Submitted to Downs-Lauritsen or Preskill's studio

Aspects of Cyberpunkian Quantum Field Theory

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Abstract: In this note, we define and discuss some aspects of the so-called *Cyberpunkian Quantum Field Theory*, referring to the connection between fundamental physics and cutting-edge information technology, classical or quantum. A significant part of this article will become part of my Ph.D. thesis expected to appear in 2021 summer.

Contents

1 My childhood, Space opera and Cyberpunk

I feel that the best way to start this article is to introduce myself. My personal experience during my life is closely related to scientific motivations mentioned in this article.

I am Junyu Liu, a fourth-year graduate student studying theoretical physics at the California Institute of Technology.

I was born in Jiangyou, a small peaceful city in Sichuan Province in mainland China. Sichuan is a pretty special place in many senses. Surrounding by huge mountains in Inland Asia, Sichuan is geologically and politically, pretty isolated from the central government in the long history of ancient China. Some cultural activities about Taoism, a local religion in China, are very active, and partially originated, from Sichuan. A plain philosophical thought from Taoism is so-called cultivation: after certain practice, ordinary humans could understand and control the nature of the world, and become celestial beings. In fact, Bai Li, the most important poet in ancient China with thousand years of history (the role of him is similar to the role of Shakespeare in Western literature), one of the earliest role models of Taoism and Chinese martial arts, was from Jiangyou, sharing the same hometown with me.

I am not sure if it is really related, but I do feel that the cultural environment in Sichuan makes people interested in looking for something eternal and spiritual, outside from boring real-life with business and money. Sichuan is a center of spicy food, a center of feminism and LGBT activity (in fact, it is pretty common in Sichuan that women have higher power than men in the family), and a center of the singing competition. Pure mathematics is also a pretty popular subject for young kids interested in STEM. In fact, if one counts the hometowns of leading young experts in the world working in pure math (for instance, arithmetic algebraic geometry), probably Sichuan is a pretty common origin. One example is Xinwen Zhu, a Caltech professor working on the Langlands program and a winner of the 2020 New Horizon Prize, is a Sichuanian, the same as one of his graduate students in the same academic age as me[1]. Some people told me that maybe Sichuanians have some local childhood environment in number theory, while I guess I, unfortunately, don't have any. But I do have lots of graduate student friends who are working on algebraic geometry, keeping talking about representations theories on the rational number field, which I completely don't know.

The above discussions might be closely related to a fact, that Sichuan is a center of science fiction in China. In my childhood, I guess everyone in my class in the elementary middle school read science fiction books. One most important magazine in China around those years, is called *Science Fiction World*, which includes native authors in China and introductions to translations of reputable science fiction stories internationally (for instance, Neil Gaiman or Robert Heinlein). I still remember that those days our class forms a small group and try to share good science fiction stories, and even try to write some by ourselves. In those stories, I know some basic concepts about black holes, time machine, colliders, and robots. One of the most remarkable science fiction stories around that days, is called *The Three-Body Problem*, for which I read each chapter originally in the magazine. Nowadays, The author Cixin Liu and

[1]Similar origins include Chenyang Xu, a professor at MIT who wins the 2019 New Horizon Prize for his work in birational geometry, and Wei Zhang, a professor at MIT who wins the 2017 New Horizon Prize for his work in number theory and representation theory.

his story win the Hugo Award in 2015[2], while his another story, *The wandering earth*, has been adapted to a popular movie. I am very glad to see that, Cixin Liu, an early hero of me, has such a huge impact in his own field.

Besides basic concepts about physics in those stories, theoretical physicists are often important roles in the plots, which sound like a good job. In my middle school life, there is an important story changing the worldline of me. The headteacher asks us to submit a note describing a possible future job to a bottle. She will keep it until a future meeting roughly ten years later, to see if the note matches our dream. I even cannot remember what I have written, and I fail to attend the ten-year meeting happening recently due to many reasons, for instance, the coronavirus outbreak. But I remember that around that time I hope to be an editor of the Science Fiction World.

An event happens around the high school, where one of my best friends, DC, has a long discussion with me. Around that time, he has some problems with his parents and feels sad about his family. As one of his closest friends, I hang out with DC around the city for the whole day. At the end of the day, DC tells me the note he has written before: he wants to become a theoretical physicist. I still remember that he cries at that afternoon, saying that he feels sad about his family environment, and he feels that he is not good at math. And he says, "You can".

We lose most connections after high school. Nowadays, DC becomes an editor (not about science fiction). And I become a graduate student studying theoretical physics on the other side of the earth. The decision of Goddess of Destiny is so funny! I am still not confident enough to say if I could be called a theoretical physicist, but now I am confident enough to say that I have a great reason to study theoretical physics: to my unforgettable memories about my best friend, and beautiful imaginations about science, starry night and the universe in my childhood[3].

Those discussions form the story of me. Now we move to the discussion a little bit about the main topics of this article. Generically, there are many ways to classify science fiction stories[4]. One example is through the contents. If a science fiction story is mainly talking about interstellar wars, outer-space civilizations, and spacetime traveling, it is usually called "Space opera". If a science fiction story is mainly talking about the relationships among digital technologies, robots, and humans, it is called

[2] The Hugo Award is the Nobel Prize in the world of science fiction.

[3] Believe it or not, I completely didn't polish the story.

[4] The classification is in the non-academic sense. For a long time, science fiction novels are not recognized in the mainstream of literature.

"Cyberpunk"[5][6].

As one of the most important subgenres, space opera has a longer history. Currently, some people believe that it originally appeared in some American magazines in the 1920s. After people understand much better about our universe during and after the wars, space operas have been significantly developed, especially around the Cold War. On the other hand, cyberpunkian stories are relatively new. They have been widely created and discussed after people realize the potential of digital technologies, computer science, and the Internet. If I am allowed to choose two representatives for those two subgenres, I wish to choose the film series *Star Wars* by George Lucas for space opera, and the novel *Do Androids Dream of Electric Sheep?* by Philip Dick for cyberpunk[7].

Science, a systematic and fundamental understanding of the nature, and science fiction, a fantastic imagination of how science and technology could change human society in the future, might be closely related to the development of human society itself. I firstly start to understand this when I read the lecture notes, *Nature and the Greeks* and *Science and Humanism* by Erwin Schrödinger [1], who partially expresses similar feelings from my understanding. During the Cold War, with the fierce competition between the United States and the Soviet Union, mankind has made tremendous progress in the field of science and technology. The possible nuclear war promoted the great development of nuclear physics. Related basic sciences, such as particle physics and collision physics, have made great strides. We have established the Standard Model of particle physics. At the same time, humans are trying to develop space science in response to possible space races. During this time, the understanding of general relativity and black hole physics has also been significantly improved. People discovered the laws of black hole thermodynamics and the existence of Hawking radiation. Later, the thirst for unified theory prompted people to construct string theory. In the field of science fiction, people create a variety of space operas, acclaiming their own fantasy about the future. In those fantasy stories, people conquered the stars, battles broke out on the back of the moon, and restaurants were opened at the end of the universe. The dolphins left the earth and told humans, bye, thank you for your fish[8]. I don't know if all those stories are really logically connected, but in practice, they happened

[5]There are some other topics, for instance, Steampunk. Another more common way to classify science fiction is through *hard* or *soft* science fiction, referring to roughly speaking if the story is more scientific or more literary.

[6]Sometimes, cyberpunk describes an icy future world ruled by technology with a flavor of dystopia. However, we hope to use a broader definition of cyberpunk, that in the possible future, humanity will coexist in harmony with high technology.

[7]The film version of it, directed by Ridley Scott in 1982, is the celebrated *Blade Runner*.

[8]This is from *Hitchhiker's Guide to the Galaxy* by Douglas Adams.

at a similar time.

However, after the end of the Cold War, human history has undergone some changes. If you ask college students today what kind of STEM majors earn the most income, I believe a considerable number of people will answer, computer science or electronic engineering. With the development of Internet technology, the world is increasingly developing towards the predictions of cyberpunk novels. In 2020 today, the extensive application of statistical learning theory, optimization theory, and machine learning technology can make computer face recognition possible. People indulge in the new capital world built by Facebook, Youtube, Amazon, and Tiktok. Some people are beginning to worry about whether widely used information technology will affect people's privacy and freedom within certain limits.

At a similar time, physics associated with computers has been fully developed. Technically, computer programs have revolutionized the research methods of a large number of physicists. If the `Mathematica` program has a particularly serious problem at some point, I believe that a considerable number of high-energy theoretical physics papers will go wrong. With regard to the direction of computational physics, some physicists still use lattice gauge theory to accurately calculate the phenomena of strongly coupled physics, as suggested by Wilson, Feynman, and many other people. Physics related to strong correlation and complexity, such as condensed matter physics, cold atom physics, etc., has made great progress. At present, quite a lot of this type of research is motivated by so-called quantum computing. This is a possible next-generation computing technology that utilizes the fundamental principles of quantum mechanics. Conceptually, computing technology is as inseparable as physics, because the principles of physics stipulate the limits of computing technology occurring in this world. In recent years, people have also tried to discuss the application of information theory towards physics itself, such as quantum simulation and black hole information, to be discussed later. In the world of science fiction stories, from the ancient *Blade Runner* to the recent *Number One Player*, cyberpunkian masterpieces are constantly emerging, and gradually constitute one of the most important subgenres in the field of science fiction.

As a physicist rather than a sociologist, I can only state some of the facts I have observed, and I cannot assert the logical connection between social development, science fiction genre, and physics research. At the same time, as a theoretical physicist, my job is to try to understand the laws of nature and the universe. A natural question is, what can the emerging information technology bring to the development of current theoretical physics? How to use the huge power of computer science, statistical science, and complexity science based on academic, industrial and capital interaction, to promote the development of basic physics, and create a new science belonging to our cyberpunkian era?

Here, I wish to propose a research direction I am currently working on and planning to proceed. I call it *Cyberpunkian Quantum Field Theory*[9].

I am a big fan of quantum field theory itself, which for me, and for many other people, is synonymous with fundamental physics. Quantum field theory, as a basic paradigm, could describe almost everything that appears in physics books: particle scattering, gravity, black hole, string theory, condensed-matter, and the early universe. If physicists finally get to know the Theory of Everything, I believe a significant portion of it is based on quantum field theory. For me, quantum field theory is like a space opera. It describes a large number of unsolved secrets of the universe we live in. In quantum field theory, or in basic physics, you can see planets collide, particles scatter, and see the formation of black holes and the origin of the universe. In the world of theoretical physics, there are a lot of unknown parts waiting for us to explore.

When I use the term *cyberpunk*, I want to distinguish it from a common vocabulary, the so-called *computational physics*. Beyond traditional terminology, I hope to emphasize that cyberpunk quantum field theory can be based on the following two aspects. First, cyberpunkian science prefers to use information theory and technology that are cutting-edge and even under development. For instance, machine learning, optimization problems, applied mathematics and statistics, and quantum computing. Secondly, I hope that cyberpunkian physics is not only practical, but also theoretically helpful to physics itself, or even vice versa. Just as superstring theory expert Edward Witten does for the mathematical community, we could also using physics theory to guide possible computer science discoveries.

In the following discussion, I hope to describe the possible prospects of this science. Of course, technically, these stories are already happening. The Large Hadron Collider (LHC) operating in Europe is constantly using machine learning algorithms to process data on particle collisions. Dark matter detection satellites operating in the sky will also cooperate with companies in industry to deal with scientific issues of interest. However, as a theoretical physicist, I hope that in the future, people will be able to do more in-depth research on theoretical physics issues related to cutting-edge information technology. At least, I think this forms part of physical science of our generation.

In the following discussion, I will use the following three simple examples to demonstrate that cyberpunkian quantum field theory may become an important and effective science. It includes quantum simulation of quantum field theory, large-scale optimization of conformal field theory, and discussion of the relationship between quantum field

[9]I am following one of my school sisters, Nicole Yunger Halpern, who used to be one of the core members in John Preskill's quantum information group. She created a word, *Quantum Steampunk*, for the field called *quantum thermodynamics* she contributed [2].

theory landscape and big data science. I will also do a simple non-technical discussion of quantum field theory, and a simple outlook on this related issue, including black hole thought experiment and quantum information science, *It from qubit* and *the non-perturbative bootstrap*, Church-Turing Thesis, Computer Science(CS)-inspired physics and physics-inspired CS, possible future of classical and quantum technology, and finally, companies and colliders.

As a science fiction lover, I often think about such problems. What will the science I do look like in two hundred or one thousand years? Are they still meaningful? From scholasticism to modern science, it has been nearly three hundred years. The popularity of the Internet is what happened in the past three decades. What will the world look like in two thousand years? Will the banking industry be completely changed by quantum computing? Will humans make a collider as big as the Milky Way? Will the human army use Higgs particles as weapons?

Wring this article, in a sense, is to express my sincere respect for some great scientists. Lev Landau, Enrico Fermi, Richard Feynman, Steven Weinberg, Ken Wilson, Chen-Ning Yang, Steven Hawking, Edward Witten, Alexander Zamolodchikov, etc., and nowadays in our quantum era, Alexei Kitaev and John Preskill. They establish the deepest human understanding of the universe during those prosperous years, and defines the science of our time. I think that the current development of physics has given me some opportunities for fledgling young people. To me, traditional physicists are like hackers. They discovered the secrets of this world through various means. Cyberpunkian physicists seem to try to build a completely new, Turing-complete world. For me, they are all important sciences. Maybe one day, when people can find a variety of new particles on the collider, reach the boundary of the black hole horizon, or freely edit topological quantum qubits, some of them will think that, what we are doing currently, are treasures.

2 Quantum field theory

When I start to talk about cyberpunkian quantum field theory, I will probably firstly introduce what quantum field theory is. So here, I will provide a non-technical introduction about quantum field theory.

So what is quantum field theory? A possible generic description is that it is a quantum formulation of continuum physics in the spacetime. Consider that we have complicated interactions among some atoms and molecules placed discretely in the spacetime. There are physical laws governing the forces, for instance, the Van der Waals force. However, if we feel it is too complicated to keep track of interactions of all particles, we could zoom out and ask what the *emergent* description is when we are looking at a length scale that is much larger than the lattice spacing. Sometimes, we could arrive at a beautiful emergent description, for instance, if those molecules form a liquid, which is called hydrodynamics. In this case, hydrodynamics is a *field theory*. When the full procedure is treated quantumly, for instance, if we are considering some interacting quantum harmonic oscillators, the description is called quantum field theory, where we are assuming that there are an infinite number of quantum harmonic oscillators located in a continuum spacetime.

A deep interpretation between the lattice model and the quantum field theory description is given by Ken Wilson, and the above process is called renormalization. People find that the renormalization process occurs in almost all phenomena in our nature: statistical physics, string theory, gravity, particle scattering, etc.. In a sense, all physical theories should look like quantum field theory in a certain limit. Quantum field theory is, in fact, one of the deepest interpretations human beings have obtained about our nature.

There are many possible quantum field theories that describe different phenomena in our world. One basic method of classifying quantum field theories is based on the strength of couplings: weakly-coupled quantum field theory, strongly-coupled quantum field theory, and somewhere in the middle. Non-technically speaking, strongly-coupled theory means that interactions among different local degrees of freedom in the spacetime are strong. Imagine that we are starting from a free theory, which means no interaction. The theory could be described easily by quantum harmonic oscillators located on each site. Then we start to turn on the interaction in some way, where those small harmonic oscillators start to couple with each other or with itself in some non-trivial ways. When the extra coupling we have added is small enough, we could use perturbation theory to solve the system, given the fact that we already know the free theory data pretty well. When the coupling is strong, the usual perturbation theory breaks down, and it is not very easy to describe such physics in the continuum spacetime description. Now let us imagine that we turn on the coupling towards some extremely strong regime, then something funny will happen. For instance, the perturbation on one side of the system could quickly propagate towards the other side. This is somewhat similar to the *critical point* of a phase transition, where the system is changing from one phase, for instance, the solid state, towards the other phase, for instance, the liquid state. For a second-order phase transition, where non-technically speaking, some physical variables transform continuously around the critical point, one could use strongly-coupled quantum field theory to describe it. Generically, it is called *conformal field theory*.

The above procedure during increasing interactions, could be described by the theory of *renormalization group*. For a weakly-coupled theory, we have some generic frameworks to describe it based on perturbative expansions. We have some physical interpretations for terms appearing in the expansion, which is called the *Feynman diagram*. For a generic theory where the coupling is strong enough, it is usually very hard to describe if the theory is very general. Some physicists invent smart ways to solve the theory in some special cases. For instance, when the theory has conformal symmetry, which is roughly speaking, scale invariance besides the usual spacetime Lorentz symmetry, we could use the symmetry, and some other internal constraints to partially, or even completely, solve the theory [3]. One could try some other similar strategies when the theory is integrable, namely, contains infinite number of conserved charges [4]. When the theory is supersymmetric, sometimes one could do perturbative expansions easier because in this case the Feynman diagrams might have some cancellations and maybe one could use it to solve part of non-perturbative physics. Some other methods, for instance, the duality between weakly-coupled gravitational theories and strongly-coupled quantum field theories without gravity, which is called *holography* or the AdS/CFT (Anti-de Sitter Space/Conformal Field Theory) correspondence (we will mention it later) [5], might shed light on solving strongly-coupled quantum field theories. All of them are still active research directions in theoretical physics.

However, people still don't have a very good understanding of strongly-coupled quantum field theory in general. For instance, the strongly coupled regime of quantum chromodynamics(QCD) is still not clearly understood, even if we have the above theoretical methods at hand. One could measure several properties of strongly-coupled QCD in some low energy colliders, and it is extremely hard to predict some bound states using theoretical calculations from quantum field theories. The Yang-Mills existence and mass gap problem defined as one of the Millennium Prize Problems is also about field theories beyond the weakly-coupled regime, and it is still an open problem even without a very precise mathematical definition. The high-temperature superconductivity phenomenon might also admit a low energy effective field theory description around the critical point of their phase diagrams, but it is still far from a very concise formulation and a reasonable prediction. I probably could list many problems of this type, involving theoretical understandings and phenomenological predictions of quantum field theories. All of them are closely related to the universe we live in, and all of them seem challenging. Maybe for some people, it is fair to say that we still don't understand quantum field theories, although it is already at least half a century after its birth.

Another particularly important example is string theory, which is a candidate for a consistent theory that could describe everything appearing in this world, from quantum black holes, big bang physics, to subatomic, atomic, and molecular physics. String theory itself could be formulated in a quantum field theory manner. In particular,

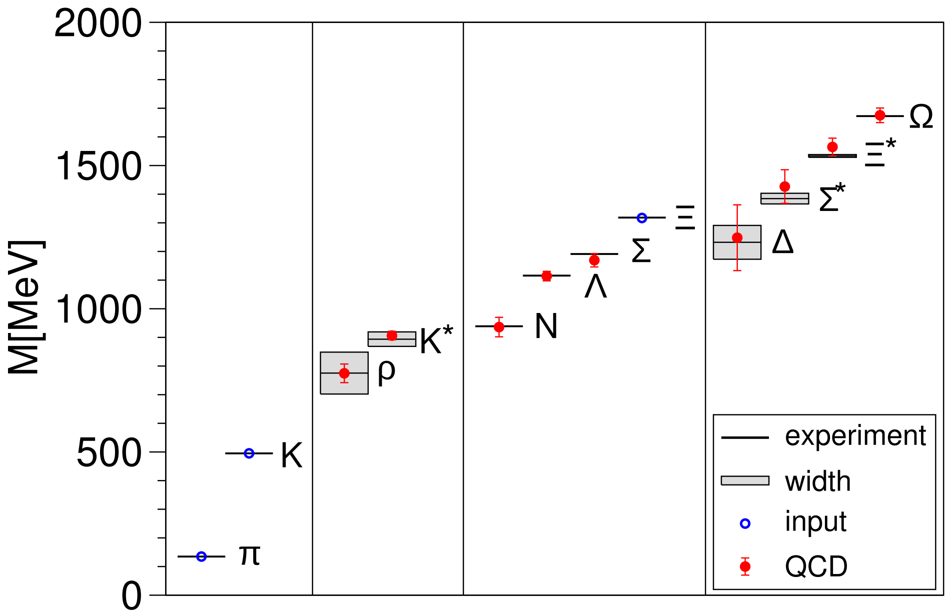

Figure 1: A remarkable prediction from the lattice gauge theory community. Some light hadrons have been predicted using lattice QCD. This is from Figure 3 of [6].

quantum black holes could also be understood as a specific strongly-coupled quantum field theory phenomenon. If we address the weakly-coupled limit, one could compute graviton exchange in a semiclassical fashion of quantum field theory in the curved spacetime, which is called gravitational waves.

Okay, so some people might say that, if pure theoretical methods fail, why we don't try numerics? This is a very fair statement, and yes, we have already tried a lot. Ken Wilson and other people suggest that maybe we could solve strongly-coupled quantum field theories by making a lattice regularization. That is, trying to discretize your space in a lattice. One could try to solve the theory in the lattice, and take some reasonable limits towards the continuum. For gauge theories used in particle physics, this subject is usually called the *lattice gauge theory*.

Nowadays, the idea about regularizing field theories in a lattice has made significant progress. In Figure 1, where I am quoting Figure 3 of [6], people could match some experimental observations about the light hadron spectrum with QCD by a first-principle calculation. It agrees very well! This type of agreement could not only show powerful predictability of quantum field theories but also show the fact that nature is a good computer!

However, despite its glorious success, there are several fundamental limitations to the current algorithms. The main problem is that, in principle, quantum field theory contains an infinite large Hilbert space on each site located in the spacetime. This demands a huge amount of computational resources! Here, I am claiming that, in order to solve more important problems, we have to be smarter: the numerical challenge we face on simulating and predicting quantum field theories forces us to use the most cutting-edge methods from information technology, while some novel, fundamental understanding of quantum field theories and fundamental physics themselves will come from computer science, classical or quantum. This is the place where cyberpunkian physicists should go.

In the following discussions, I will mainly describe three cyberpunkian research directions I have worked on: simulating quantum field theories using quantum devices, conformal field theory and large-scale optimization, and string theory versus data science. Later, I will discuss some general comments about fundamental physics and information technology.

3 Simulating quantum field theory using quantum devices

Going back to the story of lattice gauge theory, here I am pointing out some difficulties in solving quantum field theories by putting them in a lattice only with a classical computer and brute force methods.

The first problem is the computational power. Lattice quantum field theory has a very large Hilbert space. In principle, we have a continuum number of sites located in the spacetime, while each site has an infinite Hilbert space dimension. By truncating the local Hilbert space and choosing a cutoff for lattice spacing, we are able to solve the theory in a finite, but large, Hilbert space dimension, with proper treatment of an extrapolation of numerical results towards the continuum. This is a very high computational cost. Firstly, it is extremely hard to do it naively using the way of exact diagonalization, namely, diagonalize a large Hamiltonian directly. Secondly, one could try to measure some correlation functions using random algorithms, for instance, some versions of Monte Carlo methods. This is usually cheaper than exact diagonalization, but it is still hard to operate due to a large number of sites and a large number of configurations to sample. The second problem is the sign problem. For fermionic theories, when we compute some predictions using Monte Carlo method by doing some samplings of path integrals, we will often encounter oscillating amplitudes, making the result hard to converge. Those problems challenge the current lattice gauge theory community for a long time, and people find it is extremely hard to make predictions, for instance, for real-time physics.

Thus, in order to solve quantum field theory in general, especially for strongly-coupled theory in a lattice, one might consider some potential future computational devices. One could imagine that the computation could be done in a quantum computer, which could simulate physical process of quantum field theory itself. I find that many quantum computing people like to quote what Richard Feynman said in his paper [7], and I am happy to quote it again:

> *... trying to find a computer simulation of physics, seem to me to be an excellent program to follow out.... and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy.*

Richard Feynman is, at least partially, a particle theorist. In fact, indicated from his paper [7], it seems that one of the earliest motivations for quantum computing is to simulate quantum field theories. (See a review article given by John Preskill [8].)

Nowadays, in 2020, quantum computing becomes one of the most exciting scientific areas, receiving significant attention from academia, industry, government, and the whole society. John Preskill [9] announces that nowadays we are living in a quantum era which is called NISQ (Noisy Intermediate-Scale Quantum), where a quantum computer with 50-100 qubits may be able to perform tasks that exceed the capabilities of today's classic digital computers, but the noise of quantum gates will limit the size of quantum circuits that can be reliably executed. In fact, Google already claims that they have achieved quantum supremacy, that is, quantum computers can accomplish tasks that classic computers cannot [10]. For simulating quantum field theories themselves, quantum computing methods could provide certain advantages against two main problems I have mentioned before for simulating quantum field theory in a classical computer. Firstly, quantum computing is proceeded by quantum states made by qubits, and unitary evolution made by unitary operators acting on the Hilbert space. Roughly speaking, the space it contains, is naturally, exponentially large than classical computation. Secondly, quantum computing is able to solve the sign problem naturally [11], which might potentially remove the sign problem difficulty appearing in the fermionic quantum Monte Carlo simulation.

One early remarkable quantum algorithm to simulate quantum field theories is called the Jordan-Lee-Preskill algorithm (see the original papers [12, 13], and a series of related papers [14, 15]). This type of algorithm contains state preparation, time evolution, and measurement of some specific quantum field theory tasks happening at strong coupling. One could also associate the above algorithm into some certain complexity classes [15]. This algorithm, especially the time evolution of the quantum field theory Hamiltonian, is shown to be polynomial in system size, sharpening the potential quantum advantage for simulating quantum field theories in quantum computers.

In the above framework, simulating quantum field theories could be generally regarded as simulating some specific Hamiltonians. Thus, it is natural to utilize methods from general Hamiltonian simulations developed by the quantum algorithm community. When simulating a quantum Hamiltonian, one could roughly classify quantum simulation algorithms in the following three types: digital, analog and variational quantum simulation. The above Jordan-Lee-Preskill algorithm is a typical algorithm for digital simulation, where we assume a possible universal quantum computer when we are constructing the algorithm. For analog simulation, the algorithm is developed by constructing an actual Hamiltonian in the cold-atomic lab, for instance, the Hamiltonian made by Rydberg atoms. Variational algorithms are somehow in the middle: it will make use of variational methods, only covering a subset of the whole Hilbert space. Variational algorithms might be constructed in a hybrid quantum-classical way, which is made suitable for near-term quantum devices. All of them are potentially useful for simulating quantum field theories.

When constructing quantum simulation algorithms or actually doing simulations in a quantum computer or in the lab, classical simulation might play an important and specific role. Firstly, quantum-classical hybrid algorithms are widely used. Especially in the near-term, quantum algorithms are only helpful to speed up calculations in certain steps in a whole classical algorithm. Those classical pieces may not be replaceable. Secondly, classical algorithms might be helpful to find limitations of classical computations, and understand conceptually and technically where quantum algorithms might play a role. Here I wish to mention specifically two types of algorithms: matrix product state (MPS) algorithms and semidefinite programming (SDP) algorithms. Of course, both of those algorithms have very wide applications that are even beyond the scope of physics. MPS algorithms are helpful for identifying some low energy states of quantum many-body systems in the 1+1 dimension, which could have emergent field theory behaviors around critical points. SDP algorithms are basics of convex programming that are widely used in operations research and optimization, which are also basic algorithms for solving higher-dimensional conformal field theories numerically (we will describe this in more detail in the next section). Both of them are important classical algorithms. It is important to understand their advantages and limitations comparing to quantum computation, where quantum field theories are perfect playgrounds to test them.

I also wish to mention here my own main contributions. This includes two ongoing works which will hopefully appear soon. With one of my advisors, John Preskill, I am exploring quantum simulation of domain wall scattering in 1+1 dimensional quantum field theories. Domain walls, or kinks, in the 1+1 dimensional scalar field theories, are the simplest examples of topological defects. They are like walls splitting two different field configurations in the theory. The existence of domain walls is closely related to

Figure 2: An artist's creation of the quantum simulation projects of kink scattering [18, 19]. The depiction of characters is based entirely on their images in reality. From left to right: Burak Sahinoglu, Ashley Mislted, Junyu Liu, John Preskill, and Guifre Vidal. Other ingredients include cosmic bubbles (physical objects that are similar to kinks), a spacecraft, a cat (Schrödinger's cat), and the Bell state. The figure is credited to Jinglin Nicole Gao. Figures shown in the screen utilize the figures in our scientific paper [19].

vacuum decay in cosmology, sharpening its relevance to the real world. Historically, there are many authors who studied kinks in quantum field theories at weak or strong coupling (for instance, [16, 17]), but strongly-coupled kinks are extremely hard to solve at strong-coupling for non-integrable, 1+1 dimensional quantum field theories. In the work with John Preskill and Burak Sahinoglu, we are trying to construct theoretical algorithms to simulate scattering process of kinks, while in the work with Ashley Milsted, John Preskill and Guifre Vidal, we are trying to study analog models in spin chains and simulate the kink scattering process in the MPS approximation [18, 19]. (see Figure 2 for an artistic illustration.)

Simulating quantum field theories are generically helpful for studying quantum field theories appearing in the formal high energy theory community, for instance, theories with supersymmetry, in higher dimensions or containing gravitational sectors. One possible ambitious goal might be studying large-N supersymmetric gauge theory and trying to verify Maldacena's conjecture about the AdS/CFT correspondence [5]. It might also be helpful for studying high energy phenomenology, experiments or observations, for instance, solving QCD in the strongly-coupled regime. Those studies might also benefit the community of quantum algorithms, which will provide novel, clear tasks, cool applications, and good targets for benchmarks. Finally, it might be helpful for conceptual understanding of quantum simulation in our physical world, namely, the Church-Turing Thesis. We will discuss those issues later.

4 Conformal field theory and large-scale optimization

In this section, we will move to another topic that is more related to classical computation instead of quantum. That is, conformal bootstrap and its relation to large-scale optimization.

We discuss before the concept conformal field theory, which appears in some statistical models as a low energy effective description around the second-order phase transition. Around the critical point of some statistical models, partially because of the scale invariance, the spacetime symmetry of the theory has been extended from the usual rotational or Lorentzian symmetry towards a larger symmetry: conformal symmetry[10]. Such a theory might be a little counter-intuitive: one could make a transformation from the far infinity to the origin of the coordinate system, and the action of the theory is still invariant. Thus, conformal field theories are used to describe violent behaviors around the critical point, which experiences a drastic change between different two phases. The behavior is *universal*, which means that multiple microscopic models might correspond to the same conformal field theory. The low energy spectra of conformal field theories will provide some universal numbers that are measurable in the statistical system, which are called critical exponents. Thus, multiple microscopic models might share the same critical exponents. One standard example is that the phase transition of the boiling water is sharing the same universality class with the 3d Ising model, a model made by physicists to describe the dynamics of magnets. Because of universality, conformal field theory is a very generic concept that could be applied in many places that admit second-order phase transitions. Moreover, conformal field theory technologies are directly applicable for string theories, since the worldsheet theory of string theories is conformally invariant.

Non-trivial conformal field theories are typical strongly-coupled quantum field theories, making them very hard to solve. However, conformal invariance strongly constraints the behaviors of the theory. For instance, some correlation functions are directly

[10] Although there are still some technical differences between scale invariance and conformal invariance.

constrained as some specific forms. Some people believe that conformal field theories, and some other strongly-coupled field theories, are fragile in the following sense. These theories are like precise gears: as long as few conditions are input, the strong limitation of conformal symmetry will isolate or even uniquely determine these theories. This philosophy of understanding quantum field theory is called bootstrap, a possible way of understanding strong coupling without really quantize those theories from classical actions.

The bootstrap philosophy in particle physics is studied widely in some certain time scales around the last century (for instance, [20, 21]), but quickly decays with many open problems unsolved, replaced by related studies about QCD. However, recently, the idea of bootstrap in field theories has returned to be a hot topic in the high energy physics community, since we become more cyberpunkian. People notice that one could solve bootstrap equations, the consistency equations appearing in strongly-coupled quantum field theories, by optimization technics. For instance, bootstrap equations in conformal field theories are identities where a sum over contributions from different sectors of the theory is equal to zero, which looks like a hyperplane in some higher dimensional Euclidean spaces. Roughly speaking, the hyperplane could be located by finding some other optimal hyperplanes cutting the space towards small pieces, while the methods for finding optimal planes are standard in optimization and operations research: the semidefinite programming (SDP). The modern technologies of computer science allow people to work on optimization problems numerically at large scale, making numerical bootstrap possible (see a summary by [3, 22]). In fact, conformal bootstrap holds the world record for solving the most digests of the Holy Grail problem in statistical physics: determining the critical exponents for the 3d Ising model [23]. Considering the fact that the 3d Ising model shares the same critical exponents with the boiling water, and that water is the basic substance of life, we can even use those bootstrap results about the critical exponents to communicate with outer space: If an extraterrestrial life responds to the critical exponents we sent about boiling water, we might think that the alien has a high level of civilization because they can use conformal field theory and large-scale optimization to accurately calculate the critical exponents. Furthermore, numerical bootstrap using large-scale optimization inspires a flow of theoretical research about conformal field theory (see, for instance, [24]), which are helpful for other parts of theoretical physics like string theory.

The study of the conformal bootstrap is also helpful for experiments since quantities like critical exponents are universal and measurable in principle. Historically, there is an interesting experiment happening at the Space Shuttle Columbia measuring the critical exponents of superfluid helium phase transition. The experiment is claimed to be the most accurate measurement of critical exponents in human history

Figure 3: An artist's creation about the superfluid helium conformal bootstrap project [25] and [26]. The depiction of characters is based entirely on their images in reality. From left to right: Shai Chester, David Meltzer, Junyu Liu, Walter Landry, Alessandro Vichi, David Poland, David Simmons-Duffin, and Ning Su. Other ingredients include islands (a theoretical physics terminology referring to the isolated region in the theoretical space using the bootstrap method), a spacecraft (referring to the Space Shuttle Columbia experiment), a diagram as stars in the sky (referring to the conformal block expansion, the basics of the bootstrap equation in the conformal field theory). The figure is credited to Jinglin Nicole Gao.

up to now[11]. However, the experimental results from the measurement are inconsistent with the theoretical Monte Carlo simulation by 8σ. Recently, a collaboration in the conformal bootstrap community, including me, successfully verifies the theoretical result and significantly improves the accuracy of Monte Carlo simulation. Although the explanation of the inconsistency between theory and experiment is still unknown, this work shows that the conformal bootstrap method is useful for predicting important real-world physics. (See the papers [25] and [26], and an artistic description of the collaboration 3.)

Of course, solving conformal field theories using the bootstrap philosophy is closely related to cyberpunkian physics, where large-scale optimization method associated with hardcore cluster computation plays a crucial role. Nowadays, conformal bootstrap becomes one of the most important mainstream in the area of theoretical physics, which

[11]The measurement is happening in a space shuttle because the measurement involves the heat capacity at constant pressure, which requires a zero-gravity environment to mitigate the error.

has wide potential applications among string theory, condensed matter physics, and particle physics. In the algorithm level, Simons Foundation launches a collaboration, *the non-perturbative bootstrap*, to support our research, and we have a professional soft engineer, Walter Landry, helping us make the best software for solving SDPs for our physical purpose. Although we believe that we are currently using the most cutting-edge optimization results from the operations research community [27], the current algorithms still have a significant potential opportunity to get improved. We also wish to mention that SDP is also an extremely useful algorithm that admits a large quantum speedup. Thus, conformal bootstrap might potentially provide clear physical applications for the quantum SDP solver, and will be helpful for benchmarking quantum algorithms and devices [28].

5 The theoretical landscape and data science

In this section, I wish to comment on the landscape of quantum field theories and its relation to data science.

Quantum field theory (or the whole fundamental theoretical physics), at least for many people, including me, is an extremely difficult subject. Theorists have constructed a large number of quantum field theories, which describe some general phenomena in this world or a certain universe. Some theories live in high dimensions or some highly-curved spacetime that humans cannot easily understand. The various counter-intuitive phenomena appearing in the strongly-coupled theory make it more difficult for physicists to control. Some quantum field theories even cannot be precisely defined mathematically. Moreover, quantum field theory can have many parameters and many possible descriptions, which may lead to the same or different predictions. I think, at least for me, many problems cannot be thoroughly studied in my whole life. If I am supposed to give a name for the space of quantum field theories, I will call it the *landscape*, a common term used by high energy physicists.

Another difficulty of quantum field theory lies in its experimental difficulty. Probably the best way to verify quantum field theory in the subatomic world is various high-energy physics experiments, especially collider experiments. Experimental results from colliders could verify or expand predictions from some quantum field theories by colliding subatomic particles at some certain energies. This is an extremely complicated process. From the various nuclear resonance states of the low energy collider to the hadron jet on the hadron collider, physics involved in those processes is very difficult to calculate and measure. This often requires a huge amount of engineering and the efforts of countless researchers to achieve.

Perhaps physicists should thank themselves for being in this cyberpunk era. The famous hadron collider, LHC, generates a lot of data every day. A considerable part of the data will be processed by professional data scientists or particle physicists. Therefore, big data science is an important means of contemporary particle physics research. For example, machine learning is becoming an important means of processing experimental data of particle physics. In terms of phenomenological theories that are closer to experimental observations, data science has also gradually become an important way to explore the predictions brought by different effective field theories and Wilson parameters, or to simulate experimental data to reconstruct particle resonance states. I here cite two related works on experiment and phenomenology [29, 30]. Interested readers can easily find more works on the Internet.

Here, I prefer to discuss a story that is mainly about formal high energy theory. Perhaps the most sophisticated networks of quantum field theories are constructed by string theorists. String theory itself could also be understood as a paradigm adapting numerous quantum field theory descriptions. One way to quantify the complexity of string theory is to count its vacua. In some simplest quantum mechanical models, we are familiar with, for instance, hydrogen atoms with Coulomb's force, the degeneracy of the vacuum states is usually very few. However, there is potentially a very large amount of vacuum degeneracy in string theory. There are so many choices of microscopic theory, compactification manifold, bundle or brane configuration, flux, e.t.c. Some people believe that the total number of string theory vacua might be finite, and the estimate is usually huge numbers, for instance, 10^{500} (see some early papers, [31–33]).

The gigantic possible choices of string theory vacua seem leading to many different possibilities of physical predictions, for instance, different realizations of effective field theories at low energies, and different possibilities of constants appearing in our universe, for instance, the mass of the electron. The physical interpretation of the string theory landscape and its possible relationship with some *illegal theories* which could not correspond to any realizations of quantum gravity, are still open problems. People call those the collection of illegal theories the *swampland*.

The study of string theory landscape and the swampland is a very difficult subject, partially due to the complexity of string theory itself. If we assume that string theory is the Theory of Everything, can it lead to a consistent description of our world and our energy scales, for instance, the standard model? If so, how is it located in the string theory landscape?

Currently, many people are very interested in the so-called *swampland program*. This is a research direction that is aiming to possible interpretations of the boundary between the landscape and the swampland (which is called the *swampland criterion*). In fact, the space of the swampland is also very large and nontrivial. There are many low

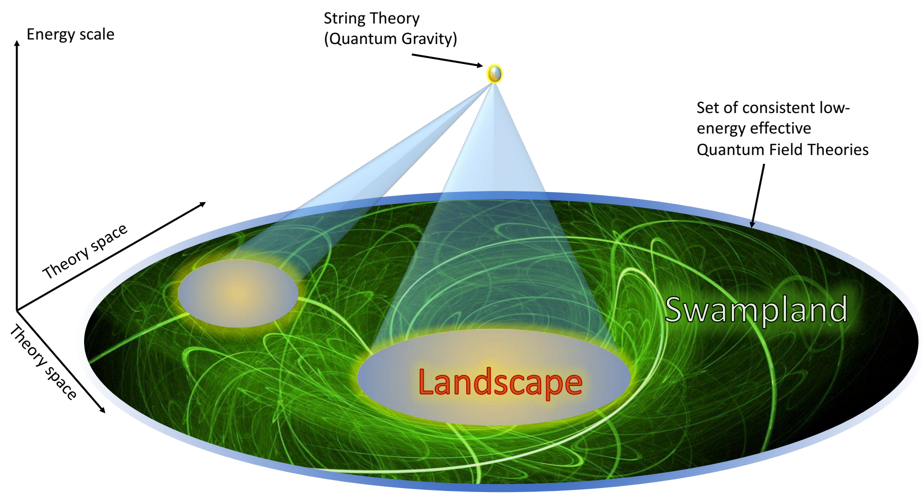

Figure 4: An illustration of the string theory landscape and the swampland. This is from Figure 1 of [35].

energy effective actions that may not be allowed by any formulations of string theories, and it is very important to understand why. Currently, people formulate a large web of conjectures and statements about the landscape and swampland and try to test them by explicit examples, physical or mathematical proofs. (see Figure 4). One of the most important statements among so many swampland conjectures is called the *weak gravity conjecture*. The statement is that for theories in the landscape allowing gauge symmetry, they have to allow quantum states that are sufficiently charged. Roughly speaking, that is to say, gravity is always weak compared to the electromagnetic force. This could serve as a swampland criterion. In the work [34], with Clifford Cheung and Grant Remmen, we prove this statement for a very generic setup of gravitational theories containing charges. We show that the weak gravity conjecture naturally follows from the saddle point analysis of black hole solutions in the gravitational path integral, which could be partially understood as an infrared consistency requirement of the low energy effective description of string theory.

Despite some partial theoretical success, the landscape is still extremely hard to study. Even if we could formulate conjectures, it is very hard to test them among 10^{500} different vacua. In fact, this huge number is larger than the number of atoms in the whole visible universe. So can we finally study them towards the bottom, and finally find a successful explanation of our universe?

My personal view is that maybe currently, some of us could also stick on pure theoretical research, but eventually, maybe we have to rely on cyberpunkian technologies to find the final answer. The data space is too large, but in an optimistic point of view, I think using data science like technics about machine learning, it is not hopeless to find the answer accurately. Let me give an example of Go. The number of variations of strategy in Go is infinity. But we could roughly count its complexity as the following: notice that the standard Go board has 361 points, so we could have an estimate of possible methods for placing black and white stones as $361! \sim 10^{678}$, which is also a very large number. However, machine learning algorithms could still handle Go right now, and we all remember the famous event in 2016, where the computer program AlphaGo beats the best human player Lee Sedol. Maybe one day, we could use machines to resolve all puzzles in quantum field theory and string theory. One could regard all theoretical efforts we have made now as training data, and currently, we are still mostly trying to produce valuable training data. Eventually, we might need a machine to resolve the puzzle of our universe. I think maybe machines are good at questions of the following type: Can we predict the probability of obtaining a Standard Model gauge group at low energy inside the string landscape?

In fact, there are already some works about machine learning and string theory. Some of the early comments about string theory landscape and computational complexity are made by Michael Douglas, one of the founders of the concept *string theory landscape* (see [36–38]). I used to think about a related problem if one could use neural networks to predict random inflationary potentials induced by string landscape in the early universe cosmology when I was an undergrad student in 2014, and write a paper in 2017 [39]. Nowadays, some string theorists and data scientists are now actively initialization collaborations and obtain good results to explore the string theory landscape using cyberpunkian tools (see for instance [40–42]). I feel that it will be great where people might potentially gain great insight inside the landscape from those fancy machines.

6 Some comments

Finally, we will arrive at some comments about physics and computer science.

6.1 Some physics

6.1.1 Black hole thought experiment and quantum information science

There is a particularly interesting direction appearing recently addressing the connection between quantum black holes, spacetime and quantum information science in the high energy physics community. Here, we will review some recent developments in this direction, and address its connection with cyberpunkian quantum field theory.

After Hawking discovered the area law formula and information paradox of black holes [43, 44], understanding quantum information content in the quantum black hole and its radiation process becomes a Holy Grail of theoretical physicists. Partially based on the observation of Hawking, the work of Juan Maldacena in 1997 [5] and other related works formulate a greater picture that connects a higher-dimensional quantum gravitational theory and a lower-dimensional quantum field theory living in the boundary of the spacetime. This proposal, which we call *holography* or AdS/CFT, has some explicit realizations in string theory and becomes a compelling paradigm for a theory of quantum gravity. In 2006, Ryu and Takayanagi proposed a formula that connects quantum entanglement in the boundary theory towards the extremal surface in the quantum gravitational system [45]. Further connections include: the nature of the Ryu-Takayanagi formula could be understood in the language of quantum error correction [46]; quantum black holes could quickly scramble the information and recovery of black hole information from the Hawking radiation could be interpreted from the quantum Shannon theory [47]; the quantum complexity of quantum states could be understood from the gravitational action or spacetime volume in some circumstances [48]; and many other amazing discoveries.

Recent activities in the theoretical physics community about the connection between quantum information theory and quantum spacetime has a slogan, *It from qubit* [49]. There is a productive collaboration named by this slogan, funded by Simons Foundation, focusing on leading research along this direction. The philosophy behind this seems to imply that all realities in this world, including spacetime, matter, and energy, are inextricably linked to quantum information. In my opinion, this can also be regarded as part of cyberpunkian quantum field theory. After all, a considerable part of this picture needs to be explained by some weakly-coupled or strongly-coupled quantum field theories. In this process, first of all, quantum information theory, or computer science in general, play a heuristic role in the study of quantum gravity. Second, information loss is not only a quantum information process but also a physics process, so describing this process requires the organic cooperation of computer scientists and physicists. Finally, physics, in turn, inspires some results of quantum information, such as guiding the establishment of some new properties of quantum error correction codes.

There are many works currently in this field are completely about black holes. However, if we are tired a little bit about black holes, we could consider quantum cosmology, another interesting and possibly observable resource of quantum gravity. Recently, there is a new version of holography beyond the usual asymptotic AdS boundary condition, which is called $T\overline{T}$ holography (see [50, 51]) where I help established, that is potentially useful for the theoretical study of de Sitter space and quantum simulation of quantum cosmology (see [52–54]).

6.1.2 It from qubit and the non-perturbative bootstrap

At the same time, I would like to mention again another Simons Collaboration project that is going on almost simultaneously, *the non-perturbative bootstrap* [55]. The research I mentioned earlier about the relationship between conformal field theory and large-scale optimization is one of the most important components of this cooperative program. Up to now, this plan also includes some other parts, such as S-matrix bootstrap, Hamiltonian truncation, and some other supersymmetric and string theory research. Some of them also use large-scale optimization methods. Their common purpose is probably to use the bootstrap method to solve a large number of non-perturbative quantum field theory related problems.

In my Ph.D. research career, I am very lucky to join these two great research projects at the same time. One of my Ph.D. advisors, John Preskill, is the leader of *it from qubit* collaboration. My other doctoral advisor, David Simmons-Duffin, is one of the main forces of *the non-perturbative bootstrap*. Their profound wisdom and research style deeply influenced me. I realize that I am in a lucky *middle position* and had the opportunity to learn the core content of these two sciences.

Obviously, these two plans are complementary. For example, conformal field theory is actually the boundary theory of quantum gravity, so conformal bootstrap is likely to be a concrete realization of some black hole information problems. In a sense, the cyberpunk quantum field theory I studied can be regarded as a cross between these two sciences. It is somewhat different from the two, but it can also complement each other and form part of a larger picture of theoretical physics and computer science.

For example, a considerable part of the research on *it from qubit* is based on toy models of quantum circuits, but I hope to generalize them as hard-core field theory stories. Unlike the problem of formal theory that *it from qubit* mainly focuses on, I also hope that we can discuss some problems that are closer to real experiments or observations, such as particle phenomenology, cosmology, and statistical physics. Furthermore, I do not want to use only quantum information tools, but more general computer science, such as data mining and machine learning. These can be regarded as the differences between *it from qubit* and cyberpunkian quantum field theory.

On the other hand, my main research direction and *the non-perturbative bootstrap* have the following differences. First of all, researchers of the non-perturbative bootstrap tend to use the field theory method, but I also hope to combine the field theory method with the lattice-based method and make them complementary. On the other hand, *the non-perturbative bootstrap* tends to use more theoretical research methods, but I also hope to extend these issues to experimental simulations, such as experiments on quantum devices based on cold atom physics, or demonstrations of some thought experiments in conformal field theories, like conformal collider physics, in the lab. Finally, at present, the non-perturbative bootstrap technology mainly adopts classical computing, but I also tend to extend them to the field of quantum computing, and moreover, push the algorithms used in the cutting-edge quantum field theory research towards the industry level.

6.1.3 Church-Turing Thesis in 2020

In addition, I hope to discuss a more *metaphysical* issue that has emerged in recent years in the physics community, namely, the research on the Church-Turing Thesis.

A thesis is not a theorem, it is just a proposal or a conjecture. In other words, it may be right or wrong. The Church-Turing thesis is an argument about the Turing machine's ability to interpret the world. We will use the original words by Susskind in his recent paper [56]

Thesis 1. *Any computation that can be done by a physical system can be done by a Turing machine.*

The Church-Turing thesis is believed to be correct. However, the thesis itself does not really address anything about the efficiency of the computation. When we are addressing the efficiency of the Turing machine, we sometimes say that the thesis is *extended*. In fact, we have the following *quantum-Extended Church Turing* thesis,

Thesis 2. *Any calculation that cannot be done efficiently by a quantum Turing machine (or quantum circuit), cannot be done efficiently by any physical system consistent with the laws of physics.*

When we are addressing the complexity or efficiency of our computation in a quantum circuit, the above thesis is highly informal and needs to be formalized. For instance, the efficiency, which means the number of basic operations in the quantum circuits, seems to be dependent on the choice of the time coordinate, and thus inconsistent naively with special or general relativity. In fact, there are constructions in the general relativity, where we call the Malament-Hogarth spacetime, such that the halting problem could even be solved [57] (See a related discussion by [58] about computability and summation over topologies in the gravitational path integral). Secondly, there are confusions about holographic duality and quantum Church-Turing Thesis: It seems that measuring entanglement entropies is hard, but measuring area of the extremal surface is easy; It seems that measuring computational complexity for quantum states is hard, but measuring volume or action in the gravitational theory is easy. But based on holographic correspondence, entropies and areas are connected, as complexities and volumes are also connected. So what is the magic? Is it because the holographic mapping itself is computationally hard, or it is a violation of the quantum-extended Church-Turing Thesis? The situation becomes more intriguing when the gravitational system involves a black hole, and the answers towards this question are still not completely known [56, 59–61].

Here, I wish to add two comments about the current status of research along the line of Church-Turing Thesis.

- Some aspects of the study of the quantum-extended Church-Turing thesis could be addressed concretely using quantum field theories, at least in some latticed versions. This type of research will involve concretely about designing algorithms for a given setup of quantum field theory and prove the statement about computational complexity. We regard this as part of our cyberpunkian quantum field theory program.

- The above discussion about AdS/CFT shows that understanding the complexity of duality maps themselves might be important. Duality is usually understood as a reformulation of one theory to the other theory, one Lagrangian to the other Lagrangian, one state to the other state. It might be interesting to discuss the complexity of AdS/CFT, and also, other dualities established among several quantum field theories and string theories [62], which are actually, hot topics in the frontier of theoretical physics that have profound applications in particle physics and condensed-matter systems [63]. For instance, one could ask, what is the complexity of S or T duality in some specific setups? The *complexity web* of duality webs among the landscape of field theories might play an important role in understanding Church-Turing Thesis.

6.2 CS-inspired physics and physics-inspired CS

6.2.1 Theoretical considerations

As we discussed before, many examples in this article show that concepts and results from computer science are helpful for the development of physics in recent years. This could happen in a purely theoretical or conceptual level. Here we wish to discuss another possibility, where physics goes backward to inspire interesting progress in computer science. We call it *physics-inspired computer science*.

There are several typical examples recently happening, based on the development of the connection between quantum information theory and quantum gravity. For instance, the original proof of the strong subadditivity of von Neumann entropy is very technical [64, 65], but the holographic version of the proof based on AdS/CFT is highly intuitive and simplified [66]. Moreover, the linear growth of complexity in some setups of local random circuits proved recently in [67, 68], is partially inspired by Susskind based on the wormhole growth in AdS/CFT [69]. There is also an ongoing work about relationships between black hole microstates and large violations of additivity conjecture, one of the most important problems in quantum information theory [70].

Of course, other aspects of theoretical computer science are also possible to be inspired by physics. A particularly interesting discussion recently is about a possible connection between renormalization group theory and machine learning [71]. In some formulations, some people believe that the optimization and learning process in the parameters of the neural network could be understood as renormalization. Maybe one could derive some renormalization group flow equation for those parameters. One might even consider discussing phase transitions in the neural networks. If it is a second-order phase transition, conformal field theory might be helpful in predicting phenomena happening in the network. There are some impressive works done by Google recently, about generically using quantum field theory and tensor network technics for machine learning problems (see for instance [72]).

6.2.2 Benchmarking quantum devices using fundamental physics

Currently, we are still in a very early stage towards the great plan where quantum devices are able to provide impressive computational powers against classical computation or find some other remarkable applications in our ordinary life. Currently, quantum devices are still in the lab where people have to deal with the mitigation of noise and errors. It is important to find some clear targets where people have some universal, useful standards to show their computational capability of quantum devices. Here I am providing a possibility where fundamental physics should be helpful for benchmarking quantum devices.

Fundamental physics in general, or quantum field theory in a more specific sense, have many unsolved and important problems. For instance, as introduced before, strongly-coupled quantum field theories are very hard to solve. If one could simulate some non-perturbative physics using quantum devices, which is far beyond the limitation of classical computation, it could clearly show the capacity of the devices. This is not only following the original intuition of Richard Feynman about quantum computation, but also practical for the current development of quantum hardware.

Let me give a more precise example, evaluation of critical exponents in some critical systems admitting a second-order phase transition and an emergent conformal field theory. For some complicated systems where the critical exponents are not analytically solved, the critical exponents are only known to some digits. Those numbers are universal, namely, independent of, for instance, metrology, or the unit we use. The error bars of those critical exponents could be clear targets for benchmarking quantum devices. This could clearly be a win-win situation for both fundamental physics and quantum industry since it will not only be helpful for devices themselves, but also for exploring something unknown about our nature. This potentially requires fruitful collaborations between physicists, computer scientists, and engineers.

6.2.3 High energy physics in the low energy lab

There is another aspect of the above story, where some quantum simulation tasks might be more motivated to explore physics itself. This could be understood partly as a mostly non-commercial application of quantum computing in the NISQ era. Since a large part of me is a high energy physicist, I will be mostly appreciated if we could explore high energy physics problems using quantum devices. I wish to call this as *high energy physics in the low energy lab*.

Simulating high energy physics in the cold-atomic or condensed-matter labs might already have a long history. For instance, topological condensed-matter physicists could nowadays measure topological invariants directly in their labs. It has its own interests, of course, to measure topological phenomena in the statistical-mechanical systems. On the other hand, it will be no hurt to understand those experiments alternatively as simulators of emergent topological quantum field theories, originally designed for applications in string theory.

Aside from simulating quantum field theories, which we have discussed before, people have rising interests recently for simulating quantum gravity toy models. For example, people discuss recently *quantum gravity in the lab* to simulate some thought experiments using their quantum devices [73]. I am not sure if those simulations will be able to simulate physics that is beyond the current capability of classical computations nowadays, but I believe that future simulation will tell us much more fruitful knowledge that is far beyond what we currently know. Moreover, at least, simulating high energy physics in the low energy lab, is helpful for demonstration of principles, that we are able to simulate some exotic physical phenomena and bring those experiments from high energy physics itself to more general physicists. For instance, a particularly interesting example I have in mind is the so-called *conformal collider physics* largely due to the work of Hofman and Maldacena [74]. This experiment considers particle colliders established on the celestial sphere of conformal field theories, which is closely related to the black hole information paradox [75], and the electron-electron collider in particle physics [76, 77]. One could actually consider simulating this experiment in the critical cold-atomic or condensed-matter systems in the lab and compare it with theory, to show that quantum devices are able to simulate novel strongly-coupled emergent field theory dynamics. Another side of the story is to detect some experimental or phenomenological problems in high energy physics that might be answered using cold-atomic, condensed-matter, or quantum information technology, where I believe are, in rapid development (see a list of this type of projects announced by Fermilab [78]).

6.3 Towards the future

6.3.1 Waiting for quantum technology

Although many theoretical, numerical, simulation and experimental works have been done about our quantum devices, a fault-tolerant, universal quantum computer until June, 2020, has not appeared on the earth. Although many people believe that finally human will have such a computer at some point in the future, it is not super clear when precisely the day will come.

For some people, it is a little confusing why people need to do so much theoretical research by assuming a currently imaginary machine with quantum computational power. However, my personal view about this question is that science is always looking at the future. For instance, for detecting gravitational waves, we have waited nearly one hundred years, from pure theoretical constructions towards practical detections. For particle colliders, people propose some possibility of new particles, and particle physicists are still trying to detect them at least for half a century. The future attributes of science and technology could probably also be described by cyberpunk.

The modern development of science and technology is always associated with risk. If there is no risk and everything is definite, it may not be good science. If we are allowed to have a bet for detecting gravitational waves or detecting new particles, it is natural that some people will bet a useful quantum computer will appear at some point or even in the near future, and I am sure that for some people it is a pretty safe bet comparing to other physics and technology challenges. During the development, there are many byproducts that we have mentioned above, which could be regarded as rewards towards the final achievement of quantum computing.

6.3.2 Fundamental science using oracles

Here we wish to discuss a word, *oracle*, to emphasize a possible future where more cyberpunkian technologies have been used for scientific research.

The word "oracle" usually means that there is an existence which could provide some wise suggestions or reasonable predictions of the future, inspired by the gods. Related concepts are widely existing from ancient history, for instance, the Oracle of Delphi in ancient Greece. Nowadays, some computer scientists use the word "oracle" in the complexity theory, usually means a black box function in an algorithm. However, here we wish to use this word for something more general: in modern research, many aspects of our work have to rely on oracles made by information technologies.

In a very general sense, our personal computers and mobile phones could be understood as oracles: most of us don't understand how those machines are running, and we are still using them without that much verifications. For physicists, mathematicians, their books, and well-established results published in, for instance, *Annals of mathematics*, could be regarded as oracles, since usually, physicists don't want to prove them, but instead directly use them when needed. For some theoretical physicists, if they don't want to study in detail about some aspects of string theory, but they are willing to use the results, they could cite Edward Witten's paper and use the result by the trust without checking. In this sense, Edward Witten's word is an oracle (just like what I am doing now [62]). For high energy theoretical physicists, the software `Mathematica` is one of the most common oracles. Because of this oracle, theoretical physicists don't need to check how to play with Taylor expansions of some special functions or computing the Riemann tensor for a given metric by hand [79]. This hugely speeds up our modern development of theoretical physics[12].

Here, I am claiming that future information technology might significantly change the way we are doing research even further, towards somewhere beyond our imagination. Maybe at some point, we don't need to actually write any papers, and all operations are somehow collaboratively appearing in some universal, well-established framework on the internet, speeded-up by artificial intelligence and quantum computing. Maybe we don't need to provide any technical details of any works while machines will help us figure it out, and humans are just able to provide some generic views. Anyway, I think some aspects of those stories might happen someday, even during my life. These imaginations mean that we need more and more oracles.

Aside from the way we are practically doing science, oracles also often appear in the scientific contents itself. For instance, the existence of the 3d Ising bootstrap island for mixed operators is still mysterious. People don't have enough theoretical understanding of it. The way we obtain it is from complicated crossing equations and large-scale optimization, which could be regarded as oracles. What is the final answer to the critical exponents of the 3d Ising model? If we think about this problem in terms of crossing equations, the answer is obtained by the consistency of four-point correlation functions with mixing operators. If we transform it into semidefinite programming, it will be obtained from some super complicated crossing equations. If it turns out that the answer could be represented by some numbers where human beings are familiar with, it might be a very deep fact about the transcendental nature of hypergeometric functions, or representation theories about the conformal group. Maybe there is a

[12]However, there are still some theoretical physicists who claim that they are Luddites [80] and don't wish to use `Mathematica`. Some of them are also doing great jobs on hardcore computations.

Ramanujan-type formula hidden there, which might be indicated by oracles of large-scale optimization, or maybe machine learning [81].

Taking about Ramanujan, I think there are some better examples in mathematics instead of physics. In fact, the story of Srinivasa Ramanujan himself is highly related to the original meaning of oracles. During the time Ramanujan lived in the last century, he did not have a complete education in mathematics, but he could still discover a large set of amazing formulas about special functions and prime numbers. Many of them were highly intriguing but not proved, inspiring many potential discoveries from algebraic geometry to number theory[13]. So how was he able to find those magic formulas? He said, "An equation for me has no meaning unless it expresses a thought of God". It seems that he was crediting his formulas to his family goddess Namagiri Thayar, although some people believe that it was from intuitions behind thinking about math for a long time. Of course, Ramanujan is pretty unique in history, and I am not sure if it is wise enough to choose some beliefs in order to make some scientific discoveries, but I am saying that some future information technology will bring people solid, incomprehensible predictions, serving as oracles. In fact, people already start to do this. There is a machine learning project made by Google called the *Ramanujan Machine*, which is trying to discover some conjectural identities about special constants and continued fractions [83]. Based on their website [84], they are already able to generate conjectures by neural networks, and some of them seem not yet proved by professional mathematicians.

Besides discovering new conjectures, one of the first steps is probably to try to verify the known proof. About this, I wish to quote some recent activities by a well-established number theorist, Kevin Buzzard (see, for instance, this article [85]). According to him, there is no person on earth who could completely understand all details of Fermat's Last Theorem: the proof is so complicated, and people have to use many known results by trusting the original author, and all those details lead to a huge amount of literature. Nowadays, many aspects of mathematics, for instance, arithmetic algebraic geometry, Langlands program, or closer to physics, symplectic geometry, become extremely technical, and there is usually a very limited number of persons who could understand details of the proof. Thus, maybe it is necessary to try to verify some proofs based on machine, just in the aspects of logical consistency, since unlike modern physics allowing some degrees of fuzzy logic, mathematical proofs only allow two consequences: correct or wrong.

Kevin Buzzard is working on gathering fundings and establish codes to verify known mathematical proofs, and some concepts of new mathematics, for instance, perfectoids

[13] If you don't know his story, you could look at the movie *The Man Who Knew Infinity* [82].

introduced by Peter Scholze, could be realized by codes. Maybe this is a promising direction that is helpful for future mathematics, although young people in this field have to prove themselves by proving theorems. In physics, parts of theoretical physics directions are more rigorous in the mathematical sense, especially some aspects of quantum field theory or quantum information science, since the basic rule is more or less well-established. In other parts, for instance, quantum gravity, people have to make conjectural guess since the building blocks are not completely developed. Maybe for the former, it makes sense to do some verifications also. And in the long-term future, when people really discover a theory of everything, people could put all physics and mathematics axioms and theorems in a computer, to make solid predictions in our cyberpunkian future.

The current progress of number theory often tells us how limited people know about some simple concepts like prime numbers or rational numbers. For instance, about the Diophantine equation, the celebrated Birch-Swinnerton-Dyer (BSD) conjecture, one of the Millennium Prize Problems, could tell us something about the structures of solutions for the cubic equations (not proven). Problems in more general cases, higher degrees, more variables, are extremely hard to answer, while some of them are approaching some deepest sides of modern mathematics, where it is relatively easy to formulate a question that no one on the earth could solve. I would feel that maybe many of those problems are too hard for human brains, and in the future, we have to rely on oracles made by cyberpunkian technologies.

6.3.3 Companies, colliders

Here, we wish to comment on the relations between cyberpunkian quantum field theory and phenomenology. In many parts of this article, I am talking about some formal research, which seems to be not that related to real observations and experiments. However, it is not true. As we mentioned before, strongly-coupled quantum field theories are everywhere: people need to use strongly-coupled QCD to predict meson spectra and real-time dynamics happening in some colliders. In the condensed-matter system and statistical physics, predictions from strongly-coupled field theory are helpful to study strong-correlated systems, and they are directly measurable as quantum materials. In the sky, models with dark matter and dark energy might need strongly-coupled field theories to understand, cosmic phase transitions happening in the early universe might also be an exotic strongly-coupled field theory phenomena. Black hole physics is directly related to observations from event horizon telescope and LIGO (Laser Interferometer Gravitational-Wave Observatory) experiments about gravitational waves. I feel that all of them might need potential computational speedup or formal understanding from information theory. In a sense, they are all cyberpunkian physics!

It might be interesting to comment on some modern aspects of relations between academia and industry. Traditionally, some people studying fundamental physics might feel that pure potential physical breakthroughs may not be related to any commercial companies. However, I feel that in our quantum era, it might be common that academia and industry will have more communications.

Many companies, for instance, Google, Amazon, Microsoft, IBM, etc., have the ambition nowadays to make useful quantum computers for potential commercial purposes. Scientific academia, as part of public service sometimes funded by the government and donation, is aiming at providing high-quality research about our nature. In our quantum era, people start to communicate with each side frequently. We often see examples where quantum information scientists switch themselves back and force between two sides, and make great progress for both. There are several quantum centers from commercial companies established around the university campus, for instance, Microsoft Station Q at Santa Barbara, and the new Amazon quantum center at Pasadena. One remarkable work done recently, about simulating quantum gravity in the lab, is also such a great collaboration between company and university [73]. For me, it is exciting to imagine that Google is starting to probe properties of traversable wormholes.

It is exciting to see that both government and private industrial communities are willing to help establish some exciting new areas relating to fundamental physics and information technology. Previously, I am impressed by some high energy physics research collecting data from completely different experimental organizations and comparing them with each other. For instance, the electroweak phase transition happening in the early universe, might need observational and experimental data both from the ground (colliders) and the sky (gravitational wave detectors), and the data analysis might be made in the same plot (see, for instance, Figure 2 of [86]). I am imagining that one day, people will make plots which mention companies like Google and IBM, experimental organizations like LHC and LIGO in the same place (See Figure 5). I hope that the day may not be too far.

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A significant part of this note will be served as an introduction section in my Ph.D. thesis hopefully appearing in 2021, while one could also somehow regard this paper as an independent introductory article. I thank my advisors Cliff Cheung, John Preskill and David Simmons-Duffin for their numerous guidances and supports during my graduate study. I thank Sean Carroll for going through my draft. There is a much larger thank list I wish to give, in the final version of the thesis.

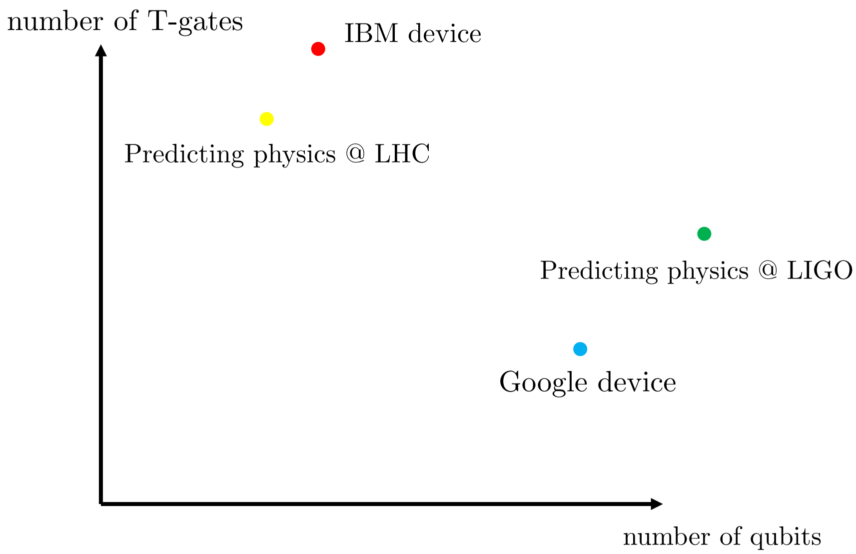

Figure 5: An imaginary plot might be made by future cyberpunkian physicists, especially high energy phenomenologists. This kind of plot includes the required computational resource needed for observations and existing computational resources provided by companies. As far as I know, there is no such plot existing until July 2020, which put together experimental organizations and quantum companies. I am conjecturing here that this type of plot will appear in the future.

References

[1] E. Schrödinger, "Nature and the greeks, science and humanism,".

[2] N. Y. Halpern, "Quantum steampunk: Quantum information, thermodynamics, their intersection, and applications thereof across physics," *PhD. Thesis, Caltech, 2018, arxiv:1807.09786* (2018) .

[3] D. Simmons-Duffin, "The Conformal Bootstrap," in *Theoretical Advanced Study Institute in Elementary Particle Physics: New Frontiers in Fields and Strings*, pp. 1–74. 2017. arXiv:1602.07982 [hep-th].

[4] L. F. Alday, J. Maldacena, A. Sever, and P. Vieira, "Y-system for Scattering Amplitudes," *J. Phys. A* **43** (2010) 485401, arXiv:1002.2459 [hep-th].

[5] J. M. Maldacena, "The Large N limit of superconformal field theories and supergravity," *Int. J. Theor. Phys.* **38** (1999) 1113–1133, arXiv:hep-th/9711200.

[6] S. Durr *et al.*, "Ab-Initio Determination of Light Hadron Masses," *Science* **322** (2008) 1224–1227, arXiv:0906.3599 [hep-lat].

[7] R. P. Feynman, "Simulating physics with computers," *Int. J. Theor. Phys.* **21** (1982) 467–488.

[8] J. Preskill, "Simulating quantum field theory with a quantum computer," *PoS* **LATTICE2018** (2018) 024, arXiv:1811.10085 [hep-lat].

[9] J. Preskill, "Quantum computing in the nisq era and beyond," *Quantum* **2** (2018) 79.

[10] F. Arute, K. Arya, R. Babbush, D. Bacon, J. C. Bardin, R. Barends, R. Biswas, S. Boixo, F. G. Brandao, D. A. Buell, *et al.*, "Quantum supremacy using a programmable superconducting processor," *Nature* **574** no. 7779, (2019) 505–510.

[11] G. Ortiz, J. Gubernatis, E. Knill, and R. Laflamme, "Quantum algorithms for fermionic simulations," *Phys. Rev. A* **64** (2001) 022319, arXiv:cond-mat/0012334. [Erratum: Phys.Rev.A 65, 029902 (2002)].

[12] S. P. Jordan, K. S. Lee, and J. Preskill, "Quantum Algorithms for Quantum Field Theories," *Science* **336** (2012) 1130–1133, arXiv:1111.3633 [quant-ph].

[13] S. P. Jordan, K. S. Lee, and J. Preskill, "Quantum Computation of Scattering in Scalar Quantum Field Theories," *Quant. Inf. Comput.* **14** (2014) 1014–1080, arXiv:1112.4833 [hep-th].

[14] S. P. Jordan, K. S. M. Lee, and J. Preskill, "Quantum Algorithms for Fermionic Quantum Field Theories," arXiv:1404.7115 [hep-th].

[15] S. P. Jordan, H. Krovi, K. S. M. Lee, and J. Preskill, "BQP-completeness of Scattering in Scalar Quantum Field Theory," arXiv:1703.00454 [quant-ph].

[16] S. R. Coleman, "Classical Lumps and their Quantum Descendents," *Subnucl. Ser.* **13** (1977) 297.

[17] T. Lee and Y. Pang, "Nontopological solitons," *Phys. Rept.* **221** (1992) 251–350.

[18] J. Liu, J. Preskill, and B. Sahinoglu, "Simulating kink scattering in a quantum computer," to appear. https://drive.google.com/file/d/1wOrPmO7lfutZlLEj-12JiMUAVg4nOdQr/view.

[19] A. Milsted, J. Liu, J. Preskill, and G. Vidal, "Simulating kink scattering in tensor networks," to appear. https://www.youtube.com/watch?v=9Om--8LsqFw.

[20] G. F. Chew, "S-Matrix Theory of Strong Interactions without Elementary Particles," *Rev. Mod. Phys.* **34** no. 3, (1962) 394–401.

[21] A. Polyakov, "Nonhamiltonian approach to conformal quantum field theory," *Zh. Eksp. Teor. Fiz.* **66** (1974) 23–42.

[22] D. Simmons-Duffin, "A Semidefinite Program Solver for the Conformal Bootstrap," *JHEP* **06** (2015) 174, arXiv:1502.02033 [hep-th].

[23] S. El-Showk, M. F. Paulos, D. Poland, S. Rychkov, D. Simmons-Duffin, and A. Vichi, "Solving the 3D Ising Model with the Conformal Bootstrap," *Phys. Rev. D* **86** (2012) 025022, arXiv:1203.6064 [hep-th].

[24] S. Caron-Huot, "Analyticity in Spin in Conformal Theories," *JHEP* **09** (2017) 078, arXiv:1703.00278 [hep-th].

[25] S. M. Chester, W. Landry, J. Liu, D. Poland, D. Simmons-Duffin, N. Su, and A. Vichi, "Carving out OPE space and precise $O(2)$ model critical exponents," *JHEP* **06** (2020) 142, arXiv:1912.03324 [hep-th].

[26] J. Liu, D. Meltzer, D. Poland, and D. Simmons-Duffin, "The Lorentzian inversion formula and the spectrum of the 3d O(2) CFT," arXiv:2007.07914 [hep-th].

[27] W. Landry and D. Simmons-Duffin, "Scaling the semidefinite program solver SDPB," arXiv:1909.09745 [hep-th].

[28] N. Bao and J. Liu, "Quantum algorithms for conformal bootstrap," *Nucl. Phys. B* **946** (2019) 114702, arXiv:1811.05675 [hep-th].

[29] **CMS** Collaboration, A. M. Sirunyan *et al.*, "Identification of heavy, energetic, hadronically decaying particles using machine-learning techniques," *JINST* **15** no. 06, (2020) P06005, arXiv:2004.08262 [hep-ex].

[30] T. Roxlo and M. Reece, "Opening the black box of neural nets: case studies in stop/top discrimination," arXiv:1804.09278 [hep-ph].

[31] R. Bousso and J. Polchinski, "Quantization of four form fluxes and dynamical neutralization of the cosmological constant," *JHEP* **06** (2000) 006, arXiv:hep-th/0004134.

[32] L. Susskind, "The Anthropic landscape of string theory," arXiv:hep-th/0302219.

[33] S. Ashok and M. R. Douglas, "Counting flux vacua," *JHEP* **01** (2004) 060, arXiv:hep-th/0307049.

[34] C. Cheung, J. Liu, and G. N. Remmen, "Proof of the Weak Gravity Conjecture from Black Hole Entropy," *JHEP* **10** (2018) 004, arXiv:1801.08546 [hep-th].

[35] E. Palti, "The Swampland: Introduction and Review," *Fortsch. Phys.* **67** no. 6, (2019) 1900037, arXiv:1903.06239 [hep-th].

[36] F. Denef and M. R. Douglas, "Computational complexity of the landscape. I.," *Annals Phys.* **322** (2007) 1096–1142, arXiv:hep-th/0602072.

[37] M. R. Douglas, "Spaces of Quantum Field Theories," *J. Phys. Conf. Ser.* **462** no. 1, (2013) 012011, arXiv:1005.2779 [hep-th].

[38] F. Denef, M. R. Douglas, B. Greene, and C. Zukowski, "Computational complexity of the landscape II—Cosmological considerations," *Annals Phys.* **392** (2018) 93–127, arXiv:1706.06430 [hep-th].

[39] J. Liu, "Artificial Neural Network in Cosmic Landscape," *JHEP* **12** (2017) 149, arXiv:1707.02800 [hep-th].

[40] Y.-H. He, "Deep-Learning the Landscape," arXiv:1706.02714 [hep-th].

[41] F. Ruehle, "Data science applications to string theory," *Phys. Rept.* **839** (2020) 1–117.

[42] J. Halverson and C. Long, "Statistical Predictions in String Theory and Deep Generative Models," *Fortsch. Phys.* **68** no. 5, (2020) 2000005, arXiv:2001.00555 [hep-th].

[43] S. Hawking, "Particle Creation by Black Holes," *Commun. Math. Phys.* **43** (1975) 199–220. [Erratum: Commun.Math.Phys. 46, 206 (1976)].

[44] S. Hawking, "Black hole explosions," *Nature* **248** (1974) 30–31.

[45] S. Ryu and T. Takayanagi, "Holographic derivation of entanglement entropy from AdS/CFT," *Phys. Rev. Lett.* **96** (2006) 181602, arXiv:hep-th/0603001.

[46] A. Almheiri, X. Dong, and D. Harlow, "Bulk Locality and Quantum Error Correction in AdS/CFT," *JHEP* **04** (2015) 163, arXiv:1411.7041 [hep-th].

[47] P. Hayden and J. Preskill, "Black holes as mirrors: Quantum information in random subsystems," *JHEP* **09** (2007) 120, arXiv:0708.4025 [hep-th].

[48] A. R. Brown, D. A. Roberts, L. Susskind, B. Swingle, and Y. Zhao, "Holographic Complexity Equals Bulk Action?," *Phys. Rev. Lett.* **116** no. 19, (2016) 191301, arXiv:1509.07876 [hep-th].

[49] "*It from qubit*, https://www.simonsfoundation.org/mathematics-physical-sciences/it-from-qubit/.,".

[50] L. McGough, M. Mezei, and H. Verlinde, "Moving the CFT into the bulk with $T\overline{T}$," *JHEP* **04** (2018) 010, arXiv:1611.03470 [hep-th].

[51] P. Kraus, J. Liu, and D. Marolf, "Cutoff AdS_3 versus the $T\overline{T}$ deformation," *JHEP* **07** (2018) 027, arXiv:1801.02714 [hep-th].

[52] X. Dong, E. Silverstein, and G. Torroba, "De Sitter Holography and Entanglement Entropy," *JHEP* **07** (2018) 050, arXiv:1804.08623 [hep-th].

[53] V. Gorbenko, E. Silverstein, and G. Torroba, "dS/dS and $T\overline{T}$," *JHEP* **03** (2019) 085, arXiv:1811.07965 [hep-th].

[54] A. Lewkowycz, J. Liu, E. Silverstein, and G. Torroba, "$T\overline{T}$ and EE, with implications for (A)dS subregion encodings," *JHEP* **04** (2020) 152, arXiv:1909.13808 [hep-th].

[55] "*The non-perturbative bootstrap*, https://bootstrapcollaboration.com.,".

[56] L. Susskind, "Horizons Protect Church-Turing," arXiv:2003.01807 [hep-th].

[57] M. Hogarth, *Predictability, computability, and spacetime*. PhD thesis, University of Cambridge, 1996.

[58] R. Geroch and J. B. Hartle, "Computability and physical theories," *Foundations of Physics* **16** no. 6, (1986) 533–550.

[59] A. Bouland, B. Fefferman, and U. Vazirani, "Computational pseudorandomness, the wormhole growth paradox, and constraints on the AdS/CFT duality," arXiv:1910.14646 [quant-ph].

[60] I. Kim, E. Tang, and J. Preskill, "The ghost in the radiation: Robust encodings of the black hole interior," *JHEP* **20** (2020) 031, arXiv:2003.05451 [hep-th].

[61] B. Yoshida, "Remarks on Black Hole Complexity Puzzle," arXiv:2005.12491 [hep-th].

[62] E. Witten, "String theory dynamics in various dimensions," *Nucl. Phys. B* **443** (1995) 85–126, arXiv:hep-th/9503124.

[63] P.-S. Hsin and N. Seiberg, "Level/rank Duality and Chern-Simons-Matter Theories," *JHEP* **09** (2016) 095, arXiv:1607.07457 [hep-th].

[64] E. H. Lieb and M. B. Ruskai, "A Fundamental Property of Quantum-Mechanical Entropy," *Phys. Rev. Lett.* **30** (1973) 434–436.

[65] E. Lieb and M. Ruskai, "Proof of the strong subadditivity of quantum-mechanical entropy," *J. Math. Phys.* **14** (1973) 1938–1941.

[66] M. Headrick and T. Takayanagi, "A Holographic proof of the strong subadditivity of entanglement entropy," *Phys. Rev. D* **76** (2007) 106013, arXiv:0704.3719 [hep-th].

[67] T. C. Bohdanowicz and F. G. Brandao, "Universal Hamiltonians for Exponentially Long Simulation," arXiv:1710.02625 [quant-ph].

[68] F. G. Brandao, W. Chemissany, N. Hunter-Jones, R. Kueng, and J. Preskill, "Models of quantum complexity growth," arXiv:1912.04297 [hep-th].

[69] L. Susskind, "Computational Complexity and Black Hole Horizons," *Fortsch. Phys.* **64** (2016) 24–43, arXiv:1403.5695 [hep-th]. [Addendum: Fortsch.Phys. 64, 44–48 (2016)].

[70] P. Hayden and G. Pennington, "Working in Progress, http://online.kitp.ucsb.edu/online/qgravity-c20/hayden/,".

[71] P. Mehta and D. J. Schwab, "An exact mapping between the variational renormalization group and deep learning," *arXiv preprint arXiv:1410.3831* (2014) .

[72] E. Dyer and G. Gur-Ari, "Asymptotics of Wide Networks from Feynman Diagrams," arXiv:1909.11304 [cs.LG].

[73] A. R. Brown, H. Gharibyan, S. Leichenauer, H. W. Lin, S. Nezami, G. Salton, L. Susskind, B. Swingle, and M. Walter, "Quantum Gravity in the Lab: Teleportation by Size and Traversable Wormholes," arXiv:1911.06314 [quant-ph].

[74] D. M. Hofman and J. Maldacena, "Conformal collider physics: Energy and charge correlations," *JHEP* **05** (2008) 012, arXiv:0803.1467 [hep-th].

[75] S. W. Hawking, M. J. Perry, and A. Strominger, "Soft Hair on Black Holes," *Phys. Rev. Lett.* **116** no. 23, (2016) 231301, arXiv:1601.00921 [hep-th].

[76] L. J. Dixon, M.-X. Luo, V. Shtabovenko, T.-Z. Yang, and H. X. Zhu, "Analytical Computation of Energy-Energy Correlation at Next-to-Leading Order in QCD," *Phys. Rev. Lett.* **120** no. 10, (2018) 102001, arXiv:1801.03219 [hep-ph].

[77] M. Kologlu, P. Kravchuk, D. Simmons-Duffin, and A. Zhiboedov, "The light-ray OPE and conformal colliders," arXiv:1905.01311 [hep-th].

[78] "https://news.fnal.gov/2018/09/department-of-energy-awards-fermilab-more-than-10-million-for-quantum-science/,".

[79] "http://www.xact.es,".

[80] J. Polchinski, "Memories of a Theoretical Physicist," arXiv:1708.09093 [physics.hist-ph].

[81] "Private communications with Ning Su,".

[82] "The man who knew infinity, https://en.wikipedia.org/wiki/The_Man_Who_Knew_Infinity_(film),".

[83] G. Raayoni, S. Gottlieb, G. Pisha, Y. Harris, Y. Manor, U. Mendlovic, D. Haviv, Y. Hadad, and I. Kaminer, "The ramanujan machine: automatically generated conjectures on fundamental constants," *arXiv preprint arXiv:1907.00205* (2019) .

[84] "The ramanujan machine. http://www.ramanujanmachine.com/.,".

[85] "Number theorist fears all published math is wrong. https://www.vice.com/en_us/article/8xwm54/number-theorist-fears-all-published-math-is-wrong-actually.,".

[86] P. Huang, A. J. Long, and L.-T. Wang, "Probing the Electroweak Phase Transition with Higgs Factories and Gravitational Waves," *Phys. Rev. D* **94** no. 7, (2016) 075008, arXiv:1608.06619 [hep-ph].