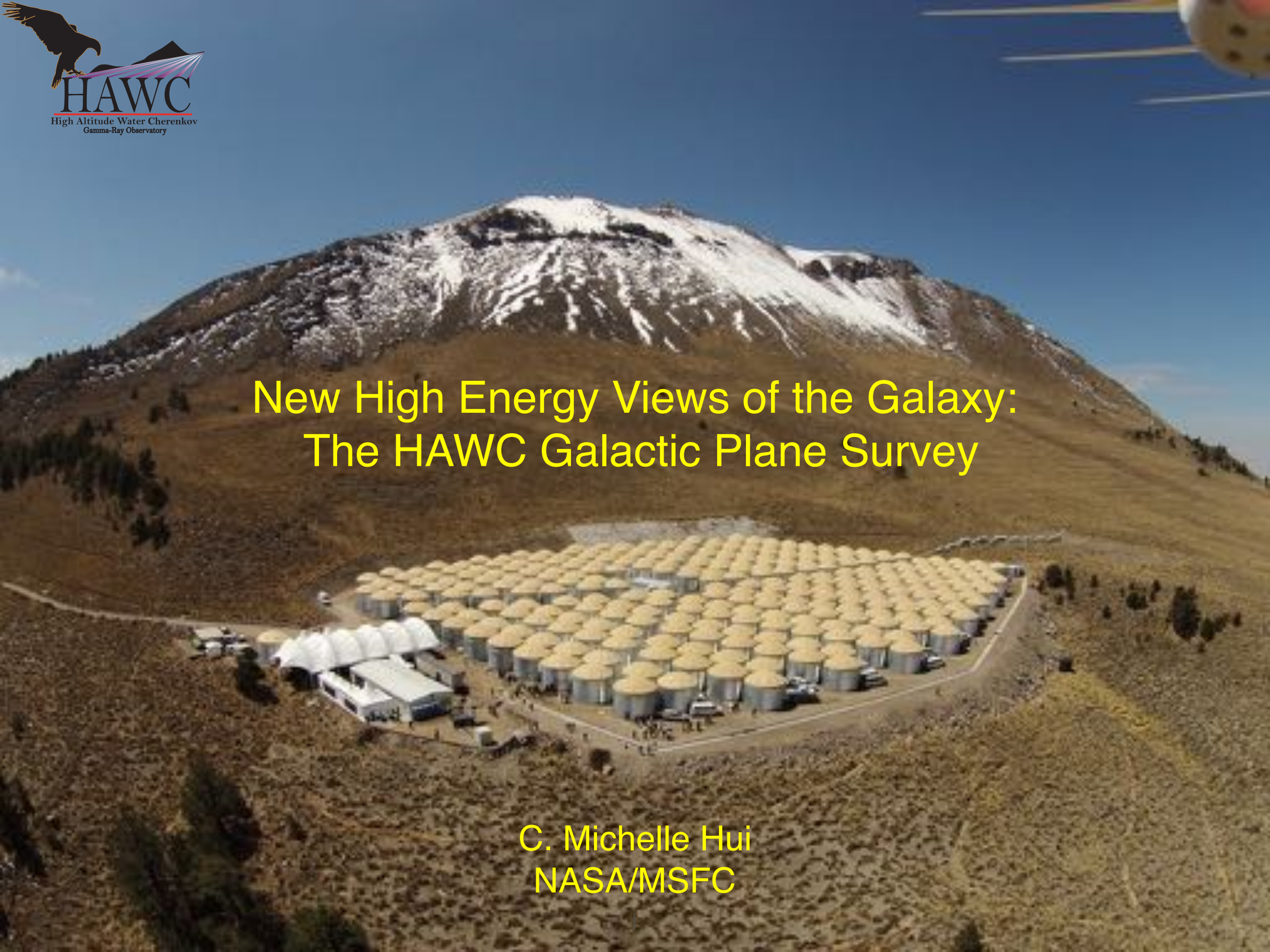
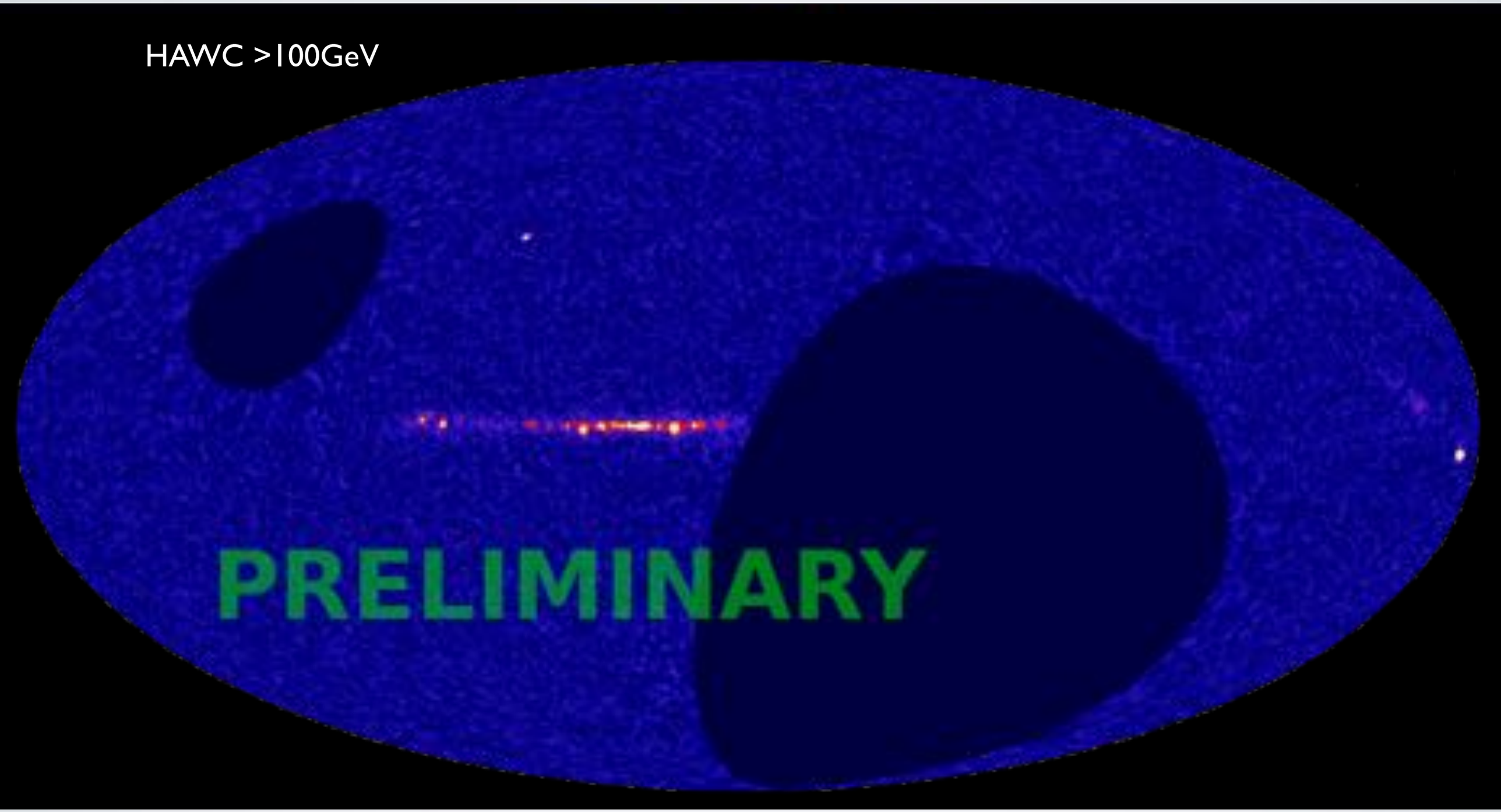


New High Energy Views of the Galaxy: The HAWC Galactic Plane Survey

C. Michelle Hui
NASA/MSFC

Multi-Wavelength View of our Galaxy



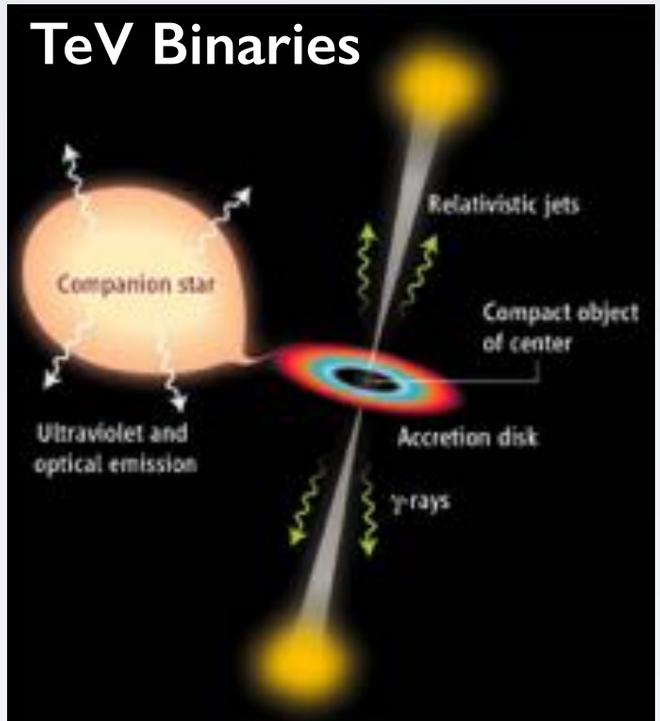
Galactic Science Topics

Pulsar Wind Nebulae

credit: NASA / CXC / SAO / F. D. Seward, W. H. Tucker, R. A. Fesen

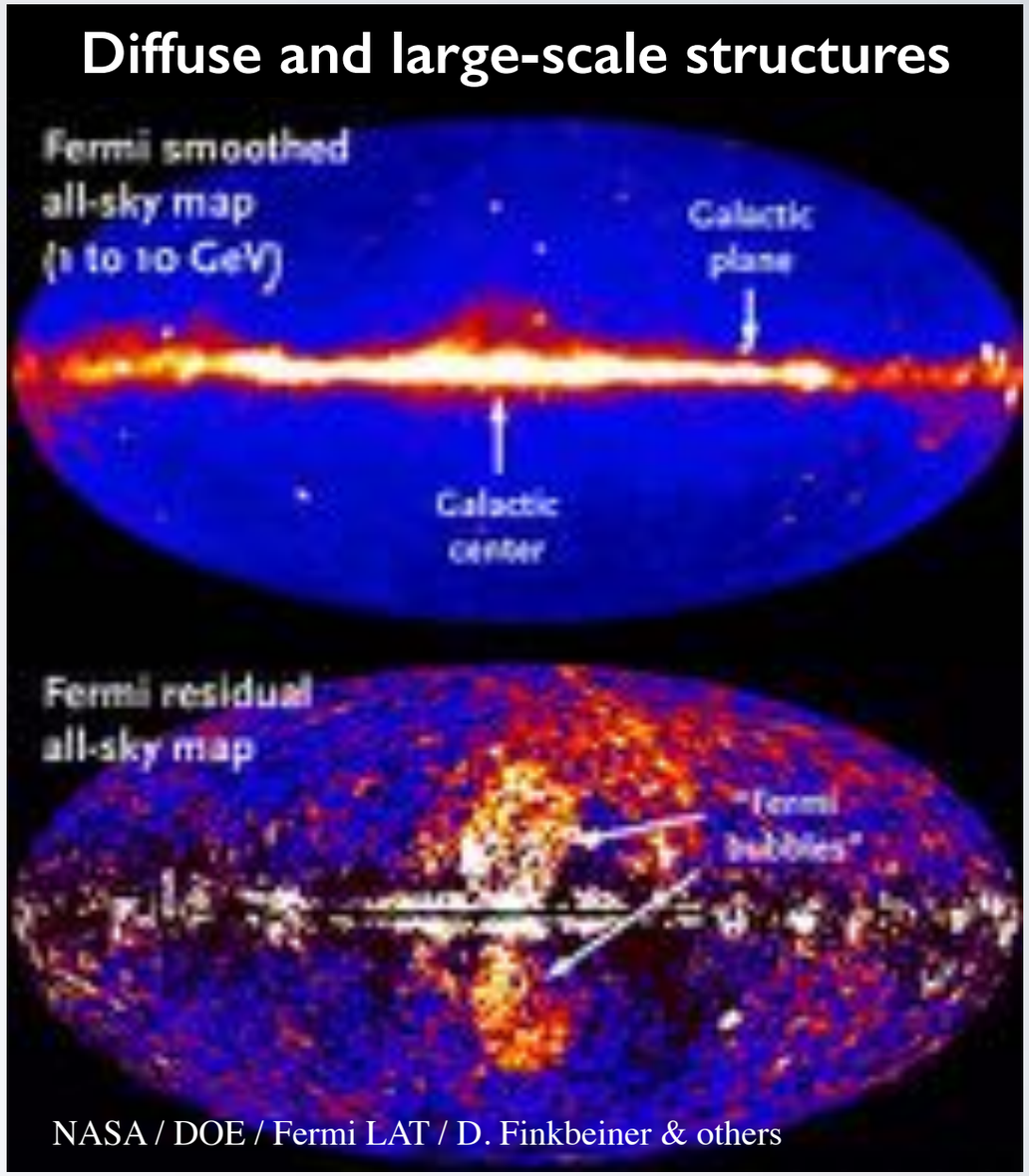
Supernova Remnants

TeV Binaries



Mirabel, Science, 312, 1759

Diffuse and large-scale structures



NASA / DOE / Fermi LAT / D. Finkbeiner & others

Gamma-Ray Detectors

HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

Wide Field of View, C
Operations

ensitivity

MAGIC
VERITAS

HAWC collaboration

Georgia Institute of Technology
George Mason University
Los Alamos National Laboratory
Michigan State University
Michigan Technological University
NASA/Goddard Space Flight Center
NASA/Marshall Space Flight Center
University of New Hampshire
Pennsylvania State University
University of California, Irvine
University of California, Santa Cruz
University of Maryland
University of New Mexico
University of Rochester
University of Wisconsin-Madison
University of Utah

Centro de Investigacion en Computacion, IPN
Centro de Investigacion y de Estudios Avanzados del IPN
Benemérita Universidad Autónoma de Puebla
Universidad Nacional Autónoma de México:
- Instituto de Astronomía
- Instituto de Ciencias Nucleares
- Instituto de Física
- Instituto de Geofísica

Instituto Nacional de Astrofísica, Óptica y Electrónica
Universidad Autónoma del Estado de Hidalgo
Universidad Michoacana de San Nicolás de Hidalgo
Universidad Autónoma de Chiapas
Universidad Politecnica de Pachuca
Universidad de Guadalajara
Instytut Fizyki Jadrowej im Henryka Niewodniczanskiego
Polskiej Akademii Nauk, IFJ-PAN

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Red de Física de Altas Energías, México;
DGAPA-UNAM, México;
and the University of Wisconsin Alumni Research Foundation.

Mapping the Northern Sky in High-Energy Gamma Rays

HAWC Observatory

HAWC operates day and night, providing a large field of view for the observation of the highest energy gamma rays.

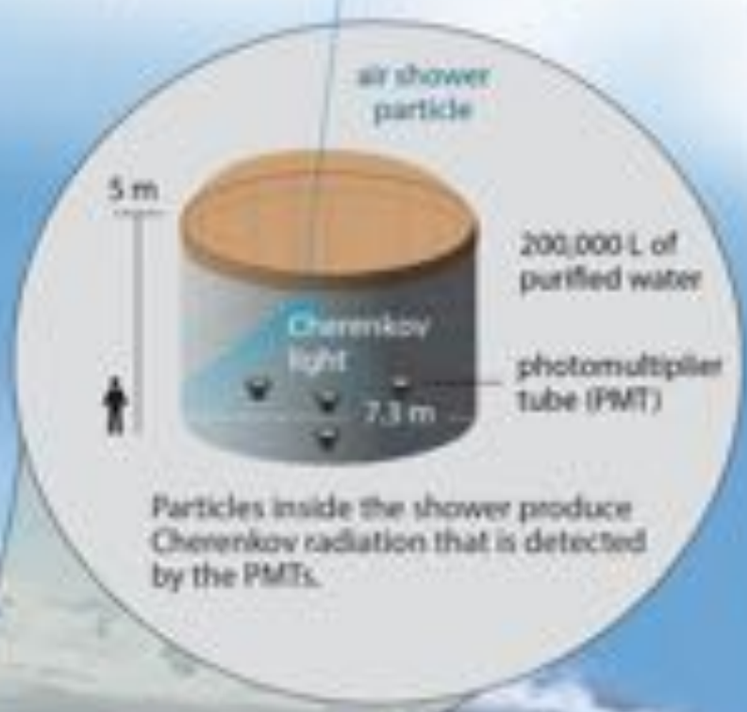
Pico de Orizaba
(5,626 m)

HAWC is located at 4,100 m above sea level, covering an area of 20,000 m².

150 m

Water Cherenkov tank

HAWC comprises an array of 300 tanks that record the particles created in gamma-ray and cosmic-ray showers.



Particles inside the shower produce Cherenkov radiation that is detected by the PMTs.

Gamma rays vs cosmic rays

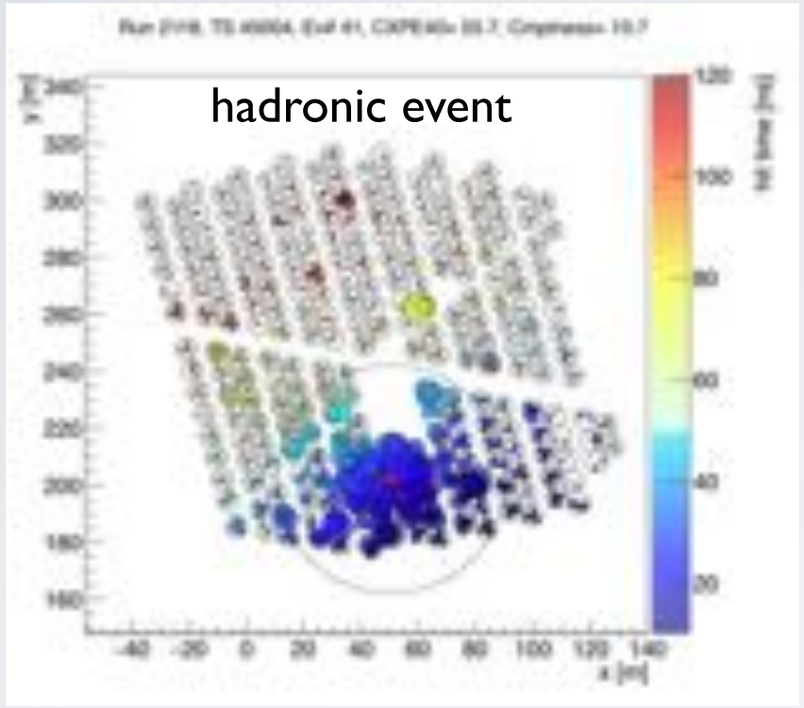
HAWC selects gamma rays from among a much more abundant background of cosmic rays.

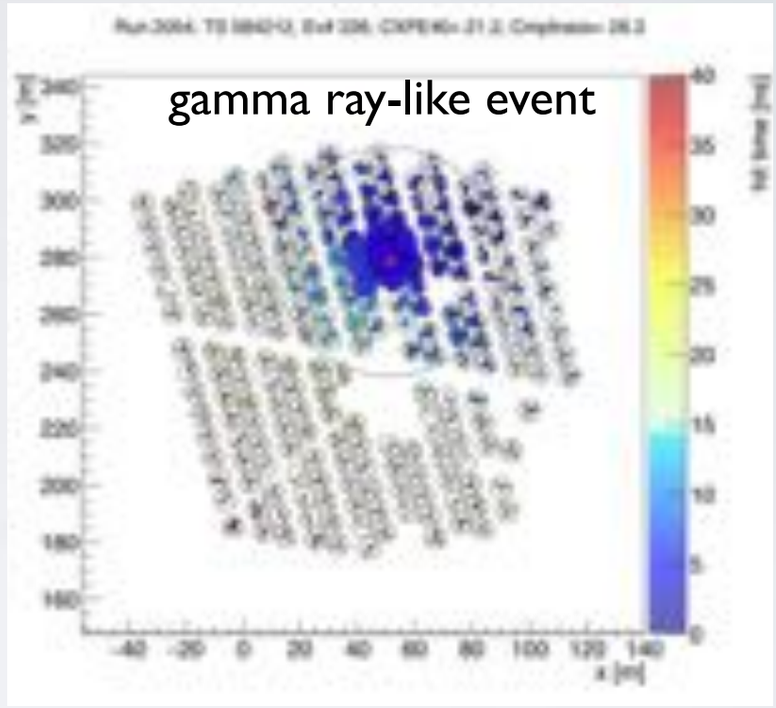
"hot" spots concentrate around the core

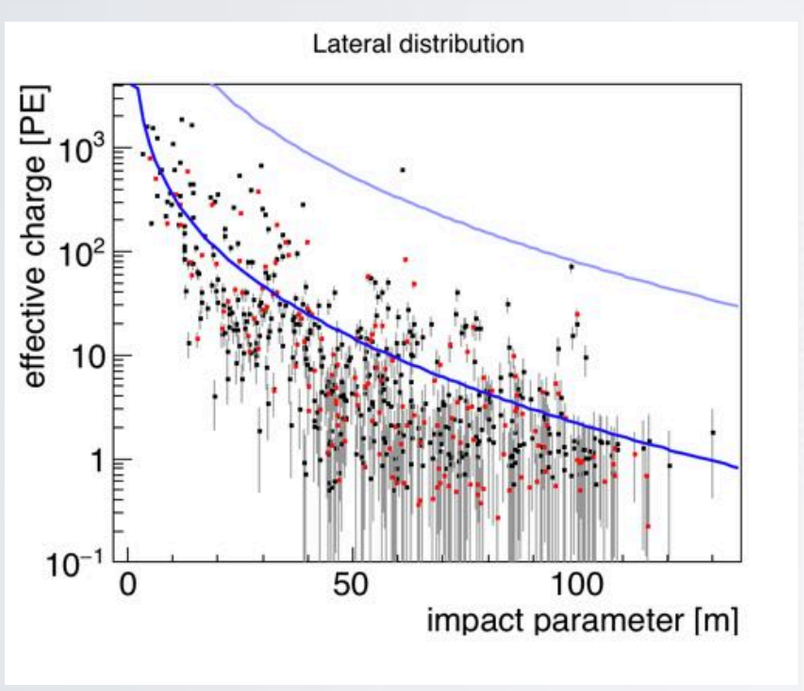
"hot" spots are more dispersed

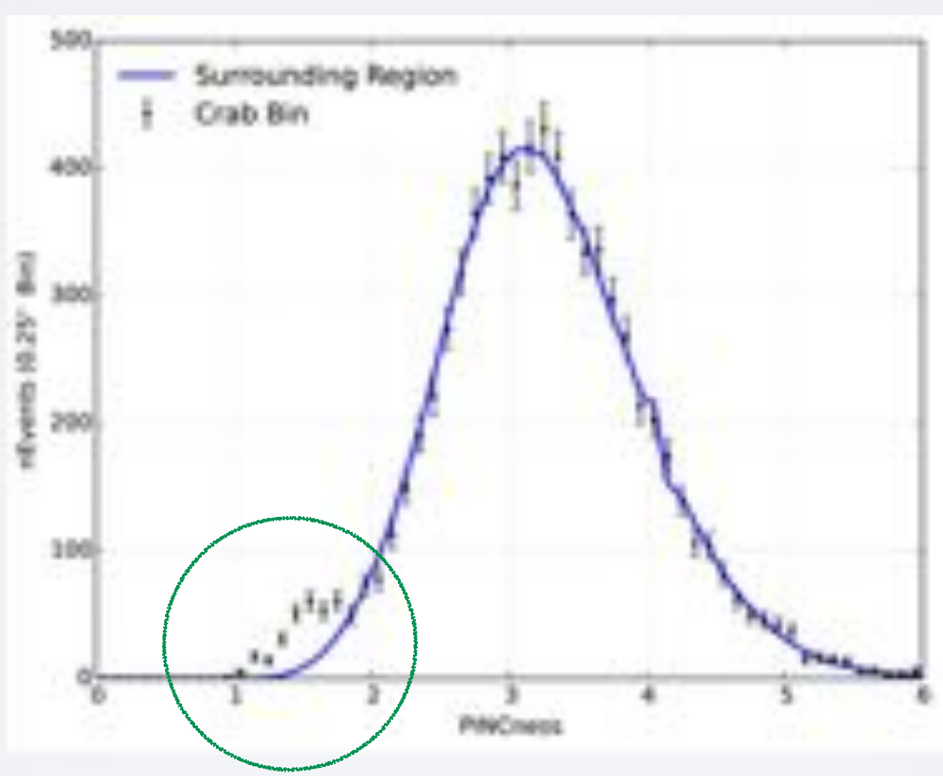
More on HAWC:
M. Mostafa (E13, Apr 16)

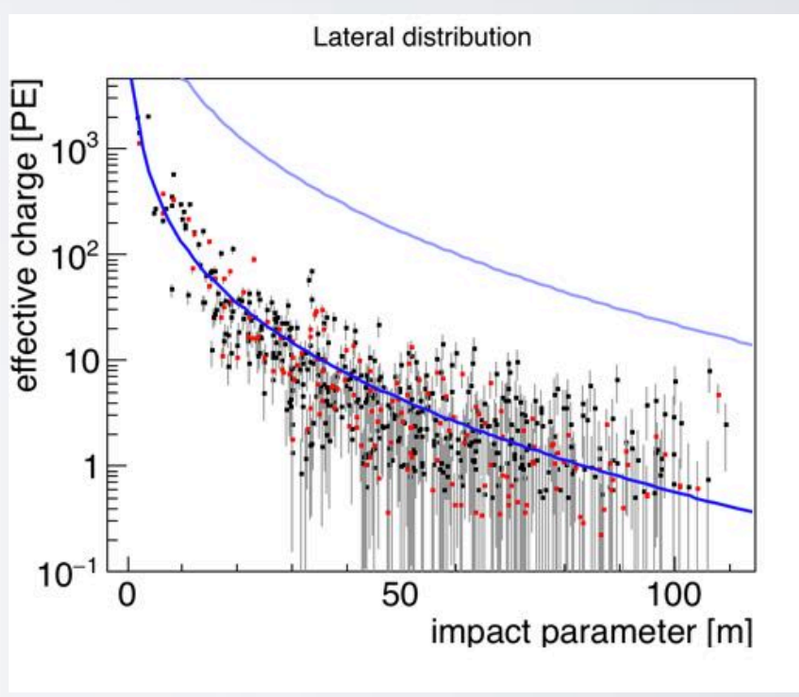
Gamma/Hadron Separation



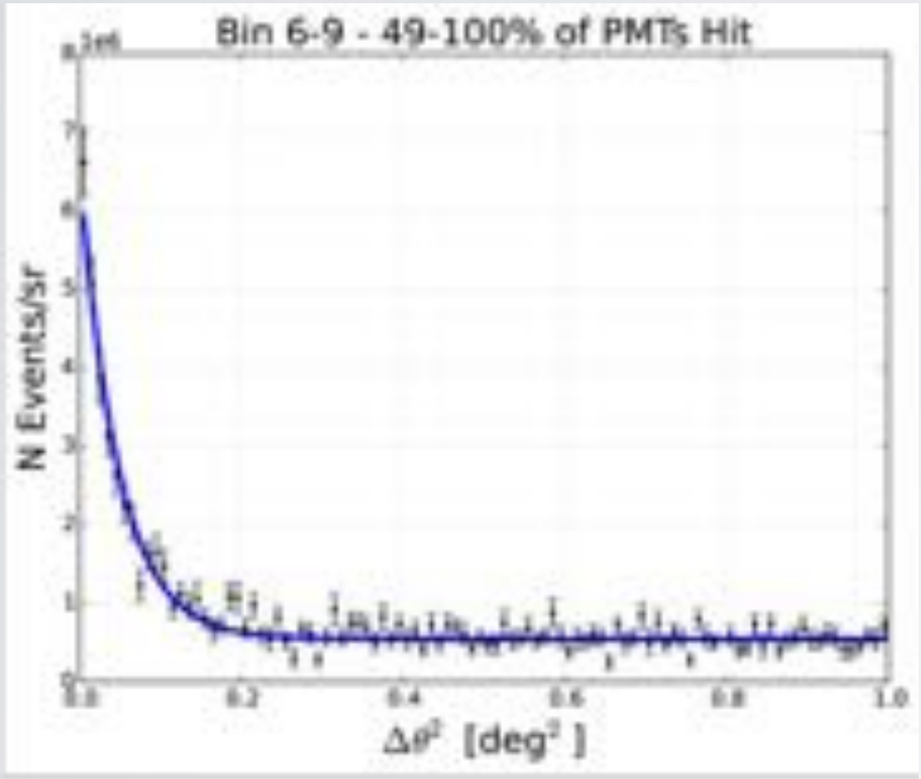


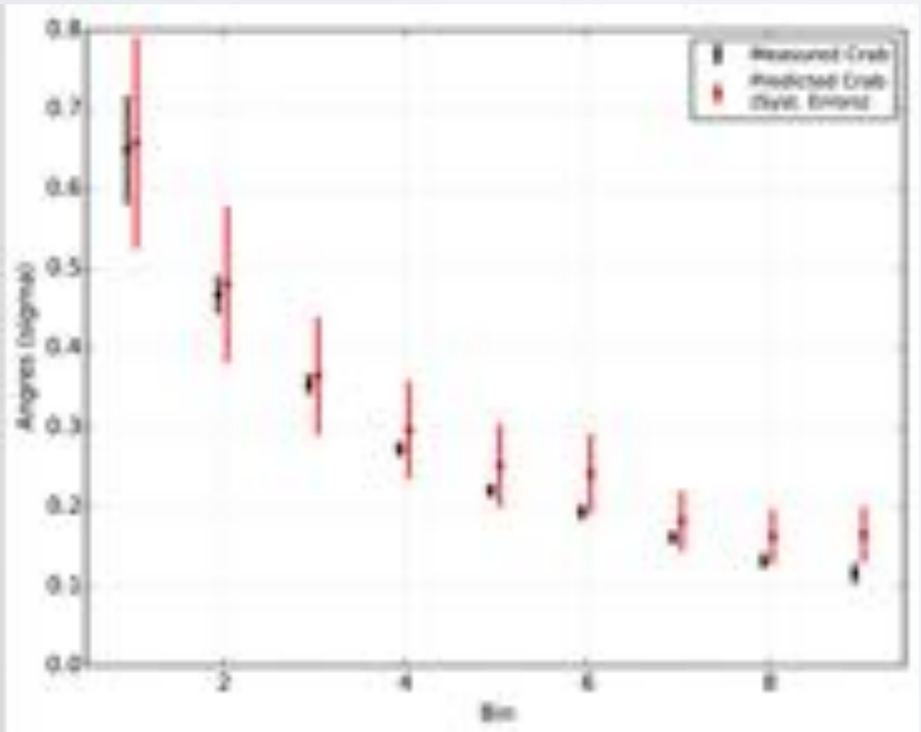




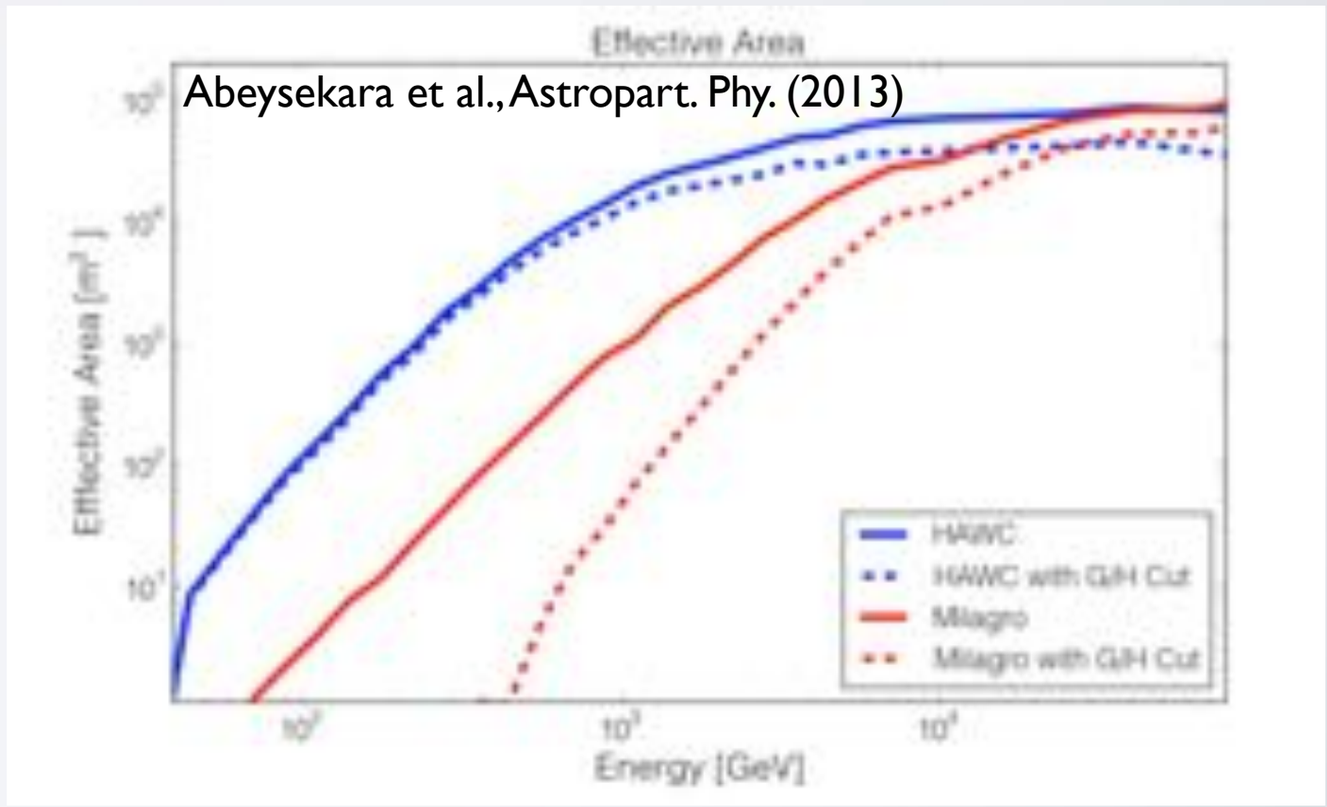


HAWC Characteristics

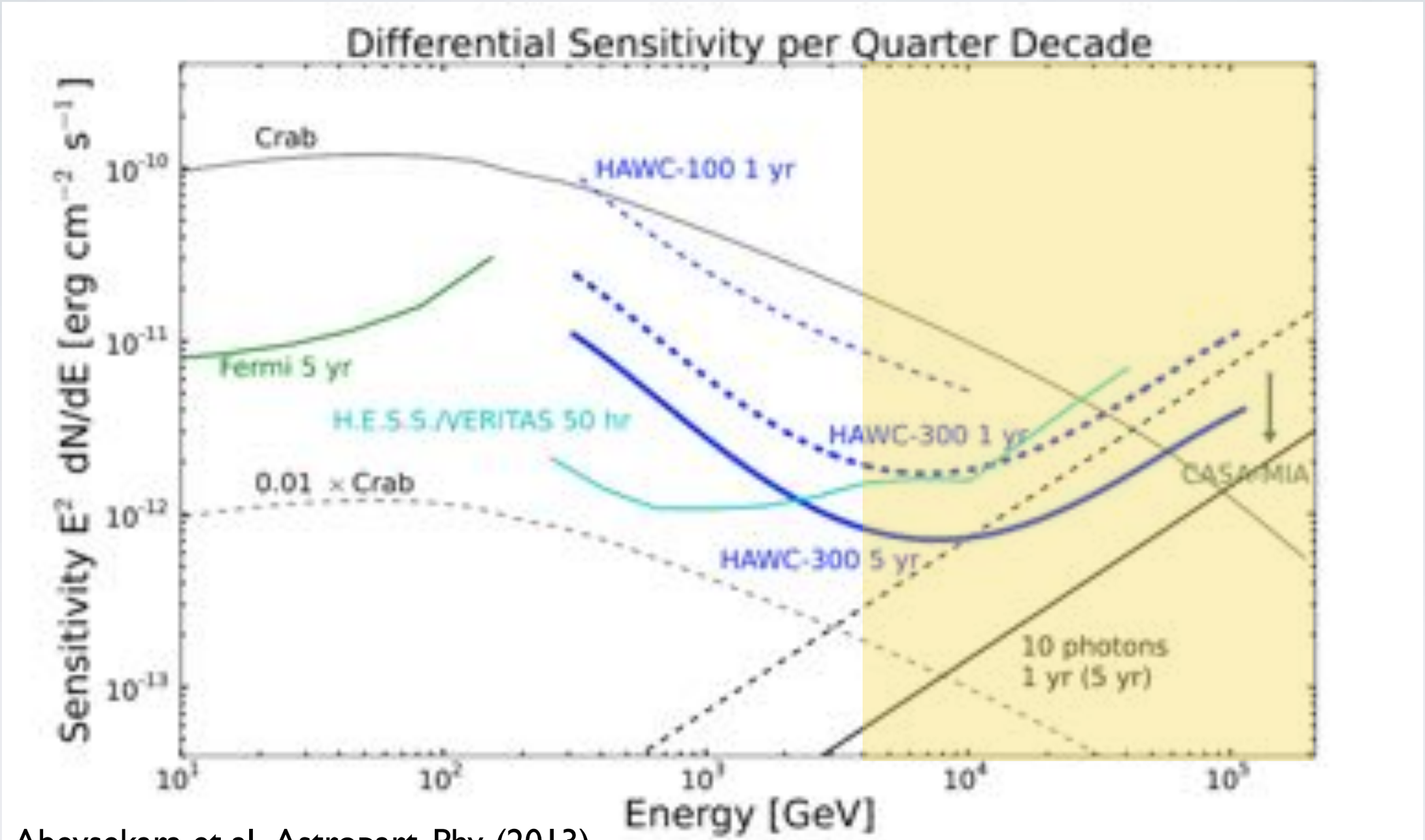




- 0.15° PSF at highest energy.
- Larger effective area below 1 TeV.



HAWC Differential Sensitivity

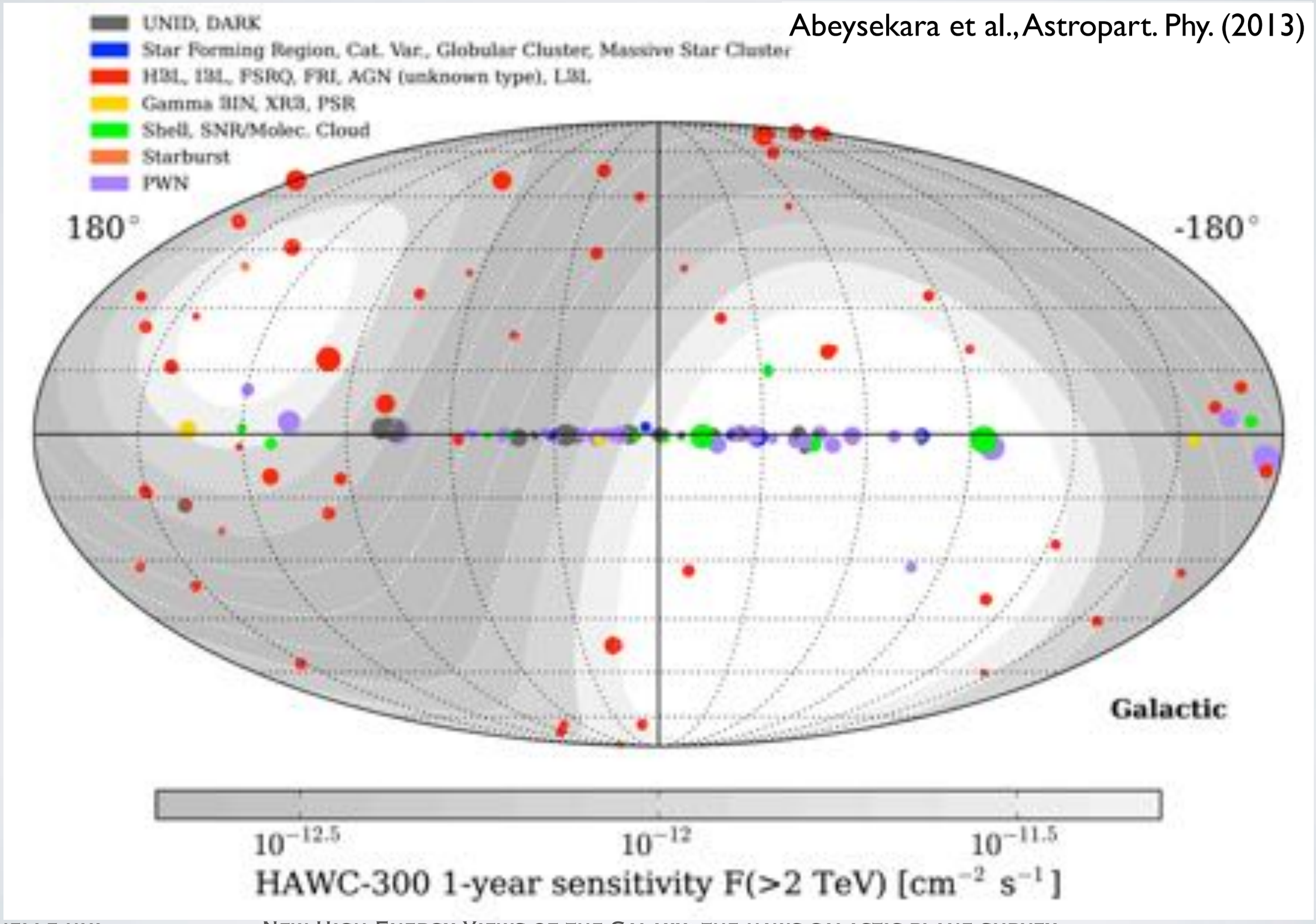


Abeysekara et al., Astropart. Phy. (2013)

Equivalent of a 50-hour observation above a fewTeV on **every source** in 1 year.

HAWC All-sky Sensitivity

Abeysekara et al., Astropart. Phy. (2013)



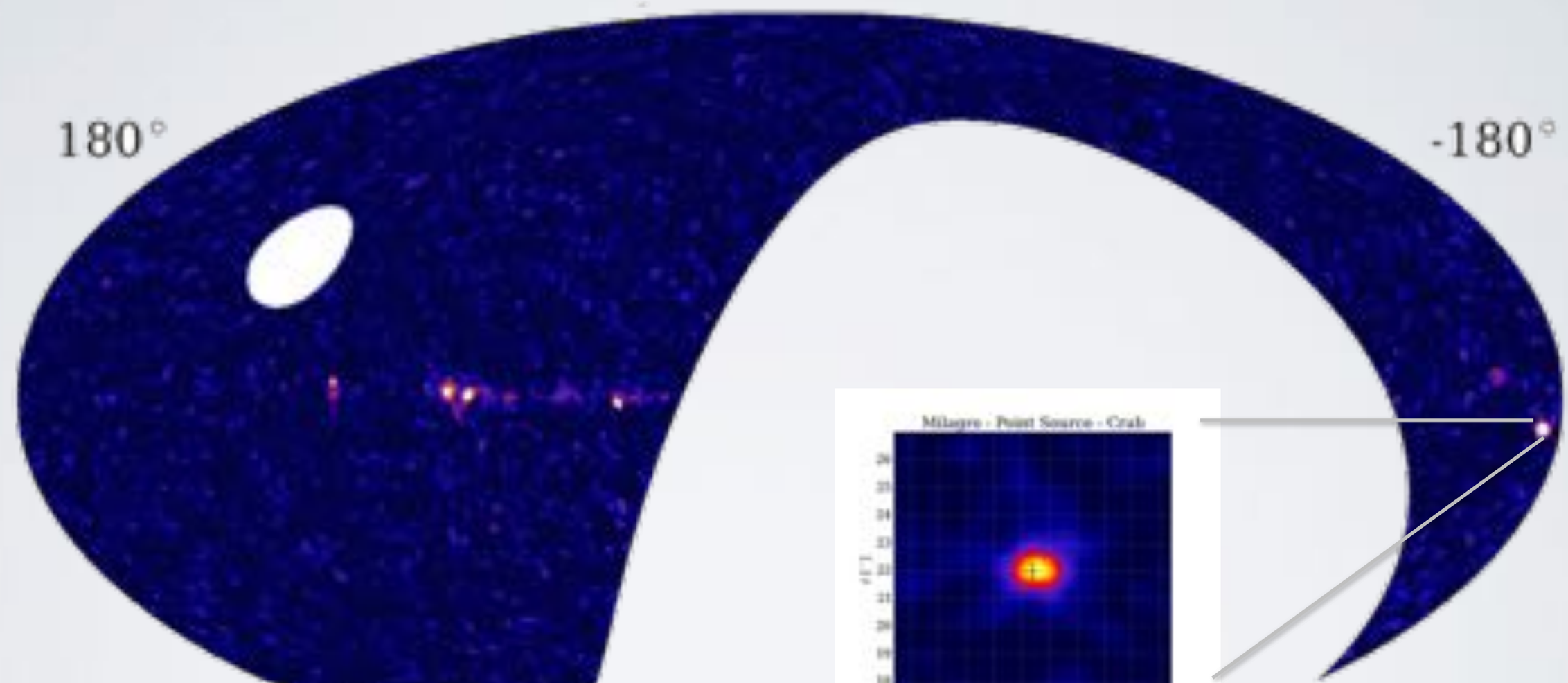
High Altitude Water Cherenkov Gamma-ray Observatory

- Sensitive from 100 GeV to 100 TeV.
- Angular resolution 0.12-0.65 degrees.
- 2sr instantaneous field of view, 2/3 of sky each day.
- >95% duty cycle.
- **Strengths:**
  Extreme high-energy reach.
  Wide field-of-view: ideal for transients and extended objects.
  High duty cycle.

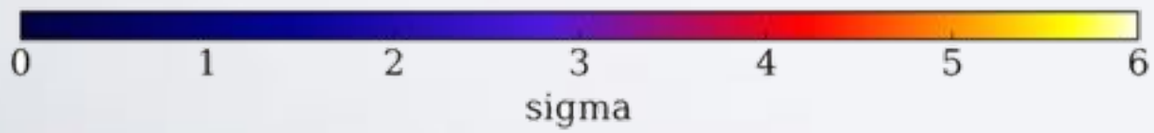
HAWC-30: began Aug 2012
HAWC-111: Jun 2013 (~280 days)
HAWC: Nov 2014 (341+ days)
Inauguration Mar 2015

Milagro 8-Year TeV Sky Survey

HAWC predecessor

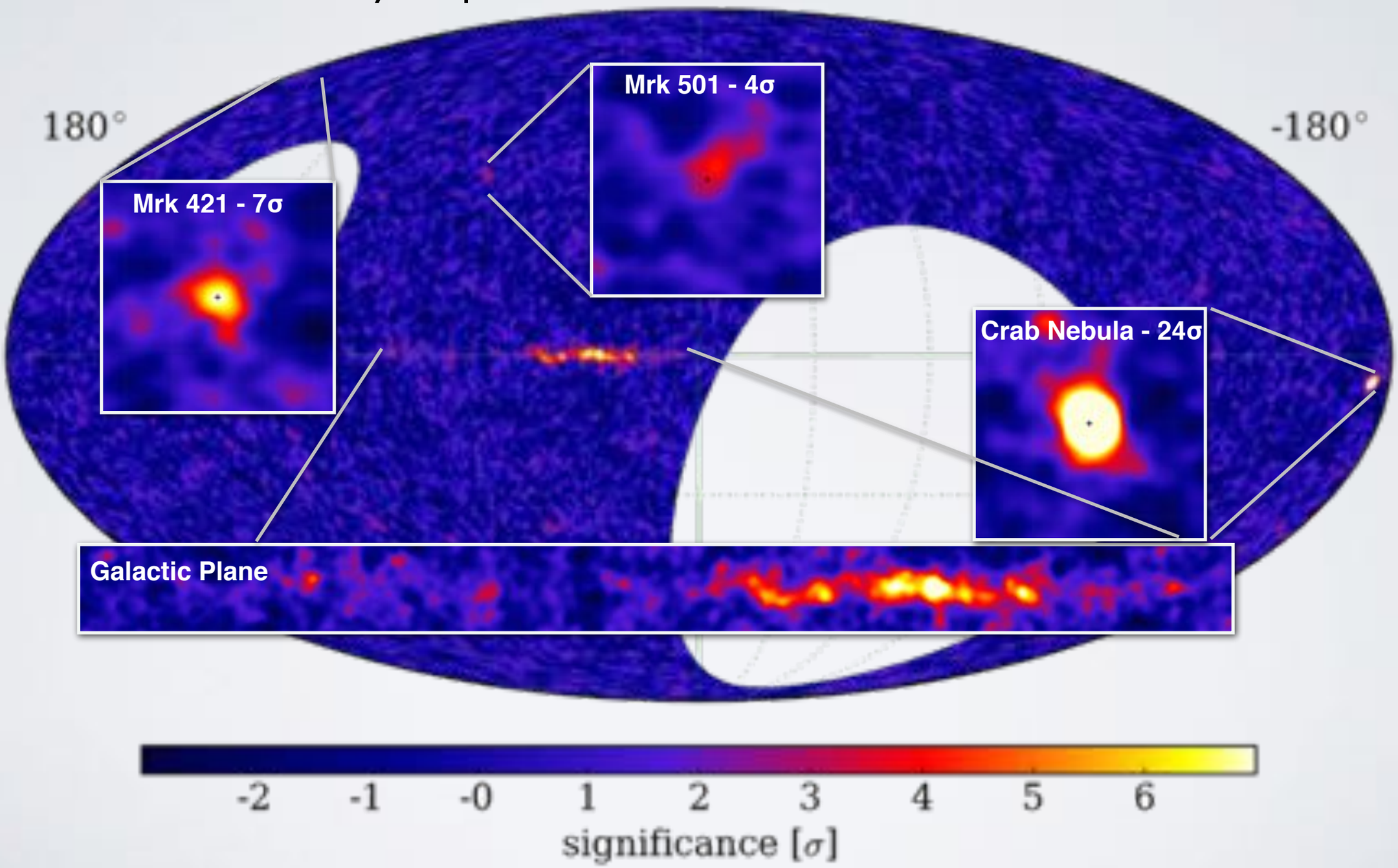


Crab at 17σ in 8 years.



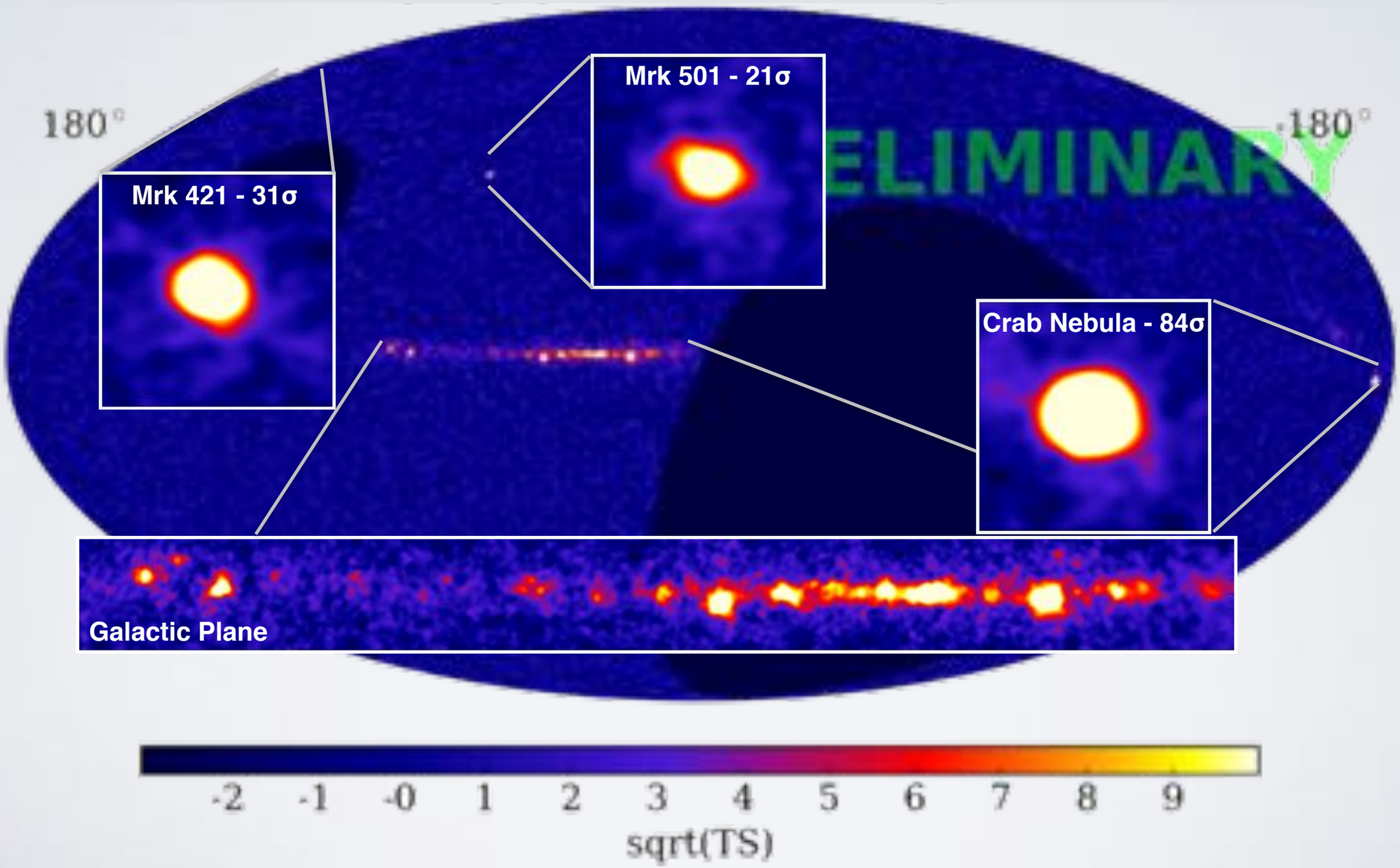
HAWC-111 Sky Map
Pass 1 Analysis

- Skymap from 283 days of data taken with 1/3 of the HAWC array.
- Point source analysis optimized on the Crab Nebula.



HAWC 341-Day TeV Sky Survey

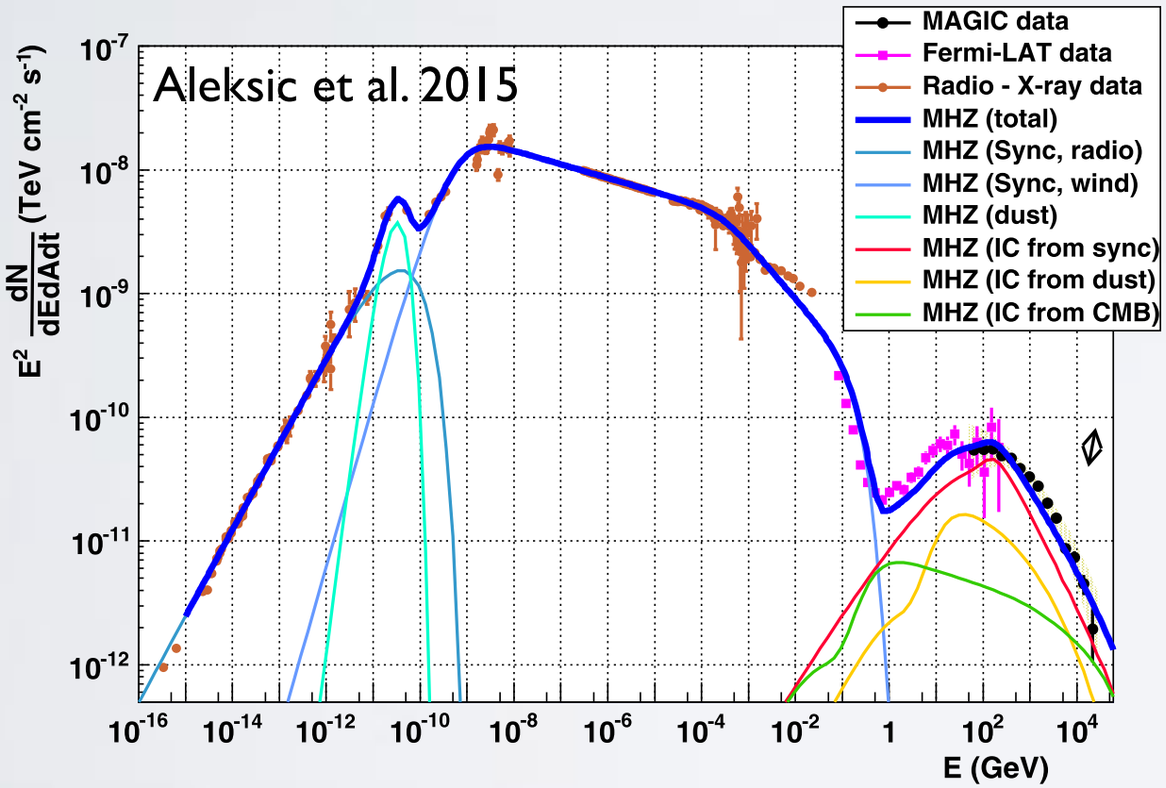
- Skymap from 341 days of data taken with the finished HAWC array.
- Point source analysis assuming power-law index of 2.7.

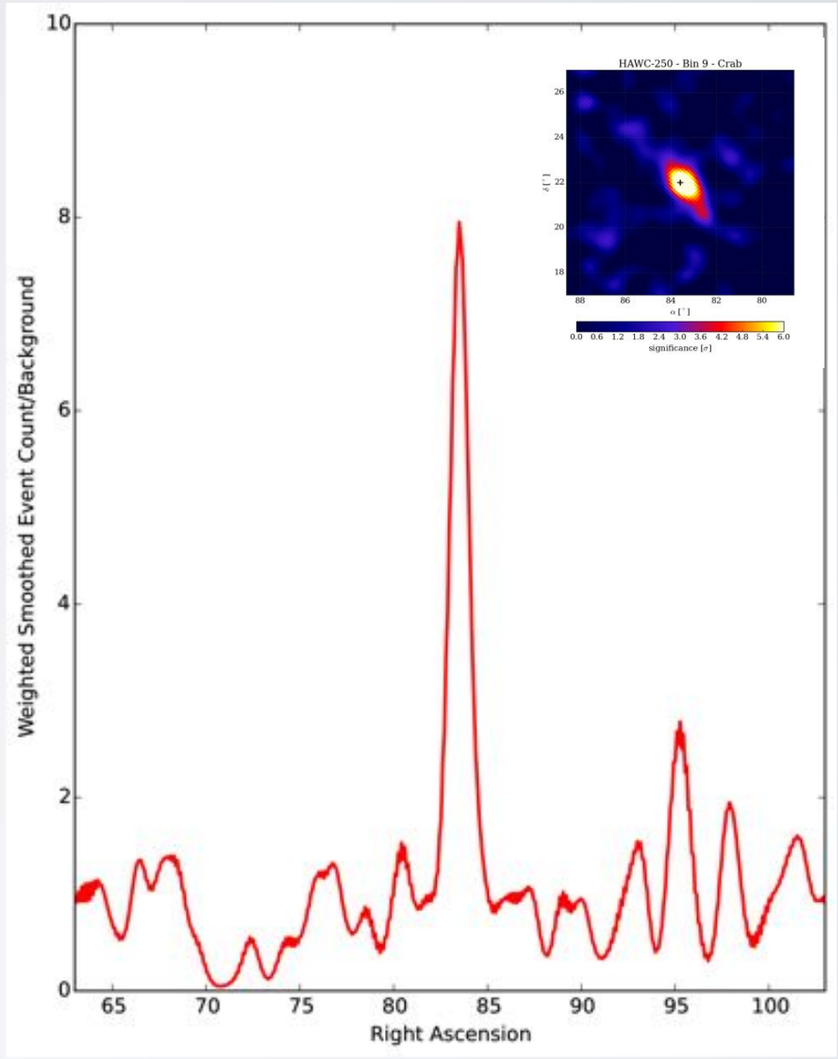


Pulsar Wind Nebulae

Crab Nebula at highest energies

- photons up to 80TeV reported by IACTs
- insight into magnetic field environment and efficiency of particle acceleration





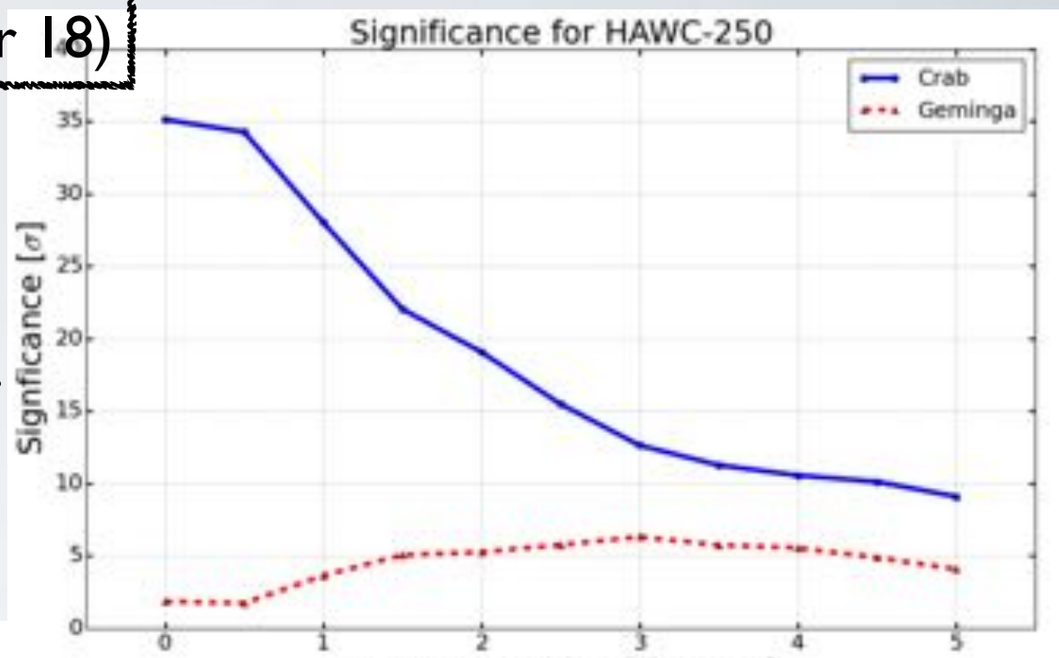
More on high energy:
S. Marinelli, K. Malone (K12: Astrophys. Data Analysis, Apr 17)

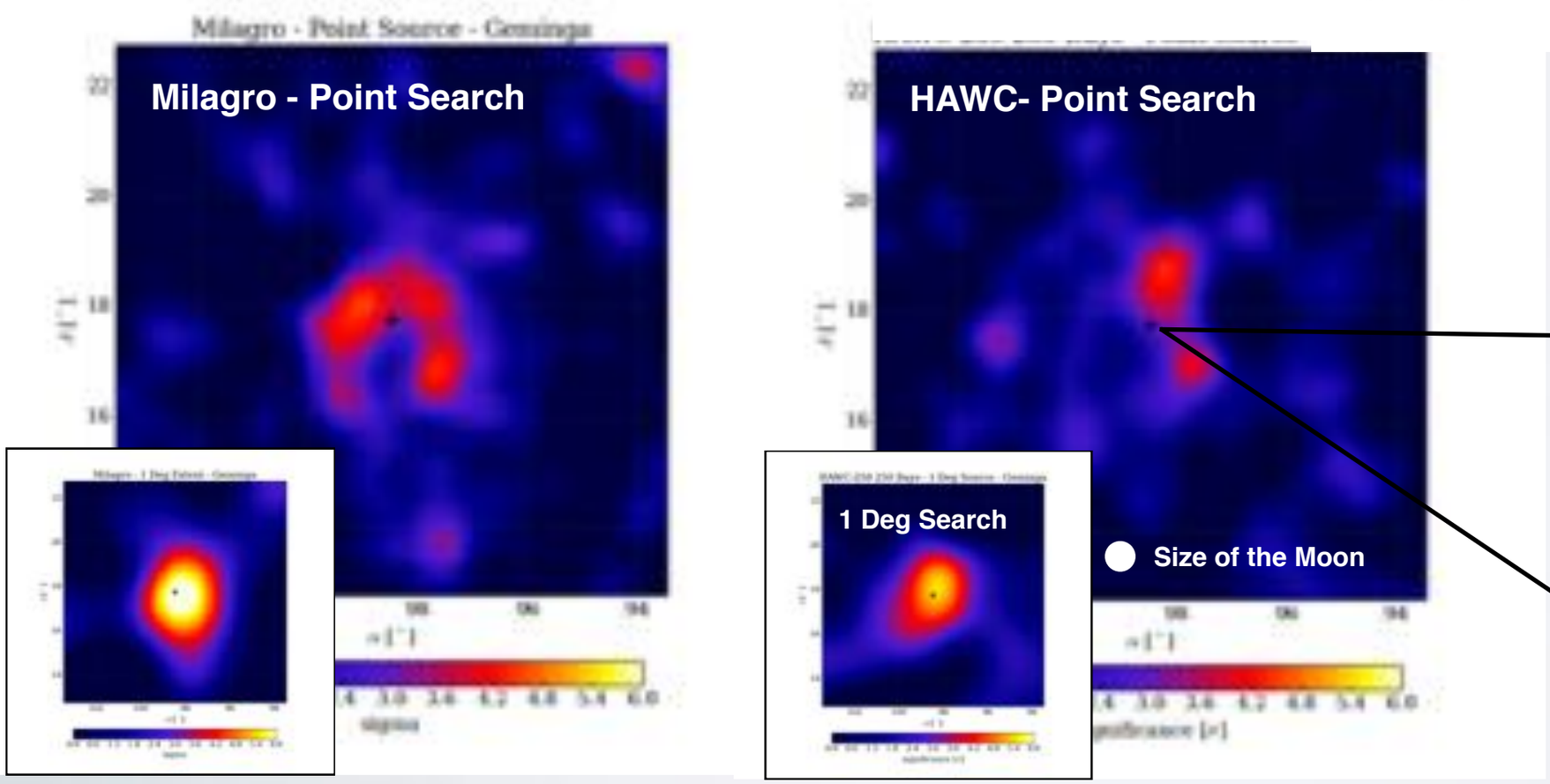
Pulsar Wind Nebulae

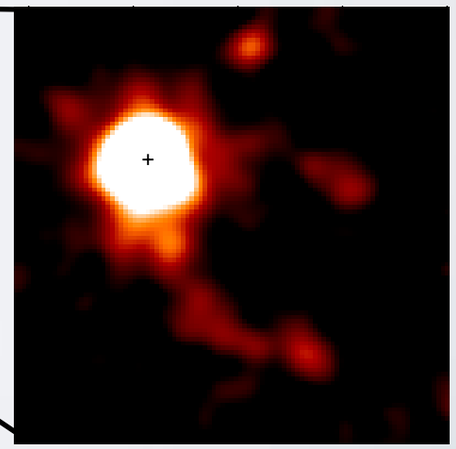
Geminga

H. Zhou (R13: Fermi-HAWC-VERITAS, Apr 18)

- Closest known middle aged pulsar
- Possible nearby cosmic ray acceleration site
  — explanation for positron excess (Yuksel et al. 2009)
- Not seen by IACTs, extent maybe larger than IACT FOV.
- In 150 days of HAWC data, ~4σ in point-like analysis, up to 6σ in extended search.





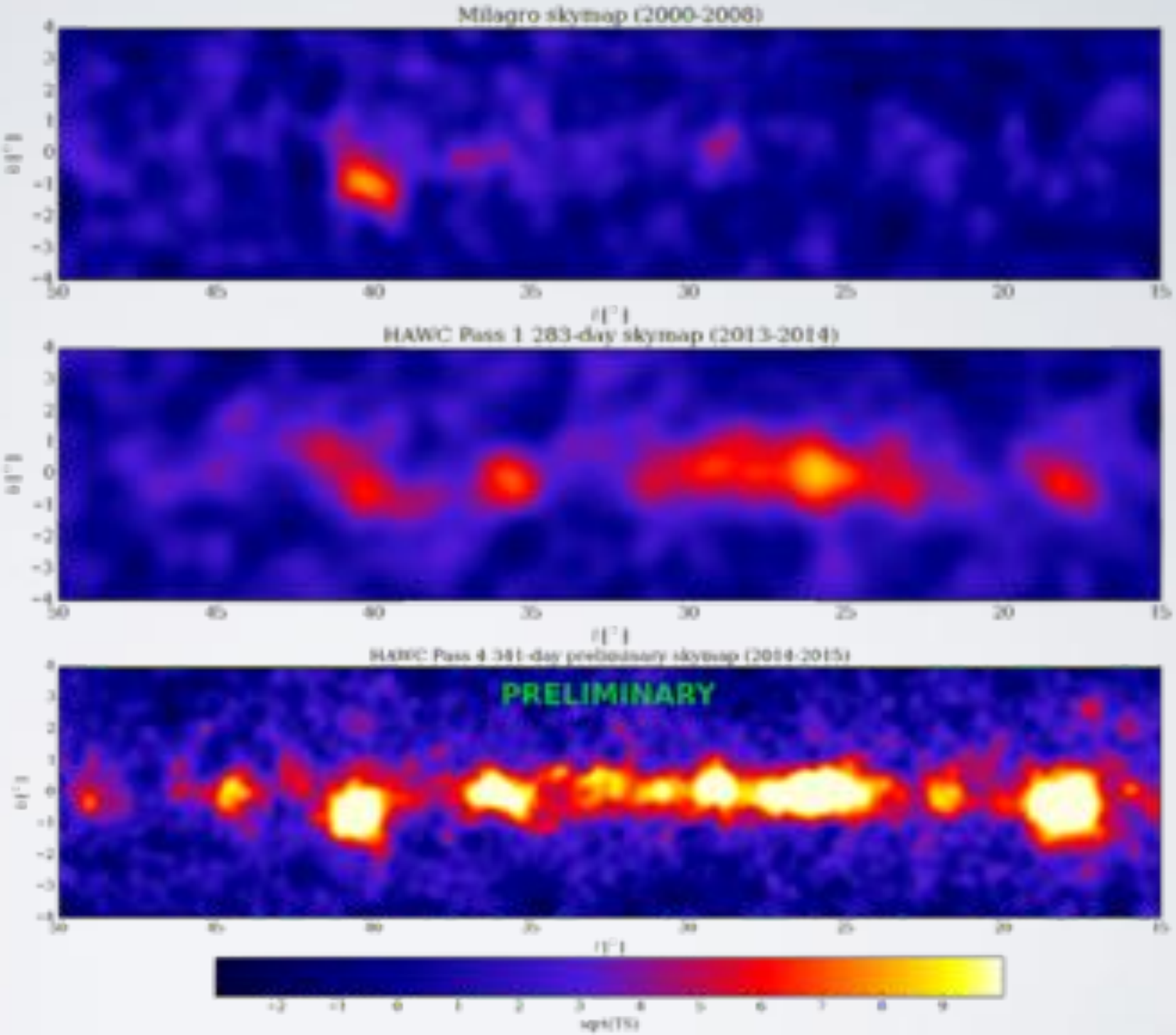


XMM, Pavlov et al. 2010

Galactic Plane

Milagro is located near Los Alamos, New Mexico

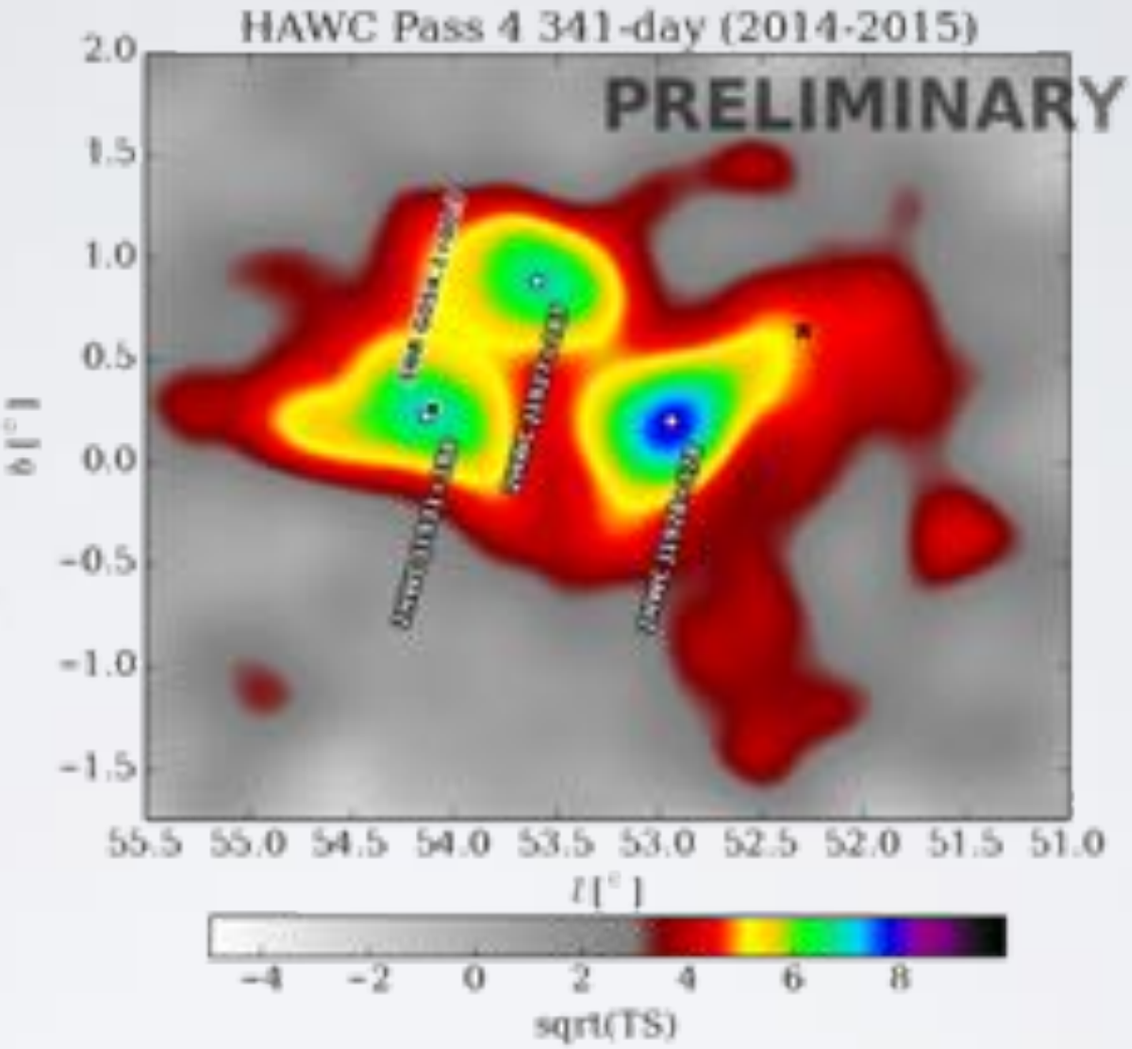
- different sensitivity by declination along Galactic plane.



HAWC is ~15x more sensitivity with lower energy threshold compared to Milagro, and more sensitive towards Galactic center.

Galactic Plane

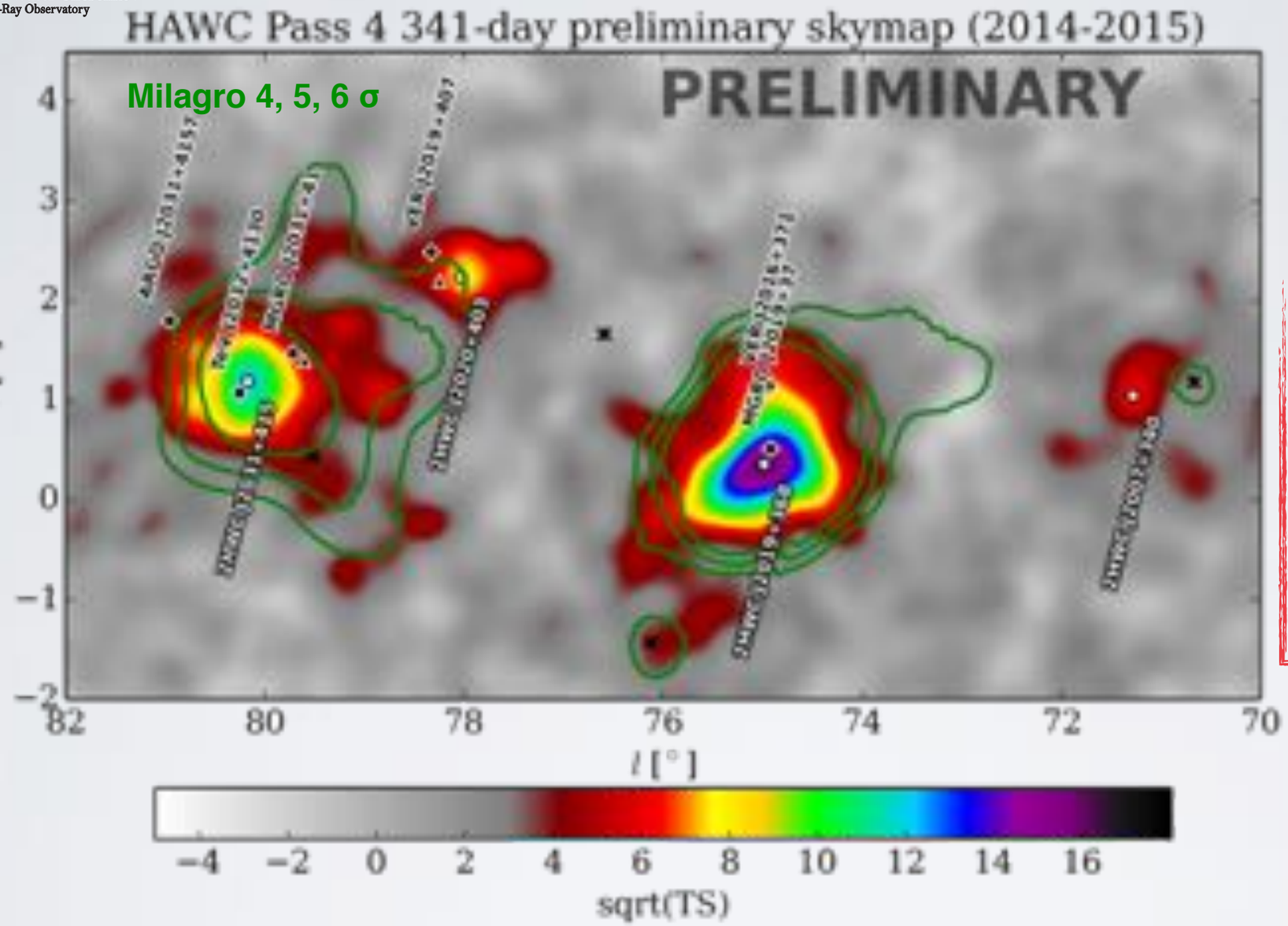
New TeV emission region
2HWC J1927+187*
- ~7σ pre-trials
- current blind search algorithm identify this region associated with 2HWC J1831+188, analysis is still ongoing



New TeV source
2HWC J1928+178
- ~8σ pre-trials
- coincident with PSR J1928+1746

2HWC J1831+188
- coincident with VER J1930+188 (SNR G54.1+00.3 / PSR J1930+1852)
- TeV emission was reported to be point-like and likely from PWN
- nearby molecular CO cloud

Cygnus Region



New TeV source
2HWCJ2007+340:

- >6σ pre-trials
- 0.6° from unidentified source 3FGL J2004.4+3338
- 0.5° from PSR J2004+3429, a young radio pulsar

MGRO J2031+41 is resolved into two distinct TeV sources:

- 2HWC J2031+415 — TeV J2032+4130, a PWN
- 2HWC J2020+403 — VER J2019+407, UID encompassing SNR G78.2+2.1 and PSR J2021+4026

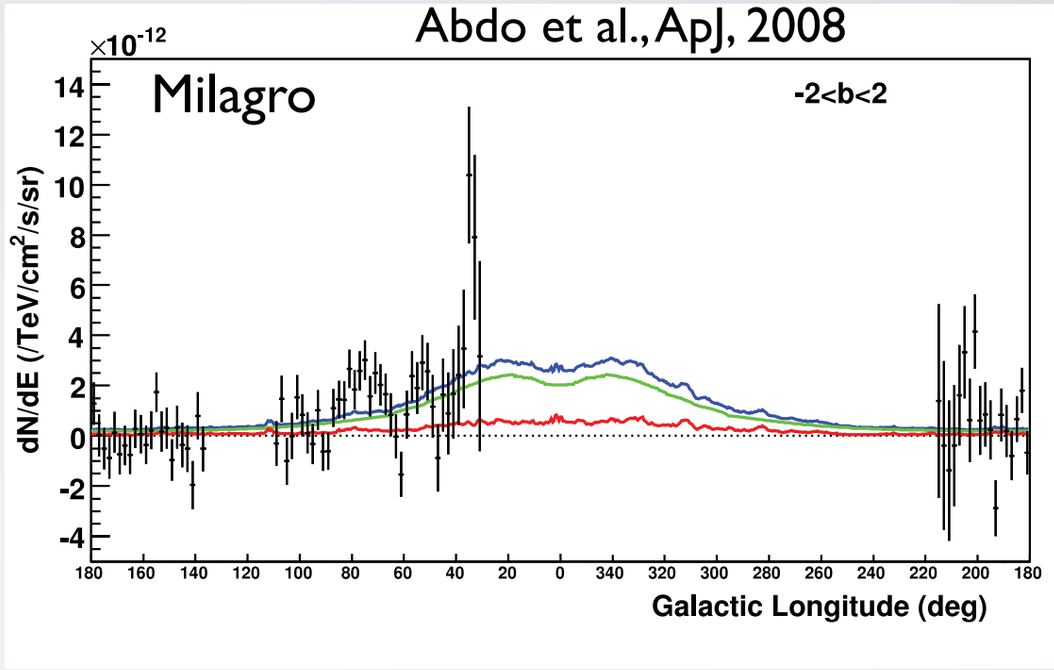
2HWC J2019+368 is coincident with MGRO J2019+37 and VER J2019+368

- extended emission including PSR J2021+3651 and HII region Sh 2-104

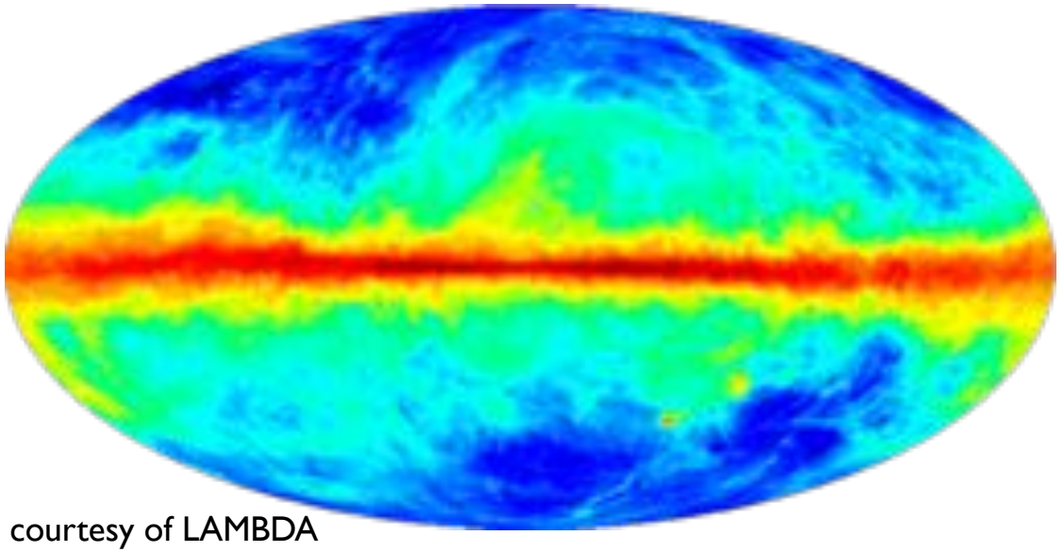
Galactic Diffuse — Limit from Pass 1

Diffuse contributions:

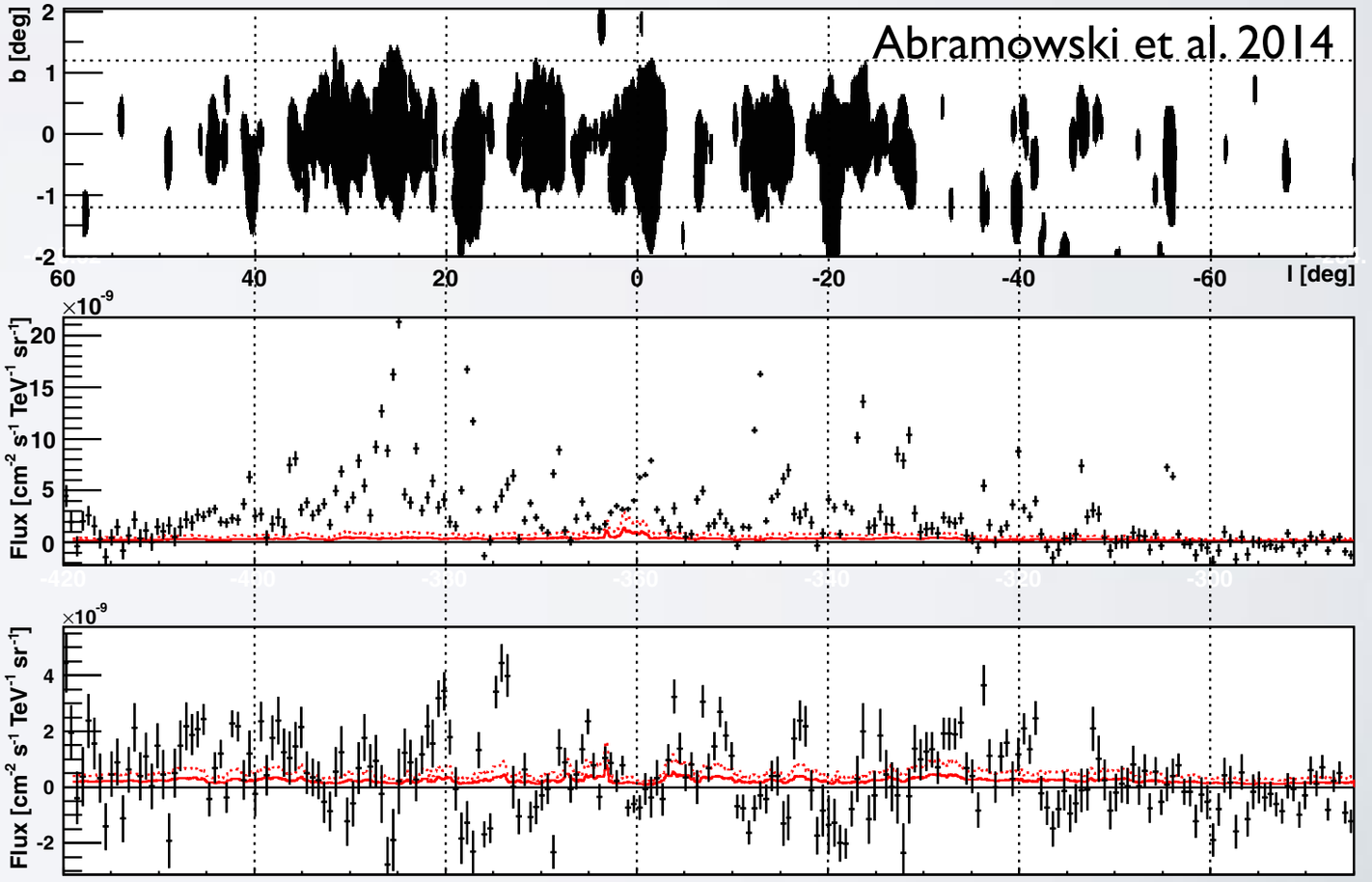
- Cosmic-ray interactions
  - molecular clouds
  - interstellar gas
- Inverse Compton
- Unresolved sources.



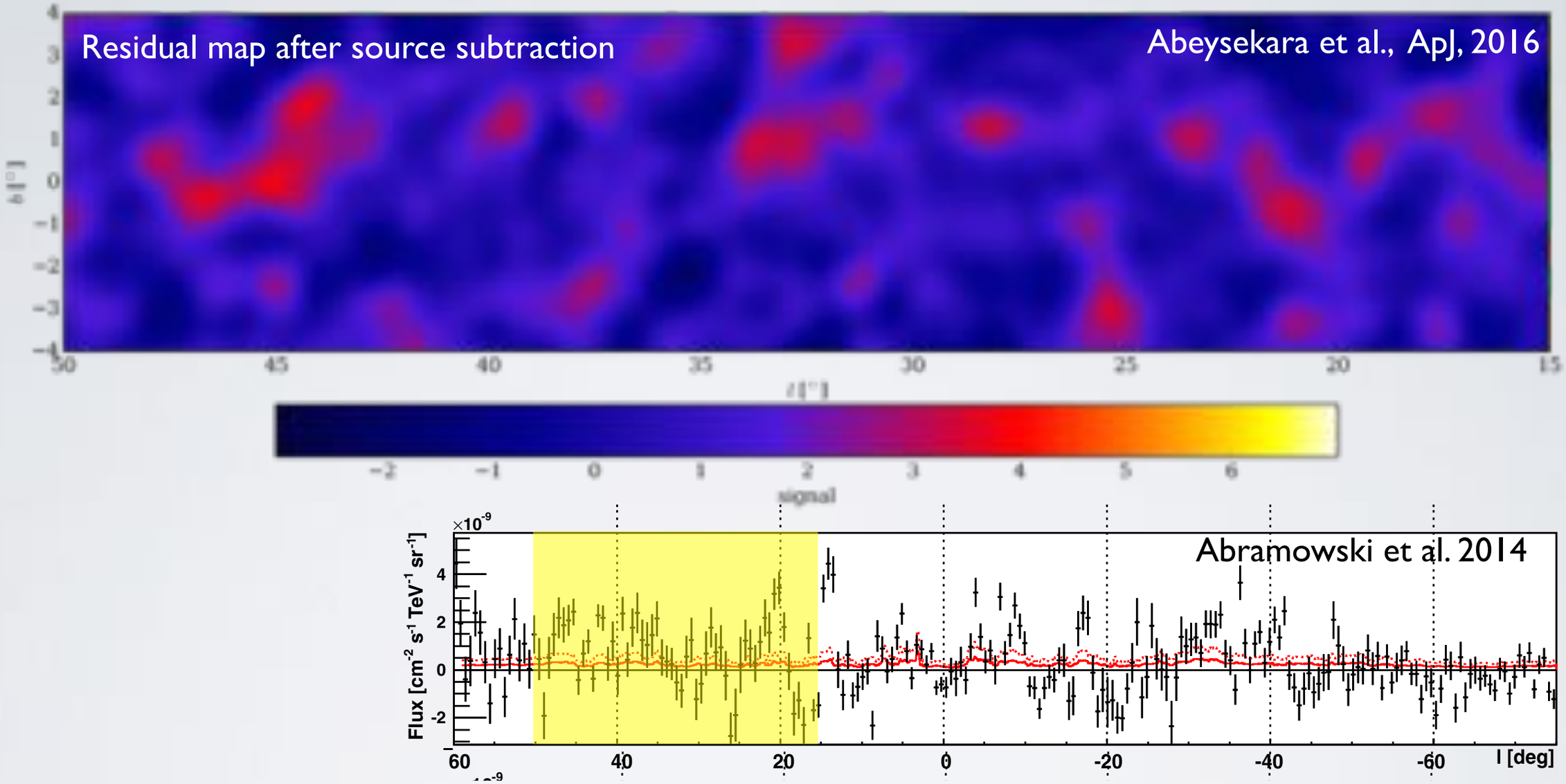
Leiden/Argentine/Bonn (LAB) Survey of Galactic HI



courtesy of LAMBDA



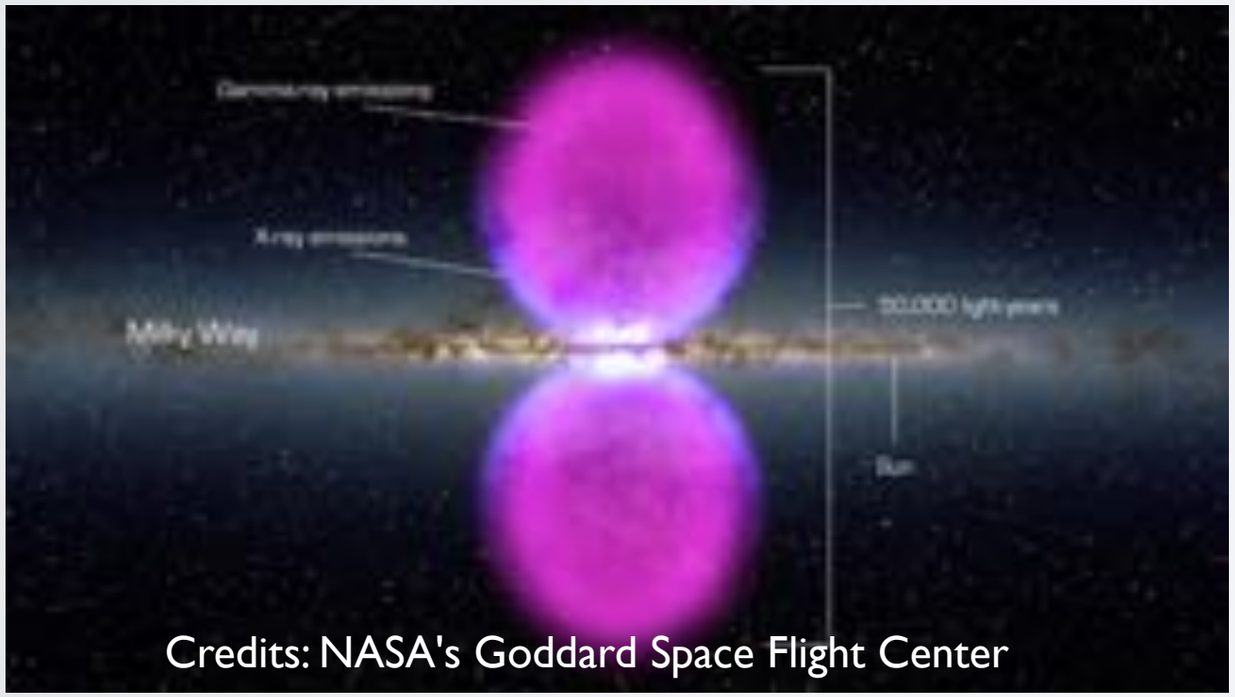
Galactic Diffuse — Limit from Pass 1

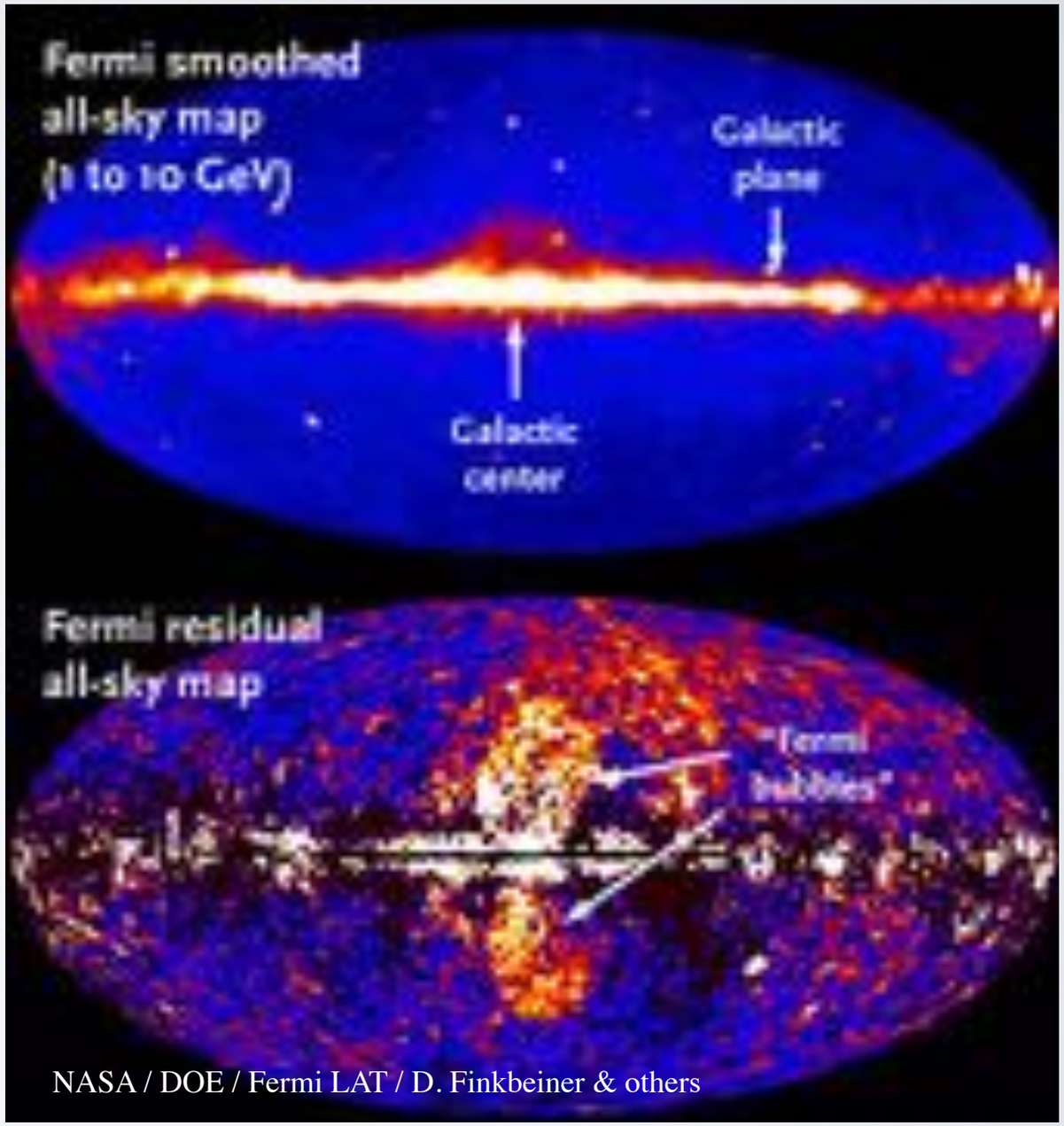


- A uniform surface brightness fit in addition to source model is preferred at **5.7σ**.
- The fitted surface brightness at 5 TeV is 1.6±0.4e-11 TeV^{-1} cm^{-2} s^{-1} sr^{-1}.
- HESS average diffuse extrapolated to 5 TeV is 1.0±0.2e-11 TeV^{-1} cm^{-2} s^{-1} sr^{-1}.
- Current limit from HAWC-111 dataset includes unresolved sources.

Large-scale structures e.g. Fermi Bubbles

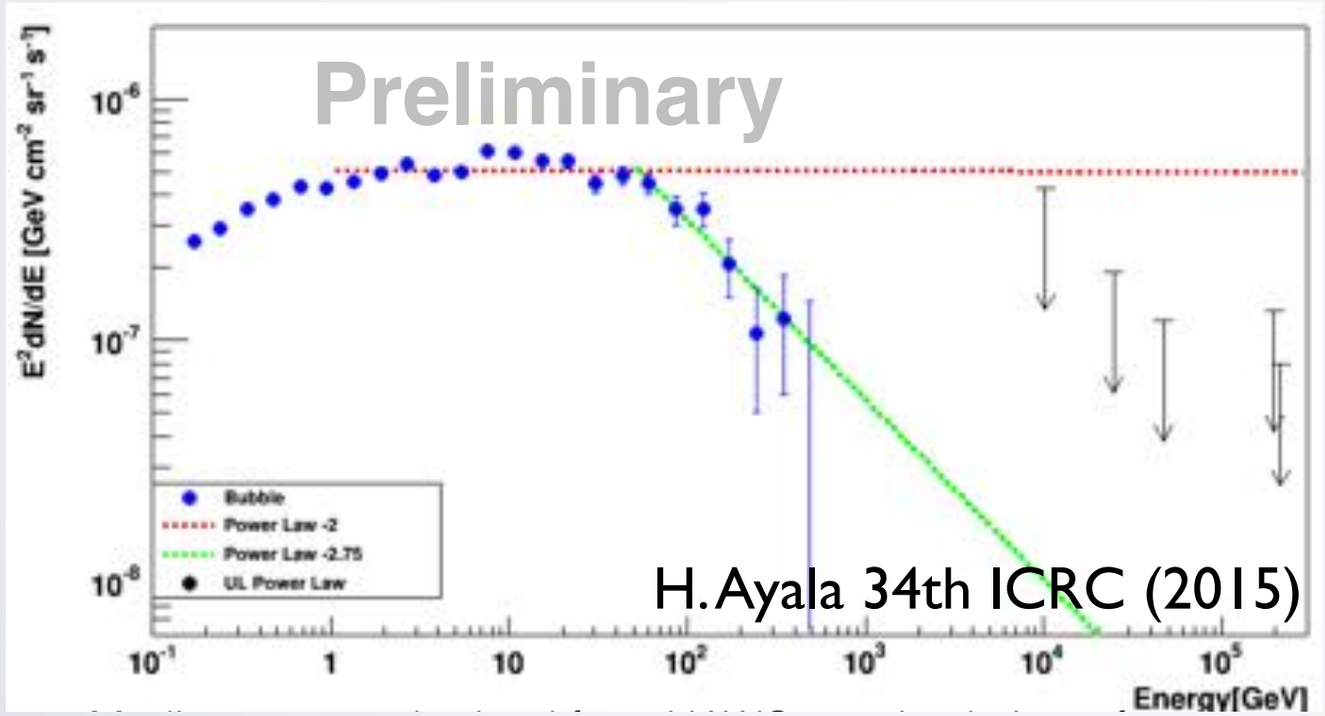
- Large scale, non-uniform structures extending above and below the Galactic center.
  - Edges line up with X-ray features.
  - Correlate with microwave excess (WMAP haze)
  - Both hadronic and leptonic model fit Fermi LAT data. Leptonic model can explain both gamma ray and microwave excess.



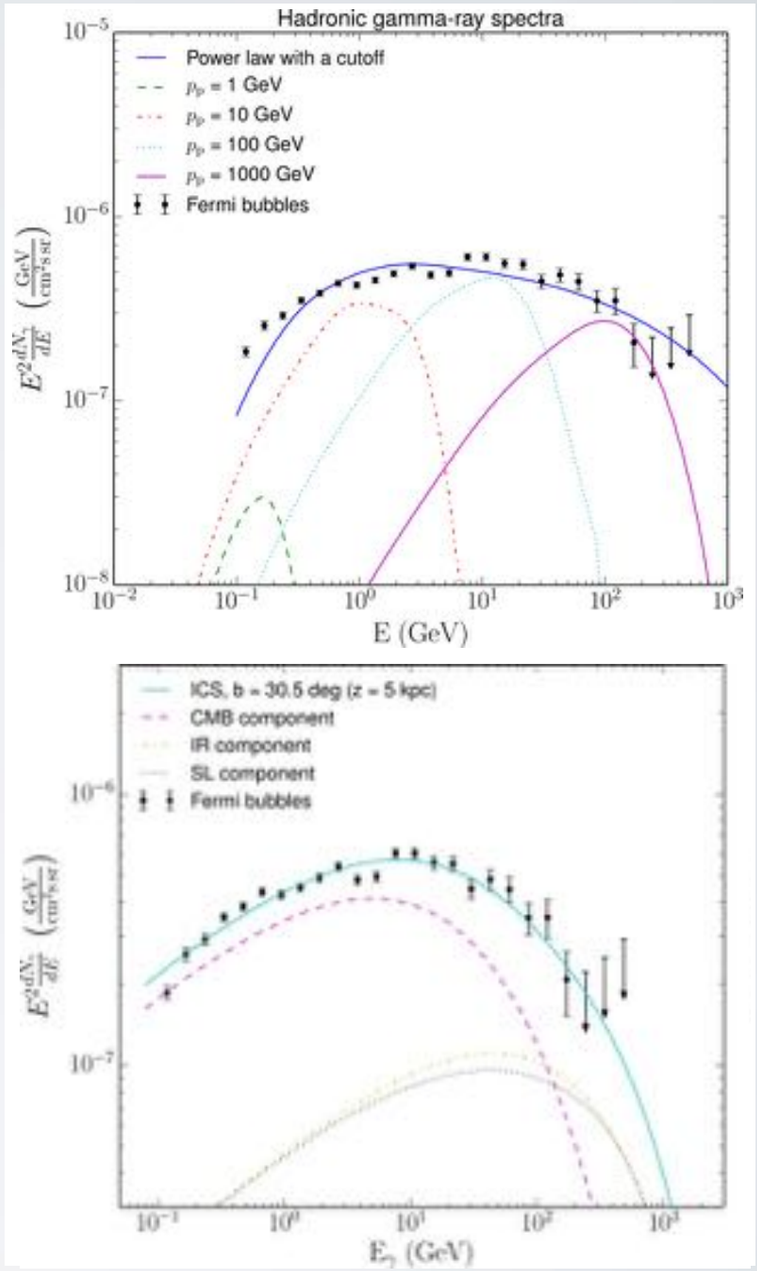


Large-scale structures e.g. Fermi Bubbles

- Large scale, non-uniform structures extending above and below the Galactic center.
  - Edges line up with X-ray features.
  - Correlate with microwave excess (WMAP haze)
  - Both hadronic and leptonic model fit Fermi LAT data. Leptonic model can explain both gamma ray and microwave excess.
- First limits in TeV, **hard spectrum is highly unlikely.**
- H. Ayala (E13: DM, Indirect, Gamma-rays, Apr 16)



H. Ayala 34th ICRC (2015)



Ackermann et al. 2014

Transient Search

Crab Nebula

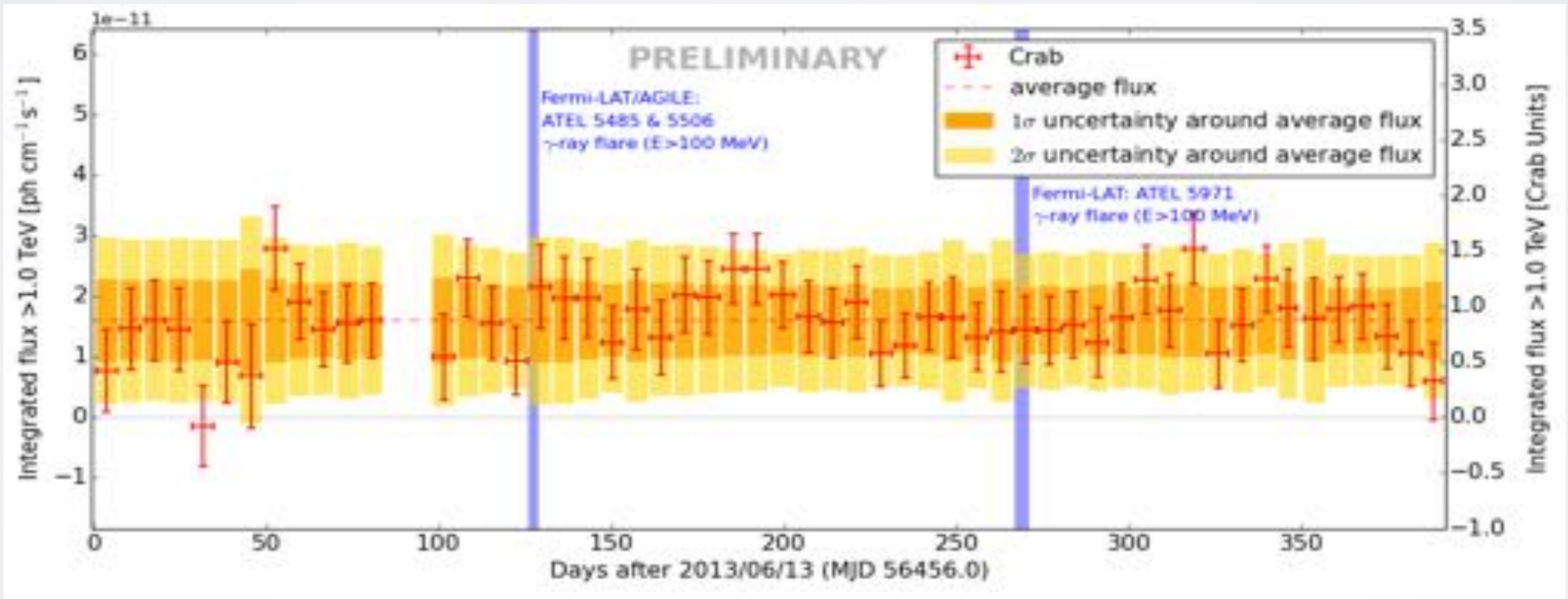
- Crab flares, continue up to TeV?
- No activity in radio, IR, and X-rays.

HAWC observation:

- HAWC-111 data from June 13 2013 to July 9 2014.
- >20σ in 280 transits.
- Lightcurve binned in 7-day intervals.
- Consistent with constant flux.

MeV-GeV gamma ray

Credit: NASA/DOE/Fermi LAT/R. Buehler



Transient Search

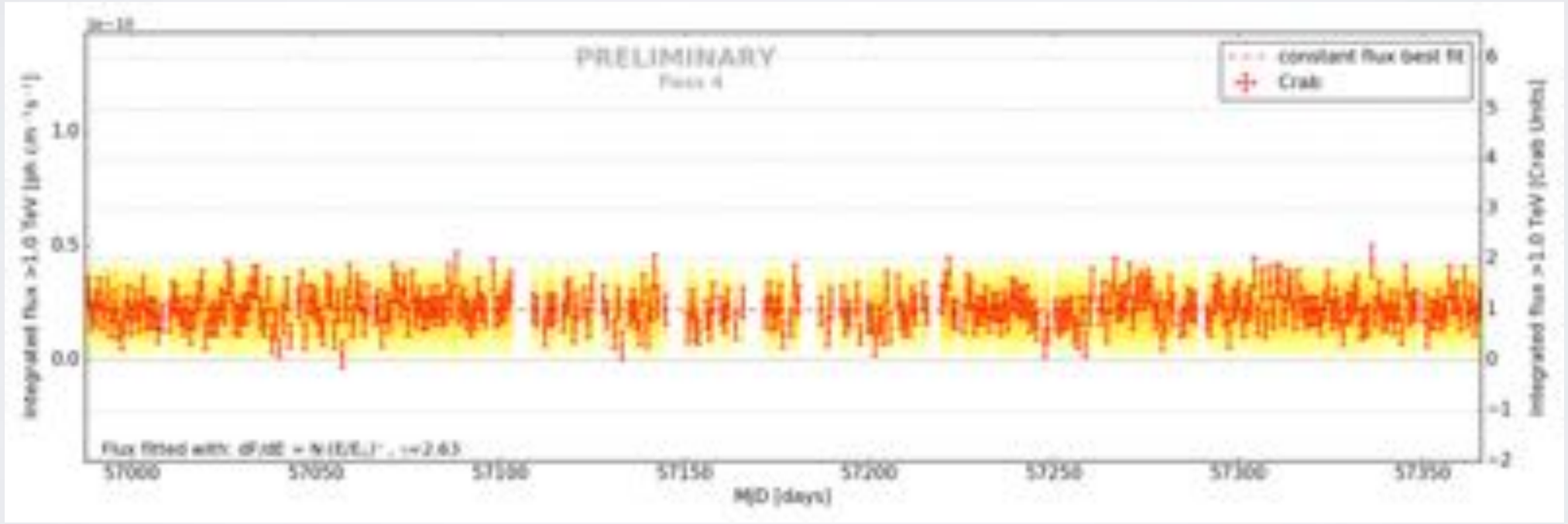
Crab Nebula

- Crab flares, continue up to TeV?
- No activity in radio, IR, and X-rays.

More on Transients:
T. Weisgarber, I. Wisher (M18: AGN, Apr 17)
R. Lauer (R13: Fermi-HAWC-VERITAS, Apr 18)

HAWC observation:

- HAWC Pass 4 data from Nov 26 2014 to Dec 9 2015.
- >80σ in 315 transits.
- Lightcurve binned in sidereal day.
- Consistent with constant flux.



Multi-wavelength / Multi-messenger

Have follow-up agreement with:
- Swift
- Fermi-LAT
- IACTs
  - FACT
  - HESS
  - MAGIC
  - VERITAS
- AMON
- IceCube
- ANTARES
- LIGO/VIRGO

HAWC-triggered:
- New source candidates list.
  - follow-up observations by IACTs such as VERITAS and MAGIC from Pass 1 release.
- Flares from known gamma-ray sources.

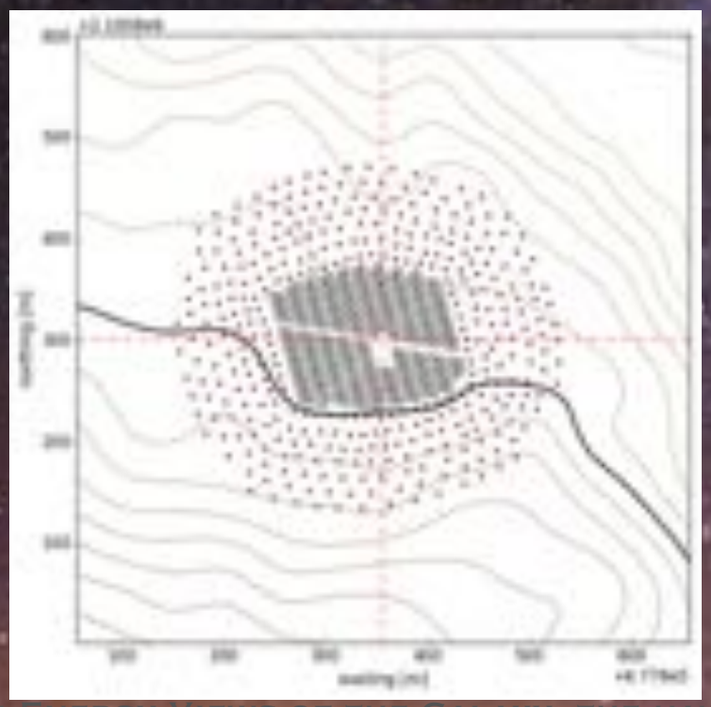
HAWC ATel #8922 on Mrk 501 flare

Externally triggered:
- IceCube alert on high confidence neutrino event (highest energy pointed astrophysical track-like).
- Fermi alerts on flaring activities.
- LIGO/VIRGO gravitation wave event follow-up

IceCube ATel: #7856
HAWC Follow-up ATel: #7868

Outlook

- The HAWC observatory has been completed and inaugurated in March 2015.
- Catalog of first year full operation coming soon (2HWC), with new TeV sources!
- Diverse science results, stay tuned!
- Upgrade to expand the array to enhance effective area >10 TeV by 3-4x is currently under installation.



HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

BACK UP

Galactic Plane Pass 1 Analysis

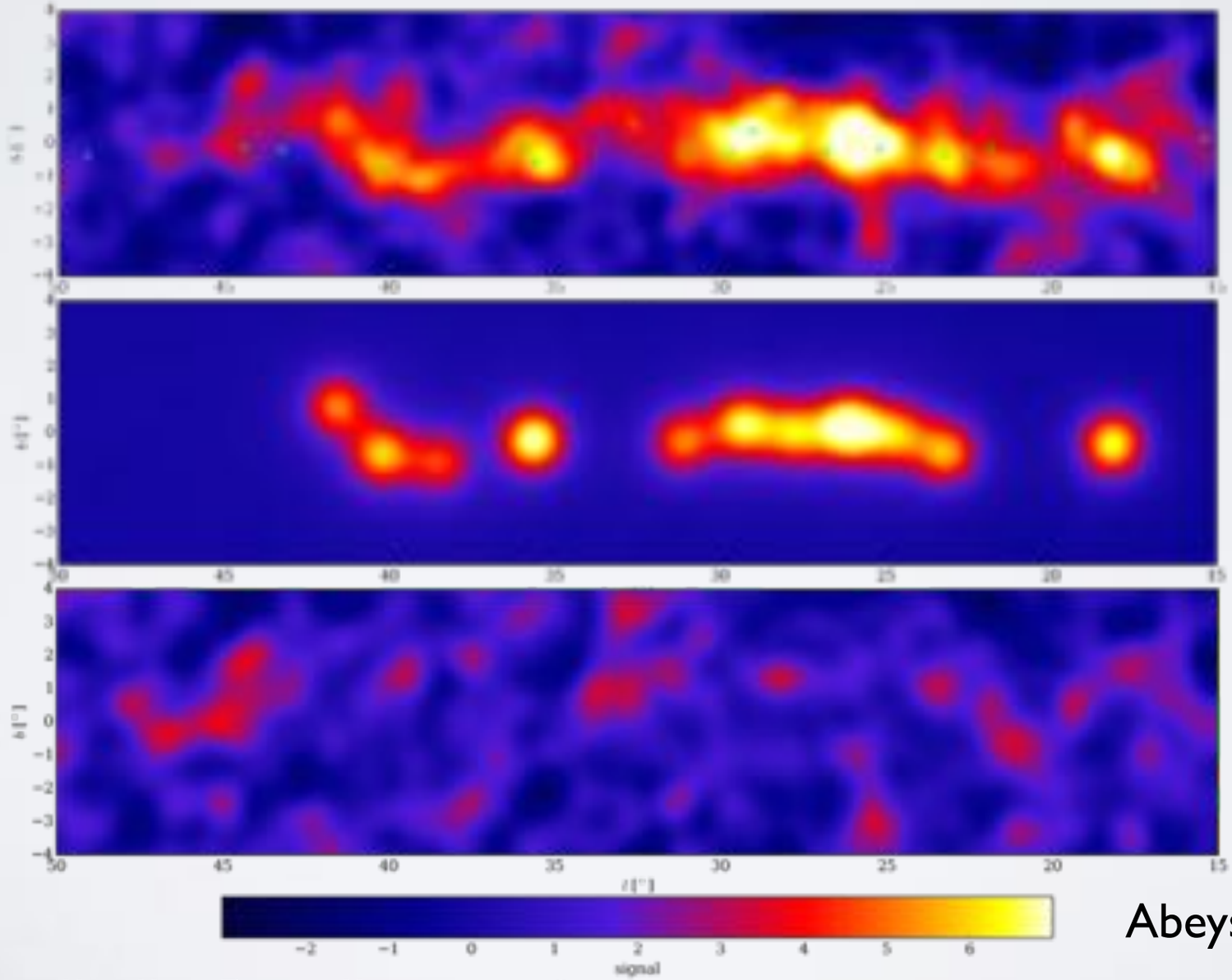
Maximum Likelihood analysis:

- 15<l<50, -4<b<4.
- Fixed spectral index assumption of 2.3.
- Point source analysis fitting positions and flux.
- 10 sources and candidates with post-trials significance >3σ are identified.

Data Map

Model Map

Residual Map



Abeysekara et al., ApJ, 2016