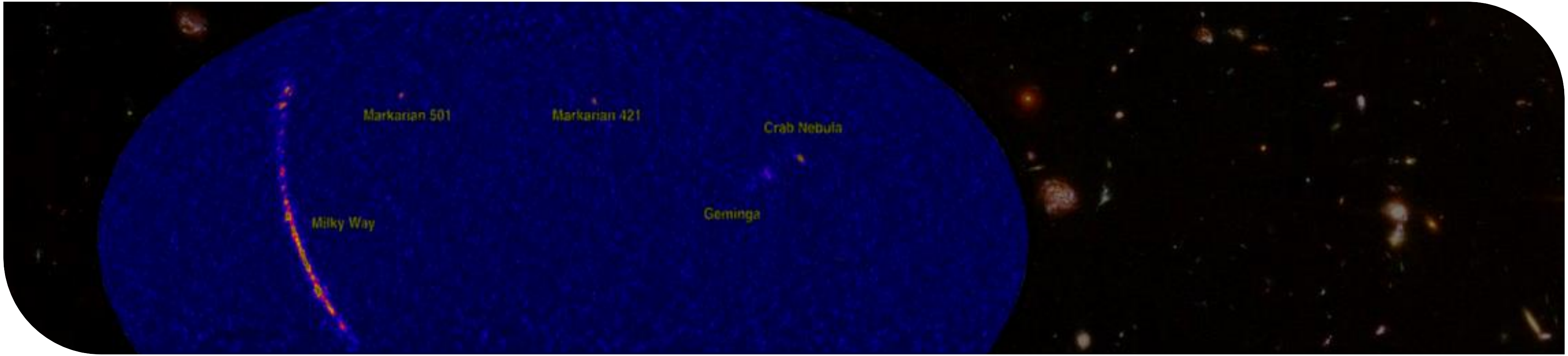
The HAWC-Observatory

High Altitude Water Cherenkov Gamma-Ray Observatory

Talk by Paul Filip (presentee), Markus Roth (supervisor), Maximilian Stadelmaier (supervisor)



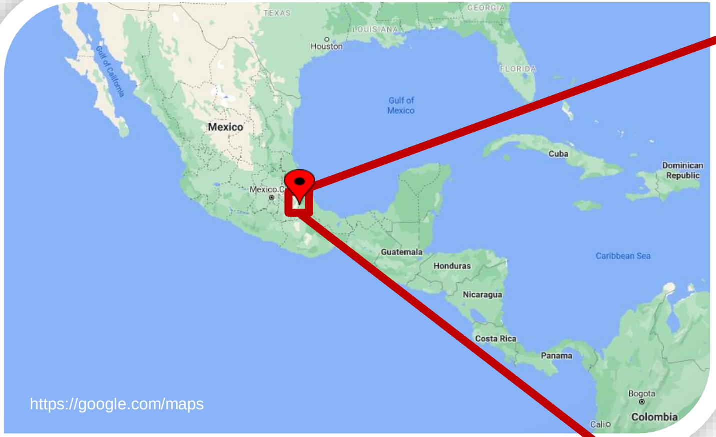
Outline

- **HAWC collaboration, location & goals**
- **The HAWC observatory in detail**
  - Measurement principle
  - Experimental setup
  - Event reconstruction
  - Sensitivity & Uncertainty
  - Data analysis & Hadron rejection
- **Results (so far!)**

A multinational collaboration

- **And many more!**
  - 37 universities and institutes
  - eight different countries, four continents

Location of the experiment



- Puebla, Mexico
- Located in national park
- Next to radio telescope LMT
- 4100 m above sea level **(!)**

Scientific goals

- Observe TeV gamma-rays
- Sensitivity of $50\ \mathrm{mCrab}$ at 5σ over $1\ \mathrm{yr}$.
  - $1\ \mathrm{mCrab} = 10^{-3}\ \times$ 
  - $50\ \mathrm{mCrab} \approx 1.2 \times 10^{-12}\ \frac{\mathrm{J}}{\mathrm{m^2 s}}$
- $2\pi\ \mathrm{sr}$ instantaneous field of view
- Angular resolution $0.2° - 2°$ of events

HAWC (High Altitude Water Cherenkov) Observatory for Surveying the TeV Sky

Brenda L. Dingus for the HAWC Collaboration[1]

Los Alamos National Lab, Los Alamos, NM 87545
dingus@lanl.gov

Abstract. The HAWC observatory is a proposed, large field of view (~2 sr), high duty cycle (>95%) TeV gamma-ray detector which uses a large pond of water (150 m x 150 m) located at 4300 m elevation. The pond contains 900 photomultiplier tubes (PMTs) to observe the relativistic particles and secondary gamma rays in extensive air showers. This technique has been used successfully by the Milagro observatory to detect known, as well as new, TeV sources. The PMTs and much of the data acquisition system of Milagro will be reused for HAWC, resulting in a cost effective detector (~6M$) that can be built quickly in 2-3 years. The improvements of HAWC will result in ~15 times the sensitivity of Milagro. HAWC will survey 2π sr of the sky every day with a sensitivity of the Crab flux at a median energy of 1 TeV. After five years of operation half of the sky will be surveyed to 20 mCrab. This sensitivity will likely result in the discovery of new sources as well as allow the identification of which GLAST sources extend to higher energies.

Keywords: Gamma rays; Cosmic rays; Instrumentation
PACS: 95.55.Ka, 95.55.Vj, 95.75.-z, 95.85.Pw, 95.85.Ry

HAWC DESIGN BASED ON MILAGRO EXPERIENCE

Milagro detects extensive air showers by observing the Cherenkov light produced by relativistic particles hitting a $3500 m^2$ pond of water. Milagro has successfully used this technique to detect new sources of TeV gamma-rays [1, 2, 3] as well as diffuse emission from the Galactic plane [3, 4]. The technique of water Cherenkov detection can be enhanced to give a dramatic increase in sensitivity [5].

HAWC is such a water Cherenkov TeV observatory with a large field of view and high duty cycle that will complement the large field of view and high duty cycle of the GLAST GeV gamma-ray observatory. HAWC will reuse the 900 Milagro photomultiplier tubes (PMTs) and much of Milagro's data acquisition system in a pond that is 6 times larger than Milagro and placed at an altitude of ~4300m above sea level as compared to the elevation of Milagro at 2650 m. The increase in elevation will reduce the energy threshold giving significant effective area at energies below a TeV as seen in Figure 1. The large size of HAWC will result in an improved point spread function of two dimensional Gaussian sigma of 0.25° to 0.4° depending on the number of PMTs hit. The ability to reject the cosmic ray background will also be improved because the larger area increases the probability of detecting the penetrating muons which are more prevalent in cosmic-ray versus gamma-ray initiated showers. The design and sensitivity of HAWC is based on the same Monte Carlo technique that has confirmed the performance of Milagro.

https://aip.scitation.org/doi/pdf/10.1063/1.2757390

Why look for γ-rays in particular?

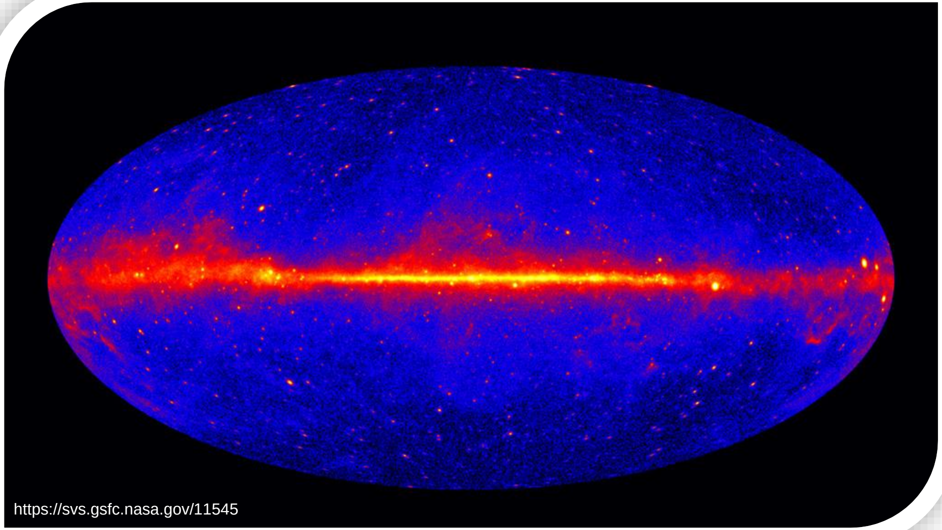
- Photon trajectory unaffected by cosmic E- and B-Fields
- Identification of emitter possible!

➡ Detect origins of HE cosmic rays

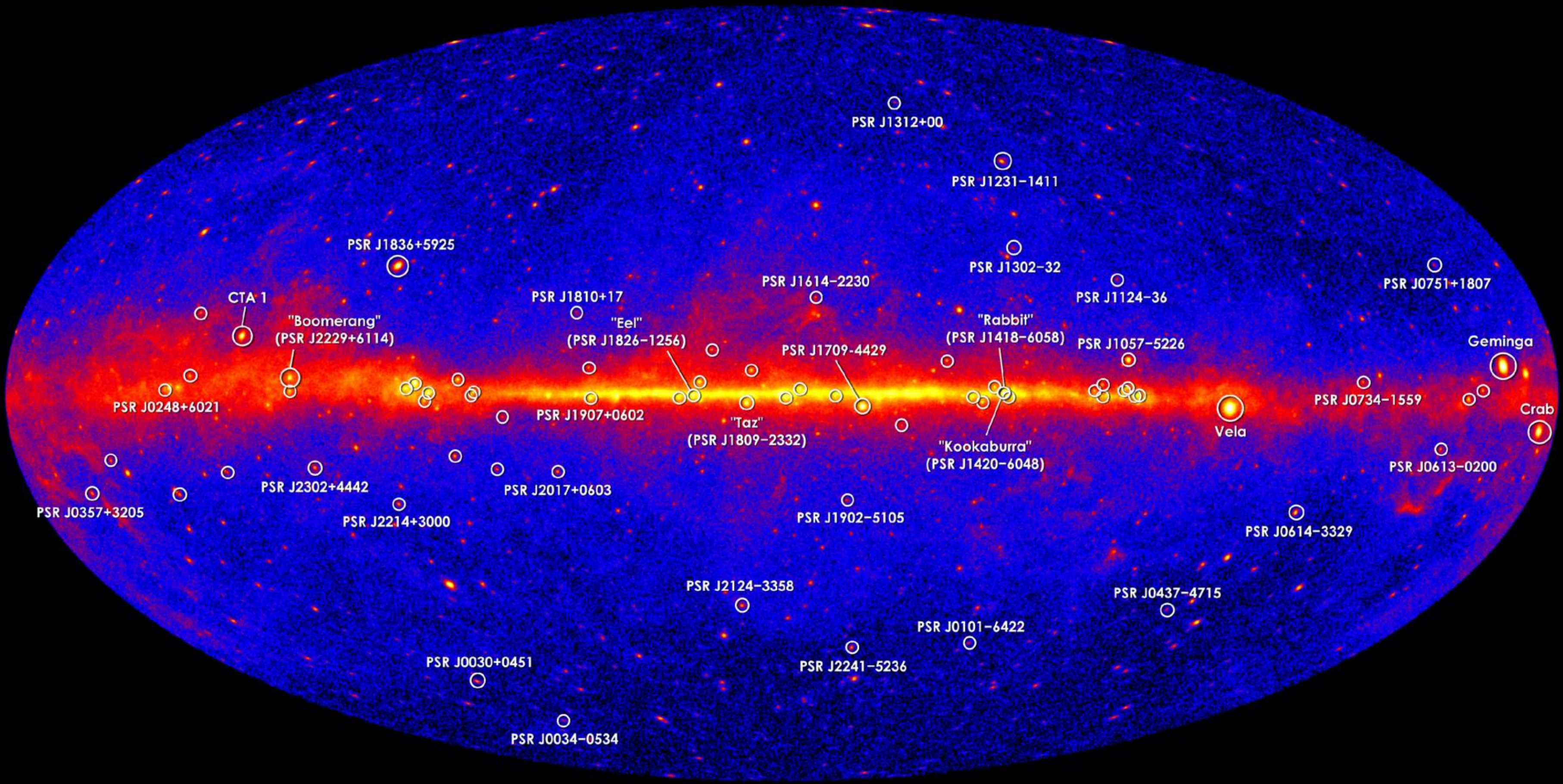
➡ Discover accelerator mechanisms

➡ Identify astronomical objects

➡ Observe new physical phenomena

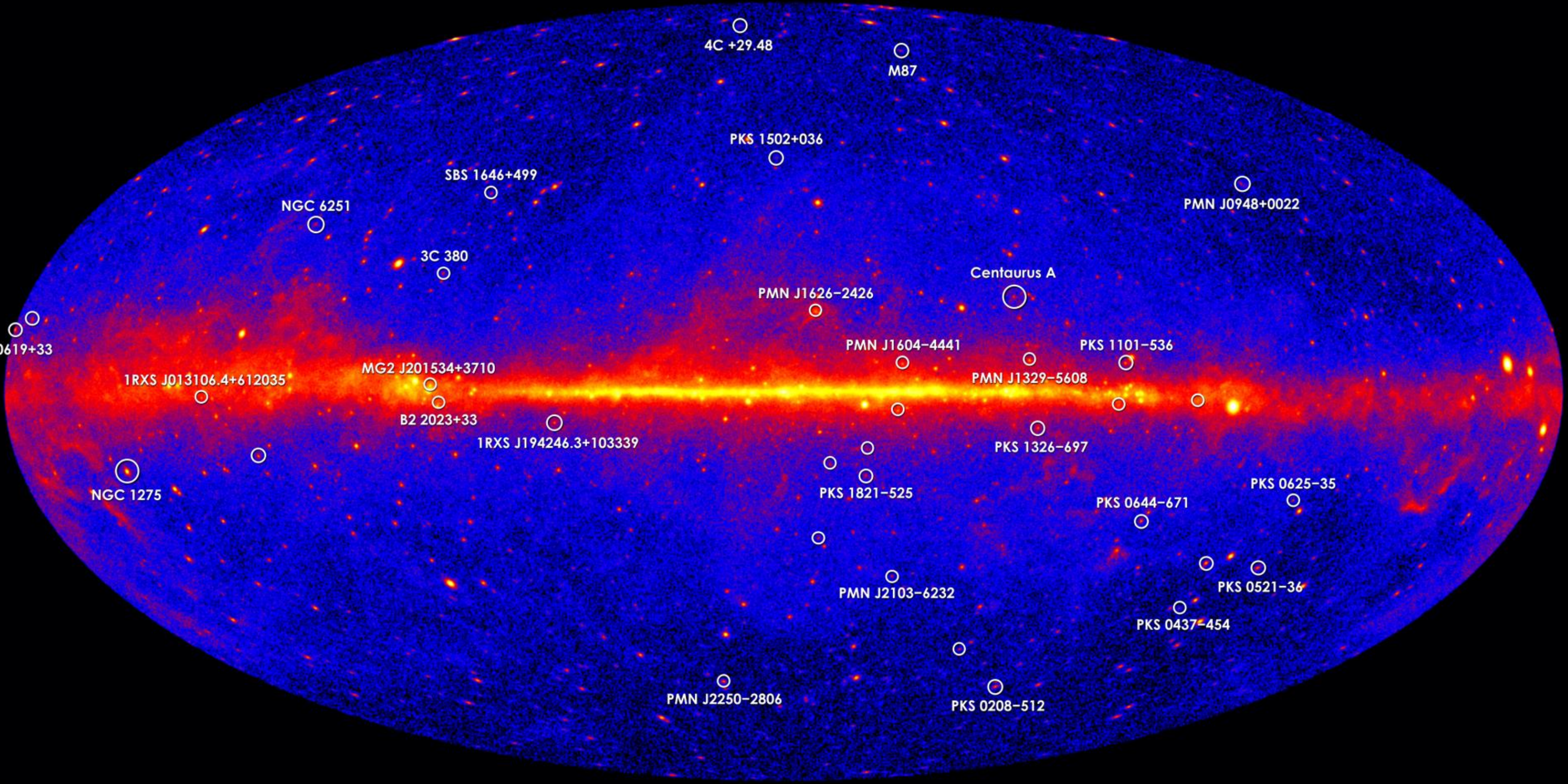


Known γ-ray sources: Pulsars



https://svs.gsfc.nasa.gov/11545

Known γ-ray sources: Active Galactic Nuclei



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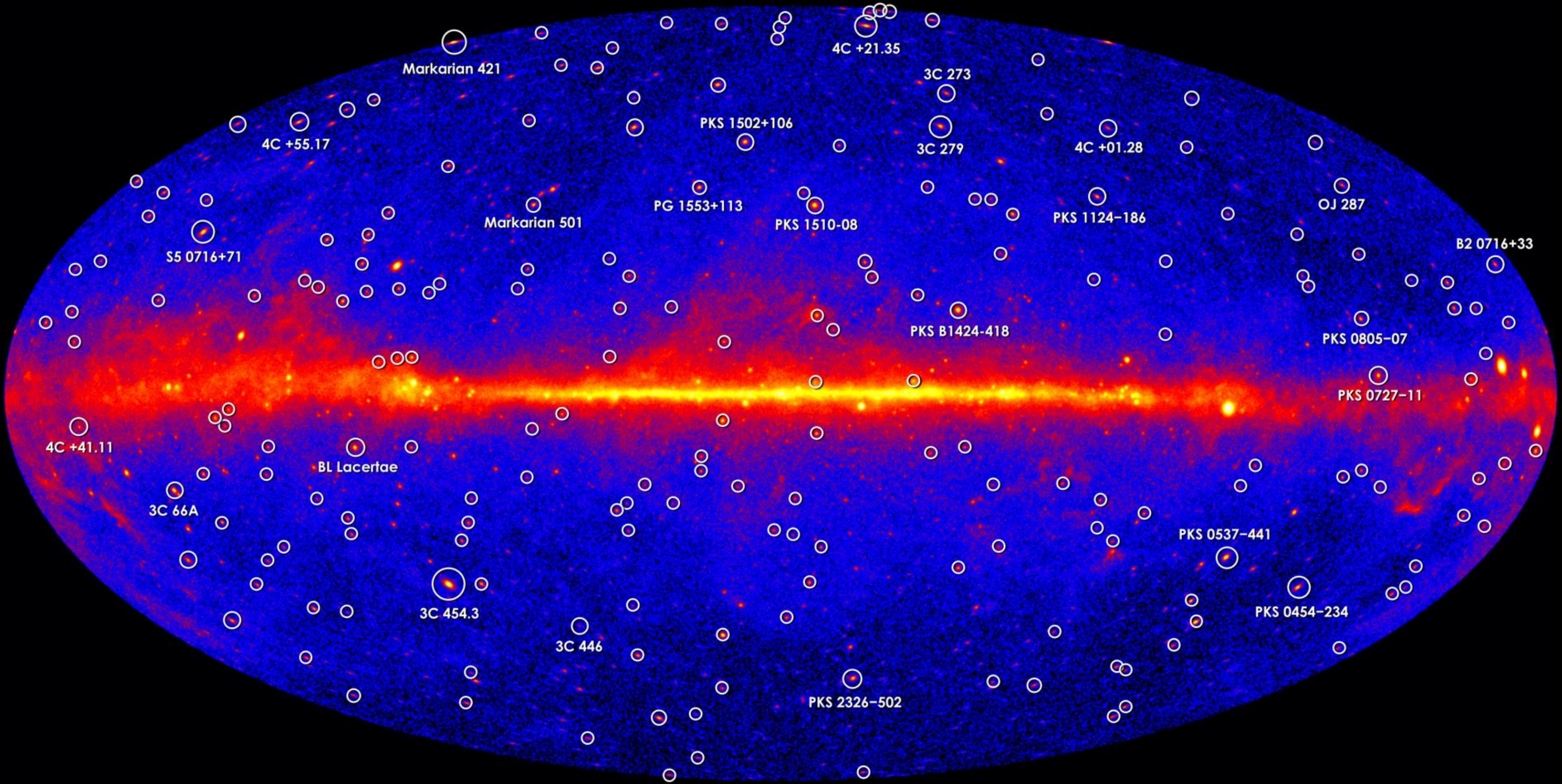
Known γ-ray sources: Blazars



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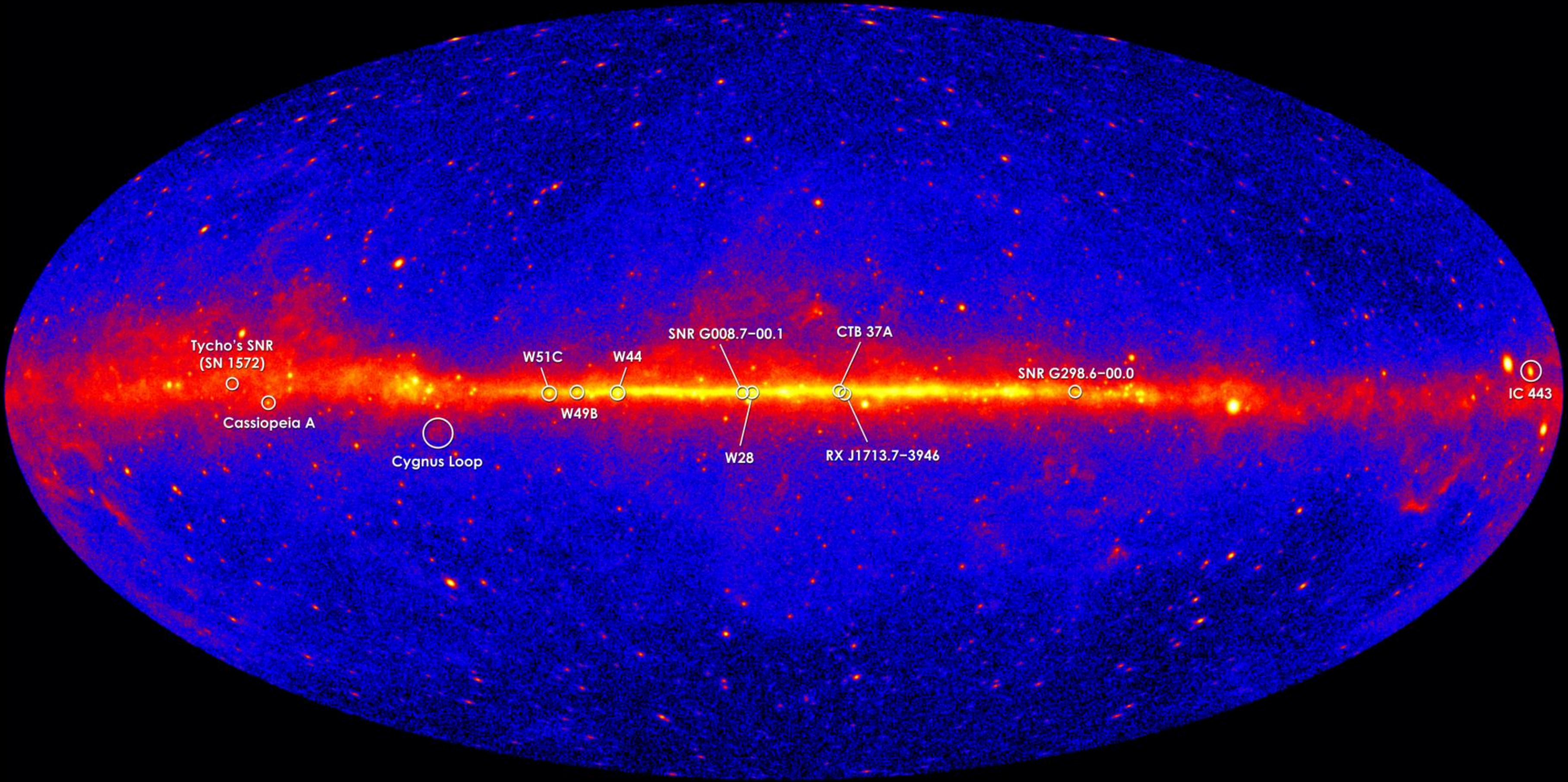
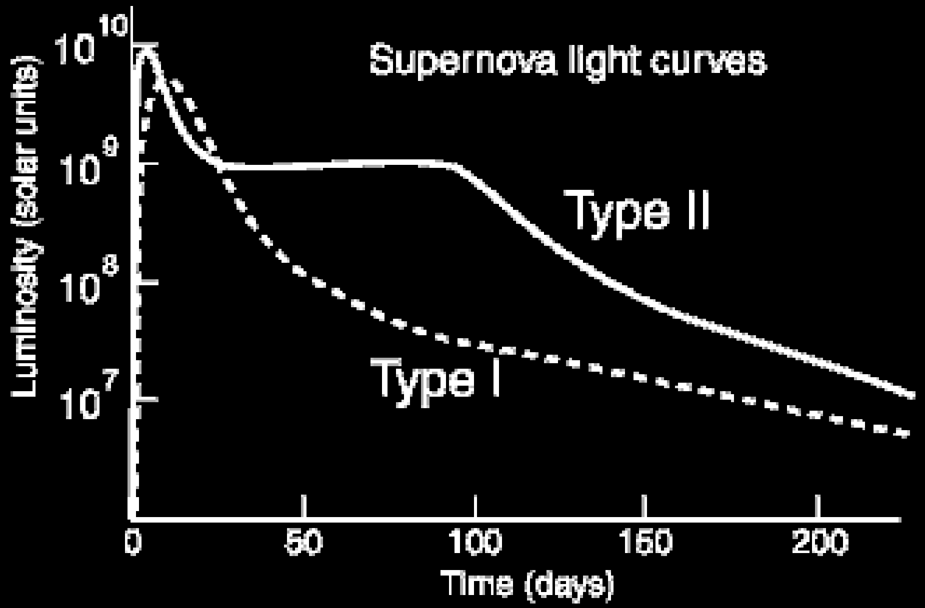
Known γ-ray sources: Supernova remnants



https://svs.gsfc.nasa.gov/11545

Known γ-ray sources: Transient events

- Gamma Ray Bursts (GRBs)
- Neutron star merger
- Novae and Supernovae
- X-Ray binaries
- Unknown phenomena



Adapted from Chaisson & McMillan

The HAWC-Observatory in detail

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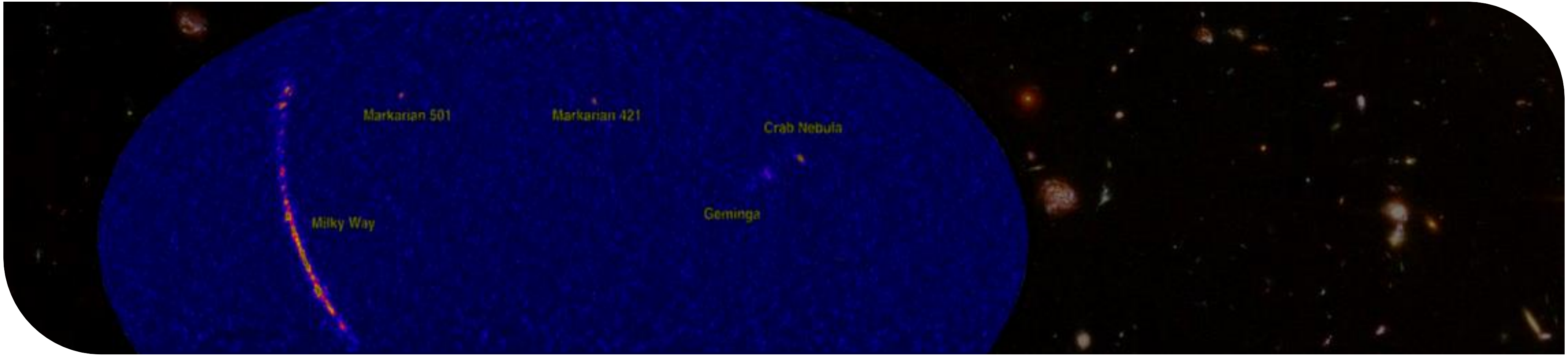


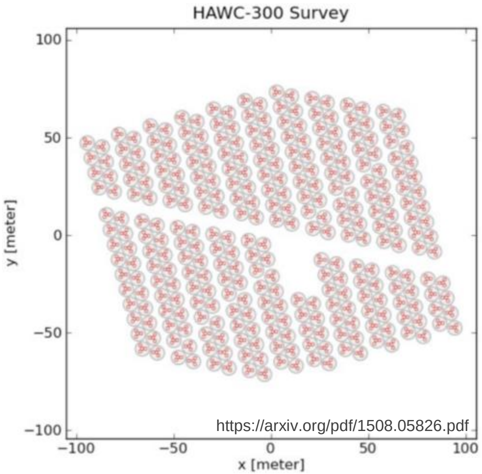
Measurement principle

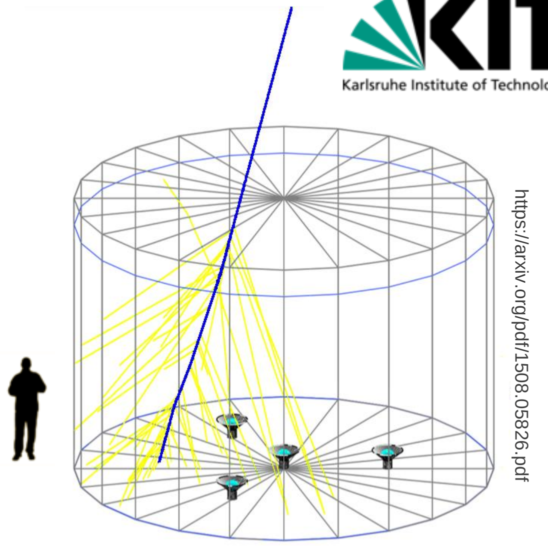
- High energy ($\approx 10^{12}$ eV) γ introduces EM-shower in air
- Electrons produce Cherenkov radiation in water tanks
- Cherenkov light detected by Photomultipliers (PMT)
- Use arrival time to reconstruct incident particle direction

- Signal amplitude holds information about incident particle energy

Experimental setup

- 300 tanks with $200\,000\ \mathrm{l}$ purified water (each)
- Every tank equipped with four PMTs
- Roughly $12\,000\ \mathrm{m}^2$ active detector area
- Outrigger array with 345 small water tanks





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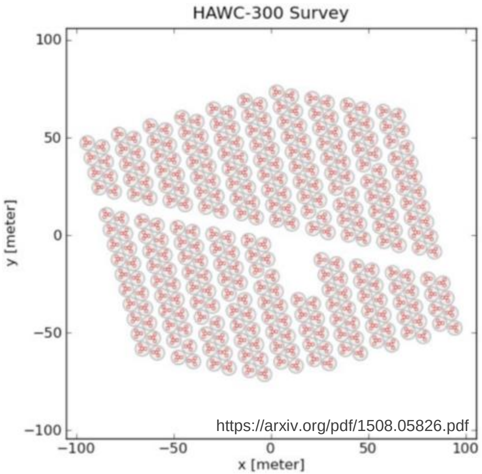
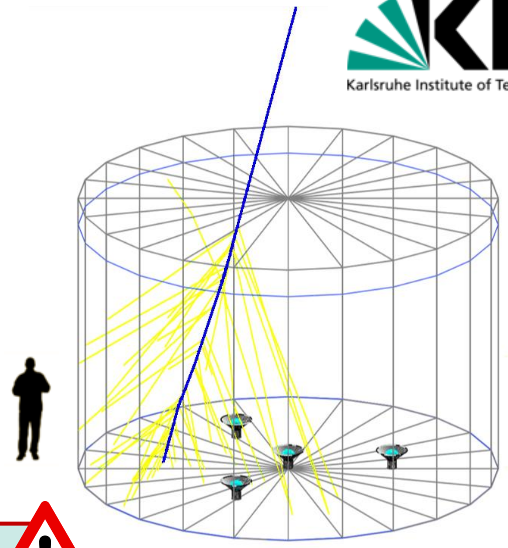




https://arxiv.org/pdf/1508.05826.pdf

Why only four PMTs ?

$$\theta = \arccos\left(\frac{1}{n_{H_2O}\ \beta}\right) \approx \arccos\left(\frac{1}{1.33}\right) = 43^{\circ}$$

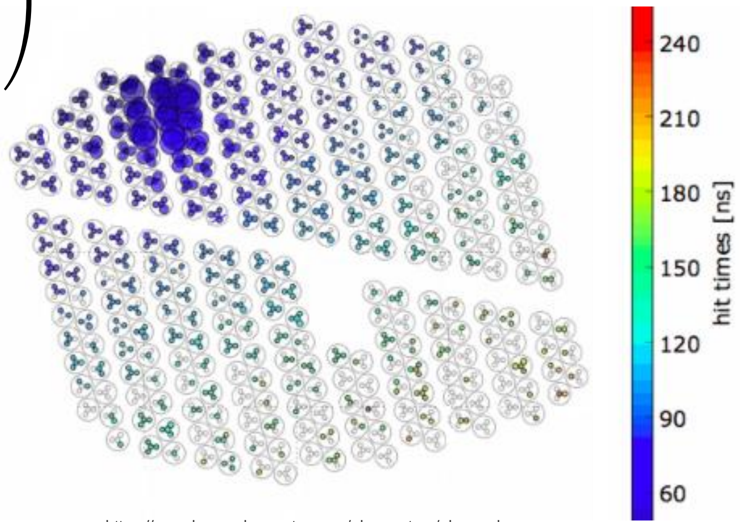
Large Cherenkov cone reaches at least one PMT regardless of incident particle direction

Event Reconstruction

- Consider signals in > 15 PMTs within $150\ \mathrm{ns}$ an „event“
- Fit lateral shower distribution to signal shape to find „shower core“

$$S_i(A, r_0, r_i) = A \cdot \left(\frac{1}{2\pi\sigma^2}\, e^{-\left(\frac{r_i - r_0}{2\sigma^2}\right)^2} + \frac{N}{\left(0.5 + \frac{r_i - r_0}{r_\mathrm{M}}\right)^3} \right)$$

  - Signal amplitude A (correlates with E_0)
  - Shower core location r_0
  - Photomultiplier location r_i
  - Molière radius $r_\mathrm{M} \approx 120\ \mathrm{m}$ (material specific)
  - Gaussian shower width $\sigma \approx 10\ \mathrm{m}$
  - Tail normalisation $N \approx 5 \times 10^{-5}$

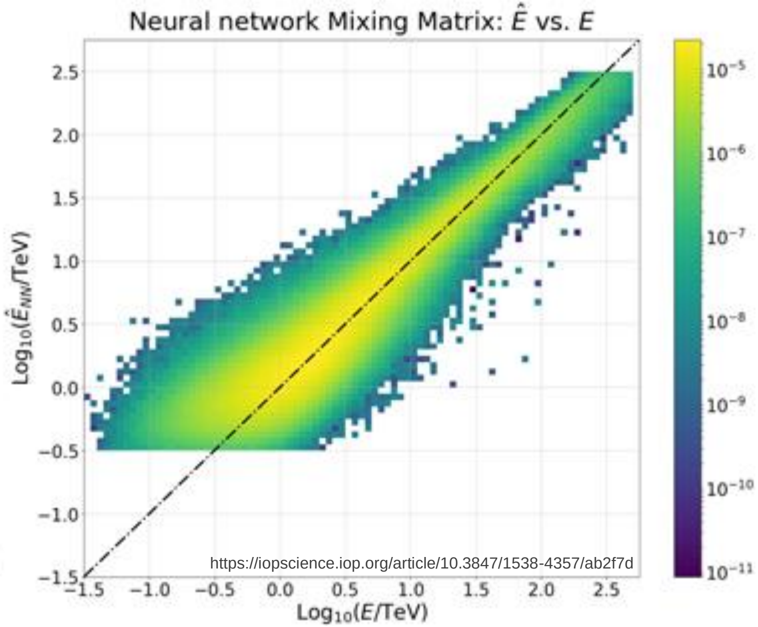


https://www.hawc-observatory.org/observatory/ghsep.php

Event Reconstruction

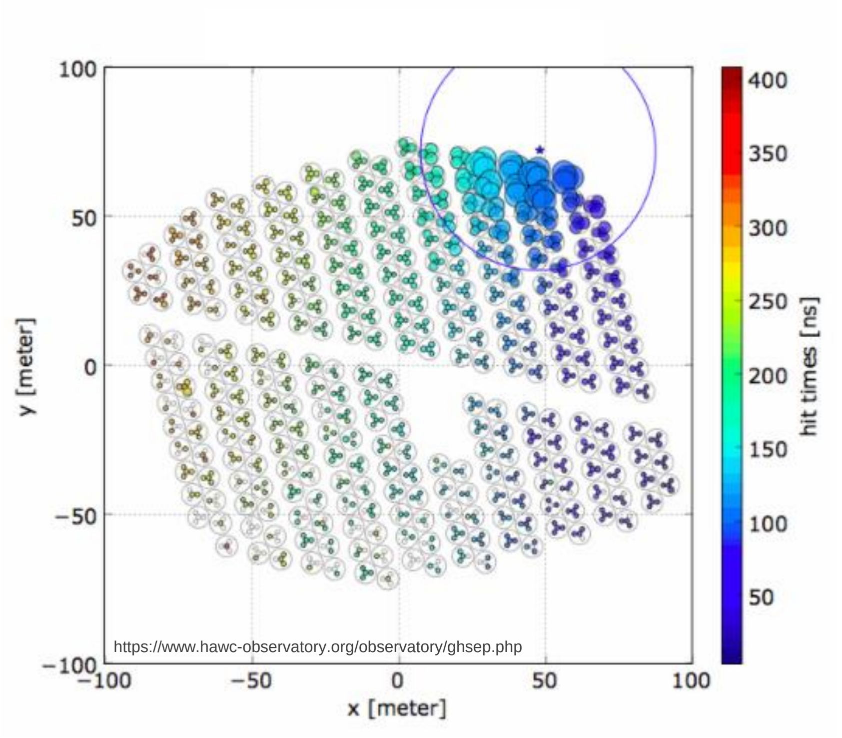
- Fit signal arrival times to shower plane hypothesis* to collect information about origin and direction of the incident particle

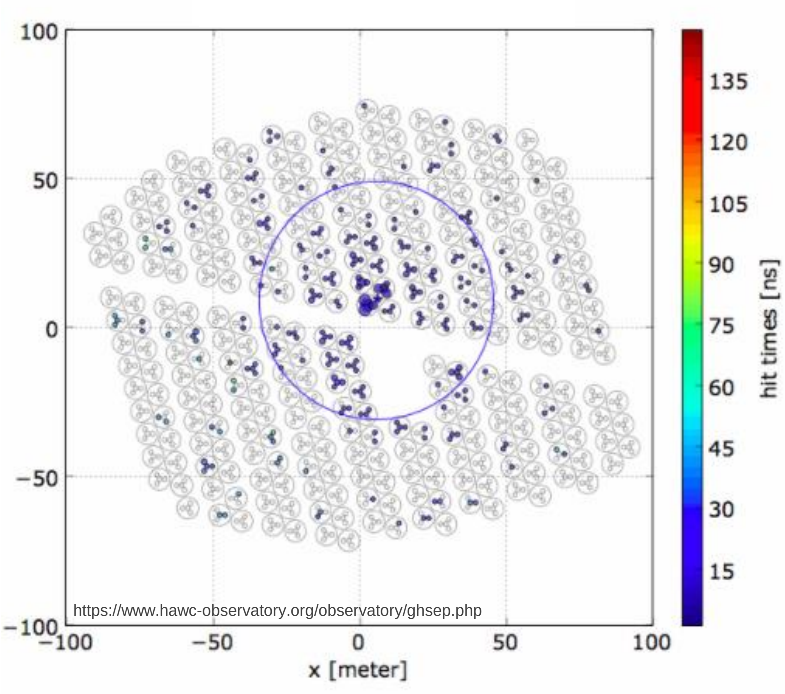
- Use artificial neural network to estimate E_0
  - Two hidden layers, 14 and 15 nodes
  - Train neural network with MC simulations
  - Rely on three input parameters:
    - Energy deposited in detectors E_{dep}
    - Ratio of shower footprint contained in HAWC
    - Attenuation of shower by atmosphere



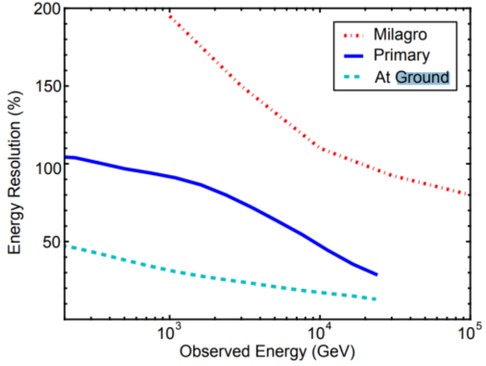
* After correcting for shower curvature + sampling

Event Reconstruction



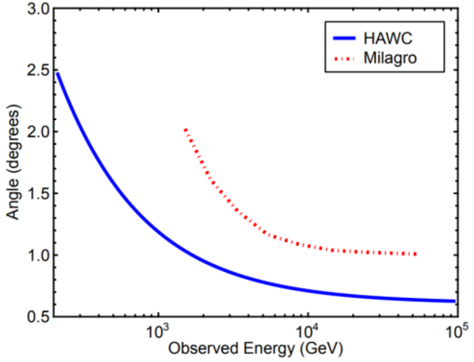


Sensitivity & Uncertainty



Energy resolution

- Primary energy is reconstructed to $\pm$X % of true E_0
- Energy resolution shrinks with higher energy
- Major improvement to previous experiments



Angular resolution

- Standard deviation on plane wave fit
- Decreases with energy as well ➡ **Why**
- Sensitivity on γ-ray point sources
- Comparable to IACTs like **H.E.S.S.** or **VERITAS**

https://iopscience.iop.org/article/10.1088/1742-6596/375/1/052026

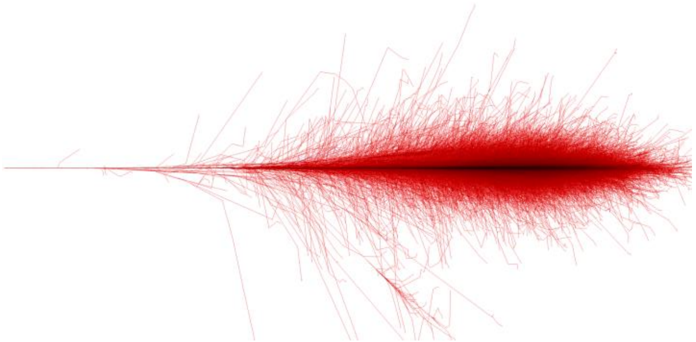
Data Analysis & Hadron rejection

- Expected trigger rate from **Cosmic rays**

$$R(1\ \mathrm{TeV}) = \int \left.\frac{\mathrm{d}\Phi_{\mathrm{CR}}}{\mathrm{d}\Omega}\right|_{1\ \mathrm{TeV}} \mathrm{d}\Omega \times A_{\mathrm{D}} \approx 1\ \mathrm{m}^{-2}\mathrm{s}^{-1} \times 12\,000\ \mathrm{m}^2 \geq \mathbf{10\ kHz}$$

- Events introduced by all sorts of incident particles
- Desire to distinguish between γ- and hadron showers
- Need to filter hadronically induced showers

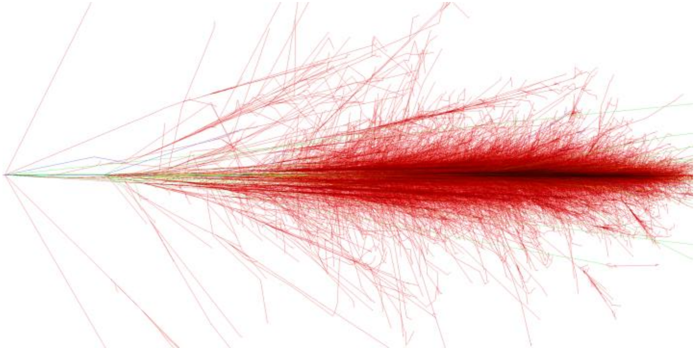
Hadron Rejection



https://www.iap.kit.edu/corsika/

Photon induced air-shower

- no muons, hadrons, mesons
- Smooth(er) transversal shape
- Expect smooth signal shape

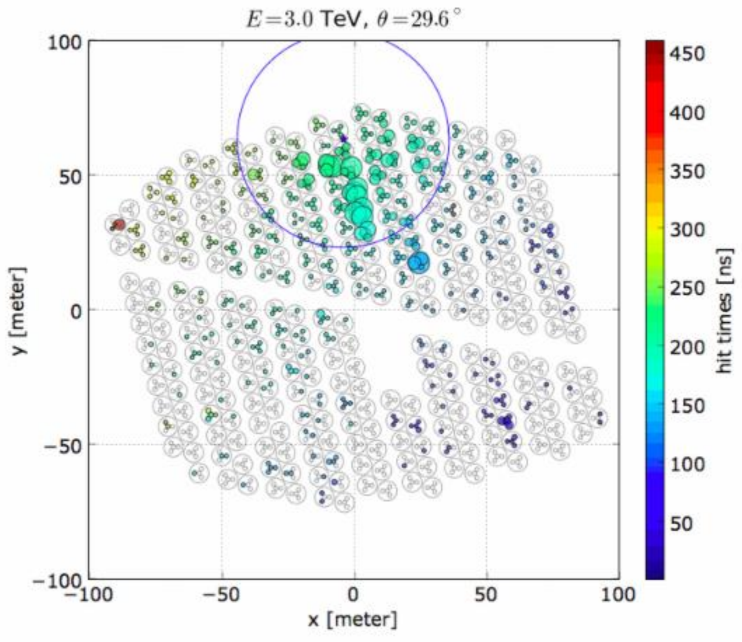


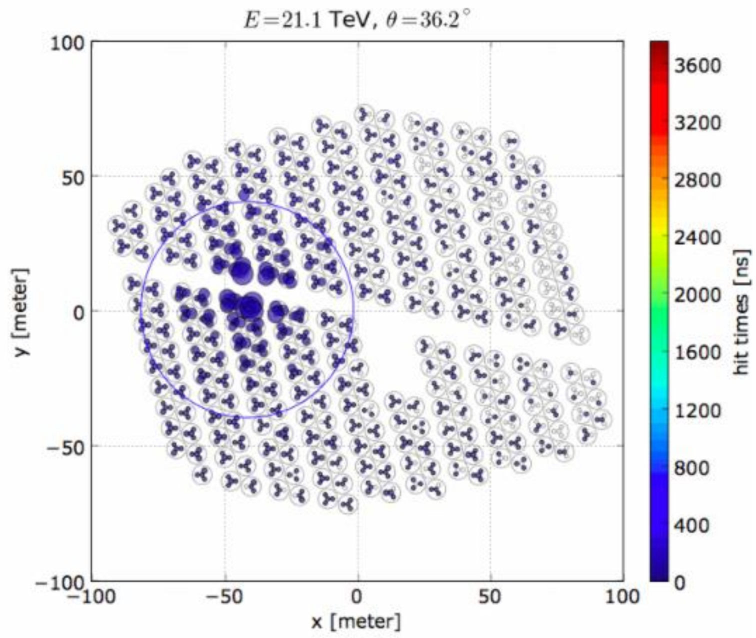
https://www.iap.kit.edu/corsika/

Proton induced air-shower

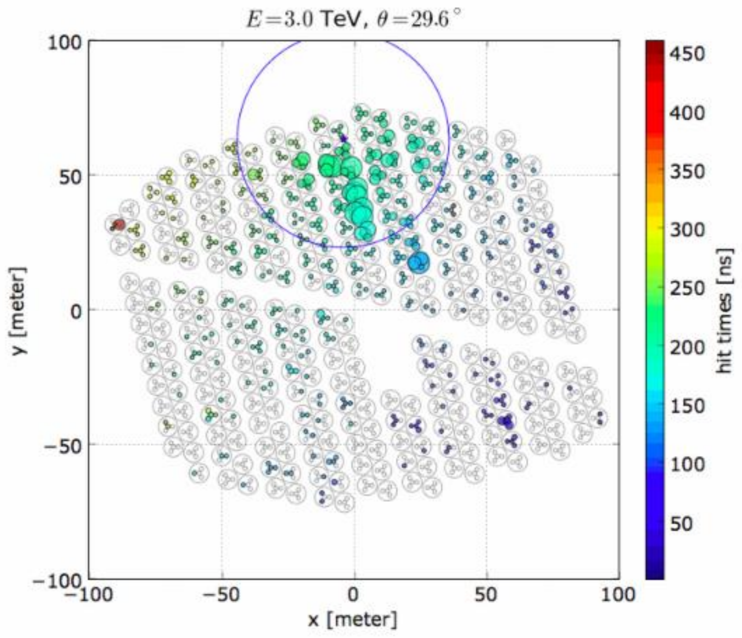
- Many muons, hadrons, mesons
- „patchy“ shower footprint
- Expect far away muon signals

Hadron Rejection

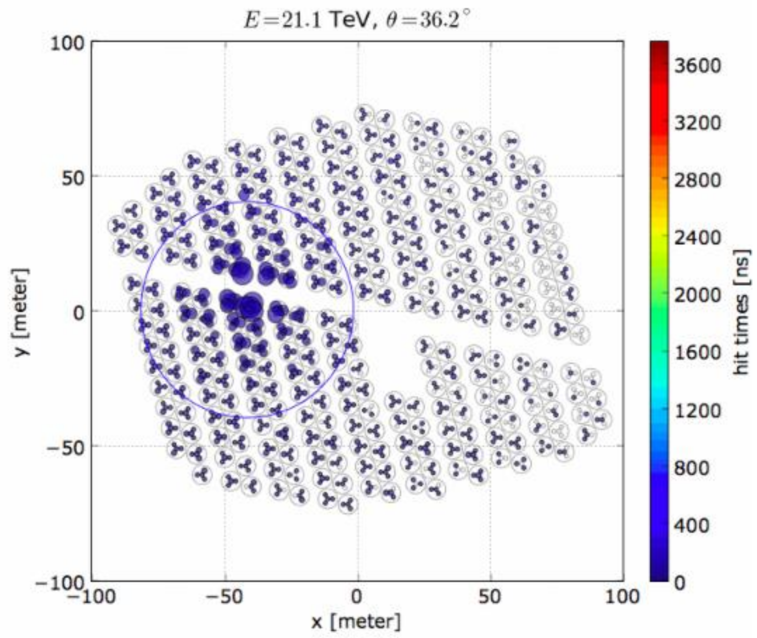




Hadron Rejection

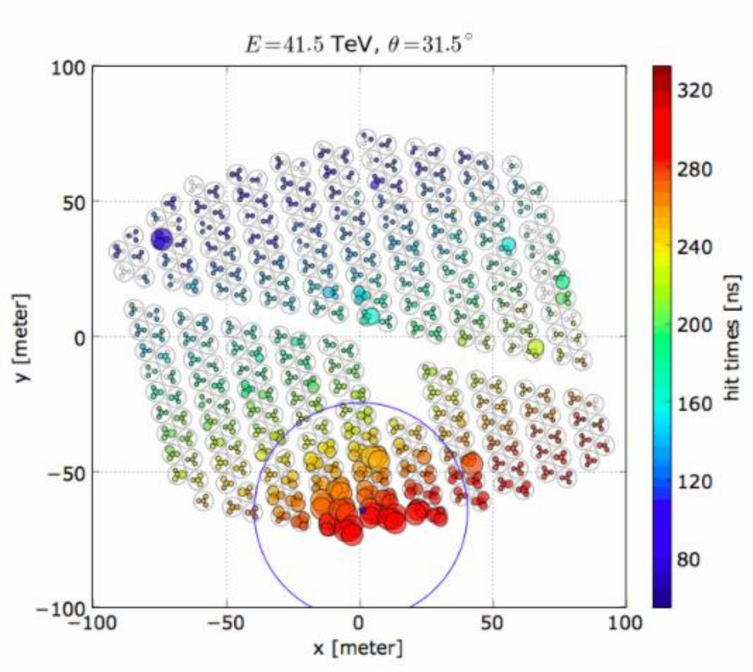


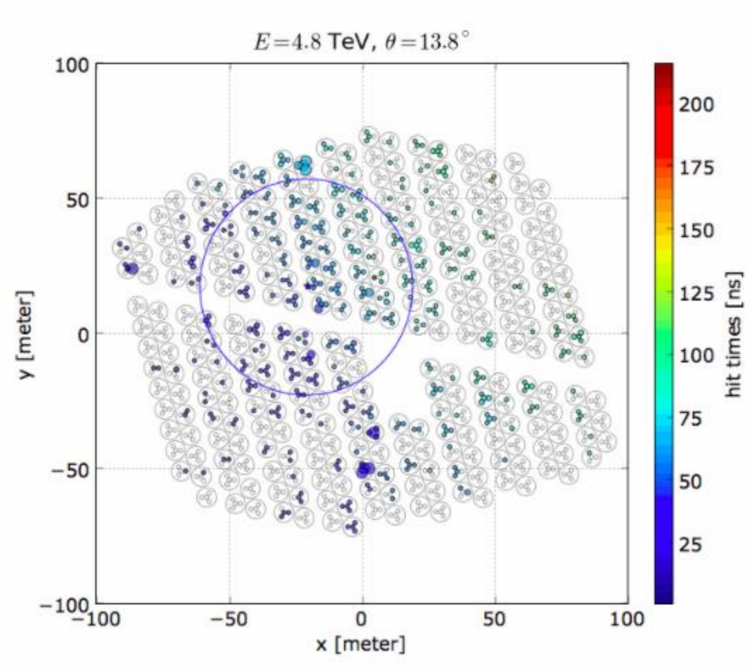
➡ Hadron shower



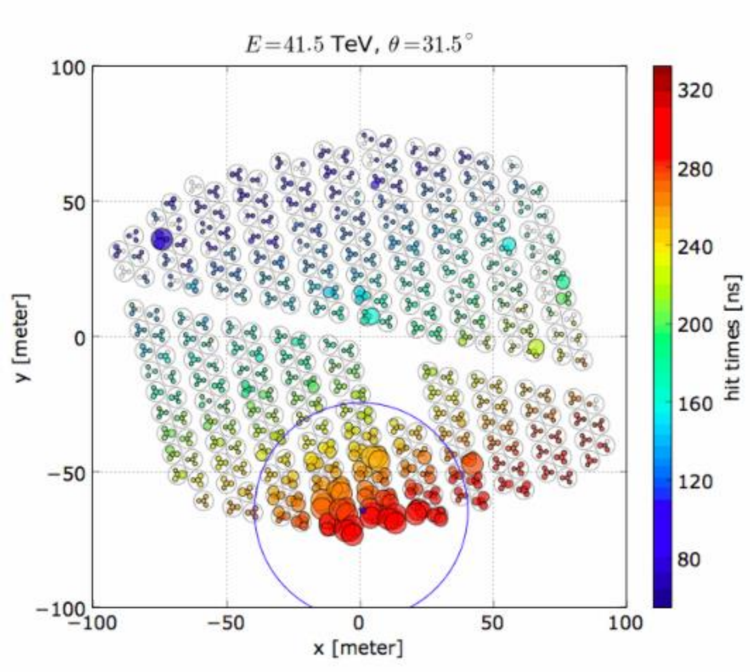
➡ Gamma shower

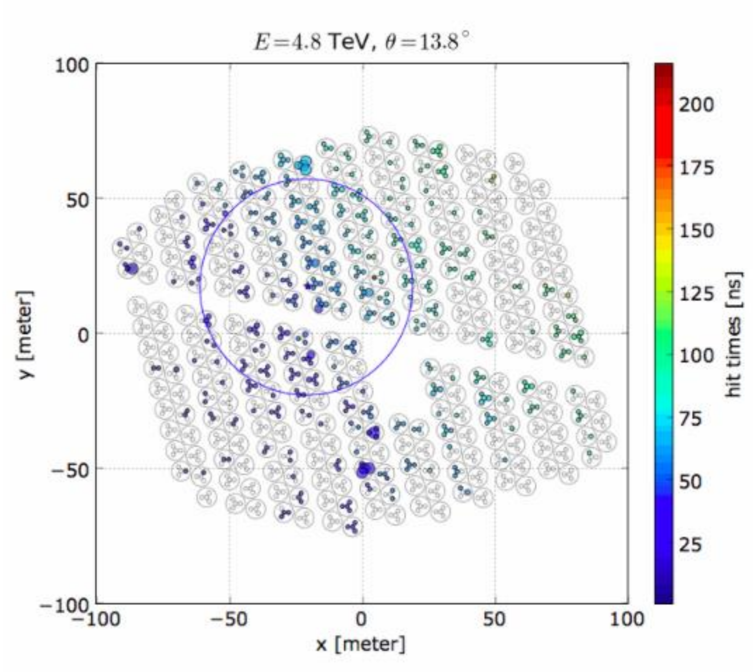
Hadron Rejection





Hadron Rejection





➡ Hadron shower?

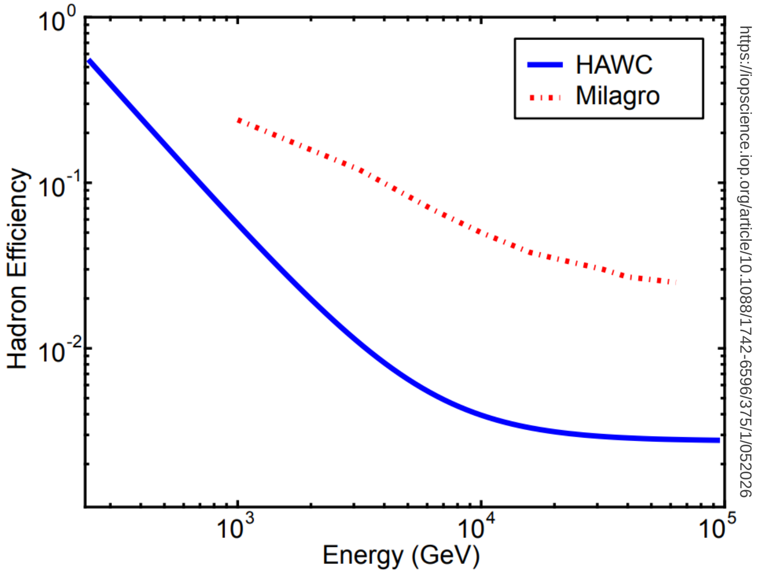
➡ Hadron shower

Hadron Rejection

- Try it out yourself on the HAWC **website** [1]
- Identify „incompact“ and „clumpy“ events

$$\mathcal{C} = \frac{N_{\text{hit}}}{\text{CxPE}_{40}} \qquad \mathcal{P} = \frac{1}{N}\sum_{i=0}^{N} \frac{(\xi_i - \langle \xi_i \rangle)^2}{{\sigma_{\xi_i}}^2}$$

- Cuts reliably identify hadron events with $> 99\%$ confidence above ~ 3 TeV
- Major improvement from predecessors



[1] - https://www.hawc-observatory.org/observatory/ghsep.php

Karlsruhe Institute of Technology

Results (so far)

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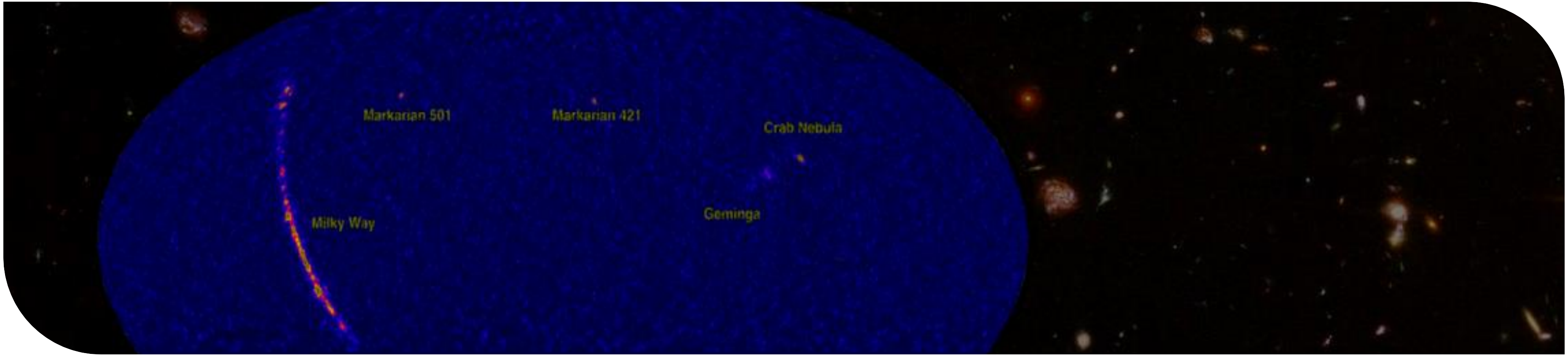
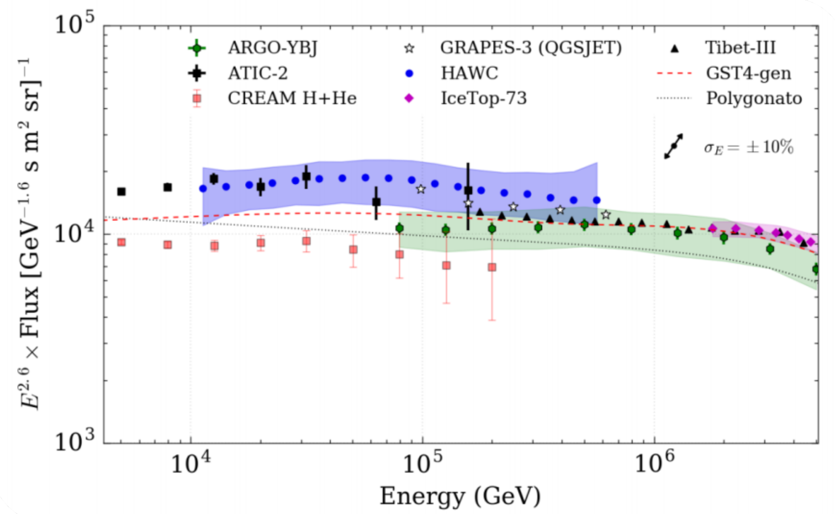


The cosmic ray flux as seen by HAWC

- Conforms to results of previous experiments within uncertainties
- Offset in data may be caused by errors in the energy calibration
- Kink in flux may originate from helium and proton spectrum
- Further data taking to probe higher energies is planned



https://arxiv.org/pdf/1710.00890.pdf

Results (so far)

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Link	Paper	Comment
ArXiv	“All-particle cosmic ray energy spectrum measured by the HAWC experiment from 10 to 500 TeV”	Measure CR flux and confirm power law dependancy for CR from 10 to $500\ \mathrm{TeV}$
ApJ	“Observation of the Crab Nebula with the HAWC Gamma-Ray Observatory”	Observe Crab nebula and confirm analysis methods employed by HAWC are up to par
PhysRev	“Constraints on Lorentz invariance violation from HAWC observations of gamma rays above 100 TeV"	Improve energy treshold below which Lorentz invariance holds up to 2.2×10^{31} electronvolts
ArXiv	“Multi-messenger observations of a flaring blazar coincident with neutrino IceCube-170922A”	First multi-messenger detection of extrasolar neutrinos (ignoring SN1987A) with IceCube
Science	“Extended gamma-ray sources around pulsars constrain the origin of the positron flux at Earth”	Rule out pulsars Geminga, PSR B0656+14 as possible sources for CR positron excess

- See full list of HAWC results (Articles, papers, theses) on their **website**[1]

[1] - https://www.hawc-observatory.org/publications/