HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

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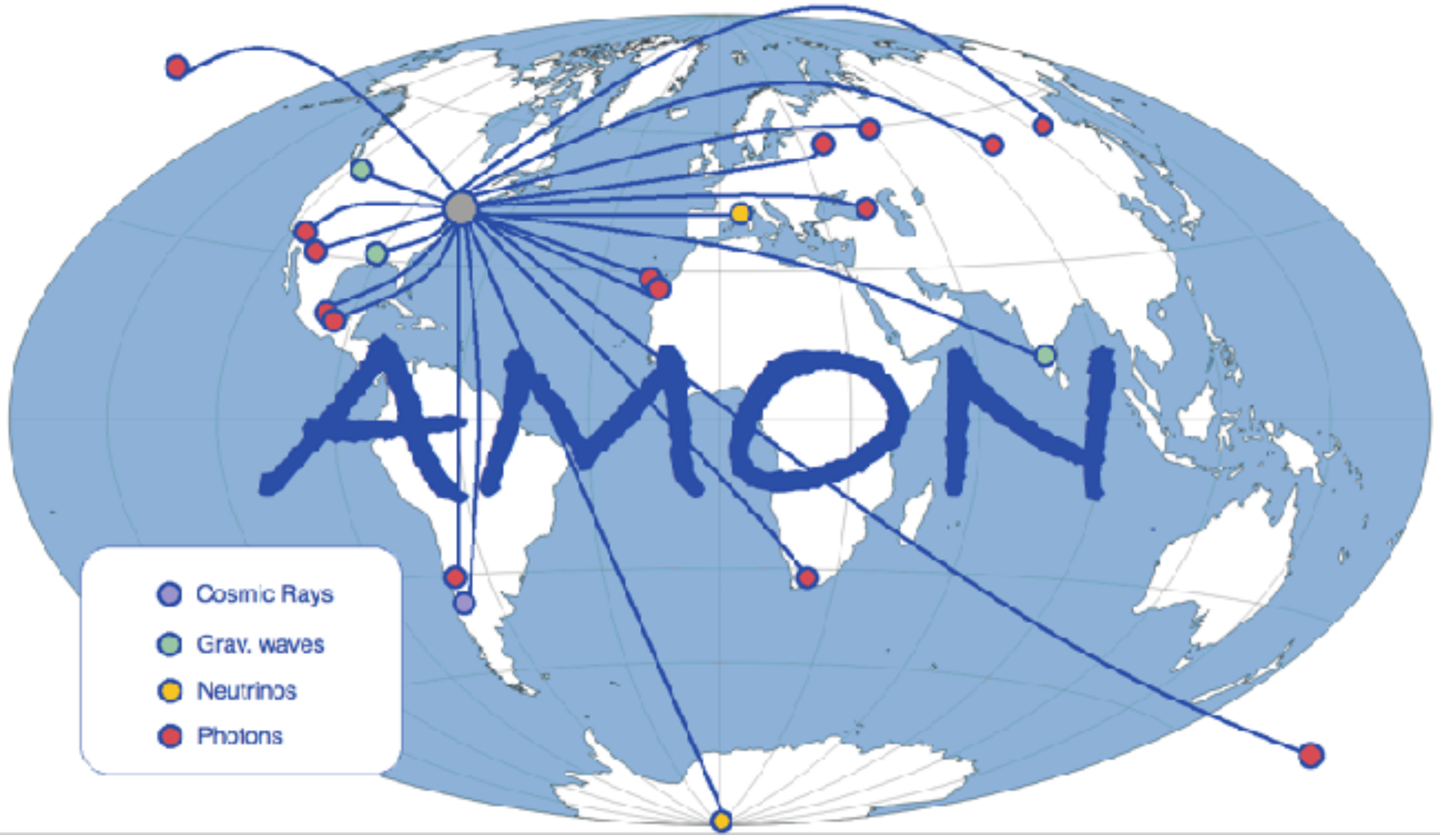
Eberly College of Science

and its connection to



AMON workshop @ Chiba University - May 22-23, 2019

NSF

Outline

Very brief introduction 1

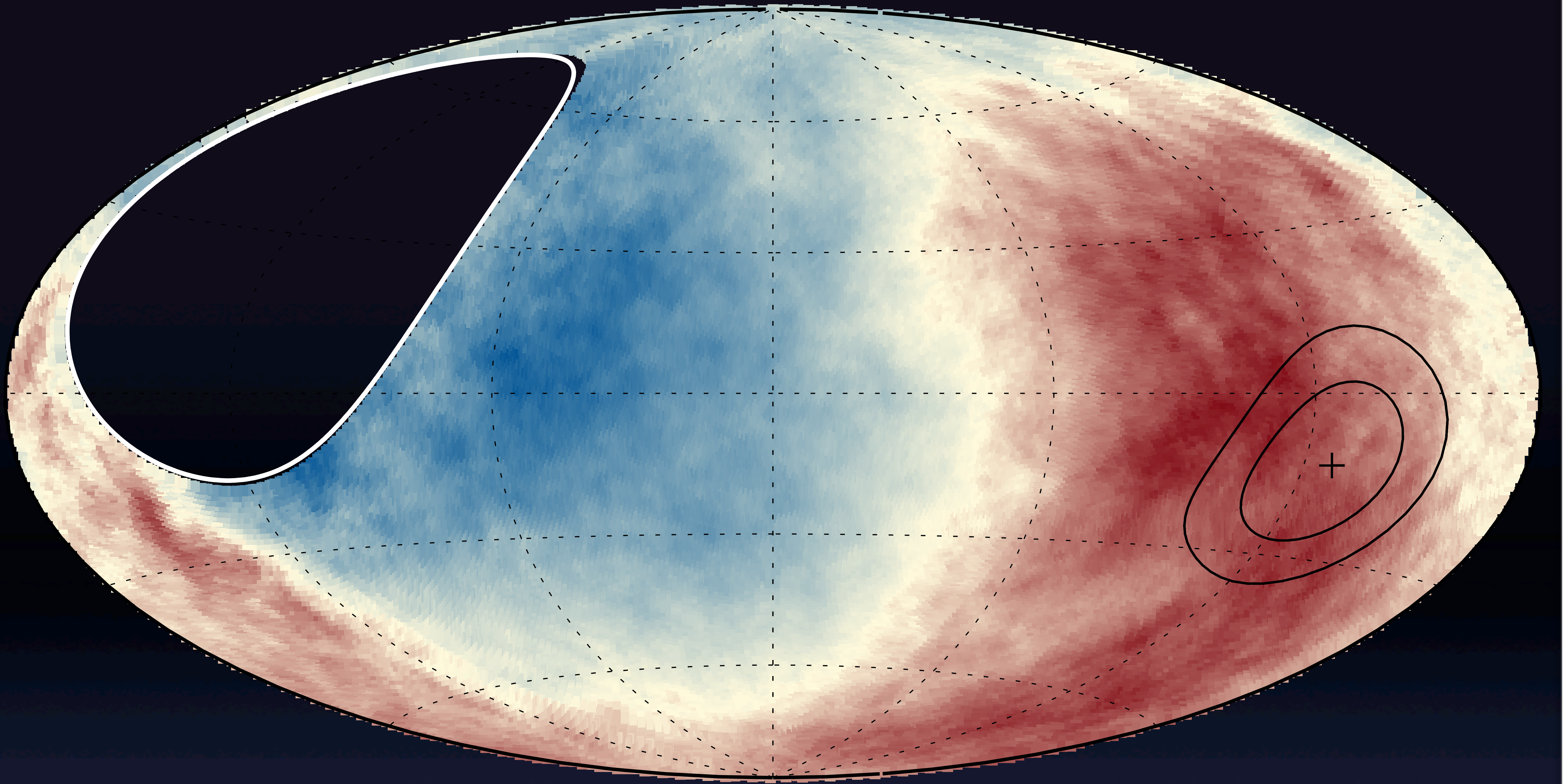
Selected recent results 2

Sub-threshold events
& correlations 3

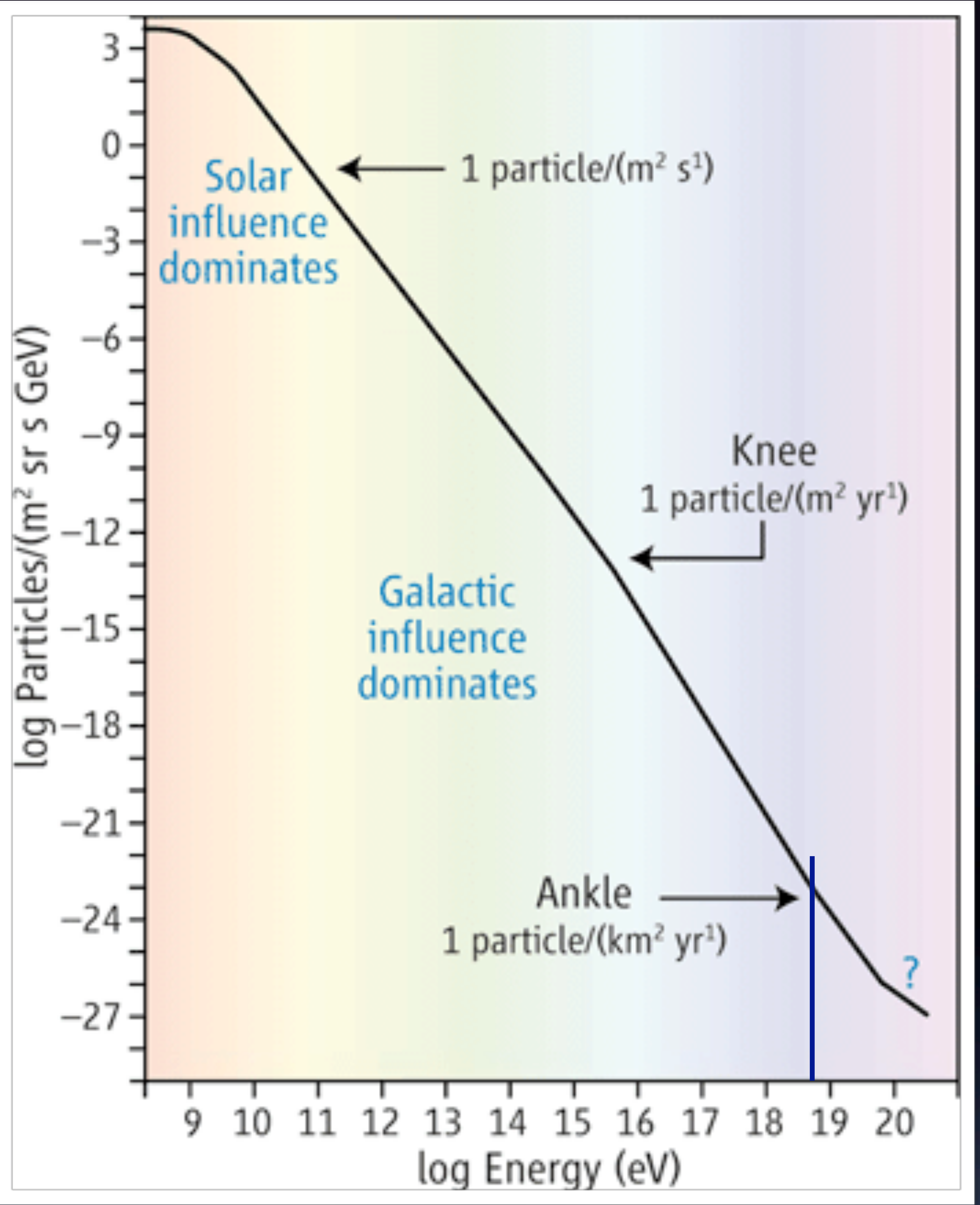
Outlook 4

Cosmic Rays

5% dipole above 8 EeV



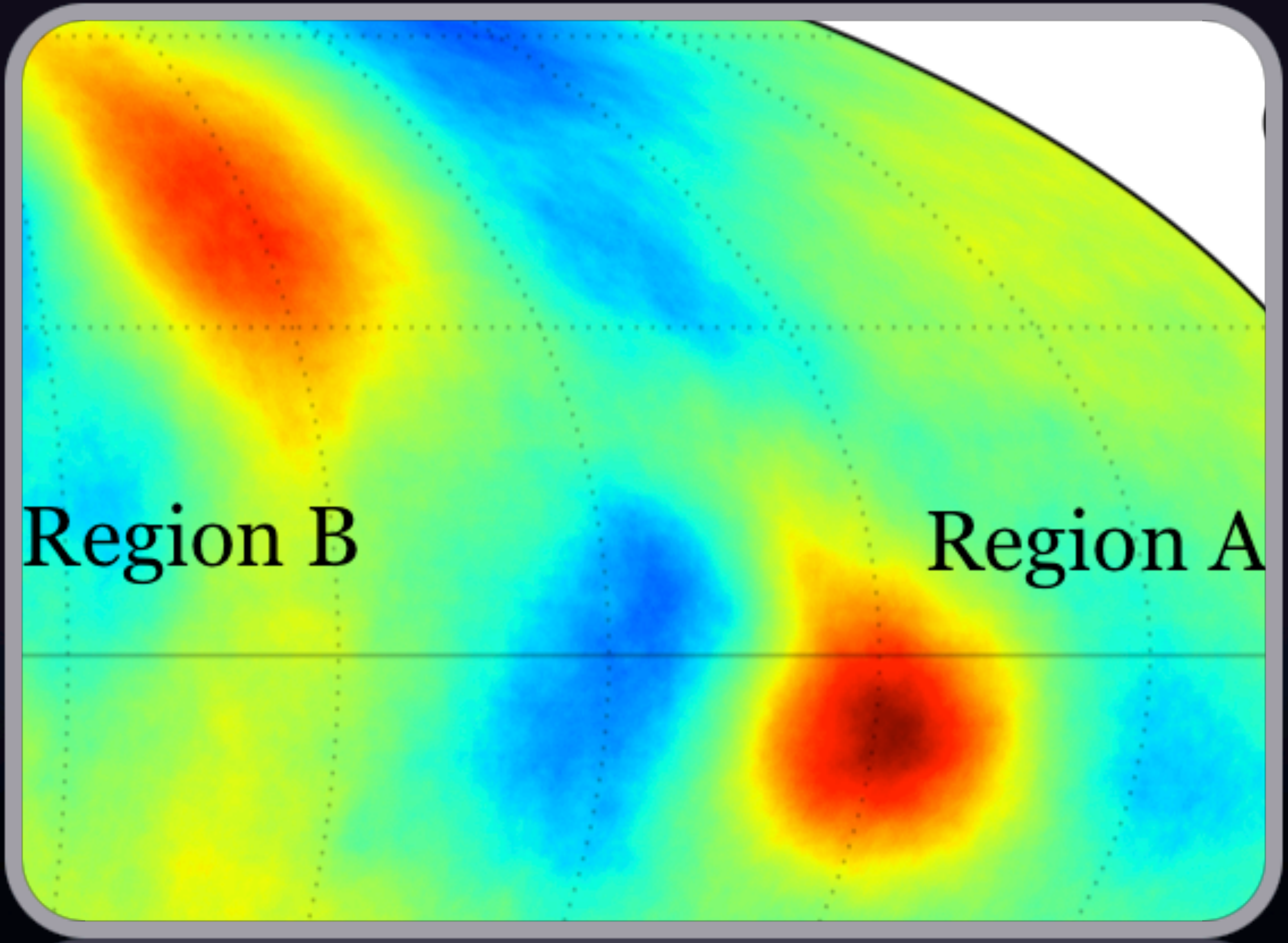
Auger Collab., Science **357** (2017) 1266-1270



Duldig, Science **314** (2006) 429-430

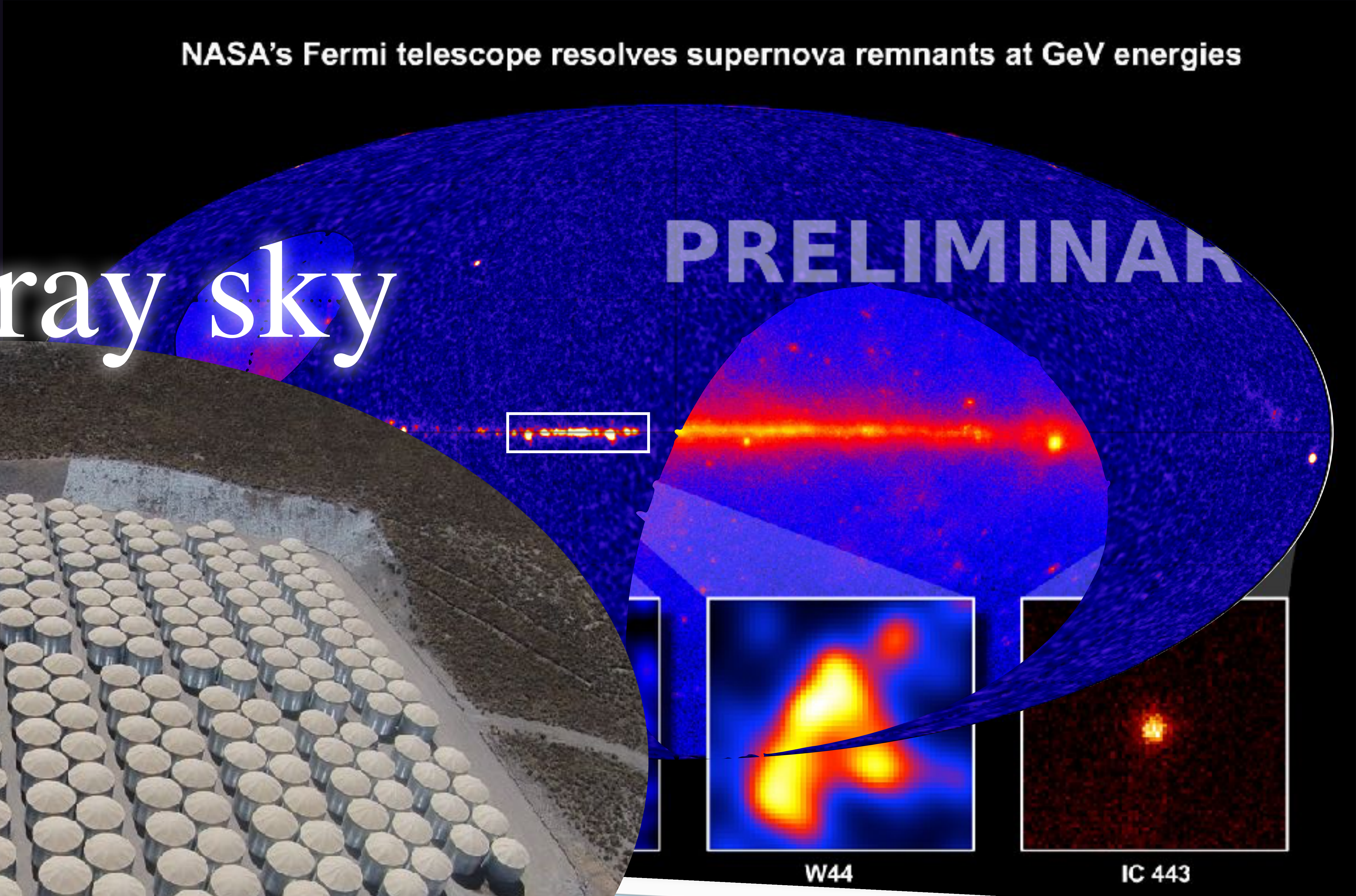

Gamma Rays
Cas A
W51C
W44
IC 443

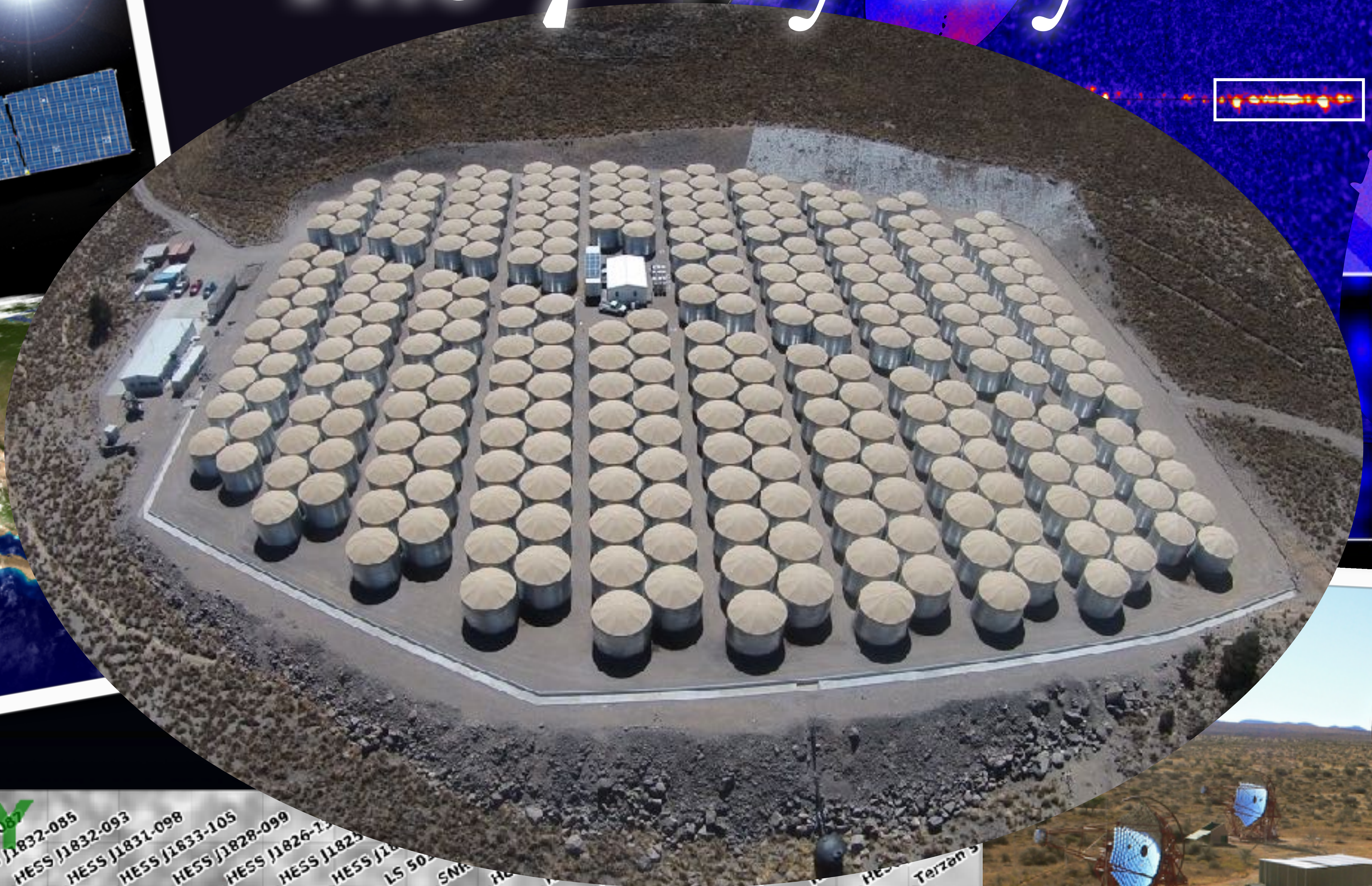
Motivation

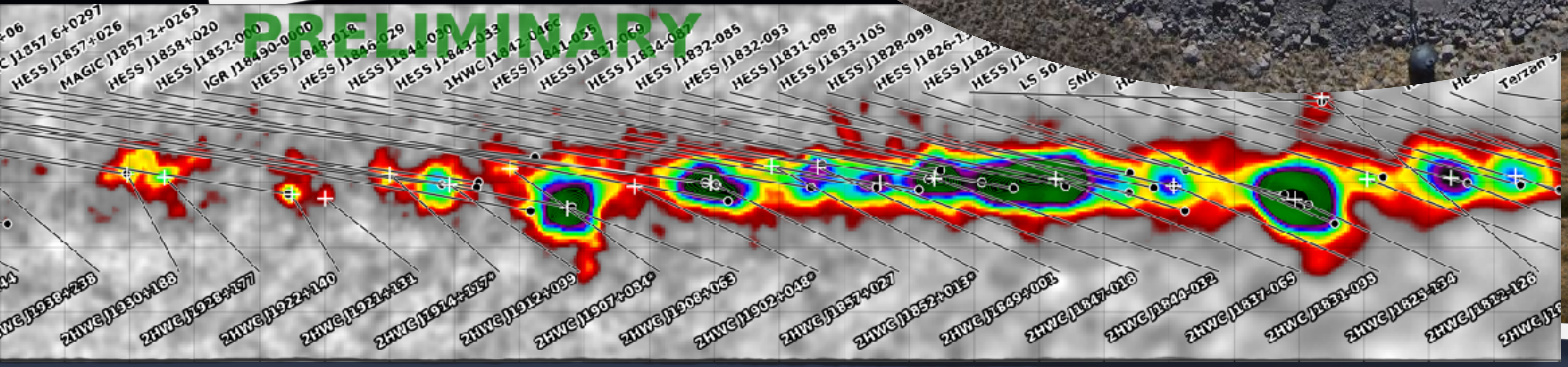


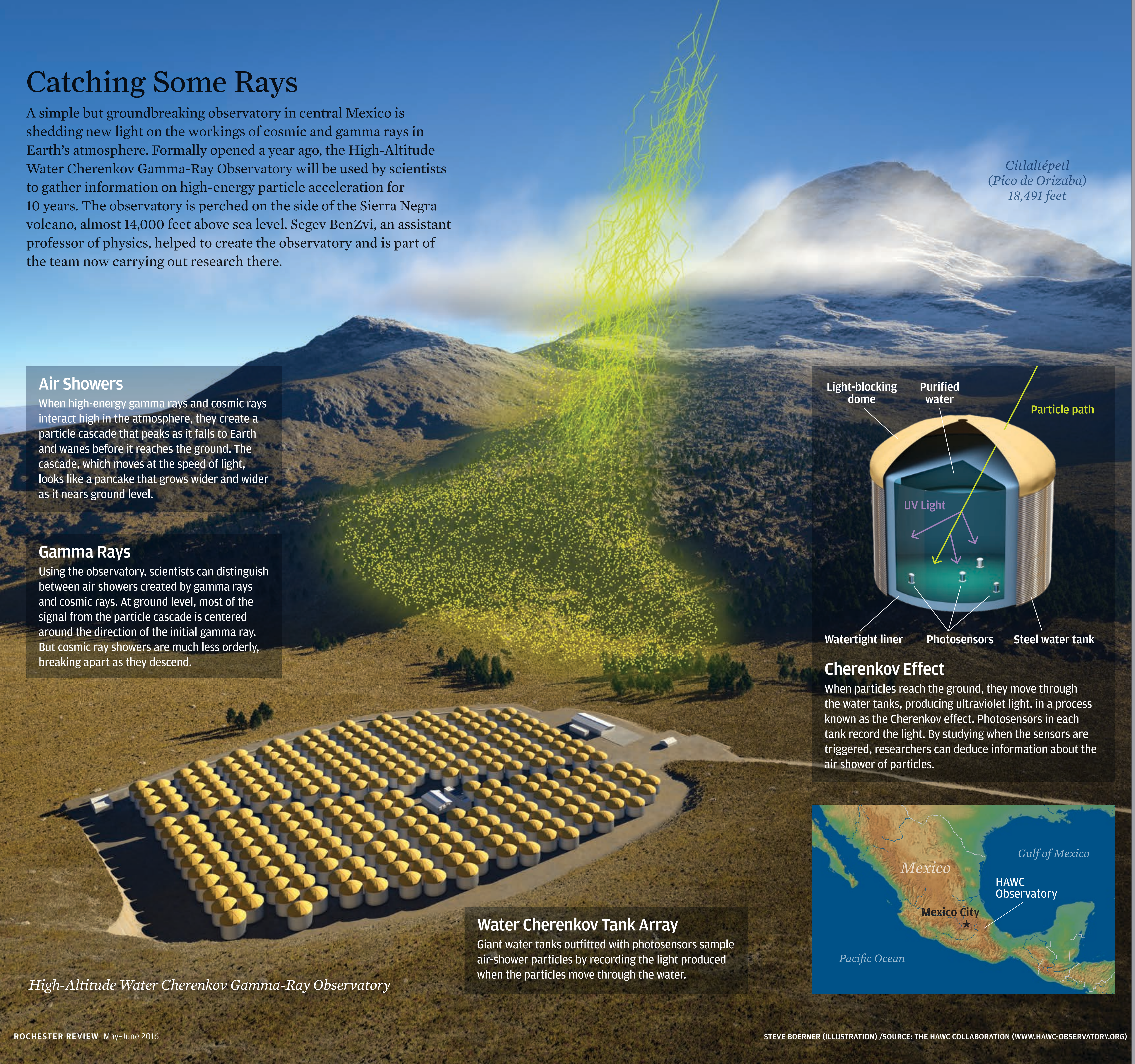
- Constrain the **origin of cosmic rays** by measuring gamma-ray spectra to 100 TeV.
- Probe **particle acceleration** in astrophysical jets with wide field of view, high duty factor observations.
- Explore **new physics** with an unbiased survey of the TeV sky.

The γ-ray sky









Catching Some Rays

A simple but groundbreaking observatory in central Mexico is shedding new light on the workings of cosmic and gamma rays in Earth's atmosphere. Formally opened a year ago, the High-Altitude Water Cherenkov Gamma-Ray Observatory will be used by scientists to gather information on high-energy particle acceleration for 10 years. The observatory is perched on the side of the Sierra Negra volcano, almost 14,000 feet above sea level. Segev BenZvi, an assistant professor of physics, helped to create the observatory and is part of the team now carrying out research there.

Air Showers

When high-energy gamma rays and cosmic rays interact high in the atmosphere, they create a particle cascade that peaks as it falls to Earth and wanes before it reaches the ground. The cascade, which moves at the speed of light, looks like a pancake that grows wider and wider as it nears ground level.

Gamma Rays

Using the observatory, scientists can distinguish between air showers created by gamma rays and cosmic rays. At ground level, most of the signal from the particle cascade is centered around the direction of the initial gamma ray. But cosmic ray showers are much less orderly, breaking apart as they descend.

Cherenkov Effect

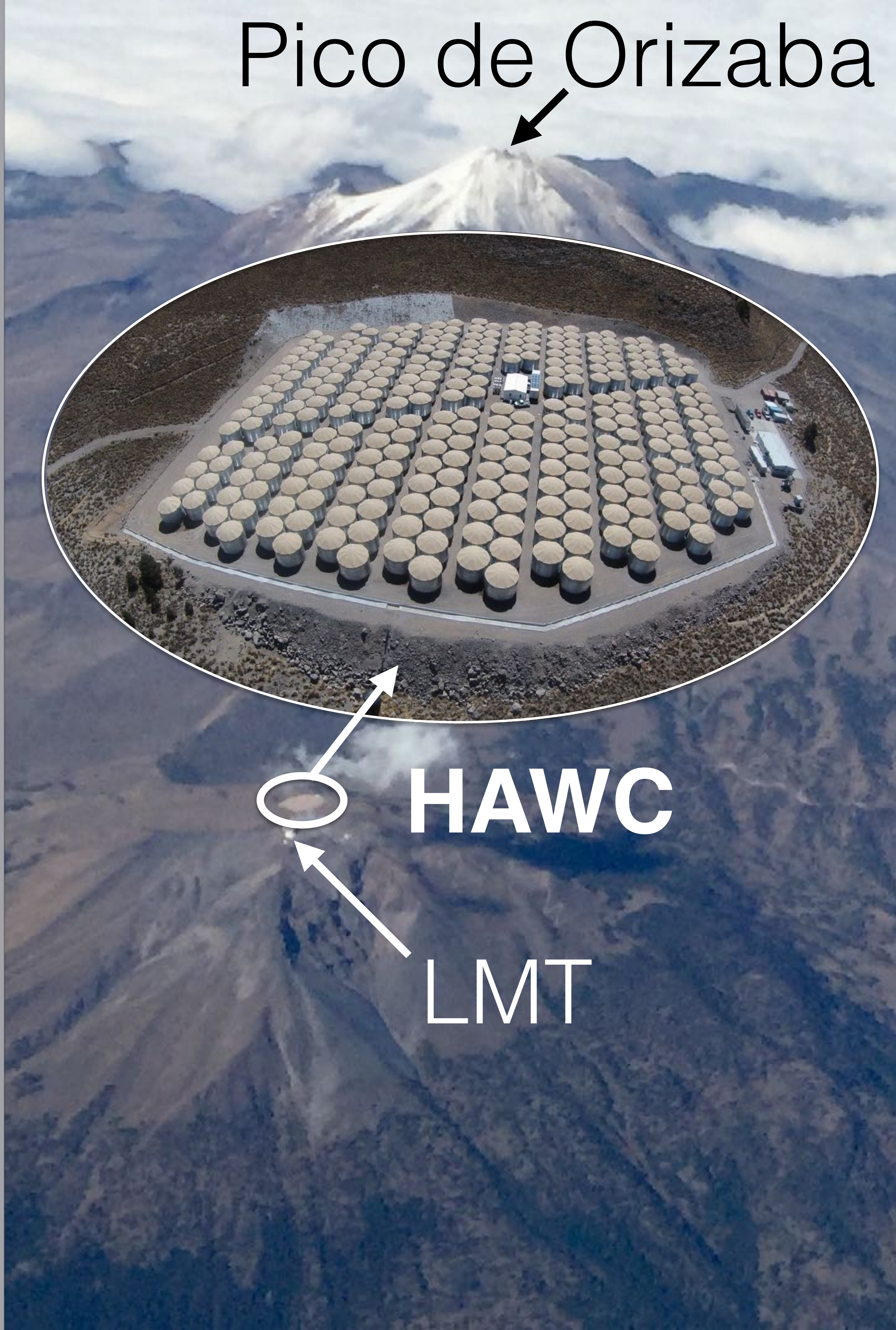
When particles reach the ground, they move through the water tanks, producing ultraviolet light, in a process known as the Cherenkov effect. Photosensors in each tank record the light. By studying when the sensors are triggered, researchers can deduce information about the air shower of particles.

Water Cherenkov Tank Array

Giant water tanks outfitted with photosensors sample air-shower particles by recording the light produced when the particles move through the water.

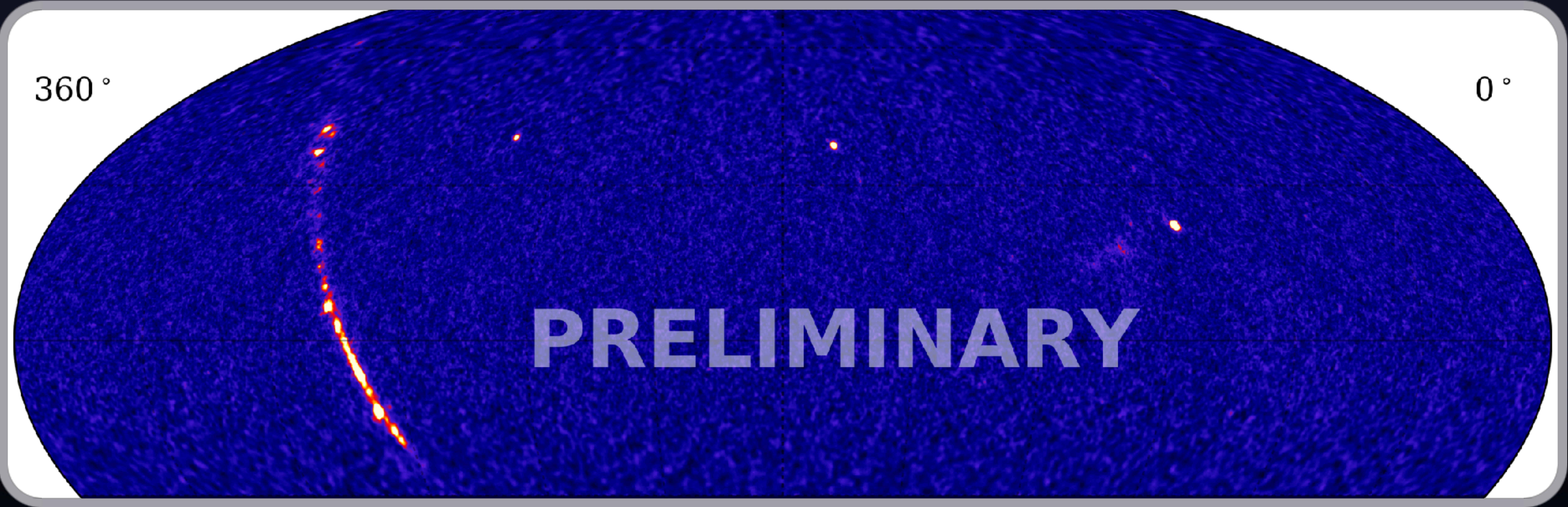
High-Altitude Water Cherenkov Gamma-Ray Observatory

STEVE BOERNER (ILLUSTRATION) /SOURCE: THE HAWC COLLABORATION (WWW.HAWC-OBSERVATORY.ORG)



Fermi-LAT sky smoothed map
E > 50 GeV (Pass 8 - 6 years of data)
(courtesy of M. Ajello)

HAWC — 2-year TeV sky



HAWC smoothed map
E > 500 GeV (Pass 4 ~2 years of data)

Abeysekara *et al* [HAWC] ApJ **843** (2017) 40

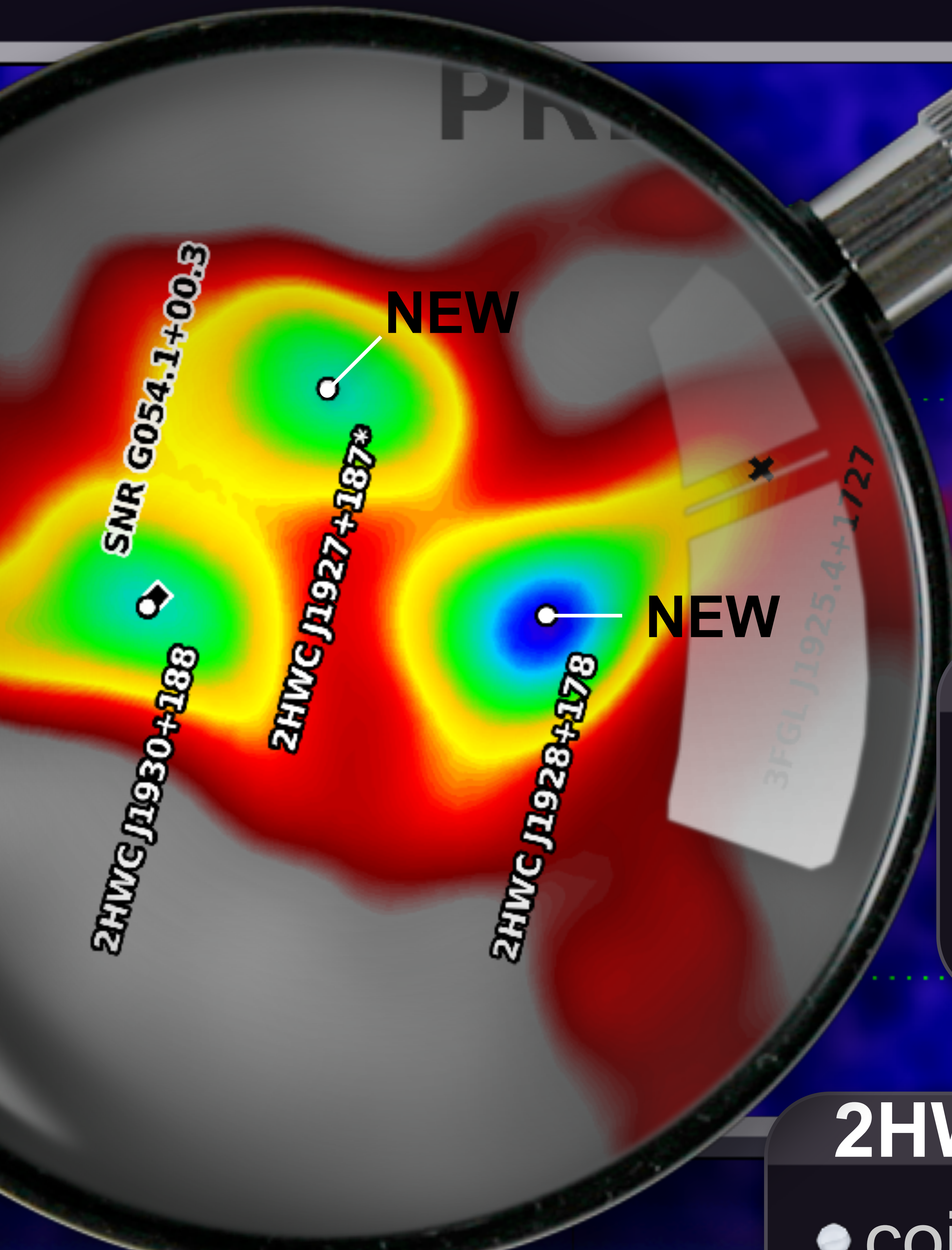
First HAWC catalog

…kara *et al* [HAWC] ApJ **843** (2017) 40

2HWC J1839-058 & 2HWC J1837-066*

- Point source fluxes consistent with TeV sources **HESS J1841-055** and **HESS J1837-069**
- Complex region with multiple pulsars and supernova remnants: 5 **2FHL** sources: 2 PWNe and 3 UIDs

Abeysekara *et al* [HAWC] ApJ **843** (2017) 40



2HWC J1930+188

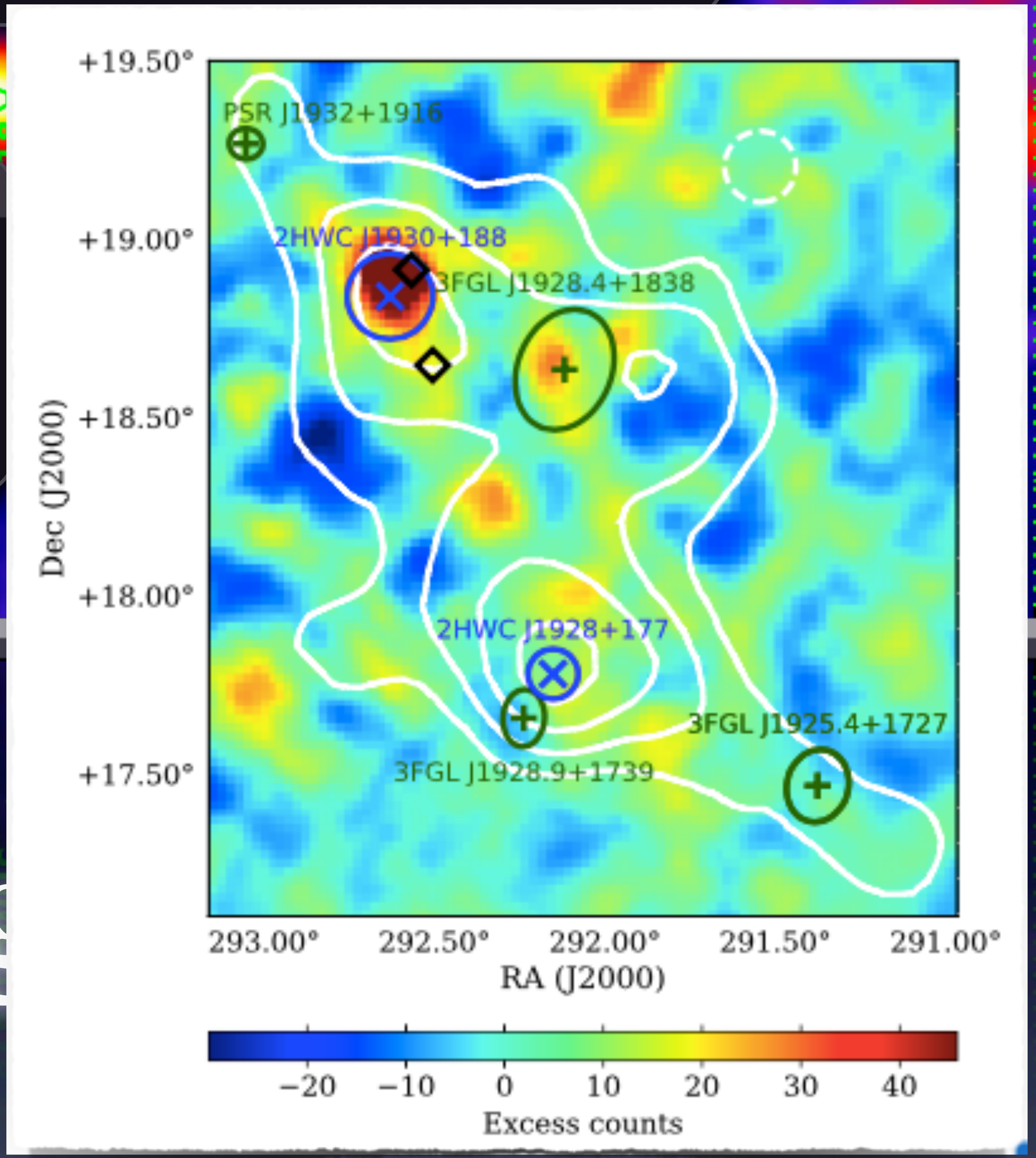
- coincident with **VER J1930+188**
  SNR G54.1+00.3 — PSR J1930+1852
- TeV emission was reported to be point-like and likely from PWN
- nearby molecular CO cloud

2HWC J1927+187*

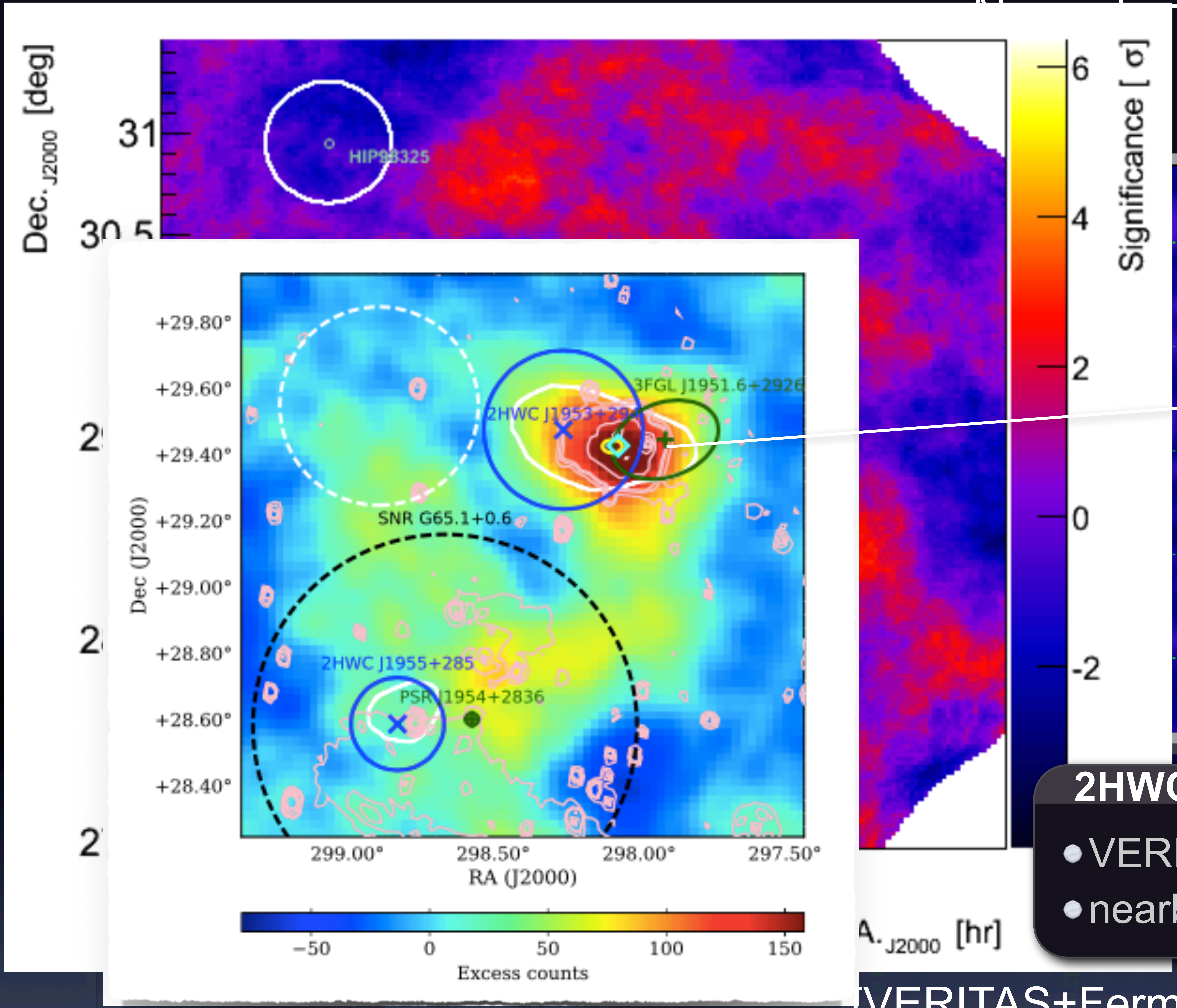
- associated with **2HWC J1930+188**?
- ongoing analysis on spatial morphology

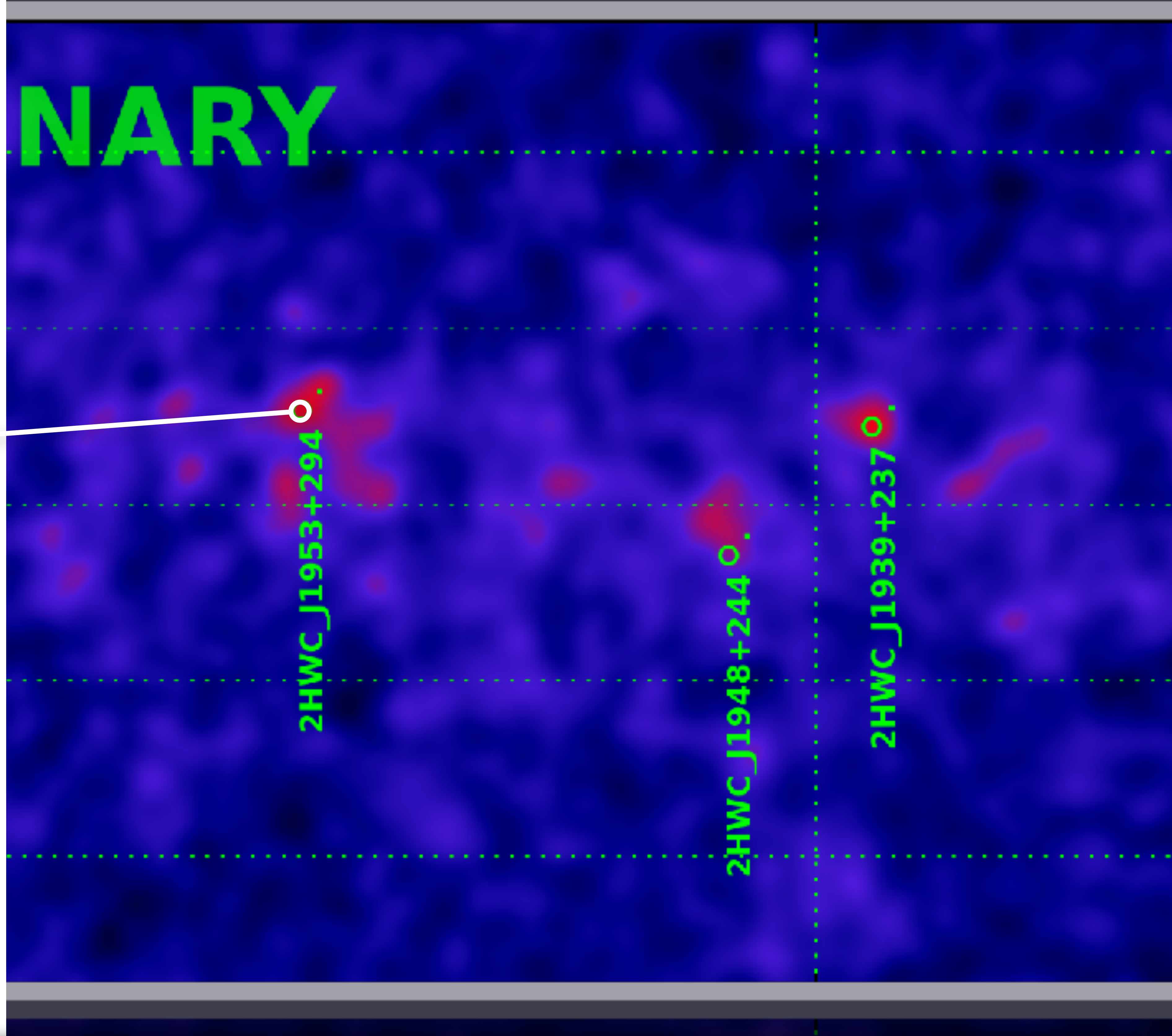
2HWC J1928+178

- coincident with **PSR J1928+1746**
- tail towards unidentified source **3FGL J1925.4+1727**
- VERITAS pt-src upper limit ~1.4% of Crab



A... ra *et al* [HAWC] ApJ **843** (2017) 40



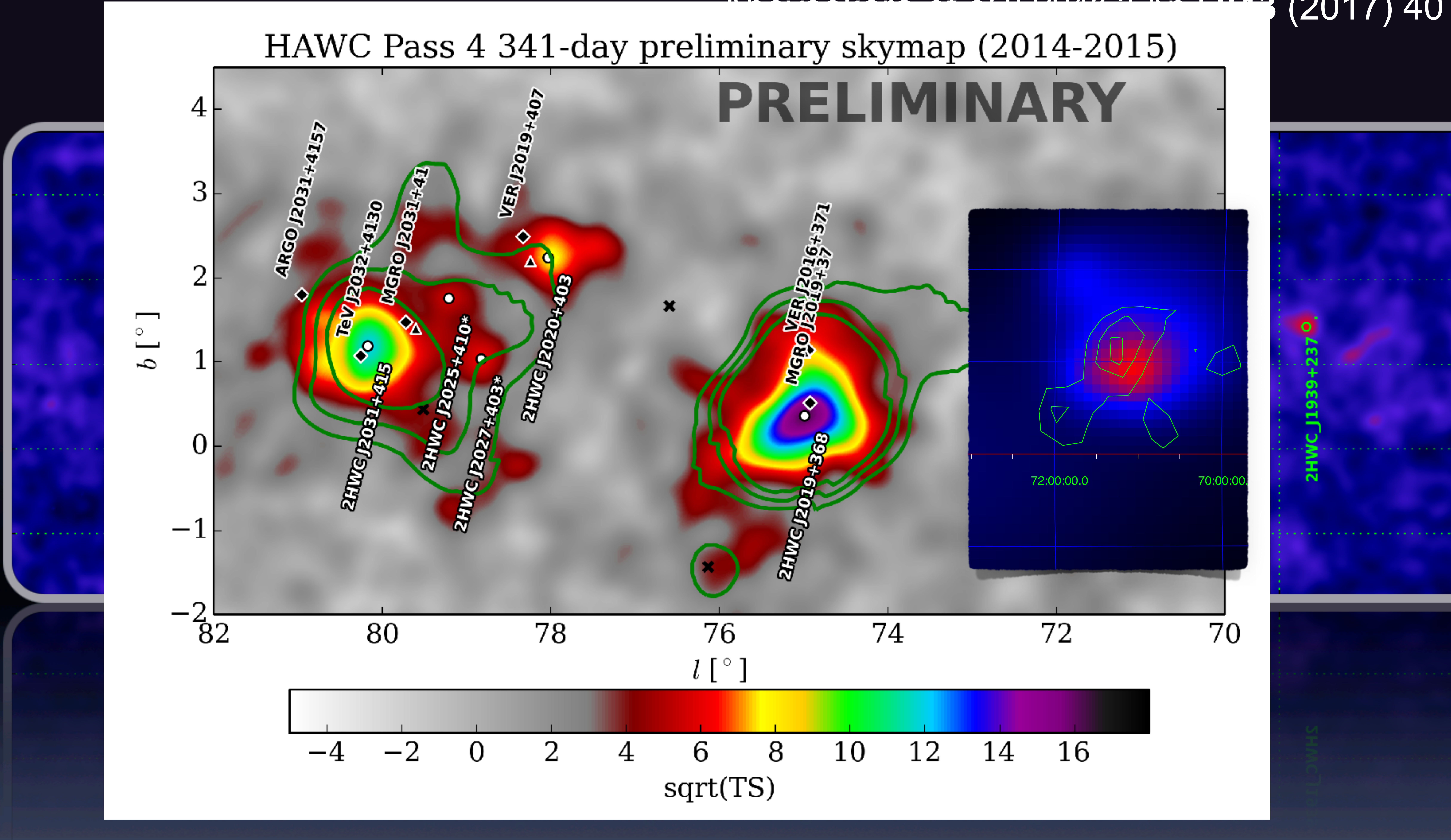


2HWC J1953+294

- VERITAS confirms **HAWC detection**
- nearby PWN likely counterpart

[VERITAS+Fermi-LAT+HAWC!] ApJ **866** (2018) 24

(2017) 40

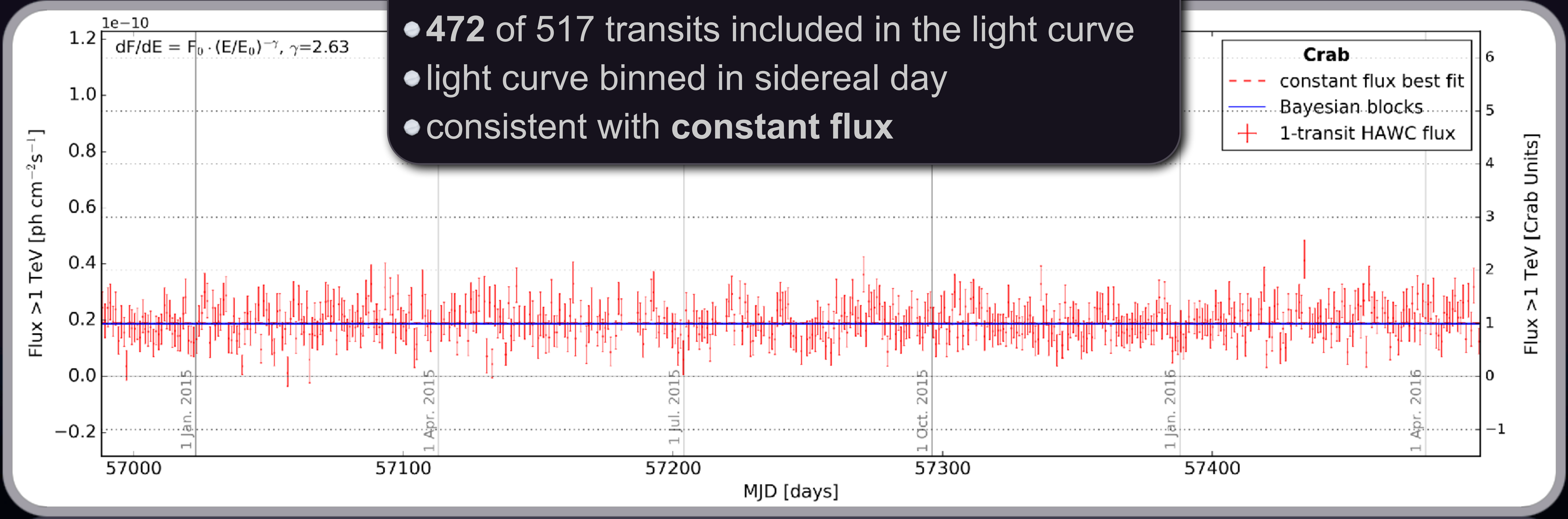


HAWC Pass 4 341-day preliminary skymap (2014-2015)
PRELIMINARY
ARGO J2031+4157
TeV J2032+4130
MGRO J2031+41
VER J2019+407
2HWC J2031+415
2HWC J2025+410*
2HWC J2027+403*
2HWC J2020+403
VER J2016+371
MGRO J2019+37
2HWC J2019+368
72:00:00.0
70:00:00.
2HWC J1939+237
b [°]
l [°]
sqrt(TS)

Abeysekara *et al* [HAWC] ApJ **841** (2017) 100

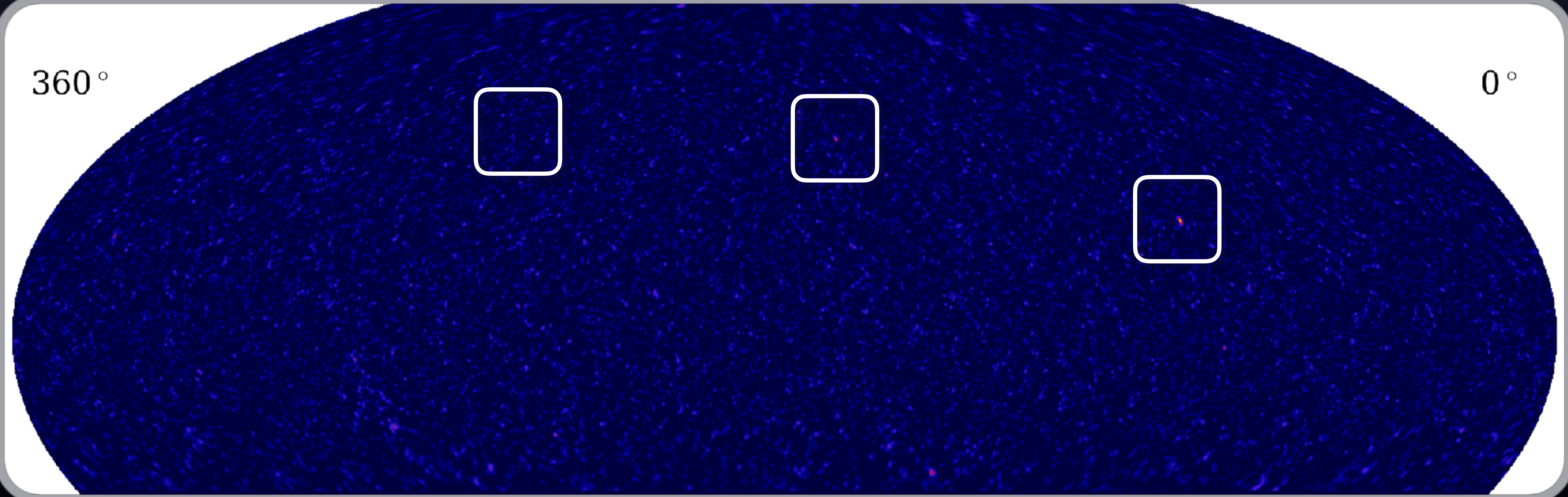
Crab

- Pass 4 data from 26 Nov **2014** to 20 Apr **2016**
- **472** of 517 transits included in the light curve
- light curve binned in sidereal day
- consistent with **constant flux**



Transient searches

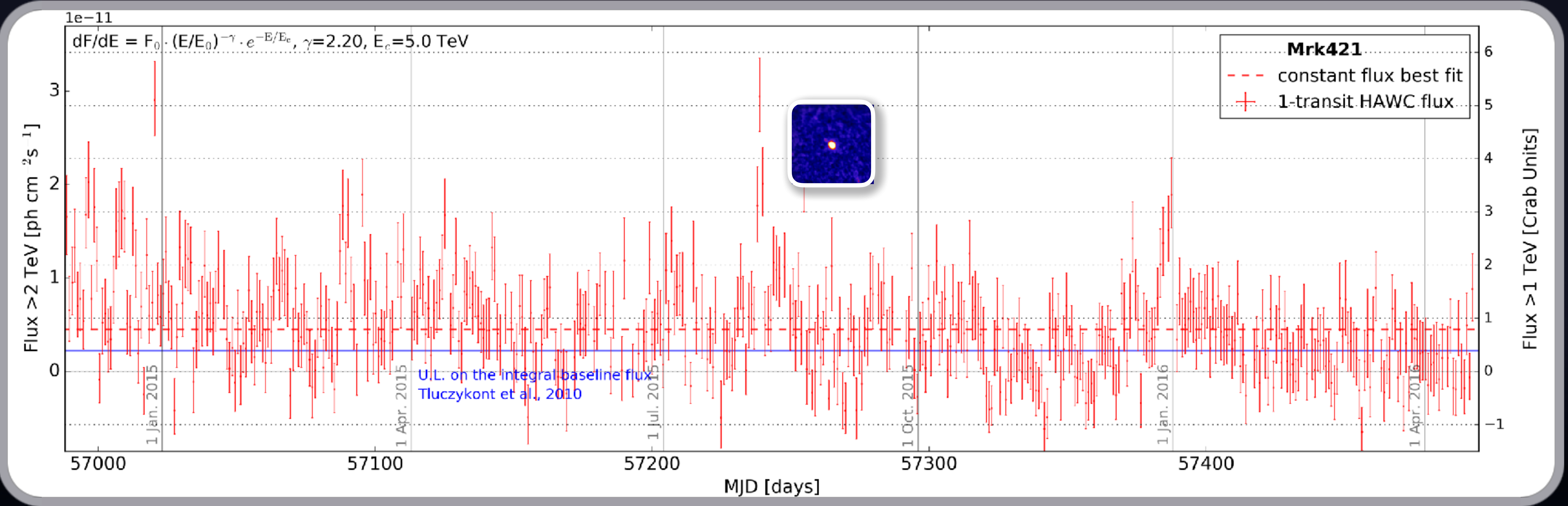
HAWC — daily fluxes in Aug 2015



Transient searches

Abeysekara *et al* [HAWC] ApJ **841** (2017) 100

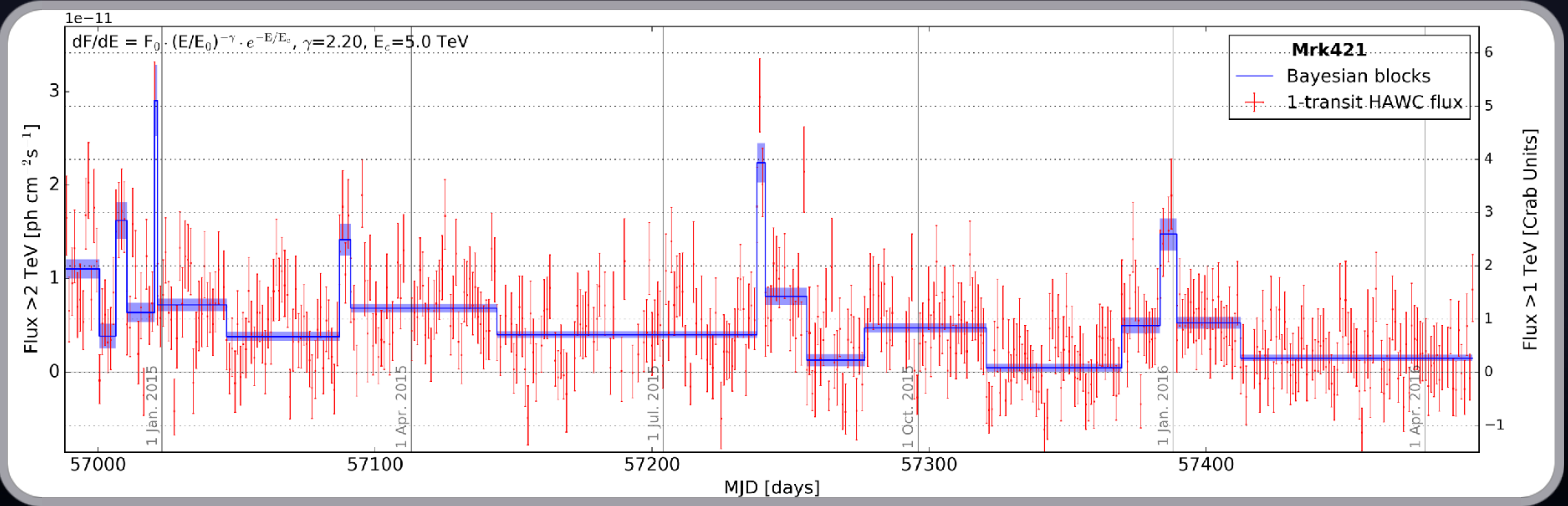
Mrk 421 — light curve



Transient searches

Abeysekara *et al* [HAWC] ApJ **841** (2017) 100

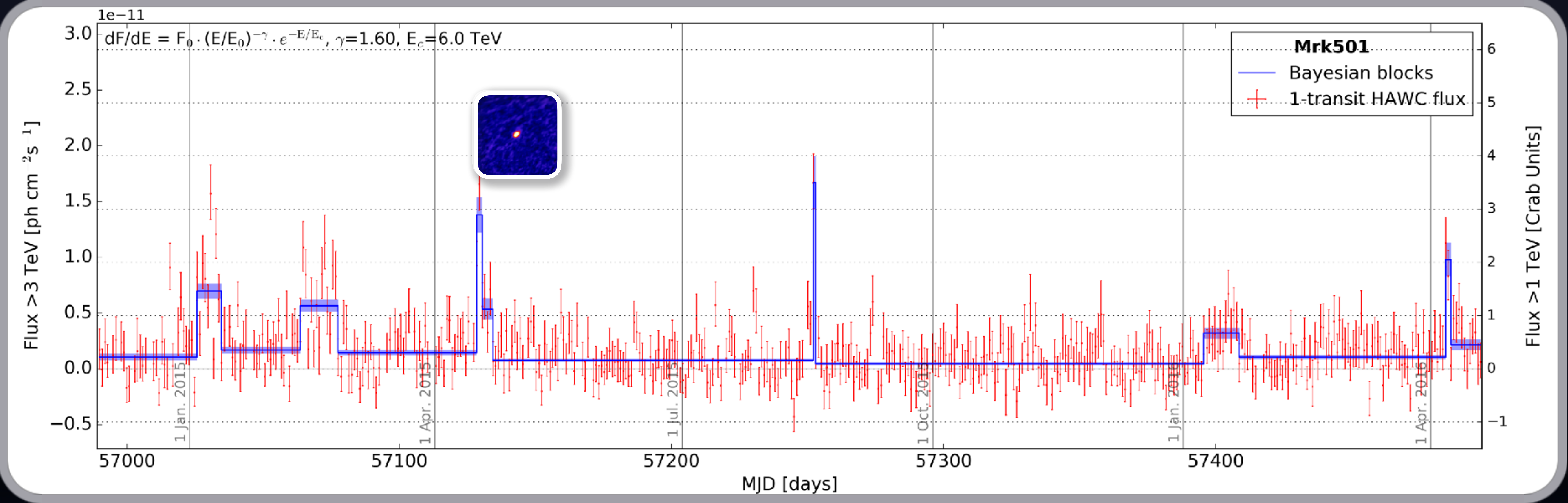
Mrk 421 — light curve



Transient searches

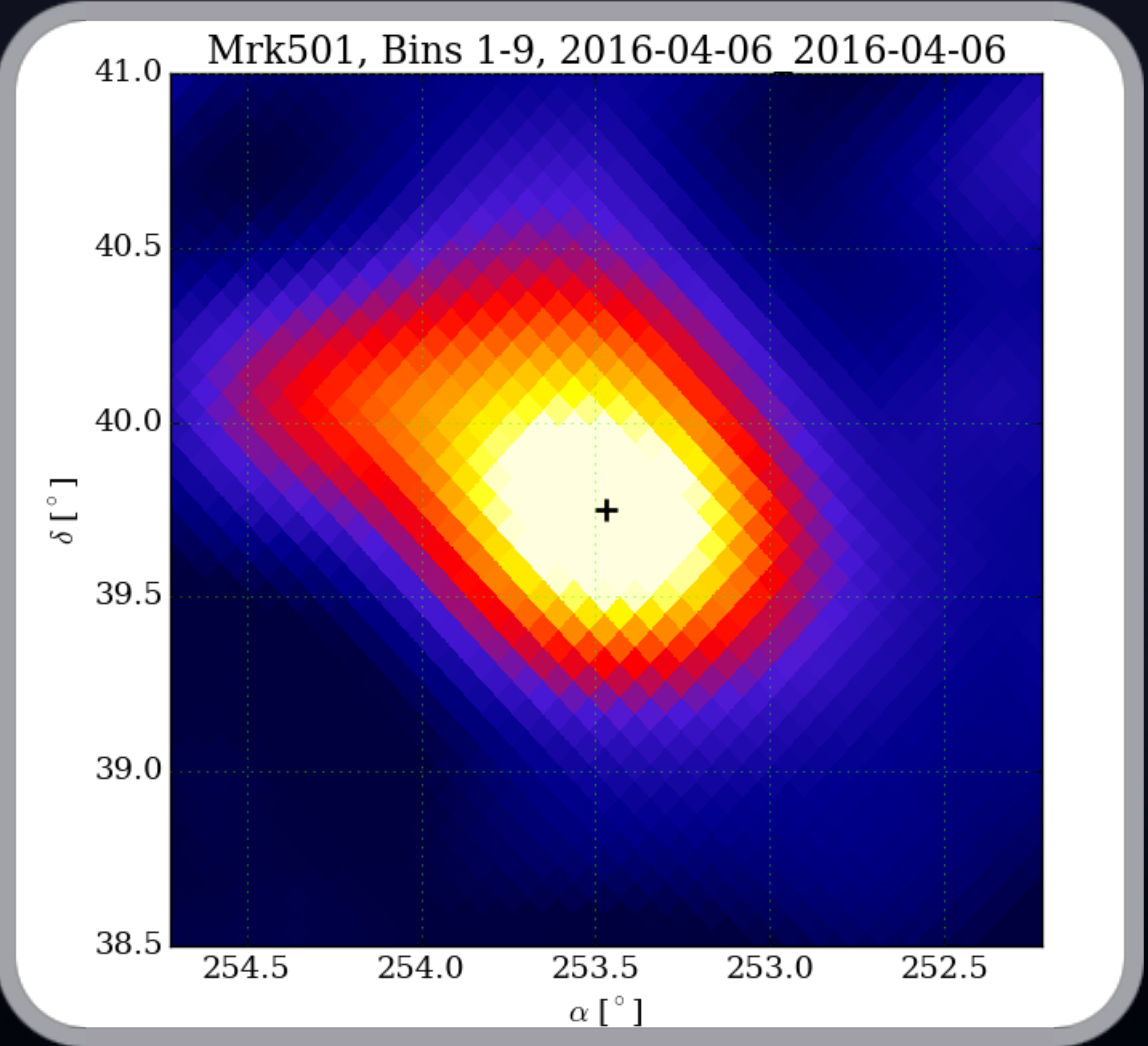
Abeysekara *et al* [HAWC] ApJ **841** (2017) 100

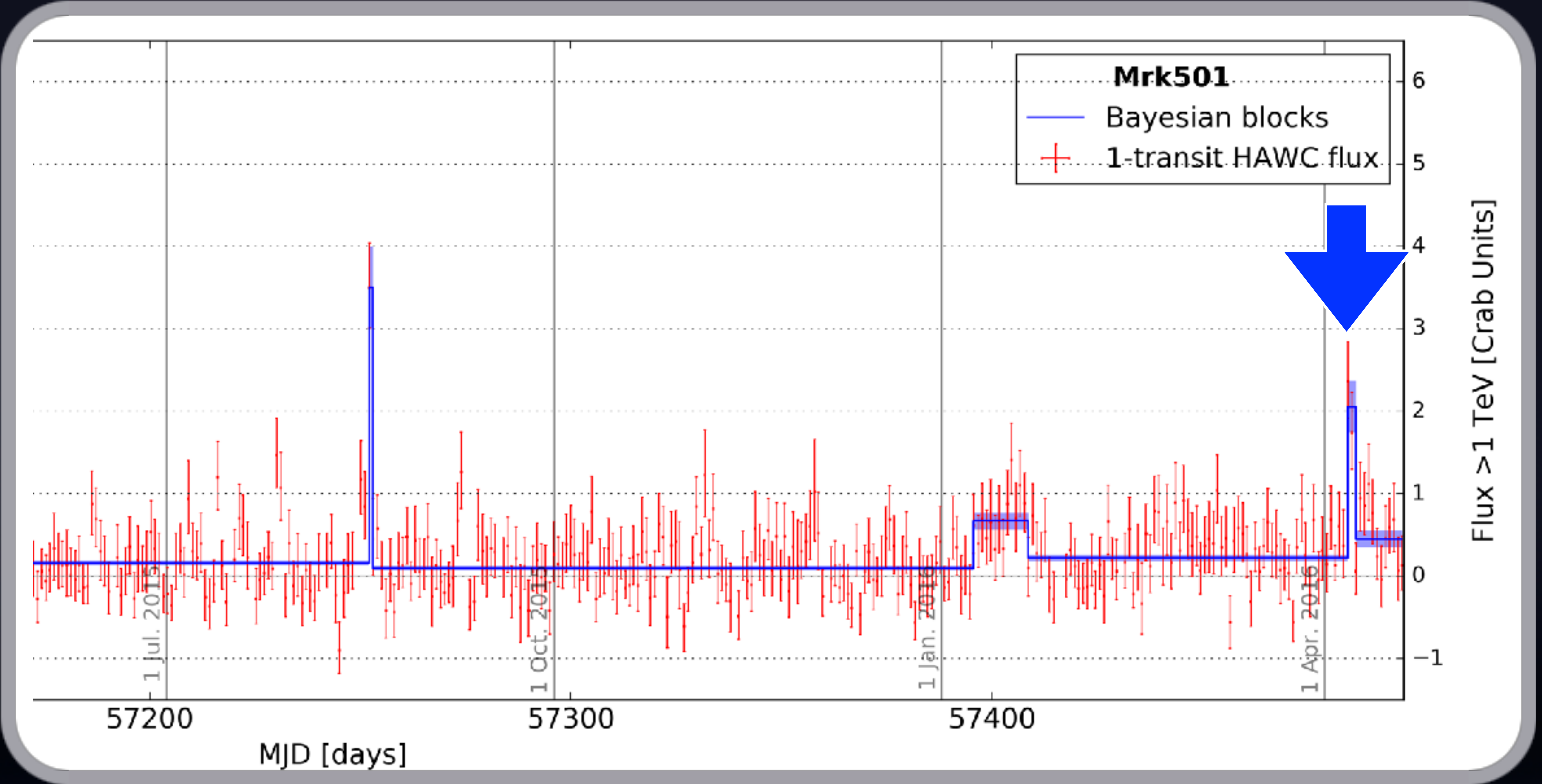
Mrk 501 — light curve



Transient searches

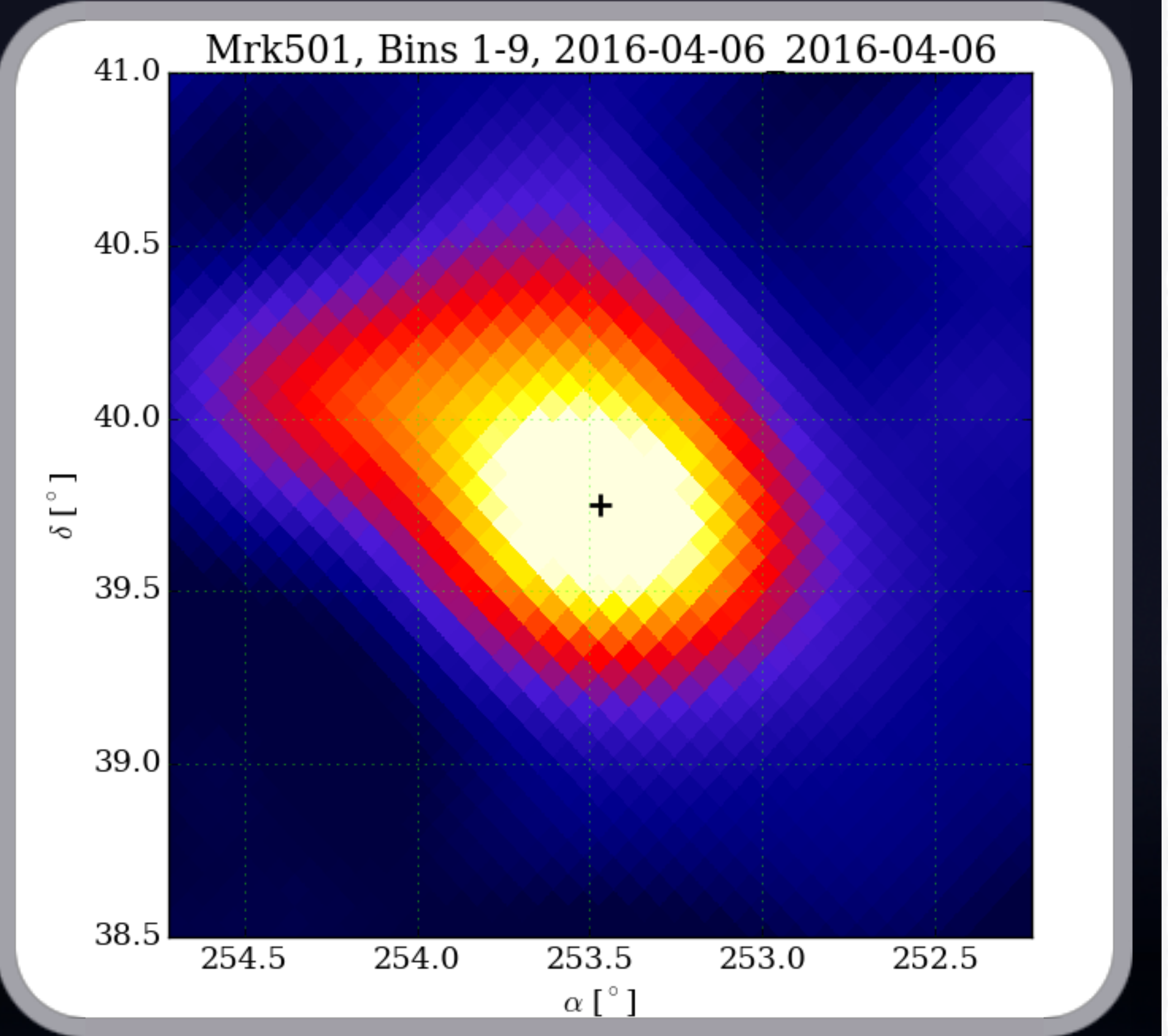
Mrk 501 — light curve





April 6, 2016

AGN flares with HAWC



April 6, 2016

AGN

HAWC detection of increased TeV flux state for Markarian 501

ATel #8922; *Andrés Sandoval (IF-UNAM), Robert Lauer (UNM), Joshua Wood (UMD) on behalf of the HAWC collaboration*
on 7 Apr 2016; 23:38 UT
Credential Certification: C. Michelle Hui (c.m.hui@nasa.gov)

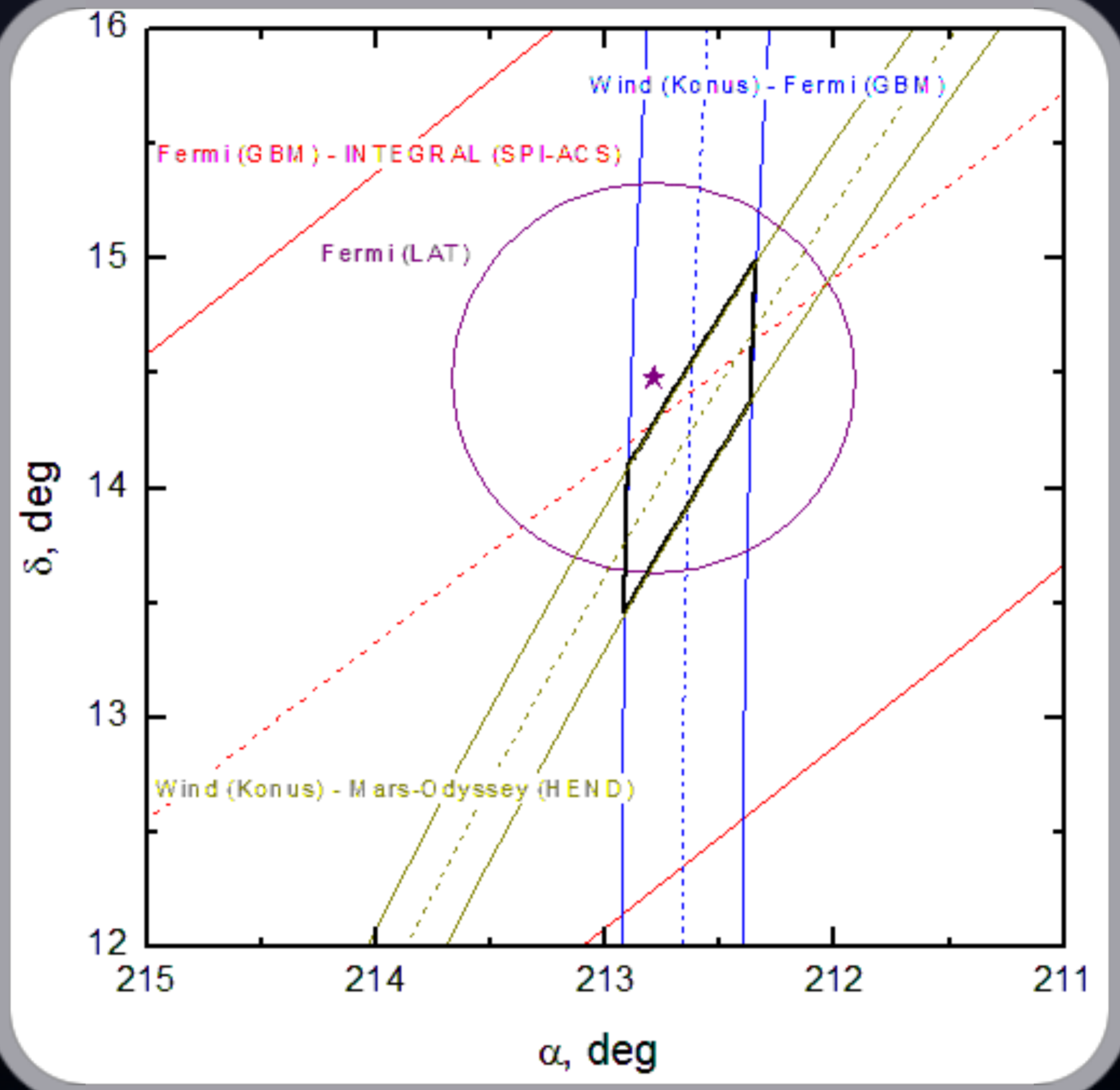
Subjects: Gamma Ray, TeV, VHE, Request for Observations, AGN, Blazar

Tweet Recommend 15

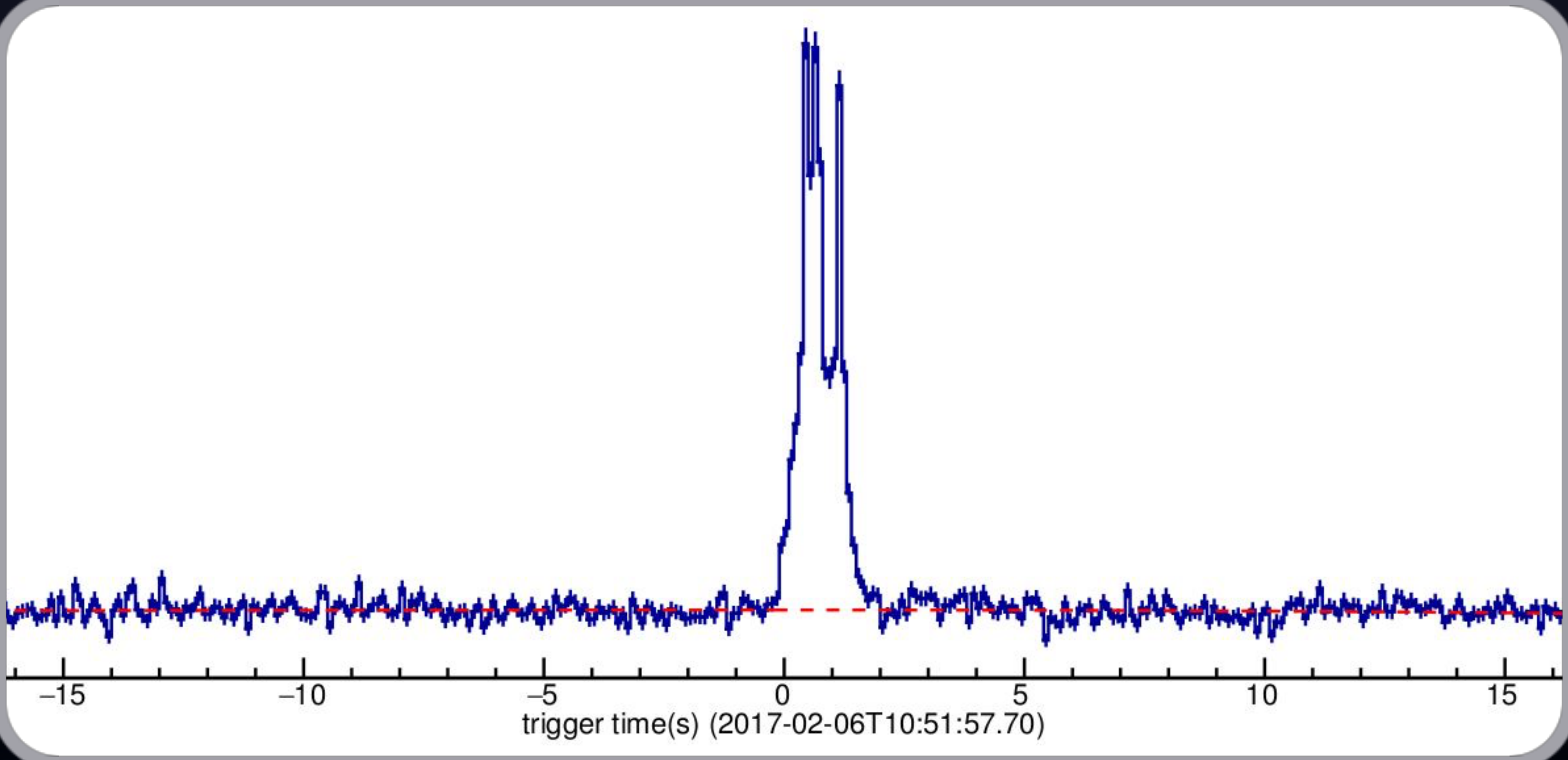
The HAWC Observatory measured an increased gamma-ray flux from the direction of the BL Lac Markarian 501 (z=0.033) at the level of (4.88 +/- 1.05) x 10e-11 photons cm^-2 s^-1 above 1 TeV when averaged during the 6 hour transit over HAWC on April 6, 2016 (MJD 57484.31 - 57484.56) which is 2.2 times the average Crab flux observed by HAWC. For the following transit on April 7, 2016 (MJD 57485.30 - 57485.55), a decreased but still above-average flux of (2.78 +/- 0.09) x 10e-11 photons cm^-2 s^-1 was observed, 1.3 times the Crab flux seen by HAWC. The flux on April 6 lies 4 sigma above the average flux of 0.89 x 10e-11 photons cm^-2 s^-1 that was measured for this source by HAWC during the previous year. The flux level on April 7 is 2 sigma above this average and seems to indicate a declining but on-going high flux state. All flux values are obtained from a maximum likelihood fit under the assumption of a fixed spectral shape with power law index of 1.8 and exponential cut-off at 6 TeV. These spectral parameters are the best fit results for HAWC data from Markarian 501 collected between November 2014 and December 2015. HAWC is a TeV gamma ray water Cherenkov array located in the state of Puebla, Mexico that monitors 2/3 of the sky every day with an instantaneous field of view of ~2 sr. The HAWC contact people for this analysis are Robert Lauer (University of New Mexico, rjlauer@unm.edu) and Michelle Hui (Marshall Space Flight Center, c.m.hui@nasa.gov).

Alfaro *et al* [HAWC] ApJ **843** (2017) 88

IPN triangulation map



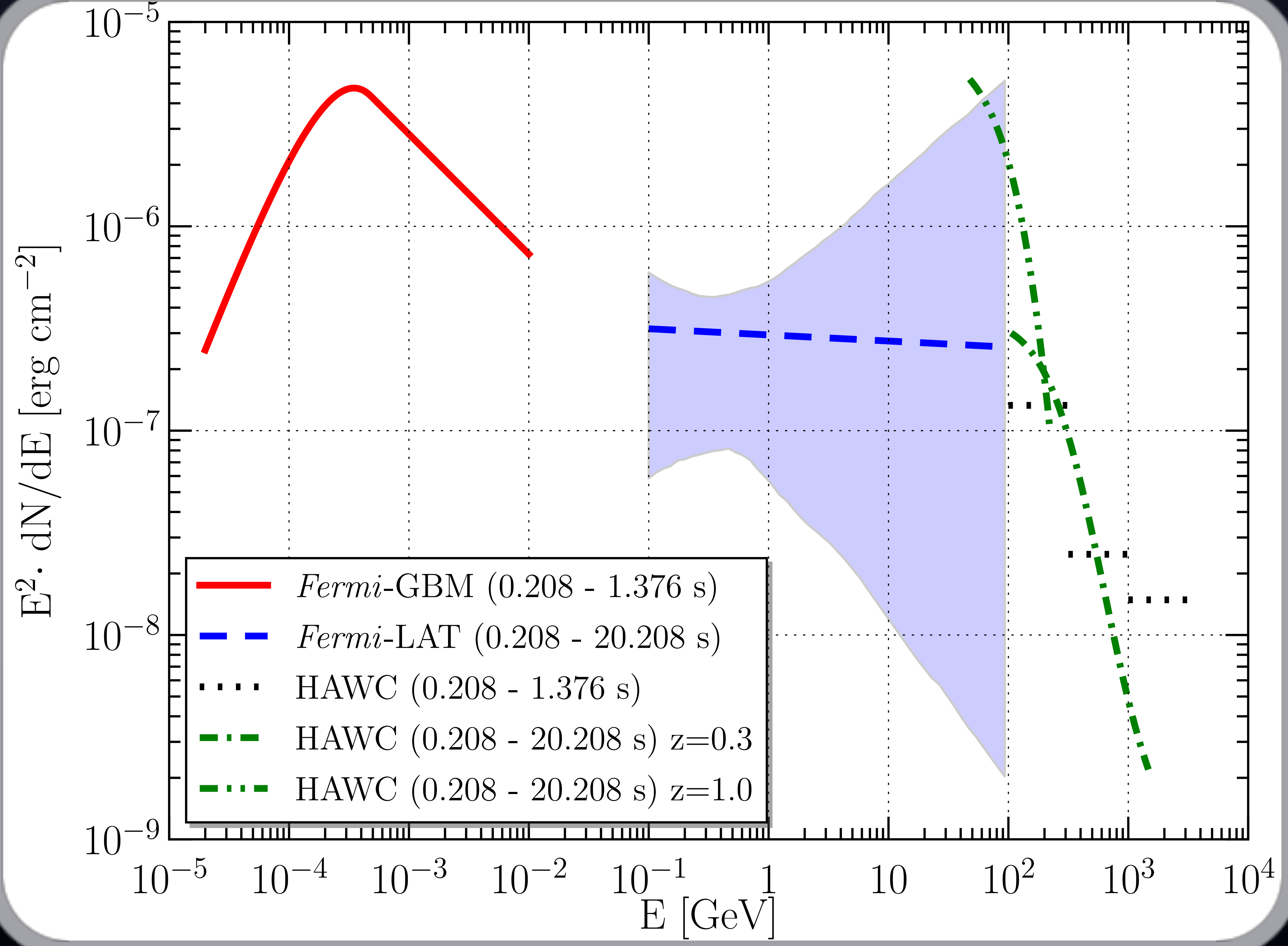
GBM light curve



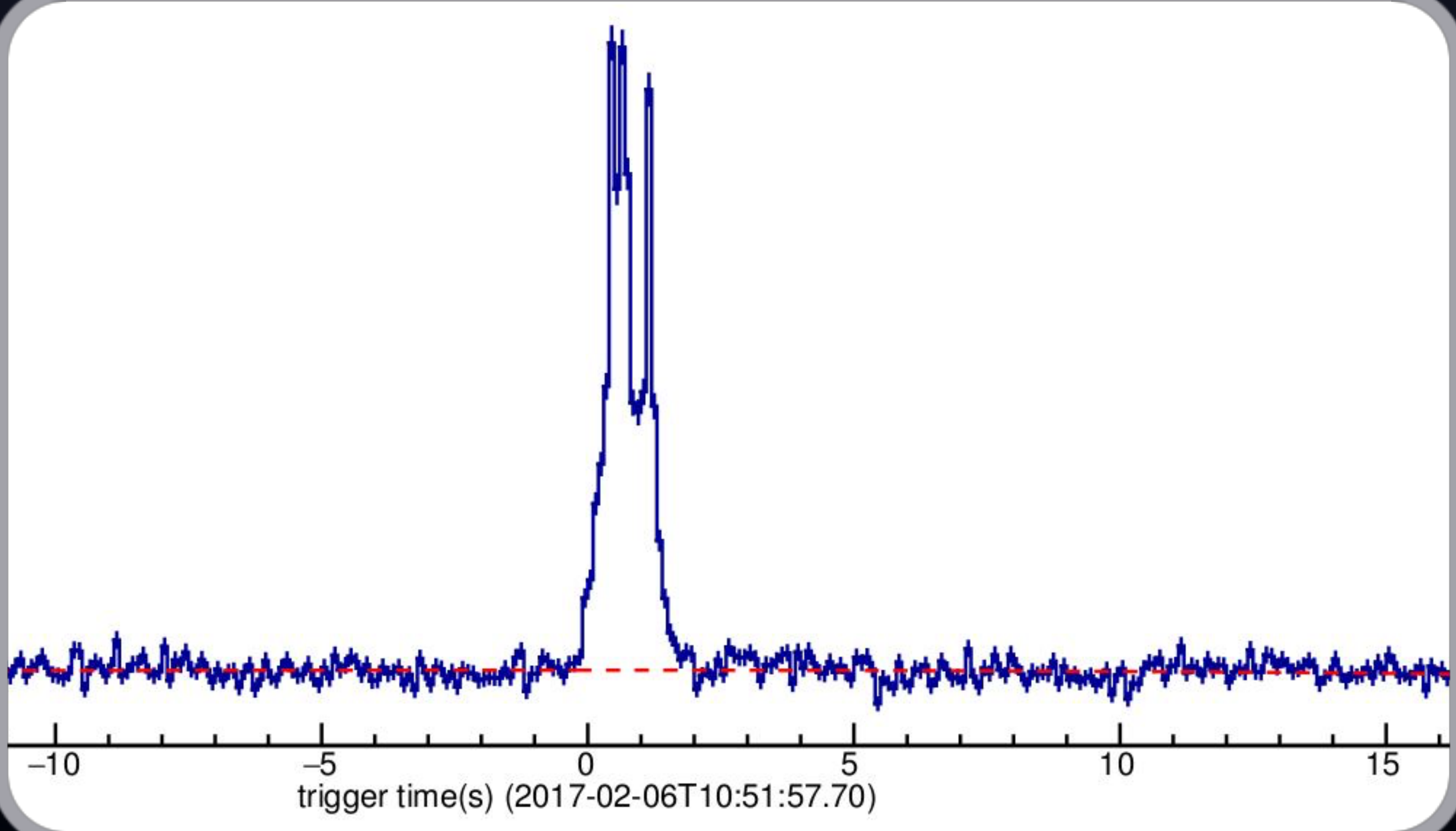
GRB 170206A

Alfaro *et al* [HAWC] ApJ **843** (2017) 88

HAWC limits



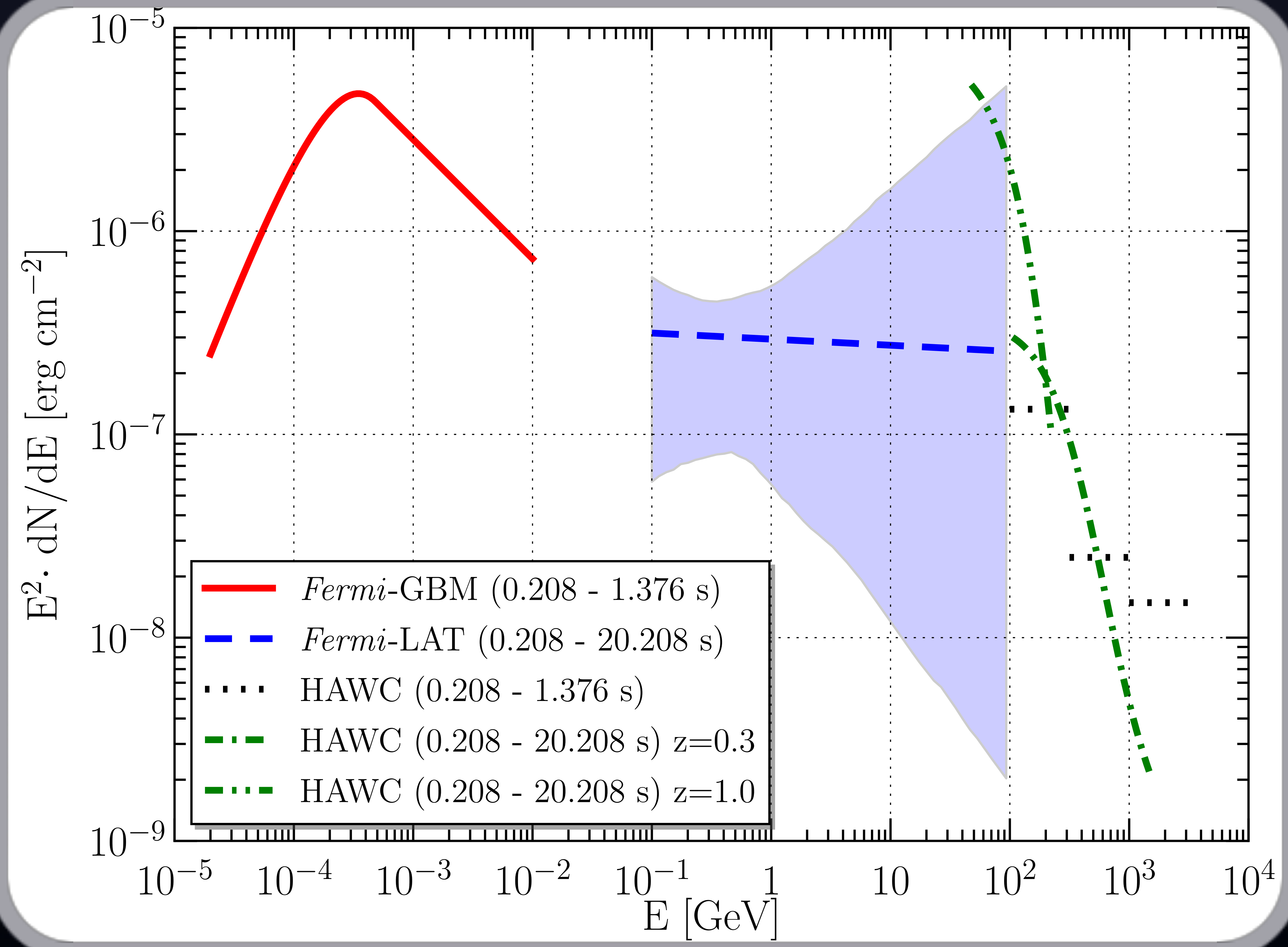
GBM light curve



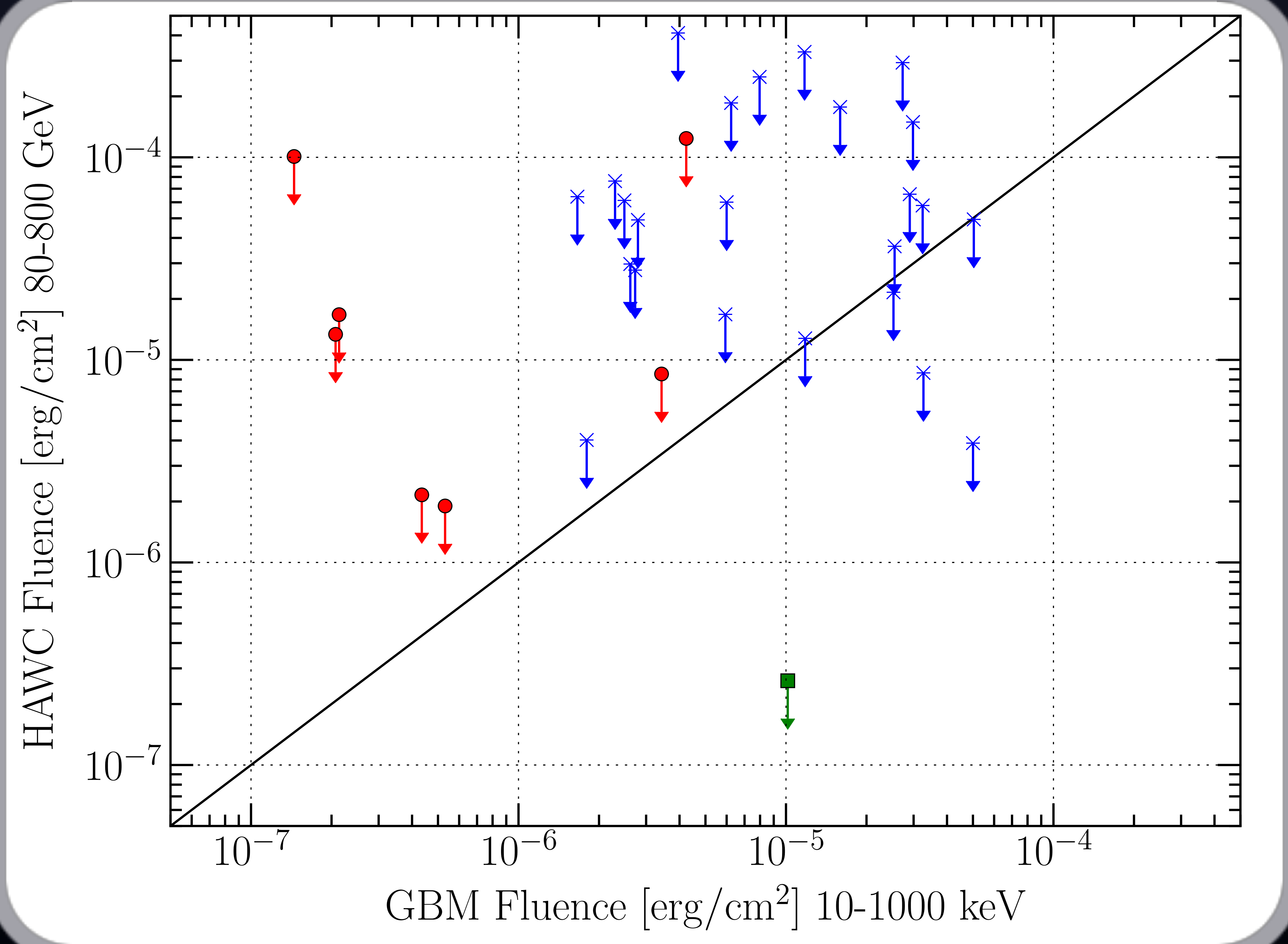
GRB 170206A

Alfaro *et al* [HAWC] ApJ **843** (2017) 88

HAWC limits



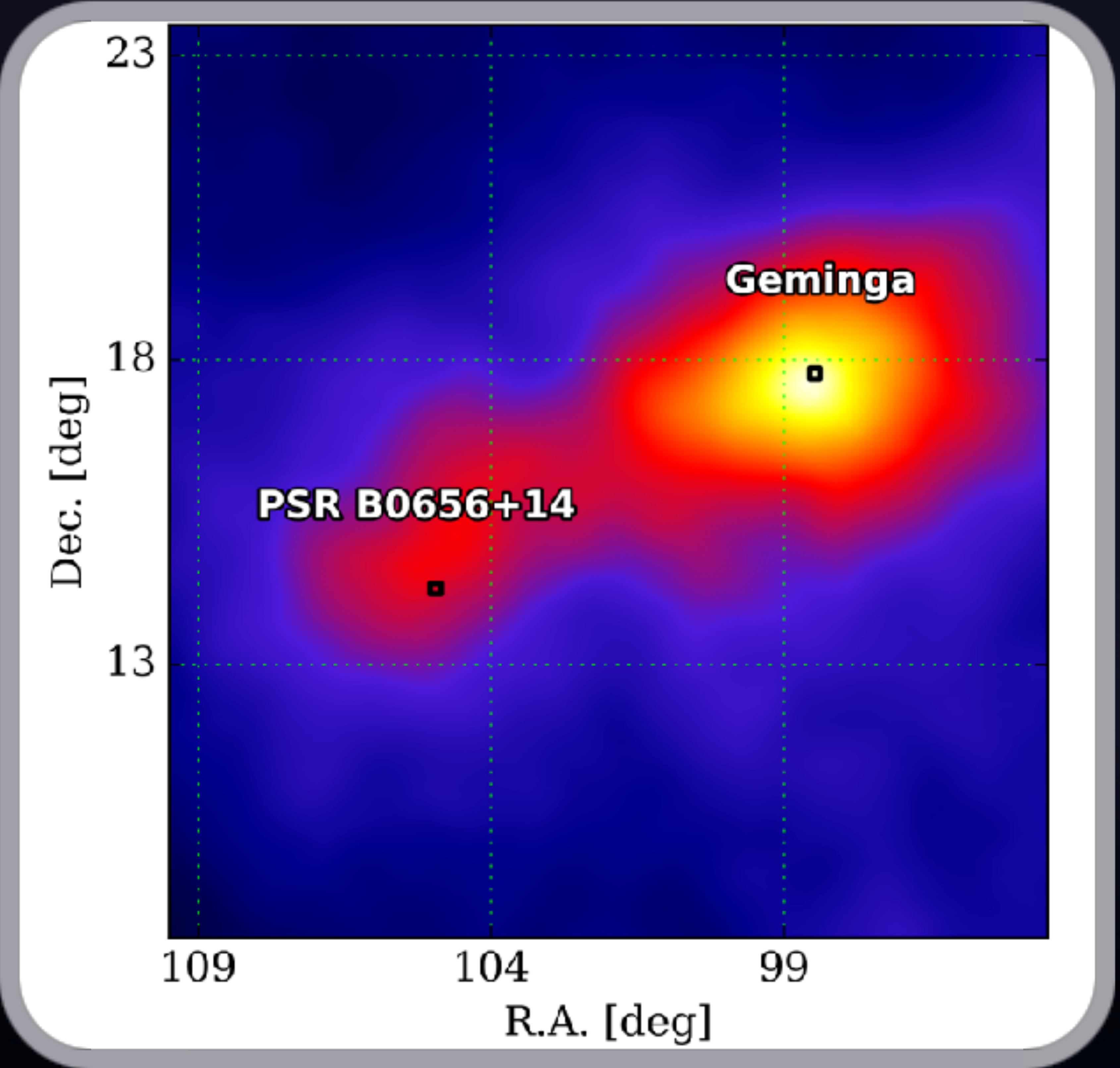
HAWC *vs.* GBM fluence

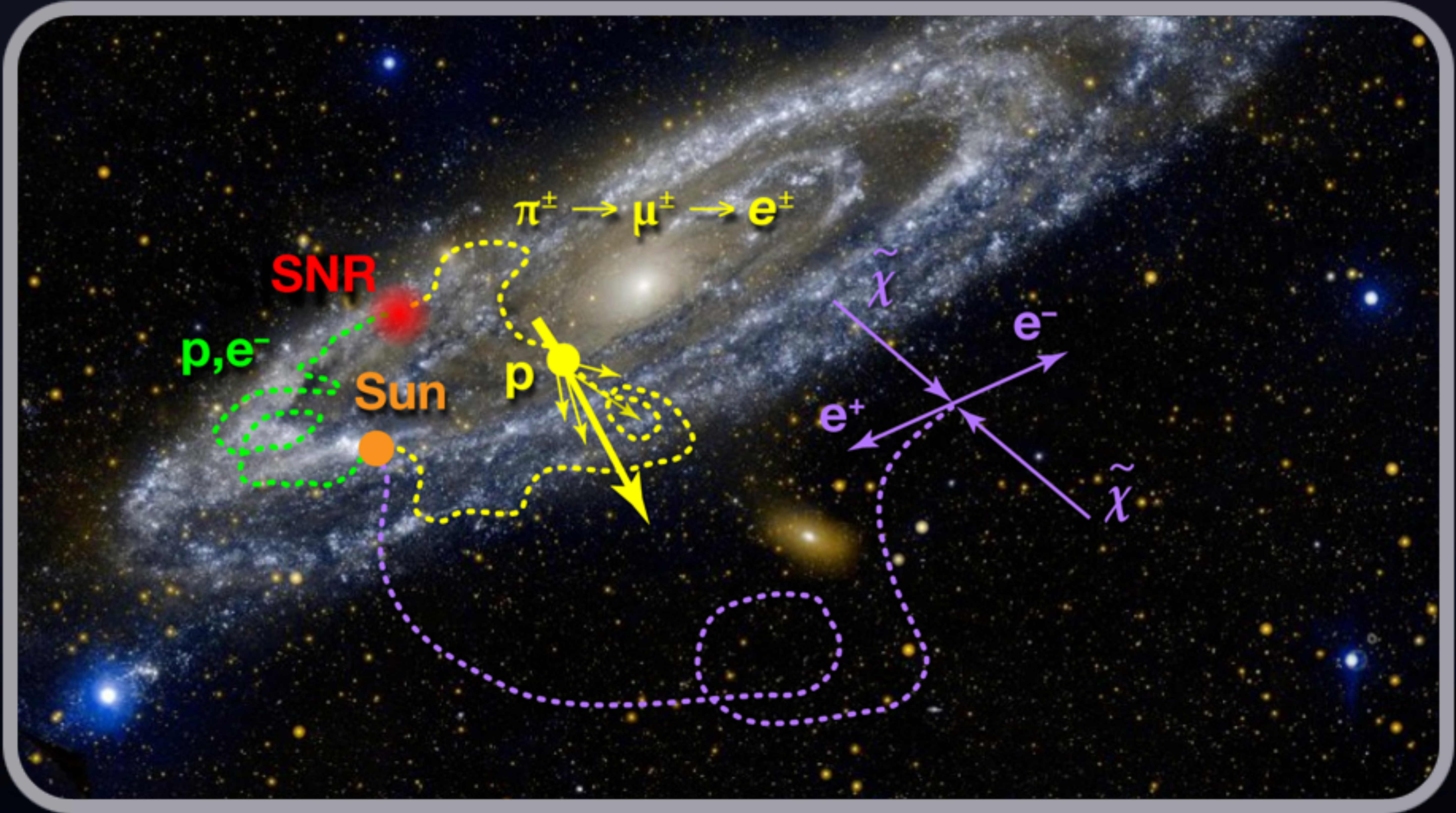


GRB 170206A

Positron excess from nearby pulsars?

Abeysekara *et al* [HAWC] Science **6365** (2017), 911-914

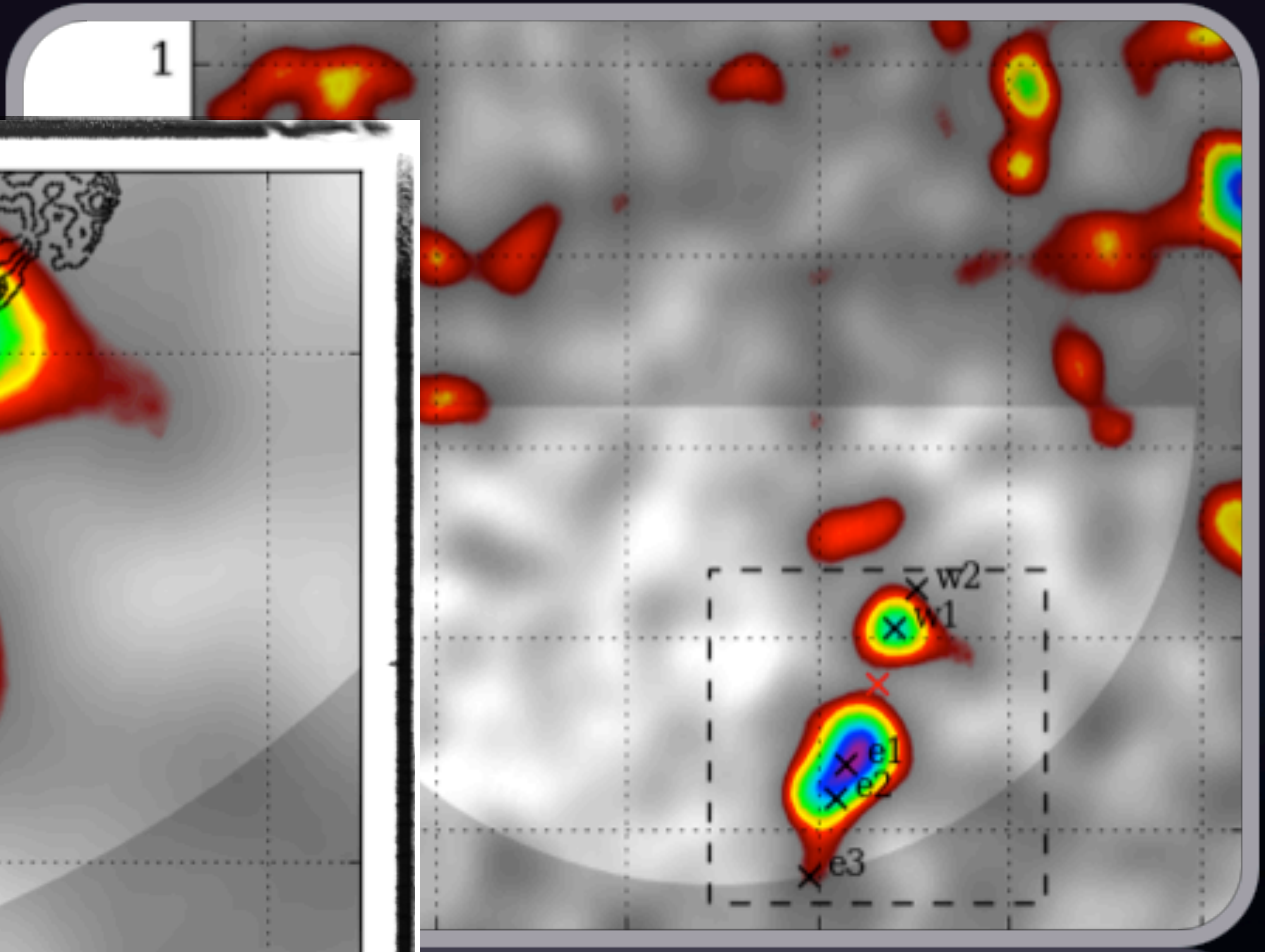


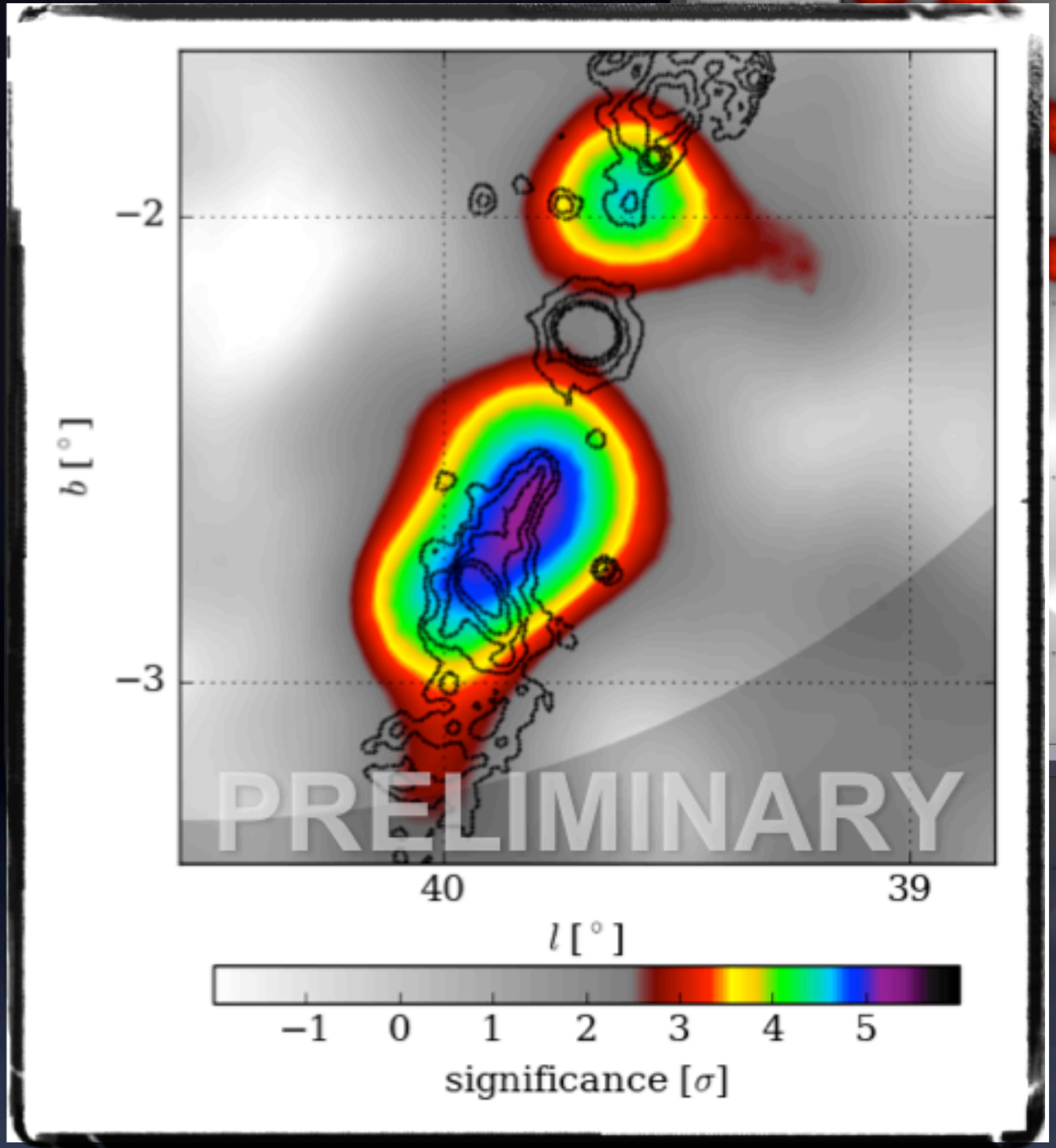


Extended emission

VHE emission from the jets of a microquasar

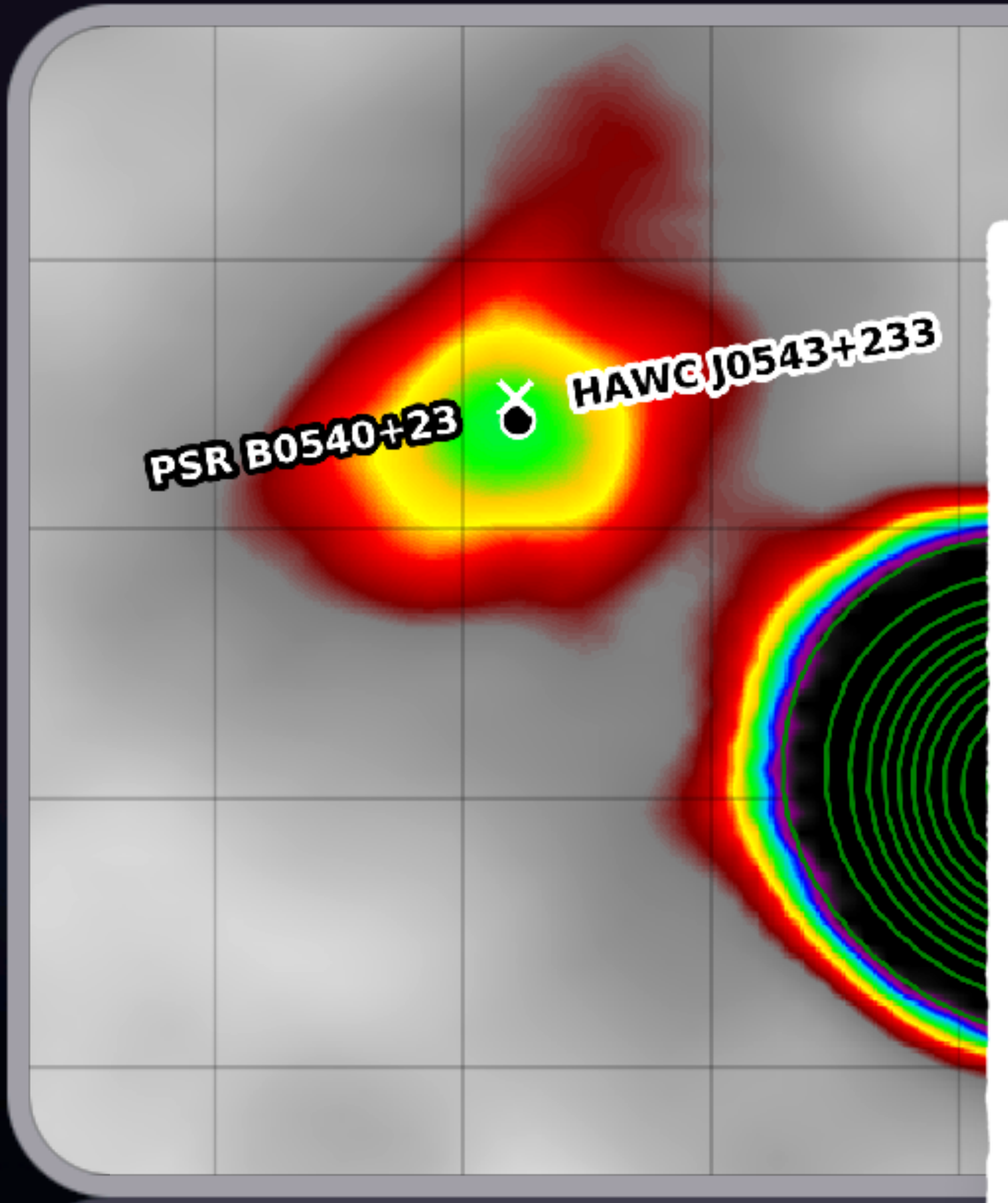
Abeysekara *et al* [HAWC] Nature **562** (2018), 82-85





SS 443

The Crab on fire



B054

ATel #10941

HAWC detection of TeV emission near PSR B0540+23

ATel #10941; ***Colas Riviere (University of Maryland), Henrike Fleischhack (Michigan Technological University), Andres Sandoval (Universidad Nacional Autonoma de Mexico) on behalf of the HAWC collaboration***
*on **9 Nov 2017; 23:11 UT***
Credential Certification: Colas Riviere (riviere@umd.edu)

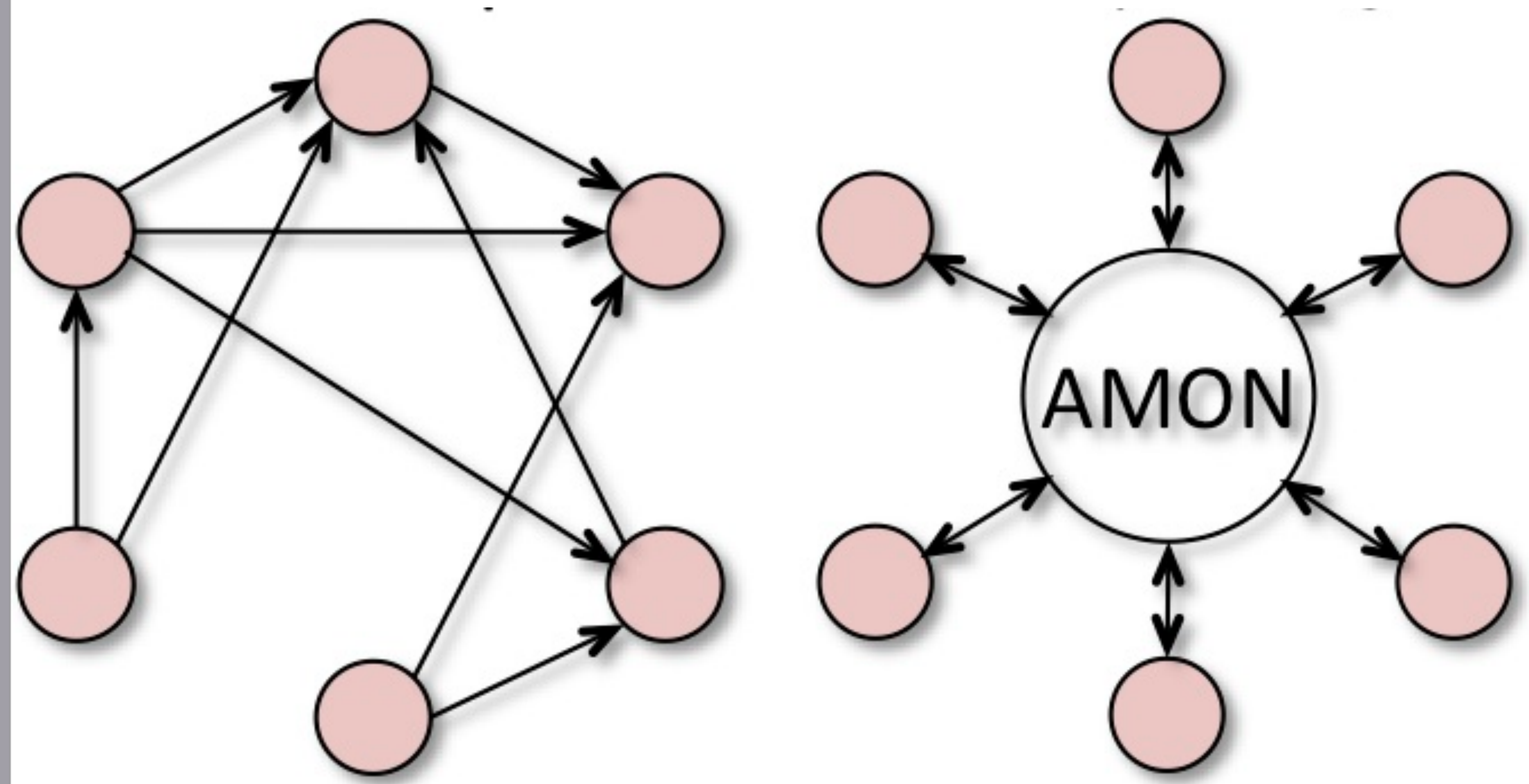
Subjects: Gamma Ray, TeV, VHE, Pulsar

Tweet Recommend 5

The High Altitude Water Cherenkov (HAWC) collaboration reports the discovery of a new TeV gamma-ray source HAWC J0543+233. It was discovered in a search for extended sources of radius 0.5° in a dataset of 911 days (ranging from November 2014 to August 2017) with a test statistic value of 36 (6σ pre-trials), following the method presented in Abeysekara et al. 2017, ApJ, 843, 40. The measured J2000.0 equatorial position is RA=85.78°, Dec=23.40° with a statistical uncertainty of 0.2°. HAWC J0543+233 was close to passing the selection criteria of the 2HWC catalog (Abeysekara et al. 2017, ApJ, 843, 40, see HAWC J0543+233 in 2HWC map), which it now fulfills with the additional data.
HAWC J0543+233 is positionally coincident with the pulsar PSR B0540+23 (Edot = 4.1e+34 erg s-1, dist = 1.56 kpc, age = 253 kyr). It is the third low Edot, middle-aged pulsar announced to be detected with a TeV halo, along with Geminga and B0656+14. It was predicted to be one of the next such detection by HAWC by Linden et al., 2017, arXiv:1703.09704.
Using a simple source model consisting of a disk of radius 0.5°, the measured spectral index is -2.3 ± 0.2 and the differential flux at 7 TeV is (7.9 ± 2.3) × 10^-15 TeV-1 cm-2 s-1. The errors are statistical only. Further morphological and spectral analysis as well as studies of the systematic uncertainty are ongoing.

Sub-Threshold Events

The AMON concept

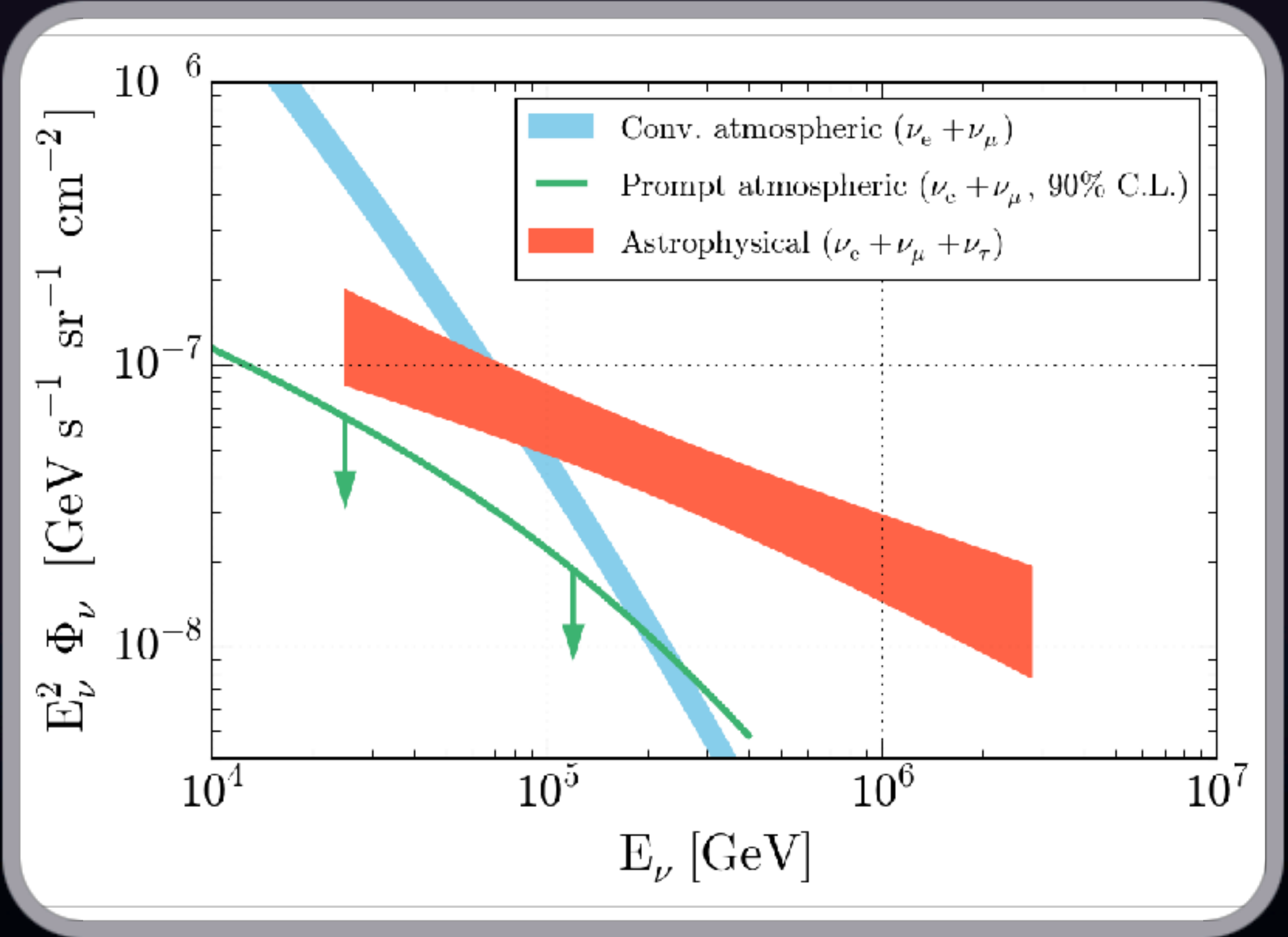


Astrop.Phys. Vol. 45, 56–70, 2013

AMON provides the **framework** for:

- **Real-time** and near real-time sharing of *subthreshold* data among *multimessenger* observatories
- Real-time and archival searches for any **coincident** (in time and space) signals.
- Prompt distribution of **alerts** for follow-up observations

The AMON concept



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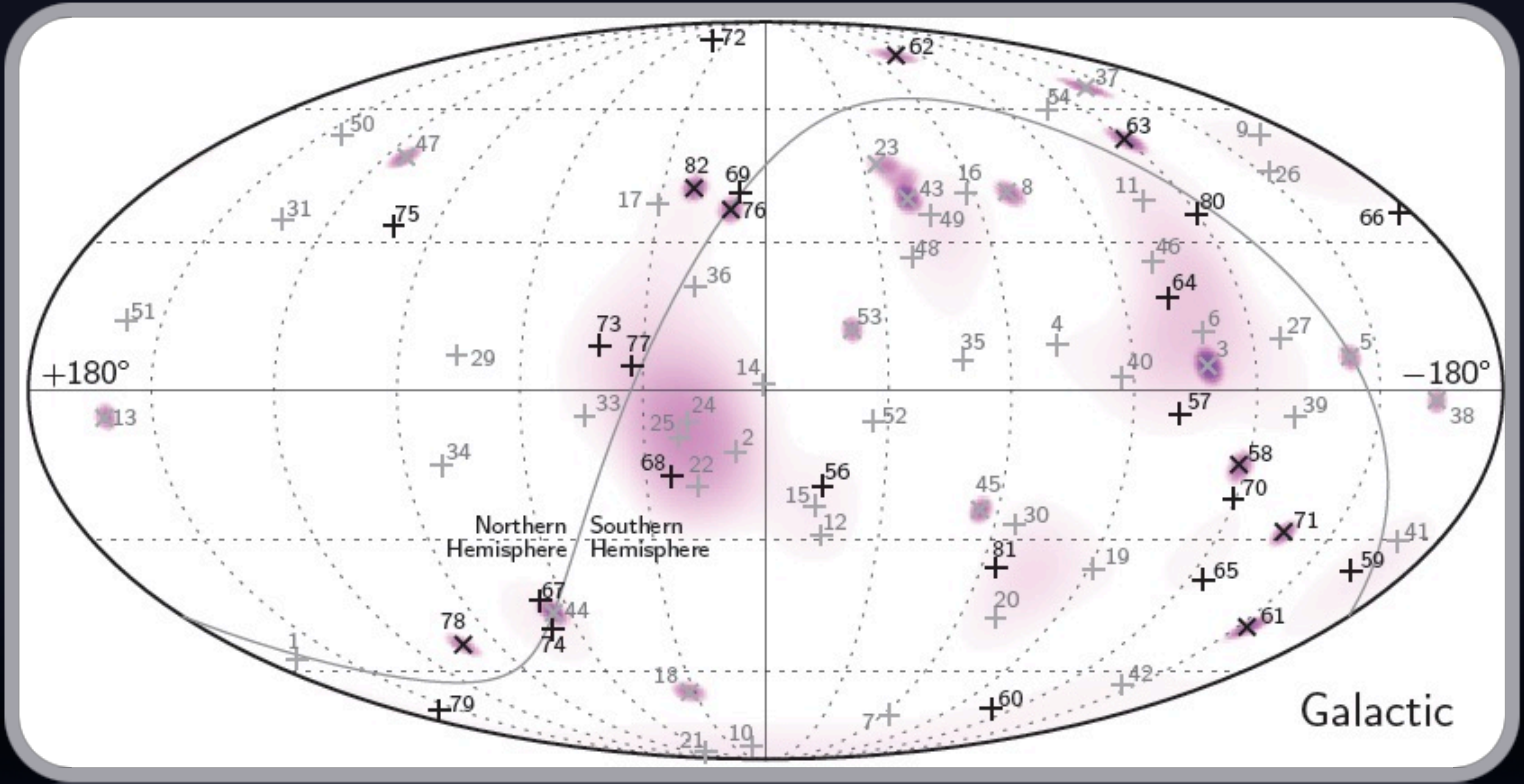
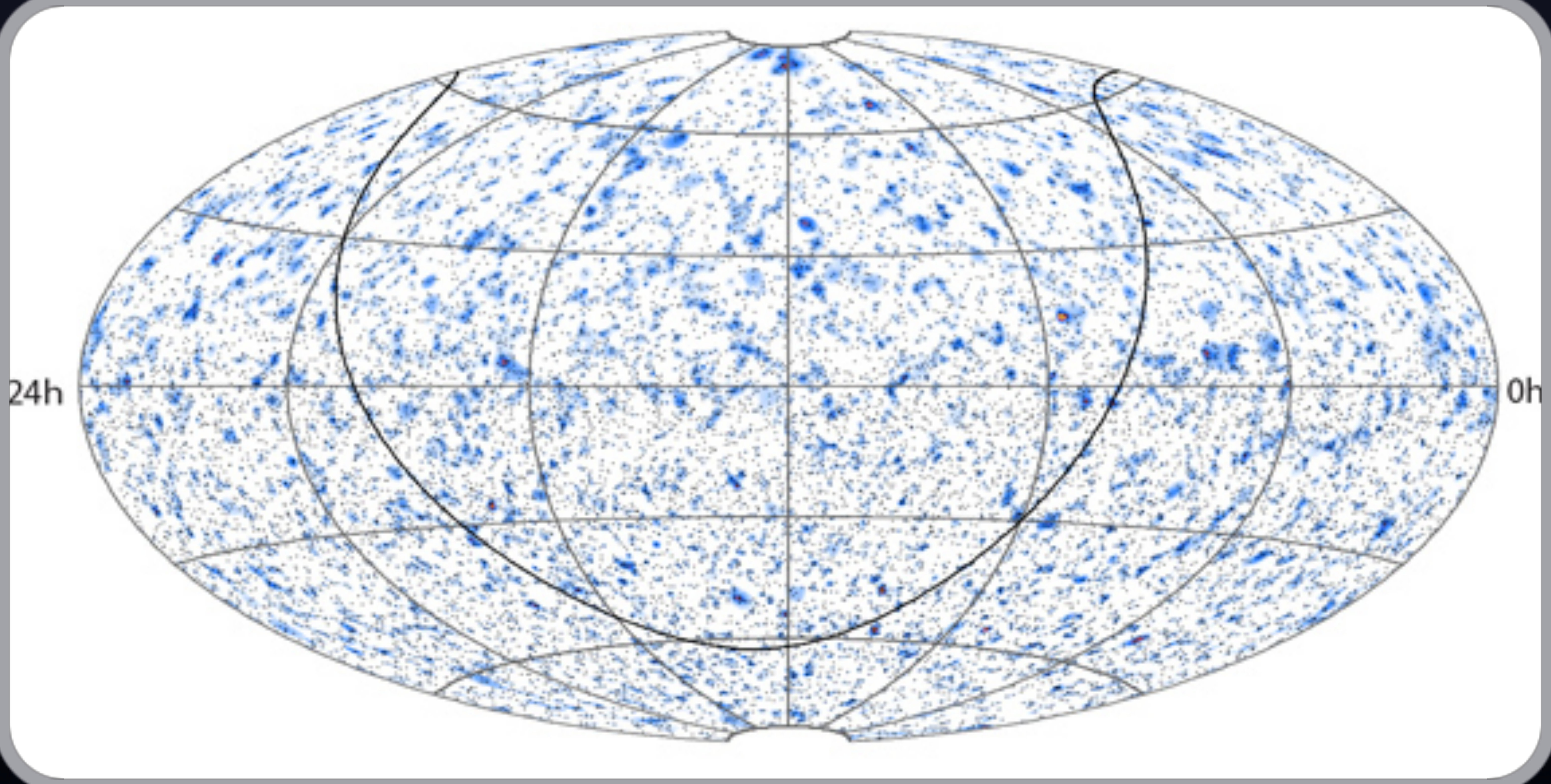


HE neutrinos

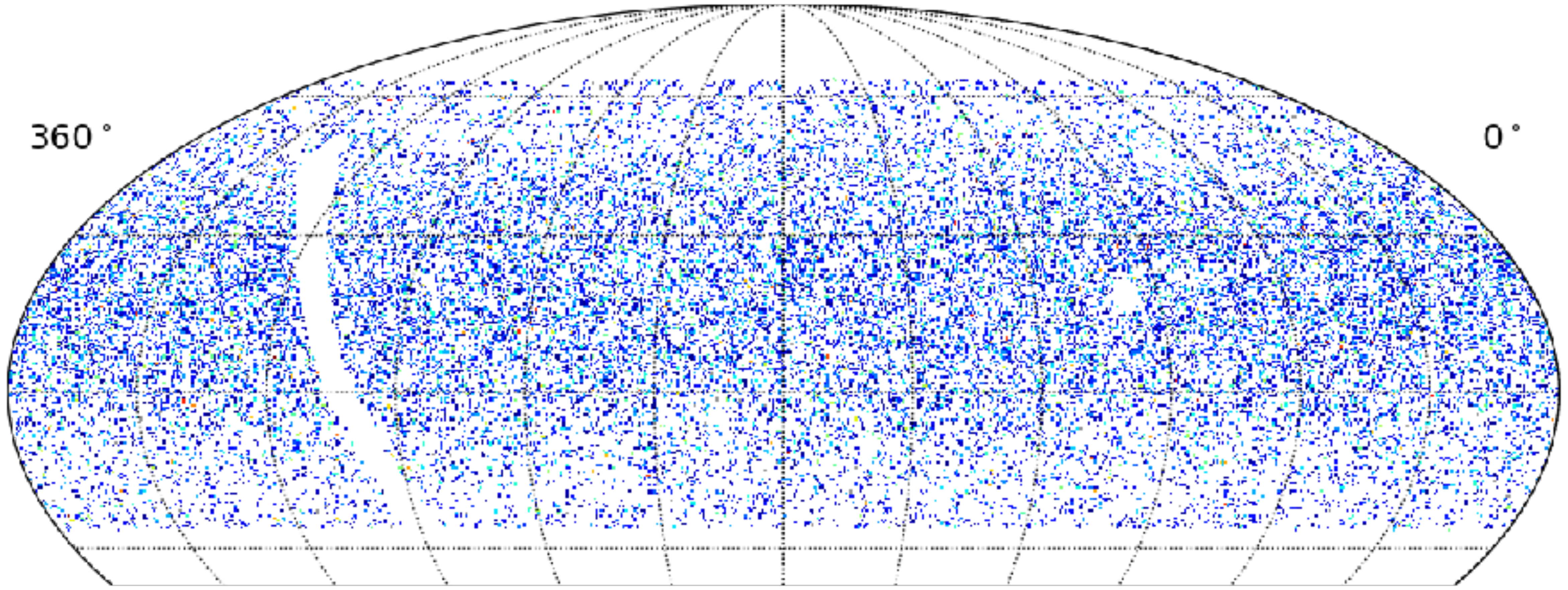


“singlet” neutrinos

Coincidence alerts: IC + HAWC

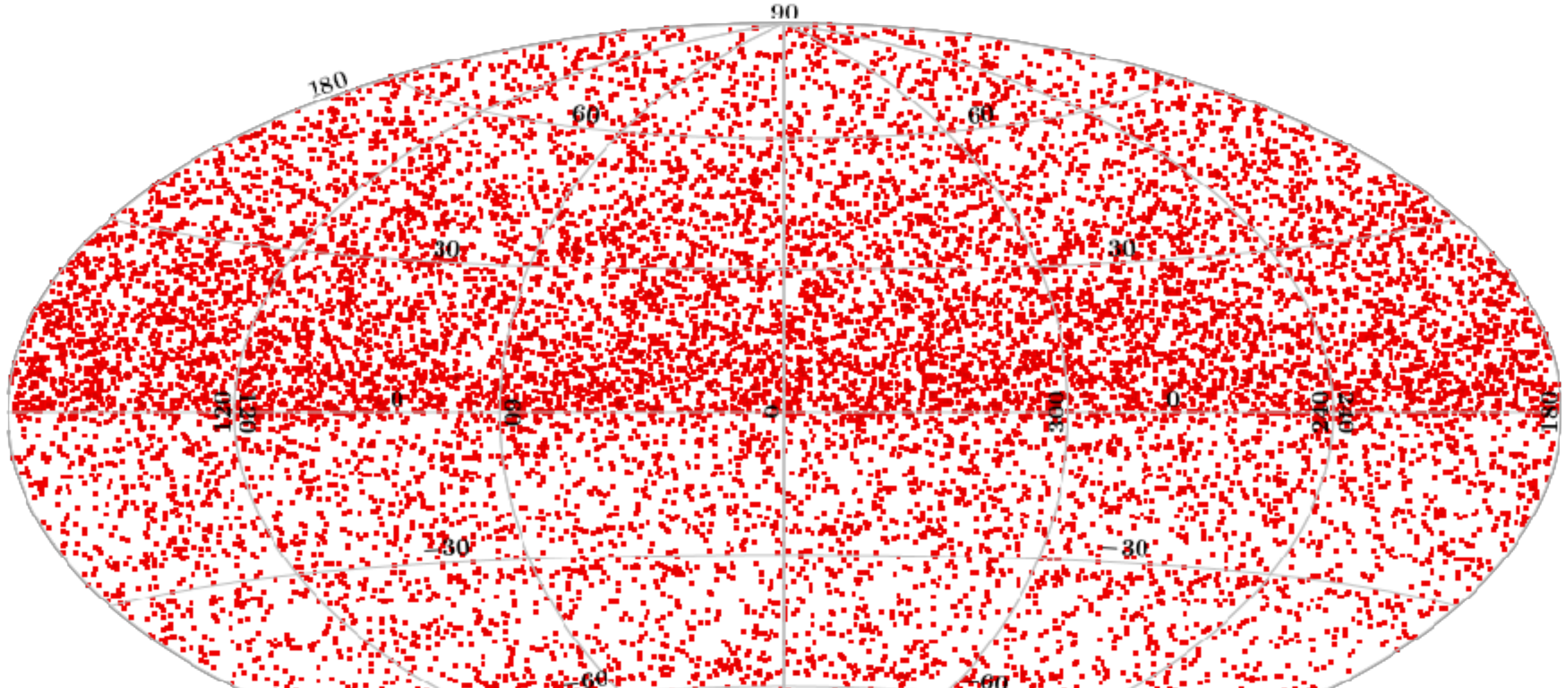
- Proof-of-concept dataset (**1 month**)

  - HAWC daily *sub-threshold* **hotspots**



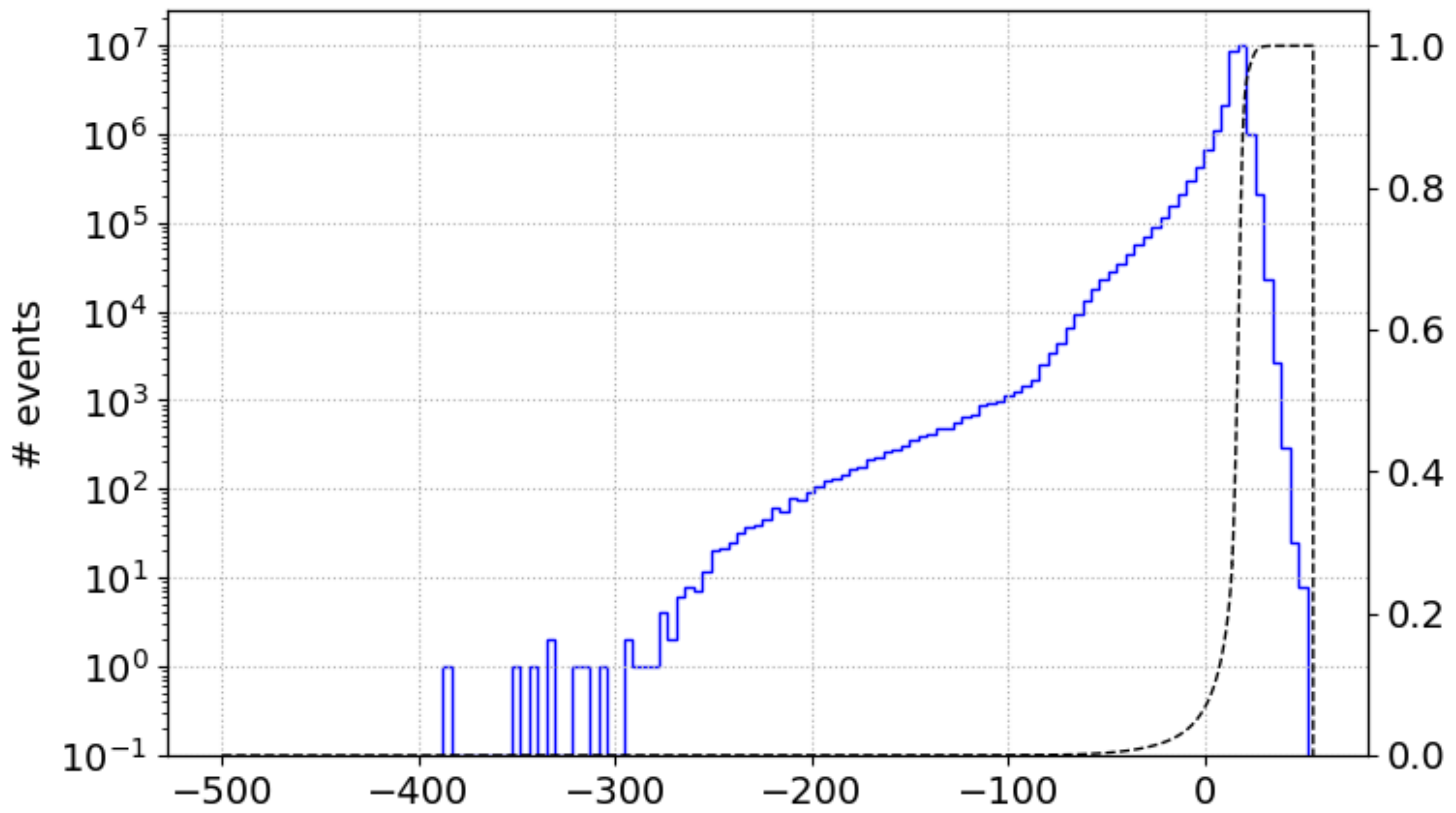
Parameters: position, error in position, significance (>2.75), start time of transit, end time of transit

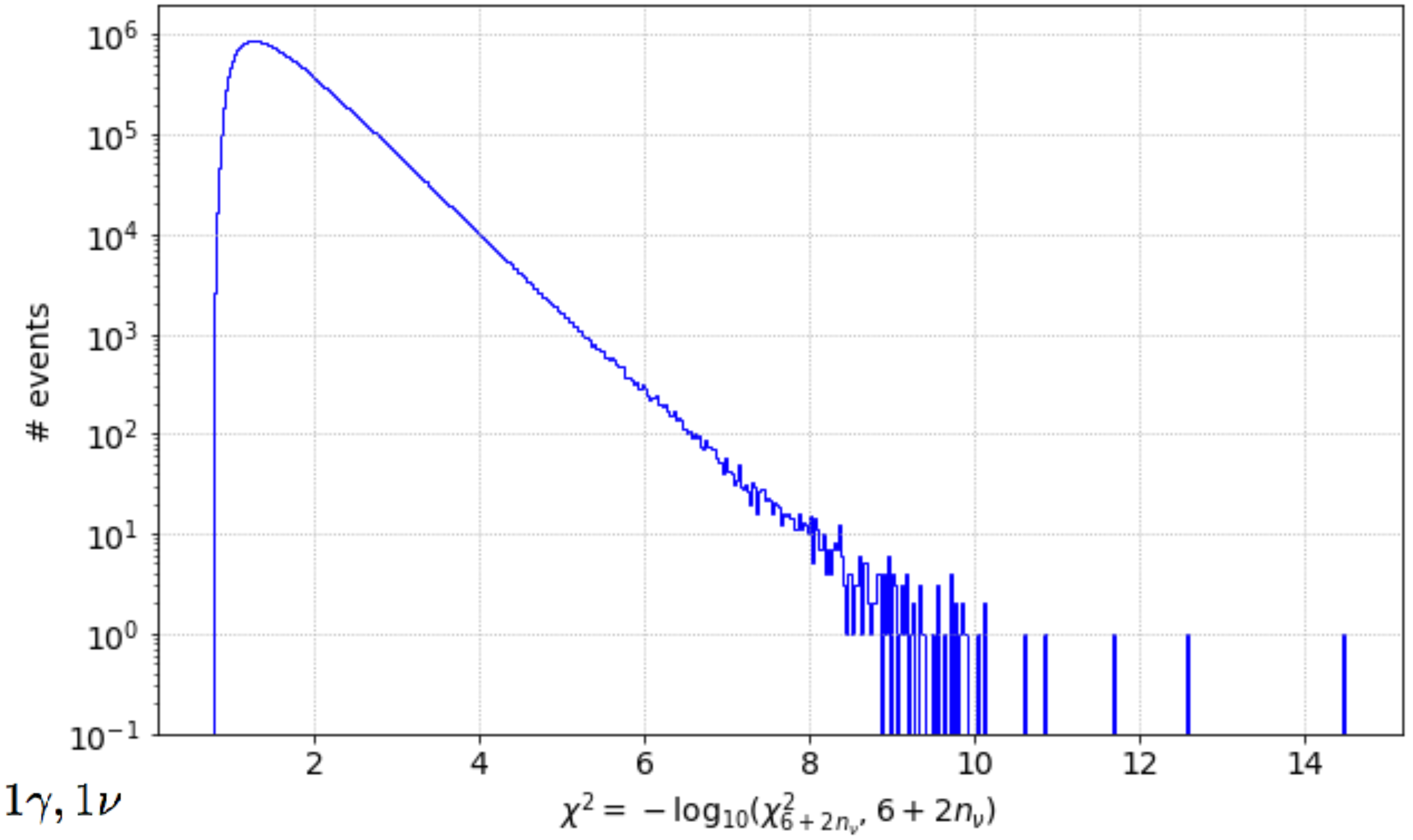
  - IC **track-like** events



Parameters: position, time of event, false positive rate density (FPRD), signal acceptance, PSF

- Results for scrambled data (~**722 years**)

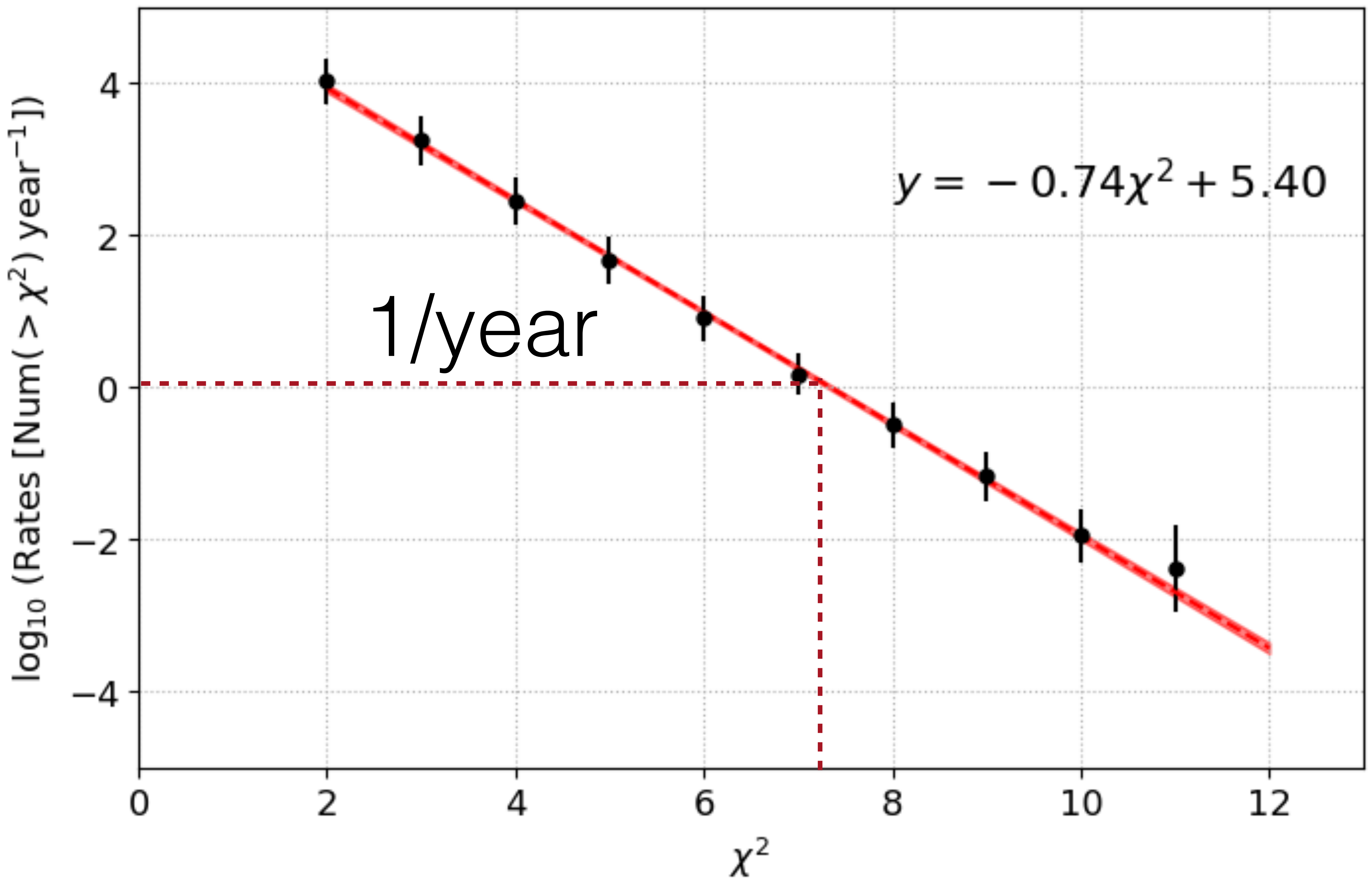




$$\lambda(\vec{x}) = \begin{cases} \sum_{i=1}^{2}(\ln(\mathcal{S}_i(\vec{x})) - \ln(\mathcal{B}_i)) & 1\gamma, 1\nu \\ \sum_{i=1}^{N}(\ln(\mathcal{S}_i(\vec{x})) - \ln(\mathcal{B}_i)) + \sum_{i=2}^{N-1}\sum_{j=i+1}^{N} \ln T_{HWC} - \ln|\Delta T_{ij}| & 1\gamma, >1\nu. \end{cases}$$

Coincidence alerts: IC + HAWC

- Results for scrambled data (~**722 years**)

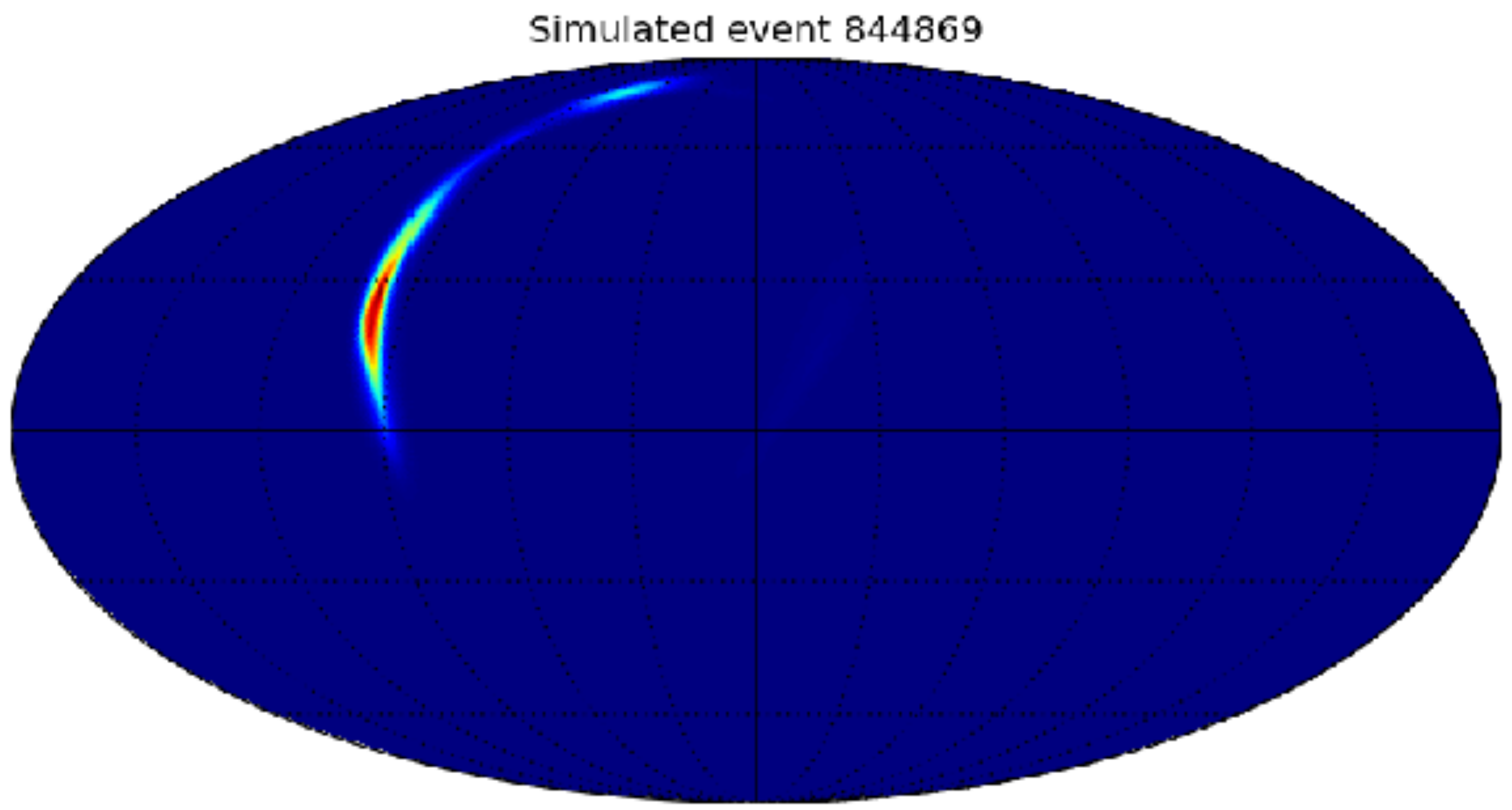


FAR (yr^{-1})	Chi2
12	5.9
1	7.3
0.5	7.7
0.1	8.6

Coincidence alerts: IC + HAWC

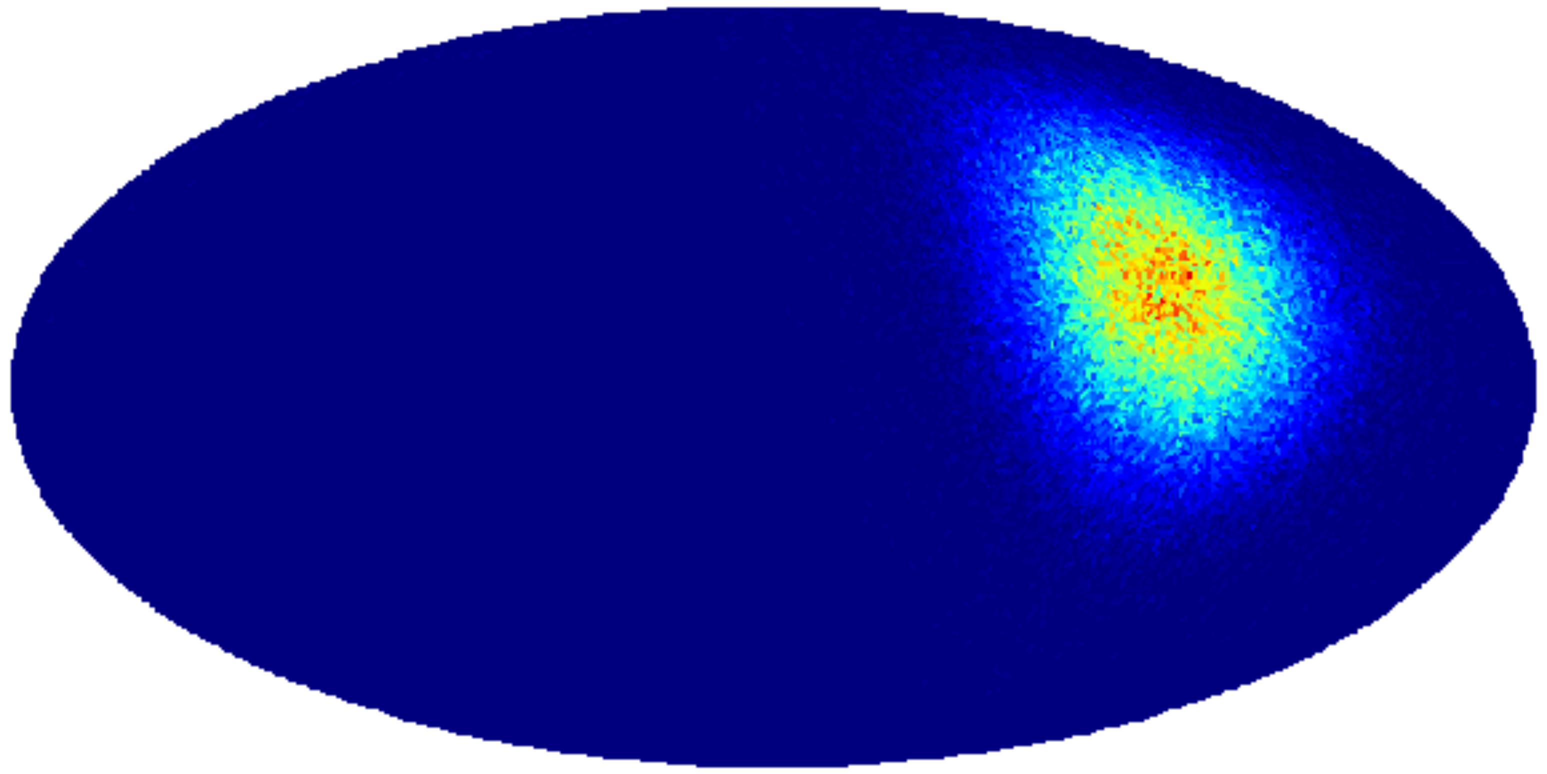
Coincidence alerts: LIGO + HAWC

(Galactic coordinates)



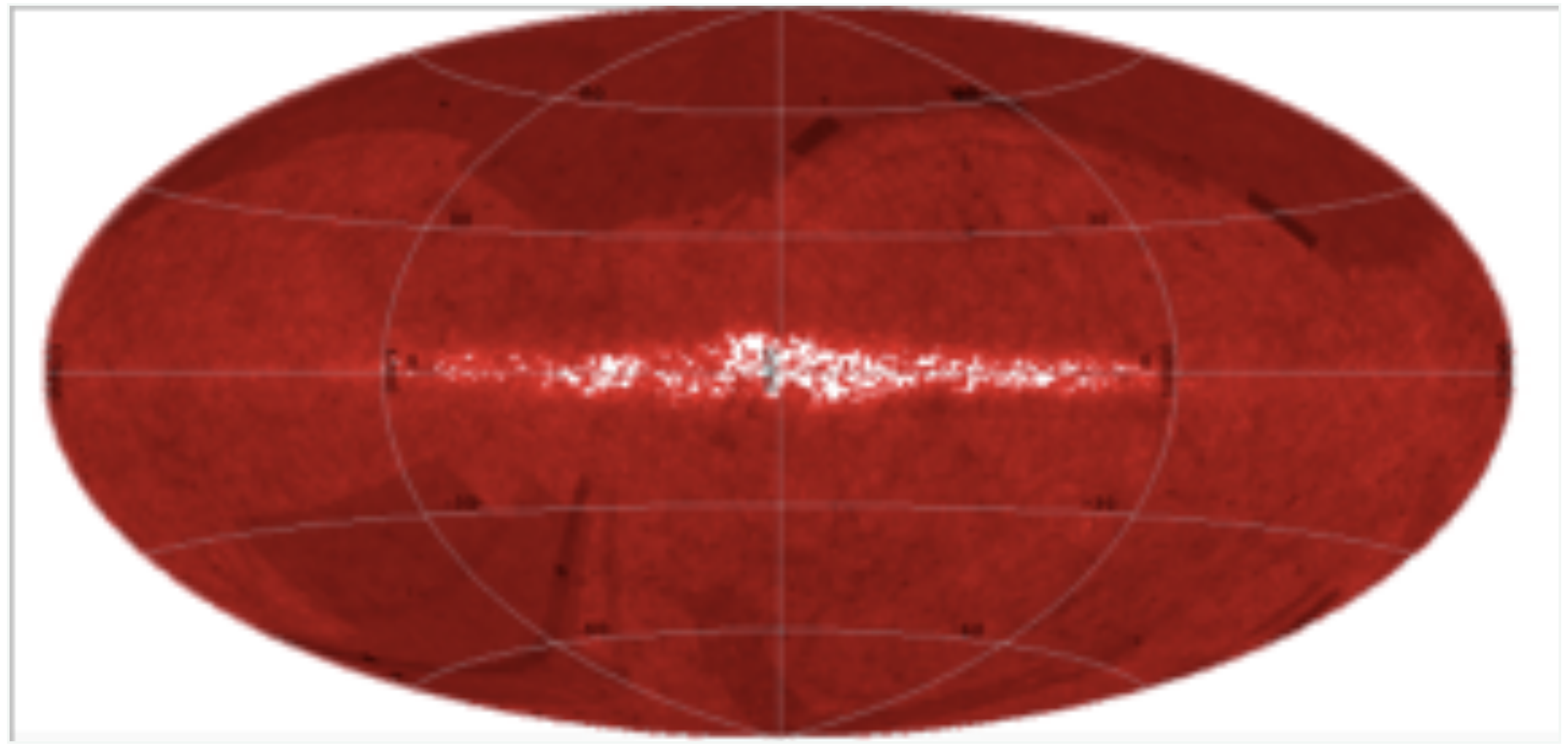
LIGO simulated event

$\otimes$



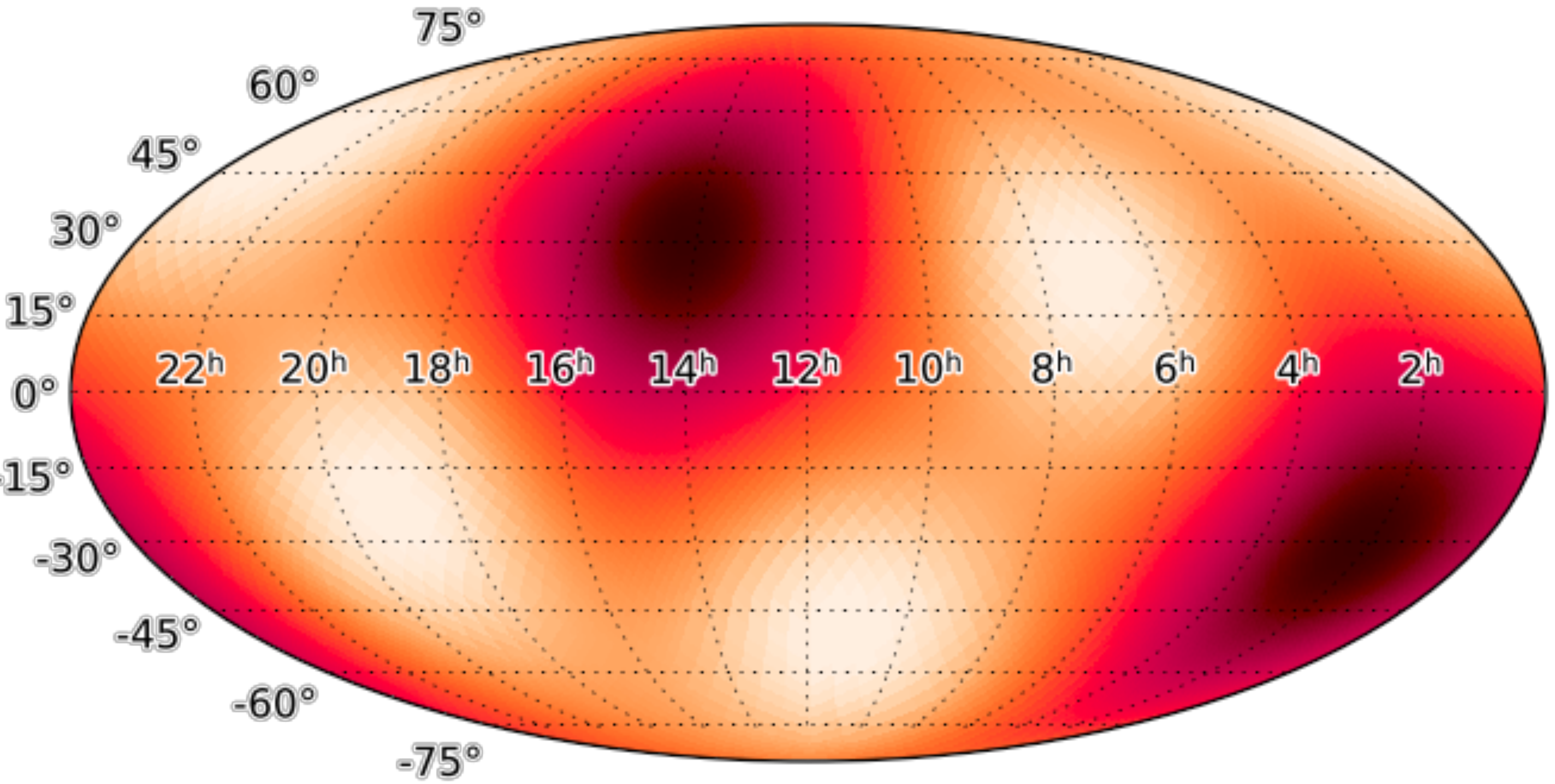
HAWC exposure per 4 min

$\otimes$



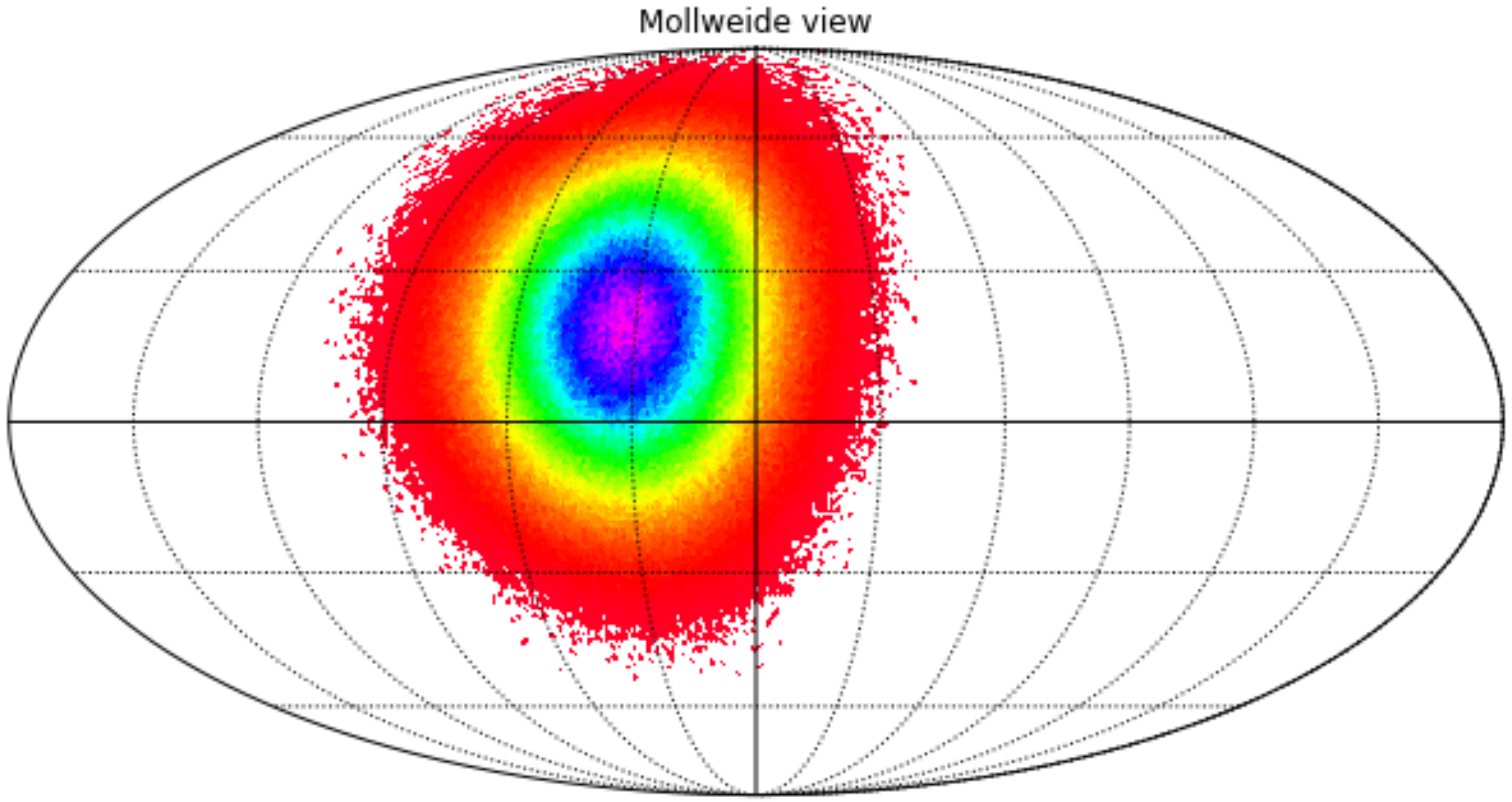
GLADE galaxy catalog

http://aquarius.elte.hu/glade/



LIGO “subthrehold” event

⊗

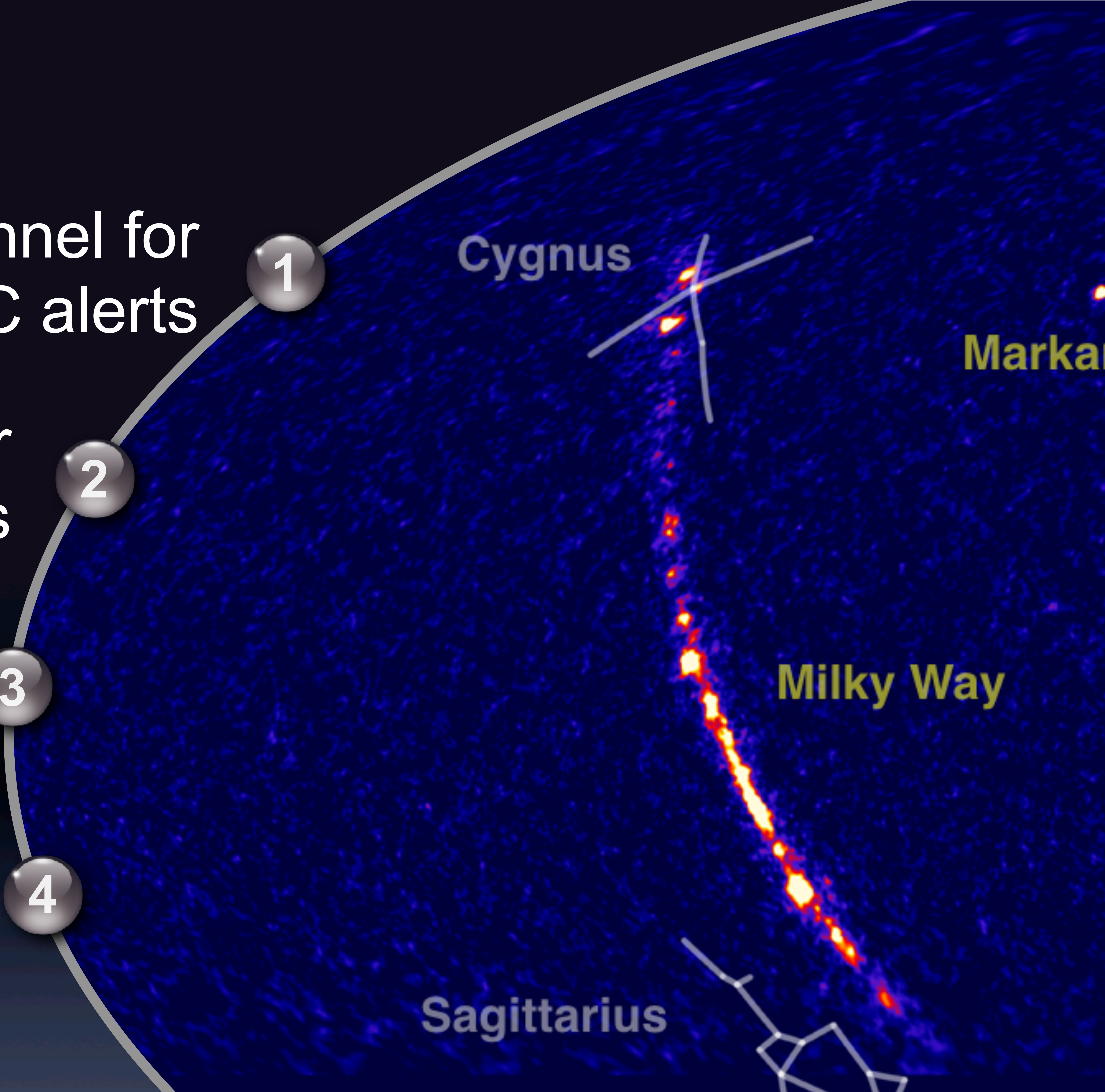


HAWC “instantaneous” exposure

Coincidence alerts: LIGO + HAWC

Outlook

1. New GCN channel for IceCube-HAWC alerts
2. New GCN channel for HAWC GRB-like notices
3. GW subthrehold stream
4. Flares from known sources




GAP
Thank you very much

Recent HAWC papers

- “Very high energy particle acceleration powered by the jets of the microquasar SS 433,” HAWC Collaboration: A.U. Abeysekara et al., Nature 562 (2018), 82-85.
- “Constraints on Spin-Dependent Dark Matter Scattering with Long-Lived Mediators from TeV Observations of the Sun with HAWC,” HAWC Collaboration: A. Albert et al., submitted to PRD.
- “First HAWC Observations of the Sun Constrain Steady TeV Gamma-Ray Emission,” HAWC Collaboration: A. Albert et al., submitted to PRD.
- “Multi-messenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A,” The IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC Collaborations, etc., Science 361 (2018), 146-155.
- “Observation of Anisotropy of TeV Cosmic Rays with Two Years of HAWC,” HAWC Collaboration: A.U. Abeysekara et al., ApJ 865 (2018), 57-71.
- “Search for Dark Matter Gamma-ray Emission from the Andromeda Galaxy with the High-Altitude Water Cherenkov Observatory,” HAWC Collaboration: A.U. Albert et al., JCAP 1806 (2018), 043.

Coincidence alert: IC+HAWC

- Temporal and spatial coincidence

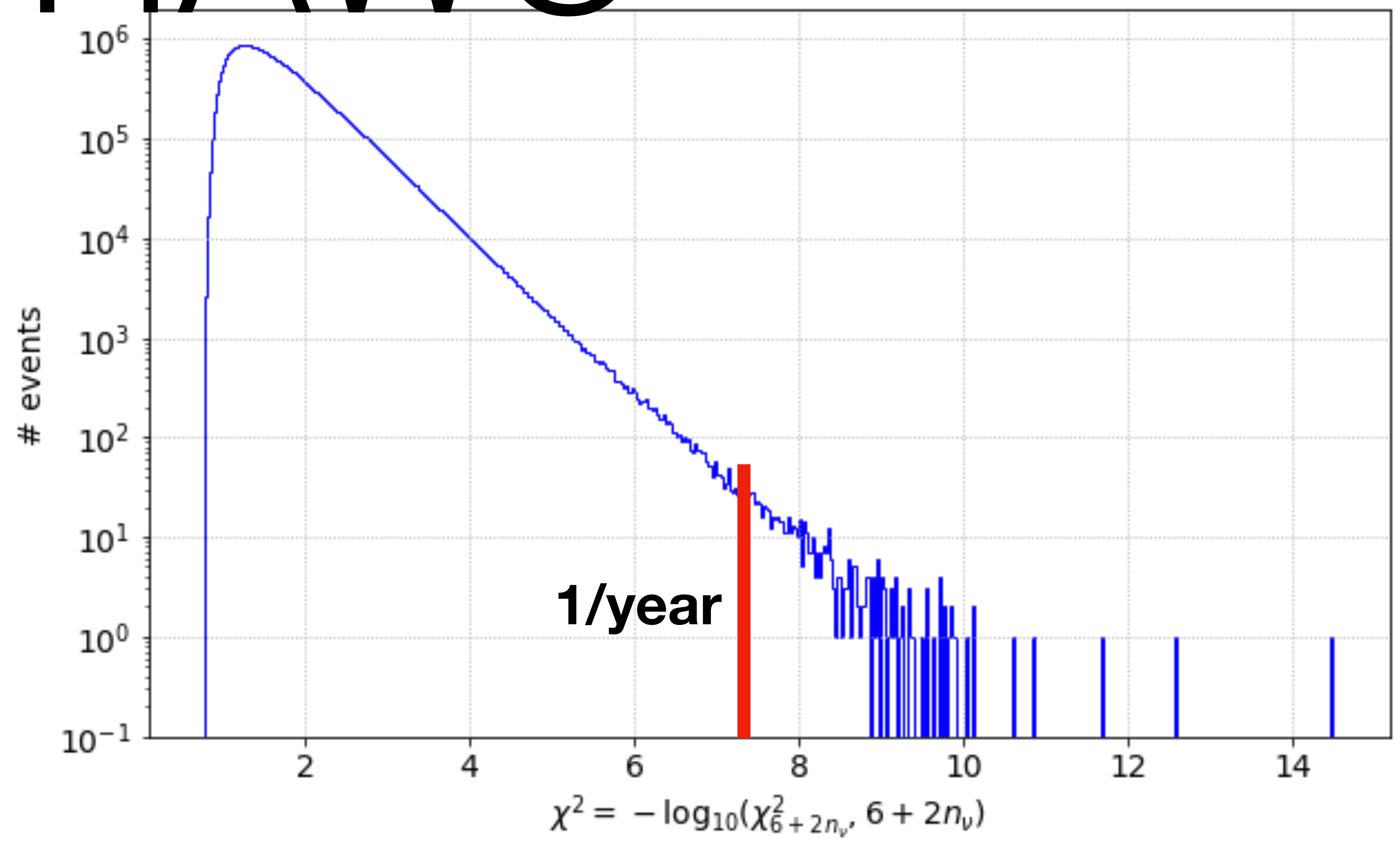
- Best position of the coincidence

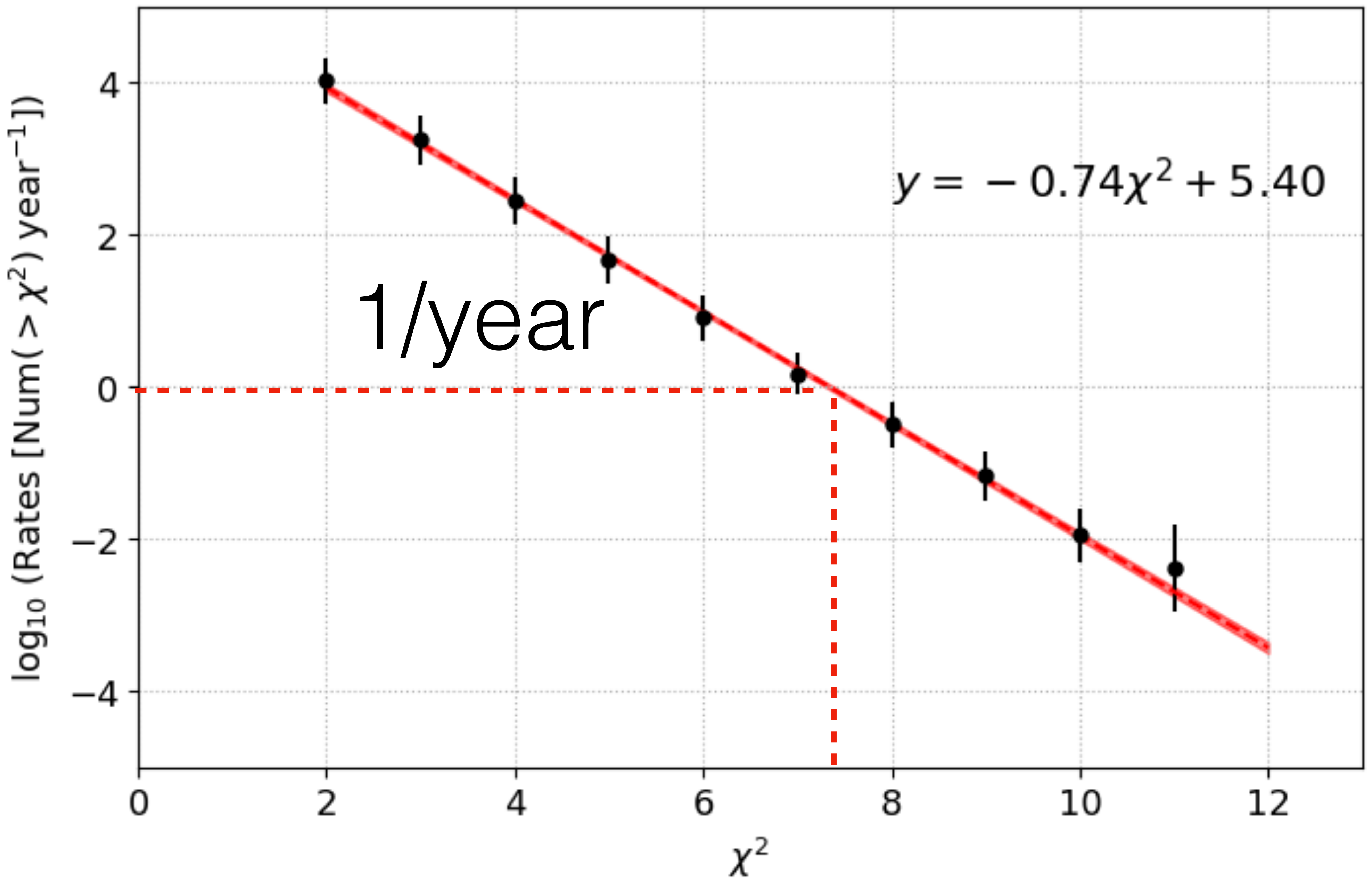
$$\lambda(\vec{x}) = \begin{cases} \sum_{i=1}^{2} (\ln(\mathcal{S}_i(\vec{x})) - \ln(\mathcal{B}_i)) & 1\gamma, 1\nu \\ \sum_{i=1}^{N} (\ln(\mathcal{S}_i(\vec{x})) - \ln(\mathcal{B}_i)) + \sum_{i=2}^{N-1} \sum_{j=i+1}^{N} \ln T_{HWC} - \ln |\Delta T_{ij}| & 1\gamma, > 1\nu. \end{cases}$$

- Combine p values using Fisher's method

$$\chi^2 = -2 \ln[p_\lambda \, p_{HWC} \, p_{cluster} \prod_i^{n_\nu} p_{i_{IC}}]$$

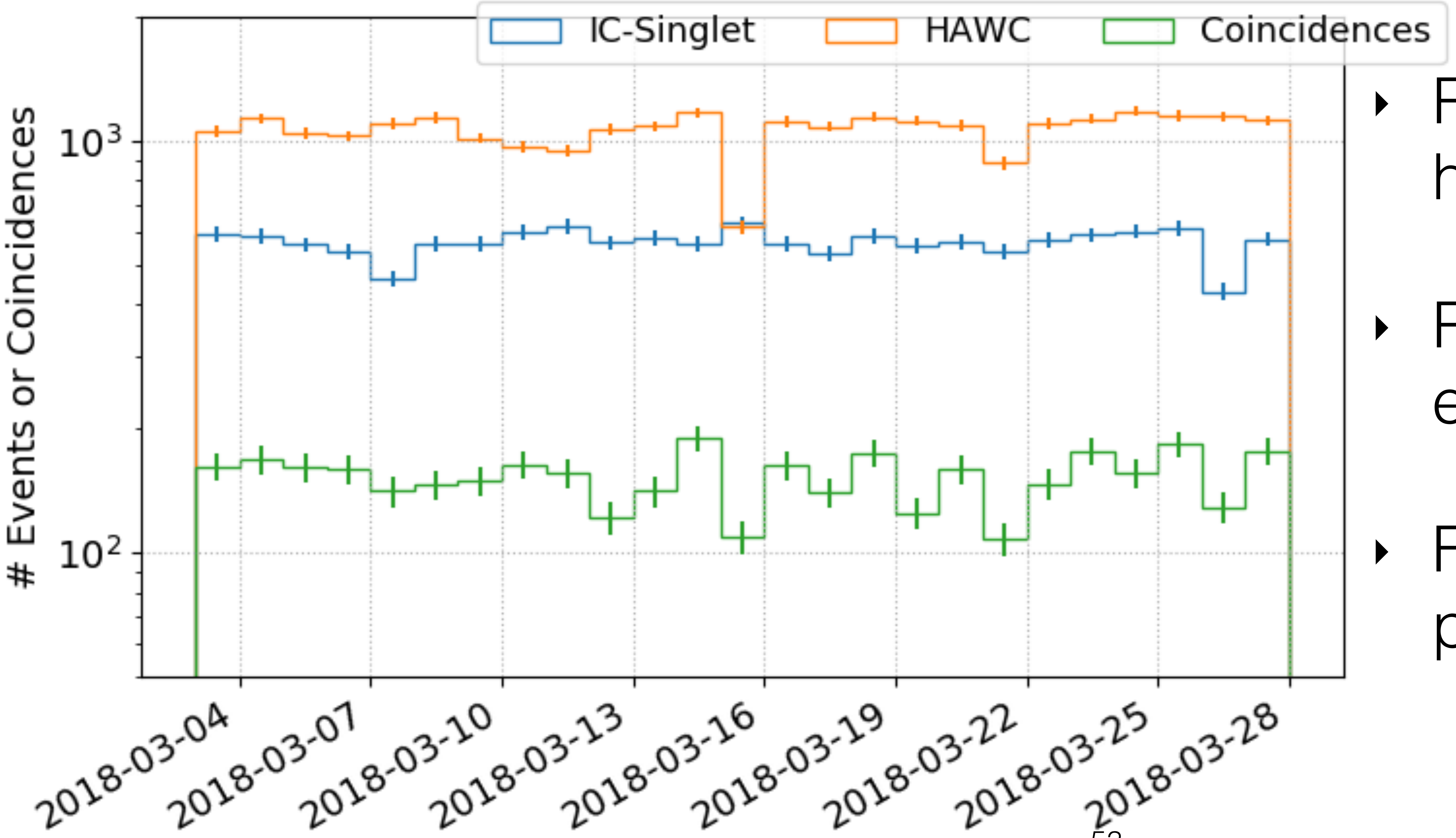
- Account for different DoF for different multiplicities, and use $-\log[p(\chi^2 > \chi^2_{obs})]$ to rank coincidences





Coincidence alert: IC+HAWC

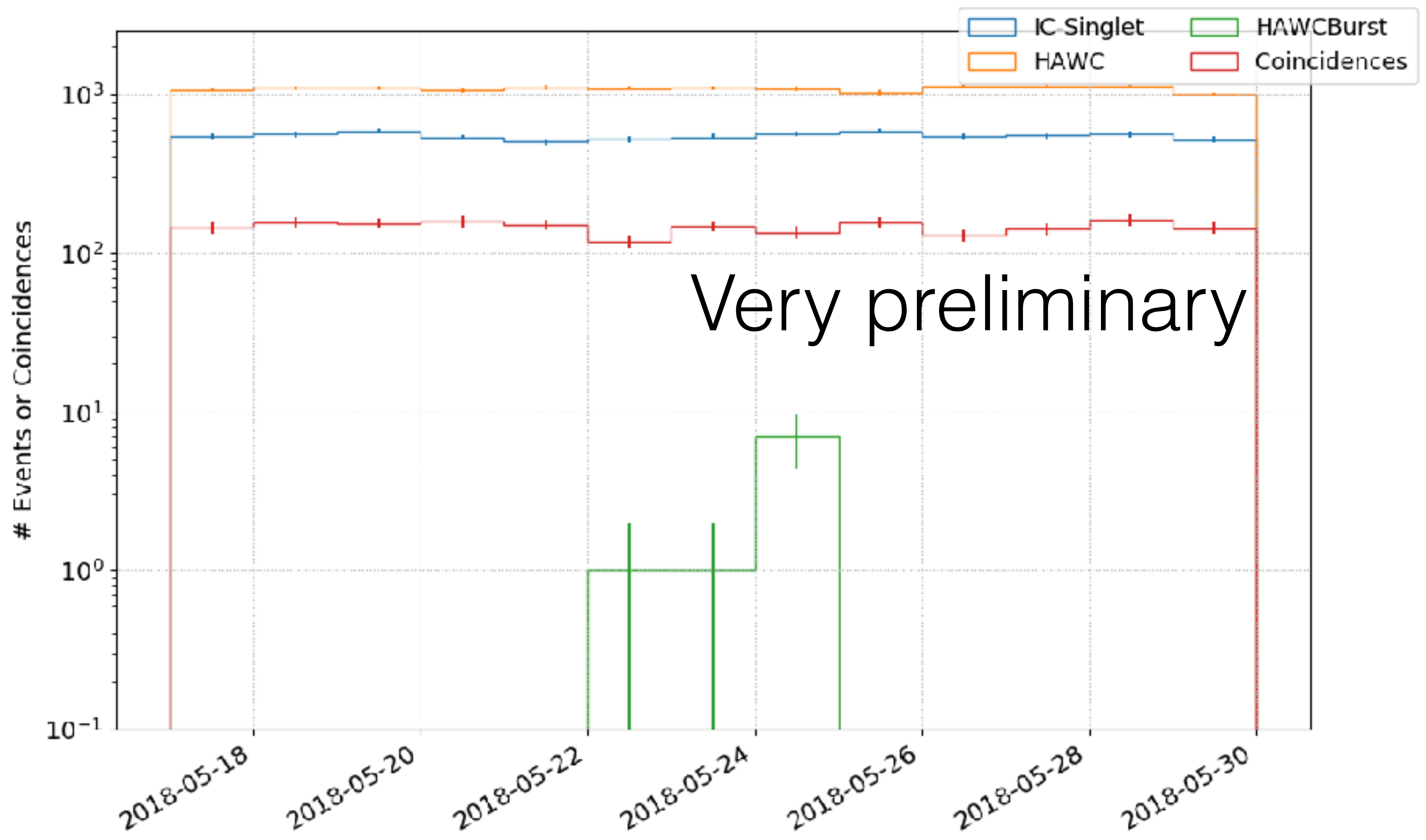
- Moving to **real-time** analysis!



- Receiving ~1000 HAWC daily hotspot per day
- Receiving ~600 IC track-like events per day
- Finding ~150 coincidences per day

VHE γ Notices

- Add HAWC's own GRB *sub-threshold* triggers
- studying FARs
  - internal a few/day
  - send to GCN the 1/year events



Coincidence alert: γ+GW

Proposed scheme

HAWC TRIGGER

- Real-time GRB search
- 0.2,1,10,100s

GW TRIGGER

GALAXY CATALOGUE

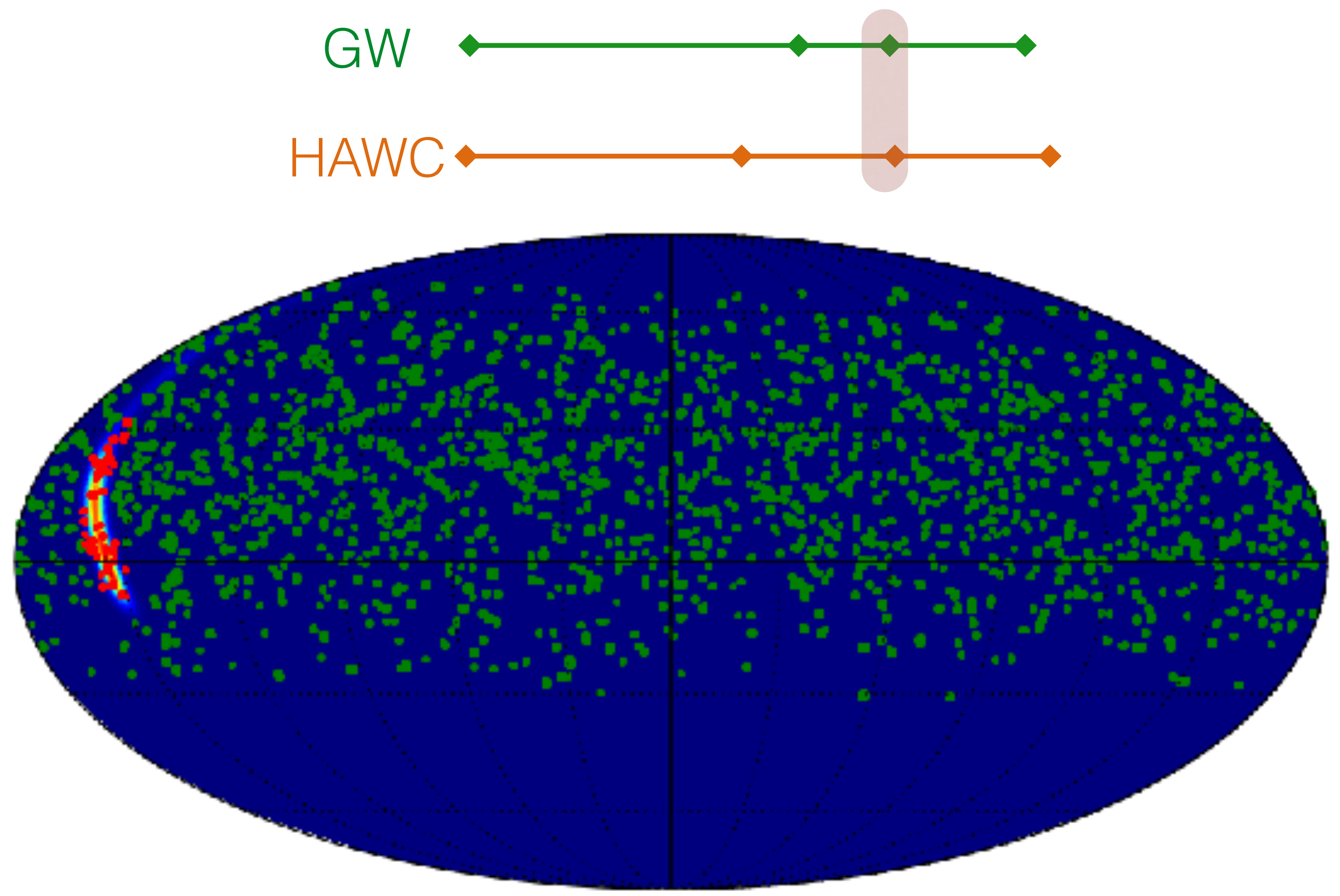
TEMPORAL COINCIDENCE (500s WINDOW)

SPATIAL COINCIDENCE

HAWC candidate is in the 90% GW area?

LIKELIHOOD COMPUTATION

P-VALUE OF THE DETECTION

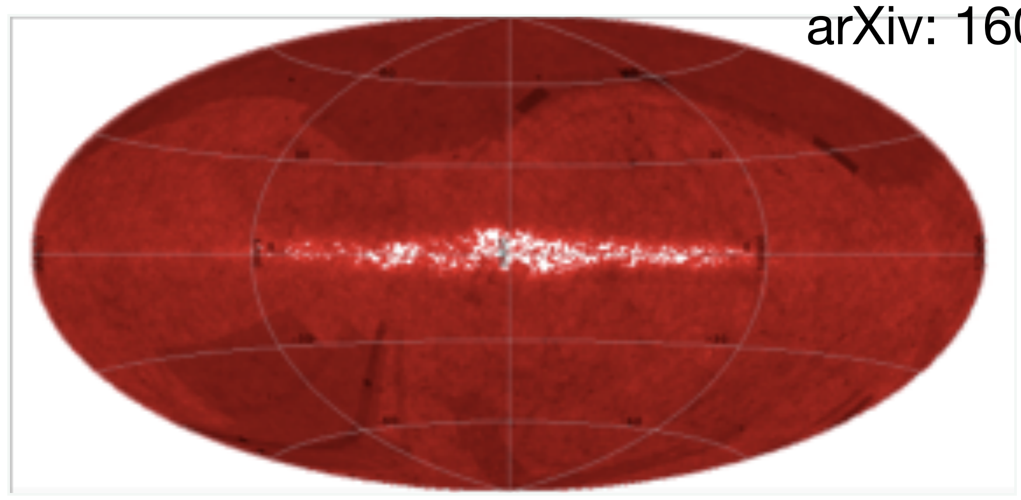


$$\lambda(\vec{x}_S) = \frac{H_1^{GW}(\vec{x}_S)\cdot H_1^{Gal}(\vec{x}_S)\cdot H_1^{\gamma_j}(\vec{x}_S)}{H_0^{GW}\cdot H_0^{Gal}\cdot H_0^{\gamma}}$$

$$\chi^2 = -2\cdot ln(p_{spatial}\cdot p_{gw}\cdot p_{\gamma})$$

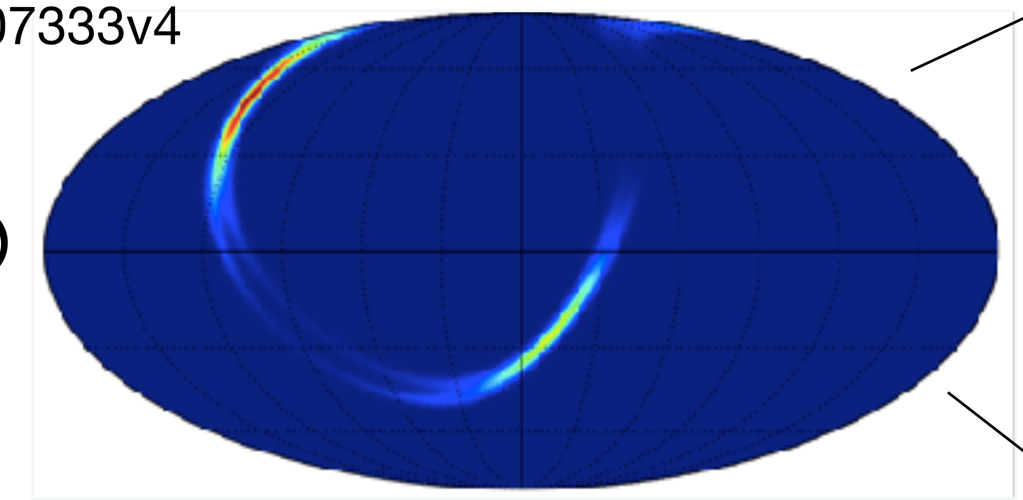
$$p_{GW\gamma} = \int_{\chi^2}^{\infty} P_{BG}(\chi'^2)d\chi'^2$$

arXiv: 1603.07333v4

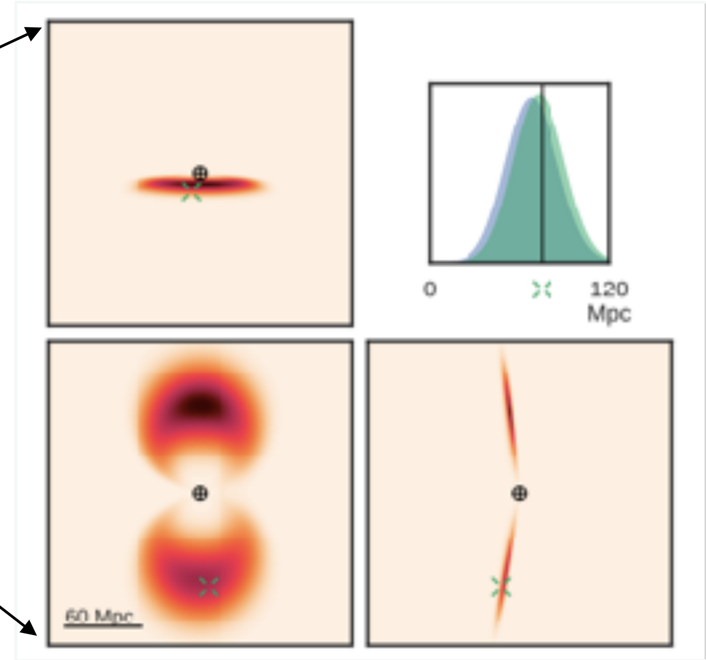


GLADE: galaxy distribution

$\otimes$

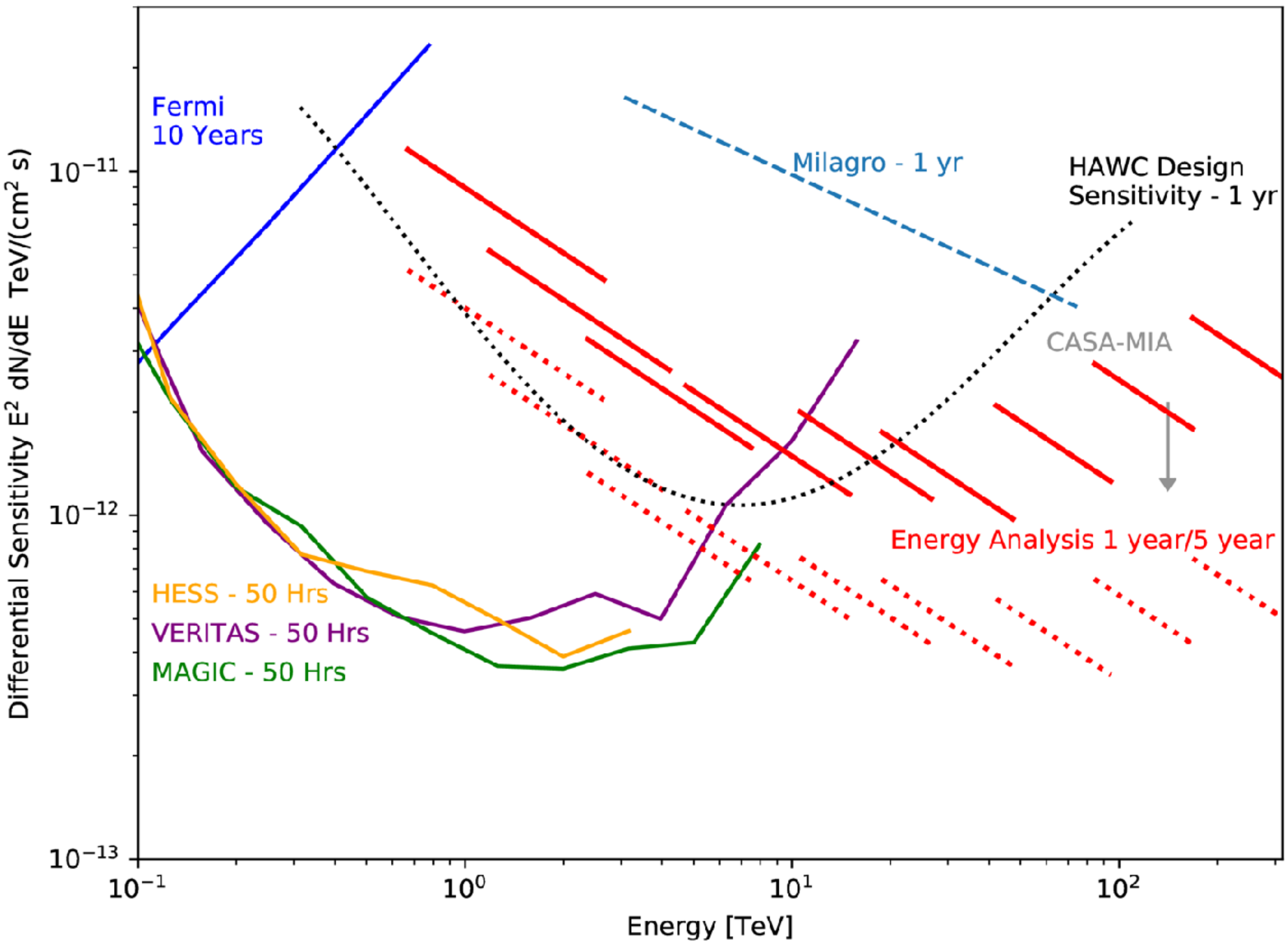


LIGO-Virgo map



4-layers information:

- the posterior probability ρ
- Distance estimate
- Dispersion
- Normalization



Fermi
10 Years
Milagro - 1 yr
HAWC Design
Sensitivity - 1 yr
CASA-MIA
Energy Analysis 1 year/5 year
HESS - 50 Hrs
VERITAS - 50 Hrs
MAGIC - 50 Hrs
Differential Sensitivity E² dN/dE TeV/(cm² s)
Energy [TeV]

Hardly working at the HAWC site