Investigating neutrino signals associated with candidate neutrino-emitter blazars

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Introduction

Motivation

- The origin of the astrophysical diffuse flux observed by the IceCube Neutrino Observatory is still mostly unknown.
- The first candidate point-like sources are of blazar (TXS0506+056) or AGN (NGC 1068) nature.
- Neutrinos are a key messenger to probe hadronic processes in astrophysical sources.

Strategy

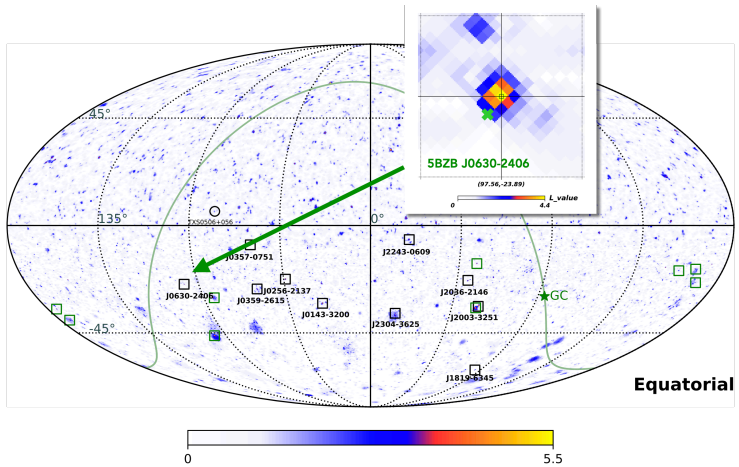
Aim: study blazars as promising neutrino sources beyond the TXS0506+056 case.

- Least number of assumptions on neutrino observational strategy $\rightarrow$ use of the 5BZCat blazar catalog;
- Theoretical modeling, using AM3 framework;
- Multi-wavelength observational strategy

Initial results

Evidence for correlation between IceCube hotspots and 5BZcat blazars. Statistical significance at the 5σ post-trial level.

- Small subset of 52 blazars proposed as candidate neutrino emitters.

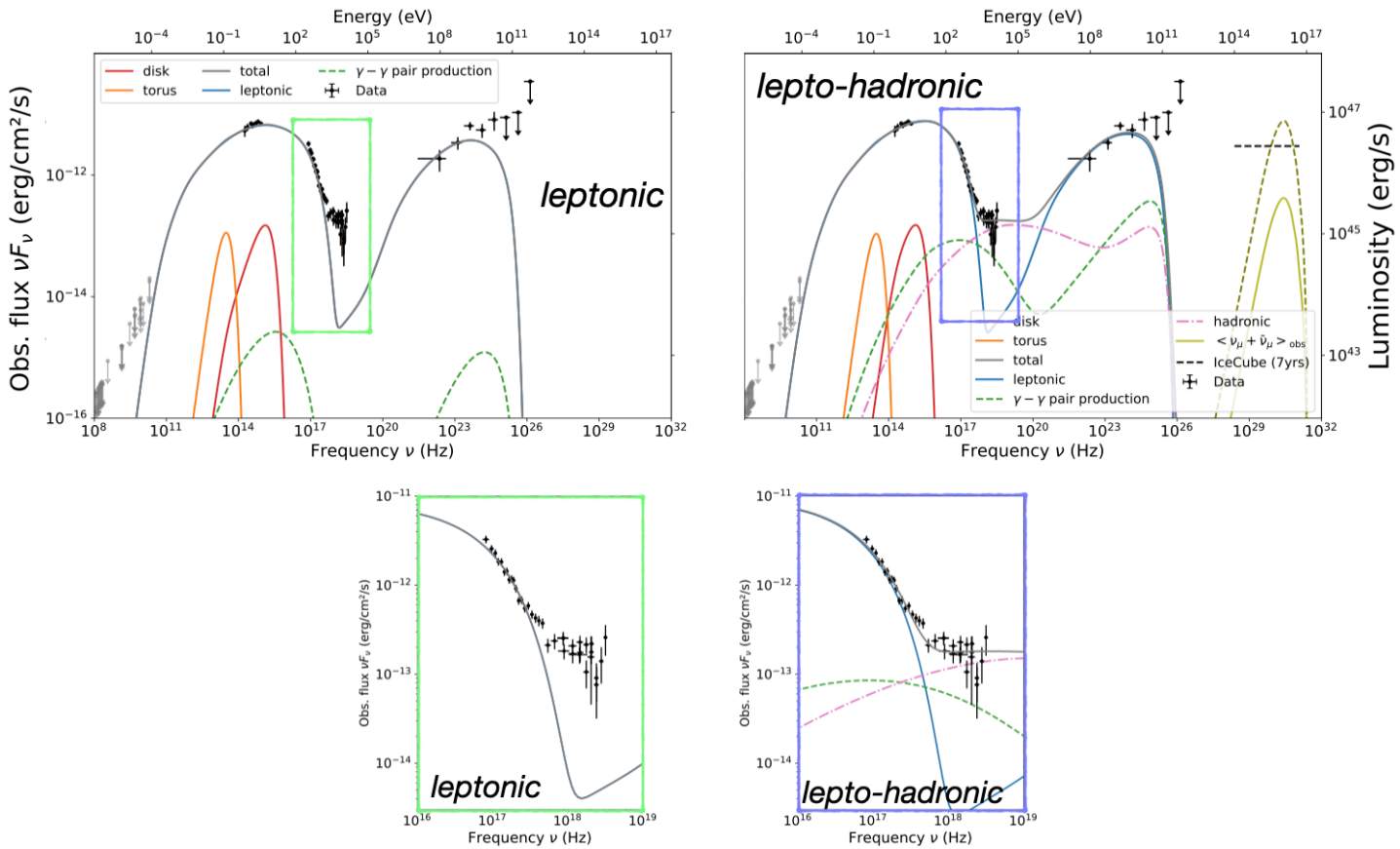


The 5BZB J0630-2406 case

- Classified as a BL Lac due to the lack of optical spectral lines;
- high-power, radiatively efficient blazar, hosting a standard accretion disk, "blue flat spectrum radio quasar", "masquerading BL Lac" (Fichet de Clairfontaine *et al.*, ApJL. 958 (2023) 1, L2.)
- Overall properties similar to TXS 0506+056 (and PKS 1424+240).

Hadronic processes at work in 5BZB J0630-2406

- Evidence for a break in the X-ray spectra ($3\,\sigma$);
- Standard single-zone leptonic models face challenges in reproducing the X-ray break;
- In lepto-hadronic models, the break is naturally explained by the kick-in of the hadronic contribution.



IceCube public 10 year data sample

- 10 year track-like (muon) neutrino sample released in 2020 (IceCube Coll., Phys. Rev. Lett. 124, 051103 (2020));
- energy and declination- dependent effective area;
- smearing matrix (necessary to simulate *signal-like* properties of neutrinos) is provided with only *three* bins in declination: [-90,-10], [-10,+10], [+10,+90] deg (no Monte Carlo);
- No public analysis tool released along with the dataset
- `SkyLLH` (IceCube software) extension for public data released in 2023 (Bellenghi et al., PoS ICRC2023 (2023) 1061)

IceCubePy: a framework for analyzing public IceCube data

Aim: study blazars from the neutrino perspective, taking advantage of publicly accessible IceCube observations.

- **Method**: develop an open source software for the analysis of the 10yr IceCube public neutrino data;
- **Focus**: point-source likelihood, neutrino spectral energy distributions, neutrino skymaps.

Unbinned likelihood built as joint PDF of neutrino event observables:

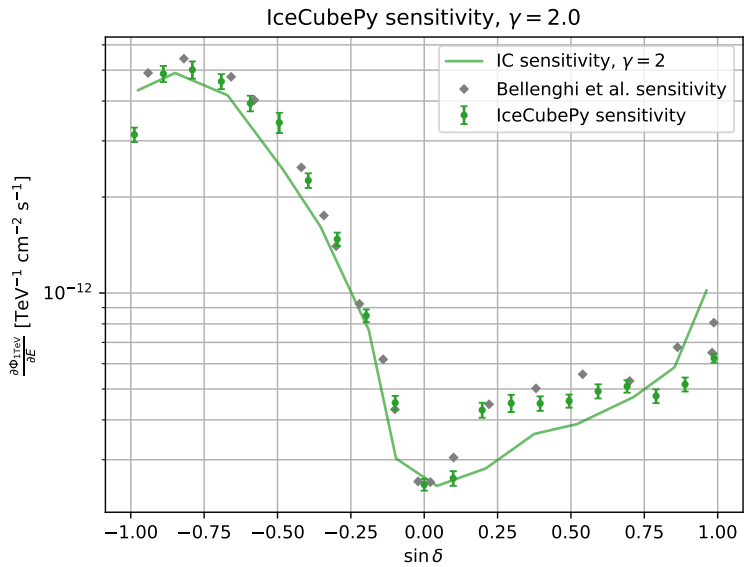
$$\mathcal{L}(n_{\mathrm{s}}, \gamma) = \prod_{\mathrm{i}=0}^{\mathrm{N}} \left[\frac{n_s}{\mathrm{N}} \mathcal{S}(\nu_{\mathrm{i}}, \gamma) + \left(1 - \frac{n_{\mathrm{s}}}{\mathrm{N}}\right) \mathcal{B}(\nu_{\mathrm{i}}) \right]$$

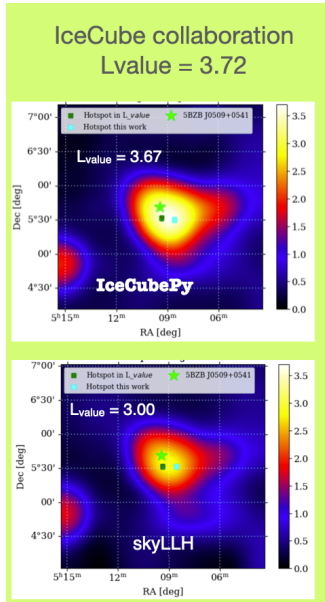
Test statistic definition: $TS = 2 \log \frac{\mathcal{L}(\hat{n}_{\mathrm{s}}, \hat{\gamma})}{\mathcal{L}(n_{\mathrm{s}}=0)}$ for an excess of n_s neutrinos that follow a signal probability density function $\mathcal{S}$.

- $\mathcal{S}$ **spatial term**: (Rayleigh distribution) $\times$ **energy term**: power-law with spectral index γ;
- $\mathcal{B}$: background PDF built from data.
- Signal simulation code adapted from M. Larson (mlarson/I3PublicDataSampler, GitHub).

IceCubePy analysis performance

- **Sensitivity**: background data samples (scrambling in right ascension); simulated signal with spectral index $\gamma = 2.0$.
- **TXS0506+056 L-value map**: background TS distributions $\rightarrow$ map TS value to local p-value. L-value $= -\log_{10}(p)$.

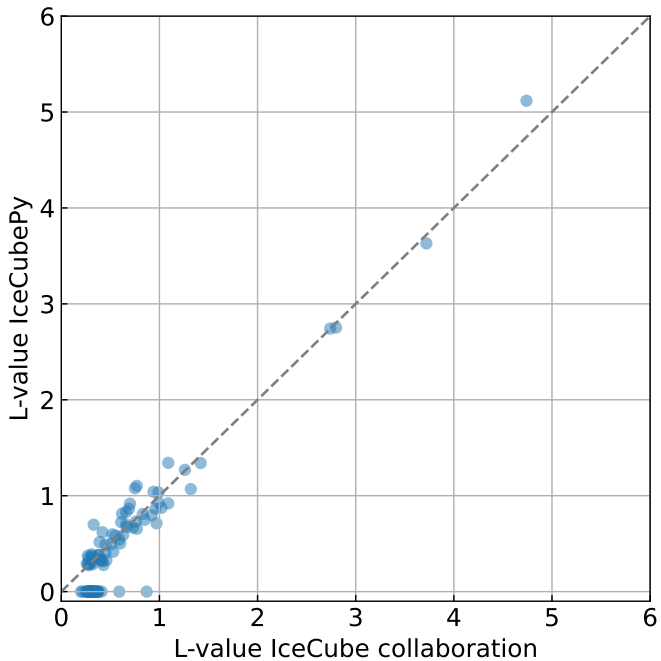


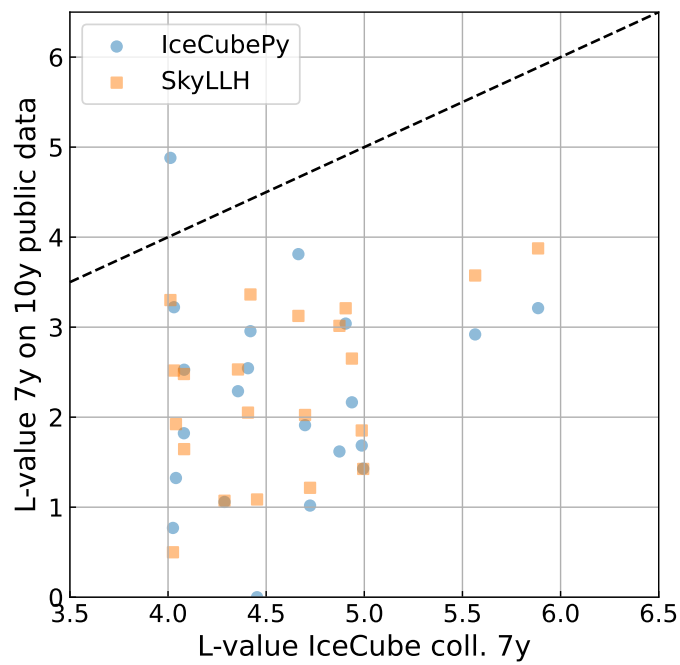


- Consistent with the sensitivity published by IceCube coll. *and* with sens. estimated with SkyLLH on public data;
- L-value at the coordinates of TXS0506+056 = 3.6 (consistent with IceCube coll.: 3.72).
- Caveats: limited information in instrument response functions released by IceCube.

Comparison to IceCube results

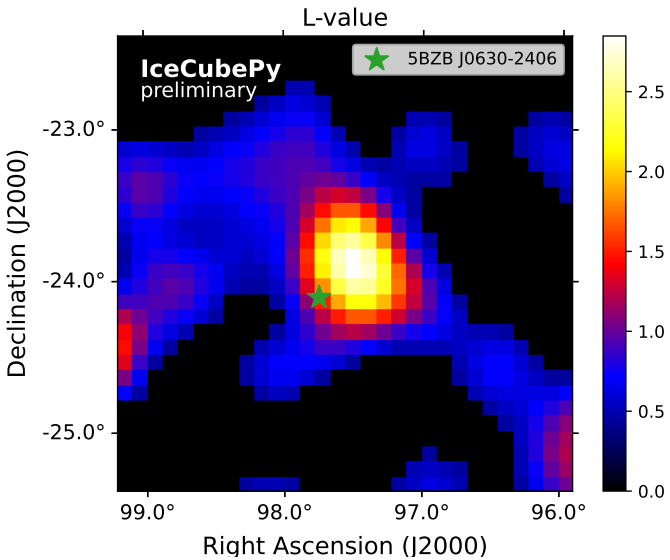
- Northern hemisphere (10yr): results broadly consistent with IceCube coll. **Left:** IceCubePy L-values for candidate source list compared to 10yr IceCube L-values
- Southern hemisphere (7yr): discrepancy in the analysis results when comparing the p-value results. **Right:** 7yr L-values evaluated with IceCubePy and SkyLLH using the public dataset → systematically lower than the IceCube collaboration 7-year skymap.

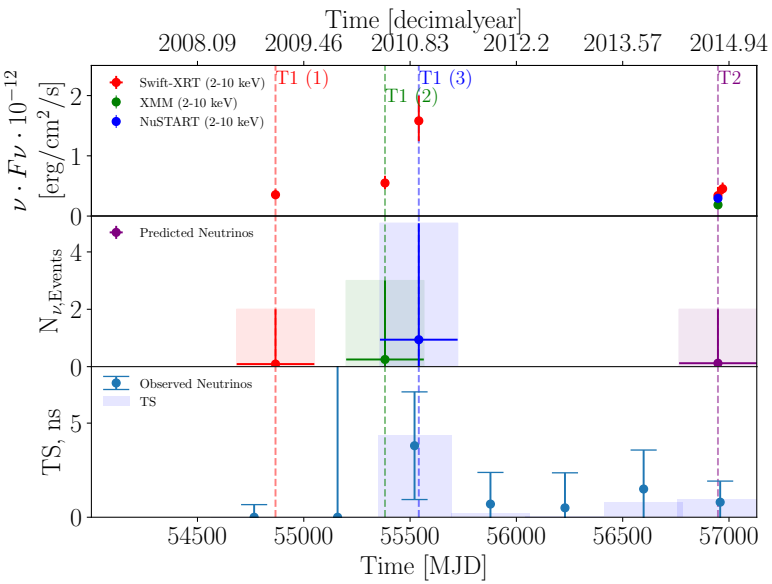




Investigating neutrino properties of 5BZB J0630-2406

- **Left:** J0630-2406 hotspot region analysed with IceCubePy (L-value map).
- **Right:** SED modeling of the source predicts variable neutrino emission tied to X-ray variability. Time-dependent study of the hotspot neutrino data consistent with theory prediction.





Summary and Outlook

- A subsample of candidate PeVatron blazars proposed as associated with IceCube neutrino hotspots; post-trial chance probability of $\sim 2.59 \times 10^{-7}$.
- Theoretical modeling of multiwavelength SED confirms one of the southern hemisphere objects as plausible neutrino emitter: **5BZB J0630-2406**. The blazar exhibits an X-ray flare during the 7 year IceCube observation, consistent in time with an increase in the observed neutrino event rate.
- **IceCubePy**: A framework for analyzing public IceCube data.
  – Aim to study blazars from the neutrino perspective, while enabling reproducibility of analysis and results.
  – Promising preliminary performances based on simulations and cross-checks.
  – Code hosted in GitHub; planning public release (Lincetto et. al, *in prep*).