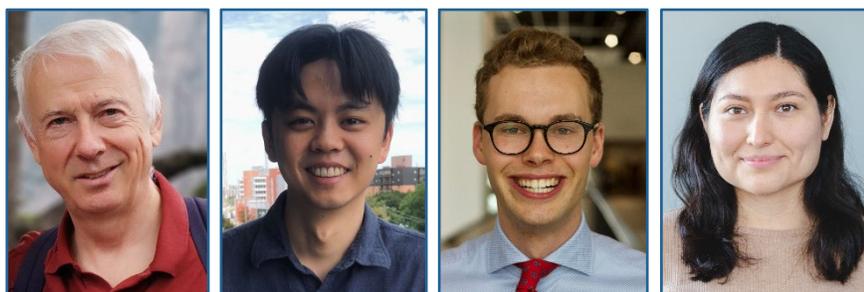


FROM QUANTUM FOUNDATIONS TO QUANTUM GRAVITY: A BRIEF HISTORY OF RELATIVISTIC QUANTUM INFORMATION

SUMMARY: We review the history of Relativistic Quantum Information (RQI) from its antecedent roots in the 1970s, to its emergence 20 years ago, to its status as a new research field today.



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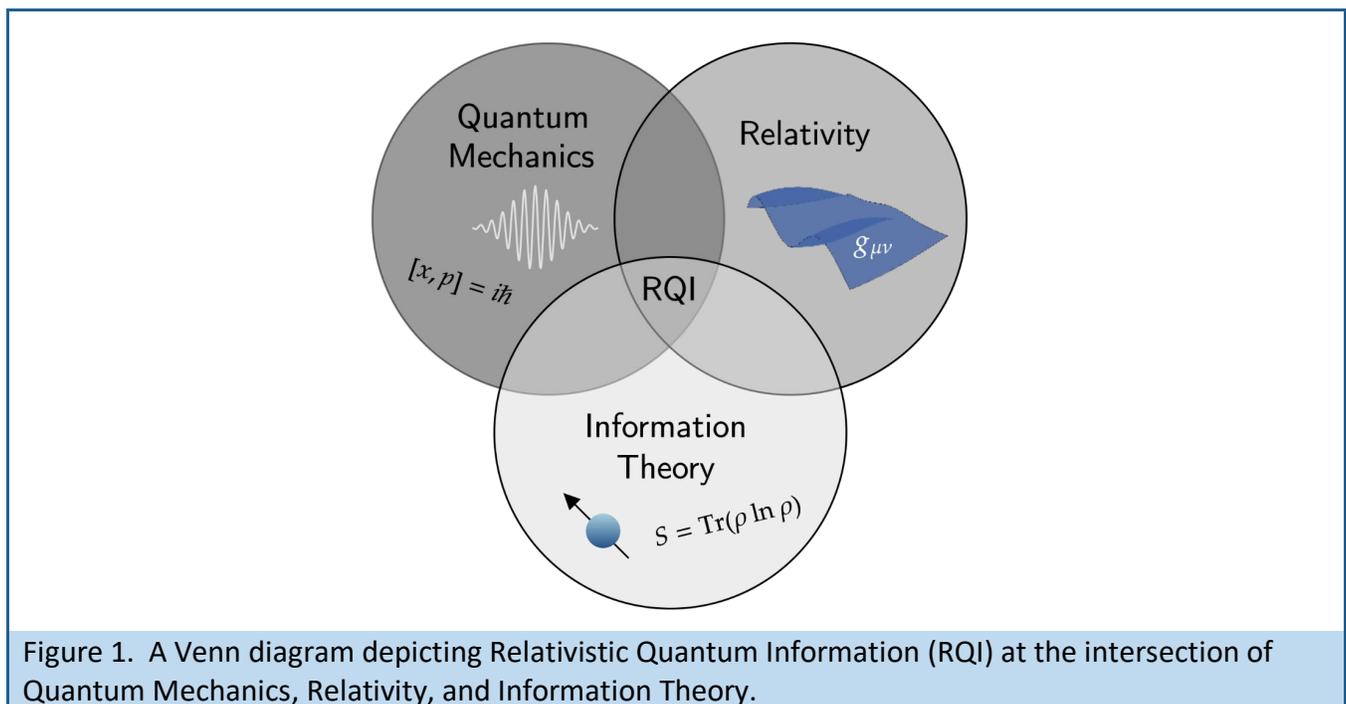
At the beginning of the 20th century, it was believed that our description of the world was complete, with the exception of a few problems like the distribution of black body radiation and Mercury's perihelion precession. However, this belief was soon overturned in the wake of two revolutions in physics: quantum theory and relativity. The former challenged the mechanistic, “classical” view of the world held since Newton, introducing notions of indeterminism and discreteness into our understanding of reality. Quantum Mechanics (QM) was formalized in 1925 by pioneers Erwin Schrödinger and Werner Heisenberg, giving rise to the so-called “first quantum revolution.” The latter, discovered by Einstein in 1905, provided a new description of space and time as two facets of a unified fabric of spacetime, allowing for consistent descriptions of events according to observers in relative motion. Ten years later, Einstein showed that gravity arises due to the curvature of spacetime in his theory of General Relativity (GR).

These two theories form the pillars of modern physics. GR predicted the existence of black holes and gravitational waves, both of which have been confirmed observationally in the past decade [1,2]. GR has also played an important role in efforts to explore space beyond our solar system, as well as in the development of the Global Positioning System here on Earth. QM, by contrast, is best suited to

describing the smallest building blocks of our universe, from molecules and atoms and even fundamental forces like electromagnetism, whilst enabling a host of modern technologies such as lasers, computers, photography, and LEDs.

In the second half of the 20th century, a new paradigm for physics emerged: information theory. Based on the work of Claude Shannon [3], the idea that information was physical became a key principle of modern physics [4,5], ranking alongside the GR notion of spacetime curvature and the QM concepts of uncertainty and discreteness. Describing information from a physical perspective naturally led to the subdiscipline of quantum information, which was founded on the insight that quantum systems like atoms and photons carry information. Storing and processing information using quantum systems allows quantum phenomena, like superposition and entanglement, to be harnessed as computational resources, paving the way towards the development of quantum computers [6].

But how do relativity, quantum mechanics, and information theory interact? Physicists seeking a unified description of the world have long wondered whether an answer may lie at the intersection of these disciplines. It turns out that Canada would serve as the breeding ground for a new interdisciplinary research field, now known as Relativistic Quantum Information (RQI), whose central motivation would be to understand this question.



EARLY DAYS OF RQI

The seeds of RQI were sown in the 1970s via the work of William Unruh and Stephen Hawking. In 1974, Hawking showed that black holes radiate particles thermally (like a blackbody), contrary to classical

intuition that they should be perfect absorbers with zero temperature [7,8]. This remarkable finding led to the infamous information loss problem, which remains controversial to this day. Specifically, the eventual evaporation of the black hole into thermal radiation (a statistical mixture¹ without any traces of the black hole's origin) eliminates all information about its initial state, contradicting the unitarity² of the quantum physics that made its radiation possible in the first place. Building on work by Steve Fulling and Paul Davies, two years later, Unruh, then faculty at McMaster University, showed [9] that this phenomenon is more general, arising even in the absence of gravity. He showed that uniformly accelerated observers in flat spacetime likewise see a “hot” bath of thermal particles, even though an inertial observer would see nothing. This demonstrated that Hawking's prediction was rooted in a more generic mechanism, namely the observer-dependence of quantum states.

In the early 2000s, information-based approaches to relativistic quantum physics took on more prominence as an exciting playground for studying new phenomena. A review article by Asher Peres and Daniel Terno (then a postdoc at the Perimeter Institute (PI) in Waterloo), set the stage for the early days of RQI research, providing examples of how quantum measurements and quantum information are affected by relativistic motion [10]. This newly-founded institute for theoretical physics proved to be fertile ground for RQI-related research. Following a seminar at PI by Gerard Milburn on relativistic quantum teleportation [11], postdoctoral fellow Ivette Fuentes and the University of Waterloo's then-Department Chair, Robert Mann, showed how relativistic acceleration degrades the entanglement between a pair of observers [12]. This work ushered in a new range of foundational questions in physics lying squarely at the intersection of relativity, quantum, and information theory. In 2012, the journal *Classical and Quantum Gravity* devoted a special issue to RQI [13]; co-edited by Mann and Tim Ralph of the University of Queensland, this became a benchmark that attracted many new researchers to the field.

At its core, RQI provides a new perspective on what is arguably the paramount goal of modern theoretical physics: unifying quantum theory with gravity. What if information theory—long regarded as a bystander in advancing our understanding of physics—was instead promoted to a main character in the quest for a quantum theory of gravity? Rather than “top-down” attempts at quantizing gravity, RQI offered a “bottom-up” approach that allowed theorists and experimentalists to investigate quantum gravity from an information-theoretic operational perspective, namely one based on “measurements” made by rods, clocks, and detectors.

¹ A statistical mixture occurs when a system is prepared in one of several states with a probability, and the observer doesn't know which state was chosen. For the black hole, the radiation is in a mixture given by a thermal probability distribution.

² Unitarity refers to the condition that the time evolution of a quantum state is mathematically represented by a unitary operator; if unitarity breaks down then quantum states do not have well-defined time-evolution.

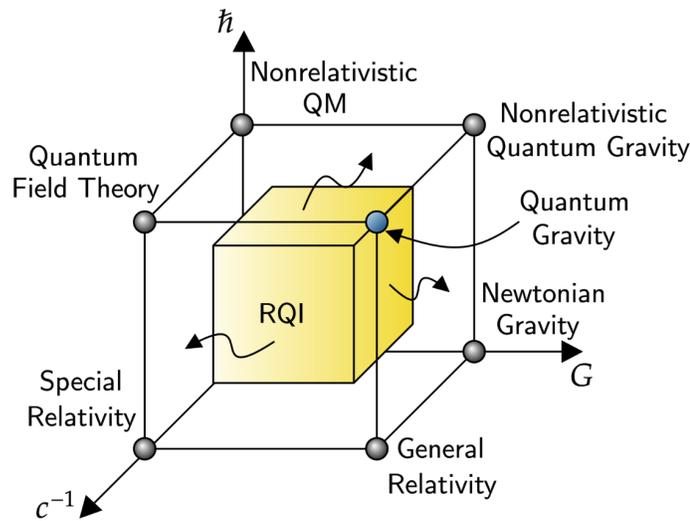


Figure 2. A Bronstein cube organizing different physical theories based on their dependence on the fundamental constants: \hbar (Planck's constant), c (speed of light in vacuum), and G (the gravitational constant). RQI research is generally interested in understanding new physics in regimes where all three constants are relevant.

RQI TODAY

The first breakthrough made by the RQI community was to provide an information-first approach to quantum field theory (QFT), which has come to define the Waterloo branch of the RQI community. Despite QFT's resounding success in the field of particle physics, its application to understanding relativity and the structure of spacetime had been limited. Then-Ph.D. student Eduardo Martín-Martínez, now a Professor at the University of Waterloo, generalized Fuentes and Mann's earlier work to account for gravitational effects [14], while Professor Achim Kempf explored the role of quantum information in cosmological settings and the emergence of spacetime itself [15,16]. Mann's group, based on early work by Benni Reznik [17,18] and Nicholas Menicucci [19], advanced investigations in extracting quantum vacuum entanglement with local probes (building on pioneering work by Jorma Louko [20]), a protocol now known as entanglement harvesting [21,22]. Recent efforts at Waterloo, spearheaded by Martín-Martínez in collaboration with Institute of Quantum Computing Professor Adrian Lupascu, has brought entanglement harvesting within reach of experimental superconducting circuit platforms [23].

European researchers in particular began asking questions about how gravity affects quantum systems like atoms, molecules, and photons. These questions were inspired by the record-breaking precision achieved in experiments in quantum optics and matter-wave interferometry. The first such proposals arose from the "Vienna School of Quantum Foundations," led by Caslav Brukner. Prior to this, probing quantum gravity in low-energy systems was not thought to be possible. Brukner's then-Ph.D. student Igor Pikovski showed that tabletop quantum optomechanical systems offered the possibility of testing

such effects in a controlled laboratory setting [24]. Concurrently, Magdalena Zych, also a Ph.D. student of Brukner's, made new predictions about the behaviour of time according to "quantum clocks" in the presence of gravity [25]. Perhaps the most influential contribution came in 2017, when two papers including eminent quantum physicists like Sougato Bose and Vlatko Vedral proposed experiments showing that particles interacting via gravity could become entangled; its observation would provide strong evidence that gravity acts as a "quantum information channel" [26,27].

Last but not least, the RQI community has made seminal contributions to the development of a quantum information approach to causality and reference frames. These ideas are all central features of GR, but until recently had not been generalized to the quantum domain. PI scientist Lucien Hardy proposed that causal order itself was quantum mechanically indefinite [28], an idea furthered by PI postdoc Giulio Chiribella and collaborators in 2013 [29]. Concurrently, Brukner, with then-postdocs Fabio Costa and Ognjan Oreshkov, provided a new formulation of quantum mechanics without reference to time [30]. This overturned our classical understanding of causality, in which the ordering of events and their temporal relationship is fixed. Université de Montréal Professor Hlér Kristjánsson was instrumental in conducting early experiments verifying advantages that arise when performing operations without a fixed causal order—i.e., in a "superposition of causal orderings" [31]. The extension of quantum theory to reference frames (the set of coordinates used by observers to measure quantities like position and velocity) was achieved in 2019, again in a paper by Brukner and his then-students Esteban Castro-Ruiz and Flaminia Giacomini [32]—the latter of whom went on to be a Yvonne Choquet-Bruhat fellow at PI. A collaborative effort by the groups of Brukner and Mann showed that indefinite causal ordering measurably affected processes such as entanglement harvesting [33].



Figure 3. The group picture from the RQI-North 14 Conference held at Charles University, Prague, from August 5-9, 2024. Many of the authors cited in this article can be found in the picture.

CONCLUSION

Since the inaugural RQI publications and workshops in the early 2000s, the community, which now gathers bi-annually under the auspices of the International Society for Relativistic Quantum Information (ISRQI)³, has expanded far beyond what its founders envisioned. In 2023, IQC and PI Ph.D. student Tales Rick Perche began a global initiative called the RQI Circuit, leading a movement of student-led RQI-research hubs in Canada, Europe, and Australia to live-broadcast their research on YouTube⁴. In 2024, a consortium of RQI researchers secured a multi-year international grant to facilitate collaboration and cooperation in RQI research⁵. Interest in the field has grown rapidly, especially with the increased level of dialogue between theorists and experimentalists. An example of this has been the implementation of landmark analogue gravity experiments (led by Silke Weinfurter's group at the University of Nottingham) simulating phenomena ranging from black holes to early-Universe physics [34]. The community's research focuses have also diversified, with current problems including the operational description of spacetimes in superposition [35], proposals for detecting single "quanta" of gravitational radiation [36], and experimentally probing quantum vacuum entanglement [37], to name a few. The opportunities for new researchers entering the field are boundless, and the most exciting days for the community lie ahead.

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³ More information about the International Society for Relativistic Quantum Information can be found on their webpage: <https://www.isrqi.net>

⁴ The videos recorded during the RQI Circuit can be found on the ISRQI's YouTube Channel: <https://www.youtube.com/@ISRQI-gp3ci/featured>. These videos were meant to be accessible to a wider audience and are a great way to learn more about the research being done within the RQI community.

⁵ The Relativistic Quantum Information (RQI) Action is in its infancy, with more details and opportunities to get involved listed on the Action's webpage: <https://www.cost.eu/actions/CA23115/>

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