Gamma -ray astronomy with SST-1M Imaging Atmospheric Cherenkov Telescopes

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6.6.-8.6.2025

Credit: Jiří Srba

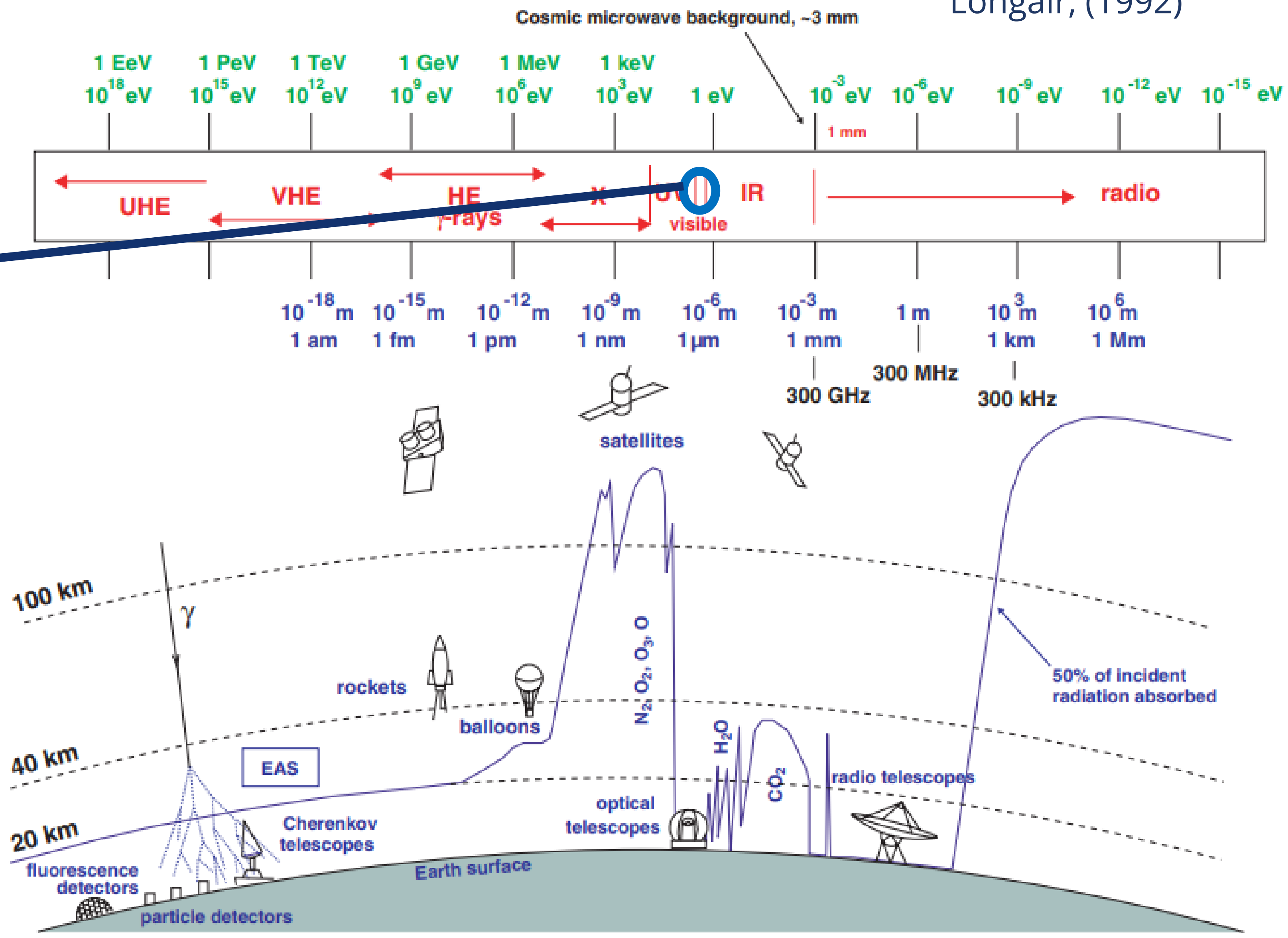
SST-1M Single-Mirror Small Size Telescope
FZU Institute of Physics of the Czech Academy of Sciences
PHYSICS FOR FUTURE
Co-funded by the European Union

Outline

- **Imaging Atmospheric Cherenkov Telescopes**
- **Single Mirror Small Size Telescopes – SST-1M project**
- **Performance and scientific results of SST-1M**

Transparency of the atmosphere in different domains of electromagnetic spectrum

Longair, (1992)



Barbosa, (2022)

PHYSICS FOR FUTURE

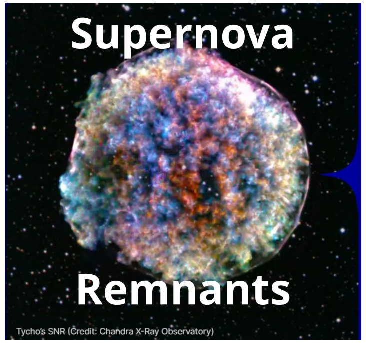
Very-high-energy gamma rays

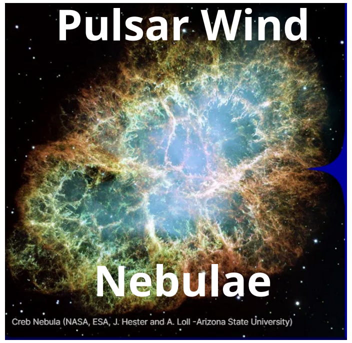
- **Energies**: tens of GeV and more = VHEGR
- **Sources**: non-thermal Universe
  - regions where charged particles are accelerated
  - magnetic fields and shock waves
  - supernova remnants, pulsar wind nebulae, active galactic nuclei …

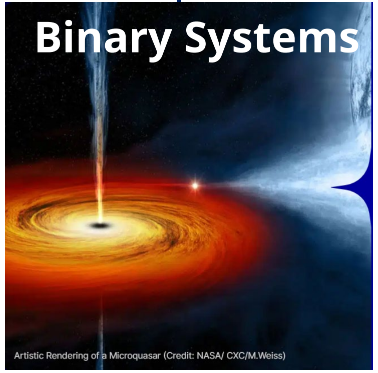
- **Objectives**:
  - search for origin of charged cosmic rays
  - study of the processes near neutron stars and black holes
  - search for dark matter signatures
  - study of exotic phenomena (Lorentz inv. violation)
  - study extragalactic background light

PHYSICS
FOR
FUTURE

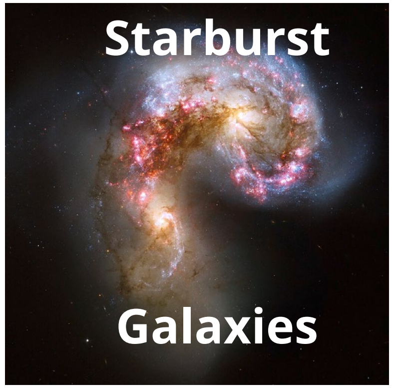
Galactic sources
Supernova remnants, microquasars, …



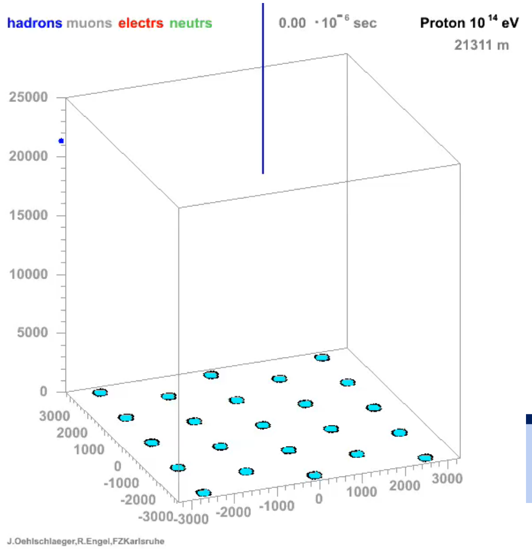




Extragalactic sources
AGNs, neutron star mergers (GRBs), …



Detection techniques in gamma-ray astronomy



Credit: The University of Sheffield

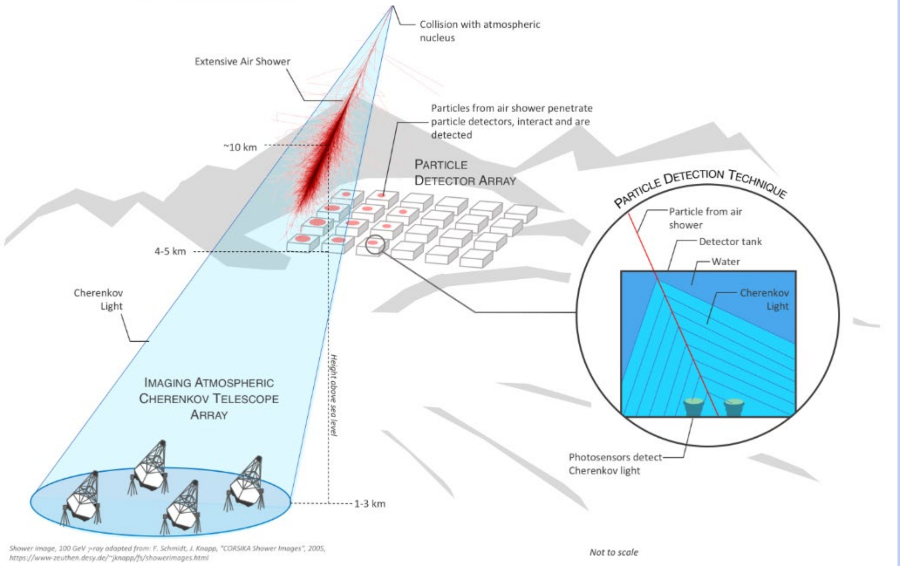
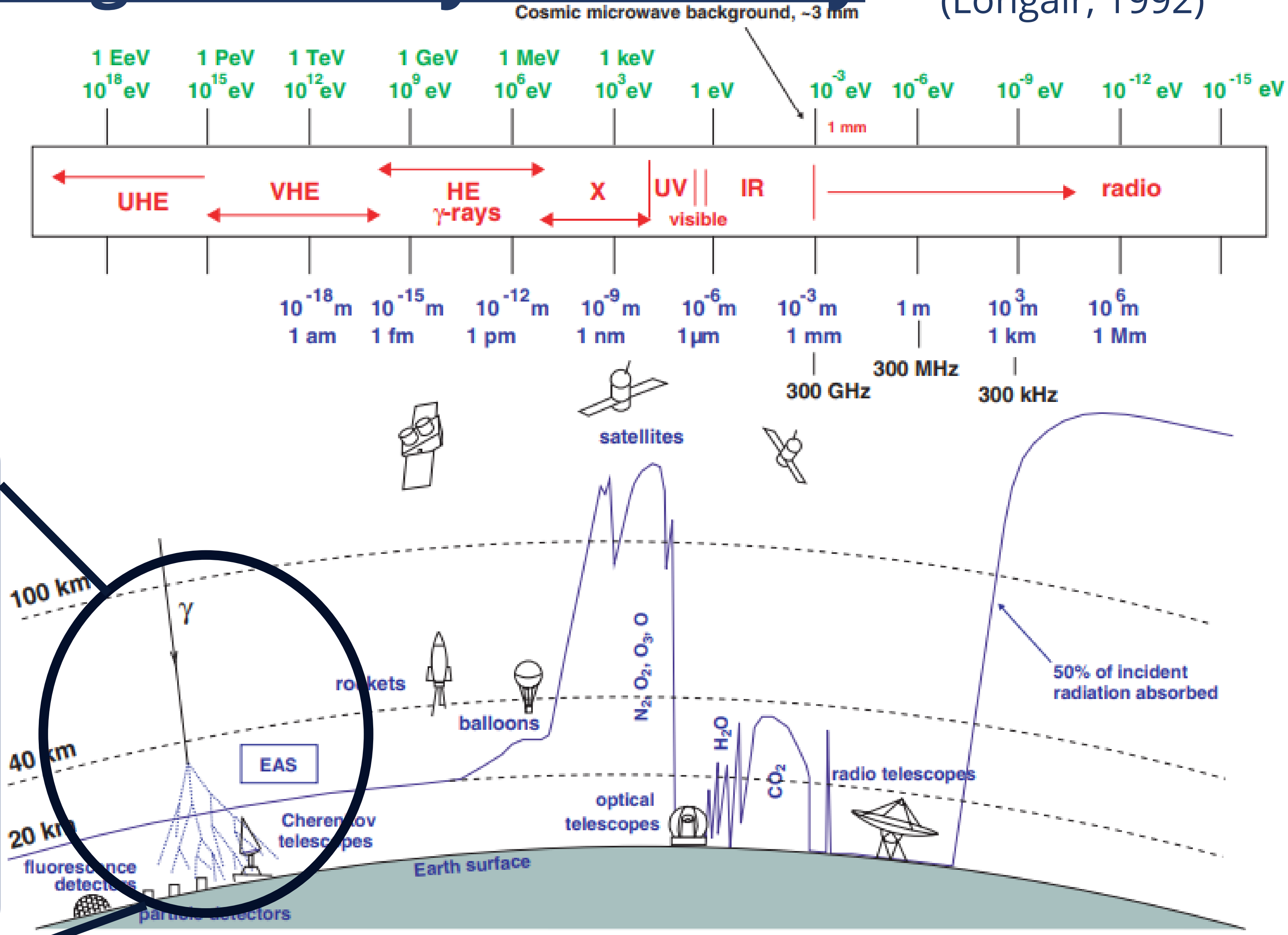
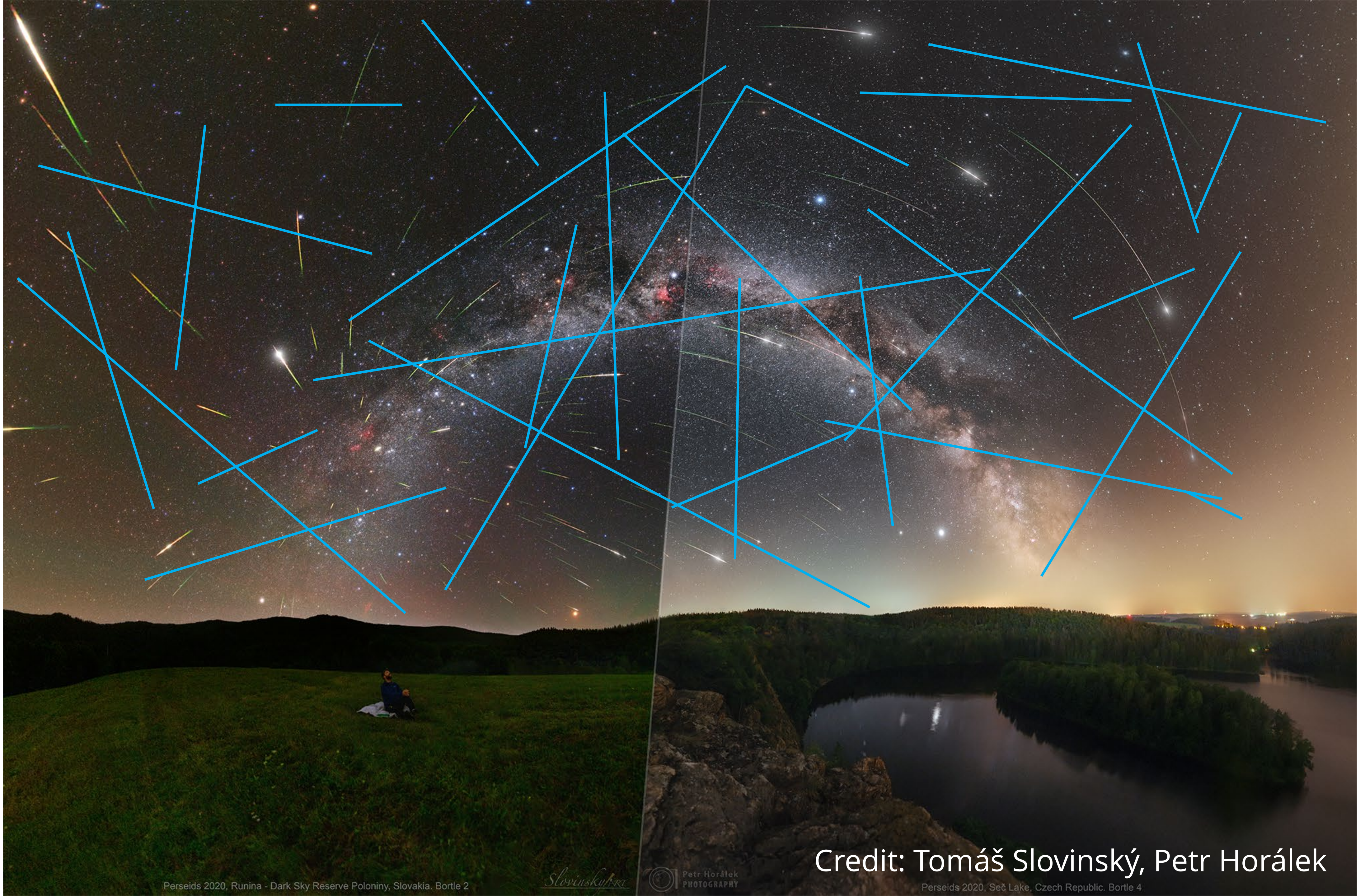


Illustration of the complementary detection techniques of high-energy gamma rays on ground. (Credit: Richard White, MPIK)

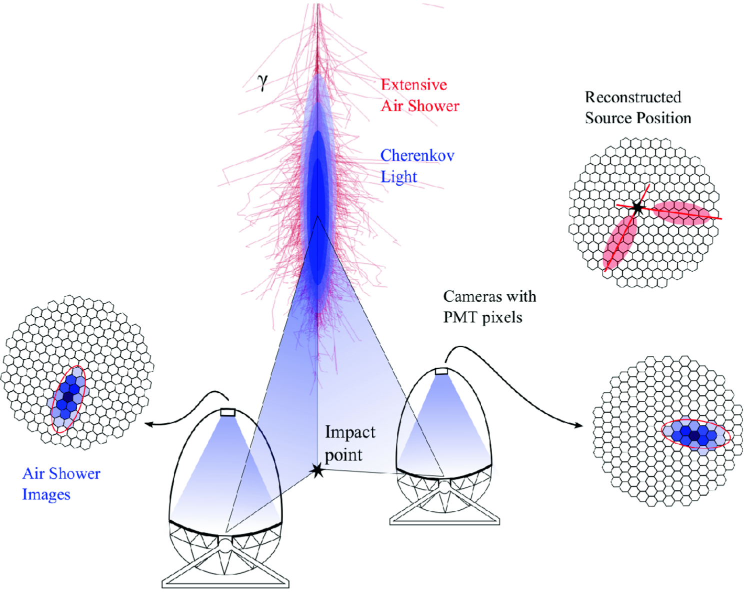
(Longair, 1992)





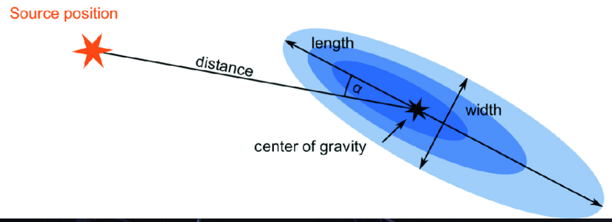
Credit: Tomáš Slovinský, Petr Horálek

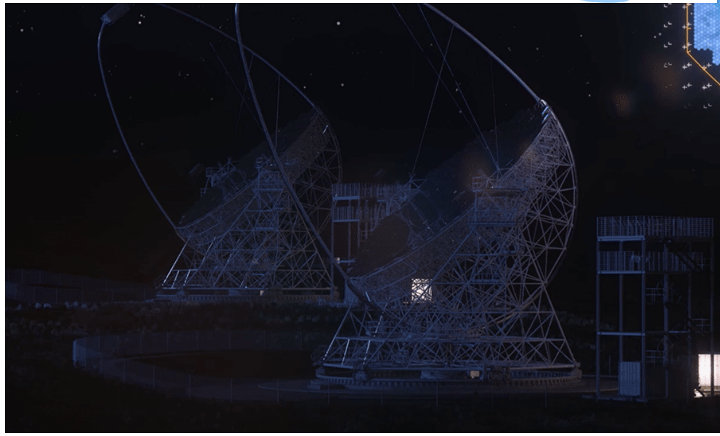
Credit: MAGIC collaboration



Imaging Atmospheric Cherenkov Telescopes

- **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

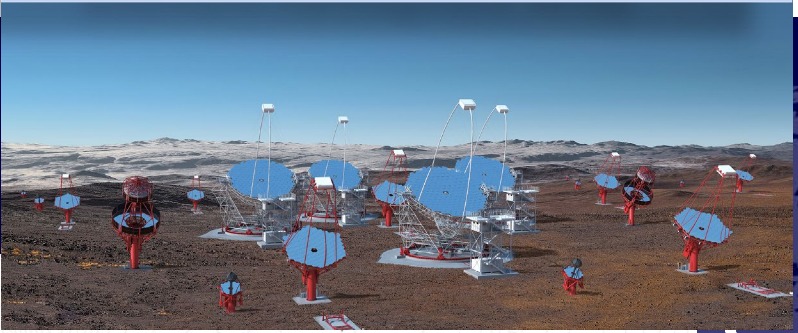
Credit: CTAO

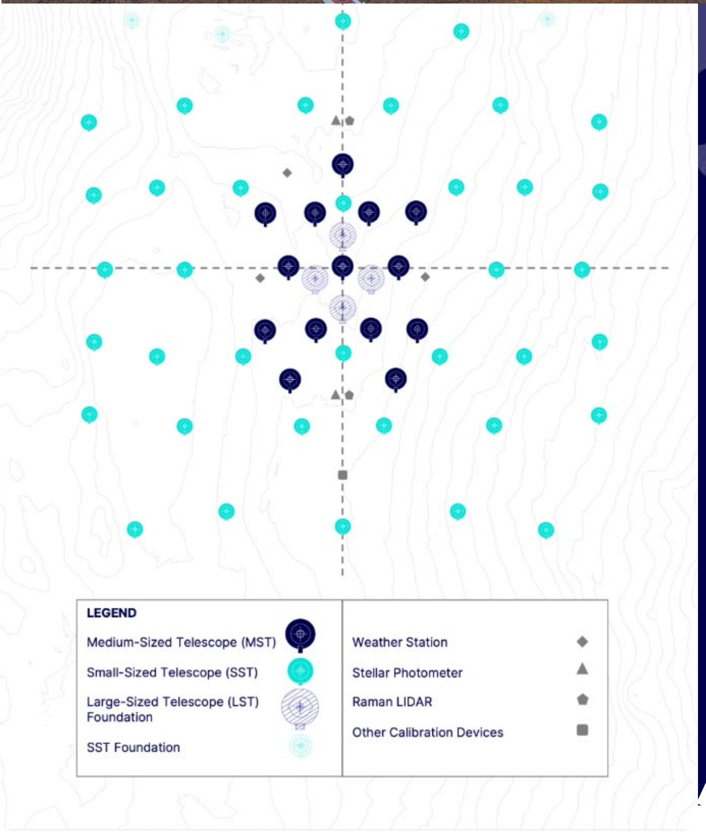
Imaging Atmospheric Cherenkov Telescopes (IACTs) across the world

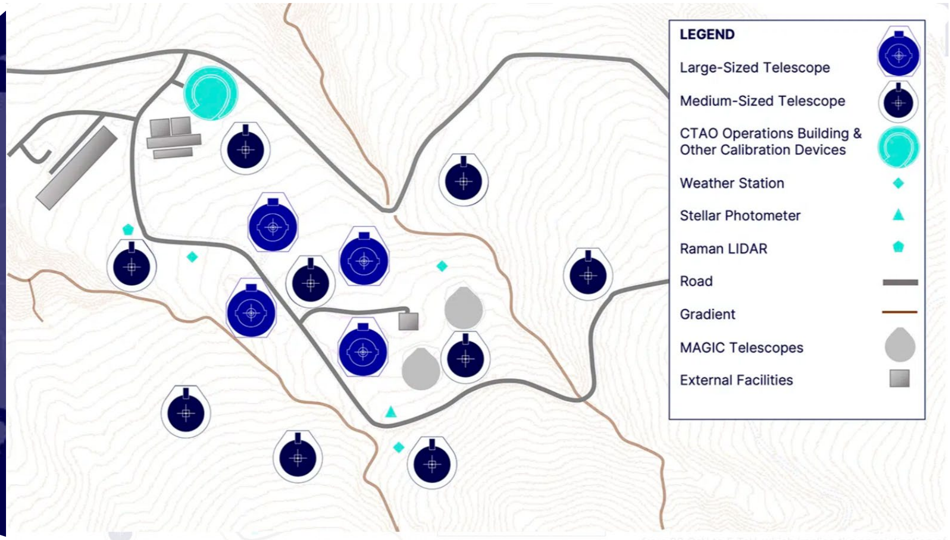
Credit: Wikipedia

Cherenkov Telescope Array Observatory (CTAO)

Southern Hemisphere Array

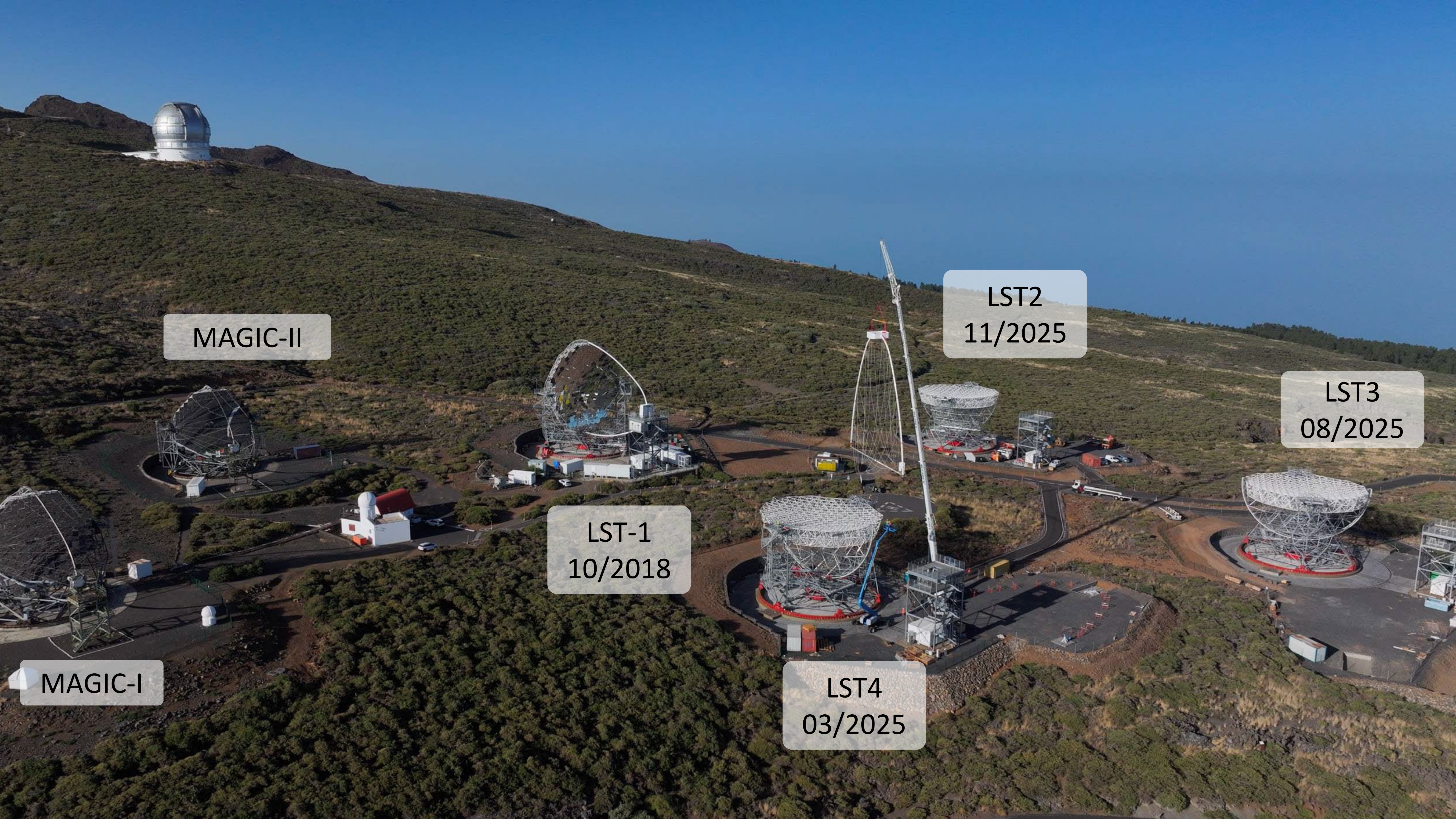






Northern Hemisphere Array

Credit: CTAO


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

SST-1M project

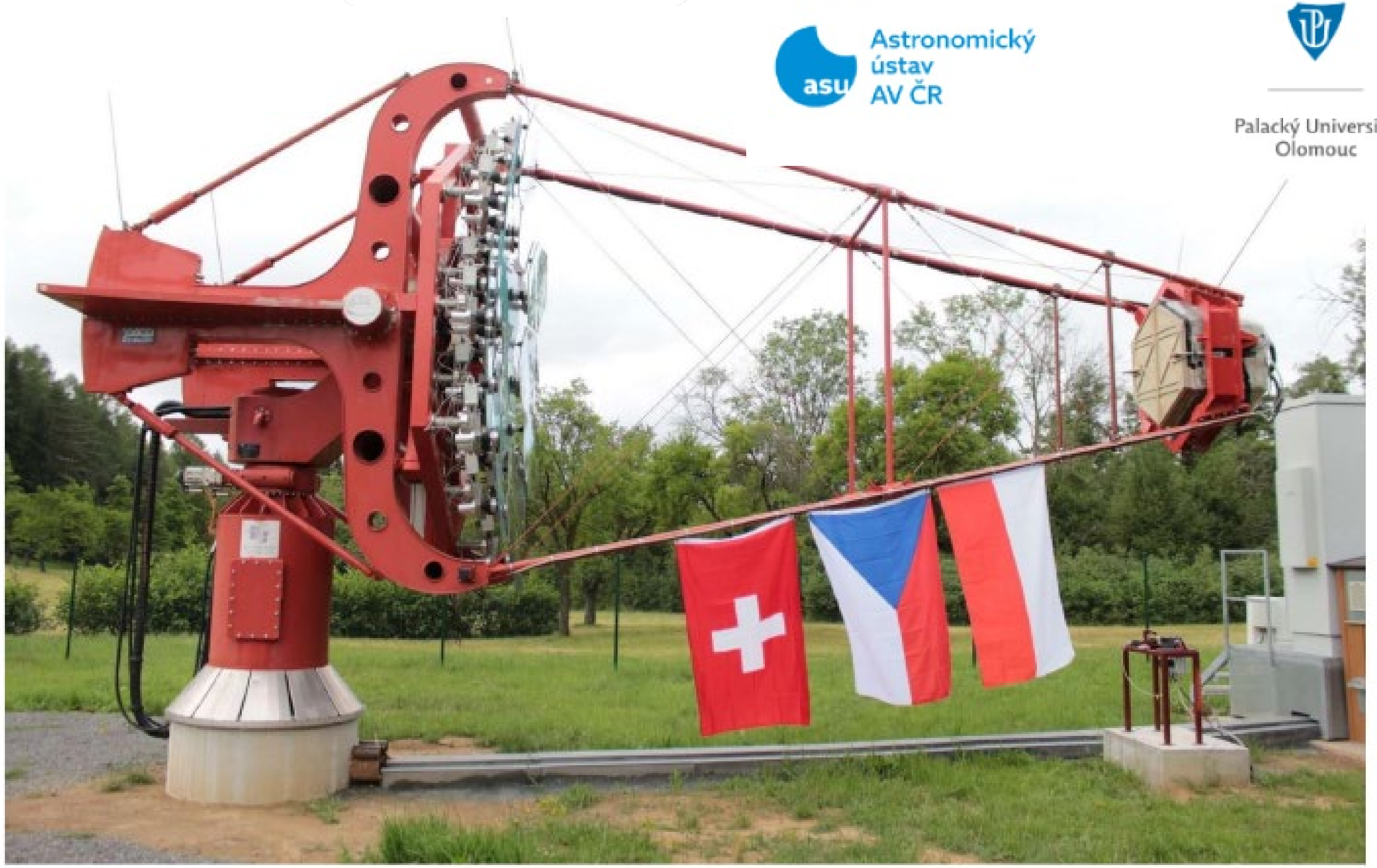
SST-1M
Single-Mirror
Small Size Telescope

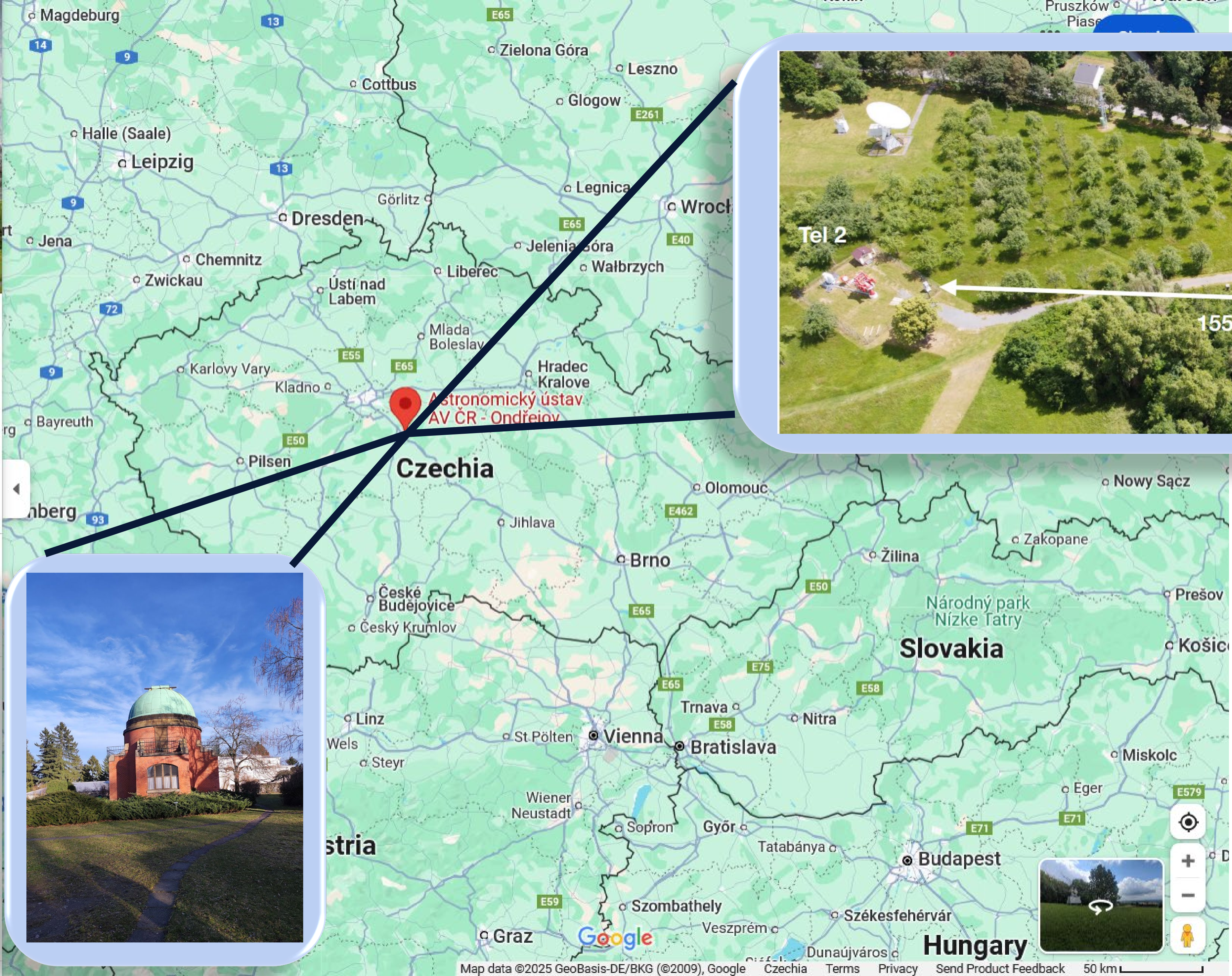
https://sst-1m.science/

SST1M_SPACE

- 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

Nicolaus Copernicus Astronomical Center
CBK Centrum Badań Kosmicznych Space Research Centre
The Henryk Niewodniczański Institute of Nuclear Physics Polish Academy of Sciences
AGH University of Science and Technology
Jagiellonian University in Krakow
Université de Genève Faculté des Sciences
ISDC
FZU Fyzikální ústav Akademie věd České republiky
Uniwersytet Warszawski
asu 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

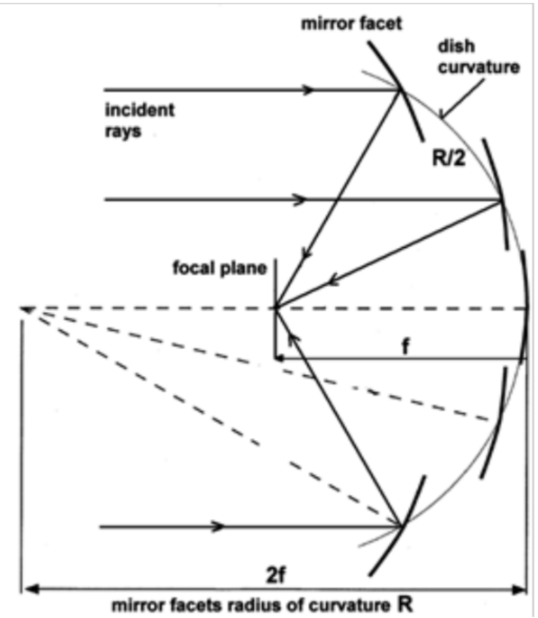
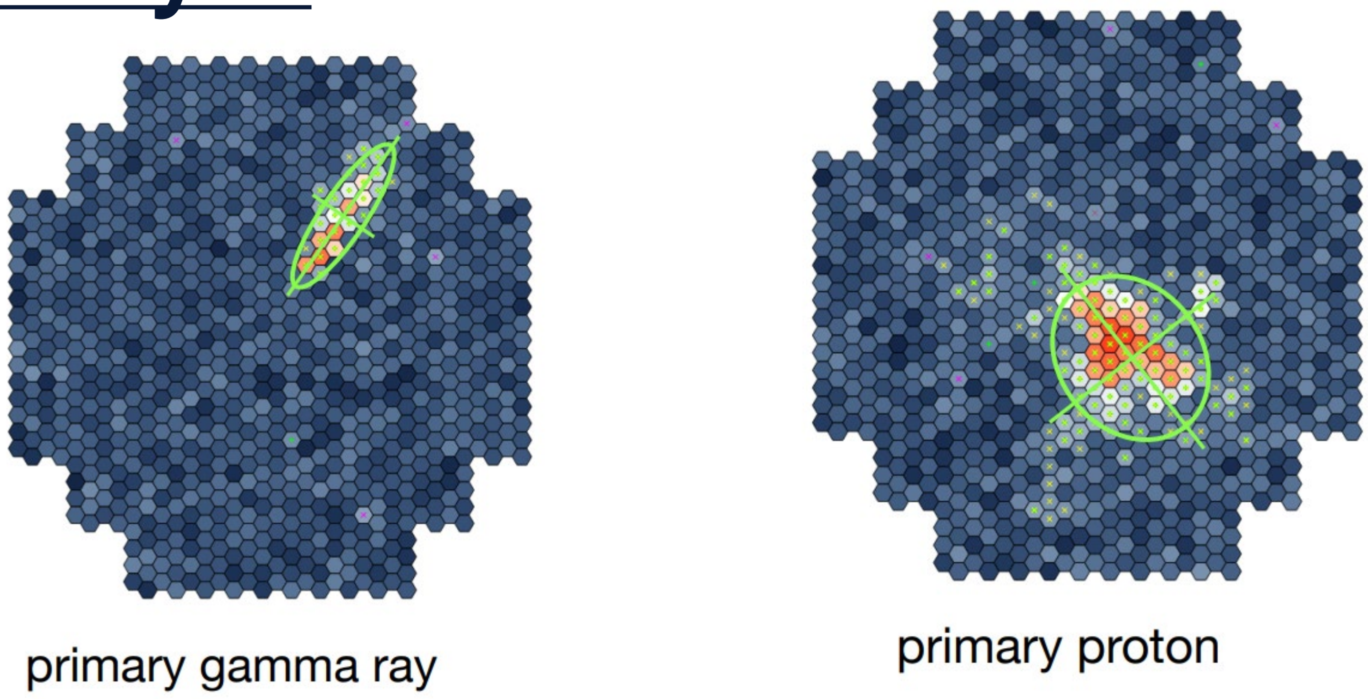
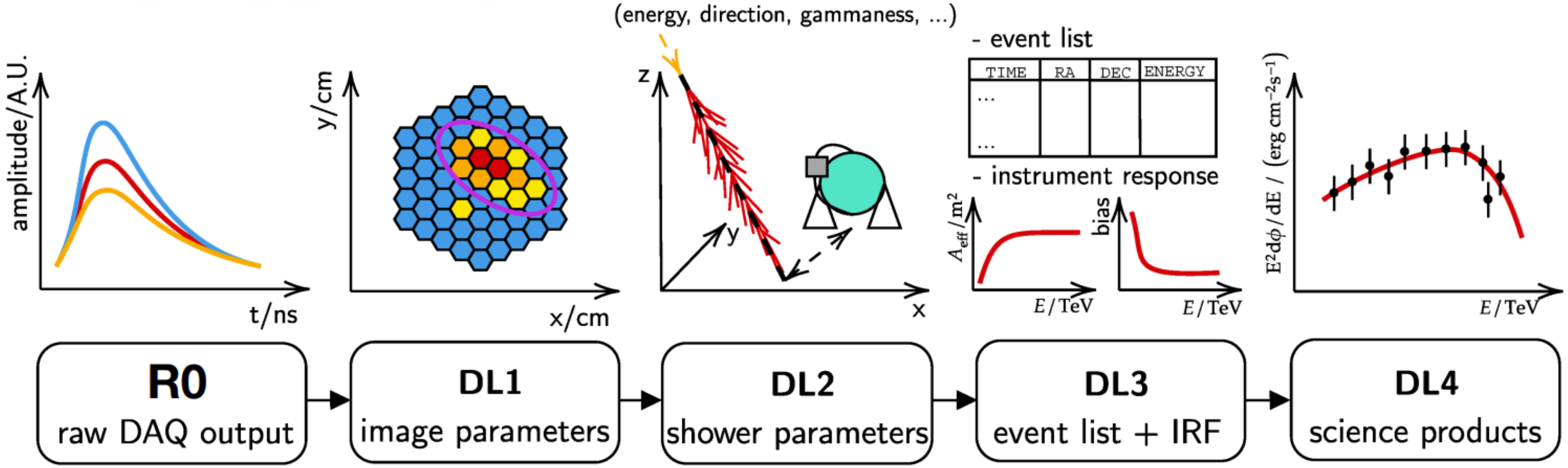


Figure adopted from Actis et al., (2011)

Pipeline and analysis



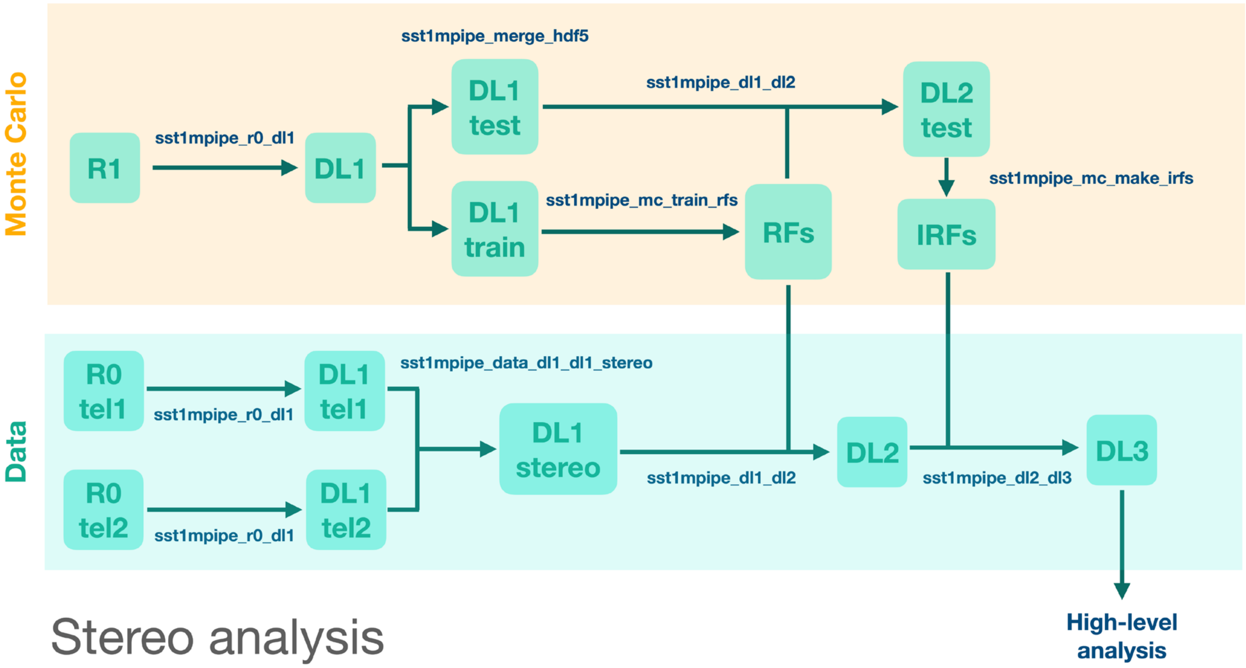


PHYSICS FOR FUTURE

sst1mpipe

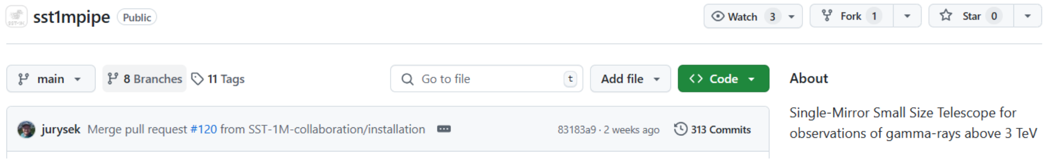
- Data and Monte Carlo analysis **software for low-level analysis** – waveform calibration and integration, shower-image parametrisation, stereo reconstruction, random forest training, instrument response function (IRF) calculation
- Pipeline is divided into several steps (r0 -> dl1 -> dl2 -> dl3) – 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

ctapipe



Stereo analysis

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

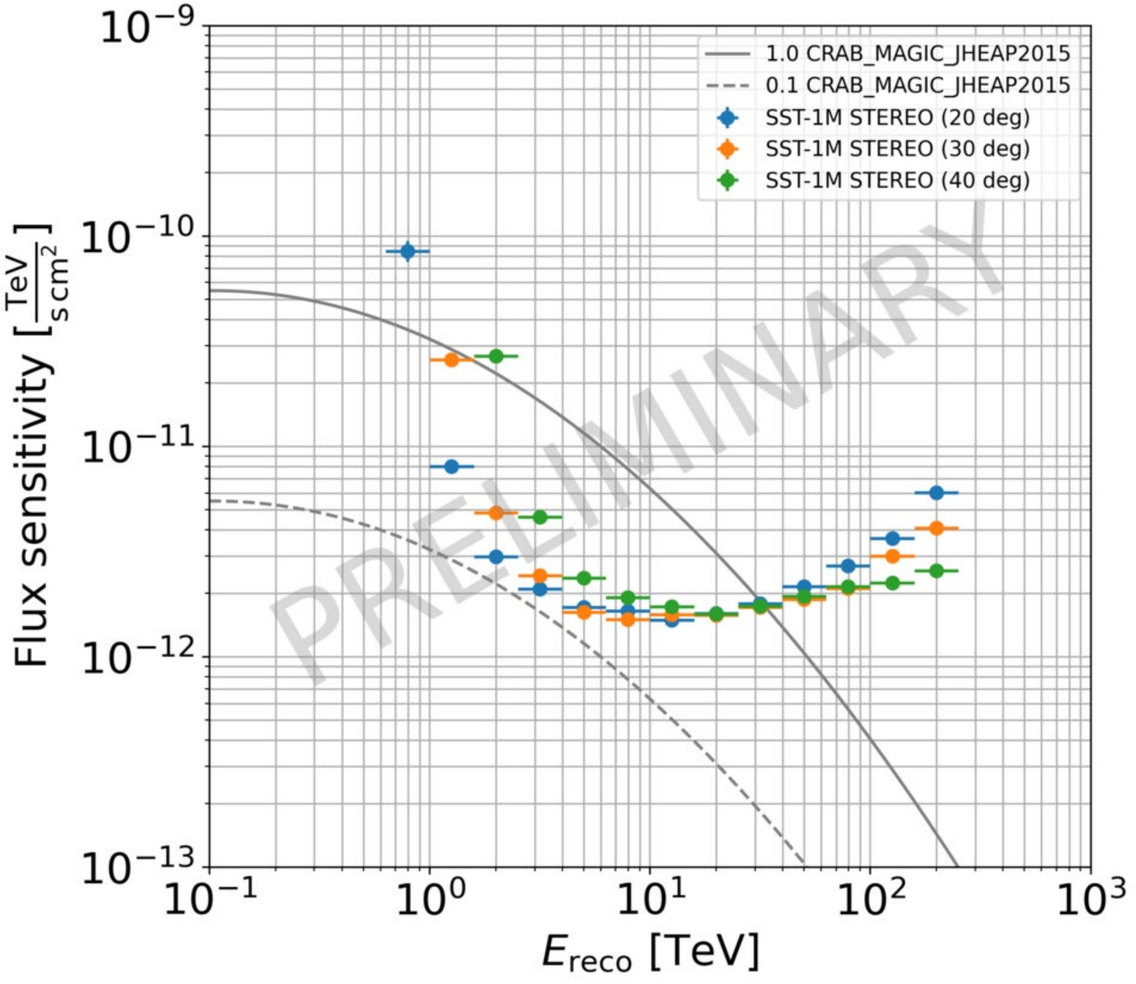


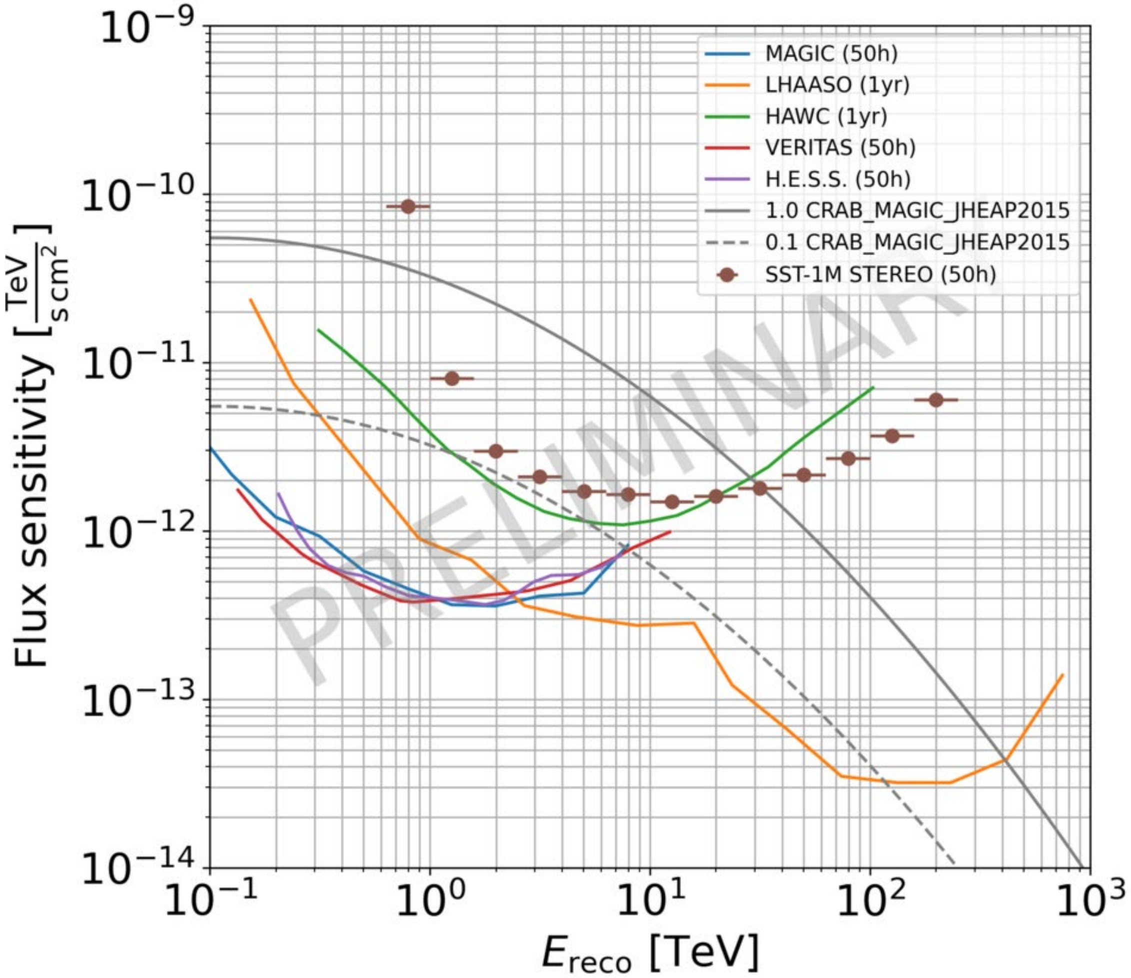
PHYSICS FOR FUTURE

Perfomance of SST-1M (Ondřejov)

- Sensitivity in energy domain approx. 1 TeV – 100 TeV
- Significant improvement of performance in stereo mode comparing to mono mode
- Results in stereo mode

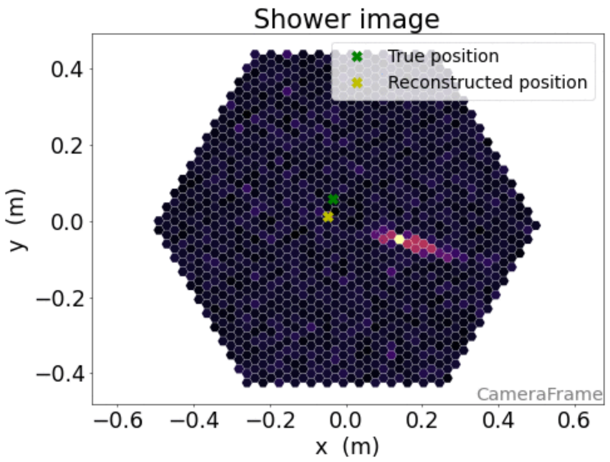
Juryšek et al., (2023), PoS(ICRC2023)592

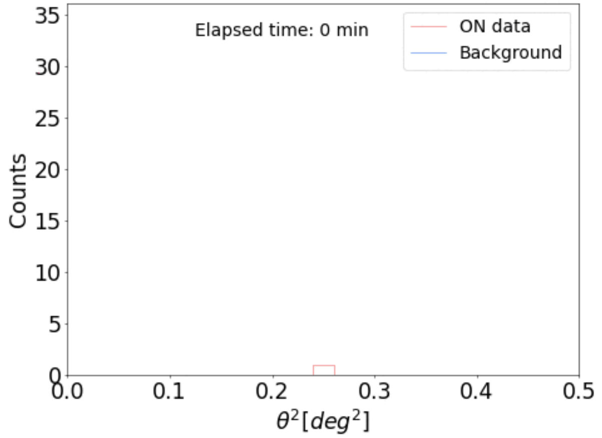




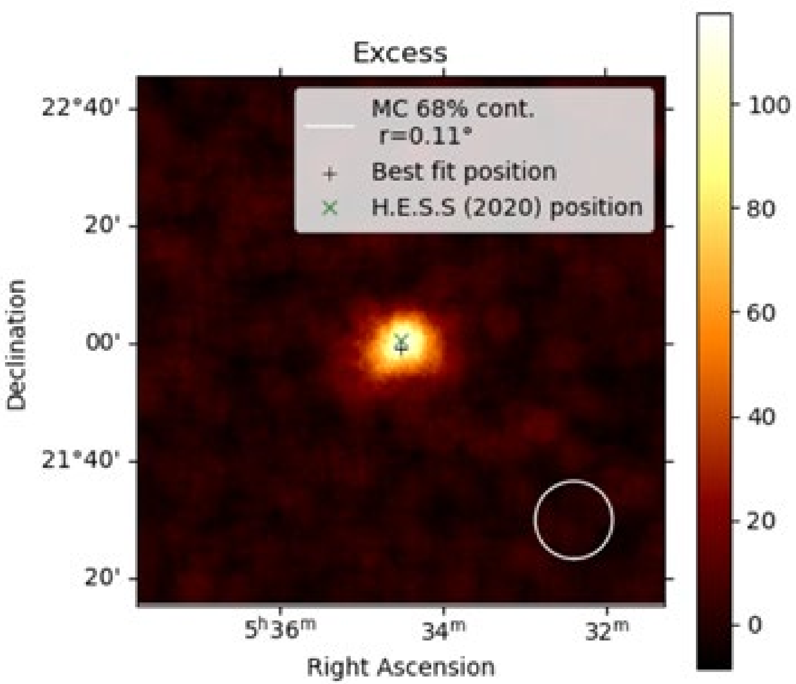
Crab Nebula (M1) observation

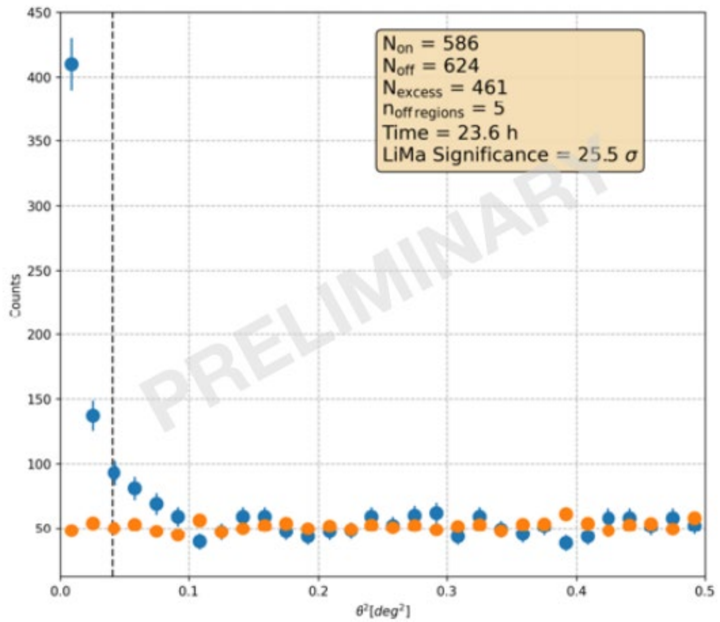
- Standard candle in gamma-ray astronomy
- Obs. campaign 2023/2024 - approx. 23 hours of stereo data quality cuts
- Data zenith angle < 45° and energy treshold 2-3 TeV
- 5σ detection in less than 2 hours in stereo (in less than 3 ho for mono)

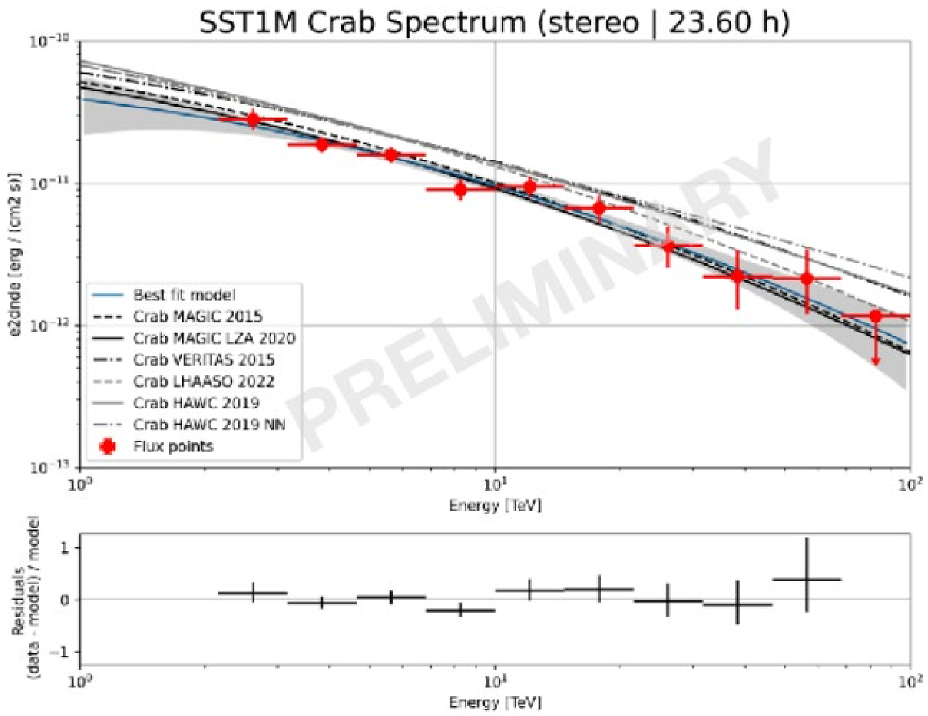




Tavernier et al., (2023,) PoS(ICRC2023)741
Alispach et al., (2025) accepted to A&A







arXiv:2506.01733

Astronomy & Astrophysics manuscript no. aa55292-25
June 3, 2025

Observation of the Crab Nebula with the Single-Mirror Small-Size Telescope stereoscopic system at low altitude

C. Alispach[1], A. Araudo[2], M. Balbo[1], V. Beshley[3], J. Blažek[2], J. Borkowski[4], S. Boula[5], T. Bulik[6], F. Cadoux[1], S. Casanova[5], A. Christov[2], J. Chudoba[2], L. Chytka[7], P. Čechvala[2], P. Dědic[2], D. della Volpe[1], Y. Favre[1], M. Garczarczyk[8], L. Gibaud[9], T. Gieras[5], E. Głowacki[9], P. Hamal[7], M. Heller[1], M. Hrabovský[7], P. Janeček[2], M. Jelínek[10], V. Jílek[7], J. Juryšek[2⋆], V. Karas[11], B. Lacave[1], E. Lyard[12], E. Mach[5], D. Mandát[2], W. Marek[5], S. Michal[7], J. Michałowski[5], M. Miroń[9], R. Moderski[4], T. Montaruli[1], A. Muraczewski[4], S. R. Muthyala[2], A. L. Müller[2], A. Nagai[1], K. Nalewajski[5], D. Neise[13], J. Niemiec[5], M. Nikołajuk[9], V. Novotný[2,14⋆], M. Ostrowski[15], M. Palatka[2], M. Pech[2], M. Prouza[2], P. Schovanek[2], V. Sliusar[12], Ł. Stawarz[15], R. Sternberger[8], M. Stodulska[1], J. Świerblewski[5], P. Świerk[5], J. Štrobl[10], T. Tavernier[2⋆], P. Trávníček[2], I. Troyano Pujadas[1], J. Vícha[2], R. Walter[12], and K. Ziętara[15]

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Received ... / Accepted ...

ABSTRACT

The Single-Mirror Small-Size Telescope (SST-1M) stereoscopic system is composed of two Imaging Atmospheric Cherenkov Telescopes (IACTs) designed for optimal performance for gamma-ray astronomy in the multi-TeV energy range. It features a 4-meter-diameter tessellated mirror dish and an innovative SiPM-based camera. Its optical system features a 4-m diameter spherical mirror dish based on the Davies-Cotton design, maintaining a good image quality over a large FoV while minimizing optical aberrations. In 2022, two SST-1M telescopes were installed at the Ondřejov Observatory, Czech Republic, at an altitude of 510 meters above sea level, and have been collecting data for commissioning and astronomical observations since then.
We present the first SST-1M observations of the Crab Nebula, conducted between September 2023 and March 2024 in both mono and stereoscopic modes. During this observation period, 46 hours for the SST-1M-1 and 52 hours for the SST-1M-2 were collected for which 33 hours are in stereoscopic mode. We use the Crab Nebula observation to validate the expected performance of the instrument, as evaluated by Monte Carlo simulations carefully tuned to account for instrumental and atmospheric effects. We determined that the energy threshold at the analysis level for the zenith angles below 30° is 1 TeV for mono mode and 1.3 TeV for stereo mode. The energy and angular resolutions are approximately 20% and 0.18° for mono mode and 10% and 0.10° for stereo mode, respectively.
We present the off-axis performance of the instrument and a detailed study of systematic uncertainties. The results of a full simulation of the telescope and its camera is compared to the data for the first time, allowing a deep understanding of the SST-1M array performance.

Key words. Instrumentation: detectors – Methods: data analysis – ISM: individual objects: Crab Nebula – gamma rays: general

PHYSICS FOR FUTURE

Active Galactic Nuclei (AGN) monitoring

Markarian (Mrk) 421, stereo data

Mrk 421 Credit : Sloan Digital Sky Survey - http://skyserver.sdss.org/

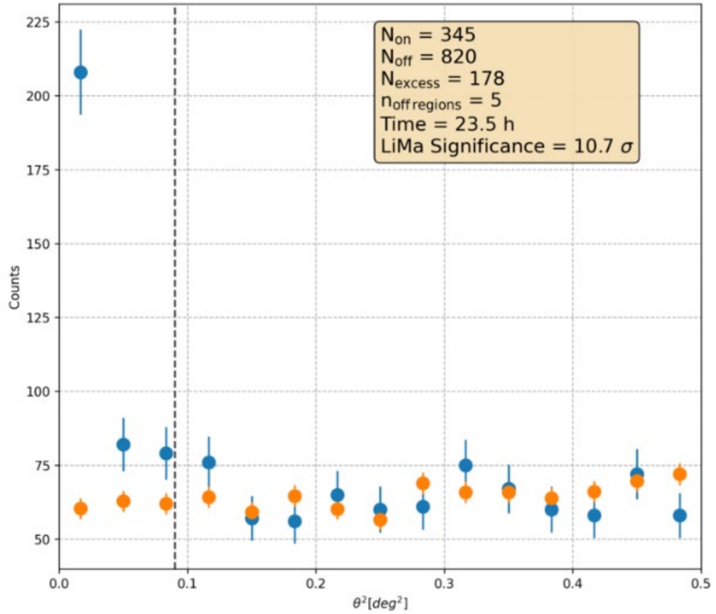
- First extragalactic source in true stereo detected by SST-1M
- Observation during increased activity on 15.3.2024 – ATel #16533, https://www.astronomerstelegram.org/
- Observed spectral index - **2.6 ± 0.3**
- The result is compatible with result published by HAWC collaboration A. Albert et al., 2022 ApJ 929 125, **2.26 ± 0.12**
- Maximum energies compatible with HAWC (9 TeV)

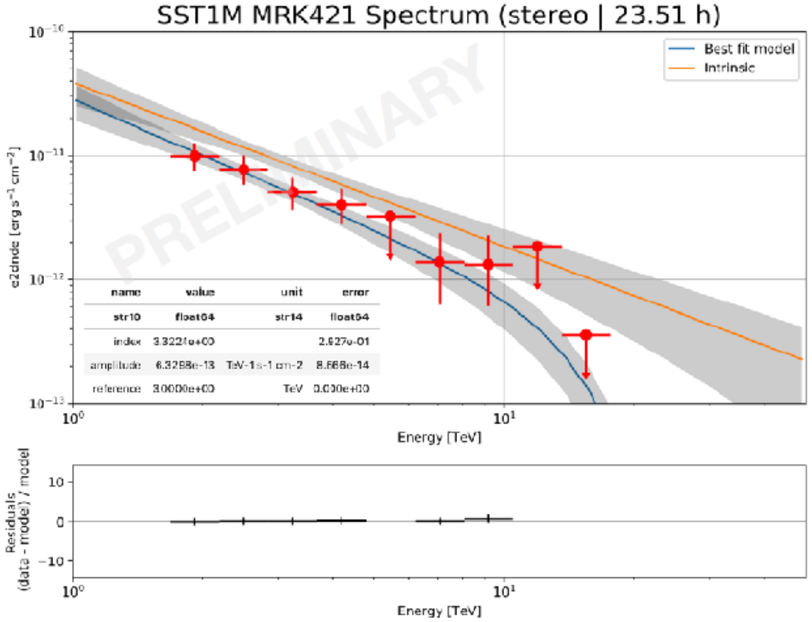
Detection of enhanced very-high-energy gamma-ray emission from Markarian 421

ATel #16533; *Thomas Tavernier, in the behalf of SST-1M Consortium*

on ***15 Mar 2024; 16:55 UT***

Credential Certification: Thomas Tavernier (tavernier@fzu.cz)





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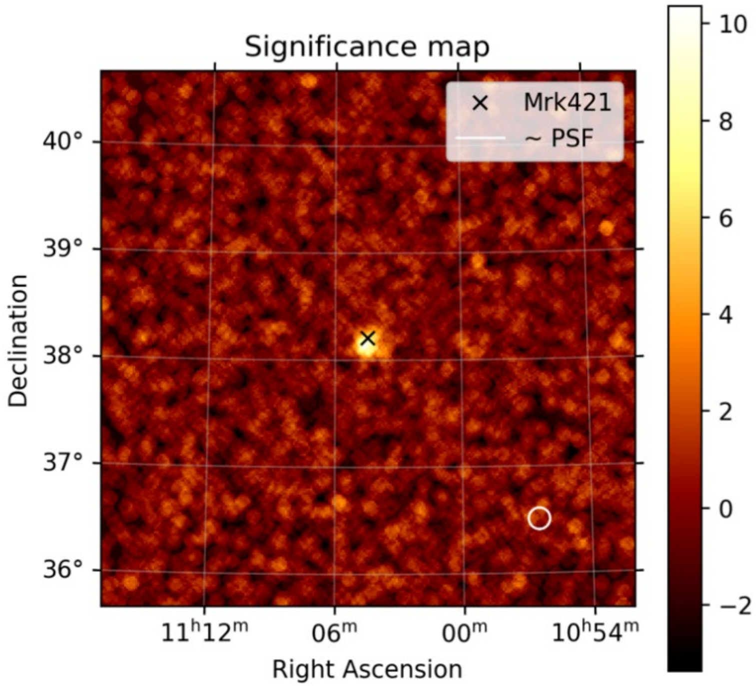
amplitude	6.3298e-13	TeV-1 s-1 cm-2	8.668e-14
reference	3.0000e+00	TeV	0.000e+00



References

- Crab Nebula image: Based on File:Crab Nebula in multiwavelength.png by Torres997 Radio: NRAO/AUI and M. Bietenholz; NRAO/AUI and J.M. Uson, T.J. Cornwell Infrared: NASA/JPL-Caltech/R. Gehrz (University of Minnesota) Visible: NASA, ESA, J. Hester and A. Loll (Arizona State University) Ultraviolet: NASA/Swift/E. Hoversten, PSU X-ray: NASA/CXC/SAO/F.Seward et al. Gamma: NASA/DOE/Fermi LAT/R. Buehler - Radio: http://images.nrao.edu/393; http://images.nrao.edu/34 (Very Large Array, {{NRAO}}: CC-by-3.0)
  Infrared: http://www.nasa.gov/multimedia/imagegallery/image_feature_567.html (Spitzer, {{PD-USGov-NASA}}: Public domain)
  Visible: http://hubblesite.org/newscenter/archive/releases/2005/37/image/a/ (Hubble, {{PD-Hubble}}: Public domain)
  Ultraviolet: http://www.nasa.gov/mission_pages/swift/bursts/swift-images.html (Swift, {{PD-USGov-NASA}}: Public domain) X-ray: http://chandra.harvard.edu/photo/2008/crab/ (Chandra, {{PD-USGov-NASA}}: Public domain) Gamma: http://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=10767 (Fermi, {{PD-USGov-NASA}}: Public domain)
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- MAGIC photo – Patrik Čechvala
- LST photo – Adriana Pisarčíková
- MACE photo - Singh, K. K., & Yadav, K. K. (2021). 20 Years of Indian Gamma Ray Astronomy Using Imaging Cherenkov Telescopes and Road Ahead. *Universe*, *7*(4), 96. https://doi.org/10.3390/universe7040096
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- Pulsar picture - NASA Goddard/Walt Feimer
- Starburst galaxy picture – NASA/ESA
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Conclusion

- **Bright future for gamma-ray astronomy in the nex years**
- **2 prototypes of SST-1M telescopes successfully built and currently gathering data in stereo regime in Ondřejov**
- **First detected sources both galactic and extragalactic**
- **Perspective for interesting scientific results from SST-1M mini-array in near future – first scientific paper showing actual data already accepted**

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PHYSICS FOR FUTURE

SST-1M Single-Mirror Small Size Telescope

FZU Institute of Physics of the Czech Academy of Sciences

Co-funded by the European Union

Thank you for your attention

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https://sst-1m.science/

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