An Overview of the SST-1M Telescopes: Design, Calibration and Results

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on behalf of the SST1M collaboration

FZU

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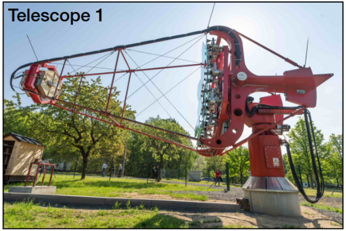
SST-1M project

- Consortium of research institutions from Poland, Switzerland and Czech Republic
- SST-1M was a prototype designed for the CTA Observatory
- It satisfied all the CTA requirements. However, another design was ultimately chosen.
- Two SST-1M prototype telescopes were relocated from Poland to the Czech's Republic and were commissioned at the Ondrejov Observatory (alt 500m).

Ondřejov Observatory

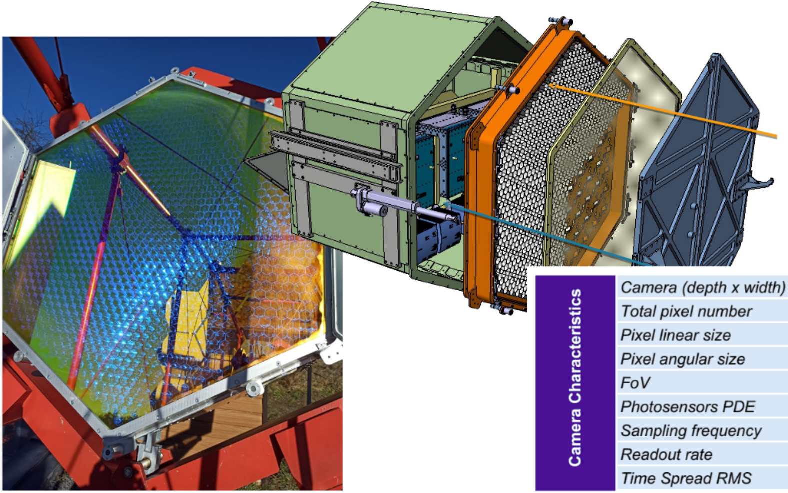
SST-1M telescopes

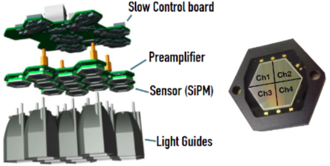


- 18 mirrors facets
- 4m diameter
- 5.6m Focal lenght
- 9.1° FOV
- 6.47 m^2 mirror effective area

- Observations carried out entirely remotely

SST-1M camera : SiPM and fully digital readout

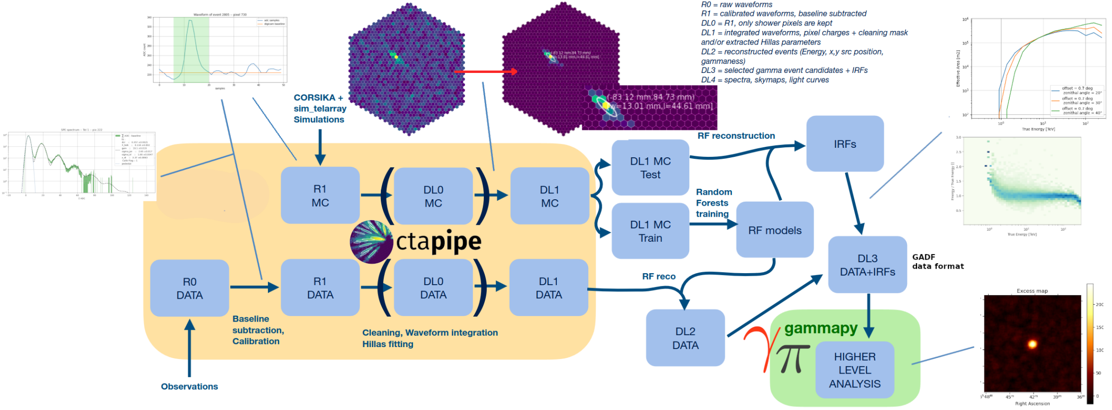




Camera Characteristics		
	Camera (depth x width)	60 cm x 90 cm
	Total pixel number	1296
	Pixel linear size	23.2 mm
	Pixel angular size	0.24°
	FoV	9.1°
	Photosensors PDE	> 30%
	Sampling frequency	250 MHz
	Readout rate	0.6-1 kHz
	Time Spread RMS	< 0.25 ns

sst1mpipe : SST-1M analysis pipeline

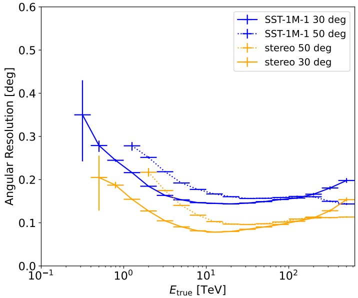
- Analysis pipeline is heavily based on `ctapipe` and inspired by `lstchain` and `magic-ctapipe`
- Event reconstruction and classification is done using random forest trained on Monte-Carlo
- Available in public repository: `https://github.com/SST-1M-collaboration/sst1mpipe`

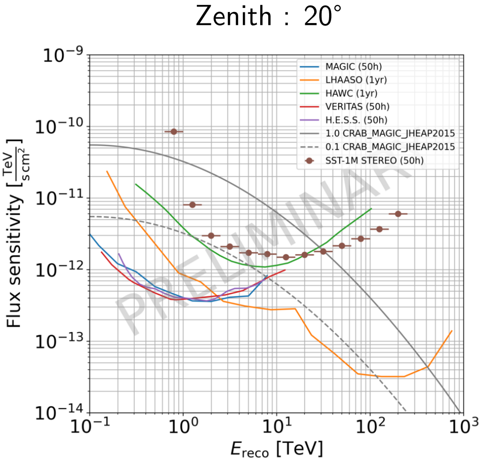


Jurysěk et al. (2025). sst1mpipe: v0.9.0. 13 Nov 2025. Zenodo

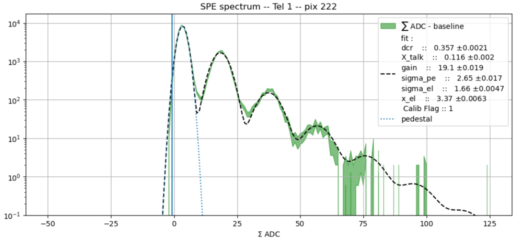
SST-1M performances

- Low altitude of the site (500 m) leads to an energy threshold > 1TeV
- But also very good performances above few tens of TeV!
- Stereo gamma-ray PSF: $\sim 0.1°$





Calibration from Dark runs



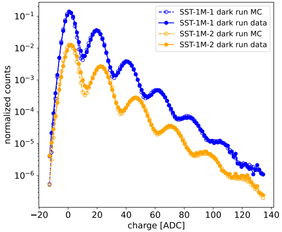
- Dark runs are taken every night before and after the observations
- Photo-sensor's response can be estimated trough the photoelectron spectrum produced by thermal charges.

internal (in one pixel) X-talk → Borel distribution :

$$B_{\nu^*,n} = \frac{e^{-n\nu^*}(n\nu^*)^{n-1}}{n!}.$$

$$A_{\mathrm{pe}} = \sum_{n=1}^{\infty} B_{\nu^*,n} \mathrm{G}\left(n_0 + ng, \sqrt{\sigma_{\mathrm{el}}^2 + n\sigma_{\mathrm{pe}}^2}\right)(n_{\mathrm{ADC}})$$

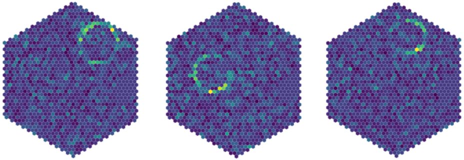
- MC electronic adjusted to match average distribution :



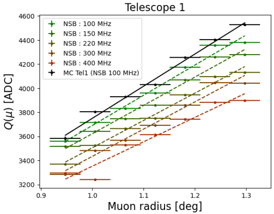
Conversion factor from ADC counts to photo-electrons is given by : $\frac{1-\nu}{g}$

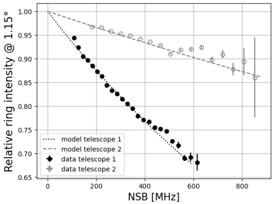
Calibration from Muons

- 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



- Sensor's response (gain, optical efficiency, x-talk) are affected by the NSB level.
    - Studied through electronic MC [1]
- This effect and the optical efficiency of the telescope can be evaluated using muons.
- Observation under moonlight.

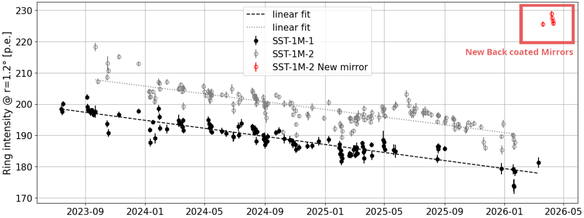




[1] SiPM behaviour under continuous light [10.1088/1748-0221/14/12/P12016]

Optical efficiency with Muons

- Optical efficiency of the instrument is monitored through muon analysis.
- The long-term evolution is dominated by the degradation of the mirror reflectance over time.

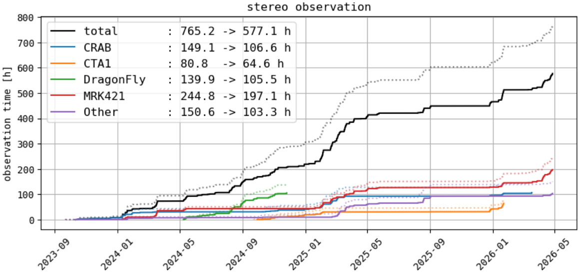


Mirror upgrade :

- Back coated mirror have been recently installed on telescope 2
- Back coated mirror reflectance is expected to remain significantly more stable over time.

Commissioning and Early Science Observation Program

- Crab Nebula Observation
- Galactic sources :
  - Dragonfly Nebula
  - CTB 87
  - CTA 1
- AGN Monitoring :
  - Mrk 421
  - Mrk 501
  - 1ES 1959+650
- ToO and Transient Trigger :
  - Flaring nearby AGNs
  - AMON ν-EM Alerts
  - GW Alerts (NS-NS Merger) - No Follow-up for now



- Total time : 765 h
  (577 h after quality selection)

Crab observation Dataset

Crab Observation campaigns:

2022-2023

2.5 h
[ICRC(2023)741]

2023-2024

43.4 h (30.8 h)
[A&A, 699, A255 (2025)]

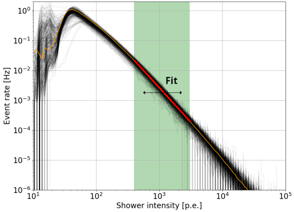
2024-2025

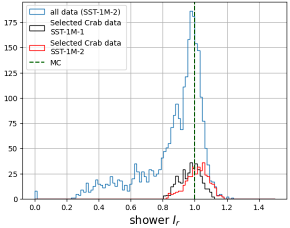
84.0 h (61.8 h)
[ICRC(2025) 746]

2025-2026

15.8 h (8.6 h)‘

- Livetime after quality cuts : 92.7 h
- Data quality selection
  - Fit relative intensity: I_r
    $R(I_{sh} I_r) = A * (I_{sh} I_r)^{-B}$
  - Systematic uncertainty from attenuation : $\sim 7\%$
- Observation wobble : 0.7°, 1.4°,2.1° & 3.0° offset
- Zenith angle range : 28° to 55°





Crab SED (Stereo data)

Reflected bkg

- Excess : 976.5
- counts ON : 1172
- counts OFF : 195.4
- significance : $>45\sigma$

SED fit (log parabola)

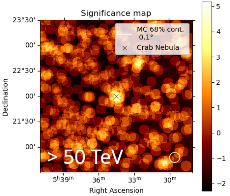
$$\Phi_0 \left(\frac{E}{10\,\mathrm{TeV}}\right)^{-\alpha-\beta\log\left(\frac{E}{10\,\mathrm{TeV}}\right)}$$

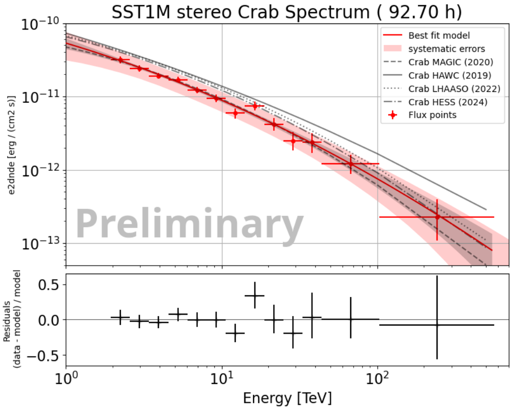
- $\Phi_0 = (5.5 \pm 0.3) \times 10^{-14}$ $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{TeV}^{-1}$
- $\alpha = 2.92 \pm 0.05$
- $\beta = 0.063 \pm 0.04$

- Crab is seen at 5σ in $\sim$1.5h of observation.
- No statistical evidence for curvature ($\sim 2\sigma$)

>50 TeV

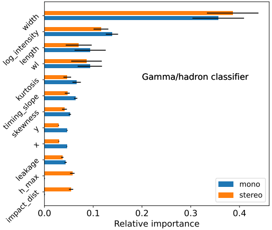
- counts ON : 12
- counts OFF : 2.3
- Excess : 9.7
- significance : 4.4σ



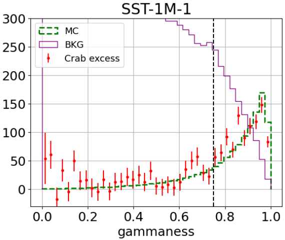


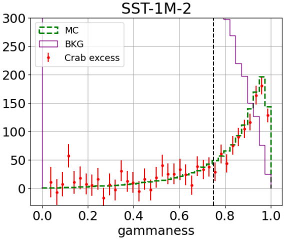
Gamma-hadron discrimination

- **Gammaness:** assigned by a Random Forest classifier trained on MC



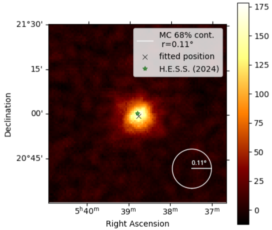
- Distribution of Gammaness for excess events:
  - Zenith angle: 25°–35°
  - Within 0.12° of the Crab position
  - Using 5 OFF regions
  - MC: point-like gamma rays weighted to MAGIC Crab spectrum

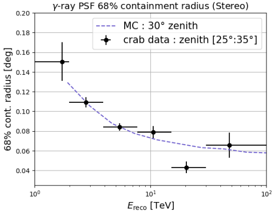


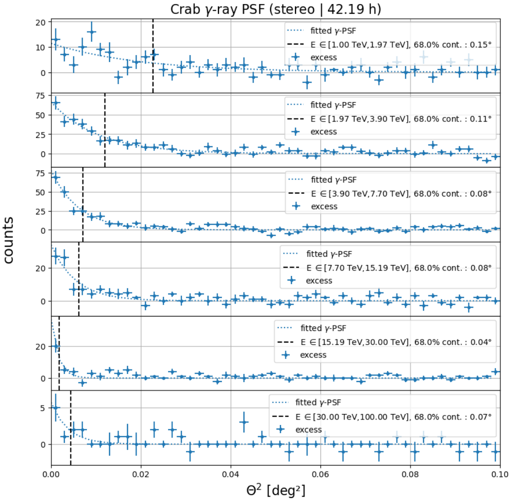


Gamma-ray PSF

- Crab is not exactly point-like.
  - H.E.S.S. : $\sim$ 1 arcmin >3 TeV
  - No extension seen in our data.
- Gaussian gamma-ray PSF is fitted
- Same procedure with MC simulations shows good agreement.





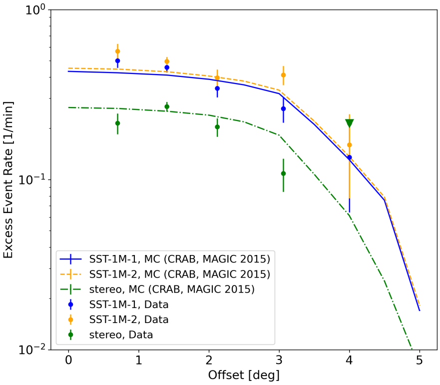


Sensitivity at large offset

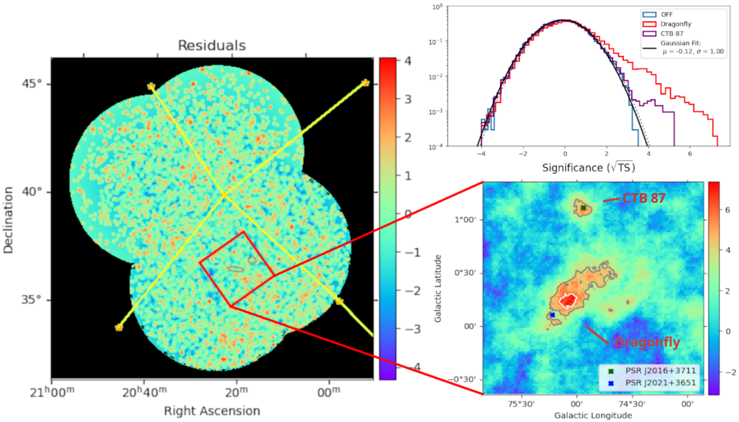
SST-1M FZU

- Comparison between Crab observation and MC simulation at 30° zenith angle shows good agreement.
- Radial gamma acceptance is reasonably flat up to 3 deg offset.

Acceptance of SST-1M Vs offset.



Observations of two evolved PWN in Cygnus region.



CTB 87 (VER J2016+371)

Age ~10–20 kyr
Distance ~ 6.1 kpc
Assoc. PSR J2016+3711 :
– Spin period : 50.81 ms
– $\dot{E} = 2.2 \times 10^{37}$ erg s^{-1}
– τ_c ~11 kyr

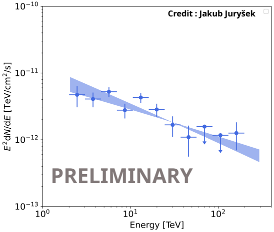
Dragonfly Nebula (VER J2019+368)

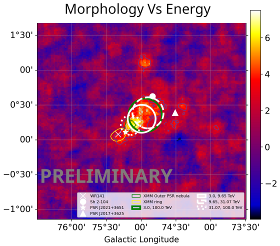
Age ~17 kyr
Distance ~ 1.8 kpc
Assoc. PSR J2021+3651 :
– Spin period : 103.7 ms
– $\dot{E} = 3.4 \times 10^{36}$ erg s^{-1}
– τ_c ~17 kyr

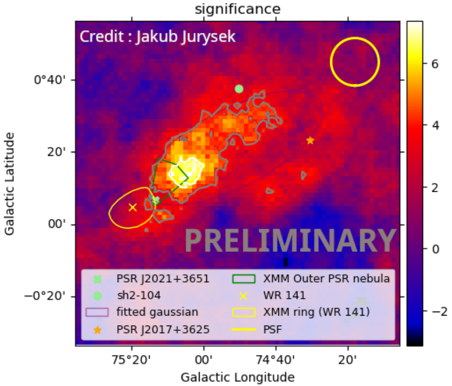
Dragonfly Nebula

3D analysis

- 120 hours
- Background model : Baccmod
- source model : Asymmetric Gaussian + PWL SED

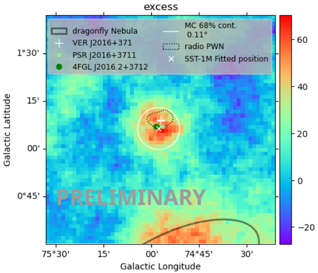






Spatial model					Spectral model	
α [deg]	δ [deg]	σ [deg]	e	ϕ [deg]	ϕ_0 $\times 10^{-14}$ cm^{-2}s^{-1}TeV^{-1}	Γ
304.830 ± 0.002	36.737 ± 0.001	0.372 ± 0.001	0.889 ± 0.001	65.93 ± 0.28	3.16 ± 0.33	2.49 ± 0.09

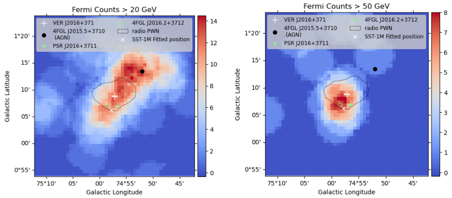
CTB 87



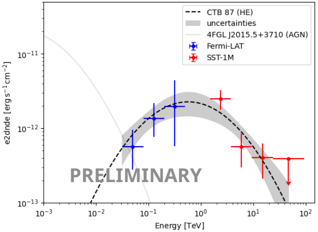
SST-1M Reflected background analysis

- Energy range: **1.5–20 TeV**
- Exposure: **101 h**
- N_{on} : **124**
- N_{off} : **1750** ($\alpha = 0.042$)
- Excess: **51**
- Li&Ma significance: **5.2** σ

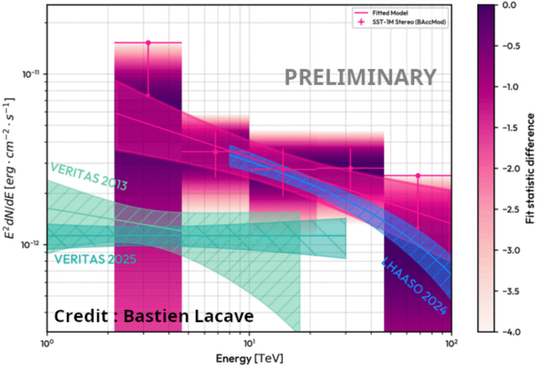
Fermi analysis :



Joint Likelihood Fit (Fermi-LAT+SST-1M) :



CTA 1



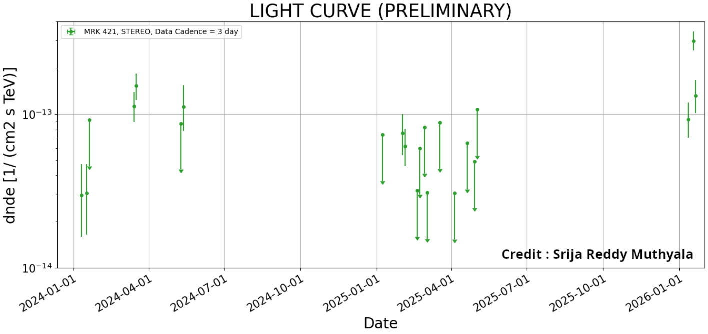
- Evolved PWN powered by PSR J0007+7303
  - Distance : 1.4 - 1.8 kpc
  - Age: $\sim$ 13 kyr
  - $\dot{E} \sim 4.5 \times 10^{35}$

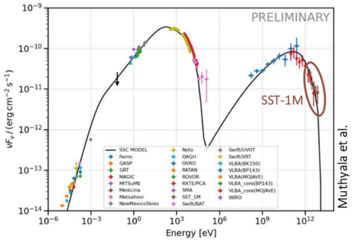
SST-1M 3D Analysis

- 60 h of observation
- 3D Background modelling estimated with Baccmod
- Extended (gaussian) source fit with gammapy

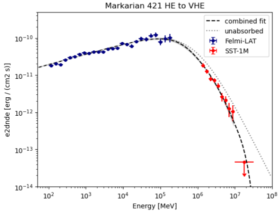
Monitoring AGNs : Markarian 421

- Markarian 421 is the brightest AGN at TeV energy.
- It has been monitored since the beginning of operations.
- Almost 200 h in total.





Fermi-LAT + SST-1M joint fit :



Monitoring AGNs : Markarian 421

SST-1M FZU

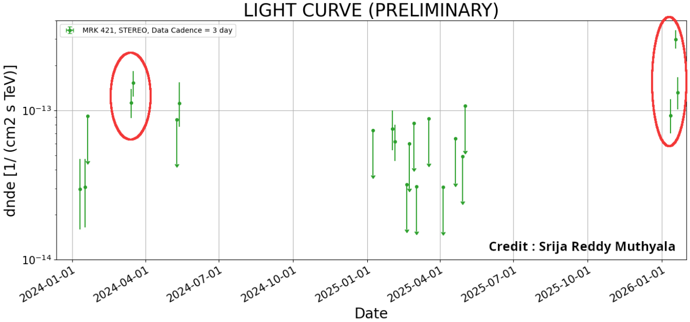
2 bright activity reported on Astronomer's Telegram

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

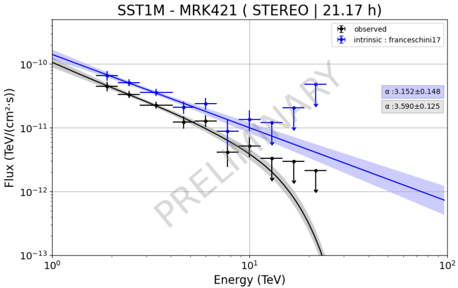
ATel #16533; *Thomas Tavernier, in the behalf of SST-1M Consortium*
on 15 Mar 2024; 16:55 UT

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

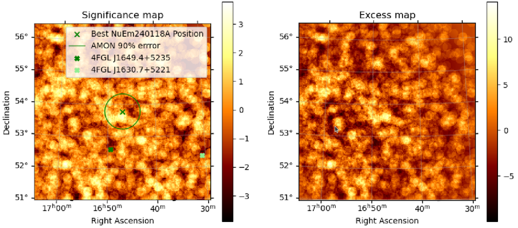


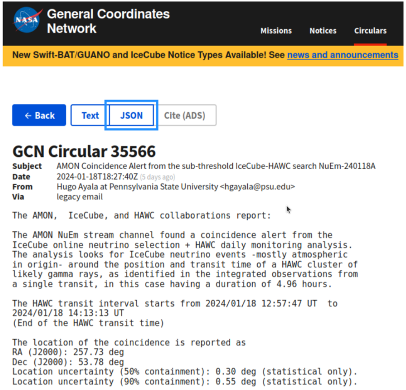
- January 2026 activity :
  - 21 h
  - 247 excess events
  - 29 σ



Transient Observation : Amon Alert NuEm240118A

- AMON :Astrophysical Multimessenger Observatory Network
- NuEm Alerts :
  IceCube Bronze event + HAWC 3σ hotspot.
  - False alarm rate $\sim 2/\text{yr}$
  - Genuine 3σ seen during one HAWC transit could be confirmed in few hours with SST-1M
- NuEm-240118A : 5h of observation in 2 nights
  - No Significant detection





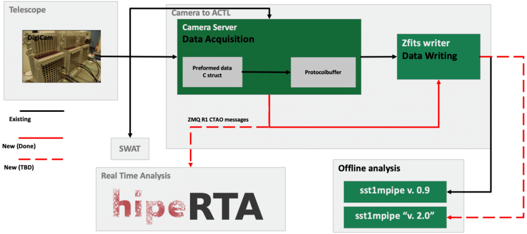
GCN Circular 35566

Subject AMON Coincidence Alert from the sub-threshold IceCube-HAWC search NuEm-240118A
Date 2024-01-18T18:27:40Z (5 days ago)
From Hugo Ayala at Pennsylvania State University <hgayala@psu.edu>
Via legacy email

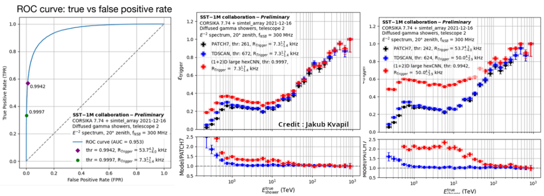
```
The AMON,  IceCube, and HAWC collaborations report:

The AMON NuEm stream channel found a coincidence alert from the
IceCube online neutrino selection + HAWC daily monitoring analysis.
The analysis looks for IceCube neutrino events -mostly atmospheric
in origin- around the position and transit time of a HAWC cluster of
likely gamma rays, as identified in the integrated observations from
a single transit, in this case having a duration of 4.96 hours.

The HAWC transit interval starts from 2024/01/18 12:57:47 UT  to
2024/01/18 14:13:13 UT
(End of the HAWC transit time)

The location of the coincidence is reported as
RA (J2000): 257.73 deg
Dec (J2000): 53.78 deg
Location uncertainty (50% containment): 0.30 deg (statistical only).
Location uncertainty (90% containment): 0.55 deg (statistical only).
```

Current development

- Implementation of hipeRTA
  - Real Time Analysis
  - Gives feed back to the observers
  - Optimise transient observation

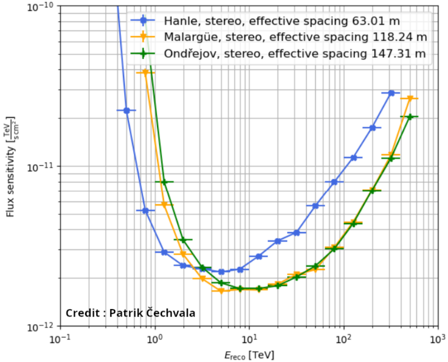


- Smart trigger:
  - TDScan (Trigger Distributed Spatial Convolution Accelerator Network)
  - Hexagonal CNN with ∼40k trainable weights
  - Aims to lower the threshold



Future of SST-1M telescopes

- Relocation of SST-1M telescope is under discussion.
- Different relocation sites are considered, including :
    - Hanle (4270 m a.s.l.)
    - Malargüe (1420 m a.s.l.)
- MC simulations were performed for different altitudes to optimise telescope placement.



Summary

SST-1M FZU

- The SST-1M stereo system has been operating routinely since 2023
- Calibration and reconstruction are fully validated and meets the expectation.
  - Performance paper : [A&A, 699, A255 (2025)]
- Early science programme is well underway, including observations of PWNe/SNRs, AGN monitoring, and transient/ToO follow-up.
  - ICRC 2025 : Mrk 421, Dragonfly, CTA1...
  - Upcoming TeVPA / gamma 2026 : Proton spectrum, Mrk 421 ...

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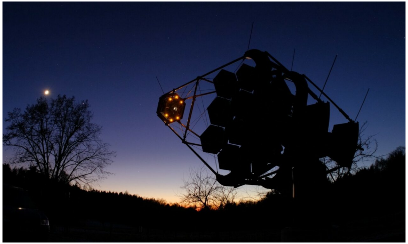


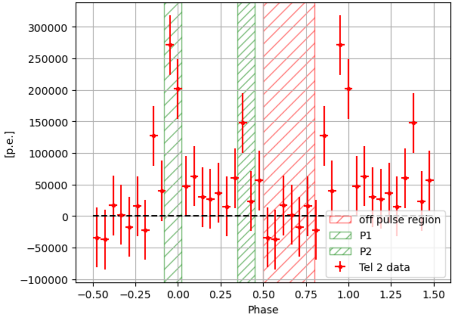
Thank you

Backup

Timing test with Crab Pulsar

- Test timestamps accuracy with B-UVB modulated signal from Crab Pulsar:
  - No frequency filter : DC
  - Baselines are evaluated averaging 1024 samples of 4 ns for each events.
    - No dedicated setup
    - Very poor duty cycle : 50 h -> 5 min effective exposure
  - Timing correction : PINT
  - Ephemerides : Jodrell Bank
- White rabbit network installed in 2023
- Connection with GPS reference in March 2024

B-UVB band : **NOT gamma-ray**



- No pulsed signal detected in gamma-ray by SST-1M yet

CTB 87 : MWL

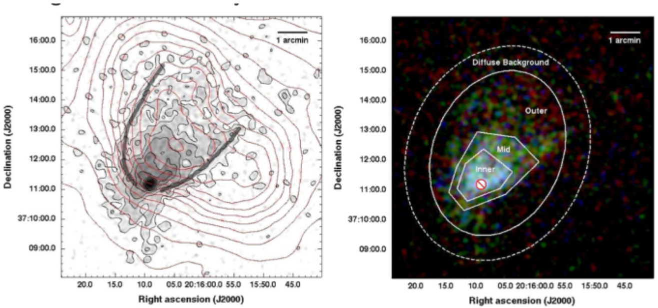
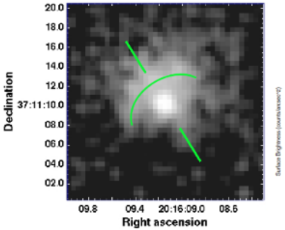
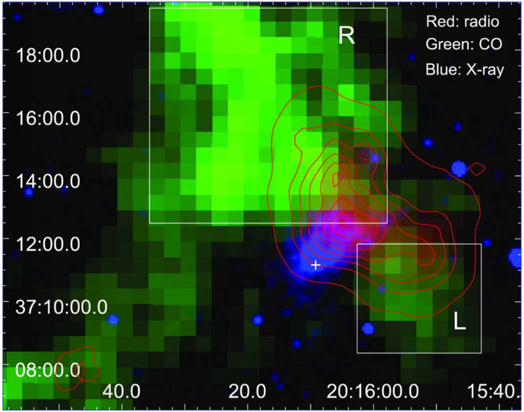


Figure 1. Left: 0.3–7.0 keV *Chandra* 87.1 ks image of CTB 87. Logarithmic scaling is used and the image is smoothed with a 2D Gaussian ($\sigma = 3''$). Black contours highlight the X-ray morphology. Overlaid arcs highlight the brightening along the edge of the X-ray PWN. Red contours correspond to the radio 21 cm emission (CGPS data) and define the brightness temperature at the following levels: 93.0, 86.0, 78.9, 71.9, 64.9, 57.8, 50.8, 43.8, 36.8, 29.7, 22.7, 15.7, 8.6, 1.6 K. Right: RGB *Chandra* image (red = 0.3–2.0 keV, green = 2.0–4.0 keV, blue = 4.0–7.0 keV). Regions overlaid were used to extract spectra of the diffuse emission. Inner regions were excluded when extracting a spectrum for an outer region. The fit to all of the diffuse emission (Section 4.2, Table 2) includes emission from the inner + mid + outer regions. The outer annulus shows the background region used for the diffuse emission spectra.



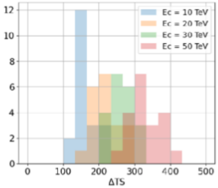
CTB 87 : MWL


Red: radio
Green: CO
Blue: X-ray
R
L
18:00.0
16:00.0
14:00.0
12:00.0
37:10:00.0
08:00.0
40.0
20.0
20:16:00.0
15:40.

Observability of the Galactic Center from the south

- All models fitted using full 3D likelihood approach (gammapy)
- Likelihood ratio to evaluate the **significance of the diffuse emission detection** (for each realisation)**:**
  - **H0** - no diffuse emission (only point-like sources in the model)
  - **H1** - full model

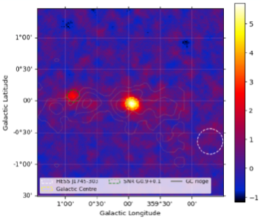
Likelihood ratio for the diffuse emission component. Different assumptions on the cutoff energy (20 realisations each)



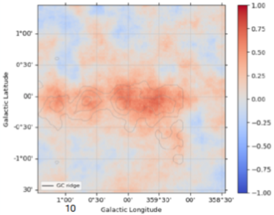
The Galactic Center as seen with SST-1M in the South

- **Other sources in the FoV**
  - Sgr A*: 18σ detection
  - SNR G0.9+0.1: 7σ detection
  - HESS J1745: no detection

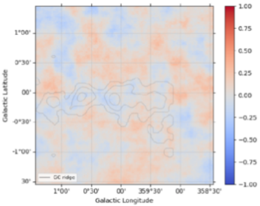
Number of excess gamma-ray events per bin. Bin size 0.02°, smoothed with a 0.08° radius disk convolution.



Residuals after the likelihood fit (**Diffuse emission removed from the model**)



Residuals after the full likelihood fit

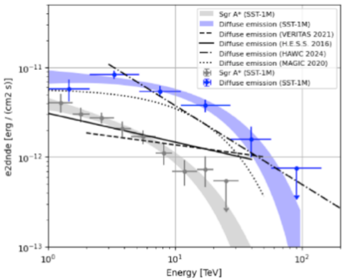


SST-1M FZU

Monte Carlo

Observability of the Galactic Center from the south

- All models fitted using full 3D likelihood approach (gammapy)
- Likelihood ratio to evaluate the **significance of cutoff detection** (for each realisation):
  - **H0** - diffuse emission fitted with PL spectrum
  - **H1** - diffuse emission fitted with ECPL spectrum



Spectrum of the Galactic Center and the diffuse emission as seen with SST-1M in the South

Significance of the cutoff detection for different assumptions of the cutoff energy (20 realisations each)