HAWC results and future development

C. Michelle Hui, NASA/MSFC
for the HAWC collaboration

IPA 2017 May 10, 2017

Gamma-Ray Astrophysics

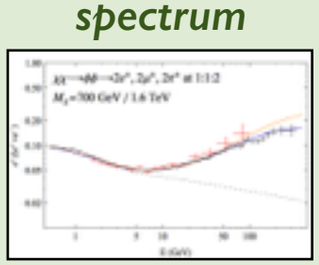
Astrophysics

SNRs, Pulsars, *Binaries*, etc.

AGN Flares

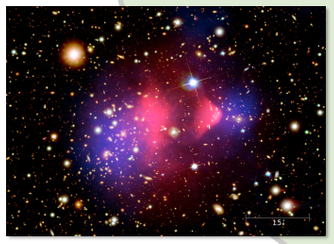
Dark Matter

Cosmic electron spectrum

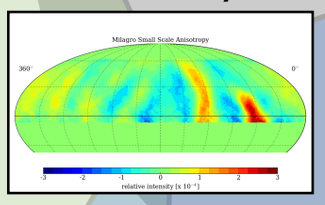


e^+/e^- *ratio*

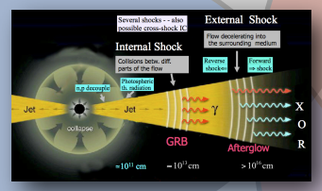
Indirect DM Searches



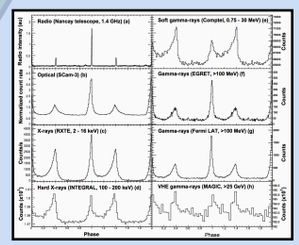
Cosmic Rays



GRBs



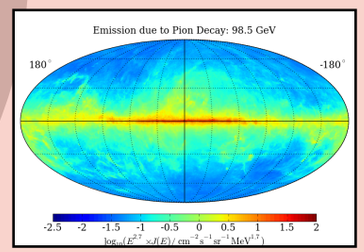
Lorentz Invariance Violation



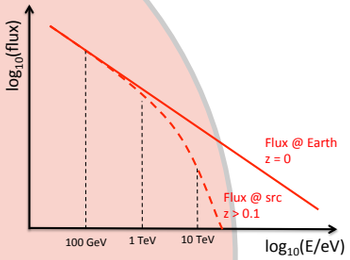
Exotic Particles

Cosmology

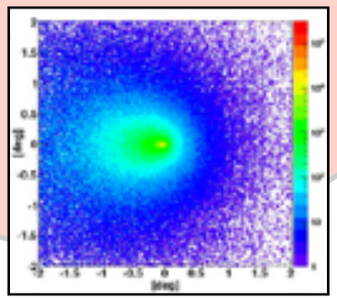
Diffuse Emission



Extragalactic Background Light (IR)



Intergalactic Magnetic Fields



Monopoles, Axions, Q-balls, etc.

Fundamental Physics

Gamma-Ray Detectors

<u>Wide Field of View, Continuous Operations</u>

100 MeV to >100 GeV

Fermi
AGILE
EGRET

100 GeV to >100 TeV

HAWC
ARGO
Milagro
Tibet ASγ

<u>TeV Sensitivity</u>

pointing instrument
<0.1° angular resolution
10s GeV to 10s TeV

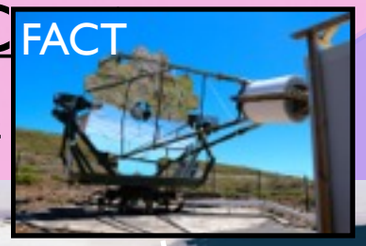
HESS
FACT
MAGIC
VERITAS

Gamma-Ray Detectors

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
Pennsylvania State University
Stanford University
University of California, Irvine
University of California, Santa Cruz
University of Maryland
University of New Hampshire
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
Max-Planck Institute for Nuclear Physics
Instytut Fizyki Jadrowej im Henryka Niewodniczanskiego
Polskiej Akademii Nauk

supported by:
US National Science Foundation (NSF);
US Department of Energy Office of High-Energy Physics;
The Laboratory Directed Research and Development (LDRD)
program of Los Alamos National Laboratory;
Consejo Nacional de Ciencia y Tecnología (CONACyT), México;
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

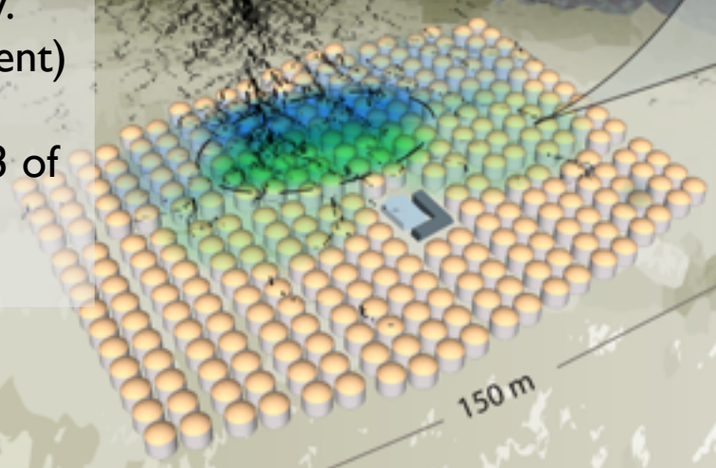
HAWC Observatory

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)

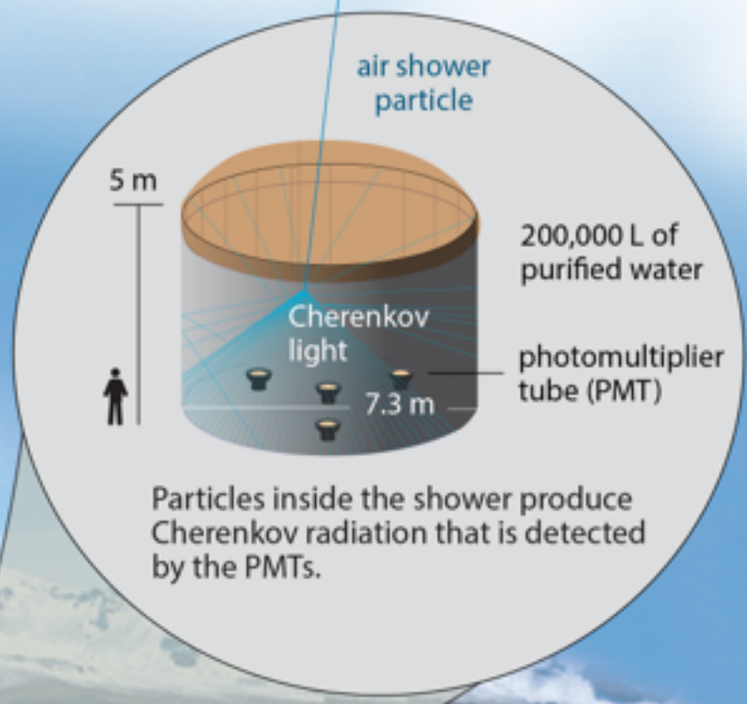
- Sensitive from 100 GeV to 100 TeV.
- Angular resolution (68% containment) 0.2-1.0 degrees.
- 2 sr instantaneous field of view, 2/3 of sky each day.
- >90% duty cycle.

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



Water Cherenkov tank

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

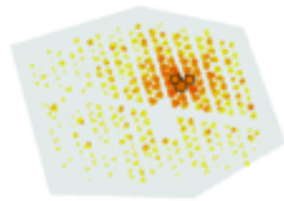


Particles inside the shower produce Cherenkov radiation that is detected by the PMTs.

Gamma rays vs cosmic rays

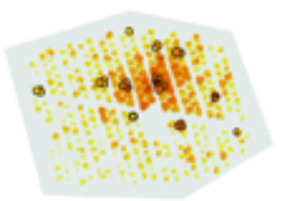
HAWC selects gamma rays from among a much more abundant background of cosmic rays.

gamma-ray shower



"hot" spots concentrate around the core

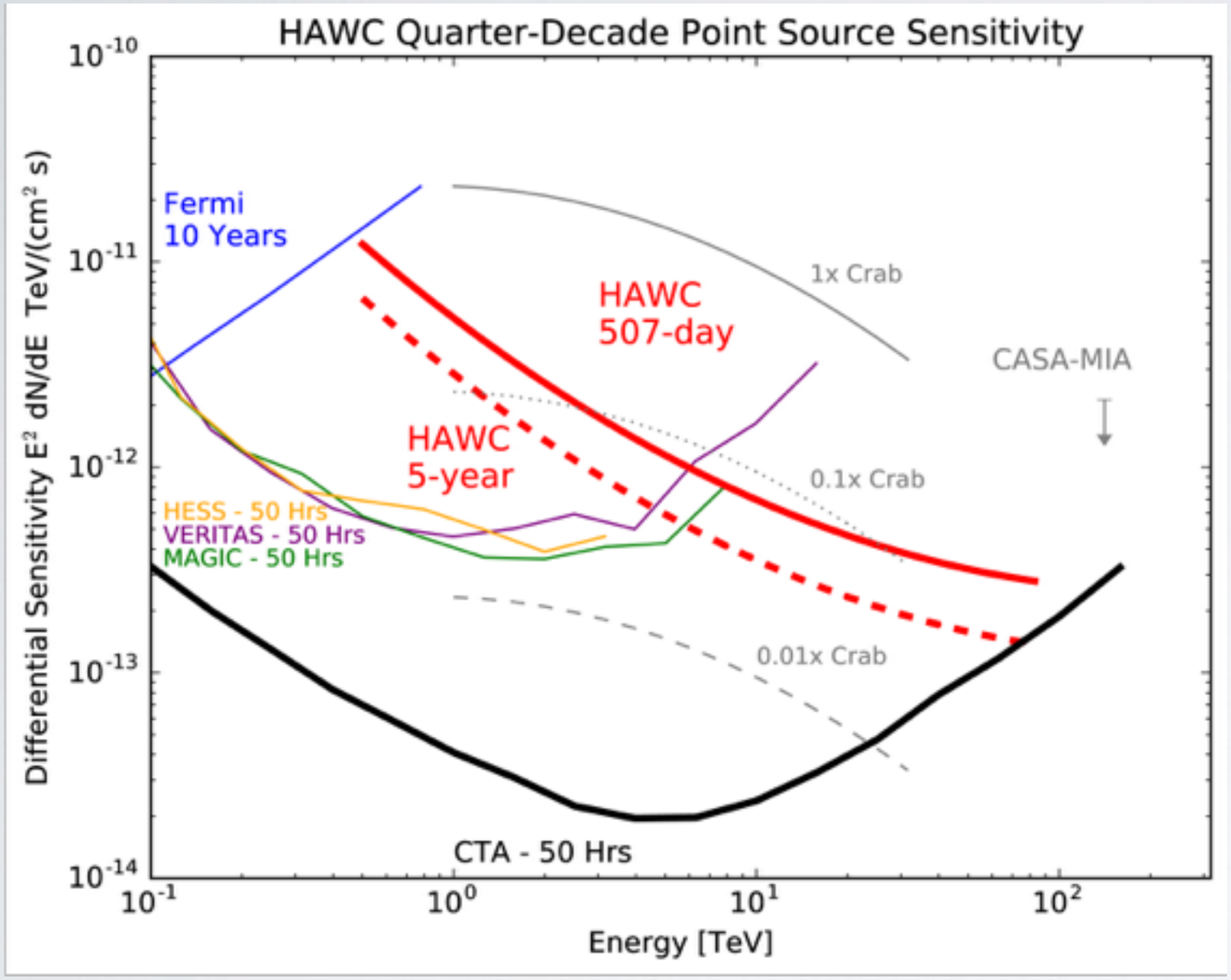
cosmic-ray shower

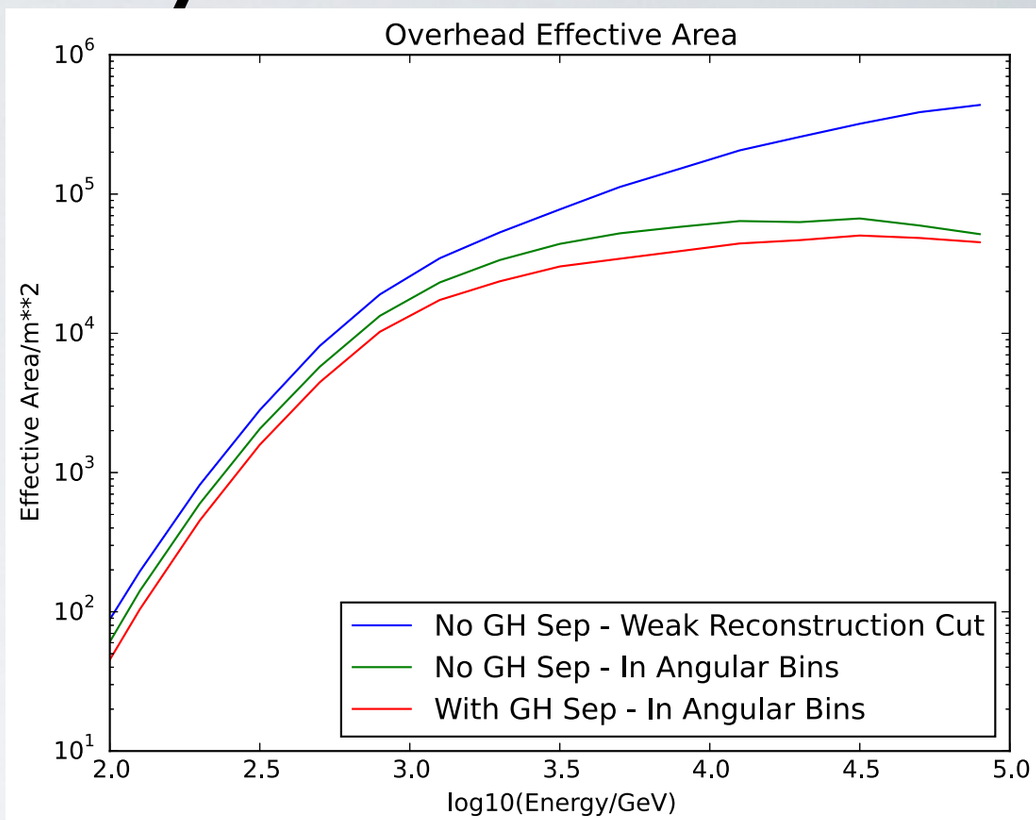


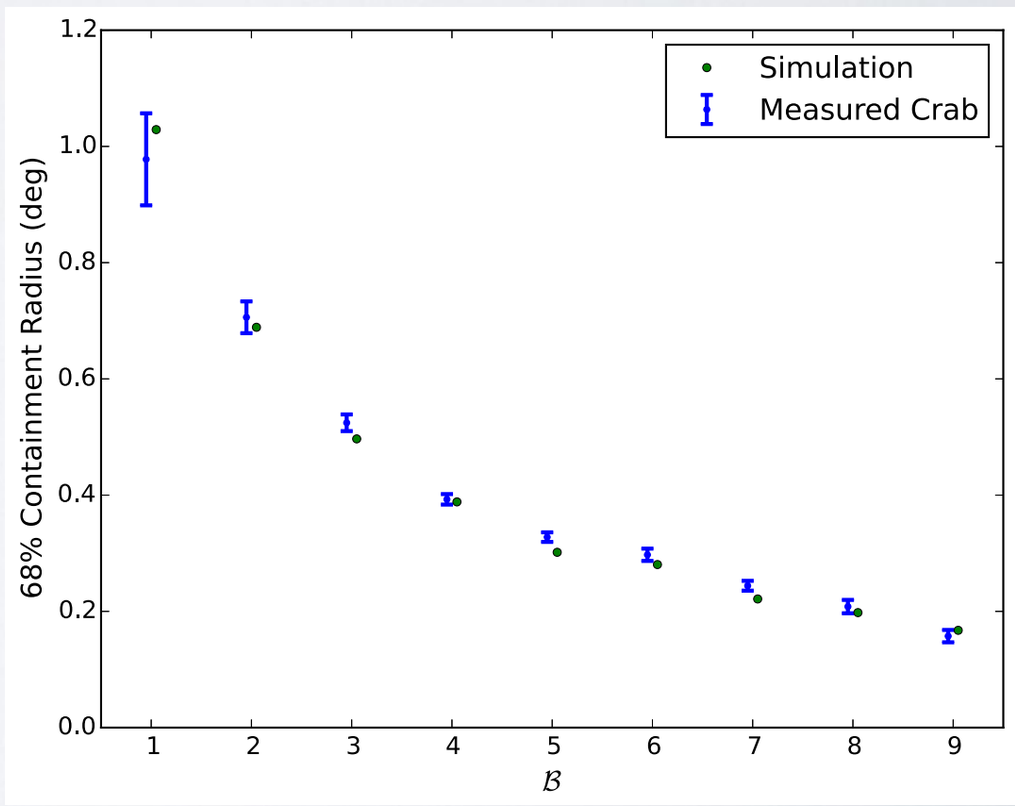
"hot" spots are more dispersed

HAWC Sensitivity

arXiv:1701.01778





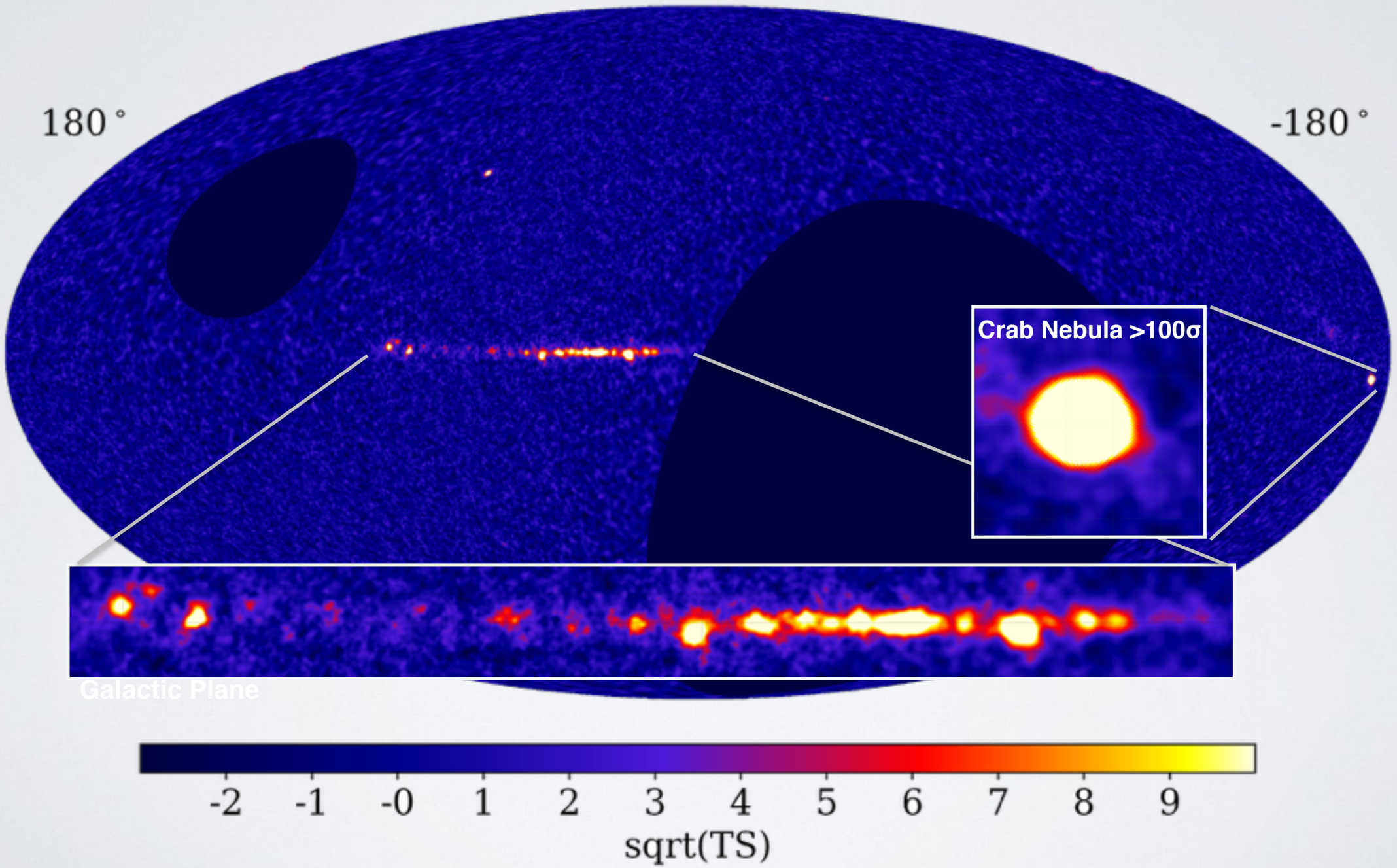


HAWC TeV Sky Survey

- Most sensitive wide-field survey in TeV.
- Skymap from 507 days of data taken between Nov 2014 to Jun 2016.
- Point source analysis assuming power-law index of 2.7.
- 39 2HWC sources: 2 blazars, 5 UID off the Galactic plane.

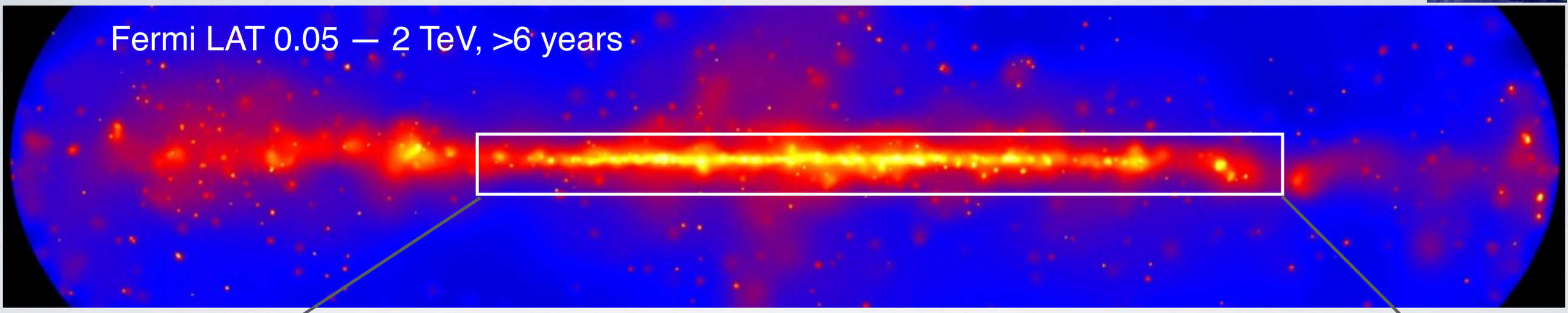
High Altitude Water Cherenkov Gamma-Ray Observatory

arXiv:1702.02992

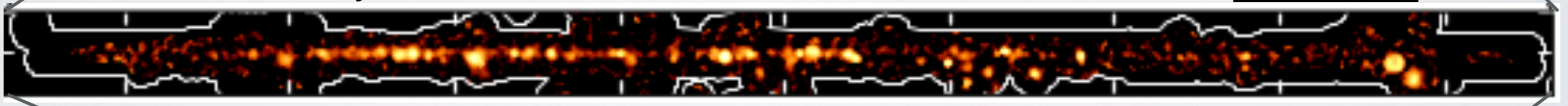


Gamma-ray view of our Galaxy

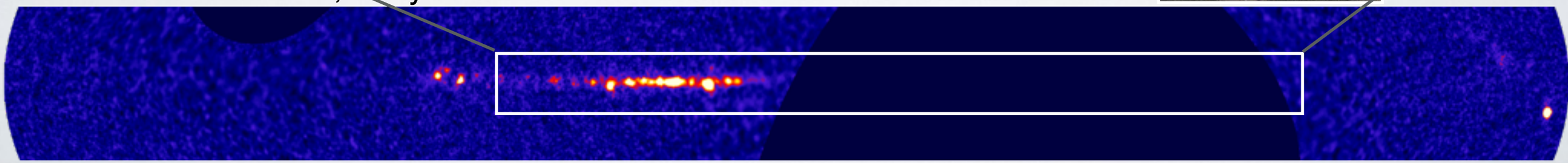
Fermi LAT 0.05 — 2 TeV, >6 years



HESS >1TeV, 10 years

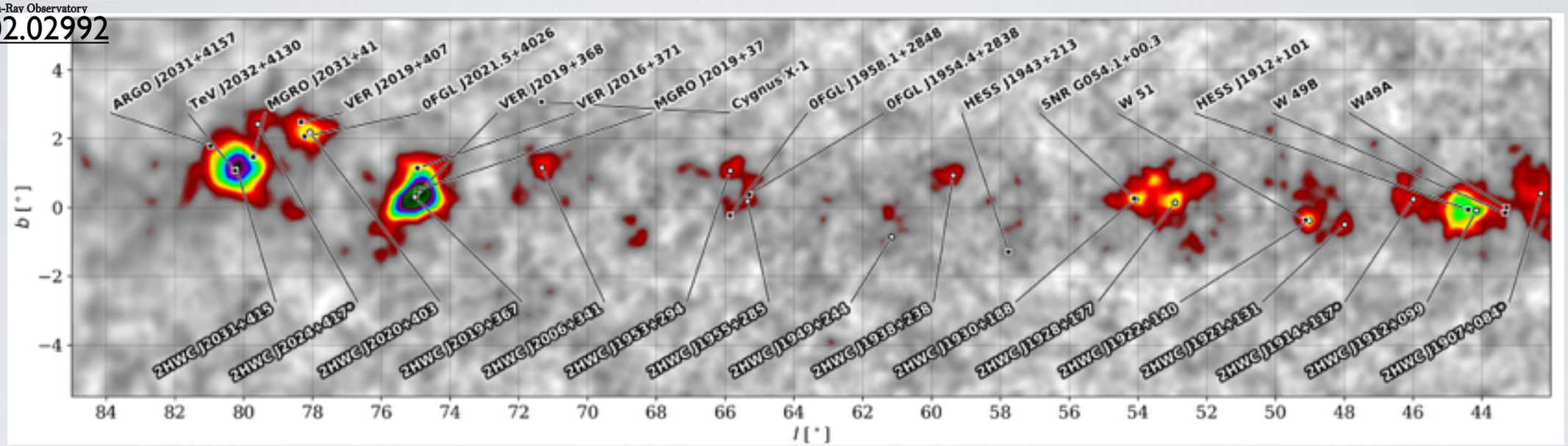


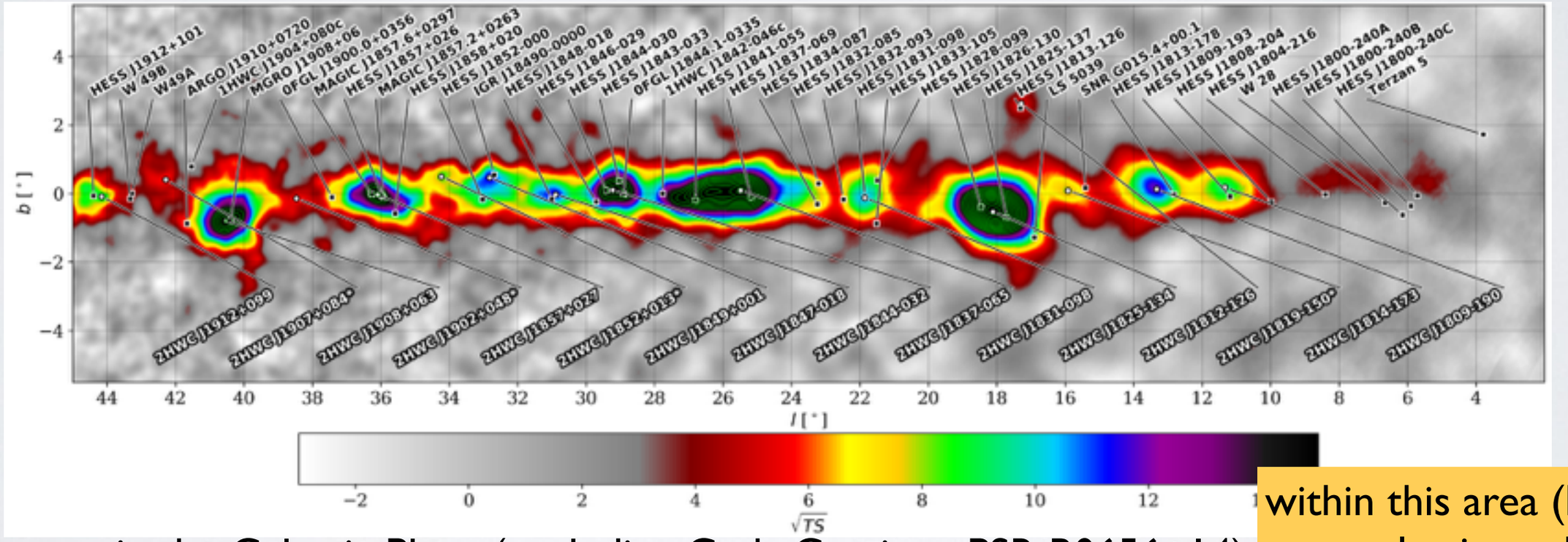
HAWC 0.1—100 TeV, 1.5 year



Galactic Plane

arXiv:1702.02992





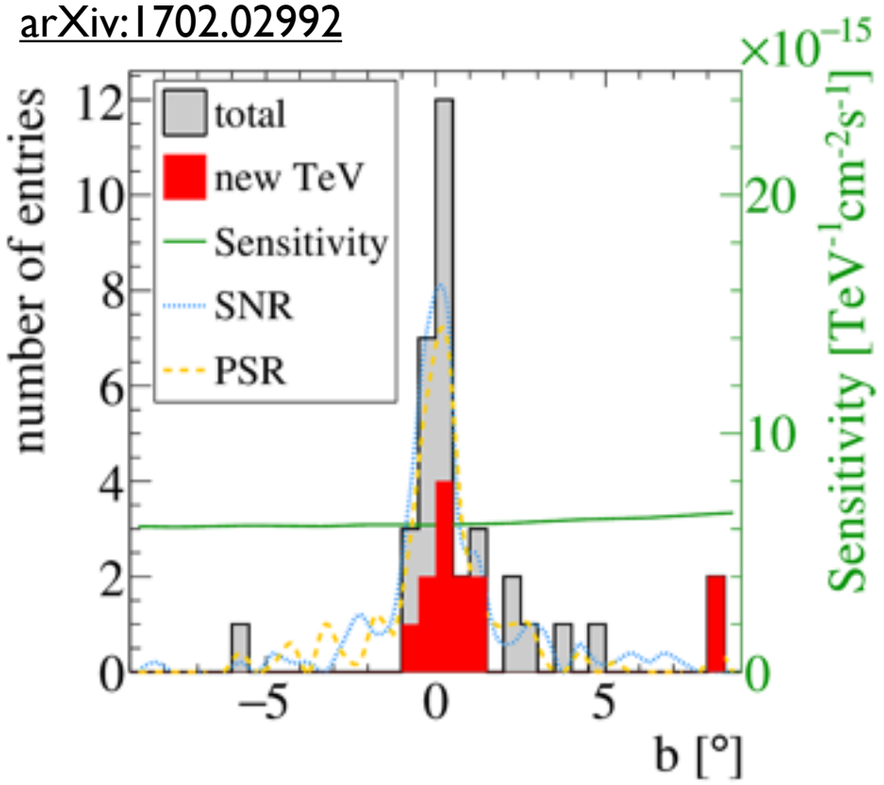
- 30 sources in the Galactic Plane (excluding Crab, Geminga, PSR B0656+14)
  - 19 likely associated with known TeV sources
  - 11 unassociated

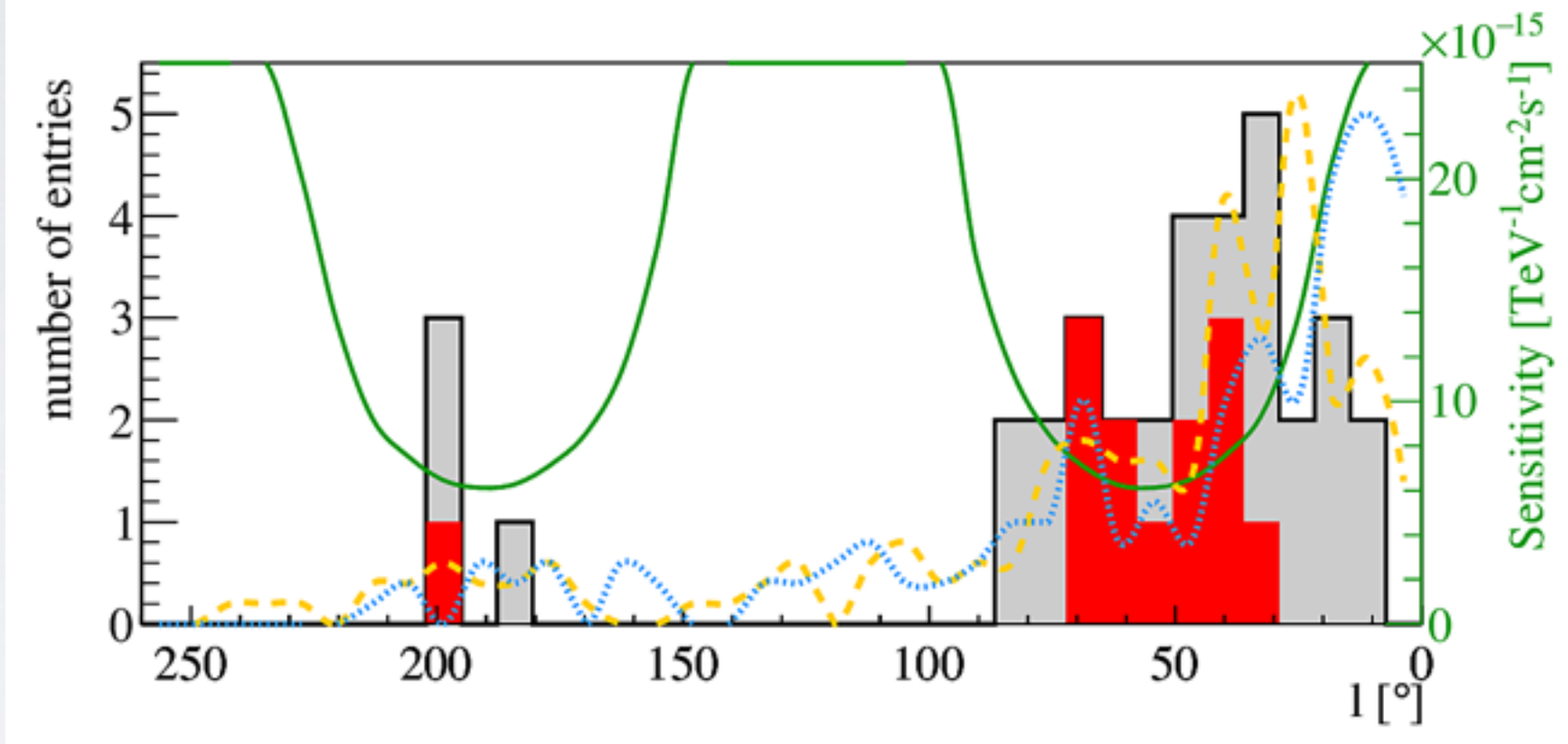
within this area (known extragalactic excluded):

- 150 3FGL sources
- 56 3FHL sources

Galactic Plane Source Distribution

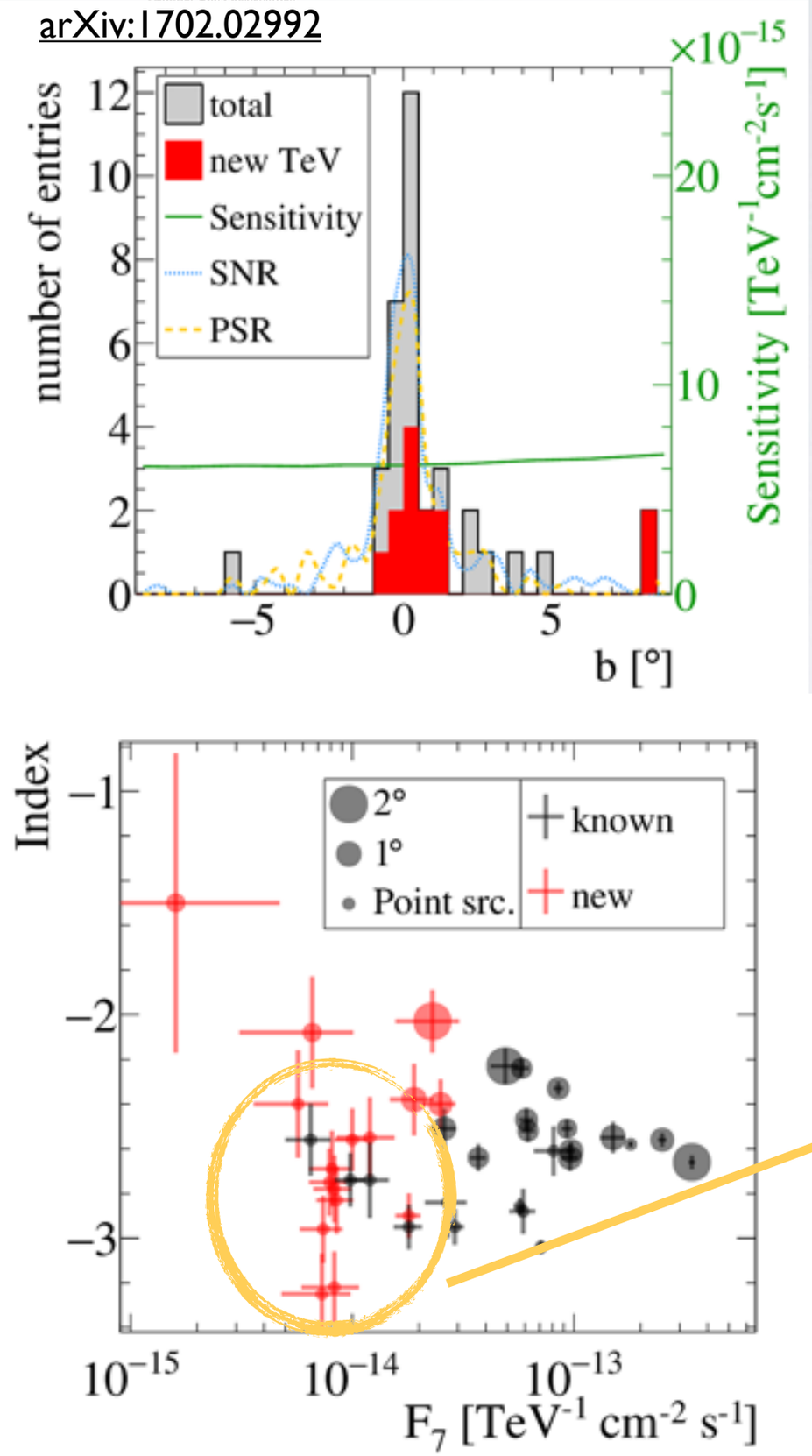
arXiv:1702.02992

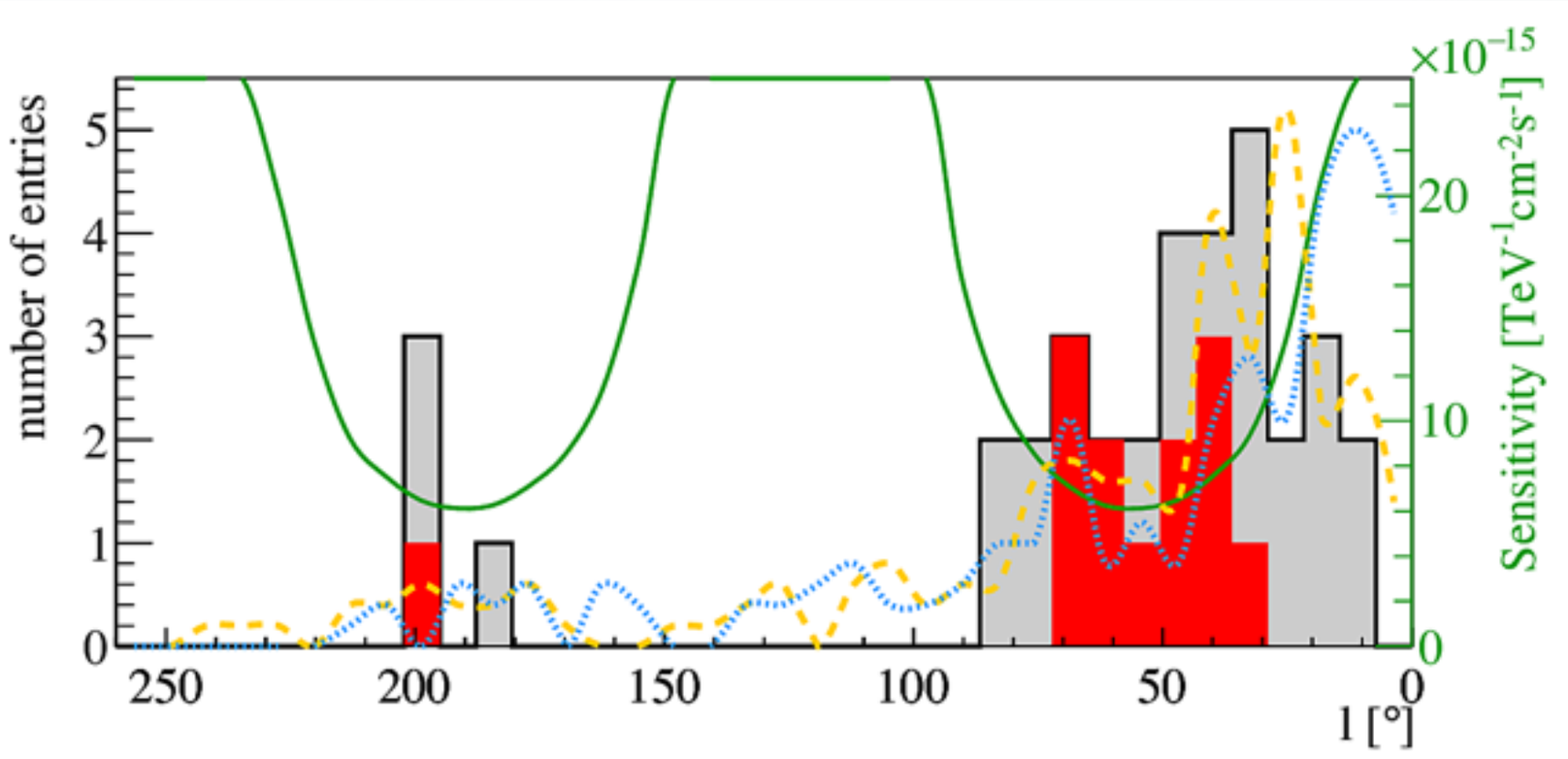




Galactic Plane Source Distribution

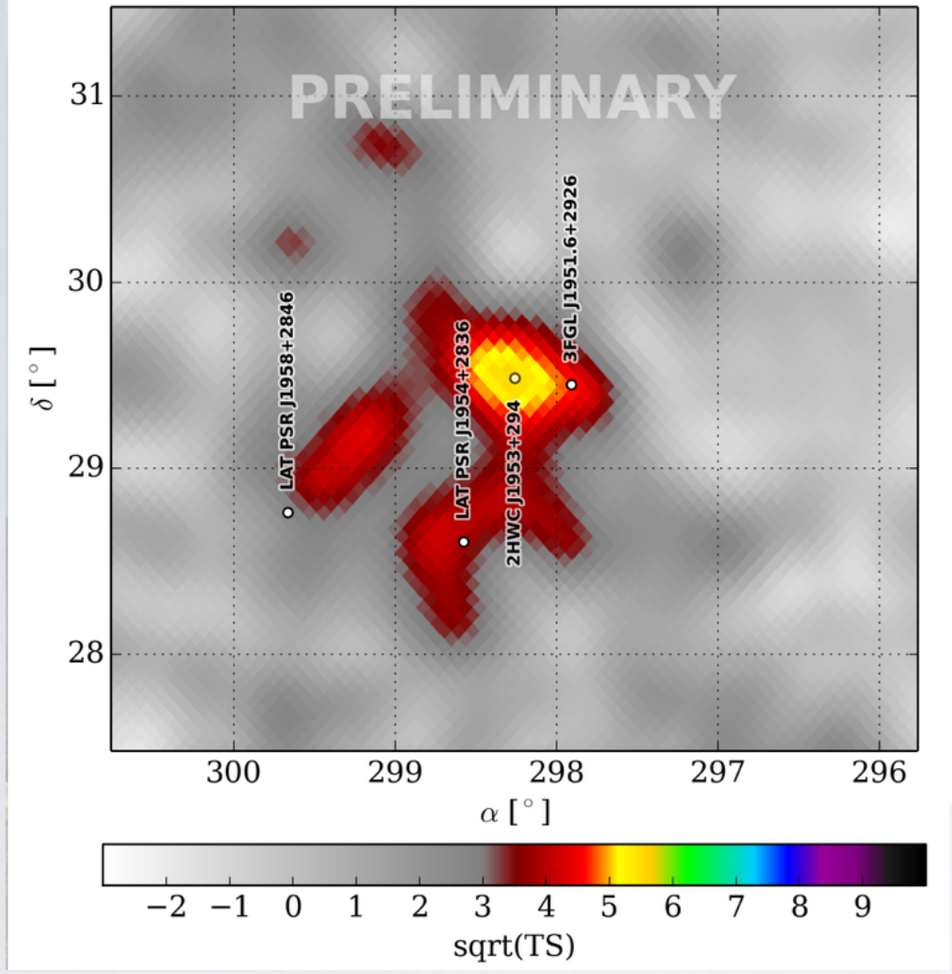
arXiv:1702.02992

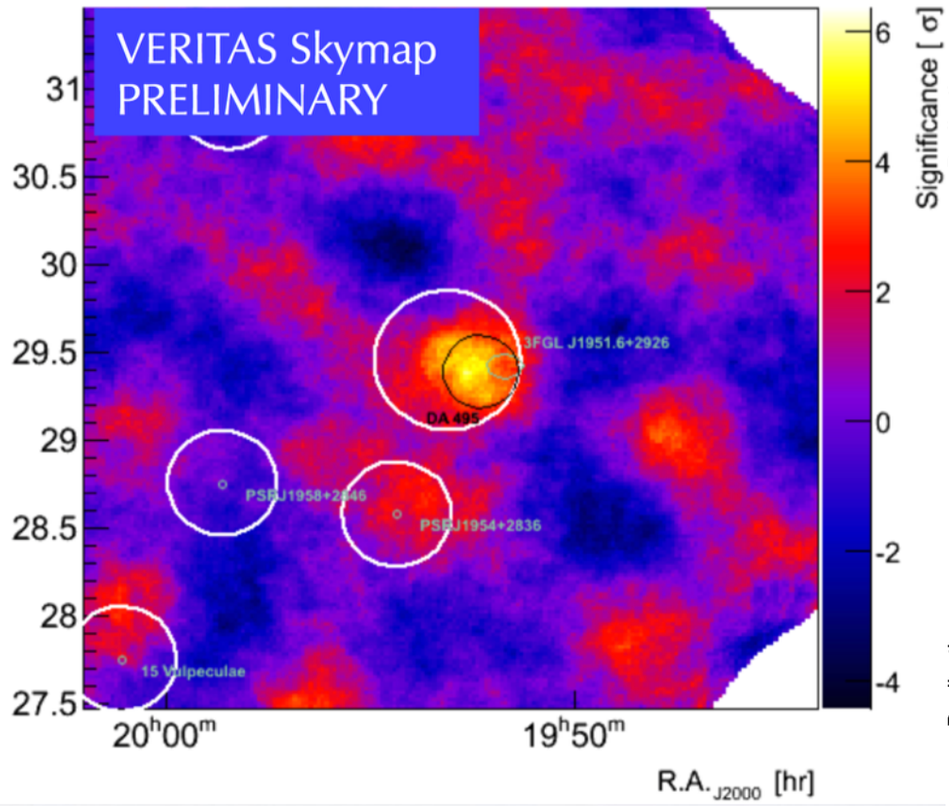




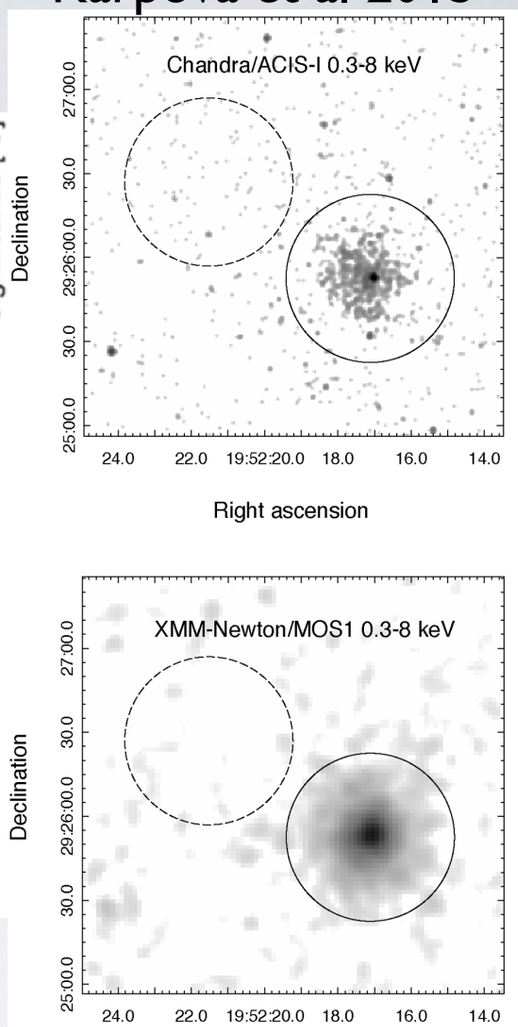
Good candidates for follow-up by pointing instruments.

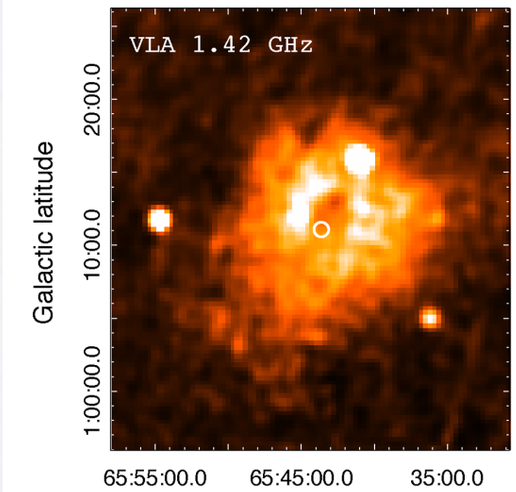
New TeV Sources!





Karpova et al 2015

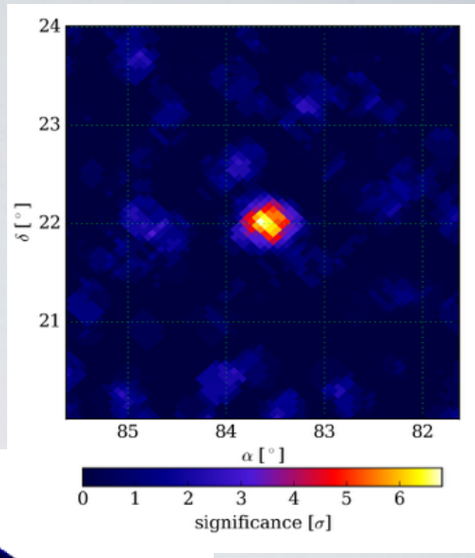




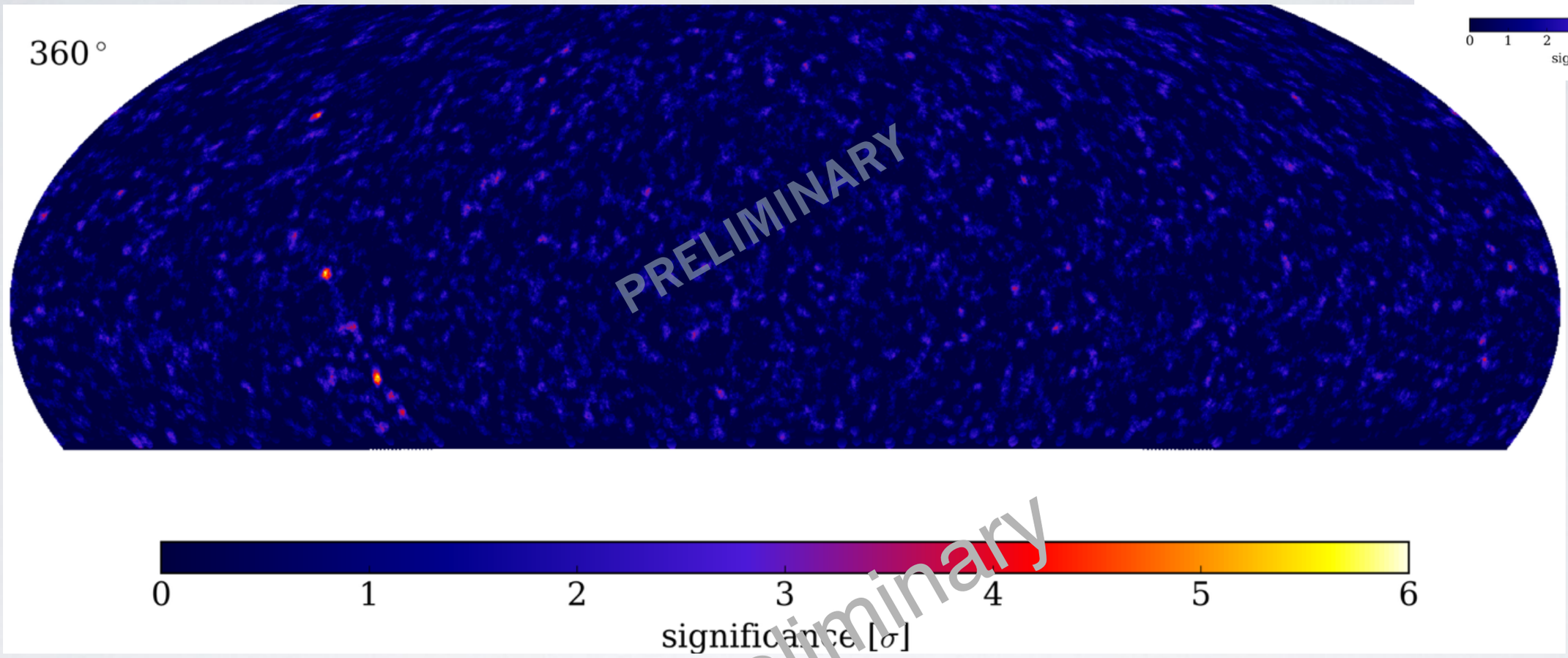
New TeV source
2HWC J1953+294

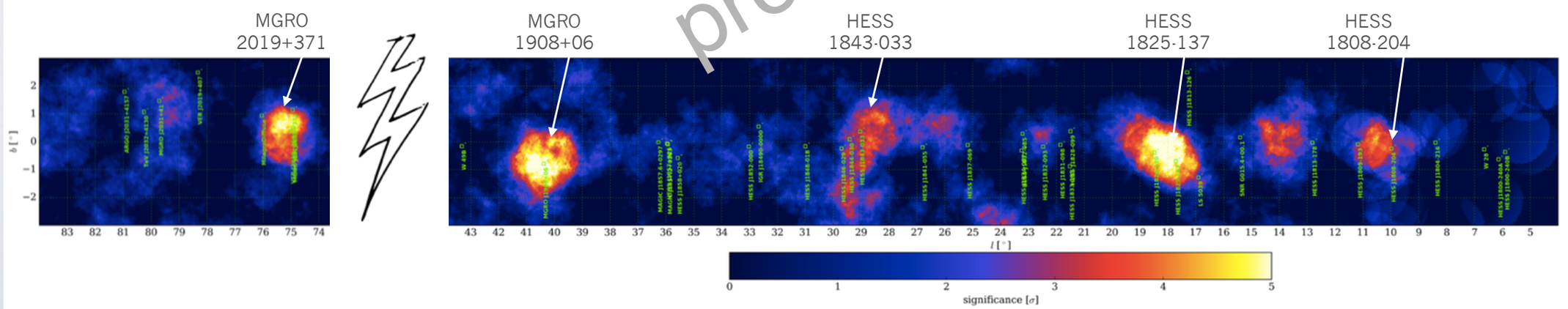
- confirmed by VERITAS, announced in Gamma16
- potential association:
  - PWN DA 495 seen in X-rays
  - 3FGL J1951.6+2926
- Joint paper in prep

Galactic Plane at >50 TeV



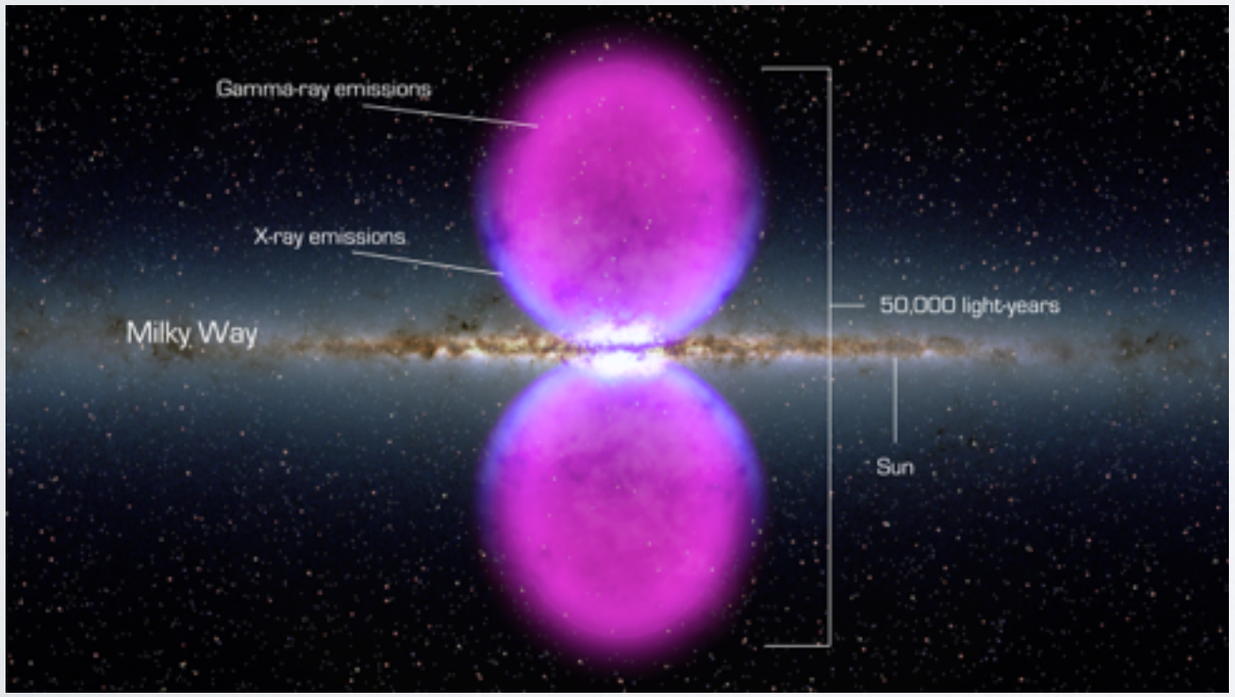
1 deg extended map at >50 TeV

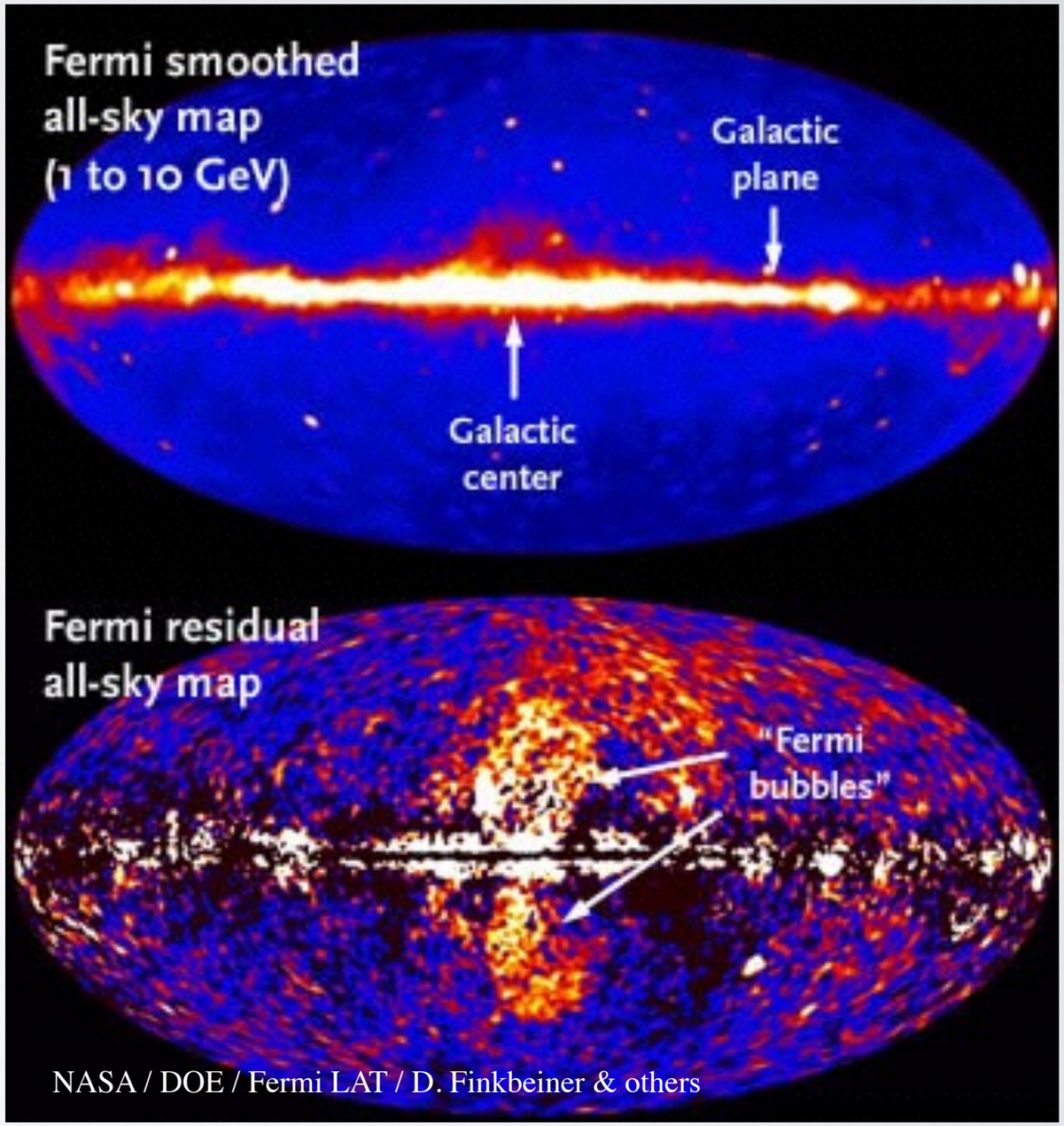




Large-scale structures e.g. Fermi Bubbles

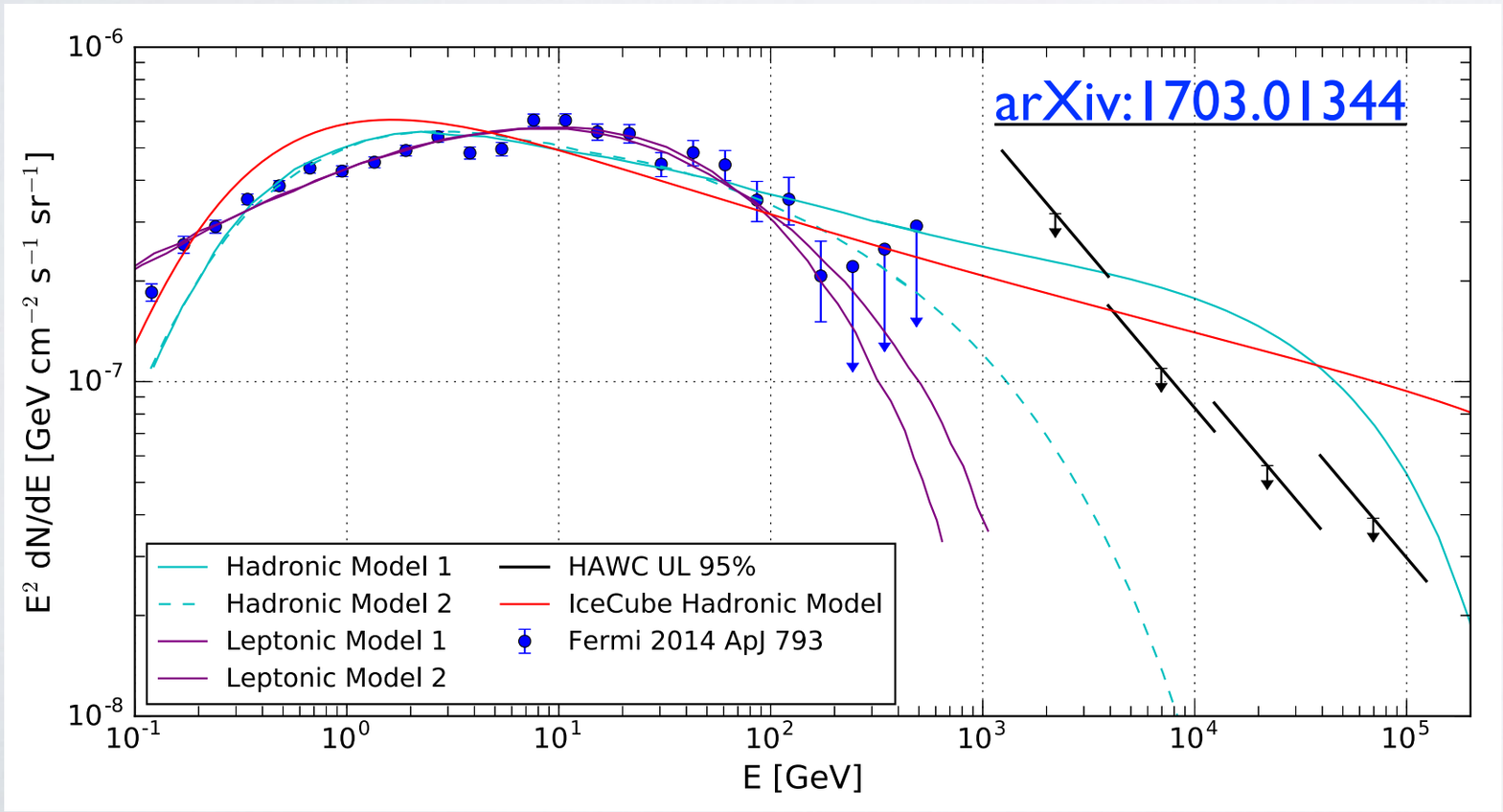
- Large scale, non-uniform structures extending above and below the Galactic center.
  - Edges line up with X-ray features.
  - Correlate with microwave excess (WMAP haze)
  - Both hadronic and leptonic model fit Fermi LAT data. Leptonic model can explain both gamma ray and microwave excess.

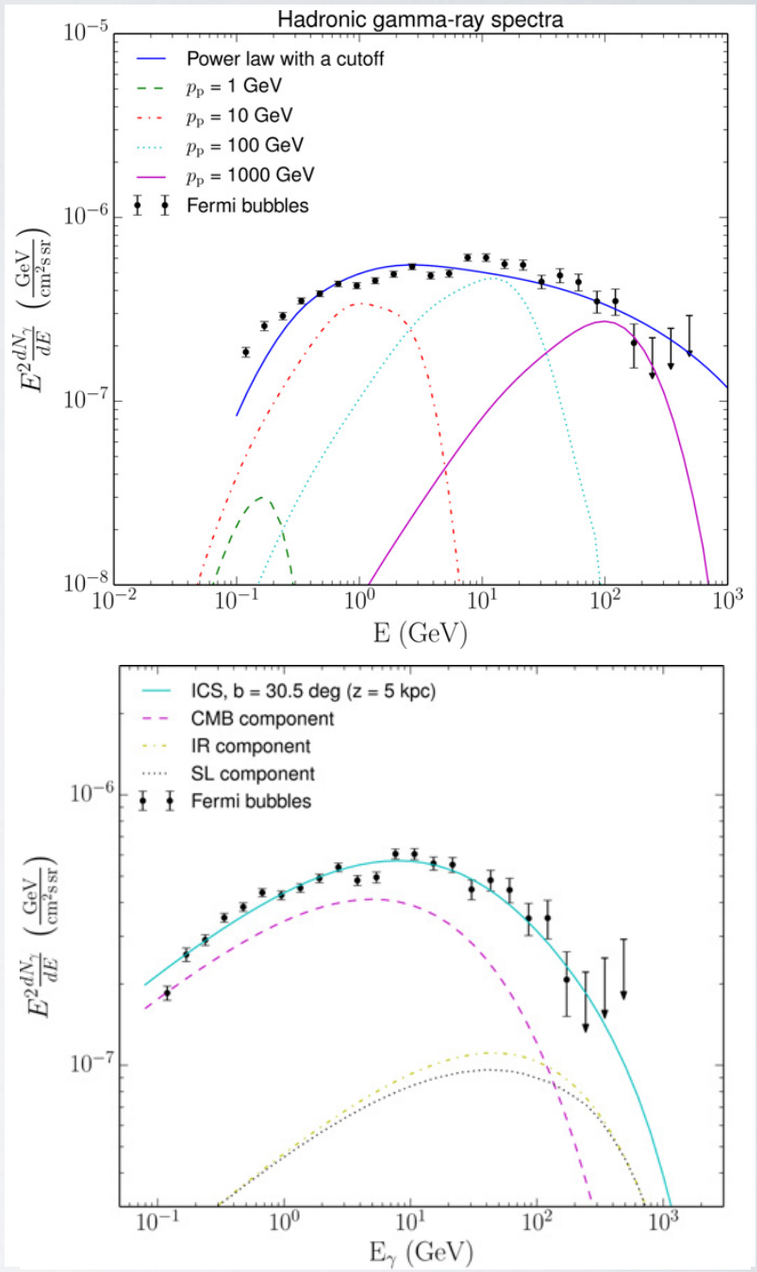




Large-scale structures e.g. Fermi Bubbles

- Hadronic model:
  - cosmic ray interacting with interstellar matter
  - hard to explain microwave haze
- Leptonic model:
  - electron population produced by outflow from Galactic center, or reaccelerated inside the bubble
- First limits in TeV, **hard spectrum is highly unlikely.**



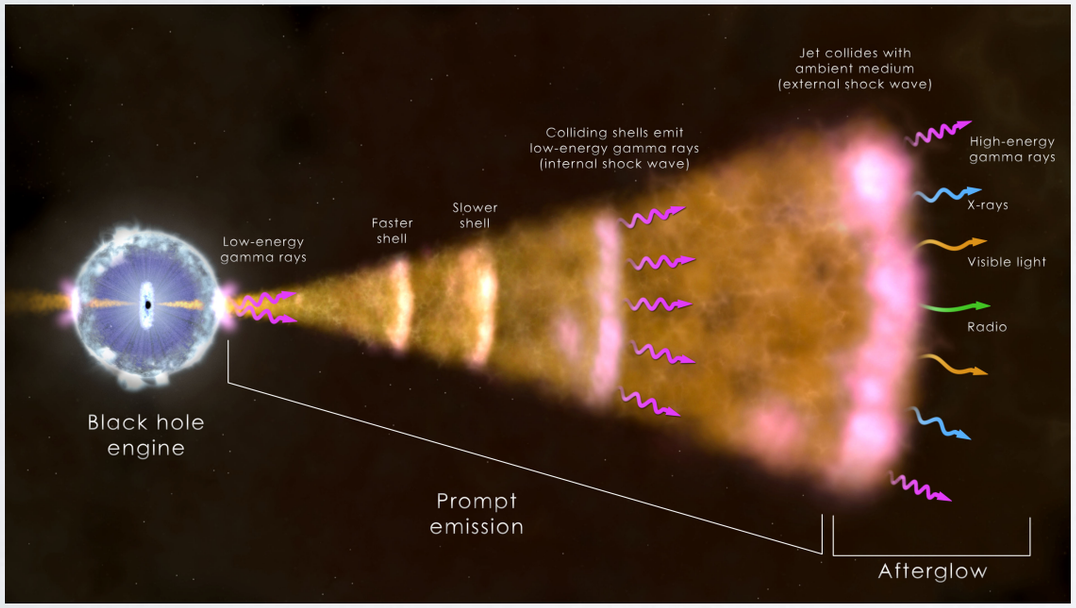


Ackermann et al. ApJ (2014)

Transient Search

- triggered GRB search: 0.2s — 300s
  - external alerts, searching for temporal and spatial coincidence.
- blind GRB-like search: 0.2s — 10s
  - search entire FOV for burst events.

Upper limits of 64 GRBs in 18 months of HAWC data
arXiv:1705.01551



- rapid flare monitor: 2min — 10hr
  - fast rising flux from known blazars.
  - arXiv:1704:07411
- daily maps: ~6hr
  - flux in every point in all visible sky.
  - arXiv:1703.06968

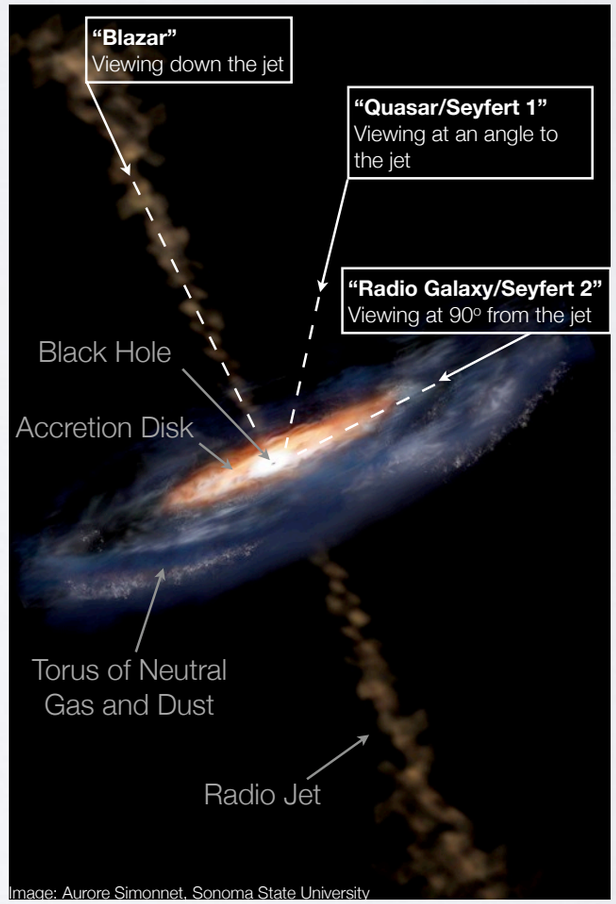


Image: Aurore Simonnet, Sonoma State University

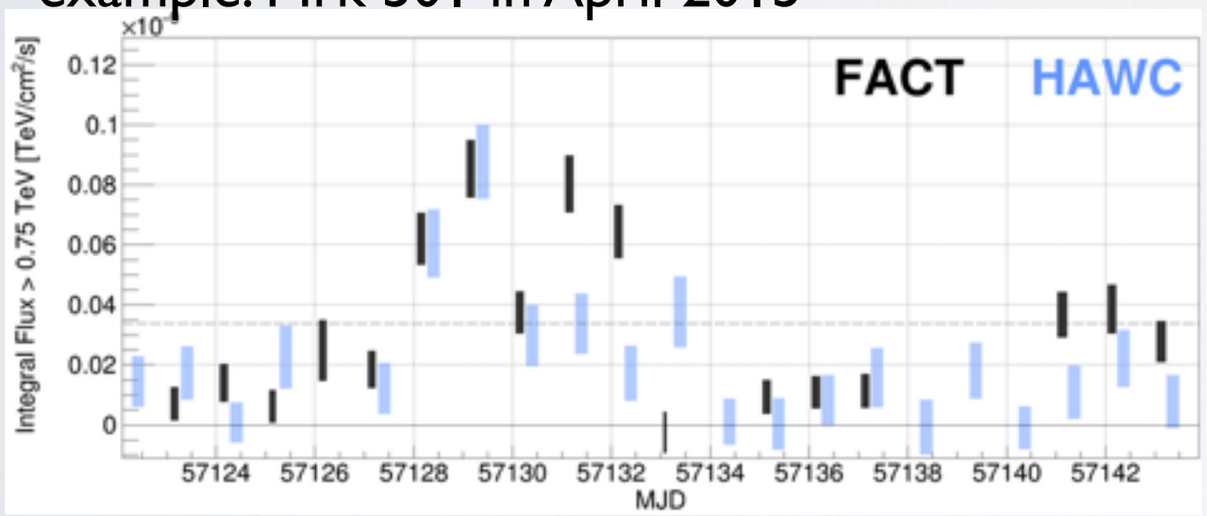
Transient Search

- triggered GRB search: 0.2s — 300s
  - external alerts, searching for temporal and spatial coincidence.
- blind GRB-like search: 0.2s — 10s
  - search entire FOV for burst events.

- rapid flare monitor: 2min — 10hr
  - fast rising flux from known blazars.
  - arXiv:1704:07411
- daily maps: ~6hr
  - flux in every point in all visible sky.
  - arXiv:1703.06968

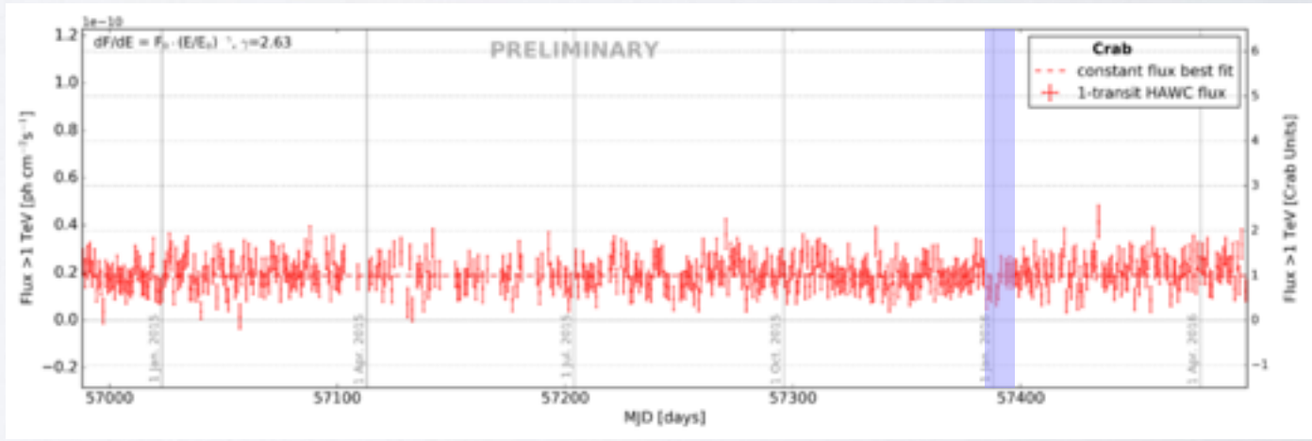
Upper limits of 64 GRBs in 18 months of HAWC data
arXiv:1705.01551

Joint monitoring with FACT
example: Mrk 501 in April 2015



Crab light curve from Nov 2014 to April 2016

- consistent with constant flux



Fermi-LAT: ATEL 8519
gamma-ray flare (E>100MeV)

Transient Search

AGN Mrk 421

- Daily flux lightcurve from Nov 2014 to Apr 2016.
- Inconsistent with constant flux at p-value <1e-10.
- Large number of high states, year-average flux ~ Crab flux
- Best fit constant flux for this period is higher than upper limit on integral baseline flux derived in Tluczykont et al. 2010.

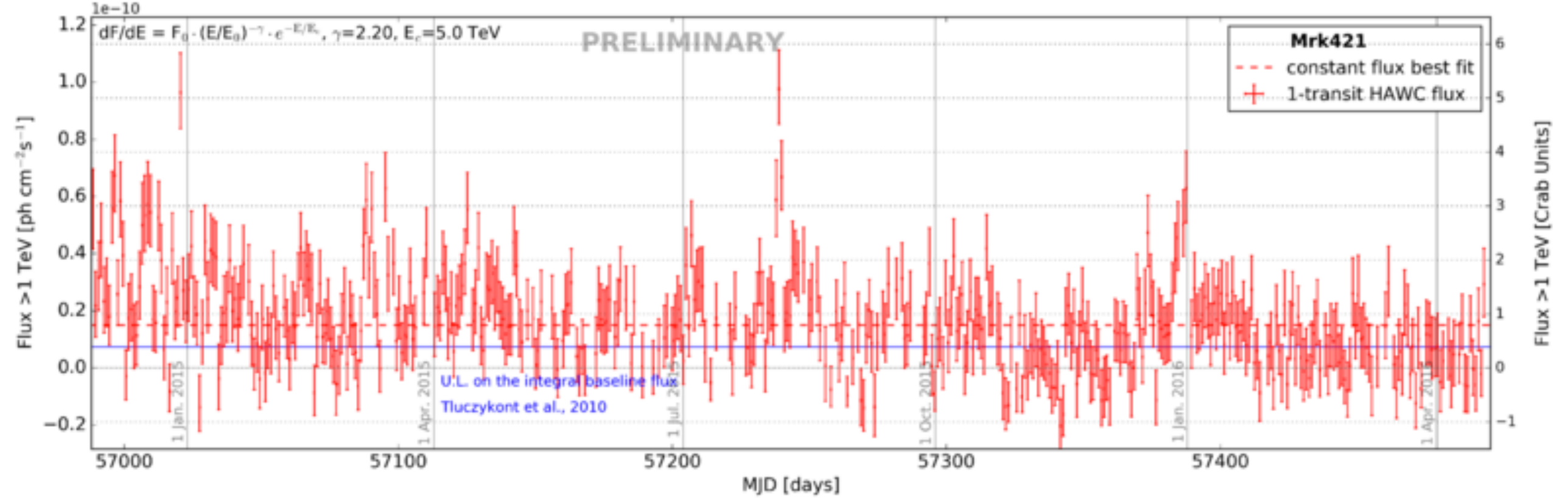
First joint FACT-HAWC-SWIFT ATEL:

Enhanced and increasing activity in gamma rays and X-rays from the HBL Mrk421

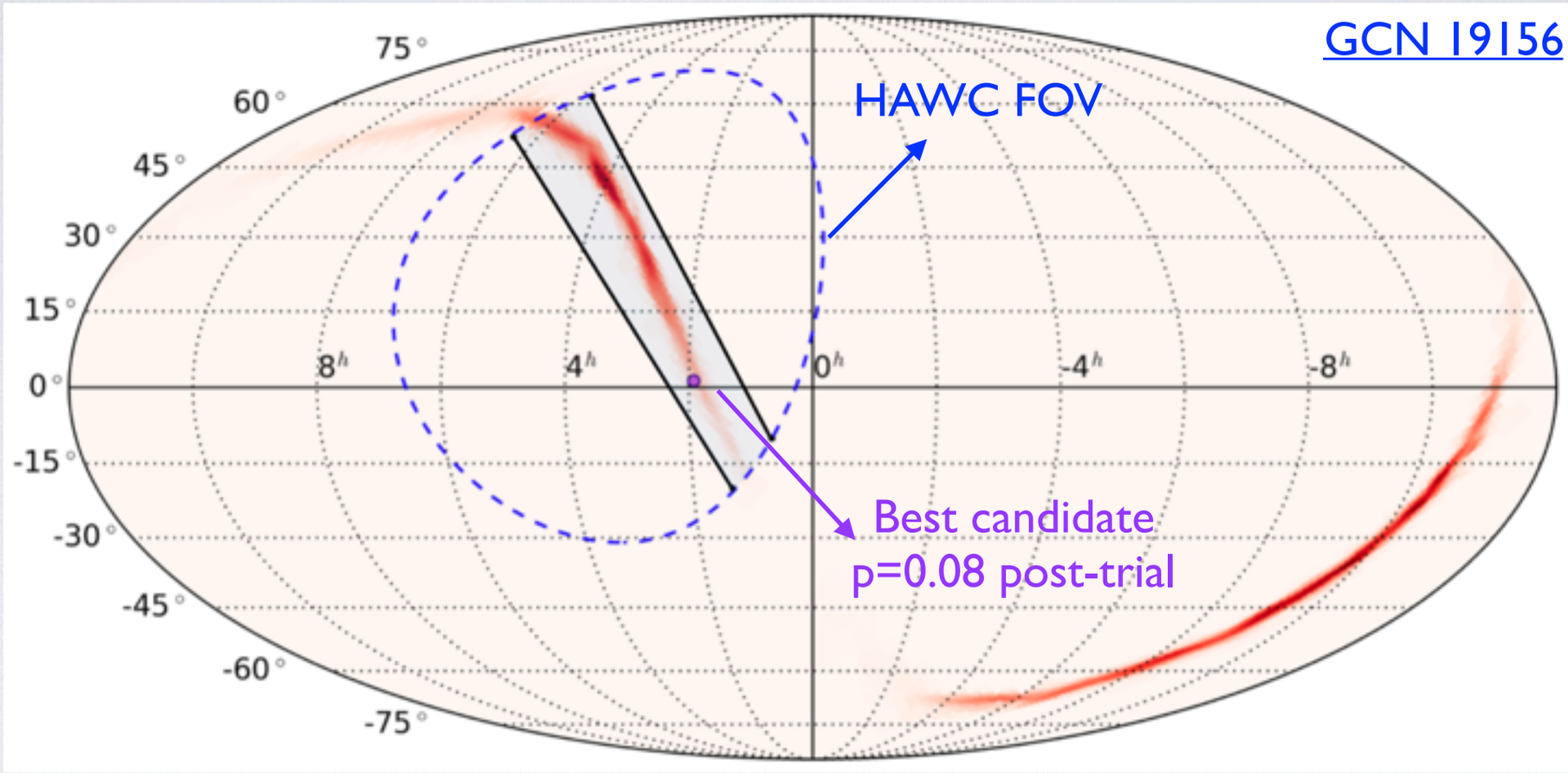
ATel #9137; *A. Biland (ETH Zurich) and D. Dorner (University of Wuerzburg, FAU Erlangen) for the FACT Collaboration, R. Lauer University of New Mexico) and J. Wood (University of Maryland) for the HAWC Collaobration, B. Kapanadze (Abastumani Astrophysical Observatory, Ilia State University), A. Kreikenbohm (University of Wuerzburg)*
on *10 Jun 2016; 19:00 UT*

- **FACT and HAWC with daily TeV coverage** and complementary observation times.
- HAWC, FACT and SWIFT all show **rising fluxes with highest values on June 9, 2016** (~3 x Crab flux).
- SWIFT observations at 0.3-10 keV:
  "Note that higher or comparable X-ray fluxes were observed only four times so far."

arXiv:1703.06968



LIGO Follow-up



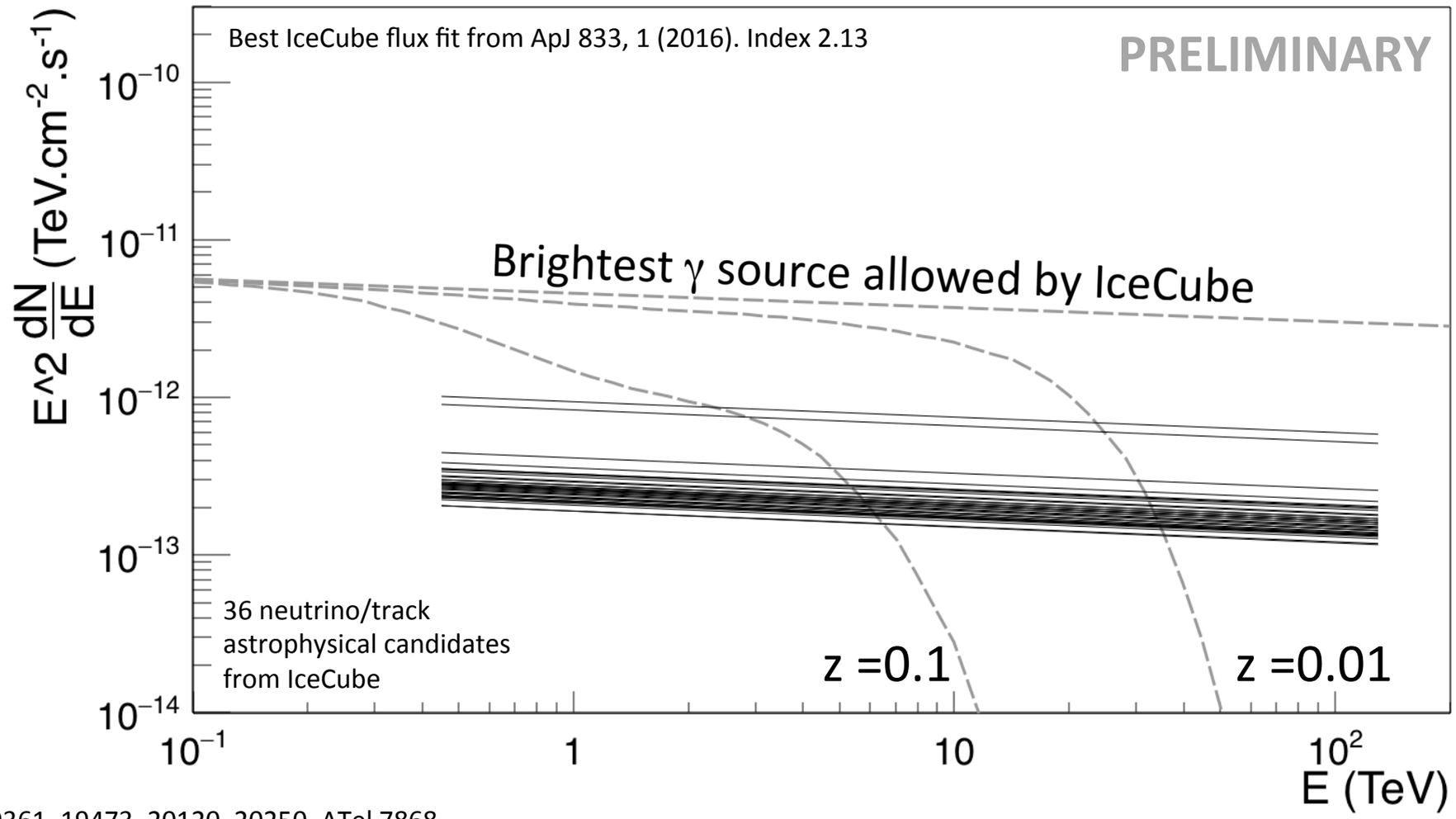
GW151226:
- 2015 Dec 26 03:38:53.6 UTC
- z=0.09 +0.03 -0.04
- 14.2M⊙ + 7.5M⊙ ➡20.8M⊙

Real-time all-sky GRB search:
- 4 sliding windows (0.1, 1, 10, 100 seconds)
- ±10s of LIGO trigger
- 15deg within LIGO contours

Best candidate 9.98s after LIGO trigger
- post-trial p-value 0.08, consistent with background

Neutrino Follow-up

Neutrino Follow up – HAWC Limits: 507 days livetime

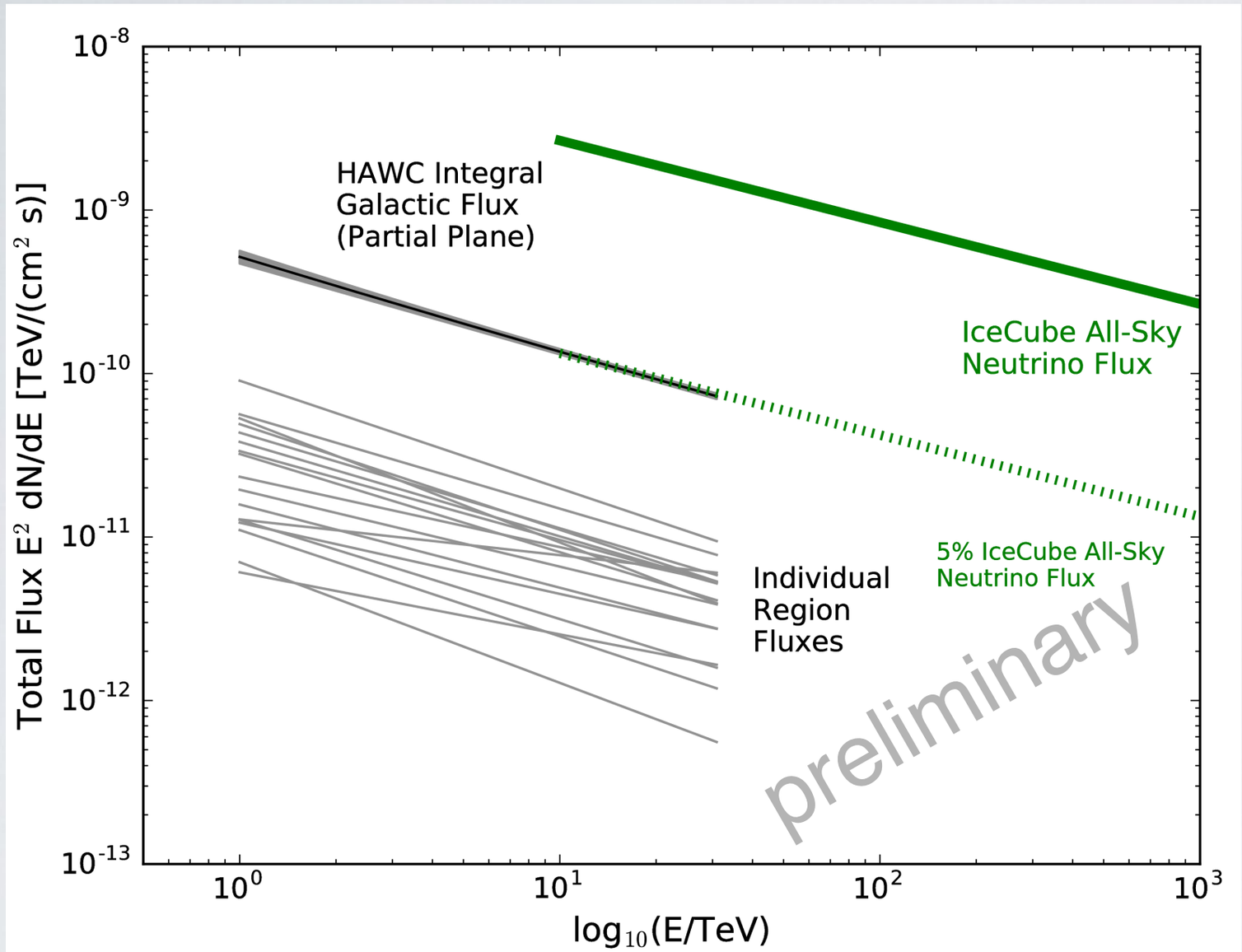


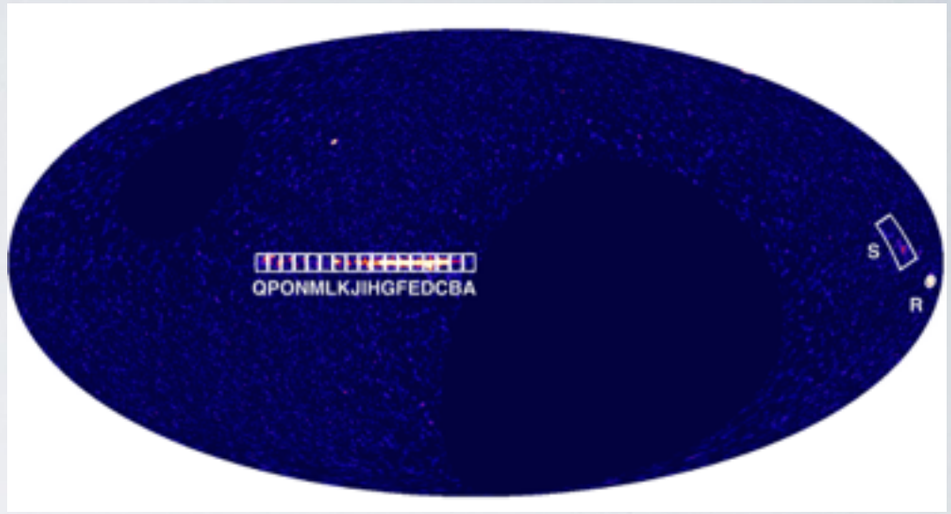
GCN Circ. 19361, 19473, 20120, 20250. ATel 7868

Lack of a coincident observation interpretation:

- If local sources, fluxes are weaker than implied by an order of magnitude
- Opaque to gamma rays (and to cosmic rays!)
- High redshift
- Transient source
- Incorrect extrapolation to lower energies

Galactic Origin of IceCube Neutrinos?





- Integrated all emission in 19 regions (5°x6°) along Galactic plane (~47% of Galactic plane coverage)
- Caveats:
  - Simple model for photon/neutrino flux connection
  - Extrapolation to HAWC energies
  - Assumed hadronic emission (unlikely best-case scenario)
  - Galactic center and half of Galactic plane are not observed

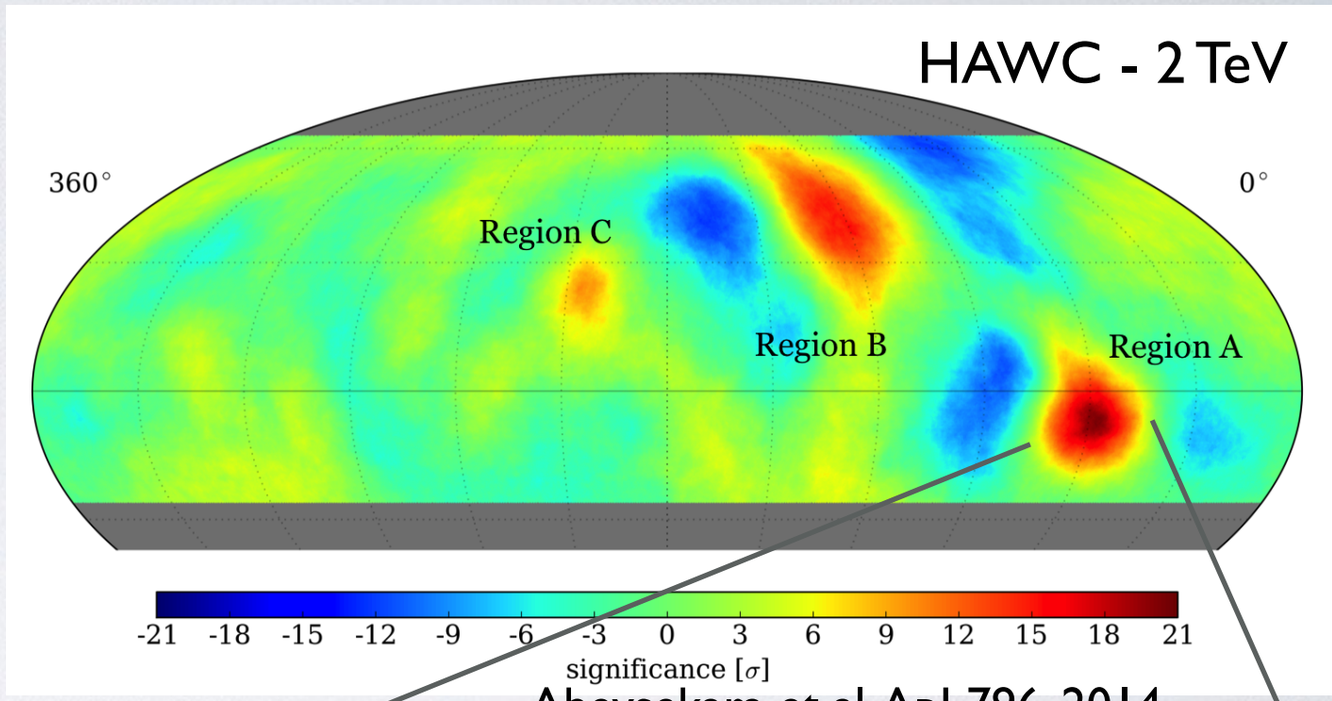
HAWC Galactic plane emission accounts for ~5% of IceCube all-sky flux

Cosmic-Ray Anisotropy

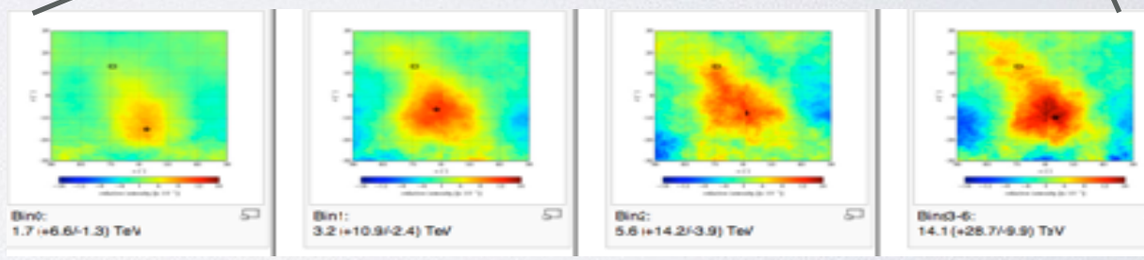
Abeysekara et al., ApJ 796 108 (2014)

HAWC observation

- 180 days
- 10° smoothing
- Region A — hardening spectrum, 4.3σ effect.
- Region B — most extended.
- Region C — confirm ARGO-YBJ observation.
- Ongoing work on joint analysis with IceCube.



Abeysekara et al. ApJ 796, 2014

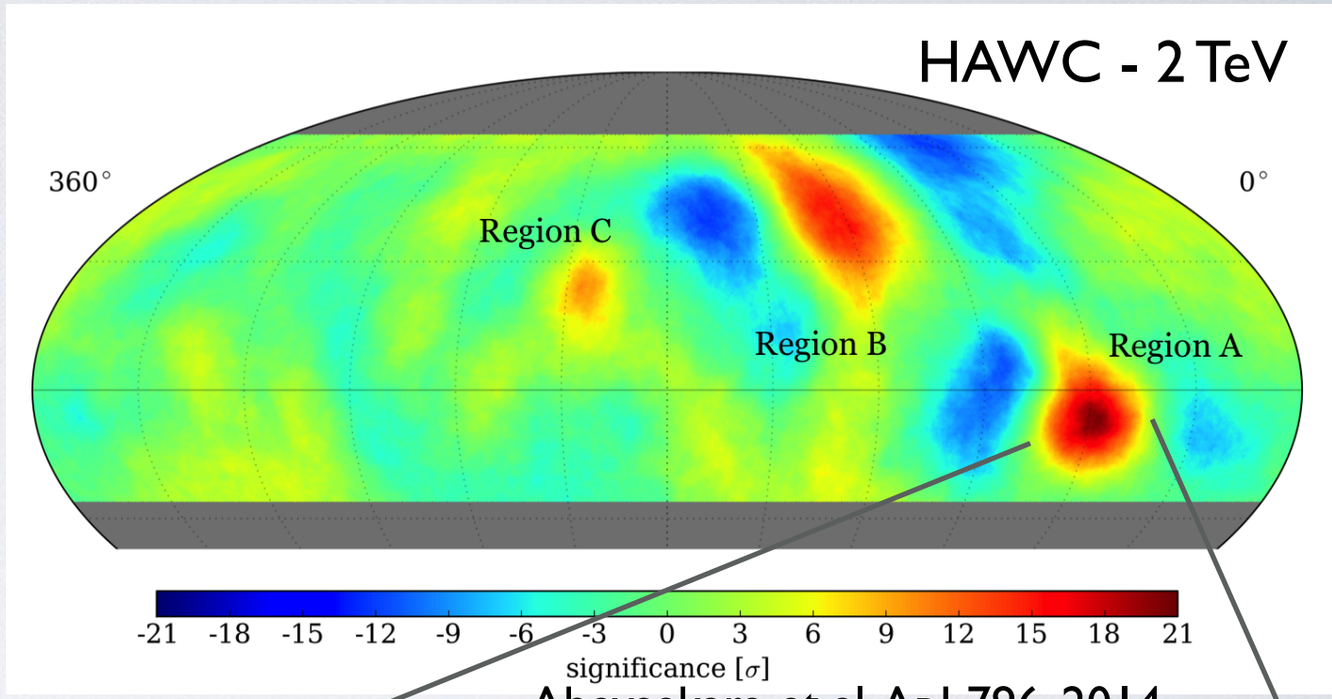


Cosmic-Ray Anisotropy

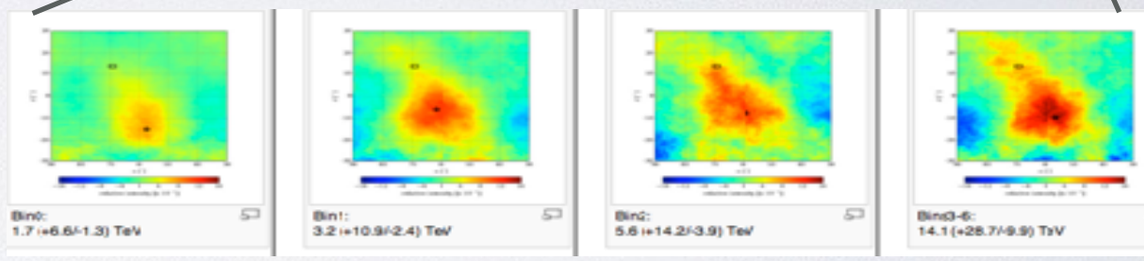
Abeysekara et al., ApJ 796 108 (2014)

HAWC observation

- 180 days
- 10° smoothing
- Region A — hardening spectrum, 4.3σ effect.
- Region B — most extended.
- Region C — confirm ARGO-YBJ observation.
- Ongoing work on joint analysis with IceCube.

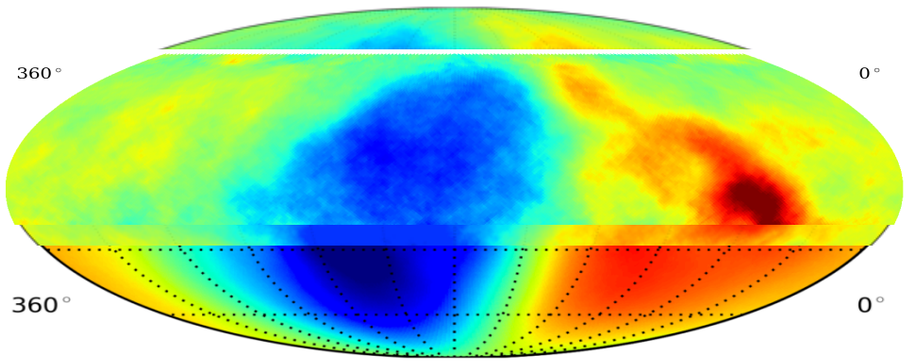


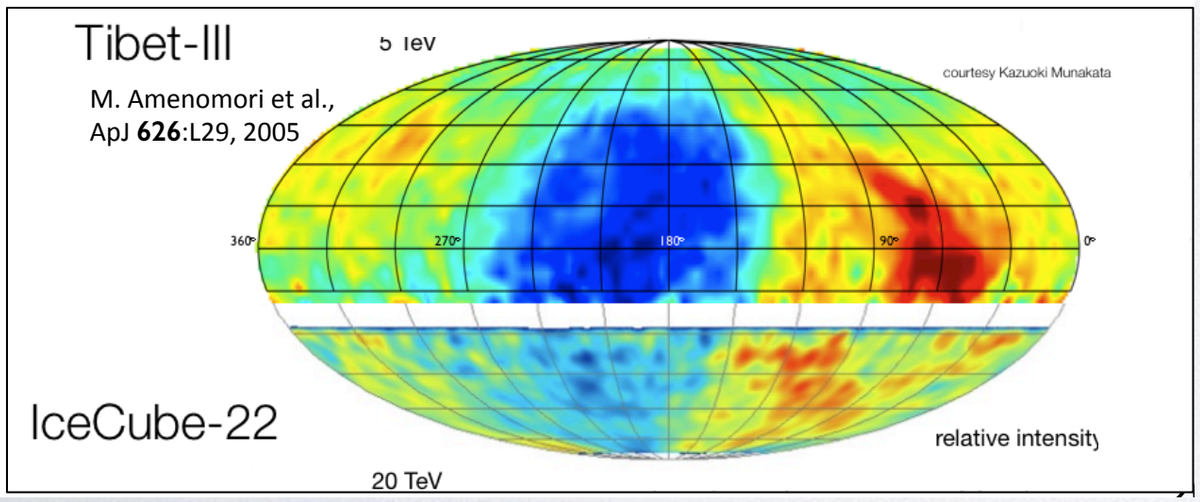
Abeysekara et al. ApJ 796, 2014



HAWC
~ 11 TeV

IceCube
~13 TeV





Large-scale anisotropy

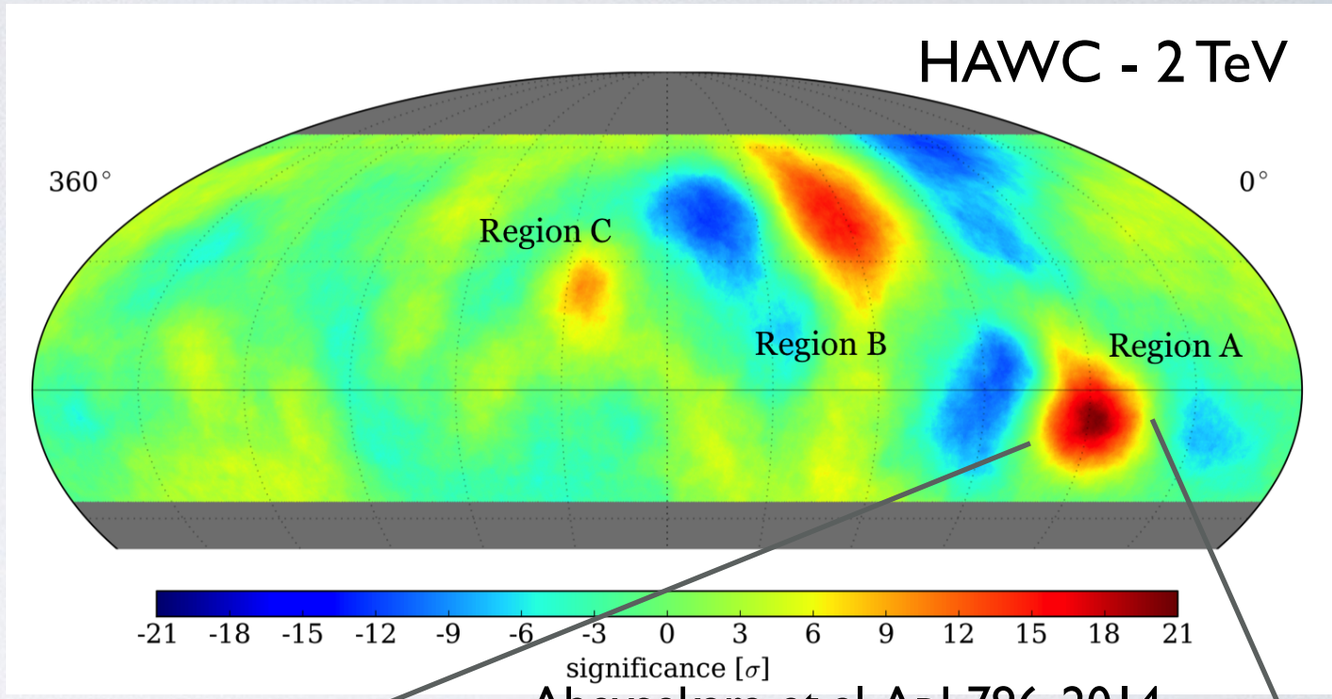
- HAWC observations: 241 days, 10° smoothing
  - partial year coverage — seasonal effect
- observed from 500GeV to 1PeV by IceCube, Tibet
  - invariant in time
  - phase change at 100TeV

Cosmic-Ray Anisotropy

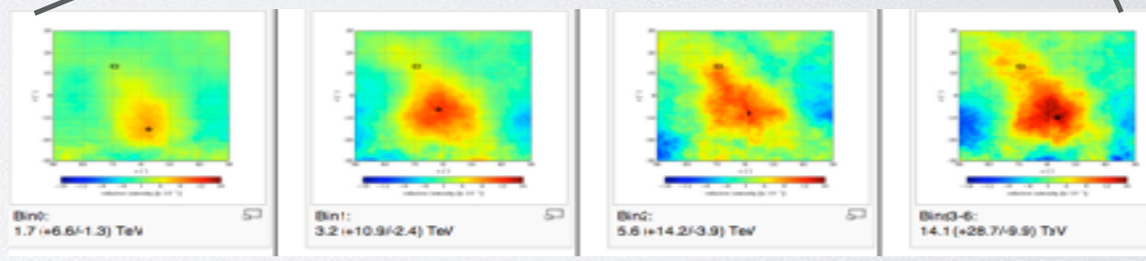
Abeysekara et al., ApJ 796 108 (2014)

Possible explanations

- Inhomogeneous source distribution
- Turbulence in Galactic magnetic field
  — doesn't explain region A hardening
- Exotic scenarios — new particles?

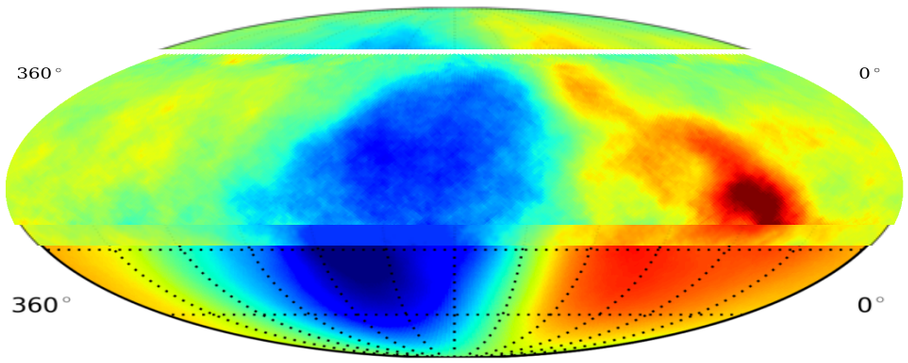


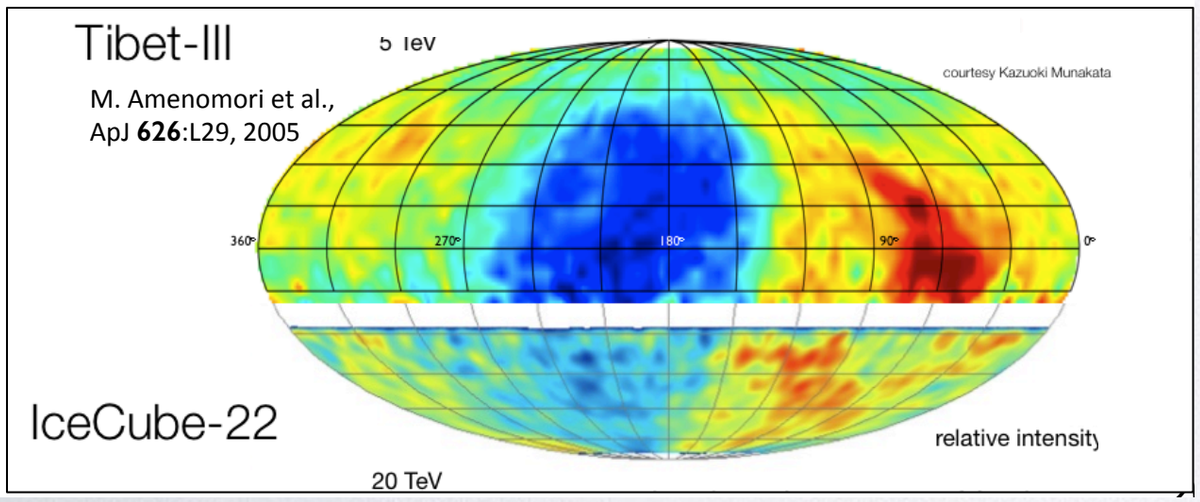
Abeysekara et al. ApJ 796, 2014



HAWC
~ 11 TeV

IceCube
~13 TeV





Large-scale anisotropy

- HAWC observations: 241 days, 10° smoothing
  - partial year coverage — seasonal effect
- observed from 500GeV to 1PeV by IceCube, Tibet
  - invariant in time
  - phase change at 100TeV

Multi-wavelength / Multi-messenger

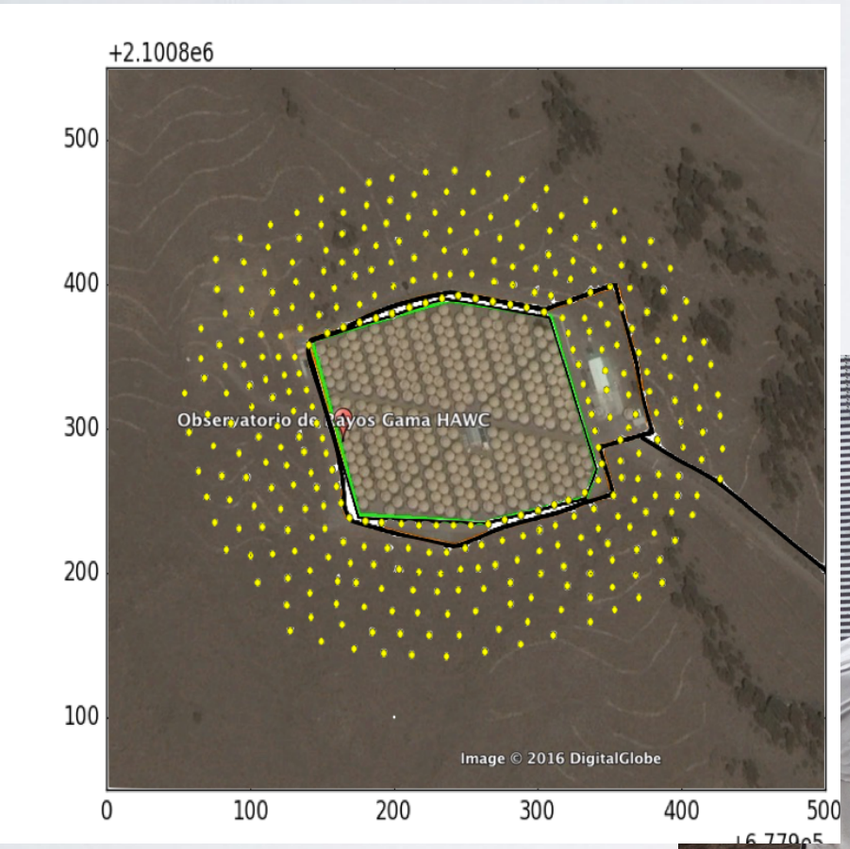
Have follow-up agreement with:
- Swift
- NuSTAR
- Fermi
- IACTs
  - FACT
  - HESS
  - MAGIC
  - VERITAS
- AMON
- IceCube
- ANTARES
- LIGO/VIRGO

HAWC-triggered:
- New source candidates lists.
  - follow-up observations by IACTs such as VERITAS and MAGIC.
- Flares from known gamma-ray sources.
  - joint monitoring with FACT.

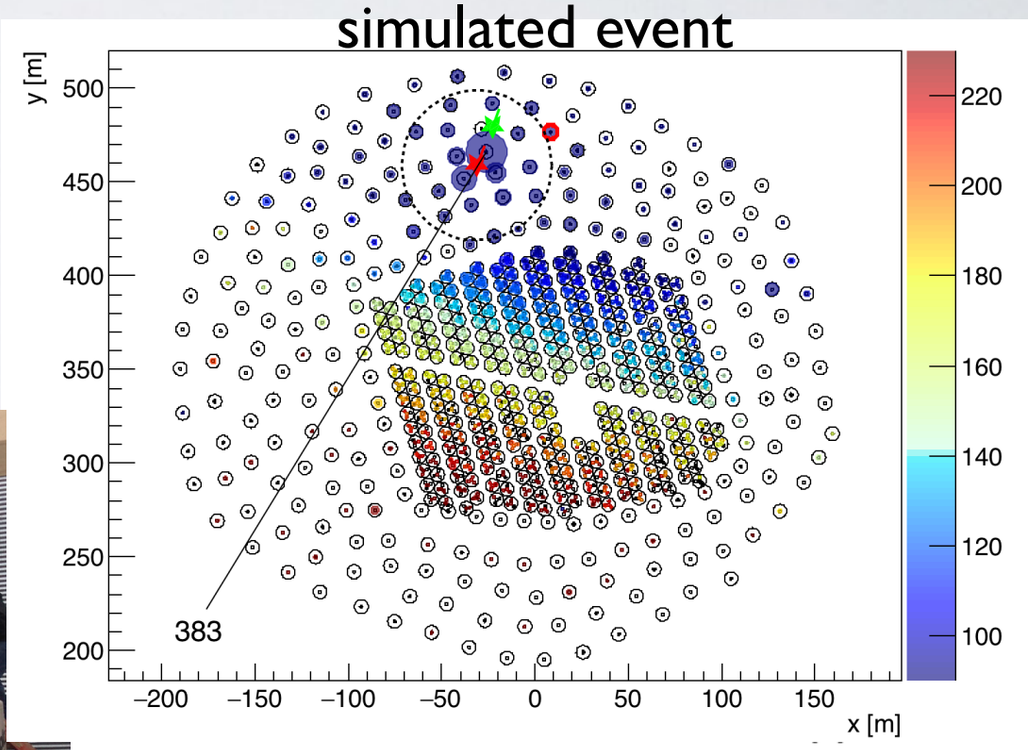
Externally triggered:
- IceCube alert on high confidence astrophysical neutrino event.
  - MW follow-up of IceCube multiplet arXiv:1702.06131
- Fermi alerts on flaring activities.
- LIGO/VIRGO gravitational wave event follow-up.

HAWC Upgrade

- 350 small WCD outrigger detectors.
- Cover an area 4x HAWC.
- Sensitivity increase by 3-4x the sensitivity at 50 TeV.
- Deployment in progress.



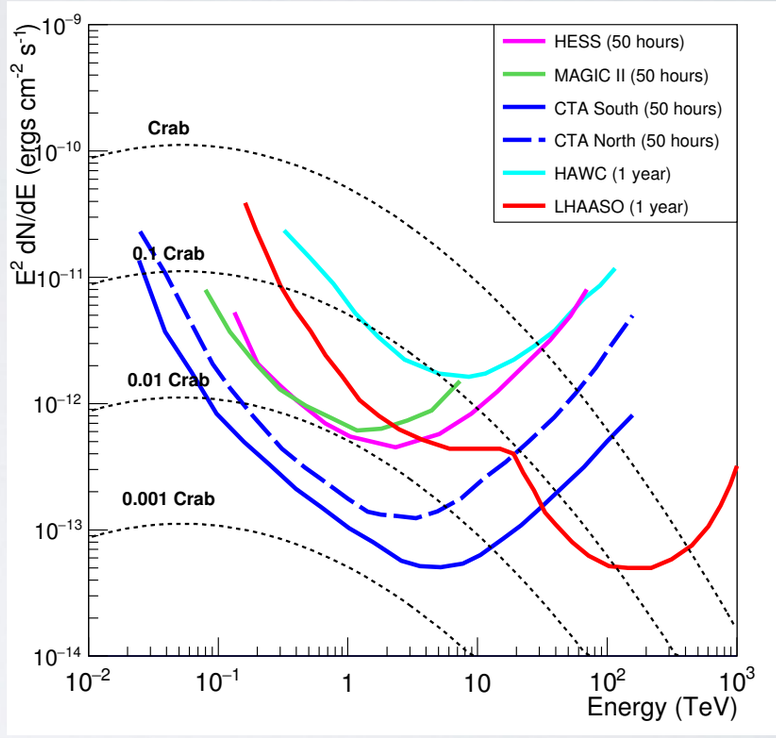
simulated event

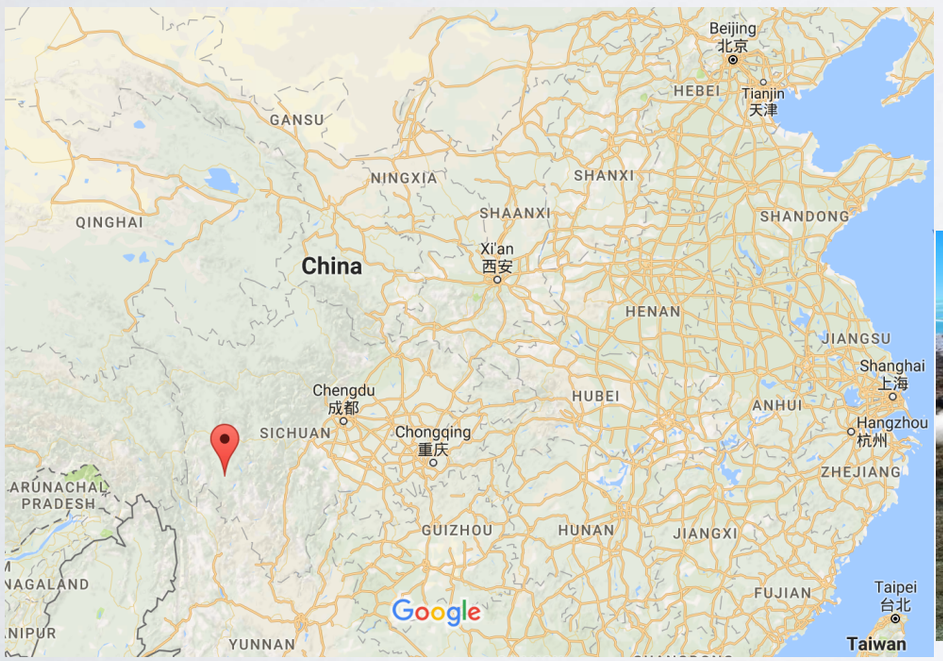


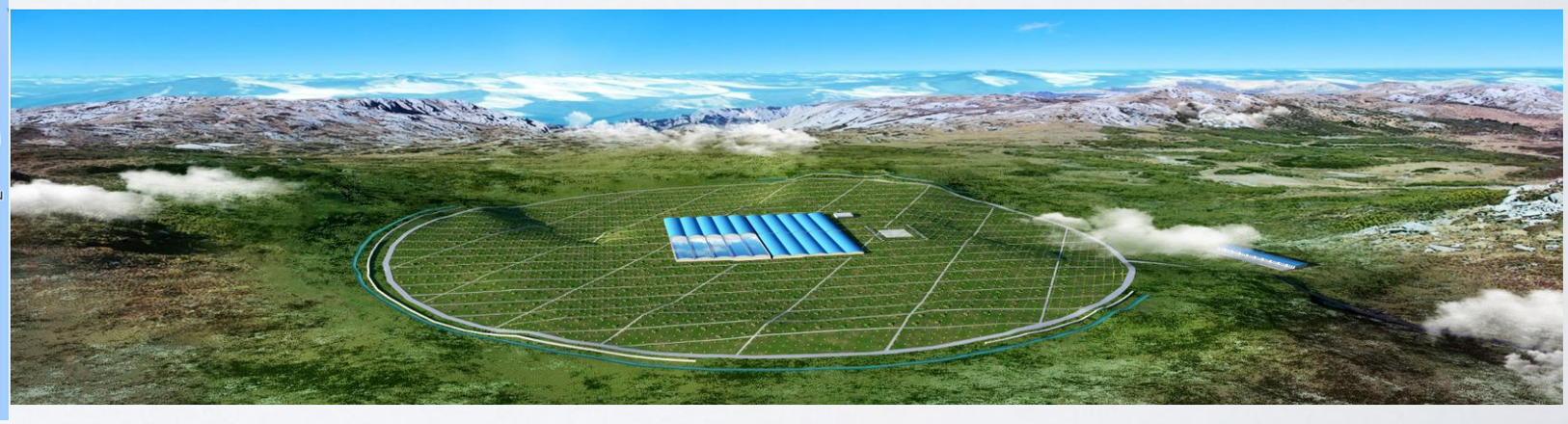
Future Observatories

LHAASO (Large High Altitude Air Shower Observatory)

- Array in Sichuan province, China at 4410m
  - scintillator detectors (1km^2)
  - underground water Cherenkov detectors (1km^2)
  - surface water Cherenkov detectors (80,000m^2)
  - 12 wide FOV air Cherenkov/Fluorescence telescopes
- Commissioning in 2018, expect to be fully installed in 2021



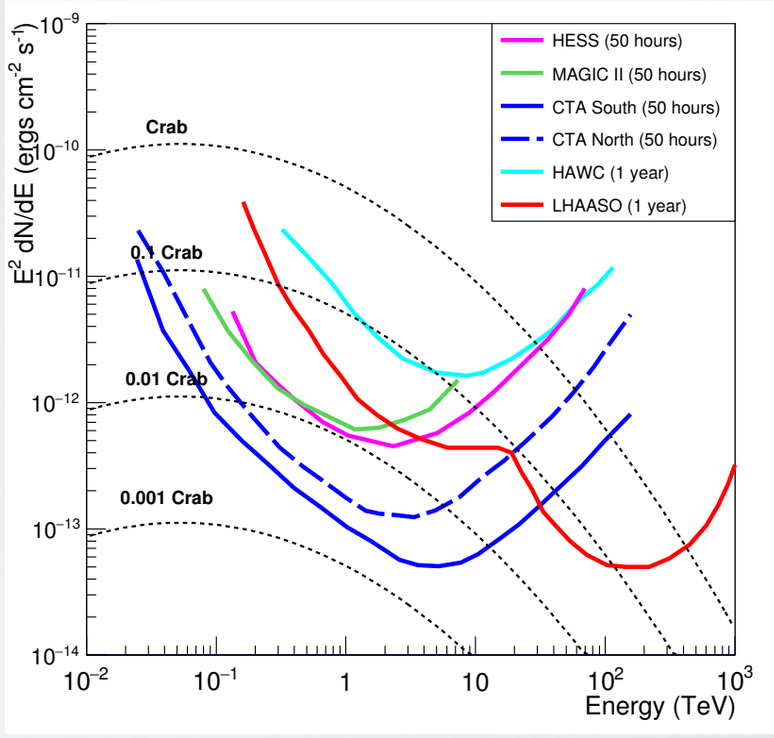




Future Observatories

LHAASO (Large High Altitude Air Shower Observatory)

- Array in Sichuan province, China at 4410m
  - scintillator detectors (1km^2)
  - underground water Cherenkov detectors (1km^2)
  - surface water Cherenkov detectors (80,000m^2)
  - 12 wide FOV air Cherenkov/Fluorescence telescopes
- Commissioning in 2018, expect to be fully installed in 2021



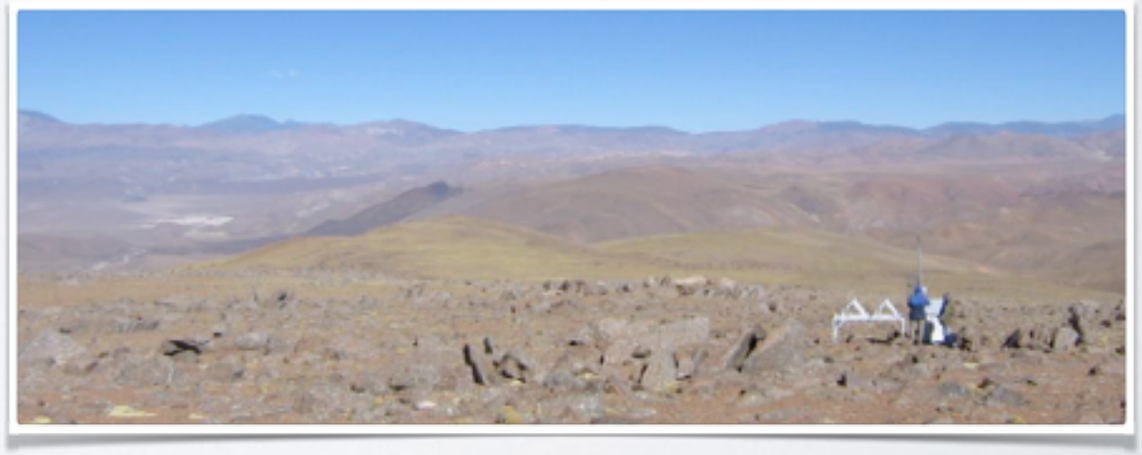
Southern Gamma-ray Observatory

- Potential sites:

  Argentina

  Bolivia

  Chile
- Investigating sites at 4800m — 5600m



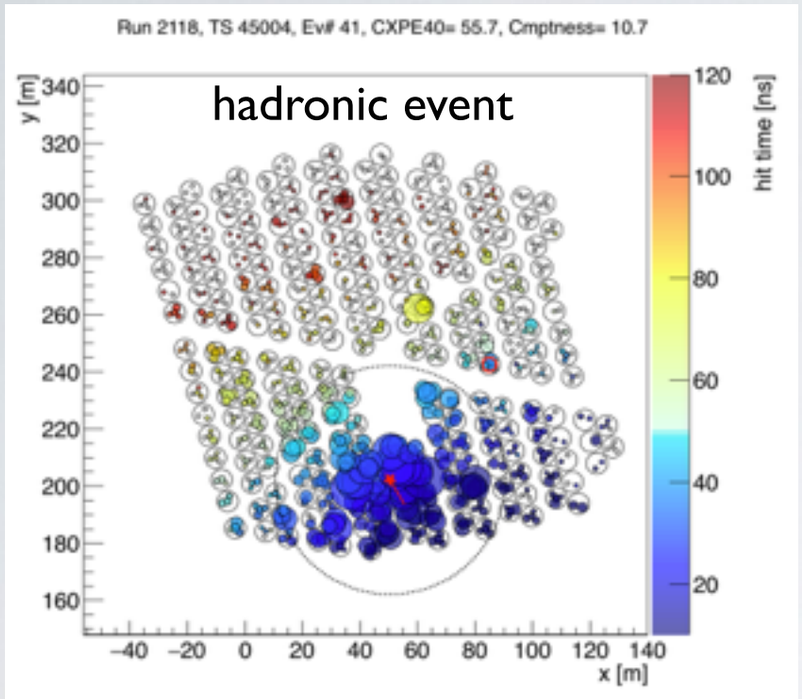
Southern Gamma-ray Observatory workshop Jun 8-9 at Rochester NY

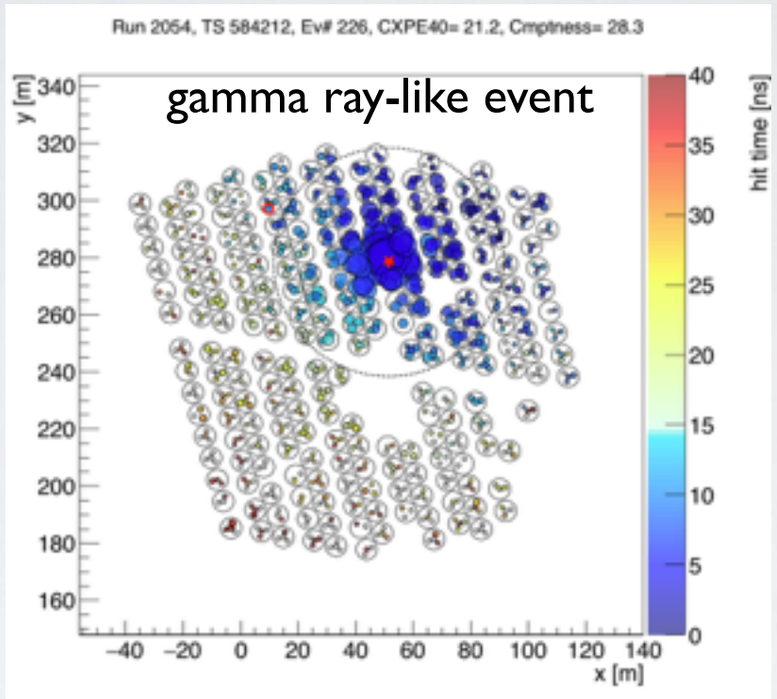
Outlook

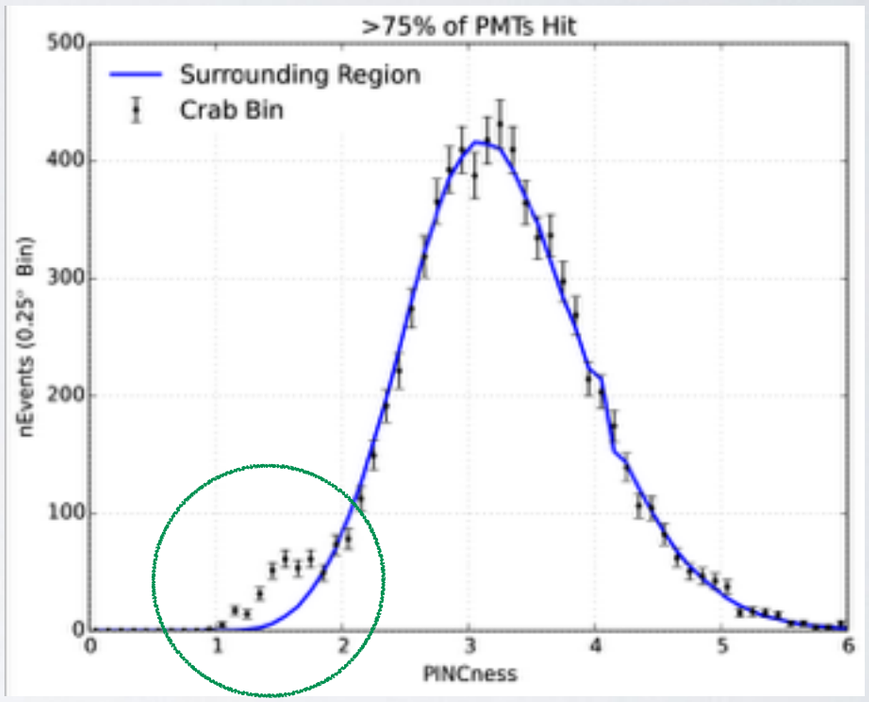
- HAWC is surveying and monitoring the gamma-ray sky, searching for extended structures and transients.
- Many instruments from different waveband/messenger (X rays, gamma rays, neutrinos, gravitational waves) available for simultaneous observations.
- Both wide-field and pointing instruments in development and coming online in the next decade.

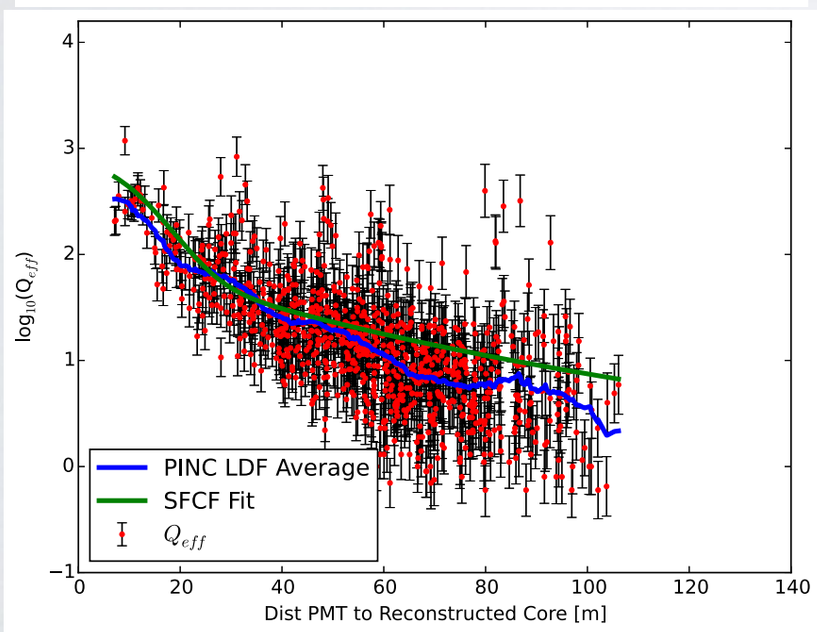
BACKUP

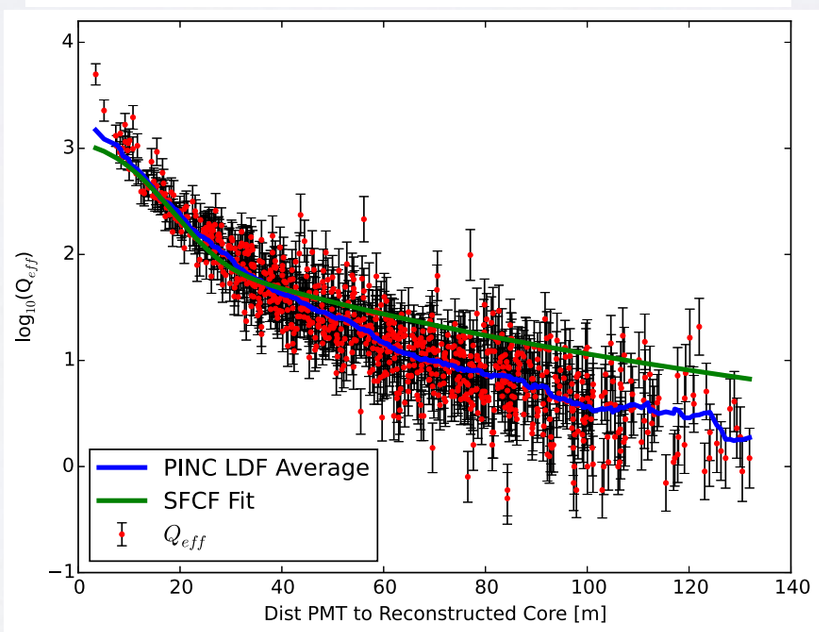
Gamma/Hadron Separation



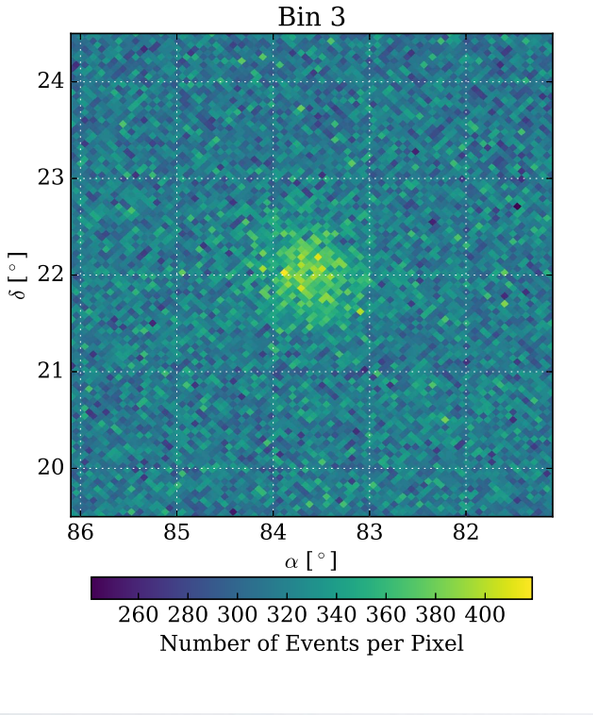




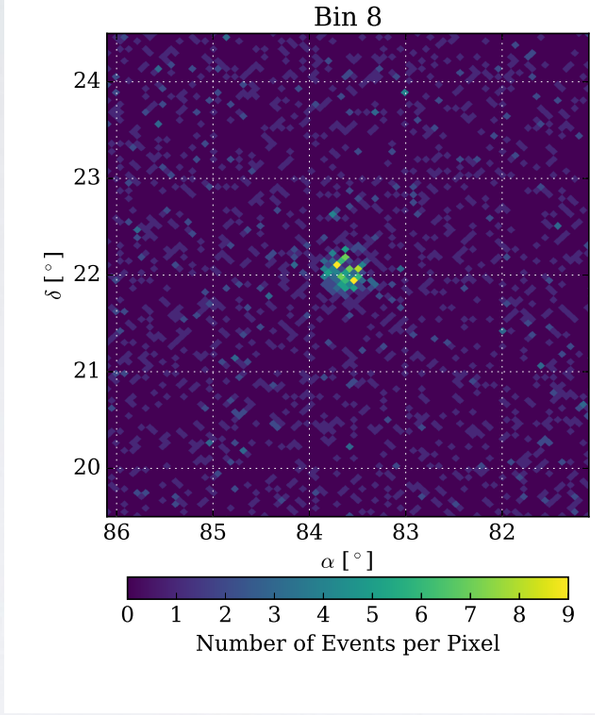




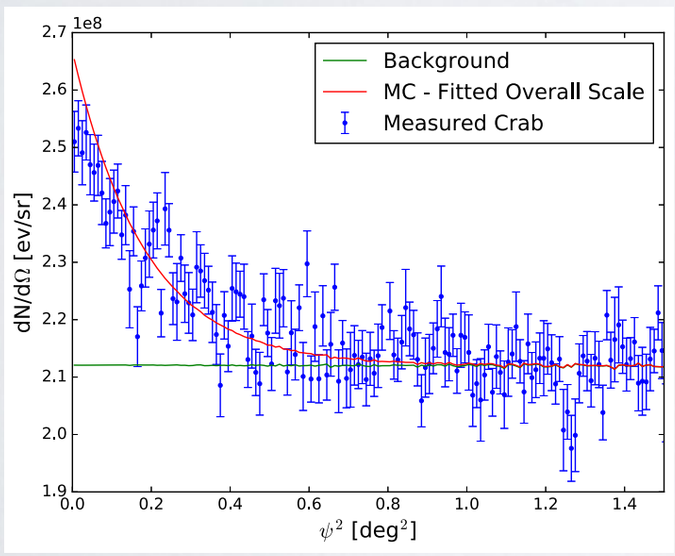
Angular Resolution



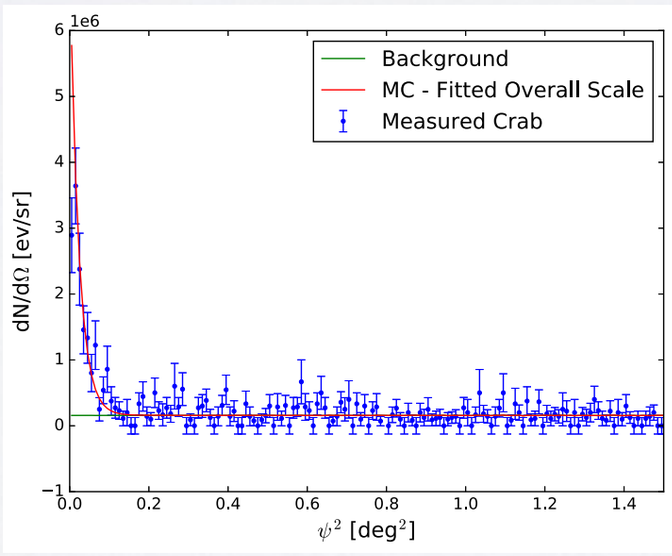
(a) $\mathcal{B} = 3$ Event Counts



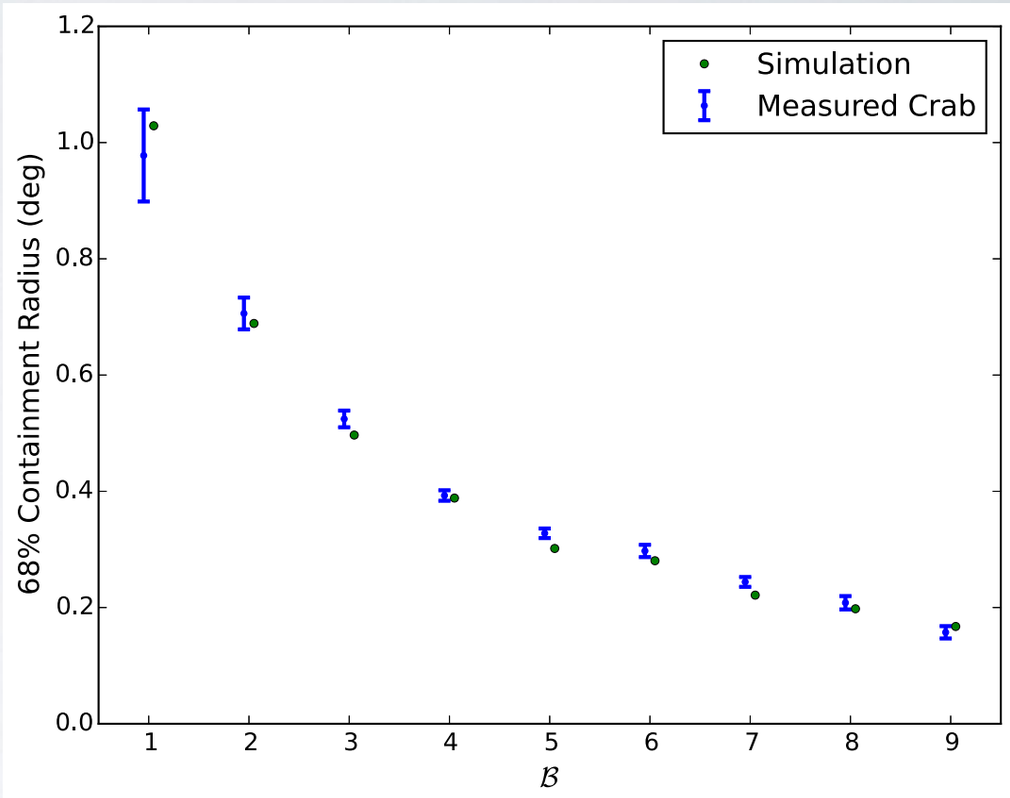
(b) $\mathcal{B} = 8$ Event Counts



(c) $\mathcal{B} = 3$ Angular Profile



(d) $\mathcal{B} = 3$ Angular Profile



HAWC Sensitivity