The Multi-Messenger Astrophysics of the Galactic Centre
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High Energy Gamma Rays and Neutrinos from Star-forming Activities in the Galactic and Extragalactic Sources

Soebur Razzaque

Department of Physics, University of Johannesburg,
PO Box 524, Auckland Park 2006, South Africa
email: `srazzaque@uj.ac.za`

Abstract. The origin of the IceCube astrophysical neutrinos is an outstanding question. Star-forming activities which can accelerate particles to very high energies have been suggested as possible origin of these neutrinos. I will present a scenario where a subset of the neutrino events originate from the Galactic center region and Fermi Bubbles, resulting from star-forming activities. Multi-messenger signal in high energy gamma rays and neutrinos can probe this scenario. I will also present an analysis of the statistical association of the star-forming sources in our Galaxy and outside, with astrophysical neutrinos, as well as expected neutrino signal from these sources by fitting gamma-ray data.

Keywords. neutrinos, gamma rays: theory, Galaxy: center

1. Introduction

The origin of Astrophysical neutrinos, so called High Energy Starting Events (HESE), detected by IceCube (Aartsen *et al.* 2014) is currently a hot topic for debate. The published 4-year HESE sample contains 54 neutrinos with energy between $\sim$20 TeV and $\sim$2 PeV (Kopper 2015). It has been argued that a subset of these HESE neutrinos are of Galactic origin (Razzaque 2013). Extragalactic sources, such as the sources of ultrahigh-energy cosmic rays (Moharana & Razzaque 2015) and star-forming objects (Emig *et al.* 2015) have also been used to study angular correlation with HESE neutrinos. Fermi bubbles at the Galactic centre (Su *et al.* 2010) may produce high energy neutrinos (Crocker & Aharonian 2011; Lunardini & Razzaque 2012) and some HESE neutrinos might be from the Fermi bubbles (Lunardini *et al.* 2014).

Here we present results from our recent studies about very high-energy gamma-ray emission from the Fermi bubbles, which can be detected with High Altitude Water Cherenkov (HAWC) detector (Goodman 2016), that may constrain the hadronic model, together with neutrino detection (Lunardini *et al.* 2015). We also present results from our study of angular correlations of HESE neutrinos with Galactic and extragalactic sources related to star formation (Moharana & Razzaque 2016).

2. Results

We find that by modelling the γ-ray emission of the Fermi bubbles (Ackermann *et al.* 2014) to 100 TeV, HAWC will be complementary to neutrino searches, realising true multi-messenger astronomy with overlapping energy ranges. It will be possible to constrain the hadronic γ-ray emission, in particular the spectral features of the cosmic rays, within a few years. A negative result by IceCube will be compatible with either a hadronic scenario with sub-PeV cutoff, or a primary leptonic origin of the Fermi bubbles.

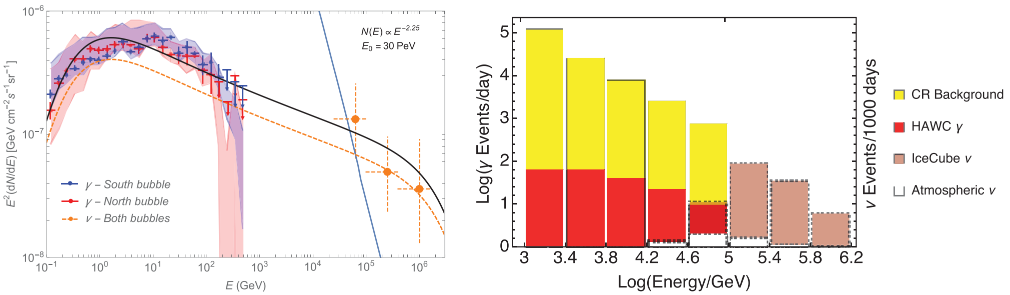

Figure 1. Left panel: Hadronic model for γ-ray and neutrino data from the Fermi bubbles. Right panel: Expected event rates in HAWC and IceCube from Fermi bubbles in hadronic model. Figures taken from Lunardini *et al.* (2015).

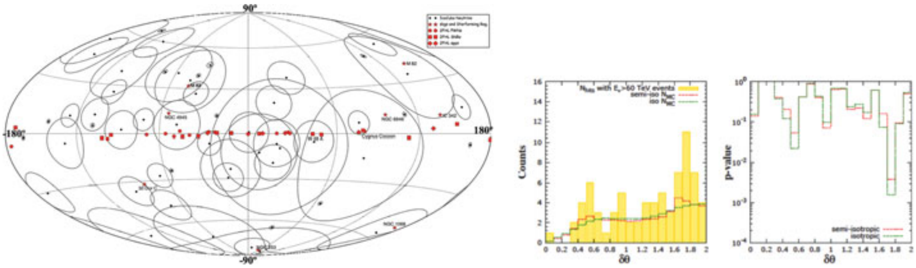

Figure 2. Left panel: Arrival directions of the 53 IceCube HESE neutrinos with their uncertainty ellipses in Galactic coordinates. Also shown are 33 Galactic objects from the Fermi-LAT 2FHL catalog. Right panel: Angular correlation between the HESE neutrinos and the 2FHL Galactic objects. Figures taken from Moharana & Razzaque (2016).

We have performed a cross correlation study for the highest energy gamma ray sources in the *Fermi* 2FHL catalog (Ackermann *et al.* (2016)) that includes 33 Galactic sources such as supernova remnants and pulsar wind nebulae, which are associated to star formation. These Galactic sources show a significant correlation with the HESE neutrinos, giving p-value (pre-trial) 0.017 for all neutrino energies and a lower p-value (pre-trial) 0.0016 for neutrinos with energy greater than 60 TeV. The post-trial p-value is 0.06 for these 2FHL Galactic sources.

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