Recent Results from The HAWC Gamma Ray Observatory

Mexican Physical Society

Jordan Goodman for the
HAWC Collaboration
November 2020

The HAWC Collaboration

USA

Mexico

United States
University of Maryland
Los Alamos National Laboratory
University of Wisconsin
University of Utah
University of New Hampshire
Pennsylvania State University
University of New Mexico
Michigan Technological University
NASA/Goddard Space Flight Center
Michigan State University

Mexico
Instituto Nacional de Astrofísica,
Óptica y Electrónica (INAOE)
Universidad Nacional Autónoma
de México (UNAM)
Instituto de Física
Instituto de Astronomía
Instituto de Geofísica
Instituto de Ciencias Nucleares
Universidad Politécnica de Pachuca
Benemérita Universidad Autónoma de Puebla
Universidad Autónoma de Chiapa
Universidad Autónoma del Estado de Hidalgo
Universidad de Guadalajara
Universidad Michoacana de San Nicolás de Hidalgo
Centro de Investigación y de Estudios Avanzados
Instituto Politécnico Nacional
Centro de Investigación en Computación - IPN

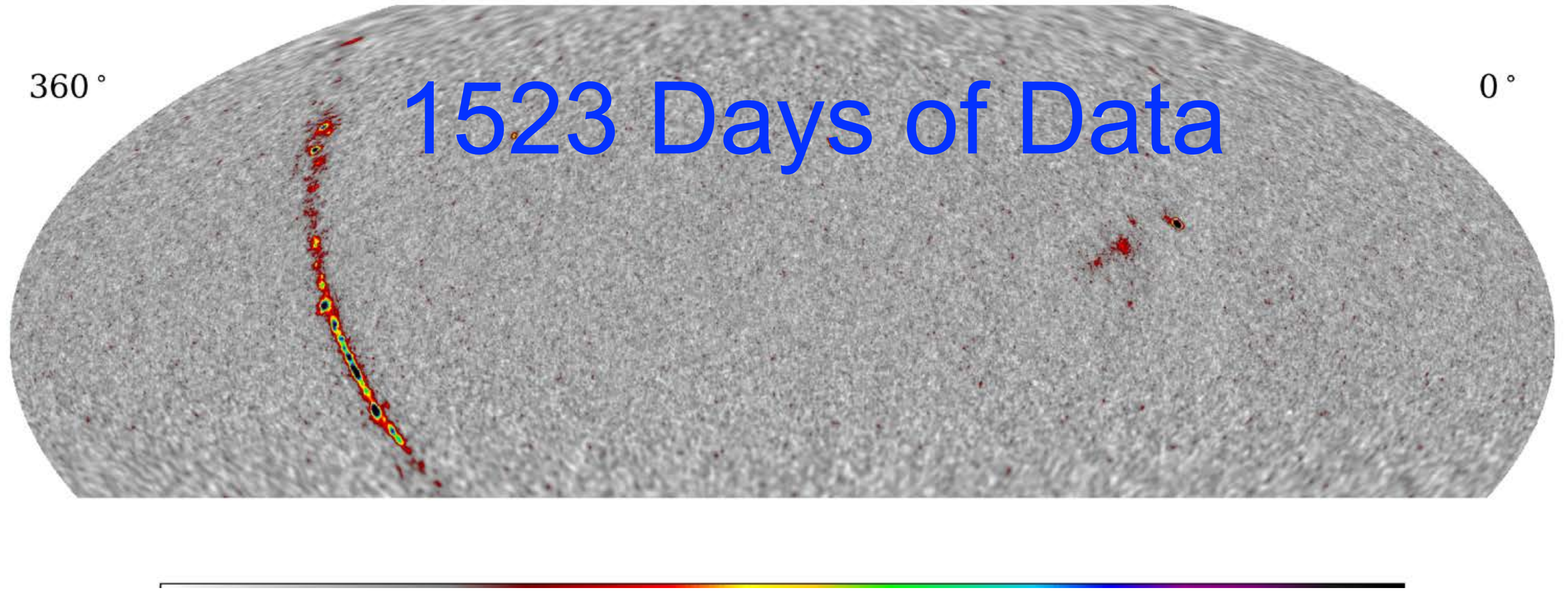
Europe
Max-Planck Institute for Nuclear Physics
IFJ-PAN, Krakow, Poland
National Institute for Nuclear Physics, Padova, Italy

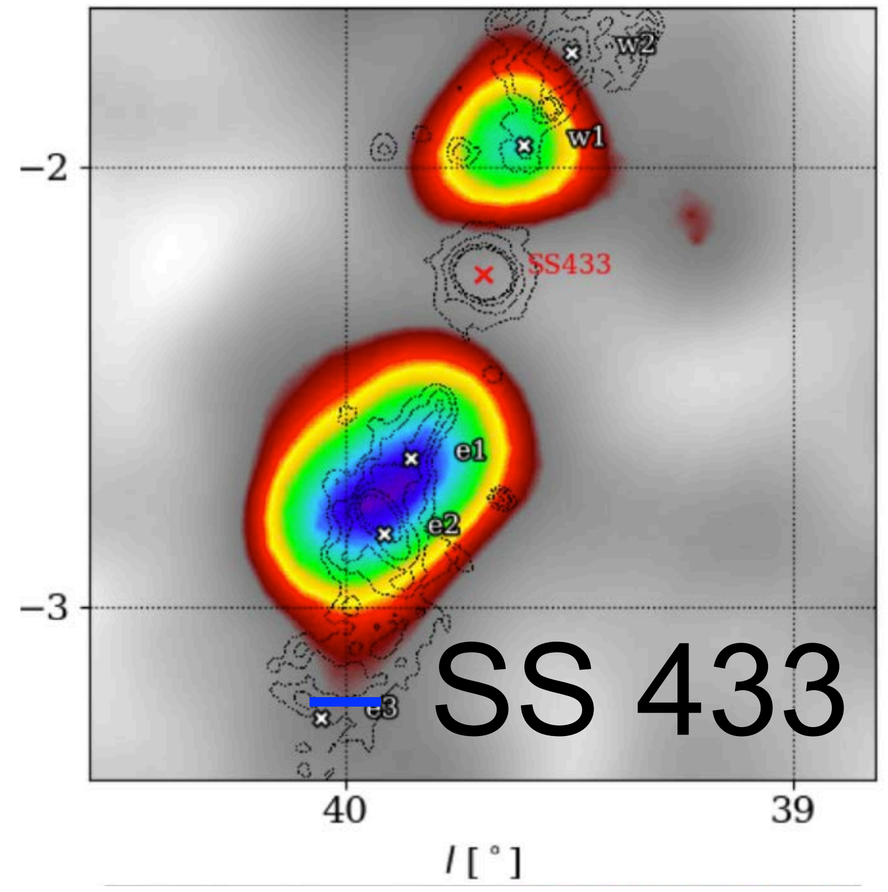
Asia
Shanghai Jiao Tong University
Sungkyunkwan University, South Korea

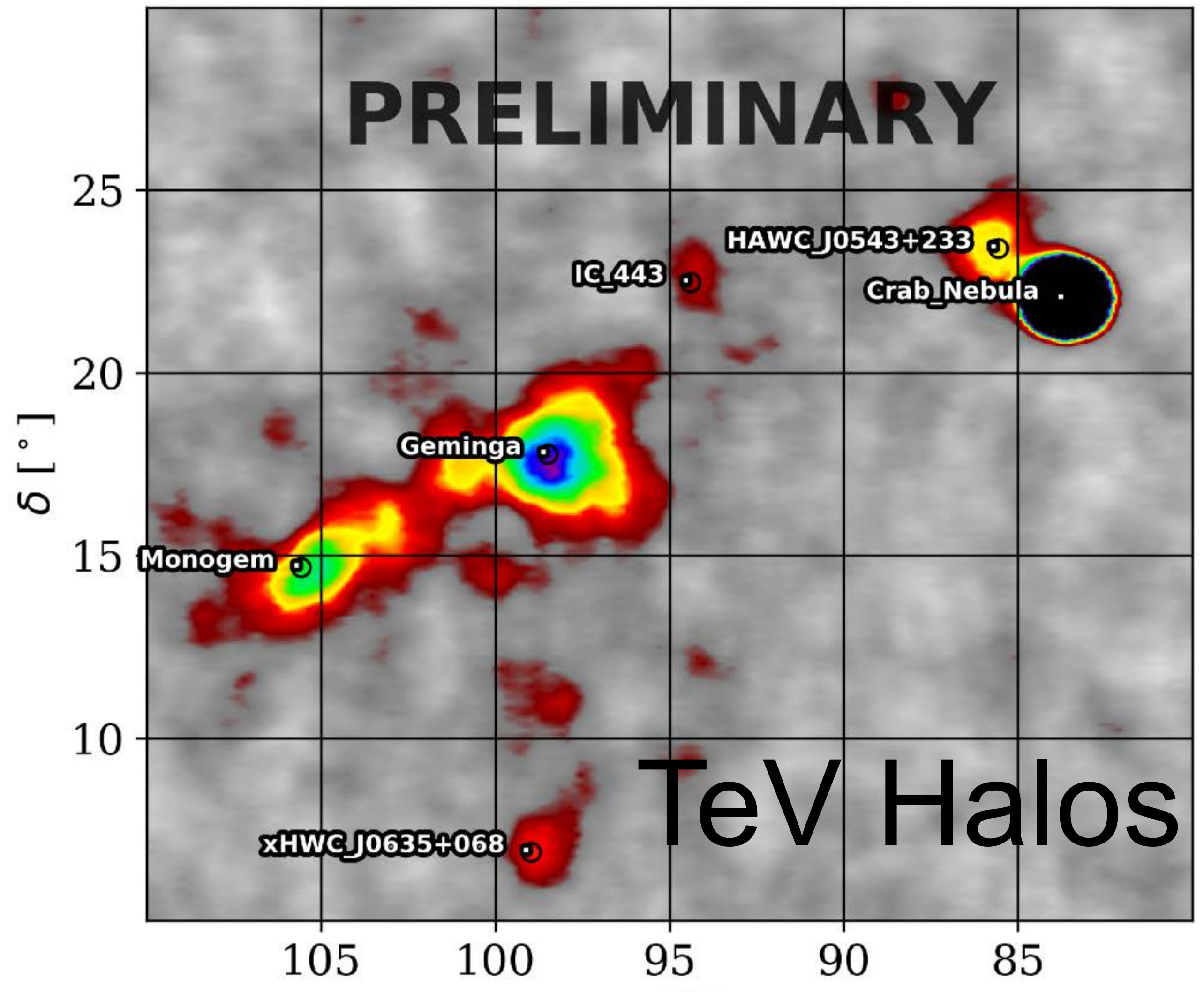
High Altitude Water Cherenkov

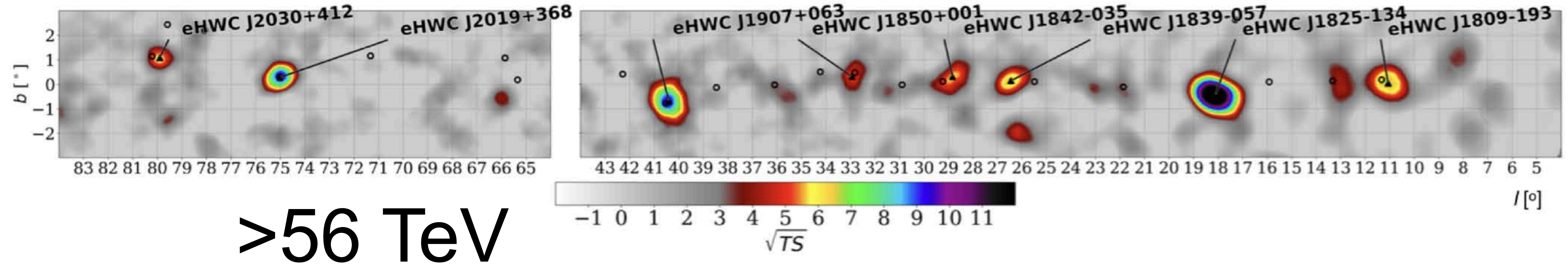
HAWC - Recent Results

- New sky maps
  - 50 Sources - many previously unseen
  - New Source classes - TeV Halos, Micro-Quasar
- Highest Energy Sky
- Multimessenger Observations
  - LIGO
  - IceCube
- Other exciting science
  - Dark Matter Limits
  - Fermi Bubbles
  - Anisotropy
  - Primordial Black Holes
  - Lorentz Invariance Violation
  - Fast Radio Bursts



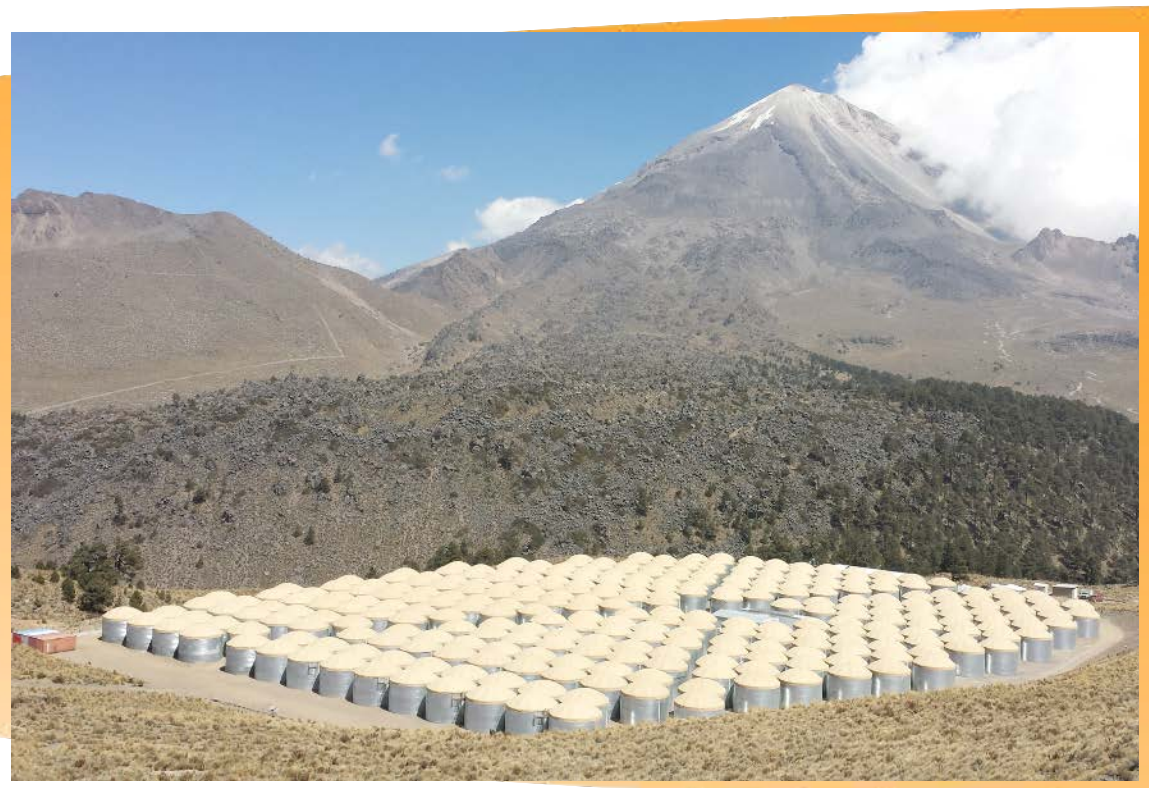






>56 TeV

High energy gamma rays



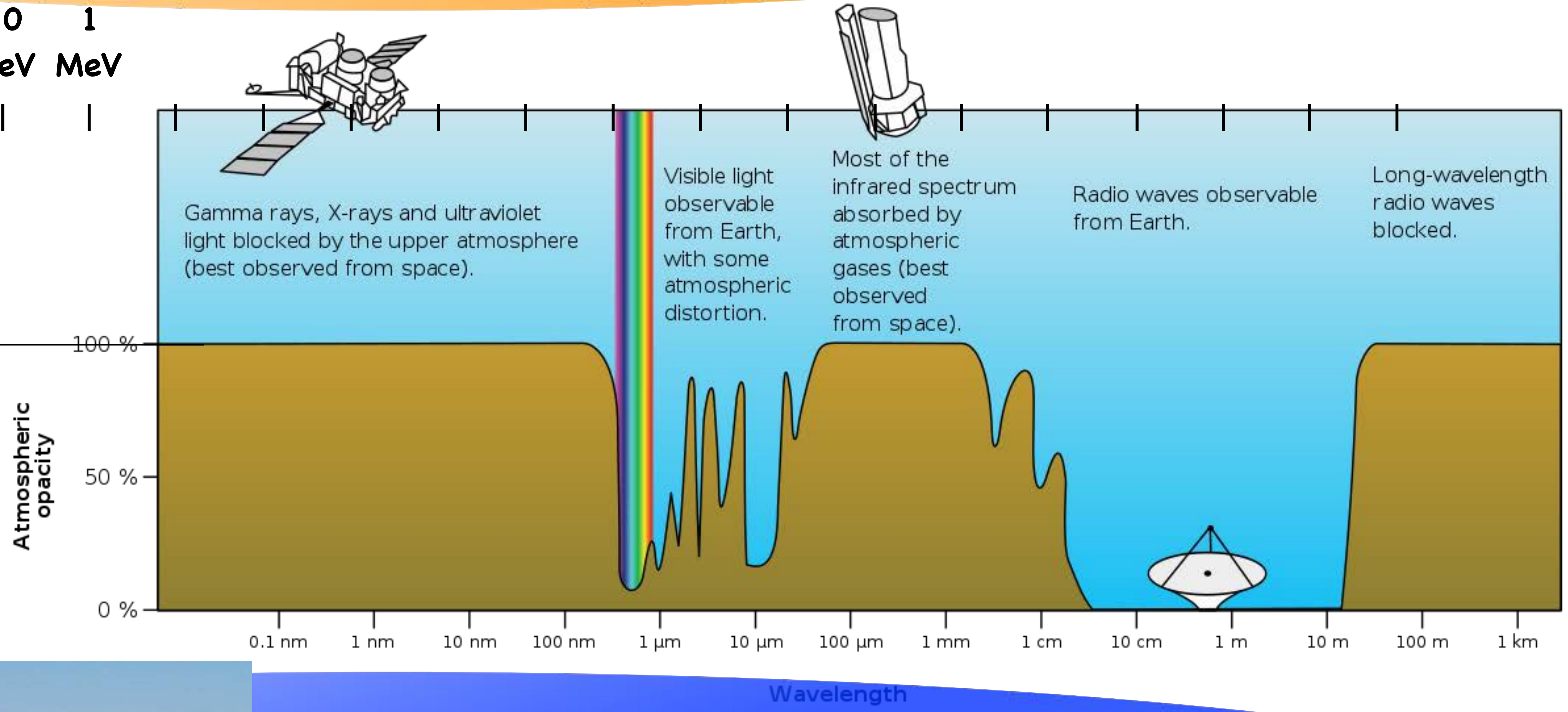
- Wide field of view
- High duty cycle (~95%)
- Good sensitivity

100 TeV	10 TeV	1 TeV	100 GeV	10 GeV	1 GeV	100 MeV	10 MeV	1 MeV

HAWC

LHASSO | Fermi-LAT

IACTs



- Narrow field of view
- Limited duty cycle (~15%)
- Excellent sensitivity

The HAWC Site

Latitude: 18°59.7’N

Longitude: 97°18.6’W


High-Altitude Water Cherenkov
Gamma-Ray Observatory
Pico de Orizaba
Puebla, Mexico (19°N)
Energy range:
~100 GeV - 100TeV
Field of view:
45° from zenith
Observing time:
>95% of the time
Angular resolution:
~0.1° - 1°
300 ×
5m tall, 7.3 m diameter
~200,000 L of water
4 PMTs facing upwards collect
Cherenkov light produced by secondary particles
22,000 m²
T-rex for scale
4,100 m.a.s.l.
7


HAWC

HAWC

HAWC-30: Engineering Test of full detector

HAWC-111: Operations Begins: August 2013 (283 days)

HAWC-250: November, 2014 (~150Days)

HAWC-300: March 2015 – Present : >95% uptime

Outriggers in operation since August 2018


300th WCD tank constructe
~3,900 tanker truck trips

HAWC Electronics

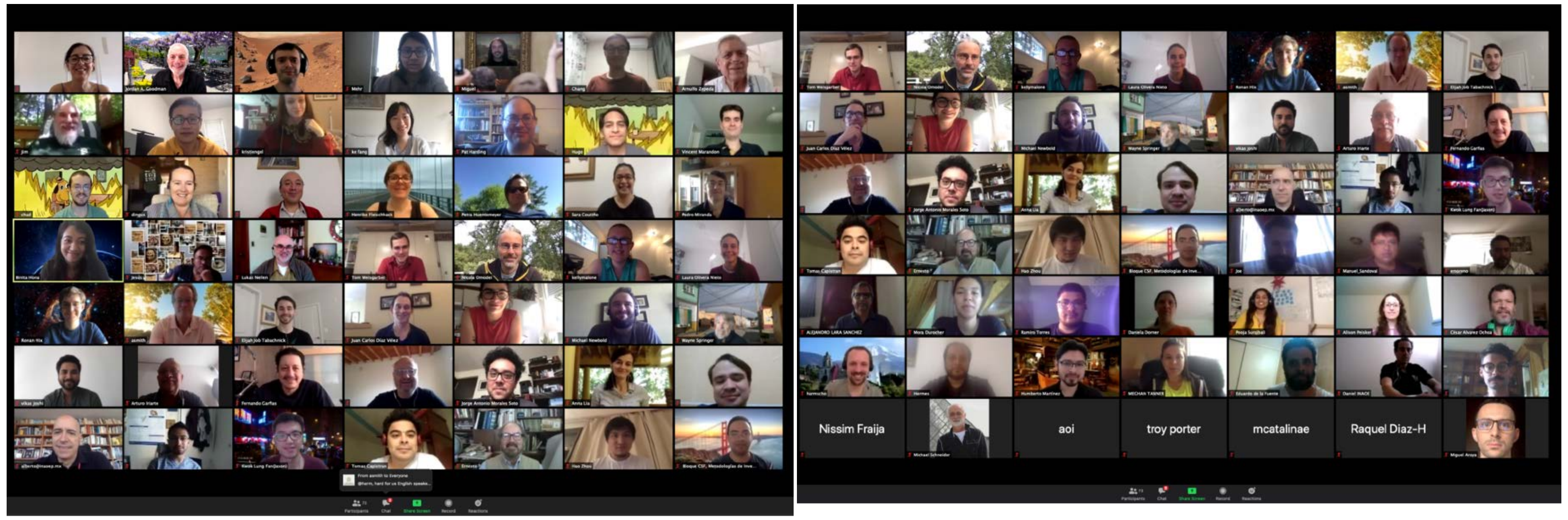
HAWC Data

- We read in every PMT hit all the time
  - Raw data rate - 500MB/s -10 VME Backplanes
- Trigger in Software
  - Trigger rate requiring ~30 hits in 300ns is ~25kHz
- Process in near real time
- Rate to disk ~24MB/s -> ~2TB/day (everyday)
- Data is moved by portable disk arrays to UNAM
  - About once a week it's driven to Mexico City (pre-Covid)
  - Moved over Internet II to UMD
- Raw Data plus processed data is stored in Mexico and Maryland
  - About a petabyte a year
  - Currently we have about 7.5 PB of storage at UMD and about 6 PB at UNAM

The Data Bus

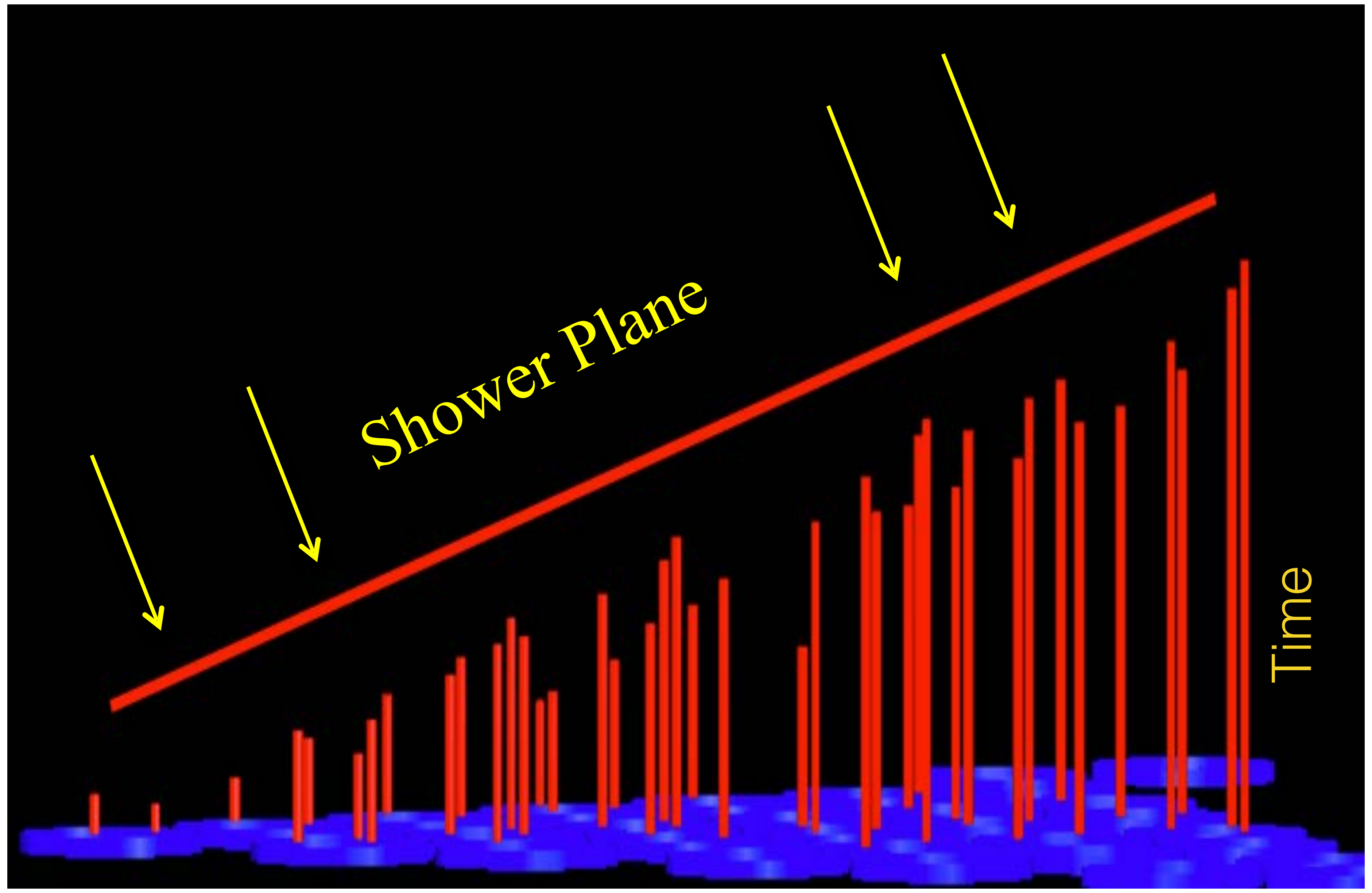
HAWC Operations During Covid-19

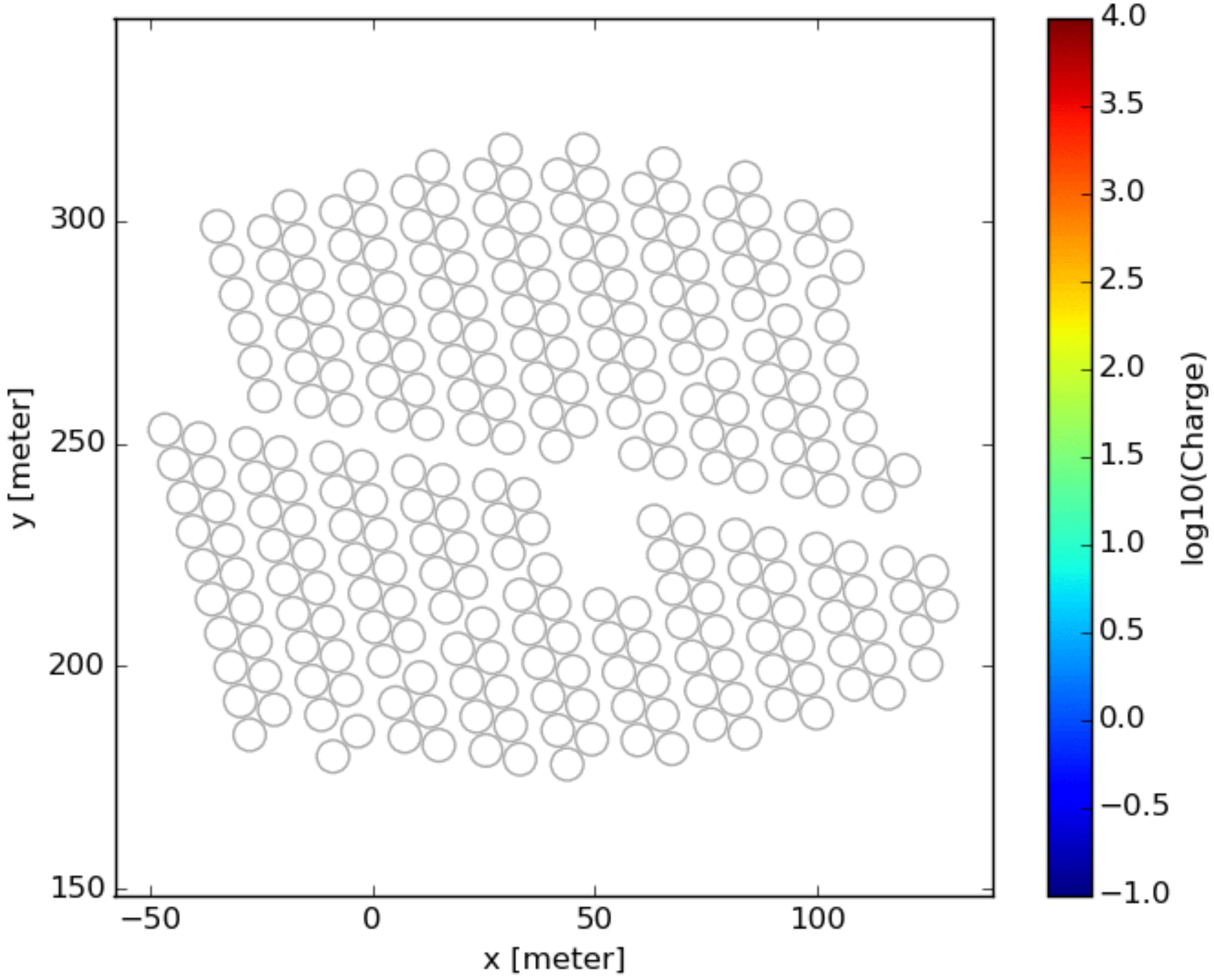
- HAWC continues to operate during the pandemic
  - Experiment can be completely controlled remotely
  - Workers from the nearby town went to the site weekly - now daily
  - HAWC produces 2TB of data/day which is stored on portable arrays in the local town with ~90 days capacity
  - Data is transferred to Mexico City (via Uber) and is being copied and transferred to UMD
  - Data arrays are returned to the site giving us another 90 days of capacity
- Zoom Collaboration Meeting, June 2020



Direction reconstruction

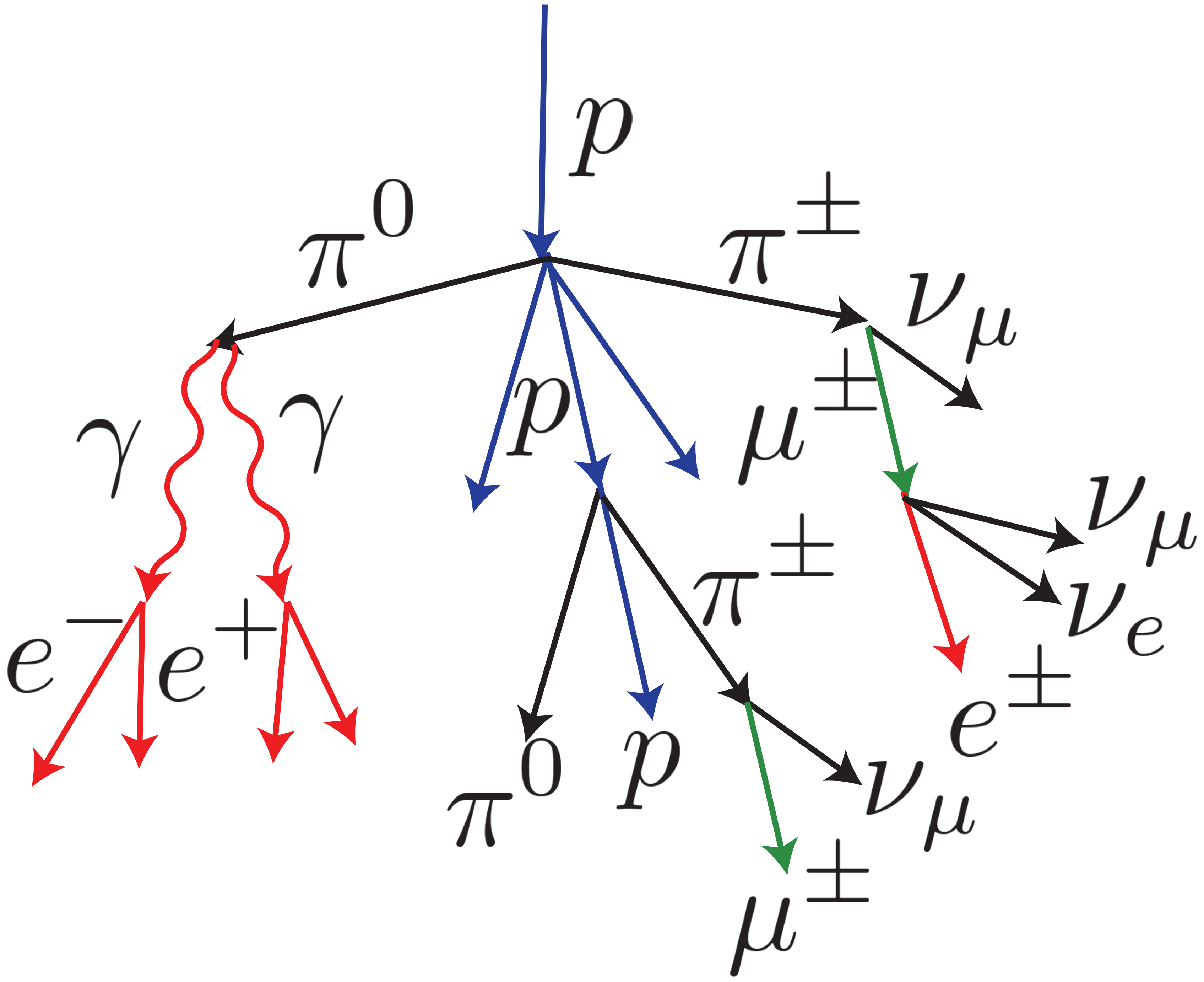
- At first order, we fit a plane to the relative timing of each PMT
- Sub-nanosecond precision is needed

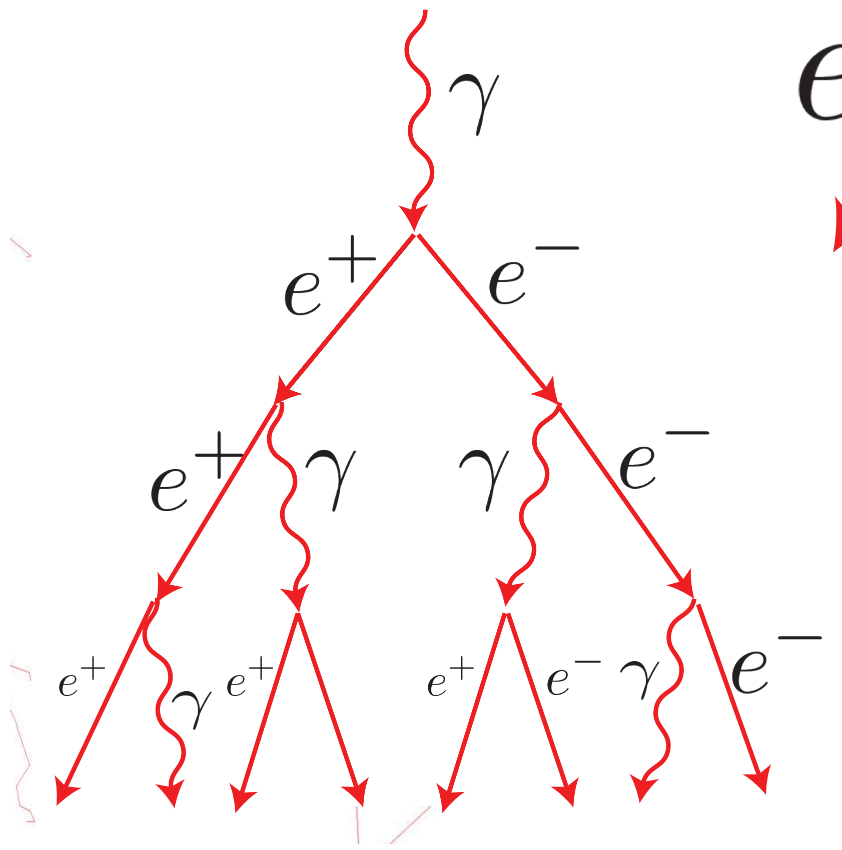


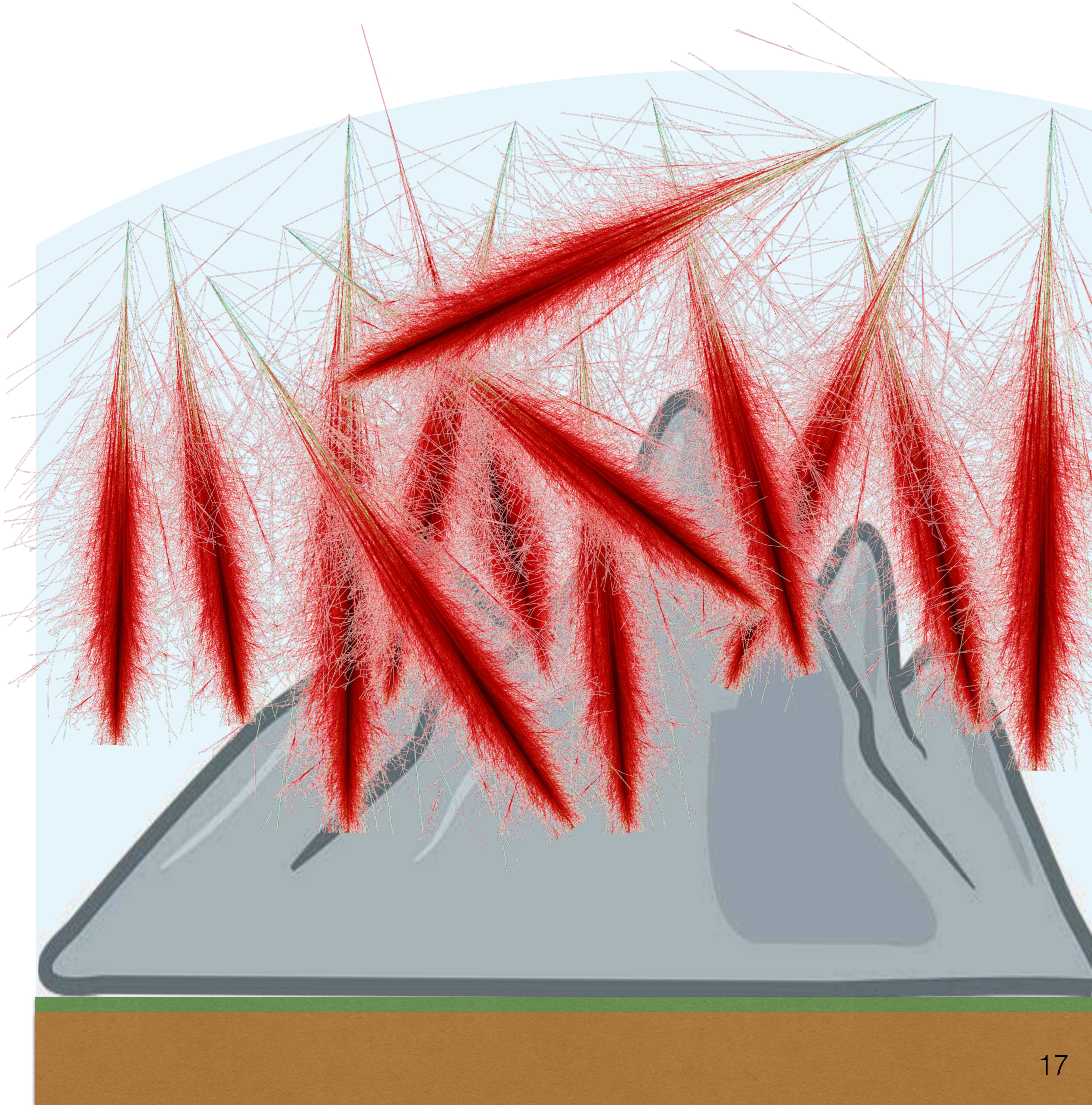


The cosmic ray background

- Charged particles more abundant than γ-rays
- They produce similar showers

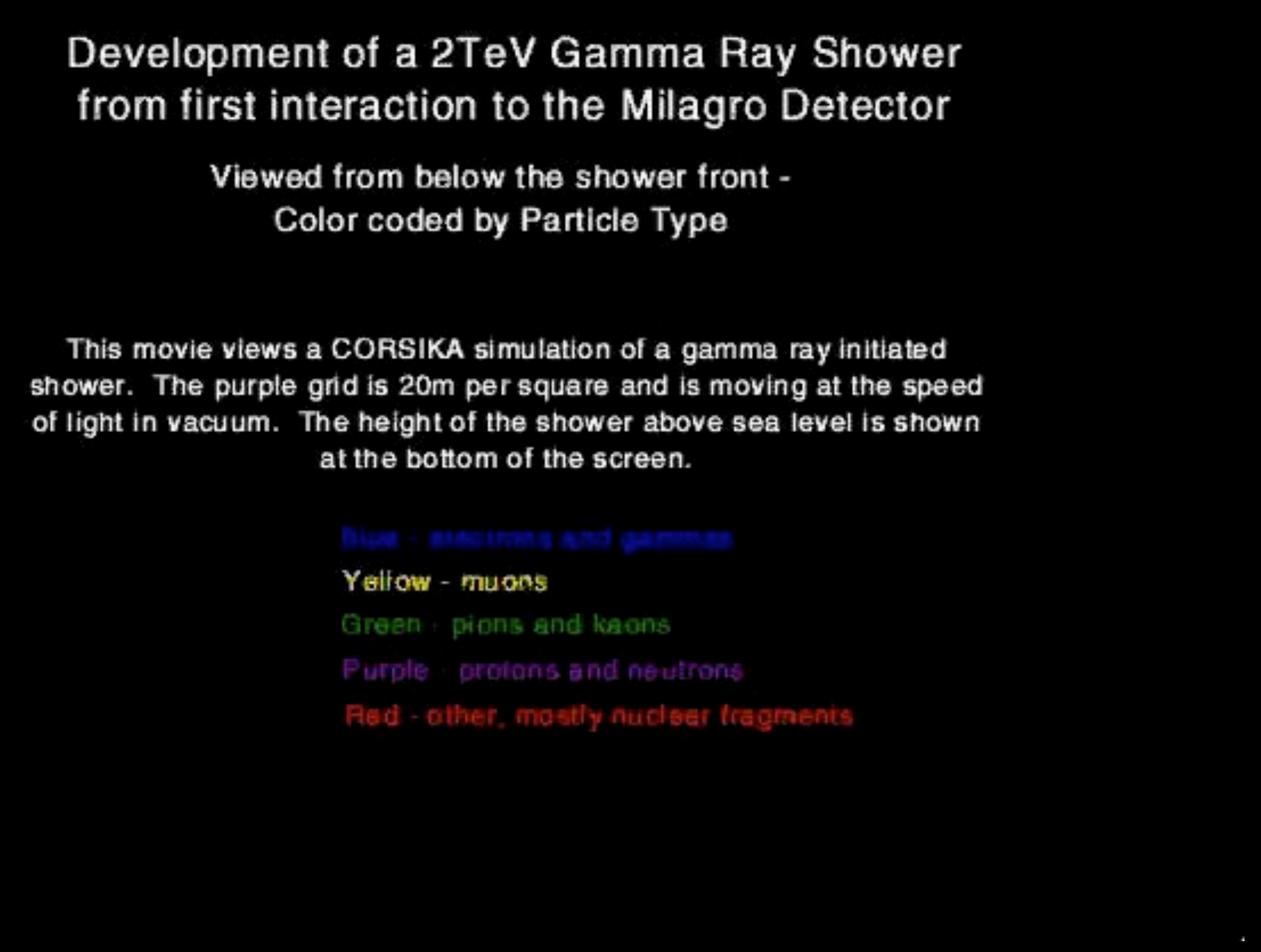




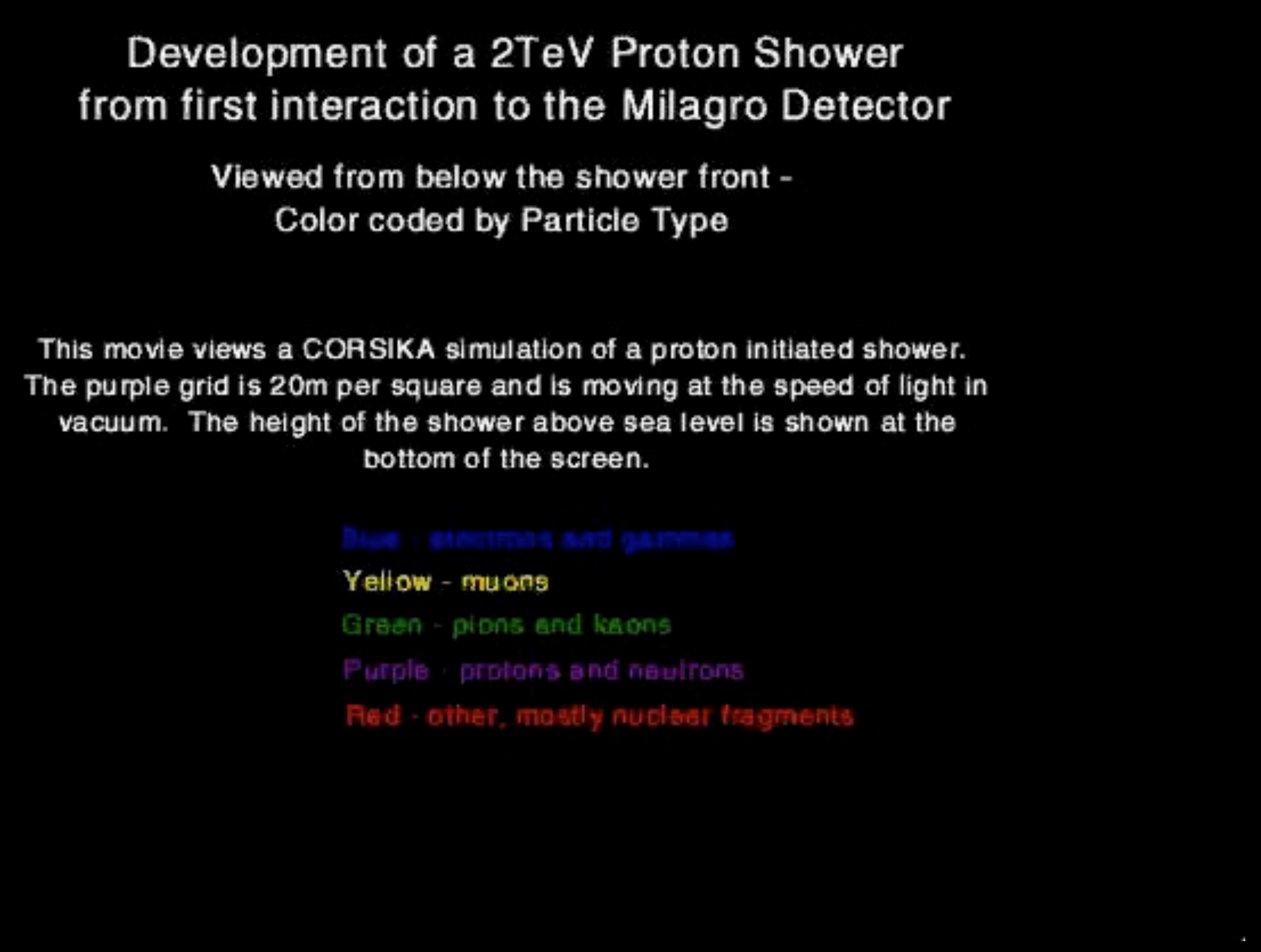


Background rejection

Gamma shower



Hadronic Shower

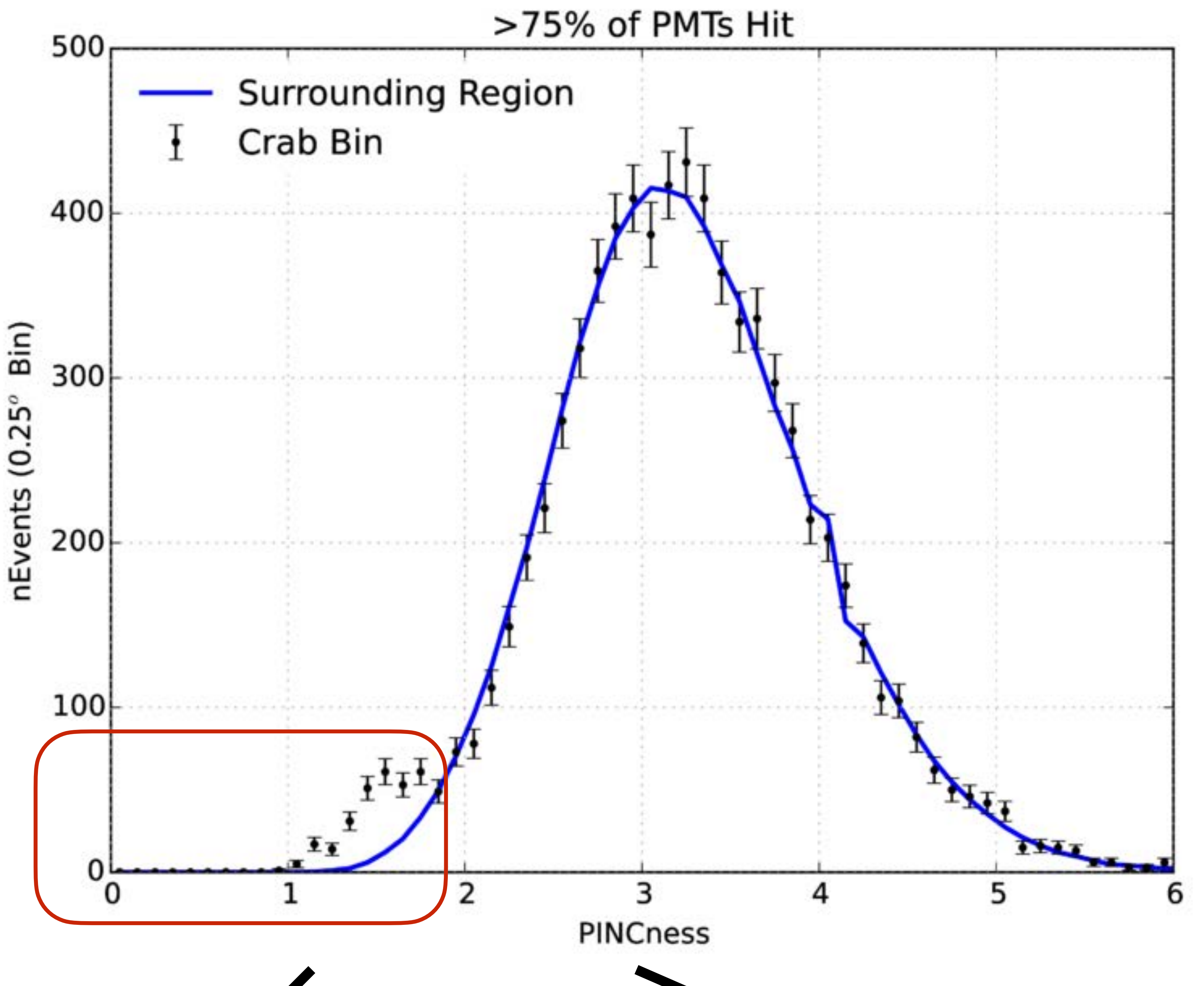


electrons and photons
muons
pions and kaons
protons and neutrons
other (mostly nuclear fragments)

Main differences:

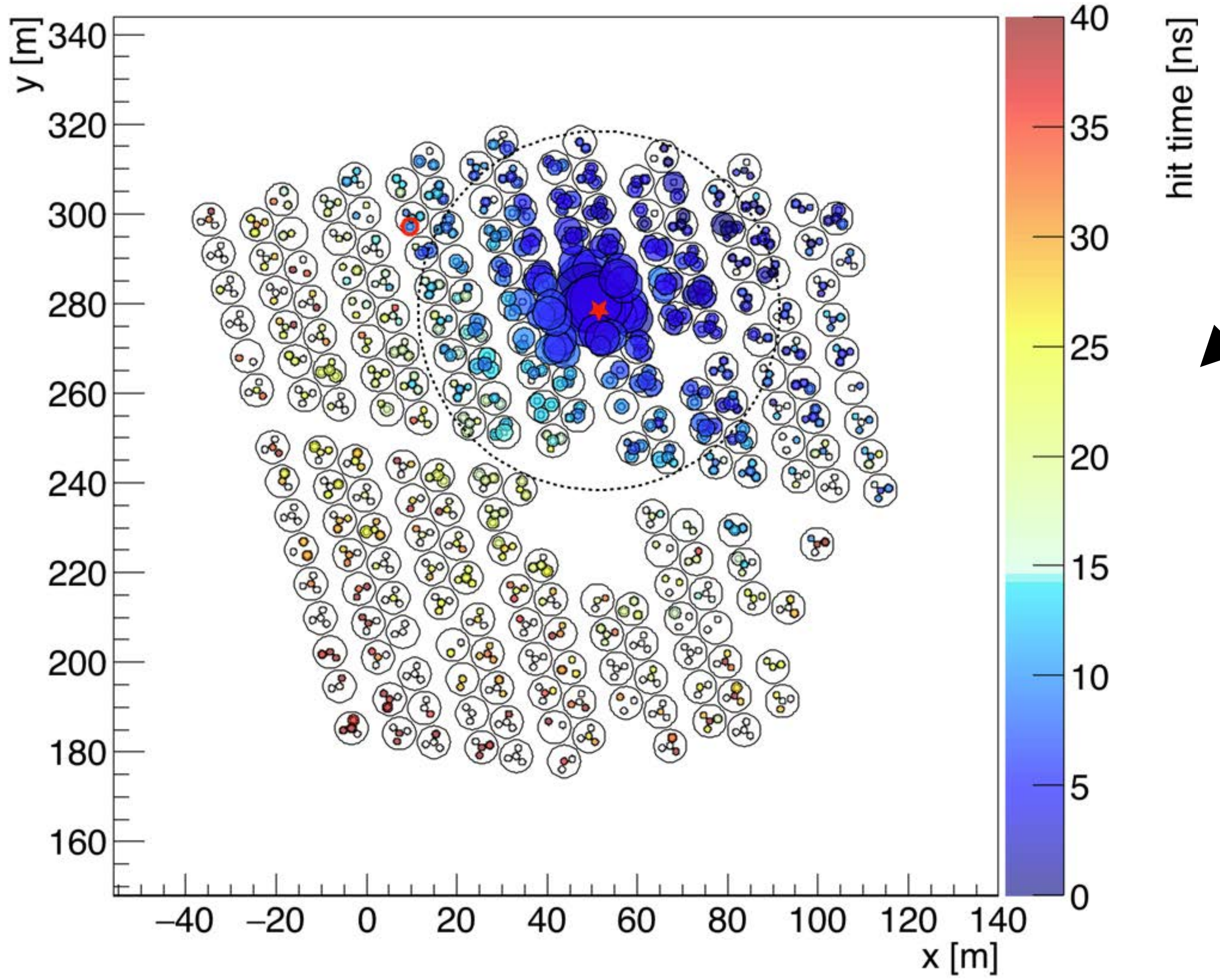
- azimuthal symmetry
- muon content

Background rejection

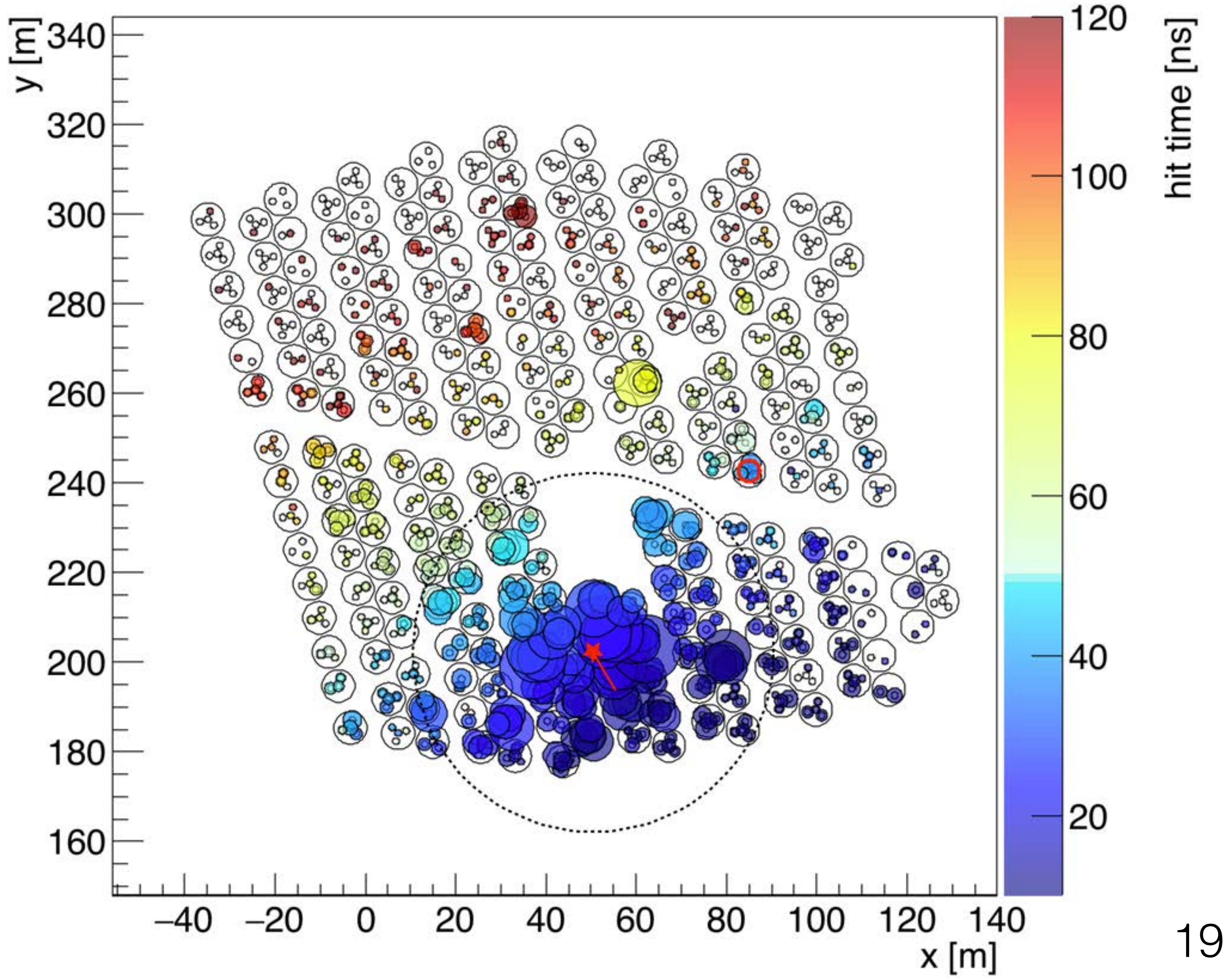


>99.9% rejection for large showers

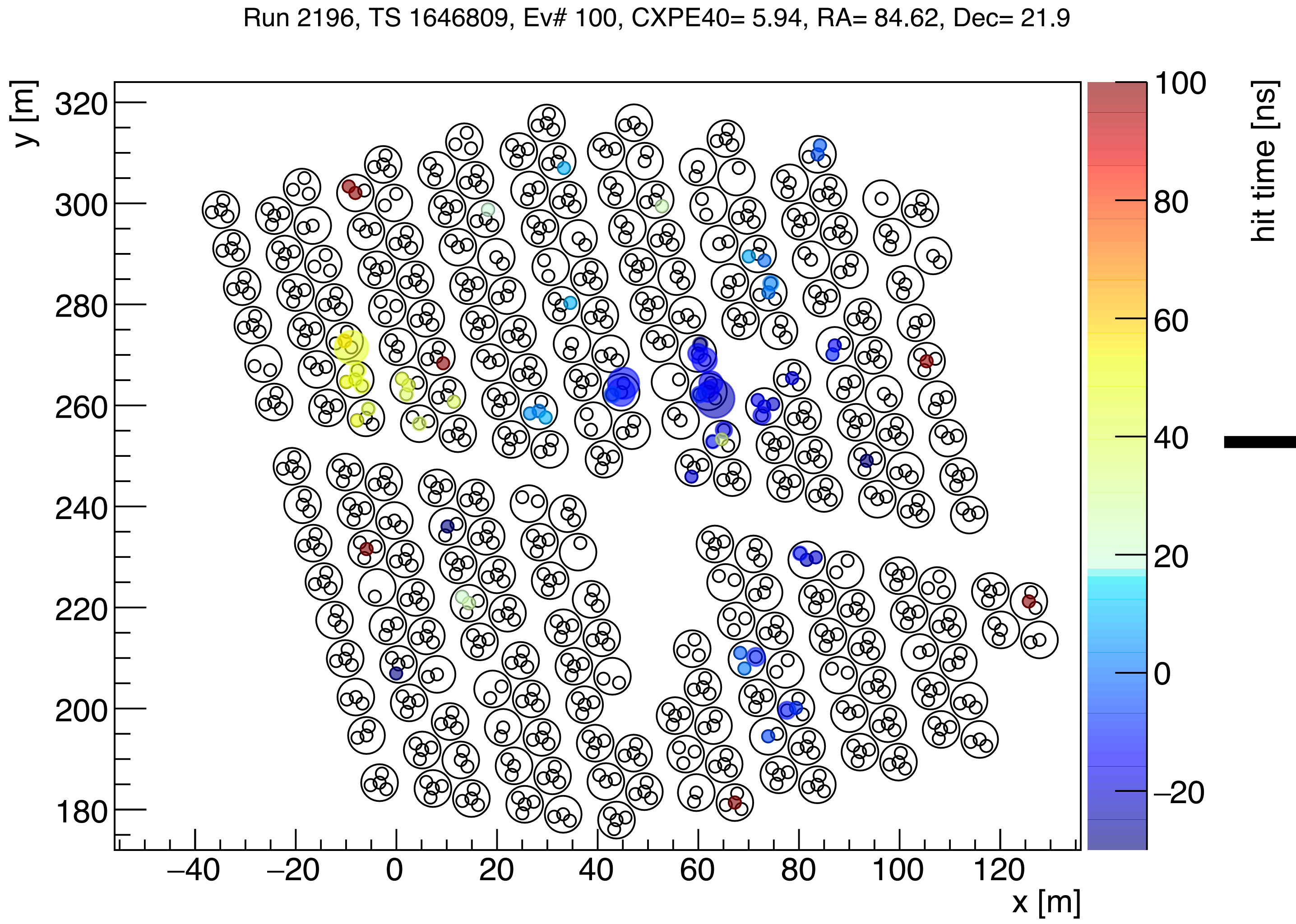
Likely gamma shower

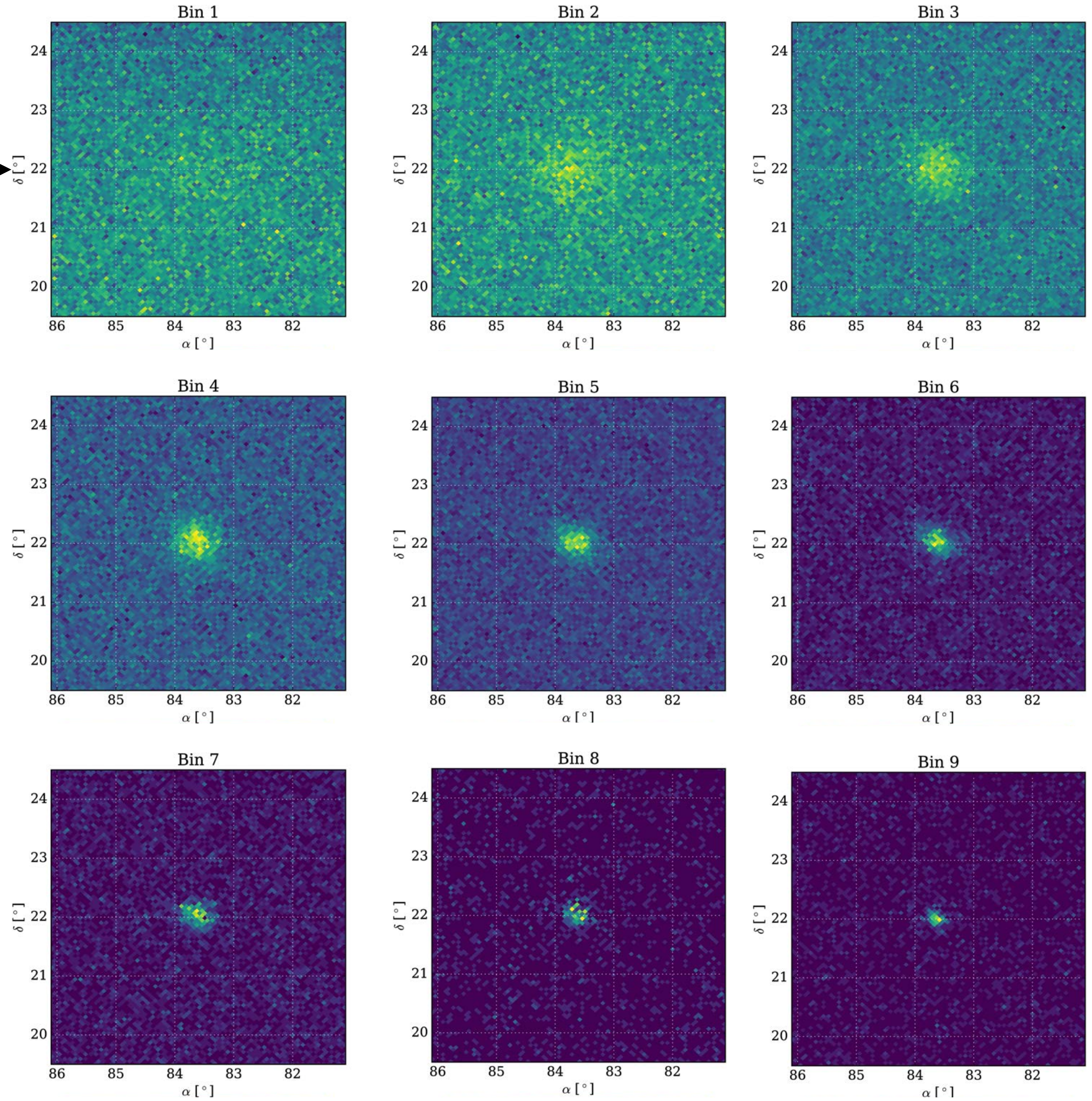


Likely hadron shower



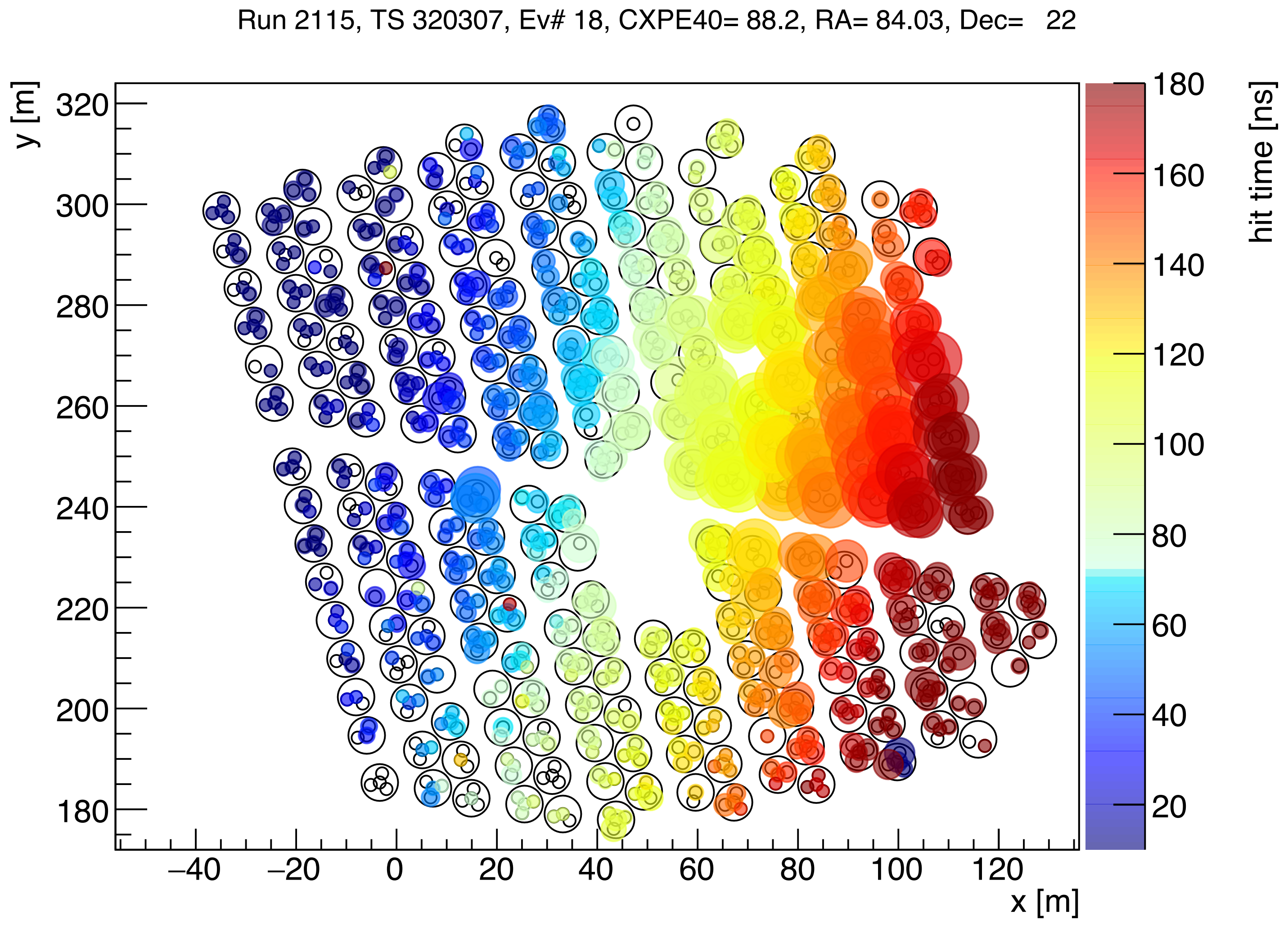
Sensitivity dependence on shower size





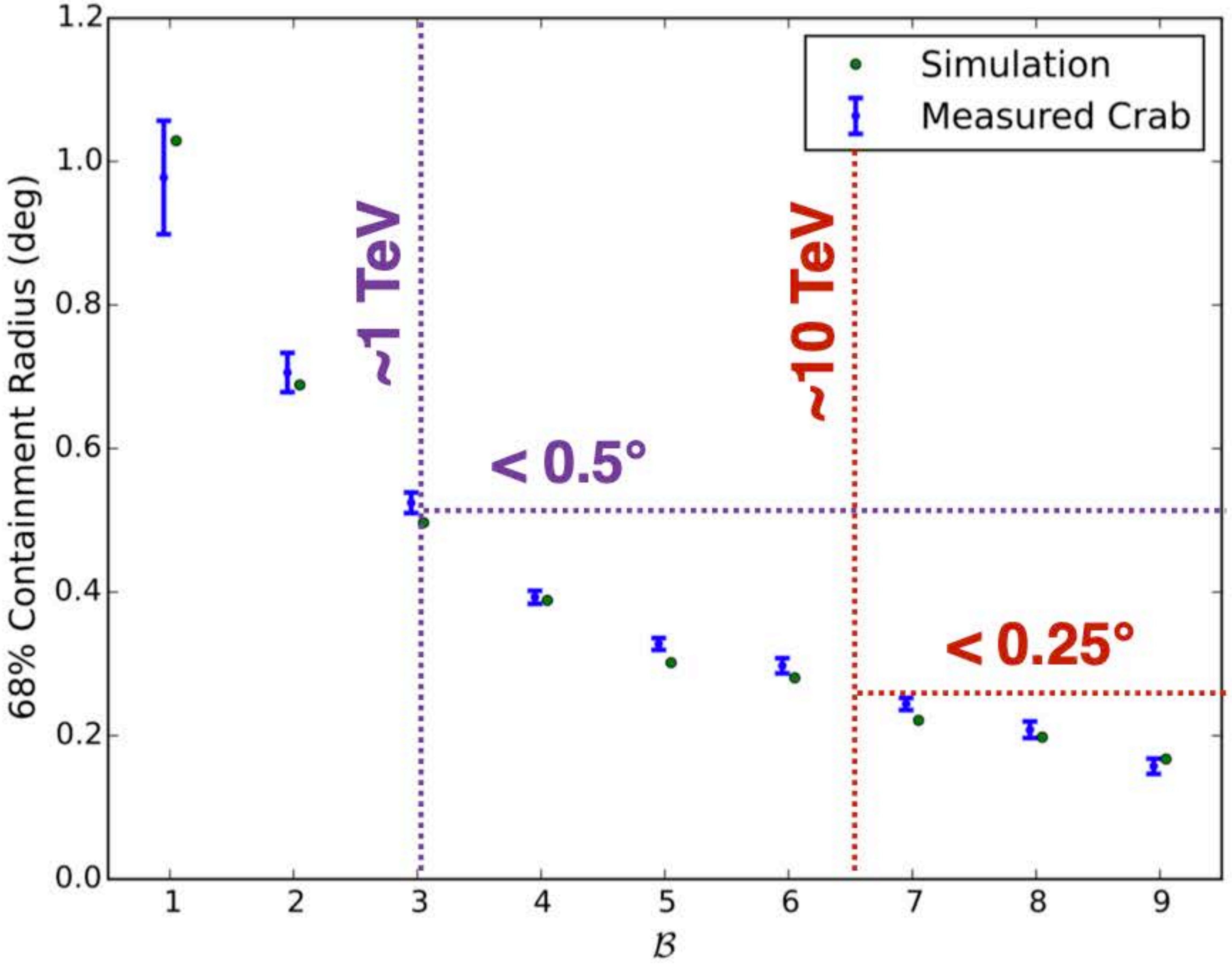
The bigger the shower the:

- the better the angular resolution
- the better the background rejection
- the higher the energy
- the fewer the events

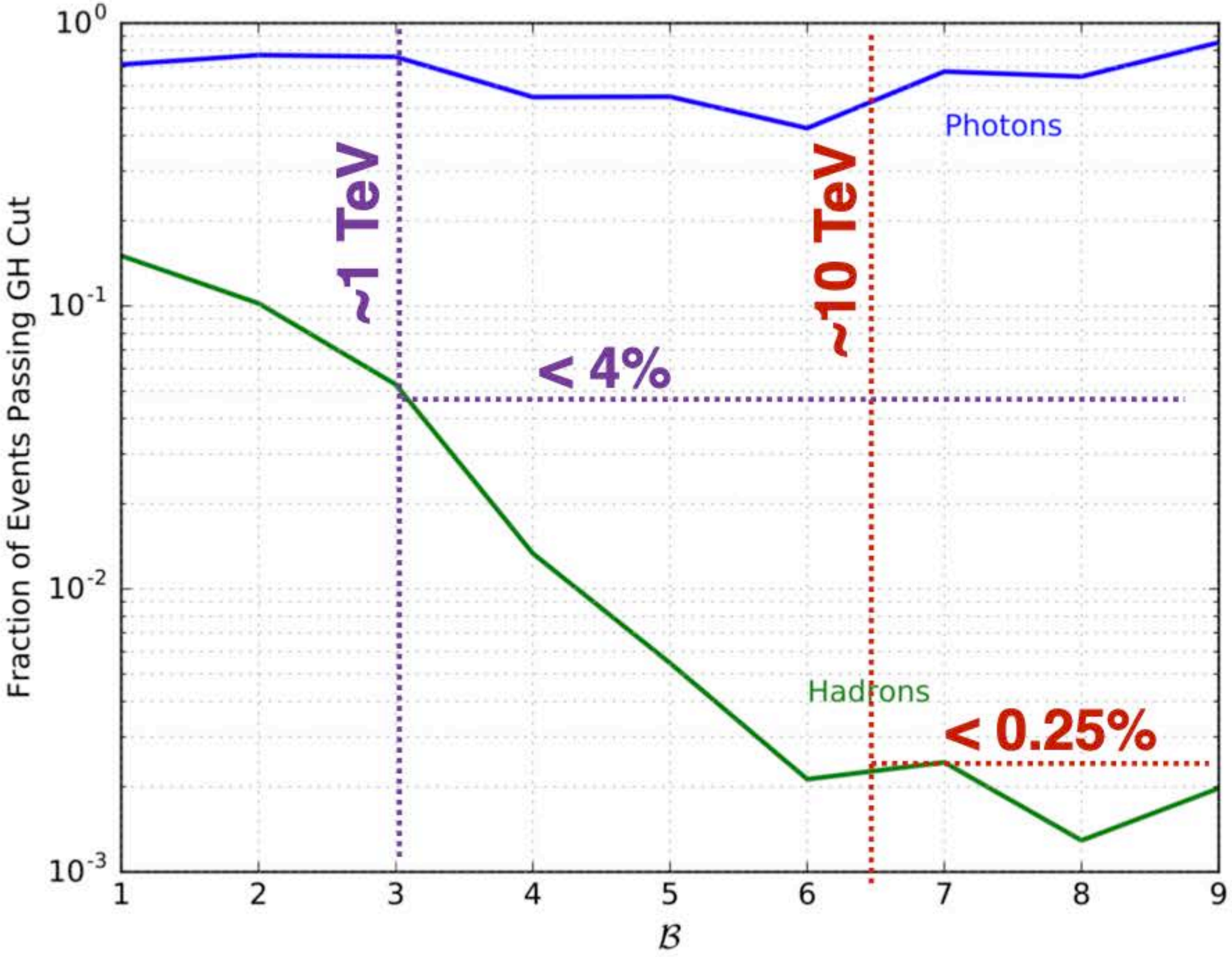


HAWC Reconstruction

Angular resolution



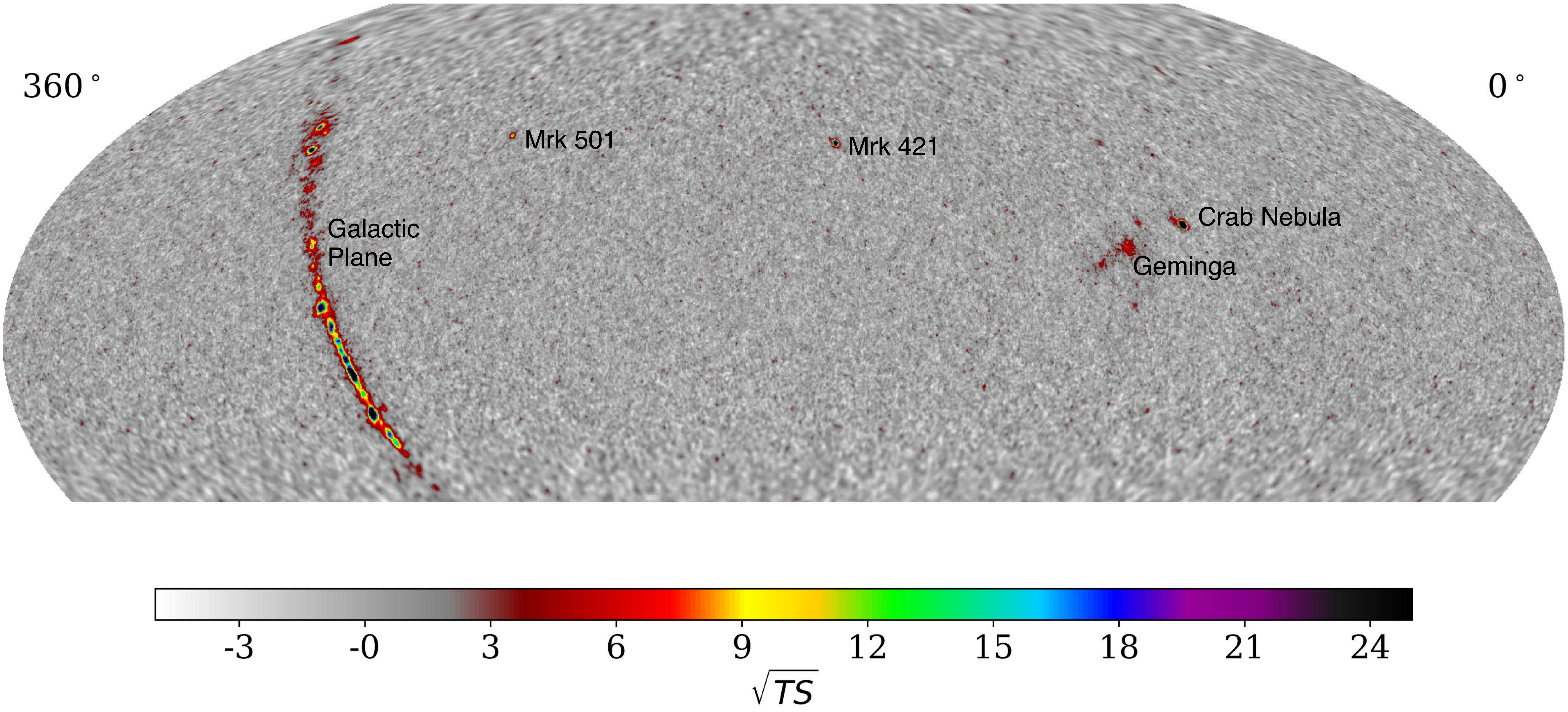
Gamma / Hadron - Cut efficiency



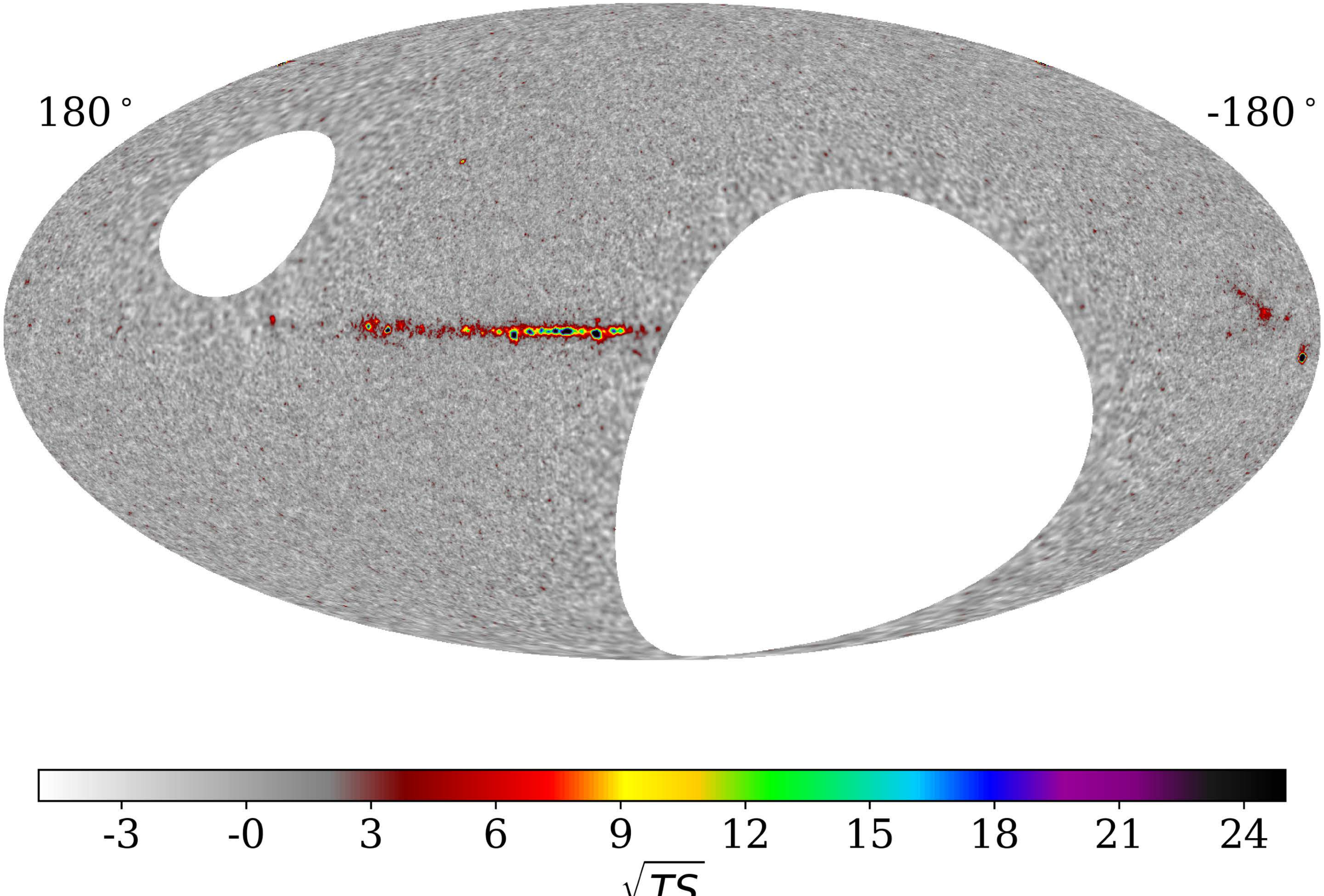
A. U. Abeysekara, *et al*, *ApJ*, **843**, 2017 / arXiv:1701.01778

HAWC Sky Map 1523 Days of Data

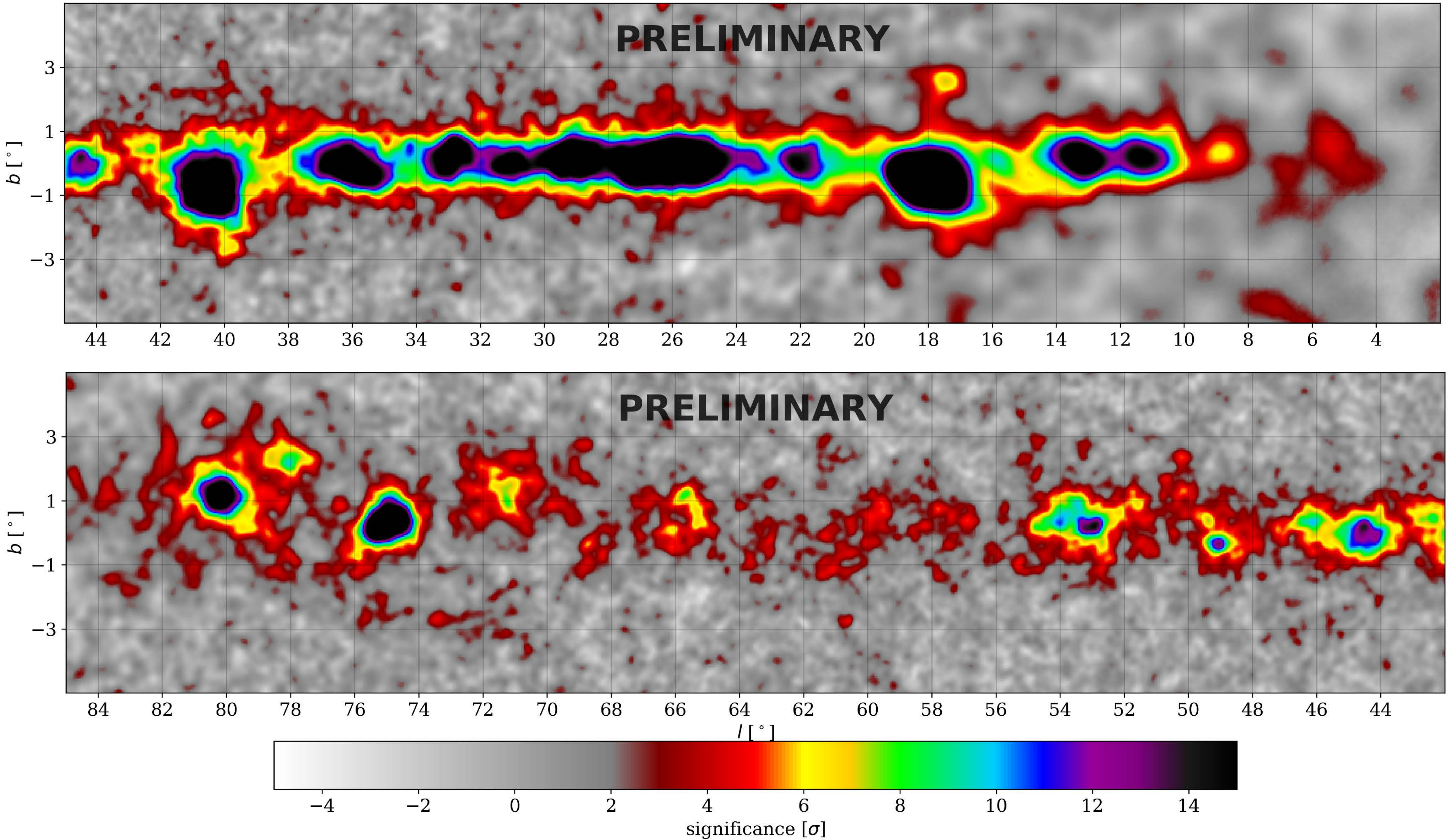
3HWC catalog paper



HAWC 1523-Day TeV Sky Survey

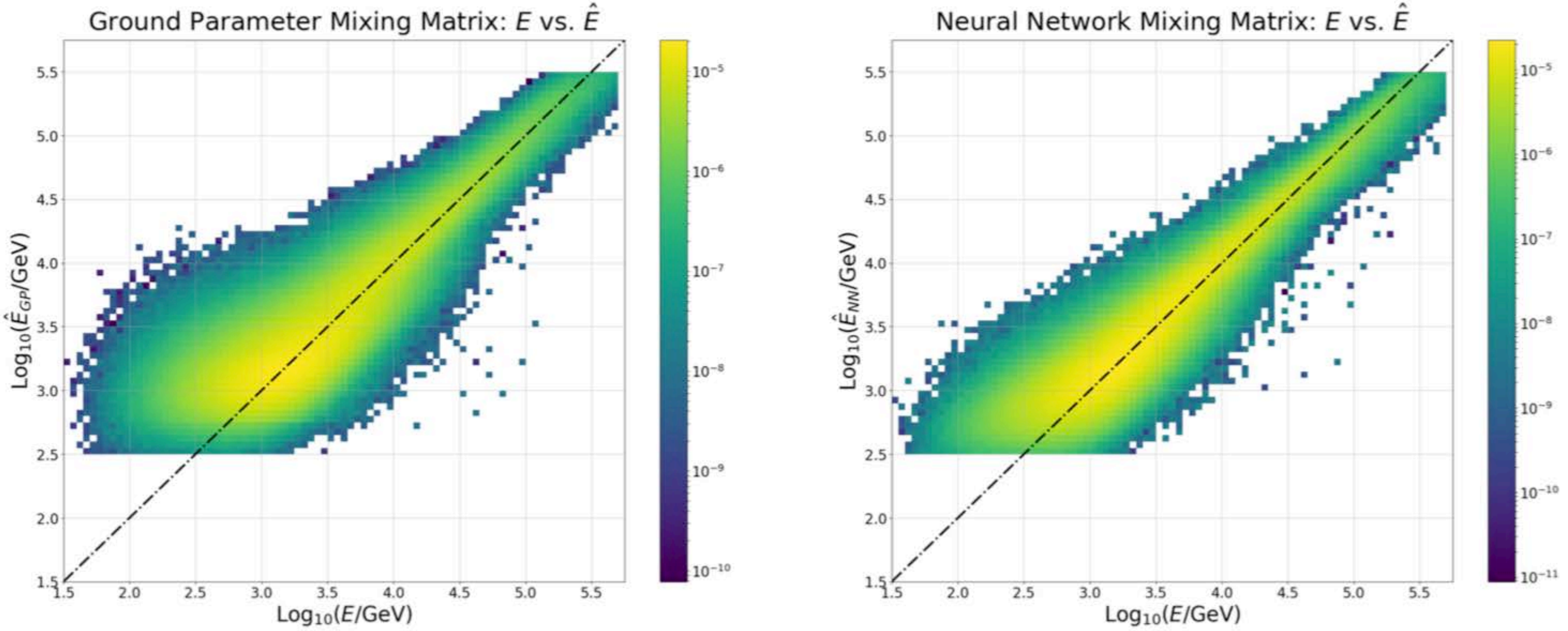


1523 Days of Data



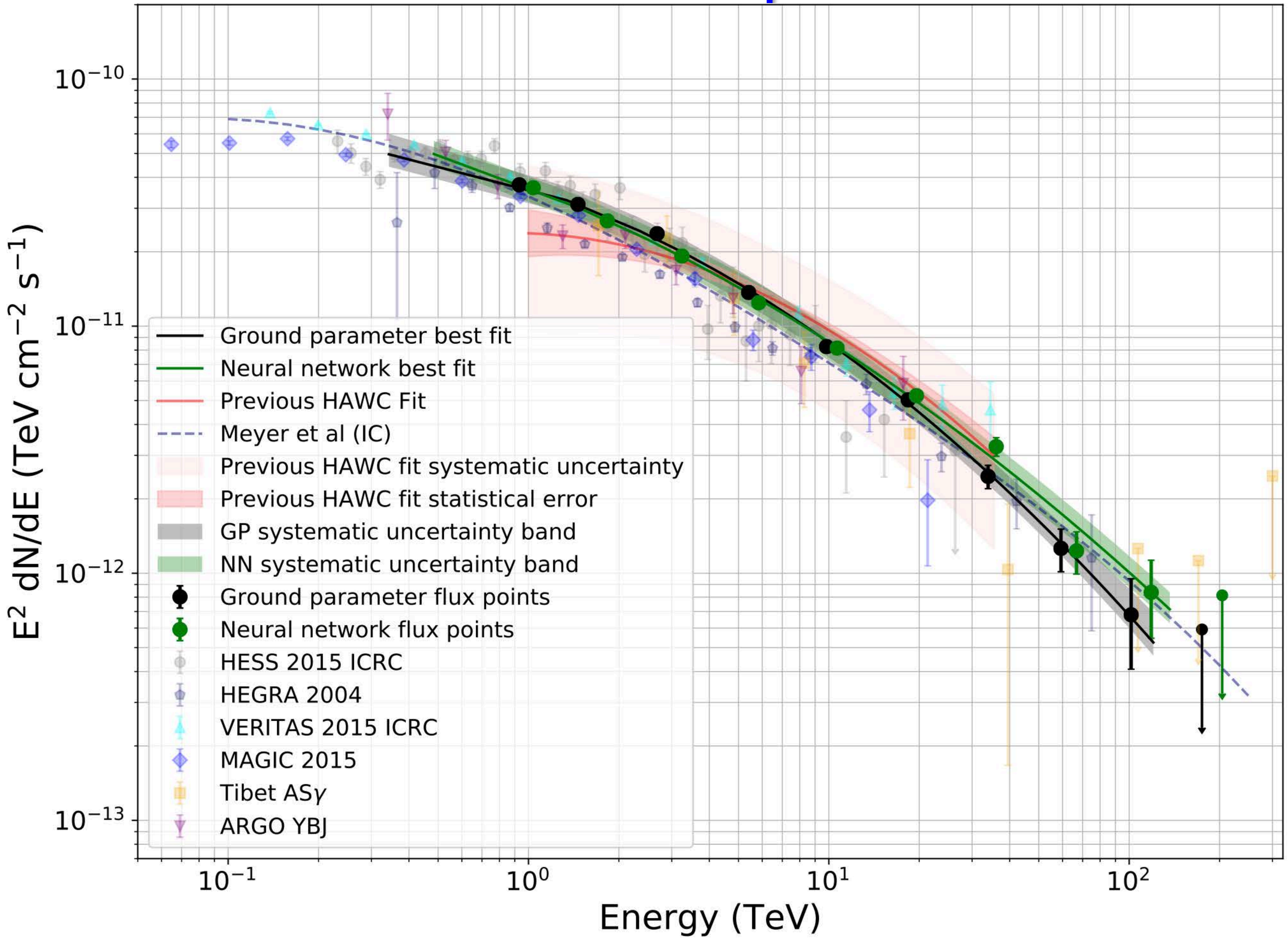
)20

Two Energy Analysis



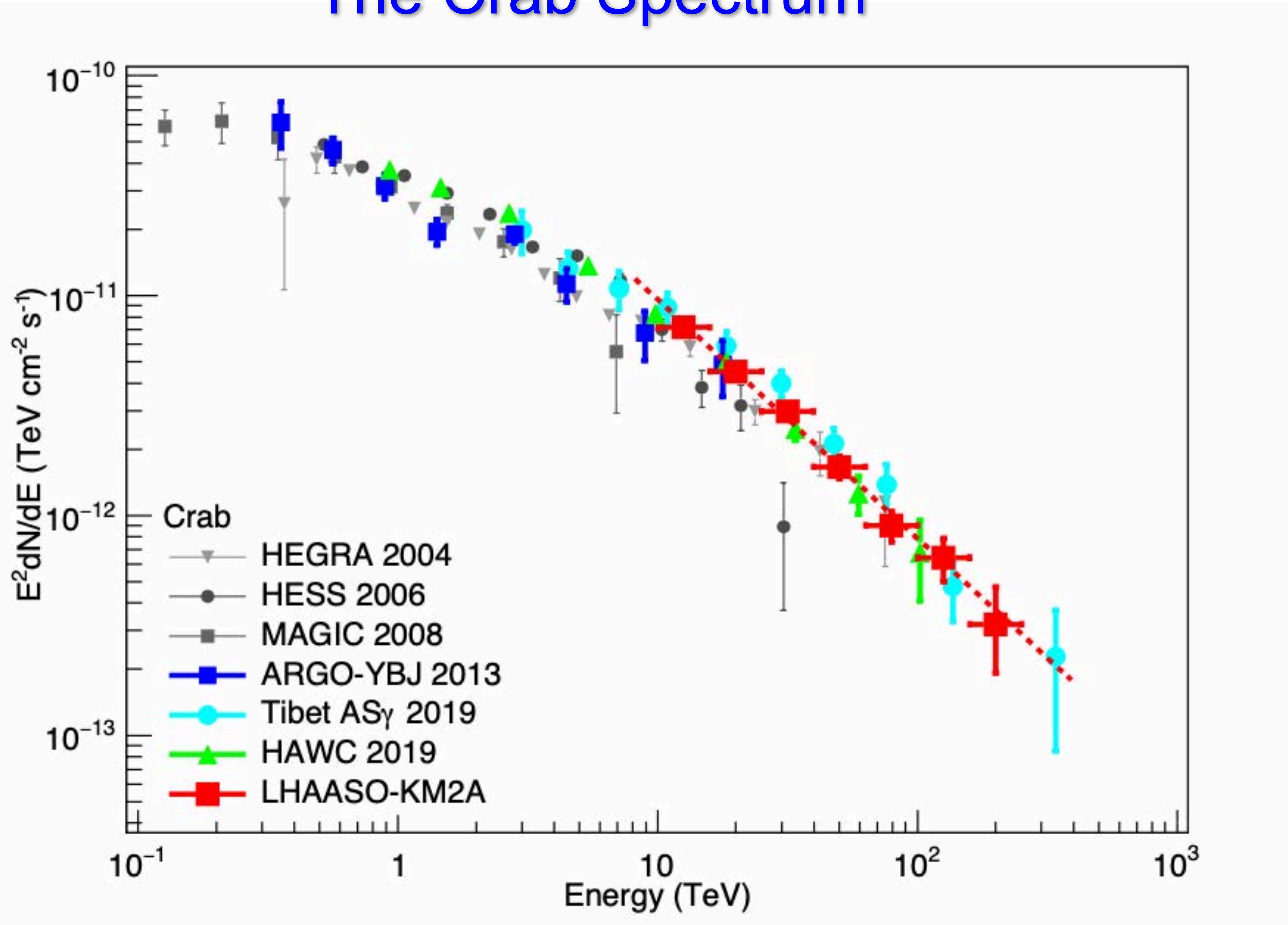
Kelly Malone (PSU/LANL)
Sam Marinelli (MSU)

The Crab Spectrum



Highest Energies ~100 TeV

The Crab Spectrum



Highest Energies ~100 TeV

Pushing to the highest energies (>56 TeV)

- Acceleration mechanisms: hadronic or leptonic?
- Correlation with neutrinos?
- Prospects for testing Lorentz Invariance Violation.

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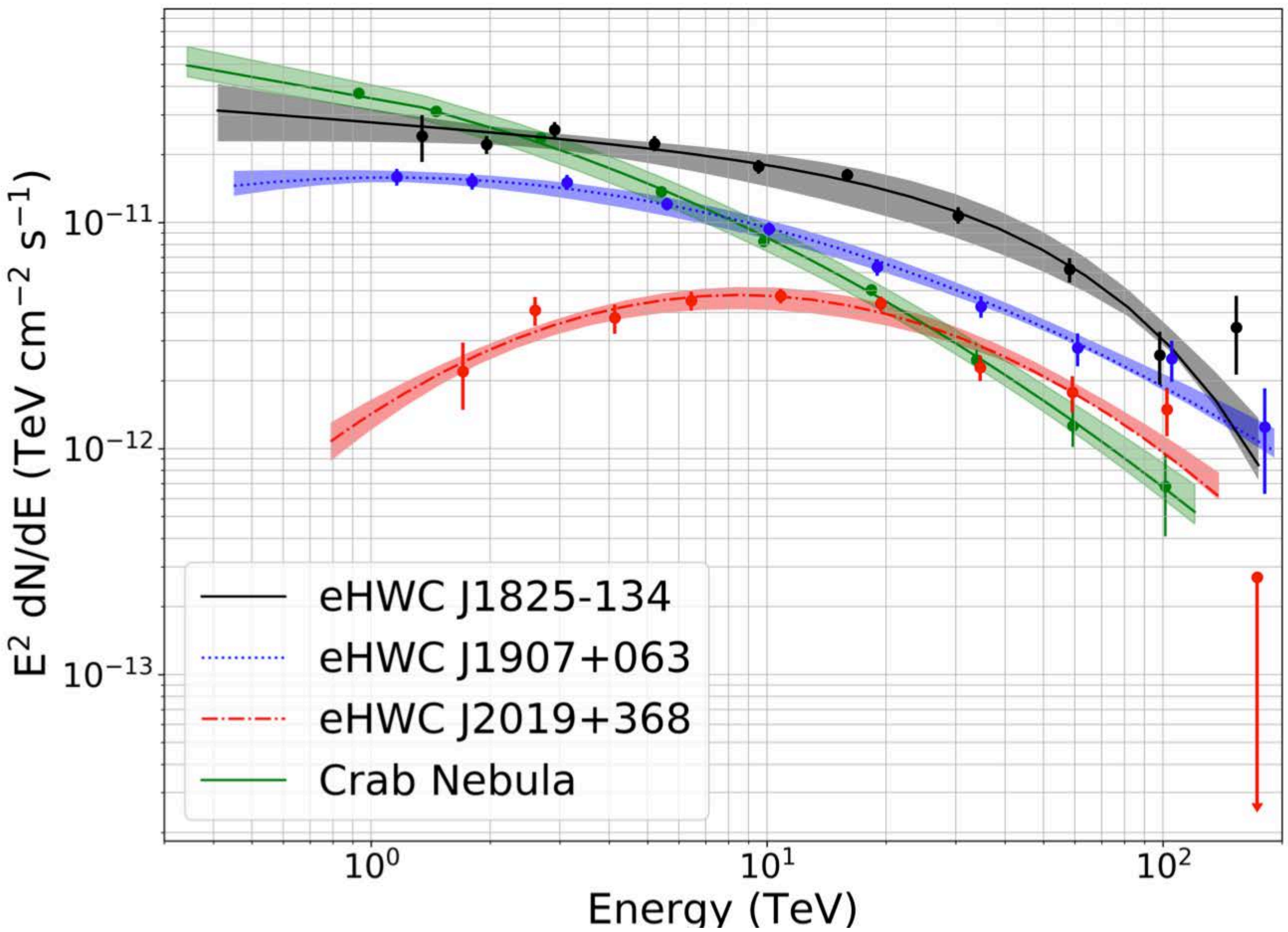
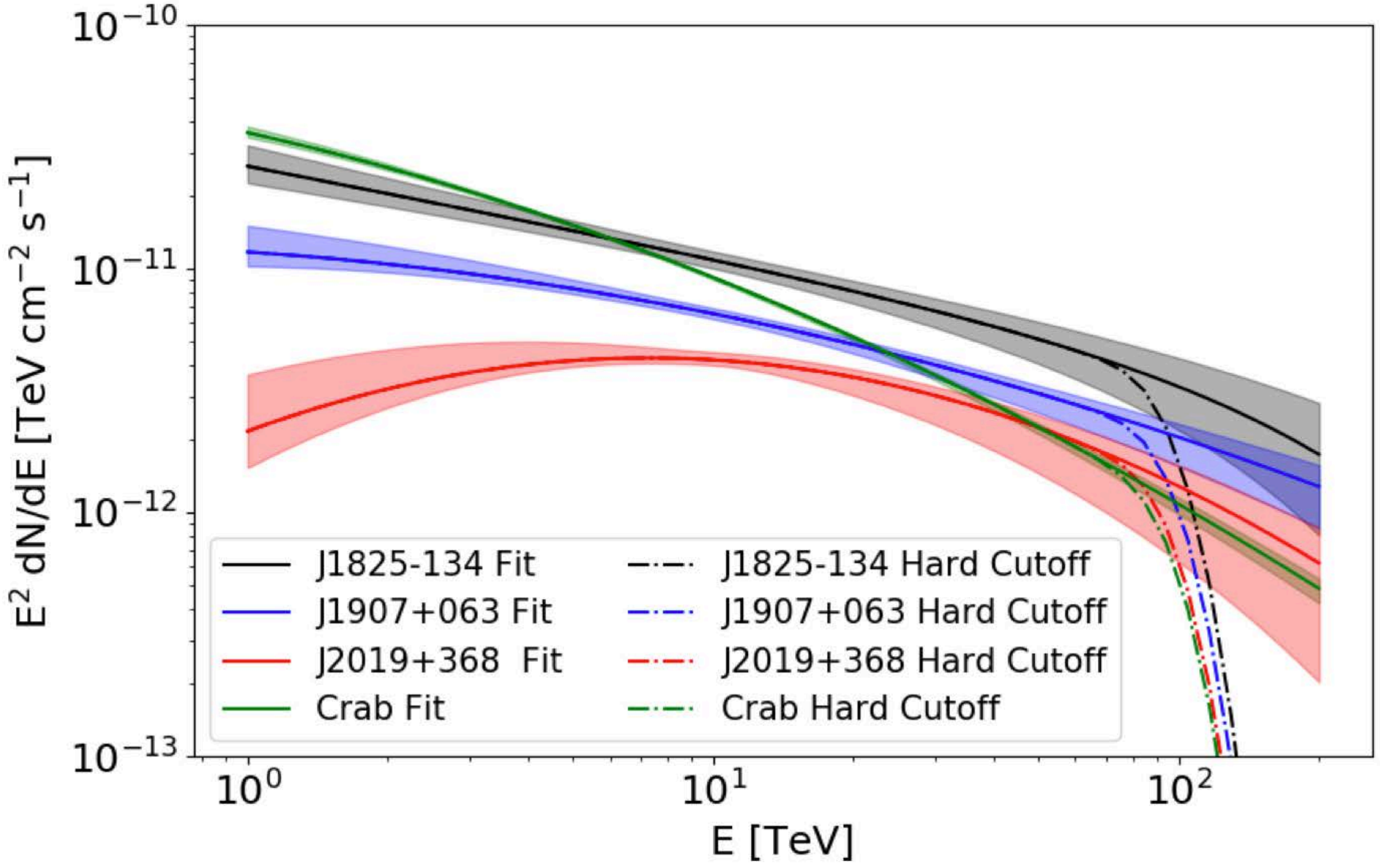
Pushing to the highest energies



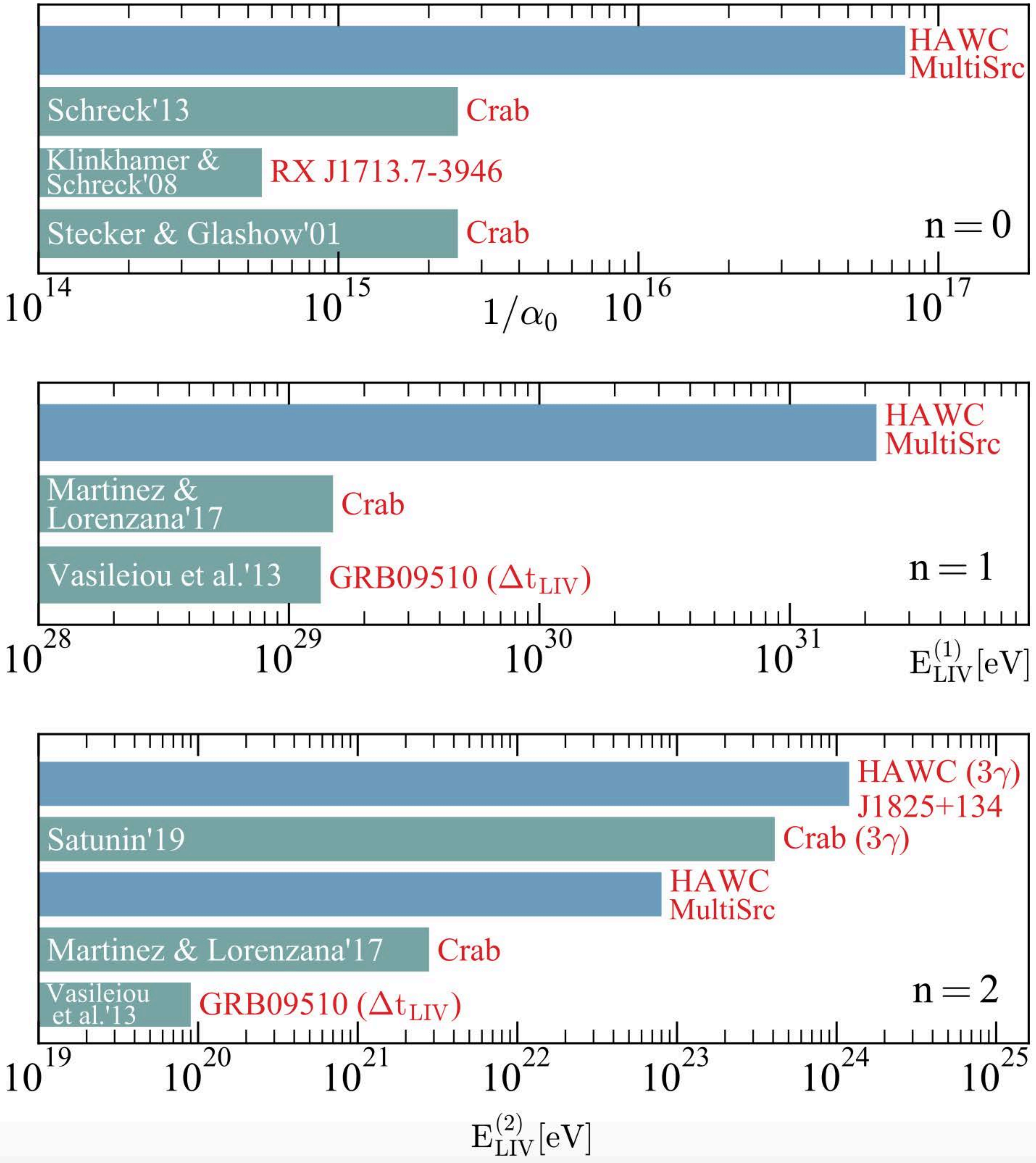
Lorentz Invariance Violation (LIV)

- Photon decays are kinematically forbidden in classical relativity
- If there were Lorentz Invariance Violation
  - there are various forms of modified dispersion relation (MDR)
  - $E_\gamma^2 - p_\gamma^2 = \pm |\alpha_n| p_\gamma^{n+2}$
  - This would allow photons to decay - producing a cut-off in the highest energy photons
- We set LIV limits by because HAWC finds evidence of >100 TeV photons with no hard cut-off

LIV



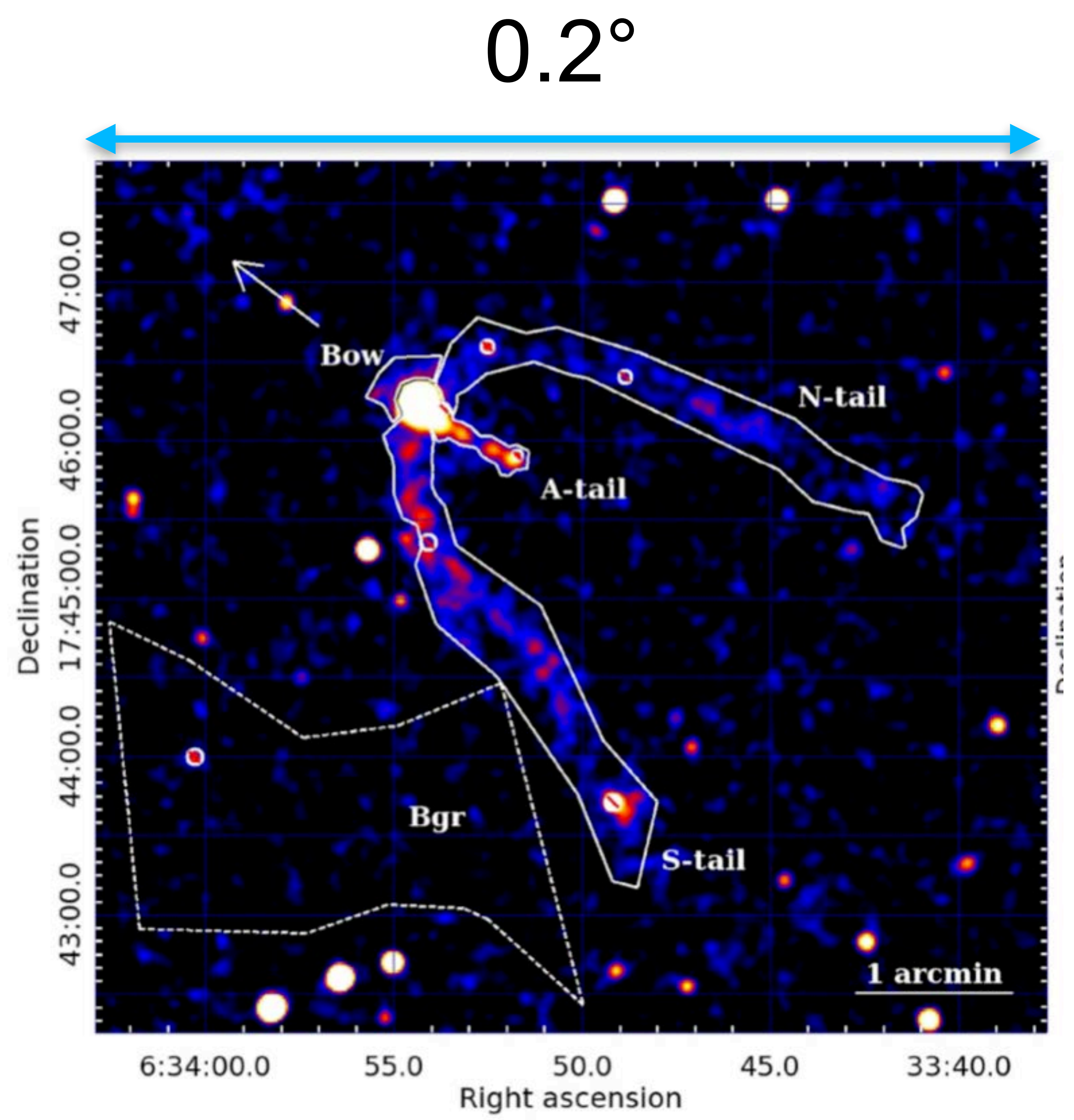
Source	p-value	$E_c(95\%)$	$E_c(3\sigma)$
eHWC J1825-134	1.000	244	158
eHWC J1907+063	0.990	218	162
eHWC J0534+220 (Crab)	1.000	152	104
eHWC J2019+368	0.828	120	88



$$E_\gamma^2 - p_\gamma^2 = \pm |\alpha_n| p_\gamma^{n+2}$$

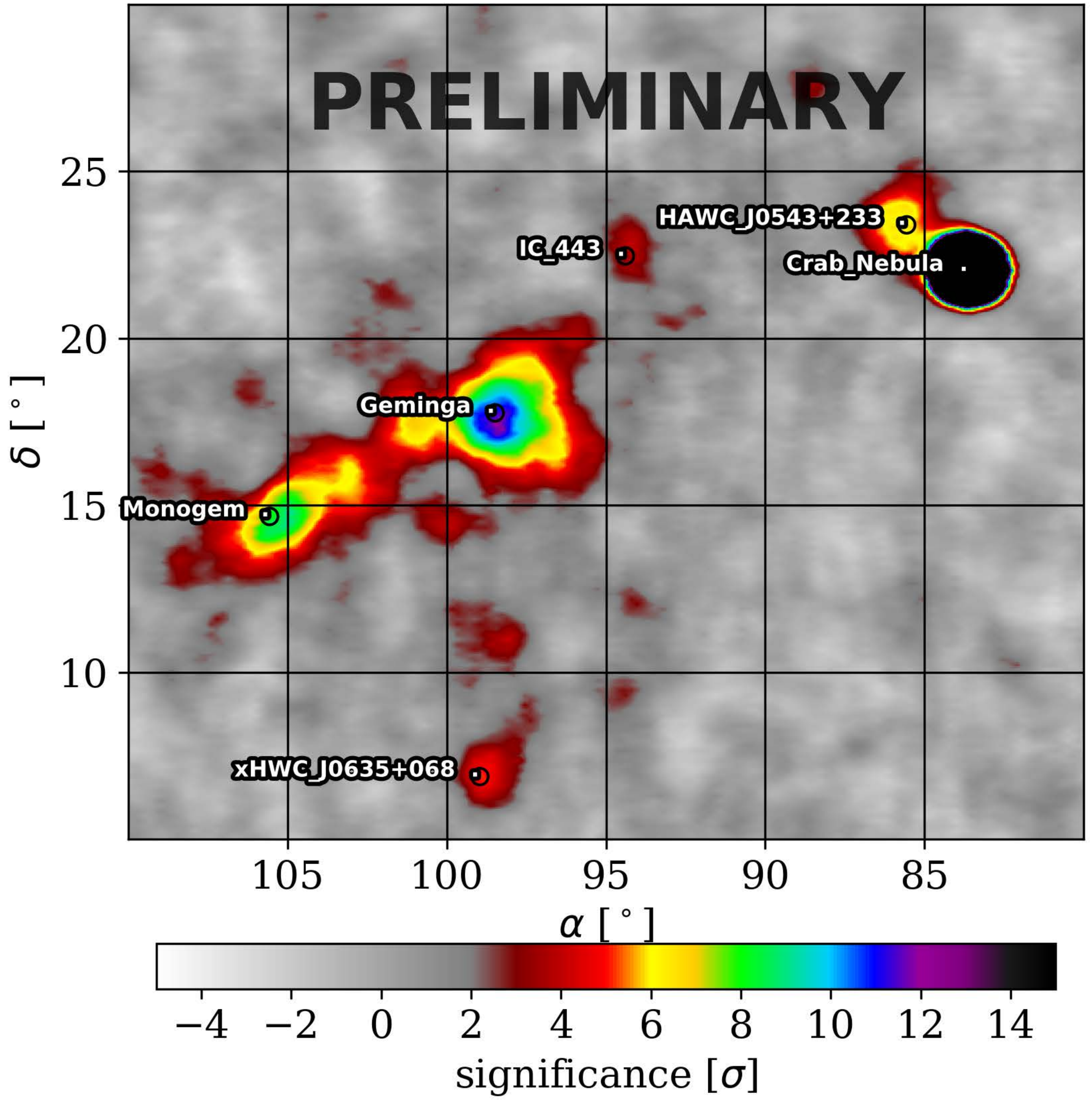
Geminga - PWN

- Geminga is one of the brightest GeV sources in the northern sky
- It's a middle-aged 340kyr, pulsar T=0.237s
- It's close to earth - 250^{+250}_{-62} pc
- X-Ray PWN seen to be very small
- First seen in TeV by Milagro at 40 TeV
- HAWC also sees energies above 25TeV
- Very extended in the TeV - ~5 degrees across
- Not easily seen by IACTs



The Galactic Anti-Center

- New class of sources
  - Highly extended hard spectrum sources surrounding PWN
  - Labeled TeV Halos because their extension is much larger than the PWN
  - In the outer galaxy where there is little source confusion
  - Geminga and PSR B0656+14
    - Two middle-aged close-by PWN
    - Very extended in the sky
    - Thought to be a possible source of the positron excess



Where do these gammas come from?

- Inverse Compton Scattering
  - Off of what?
- HAWC sees gammas above 25 TeV from these sources
  - These must come from >100 TeV electrons
  - At these energies the Compton Cross section is suppressed for scattering off of IR or optical photons
    - Why?

Compton Scattering Cross Section

- Thompson cross section (non-relativistic)

$$\sigma_T = \frac{8\pi}{3} r_e^3$$

r_e is the classical radius of the electron

- This applies when the photon energy in the rest frame of the electron is $<< m_e c^2$
- If the photon energy is $> m_e c^2$ you need to use the relativistic formulation

Klein Nishina Scattering

$$\sigma = 2\pi \int_0^\pi \frac{d\sigma}{d\Omega} \sin\theta d\theta$$
$$= \ldots..$$
$$= \frac{3}{4}\sigma_T \left[\frac{1+x}{x^3}\left(\frac{2x(1+x)}{1+2x} - \ln(1+2x)\right) + \frac{1}{2x}\ln(1+2x) - \frac{1+3x}{(1+2x)^2}\right]$$

where

$$x \equiv \frac{h\nu_i}{m_e c^2}$$

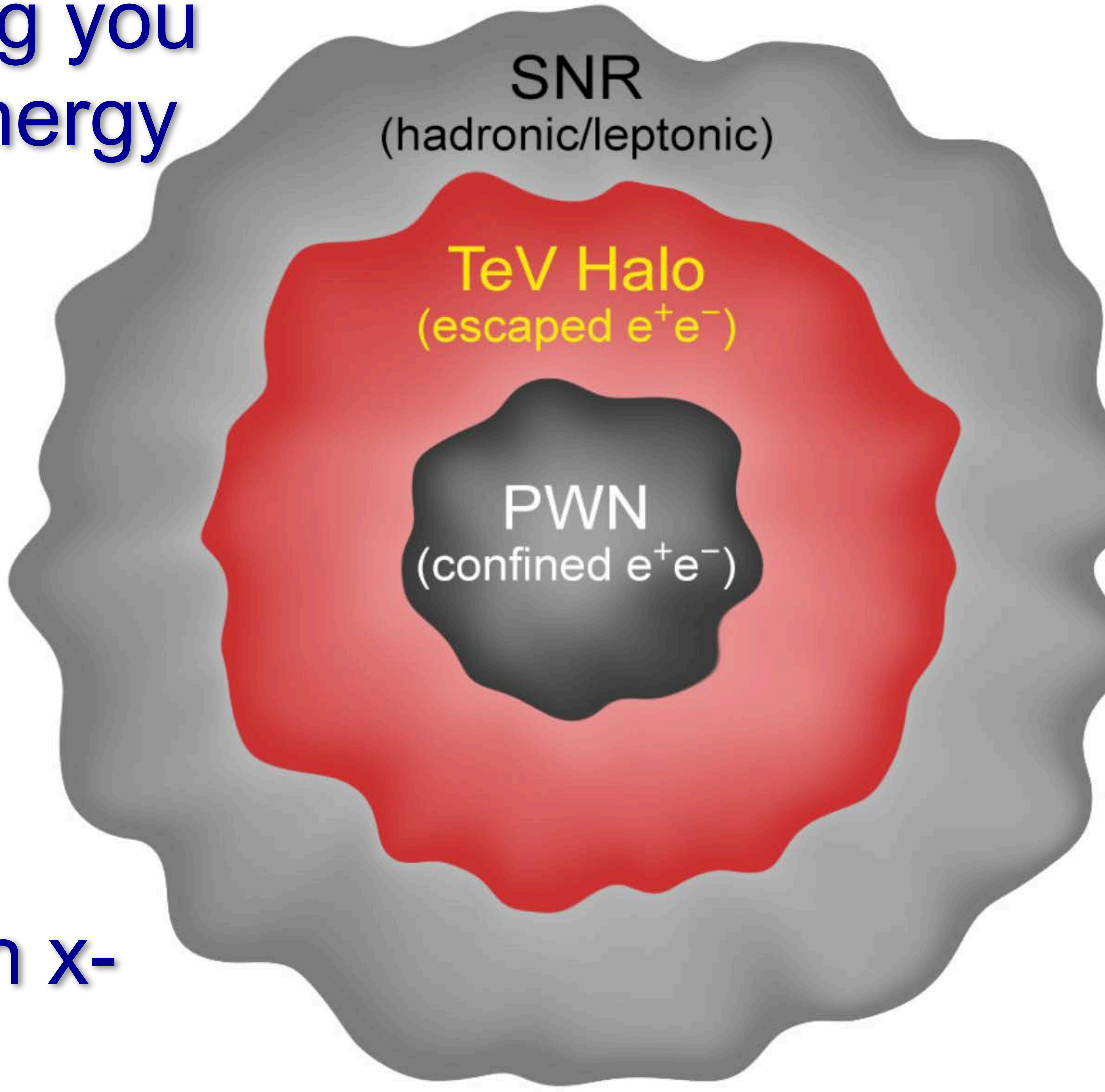
Limits:

$$\sigma(x) \simeq \sigma_T (1 - 2x + \ldots) \quad \text{for} \quad x \ll 1 \quad \text{(Thomson)}$$

$$\sigma(x) \simeq \frac{3}{8}\sigma_T \frac{1}{x}\left(\ln 2x + \frac{1}{2}\right) \quad \text{for} \quad x \gg 1 \quad \text{(extreme KN)}$$

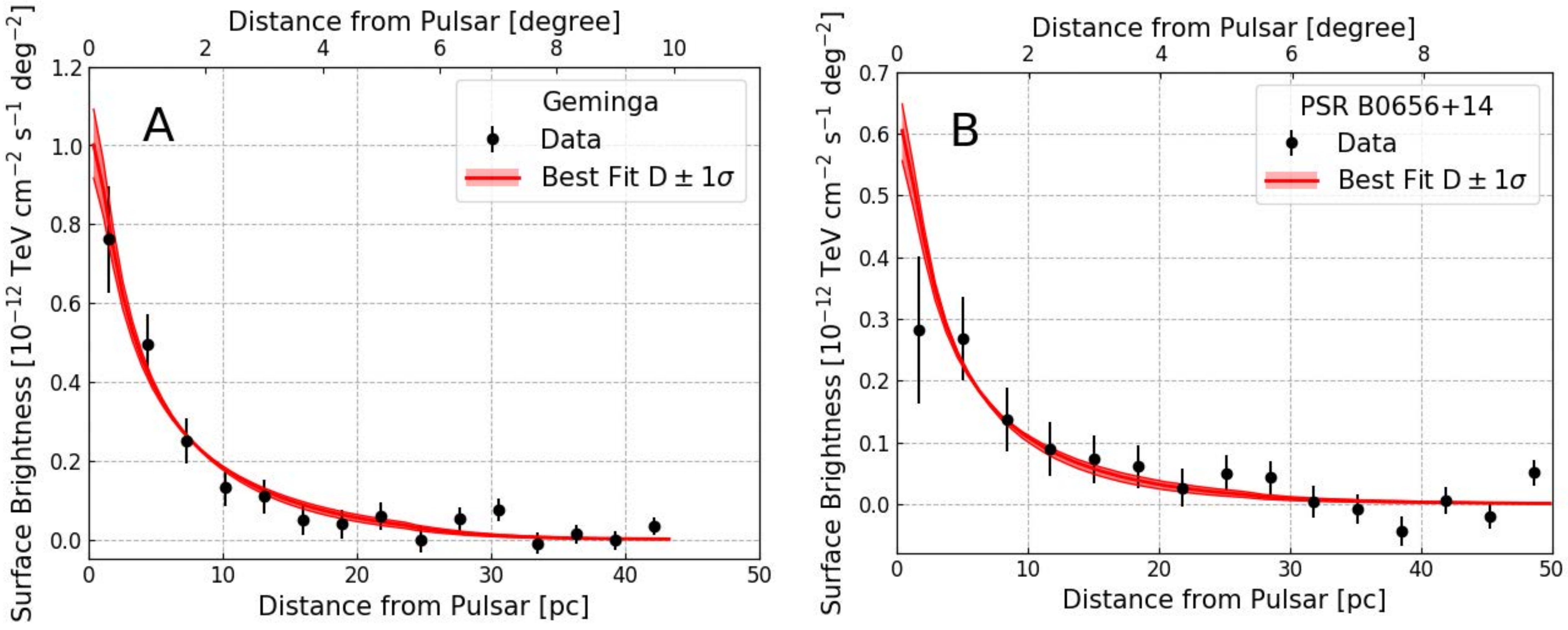
TeV Halos

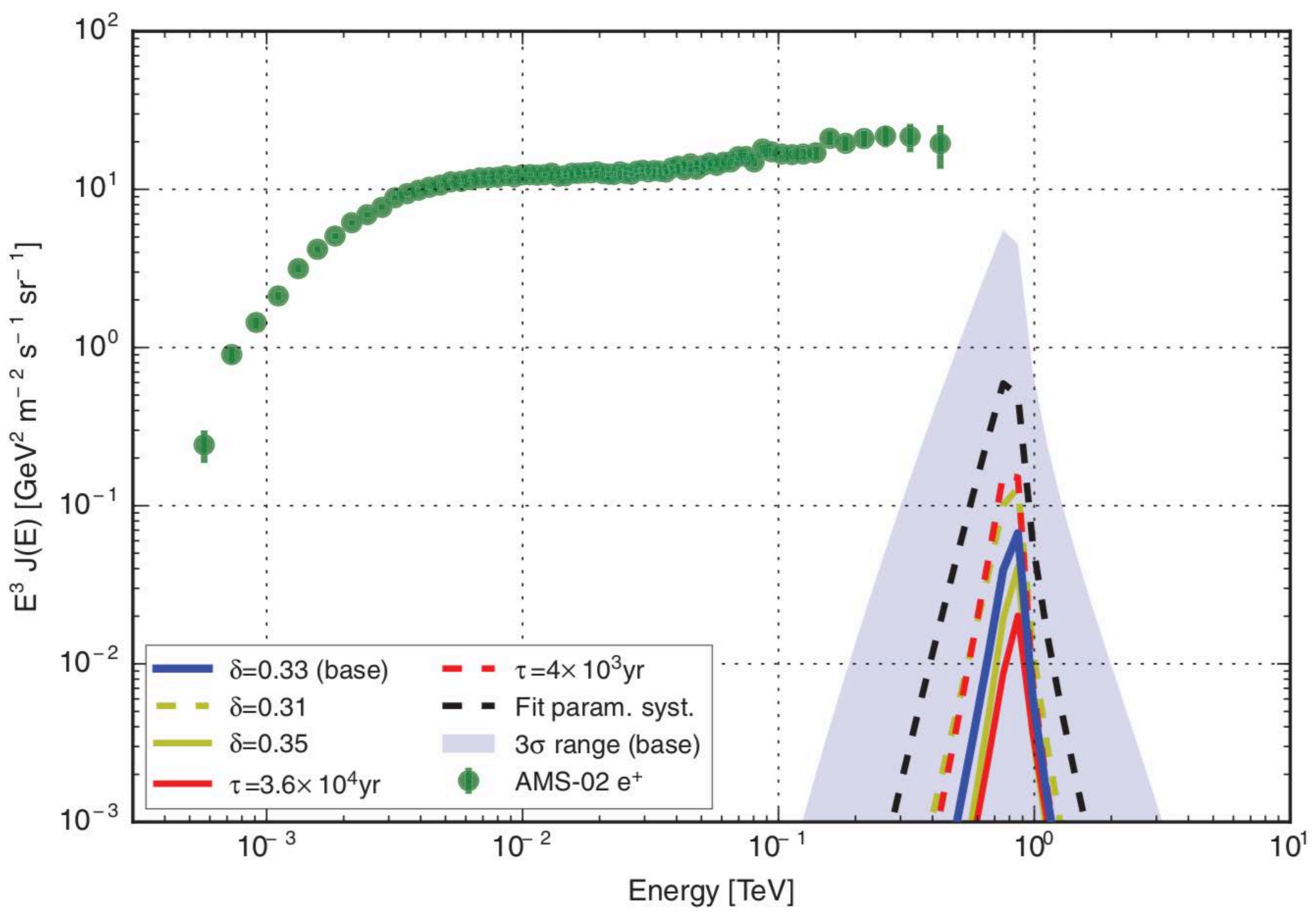
- For electrons above ~100 TeV the only thing you can scatter off of is the CMB because its energy is so low
  - OTH you know what it is everywhere
- The x-ray emission is from synchrotron radiation, where the B field is enhanced by the pulsar to 10 to 20 μG
- The spatial extent of these two sources at TeV is tens of parsecs, which is much greater than the <0.1 pc nebula observed in x-rays so the B is like ISM values of ~ 3 μG



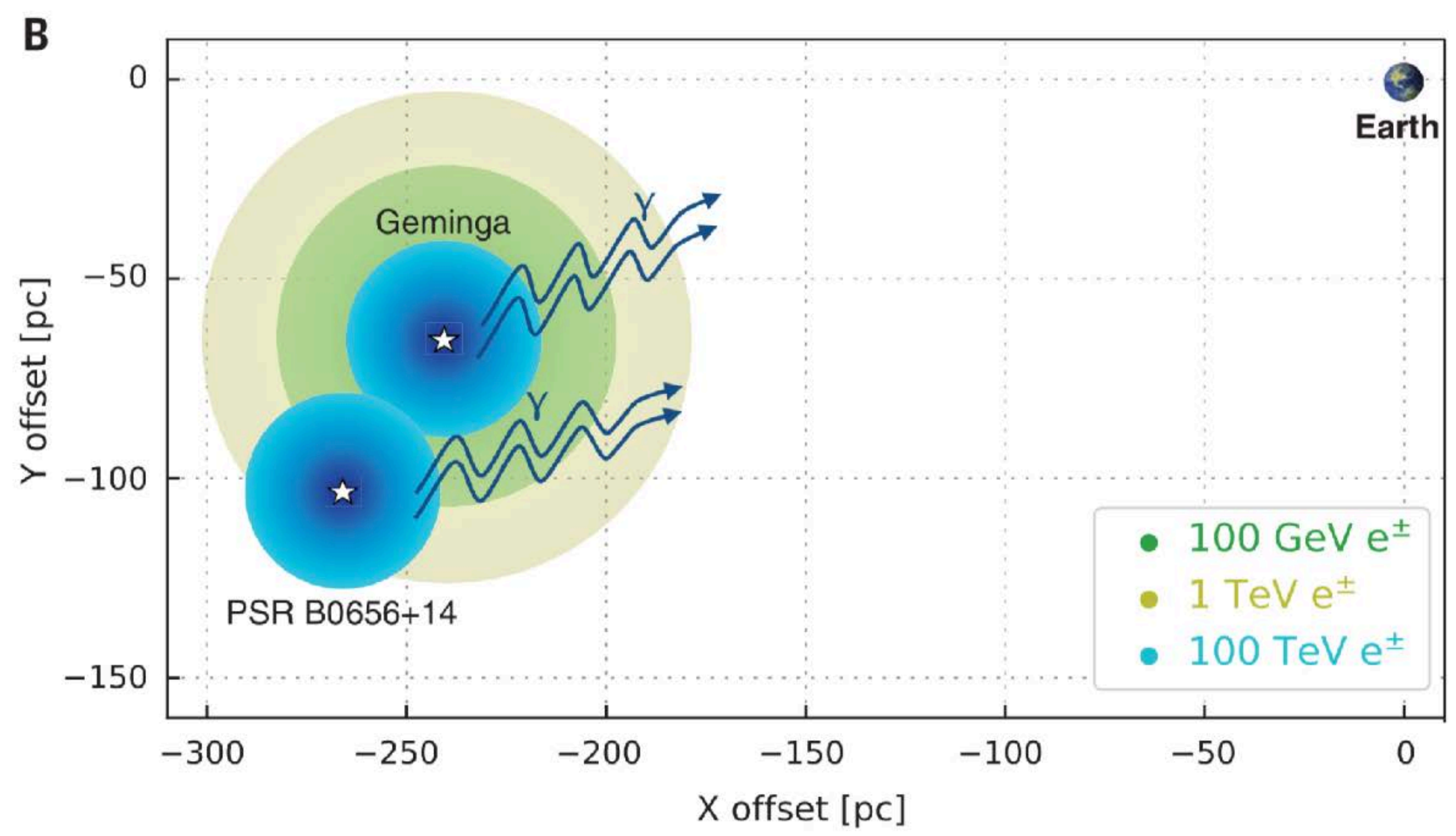
Sudoh, T., Linden, T., & Beacom, J. F. 2019, arXiv:1902.08203.

Geminga and Monogem



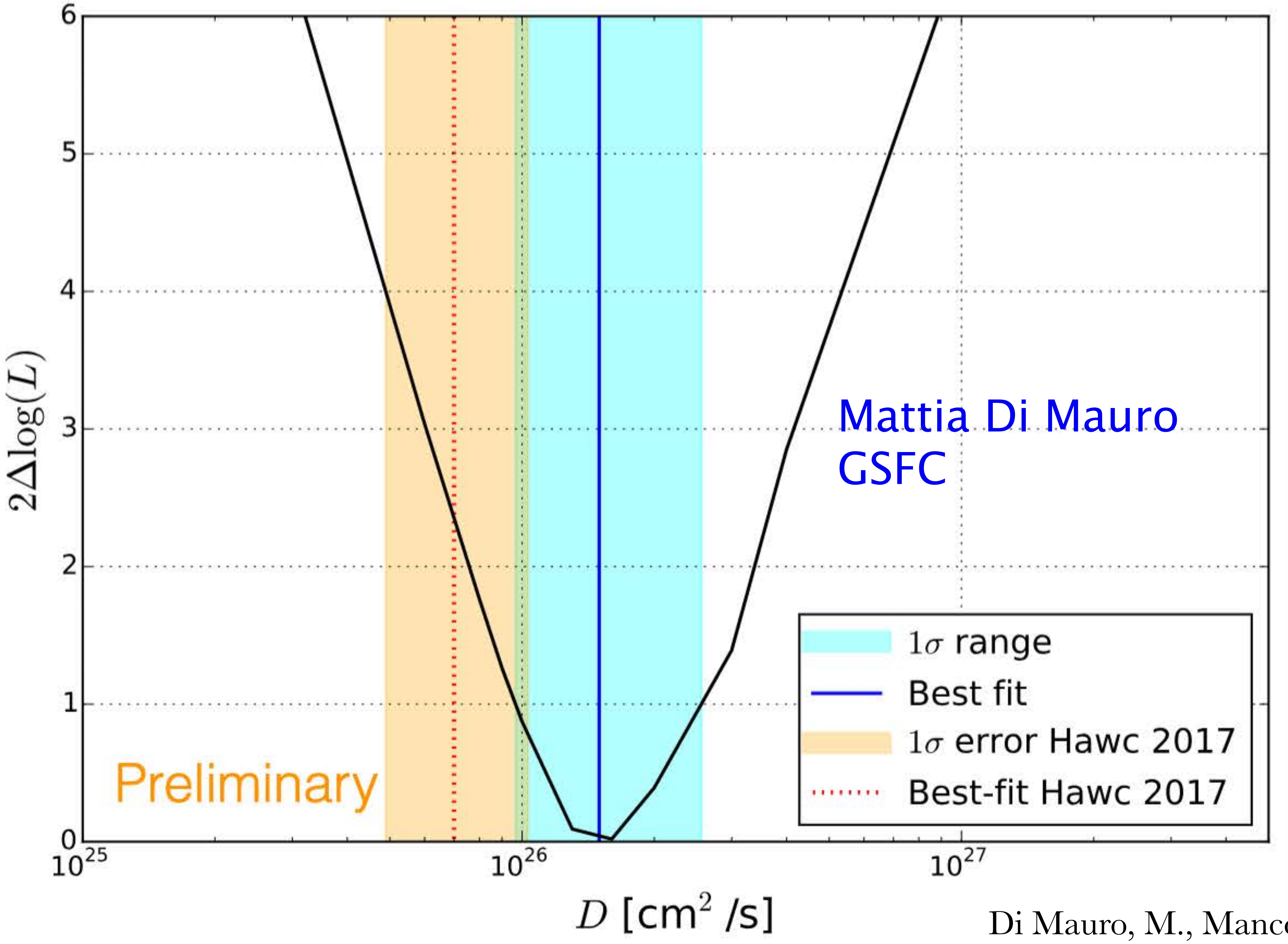


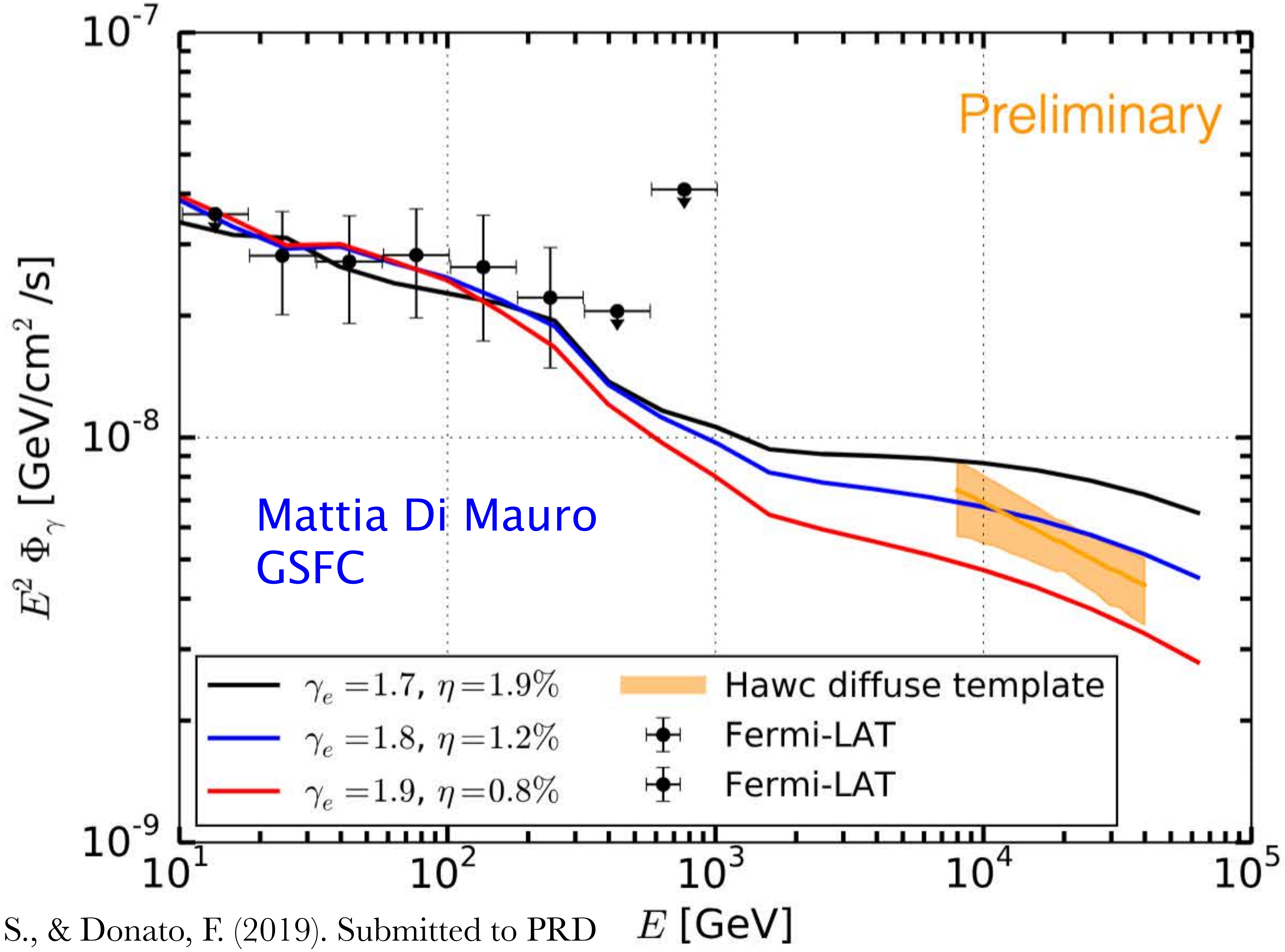
- 100 TeV e- inverse Compton scattering off CMB
- Measured size 10x smaller than expected from expected standard value of $D_{100\ TeV}$
- Assuming a simple model - they can't be the source of the positron excess



Geminga Halo Recently Confirmed by Fermi LAT

- Diffusion Coefficient is consistent with HAWC Observation (left)
- Joint Fermi HAWC Spectrum constrains acceleration efficiency (right)





Di Mauro, M., Manconi, S., & Donato, F. (2019). Submitted to PRD
https://arxiv.org/abs/1903.05647

New PWN / TeV Halos?

- Linden suggest that there are more nearby PWN to be found based on spin down power and distance - $\frac{\dot{E}}{r^2}$
- HAWC has already seen several of these

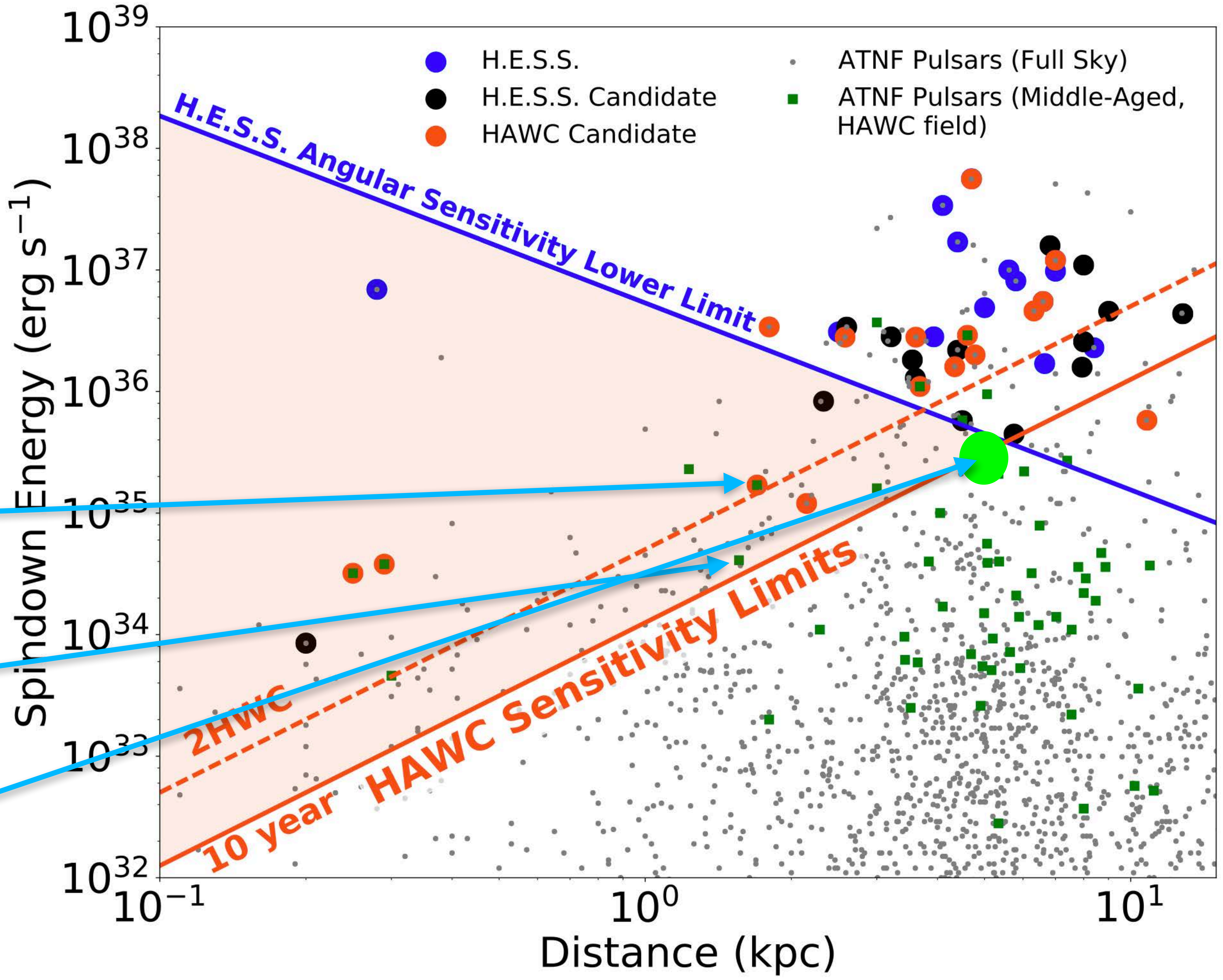
HAWC detection of TeV source HAWC J0635+070

ATel #12013; *Chad Brisbois (Michigan Technological University), Colas Riviere (University of Maryland), Henrike Fleischhack (Michigan Technological University), Andrew Smith (University of Maryland) on behalf of the HAWC collaboration*
*on **6 Sep 2018; 14:47 UT***
Credential Certification: Colas Riviere (riviere@umd.edu)

HAWC detection of TeV emission near PSR B0540+23

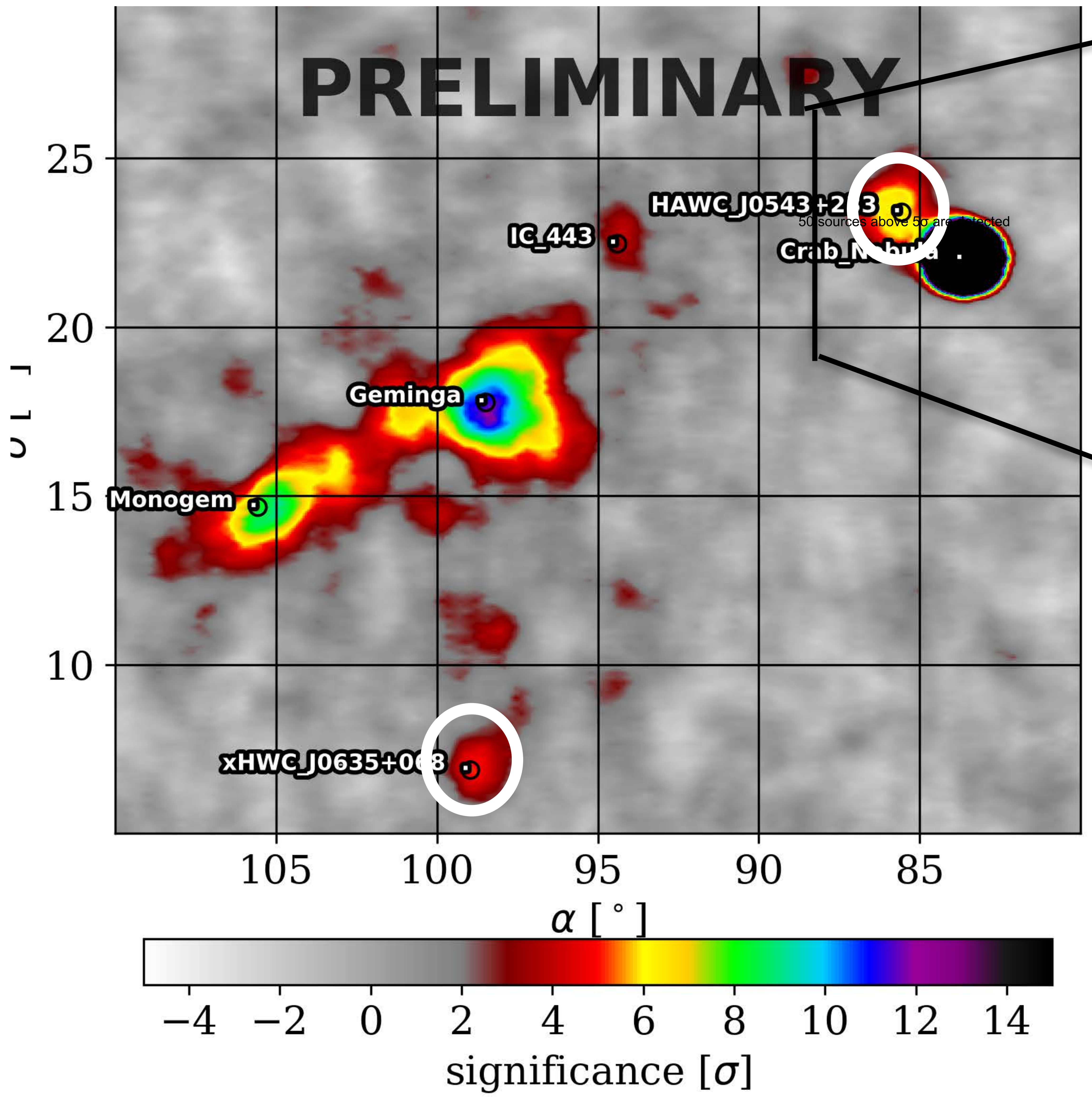
ATel #10941; *Colas Riviere (University of Maryland), Henrike Fleischhack (Michigan Technological University), Andres Sandoval (Universidad Nacional Autonoma de Mexico) on behalf of the HAWC collaboration*
*on **9 Nov 2017; 23:11 UT***
Credential Certification: Colas Riviere (riviere@umd.edu)

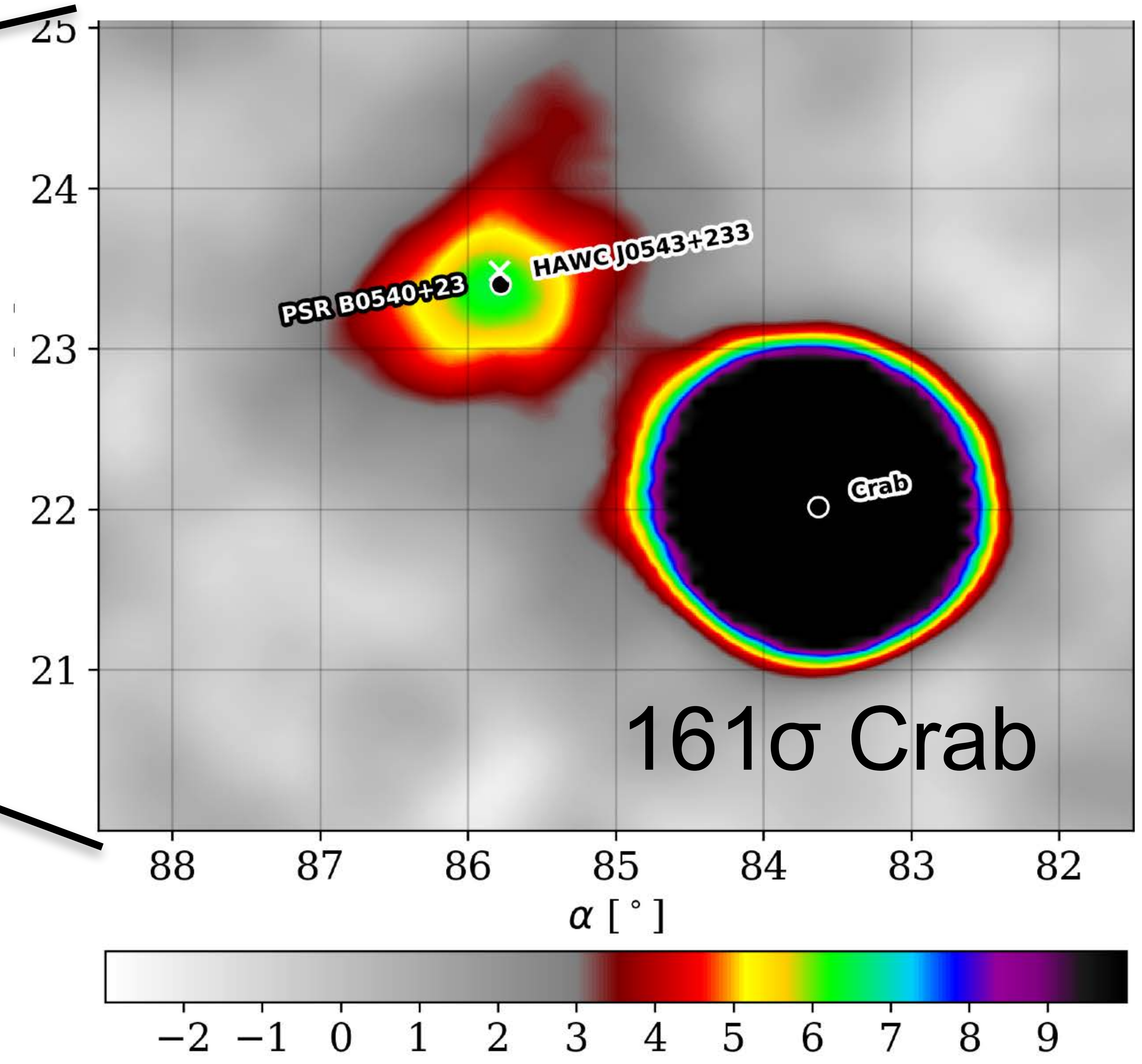
xHWC J2005+311
Shared with MOU partners
Newly discovered Fermi Pulsar



Linden et. al 2017 PhysRevD.96.103016

Hiding in Plain Sight J0543+233

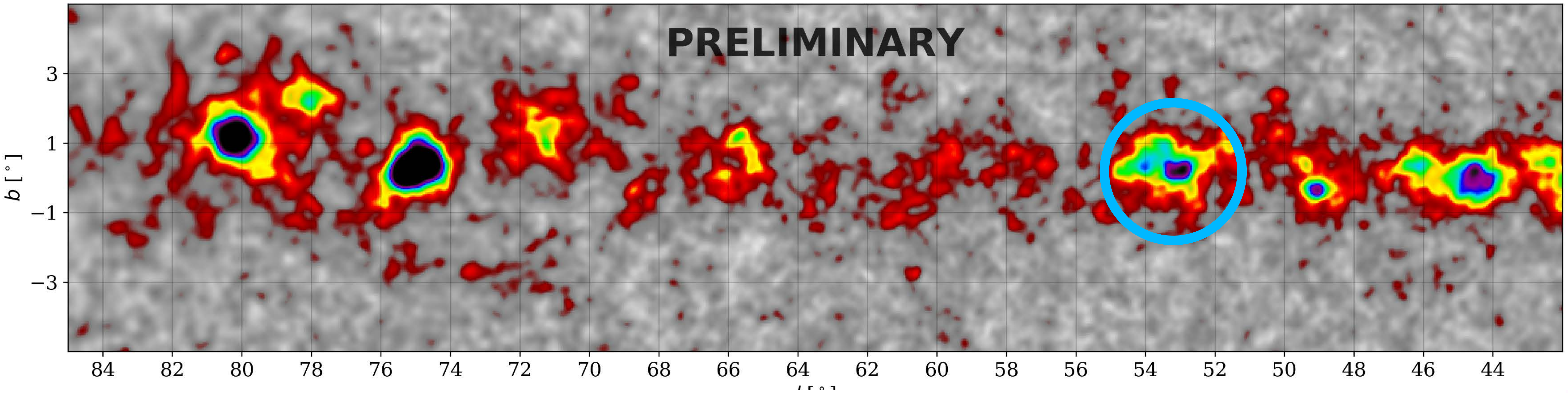


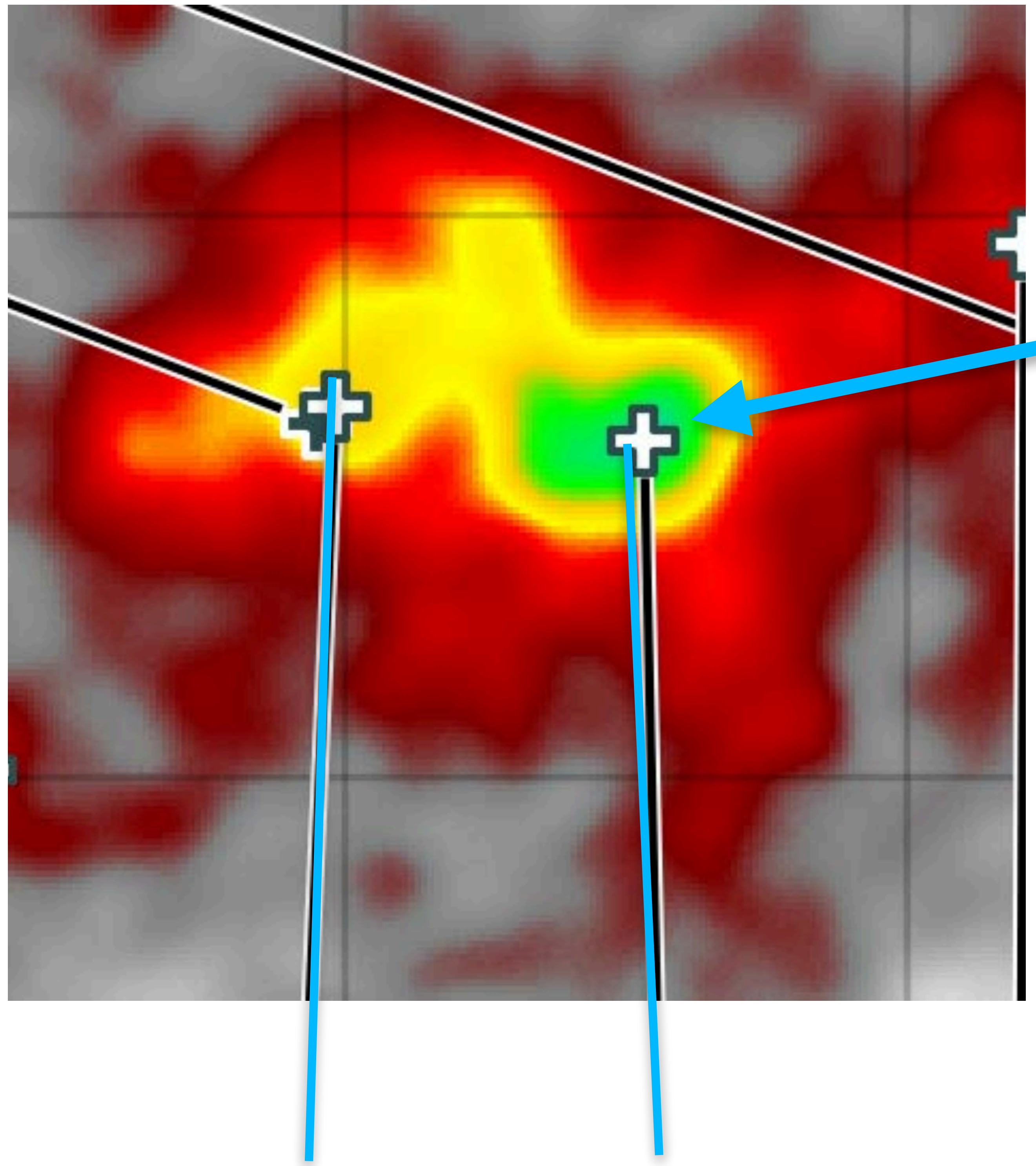


Another middle age PWN similar to Geminga and B0656+14
E˙ = 4.1 × 10^{34} erg s−1,
d = 1.56 kpc, τ = 253 kyr

Can test if all are Geminga-like

3HWC J1928+178 Region

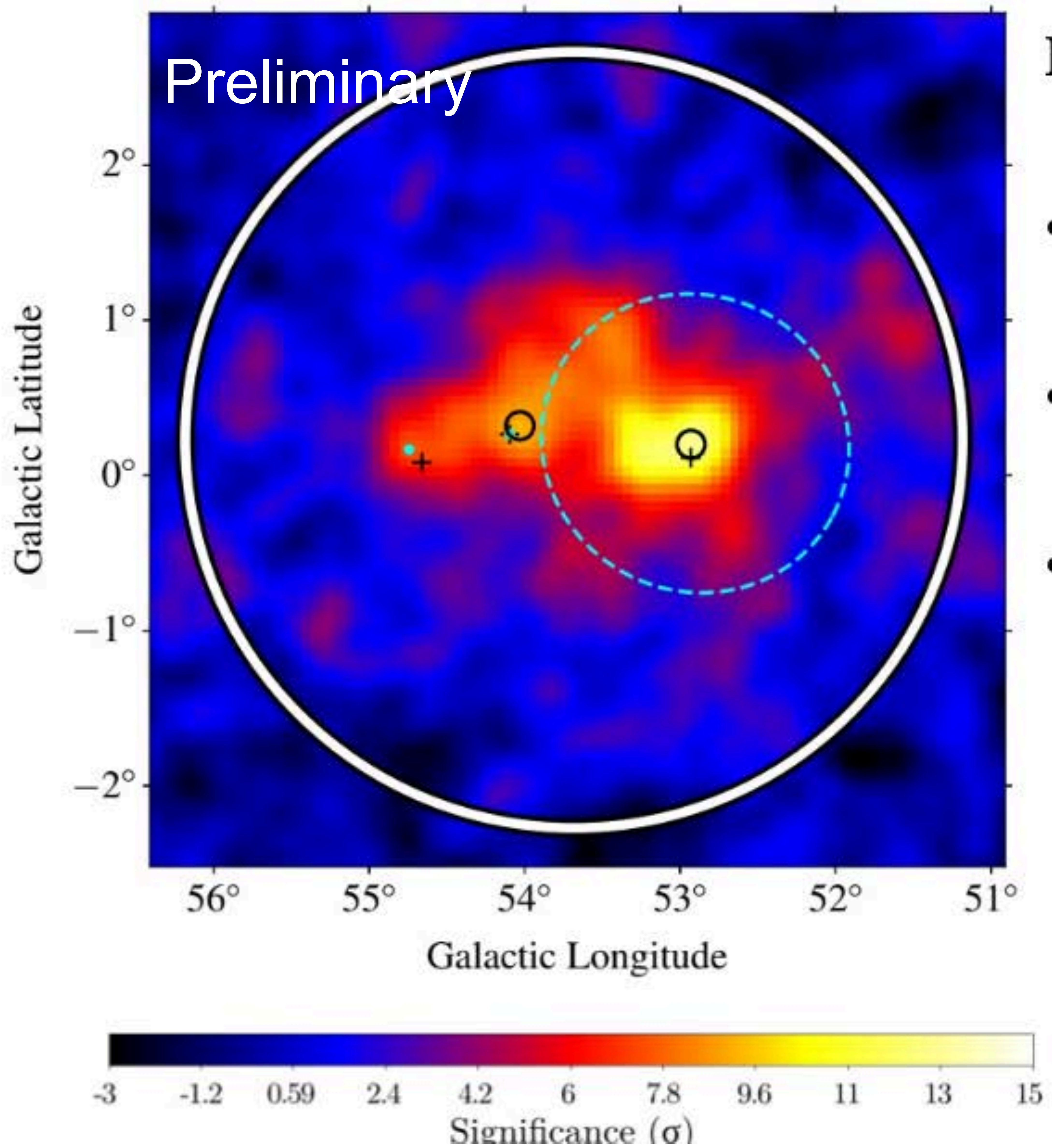




PSR J1928+1746
Distance D = 4 kpc
Age = 82 kyr
Period P = 68.7 ms
$\dot{P} = 1.32\ 10^{-14}$
$\dot{E} = 1.6\ 10^{36}$ erg s^{-1}

Detected in radio
No detection in X-ray

Model of the region and 3ML fit



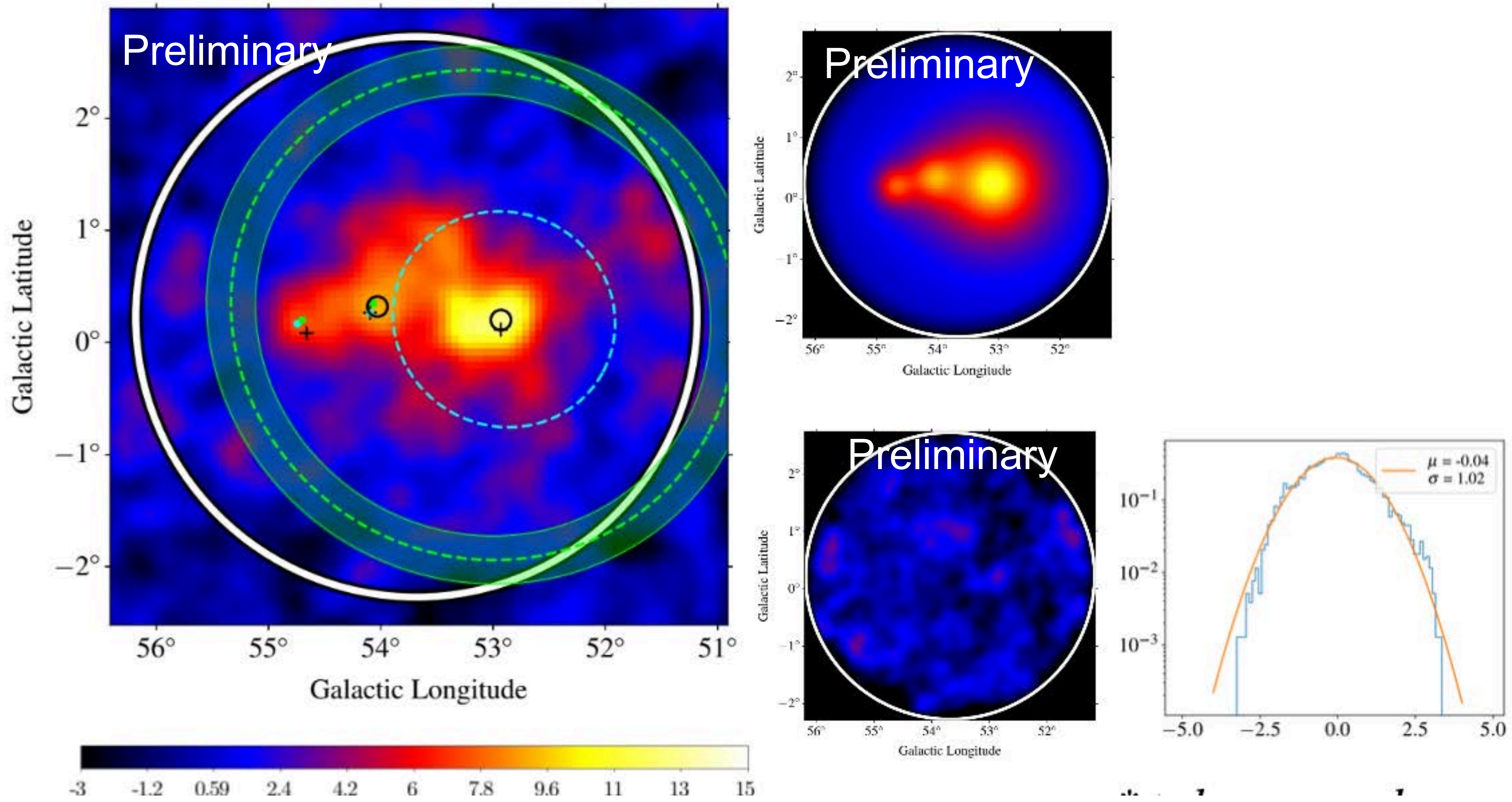
Model :

- 1 point source for 3HWCJ1930+188 (**J1930**)
- 1 point source at the location of the excess near PSR J1932+1916 (**J1932**)
- 1 extended source + a continous injection diffusion at the location of the excess for 3HWC J1928+178 (**J1928**)

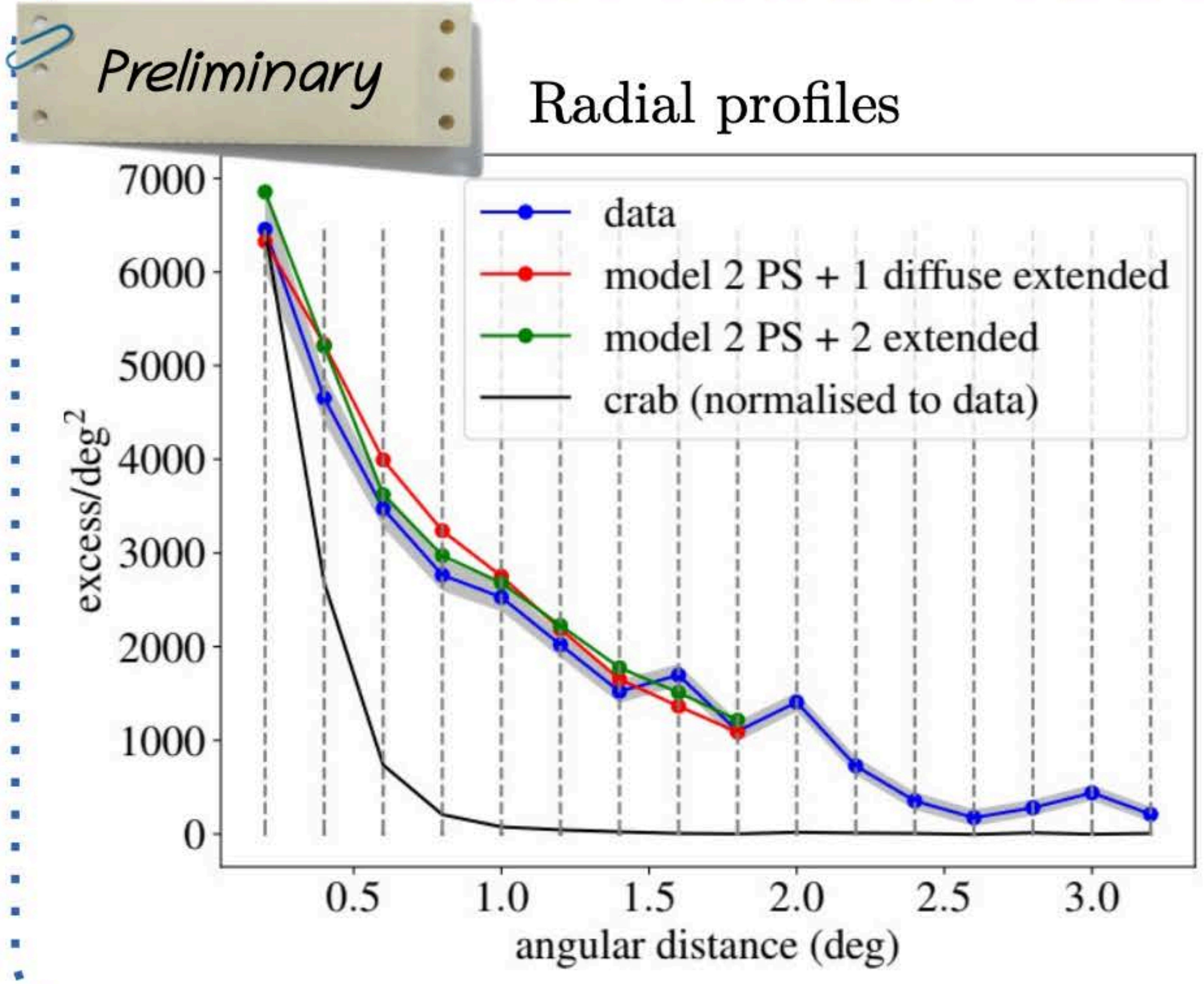
The gamma-ray flux as a function of the distance d is approximately proportional to

$$f_d = \frac{1.22}{\pi^{3/2} r_d (d + 0.06 r_d)} exp(-d^2/r_d^2)$$

3HWC J1928+178 Region



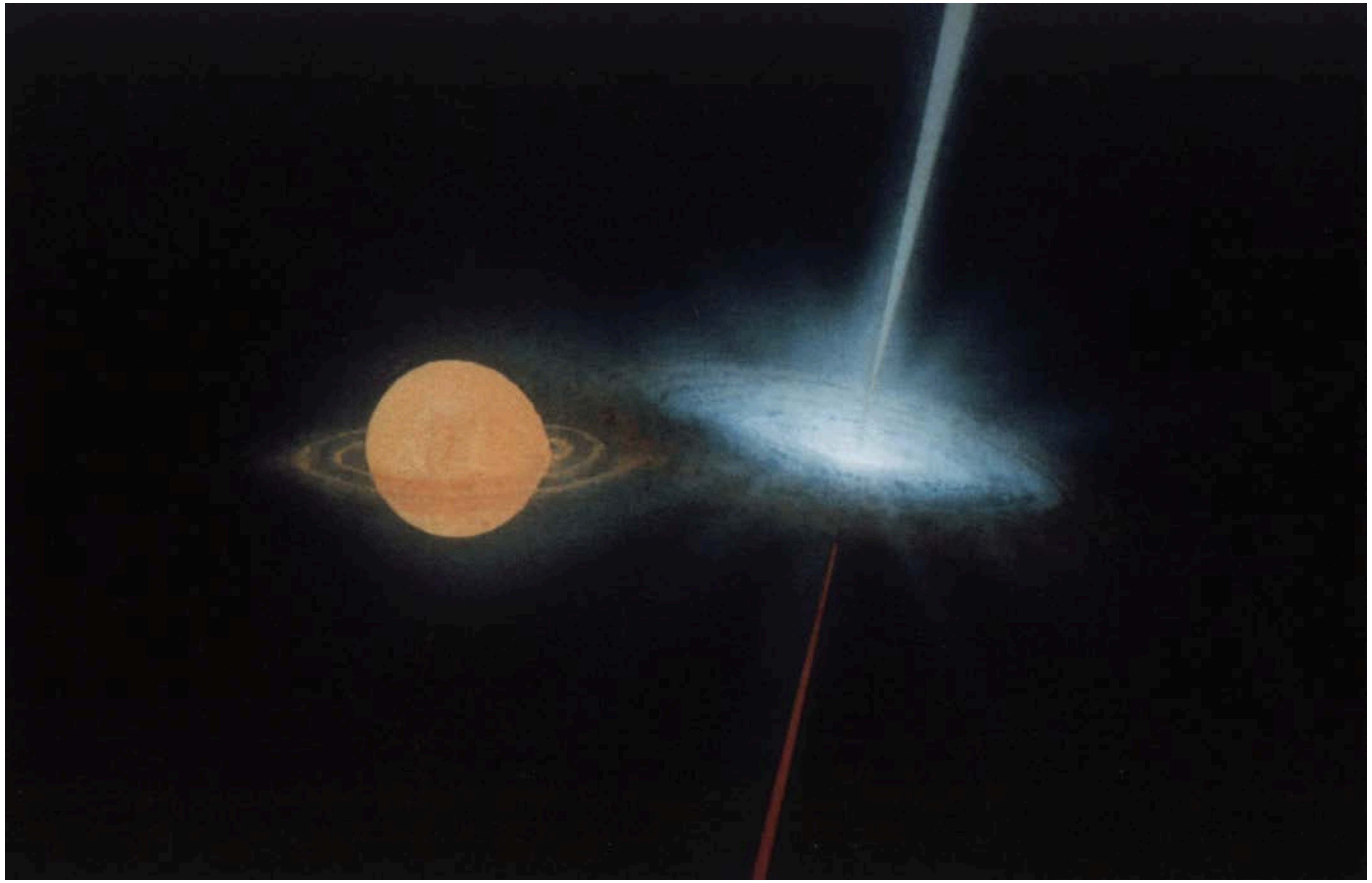
3HWC J1928+178 Region



Properties of 3HWC J1928+178 from the fit

	3HWC J1928+178
Diffusion radius	$2.27^{\circ}{\pm 0.2}$
Diameter	~ 340 pc
Energy flux > 1 TeV	$3.8{\pm 0.4}\ 10^{-11}$ erg cm^{-2} s^{-1}
Spectral index	$-2.56{\pm 0.05}$

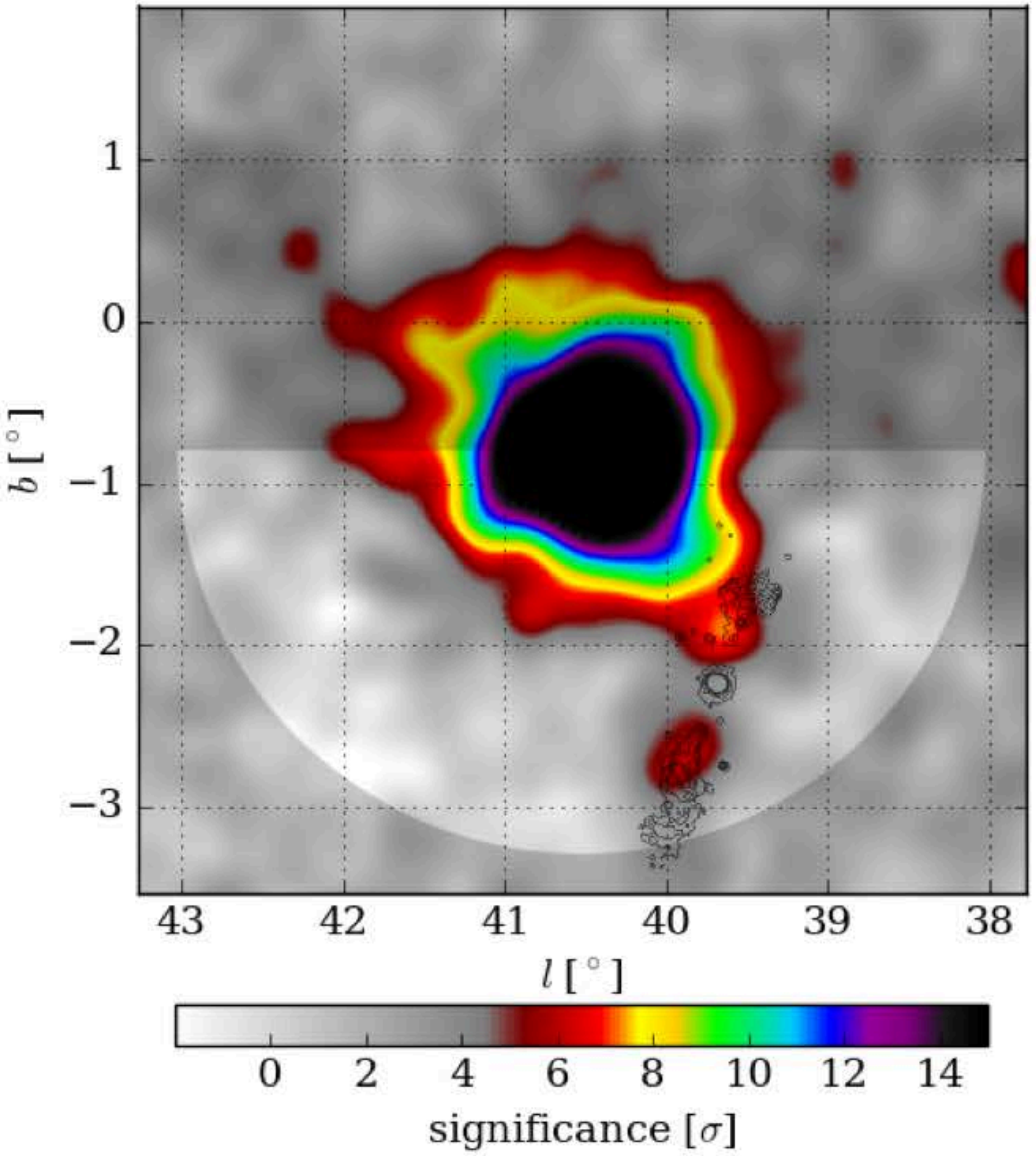
Microquasar SS433

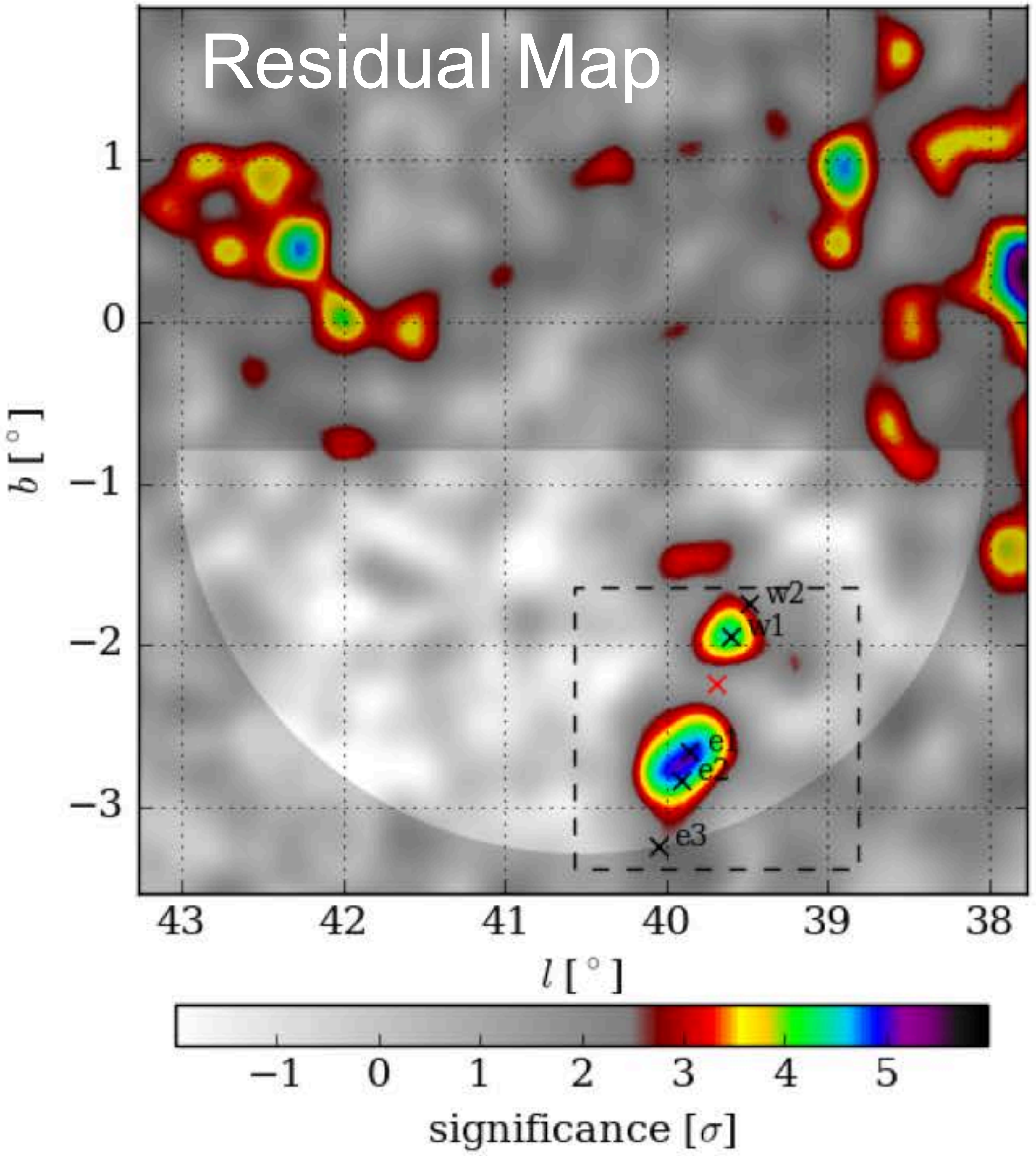


Possible an A-type supergiant and a very extended disk around a black hole.
The jets from SS 433 precess with a period of 13 days.

SS-433

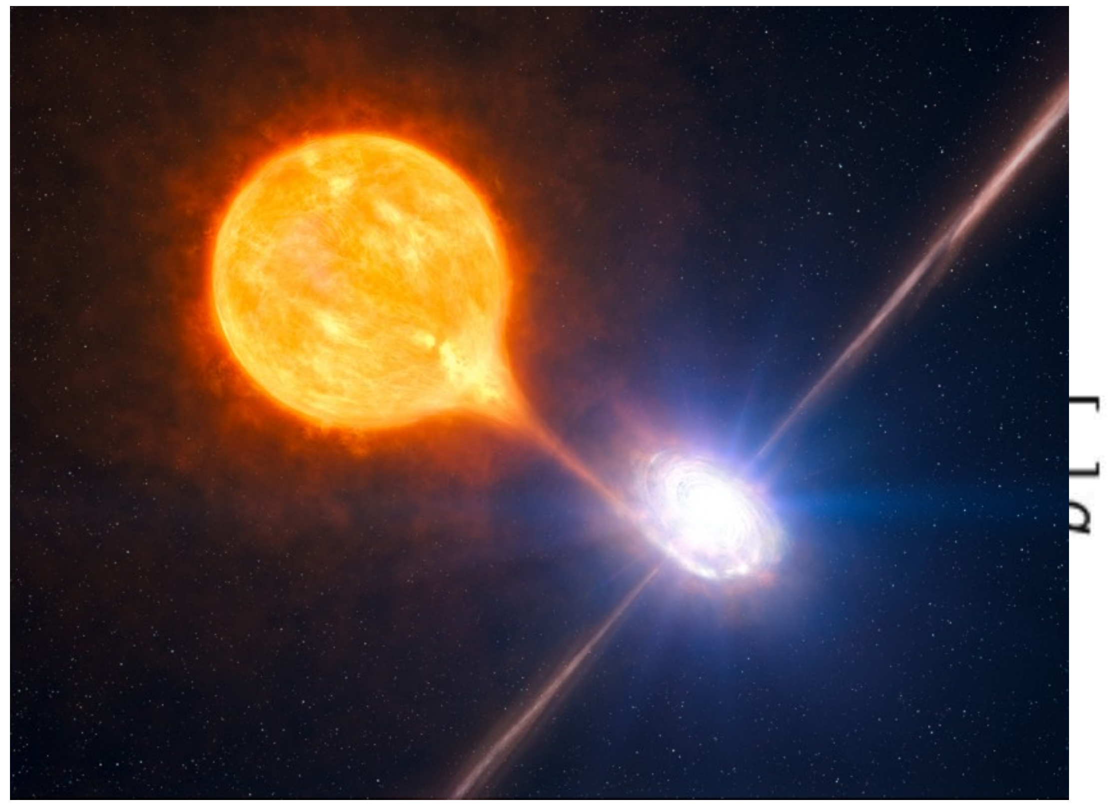
The central source is MGRO J1908+06 and below it are the lobes of SS 433

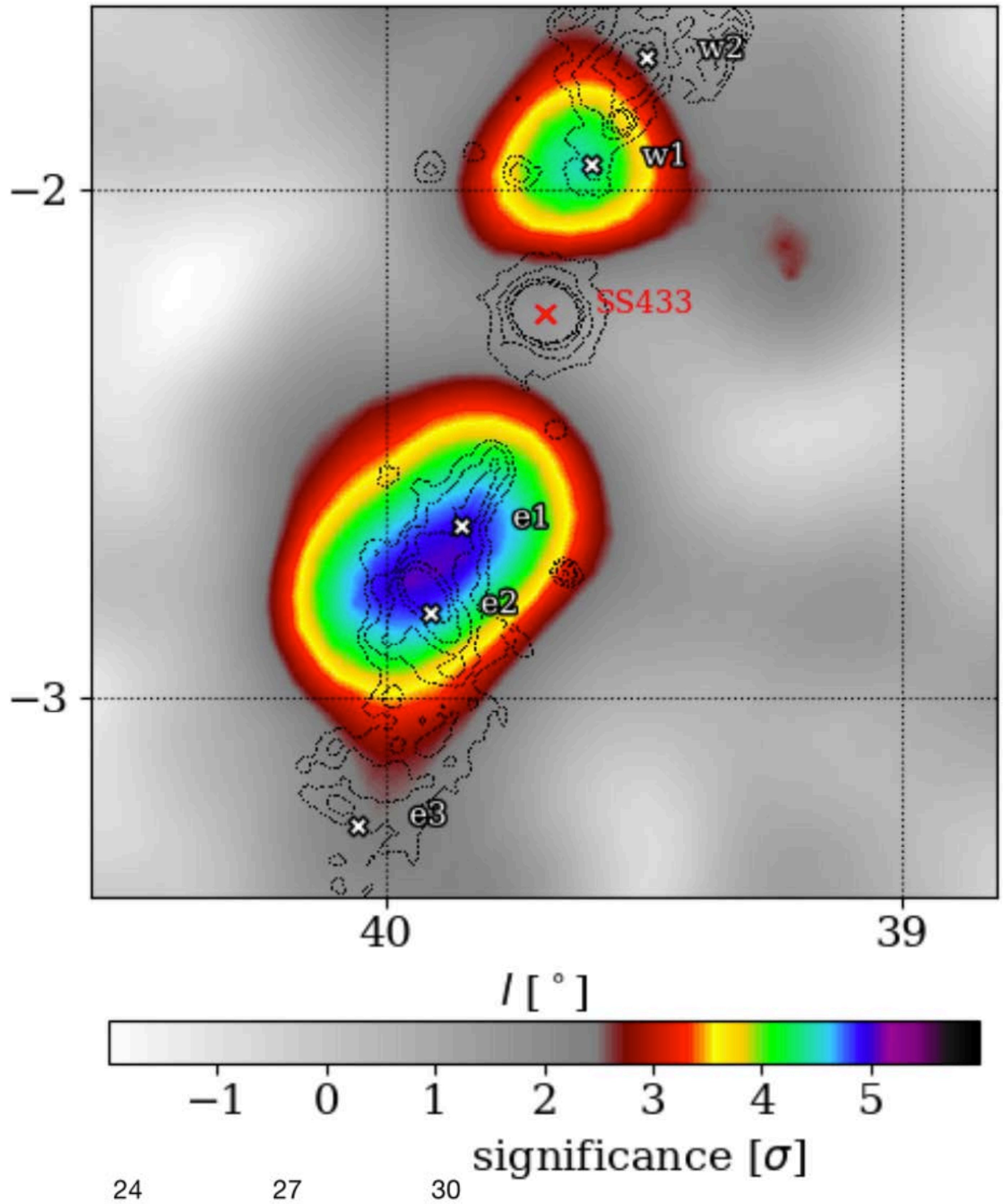


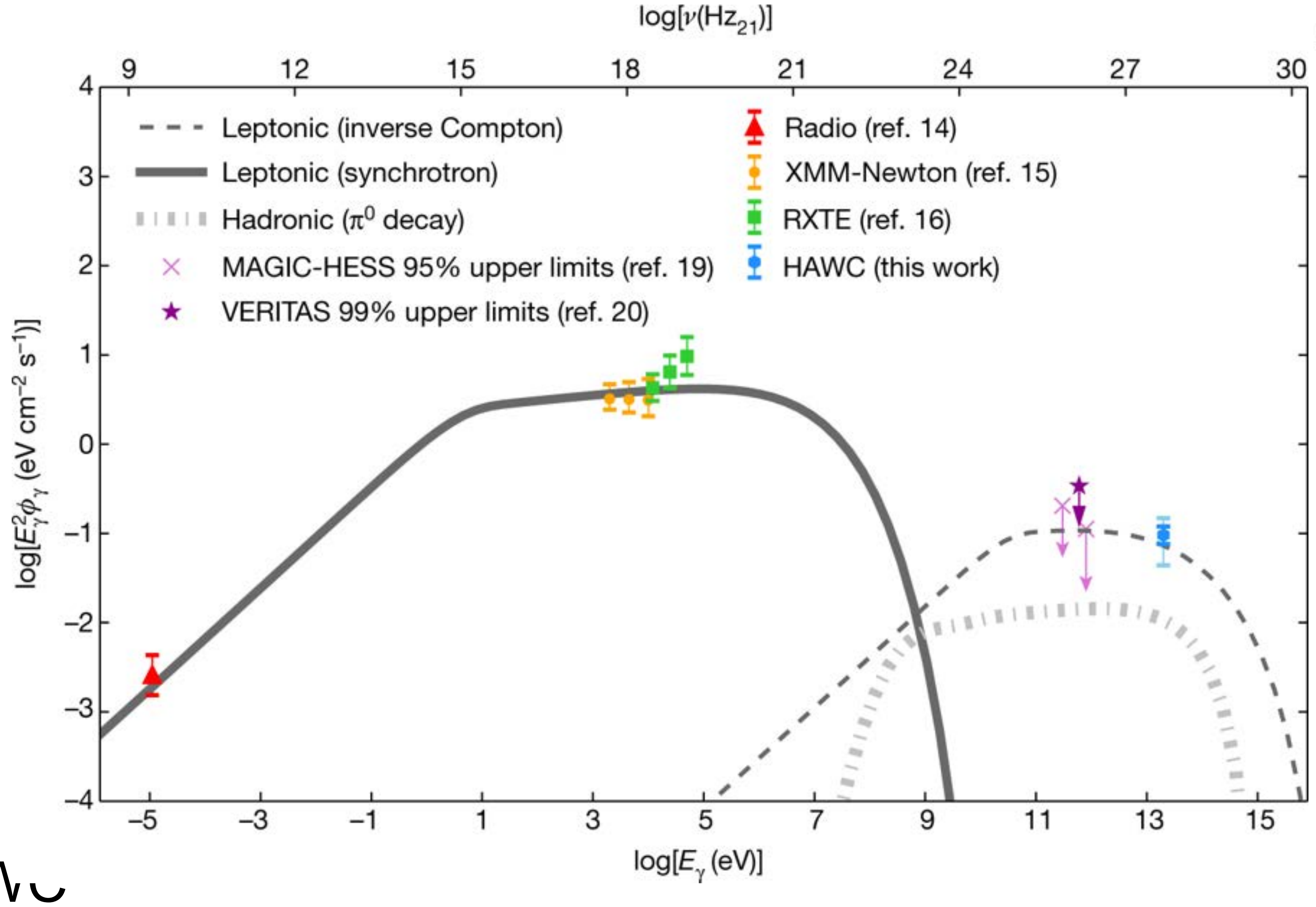


Microquasar SS-433

- HAWC observation of SS433 is the first direct evidence of particle acceleration to ~PeV in jets
  - Jets are observed edge-on so the gamma rays are not Doppler boosted to higher energies or higher luminosities
  - Hadronic acceleration disfavored due to extreme energetics required
  - Acceleration does not happen at the black hole because the cooling time of the electrons is too short to make the observed gamma-rays
- Fermi observes similar phenomena in AGN (Cen A & Fornax)



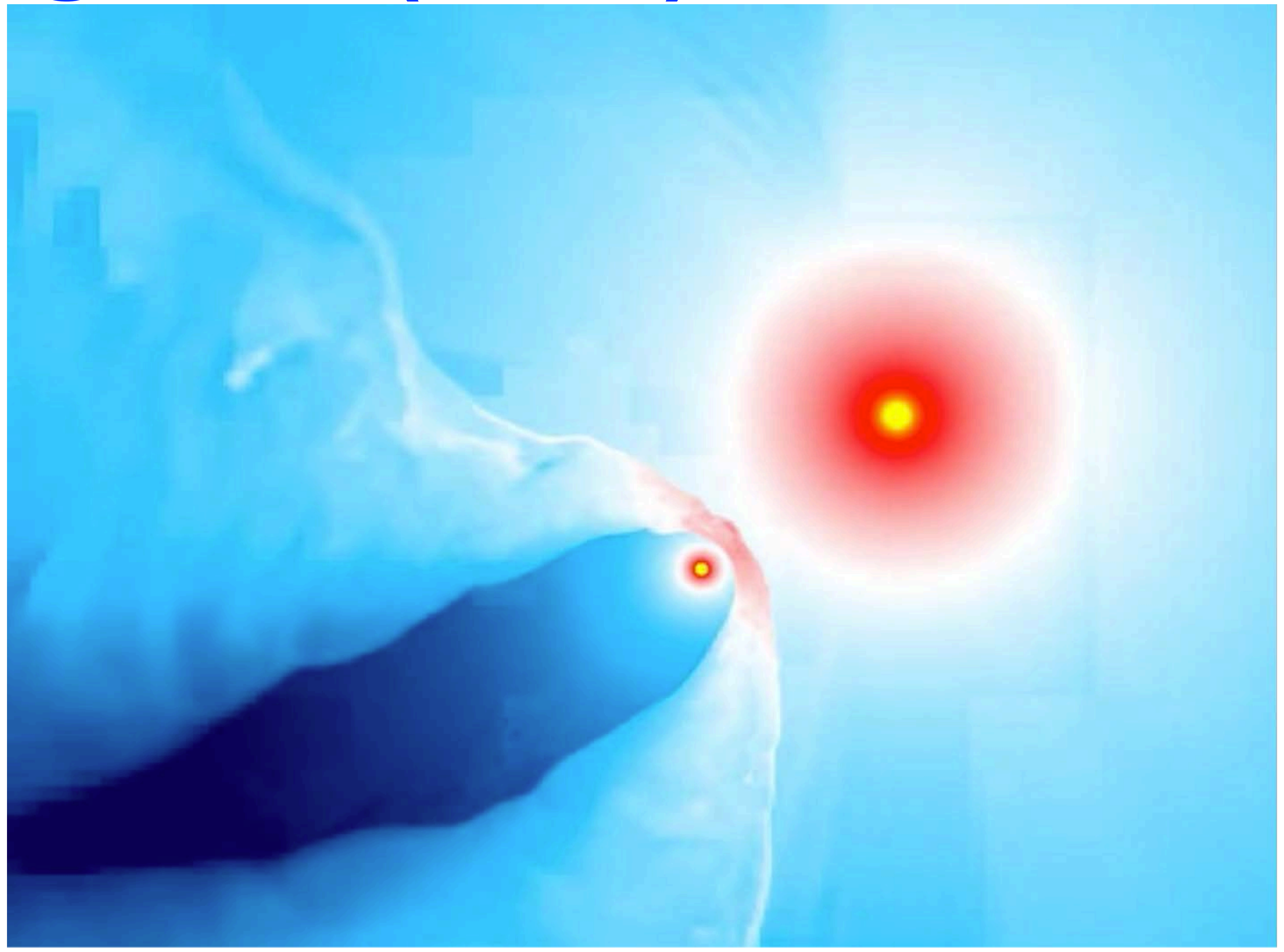


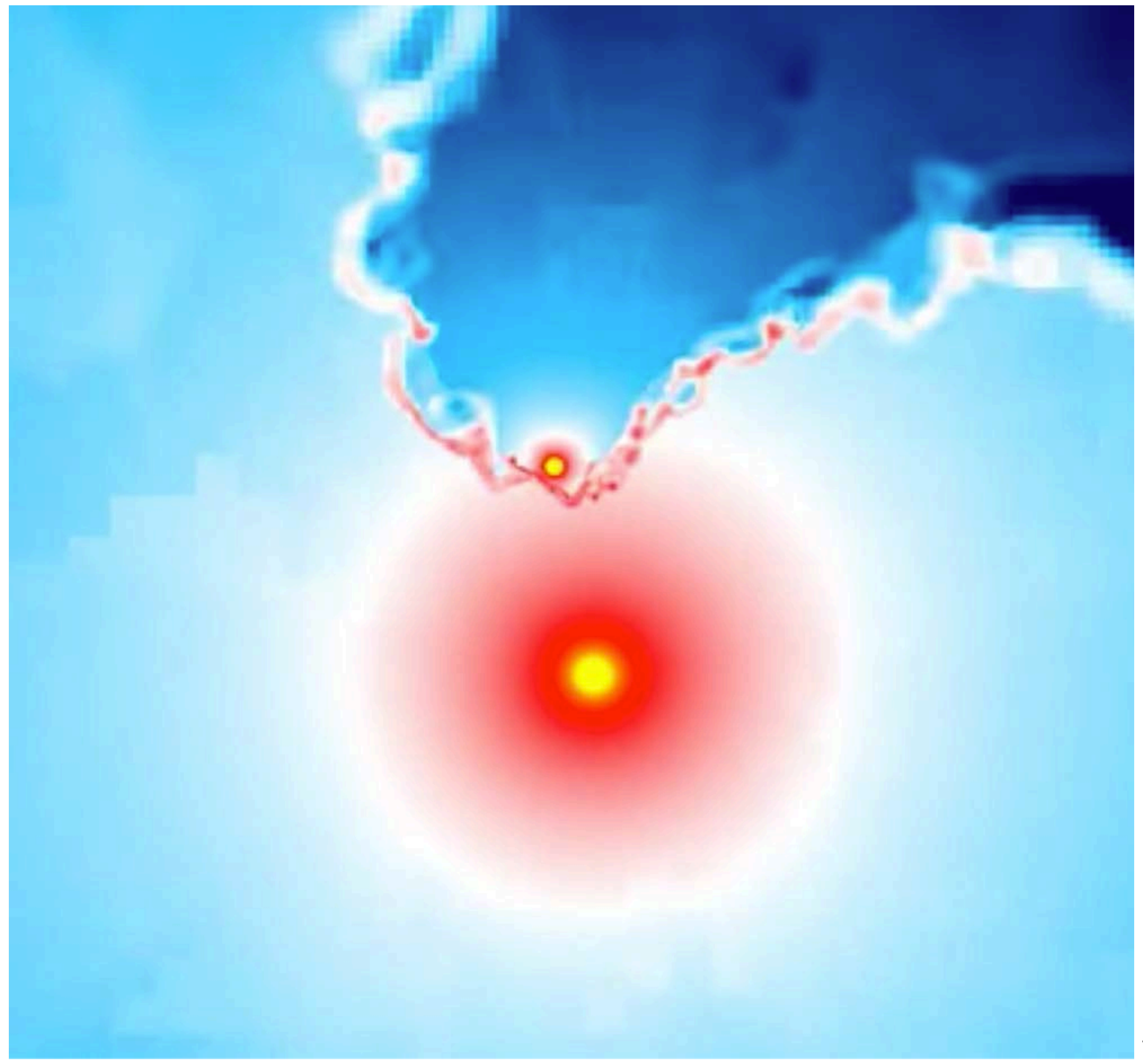


Published in Nature Oct 4, 2018

CR Origin: Star Forming Regions (SFR)

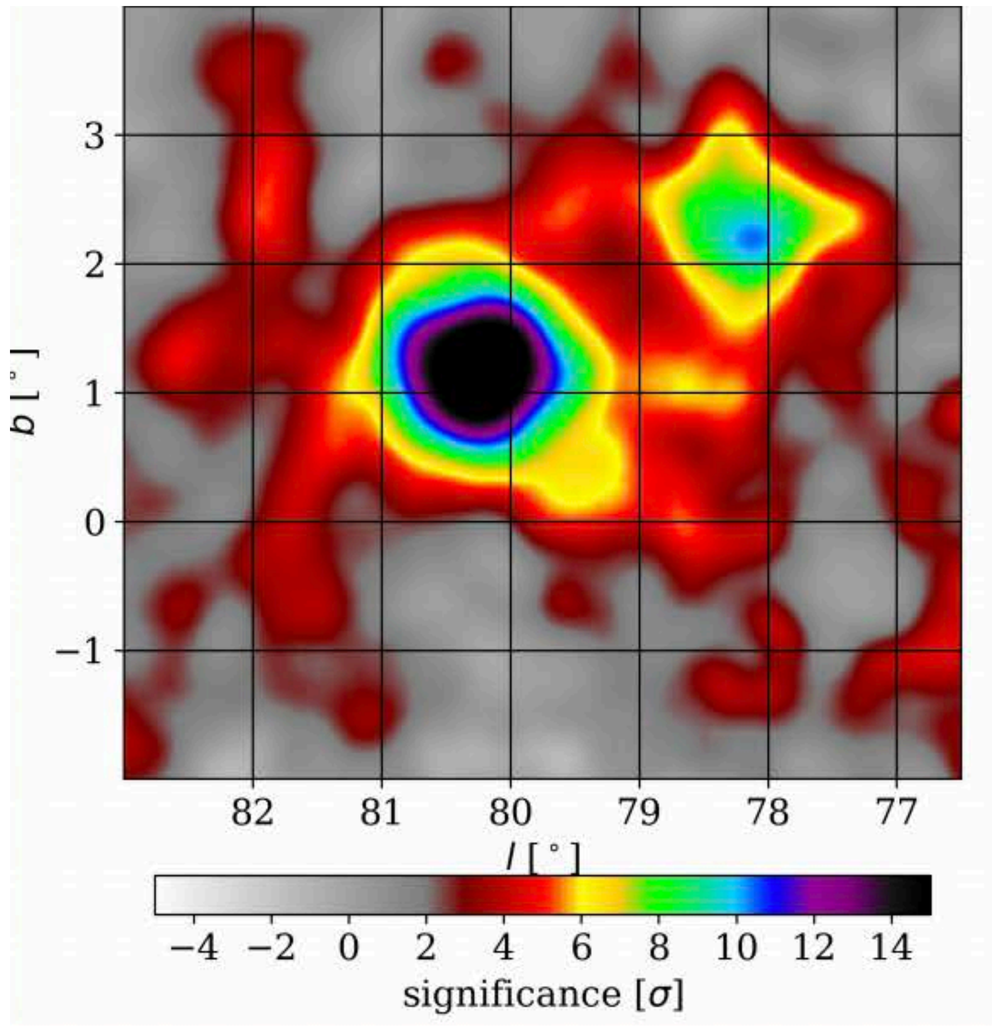
- No evidence of particle acceleration in **SNRs** beyond 100s of TeV
- Can SFRs provide this energy via e.g. collective star winds?
- Candidate: OB2 association in Cygnus Region
- *Cygnus OB2 is an OB association that is home to some of the most massive and most luminous stars known*
  - *It is hidden behind a massive dust cloud known as the Cygnus Rift, which obscures many of the stars in it. This means that despite its large size, it is hard to determine its actual properties.*
- *Including* two Massive stars orbiting tightly
  - Steller Winds collide producing x-rays
  - These can influence star formation and possibly accelerate particles

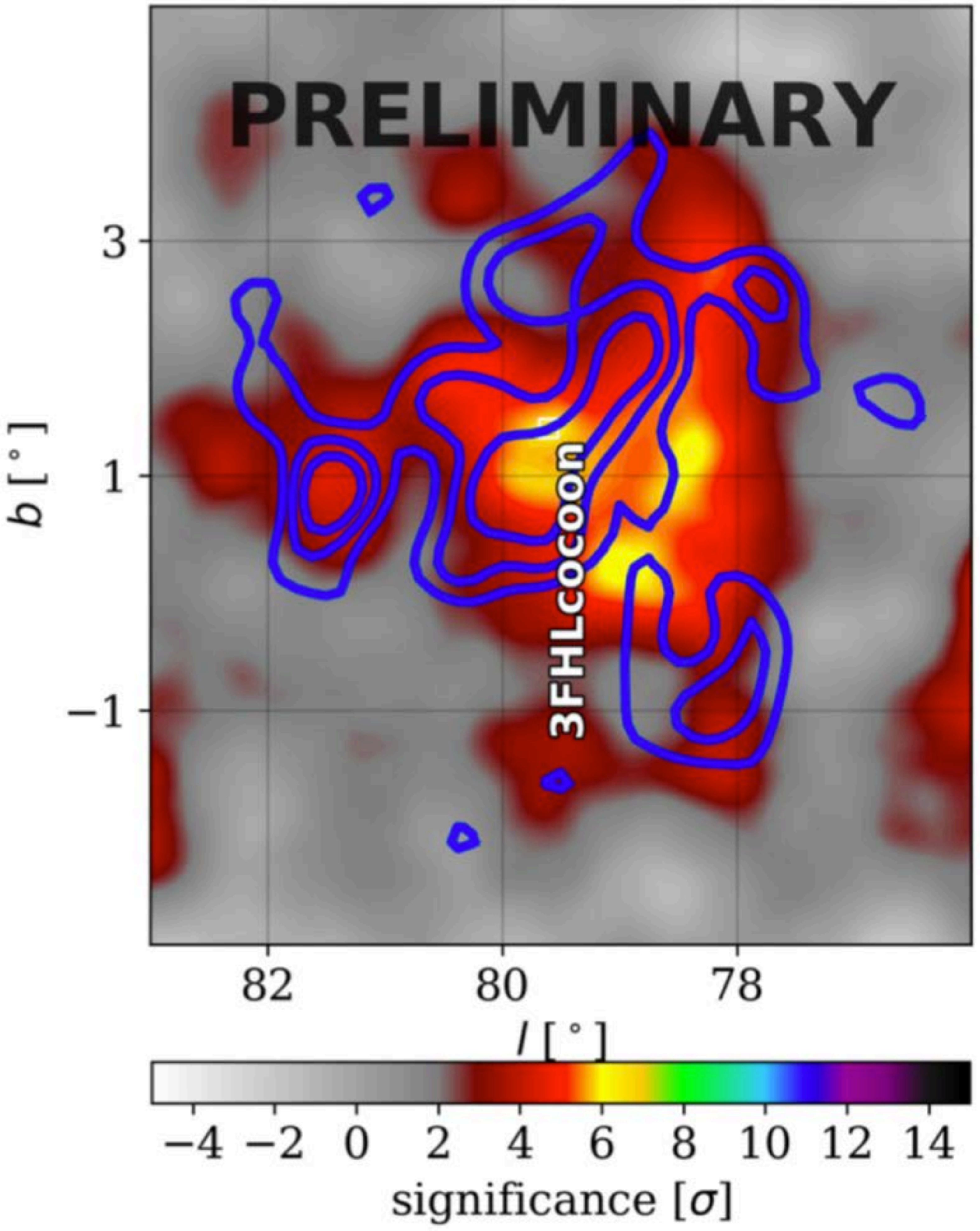




The Cygnus Cocoon

- Can these SFR accelerate particles to high energies?
- **Candidate: OB2 association in Cygnus Region**
  - *Fermi detection at GeV* (Ackermann et al., ***Science*** 334, 2011, '*The Cocoon*')
  - *HAWC detection of a likely TeV counterpart*
  - **Only SFR seen from GeV to TeV!**
- Energy budget and diffusion profile consistent with proton acceleration in collective star winds

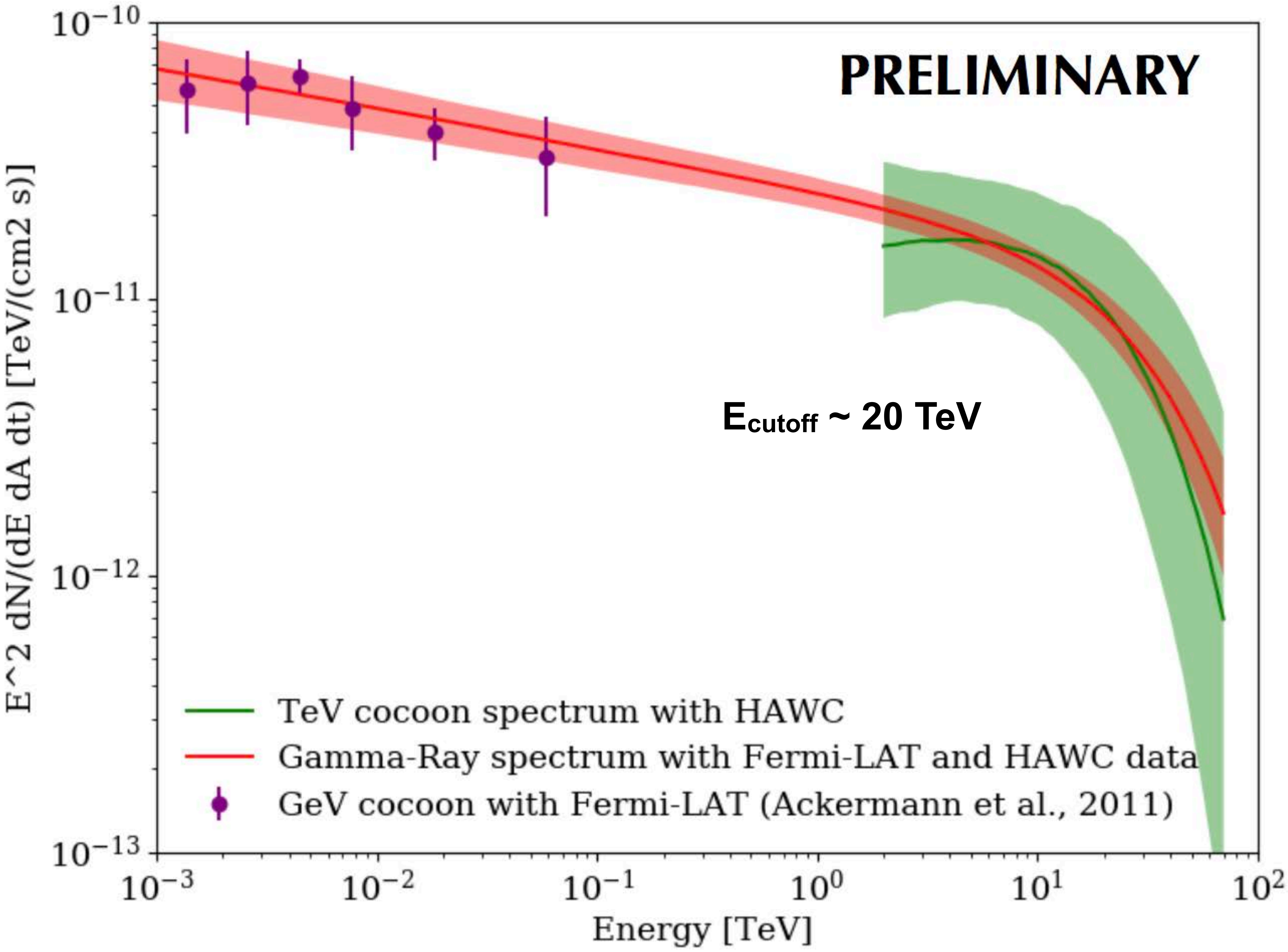




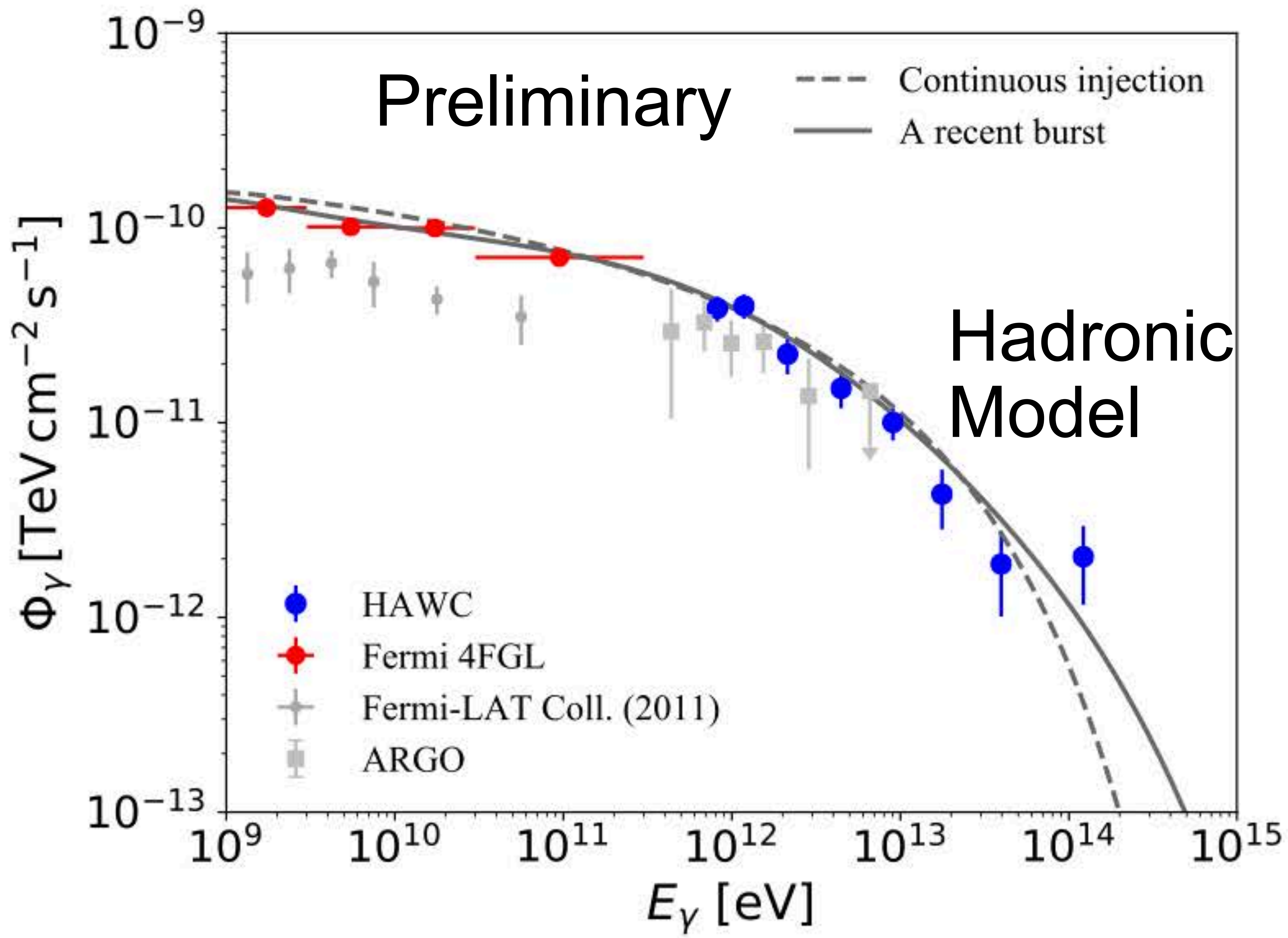
Fermi-LAT Contours

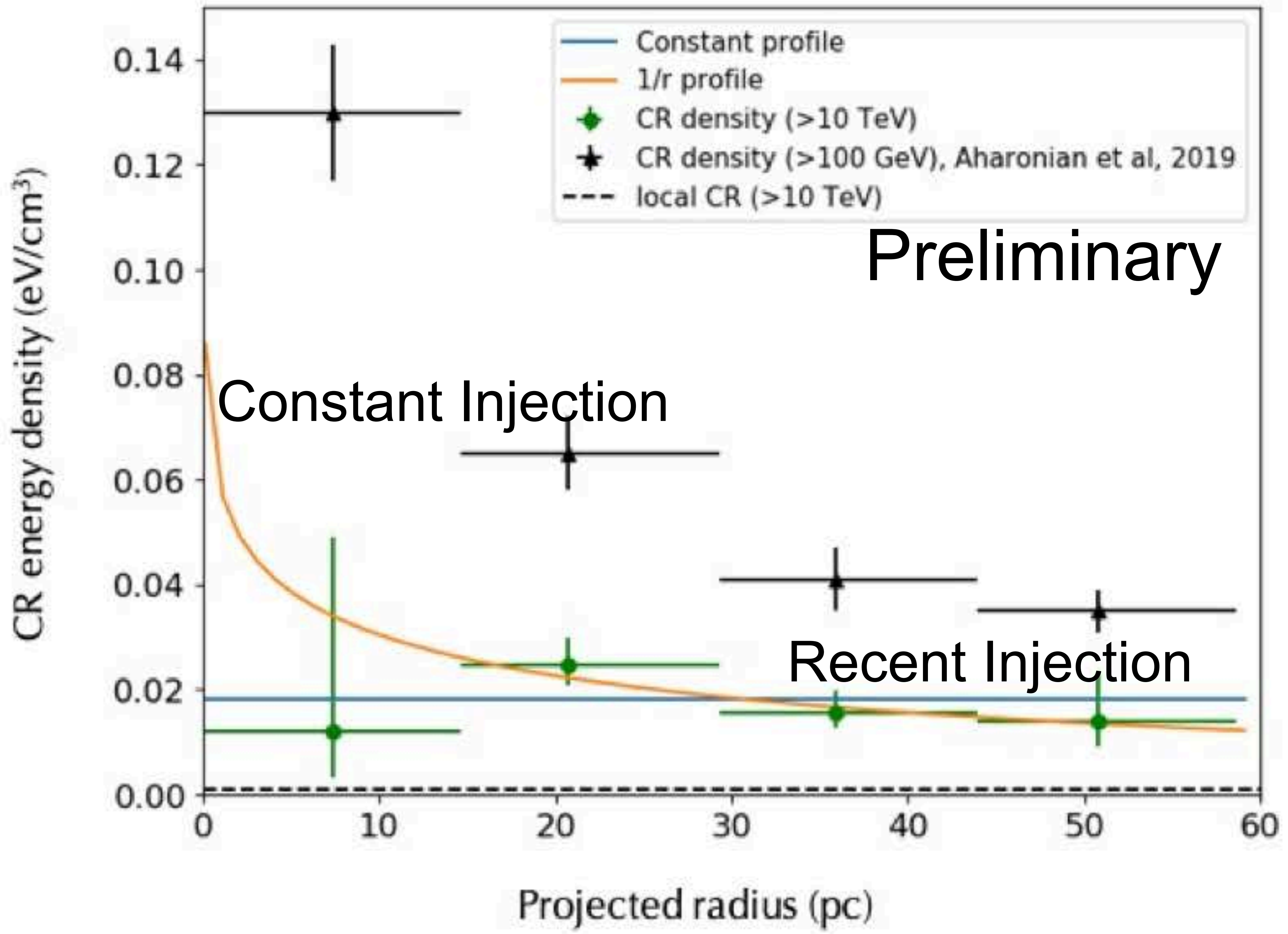
HAWC Map after subtraction of PWN & γ-Cygni

Cygnus Cocoon



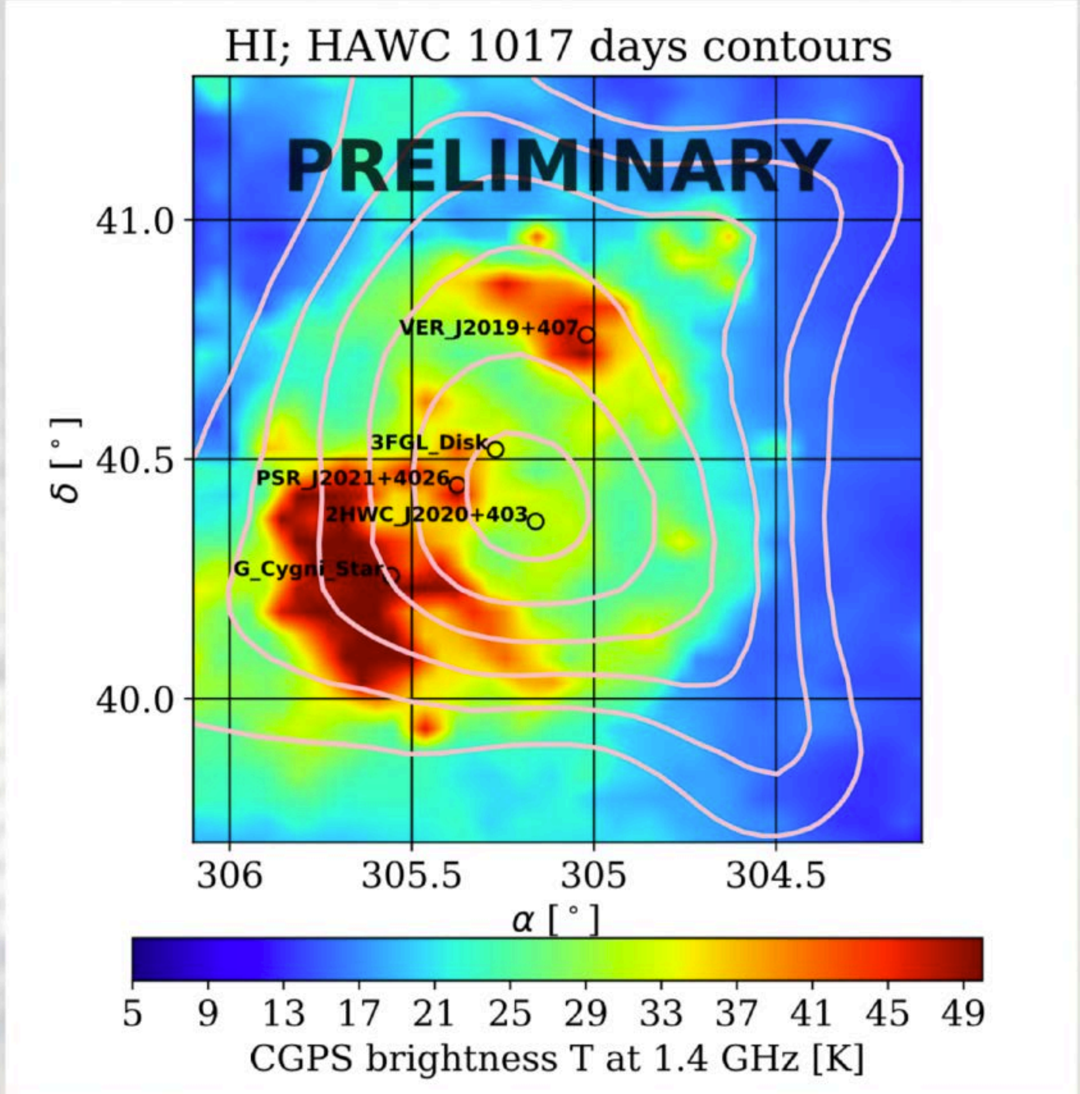
Cygnus Cocoon

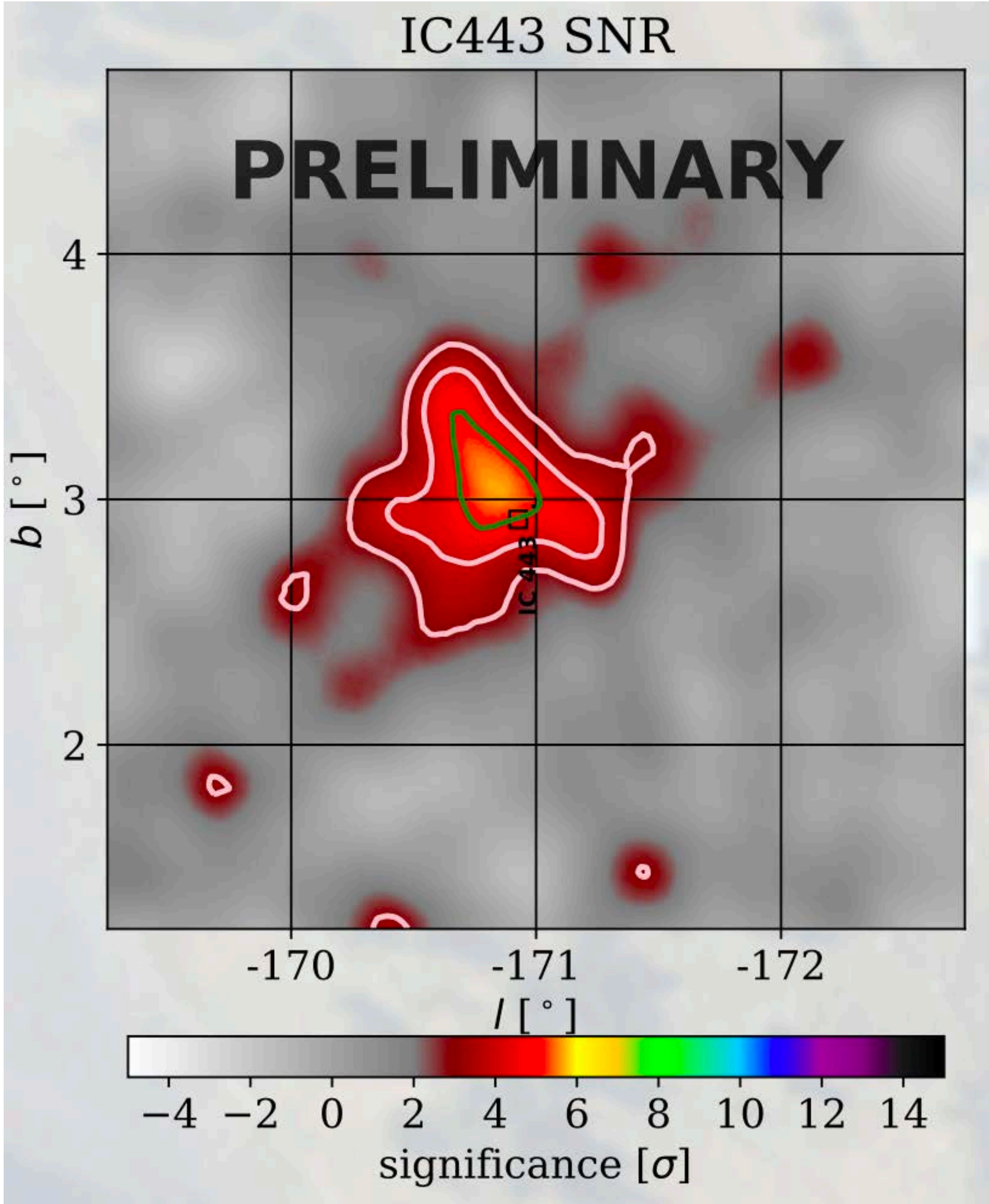


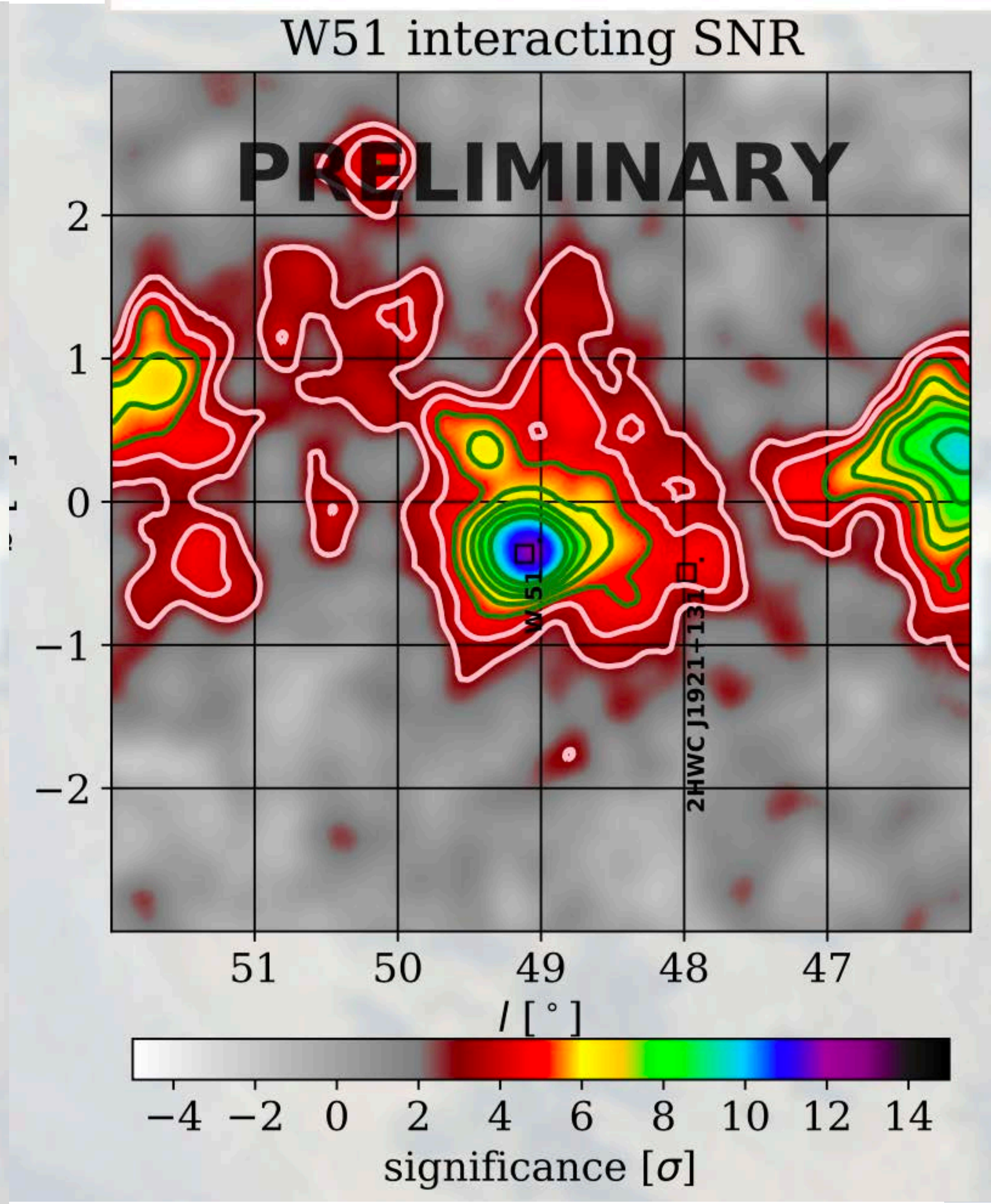


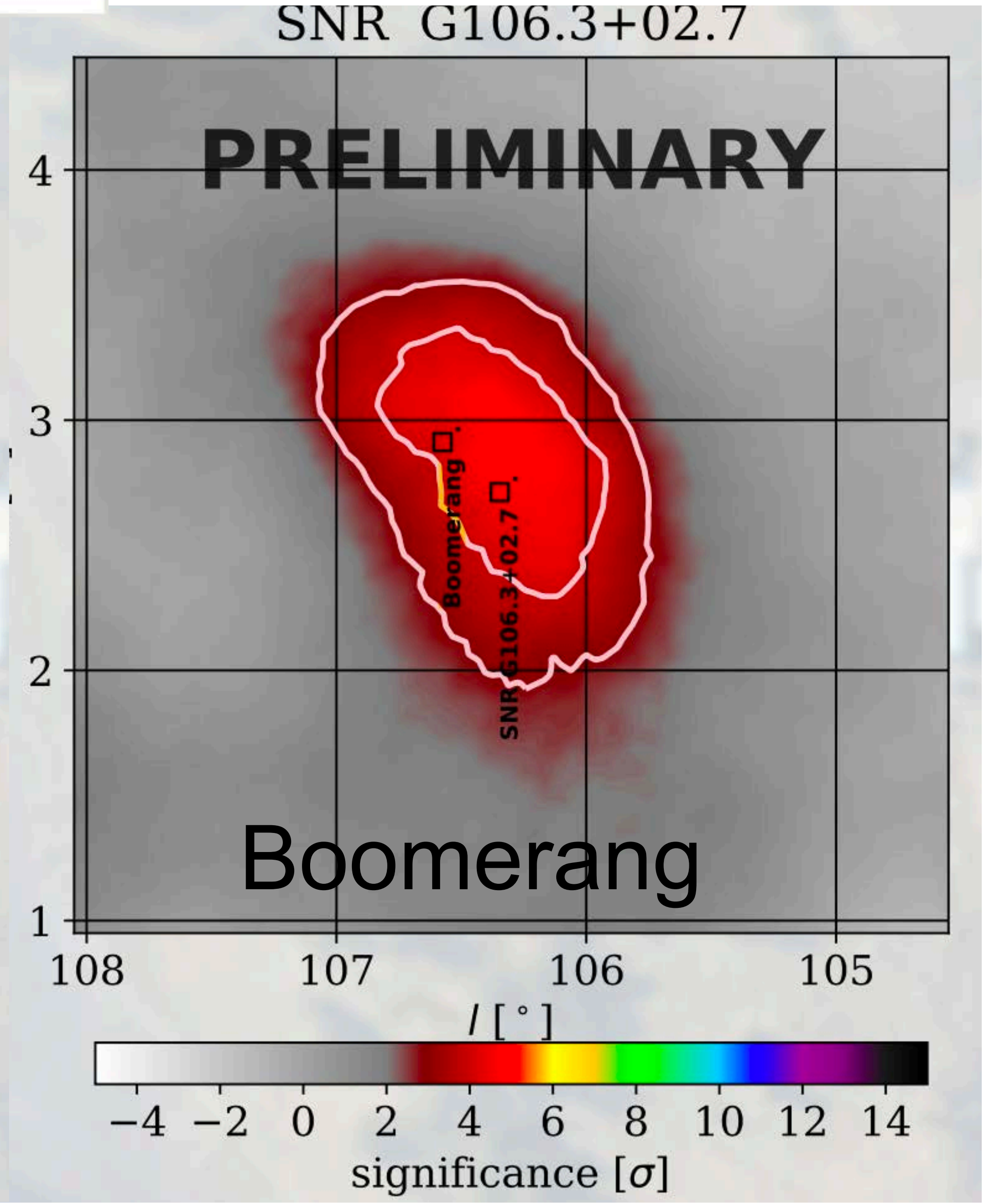
CR Origin: Super Nova Remnants (Henrike Fleischhack - MTU)

- **HAWC detection of** significant TeV γ-ray emission from middle-aged **Four SNRs:** γ-Cygni, IC 433, W51C, and Boomerang.
- **Combined fits of Fermi and HAWC data** describing the GeV-TeV emission as pion decay spectrum
- **Boomerang** detection now above threshold significance (HAWC J2227+610)





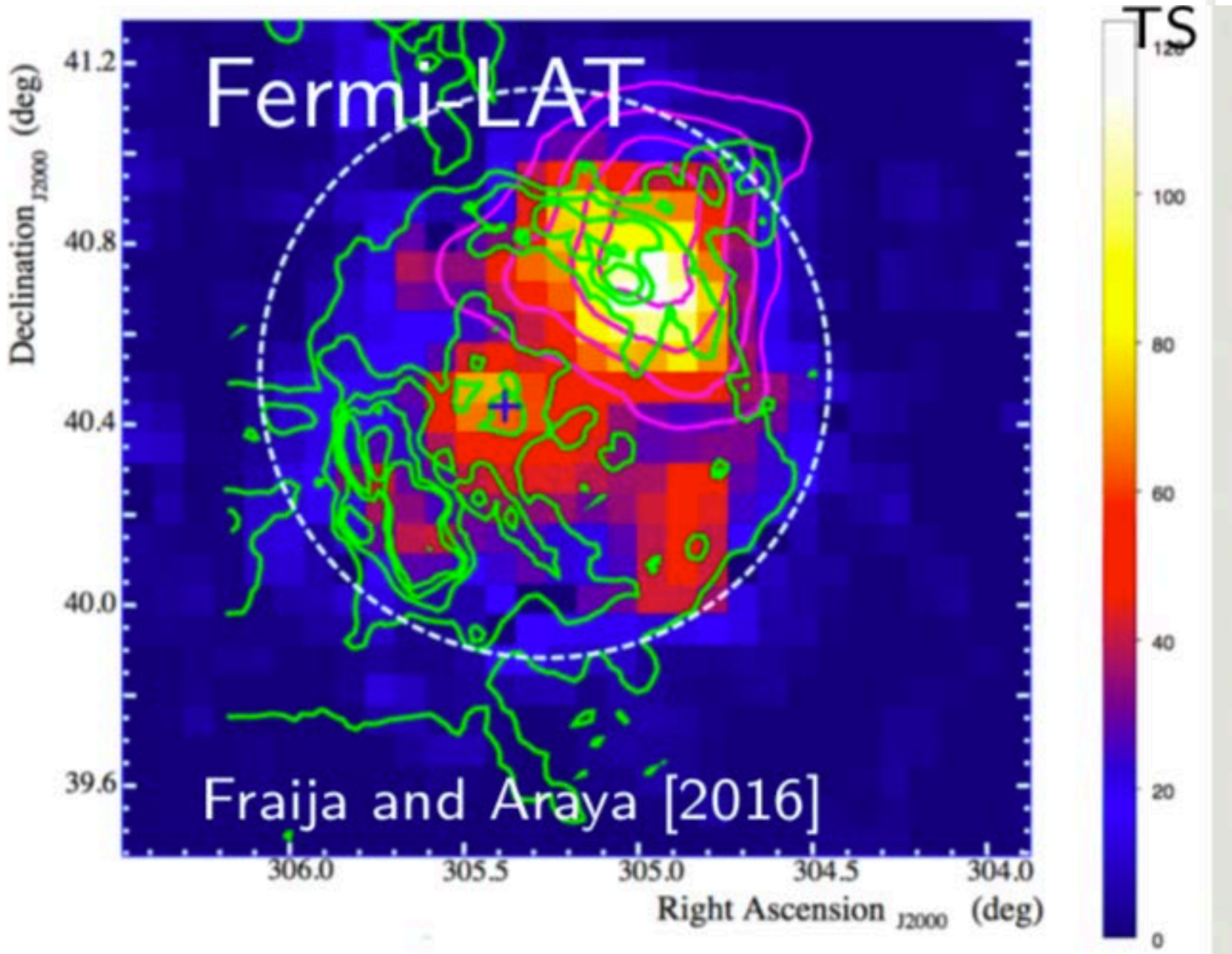


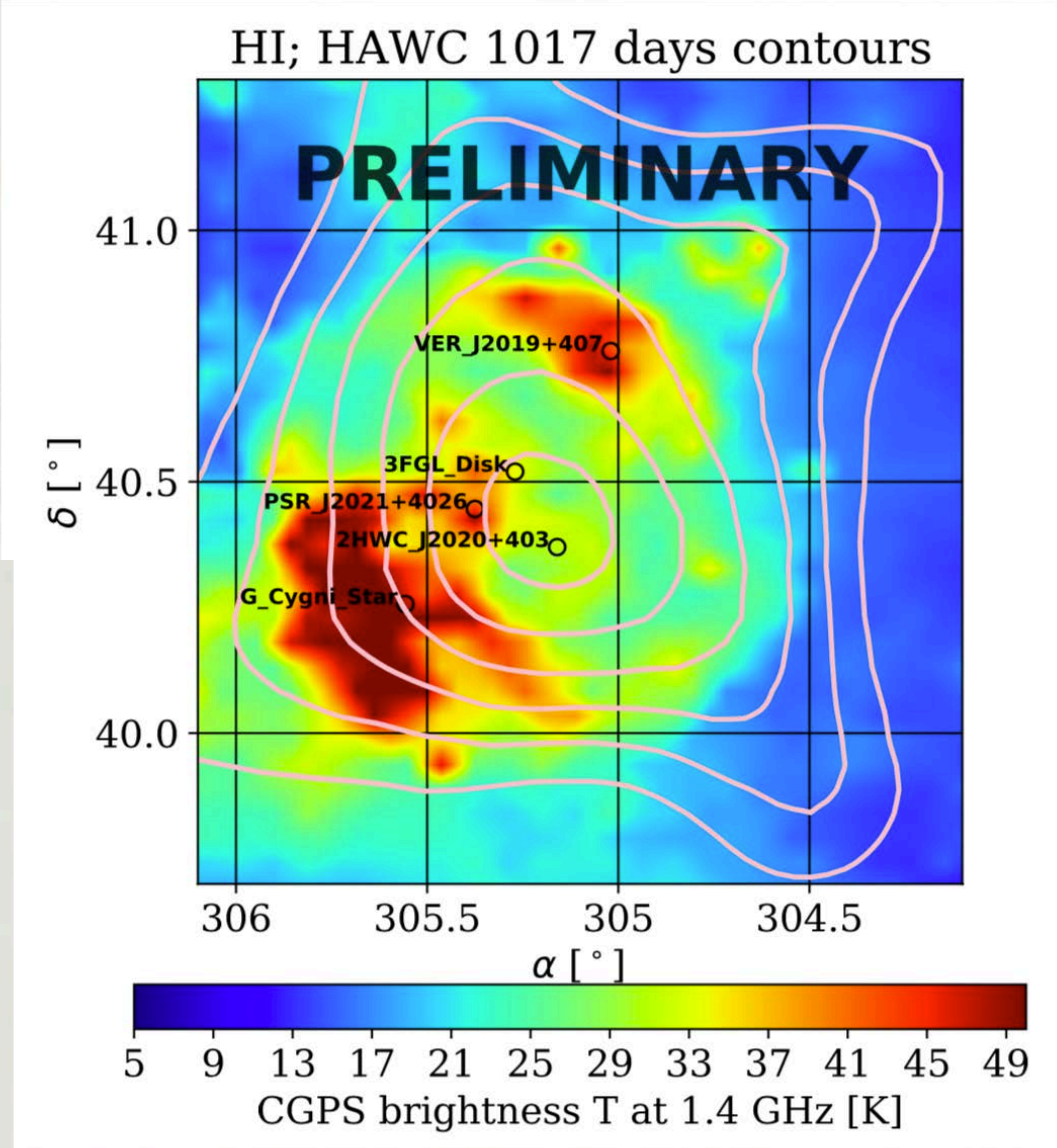


- **Future prospect:**
  - Stricter constraints on **maximum particle energy** through improved HAWC sensitivity at high energy
  - Improved morphology studies

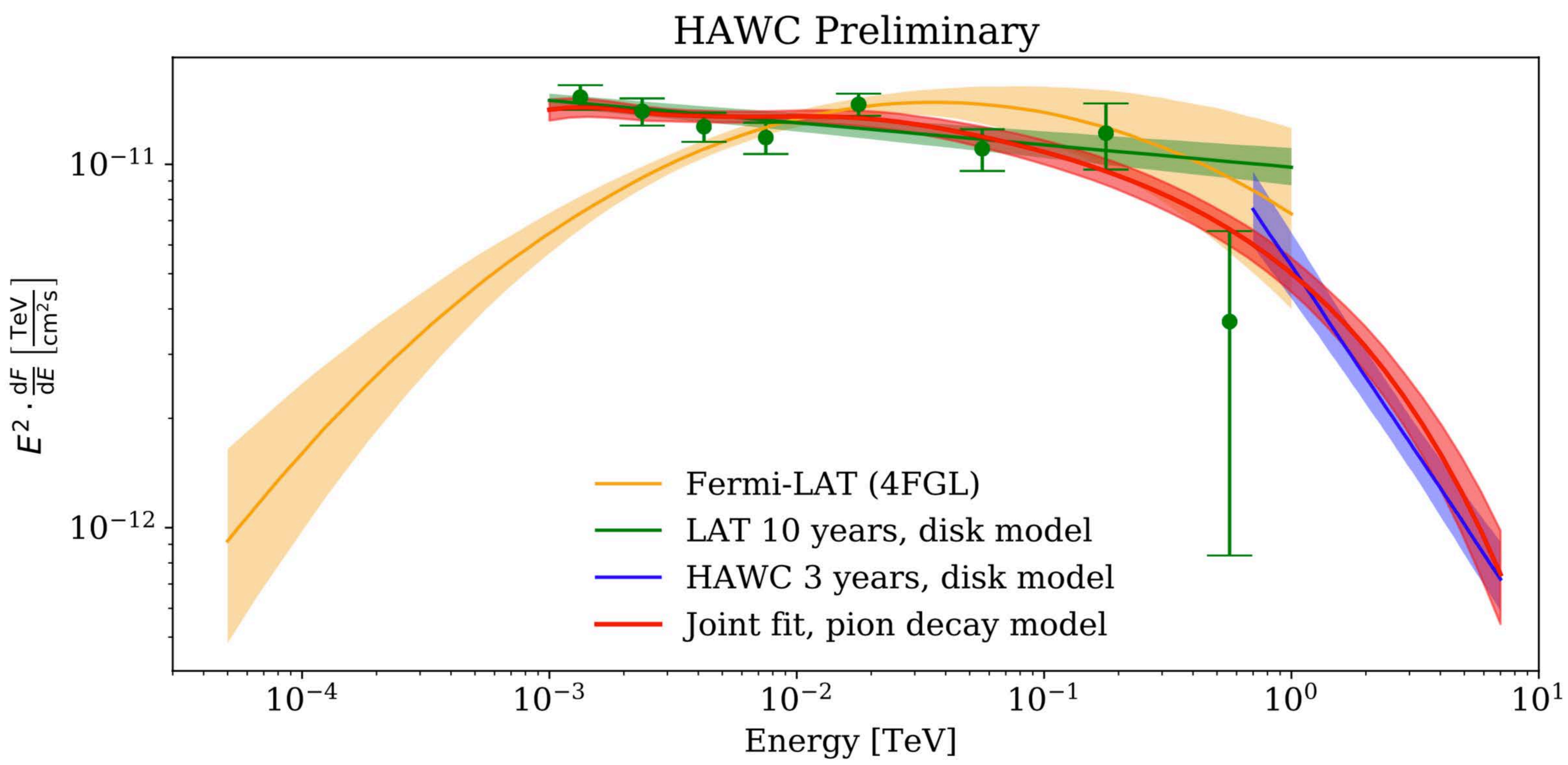
γ Cygni SNR (G78.2+2.1 aka J2021.0+4031)

- Middle-aged SNR, ~6000 yrs [Lozinskaya et al., 2000]).
- Distance: ~1.7 kpc.
- X-ray/radio shell, enhanced emission at nothern/southern edge.
- Seen up to TeV energies.
- Leptonic or hadronic emission?
- Fermi fit with disk and hotspot
- HAWC removes Cocoon and J2032+4130



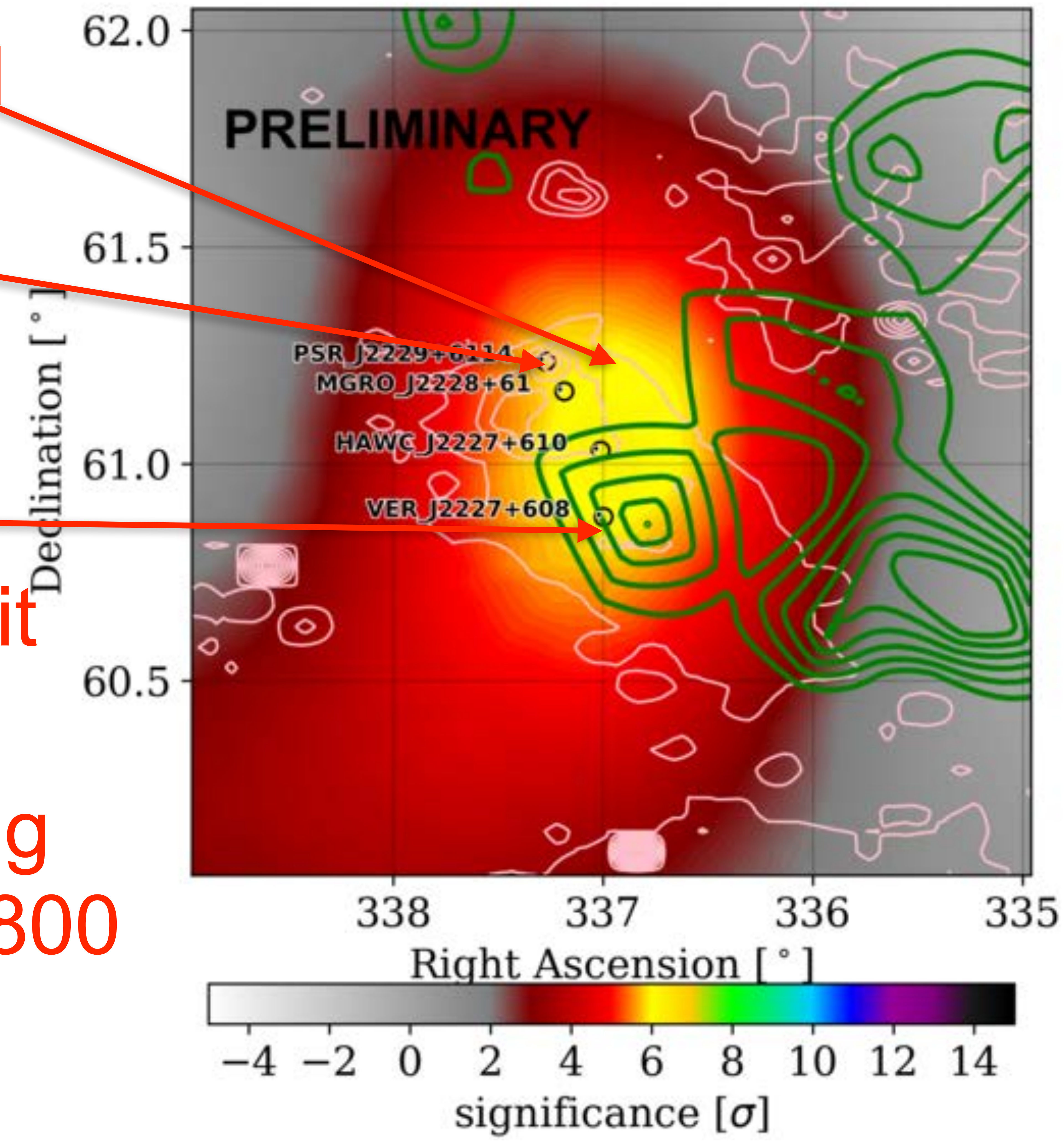


Combined Fermi - HAWC fit to γ Cygni

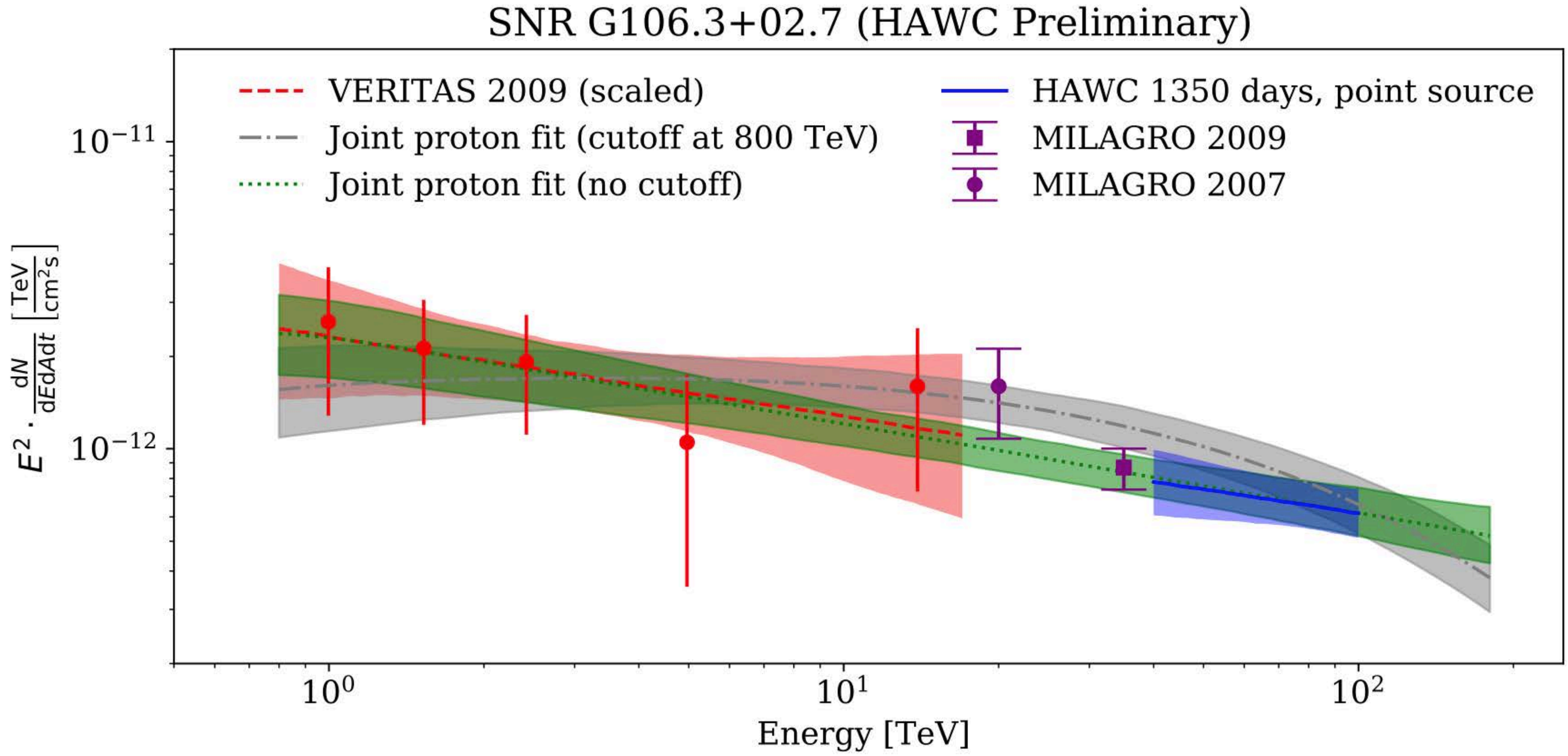


Boomerang - A Galactic Pevatron

- SNR G106.3+2.7 is a comet-shaped radio source
- PSR J2229+6114, seen in radio, X-rays, and gamma rays
- Boomerang Nebula is contained in the remnant (coldest spot in the Universe?)
- VERITAS source
- The joint VERITAS-HAWC spectrum is well fit by a power law from 800 GeV to 180 TeV
- If hadronic, the cutoff energy in the underlying proton spectrum is constrained to be above 800 TeV

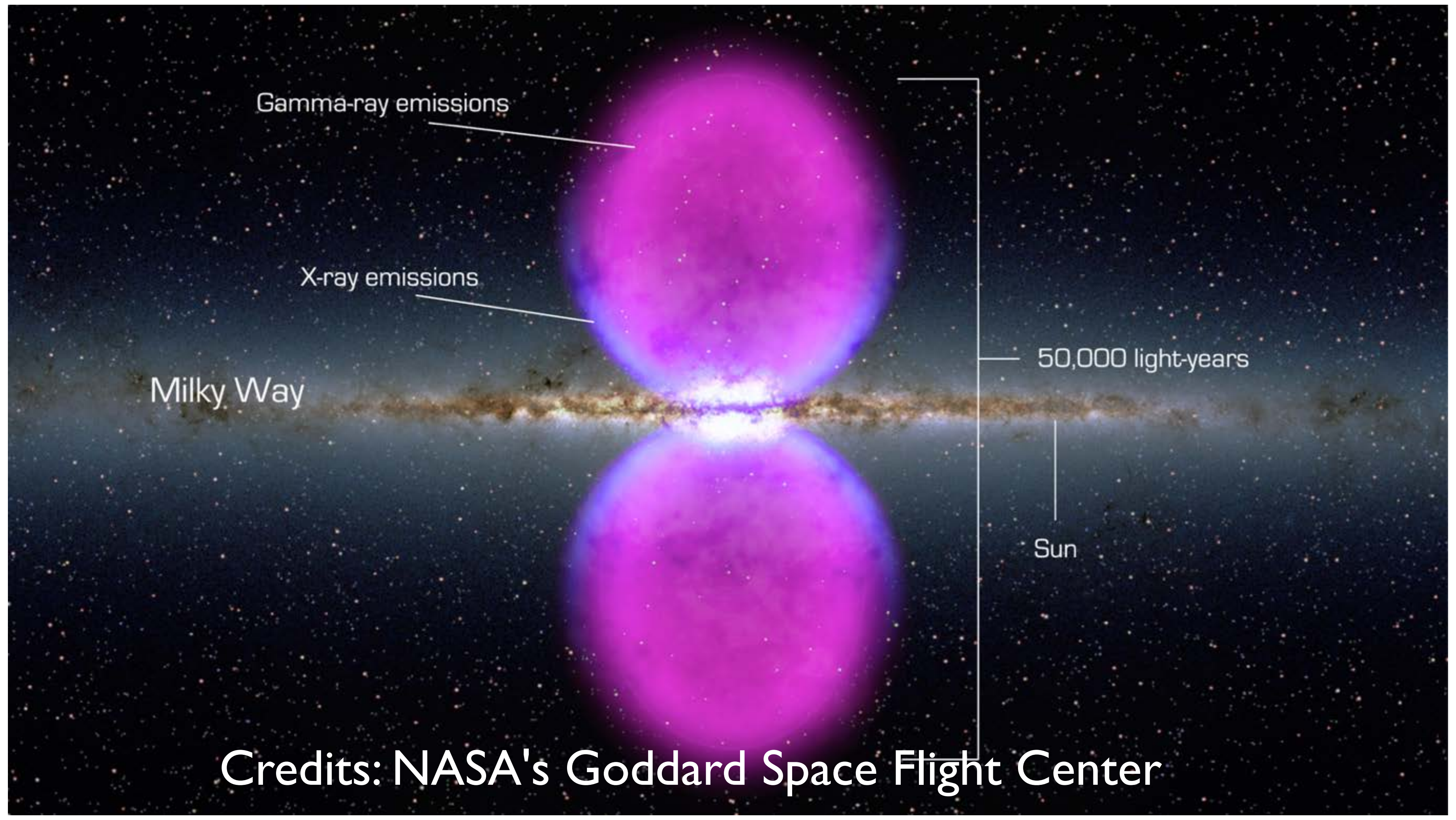


Boomerang - A Galactic Pevatron?

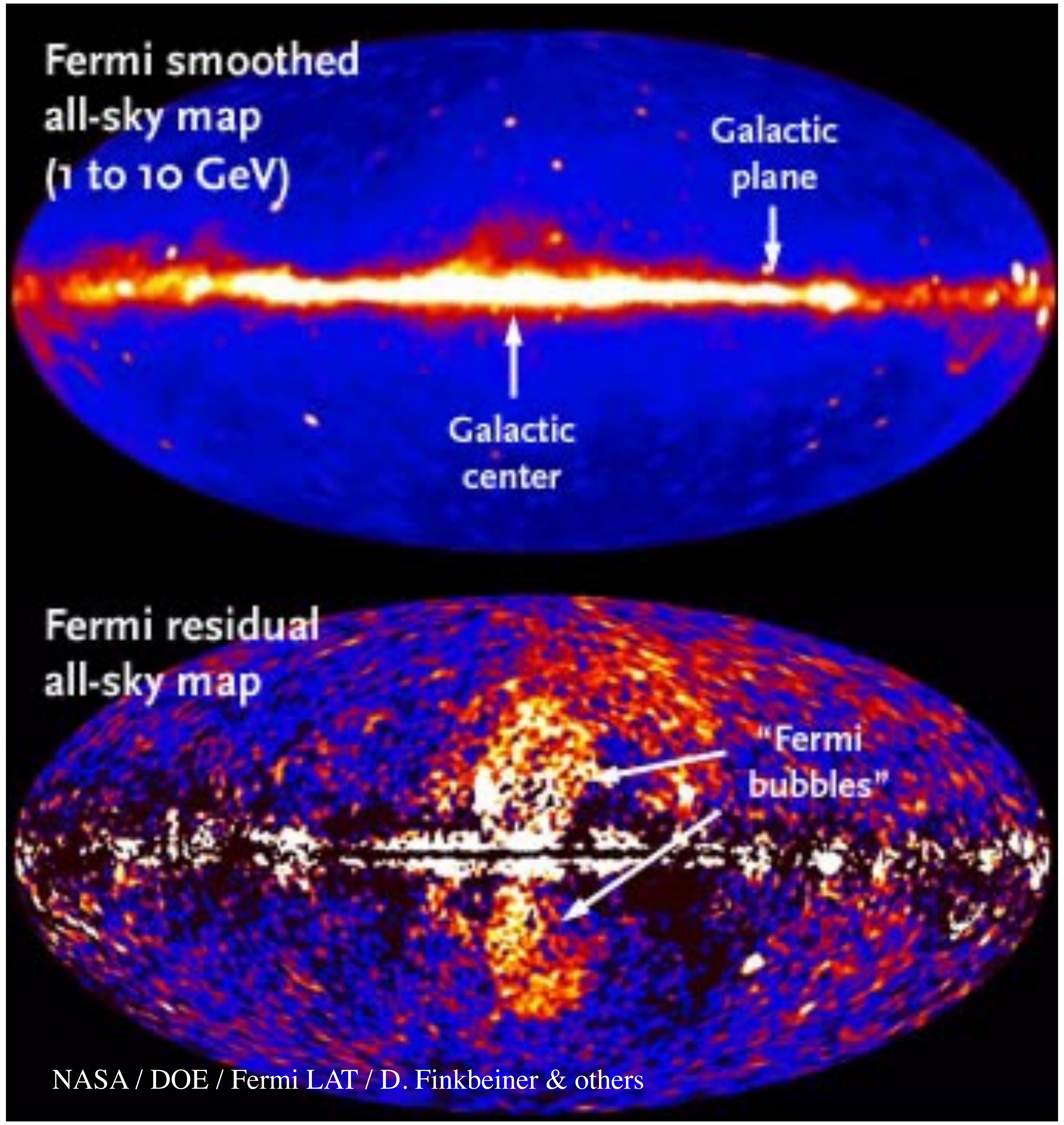


Large-scale structures e.g. Fermi Bubbles

- 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.**

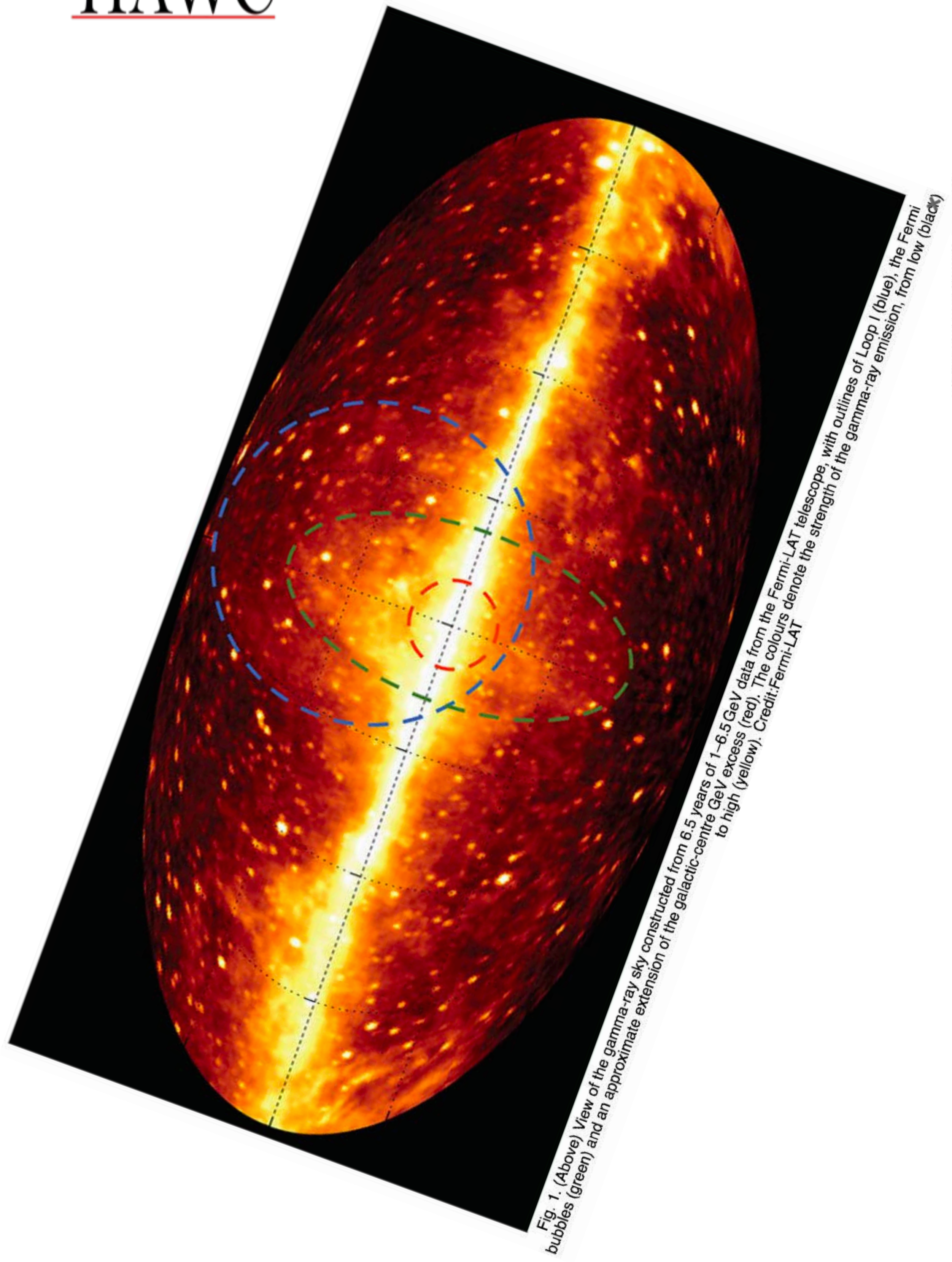


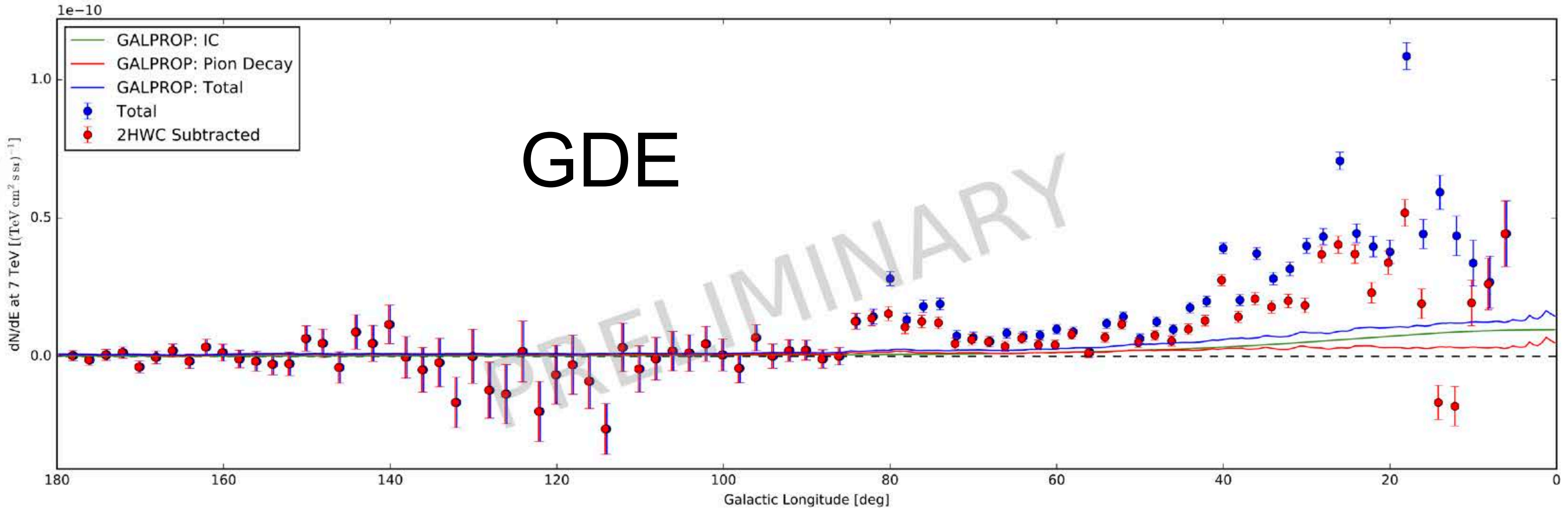
Credits: NASA's Goddard Space Flight Center

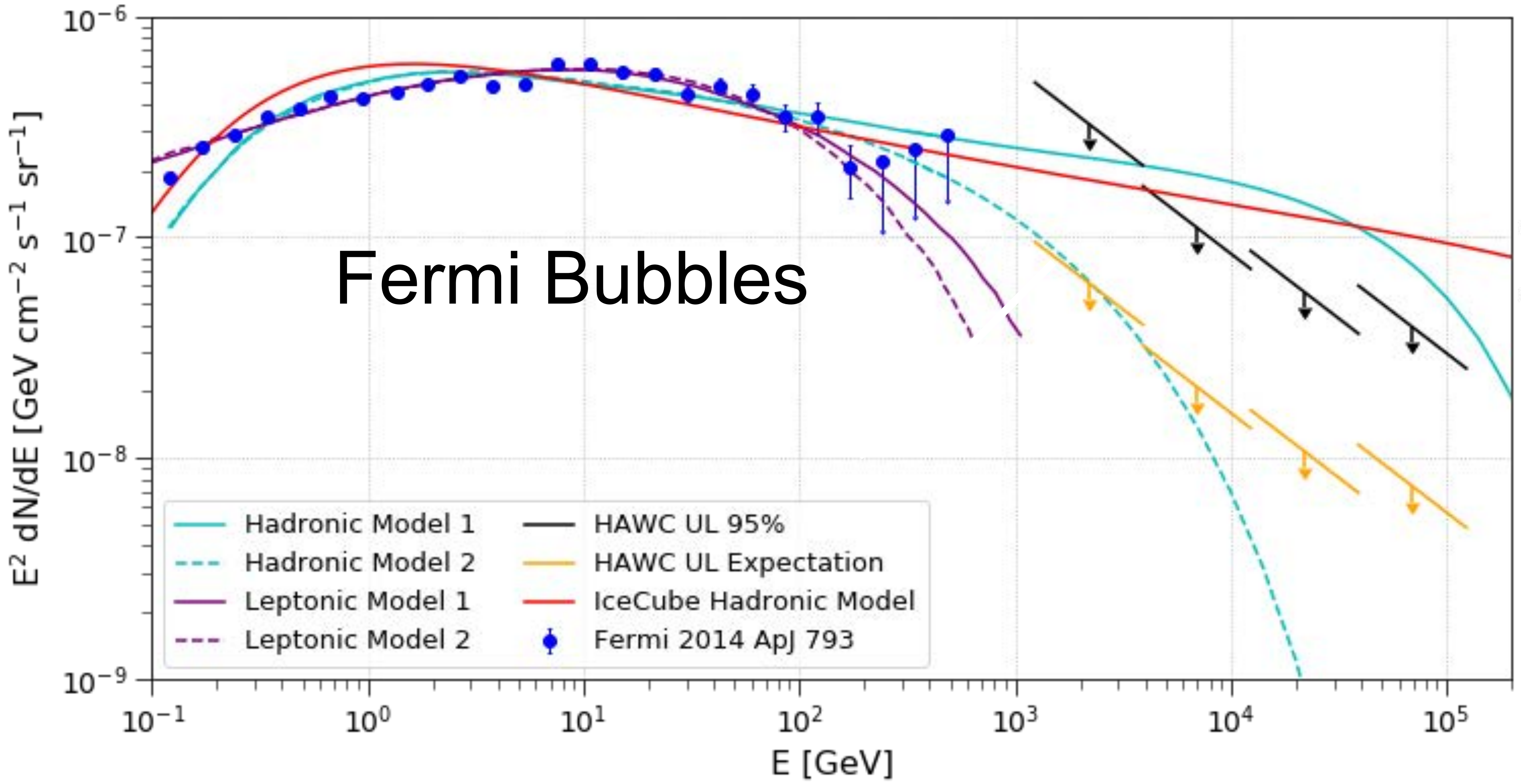


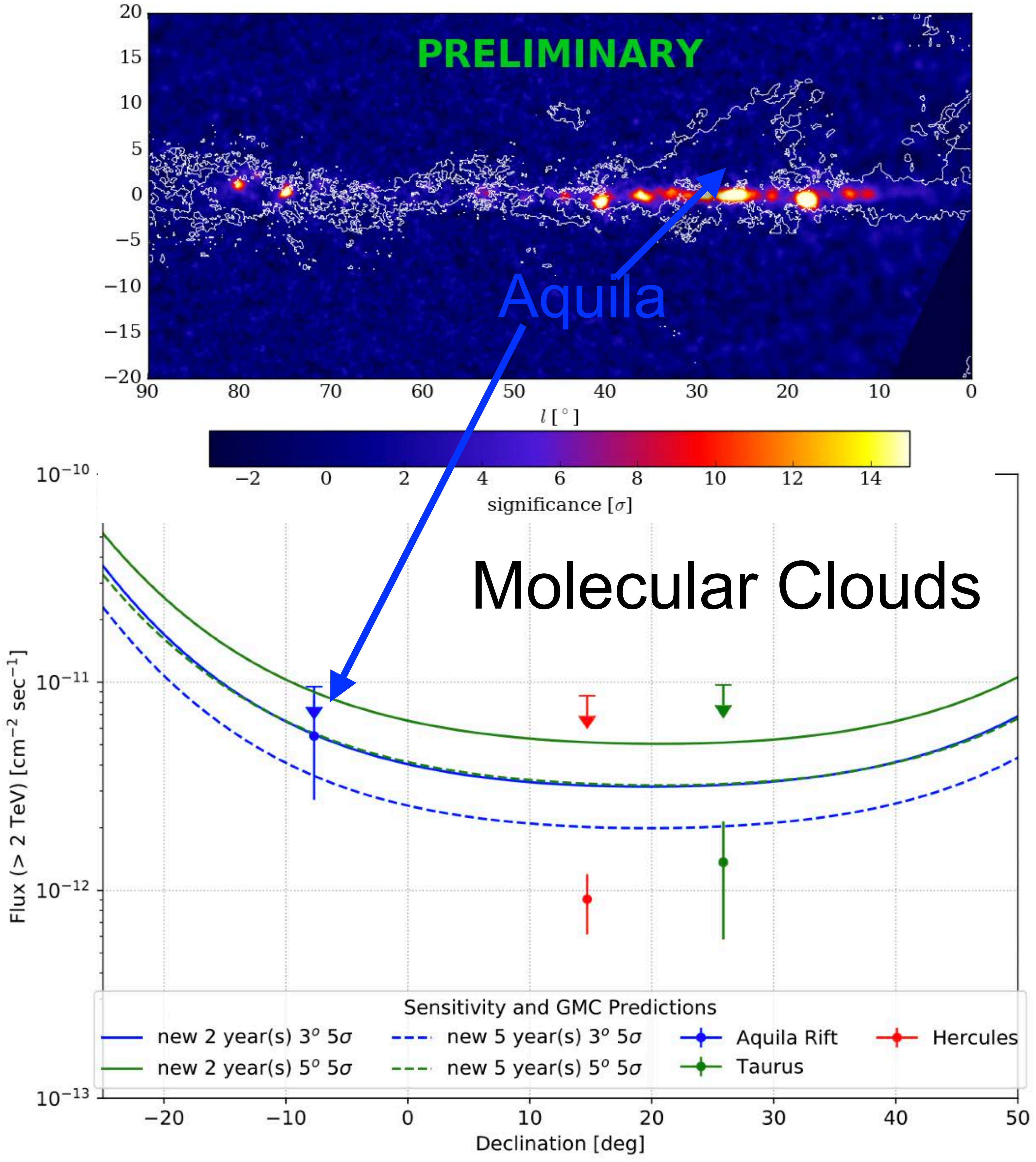
NASA / DOE / Fermi LAT / D. Finkbeiner & others

CR Transport: GDE, Fermi Bubbles & Molecular Clouds





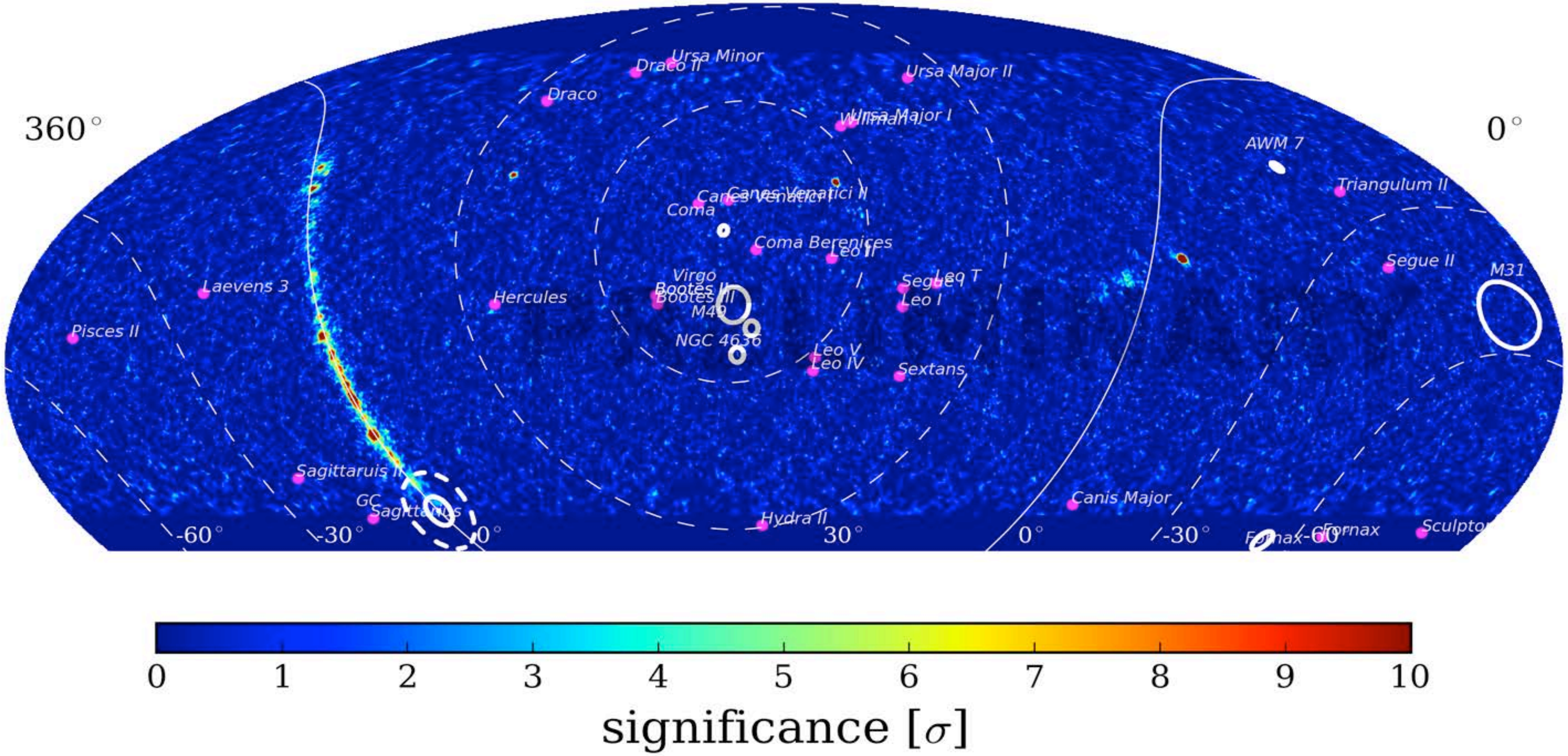




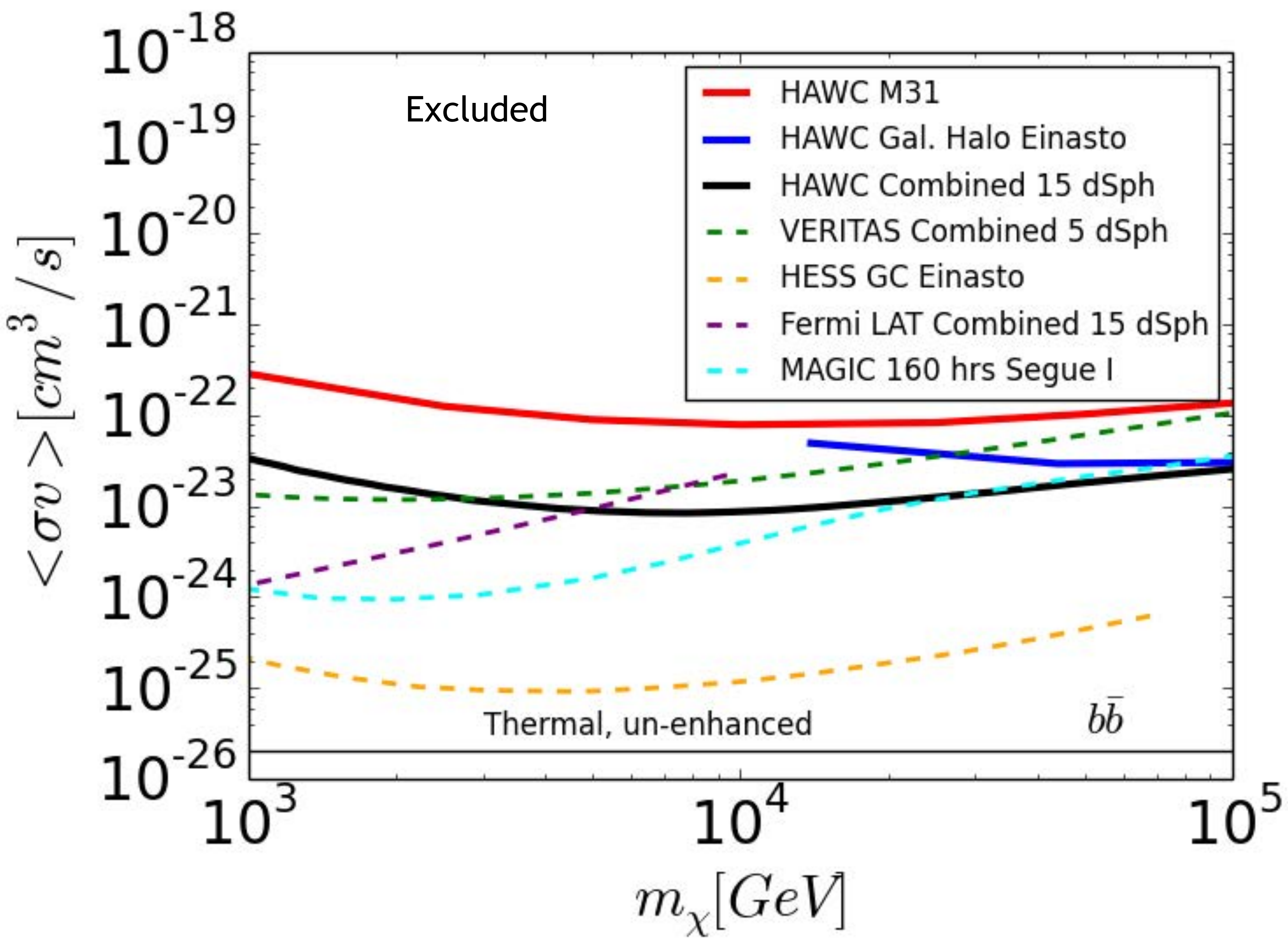
- **Future Prospects:**
  - Test of **Galactic Diffuse Emission** Models at multi-TeV (GALPROP, DRAGON)
  - Improve upper limits on **Fermi Bubbles** by almost an order of magnitude
  - Unprecedented probe of CR flux a distant galactic regions through their interaction with **Large Molecular Clouds** using multi-TeV gamma-ray
  - **Direct CR measurement:** Update of Large scale anisotropy and localized excesses measurements

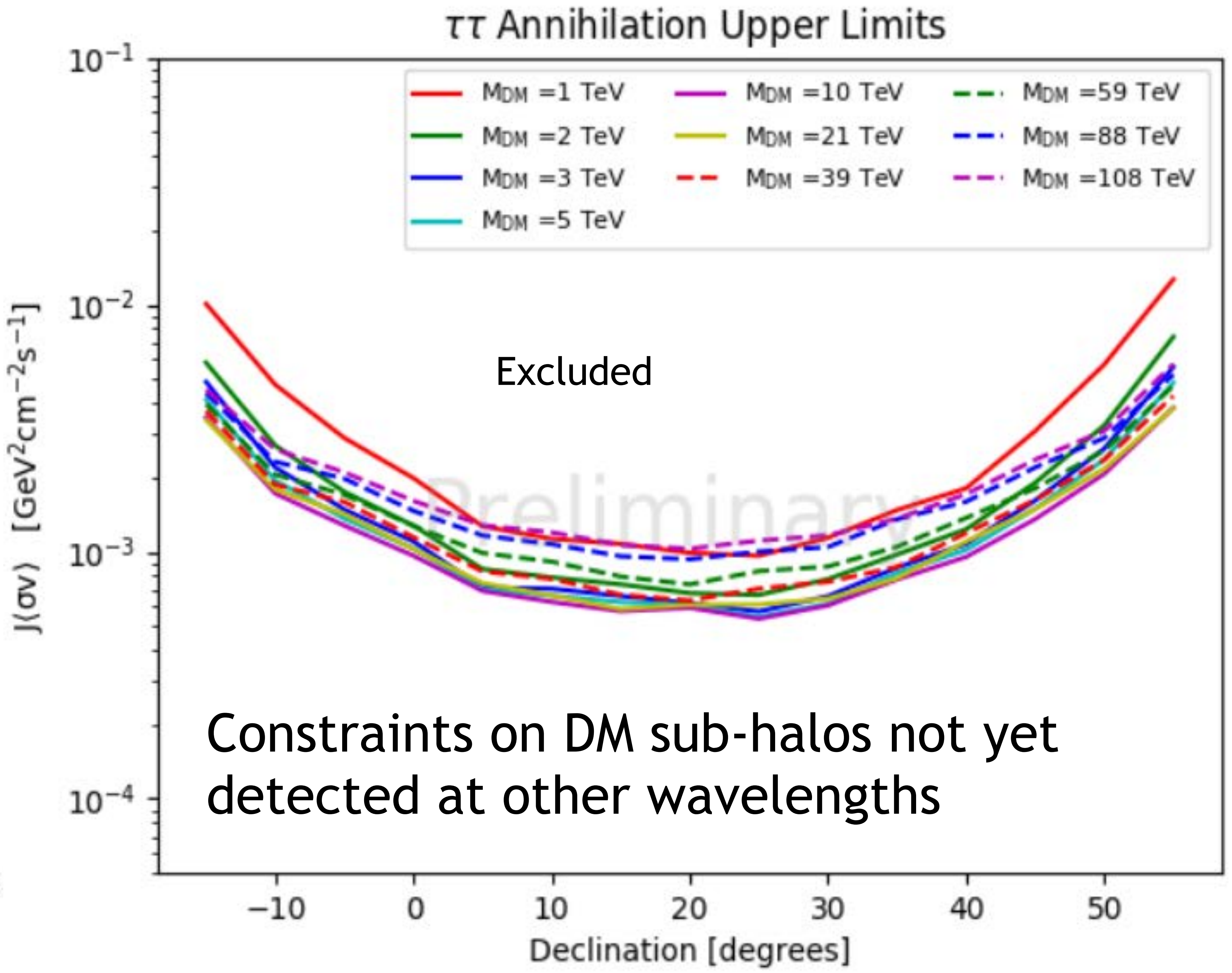
Many Dark Matter Targets in HAWC's Sky

- DM rich sources are dwarf spheroidal galaxies (pink dots), M31, Galactic center halo, and galaxy clusters (white circles).
- DM annihilation or decay produces gamma-rays
- HAWC has placed strong limits on multi-TeV DM (i.e. masses > than testable with direct detection or the LHC)



Dark Matter Searches with HAWC



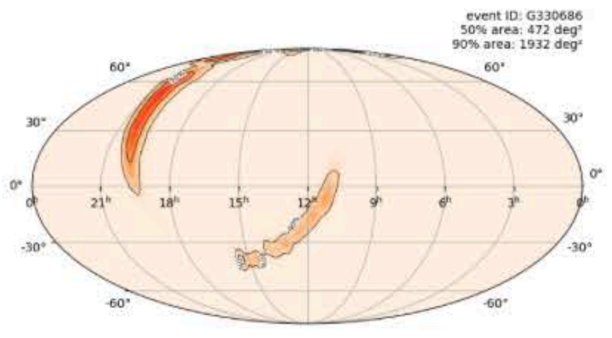


- HAWC's wide field of view plus daily exposure of several dark matter targets yields best limits on dwarf spheroidal galaxies for highest DM masses
- HAWC published limits from 15 dSphs, M31, and the Galactic Halo
- Currently analyses include Irregular dSphs, the Virgo Cluster, unknown sub-halos, and gamma-ray lines

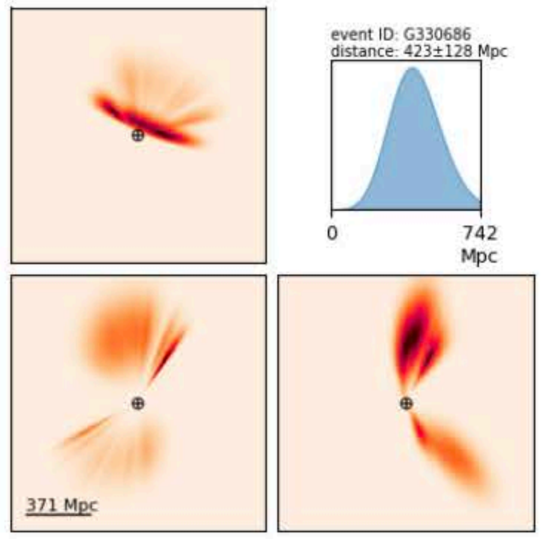
LIGO Events - Run O3

Superevent Log Messages

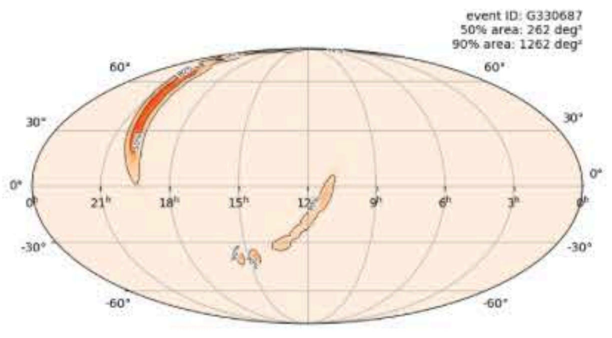
Sky Localization



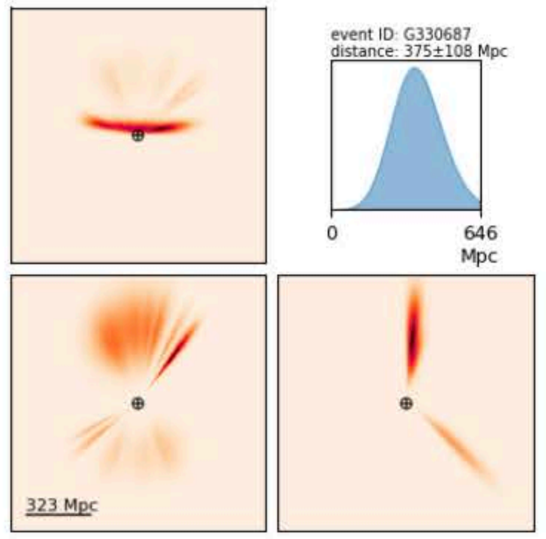
Mollweide projection of bayestar.fits bayestar.png. Submitted by LIGO/Virgo EM Follow-Up on Apr 26, 2019 15:46:58 UTC



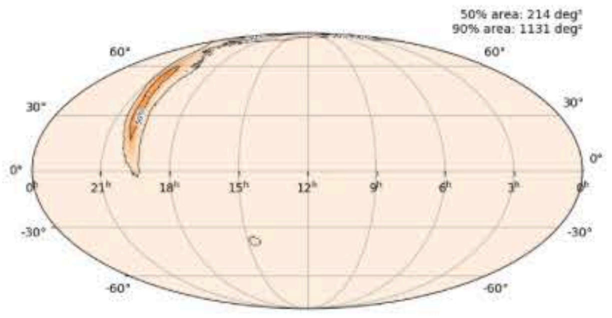
Volume rendering of bayestar.fits bayestar.volume.png. Submitted by LIGO/Virgo EM Follow-Up on Apr 26, 2019 15:47:24 UTC



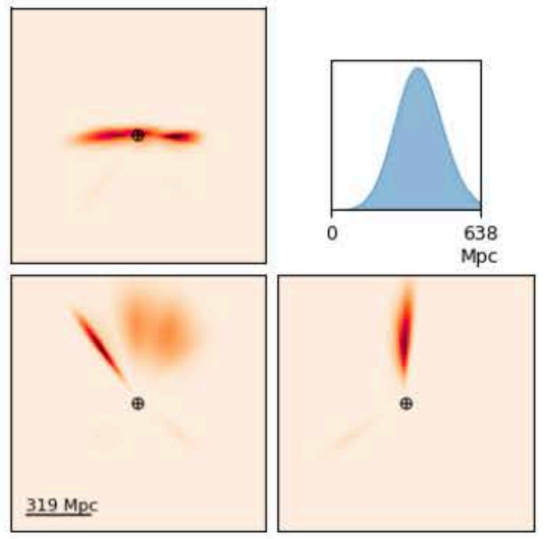
Mollweide projection of bayestar1.fits bayestar1.png. Submitted by LIGO/Virgo EM Follow-Up on Apr 26, 2019 16:21:03 UTC



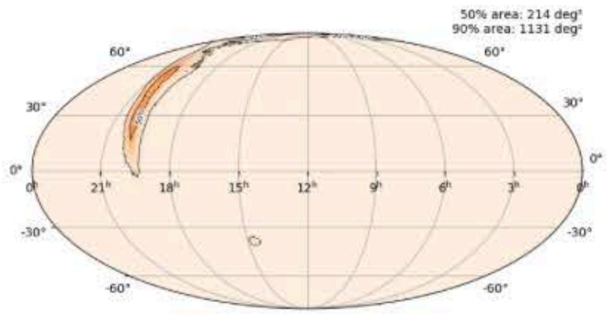
Volume rendering of bayestar1.fits bayestar1.volume.png. Submitted by LIGO/Virgo EM Follow-Up on Apr 26, 2019 16:21:30 UTC



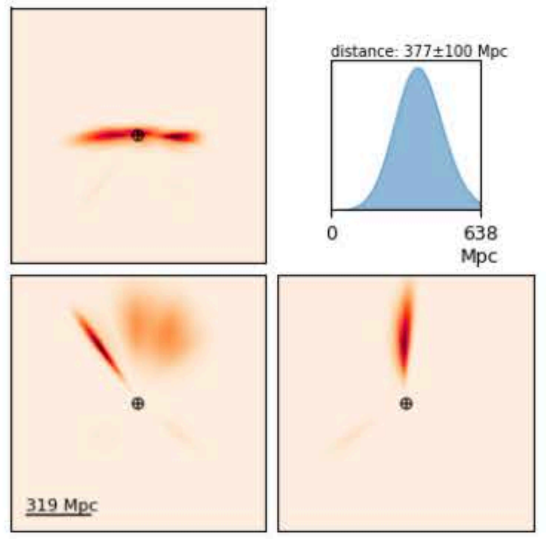
manually uploading LALInference.png LALInference.png. Submitted by Shaon Ghosh on Apr 27, 2019 10:07:58 UTC



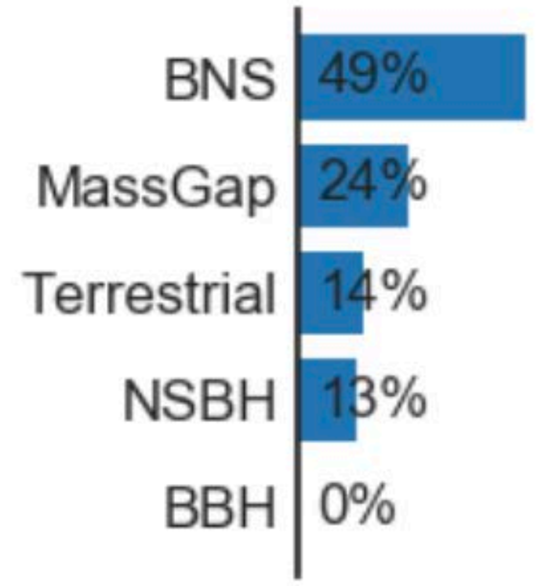
manually uploading LALInference_volume.png LALInference_volume.png. Submitted by Shaon Ghosh on Apr 27, 2019 11:28:51 UTC



Mollweide projection of LALInference1.fits LALInference1.png. Submitted by LIGO/Virgo EM Follow-Up on Apr 27, 2019 11:51:20 UTC



Volume rendering of LALInference1.fits LALInference1.volume.png. Submitted by LIGO/Virgo EM Follow-Up on Apr 27, 2019 11:51:49 UTC

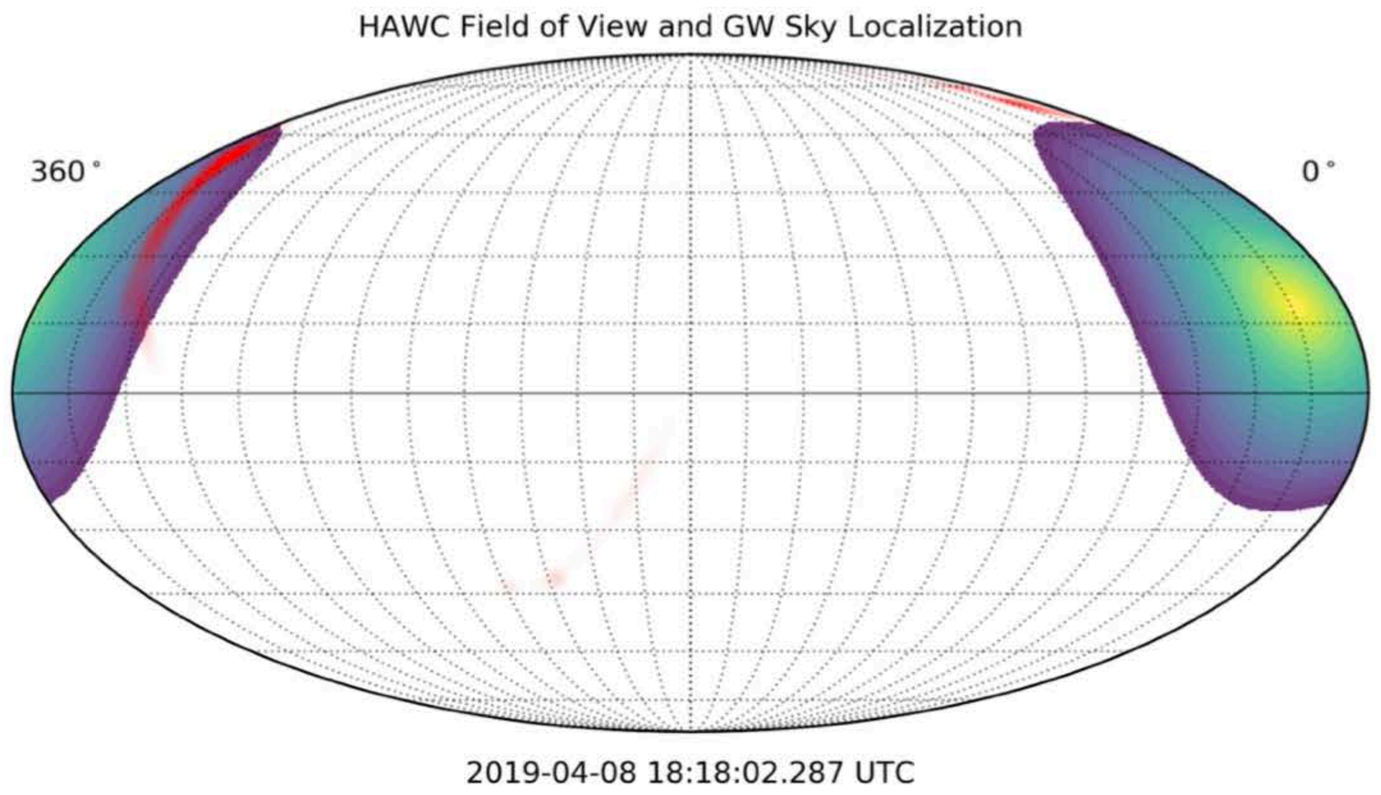


Source classification visualization from p_astro.json p_astro.png. Submitted by LIGO/Virgo EM Follow-Up on Apr 26, 2019 15:47:04 UTC

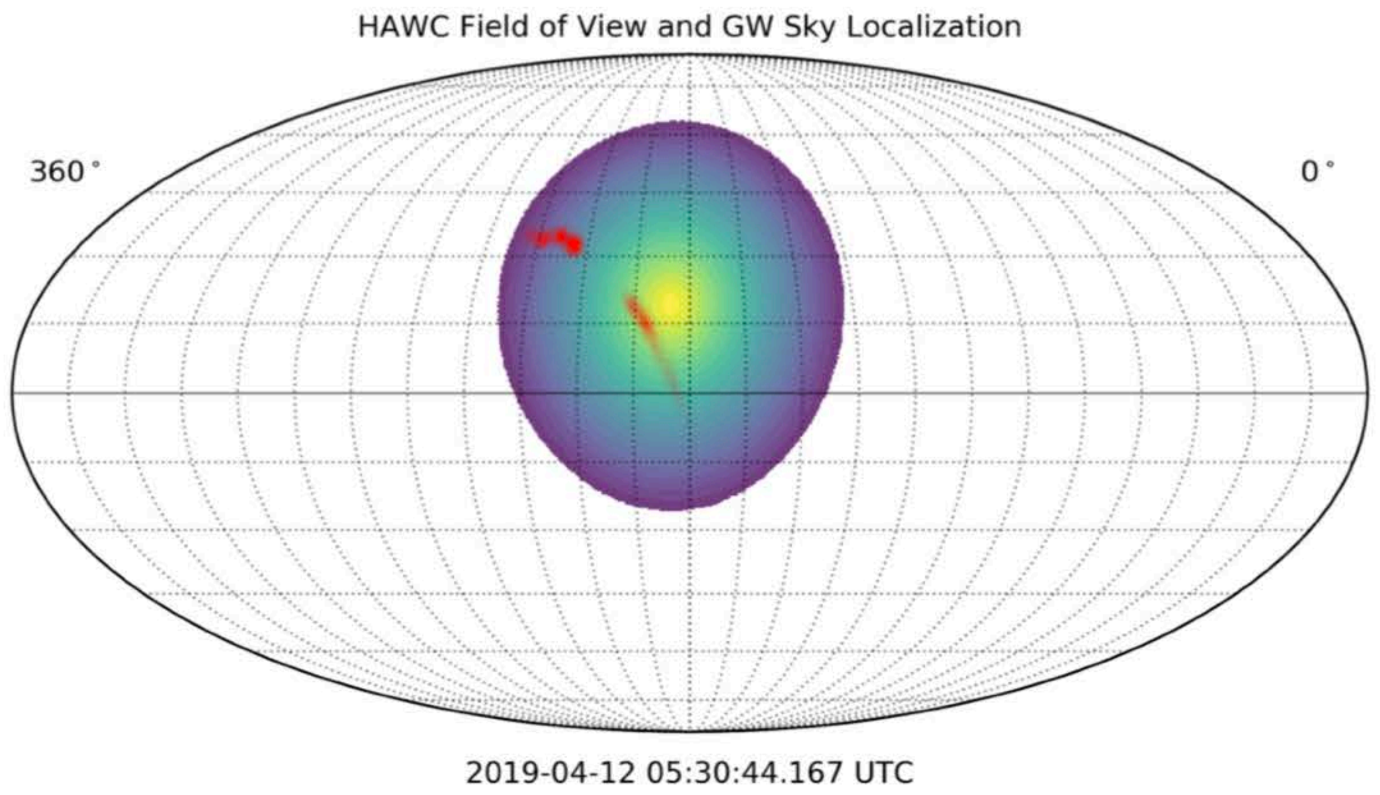
UTC

Log Entry Created	Submitter	Comment
Apr 27, 2019 11:51:17 UTC	LIGO/Virgo EM Follow-Up	FITS headers for LALInference1.fits LALInference1.html
Apr 27, 2019 11:50:29 UTC	LIGO/Virgo EM Follow-Up	Flattened from multiresolution file LALInference1.fits LALInference1.fits.gz
Apr 27, 2019 11:48:44 UTC	Leo Singer	Multi-resolution FITS file LALInference1.fits
Apr 27, 2019 10:00:15 UTC	Shaon Ghosh	manually uploading lalinference.fits.gz lalinference.fits.gz
Apr 26, 2019 16:20:59 UTC	LIGO/Virgo EM Follow-Up	FITS headers for bayestar1.fits bayestar1.html
Apr 26, 2019 16:19:18 UTC	LIGO/Virgo EM Follow-Up	Flattened from multiresolution file bayestar1.fits bayestar1.fits.gz
Apr 26, 2019 16:17:05 UTC	LIGO/Virgo EM Follow-Up	Copy of bayestar.fits bayestar1.fits
Apr 26, 2019 15:46:59 UTC	LIGO/Virgo EM Follow-Up	Flattened from multiresolution file bayestar.fits bayestar.fits.gz
Apr 26, 2019 15:46:54 UTC	LIGO/Virgo EM Follow-Up	Localization copied from G330687 bayestar.fits
Apr 26, 2019 15:46:54 UTC	LIGO/Virgo EM Follow-Up	FITS headers for bayestar.fits bayestar.html

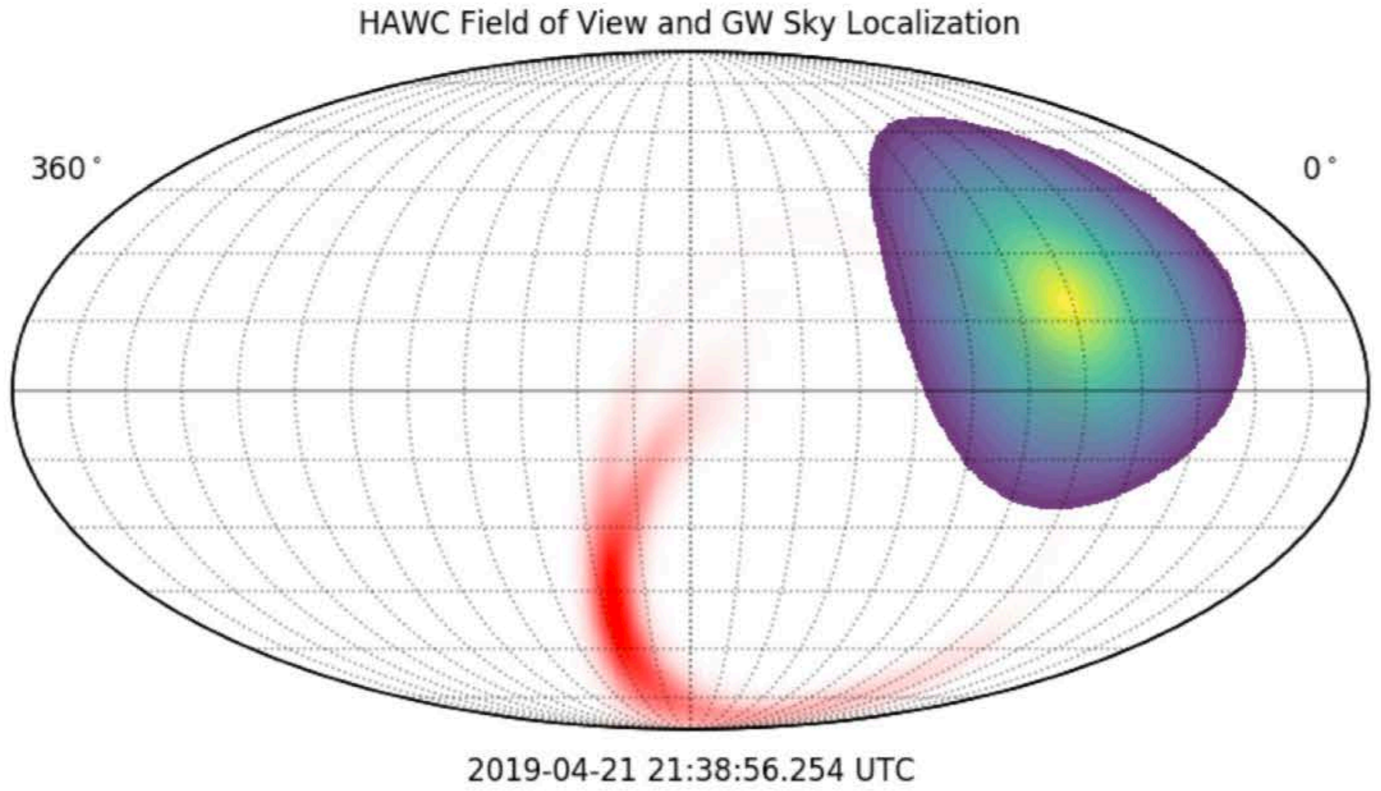
LIGO Alerts Run O3



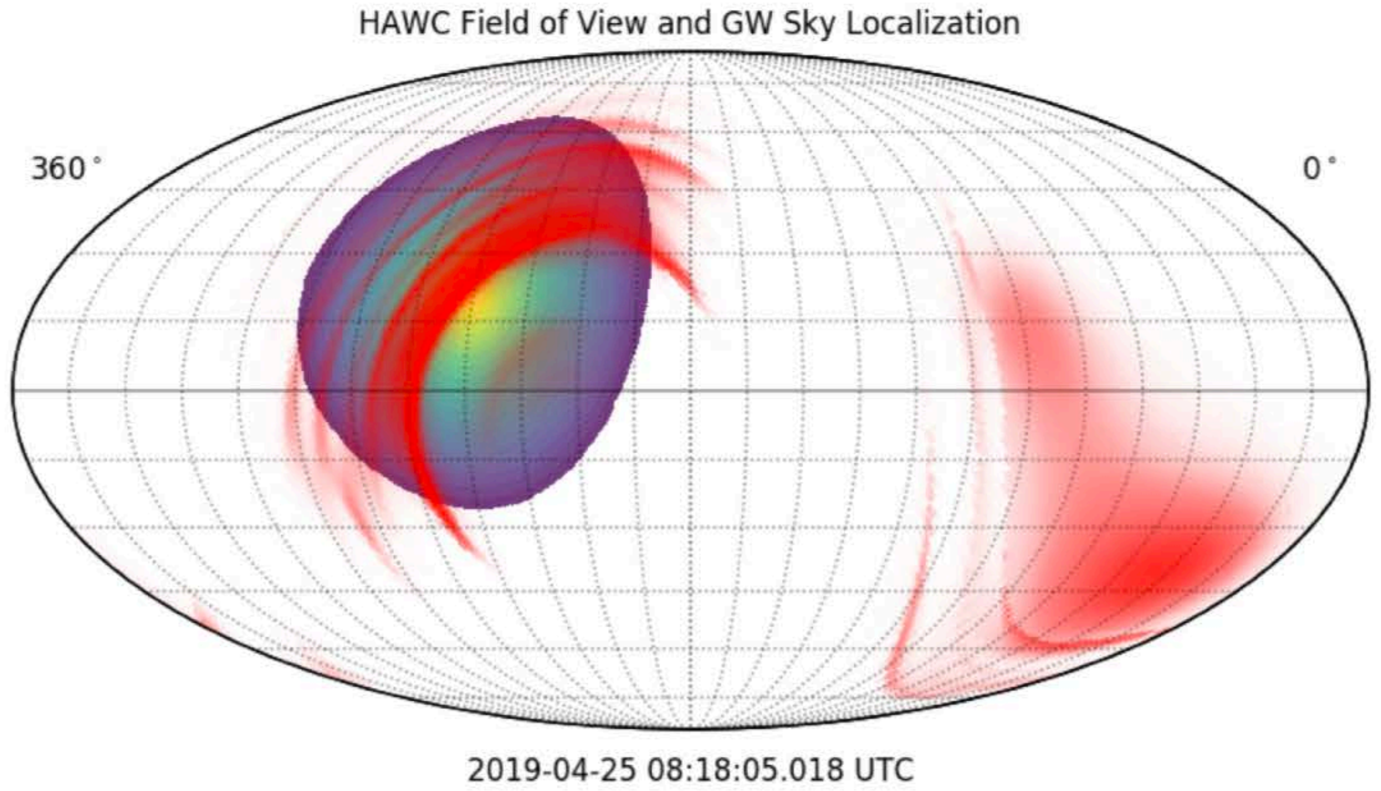
S190408an



S190412m



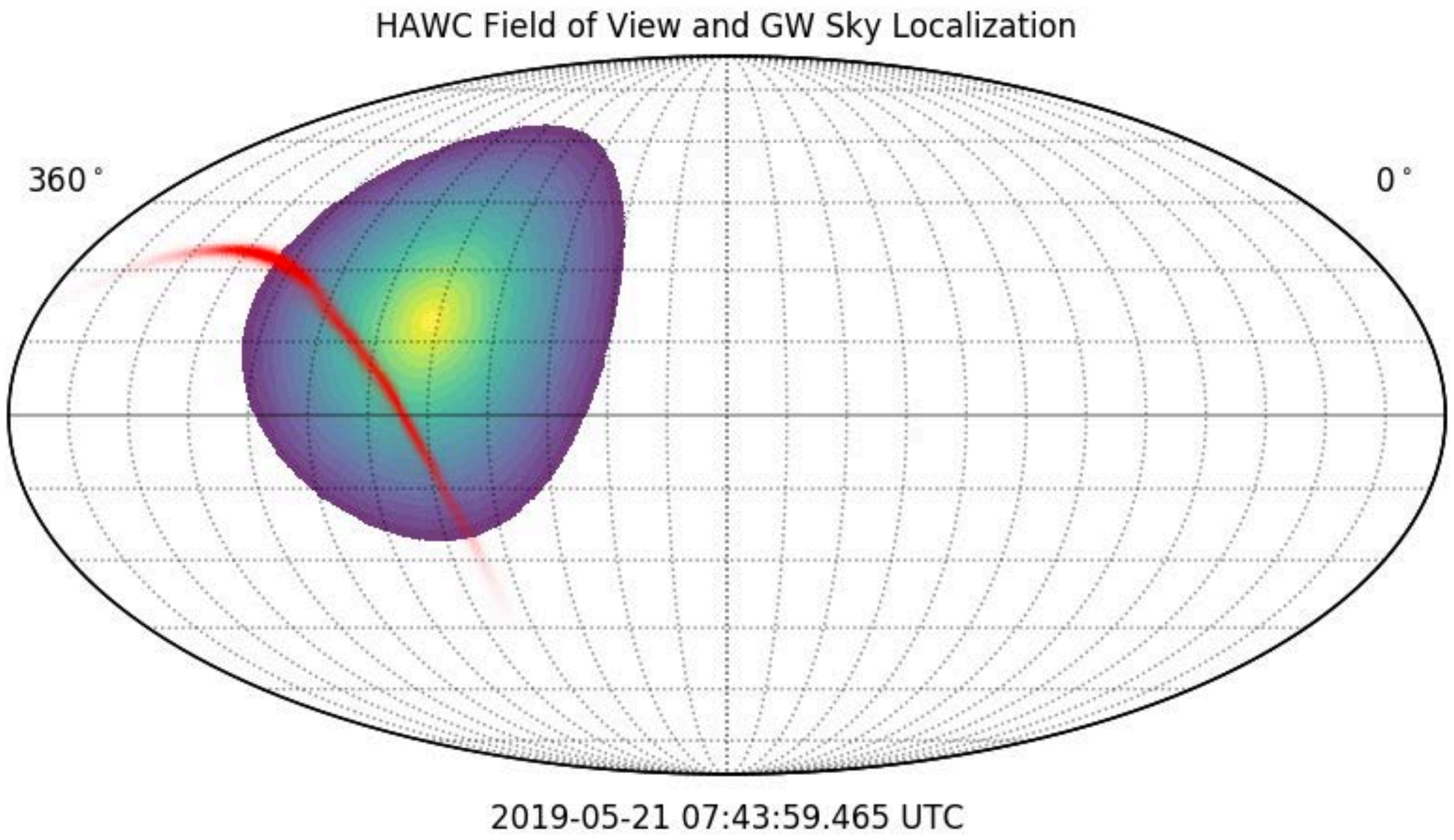
S190421ar



S190425z

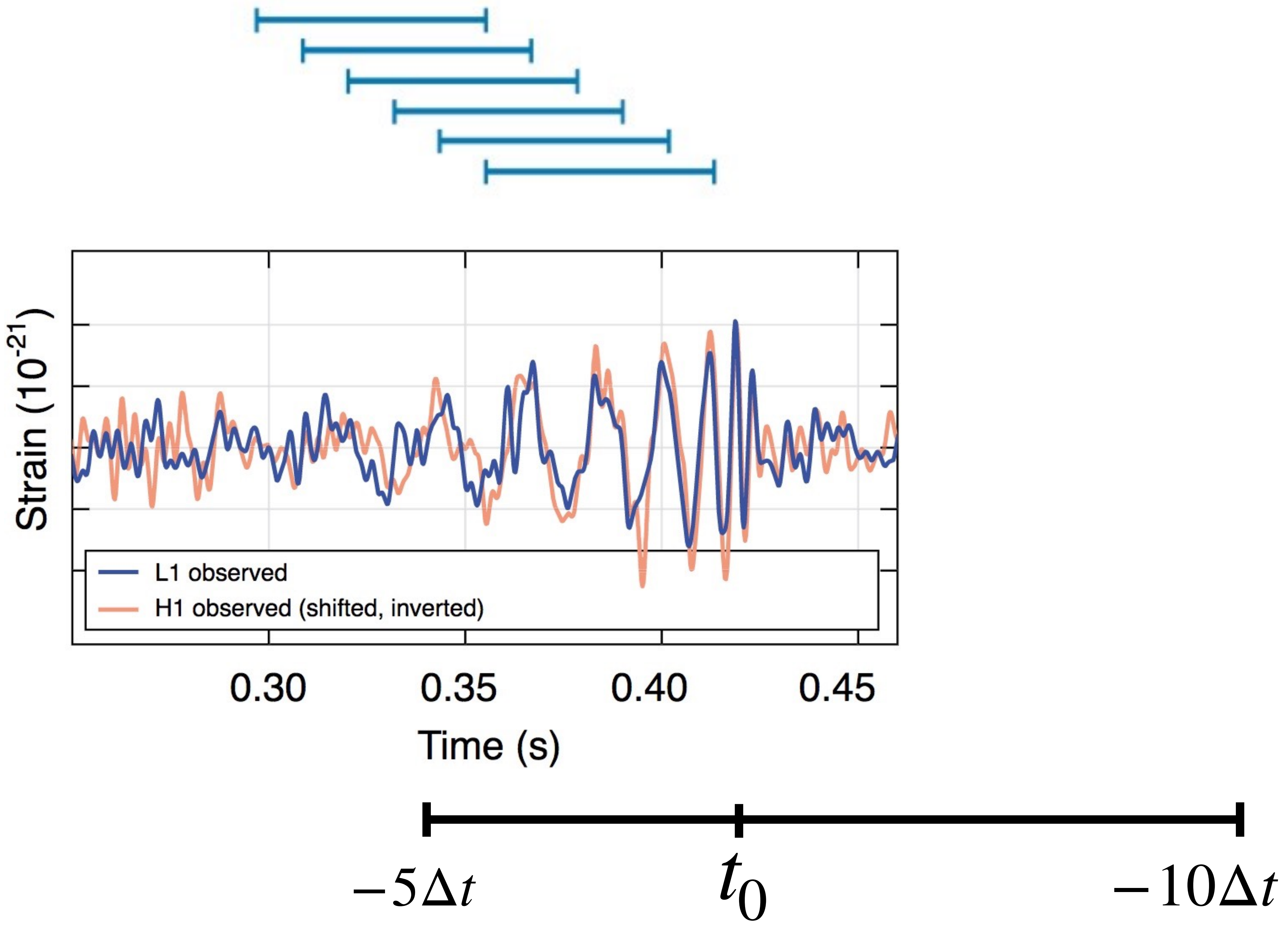
Gravitational wave follow-up

- We run the maximum likelihood analysis testing many locations and time intervals:
  - 95% of the sky localization probability
  - Different timescales: 0.3s to 1000s
  - Overlapping time windows by 80%
  - Total search duration depends on the timescale



Time window widths

$$\Delta t = 0.3\text{s} - 1000\text{s}$$



Processing Alerts (Israel Martinez)

- When HAWC gets a GCN alert from LIGO
- We automatically start a
- Running zebra-transient-search
  95% containment of the sky localization probability
- Testing with time windows Δt = 0.3s, 1s, 3s, 10s, 30 and 100s
- Search from t0 - 5Δt to t0 + 10Δt The whole analysis takes ~30min
- Timescales are processed sequentially (e.g. 0.3s might finished after a few minutes) If a hotspots is detected, an alert is sent ASAP
  The same event might trigger multiple hotspot alerts from different timescales

Processing Alerts

Starting automatic analysis [2019-04-25 09:01:02 UTC]
Timescales: (0.3s, 1.0s, 3.0s, 10.0s, 30.0s, 100.0s)

EVENT ID:	S190425z
REVISION:	1
95% CONT. AREA:	12548.96 deg2
AREA IN FOV:	4941.81 deg2
PROB. IN FOV:	0.48
HAWC ZENITH RA/DEC:	(240.1 deg, 19.0 deg)
ZENITH RANGE:	0.0 - 45.0 deg
1s 80-800GeV SENSI:	1.2e-06 - 1.1e-04 erg/cm2
100s 80-800GeV SENSI:	6.4e-06 - 5.0e-04 erg/cm2

gw-bot APP 13:22
TEST: Hotspot detected [2019-04-18 17:22:35 UTC]

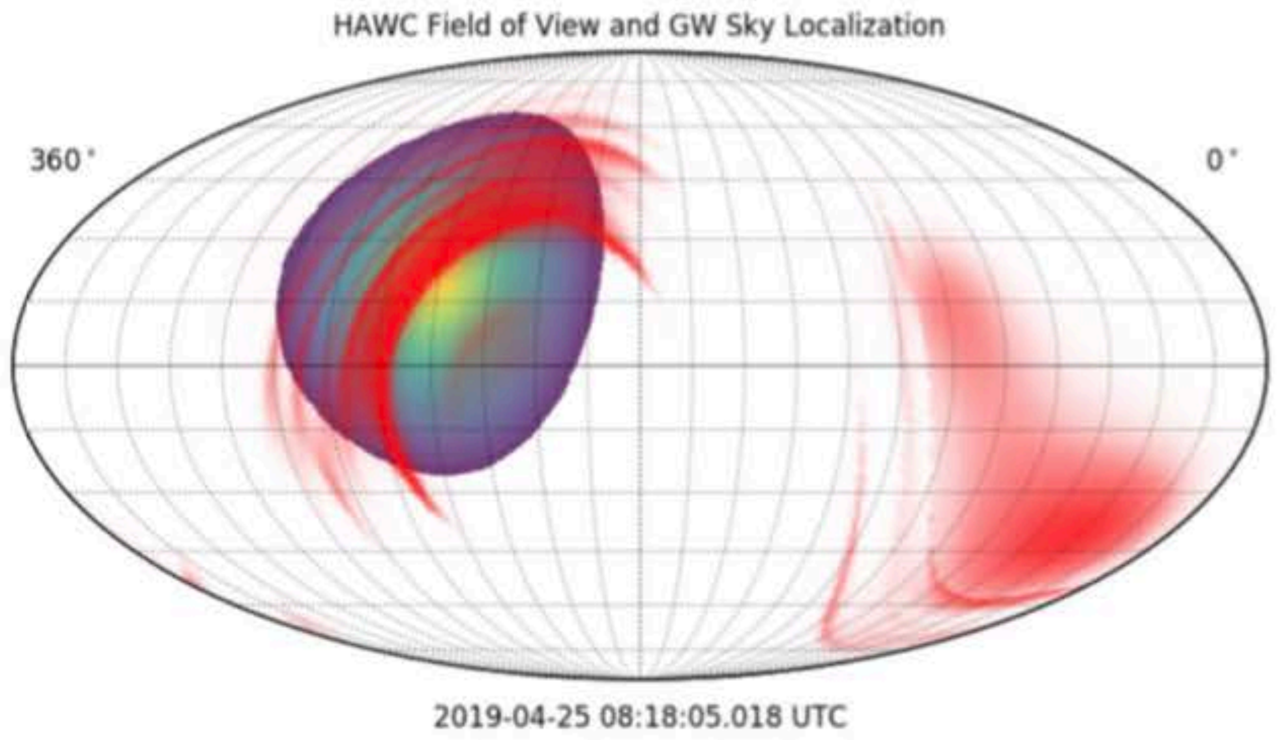
EVENT ID:	MS190324o
REVISION:	1
GW TRIGGER TIME:	2019-03-24 14:36:30.034 UTC
TIMESCALE:	0.3s
TS:	36.1
SIGNIFICANCE:	4.06 sigma
HAWC TRIGGER TIME:	2019-03-24 14:36:28.686 UTC
TIME DIFFERENCE:	-1.3s
RIGHT ASCENSION:	278.70deg
DECLINATION:	15.71deg
POS. ERROR:	0.96deg

Note: significance includes trials

HAWC Alert Page (Internal)

Link to LIGO-Virgo event webpage → S190425z

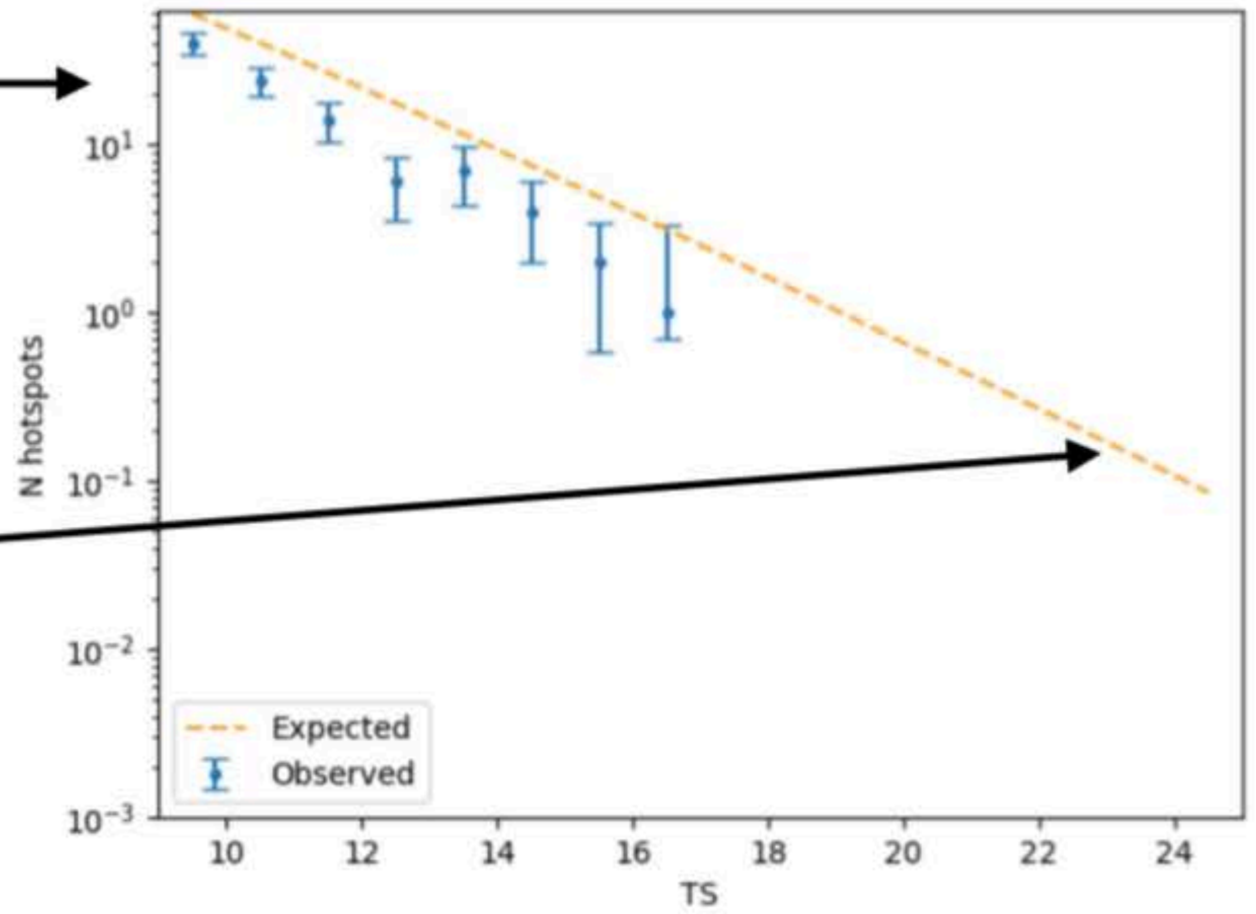
confirmed or retracted → This event has been confirmed.



Result are posted for each timescale as soon as they are done

Results:
Timescale: 0.30 s

Hotspot TS distribution vs expectation.
Serves as a quick check that things are working correctly



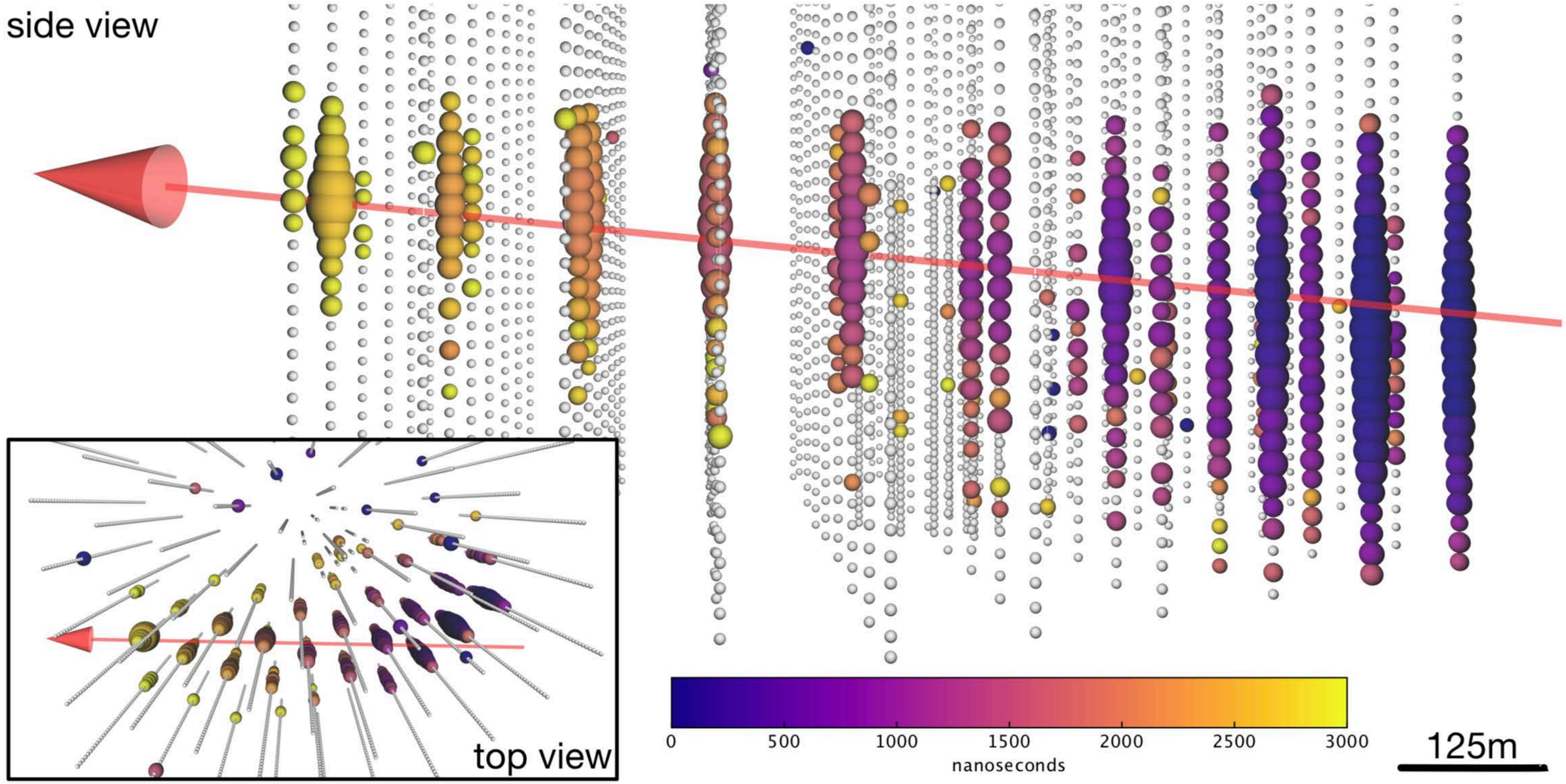
The expected number of hotspots is estimated at zenith, where we have better angular resolution, so it might be off by a factor of ~2

List of sub-threshold hotspots.
For a quick look in case someone else detects something

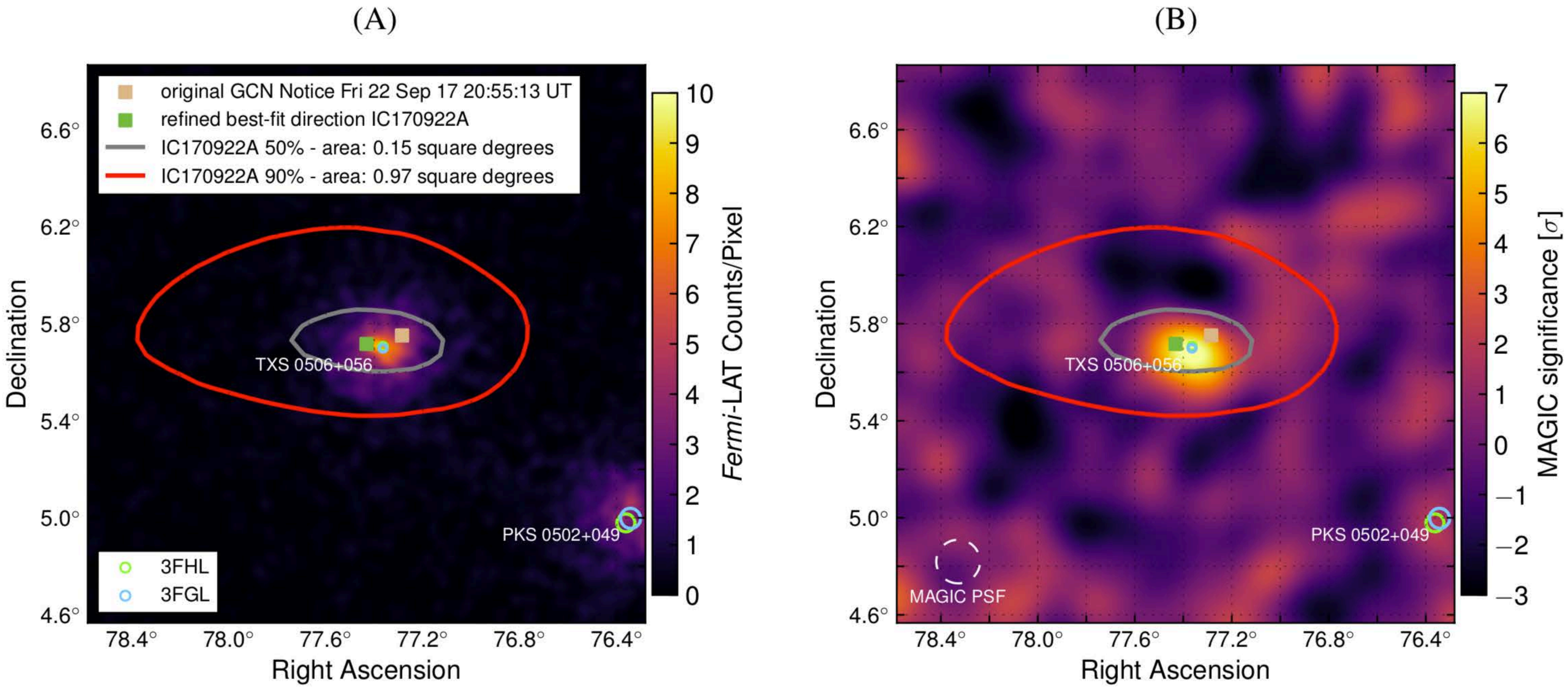
#RA[deg]	DEC[deg]	POS_ERR[deg]	TS	SIGNIFICANCE	START_TIME[gps]	STOP_TIME[GPS]
196.00	38.59	0.77	9.59	<3.00	1240215505.12	1240215505.42
196.52	34.32	0.84	9.08	<3.00	1240215501.82	1240215502.12
199.16	30.60	0.38	14.13	<3.00	1240215502.72	1240215503.02
204.70	0.90	0.65	9.11	<3.00	1240215503.02	1240215503.32
209.27	38.87	0.59	9.15	<3.00	1240215503.32	1240215503.62
211.82	5.30	0.35	11.37	<3.00	1240215504.22	1240215504.52
213.93	4.41	0.57	12.62	<3.00	1240215502.12	1240215502.42
214.28	4.86	0.80	10.00	<3.00	1240215502.72	1240215503.02
215.00	59.20	0.78	12.32	<3.00	1240215502.42	1240215502.72
216.30	8.99	0.54	13.41	<3.00	1240215503.32	1240215503.62

- We are pre-approved to send detection and non-detection alerts as GCN Circulars
- There are templates available for both cases
  - Can be completely filled with info from messages posted in Slack by gw-bot If no detection
- If **NO** detection (by HAWC)
  - Wait for initial alert (confirmation)
  - Wait for all timescales to finish
  - Provide our sensitivity range depending on the zenith angles covered
- If there is a hotspot (>3σ post-trials):
  - We send the circular as soon as possible (don’t wait for confirmation or unfinished timescales) - Provide hotspot coordinates.

IceCube 170922A - TXS0506+056

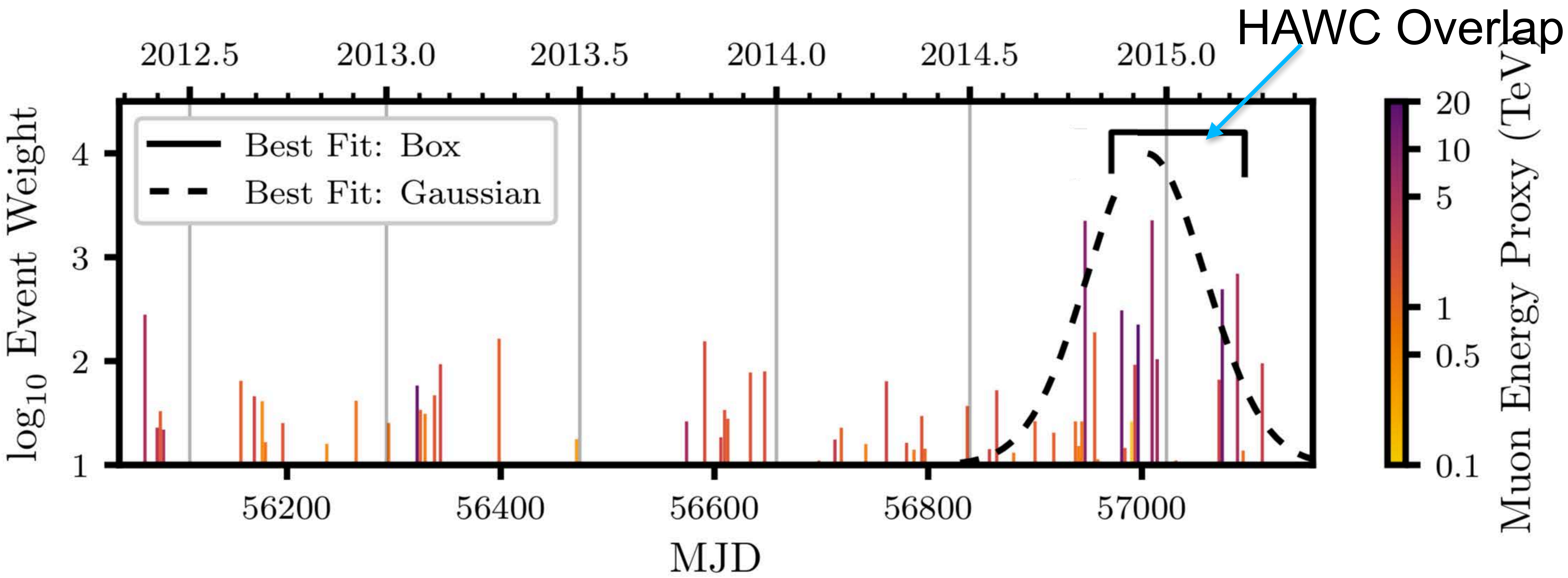


IceCube 170922A - TXS0506+056



IceCube 170922A - TXS0506+056

IceCube Followup - TXS0506+056

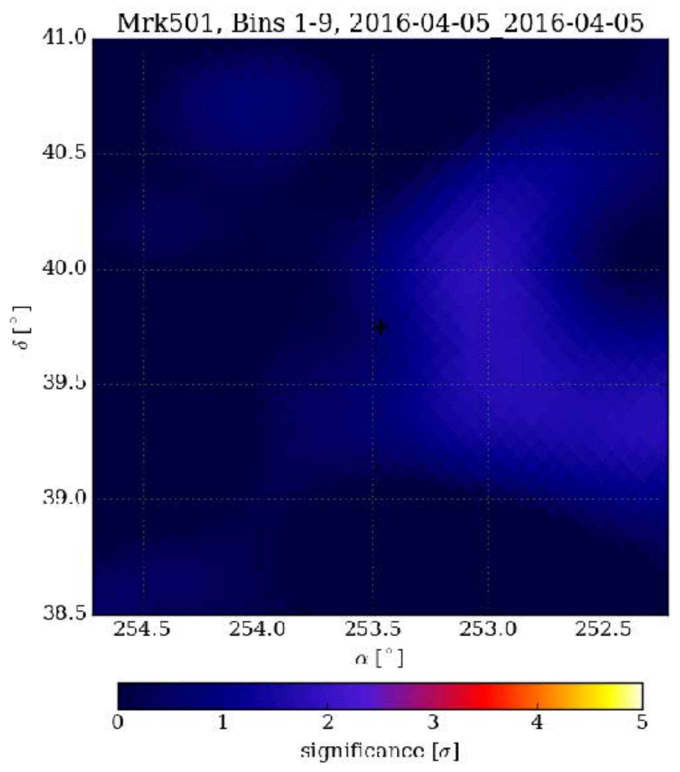


- IceCube - neutrino emission from TXS 0506+056 prior to the alert
- HAWC started operation Nov 2014 - just during this period
- No detection - but interesting limits - paper in the works

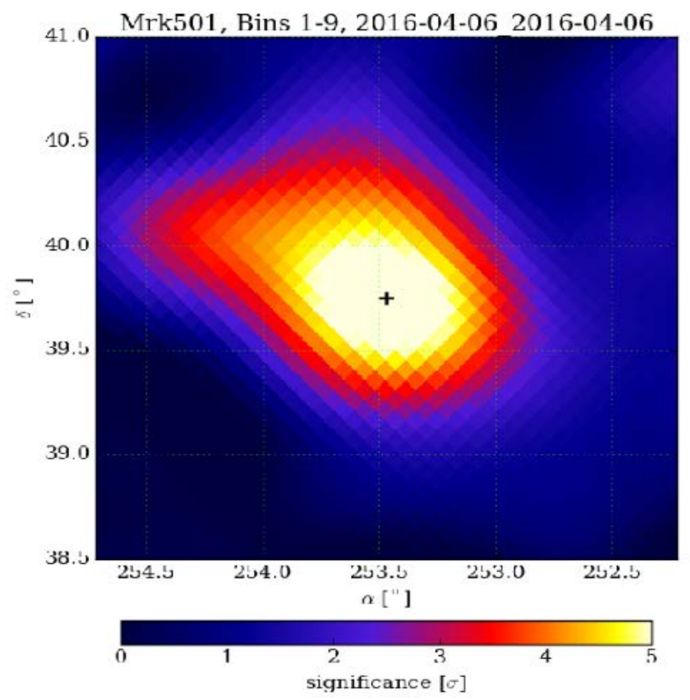
HAWC detection of increased TeV flux state for Markarian 501

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

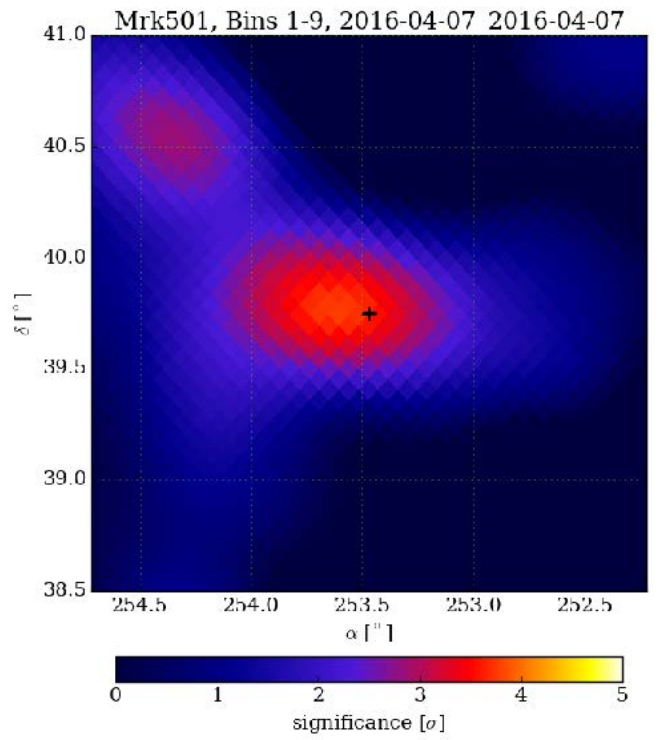
Astronomer's Telegram to immediately alert community of activity.



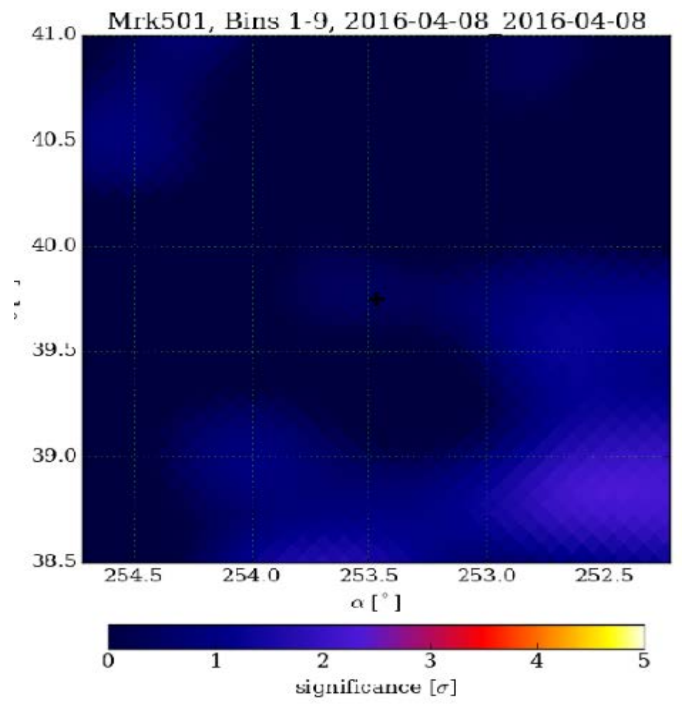
April 5, 2016



April 6, 2016



April 7, 2016

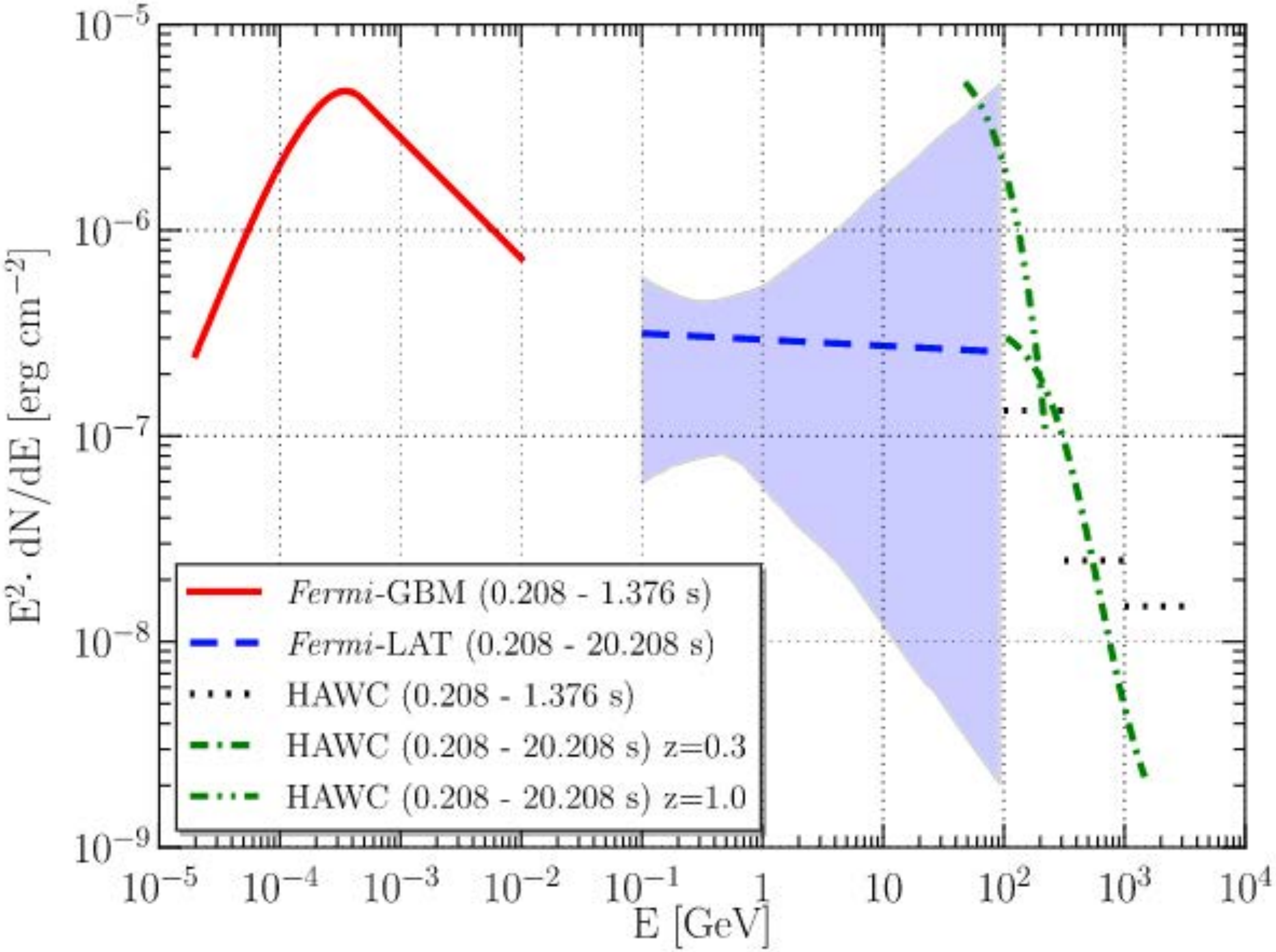


April 8, 2016

Monitoring all gamma-ray sources visible to HAWC every day.

Mrk421 Transients

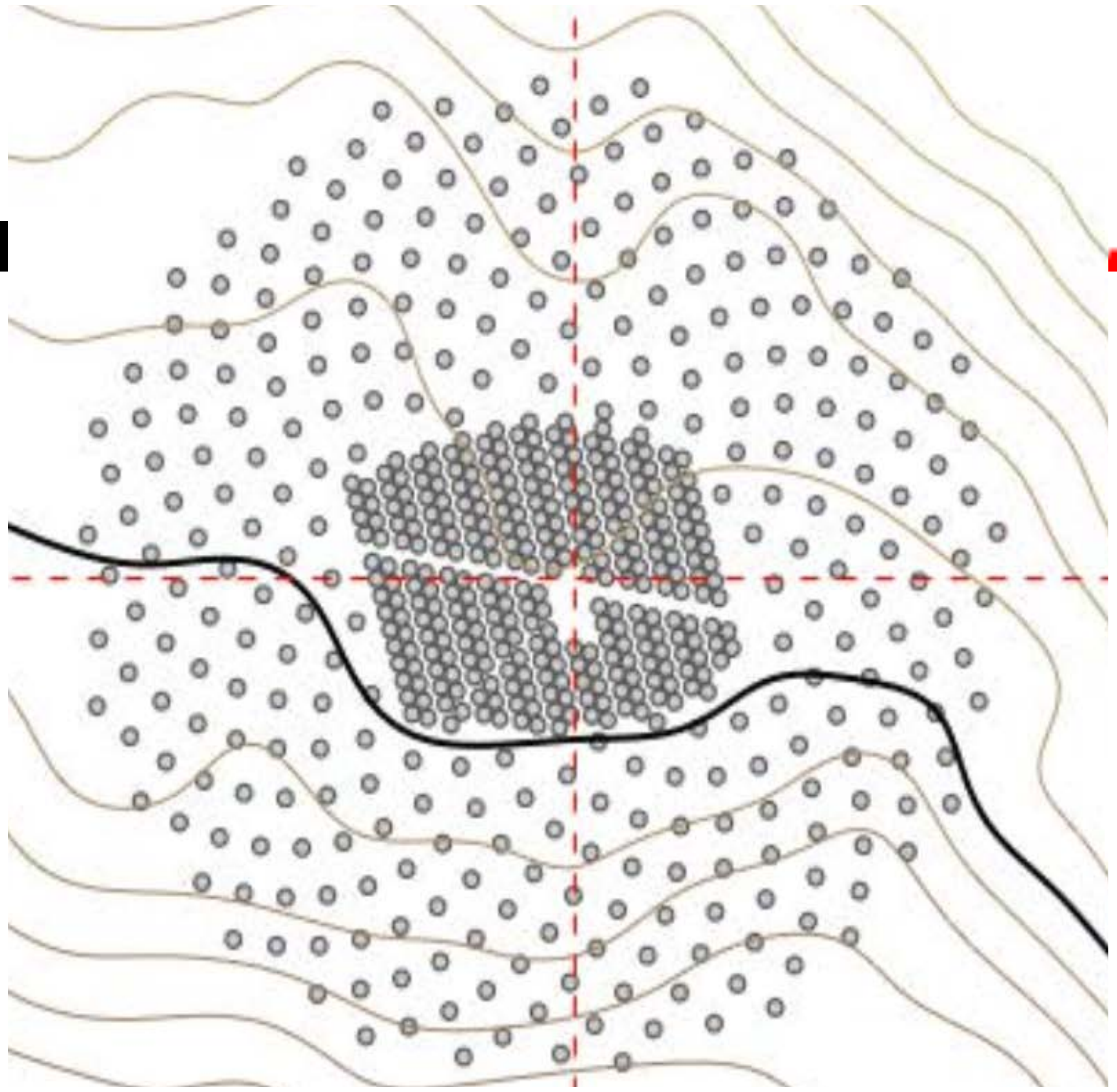
HAWC limits on GRBs



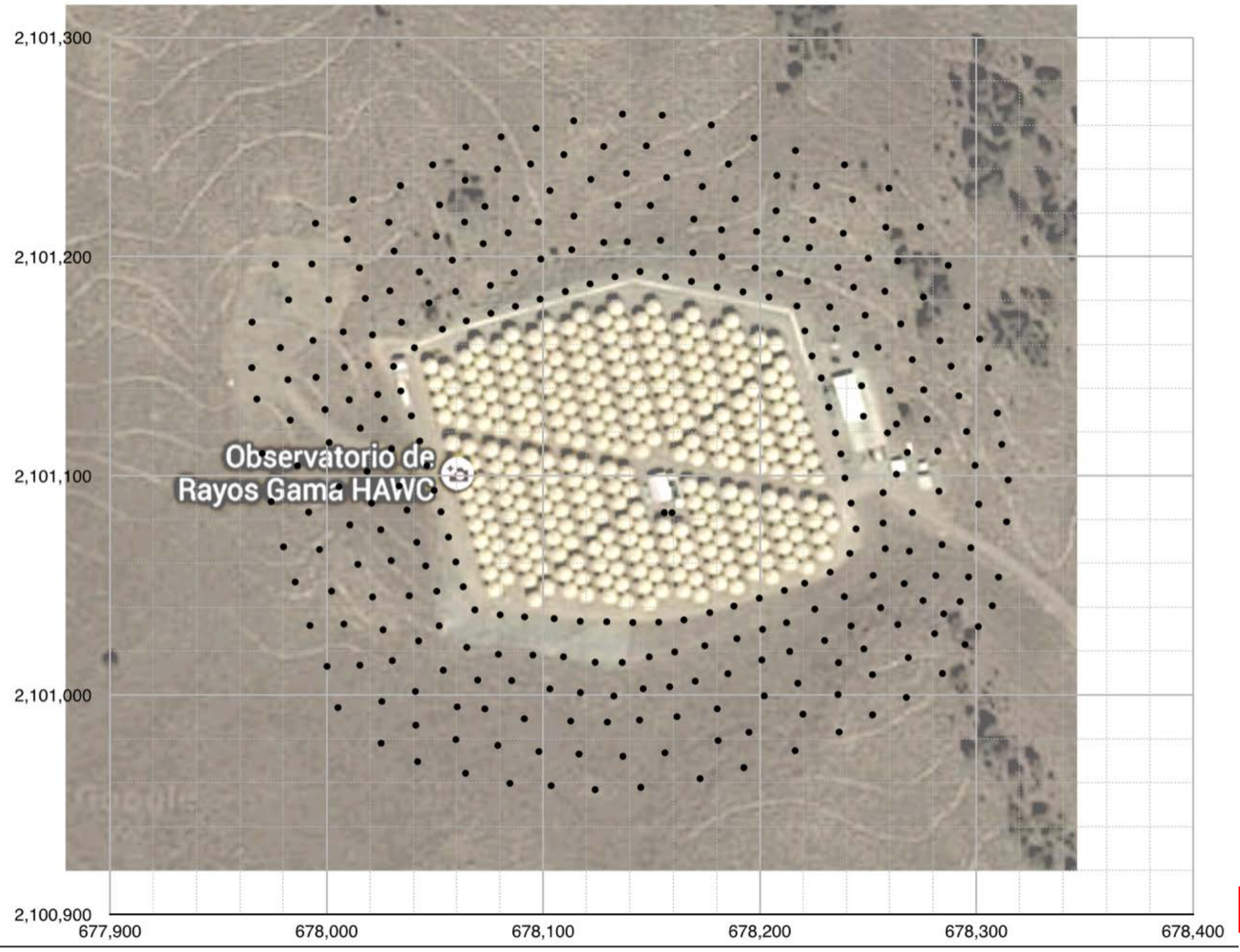
Alfaro et al., ApJ **843**, 88 (2017)

- HAWC has produced constraining upper limits on several GRBs
- Observations of GRB 170206A suggest a cutoff at less than 100 GeV
- GRB 170817A, associated with GW170817, was not immediately in the field of view—upper limit from observations 7 hours later

Outriggers

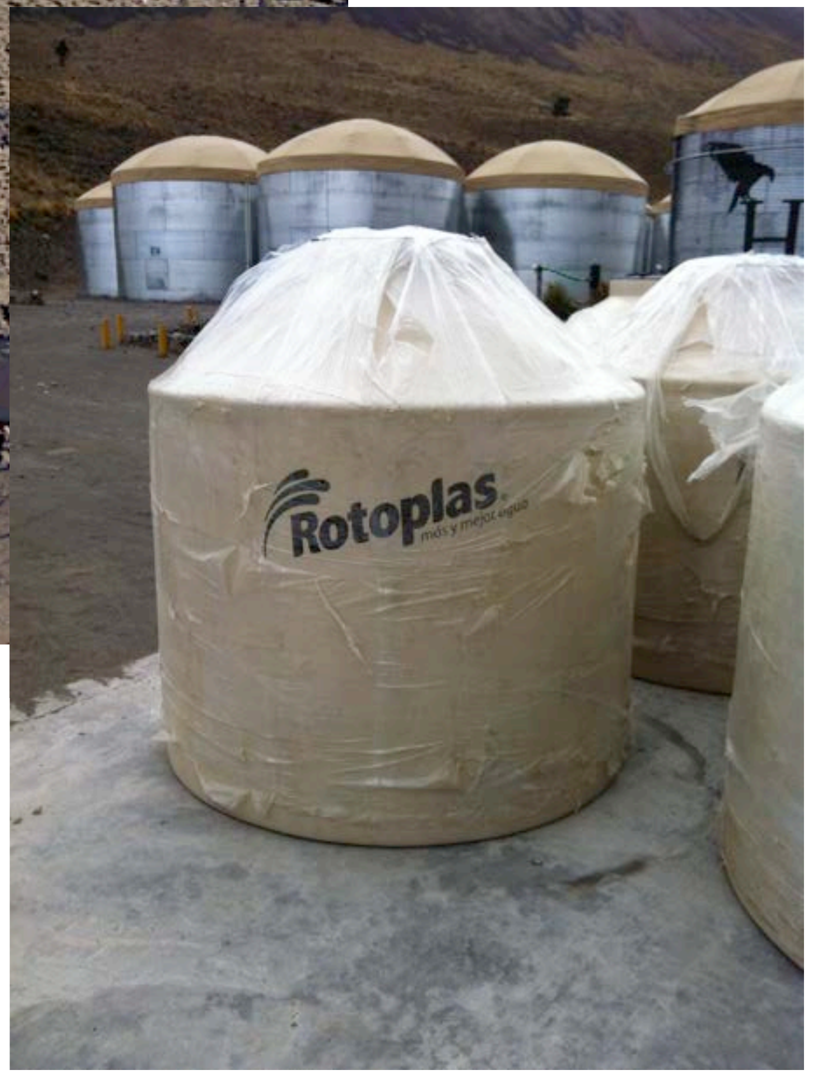


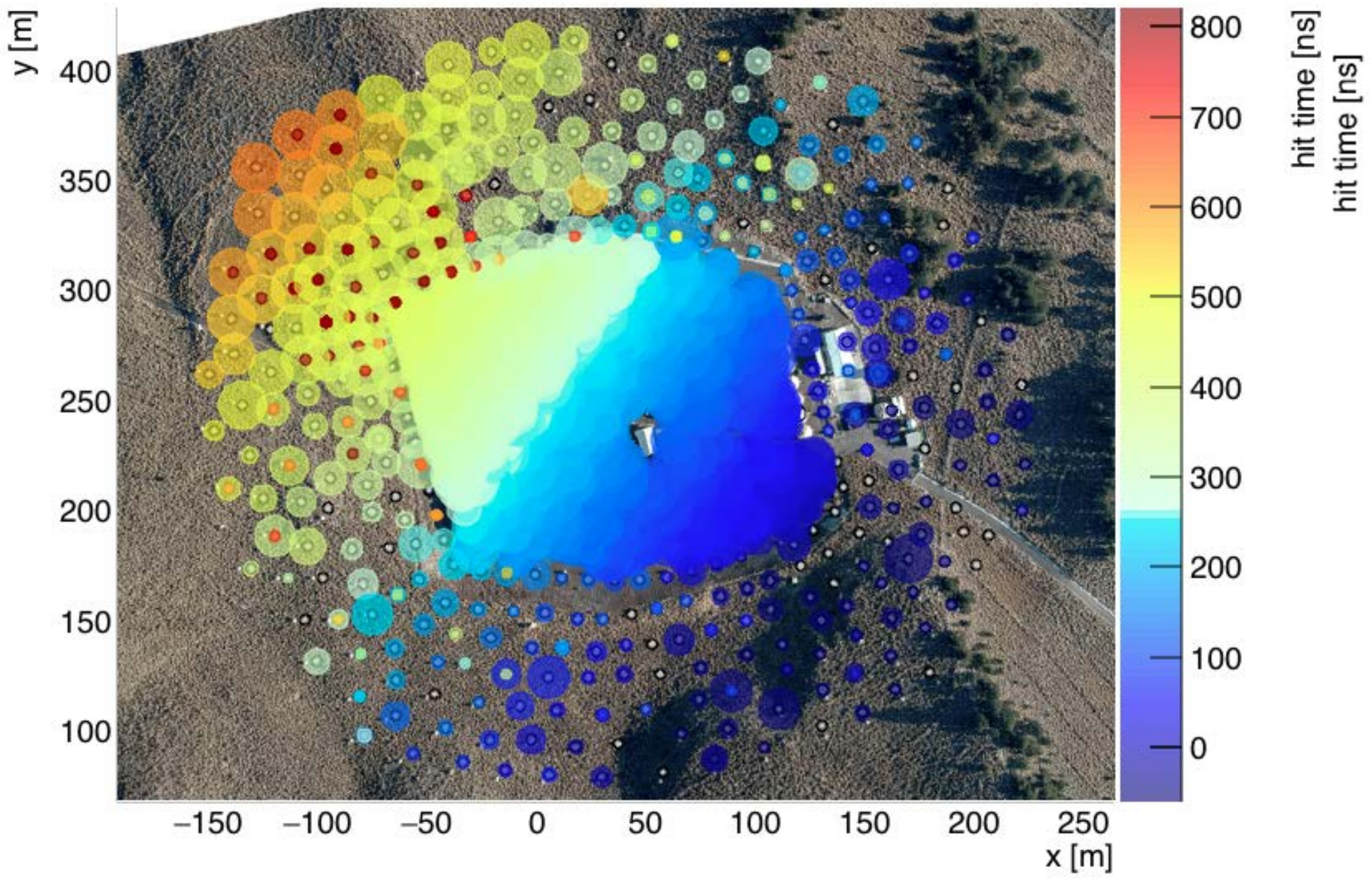
- HAWC Sparse Outrigger Array: Enhanced Sensitivity above 10 TeV
  - Accurately determine core position for showers off the main tank array.
- Increase effective area above 10 TeV by 3-4x
- Funded by LANL/Mexico.
- 2500 liter tanks: 1/80th size of HAWC tanks.

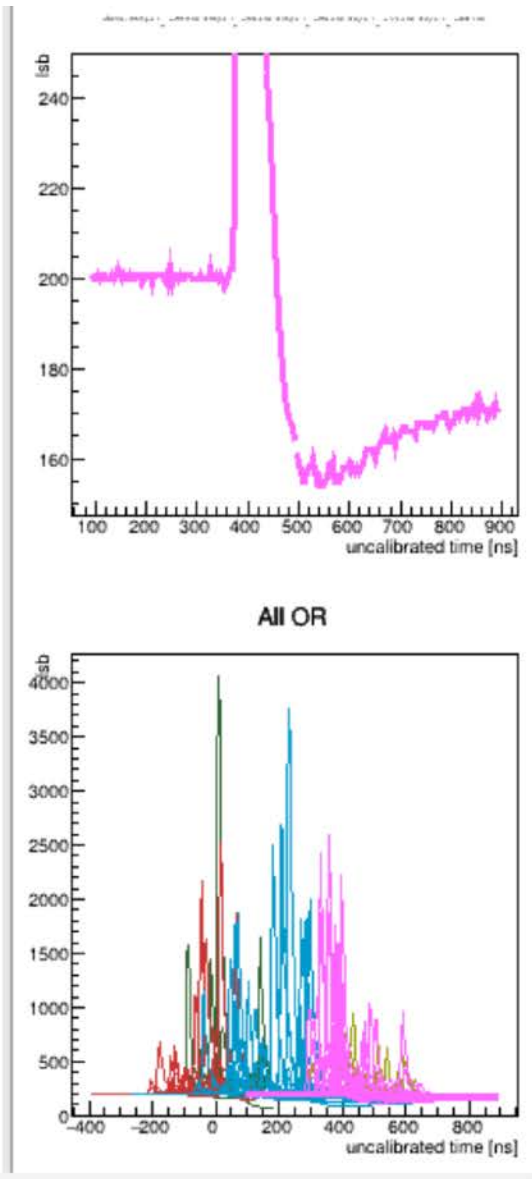


High Energy Upgrade: Outrigger Array begins Operation

- Funded by LANL LDRD, Max Planck Institute in Heidelberg, and CONACyT in Mexico
- Gives angle and energy reconstruction for showers that trigger HAWC but have the core outside the HAWC array
- Expands total effective area by a factor of ~4 above ~10TeV with the addition of 350 outrigger tanks
- 100% operational and taking data since August 2018, but we’re still refining calibration, reconstruction and analysis algorithms
- HAWC already detects multiple sources greater than 100 TeV. Outriggers will increase this number of sources and characterize their spectra.

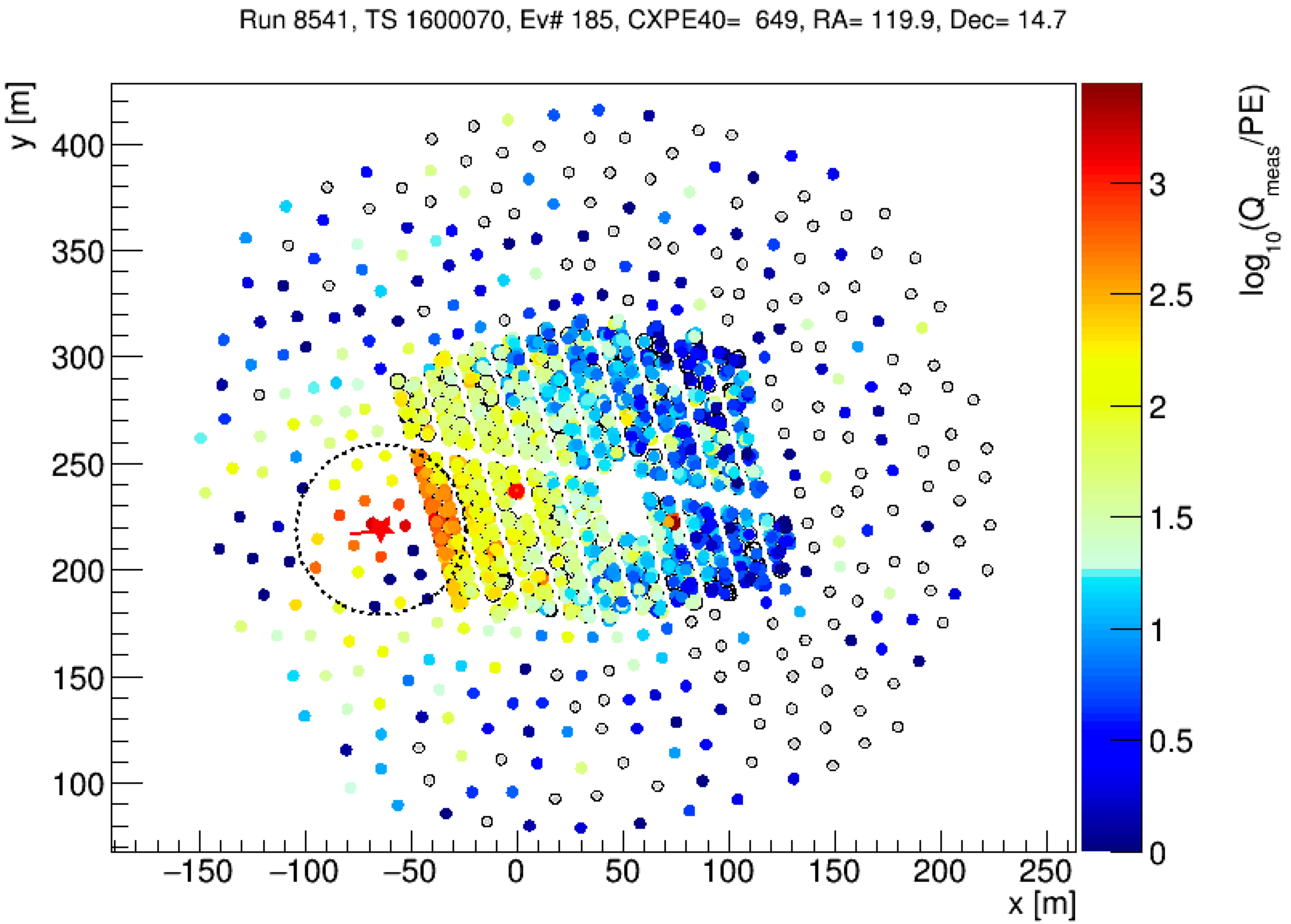




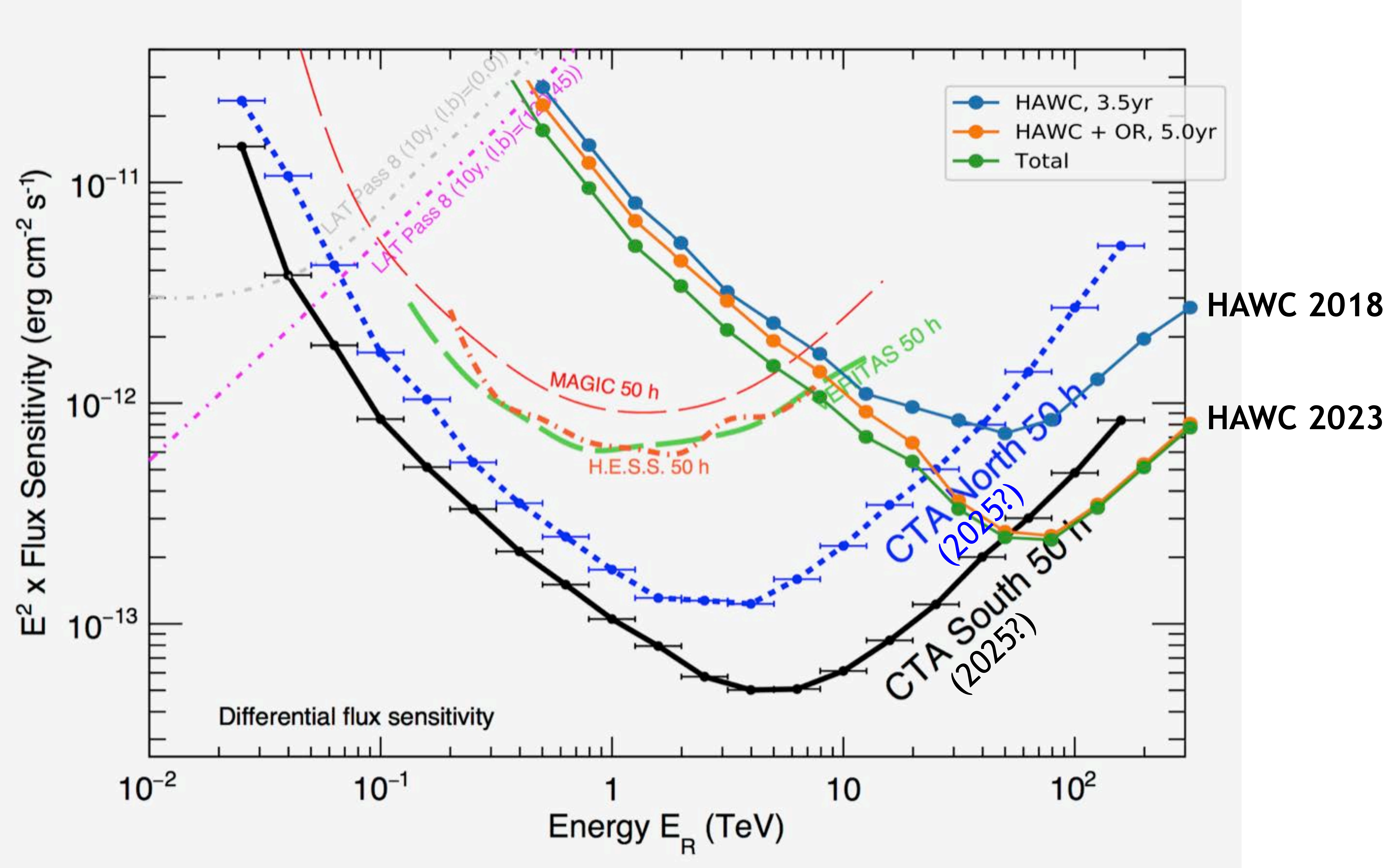


MPI provided FADC electronics that were developed for CTA

Outrigger Data



HAWC sensitivity with outriggers



Planned improvements in HAWC reconstruction and analysis algorithms (which are about to be implemented retroactively with Pass 5) will increase sensitivity even more.

- HAWC surveying the TeV sky with a wide-field of view
- Discovering new classes of sources
- Doing exciting physics
- Viewing the highest energy sky
- Playing an important role in Multi-messenger astrophysics
- With outriggers and new algorithms we are not in the $\sqrt{\text{Time}}$ regime

HAWC

SWGO

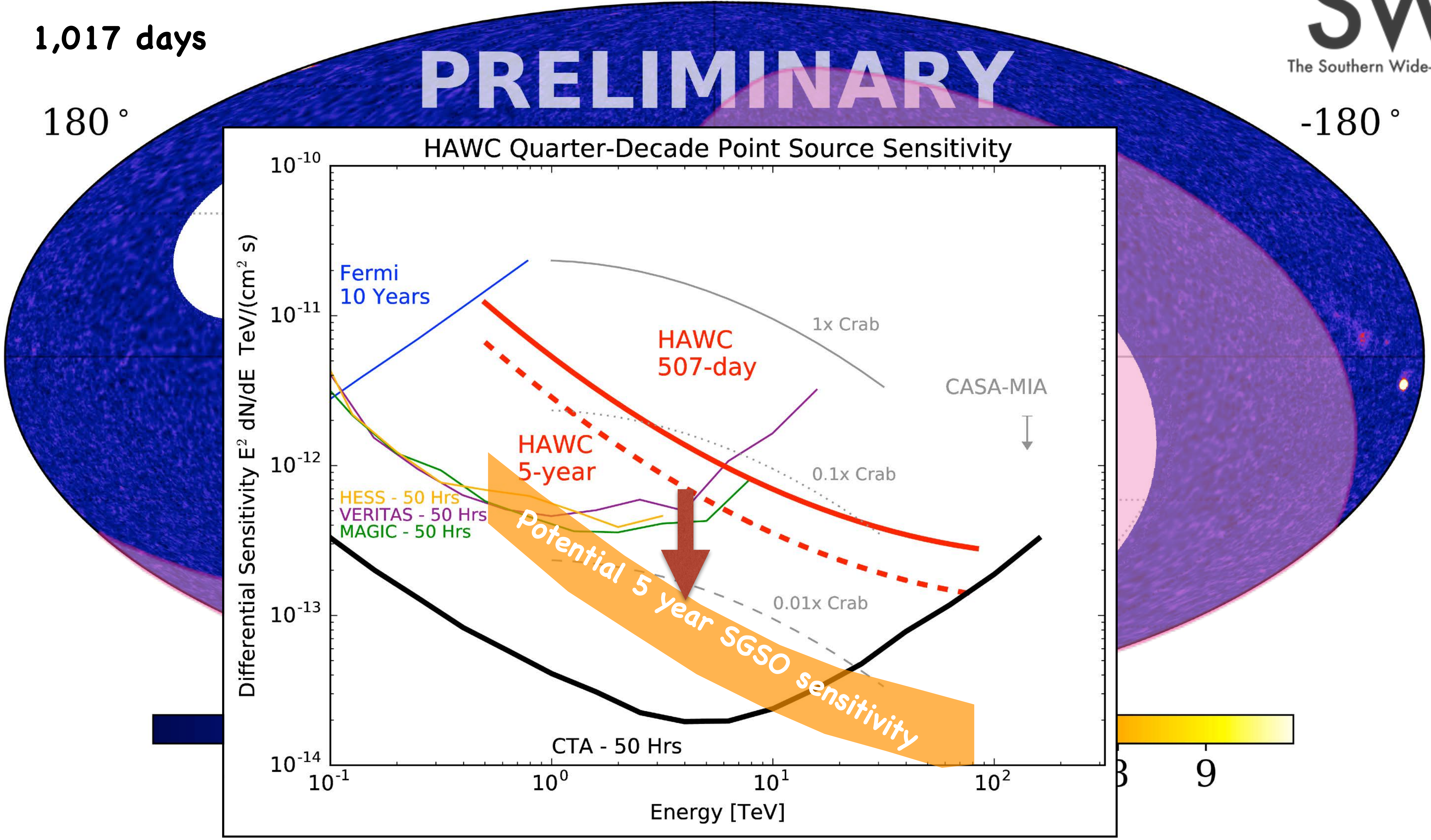
The Southern Wide-field Gamma-ray Observatory

The Southern Wide-field Gamma-ray Observatory

SGSO

- Southern Gamma-Ray Survey Observatory
- Proposed HAWC-like detector to be located in the southern hemisphere
- Several candidate sites considered, including in Argentina, Chile, Bolivia, and Peru
- Latitude of ~24° S optimizes sensitivity to Galactic sources, especially Galactic Center
- Improvements to sensitivity
  - Higher altitude: extend sensitivity to lower energies (aim for 200–300 GeV)
  - Larger detector
  - Better gamma/hadron separation
  - Better electronics

HAWC sky map



The Southern Wide-field Gamma-ray Observatory

- Significant emission from Galactic Plane, Crab Nebula, Geminga, Mrk 421, Mrk 501
- SGSO would have optimal sensitivity to Galactic Center
- Improvement in sensitivity by ~10x over HAWC would yield complementarity with CTA similar to present instruments

SWGO

- Collaboration established July 2019
- 3 Year development proposal to NSF
- 9 Countries + supporting scientists

SWGO
The Southern Wide-field Gamma-ray Observatory