The SST-1M project: update and future prospects

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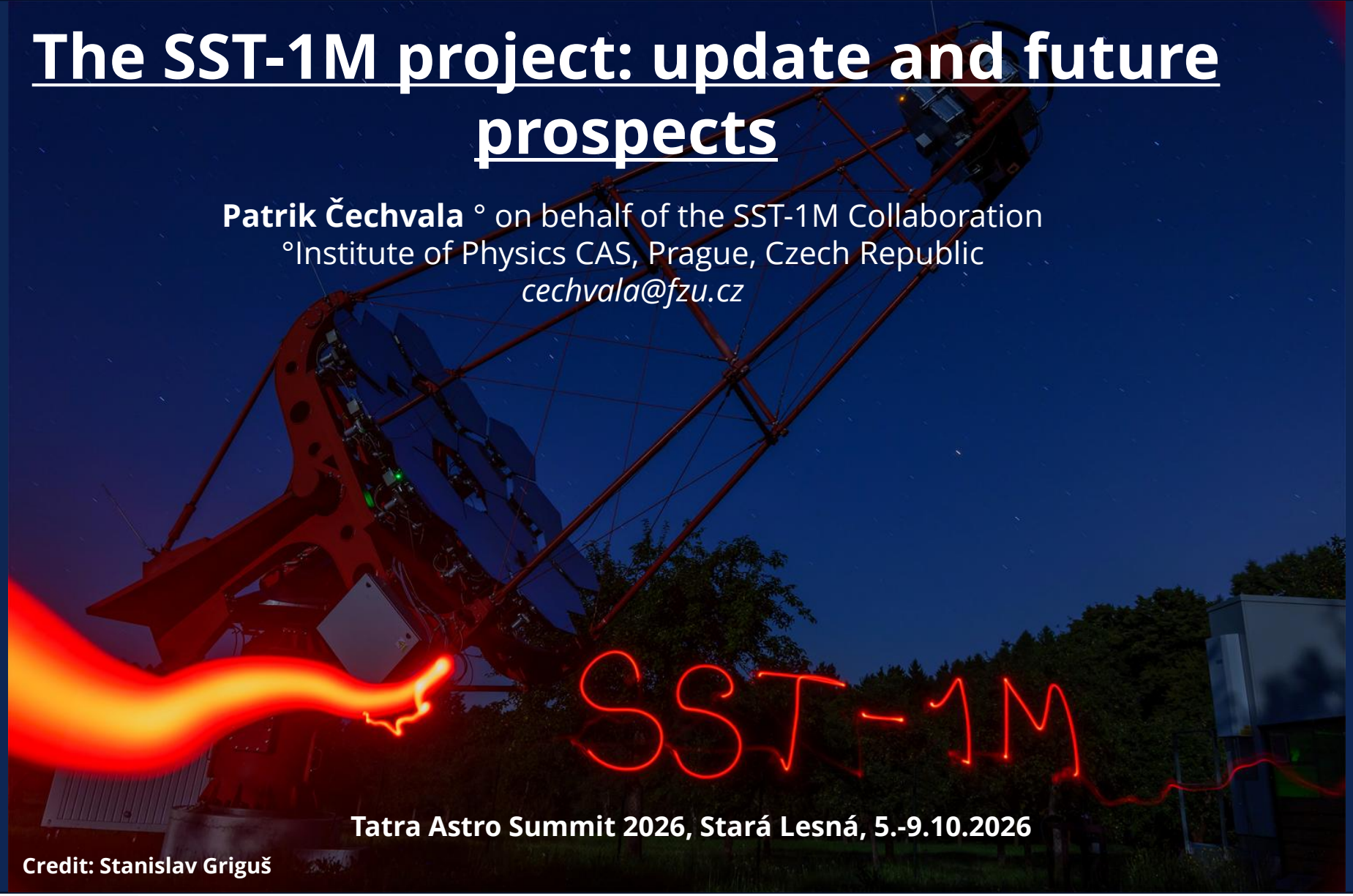

Tatra Astro Summit 2026, Stará Lesná, 5.-9.10.2026

Credit: Stanislav Griguš

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

- **Gamma-ray astronomy**
- **Imaging Atmospheric Cherenkov Telescopes – how do they work**
- **Single Mirror Small Size Telescopes – SST-1M project**
- **Recent scientific achievements**

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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 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 of extragalactic background light

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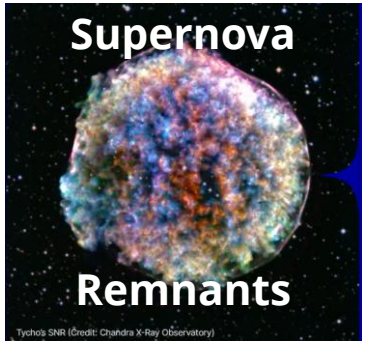
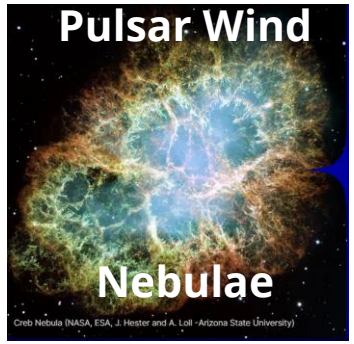
Galactic sources

Supernova remnants, microquasars, …









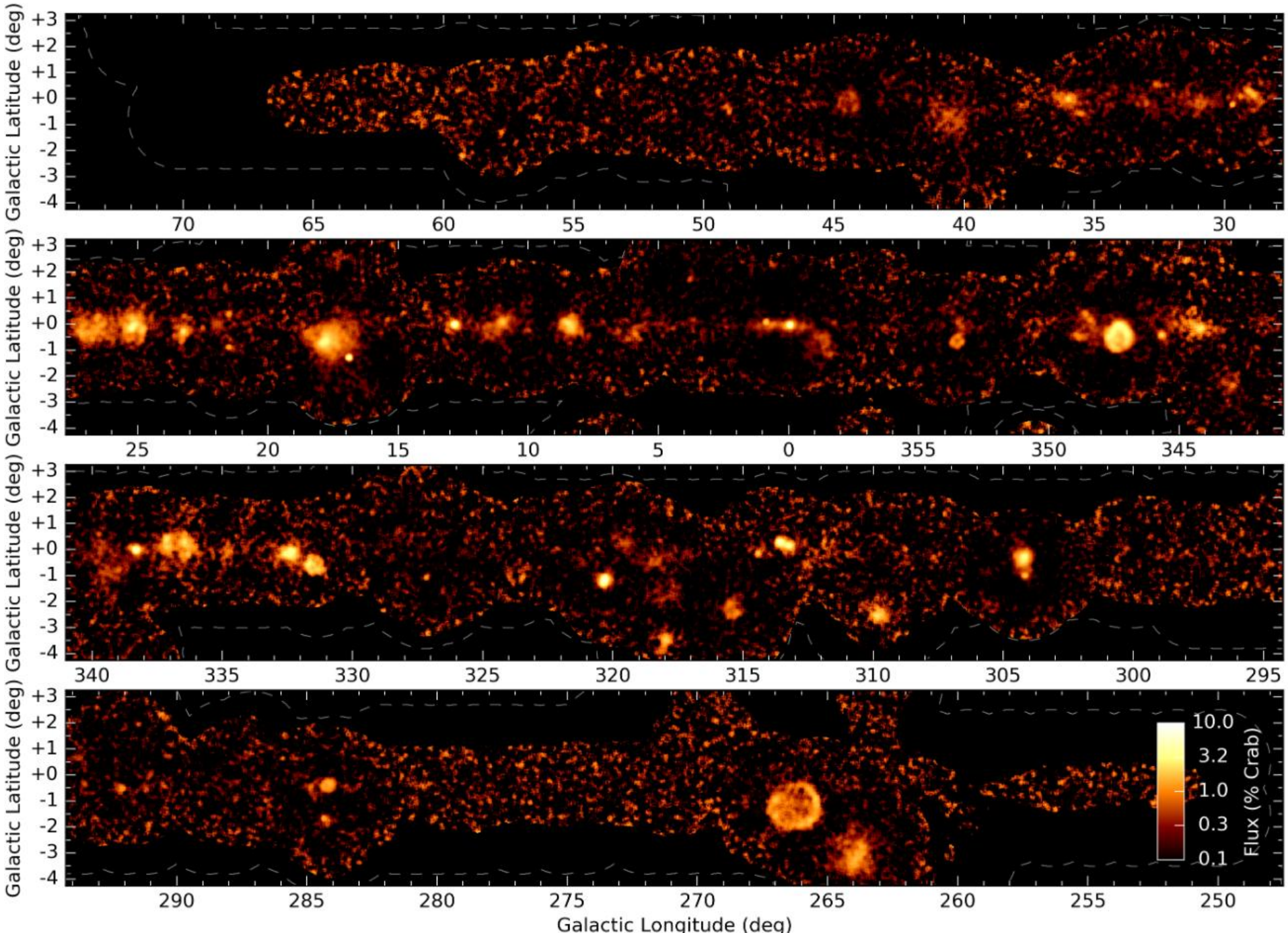
Extragalactic sources

AGNs, neutron star mergers (short GRBs), hypernovae (long GRBs) …









Hess Collaboration,
A&A 612, A1 (2018)

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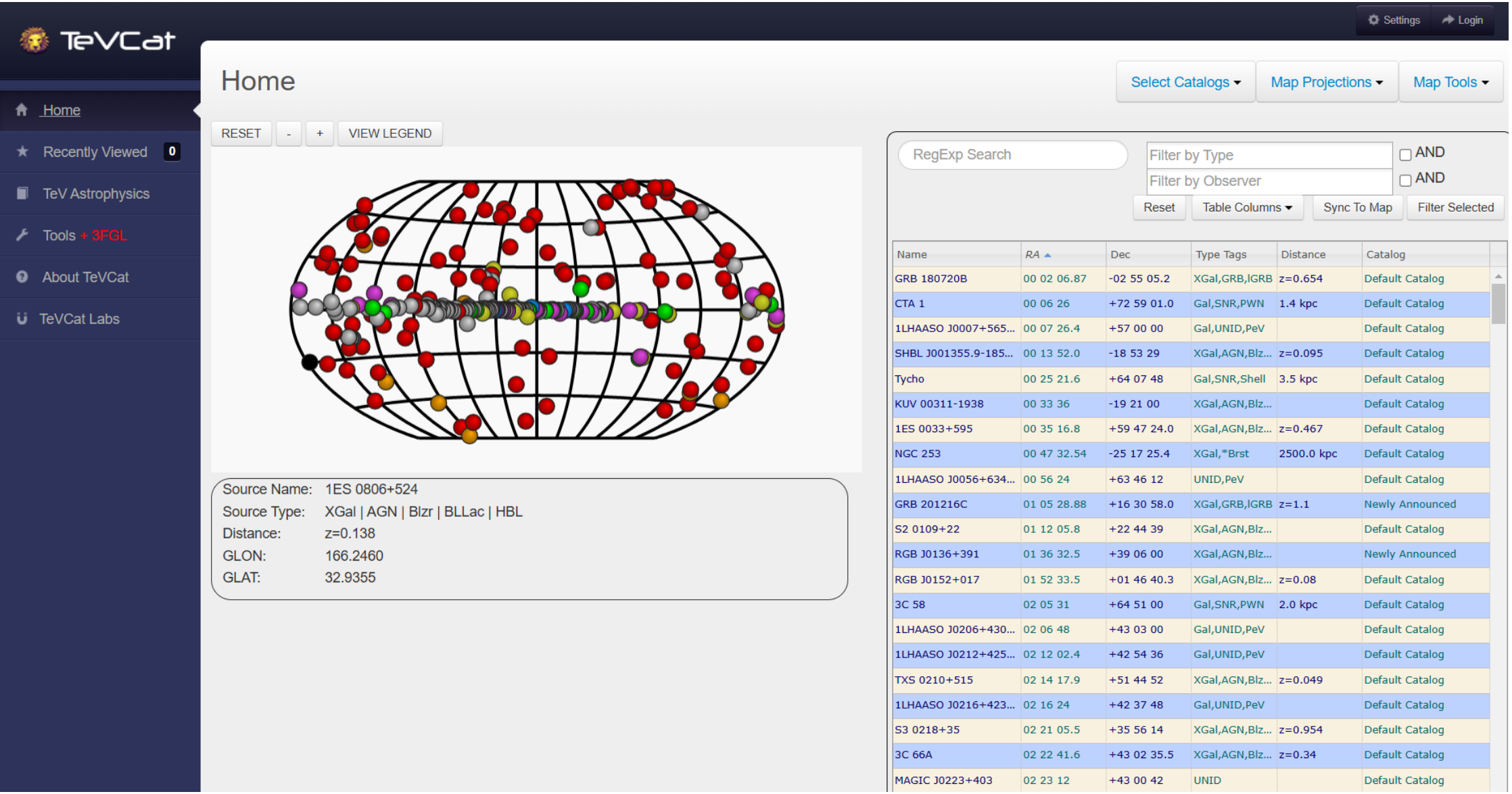

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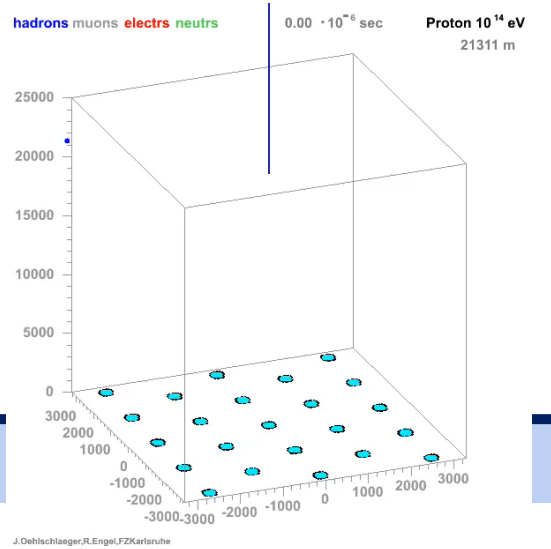
Source: http://tevcat2.uchicago.edu/

Detection techniques in gamma-ray astronomy

Longair, 1992



Credit: The University of Sheffield

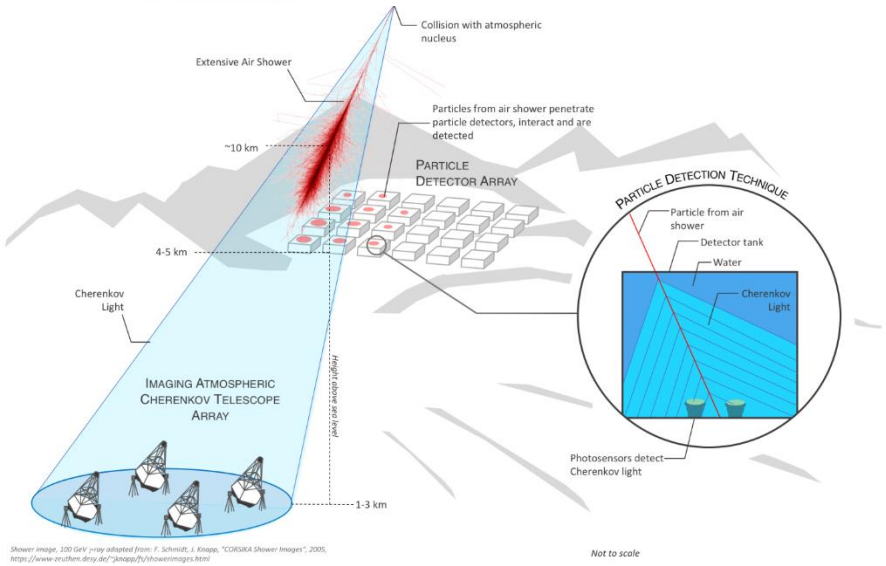
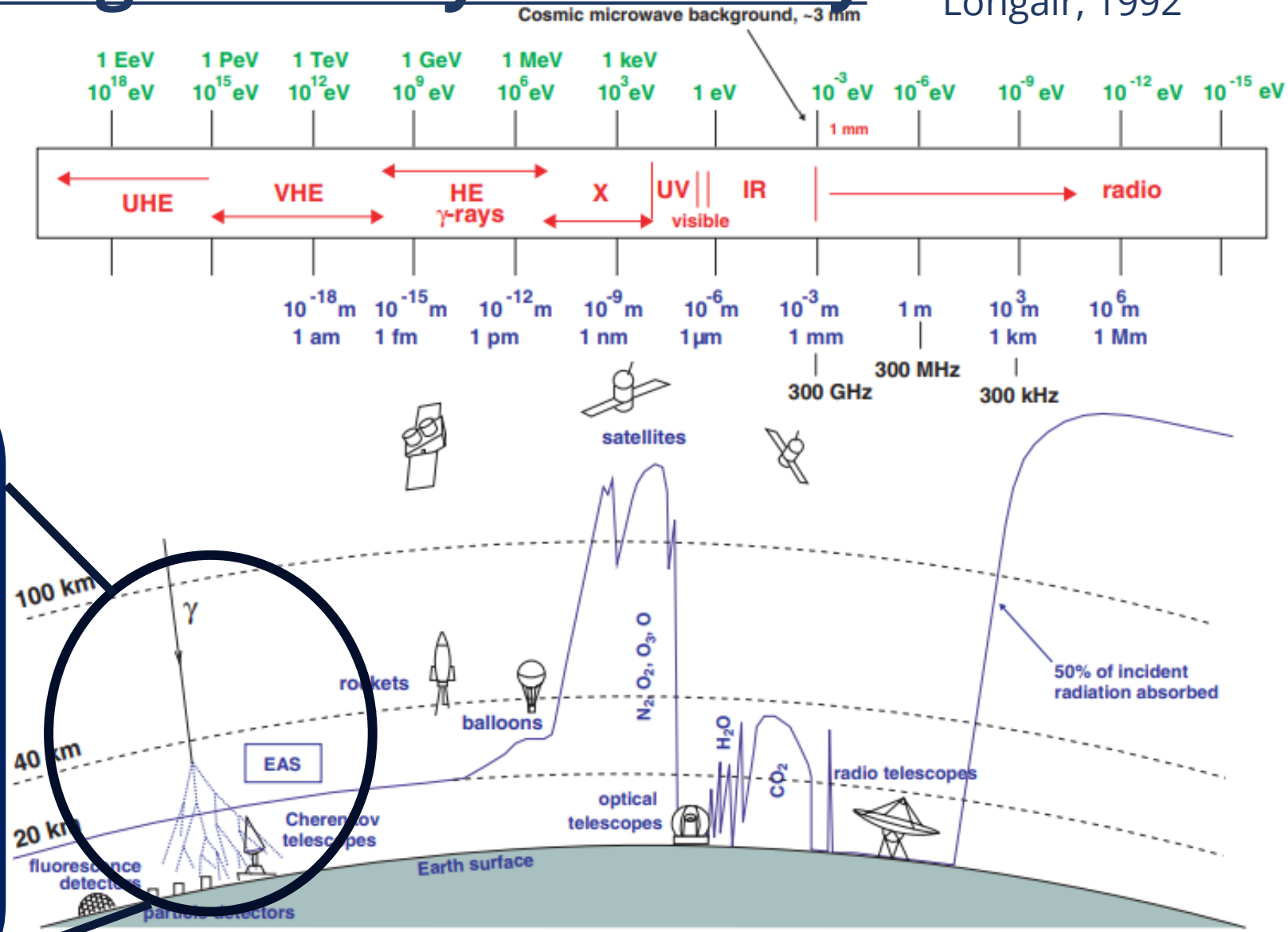
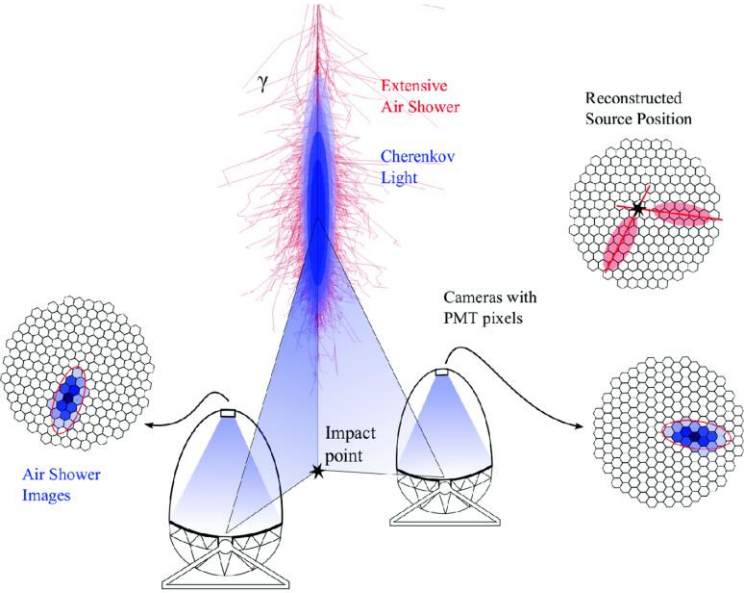


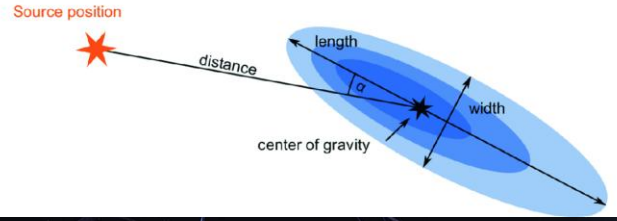
Illustration of the complementary detection techniques of high-energy gamma rays on ground. (Credit: Richard White, MPIK)



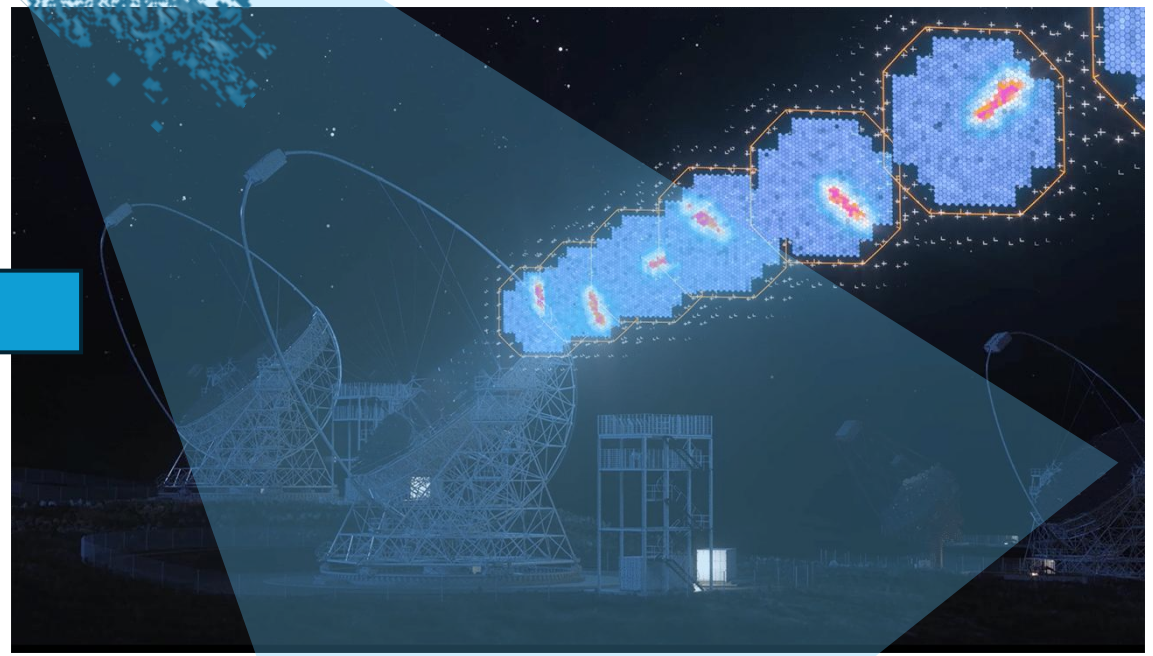
Credit: MAGIC collaboration

Imaging Atmospheric Cherenkov Telescopes





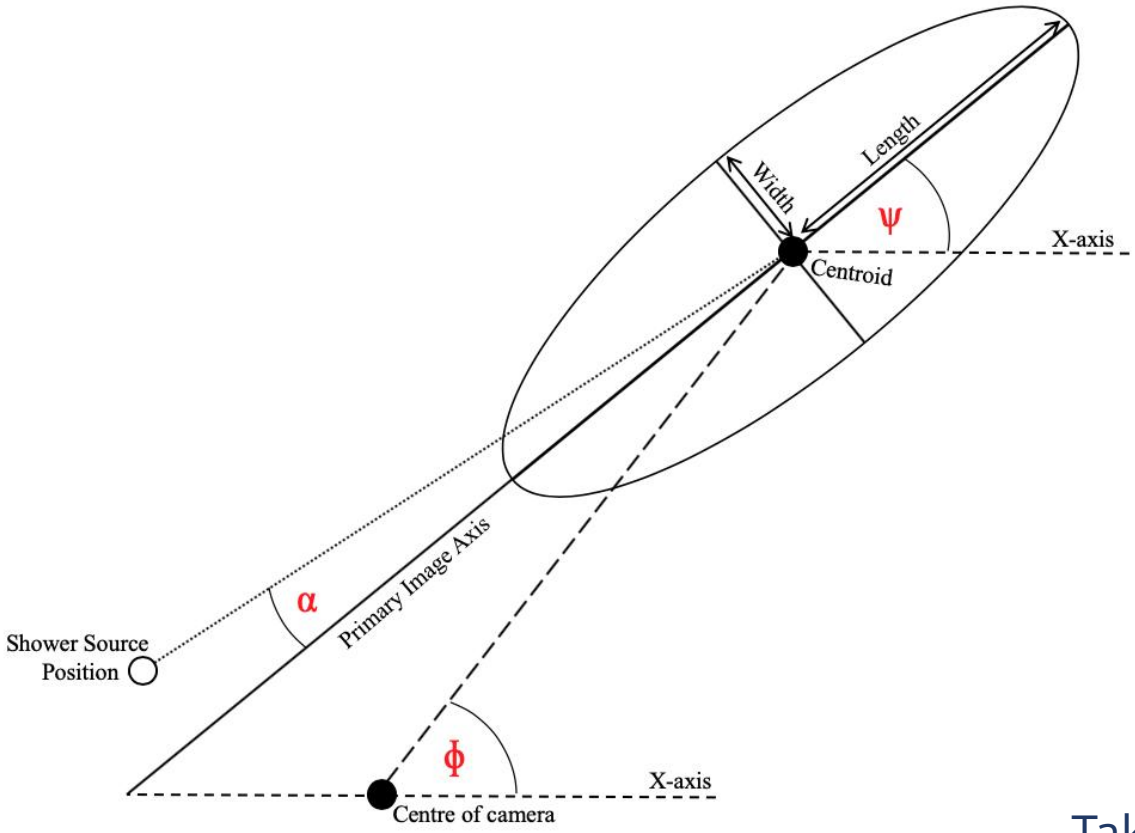
- **Reflective telescopes** on Alt-Az mounts – first in 1980s Whipple telescope
- Sensitive camera photo-detection plane composed of an array of silicon photomultipliers
- Parametrisation of the shower image – **Hillas parameters** (Hillas, 1985)
- For multiple telescopes, possibility to operate in **stereo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



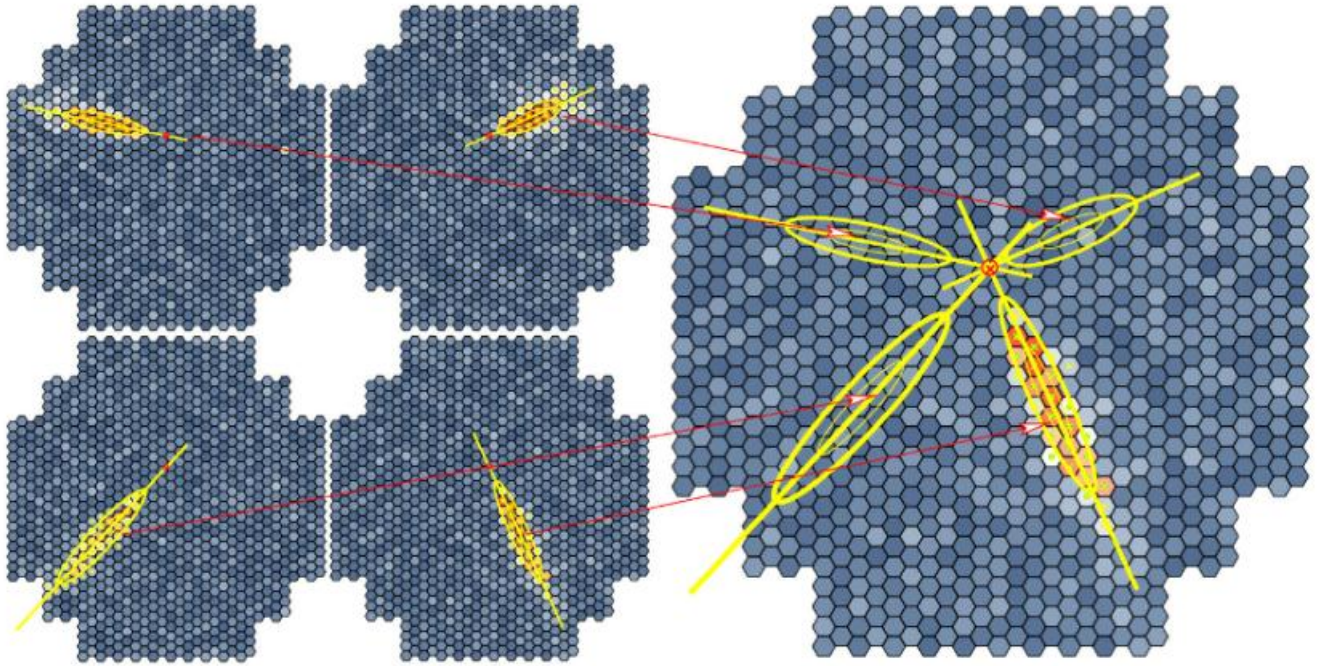
Credit: CTAO



Credit: CTAO



Credit: https://github.com/watsonjj



Taken from the lecture of F. Bradascio, CADS School 2025,

https://github.com/bkhelifi/CADS_2025/blob/main/Lectures/gamma_detectors_cads_school_2025.pdf

Imaging Atmospheric Cherenkov Telescopes (IACTs) across the world



PANOSETI

VERITAS



SST-1M





LHAASO, LACT

ASTRI



MAGIC



MACE

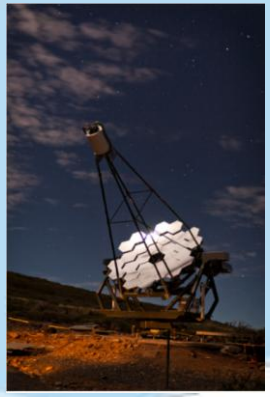


H.E.S.S.



LST





FACT

Credit:
Wikipedia

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 Size 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

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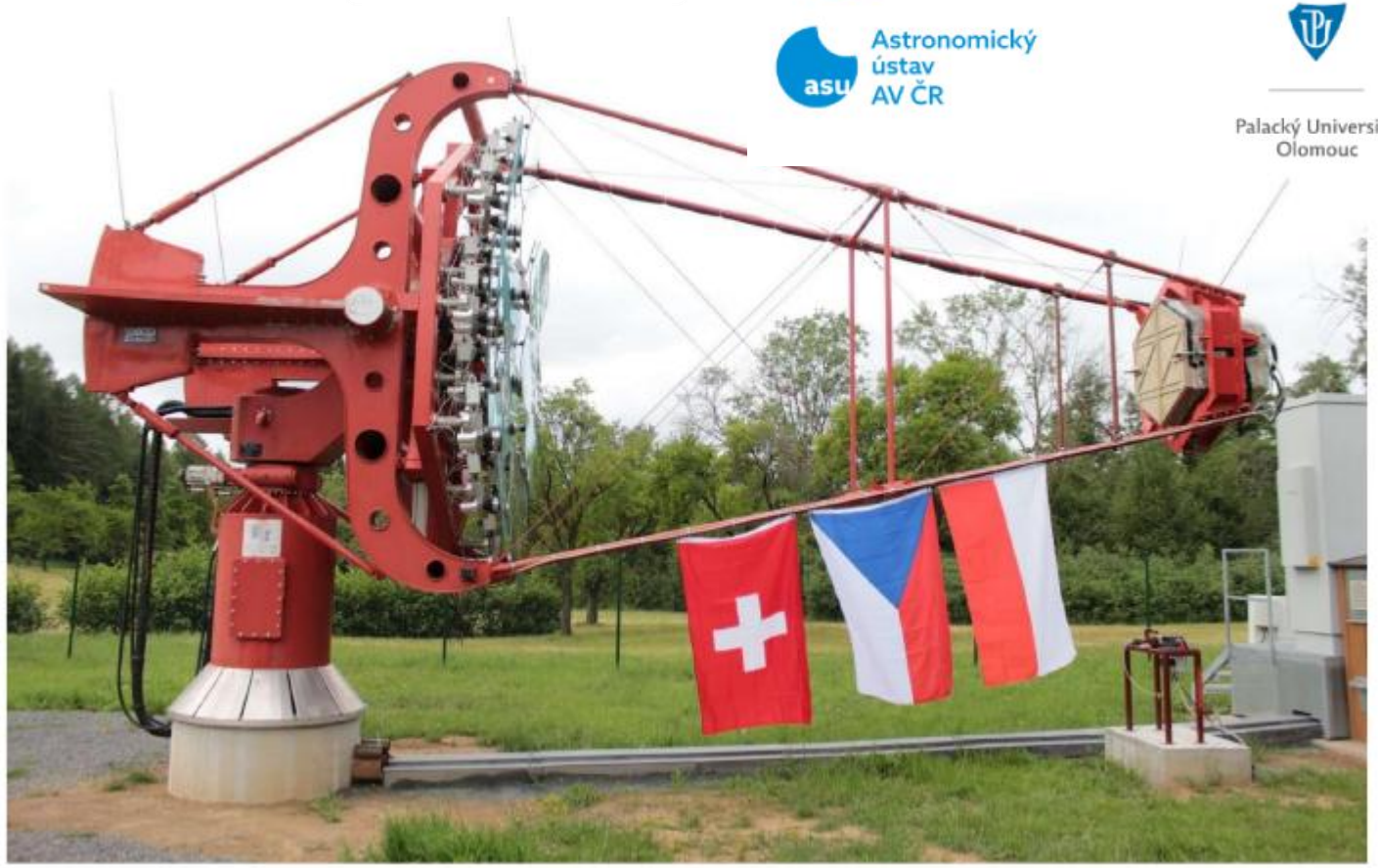
https://sst-1m.science/

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





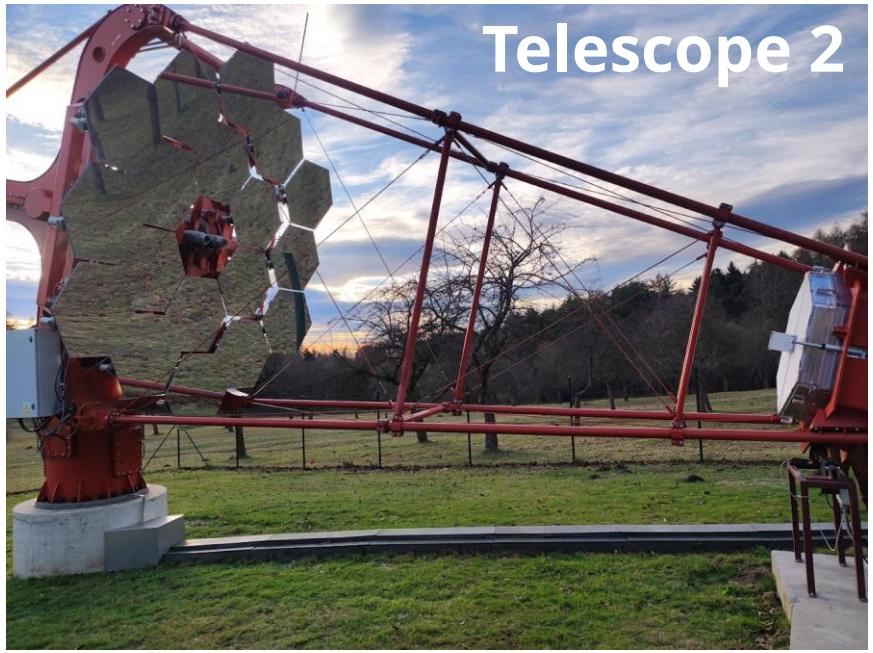


Ondřejov Observatory

https://asu.cas.cz/

Source: Google maps





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

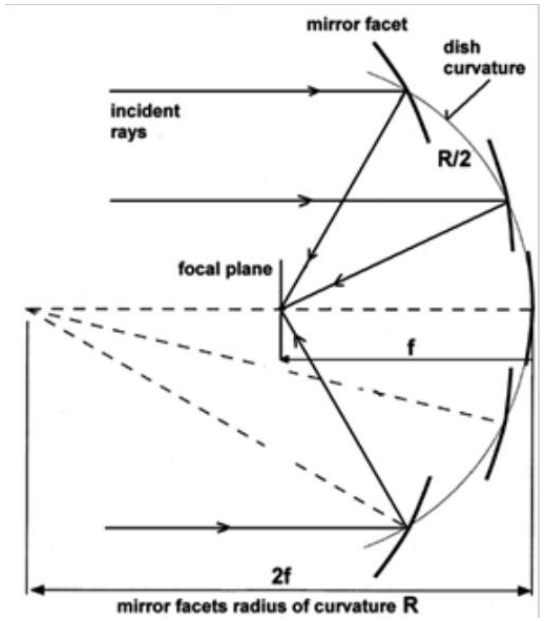
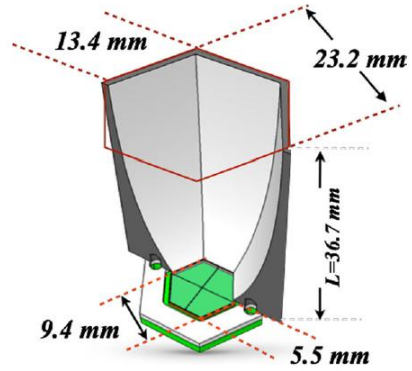


Figure adopted from
Actis et al., (2011)

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

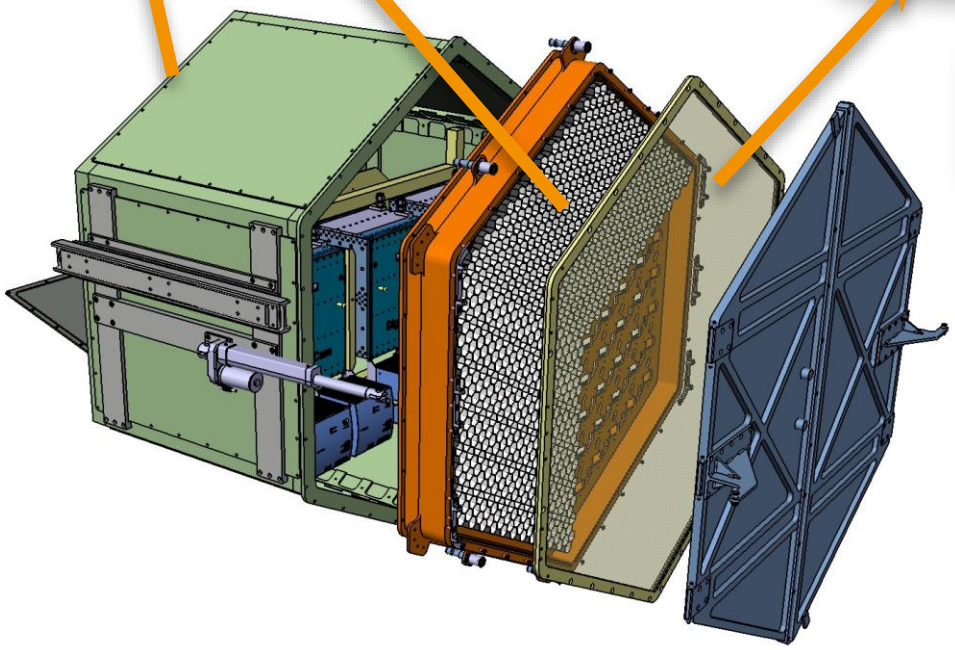


Digital electronics (DigiCam):
- 12 bits FADC @ 250 MS/s
- Fully digital trigger
- Power consumption 1200 W

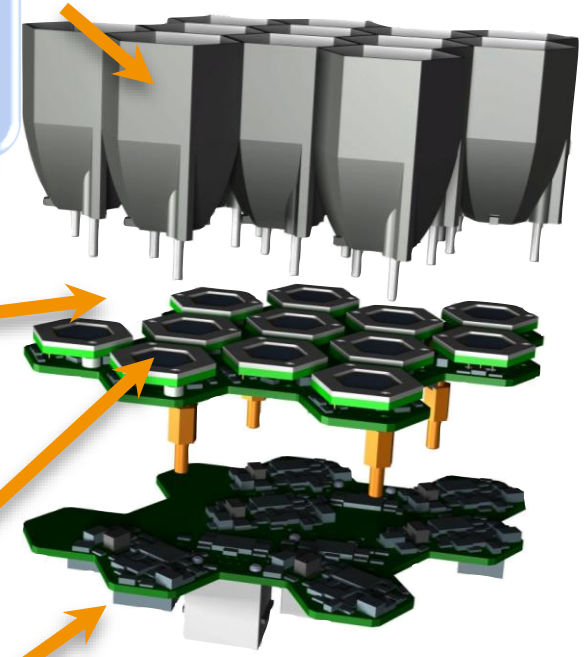
Photo-detection plane:
- 1296 pixels
- Power consumption 500 W

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



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



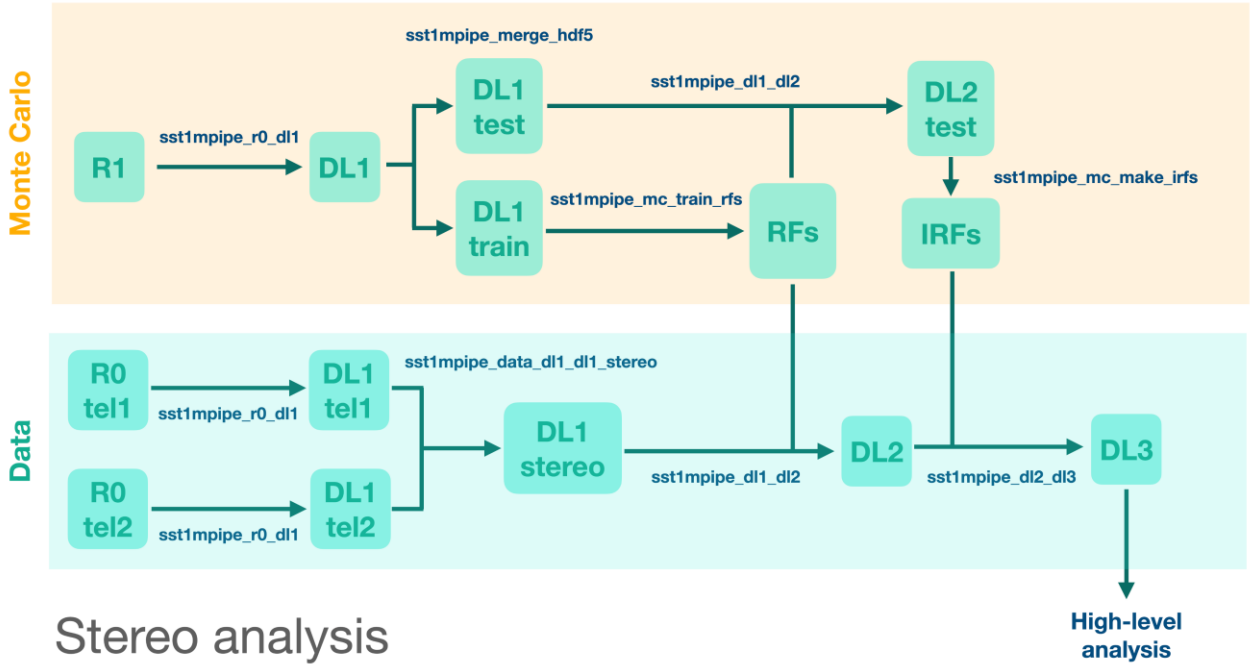
Preamplifier board:
- 2 operational amplifiers per sensor to reduce pulse length
- DC coupling

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

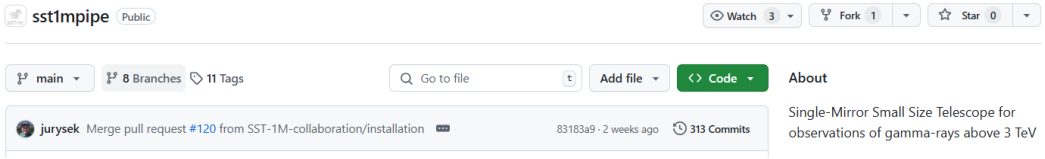
C. Alispach et al JCAP02(2025)047

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



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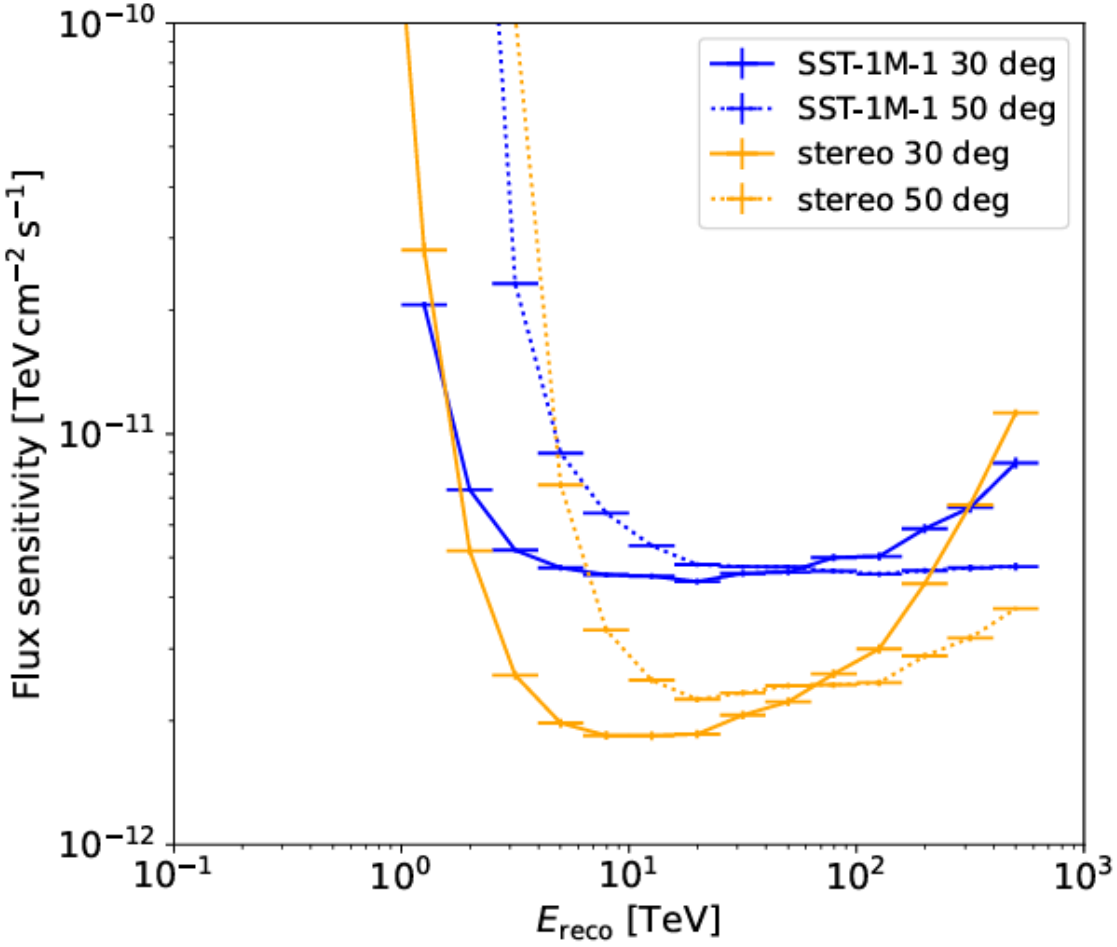
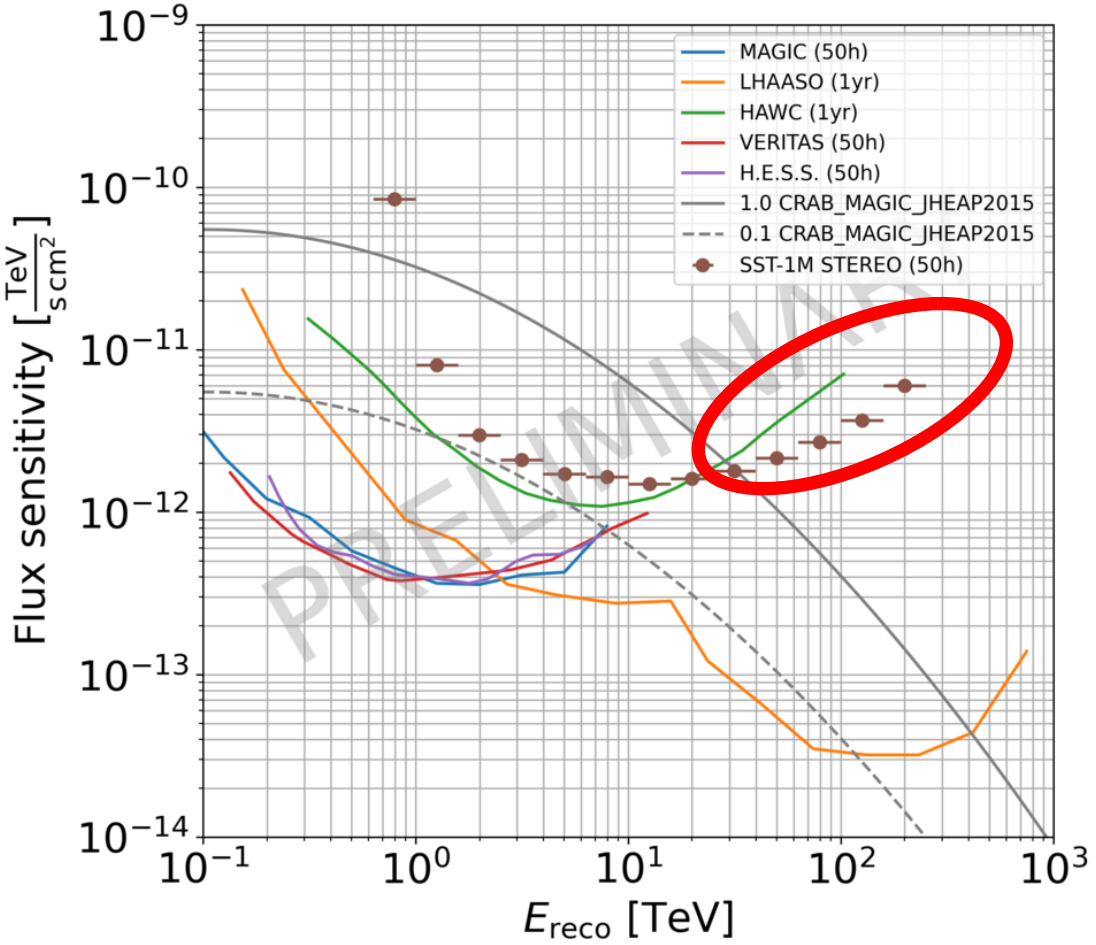
Perfomance of SST-1M (Ondřejov)

Juryšek et al., (2023), PoS(ICRC2023)592
Alispach et al., (2025), A&A

- Sensitivity in energy domain approx. 1 TeV – 100 TeV
- Significant improvement of performance in stereo mode comparing to mono mode
- Results in stereo mode
- Angular resolution in stereo ≈ 0.1°
- Energy resolution in stereo ≈ 10%-15%

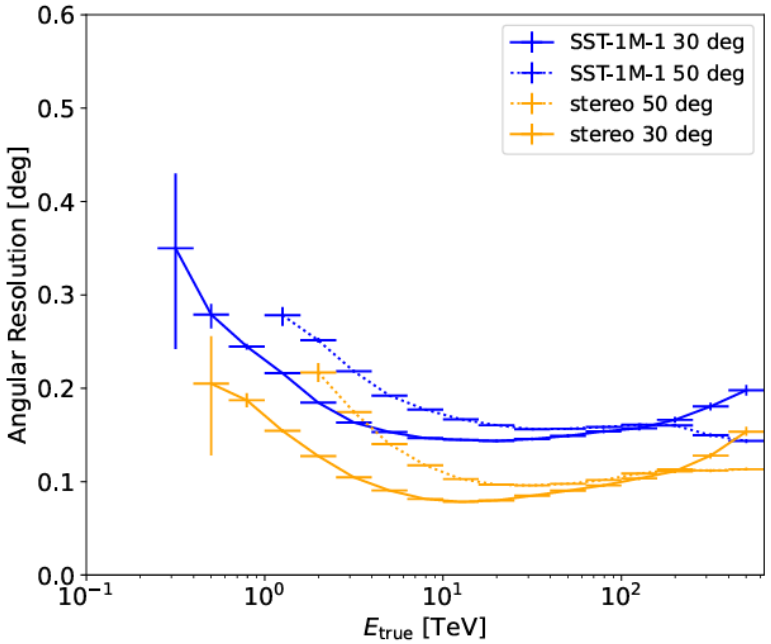


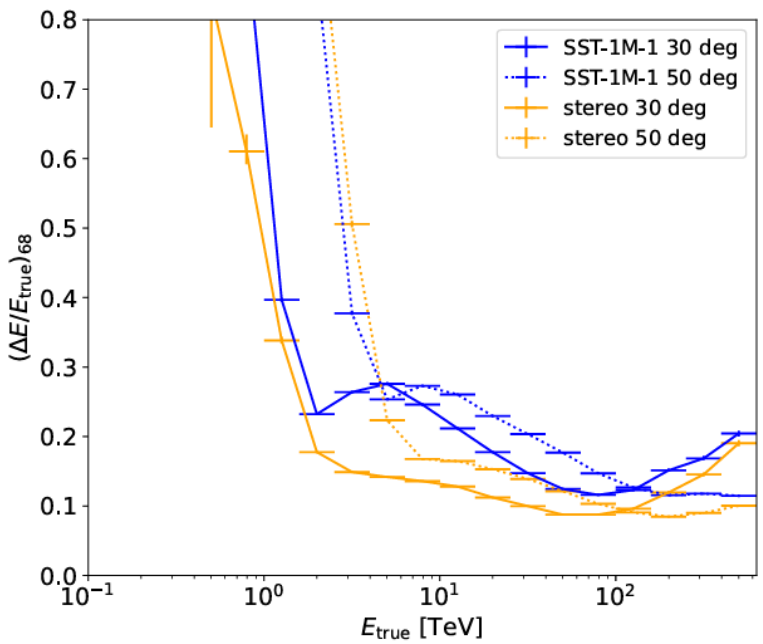


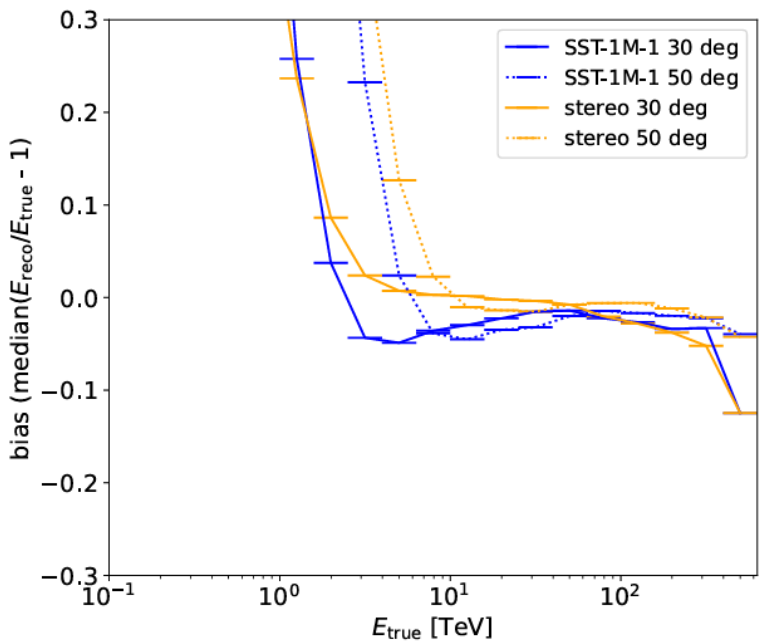
Perfomance of SST-1M (Ondřejov)

- Significant improvement of parameters in stereo mode

Alispach et al., (2025), A&A







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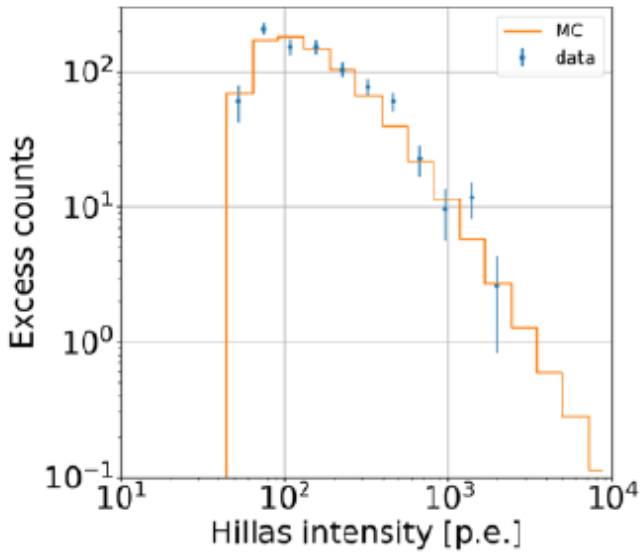
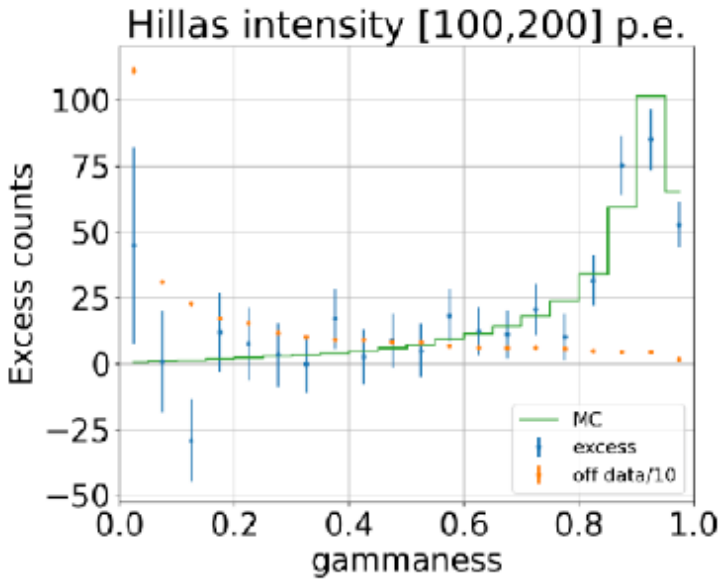
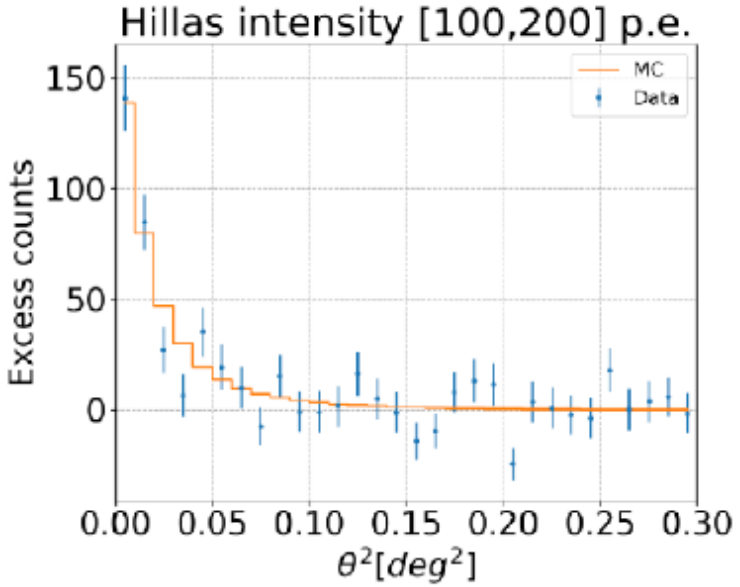
Data – Monte Carlo confrontation

Crab excess events

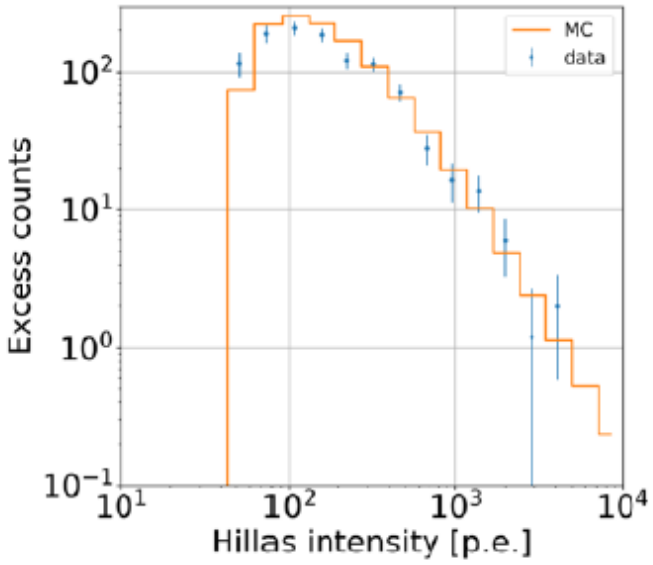
Alispach et al., (2025), A&A

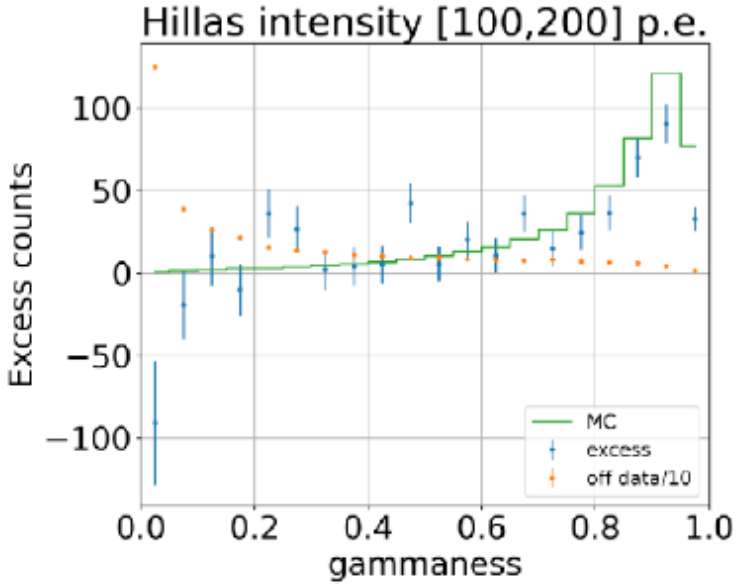


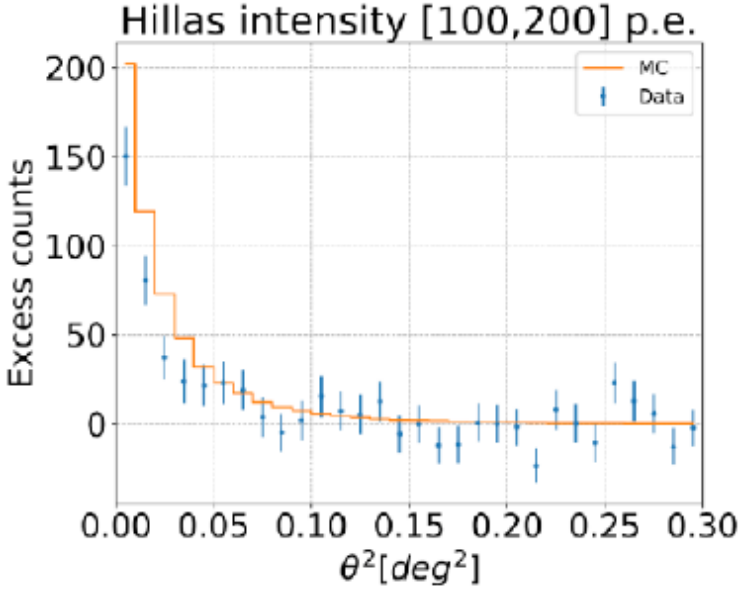




Tel 1







Tel 2

Detailed study of systematic uncertainties

Energy scale	
Atm. (VAOD)	5%
Atm. (seasonal)	<3%
Optical eff.	5% (SST-1M-1) 6% (SST-1M-2)
Reco. charge	<4%
NSB (voltage-drop)	<2%
NSB (RFs)	<2%
Total	<10%

Flux normalization (ϕ_0)	
Energy scale	19% (stereo) 18% (SST-1M-1/2)
Bkg. norm	≈5%
NSB	10%
MC and data diff.	6% (stereo) 5% (SST-1M-1) 7% (SST-1M-2)
Total	23% (stereo) 22% (SST-1M-1/2)

Spectral index (Γ)	
Energy scale	<1%
Bkg. norm	<1% (stereo), 2% (SST-1M-1/2)
MC and data diff.	3% (stereo, SST-1M-1) 6% (SST-1M-2)
Total	3% (stereo) 4% (SST-1M-1) 6% (SST-1M-2)

Alispach et al., (2025), A&A

Scientific results

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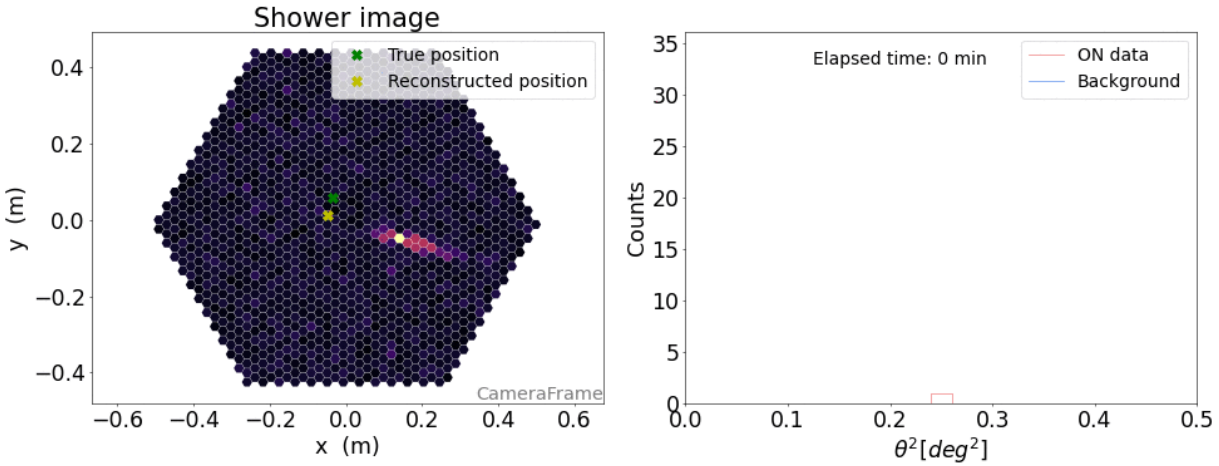
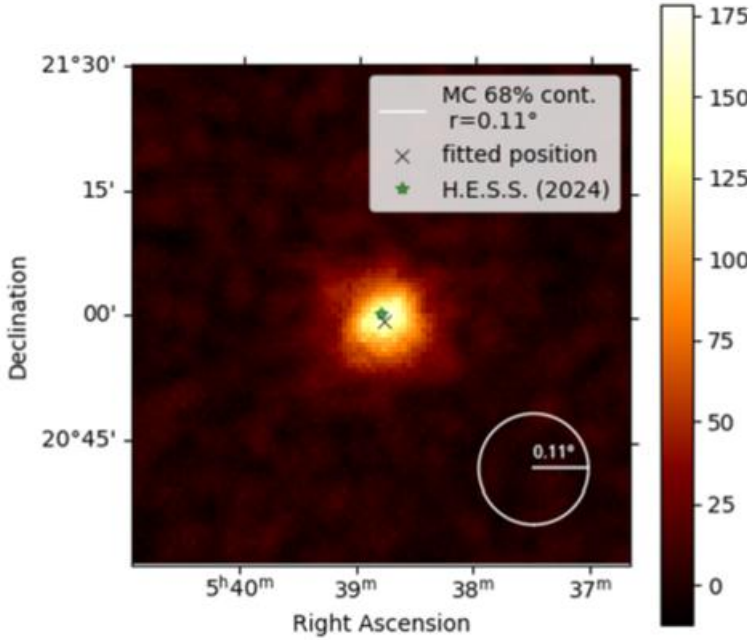
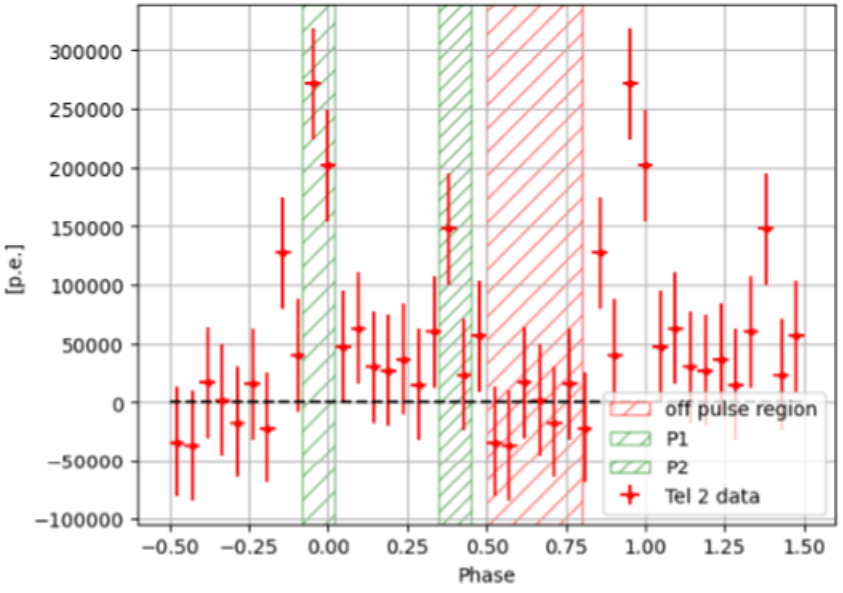
Crab Nebula (M1) observation

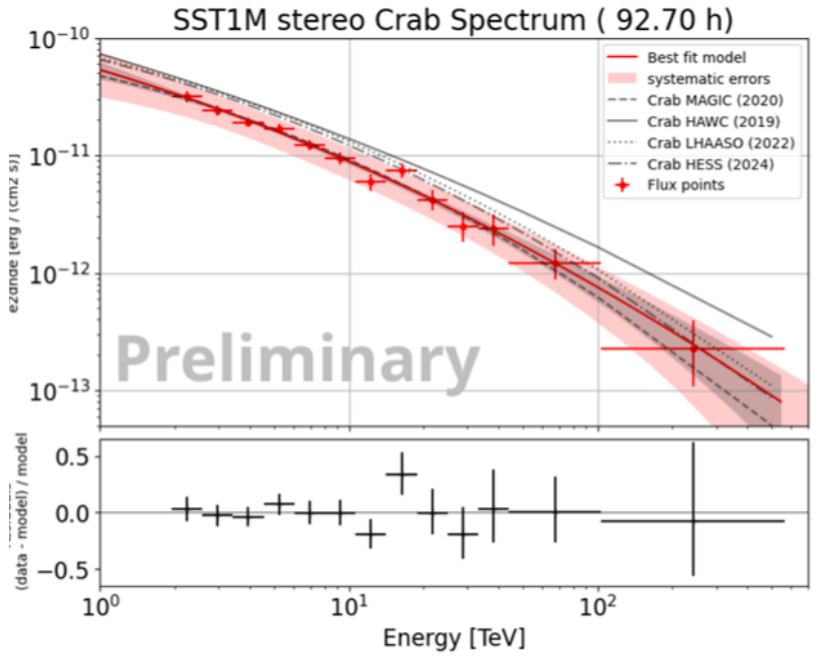
- Standard candle in gamma-ray astronomy
- Obs. campaign 2023/2024 - approx. 25 hours of stereo data after quality cuts
- Data zenith angle < 53° and energy threshold 1.0 TeV (mono), 1.3 TeV (stereo)
- 5σ detection in less than 2 hours in stereo (in less than 3 hours for mono)



Tavernier et al., (2023,) PoS(ICRC2023)741
Alispach et al., (2025), A&A
Tavernier et al., (2025), PoS(ICRC2025)861



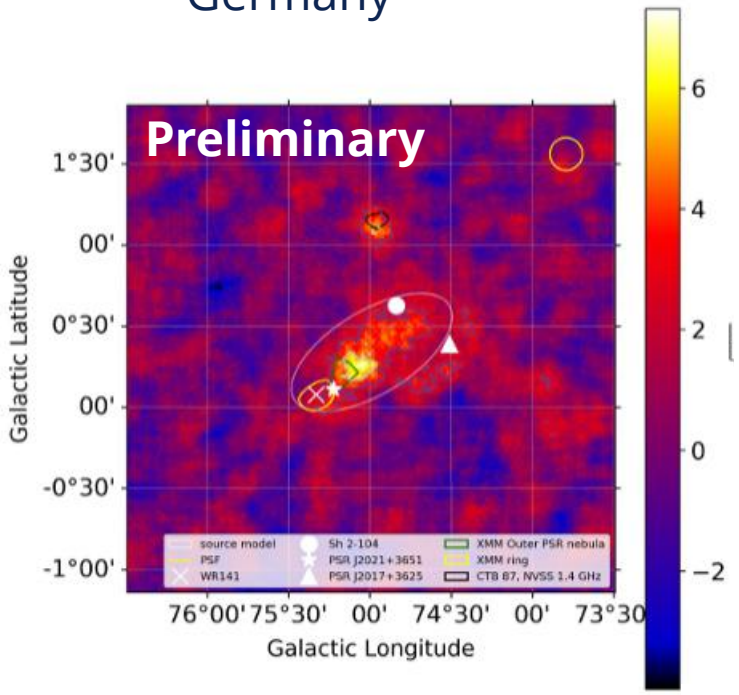




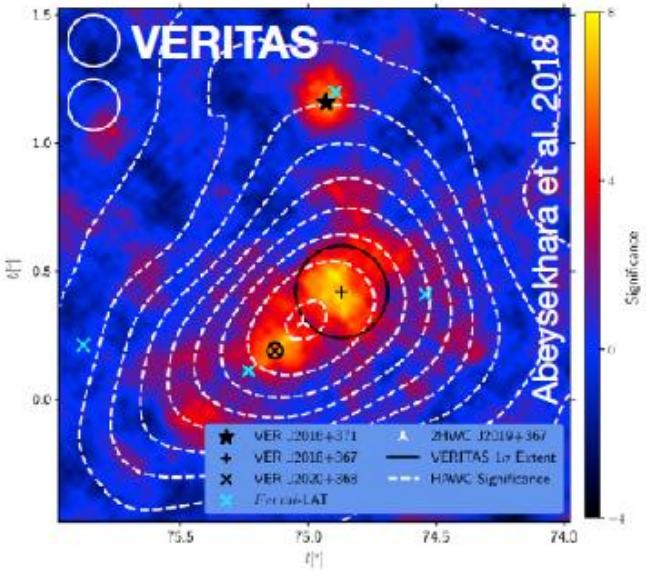
VER J2019+368 (Dragonfly)

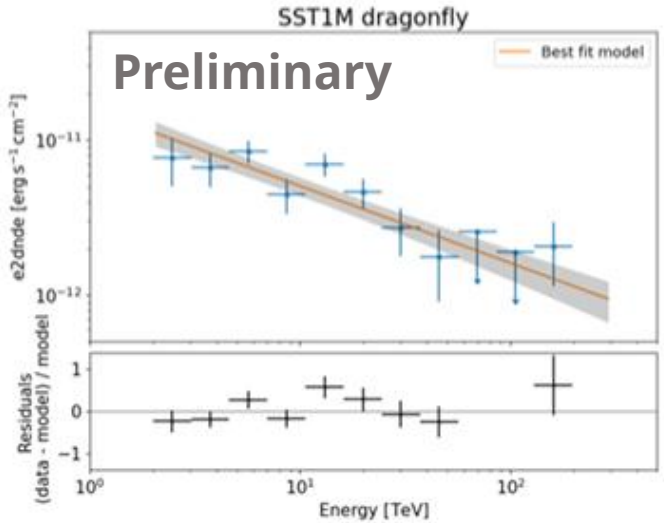
Juryšek et al., PoS(ICRC2025)703
Müller et al., Gamma Symposium 2026, Heidelberg, Germany

- Complex region with multiple sources – in radio, in X-rays and in gamma rays
- Extended source (approx. 0.5°)
- Observational campaign in 2024 – zenith angle ranging 5°-60°
- Region discovered by MILAGRO (A. A. Abdo *et al* 2007 *ApJ* 658 L33)
- Resolved into different sources by VERITAS (A. U. Abeysekara et al 2018 ApJ 861 134)
- Source(s) resolved – VER 2019+368 together with CTB 87
- Ongoing analysis



Contours are 3σ, 5σ, and 8σ of local significance



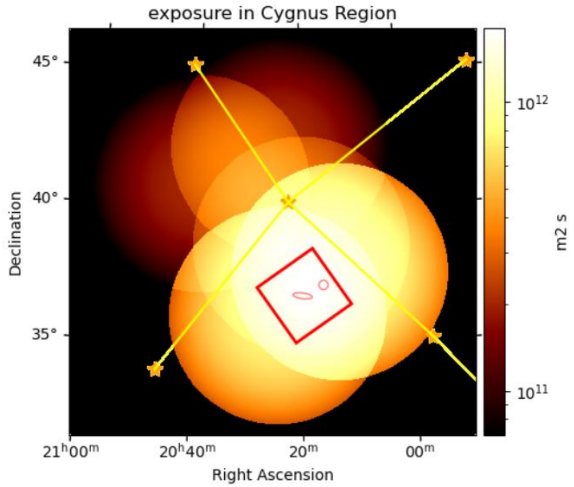


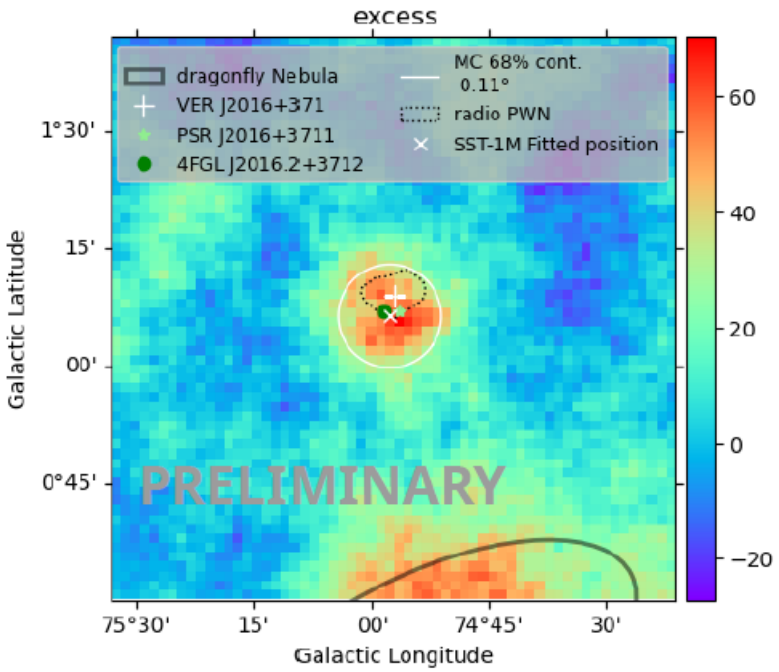
PHYSICS FOR FUTURE

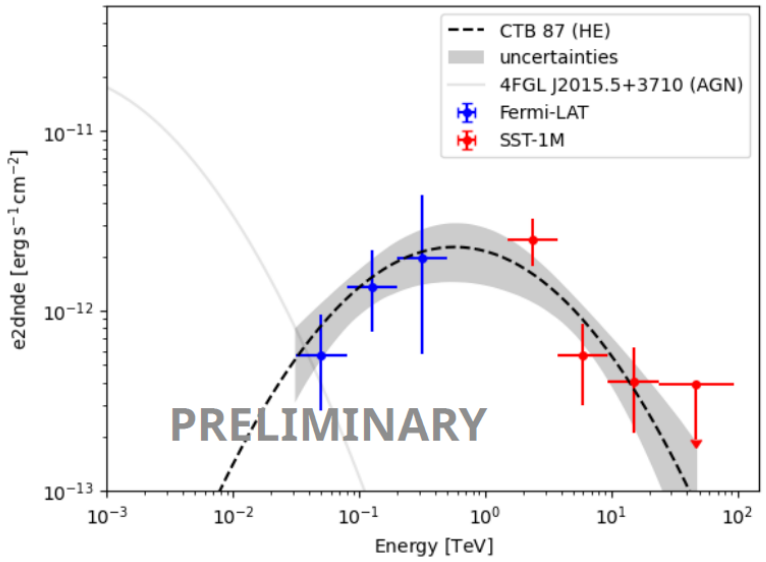
CTB87 (VER J2016+371)

Tavernier et al., EAS 2026, Lausanne, Switzerland

- SNR/PWN at a distance approx. 6.1 kpc
- By-product of Cygnus region observations
- 101 hours of exposure
- Detection on the level of 5.2σ
- Joint SST-1M and Fermi analysis is currently ongoing







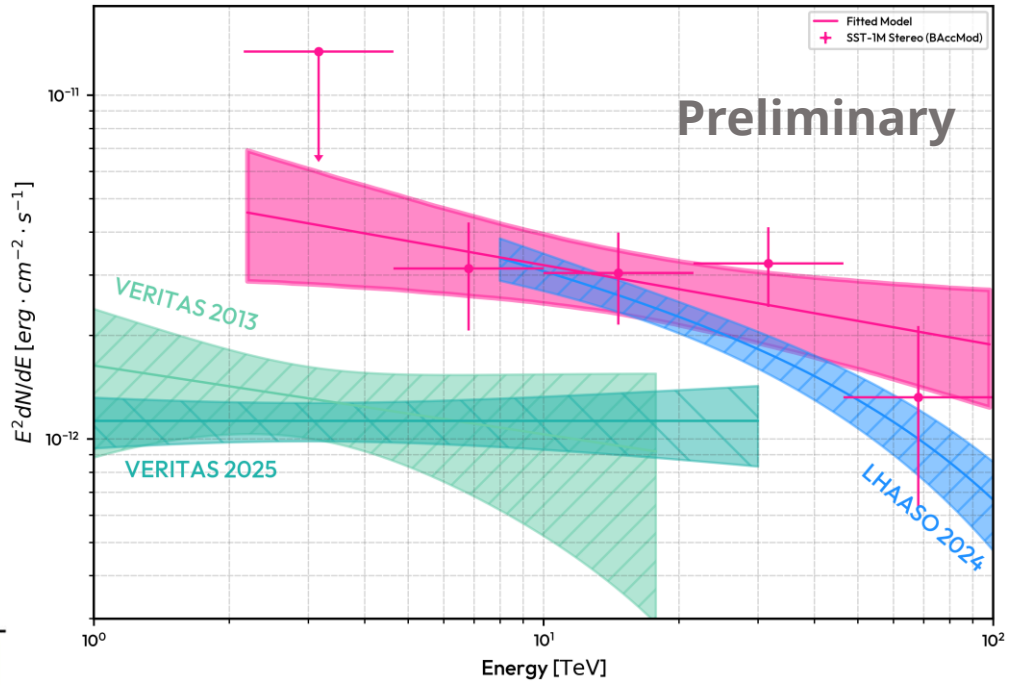
PHYSICS FOR FUTURE

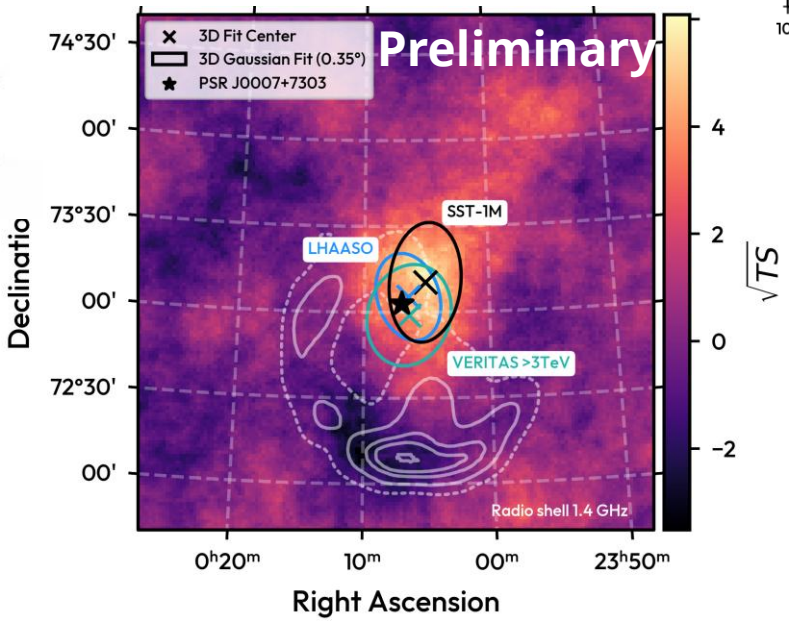
CTA1

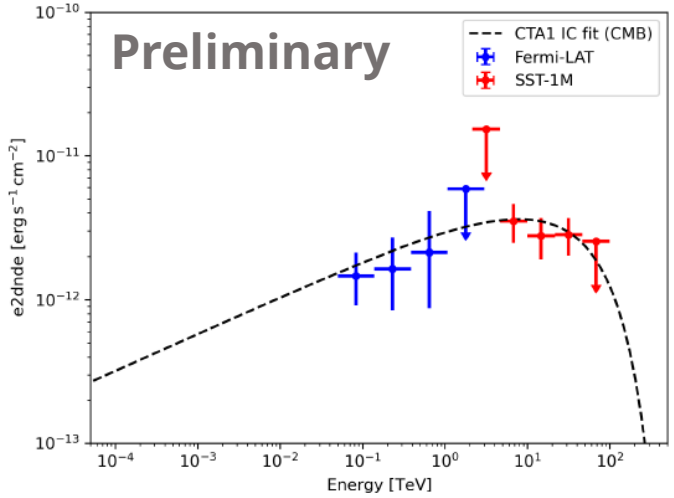
Lacave et al., PoS(ICRC2025)719
Lacave et al., Gamma Symposium 2026, Heidelberg, Germany

- Composite supernova remnant, distance 1.4 kpc
- 53 hours of good-quality data
- Discrepancies between VERITAS and LHAASO observations

	Parameter	Free spatial + PL
PL	Spectral index	2.40 ± 0.21
	Amplitude at $E_0 = 10$ TeV [TeV^{-1} s^{-1} cm^{-2}]	$2.03 \pm 0.51 \times 10^{-14}$
2D Gaussian	Right Ascension [deg]	1.27 ± 0.19
	Declination [deg]	73.18 ± 0.09
	Sigma [deg]	0.33 ± 0.09
	Ellipticity	0.8 ± 0.17
	Phi [deg]	-8.67 ± 19
Bkg	Tilt correction ($\rightarrow 0$)	0
	Norm correction at $E_0 = 1$ TeV ($\rightarrow 1$)	0.84 ± 0.05
Fit significance		$4.47\,\sigma$







PHYSICS FOR FUTURE

AGN activity monitoring – Mrk 421, 1ES 1959+650

Mrk 421

- First extragalactic source in true stereo detected by SST-1M
- Higher activity detected on 13th of March 2024 (ATel #16533), 12th of January 2026 (ATel #17597)
- **See the talk of Srija Reddy Muthyala**

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)

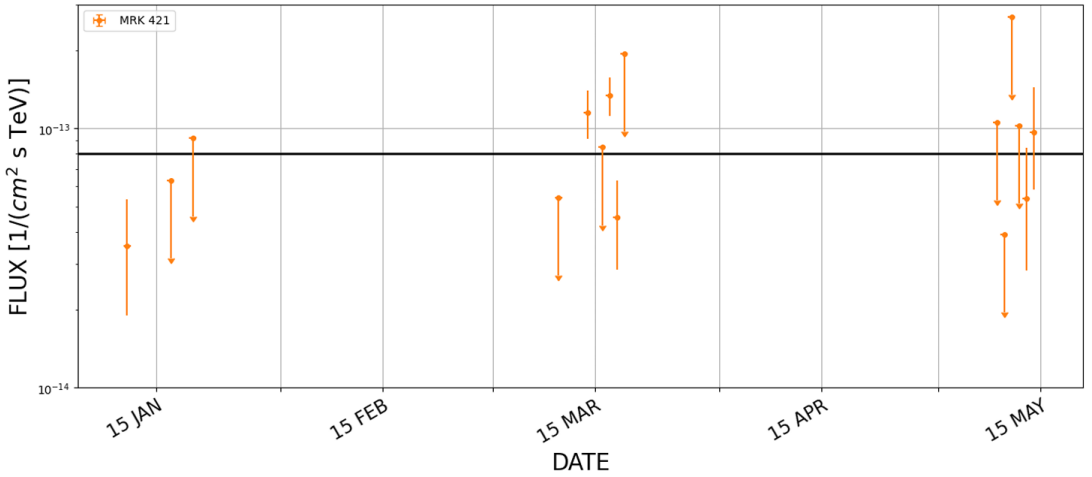
SST-1M detection of increased very-high-energy gamma-ray activity of Mrk 421

ATel #17597; *Srija Reddy Muthyala (FZU), for the SST-1M Collaboration*
on 14 Jan 2026; 20:32 UT
Credential Certification: Thomas Tavernier (tavernier@fzu.cz)

Subjects: Gamma Ray, TeV, VHE, AGN, Blazar

Referred to by ATel #: 17602, 17622

Muthyala et al., PoS(ICRC2025)776



1ES 1959+650

- BL Lac object, z = 0.047
- Observation of increased activity during the nights 18th and 19th of September 2026 (ATel #18065)
- Ongoing analysis

[Previous | Next | ADS]

Bright TeV gamma-ray emission from 1ES 1959+650 detected with SST-1M

ATel #18065; *Thomas Tavernier, for the SST-1M Collaboration*
on 21 Sep 2026; 15:34 UT
Credential Certification: Thomas Tavernier (tavernier@fzu.cz)

Subjects: Gamma Ray, TeV, VHE, AGN, Blazar

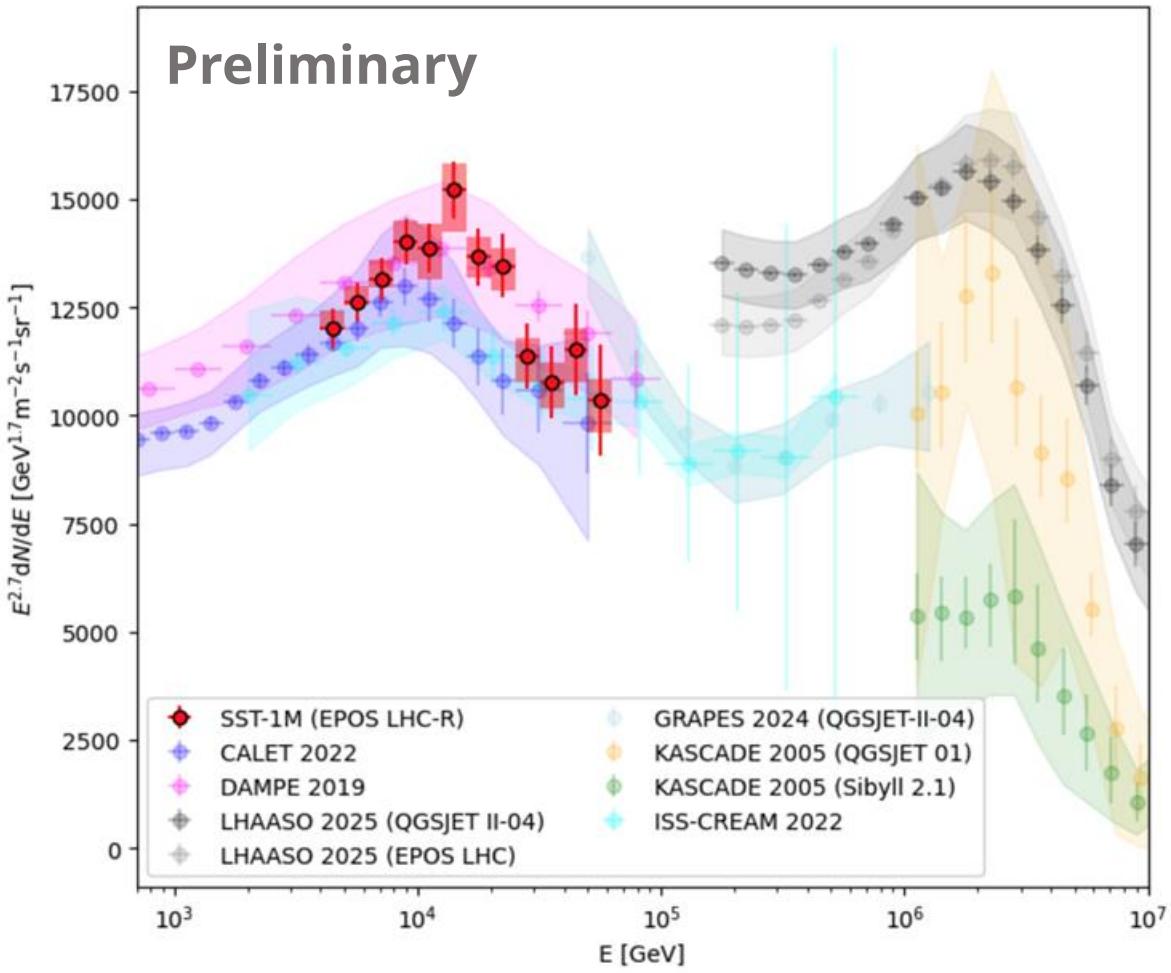
Referred to by ATel #: 18072, 18077

PHYSICS FOR FUTURE

SST-1M proton spectrum

Juryšek et al., TeVPa 2026, Tendo, Japan

- Side project – gamma-ray telescopes used to measure cosmic-ray (CR) proton spectrum
- SST-1M sensitive to CRs at energies particularly interesting for galactic science
- Joint analysis on Dragonfly and Markarian 421 data
- 60 hours of good quality data for zenith angles < 23°
- Likelihood ratio test of BPL vs PL => Broken PL with spectral break at 13.87 +/- 0.93 TeV strongly preferred over single PL
- Ongoing analysis

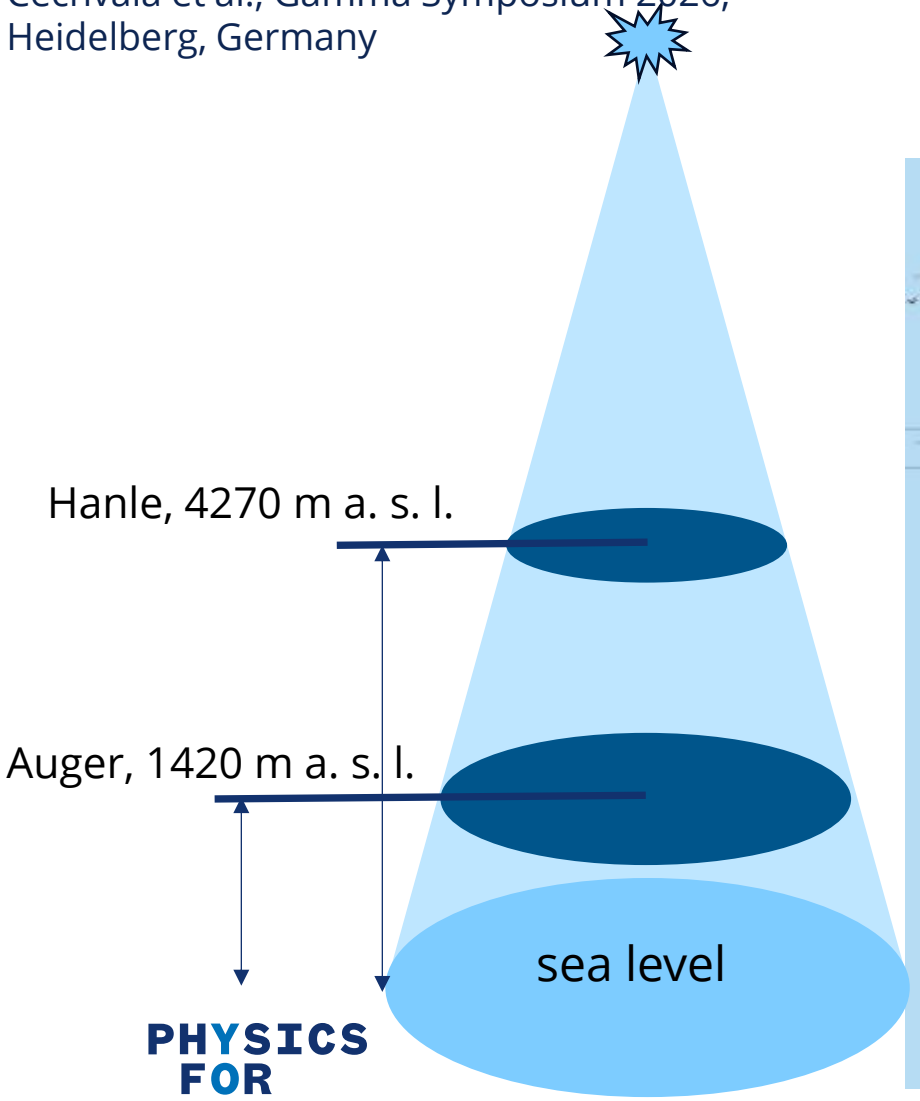


PHYSICS FOR FUTURE

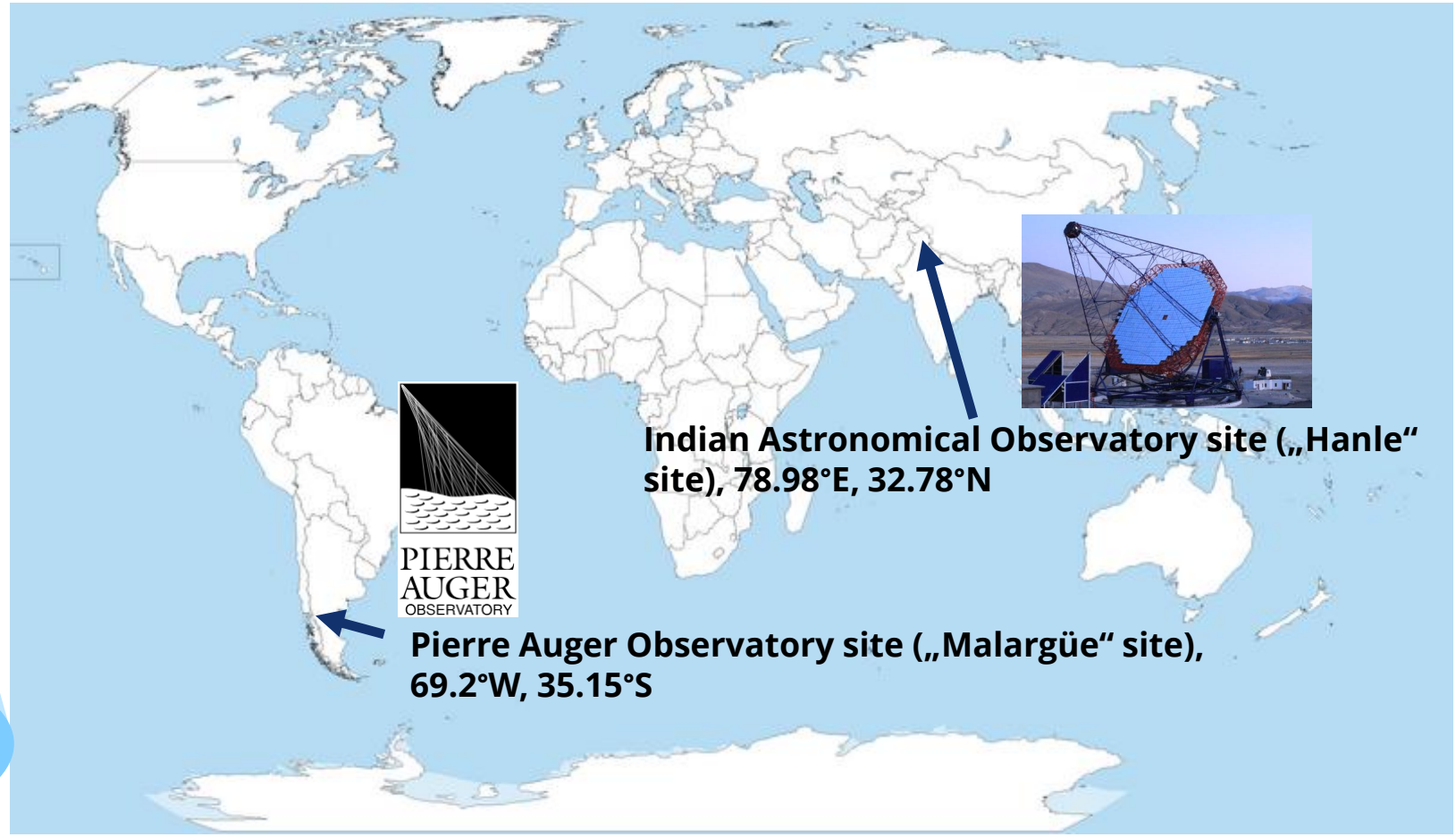
Searching for a new home for SST-1M telescopes

Čechvala et al., PoS(ICRC2025)908
Čechvala et al., Gamma Symposium 2026, Heidelberg, Germany

- Atmospheric conditions in Ondřejov are not satisfactory – number of clear-sky nights



Credit: Wikipedia



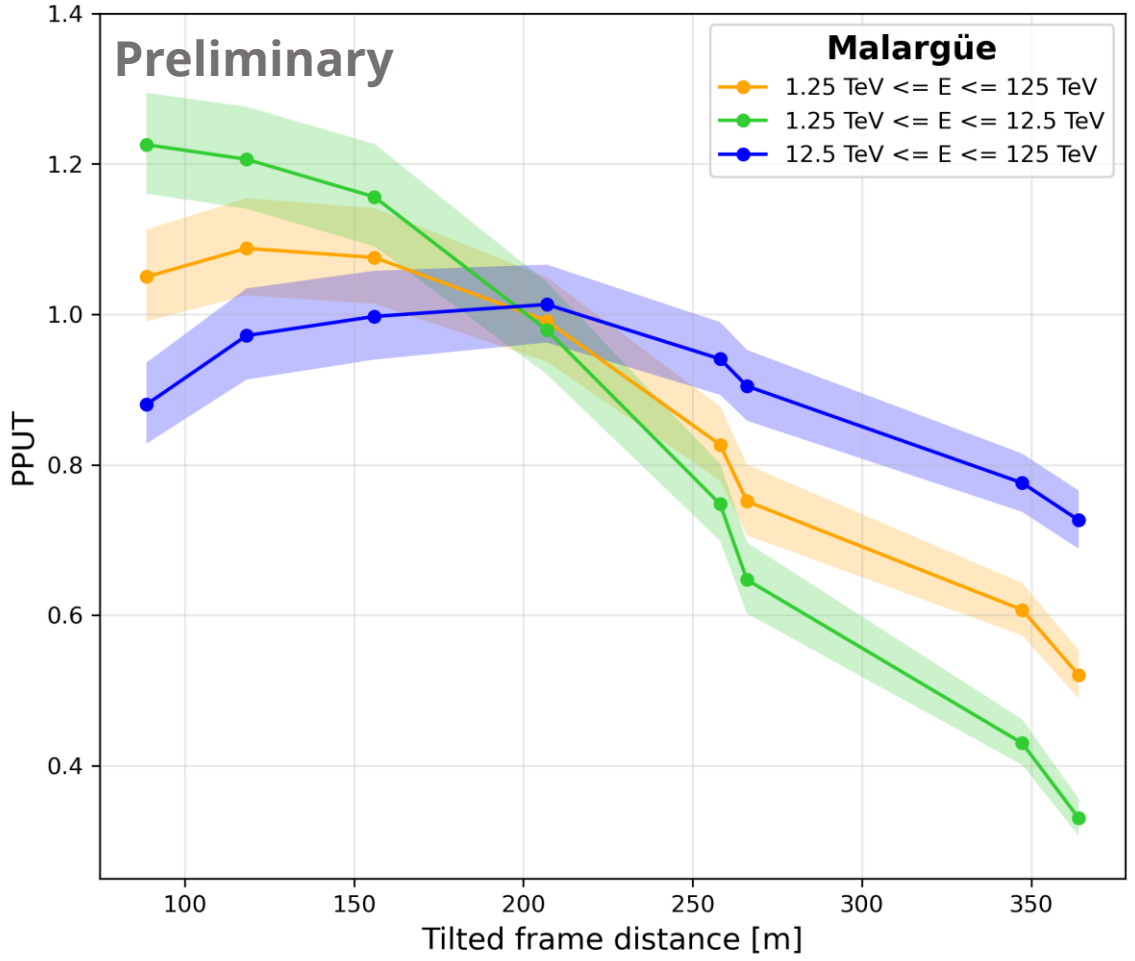
PHYSICS FOR FUTURE

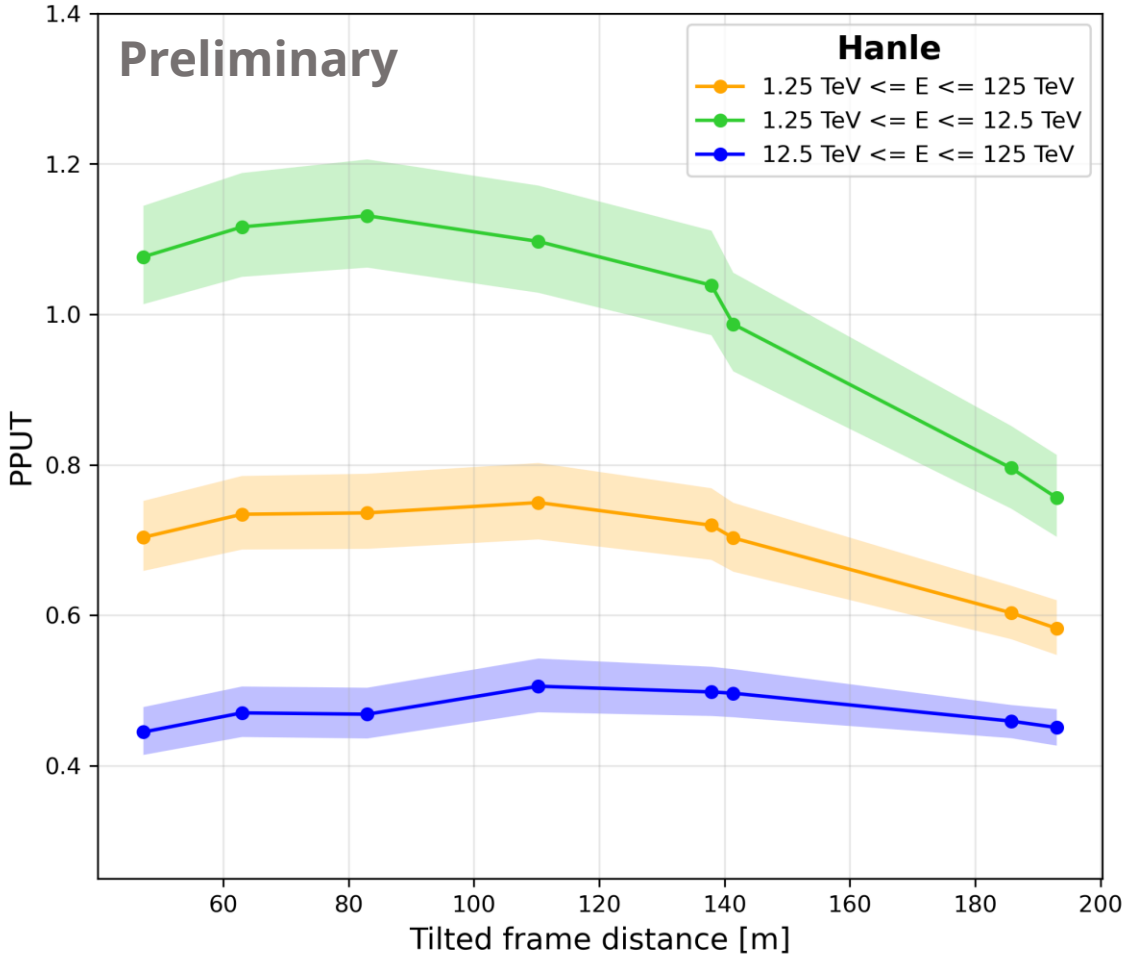
Future of SST-1M telescopes

Hassan et al, Astroparticle Physics 111 (2019)

Čechvala et al., Gamma Symposium 2026, Heidelberg, Germany

$$\mathrm{PPUT} = \left(\prod_{i=1}^{N} \frac{F_{\mathrm{sens,ref}}(i)}{F_{\mathrm{sens}}(i)} \right)^{1/N}$$



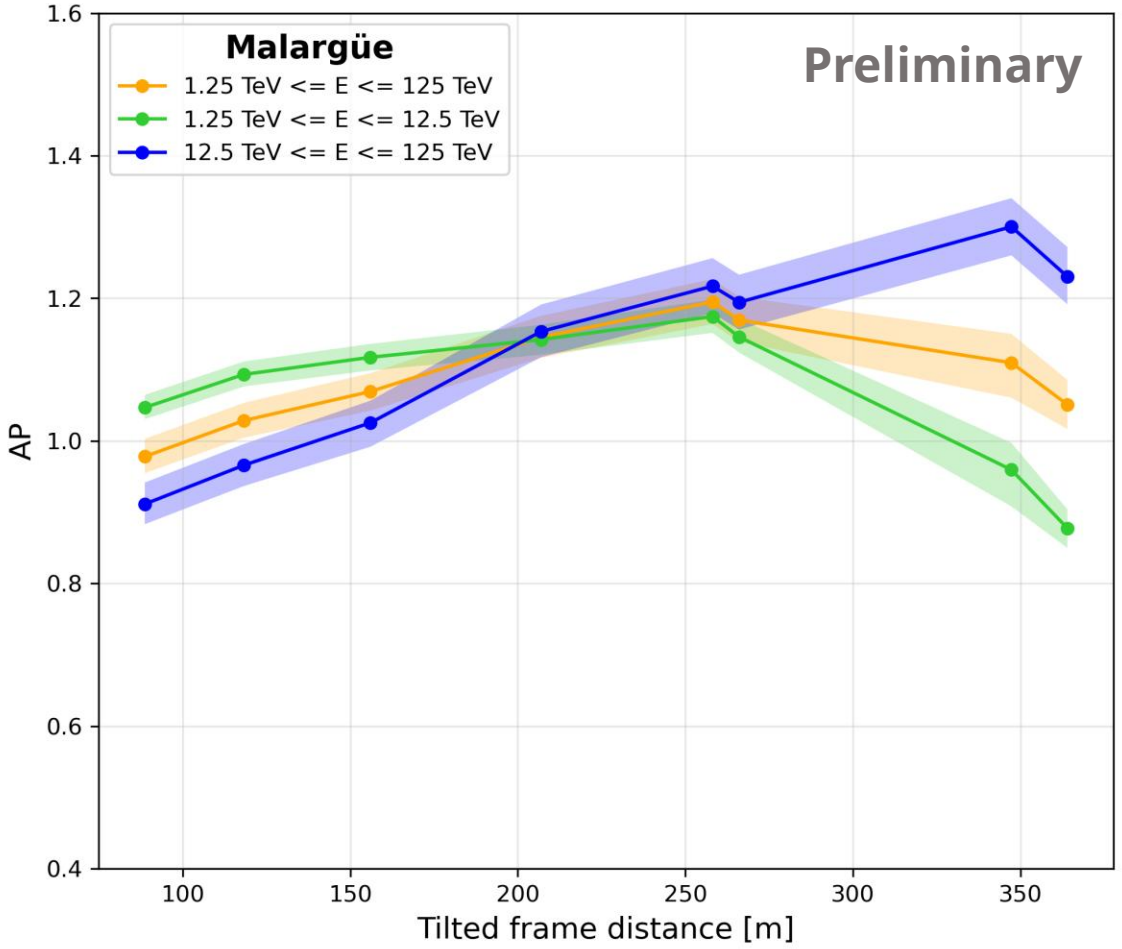


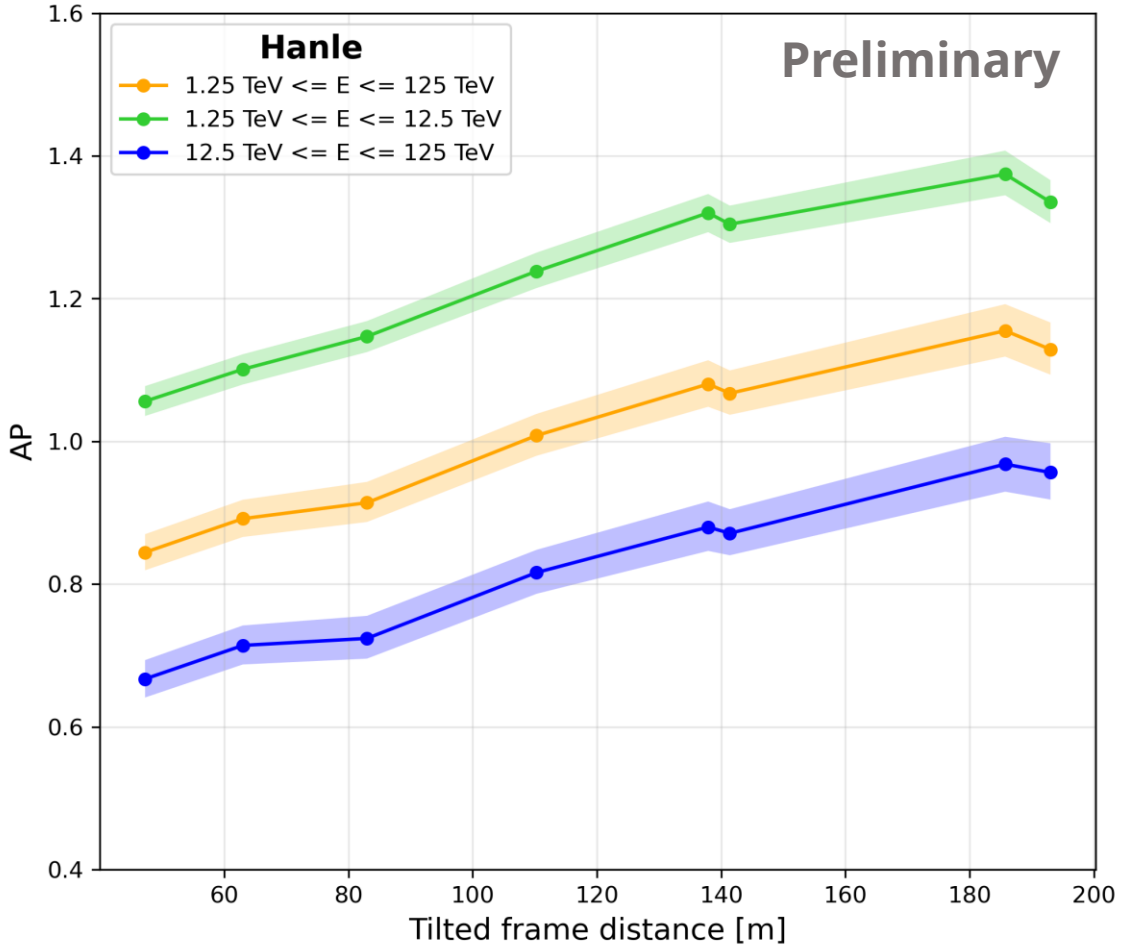
Future of SST-1M telescopes

Hassan et al, Astroparticle Physics 93 (2017)

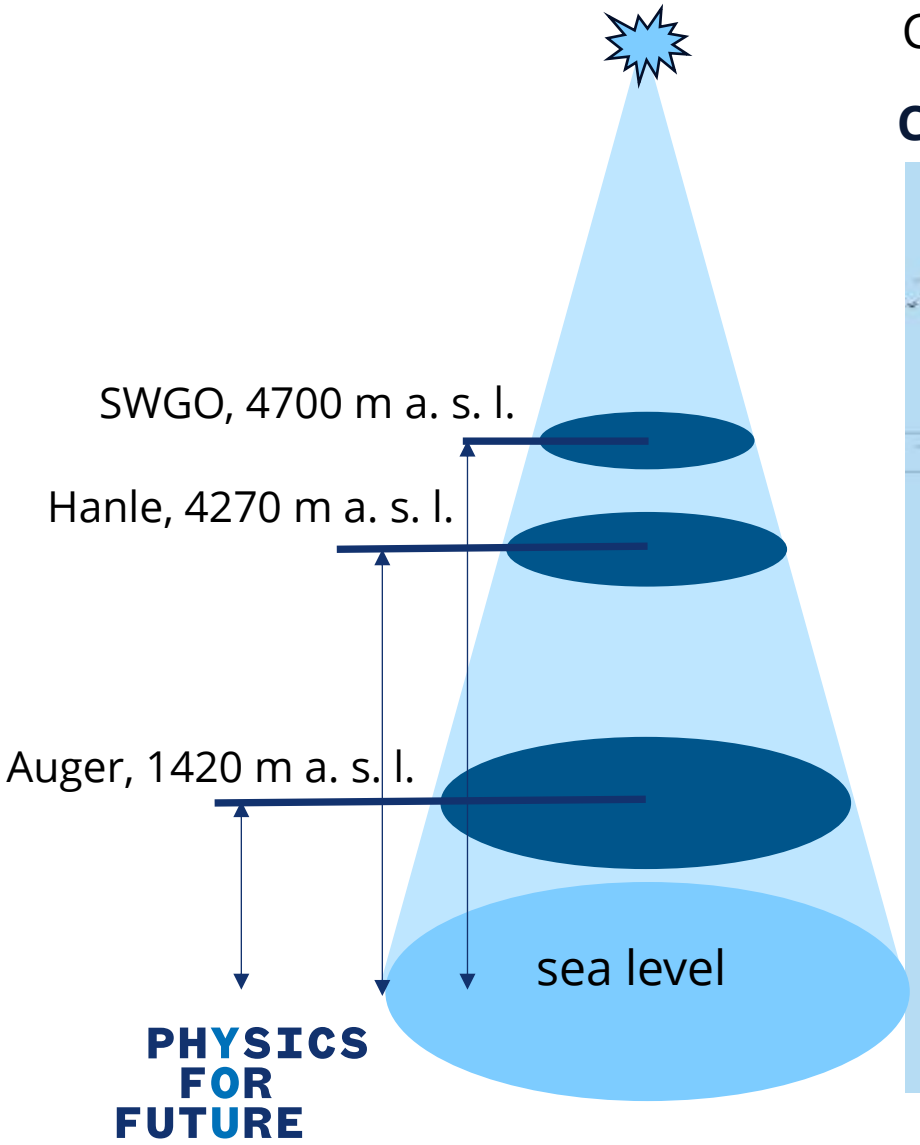
Čechvala et al., Gamma Symposium 2026, Heidelberg, Germany

$$\mathrm{AP} = \left(\prod_{i=1}^{N} \frac{\Theta_{0.68,\mathrm{ref}}(i)}{\Theta_{0.68}(i)} \right)^{1/N}$$





Exploring the possibility of hybrid detection technique



PHYSICS FOR FUTURE

Bakalová et al., PoS(ICRC2025)558
C. Alispach et al. Astropart. Phys. (2026)

Credit: Wikipedia

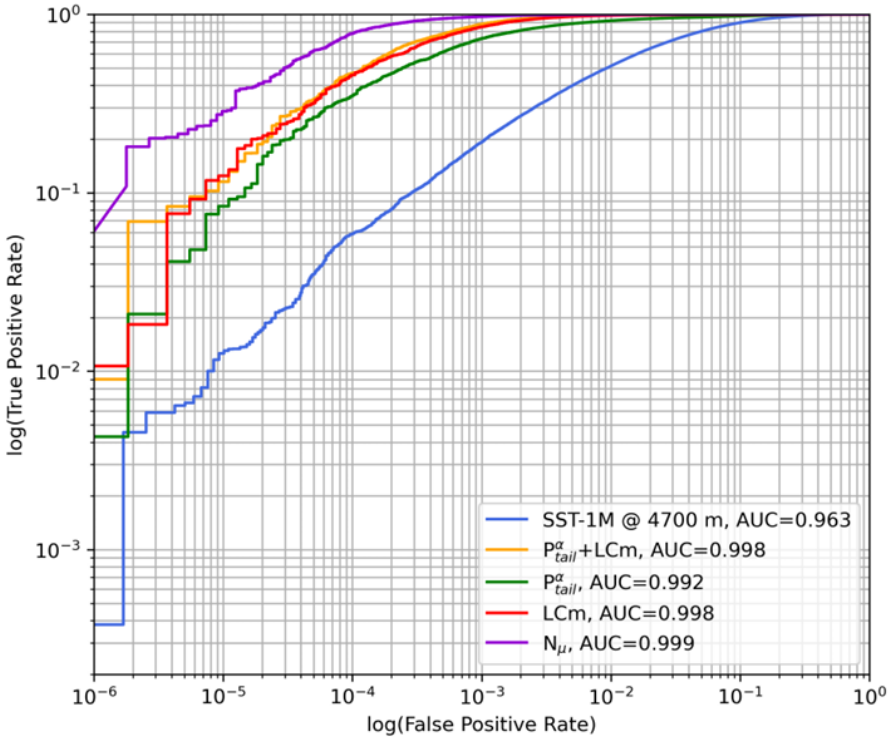


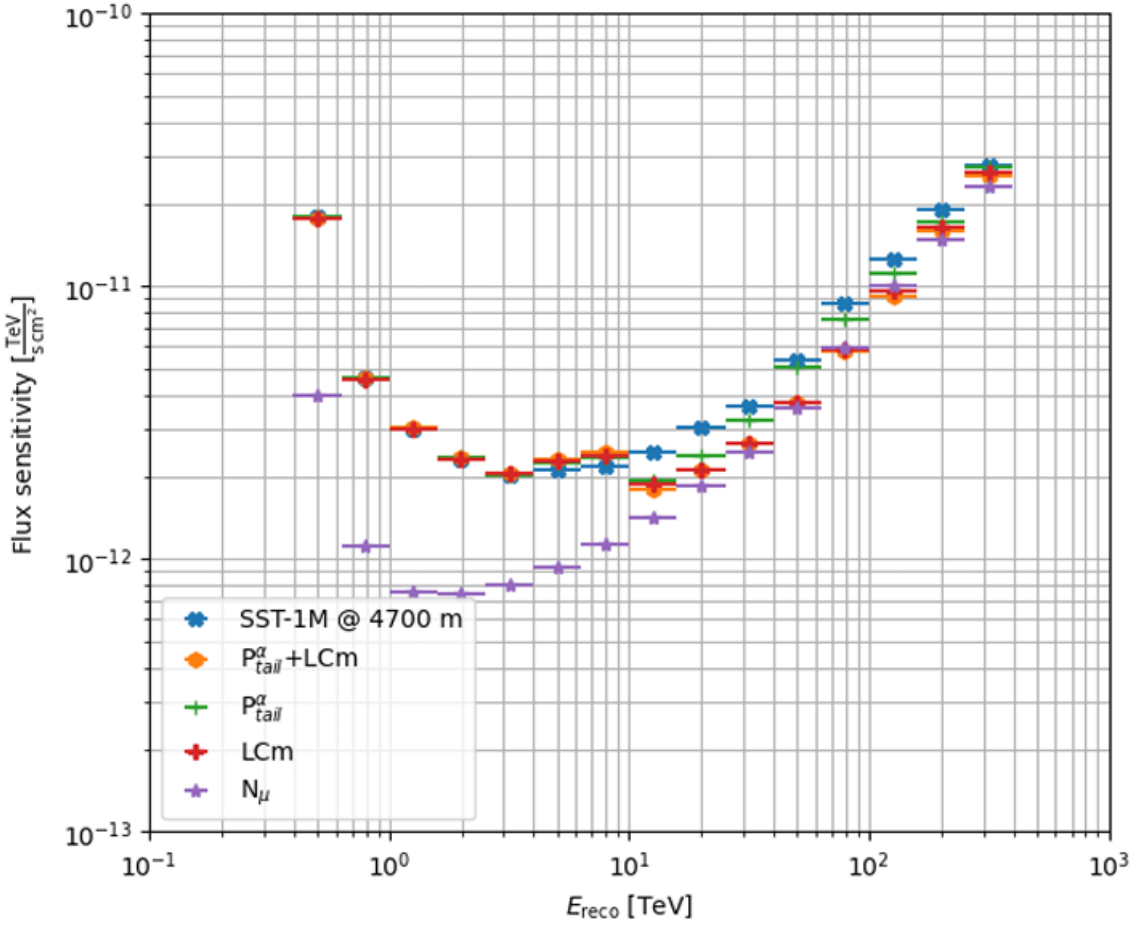
Exploring the possibility of hybrid detection technique

- Use of surface array parameters in *sst1mpipe* – LCm, P^{α}_{tail}

  R. Conceição *et al* JCAP10(2022)086
  R. Conceição, 2024 arXiv:2309.17217

- Significant improvement of g/h separation

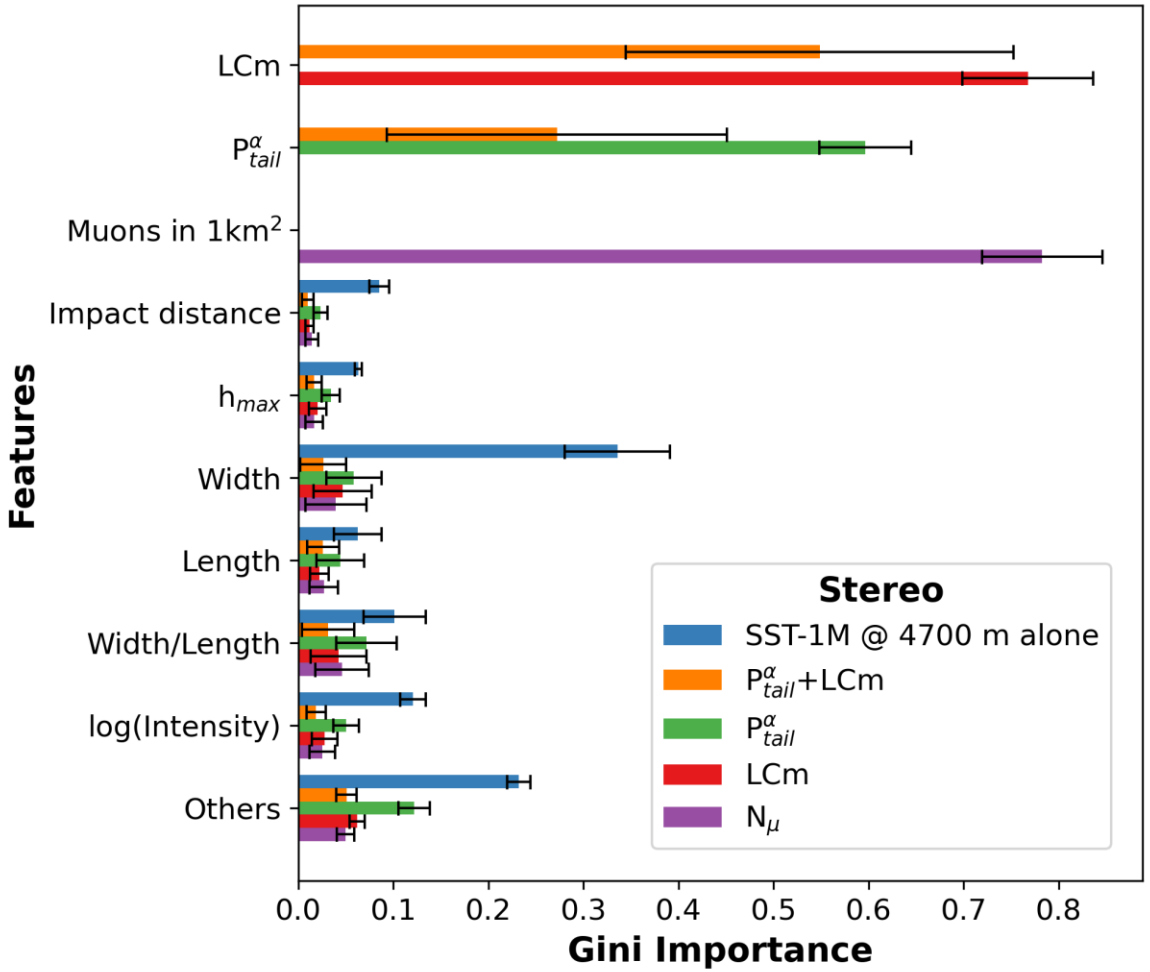


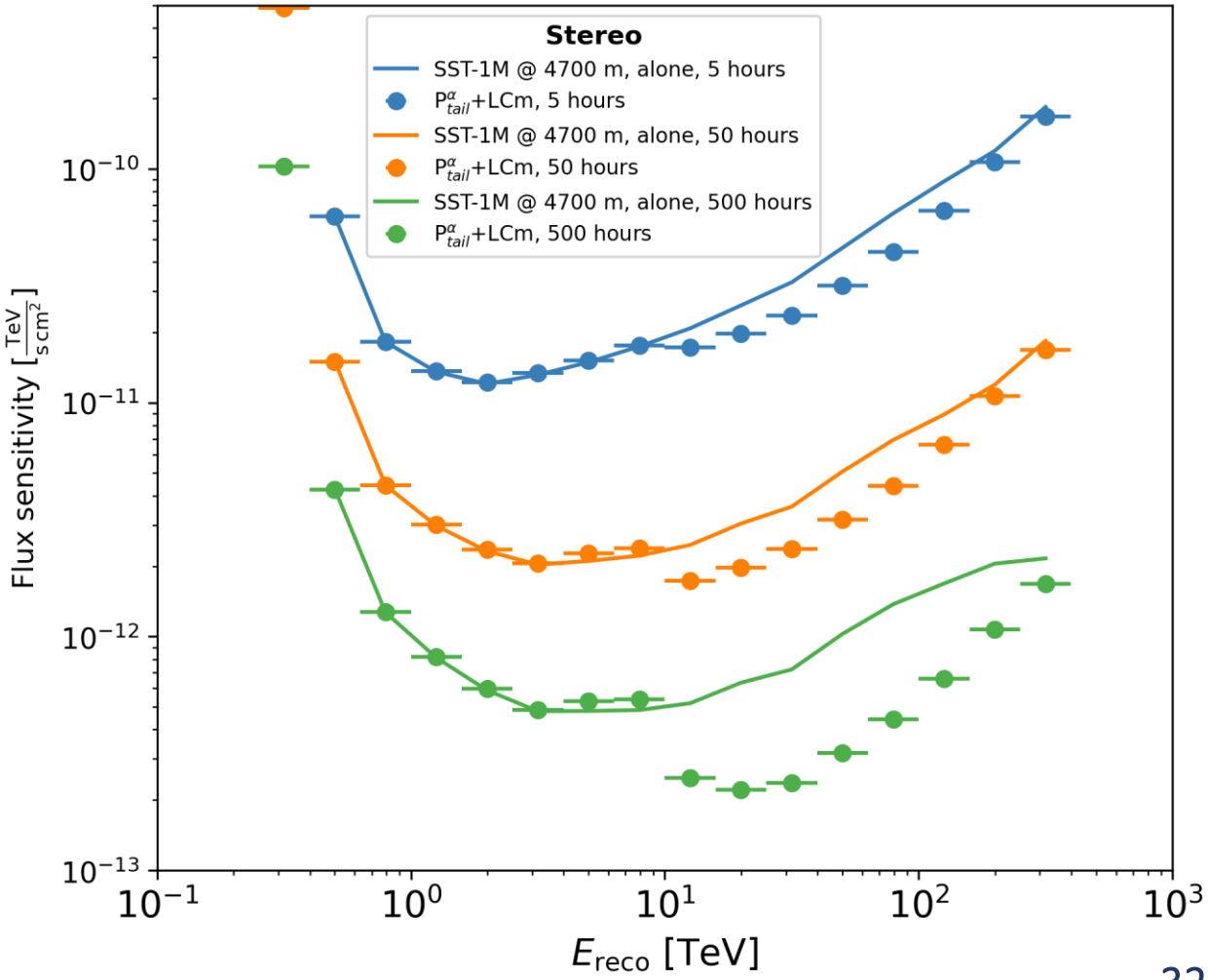


Bakalová et al., PoS(ICRC2025)558

Exploring the possibility of hybrid detection technique

C. Alispach et al. Astropart. Phys. (2026)





Acknowledgements

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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

Conclusion

- **IACT method**
- **SST-1M telescopes are successfully observing for more than 3 years**
- **Detection of several cosmic sources – first results published, more on the way**
- **Studies of a new site for SST-1M**

PHYSICS FOR FUTURE

Thank you for your attention

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https://sst-1m.science/

SST1M_SPACE

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PHYSICS FOR FUTURE

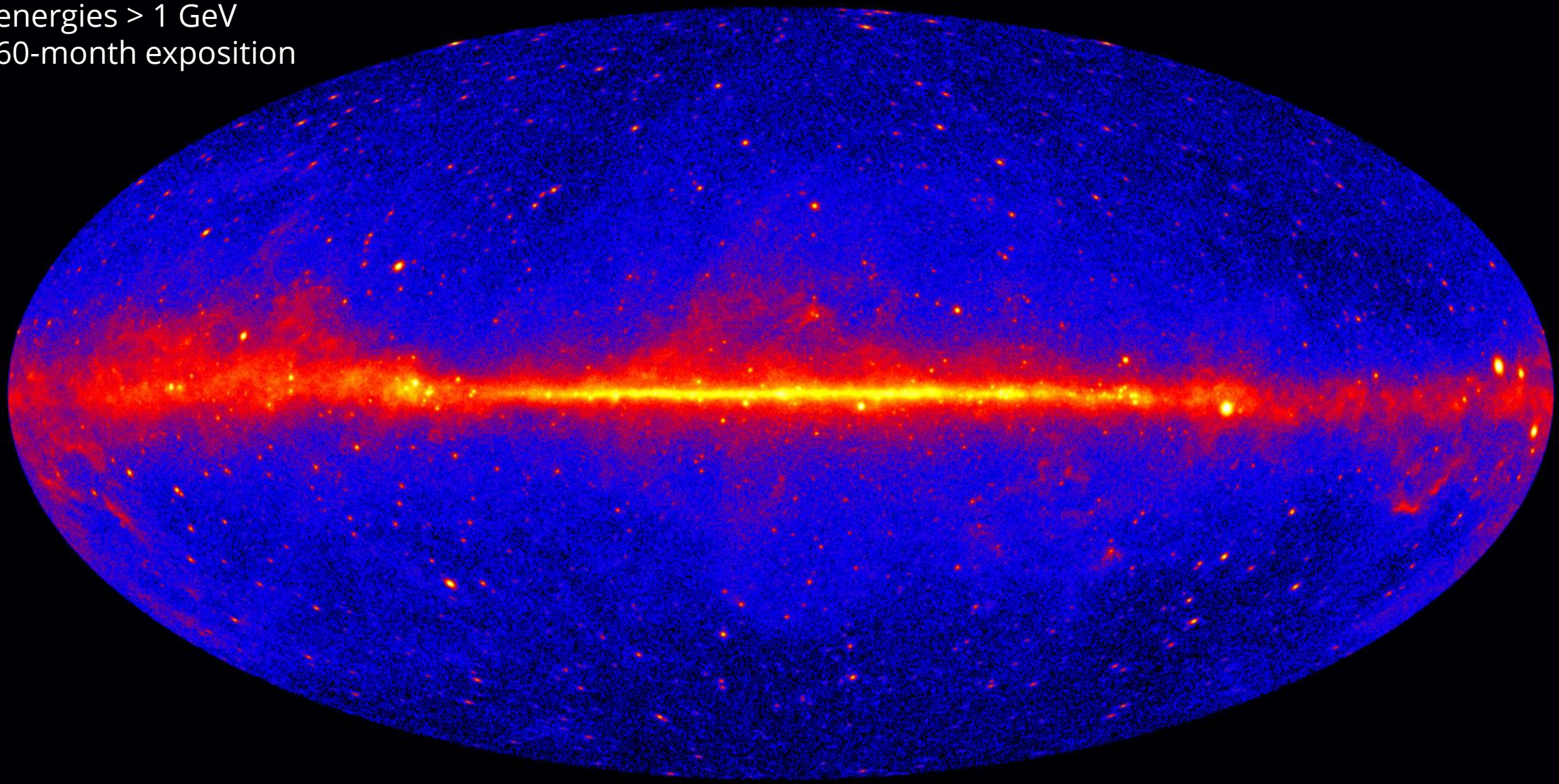
SST-1M
Single-Mirror
Small Size Telescope

FZU Institute of Physics of the Czech Academy of Sciences

Co-funded
by the European Union

Gamma-ray sky

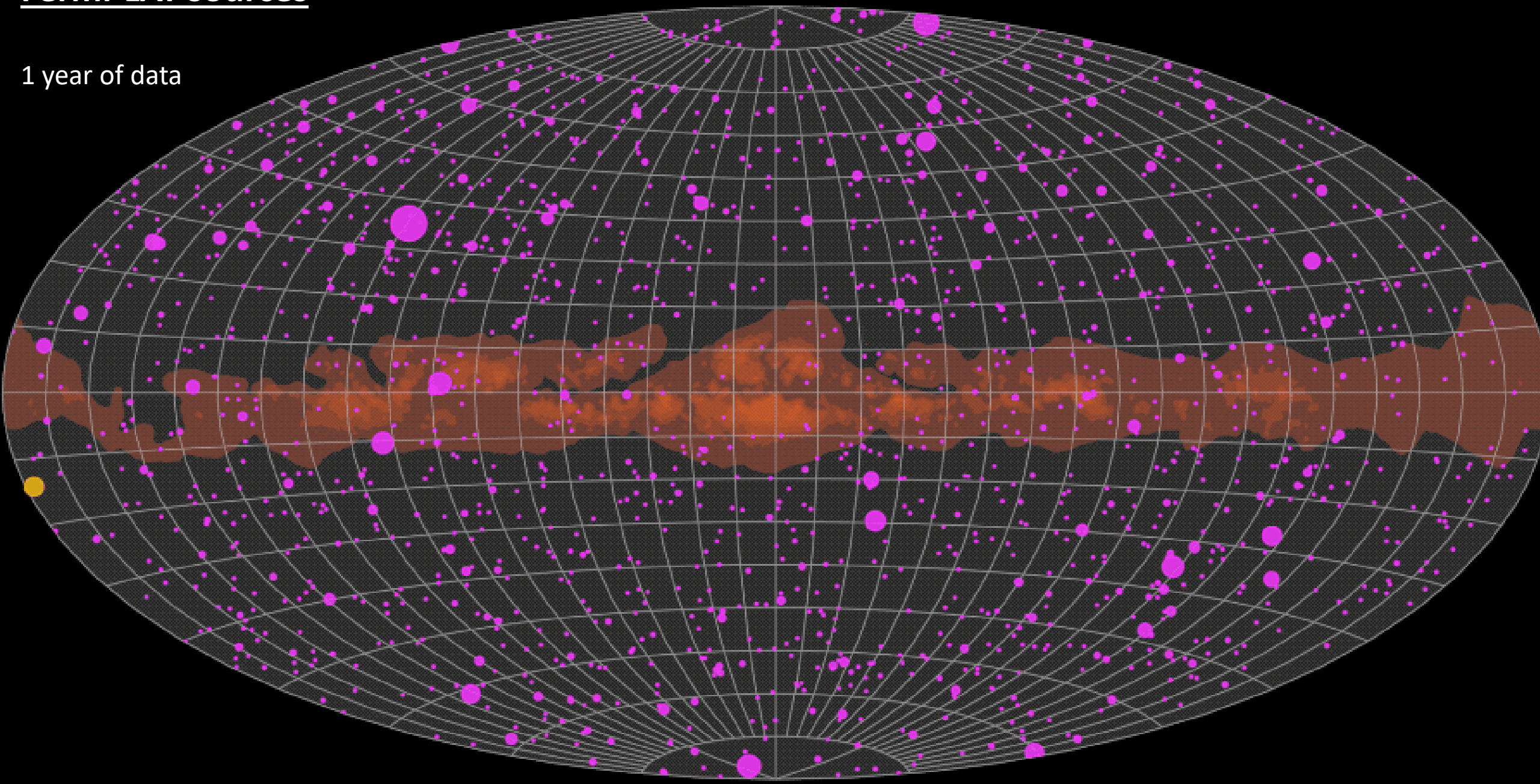
- energies > 1 GeV
- 60-month exposition



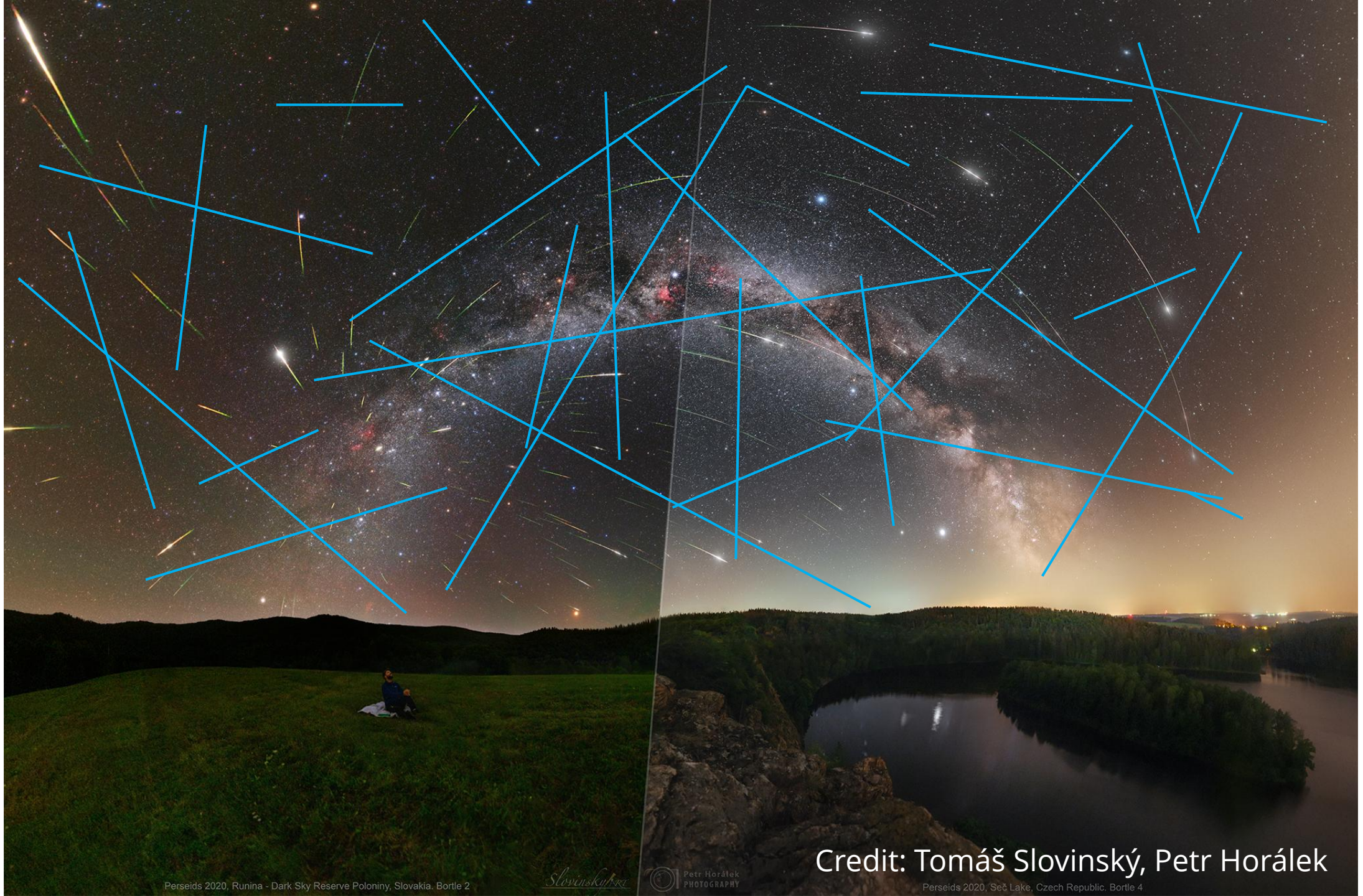
Credit: NASA/DOE/Fermi LAT Collaboration

Fermi-LAT sources

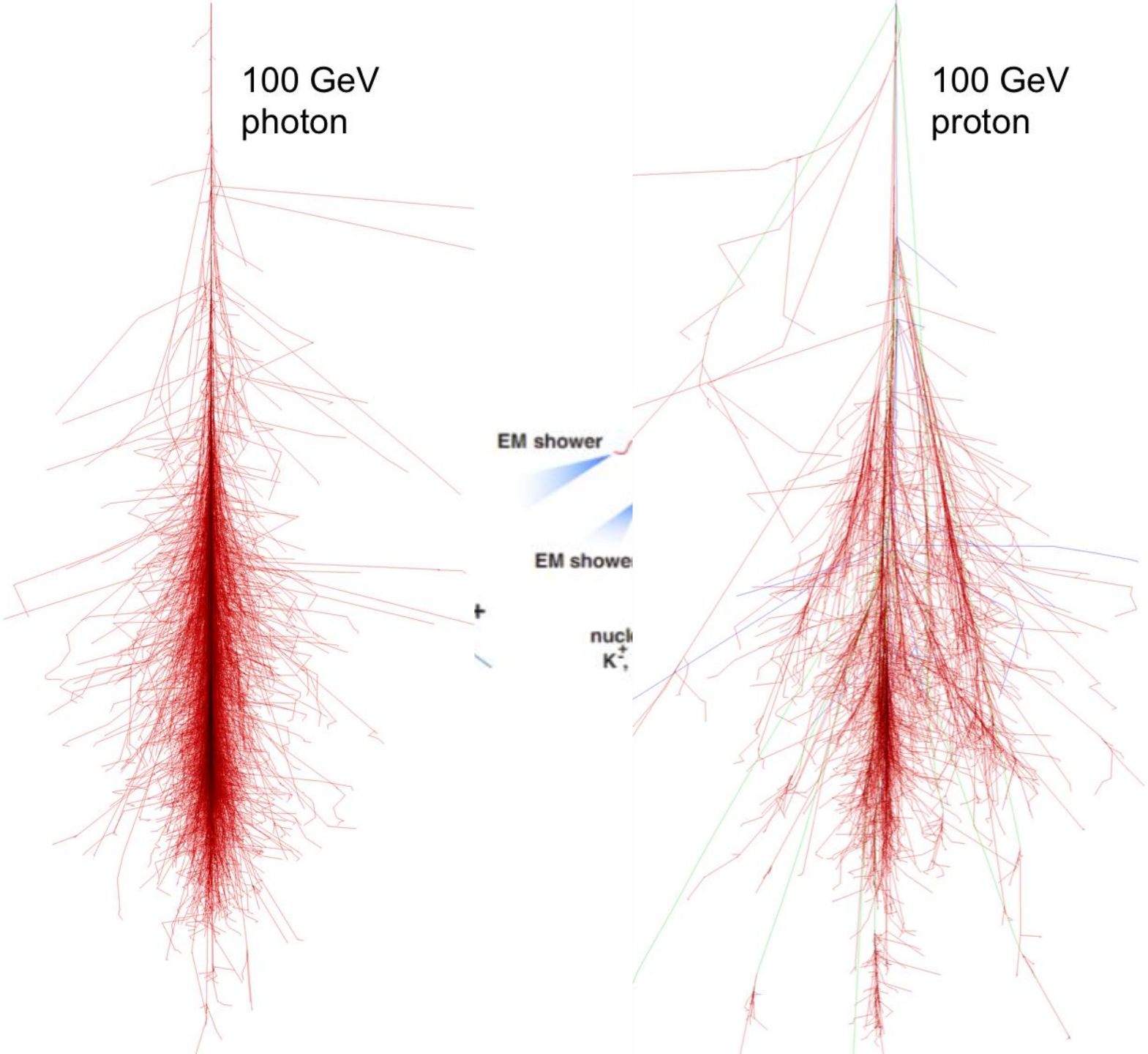
1 year of data



Credit: NASA’s Marshall Space Flight Center/Daniel Kocevski

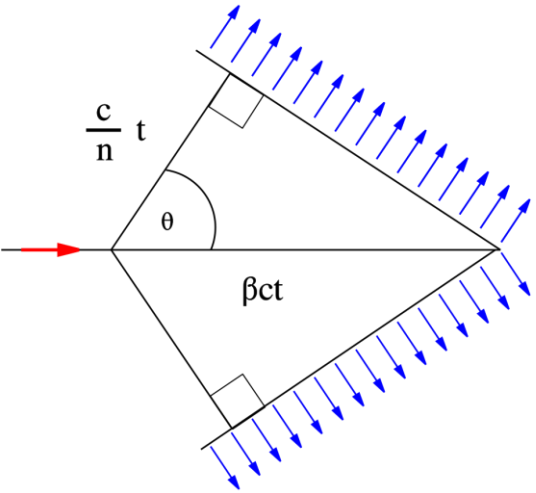


Credit: Tomáš Slovinský, Petr Horálek



Barral, PhD thesis
2017

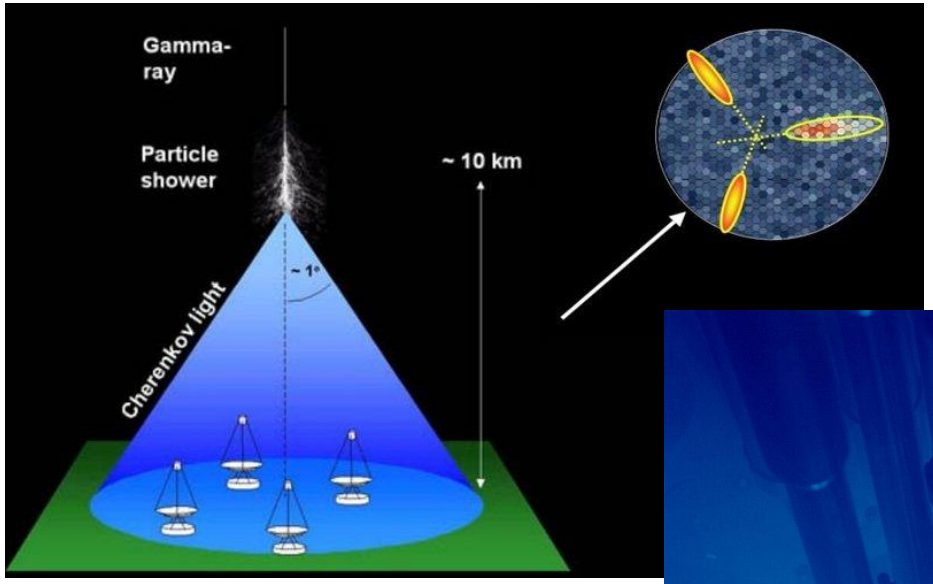
Cherenkov radiation

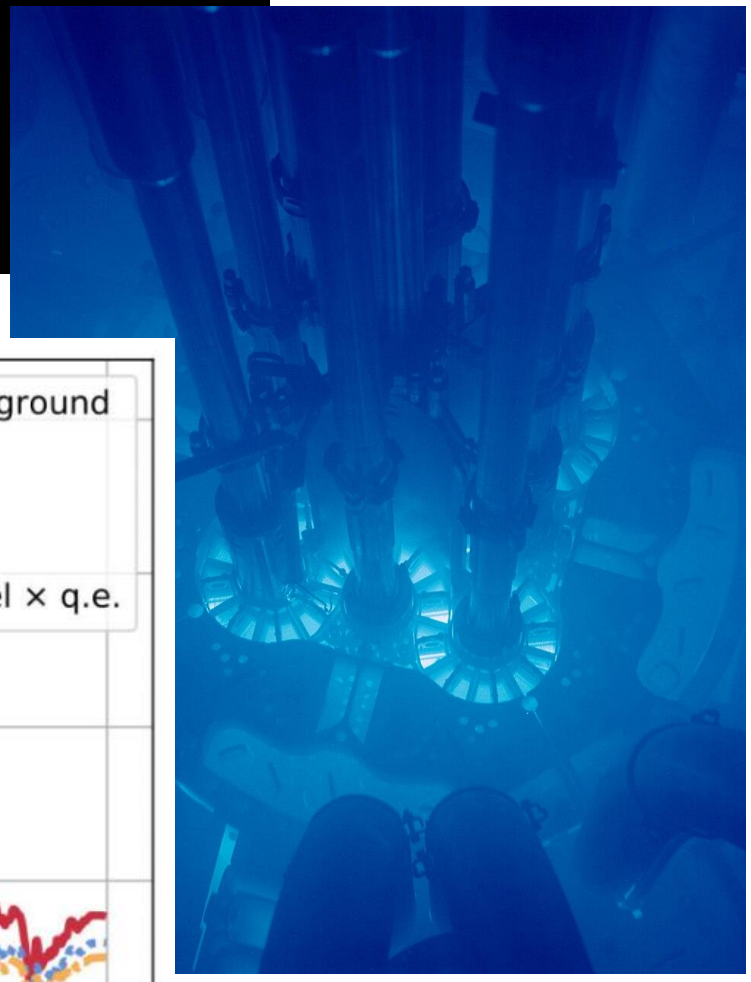


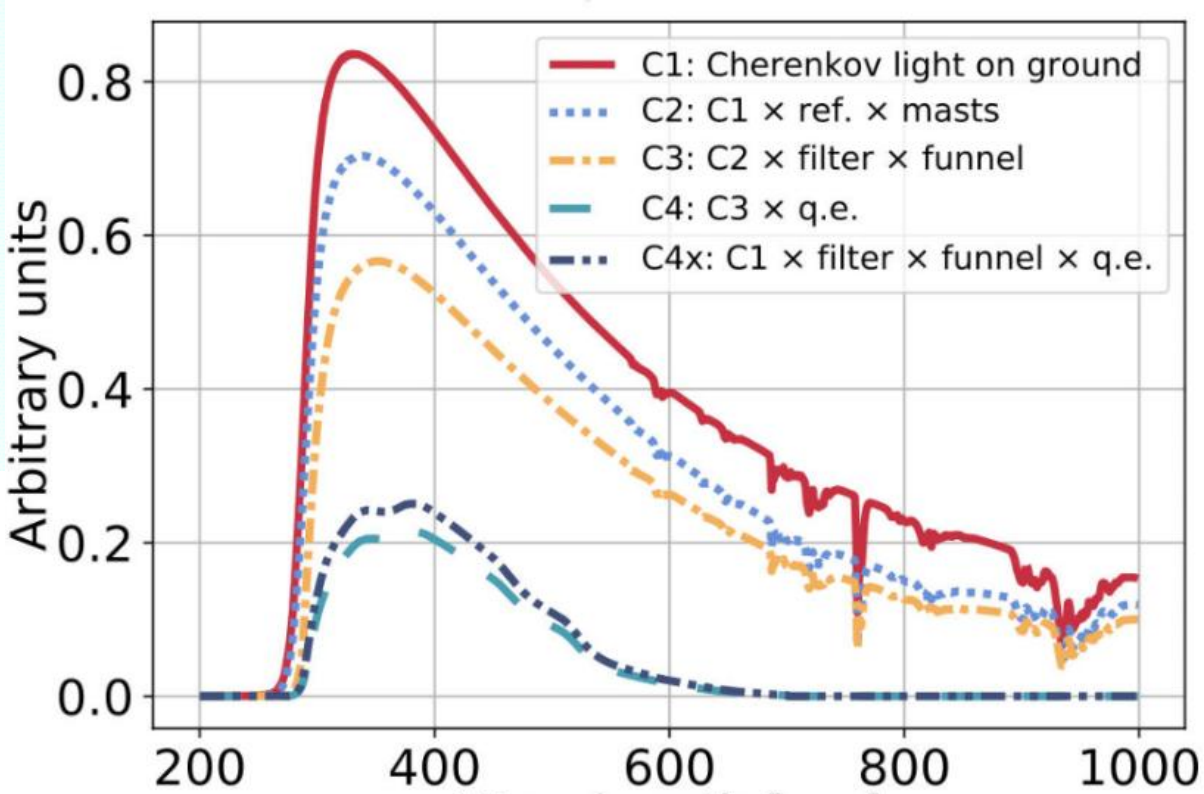
$$\beta = \frac{v_{\mathrm{p}}}{c}$$

$$v_{\mathrm{em}} = \frac{c}{n}$$

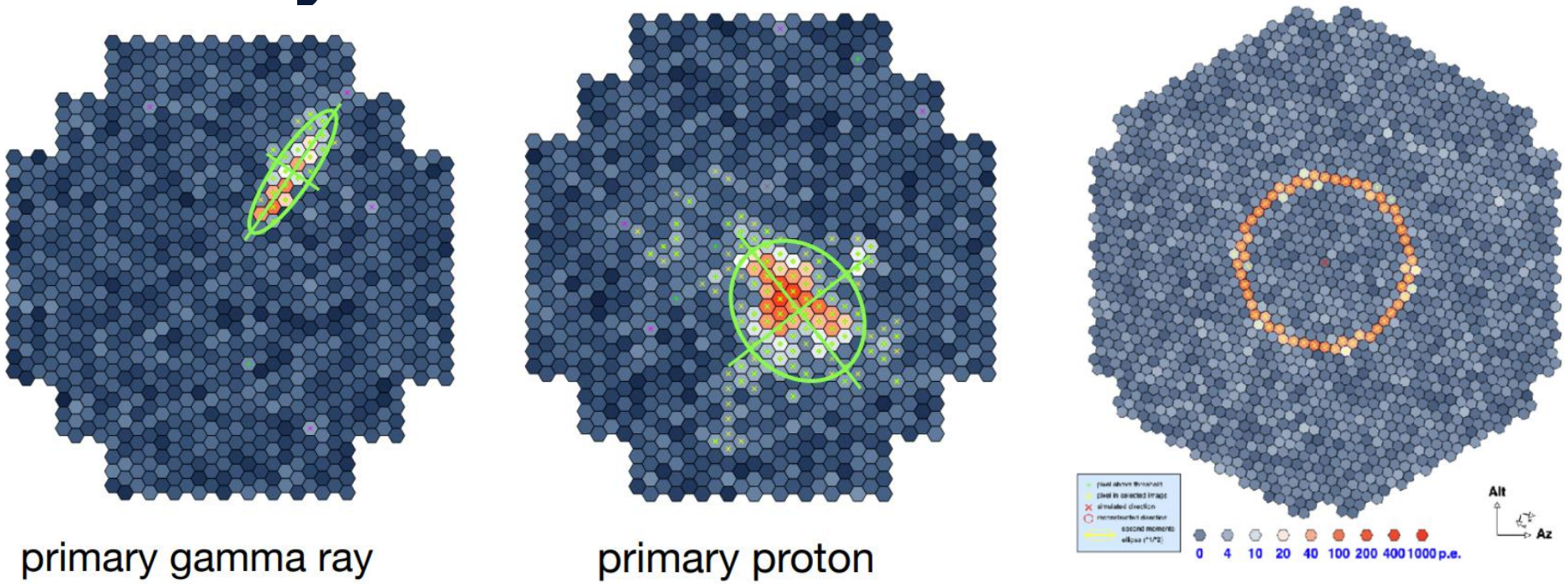
$$\cos\theta = \frac{1}{n\beta}$$

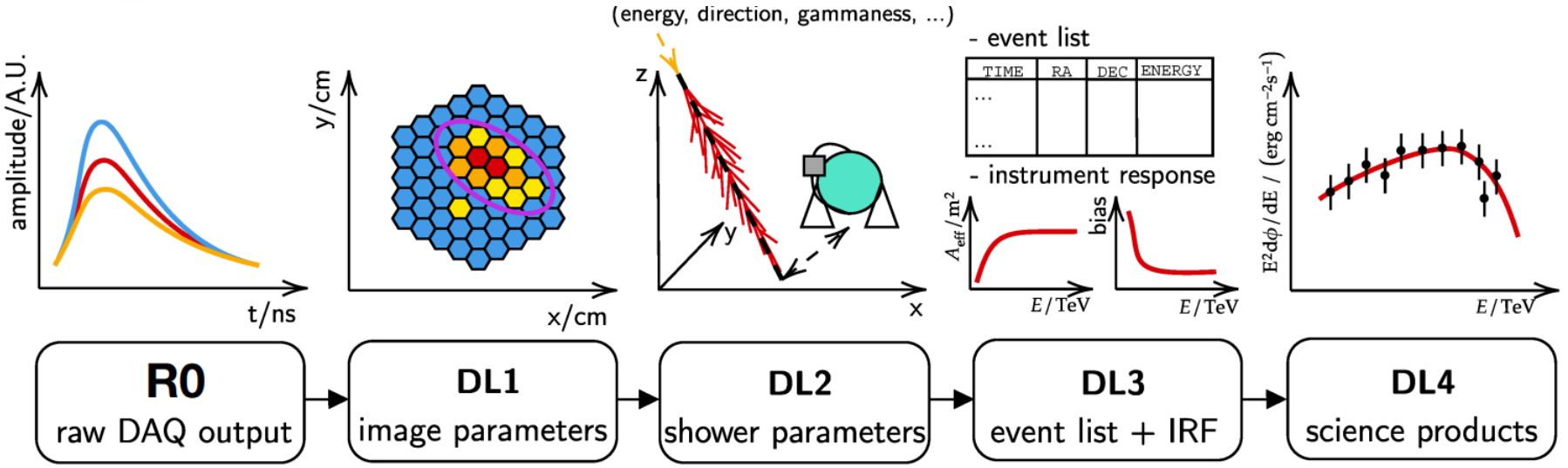






Pipeline and analysis

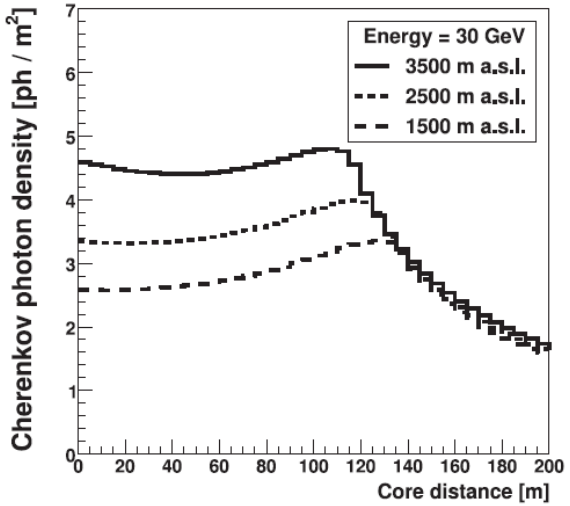


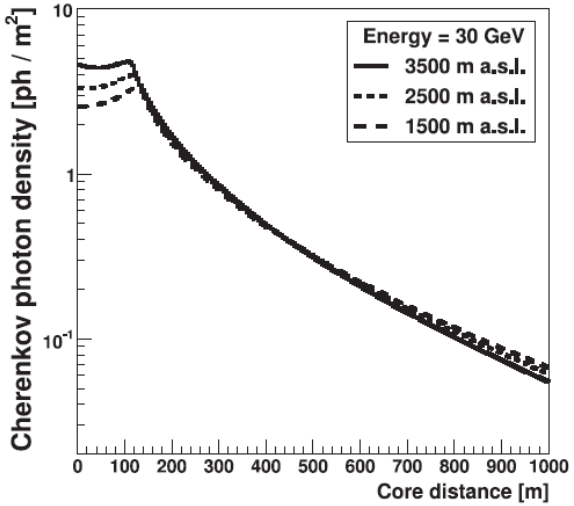


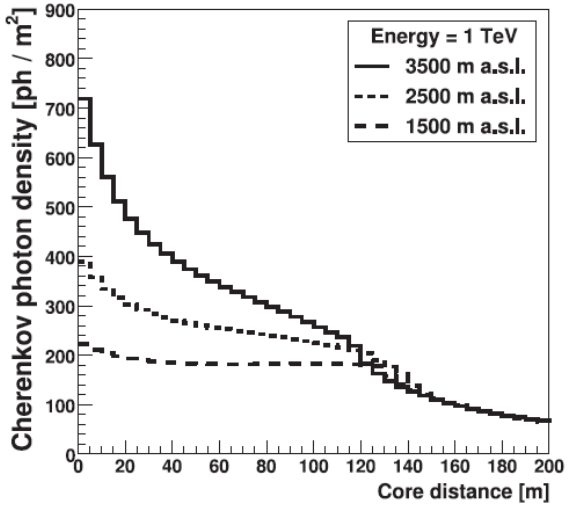
PHYSICS FOR FUTURE

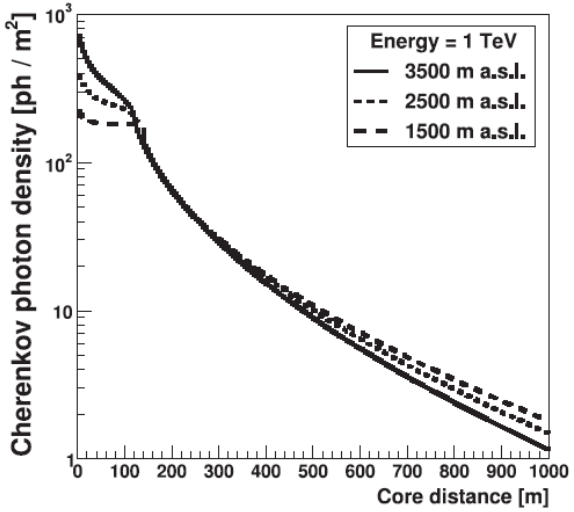
Nigro et al., Universe, 2021 https://doi.org/10.3390/universe7100374

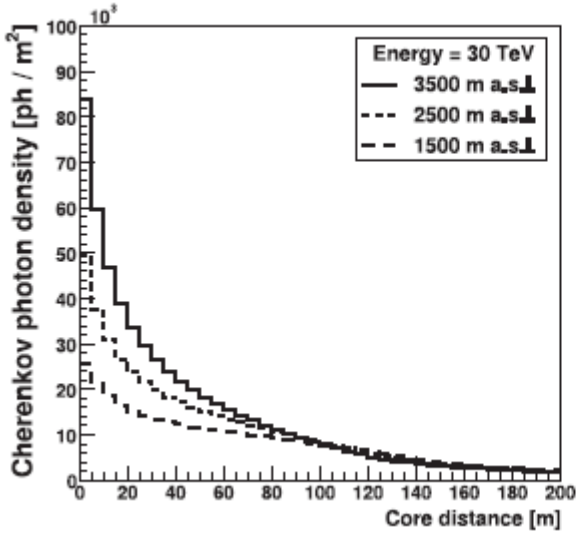
Cherenkov photon density at different altitudes

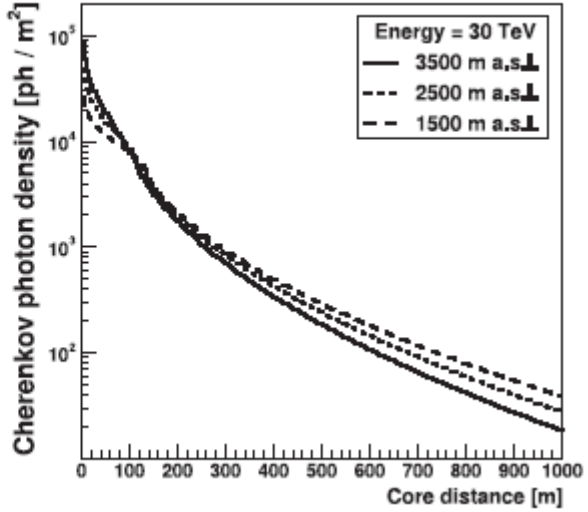








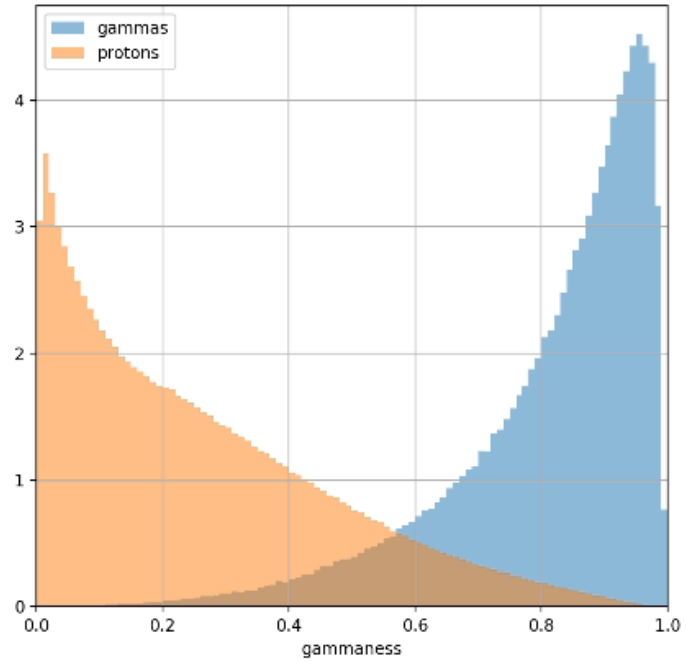




Hassan et al., 2017

Random forest implementation

- **Gamma/Hadron separation**
  - classifier, trained on diffuse gammas and diffuse protons
  - provides parameter - ***gammaness***
- **Energy regressor**
  - regressor, trained on diffuse gammas
- **Direction reconstruction**
  - trained on diffuse gammas

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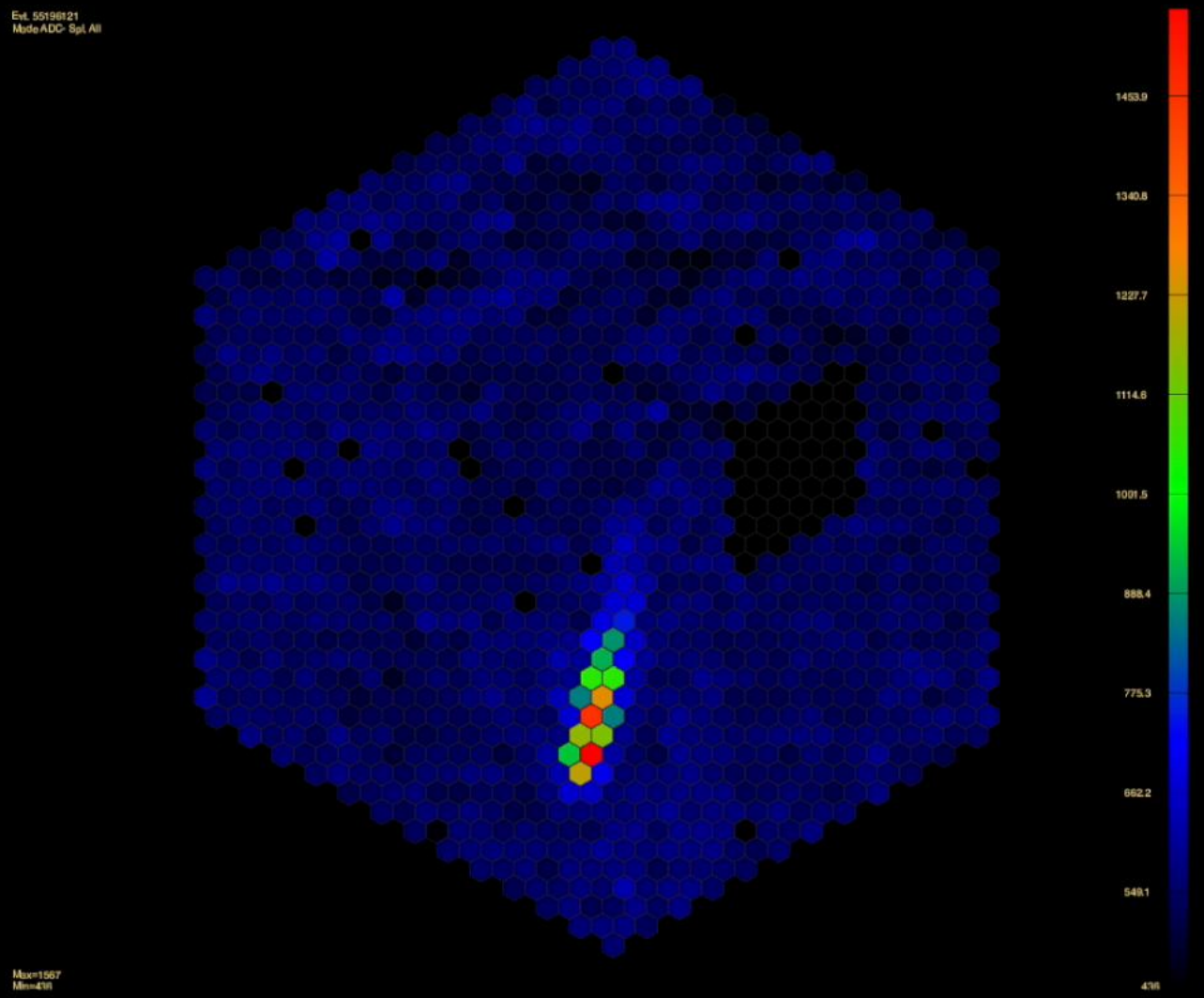
PHYSICS FOR FUTURE



SST1M First Light

Future of SST-1M telescopes

Čechvala et al., PoS(ICRC2025)908

