SST-1M
Single-Mirror
Small Size Telescope

Institute of Physics of the
Czech Academy of Sciences

SST-1M: Status of the data analysis

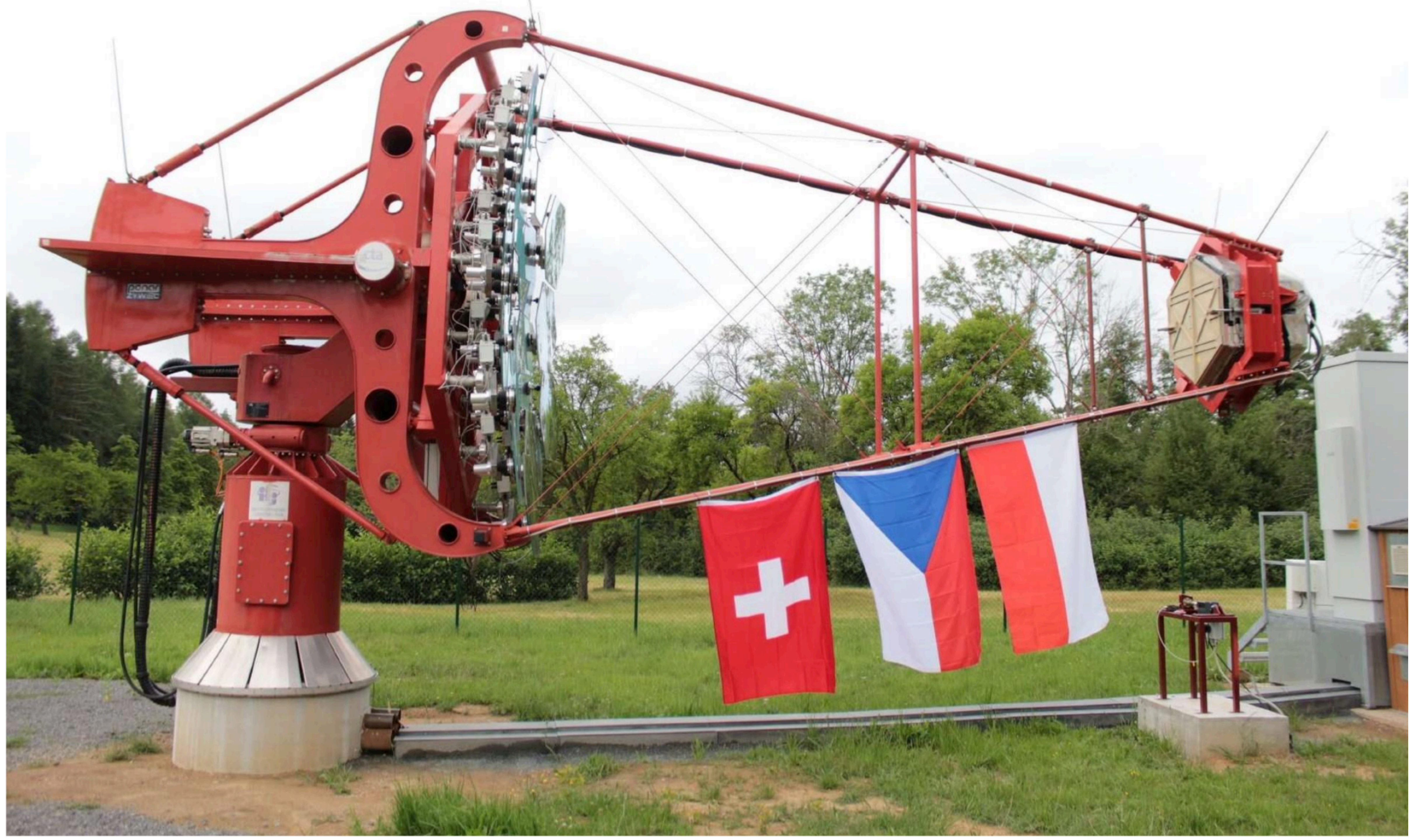
Jakub Juryšek & Thomas Tavernier
Institute of Physics of the Czech Academy of Sciences
For the SST-1M analysis team

The SST-1M project

SST-1M
Single-Mirror
Small Size Telescope

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
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

- 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

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

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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

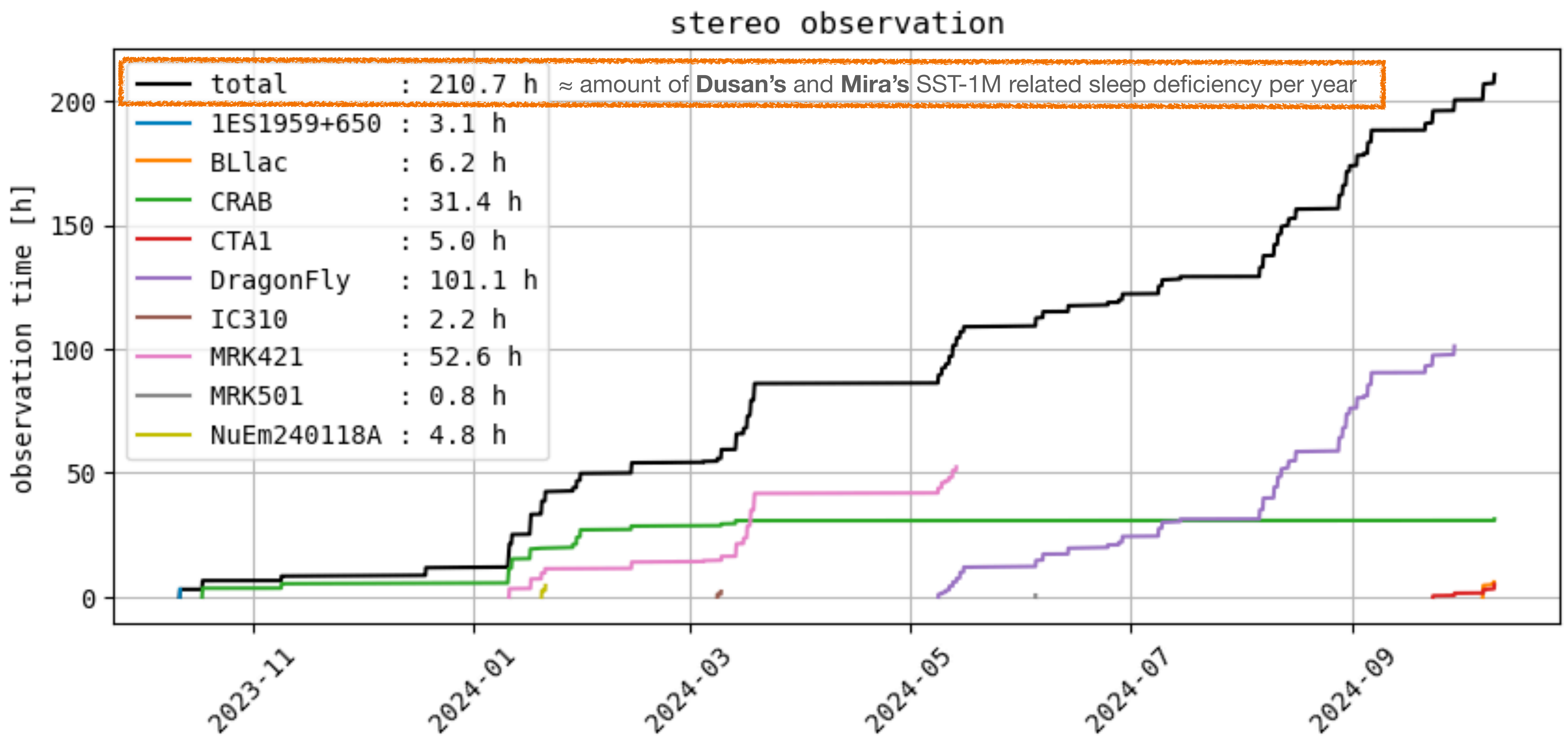
Thomas Tavernier, for the SST-1M Collaboration
FZU - Institute of Physics of the Czech Academy of Sciences
Na Slovance 1999/2 182 00 Prague 8, Czechia

zenodo

sst1mpipe: v0.4.1. 21 March 2024

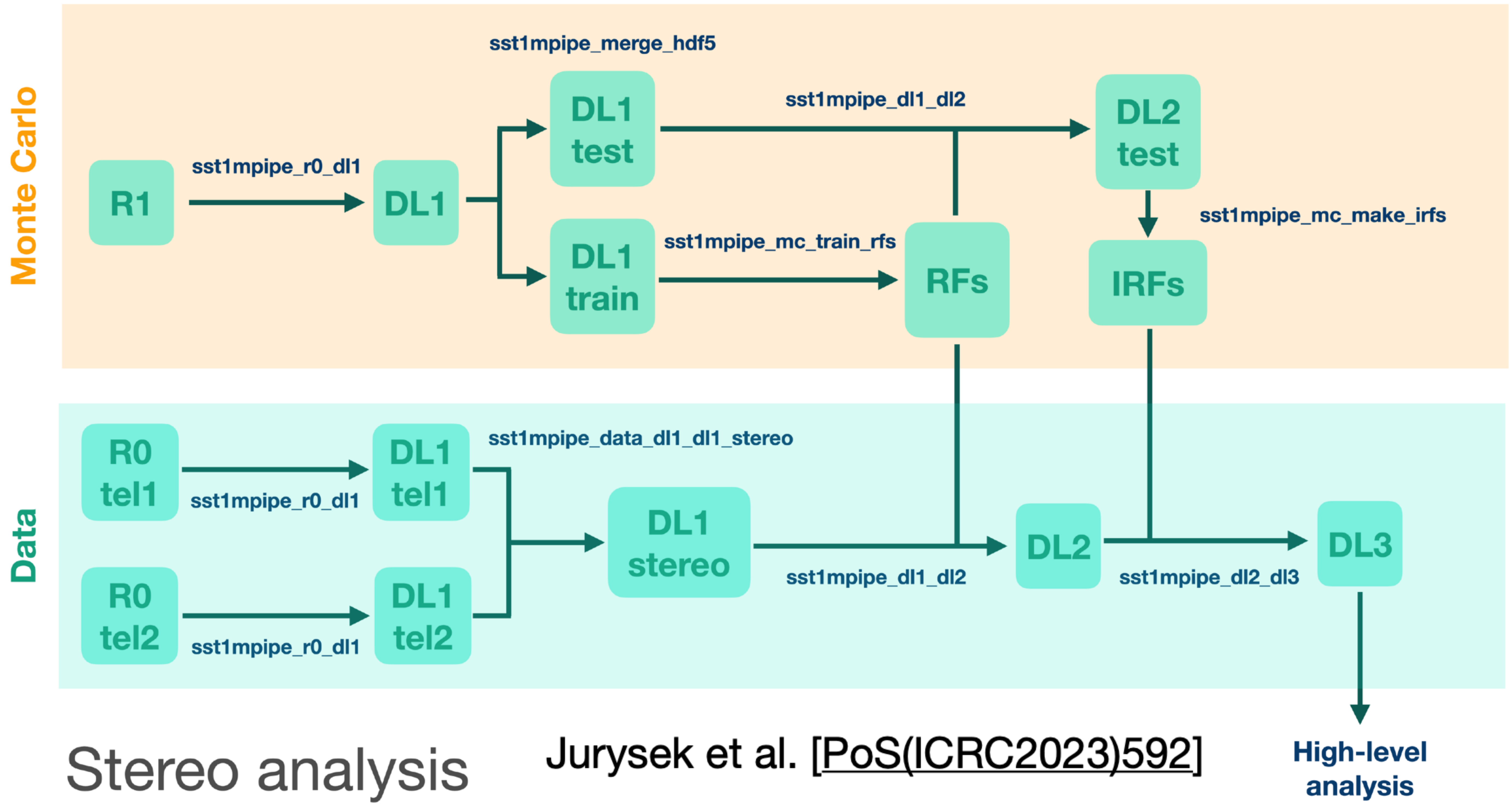
Jurysek, Jakub[1]; Tavernier, Thomas[1]; Novotny, Vladimir[2]; Hamal, Petr[3]; Heller, Matthieu[4]; Blazek, Jiri[1]; Muraczewki, Adam[5]; Muthyala, Srija Reddy[1]; Alispach, Cyril[4]; Renier, Yves[4]; Coco, Victor[4]

The data accumulated so far (only WR stereo)



sst1mpipe

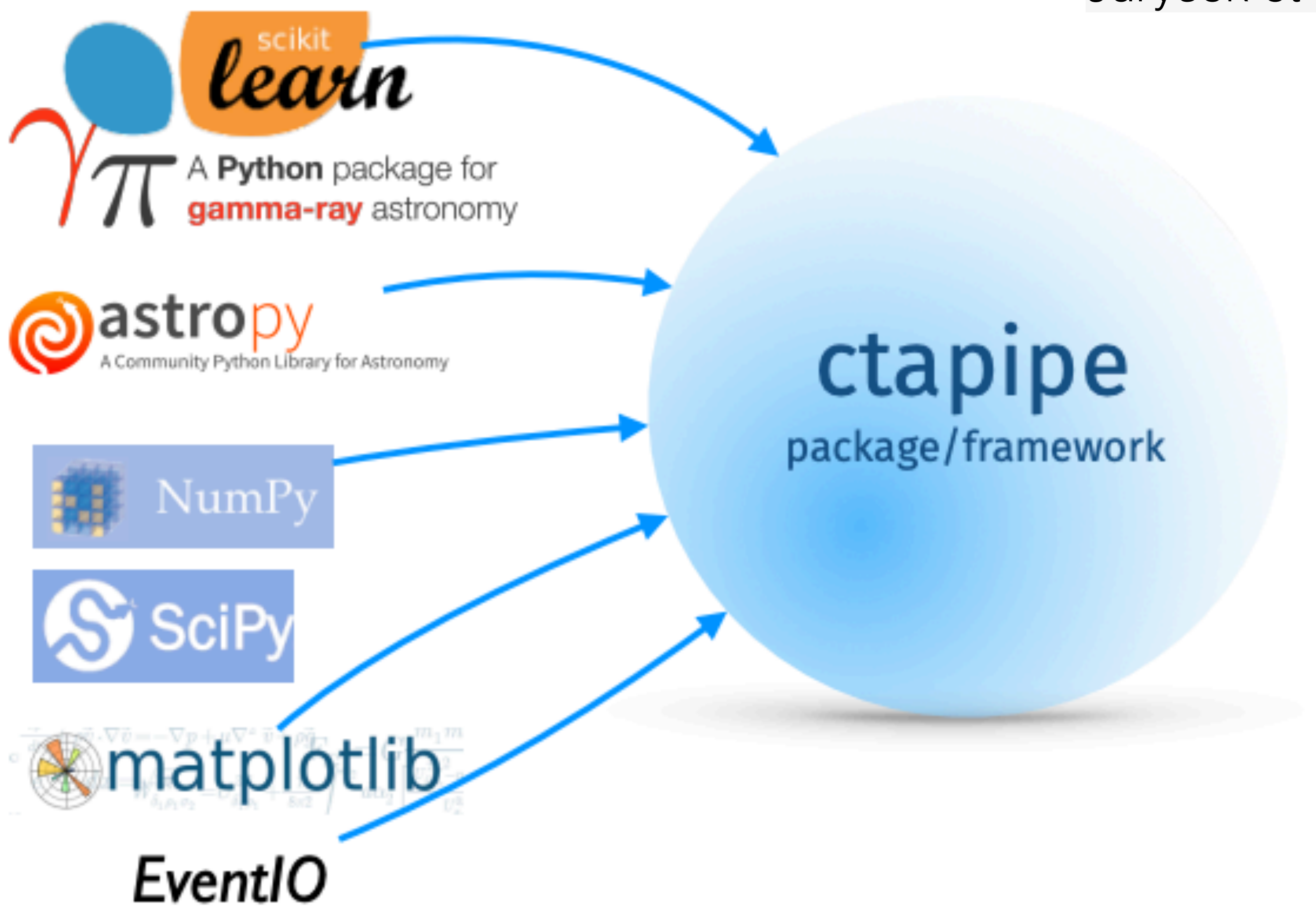
- Data and MC analysis pipeline
    - Raw waveform calibration and integration
    - Removing noise pixels and parametrisation of the shower images
    - Random Forest reconstruction
- Heavily based on **ctapipe** libraries, logic behind the analysis chain follows the **lstchain**
- Follows the data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

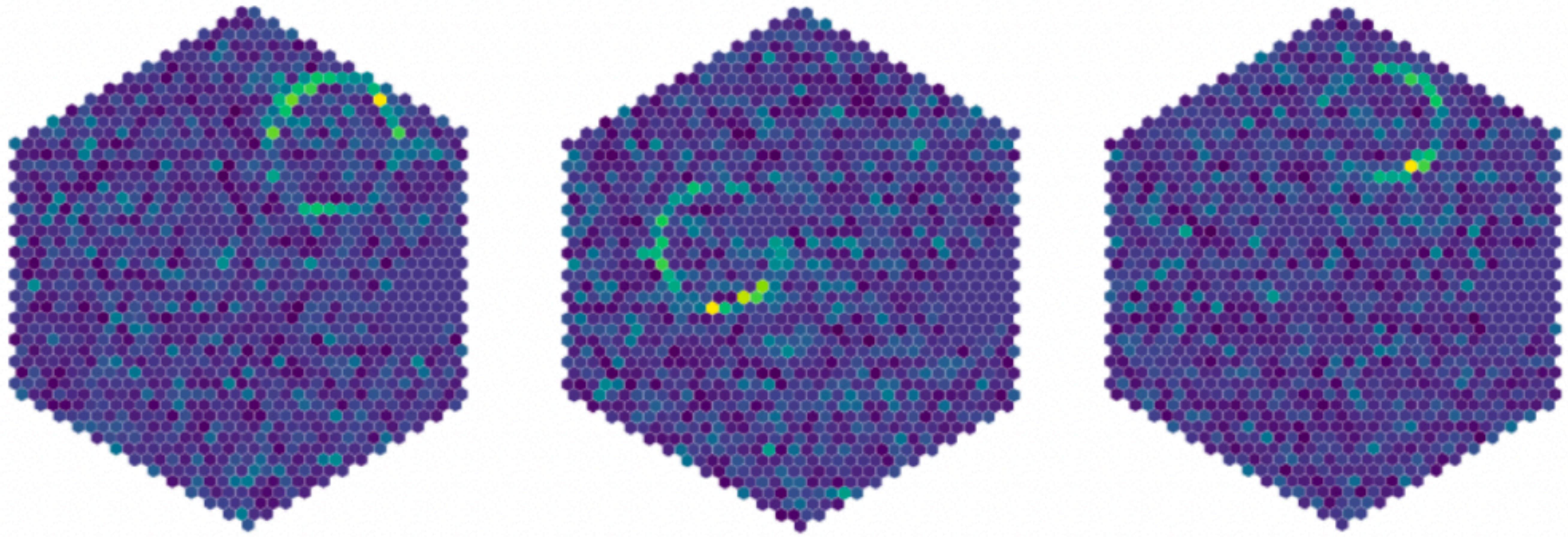


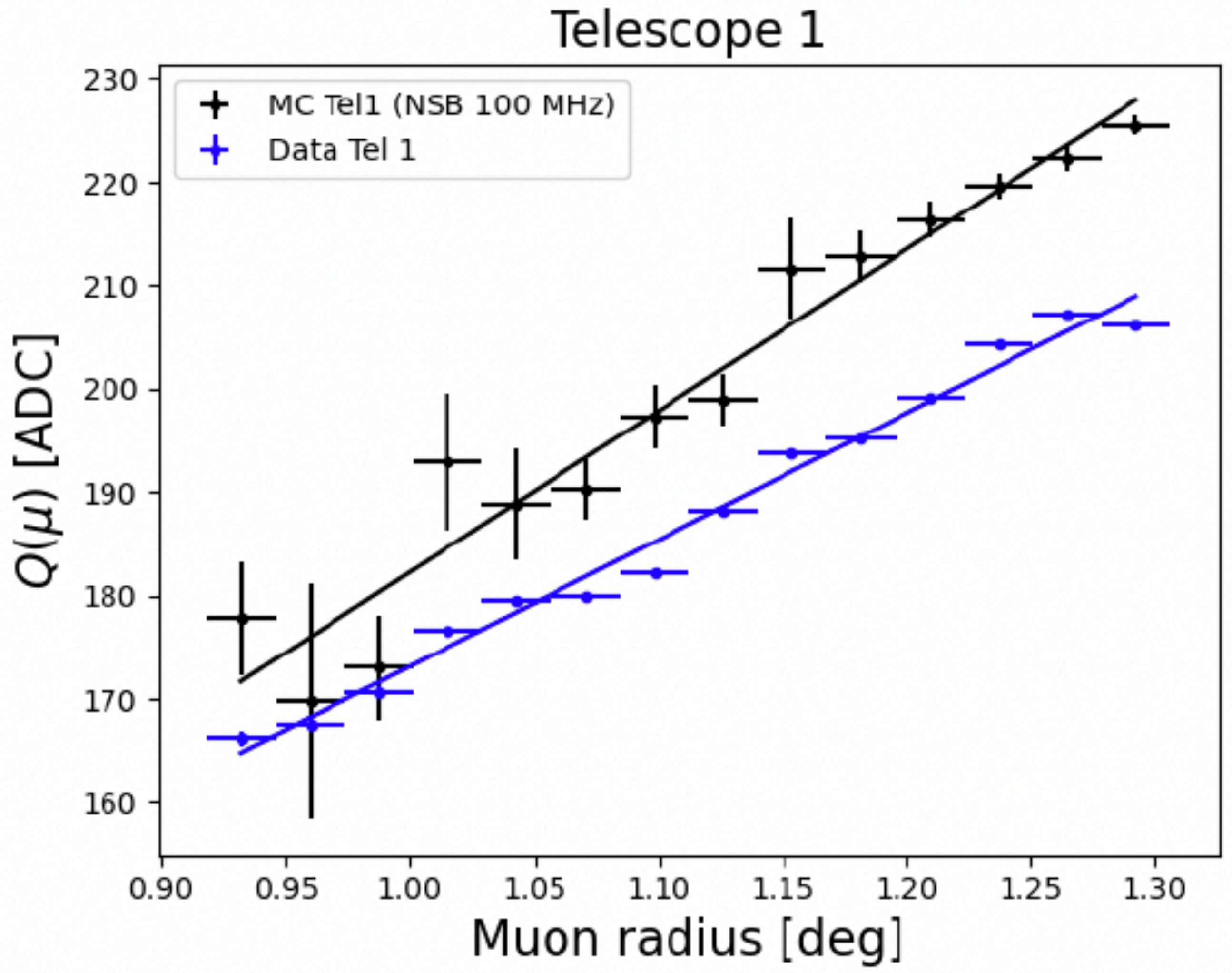
ctapipe

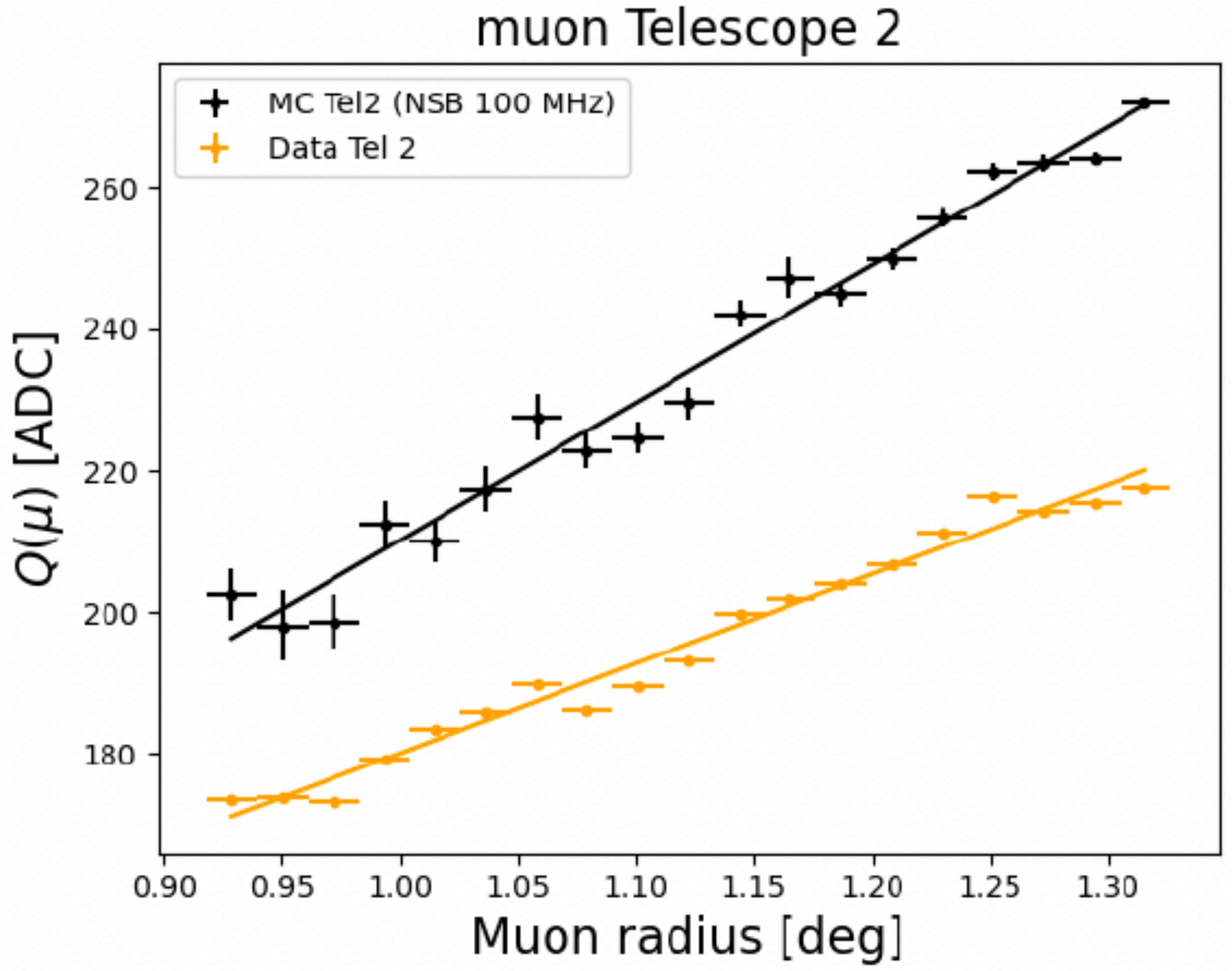
A **Python** package for **gamma-ray** astronomy

Calibration: The optical throughput

- **Muons** are known to be valuable test beams for IACT astronomy
- Typical ring images at the focal plane
- **Light intensity is proportional to the ring radius**

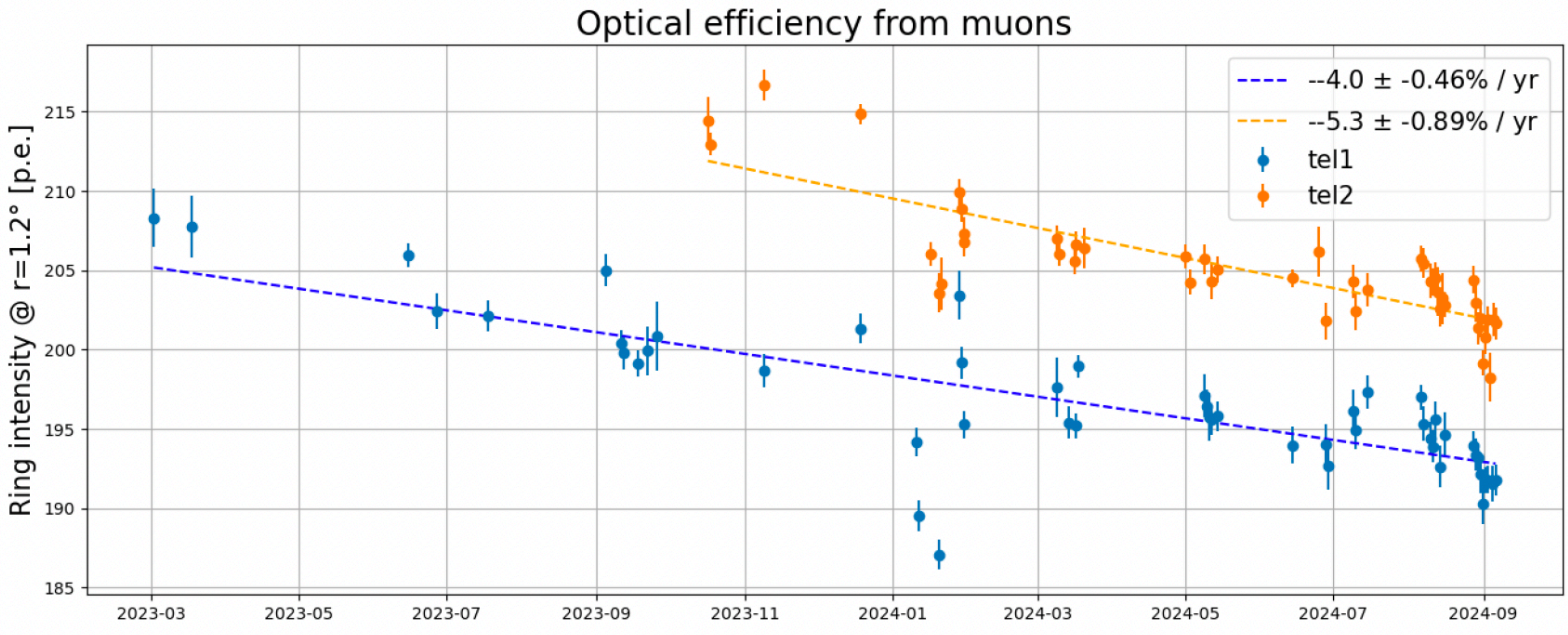






Thomas Tavernier

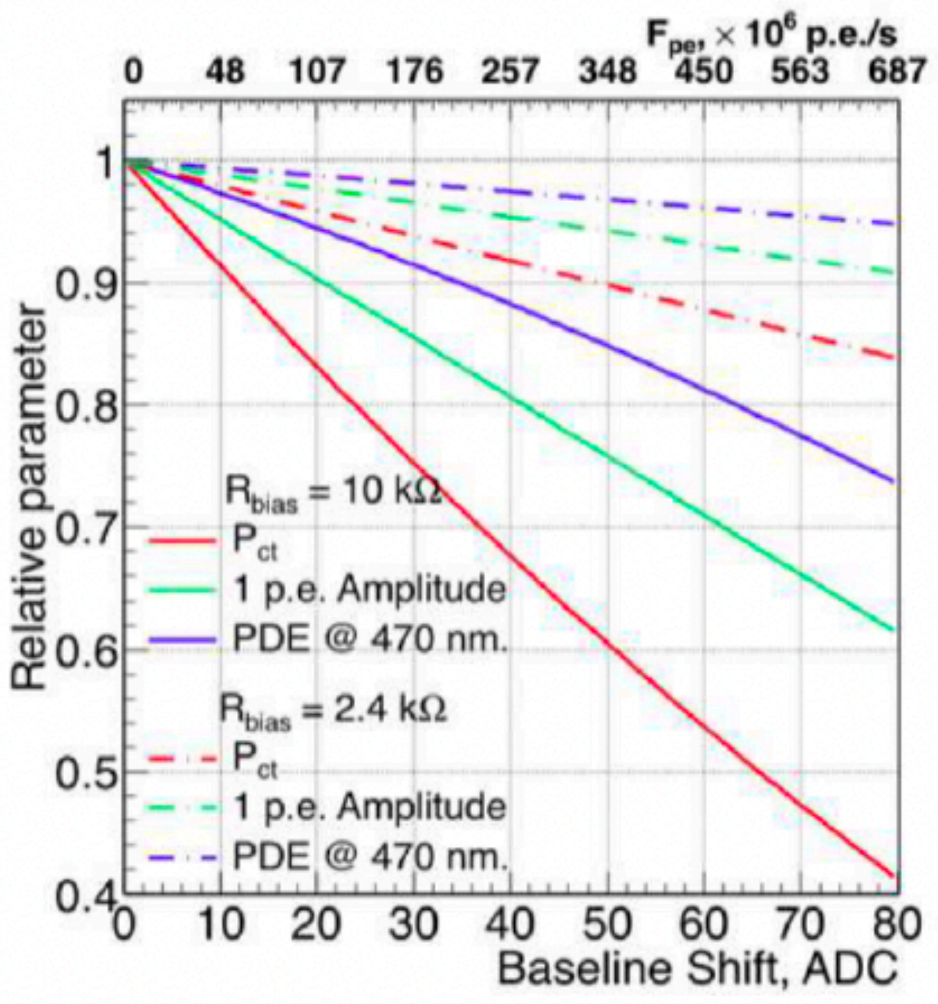
Calibration: The optical throughput



Thomas Tavernier

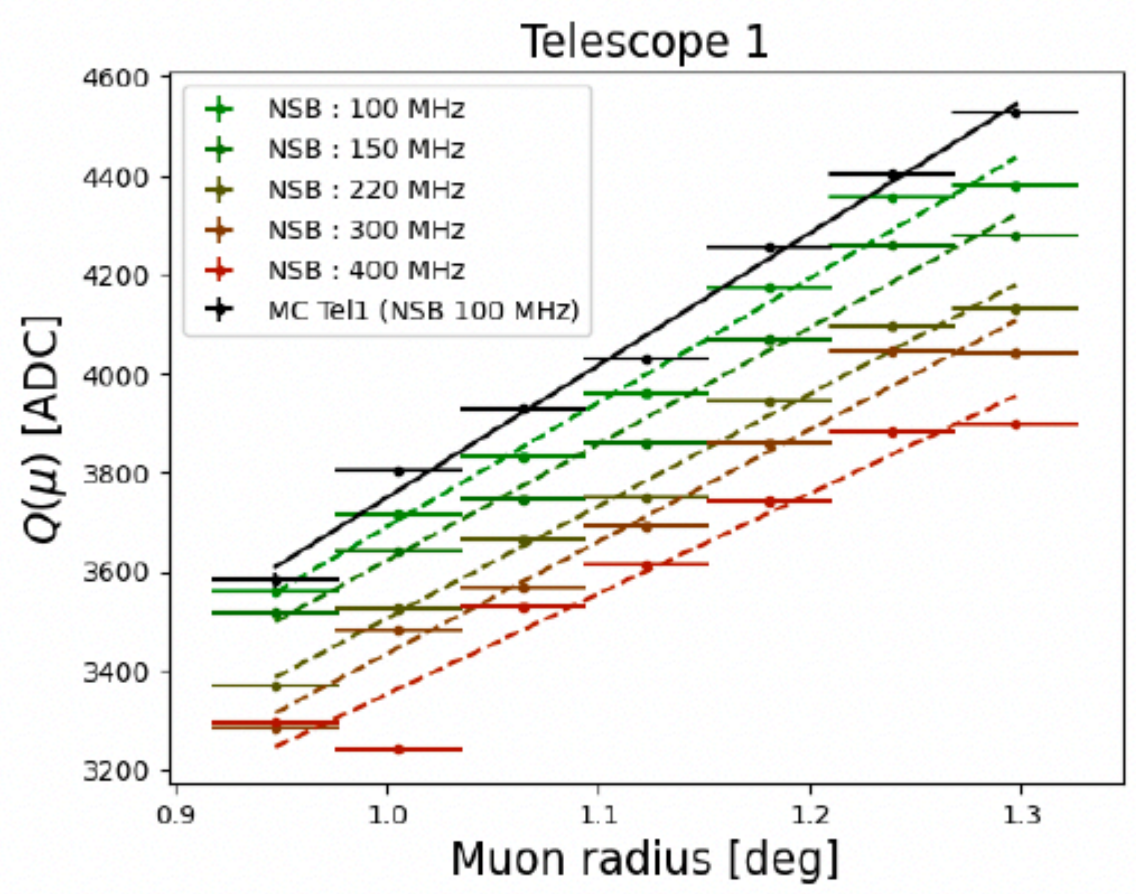
Calibration: The voltage drop

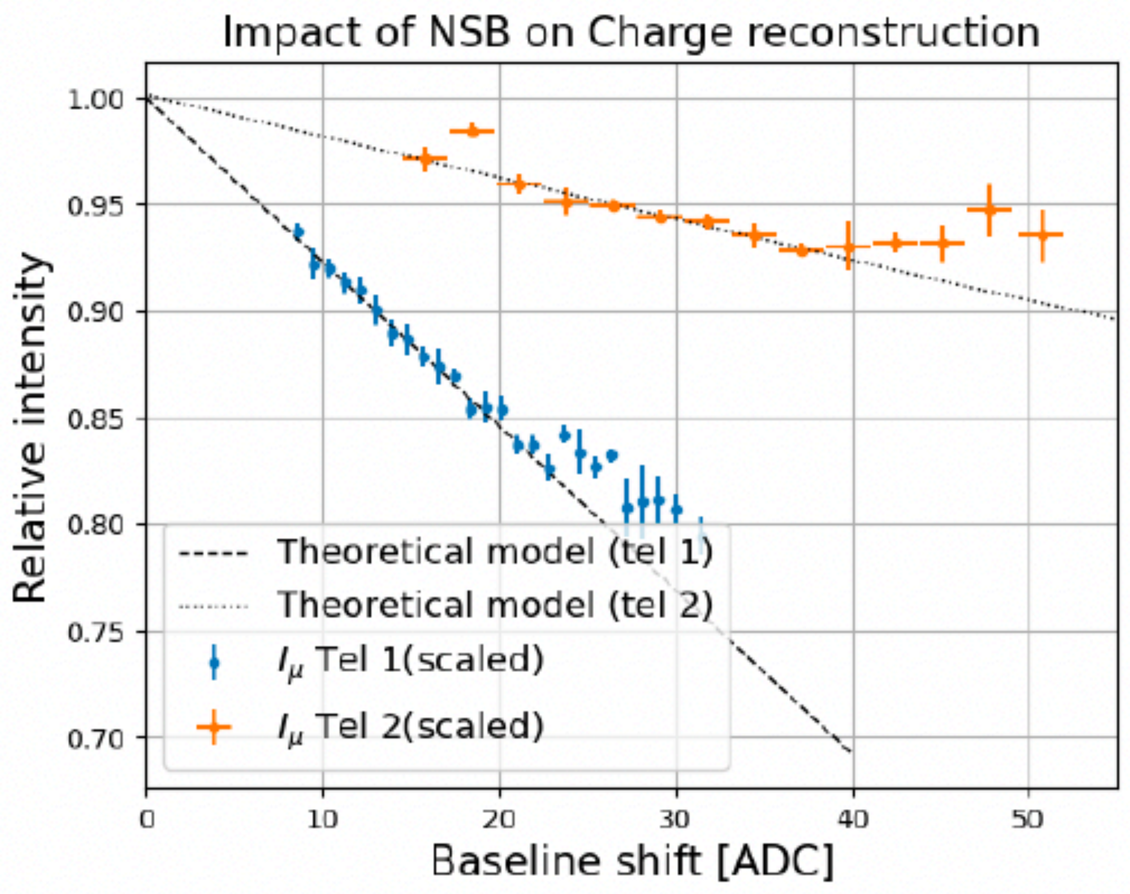
- **SiPM characteristics** (gain, optical efficiency, x-talk) are affected by the **NSB level**.
- In general **the integrated charges drop with NSB**
- This effect and the optical efficiency of the telescope can be evaluated using muons.
- Correction of The Voltage drop included in the analysis



Thomas Tavernier

Important effect - if not corrected for, the **energy scale** can be underestimated up to **20%, or 5%** in case of Tel1 and tel2, respectively (in the typical NSB conditions, not accounting for the extremes with strong Moonlight).



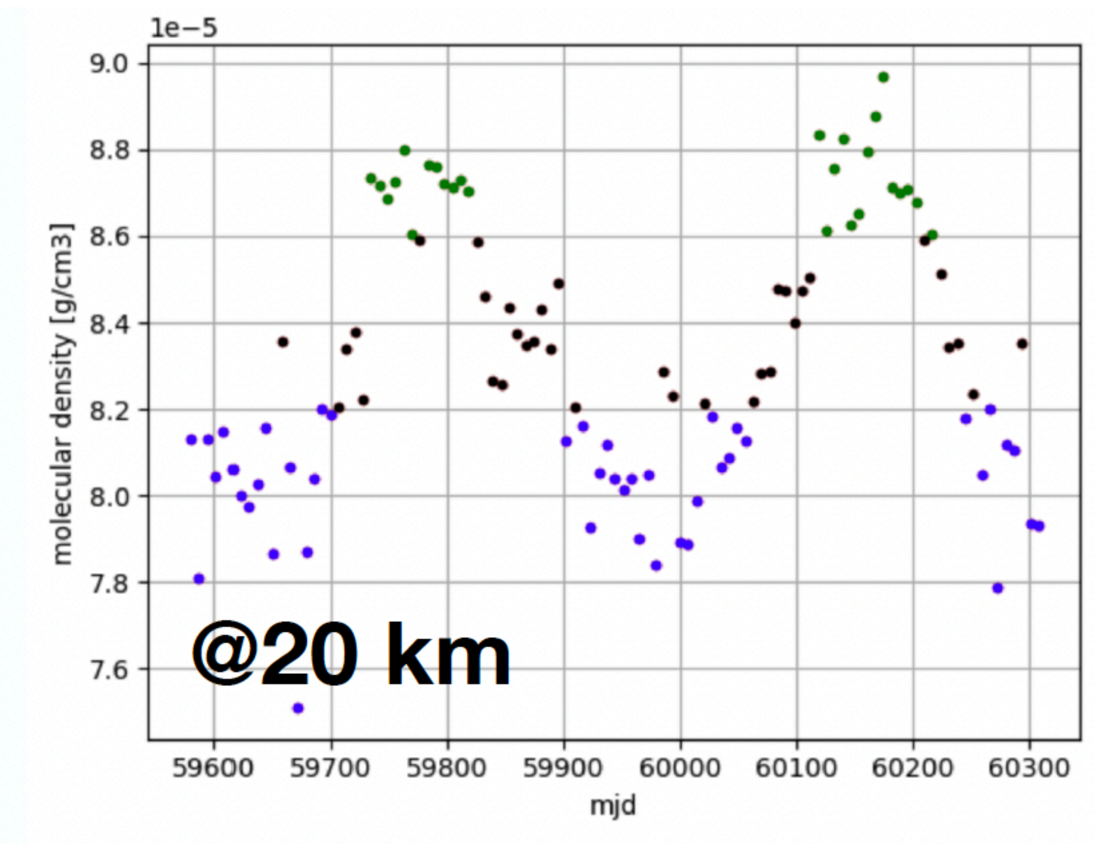


Calibration: The atmosphere

Systematic in energy scale:

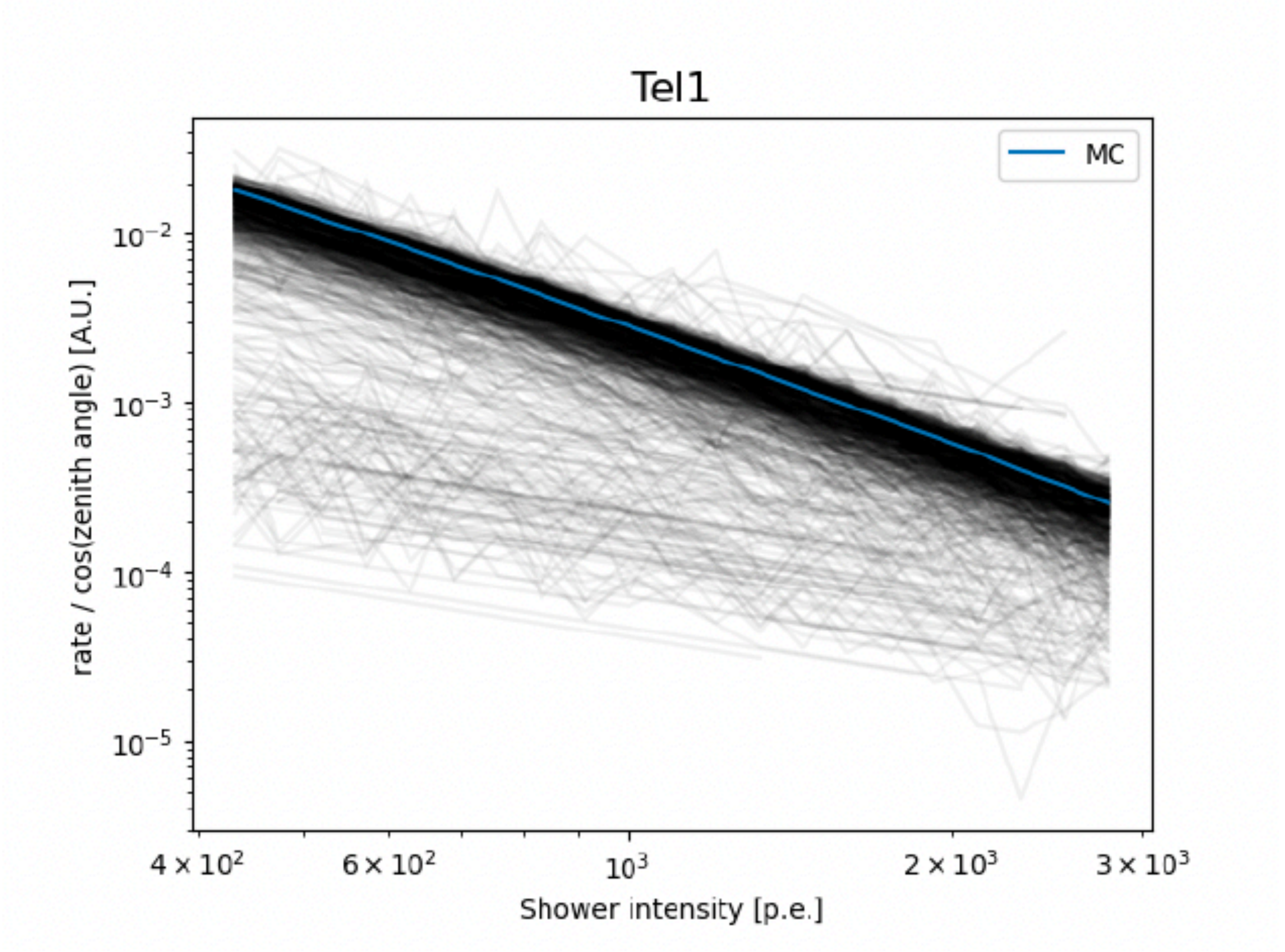
- 0.1 error in VAOD -> 10%
- long term variations -> <5%

- Short-term (aerosols) and long-term component (seasonal changes of molecular profiles)
- Missing calibration leads to systematic in the energy scale
- VAOD estimated from a Sun-Moon photometer 50 km away from the observatory - ranges from 0.05-0.4
- Seasonal atm profiles from ECMWF

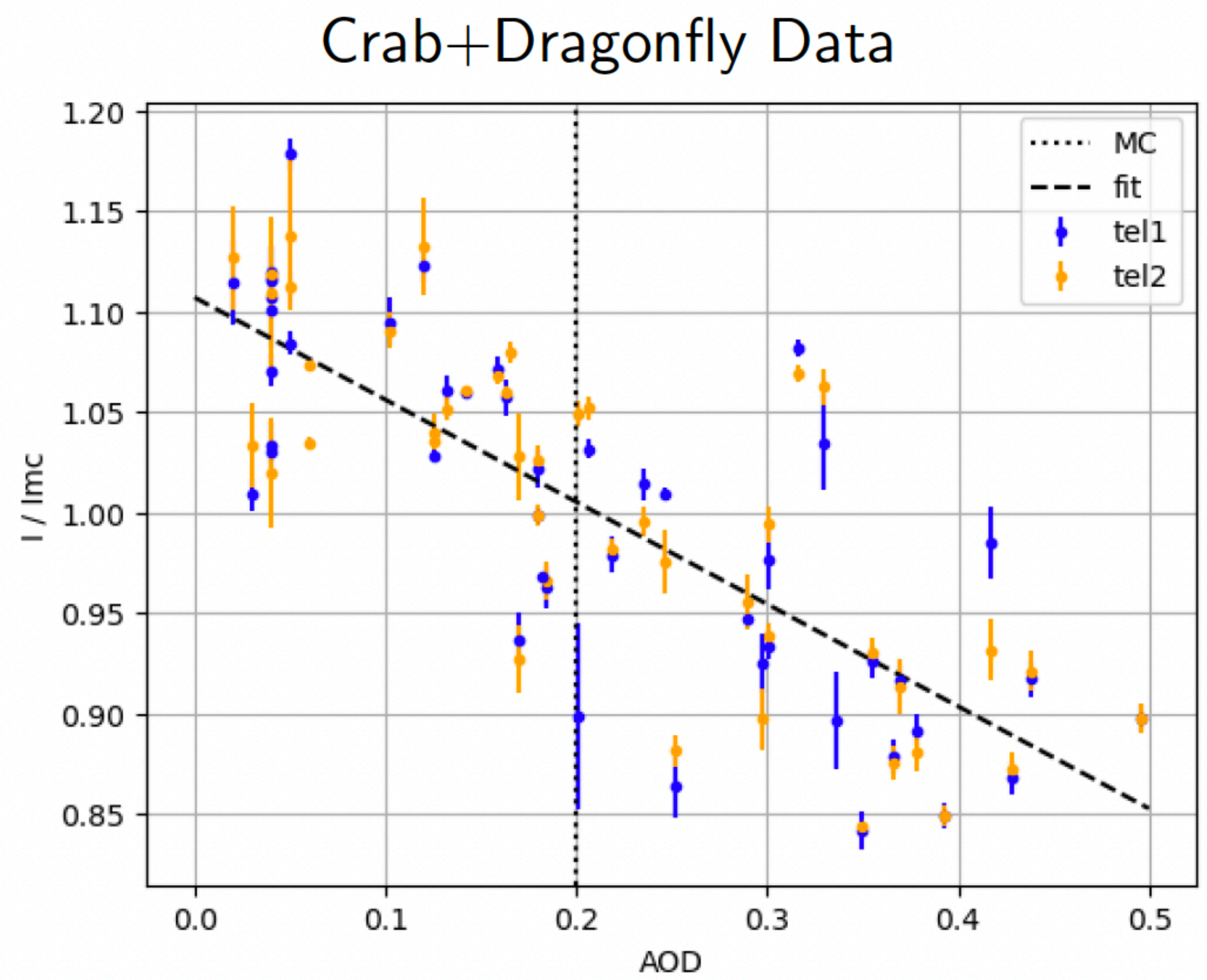


T. Tavernier

Jiri Blazek



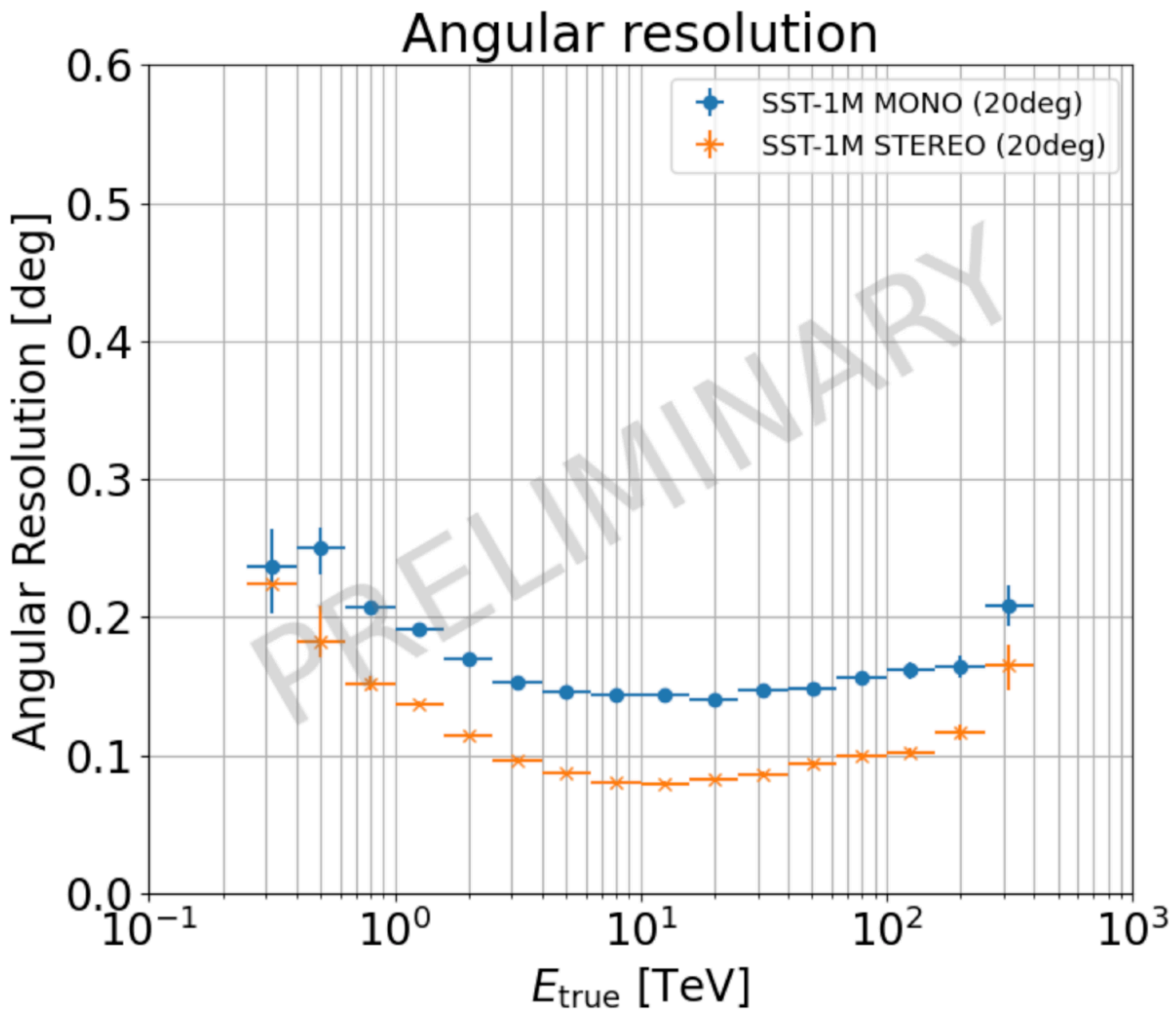
- **Proton rates** far from the intensity threshold (corrected from opt throughput) tells us about atmospheric transparency
- **VAOD scales the shower integrated charges wrt to the MC**
- **I/Imc correlates well with the VAOD**
- => we can believe that the "50km away VAOD is about right"
- => We can probably correct for the atmospheric effect just by scaling the integrated charge



SST1-M physics performance

Energy and angular resolution

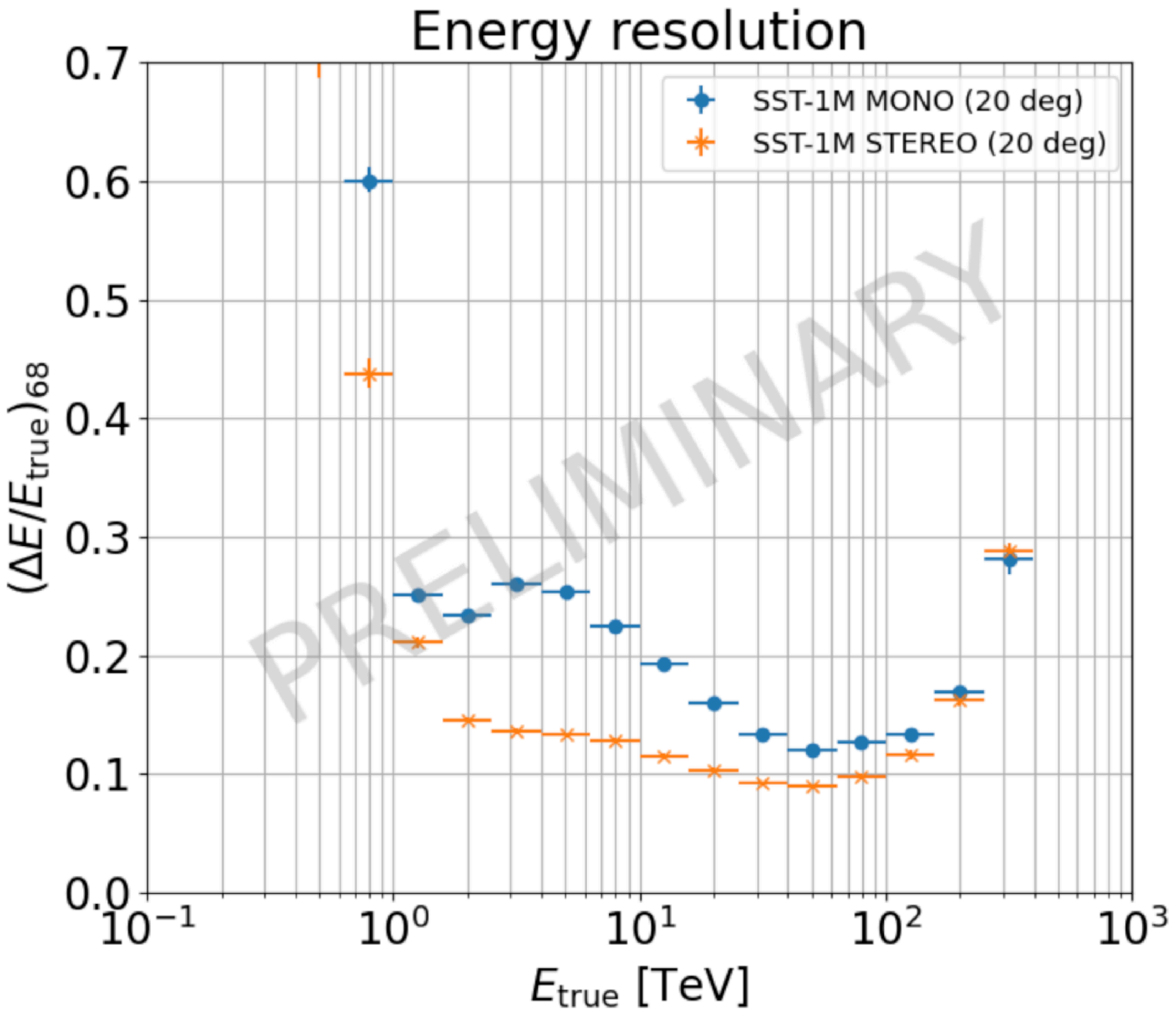
- Difficult conditions in Ondrejov - low altitude and high NSB both increase the energy threshold (~1 TeV@20 deg zenith angle)
- Angular and energy resolution sufficient for physics cases despite that

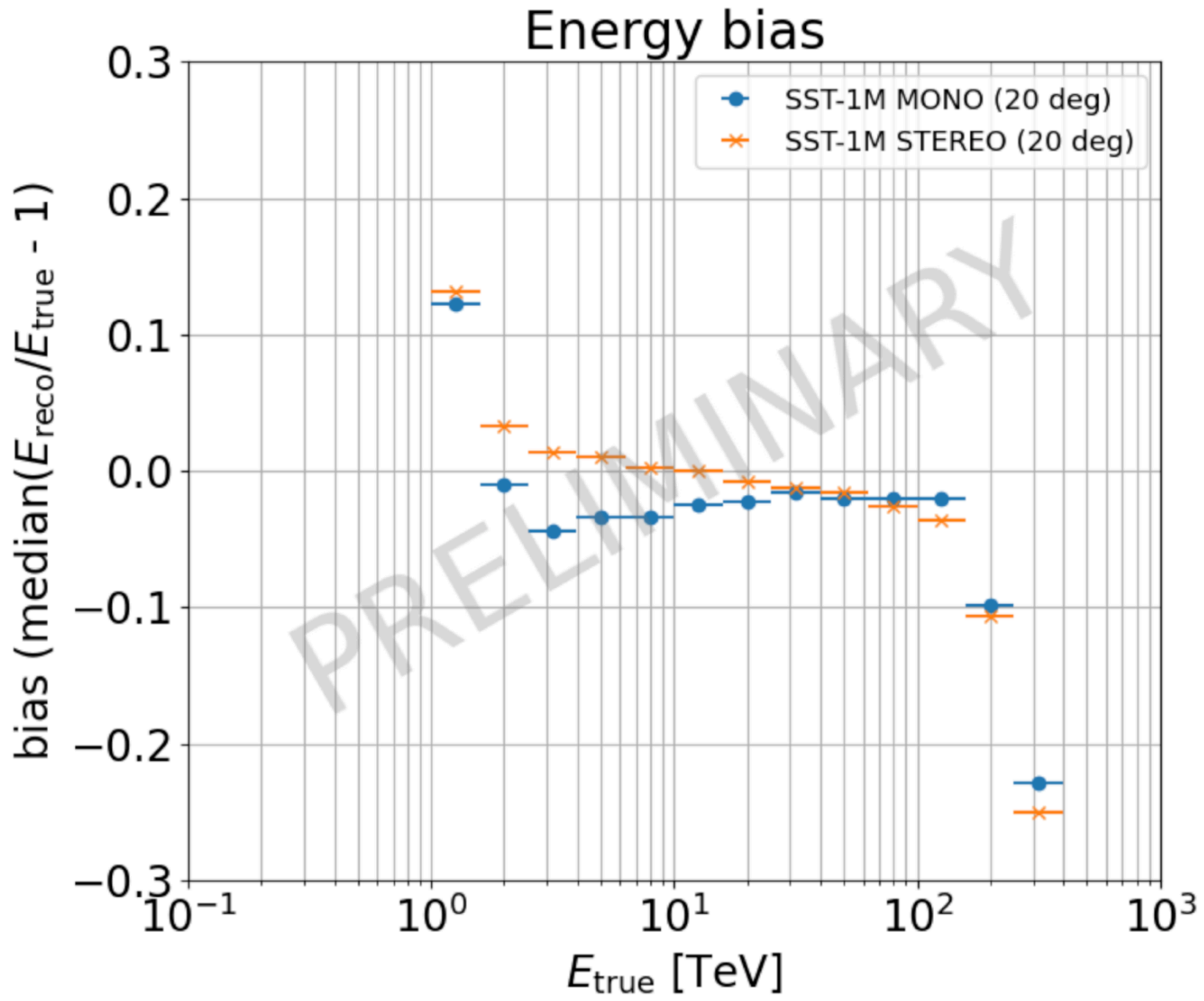


Monte Carlo

- **Angular resolution:**
  - 0.15 deg (mono)
  - 0.10 deg (stereo)

- **Energy resolution:**
  - 15-25% (mono)
  - 10-15% (stereo)





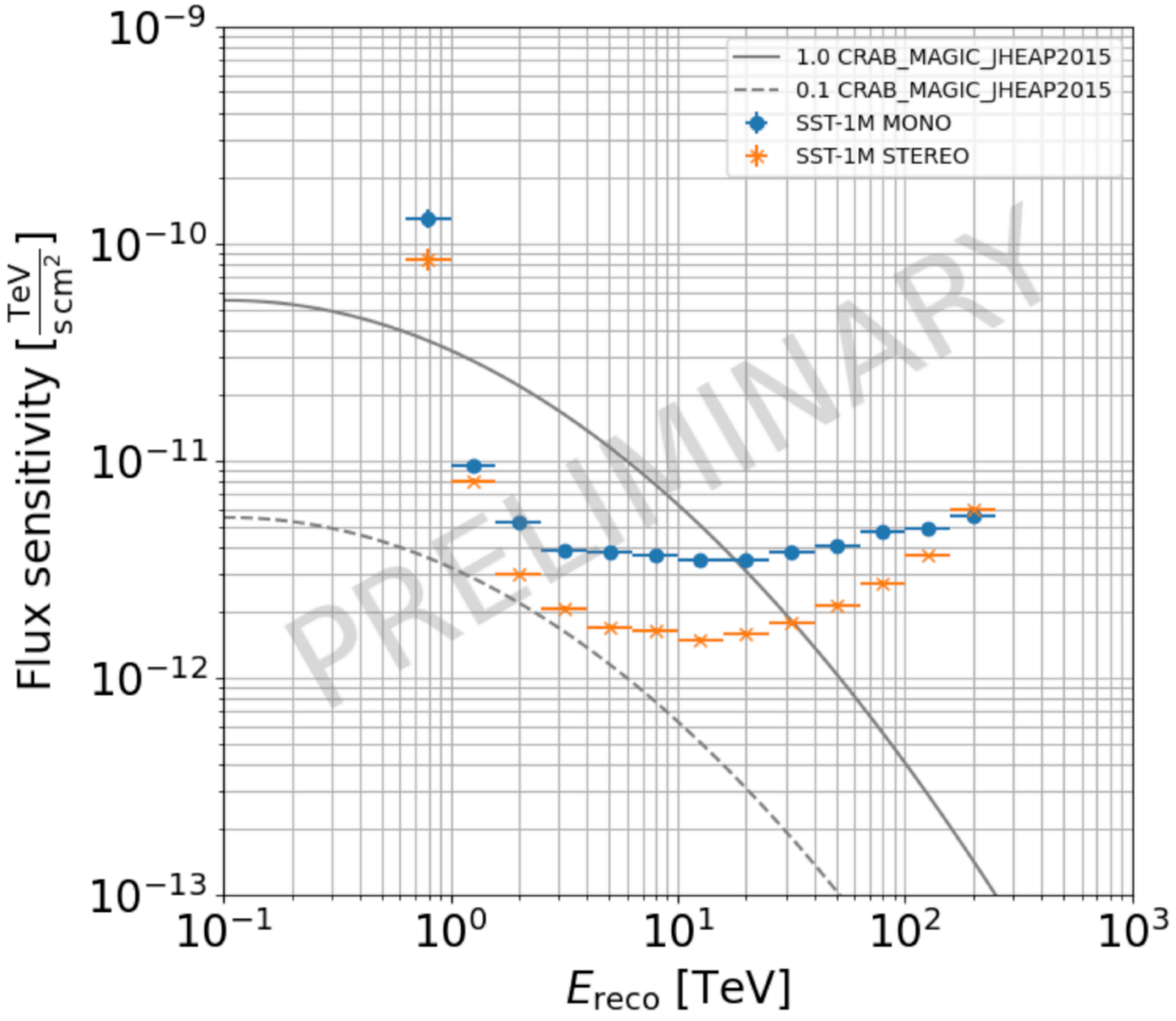
SST1-M physics performance

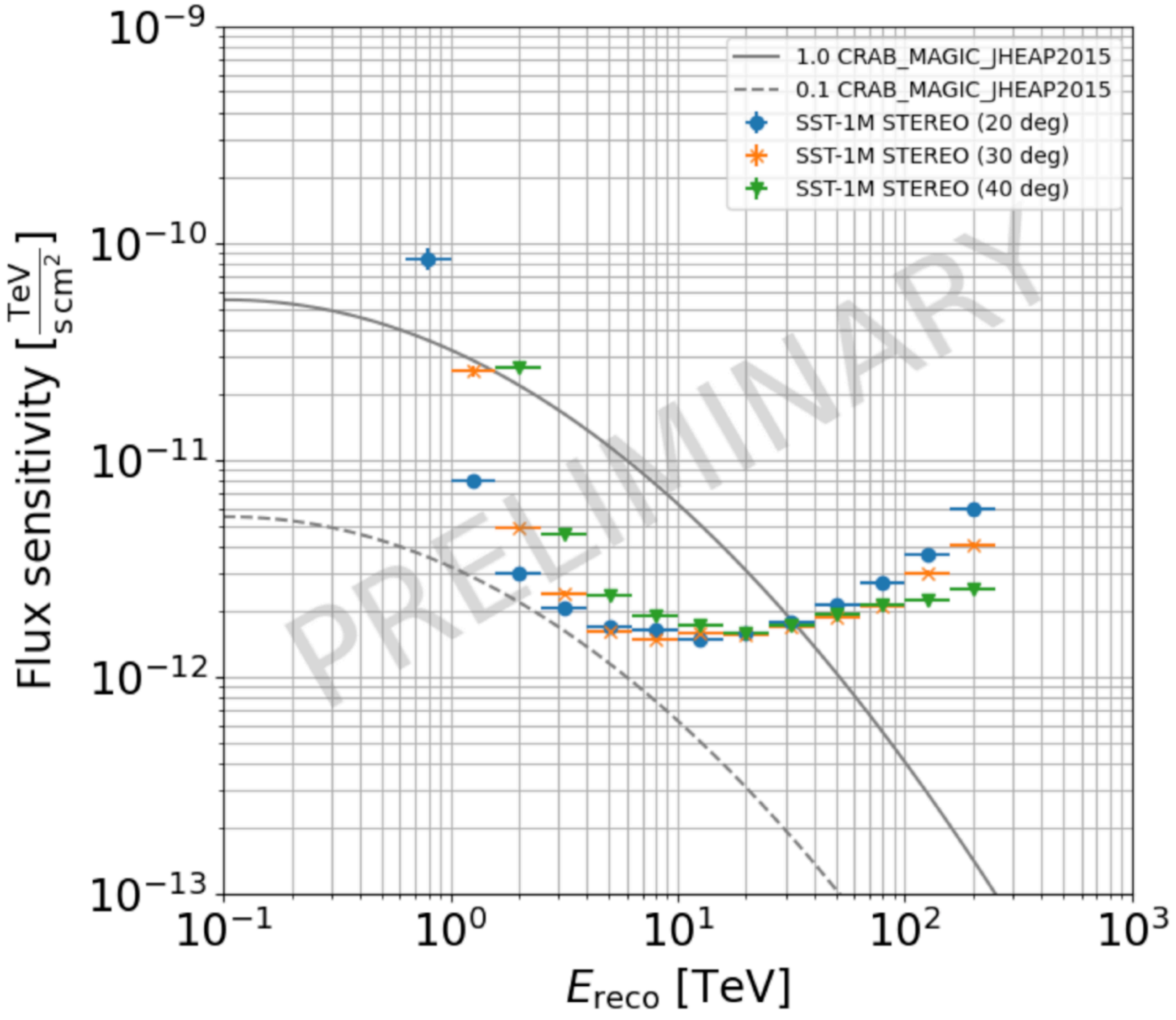
Differential sensitivity

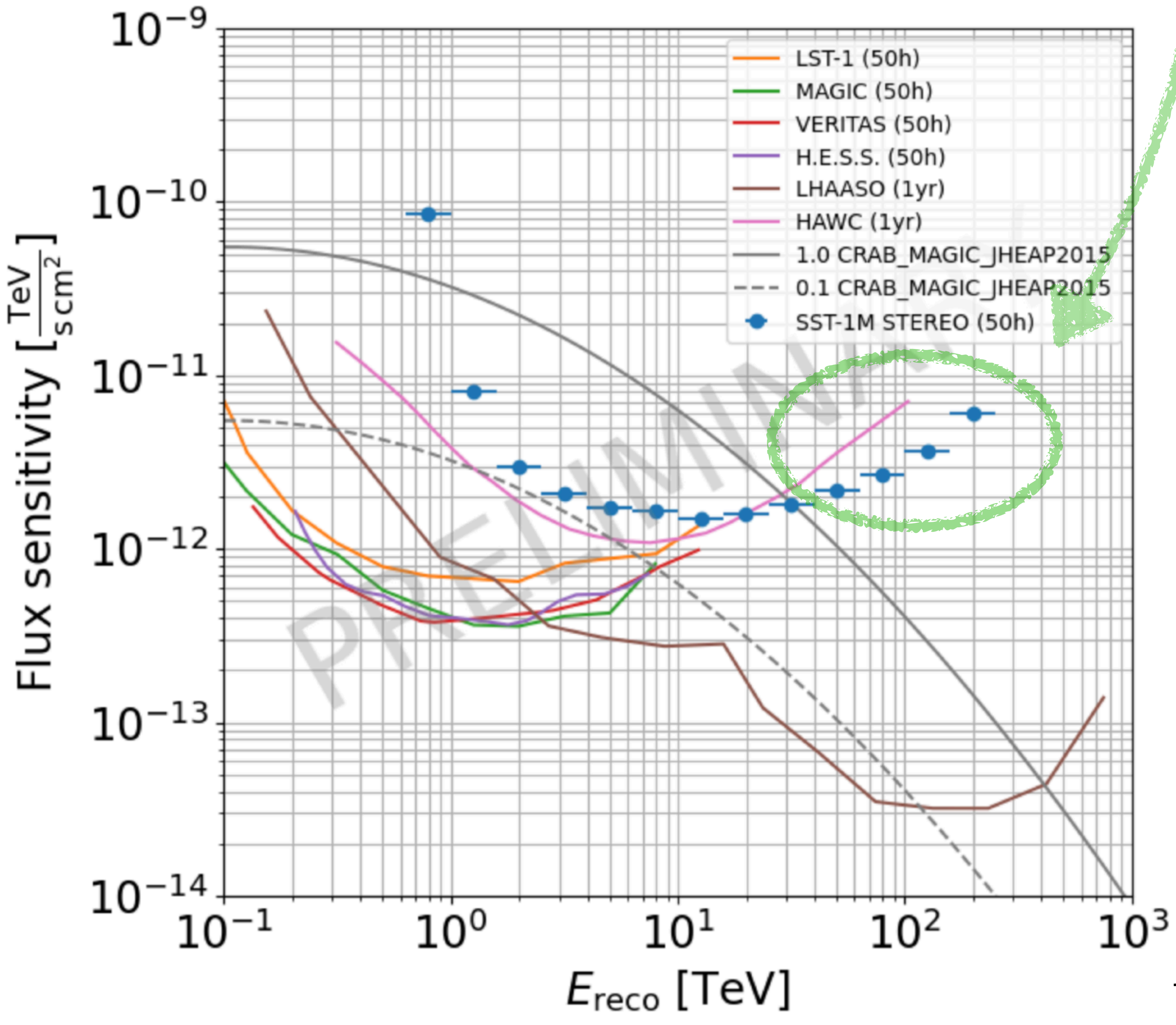
Monte Carlo

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!



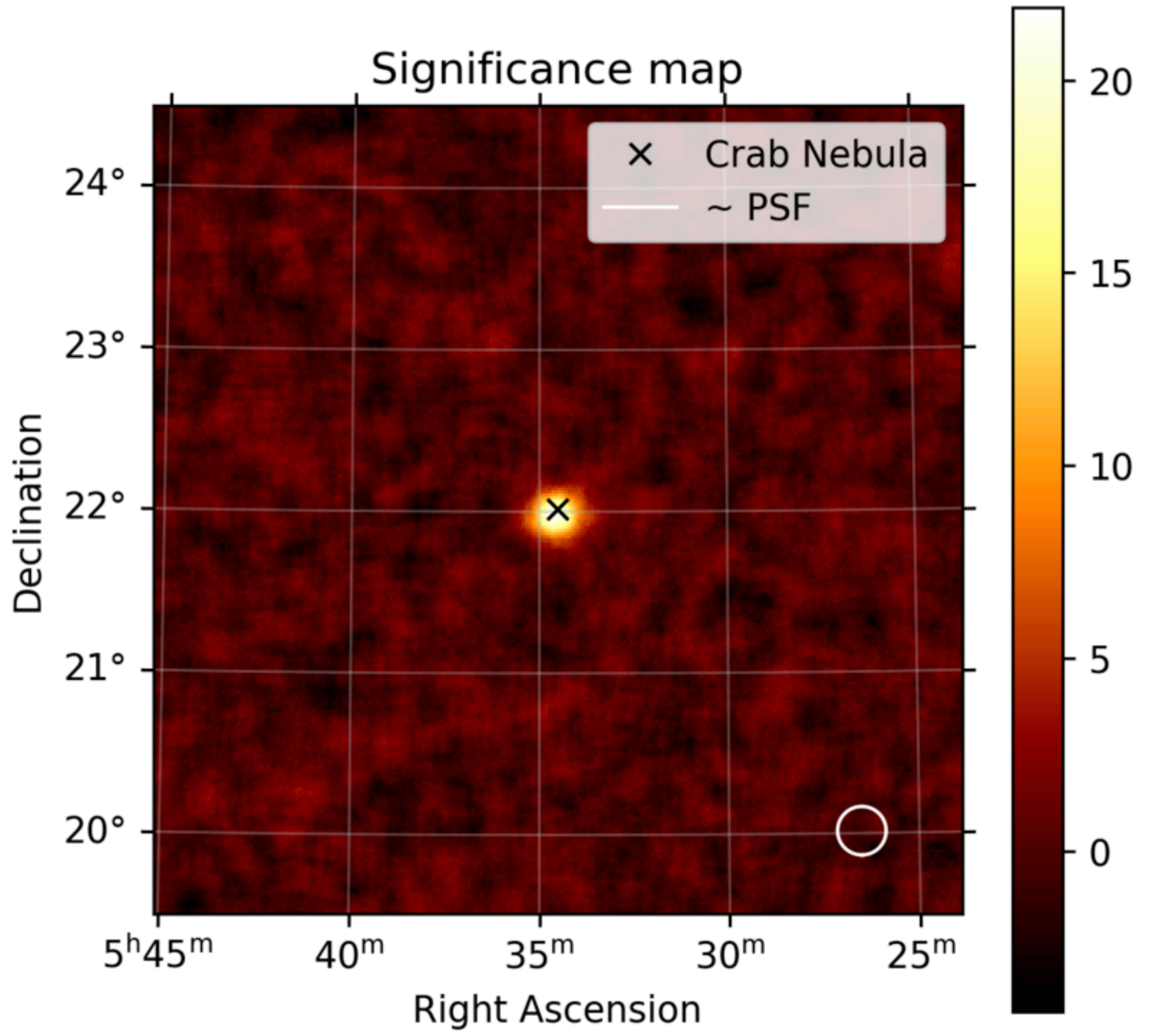


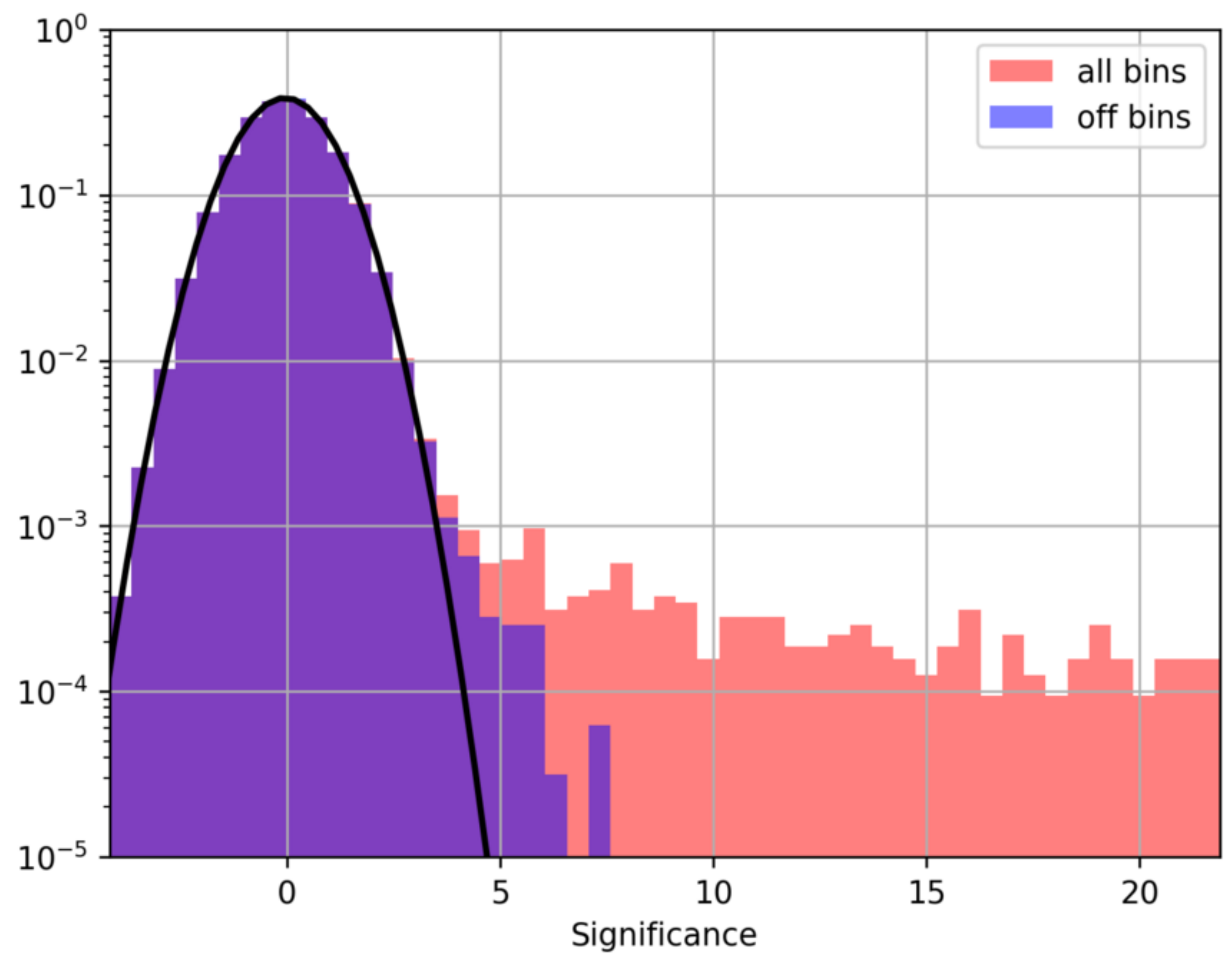


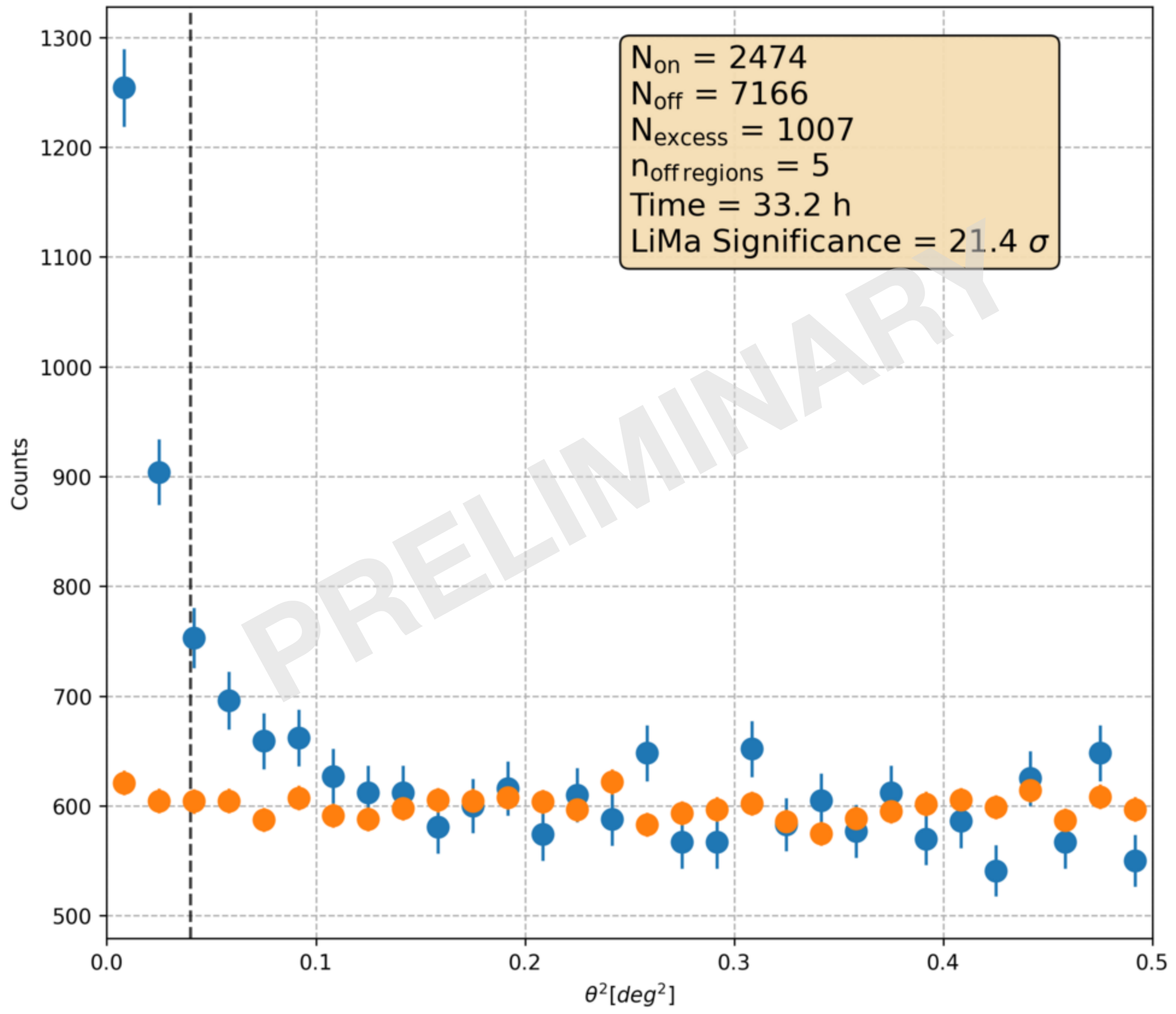
Crab Nebula observation - MONO

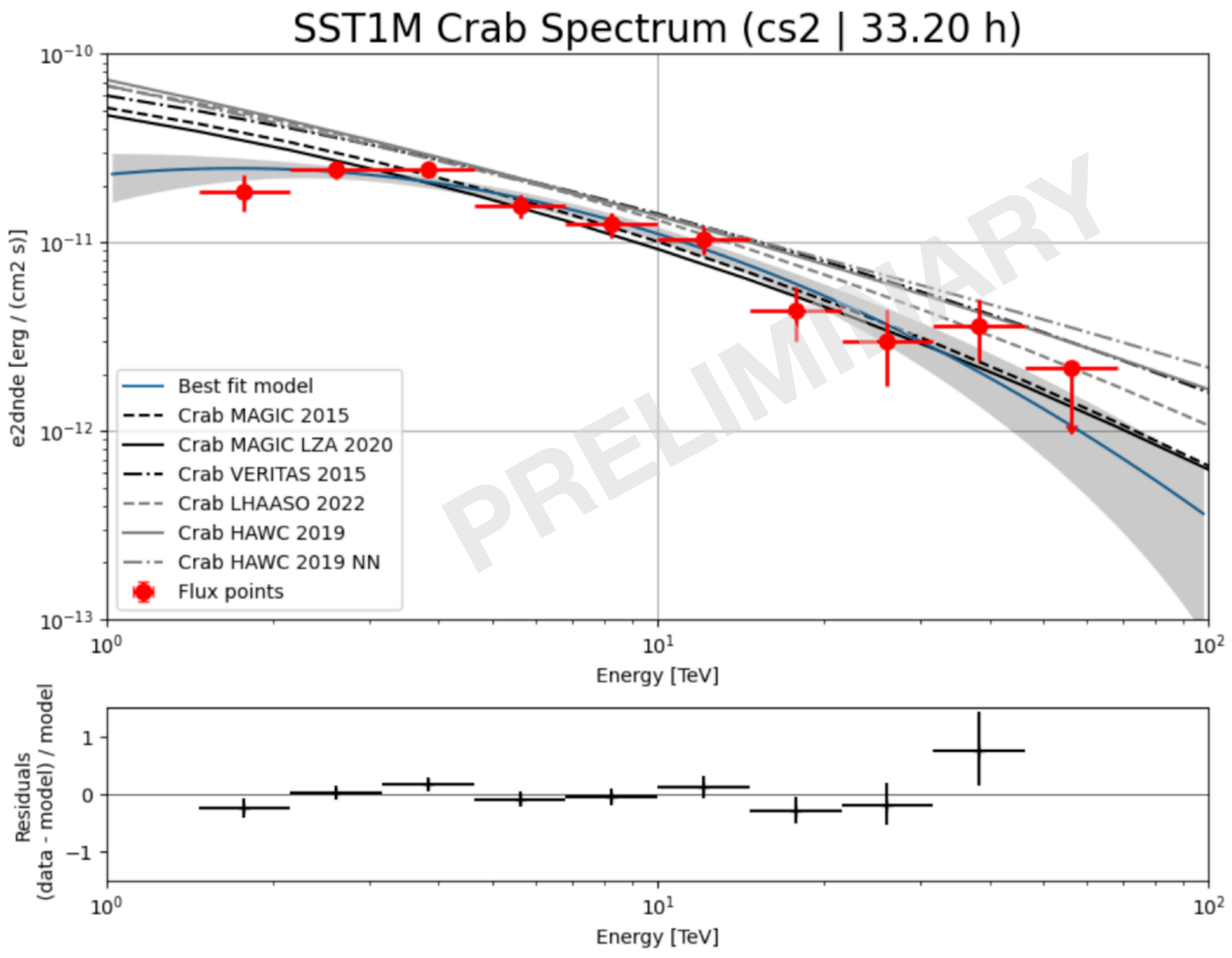
Real data

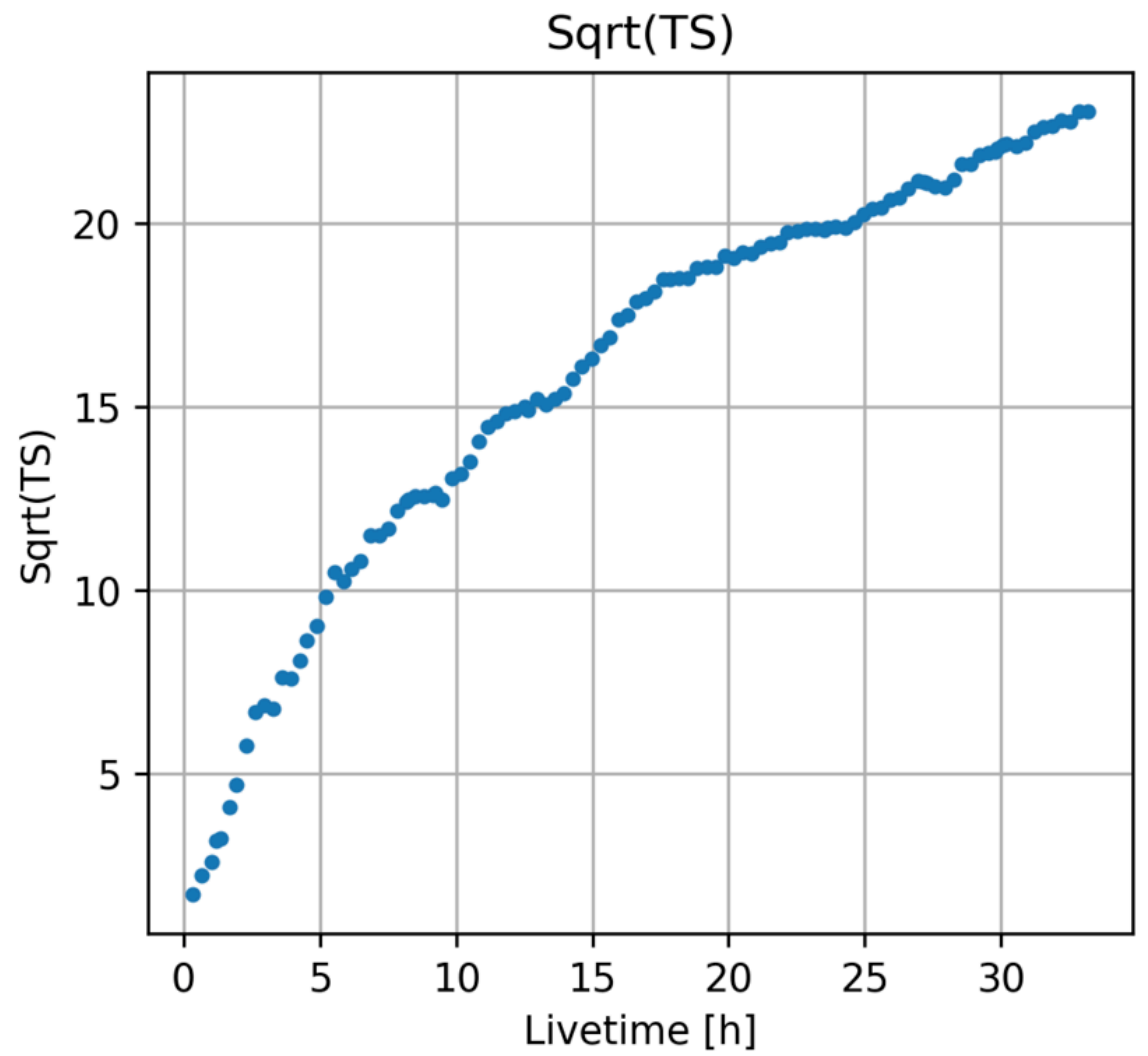
- Obs campaign 2023-2024, zenith angle 25-45 deg, energy threshold ~2-3 TeV
- ~33 hours of good mono data after quality cuts, **5sigma detection in ~2.5h**
- **Excellent agreement** of the SED with the results of other experiments (**note the tension** between different observatories)









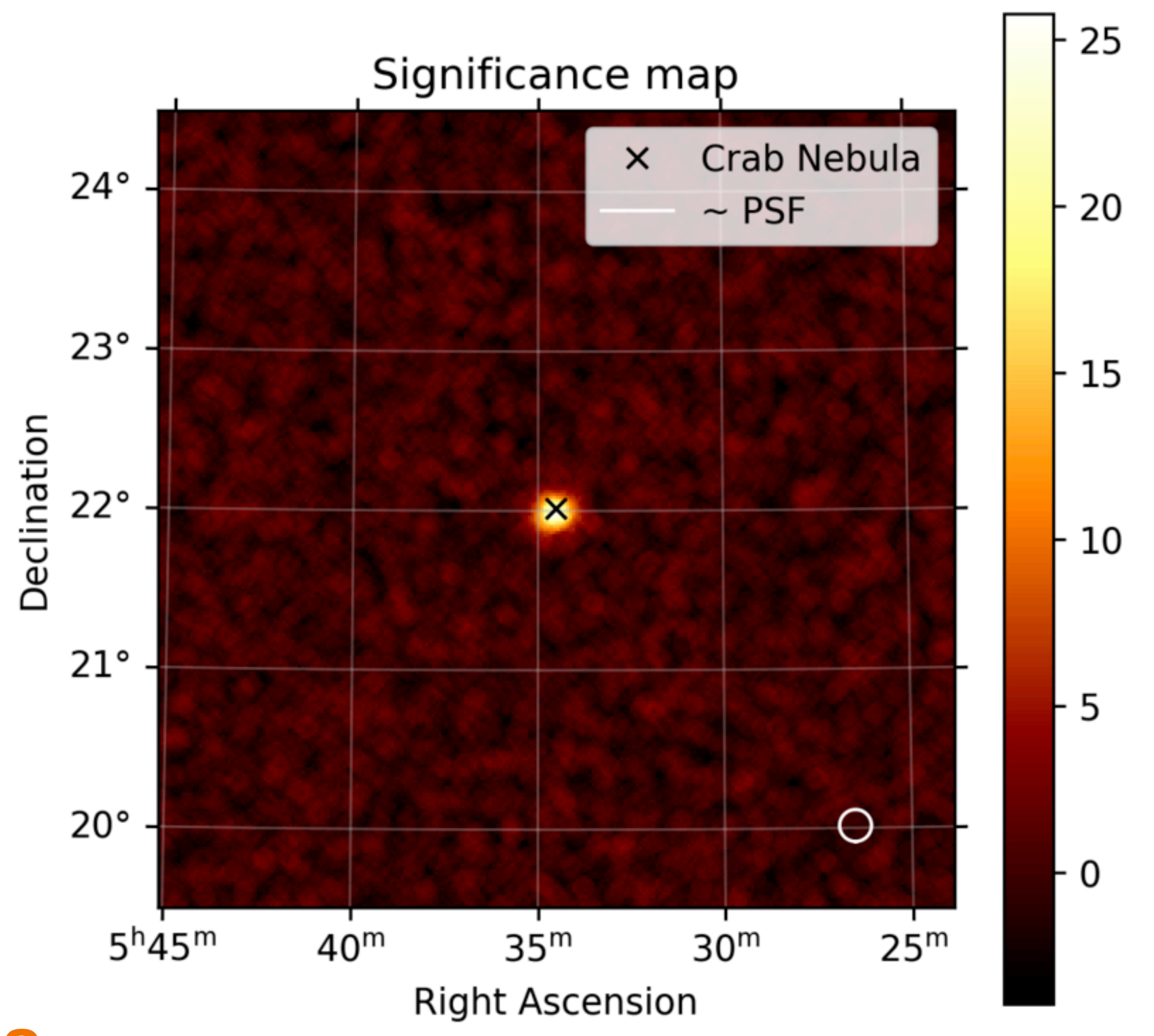


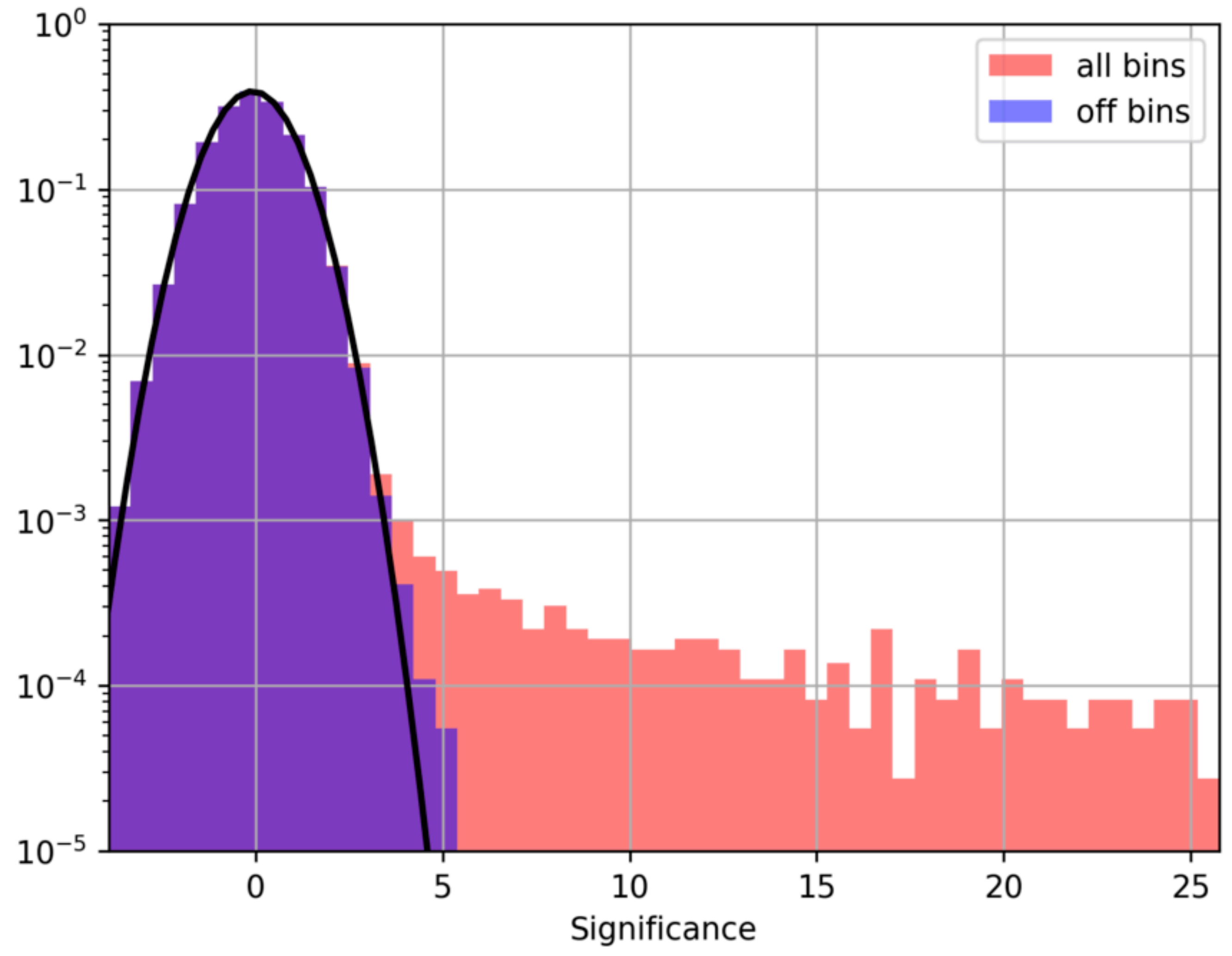
Crab Nebula observation - STEREO

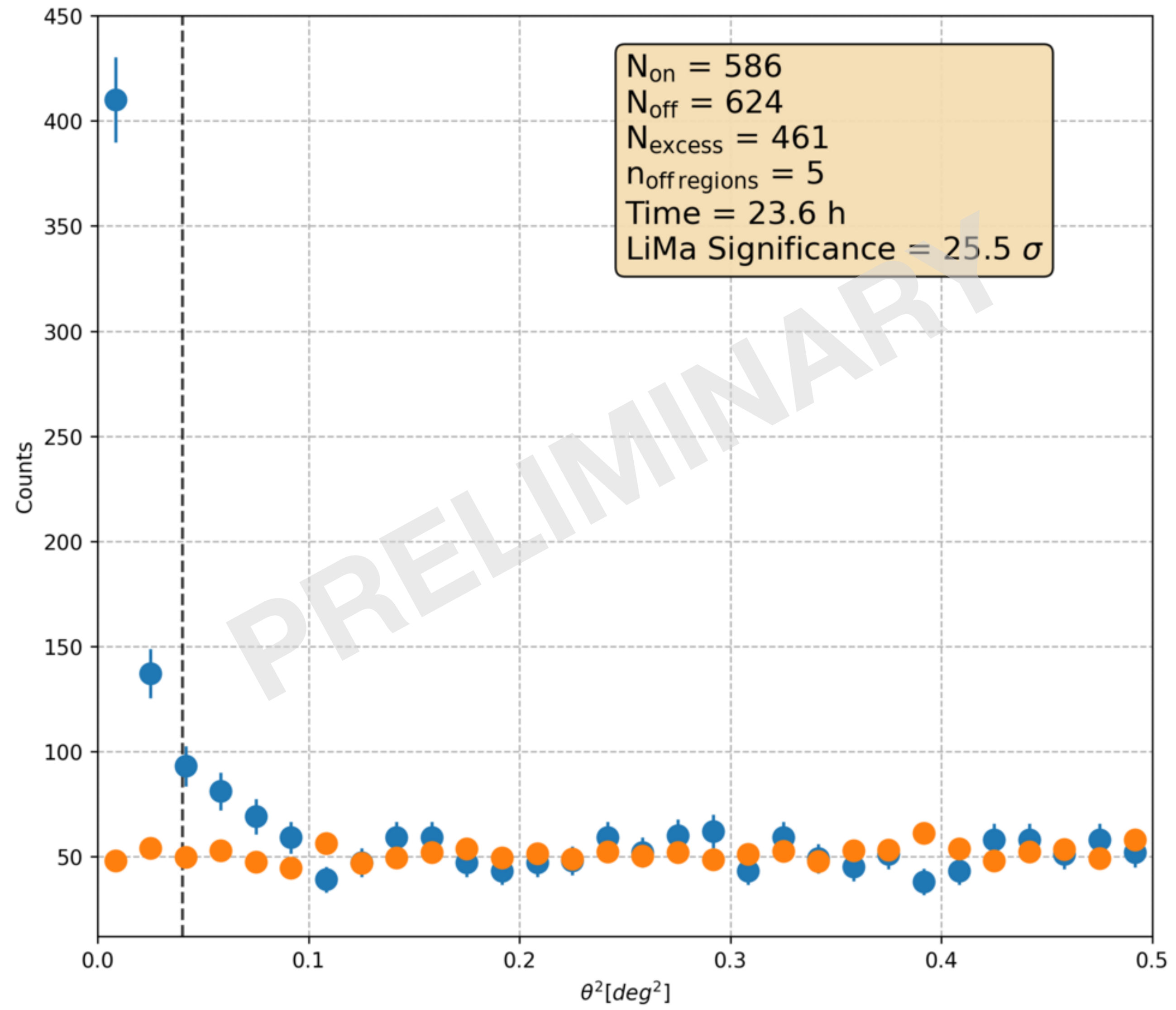
Real data

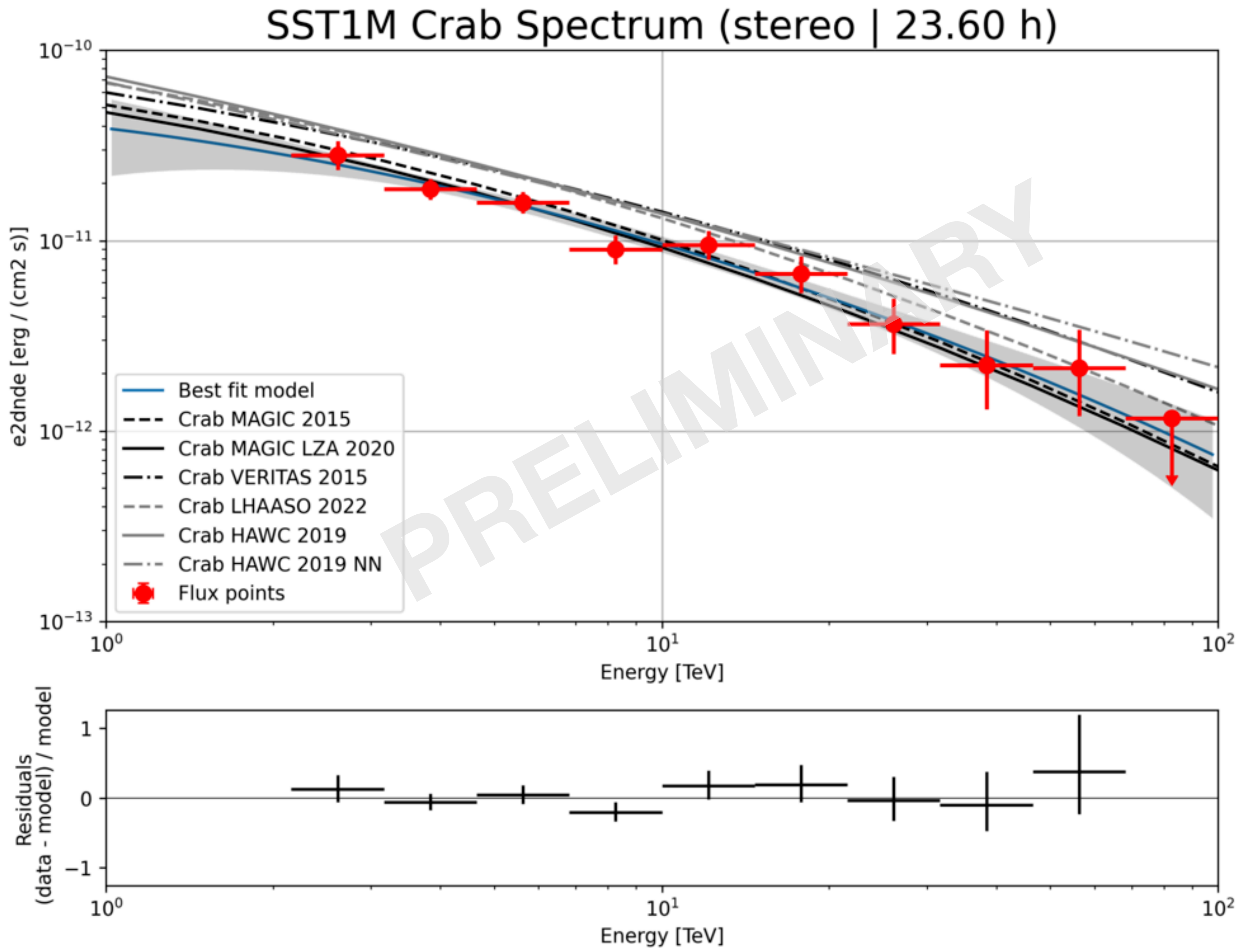
- Higher energy threshold due to not fully optimised distance between the telescopes
- ~23h of good stereo data after quality cuts, **5sigma detection in ~1.5h**
- Expected performance improvement - angular resolution and sensitivity
- **Remarkable background homogeneity on a scale of a few degrees**

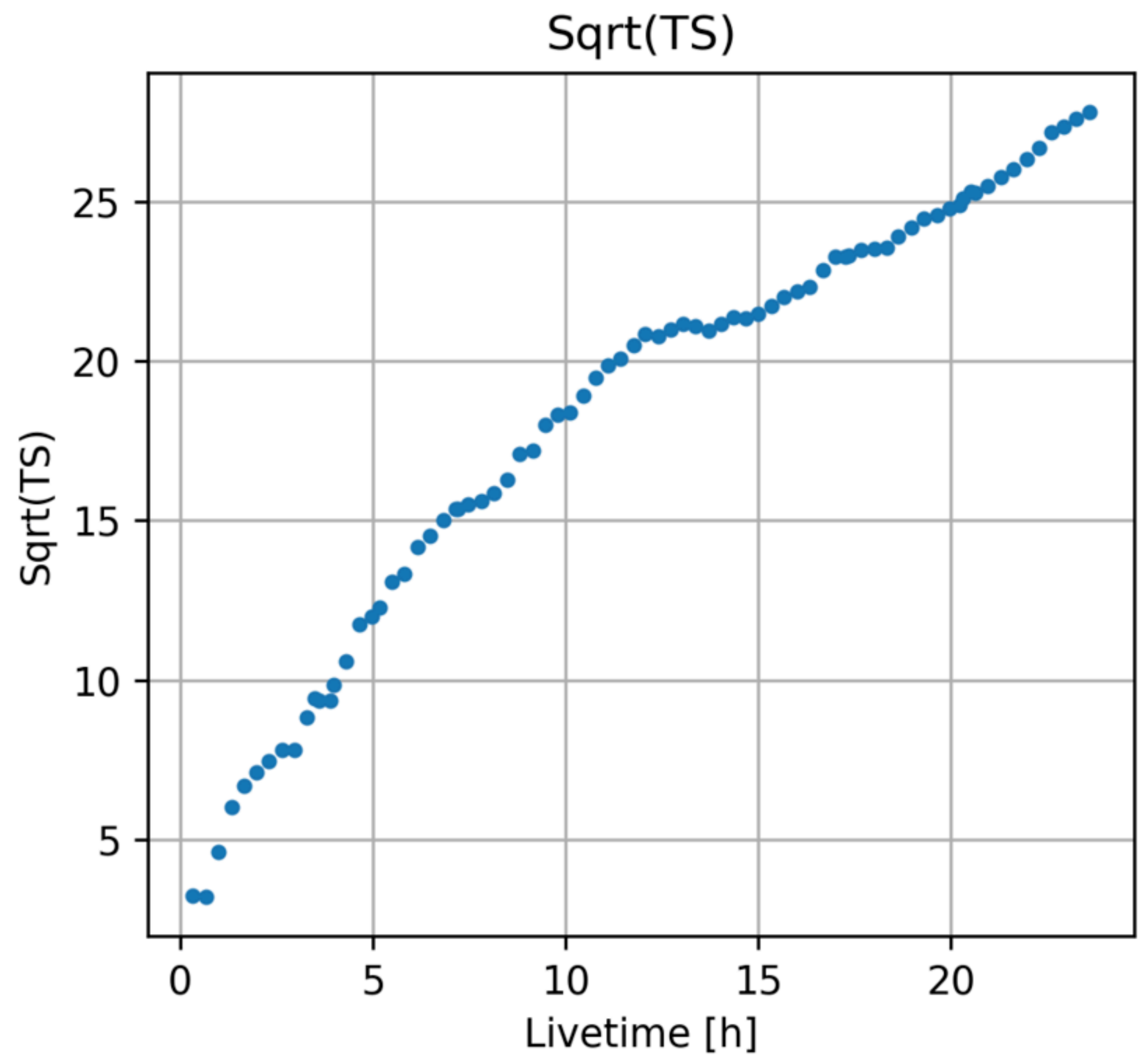
Excellent instrument for observation of extended sources









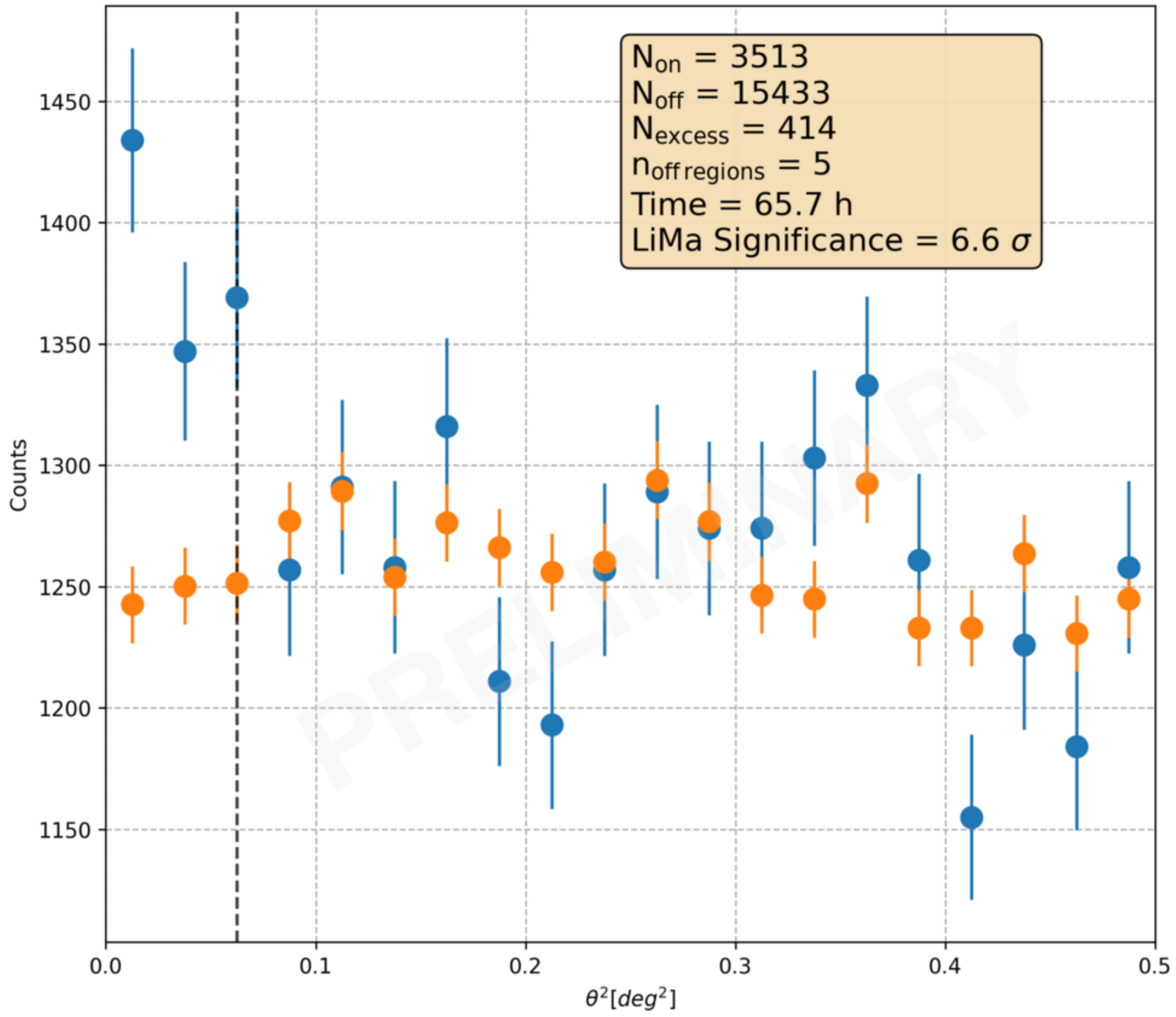


Nearby AGN monitoring

Observation campaign of several bright blazars

Real data

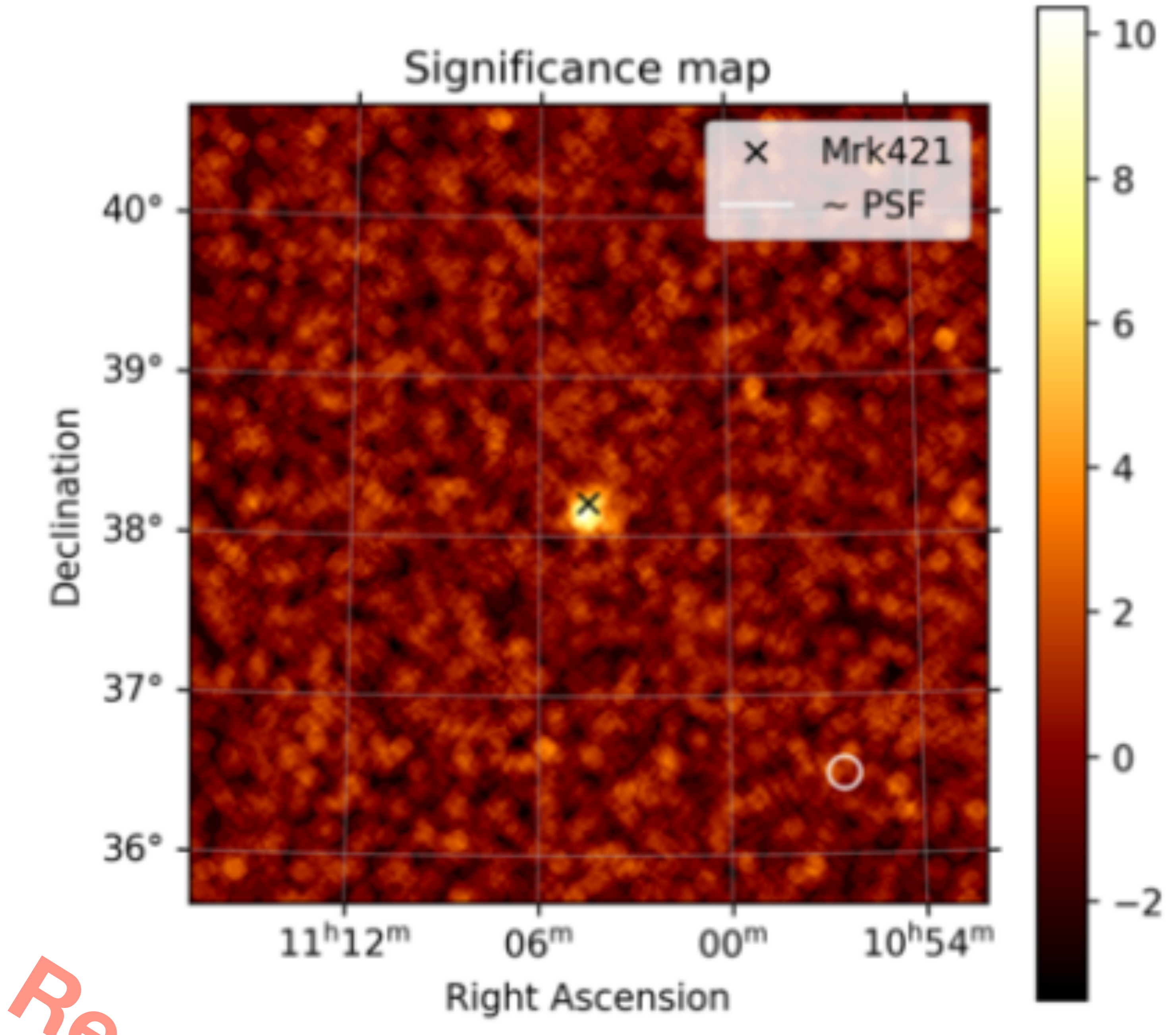
- **1ES1959+650** - first extragalactic source detected with SST-1M (Summer 2023)
- Maintenance of Tel2 camera - Tel1 **mono** only
- Long period of low activity, 5sigma detection in ~20h
- Preliminary analysis using proto-pipeline. No spectral analysis, but **proving SST-1M capabilities for AGN monitoring**



Nearby AGN monitoring

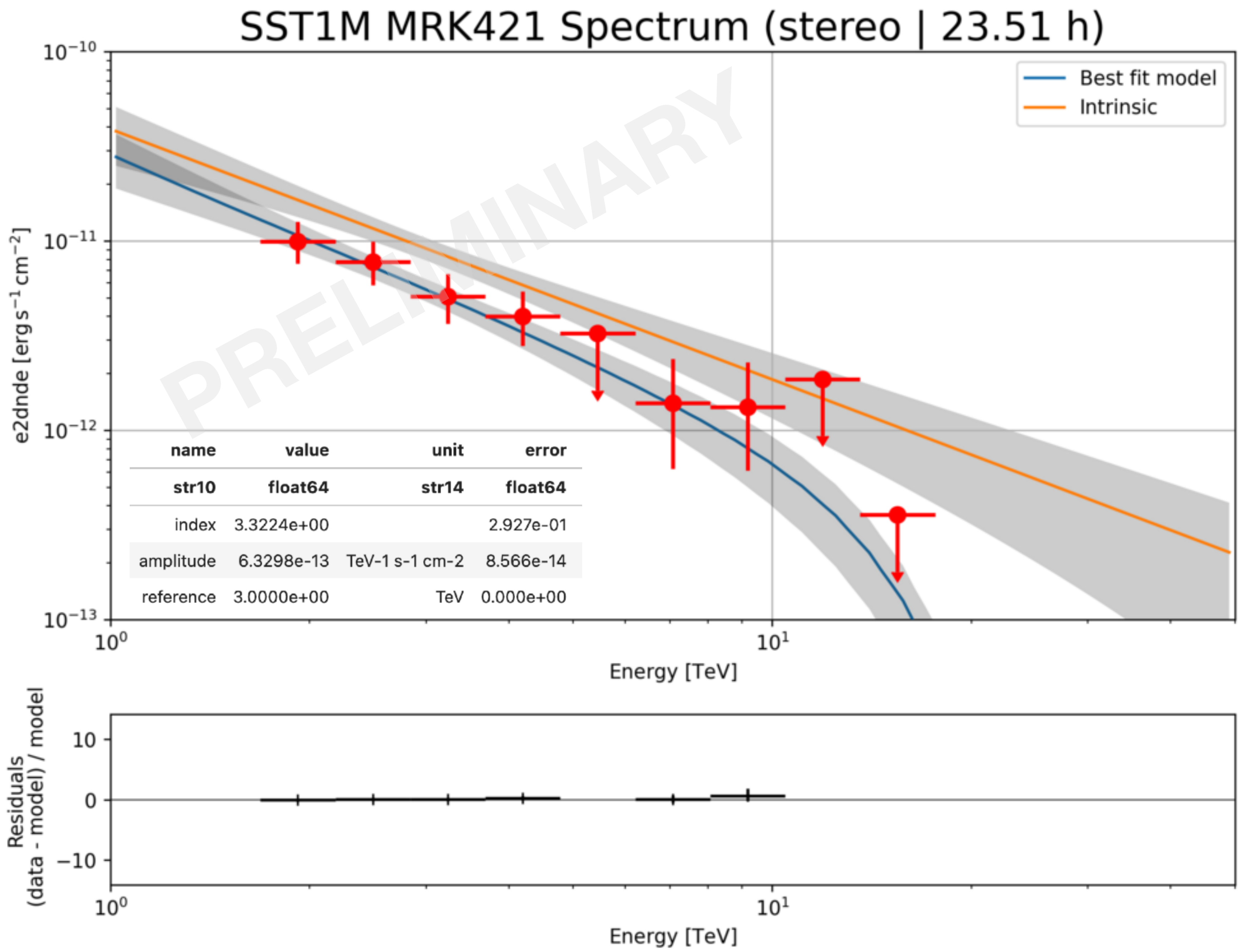
Observation campaign of several bright blazars

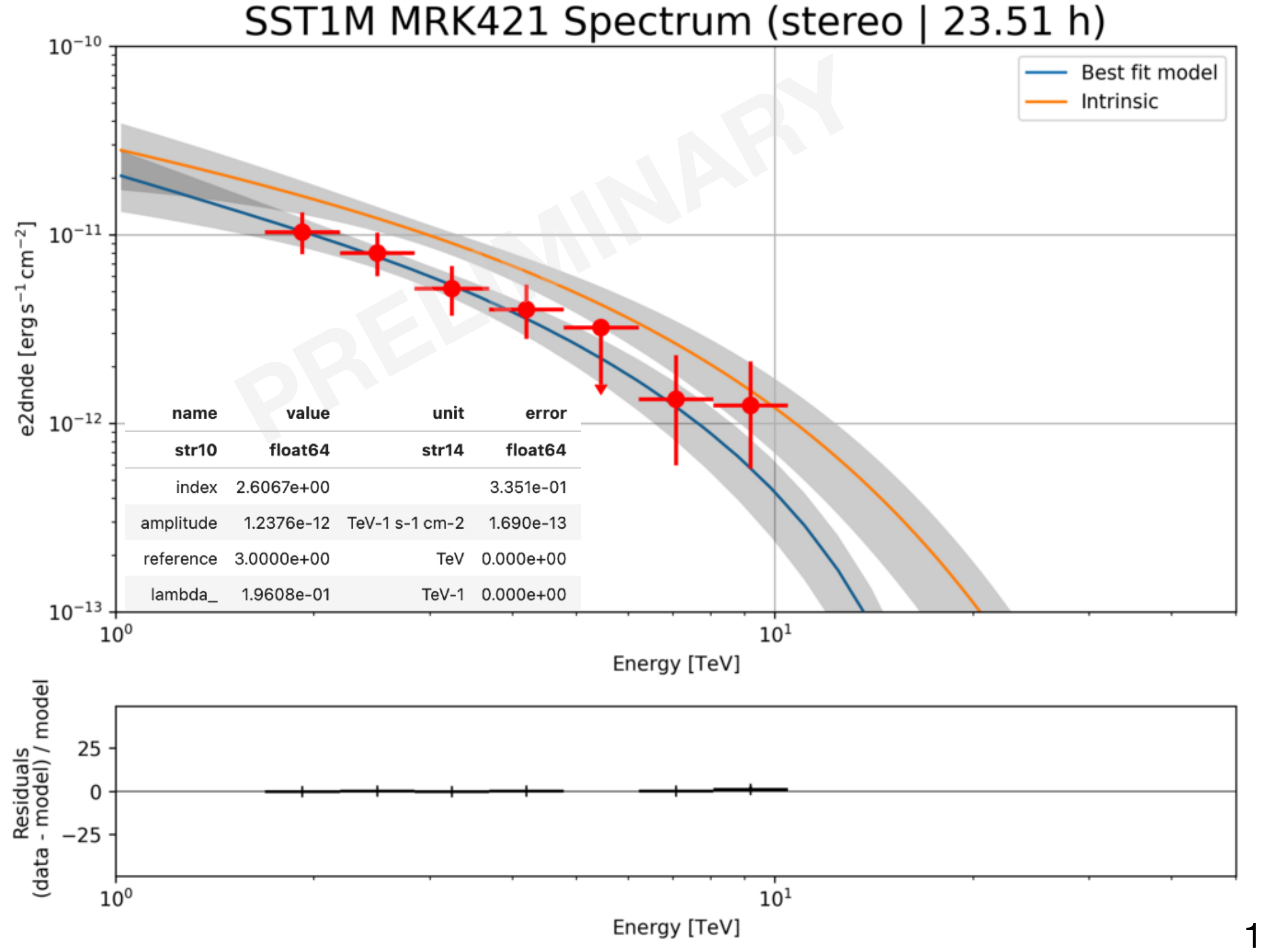
- **Mrk 421** - first extragalactic source detected in **stereo** mode (Spring 2024)
- High state detected on 15 March 2024: ATel #16533



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

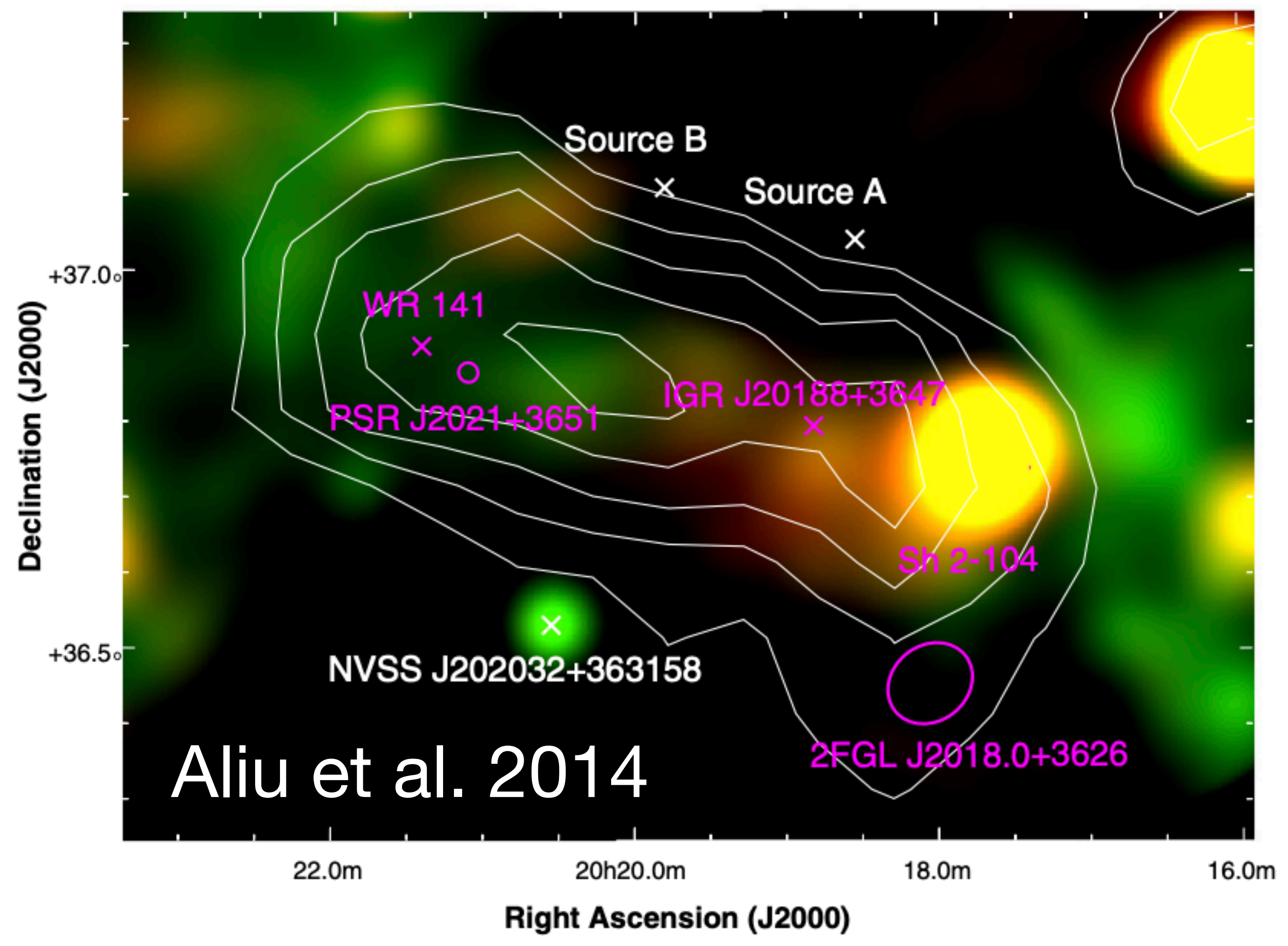
- Discovered by MILAGRO (Abdo et al. 2009)
- Later resolved into 2-3 sources by VERITAS (Abeysekhara et al. 2014, 2018)
- Photons up to 0.27 PeV (LHAASO 2021)
- Slightly extended: ~0.5 deg, highly asymmetric, energy dependent morphology

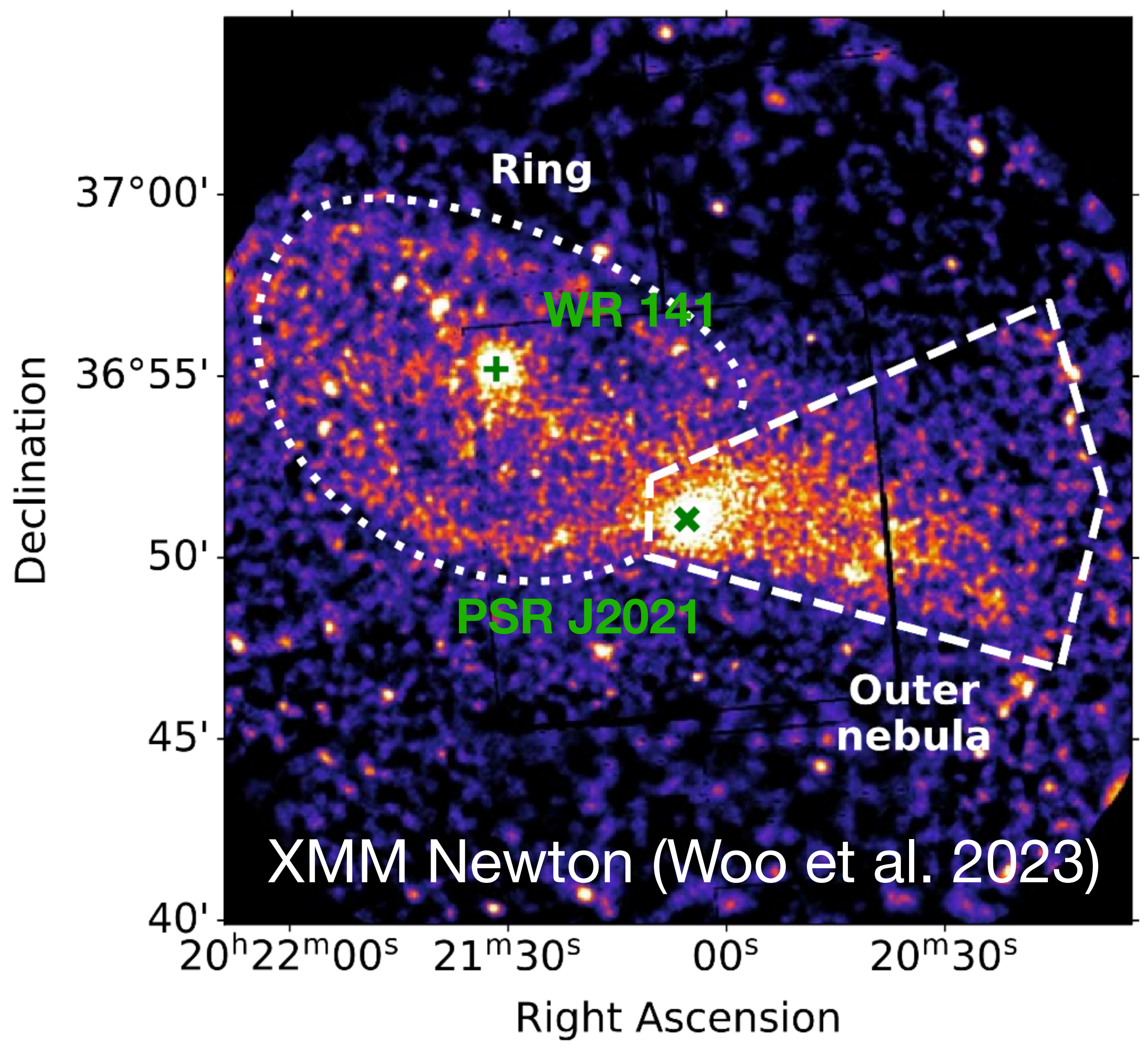
- **Complex region:**
  - Several radio, X-ray, HE and VHE sources
  - Supernova Remnant CTB 87
  - Two pulsars
  - Sh 2-104 - Star forming HII region
  - G75.2+0.1 - PWN
  - IGR J20188 - fast X-ray transient
  - Wolf-Rayet star WR 141

- **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



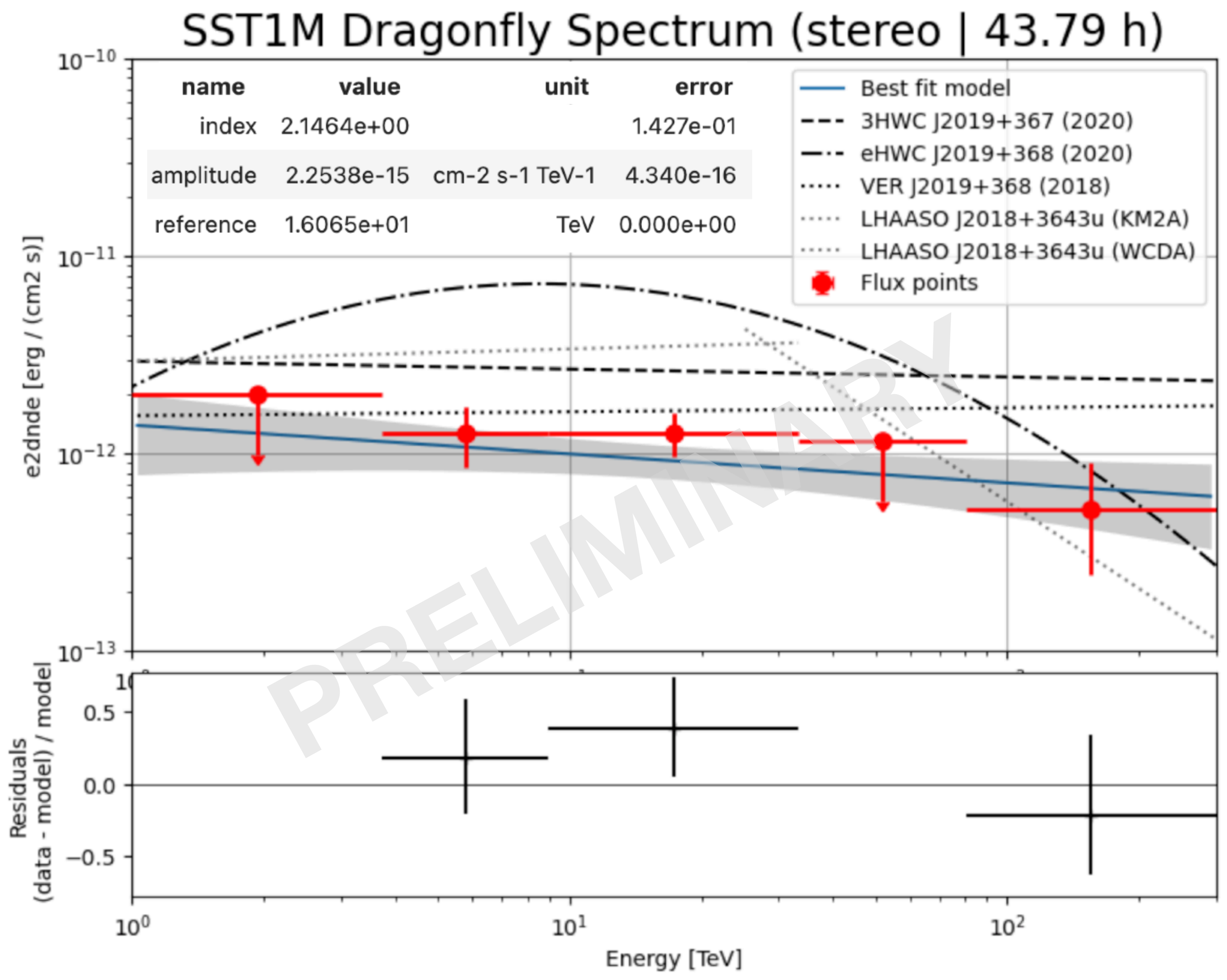


Real data

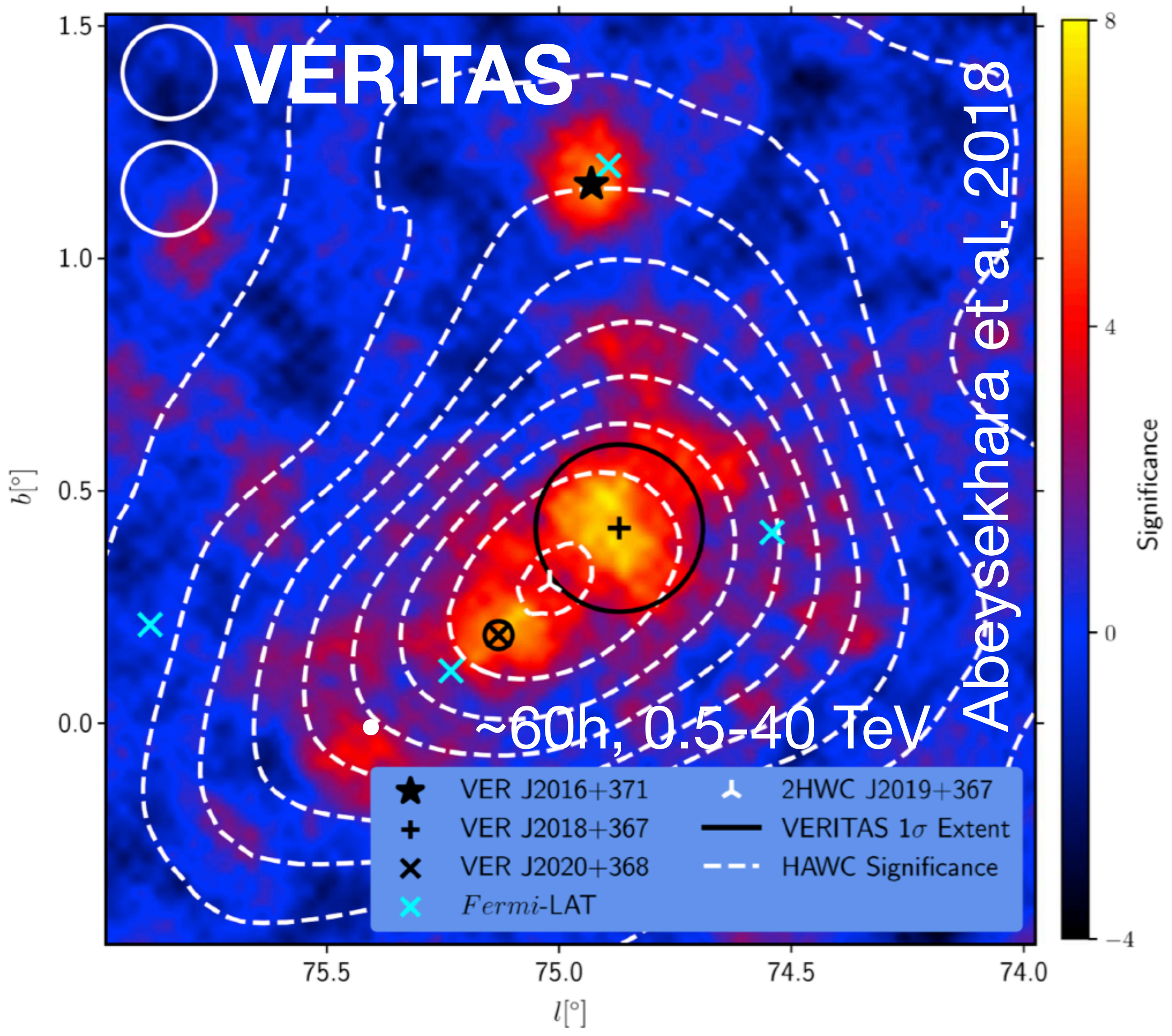
VER 2019+368 (Dragonfly)

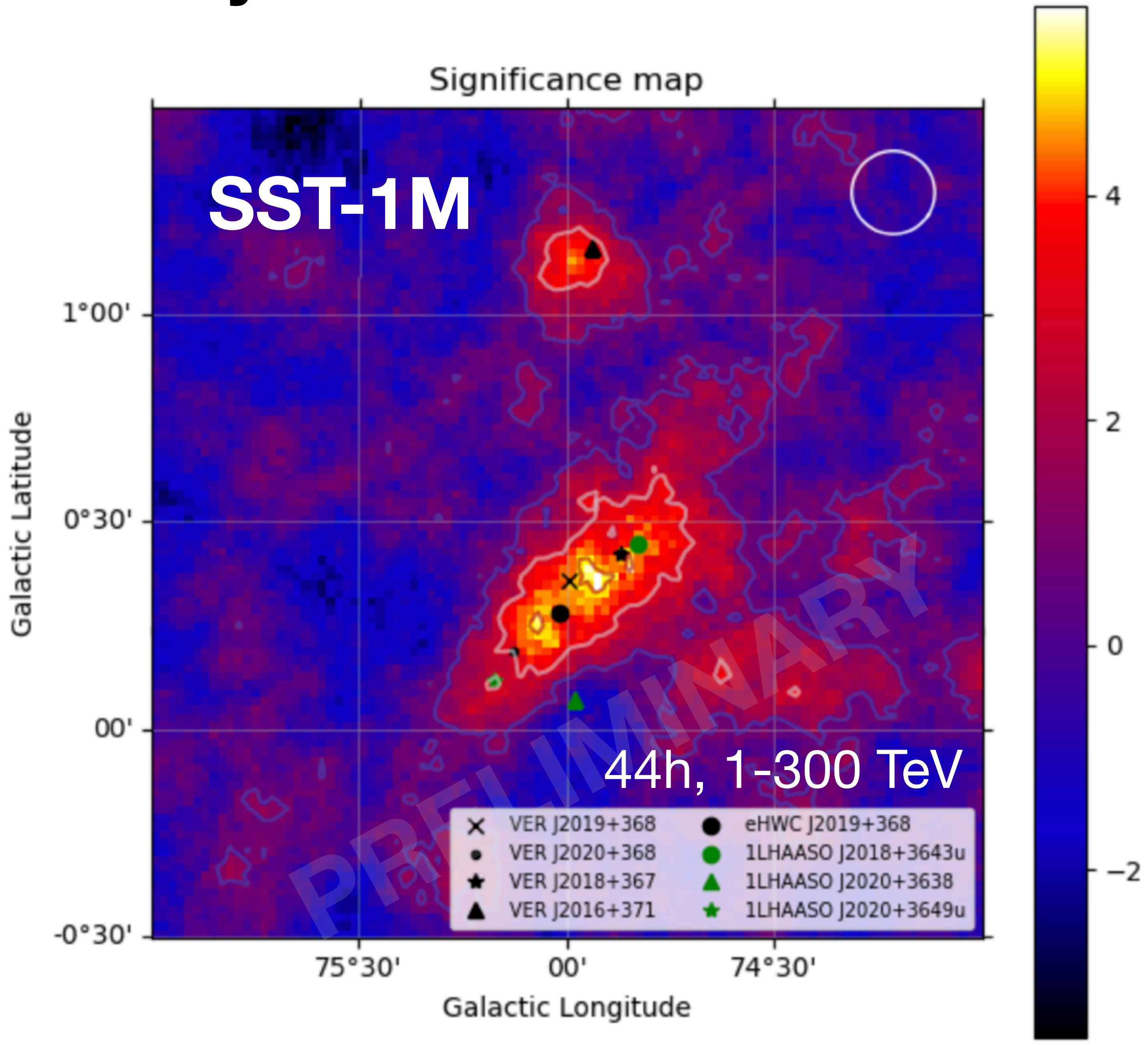
SST-1M enters the realm of extended sources

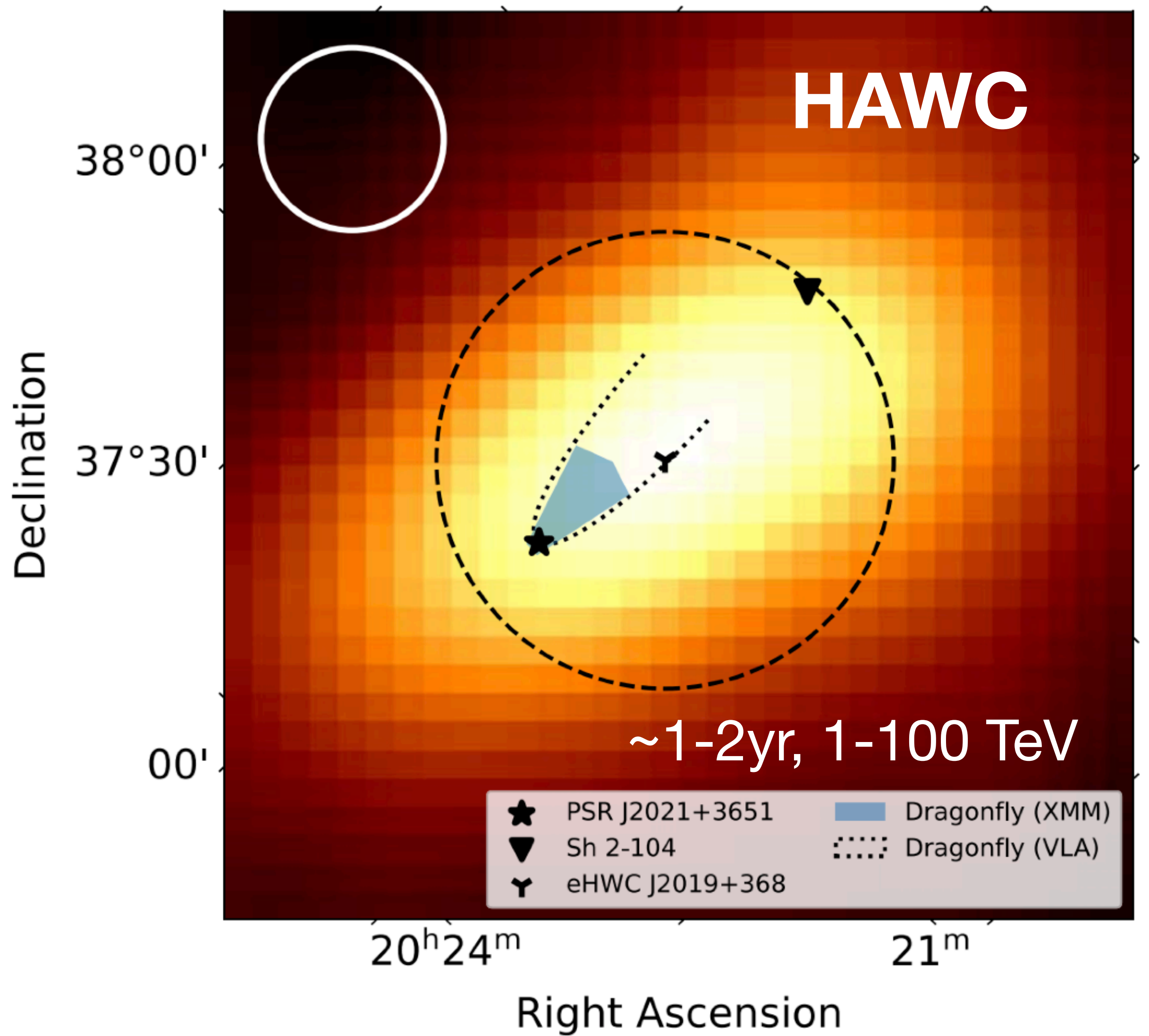
- Obs campaign in 2024, zenith angle 5-60 deg, ~44 hours of good stereo data after quality cuts
- **Preliminary results:**
  - Source position and integration region for SED fixed at VERITAS reported values (Abeysekhara et al. 2018)
  - **6sigma (p-value 2e-9)** of PL source over "no source" hypothesis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

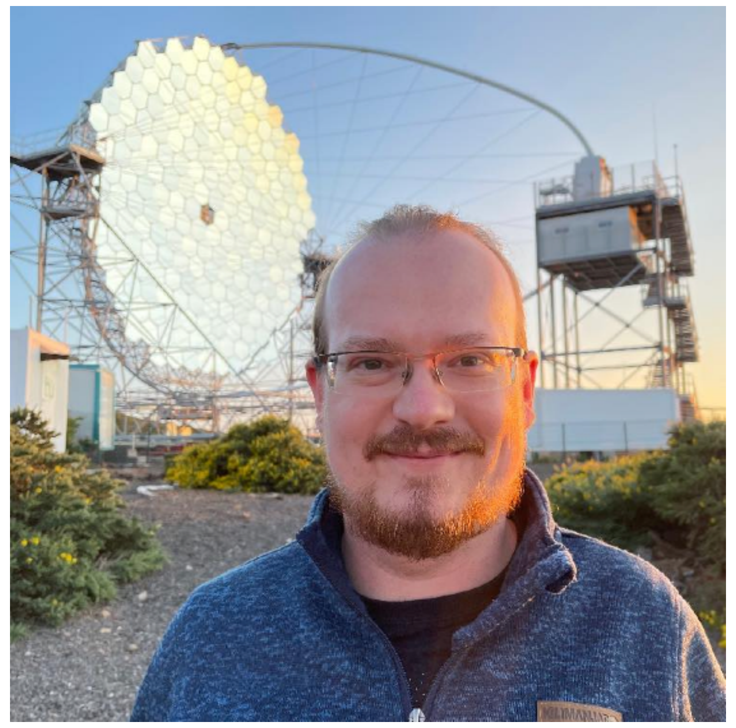
Our Prague analysis team

Ana Laura Müller
- MC simulation of g-ray sources
- Burst advocate
- Science

Thomas Tavernier
- All sorts of calibrations
- pipeline development
- Data analysis
- Science

Vladimír Novotný
- MC productions
- Low level MC/data tuning
- Advanced image cleaning

Petr Trávníček
- Steering the project



Jakub Juryšek
- Leading the group
- Event reconstruction
- pipeline development
- Data analysis
- Science

Srija Reddy Muthyala
- Image cleaning
- Data analysis
- Modelling of blazars

Patrik Čechvala
- Improvements of stereo reco
- Performance at different sites

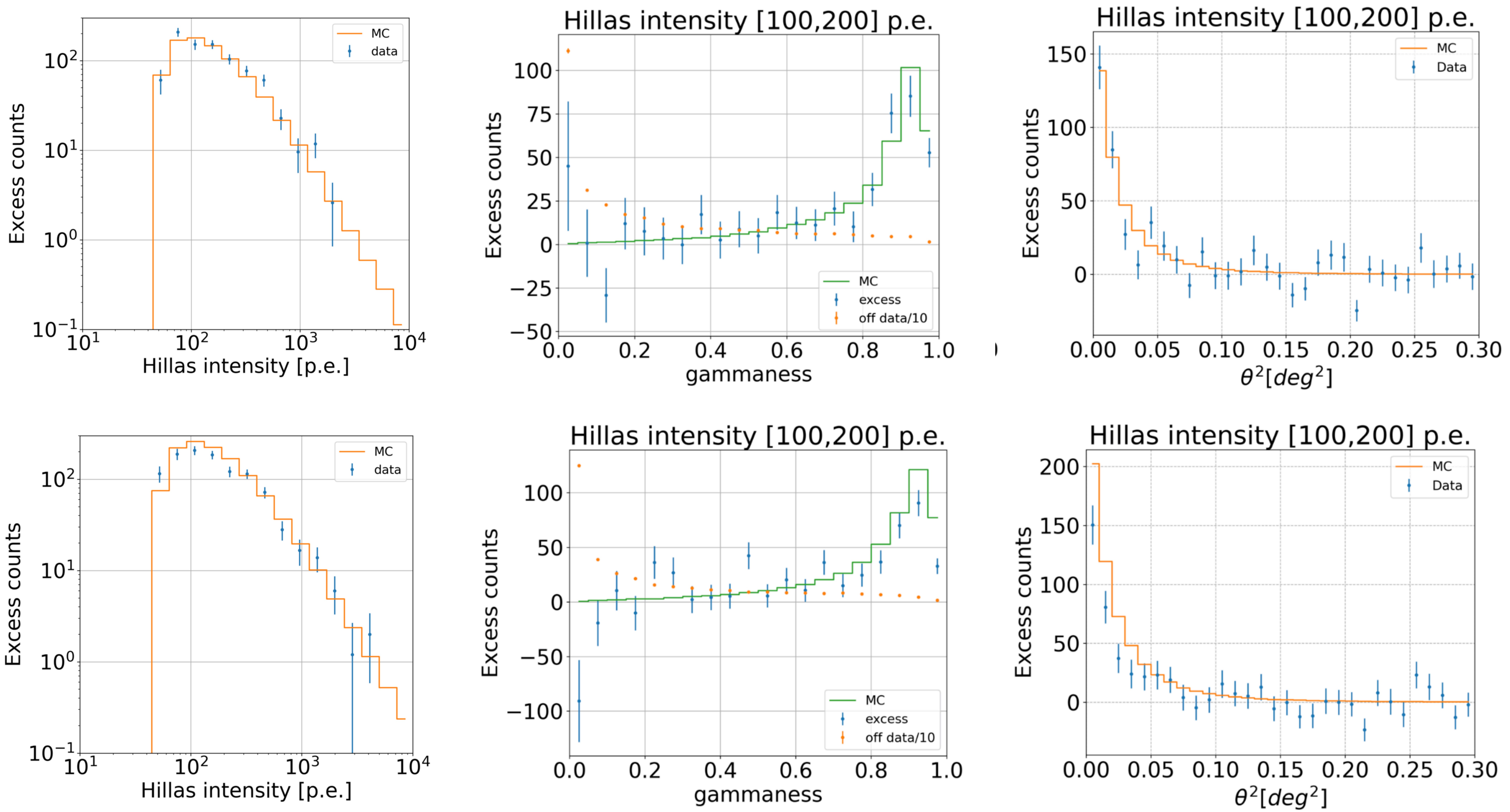
Jiří Blažek
- VAOD studies
- atmospheric molecular profiles

Přemysl Dědic
- Project webpages
- Project wiki
- Database of observations

MC - data agreement

Crab excess events

Real data + MC



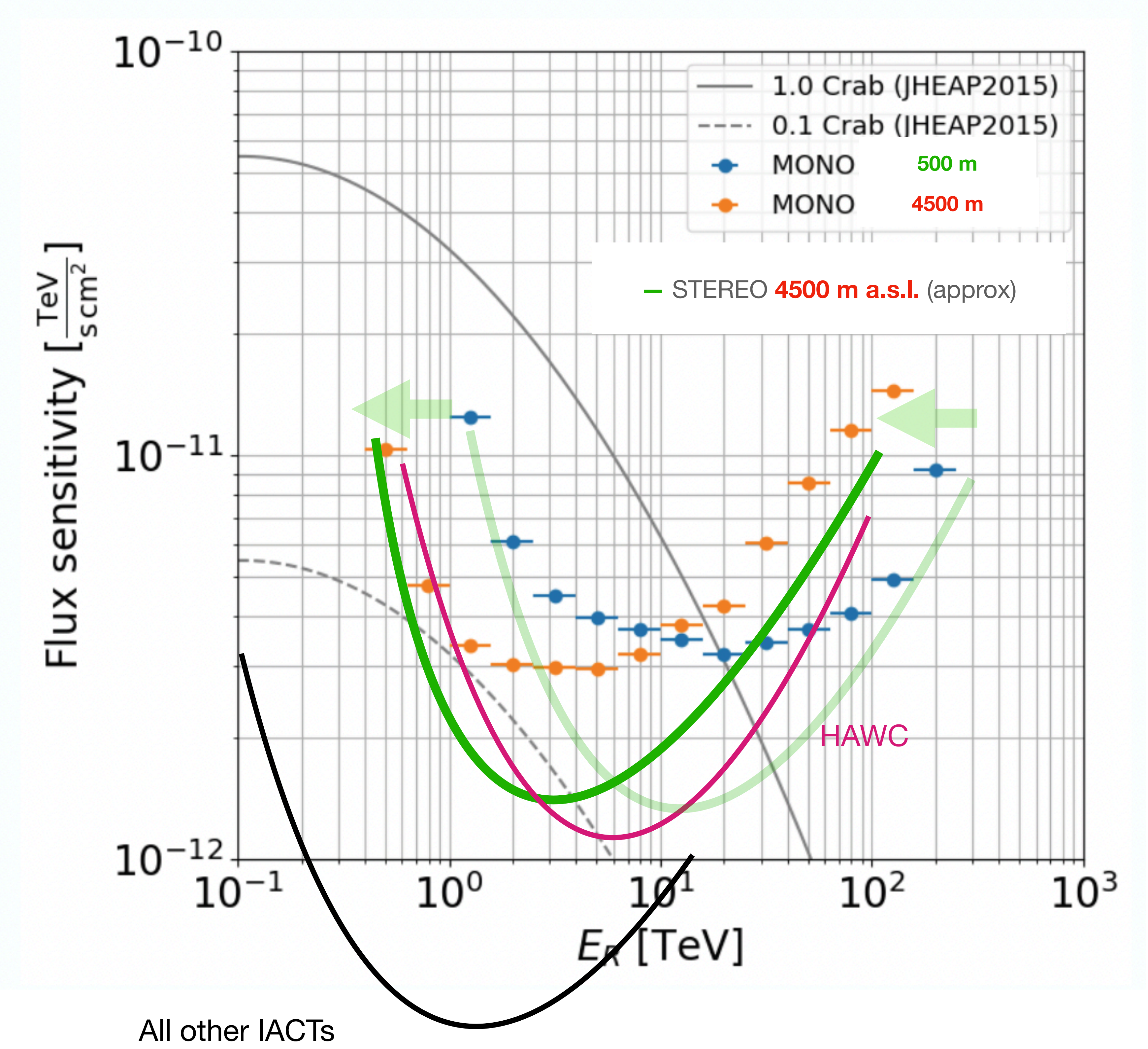
Tel 1

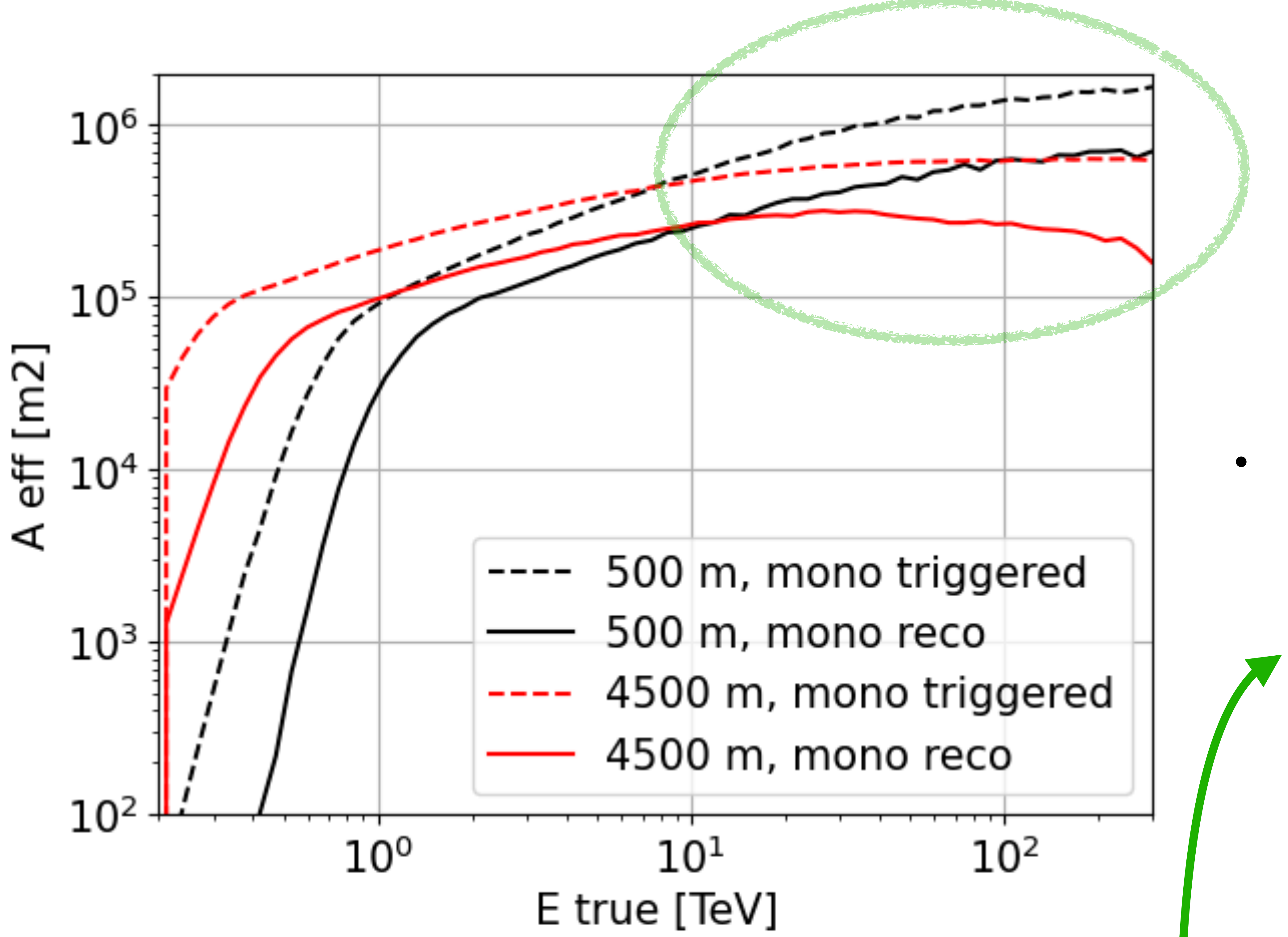
Tel 2

Increasing altitude = lost of the unique science case

..for IACTs alone, joining SWGO is completely different story

- Higher altitude means **smaller Cherenkov pool*** and higher probability of having **VHE/UHE showers out of FoV** - lost of UHE sensitivity, **no astronomy beyond few tens of TeV..**
- Going to India means building third IACT array with the same (or worse) sensitivity as MAGIC and VERITAS on the North
- One may argue with "continuous coverage", but using SST-1M with 9 deg FoV for monitoring of point-like transients is a waste of money





Patrik Cechvala's P4F project

* Can be compensated with building more tels, but what is the realistic timescale of this, and how it compares with expected decommissioning of the two prototypes?

- **To be checked:**
  - we do not have stereo for high altitude
  - telescope distances not optimised
  - performance at different altitudes to be studied and evaluated wrt expected science prospects