An upgraded way to identify sources of ultra-high-energy photons from astrophysical flares

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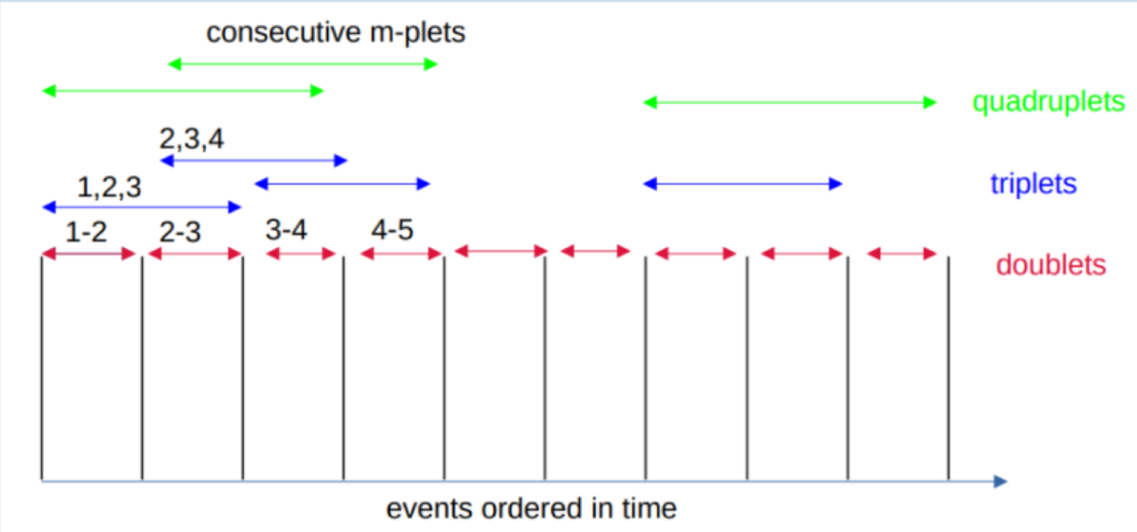
Motivation

Astrophysical flares are one of the prominent sources of ultra-high-energy (UHE, $E > 10^{17} eV$) particles, which can be detected by recording extensive air showers in arrays of detectors. The search for the sources of UHE neutral particles is easier than for those of UHE charged particles as the former are not affected by magnetic fields, and thus may be detected as groups of clustered events, correlated temporally and directionally.

Standard clustering method

The standard approach in identifying astrophysical flare/s from a point source uses the unbinned likelihood method [1] + a search for time correlation. This is carried out in the following steps,

- For a dataset with N events and spread across ΔT period, if there are n flare signal events, evaluate the space-time PDF of both signal, s_i and background, b_i events,



- Evaluate the likelihood for each possible multiplets (doublets, triplets, quadruplets, etc) combination in the dataset,

$$\mathcal{L}(\mathbf{n}, \mathbf{\Delta t_j}, \vec{r_s}) = \prod_{i=1}^{N} \left(\frac{n}{N} \mathbf{s_i} + (1 - \frac{n}{N}) \mathbf{b_i} \right)$$

- and maximize it to get the test statistic, $\mathbf{TS(n)} = -2 \log \left[\frac{\mathcal{L}(0, \Delta t_j, \vec{r_s})}{\mathcal{L}(n, \Delta t_j, \vec{r_s})} \right]$

Combined signal PDF: $\mathbf{s_i} = \mathbf{s_i^{space}} \cdot \mathbf{s_i^{time}}$

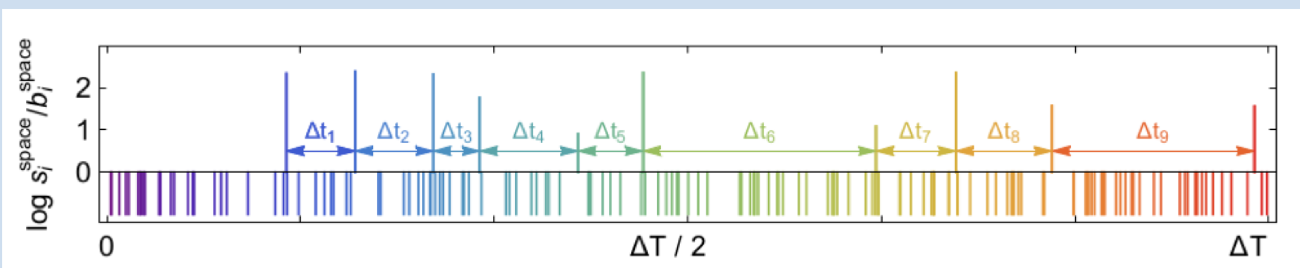
Combined background PDF: $\mathbf{b_i} = \mathbf{b_i^{space}} \cdot \mathbf{b_i^{time}}$ where $\mathbf{b_i^{space}} = \frac{1}{\Delta\Omega}, \mathbf{b_i^{time}} = \frac{1}{\Delta T}$

where, the angular resolution and the direction of each event are σ_i and r_i, within a time window of $\Delta t_j = t_j^{max} - t_j^{min}$, and $\Delta\Omega$ is the solid angle of the sky region used in the analysis.

Update on standard clustering method

The doublet stacking method [2] builds upon the standard method. This works in 3 steps,

1: Selecting flare event candidates, only based on spatial information - the ratio of signal PDF to background PDF of each event be greater than a threshold S/B, i.e. $\mathbf{s_i^{space}/b_i^{space} > S/B}$

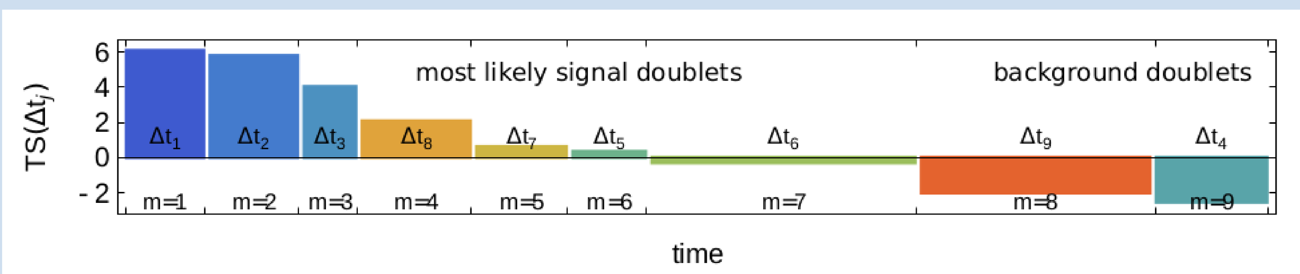


Extract all consecutive doublets to identify all possible time windows Δt_j that contribute to the flares.

2: For each doublet j, maximize the $\mathbf{TS_{\Delta t_j}(n)}$ using the standard method, with an additional *marginalization* term to provide a more uniform exposure for finding doublets of different widths,

$$TS_{\Delta t_j}(n) = -2 \log \left[\frac{\Delta T}{\Delta t_j} \frac{\mathcal{L}(0)}{\mathcal{L}(n)} \right]$$

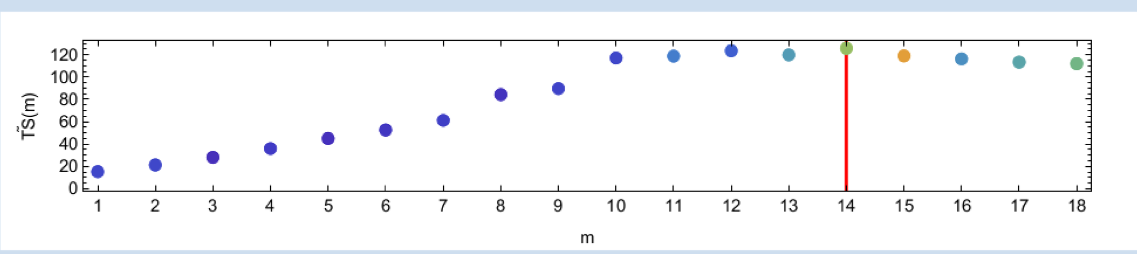
This allows only including events within Δt_j window. Next, sort the doublets according to the $TS_{\Delta t_j}$ and change the numbering of the doublets, introducing a multiplicity index, $\mathbf{m}$.



3: Replace each event's signal PDF with a *weighted* sum of signal sub-terms over m doublets,

$$\mathbf{s_i} \rightarrow \mathbf{s_i^{tot}(m)} = \sum_{j=1}^{m} w_j s_i^j / \sum_{j=1}^{m} w_j \quad \text{where } w_j = TS_{\Delta t_j}$$

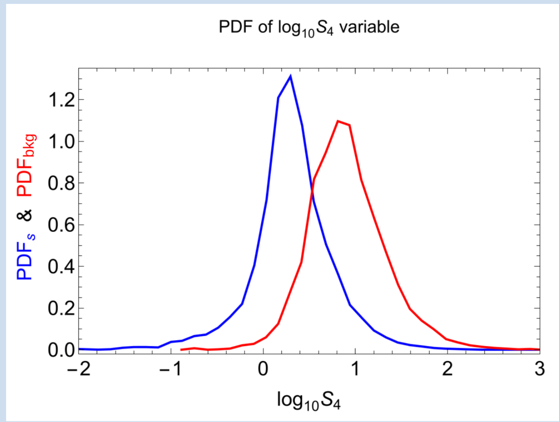
$$\Rightarrow \mathcal{L}(n) \rightarrow \mathcal{L}(n, m) \Rightarrow TS \rightarrow \widetilde{TS}(m) = -2 \log[\mathcal{L}(0)/\mathcal{L}(n, m)]$$



Maximize $\mathbf{m}$ to find the optimal total number of doublets in all flare/s, $\mathbf{M_{opt}}$, which determines the total flare duration. It is the number of most significant (**not necessarily consecutive**) doublets: $\Delta T = \sum_{m=1}^{M_{opt}} \Delta t_m$

Application of signal discriminator - photon tag, S_b

A common variable used to discriminate between photon- and hadron-initiated showers is $\mathbf{S_b} = \sum_k S_k (\frac{R_k}{1000m})^b$ [3, 4], where S_k is the signal in the k-th detector, and R_k is the distance of the k-th detector from the shower axis.

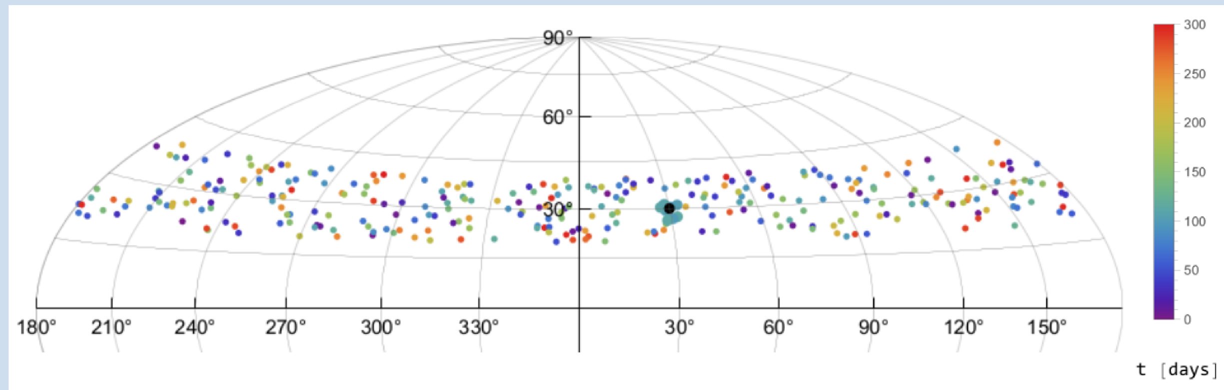


$$\mathbf{s_i^{space}} \Rightarrow \mathbf{s_i^{space}} \cdot \mathbf{PDF_s}(\log \mathbf{S_{b=4}^i})$$

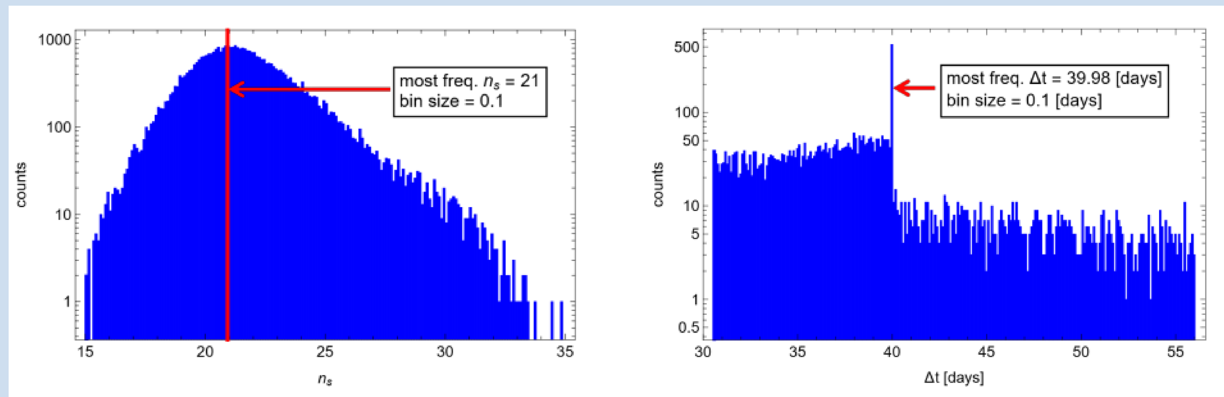
$$\mathbf{b_i^{space}} \Rightarrow \mathbf{b_i^{space}} \cdot \mathbf{PDF_{bkg}}(\log \mathbf{S_{b=4}^i})$$

Monte Carlo test

Randomly generate many scrambled sky maps with background and signal events, uniformly distributed over a sky region around an assumed flare location and duration.



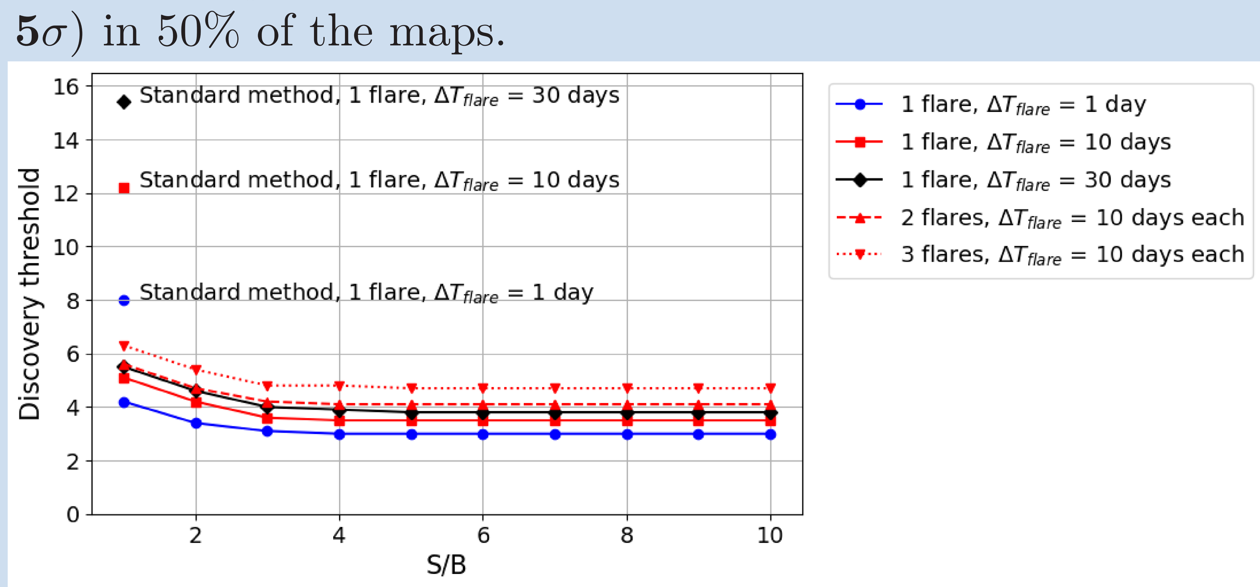
For each map, obtain the distributions of the estimators, $\mathbf{n_s}$ for the number of signal events, $\mathbf{\Delta T}$ for the flare duration, $\mathbf{\Delta T_{flare}}$ and the value of the test statistic for $\mathbf{M_{opt}}$. The tests are able to recover these estimators with a good accuracy.



An example of 3 flares with a total of 20 signal events and 40 days flare (20+10+10).

Discovery potential of the clustering method

Discovery potential is the **minimum** number of signal events required to claim discovery. This claim is generally assumed for a **p-value of less than** $\mathbf{2.87 \times 10^{-7}}$ (**one-sided** $\mathbf{5\sigma}$) in 50% of the maps.



Fewer events are required to claim discovery, even at a higher S/B threshold!

Summary

We demonstrate the advantages of using the updated clustering algorithm, which could help provide evidence of UHE-neutral particles. The stacking method is,

- *faster* than the standard method
- more *sensitive* to weak or **multiple** flares of any shape
- further enhanced in its performance with the addition of a *better* signal discriminator

A discovery of UHE-neutral particles, would set another milestone in the ever-advancing multi-messenger astronomy and broaden our understanding of astrophysics.

References and Acknowledgements

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