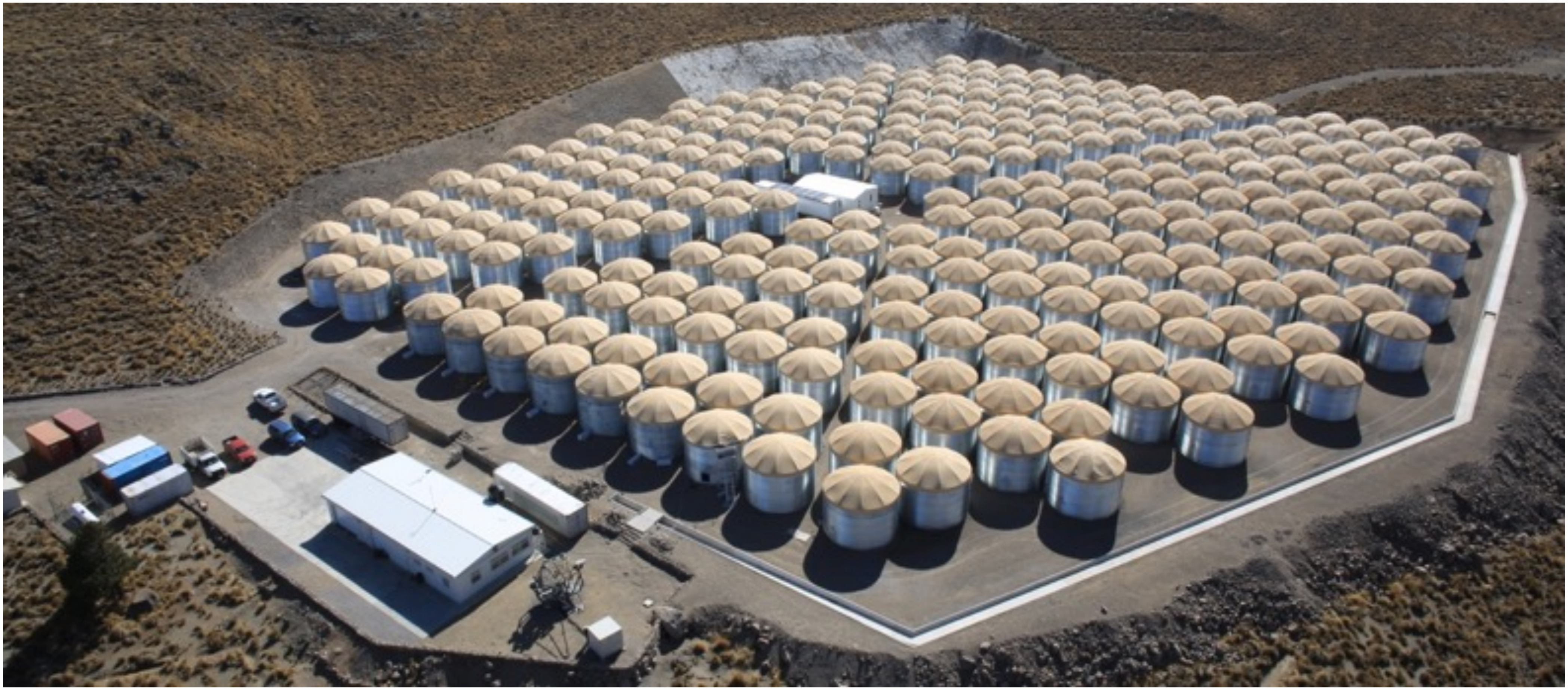


Status and (some, highly biased) recent results from HAWC

Hermes León Vargas
Instituto de Física, UNAM

RADPyC 2024
June 5, 2024

USA Mexico

HAWC Collaboration (2014)

- Integrated by 14 Mexican and 19 US Institutions
- Mainly founded by NSF and DOE in the US, CONAHCyT, UNAM and INAOE in Mexico
- Around 100 members from both countries

NSF CONACYT

HAWC Collaboration (2024)

United States:

- Pennsylvania State University
- University of Maryland
- Los Alamos National Laboratory
- University of Wisconsin
- University of Utah
- Univ. of California, Irvine
- University of New Hampshire
- California University of Pennsylvania
- Stanford University
- University of New Mexico
- Michigan Technological University
- NASA/Goddard Space Flight Center
- NASA/Marshall Space Flight Center
- Georgia Institute of Technology
- Colorado State University
- Michigan State University
- University of Rochester
- George Mason University

Europe:

- IFJ-PAN, Krakow, Poland
- Max-Planck-Institut für Kernphysik, Heidelberg
- Erlangen Centre for Astroparticle Physics

Asia:

- Tsung-Dao Lee Institute, Shanghai, China
- University of Seoul, South Korea
- Sungkyunkwan University, South Korea

Mexico:

- Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE)
  Universidad Nacional Autónoma de México (UNAM)
- **Instituto de Física**
- **Instituto de Astronomía**
- **Instituto de Geofísica**
- **Instituto de Ciencias Nucleares**
- Universidad Politécnica de Pachuca
- Benemérita Universidad Autónoma de Puebla
- Universidad Autónoma de Chiapas
- Universidad Autónoma del Estado de Hidalgo
- Universidad de Guadalajara
- Universidad Michoacana de San Nicolás de Hidalgo
- Centro de Investigación y de Estudios Avanzados
- Centro de Investigación en Computación - IPN

South America:

- Sao Carlos Institute of Physics, Brazil

NSF CONACYT

HAWC in Mexico

- Unique opportunity for collaboration among Mexican Institutions
- Presence in institutions at seven states

Why Mexico?

Site requirements:

- High elevation > 4000 m a.s.l.
- ~Flat geometric area of ~ 20,000 m^2
- Manageable weather conditions for human builders and operators
- Availability of ~120 000 m^3 of water
- Support infrastructure (road, electricity and internet)
- 5 years operation with possible extension for 5 more years

Candidates: Sierra Negra in Mexico and Tibet in China

Mexico offered a stablished community of high-energy physicists with experience at:
Milagro, Auger, ALICE, CMS, AMS, CREAM, Fermilab and LMT

Existing infrastructure from LMT

Building HAWC

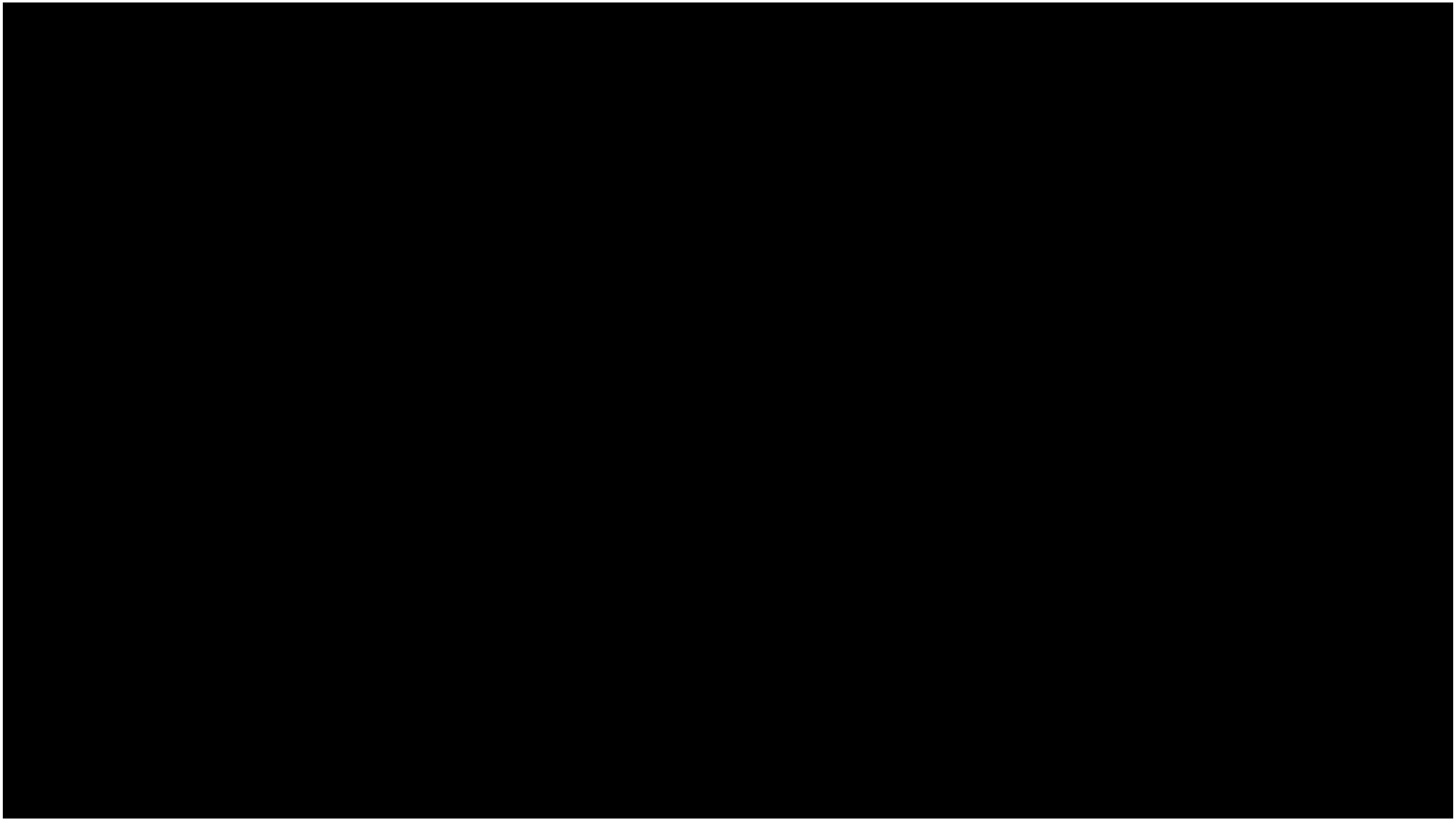
Construction:
2011-2015

Operations
2013 - 2025?

HAWC Inauguration: March 2015

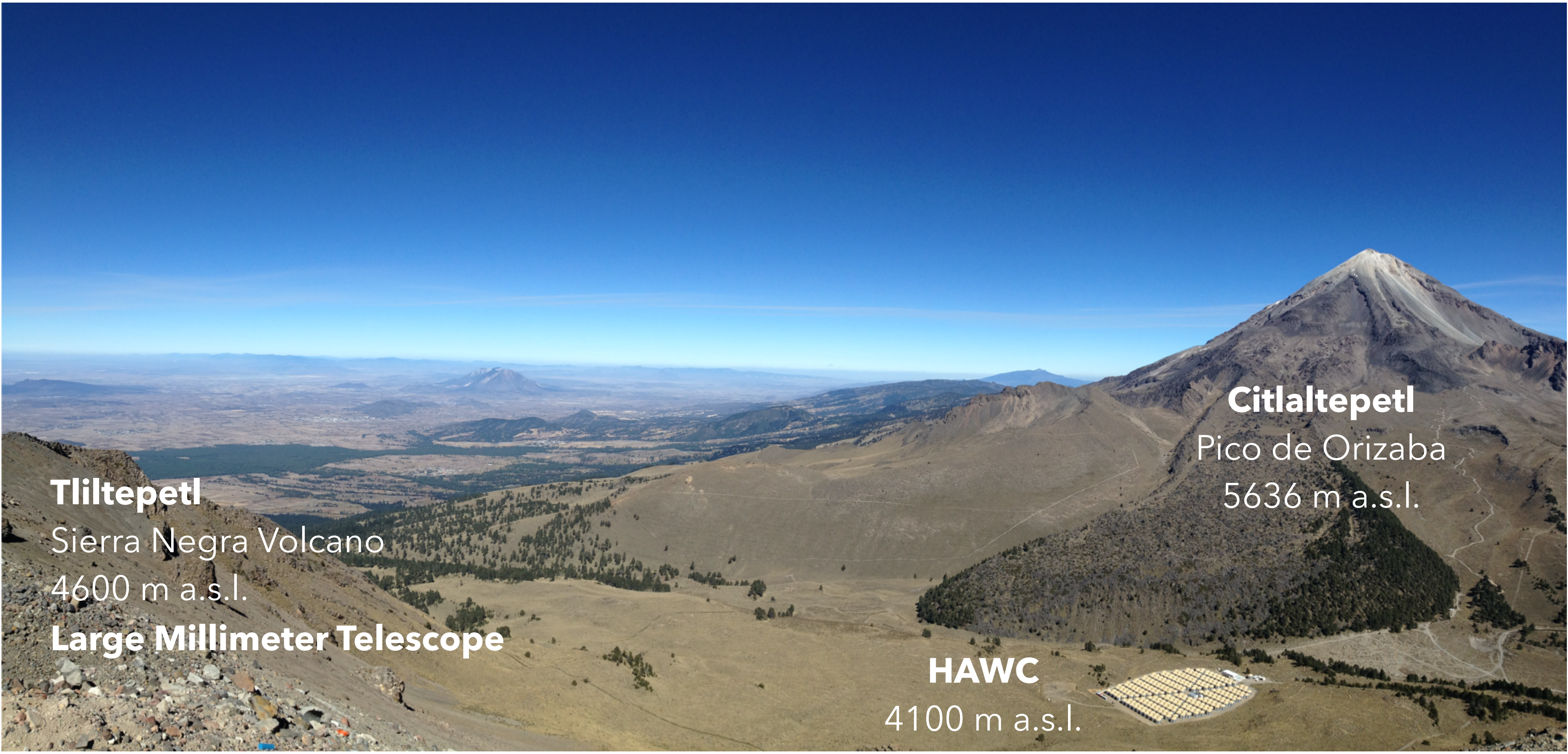
High Altitude Water Cherenkov

HAWC Collaboration: A.U. Abeysekara et al. 2023, NIM A **1052** (2023), 168253



First state-of-the-art high-energy physics experiment installed in Mexico

The HAWC site

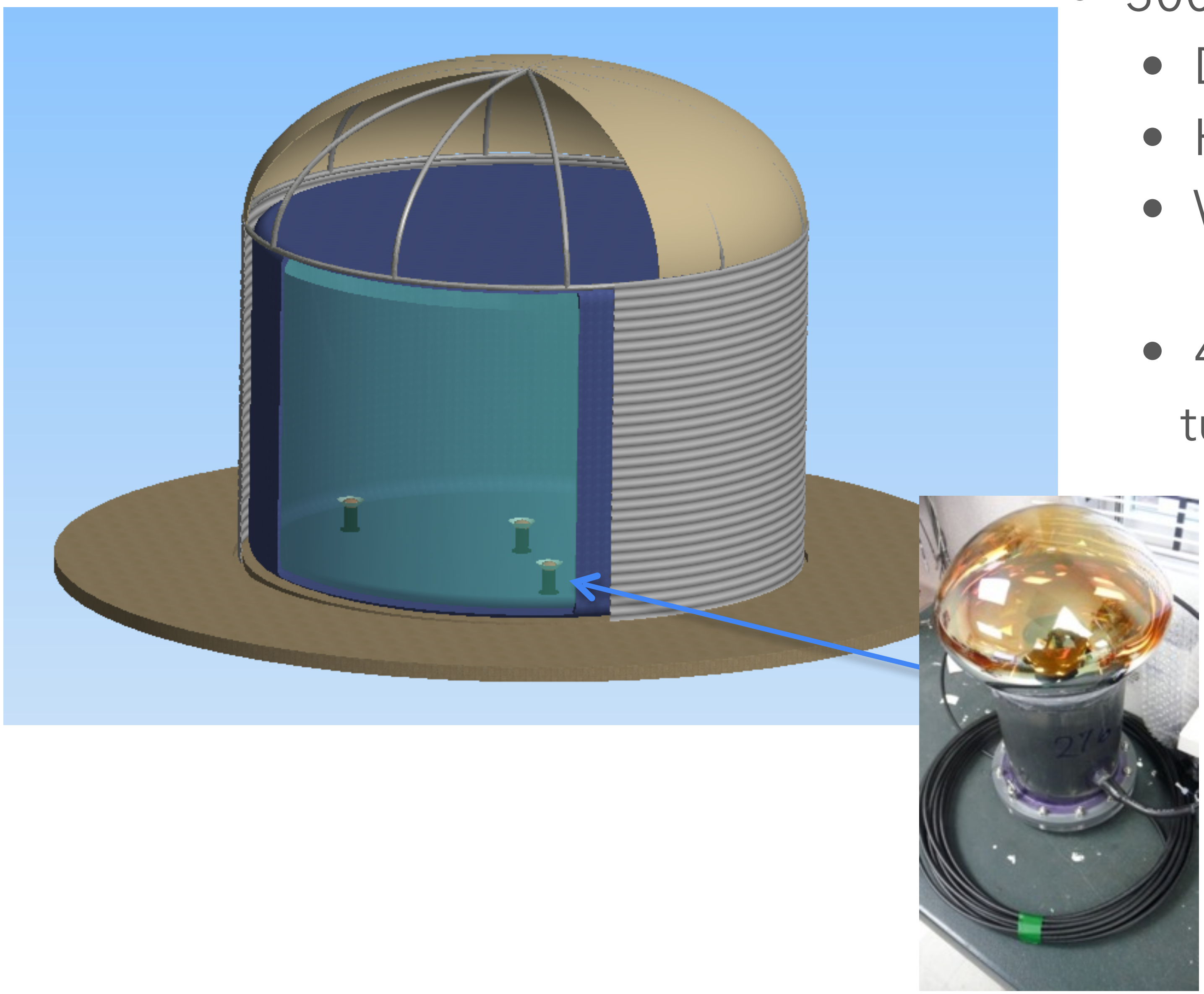


HAWC size

Google Maps

Datos del mapa © 2022 INEGI, Google 50 m

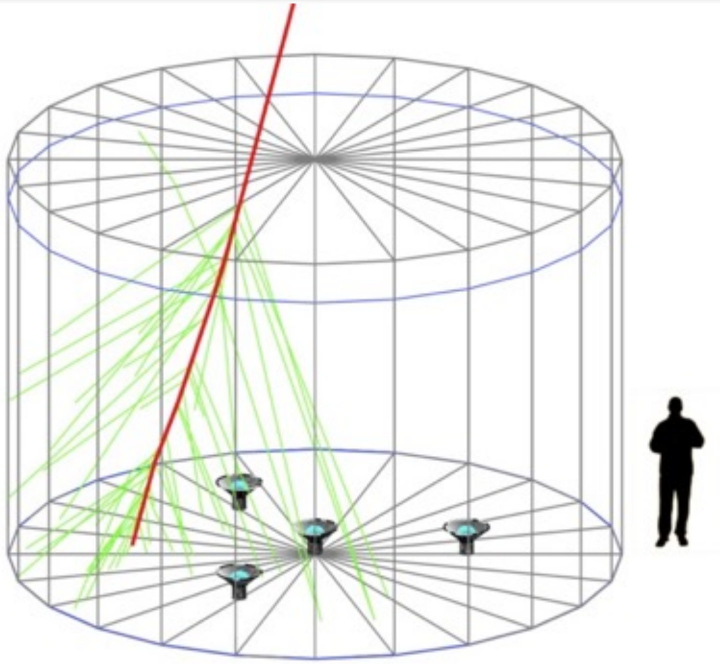
Water Cherenkov Detectors (WCDs)

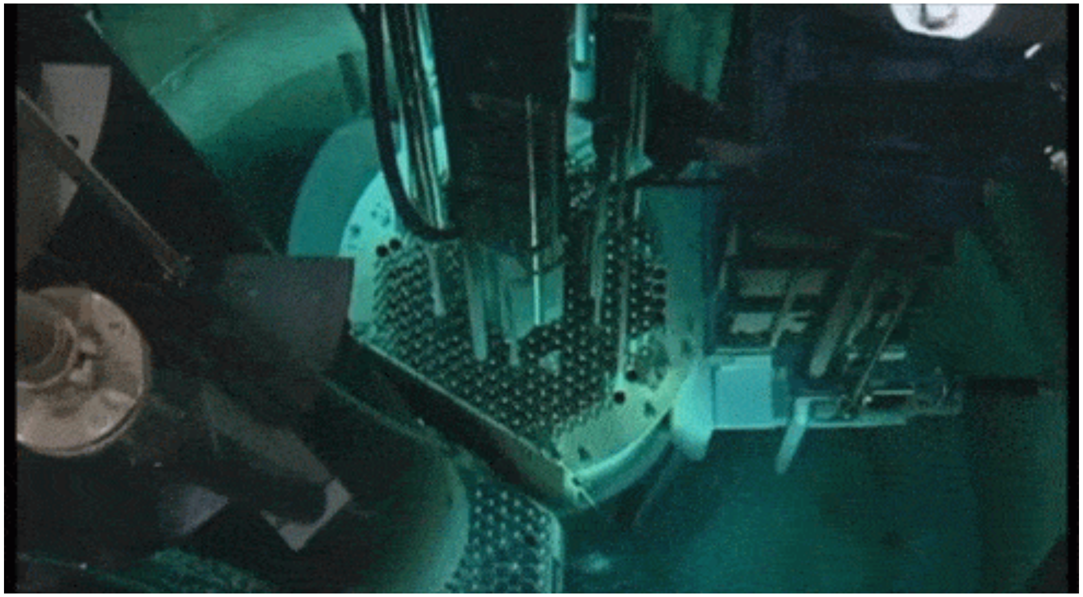


- 300 WCDs
  - Diameter: 7.3 m
  - Height: 5 m
  - Water volume:
    - 200,000 liters
  - 4 photomultipliers tubes:

    Convert light pulses to electric signals

Cherenkov light





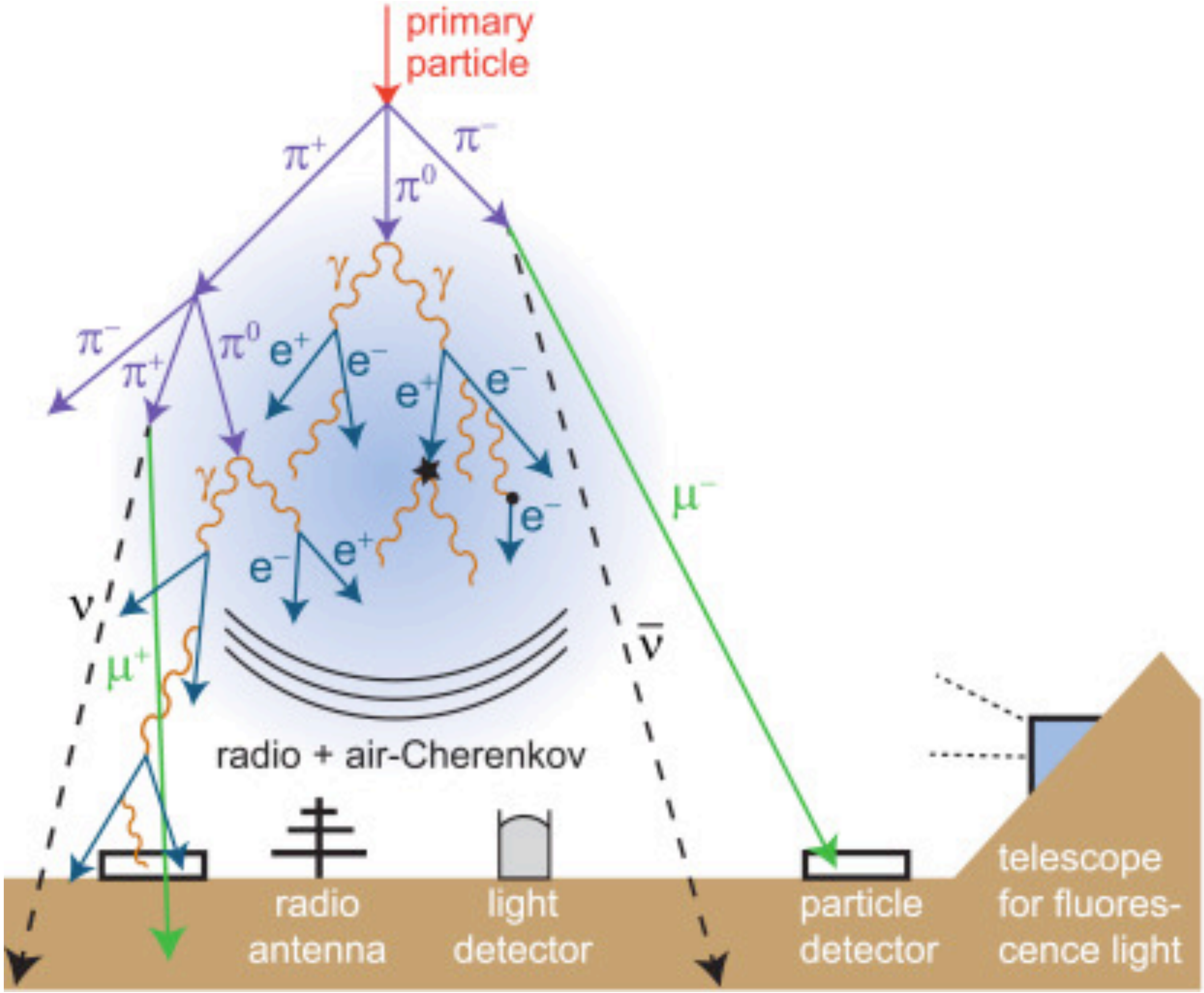
TRIGA (General Atomics)

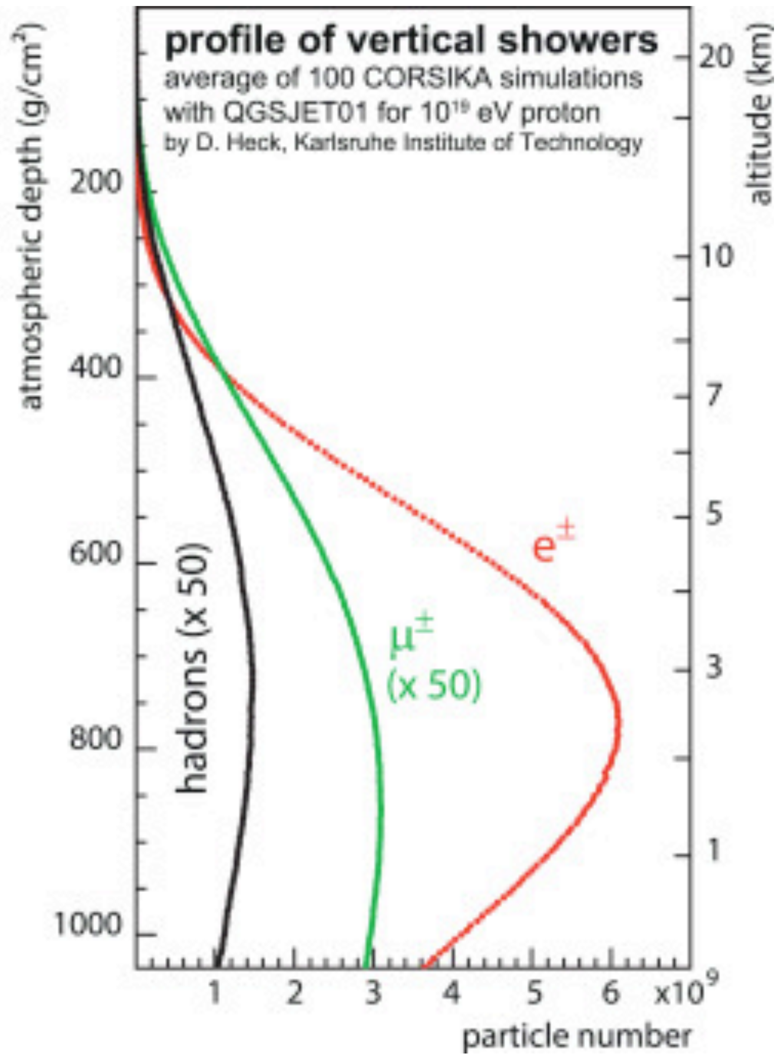
Simulated Cherenkov light in a HAWC WCD

Happens when a charged particle moves in a transparent medium faster than the speed of light in that medium

The discovery and interpretation of this effect deserved the Nobel Prize in 1958

Why the High Altitude?

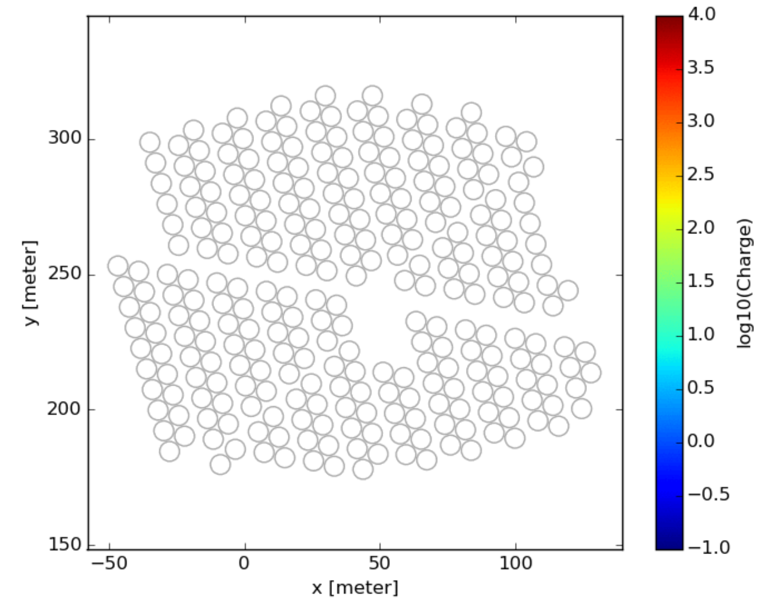




Progress in Particle and Nuclear Physics
F. G. Schröder, 93 (2017) 1-68

Air showers

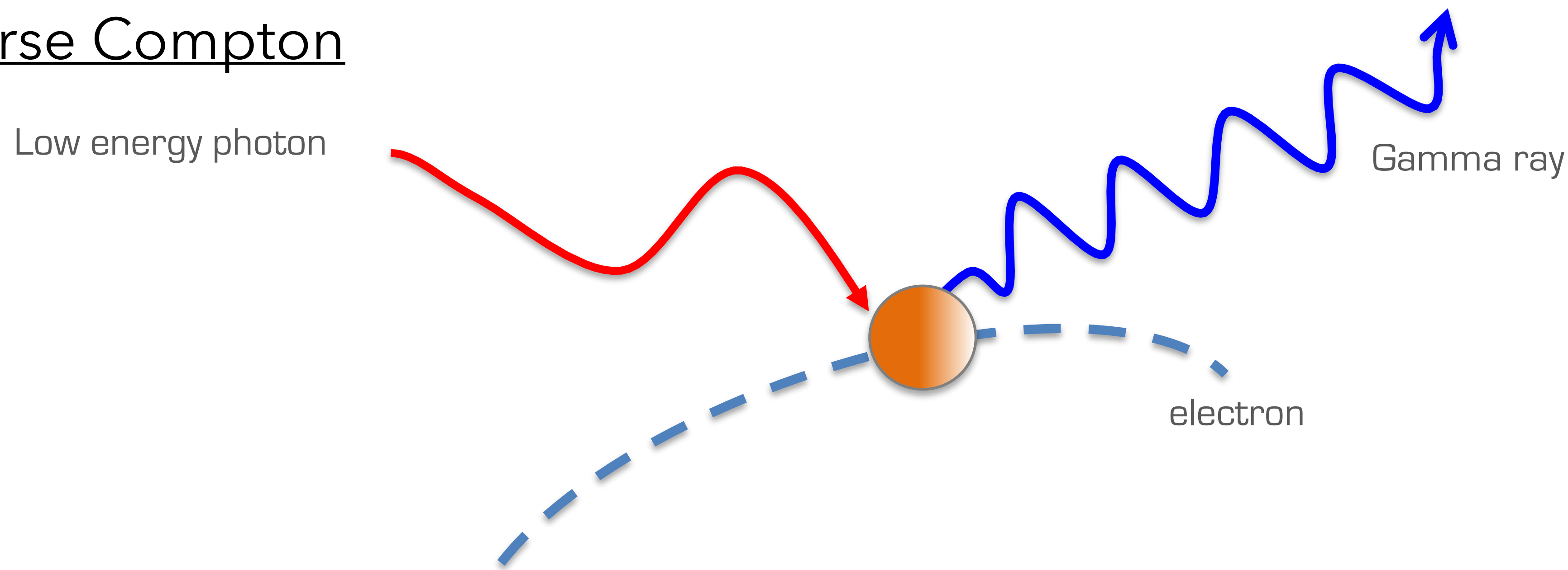
Institute für Kernphysik
Forschungzentrum Karlsruhe



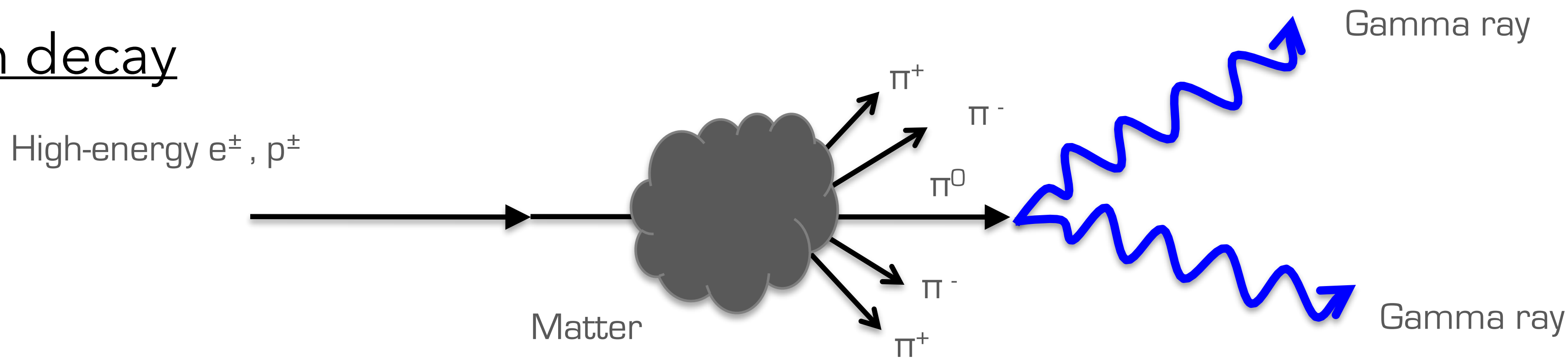
HAWC Data
10^7 times slower than reality

VHE gamma rays

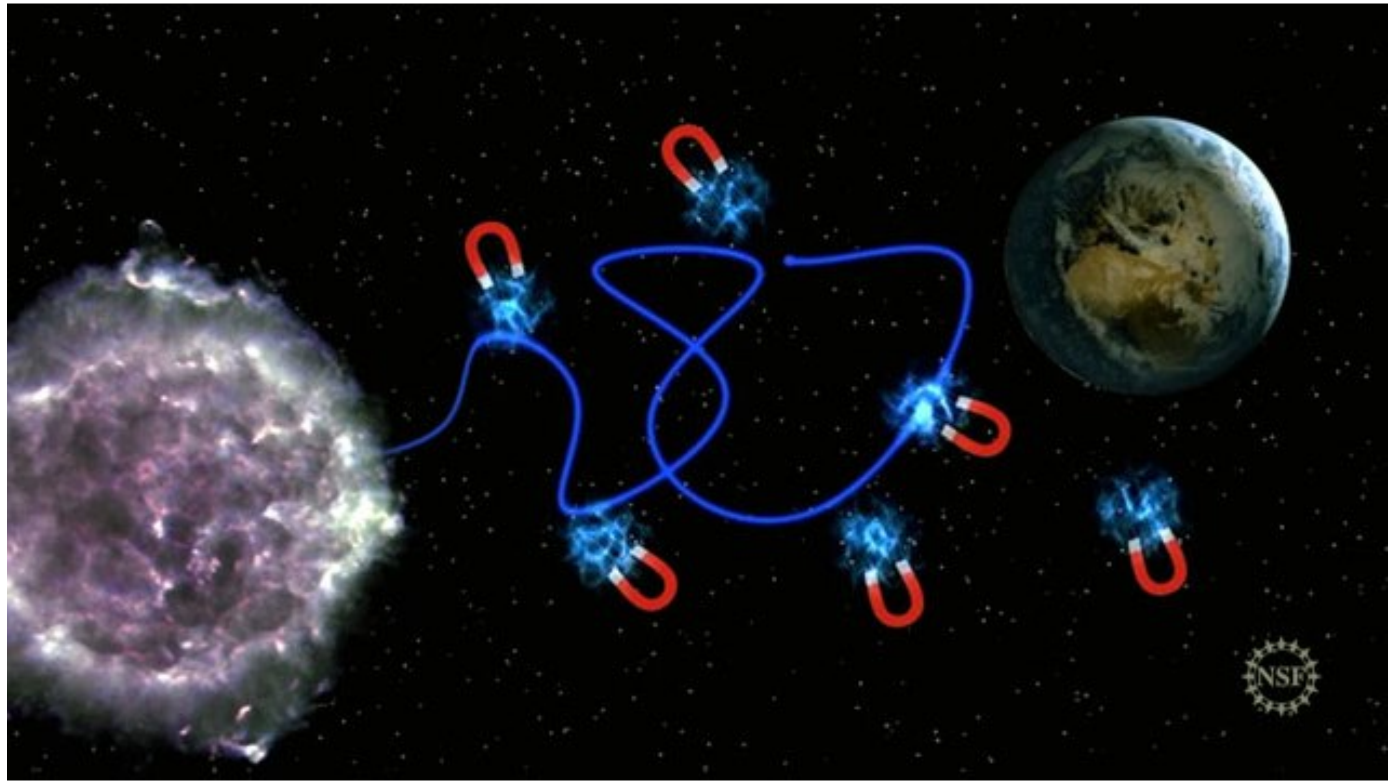
Inverse Compton



Pion decay



Why gamma rays?



Lorentz force

$$\vec{F} = q\vec{v} \times \vec{B}$$

Interstellar magnetic fields:
$\sim 10^{-10}$ T
Distances : kpc-Mpc

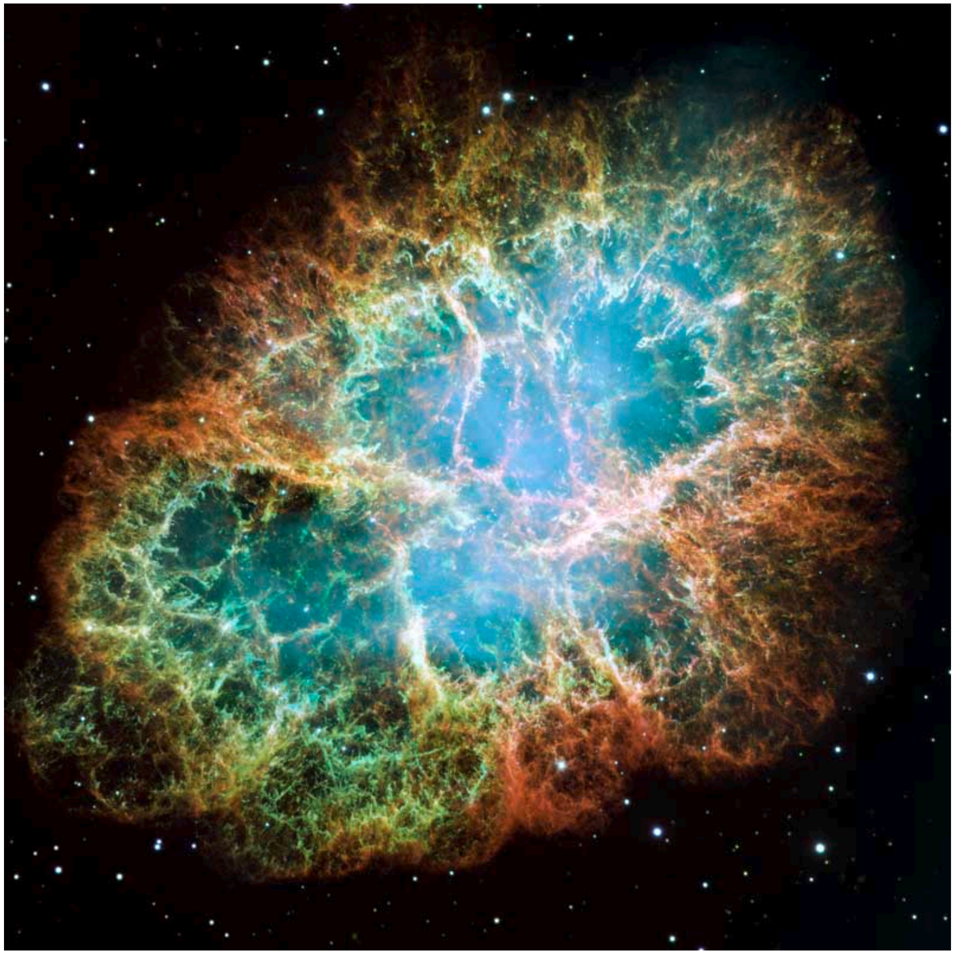
Charged particles are not useful to identify the cosmic ray sources

Earth magnetic field: 2.5-6.5 × 10^{-5} T

Cosmic accelerators in our Galaxy

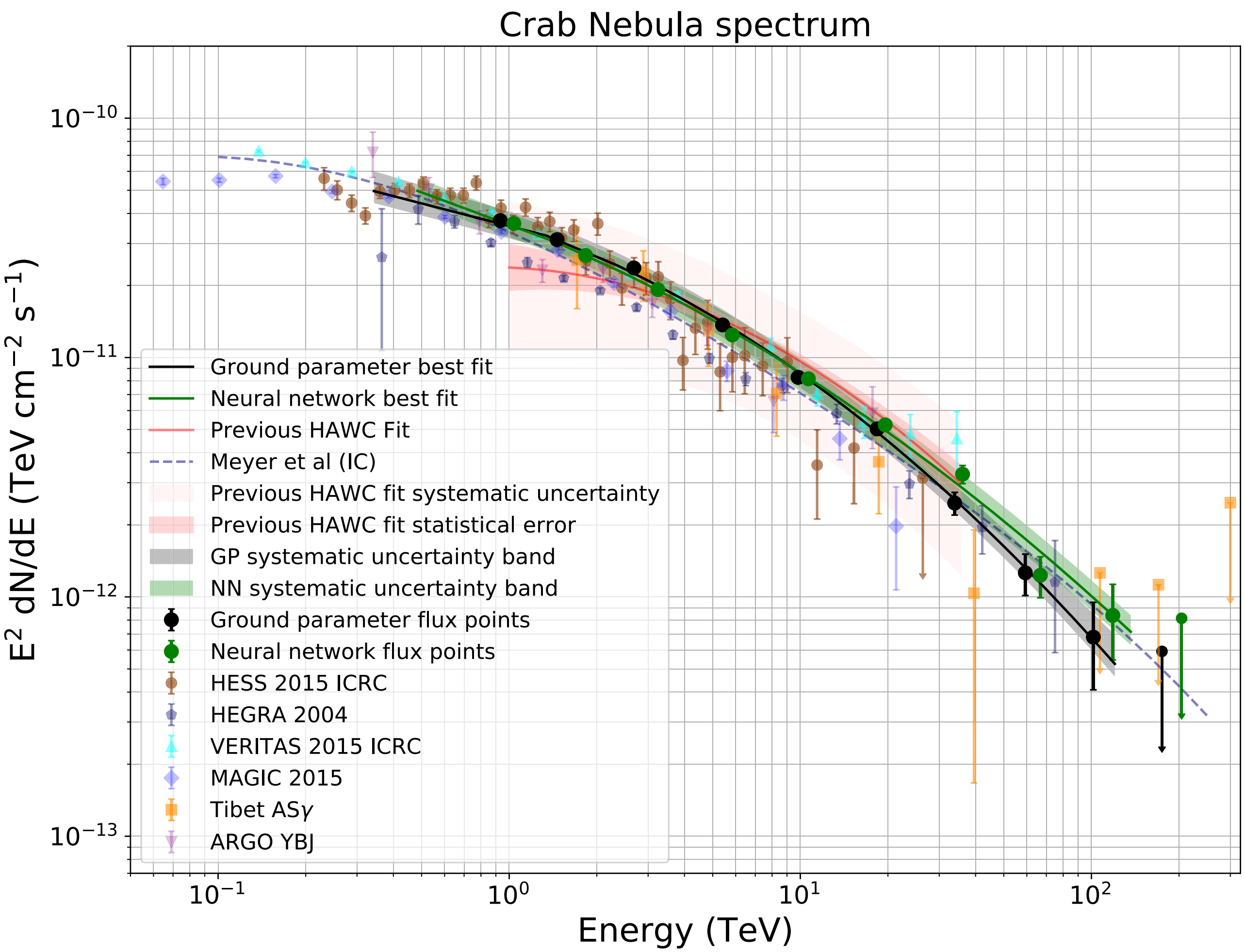
Crab Nebula

- Supernova observed by Chinese astronomers in 1054
- Approximately at 6500 light years from Earth
- Diameter of 11 light years and expanding at ~0.5 c



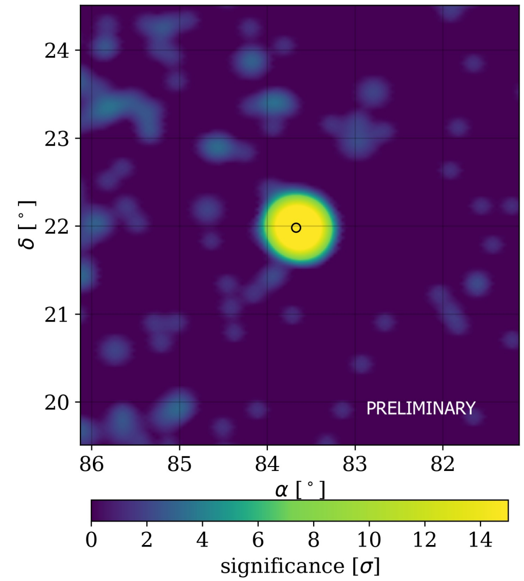
NASA

Cosmic accelerators in our Galaxy

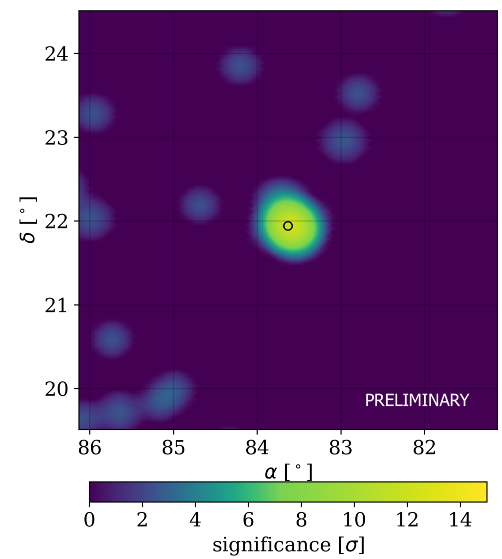


HAWC Collaboration, APJ 881 (2019) 2

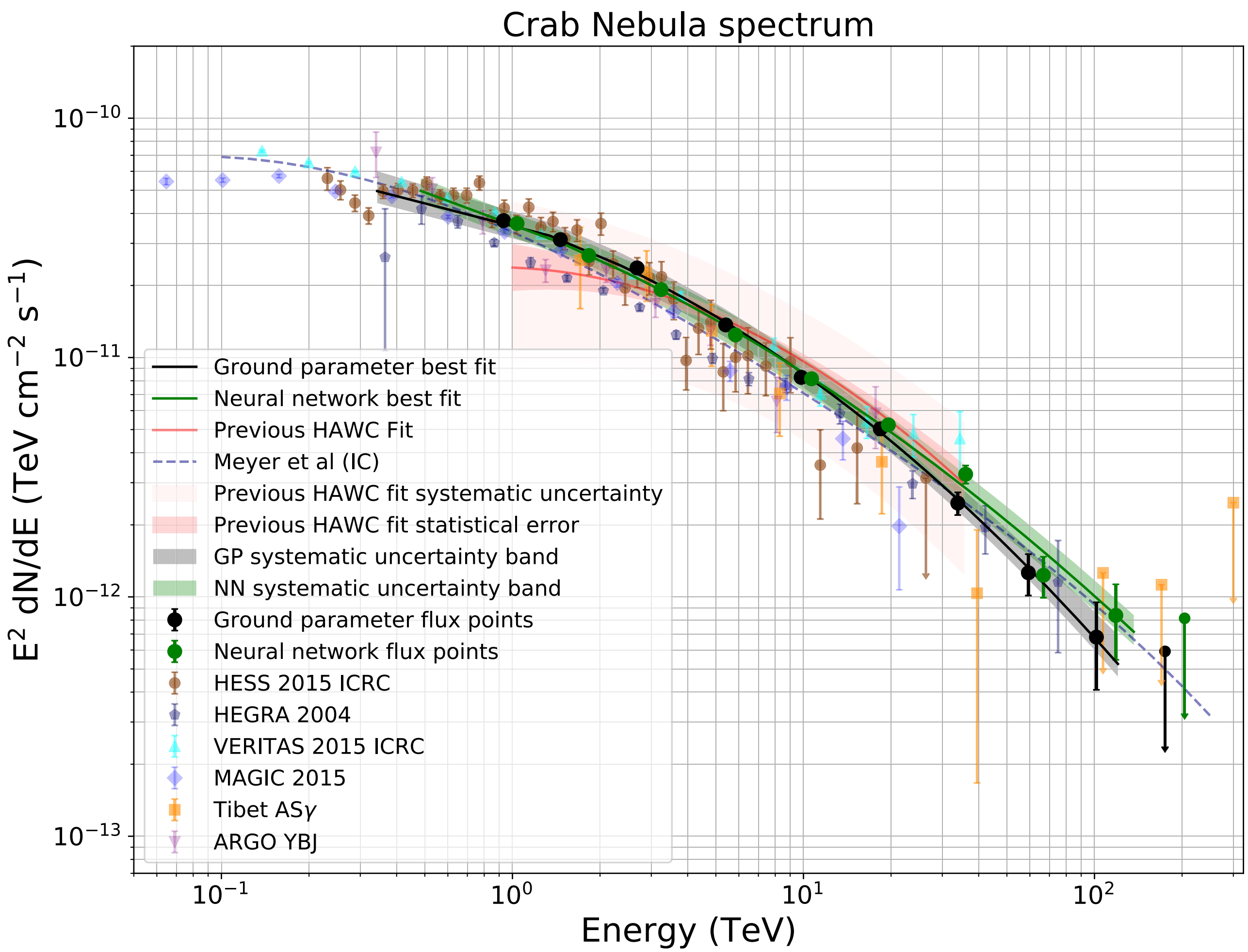
24σ above 56 TeV



12σ above 100 TeV



Cosmic accelerators in our Galaxy



HAWC Collaboration, APJ 881 (2019) 2

2021:

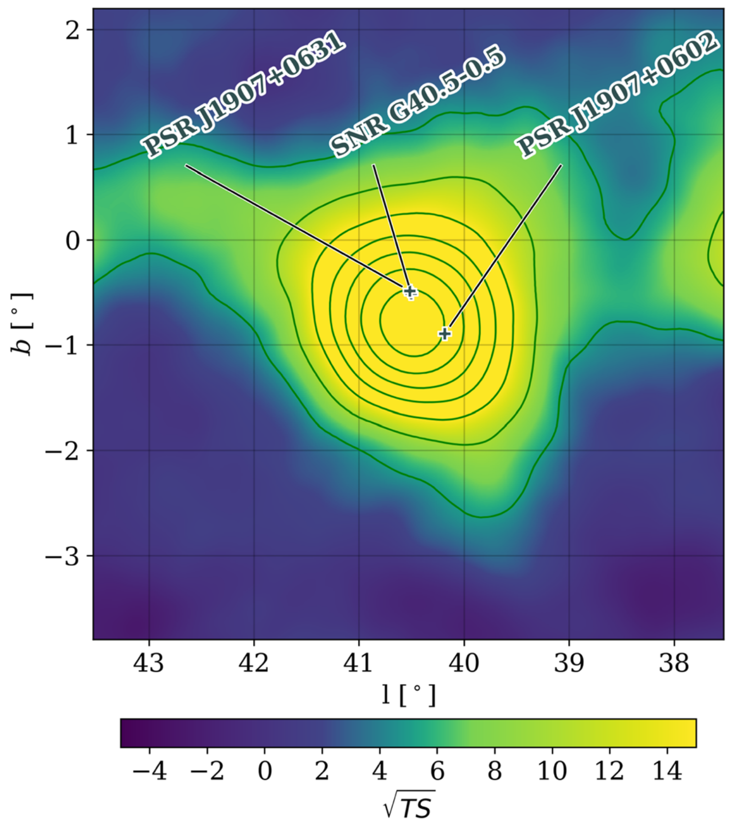
2 photons detected by LHAASO

- 880 TeV
- 1 PeV –> electron of > 2 PeV

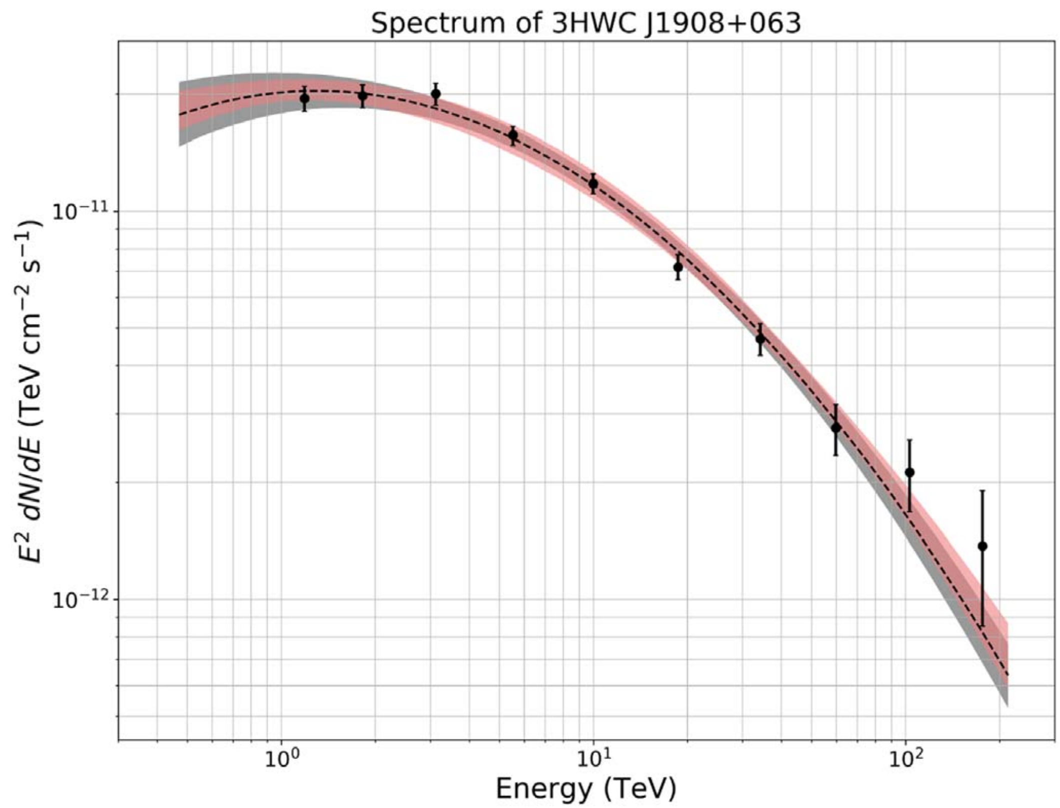
10 times the kinetic energy of a ping pong ball!

Ultra-high-energy source MGRO J1908+06

Extended source confirmed by H.E.S.S., VERITAS and ARGO



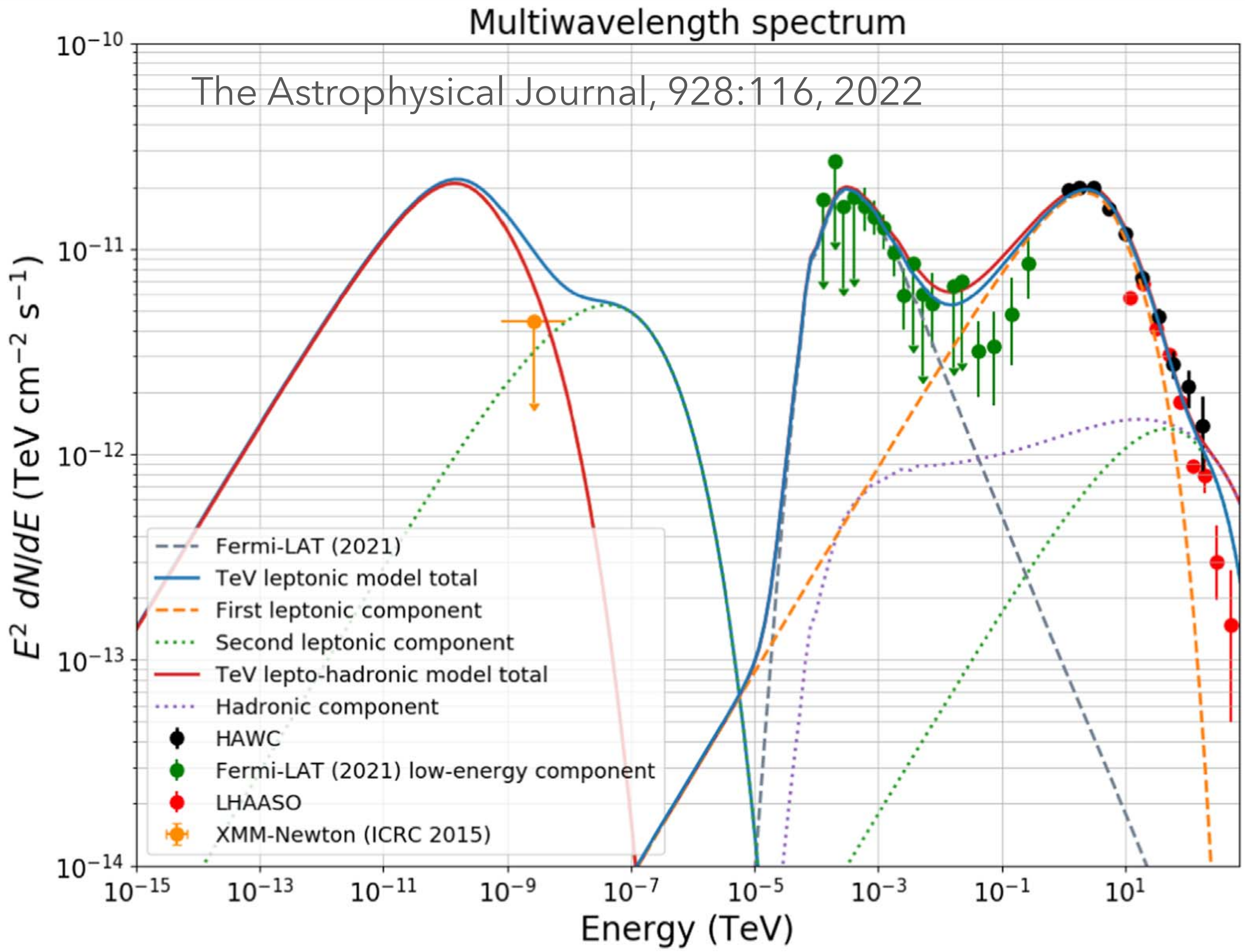
The Astrophysical Journal, 928:116, 2022



Photons with > 200 TeV

If hadronic in nature ⟶ PeVatron

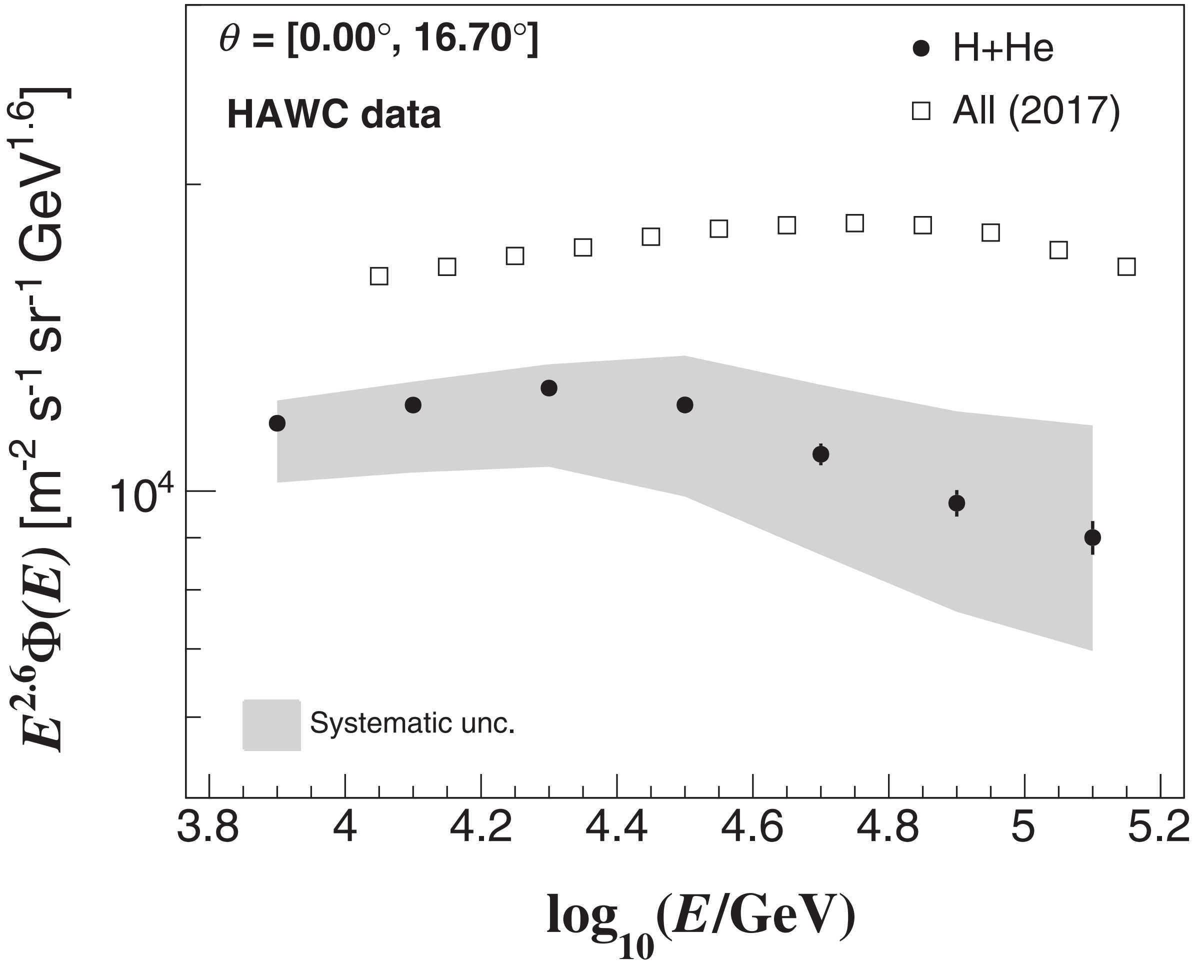
Ultra-high-energy source MGRO J1908+06



- Importance of multiwavelength studies to understand the nature of the source

- The data shows that it is mainly a leptonic source, not ruling out an hadronic component at the highest energies

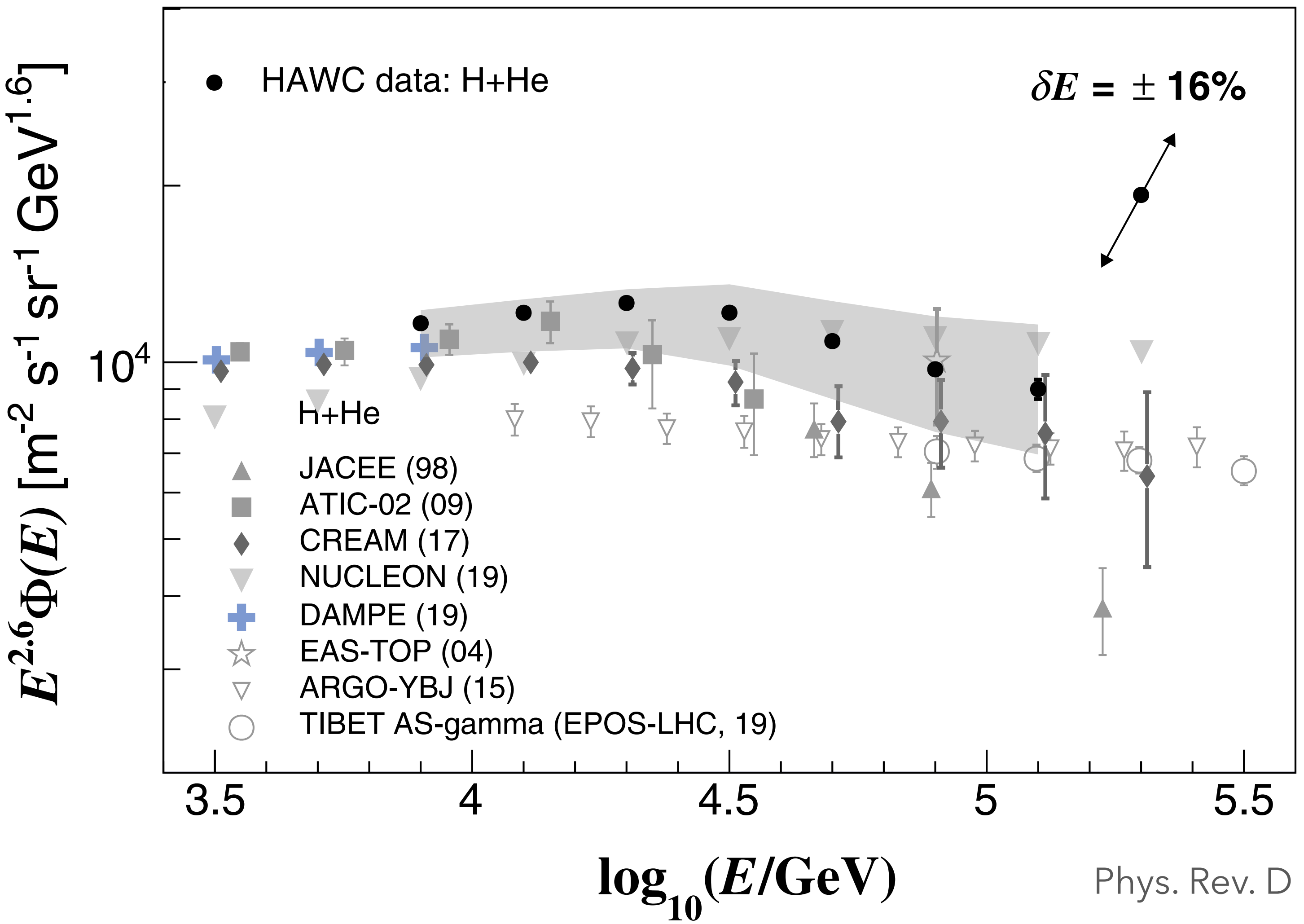
VHE H & He spectra



Phys. Rev. D 105, 063021 (2022)

- Very large statistics analysis (there are uncertainties in the data points)
- Energy region between direct measurements and UHE experiments

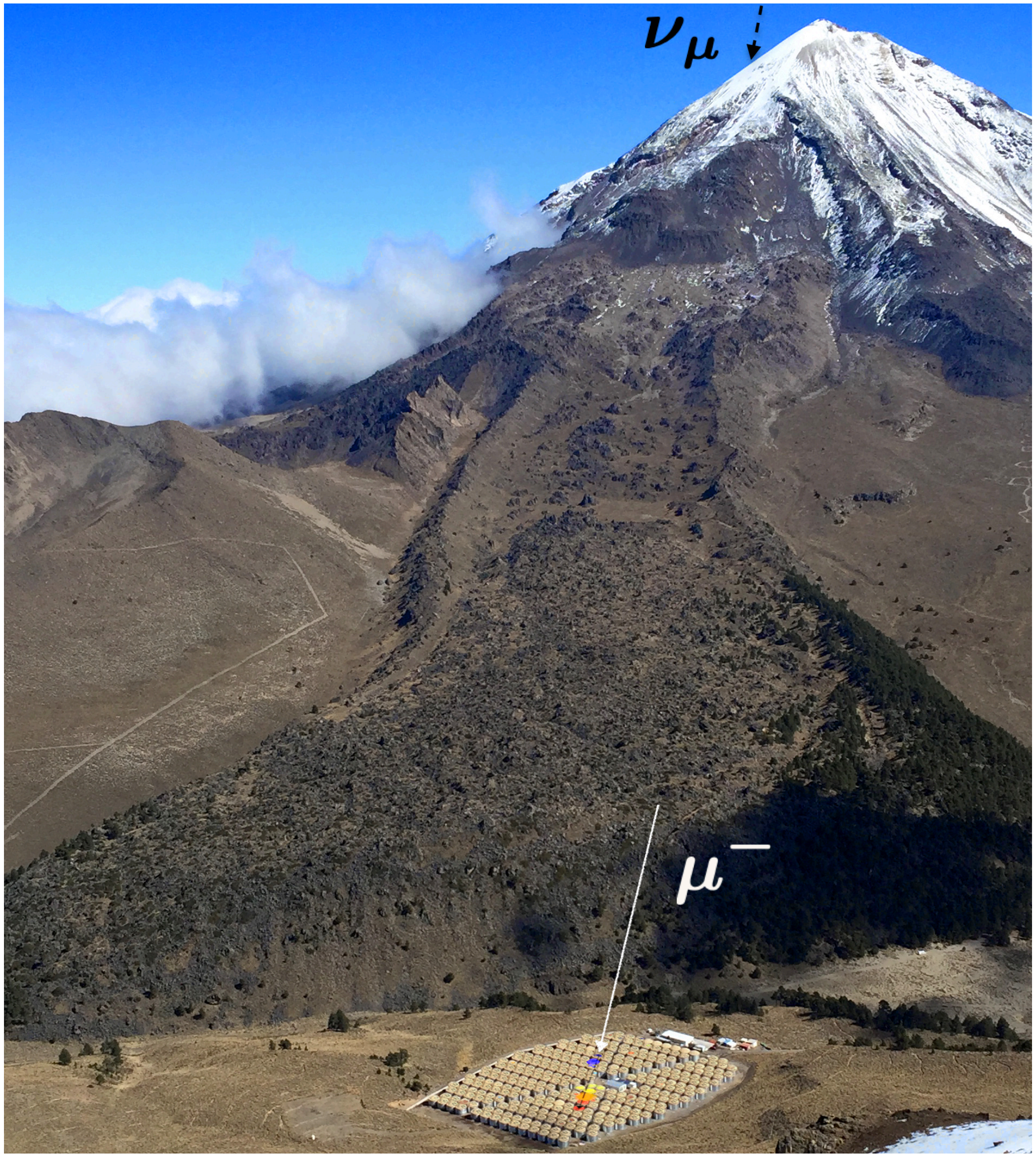
VHE H & He spectra



Phys. Rev. D 105, 063021 (2022)

- Apparent cut at 24 TeV
- New structures can be related to different cosmic ray sources in the galaxy

Neutrino search with HAWC



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Astroparticle Physics
journal homepage: www.elsevier.com/locate/astropartphys
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Characterization of the background for a neutrino search with the HAWC observatory

A. Albert [1], R. Alfaro [2], C. Alvarez [3], J.R. Angeles Camacho [2], J.C. Arteaga-Velázquez [4], K.P. Arunbabu [5], E. Belmont-Moreno [2], K.S. Caballero-Mora [3], T. Capistrán [6], A. Carramiñana [7], S. Casanova [8], U. Cotti [4], J. Cotzomi [9], S. Coutiño de León [7], E. De la Fuente [10,11], R. Diaz Hernandez [7], M.A. DuVernois [12], M. Durocher [1], C. Espinoza [2], K.L. Fan [13], N. Fraija [6], D. Garcia [2], J.A. García-González [14], F. Garfias [6], M.M. González [6], J.A. Goodman [13], D. Huang [15], F. Hueyotl-Zahuantitla [3], P. Hüntemeyer [15], A. Iriarte [6], A. Jardin-Blicq [16,17,18], D. Kieda [19], A. Lara [5], W.H. Lee [6], H. León Vargas [2,*], A.L. Longinotti [6], G. Luis-Raya [20], K. Malone [1], J. Martínez-Castro [21], J.A. Matthews [22], P. Miranda-Romagnoli [23], J.A. Morales-Soto [4], E. Moreno [9], A. Nayerhoda [8], L. Nellen [24], R. Noriega-Papaqui [23], N. Omodei [25], A. Peisker [26], E.G. Pérez-Pérez [20], C.D. Rho [27], D. Rosa-González [7], A. Sandoval [2], J. Serna-Franco [2], R.W. Springer [19], K. Tollefson [26], I. Torres [7], R. Torres-Escobedo [10,28], F. Ureña-Mena [7], L. Villaseñor [9], H. Zhou [28], C. de León [4]

[1] *Physics Division, Los Alamos National Laboratory, Los Alamos, NM, USA*
[2] *Instituto de Física, Universidad Nacional Autónoma de México, Ciudad de México, Mexico*
[3] *Universidad Autónoma de Chiapas, Tuxtla Gutiérrez, Chiapas, Mexico*
[4] *Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Mexico*
[5] *Instituto de Geofísica, Universidad Nacional Autónoma de México, Ciudad de Mexico, Mexico*
[6] *Instituto de Astronomía, Universidad Nacional Autónoma de México, Ciudad de Mexico, Mexico*
[7] *Instituto Nacional de Astrofísica, Óptica y Electrónica, Puebla, Mexico*
[8] *Institute of Nuclear Physics Polish Academy of Sciences, PL-31342 IFJ-PAN, Krakow, Poland*
[9] *Facultad de Ciencias Físico Matemáticas, Benemérita Universidad Autónoma de Puebla, Puebla, Mexico*
[10] *Departamento de Física, Centro Universitario de Ciencias Exactas e Ingenierias, Universidad de Guadalajara, Guadalajara, Mexico*
[11] *Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Kashiwanoha, Japan*
[12] *Department of Physics and Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin-Madison, Madison, WI, USA*
[13] *Department of Physics, University of Maryland, College Park, MD, USA*
[14] *Tecnologico de Monterrey, Escuela de Ingeniería y Ciencias, Ave. Eugenio Garza Sada 2501, Monterrey, N.L., 64849, Mexico*
[15] *Department of Physics, Michigan Technological University, Houghton, MI, USA*
[16] *Max–Planck Institute for Nuclear Physics, 69117 Heidelberg, Germany*
[17] *Department of Physics, Faculty of Science, Chulalongkorn University, 254 Phayathai Road, Pathumwan, Bangkok 10330, Thailand*
[18] *National Astronomical Research Institute of Thailand (Public Organization), Don Kaeo, MaeRim, Chiang Mai 50180, Thailand*
[19] *Department of Physics and Astronomy, University of Utah, Salt Lake City, UT, USA*
[20] *Universidad Politecnica de Pachuca, Pachuca, Hgo, Mexico*
[21] *Centro de Investigación en Computación, Instituto Politécnico Nacional, México City, Mexico*
[22] *Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, USA*
[23] *Universidad Autónoma del Estado de Hidalgo, Pachuca, Mexico*
[24] *Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de Mexico, Ciudad de Mexico, Mexico*
[25] *Department of Physics, Stanford University, Stanford, CA 94305–4060, USA*
[26] *Department of Physics and Astronomy, Michigan State University, East Lansing, MI, USA*
[27] *University of Seoul, Seoul, Republic of Korea*
[28] *Tsung-Dao Lee Institute & School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai, People's Republic of China*

A R T I C L E I N F O

Keywords:
Muons

A B S T R A C T

The close location of the HAWC observatory to the largest volcano in Mexico allows to perform a search for neutrino-induced horizontal muon and tau charged leptons. The section of the volcano located at the

* Corresponding author.
E-mail address: hleonvar@fisica.unam.mx (H. León Vargas).

https://doi.org/10.1016/j.astropartphys.2021.102670
Received 19 August 2021; Received in revised form 29 October 2021; Accepted 24 November 2021
Available online 18 December 2021

Characterization of the background for a neutrino search with the HAWC observatory

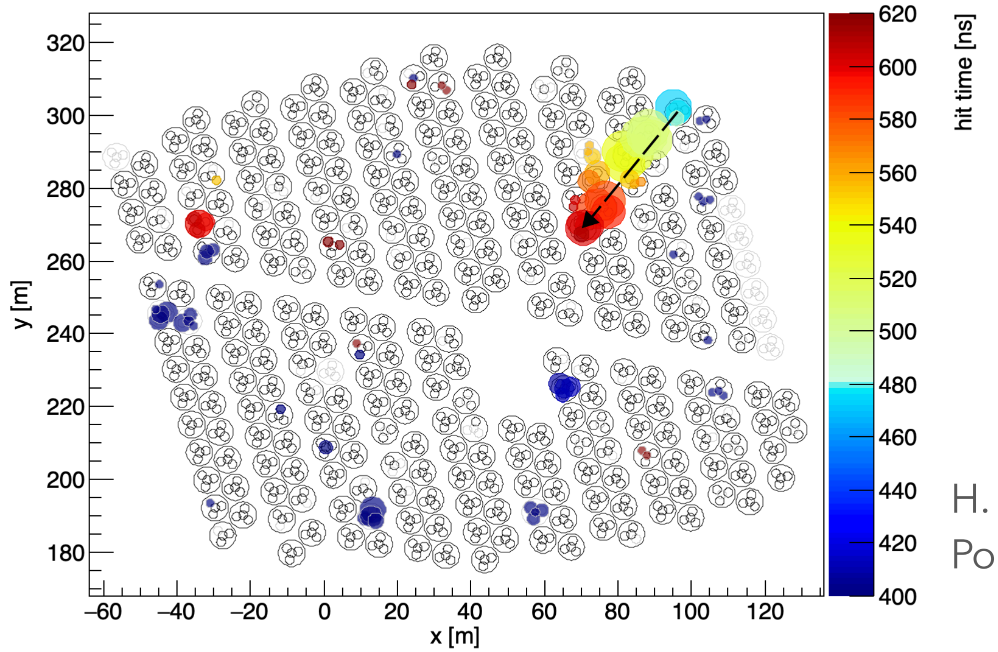
Astroparticle Physics 137 (2022) 102670

How many neutrino interactions?

$N = I_{\mu}^{\nu} \times \Delta T \times A\Omega$ and using the neutrino-induced muon intensity from LVD

$I_{\mu}^{\nu} = 8.3\times10^{-9}\, m^{-2} s^{-1} sr^{-1}$

N(1 year) ≈ 1.6



3×10^{11} events

260 TB of data

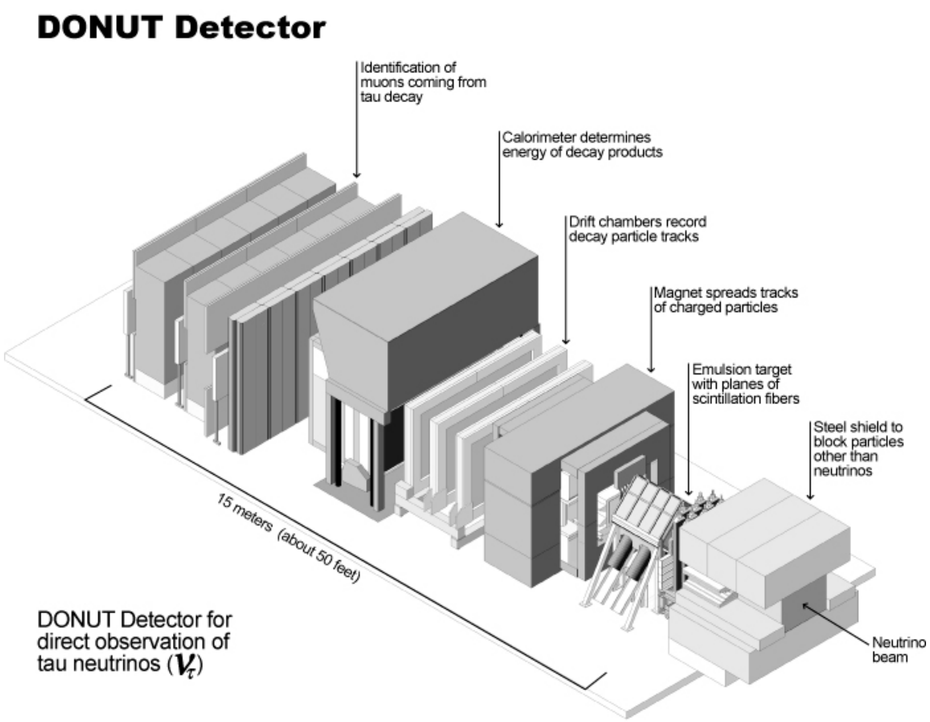
7×10^{6} CPU hours

H. León Vargas for the HAWC Collaboration
PoS (ICRC2019) 940

This number may seem too low but:

- An above ground detector is much less expensive than those underground
- If we observe a very high energy signal, due to the lepton energy loss, is more likely to be a tau lepton

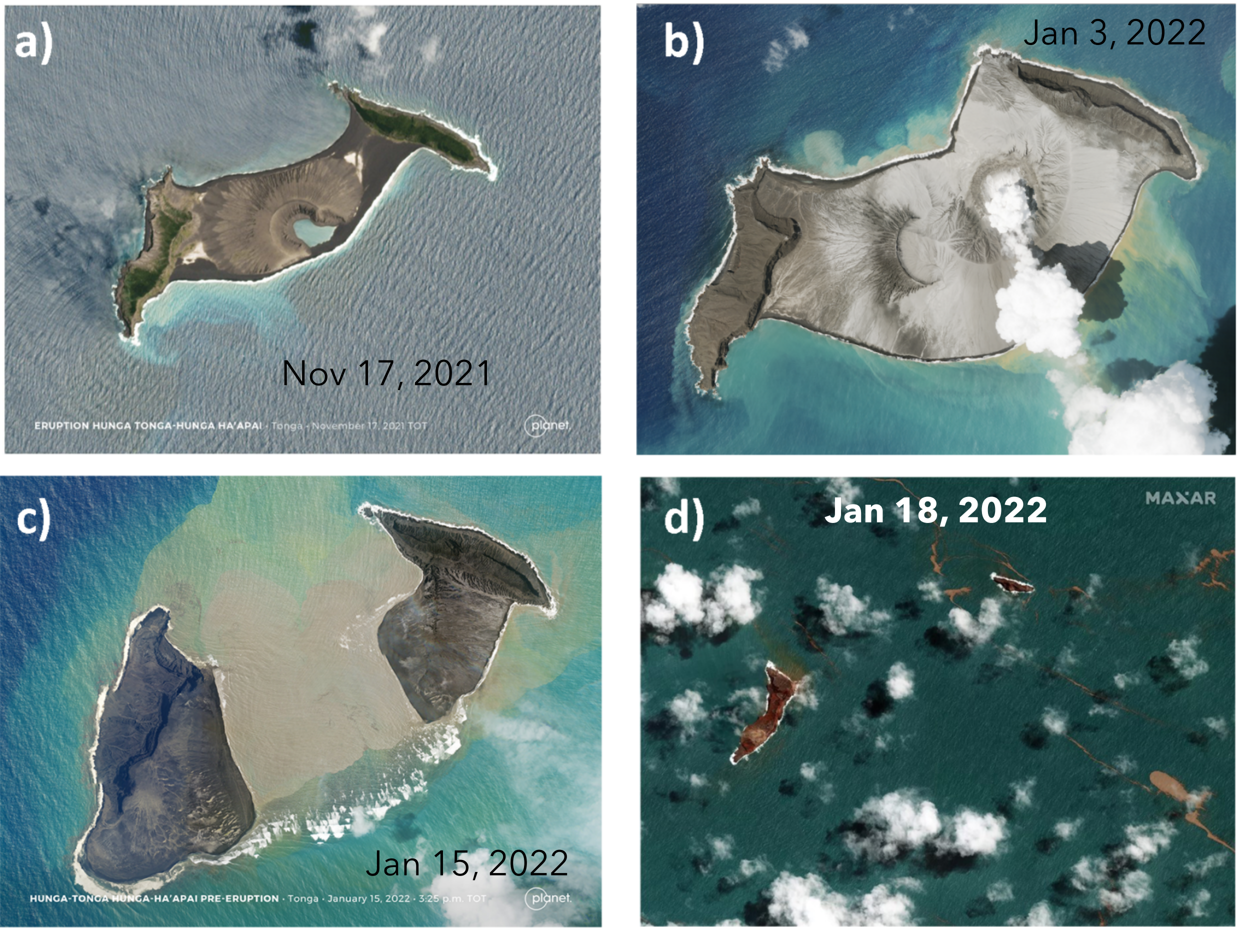
Tau neutrino direct detections



- Discovered in 2000 at FNAL
- Penultimate SM particle to be discovered
- 4 events, 3.5σ
- 2007: 9 tau neutrino candidates
- 2018: OPERA reports 10 candidates
- 7 more by IceCube (*11 April, 2024)*

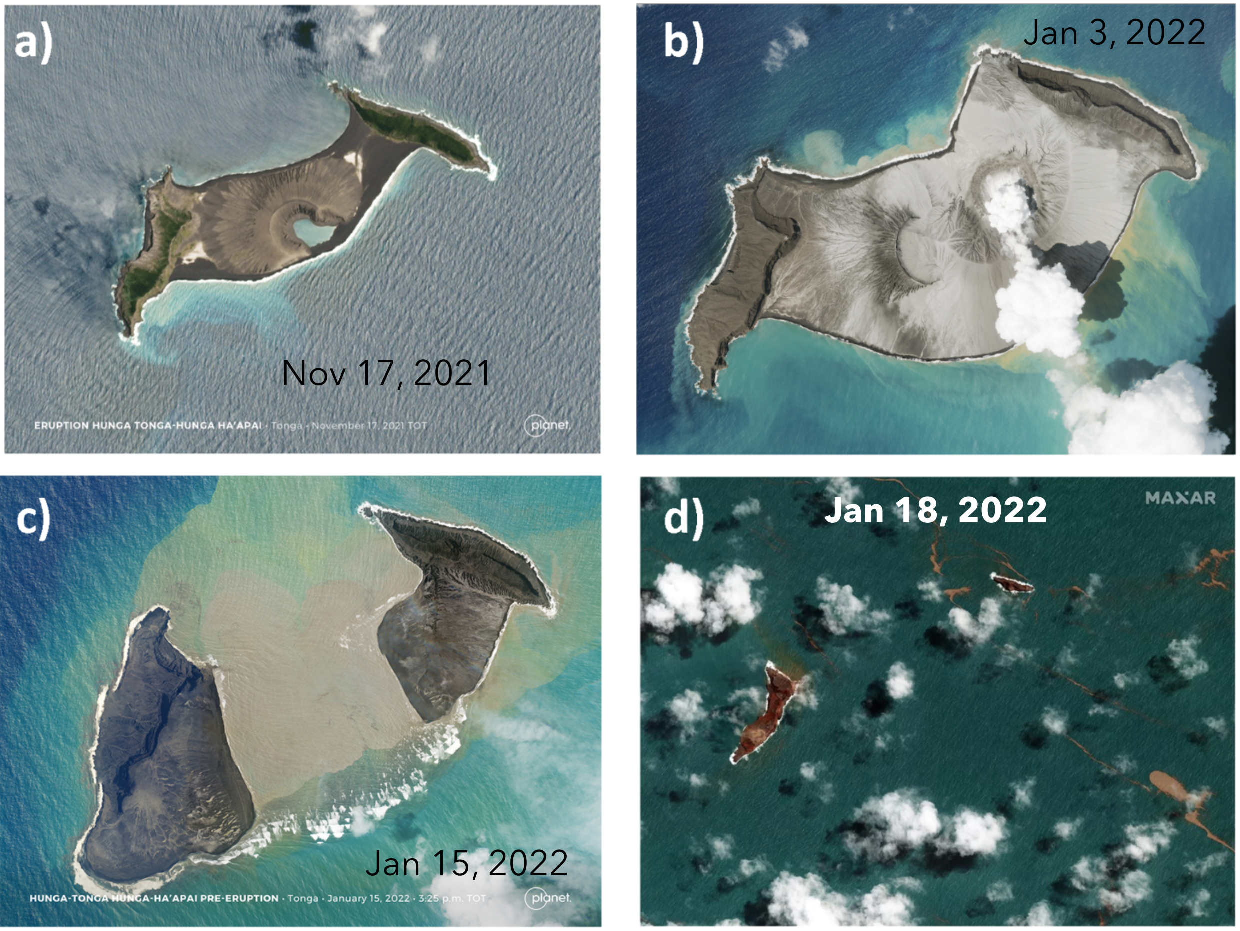
26 detections so far

Hunga Tonga-Hunga Ha’pai eruption

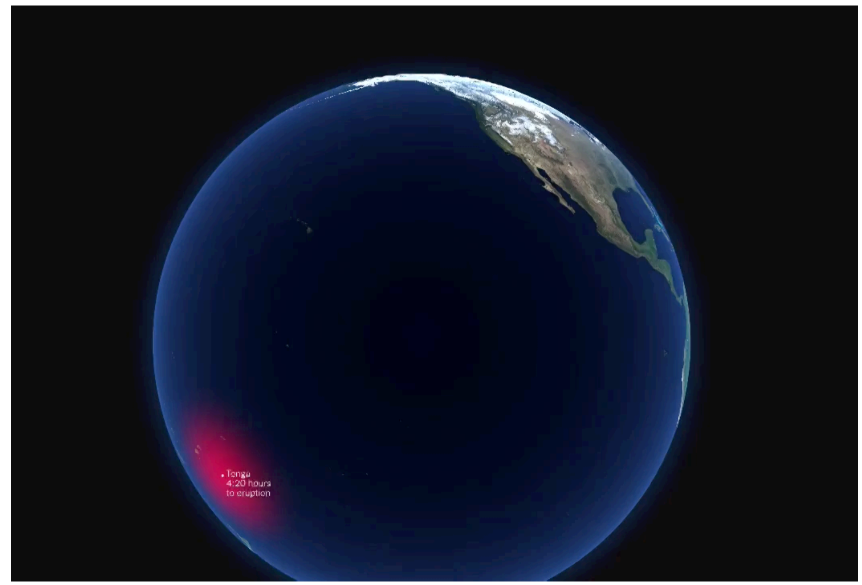


Planet Labs PBC, Maxar Technologies, Brumfiel (NPR)

Hunga Tonga-Hunga Ha’pai eruption



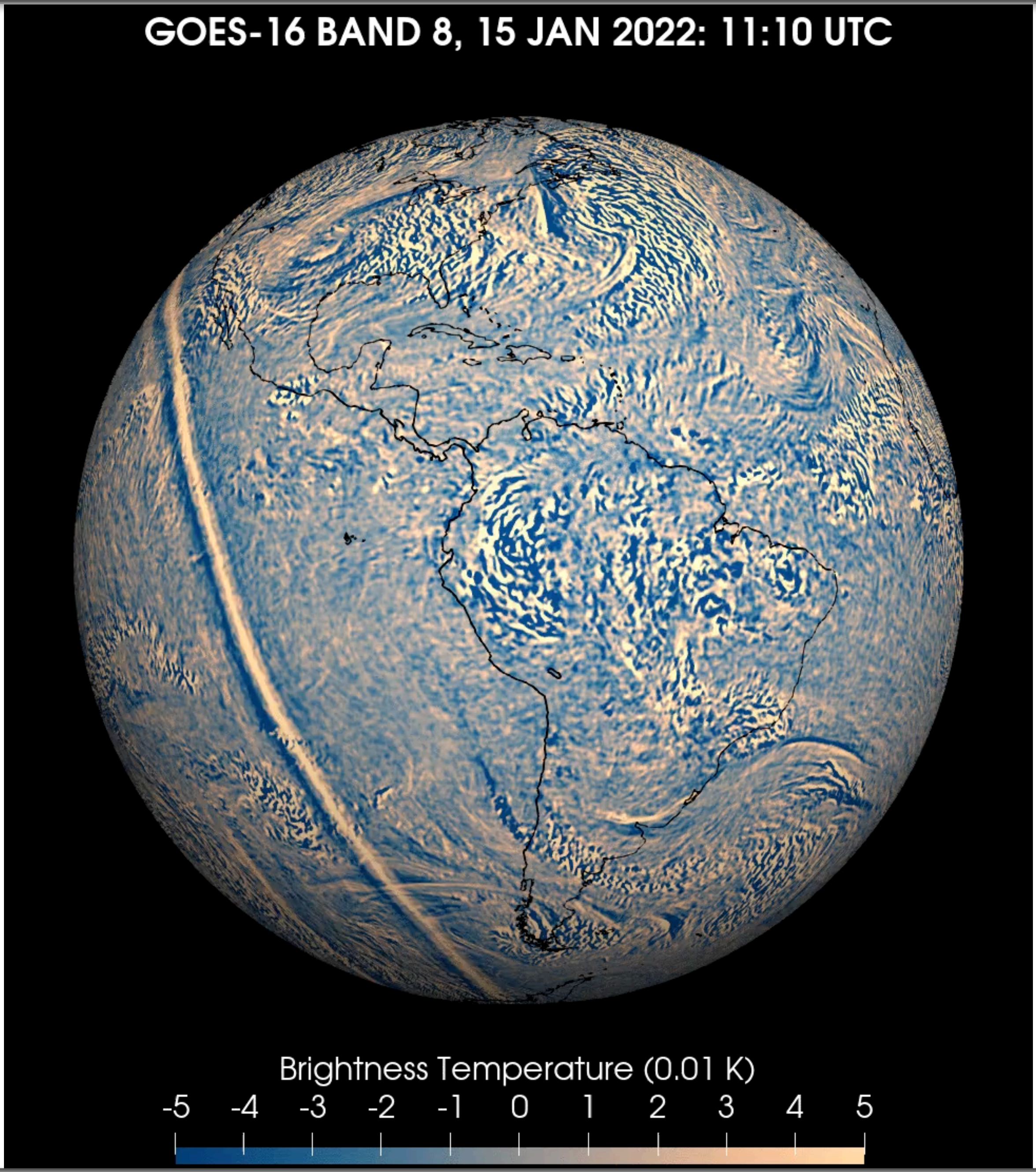
Planet Labs PBC, Maxar Technologies, Brumfiel (NPR)



New York Times, 2022
A. Amores et al. Geophysical Reseach Letters 49 (2022) 6

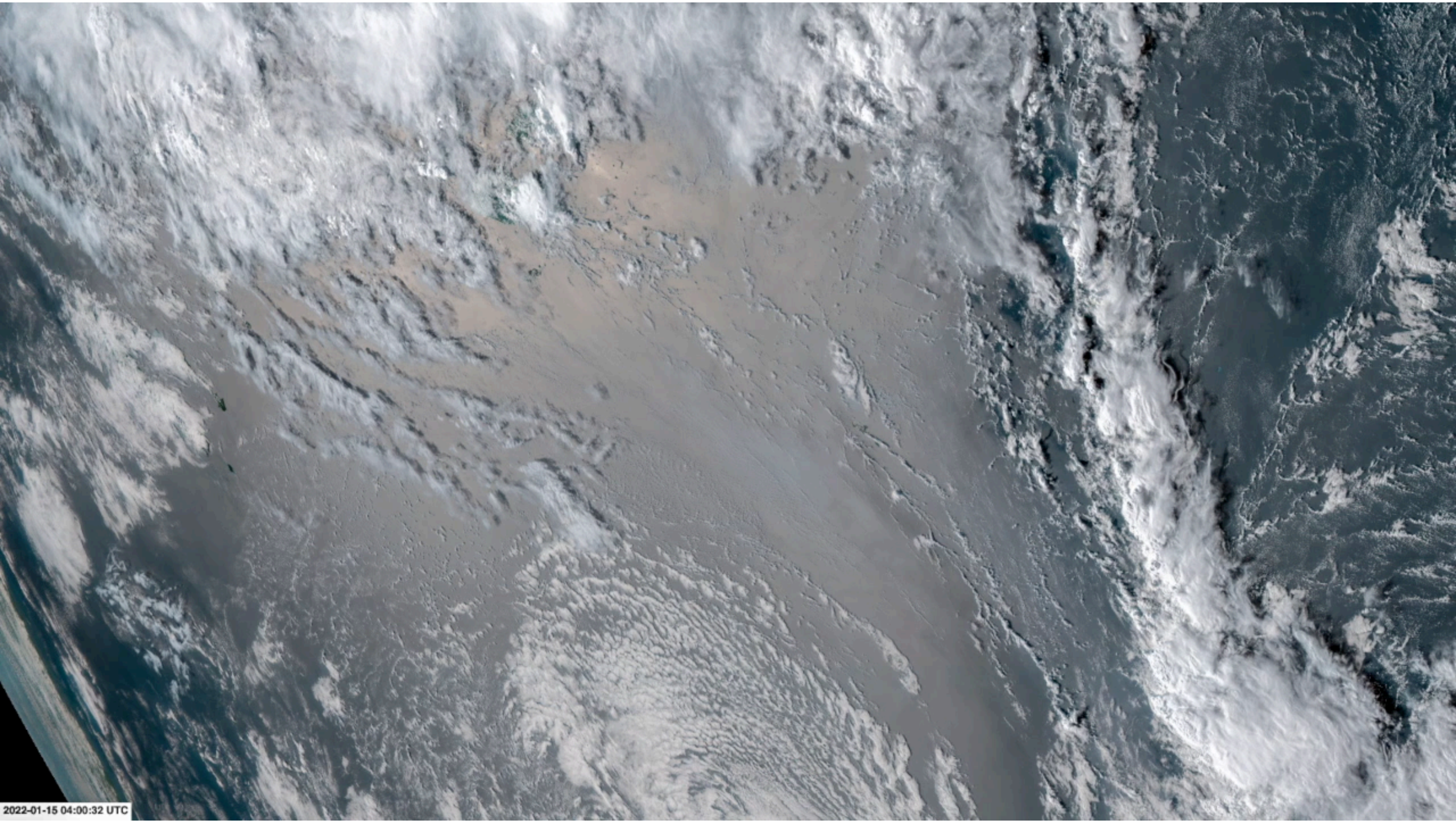
The estimation is that the energy release is ~10 times smaller than Krakatoa, but still hundreds of times larger than Hiroshima.

Hunga Tonga-Hunga Ha’pai eruption



Infrared

Hunga Tonga-Hunga Ha'pai eruption



Not just a shock wave

December 30, 2021
Tonga Geological Services

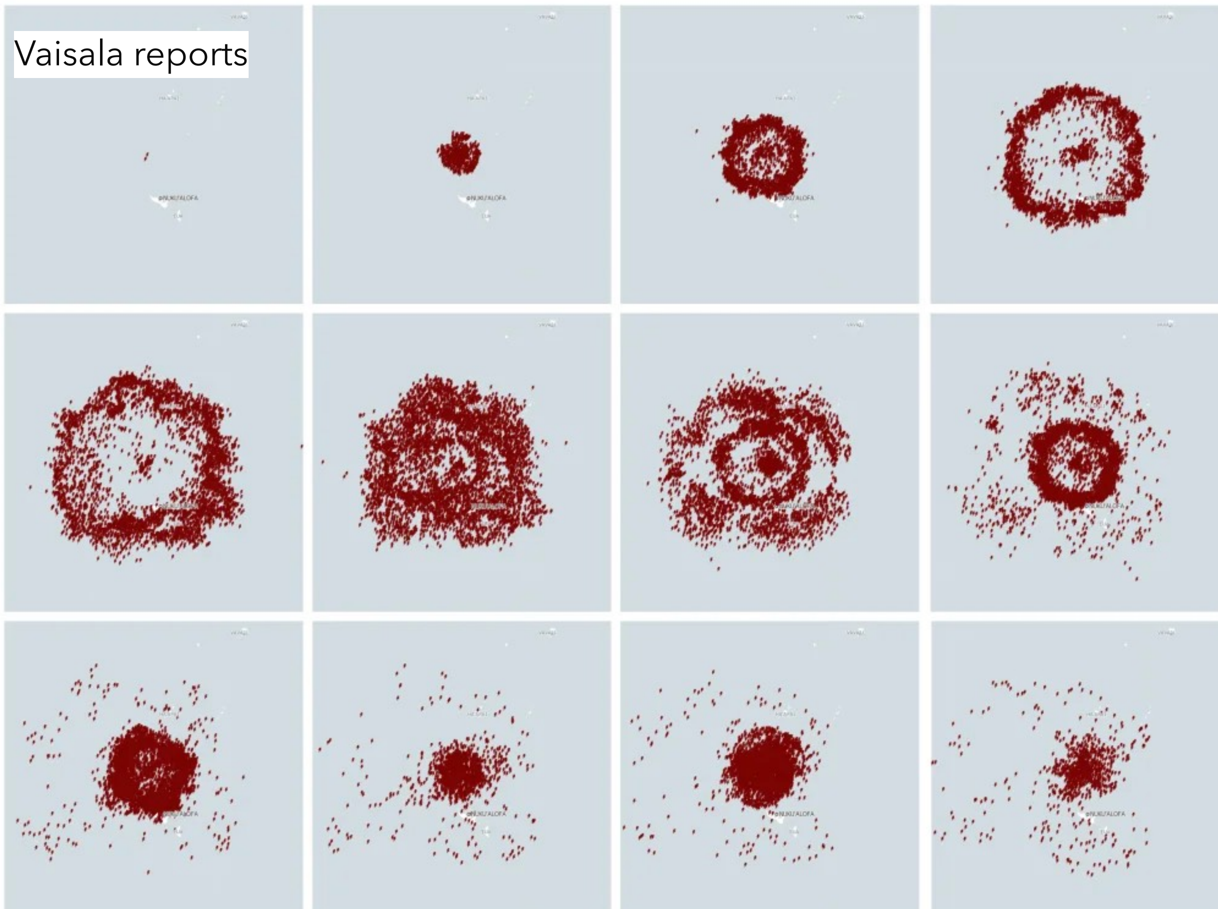
Not just a shock wave

At the highest intensity stage of the activity, the volcano emitted as much matter as 15 Empire State buildings, each second

Intermediate explosion
January 14, 2022
Tonga Geological Services

Not just a shock wave

- In 5 minutes: ~ 25 500 lightnings
- 6 hours: ~ 400 000 lightnings
  - ➡~1/2 half of the worldwide activity!



Hunga Tonga-Hunga Ha'pai eruption

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NEWS | 18 January 2022

Tonga volcano eruption created puzzling ripples in Earth's atmosphere

Powerful waves ringing through the atmosphere after the eruption of Hunga Tonga–Hunga Ha'apai are unlike anything seen before.

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HOME > SCIENCE > VOL. 377, NO. 6601 > ATMOSPHERIC WAVES AND GLOBAL SEISMOACOUSTIC OBSERVATIONS OF THE JANUARY 2022 HUNGA ERUPTION,...

REPORT | NATURAL HAZARDS

Atmospheric waves and global seismoacoustic observations of the January 2022 Hunga eruption, Tonga

ROBIN S. MATOZA, DAVID FEE, JELLE D. ASSINK, ALEXANDRA M. IEZZI, DAVID N. GREEN, KEEHOON KIM, LIAM TONEY, THOMAS LECOCQ, SIDDHARTH KRISHNAMOORTHY, [...] DAVID C. WILSON +67 authors Authors Info & Affiliations

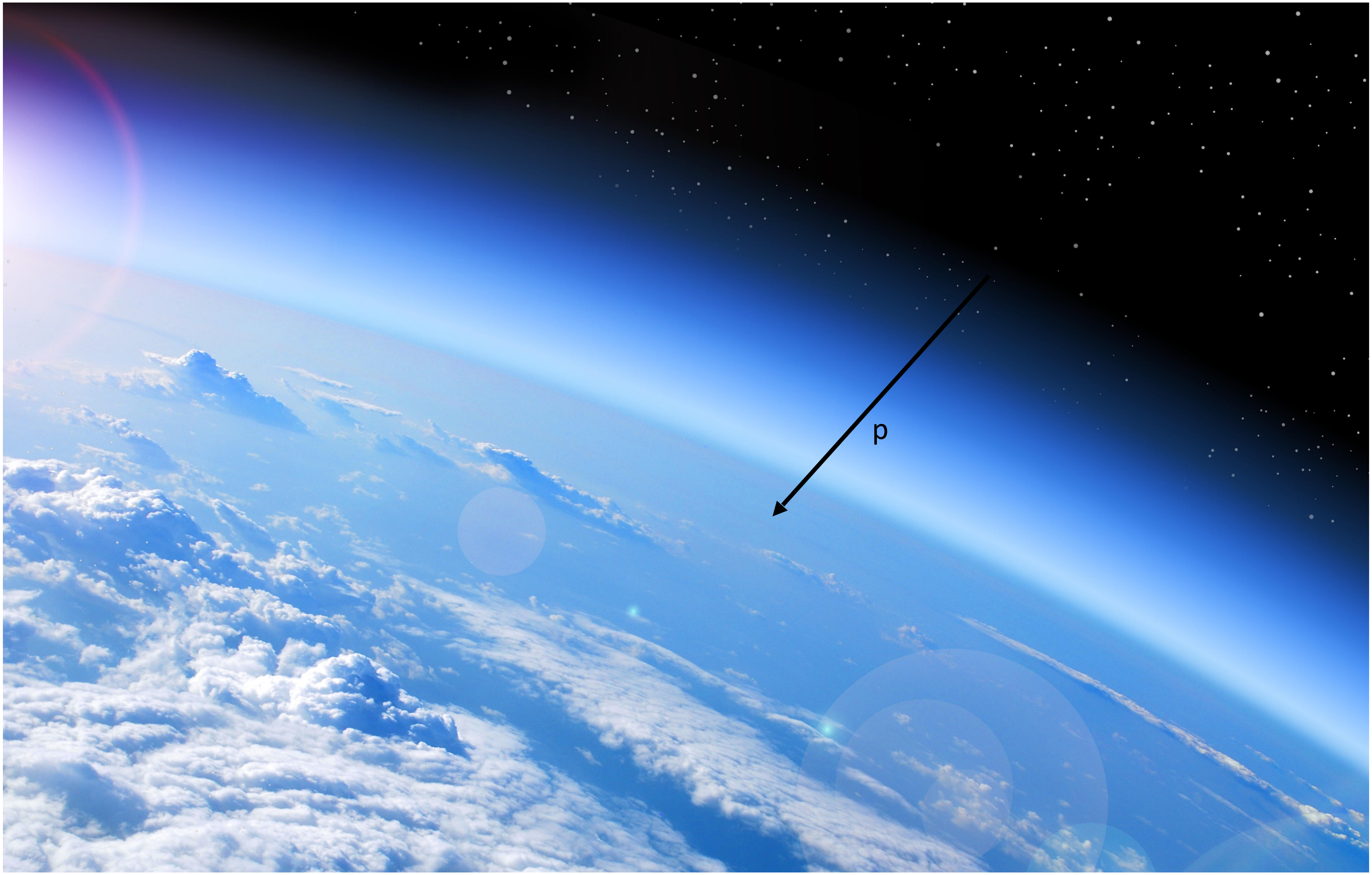
SCIENCE • 12 May 2022 • Vol 377, Issue 6601 • pp. 95-100 • DOI: 10.1126/science.abo7063

Going on the lamb

Particle physics in the atmosphere

Muons and atmospheric temperature

Copernicus Atmosphere Monitoring Service



Particle physics in the atmosphere

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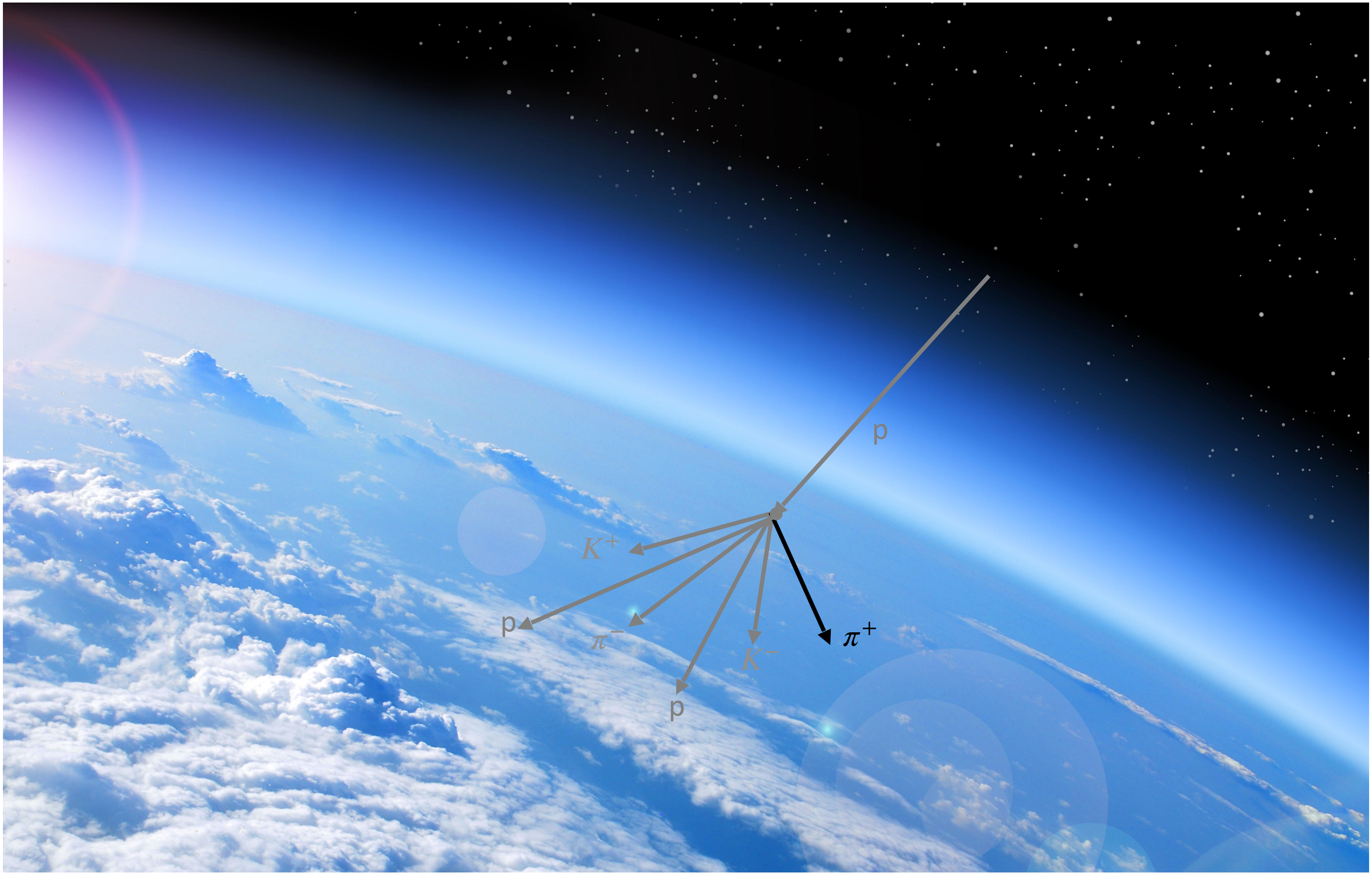
Particle physics in the atmosphere

Muons and atmospheric temperature

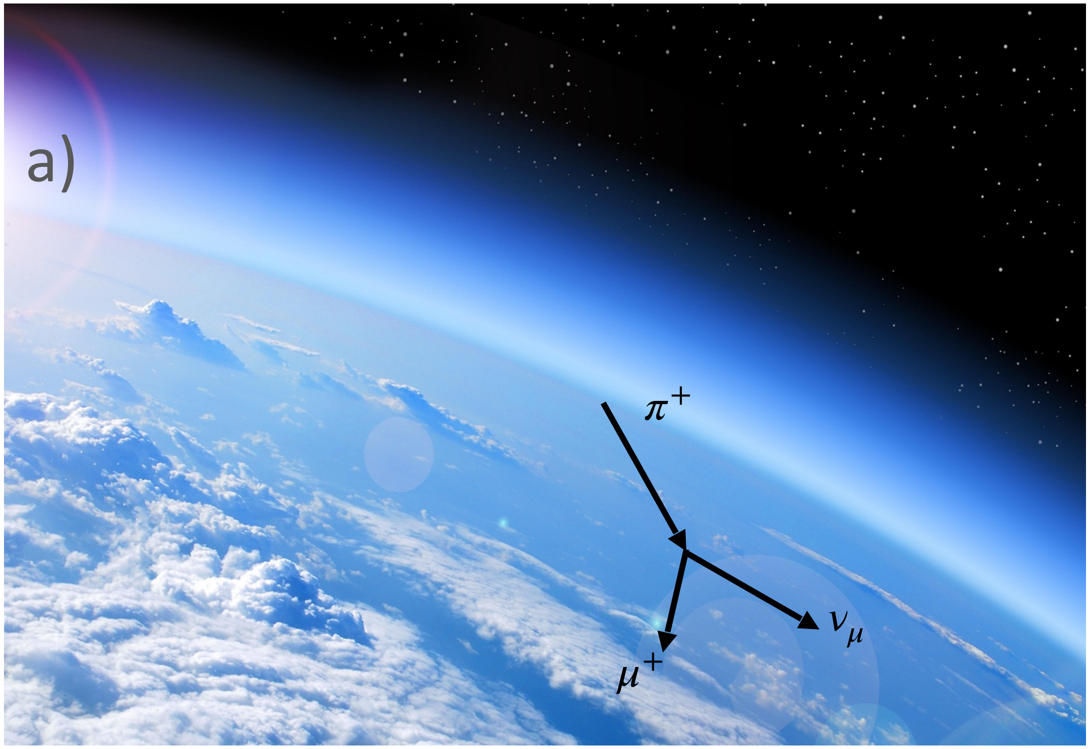
Copernicus Atmosphere Monitoring Service



Particle physics in the atmosphere

Muons and atmospheric temperature

Copernicus Atmosphere Monitoring Service



If the pion decays:

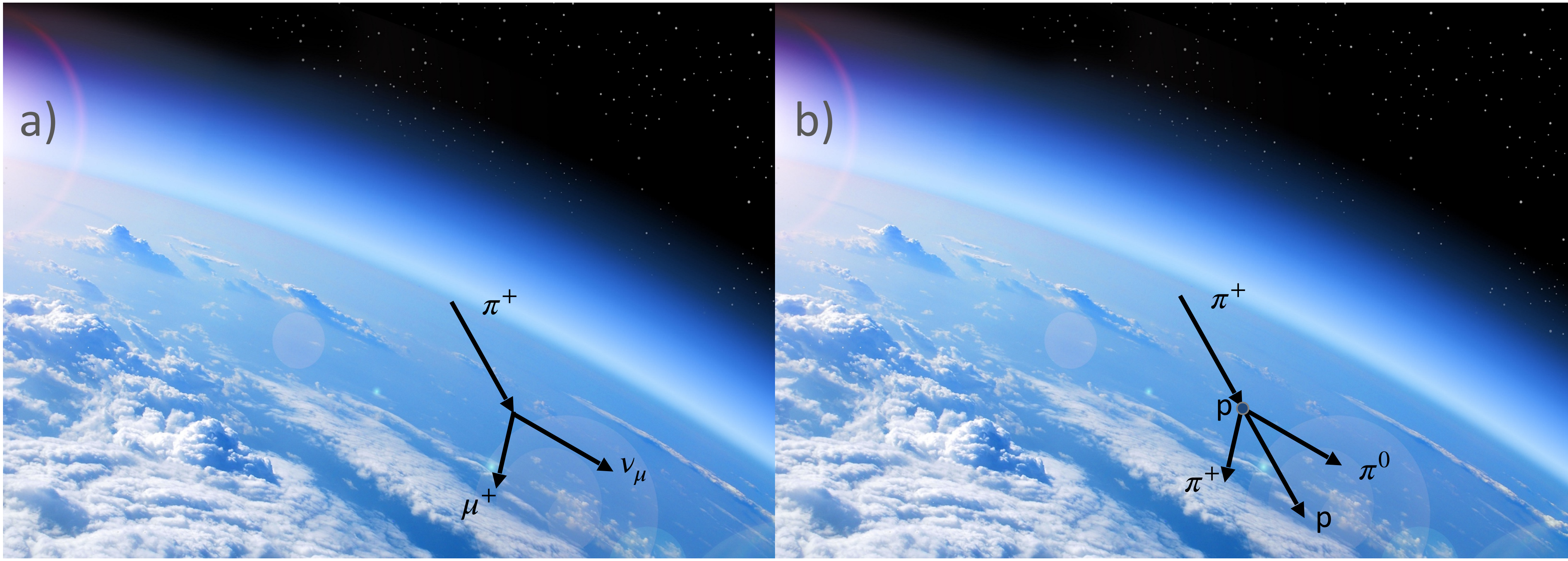
- A high energy muon is produced

More likely in thinner atmosphere
(**higher** temperatures than the average)

Particle physics in the atmosphere

Muons and atmospheric temperature

Copernicus Atmosphere Monitoring Service



If the pion decays:

- A high energy muon is produced

More likely in thinner atmosphere
(**higher** temperatures than the average)

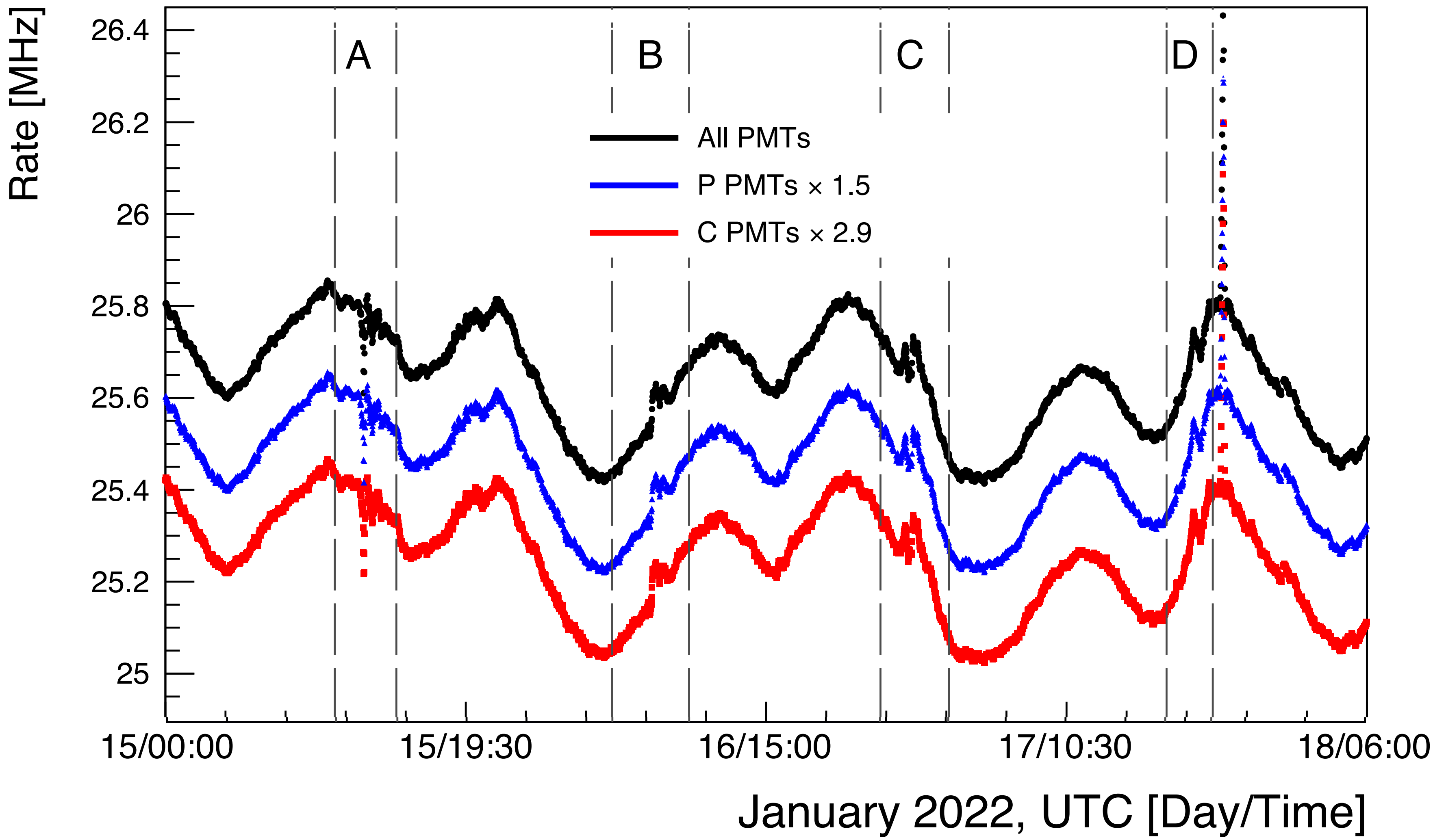
If the pion suffers another interaction:

- Additional mesons are produced
- The charged pions decay in muons with less energy than in a)

More likely in a dense atmosphere
(**lower** temperatures than the average)

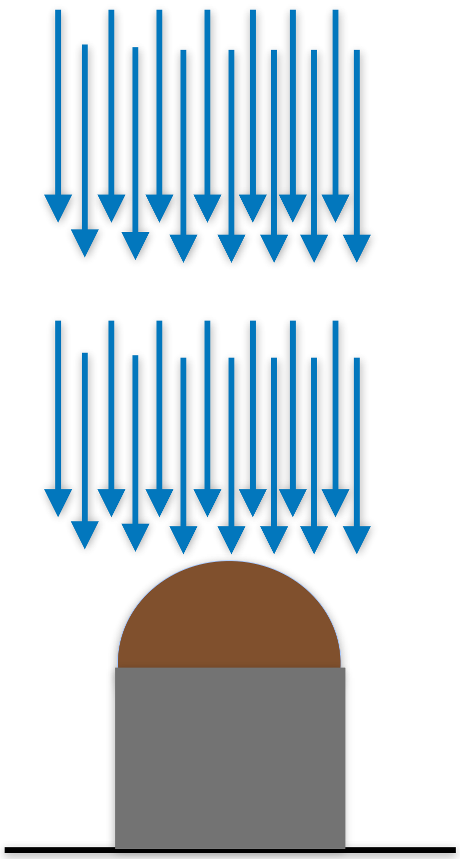
Something similar for K mesons

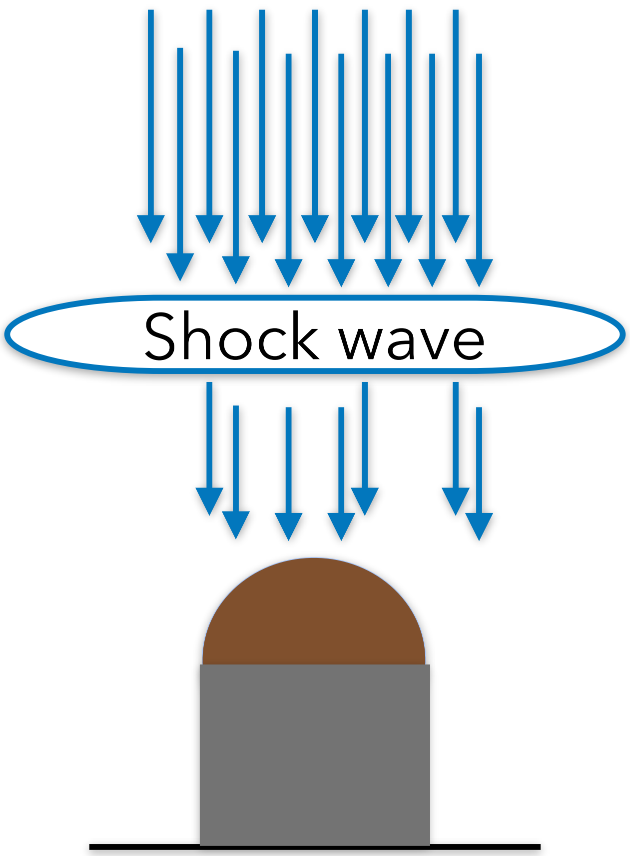
Detection of the pressure wave using cosmic rays



- Secondary particle detection rate, four days of data
- Modulated by the atmospheric conditions

Detection of the pressure wave using cosmic rays

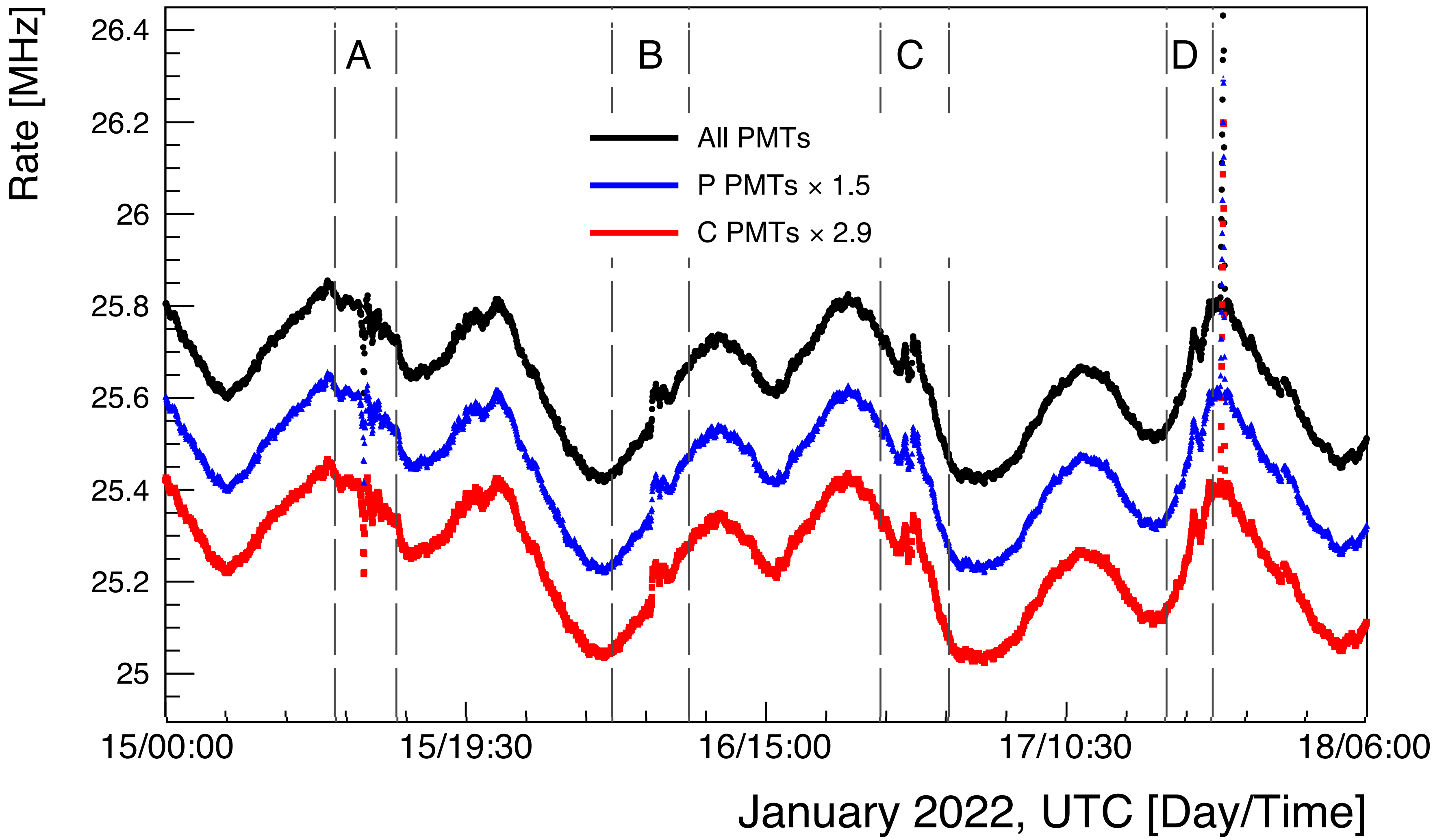




- Average atmospheric conditions

- Anomalous conditions
- Sudden increase in pressure
  → attenuate particle rate

Detection of the pressure wave using cosmic rays



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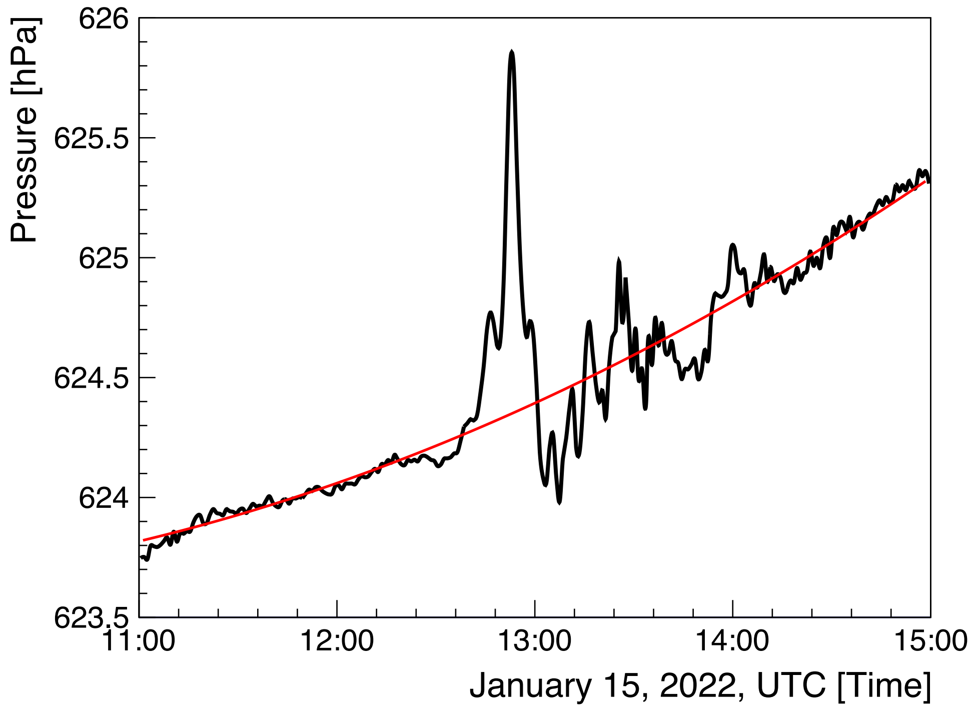
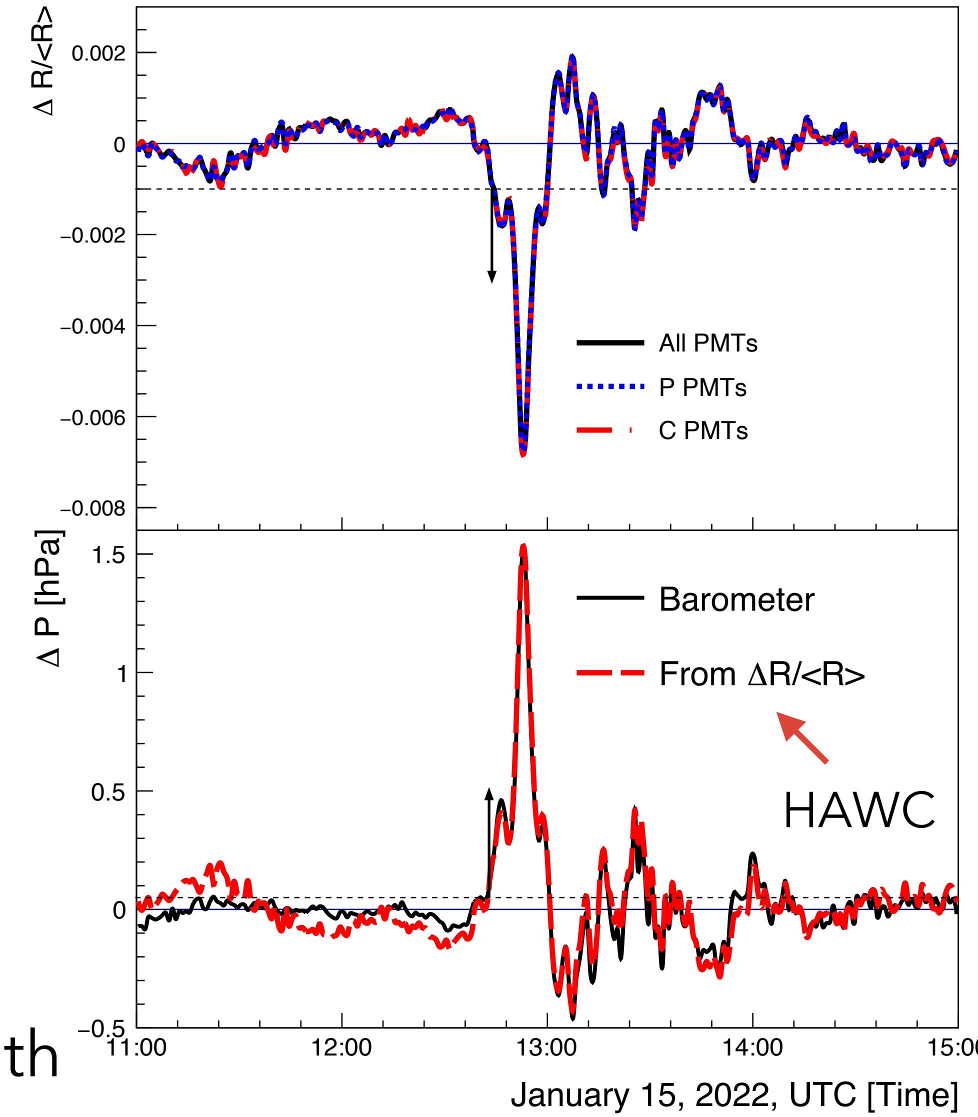
Detection of the pressure wave using cosmic rays

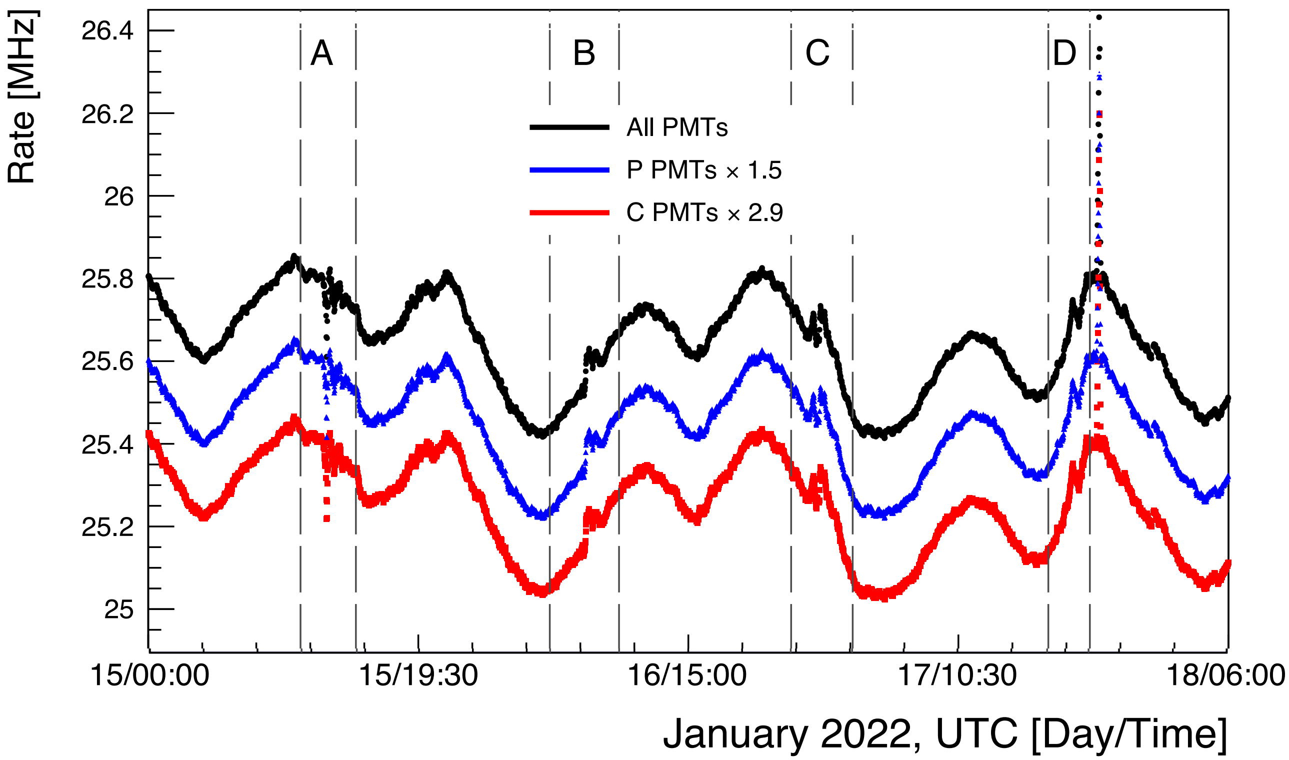


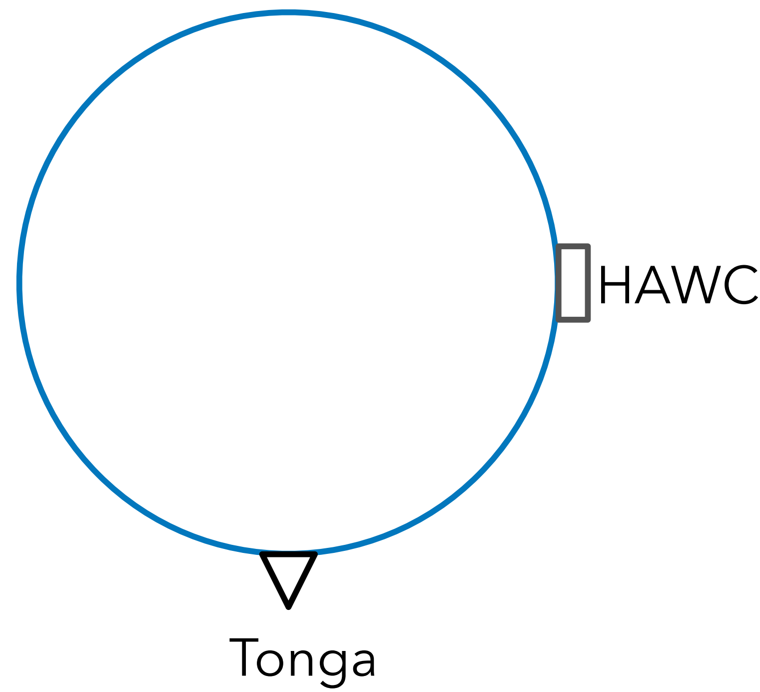


$$\frac{\Delta R}{< R >} = \alpha \Delta P + b$$

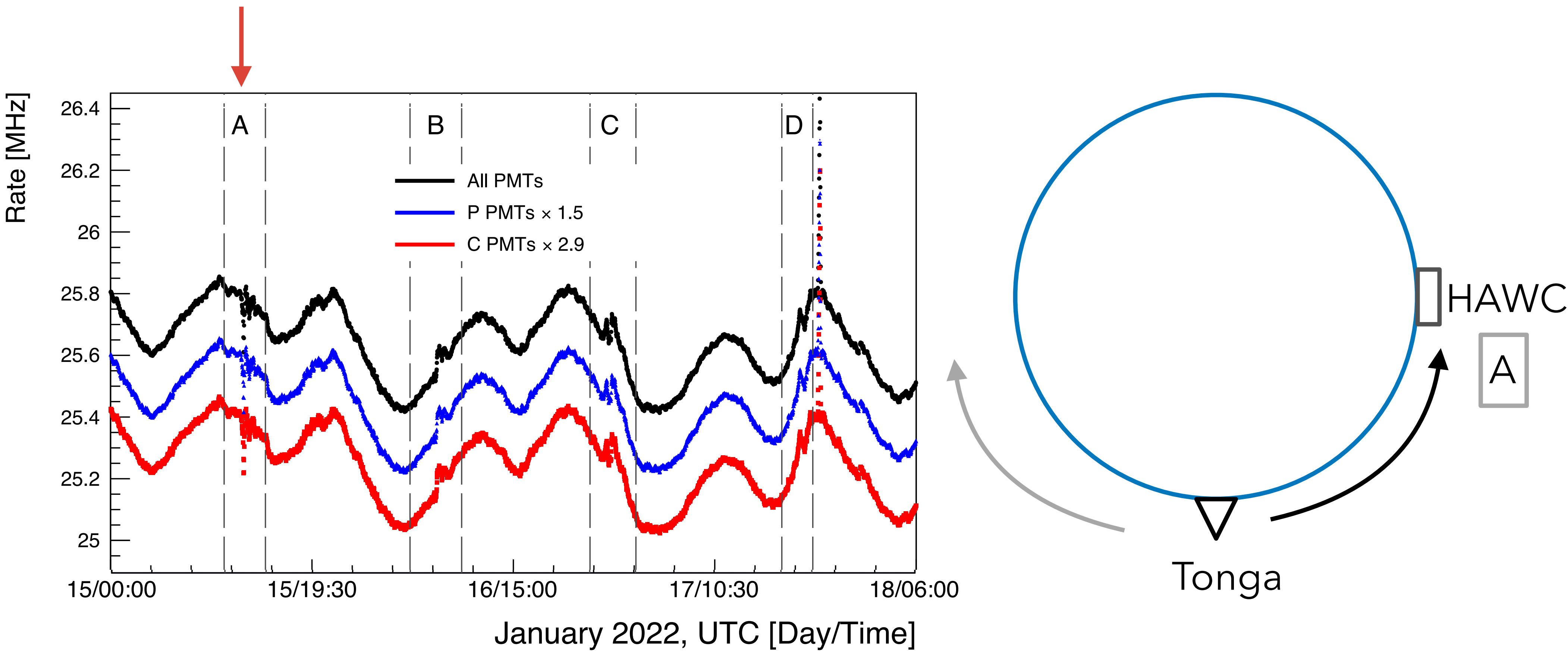
We can correlate the particle rate with a pressure sensor and turn HAWC into a barometer

Detection of the pressure wave

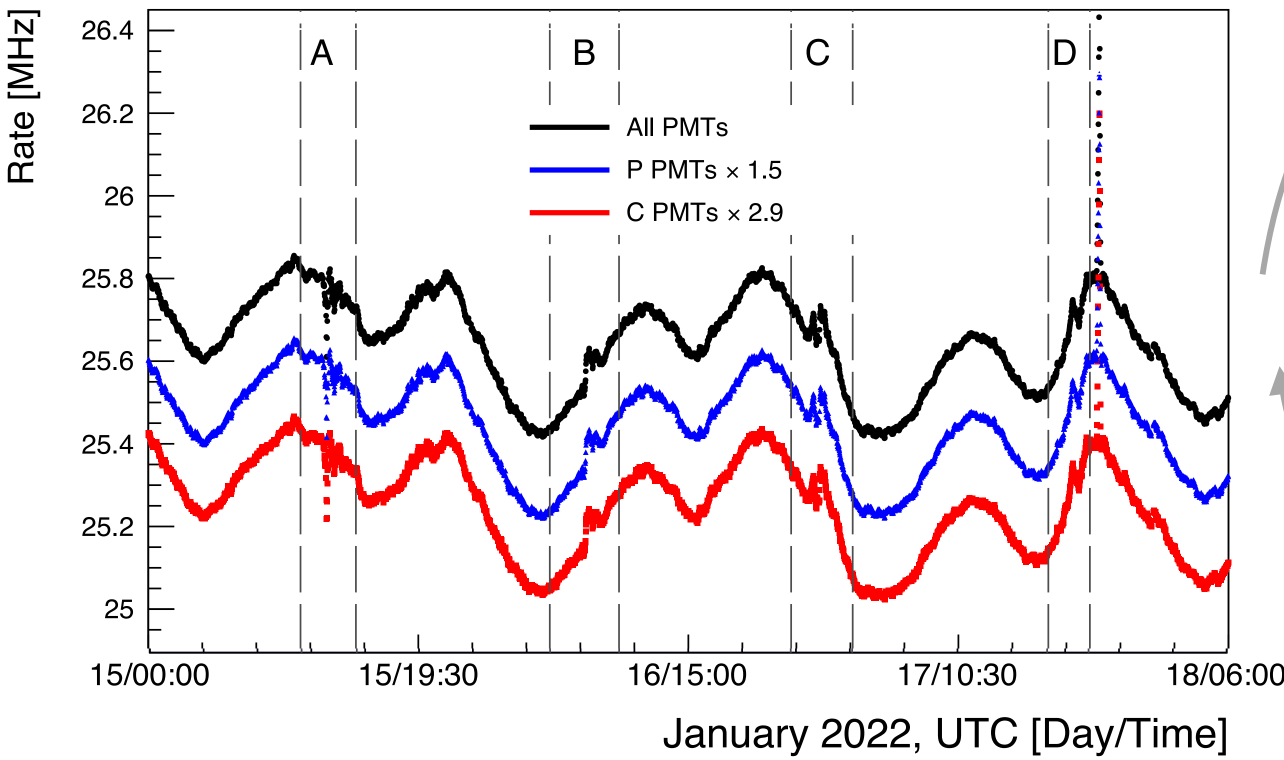


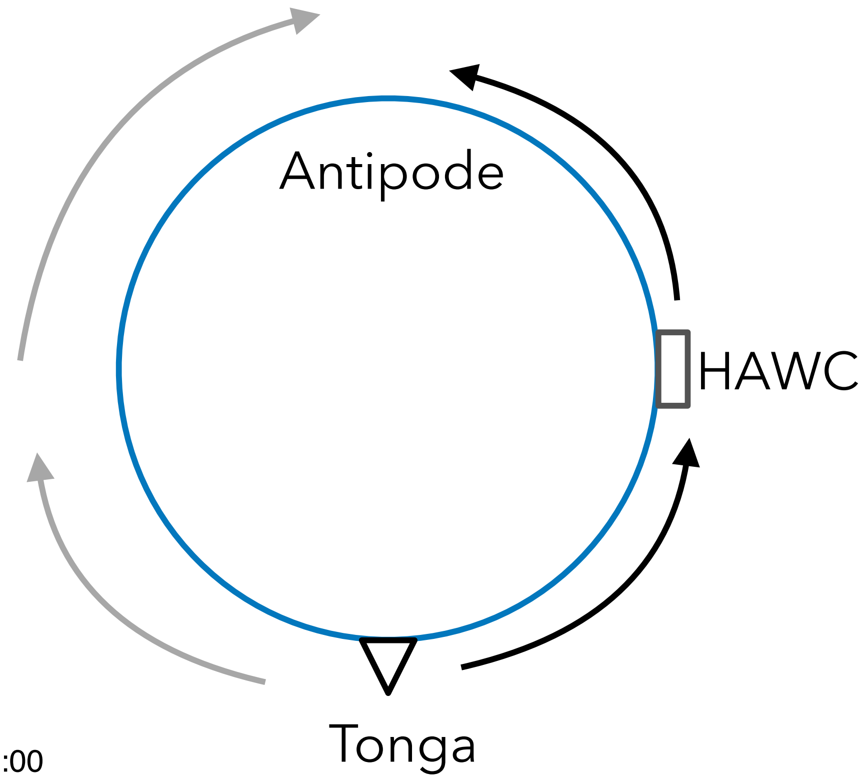


Propagation of the pressure wave

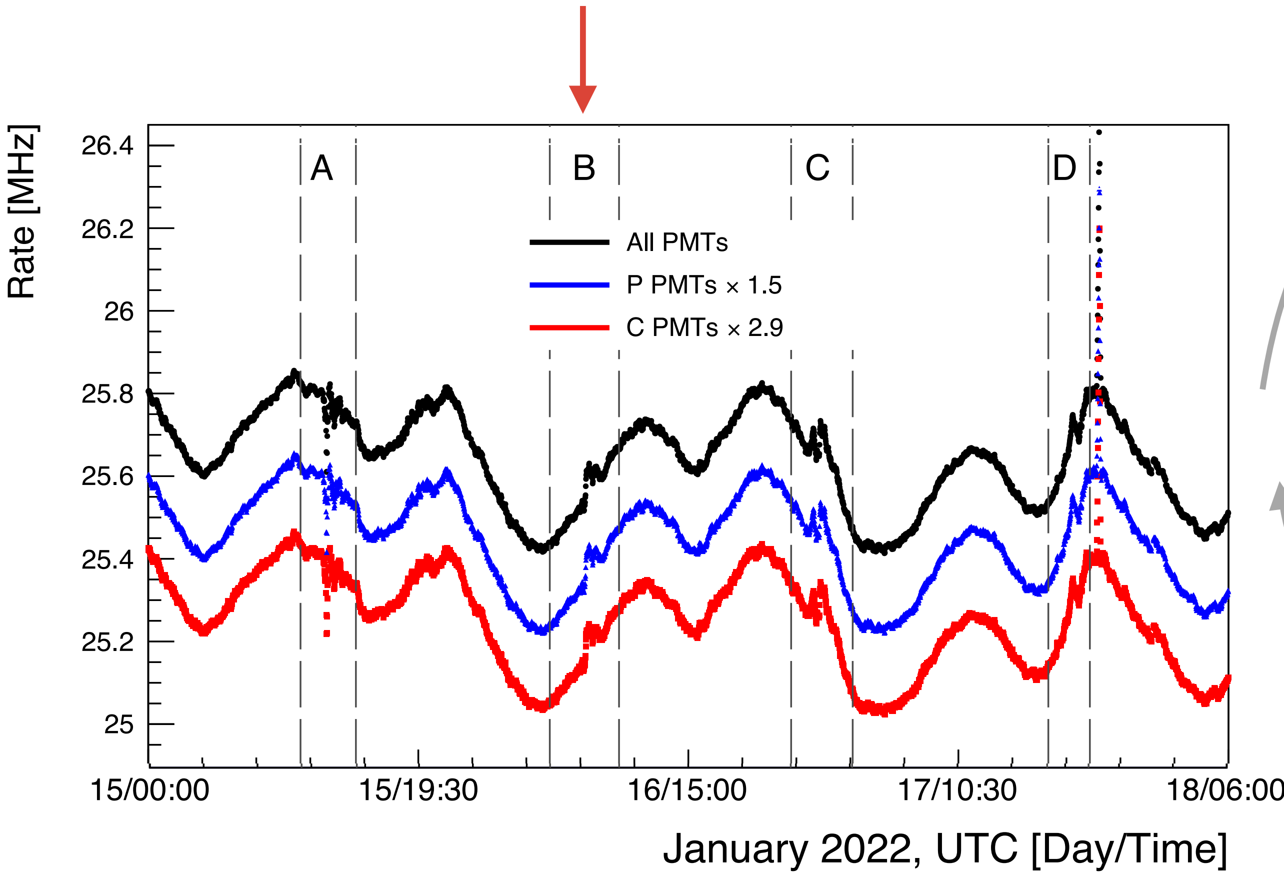


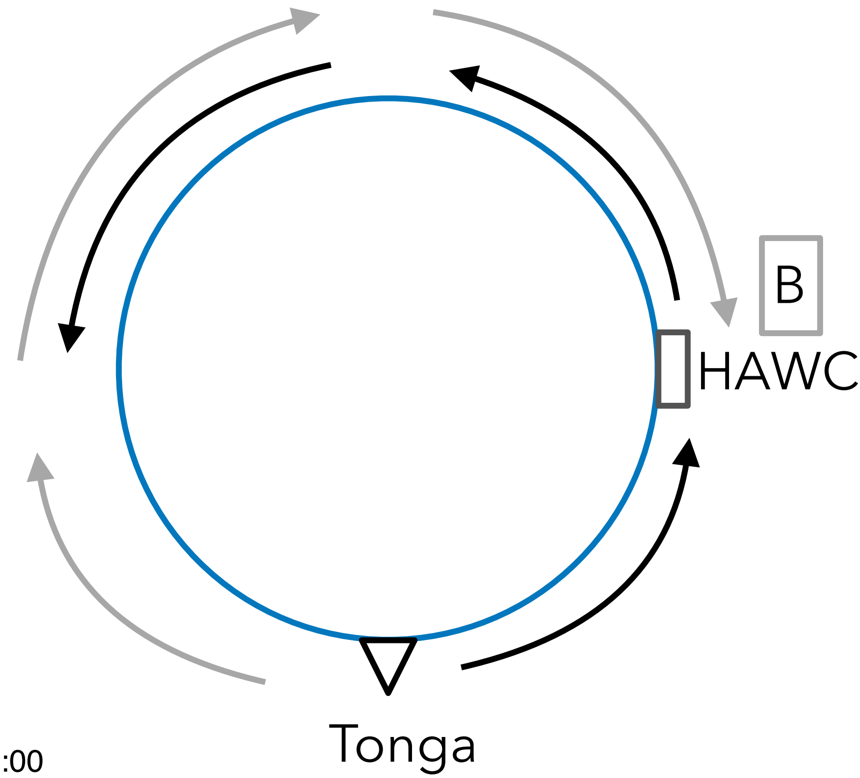
Propagation of the pressure wave





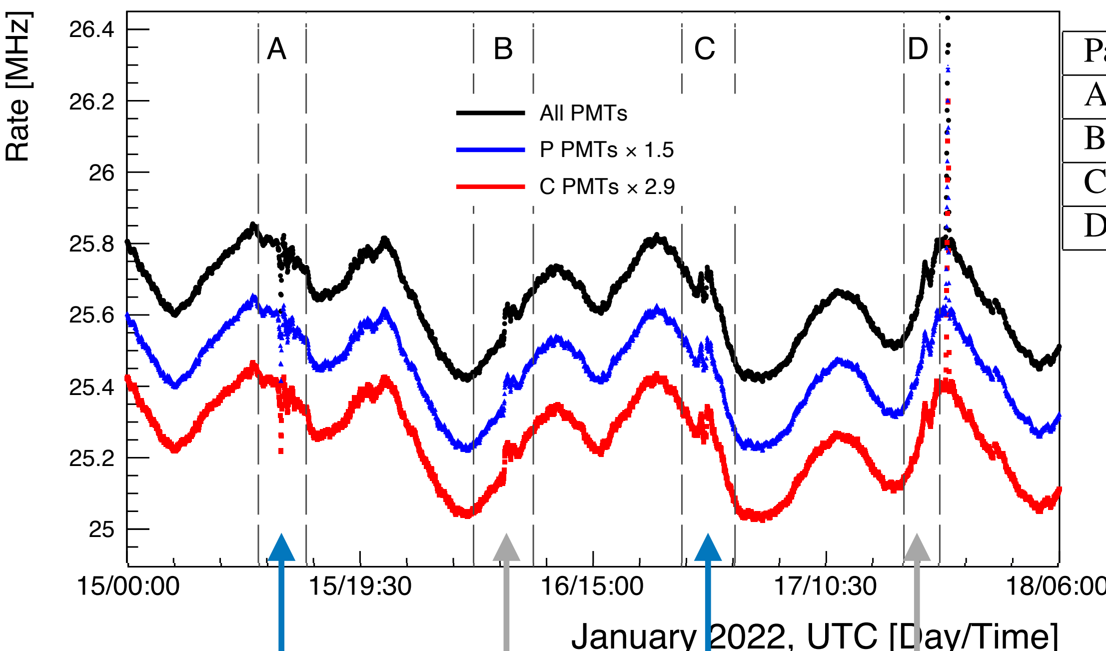
Propagation of the pressure wave





Speed of the pressure wave

Distances with the de Haversine formula and the L3 software. The difference is an uncertainty.



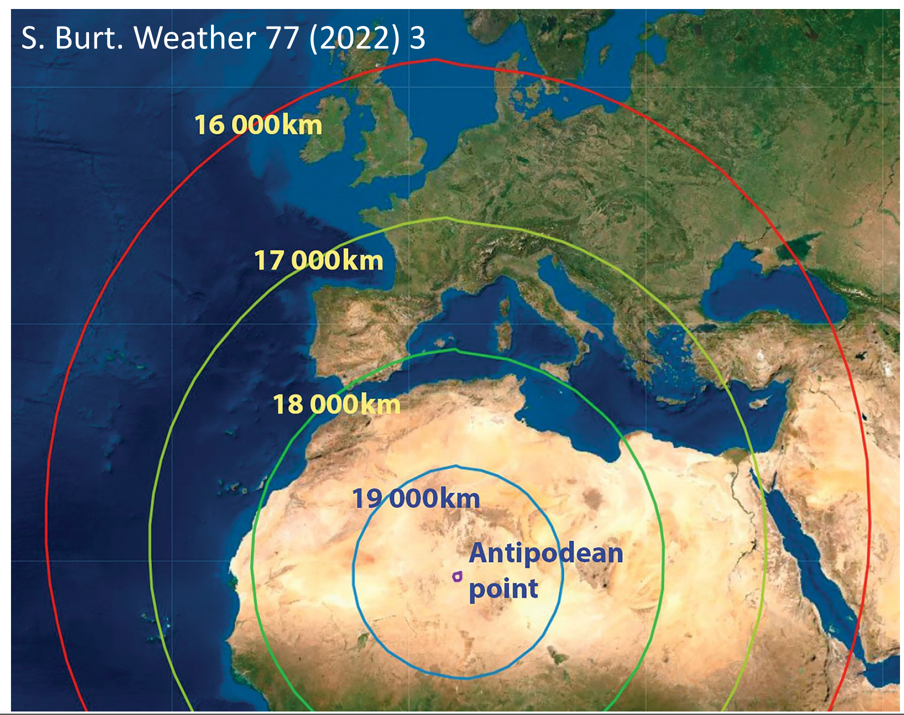
Tonga to HAWC

Tonga to HAWC

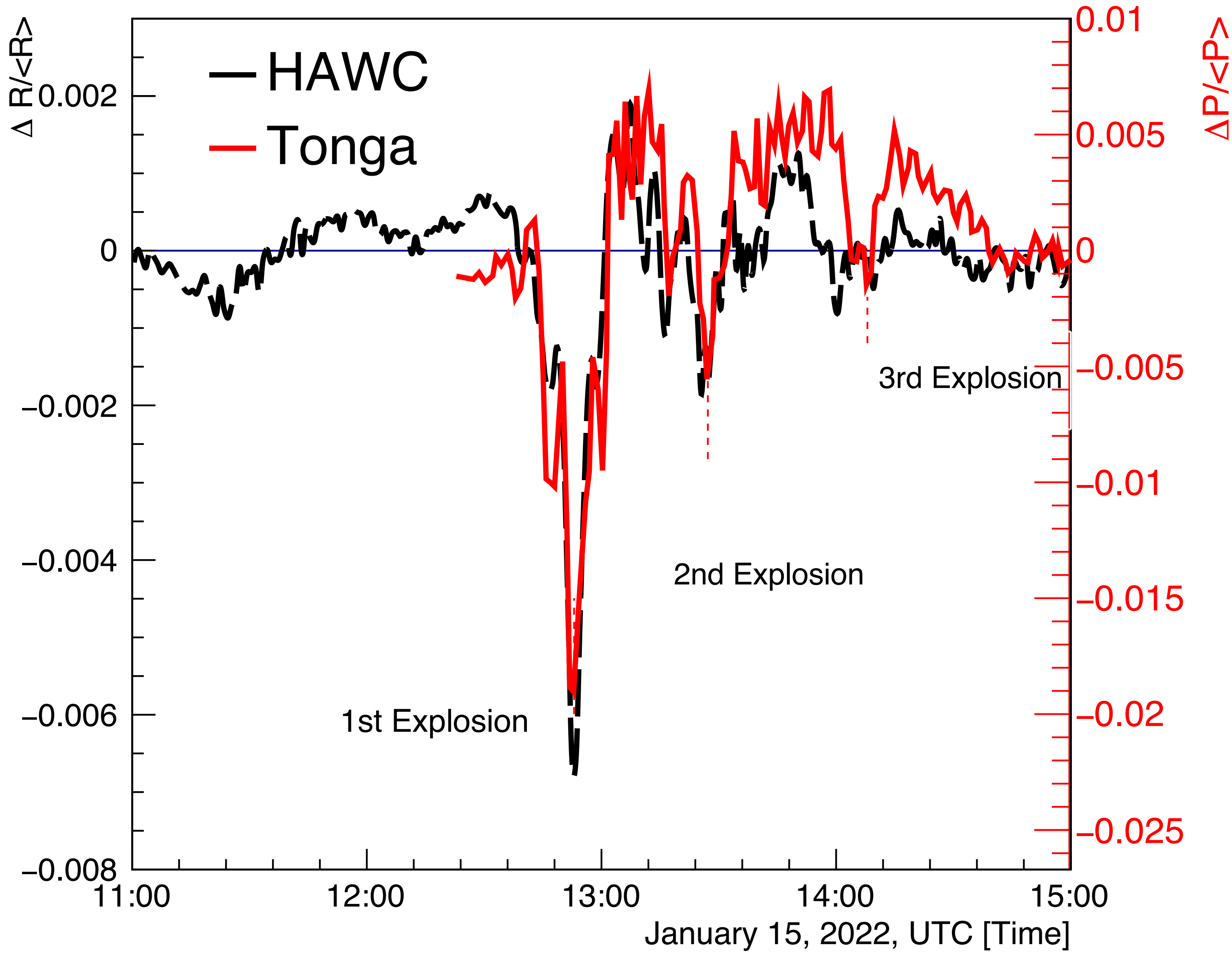
Africa to HAWC

Africa to HAWC

Pass	Date [UTC]	Arrival time [UTC Time]	Speed [m/s]	Type
A	Jan. 15	12:43 ± 00:01	316.2 ± 1.3	Short
B	Jan. 16	07:25 ± 00:01	312.4 ± 0.2	Long
C	Jan. 16	23:48 ± 00:03	316.9 ± 1.9	Short
D	Jan. 17	19:02 ± 00:05	312.4 ± 0.9	Long



Structure of the pressure wave



The first detection of Lamb waves using Cosmic Rays

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High-altitude characterization of the Hunga pressure wave with cosmic rays by the HAWC observatory

Ruben Alfaro [a], César Alvarez [b], Juan Carlos Arteaga-Velázquez [c], Arun Babu Kollamparambil Paul [ac], Daniel Avila Rojas [a], Hugo Alberto Ayala Solares [e], Rishi Babu [f], Ernesto Belmont-Moreno [a], Chad Brisbois [n], Karen S. Caballero-Mora [b], Tomás Capistrán [g], Alberto Carramiñana [h], Sabrina Casanova [i], Oscar Chaparro-Amaro [j], Umberto Cotti [c], Jorge Cotzomi [k], Eduardo De la Fuente [l], Raquel Diaz Hernandez [h], Michael A. DuVernois [m], Mora Durocher [s], Juan Carlos Díaz-Vélez [l], Kristi Engel [n], Catalina Espinoza [a], Kwok Lung Fan [n], Nissim Fraija [g], José Andrés García-González [o], Fernando Garfias [g], María Magdalena González [g], Jordan A. Goodman [n], J. Patrick Harding [s], Sergio Hernandez [a], Dezhi Huang [f], Filiberto Hueyotl-Zahuantitla [b], Thomas Brian Humensky [n], Petra Hüntemeyer [f], Arturo Iriarte [g], Vikas Joshi [p], Sarah Kaufmann [q], David Kieda [aa], Alejandro Lara [d,*], Jason Lee [x], Hermes León Vargas [a,*], James T. Linnemann [r], Anna Lia Longinotti [g], Gilgamesh Luis-Raya [q], Kelly Malone [ab], Oscar Martinez [k], Jesús Martínez-Castro [j], John A.J. Matthews [t], Pedro Miranda-Romagnoli [u], Jorge Antonio Morales-Soto [c], Eduardo Moreno [k], Amid Nayerhoda [i], Lukas Nellen [v], Roberto Noriega-Papaqui [u], Nicola Omodei [w], Yunior Pérez Araujo [g], Eucario Gonzalo Pérez-Pérez [q], Chang Dong Rho [ad], Daniel Rosa-González [h], Edna Ruiz-Velasco [y], Humberto Salazar [k], Daniel Salazar-Gallegos [r], Andres Sandoval [a,*], Michael Schneider [n], José Serna-Franco [a], Andrew James Smith [n], Youngwan Son [x], Robert Wayne Springer [aa], Omar Tibolla [q], Kirsten Tollefson [r], Ibrahim Torres [h], Ramiro Torres-Escobedo [z], Rhiannon Turner [f], Fernando Ureña-Mena [h], Enrique Varela [k], Luis Villaseñor [k], Xiaojie Wang [f], Elijah Willox [n], Hao Zhou [z], Cederik de León [c]

[a] *Instituto de Física, Universidad Nacional Autónoma de México, Circuito de la Investigación Científica, Ciudad Universitaria, Ciudad de México 04510, Mexico*
[b] *Universidad Autónoma de Chiapas, Carretera Emiliano Zapata Km. 8, Rancho San Francisco, Tuxtla Gutiérrez 29050, Mexico*
[c] *Universidad Michoacana de San Nicolás de Hidalgo, Edifico C-3, Ciudad Universitaria, Morelia 58040, Mexico*
[d] *Instituto de Geofísica, Universidad Nacional Autónoma de México, Ciudad Universitaria, Ciudad de México 04510, Mexico*
[e] *Department of Physics, Pennsylvania State University, 104 Davey Lab, University Park, PA 16802, USA*
[f] *Department of Physics, Michigan Technological University, 1400 Townsend Drive, Houghton, MI 49931-1295, USA*
[g] *Instituto de Astronomía, Universidad Nacional Autónoma de México, Ciudad Universitaria, Ciudad de México 04510, Mexico*
[h] *Instituto Nacional de Astrofísica, Óptica y Electrónica, Luis Enrique Erro # 1, San Andres Cholula 72840, Mexico*
[i] *Institute of Nuclear Physics Polish Academy of Sciences, ul. Radzikowskiego 152, Krakow PL-31342, Poland*
[j] *Centro de Investigación en Computación, Instituto Politécnico Nacional, Av. Juan de Dios Bátiz s/n esq. Miguel Othon de Mendizabal, Ciudad de México 07738, Mexico*
[k] *Facultad de Ciencias Físico Matemáticas, Benemérita Universidad Autónoma de Puebla, Av. San Claudio y 18 Sur, Ciudad Universitaria, Puebla 72570, Mexico*
[l] *Departamento de Física, Centro Universitario de Ciencias Exactas e Ingenierias, Universidad de Guadalajara, Blvd. Marcelino García Barragán No. 1451, Guadalajara 44430, Mexico*
[m] *Department of Physics, University of Wisconsin-Madison, 222 West Washington Ave., Suite 500, Madison, WI 53707, USA*
[n] *Department of Physics, University of Maryland, College Park, MD 20742-4111, USA*

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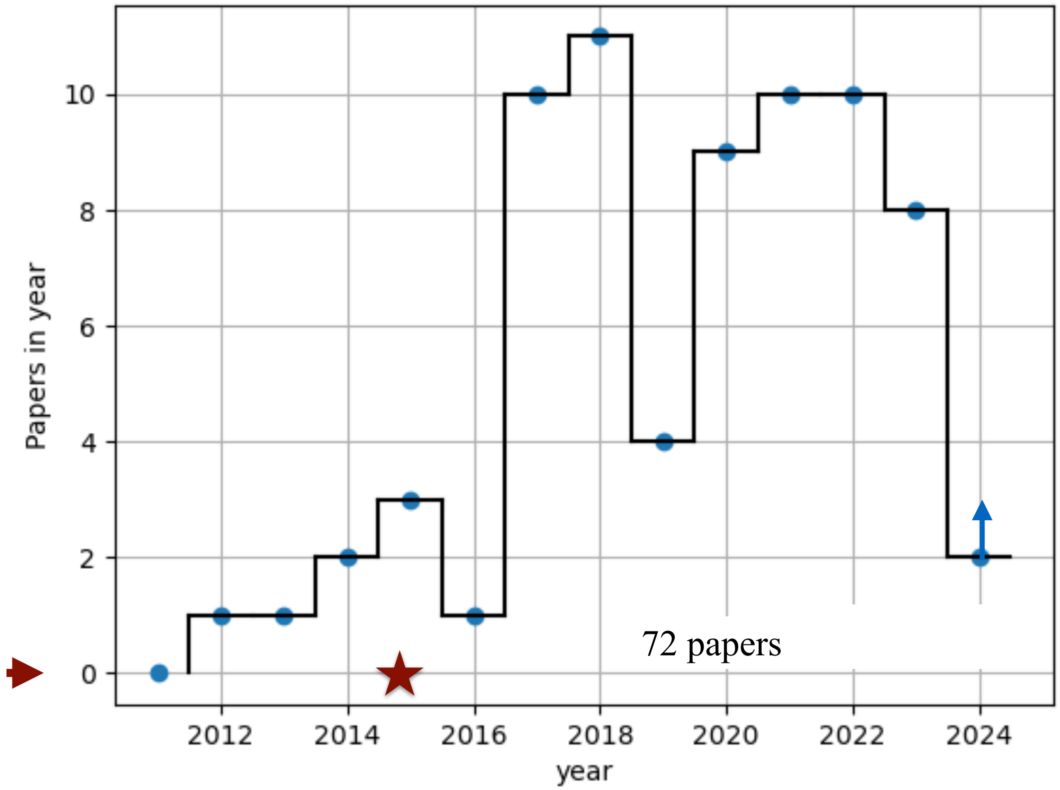
- Published last January 1
- We observed a very rare phenomenon: the largest volcanic explosion in 138 years.
- First time that a Lamb wave is detected using cosmic rays.
- A rare observation because of the high altitude.
- We can performed a more detailed study with sub second accuracy, and perhaps “directional” pressure measurements.

Scientific impact of HAWC



A. Carramiñana

PRL, APJL, Nature, Science, PRD, APJ, Astroparticle Physics …

<u>Thesis in Mexico</u>

PhD: 7

Masters: 18

Undergrad: 21

Conclusions

Next March 20, it is going to be 10 years since HAWC was inaugurated!

- HAWC has detected > 25 sources emitting gamma rays > 56 TeV
  - Most located near pulsars: lepton accelerators
- Finding or confirming structures in the cosmic ray spectrum
- Some not expected applications of HAWC:
  - Neutrino detection method above ground
  - First detection of Lamb waves using cosmic rays


Earth Science and Remote Sensing Unit, NASA Johnson Space Center / Adivulgando