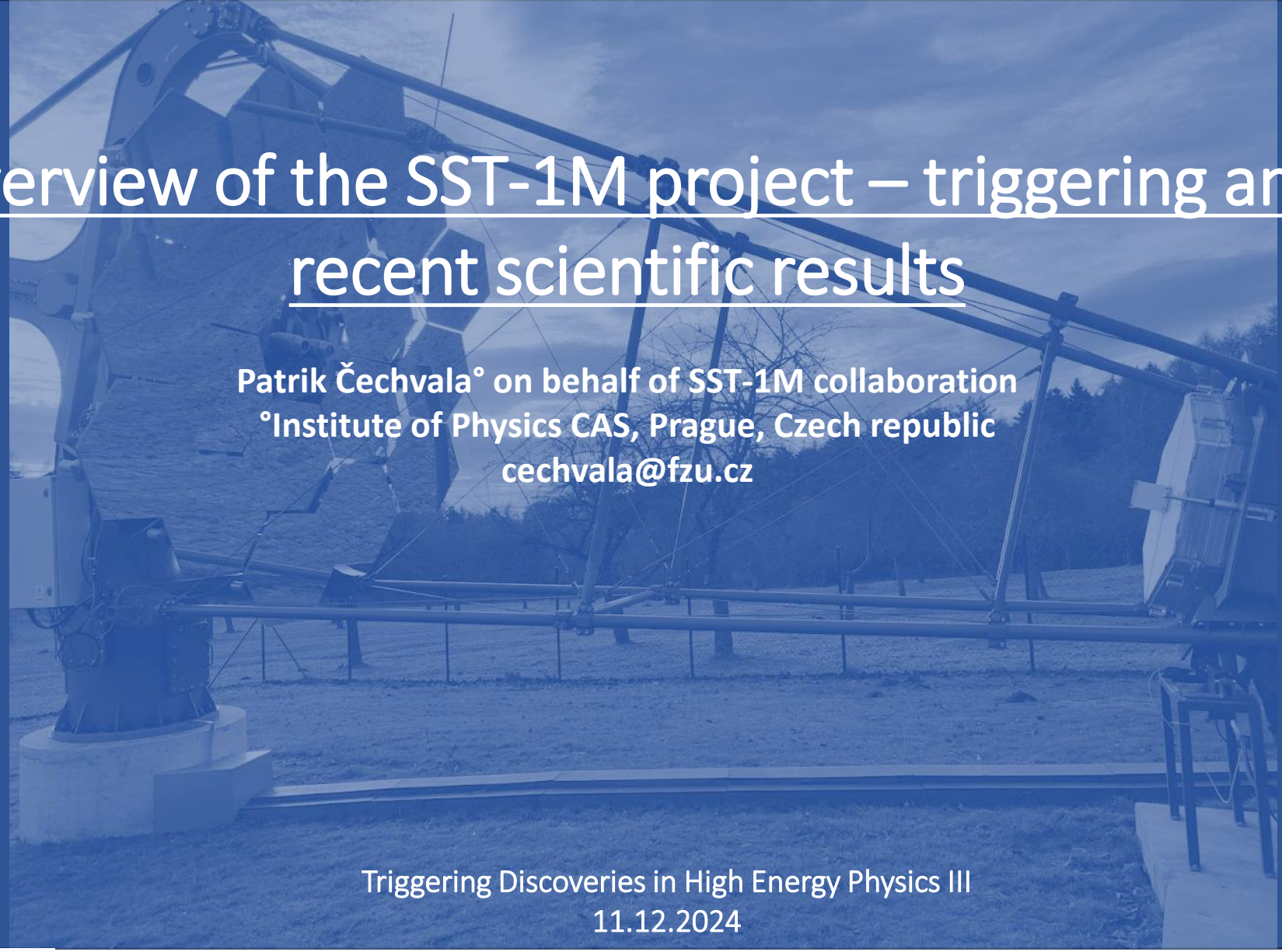


Overview of the SST-1M project – triggering and recent scientific results

Patrik Čechvala° on behalf of SST-1M collaboration
°Institute of Physics CAS, Prague, Czech republic
cechvala@fzu.cz

Triggering Discoveries in High Energy Physics III
11.12.2024

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

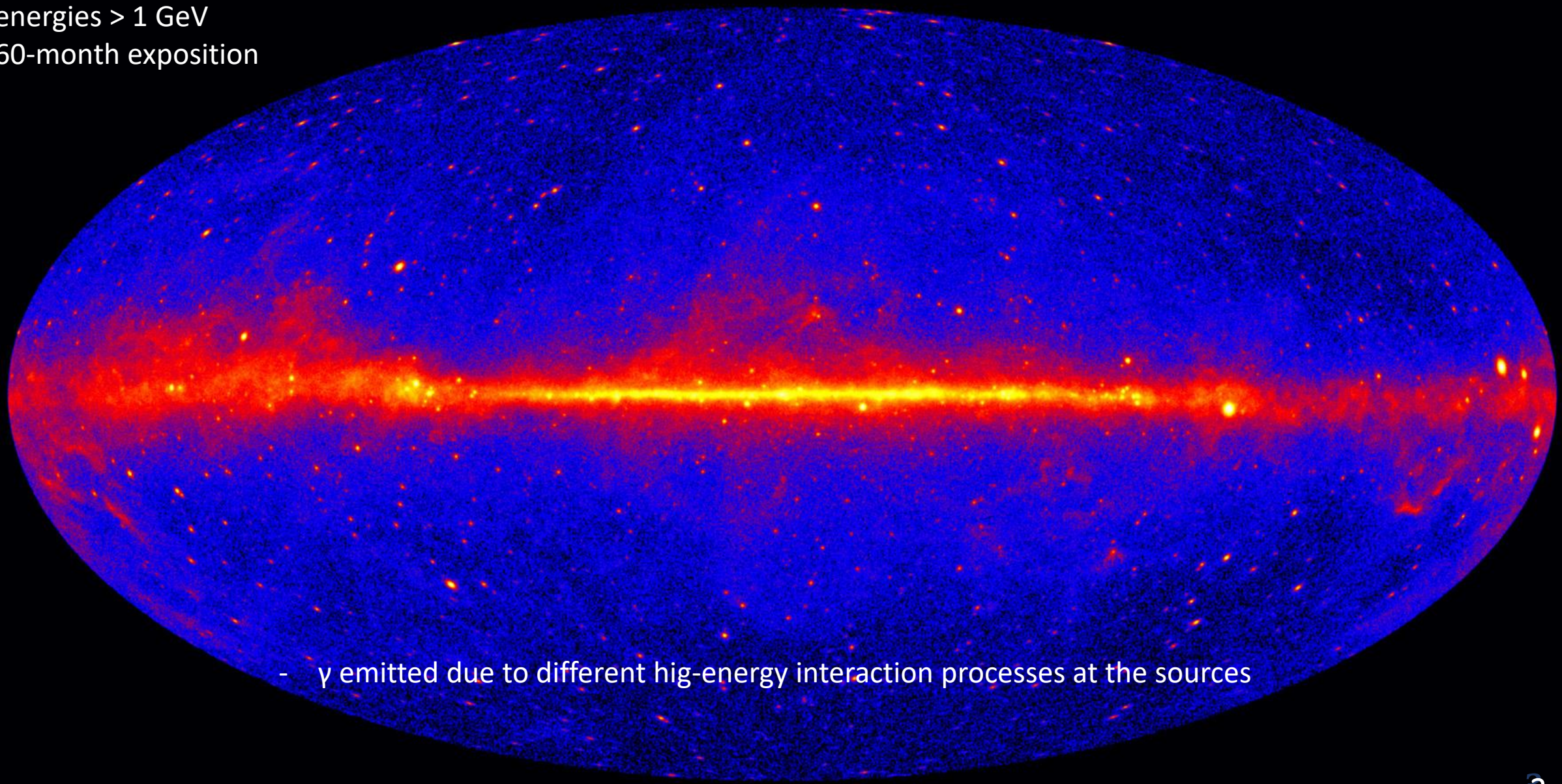
Outline

- SST-1M project
- Camera overview and trigger
- Stereo trigger
- Recent scientific results

Gamma-ray sky

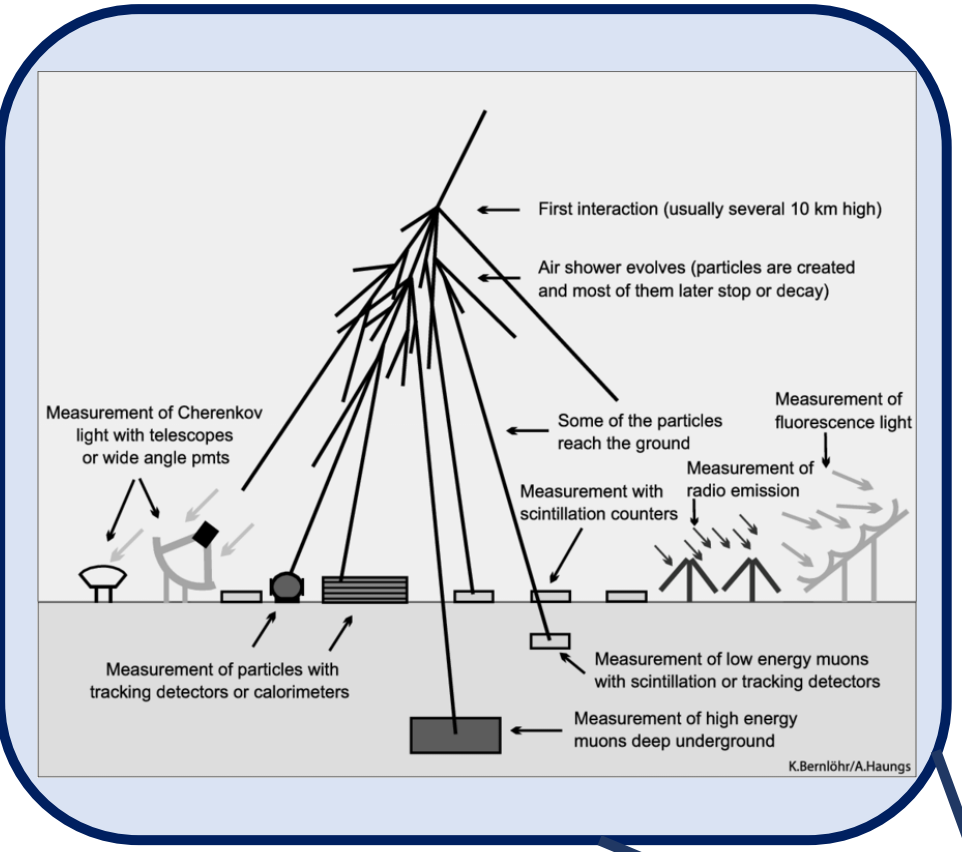
Credit: NASA/DOE/Fermi LAT Collaboration

- energies > 1 GeV
- 60-month exposition



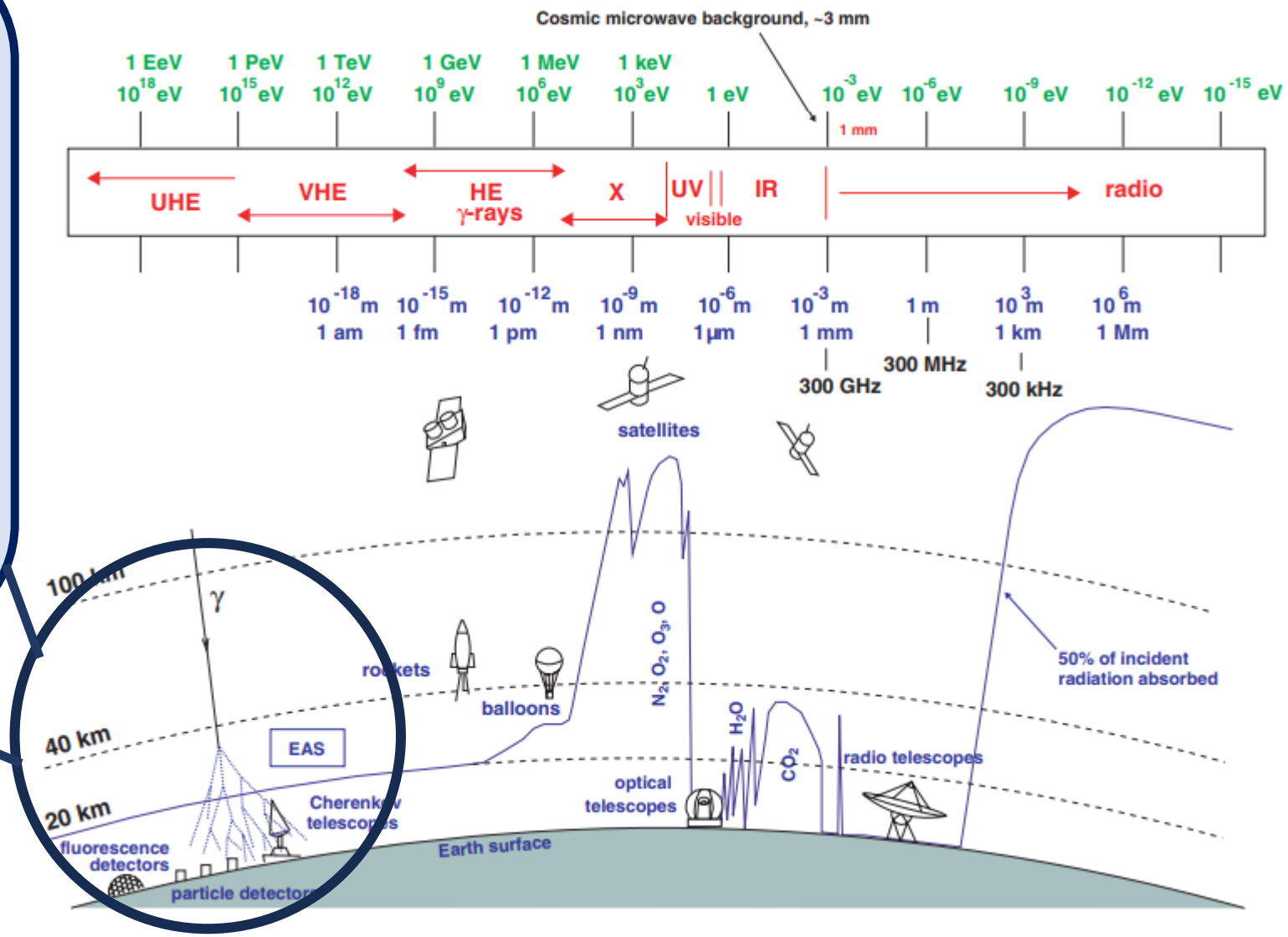
- γ emitted due to different hig-energy interaction processes at the sources

Imaging Atmospheric Cherenkov Telescopes



Haungs et al. 2011

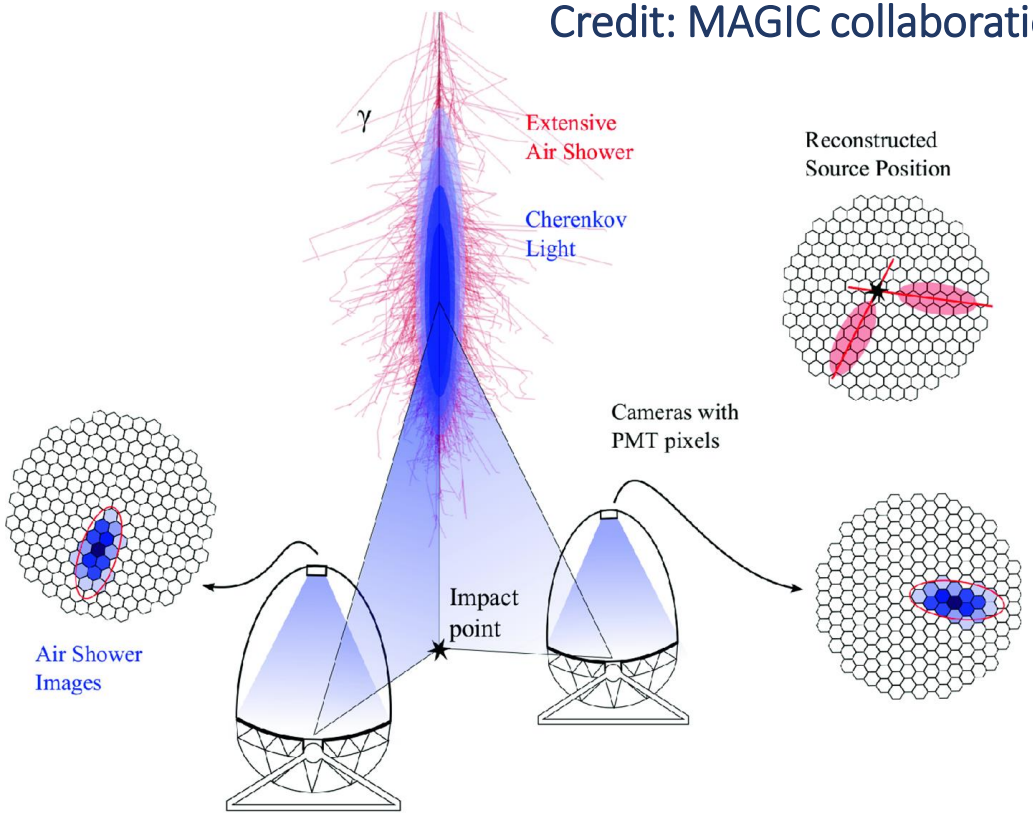
Longair, 1992

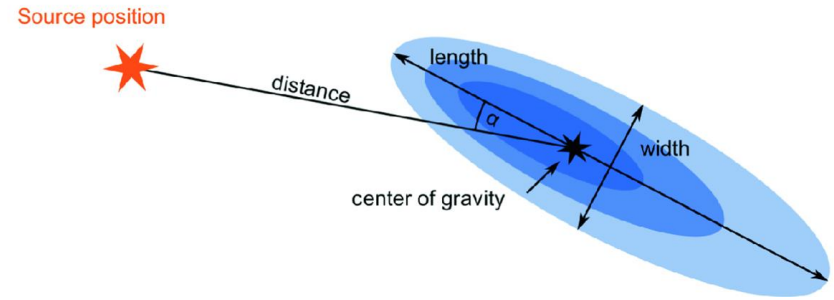


Imaging Atmospheric Cherenkov Telescopes

- Detection of Cherenkov light emitted by the particles of Extensive Atmospheric Showers
- **Reflective telescopes** on Alt-Az mounts
- Sensitive camera photo-detection plane composed of an array of photomultipliers
- For multiple telescopes, possibility to operate in **stereo regime** – improvement of **γ/hadron separation** and **energy regression**

Credit: MAGIC collaboration





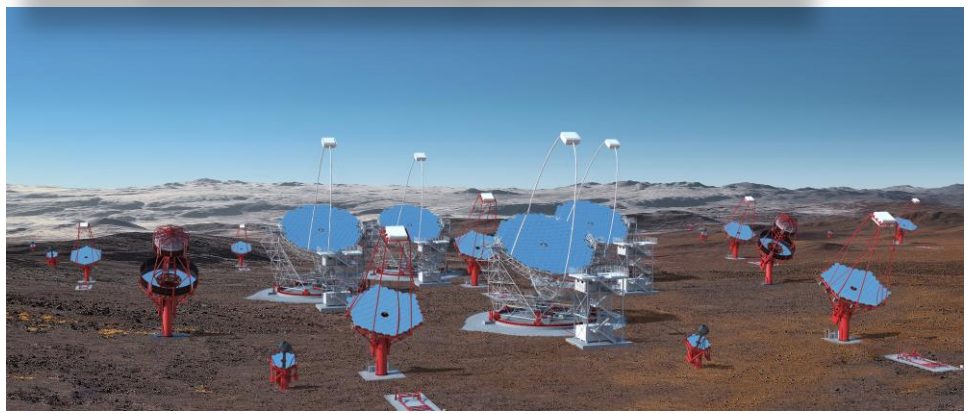
Imaging Atmospheric Cherenkov Telescopes across the world

Credit: Wikipedia

Cherenkov Telescope Array Observatory (CTAO)

Northern Hemisphere Array

Southern Hemisphere Array



Credit: Gabriel Pérez Diaz, IAC/ Marc-André Besel CTAO

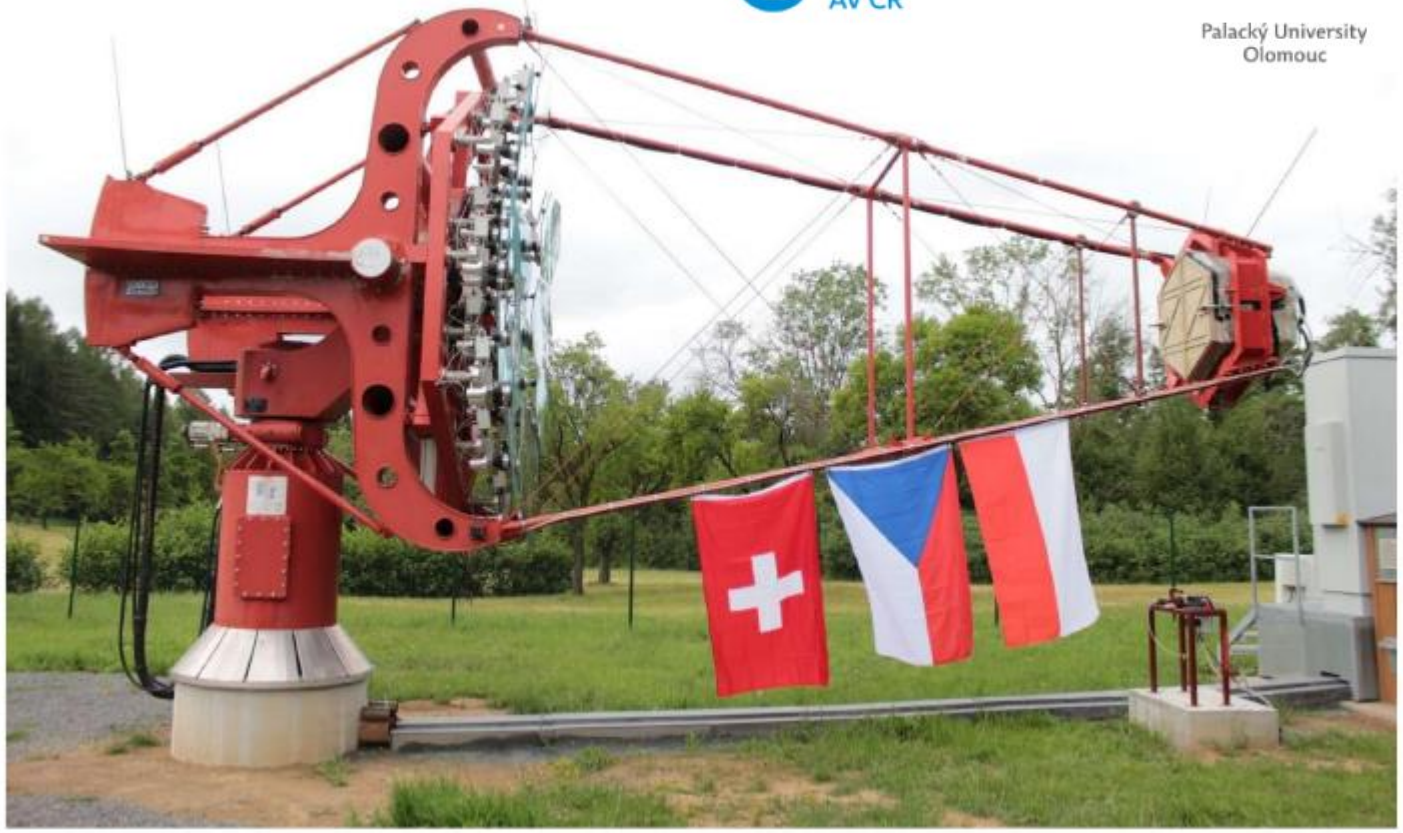
SST-1M project

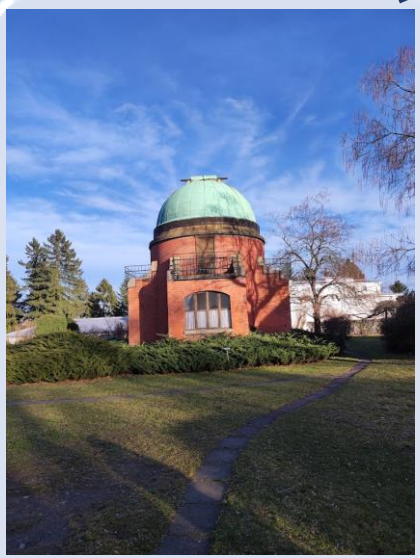
SST-1M
Single-Mirror
Small Size Telescope

- 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/

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

(510 m a.s.l.)

https://asu.cas.cz/

Source: Google maps

SST-1M telescopes

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

Alispach et al., in press

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)

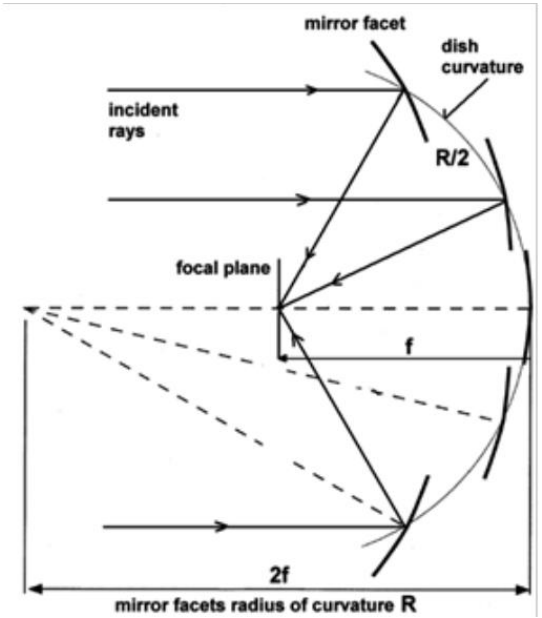
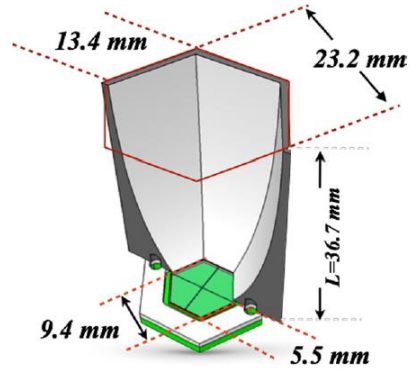


Figure adopted from Actis et al., 2011

SST-1M camera

Alispach et al., in press

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

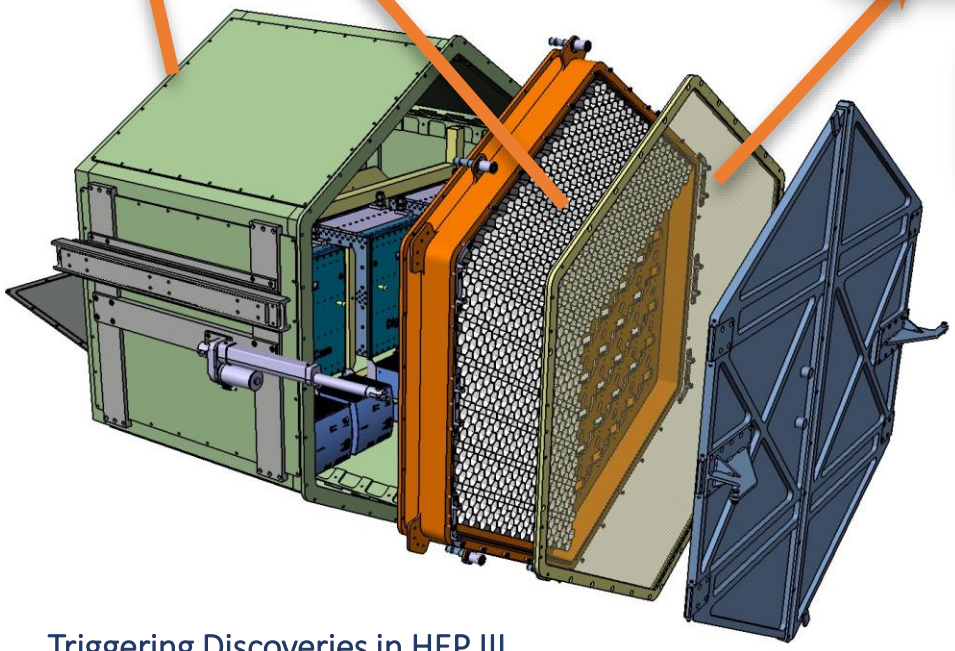


Digital electronics (DigiCam):
- 12 bits FADC @ 250 MS/s
- Fully digital trigger
- Power consumption 1200 W

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

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

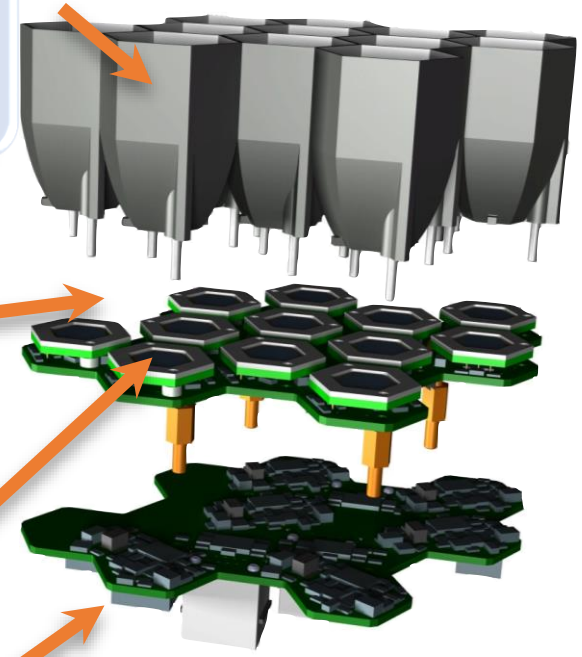
Hollow light guides:
- Cut-off at 24°
- 2.32 cm linear size
- Compression factor of 6



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

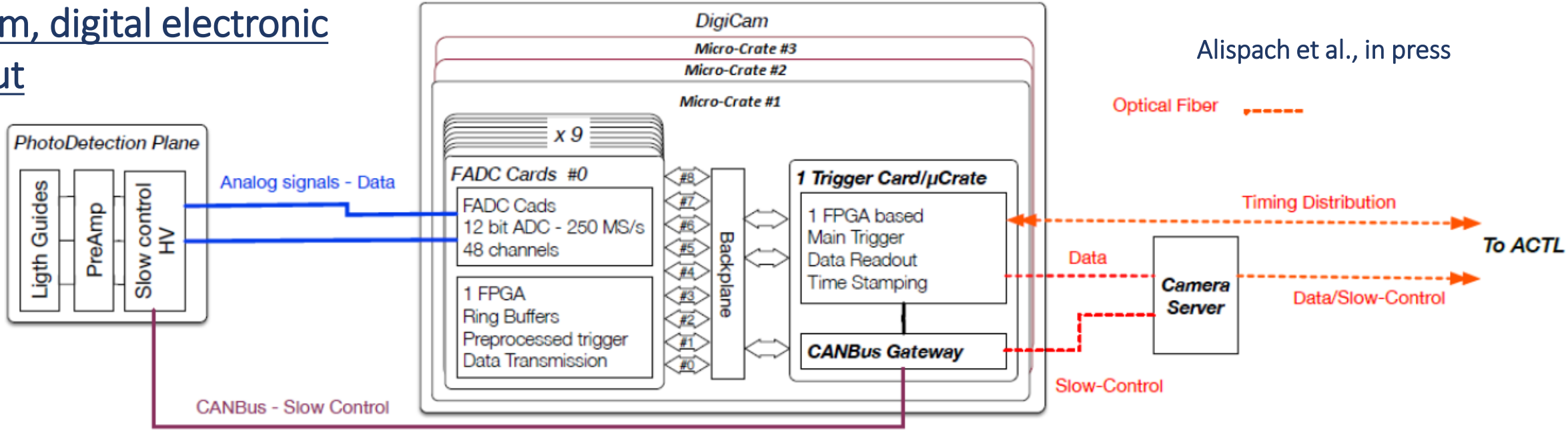
Preamplifier board:
- 2 operational amplifiers per sensor to reduce pulse length
- DC coupling

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



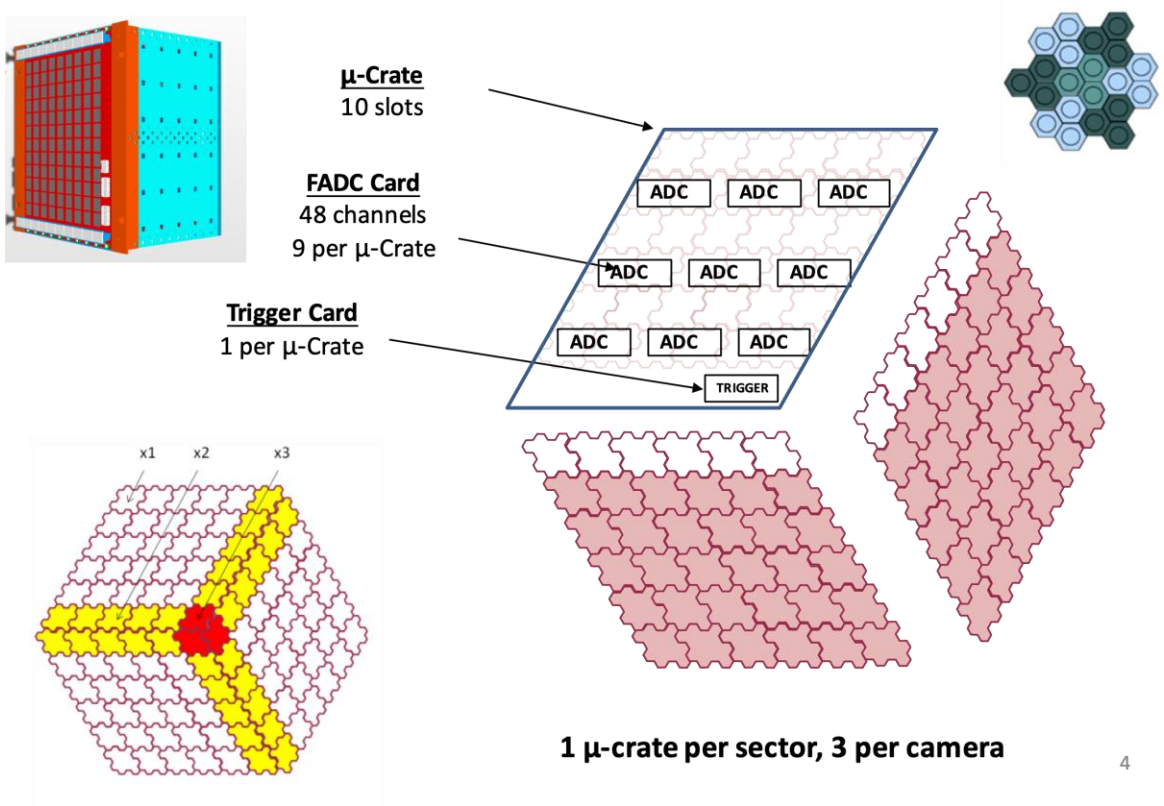
DigiCam, digital electronic readout

Alispach et al., in press



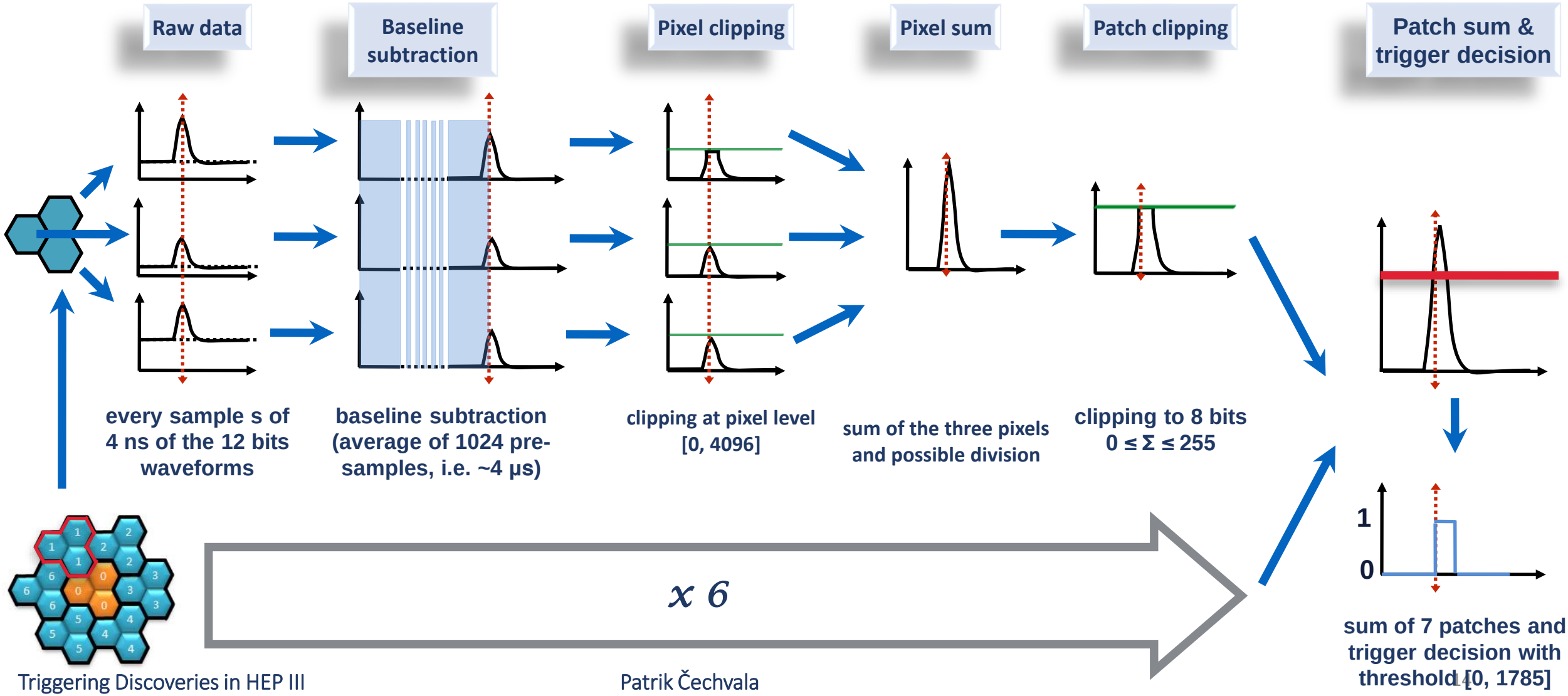
- Fully digital trigger – path with reconfigurable algorithms and signal processing
- Camera is using 10G Ethernet interface and optimized FPGA
- Readout distributed in 3 micro-crates each equipped with 9 FADC boards (27 in total) and 1 trigger board (3 in total, connecting micro-crates)
- Digitisation of the signal by FADC and stored in ring buffers

DigiCam, trigger

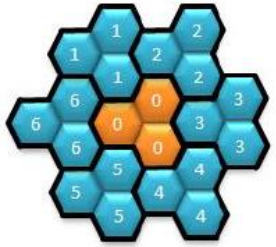


- From readout view – PDP **divided into 3 sectors** of 432 pixels (36 modules) each connected to one micro-crate
- To reduce the size of data processed by trigger board – **coupling into triplets** and re-binned to **8 bits**
- **Each trigger** board processing **one sector** of PDP (144 triplets) + border (48) triplets
- Possibility to modify tresholds per triplet and algorithm
- Application of **White Rabbit** for clock synchronisation and time management
- Clocked trigger generator with programmable frequency and pulse length

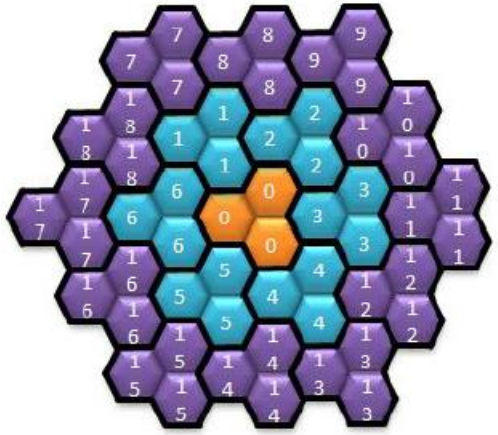
The DigiCam, trigger



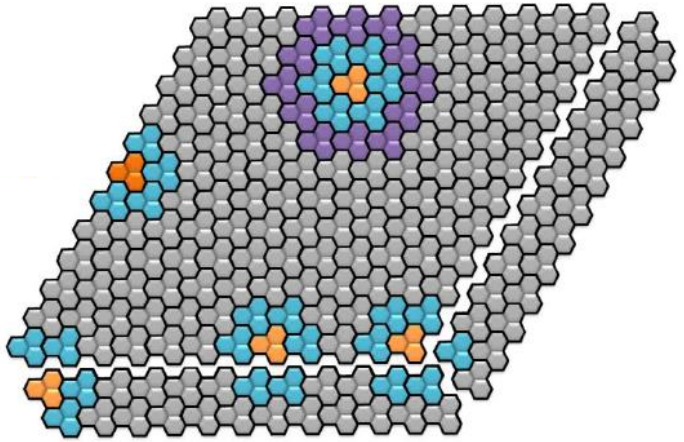
DigiCam, trigger algorithms implemented

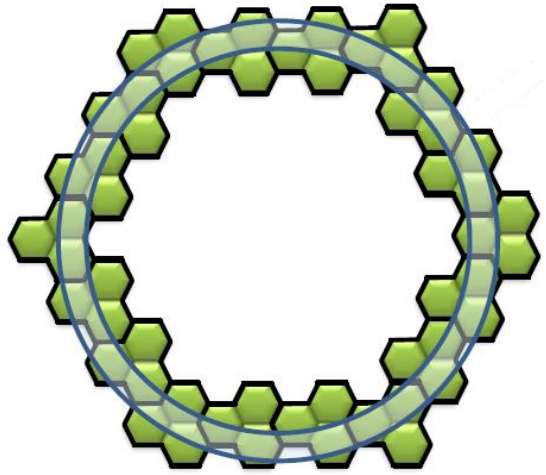


$$PATCH7 = \sum_{k=0}^{6} Trp[k]$$



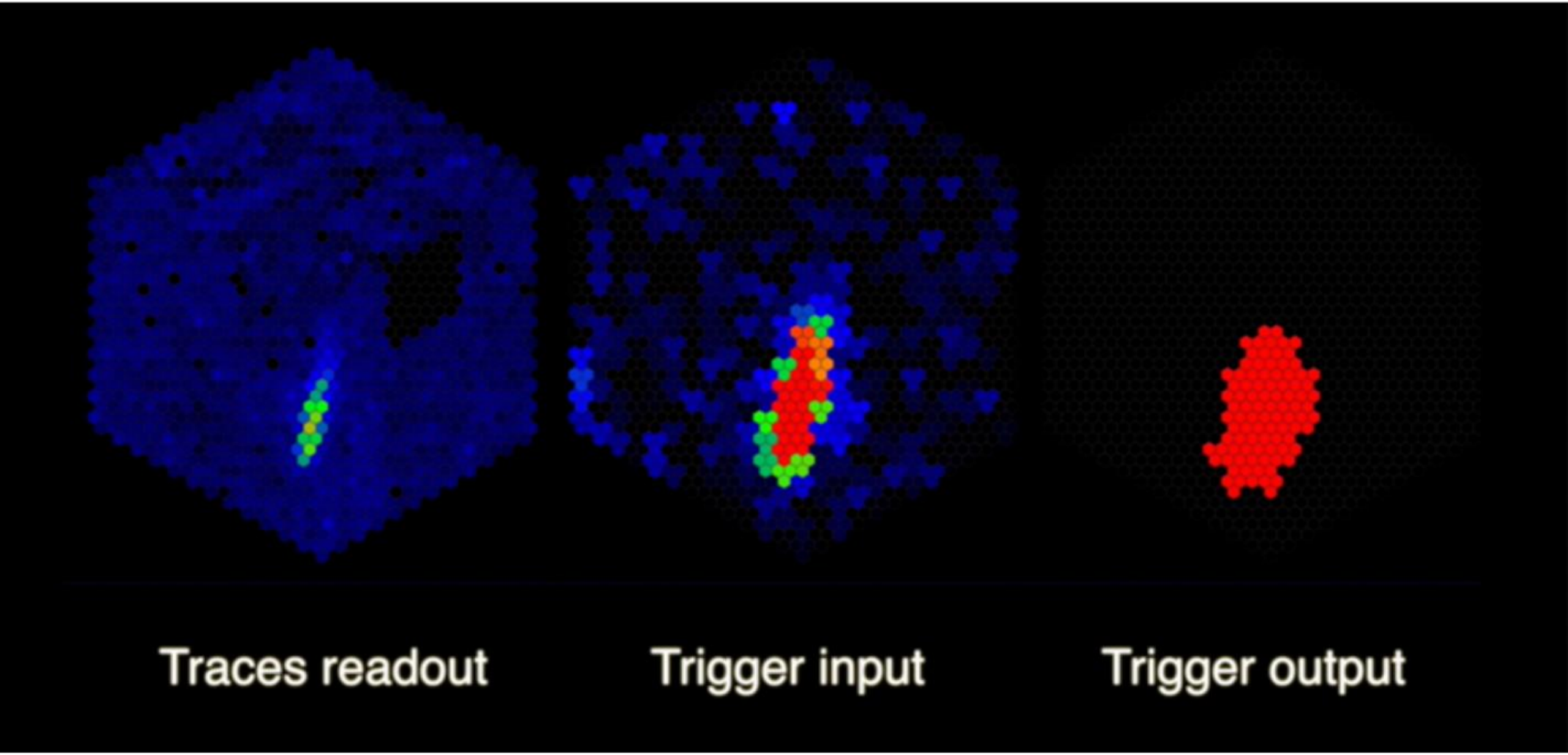
$$PATCH19 = \sum_{k=0}^{18} Trp[k] = PATCH7 + \sum_{k=7}^{18} Trp[k]$$

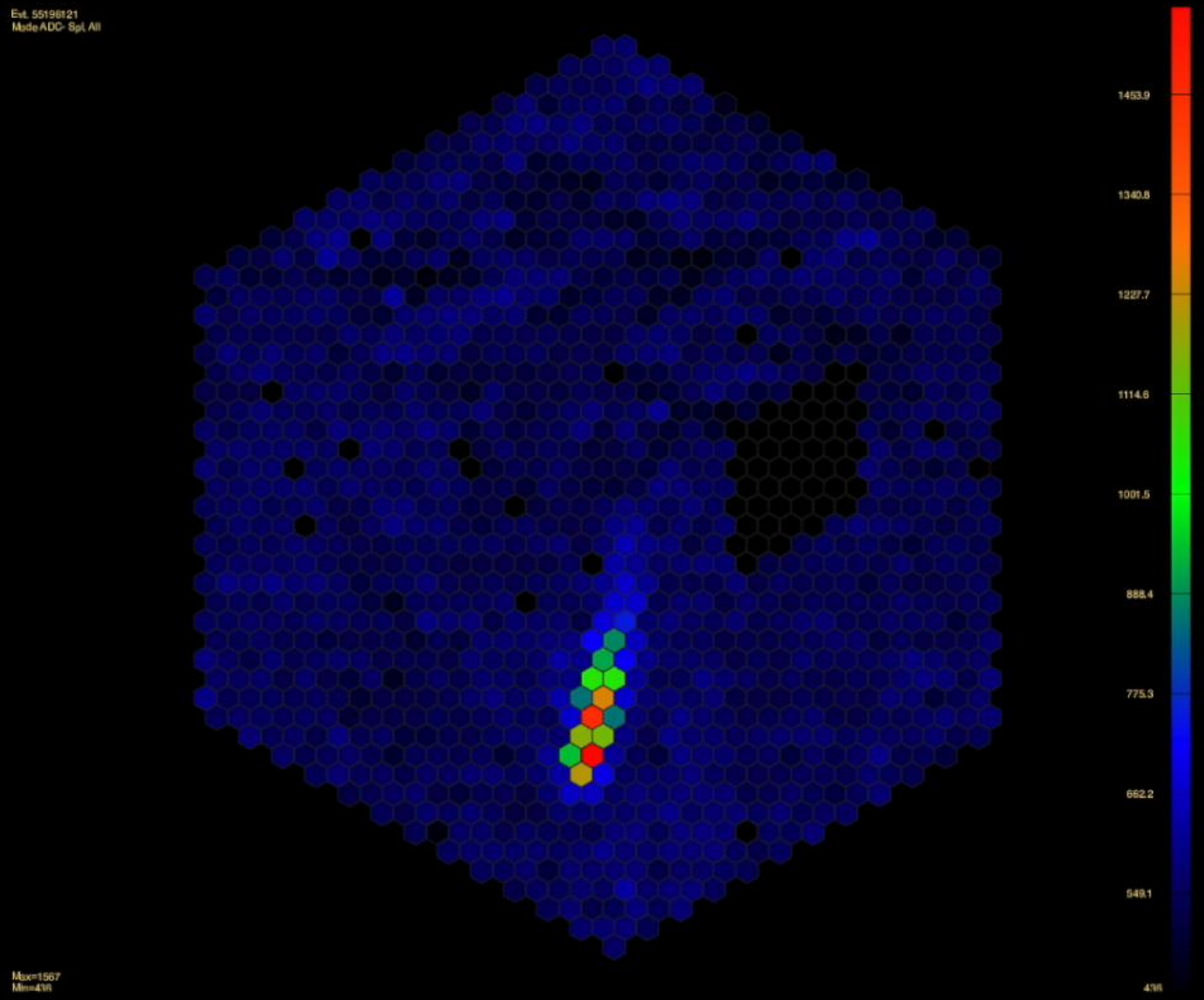




$$MUON = \sum_{k=0}^{17} Trp[k]$$

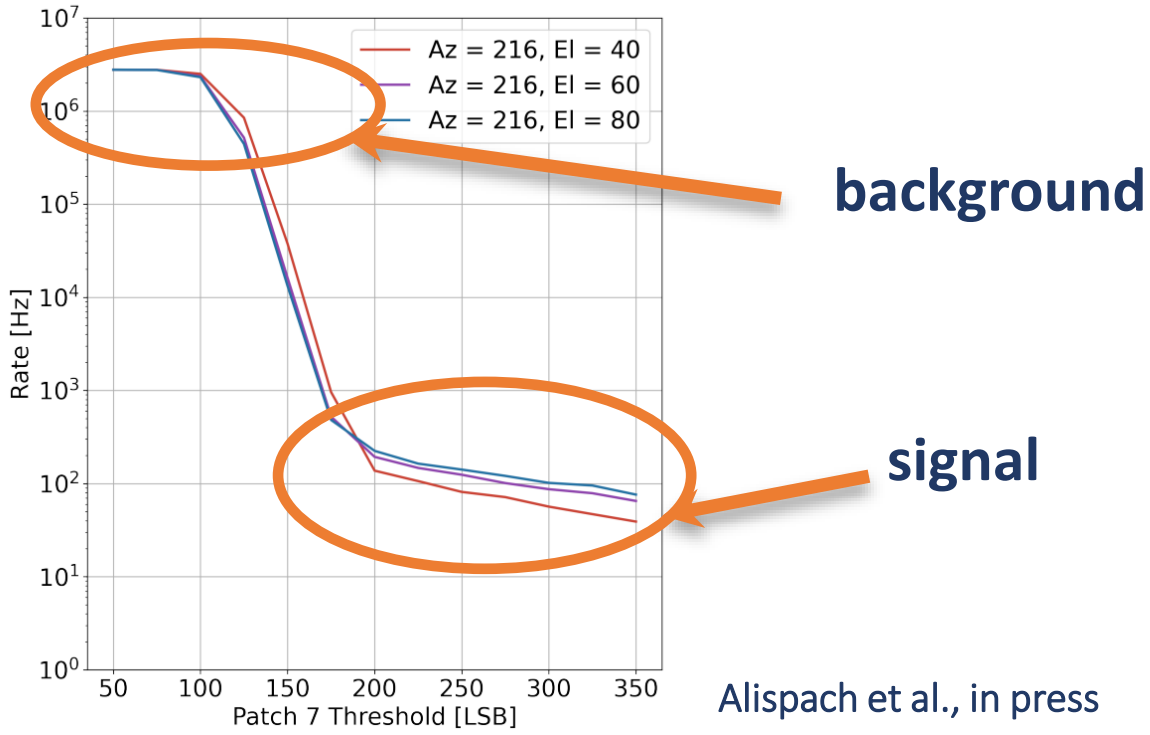
- several trigger algorithms can run in parallel (different size, shape, ...)
- Future prospects
  - possibility of the involvement of convolutional neural network for improvement of shower/nigh-sky background discrimination
  - real-time analysis pipeline – reaction to alerts and fast-evolving processes


Traces readout
Trigger input
Trigger output

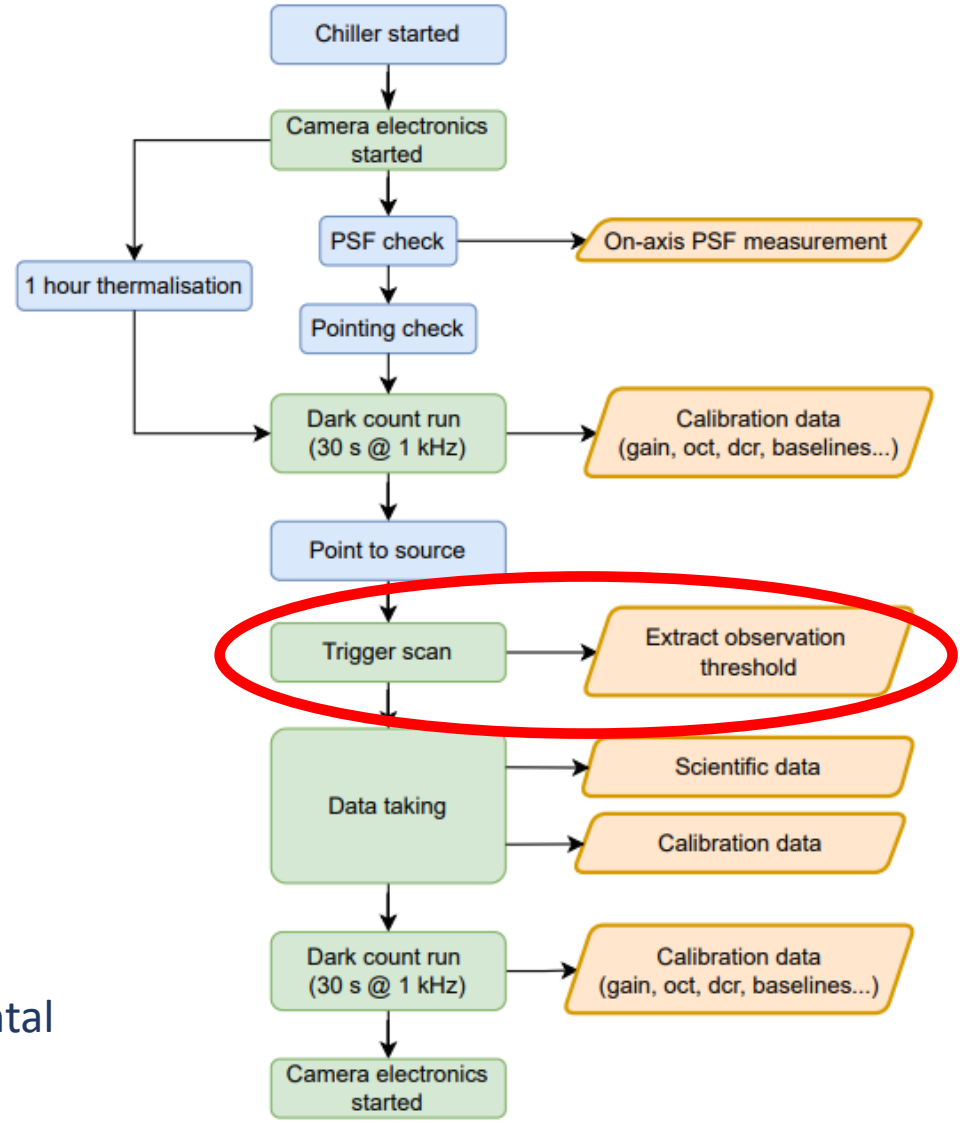


SST1M First Light

Trigger scan



Alispach et al., in press

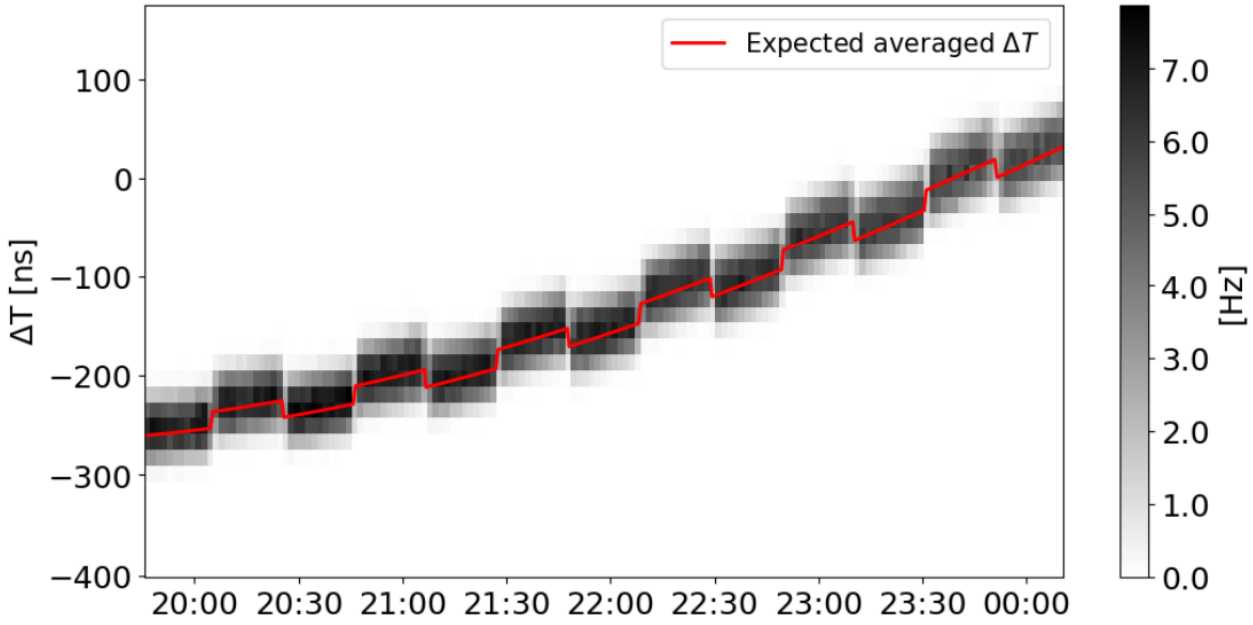


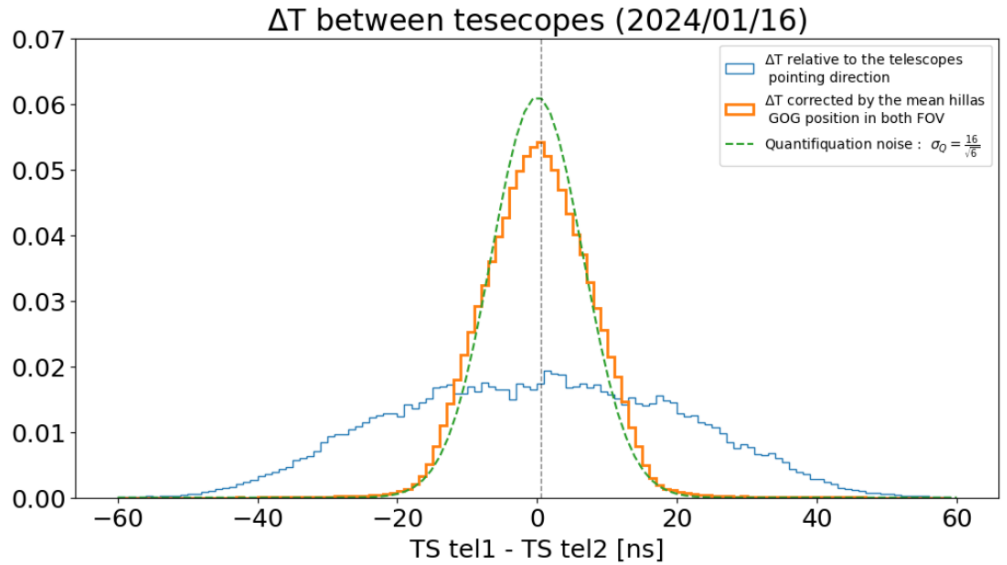
- Performed for the estimation of the treshold for telescope operation
- Performed for source position but also for a grid of positions – environmental conditions estimation

Stereo trigger

- After trigger – data packed into UDP packets and sent to Camera Server software to assemble the whole event
- SST1M use software-based stereo trigger
- The timestamps are transmitted to the Software Array Trigger (SWAT) – merge the triggers into one stream sorted by time and application of sliding window to search for pairs
- Once found ID is attributed
- Internal synchronisation of the clocks of the cameras by the White Rabbit
- Prospective use of hardware stereo trigger – interconnection of cameras with optical fibers

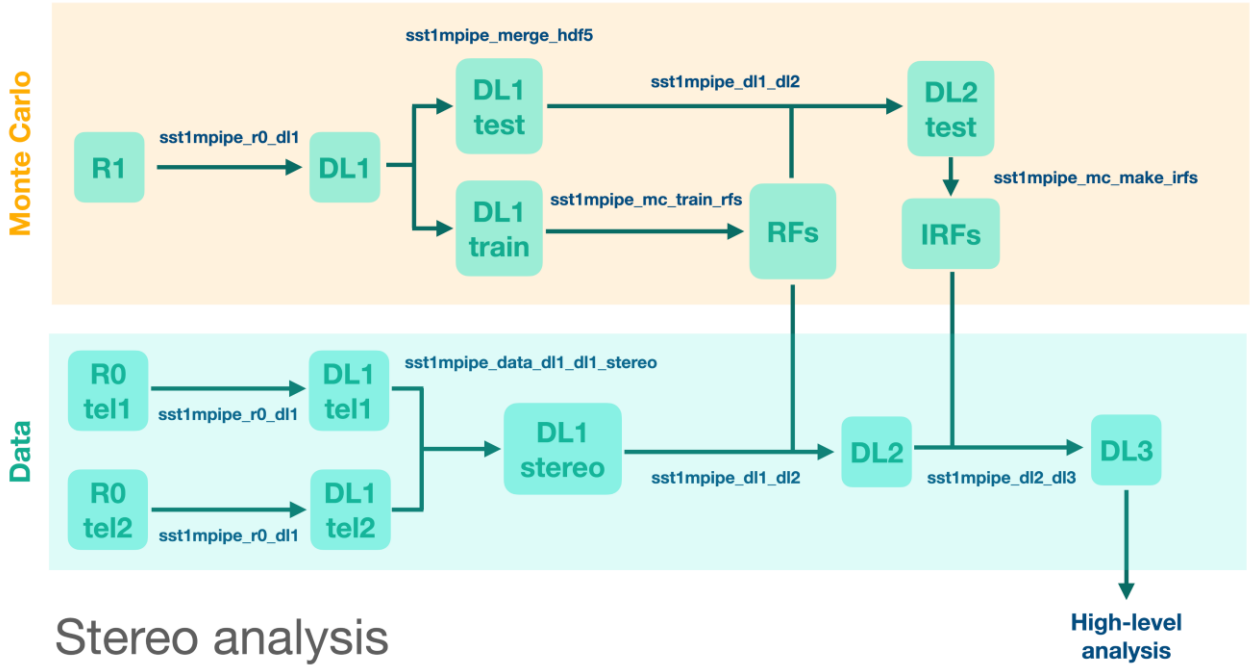
Alispach et al., in press





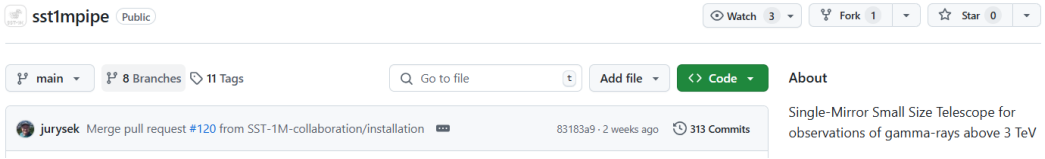
sst1mpipe

- 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



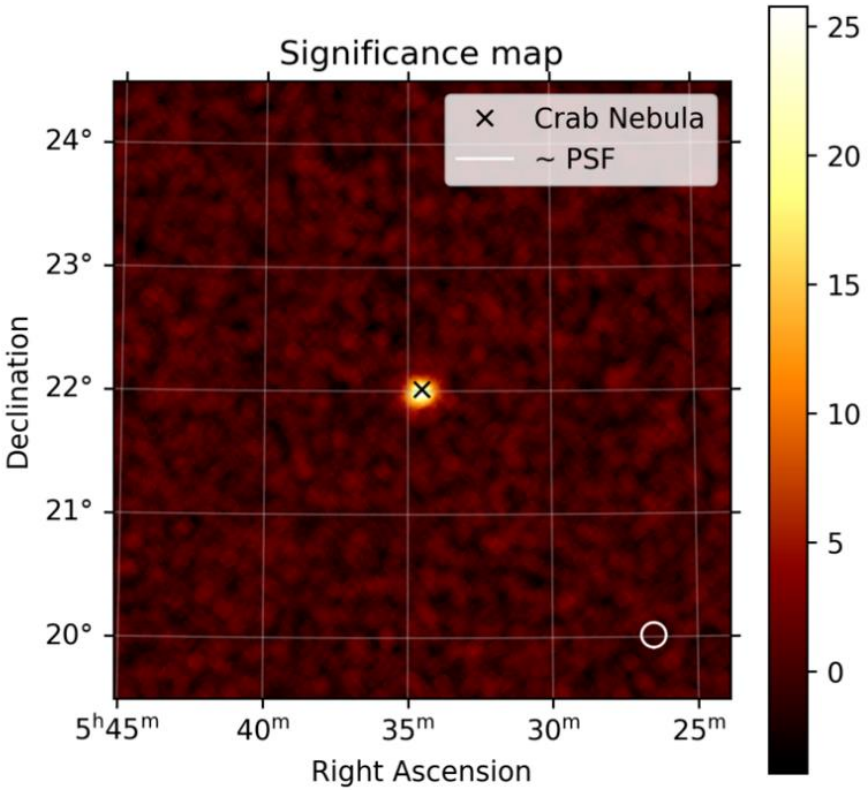
Stereo analysis

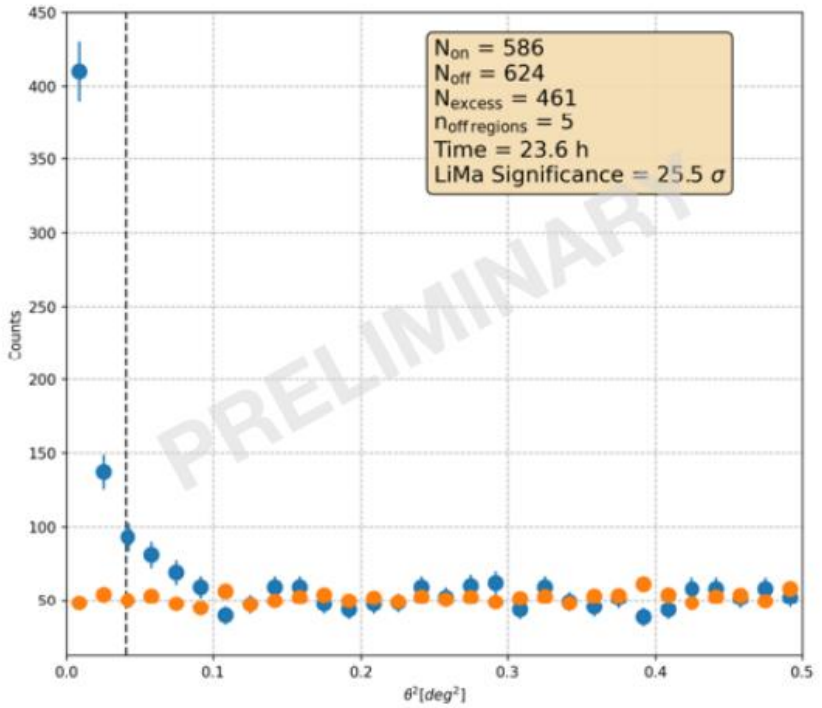
- Juryšek et al., PoS(ICRC2023)592
- Juryšek et al., 2024, sst1mpipe v.0.4.1, Zenodo
- https://github.com/SST-1M-collaboration/sst1mpipe

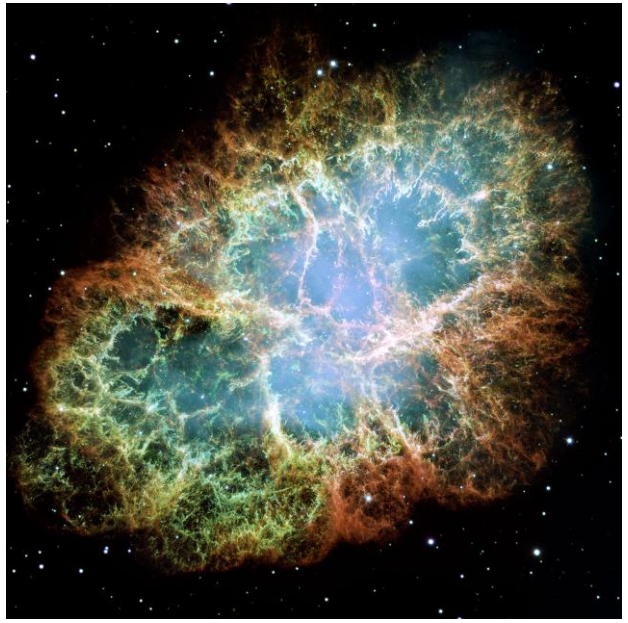


Crab Nebula (M1) observation

- Standard candle in gamma-ray astronomy
- Obs. campaign 2023/2024 (currently ongoing 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)







M1 Credit:NASA, ESA and Allison Loll/Jeff Hester (Arizona State University). Acknowledgement: Davide De Martin (ESA/Hubble)

Tavernier et al., PoS(ICRC2023)741

Crab Nebula (M1) observation

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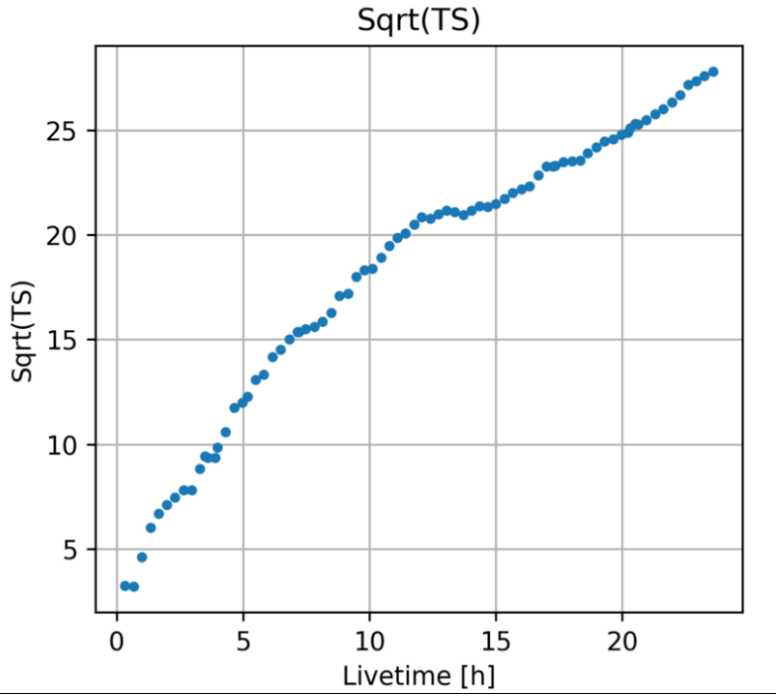
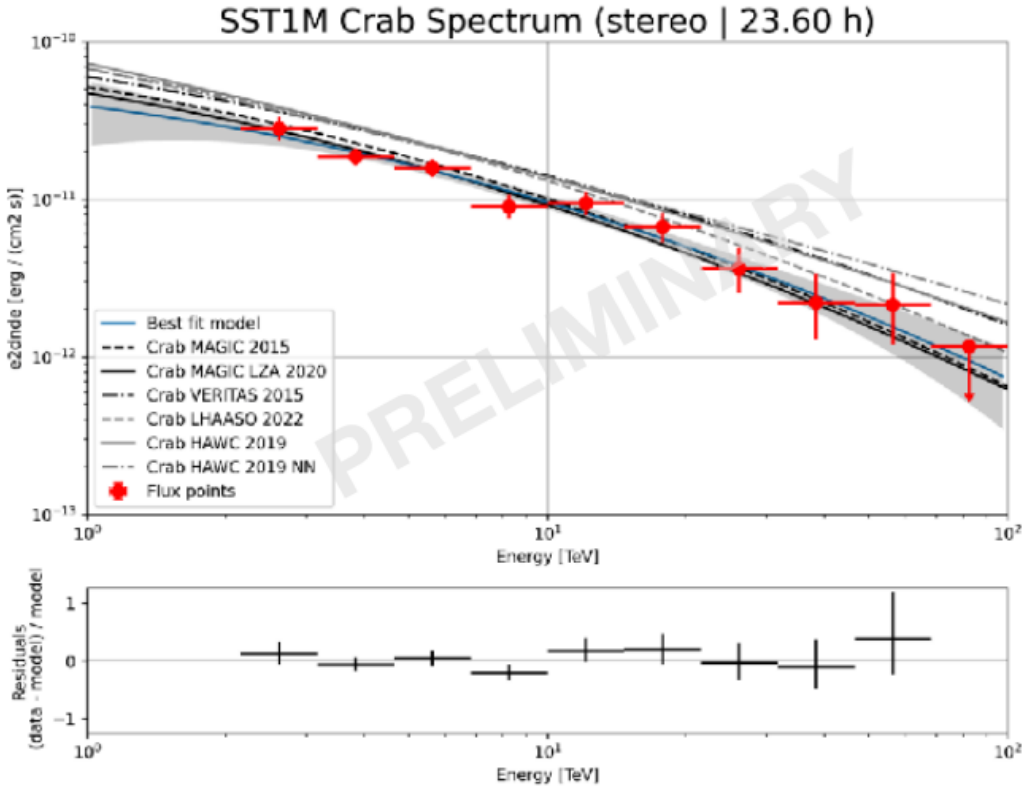
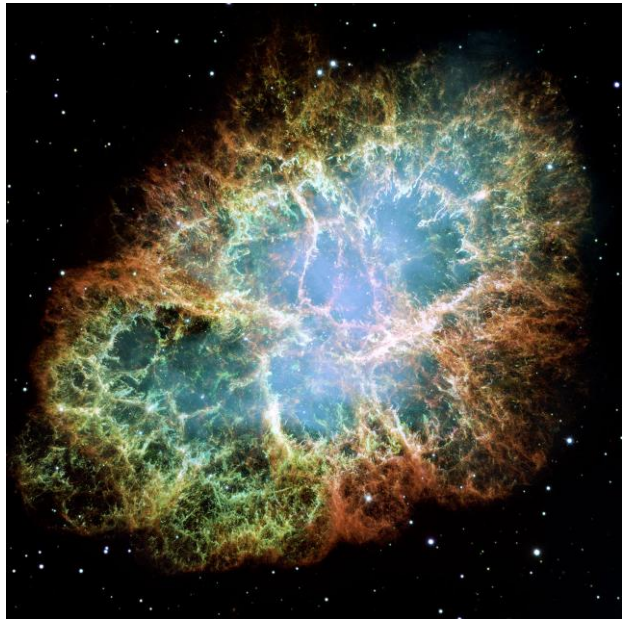






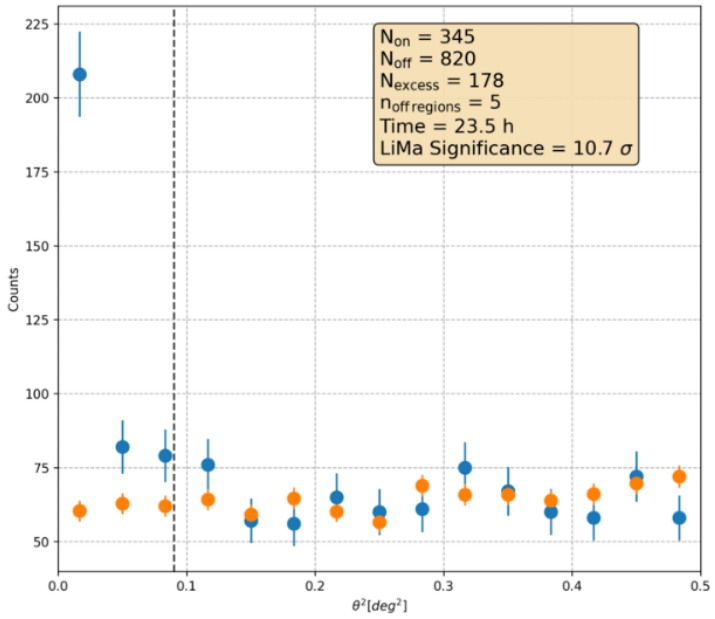
M1 Credit:NASA, ESA and Allison Loll/Jeff Hester (Arizona State University). Acknowledgement: Davide De Martin (ESA/Hubble)

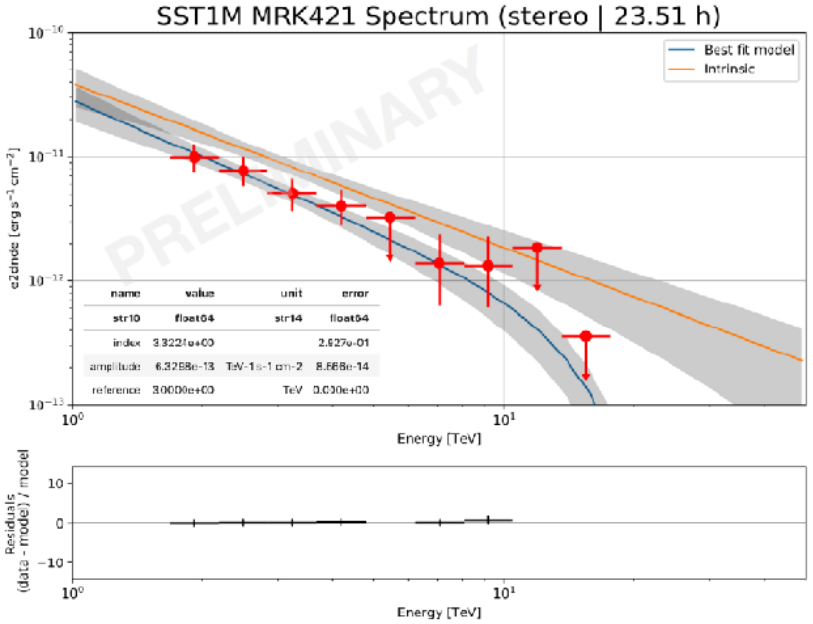
Active Galactic Nuclei (AGN) monitoring

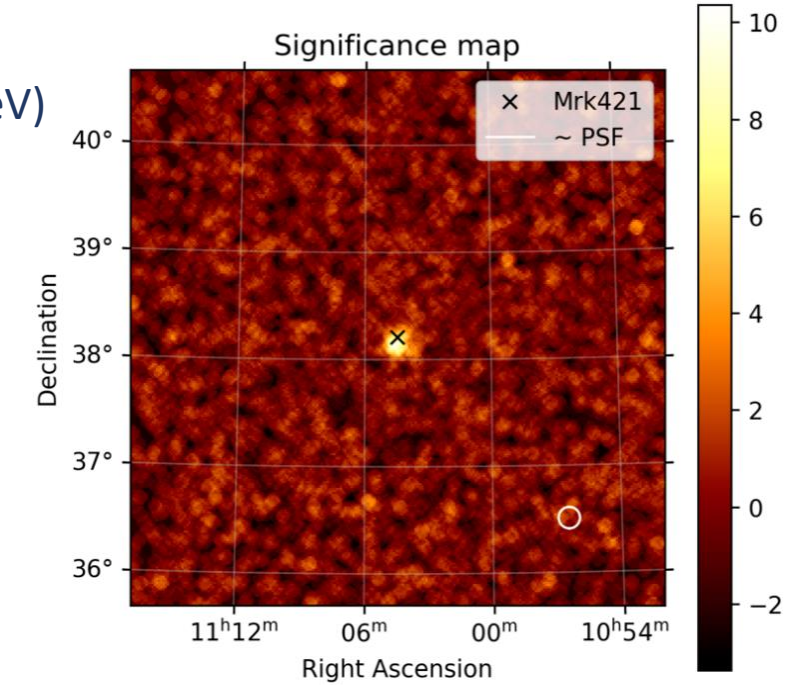
Markarian (Mrk) 421, stereo data

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 (Albert et al., 2022) 2.26 ± 0.12
- Maximum energies compatible with HAWC (9 TeV)

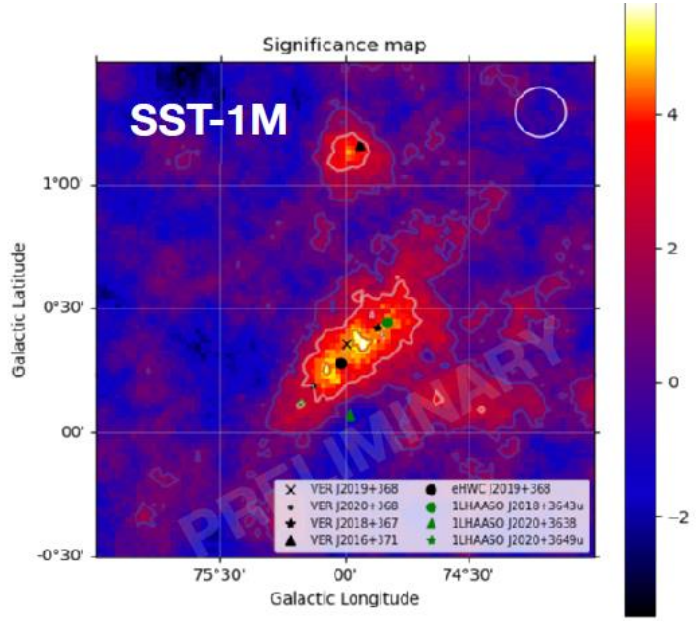


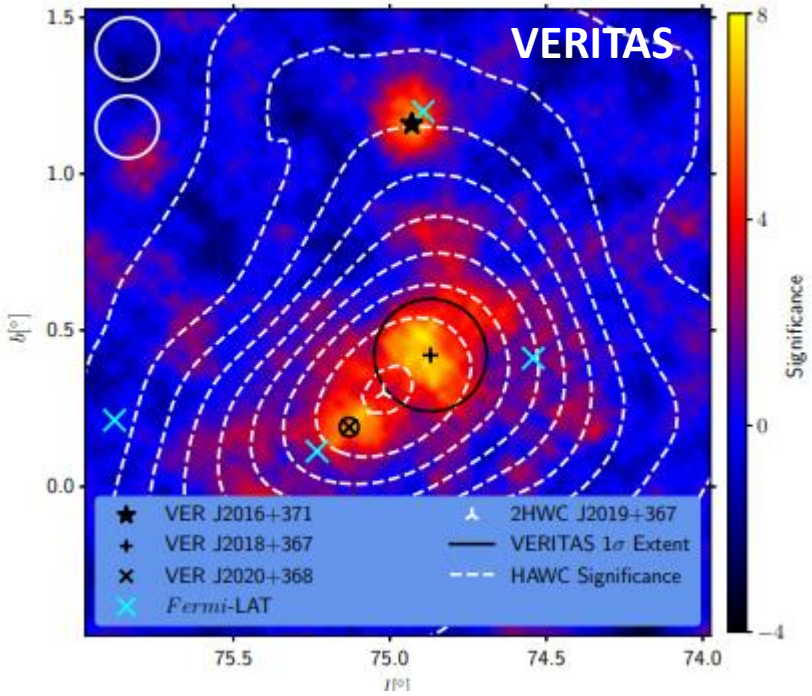




VER 2019+368 (Dragonfly)

- Complex region with multiple sources – in radio, in X-rays and in gamma rays
- Slightly extended source (approx. 0.5°)
- Observational campaign in 2024 – zenith angle ranging 5°-60°
- Region discovered by MILAGRO (Abdo et al., 2009)
- Resolved into different sources by VERITAS (Abeysekhara et al. 2014, 2018)
- Source(s) resolved – VER 2019+368 together with CTB 87
- Ongoing analysis





Conclusions

- Field of gamma-ray astronomy is swiftly developing
- 2 prototypes of SST-1M successfully built and currently gathering data in stereo regime
- Implementation of inovative photo-detection plane – use of SiPMs
- Use of fully digital readout (DigiCam)
- First detected sources both galactic and extragalactic
- Perspective for interesting scientific results in near future (stay tuned!)

References

- Aquilar et al., DigiCam – fully digital compact camera for SST-1M telescope, 2014, Proc. of SPIE Vol. 9147 91475F-2, DOI: 10.1117/12.2055796
- Actis et al. Design concepts for the CherenkovTelescope Array CTA: an advanced facility for ground-based high-energy gamma-ray astronomy. Experimental Astronomy, 32(3):193–316, December 2011, https://doi.org/10.1007/s10686-011-9247-0
- Tavernier et al., (2023), PoS(ICRC2023)741, https://doi.org/10.22323/1.444.0741
- Alispach et al., The SST-1M imaging atmospheric Cherenkov telescope for gamma-ray astrophysics, in press, https://doi.org/10.48550/arXiv.2409.11310
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Thank you very much for your attention

SST-1M
Single-Mirror
Small Size Telescope

FZU
Institute of Physics
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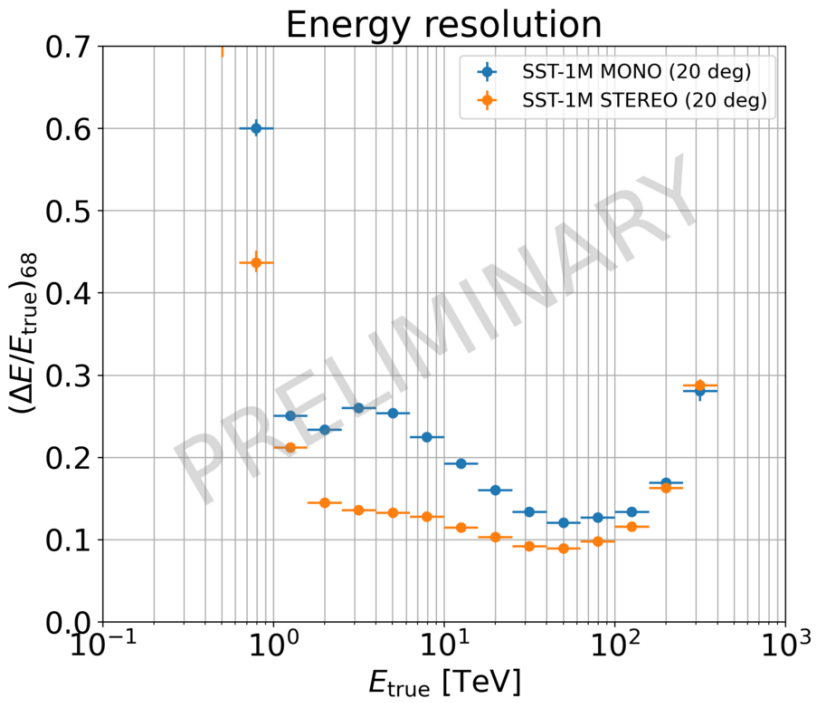
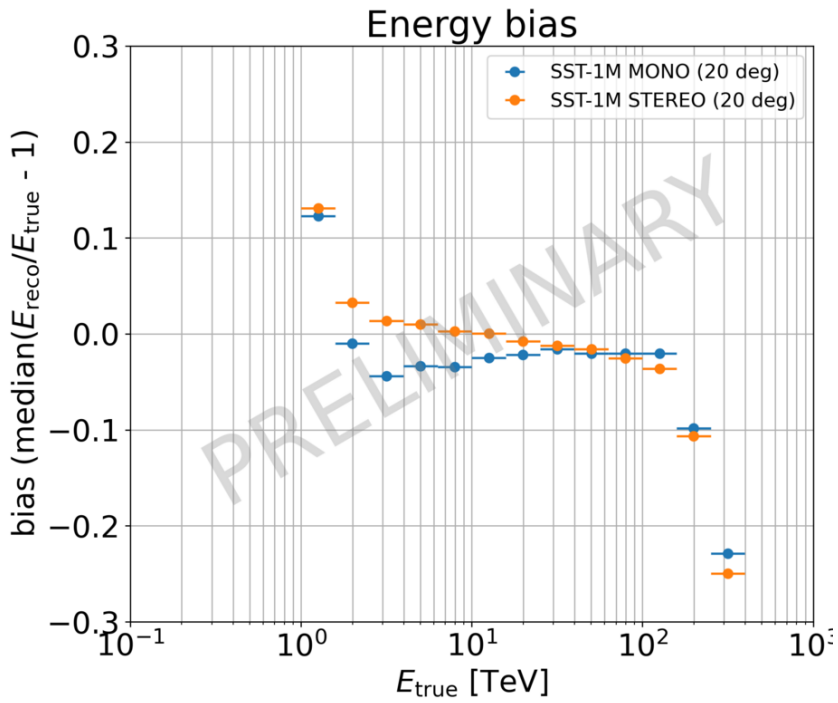
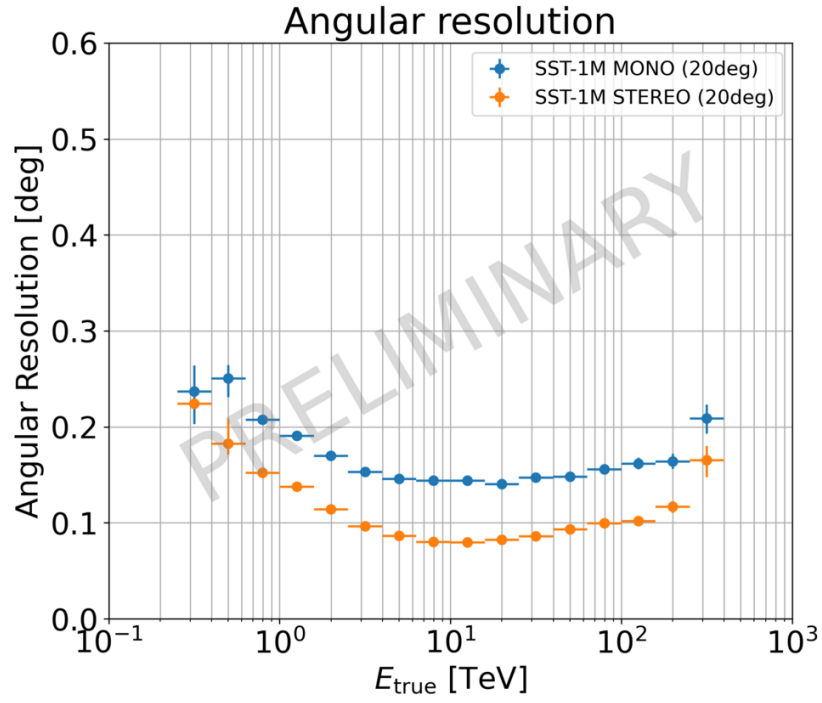
Backup

Mono and stereo performance comparison

- Significant improvement of parameters in stereo mode



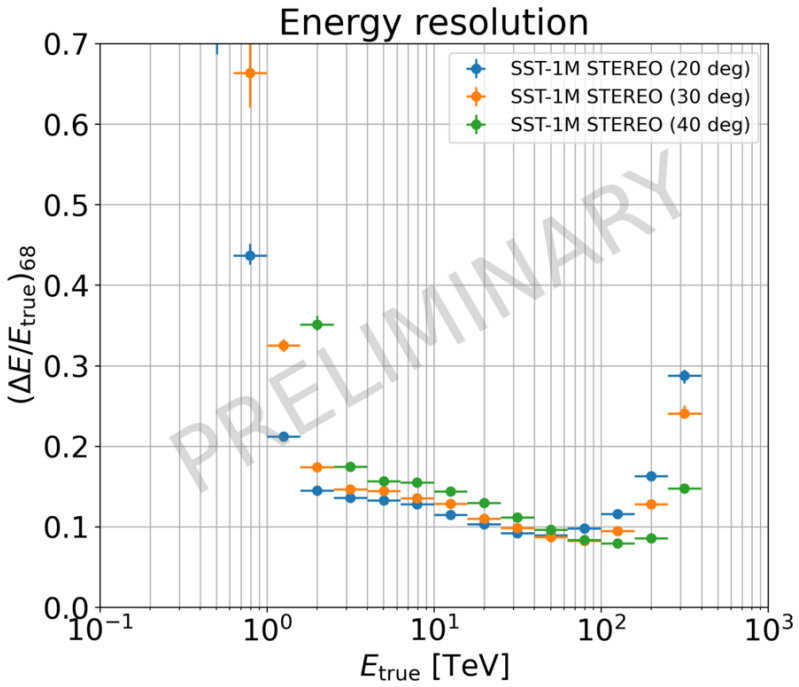


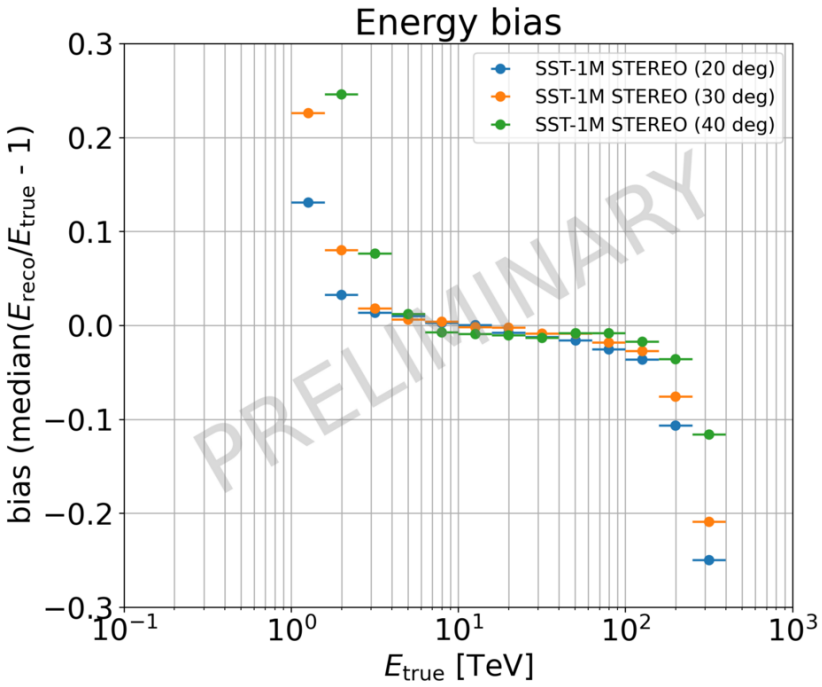


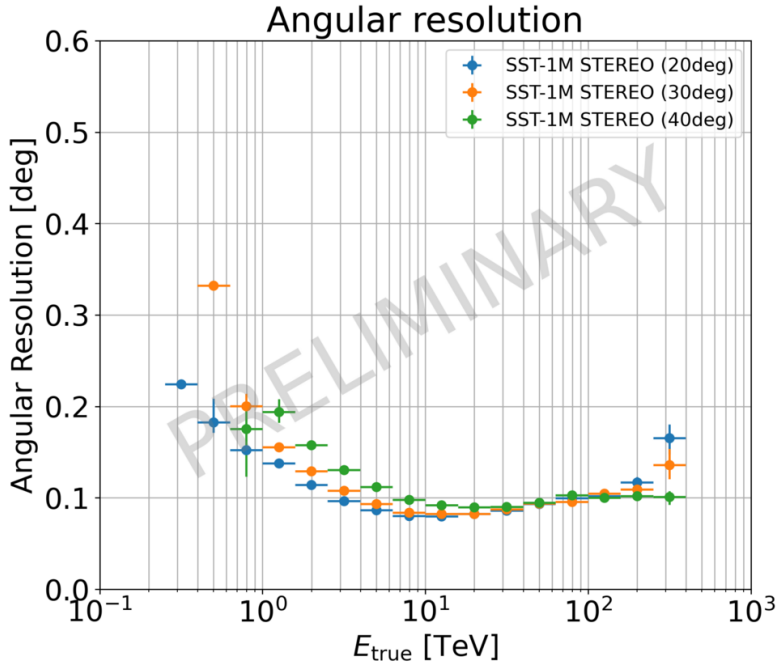
Backup

Perfomance of SST-1M

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







Perfomance of SST-1M

- Significant improvement of parameters in stereo mode
- Results in stereo mode