Improved method of searching for flares of neutral particles from point sources

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Motivation

Astrophysical flares may be the sources of some cosmic rays, which, if they are neutral particles, should group into clusters of events correlated in space and time – pointing to their sources.

Search for such clustering in data would provide important evidence for the existence (or set upper limits on flux) of UHE ($E > 10^{17}$ eV) neutral particles.

Standard space-time clustering analysis

To identify flare/flares from a point source, we have to find an excess of events from a particular direction over the background. (J. Braun et al., Astropart. Phys. 29 (2008) 299 + time search)

Maximize the likelihood of possible multiplets in a data sample (doublets, triplets, quadruplets, etc.) and calculate test statistic:

- likelihood that flare consists of **n** signal events within a given multiplet time window ΔT_j :

$$\mathcal{L}(n) = \prod_{i=1}^{N}\left(\frac{n}{N}s_i + (1-\frac{n}{N})b_i\right)$$

- the test statistic: $\mathrm{TS_j(n)} = -2\log\left(\mathcal{L}(0)/\mathcal{L}(n)\right)$

Combined signal PDF $\quad s_i = s_i^{\mathrm{space}} s_i^{\mathrm{time}}$

Gaussian spatial PDF $\quad s_i^{\mathrm{space}} = \frac{1}{2\pi\sigma_i^2}\exp\left(-\frac{|\vec{r}_i - \vec{r}_s|^2}{2\sigma_i^2}\right)$

Heaviside temporal PDF $\quad s_i^{\mathrm{time}} = \frac{H(t_j^{\max} - t_i)H(t_i - t_j^{\min})}{\Delta t_j}$

time span of a given multiplet

Background PDF $\quad b_i = b_i^{\mathrm{space}} b_i^{\mathrm{time}}$

$b_i^{\mathrm{space}} = 1/\Delta\Omega$

$b_i^{\mathrm{time}} = 1/\Delta t_{\mathrm{data}}$

N - number of all events
σ_i - angular reconstruction uncertainty of event i
$\vec{r}_i$, $\vec{r}_s$ - direction to event i and source
$\Delta\Omega$ - solid angle

We obtain estimates of:

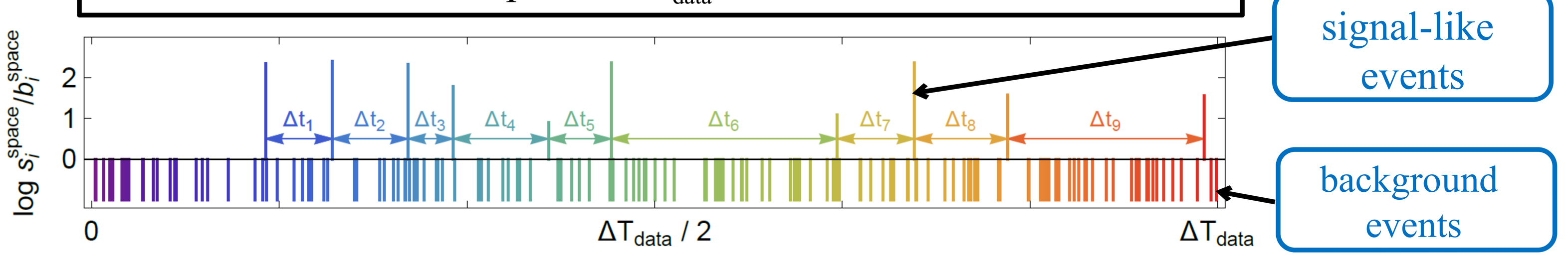
- number of signal events ($\mathbf{n_s}$)
- the flare duration (**ΔT**), i.e. time span $\mathbf{\Delta T_j}$ of the most significant multiplet (multiplet with the highest $\mathrm{TS_j}$)

Improved method of space-time clustering analysis

Stacking method (D. Góra et al. Astropart. Phys. 35 (2011) 201) uses only doublets, consists of 3 steps.

1: Select flare candidates from the data using solely space information:
identify signal-like events based on the ratio of the signal PDF to background PDF > threshold S/B, i.e. $\mathbf{s_i^{space}/b_i^{space} > S/B}$

Data collected over time period ΔT_{data}. Time of events is color coded.



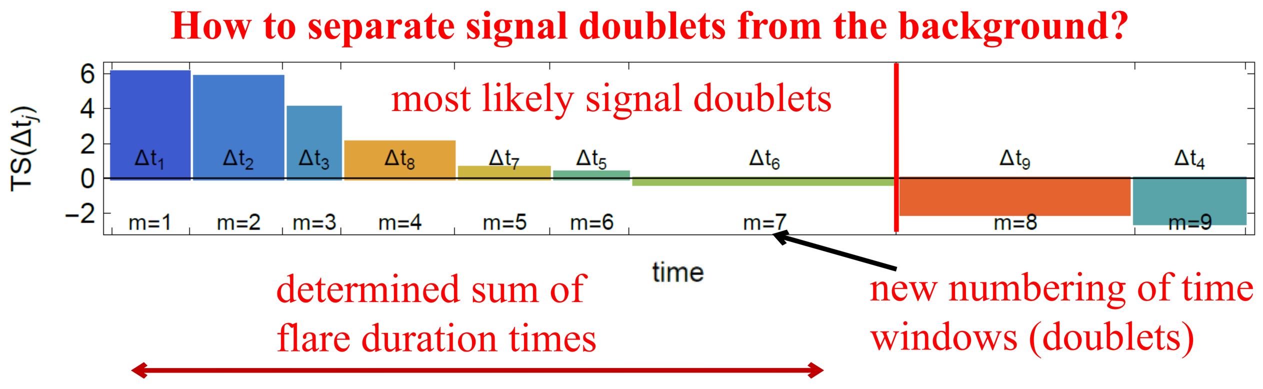
Extract all consecutive doublets to isolate all possible time windows $\mathbf{\Delta t_j}$ that compose the flares contribution.

2: For each doublet j maximize test statistic $\mathbf{TS_{\Delta tj}(n)}$ **(calculate doublet significance)** using standard method with marginalization term to provide more uniform exposure for finding doublets of different widths:

$$\mathrm{TS}_{\Delta t_j}(\mathrm{n}) = -2\log\left[\frac{\Delta T_{\mathrm{data}}}{\Delta t_j}\mathcal{L}(0)/\mathcal{L}(\mathrm{n})\right]$$

Only events within $\mathbf{\Delta t_j}$ interval are taken into account, thus in this step both space and time information is used.
Sort doublets according to the value of $\mathbf{TS_{\Delta tj}}$, i.e. to their significance, and change numbering of doublets introducing multiplicity index **m**.

How to separate signal doublets from the background?



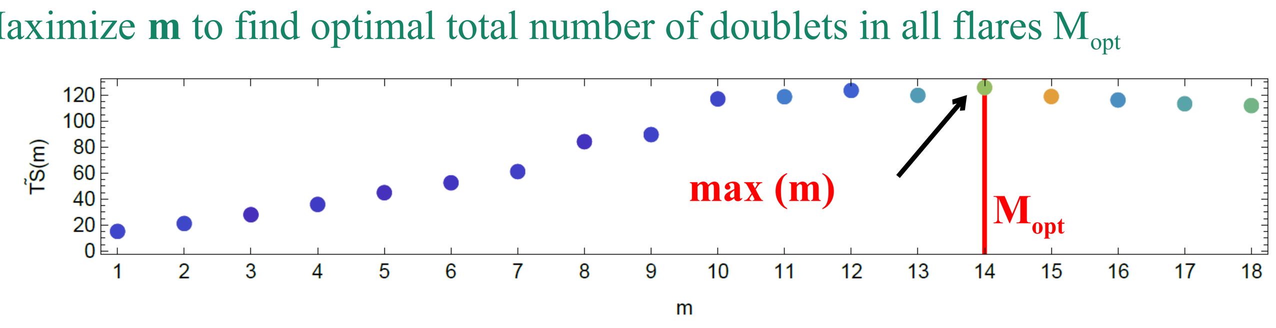
3: Stacking analysis:
one-event signal PDF $\mathbf{s_i}$ is replaced by the weighted sum of signal sub-terms over m doublets:

$$s_i \rightarrow s_i^{\mathrm{tot}}(m) = \Sigma_{j=1}^{m} w_j s_i^j / \Sigma_{j=1}^{m} w_j \qquad \text{with weights } \mathbf{w_j = TS(\Delta t_j)}$$

use standard likelihood and test statistic with stacking term $\mathbf{s_i^{tot}(m)}$:

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

Maximize **m** to find optimal total number of doublets in all flares M_{opt}



M_{opt} determines **total flares duration.** It is **estimated as a sum of most significant (not necessarily consecutive)** doublets: $\Delta T = \Sigma_{m=1}^{M_{opt}} \Delta t_m$

Application of the S_b photon tag to enhance sensitivity for photons search

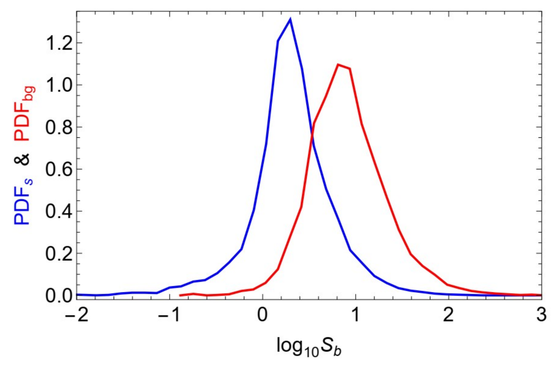
S_b variable is used to discriminate between photons and background showers
(G. Ros et al.. Astropart. Phys. 35 (2011) 140)

$$S_b = \Sigma_{i=1}^{n} S_i\left(\frac{R_i}{1000\ \mathrm{m}}\right)^4$$

detector signal

distance from the shower axis

PDF of $\log_{10} S_b$ variable

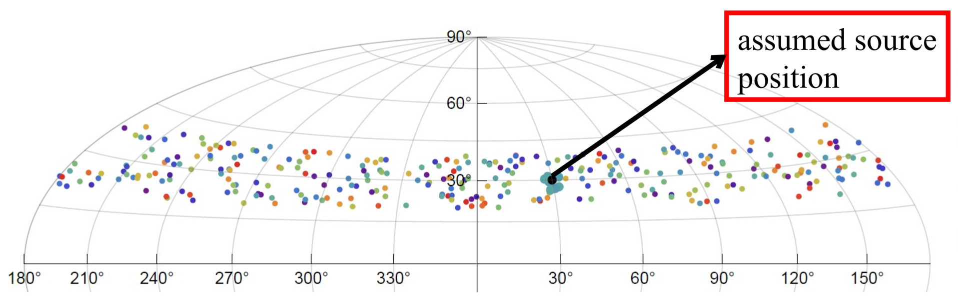


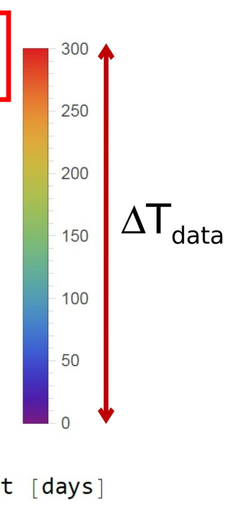
Photon tag: Probability Distribution Functions of $\log_{10} S_b$ for **photons** ($\mathrm{PDF_s}$) and **protons** (background) ($\mathrm{PDF_{bg}}$), make the replacement:

$s_i^{\mathrm{space}} \Rightarrow s_i^{\mathrm{space}} * \mathrm{PDF_s}(S_b)$
$b_i^{\mathrm{space}} \Rightarrow b_i^{\mathrm{space}} * \mathrm{PDF_{bg}}(S_b)$

Monte Carlo test

Randomly generate many sample maps with background and signal events (distributed around an assumed source position and within assumed flares duration $\Delta T_{\mathrm{flare}}$)

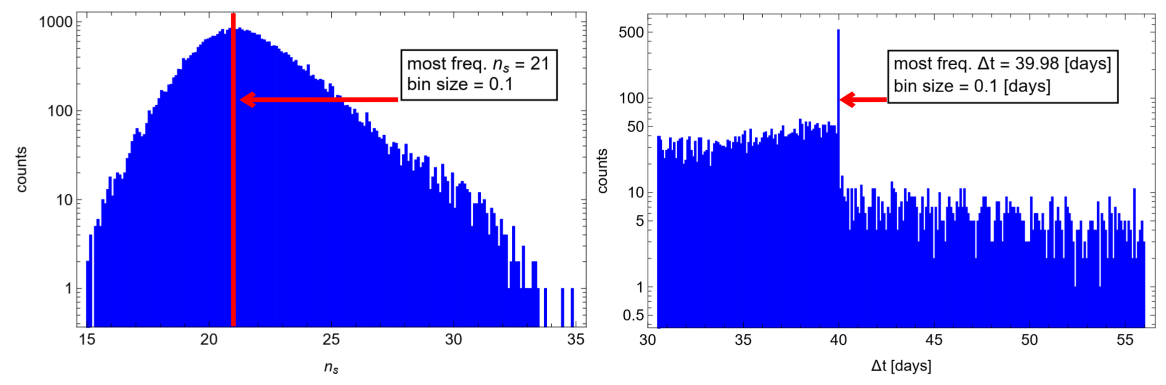




For each map we obtain:

- estimator $\mathbf{n_s}$ of number of signal events $\mathbf{N_s}$
- estimator **ΔT** of the flares duration $\mathbf{\Delta T_{flare}}$
- value of the test statistic for $\mathbf{M_{opt}}$

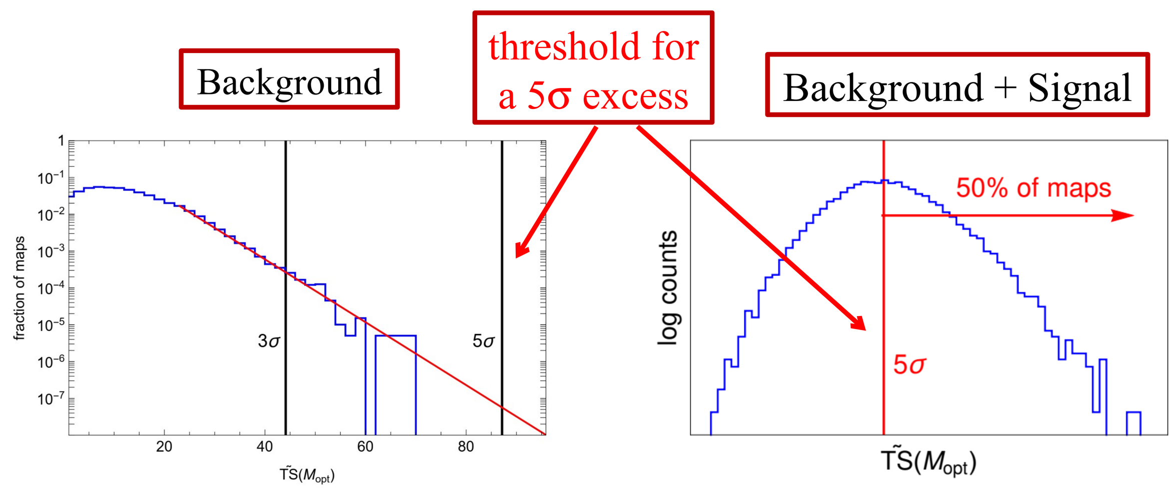
3 flares (duration 20, 10 and 10 days), number of signal events $N_s = 20$:



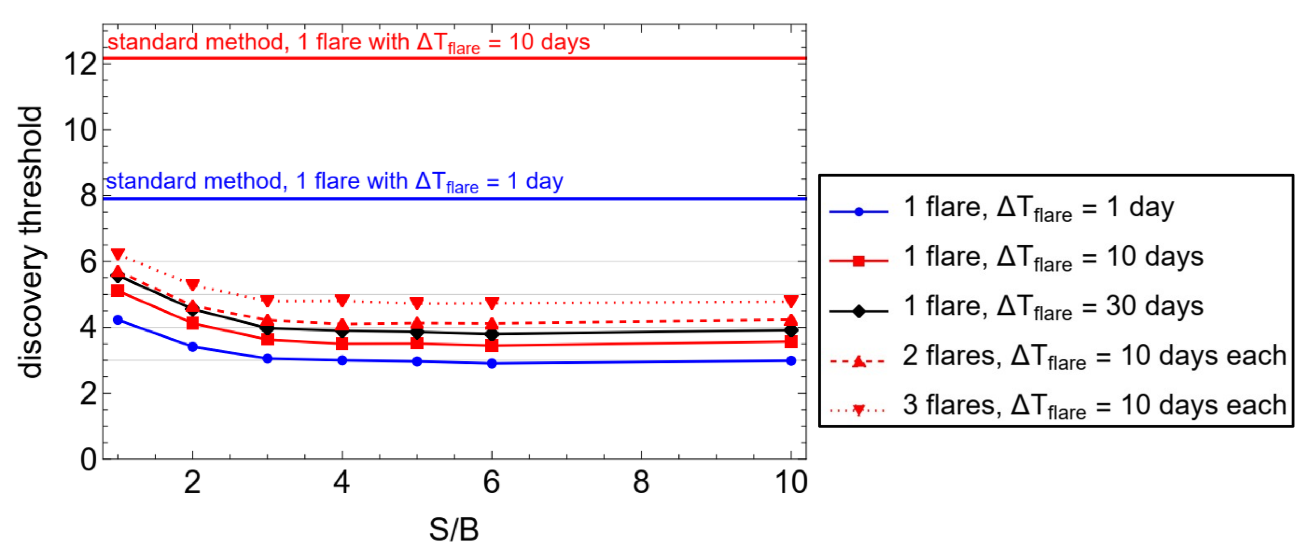
Number of signal events $\mathbf{N_s = 20}$ and total flares duration $\mathbf{\Delta T_{flare} = 40}$ **days** are recovered.

Discovery potential of the stacking clustering method with S_b photon tag

Discovery potential tells us how many signal events are needed to claim discovery of a cluster of events in data. It can be used to compare different methods.
Definition: The discovery threshold is the number of signal events required to achieve a p-value less than 2.87×10^{-7} (one-sided 5σ) in 50% of the maps (i.e. the number of signal events for which median of M_{opt} test statistic distribution is at 5σ threshold).



Discovery thresholds vs threshold for signal-like events S/B



Only a few events are needed to detect flares at a higher S/B threshold for signal-like events.

Summary

Identification of clustering in cosmic-ray data would provide evidence for possible existence of UHE neutral particles and could potentially help identify their sources.

Advantages of the stacking method:
- it is faster than the standard method
- more sensitive to weak flares of any shapes
- able to detect multiple flares.

The stacking method is able to recover the number of signal events and flares duration with small uncertainty.

The stacking method with S_b photon tag requires only 3 to 5 events to discover photon flares!

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