2IceCube-Gen2

Snowmass2021 - Letter of Interest

Opportunities for multi-messenger observations with neutrinos and tests of fundamental physics over the next decade

Thematic Areas: (check all that apply □/■)
□ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
□ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
■ (Other) (NF04) Neutrinos from Natural Sources
■ (Other) (NF05) Neutrinos Properties
■ (Other) (NF10) Neutrino Detectors

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Collaboration : IceCube-Gen2

Abstract:

IceCube is a gigaton-scale instrument that has discovered an all-sky unresolved flux of astrophysical neutrinos in the TeV - PeV energy range. IceCube has also found the first candidate neutrino source: the blazar TXS 0506+56. High-energy neutrino astrophysics is currently limited by statistics and by pointing resolution. This decade will witness dramatic improvements in the sensitivity to high-energy neutrinos. IceCube is the first of a network of gigaton-scale neutrino telescopes, either proposed or in construction, expected to become operational within ten years (KM3NeT, GVD, P-ONE), and jointly they will monitor the entire sky (4π sr). The proposed IceCube-Gen2, focus of this letter, is a proposed high-energy neutrino telescope monitoring $\sim$8 gigatons of ice using optical (Cherenkov) detection. IceCube-Gen2 will have 5 times better sensitivity than IceCube for steady point sources and the rate of astrophysical neutrinos will increase tenfold. IceCube-Gen2 will include a radio array covering 500 km^2, expanding its energy range up to 10^{19} eV. A joint observation of neutrinos with photons and/or gravitational waves will have profound consequences for astrophysics. These observations enable the study of neutrino properties and the search for physics beyond the Standard Model at energies and distance scales not reachable in human-made accelerators.

Motivation and current status of multimessenger high-energy neutrino astrophysics

High-energy astrophysical neutrinos (HEν) are expected to be produced in hadronic cosmic-ray (CR) interactions, either at their source or during propagation, via meson decays which should also result in the emission of γ-rays . Gravitational waves (GW) may also be accompanied by HEνs as compact object mergers can launch astrophysical jets capable of energetic particle acceleration. Thus, multimessenger (MM) studies that combine HEν, electromagnetic (EM), GW, and CR observations can provide unique insights into extreme astrophysical environments and enable sensitive tests of fundamental physics.

The most sensitive HEν telescope in operation is IceCube[1;2], a km^3-scale Cherenkov detector deployed deep within the South Pole glacier that detects TeV neutrinos of all flavors across the entire sky (4π) and with $\gtrsim 99\%$ uptime. In 2013 IceCube announced the discovery of an all-sky astrophysical HEν flux in the TeV-PeV range[3;4]. This groundbreaking result was followed in 2017 by the identification of a first HEν source candidate thanks to the detection of a 290 TeV neutrino event from the direction of the γ-ray blazar TXS 0506+056, at a distance of 1.76 Gpc[5]. At the time of the IceCube detection, the blazar was strongly flaring in GeV γ-rays as observed by *Fermi*-LAT, which also led to a first detection of the source in very-high-energy γ-rays (>100 GeV) by MAGIC[6], and later on by VERITAS[7]. A subsequent analysis of IceCube archival data revealed additional evidence of neutrino emission from the direction of TXS 0506+056 over a ~ 150-day period in 2014-2015, although with no accompanying EM flare[8].

IceCube conducts searches for HEνsources that are active over different time scales[9;10] and performs correlation studies with known EM emitters such as γ-ray blazars[11], γ-ray bursts (GRB)[12], tidal disruption events[13], fast radio bursts[14] and galaxies in the local universe[15], as well as correlated searches with GWs[16]. These correlated studies offer an opportunity to conduct MM astrophysics. Of particular interest for tests of fundamental physics are those MM identifications that provide a measurement of distance or redshift, or that are very brief and contemporaneous with neutrinos, as an imprint of new physics may be measurable as particles propagate over cosmic distances. The identification of a GW or EM counterpart to a HEν signal, specially for impulsive events such as a short GRB (lasting $\lesssim 2$ s) or a GW trigger, provide good opportunities for these tests.

The identification of TXS 0506+056 as a potential HEν counterpart provided a prime example of how these observations can test fundamental physical laws on cosmic scales and at extreme neutrino energies, both conditions well beyond the reach of human-made accelerators. The construction of IceCube-Gen2, the next-generation HEν observatory, and its simultaneous operation with an expanding network of MM observatories will greatly improve the sensitivity of these searches for new physics.

Prospects for multimessenger high-energy neutrino astrophysics in the coming decade

Over the coming decade, the construction and operation of IceCube-Gen2 will result in an increase in a factor of 5 in sensitivity to steady HEν sources as well as an increase of a factor of 10 in the rate of detections of astrophysical neutrinos[17]. Part of the increase in sensitivity to point sources is due to Gen2's better angular resolution for individual neutrinos - a boon for MM identifications. The increase in sensitivity is enough to resolve all proposed candidate steady neutrino sources[17;18]. For both gravitational waves[19;20] and GRBs[21], the improved sensitivity of IceCube-Gen2 will enable neutrino observations IceCube is insensitive to.

IceCube-Gen2 will feature an 8-gigaton optical (Cherenkov) array as well as a 500 km^2 radio array. The radio array detects coherent radio emission by charged particles in a particle shower, extending the sensitivity of Gen2 up to the 10^{19} eV energy range[17]. With an expected completion date of 2033, IceCube-Gen2 will be in simultaneous operation with MM facilities such as CTA[22], the Vera Rubin Observatory[23], AugerPrime[24], an advanced and expanding network of GW detectors (LIGOA+[25], Virgo, KAGRA, LIGO-India, LISA, and pulsar-timing arrays), as well as proposed γ-ray space telescopes such as AMEGO[26] and e-ASTROGAM. The detection of one or more of these MM source classes provides an astrophysical neutrino beamline that can be used to test fundamental physics. Other neutrino telescopes (such as KM3NeT[27], GVD[28], and P-

ONE[29]) are expected to be built and reach a size comparable to that of the current generation IceCube in the coming decade, and will provide a complementary view of the HEν sky to the one delivered by IceCube-Gen2.

Neutrino decay and MM observations

Under naïve assumptions of astrophysical production and standard 3-flavor neutrino oscillations, the flavor flux ratio of neutrinos at Earth is expected to be 1:1:1. Taking into account astrophysical neutrino production effects like, e.g. muon cooling[30] the neutrino flavor flux ratio at Earth is modified slightly. However, neutrino decay can have a dramatic impact on flavor flux ratios at Earth[31]. Discovering an anomalous flavor flux ratio can be done by IceCube/IceCube-Gen2 alone. However a MM association provides a distance/redshift measurement which also enables the measurement of neutrino lifetime[32;33].

Lorentz Invariance Violation (LIV) enabled by MM observations

A signature for LIV is an energy-dependent time dispersion in the arrival of a signal at Earth from an astrophysical source. The time difference can be derived from EM and neutrino data under the assumption that there is no intrinsic delay in the emission of both signals at the source. This LIV-induced vacuum dispersion is usually parametrized with linear or quadratic leading-order terms in energy. The observation of IceCube-170922A and associated MM studies of TXS 0506+056 triggered several theoretical interpretations of this type[34–36] which resulted in strong LIV constraints.

A recent study presented a claim for a correlation between TeV-PeV IceCube neutrinos with GRBs[37] and a time difference between neutrinos and the GRB prompt phase (characterized by keV-MeV photons). As neutrinos arriving both before and after the GRBs were noted, the authors claim that these correspond to superluminal neutrinos and subluminal anti-neutrinos, due to their opposite signs on the LIV effect. While IceCube itself has not found a HEν association of with GRBs[38], these publications show the potential for MM studies. Without the need to measure times, and assuming an extragalactic origin, PeV IceCube neutrinos have also been used to set stringent LIV constraints[39]. The detection of MM counterparts to these neutrinos would ratify their extragalactic origin and significantly improve the accuracy of these constraints.

Other tests of fundamental physics enabled by MM observations

IceCube-170922A and the associated γ-ray emission, as well as the apparent neutrino flare detected in 2014-2015, can also be used to set strong constraints on the speed of neutrinos, dual lensing effects, and the weak equivalence principle[35;36]. Since the distance to the source candidate was known, the detection of neutrinos can also act as a probe of secret neutrino interactions mediated by a new neutral boson[40;41]. A similar approach can be used to set strong constraints on neutrino scatterings on relic keV-GeV dark matter, neutrino-axion couplings, and the neutrino mean free path[40].

As with SN1987A[42], a new MM detection of photons and MeV neutrinos fom a nearby core-collapse supernova - to which IceCube /IceCube-Gen2 are sensitive - will also enable strong tests of physics beyond the Standard Model and studies of neutrino properties[43;44]. Core-collapse supernovae in our Galaxy may also be detected by GW observatories, allowing measurements of the speed of GWs[45]. Similarly, the observation of HEν and GWs from other processes, such as neutron star or black hole mergers[46;47], would not only provide a new MM source class but also improve current GW speed constraints[48] and enable the study of particle acceleration in strong-field gravitational environments.

Outlook for tests of fundamental physics with IceCube-Gen2

Recent studies illustrate the power of MM observations involving astrophysical HEνs as a framework to test fundamental laws of physics. The increased sensitivity of IceCube-Gen2, and its potential to identify multiple MM sources of HEν[17] holds the promise of unveiling new physics in the neutrino sector, or strongly constraining theoretical models in the next decade.

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