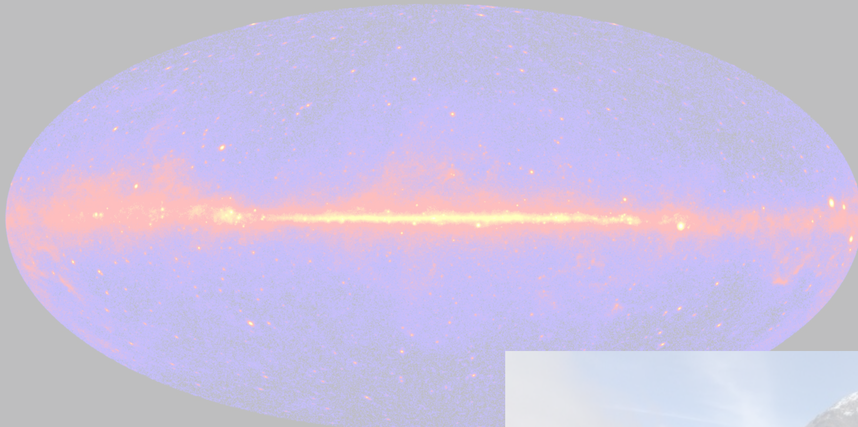
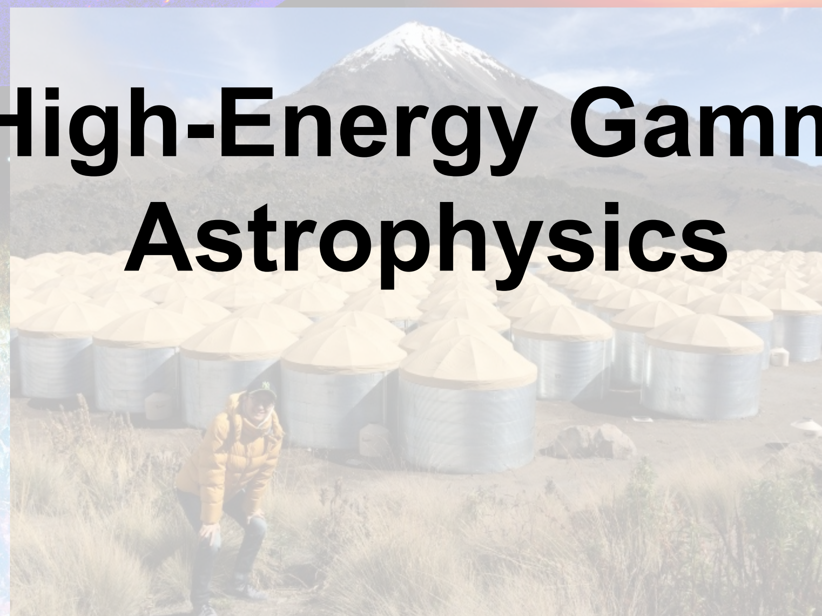




Very-High-Energy Gamma-Ray Astrophysics

Chang Dong Rho

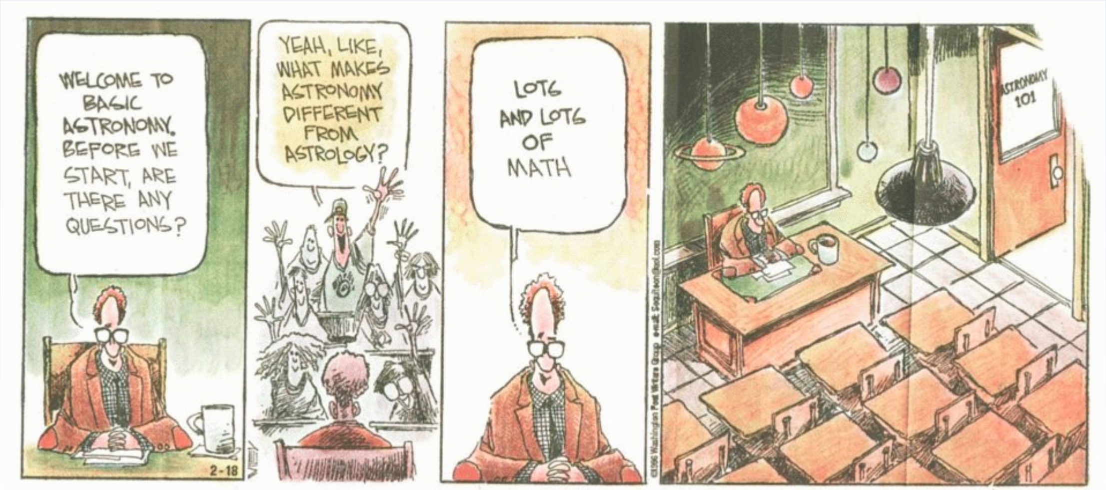
Sungkyunkwan University

21st Saga-Yonsei Workshop

05/11/2024

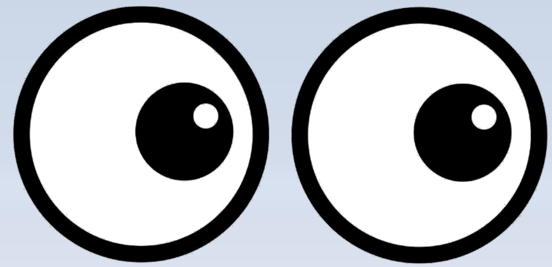
Astronomy & Astrophysics

- **Astronomy** is the science of measuring the positions and characteristics of heavenly bodies
- **Astrophysics** is the application of physics to understand **astronomy**
- But, nowadays the two are interchangeable



Astrophysics without systematics is astrology

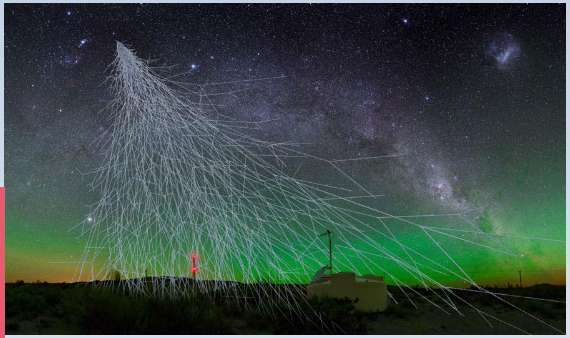
History of Astronomy & Astrophysics

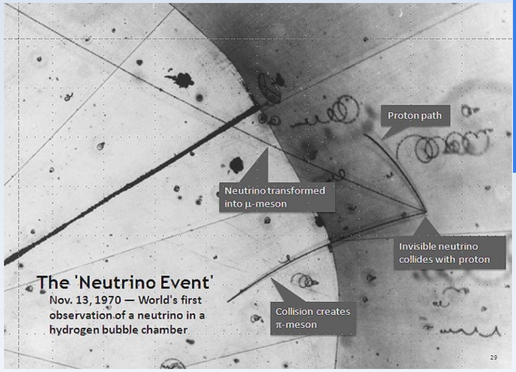


Messengers

Electromagnetic Radiation

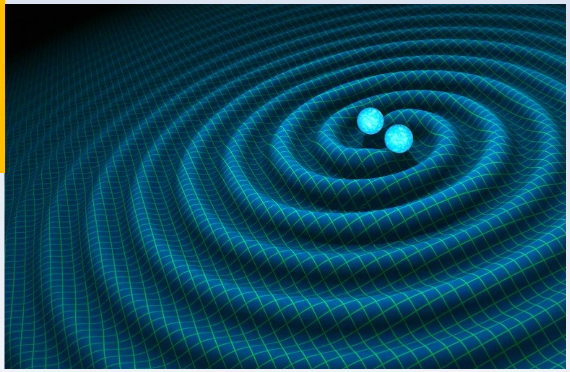
Cosmic Rays





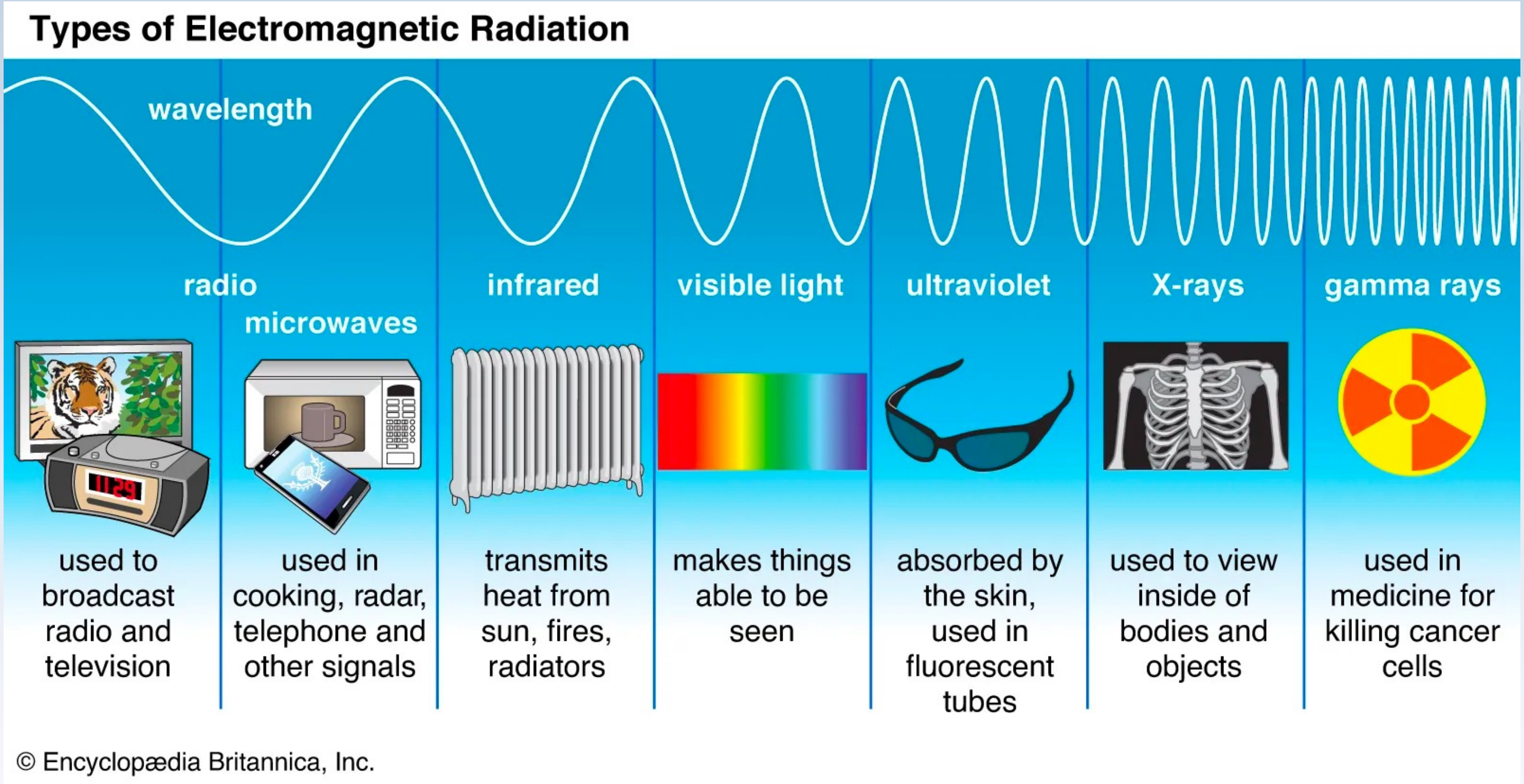
Neutrinos

Gravitational Waves



Electromagnetic Radiation (photons)

- Photons are still most important and carry the most amount of info



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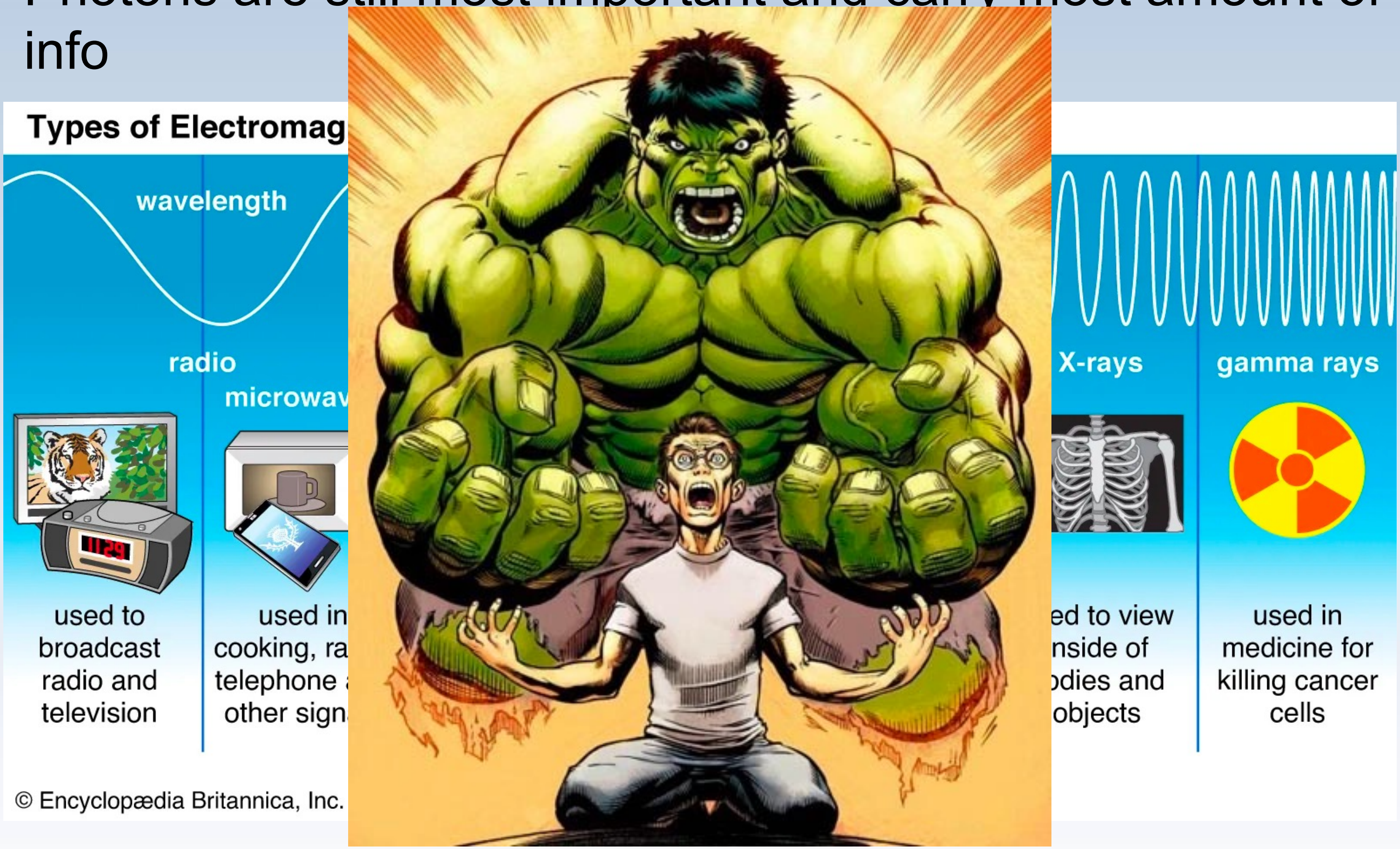
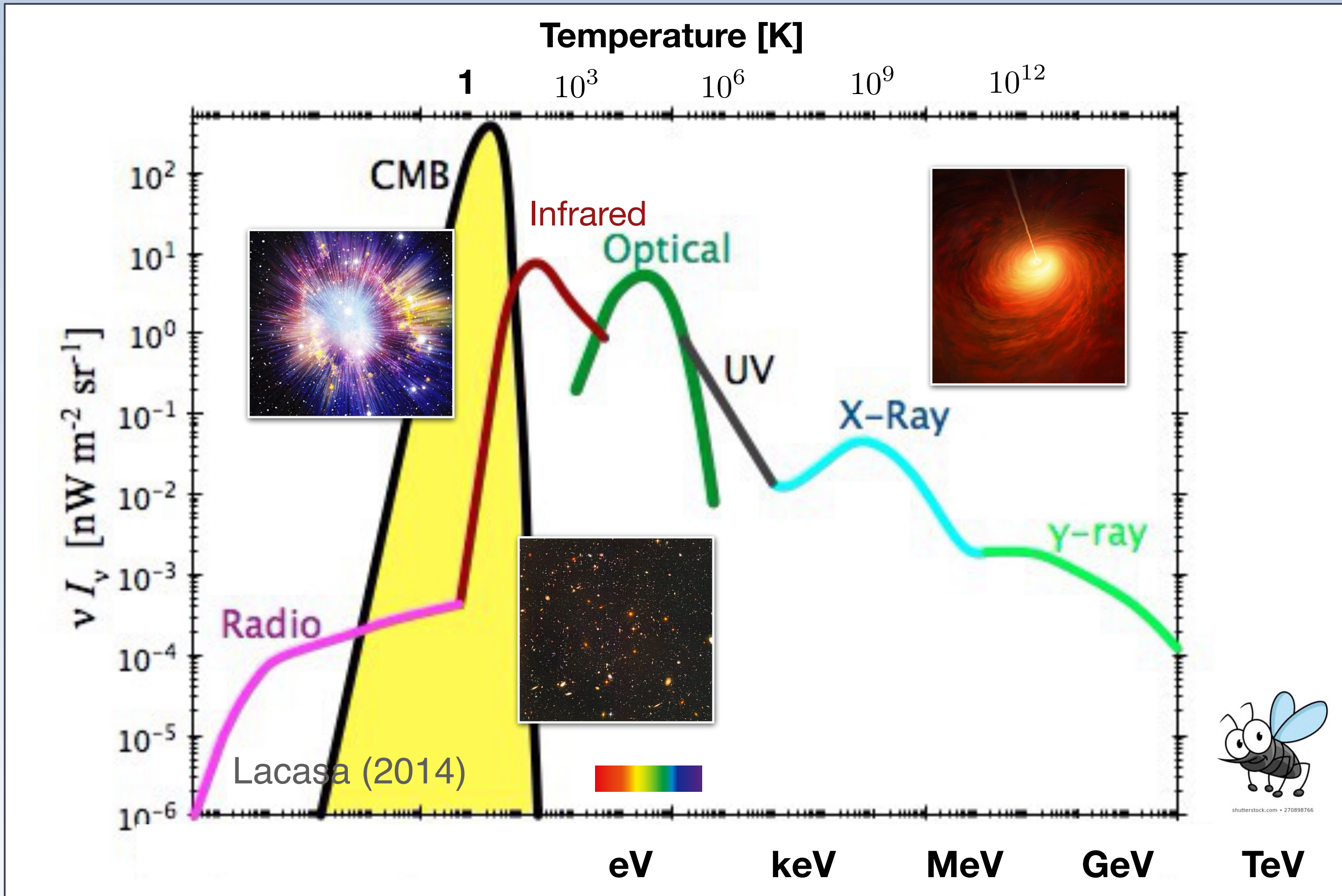


- Gamma rays are not very familiar to us

Electromagnetic Radiation (photons)



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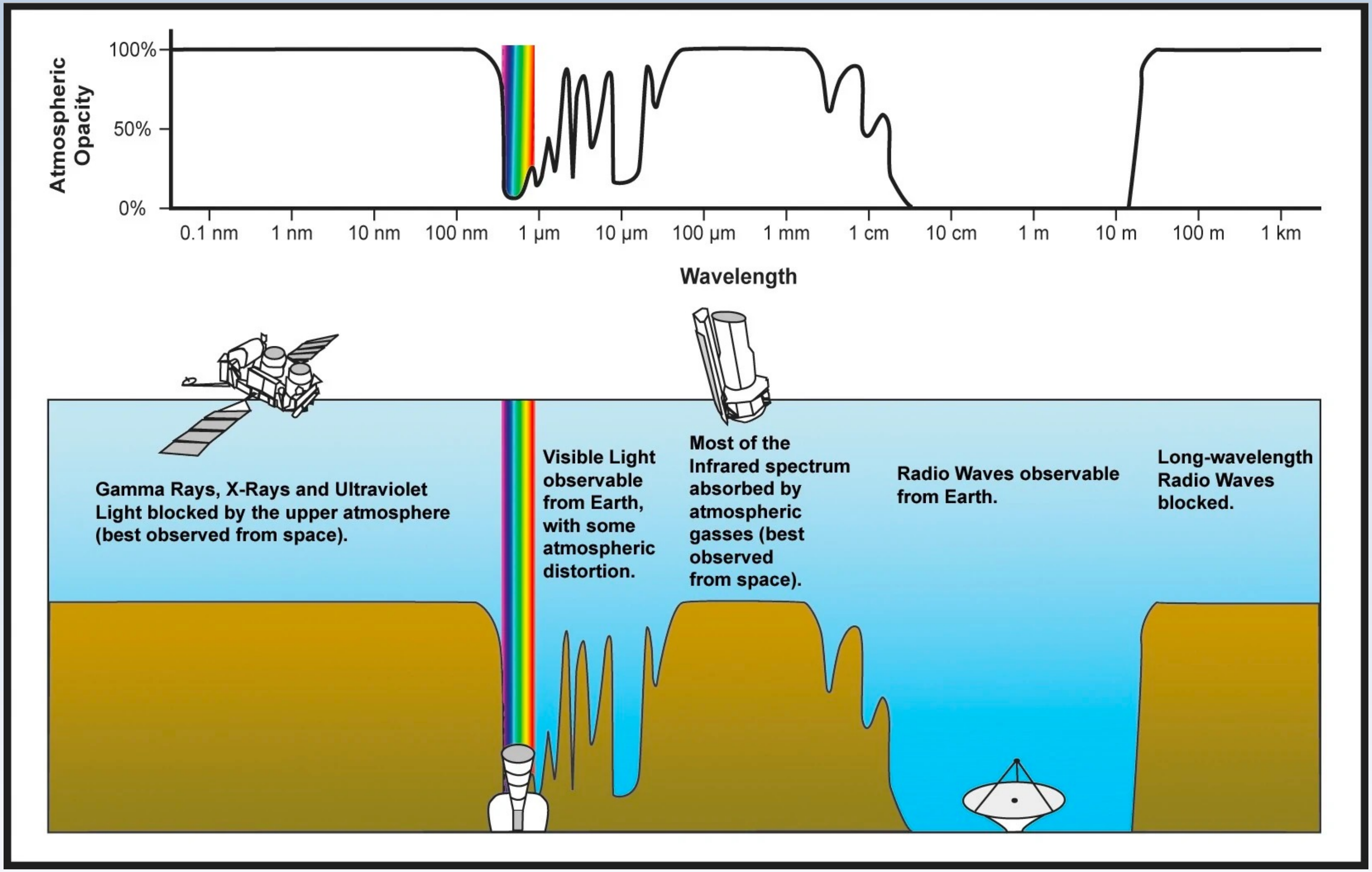
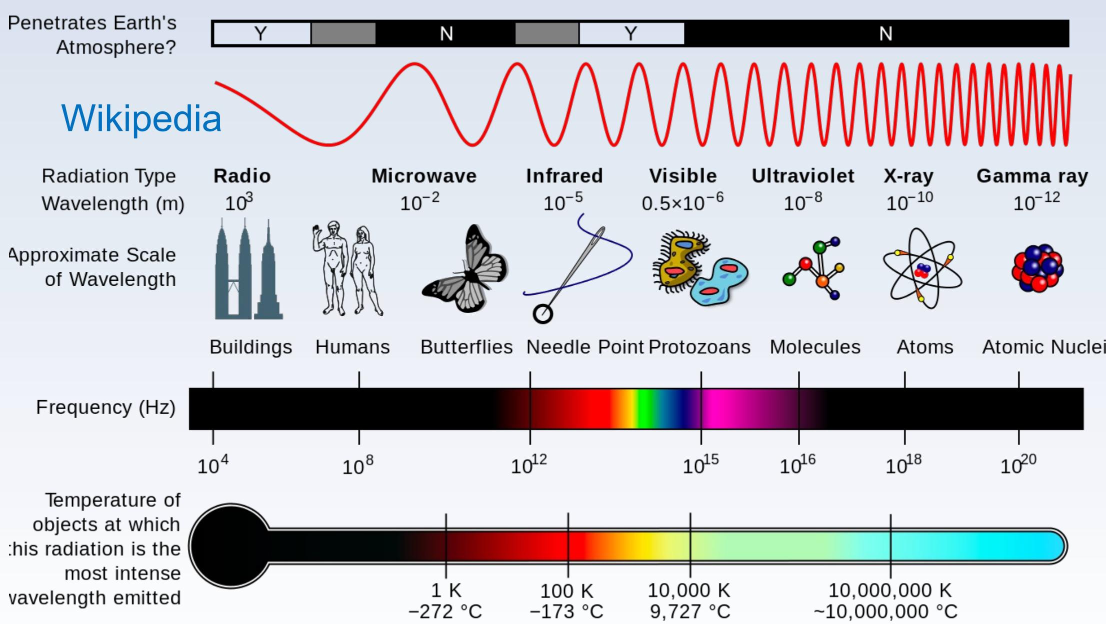


High Energy Astrophysics

- Q: What does *high energy* mean?
  A: Ionization ($\varepsilon > 13.6$ eV)

EUV X-ray γ-ray

$$13\ \mathrm{eV} \leftrightarrow 100\ \mathrm{eV} \leftrightarrow 100\ \mathrm{keV} \rightarrow$$



Wikipedia

My Field of Research

Physics
물리

↓

Astrophysics
천체물리

↓

High Energy Astrophysics
고에너지 천체물리

↓

Gamma-Ray Astrophysics
감마선 천체물리

↓

Very-High-Energy Gamma-Ray Astrophysics
매우(?) 고에너지 감마선 천체물리

VHE (GeV – TeV) Gamma-Ray Production Mechanisms

- Thermal
- Line
- Nonthermal
  - Bremsstrahlung & synchrotron
  - Inverse Compton scattering
  - Neutral pion (π^0) decay
  - Pair annihilation

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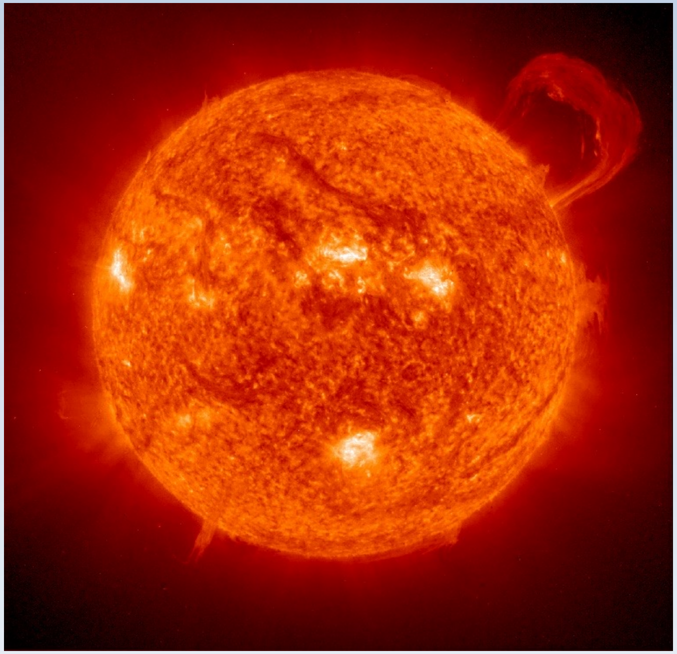
  - Etc.



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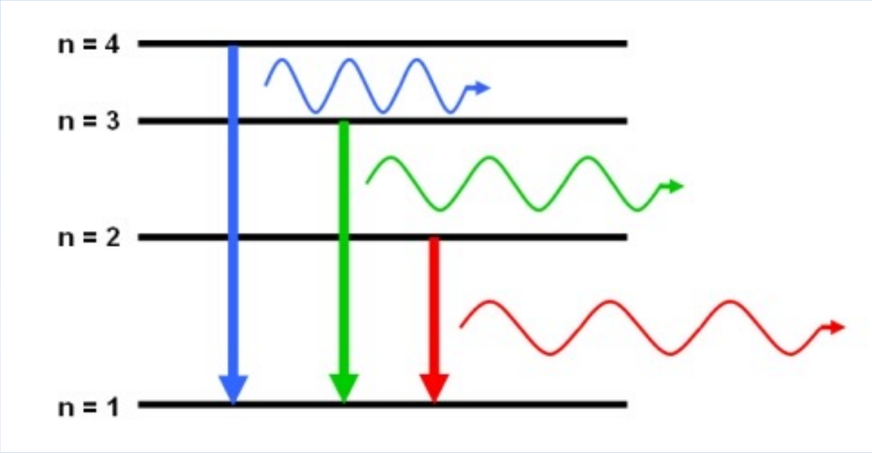

VHE (GeV – TeV) Gamma-Ray Production Mechanisms

- ~~Thermal~~
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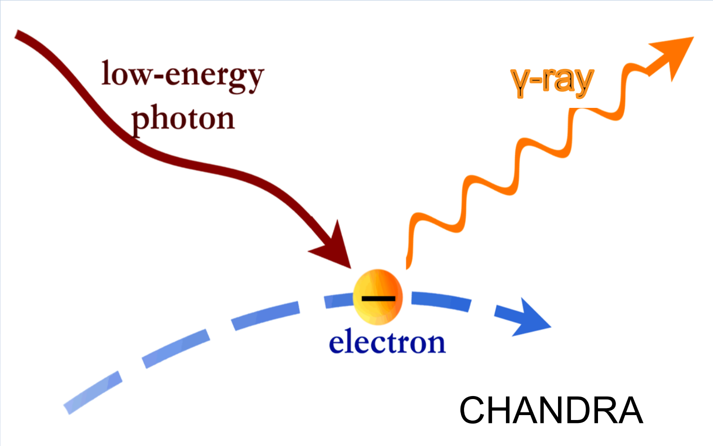
  - ~~Bremsstrahlung & synchrotron~~
  - Inverse Compton scattering
  - Neutral pion (π^0) decay
  - ~~Pair annihilation~~
  - ~~Etc.~~

Inverse Compton – LEPTONIC

- Inverse Compton scattering is transfer of energy from a charged relativistic particle to a photon via inelastic collision.



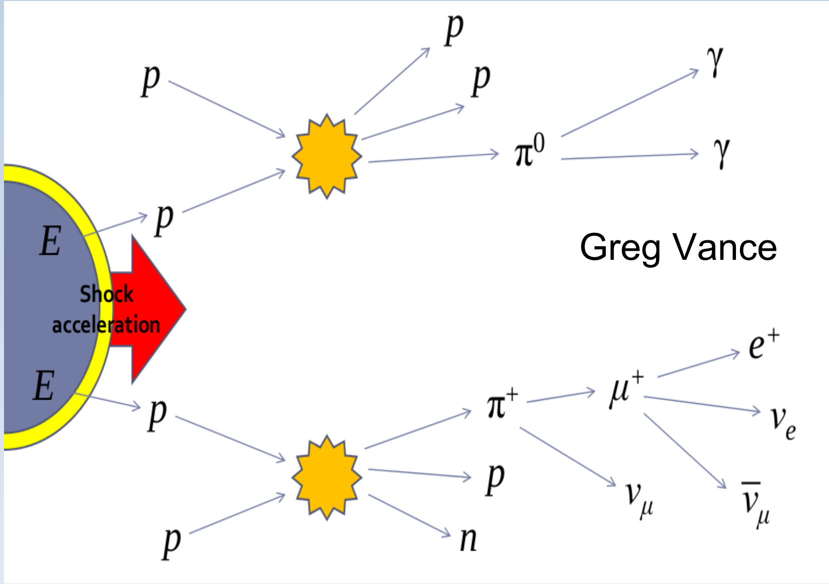
$$P = \frac{4}{3}\sigma_{\mathrm{T}} c U_{\mathrm{rad}} \beta^2 \gamma^2$$

- Target photons to produce TeV photons: CMB, infra-red, optical

- Also features a power-law energy spectrum.

Neutral Pion Decay – HADRONIC

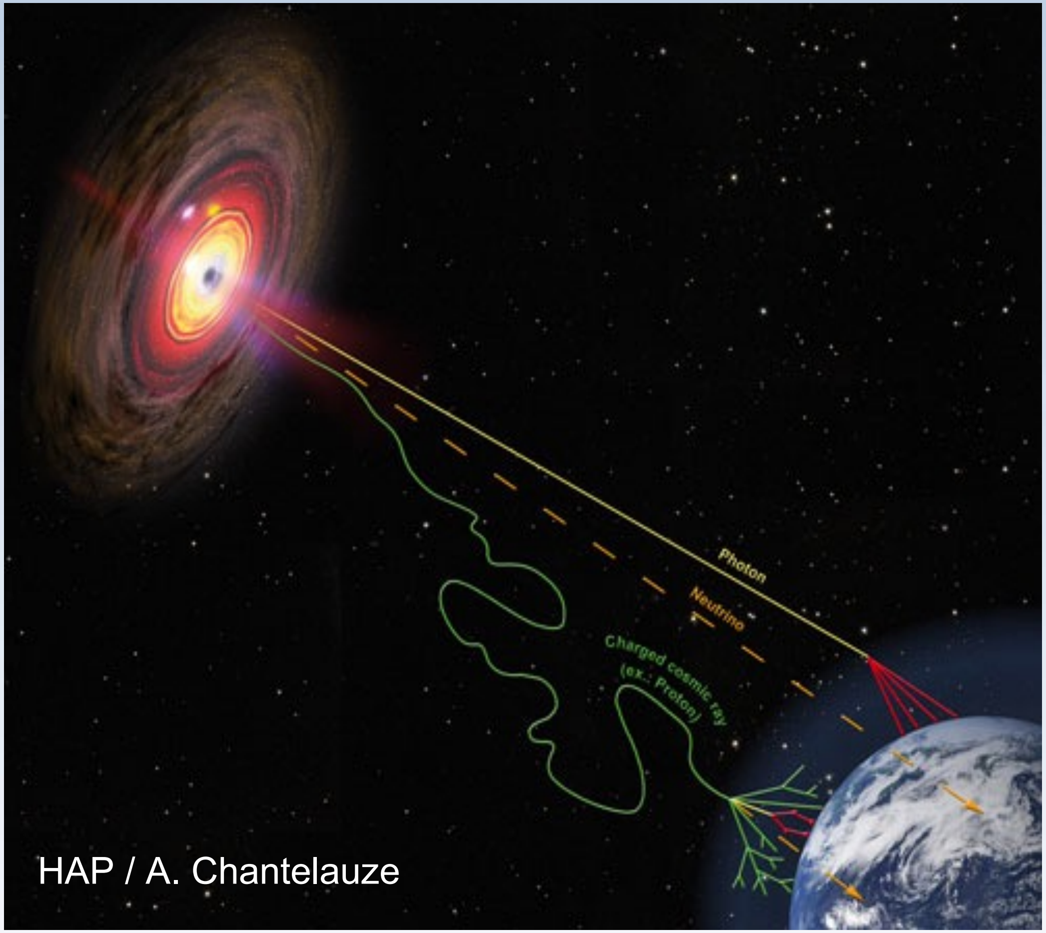
- Referred to as "hadronic process" because pion decay is the dominant process.



- Observed gamma-ray spectrum from π^0 decay is expected to follow cosmic-ray proton spectrum + "π^0-bump".

- Electrons and positrons from charged pion decay can also produce synchrotron emission.

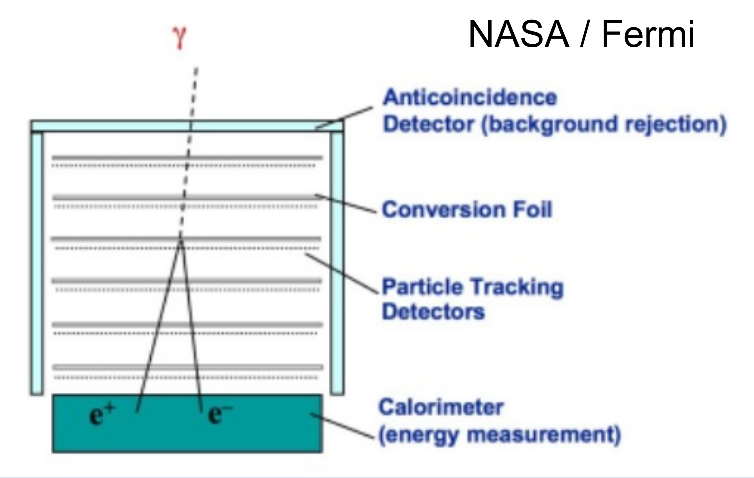
Why Observe Cosmic Gamma Rays?

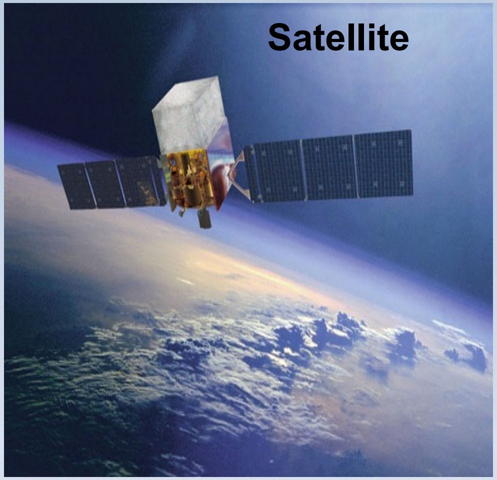


- ❖ Observing and studying the highest energy sources
- ❖ New Science
- ❖ Finding the origin of cosmic rays

- ❖ Neutrinos are very rare (to detect), cosmic rays are difficult to trace, gravitational waves are very weak, and gamma rays can be produced from multiple processes…

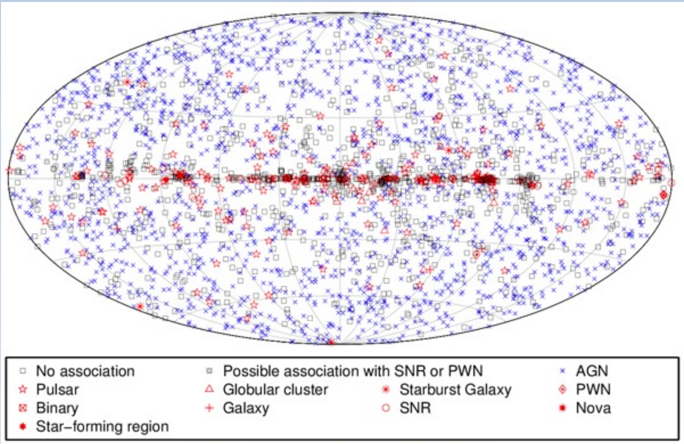
Detecting Cosmic Gamma Rays

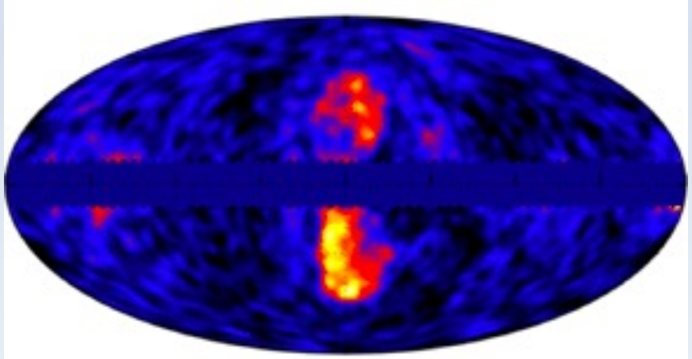


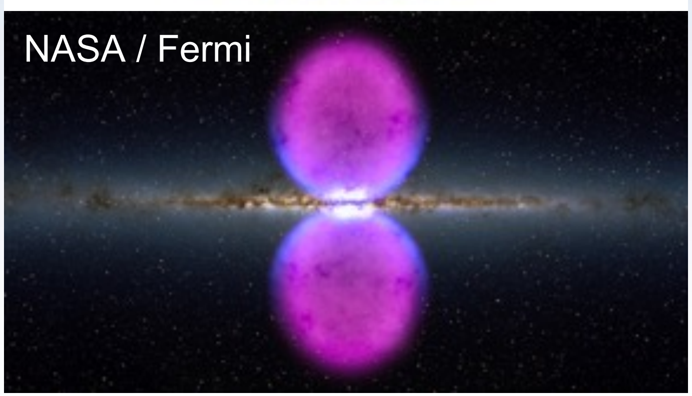


- Fermi Large Area Telescope (LAT) is a detector (left) on board a satellite
- Protons filtered out using anticoincidence detector
- Gamma-ray shower forms within the detector itself and tracks are reconstructed to find the direction of original γ-ray photon
- Calorimeter at the end measures energy (high MeV – low GeV)

Fermi LAT

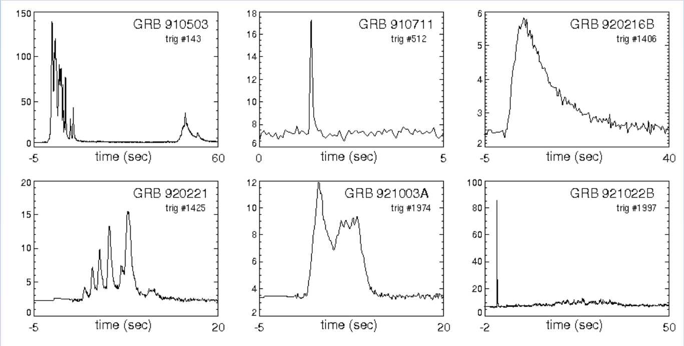




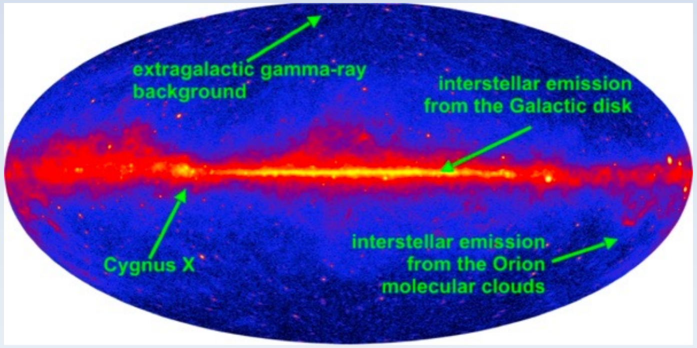


- Fermi Catalog (>5000 sources)
  - Galactic: Binaries, pulsars, PWNe, etc
  - Extra-galactic: AGN, galaxies, etc
- Fermi Bubbles
  - Two bubble-like features above and below the center of our Galaxy
  - 50,000 LY in length
  - Possibly due to the release of energetic particles from the supermassive black hole at the center of MW

Fermi LAT



Daniel Perley



NASA / Fermi

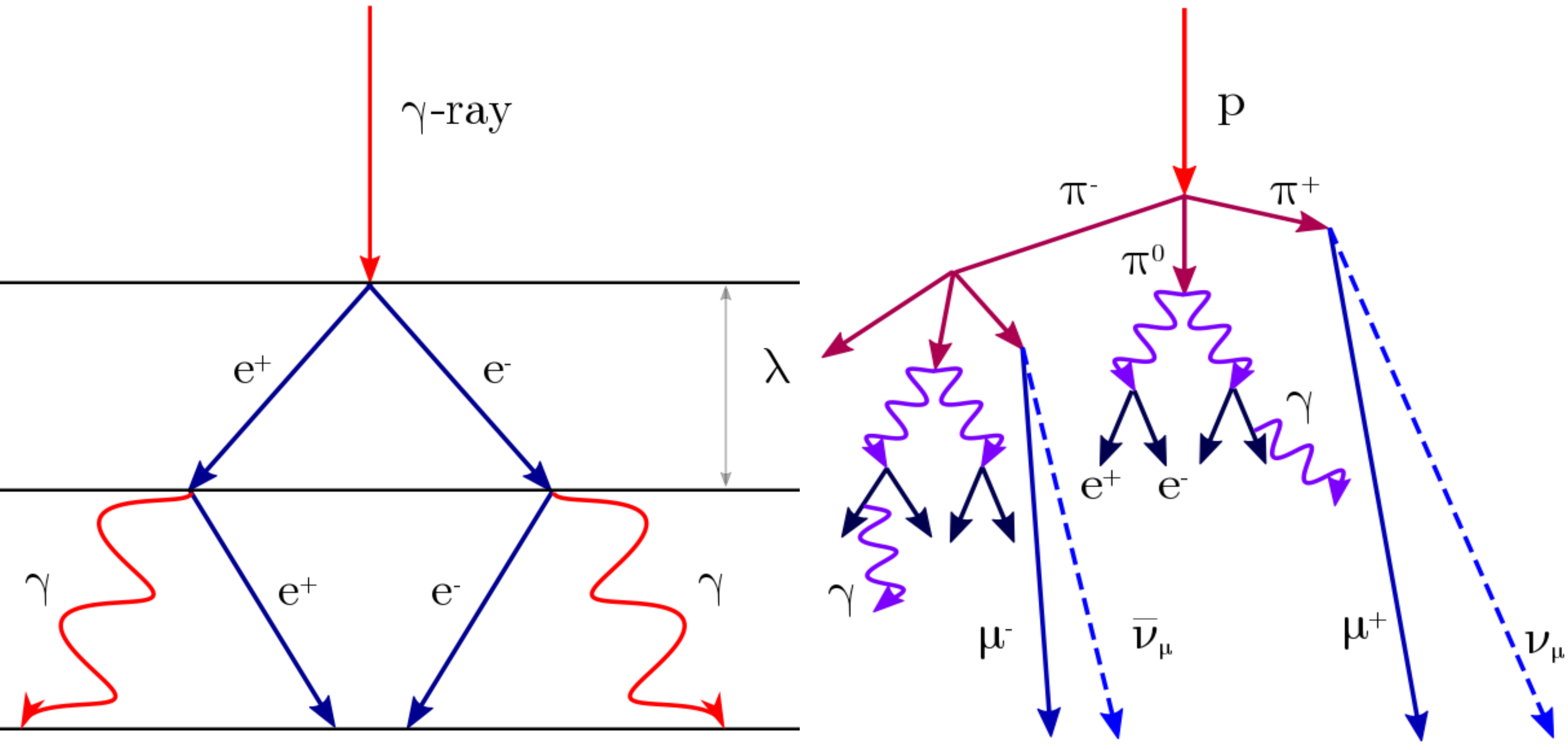
- Fermi LAT observed a lot of GRBs
  - Most energetic EM events known
  - Sudden spike in light curve
  - Showed coincidence with GW event

- Galactic diffuse emission (GDE)
  - Interactions between CR particles, interstellar medium, and radiation fields
  - Bremsstrahlung, inverse Compton, and pion decay

Extensive Air Shower (EAS)

❖ The atmosphere of Earth is opaque to gamma rays -> It produces an extensive air shower.

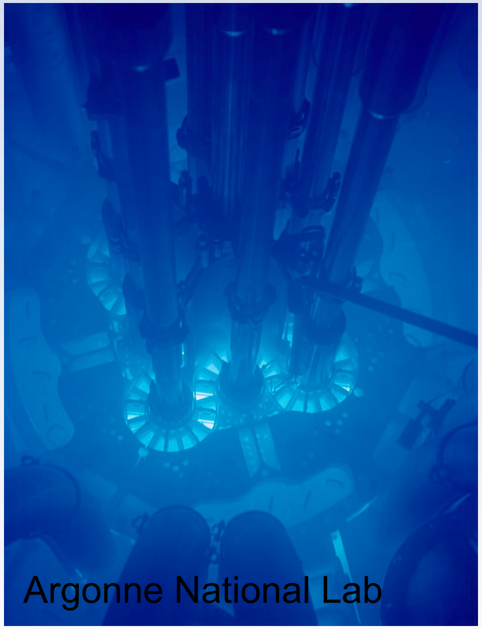
Z. Hampel



Cherenkov Radiation

- Charged particle emits Cherenkov radiation at Cherenkov angle when it travels faster than the speed of light in a medium.

$$\cos(\theta_{\mathrm{Ch}}) = \frac{c}{nv}$$



Analogous to sonic boom only with light.

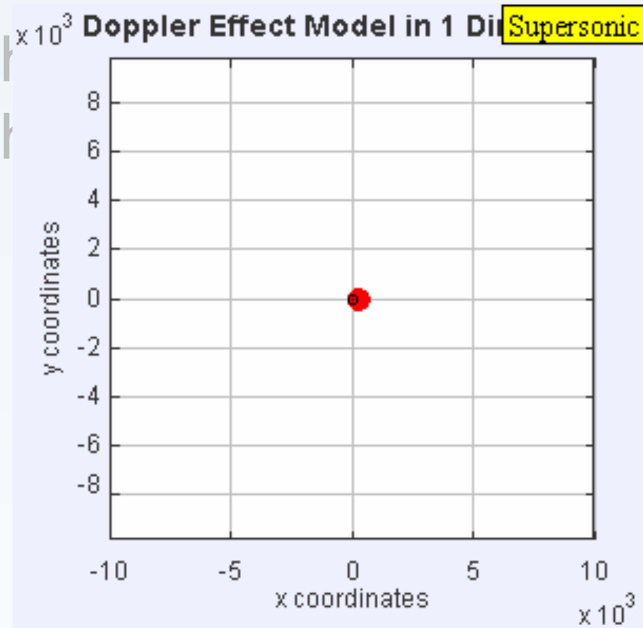
Actually possible to see Cherenkov light!

Other Important Process: Cherenkov Radiation

- Ch… Cherenkov radiation at Cherenkov angle wh… n the

$\cos(\theta$

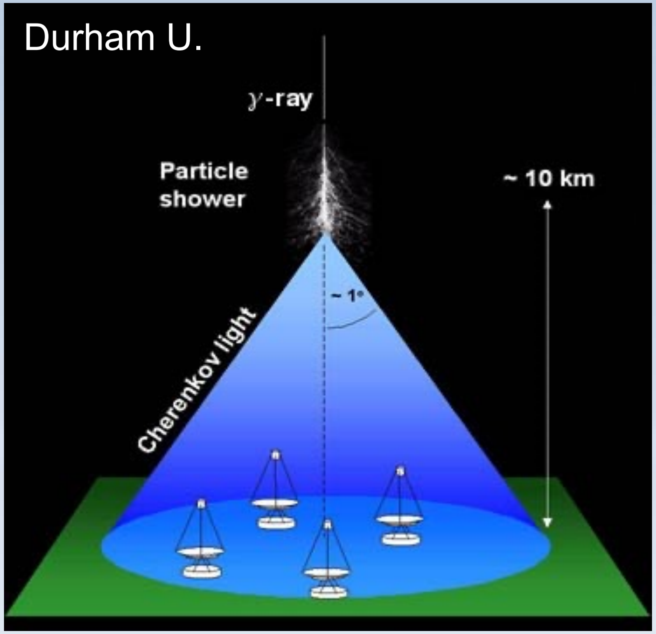
…tually possible to see Cherenkov light!



Argonne National Lab

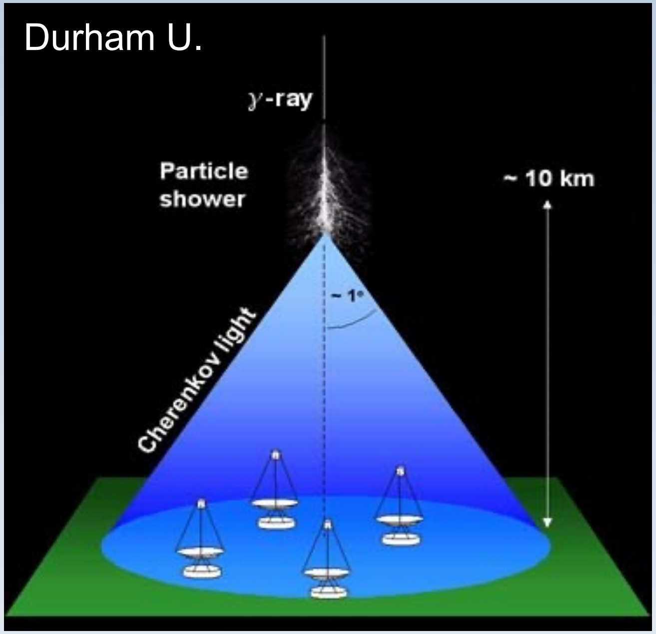
Wikipedia

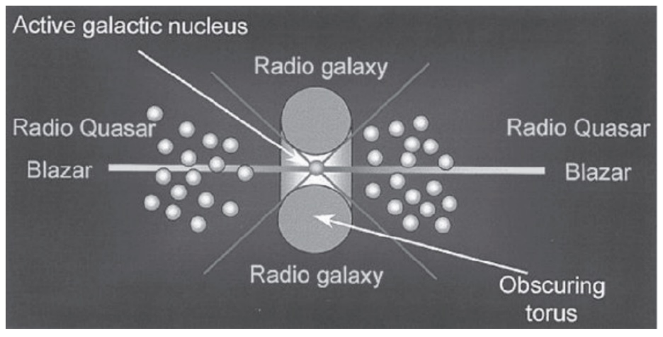
IACTs



- IACTs use extensive showers (relativistic charged particles) emitting Cherenkov light in the air.
- Huge mirrors to collect Cherenkov radiation and point to photodetectors at the tip.
- VERITAS and MAGIC observing the Northern hemisphere. H.E.S.S. observing the Southern hemisphere.

IACTs

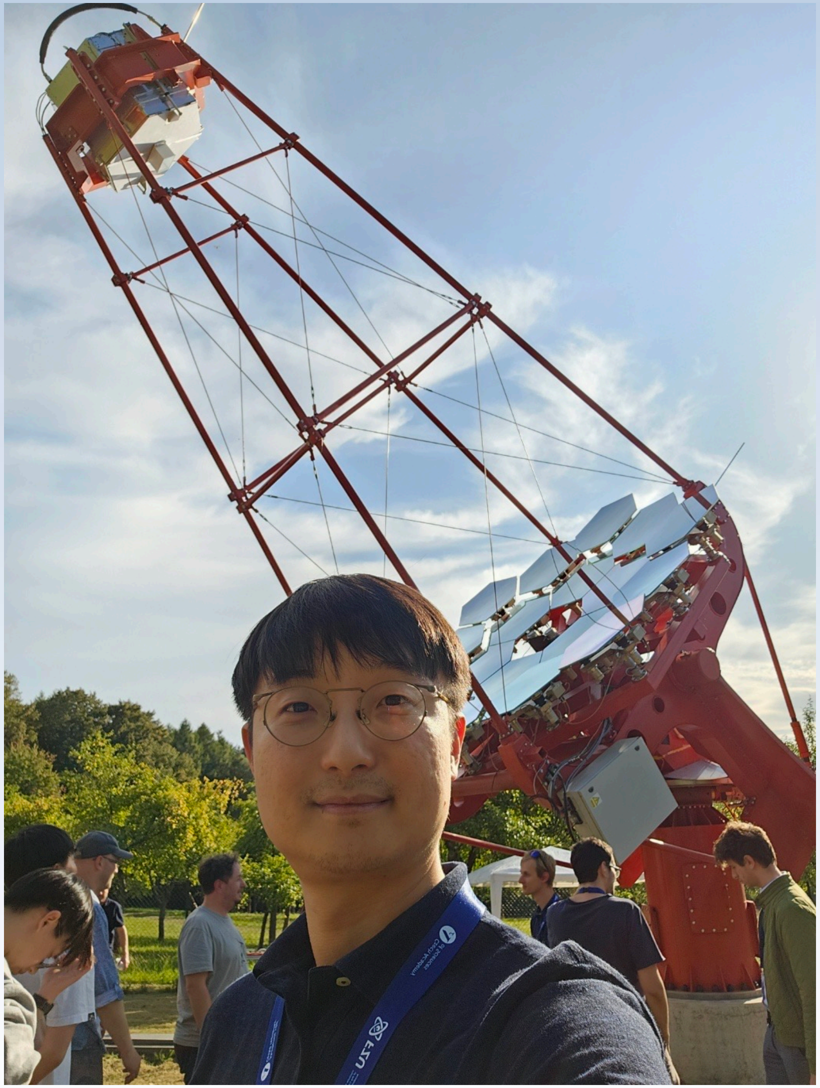




- VHE GRBs
  - VHE emission from GRBs. Most energetic of the most energetic events
  - Only three observed so far
- Pevatron in Galactic centre
  - Galactic cosmic rays reaching > 1 PeV producing gamma rays
  - Evidence from supermassive black hole Sagittarius A*
- VHE blazars & binaries
  - Blazars are quasars (AGN) with their jet pointing right at us
  - Seven VHE gamma-ray binaries found

IACTs

IACTs



IACTs

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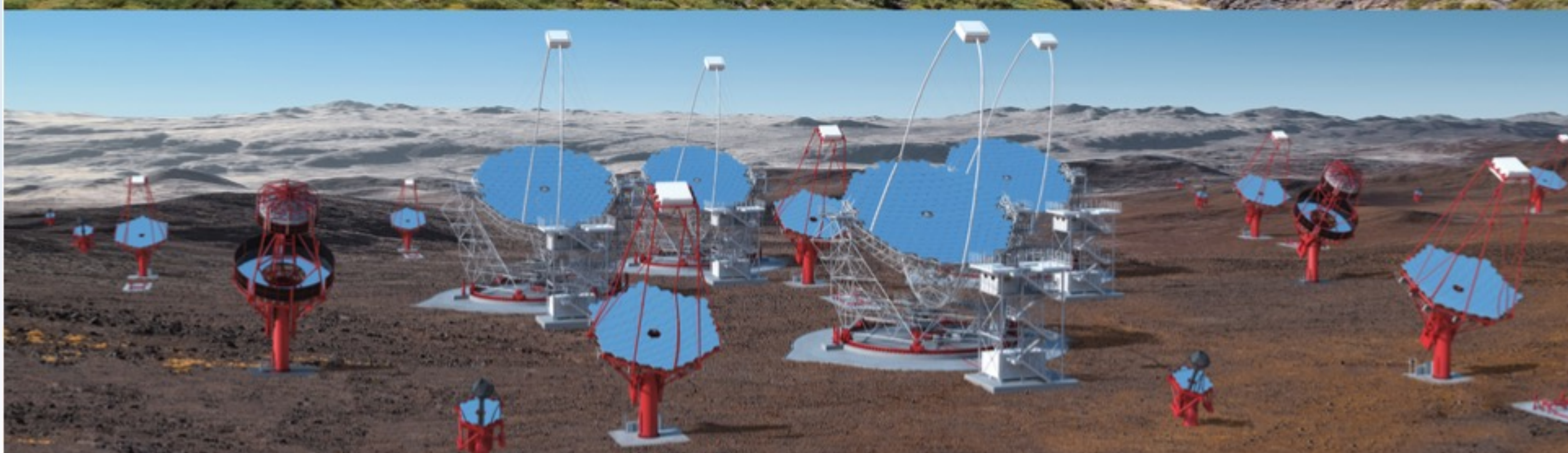
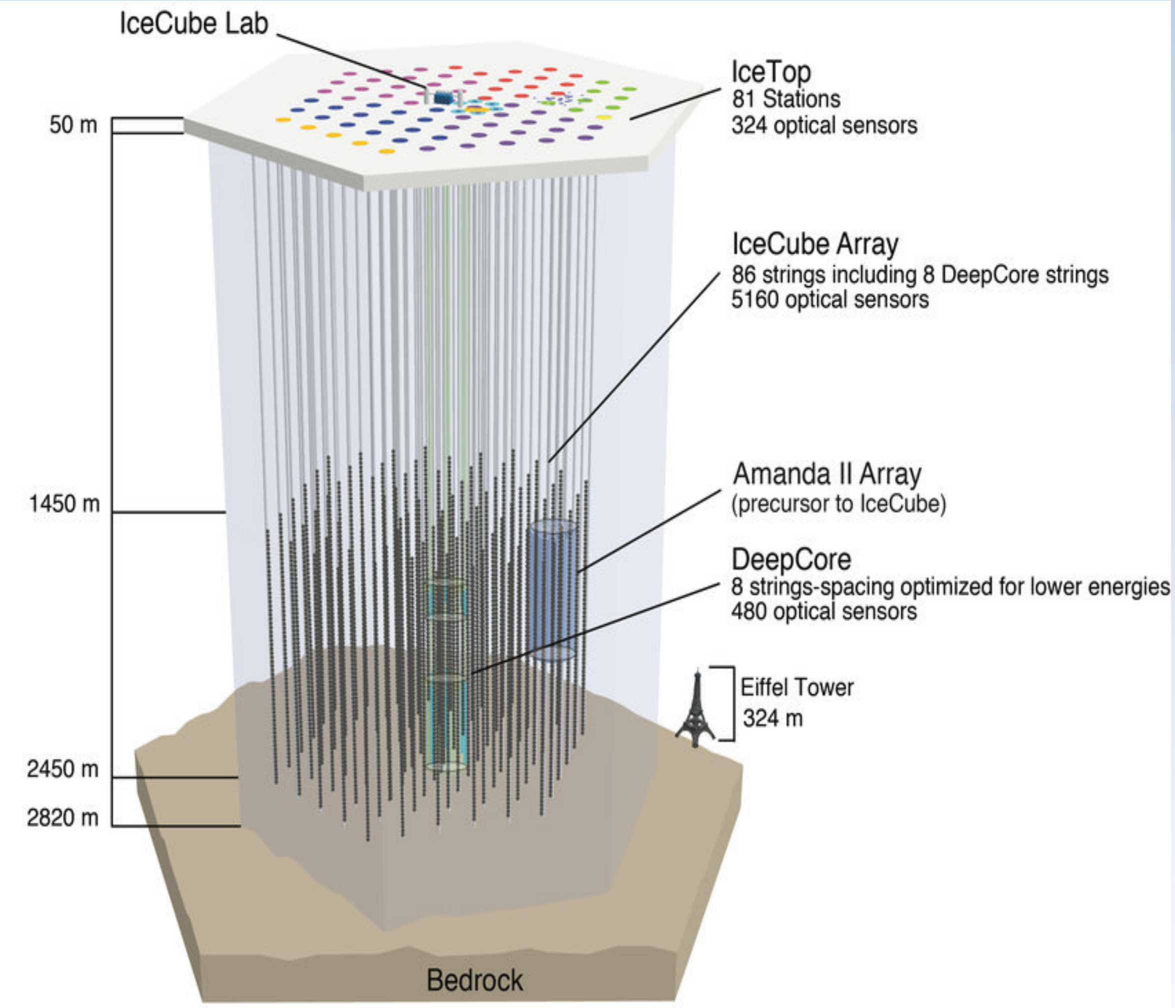
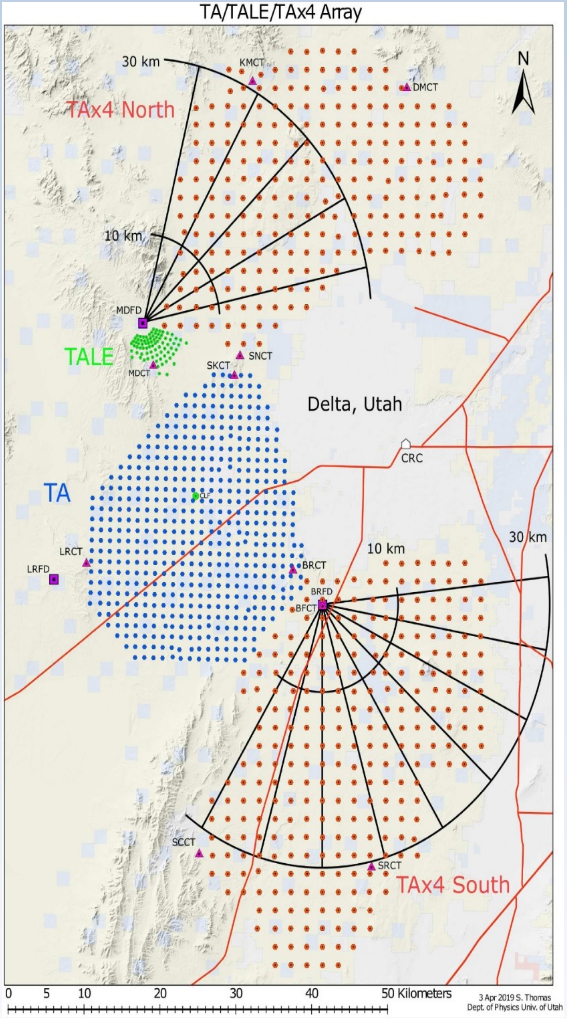


IACTs

Cherenkov in Other Experiments

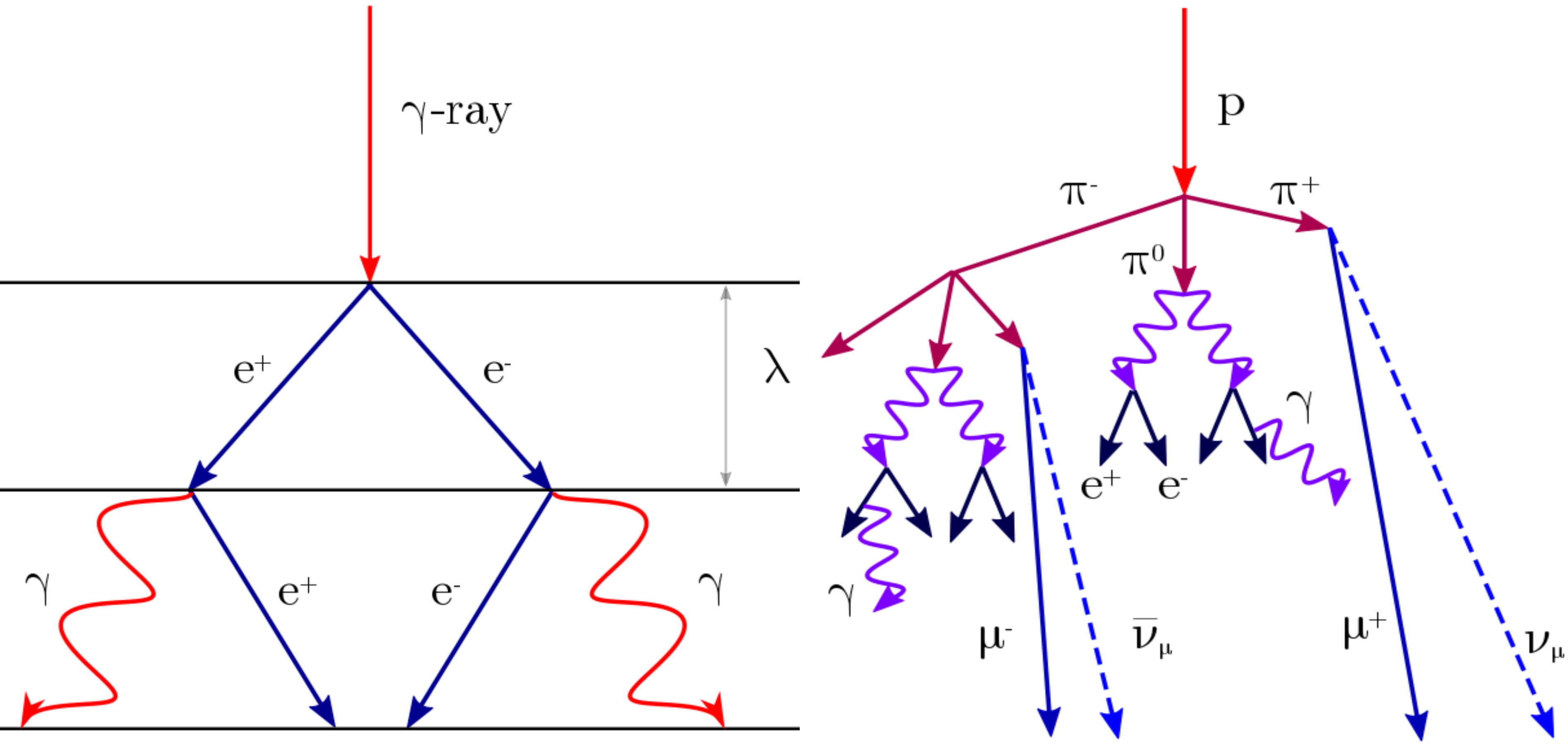




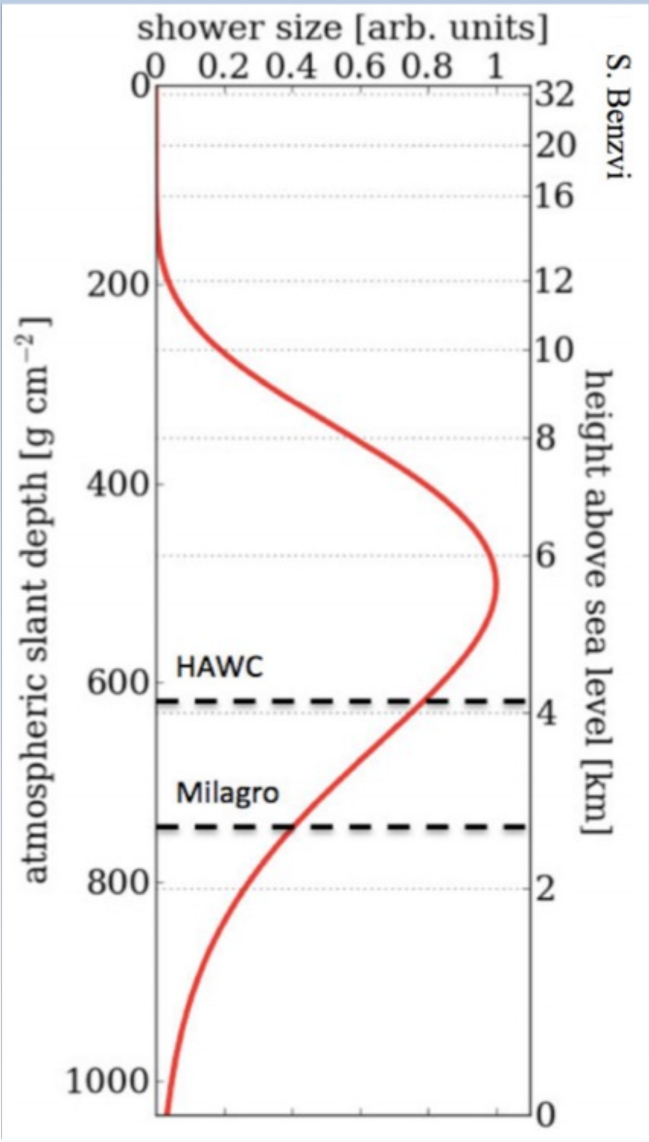
Extensive Air Shower (EAS)

- The atmosphere of Earth is opaque to gamma rays -> It produces an extensive air shower.

Z. Hampel

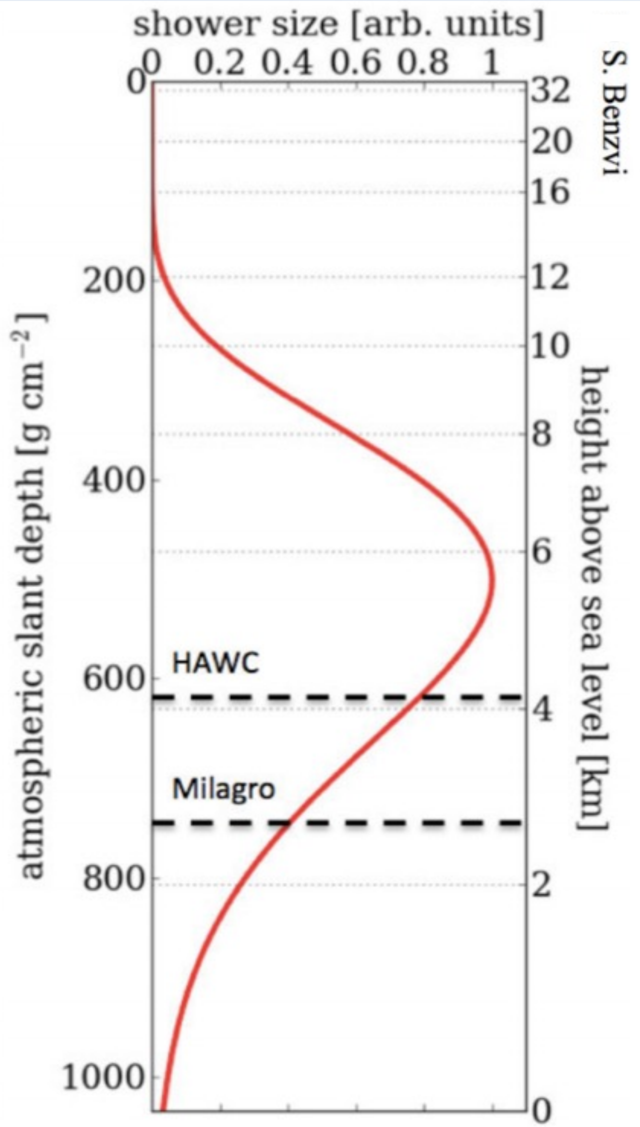


Air Showers – Detection Techniques

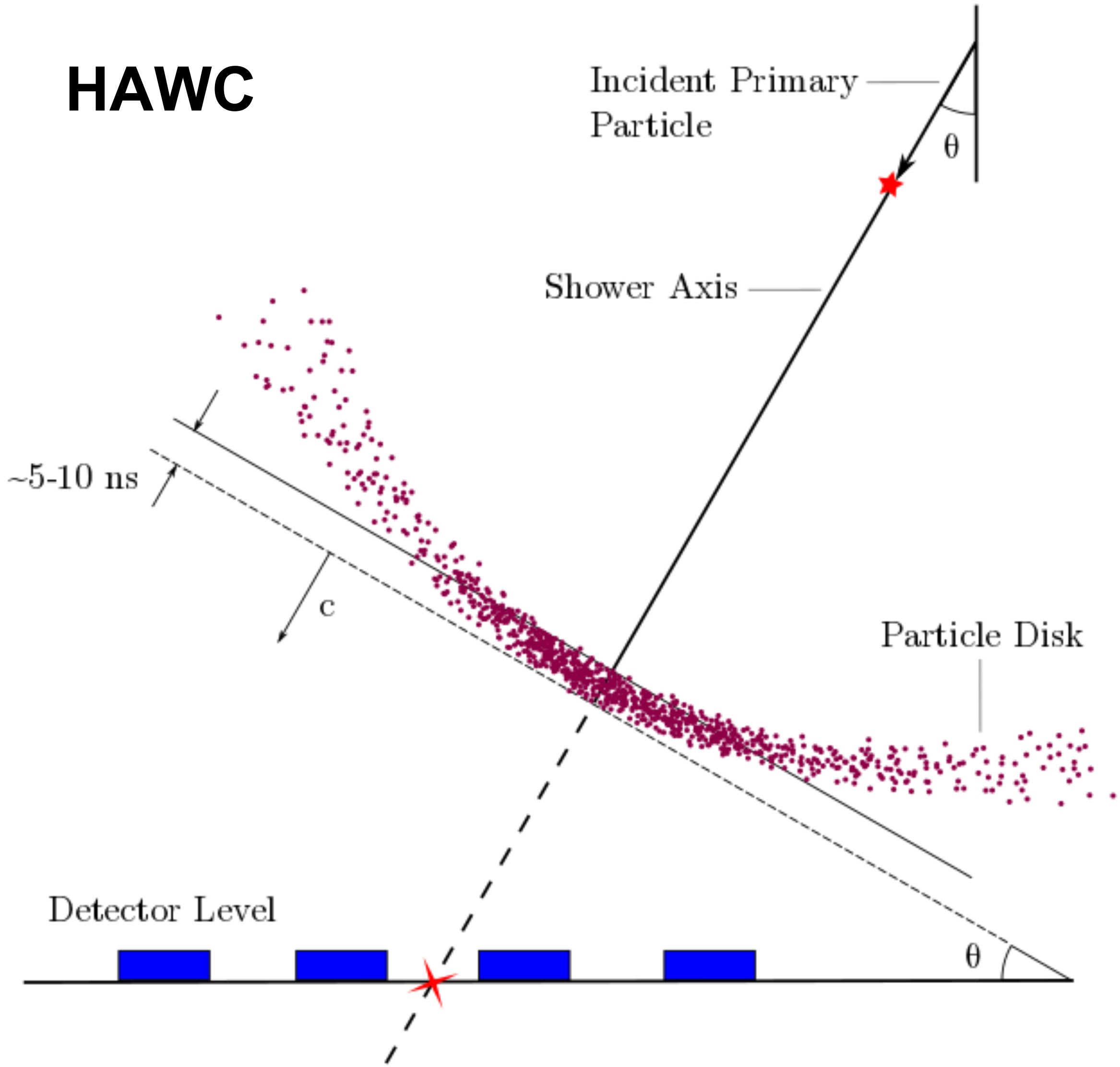


- Gamma-ray air shower grows in size and population as it propagates until energy limit is reached.
- Shower size decreases afterwards.
- Hence, gamma-ray detectors (HAWC) that collect charged particles in EAS need to be located at a high enough altitude.

Air Showers – Detection Techniques



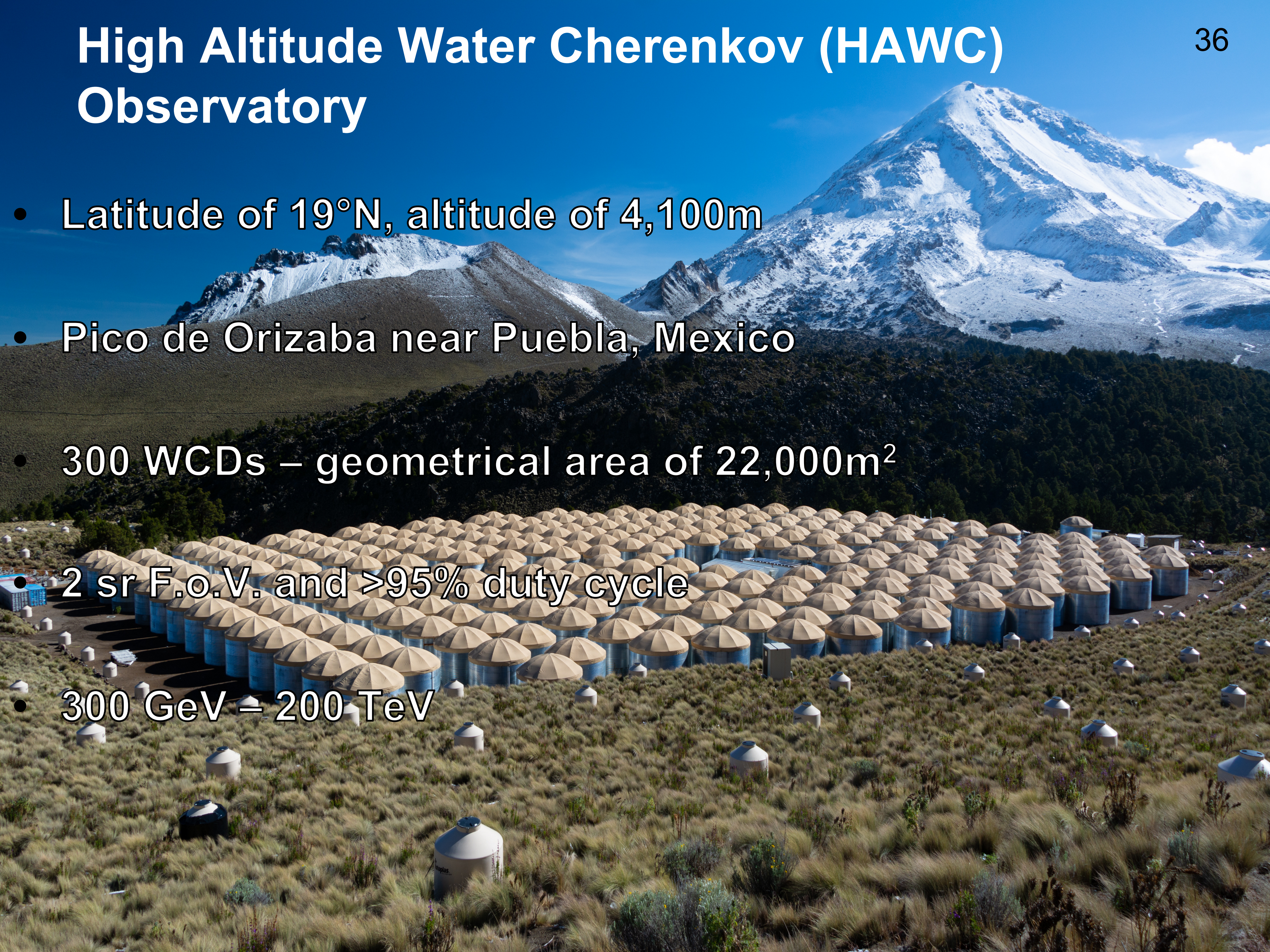
HAWC



Air Showers – Detection Techniques

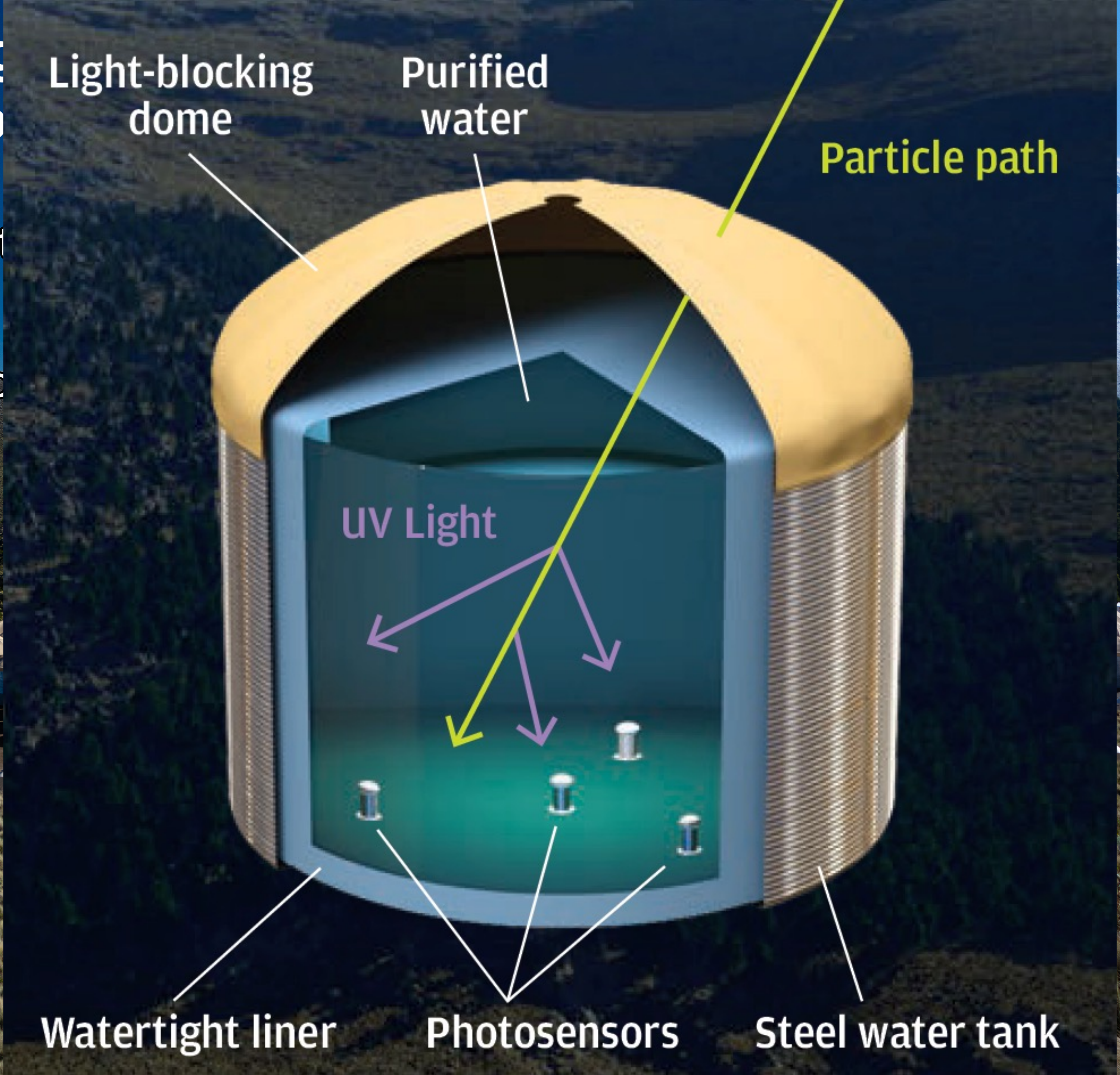
High Altitude Water Cherenkov (HAWC) Observatory

- Latitude of 19°N, altitude of 4,100m
- Pico de Orizaba near Puebla, Mexico
- 300 WCDs – geometrical area of 22,000m^2
- 2 sr F.o.V. and >95% duty cycle
- 300 GeV – 200 TeV



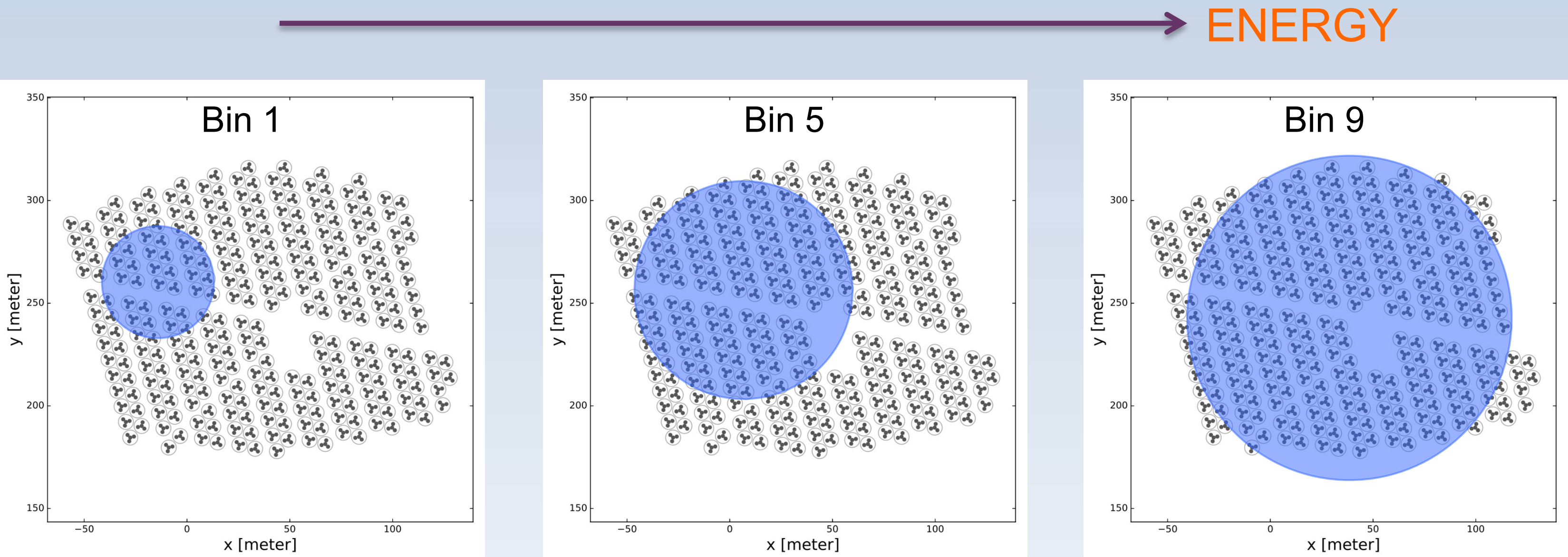
Hig
Ob

- Latit
- Pico
- 300
- 2 sr
- 300



Fractional Hit Bins

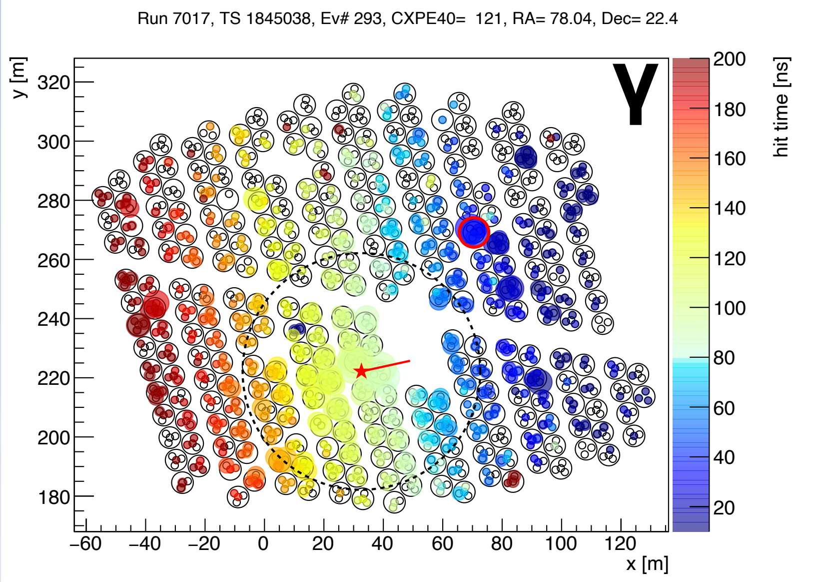
- Every gamma-ray event will hit a particular fraction of PMTs so we bin the events according to this fhit PMTs to estimate their energies.

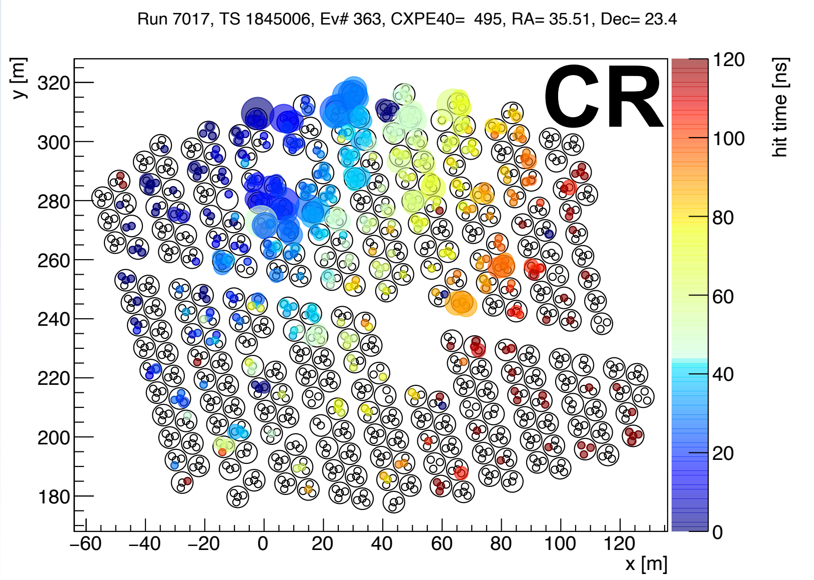


The higher the energy, the larger the size!

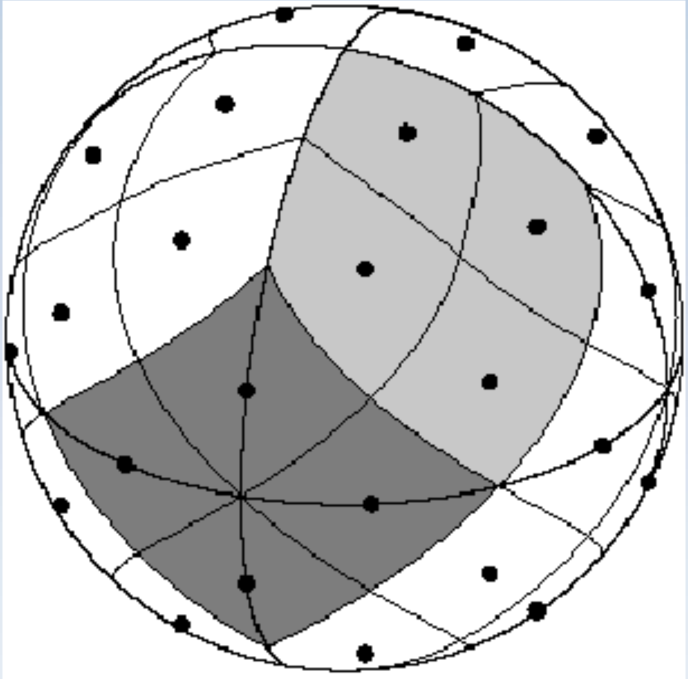
Gamma-Hadron Separation

- Cosmic-ray events outnumber gamma-ray events by 1000:1.
- Two techniques are used to separate the two types of events:
  - PINCness: Smoothness of charge distribution (CRs have miniature showers).
  - Compactness: Charge away from core (CRs have high no. of muons).





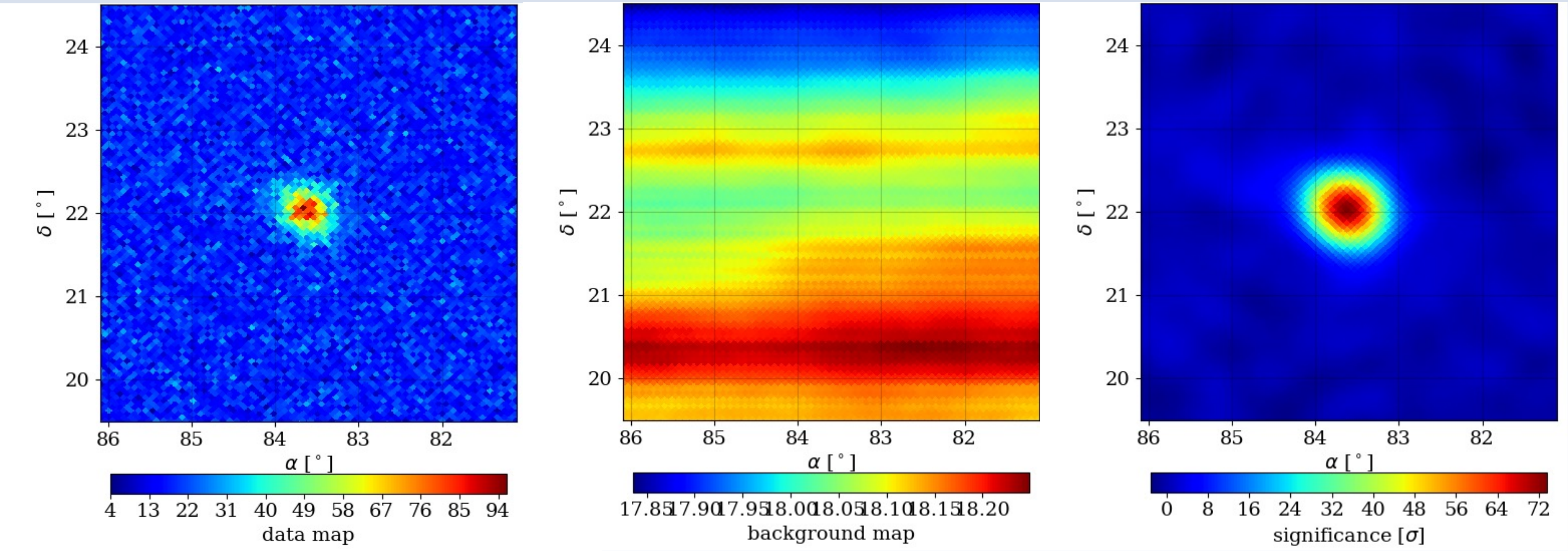
Map Making



- To make maps, we pixelize the sky (Hierarchical equal area isolatitude pixelization; Healpix)
- Count events in each pixel, N_i
- Estimate expected counts in each pixel $\langle N_i \rangle$
- Search for excess counts above expectation

All-Sky Map with Likelihood Fitting

- (raw) Data map contains photon counts after γ – hadron cuts.
- Bkgd. map contains CR counts that pass γ – hadron cuts.
- Sig. map, one parameter (normalization) fit for each pixel.



All-Sky Map with Likelihood Fitting

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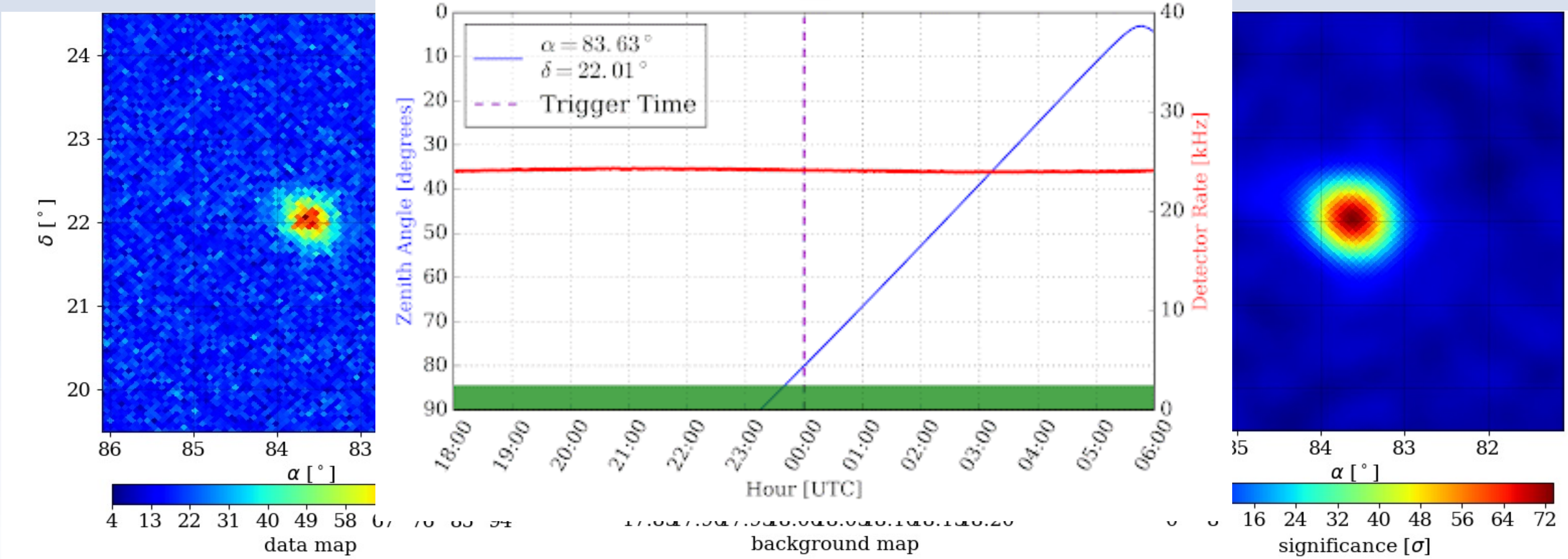
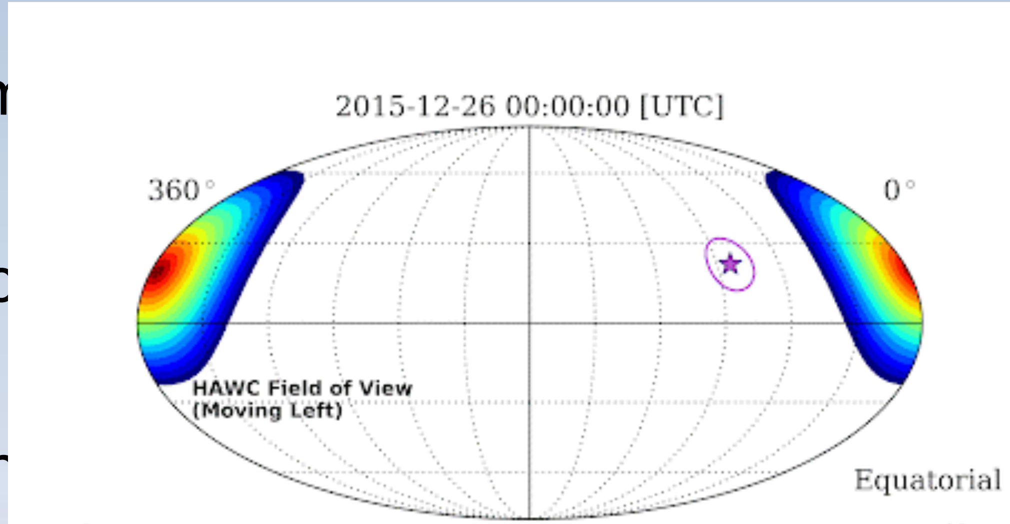


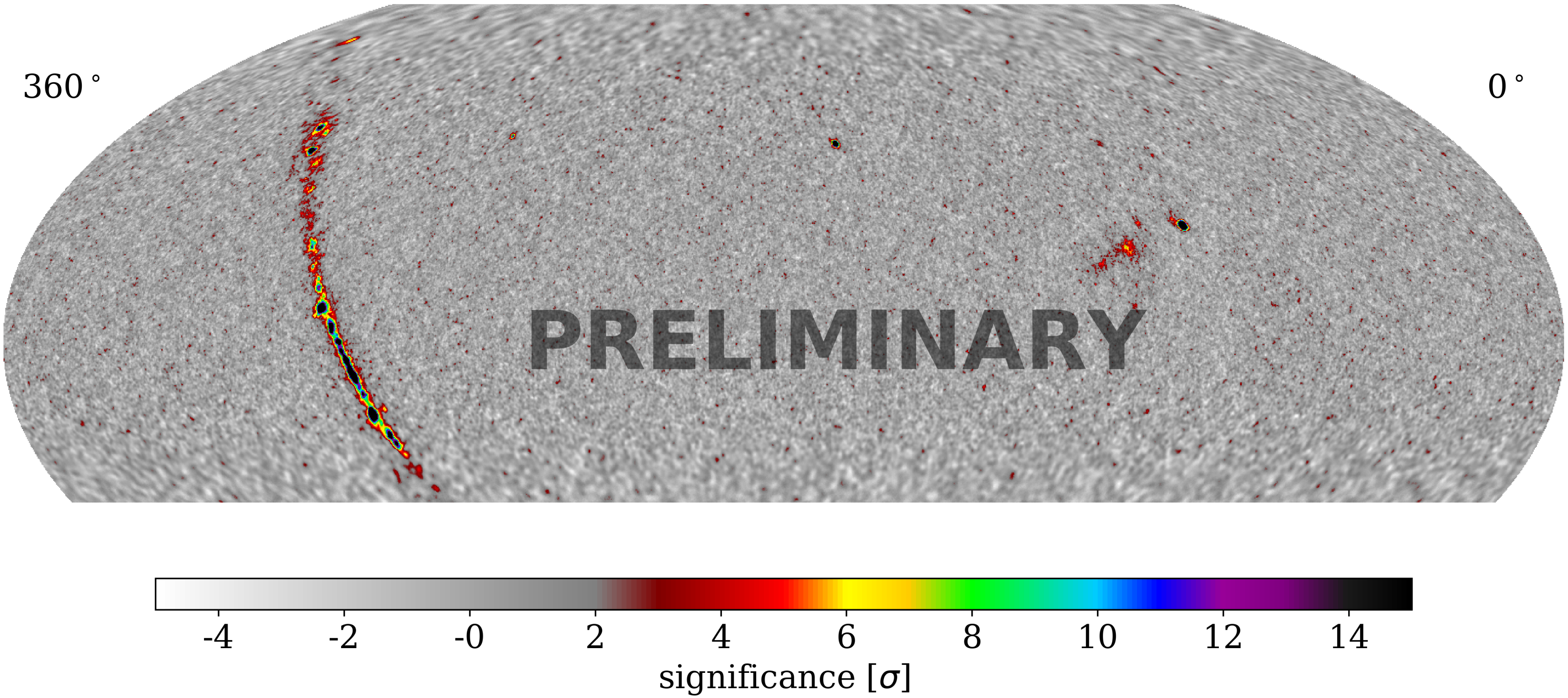


All-Sky Map with Likelihood Fitting

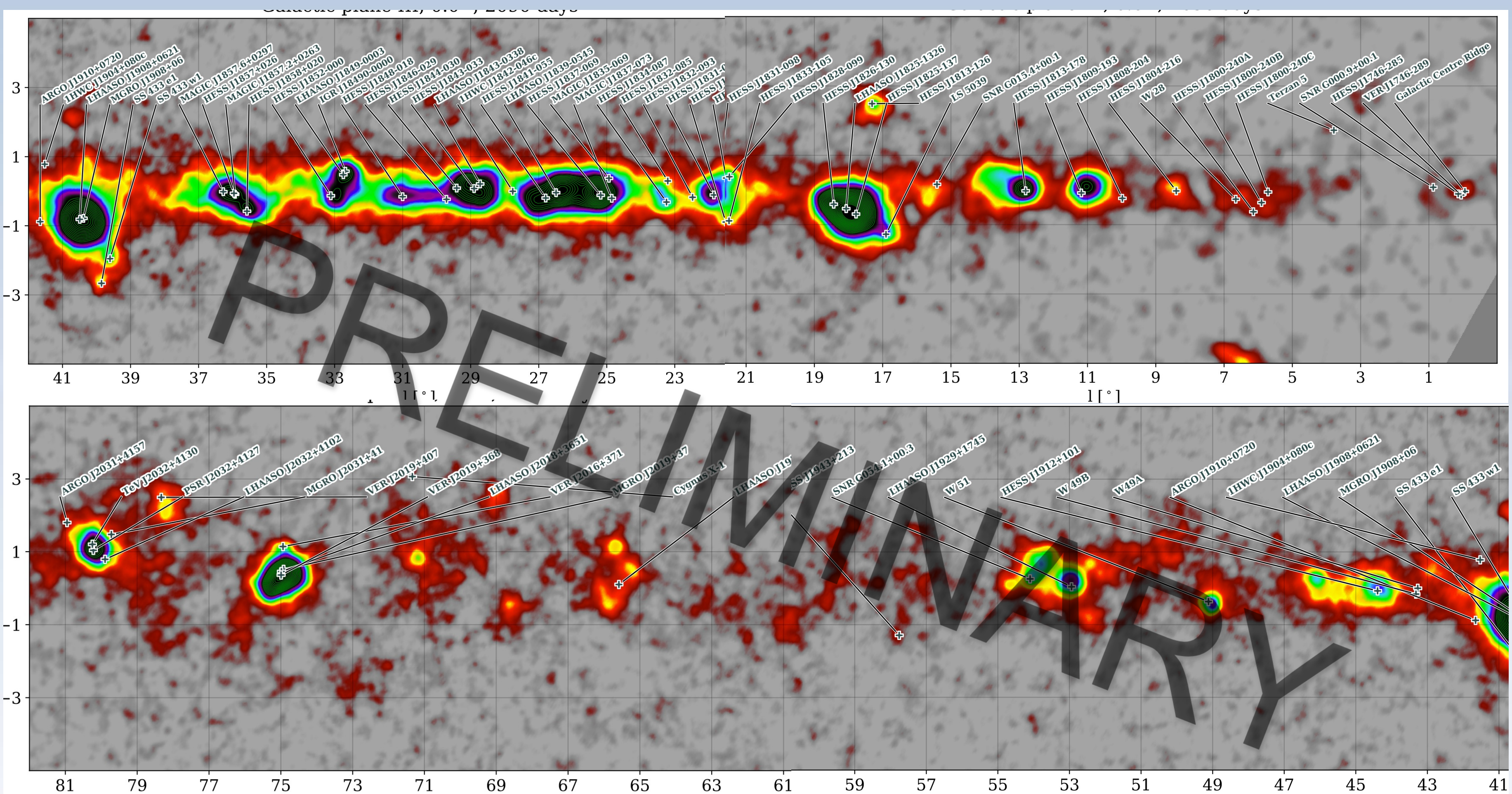
- (raw) Data map contains photon counts after γ – hadron cuts.

HAWC Sky Map 1523 Days of Data

2HWC catalog paper was 507 days



Highlight Results from HAWC



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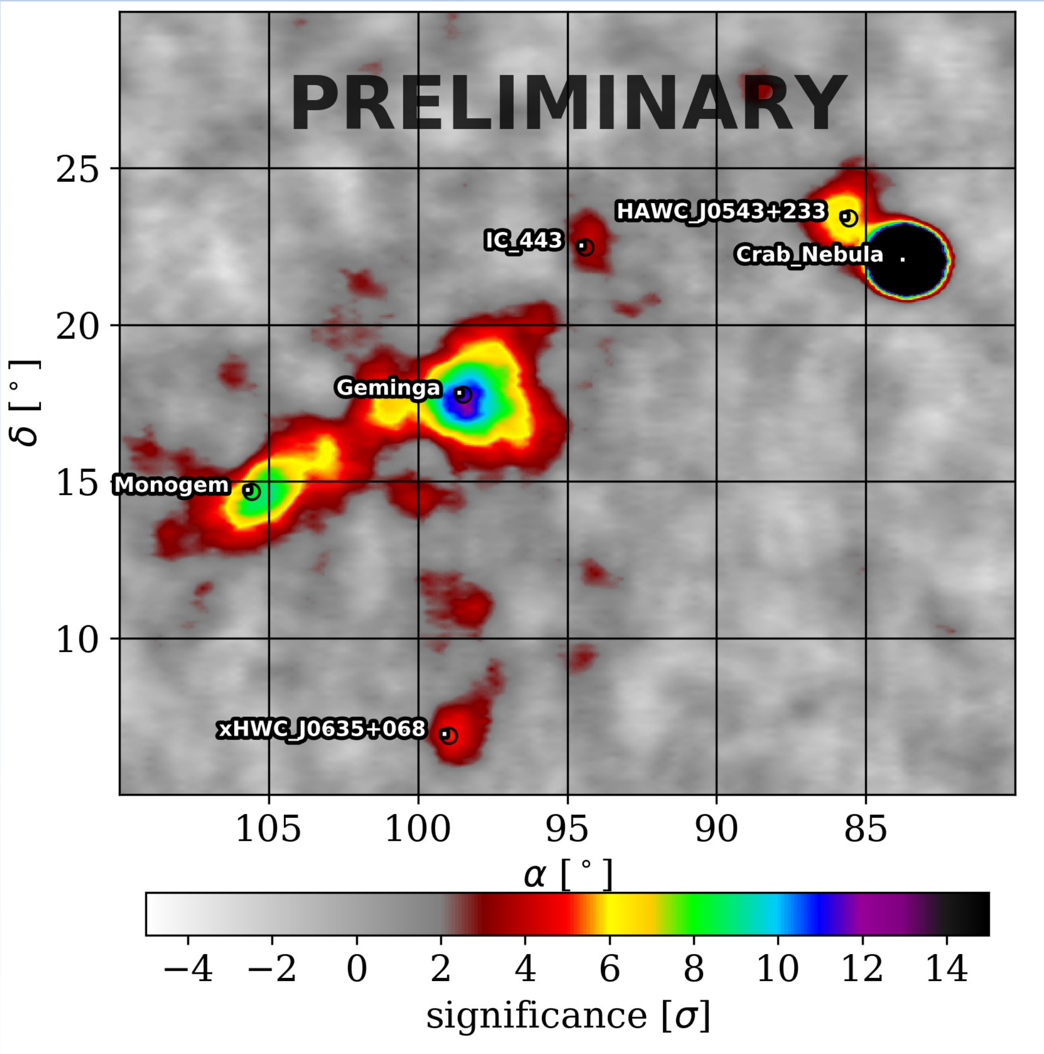

Highlight Results from HAWC

PARTICLE ASTROPHYSICS

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

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The unexpectedly high flux of cosmic-ray positrons detected at Earth may originate from nearby astrophysical sources, dark matter, or unknown processes of cosmic-ray secondary production. We report the detection, using the High-Altitude Water Cherenkov Observatory (HAWC), of extended tera–electron volt gamma-ray emission coincident with the locations of two nearby middle-aged pulsars (Geminga and PSR B0656+14). The HAWC observations demonstrate that these pulsars are indeed local sources of accelerated leptons, but the measured tera–electron volt emission profile constrains the diffusion of particles away from these sources to be much slower than previously assumed. We demonstrate that the leptons emitted by these objects are therefore unlikely to be the origin of the excess positrons, which may have a more exotic origin.

Cosmic rays are high-energy particles from space that have been known for more than a century. The origin of high-energy cosmic rays and how they are accelerated remains unclear. Most cosmic rays are protons or atomic nuclei, but positrons and electrons also are a small fraction of the total cosmic-ray flux. Positrons are especially puzzling because the PAMELA (Payload for Anti-matter Matter Exploration and Light-nuclei Astrophysics) detector observed an unexpected excess of positrons at energies >10 GeV, compared with the predicted flux that originates from interactions of cosmic-ray protons propagating through the Galaxy (*1*). Confirmation of these results has come from the Fermi Large Area Telescope (*2*) and AMS [Alpha Magnetic Spectrometer (*3*)] experiments; the latter also showed that the excess signal extends to hundreds of giga–electron volts.

Energy losses experienced in interstellar magnetic and radiation fields by the highest-energy positrons require that their sources lie within a few hundred parsecs from Earth (*4*). Nearby potential cosmic-ray accelerators—for example, pulsar wind nebulae (PWNe)—have been proposed as the sources of these extra positrons (*5*, *6*). A PWN consists of a rapidly spinning neutron star (pulsar) that produces a wind of electrons and positrons that are further accelerated by the surrounding shock with the interstellar medium (ISM). There are a handful of known pulsars that are both close enough to be candidate sources and sufficiently old for the highest-energy positrons to have had time to arrive at Earth (*7*, *8*). Nearby dark matter particle interactions could also produce positrons (*9*). Both PWNe and dark matter sources should also produce gamma rays that could potentially be observed coming from the sources, unlike positrons (whose paths are deflected by magnetic fields).

Recently, the High-Altitude Water Cherenkov Observatory (HAWC) collaboration reported the detection of tera–electron volt gamma rays around two nearby pulsars, which are among those proposed to produce the local positrons (*10*). HAWC is a wide-field-of-view, continuously operating detector of extensive air showers initiated by gamma rays and cosmic rays interacting in the atmosphere (*11*). The angular resolution improves from 1.0° to 0.2° with the size of the air shower. HAWC is the most sensitive survey detector above 10 TeV and is well suited to detecting nearby sources, which would have a greater angular extent. Operation of the full detector began in March 2015, and the data set presented here includes 507 days, as described in (*11*).

Tera–electron volt gamma-ray emissions from the pulsars Geminga and PSR B0656+14 were found in a search for extended sources that was performed for the HAWC catalog, in which these two pulsars have the designations 2HWC J0635+180 and 2HWC J0700+143 (*10*). By fitting to a diffusion model (*12*), the two sources were detected with a significance at the pulsar location of 13.1 and 8.1 standard deviations (σ), respectively (Fig. 1A). The tera–electron volt emission region is several degrees across, which we attribute to electrons and positrons diffusing away from the

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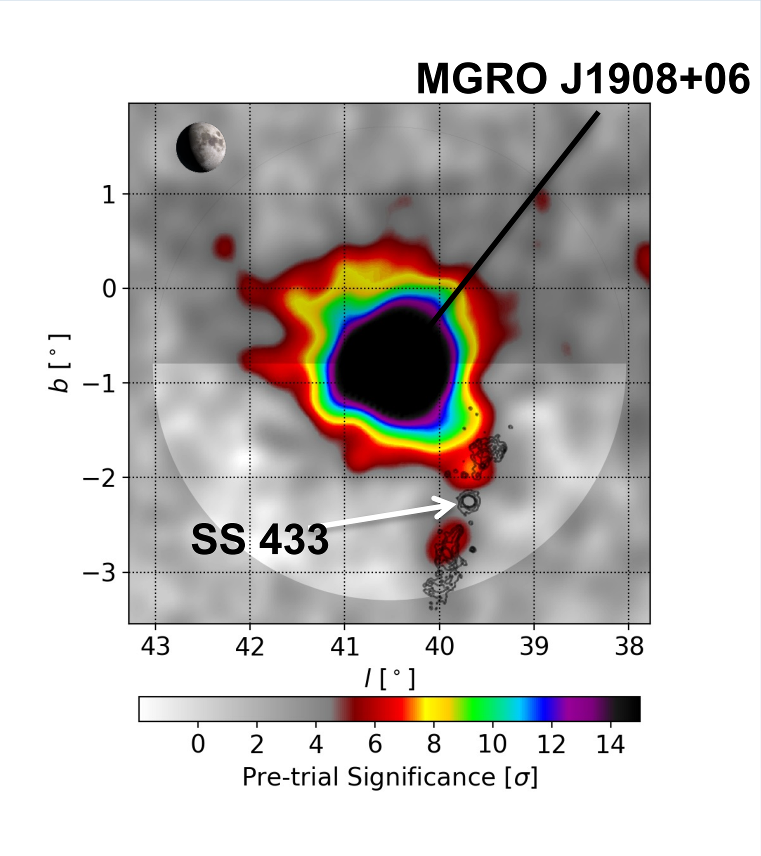
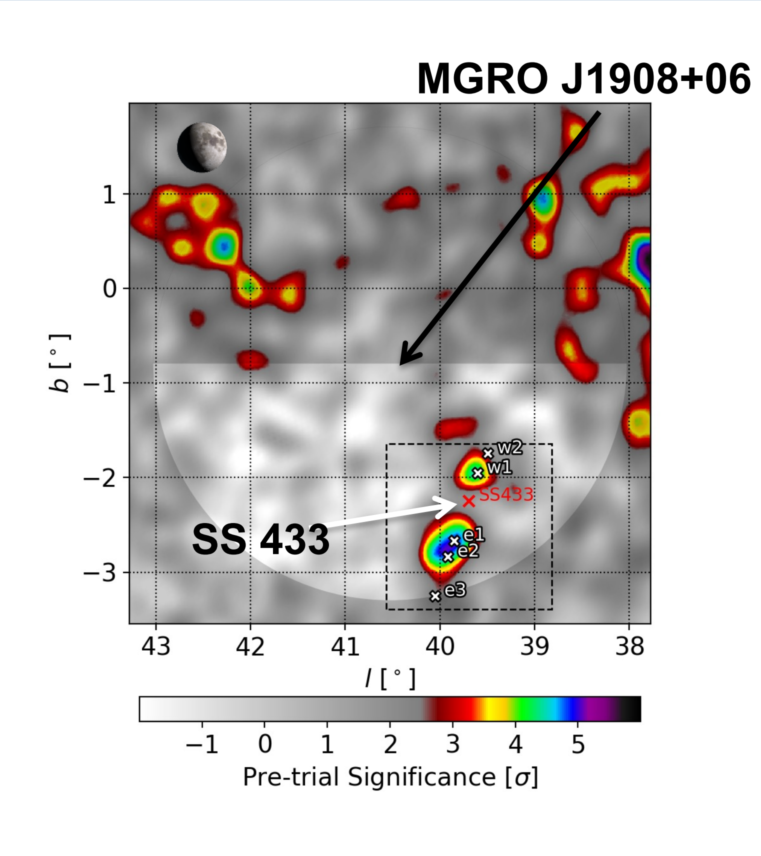
Highlight Results from HAWC





Highlight Results from HAWC

LETTER

Corrected: Publisher Correction

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Very-high-energy particle acceleration powered by the jets of the microquasar SS 433

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SS 433 is a binary system containing a supergiant star that is overflowing its Roche lobe with matter accreting onto a compact object (either a black hole or neutron star)[1–3]. Two jets of ionized matter with a bulk velocity of approximately 0.26*c* (where *c* is the speed of light in vacuum) extend from the binary, perpendicular to the line of sight, and terminate inside W50, a supernova remnant that is being distorted by the jets[2,4–8]. SS 433 differs from other microquasars (small-scale versions of quasars that are present within our own Galaxy) in that the accretion is believed to be super-Eddington[9–11], and the luminosity of the system is about 10^{40} ergs per second[2,9,12,13]. The lobes of W50 in which the jets terminate, about 40 parsecs from the central source, are expected to accelerate charged particles, and indeed radio and X-ray emission consistent with electron synchrotron emission in a magnetic field have been observed[14–16]. At higher energies (greater than 100 gigaelectronvolts), the particle fluxes of γ-rays from X-ray hotspots around SS 433 have been reported as flux upper limits[6,17–20]. In this energy regime, it has been unclear whether the emission is dominated by electrons that are interacting with photons from the cosmic microwave background through inverse-Compton scattering or by protons that are interacting with the ambient gas. Here we report teraelectronvolt γ-ray observations of the SS 433/W50 system that spatially resolve the lobes. The teraelectronvolt emission is localized to structures in the lobes, far from the centre of the system where the jets are formed. We have measured photon energies of at least 25 teraelectronvolts, and these are certainly not Doppler-boosted, because of the viewing geometry. We conclude that the emission—from radio to teraelectronvolt energies—is consistent with a single population of electrons with energies extending to at least hundreds of teraelectronvolts in a magnetic field of about 16 microgauss.

In the SS 433/W50 complex, several regions located west of the central binary (w1 and w2) and east (e1, e2, e3) are observed to emit hard X-rays[6]. Previous searches for very high-energy (VHE) γ-ray emission from the hotspots between roughly 100 GeV and 10 TeV have produced null results[17–20], though an excess observed at about 800 MeV may be associated with SS 433 and W50[21]. The High Altitude Water Cherenkov (HAWC) observatory, Mexico, is a wide field-of-view VHE γ-ray observatory surveying the Northern Hemisphere above 1 TeV, and is optimized for photon detection above 10 TeV[22]. SS 433 transits 15° from the zenith of the HAWC detector each day, and has been observed with >90% uptime since the start of detector operations in 2015.

In 1,017 days of measurements with HAWC, an excess of γ-rays with a post-trials significance of 5.4σ has been observed in a joint fit of the eastern and western interaction regions of the jets of SS 433. The emission is plotted in galactic coordinates in Fig. 1, which includes an overlay of the X-ray observations of the jets and the central binary. The γ-ray emission is spatially coincident with the X-ray hotspots w1 and e1; no significant emission is observed at the location of the central binary where the jets are produced.

Spatial and spectral fits to SS 433 are performed in a semicircular region of interest (ROI) designed to mask out diffuse emission from

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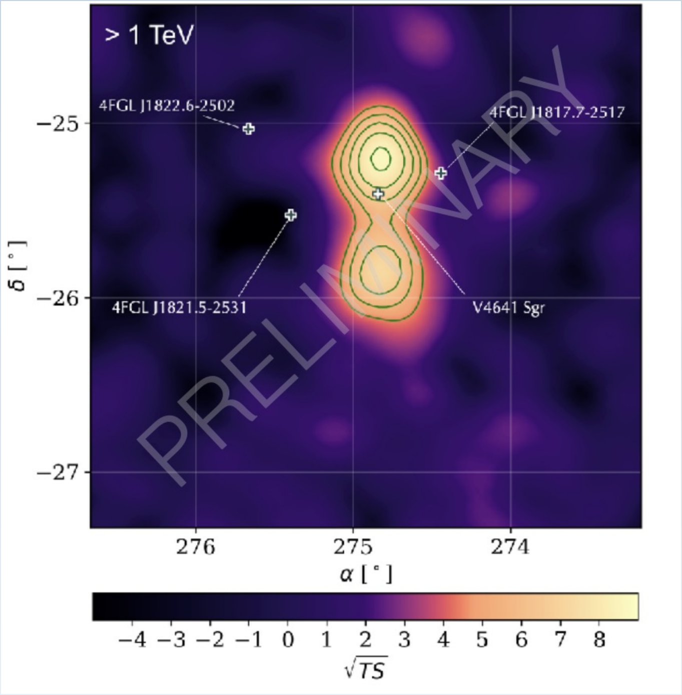

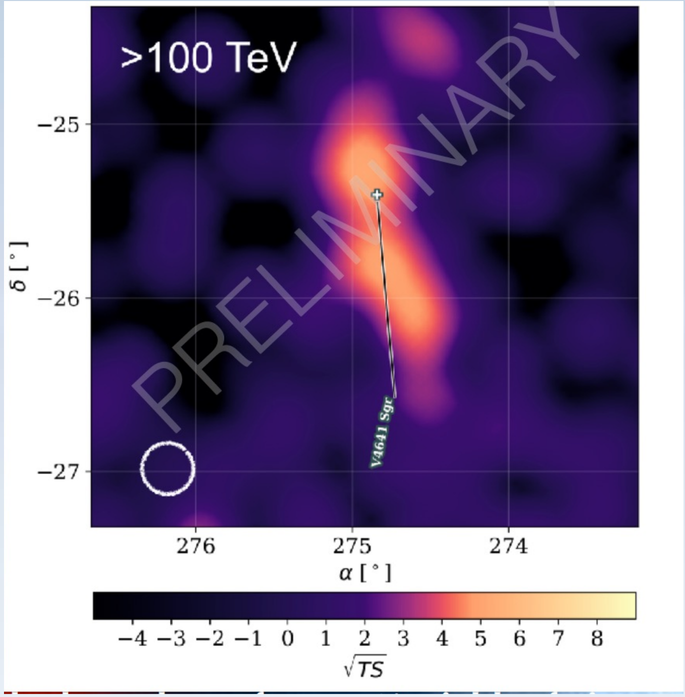

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Article

Ultra-high-energy gamma-ray bubble around microquasar V4641 Sgr

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Microquasars are laboratories for the study of jets of relativistic particles produced by accretion onto a spinning black hole. Microquasars are near enough to allow detailed imaging of spatial features across the multiwavelength spectrum. The recent extension measurement of the spatial morphology of a microquasar, SS 433, to TeV gamma rays[1] localizes the acceleration of electrons at shocks in the jet far from the black hole[2]. V4641 Sagittarii (V4641 Sgr) is a similar binary system with a black hole and B-type main-sequence companion star and has an orbit period of 2.8 days (refs. 3,4). It stands out for its super-Eddington accretion[5] and for its radio jet, which is one of the fastest superluminal jets in the Milky Way. Previous observations of V4641 Sgr did not report gamma-ray emission[6]. Here we report TeV gamma-ray emission from V4641 Sgr that reveals particle acceleration at similar distances from the black hole as SS 433. Furthermore, the gamma-ray spectrum of V4641 Sgr is among the hardest TeV spectra observed from any known gamma-ray source and is detected above 200 TeV. Gamma rays are produced by particles, either electrons or protons, of higher energies. Because energetic electrons lose energy more quickly the higher their energy, such a spectrum either very strongly constrains the electron-production mechanism or points to the acceleration of high-energy protons. This suggests that large-scale jets from microquasars could be more common than previously expected and that they could be a notable source of galactic cosmic rays[7–9].

Observations from 2015 to 2022 by the High-Altitude Water Cherenkov (HAWC) Observatory[10] have revealed notable gamma-ray emission coincident with the location of V4641 Sgr, as shown in Fig. 1. The excess over the estimated cosmic-ray background flux reaches a maximum significance of 8.8σ above 1 TeV and 5.2σ above 100 TeV. After ruling out an association with extragalactic background sources and other high-energy sources in the galaxy, we conclude that V4641 Sgr is the probable source of the observed gamma-ray excess (see details in Methods).

On the basis of a systematic multisource analysis method on a 3° radius region of interest (ROI) around the gamma-ray emission, the excess may be described as either two point-like sources or one extended source with an asymmetric Gaussian distribution (see details in Methods). The present statistics do not allow us to distinguish between the two spatial models. When adopting a two-point-source model, the northern source and the southern source are detected at 8.1σ and 6.7σ, respectively The 95% upper limits on the extensions of the two sources are found to be 0.17° and 0.23°, respectively, when fitting

A list of affiliations appears at the end of the paper.

HAWC Search for New Physics

- LIV: $E_\gamma^2 - p_\gamma^2 = \pm|\alpha_n|p_\gamma^{n+2}$
  - Photon decays forbidden in classical relativity but allowed in LIV

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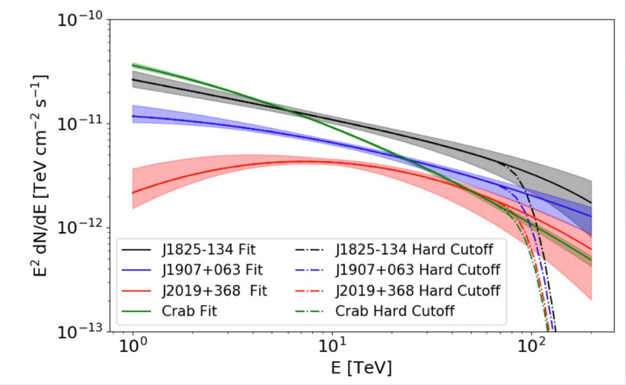
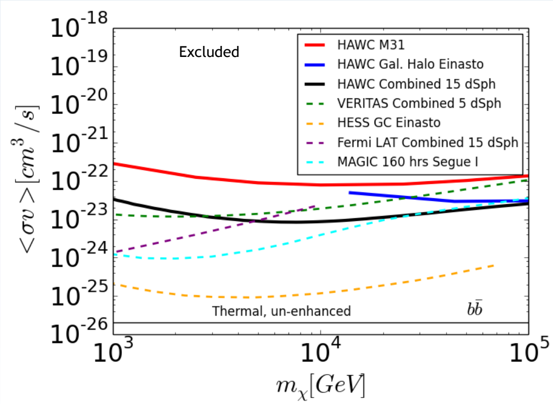
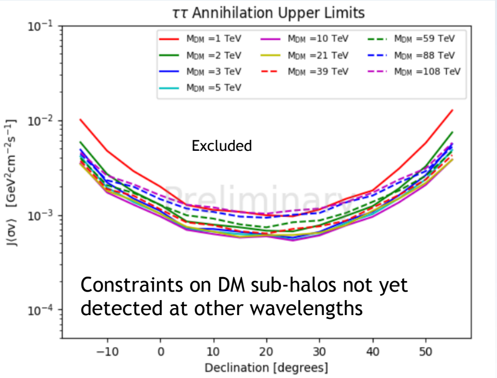


- Dark matter: many dark matter targets in HAWC F.o.V.
  - HAWC's wide F.o.V. and daily exposures of several dark matter targets yield best limits on dwarf spheroidal galaxies for highest DM masses

Phys. Rev. D **101**, 103001, May 2020

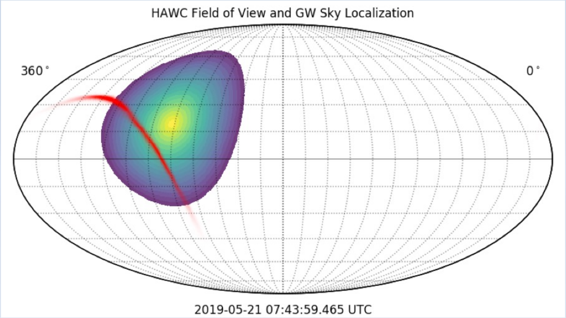




Multi-messenger Astronomy

- Gravitational Waves – LIGO
  - Automatic search of GRB when GCN alert (LIGO)
  - $\Delta t = 0.3, 1, 3, 10, 30, 100$ seconds

B. P. Abbott et al. Astrophys. J., 848(2):L12, 2017



- Neutrinos – IceCube
  - Simultaneous detection of gamma rays and neutrinos can provide evidence of CR accelerator

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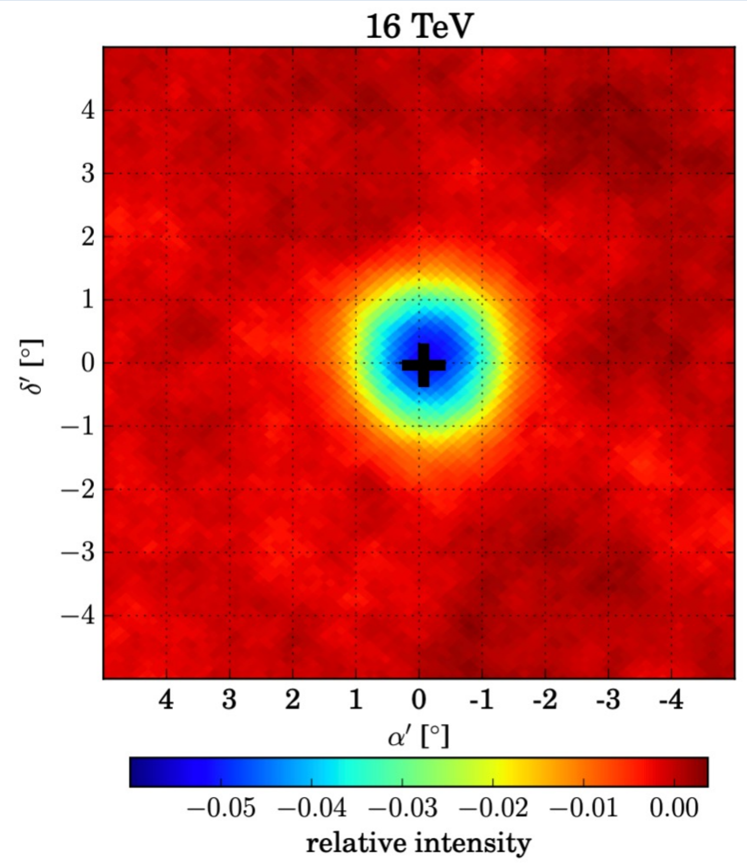
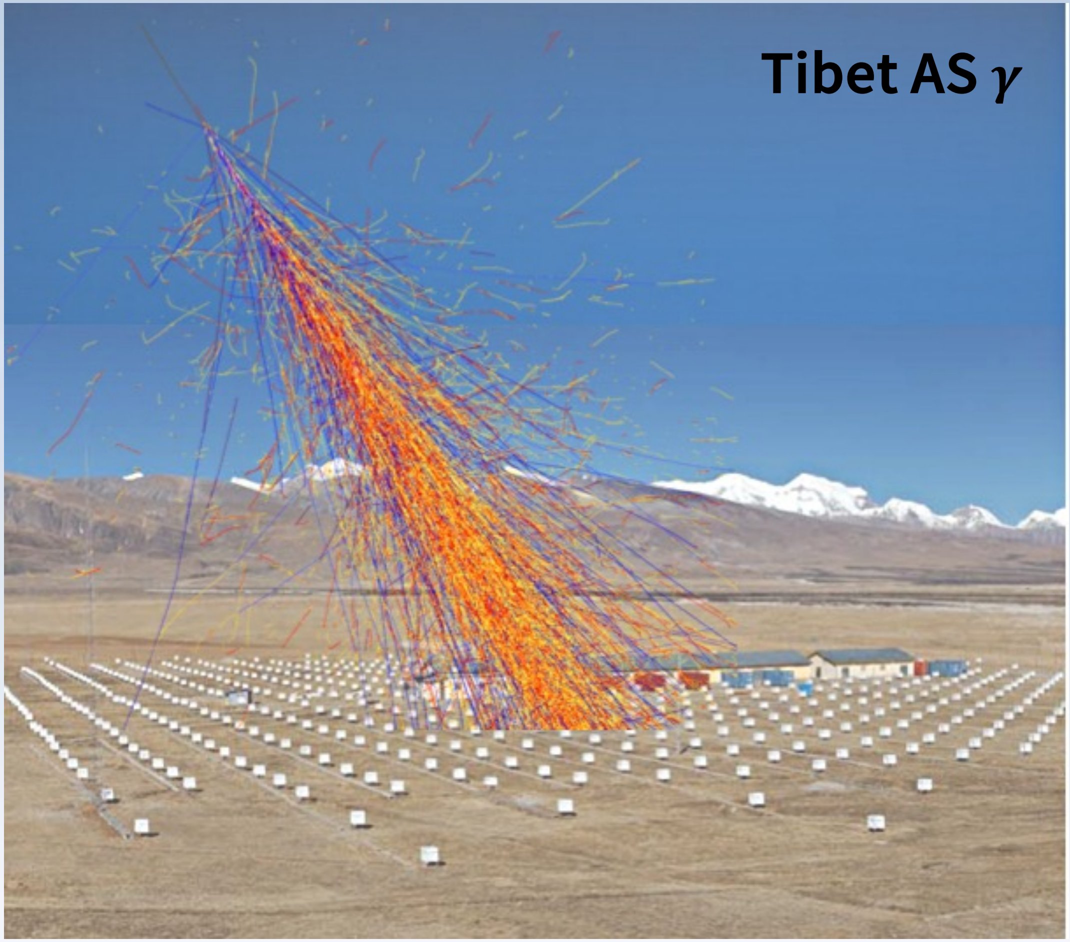
Moon Shadow



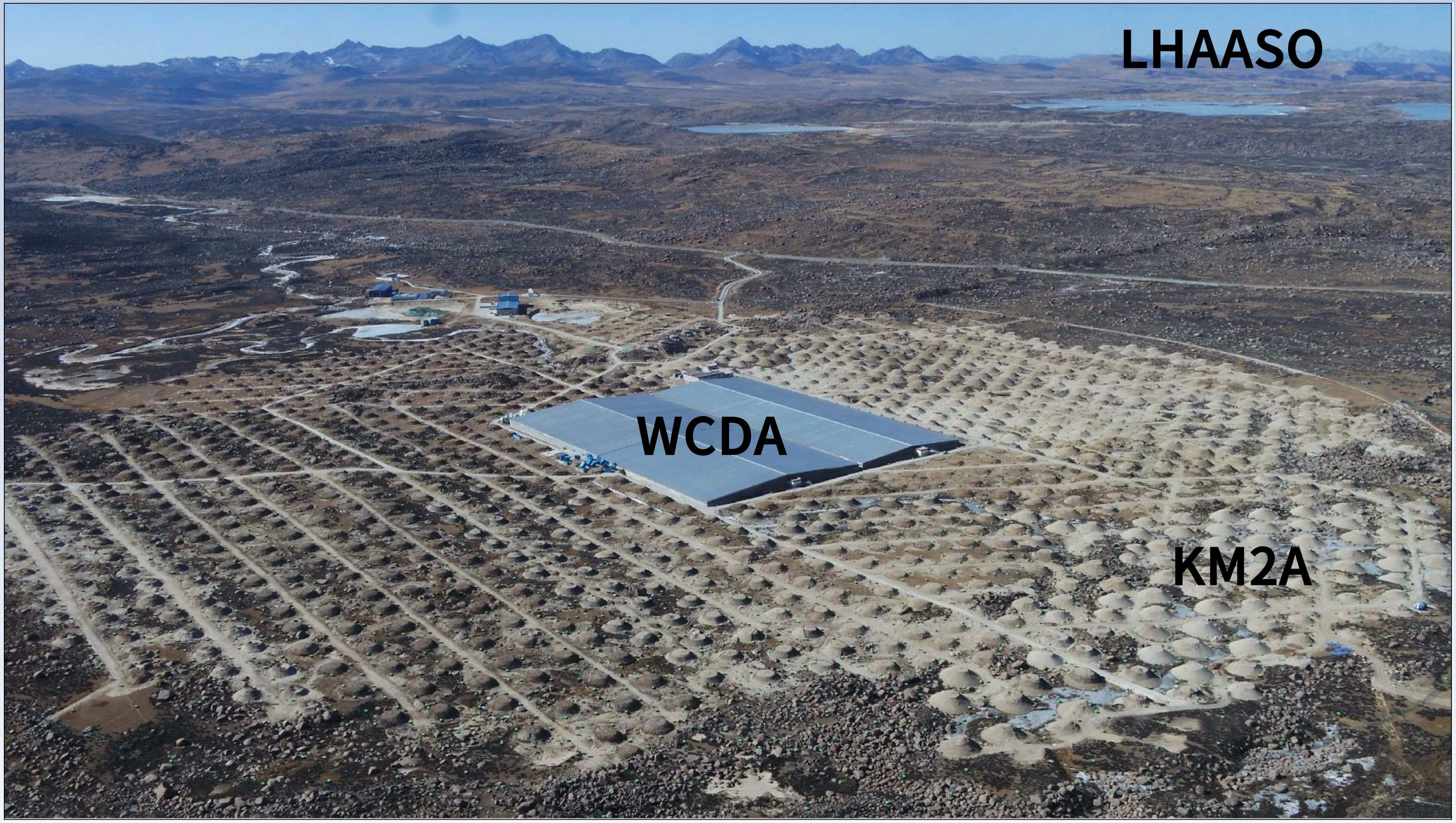
- Moon blocks cosmic rays forming a “cosmic-ray shadow”
- Moon shadow slightly shifted because Earth’s magnetic field deflects incoming cosmic rays
- If anti-particle, shadow would be formed in the other way

A. U. Abeysekara et al. Phys. Rev., D97(10):102005, 2018

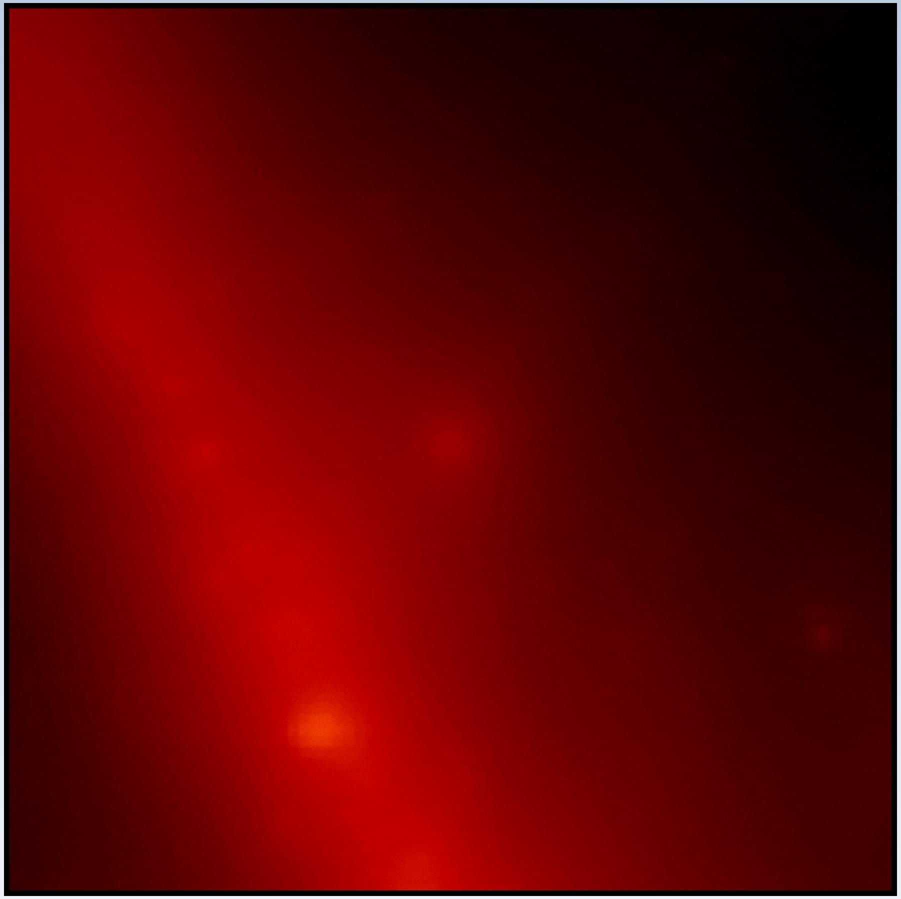
Tibet AS γ



LHAASO



LHAASO



- **GRB 221009A**
- **BOAT** (Brightest Of All Time) **7 minutes, but for several hours it was bright enough in visible frequencies to be observable by amateur astronomers**
- **1.9 billion years ago**
  (2.4 billion light-years away)
- **Fully saturated Fermi LAT**
- **LHAASO detected with**

LHAASO

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The First LHAASO Catalog of Gamma-Ray Sources

Zhen Cao[1,2,3], F. Aharonian[4,5], Q. An[6,7], Axikegu[8], Y. X. Bai[1,3], Y. W. Bao[9], D. Bastieri[10], X. J. Bi[1,2,3], Y. J. Bi[1,3], J. T. Cai[10], Q. Cao[11], W. Y. Cao[7], Zhe Cao[6,7], J. Chang[12], J. F. Chang[1,3,6], A. M. Chen[13], E. S. Chen[1,2,3], Liang Chen[14], Lin Chen[8], Long Chen[8], M. J. Chen[1,3], M. L. Chen[1,3,6], Q. H. Chen[8], S. H. Chen[1,2,3], S. Z. Chen[1,3], T. L. Chen[15], Y. Chen[9], N. Cheng[1,3], Y. D. Cheng[1,3], M. Y. Cui[12], S. W. Cui[11], X. H. Cui[16], Y. D. Cui[17], B. Z. Dai[18], H. L. Dai[1,3,6], Z. G. Dai[7], Danzengluobu[15], D. della Volpe[19], X. Q. Dong[1,2,3], K. K. Duan[12], J. H. Fan[10], Y. Z. Fan[12], J. Fang[18], K. Fang[1,3], C. F. Feng[20], L. Feng[12], S. H. Feng[1,3], X. T. Feng[20], Y. L. Feng[15], S. Gabici[21], B. Gao[1,3], C. D. Gao[20], L. Q. Gao[1,2,3], Q. Gao[15], W. Gao[1,3], W. K. Gao[1,2,3], M. M. Ge[18], L. S. Geng[1,3], G. Giacinti[13], G. H. Gong[22], Q. B. Gou[1,3], M. H. Gu[1,3,6], F. L. Guo[14], X. L. Guo[8], Y. Q. Guo[1,3], Y. Y. Guo[12], Y. A. Han[23], H. H. He[1,2,3], H. N. He[12], J. Y. He[12], X. B. He[17], Y. He[8], M. Heller[19], Y. K. Hor[17], B. W. Hou[1,2,3], C. Hou[1,3], X. Hou[24], H. B. Hu[1,2,3], Q. Hu[7,12], S. C. Hu[1,3,25], D. H. Huang[8], T. Q. Huang[1,3], W. J. Huang[17], X. T. Huang[20], X. Y. Huang[12], Y. Huang[1,2,3], Z. C. Huang[8], X. L. Ji[1,3,6], H. Y. Jia[8], K. Jia[20], K. Jiang[6,7], X. W. Jiang[1,3], Z. J. Jiang[18], M. Jin[8], M. M. Kang[26], T. Ke[1,3], D. Kuleshov[27], K. Kurinov[27], B. B. Li[11], Cheng Li[6,7], Cong Li[1,3], D. Li[1,2,3], F. Li[1,3,6], H. B. Li[1,3], H. C. Li[1,3], H. Y. Li[7,12], J. Li[7,12], Jian Li[7], Jie Li[1,3,6], K. Li[1,3], W. L. Li[20], W. L. Li[13], X. R. Li[1,3], Xin Li[6,7], Y. Z. Li[1,2,3], Zhe Li[1,3], Zhuo Li[28], E. W. Liang[29], Y. F. Liang[29], S. J. Lin[17], B. Liu[7], C. Liu[1,3], D. Liu[20], H. Liu[8], H. D. Liu[23], J. Liu[1,3], J. L. Liu[1,3], J. Y. Liu[1,3], M. Y. Liu[15], R. Y. Liu[9], S. M. Liu[8], W. Liu[1,3], Y. Liu[10], Y. N. Liu[22], R. Lu[18], Q. Luo[17], H. K. Lv[1,3], B. Q. Ma[28], L. L. Ma[1,3], X. H. Ma[1,3], J. R. Mao[24], Z. Min[1,3], W. Mitthumsiri[30], H. J. Mu[23], Y. C. Nan[1,3], A. Neronov[21], Z. W. Ou[17], B. Y. Pang[8], P. Pattarakijwanich[30], Z. Y. Pei[10], M. Y. Qi[1,3], Y. Q. Qi[11], B. Q. Qiao[1,3], J. J. Qin[7], D. Ruffolo[30], A. Sáiz[30], D. Semikoz[21], C. Y. Shao[17], L. Shao[11], O. Shchegolev[27,31], X. D. Sheng[1,3], F. W. Shu[32], H. C. Song[28], Yu. V. Stenkin[27,31], V. Stepanov[27], Y. Su[12], Q. N. Sun[8], X. N. Sun[29], Z. B. Sun[33], P. H. T. Tam[17], Q. W. Tang[32], Z. B. Tang[6,7], W. W. Tian[2,16], C. Wang[33], C. B. Wang[8], G. W. Wang[7], H. G. Wang[10], H. H. Wang[17], J. C. Wang[24], K. Wang[9], L. P. Wang[20], L. Y. Wang[1,3], P. H. Wang[8], R. Wang[20], W. Wang[17], X. G. Wang[29], X. Y. Wang[9], Y. Wang[8], Y. D. Wang[1,3], Y. J. Wang[1,3], Z. H. Wang[26], Z. X. Wang[18], Zhen Wang[13], Zheng Wang[1,3,6], D. M. Wei[12], J. J. Wei[12], Y. J. Wei[1,2,3], T. Wen[18], C. Y. Wu[1,3], H. R. Wu[1,3], S. Wu[1,3], X. F. Wu[12], Y. S. Wu[7], S. Q. Xi[1,3], J. Xia[7,12], J. J. Xia[8], G. M. Xiang[2,14], D. X. Xiao[11], G. Xiao[1,3], G. G. Xin[1,3], Y. L. Xin[8], Y. Xing[14], Z. Xiong[1,2,3], D. L. Xu[13], R. F. Xu[1,2,3], R. X. Xu[28], W. L. Xu[26], L. Xue[20], D. H. Yan[18], J. Z. Yan[12], T. Yan[1,3], C. W. Yang[26], F. Yang[11], F. F. Yang[1,3,6], H. W. Yang[17], J. Y. Yang[17], L. L. Yang[17], M. J. Yang[1,3], R. Z. Yang[7], S. B. Yang[18], Y. H. Yao[26], Z. G. Yao[1,3], Y. M. Ye[22], L. Q. Yin[1,3], N. Yin[20], X. H. You[1,3], Z. Y. You[1,3], Y. H. Yu[7], Q. Yuan[12], H. Yue[1,2,3], H. D. Zeng[12], T. X. Zeng[1,3,6], W. Zeng[18], M. Zha[1,3], B. B. Zhang[9], F. Zhang[8], H. M. Zhang[9], H. Y. Zhang[1,3], J. L. Zhang[16], L. X. Zhang[10], Li Zhang[18], P. F. Zhang[18], P. P. Zhang[7,12], R. Zhang[7,12], S. B. Zhang[2,16], S. R. Zhang[11], S. S. Zhang[1,3], X. Zhang[9], X. P. Zhang[1,3], Y. F. Zhang[8], Yi Zhang[1,12], Yong Zhang[1,3], B. Zhao[8], J. Zhao[1,3], L. Zhao[6,7], L. Z. Zhao[11], S. P. Zhao[12,20], F. Zheng[33], B. Zhou[1,3], H. Zhou[13], J. N. Zhou[14], M. Zhou[32], P. Zhou[9], R. Zhou[26], X. X. Zhou[8], C. G. Zhu[20], F. R. Zhu[8], H. Zhu[16], K. J. Zhu[1,2,3,6], and X. Zuo[1,3]
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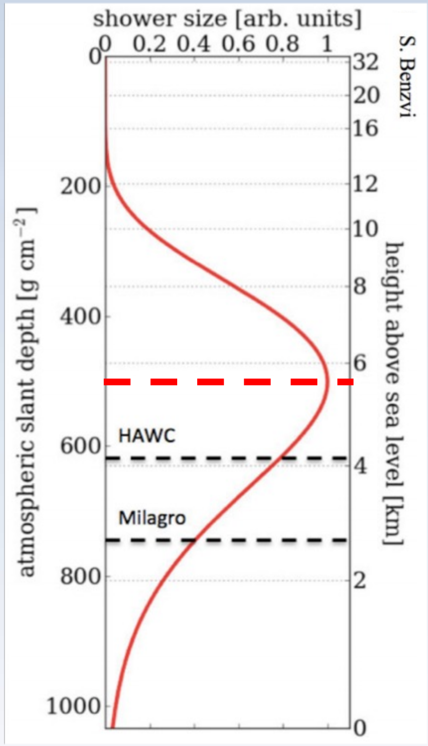
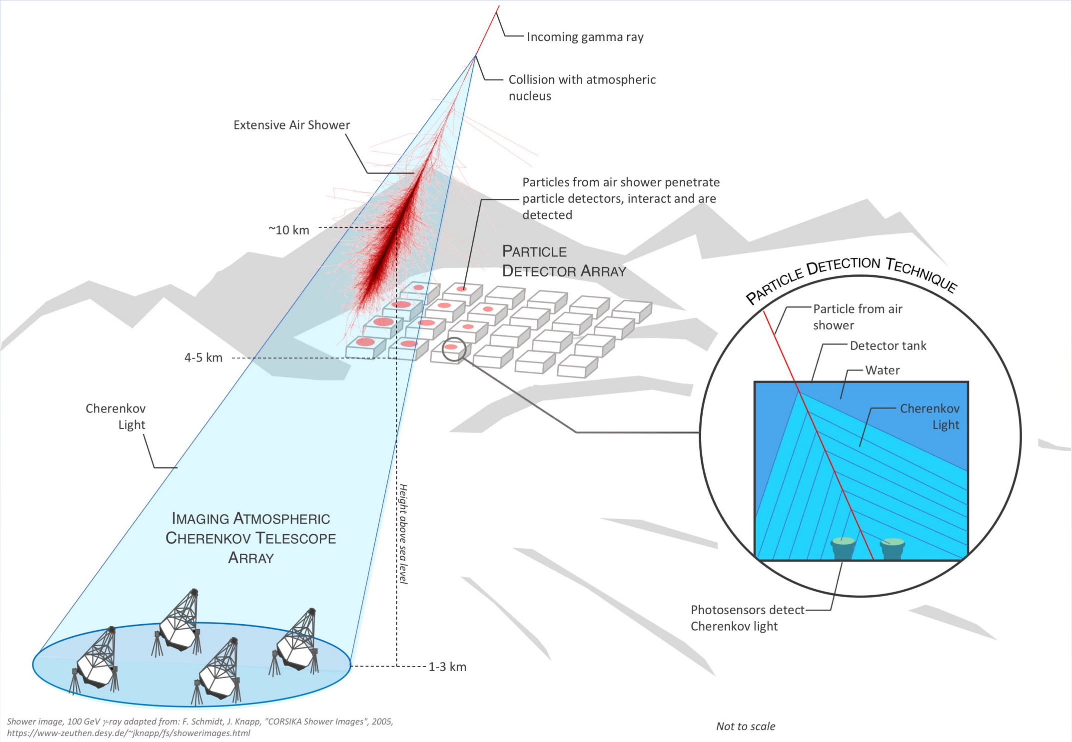
Future of HAWC – SWGO

- HAWC getting close to the end of its research cycle

Not the end of HAWC!



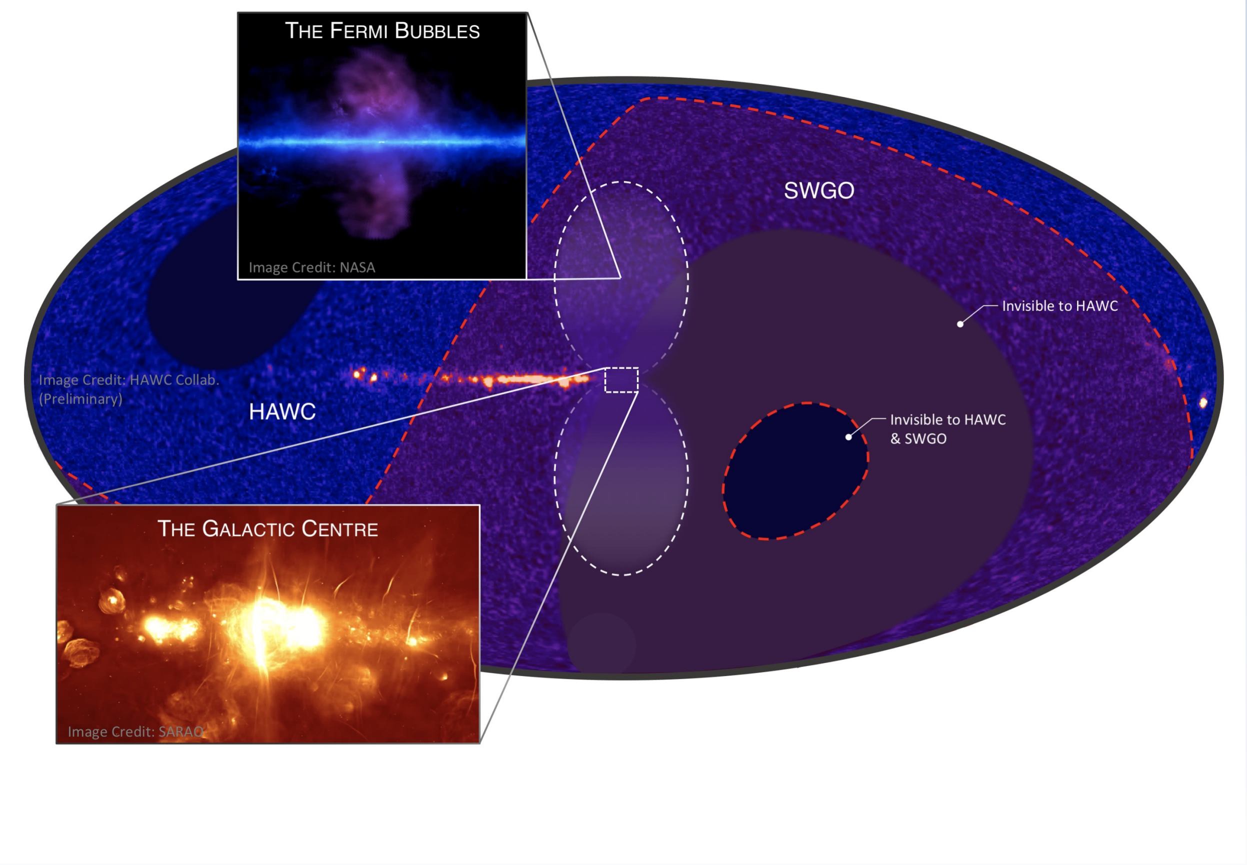


- Collaboration founded on July 1st 2019
  - 42 institutions from 11 countries

Future of HAWC – SWGO

- Southern Wide-field Gamma-ray Observatory

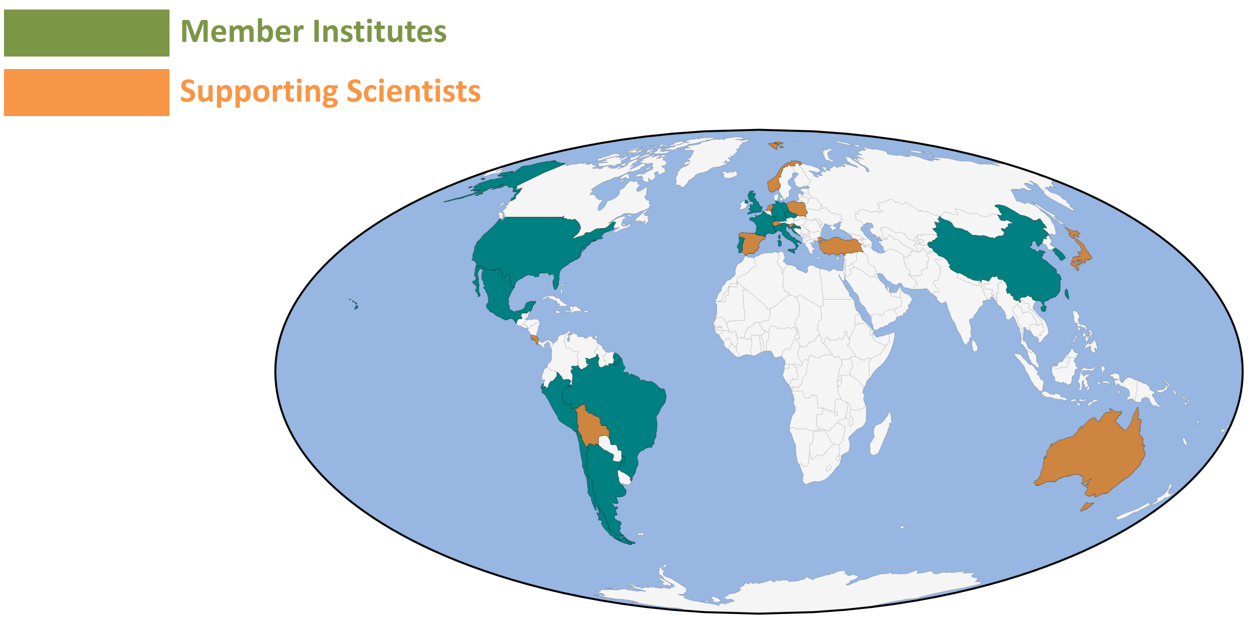
Not the end of HAWC!

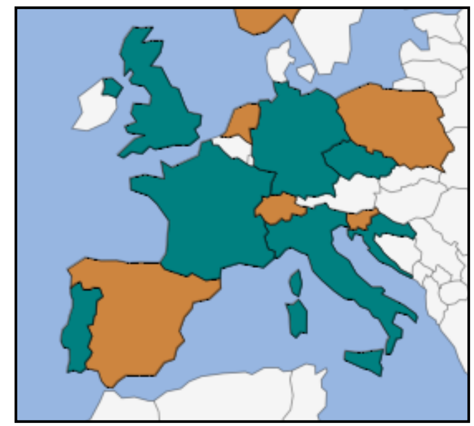


Future of HAWC – SWGO

Future of HAWC – SWGO

SWGO Collaboration





Argentina
Brazil
Chile
China
Croatia
Czech Republic
France
Germany
Italy
Mexico
Peru
Portugal
South Korea
United Kingdom
United States

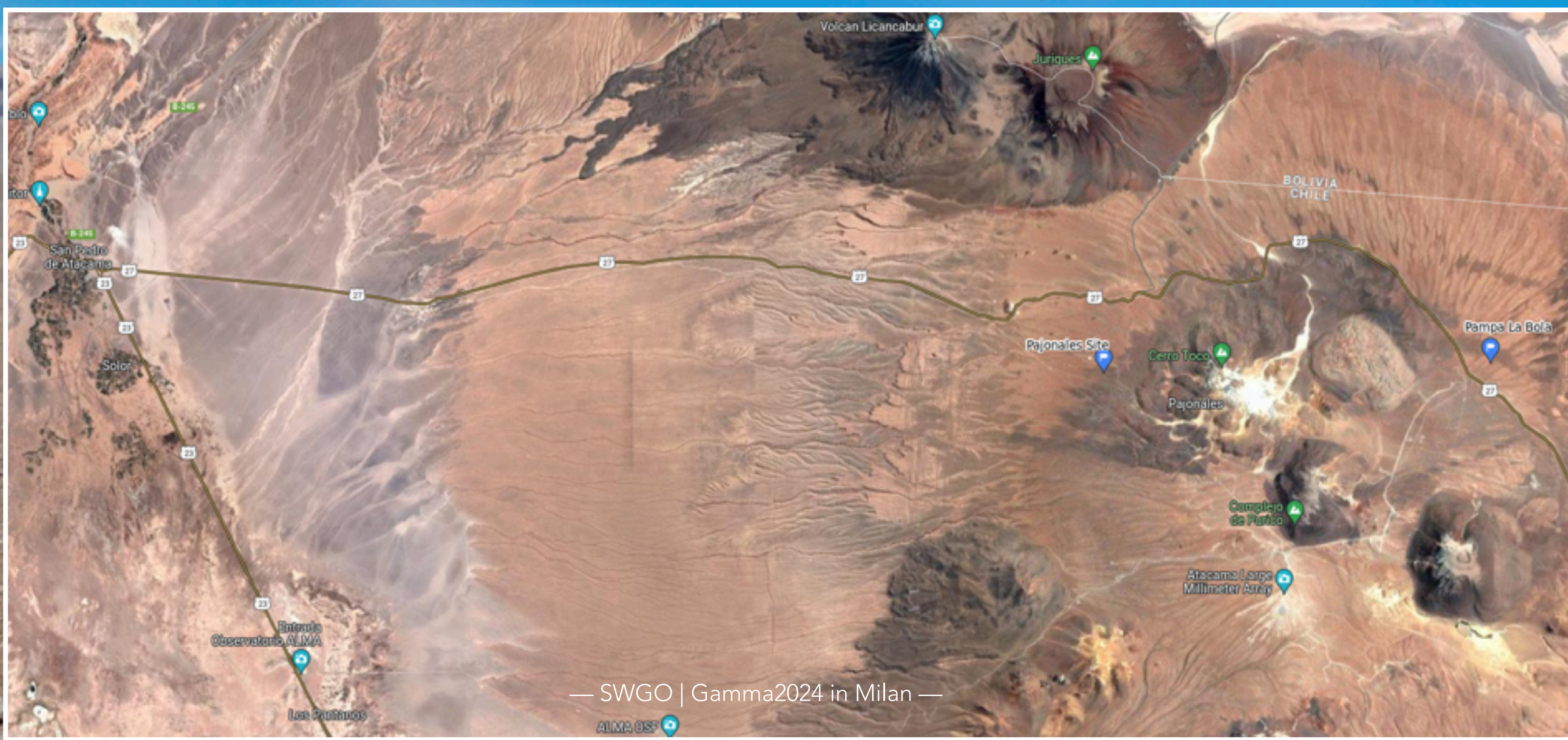
- SWGO partners
  - → 15 countries, over 90 institutes
  - → + supporting scientists

Future of HAWC – SWGO

The Southern Wide-field Gamma-ray Observatory

Site Selection

- Pampa La Bola, Atacama Astronomical Park (Chile)

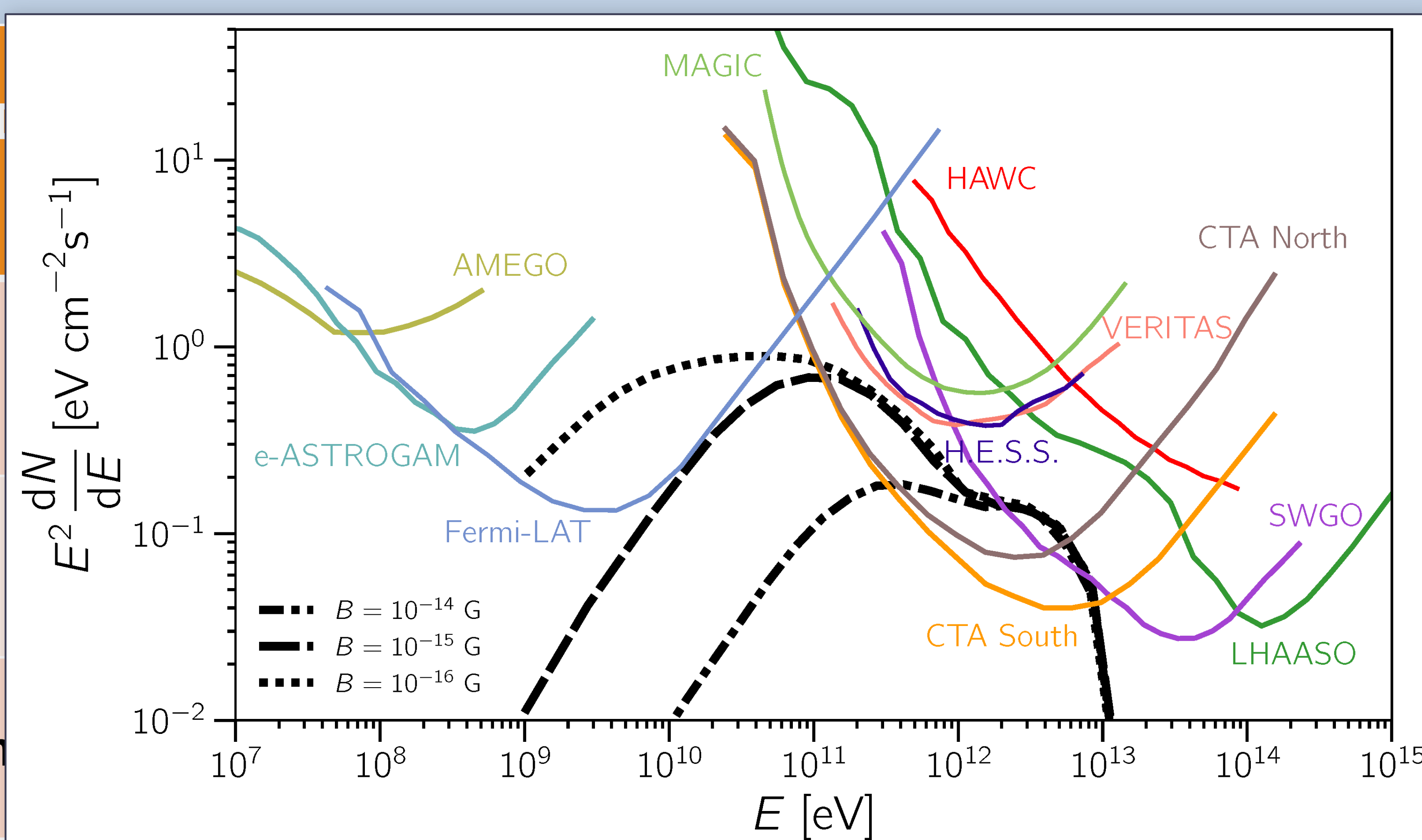


Air Showers – Detection Techniques

Detection Method	Advantages	Disadvantages	Energy Range
Satellite	- F.o.V. - Energy Res. - Uptime	- Ang. Res. - Area – Cost - Maintenance	MeV - GeV
IACT	- Energy Res. - Angular Res.	- F.o.V. - Uptime	GeV - TeV
Sampling Array	- F.o.V. - Uptime	- Energy Res. - Ang. Res.	TeV

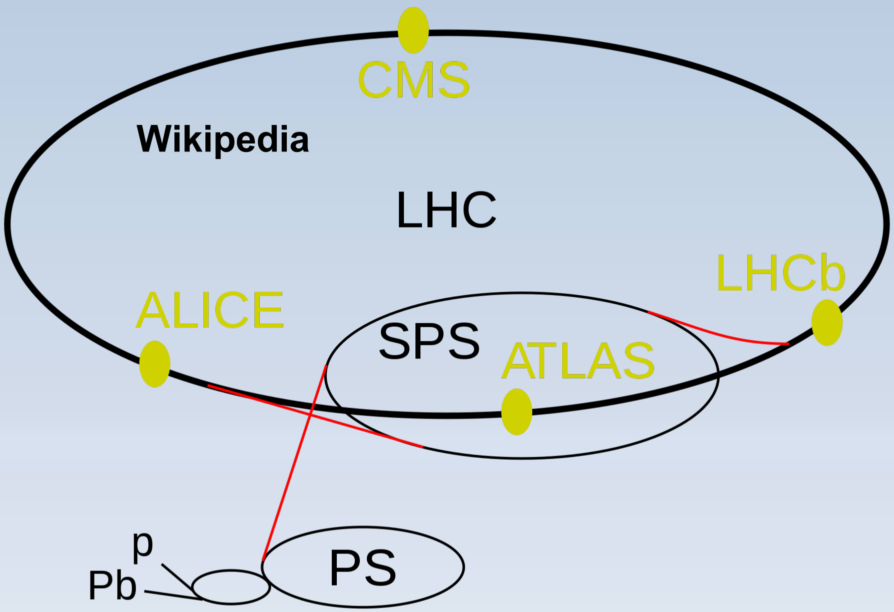
Since the techniques are complementary, we cooperate.

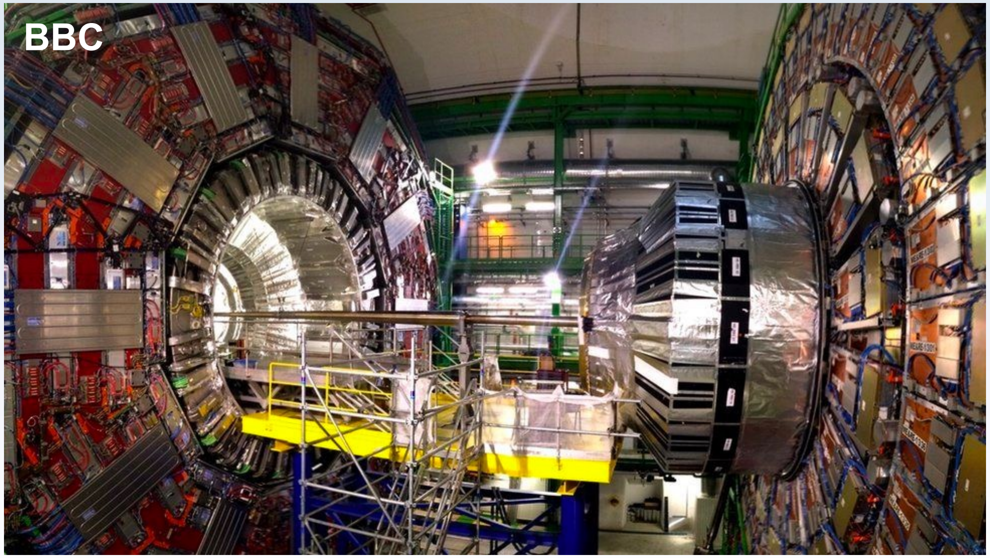
Air Showers – Detection Techniques



Since the techniques are complementary, we cooperate.

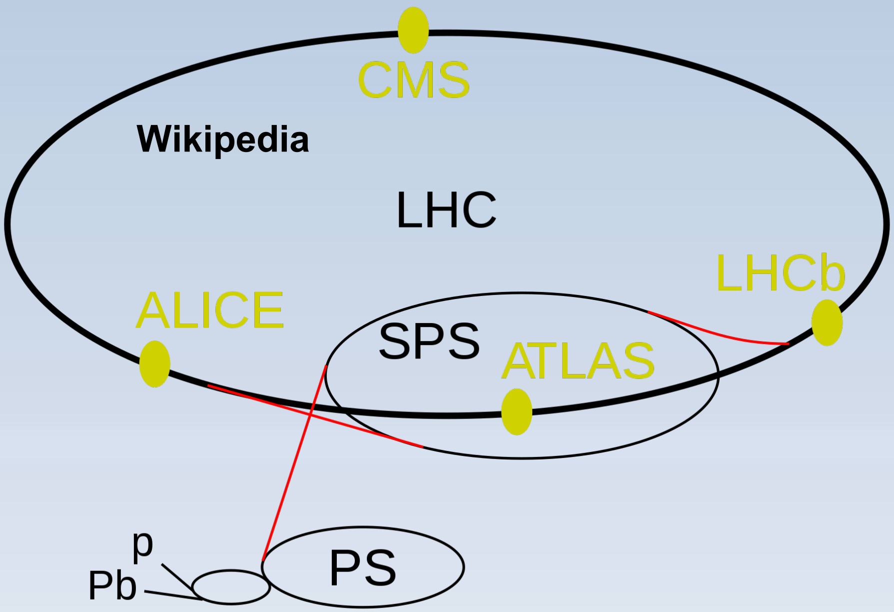
Comparing with LHC

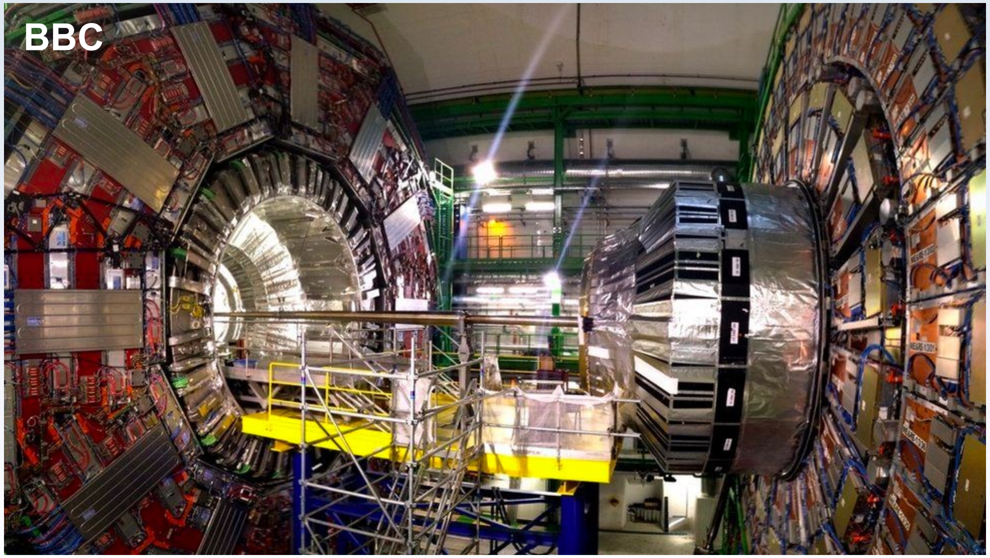




- LHC composed of particle accelerator and detector (tracker + calorimeter)
- HE astrophysics experiments composed of particle accelerator (star) and detector (various type)
- Two experiment types have very similar tech used for detection

Comparing with LHC





- **ADVANTAGES**

Particle:

1. You know which particles of what energy are being collided
2. Detector completely envelops the interaction site

Astro:

1. Particle acceleration to much higher energy free of charge
2. You can learn about other natural objects

THANK YOU!