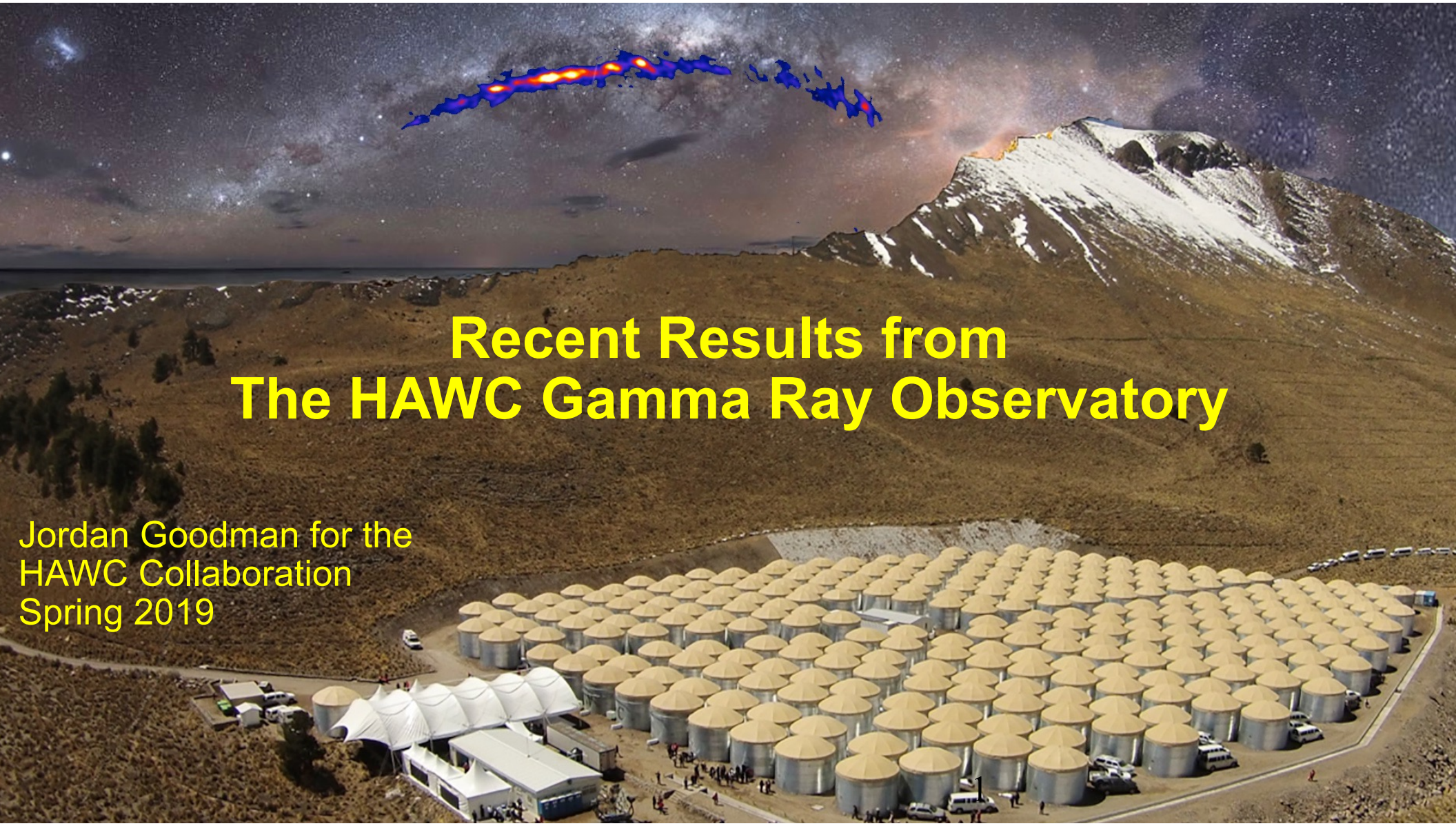


Recent Results from The HAWC Gamma Ray Observatory

Jordan Goodman for the
HAWC Collaboration
Spring 2019

The HAWC Collaboration

USA Mexico Europe

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
Georgia Institute of Technology
Michigan State University
University of Rochester

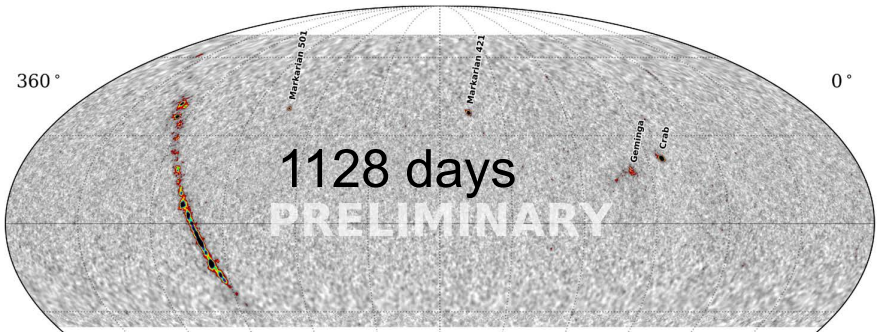
Mexico
Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE)
Universidad Nacional Autónoma de México (UNAM)
- Instituto de Física
- Instituto de Astronomía
- Instituto de Geofísica
- Instituto de Ciencias Nucleares

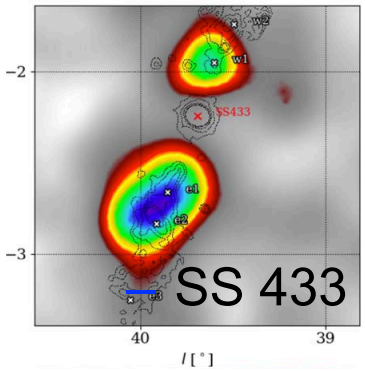
Universidad Politécnica de Pachuca
Benemérita Universidad Autónoma de Puebla
Universidad Autónoma de Chiapa
Universidad Autónoma del Estado de Hidalgo
Universidad de Guadalajara
Universidad Michoacana de San Nicolás de Hidalgo
Centro de Investigación y de Estudios Avanzados
Instituto Politécnico Nacional
Centro de Investigación en Computación - IPN

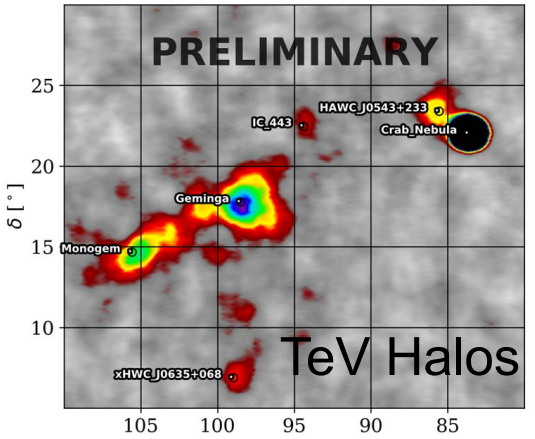
Europe
Max-Planck Institute for Nuclear Physics
IFJ-PAN, Krakow, Poland

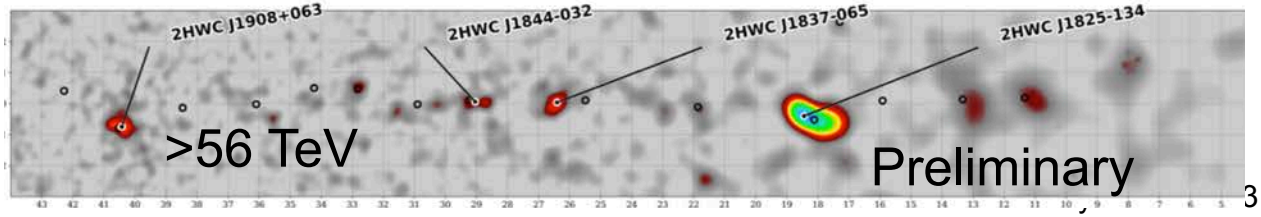
HAWC - Recent Results

- 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







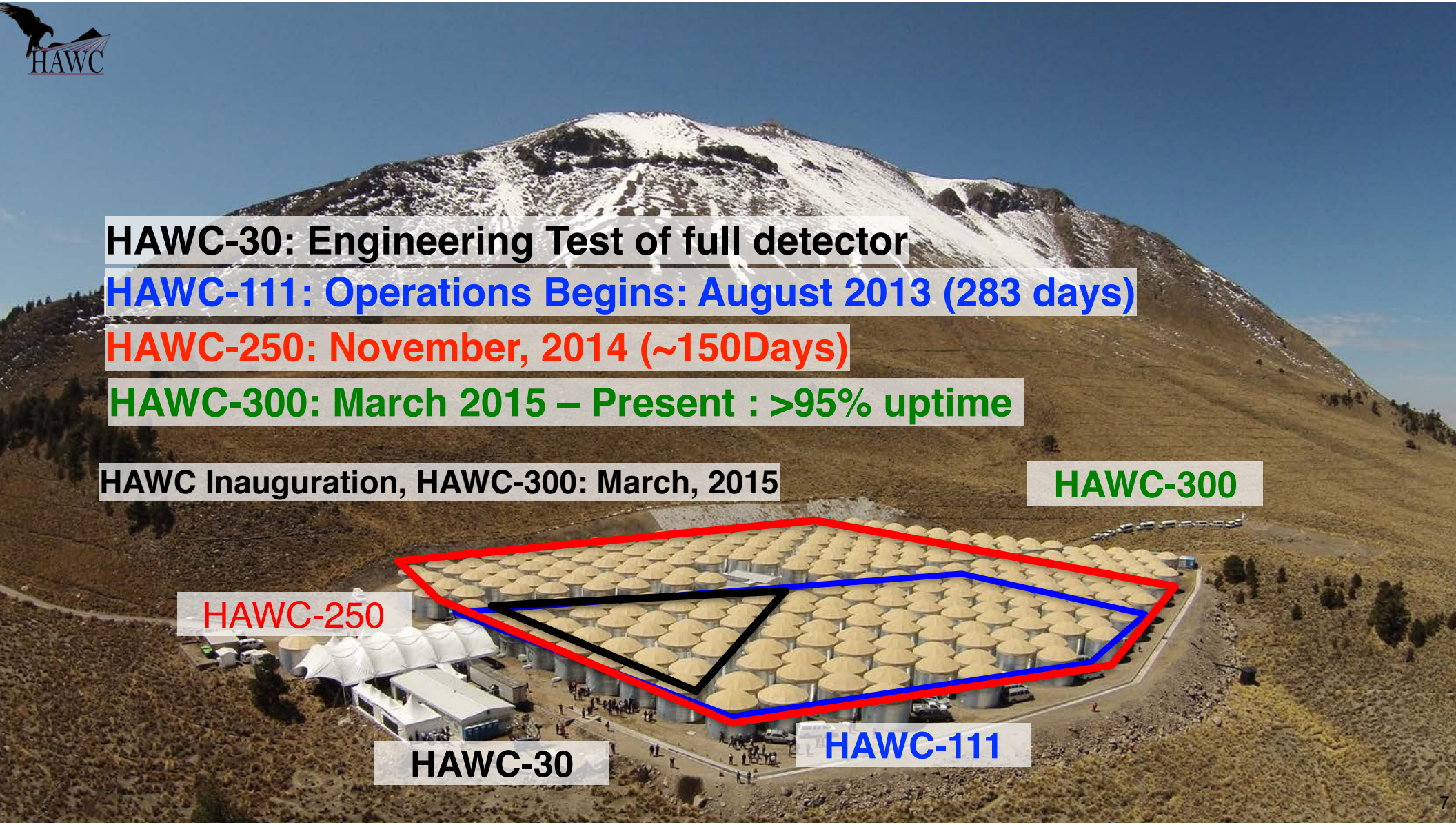


Since the beginning of 2017

- HAWC has published 24 papers in refereed journals
- Science Topics
  - Sky maps and catalogs of Galactic sources [5 papers]
  - Transient Studies [3 papers]
  - Multi-wavelength/ multi-messenger observations (with LIGO, IceCube) [4 papers]
  - Dark Matter Searches [6 papers]
  - Cosmic Rays [5 papers]
  - Technique[1 papers]
- Plus issued 13 ATELs
- Conferences
  - 18 talks and 24 posters at the “April Meeting” of the APS in 2018
  - 13 talks and 24 posters at the ICRC 2017 in Busan South Korea
  - 15 talks and posters at TeVPA 2018 in Berlin, Germany


HAWC

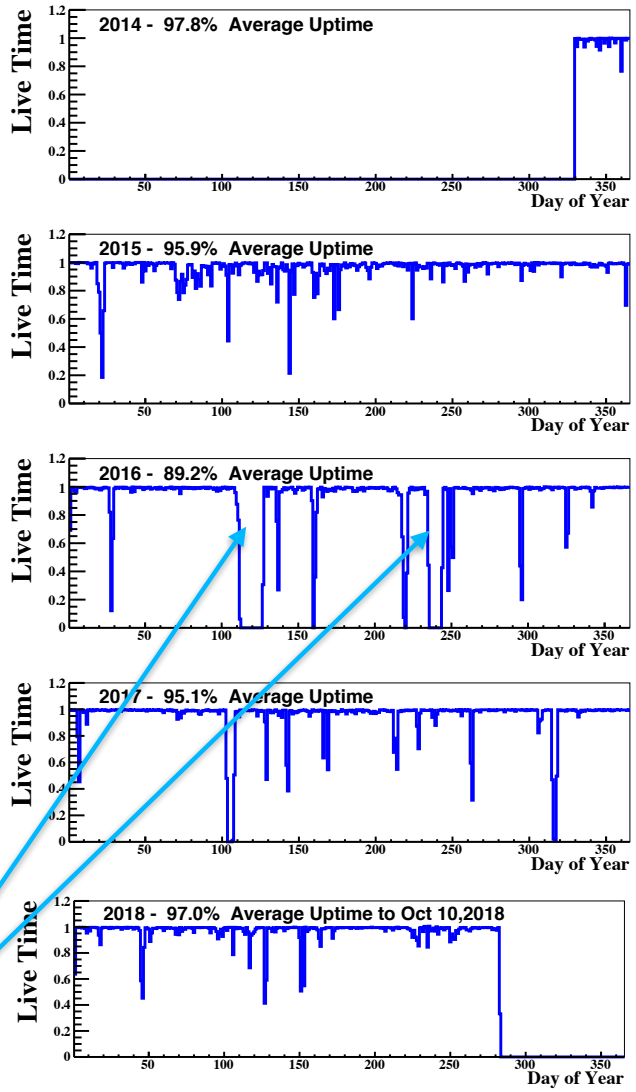
HAWC


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
HAWC Inauguration, HAWC-300: March, 2015
HAWC-300
HAWC-250
HAWC-111
HAWC-30

Outriggers in operation since August 2018

Data Collection

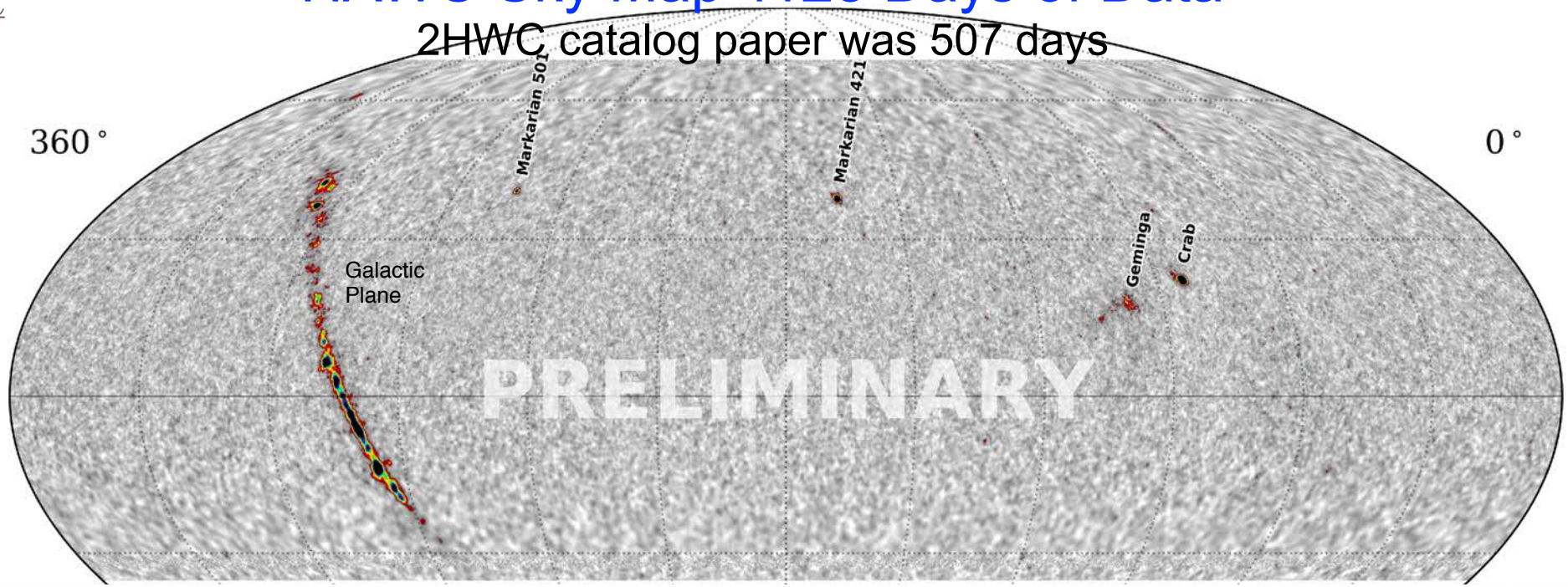
- HAWC has been operating since Nov 2014 (250 Operational WCDs) and since Mar 2015 (293 Operational WCDs).
- Average uptime >90% and >95% in last 2 years.
- In 2016, we had 2 prolonged outages due to transformer failures. We now have spares.
- Not down for more than 24hrs since Nov 2017.
- Can tolerate brief power outages (everything on UPS).
- Can restart remotely after prolonged outages.

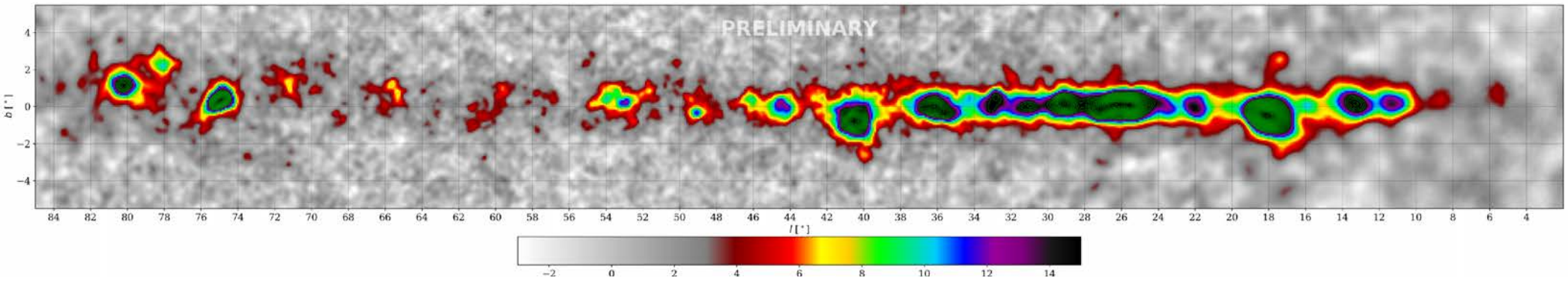


Transformer failures

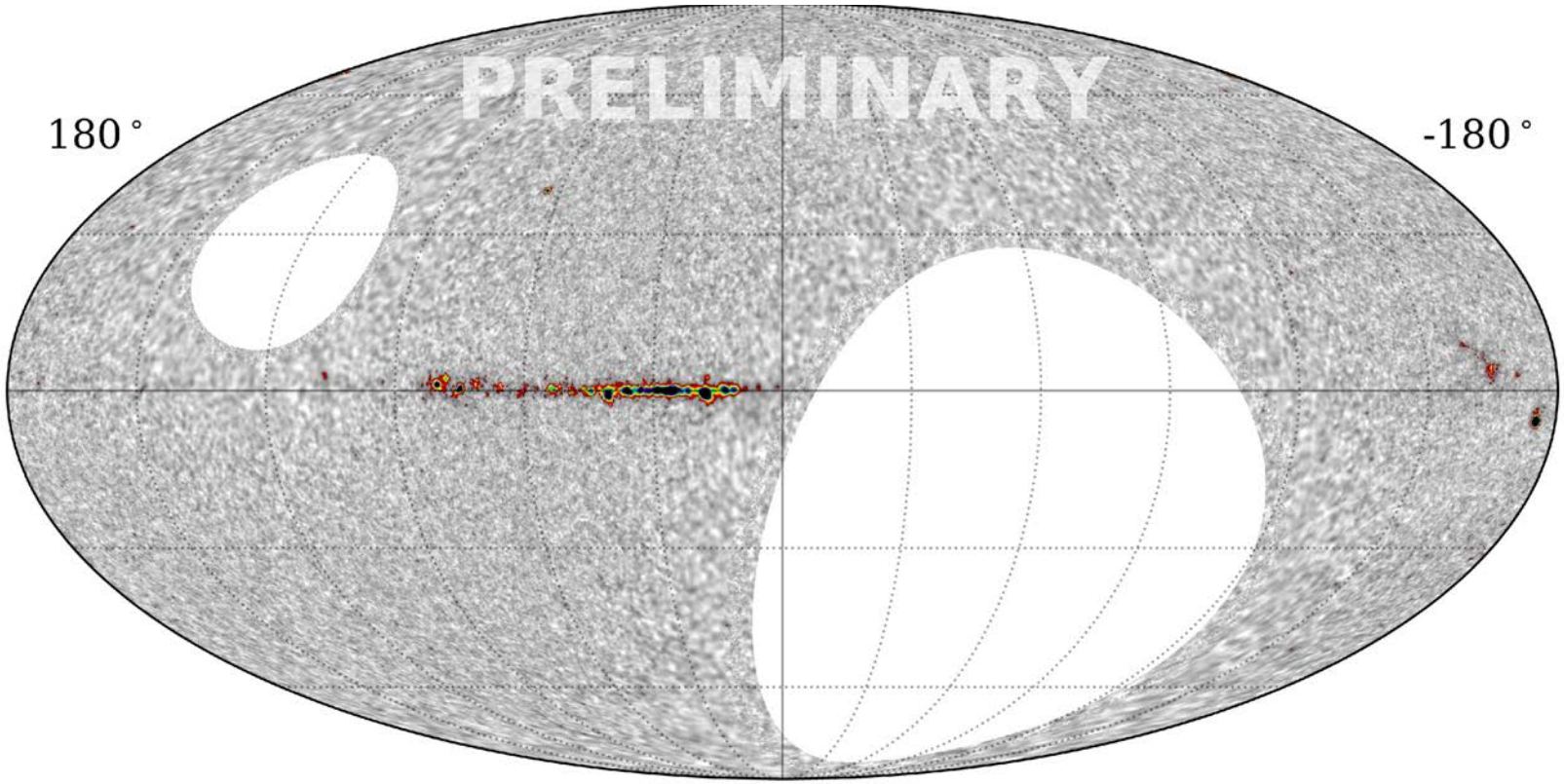
HAWC Sky Map 1128 Days of Data

2HWC catalog paper was 507 days



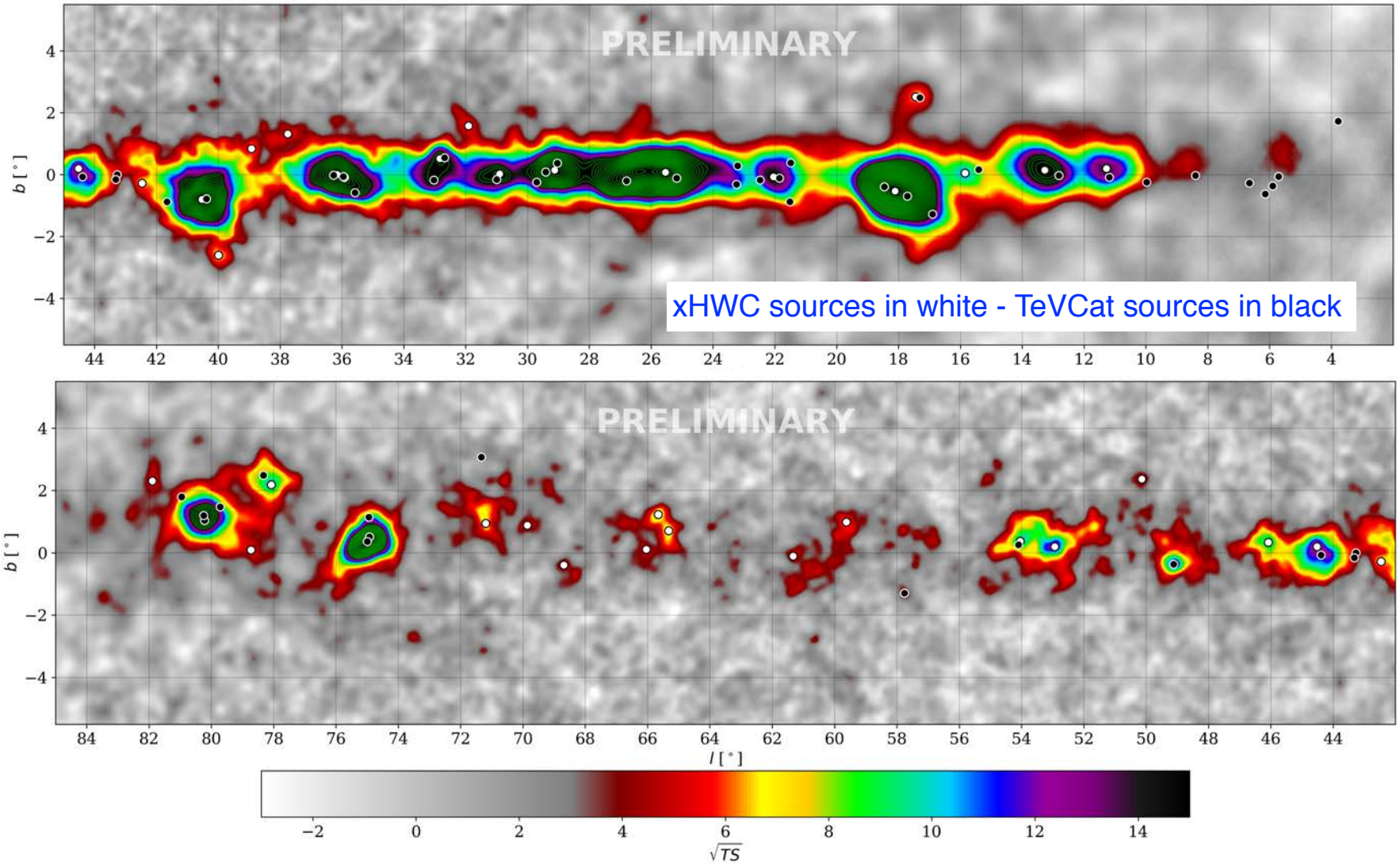


HAWC 1128-Day TeV Sky Survey

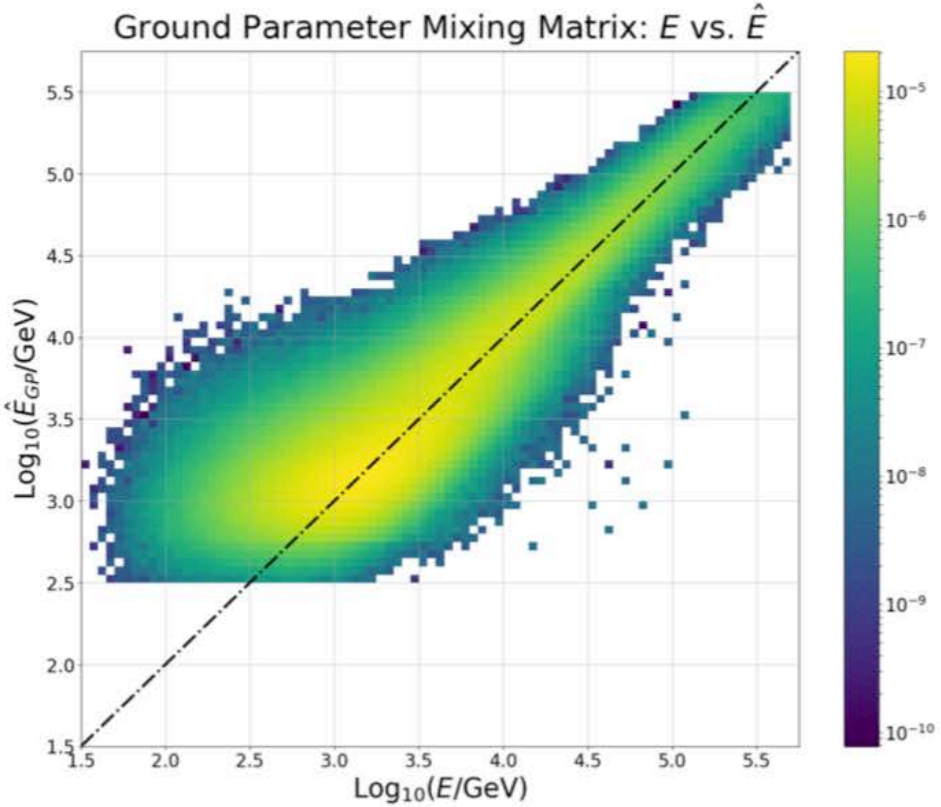


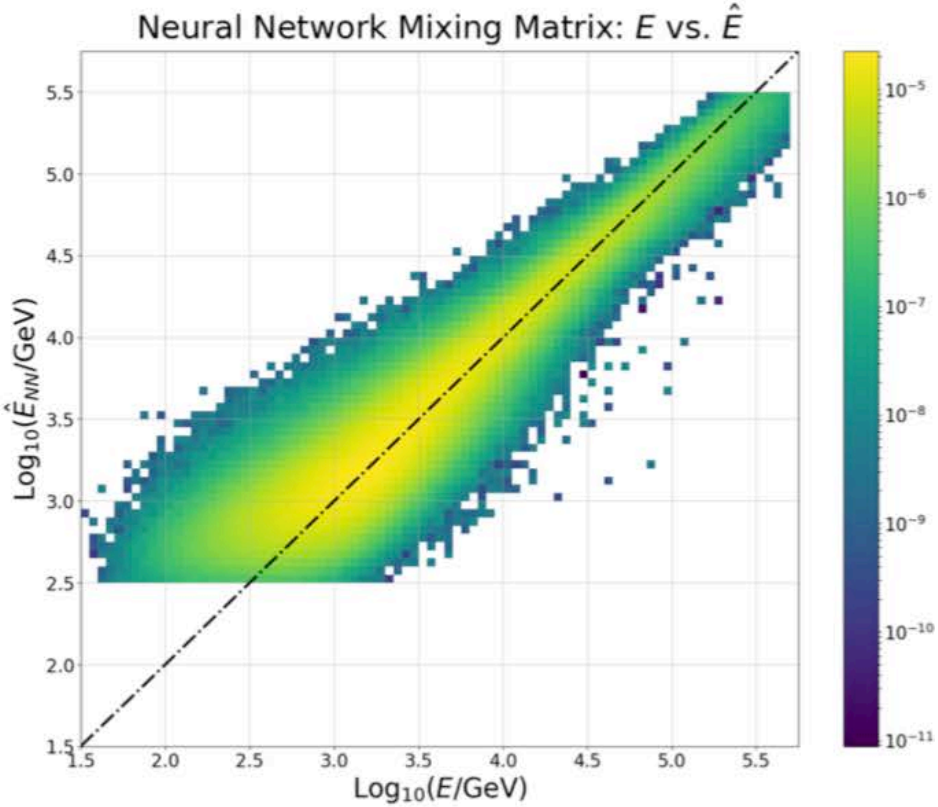
50 sources >5σ are detected — >20 previously unseen

1128 Days of Data



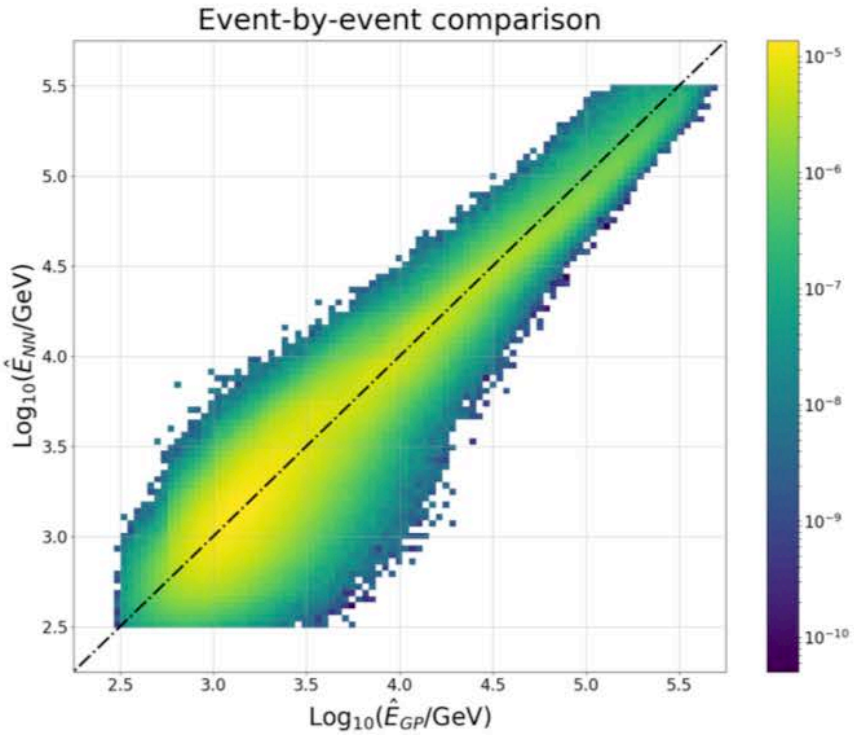
Two Energy Analysis

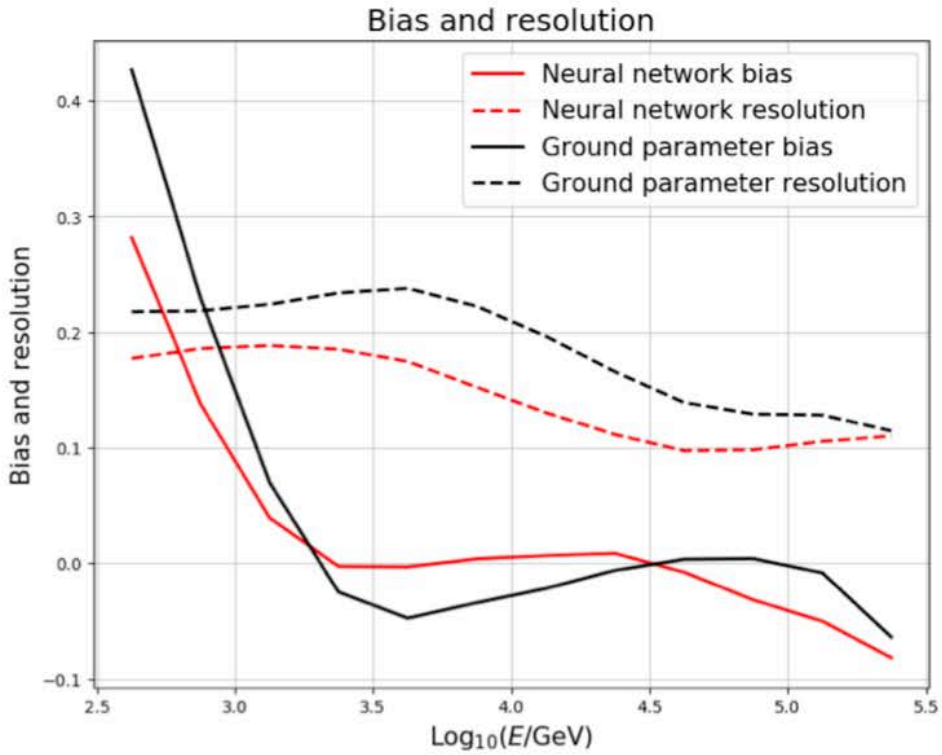




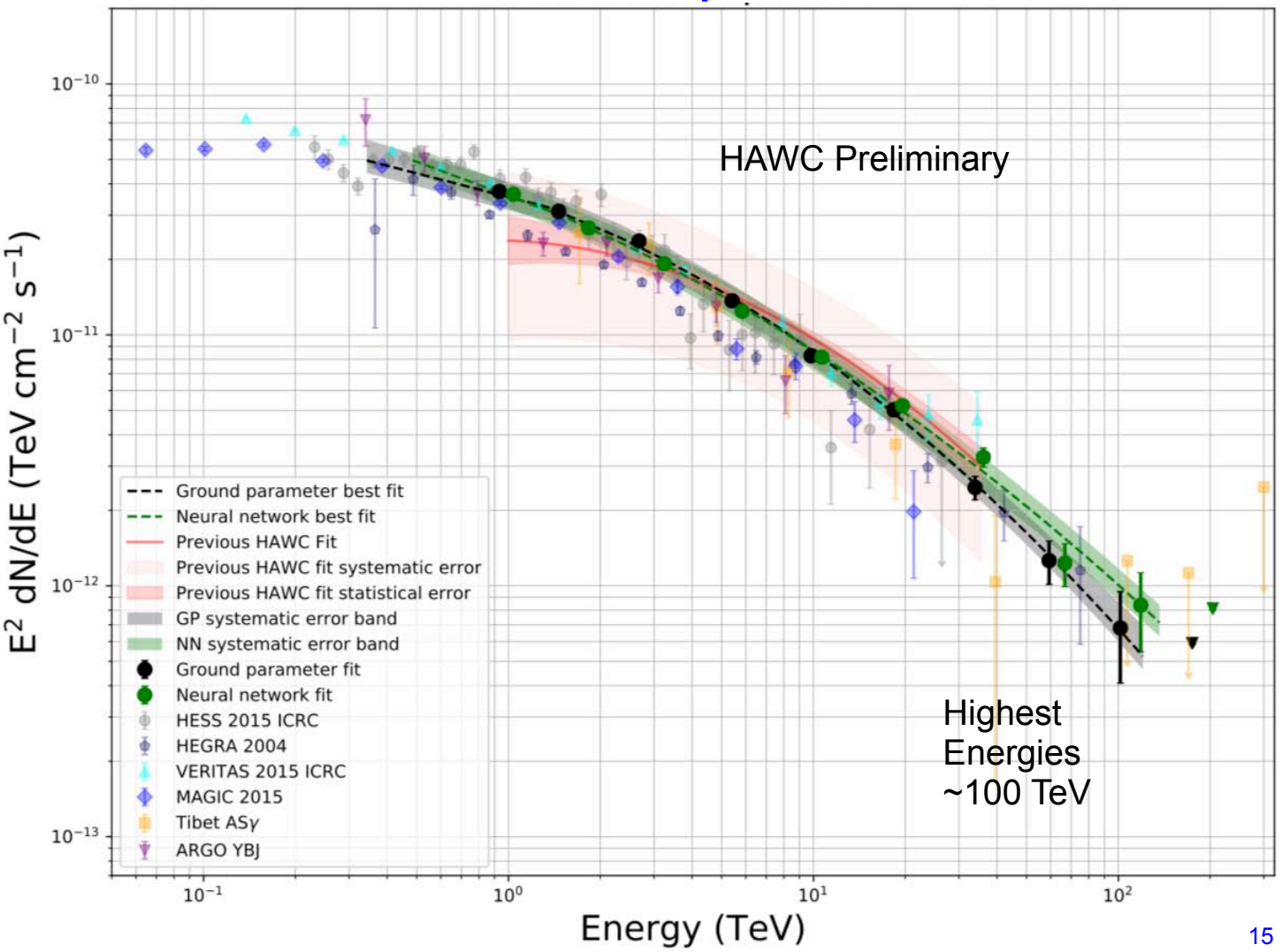
Kelly Malone (PSU/LANL)
Sam Marinelli (MSU)

Two Energy Analysis

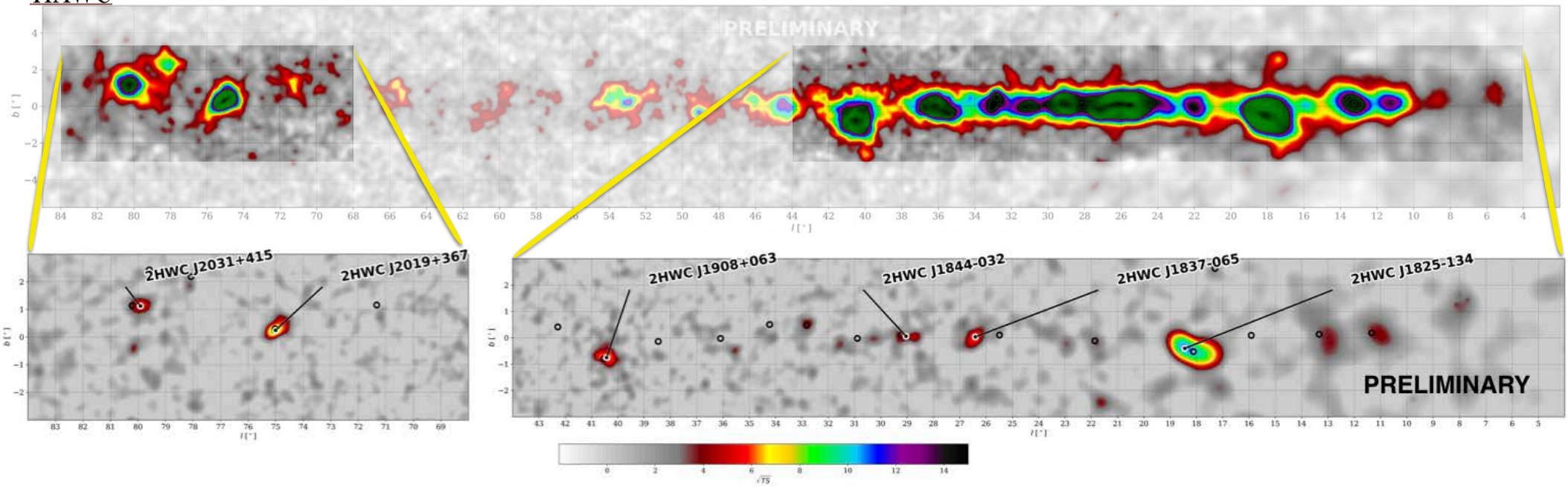




The Crab Spectrum

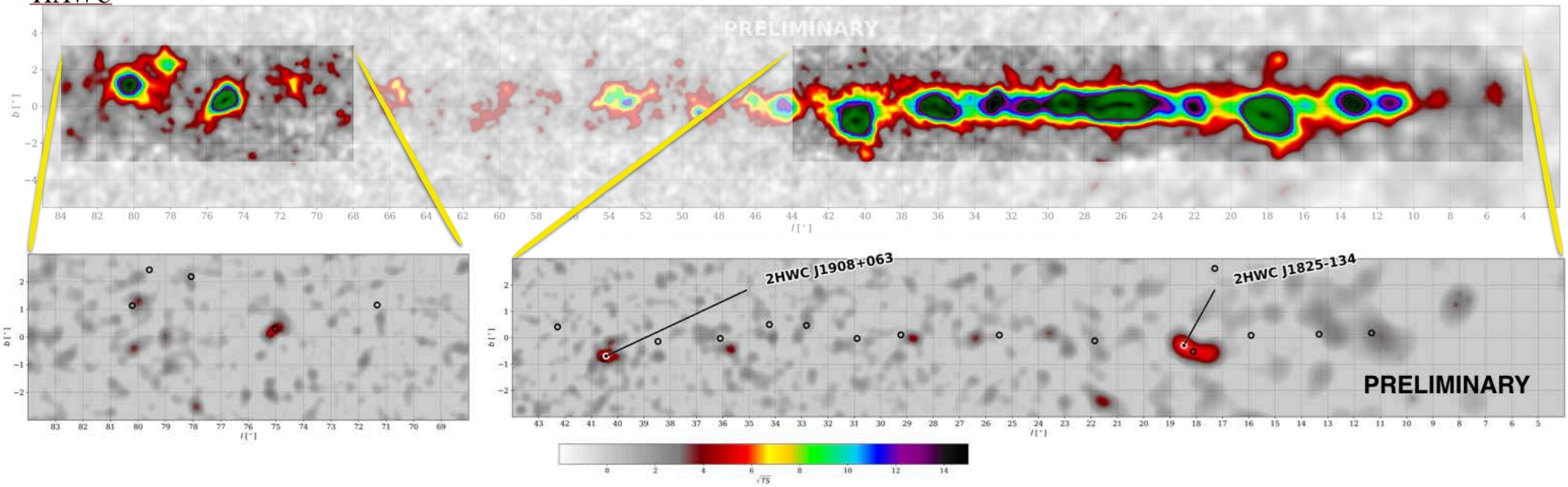


Pushing to the highest energies (>56 TeV)



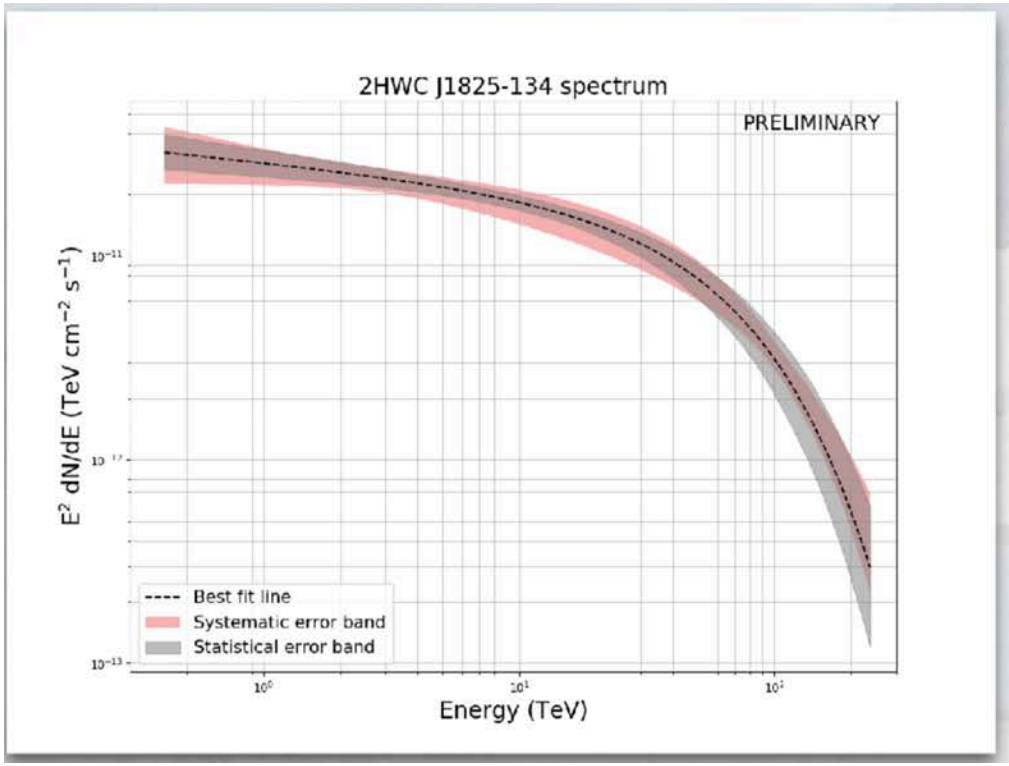
- Acceleration mechanisms: hadronic or leptonic?
- Correlation with neutrinos?
- Prospects for testing Lorentz Invariance Violation.

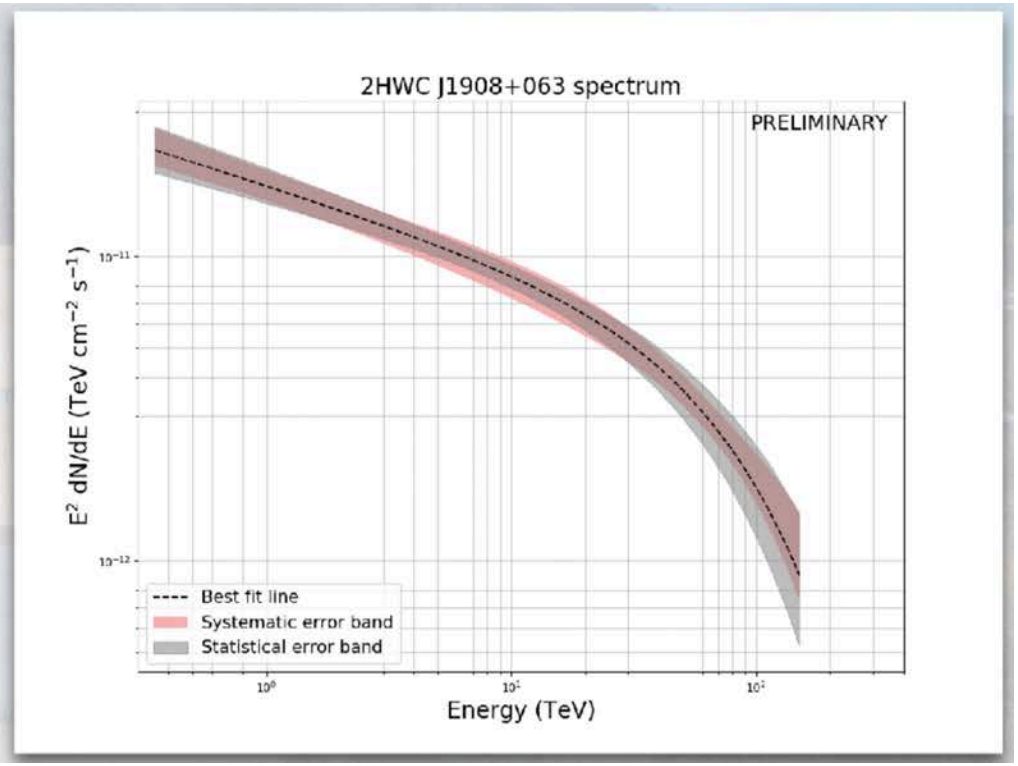
Pushing to the highest energies (>100 TeV)



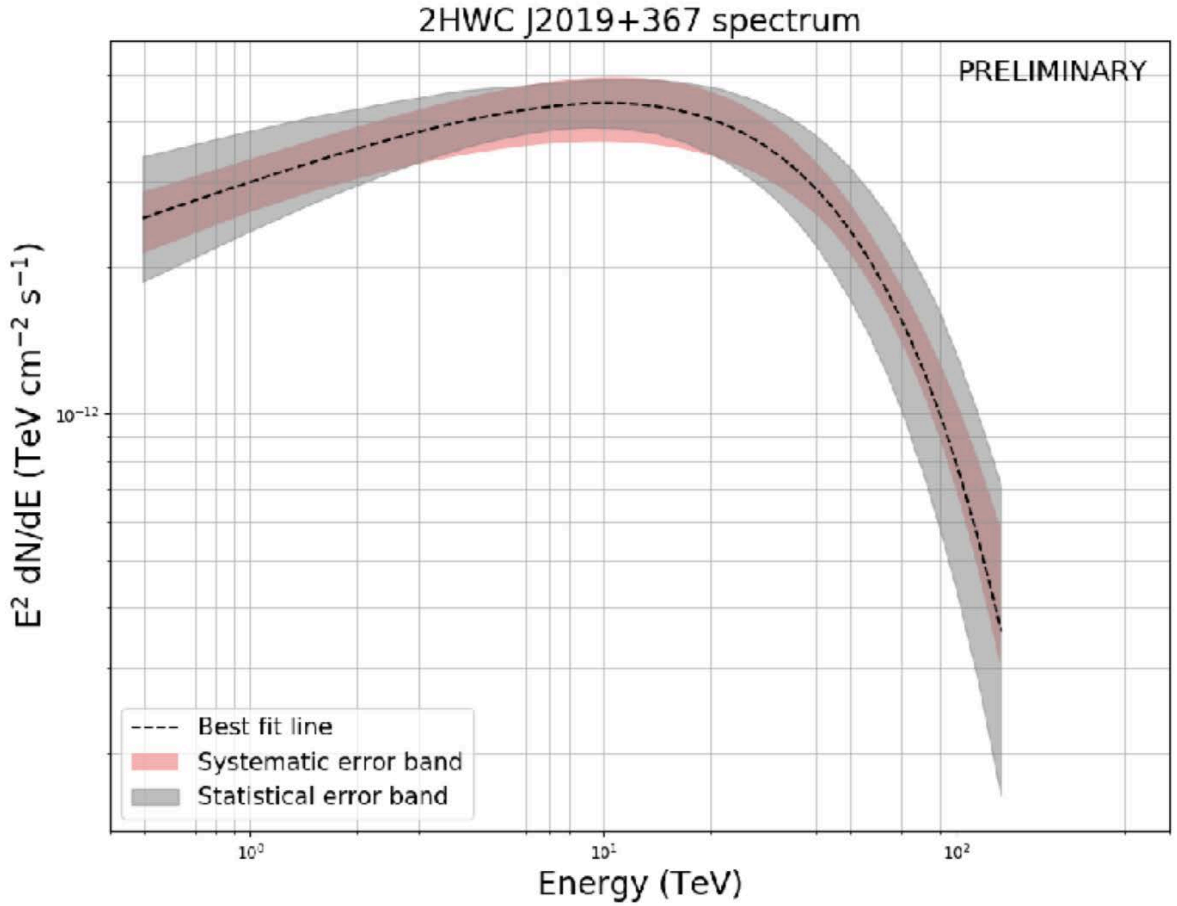
- Acceleration mechanisms: hadronic or leptonic?
- Correlation with neutrinos?
- Prospects for testing Lorentz Invariance Violation.

Spectra of Highest Energy Sources



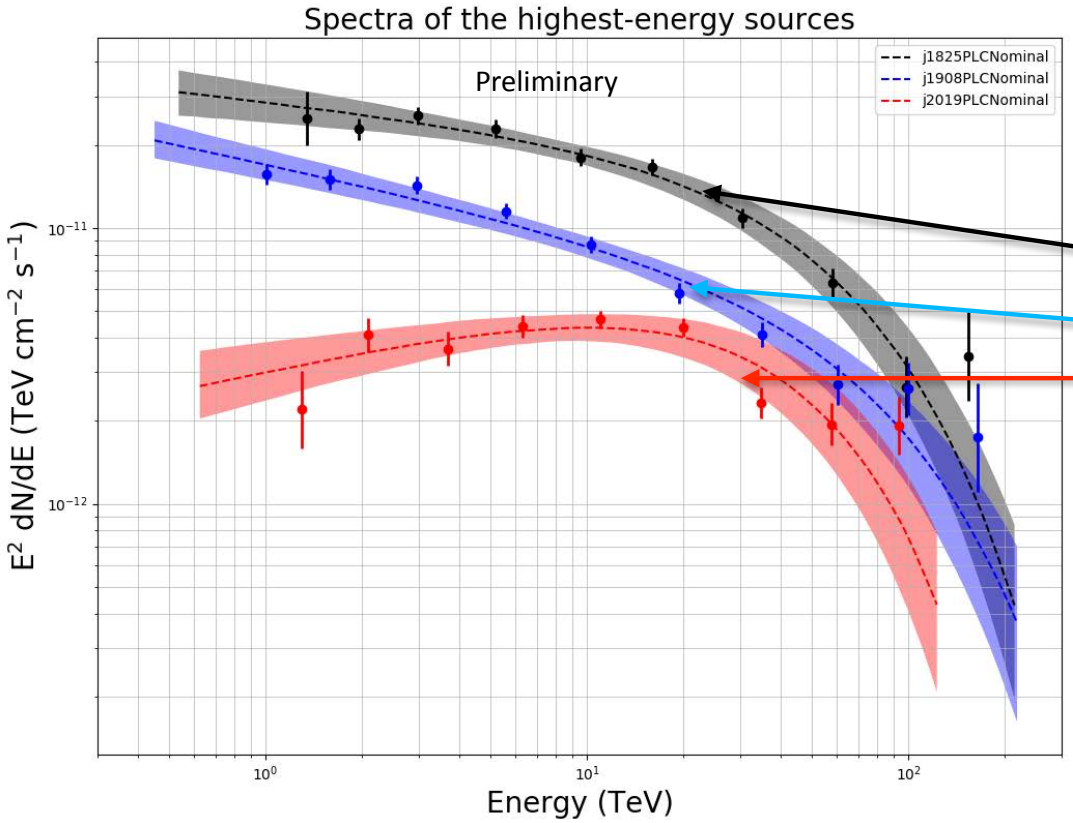


Spectra of Highest Energy Sources



Hardest Spectrum

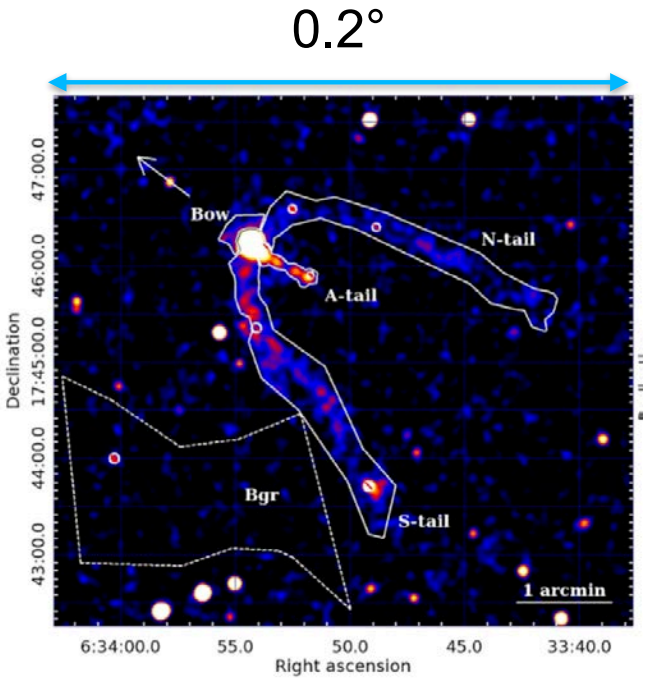
HAWC Spectra at the Highest Energies



2HWC source	Pulsar name	Pulsar age (kyr)	Pulsar distance (kpc)	E dot (ergs/s)
J1825-134	J1826-1334	21.4	3.61	2.8e36
J1908+063	J1907+0602	19.5	2.37	2.8e36
J2019+367	J2021+3651	17.2	1.80	3.4e36

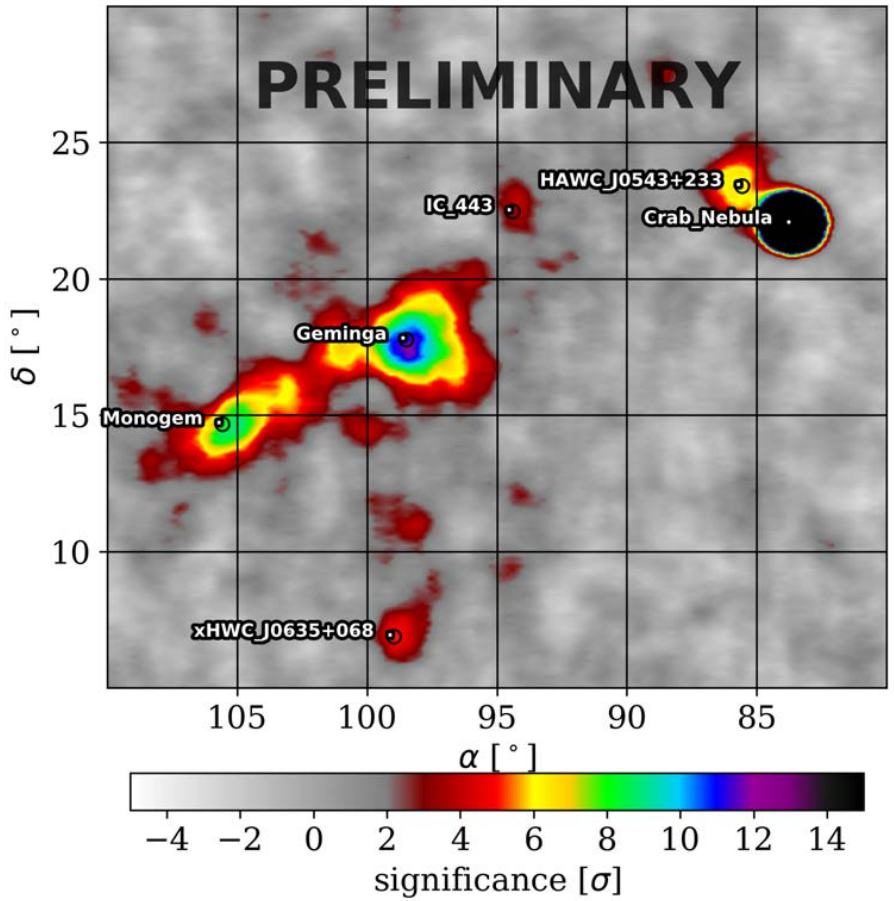
Geminga - PWN

- 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^{+120}_{-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



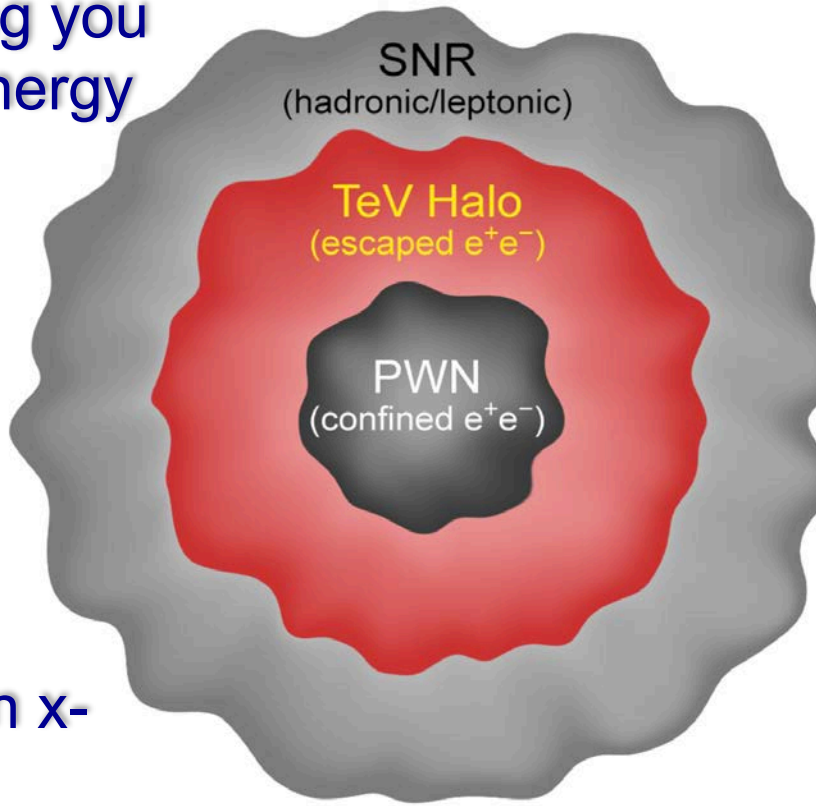
The Galactic Anti-Center

- 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



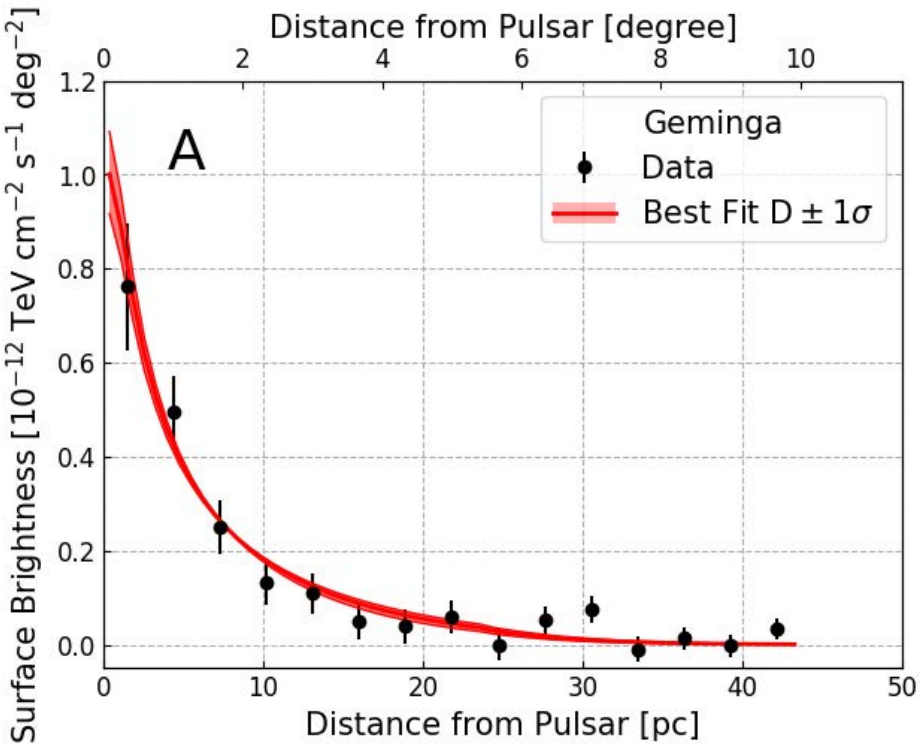
TeV Halos

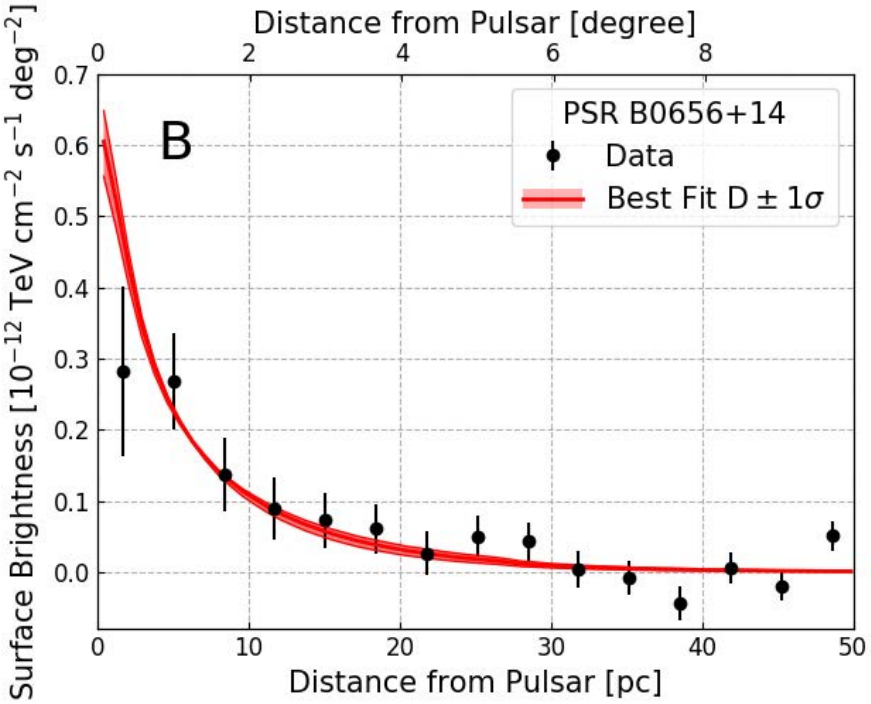
- For electrons above ~100 TeV the only thing you can scatter off of is the CMB because its energy is so low
  - OTH you know what it is everywhere
- The x-ray emission is from synchrotron radiation, where the B field is enhanced by the pulsar to 10 to 20 μG
- The spatial extent of these two sources 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

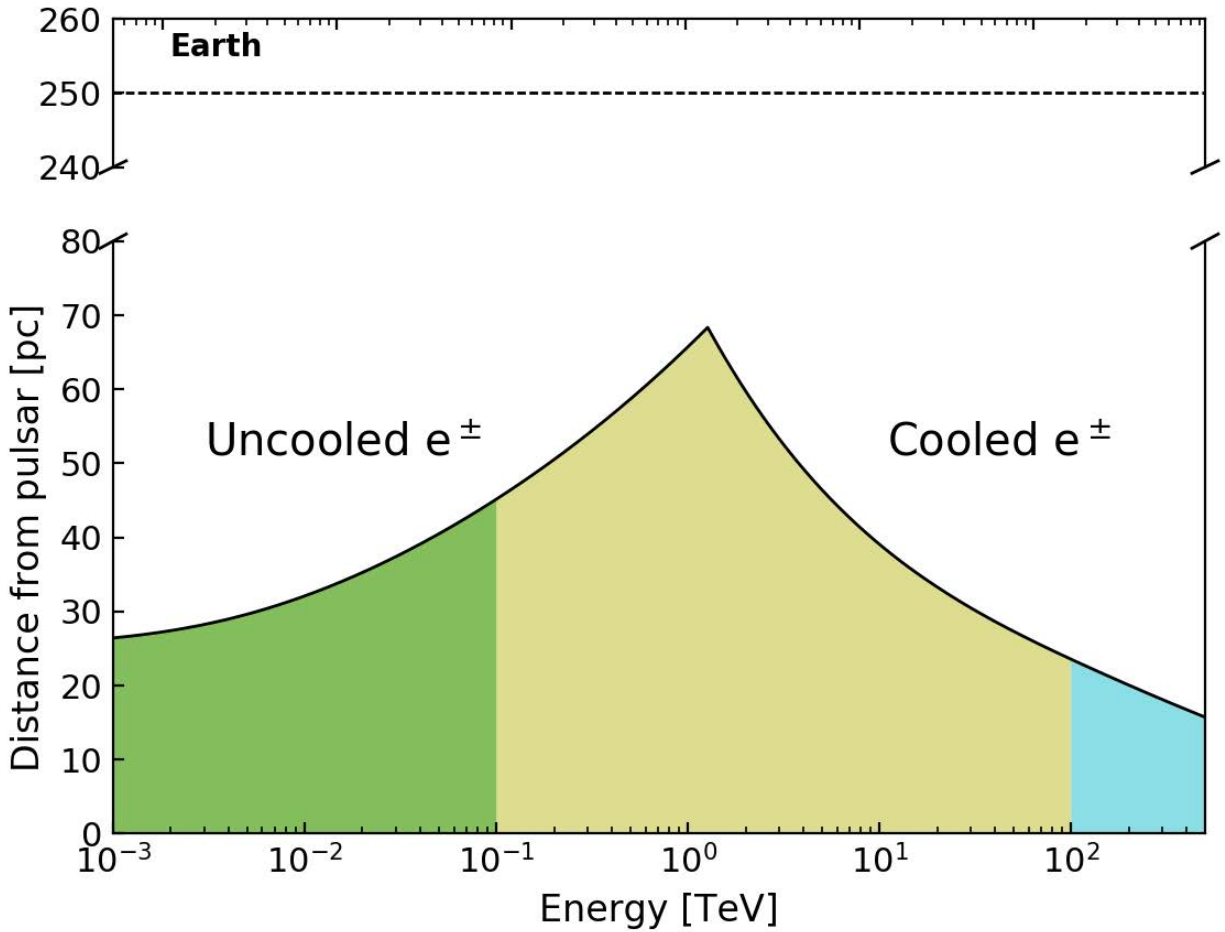


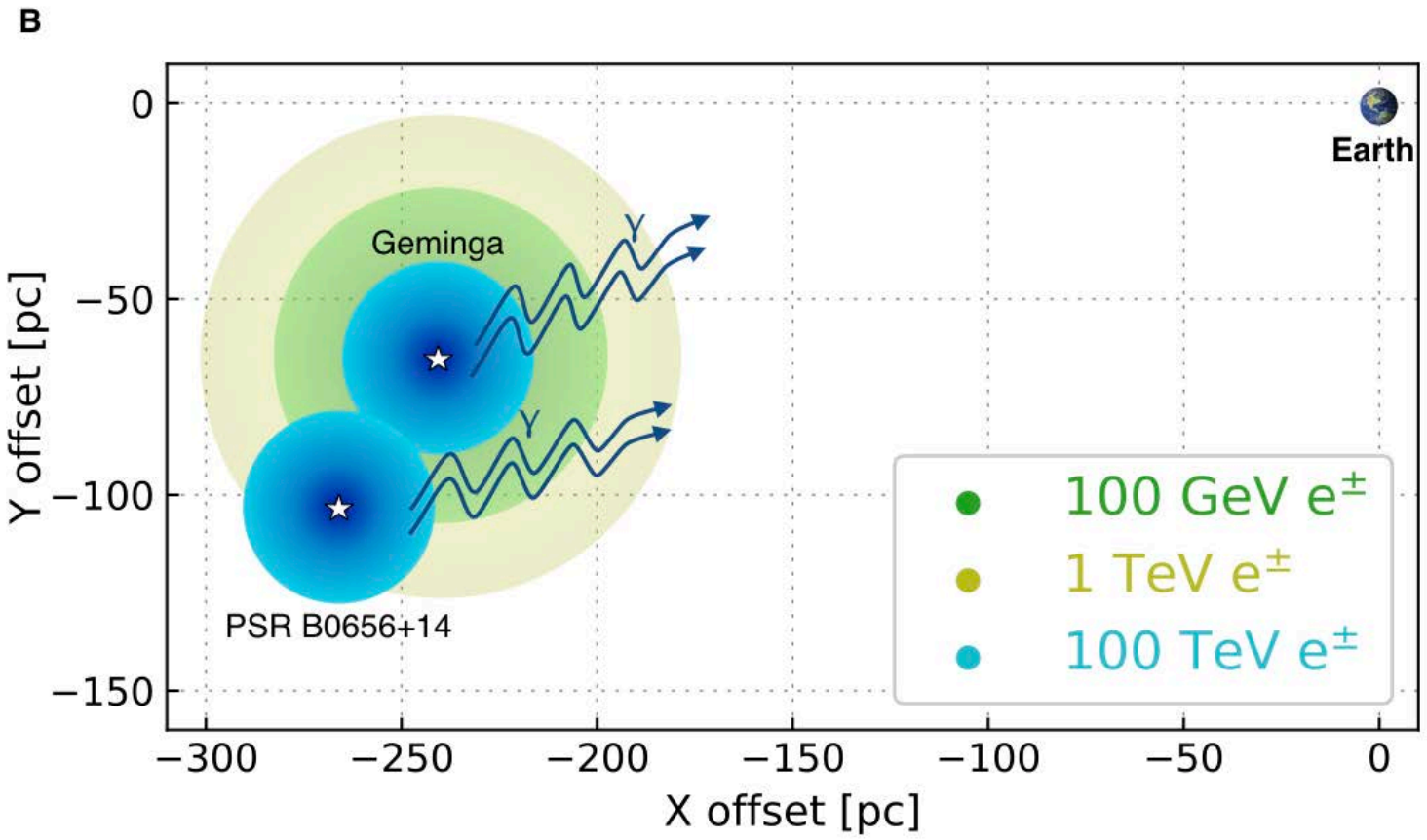
Sudoh, T., Linden, T., & Beacom, J. F. 2019, arXiv:1902.08203.

Radial Distribution

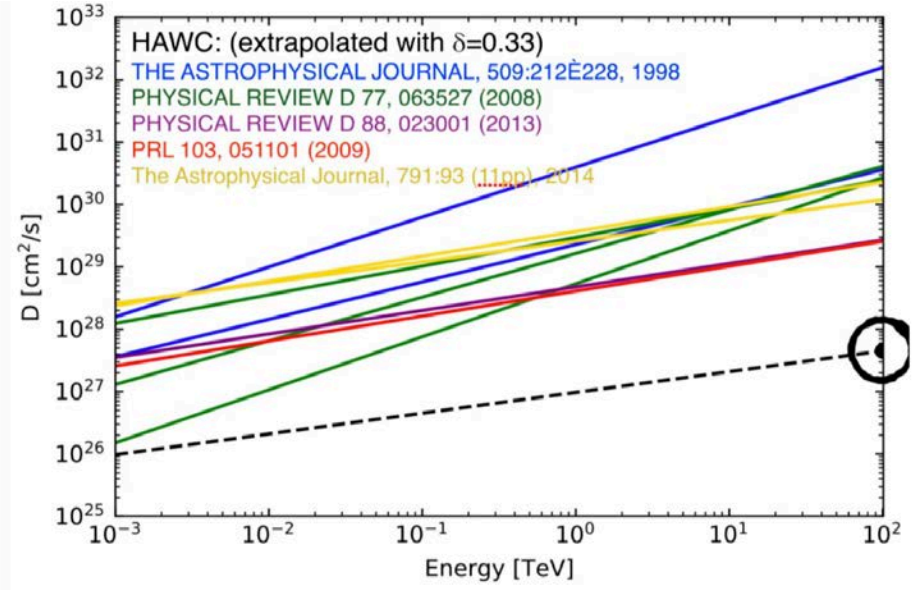


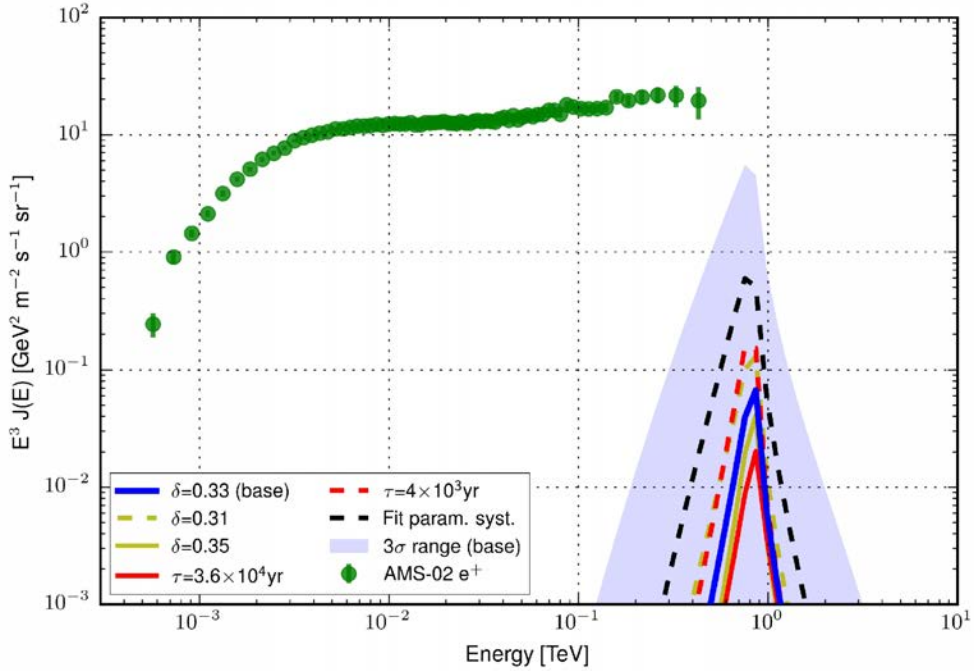



Earth
260
250
240
80
70
60
50
40
30
20
10
0
Distance from pulsar [pc]
Uncooled e ±
Cooled e ±
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
Energy [TeV]


B
0
−50
−100
−150
Y offset [pc]
−300
−250
−200
−150
−100
−50
0
X offset [pc]
Earth
Geminga
γ
γ
PSR B0656+14
100 GeV e±
1 TeV e±
100 TeV e±

Unlikely Source of Positron Excess

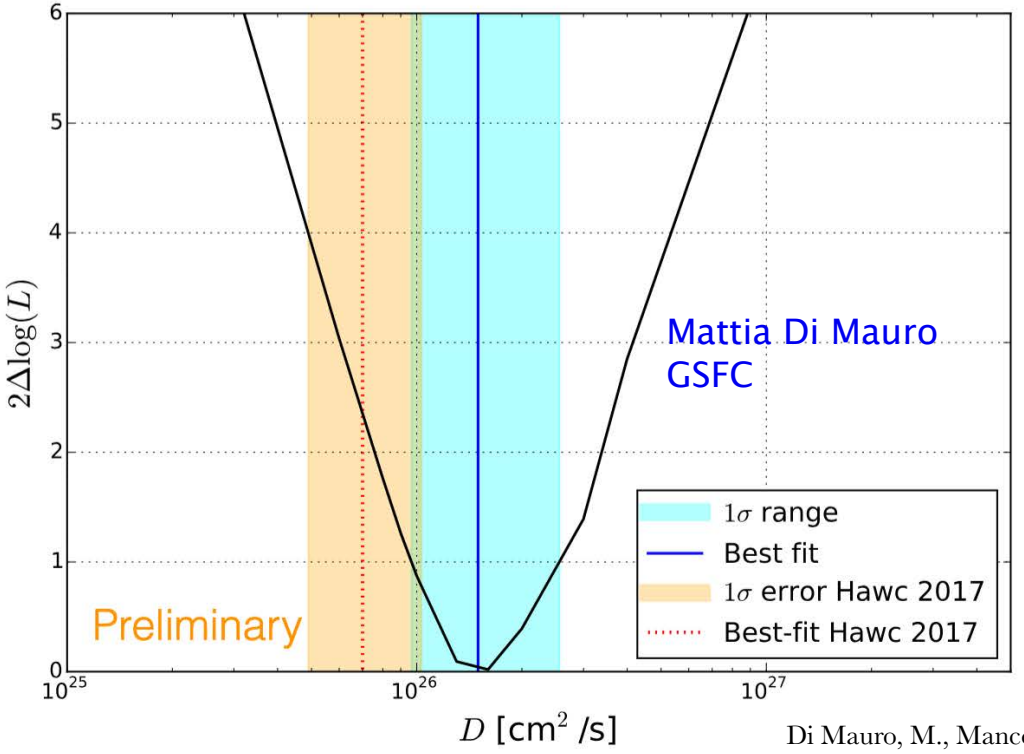


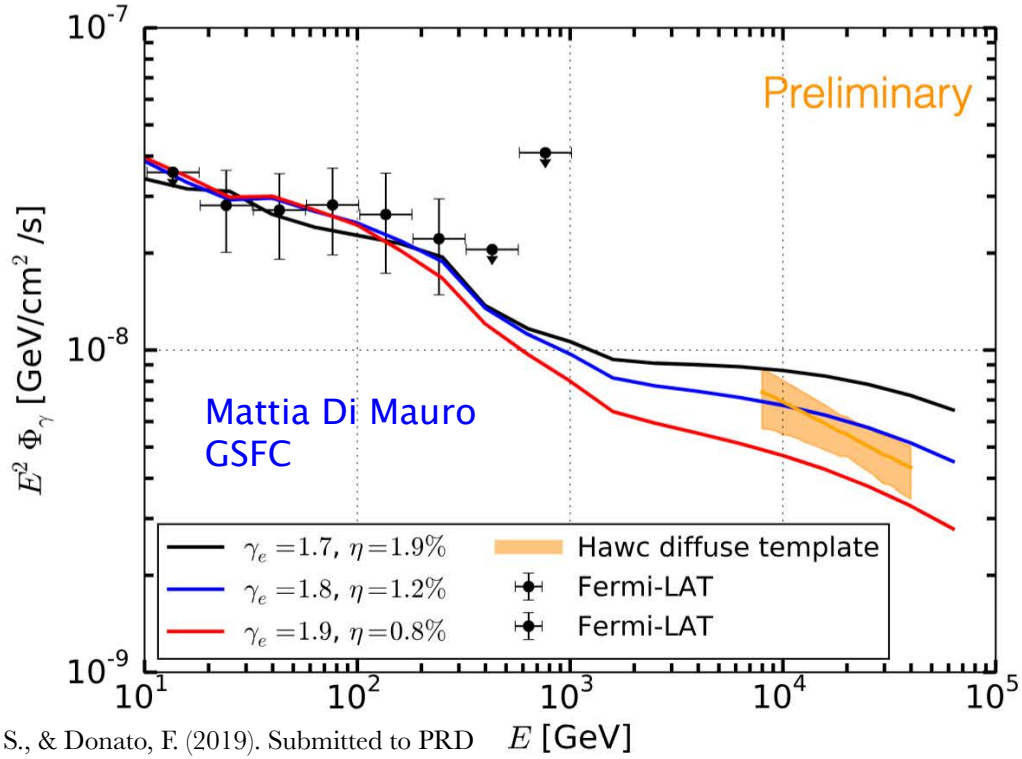


Published in Science Nov. 17, 2017

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?

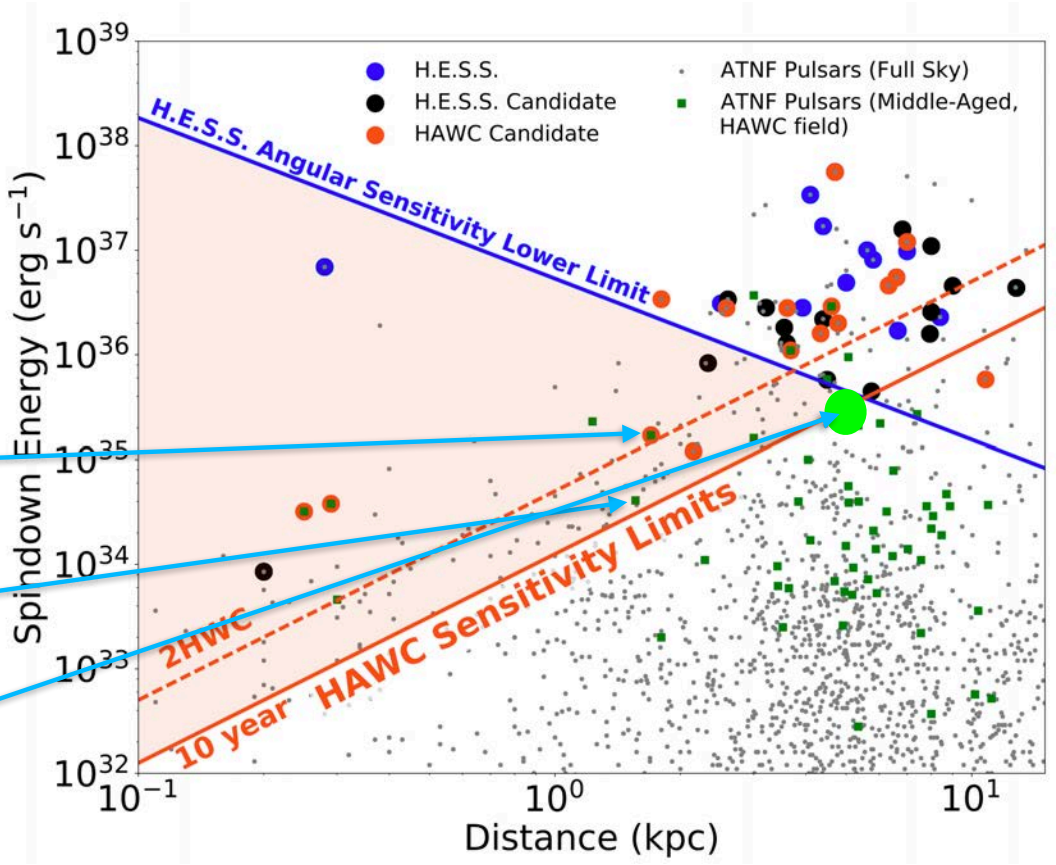
- Linden suggest that there are more nearby PWN to be found based on spin down power and distance
- HAWC has already seen several of these

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

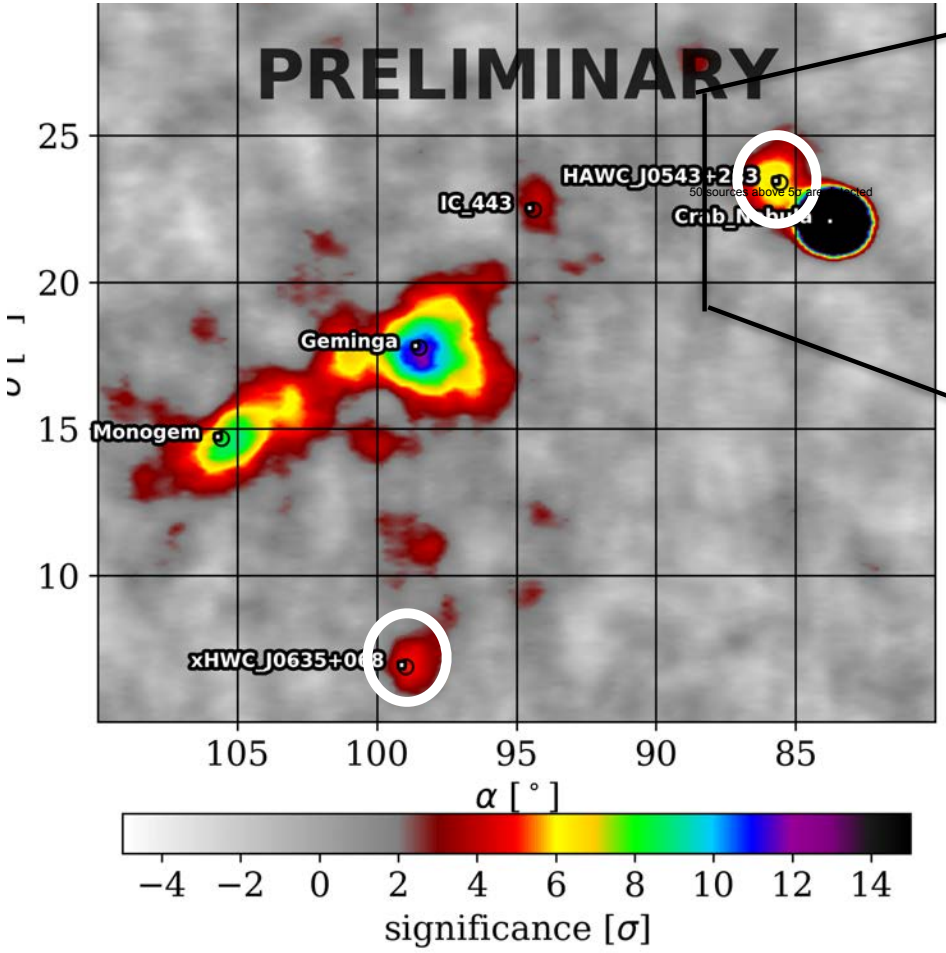
ATel #10941; *Colas Riviere (University of Maryland), Henrike Fleischhack (Michigan Technological University), Andres Sandoval (Universidad Nacional Autonoma de Mexico) on behalf of the HAWC collaboration*
on 9 Nov 2017; 23:11 UT
Credential Certification: Colas Riviere (riviere@umd.edu)

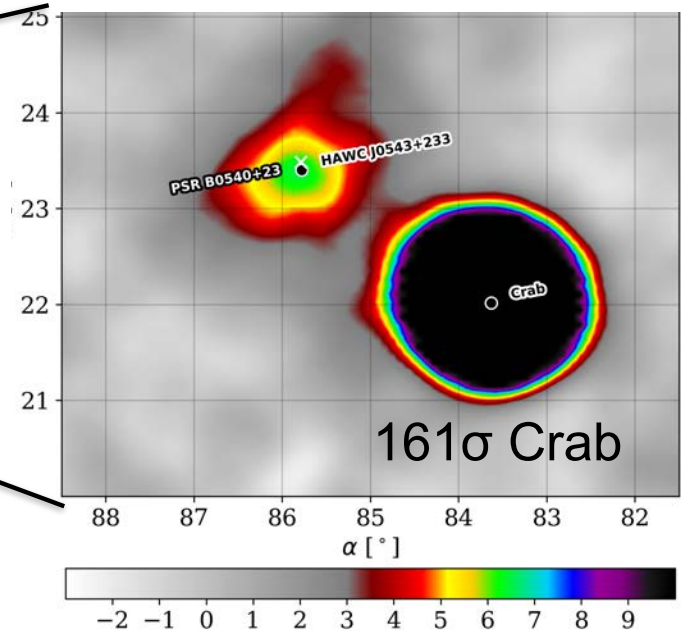


Linden et. al 2017 PhysRevD.96.103016

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

Hiding in Plain Sight J0543+233

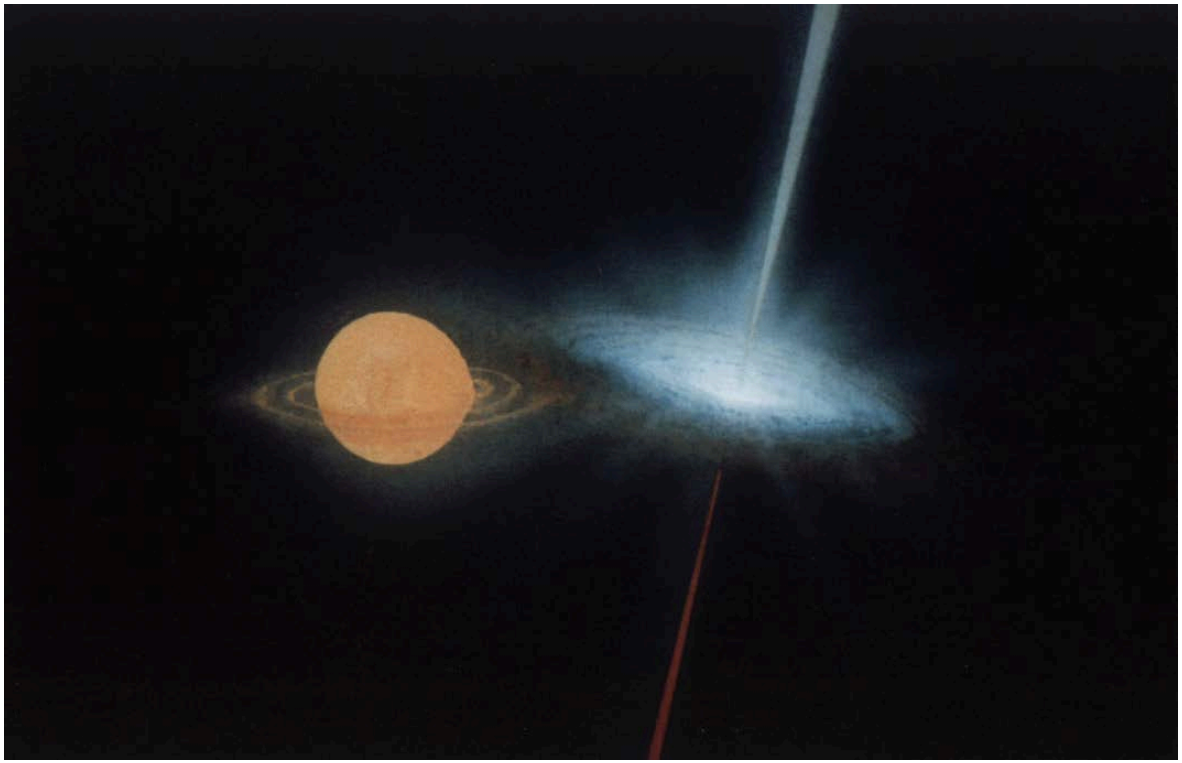




Another middle age PWN
similar to Geminga and B0656+14
$\dot{E} = 4.1 \times 10^{34}$ erg s−1,
d = 1.56 kpc, τ = 253 kyr

Can test if all are Geminga-like

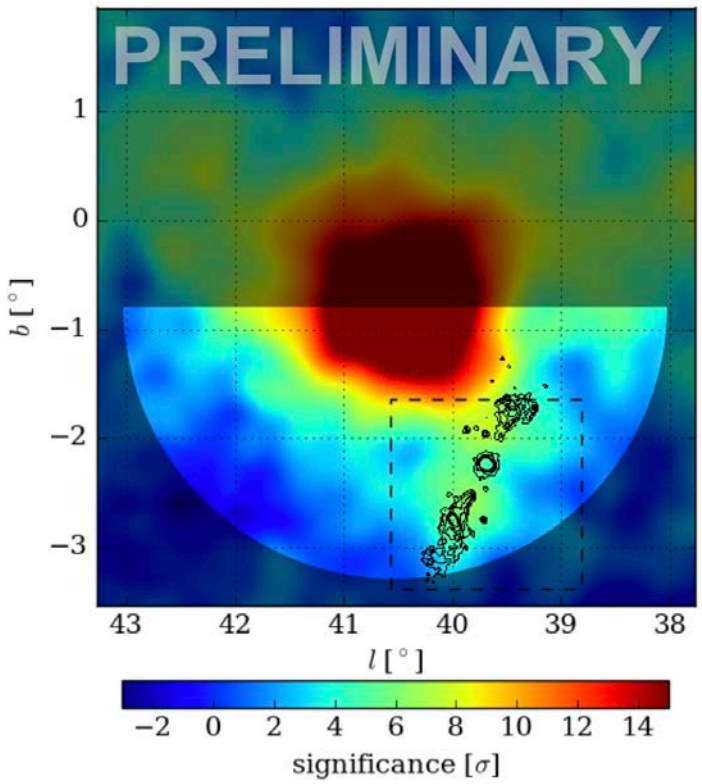
Microquasar SS433

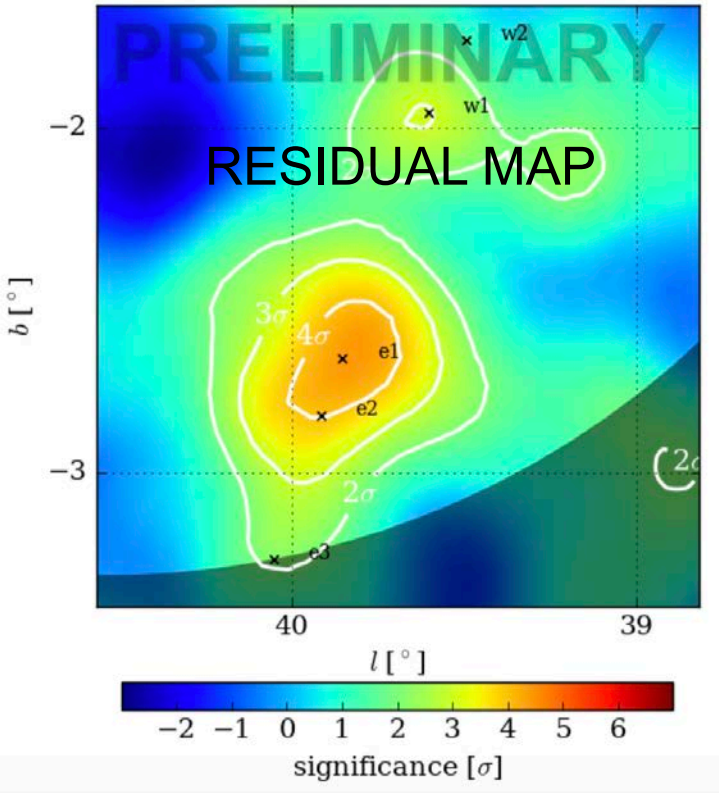


Possible an A-type supergiant and a very extended disk around a black hole.
The jets from SS 433 precess with a period of 13 days.

SS-433

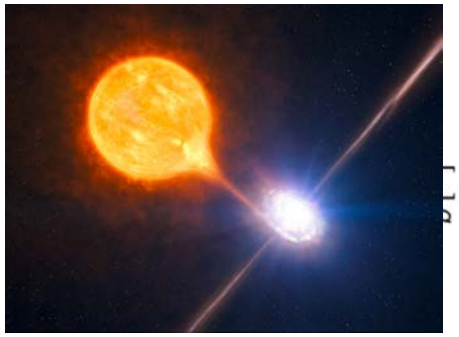
The central source is MGRO J1908+06 and below it are the lobes of SS 433

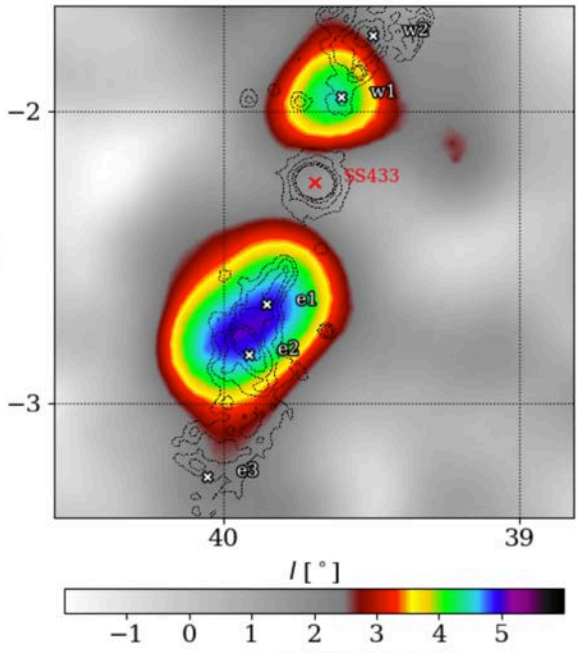


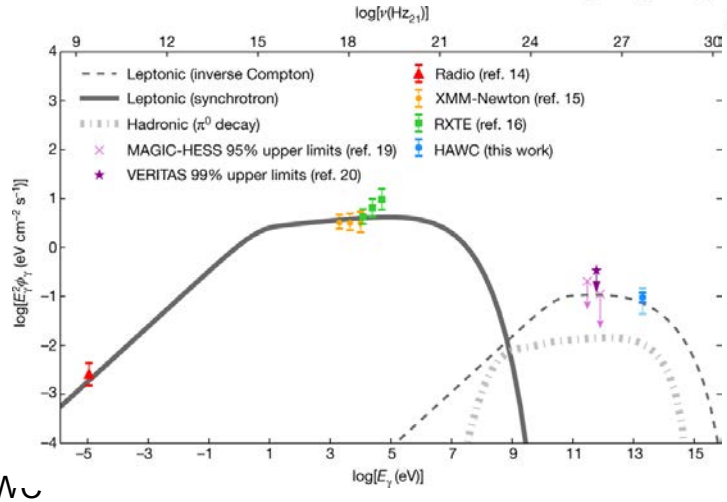


Microquasar SS-433

- 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)



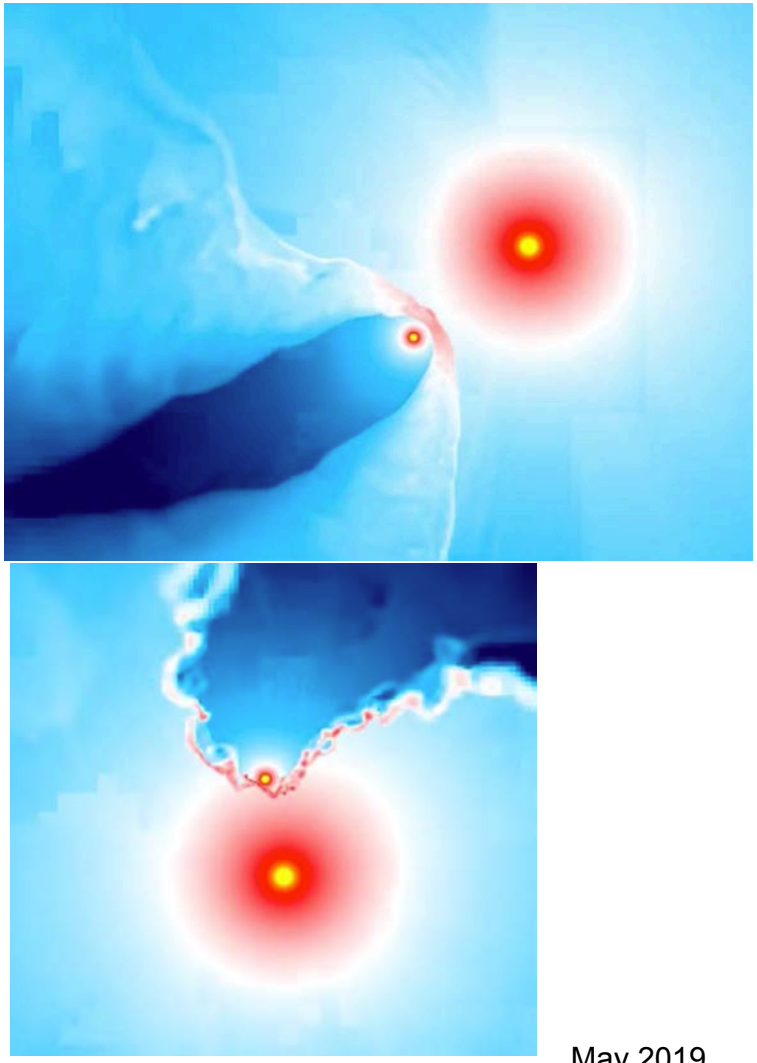




Published in Nature Oct 4, 2018

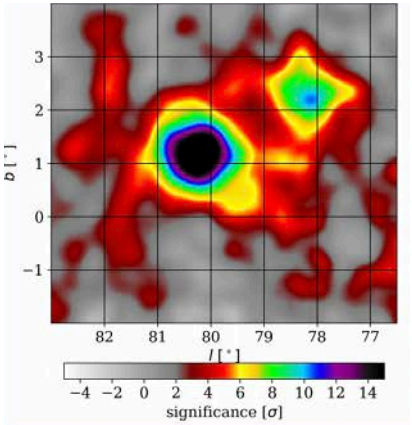
CR Origin: Star Forming Regions (SFR)

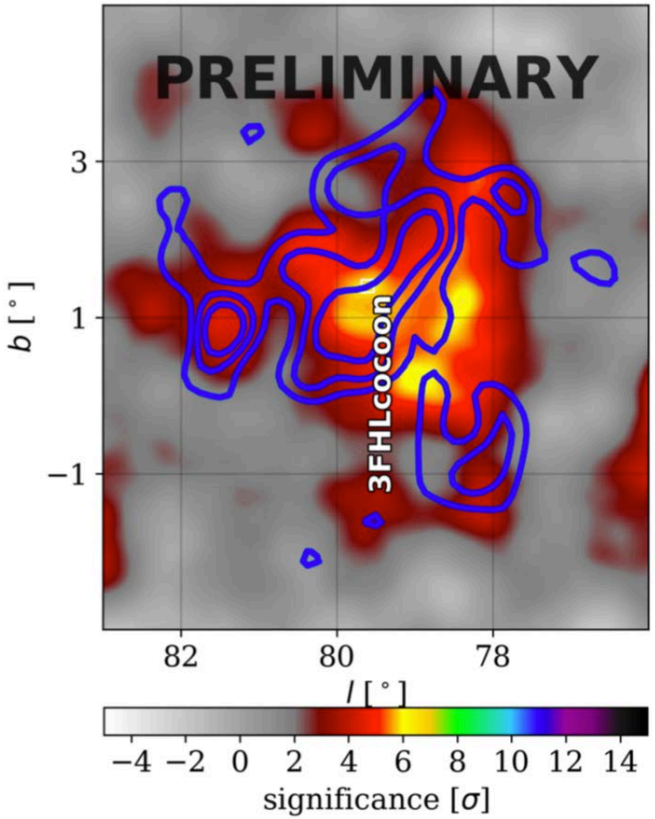
- No evidence of particle acceleration in **SNRs** beyond 100s of TeV
- **Can SFRs provide this energy via e.g. collective star winds?**
- **Candidate: OB2 association in Cygnus Region**
  - *Fermi detection at GeV* (Ackermann et al., ***Science*** 334, 2011, '*The Cocoon')*
- ***Cygnus OB2 is an OB 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**



CR Origin: Star Forming Regions (SFR)

- 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

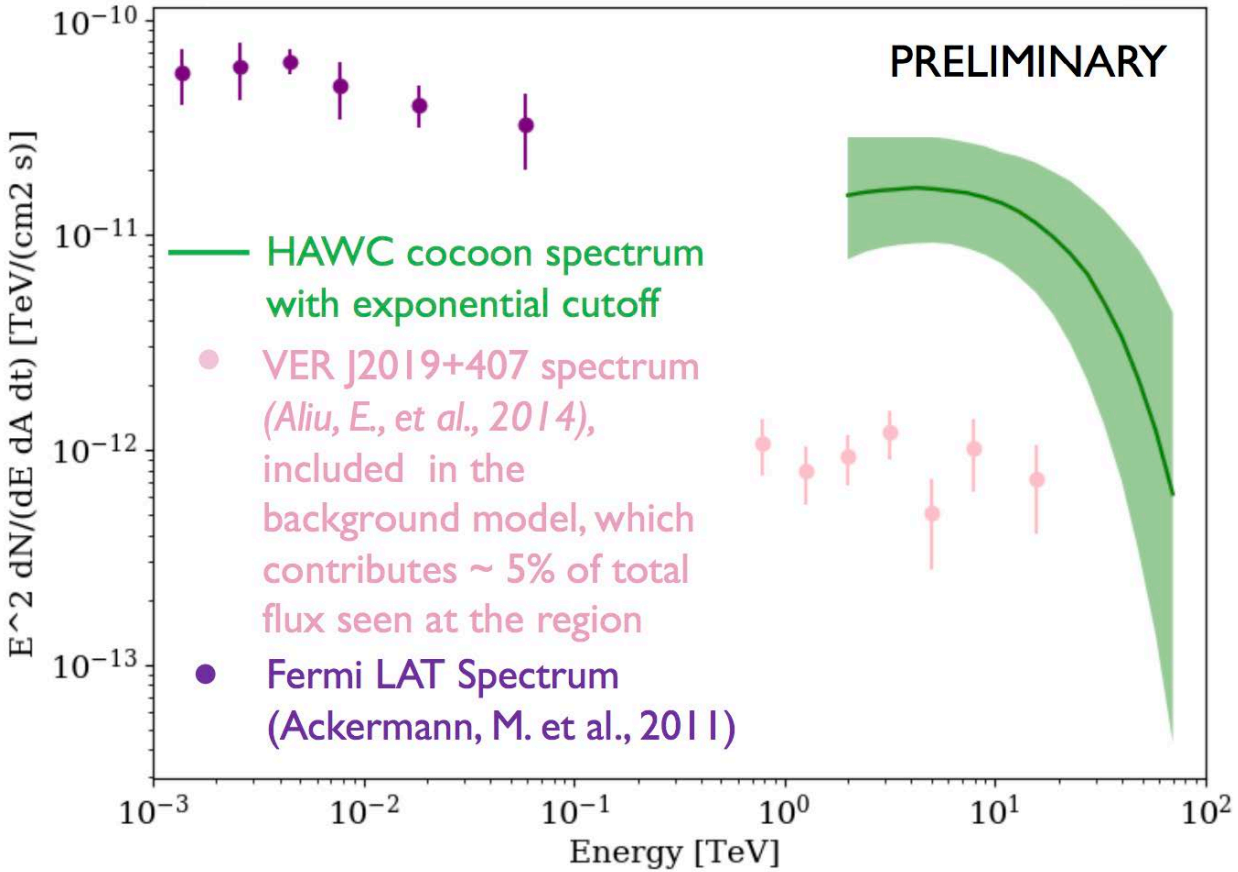




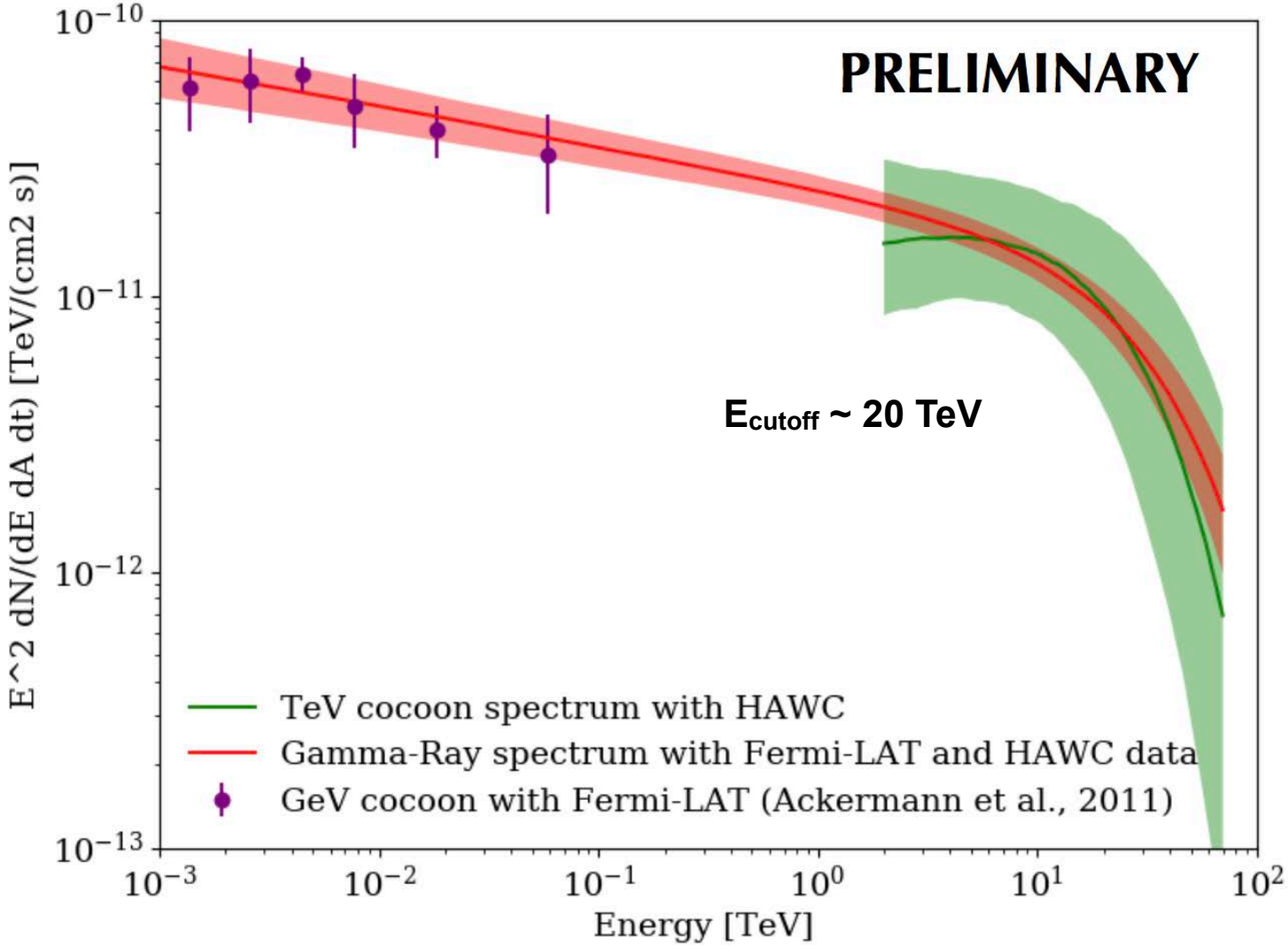
Fermi-LAT Contours

HAWC Map after subtraction of PWN & γ-Cygni

Binita Hona
MTU

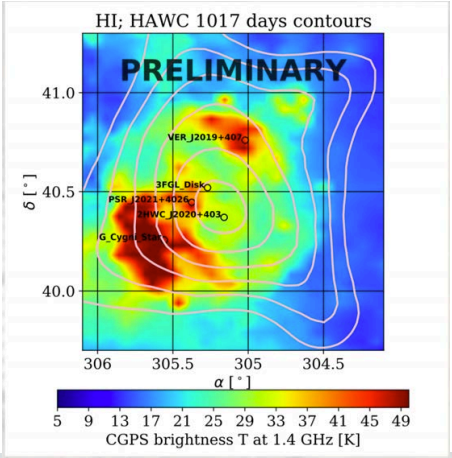

PRELIMINARY
HAWC cocoon spectrum with exponential cutoff
VER J2019+407 spectrum (Aliu, E., et al., 2014), included in the background model, which contributes ~ 5% of total flux seen at the region
Fermi LAT Spectrum (Ackermann, M. et al., 2011)
E^2 dN/(dE dA dt) [TeV/(cm2 s)]
Energy [TeV]
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}

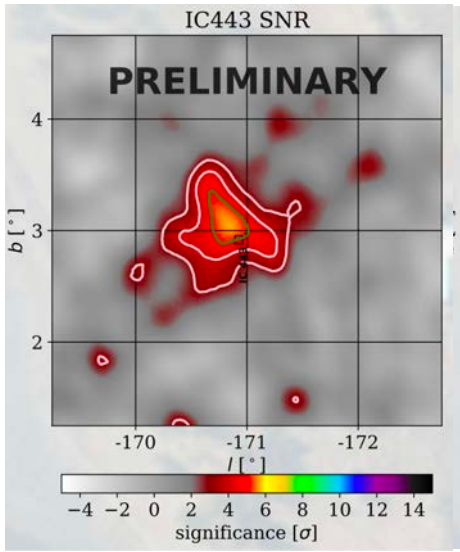
Cygnus Cocoon

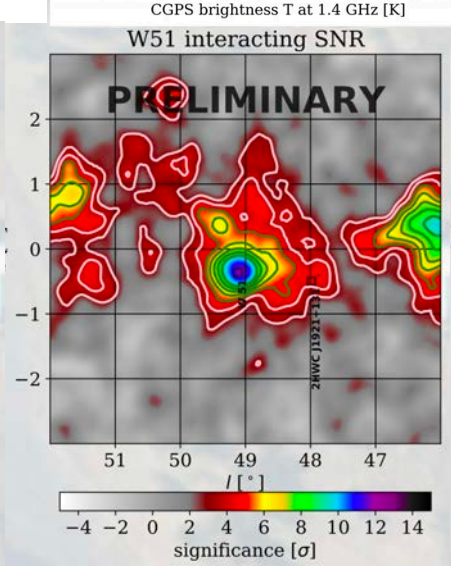


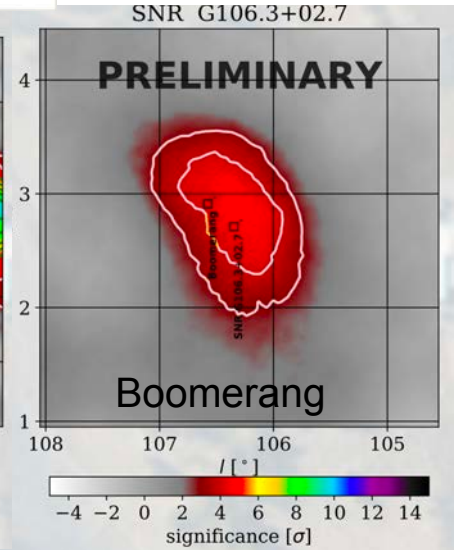
CR Origin: Super Nova Remnants (Henrike Fleischhack - MTU)

- **HAWC detection of** significant TeV γ-ray emission from middle-aged **three SNRs:** γ-Cygni, IC 433, and W51C (plus almost Boomerang).
- **Combined fits of Fermi and HAWC data** describing the GeV-TeV emission as pion decay spectrum
- **Boomerang** detection at threshold significance





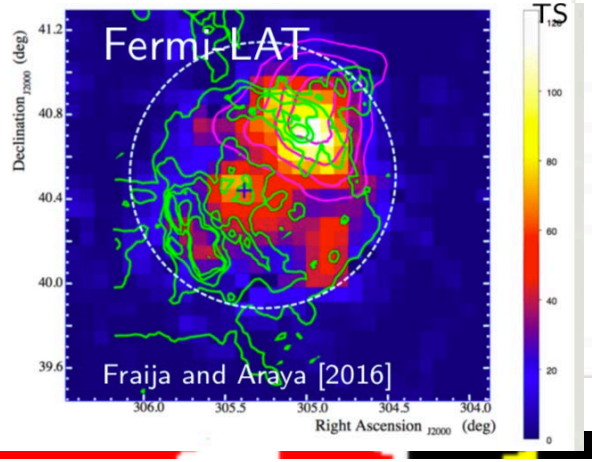


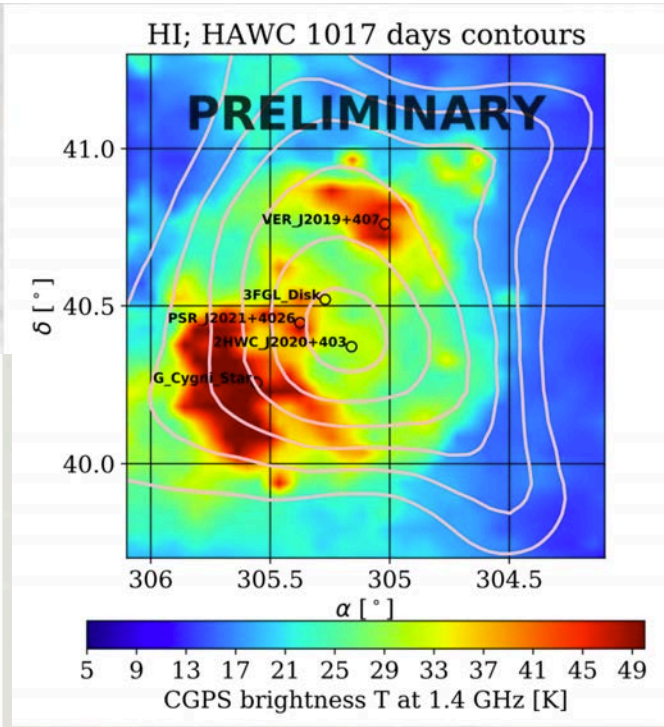


- **Future prospect:**
  - Stricter constraints on **maximum particle energy** through improved HAWC sensitivity at high energy
  - Improved morphology studies

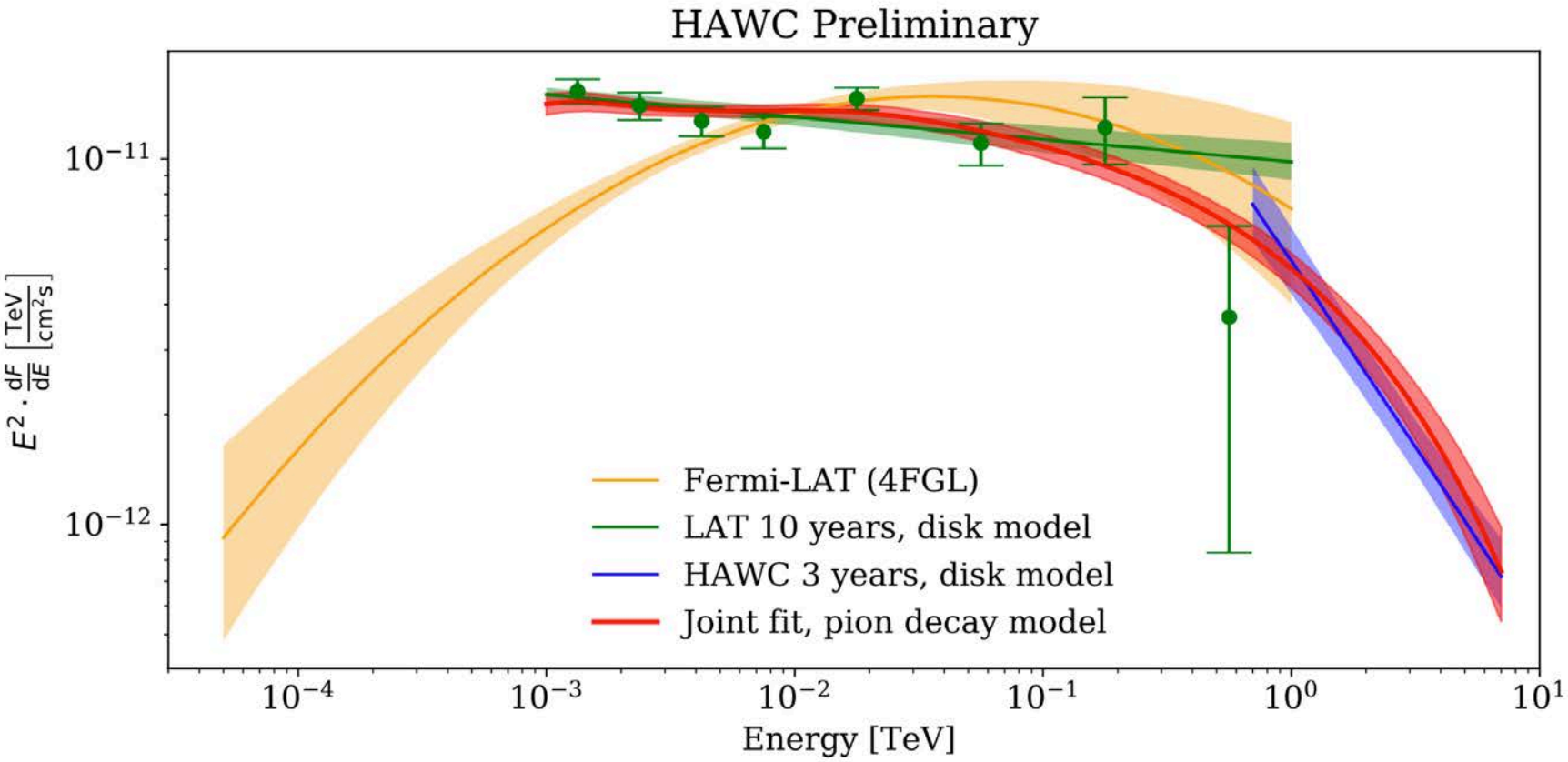
γ Cygni SNR (G78.2+2.1 aka J2021.0+4031)

- 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





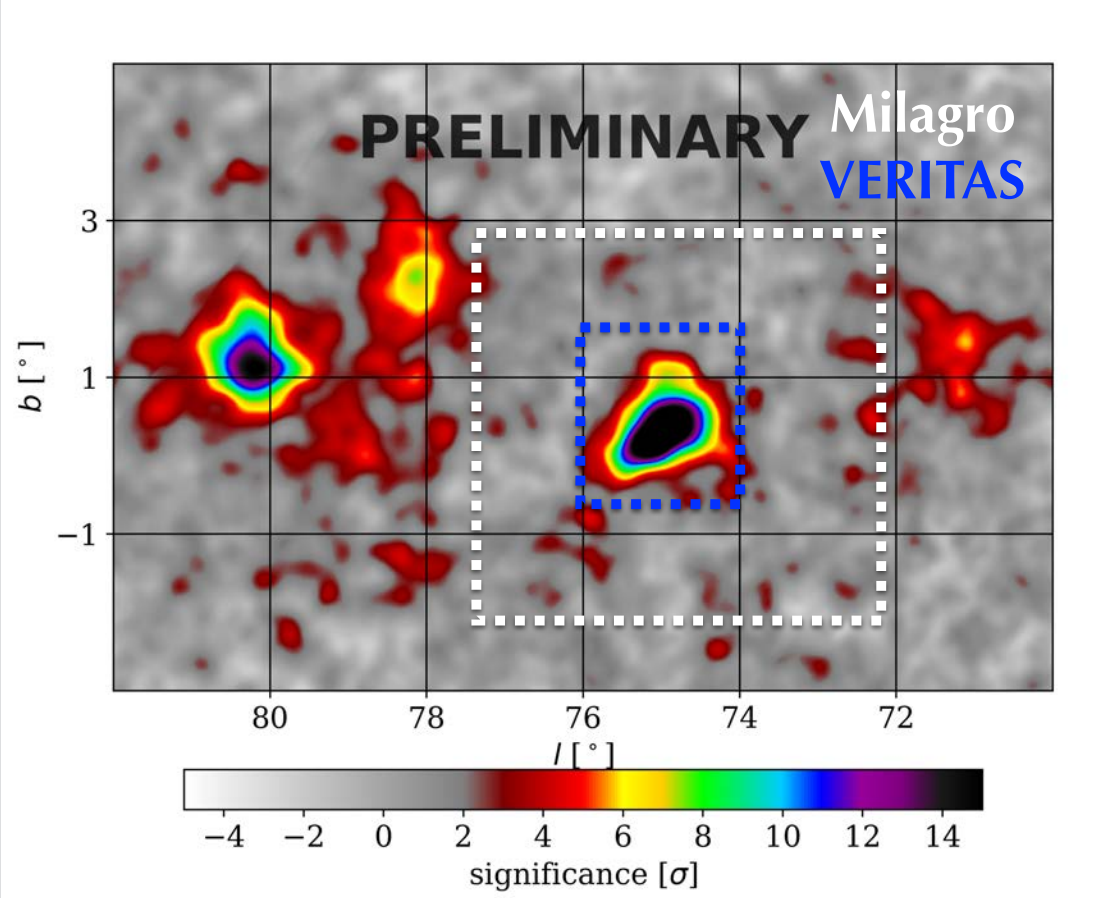
Combined Fermi - HAWC fit



Cygnus Region

TeV Sources:
Cygnus Cocoon
γ-Cygni SNR
2HWC J2019+367
2HWC J2031+415
2HWC J2006+341
VER J2019+368
VER J2016+371
MGRO J2019+37

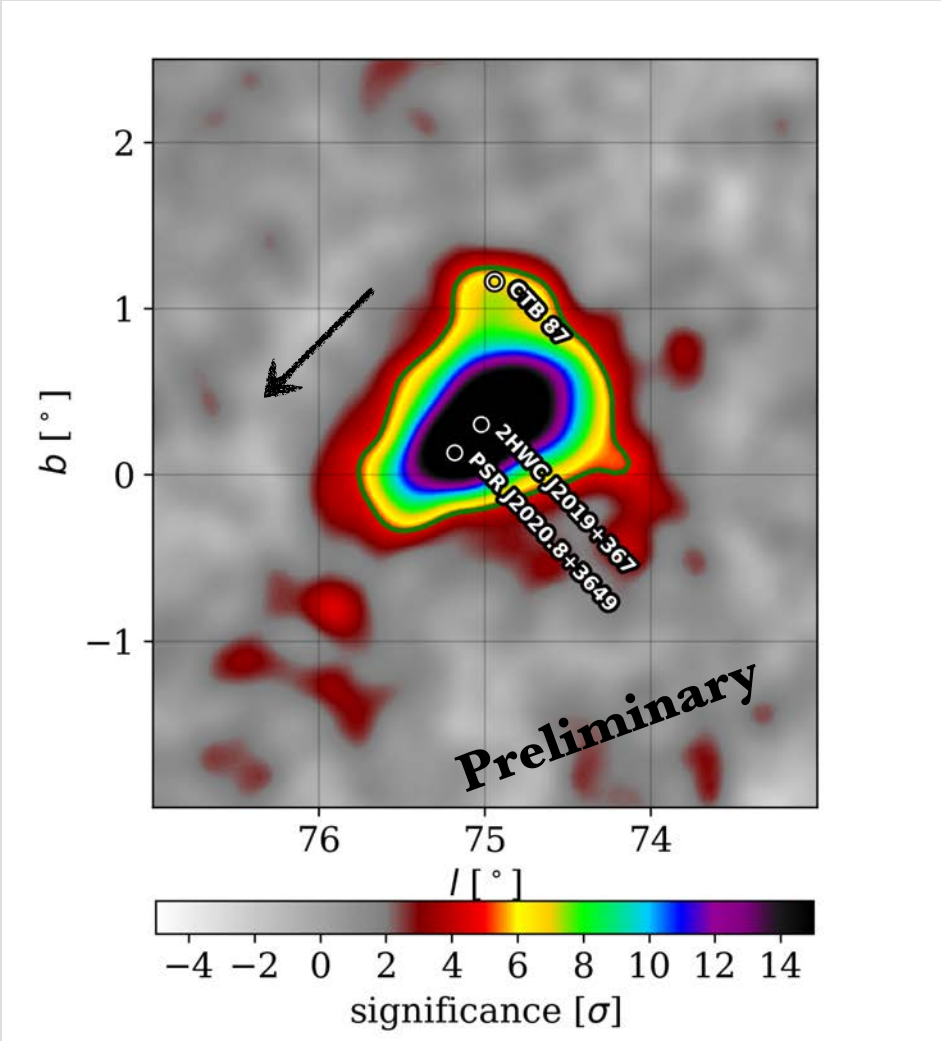
Chad Brisbois (MTU)



2HWC J2019+367

All HAWC energies

Spatially extended
emission region

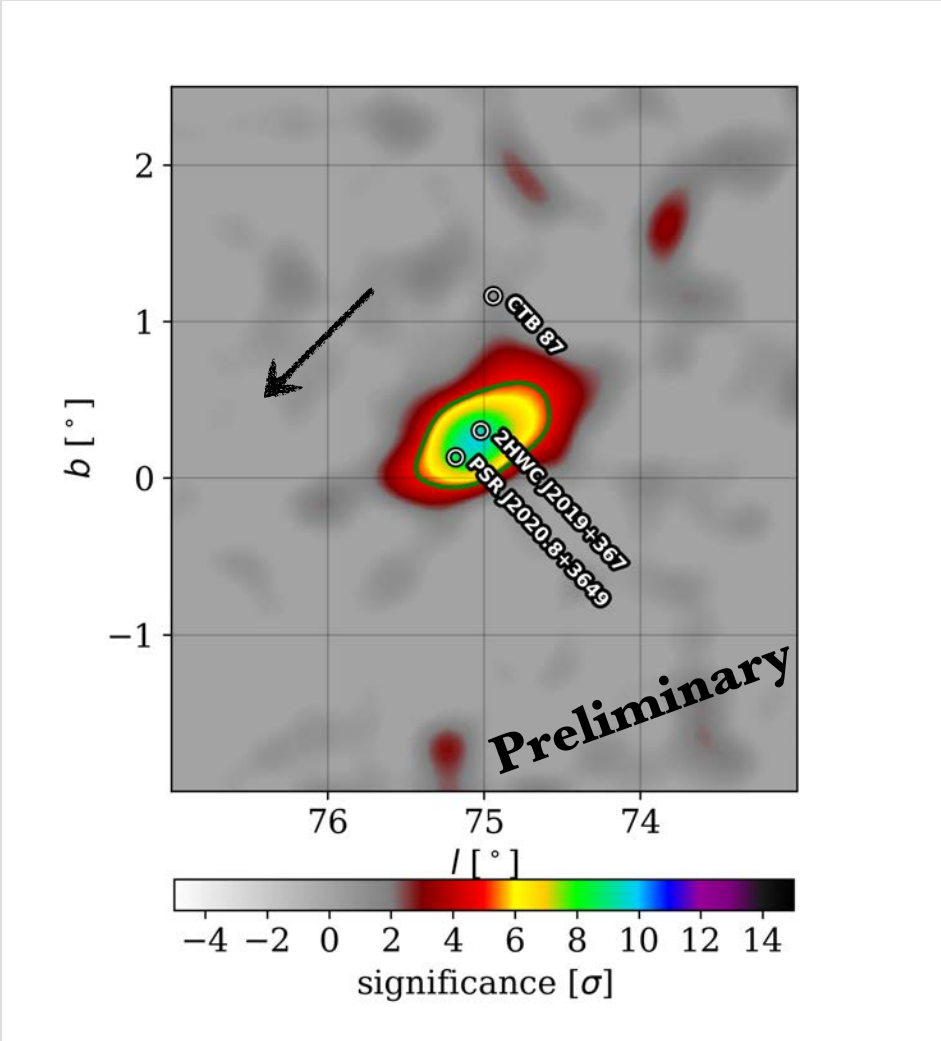


Arrow — pulsar proper motion

2HWC J2019+367

Above 50 TeV

Higher energies, smaller emission region



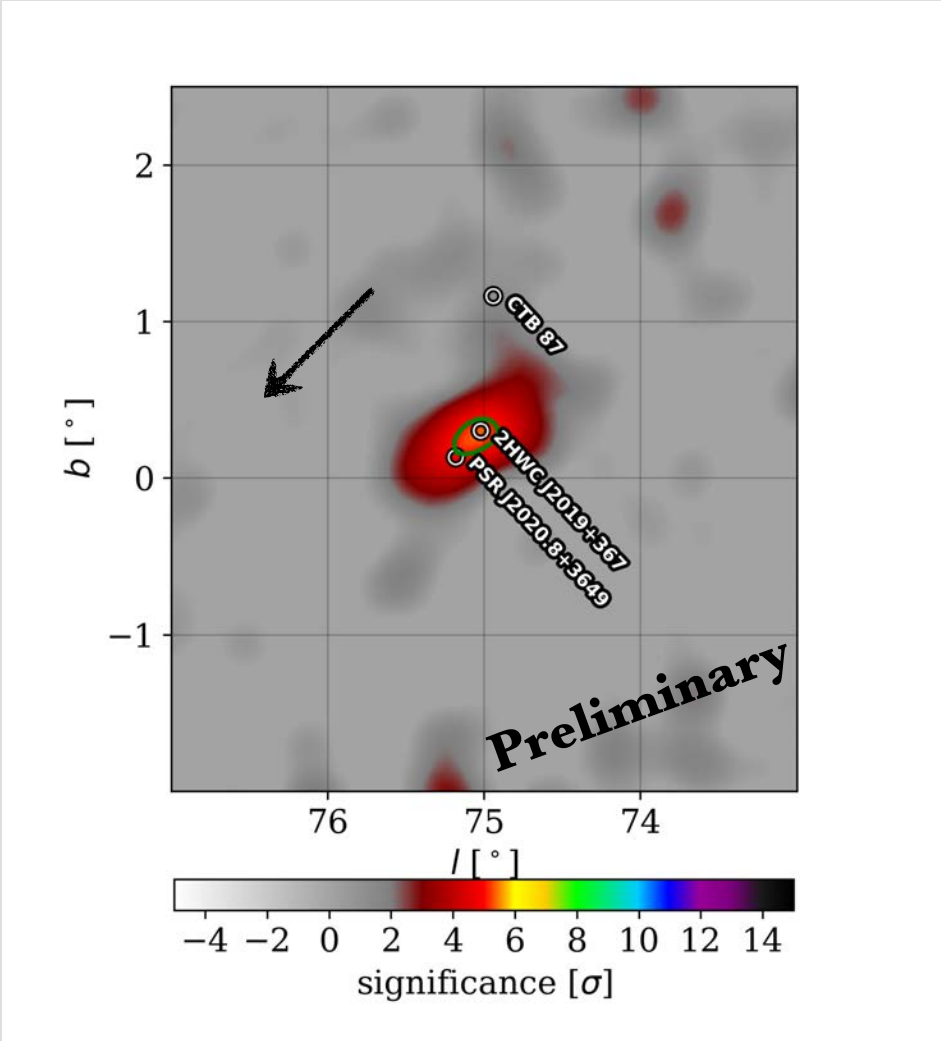
Arrow — pulsar proper motion

2HWC J2019+367

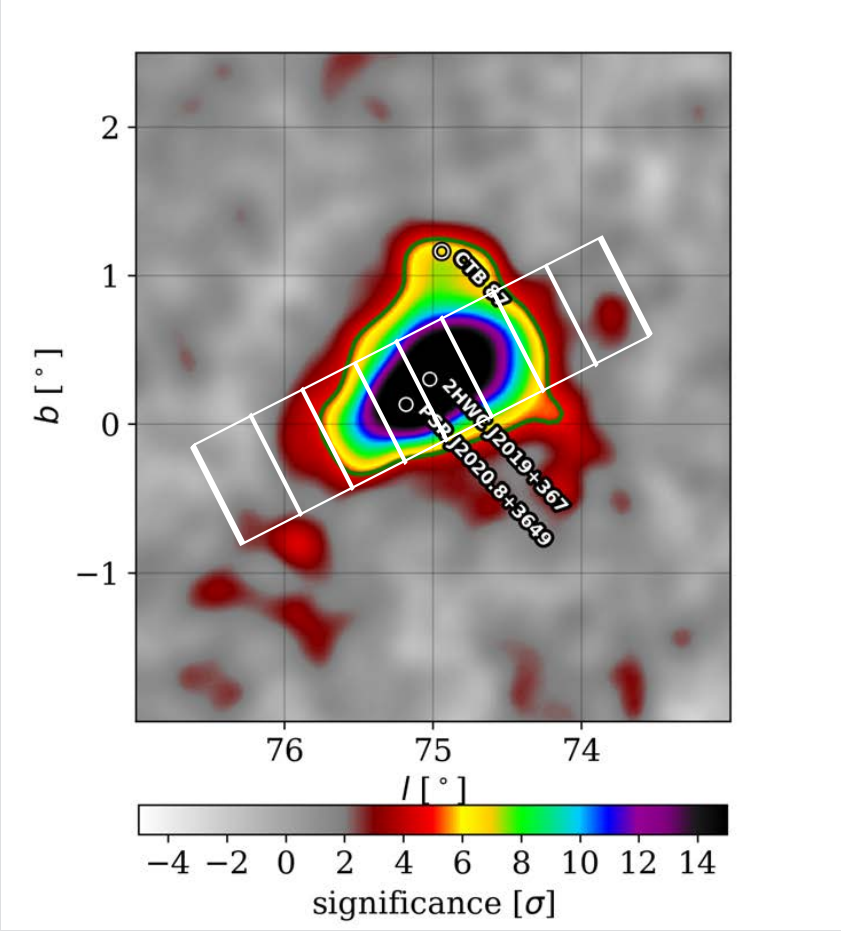
Above 100 TeV

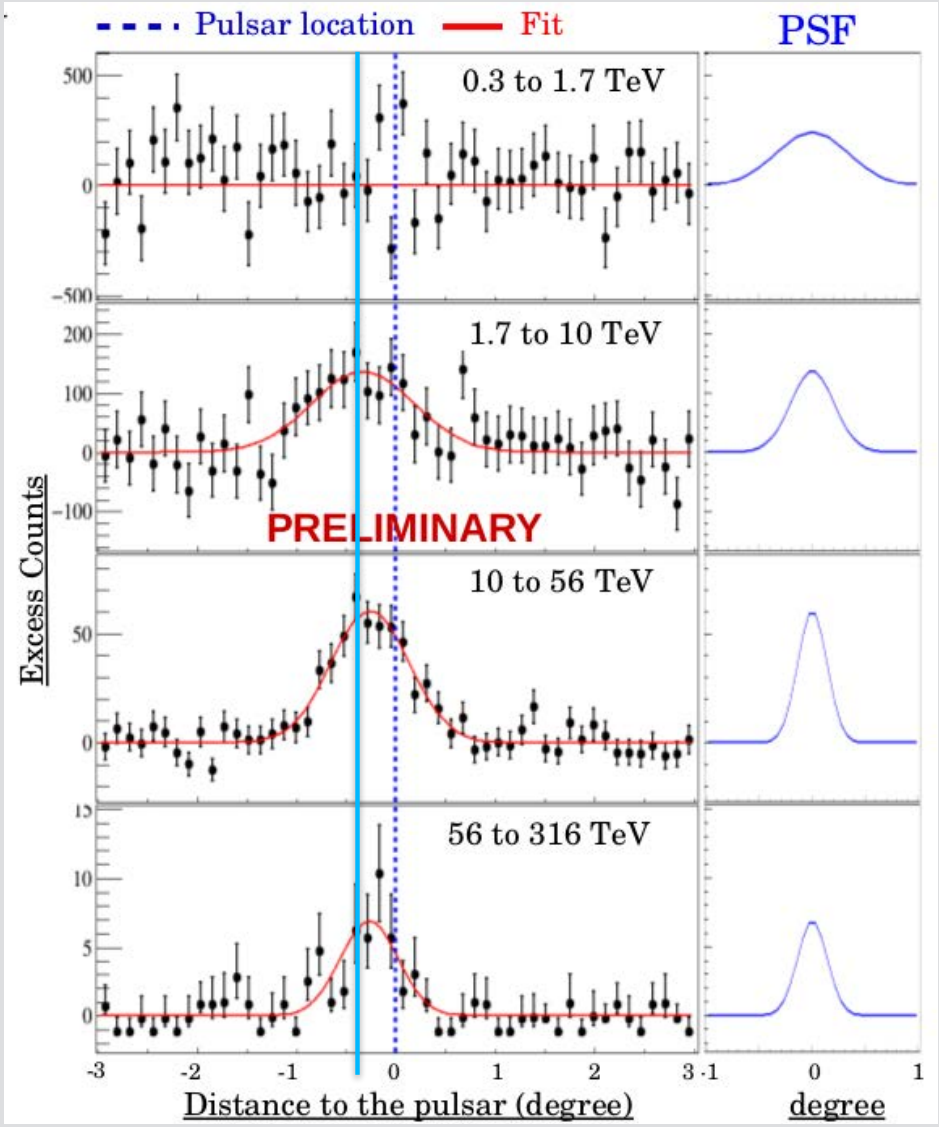
Centroid of significant emission compatible with pulsar position

Arrow — pulsar proper motion



Energy Dependent Morphology





HAWC Spectrum: J2019+367

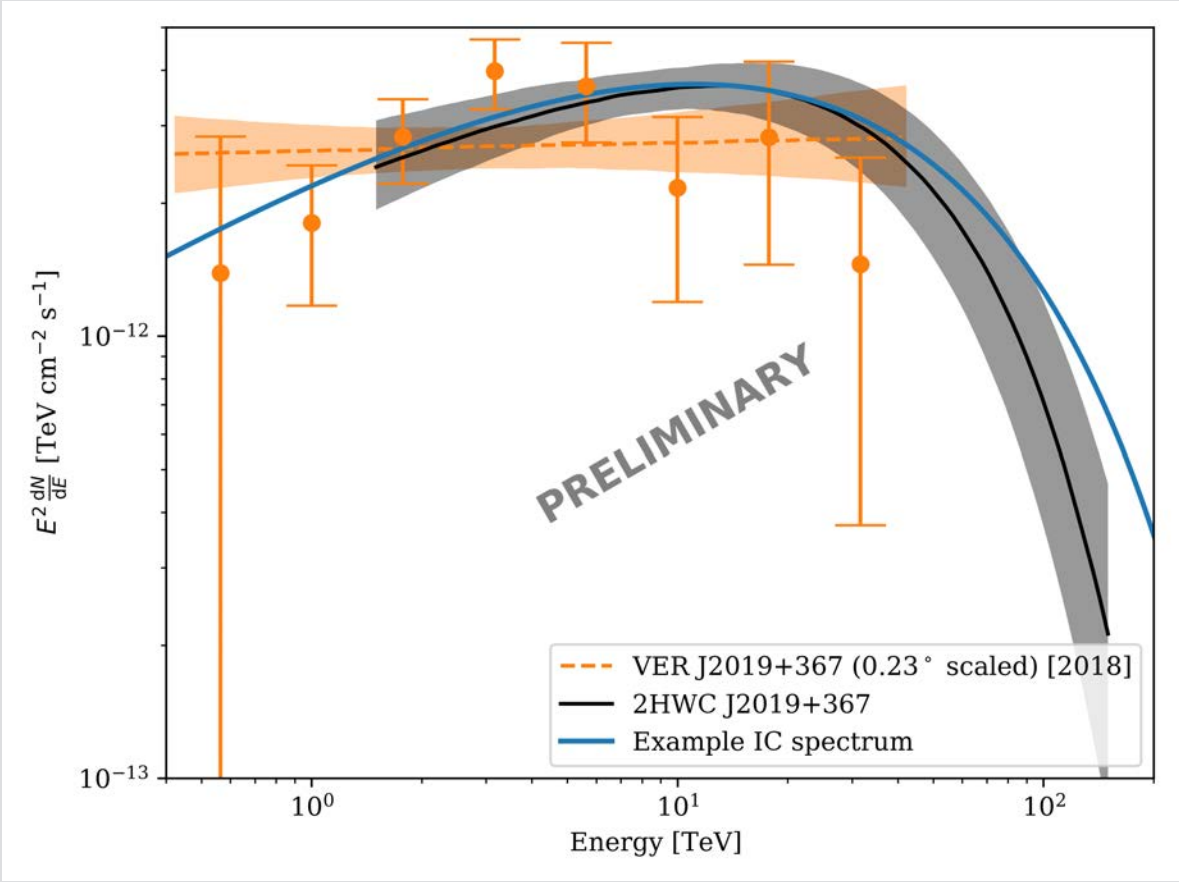
HAWC spectrum seems compatible with Inverse Compton emission off CMB, IR fields

Detailed modeling in progress including:

realistic ISRFs at location of pulsar

Caveat: IC spectrum made using default radiation fields in naima

$$\frac{dN_e}{dE} \propto E^{-1.9} exp\left(\frac{-E}{100\ \text{TeV}}\right)$$



Abeysekara, A. U., *et al* (2018). The Astrophysical Journal, 861(2), 134.

HAWC Spectrum: J2019+367

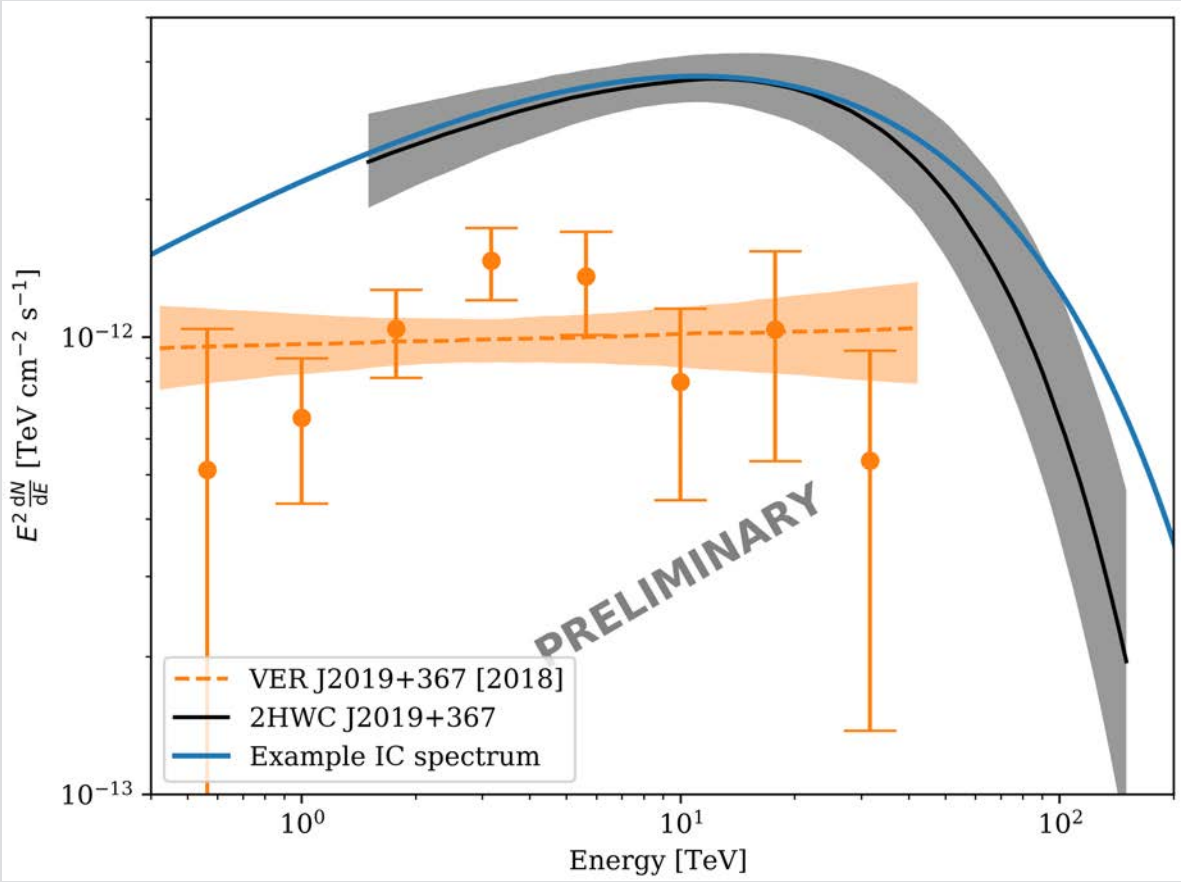
HAWC spectrum seems compatible with Inverse Compton emission off CMB, IR fields

Detailed modeling in progress including:

realistic ISRFs at location of pulsar

Caveat: IC spectrum made using naima *and default radiation fields*

$$\frac{dN_e}{dE} \propto E^{-1.9} exp\left(\frac{-E}{100\ \text{TeV}}\right)$$



Abeysekara, A. U., *et al* (2018). The Astrophysical Journal, 861(2), 134.

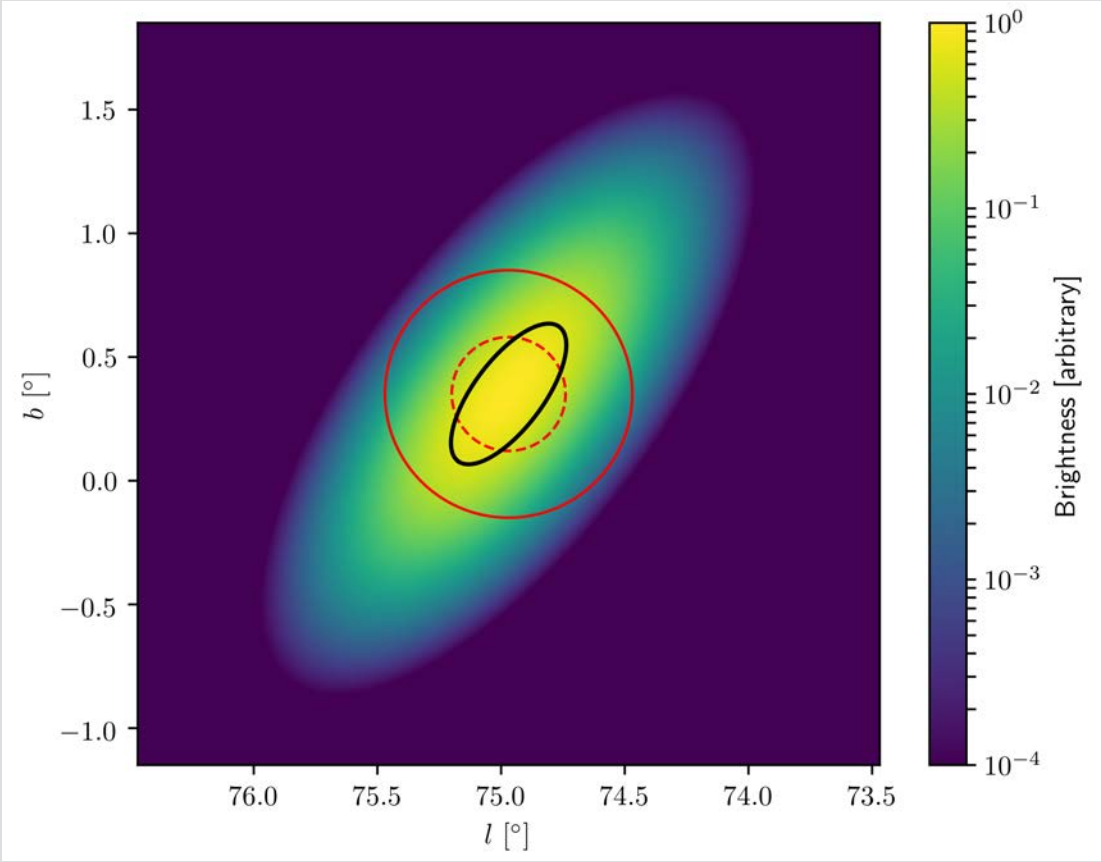
Why the discrepancy?

VERITAS morphology drawn
2014 paper used 0.5° extraction region

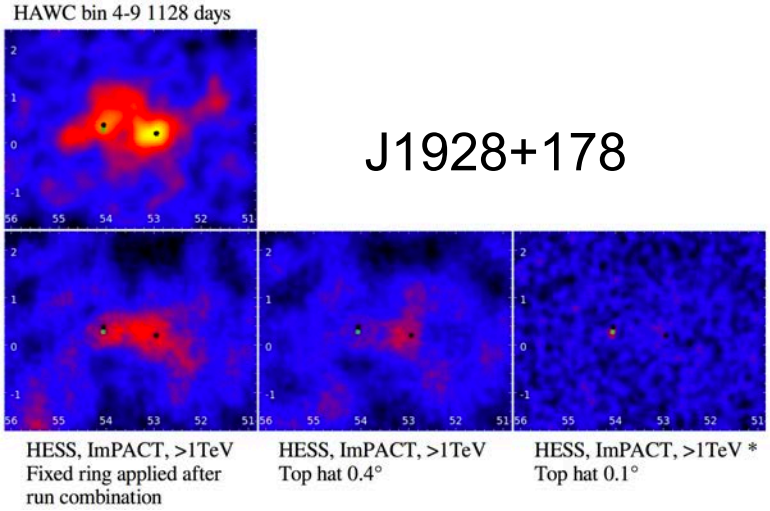
2018 paper used 0.23° extraction region

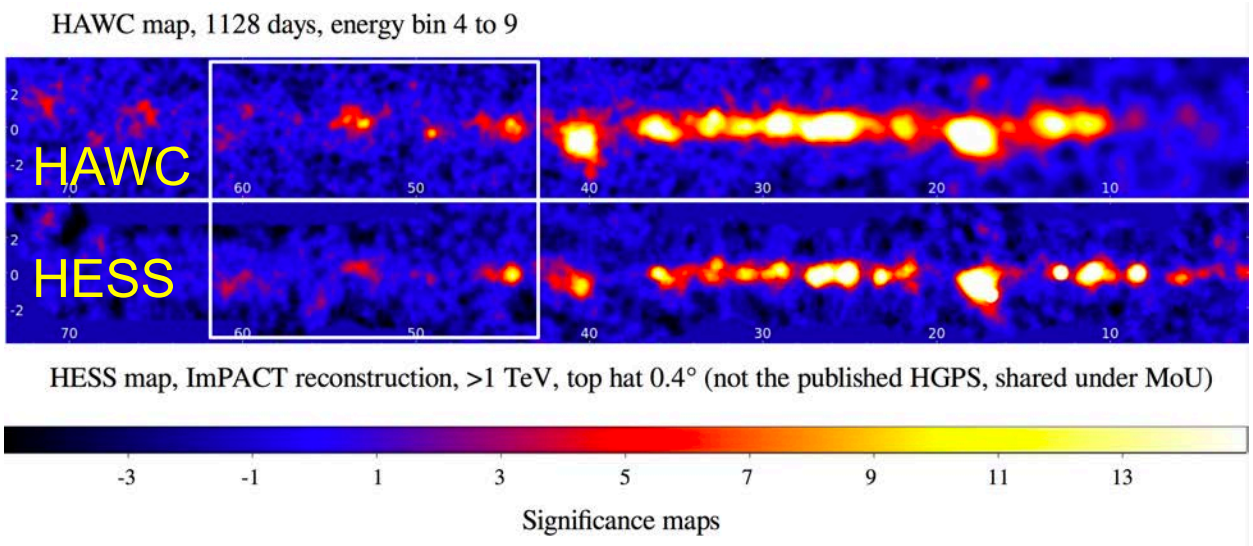
1σ contour given in black

HAWC fits morphology+ spectrum simultaneously



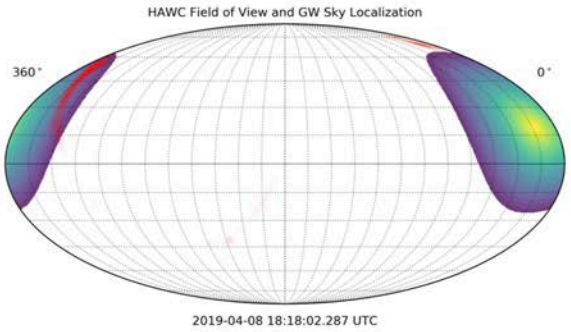
Multi-Wavelengths/-Instrument Synergies: Eg. H.E.S.S.



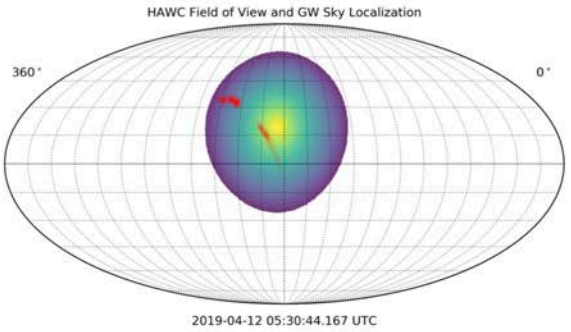


- Analysis of H.E.S.S. Legacy Survey data (> 1 TeV) with HAWC-like background estimation shows **great agreement** with HAWC & leads to **discovery of 'new' sources in H.E.S.S. data**
- Further support for:
  - Multi-source fits with HAWC informed by IACTs
  - Multi-instrument fits combining data from HAWC, IACTs, Fermi etc.
- **Future Prospect:** Multi wavelength/messenger research will require further software development over the next few years (e.g. The Multi-Mission Maximum Likelihood Framework, 3ML)

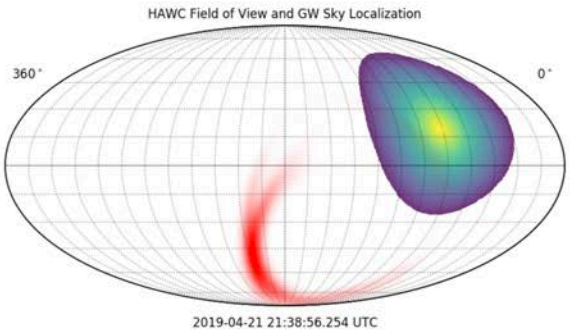
LIGO Alerts Run O3



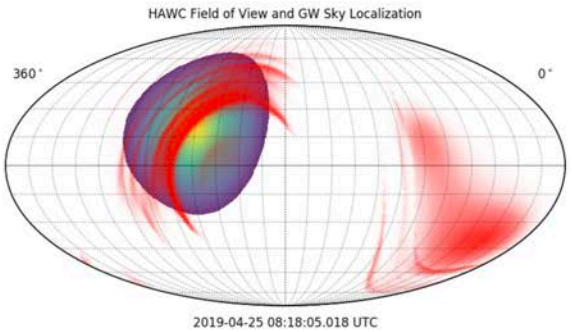
S190408an



S190412m



S190421ar



S190425z

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 dt = 0.3s, 1s, 3s, 10s, 30 and 100s
- Search from t0 - 5dt to t0 + 10dt 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]

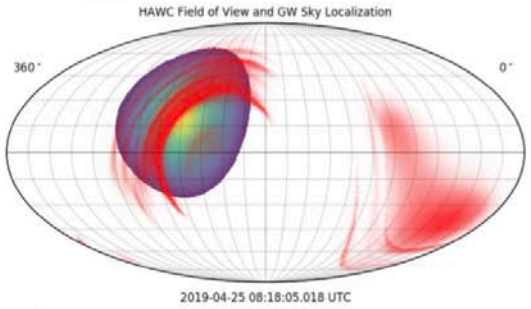
```
EVENT ID:           MS190324o
REVISION:           1
GW TRIGGER TIME:    2019-03-24 14:36:30.034 UTC
TIMESCALE:          0.3s
TS:                 36.1
SIGNIFICANCE:       4.06 sigma
HAWC TRIGGER TIME:  2019-03-24 14:36:28.686 UTC
TIME DIFFERENCE:    -1.3s
RIGHT ASCENSION:    278.70deg
DECLINATION: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

Note: significance includes trials

HAWC Alert Page (Internal)

Link to LIGO-Virgo event webpage → S190425z

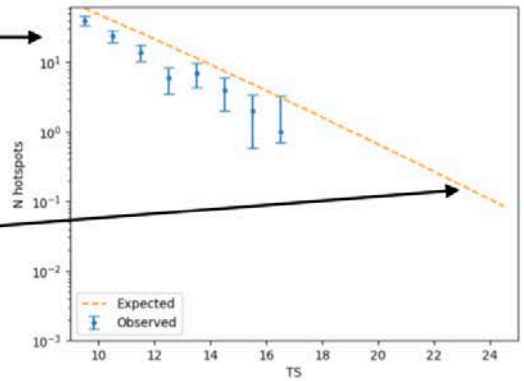
confirmed or retracted → This event has been confirmed.



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



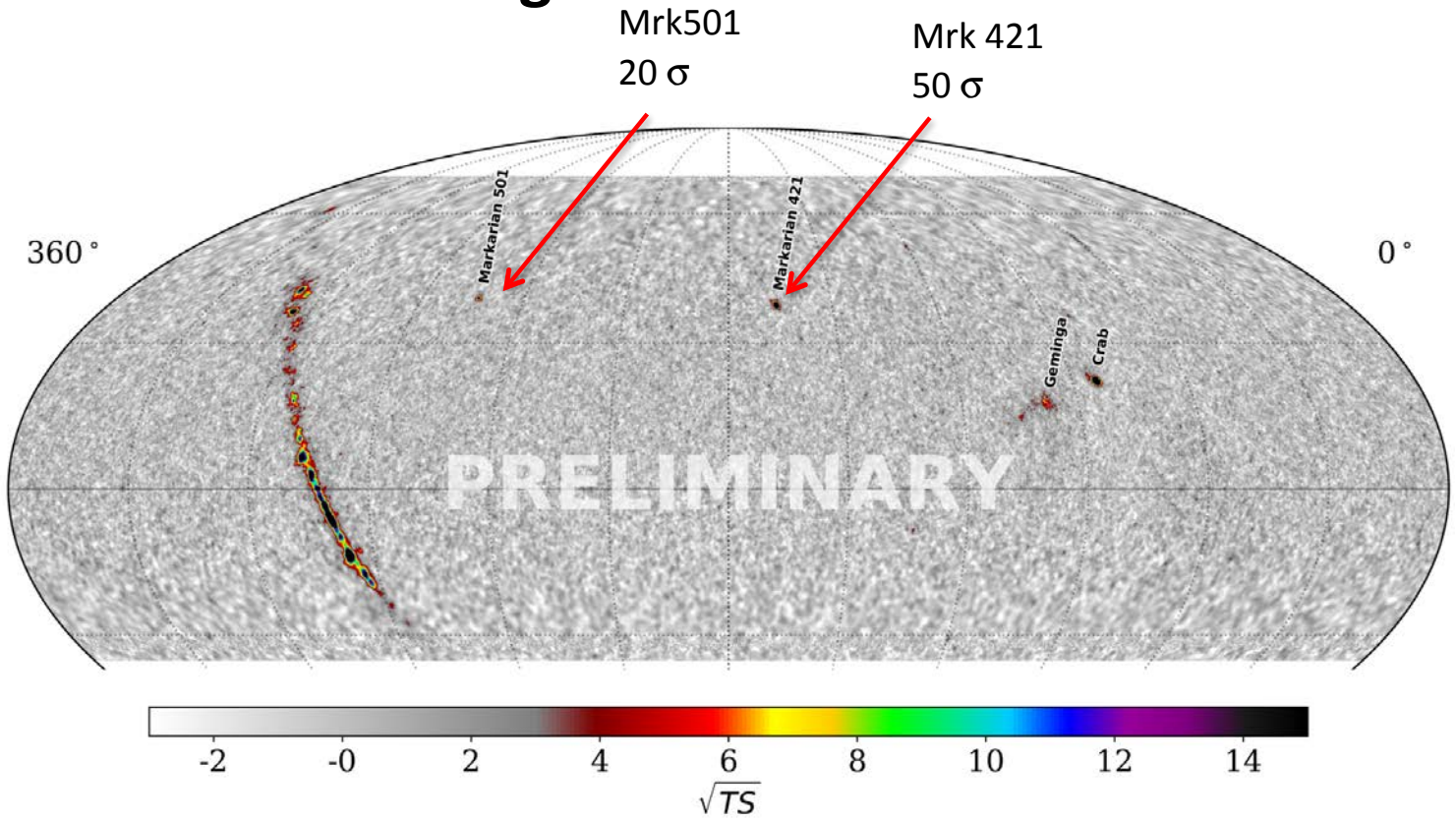
The expected number of hotspots is estimated at zenith, where we have better angular resolution, so it might be off by a factor of ~2

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

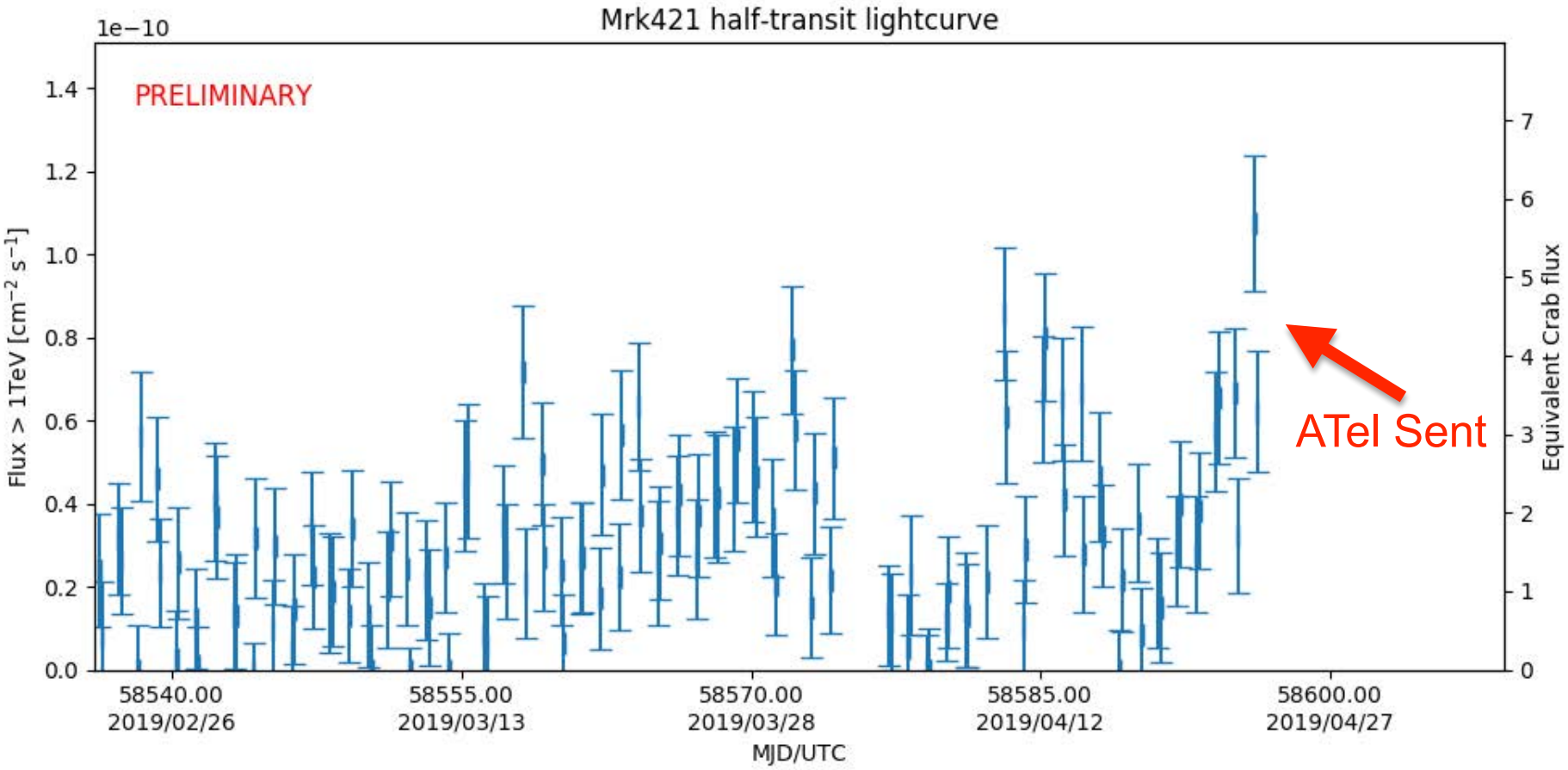
#RA[deg]	DEC[deg]	POS_ERR[deg]	TS	SIGNIFICANCE	START_TIME[gps]	STOP_TIME[GPS]
196.00	38.59	0.77	9.59	<3.00	1240215505.12	1240215505.42
196.52	34.32	0.84	9.08	<3.00	1240215501.82	1240215502.12
199.16	30.60	0.38	14.13	<3.00	1240215502.72	1240215503.02
204.70	0.90	0.65	9.11	<3.00	1240215503.02	1240215503.32
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.

HAWC's 3.5 year Sky Map has 2 Extragalactic Sources



Mrk421 April 2019



HAWC Searches for Sources

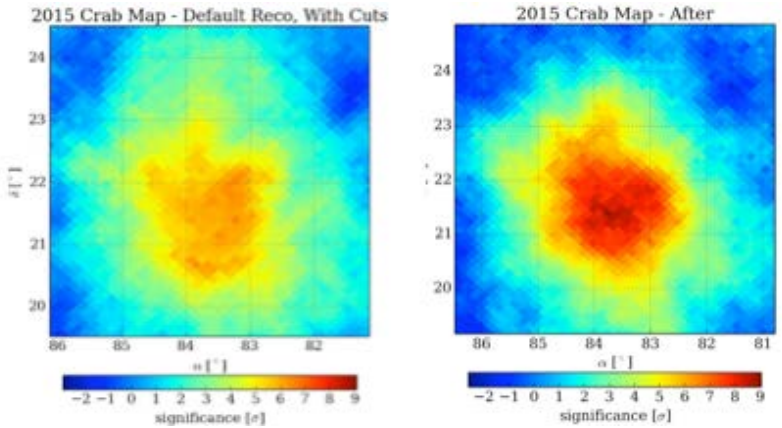
HAWC searches of 2 sr instantaneous field of view with 8 sr observed daily

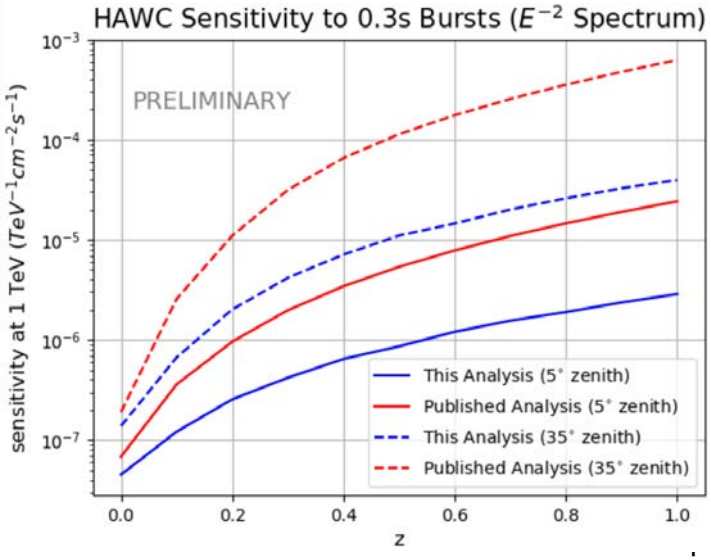
- VHE γ-rays from Dark Matter Annihilation or Decay
- VHE γ-rays from the northern Fermi Bubble
- VHE γ-rays from same direction as IceCube PeV ν
- VHE γ-rays from gravitational wave sources
- VHE γ-rays from satellite-detected GRBs
- VHE γ-ray transients self-triggered by HAWC with time scales of < 1 sec to 1 day

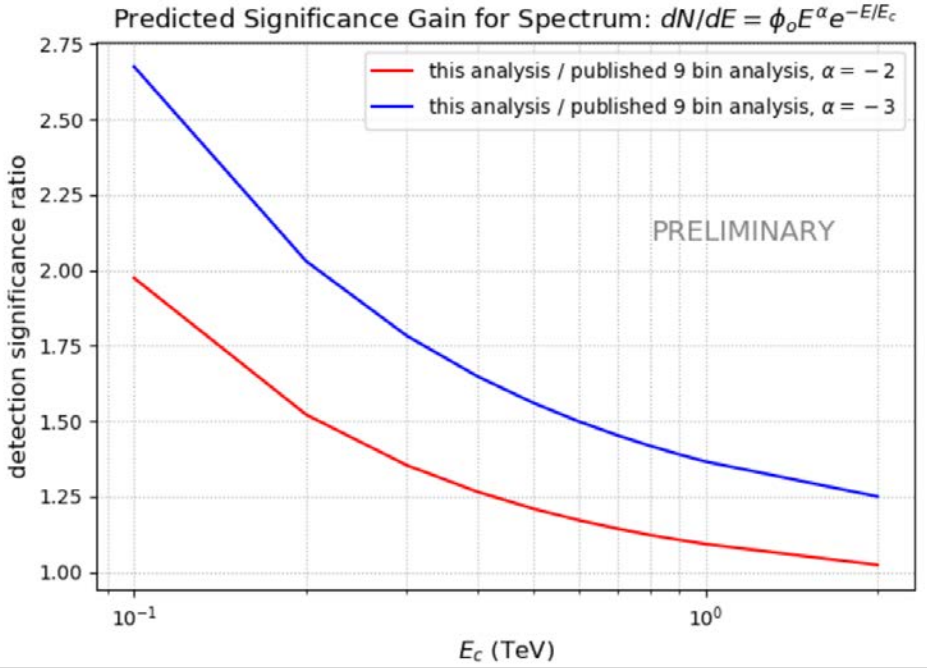
Correlated Background

- Smaller showers overlap in time.
- New multiplane angle fitter improves HAWC sensitivity at lowest energies.
- Tests on Crab confirm.
- Pass 5 reconstruction of past data will occur soon.

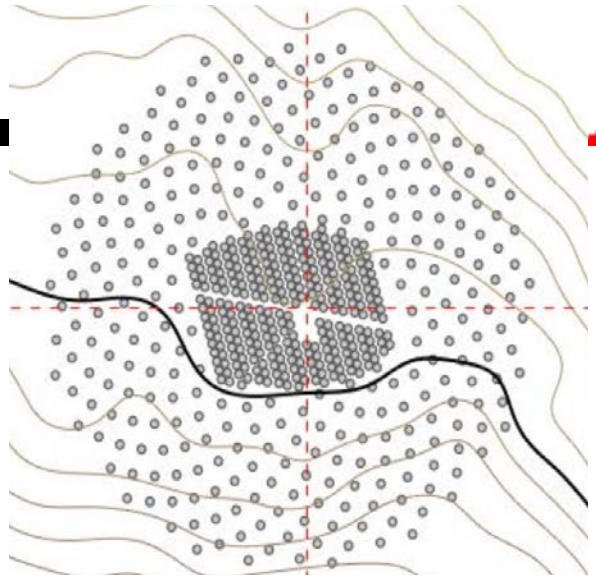
What's Next: Improving HAWC's low E



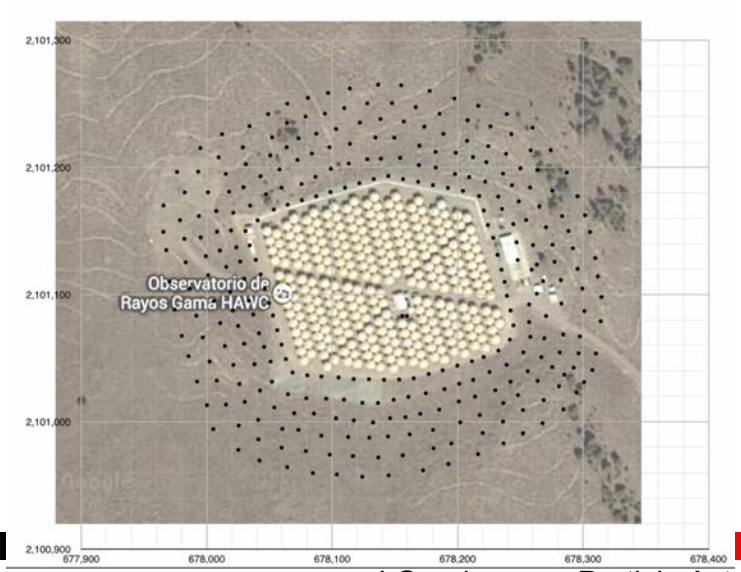




Outriggers

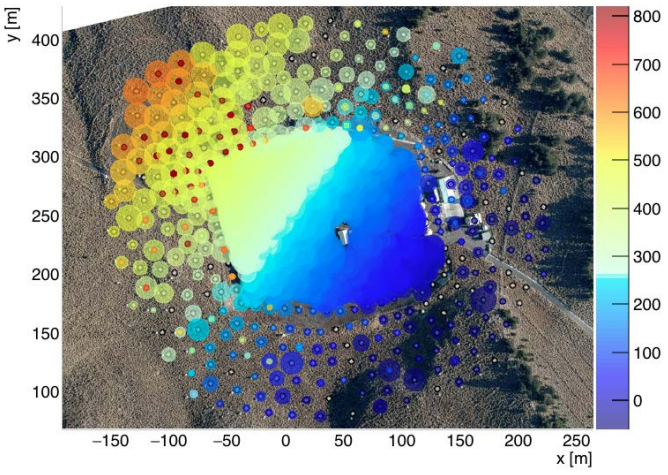


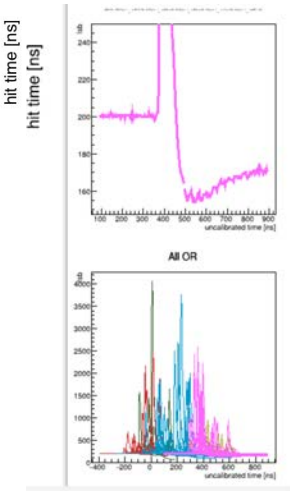
- HAWC Sparse Outrigger Array: Enhanced Sensitivity above 10 TeV
  - Accurately determine core position for showers off the main tank array.
- Increase effective area above 10 TeV by 3-4x
- Funded by LANL/Mexico.
- 2500 liter tanks: 1/80th size of HAWC tanks.



High Energy Upgrade: Outrigger Array begins Operation

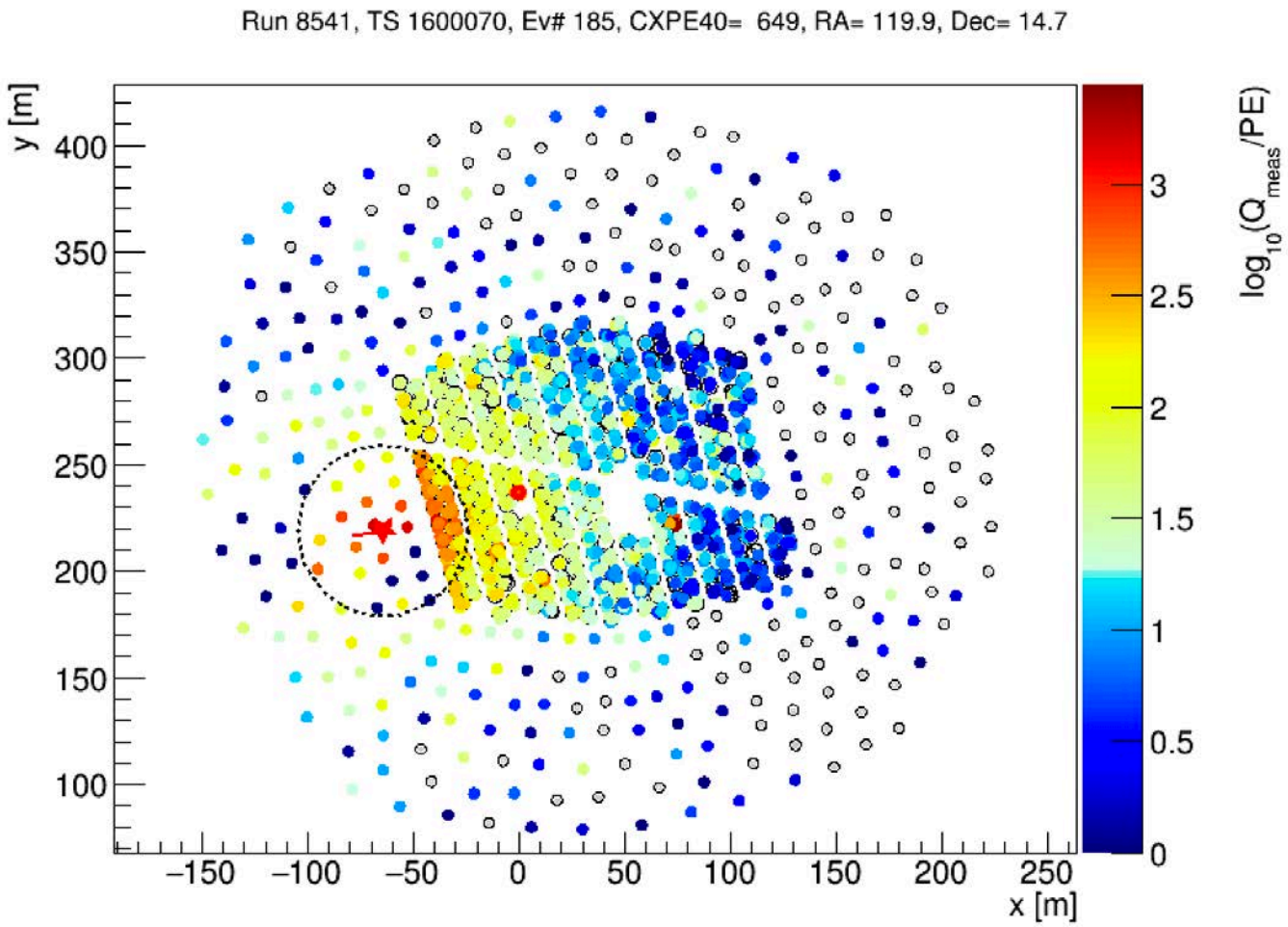
- Funded by LANL LDRD, Max Planck Institute in Heidelberg, and CONACyT in Mexico
- Gives angle and energy reconstruction for showers that trigger HAWC but have the core outside the HAWC array
- Expands total effective area by a factor of ~4 above ~10TeV with the addition of 350 outrigger tanks
- 100% 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.



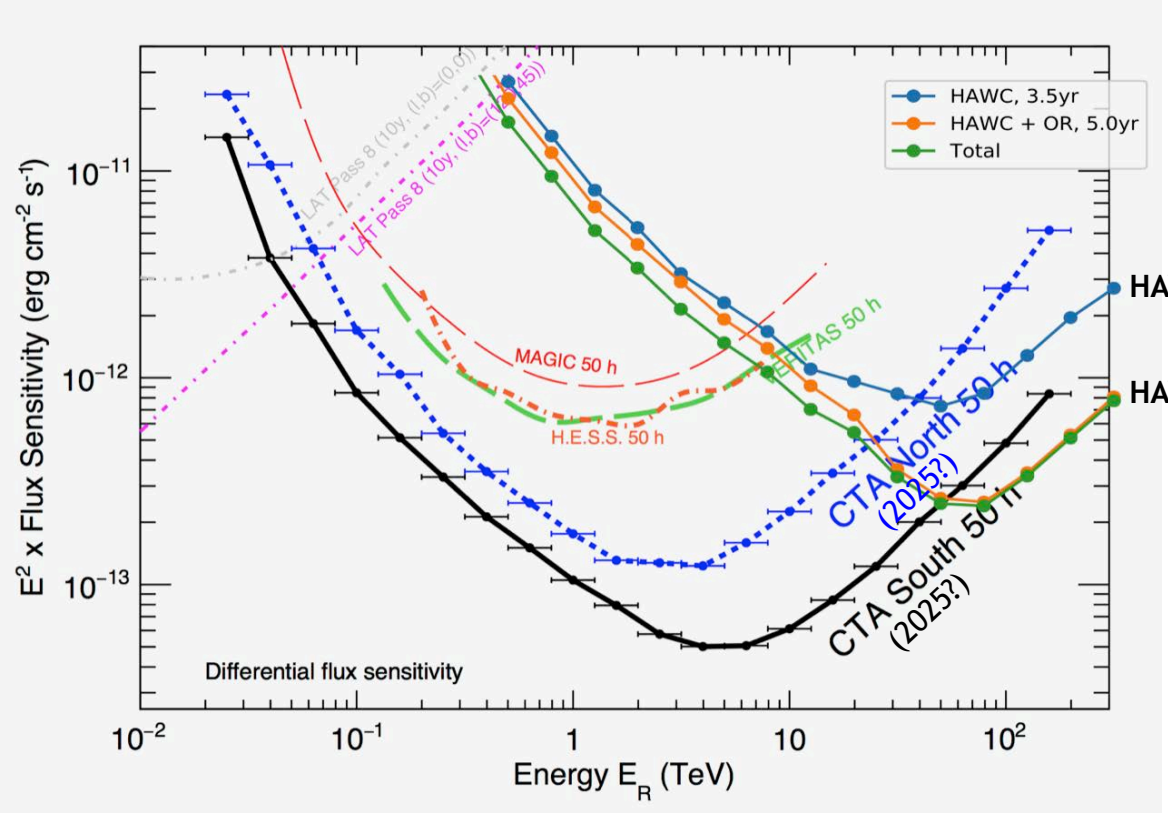


MPI provided FADC electronics that were developed for CTA

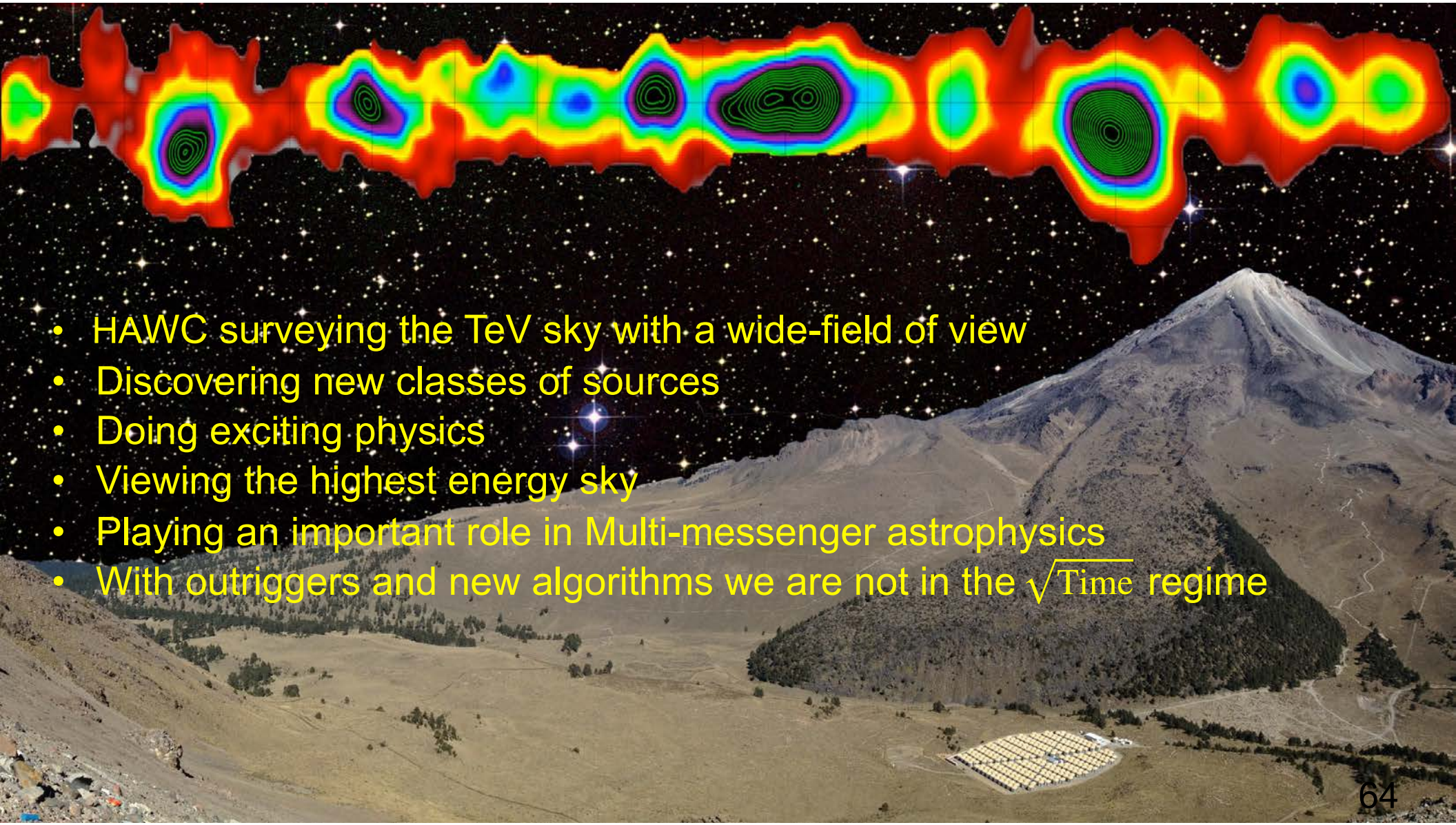
Outrigger Data



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

Stuff Not Covered in Grad School

MENU nature International journal of science
Subscribe Search Login

NEWS · 12 FEBRUARY 2019

Violent drug cartels stifle Mexican science

Abandoned projects and delayed research have become common problems as security issues crop up across the country.

Emiliano Rodríguez Mega

Astronomical research is put on pause at the Large Millimeter Telescope in Mexico due to gang violence. Credit: Meridith Kohut/NYT/Redux/eyevine

PDF version

RELATED ARTICLES

Colombia: after the violence

Political upheaval in Nicaragua leaves scientists under siege

War zone complicates roll-out of Ebola vaccine in latest outbreak

SUBJECTS

Developing world Politics Society