DEPARTMENT OF EXPERIMENTAL PARTICLE PHYSICS — F9

Astroparticle Physics at F9

Ultra-high-energy cosmic rays and very-high-energy gamma rays

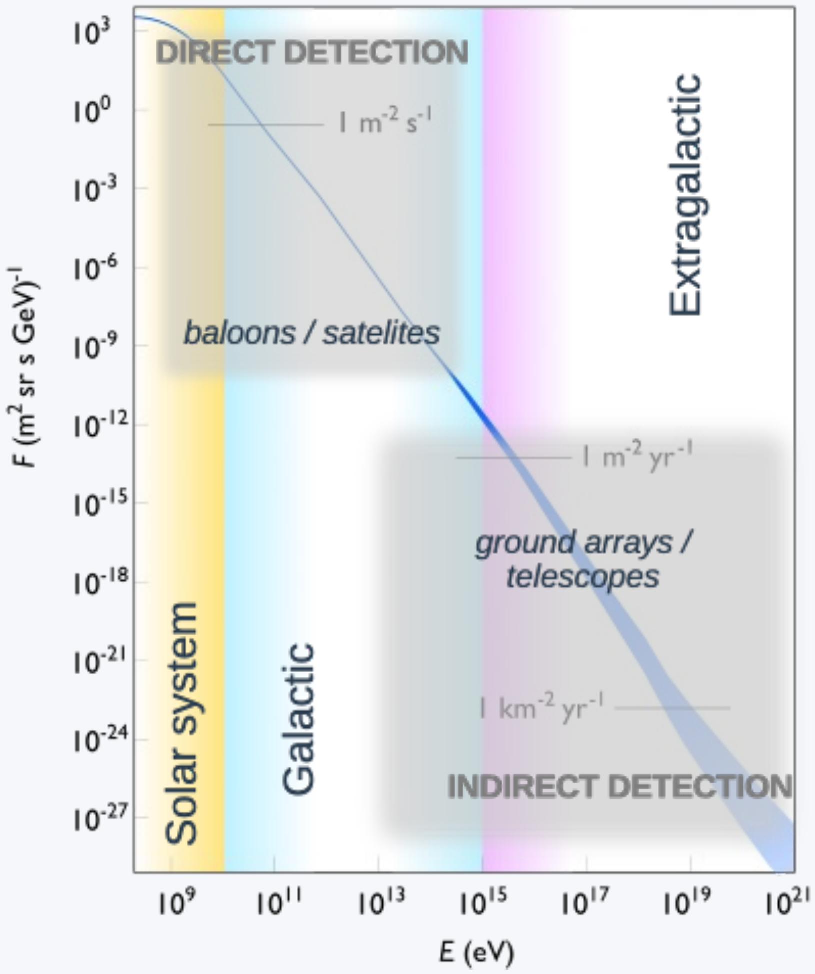
Pierre Auger Observatory · CTAO

Jožef Stefan Institute, Ljubljana
in collaboration with the Center for Astrophysics and Cosmology (CAC), University of Nova Gorica

15-minute overview · Group activities & collaboration

Outline

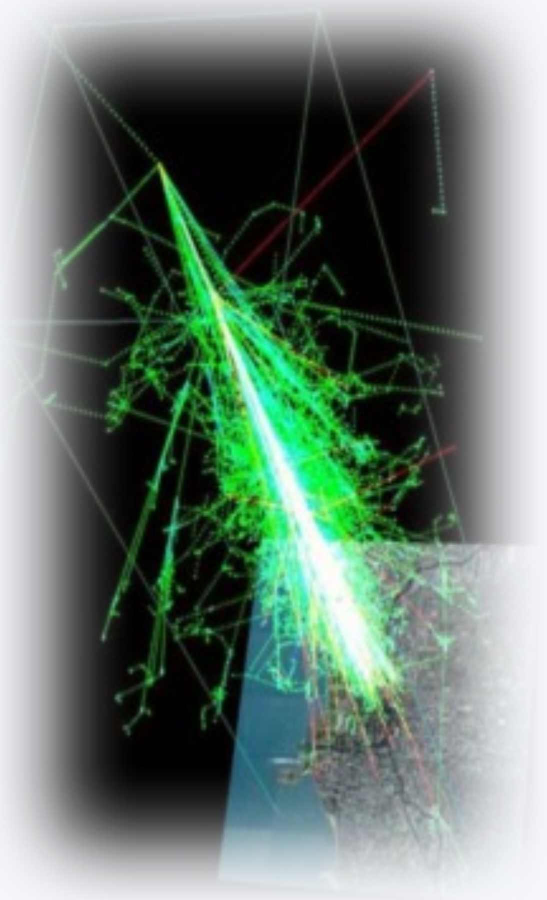
The highest-energy particles in the Universe



- The flux and the energy spans over tens of order of magnitudes.
- By source they are solar, galactic and extragalactic
- High-energy CR create showers in the atmosphere
- Depending on energy we can detect them
  - Directly
  - Indirectly

The main challenge is owerwhelming backgrounds

(atmospheric muons: 10,000 per square meter per second at sea level + background radiation)



UHECR >10^{18} eV, EECR > 5×10^{19} eV

01 · THE PROBLEM

The highest-energy particles in the Universe

Ultra-high-energy cosmic rays (UHECRs) reach energies beyond 10^{20} eV — millions of times higher than any accelerator on Earth can produce. Fundamental questions remain open:

1

Origin

Where and how are these particles accelerated? Which astrophysical sources reach such extreme energies?

2

Composition

Are the primaries protons, or heavier nuclei? The answer shapes every other conclusion.

3

Propagation

How do cosmic magnetic fields and interactions with the CMB (the GZK effect) shape what we observe?

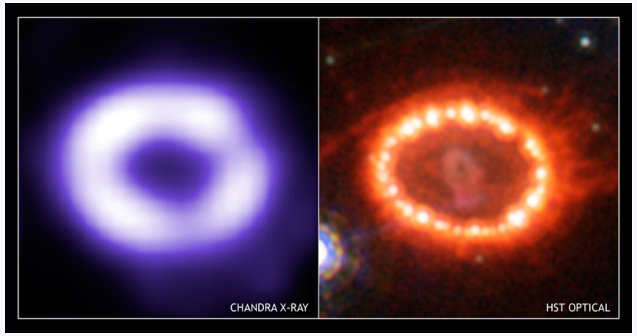
4

New physics

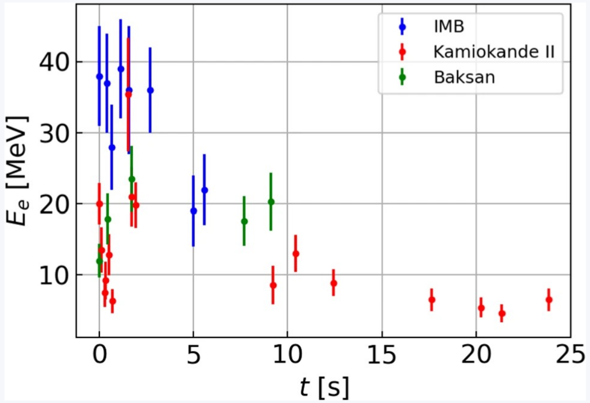
Do interactions at these energies, far above collider reach, hint at physics beyond the Standard Model?

Two windows on the extreme Universe

Cosmic rays and gamma rays are two messengers from the same extreme accelerators *(there are others like Neutrinos, Gravitational waves, WIMPs ..)*
Studying them together is the core motivation for **multi-messenger astrophysics**.



SN1987A → Kamiokande II



Ultra-high-energy cosmic rays

charged nuclei, 10^18–10^20+ eV

- Deflected by galactic & extragalactic magnetic fields
- Traced indirectly via giant particle showers in the atmosphere
- Pierre Auger Observatory

Very-high-energy gamma rays

neutral photons, 20 GeV–300 TeV

- Travel in straight lines — point back to their sources
- Probe particle acceleration, dark matter, extreme environments
- CTAO (Cherenkov Telescope Array Observatory)

Pierre Auger Observatory

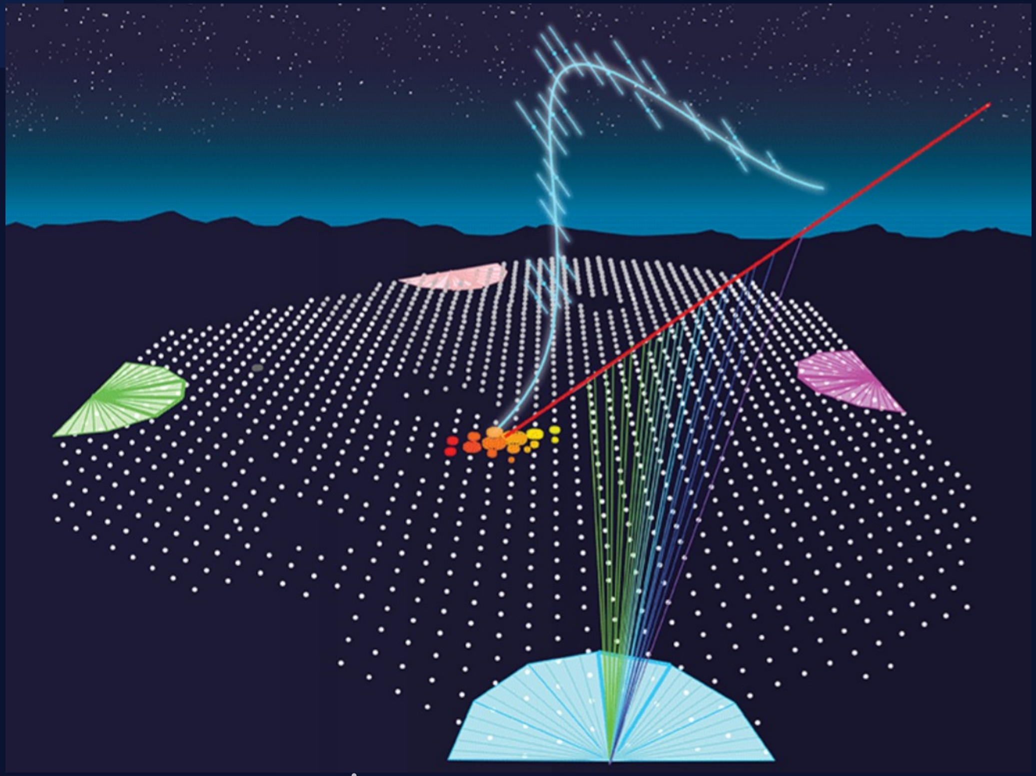
The world's largest cosmic-ray observatory — Malargüe, Mendoza Province, Argentina

3,000 km²
surface array area

1,660
water-Cherenkov stations

27
fluorescence telescopes

17
countries



Hybrid detection technique

Surface Detector (SD)

Water-Cherenkov tanks sample the shower's particle footprint at ground level — full duty cycle, day and night.

Fluorescence Detector (FD)

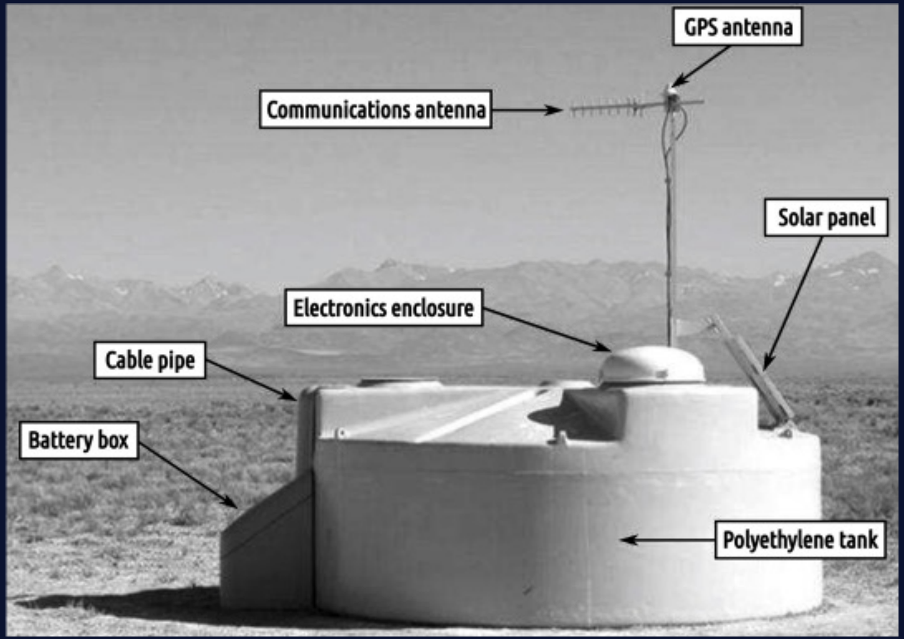
Telescopes image the faint UV fluorescence trail of a shower developing in the atmosphere, on clear moonless nights.

Hybrid events

Combining SD and FD data cross-calibrates energy and direction, anchoring the observatory's whole energy scale.

Pierre Auger Observatory

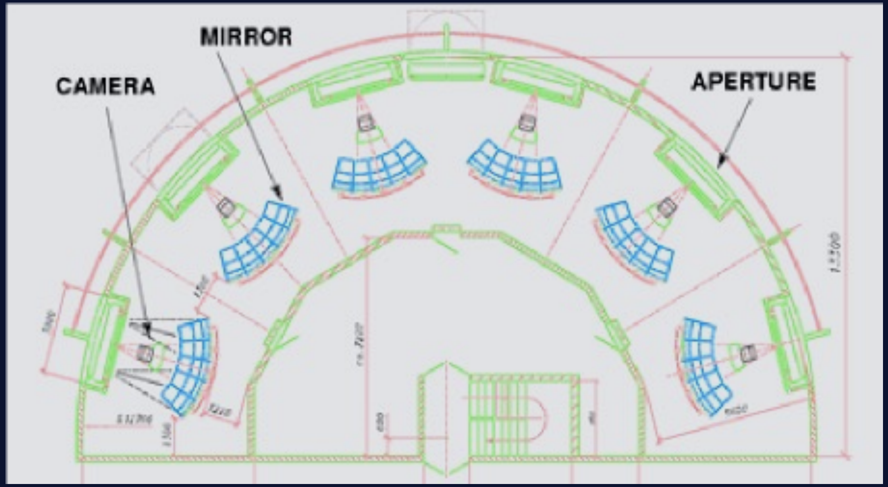
Ground Detector



1.6 m height, 3,6 m radius, 12 t deionized water
Solar cell power supply 110W + 210 Ah batterie
3x Photonis XP1805
GPS Oncore UT for timming (10 ns RMS)
Extended WLAN 902-928 Mhz for coms.

Fluorescence Detector

4 buildings
6 sectors each with camera
Reflector: r=3,4m, 13m2
Camera: 440hex xp3062 PM
(30 x 30)º field of view



AugerPrime — upgrading the Observatory

Auger data show the highest-energy cosmic rays are dominated by heavy nuclei — but disentangling the muonic and electromagnetic parts of a shower, event by event, needs new instrumentation.

Scintillator panels

Installed atop every water-Cherenkov station to separate the muonic and electromagnetic shower components.

Underground muon detectors (AMIGA)

Buried particle counters give a direct, shielded measurement of the shower muon content.

Radio antennas

Extend measurements to showers arriving at high zenith angles, complementing the surface array.

Upgraded electronics

Faster sampling and small-area PMTs extend the dynamic range of every station.

Spectrum, Composition, Anisotropy, Sources, Multi-messenger

Multi-messenger observations of a binary neutron star merger. *The astrophysical journal. Letters*. 2017, vol. 848, no. 2, str. 1-59, ilustr.

3614 co-authors
LIGO, Virgo, Auger, IceCube, Antares, Fermi-LAT, Agile, AstroSat, ALMA, LOFAR …

CTAO — Cherenkov Telescope Array Observatory

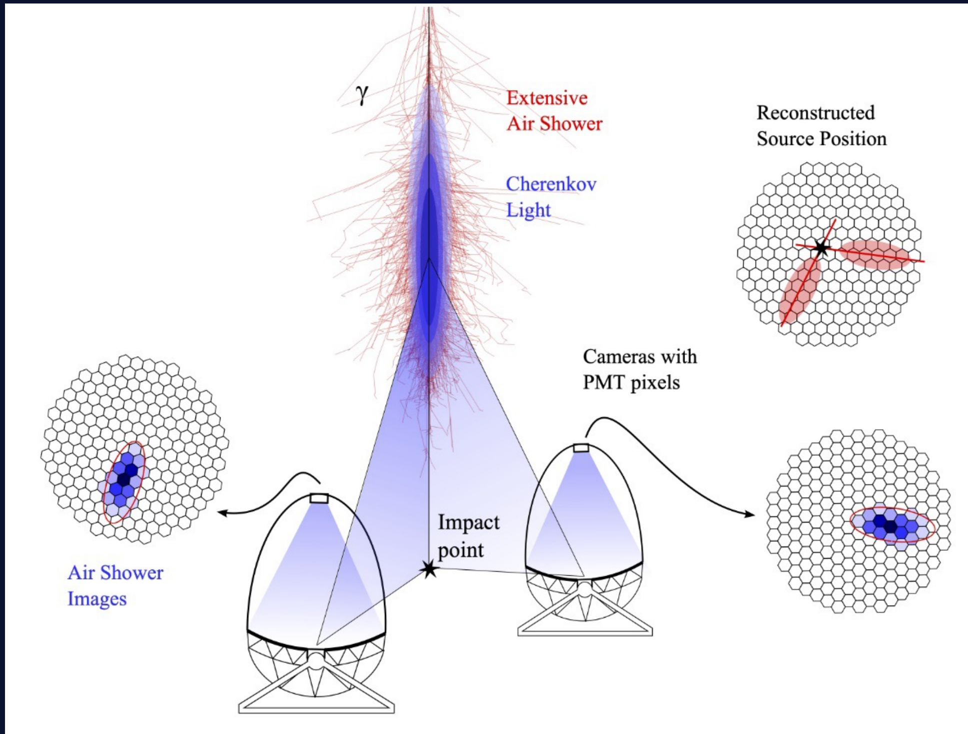
The next-generation ground-based observatory for very-high-energy gamma-ray astronomy — established as a European Research Infrastructure Consortium (ERIC) in January 2025, with Slovenia a founding member.

2 sites	**64 telescopes**	**20 GeV–300 TeV**	**10×**
La Palma & Paranal, Chile	large, medium & small	energy range covered	sensitivity vs. current arrays

How it works

A gamma ray striking the atmosphere produces a cascade of secondary particles that briefly emit **Cherenkov light** — a faint blue flash a few nanoseconds long. Telescope arrays image the flash to reconstruct the gamma ray's energy and direction, and reject the much larger cosmic-ray background.

Science goals: cosmic-ray origins, extreme accelerators (black holes, pulsars, supernova remnants), dark matter, fundamental physics.



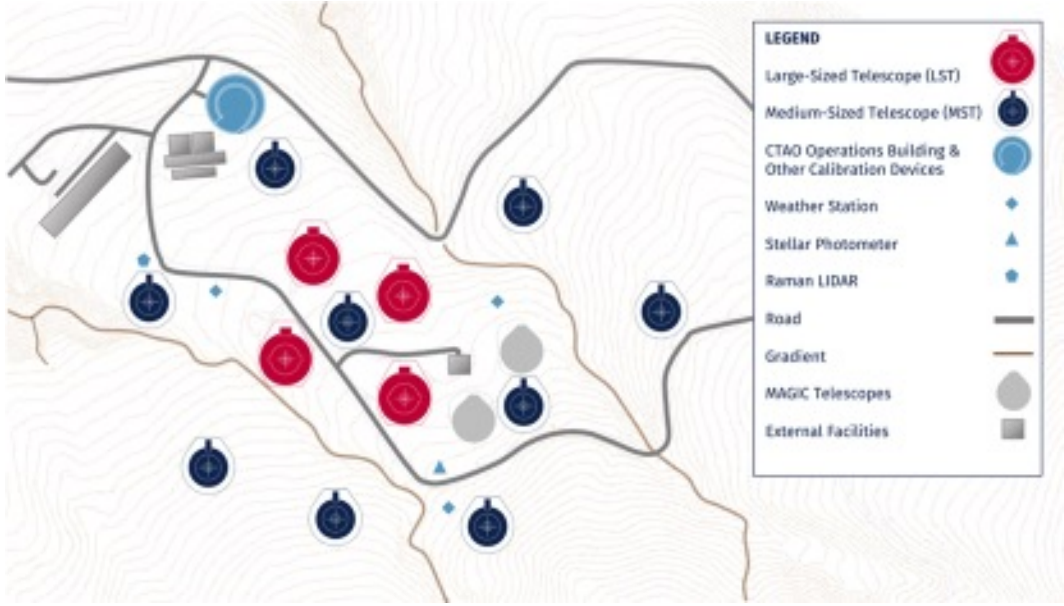
An imaging atmospheric Cherenkov telescope, capturing the blue flash of an air shower

CTAO — Cherenkov Telescope Array Observatory

Northern site

Instituto de Astrofisica de Canarias, Roque de los Muchacos, La Palma, Canarias

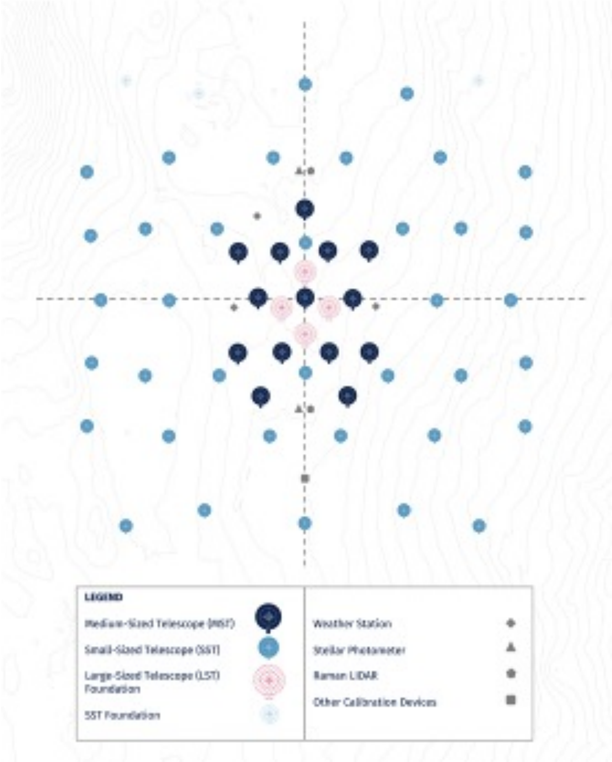
SST 0, MST 15, LST 4



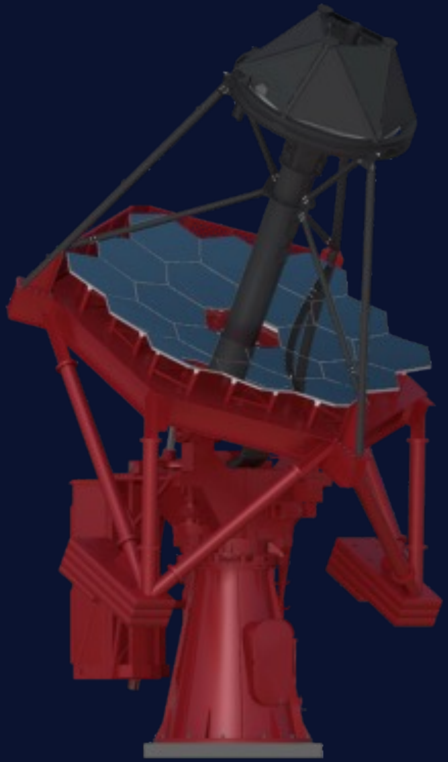
Southern site

European Southern Observatory, Paranal, Chile

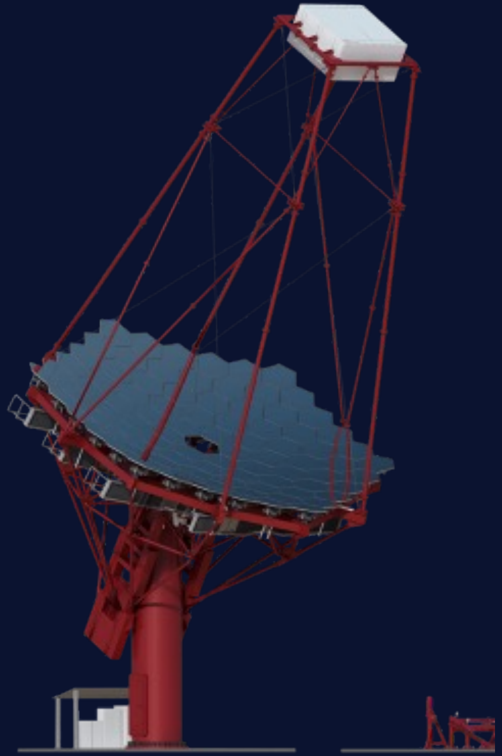
SST 70, MST 25, LST 4



CTAO — SST MST

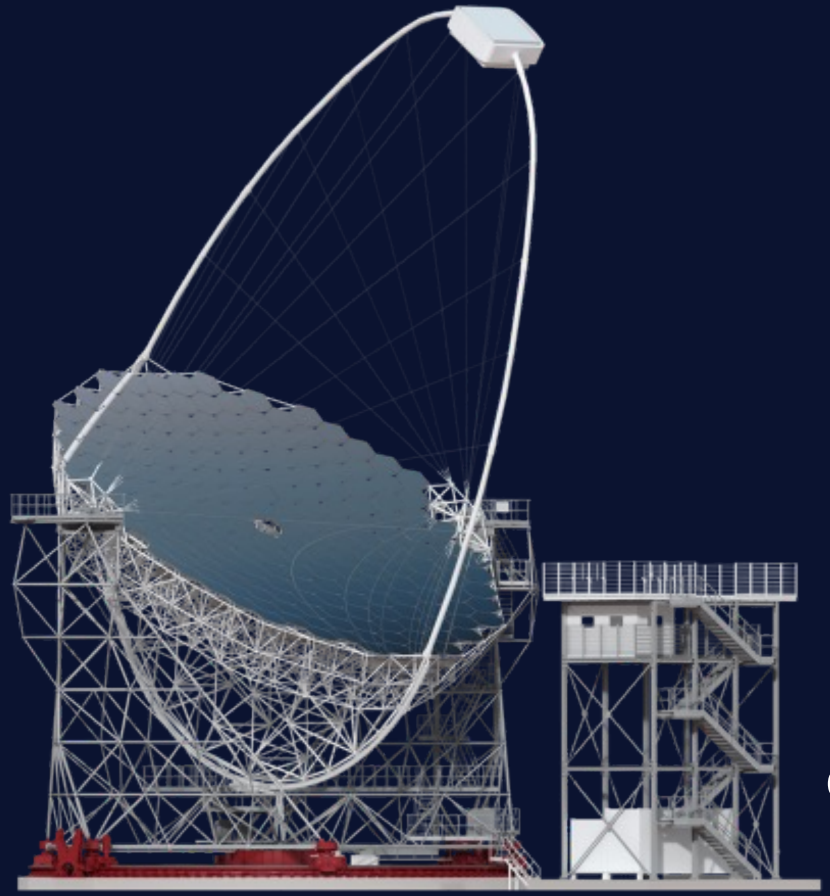


5 Tev – 300 TeV
4,3 m diameter
70 S, 0 N



150 GeV – 5 TeV
12,5 m diameter
25 S, 15 N

CTAO — LST



20 Gev – 150 GeV
23 m diameter
400 m2
Camera: 1855 PM, 2T
4 S, 4 N

CTAO — Current Activities

Cherenkov Telescope Array Observatory · status as of September 2026

CTAO-North (La Palma, Spain)

- LST-1 operating; LST-2–4 under deployment at ORM
- LST-4 camera installed, commissioning underway
- Inauguration of the 4 LSTs planned for Oct 2026
- First 5 MST installations progressing; infrastructure tenders launching

CTAO-South (Paranal, Chile)

- Groundbreaking held; telescope foundation construction begun
- First SSTs and MSTs expected by early/late 2027
- MST and SST pathfinders to be deployed in 2027

Organization & Operations

- Established as a European Research Infrastructure Consortium (ERIC), Jan 2025
- ERIC enables construction of full 64-telescope array to begin
- ACADA control & data-processing software being integrated
- Intermediate array configurations targeted from 2026, ahead of full science operations

Source: CTAO, ESO, IAC public updates (2025–2026)

CTAO — Current Analysis & Simulation Results

Monte Carlo–based performance and recent science-simulation studies

Baseline Performance (Alpha Configuration)

- Official sensitivity curves from Prod5 Monte Carlo simulations (CORSIKA + sim_telarray)
- North: 4 LSTs + 9 MSTs (~0.25 km²); South: 14 MSTs + 37 SSTs (~3 km²)
- 5σ point-source sensitivity published for 0.5h, 5h and 50h exposures
- Instrument Response Functions (IRFs) define effective area, angular/energy resolution, background

Recent Science Simulation Studies

- PeVatron candidates (Cas A, RX J1713.7-3946, HESS J1731-347) excluded at >5σ using simulated CTAO data
- Simulations show sensitivity to cosmic-ray spectral cutoff shape (β) in SNRs, aiding proton-vs-heavy-ion discrimination
- Forecasts for blazar jets, FR0 radio galaxies and binary neutron star mergers assess multi-messenger detectability

Tools & Methodology

- Gammapy used for ON/OFF simulated observations and IRF-based forecasting
- Visibility and zenith-angle studies (North vs South) optimize simulated exposure times
- MC simulation remains the primary basis for analysis ahead of on-sky science data

Source: CTAO Performance page (ctao.org), arXiv:2410.21199, arXiv:2603.05927, arXiv:2605.21320, arXiv:2604.08748

F9 in the Pierre Auger Collaboration

The F9 astroparticle group has been a member institution of the Pierre Auger Collaboration for over two decades, contributing to both hardware and physics analysis.

Physics analysis

- Mass composition studies (X_max, muon content) of ultra-high-energy cosmic rays
- Searches for large- and small-scale anisotropies in arrival directions
- Searches for ultra-high-energy photons and neutrinos
- Machine-learning-based mass reconstruction with AugerPrime data

Instrumentation

- Design and characterisation of the silicon photomultiplier (SiPM) front-end for AMIGA underground muon detectors
- Contributions to the AugerPrime detector upgrade

Atmospheric monitoring

- Involvement in atmospheric monitoring instrumentation (LIDAR and robotic photometric telescopes such as FRAM) that calibrates fluorescence measurements

M. Zavrtanik – *PAO CB member*

F9 in the CTA Consortium / CTAO

Since 2013, F9 has been part of the Cherenkov Telescope Array Consortium (CTAC), together with CAC UNG, helping shape the observatory's design, strategy and early science.

Dark matter & new physics

- Searches for dark-matter signatures in gamma-ray data using machine-learning methods
- Preparatory studies for CTAO's sensitivity to new physics beyond the Standard Model

Site & atmospheric infrastructure

- Co-development of a Raman LIDAR system for atmospheric monitoring at the La Palma (north) site
- Joint work with IFAE Barcelona, Universitat Autònoma de Barcelona and Università di Padova

Strategy & governance

- Contributions to the CTAO scientific programme and publications during the preparatory phase
- Slovenia is a founding member of CTAO ERIC (2025); UNG represents Slovenia in CTAO bodies

M. Zavrtanik – ***vice-chair of the CTAO ERIC AFC,*** **K.Schlegel –** ***member CTAO ERIC AFC***
K. Schlegel & S. Stanic – ***CTAO Council members***

05 · COLLABORATION

A joint Slovenian astroparticle effort

F9 (JSI) and the Center for Astrophysics and Cosmology (CAC) at the University of Nova Gorica form Slovenia's astroparticle physics community, active together in both experiments since 2013.

Shared publications

F9 and CAC UNG appear together as co-authors on Pierre Auger Collaboration papers, e.g. searches for ultra-high-energy photons.

Joint CTAC / CTAO membership

Both institutes have been members of the CTA Consortium since 2013, contributing jointly to design and strategy.

Instrument development

Collaboration extends to shared infrastructure work, such as atmospheric-monitoring instrumentation for CTAO.

National representation

CAC and F9 represents Slovenia in CTAO governance bodies; F9 and UNG together sustain Slovenia's role as a CTAO ERIC founding member.

BEYOND RESEARCH

Education & outreach

The Pierre Auger Collaboration runs education and outreach activities across its 17 member countries — International Masterclasses, European Researchers' Night events, and remote observatory visits bring cosmic-ray physics to students and the public, with Slovenian participation part of this wider effort.

1

International Masterclasses

Students analyse real Auger data remotely, guided by collaboration scientists.

2

European Researchers' Night

Public demonstrations — from fluorescence-light displays to VR air-shower experiences.

3

Public engagement in Slovenia

F9 and CAC UNG bring astroparticle physics to Slovenian students and the public.

SWOT analysis

F9's position in the Pierre Auger and CTAO collaborations, and in the partnership with CAC UNG.

Strengths

- 20+ years in Auger, 10+ in CTAO — deep institutional knowledge
- Combined hardware (SiPM/AMIGA, atmospheric monitoring) and analysis expertise
- Close, complementary partnership with CAC UNG
- Direct access to unique, large-scale research infrastructure

Weaknesses

- Small group size relative to large international collaborations
- Limited local computing/data infrastructure for large-scale analysis
- Hands-on hardware work depends on remote sites (Argentina, La Palma, Chile)
- Funding tied to national research-agency cycles

Opportunities

- CTAO entering construction and early-science phase — room to grow scientific role
- AugerPrime data enabling new machine-learning-based analyses
- Growing multi-messenger astrophysics field and visibility
- EU/ERC project funding to recruit PhD students and postdocs

Threats

- Competition from larger, better-resourced groups for leading analysis roles
- Budget pressure on national science funding
- Coordination overhead in large international collaborations
- Long observatory-upgrade timelines can delay scientific payoff

Summary

- Open questions about UHECR origin, composition and propagation, and about the extreme gamma-ray Universe, motivate two flagship experiments.
- Pierre Auger Observatory (surface + fluorescence detectors, now upgraded as AugerPrime) and CTAO (arrays of Cherenkov telescopes) tackle these from complementary angles.
- F9 contributes hardware, atmospheric monitoring and physics analysis to both, building on more than two decades of involvement in Auger and over a decade in CTAO.
- This work is carried out in close, long-standing collaboration with the Center for Astrophysics and Cosmology at the University of Nova Gorica — together forming Slovenia's astroparticle physics community.

Looking ahead: continued AugerPrime data taking and analysis, and growing involvement as CTAO construction and early science proceed at La Palma and Paranal.

Thank you

Questions & discussion welcome

F9 — Department of Experimental Particle Physics, Jožef Stefan Institute
Center for Astrophysics and Cosmology, University of Nova Gorica