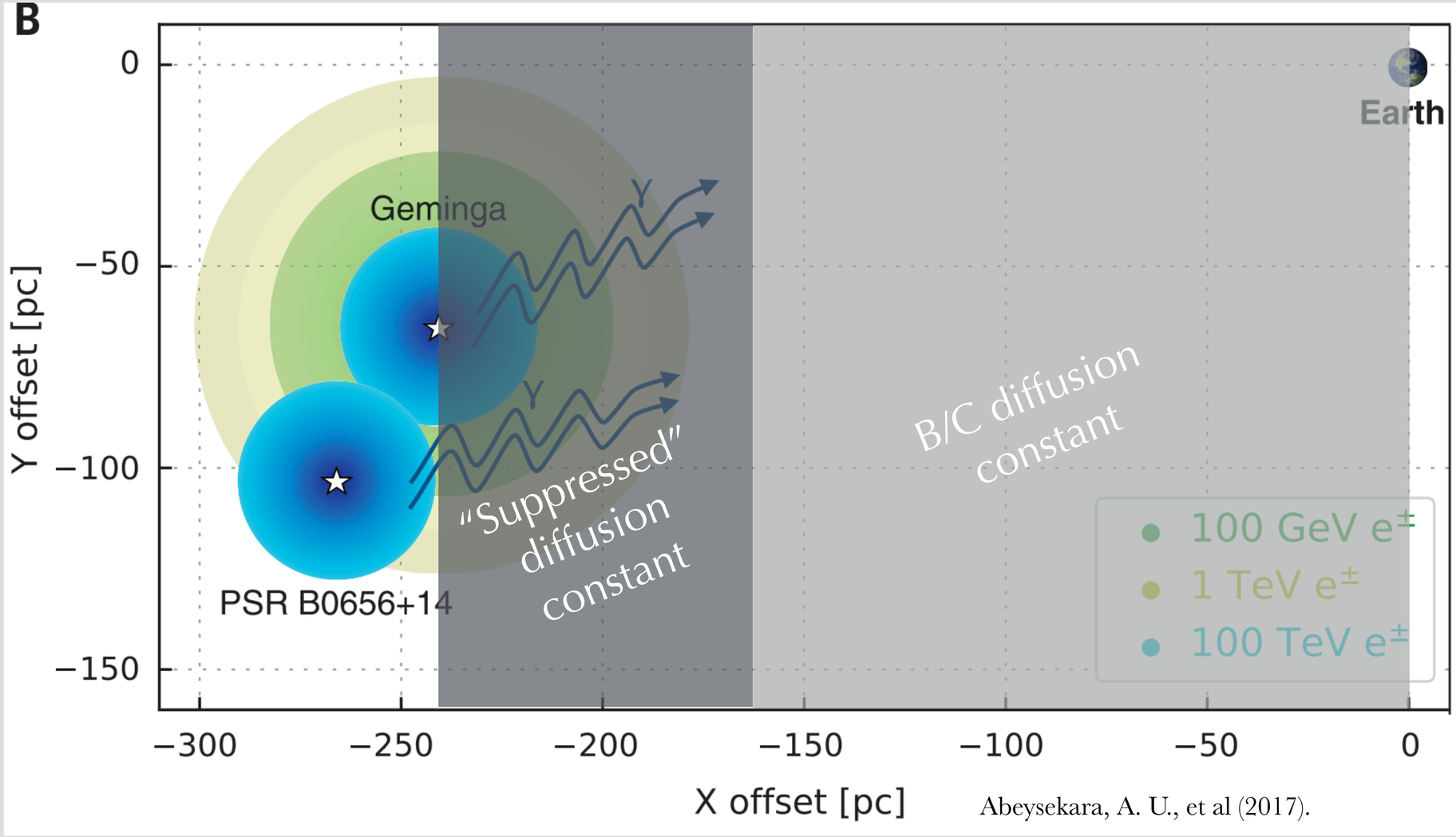


Abeysekara, A. U., et al (2017).

Fermi-HAWC Synergies

Geminga & The Positron Excess

2 Zone



Abeysekara, A. U., et al (2017).

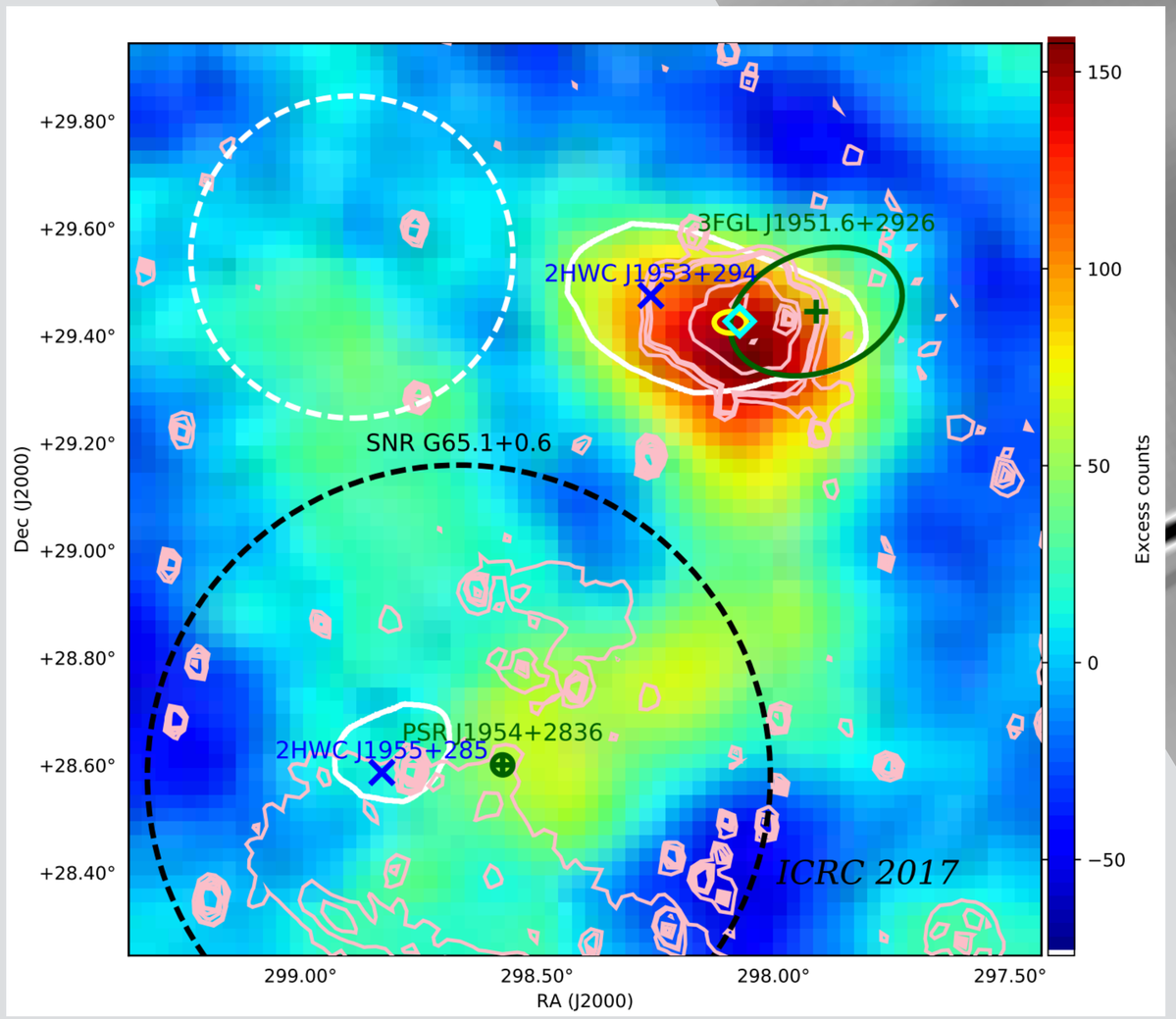
Fermi-HAWC Synergies
TeV Halos Prediction

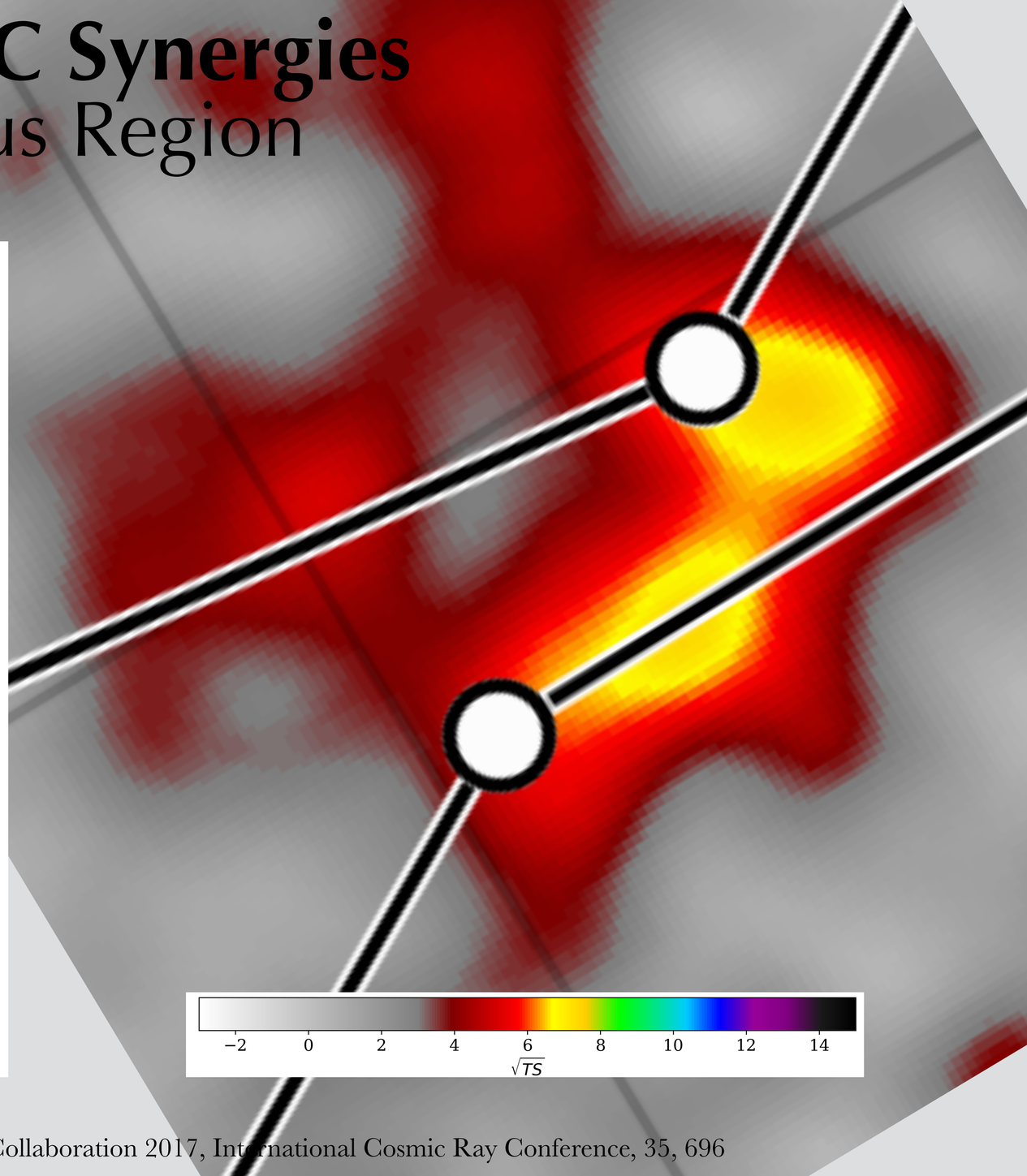
ATNF name	Dec. (°)	Distance (kpc)	Age (kyr)	Spin-down luminosity (erg s^{-1})	Spin-down flux (erg s^{-1} kpc^{-2})	2HWC
J0633+1746	17.77	0.25	342	3.2e34	4.1e34	2HWC J0631+169
B0656+14	14.23	0.29	111	3.8e34	3.6e34	2HWC J0700+143
B1951+32	32.87	3.00	107	3.7e36	3.3e34	···
J1740+1000	10.00	1.23	114	2.3e35	1.2e34	···
J1913+1011	10.18	4.61	169	2.9e36	1.1e34	2HWC J1912+099
J1831-0952	−9.86	3.68	128	1.1e36	6.4e33	2HWC J1831-098
J2032+4127	41.45	1.70	181	1.7e35	4.7e33	2HWC J2031+415
B1822-09	−9.58	0.30	232	4.6e33	4.1e33	···
B1830-08	−8.45	4.50	147	5.8e35	2.3e33	···
J1913+0904	9.07	3.00	147	1.6e35	1.4e33	···
B0540+23	23.48	1.56	253	4.1e34	1.4e33	···

ATel #10941 & #12013

Table 3 from Linden, T., et al (2017). Using HAWC to discover invisible pulsars. Physical Review D, 96(10), 103016.

Fermi-HAWC Synergies
The Cygnus Region





Park, N., VERITAS Collaboration, Fermi-Lat Collaboration, HAWC Collaboration 2017, International Cosmic Ray Conference, 35, 696

Fermi-HAWC Synergies

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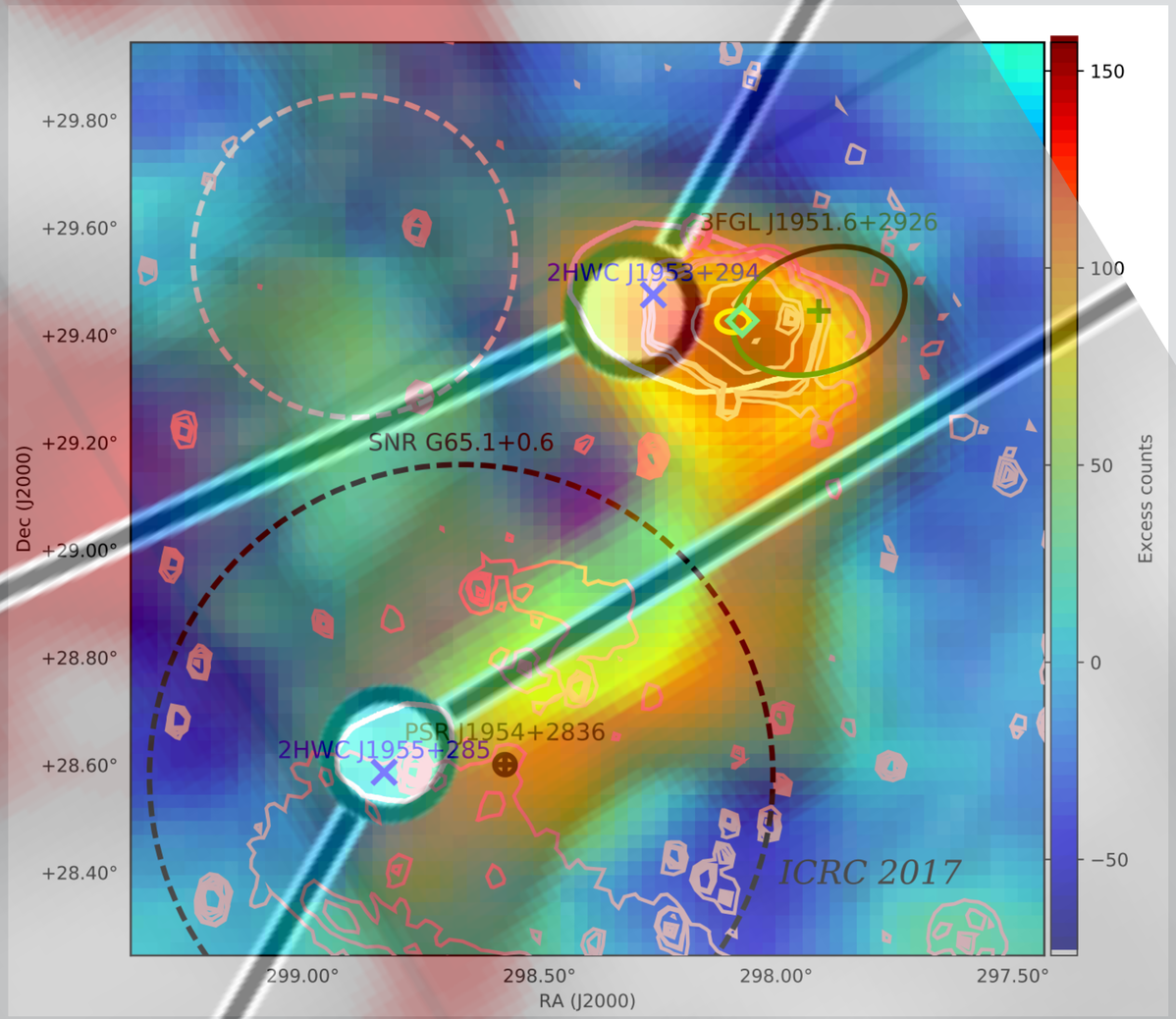

Park, N., VERITAS Collaboration, Fermi-Lat Collaboration, HAWC Collaboration 2017, International Cosmic Ray Conference, 35, 696