SST-1M
Single-Mirror
Small Size Telescope

FZU
Institute of Physics of the
Czech Academy of Sciences

Observation of Astrophysical Sources with SST-1M Telescopes

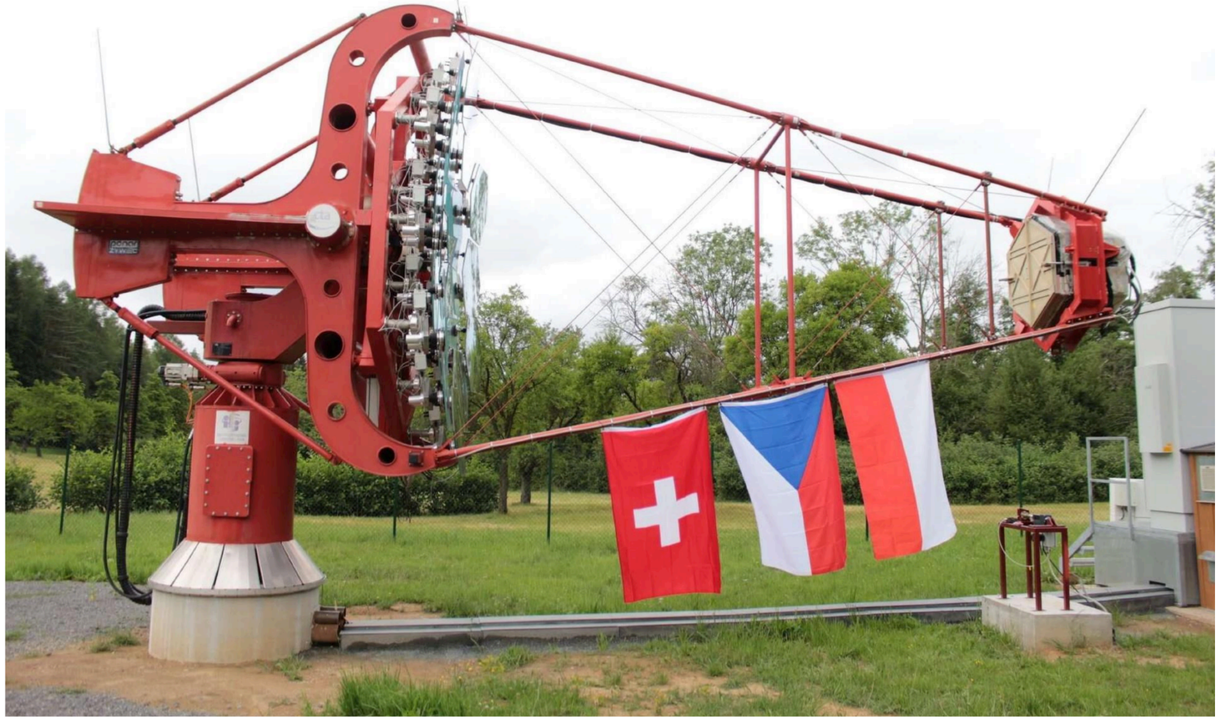
First results

Jakub Juryšek
Institute of Physics of the Czech Academy of Sciences
for the SST-1M Collaboration

The SST-1M project

SST-1M
Single-Mirror
Small Size Telescope

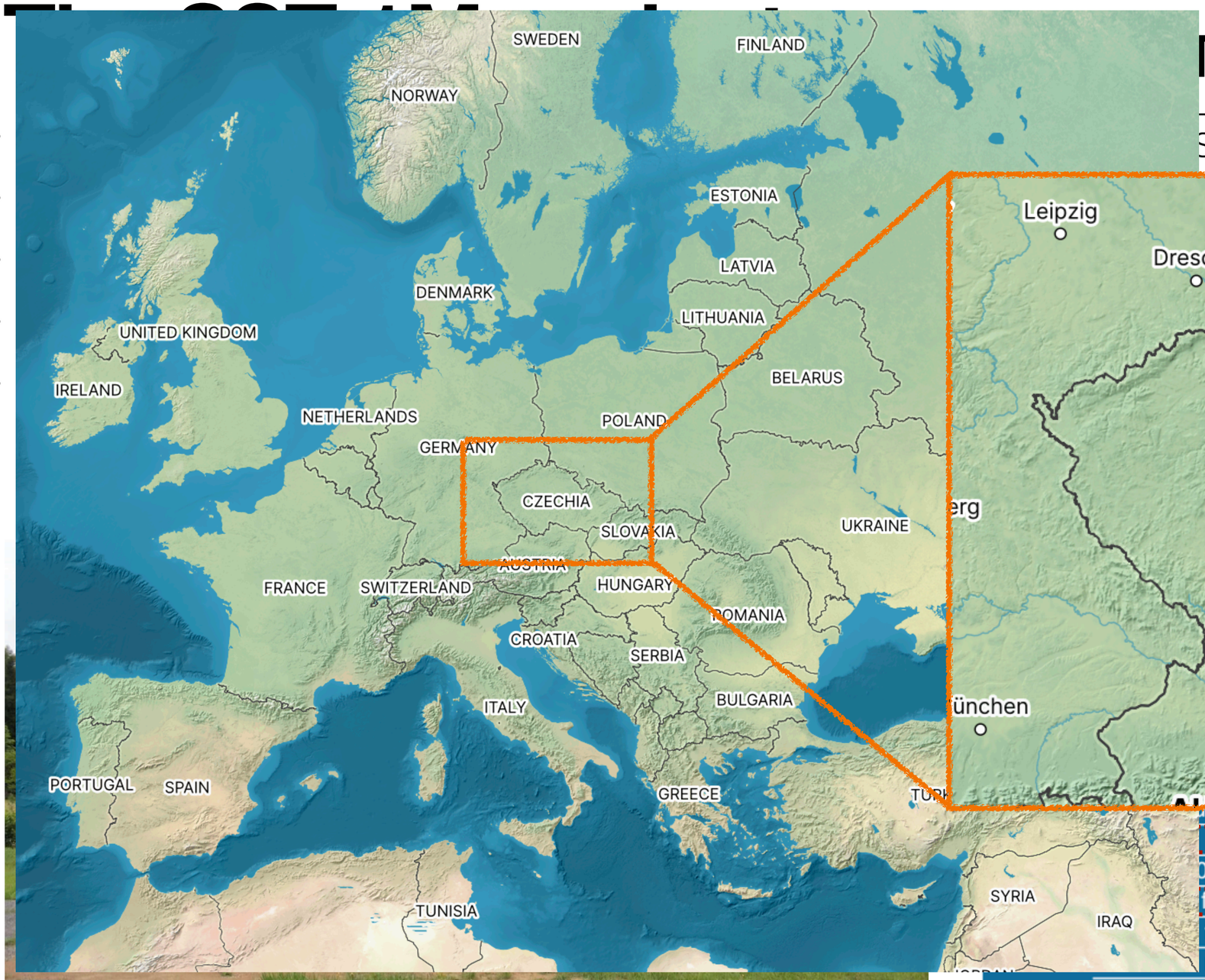
- A collaborative effort of 17 institutes in 3 countries
- **Two 4-m IACTs**, **Ondrejov observatory (500 m a.s.l.), Czech Republic**
- Davies-Cotton optical design, **innovative SiPM camera with fully digital trigger and readout**
- Commissioning phase, atmospheric conditions not optimal in Ondrejov - **'testing bench' for the telescopes**
- Operated in **mono and stereo** mode



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)
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

Г-1М

-Mirror
Size Telescope



	8.9°
0 nm, 8% X-talk (LCT/LVR)	23% / 54%
frequency	250 MHz
trigger rate (80/200 ns window)	12.5 / 5 MHz
readout rate (80/200 ns window)	22.6 / 9.4 kHz
Time Spread RMS	< 0.25 ns

SST-1M ‘mini array’

- Two telescopes 155 m apart
- **Stereo trigger** managed with **SWAT**, **White Rabbit** synchronisation of the timestamps

SST-1M major milestones

Analysis/science related

- February/November 2022 - **Telescope 2/1 installation**
- March 2023 - **first sst1mpipe prototype**
- April 2023 - **Crab detection in mono**
- June 2023 - **Crab detection in stereo** (no White Rabbit yet)
- July 2023 - **1ES 1959+650 detection**, SST-1M is going extragalactic!
- October 2023 - **First Crab detection in true stereo** with White Rabbit
- November 2023 - **First release of sst1mpipe**
- March 2024 - **Detected Mrk 421** brightening, **first ATel #16533**
- August 2024 - **First extended source detected** in stereo

Mono and stereo performance of the two SST-1M telescope prototypes

J. Juryšek,[a,*] T. Tavernier,[a] V. Novotný,[a,b] M. Heller,[c] D. Mandat,[a] M. Pech,[a] C. Alispach,[c] A. Araudo,[d,e] V. Beshley,[f] J. Blazek,[a] J. Borkowski,[g] S. Boula,[h] T. Bulik,[i] F. Cadoux,[c] S. Casanova,[h] A. Christov,[a] L. Chytka,[j] D. della Volpe,[c] Y. Favre,[c] L. Gibaud,[k] T. Gieras,[h] P. Hamal,[j] M. Hrabovsky,[j] M. Jelínek,[l] V. Karas,[d] E. Lyard,[m] E. Mach,[h] W. Marek,[h] S. Michal,[j] J. Michałowski,[h] R. Moderski,[g] T. Montaruli,[c] A. Muraczewski,[g] S. R. Muthyala,[a] A. Nagai,[c] K. Nalewajski,[h] D. Neise,[n] J. Niemiec,[h] M. Nikołajuk,[k] M. Ostrowski,[o] M. Palatka,[a] M. Prouza,[a] P. Rajda,[p] P. Schovanek,[a] K. Seweryn,[q] V. Sliusar,[m] Ł. Stawarz,[o] J. Świerblewski,[h] P. Świerk,[h] J. Štrobl,[l] J. Vícha,[a] R. Walter,[m] A. Zagdański[o] and K. Ziętara[o]

The Astronomer's Telegram http://www.astronomerstelegram.org

ATEL #16533 ATEL #16533

Title: Detection of enhanced very-high-energy gamma-ray emission from Markarian 421
Author: Thomas Tavernier, in the behalf of SST-1M Consort
Queries: tavernier@fzu.cz
Posted: 15 Mar 2024; 16:55 UT
Subjects: Gamma Ray, TeV, VHE, AGN, Blazar

Analysis of commissioning data from SST-1M : A Prototype of Single-Mirror Small Size Telescope

T. Tavernier,[a,*] J. Juryšek,[a] V. Novotný,[a,b] M. Heller,[c] D. Mandat,[a] M. Pech,[a] C. Alispach,[c] A. Araudo,[d,e] V. Beshley,[f] J. Blazek,[a] J. Borkowski,[g] S. Boula,[h] T. Bulik,[i] F. Cadoux,[c] S. Casanova,[h] A. Christov,[a] L. Chytka,[j] D. della Volpe,[c] Y. Favre,[c] L. Gibaud,[k] T. Gieras,[h] P. Hamal,[j] M. Hrabovsky,[j] M. Jelínek,[l] V. Karas,[d] E. Lyard,[m] E. Mach,[h] W. Marek,[h] S. Michal,[j] J. Michałowski,[h] R. Moderski,[g] T. Montaruli,[c] A. Muraczewski,[g] S. R. Muthyala,[a] A. Nagai,[c] K. Nalewajski,[h] D. Neise,[n] J. Niemiec,[h] M. Nikołajuk,[k] M. Ostrowski,[o] M. Palatka,[a] M. Prouza,[a] P. Rajda,[p] P. Schovanek,[a] K. Seweryn,[q] V. Sliusar,[m] Ł. Stawarz,[o] J. Świerblewski,[h] P. Świerk,[h] J. Štrobl,[l] J. Vícha,[a] R. Walter,[m] A. Zagdański[o] and K. Ziętara[o]

PoS(ICRC2023)592
PoS(ICRC2023)741
Moriond 2024

SST-1M : Commissioning and Preliminary Observation Results

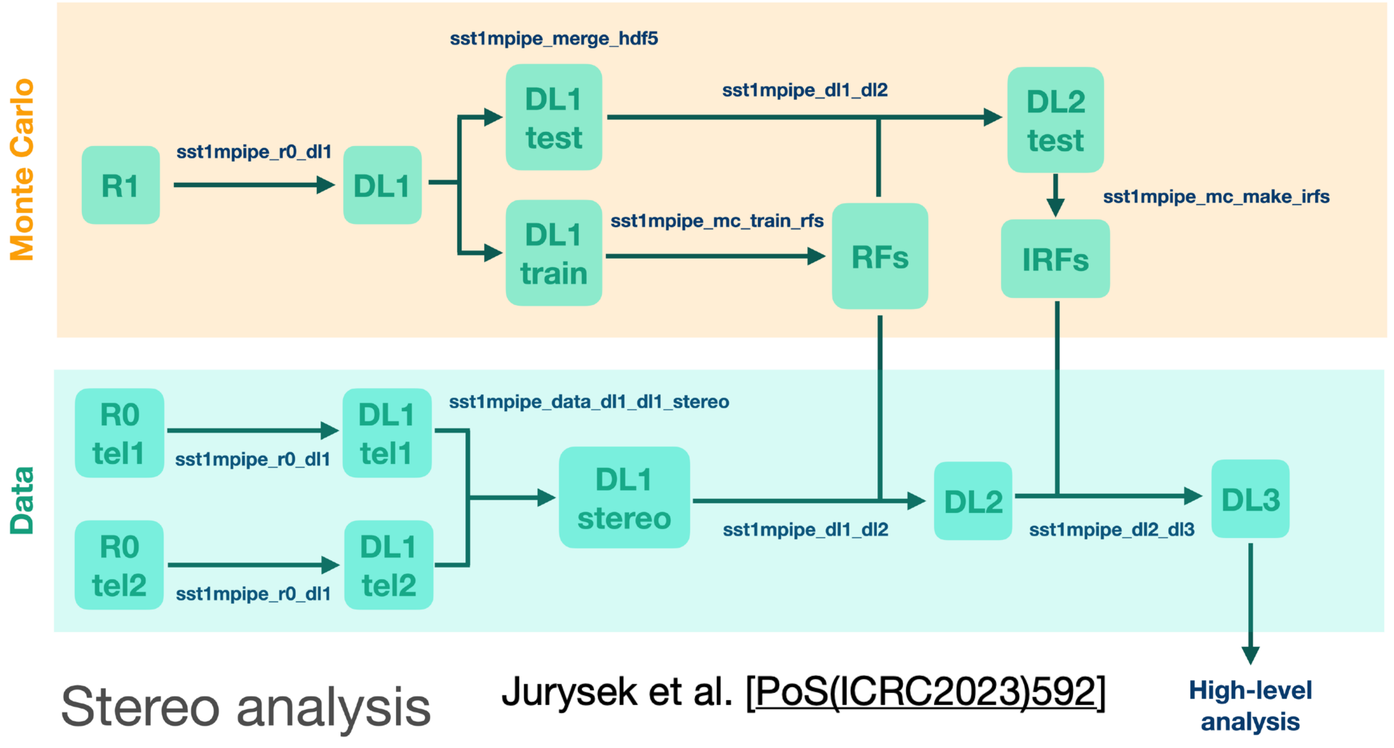
Thomas Tavernier, for the SST-1M Collaboration
FZU - Institute of Physics of the Czech Academy of Sciences
Na Slovance 1999/2 182 00 Prague 8, Czechia

sst1mpipe: v0.4.1. 21 March 2024

Jurysek, Jakub[1]; Tavernier, Thomas[1]; Novotny, Vladimir[2]; Hamal, Petr[3]; Heller, Matthieu[4]; Blazek, Jiri[1]; Muraczewki, Adam[5]; Muthyala, Srija Reddy[1]; Alispach, Cyril[4]; Renier, Yves[4]; Coco, Victor[4]

sst1mpipe

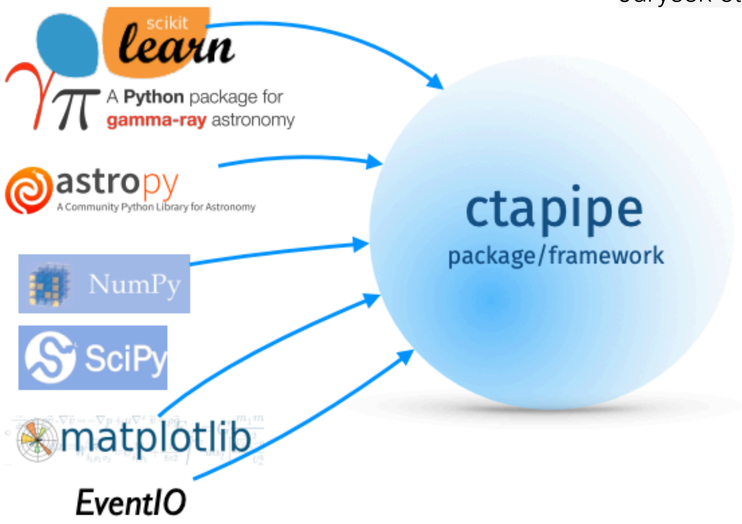
- Data and MC analysis pipeline
  - Raw waveform calibration and integration
  - Removing noise pixels and parametrisation of the shower images
  - Random Forest reconstruction
- Heavily based on **ctapipe** libraries, logic behind the analysis chain follows the **lstchain**
- Follows the data models of CTAO, compatibility with GADF for high level data analysis



Stereo analysis

Jurysek et al. [PoS(ICRC2023)592]

Jurysek et al. (2024). sst1mpipe: v0.4.1. 21 March 2024. Zenodo



A Python package for gamma-ray astronomy

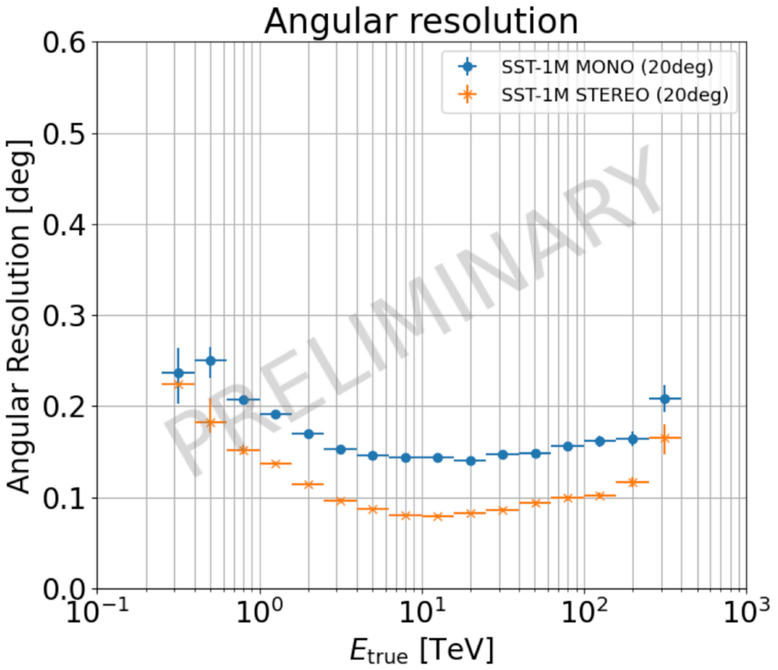
SST1-M physics performance

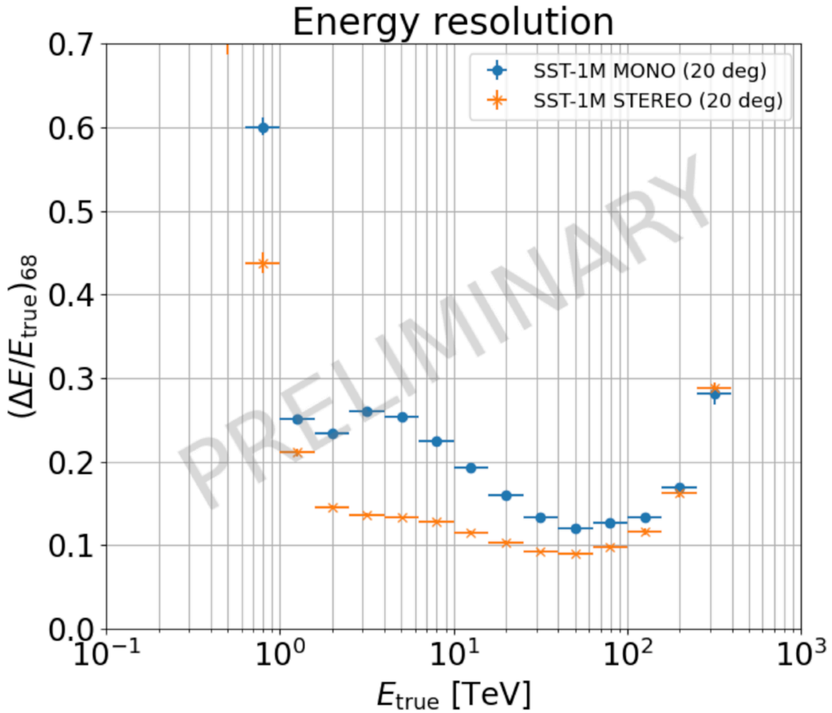
Energy and angular resolution

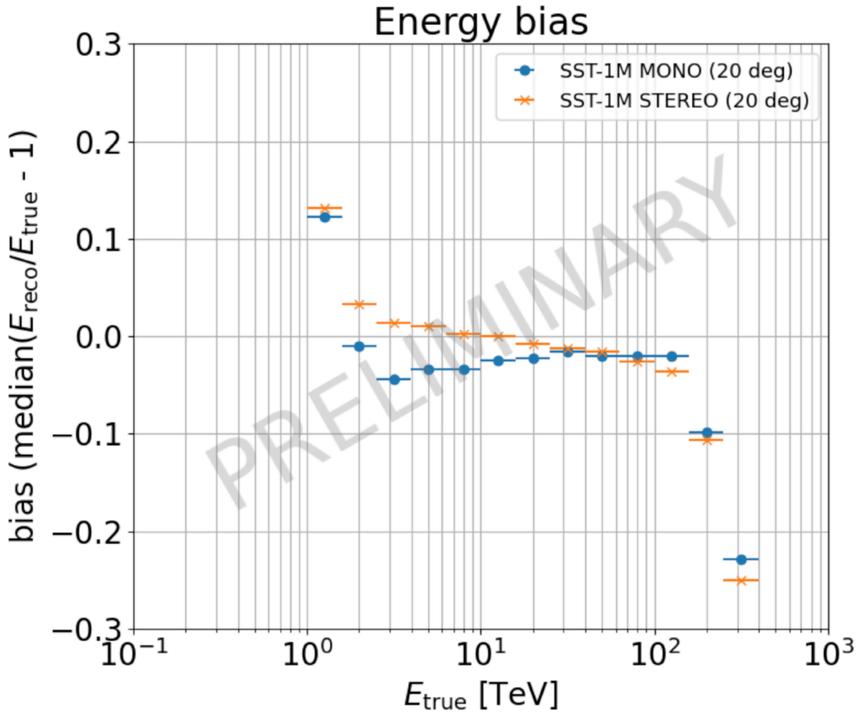
- Difficult conditions in Ondrejov - low altitude and high NSB both increase the energy threshold (~1 TeV@20 deg zenith angle)
- Angular and energy resolution sufficient for physics cases despite that

Monte Carlo

- **Angular resolution:**
  - 0.15 deg (mono)
  - 0.10 deg (stereo)
- **Energy resolution:**
  - 15-25% (mono)
  - 10-15% (stereo)







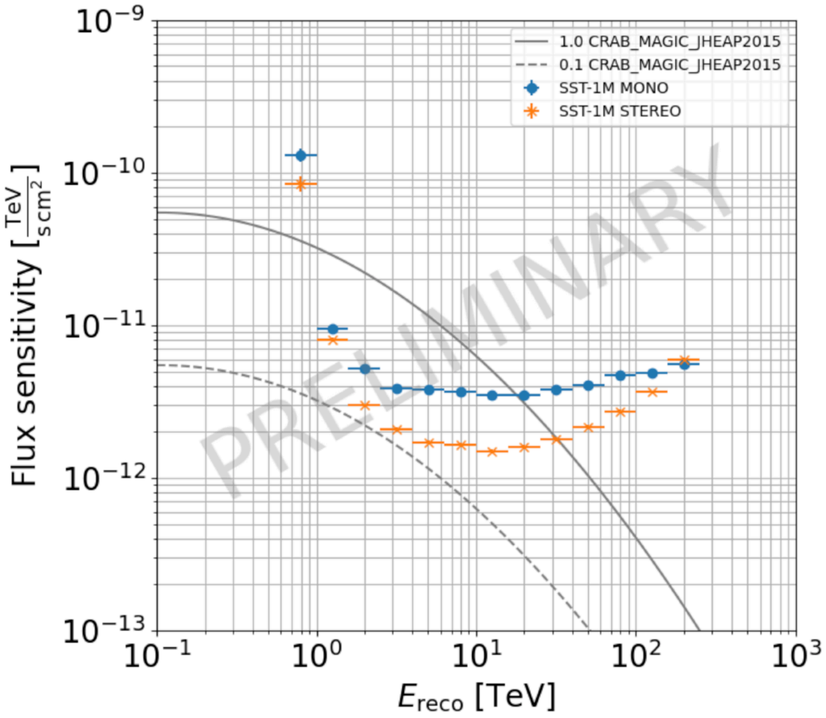
SST1-M physics performance

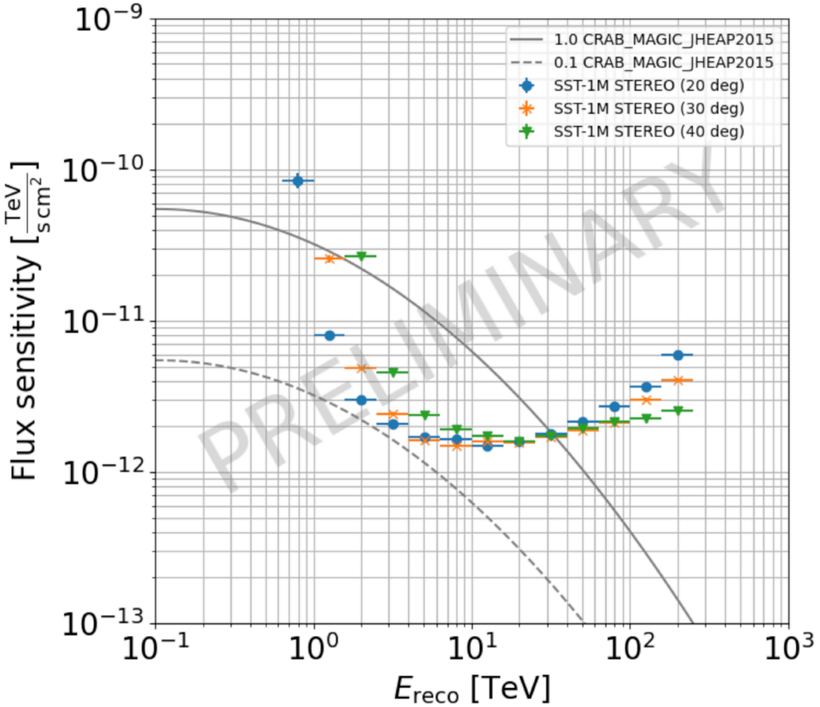
Differential sensitivity

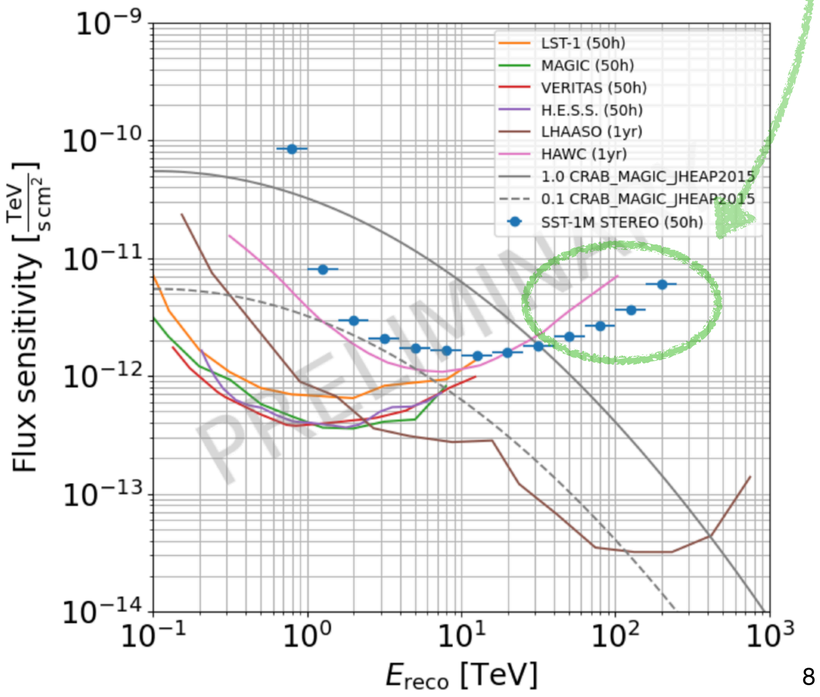
Monte Carlo

Galactic PeVatron candidate studies

- Significant improvement of stereo over mono reconstruction at all energies (except for the effect of higher energy threshold)
- Given **large FoV** and **low altitude**, SST-1M probes the highest gamma-ray energies among existing IACTs!



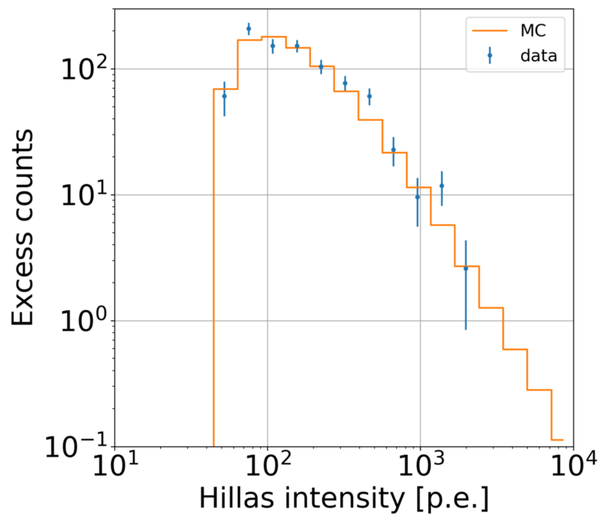


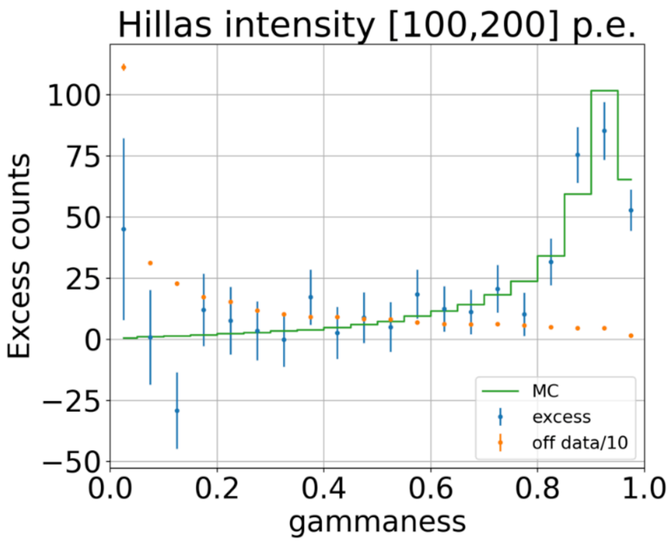


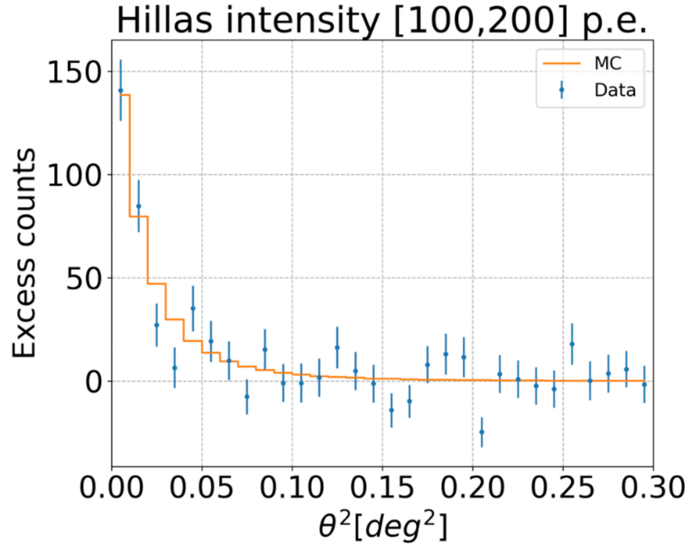
MC - data agreement

Crab excess events

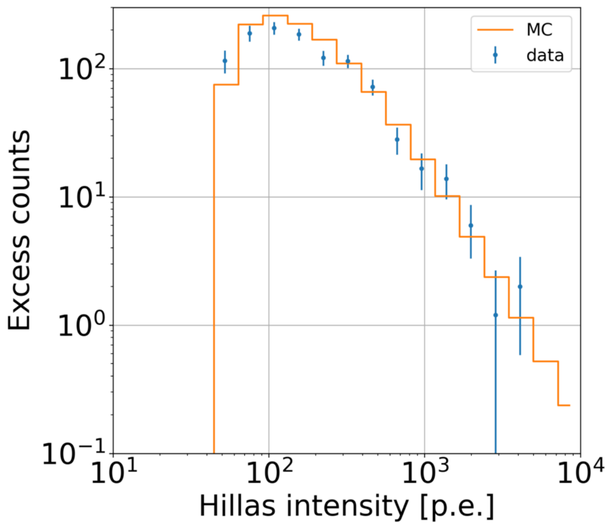
Real data + MC

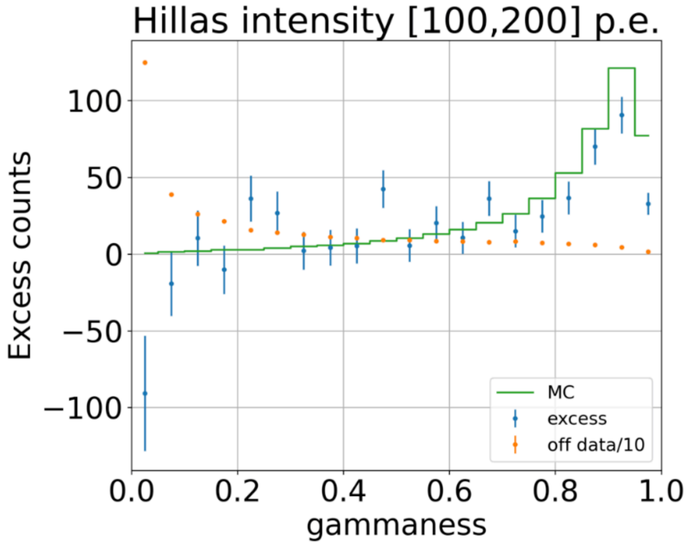


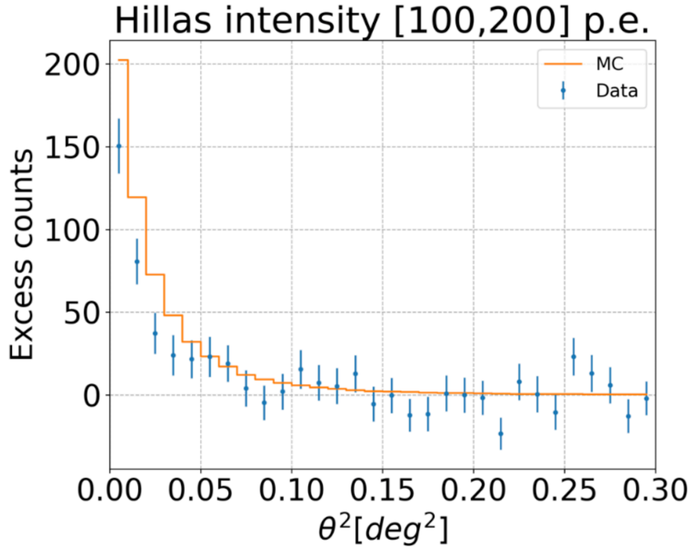




Tel 1





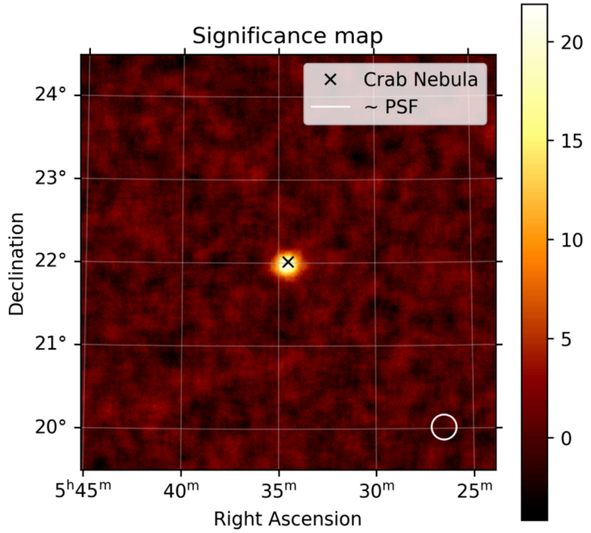


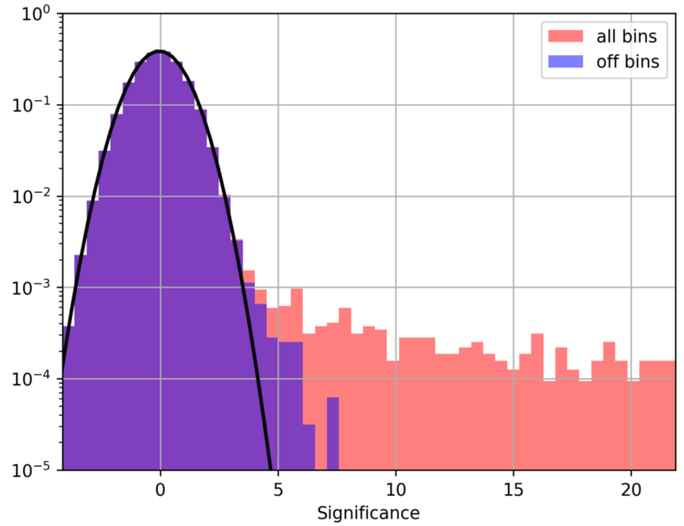
Tel 2

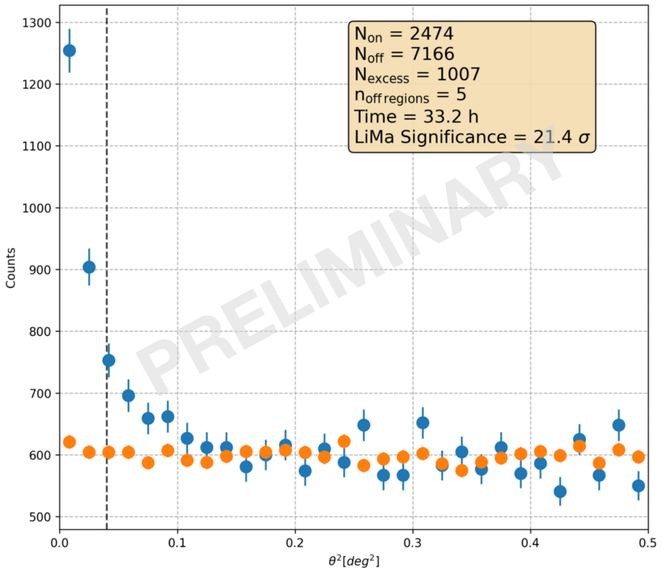
Crab Nebula observation - MONO

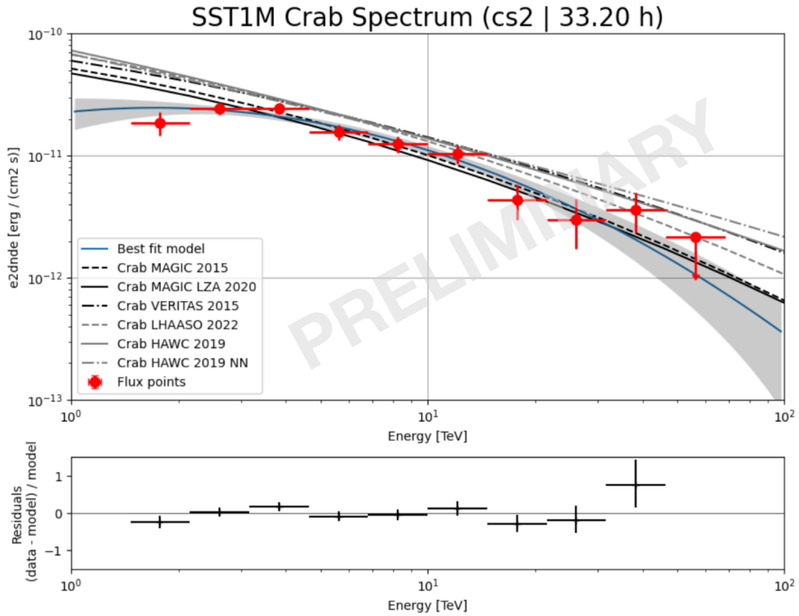
Real data

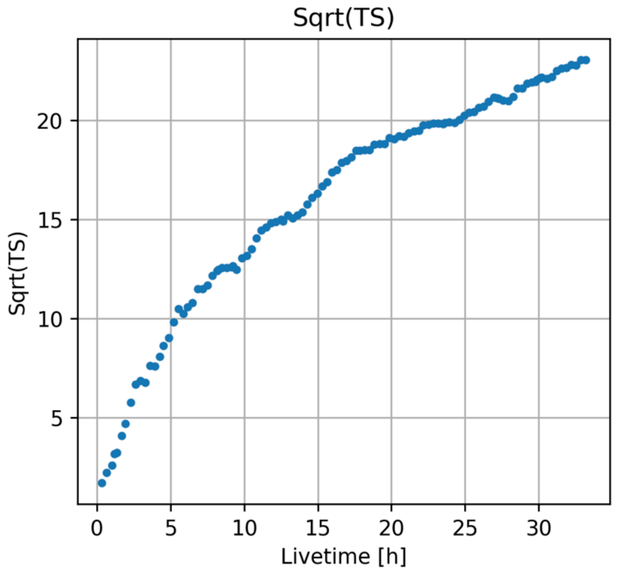
- Obs campaign 2023-2024, zenith angle 25-45 deg, energy threshold ~2-3 TeV
- ~33 hours of good mono data after quality cuts, **5sigma detection in ~2.5h**
- **Excellent agreement** of the SED with the results of other experiments (**note the tension** between different observatories)









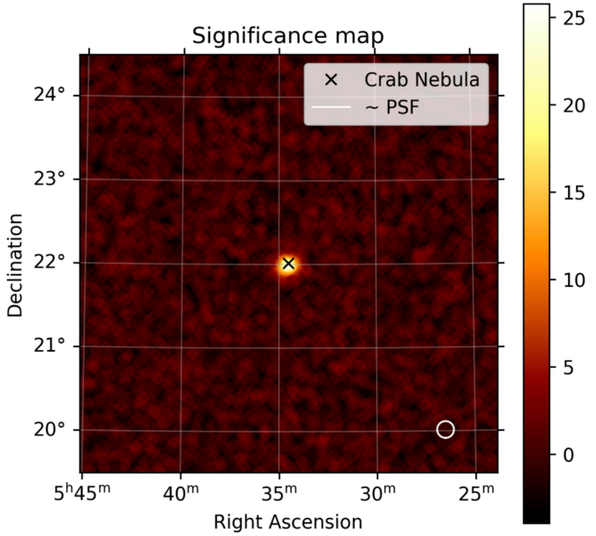


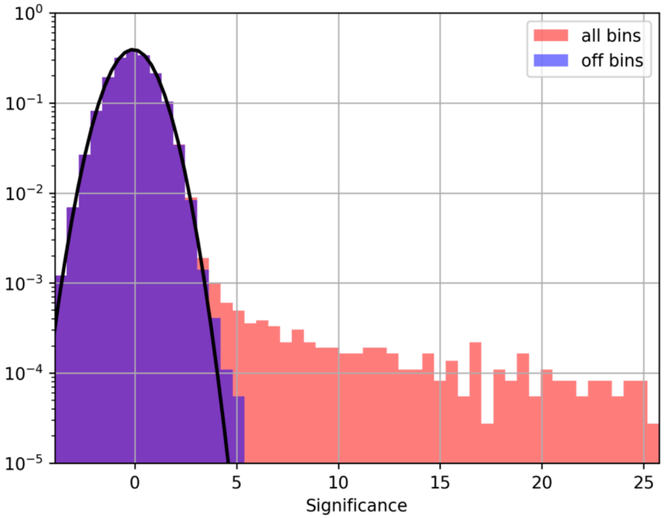
Crab Nebula observation - STEREO

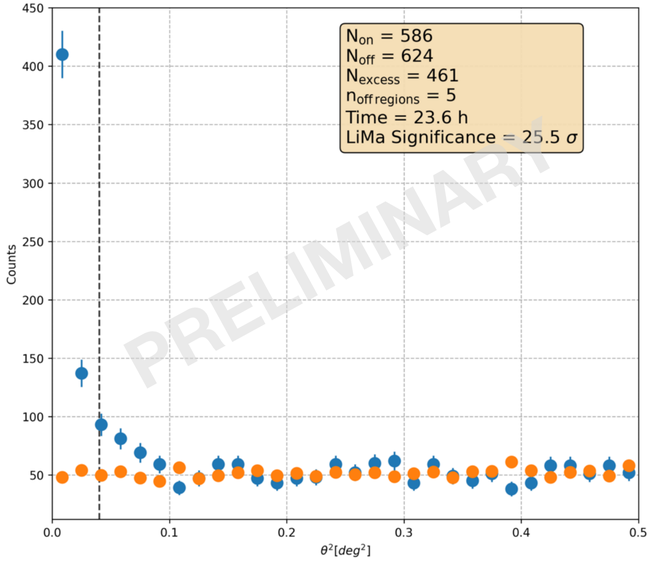
Real data

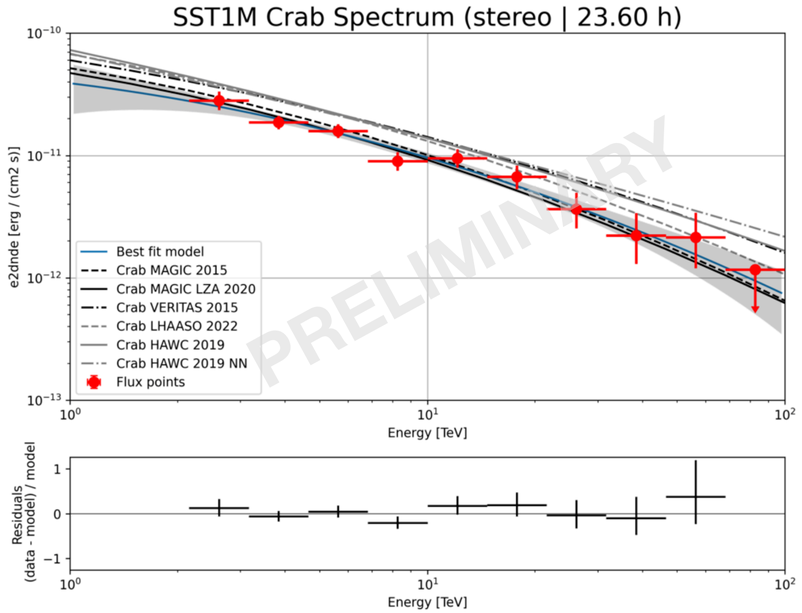
- Higher energy threshold due to not fully optimised distance between the telescopes
- ~23h of good stereo data after quality cuts, **5sigma detection in ~1.5h**
- Expected performance improvement - angular resolution and sensitivity
- **Remarkable background homogeneity on a scale of a few degrees**

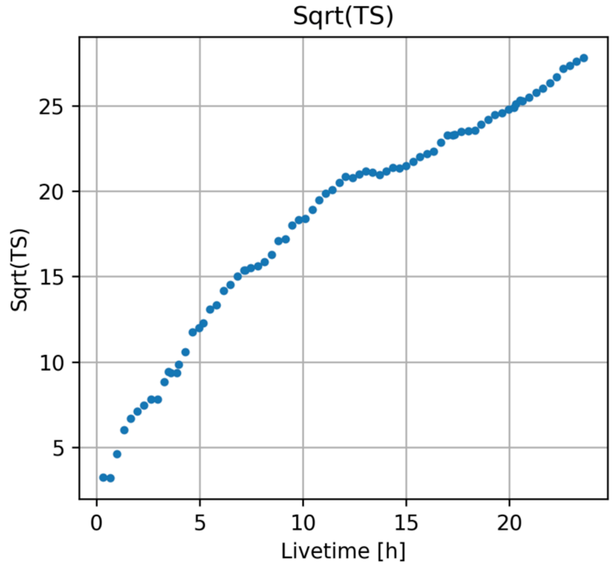
Excellent instrument for observation of extended sources









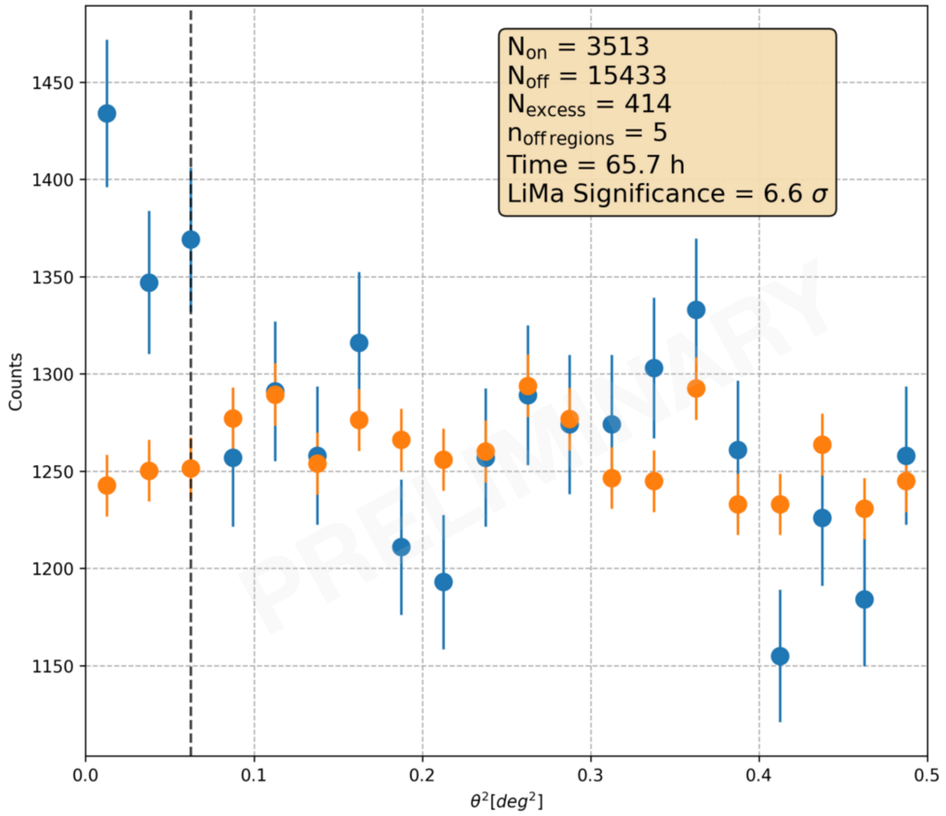


Nearby AGN monitoring

Observation campaign of several bright blazars

Real data

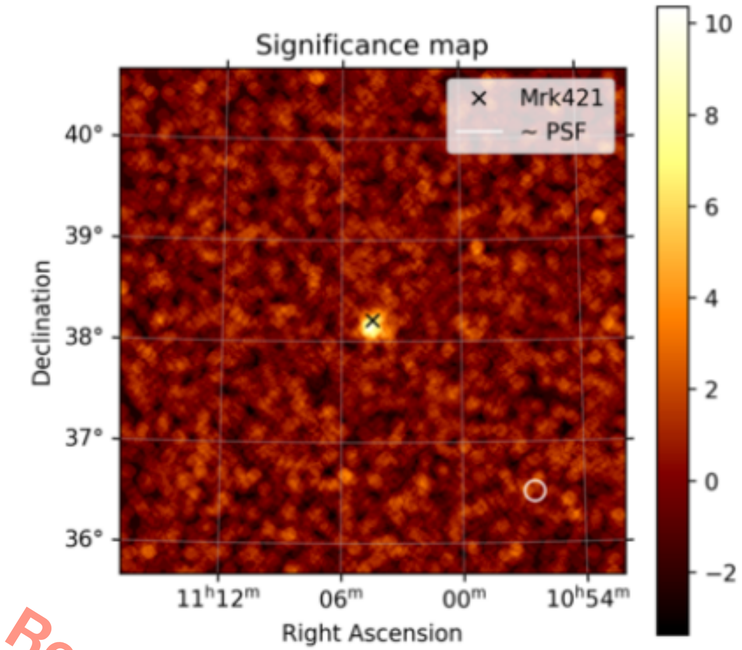
- **1ES1959+650** - first extragalactic source detected with SST-1M (Summer 2023)
- Maintenance of Tel2 camera - Tel1 **mono** only
- Long period of low activity, 5sigma detection in ~20h
- Preliminary analysis using proto-pipeline. No spectral analysis, but **proving SST-1M capabilities for AGN monitoring**



Nearby AGN monitoring

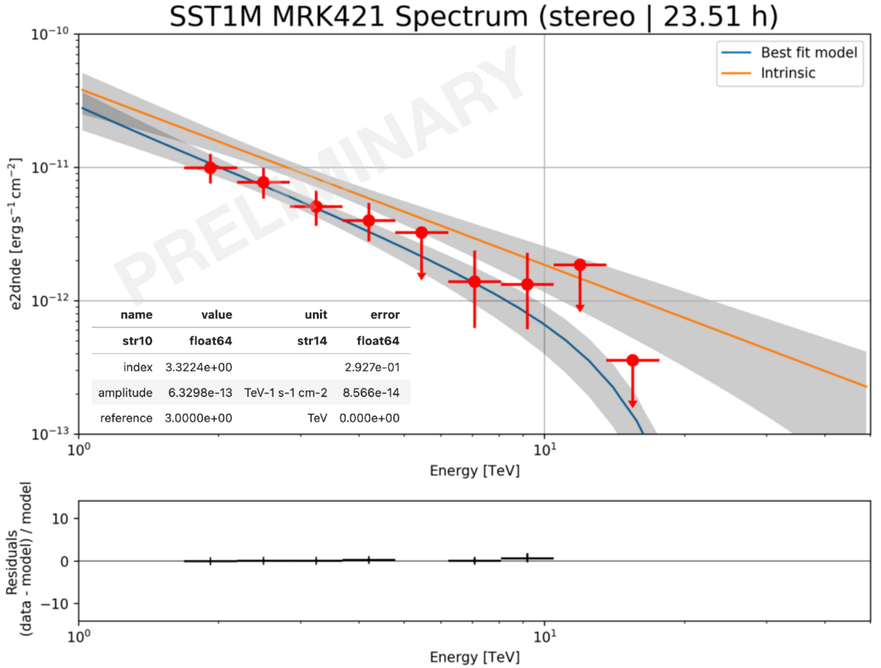
Observation campaign of several bright blazars

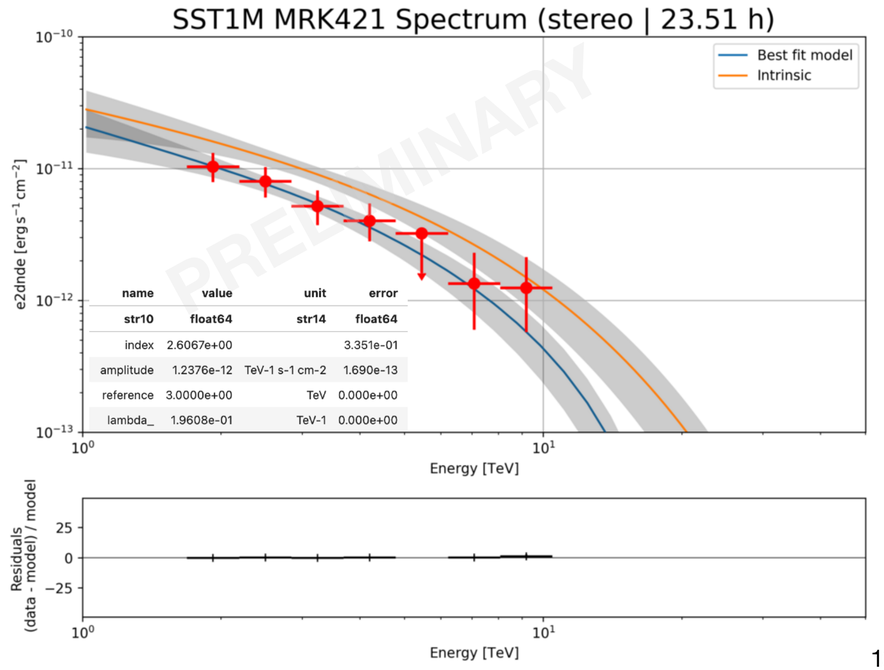
- **Mrk 421** - first extragalactic source detected in **stereo** mode (Spring 2024)
- High state detected on 15 March 2024: ATel #16533



Real data

- **Mid-term monitoring (~4 months):**
  - integrated SED shows no spectral curvature*
  - Sp index from ECPL fit (2.6+-0.3) compatible with HAWC 2022 (2.26+-0.12)
  - last 2sigma fluxpoint at 9 TeV (compare with HAWC 2022)



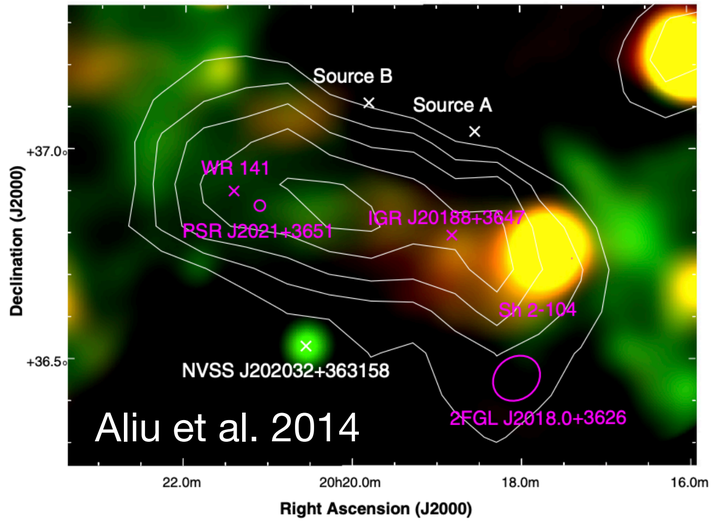


* DeltaTS=0.03 for intrinsic ECPL over PL, probably because we probe energies already above the E_{cutoff} = 5.1 TeV (HAWC, fixed in the fit)

VER 2019+368 (Dragonfly)

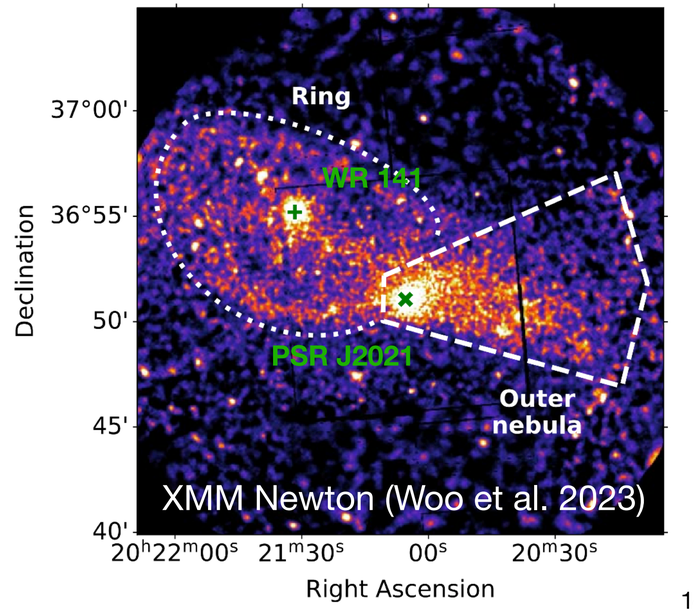
SST-1M enters the realm of extended sources

- Discovered by MILAGRO (Abdo et al. 2009)
- Later resolved into 2-3 sources by VERITAS (Abeysekhara et al. 2014, 2018)
- Photons up to 0.27 PeV (LHAASO 2021)
- Slightly extended: ~0.5 deg, highly asymmetric, energy dependent morphology



- **Complex region:**
  - Several radio, X-ray, HE and VHE sources
  - Supernova Remnant CTB 87
  - Two pulsars
  - Sh 2-104 - Star forming HII region
  - G75.2+0.1 - PWN
  - IGR J20188 - fast X-ray transient
  - Wolf-Rayet star WR 141

- **Recent modeling** (Woo et al. 2023):
  - PSR J2021+3651 (17 kyr, 10^{36} erg/s) + PWN (G75.2+0.1/Dragonfly) interacting with SNR reverse shock



Tension between SED from different experiments

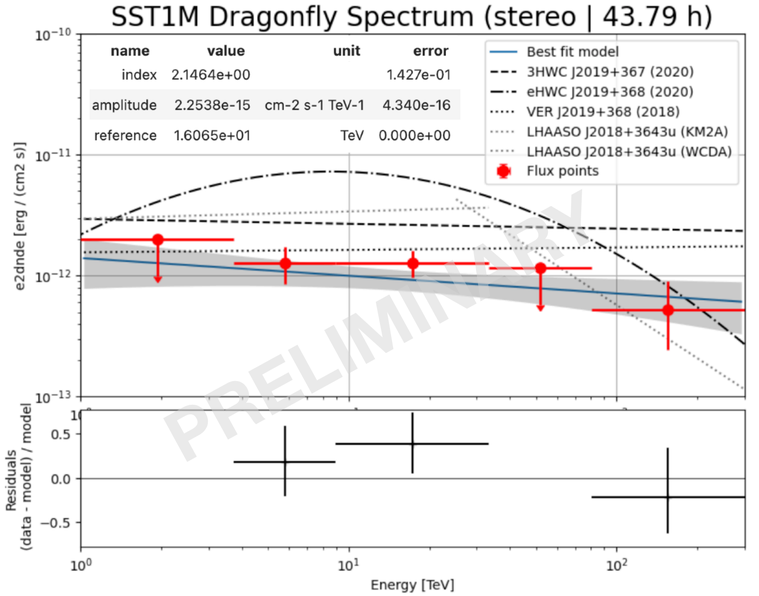
There is no detailed study of VHE morphology

VER 2019+368 (Dragonfly)

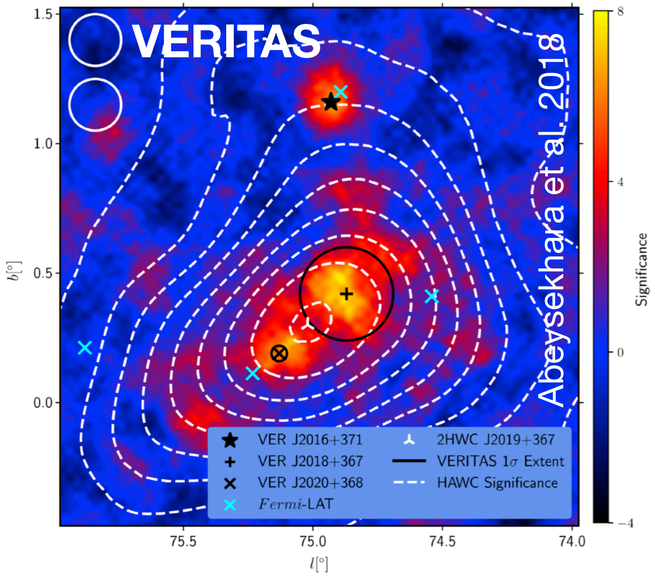
SST-1M enters the realm of extended sources

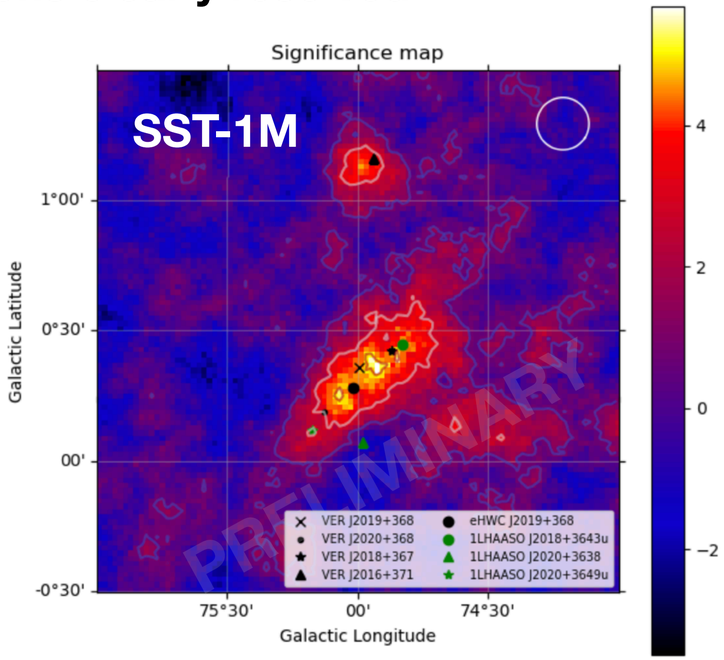
Real data

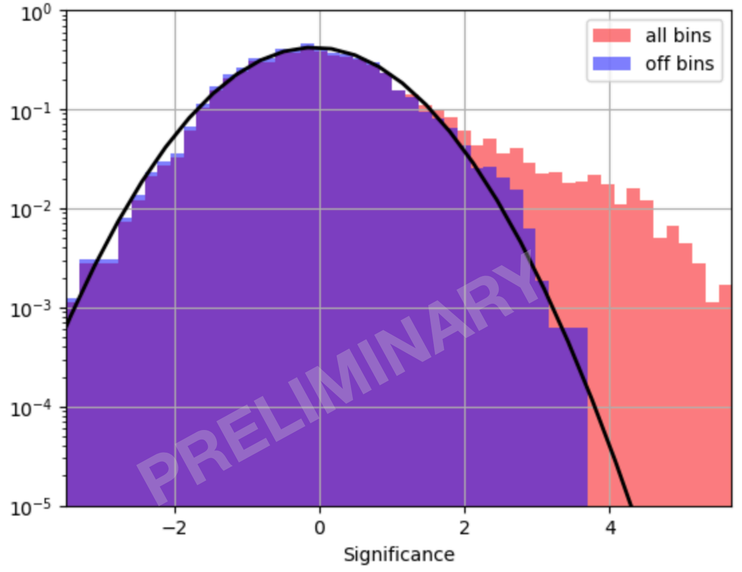
- Obs campaign in 2024, zenith angle 5-60 deg, ~44 hours of good stereo data after quality cuts
- **Preliminary results:**
  - Source position and integration region for SED fixed at VERITAS reported values (Abeysekhara et al. 2018)
  - **6sigma (p-value 2e-9)** of PL source over “no source” hypothesis (pre-trial)
  - **CTB 87 and VER J2019 regions clearly resolved**



N of stereo events: 57 69 54 9 5







Conclusions

SST-1M
Single-Mirror
Small Size Telescope

- Commissioning of two SST-1M telescopes continues in Ondrejov, Czech Republic
- **The telescopes operate in stereo mode**
- The telescopes have proven to meet the expected performance
- **First astrophysical sources detected in stereo**, including extragalactic or extended sources
- SST-1M stereo observatory combines **large FoV**, **good angular resolution** and **low altitude**, which makes it an ideal instrument for morphological studies of extended galactic PeVatron candidates - **unique science case**