HAWC results and future development

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NASA/MSFC

IPA 2017
May 10, 2017

Gamma-Ray Astrophysics

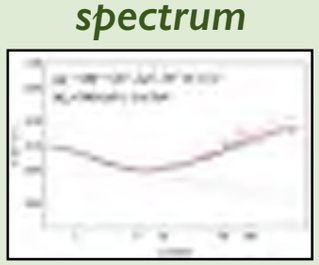
Astrophysics

SNRs, Pulsars, *Binaries*, etc.

AGN Flares

Dark Matter

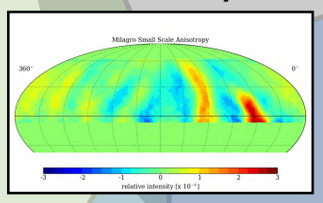
Cosmic electron spectrum



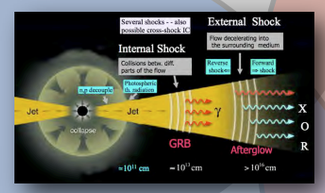
e^+/e^- *ratio*

Indirect DM Searches

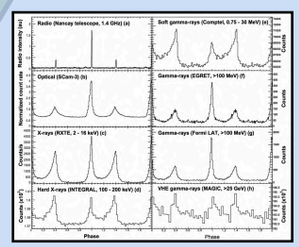
Cosmic Rays



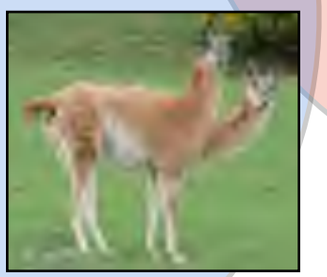
GRBs



Lorentz Invariance Violation

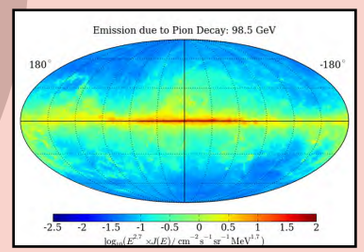


Exotic Particles

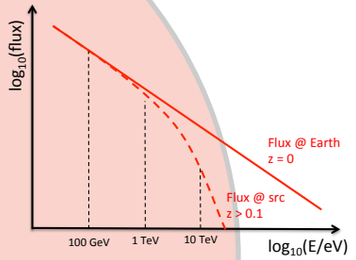


Cosmology

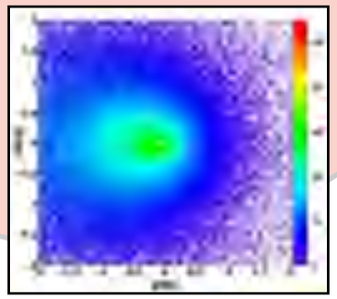
Diffuse Emission



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

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DGAPA-UNAM, México;
and the University of Wisconsin Alumni Research Foundation.

HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

Mapping the Northern Sky in High-Energy Gamma Rays

HAWC Observatory

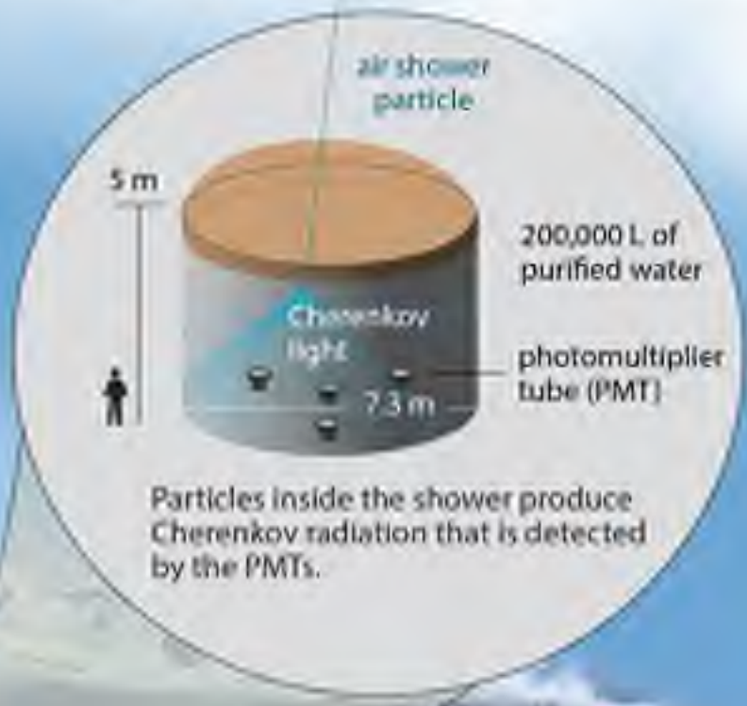
HAWC operates day and night, providing a large field of view for the observation of the highest energy gamma rays.

- 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

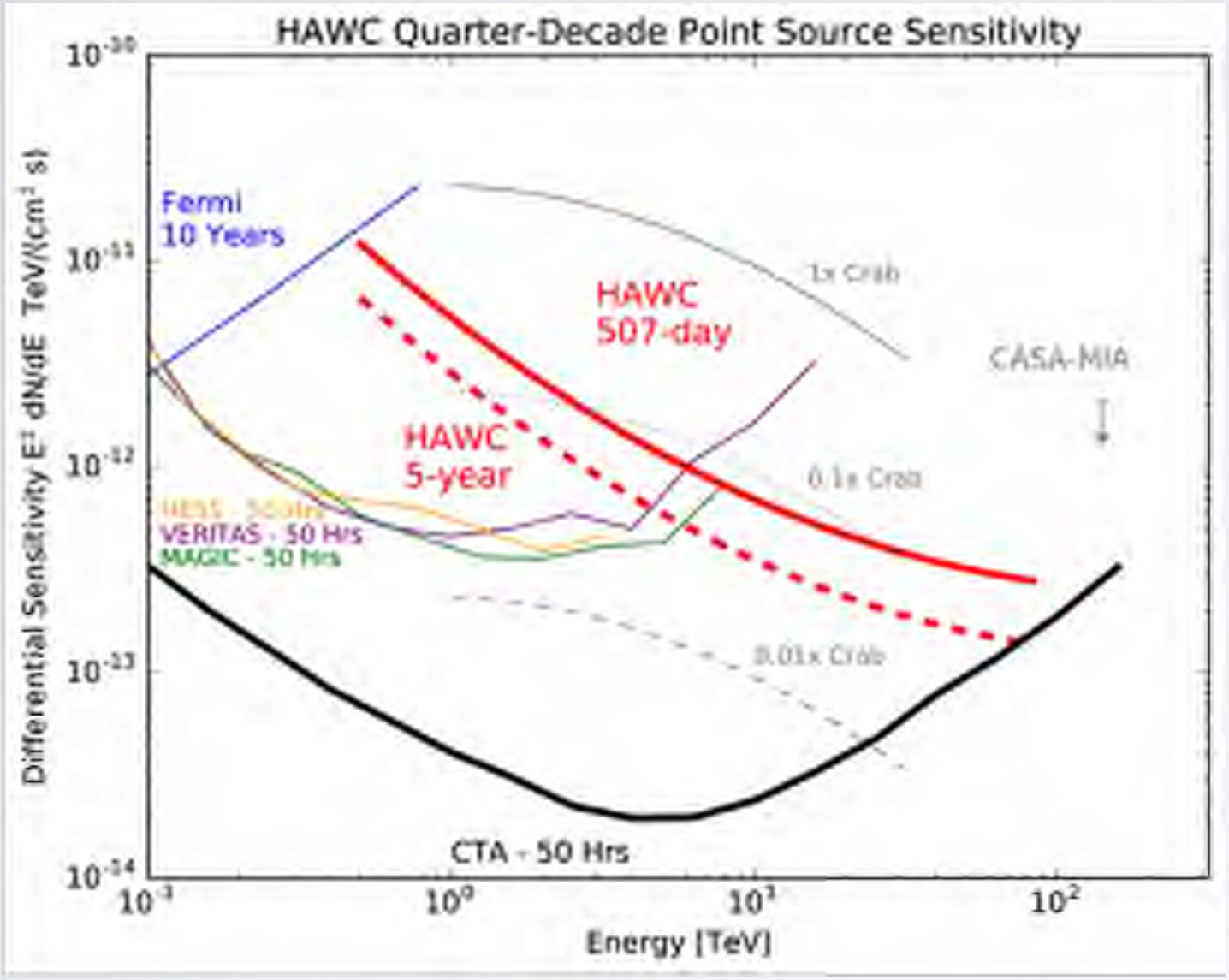
HAWC selects gamma rays from among a much more abundant background of cosmic rays.

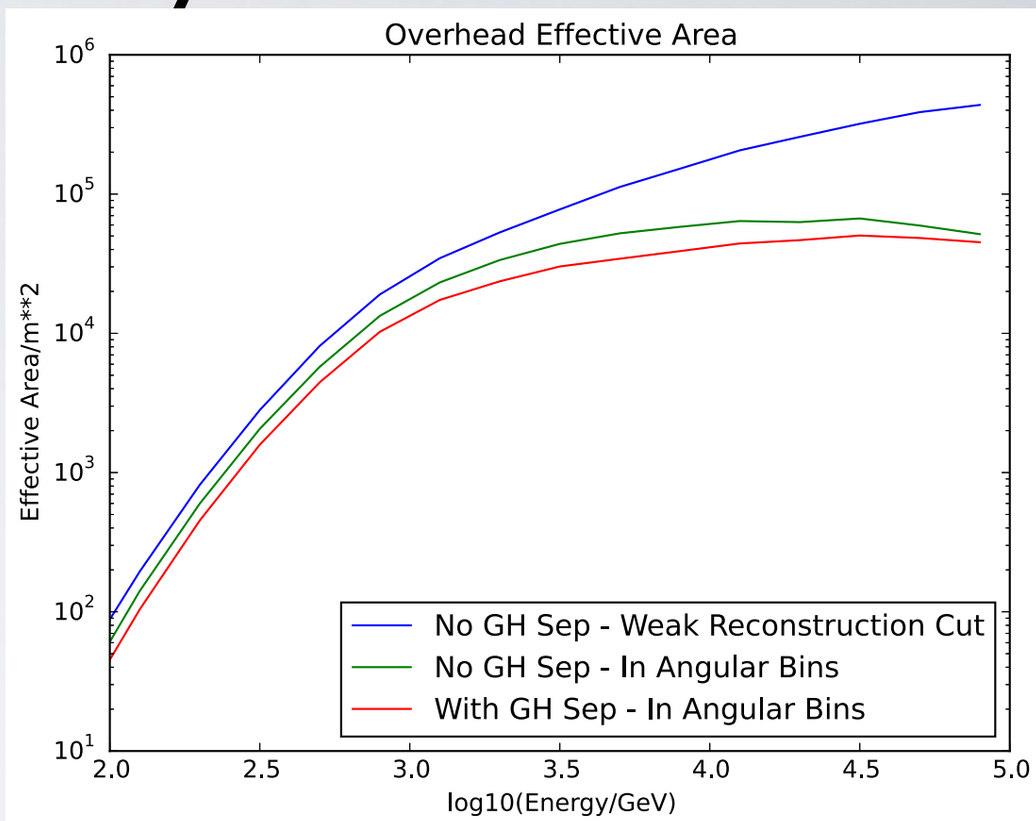
"hot" spots concentrate around the core

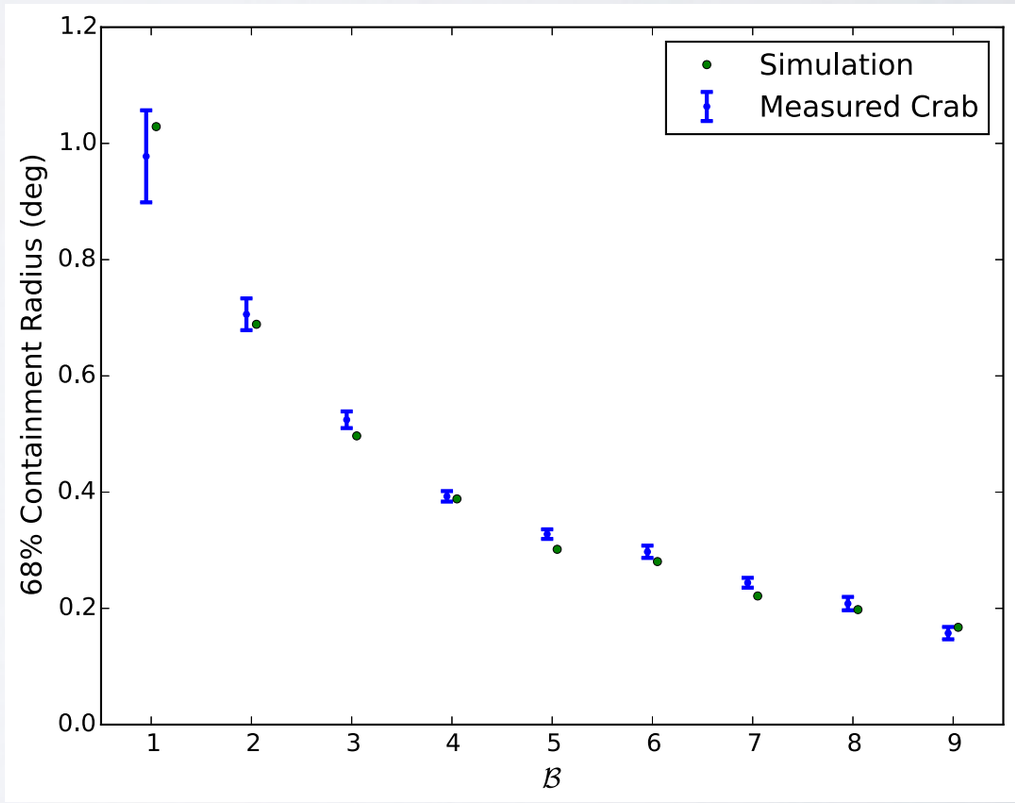
"hot" spots are more dispersed

Abeysekara et al., arXiv 1701.01778

HAWC Sensitivity



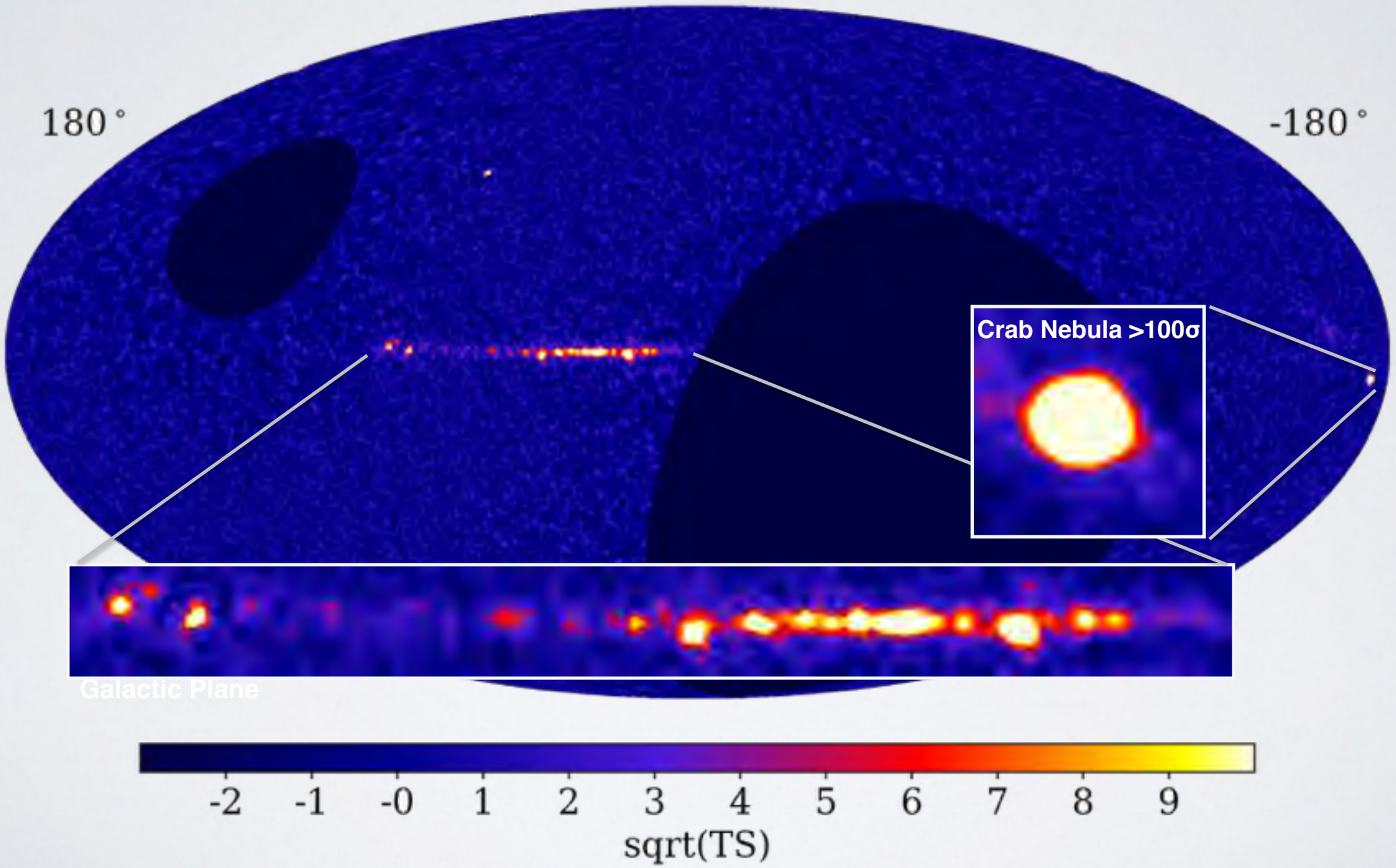




HAWC TeV Sky Survey

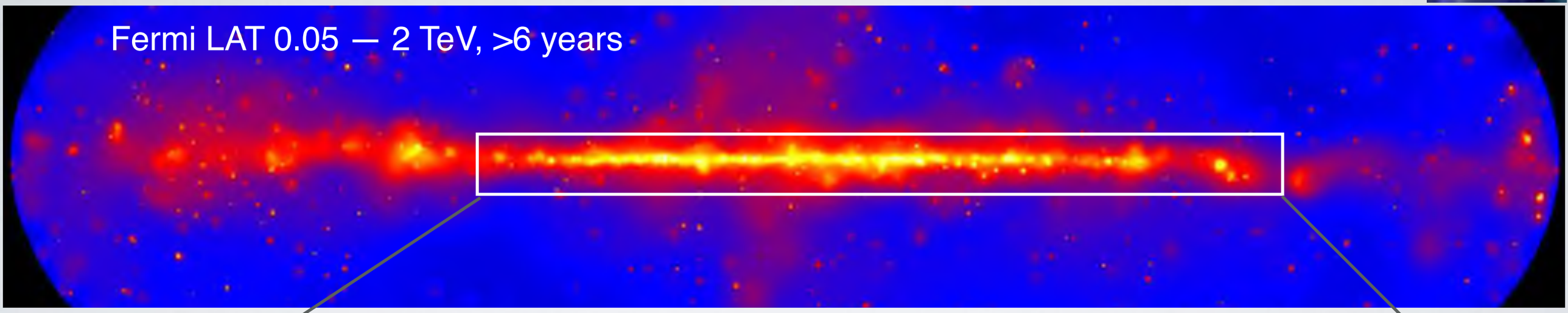
Abeysekara et al., arXiv 1702.02992

- 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.



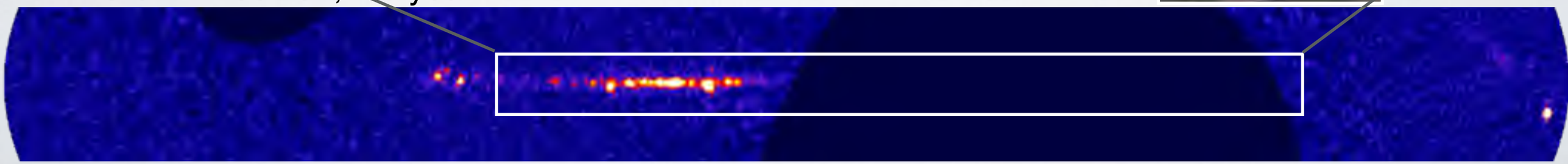
Gamma-ray view of our Galaxy

Fermi LAT 0.05 — 2 TeV, >6 years



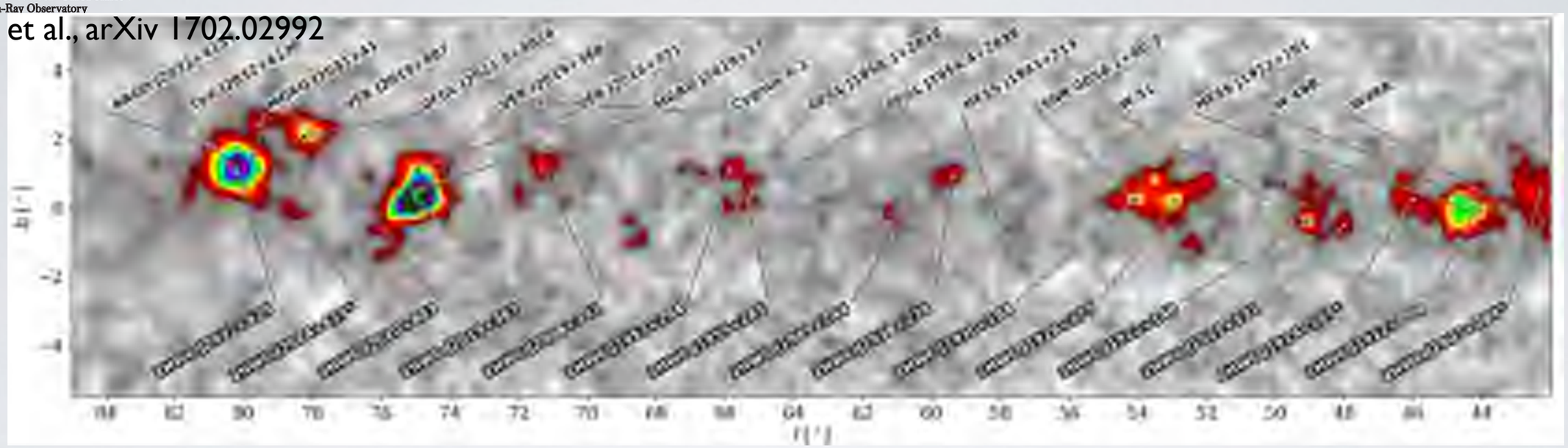
HESS >1TeV, 10 years

HAWC 0.1—100 TeV, 1.5 year



Galactic Plane

Abeysekara et al., arXiv 1702.02992



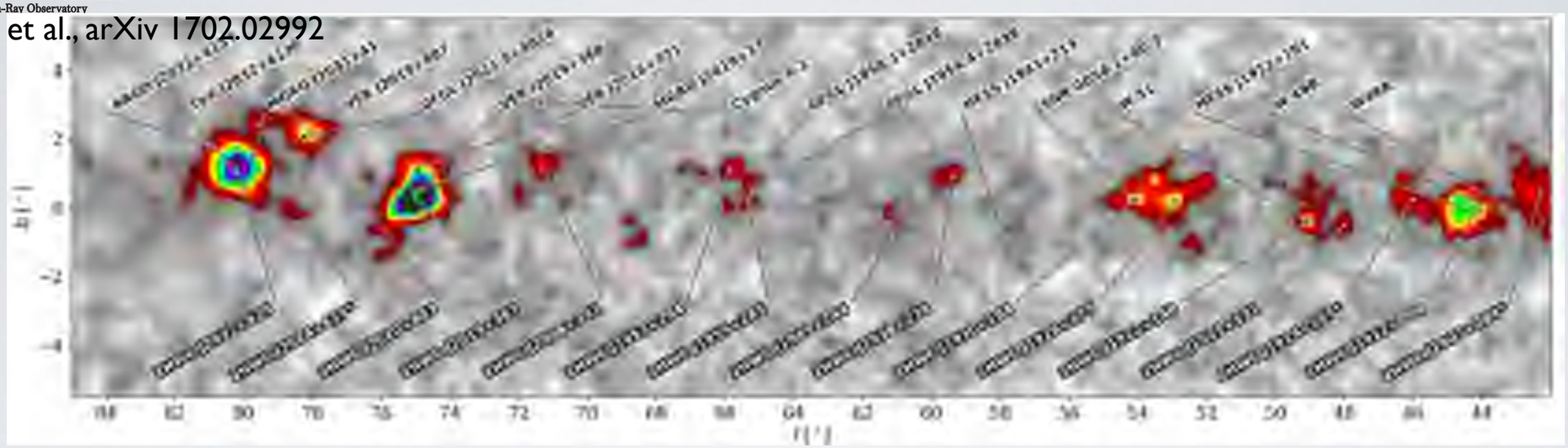
- 30 sources in the Galactic Plane (excluding Crab, Geminga, PSR B0656+14)
  - 19 likely associated with known TeV sources
  - 11 unassociated

within this area (known extragalactic excluded):

- 150 3FGL sources
- 56 3FHL sources

Galactic Plane

Abeysekara et al., arXiv 1702.02992



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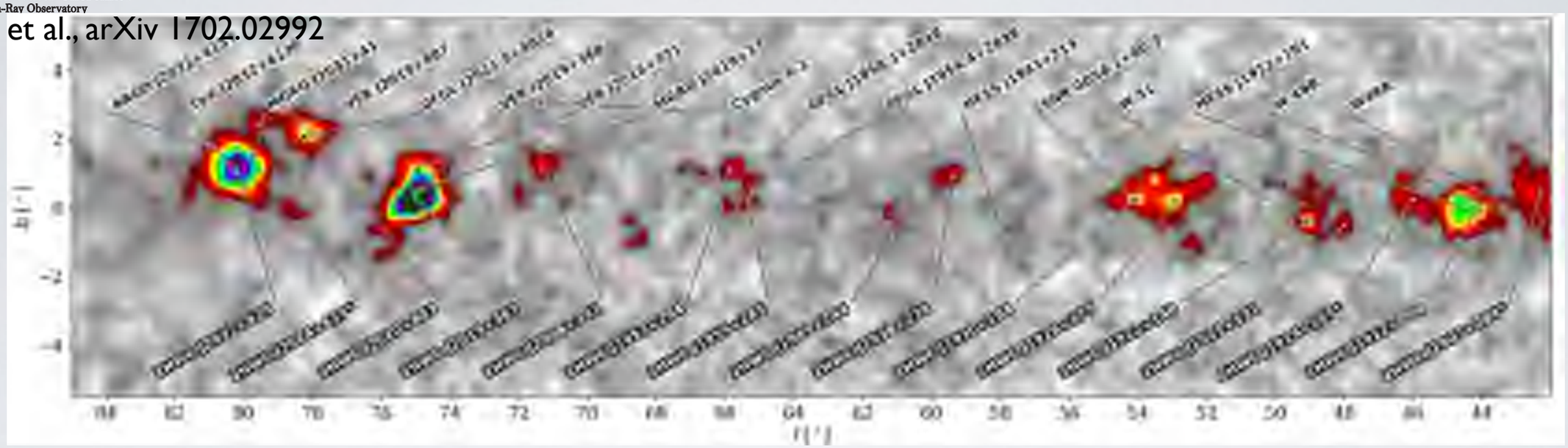

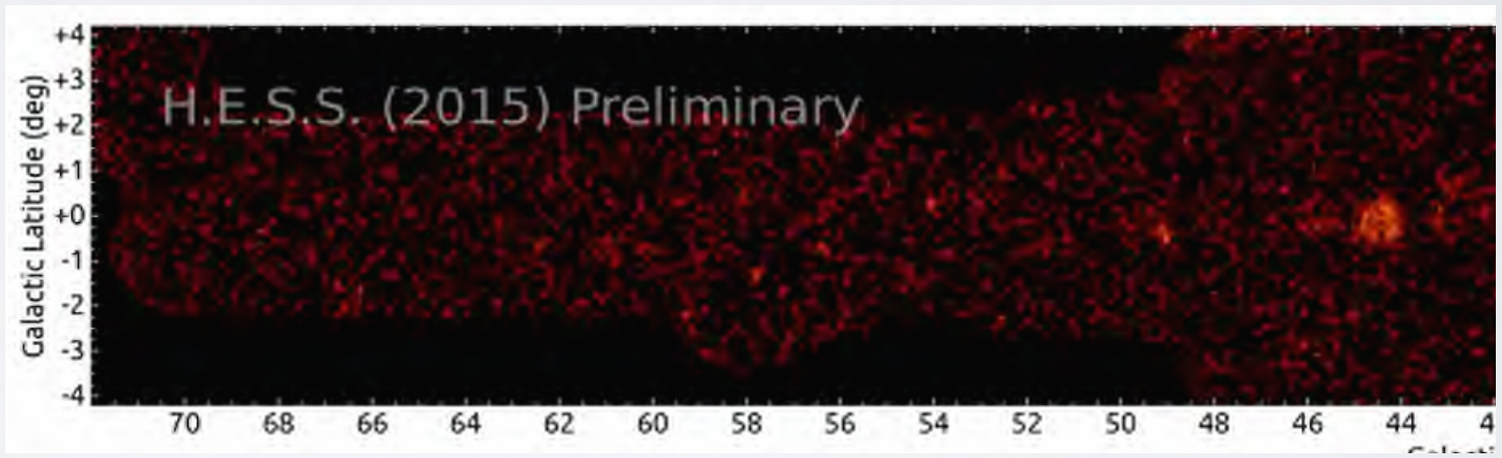

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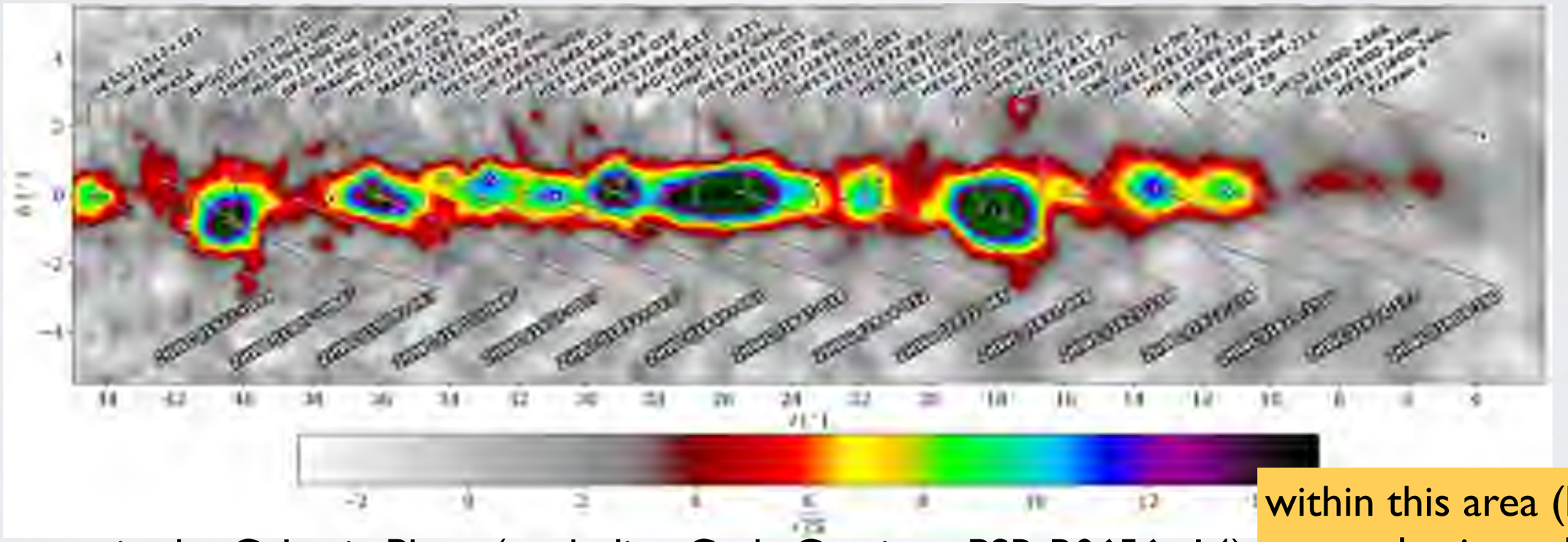

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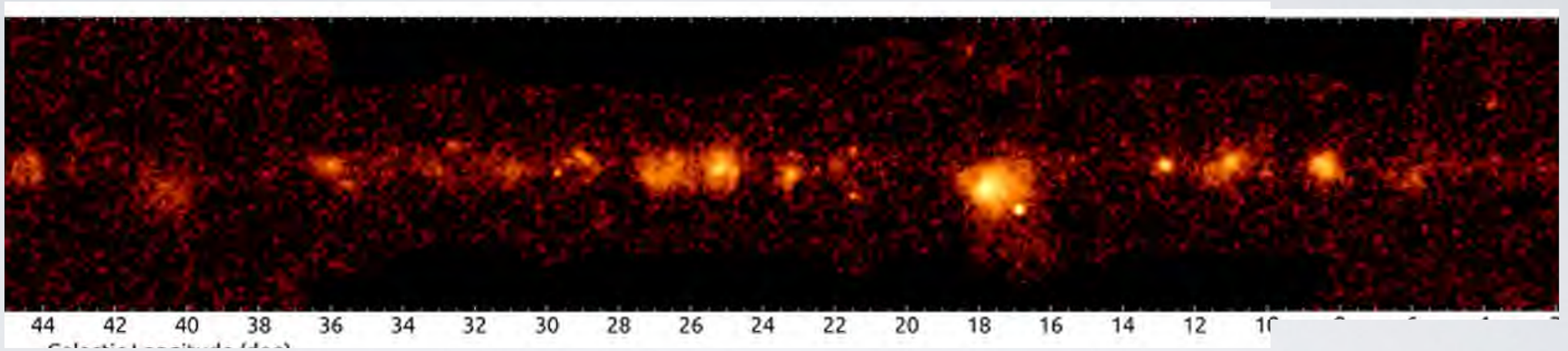

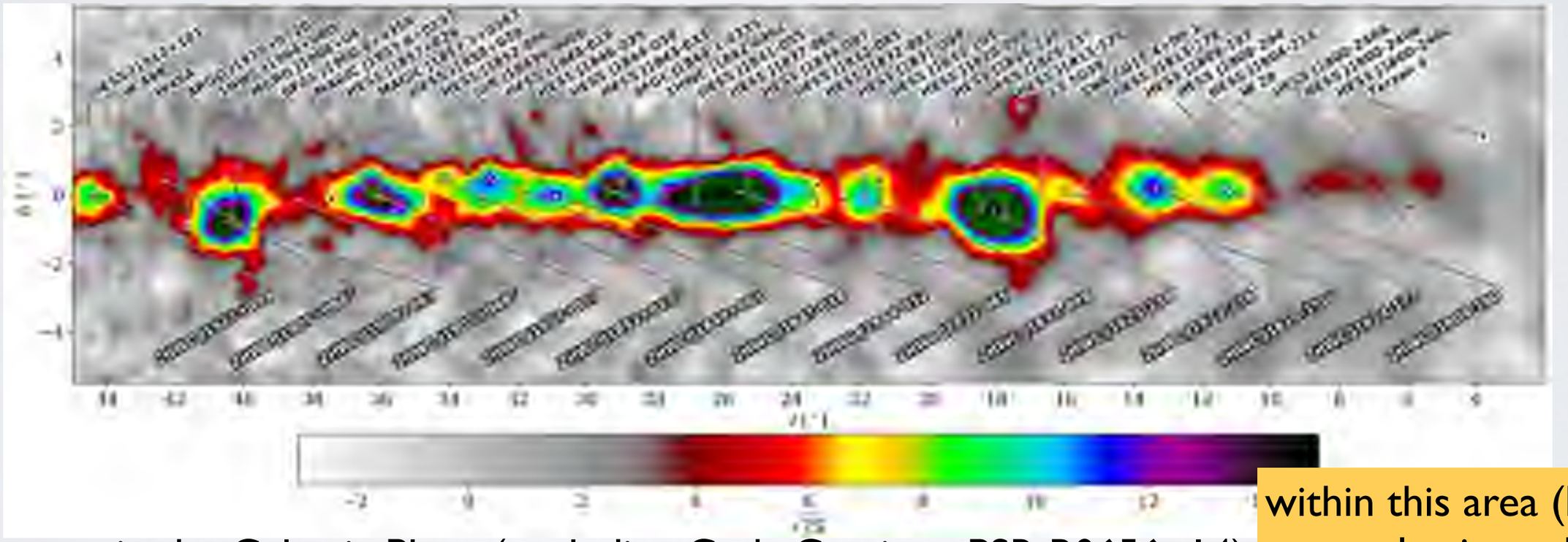

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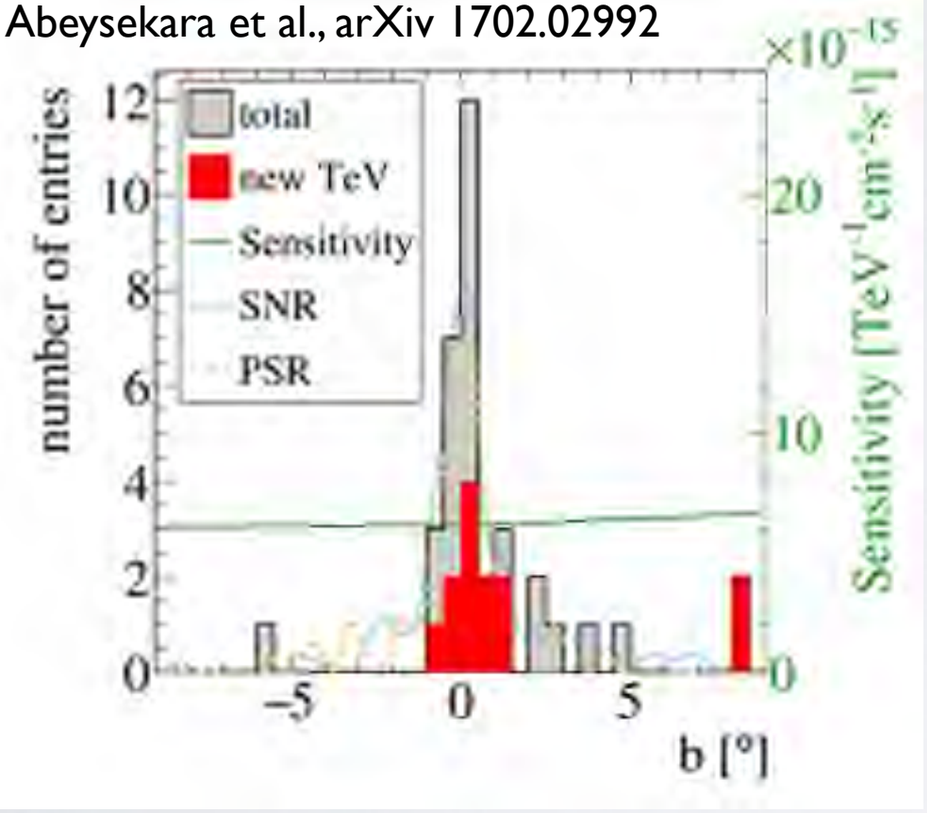
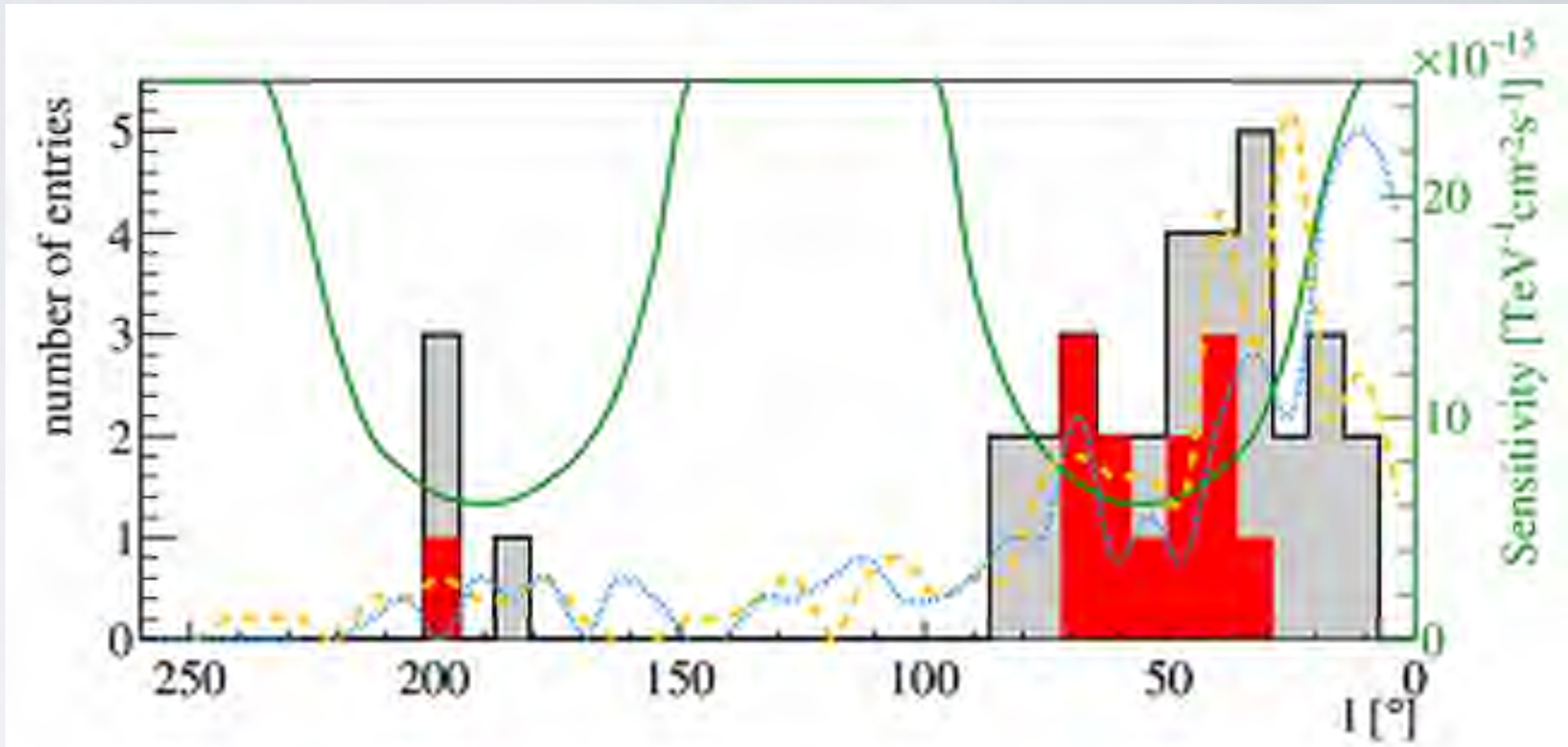
Galactic Plane Source Distribution

Abeysekara et al., arXiv 1702.02992





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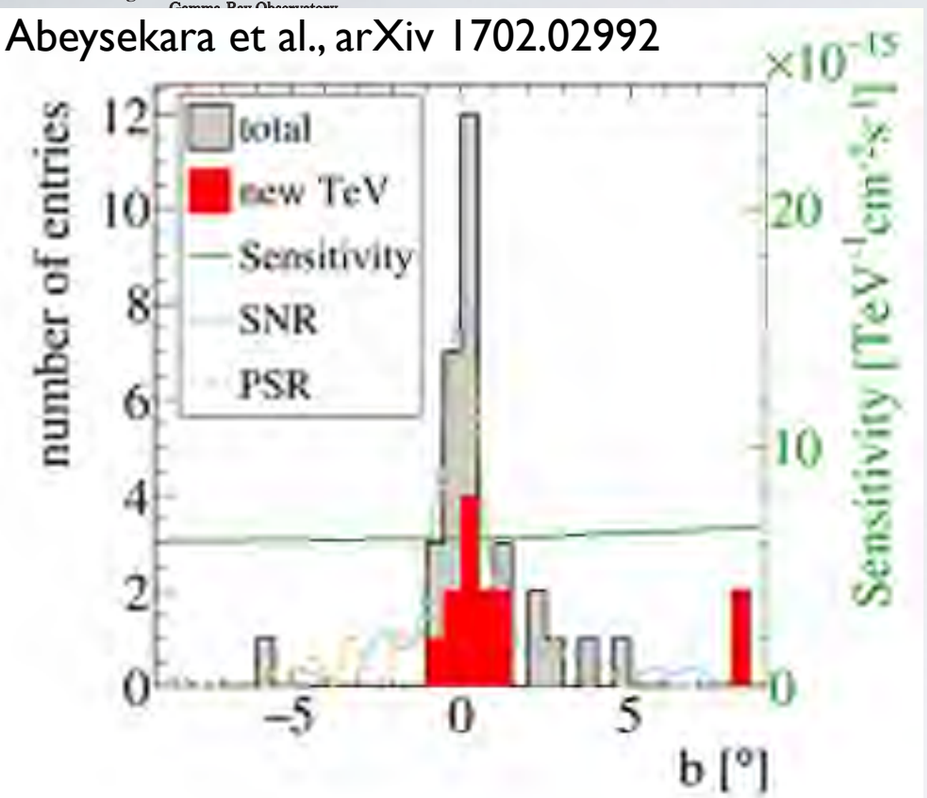
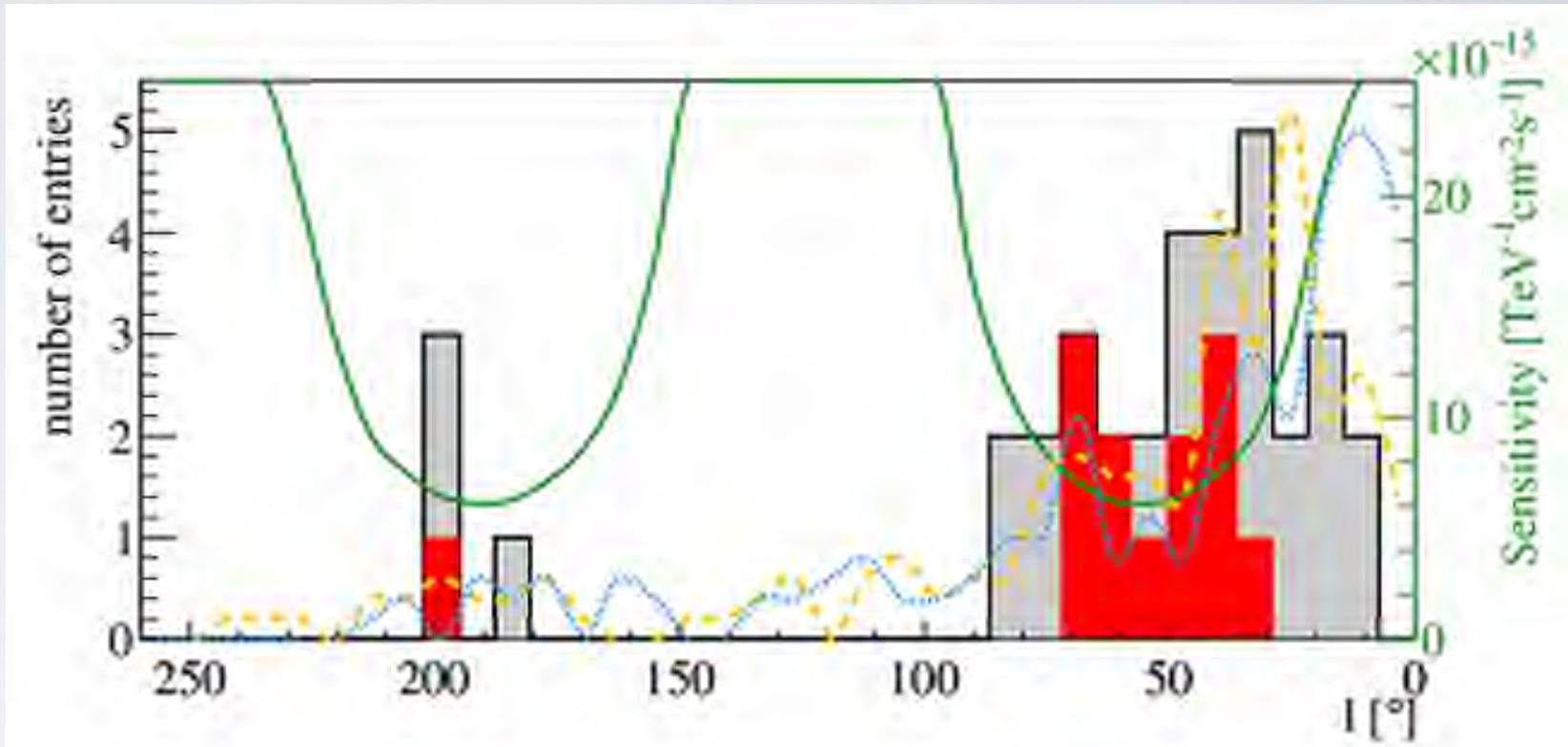
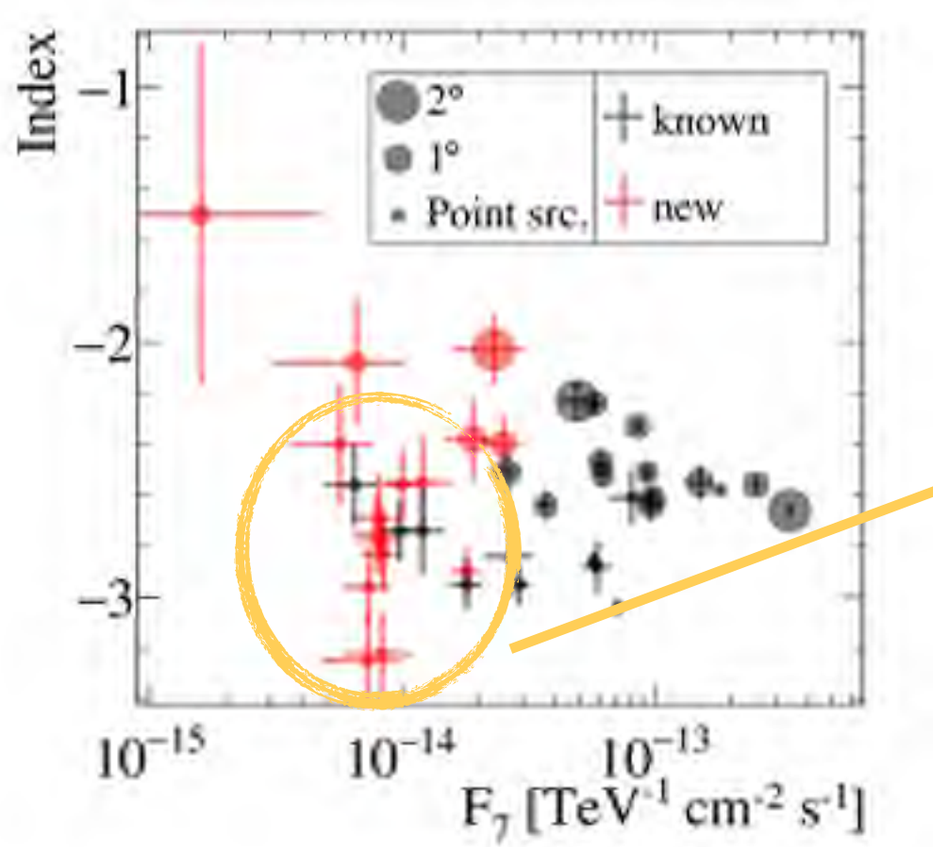
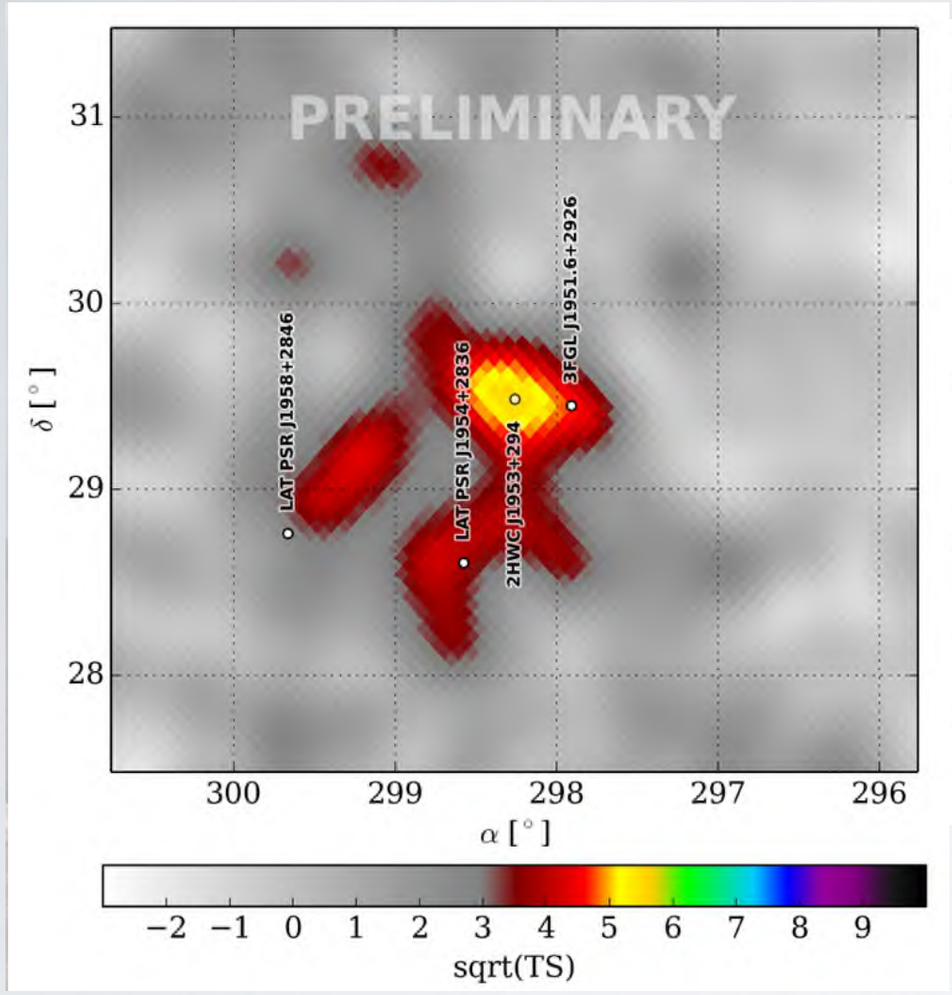


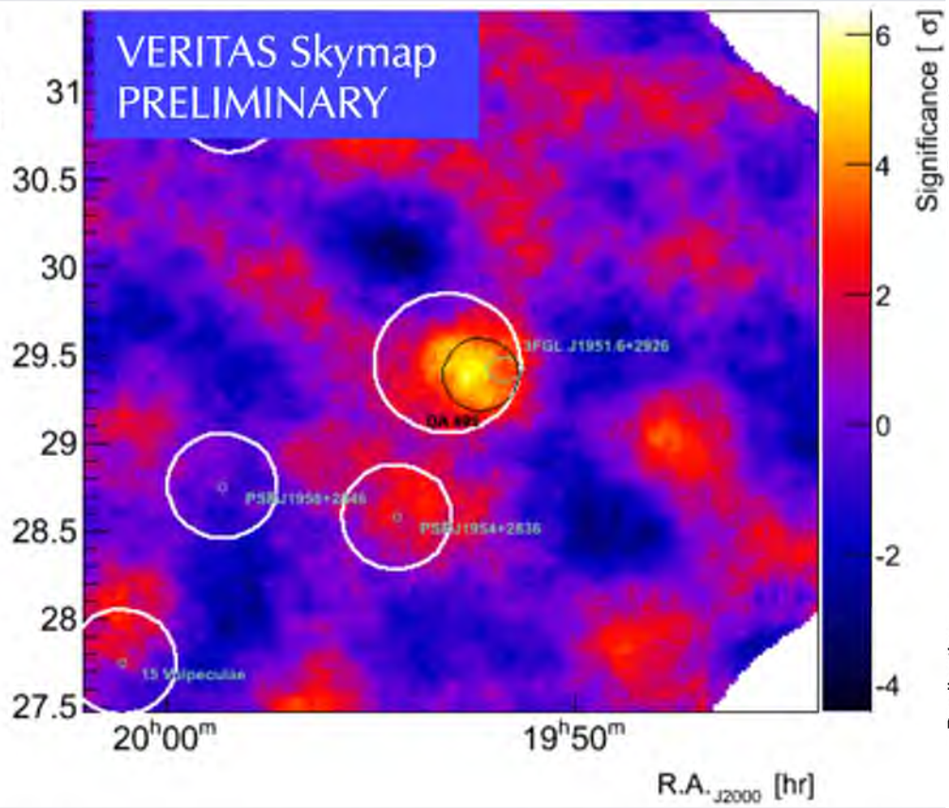




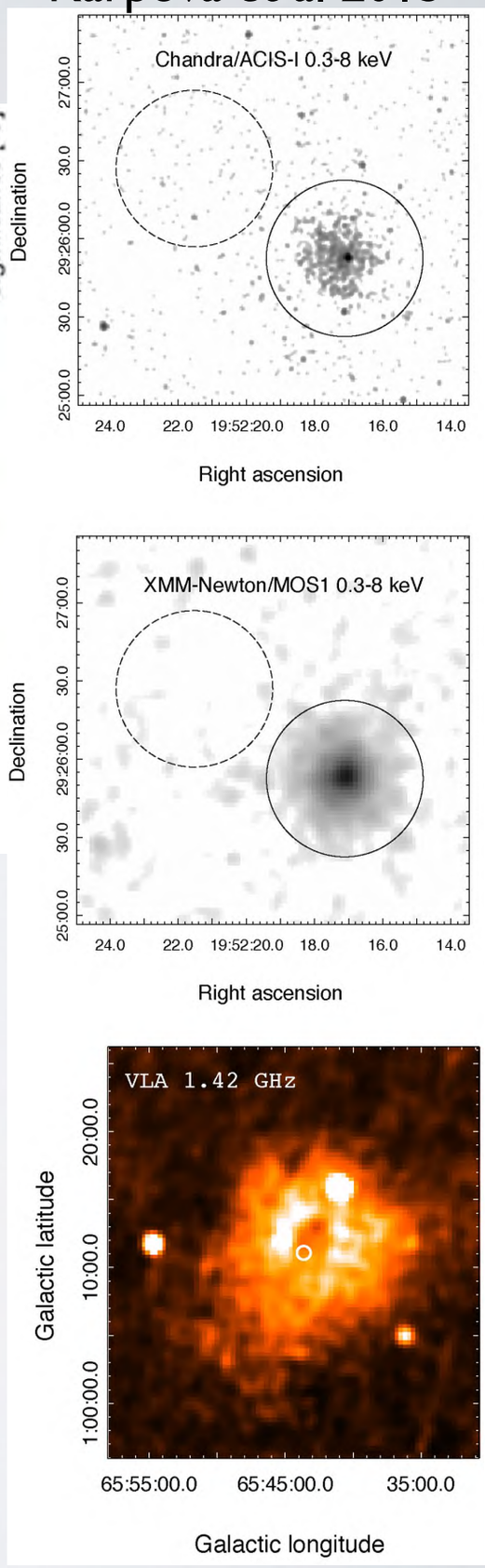
Good candidates for follow-up by pointing instruments.

New TeV Sources!





Karpova et al 2015



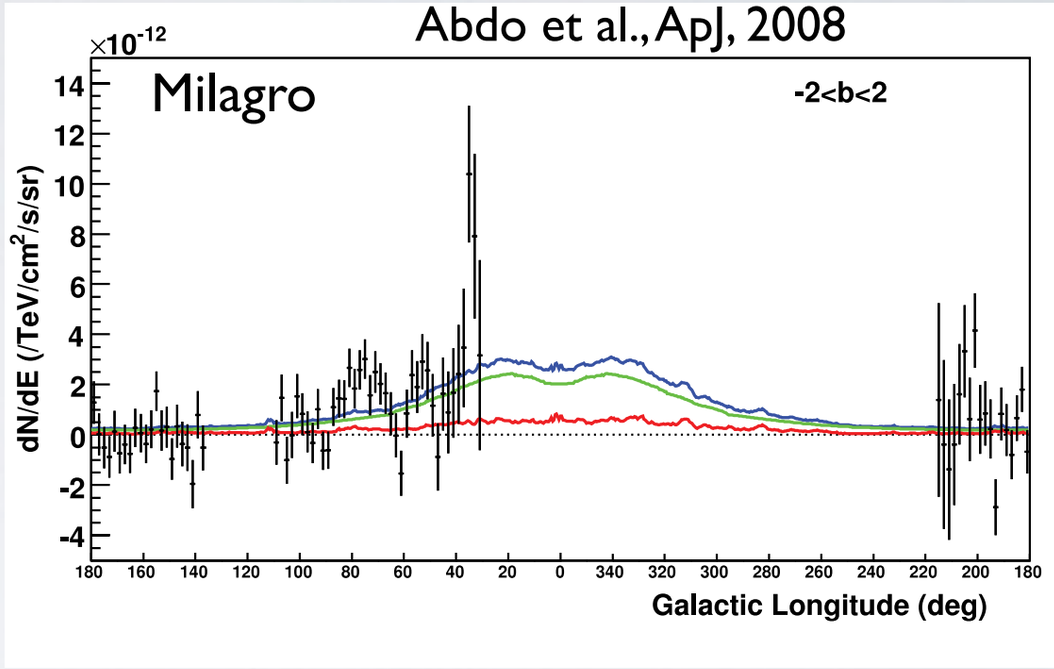
New TeV source
2HWC J1953+294

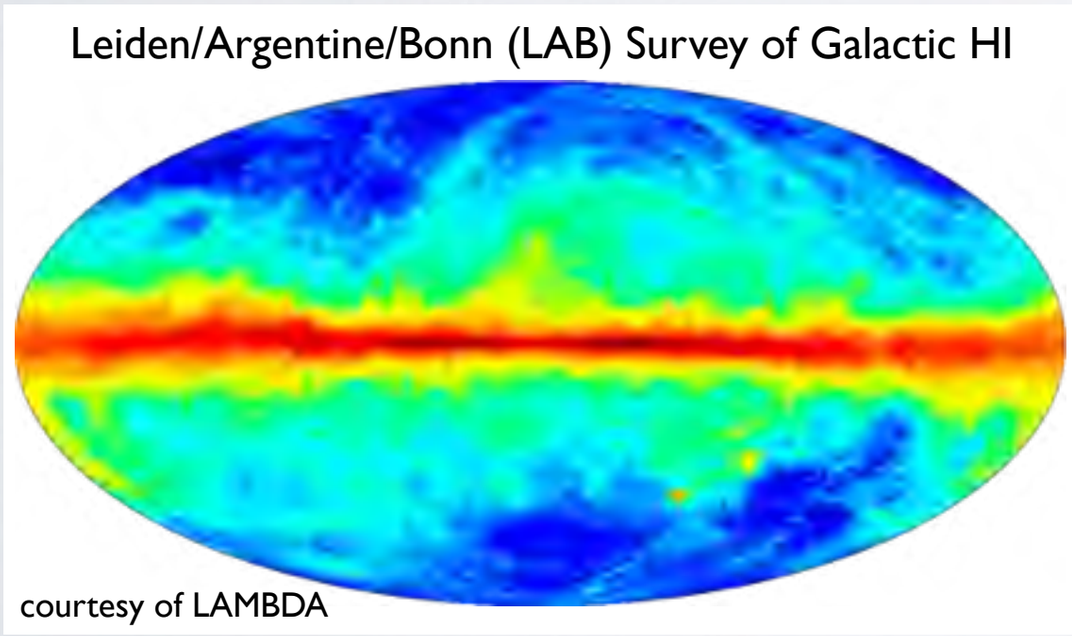
- <u>confirmed</u> by VERITAS, announced in Gamma16
- potential association:
  - PWN DA 495 seen in X-rays
  - 3FGL J1951.6+2926
- Joint paper in prep

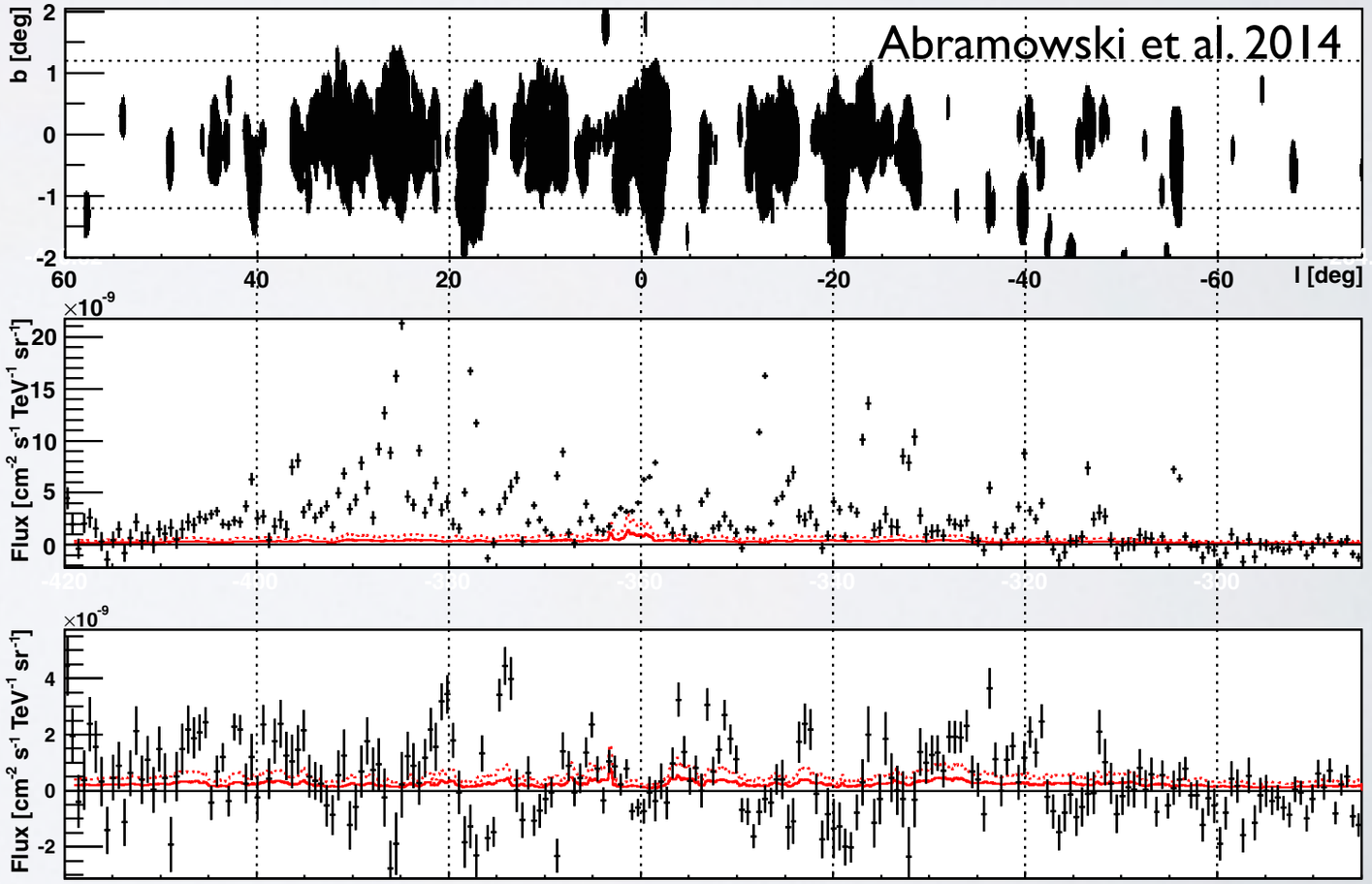
Galactic Diffuse Emission

Diffuse contributions:

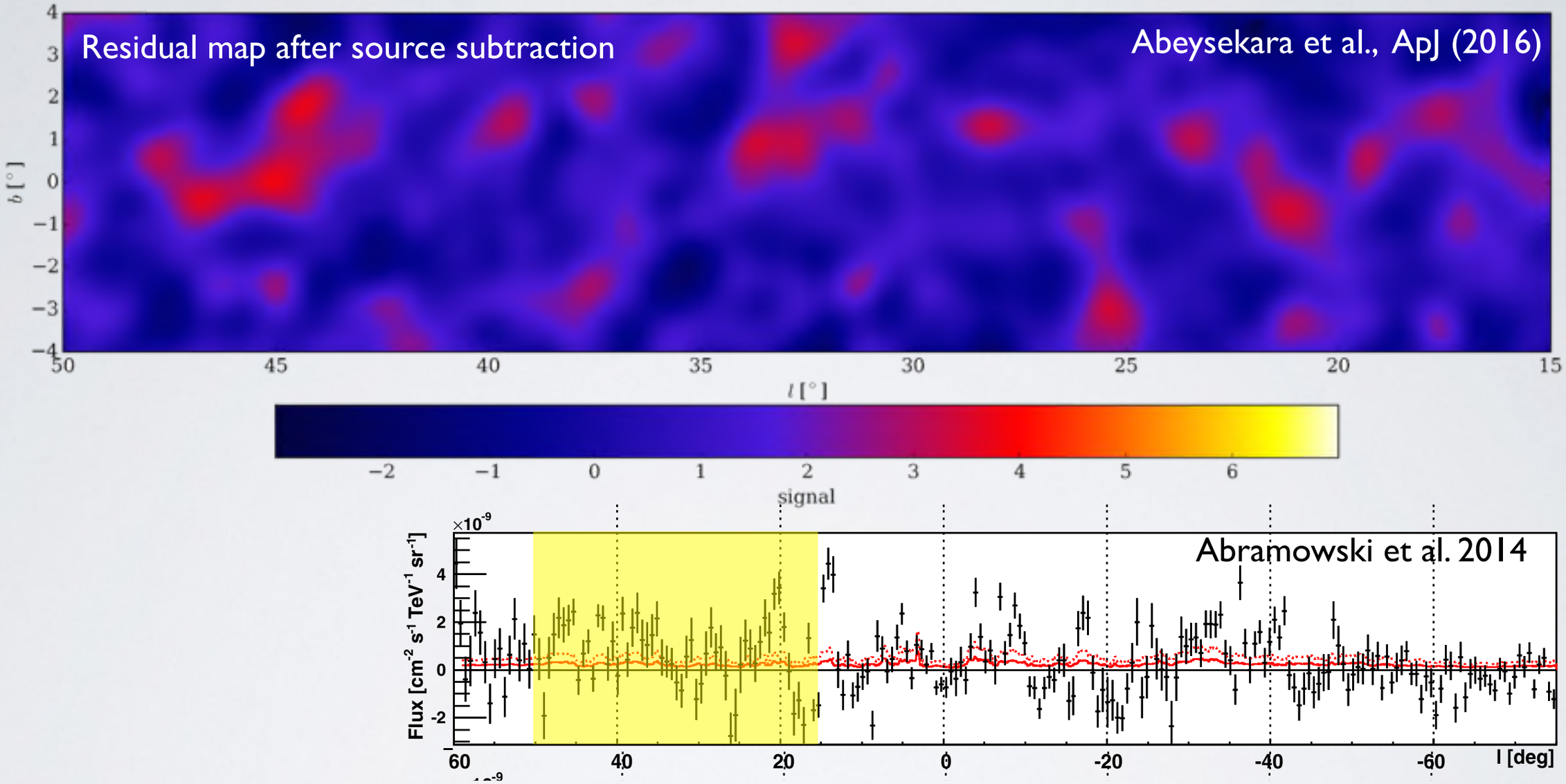
- Cosmic-ray interactions
  - molecular clouds
  - interstellar gas
- Inverse Compton
- Unresolved sources







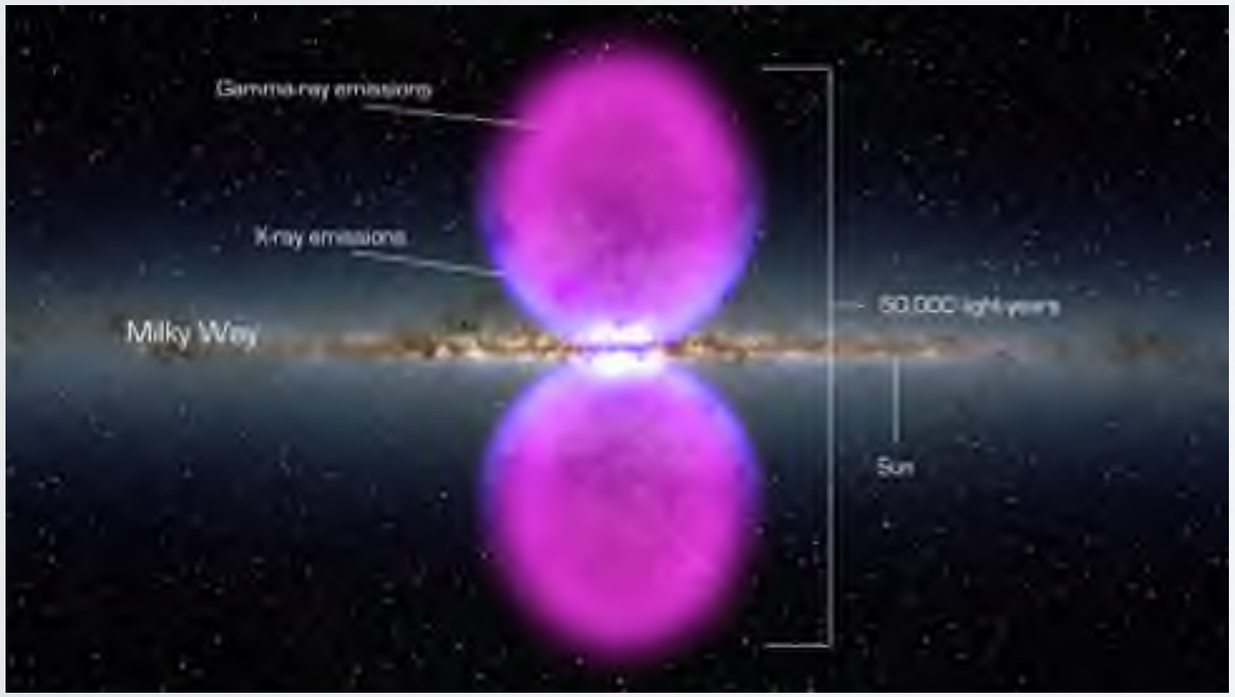
Galactic Diffuse — Limit from Pass 1

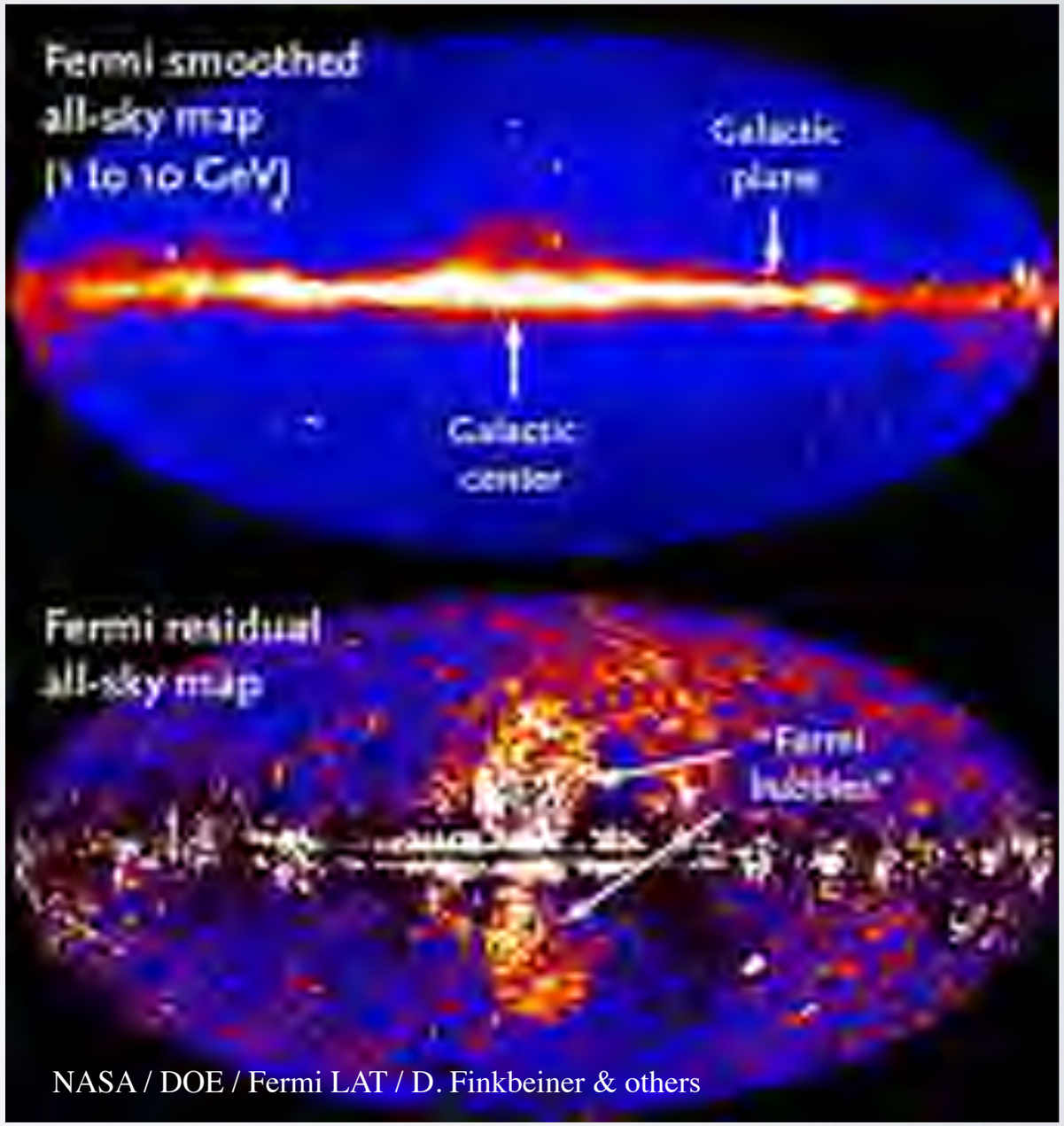


- A uniform surface brightness fit in addition to source model is preferred at **5.7σ**.
- The fitted surface brightness at 5 TeV is 1.6±0.4e-11 TeV^{-1} cm^{-2} s^{-1} sr^{-1}.
- HESS average diffuse extrapolated to 5 TeV is 1.0±0.2e-11 TeV^{-1} cm^{-2} s^{-1} sr^{-1}.
- Current limit from HAWC-111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

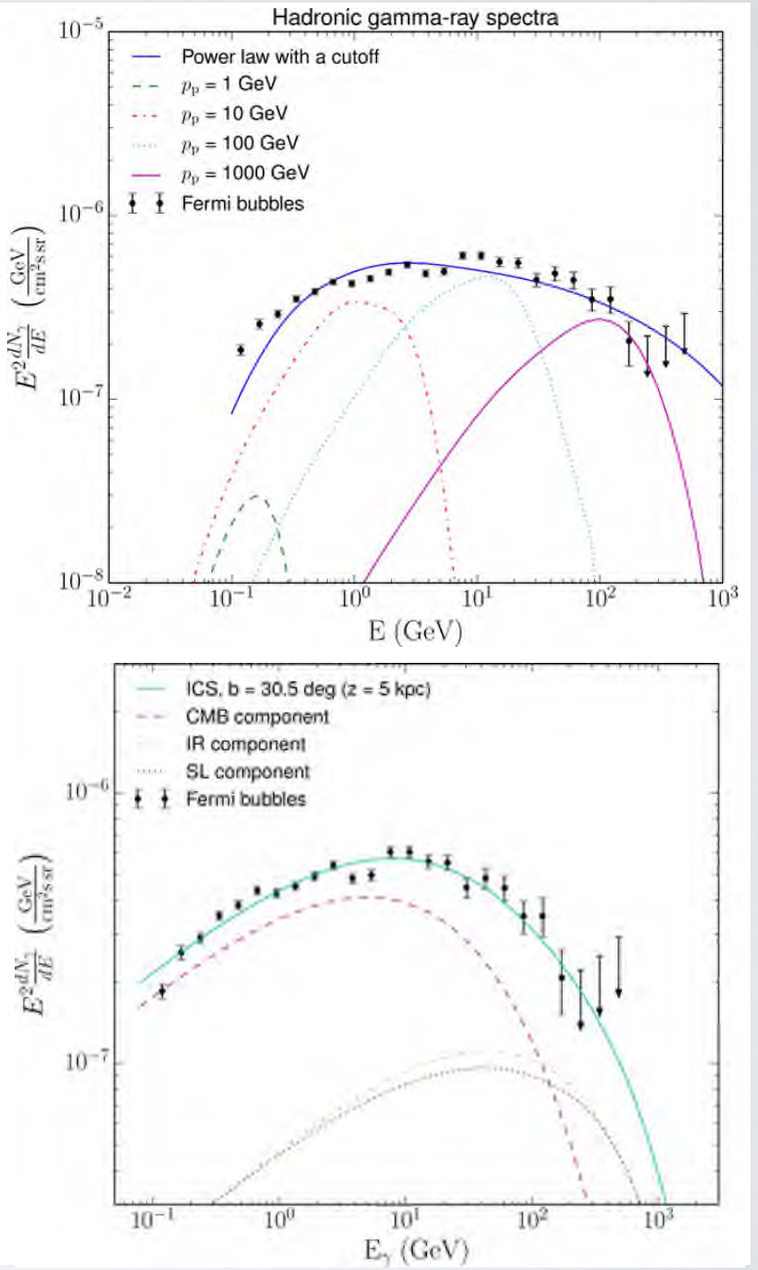


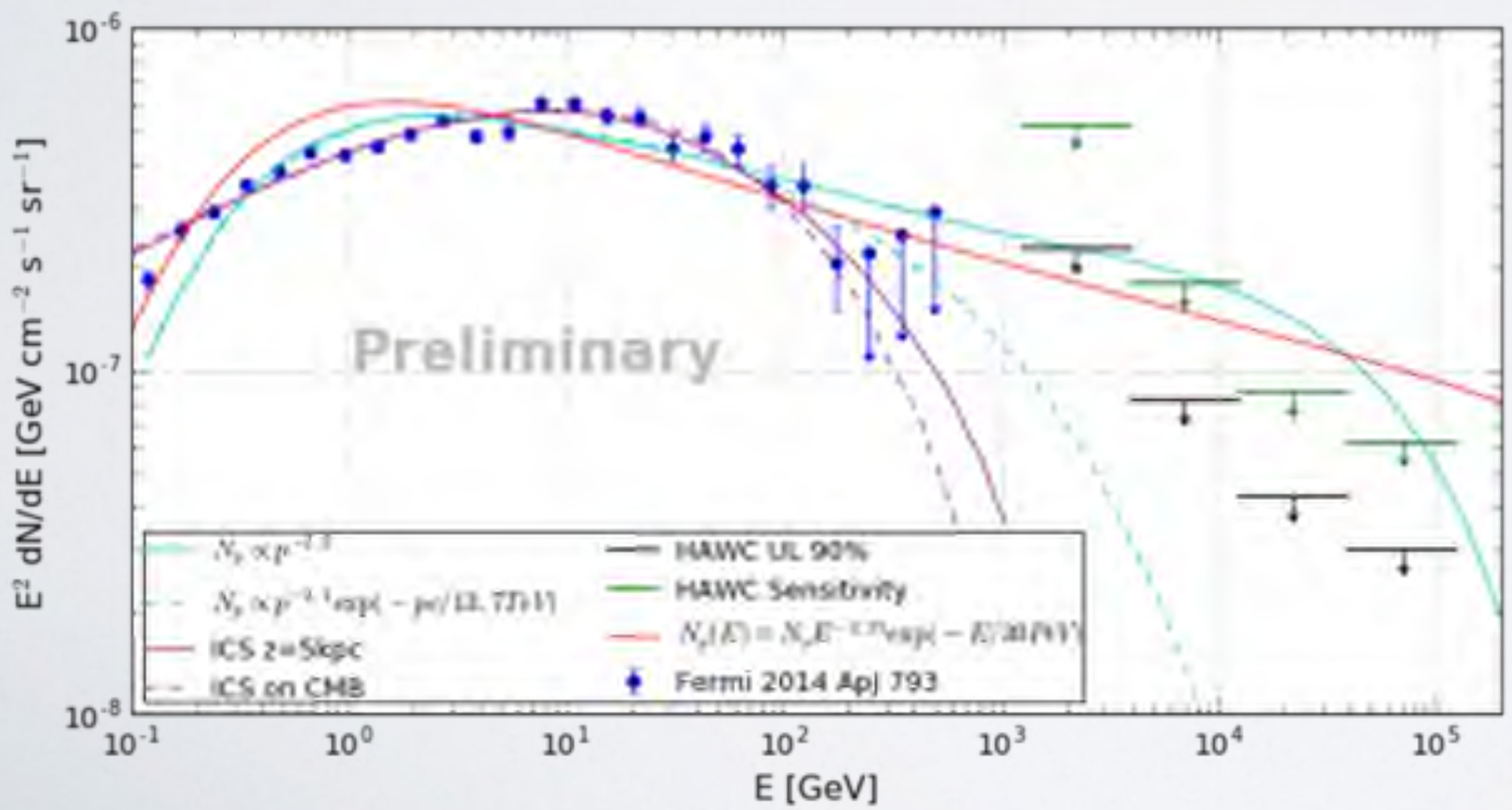


NASA / DOE / Fermi LAT / D. Finkbeiner & others

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

online transient analyses

- triggered GRB search: 0.2s — 30min
  - 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.

- daily maps: ~6hr
  - flux in every point in all visible sky.

Transient Search

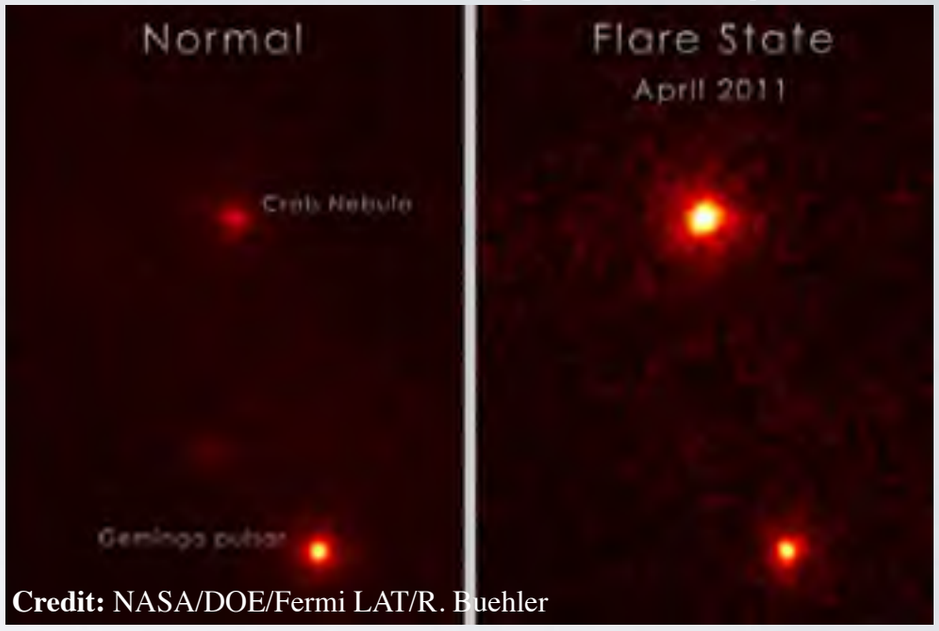
Crab Nebula

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

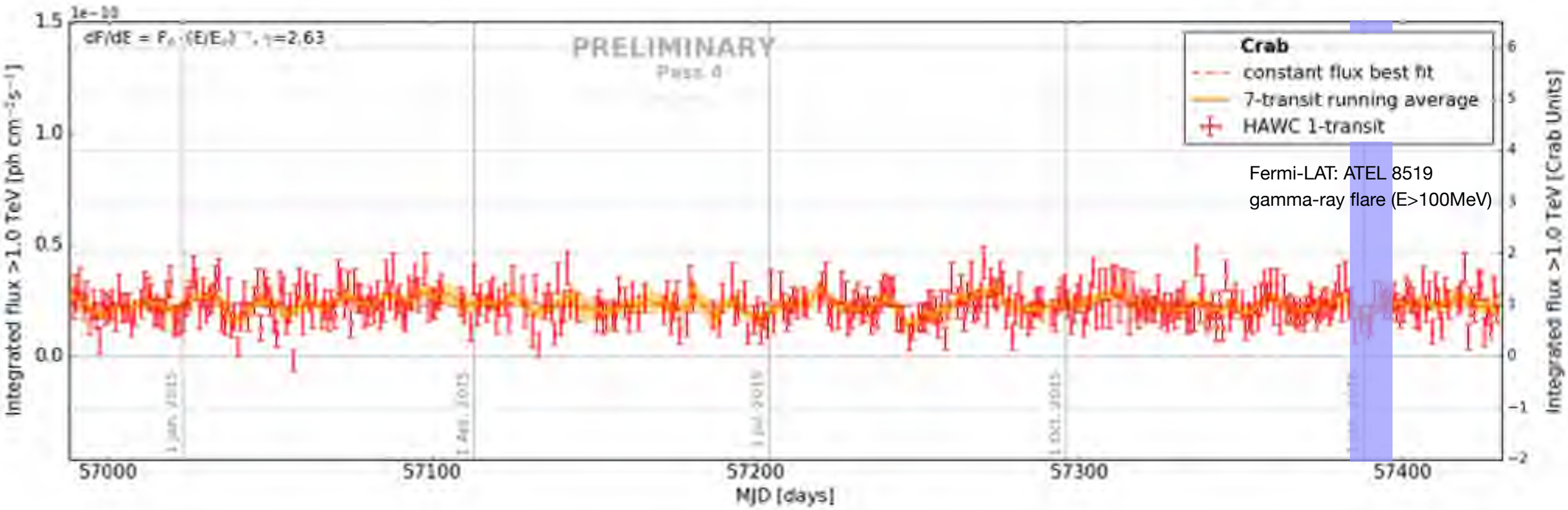
HAWC observation:

- Data is consistent with a constant flux.
- Coincident observation with Fermi-LAT reported Crab flare starting Jan 7 2016.
- 95% C.L. upper limit on 13-day average flux above 1TeV is 1.01x average Crab flux.

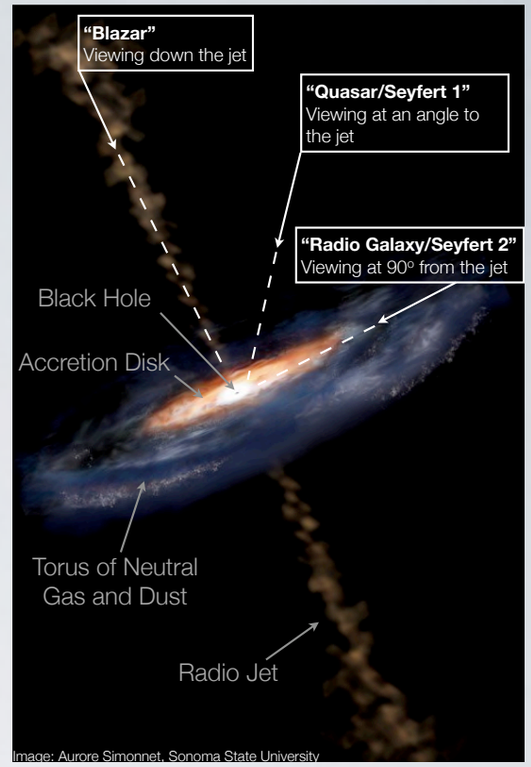
MeV-GeV gamma ray



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



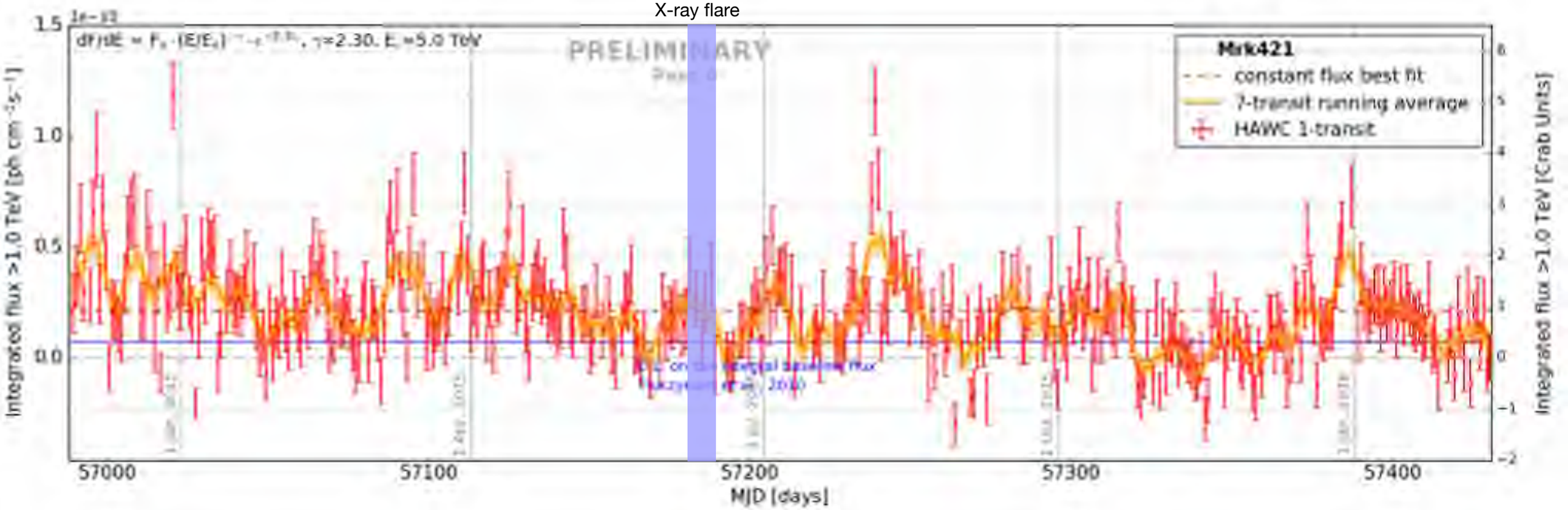
Transient Search



AGN Mrk 421

- Daily flux lightcurve from Nov 2014 to Feb 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 ~3x higher than upper limit on integral baseline flux derived in Tluczykont et al. 2010.

Swift:
ATEL 7654
X-ray flare



Transient Search

AGN Mrk 421

- Daily flux lightcurve from Nov 2014 to Feb 2016.

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. Horns (University of Wuerzburg, FAU Erlangen) for the FACT Collaboration, R. Lauer (University of New Mexico) and J. Wood (University of Maryland) for the HAWC Collaboration, 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."

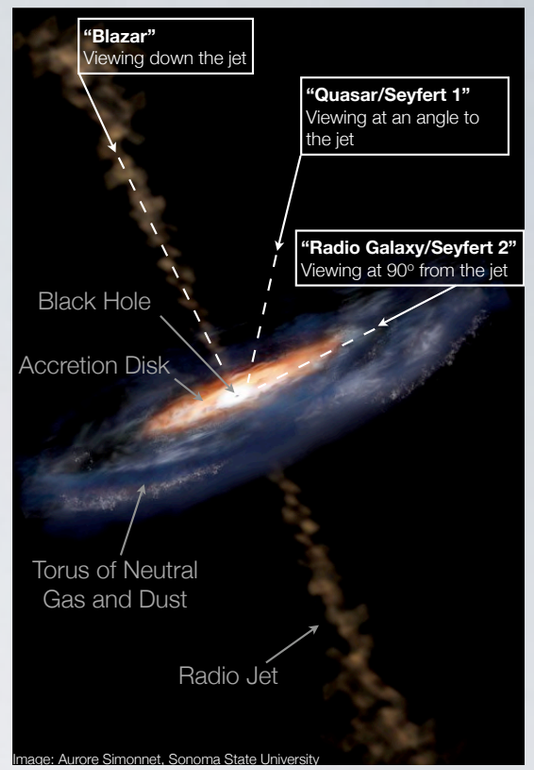
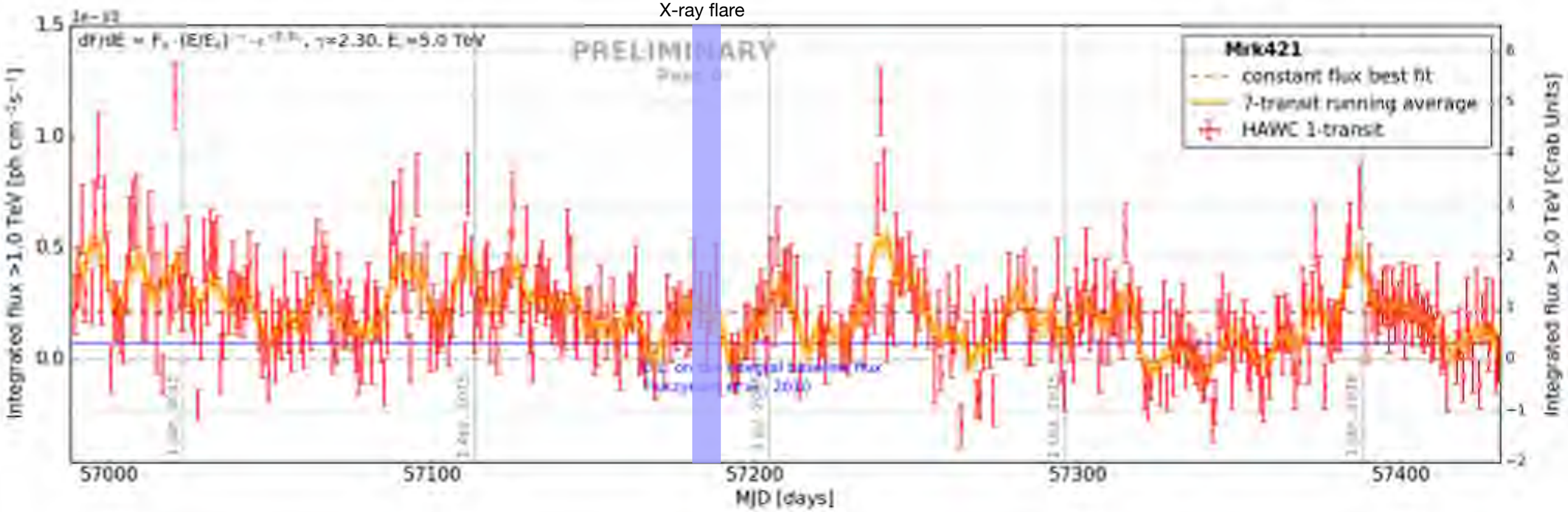


Image: Aurore Simonnet, Sonoma State University

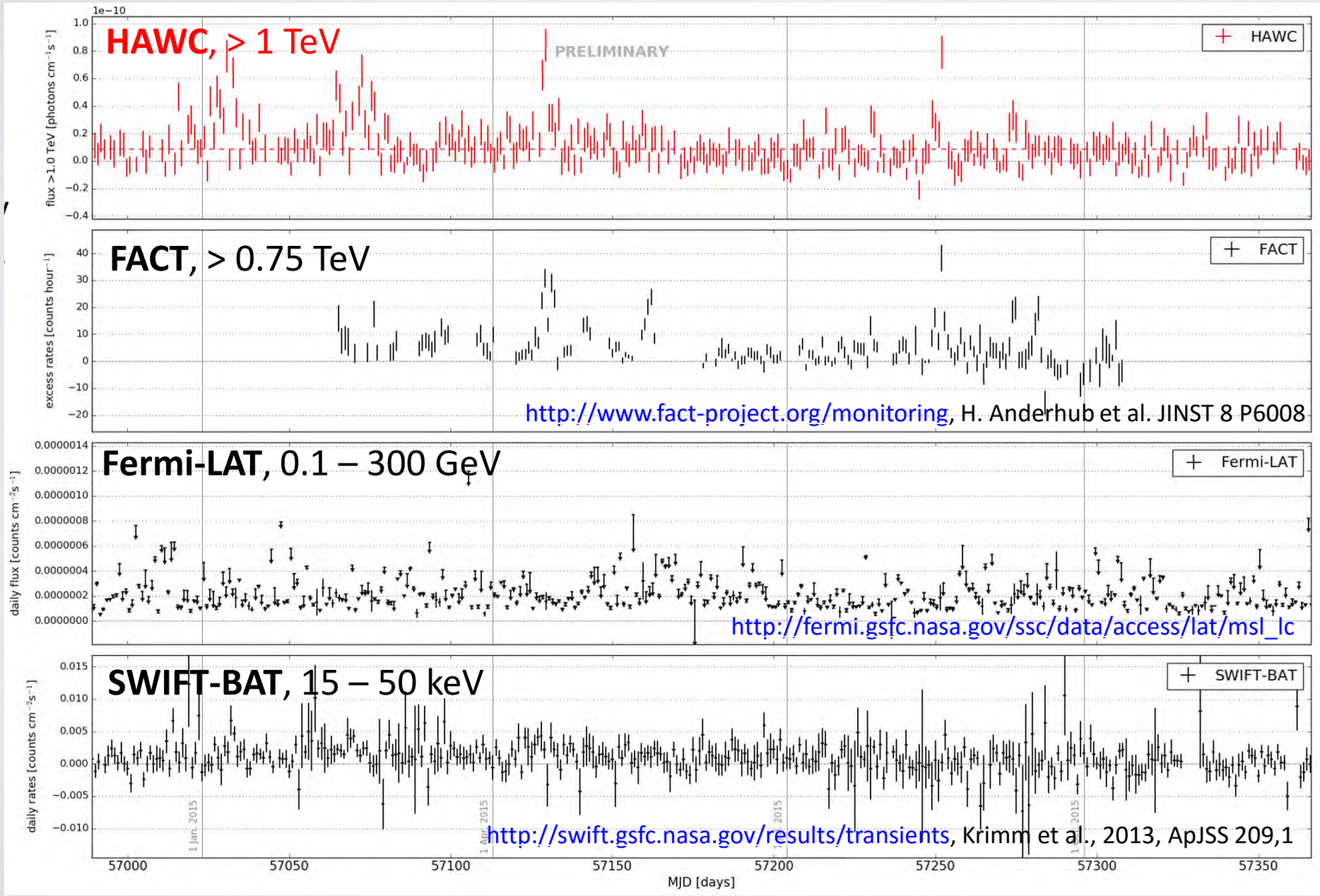
Swift:
ATEL 7654
X-ray flare



Transient Search

AGN Mrk 501

- Daily flux lightcurve from Nov 2014 to Feb 2016.
- Inconsistent with constant flux at p-value <1e-10.



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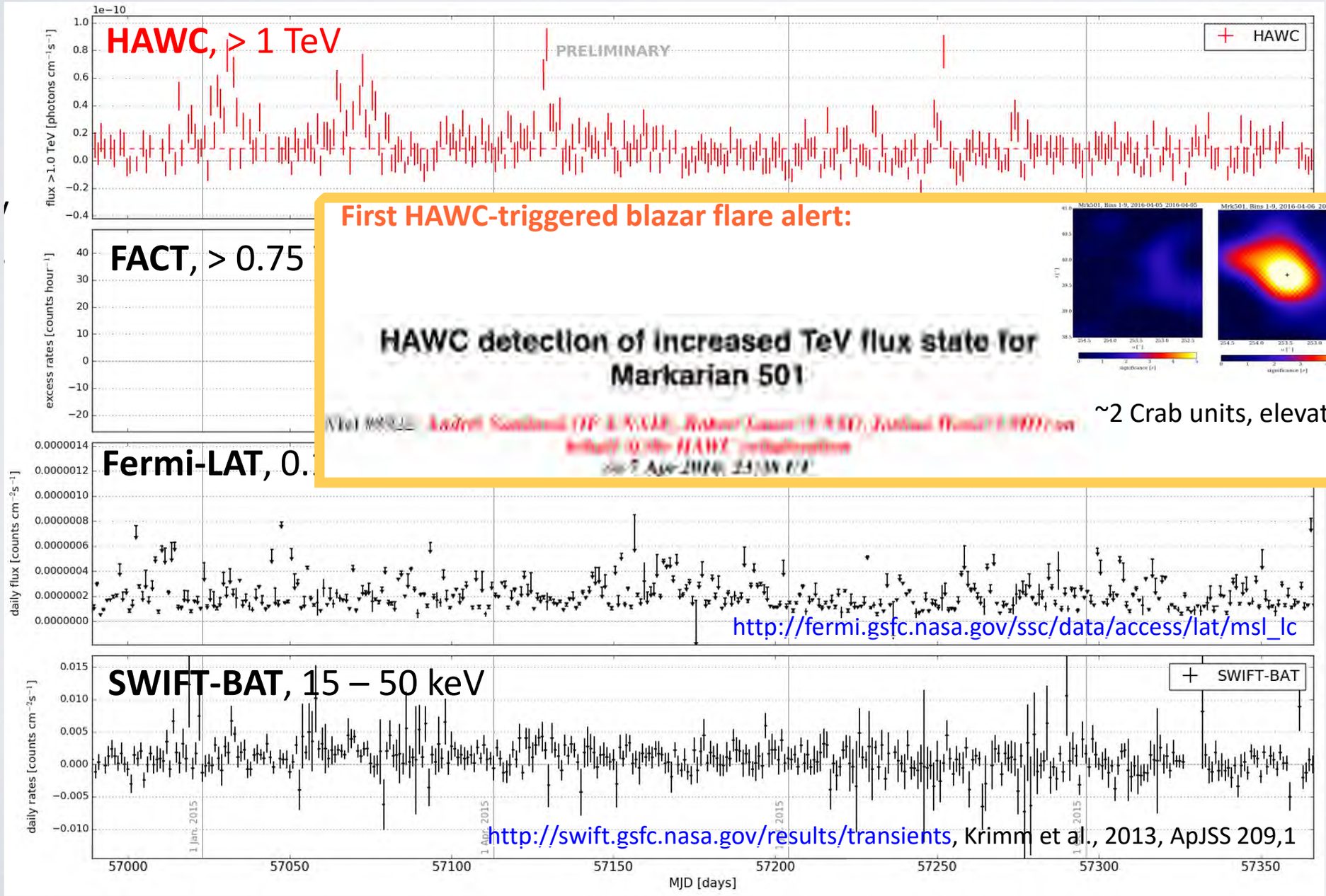
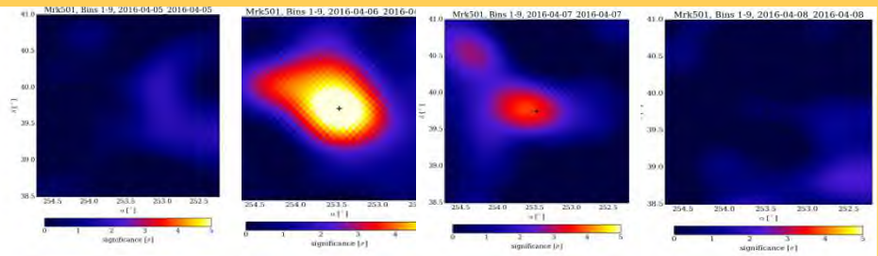


First HAWC-triggered blazar flare alert:



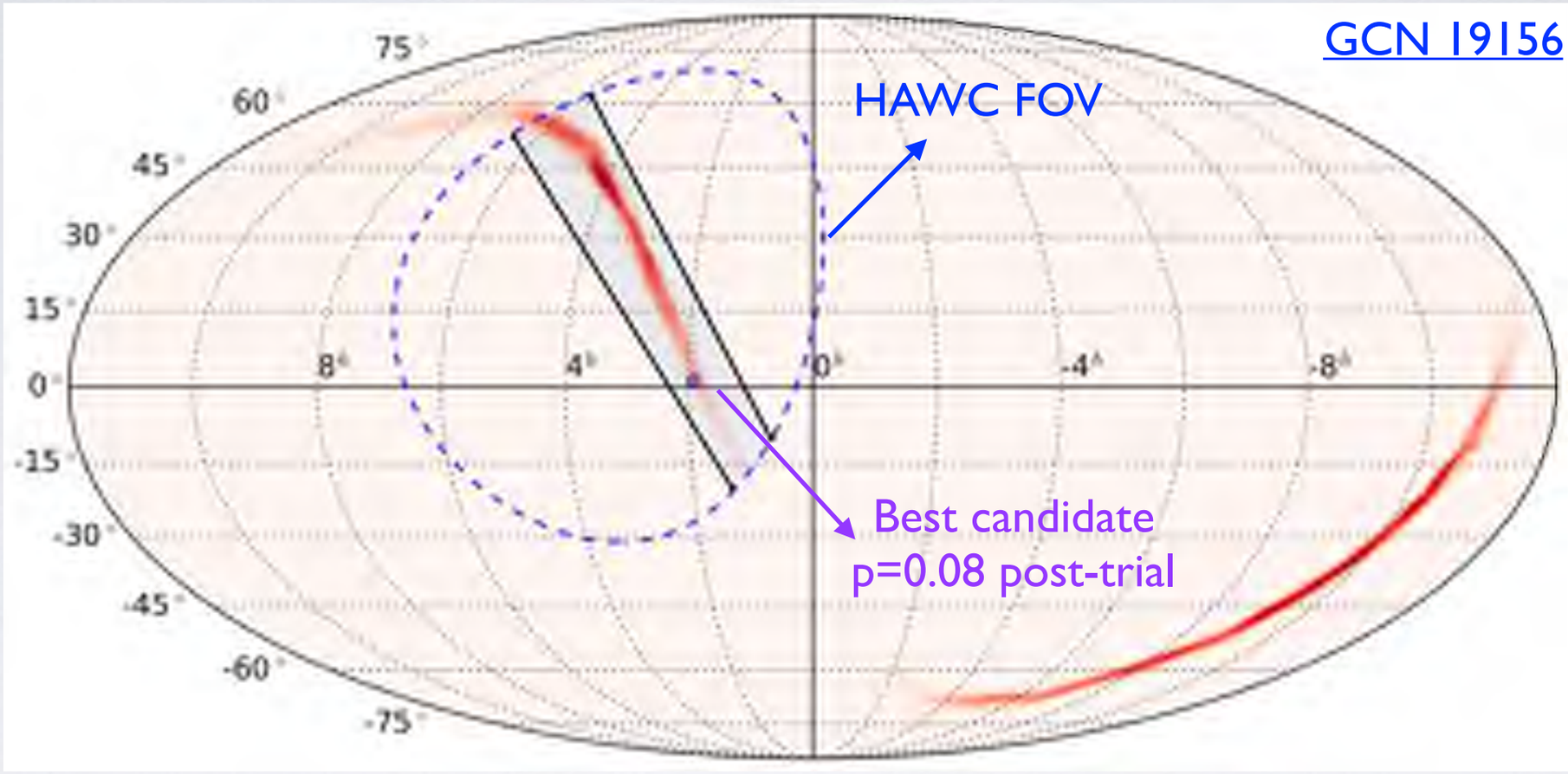
HAWC detection of increased TeV flux state for Markarian 501

~2 Crab units, elevated flux for ~2 days

http://fermi.gsfc.nasa.gov/ssc/data/access/lat/msl_lc

http://swift.gsfc.nasa.gov/results/transients, Krimm et al., 2013, ApJSS 209,1

LIGO Follow-up



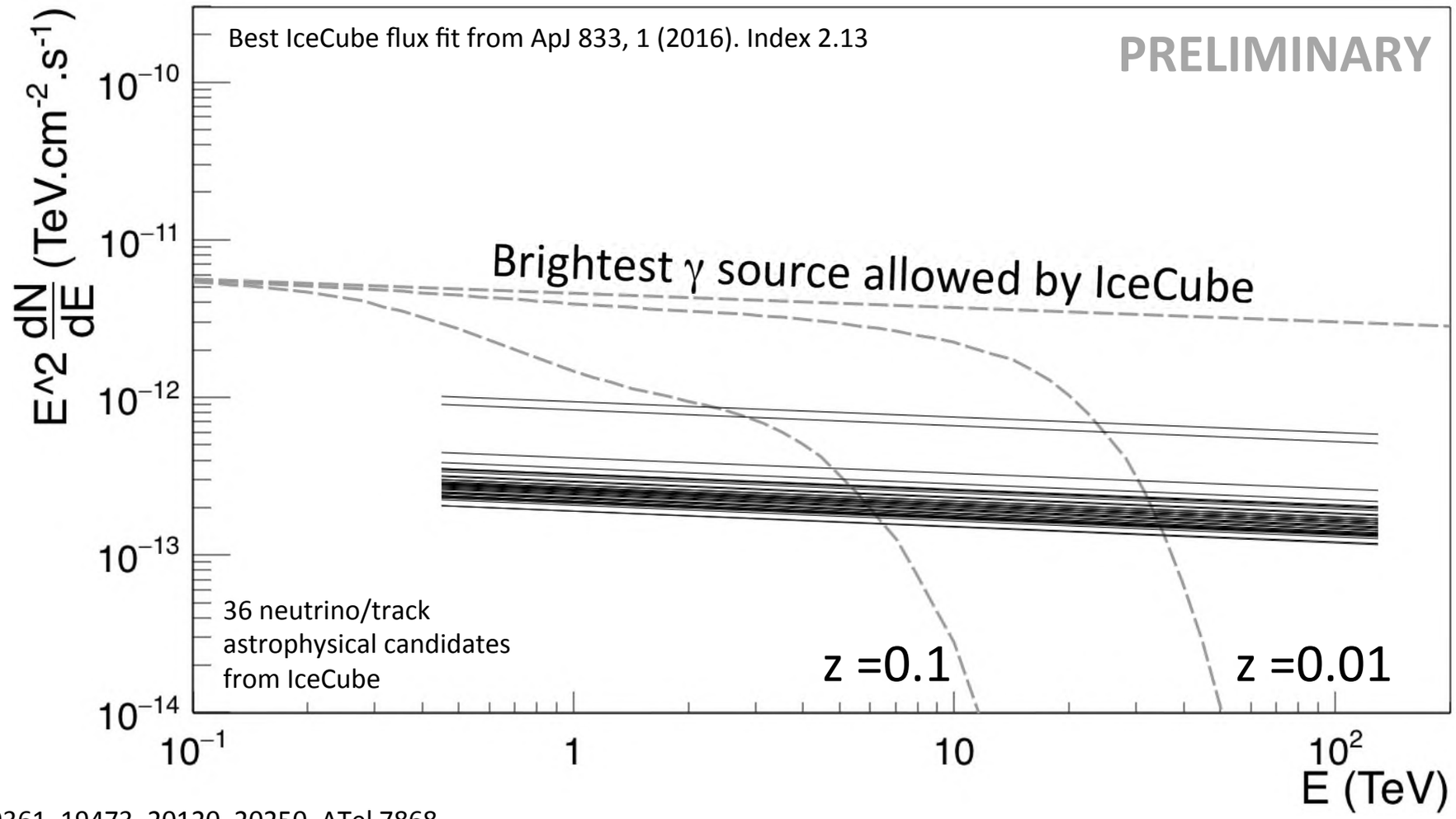
GW151226:
- 2015 Dec 26 03:38:53.6 UTC
- z=0.09 +0.03 -0.04
- 14.2$M_\odot$ + 7.5$M_\odot$ ➡20.8$M_\odot$

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

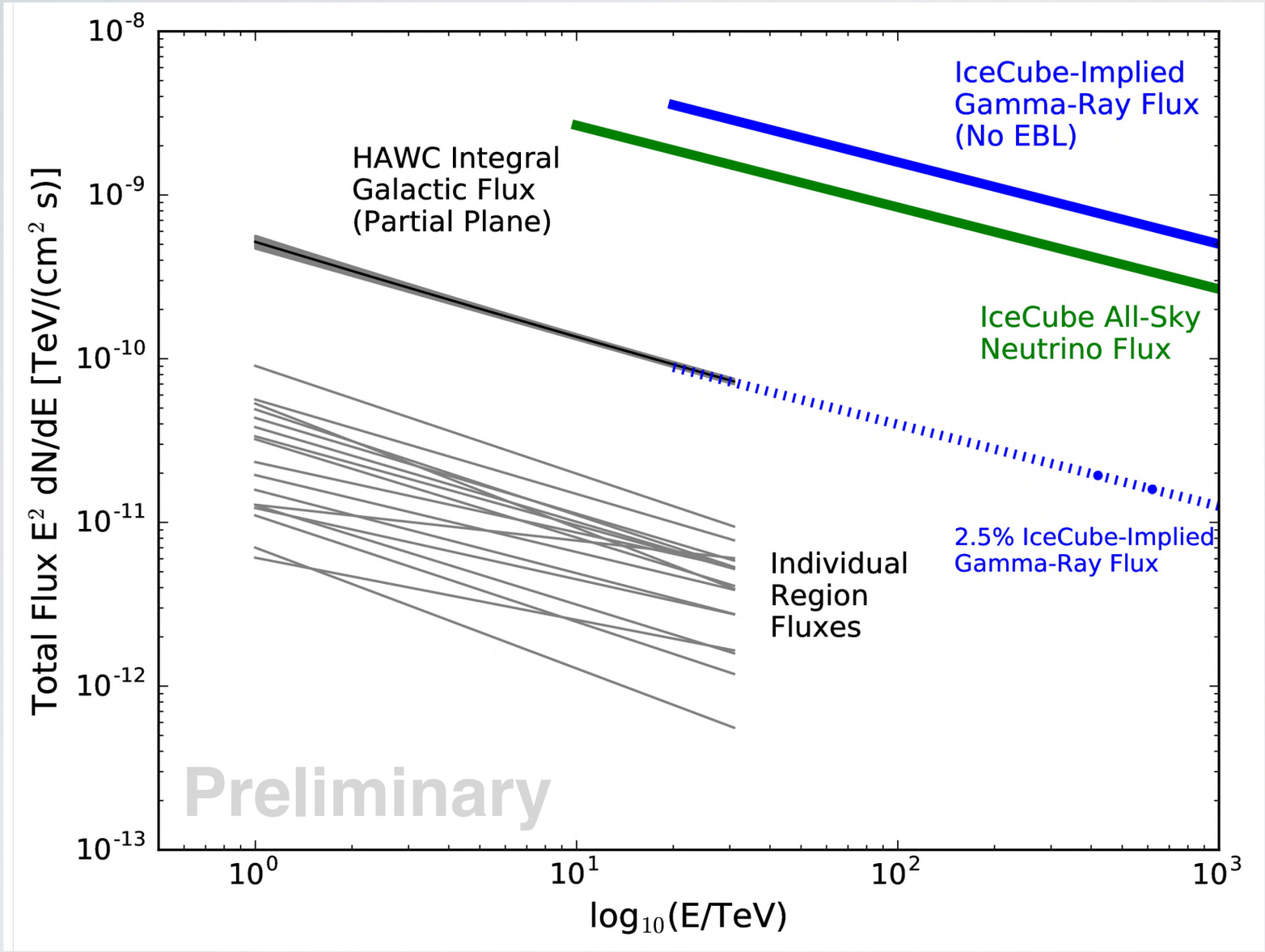


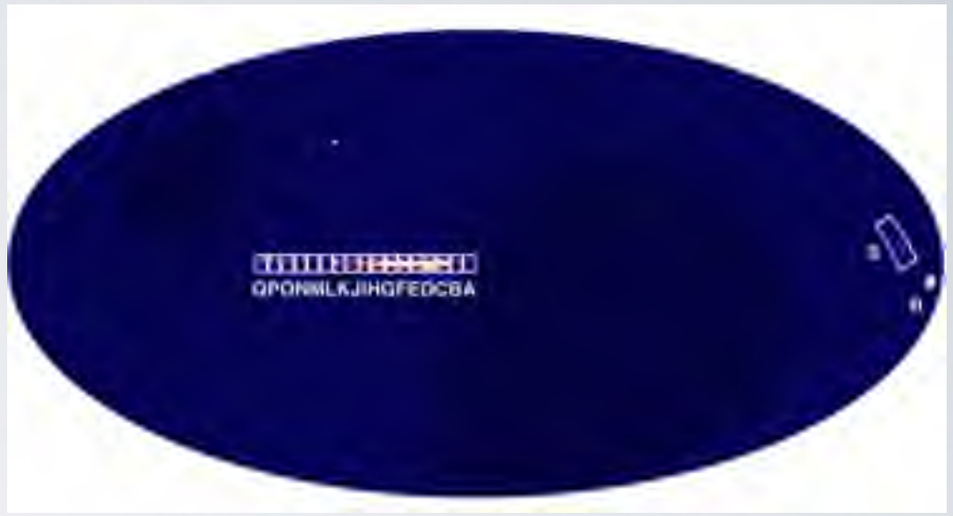
GCN Circ. 19361, 19473, 20120, 20250. ATel 7868

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 ~2.5% of IceCube flux

Cosmic-Ray Anisotropy

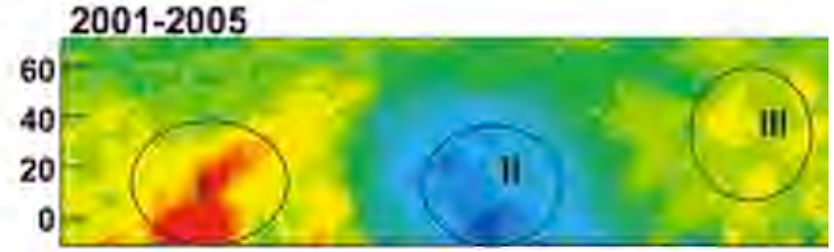
Possible explanations

- Heliospheric interactions
- Non-diffusive propagaion
- Turbulence in Galactic magnetic field — doesn't explain region A hardening
- Exotic scenarios — new particles?
- Non-uniform pitch angle diffusion

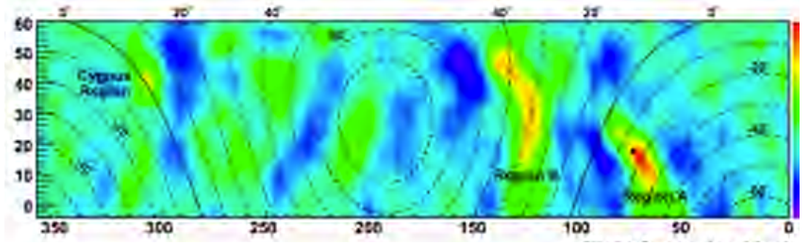
HAWC observation

- 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.

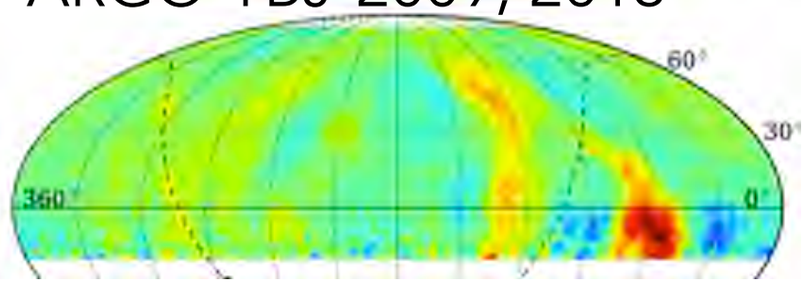
1 – Tibet-AS γ 2005



2 – Milagro 2008, 2009



3 – ARGO-YBJ 2009, 2013

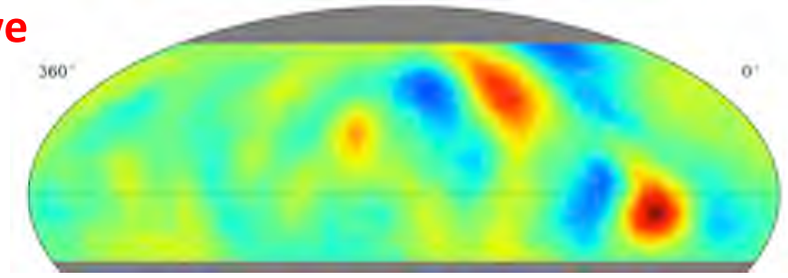


4 – IceCube 2010, 2011, 2012

active

5 – HAWC 2014

active



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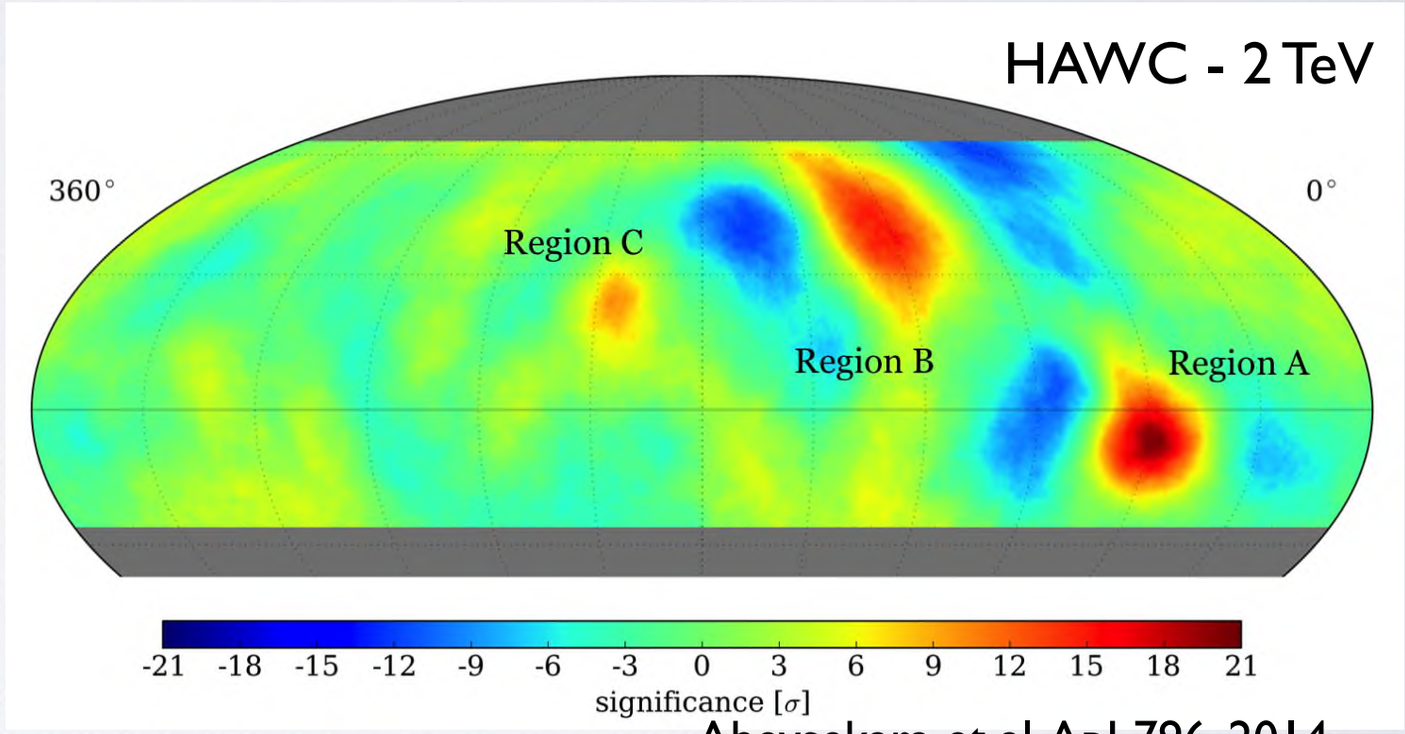

Abeysekara et al. ApJ 796, 2014

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Multi-wavelength / Multi-messenger

Have follow-up agreement with:
- Swift
- 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 from Pass 1 release.
- Flares from known gamma-ray sources.

HAWC ATel #8922 on Mrk 501 flare

FACT/HAWC/ Swift ATel #9137 on Mrk 421 flare

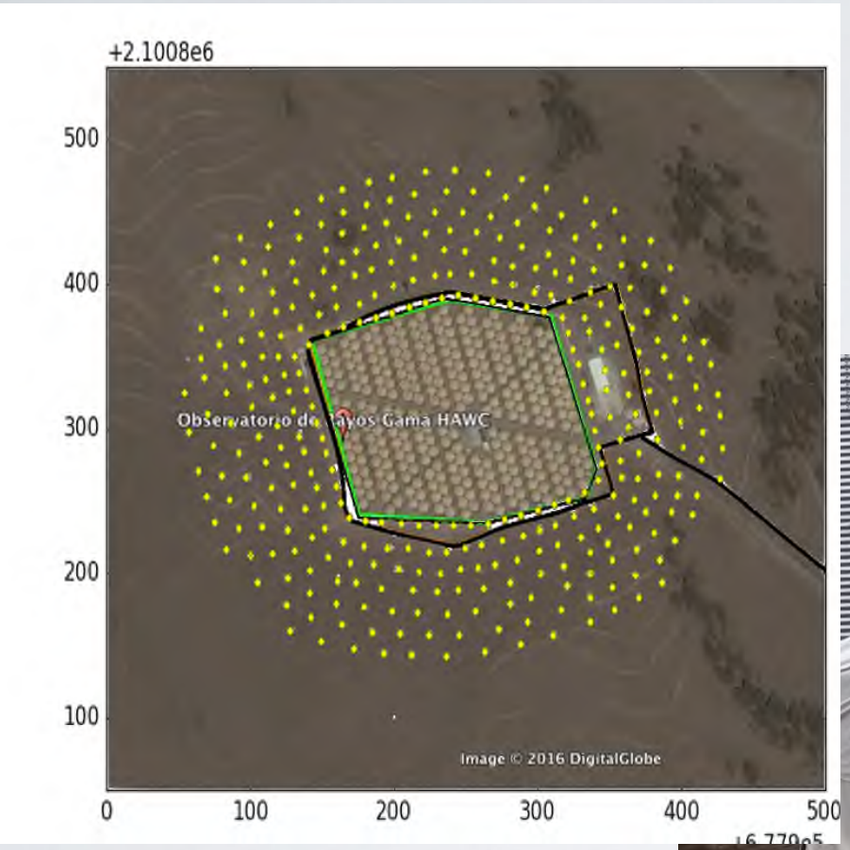
Externally triggered:
- IceCube alert on high confidence neutrino event (highest energy pointed astrophysical track-like).
- Fermi alerts on flaring activities.
- LIGO/VIRGO gravitational wave event follow-up

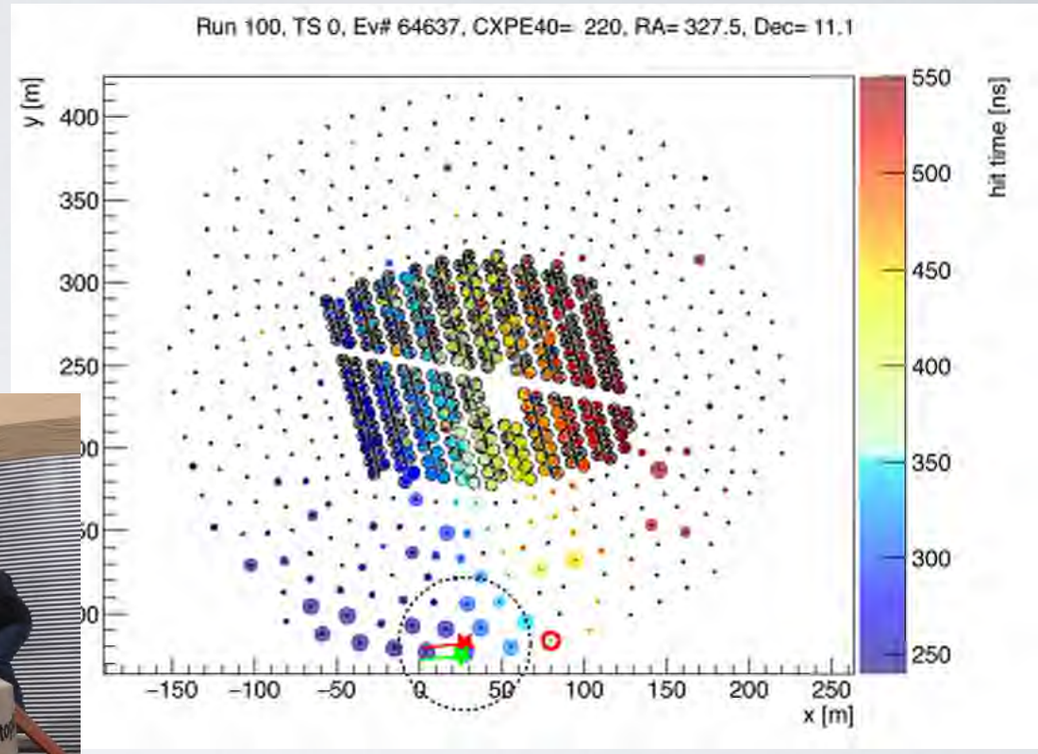
IceCube ATel #7856
HAWC Follow-up ATel #7868

IceCube GCN #20119
HAWC Follow-up GCN #20120

HAWC GRB Follow-up GCN #19423
HAWC LIGO Follow-up GCN #19156

HAWC Outrigger

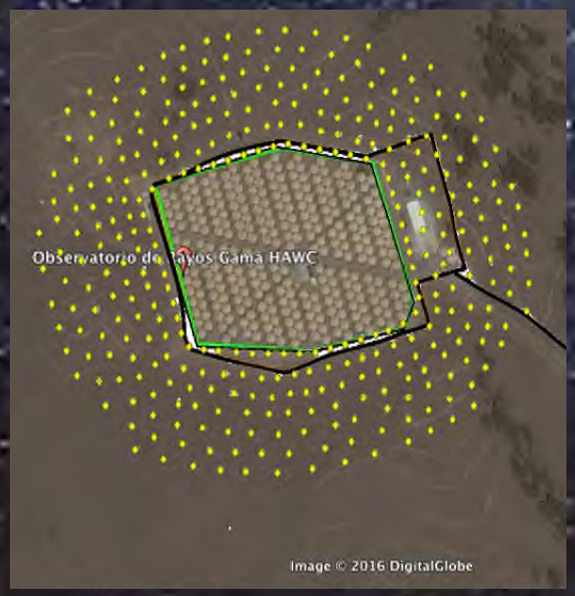




- 350 small WCD outrigger detectors.
- Cover an area 4x HAWC.
- Sensitivity increase by 3-4x the sensitivity at 50 TeV.
- Deployment in progress.

Outlook

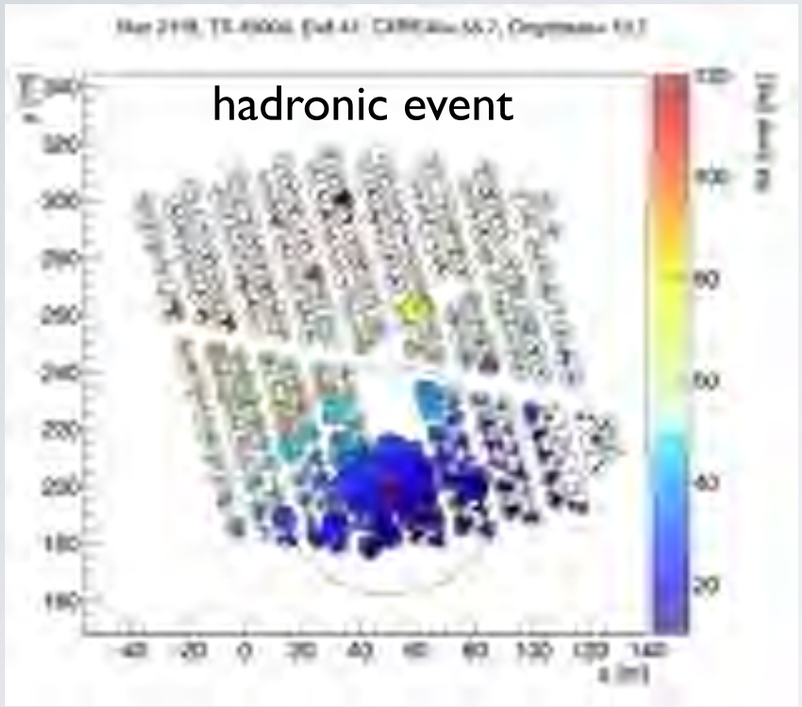
- HAWC is surveying and monitoring the gamma-ray sky, agreement with many instruments ready for follow-up.
- Many instruments from different waveband/messenger (X-rays, neutrinos, gravitational waves) available for simultaneous observation.

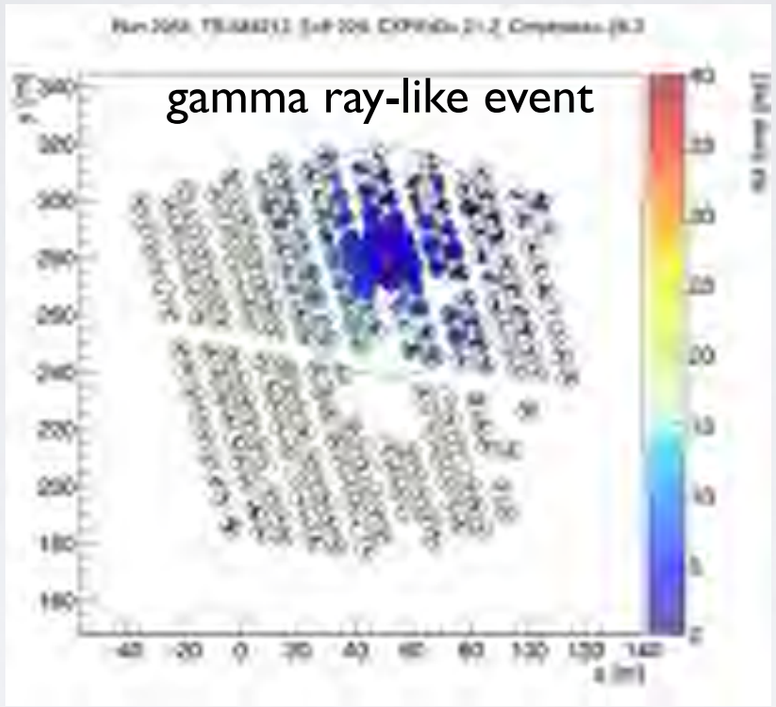


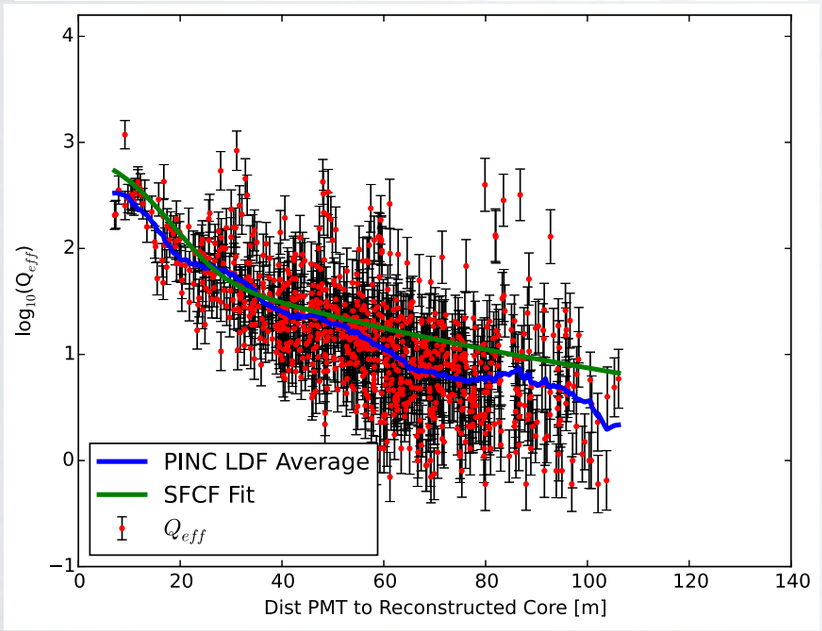
- Diverse science results in prep, stay tuned!
- Upgrade to expand the array to enhance effective area >10 TeV by 3-4x is currently under installation.

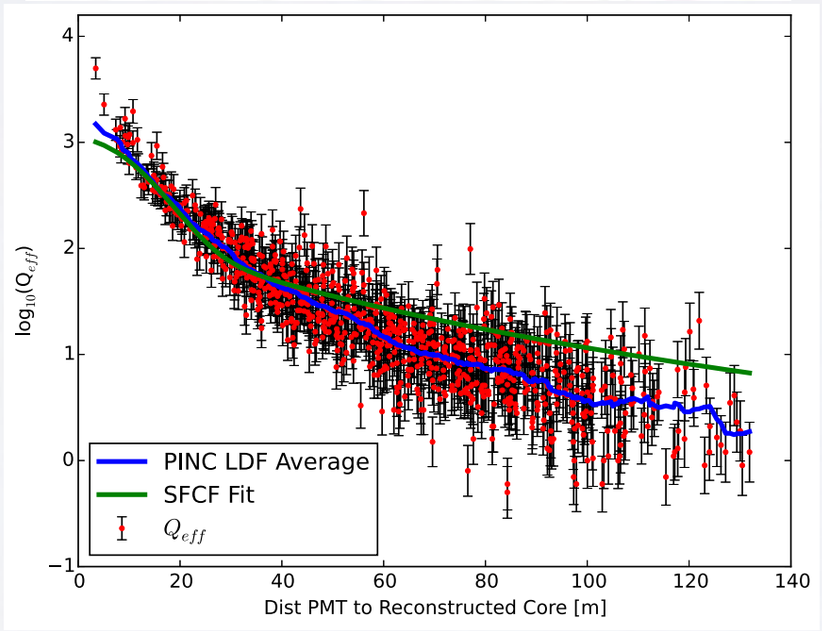
BACKUP

Gamma/Hadron Separation









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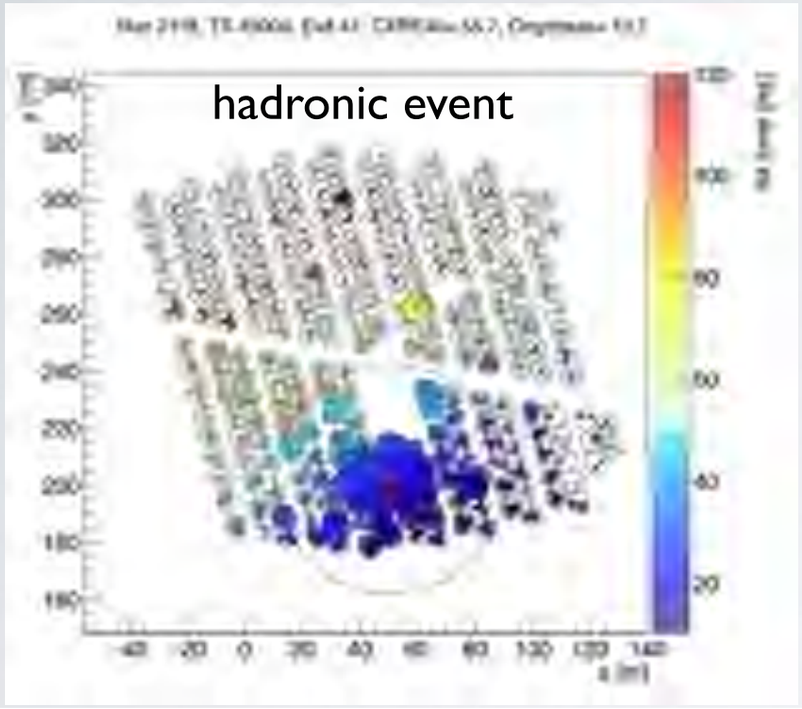
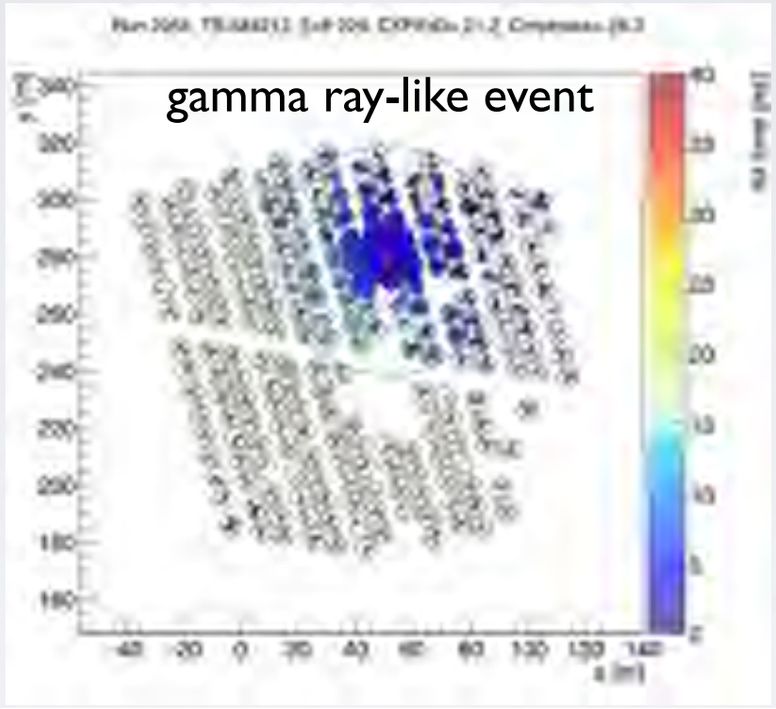
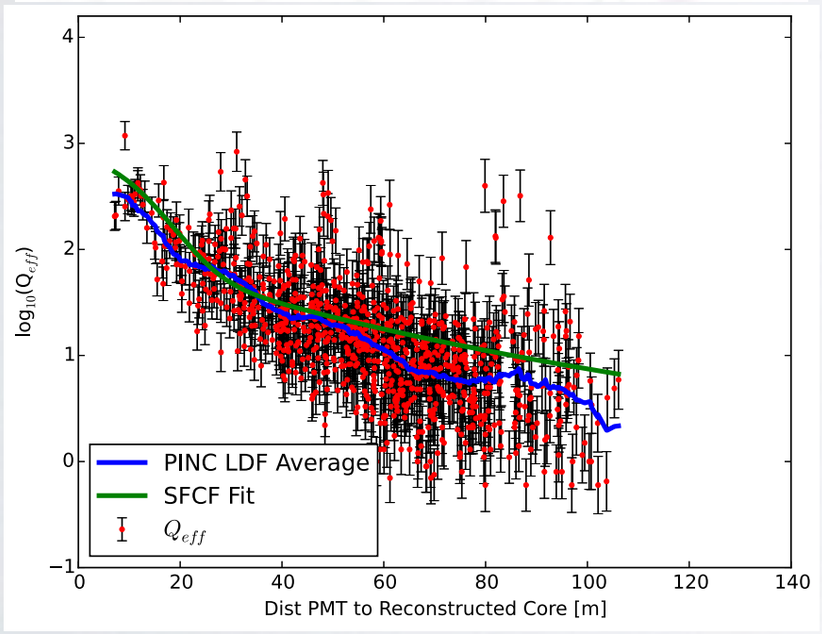
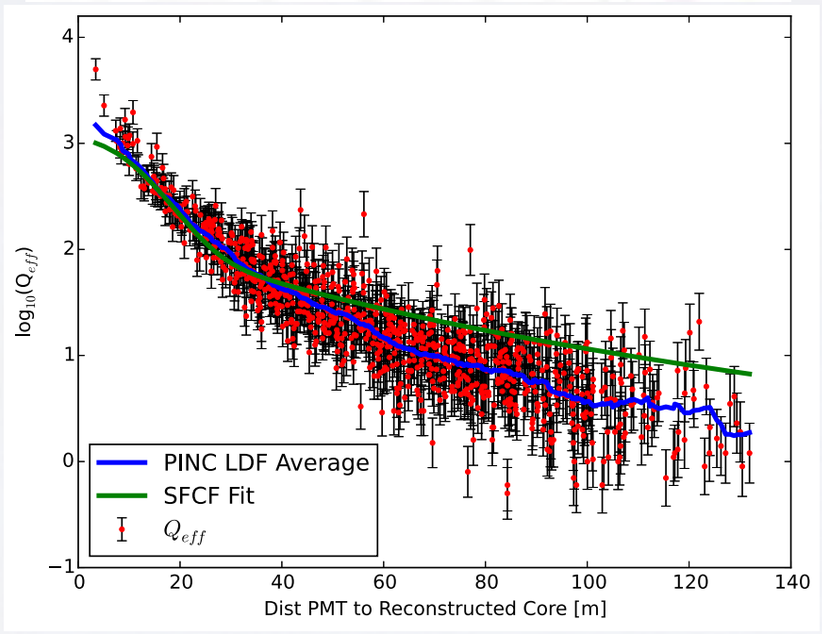
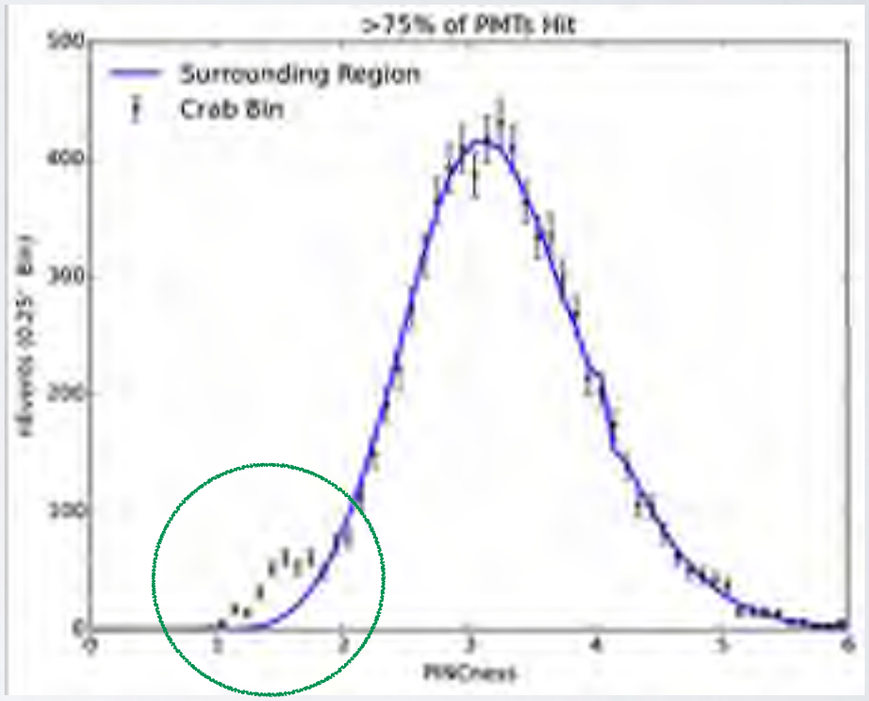


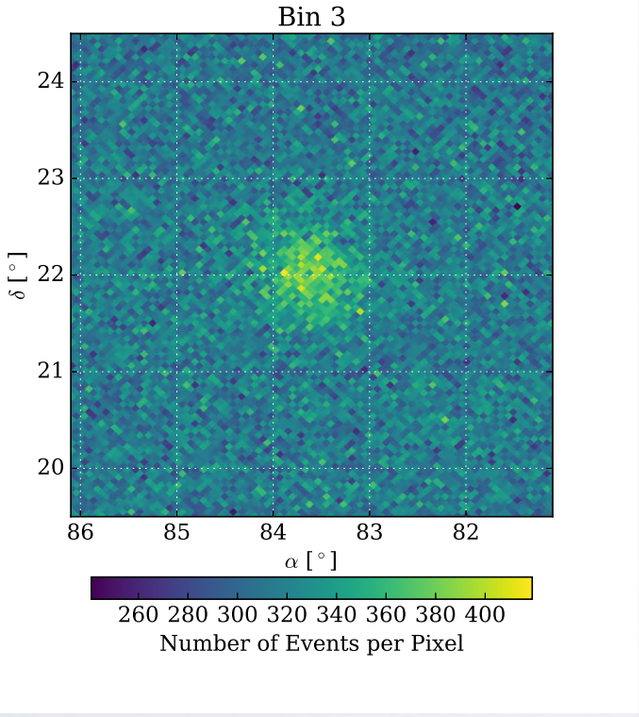




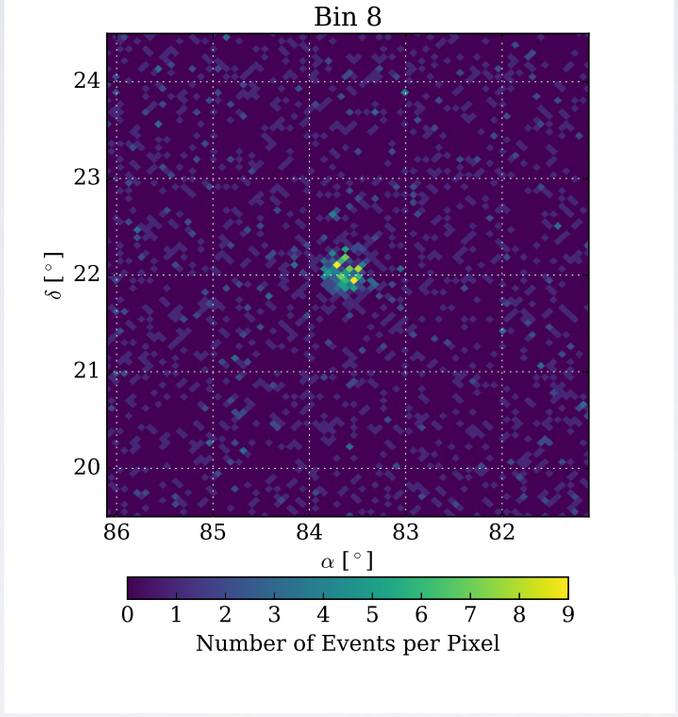




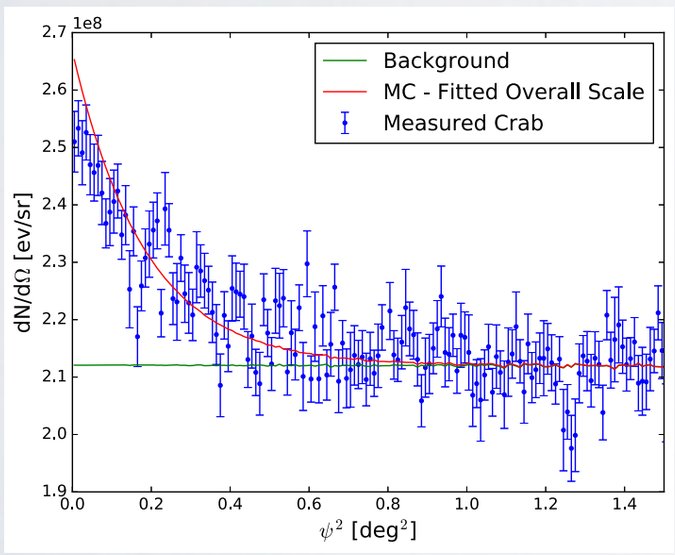
Angular Resolution



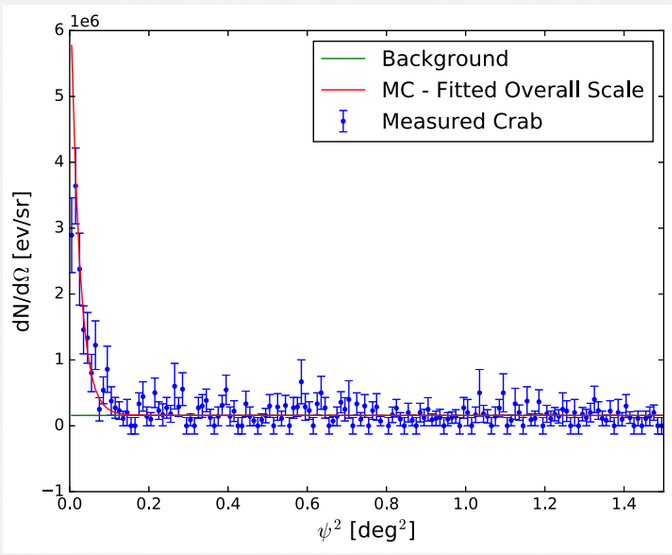
(a) $\mathcal{B} = 3$ Event Counts



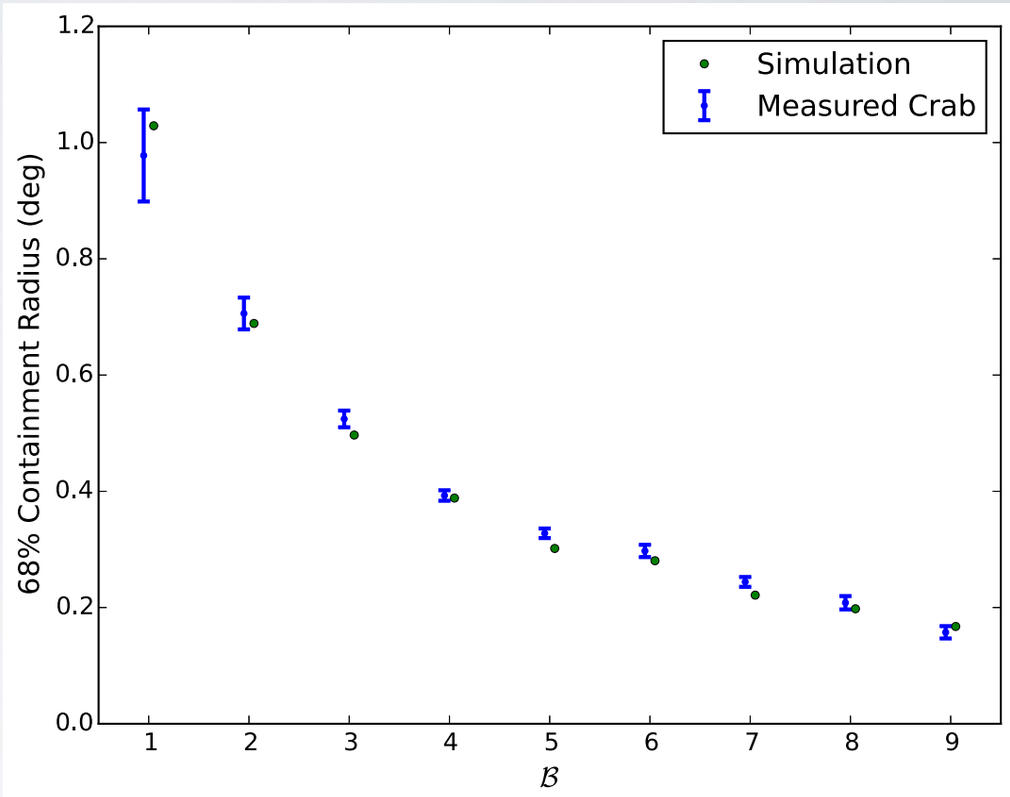
(b) $\mathcal{B} = 8$ Event Counts



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



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



HAWC Sensitivity