Snowmass2021 - Letter of Interest

IceCube and IceCube-Gen: Quantum Computing Opportunities

Thematic Areas: (check all that apply □/■)

□ (NF10) Neutrino Detectors
□ (CompF2) Theoretical Calculations and Simulation
□ (CompF3) Machine Learning
■ (CompF6) Quantum Computing

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On behalf of the IceCube[1] and IceCube-Gen2[2] collaborations.

Abstract:

The IceCube Neutrino Observatory is a gigaton-mass neutrino detector deployed in the glacial ice of the South Pole. Within the next decade two extensions of the IceCube experiment are planned; first a densely packed array called the IceCube-Upgrade, followed by the sparsely packed IceCube-Gen2. As the size and precision of all programs on the scale of IceCube increase, the computational cost of simulation and data analysis becomes ever higher, challenging conventional capabilities. Within the next Snowmass period, it is expected that novel techniques based on quantum computing will come close to maturity. We highlight here what we consider to be a key responsibility for the high-energy and astro-particle physics community over this Snowmass period: to remain diligent and continuously aware of opportunities for use of early quantum computers to enhance physics capabilities. In this letter we highlight the avenues of exploration where we foresee that quantum computing experience could be developed, advancing towards deployable solutions for key computational tasks at the IceCube South Pole Neutrino Observatory over the next ten years.

[1] https://icecube.wisc.edu/collaboration/authors/snowmass21_icecube
[2] https://icecube.wisc.edu/collaboration/authors/snowmass21_icecube-gen2

Introduction.– The IceCube Neutrino Observatory,[1] located at the South Pole, instruments a cubic kilometer of Antarctic ice. IceCube uses 5160 digital optical modules (DOMs) arranged on 86 strings in a hexagonal array to detect Cherenkov radiation from relativistic charged particles emitted during neutrino interactions. This configuration can detect neutrinos with energies as high as 1 EeV, while a more densely instrumented region, called DeepCore, is optimized to detect neutrinos with energies as low as 10 GeV. The IceCube-Upgrade serves a dual purpose: an additional seven strings concentrated around DeepCore will improve resolution for GeV neutrinos, while the various DOM designs serve as research and development for IceCube-Gen2.[2] Furthermore, Gen2 will improve the resolution and detection rate of PeV and EeV neutrinos by adding 120 new string, bringing the total detector volume to 7.9 km^3.[3]

Quantum computing has not been widely applied to to high-energy physics experiments. Its most famous algorithmic applications include database queries[4] and number factorization.[5] However, it was realized very early in the development of quantum information science,[6] that direct simulation of quantum systems in the Hilbert space of a quantum processor may lead to dramatic conceptual and computational advances. An example of a system with intrinsically quantum dynamics, amenable to direct quantum simulation, is the oscillation of neutrinos.[7]

We recently demonstrated the implementation of three-neutrino oscillations within the Hilbert space of a universal gate quantum processor,[8] an example of a direct quantum simulation problem tractable using only a small number of qubits available on publicly accessible quantum machines. This is one of the simplest quantum problems one can imagine solving via quantum computing, and truly transformative applications require far more qubits, and better performance than is presently available. Nevertheless, the project before us now appears to be an iterative one: to frame ever more complex problems in the language of quantum computers, and to develop solutions of increasing complexity to establish readiness for major advances that quantum techniques promise.

This LOI speculates about computing topics within the context of the IceCube Neutrino Observatory with aspects that may be profitably re-expressed in the language of quantum computation, over the coming Snowmass period. A small interest group has begun work toward developing demonstration-scale computations for existing systems. The growth potential for this work during the next ten years is substantial.

Opportunities.– Several applications of quantum computing have been proposed in high-energy particle physics both in simulation[9] and reconstruction.[10] Within IceCube, the following problems are plausible arenas for application of quantum techniques:

- *Underlying physics & simulation*: Two specific physics problems appear to be among the clearest applications of quantum processing for the IceCube program: 1) neutrino transport, and 2) neutrino interactions and event generation. (1) Low-energy neutrino transport implies handling neutrino flavor conversion, a phenomena often known as neutrino oscillations, but also incorporating effects of absorption, matter interactions and, in certain new physics models, potentially non-unitary evolution effects. This can be done by means of analytical approximations[11] or numerical simulations in classical computers both using CPUs[12–16] and GPUs,[17] but recently the possibility of computing this in quantum computing has been put forward.[8] Modeling transport of high-energy neutrinos in neutrino opaque-media is more complex[18–20] and often requires computationally expensive Monte Carlo packages[21–27] or systems of large number of coupled differential equations.[16;28–31] These large coupled systems are an ideal place to be embedded within quantum computers where the represented phase-space can be larger than in classical system. (2) Low-energy[32–35] and high-energy[36–40] neutrino interactions are an active field of study. Low-energy neutrino interactions are particularly susceptible to correlations between nucleons and the effects of final state interactions.[41] Recent calculations proposed for quantum computers[42] aim to compute the neutrino-nucleon cross section more accurately, an essential input for neutrino oscillation experiments.[43;44]

- *Detector simulation:* Light transport in IceCube is currently performed using ray-tracing algorithms[45;46] seeded from the expected yield of charged leptons[47] or hadrons.[48;49] Such algorithms require GPUs, and are the most computationally prohibitive aspect of IceCube's simulation chain. The problem of computing the expected light yield in the IceCube PMTs can be transformed into a classical path integral,[50] where one integrates over all possible trajectories from the emitted light source to the detectors. This large-phase space problem could be elegantly addressed using quantum computing techniques, *e.g.* the ones proposed for hadronic shower evolution or used in QFT calculations.

- *Reconstruction, classifiers, and event selection*: The increased per-event information expected in the more tightly packed IceCube-Upgrade implies a great opportunity to improve reconstruction, as well as a challenge to use all the available information. The use of classical machine learning algorithms for this purpose is a major contemporary focus (the subject of separate LoI). It is very plausible that great enhancements in this area may be enabled by quantum techniques.[51;52] Though the rate of neutrino interactions is small, the rate of penetrating muons is large, thus the first stage in reconstruction of the events is to associate light to a particular physics event, a natural application of quantum annealing pattern recognition algorithms.[10;53] In fact, quantum algorithms for particle identification have already been proposed to reconstruct specific neutrino signatures such as inverse beta decay.[54] That proposal involves construction of probability distributions in feature spaces of signal and background, then measures their separation via *e.g* the "earth-mover's distance" metric. Computation of this metric requires solving an expensive optimization problem, which can be solved on quantum annealer by a known mapping to an Ising Hamiltonian. Relevant classification problems in IceCube, and its extensions, include differentiation between charged-current and neutral-current interactions, and between neutrino flavors. A topological separation problem of special interest is the identification out tau neutrinos. Application of event selection to large datasets can also be transformed it into an annealing-compatible optimization problem[55;56] and has been studied in the context of high-energy physics analyses.[57]

Outlook– The use of classical computers in experimental high-energy physics has been central to the growth and development of the field. Quantum technologies promise to revolutionize aspects of computation in mathematics and physics, and will likely lead to advances that are difficult to anticipate at the present time.

Being able to effectively employ quantum computing for high-energy and astro-particle physics will involve a paradigm shift in our collective thinking about certain calculations. In the coming Snowmass period we consider it a key responsibility of the field to prepare for this shift in perspective. Part of this process will involve scrutinizing carefully our most difficult and prohibitive computing problems and seeking opportunities to cast them in the language of quantum computation.

At least in the short term, progress will require an exercise in creativity in trying to fit demonstration-scale versions of known problems within the imperfect capabilities of early and noisy quantum systems. We argue that even such illustrative applications have great utility in developing community expertise and intuition for quantum computing. Ideas stemming from such explorations may unlock conceptual advances that can be transformative once commercial quantum systems reach full maturity.

Conclusion– We have described several topics where we expect progress can be made using quantum computation for physics simulation and data analysis at the IceCube Neutrino Telescope. Intrepidity will be required to proceed in the short term, since it will be some time before our computational ambitions are matched by the capability of available quantum technology. Nevertheless, time spent developing understanding, skills and intuition will be well spent, and likely to return large dividends once powerful, commercial quantum computers become available. We believe the time is ripe for this work to begin.

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