Practical Quantum Advantages in High Energy Physics

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In this LOI, we discuss open questions in cosmology and particle physics whose solutions would demonstrate practical quantum advantage – solving a problem of *interest* using quantum hardware that is impractical for classical resources. Arriving at these calculation will require theoretical developments in nonperturbative and nonequilibrium physics along side improved quantum algorithms.

I. INTRODUCTION

It was inevitable: a quantum calculation has been demonstrated by Google team [1] that would not easily[1] be performed by a classical computer. This calculation, sampling pseudo-random quantum circuits, while a technical triumph, is not a practical result of use to scientists. In this way, the community is awaiting demonstrations of *practical* quantum advantage – solving a problem of *interest* using quantum hardware that is impractical for classical resources. In this LOI, we point out questions in high energy physics where practical quantum advantage could not only be shown, but may be required for their resolution. While not an exhaustive list, these problems in theoretical cosmology and collider physics highlight the potential for dramatic changes coming with quantum simulations.

Essentially, these situations all demand tools capable of the nonperturbative time-evolution of quantum fields; a very tall order! Alas, our only existing systematic and nonperturbative method, lattice field theory, is impeded in this endeavour by seemingly intractable *sign problems* from the analytic continuation required. Thus, we recourse to a mixture of nonperturbative classical time-evolution and perturbative quantum field theory. We can only overcome this roadblock with quantum simulations. Beyond the large quantum hardware requirements, theoretical development are required in connecting classical or perturbative physics intuition with well-defined matrix elements, renormalization, and algorithms to compute them – analogous to the history of lattice field theory. Thus, we anticipate that addressing the problems discussed below will in the long-run change our perspective of quantum field theory.

A pair of organizing hierarchies help understand how to demonstrate and use practical quantum advantage: model ladders and observable complexity. The first recognizes that while the standard model and extensions are of prime interest, a tower of computationally cheaper models exist. Identifying toy models with the same physical properties is key. The second hierarchy notes that while directly performing the time-evolution of a process is usually the ultimate goal, resource reductions are found by factorizing problems into nonperturbative matrix elements and larger perturbative calculations. For illustration, consider the pp cross-section at 14 TeV. It could be obtained by simulating lattice configurations of quarks and gluons colliding at immense computational expense. A first step could consider scattering in the 1+1d Thirring model. But having well-defined initial and final states still need large quantum resources. Instead, By factorize scattering into a perturbative collision convoluted with "hadronic" tensor, we need resources sufficent for just the tensor from a single initial state particle evolving for a short time – dramatically reducing the quantum resources. So a first calculation might be to compute the "hadronic" tensor of the Thirring model [2].

II. NONEQUILIBRIUM COSMOLOGY

The universe is inherently quantum. Any predictions about earlier epochs should be quantum as well. Three hypothesized phenomena – *inflation*, *baryon asymmetry*, and *dark matter* – are predicated upon nonequilibrium

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[1] Defining "easily" is a matter of personal taste. Computational complexity assures that certain problems, provided a sufficiently large number of inputs will be faster than any classical algorithm, but whether the resulting difference in time for claiming quantum advantage is days, years or lifetimes of the universe isn't.

dynamics of nonperturbative quantum fields. At present, calculations assume of classicalization, adiabatic or near-equilibrium evolution, and perturbative field theory which may receive large corrections from out-of-equilibrium or nonperturbative corrections. These corrections constitute opportunities for practical quantum advantage.

Inflation: In the inflationary paradigm, the universe experienced a period of accelerated expansion brought on by quantum fluctuations, evolving as nearly classical fields, before terminating by transferring energy to particle degrees of freedom through *reheating* and *preheating*. These far-from equilibrium and nonperturbative processes could leave imprints on the sky today [3]. While long-term, quantum simulations of 3+1d quantum inflationary fields are desired [4], near-term studies could improve calculations of the quantum back-reactions[5] onto classical inflaton fields and scalar/tensor perturbations directly from nonperturbative quantum effects.

Baryon Asymmetry: Generating the observed baryon asymmetry requires nonequilibrium dynamics [6]. Potential sources of this nonequilibrium behavior include heavy particle decays [7], the Affleck-Dine mechanism [8], and first-order phase transitions [9]. Standard calculations rely upon the interaction rates being much faster than the Hubble rate, justifying nearly equilibrium behavior and effective potentials. Condensed matter studies suggest that such simplistic comparisons can be insufficient to insure adiabatic evolution [10]. For phase transitions, the state-of-the-art computes the perturbative effective potential and extracts from it the properties of nucleating bubbles then input to classical field time-evolution. Early quantum research should focus on rigorously defining matrix elements for bubble properties and exploratory calculations of them. Additionally, the interplay between phase transitions and curved spacetime manifests nonequilibrium behavior in low-dimensional toy models can be investigated with NISQ-era resources [11, 12].

Dark Matter: Another mystery of the early universe is what accounts for around the 85% of the matter observed only via its gravitational effects. Light dark matter such as axions typically require a more complex and nonequilibrium history to be produced. For example, the axion mass [13] and strong-CP θ information are required to predict the relic abundance. Quantum computers could be used to compute the equilibrium axion mass or θ [14] as well as reduce systematic errors in bounding the nonequilibrium histories of light dark matter. Quantum advantage would allow us to probe the dynamics of other types of dark matter like topological defects [15] or primordial black holes [16] that are difficult to analyze because of their relation to strong-field theory.

III. THEORETICAL INPUTS TO COLLIDERS

While there are classical methods for computing perturbative scattering, there are known regimes where they break down: *hadronization*, *higher-order processes*, and *transport coefficients*. In the case of hadronization, the issue is strong coupling. In contrast, computing scattering processes at high-order in perturbation theory (e.g. multi-particle final states) and transport coefficients are complicated by the large particle number or subprocesses.

Hadronization: In principle, a quantum computer provides nonperturbative access to exclusive cross-sections[17], thus "solving" hadronization in the sense of providing quantitative, testable predictions. Such computations require large resources, and are thus a longer-term objective. Specific matrix elements which provide nonperturbative input to larger calculations (e.g. the parton distribution function, hadronic tensor [2], and jet functions) plausibly need much fewer resources because they avoid manipulating the asymptotic states. With even fewer quantum resources, the dynamics of confinement and string-breaking can be investigated in low-dimensional toy models [18–20] to improve phenomenological models of parton showers [21] and hadronization, e.g the Lund model [22].

Higher-Order Processes: Even at weak coupling like found in electroweak theory, perturbation series are asymptotic. These methods struggle when extended to multi-particle production or high precision. Although many studies about multi-particle production at weak coupling exist (e.g. [23–27]), the conclusion that the cross-section of N particle scattering grows as N factorial is very counter intuitive. For future colliders, the necessary N^{n}LO calculations and event generators will be increasingly burdensome to produce by hand or with classical resources. In both situations, quantum computers could prove revolutionary by computing portions or all of these processes ab-initio [20].

Transport Coefficients: Quantum computers can provides nonperturbative calculations of viscosity and other transport coefficients relevant for heavy-ion investigations of the quark-gluon plasma. These could be obtained via Kubo formula, although other strategies may be better suited for quantum computation [28–30]. The insight gained from calculating viscosity would likely inform how to obtain other transport coefficients. Gauge theories like $\mathbb{Z}_N$ or D_4 in lower dimension [31–34] should be possible near-term demonstrations of quantum advantage with phenomenological import.

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