The Journal of Open Source Software

FIRESONG: A python package to simulate populations of extragalactic neutrino sources

Chun Fai Tung[1], **Theo Glauch**[2], **Michael Larson**[3], **Alex Pizzuto**[4], **Rene Reimann**[5], **and Ignacio Taboada**[1]

1 School of Physics. Georgia Institute of Technology. Atlanta, GA 30332, USA **2** Technische Universität München, Physik-Department, James-Frank-Str. 1, D-85748 Garching bei München, Germany **3** Dept. of Physics, University of Maryland, College Park, MD 20742, USA **4** Dept. of Physics and Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin–Madison, Madison, WI 53706, USA **5** Johannes Gutenberg University Mainz, Institute of Physics - QUANTUM, 55128 Mainz, Germany

DOI: 10.21105/joss.03194

Software

- Review
- Repository
- Archive

Editor: Eloisa Bentivegna

Reviewers:

- @JostMigenda
- @rafaelab

Submitted: 09 April 2021
Published: 11 May 2021

License
Authors of papers retain copyright and release the work under a Creative Commons Attribution 4.0 International License (CC BY 4.0).

Summary

Neutrinos provide a new perspective on the universe. Due to their weak interaction with matter, neutrinos carry information from places where electromagnetic radiation, e.g., gamma rays, cannot escape. Though astrophysical neutrinos have been detected, the class or classes of objects that produce them have not been unequivocally identified. `FIRESONG` simulations populate the universe with neutrino sources. These simulations can be used, among other things, to study if a given class of astronomical sources is viable to explain measured astrophysical neutrinos.

Background

The IceCube Neutrino Observatory has discovered an all-sky neutrino flux in the 10 TeV to 10 PeV energy range (IceCube Collaboration, 2020b; Schneider & IceCube Collaboration, 2019; Stettner & IceCube Collaboration, 2019). IceCube finds that a power law in energy is a good description of the flux, with a spectral index ranging from -2.28 to -2.89, depending on the observation channel used. This flux is apparently isotropic, consistent with an extragalactic origin for these neutrinos. The flux is also consistent with equal flux for each of the three neutrino flavors (Stachurska & IceCube Collaboration, 2019), as expected for standard neutrino oscillations over astrophysical baselines. The origin of this flux is of great scientific interest as it is expected that neutrino sources are also sources of ultra-high-energy cosmic rays, which also have an unknown origin. IceCube has identified the blazar, a sub-type of Active Galactic Nuclei (AGN), TXS 0506+056 as a candidate neutrino source (IceCube Collaboration et al., 2018; IceCube Collaboration, 2018). However, there's also evidence, by IceCube, that gamma-ray bright blazars contribute to no more than approximately 27% of the diffuse flux (IceCube Collaboration, 2017). More recently, IceCube has found a neutrino point source hot-spot, just below the 3 sigma threshold normally assigned to evidence, correlated with the Seyfert II galaxy, another subtype of AGN, NGC 1068 (IceCube Collaboration, 2020a). Over the past 30 years, AGNs and Gamma Ray Bursts (GRBs) were among the most prominent proposed extragalactic neutrino sources. IceCube has ruled out GRBs as contributing more than 1% of the diffuse flux (IceCube Collaboration, 2015).

The properties of various proposed extragalactic neutrino sources and/or cosmic ray reservoir classes, such as starburst galaxies, blazars, low luminosity GRBs, Flat Spectrum Radio Quasars, BL Lacs, and galaxy clusters can be summarized in terms of the local density (or density rate for transient sources) as a function of luminosity (or per-burst equivalent isotropic energy for transient sources) (Kowalski, 2015; Murase & Waxman, 2016). The correct description of each of these classes of objects depends on, e.g., the redshift evolution of the density of sources; but more generally on the luminosity function of the objects. The existence of a diffuse extragalactic neutrino flux can be described as an inverse relationship between density (density-rate) and luminosity (isotropic equivalent energy) (Kowalski, 2015). This relationship also depends on the evolution assumed.

Identification of the main sources of the diffuse neutrino flux remains an open research topic.

Statement of Need

`FIRESONG` is a Python package to be used by researchers interested in simulating populations of neutrino sources in the universe and placing these simulations in the context of IceCube's observation of a diffuse neutrino flux. It can be used to generate the neutrino fluxes measured on Earth under different source distribution models and luminosity constraints, with cosmological effects being considered. The calculations needed to conduct these simulations are well established but also cumbersome and error prone. Indeed several authors have similar (usually private) codes. `FIRESONG` provides an open source maintained framework for these simulations. `FIRESONG` requires `numpy` (Harris et al., 2020) and `scipy` (Virtanen et al., 2020). `FIRESONG` has already been used in scientific publications by several observatories of neutrinos or gamma rays: IceCube (IceCube Collaboration, 2019), HAWC and IceCube (AMON Collaboration et al., 2021), HAWC (Taboada et al., 2018) and CTA (Satalecka et al., 2019). Though originally conceived as a stand-alone project, maintenance of `FIRESONG` is currently provided by IceCube collaboration members.

Usage

`FIRESONG` can be invoked from the command line as `Firesong.py` and configured via command line options outputting a file with a simulated list of neutrino sources each specified by a declination, redshift, and muon neutrino flux. Alternatively, `FIRESONG` can also be imported and produce a Python dictionary of the simulated neutrino sources. `FIRESONG` can be used to simulate steady or transient sources. If no luminosity (isotropic equivalent energy) is provided, `FIRESONG` calculates it, as a function of local density (density rate) and other parameters, so that the IceCube neutrino diffuse flux is fully saturated. Lack of knowledge of the properties of neutrino sources motivate simple choices for implemented luminosity distributions: a delta function (standard candle), a lognormal distribution, or a power law distribution. Various models of star formation history are implemented as well as no evolution.

`Legend` is motivated by Luminosity Dependent Density Evolution (LDDE), i.e., the source distribution depends on both redshift and luminosity. The distribution of luminosities is decided by the evolution model. It should be used when the user wants to simulate a class of celestial objects that exhibit this kind of distribution (e.g., blazars.) The model currently implemented allows the user to generate gamma-ray fluxes.
`Legend` can also be invoked from the command line as `Legend.py` and configured in a similar way as `Firesong.py`. It can also be executed in the Python console by importing the function `legend_simulation` from `Legend`. If invoked as a function, the output will be a dictionary if the filename option is set to `None`. The output dictionary contains the declinations, redshifts and fluxes of the simulated sources. Simulation of transient sources is currently not supported by `Legend`.

Luminosity functions provide the source density as a function of source luminosity and cosmological redshift. For observational purposes, however, we usually care about the source count distribution, i.e., a function giving the total number of sources with a specific flux at Earth. The `FluxPDF.py` of `FIRESONG` calculates a smooth source count distribution by marginalising over any luminosity function and summing up all the contributions after accounting for their distance. Once generated, this 1D distribution can be further used to generate specific realisations of the luminosity function. This is extremely fast, but doesn't provide any information on the sources' original redshifts. In that sense it is complementary to the sampling of `Firesong.py` and specifically useful for cases where the density of sources is extremely high, when `Firesong.py` is CPU intensive.

Acknowledgements

We acknowledge comments, support and ideas by Markus Ahlers, George Japaridze, Konstancja Satalecka, and the IceCube collaboration. CFT, ML, AP, and IT acknowledge support by NSF grant PHY-1913607.

References

AMON Collaboration, HAWC Collaboration, & IceCube Collaboration. (2021). Multimessenger gamma-ray and neutrino coincidence alerts using HAWC and IceCube subthreshold data. *The Astrophysical Journal*, *906*(1), 63. https://doi.org/10.3847/1538-4357/abcaa4

Harris, C. R., Millman, K. J., Walt, S. J. van der, Gommers, R., Virtanen, P., Cournapeau, D., Wieser, E., Taylor, J., Berg, S., Smith, N. J., Kern, R., Picus, M., Hoyer, S., Kerkwijk, M. H. van, Brett, M., Haldane, A., Río, J. F. del, Wiebe, M., Peterson, P., … Oliphant, T. E. (2020). Array programming with NumPy. *Nature*, *585*(7825), 357–362. https://doi.org/10.1038/s41586-020-2649-2

IceCube Collaboration. (2017). The Contribution of Fermi-2LAC Blazars to Diffuse TeV-PeV Neutrino Flux. *The Astrophysical Journal*, *835*(1), 45. https://doi.org/10.3847/1538-4357/835/1/45

IceCube Collaboration. (2020a). Time-Integrated Neutrino Source Searches with 10 Years of IceCube Data. *Physical Review Letters*, *124*(5), 051103. https://doi.org/10.1103/PhysRevLett.124.051103

IceCube Collaboration. (2019). Search for steady point-like sources in the astrophysical muon neutrino flux with 8 years of IceCube data. *European Physical Journal C*, *79*(3), 234. https://doi.org/10.1140/epjc/s10052-019-6680-0

IceCube Collaboration. (2015). Search for Prompt Neutrino Emission from Gamma-Ray Bursts with IceCube. *The Astrophysical Journal Letters*, *805*(1), L5. https://doi.org/10.1088/2041-8205/805/1/L5

IceCube Collaboration. (2018). Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert. *Science*, *361*(6398), 147–151. https://doi.org/10.1126/science.aat2890

IceCube Collaboration. (2020b). Characteristics of the diffuse astrophysical electron and tau neutrino flux with six years of IceCube high energy cascade data. *Physical Review Letters*, *125*, 121104. https://doi.org/10.1103/PhysRevLett.125.121104

IceCube Collaboration, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S., INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, Swift/NuSTAR, VERITAS, & VLA/17B-403 teams. (2018). Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A. *Science*, *361*(6398). https://doi.org/10.1126/science.aat1378

Kowalski, M. (2015). Status of High-Energy Neutrino Astronomy. *Journal of Physics Conference Series*, *632*, 012039. https://doi.org/10.1088/1742-6596/632/1/012039

Murase, K., & Waxman, E. (2016). Constraining high-energy cosmic neutrino sources: Implications and prospects. *Physical Review D*, *94*(10), 103006. https://doi.org/10.1103/PhysRevD.94.103006

Satalecka, K., Brown, A., Rosales de león, A., Sergijenko, O., CTA collaboration, Tung, C. F., Reimann, R., Glauch, T., & Taboada, I. (2019). Neutrino Target of Opportunity program of the Cherenkov Telescope Array. *Proceedings of Science (PoS)*, *ICRC2019*, 784.

Schneider, A., & IceCube Collaboration. (2019). Characterization of the Astrophysical Diffuse Neutrino Flux with IceCube High-Energy Starting Events. *36th International Cosmic Ray Conference (ICRC2019)*, *36*, 1004. https://doi.org/10.22323/1.358.1004

Stachurska, J., & IceCube Collaboration. (2019). First Double Cascade Tau Neutrino Candidates in IceCube and a New Measurement of the Flavor Composition. *36th International Cosmic Ray Conference (ICRC2019)*, *36*, 1015. https://doi.org/10.22323/1.358.1015

Stettner, J., & IceCube Collaboration. (2019). Measurement of the diffuse astrophysical muon-neutrino spectrum with ten years of IceCube data. *36th International Cosmic Ray Conference (ICRC2019)*, *36*, 1017. https://doi.org/10.22323/1.358.1017

Stettner, J., & IceCube Collaboration. (2019). Measurement of the diffuse astrophysical muon-neutrino spectrum with ten years of IceCube data. *36th International Cosmic Ray Conference (ICRC2019)*, *36*, 1017. https://doi.org/10.22323/1.358.1017

Taboada, I., Tung, C. F., Wood, J., & HAWC collaboration. (2018). *Constrains on the extragalactic origin of IceCube's neutrinos using HAWC*. https://doi.org/10.22323/1.301.0663

Virtanen, P., Gommers, R., Oliphant, T. E., Haberland, M., Reddy, T., Cournapeau, D., Burovski, E., Peterson, P., Weckesser, W., Bright, J., van der Walt, S. J., Brett, M., Wilson, J., Millman, K. J., Mayorov, N., Nelson, A. R. J., Jones, E., Kern, R., Larson, E., … SciPy 1.0 Contributors. (2020). SciPy 1.0: Fundamental Algorithms for Scientific Computing in Python. *Nature Methods*, *17*, 261–272. https://doi.org/10.1038/s41592-019-0686-2