Multimessenger experiments and their role in the exploration of the Universe

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Image credit: CTAO

Research Data Day & EOSC National Tripartite Event, Hotel Continental, Brno
21.-22.05.2025

SST-1M
Single-Mirror
Small Size Telescope

FZU
Institute of Physics
of the Czech
Academy of Sciences

PHYSICS
FOR
FUTURE

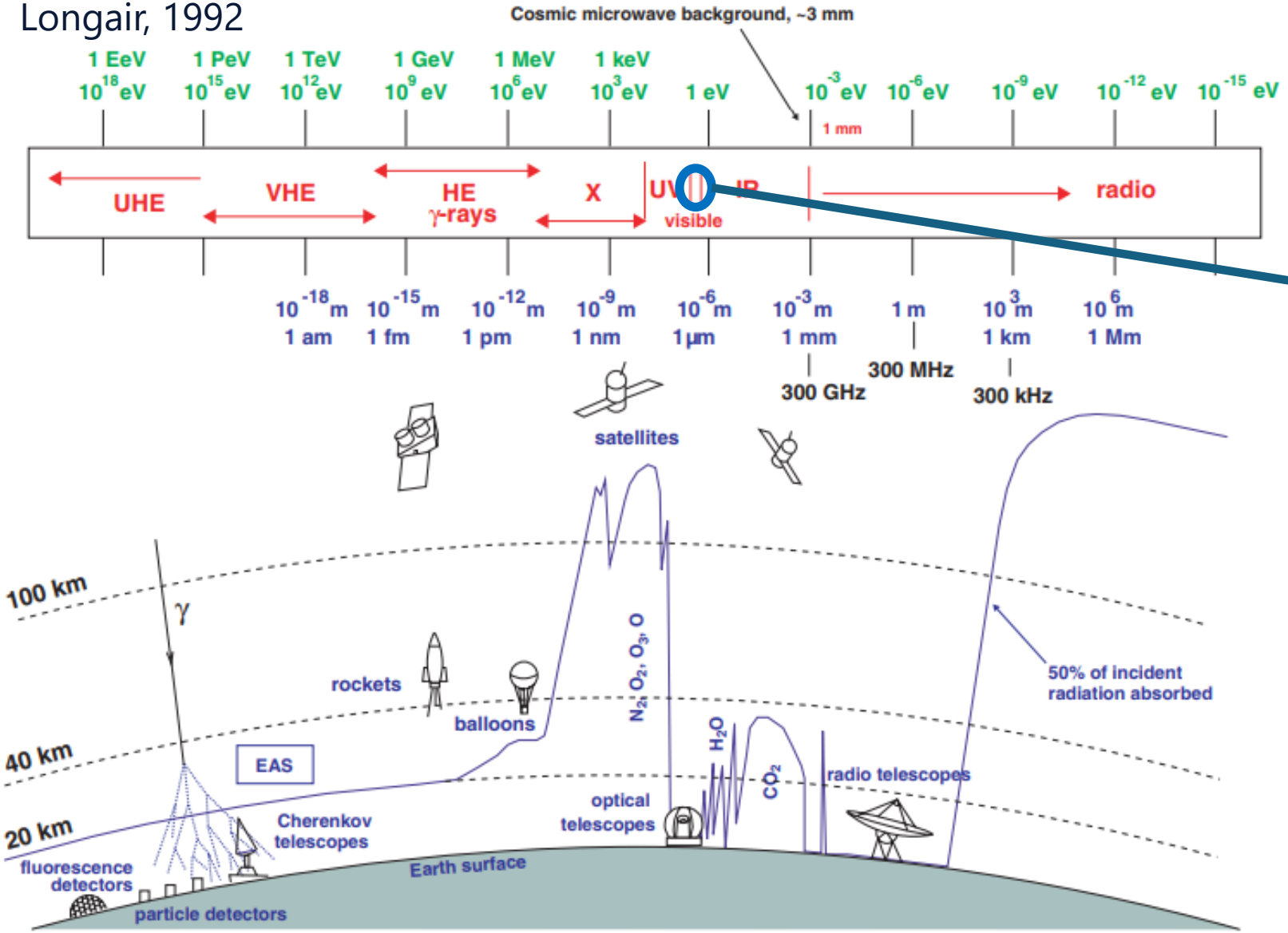
Co-funded
by the European Union

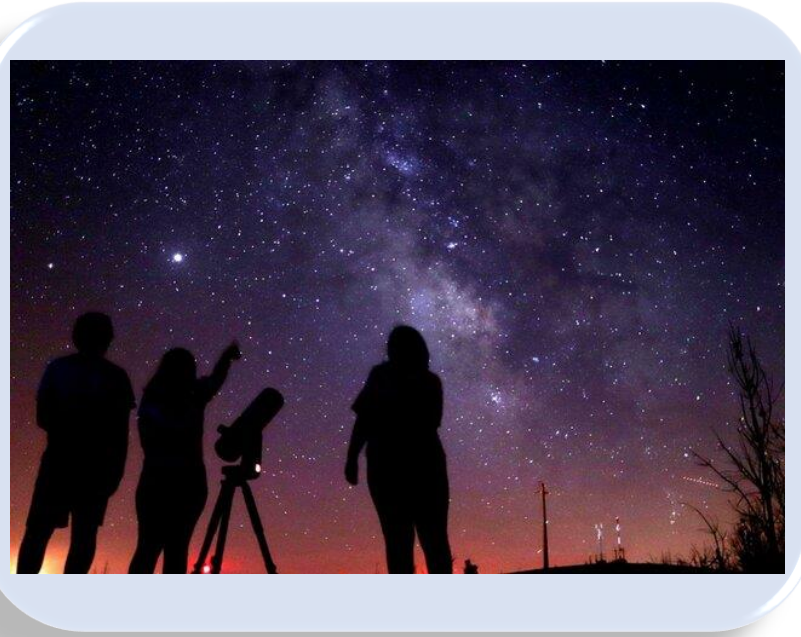
Outline

- High-energy Universe – astroparticle physics and multimessenger astronomy
- Detection techniques
- Major astroparticle-physics projects and Czech involvement

Transparency of the atmosphere in different domains of electromagnetic spectrum

Longair, 1992



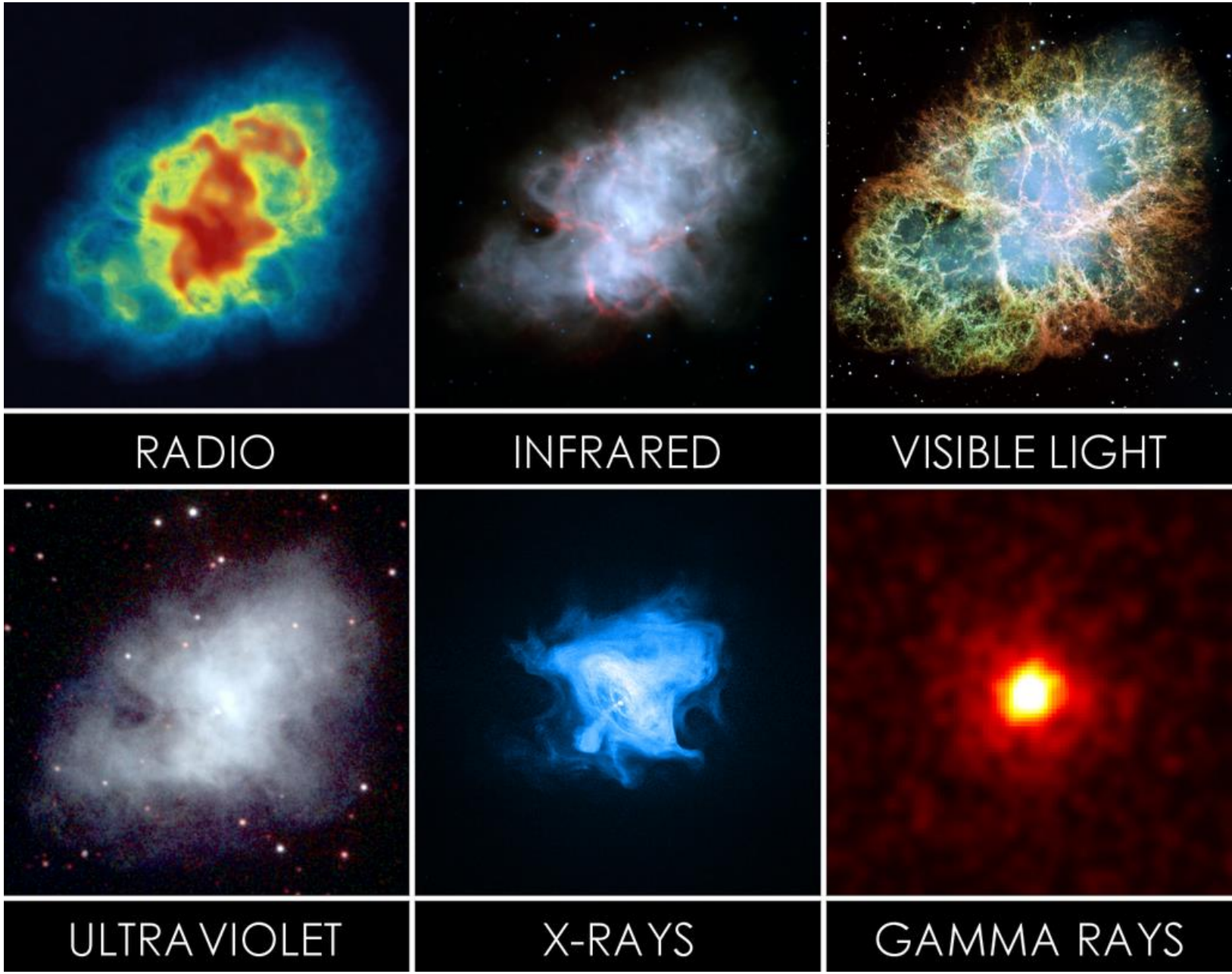


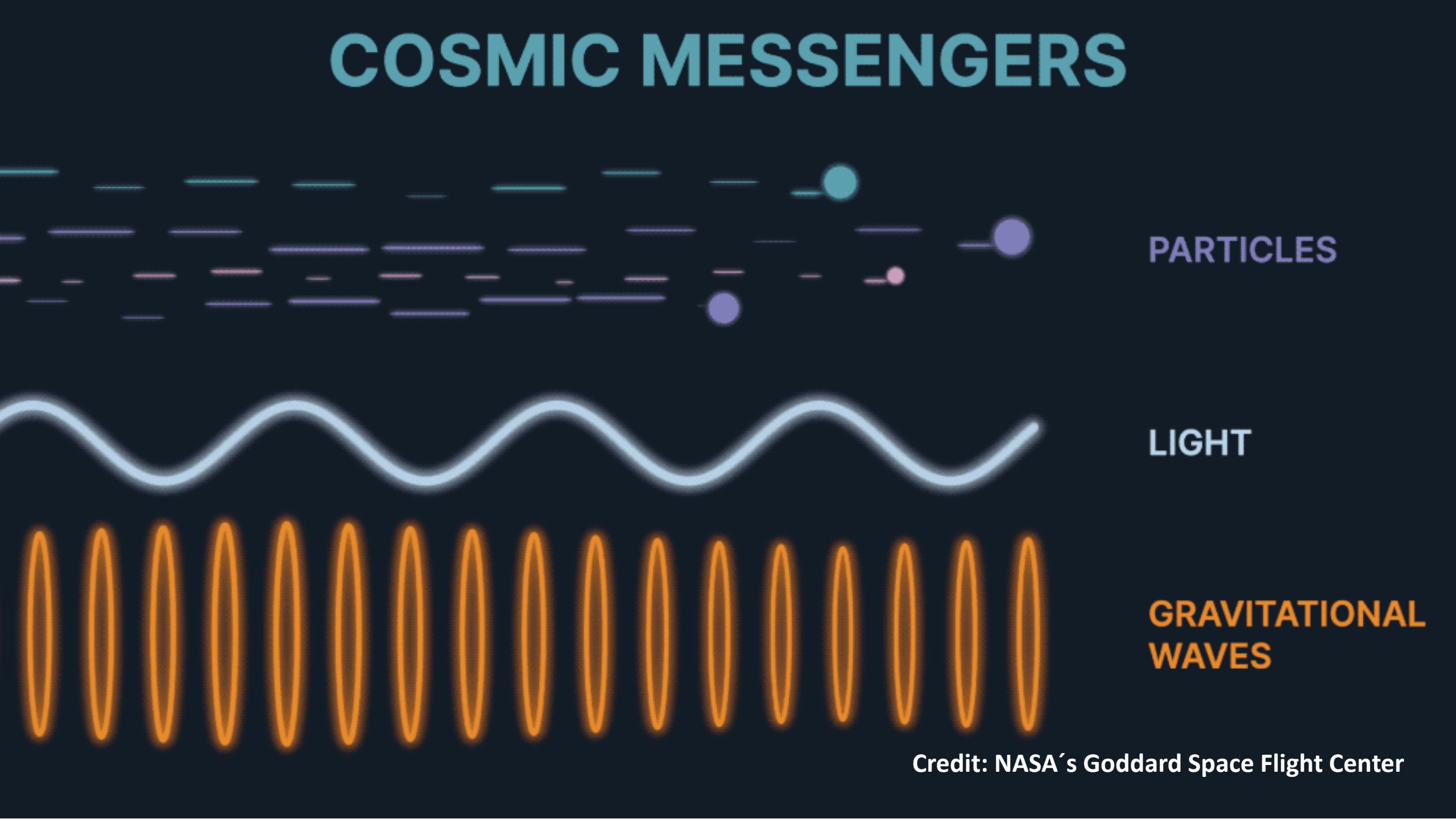
Barbosa, 2022

Crab Nebula (M1, NGC 1952)

Source: Stellarium

- Famous supernova remnant and pulsar wind nebula
- Supernova observed in 1054 C.E.



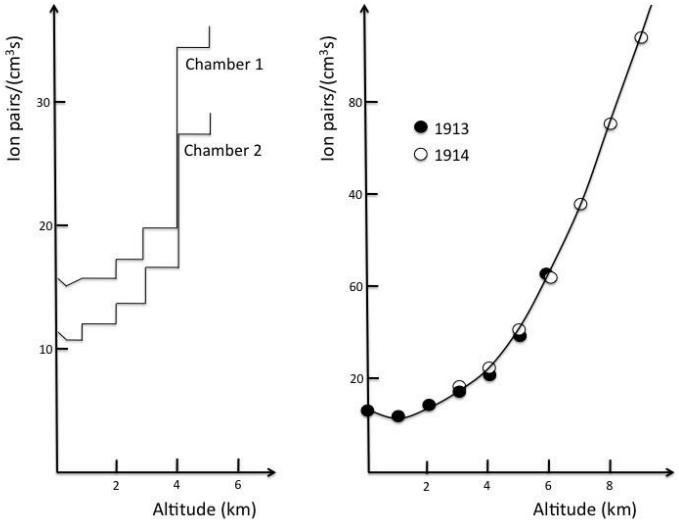


Credit: NASA´s Goddard Space Flight Center

Multimessenger astronomy

- Nowadays, we are capable to observe the Universe also by other types of ‘’messengers’’ beside electromagnetic wavelength

Cosmic rays



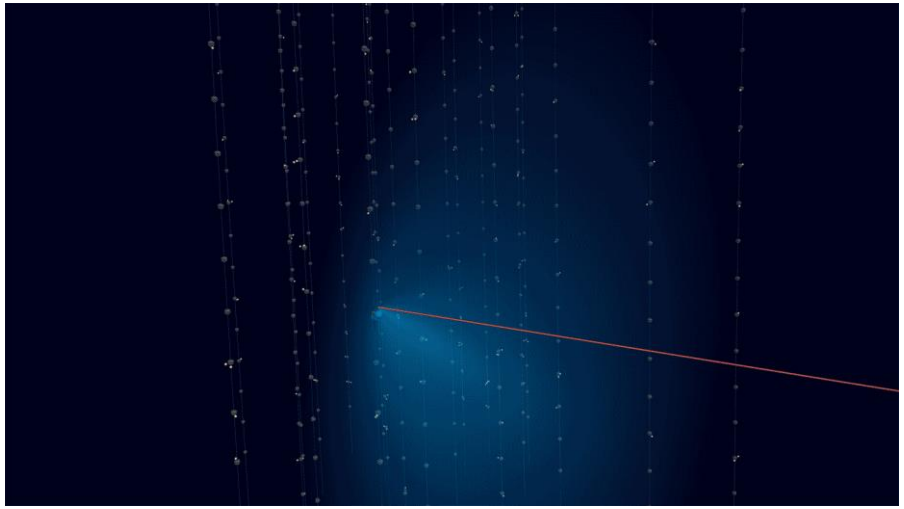
Credit: Alessandro de Angelis

- Discovered in 1912 by Victor F. Hess
- Protons and nuclei reaching ultra-high energies

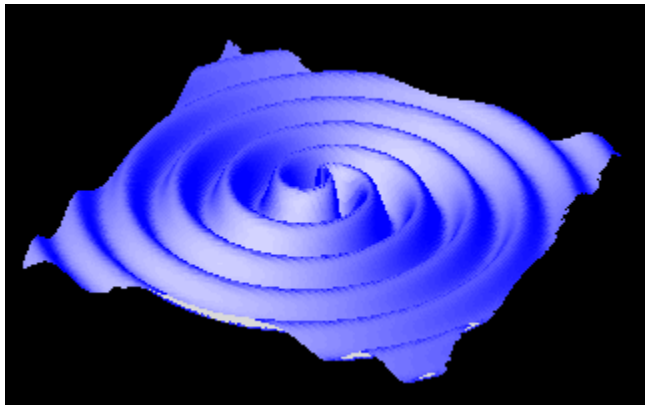
Neutrinos

- Weakly interacting elementary particles
- Existence proposed by Enrico Fermi in 1930
- Discovery in 1956

Credit: KM3NeT

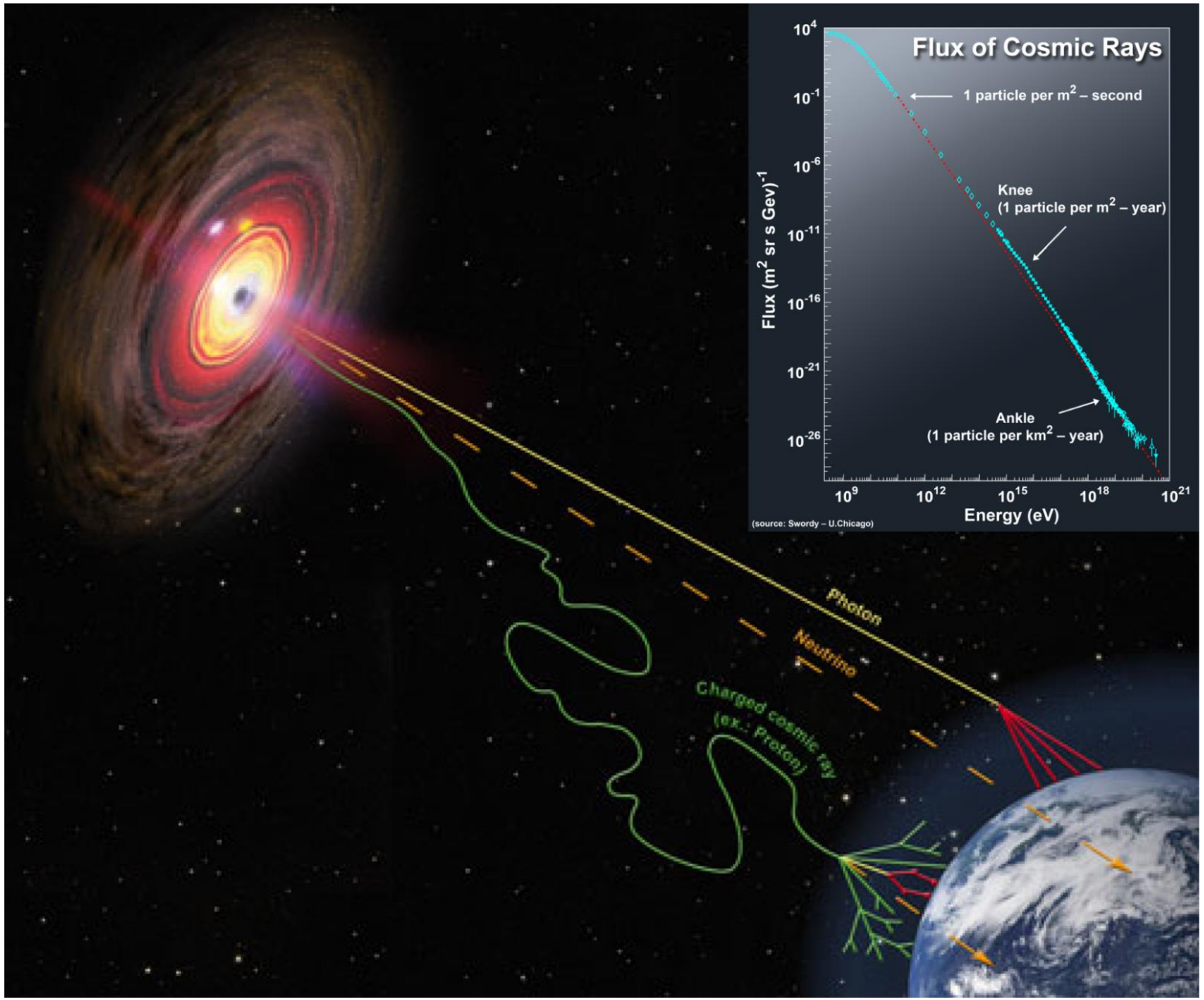


Gravitational waves

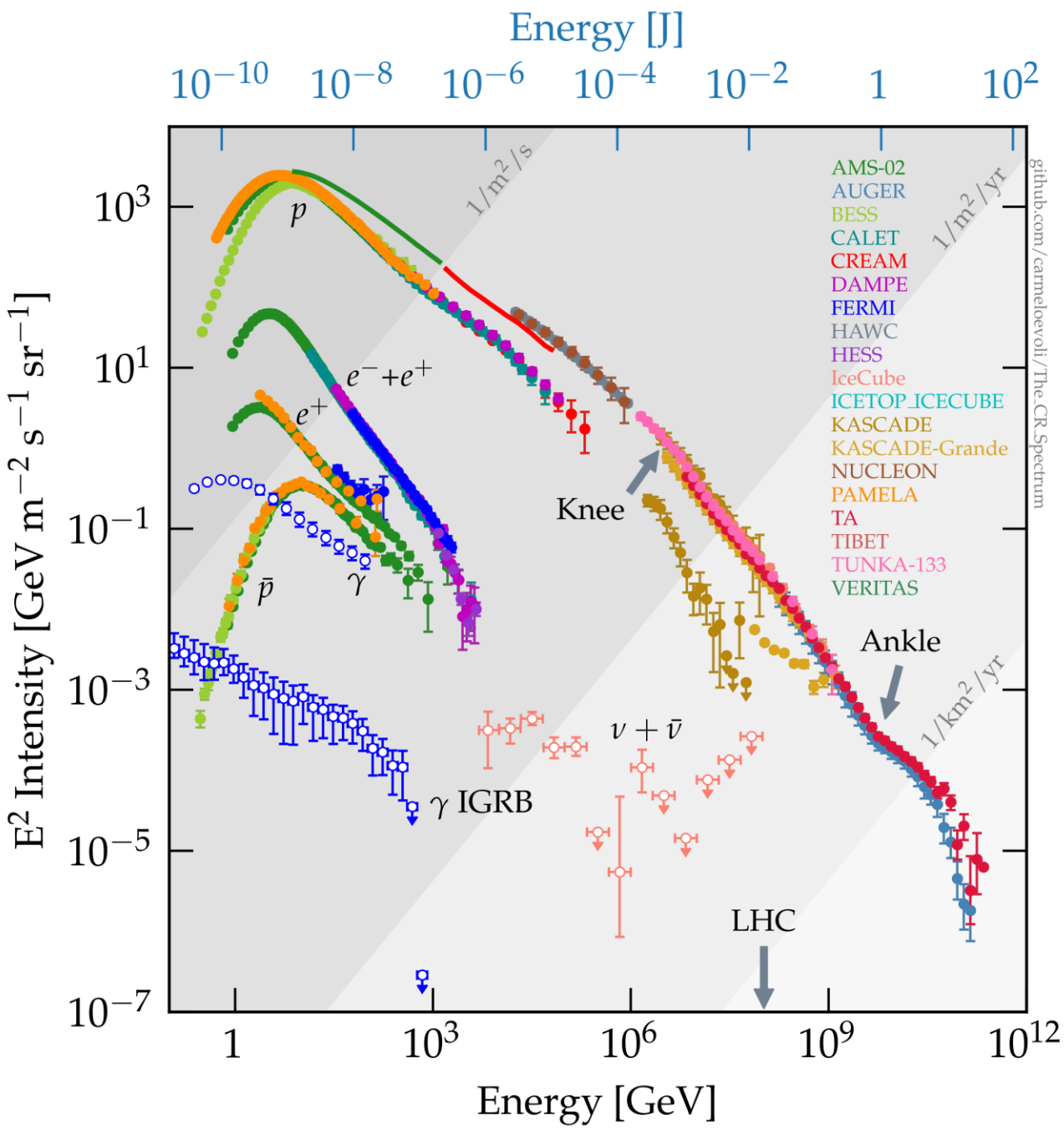


Credit: NASA/JPL

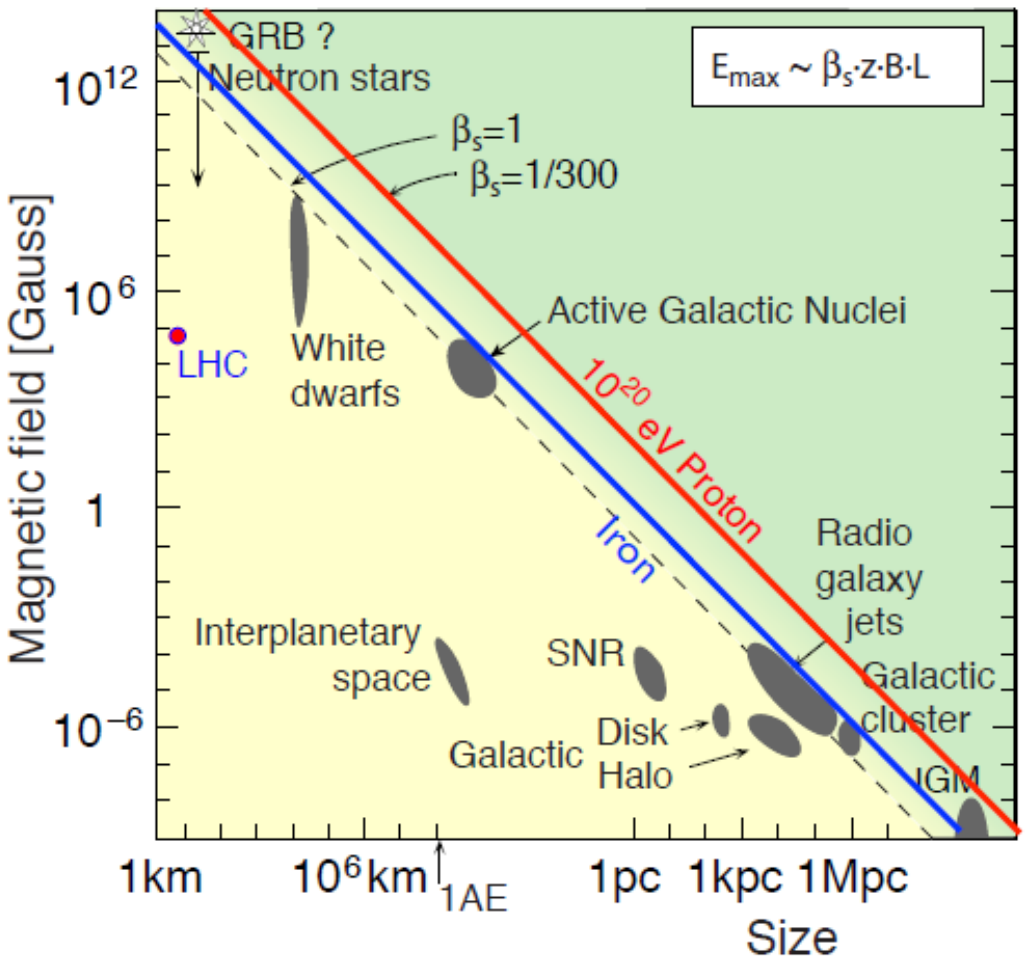
- Oscillations of the space-time generated by relative motion of gravitating masses
- Detected for the first time in 2015



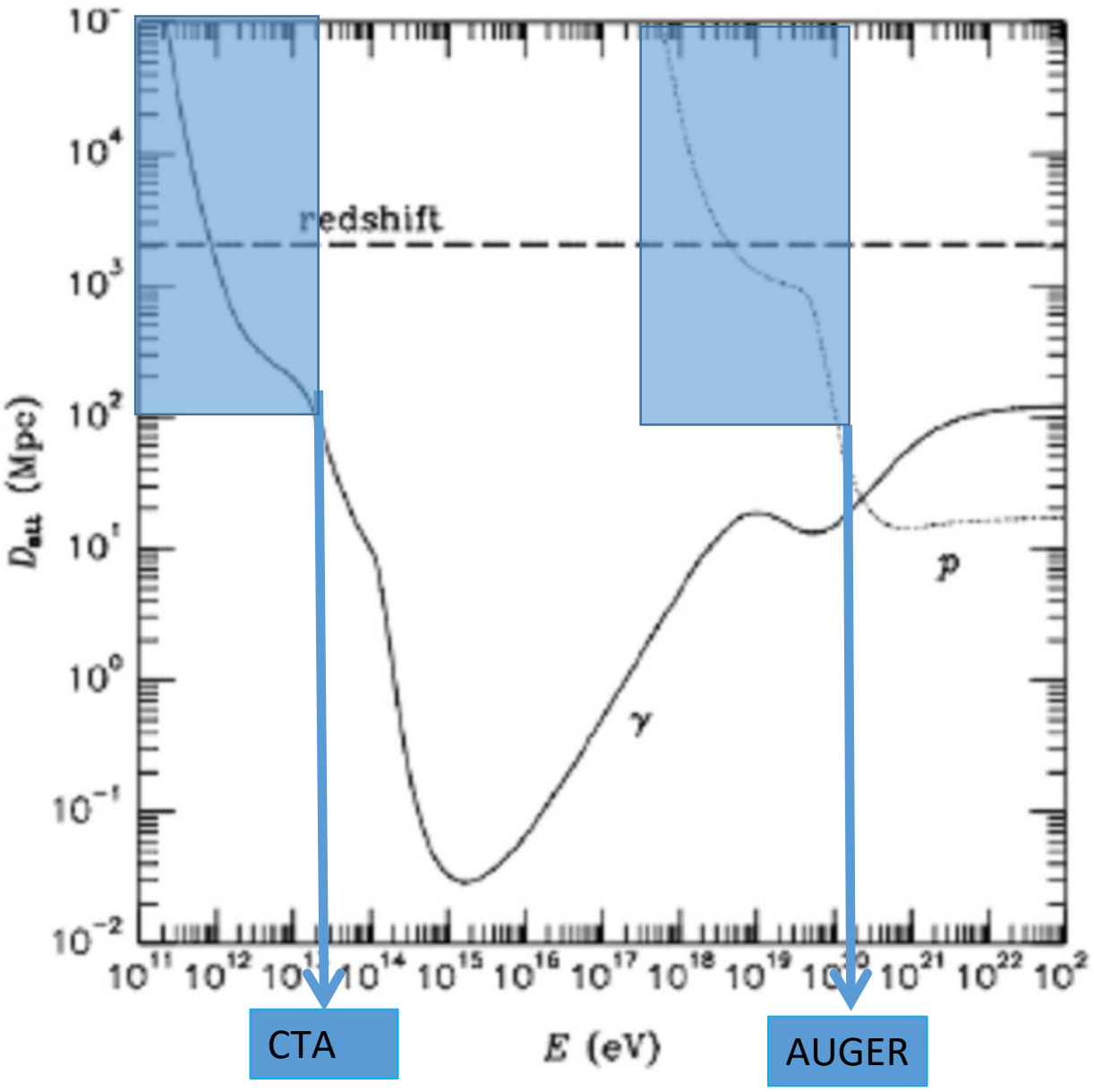
Credit: HAP/A. Chantelauze



[A. M. Hillas 1984]



Evoli, C. (2025). The Cosmic-Ray Energy Spectrum. Zenodo. https://doi.org/10.5281/zenodo.14635074



Pair production:

$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$

Energy threshold ≈ 3 x 10^{14} eV

GZK effect

$p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow n + \pi^+$

$p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow p + \pi^0$

Energy threshold 5 10^{19} eV

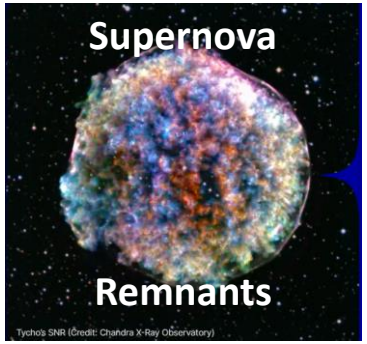
Very-high-energy gamma rays

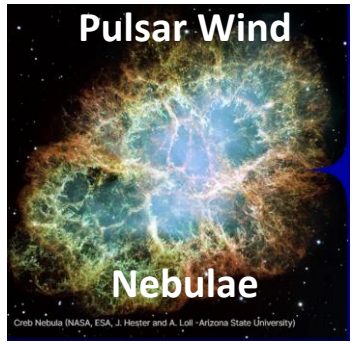
- **Energies**: tens of GeV and more = VHEGR
- **Sources**: non-thermal Universe
  - regions where charged particles are accelerated
  - magnetic fields and shock waves
  - supernova remnants, pulsar wind nebulae, active galactic nuclei ...

- **Objectives**:
  - search for origin of charged cosmic rays
  - study of the processes near neutron stars and black holes
  - search for dark matter signatures
  - study of exotic phenomena (Lorentz inv. violation)
  - study extragalactic background light

Galactic sources

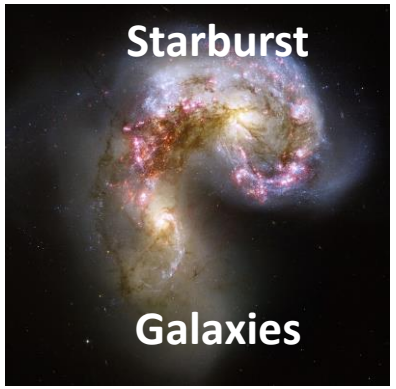
Supernova remnants, microquasars, …



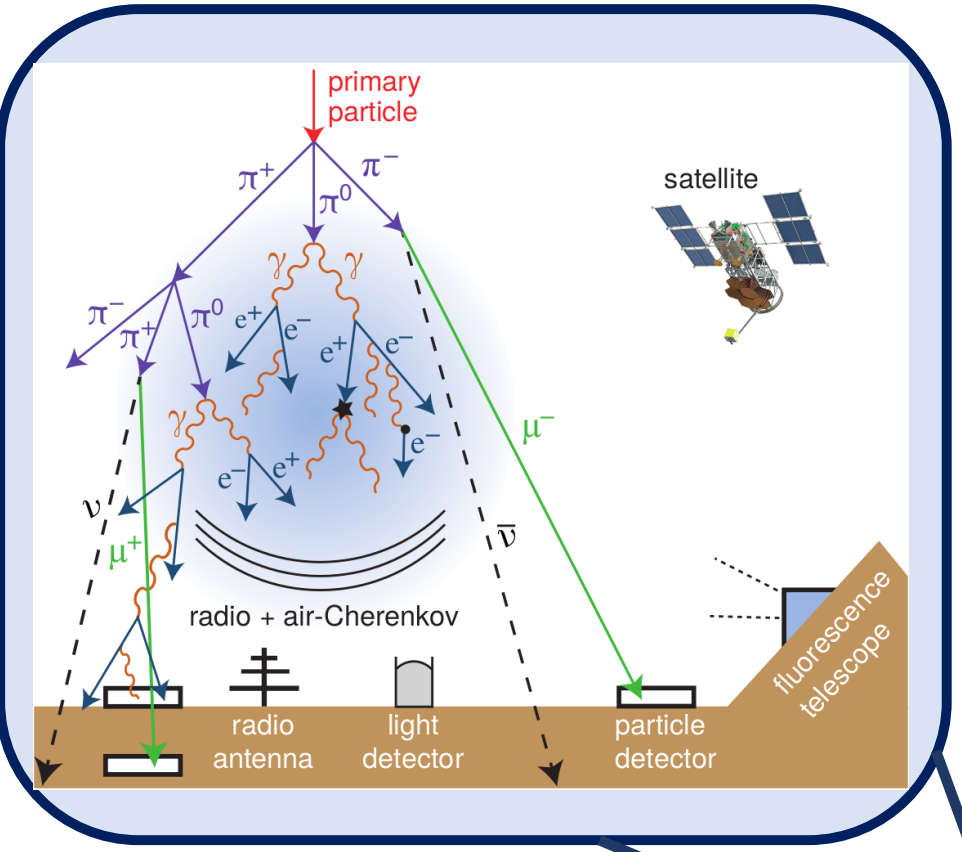


Extragalactic sources

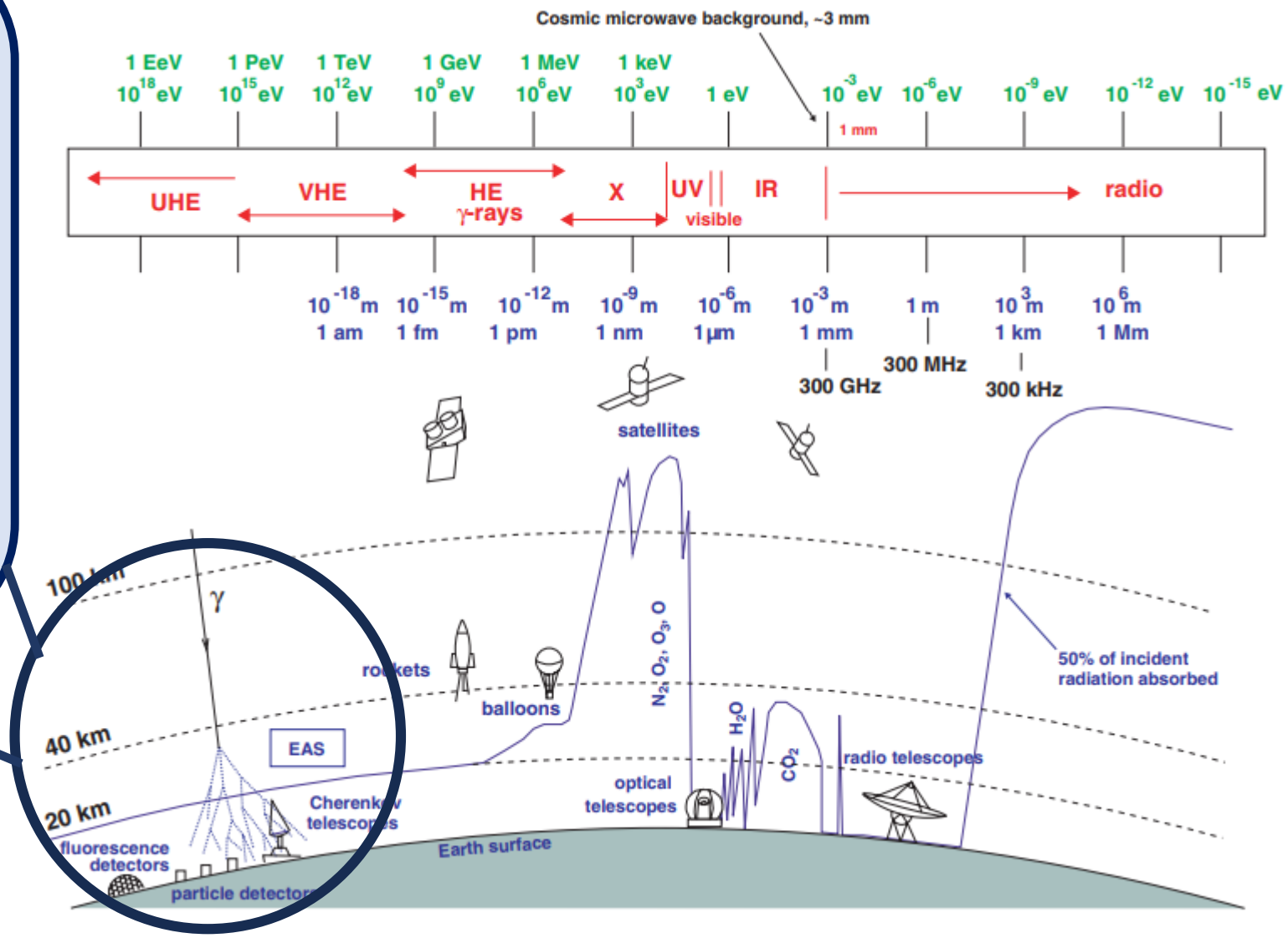
AGNs, neutron star mergers (GRBs), …



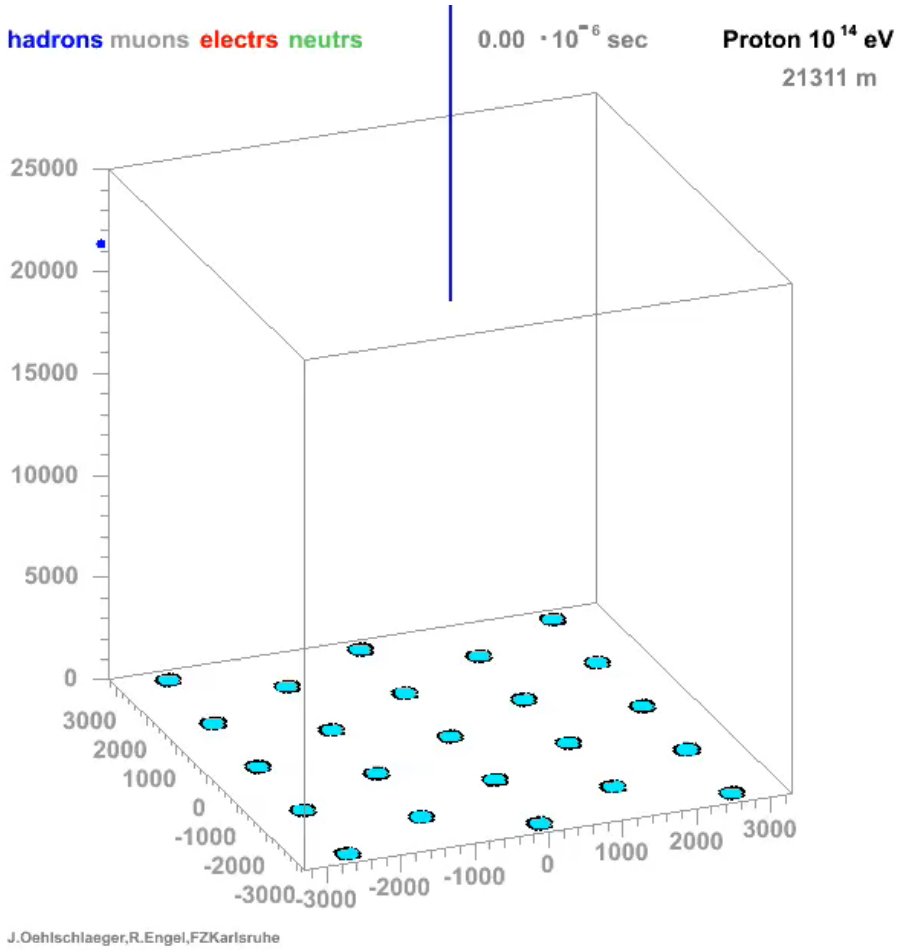
Surface detection techniques

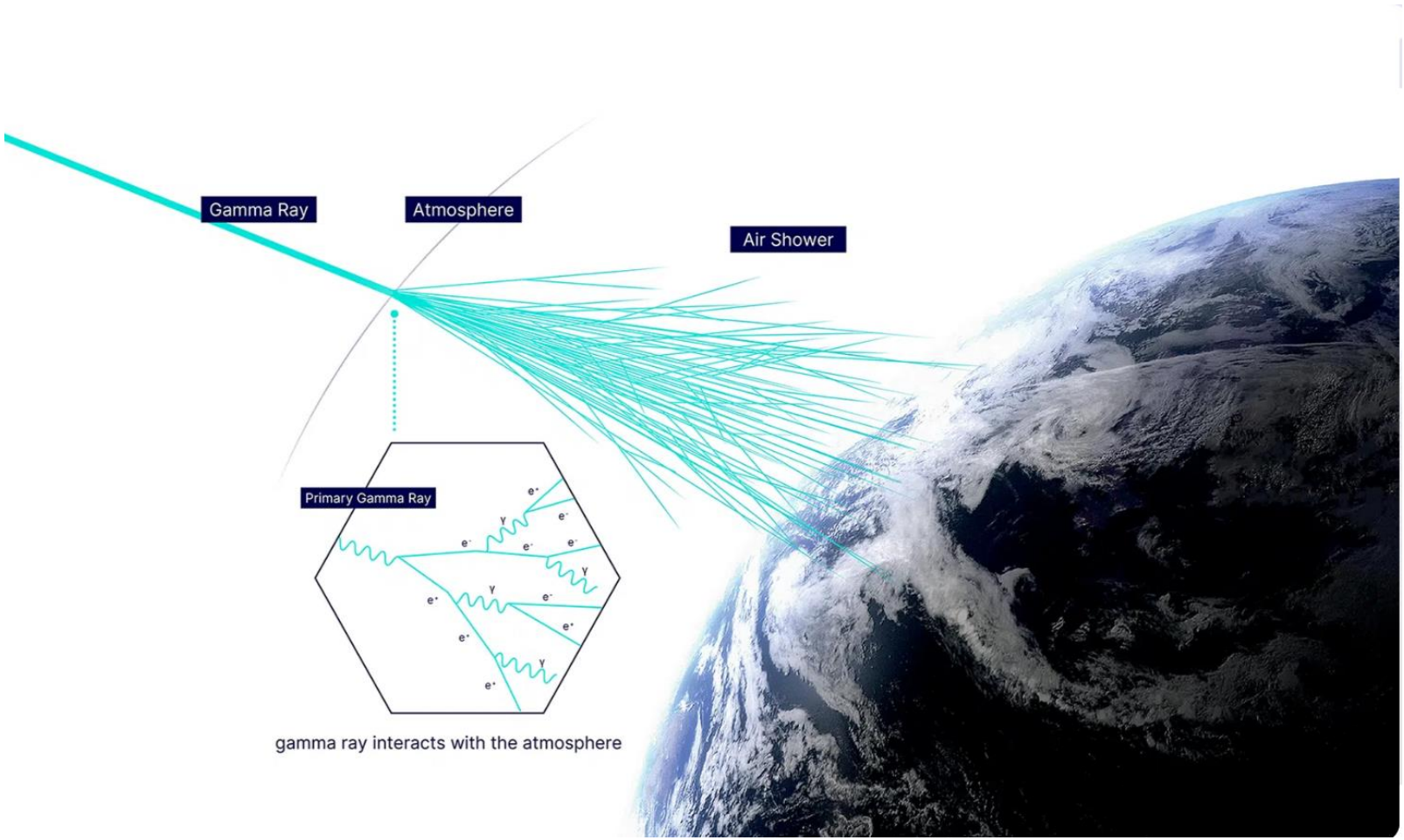


Longair, 1992



Extensive Air Showers





Source: CTAO

Department of Astroparticle Physics, Institute of Physics of the CAS

- Approximately 60 people
- Involvement in major astroparticle-physics projects
  - Pierre Auger Observatory (https://www.auger.org/)
  - Cherenkov Telescope Array Observatory (https://www.ctao.org/)
  - Single-Mirror Small Size Telescope (https://sst-1m.sience/)
  - Southern Wide-field Gamma-ray Observatory (https://www.swgo.org/SWGOWiki/doku.php)
  - Vera C. Rubin Observatory (https://rubinobservatory.org/)
  - Laser Interferometer Space Antenna (https://lisa.nasa.gov/)

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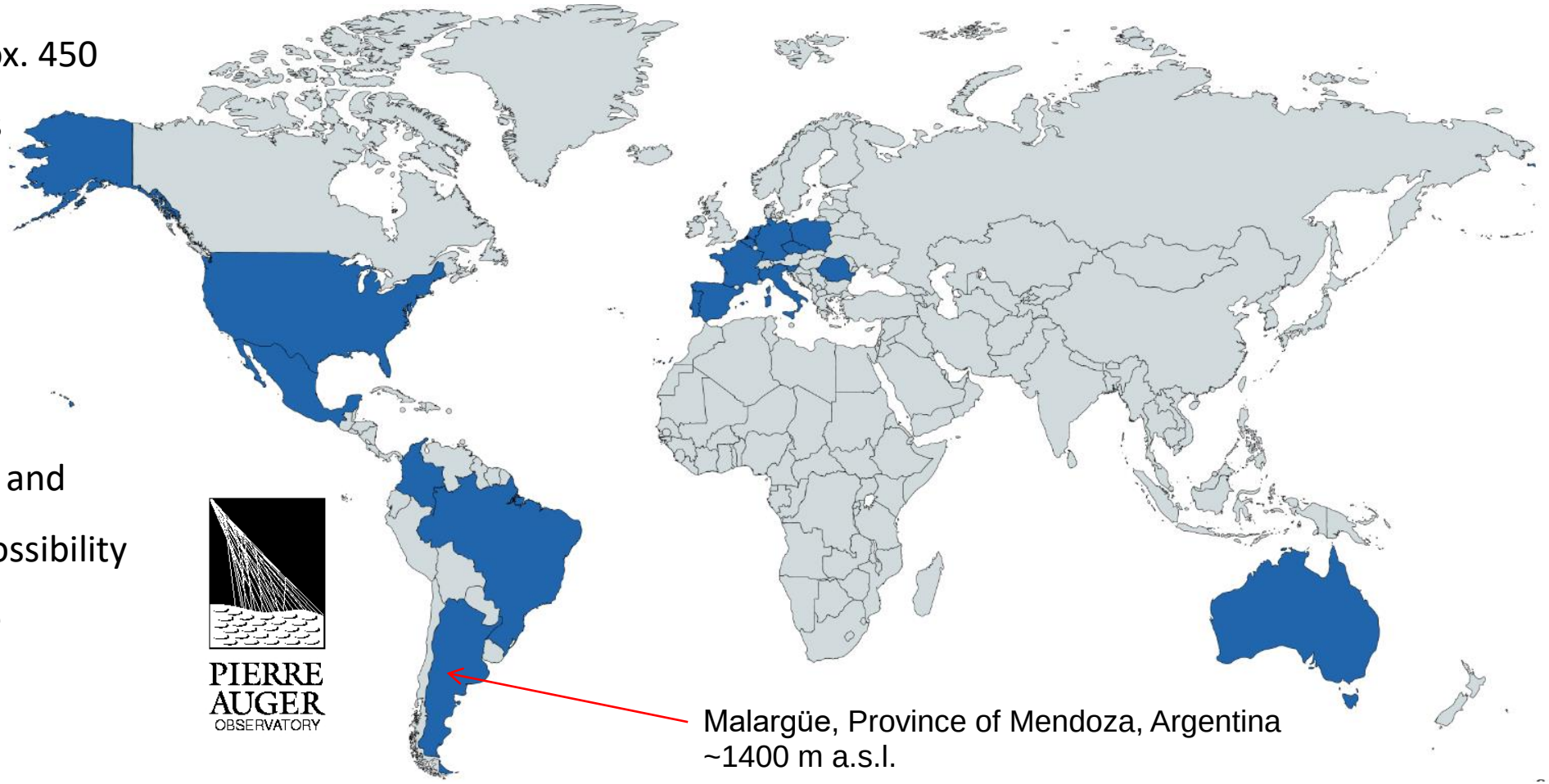
https://www.fzu.cz/en/about-fzu/main-building-na-slovance-site

Pierre Auger Observatory

- Observatory for cosmic-ray detection
- Joint collaboration of approx. 450 scientists from 17 countries

- Operational from 2004
- Uses 2 types of detectors – flurescence detectors (FDs) and surface detectors (SDs) – possibility to observe in stereo regime

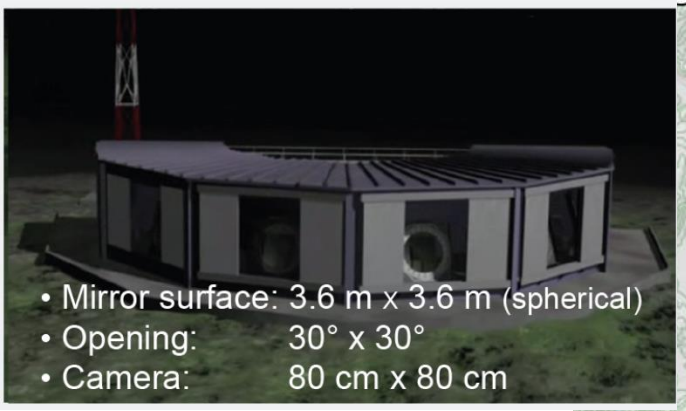


The Pierre Auger Observatory

Source: The Pierre Auger Observatory

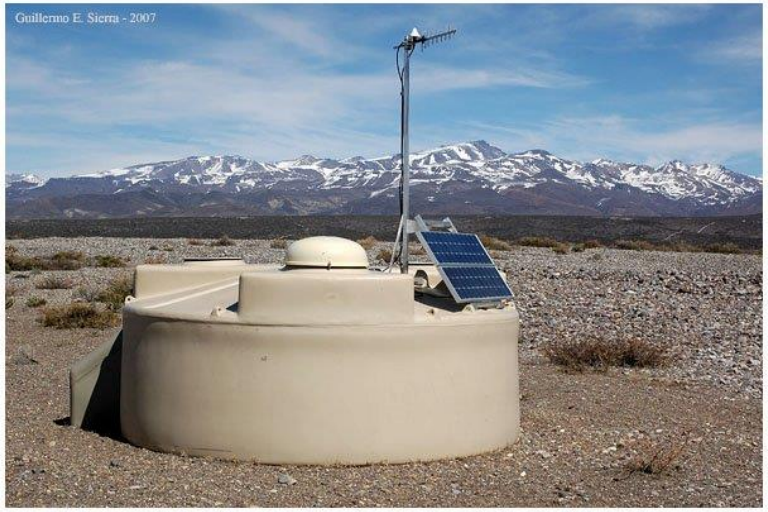
Fluorescence detectors

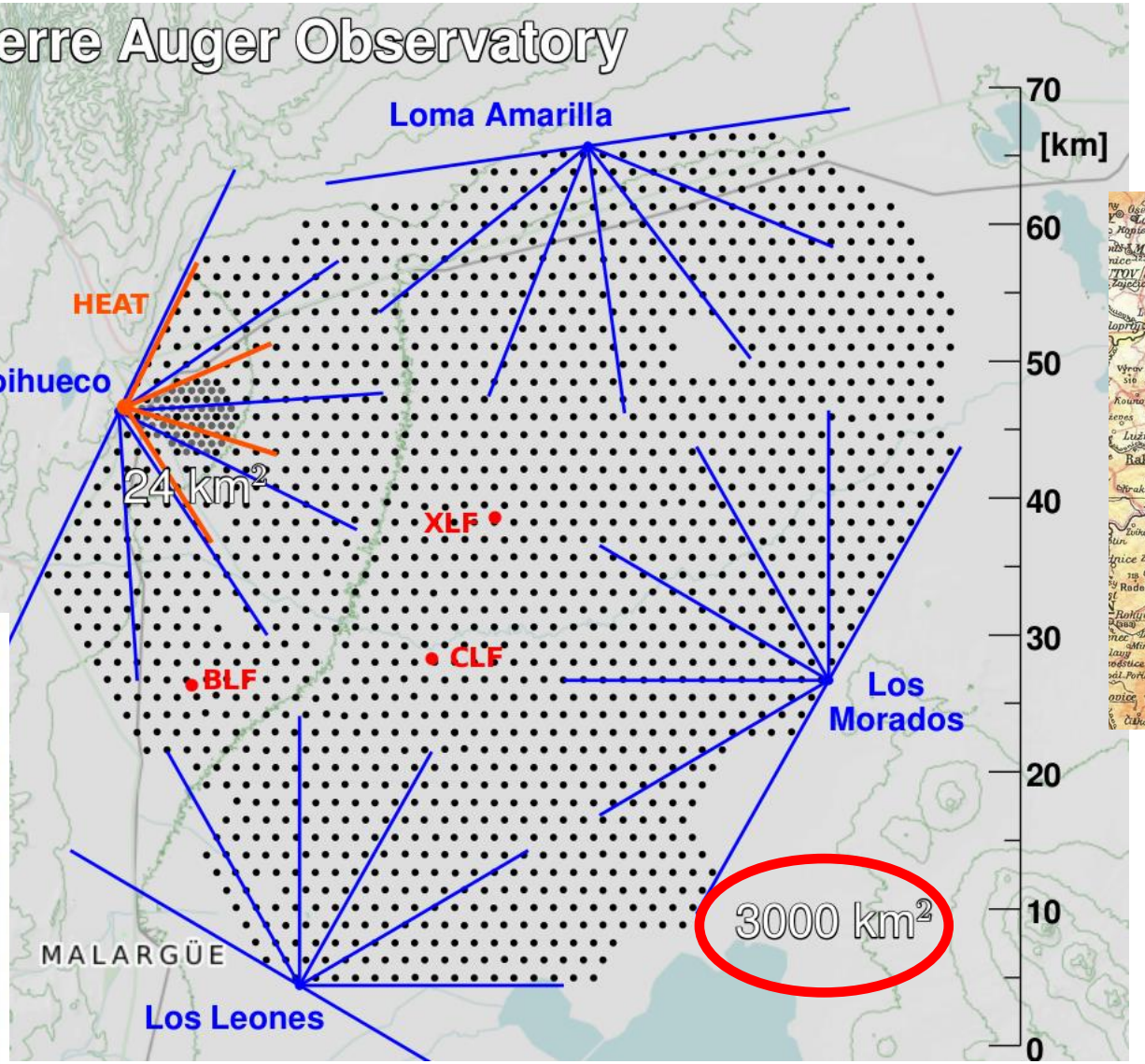
4 sites

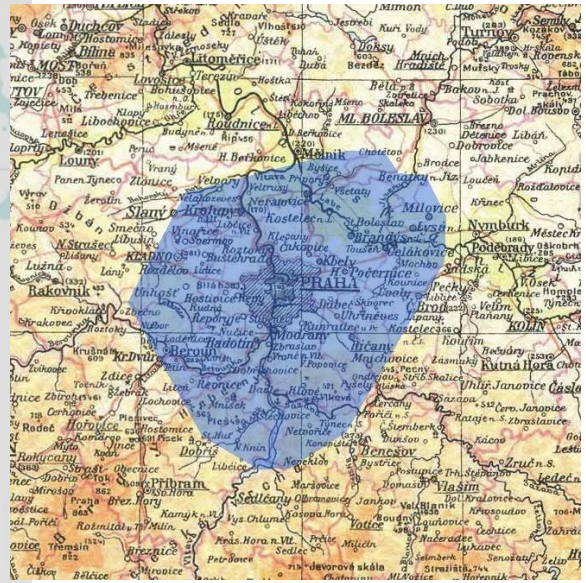


Surface detectors

1660 water Cherenkov tanks

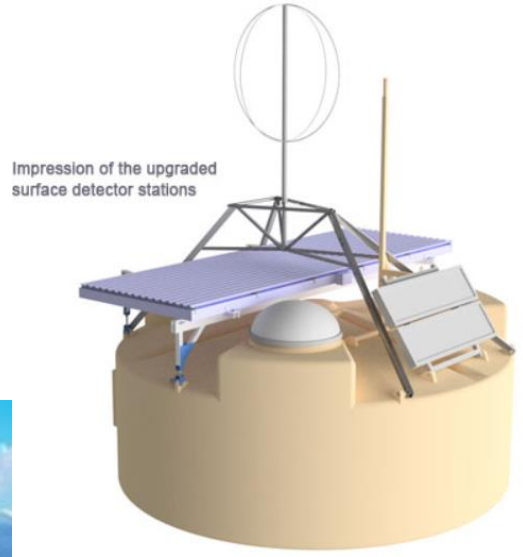




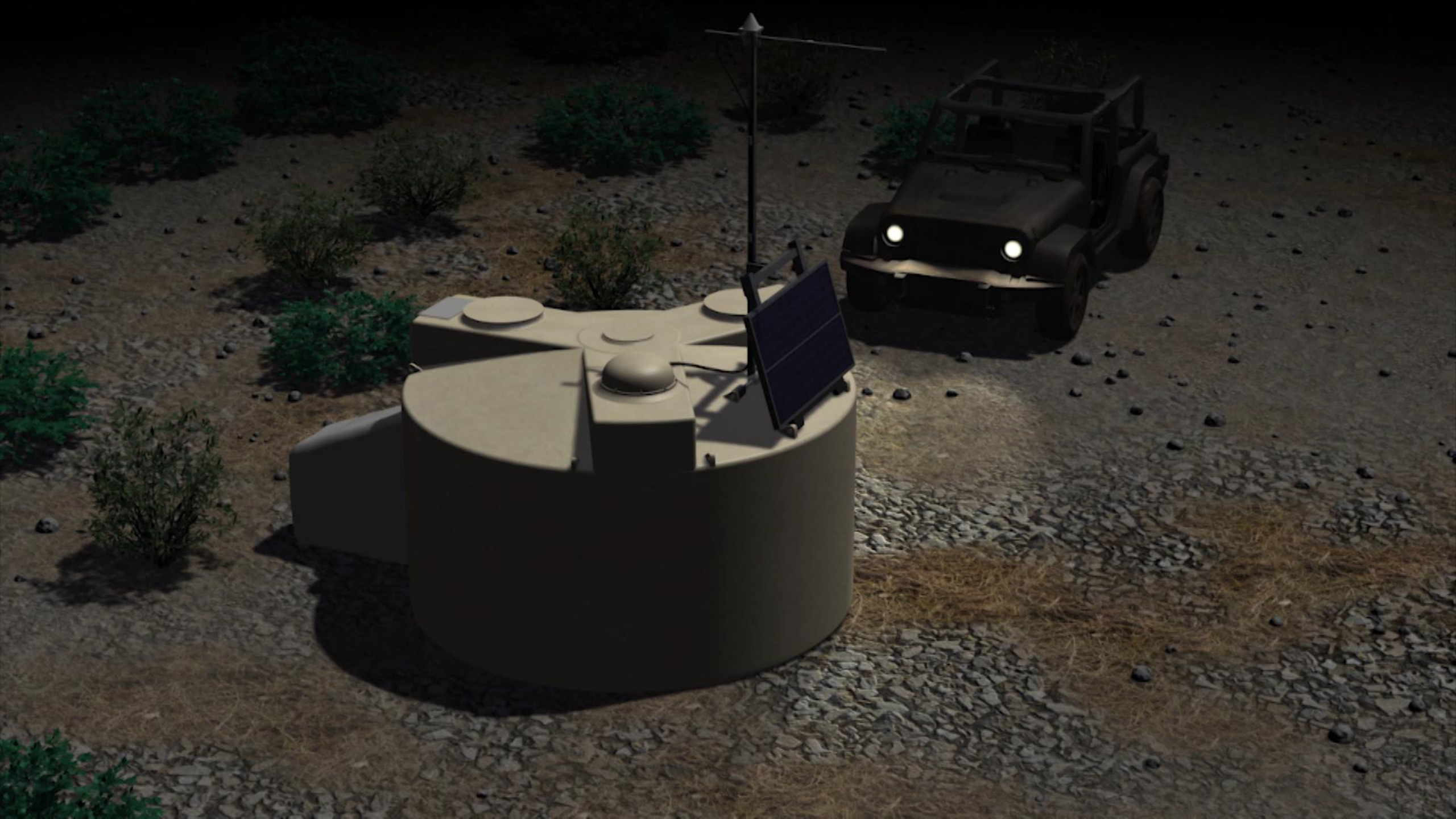


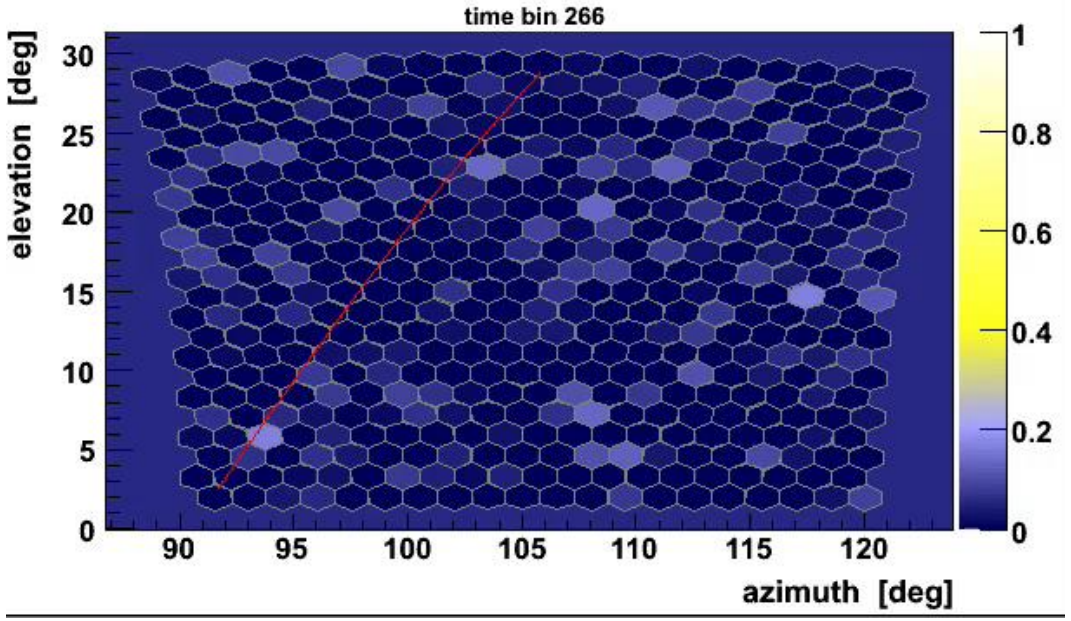
AugerPrime

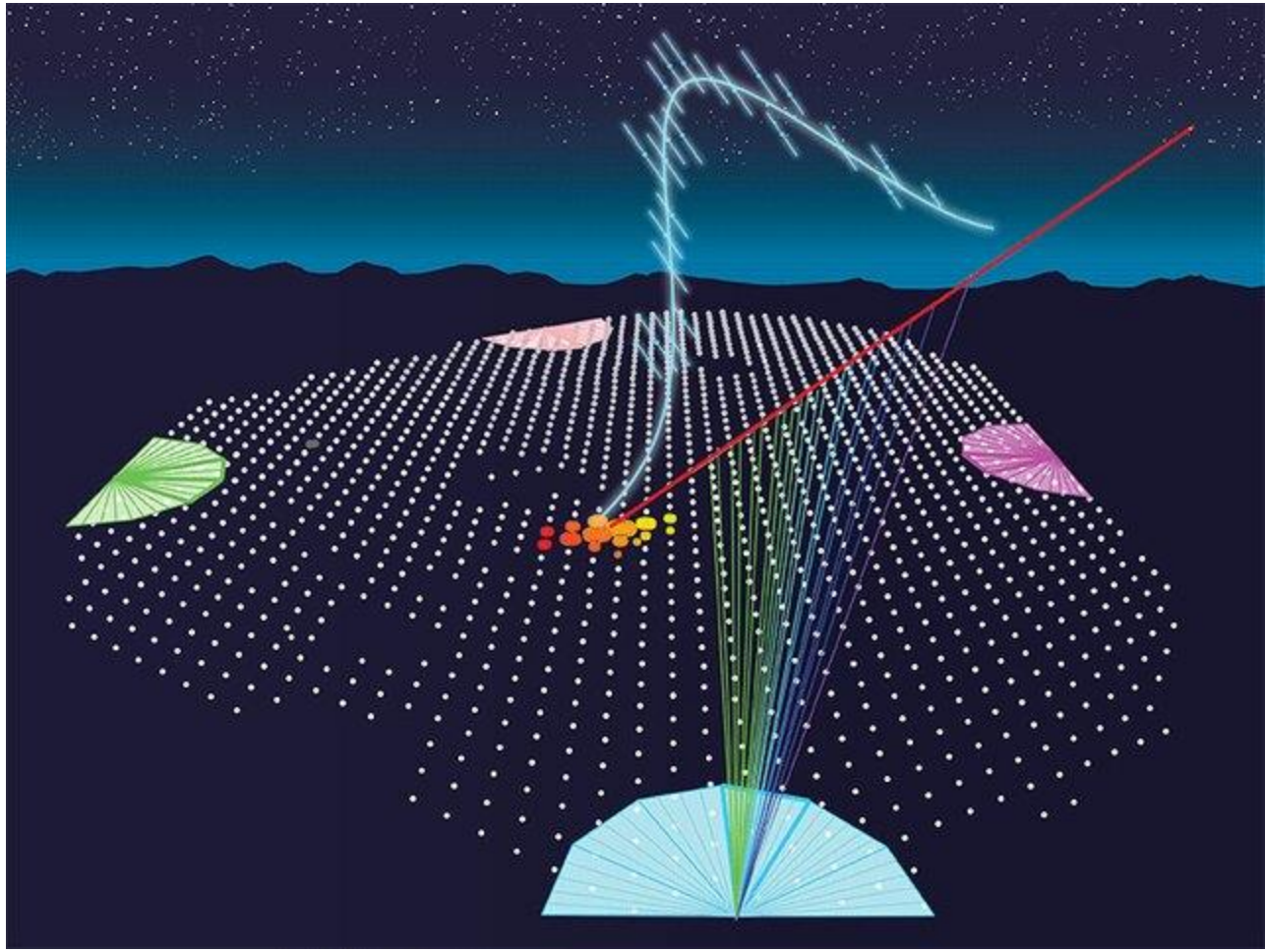
- Observatory upgrade
- Placement of plastic scintillator on top of the tanks (SSD)
- Underground plastic scintillator – AMIGA
- Photomultiplier
- Radio antennas



Source: The Pierre Auger Observatory







APS/Carin Cain, Physics 9, 125 (2016)

The Pierre Auger Observatory Scientific Highlights

Observation of a Large-scale Anisotropy in the Arrival Directions of Cosmic Rays above 8×10^{18} eV
The Pierre Auger Collaboration, Science 357 (2017)
[doi: 10.1126/science.aan4338] [arXiv: 1709.07321]

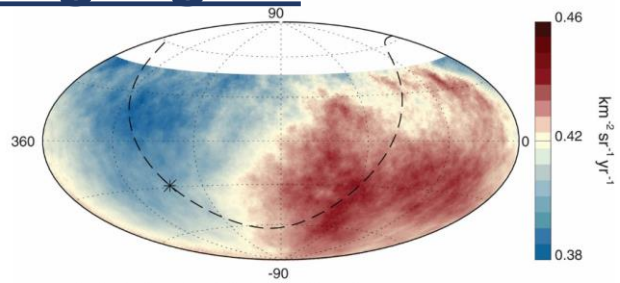


Fig. 2 **Map showing the fluxes of particles in equatorial coordinates.**
Sky map in equatorial coordinates, using a Hammer projection, showing the cosmic-ray flux above 8 EeV smoothed with a 45° top-hat function. The galactic center is marked with an asterisk; the galactic plane is shown by a dashed line.

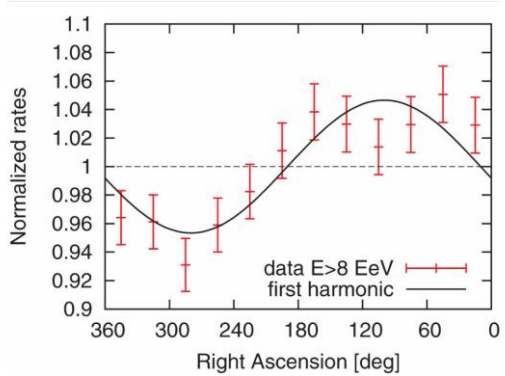
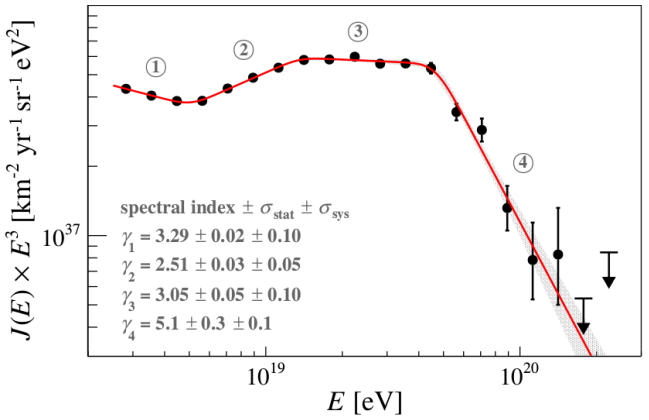


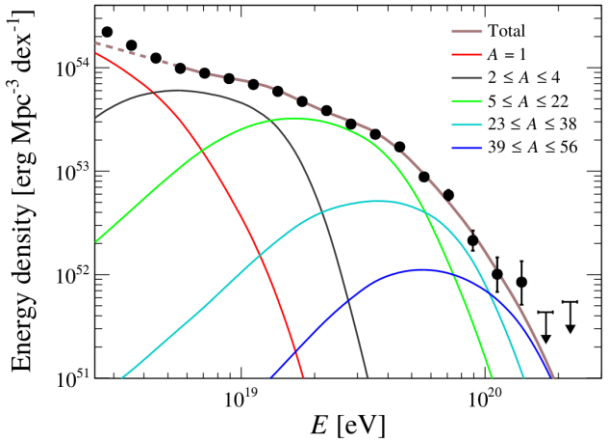
Fig. 1 **Normalized rate of events as a function of right ascension.**
Normalized rate for 32,187 events with $E \geq 8$ EeV, as a function of right ascension (integrated in declination). Error bars are 1σ uncertainties. The solid line shows the first-harmonic modulation from Table 1, which displays good agreement with the data ($\chi^2/n = 10.5/10$); the dashed line shows a constant function.

New feature in the energy spectrum

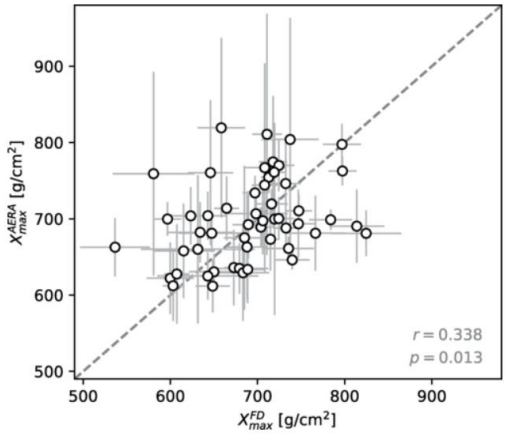
Phys. Rev. Lett. 125 (2020) 121106

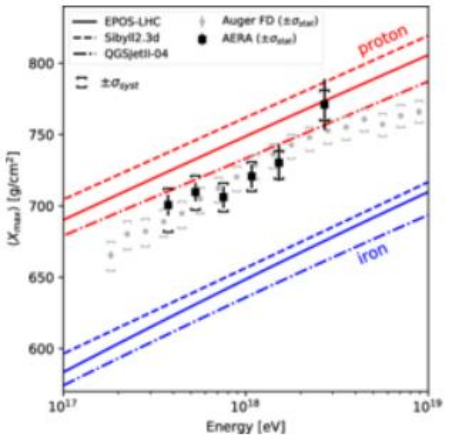
Phys. Rev. D 102 (2020) 062005





Radio Measurements of the Depths of Air Shower Maxima at the Pierre Auger Observatory
The Pierre Auger Collaboration, Phys. Rev. D 109 (2024) 022002
(sibling of a PRL)
[arxiv.org/abs/2310.19966] [doi: 10.1103/PhysRevD.109.022002]





The Pierre Auger Observatory Open Data

- In 2007 – 1% of data publicly available, 100% of space-weather information
- In 2021 – portal was released containing 10% of cosmic-ray data collected from 2004 to 2018
- In 2023 – catalog of 100 highest-energy cosmic-ray events detected between 2004 and 2020
- In June 2023 – approved the increase of the fraction of released cosmic-ray data to 30%

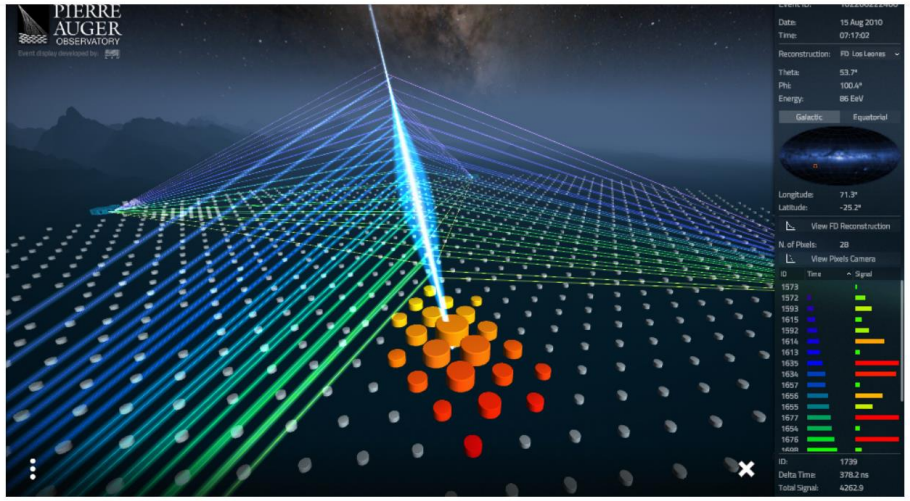


Figure 1: The highest energy multi-eye hybrid event in the UHECR catalog, PAO100815 (id 102266222400): the reconstructed zenith angle is 54° , the energy 82 EeV. It triggered 22 stations of the surface detector and four fluorescence detectors.

The Pierre Auger Collaboration. (2024). Pierre Auger Observatory Open Data (Version 3) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.10488964

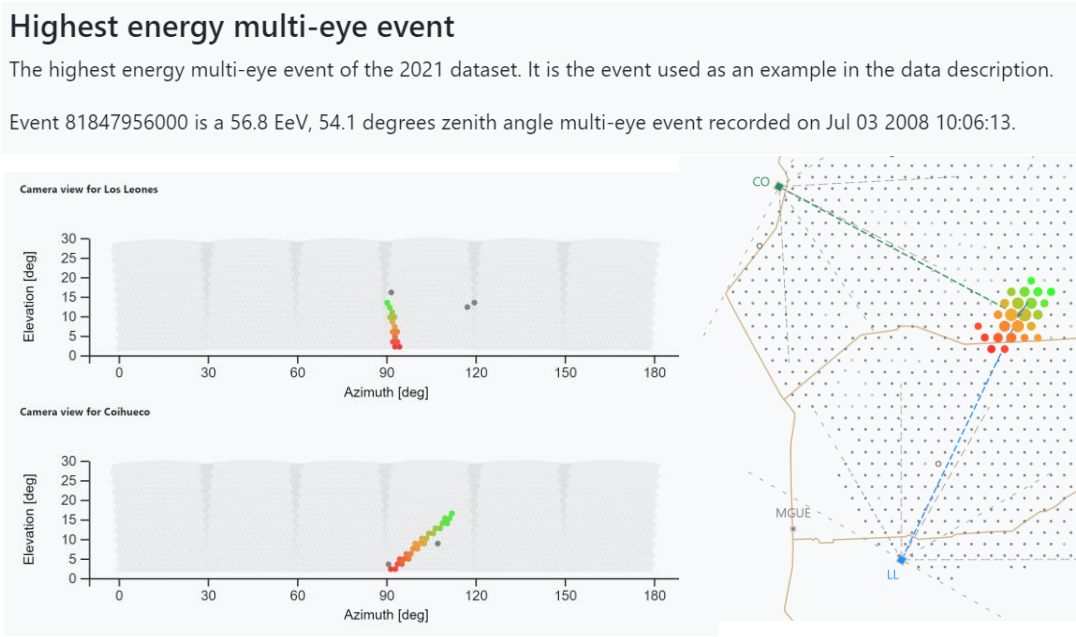
The Pierre Auger Observatory Open Data
The Pierre Auger Collaboration, Eur. Phys. J. C 85 (2025) 70 [https://arxiv.org/abs/2309.16294] [doi: 10.1140/epjc/s10052-024-13560-5]

A Catalog of the Highest-Energy Cosmic Rays recorded during Phase I of Operation of the Pierre Auger Observatory
The Pierre Auger Collaboration, Astrophys. J., Suppl. Ser. 264 (2023) 50
[arxiv.org/abs/2211.16020] [doi: 10.3847/1538-4365/aca537]

The Pierre Auger Observatory Open Data

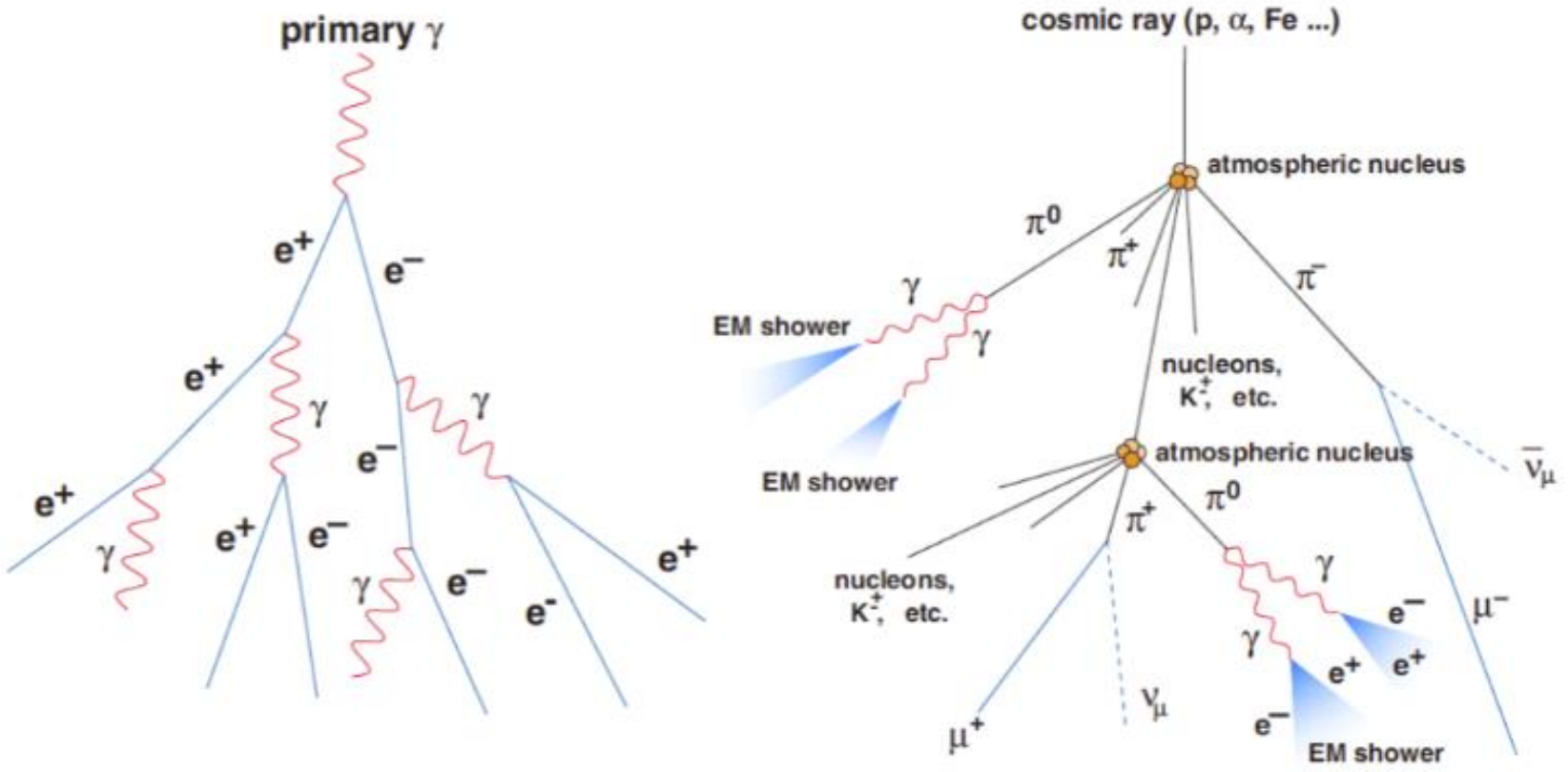
DATA:

Level 1 Open-access publication with additional numerical data provided to facilitate re-use;
Level 2 Regular release of cosmic-ray data in a simplified format, for education and outreach. This began in 2007 when 1% of the data was released and increased to 10% in 2019; increase to 50% under intensive discussion
Level 3 Release of reconstructed cosmic-ray events, selected with the best available knowledge of the detector performance and conditions at the time of data-taking. Example codes derived from those used by the Collaboration for published analyses are also provided;
Level 4 Release of close-to-raw data associated with those events.
An event-display, and codes to read these data, are also provided.

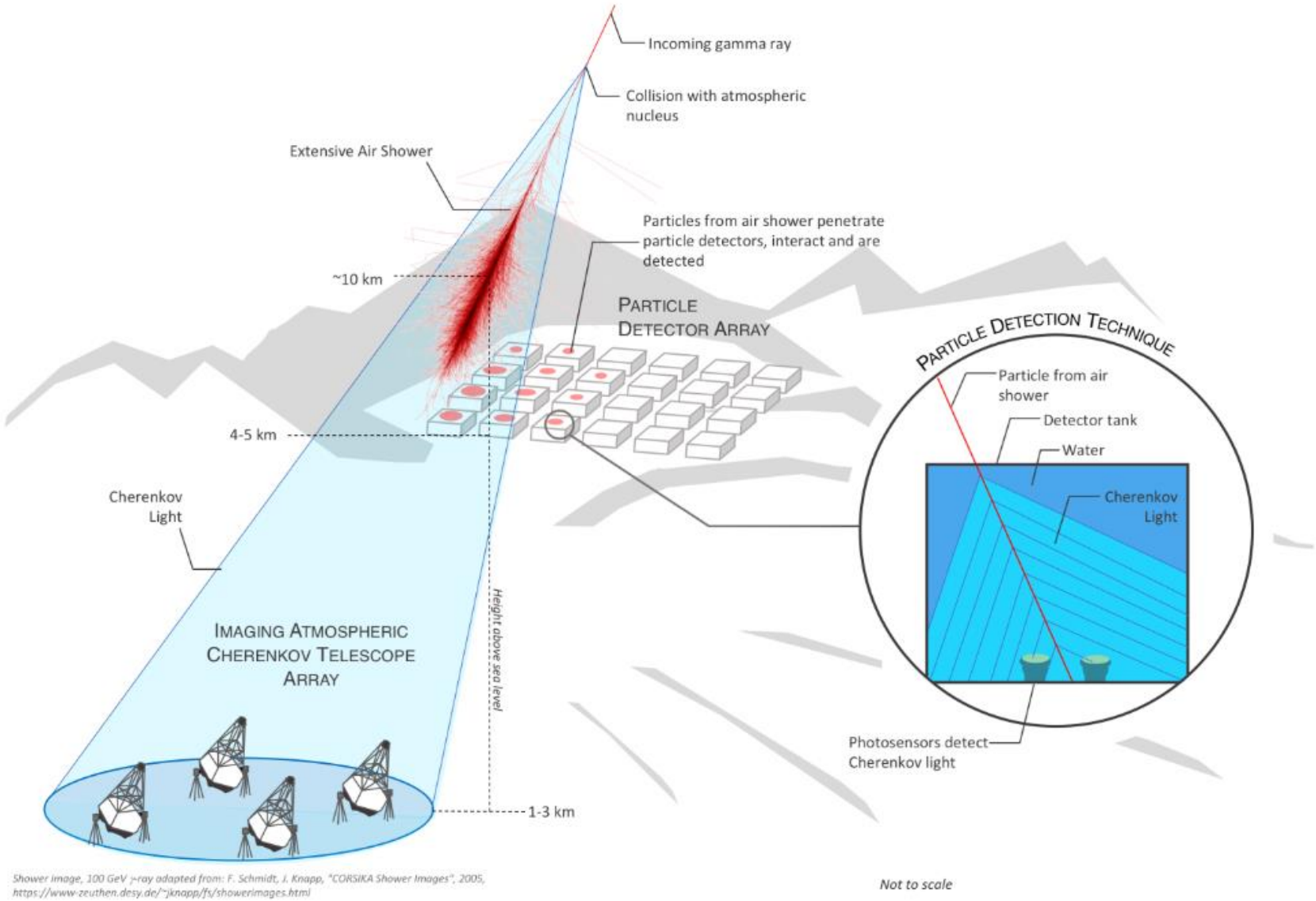


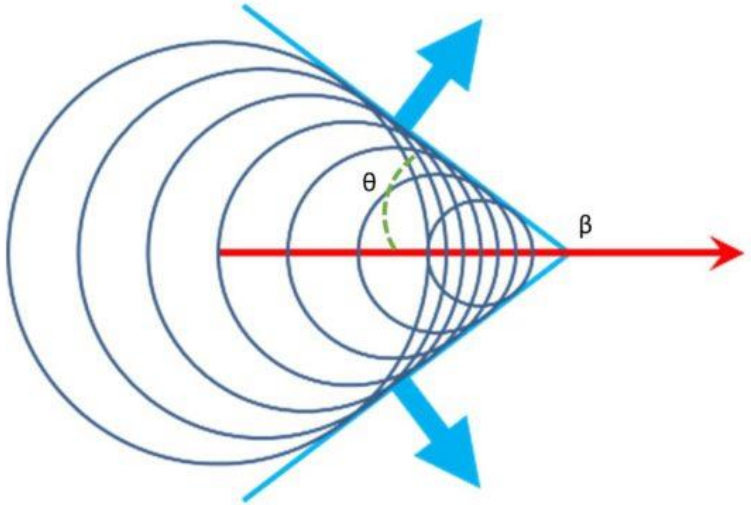
ACESS TO OBSERVATORY:

Negotiable services to experts from other fields, such as geophysics and atmospheric physics (interest also from CZ institutes)


primary γ
e+
e−
e+
γ
e+
e−
γ
γ
e−
e+
e−
γ
e−
e-
e+
cosmic ray (p, α, Fe ...)
atmospheric nucleus
π0
π+
π−
γ
EM shower
γ
nucleons,
K±, etc.
atmospheric nucleus
EM shower
ν̄μ
π0
π+
nucleons,
K±, etc.
γ
e−
μ−
γ
e+
e+
νμ
e−
μ+
EM shower

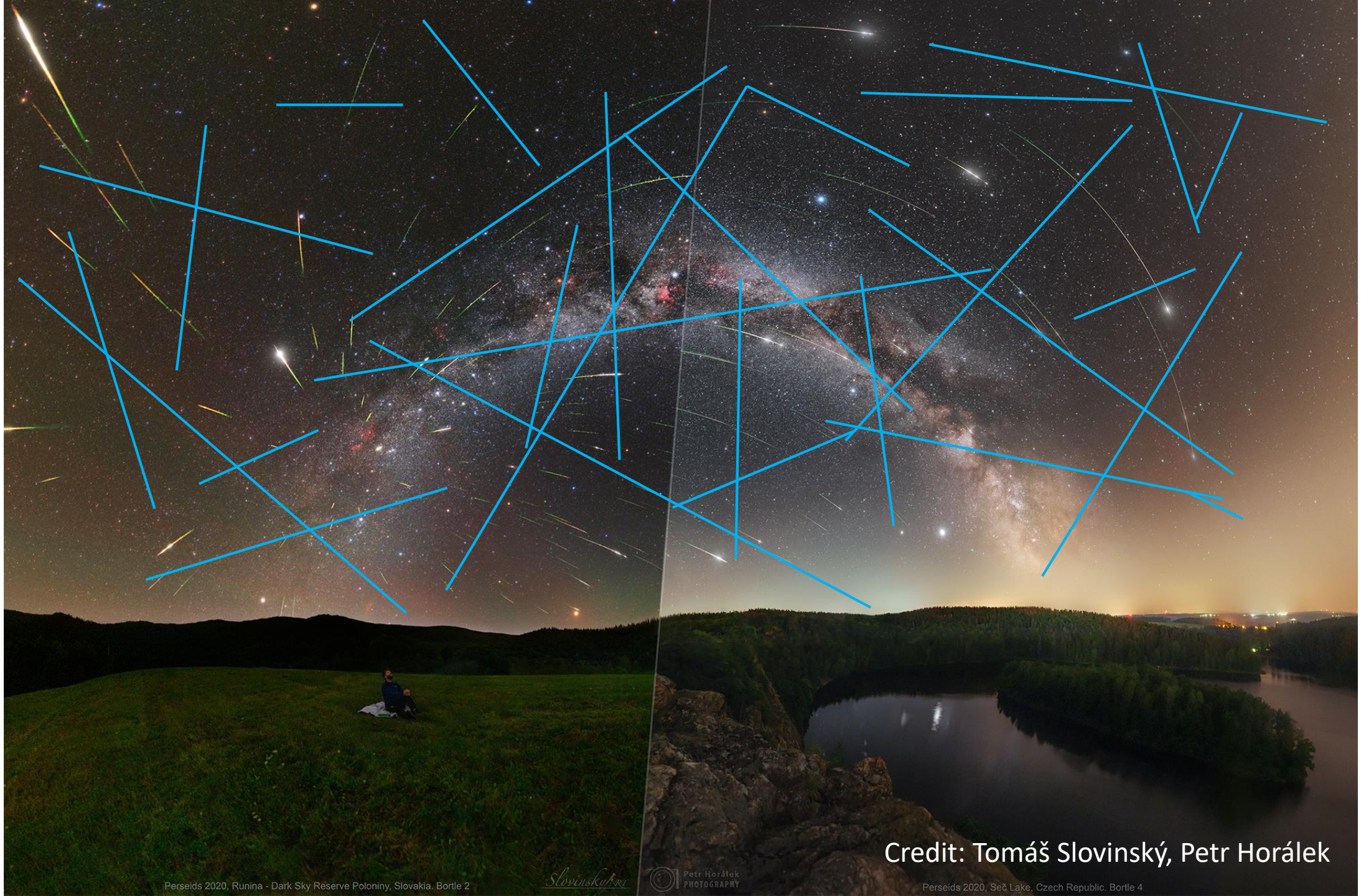
Barral, 2017



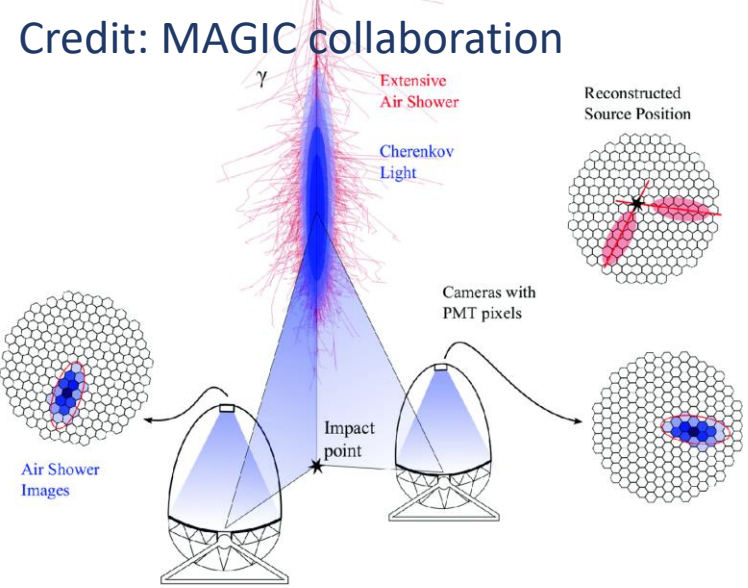


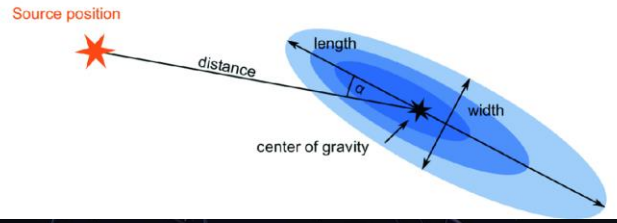
Credit: The University of Sheffield

Illustration of the complementary detection techniques of high-energy gamma rays on ground. (Credit: Richard White, MPIK)


Perseids 2020, Runina - Dark Sky Reserve Poloniny, Slovakia. Bortle 2
Slovinskyfoto
Petr Horálek
PHOTOGRAPHY
Perseids 2020, Seč Lake, Czech Republic. Bortle 4
Credit: Tomáš Slovinský, Petr Horálek

Credit: MAGIC collaboration

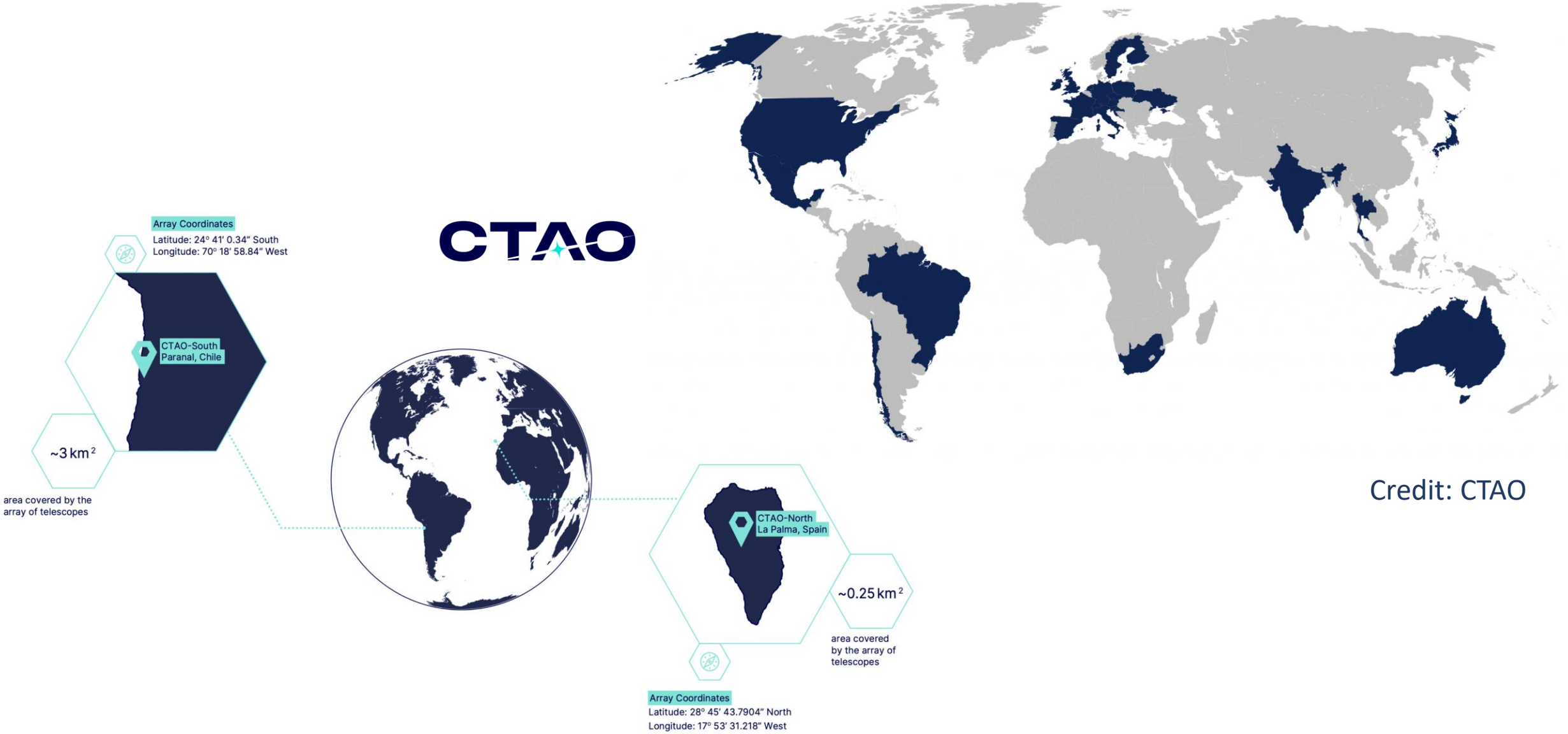




- **Reflective telescopes** on Alt-Az mounts – first in 1980s Whipple telescope
- Sensitive camera photo-detection plane composed of an array of silicon photomultipliers
- Parametrisation of the shower image – **Hillas parameters** (Hillas, 1985)
- For multiple telescopes possibility to operate in **stereo regime** – improvement of **γ/hadron separation, direction reconstruction** and **energy reconstruction**

Credit: CTAO

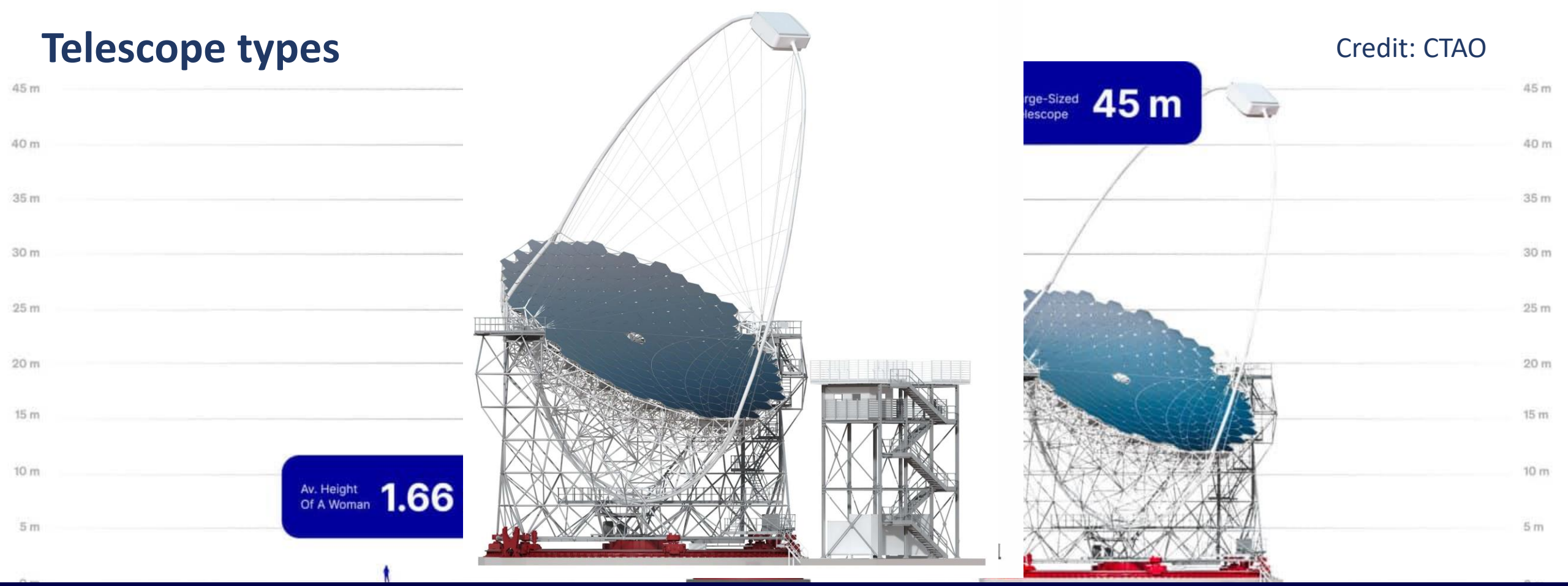
Cherenkov Telescope Array Observatory



Credit: CTAO

Telescope types

Credit: CTAO



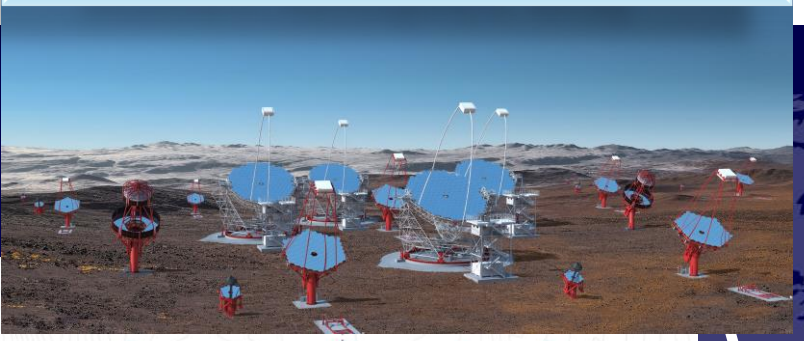
45
height in metres

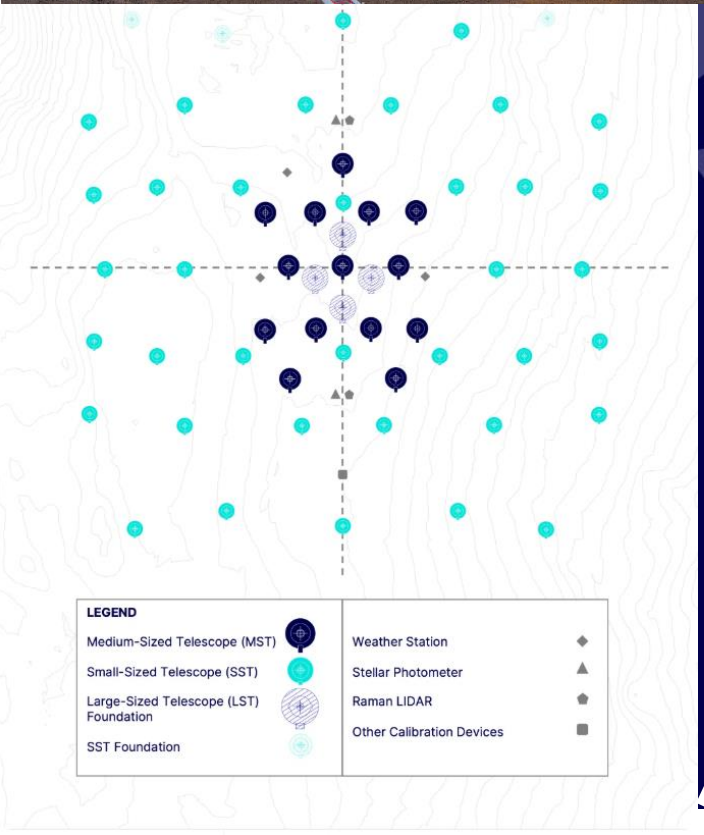
100
est. weight in tonnes

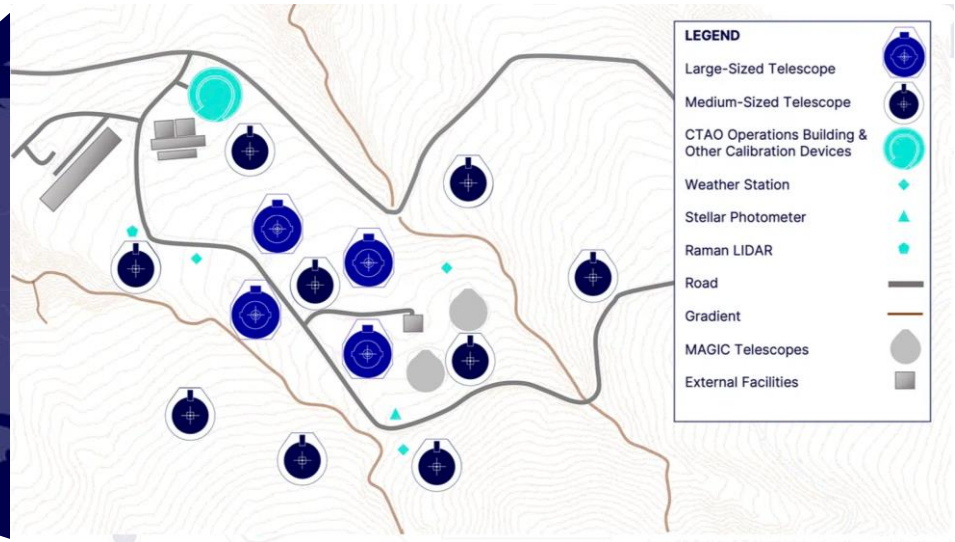
400
reflective surface in m^2

1,855
camera light sensors

Southern Hemisphere Array

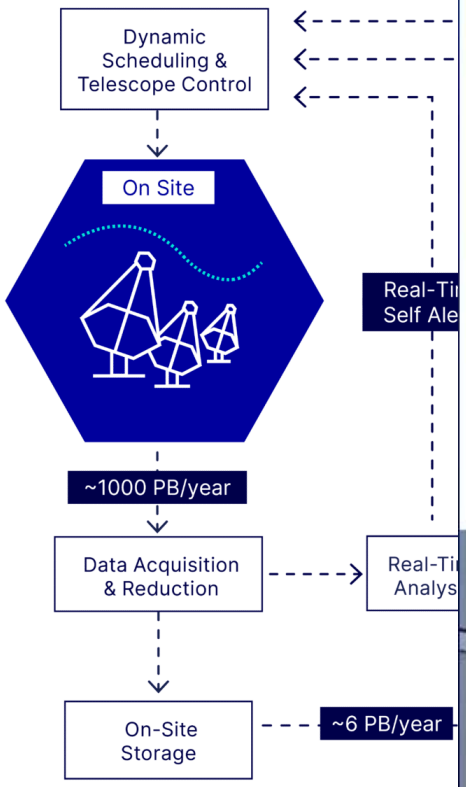






Northern Hemisphere Array

Source: CTAO



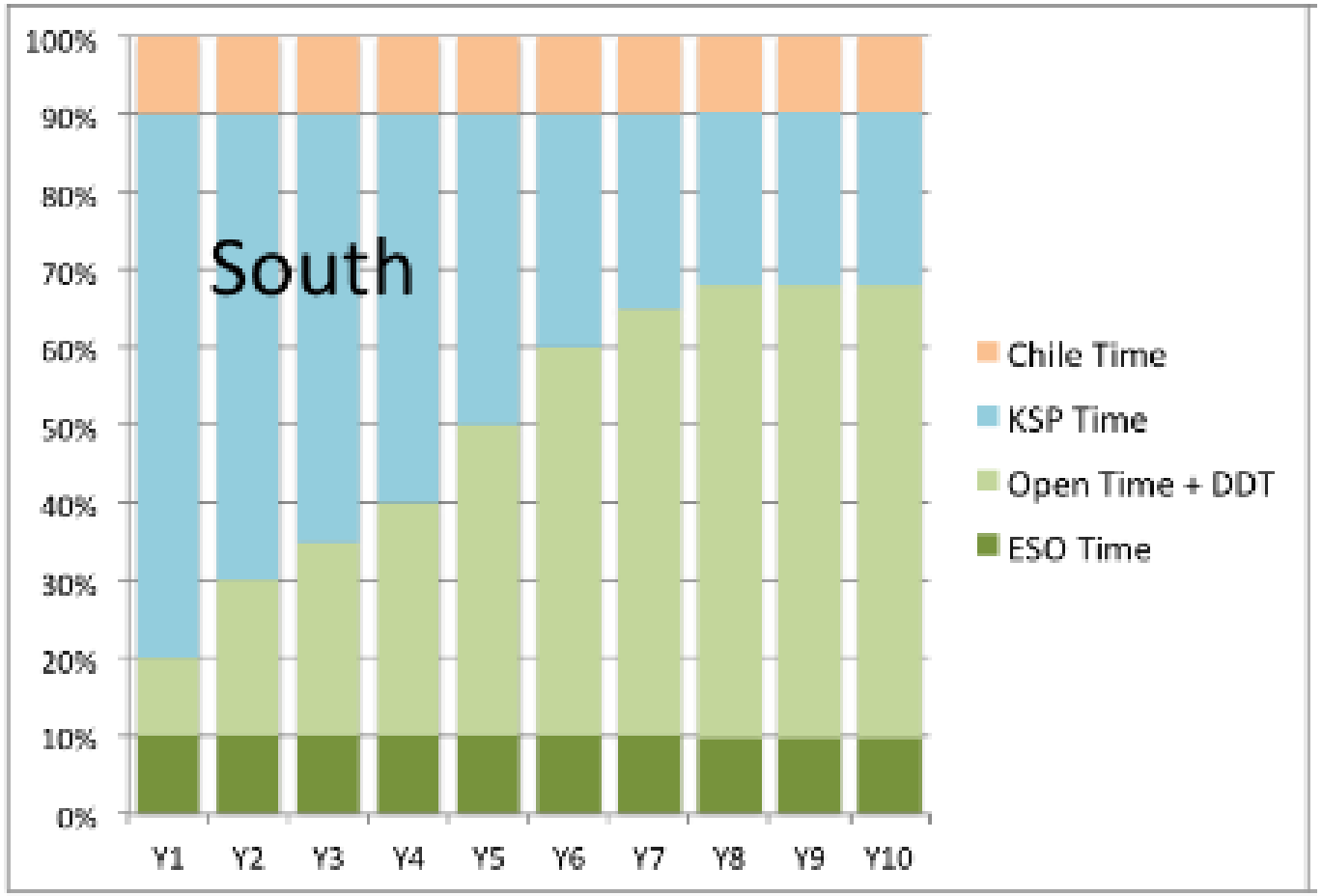
CTAO Science Data Management Centre Inauguration on 14 October 2024, Zeuthen (Germany)

DATE
08 October 2024

TOPICS
Announcements, Press Releases, Computing, Central Organisation

Credit: CTAO

CTA – open time and data



Theme I: Understanding the Origin and Role of Relativistic Particles

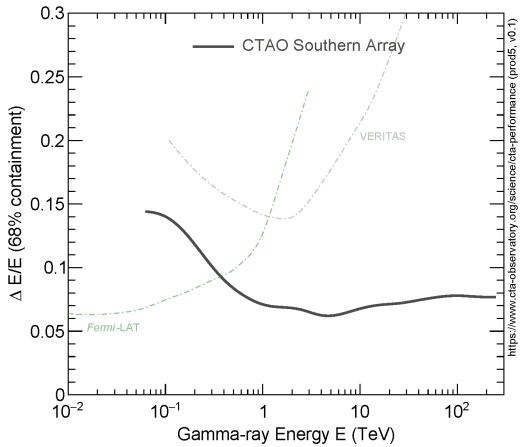
Theme II: Probing Extreme Environments

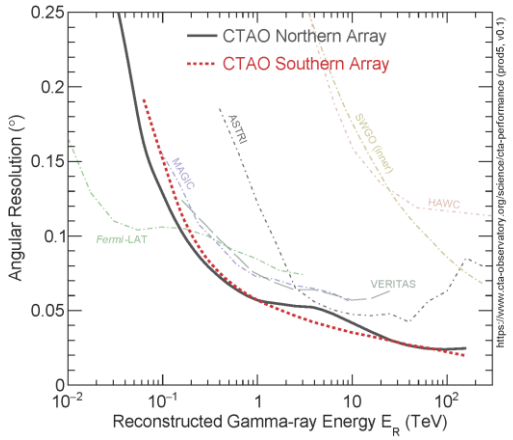
Theme III: Exploring Frontiers in Physics

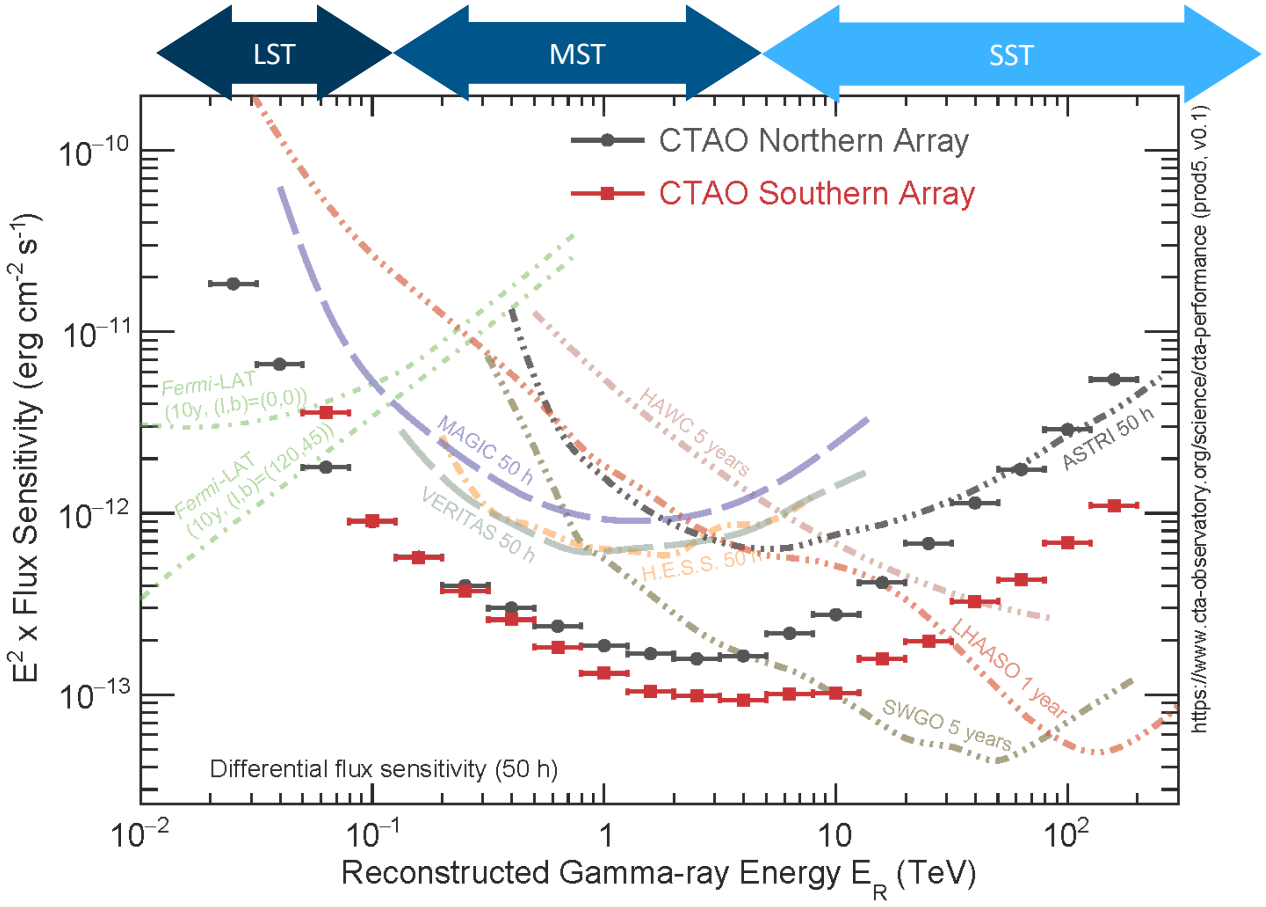
Cherenkov Telescope Array Observatory (CTAO)

- Next generation IACT observatory

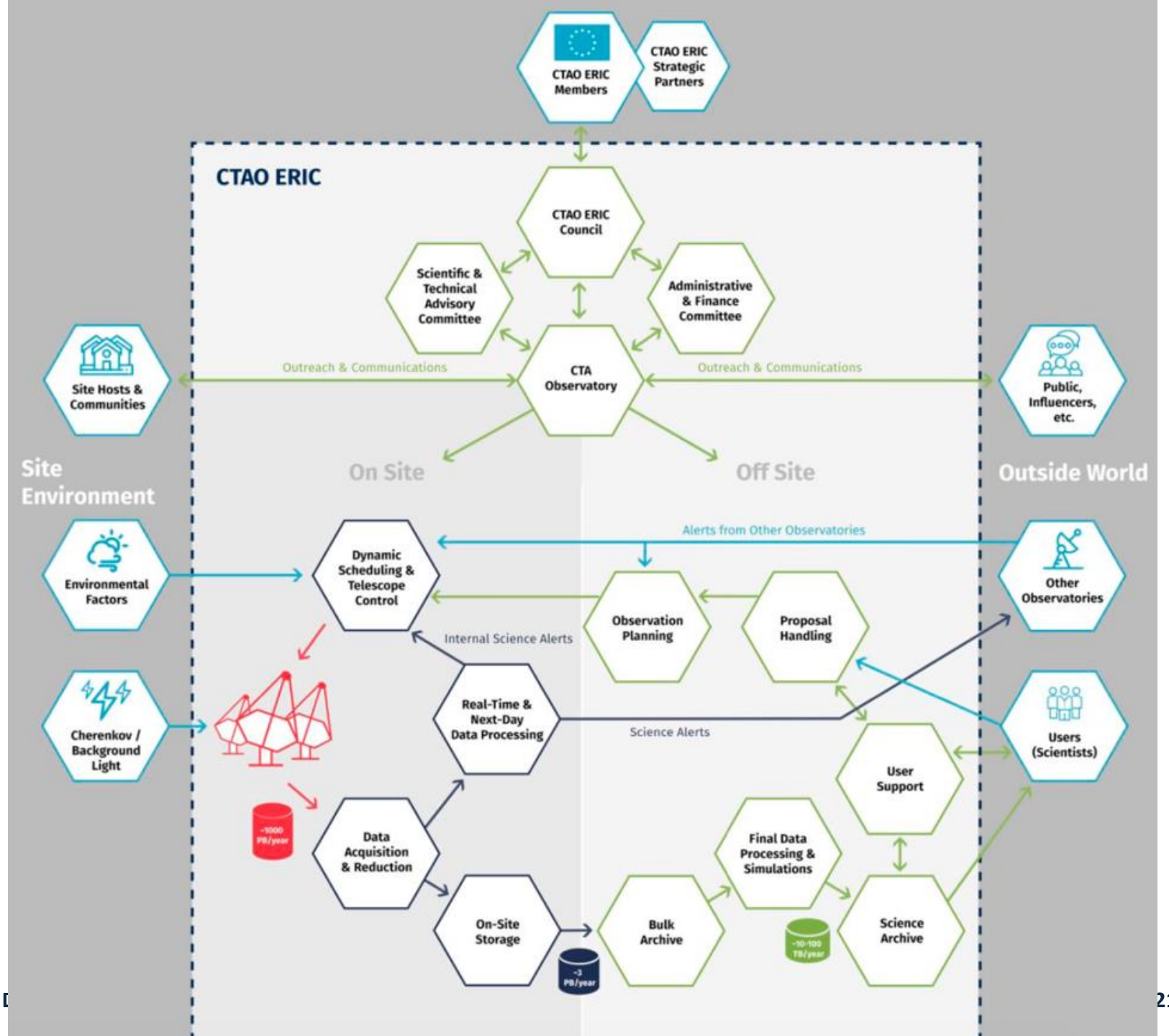
	LST	MST	SST
Effective mirror area	***370 m²***	88 m²	***8m²***
Energy range	***20GeV - 3 TeV***	80 GeV - 50 TeV	***1 TeV - 300 TeV***
Exclusive energy range	***20GeV - 150 GeV***	150 GeV - 5 TeV	***5 TeV - 300 TeV***
#telescopes North	***4***	9	***0***
#Telescopes South	***0****	14	***37****
Photo-sensors	***PMT***	PMT	***SiPM***

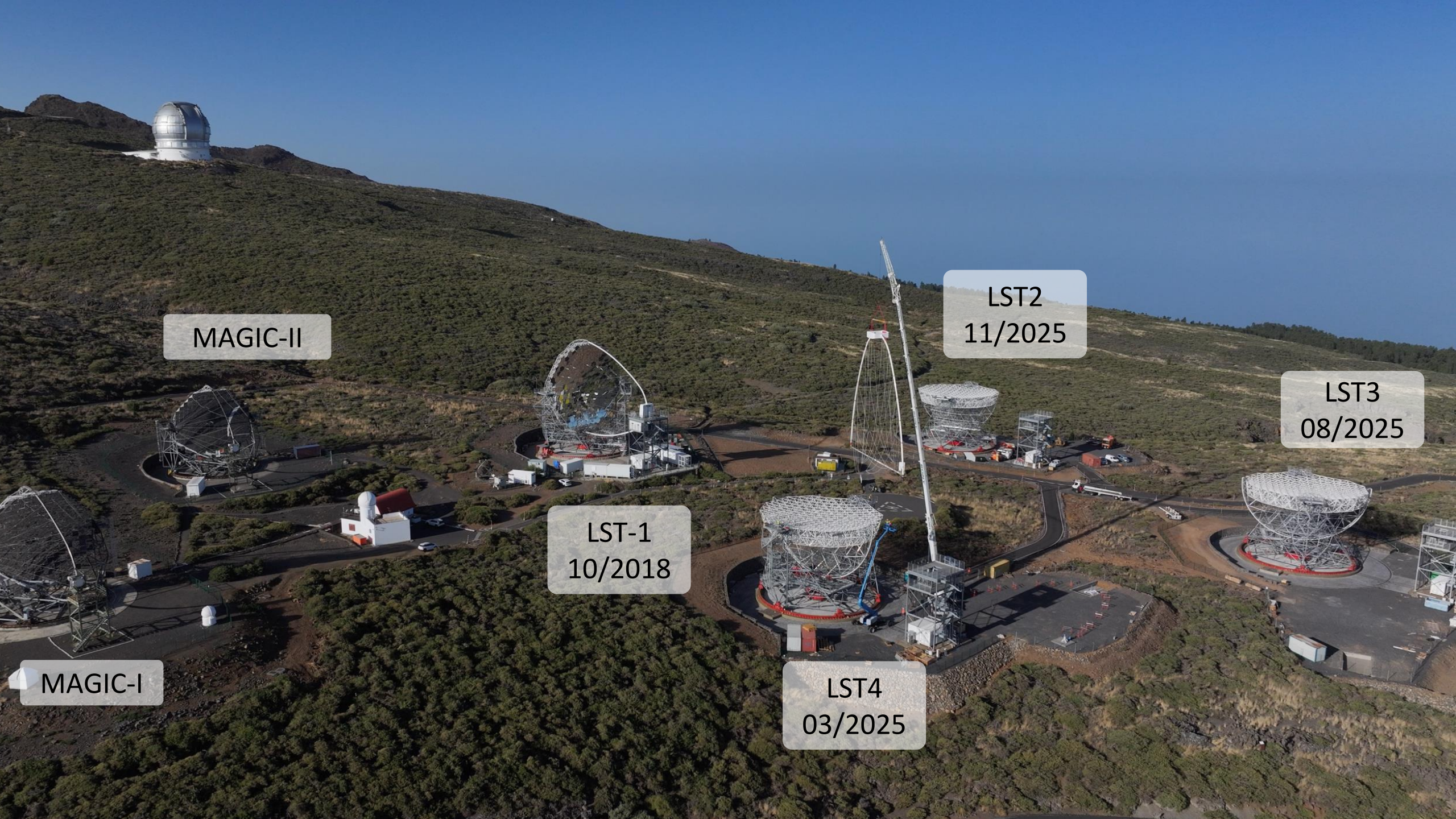




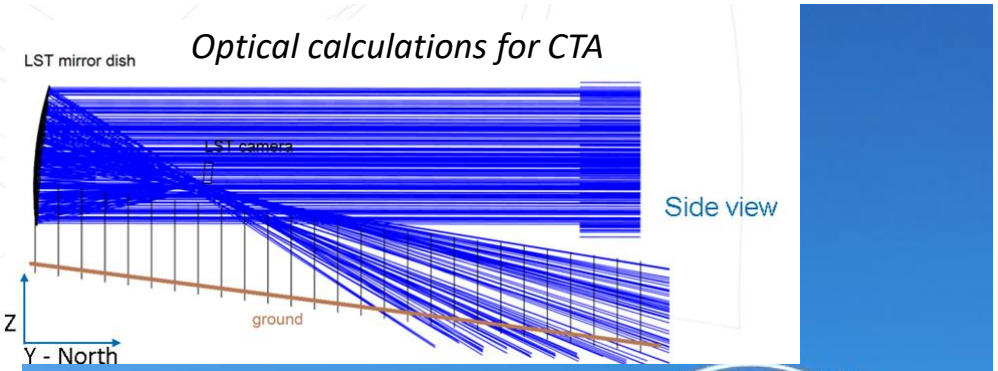


Source: CTAO


CTAO ERIC Members
CTAO ERIC Strategic Partners
CTAO ERIC
CTAO ERIC Council
Scientific & Technical Advisory Committee
Administrative & Finance Committee
CTA Observatory
Outreach & Communications
Outreach & Communications
Site Hosts & Communities
Public, Influencers, etc.
Site Environment
On Site
Off Site
Outside World
Alerts from Other Observatories
Environmental Factors
Dynamic Scheduling & Telescope Control
Other Observatories
Observation Planning
Proposal Handling
Internal Science Alerts
Cherenkov / Background Light
Real-Time & Next-Day Data Processing
Science Alerts
Users (Scientists)
User Support
~1000 PB/year
Data Acquisition & Reduction
Final Data Processing & Simulations
On-Site Storage
Bulk Archive
Science Archive
~3 PB/year
~10-100 TB/year


MAGIC-II
LST2
11/2025
LST3
08/2025
LST-1
10/2018
MAGIC-I
LST4
03/2025

CTA-CZ activities



Optical calculations for CTA


Optical maintenance of LST telescope

FRAM journey from Prague tests to installation in Chile

- **Optical lab in Olomouc**

  (one of the best equipped in central Europe)

  - Mirror production up to 1 m diameter and strong recent involvement in LST
  - Extensive tests of optical samples for the entire CTA
  - Professional optical calculations for the entire CTA consortium
- **Central calibration (leadership of M. Prouza)**
  - CTA-CZ provides several types of devices
    - FRAM devices
    - all sky cameras
    - sun moon photometers, ceilometers
- **Involvement in LST**
  - Optical maintenance
  - Optical calculations
- **SST-1M prototypes**
  - Now separate project

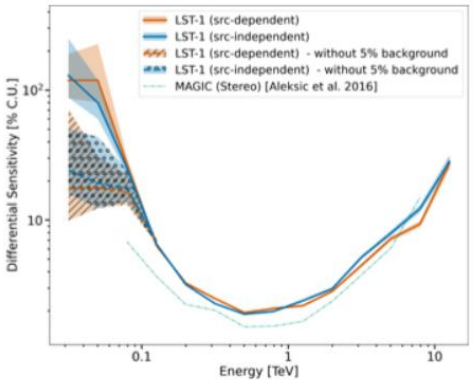

All sky camera

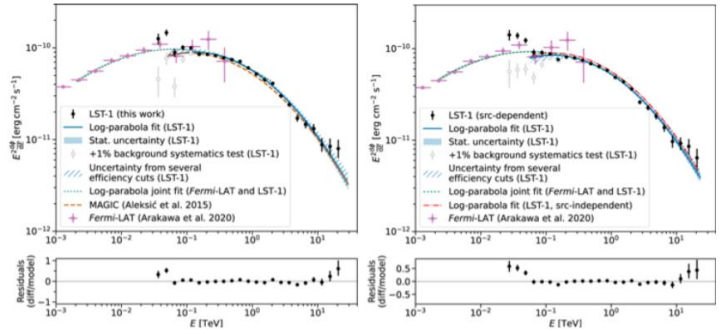

Sun moon photometer


ceilometer

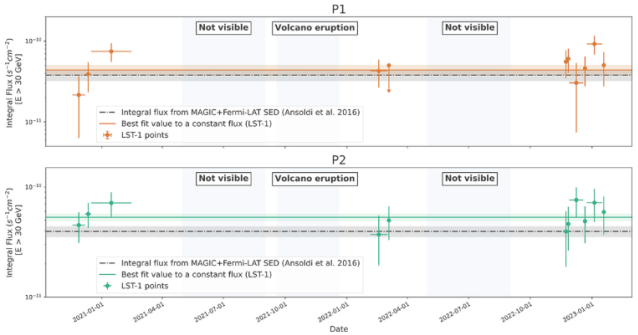
Scientific achievements already with one LST telescope

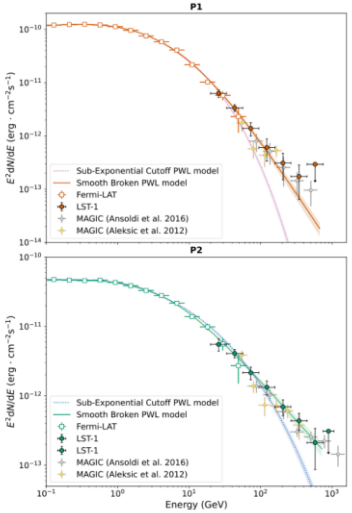
Observations of the Crab Nebula and Pulsar with the Large-sized Telescope Prototype of the Cherenkov Telescope Array ,H. Abe *et al* 2023 *ApJ* **956** 80



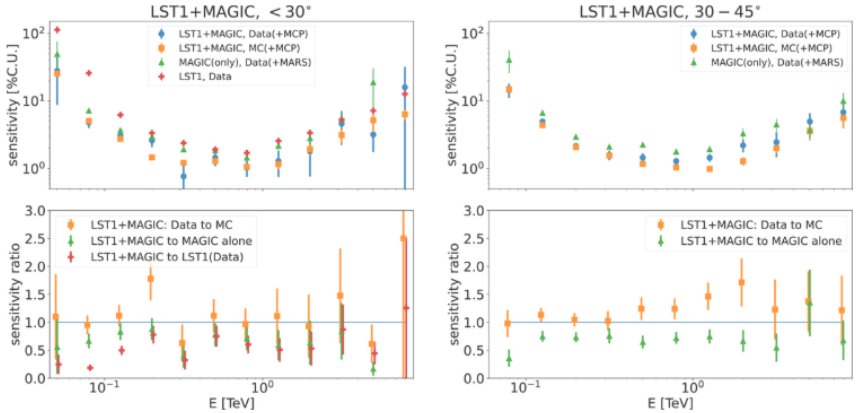


A detailed study of the very high-energy Crab pulsar emission with the LST-1, K. Abe et al A&A, 690 (2024) A167
DOI: https://doi.org/10.1051/0004-6361/202450059





Performance of the joint LST-1 and MAGIC observations evaluated with Crab Nebula data**,** H. Abe et al A&A, 680 (2023) A66, DOI: https://doi.org/10.1051/0004-6361/202346927



Source: IAC, CTAO, https://www.iac.es/en/outreach/news/lst-1-telesco palma-detects-most-distant-quasar-very-high-energies

SST-1M project

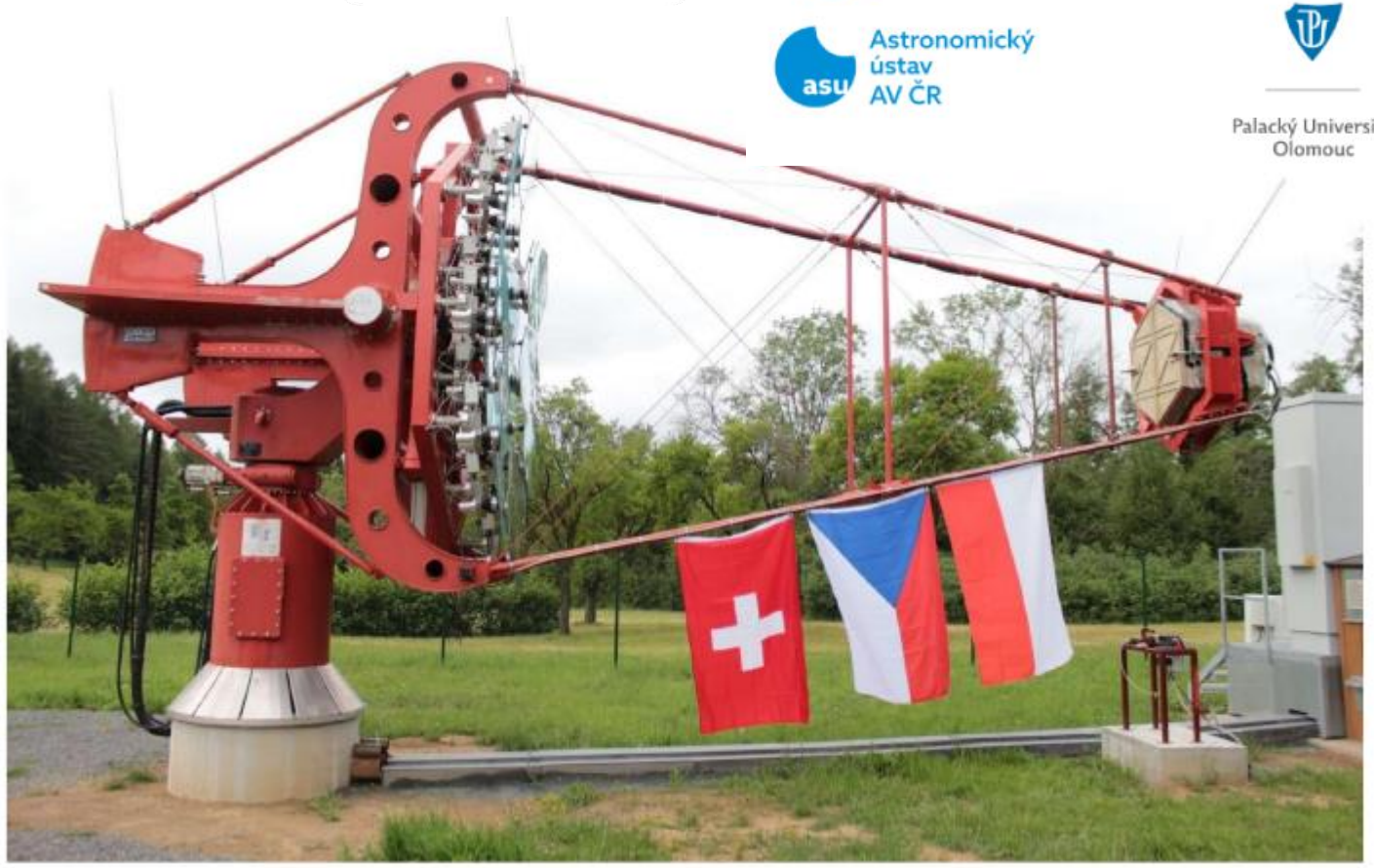
SST-1M
Single-Mirror
Small Size Telescope

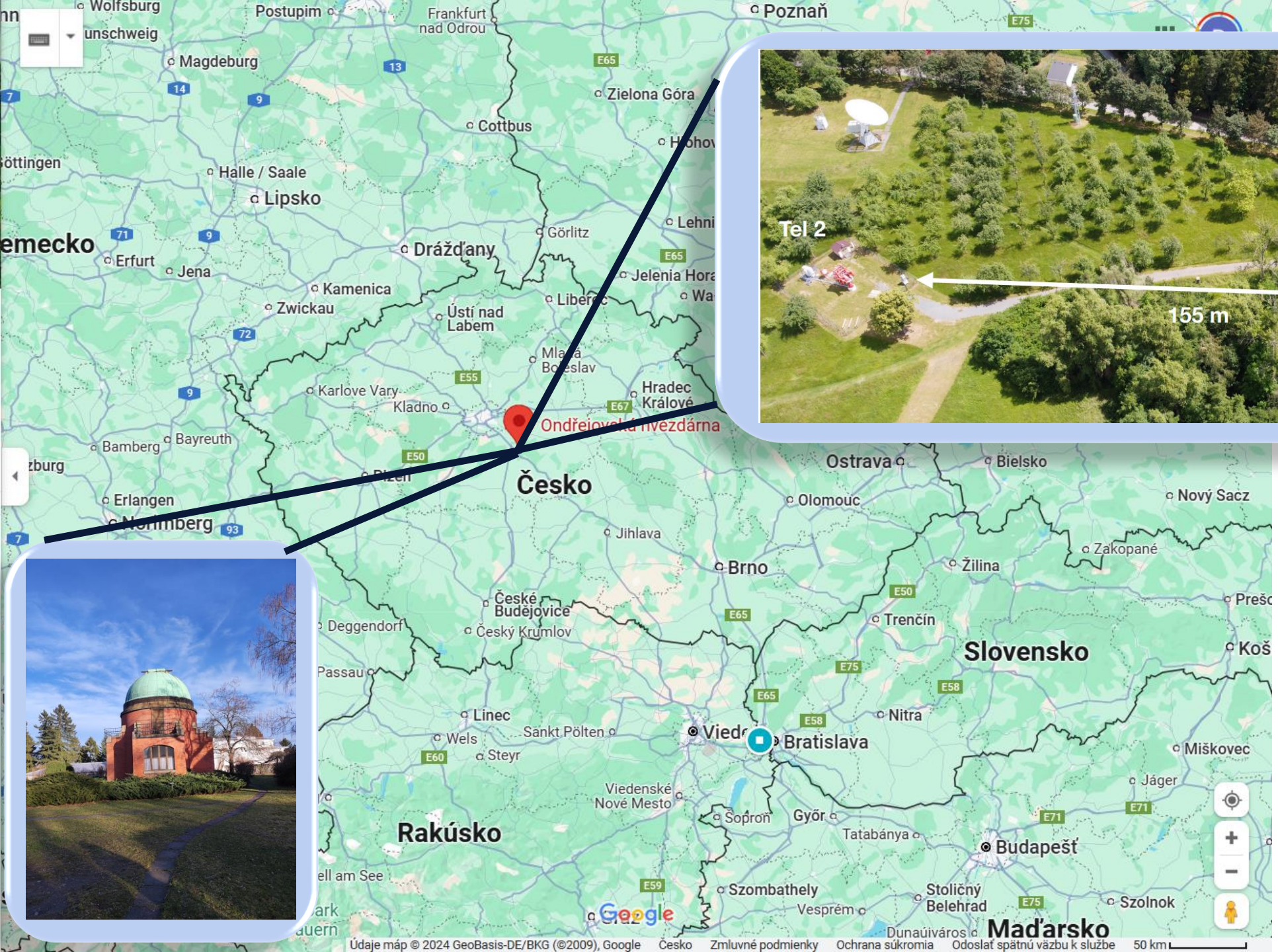
- Collaboration of 17 institutes from **3 countries – Czechia, Poland and Switzerland**
- Developed as a design of Small Sized Telescopes for CTAO – **other design was selected**
- Constructed **2 SST-1M prototypes** – relocated in 2022 from Poland to **Ondřejov Observatory** of Czech Academy of Sciences near Prague

https://sst-1m.science/

SST1M_SPACE

Nicolaus Copernicus Astronomical Center
Centrum Badań Kosmicznych Space Research Centre
THE HENRYK NIEWODNICZAŃSKI INSTITUTE OF NUCLEAR PHYSICS POLISH ACADEMY OF SCIENCES
University of Science and Technology AGH
UNIVERSITÉ DE GENÈVE FACULTÉ DES SCIENCES
ISDC
JAGIELLONIAN UNIVERSITY IN KRAKOW
FZU Fyzikální ústav Akademie věd České republiky
UNIWERSYTET WARSZAWSKI
Astronomický ústav AV ČR
Palacký University Olomouc





Ondřejov Observatory

https://asu.cas.cz/

Source: Google maps

Source: Vladimír Karas

SST-1M telescopes

- Davies-Cotton optics
- Segmented mirror – 18 hexagonal mirror facests
- Fully remote observations

Optics	Focal Length	5600 ± 5 mm
	f/D	1,4
	Dish diameter	4 m
	Mirror Area (*)	9.42 m^2
	Mirror Effective Area (*)	6.47 m^2
	Hexagonal Mirror facets	780 ± 3 mm
	Mirror PSF D_{80} (requirement)	0.082° (8.1 mm)
	Mirror PSF D_{80} (measured)	0.028° (2.7 mm)
	Telescope PSF D_{80} (required)	0.25° (24.4 mm)
	Telescope PSF D_{80} (measured) On-Axis	0.082° (8 mm)

C. Alispach et al JCAP02(2025)047

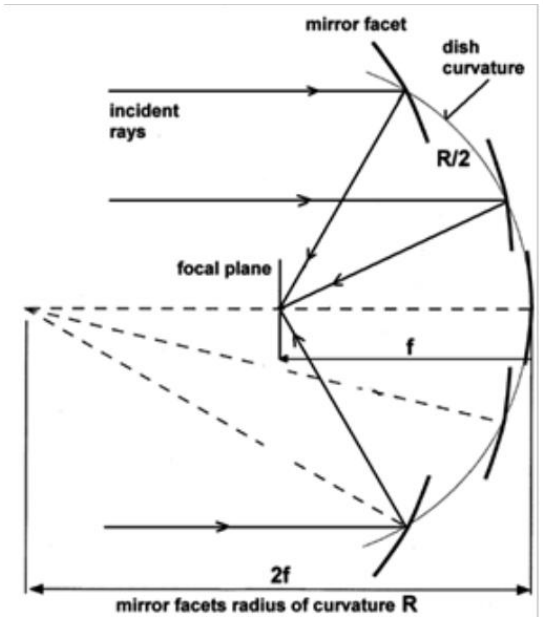
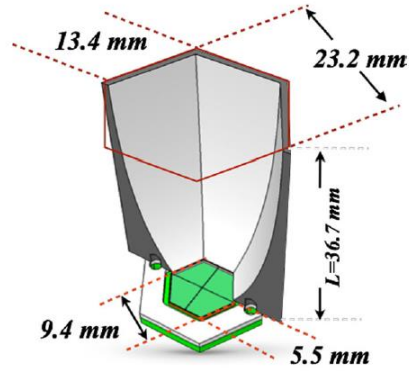


Figure adopted from Actis et al., 2011

SST-1M camera

Camera	Camera dimensione (R/thickness)	810 mm / 900 mm
	Total pixel number	1296
	Pixel linear size	23.4 mm
	Pixel angular size	0.24°
	FoV	8.9°
	PDE@470 nm, 8% X-talk (LCT/LVR)	23% / 54%
	Sampling frequency	250 MHz
	Maximum trigger rate (80/200 ns window)	12.5 / 5 MHz
	Maximum readout rate (80/200 ns window)	22.6 / 9.4 kHz
	Time Spread RMS	< 0.25 ns

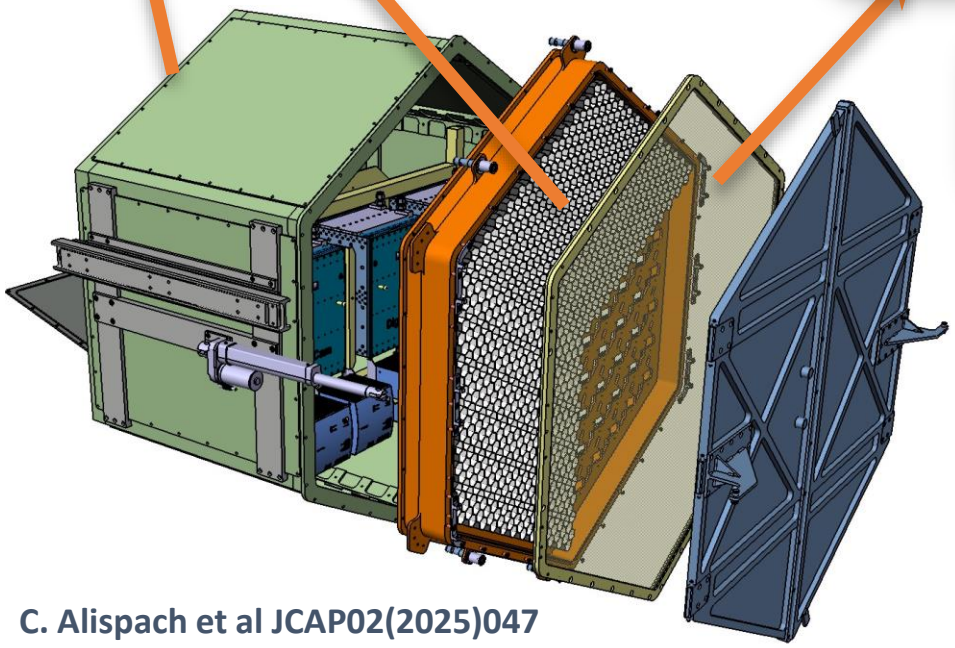


Digital electronics (DigiCam):
- 12 bits FADC @ 250 MS/s
- Fully digital trigger
- Power consumption 1200 W

Photo-detection plane:
- 1296 pixels
- Power consumption 500 W

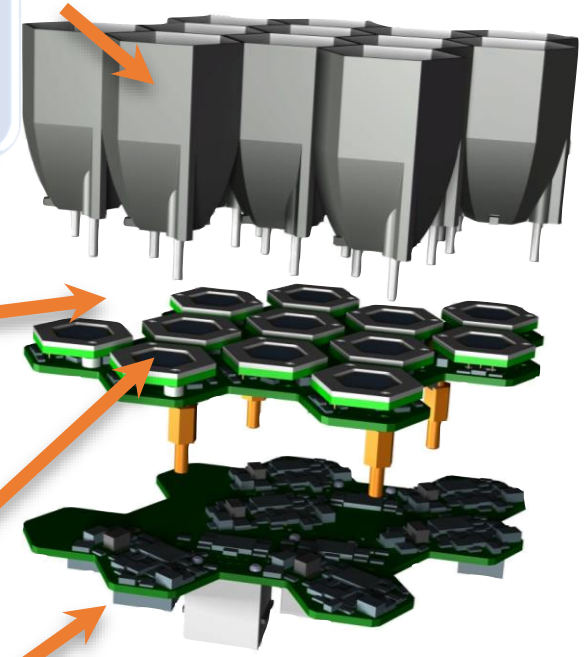
Entrance window:
- 3.3 mm Borofloat
- Cut-off filter at 540 mm for NSB rejection

Hollow light guides:
- Cut-off at 24°
- 2.32 cm linear size
- Compression factor of 6



C. Alispach et al JCAP02(2025)047

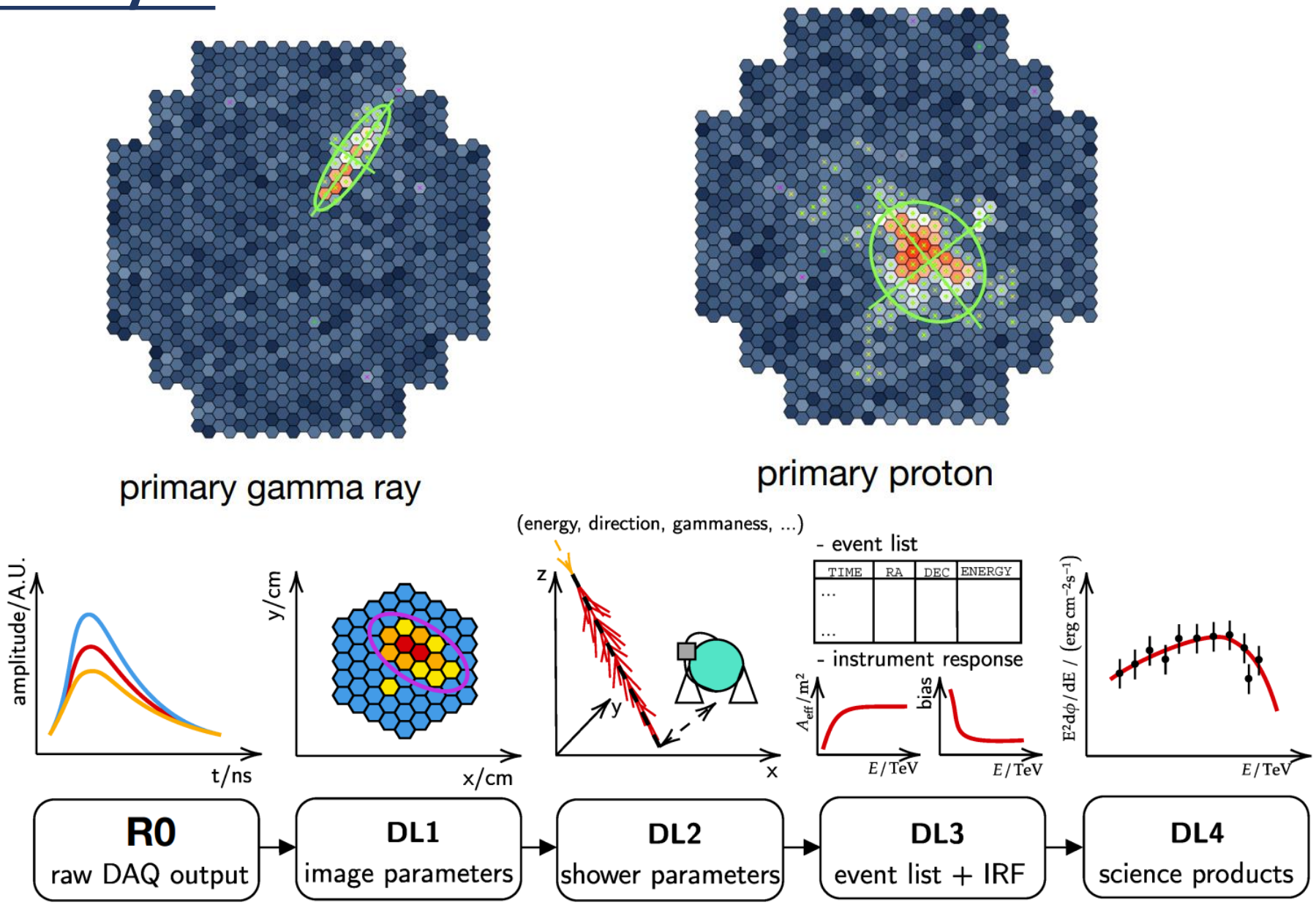
Sensor:
- Custom hexagonal Hamamatsu MPPC
- 4 anodes per pixel with one common cathode



Preamplifier board:
- 2 operational amplifiers per sensor to reduce pulse length
- DC coupling

Slow control board:
- Temperature compensation loop (2 Hz)
- HV generation, Differential output to DigiCam

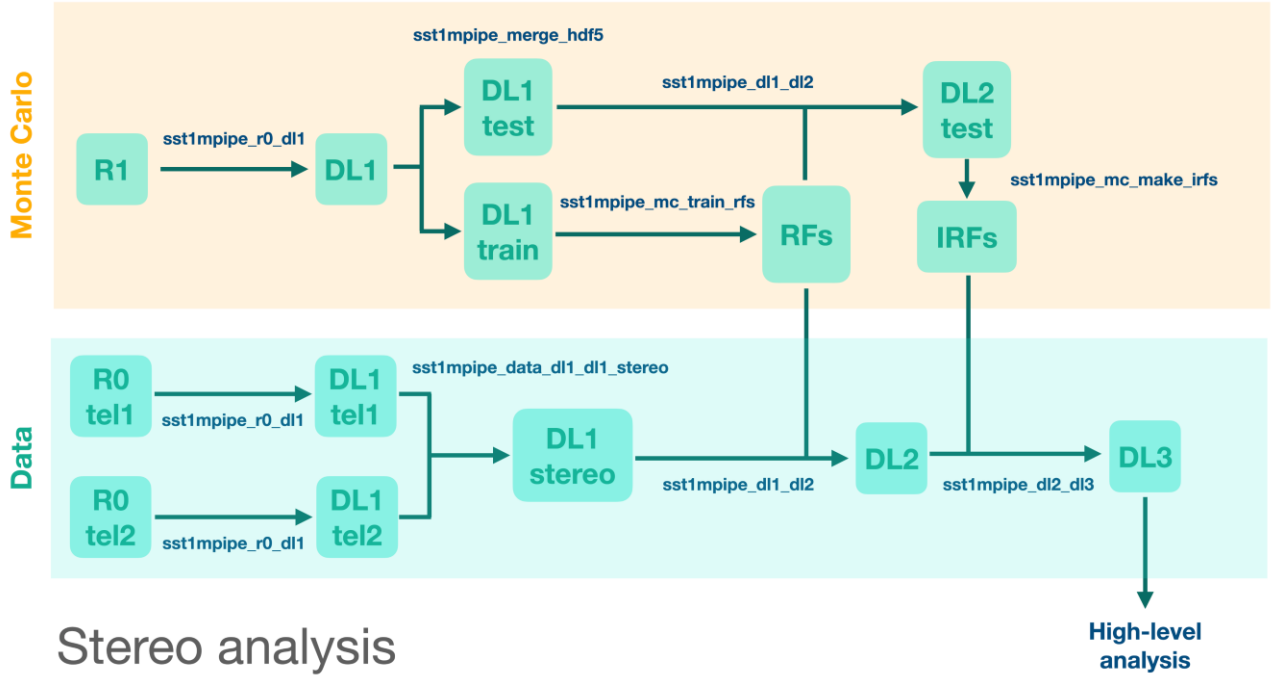
Pipeline and analysis



Pipeline and analysis

sst1mpipe

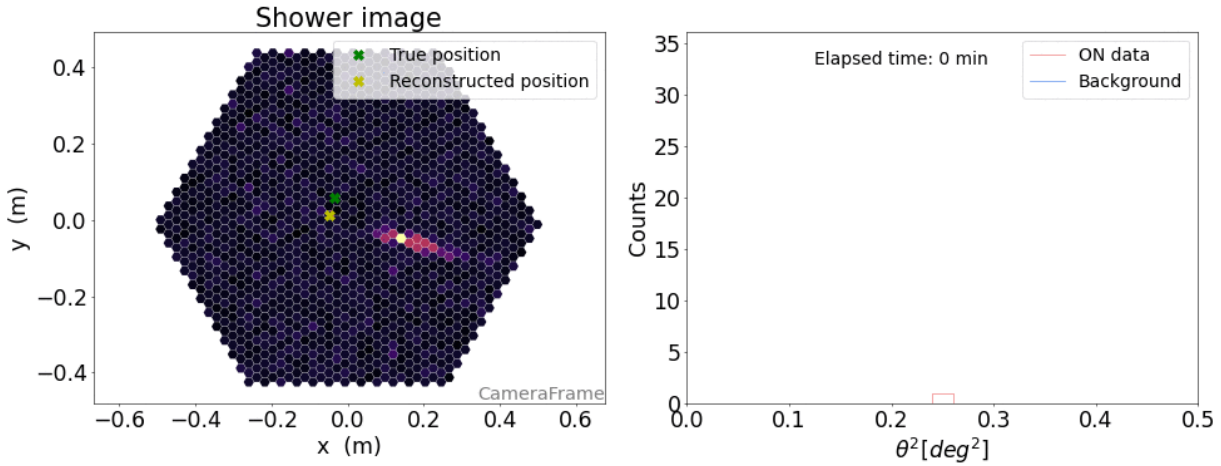
- Data and Monte Carlo analysis **software for low-level analysis** – waveform calibration and integration, shower-image parametrisation, stereo reconstruction, random forest training, instrument response function (IRF) calculation
- Pipeline is divided into several steps (r0 -> dl1 -> dl2 -> dl3) – based on **functions adopted from *ctapipe*** https://github.com/cta-observatory/ctapipe and **follows *lstchain*** cta-observatory.github.io/cta-lstchain/
- Results are **compatible with gamma-astro-data-format** (GADF) -> can be forwarded for high-level analysis (dl4/dl5/dl6) performed by *gammapy*



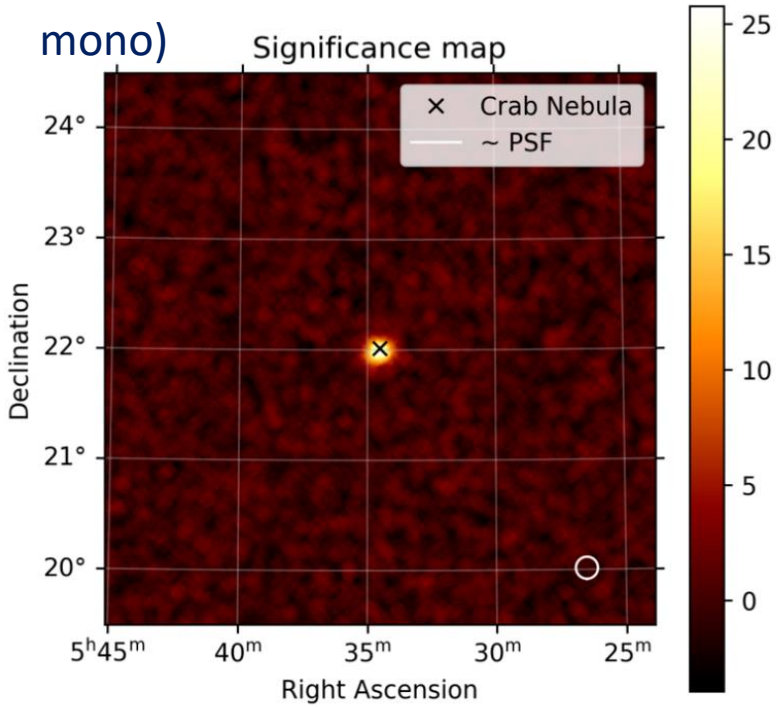
- **Juryšek et al., PoS(ICRC2023)592**
- **Juryšek et al., 2024, sst1mpipe v.0.4.1, Zenodo**
- **https://github.com/SST-1M-collaboration/sst1mpipe**

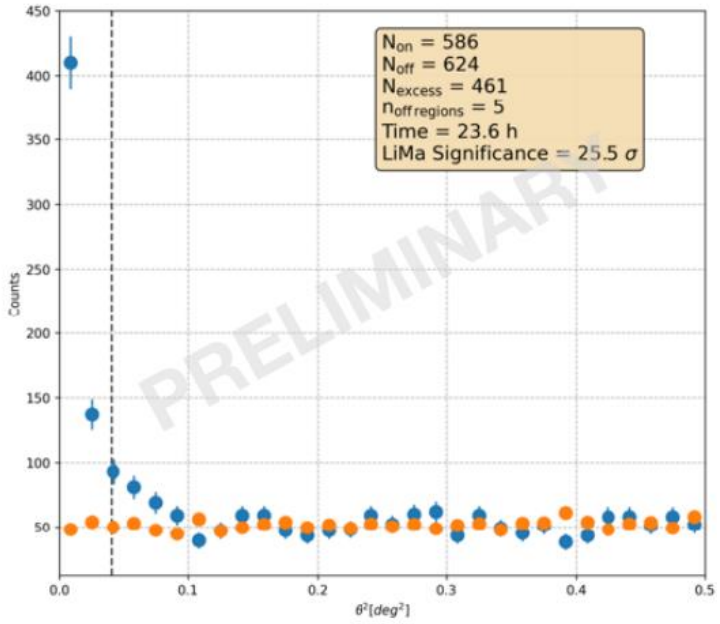
Crab Nebula (M1) observation

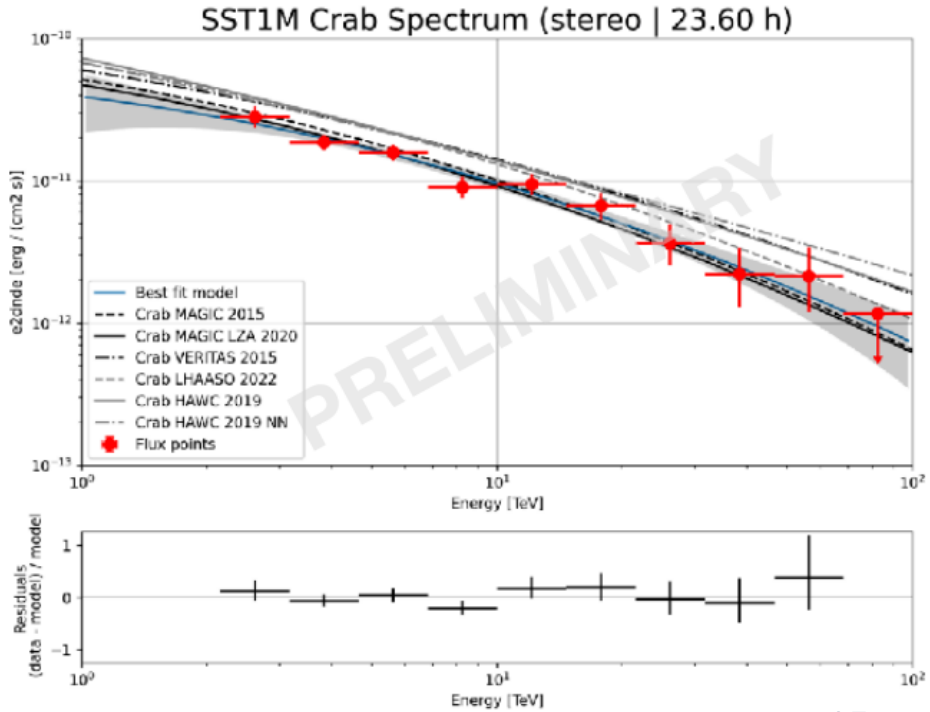
- Standard candle in gamma-ray astronomy
- Obs. campaign 2023/2024 and recently finished campaign 2024/2025
- Approx. 23 hours of stereo data after quality cuts
- Data zenith angle < 45° and energy treshold 2-3 TeV
- 5σ detection in less than 2 hours in stereo (in less than 3 hours for mono)



Tavernier et al., PoS(ICRC2023)741



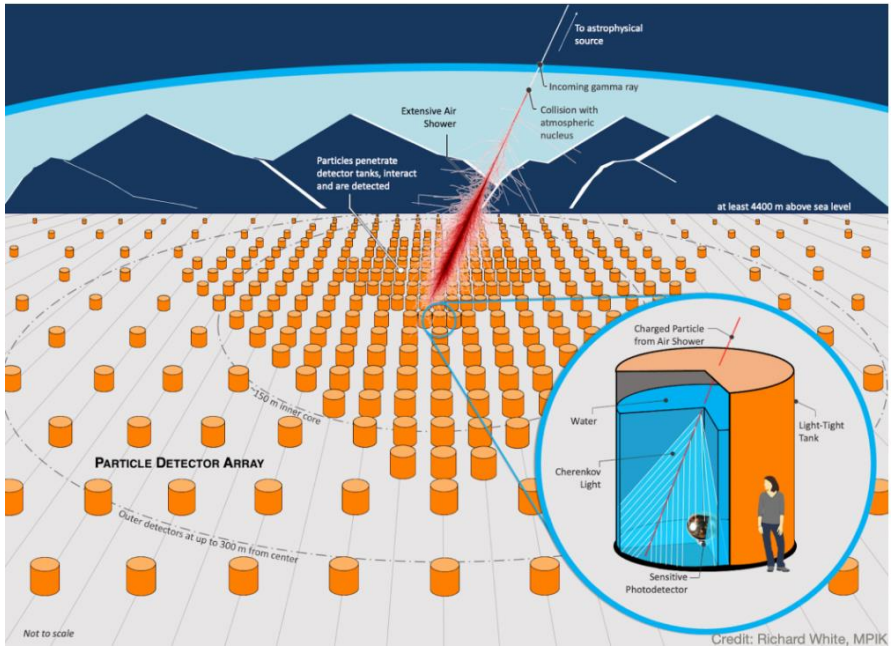


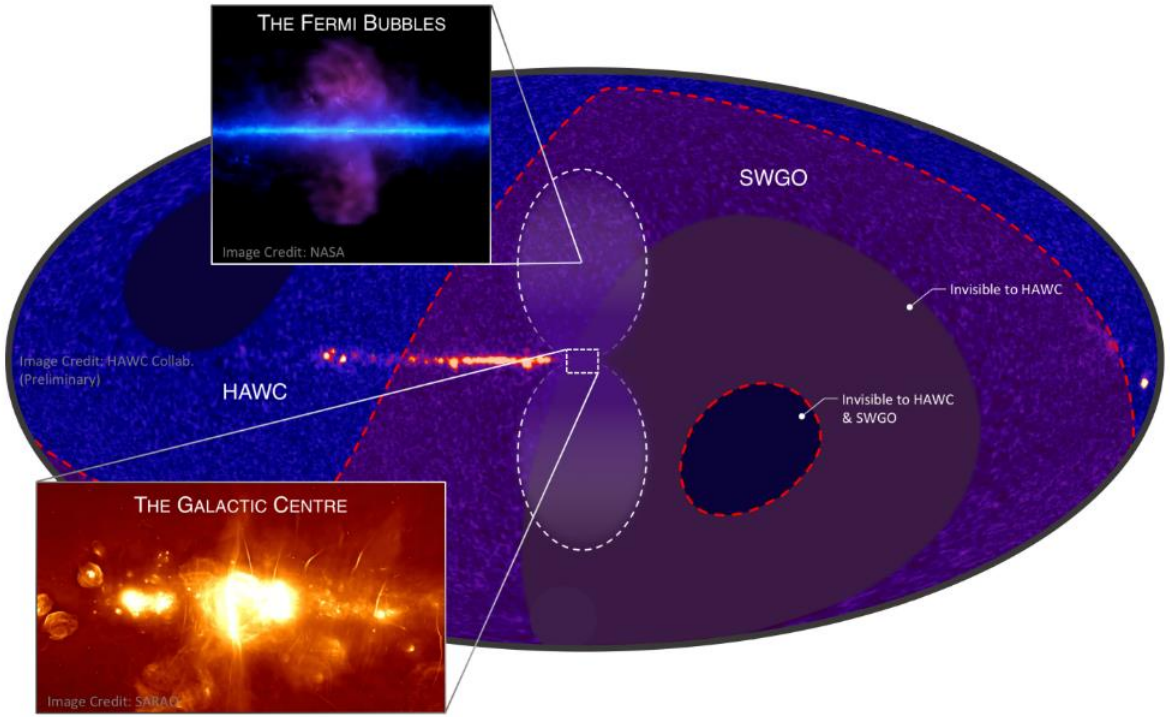


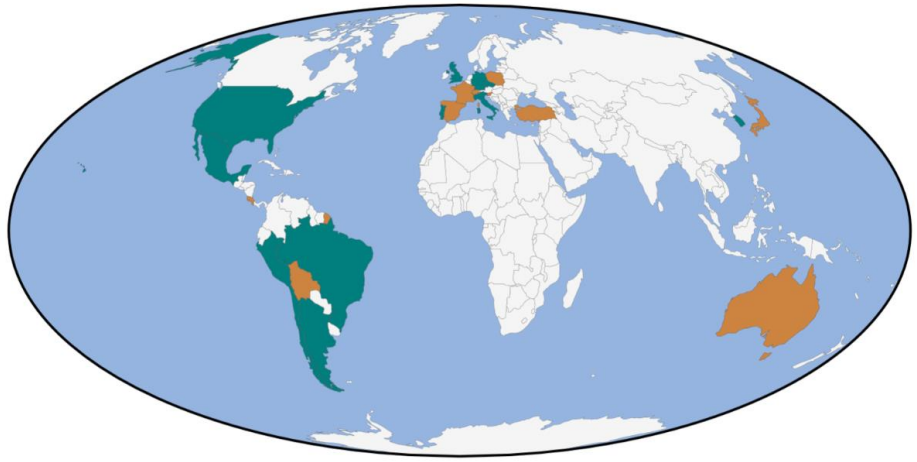
Southern Wide-field Gamma-ray Observatory

- International collaboration of approximately 150 scientists from 16 countries (approx. 90 research institutions)
- Currently no wide-field gamma-ray observatory in the southern hemisphere
- Use of water Cherenkov detectors

SWGO
The Southern Wide-field Gamma-ray Observatory







Countries in SWGO

Institutes

Argentina*, Brazil, Chile, Czech Republic, Germany*, Italy, Mexico, Peru, Portugal, South Korea, United Kingdom, United States*

Supporting scientists

Australia, Bolivia, Costa Rica, France, Japan, Poland, Slovenia, Spain, Switzerland, Turkey

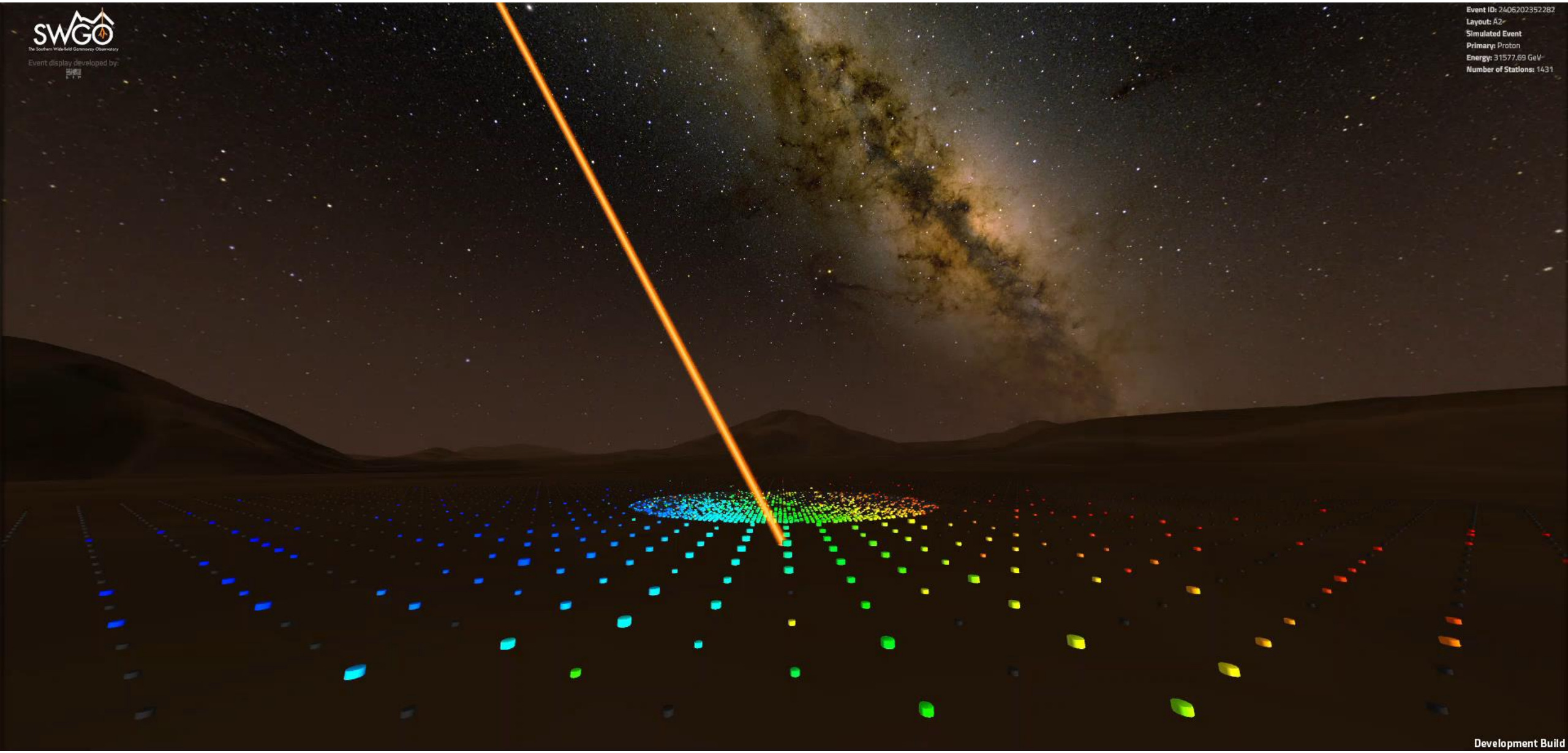
**also supporting scientists*

Credit: Richard White, MPIK

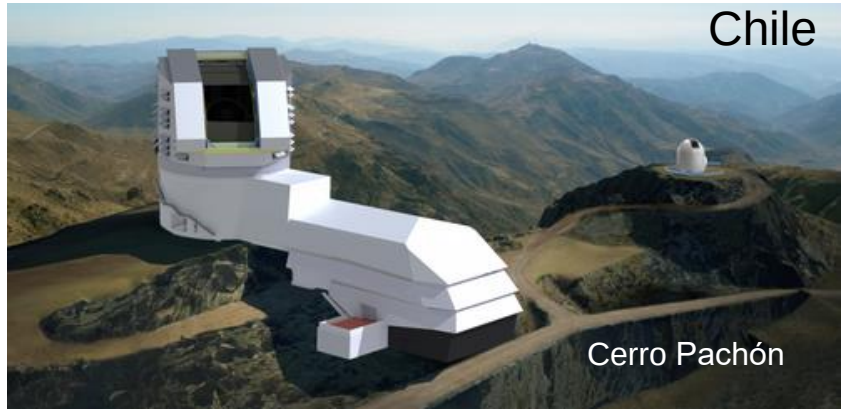
SWGO SITE SELECTION

August 12th, 2024

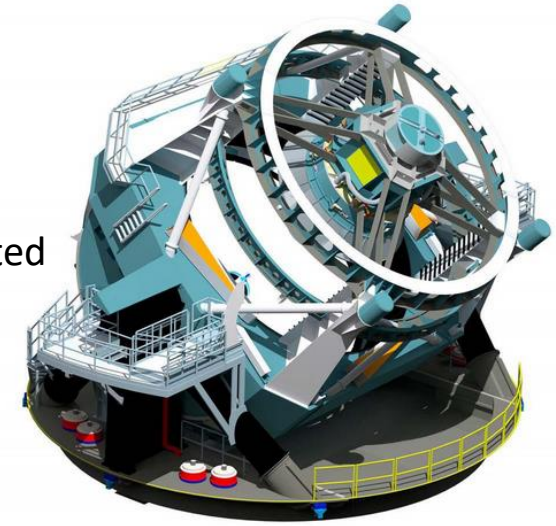
At a meeting at the Brazilian Center for Physics Research (CBPF), in Rio de Janeiro, Brazil, scientists of the SWGO Project, whose goal is to observe the sources of very-high-energy gamma rays in the Universe, announced that the Atacama Astronomical Park in Chile was selected as the site of the observatory.

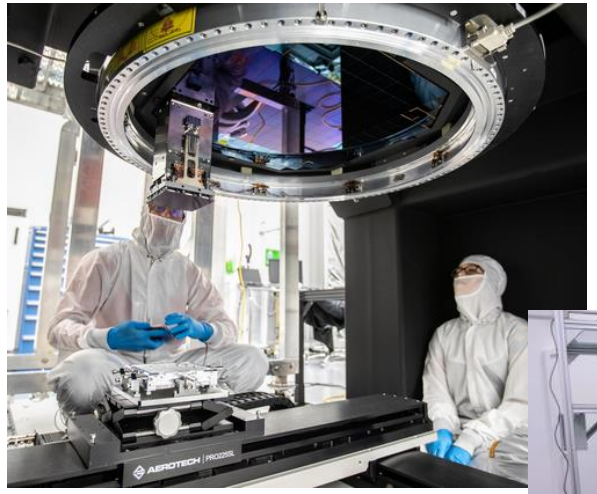

SWGO
The Southern Wide-field Gamma-ray Observatory
Event display developed by:
Event ID: 2406202352282
Layout: A2
Simulated Event
Primary: Proton
Energy: 31577.69 GeV
Number of Stations: 1431
Development Build

Vera C. Rubin Observatory



- Previous name – Large Synoptic Survey Telescope (LSST)
- Telescope focused on the detailed survey of the sky
- FZU joined the project as one of the first in Europe
- Included also in astroparticle projects – experimental cosmology (study of dark matter and dark energy)
- 8.4 m primary mirror diameter with largest ever constructed digital camera
- Laboratory in Prague is fully functional since 2020





Main science goals

- Understanding the nature of dark matter and dark energy
- Creating an inventory of the Solar System
- Mapping the Milky Way
- Exploring objects that change position or brightness over time

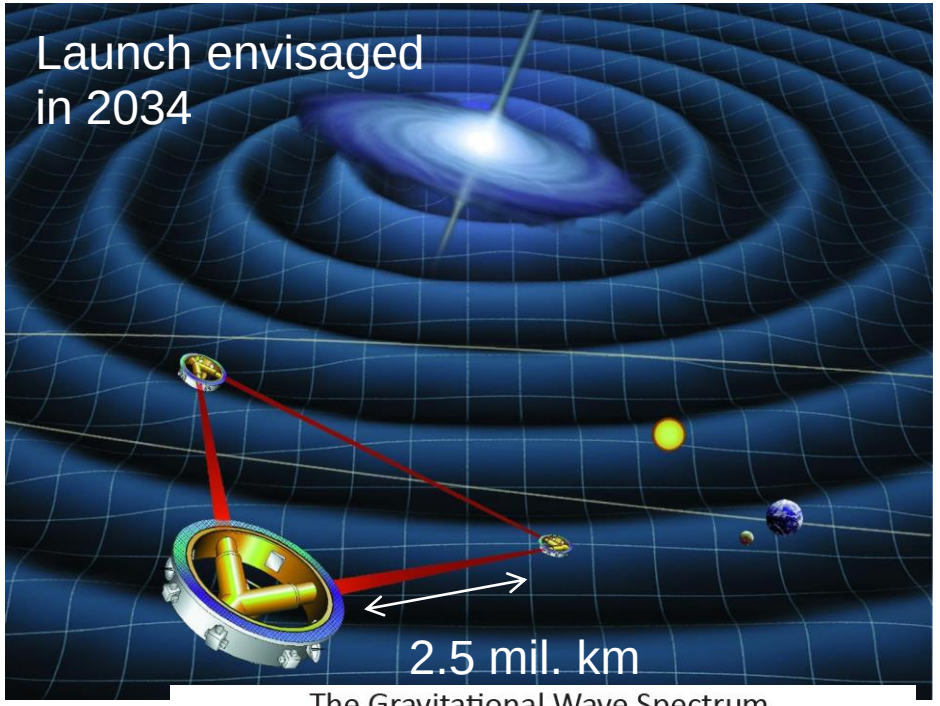
- First light expected in 2025

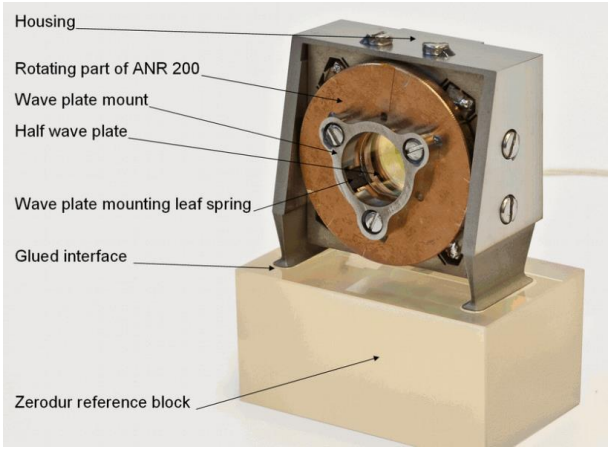
Credit: Hernan Stockebrand

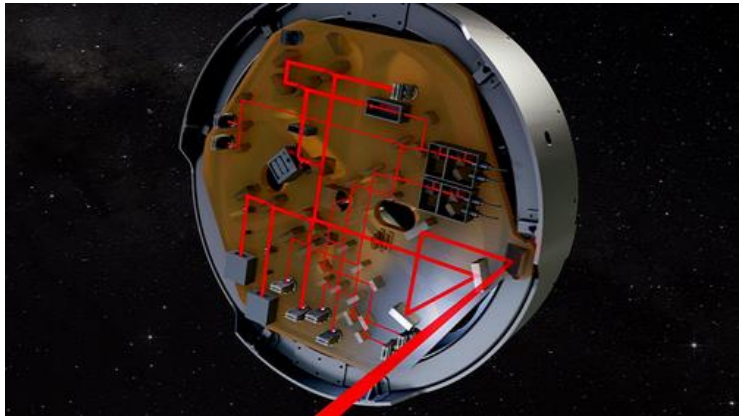
Laser Interferometer Space Antenna - LISA

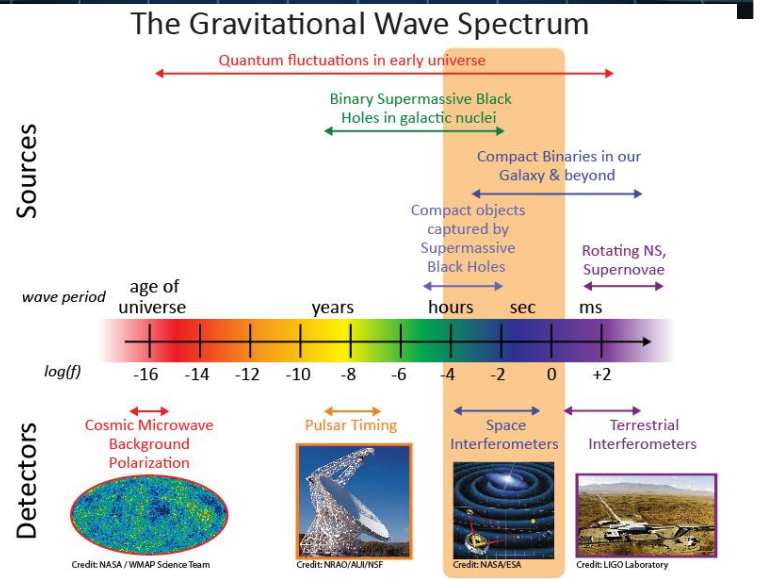
https://lisa.nasa.gov/

- Planned gravitational-wave observatory
- Czech Republic joined the project in 2020
- ESA+NASA+JAXA+international consortium lead by Germany
- Development of the LISA Fiber Switch Unit Actuator - used to switch between the main and redundant laser on the Optical Bench









References

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Thank you for your attention

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PHYSICS FOR FUTURE

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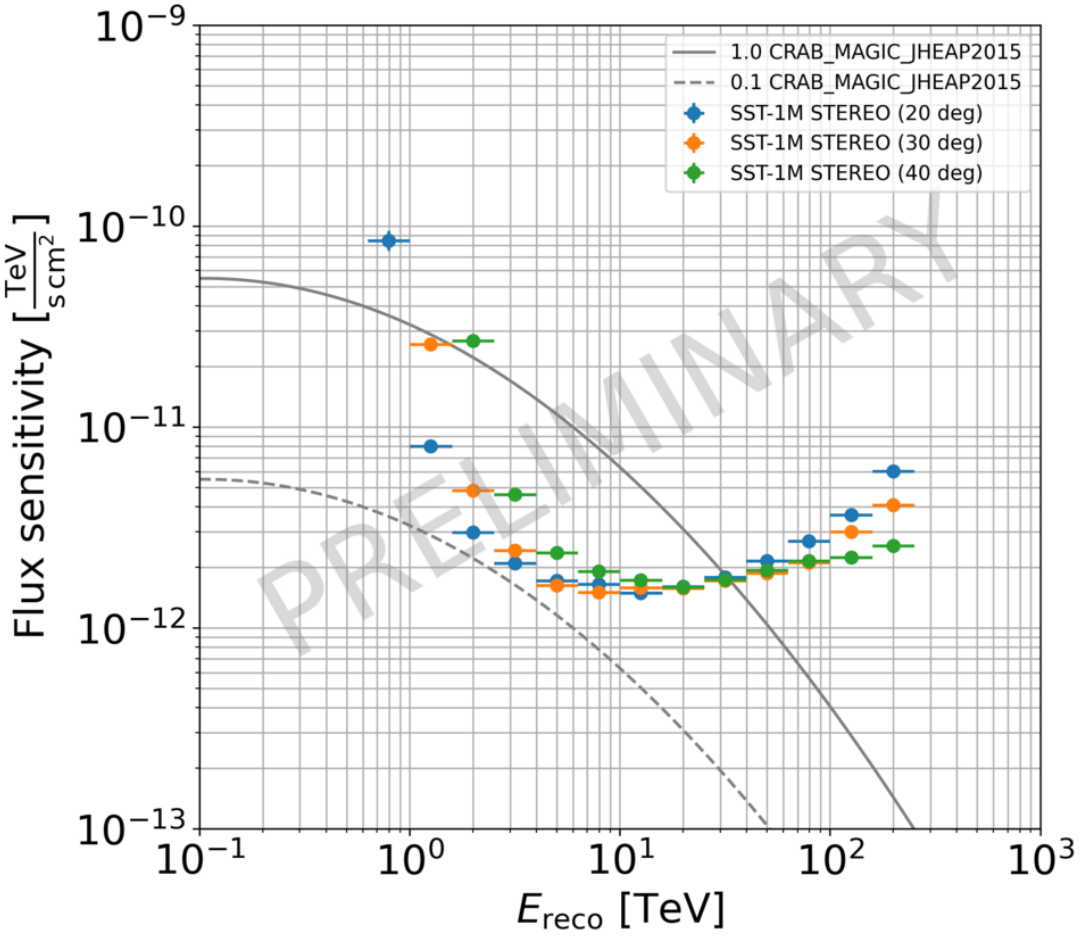
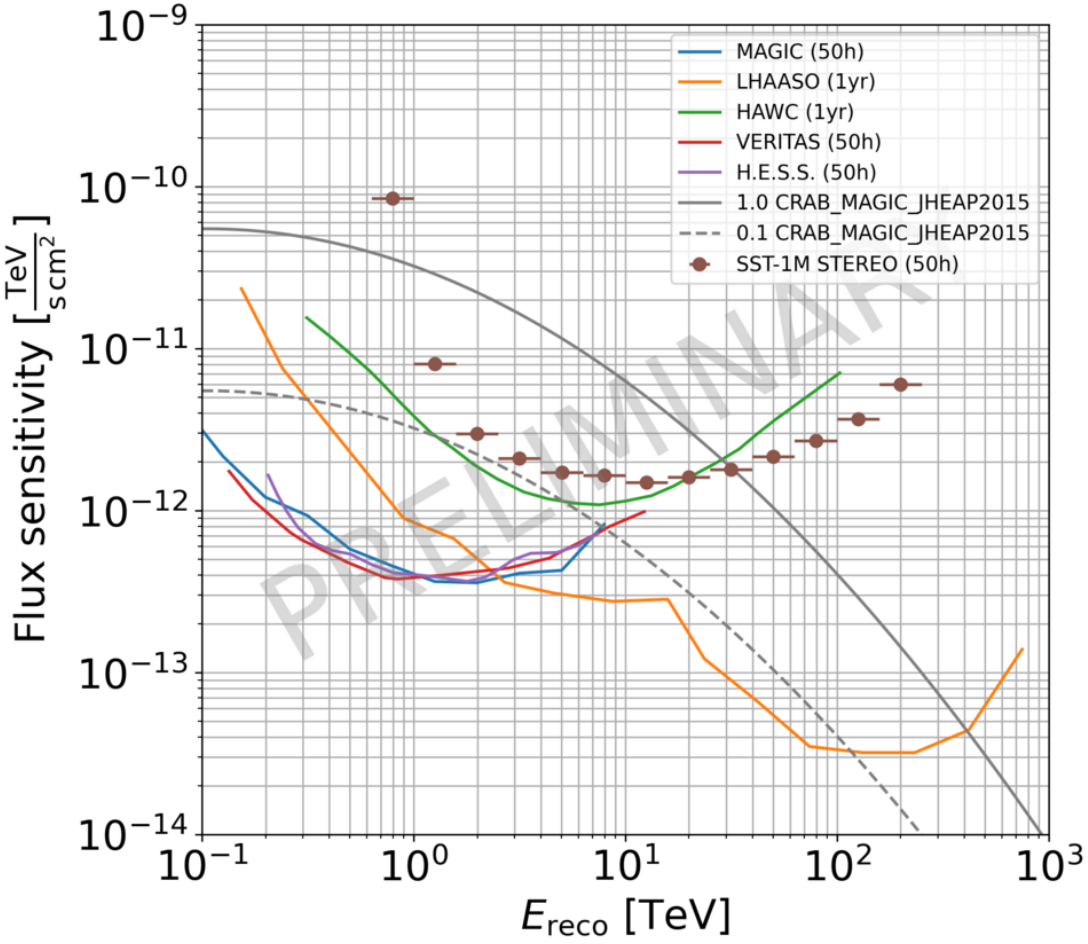
Perfomance of SST-1M

- Significant improvement of performance in stereo mode comparing to mono mode
- Results in stereo mode





Backup

Perfomance of SST-1M

- Significant improvement of parameters in stereo mode
- Results in stereo mode for different zenith angles