Astrophysical neutrino search at sub-GeV energies in IceCube

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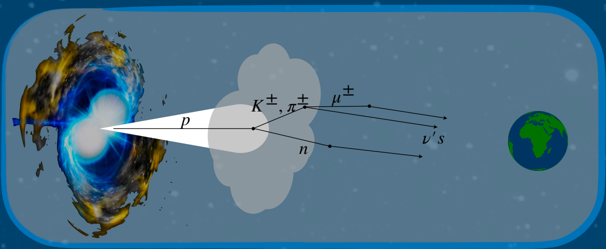
Neutrino production in compact binary coalescences

Compact binary coalescences (CBCs) emit significant gravitational waves and are plausible candidates for accompanying messengers. If the progenitor system includes a neutron star, the conditions could allow for a significant flux of secondary sub-GeV neutrinos created through hadronic processes during and succeeding the merger [1]. With the involvement of a **neutron star,** the baryonic density is sufficient to have **significant lepton production at sub-GeV energies** through the production and subsequent decay of **pions, kaons** and secondary **neutrons.**

If the merger conditions allow for **significant jet launching,** by accretion onto the resulting black hole or by the magnetohydrodynamics of the merger itself [2], the accelerated jet particles may induce a **significant neutrino emissivity** by piercing any dynamically ejected material.



HitSpooling our troubles away

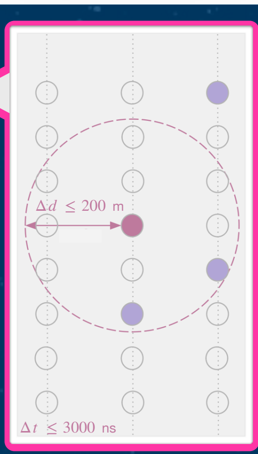
IceCube
- Is buried in the Antarctic ice ✓
- Has confirmed high-energy astrophysical neutrinos [3] ✓
- Is sensitive down to 0.5 GeV for individual astrophysical neutrinos [4] ✓
- Continuously probes neutrino interaction from MeV to PeV ✗

To keep the data rate manageable, the detector relies on certain triggering conditions, filtering out a lot of noise, but also hits potentially caused by low-energy neutrino interactions. **HitSpool** is a system that temporarily saves all signals inside the detector, allowing us to bypass these triggering conditions.

Through the use of **HitSpool**, we are looking for an increase in correlated, subthreshold interactions within the detector during significant CBC alerts. This will result in an event selection targetting transient events in the 100 MeV - 1 GeV energy range.

Burst search - a novel approach

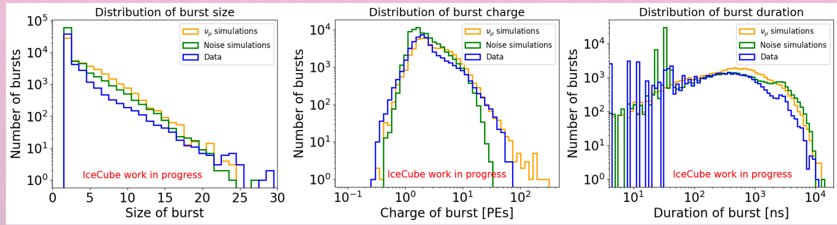
With HitSpool, we have access to the continuous, full detector output over extended periods of time. We run a **sliding time window** on the subthreshold output, looking for a **collection of hits** that are causally connected. All hits that are within a spacial distance **Δd** and within the duration **Δt** are considered to belong to the same burst.



Sub-GeV neutrinos in IceCube are buried in a large background of different noise constituents. To get a better grasp of this, **we repeat the same sliding time window search** on a set of **simulated muon neutrinos**, as well as **simulated detector dark noise** to see if this method is sensitive to their respective behaviours.

After the search algorithm has been run, we are left with a **collection of bursts** characterising the distributions of subthreshold signals inside the detector. The bursts are defined by the following **three parameters:**

- **Size** — The number of detector hits making up the burst.
- **Charge** — Total accumulated charge deposited in the burst in units of photoelectrons [PEs].
- **Duration** — The full duration of the burst in units of nanoseconds [ns].



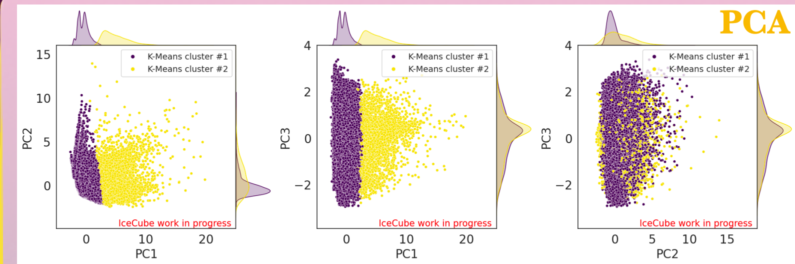
Histogram distribution of initial burst parameters for ν_μ simulations (orange), noise simulations (green) and data (blue). The ν_μ simulations follow a $\gamma = -3$ power law between $0.5 - 5$ GeV. Burst size (left), deposited charge (centre) and duration (right) are shown. We see clear differences in the behaviour of the distributions. The sizes (left) have slightly different slope characteristics going to larger bursts, the charges (centre) show different behaviour in the tails of the distributions and the duration (right) show different shapes going to higher durations.

Data analysis & dimensionality reduction

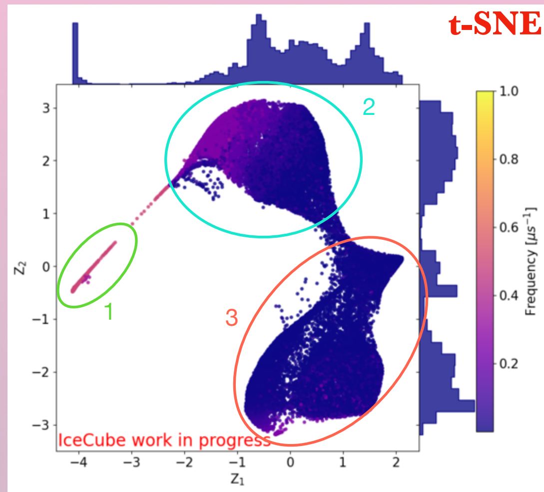
By introducing e.g., **centre of gravity**, **frequency of hits** as burst variables, we populate a higher dimensional parameter space with possible internal correlations and splitting into separate populations.

We perform a **principal component analysis (PCA)** on the burst variables. PCA is a linear dimensionality reduction that projects the points onto the eigenvectors of the original parameter space, known as the principal components, and minimises the distance. Projecting our bursts onto the 3 first principal components, **~57% of the variation within the data is preserved.**

We apply a K-Means algorithm to look for any significant clustering in the reduced parameter space. For each point, we **minimise** the distance to the **nearest collection of points**, while **maximising** the distance to the **clusters further away.** This shows that the reduced burst parameters favour a splitting into **two separate clusters.**



The left (centre / right) figure shows the distribution of bursts along the 1st and 2nd (1st and 3rd / 2nd and 3rd) principal components. The marginal plots show the kernel density estimation (KDE) along the corresponding axis. Only PC1 shows clear division into subpopulations.



The colour indicates the frequency of a burst, i.e. the number of hits per μs. Attached as marginal plots are the corresponding histograms. We see clear separation into three distinct groups, with indication of further sub-populations within these clusters.

Structure in subthreshold signals

The results from the PCA show that **linear reduction is insufficient** in separating the bursts into distinct populations, motivating the exploration of **non-linear** correlations. We use **t-distributed stochastic neighbour embedding (t-SNE)** [5], an **unsupervised statistical method** for embedding high-dimensional data down to two dimentions. Within this mapping, a **Student t-distribution** is used to sample distances between low-dimensional points. This allows for data points that are similar in the original distribution to remain similar when reduced, and dissimilar points to remain dissimilar, **preserving the density.**

Applying t-SNE to the set of bursts shows a **clear splitting into separate populations.** K-Means shows a preferance for **three distinct clusters.** The absolute values of the points in this reduced space does not carry any physical meaning, but it is rather the relative distance between the points that are of interest. The resulting distribution of burst parameters show that **there is clear structure to the subthreshold interactions in IceCube,** albeit highly non-linear.

Conclusion & Outlook

By developing a process and analysis pipeline for low-energy interactions in IceCube, preliminary results indicate a clear division into separate populations. This shows the prospect of a novel approach for detecting and classifying subthreshold signals through the use of HitSpool data. Further development, including supervised learning assisted by a citizen science project will show if this approach can be sensitive to sub-GeV neutrinos from CBCs and provide the foundation for an event selection in an unexplored energy range for IceCube.

REFERENCES

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