High Altitude Water Cherenkov
Gamma-Ray Observatory

HAWC Science

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Los Alamos NATIONAL LABORATORY EST. 1943

NNSA National Nuclear Security Administration

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The High Altitude Water Cherenkov Collaboration

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Los Alamos National Laboratory
University of Wisconsin
University of Utah
Univ. of California, Irvine
University of New Hampshire
Pennsylvania State University
University of New Mexico
Michigan Technological University
NASA/Goddard Space Flight Center
Georgia Institute of Technology
Colorado State University
Michigan State University
University of Rochester
University of California Santa Cruz

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

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Universidad Autónoma del Estado de Hidalgo
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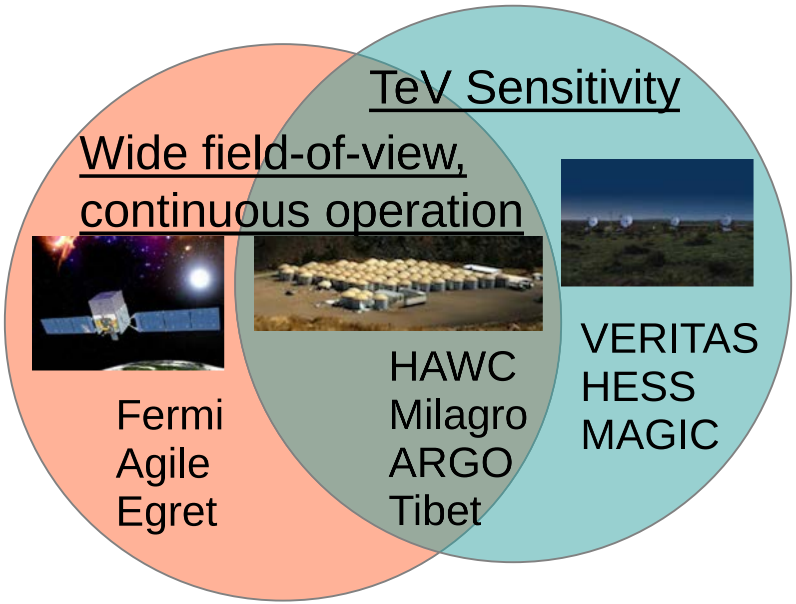
Centro de Investigación y de Estudios Avanzados
Instituto Politécnico Nacional
Centro de Investigación en Computación - IPN

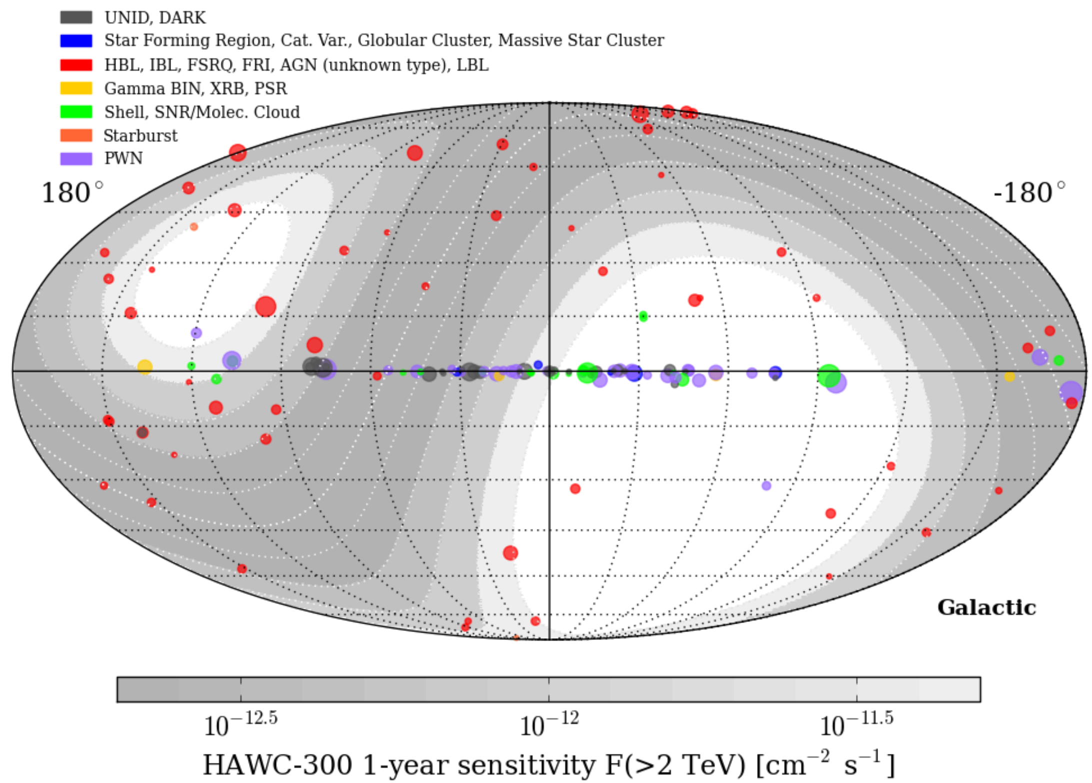
Europe
Max-Planck Institute for Nuclear Physics
IFJ-PAN, Krakow, Poland

Complementarity of Gamma-Ray Detectors

- Space-based detectors - continuous full-sky coverage in GeV
- Ground-based detectors have TeV sensitivity
- IACTs (pointed) excellent energy and angle resolution
- HAWC has 24-hour >1/2 sky coverage



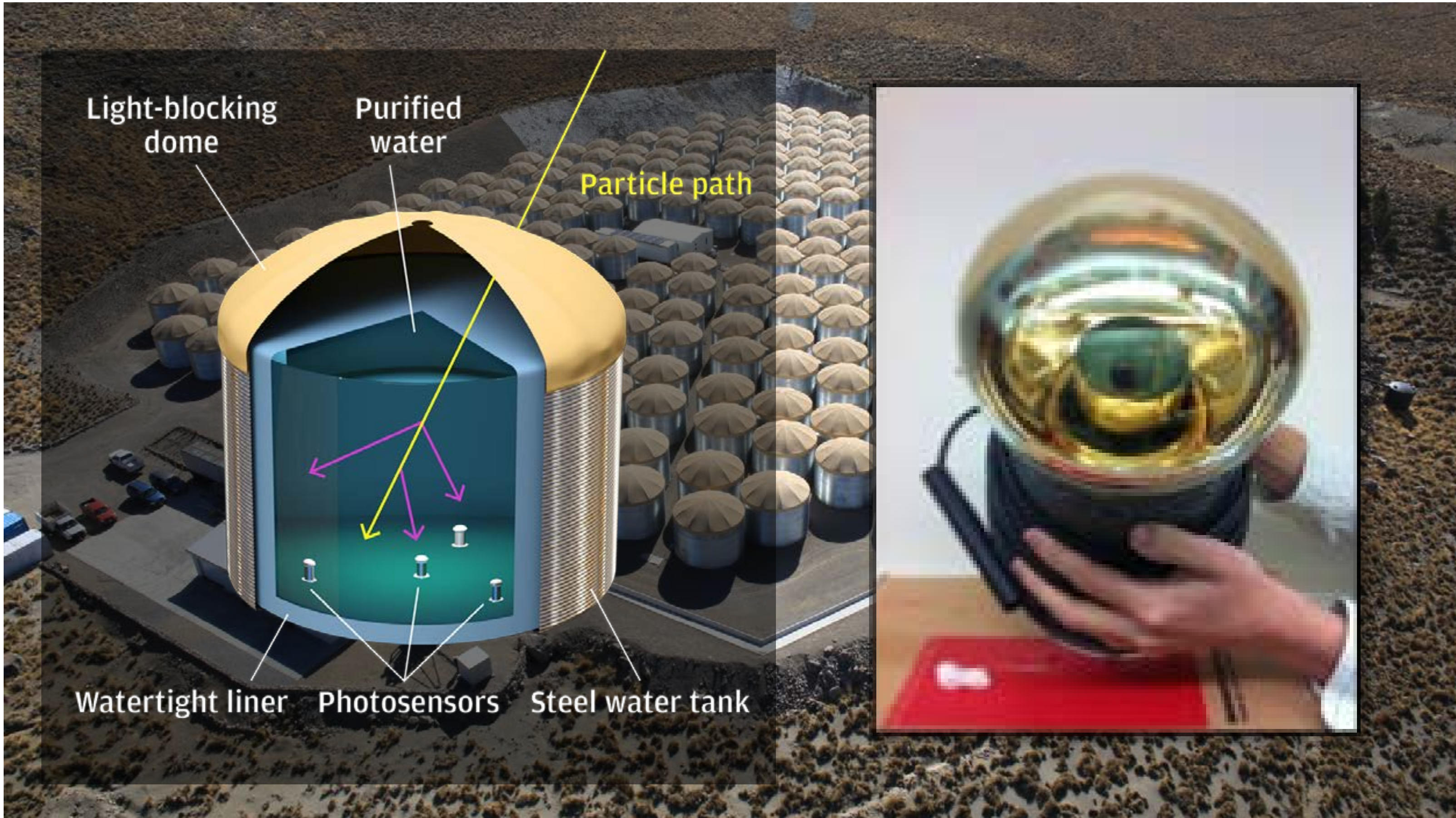
TeV Sky Observable By HAWC



An Array of Water Cherenkov Detectors

- 300 close-packed optically isolated water Cherenkov detectors
- Construction began early 2012
- Full detector inaugurated March 2015
- Funding from a combination of US and Mexican agencies
- High energy extension: Outrigger array, coming summer 2018

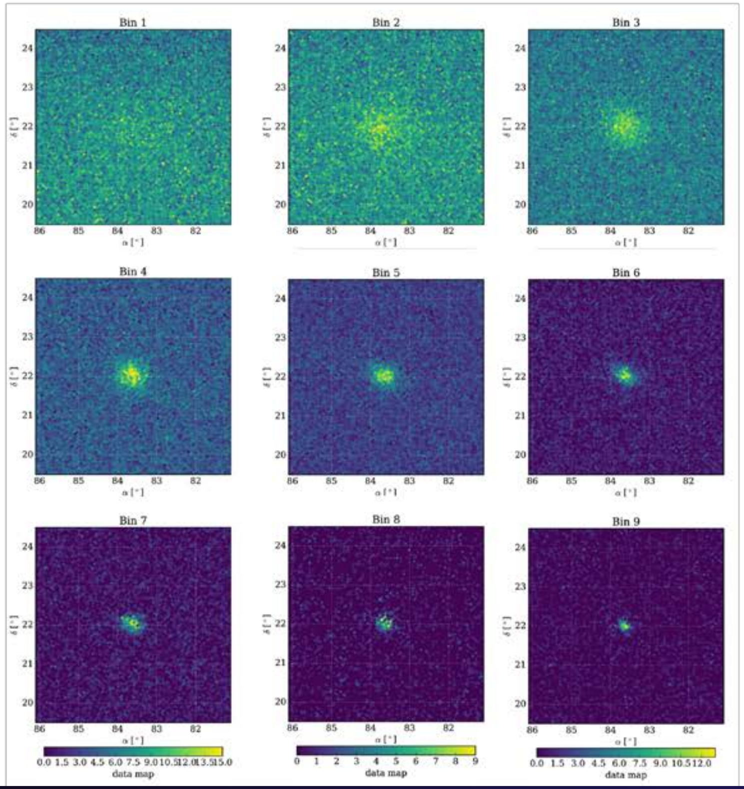
An Array of Water Cherenkov Detectors

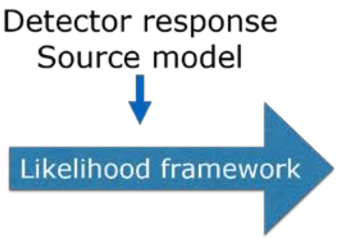


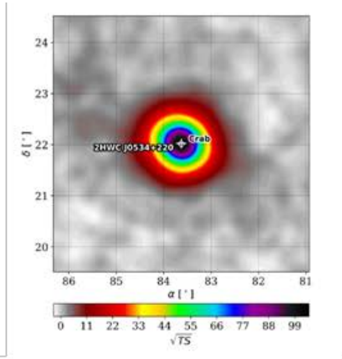
Source Characterization

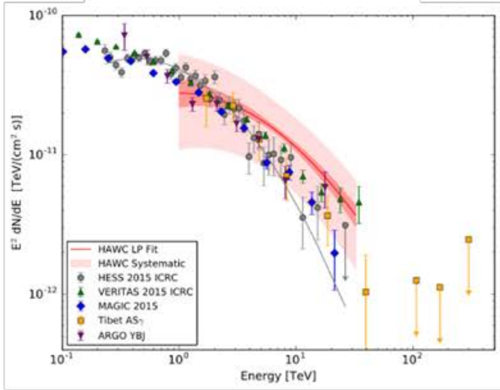
- Events sorted by “size” in n bins (with characteristic Point Spread Function, S/N ratio, energy), make n maps
- Likelihood framework uses n maps to test the presence of sources and characterize them
- Reference: Crab paper, ApJ 843 (2017), 39 (here: 507 days of data)

Crab Nebula

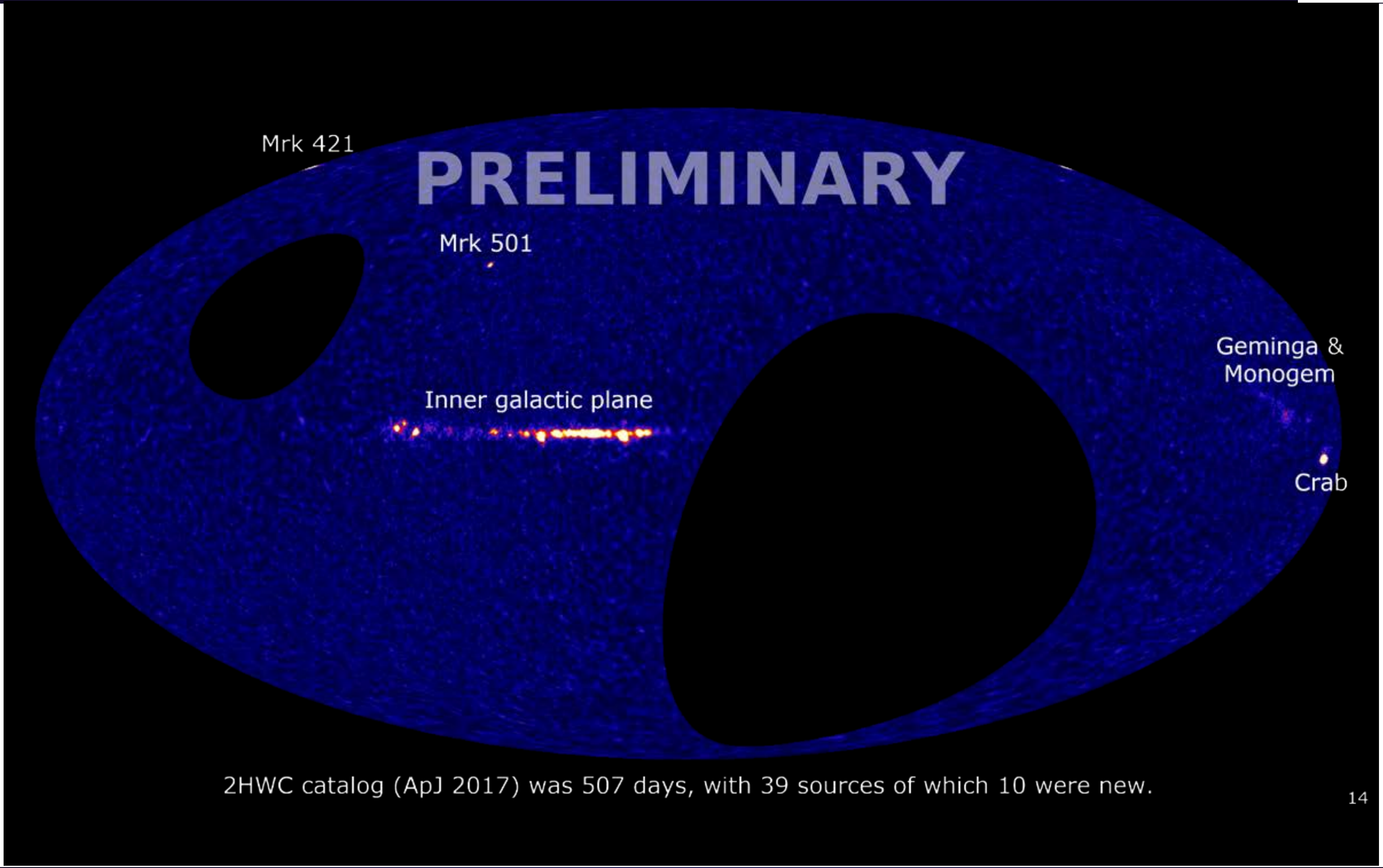




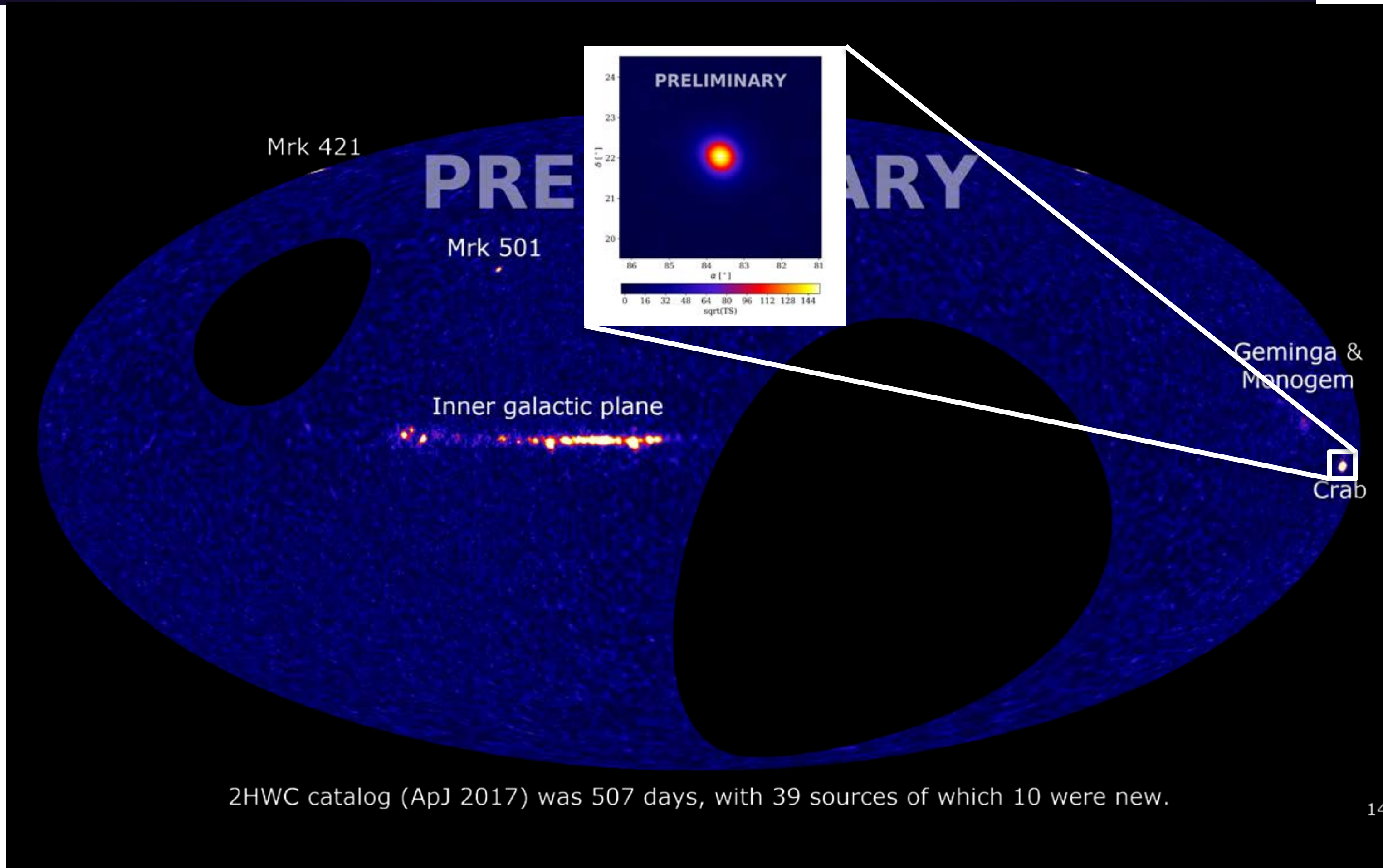




HAWC 3-year Skymap – 1017 days from 11/14 – 12/17



HAWC 3-year Skymap – 1017 days from 11/14 – 12/17



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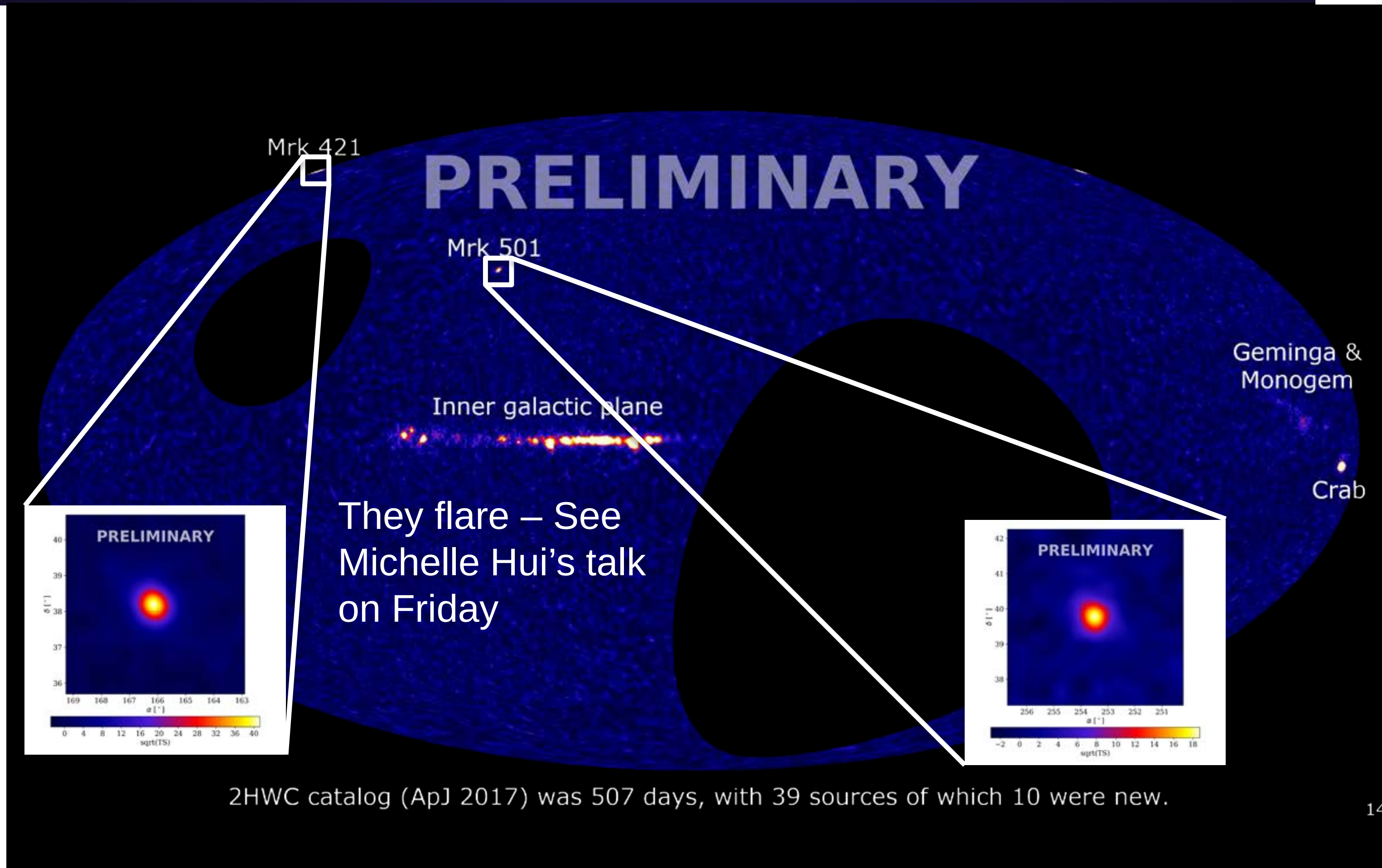
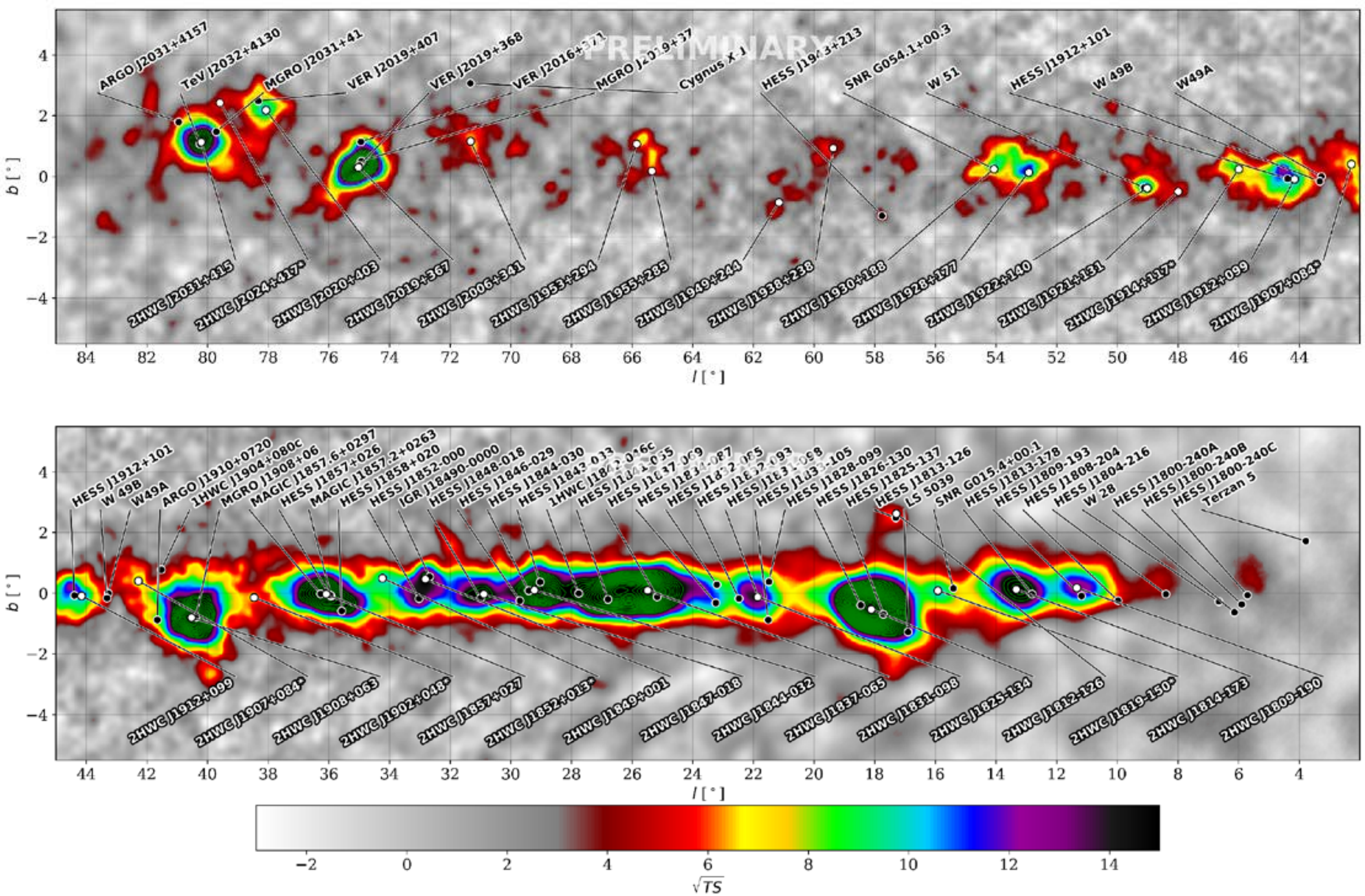
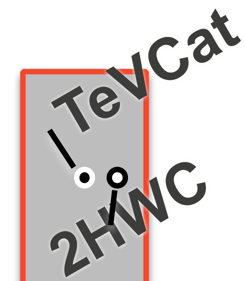


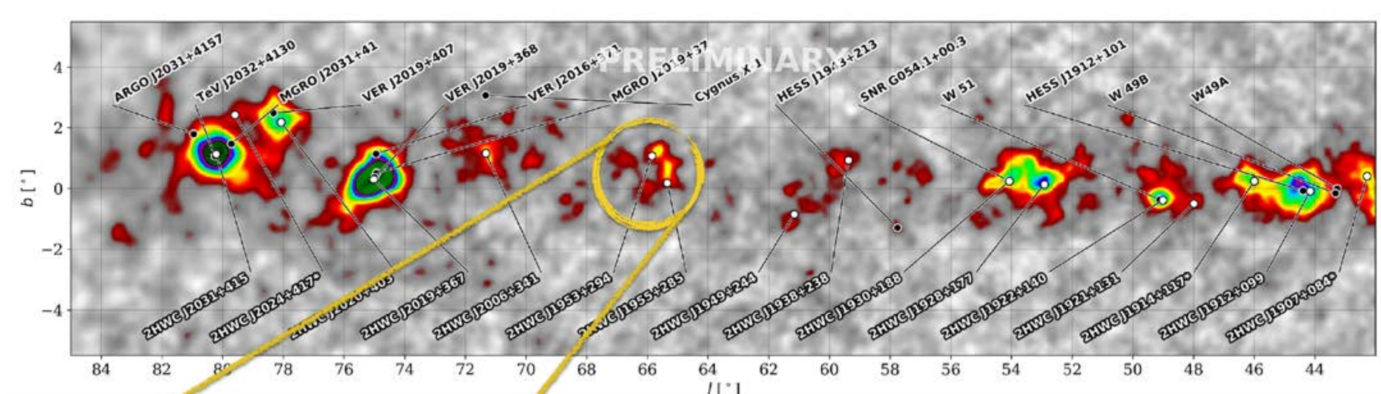
They flare – See Michelle Hui's talk on Friday

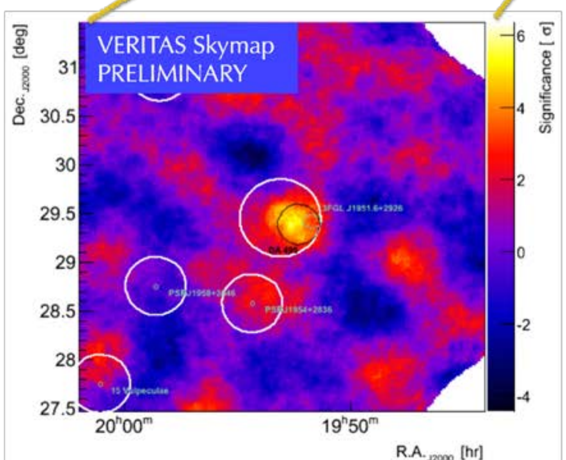
Inner Northern Galactic Plane





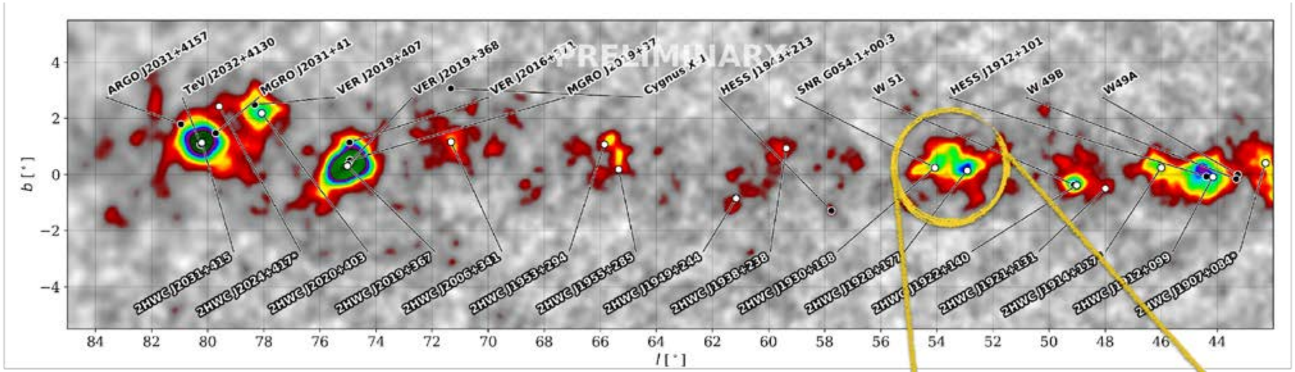
New Sources: 2HWC J1953+294



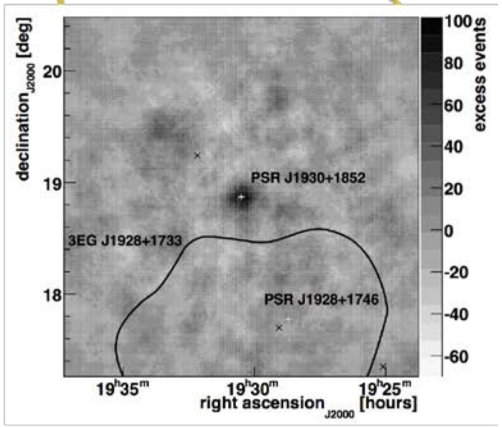


- 2HWC J1953+294: No previously known TeV sources.
- New analysis by VERITAS, archival plus new data, source confirmed.
- Tentative association 3FGL J1951.6+2926 / PWN DA 495
- *Joint paper in progress.*

New Sources: 2HWC J1928+177

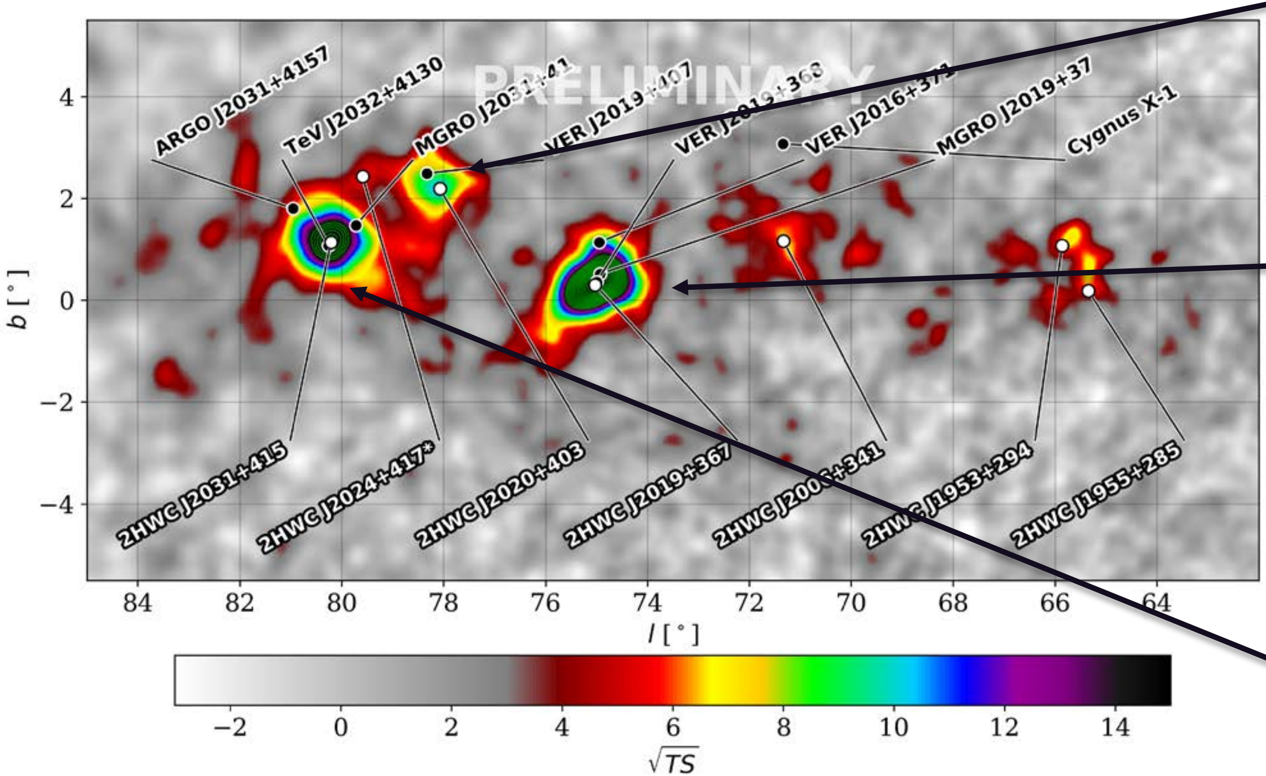


- 2HWC J1930+188 corresponds to SNR G054.1+00.3, discovered by VERITAS source.
- New source 2HWC J1928+177, likely associated with energetic PSR J1928+1746. Not seen by VERITAS, set a flux limit.
- Possibly hard spectrum or extended source.
- *Joint paper in progress.*



VERITAS, Acciari, et al. 2010

Complex Cygnus Region



G78.2+2.1 (γ Cygni SNR)

Middle aged: ~6000 yr

J2021+3651:

young pulsar: 17.2 kyr

Ė = 3.6x1036 erg/s

d = 1.8 kpc

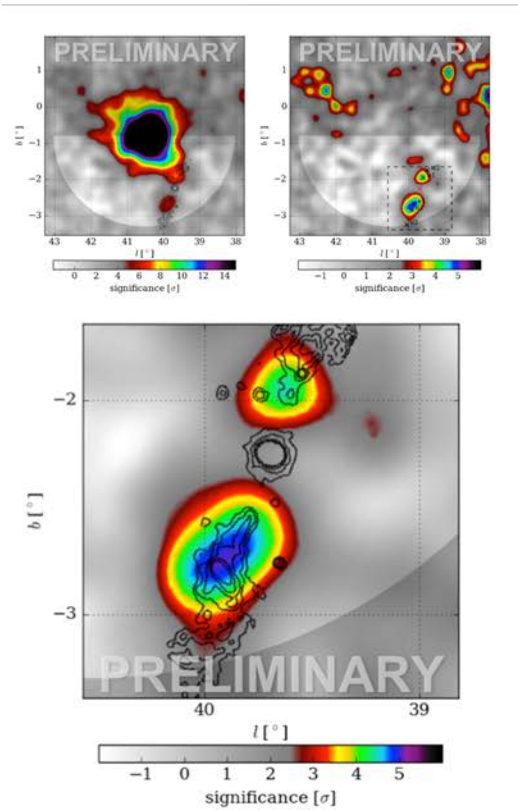
Multiple VERITAS sources.

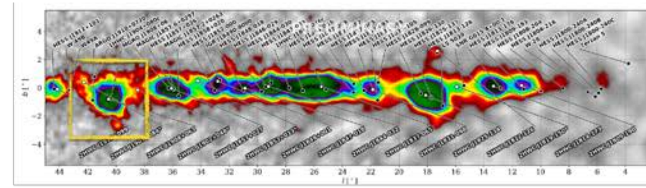
Softening above 30 TeV?

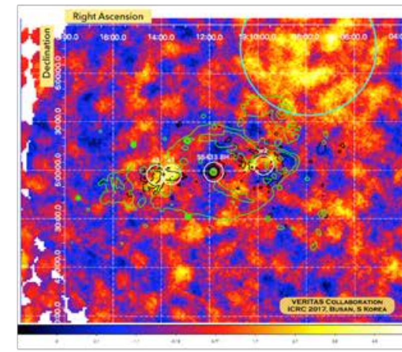
Fermi's Cygnus Cocoon: Active star formation region with freshly accelerated CR.

Hints of spectrum softening?

Microquasar SS 433: lobes detection

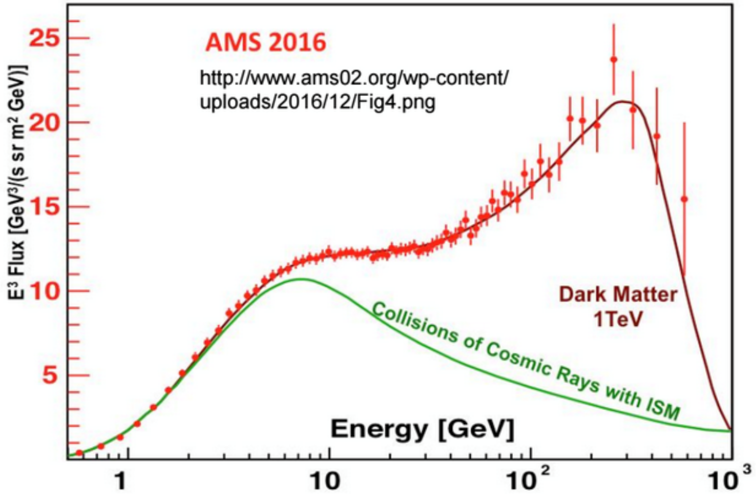


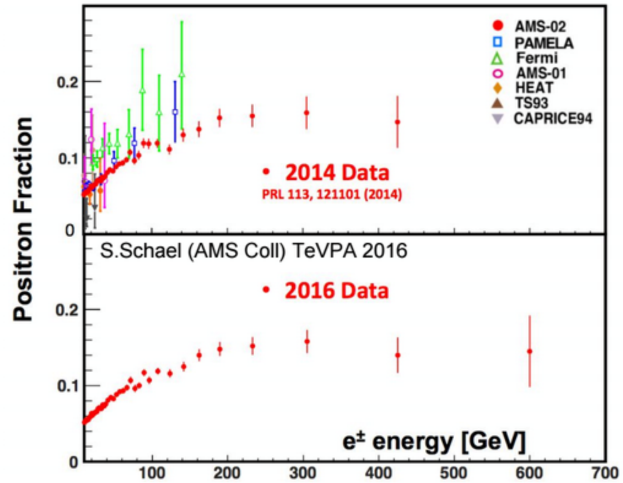




- Non detection by MAGIC & H.E.S.S. (A&A 2018)
- Some sub-threshold excess in VERITAS, ICRC2017
- **First detection of lobes in TeV**, 6σ after subtracting J1908+06
- SS 433:
  - Binary system: supermassive star (~30 $M_\odot$), compact object (~10 $M_\odot$)
  - Powerful jets: ~10^{39} erg s^{-1}, speed ~c/4
  - Termination shocks in W50 nebula
- **HAWC data favors leptonic models over hadronic:**
  - Energetics
  - Emission localization

Galactic Positron Excess

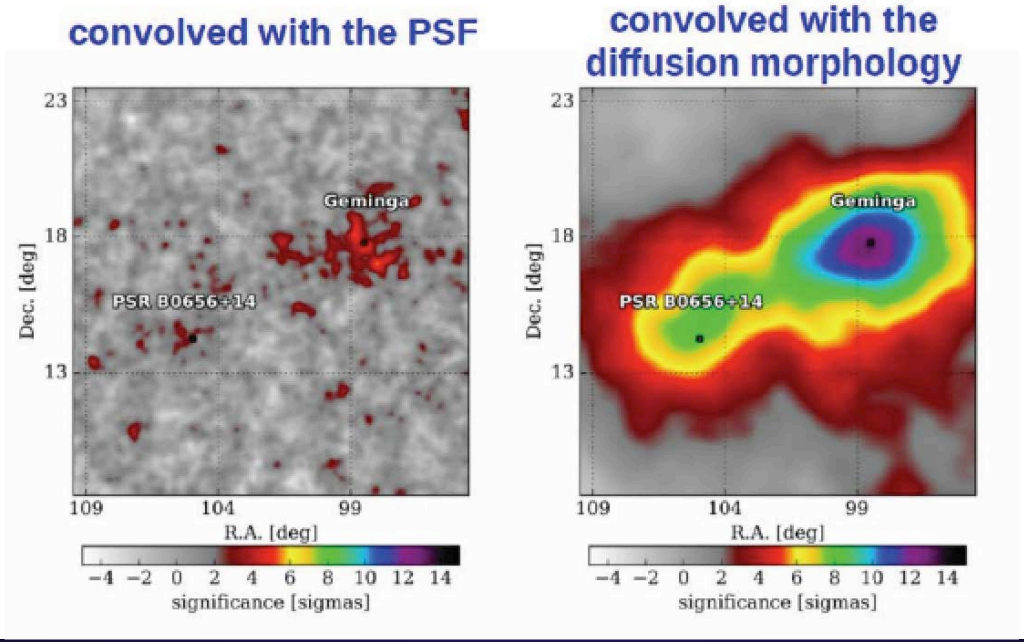




- AMS-02 on board the International Space Station observes local cosmic rays since 2011
  - excellent charge resolution and particle species discrimination
- TeV e^-e^+ lose energy quickly and therefore must be produced locally (d < ~100 pc)
  - *secondaries* produced by cosmic ray interactions with ISM (spallation)
  - *primaries* produced by local source
    - local cosmic accelerator (e.g. Geminga)? local dark matter interactions?
- Larger positron flux observed above ~10 GeV than expected from secondaries
  - First observed by Pamela in 2009, since confirmed by Fermi LAT and AMS-02
  - Are they from a local cosmic accelerator or dark matter?
    - If they are from dark matter, other annihilation products should be produced

AMS Positrons from Pulsars?

- Postulated sources of AMS positron excess are nearby, old pulsars
- Geminga and Monogem are the best candidates
- HAWC detect both as very extended TeV gamma-ray sources



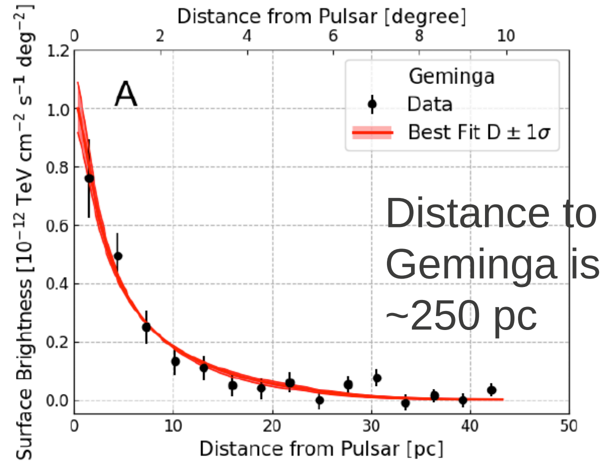
Science

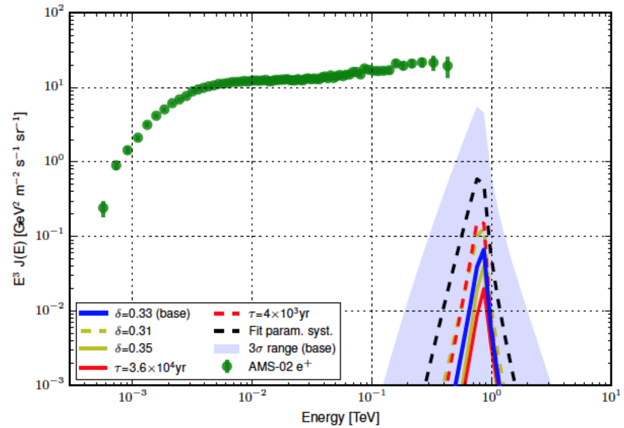
17 November 2017

Extended gamma-ray sources around pulsars constrain the origin of the positron flux at Earth

by the HAWC collaboration and LANL theorists

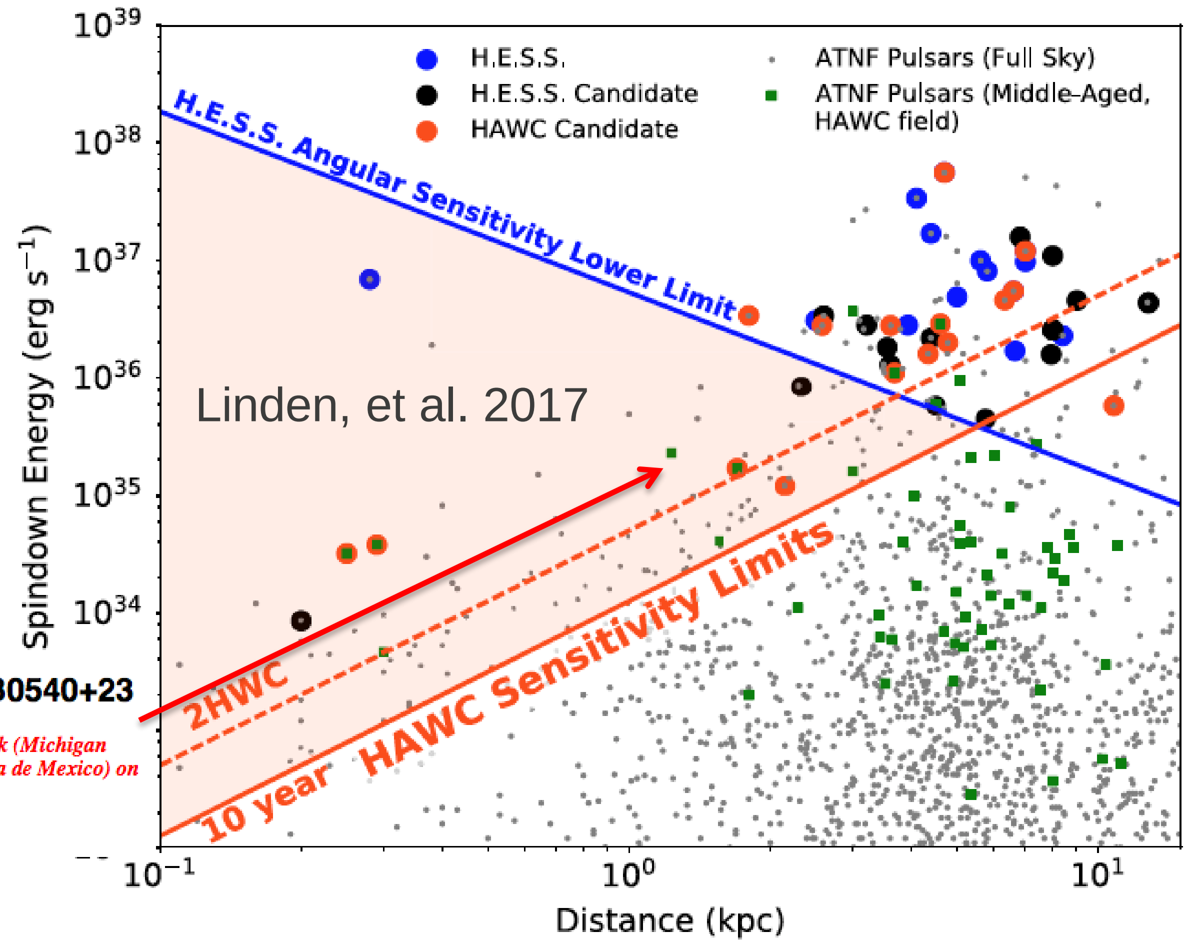
- **HAWC observations prove that these sources are accelerating electrons and positrons to multi-TeV energies.**
- **HAWC observations measure the total energy released in electrons and positrons which is high.**
- **HAWC observations of the angular extent of these TeV nebula measures the diffusion coefficient of their propagation in the interstellar medium.**
- **HAWC observations show that Geminga and Monogem either:**
  - Influence their environments out to 10-100x further than previously known
  - Do NOT contribute significantly to the AMS measured positron excess





More PWN to be seen by HAWC

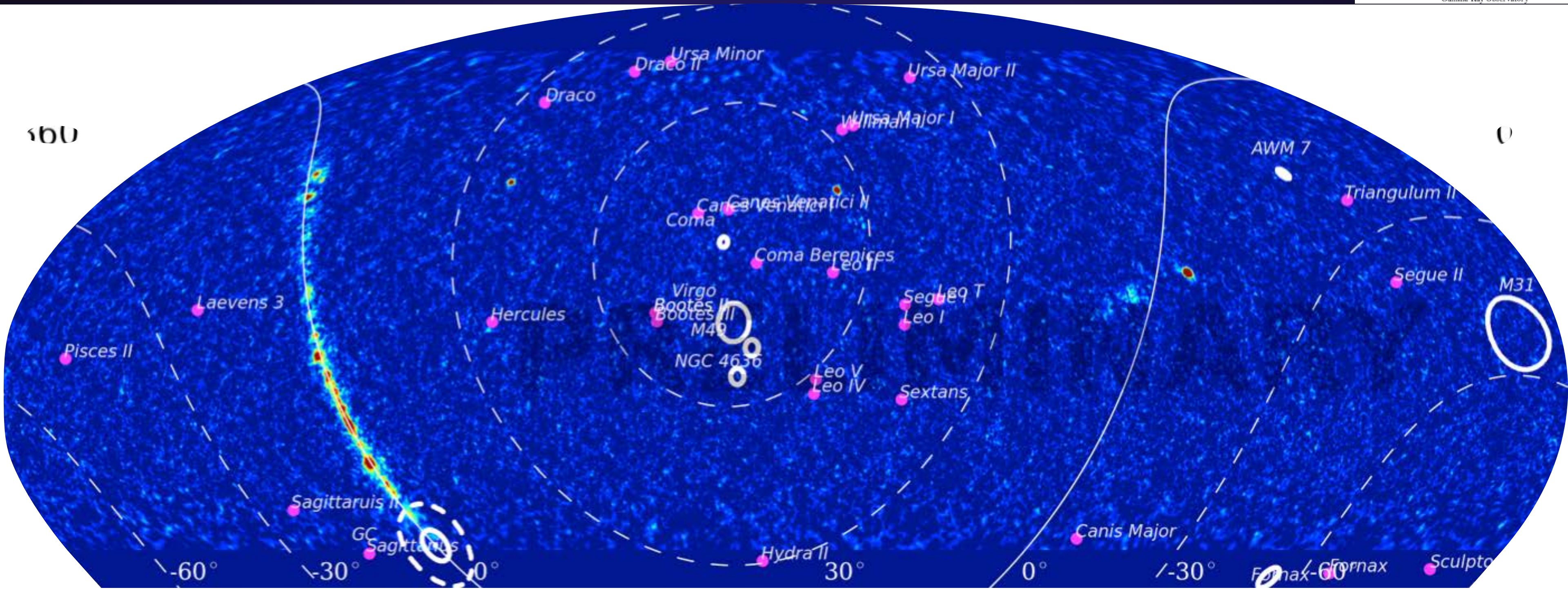
- **More observations of this population can constrain the interpretations**
- **Should be many more observable with HAWC large field-of-view**



HAWC detection of TeV emission near PSR B0540+23

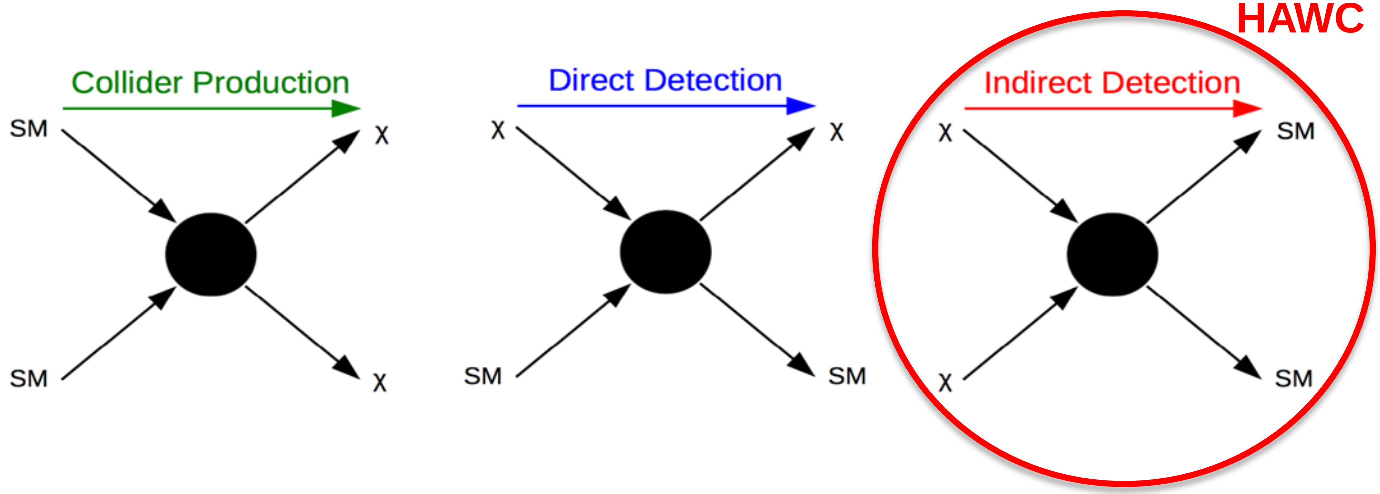
ATel #10941; *Colas Riviere (University of Maryland), Henrike Fleischhack (Michigan Technological University), Andres Sandoval (Universidad Nacional Autonoma de Mexico) on behalf of the HAWC collaboration*
on 9 Nov 2017; 23:11 UT
Credential Certification: Colas Riviere (riviere@umd.edu)

Dark Matter with HAWC

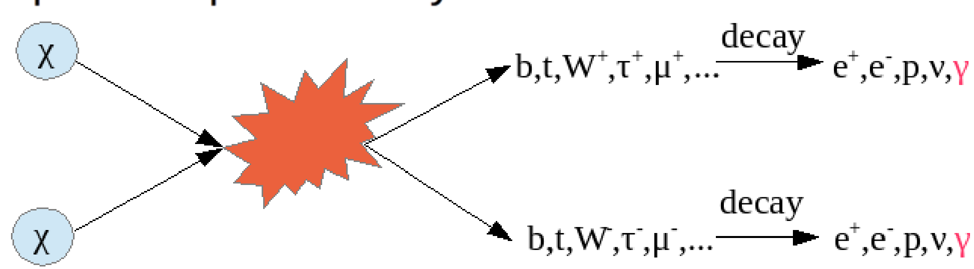


- **Lots of source classes to look at**
  - Milky Way Galactic Center, dwarf galaxies, galaxy clusters, M31 (Andromeda) galaxy
  - Large statistical sample

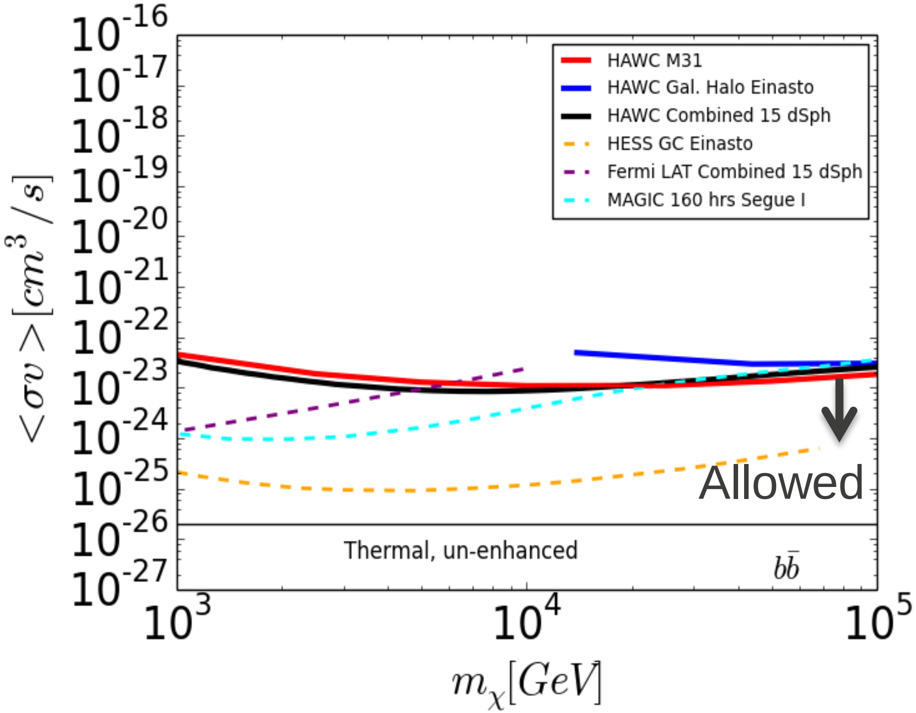
Indirect Detection of WIMP Dark Matter

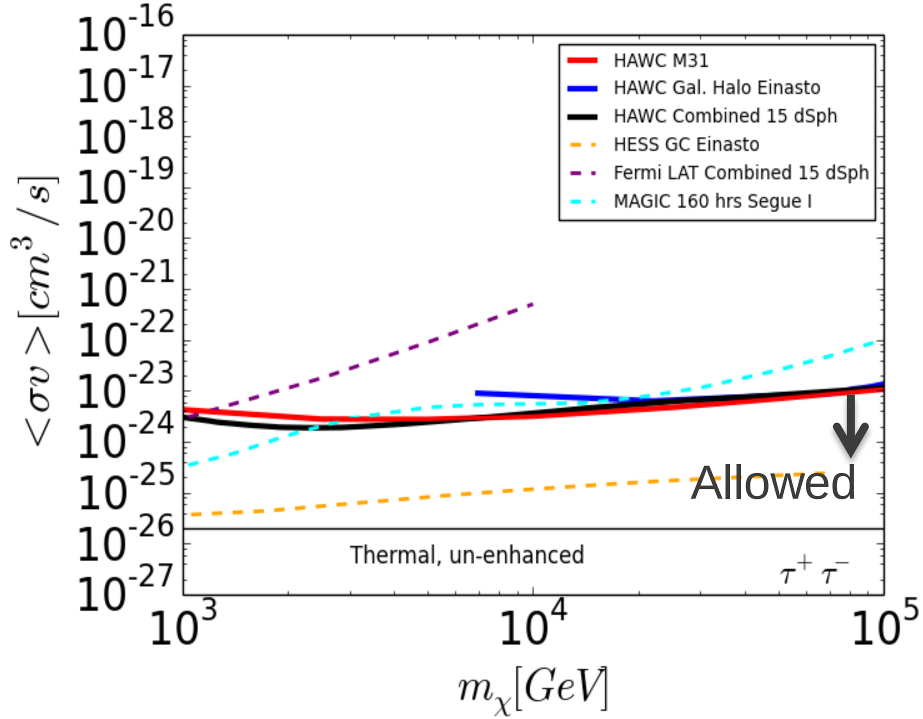


- Colliders: Produce WIMPs by colliding SM particles
- Direct Detection: Observe WIMP interaction with SM particles
- Indirect Detection: Observe SM particles produced by WIMP annihilation and decay



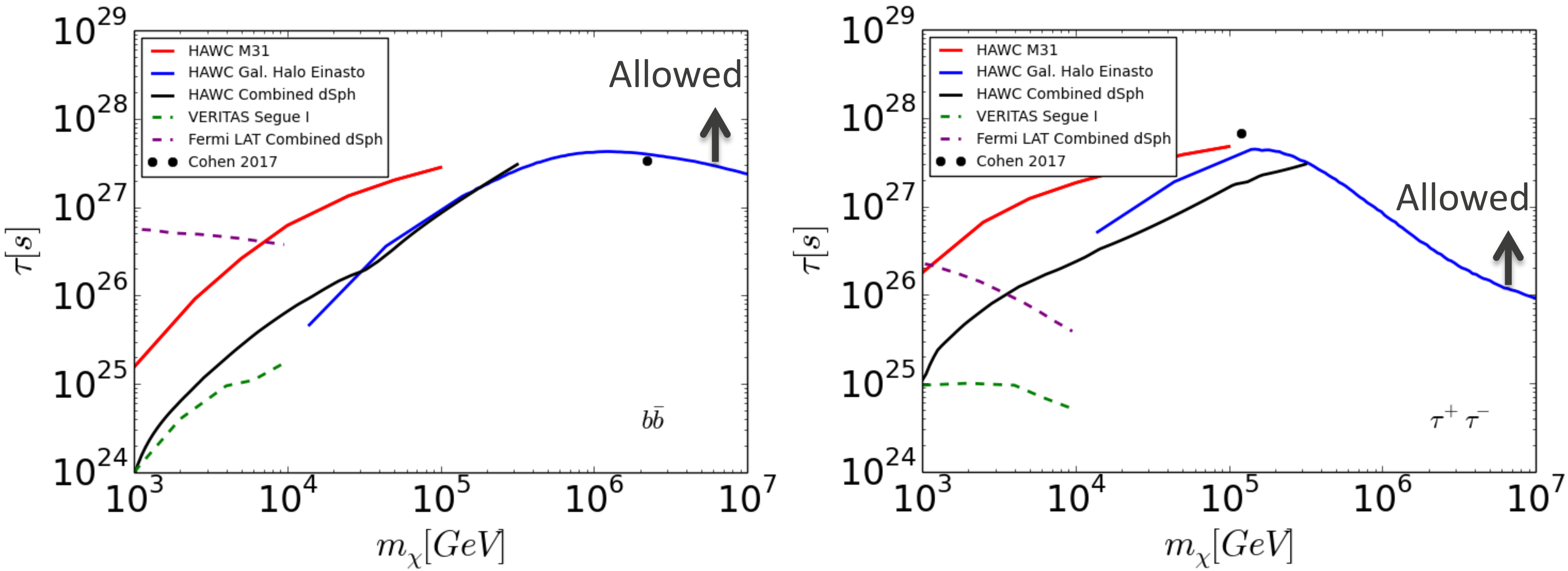
Dark Matter Annihilation Limits with HAWC





- **Multiple sources make HAWC limits robust**
  – Detection requires observations in multiple targets

Dark Matter Decay Limits with HAWC



- **DM decay signal is angularly extended so requires large field of view of HAWC**
- **DM decay is not as sensitive to DM distribution uncertainties as annihilation is**
- **HAWC can exclude IceCube DM interpretations (Cohen, 2017) for hadronic DM**

Lorentz Invariance Violation

- **HAWC can constrain violations of Lorentz invariance 2 ways:**

Observing high-energy, short-duration transients

(Nellen 2015)

$$E_\gamma^2 \approx p^2c^2\left[1+\xi_n\left(\frac{pc}{E_{scale}}\right)^n\right]$$

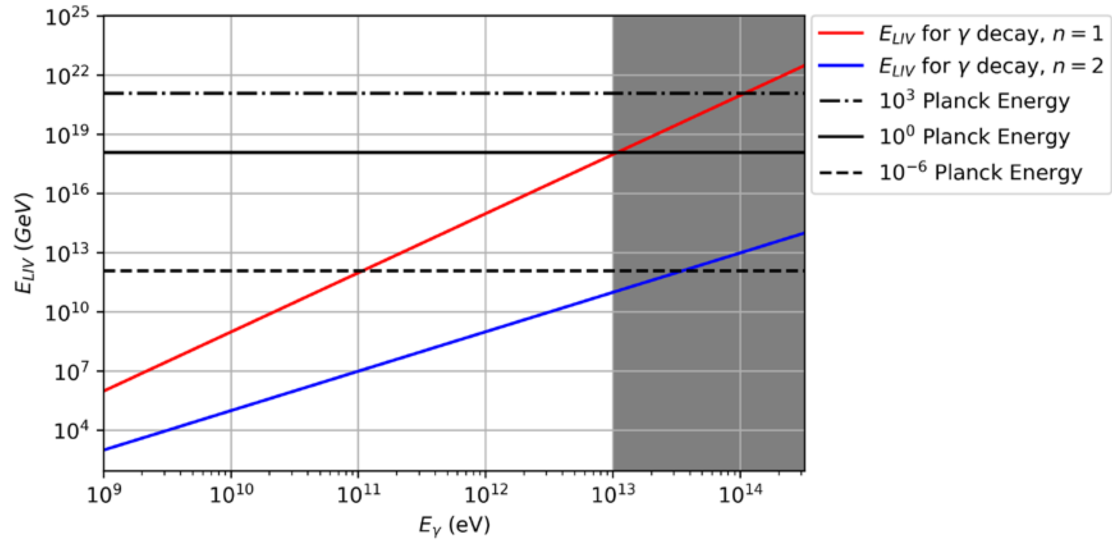
$$E_{LIV}^{(n)} > E_\gamma\left[\frac{E_\gamma^2-4m_e^2}{4m_e^2}\right]^{\frac{1}{n}}$$

$$\Delta t = \frac{n+1}{2H_0}\frac{\Delta E^n}{\left(E_{QG}^{(n)}\right)^n}\int_0^z \frac{(1+z')^n\,dz'}{\sqrt{\Omega_\Lambda+\Omega_m(1+z')^3}} = \frac{(n+1)\,d}{2c}\frac{\Delta E^n}{\left(E_{QG}^{(n)}\right)^n}$$

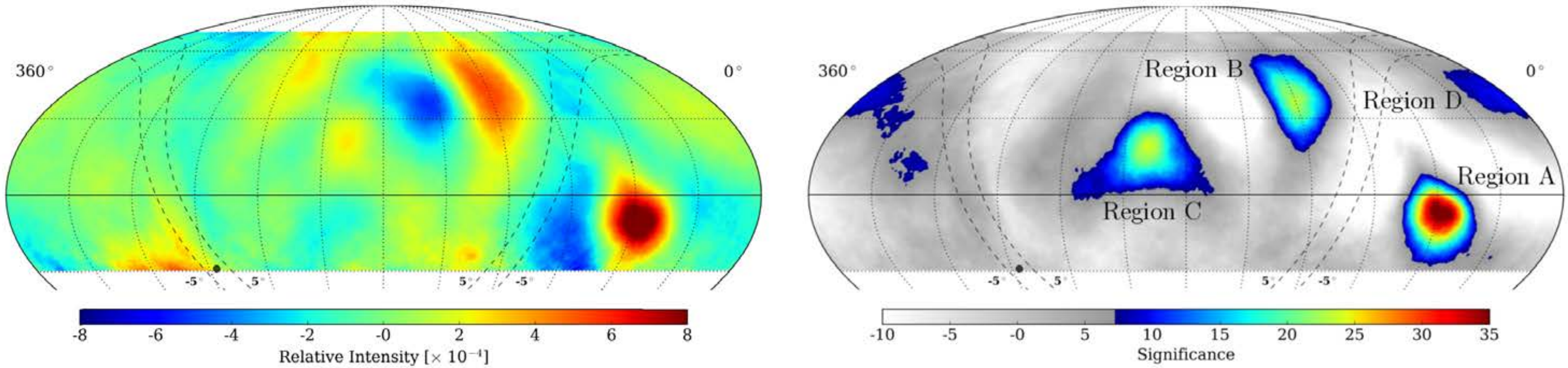
Source [Ref.]	Experiment	Limit on $E_{QG}^{(1)}$	$E_{QG}^{(2)}$
Crab [46, 47]	VERITAS	$1.7\cdot10^{17}$ GeV	$7\cdot10^{9}$ GeV
GRB090510A [51]	Fermi-LAT	$9.1\cdot10^{19}$ GeV	$1.3\cdot10^{11}$ GeV
PKS 2155-304 [48]	H.E.S.S.	$2.1\cdot10^{18}$ GeV	$6.4\cdot10^{10}$ GeV
PG 1553+113 [49]	H.E.S.S., Fermi-LAT	$4.3\cdot10^{17}$ GeV	$2.1\cdot10^{10}$ GeV

Observing extremely high-energy photons

(Martinez-Huerta & Perez-Lorenzana 2017)



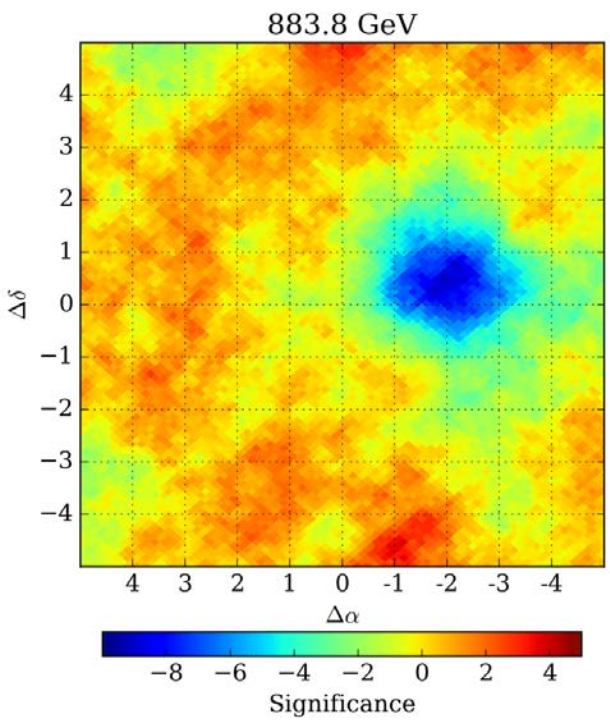
Cosmic Rays: Science in the backgrounds



- Cosmic-ray background has structure at similar level as our gamma-ray signals
- Four significant regions detected thus far
- Exact cause is still uncertain
- Working on joint analysis with IceCube to constrain across the full sky

Sun and Moon Cosmic-Ray Shadow

Moon

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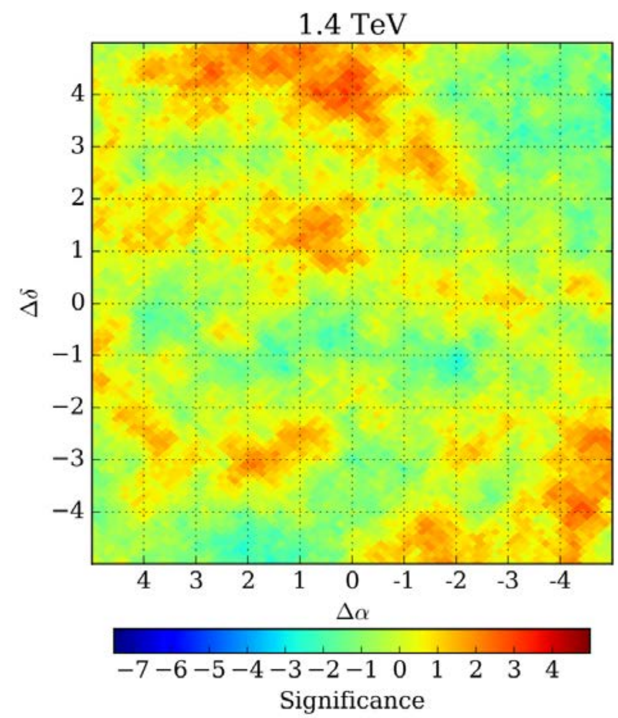
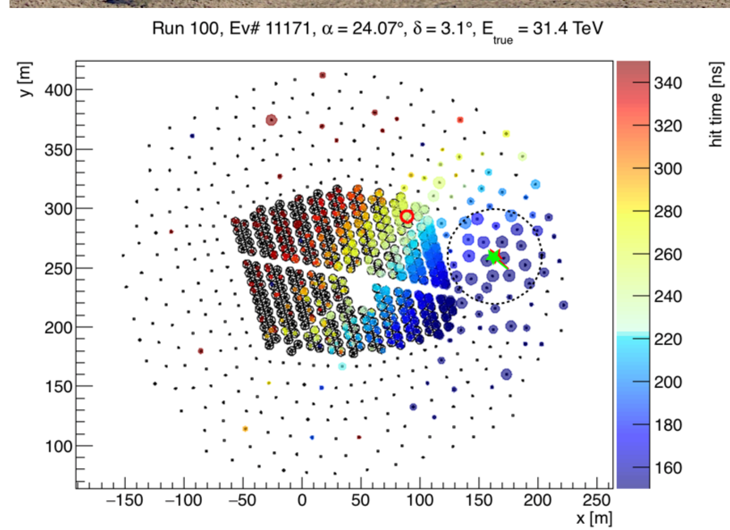
Hawc gamma-ray telescope captures its first image

Sun

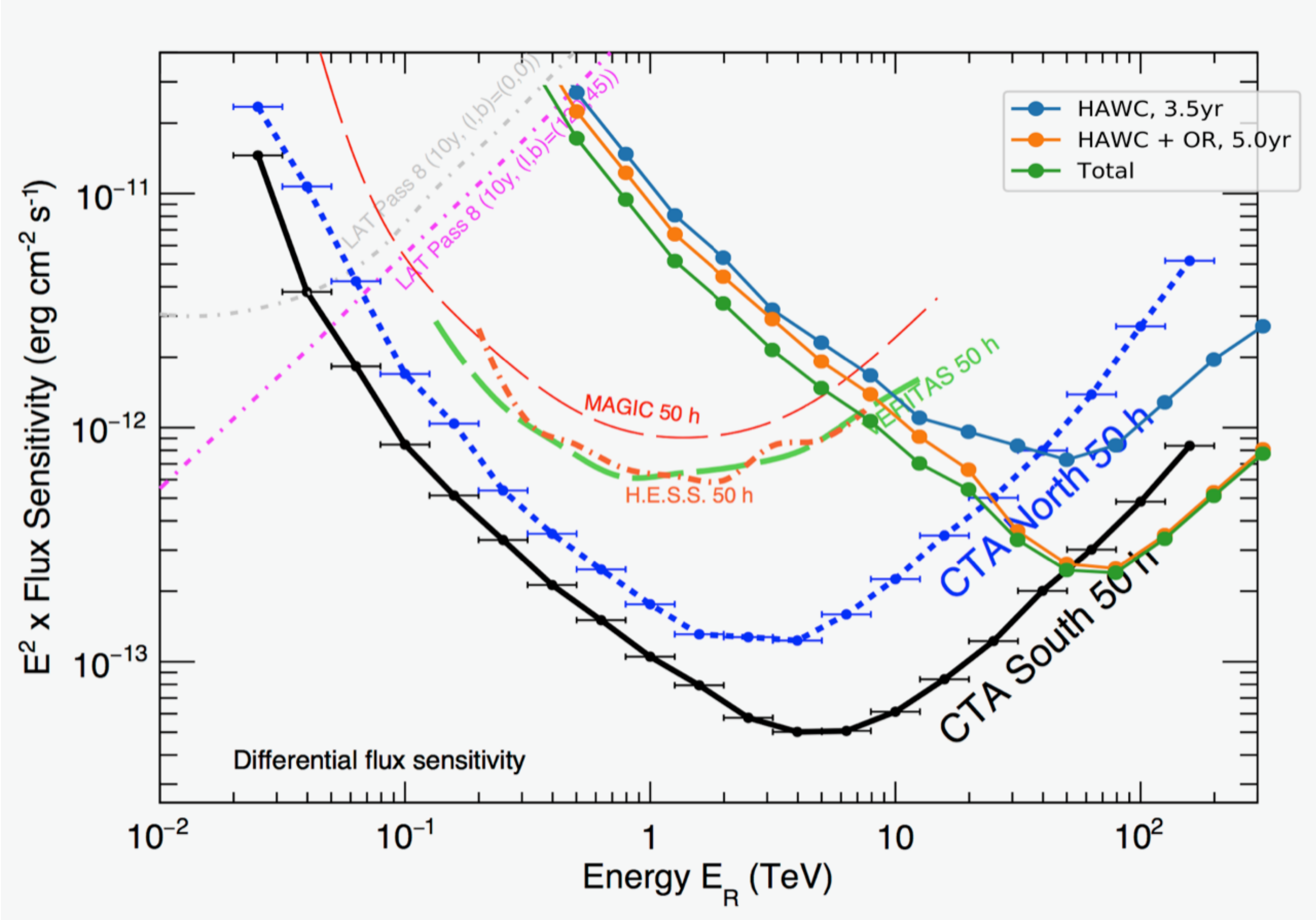


HAWC Upgrade: Outriggers

- **Expands total effective area >10TeV with the addition of 350 outrigger tanks spread over 100,000 m2**
- **Funded by LANL LDRD, Max Planck Institute in Heidelberg, and CONACyT in Mexico**
- **All tanks are deployed, 100% are cabled, and 80% are taking data**
- **100% operational by June 2018**
- **With the outriggers, HAWC will see the highest energy photon ever detected**

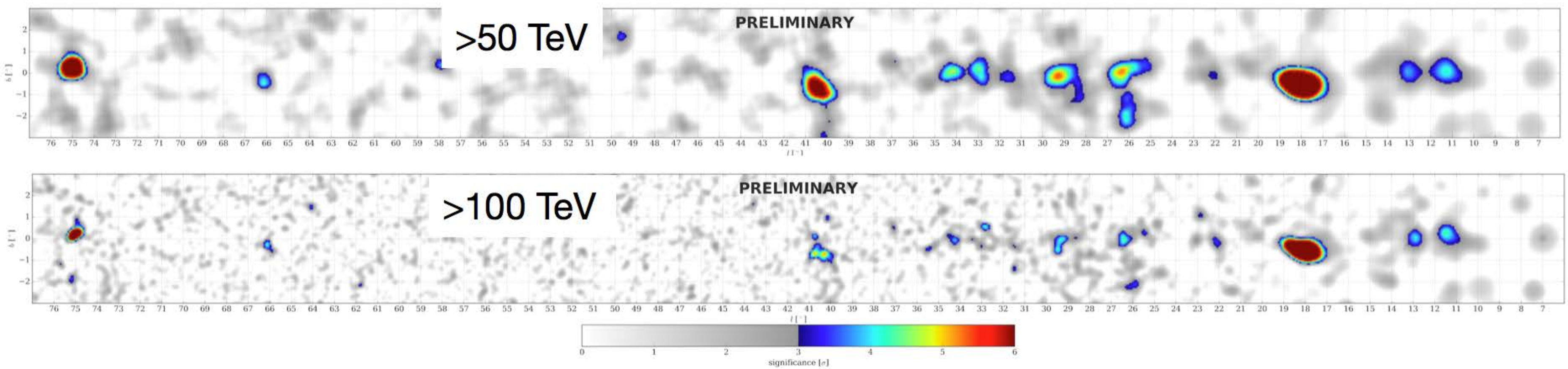


HAWC Sensitivity with Outriggers



This sensitivity does not include improvements in HAWC reconstruction and analysis algorithms which are about to be implemented retroactively

Pushing HAWC to the Highest Energies



- **HAWC already detects sources > 50 TeV, so outriggers will detect even more**
- **Detection of >100 TeV gamma-rays stresses models of particle acceleration**
- **Essential to discovering the source of cosmic rays up to the knee ($3x10^{15}$ eV protons produce 100-200 TeV gamma-rays)**
- **Algorithm development will improve HAWC energy response**
  - First papers on improvements due out later this year

Where do I get some HAWC data to play with?

- **Public data: data.hawc-observatory.org**
- **Some dataset already available, planning to add more:**
  - Significance and flux maps corresponding to the 2HWC paper (507d livetime).
  - Geminga & Monogem dataset.
  - Daily light curves (2014-11-26 to 2016-04-20):
    - Crab
    - Mrk 421
    - Mrk 501
- **Please use for your own analysis, and/or contact us if you want more information!**