VHE to UHE γ-Ray Astronomy with Ground-Based Particle Detection Arrays

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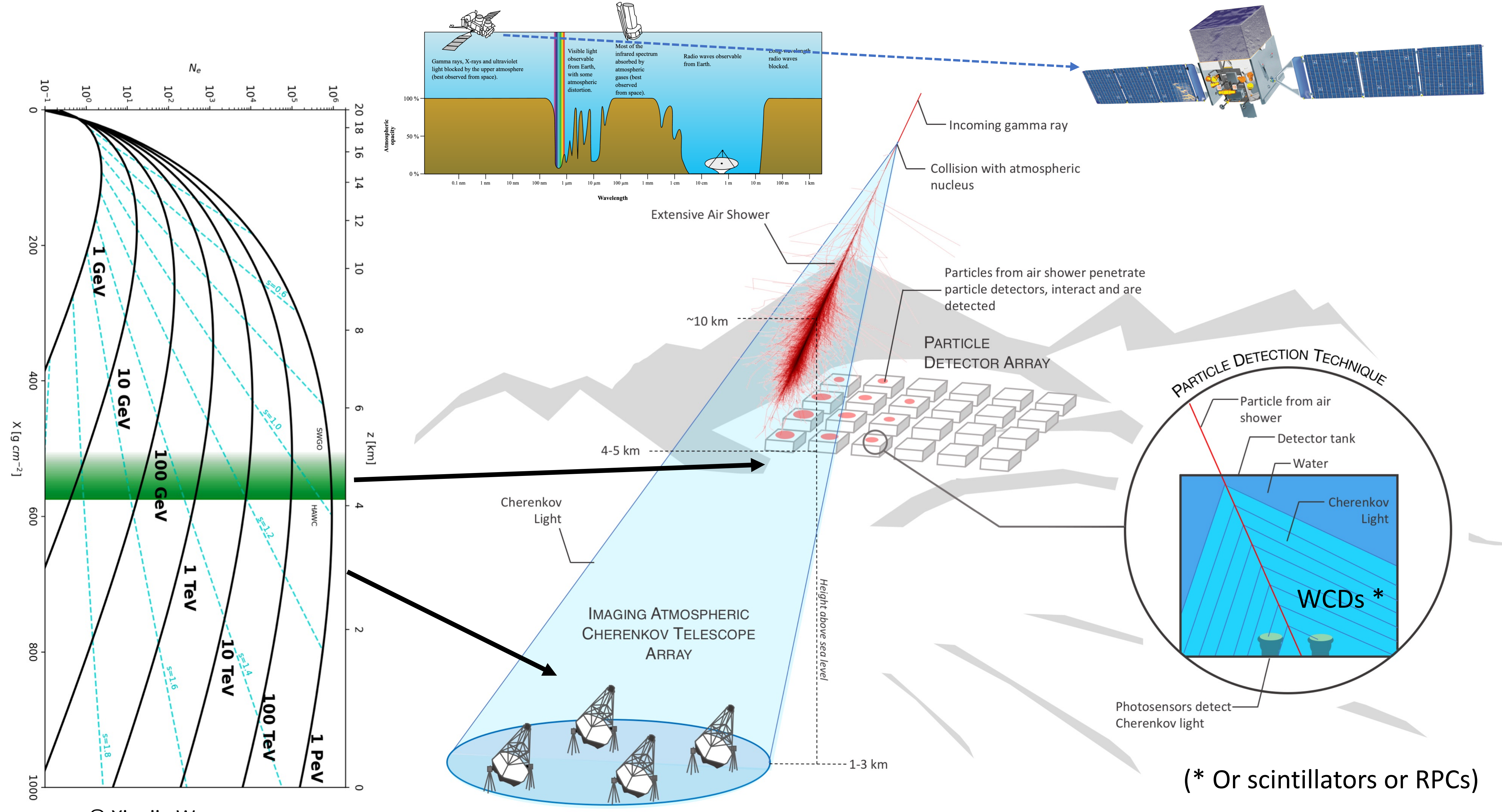
Michigan Tech



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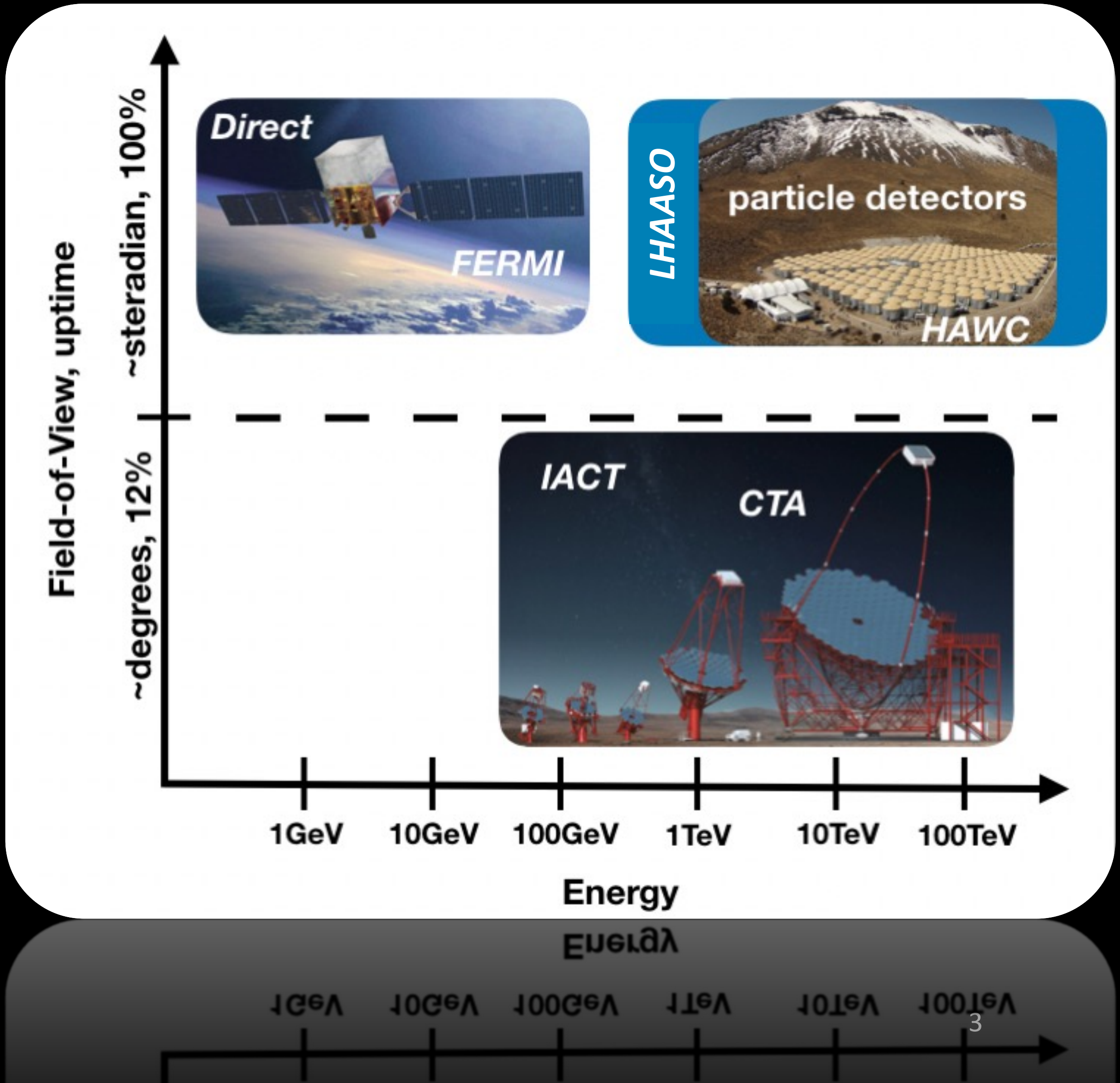
Shower image, 100 GeV γ-ray adapted from: F. Schmidt, J. Knapp, "CORSIKA Shower Images", 2005, https://www-zeuthen.desy.de/~jknapp/fs/showerimages.html

Duty Cycle, Field-of-View & Energy
3 Main Features

- High duty cycle (> 95% uptime)
  - ✓ Transients
- Wide field-of-view
  - ✓ Extended and large scale emission
- Good Sensitivity, Angular & Energy Resolution > 10 TeV
  - ✓ Highest energy accelerators

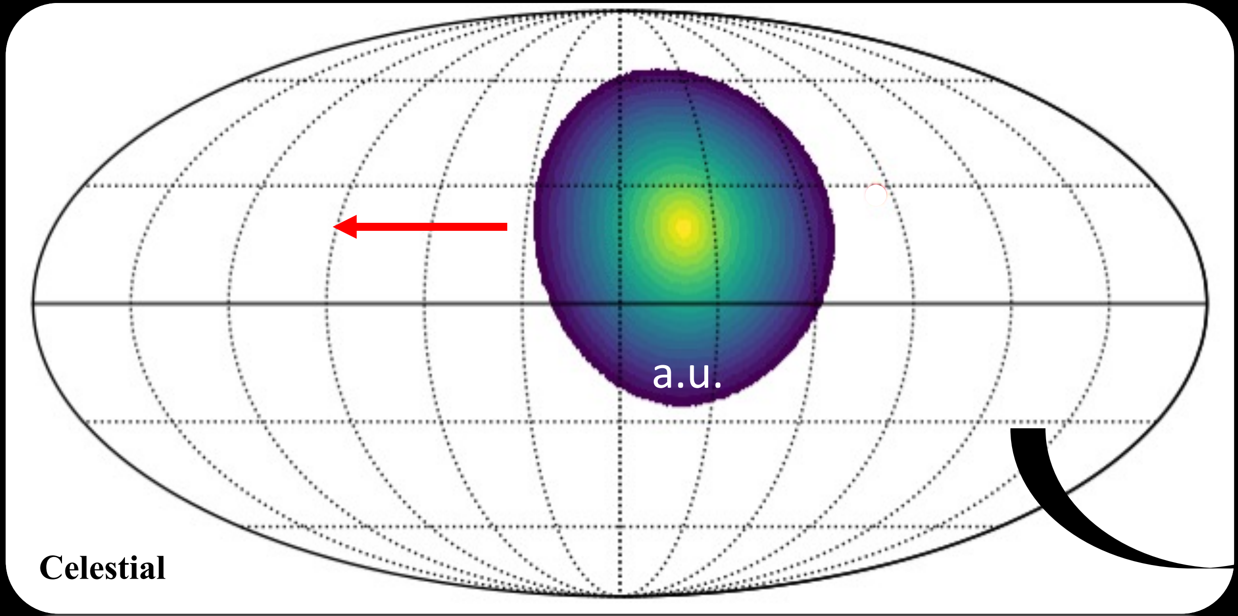


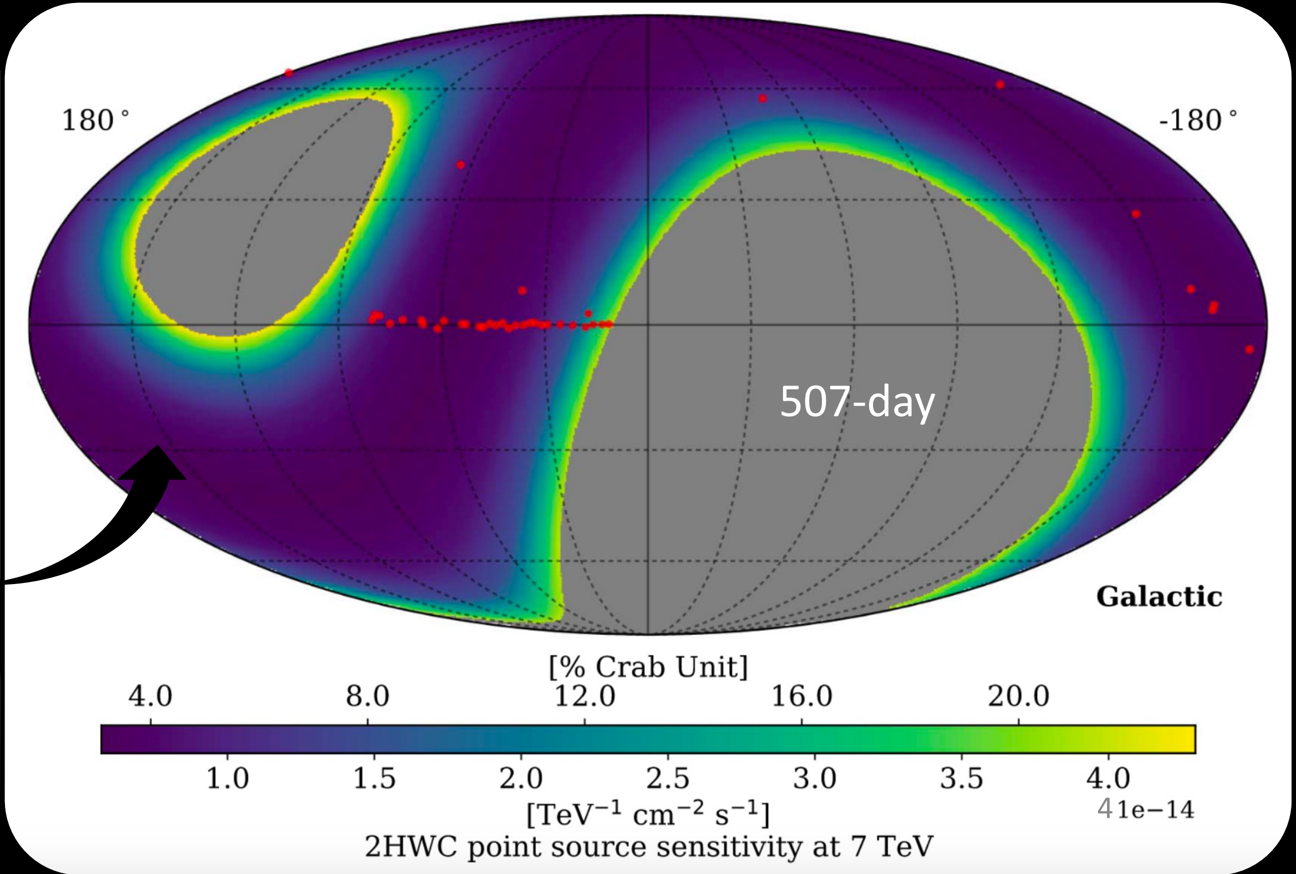
Wide Field-Of-View + High Duty Cycle

- Typical instantaneous field of view ≳ 1.8 sr (~15% of the sky)

  → surveys ~ 8.4 sr / day (~2/3 of the sky).

ApJ, Vol. 843, (1), 40 (2017)

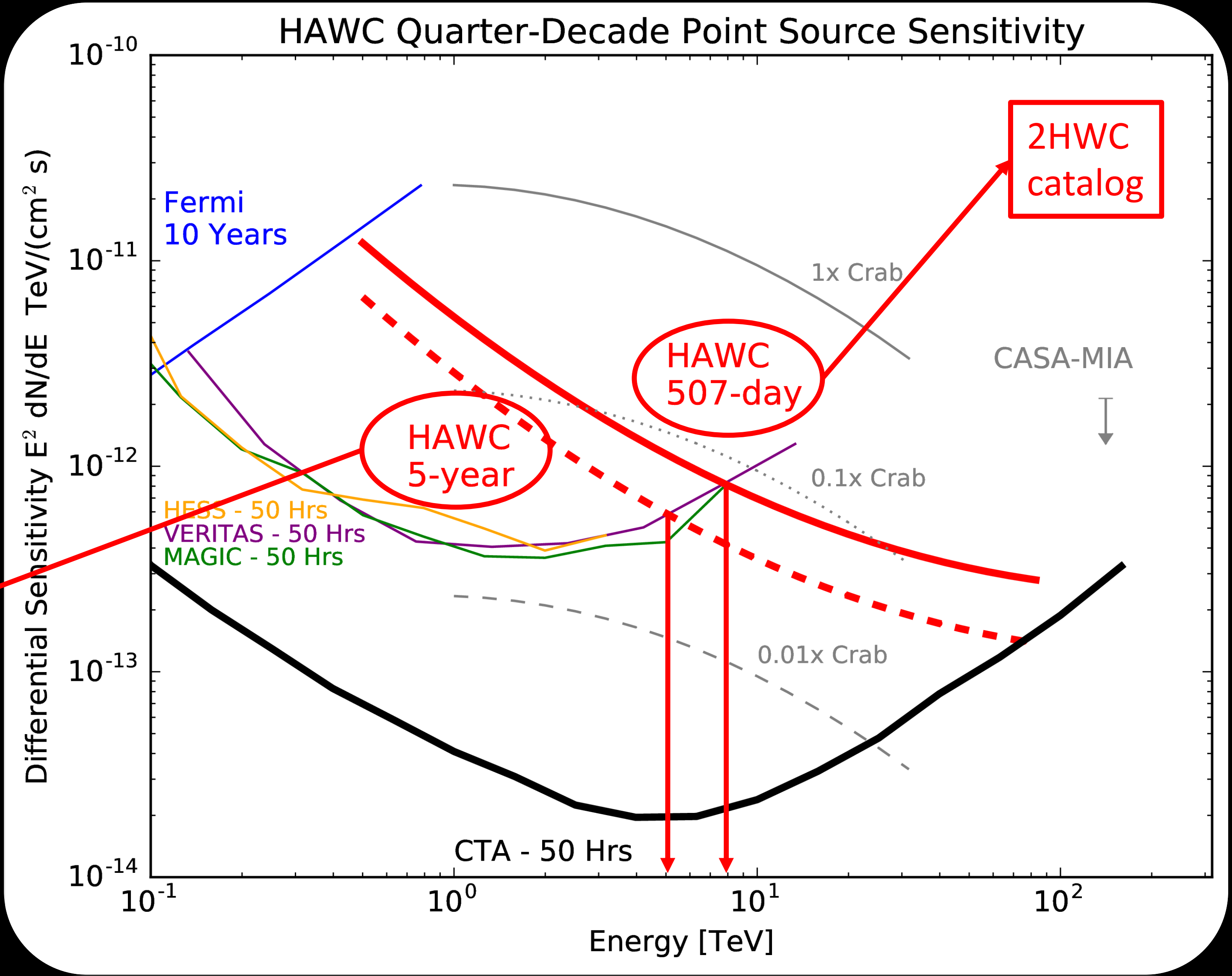




Sensitivity vs Energy, e.g. HAWC

≥ sensitivity of upcoming HAWC Catalog (in preparation)

- ≥ 5 years of data
- Improved reconstruction



ApJ, Vol. 843, (1) 39 (2017)

Main Features → Recent Results

- Survey capabilities & High Duty Cycle
  - ✓ Source searches and discoveries
  - ✓ Catalogs
  - ✓ Transients and alerts
- Extended and large scale emission sensitivity
  - ✓ New source class: halos
  - ✓ Fermi bubble
  - ✓ Molecular clouds
  - ✓ Diffuse emission
- High-energy γ-ray sensitivity
  - ✓ >10 PeVatron candidates
  - ✓ Test of fundamental physics in unique phase space

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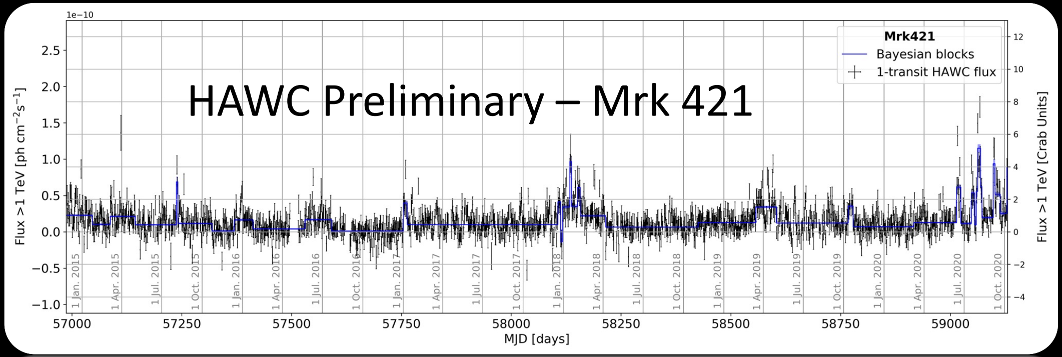

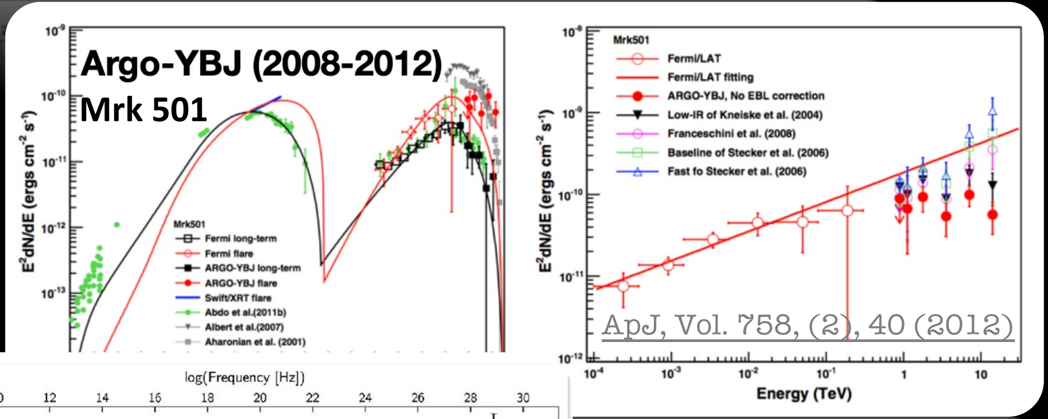

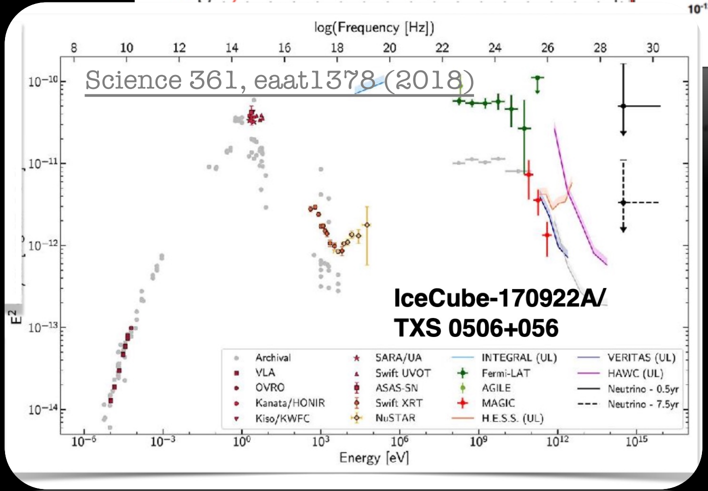

Main Features → Recent Results

- Survey capabilities & High Duty Cycle
  - ✓ Source searches and discoveries
  - ✓ Catalogs
  - ✓ Transients and alerts
- Extended and large scale emission sensitivity
  - ✓ New source class: ***halos (HAWC discovery)***
  - ✓ Fermi bubble
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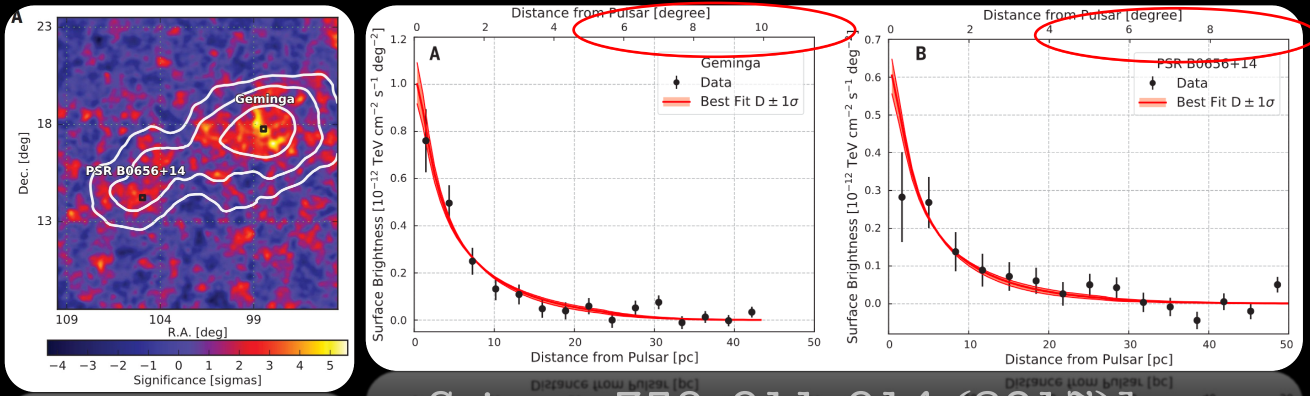
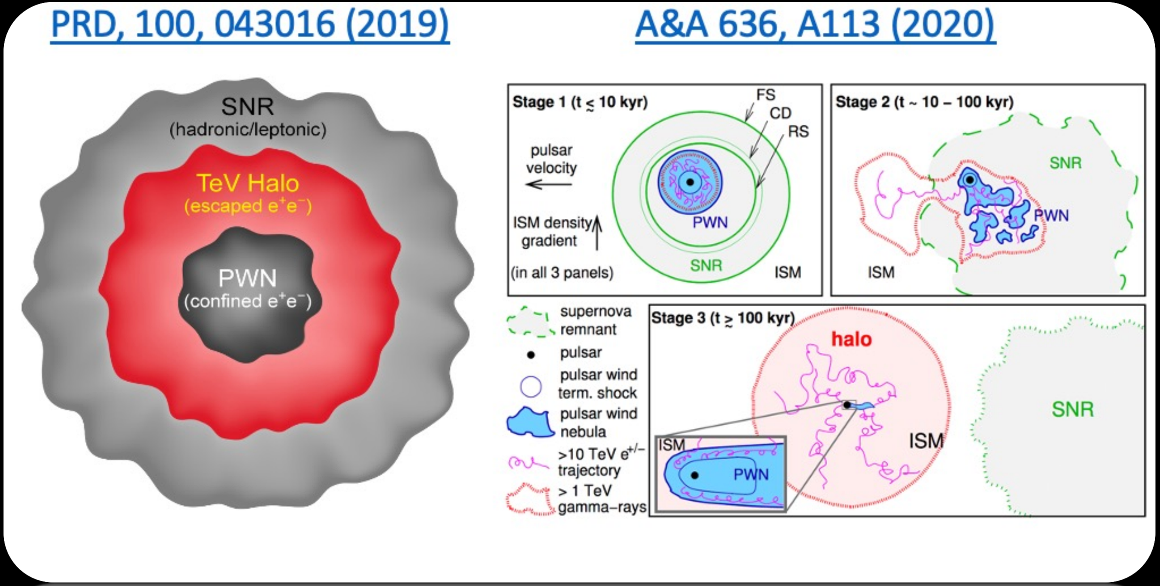


Science 358, 911-914 (2017)]



Main Features → Recent Results

[ApJ, 842 (2), 85 (2017)](#)

- Survey capabilities & High Duty Cycle
  - ✓ Source searches and discoveries
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  - ✓ Transients and alerts
- Extended and large scale emission sensitivity
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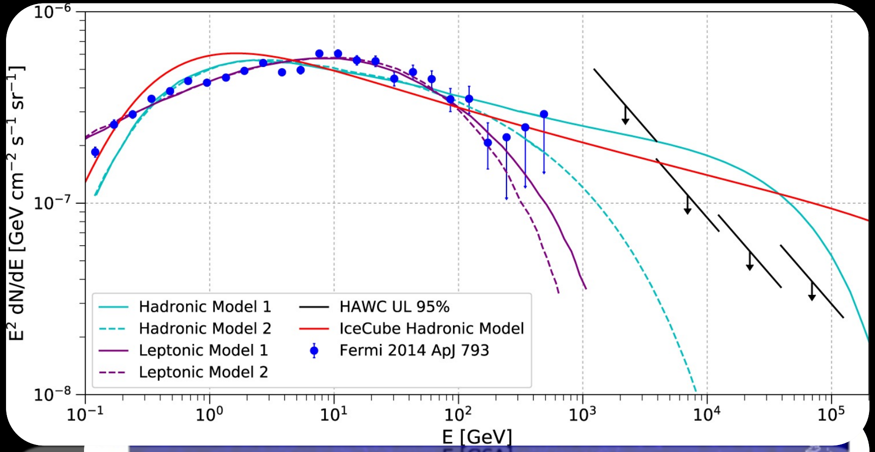
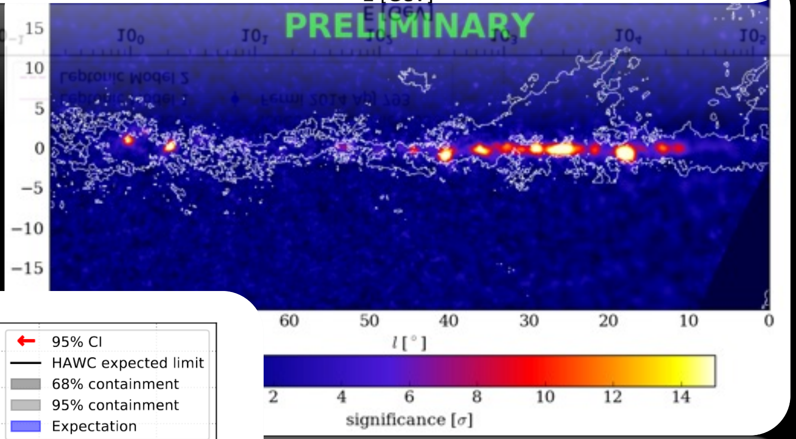
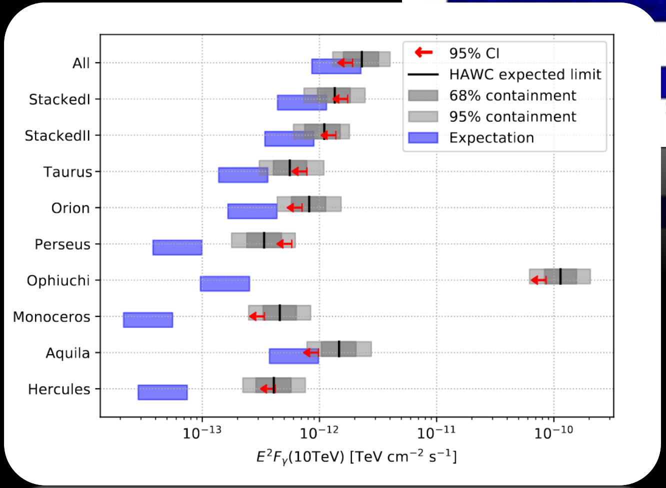


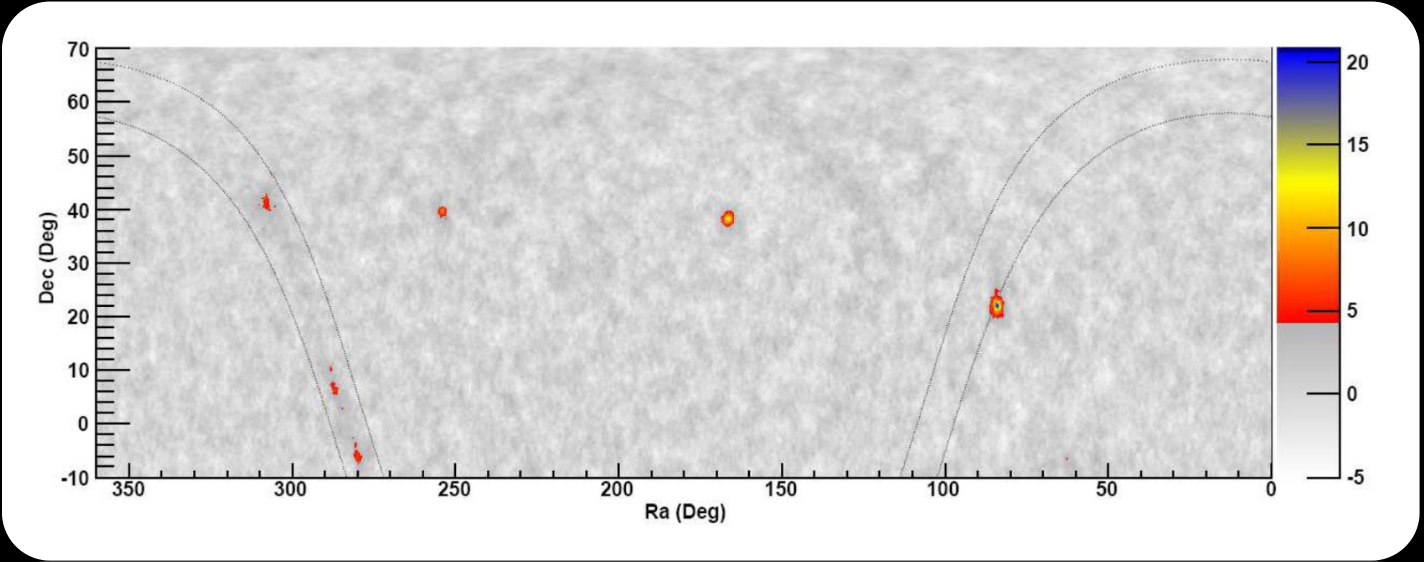




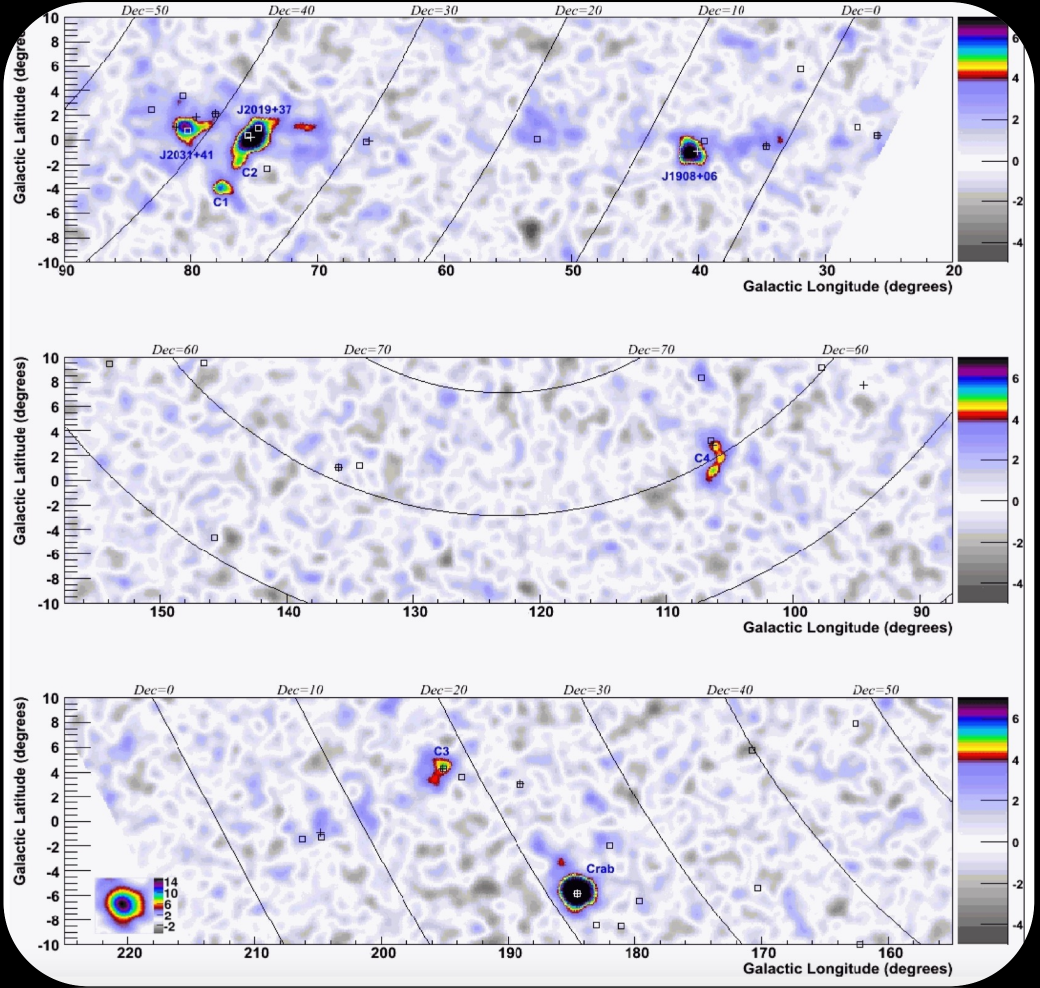
[ApJ, 914 (2) , 106 (2021)](#)

Surveys over the Years

- **Milagro:** 2000-2007,
  - 8 sources at $\sim$ 20 TeV ($> 4.5\ \sigma$)
  - Crab Nebula $\sim 15\ \sigma$
- **ARGO YBJ:** 2007-2013
  - 10 sources $>$ 0.3 TeV ($> 4.5\ \sigma$)
  - Crab Nebula $\sim 21\ \sigma$

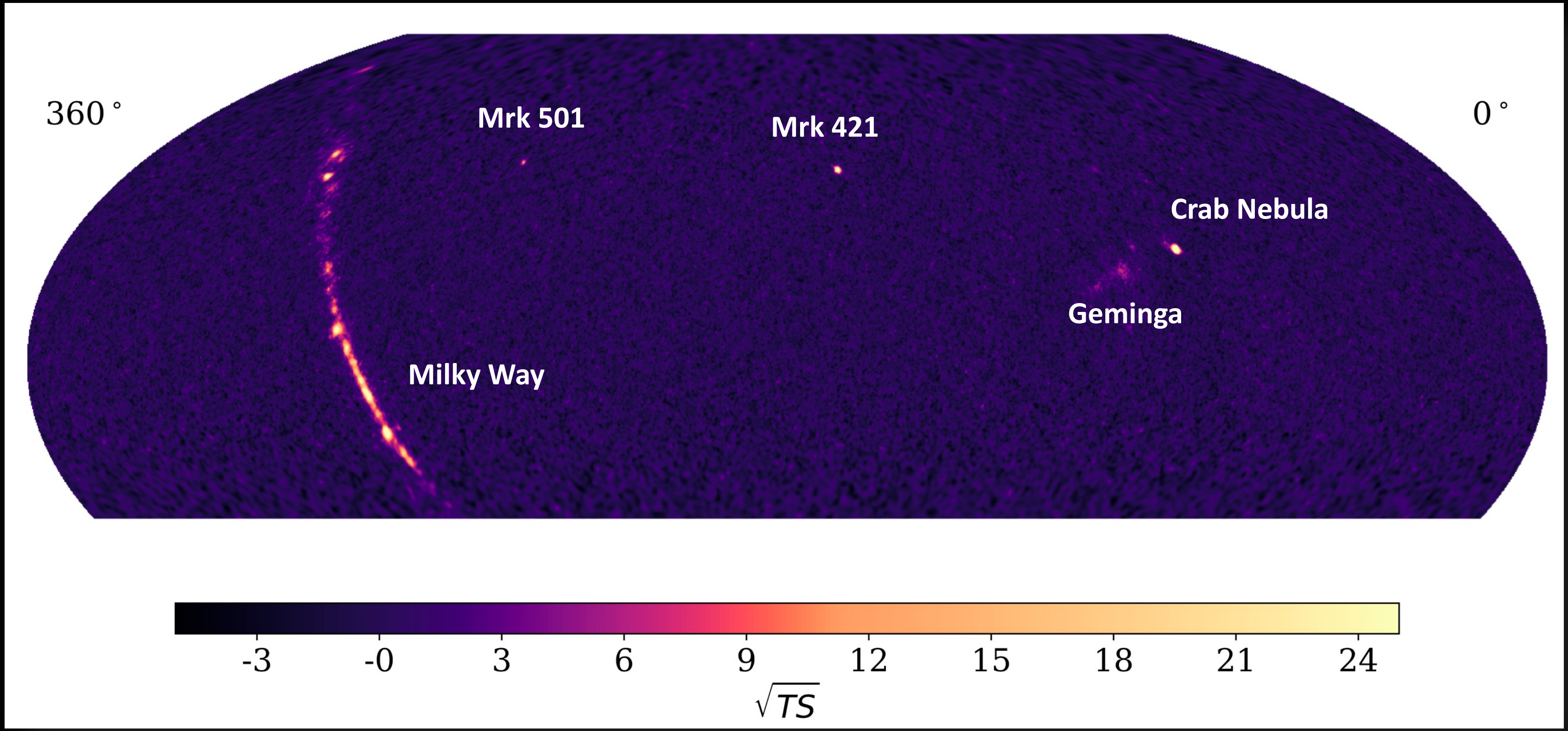


ApJ 779, 27 (2013)



ApJ 664, L91 (2007)

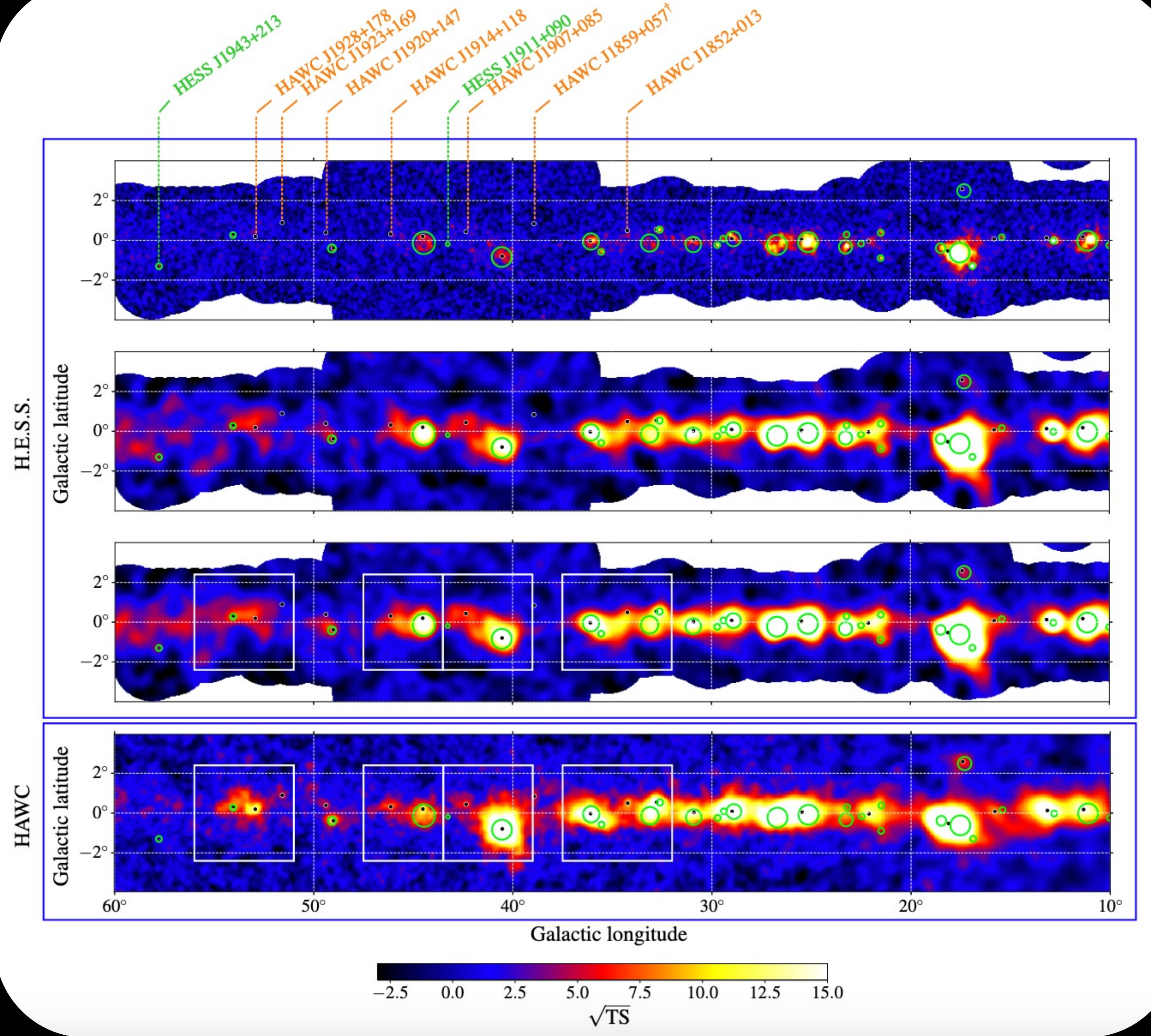
Survey of the Northern Sky: 3HWC Catalog



ApJ, Vol. 905, Is. 1, id.76, 14pp. (2020)

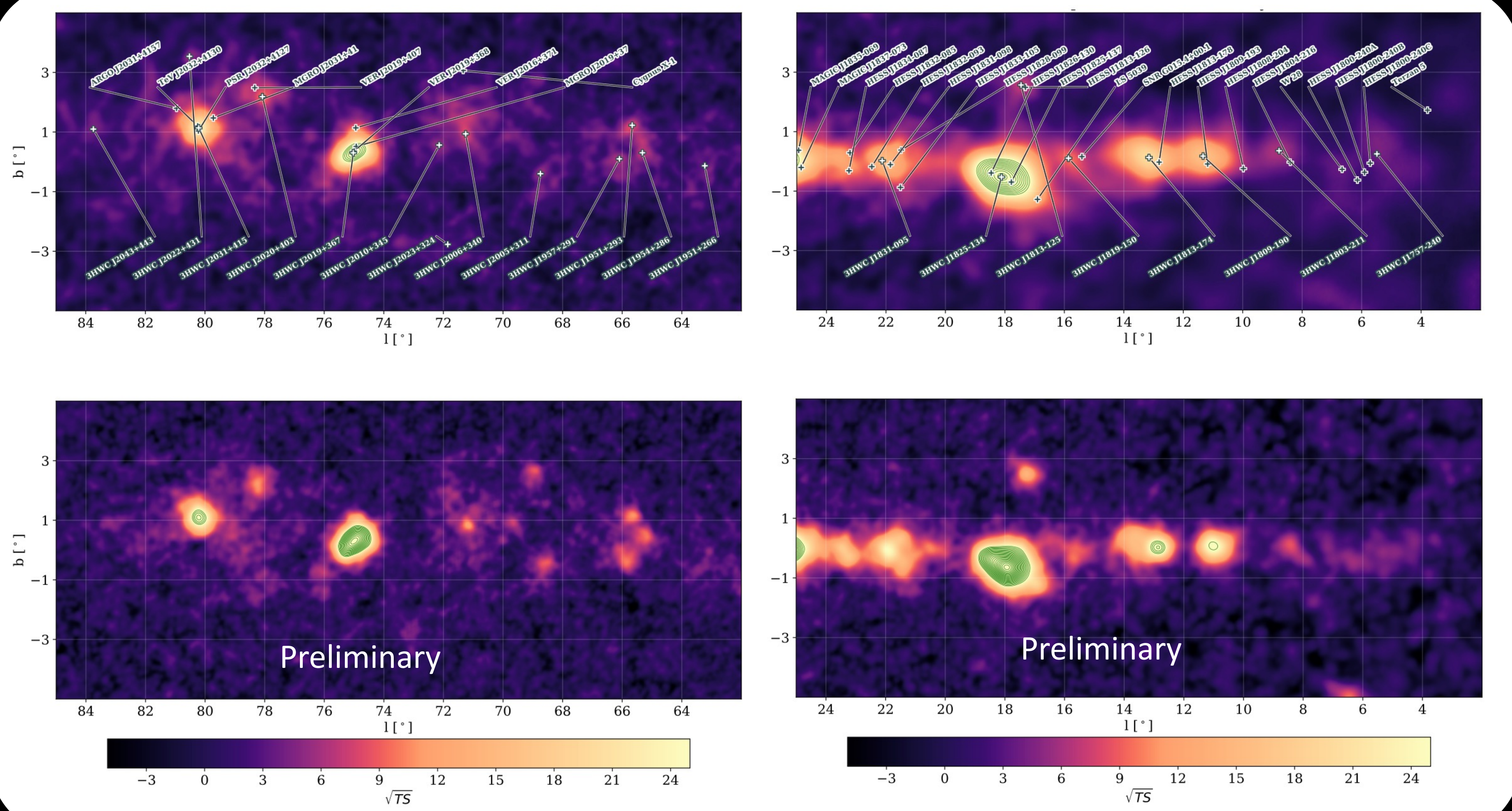
- 65 sources detected at > 5σ in a little over 4 years of data:
  - 20 sources > 1°away from previously detected TeV sources
  - 14 of these have potential counterpart in the 4th Fermi-LAT catalog
  - Crab Nebula ~190 σ

Complementarity with IACTs



ApJ 917 (1) 6 (2021)

And it Gets Better

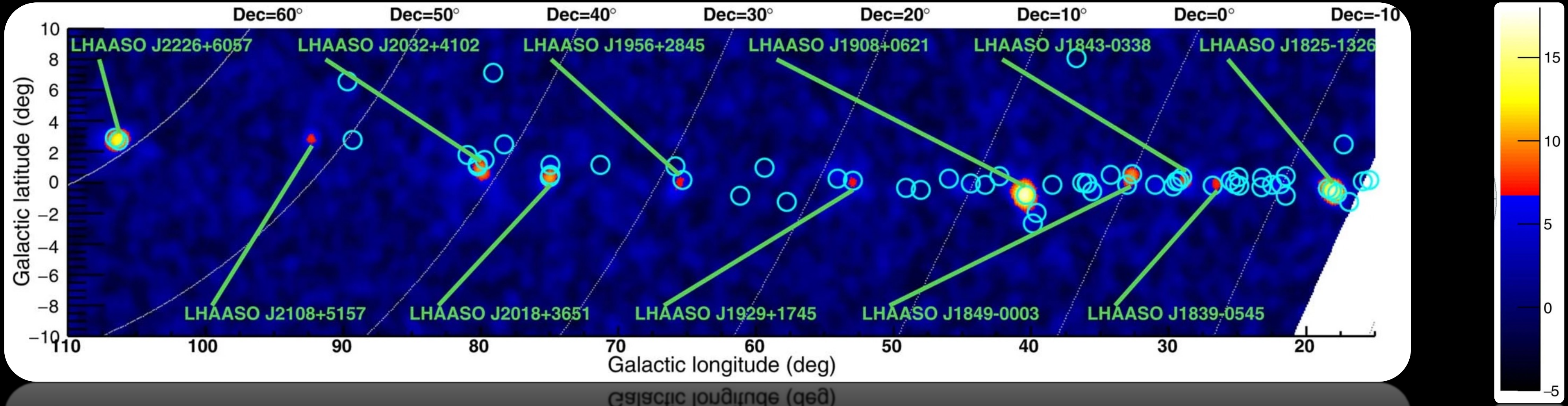


Pass 4 (1523 days)

improved background rejection and angular resolution, wider FoV 45° -> 60°

Pass 5 (>2000 days)

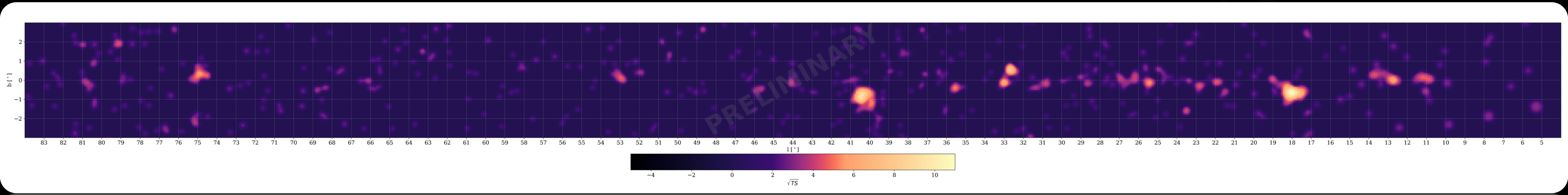
In Addition We Now Have 10-20 PeVatron Candidates



LHAASO:
- 14 > 7σ
- 530 UHE photons

(in only 6 months of KM2A data)

LHAASO *Nature* **594**, 33 (2021)

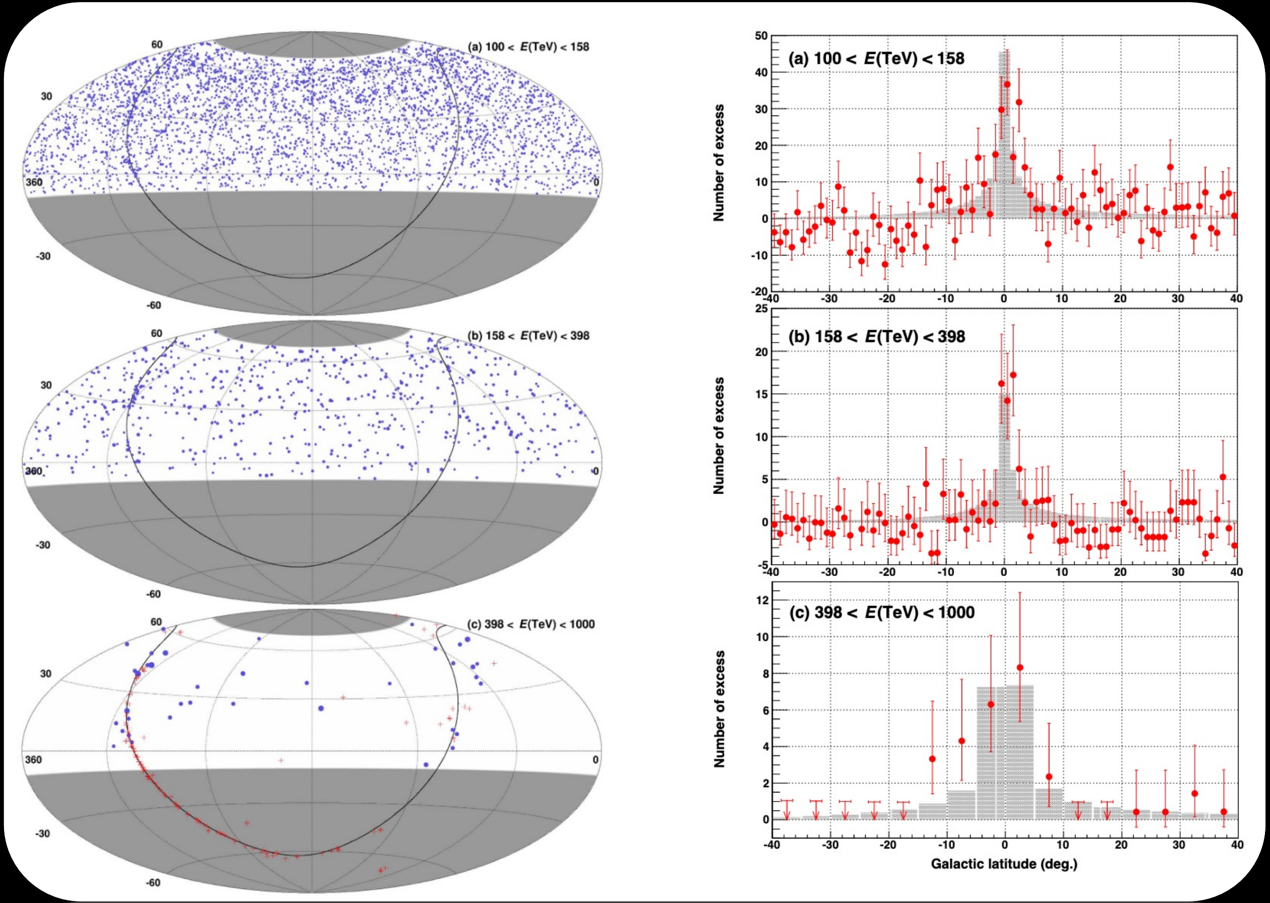


HAWC *Gamma 2022* (2022)

HAWC:
- 18 in ~2100 days

> 100 TeV

Tibet AS-γ: Sub-PeV Diffuse Emission



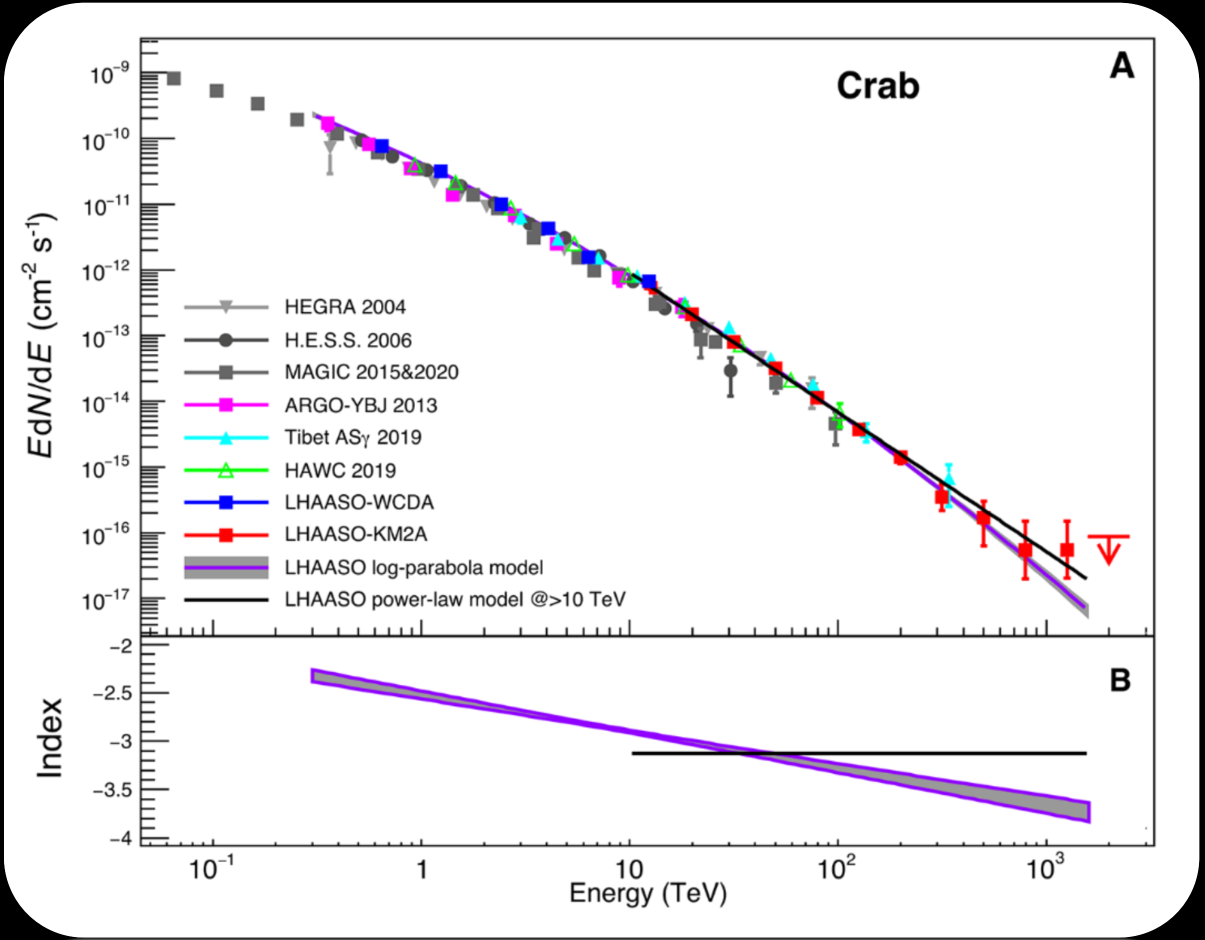
Phys. Rev. Lett. 126, 141101 (2021)

- Detection of diffuse gamma rays with energies between 100 TeV and 1 PeV in the Galactic disk by Tibet AS-γ
- All gamma rays $\gtrsim$ 400 TeV observed apart from known TeV gamma-ray sources and compatible with expectations from the hadronic emission scenario.
- Strong evidence that cosmic rays are accelerated beyond PeV energies in our Galaxy and spread over the Galactic disk.

Example of a PeVatron: Crab Nebula

LHAASO Measurement:

- Covers 3.5 decades of energy
- Agrees with other experiments below 100 TeV
- WCDA & KM2A consistent in overlapping energy region

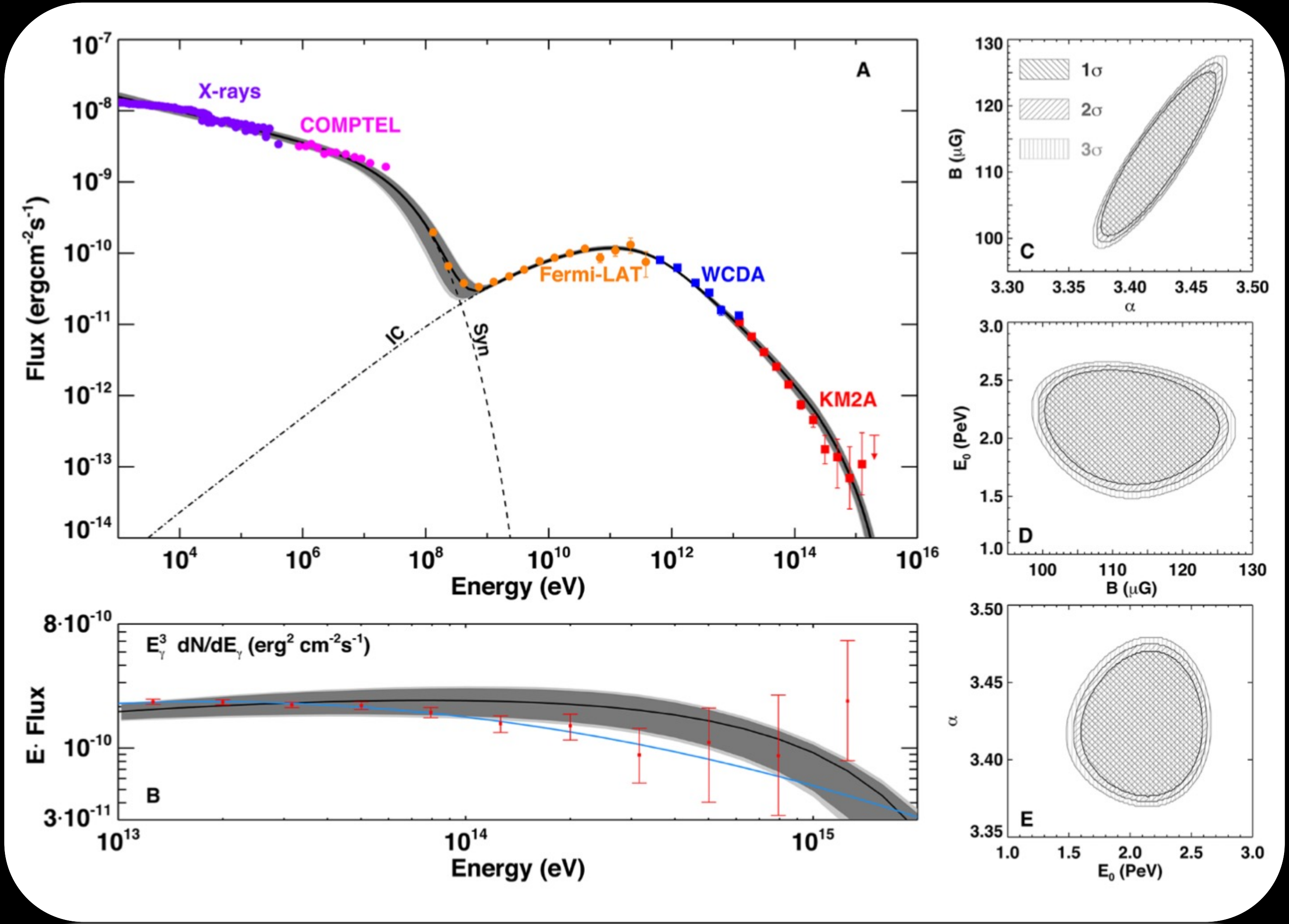


Science, 373, 425 (2021)

Example of a PeVatron: Crab Nebula

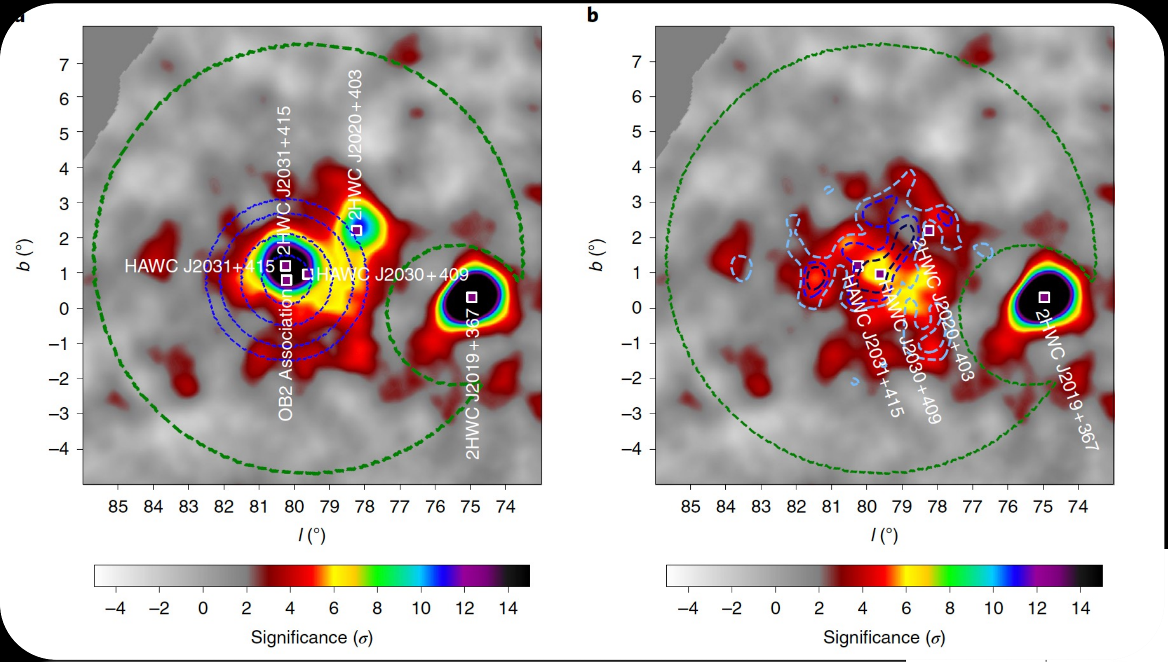
An extreme e-accelerator:

- 2.3 PeV electrons
- 0.025-0.1 pc compact region
- accelerating efficiency of 15% (1000× better than SNR shock waves)



Science, 373, 425 (2021)

Another Example: Cygnus Region

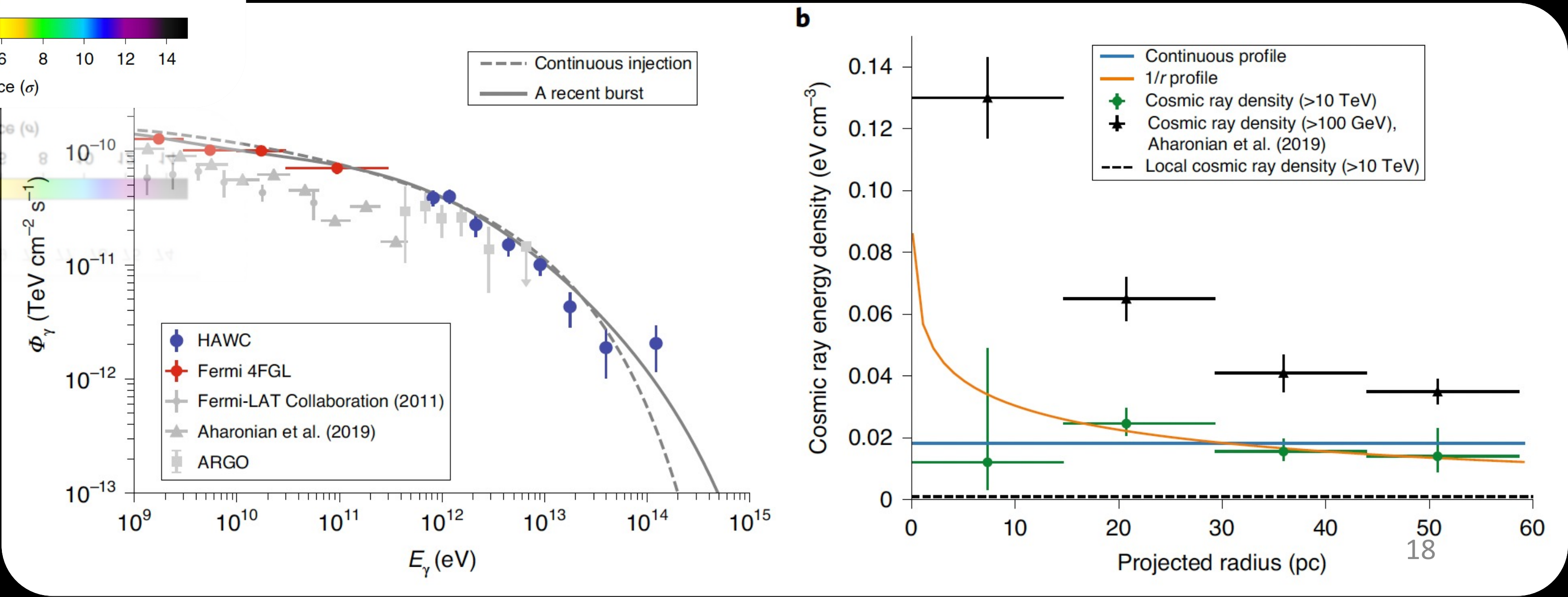


OB2 SFR
(Cygnus Cocoon)

LHAASO measured a 1.4 PeV photon from this direction

HAWC Nat. Astro., 5, 465 (2021)

- γ-rays are likely produced by 10–1,000 TeV accelerated CRs that originate from the enclosed star-forming region Cyg OB2
- Likely of hadronic nature
- Spectral shape and emission profile changes from GeV to TeV energies



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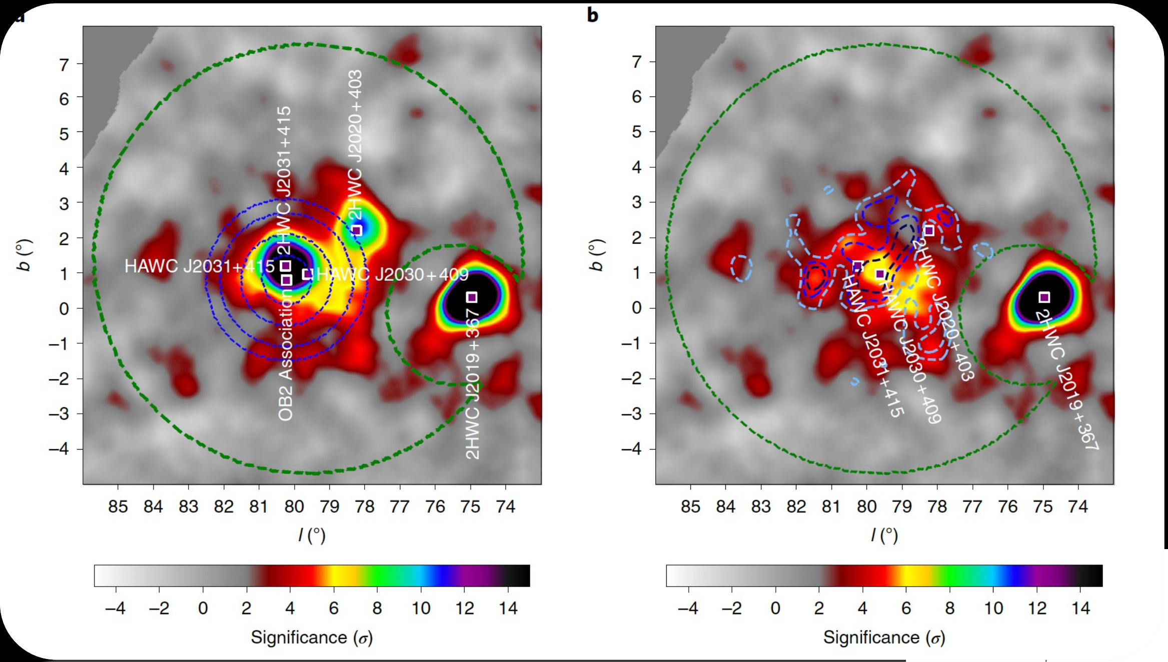

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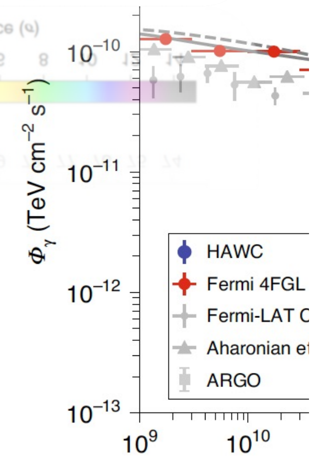
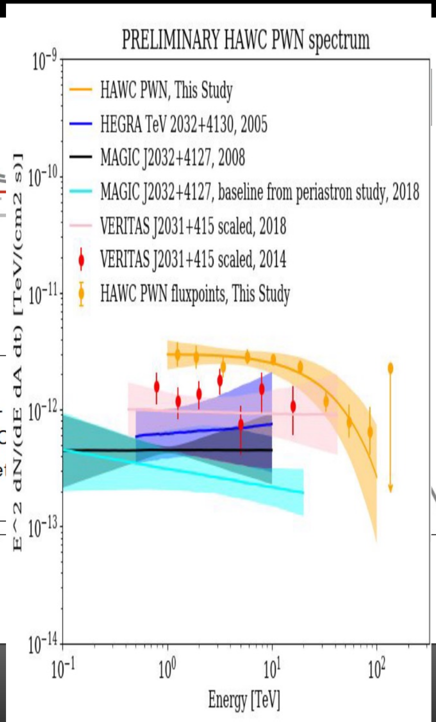
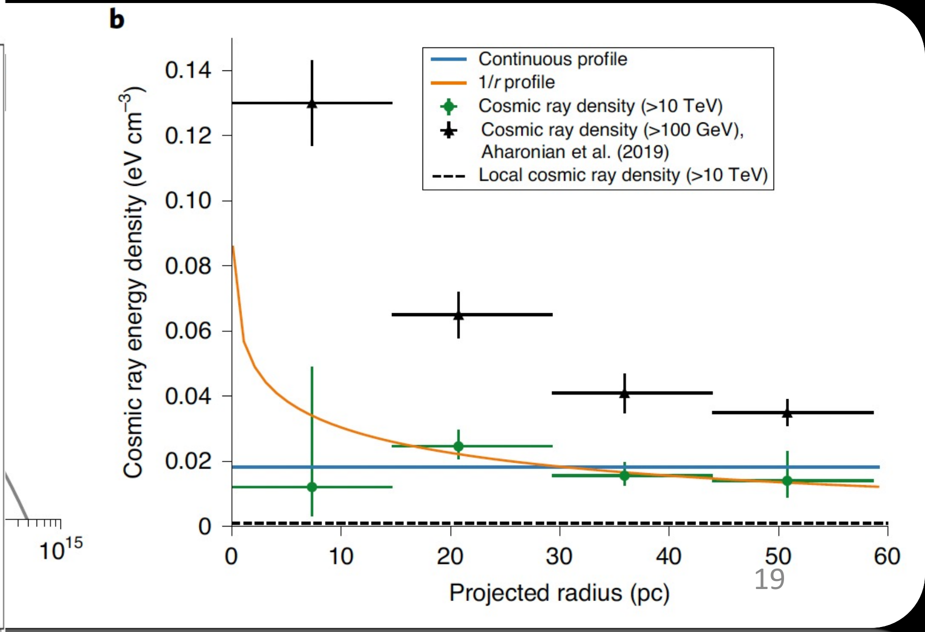
Nat. Astro., 5, 465 (2021)

PoS ICRC2021, 836 (2021)







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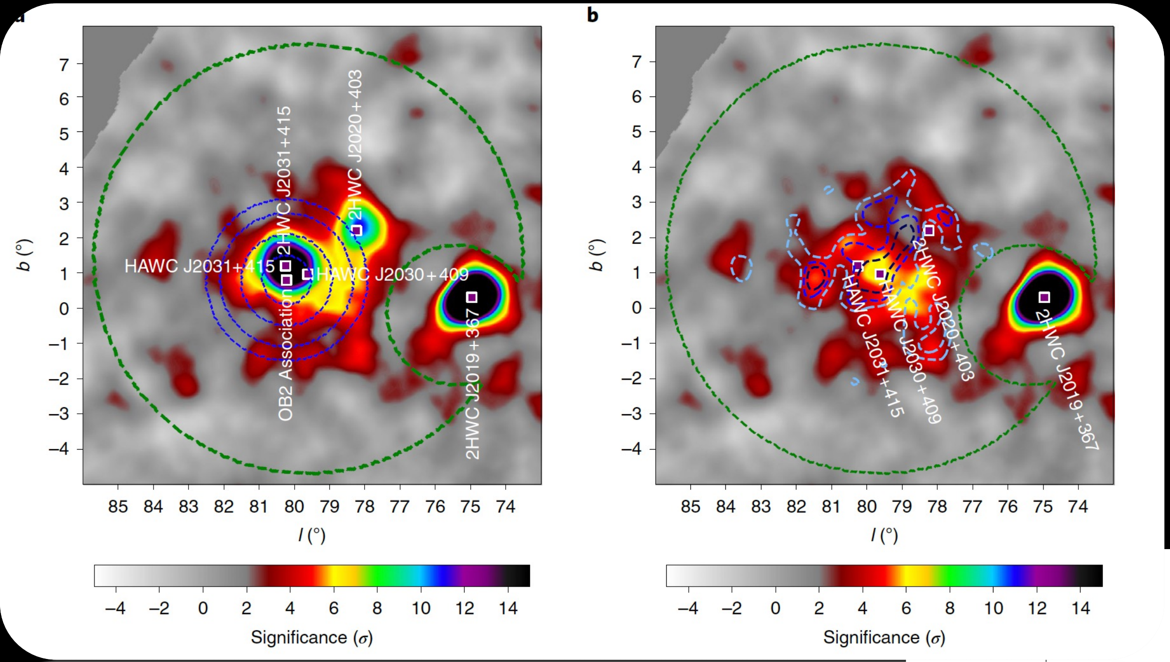


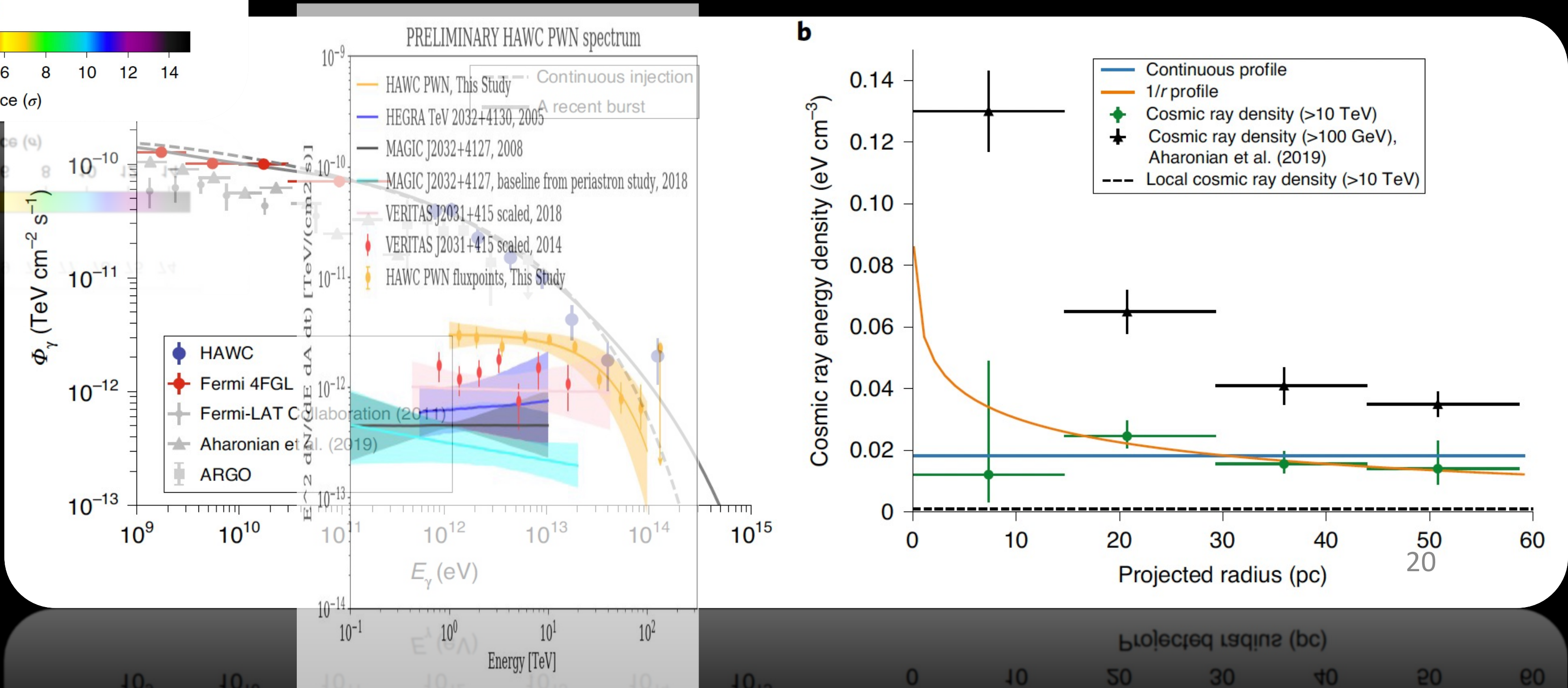
OB2 SFR
(Cygnus Cocoon)

Note: Extrapolating the Cocoon emission measured by HAWC to a 0.3 extent produces excellent agreement with the flux reported by LHAASO
Nature, **594**, 33-36 (2021)

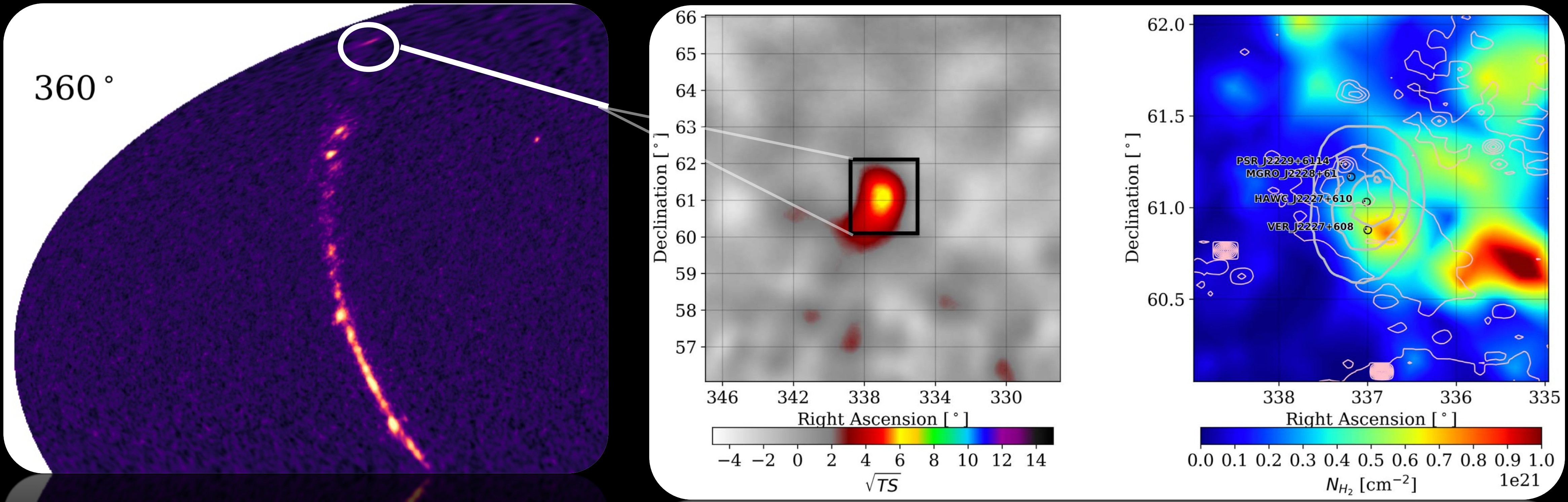
Nat. Astro., 5, 465 (2021)

PoS ICRC2021, 836 (2021)

→ Multisource fitting extremely important



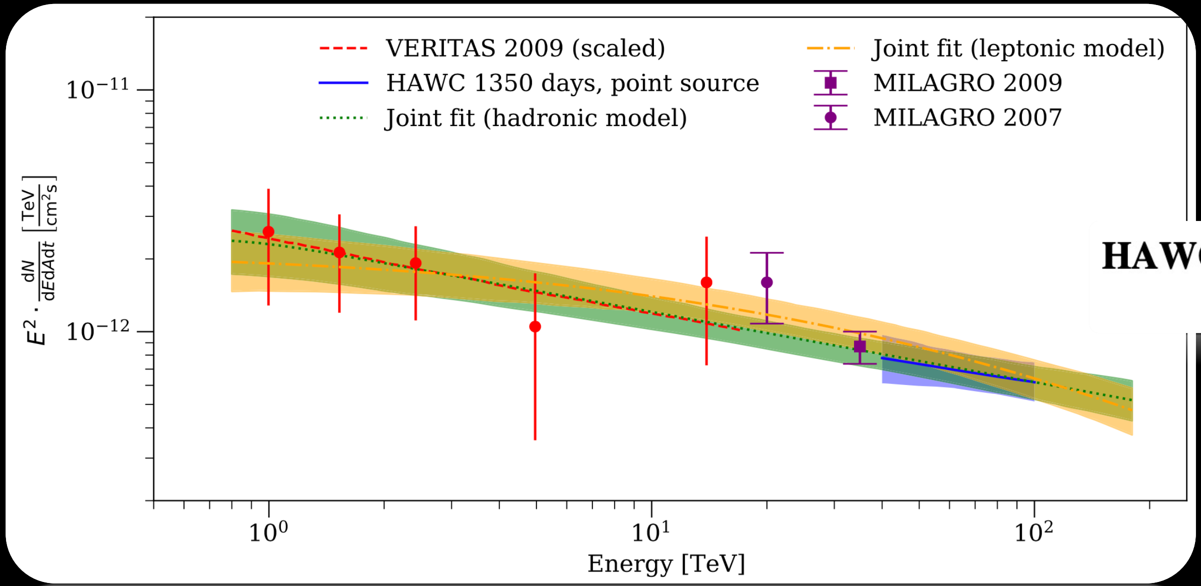
Improved Angular Resolution: The Boomerang Region



ApJL 896, (2), L29, 9(2020)

- Very-high-energy γ-ray emission > 100 TeV from HAWC J2227+610
- Excess well isolated and inconsistent with background fluctuations at the 6.2 σ level (pre-trials), or about 4.3 σ (post-trials considering HAWC's entire FoV)
- Right figure:
  - Best-fit position of HAWC J2227+610 is consistent with the VHE detections by VERITAS and Milagro, and with the position of PSR J2229+6114 (within uncertainties)
  - Heat map: Molecular column density
  - Pink contours: 1.4 GHz continuum brightness temperature from the Canadian Galactic Plane Survey

Improved Angular Resolution: The Boomerang Region



HAWC J2227+610 and Its Association with G106.3+2.7, a New Potential Galactic PeVatron

ApJL 896, (2), L29, 9(2020)

- Gaussian extent of HAWC J2227+610 is constrained to be $< \pm 0.232°$, morphology is consistent with VERITAS
- Joint VERITAS–HAWC spectrum well fit by a power law ($\gamma \approx -2.3$) from $\sim$0.9 to $\sim$180 TeV:
  - Emission can be interpreted to be originating from protons with a lower limit on their cutoff energy of 800 TeV.
  - Most likely source of the protons: the associated supernova remnant G106.3+2.7
  - But purely leptonic origin of the observed emission could not be excluded at the time
- ***Both, Tibet-ASγ and LHAASO (~570 TeV), since reported >100 TeV emission***
- ***Deeper morphological studies would be helpful***

Improved Angular Resolution: The Boomerang Region

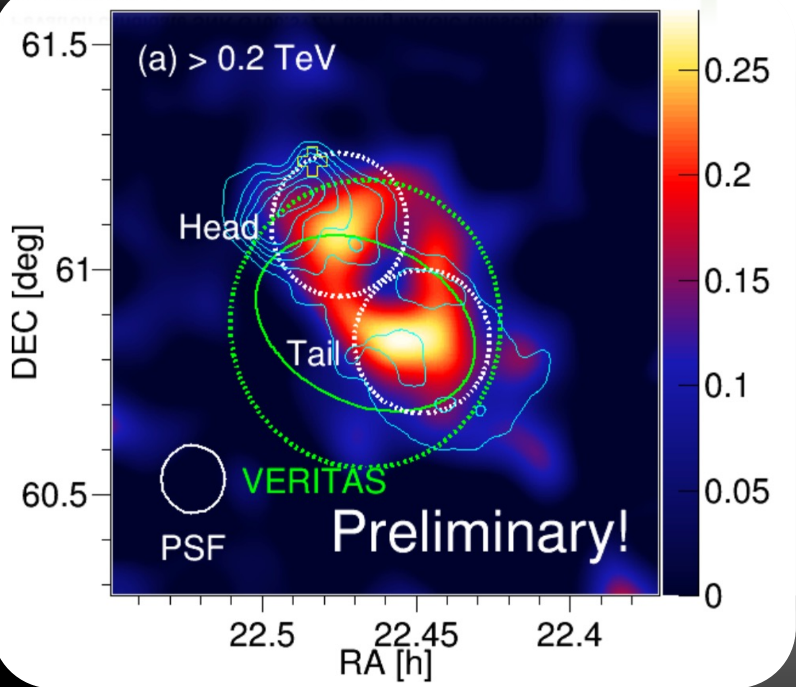
- **HAWC now resolves two sources**
- Magic sees two sources
- Head Region
  - IC scattering in the PWN
- Tail Region
  - Molecular cloud nearby
- Both pion decay and IC scattering are plausible

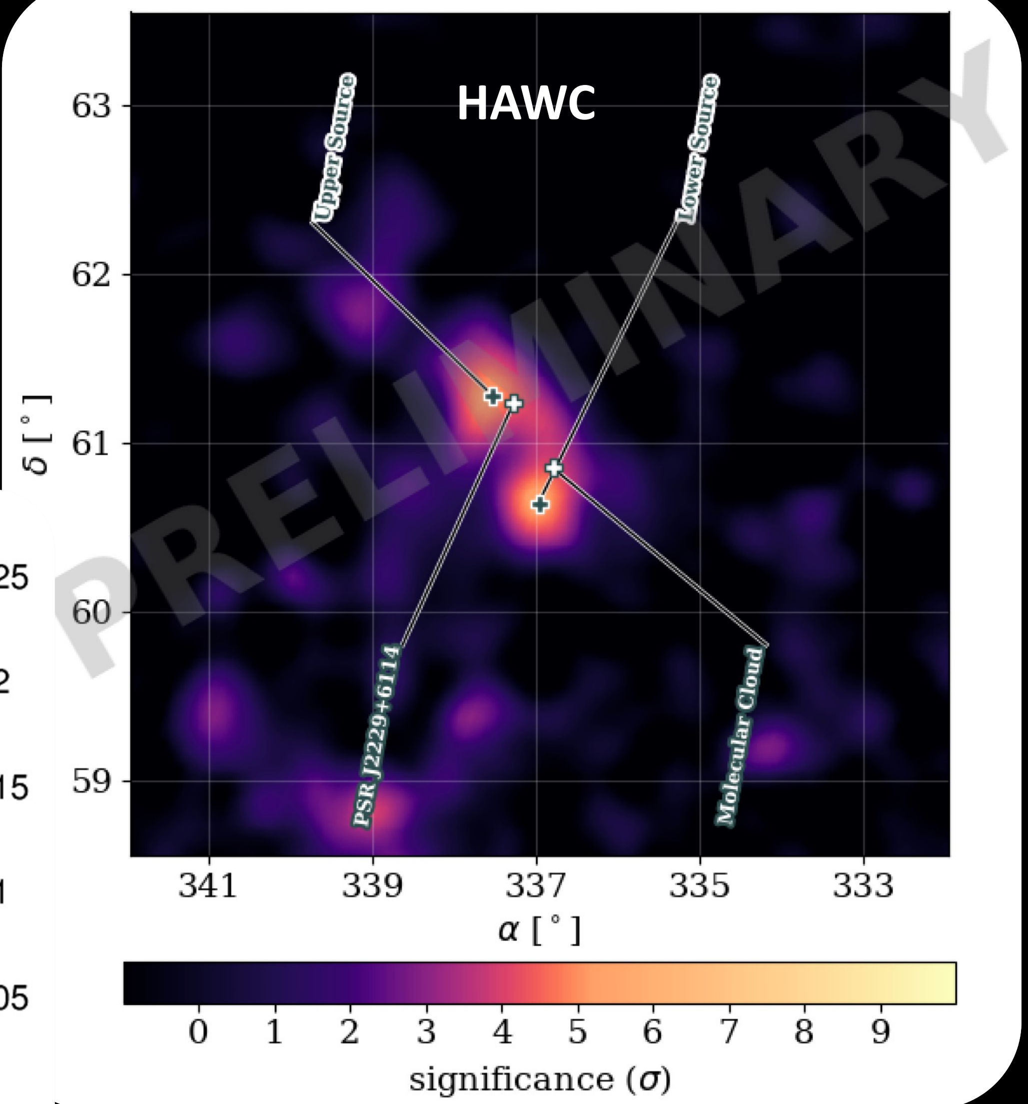
PROCEEDINGS OF SCIENCE

Volume 395 - 37th International Cosmic Ray Conference (ICRC2021) - GAI - Gamma Ray Indirect

Resolving the origin of very-high-energy gamma-ray emission from the PeVatron candidate SNR G106.3+2.7 using MAGIC telescopes

The MAGIC Collaboration, V.A. Acciari, S. Ansoldi, L.A. Antonelli, A. Arbet Engels, M. Artero, et al. (click to show)





Wide Field, VHE/UHE Sensitivity & Angular Resolution Unite: Binary Systems/Microquasars

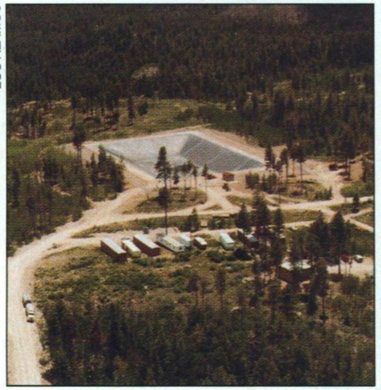
ASTROPHYSICS

Astronomers Turn New Eyes On the Cosmic Ray Sky

To understand why physicists have traditionally shunned cosmic rays, think of these mysterious visitors as gate-crashers to a party. Not only do they appear uninvited and without pedigree, but they bring with them a menagerie of other unwanted creatures whose presence can only wreak havoc. But lately, physicists have started to wonder about these mysterious strangers. Just what kind of environment could spawn this uniquely energetic lot? Cosmic rays are now in vogue.

A steady rain of these interlopers falls upon the upper atmosphere from all directions of space. As they interact with the thin gases, cascading showers of particles—billions of them—are spawned. And these, in turn, insouciantly trespass through the pristine grounds of carefully tended physics experiments, confounding detectors and ruining many a research party. But lately particle physicists have become entranced by the observation that some cosmic rays carry energies of 10^{20} electron volts (eV)—10 million times higher than will be attained by the Superconducting Super Collider (SSC).

R. ONG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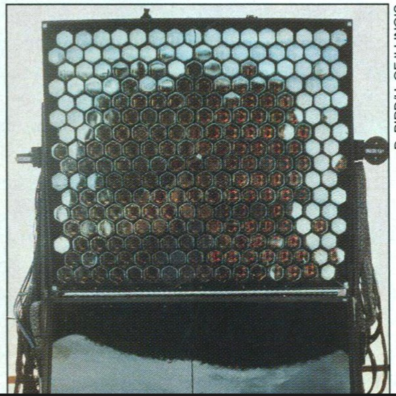

D. BIRD/U. OF ILLINOIS

as ever. The verdict on Cyg
cules X-1 is in, and it's dis
aren't the cosmic ray beac
be. But that hasn't discour
convinced the cosmic ray
for a longer haul of data ga
The challenge amounts
scramble
than 99%
charged p
and heav
helium to
magnetic
particles a
so that,
seem to
from all
neutral p
to point
origin, and of those, only gamma rays—high-energy photons—would survive the trip from source to Earth. (Neutrons, the most common neutral particles, would decay back into protons long before they reached Earth.) But gamma rays, says Cronin, constitute only one or two out of every 100,000 cosmic rays, which makes for a dismaying signal-to-background challenge.

Worse, at the highest energies even the "background" of charged cosmic rays dwindles to almost

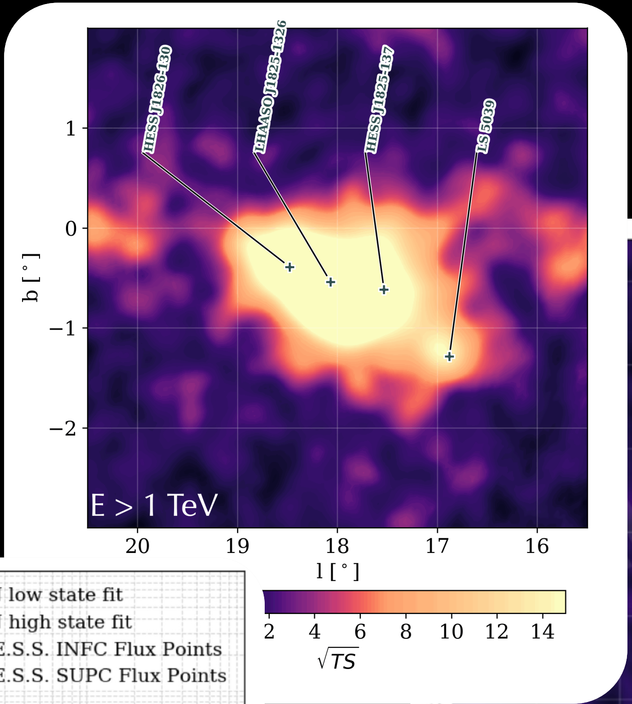
mental astrophysics."

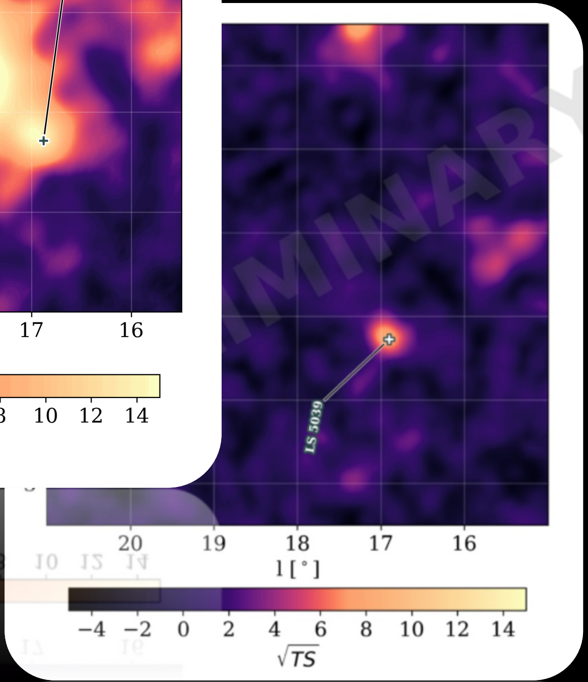
Salamon and his colleagues aren't the first generation of researchers to see potential in the cosmic interlopers, but it was only in the mid-1980s, when researchers thought they had stumbled on two potent sources of high-energy cosmic rays, the double stars Cygnus X-3 and Hercules X-1, that there seemed hope of pinning down cosmic ray origins. By now, that prospect has created a cottage in-

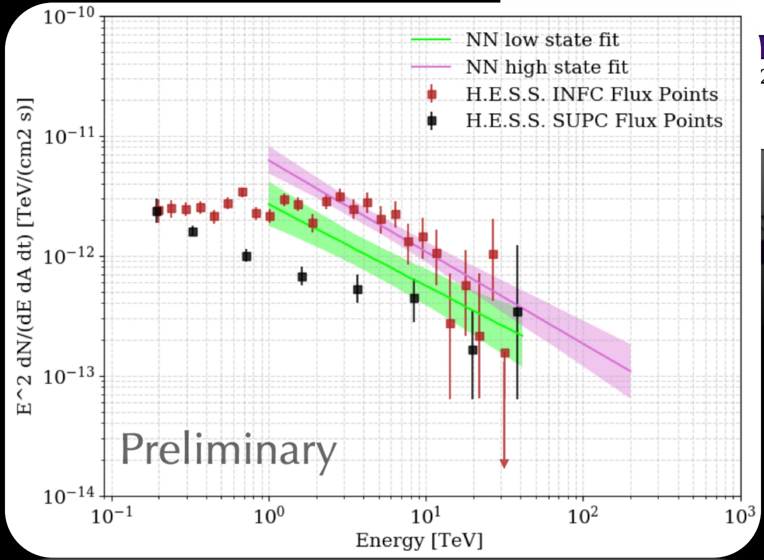
Science 08 Jan 1993:
Vol. 259, Issue 5092, pp. 177-179
DOI: 10.1126/science.259.5092.177

Wide Field, VHE/UHE Sensitivity & Angular Resolution Unite: Binary Systems/Microquasars

- Near J1825-138/J1826-34
- LS 5039 consists of a massive O-type main-sequence star, and a compact object (likely a black hole) - Radio Quiet, relatively young
- The two objects orbit each other every 3.9 days in an eccentric orbit
- HAWC detects emission (not only) > 20 TeV



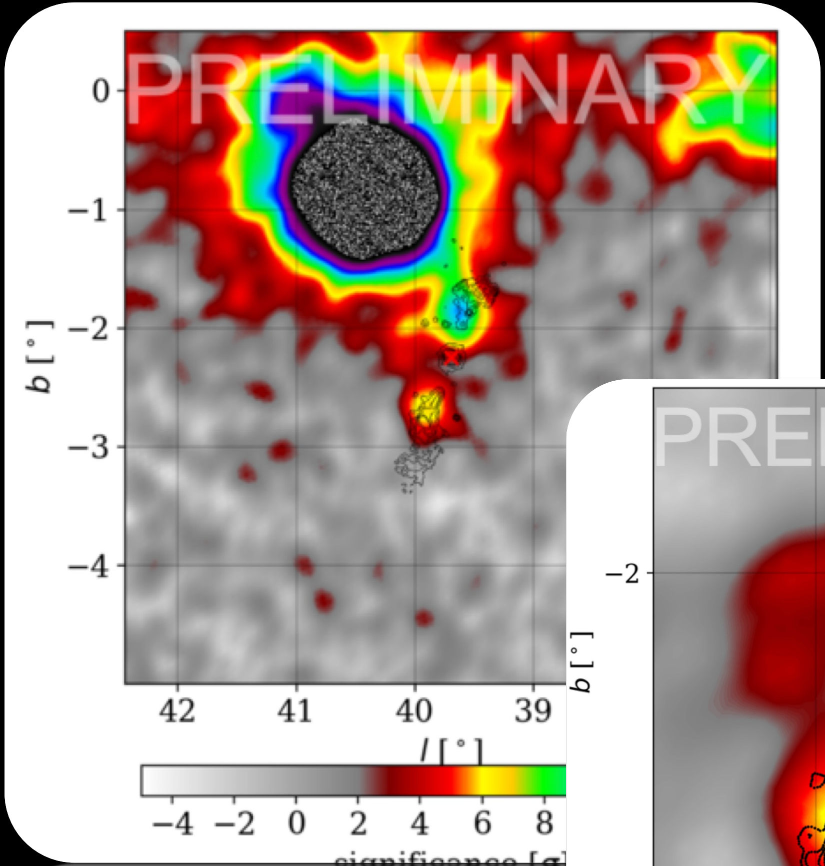


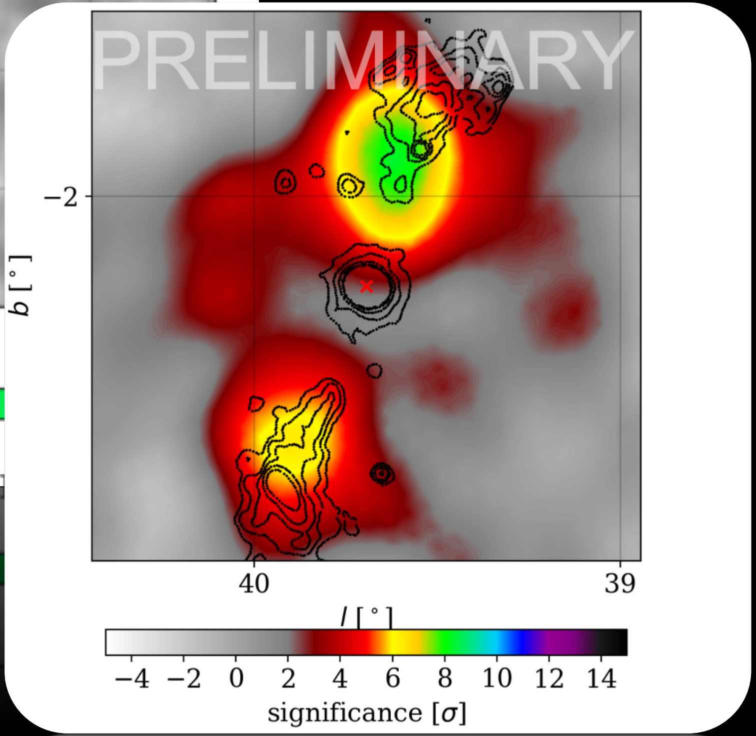


HEAD 19 (2022)

Wide Field, VHE/UHE Sensitivity & Angular Resolution Unite: Binary Systems/Microquasars

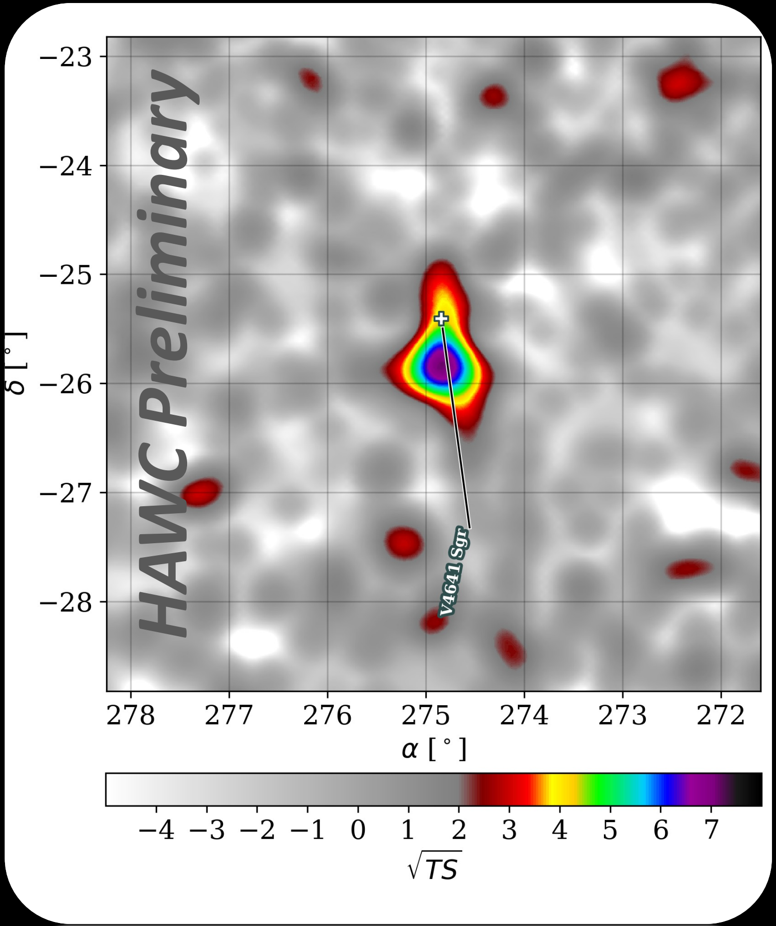
- SS433 is a microquasar near the bright extended MGRO J1908+06
- Black hole at location of red x, east and west jets form lobes of TeV emission.
- HAWC Discovery above 20 TeV (Nature 562, 82 (2018))
- Significance of each lobe is now 7-9 sigma
- H.E.S.S. confirmation reported this year

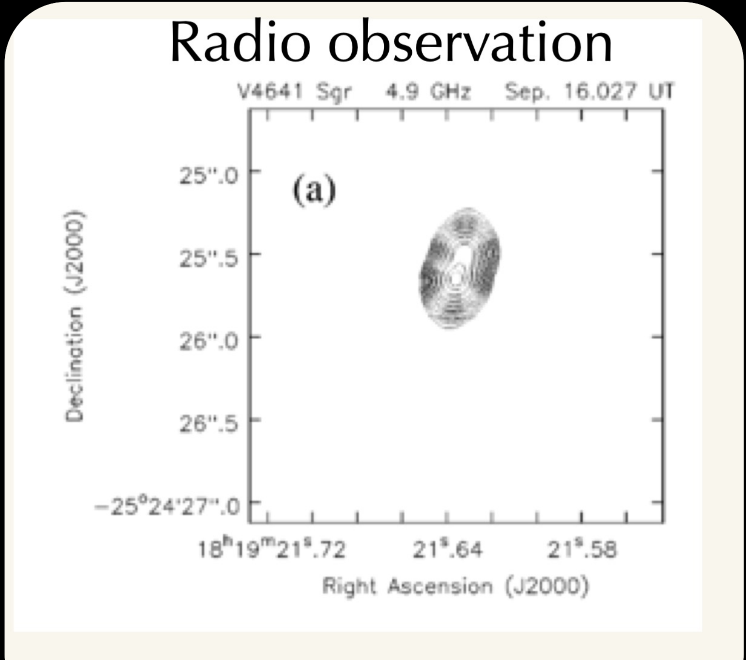




Wide Field, VHE/UHE Sensitivity & Angular Resolution Unite: Binary Systems/Microquasars

- Newly discovered emission > 20 TeV from the direction of x-ray binary V4641 Sgr
- One of the fastest superluminal jets in the Milky Way galaxy
  - Implies jet point toward Earth but radio jet is very small
- 9.7σ in latest HAWC data
  - 45° off zenith
  - Extent appears <0.25°

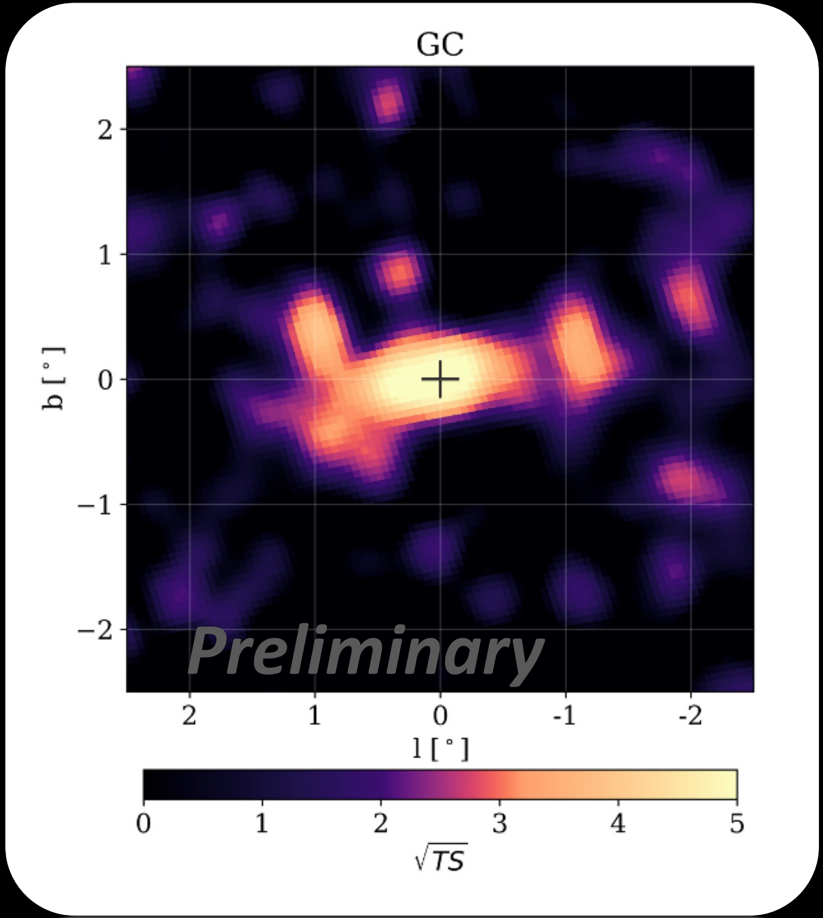




https://iopscience.iop.org/article/10.1086/317255/pdf

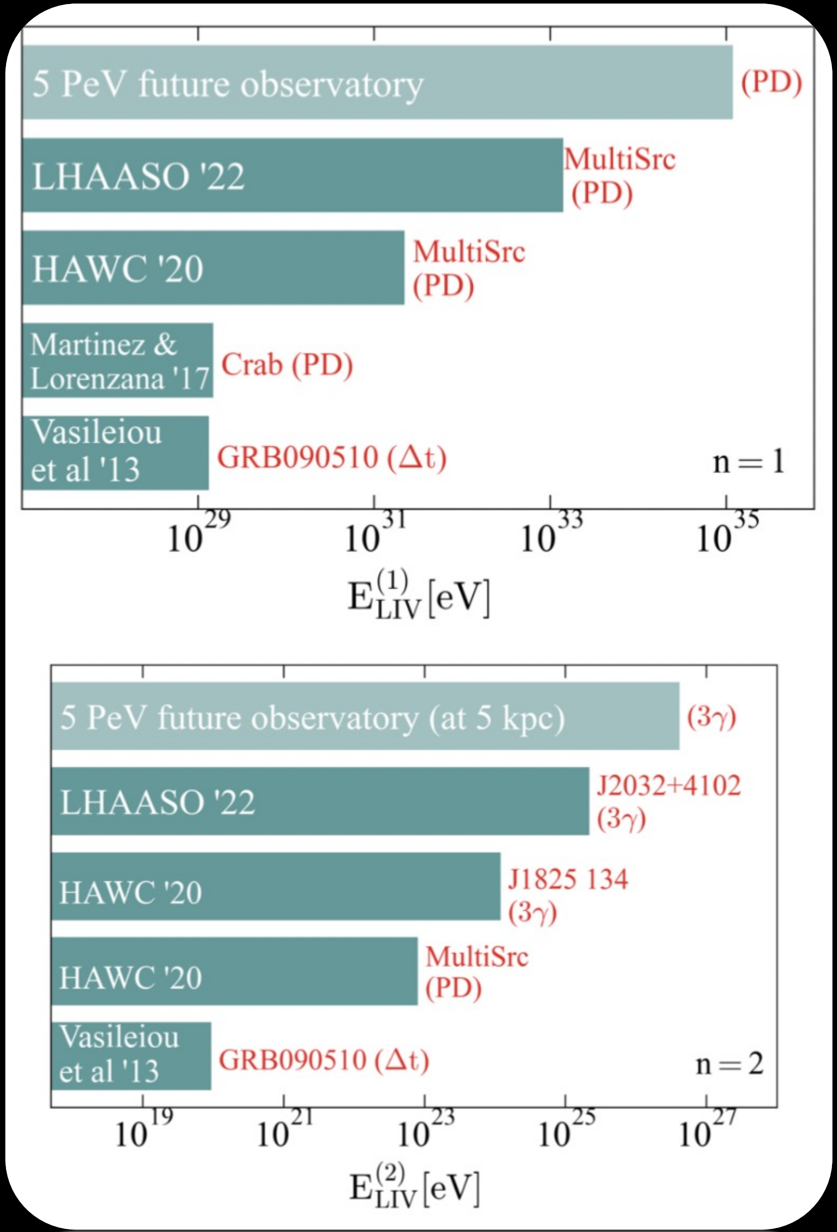
What about the Southern Hemisphere? – Galactic Center

- For HAWC: Transits with a minimum zenith angle of 47° (LHAASO/Tibet even further north)
- Preliminary spectrum comparable to H.E.S.S. beyond 20 TeV.
- Maximum Energy detected by HAWC
  - 1 sigma: 69.57 TeV
  - 2 sigma: 50.17 TeV
  - 3 sigma: 34.24 TeV



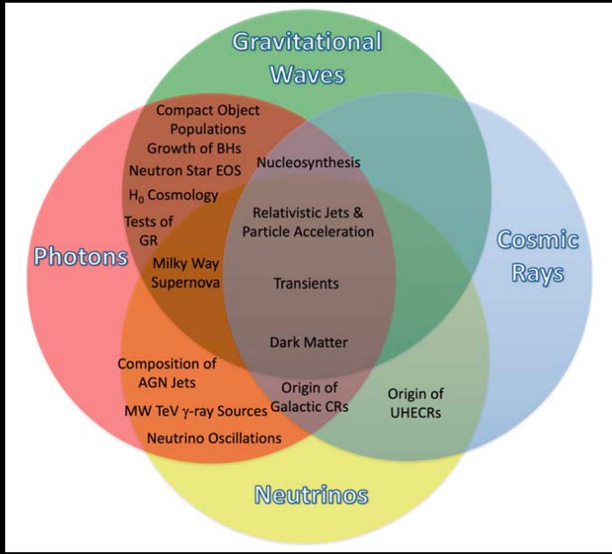
Fundamental Physics: Lorentz Invariance

- LI is a fundamental symmetry in the SM.
- GUTs/ST/QG can motivate some LIV
  - Photons of sufficient energy are unstable and decay over short timescales.
    - Photon decay (PD)
    - Photons splitting (3γ)
    - …
- **High energy photons will improve LIV limits**



Credit: H. Martínez-Huerta

What’s Next?



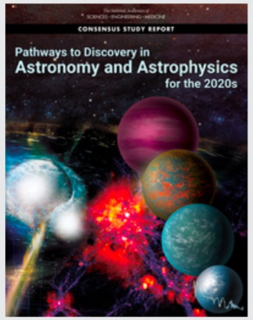
- **Southern Wide Field Gamma-Ray Observatory**

Panel on Particle Astrophysics and Gravitation recommends contributions by the U.S. to

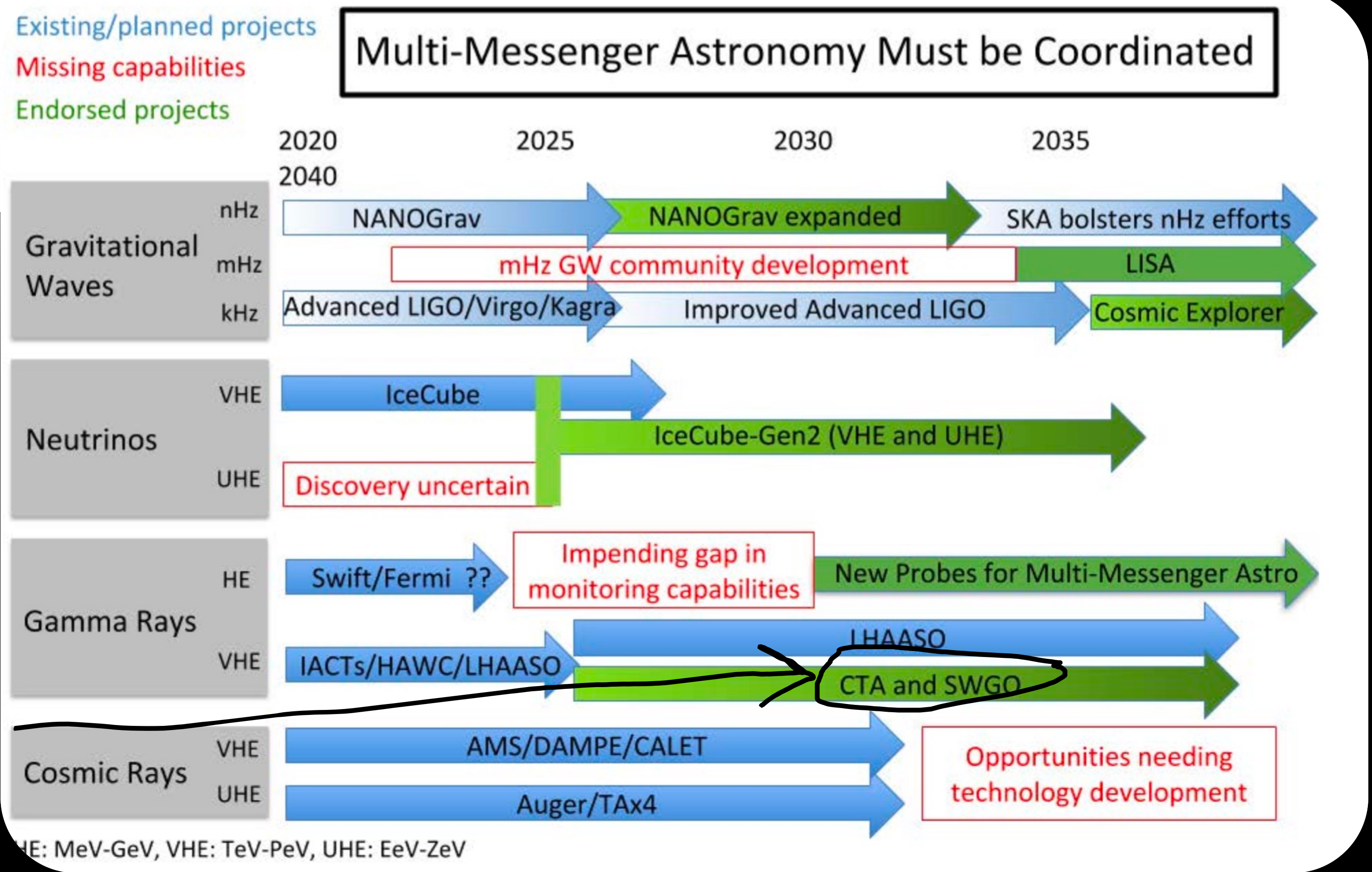
- SWGO at the level of ~$20M

The National Academies of SCIENCES ENGINEERING MEDICINE THE NATIONAL ACADEMIES PRESS

This PDF is available at http://nap.edu/26141 SHARE

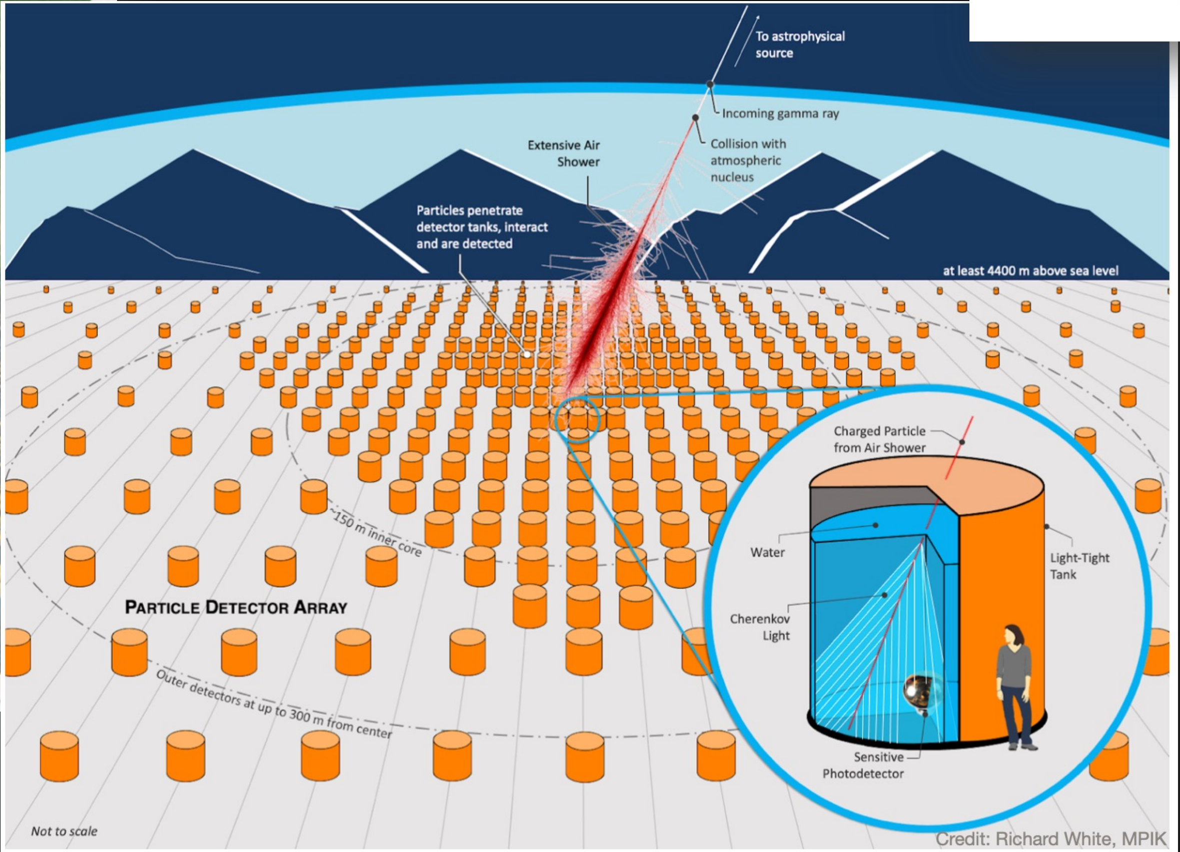


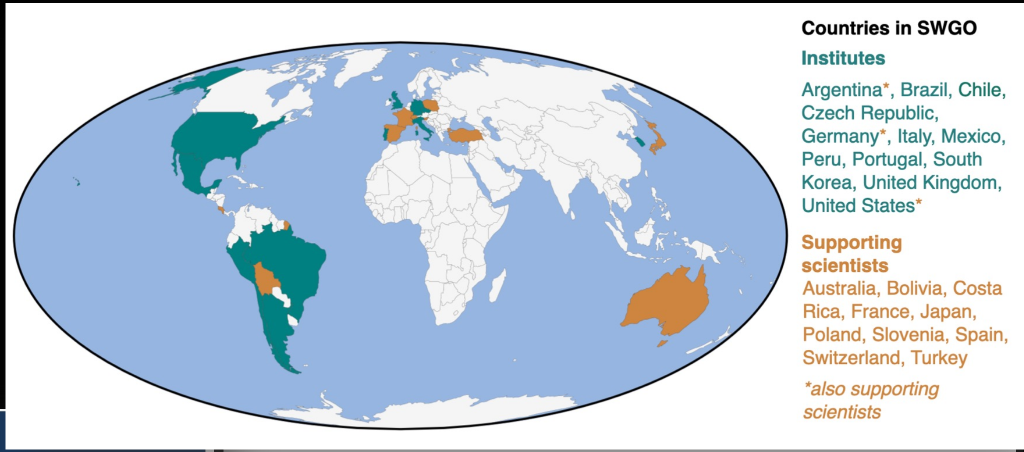
Pathways to Discovery in Astronomy and Astrophysics for the 2020s (2021)



The Future: Southern Wide Field Gamma-Ray Observatory

54 research institutions from 12 countries have signed an agreement for R&D on a gamma-ray observatory in the southern hemisphere. The aim of the collaboration is to develop a detailed proposal for the implementation of such an observatory, incl. site selection and technology choices.





Spokespersons

Spokesperson: Jim Hinton

Vice-spokespersons: Petra Huentemeyer, Ulisses Barres

Steering Committee

Countries in which institutes have signed the "Statement of Interest" in SWGO are asked to appoint a national representative to sit on the SWGO Steering Committee. The current membership of the steering committee is:

- Adrian Rovero (Argentina)
- Ronald Shellard (Brazil)
- Claudio Dib (Chile)
- Jakub Vicha (Czech Republic)
- Christopher Van Eldik (Germany)
- Alessandro de Angelis (Italy, INFN)
- Marco Tavani (Italy, INAF)
- Andres Sandoval (Mexico)
- Jose Bellido Caceres (Peru)
- Mário Pimenta (Portugal)
- Jason Lee (South Korea)
- Jon Lapington (UK)
- Pat Harding (USA)

The Spokesperson and Vice-spokespersons are ex-officio members of the steering committee.

swgo.org

SWGO
The Southern Wide-field Gamma-ray Observatory

- Four host country candidates
- Exploratory Site visits planned for this fall

The Future: Other Efforts in the Southern Hemisphere

CONDOR

Atacama Astronomical Park in Chile

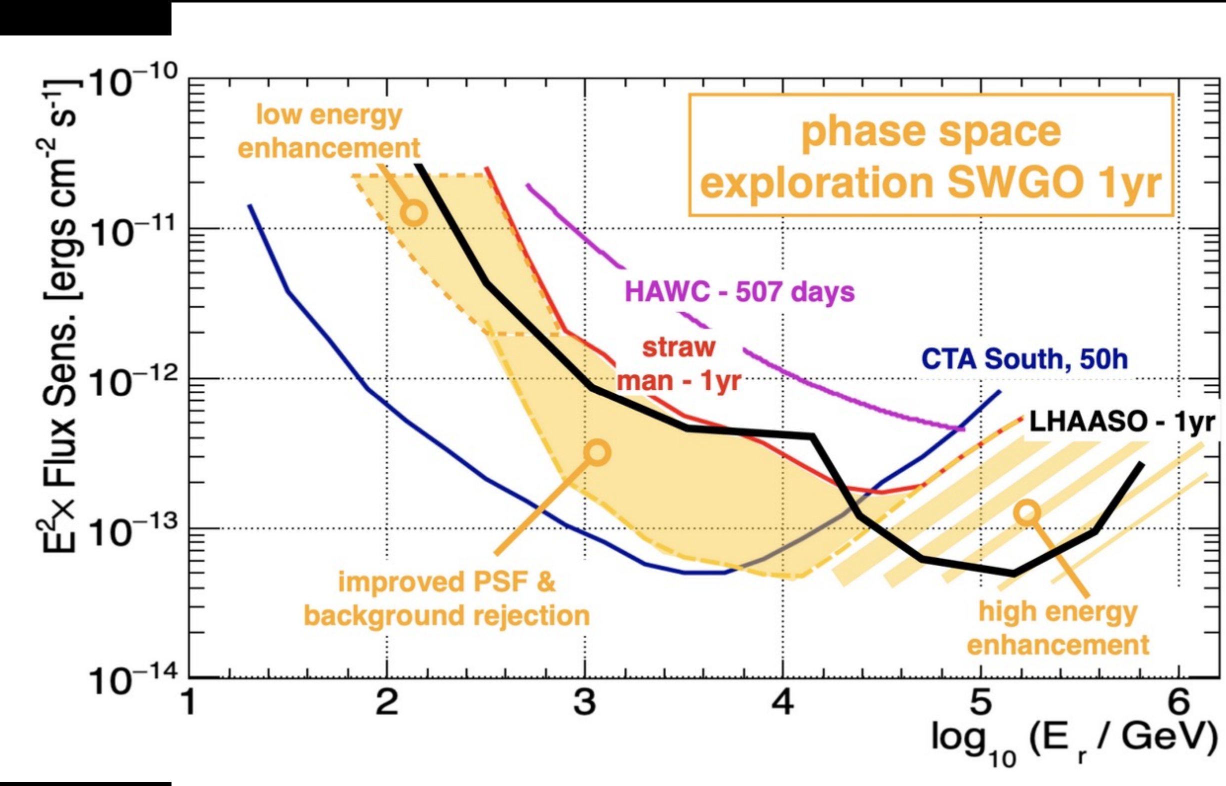
100 GeV – ~1 TeV

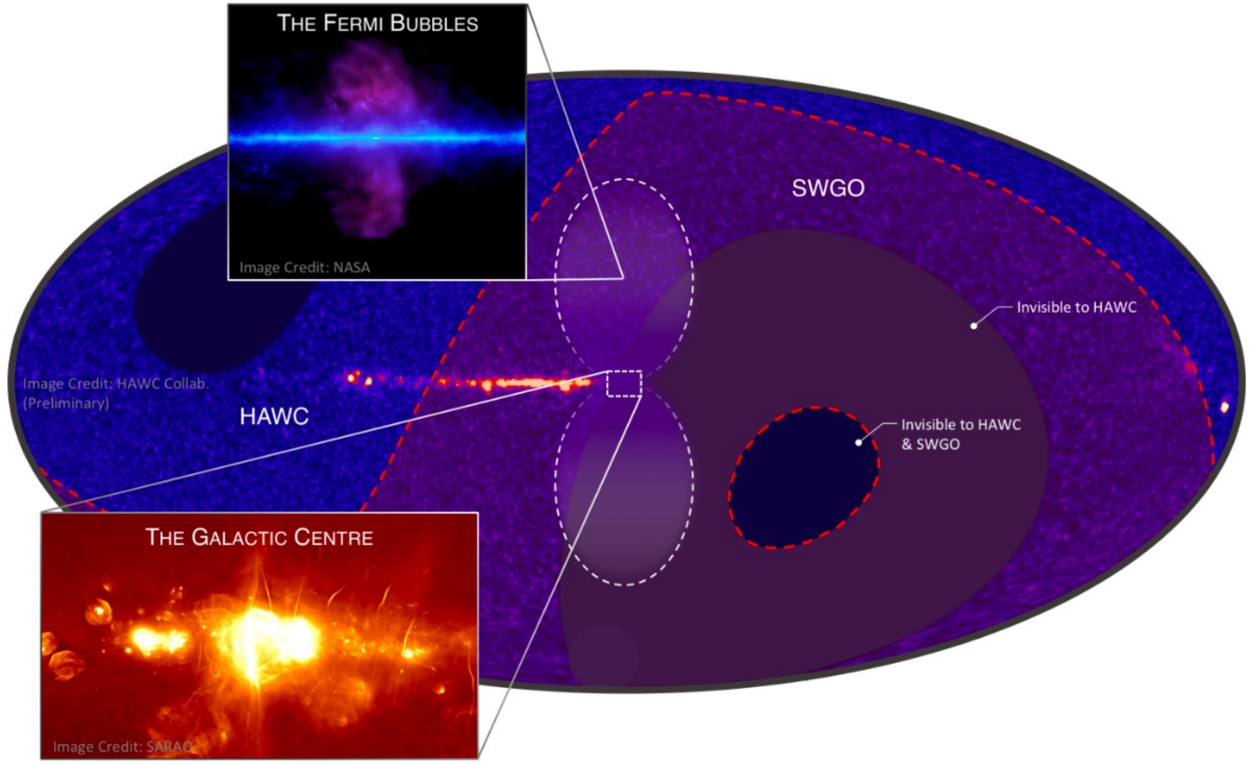
ALPACA

Outskirts of La Paz in Bolivia

10 TeV – ~1 PeV

SWGO: Sensitivity Curves and Coverage





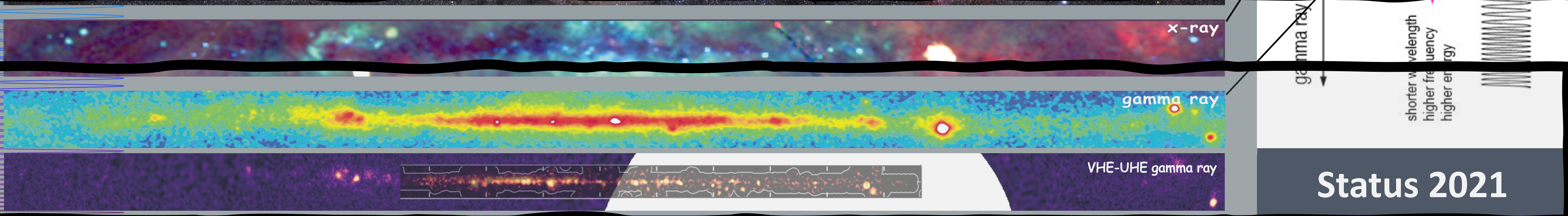
PoS ICRC2021, 903 (2021)

Astro2020: APC White Paper; BAAS, Vol. 51, Is. 7, 109 (2019)

Windows on the Universe

Final Comments:

- Advancements in ground-based Particle Detection Arrays (PDAs) have led to unexpected, sometimes paradigm-shifting discoveries
- Multi-instrument and -messenger analyses will provide unprecedented science output & gamma-ray astronomy with current and future PDAs will make crucial contributions
- Principles of open science and publicly available data will play an unprecedented role in future projects ***(Initiative for a VHE Open Data Format)***



Status 2021

NSF'S 10 BIG IDEAS

Windows on the Universe

radio continuum (408 MHz)

Final Comments:

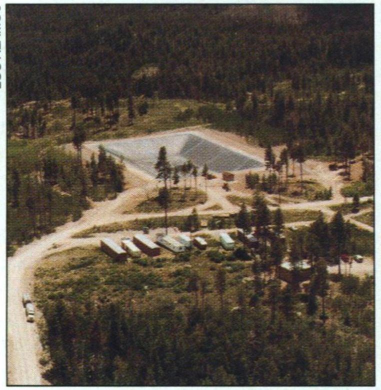
ASTROPHYSICS

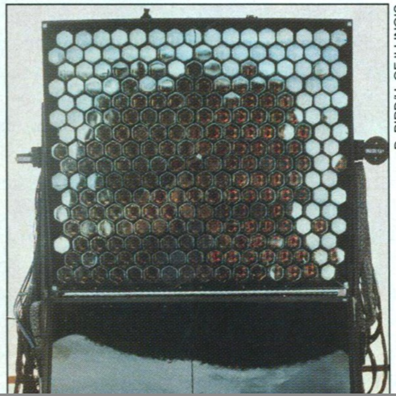
Astronomers Turn New Eyes On the Cosmic Ray Sky

To understand why physicists have traditionally shunned cosmic rays, think of these mysterious visitors as gate-crashers to a party. Not only do they appear uninvited and without pedigree, but they bring with them a menagerie of other unwanted creatures whose presence can only wreak havoc. But lately, physicists have started to wonder about these mysterious strangers. Just what kind of environment could spawn this uniquely energetic lot? Cosmic rays are now in vogue.

A steady rain of these interlopers falls upon the upper atmosphere from all directions of space. As they interact with the thin gases, cascading showers of particles—billions of them—are spawned. And these, in turn, insouciantly trespass through the pristine grounds of carefully tended physics experiments, confounding detectors and ruining many a research party. But lately particle physicists have become entranced by the observation that some cosmic rays carry energies of 10^{20} electron volts (eV)—10 million times higher than will be attained by the Superconducting Super Collider (SSC).

R. ONG


LOS ALAMOS


D. BIRD/U. OF ILLINOIS

as ever. The verdict on C... cules X-1 is in, and it's ... aren't the cosmic ray bea... be. But that hasn't disco... convinced the cosmic ra... for a longer haul of data...

The challenge amoun... scramb... than 99... charged... and he... helium... magnet... particle... so that... seem t... from a... neutral... to poin... origin, ... gamma... photons—would survive the trip from source to Earth. (Neutrons, the most common neutral particles, would decay back into protons long before they reached Earth.) But gamma rays, says Cronin, constitute only one or two out of every 100,000 cosmic rays, which makes for a dismaying signal-to-background challenge.

Worse, at the highest energies even the "background" of charged cosmic rays dwindles to almost

> To understand why physicists have traditionally shunned cosmic rays, think of these mysterious visitors as gate-crashers to a party. Not only do they appear uninvited and without pedigree, but they bring with them a menagerie of other unwanted creatures whose presence can only wreak havoc. But lately, physicists have started to wonder about these mysterious strangers. Just what kind of environment could spawn this uniquely energetic lot? Cosmic rays are now in vogue.

and gamma rays!

x-ray

Science 08 Jan 1993:
Vol. 259, Issue 5092, pp. 177-179
DOI: 10.1126/science.259.5092.177

VHE-UHE gamma ray

Status 2021