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Neutrino statistics in a single pixel

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Abstract. The IceCube data at high energies is so sparse that we cannot afford to throw away information by reducing the data to averages. In our analysis, we therefore model not only the mean neutrino flux, but the entire probability distribution of this flux. We show that the expected neutrino event rates from rare sources are suppressed by the skewness of the flux distribution, weakening upper limits on their contributions to the observed flux by up to half an order of magnitude for our model of blazars. We also predict that the contribution from our model of star-forming galaxies appears completely diffuse and isotropic in IceCube, and forecast an inevitable null result for SFG γ/ν cross-correlation studies.

The high-energy astrophysical flux discovered by IceCube [1] shows no significant evidence for anisotropy, event clustering or resolvable point sources [2, 3], so it is studied as an isotropic distribution. But if this isotropic flux is more than just a Gaussian random field, then there is potentially unexploited information hidden in the variance and higher moments of the neutrino flux. The non-Gaussian probability distribution of neutrino fluxes due to unresolved but known astrophysical populations, which captures all of this extra information, can be modelled based on observation of these populations with photon telescopes. In these proceedings, we summarise results pertaining to the neutrino flux probability distributions of Starforming Galaxies (SFG) and Blazars; further results from our one-point fluctuation analyses, which find $\sim 5\sigma$ evidence for additional components to the astrophysical flux, are not reproduced here.

Let F denote the (energy-differential) neutrino flux per pixel, with no distinctions made between flavours or between neutrinos and antineutrinos. The quantity we want to compute is the probability density function / distribution $P(F)$. We use the terminology "flux per pixel" to emphasise the importance of pixel size in computing the distribution of the neutrino intensity $P(I)$ incident on IceCube, where $I = F/\Omega_{\rm pix}$, to which we will return shortly.

Starforming Galaxies are modelled using their *Herschel* Luminosity Function $\Phi(L, z)$ [4] and a semi-empirical conversion between their IR/ν fluxes [5]; the resulting flux distribution for a single source is

$$P_1(F|E) \propto \frac{1}{|F|} \int dz \frac{dV}{dz}\, \Phi(L(F, z), z),$$

where we integrate over the redshift z, assume an isotropic distribution of sources in each comoving volume element dV/dz, and the luminosity is $L \sim F/d_L(z)^2$. Similarly, objects from the second *Fermi* catalogue of hard sources (2FHL; these are mainly blazars [6]) also contribute to the observed neutrino flux: we can easily convert their source count distribution [7] into a single-source flux distribution $P_1(F)$. Our results are contingent on these data-driven models.

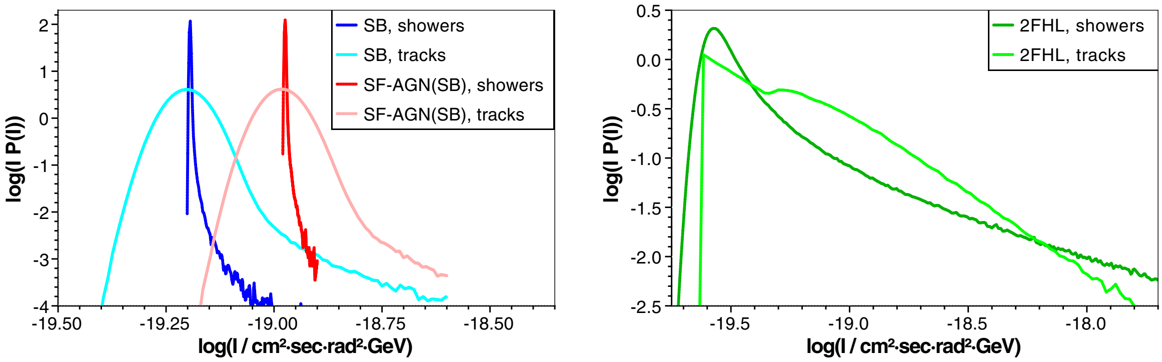

Figure 1. Intensity distributions $P(I)$ of two subpopulations of SFG (left) and of blazars (right), as seen in 30° showers (dark colors) and in 1° tracks (light colors). *left:* Starburst galaxies (blue) and SFG hosting a low-luminosity active galactic nucleus (red) [5]. The peak of $P(I)$ is thinner in showers than in tracks because the number of sources in the angular resolution of a shower is larger. *right:* Blazars are rare, so their $P(I)$ are very skewed (especially in tracks) resulting in a bias between the most likely observations and their mean (cf. main text).

Now recall that no point sources have been resolved in four years of data [3]: IceCube is not (yet) sensitive to the fluxes of individual sources, but to the joint and diffuse intensity of many unresolved sources per pixel. This large but finite number of sources per pixel is known to lead to non-Gaussian intensity distributions $P(I)$, generically taking the form of Gaussians with powerlaw tails (cf. Figure 1); they can be computed from $P_1(F)$ with no additional physical assumptions, by merging results of numerical and analytical computations [8].

The peak of $P(I)$ encodes the diffuse background when no sources are resolved. The observed intensity in the peak is the sum of all the fluxes of the unresolved sources, and (because of the Central Limit Theorem) the peak is Gaussian with a width determined by the number of sources that lie in a pixel. When a sufficiently bright source dominates the brightness of a pixel, the tail of $P(I)$ matches the powerlaw tail of the single source distribution $P_1(F)$. One consequence of this non-Gaussianity is that these $P(I)$ have non-negligible skewness, and IceCube's observations of the intensity of rare sources are biased (the most likely flux to be observed is not equal to the mean flux). For blazars, this corresponds to a $\sim 40\%$ systematic effect in showers and a factor of ~ 6.7 effect in tracks.

Another consequence of having diffuse and point-source features in the same flux distribution is that unresolved point sources are a diffuse background for point source searches. This was previously discussed in the context of Dark Matter annihilation, where the diffuse extragalactic background due to dark matter prevents us from detecting the annihilation signal from individual galaxy clusters [8]. In IceCube, this self-background effect has little to no effect on blazars, but makes it unlikely to observe SFGs as point sources over the background of other SFGs.

In tracks, $P(I)$ allows us to compute an upper limit on the number of sources detectable with a given statistical significance over the background: Indeed, $P(I)$ is the distribution that IceCube would sample from if it had an infinite exposure and if all non-SFG backgrounds were neglected. This upper limit is represented in Figure 2, which illustrates that even in these ideal circumstances we might only see ~ 25 SFGS at 3σ significance – and even these sources must be extracted from the non-SFG astrophysical backgrounds, the atmospheric foregrounds, and the shot noise present in a real instrument such as IceCube. In showers, the large number of sources per pixel increases the self-background and makes this endeavour essentially futile.

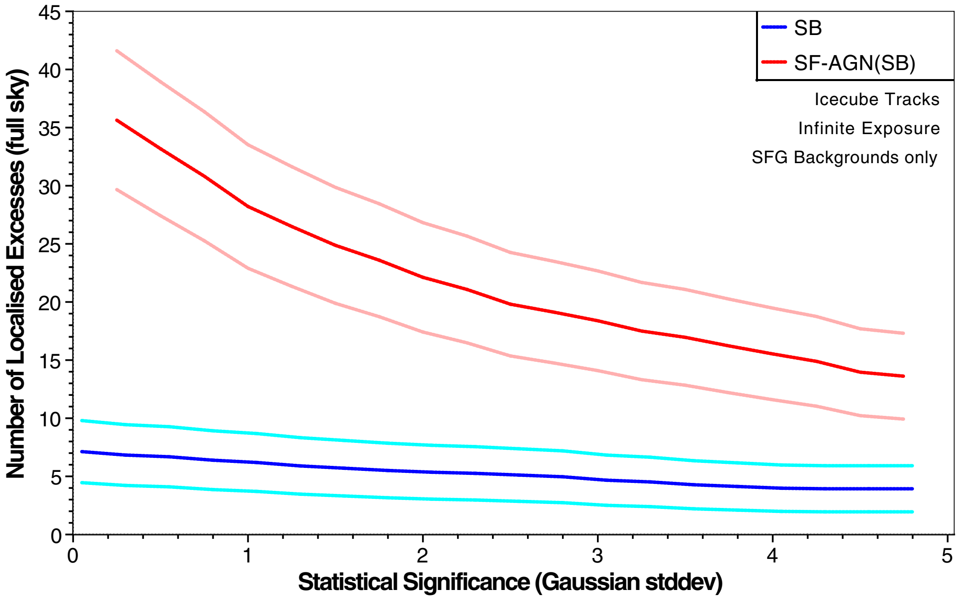

Figure 2. Point-source detection prospects for single Starburst Galaxies (blue) and SF-AGN (SB) (red) [5] in IceCube tracks. This setup assumes an infinite exposure and no backgrounds other than the SFGs that remain unresolved in the same pixel; Hence, these are conservative upper limits. The errors on the number of point sources are Poisson.

In summary, the rarity of blazars makes them prone to a skewness-induced observational bias, while the abundance of SFGs makes them prone to a self-background effect. These results have a profound impact on studies of SFGs and blazars in the high-energy IceCube data; particularly, this affects multi-messenger attempts to associate or cross-correlate sources resolved in photon catalogues to the neutrino data. Observational upper limits on the mean contribution of blazars to the IceCube flux could be between 40% and 670% weaker than expected, and SFG cross-correlations [9, 10] will continue to produce null results until a better angular resolution is achieved in the next generation of neutrino telescope.

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