Snowmass2021 - Letter of Interest

IceCube, Atmospheric Leptons, and Cosmic Rays

Thematic Areas:

- ■ (CF7) Cosmic Probes of Fundamental Physics
- ■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
- ■ (EF6) QCD and Strong Interactions: Hadronic Structure and Forward QCD
- ■ (EF7) QCD and Strong interactions: Heavy Ions
- ■ (NF1) Neutrino Oscillations
- ■ (NF4) Neutrinos from natural sources
- ■ (NF5) Neutrino properties
- ■ (NF10) Neutrino detectors

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Abstract: IceCube has a rich program of neutrino physics, to study particle acceleration in the Universe, but also neutrino properties through their production, propagation and interaction. Atmospheric leptons produced by cosmic rays are the dominant background in IceCube, as well as the beam for the neutrino physics program. Understanding the cosmic ray spectrum and composition and their hadronic interactions are limiting systematic uncertainties for IceCube and IceCube-Gen2. Including the surface detector IceTop, IceCube becomes a cosmic ray detector measuring shower energy and muon content both on the surface and deep in-ice. In the next decade, new surface instrumentation will enhance IceCube's measurements of cosmic-ray observables, including radio and optical imaging of the shower in the atmosphere. IceCube carries out a program of galactic cosmic ray physics across six orders of magnitude in energy, including high-resolution measurements of the cosmic-ray energy spectrum, characterization of the mass composition of the primary flux, sensitivity to the part-in-10^4 arrival direction anisotropy, and searches for PeV gamma rays. IceCube-Gen2 will provide a factor 50 increase in exposure for high quality events with coincident detection by surface and deep detectors, greatly reducing uncertainties in the neutrino program and providing a window into the galactic-extragalactic transition at the ankle of the cosmic ray spectrum.

Overview

IceCube is the preeminent detector of astrophysical and atmospheric neutrinos[*][1]. Astrophysical neutrinos are a key component to multi-messenger astronomy and probe cosmic accelerators[2;3] and neutrino properties[†] over cosmological distances. Atmospheric neutrinos and muons are irreducible backgrounds to the identification of astrophysical neutrinos and their sources. Atmospheric neutrinos are also used to study neutrino properties within[‡][4] and beyond the Standard Model[§]. IceCube-Gen2[¶][5] will include an array of antennas to detect radio emission induced by neutrinos with $E > 30$ PeV[‖], with a potential background due to prompt leptons from UHE cosmic rays. These science goals rely on accurate estimates of the production of conventional and prompt atmospheric leptons[6;7].

Modeling atmospheric lepton production and comparing to observation requires accurate cosmic ray spectra and composition[8–10], whole Earth time-dependent characterizations of the atmosphere[11–13], hadronic interaction models[14], and calibration of the IceCube detector. IceCube includes a surface array of ice Cherenkov tanks, IceTop[15], which produces measurements of air shower energy[16] and surface (GeV) muons[17;18]. Together with observations of in-ice (TeV) muons[19–21], one may resolve composition[22] and constrain hadronic interaction models[**][23–25], subject to uncertainties of in-ice calibration[26] and snow accumulation on IceTop tanks[27]. Enhancments to the current surface instrumentation (500 m^2 of elevated scintillator panels[28], 200 radio channels[††][29], and optical air Cherenkov telescopes[30]) should improve shower reconstruction, reduce uncertainty in atmospheric lepton production, and improve the neutrino science program.

IceCube also maintains a program to study particle production and propagation in the galaxy. This will be fully realized as surface instrumentation is extended within the larger IceCube-Gen2 footprint, increasing the rate of events with coincident surface and in-ice detection by a factor 50. With remote measurements of shower intensity and depth development, improved in-ice calibration, more stable surface instrumentation, and muon content measured at both GeV and TeV energies, IceCube will greatly improve reconstruction of single events and extend spectral and composition studies below the knee[31] and above an EeV[‡‡]. By studying cosmic ray arrival anisotropy[§§][32;33] and searching for PeV γ-rays[34], IceCube-Gen2 will enhance our knowledge of galactic cosmic rays over six decades of energy – from TeV energies, across the knee, to the ankle.

Cross-references to LoIs of Snowmass2021:

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[*] D. Grant, F. Halzen et al., *The IceCube Neutrino Observatory*

[†] M. Santander, I. Taboada et al., *Opportunities for multi-messenger observations with neutrinos and tests of fundamental physics over the next decade*

[‡] S. R. Klein et al., *Neutrino cross-sections and interaction physics*,
T. Stuttard, D. J. Koskinen et al., *Neutrino oscillations with IceCube-DeepCore and theIceCube Upgrade*

[§] A. Pollmann, I. Taboada et al., *Searches for exotic particles with the IceCube NeutrinoObservatory*

[¶] A. Karle, M. Kowalski et al., *IceCube-Gen2: The Window to the Extreme Universe*,
A. Karle, M. Kowalski et al., *IceCube-Gen2: the next generation wide band neutrino observatory*

[‖] S. Wissel et al., *The Radio Neutrino Observatory in Greenland (RNO-G)*

[**] D. Soldin et al., *Studies of the Muon Excess in Cosmic Ray Air Showers*

[††] F. G. Schröder et al., *Radio Detection of Cosmic Rays*

[‡‡] A. Haungs et al., *Highest Energy Galactic Cosmic Rays*

[§§] P. Desiati et al., *Determination of cosmic ray properties in the local interstellar medium with all-sky anisotropy observations*

References:

[1] M. G. Aartsen et al. The IceCube Neutrino Observatory: Instrumentation and Online Systems. *JINST*, 12(03):P03012, 2017.

[2] A. R. Bell. Cosmic ray acceleration. *Astroparticle Physics*, 43:56 – 70, 2013. Seeing the High-Energy Universe with the Cherenkov Telescope Array - The Science Explored with the CTA.

[3] K. Kotera and A. V. Olinto. The astrophysics of ultrahigh-energy cosmic rays. *Annual Review of Astronomy and Astrophysics*, 49(1):119–153, 2011.

[4] M. G. Aartsen et al. Measurement of the multi-TeV neutrino cross section with IceCube using Earth absorption. *Nature*, 551:596–600, 2017.

[5] M. G. Aartsen et al. IceCube-Gen2: The Window to the Extreme Universe. Aug 2020.

[6] T. K. Gaisser. Spectrum of cosmic-ray nucleons, kaon production, and the atmospheric muon charge ratio. *Astropart. Phys.*, 35:801–806, 2012.

[7] A. Fedynitch et al. Calculation of conventional and prompt lepton fluxes at very high energy. *EPJ Web Conf.*, 99:08001, 2015.

[8] T. K. Gaisser. Atmospheric Lepton Fluxes. *EPJ Web Conf.*, 99:05002, 2015.

[9] M. Benzke, M. V. Garzelli, and B. A. Kniehl. Atmospheric Charm, QCD and Neutrino Astronomy. *PoS*, Confinement2018:016, 2018.

[10] K.-H. Kampert and M. Unger. Measurements of the cosmic ray composition with air shower experiments. *Astropart. Phys.*, 35(10):660 – 678, 2012.

[11] T. K. Gaisser. Seasonal variation of atmospheric neutrinos in IceCube. In *33rd International Cosmic Ray Conference*, page 0492, 2013.

[12] S. Tilav et al. Seasonal variation of atmospheric muons in IceCube. *PoS*, ICRC2019:894, 2020.

[13] P. Heix et al. Seasonal Variation of Atmospheric Neutrinos in IceCube. *PoS*, ICRC2019:465, 2020.

[14] R. Engel, D. Heck, and T. Pierog. Extensive Air Showers and Hadronic Interactions at High Energy. *Annual Review of Nuclear and Particle Science*, 61(1):467–489, 2011.

[15] R. U. Abbasi et al. IceTop: The surface component of IceCube. *Nucl. Instr. and Meth.*, A700:188 – 220, 2013.

[16] M. G. Aartsen et al. Measurement of the cosmic ray energy spectrum with IceTop-73. *Phys. Rev. D*, 88(4):042004, 2013.

[17] J. G. Gonzalez et al. Measuring the Muon Content of Air Showers with IceTop. *EPJ Web Conf.*, 99:06002, 2015.

[18] J. G. Gonzalez et al. Muon Measurements with IceTop. *EPJ Web Conf.*, 208:03003, 2019.

[19] M. G. Aartsen et al. Characterization of the Atmospheric Muon Flux in IceCube. *Astropart. Phys.*, 78:1–27, 2016.

[20] R. U. Abbasi et al. Lateral Distribution of Muons in IceCube Cosmic Ray Events. *Phys. Rev. D*, 87(1):012005, 2013.

[21] D. Soldin et al. Atmospheric Muons Measured with IceCube. *EPJ Web Conf.*, 208:08007, 2019.

[22] M. G. Aartsen et al. Cosmic ray spectrum and composition from PeV to EeV using 3 years of data from IceTop and IceCube. *Phys. Rev. D*, 100(8):082002, 2019.

[23] S. De Ridder, E. Dvorak, T. K. Gaisser, et al. Sensitivity of IceCube Cosmic-Ray measurements to the hadronic interaction models. *PoS*, ICRC2017:319, 2017.

[24] F. Riehn et al. The hadronic interaction model sibyll 2.3c and extensive air showers. *Preprint: arXiv:1912.03300*, Dec 2019.

[25] H. P. Dembinski et al. Report on Tests and Measurements of Hadronic Interaction Properties with Air Showers. *EPJ Web Conf.*, 210:02004, 2019.

[26] D. Chirkin, M. Rongen, et al. Light diffusion in birefringent polycrystals and the IceCube ice anisotropy. *PoS*, ICRC2019:854, 2020.

[27] K. Rawlins. The Effect of Snow Accumulation on Signals in IceTop. In *33rd International Cosmic Ray Conference*, page 1106, 2013.

[28] A. Haungs et al. A Scintillator and Radio Enhancement of the IceCube Surface Detector Array. *EPJ Web Conf.*, 210:06009, 2019.

[29] F. Schroeder et al. Science Case of a Scintillator and Radio Surface Array at IceCube. *PoS*, ICRC2019:418, 2019.

[30] M. Schaufel, K. Andeen, J. Auffenberg, et al. IceAct, small Imaging Air Cherenkov Telescopes for IceCube. *PoS*, ICRC2019:179, 2020.

[31] M.G. Aartsen et al. Cosmic Ray Spectrum from 250 TeV to 10 PeV using IceTop. *Preprint: arXiv:2006.05215*, Jun 2020.

[32] M. G. Aartsen et al. Anisotropy in Cosmic-ray Arrival Directions in the Southern Hemisphere Based on six Years of Data From the Icecube Detector. *Astrophys. J.*, 826(2):220, 2016.

[33] A. U. Abeysekara et al. All-Sky Measurement of the Anisotropy of Cosmic Rays at 10 TeV and Mapping of the Local Interstellar Magnetic Field. *Astrophys. J.*, 871(1):96, 2019.

[34] M. G. Aartsen et al. Search for PeV Gamma-Ray Emission from the Southern Hemisphere with 5 Years of Data from the IceCube Observatory. *Astrophys. J.*, 891:9, 8 2019.