Quantum Information Theory in Quantum Field Theory and Cosmology (23w5092)

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1 Overview of the Field

In recent years, quantum information theory (QIT) has become a melting pot between disparate branches of physics. Within the last decade, tools and techniques from QIT are bringing new perspectives into fields such as quantum field theory (QFT) and cosmology, and are inspiring new questions and research directions.

Quantum many-body systems and quantum field theories, often found in condensed matter and particle physics, are essential for our understanding of modern physical phenomena, but can be challenging to quantitatively study and simulate, both from a theoretical and experimental point of view. Because the size of the Hilbert space grows exponentially with the number of degrees of freedom, brute force techniques for studying these systems often fail. In this context, recent progress in QIT, such as quantum computation and computational complexity, can provide important insights.

One area that has seen significant recent progress is the field of *quantum complexity*, an extension of the concept of computational complexity from classical computer science to quantum mechanics and quantum computing. Interestingly, quantum complexity can provide important insights into the simulation of a class of quantum-many body systems [1]. Since John Preskill et al. have demonstrated that quantum computers can in fact simulate certain aspects of quantum field theory exponentially faster than the classical non-perturbative algorithms [2], this naturally raises several questions: Do insights acquired from quantum complexity help simulate QFT more efficiently? What novel features of QFT can we learn from complexity? With the possibility of a working, large qubit quantum computer in the near future, techniques in QIT that may be useful in a simulation of a QFT on a quantum computer take on even greater practical importance.

Simultaneously with these recent advances in QIT, there has been considerable theoretical progress in the field of holographic duality, also known as the AdS/CFT (Anti-de Sitter/Conformal Field Theory) correspondence. AdS/CFT, as a duality between a strongly coupled quantum field theory and a weakly coupled gravity theory, provides an alternative tool for studying the behavior of QFTs in regimes where the usual perturbative tools do not apply. Recent proposals in holography have synergistically combined with advances in QIT, linking apparently disparate systems such as black holes and conformal field theories.

In one such example, geometric quantities that probe the physics beyond the horizon of a black hole in AdS spacetime are identified with the *quantum circuit complexity* of a holographically dual conformal field theory. More generally, studies of entanglement entropy, scrambling, quantum chaos, and other information-theoretic tools and their holographic duals have suggested possible limits on the dynamics of interacting systems, and have initiated several interesting new lines of research [3].

Cosmology is another arena where QIT has recently provided new insights and connections. Cosmic inflation, in which quantum vacuum fluctuations are stretched to cosmological scales by a period of rapid near-de Sitter (dS) expansion, is a leading paradigm for the dynamics of the early Universe. As with its AdS counterpart, the study of dS space with information-theoretic tools can potentially uncover new phenomena and lead to a better theoretical understanding of this important cosmological background from the perspective of quantum gravity. Recent progress, including the application of QIT concepts such as complexity, entanglement entropy, and scrambling, among others, to cosmological backgrounds, hint at potential insights for holographic descriptions of dS as well as potential fundamental limits on the duration of cosmological inflation.

2 Recent Developments and Open Problems

While progress in the different fields of QIT, QFT, AdS/CFT and cosmology has been ongoing for many years, it is only in the last few years that there has been a sustained interest in the connections between these fields. Many of these ideas have the potential to fundamentally shift our thinking about complex quantum systems to a perspective in which information and information-theoretic concepts play a primary and essential role. Below, we will highlight some recent progress made by several leading researchers working in this field. Note that it is not exhaustive and we apologise for any inadvertent omissions. We will highlight some of the works which have played an important role in the context of this workshop.

Complexity plays an important role in the link between QIT, QFT, and their applications. The properties of complexity in QFTs have been studied by several groups, e.g., Prof. Robert Myers and his group at the Perimeter Institute of Theoretical Physics in Waterloo, Canada, [4] in the context of holography, and the groups of Prof. Johanna Erdmenger of Würzburg University, and Prof. Michal Heller of the Max Planck Institute of Gravitational Physics, who have made significant complementary progress in understanding complexity in the context of Conformal Field Theory [5].

Besides complexity, various other QIT measures, such as entanglement entropy, have provided key insights for some of the longstanding problems in theoretical physics. One example is the semi-classical computation of the Page curve, which plays an important role in the context of black hole information paradox [6]. Significant contribution in this field came from the groups of e.g., Prof. Juan Maldacena, and Prof. Edward Witten of IAS Princeton, Prof. Raphael Bousso of U.C Berkeley, Prof. Aron Wall of Cambridge University, Prof. Geoff Pennington of UC-Berkeley, California, Prof. Thomas Hartman of Cornell University, and Prof. Vijay Balasubramanian of the University of Pennsylvania, among others.

Along with the high energy physics community, the condensed matter physics community has also been using QIT techniques for various interesting physical systems. Prof. Shinsei Ryu of University of Chicago, and Prof. Koji Hashimoto of Osaka University, Japan have recently made important contributions in understanding chaotic systems [7]. Note that there are a plethora of groups working in this direction and made several important contributions. Two of the organizers (Arpan Bhattacharyya and S. Shajidul Haque), along with their collaborators, have also proposed complexity as a new diagnostic for quantum chaotic systems [8].

In the past few years, QIT concepts and tools and are also enriching cosmology. Recent works by Prof. Gary Shiu of University of Wisconsin-Madison, Prof. Robert Brandenberger of McGill University, Canada, and the organizers, have described perturbations in cosmological spacetimes in the language of entanglement entropy, scrambling, complexity, and chaos. The techniques of QIT have uncovered bounds on the growth of chaos and potential limits on the amount of expansion of the Universe, suggesting that QIT has new things to teach us about the structure of our Universe on the largest scales.

Some of the significant open problems that one would like to answer in this context are the following: (1) To what extent is the effective field theory description of cosmology valid? (2) Investigate Krylov complexity for interacting quantum fields and what it teaches us about holography. (3) Do tools from holography provide any insight into the Hamiltonian simulation problem, which is important for the simulation of quantum many-body physics via state-of-the-art quantum computers? (3) Does the island proposal resolve the black hole information paradox?

3 Presentation Highlights

The 4.5 day workshop was well-attended and most participants gave talks. The only participants who did not make oral presentations were some graduate students, many of whom made poster presentations. In addition to a large number of excellent talks (6-8 per day), there were two discussion sessions spread out throughout the conference, which also saw strong participation and lively discussions. We also organized two EDI sessions, which were well-attended and led to excellent discussions. Although most of the talks were in-person, due to visa and travel issues, a few speakers (and participants) were compelled to participate online. However, due to the state-of-the-art facilities at BIRS, the online talks (total 11 in number, including the 2 EDI talks) felt no different from the ones in-person and the switch from online to hybrid and vice-versa was seamless. Presentation highlights include the following (speaker and talk):

- Cliff Burgess: *Primordial Decoherence & Reliable Late-time Predictions*
- Anatoly Dymarsky: *Chaos and complexity through the lens of dynamics in Krylov space*
- Janet Hung: *Constructing lattice integrable models from topological theories in one higher dimensions and their applications*
- Bartek Czech: *Everything Everywhere All at Once: Holographic Entropy Cone, Entanglement Wedge Nesting, Differential Entropy, Black Holes, Modular Chern Numbers, Toric Code, Cubohemioctahedron...*
- *Javier Magan: Long times, chaos, and spread complexity*
- Claire Zukowski: *State-Changing Modular Berry Phases*
- **EDI talk1:** Martha Mathurin-Moe, Vice-Provost, EDI, University of Lethbridge.
- **EDI talk2:** Glenda Bonifacio, Professor of Women and Gender Studies and EDI Scholar, University of Lethbridge. In the EDI talks, the EDI experts (Mathurin-Moe and Bonifacio) touched upon various aspects of EDI in the academia, with data, information, examples and an interactive session. The talks were attended by most of the conference participants and participation was spontaneous.

4 Scientific Progress Made

- We had arranged the daily talks based on a common theme. Each day, we started with a review talk, followed by more specialized talks. We had ample amount of time for discussion during and after the talks. We also had dedicated discussion sessions. These discussions generated many new ideas, especially in the areas of application of QIT in cosmology, effective field theory and topological theory of gravity.
- Motivated by the talk presented by Prof. Cliff Burgess on the models of the cosmological effective field theory, it was felt that it will be interesting to study them using QIT. This will help one to bring new perspective in the field of decoherence for cosmological perturbation.
- Motivated by several talks on Krylov complexity, we learned that behaviour of the Krylov complexity at late time is dictated by the density of states of the systems. Hence it will be interesting to understand it for various other cases e.g., in presence of dissipation to make this in more concrete footing.
- Prof. Hung discussed connection between tensor network and topological field theory. In light of these progress, it is reasonable to compute some QIT, e.g., Spectral Form Factor for topological gravity theory and see what happens. Do we get the same dip-ramp-plateau structure? What does it teach us about quantum gravity? One interesting thing that emerges is that, we can do these computation for 3D gravity concretely and match with tensor network predictions. This we hope to accomplish in near future.

- Lastly we clarified the importance of von-Neumann algebra in the context of cosmological spacetime and inperplay between symmetry, charged moments and entanglement for quantum many-body systems.

5 Outcome of the Meeting

- Due to the space left for for ample discussions in the workshop schedule, junior students/postdocs had the opportunity to interact with experts. We believe this benefits their future job application. In fact, students from cosmology background got interested in quantum information and vice versa.
- We list some publications as well as pre-prints which resulted form the discussion that took place at this workshop. This workshop has been acknowledged in each of these papers (names of the participants are highlighted):
  1. S. Nandy, B. Mukherjee, **Arpan Bhattacharyya** and A.Banerjee,"Quantum state complexity meets many-body scars," J. Phys. Condens. Matter **36** (2024) no.15, 155601, doi:10.1088/1361-648X/ad1a7b
  2. **Arpan Bhattacharyya**, D.Ghosh and **Poulami Nandi**, "Operator growth and Krylov complexity in Bose-Hubbard model,"JHEP **12** (2023), 112, doi:10.1007/JHEP12(2023)112
  3. **Arpan Bhattacharyya**, **S.S.Haque**, G.Jafari, J.Murugan and D.Rapotu, "Krylov complexity and spectral form factor for noisy random matrix models," JHEP **10** (2023), 157, doi:10.1007/JHEP10(2023)157.
  4. **Arpan Bhattacharyya**, M. Dogra and **Shubho R.Roy**, "CFT reconstruction of local bulk operators in half-Minkowski space", [arXiv:2308.08547 [hep-th]].
  5. **A. Bhattacharyya,** S.Ghosh and S.Pal," deformed 2D topological gravity : from partition function to late-time SFF", [arXiv:2309.16658 [hep-th]].
- Motivated by the talks on application of effective field theory in cosmology that were held at the workshop, we have started new projects with Dr. Suddhasattwa Brahma, University of Edinburgh, a former postdoc of Robert Brandenberger, in the area of deoherence of cosmological perturbation and complexity. We are in the final stage of the project and preparing the manuscript. We hope to post in on arXiv soon.
- To follow up on the discussion on Krylov complexity, **S.S.Haque** and **Arpan Bhattacharyya** gave talks on workshop (lonk of which is given here: `https://sites.google.com/view/holography2023/talks?authuser=0`) organized after our workshop by Prof. Keun-Young Kim from Gwangju Institute of Science and Technology at APCTP, South Korea. Prof. Keun-Young Kim was an invited speaker for the BIRS workshop.
- Furthermore, the success of this workshop and the positive response that we got, combined with the fact that this is a rapidly growing field, motivates us to propose another workshop with a bigger goal of keeping track of recent developments. Two of the organizers, Arpan Bhattacharyya and Saurya Das, along with Rusa Mandal, have proposed a sequel to this workshop in 2024 at the BIRS station located at CMI, Chennai, India, with another workshop titled *Quantum Gravity and Information Theory: Modern Developments*, no. 25w5386. We hope that our proposal will be accepted.

References

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[8] T. Ali, A. Bhattacharyya, S. S. Haque, E. H. Kim, N. Moynihan and J. Murugan, Phys. Rev.D101, no.2, 026021 (2020)