Optimising an Array of IACTs in Australia for the Detection of TeV Gamma-ray Transients

Simon Lee, Sabrina Einecke, Gavin Rowell

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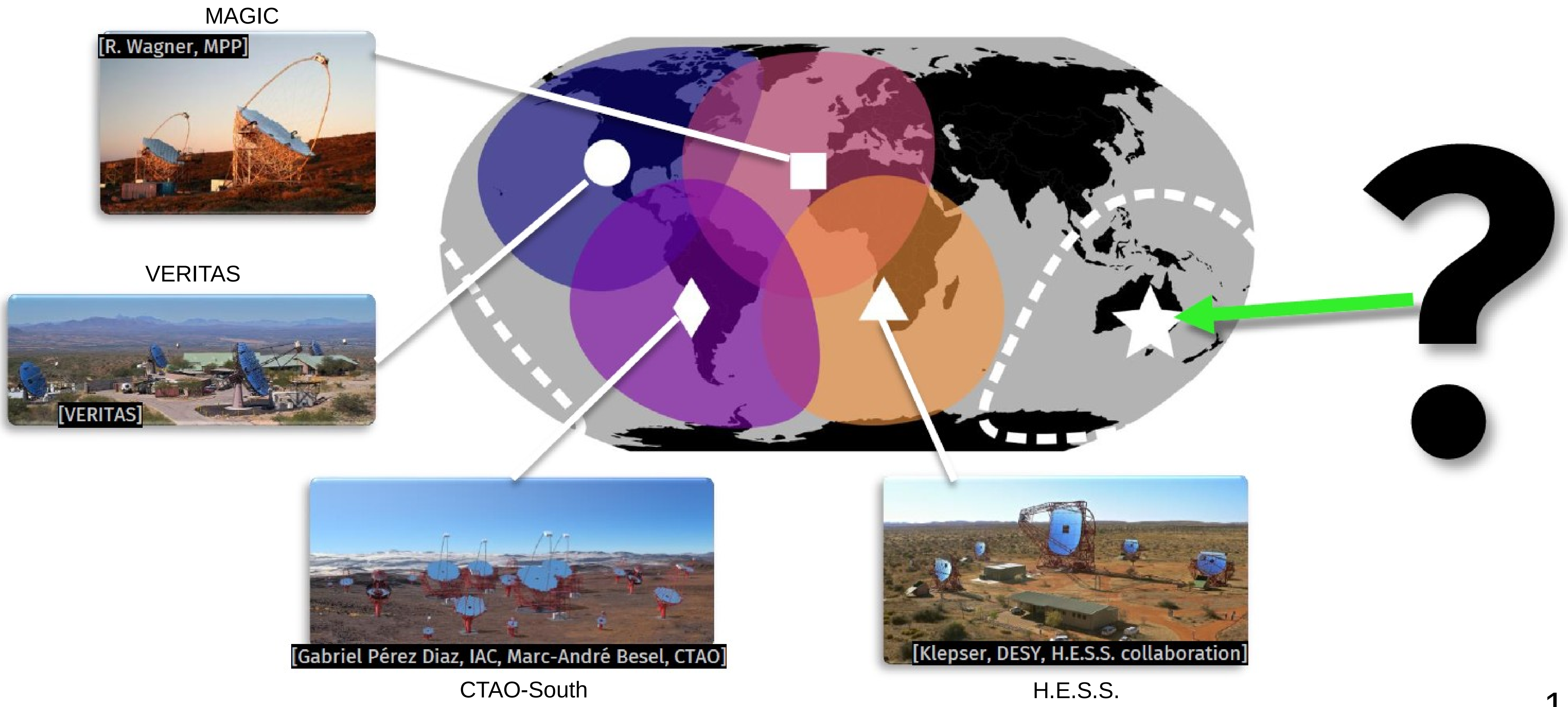
A TeV γ-ray telescope in Australia would be great for astronomy



It could help observe transient and variable phenomena

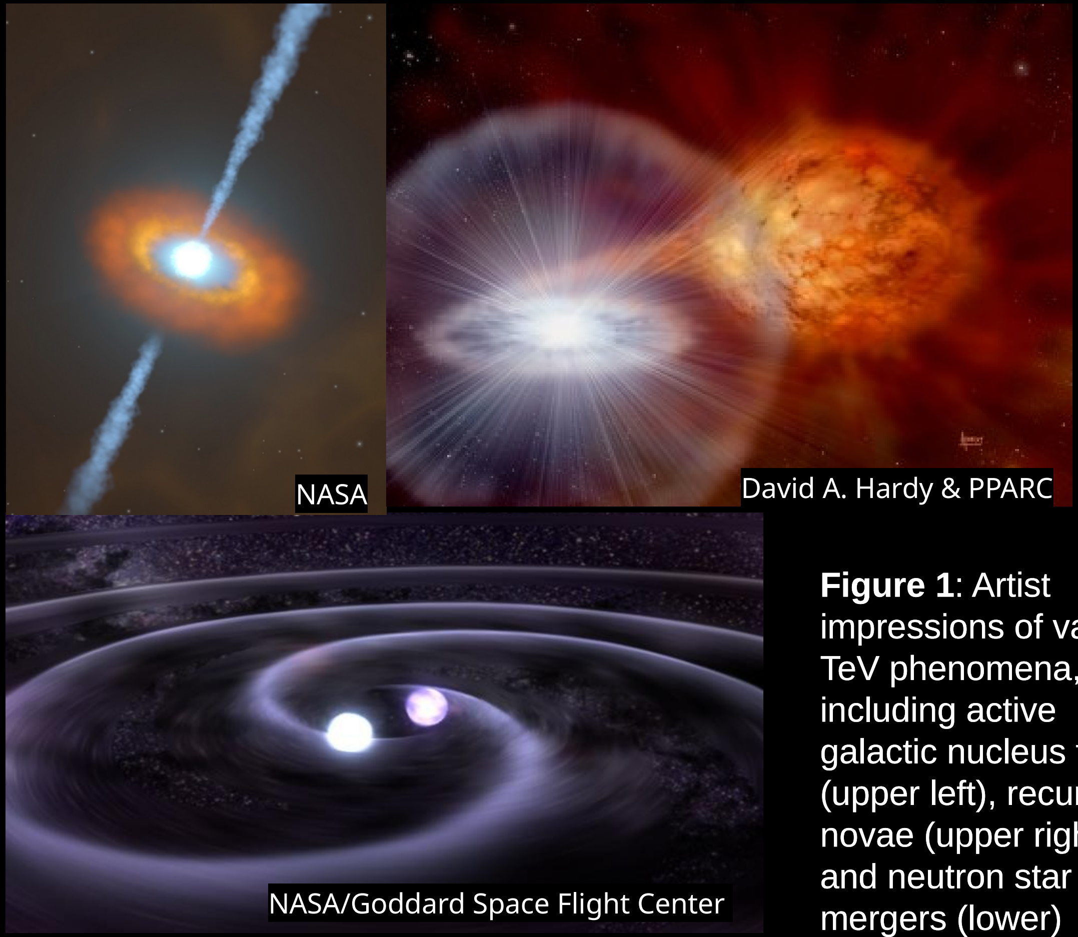


Figure 1: Artist impressions of various TeV phenomena, including active galactic nucleus flares (upper left), recurrent novae (upper right), and neutron star mergers (lower)

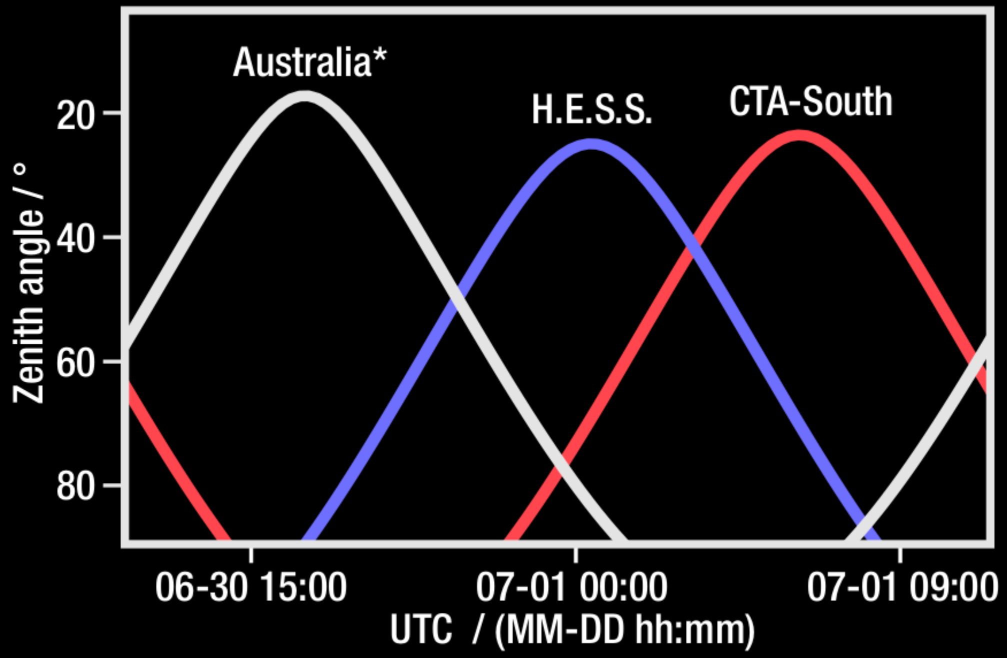
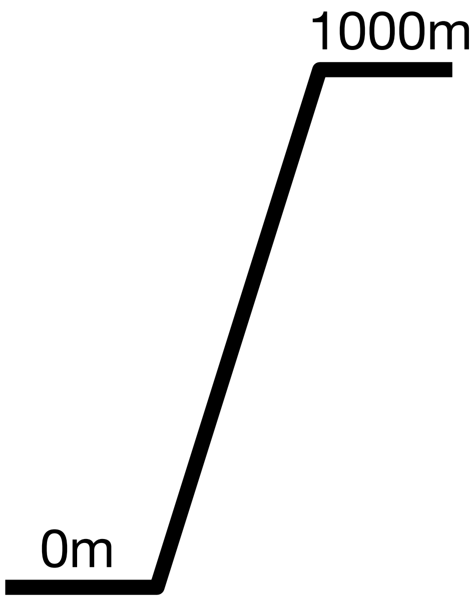


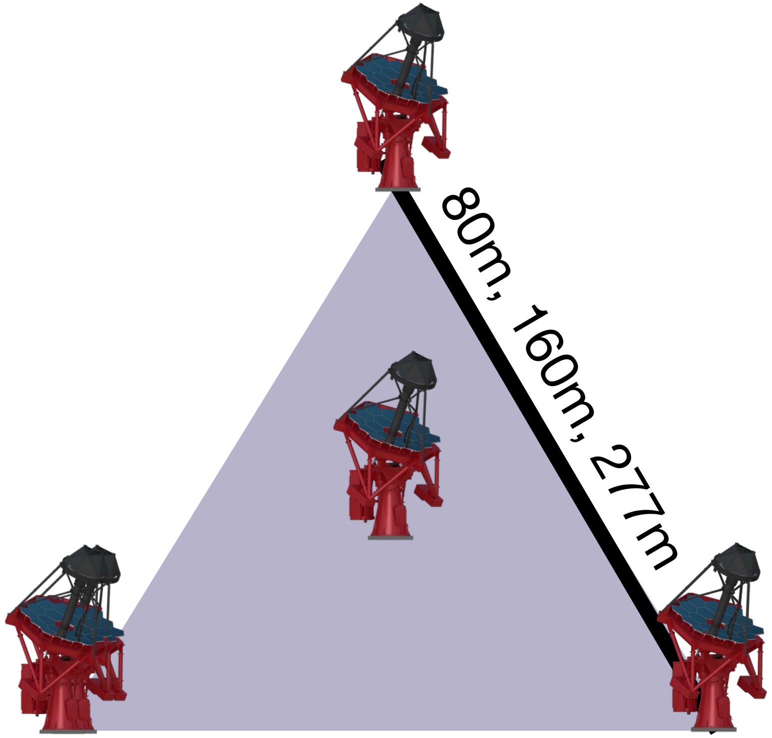
Figure 2: Visibility of the blazar PKS 2005-489 to CTA-South, H.E.S.S., and a hypothetical Australian array in the Flinders Ranges

We ran simulations to compare some arrays

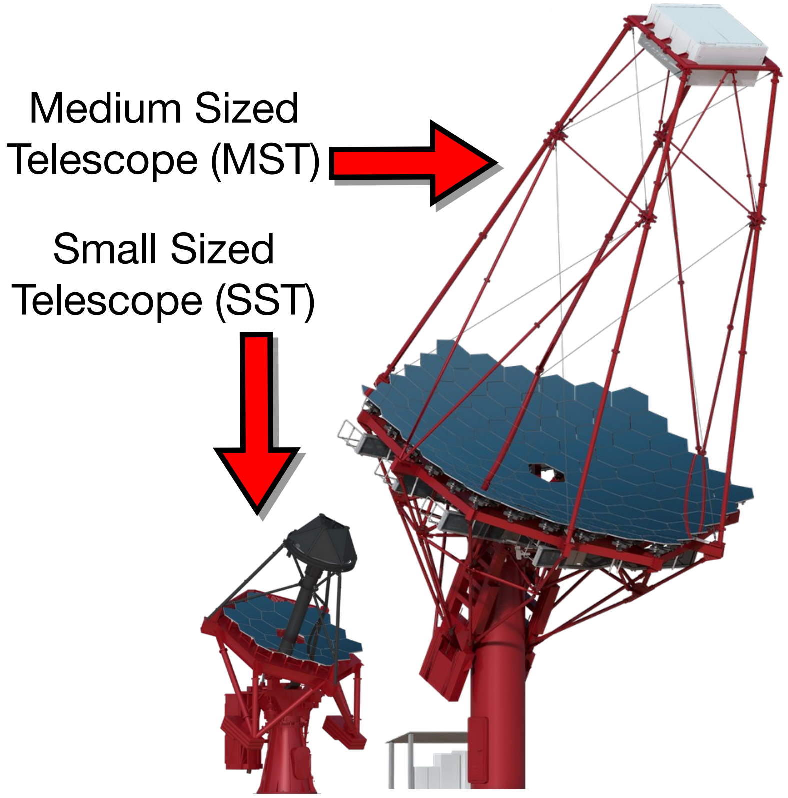
Different numbers of telescopes



Different altitudes



Different distances between telescopes



G. Pérez, IAC, SMM

Different telescope sizes (from Cherenkov Telescope Array Observatory designs)

A small IACT array in Australia would perform well

arXiv:2206.07945 Performance of a Small Array of Imaging Air Cherenkov Telescopes sited in Australia

S. Lee, S. Einecke, G. Rowell et al. *Publications of the Astronomical Society of Australia* **39**, 041 (2022)

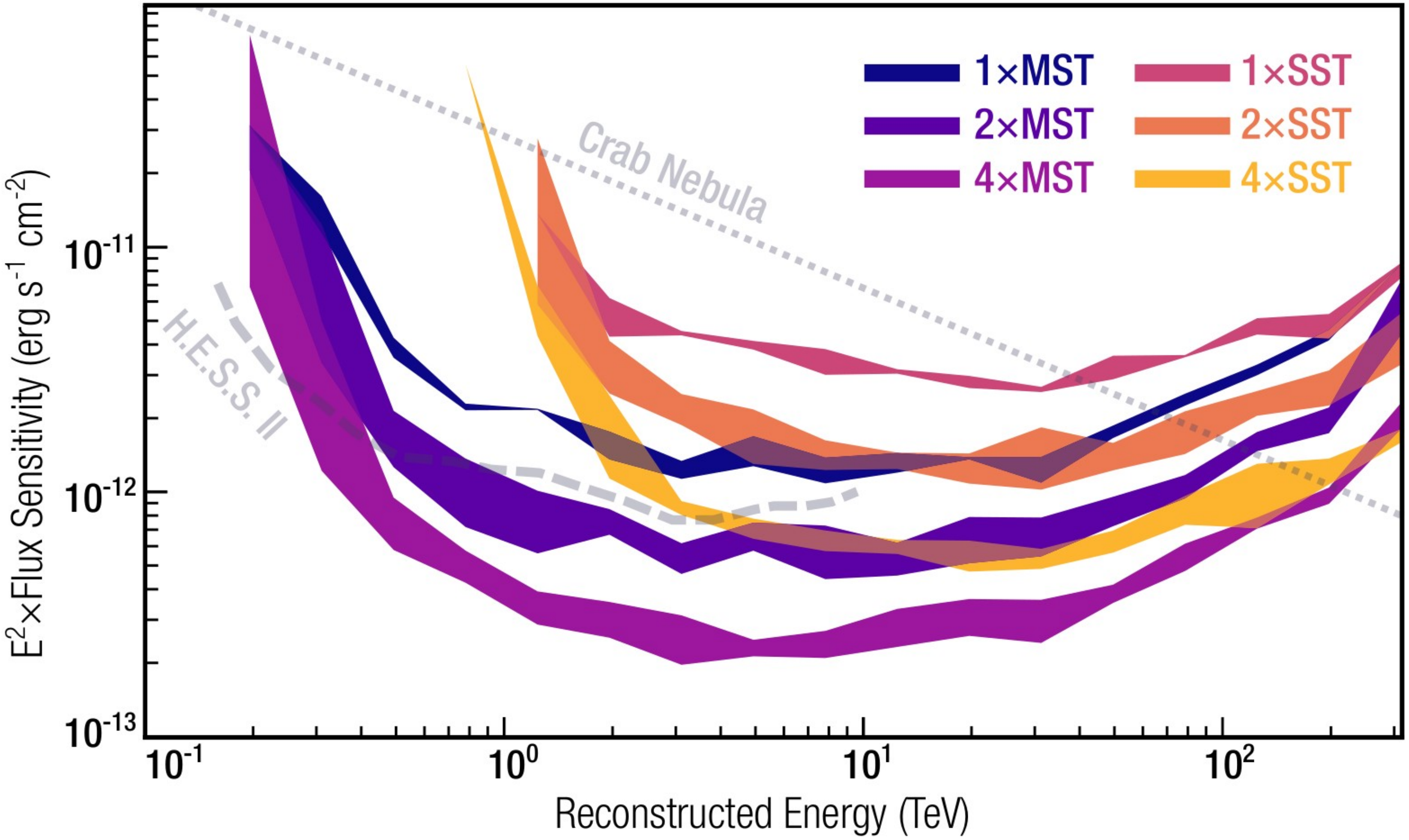


Figure 1: The lowest differential flux for a 5σ detection of a gamma-ray point-source from 50 hours of observation vs gamma-ray energy. Bands show the range of sensitivities across studied altitudes and baseline distances. H.E.S.S. is shown for comparison (Holler et al. 2015, PoS, ICRC2015)

MSTs could observe transients, like nova flares and GRBs

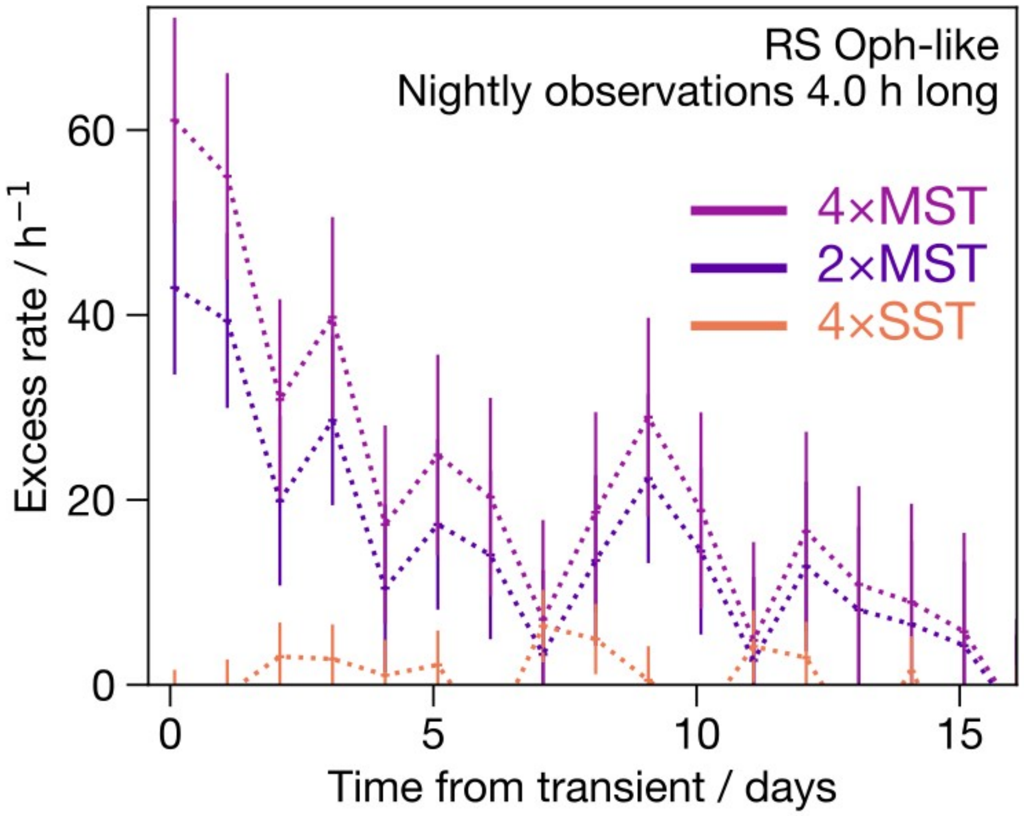


Figure 1: Simulated light curves from observing the recurrent nova RS Ophiuchi.

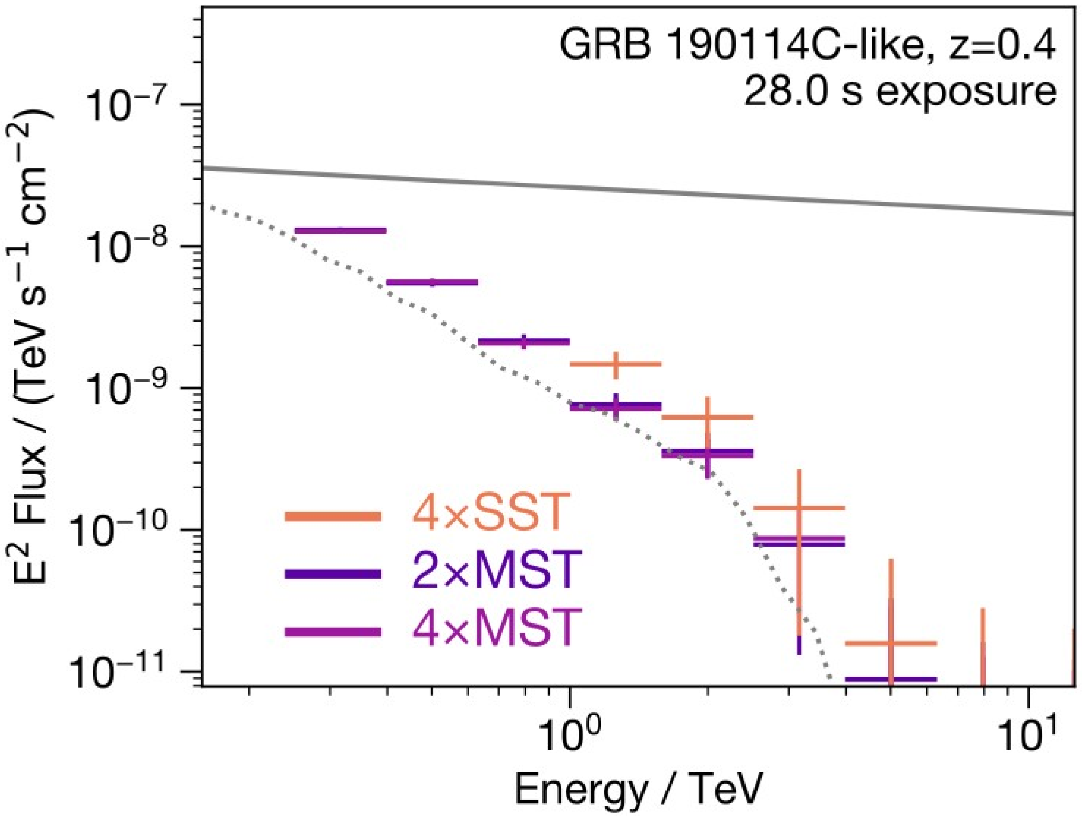


Figure 2: Simulated spectrum reconstruction from observing GRB 190114C. Also shown are the intrinsic flux (solid) and flux at Earth (dotted).

For transients, we want to capture more low-energy γ rays

- Gamma-ray spectra often follow a power law: $$\frac{dN}{dE} \propto E^{-\Gamma}$$
- As such, few photons are generated at high energies (>1 TeV)

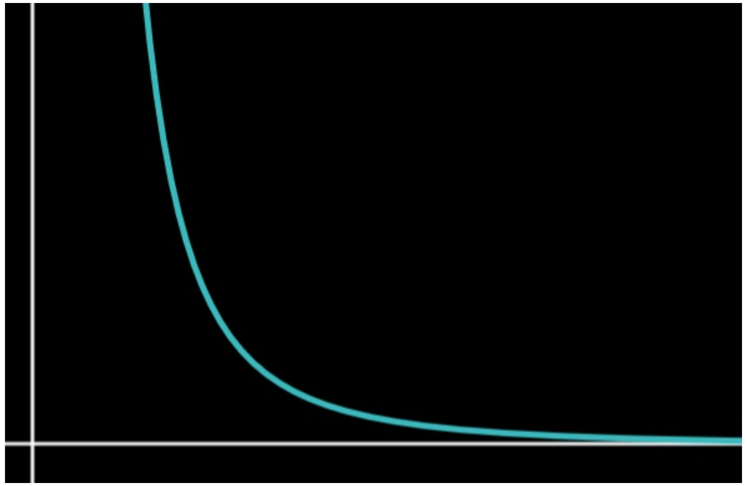


Figure 1: Shape of a power law spectrum (in linear space)

- Extragalactic sources are less visible at high energies due to Extragalactic Background Light (EBL) absorption
- $F_{\mathrm{obs.}} = F_{\mathrm{intrinsic}} \times e^{-\tau}$ where $\tau(z, E)$ is optical depth for a given redshift *z* and photon energy *E*

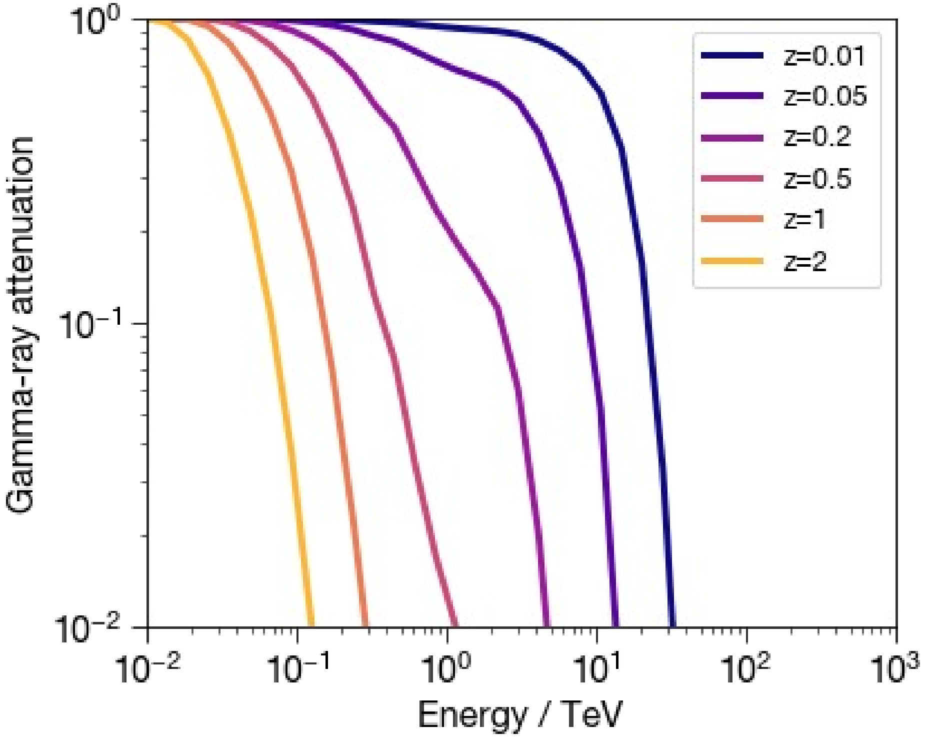
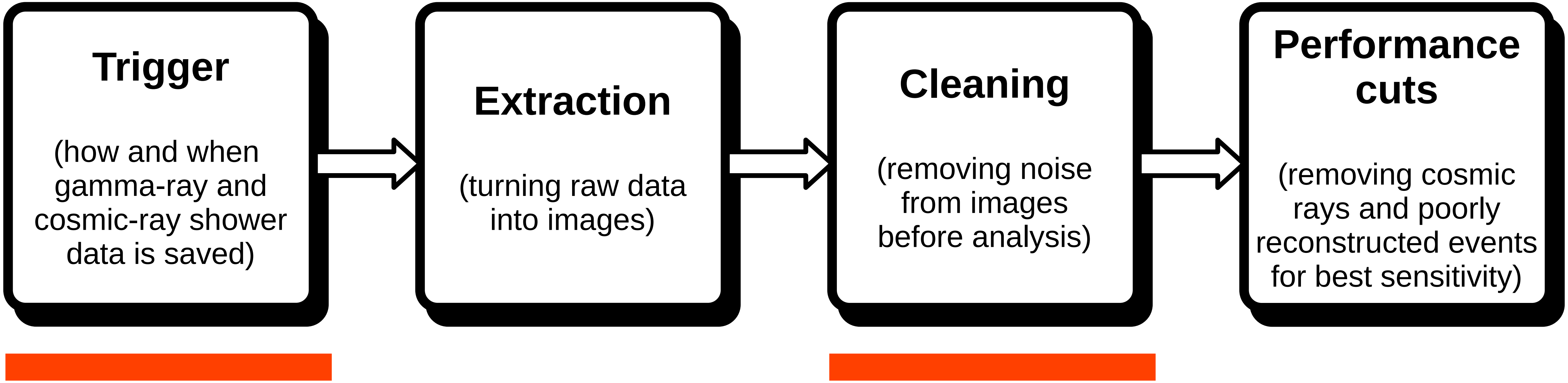
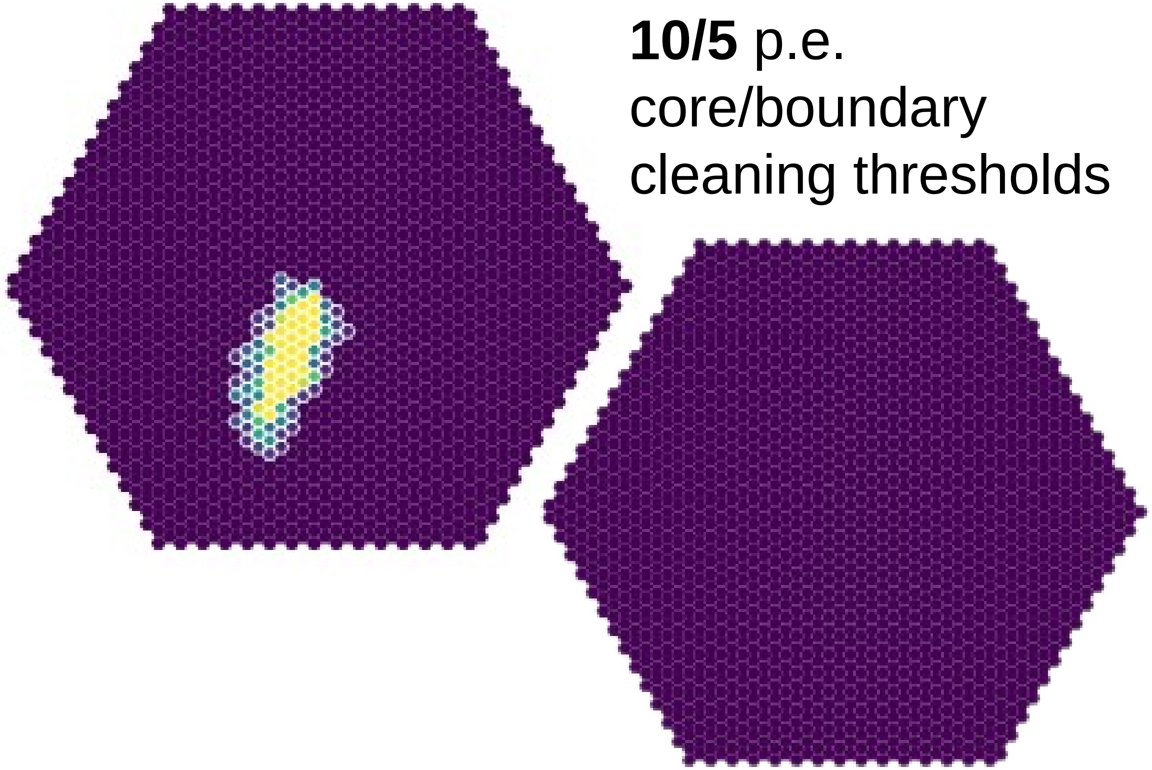


Figure 2: Gamma-ray attenuation at Earth depending on redshift (z) due to EBL absorption

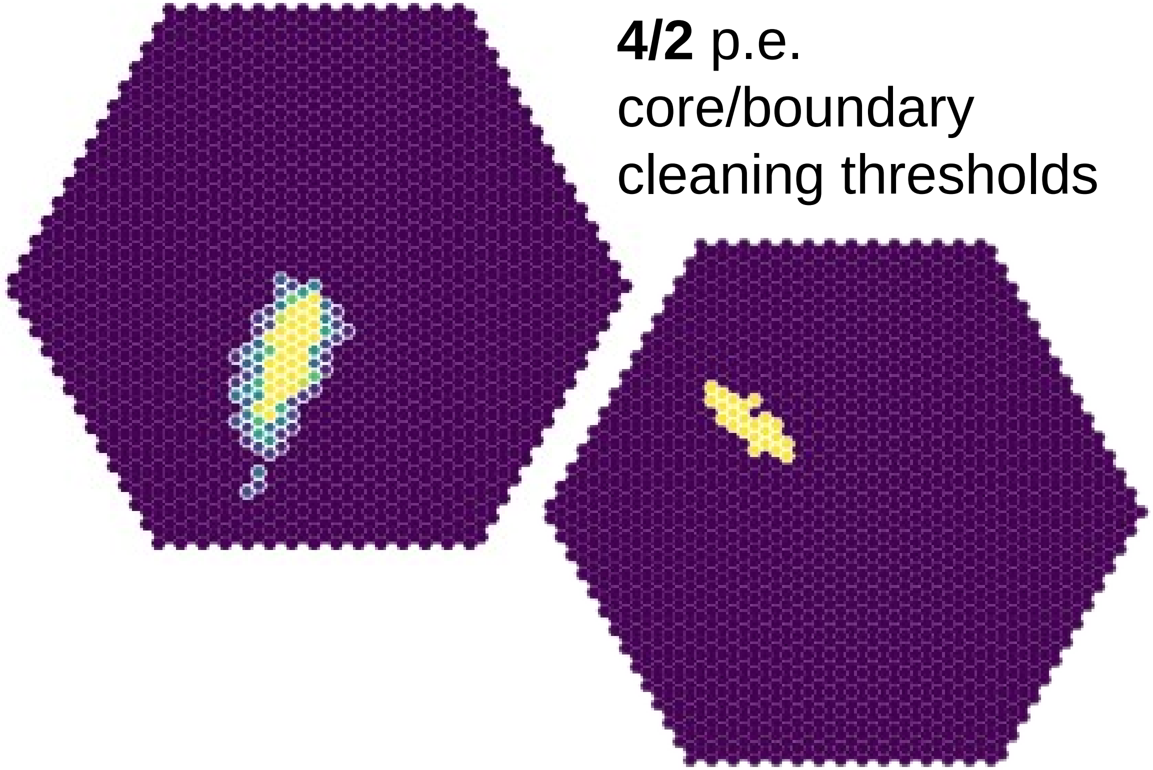
There are multiple steps that affect performance



Cleaning effects image quality and pixel survival



10/5 p.e.
core/boundary
cleaning thresholds



4/2 p.e.
core/boundary
cleaning thresholds

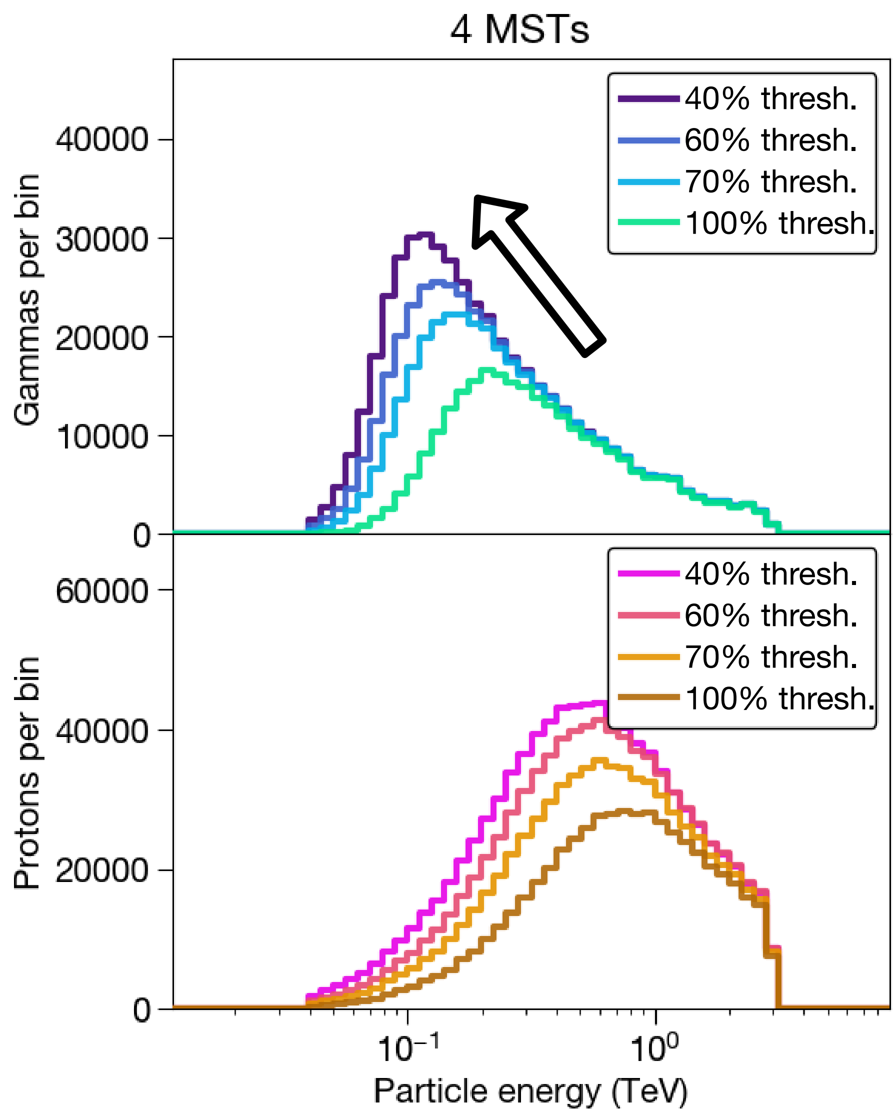
Figure 1: Two example gamma-ray shower images from FlashCam with surviving “clean” pixels highlighted, using two different cleaning thresholds

Lower cleaning thresholds let more events survive…

Good detection performance needs:

- Gamma-ray events to trigger
- Events to survive cleaning
- …

Figure 1: Distribution of surviving gamma-ray (upper) and proton (lower) events for different cleaning thresholds for an array of four MSTs using the default trigger, ***after cleaning*** *(and before performance cuts)*



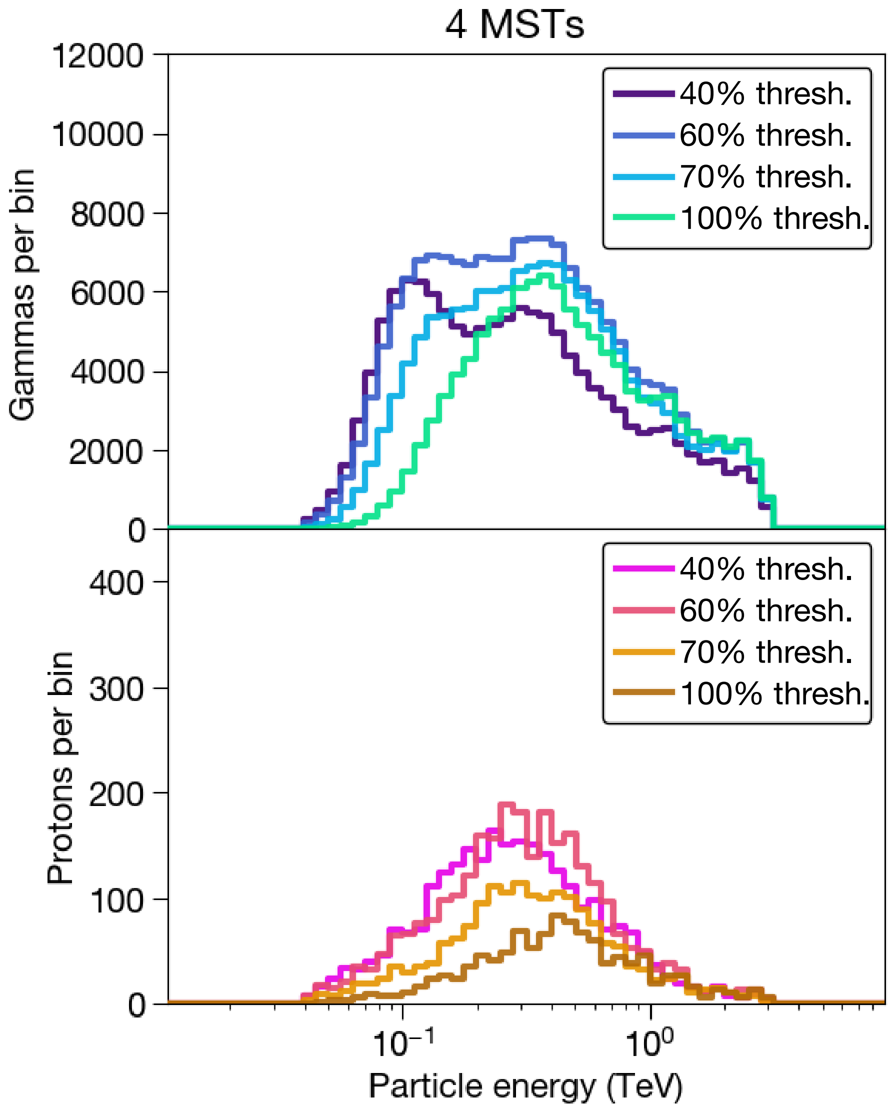
…but the end results weren't easy to decipher

Good detection performance needs:

- Gamma-ray events to trigger
- Events to survive cleaning
- Good direction reconstruction
- Good background rejection

These cannot be optimised simultaneously across all energies.

Figure 1: Distribution of surviving gamma-ray (upper) and proton (lower) events for different cleaning thresholds for an array of four MSTs using the default trigger, ***after performance cuts***



We looked at ways to reduce the trigger threshold

- The Night Sky Background (NSB) can randomly trigger cameras
- If the trigger threshold (discriminator threshold) is set too low, NSB triggers can overwhelm the hardware
- We want to reduce the camera's discriminator threshold without increasing NSB triggers
- By default, the array is triggered if any 1 telescope (monoscopic) gets triggered anywhere within its field of view
- There are other ways!

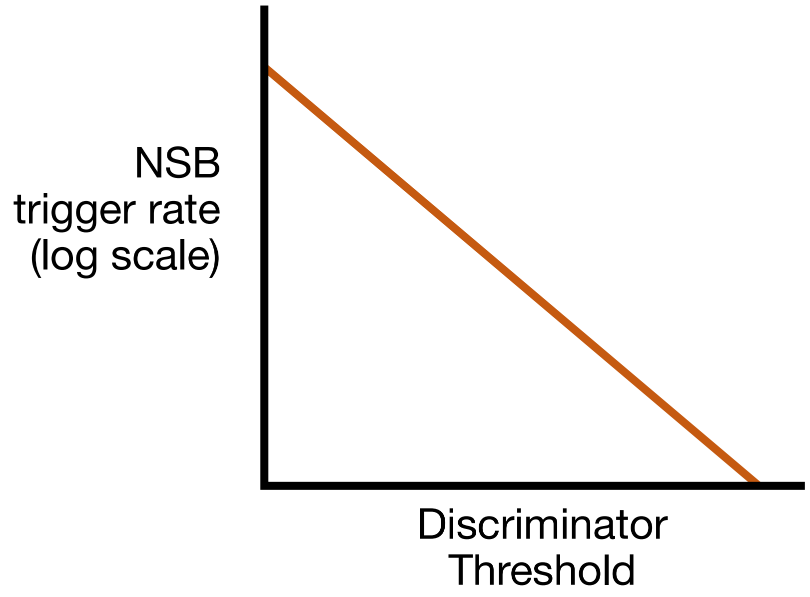


Figure 1: Relationship between discriminator threshold (DT) and the rate of camera triggers due to NSB

Stereoscopic and topological triggers were tested...

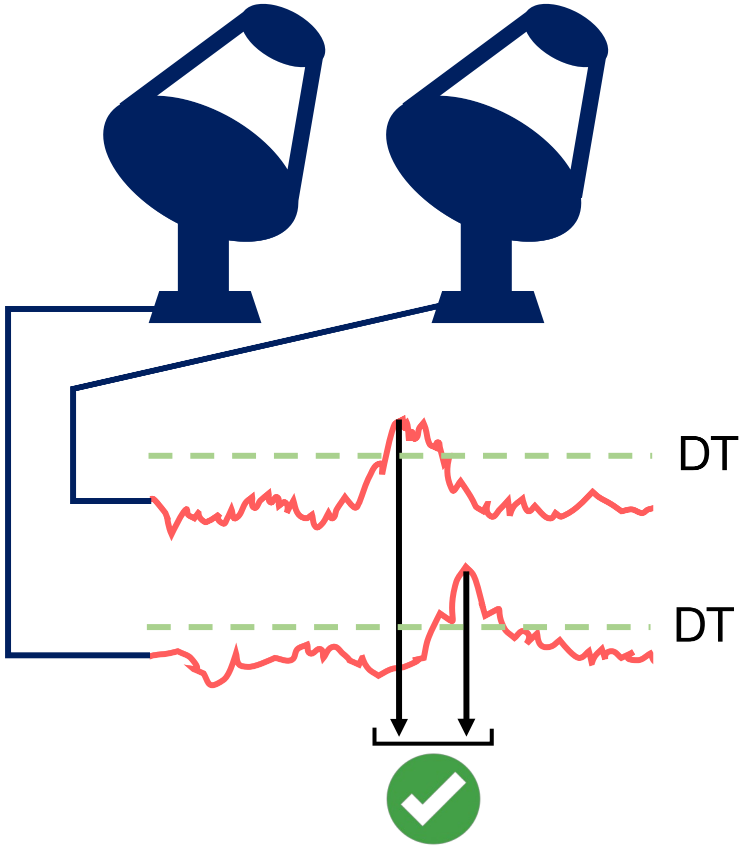


Figure 1: Diagram of how a stereoscopic array trigger works, requiring signals to cross a Discriminator Threshold in a time window

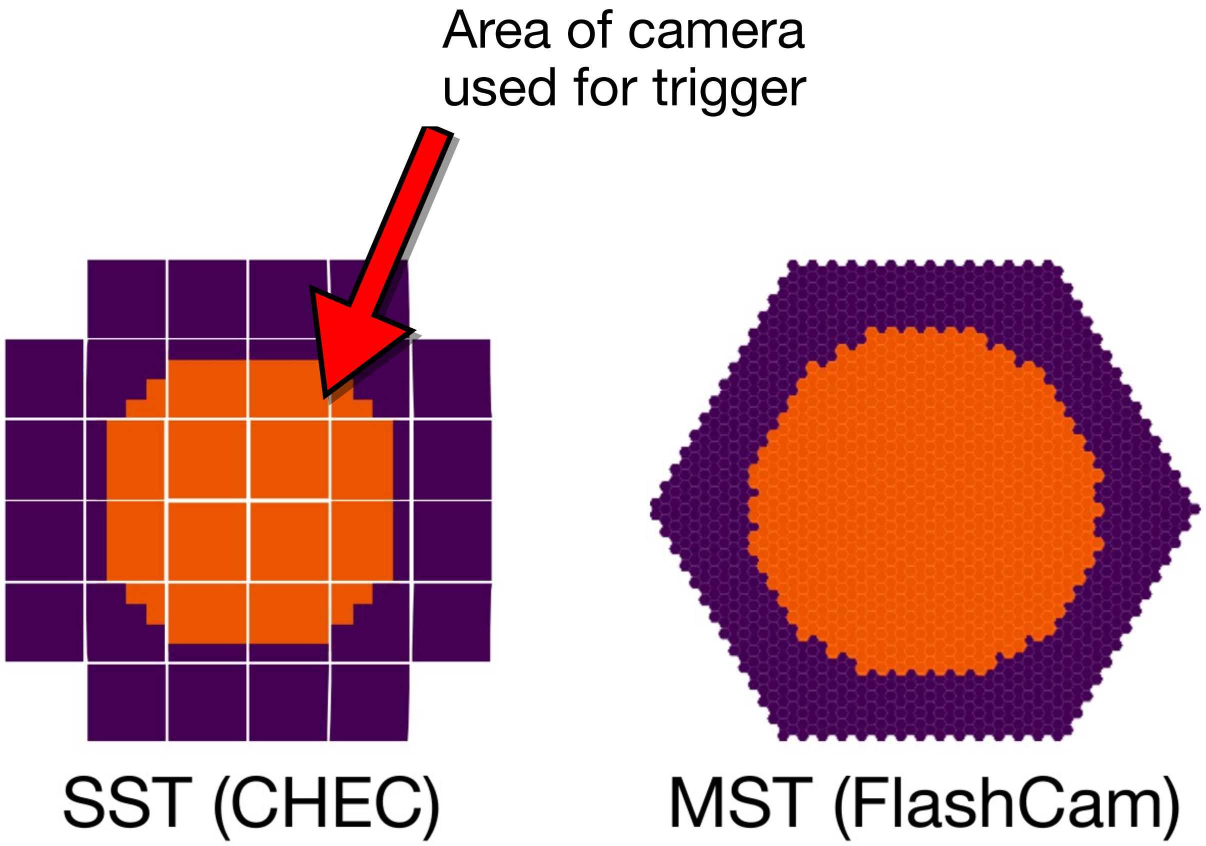


Figure 2: Central circular topological trigger areas tested to reduce NSB and proton trigger

...and the combo of both. Results varied for different arrays.

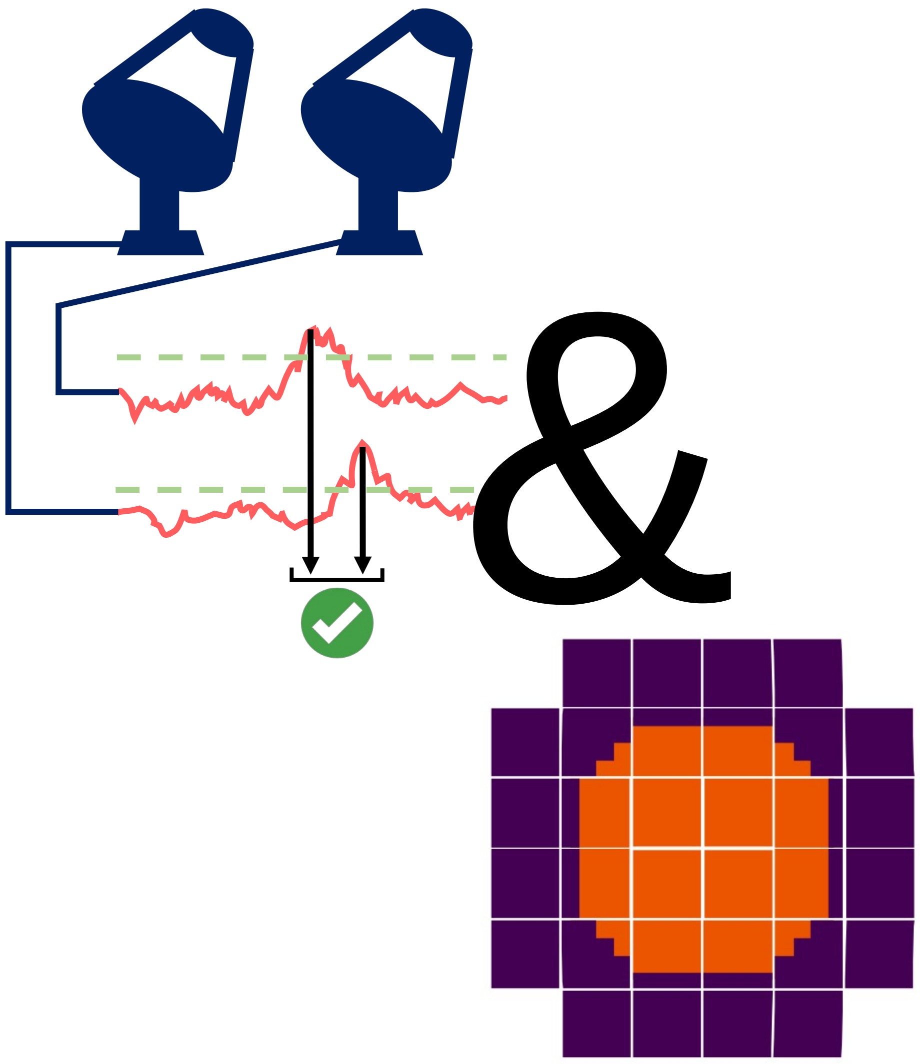
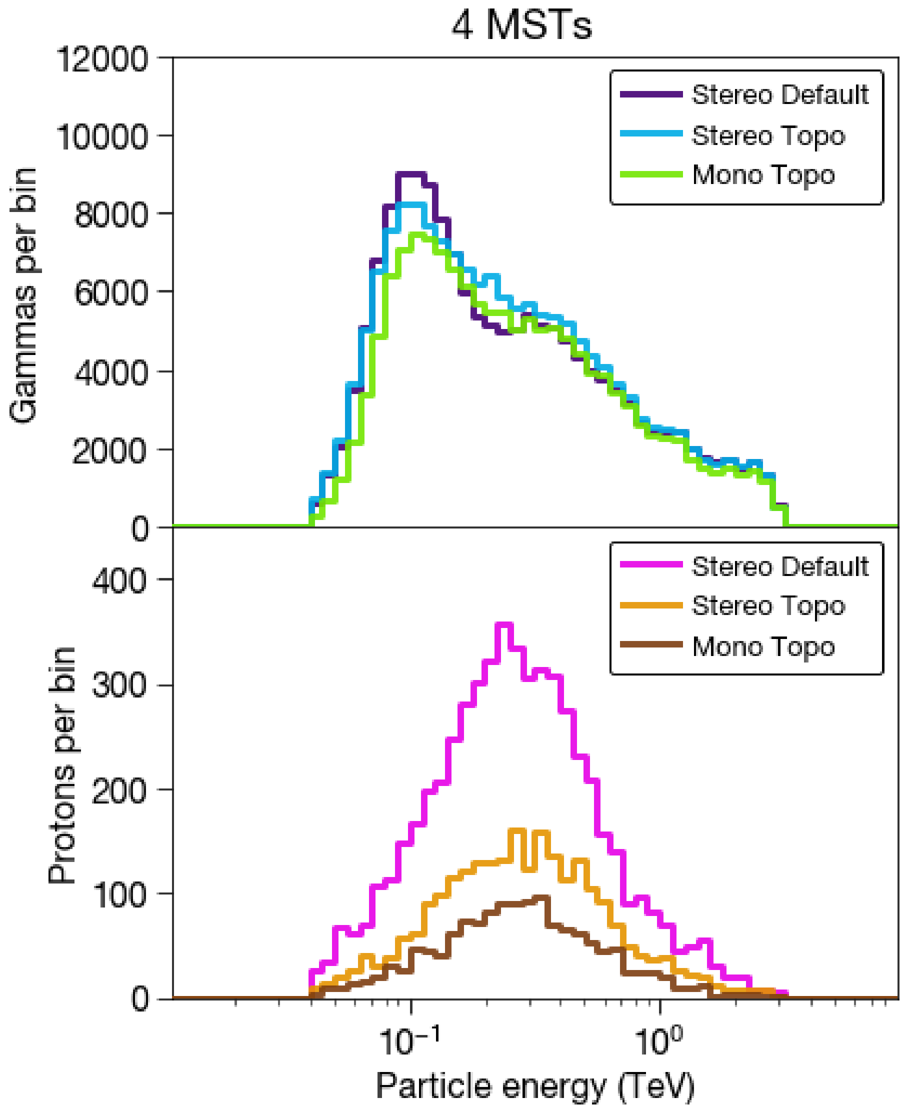


Figure 1: Distribution of surviving gamma-ray (upper) and proton (lower) events for different trigger arrangements for an array of four MSTs

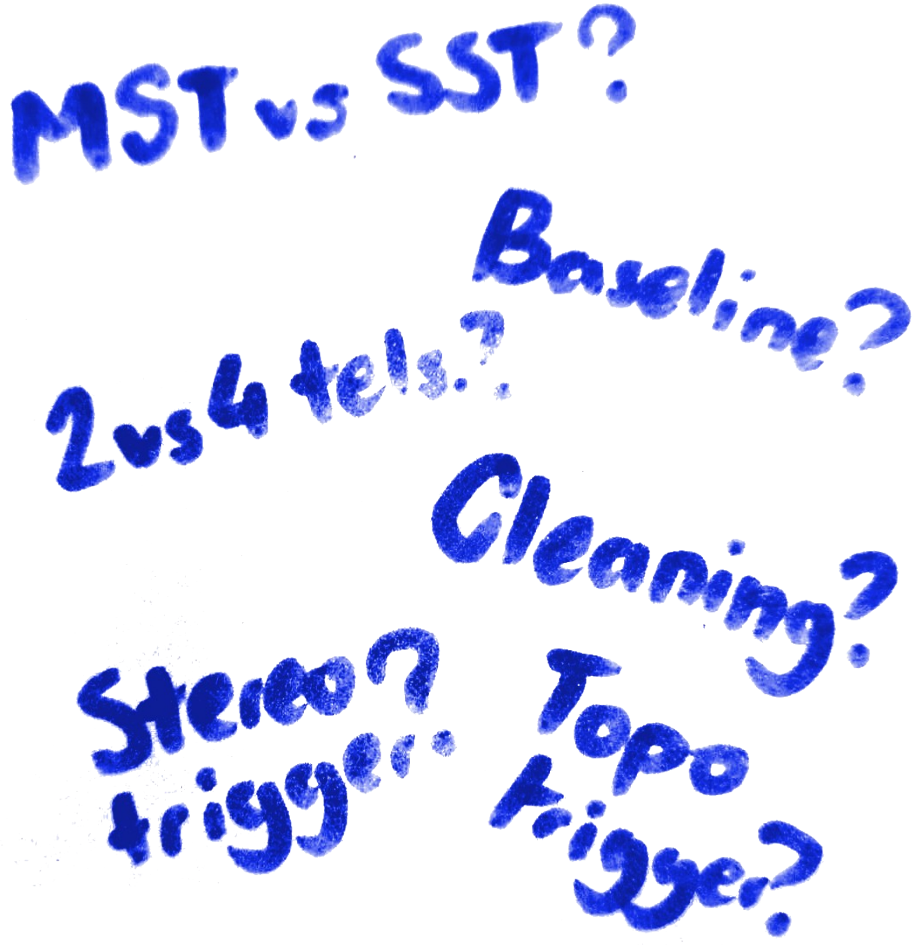


An analysis method was devised

To compare results, the analysis became a two-pronged question:

- How many γ-ray transients could an Australian IACT array detect?
- Which array configuration and processing is most suitable?

To do this, we needed to simulate all the tested arrays observing a large collection of γ-ray transients.



We simulated arrays observing *Fermi*-LAT flares

- The *Fermi* All-sky Variability Analysis catalogue is the largest collection of gamma-ray flares (over 4000 transients)
- We used flares from the second data release (S. Abdollahi *et al* 2017 *ApJ* **846** 34) and more up to 2023 from the online database

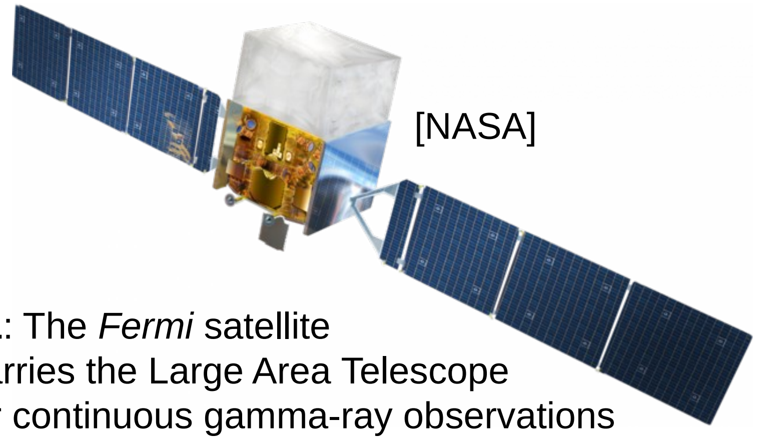


Figure 1: The *Fermi* satellite which carries the Large Area Telescope (LAT) for continuous gamma-ray observations

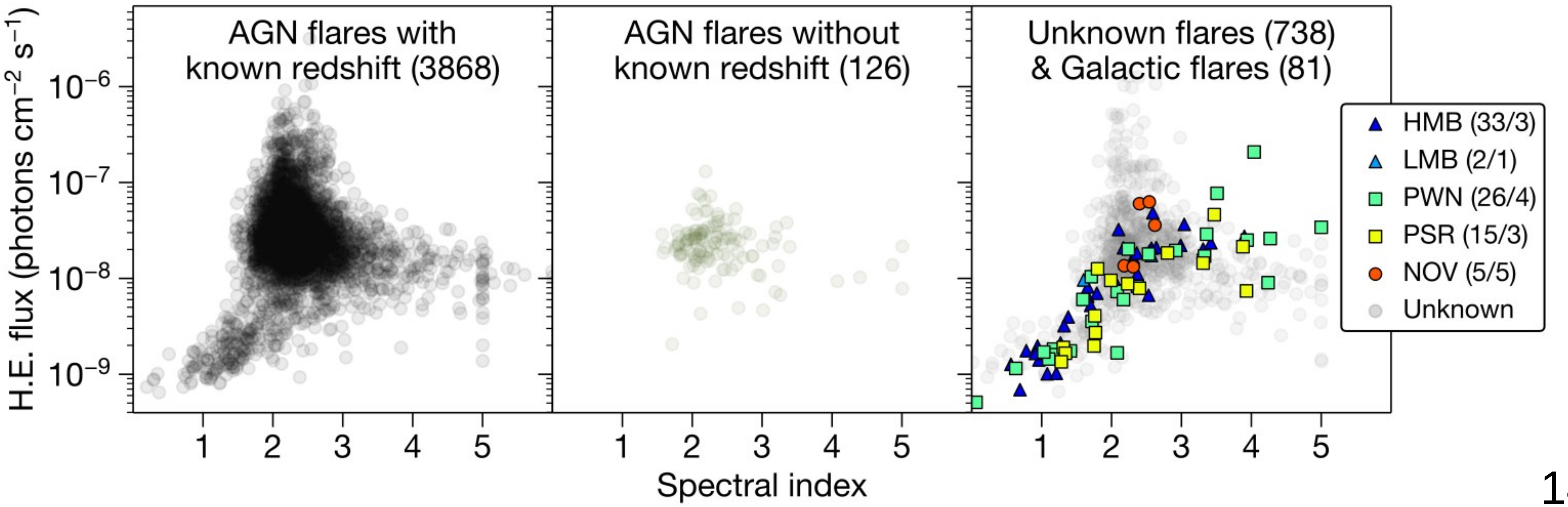


Figure 2: Flares in the FAVA weekly flare catalogue up to 2023-02-20, showing their photon flux and spectral index in the *Fermi*-LAT high-energy band (0.8–300 GeV). Only local maxima are included for multi-week flares.

We made assumptions about sources and observations…

1: Consistent spectral index **2:** 4-hour observation per flare **3:** Flare seen at 2x weekly average flux

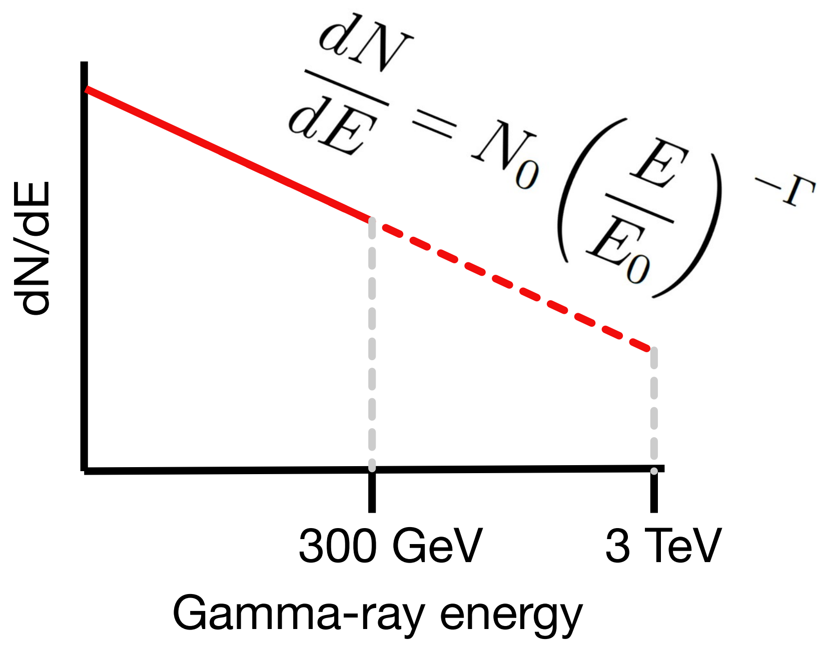


Figure 1: Sketch demonstration the modelling of intrinsic source flux with a consistent spectral index from the measured maximum of 300 GeV to the simulated maximum of 3 TeV

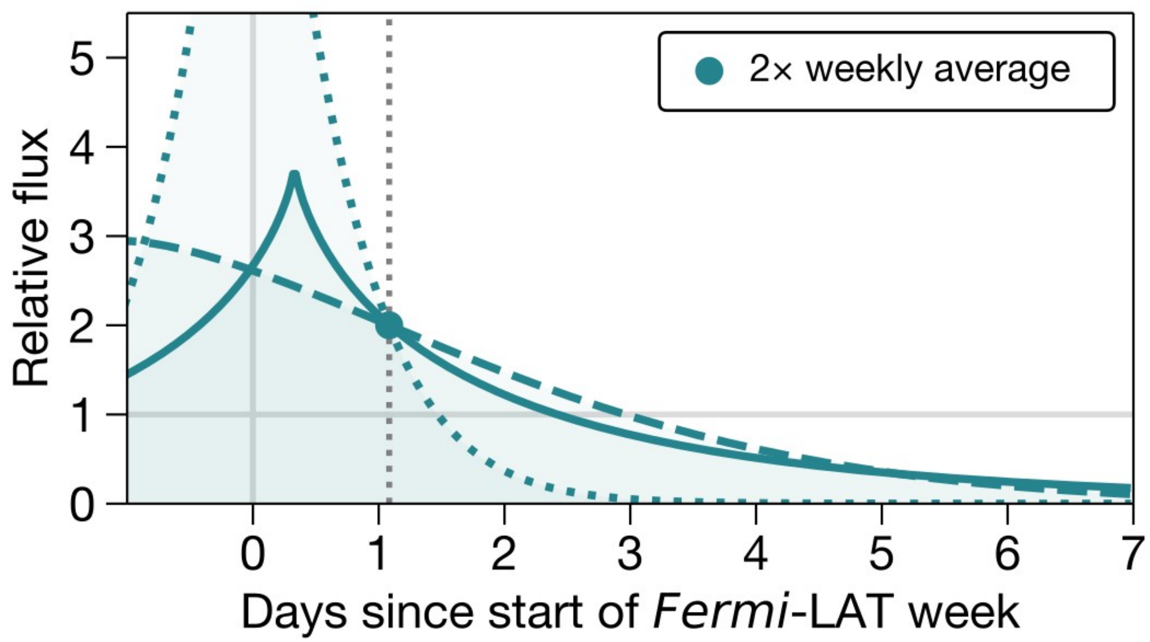
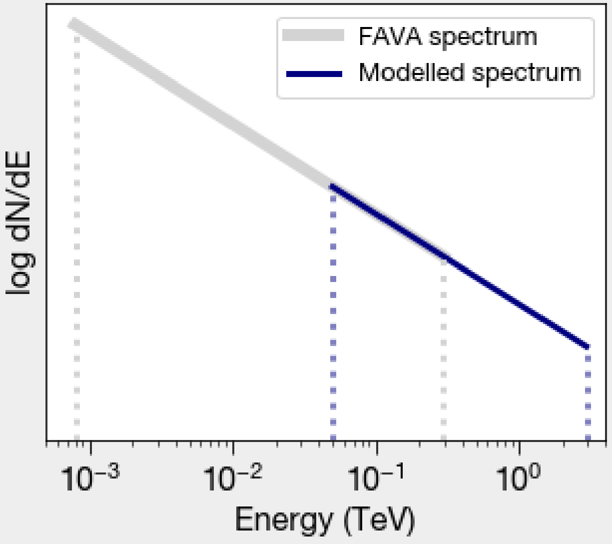


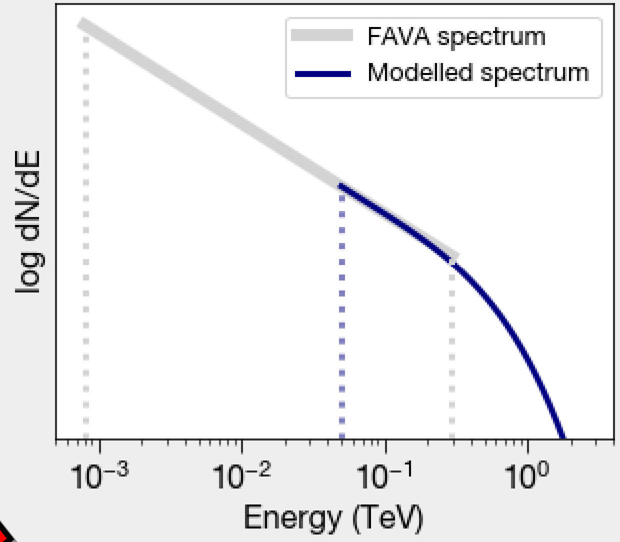
Figure 2: Demonstration of flare shapes that result in 2x relative flux 26 hours in to a Fermi-LAT week (i.e. in the middle of a four-hour observation starting after 24 hours).

…and modelled to see which transients were detectable >5σ

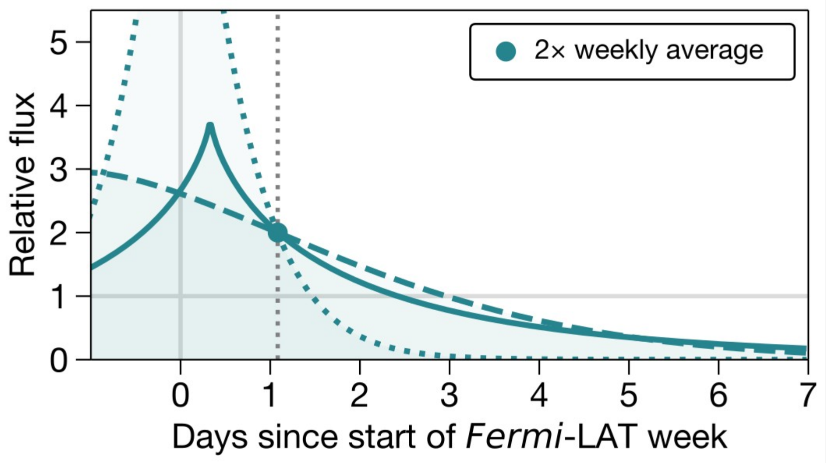
Step 1: Extend FAVA spectrum up to 3 TeV



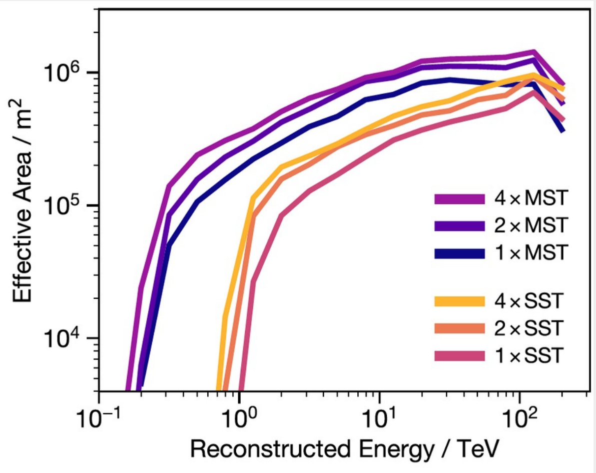
Step 2: Add EBL absorption



Step 3: Assume flux is 2x the FAVA weekly average



Step 4: Convolve with effective area of arrays for 4-hour observations



Of those 1694 flares within 30° zenith…

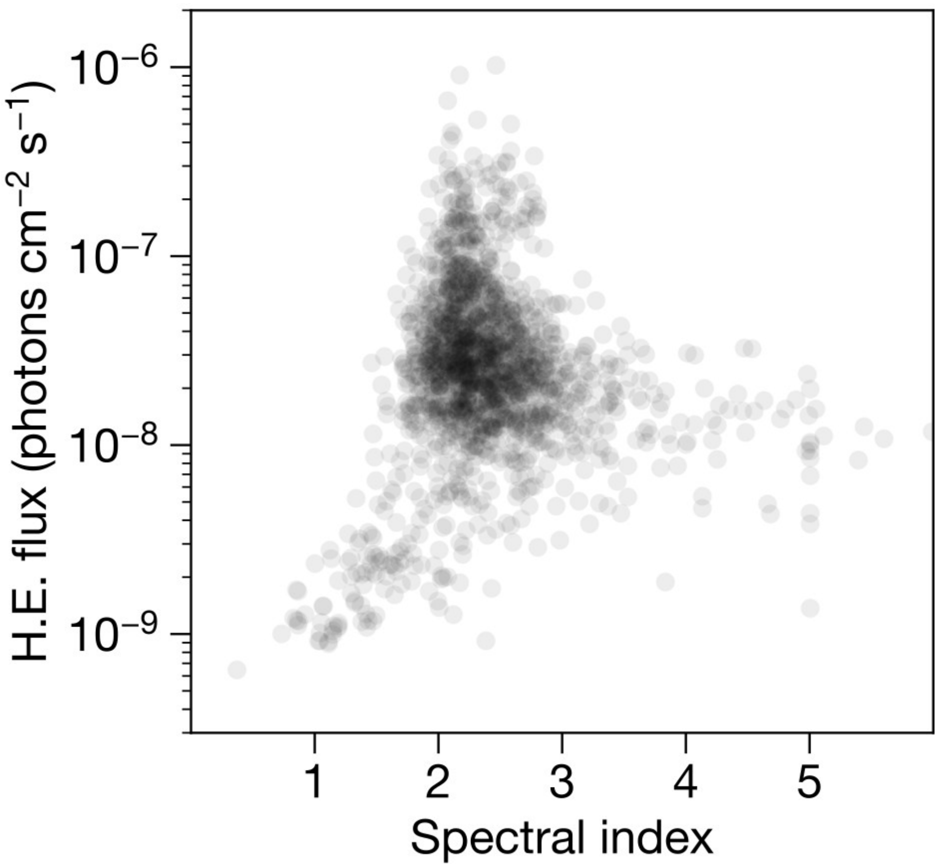


Figure 1: High-energy photon flux and spectral index of FAVA AGN flares at −60° ≤ dec ≤ 0° from August 2008 to February 2023.

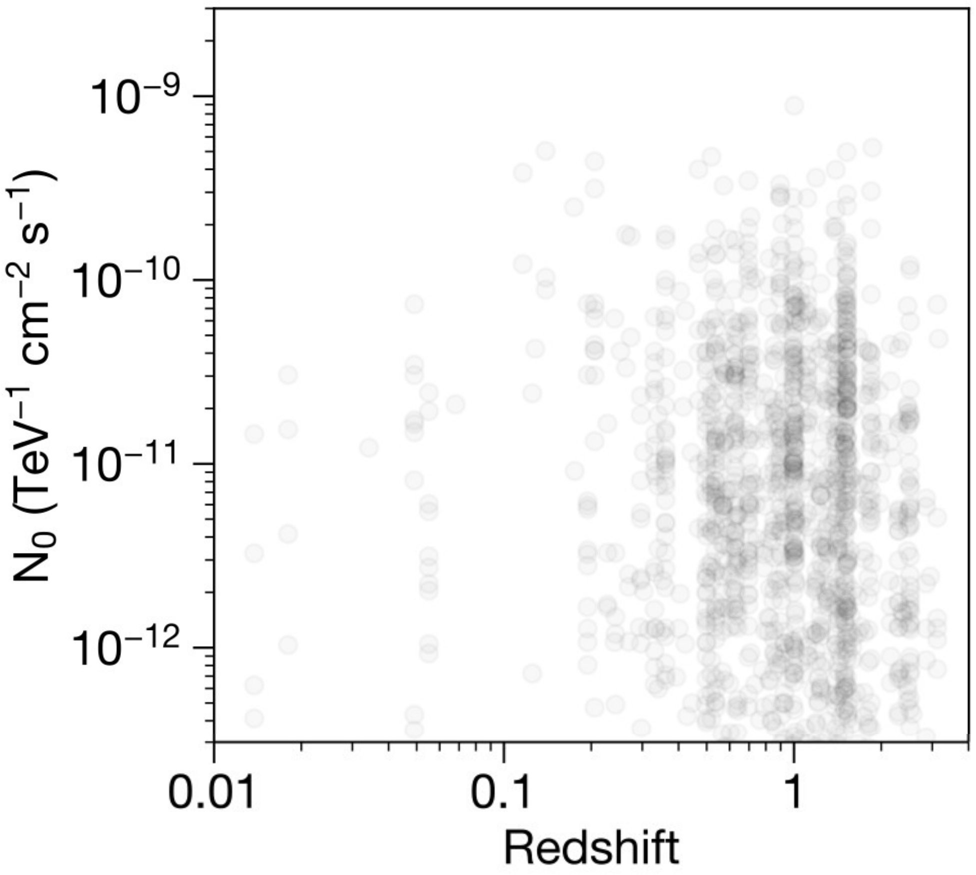


Figure 2: Normalisation constant (N_0) at 1 TeV and redshift of AGN flares from Figure 1

4×MSTs could detect out to z≈1.5, 4×SST to z≈0.7

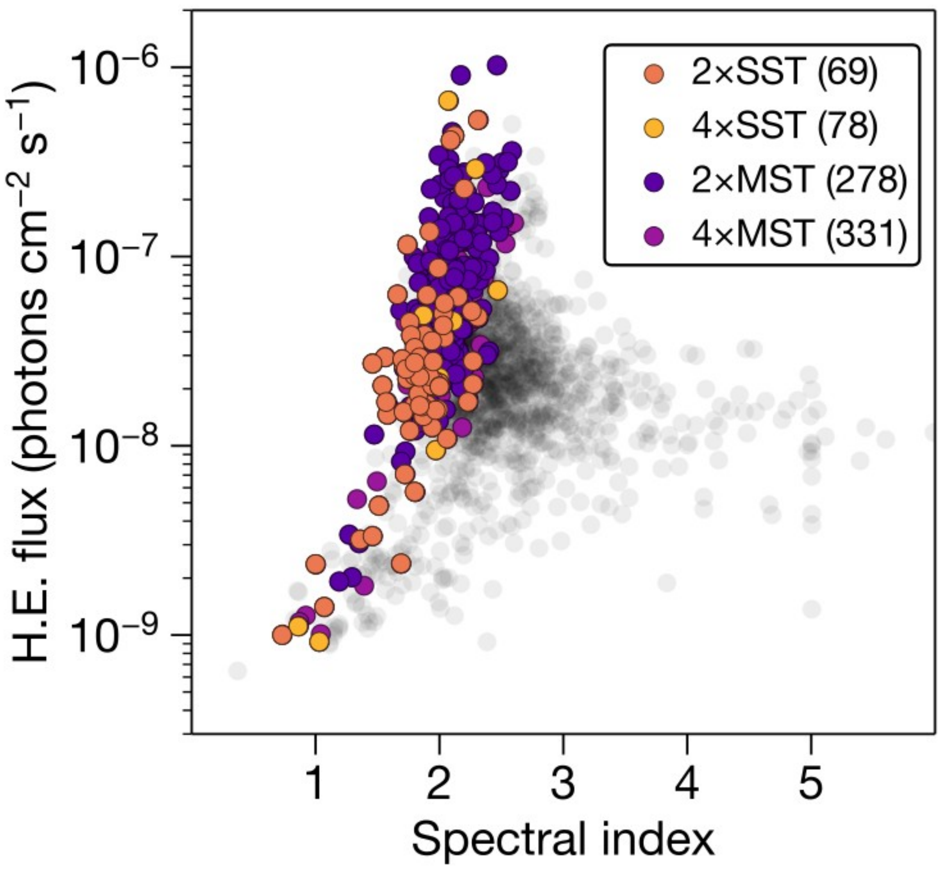


Figure 1: High-energy photon flux and spectral index of FAVA AGN flares at −60° ≤ dec ≤ 0° from August 2008 to February 2023. Highlighted points show flares detectable >5σ, with total flare counts listed in brackets.

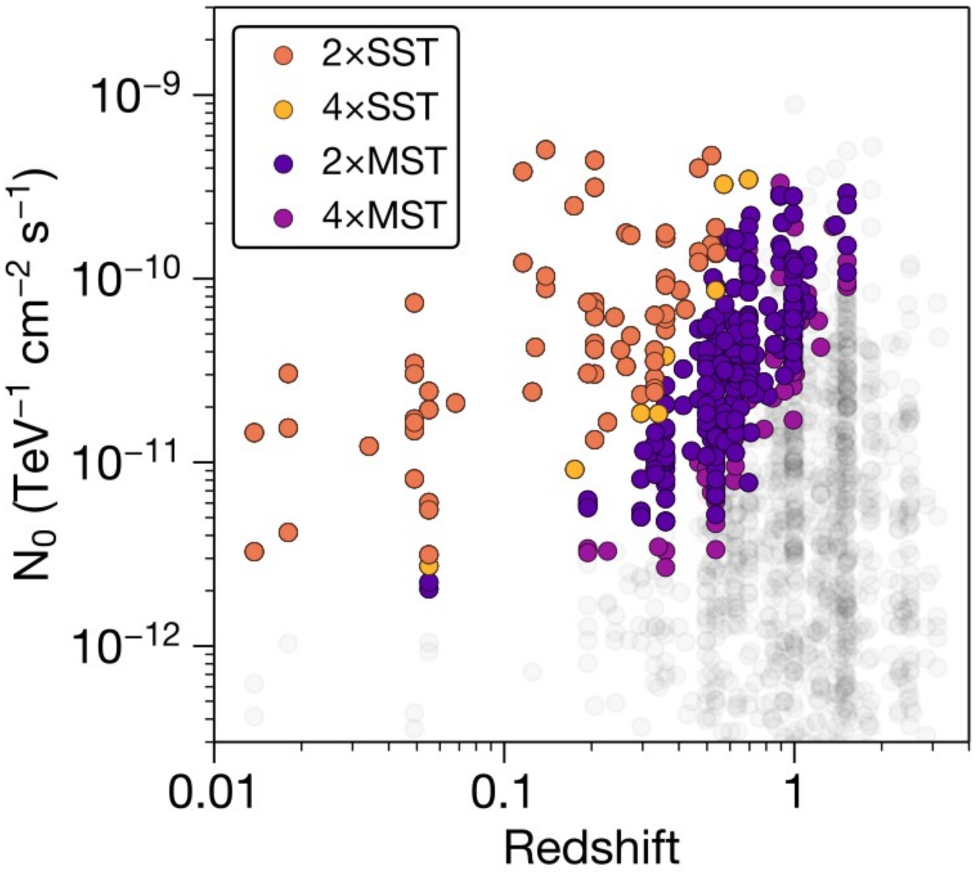


Figure 2: Normalisation constant (N_0) at 1 TeV and redshift of AGN flares from Figure 1

Different arrays performed better with different setups

4xMST

Trigger	Cleaning thresh.	Quality cuts	No. flares
Stereo default	0.54	None	346
Stereo large-topo	0.7	No intensity	341
Stereo default	0.54	No intensity	332
Stereo default	0.54	Default	331
Stereo small-topo	0.7	No intensity	331
Mono default	*0.6*	*None*	*331*

4xSST

Trigger	Cleaning thresh.	Quality cuts	No. flares
Mono large-topo	0.4	No intensity	82
Mono large-topo	0.42	No intensity	79
Stereo large-topo	0.31	No intensity	78
Stereo small-topo	0.4	No intensity	77
Mono default	*0.4*	*No intensity*	*75*
Stereo default	0.29	No intensity	75

2xMST

Trigger	Cleaning thresh.	Quality cuts	No. flares
Stereo large-topo	0.55	No intensity	292
Mono default	*0.6*	*No intensity*	*291*
Mono large-topo	0.4	No intensity	287
Mono large-topo	0.64	No intensity	287
Mono default	0.4	No intensity	281
Stereo default	0.55	No intensity	279

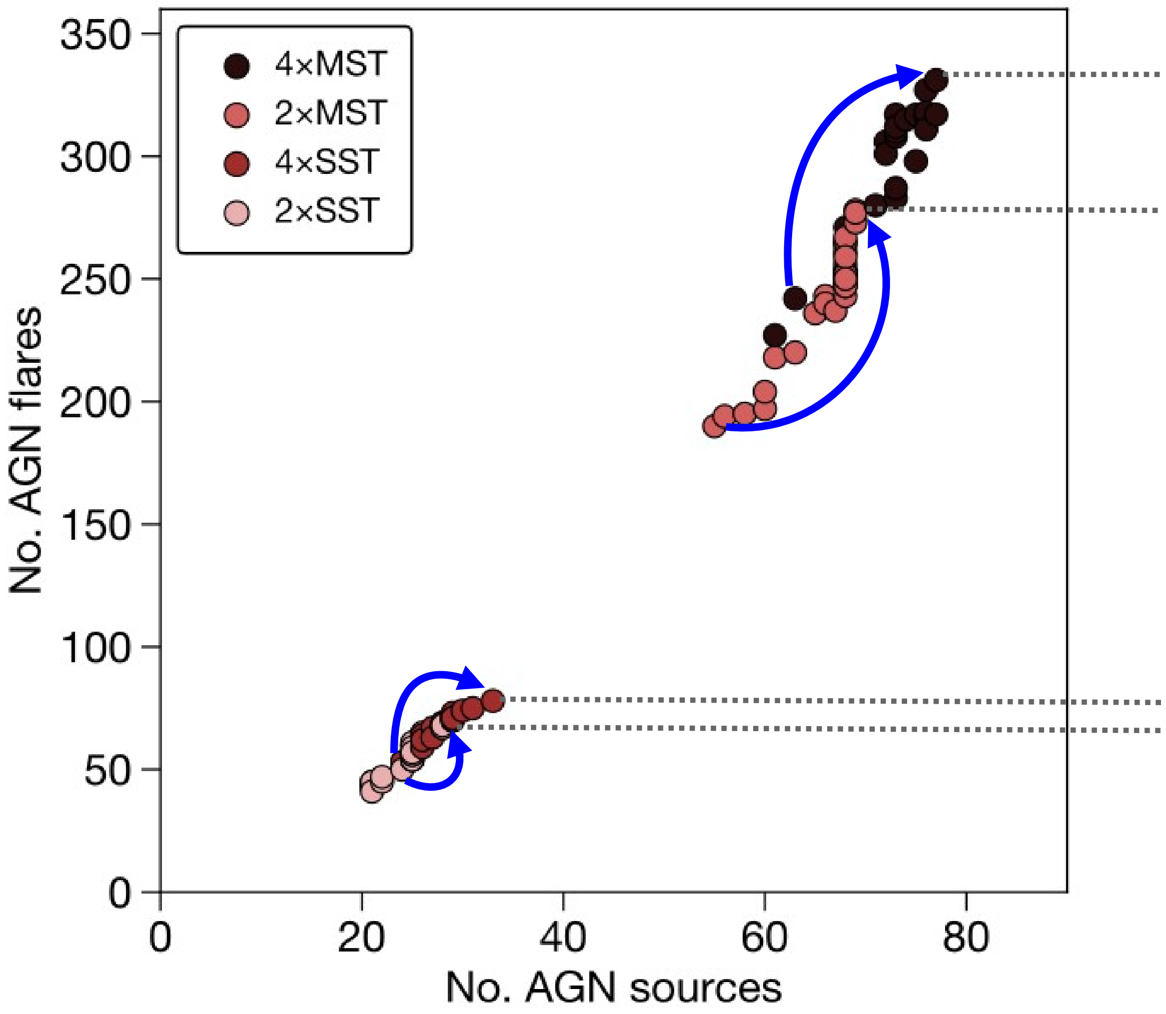
2xSST

Trigger	Cleaning thresh.	Quality cuts	No. flares
Mono default	*0.24*	*No intensity*	*72*
Mono large-topo	0.4	No intensity	71
Mono default	0.24	No intensity	70
Mono large-topo	0.42	No intensity	70
Stereo large-topo	0.3	No intensity	68
Mono large-topo	0.42	No intensity	64

Different arrays performed better with different setups

Figure 1: Number of distinct flares and sources of FAVA AGN flares for all tested array configurations (depending on baseline, trigger arrangement, cleaning threshold, and quality cuts), for different numbers and sizes of telescopes.

Blue arrows show improvement from default setups.



Setup used for best performance:

4xMST, Stereo trigger, 55% clean

2xMST, Default trigger, 60% clean

4xSST, Topo trigger, 40% clean

2xSST, Default trigger, 25% clean

A 4×MST array could see ~24 AGN flares per year

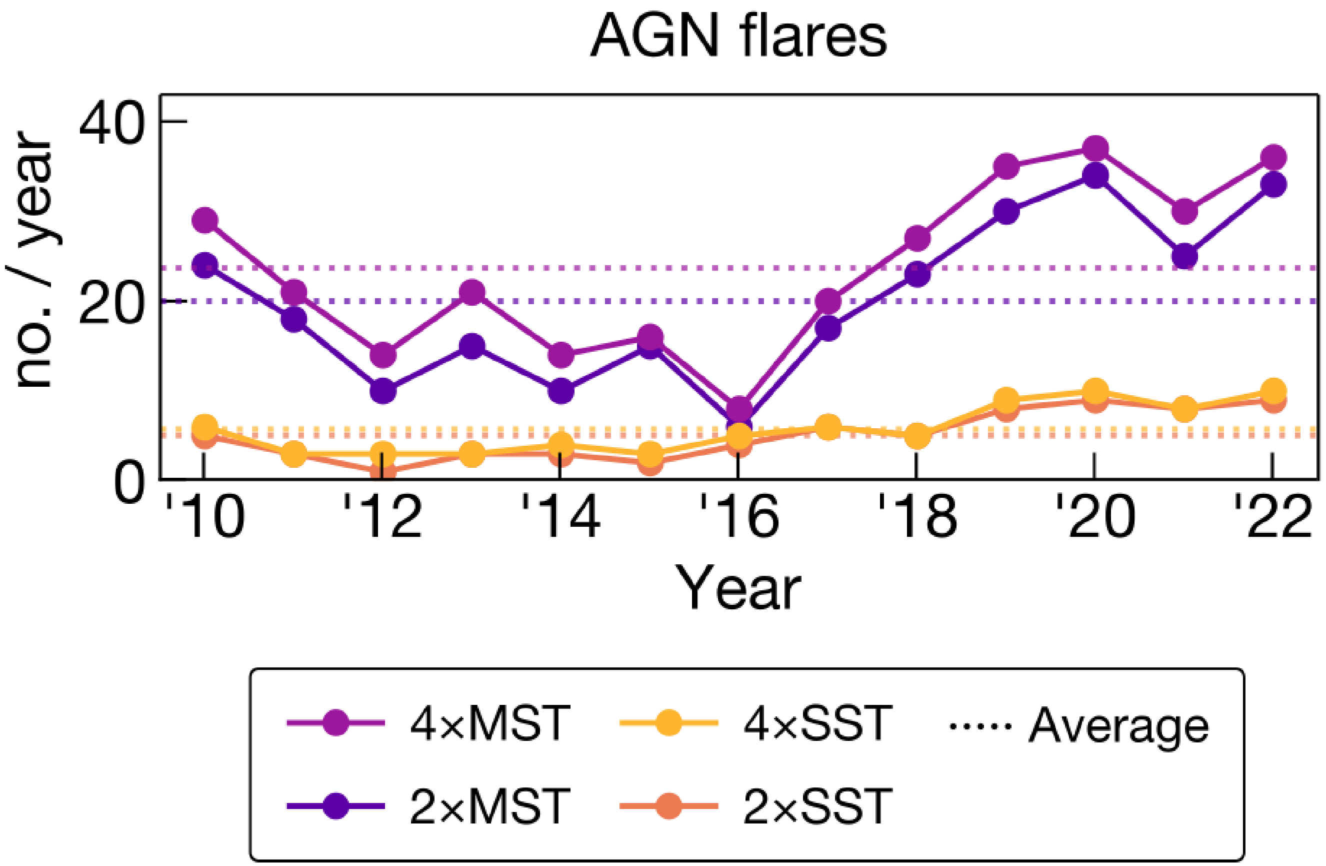


Figure 1: Number (upper) of AGN flares from the FAVA catalogue at −60◦ ≤ dec ≤ 0◦ detectable at >5σ per year from 2010 to 2022. 4-hour observations and flare fluxes 2× the recorded weekly average, emulating a flux peak.

...which is ~20% of the FAVA high-energy flares

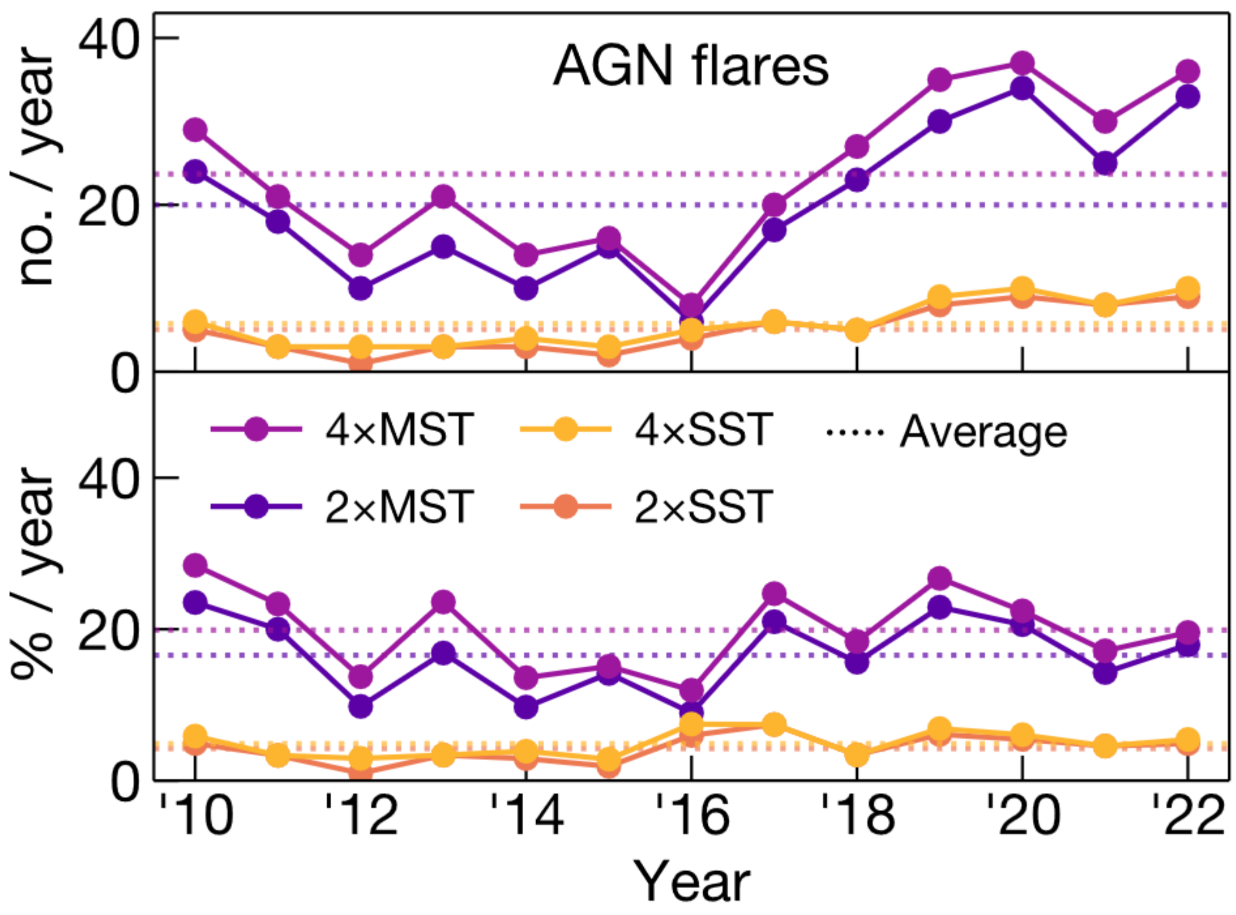


Figure 1: Number (upper) and percentage (lower) of AGN flares from the FAVA catalogue at −60◦ ≤ dec ≤ 0◦ detectable at >5σ per year from 2010 to 2022. 4-hour observations and flare fluxes 2× the recorded weekly average, emulating a flux peak.

MSTs could perhaps detect ~9% of unknown FAVA flares

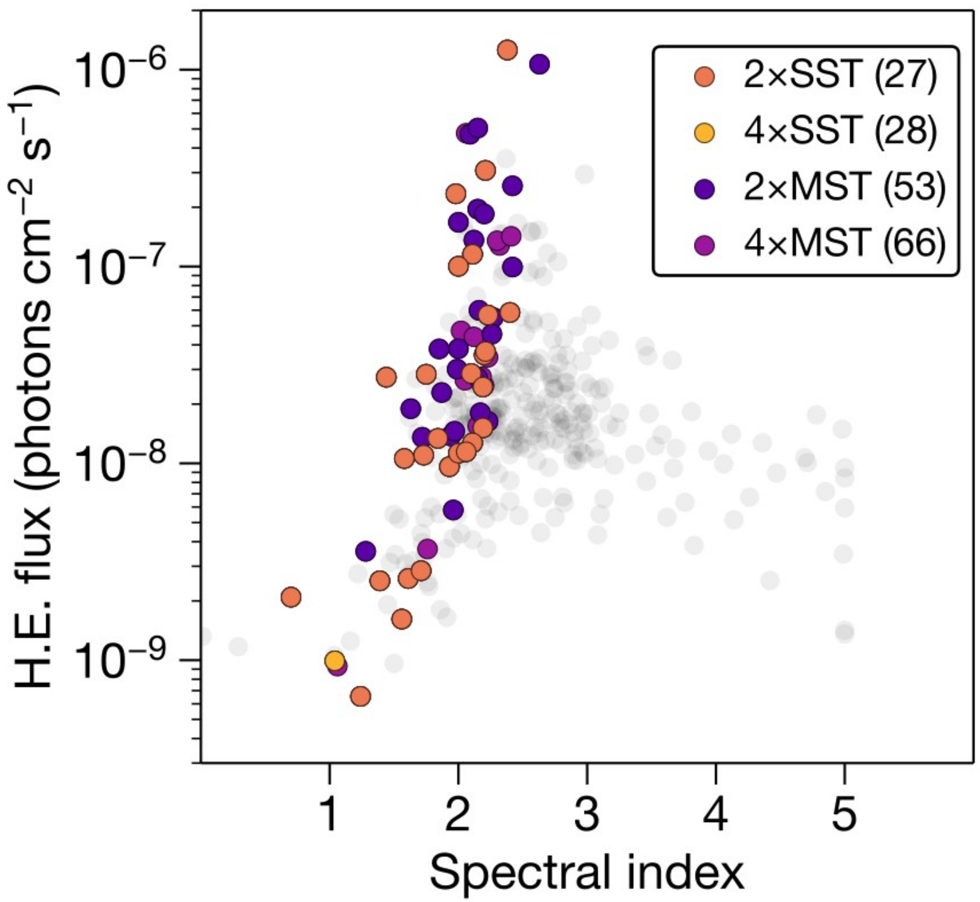


Figure 1: High-energy photon flux and spectral index of unknown FAVA flares at −60° ≤ dec ≤ 0° from August 2008 to February 2023. Highlighted points show flares detectable >5σ, with total flare counts listed in brackets.

Galactic transients and some GRBs could be detected

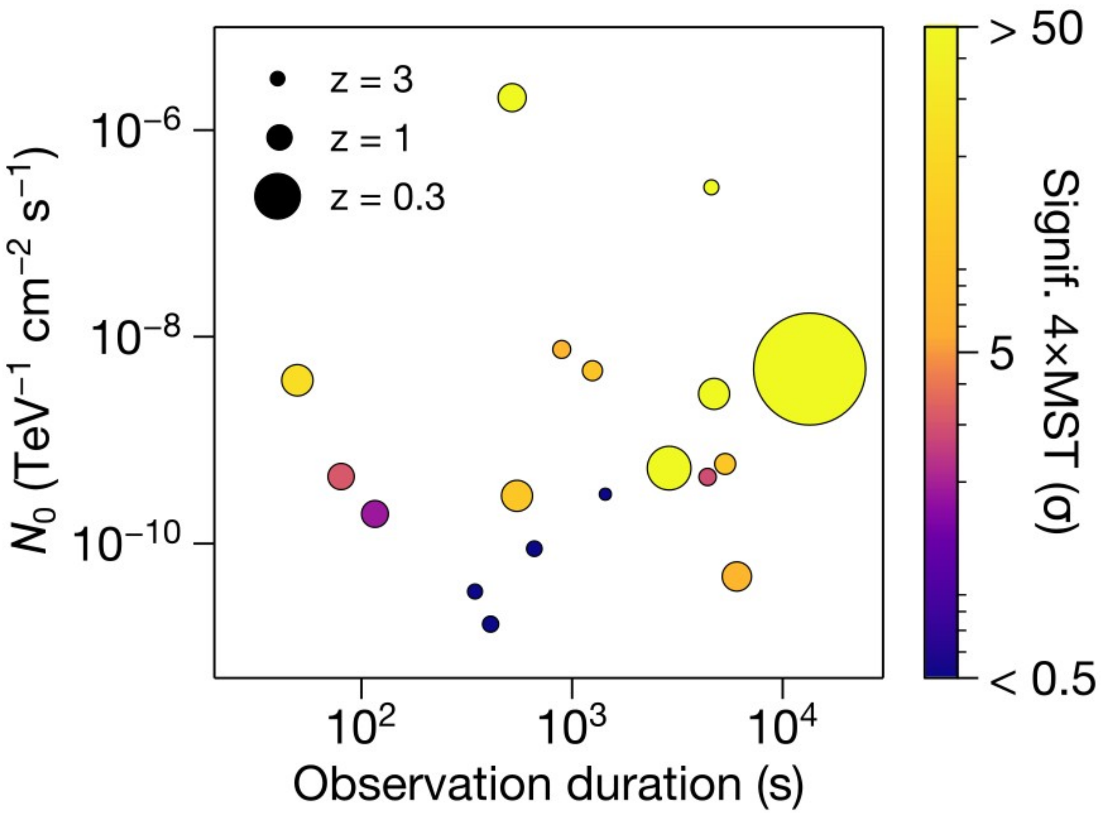


Figure 1: Southern Hemisphere GRBs with known redshift detected by *Fermi*-LAT up until June 2022. Depicted are the modelled observation time windows (from 90s post-trigger to the end of the *Fermi*-LAT observation window), normalisation constant N_0 at 1 TeV from integrating the measured flux between 100 MeV and 100 GeV, redshift, and detection significance from a 4×MST array (colour).

	4× MST	2× MST	4× SST	2× SST
PSR B1259-63	1.5 hr	1.9 hr	7.0 hr	8.5 hr
V1324 Scorpii	5.5 hr	6.0 hr	17.0 hr	18.5 hr
V1369 Centauri	9.5 hr	8.0 hr	19.0 hr	20.0 hr
HESS J1303-631	35 min	35 min	1.6 hr	1.8 hr
HESS J1813-178	5.0 hr	3.5 hr	7.0 hr	7.0 hr

Figure 2: Time for a 5σ detection of Southern Hemisphere high-energy transient Galactic sources in the FAVA catalogue for different array configurations.

These results and more are also in a paper

"Optimising an Array of Cherenkov Telescopes in Australia for the Detection of TeV Gamma-Ray Transients"

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doi:10.1017/pasa.2024.48

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Research Article

Optimising an array of Cherenkov telescopes in Australia for the detection of TeV gamma-ray transients

Simon Lee[1], Sabrina Einecke[1], Gavin Rowell[1], Csaba Balazs[2], Jose Bellido[1], Shi Dai[3], Miroslav D. Filipović[3], Violet Harvey[1], Padric McGee[1], Peter Marinos[1], Nicholas Tothill[3] and Martin White[1]

[1]School of Physics, Chemistry and Earth Sciences, The University of Adelaide, Adelaide, SA, Australia, [2]School of Physics and Astronomy, Monash University, Melbourne, VIC, Australia and [3]School of Science, Western Sydney University, Penrith, NSW, Australia

Abstract

As TeV gamma-ray astronomy progresses into the era of the Cherenkov Telescope Array (CTA), instantaneously following up on gamma-ray transients is becoming more important than ever. To this end, a worldwide network of Imaging Atmospheric Cherenkov Telescopes has been proposed. Australia is ideally suited to provide coverage of part of the Southern Hemisphere sky inaccessible to H.E.S.S. in Namibia and the upcoming CTA-South in Chile. This study assesses the sources detectable by a small, transient-focused array in Australia based on CTA telescope designs. The TeV emission of extragalactic sources (including the majority of gamma-ray transients) can suffer significant absorption by the extragalactic background light. As such, we explored the improvements possible by implementing stereoscopic and topological triggers, as well as lowered image cleaning thresholds, to access lower energies. We modelled flaring gamma-ray sources based on past measurements from the satellite-based gamma-ray telescope *Fermi*-LAT. We estimate that an array of four Medium-Sized Telescopes (MSTs) would detect ~24 active galactic nucleus flares >5σ per year, up to a redshift of $z \approx 1.5$. Two MSTs achieved ~80–90% of the detections of four MSTs. The modelled Galactic transients were detectable within the observation time of one night, 11 of the 21 modelled gamma-ray bursts were detectable, as were ~10% of unidentified transients. An array of MST-class telescopes would thus be a valuable complementary telescope array for transient TeV gamma-ray astronomy.

Keywords: Monte Carlo simulations; IACT; gamma-ray astronomy; stereo trigger; topo trigger; transients; AGN; gamma-ray bursts; novae; EBL

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1. Introduction

Extending multi-wavelength studies to GeV and TeV energies has allowed us to probe the nature of the universe's most extreme sources, environments, and phenomena. These astronomical domains also act as our highest-energy laboratories for exploring particle physics beyond the standard model. There are however deficiencies in the field compared to those concerned with other electromagnetic wavelengths. In particular, there is at present limited capacity to instantaneously follow up on and continuously monitor short-lived, variable, transient phenomena over a 24-hr period.

The flares of active galactic nuclei (AGNs) make up the vast majority of known gamma-ray transients above 10 GeV (Abdollahi et al. 2017). The great distance of most AGNs tends to make their TeV emissions subject to significant absorption by the extragalactic background light (EBL). Gamma-ray bursts (GRBs), now understood to be either from compact stellar mergers or the core collapse of massive stars, are similarly of extragalactic origin and are generally very short-lived (lasting milliseconds to, at most, days). Alongside Galactic transients like novae, pulsars, and binaries, there is a substantial collection of transient events which are either associated with objects of unknown classification, or not associated with any counterpart. Thoroughly studying these phenomena at high energies is challenging, and there is much opportunity for new discovery.

There are three broad categories of telescopes observing these photon energies, each with their advantages and limitations. *Fermi*-LAT[a] is a satellite-based direct-detection telescope providing quasi-continuous all-sky monitoring from 20 MeV to ~1 TeV (Atwood et al. 2013). Its small collection area of <1 m^2 (Maldera et al. 2021) however results in day-scale time resolution for all but the most extreme sources, and it has low sensitivity to emission above 10 GeV. Water Cherenkov detectors, such as HAWC,[b] LHAASO,[c] and the proposed SWGO,[d] measure Cherenkov radiation generated in water from passing charged particles created in gamma-ray- (or cosmic-ray-) induced particle showers in the atmosphere (HAWC Collaboration 2015; Zhang 2021; Abreu et al. 2019). These benefit from effectively continuous operation, a field-of-view covering much of the overhead sky, and energy ranges extending up to PeV energies. They are however not sensitive to

Corresponding author: Simon Lee; Email: simon.lee@adelaide.edu.au
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[a]glast.sites.stanford.edu
[b]hawc-observatory.org.
[c]english.ihep.cas.cn/lhaaso.
[d]swgo.org.

Conclusion

- A small IACT array in Australia would contribute well to a worldwide network of gamma-ray telescopes, complementing the Cherenkov Telescope Array Observatory for observations of TeV transients

- Lower cleaning thresholds can improve low-energy performance

- Implementing hardware stereoscopic and/or topological triggers can improve performance, depending on the array

- Such arrays could successfully follow up on many flares seen by *Fermi*-LAT (~dozens per year)

Thankyou