BOOK OF ABSTRACTS

Time in Quantum Theory

September 10th–September 13th 2024, Smolenice, Slovakia
http://quantum.physics.sk/tiqt2024/

TIQT 2024

TiQT 2024 is the fourth annual edition of Time in Quantum Theory, this year held in beautiful Slovakia. The conference aims to bring together disparate communities, providing a common platform to discuss questions including:
Fundamental limitations to time keeping: how accurate can physical clocks be? This includes, but is not limited to, models for clocks, quantum information theory, and thermodynamics.

Foundational aspects of time: what can philosophy and quantum foundations say about time? How does this reflect itself in theoretical models? How can the conception of time in quantum mechanics be reconciled with that of general relativity?

How can we understand time through quantum experiments?

Venue

The workshop will be held in *Smolenice Castle* which history dates back to the 15th century and currently serves as the Congress Center of Slovak Academy of Sciences. It is situated approximately 60 km northeast from Bratislava in the central area of the smallest Slovakian mountains called Malé Karpaty.

Invited speakers

- ⋆ Natalia Ares (University of Oxford)
- ⋆ Peter Asenbaum (IQOQI Vienna)
- ⋆ Lin-Qing Chen (IQOQI Vienna)
- ⋆ Flaminia Giacomini (ETH Zurich)
- ⋆ Kyungtae Kim (University of Colorado Boulder)
- ⋆ Maximilian Lock (TU Vienna)
- ⋆ Leon Loveridge (University of South-Eastern Norway)
- ⋆ Bryan Roberts (LSE London)

Organizers

- ⋆ Natália S. Móller
- ⋆ Ricardo Rivera C.
- ⋆ Saadat S. Shariff
- ⋆ Radka Hovorkova
- ⋆ S. Arash Ghoreishi
- ⋆ M. H. Mohammady
- ⋆ Mário Ziman

Program Committee

- ⋆ Magdalena Zych
- ⋆ Natália S. Móller
- ⋆ Charles Baynham
- ⋆ Matt Farr

Steering Committee

- ⋆ Mark Mitchison
- ⋆ Paul Erker

The workshop is organized by Research Center for Quantum Information, Institute of Physics, Slovak Academy of Sciences (Bratislava).

Program

Tuesady, 10.9.2024

16:00	Arrival and registration (with refreshment)
18:00	Evening session
18:20	Peter Asenbaum (I)
19:00	End of session
19:15	Dinner

Wednesday, 11.9.2024

08:00	Breakfast
09:00	Morning session
09:00	Flaminia Giacomini (I)
09:40	Kacper Prech (C)
10:05	Marco Radaelli (C)
10:30	Coffee & Refreshment
11:10	Lin-Qing Chen (I)
11:50	Philip Caesar Flores (C)
12:15	Lunch
14:00	Kyungtae Kim(I)
14:40	Sebastian Schuster (C)
15:05	Ismael Lucas de Paiva (C)
15:30	End of session
15:30	Coffee & Refreshment
15:30	Poster session
19:15	Dinner

Thursday, 12.9.2024

08:00	Breakfast
09:00	Morning session
09:00	Bryan Roberts (I)
09:40	Anton Uranga (C)
10:05	Veronika Baumann (C)
10:30	Coffee & Refreshment
11:10	Maximilian Lock (I)
11:50	Jerzy Paczos (C)
12:15	Lunch
14:00	Conference Hike
19:15	Conference Dinner

Friday, 13.9.2024

09:00	Morning session
09:00	Natalia Ares (I)
09:40	Patrick Potts (C)
10:05	James Fullwood (C)
10:30	Coffee & Refreshment
11:10	Leon Loveridge (I)
11:50	Adrian Kent (C)
12:15	Lunch
13:30	Departure

(I) Invited talk (35 + 5 min.)
(C) Contributed talk (20 + 5 min.)

Time	Event	Speaker
	Tuesday, 10.9.2024	
16:00	Arrival and registration (with refreshment)	
18:00	Evening session	
18:00	Welcome	
18:20	Peter Asenbaum	(I)
19:00	End of session	
19:15	Dinner	
	Wednesday, 11.9.2024	
08:00	Breakfast	
09:00	Morning session	
09:00	Flaminia Giacomini	(I)
09:40	Kacper Prech	(C)
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15:30	Poster session	
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	Thursday, 12.9.2024	
08:00	Breakfast	
09:00	Morning session	
09:00	Bryan Roberts	(I)
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	Friday, 13.9.2024	
09:00	Morning session	
09:00	Natalia Ares	(I)
09:40	Patrick Potts	(C)
10:05	James Fullwood	(C)
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11:10	Leon Loveridge	(I)
11:50	Adrian Kent	(C)
12:15	Lunch	
14:00	Departure	

(I) = Invited talk (35 + 5 min.), (C) = Contributed talk (20 + 5 min.)

Invited talks

1. **Natalia Ares:** Timekeeping with Nanoscale Semiconductor Devices
2. **Peter Asenbaum:** Matter-wave experiments and gravity
3. **Lin-Qing Chen:** Probing Quantum Aspects of Gravitational Fields
4. **Flaminia Giacomini:** A theory-independent approach to determining the nature of gravity in table-top experiments
5. **Kyungtae Kim:** Strontium Optical Lattice Clock: Achieving Unprecedented Precision and Accuracy
6. **Maximilian Lock:** The Emergence of the Arrow of Time in Quantum Theory
7. **Leon Loveridge:** Unsharp time observables, and their role in type reduction in algebraic quantum field theory
8. **Bryan Roberts:** Representing the arrow of time

Contributed talks

1. **Veronika Baumann:** Relational Quantum Dynamics and causality
2. **Philip Caesar Flores:** Inherent instantaneous tunneling time in Hermitian quantum systems
3. **James Fullwood:** Quantum correlations across space and time
4. **Henrique Gomes:** The many-instants formulation of quantum mechanics
5. **Adrian Kent:** Time and distance constraints for mass and charge interferometry
6. **Ismael Lucas de Paiva:** Nonunitarity in relational dynamics
7. **Patrick Potts:** A quantum-mechanical Pendulum Clock
8. **Jerzy Paczos:** Mass-energy equivalence in atom interferometers
9. **Kacper Prech:** Optimal time estimation and the clock uncertainty relation for stochastic processes
10. **Sebastian Schuster:** Relational Quantum Dynamics for Toy Models of Time Travel
11. **Anton Uranga:** Imaginary past of a quantum particle moving on imaginary time
12. **Marco Radaelli:** Parameter estimation in the presence of temporal correlations

Posters

1. **Francesca Battistoni:** Time and Causality - From Aristotle to Rovelli
2. **Joseph Balsells:** Geometry and proper time of a relativistic quantum clock
3. **Sara Butler:** Time-Energy Uncertainty from Einstein's Box
4. **Jorge Escandón-Monardes:** Quantum switch with continuous control
5. **Moritz Epple:** Towards a Relativistic Understanding of Quantum Theory
6. **Carlos Frajuca:** Derivation of a Magnetic Clock Using Page and Wooters Approach
7. **Niyusha Hosseini:** Time of Arrival in the Page-Wooters Formalism
8. **Lorenzo Maccone:** Geometric Event-Based (GEB) relativistic quantum mechanics
9. **Maik Reddiger:** On a Probabilistic Approach to the Problem of Time: The One-Body Born Rule in Curved Spacetime
10. **Bruna Sahdo:** Gravitational quantum switch on a superposition of spherical shells
11. **Lodovico Scarpa:** Observable Thermalization in Isolated Quantum Systems
12. **Nadja Simão Magalhães** Time and spacetime at the quantum limit
13. **Michael Suleymanov:** Uncertainties and covariances in the framework of spatiotemporal quantum reference frames
14. **Patrick Wong:** Quantum Sensing from Gravity as Universal Dephasing Channel for Qubits

Invited talks

1. **Natalia Ares:** TIMEKEEPING WITH NANOSCALE SEMICONDUCTOR DEVICES
   In this talk, I will discuss how semiconductor devices can reveal the thermodynamic costs of timekeeping. Using a nanometer-thick membrane, we have developed a clock that enables us to track the thermodynamic resources required by the system. We demonstrate that the clock's accuracy is directly proportional to the entropy it generates, in agreement with theoretical predictions for both classical and quantum regimes.
   I will also introduce a clock powered by single electron tunneling, where the thermodynamic resources invested in the clock's register, implemented via an electrometer, can be precisely quantified. By adjusting the signal-to-noise ratio of the register, we observe changes in clock precision. This allows us to bound the thermodynamic cost of readout, providing insights into the minimal resources required by the quantum clock.

2. **Peter Asenbaum:** MATTER-WAVE EXPERIMENTS AND GRAVITY
   Interference phenomena of massive particles in spatially extended quantum states, such as a quantum superposition, have always been a captivating topic in quantum physics. The questions of how a particle interacts while in such a delocalized state and what quantities it can measure are still of interest, especially regarding the gravitational interaction, as gravity remains mostly unexplored at the quantum level.

   I will discuss previous experiments where laser pulses prepare single atoms in large spatial quantum superpositions. With these techniques, we were able to study the gravitational interaction in the small and large quantum state regimes. Depending on the regime, a quantum superposition measures like a classical test mass or like a clock, albeit with a lot higher sensitivity.

   What needs to be explored next? Not one but two objects in spatially extended quantum states are required to enter the regime of gravitational-mediated entanglement

3. **Lin-Qing Chen:** PROBING QUANTUM ASPECTS OF GRAVITATIONAL FIELDS
   Recent progress in table-top experiments offers the opportunity to show for the first time that gravity is not compatible with a classical description. In all current experimental proposals, such as the generation of gravitationally induced entanglement between two quantum sources of gravity, gravitational effects can be explained with the Newton potential, namely in a regime that is consistent with the weak-field limit of general relativity and does not probe the field nature of gravity. Hence, the Newtonian origin of the effects is a limitation to the conclusions on the nature of gravity that can be drawn from these experiments.

   Here, we identify two effects that overcome this limitation: they cannot be reproduced using the Newton potential and are independent of graviton emission. First, we show that the phase arising from the interaction between two generic quantum sources of gravity, e.g. in wide Gaussian states, cannot be reproduced with the Newton potential nor with any limit of (classical) general relativity. Hence, observing the form of this interaction would require either modified gravity or its quantum description. Second, we show that the quantum commutator between the gravitational field and its canonically conjugate momentum appears as an additional term in the relative phase of a generic quantum source interacting with a test particle. Observing this term in the phase would be a test of the gravitational field as a quantum mediator.

   Identifying stronger quantum aspects of gravity than those reproducible with the Newton potential is crucial to prove the nonclassicality of the gravitational field and to plan a new generation of experiments testing quantum aspects of gravity in a broader sense than what proposed so far.

4. **Flaminia Giacomini:** A THEORY-INDEPENDENT APPROACH TO DETERMINING THE NATURE OF GRAVITY IN TABLE-TOP EXPERIMENTS
   Understanding the fundamental nature of gravity at the interface with quantum theory is a major open question in theoretical physics. Recently, the study of gravitating quantum systems, for instance a massive quantum system prepared in a quantum superposition of positions and sourcing a gravitational field, has attracted a lot of attention: experiments are working towards realising such a scenario in the laboratory, and measuring the gravitational field associated to a quantum source is expected to give some information about quantum aspects of gravity. However, there are still open questions concerning the precise conclusions that these experiments could draw on the nature of gravity, such as whether experiments in this regime be able to test more than the Newtonian part of the gravitational field. In my talk, I will show that a theory-independent approach allows us to derive no-go theorems that help us constrain the possible theories compatible with a certain experimental outcome. A solid theoretical investigation of these aspects is necessary to make precise claims on the nature of the gravitational field, and to translate concepts from quantum information into a physical description embedded in spacetime.

5. **Kyungtae Kim:** STRONTIUM OPTICAL LATTICE CLOCK: ACHIEVING UNPRECEDENTED PRECISION AND ACCURACY
   Optical atomic clocks have become the most precise measurement devices, now reaching fractional uncertainties below $10^{-}18$ (1). Through differential clock comparisons, we can achieve even greater precision, enabling detection of the gravitational redshift on the length scale below 1 mm (2). This advancement is driven by understanding and control of light-matter and many-body interactions, along with the integration of cutting-edge laser technologies. In this talk, we discuss the science behind the strontium optical lattice clock, focusing on quantum state engineering, the interplay of many-body physics, and their implications for metrology.

   (1) A. Aeppli et al., Phys. Rev. Lett. 133, 023401 (2024) (2) T. Bothwell et al., Nature 602, 420 (2022)

6. **Maximilian Lock:** THE EMERGENCE OF THE ARROW OF TIME IN QUANTUM THEORY
   The second law of thermodynamics states that the entropy of an isolated system can only increase over time, thereby distinguishing the past from the future. This seems to conflict with the reversible evolution of isolated quantum systems, which preserves the von Neumann entropy. However, counterintuitively, many observables in large isolated systems do reach equilibrium, despite the unitary evolution of the system's state. We characterise the extent to which any observable exhibits this emergent arrow of time by examining the relationship between effective microstates and macrostates. By considering entropy with respect to observables, we demonstrate how a version of the second law of thermodynamics can be recovered in isolated quantum systems. We also analyse the fluctuations from equilibrium that reveal the underlying reversible dynamics, showing that these fluctuations diminish as the system size increases. These findings are supported by numerical results using the paradigmatic example of a quantum Ising model.

7. **Leon Loveridge:** UNSHARP TIME OBSERVABLES, AND THEIR ROLE IN TYPE REDUCTION IN ALGEBRAIC QUANTUM FIELD THEORY
   It has long been known that typical physical Hamiltonians rule out the existence of self-adjoint time observables. However, in many cases, time-translation covariant positive operator-valued measures do exist. In this talk, after discussing some examples of such 'unsharp' time observables, I will show that unsharpness is necessary for reducing the type III von Neumann algebra of an algebraic quantum field theory in de Sitter to a II_1, which has a finite trace and therefore computable entropies. This is based on the recent work of Fewster, Janssen, LDL, Rejzner, and Waldron, arxiv2403.11973.

8. **Bryan Roberts:** REPRESENTING THE ARROW OF TIME
   Our naïve human senses often detect phenomena that appear asymmetric in time when they are not. For example, the description of motion with friction appears temporally asymmetric, but on a more careful look typically omits degrees of freedom in a way that hides an underlying temporal symmetry. This talk will develop an account of what is required to have a true arrow of time, in the sense that 'time itself' has an asymmetry. I will argue that most of what is commonly referred to as an 'arrow of time' fails to be a time asymmetry in this sense, but that the famous arrow associated with electroweak interactions does. The talk is based on my book, Reversing the arrow of time, available Open Access through Cambridge University Press: https://doi.org/10.1017/9781009122139

Contributed talks

1. **Veronika Baumann :** Relational Quantum Dynamics and Causality

Relational quantum dynamics [1,2] aims to treat time in a way similar to the way space is usually treated in quantum theory, by associating a Hilbert space with time, which is then interpreted as a quantum clock. The dynamics of a quantum system are then obtained by considering an extended system including the clock and solving a Wheeler-DeWitt-like equation with a Hamiltonian constraint operator. This ideas have been extended to multiple clock systems [3,4] in order to describe scenarios and features central to the theory of relativity, such as time dilation and changes of reference frames. Relational quantum dynamics with multiple clock systems, however, also allows for describing uniquely quantum features associated with time, like frame dependent temporal localizability or the lack of an overall well defined temporal ordering of operations [4,5]. The latter corresponds instances of indefinite casual order [6] which, in general, is a notion difficult to reconcile with relational dynamics. The notion of causality employed for indefinite causal order relies on the notion of agency and effects of applying some quantum operation on outcomes obtained when applying another quantum operation, i.e. signaling between agents. On the one hand, the subsystem structure of a system under consideration is in general not preserved in relational quantum dynamics when conditioning on one of multiple clock systems [7]. This means that a scenario well suited for investigating signaling relations according to one clock is not suited for that purpose according to another clock. Moreover, the idea of agency requires timed applications of operations (usually according the the clock associated with said agent), which means that the Hamiltonian constraint will have to contain interaction terms between the clocks and the systems the agents act upon. In this case the evolution of the systems one aims to describe is no longer unitary and can only be solved for certain instances [8]. At this conference I would like to present a selected overview on ideas and approaches around relational dynamics with multiple clocks and the possibility of investigating causality and potentially indefinite causal order within this timeless formulation of quantum theory.

Refs: [1 | Giovannetti, V., Lloyd, S., & Maccone, L. (2015). Quantum time. Physical Review D, 92(4), 045033. [2] Höhn, P. A., Smith, A. R., & Lock, M. P. (2021). Trinity of relational quantum dynamics. Physical Review D, 104(6), 066001. [3] Smith, A. R., & Ahmadi, M. (2020). Quantum clocks observe classical and quantum time dilation. Nature communications, 11(1), 5360. [4] Castro-Ruiz, E., Giacomini, F., Belenchia, A., & Brukner, Č. (2020). Quantum clocks and the temporal localisability of events in the presence of gravitating quantum systems. Nature Communications, 11(1), 2672. [5] Baumann, V., Krumm, M., Guérin, P. A., & Brukner, Č. (2022). Noncausal page-wootters circuits. Physical Review Research, 4(1), 013180. [6] Oreshkov, O., Costa, F., & Brukner, Č. (2012). Quantum correlations with no causal order. Nature communications, 3(1), 1092. [7] Ali Ahmad, S., Galley, T. D., Höhn, P. A., Lock, M. P., & Smith, A. R. (2022). Quantum relativity of subsystems. Physical Review Letters, 128(17), 170401. [8] Smith, A. R., & Ahmadi, M. (2019). Quantizing time: interacting clocks and systems. Quantum, 3, 160.

2. **Philip Caesar Flores:** Inherent instantaneous tunneling time in Hermitian quantum systems

Tunneling is one of the most well-known quantum effects and has been a long-standing important subject of quantum mechanics. However, tunneling becomes complicated when one associates the time it takes for a particle or wavepacket to traverse the classically forbidden region under the barrier. There have been several attempts to calculate the tunneling time but there is still no consensus on whether the tunneling time is instantaneous or non-zero. Moreover, several experiments to measure the tunneling time have also been performed but with conflicting results.

One of us has previously constructed a time-of-arrival (TOA) operator by quantizing the corresponding classical TOA via the Weyl-ordering rule Phys. Rev. Lett., 108 (2012) 170402 and showed that tunneling time is instantaneous. Specifically, the tunneling time was extracted from the difference in the expectation values of the corresponding TOA-operators in the presence and absence of a square potential barrier. However, there are infinitely many possible TOA-operators corresponding to the same classical TOA due to the ambiguity in the ordering of the position and momentum operators upon quantization. This now raises the question on whether the predicted instantaneous tunneling time (ITT) is a mere consequence of the Weyl-ordering rule.

Here, we will construct all possible quantum images of the classical TOA and show that ITT still persists for all the possible TOA-operators. We then show that ITT is a physical manifestation of the completeness of the TOA-eigenfunctions which leads us to hypothesize that ITT is an inherent quantum effect in Hermitian systems.

3. **James Fullwood:** Quantum correlations across space and time

While quantum correlations between two spacelike separated systems are fully encoded by the bipartite density operator associated with the joint system, in our recent work with Arthur Parzygnat we prove that there does not exist an operator representation for general quantum correlations between timelike separated quantum systems. Such a result provides a precise way in which quantum theory distinguishes between space and time, and is in stark contrast to the case of classical random variables, which make no distinction between spacelike and timelike correlations. Despite this, we show that in the restricted setting of spatiotemporal correlations between light-touch observables (i.e., observables with only one singular value), one may treat spacelike and timelike correlations in a unified way, as we show that in such a case there exists a unique operator representation of such spatiotemporal correlations for arbitrary timelike separated quantum systems.

4. **Henrique Gomes:** The many-instants formulation of quantum mechanics

In the Hamiltonian formulation of general relativity, full relativistic covariance implies that the dynamics is "fully constrained": the Hamiltonian is itself a combination of constraints. Dynamical evolution, in this picture, does not correspond to evolution under some preferred, external time parameter: the quantum wavefunction satisfies a time-independent equation, the Wheeler-DeWitt (WdW) equation. So, it behooves us to develop interpretations of quantum mechanics that take the absence of an external notion of time seriously.

Such an interpretation may have unforeseen benefits: at the heart of quantum theory is a conflict between unitary evolution and non-unitary evolution ('collapse') of the wave function. The Many-Worlds Interpretation (MWI) resolves this conflict by denying collapse. A timeless approach would, in effect, do the opposite: deny any time evolution.

In the approach to be introduced in this talk, called the many instants interpretation (MII) there is just a (relative) measure on configuration space without any external time under which this measure evolves. Here configuration space is the space of possible instantaneous states of the universe according to modern physics—spatial configurations of fields, including the metric and the fields of the standard model. This is the configuration space for the Hartle-Hawking wavefunction of the universe: a wavefunction that takes a complex value for each configuration and satisfies several constraints, including the WdW equation, which is, in the sense explained above, timeless. And one example of the timeless (relative) measure on configuration space is obtained by using the absolute value of the Hartle-Hawking wavefunction squared (i.e. by an application of the Born rule).

The MII has many similarities to the more developed interpretations. Like de Broglie-Bohm (dBB), the MII has a preferred (configuration space) basis; unlike dBB, MII doesn't endow special ontological status to any trajectory through configuration space; and it doesn't admit 'action-at-a-distance'. Like wavefunction realism, MII assigns values of the wavefunction solely to points of configuration space; unlike wavefunction realism, MII doesn't take these points to be featureless—they are fully-fledged instantaneous states of affairs. However, the MII has the most similarities to the MWI.

As in the MWI, in the MII, branches and branching events remain approximate notions. Analogously to the MWI, in the MII, each instantaneous configuration exists. Unlike the MWI, we do not need a branching structure to define an effective notion of probability: the relative probability between two subsets of configuration space can be defined by their relative measure, and it makes sense even for subsets of configurations taken to be in a coherent superposition. For better or worse, definite outcomes and probabilities come in at the ground level of the MII.

Though this interpretation is beset by challenges, these are of a completely different nature than those that beset other interpretations.

5. **Adrian Kent:** Time and distance constraints for mass and charge interferometry

We reanalyse and extend constraints on mass and charge interferometry identified by Mari et al. (2016). We show that their constraint on the time required for coherent interference can be extended by a factor of two. We extend their analysis to consider experiments in which one interferometer measures gravitational or electric fields generated by another. We note that these analyses imply a maximum separation between a mass or charge interferometer and a decohering gravitational or electric field measurement that can be carried out without backreaction. We discuss the implications for testing the quantum nature of gravity. We also discuss extensions of the analyses to a full QED/perturbative quantum gravity treatment and their foundational implications.

6. **Ismael Lucas de Paiva:** Nonunitarity in relational dynamics

Just like any physical measurement, the passage of time is always observed relative to a reference system—a reference clock in this case. Recognizing this, along with the fact that all systems, including clocks, are ultimately quantum, we are led to relational dynamics approaches in quantum theory, such as the Page and

Wootters framework. In these approaches, it is known that standard dynamics is recovered when there is no interaction between the system of interest and the clock. However, if they interact, the ensuing dynamics generally becomes time-nonlocal and may even be nonunitary. In this talk, we discuss how these features can be understood as a consequence of choosing an inappropriate clock observable. We then address whether it is always possible to define a clock observable that ensures the recovery of unitarity. Finally, we present the implications of our findings for relational approaches in quantum theory.

7. **Patrick Potts:** A QUANTUM-MECHANICAL PENDULUM CLOCK

Pendulum clocks are the quintessential time-keeping devices. I will present a model of an autonomous mechanical pendulum clock based on an optomechanical system. The pendulum clock is powered by light and its operation relies only on thermal resources. The ticks of the clocks are obtained by detecting photons emitted from the clock. Combining semi-classical analysis and conditional stochastic master equations, we describe the clock across the quantum-to-classical transition and illustrate how quantum fluctuations limit our capability of keeping time.

8. **Jerzy Paczos:** MASS-ENERGY EQUIVALENCE IN ATOM INTERFEROMETERS

State-of-the-art atom interferometers make use of optical lattices to maintain atoms in a coherent superposition of heights in a gravitational field for tens of seconds. This allows for very precise measurements of the gravitational field, but also opens up new possibilities for testing the interplay between quantum and gravity. We propose a simple modification of the state-of-the-art atom interferometers, which would set up a clock in a superposition of heights. Such a clock would read a superposition of proper times, which, as predicted in the past [Zych et. al. Nature Comm. 2, 505 (2011)], would manifest itself in the oscillations of the interferometric visibility. We analyze the phases of individual trajectories within the interferometer and conclude that, apart from the visibility oscillations, there would be an additional effect in the form of a frequency shift. We discuss the measurability of both effects with current technology and find that the frequency shift effect would be within the current measurement precision.

9. **Kacper Prech:** OPTIMAL TIME ESTIMATION AND THE CLOCK UNCERTAINTY RELATION FOR STOCHASTIC PROCESSES

Time estimation is a fundamental task that underpins precision measurement, global navigation systems, financial markets, and the organisation of everyday life. Many biological processes also depend on time estimation by nanoscale clocks, whose performance can be significantly impacted by random fluctuations. In this work, we formulate the problem of optimal time estimation for Markovian stochastic processes, and present its general solution in the asymptotic (long-time) limit. Specifically, we obtain a tight upper bound on the precision of any time estimate constructed from sustained observations of a classical, Markovian jump process. This bound is controlled by the mean waiting time between jumps: in simple terms, the more frequently a system transitions between its underlying states, the more precisely it can function as a clock. As a consequence, we obtain a universal bound on the signal-to-noise ratio of arbitrary currents and counting observables in the steady state. This bound is similar in spirit to the kinetic uncertainty relation but provably tighter and we explicitly construct the counting observables that saturate it. Our results establish ultimate precision limits for an important class of observables in non-equilibrium systems, and demonstrate that the mean waiting time, not the dynamical activity, is the measure of freneticity that tightly constrains fluctuations far from equilibrium. While our results concern classical stochastic systems and clocks, we hope they will stimulate future research on their extension to the quantum regime.

10. **Sebastian Schuster:** RELATIONAL QUANTUM DYNAMICS FOR TOY MODELS OF TIME TRAVEL

The "problem of time" that approaches to quantum gravity have to either tackle or circumvent should, naturally, also occur in models of time travel trying to move beyond (semi-)classical gravity. From a viewpoint of canonical gravity a first hurdle to time travel is that the underlying quantization procedure relies on global hyperbolicity of the space-time to be quantized. As with any new theory, it is to be expected that expectations of earlier theories (like in this case, global hyperbolicity) would have to be tempered, changed, or let go in the successor theory. Recent advances in the understanding of relational dynamics in quantum theory have greatly propelled the field of time in quantum theories forward. In this talk we will present our recent efforts to combine such relational quantum dynamics and periodic clocks in the service of toy models for time travel. The goal will be to build a collection of toy models of varying degrees of complexity that should provide a view of quantum gravity beyond global hyperbolic space-times, and thus potentially new arguments against time travel.

11. **Anton Uranga:** IMAGINARY PAST OF A QUANTUM PARTICLE MOVING ON IMAGINARY TIME

The analytical continuation of classical equations of motion to complex times suggests that a tunnelling particle spends in the barrier an imaginary duration $i|\mathcal{T}|$. Does this mean that it takes a finite time to tunnel, or should tunnelling be seen as an instantaneous process? It is well known that examination of the adiabatic limit in a small additional AC field points towards $|\mathcal{T}|$ being the time it takes to traverse the barrier. However, this is only half the story. We probe the transmitted particle's history, and find that it remembers very little of the field's past behaviour, as if the transit time were close to zero. The ensuing contradiction suggests that the question is ill-posed, and we explain why.

12. **Marco Radaelli:** PARAMETER ESTIMATION IN THE PRESENCE OF TEMPORAL CORRELATIONS

Temporal correlations are omnipresent in the physical world: generically, physical systems evolving in time contain a memory of their past past behaviour, due to environmental interactions. How does such memory influence what we can learn about a system by observing it? This talk addresses this question through the lens of parameter estimation. The first result is a general derivation of the Fisher information rate for temporally correlated stochastic processes. Here, the Fisher information rat quantifies the precision gain when estimating a quantity of interest. Memory may enhance or diminish what precision is ultimately possible. The next part of the talk is focussed on what can be learned from the emissions of an open quantum system – i.e., from an observed quantum-jump trajectory of a quantum system. This picture corresponds to a single-shot scenario, where information is continuously gathered. Here, it is generally difficult to assess the precision of the estimation procedure via the Fisher Information due to intricate temporal correlations and memory effects. I will describe a full set of solutions to this problem. First, for multi-channel renewal processes the Fisher Information can be related to an underlying Markov chain, yielding an a easily computable expression. For non-renewal processes, the picture becomes more intricate and requires a numerical approach offered by a new algorithm tailored specifically to this case of parameter estimation from open quantum system jump statistics. Lastly, it is interesting to consider the case where some information is lost in data compression/post-selection, and I will describe tools for computing the Fisher Information in this case. All scenarios are illustrated with instructive examples from quantum optics and condensed matter. Overall, this talk contributes to a broader understanding of what can be learned about a quantum system evolving in time and how temporal correlations constrain or enhance the ultimate precision of such learning.

Posters

1. **Francesca Battistoni:** TIME AND CAUSALITY - FROM ARISTOTLE TO ROVELLI

   What is time? Does it exist or does it depend only on our mind? What is the relation between time and change? Time can be a cause? Does the time's arrow exist? And the free will? These questions that Aristotle asked in the 4th century BC are the same that philosophers and scientists still ask today. The debate on time is central to contemporary physics and the treatment that Aristotle makes of it is now more relevant than ever. The purpose of my work is to analyze the Aristotelian definition of time, deepening its problematic aspects focusing in particular on the relation between time and cause, to arrive, thanks to an excursus which from Ancient times going through the different philosophical and scientific visions and the different ontologies of time comes up to today, to put it in relation with the recent time theory of quantum gravity by Carlo Rovelli. What emerges is a new vision of time, not any more linked to a directionality, to an absolute objectivity but increasingly linked to a subject, to an agent. Time is relation. Time, like causality, exists in a dimension that is the human one, the one of our perception and knowledge. The ontological problem leaves room for the gnoseological one. Thanks to the analysis of the concept of time we can discover how much even in Aristotle there is space for a knowledge that starts from the particular, that is no universal and nor necessary but related precisely to things that are affected by time. Looking for the meaning of time we come to know, as in a mirror, ourselves, how we relate and get to know the world. We are the time.

2. **Joseph Balsells:** GEOMETRY AND PROPER TIME OF A RELATIVISTIC QUANTUM CLOCK

   It is well known that classical clocks measure proper time along their worldline. (pseudo)-Riemannian geometry provides unambiguous tools for predicting the time shown by clocks in both flat and curved spacetimes. Common approaches to time in quantum systems, such as the Page-Wootters formalism, tend to obscure this geometric property at the quantum level. We demonstrate a framework for perturbing the classical path-length functional to include quantum degrees of freedom within a modified (pseudo)-Riemannian geometry. In our framework, a quantum clock travels on geodesics of a family of spacetimes deformed by parameters specifying the clock's quantum state. We obtain potentially testable corrections to gravitational time-dilation in Schwarzschild spacetime that scale with the ratio of the clock's Compton wavelength to its wave packet's spatial extent.

3. **Sara Butler:** TIME-ENERGY UNCERTAINTY FROM EINSTEIN'S BOX

   Early 20th century literature showcases the time-energy uncertainty relation (UR) as simply a vague re-expression of the momentum-position UR. Only at the sixth Solvay conference in 1930 was it directly addressed by Einstein, who proposed a gedanken experiment consisting of a box filled with radiation, a clock which controls the opening of a shutter for a time T, and the escape of a photon whose energy Einstein proposed could be measured to an arbitrary precision by weighing the box before and after the opening of the shutter. Therefore, because the energy emitted can be determined with ΔE (as precise as one wants), the product of ΔE and ΔT can be rendered less than what is implied by the UR. Bohr's response, once seen as a triumphant defense of the time-energy UR, is flawed, as, among other pointed issues, his interpretation of T changes throughout his argument.1,2 Thus, while Bohr's analysis of the UR is still widely accepted, it fails to be consistent. We thus revisit this specific case of the photon box and aim to verify whether Bohr's conclusions hold. Our results will shed the light on the proper time-energy uncertainty in a well defined formal context, and in particular, may answer the question whether there is indeed a relation between the validity of time-energy and momentum-position URs.

   This poster is based on work in progress. [1] Shi, Y. (2000). "Early Gedanken Experiments of Quantum Mechanics Revisited." arXiv preprint quant-ph/9811050v4. [2] Kiefer, C. (1994). Quantum Gravity. Oxford: Clarendon Press.

4. **Jorge Escandón-Monardes:** QUANTUM SWITCH WITH CONTINUOUS CONTROL

   Quantum mechanics allows for the application of two quantum operations in a superposition of orders, coherently controlled by an ancillary system. This transformation, known as the "quantum switch", is an example of a causally nonseparable process. The quantum switch has been proposed also as a way to study the interface between quantum mechanics and gravity. For example, an indefinite causal structure could arise from the superposition of two different geometries associated to a massive body prepared in a superposition of two distinct states. However, the state of a physical system is usually described by a wave function whose domain is continuous. Hence, the following questions arise: 1) is it possible to extend the definition of the quantum switch to a scenario with a continuous control? If so, 2) is this "continuous-control quantum switch" a causally nonseparable process?, and 3) does it provide any computational advantage over causally ordered processes as the finite-control quantum switch does? In this work we propose a definition of a continuous-control quantum switch, which is built on a periodic hamiltonian. We also discuss some possible simulations of this process. Although we do not apply our definition to a gravitational scenario, our proposal could inspire new research on the superposition of causal structures.

5. **Moritz Epple:** TOWARDS A RELATIVISTIC UNDERSTANDING OF QUANTUM THEORY

   The problem of time in quantum mechanics is one of the major challenges in the foundations of physics. The lack of a uniquely defined time of arrival (TOA) probability, the violations of relativistic causality that arise in the definition of localization observables in relativistic quantum mechanics (RQM) and quantum field theory (QFT) and the more general tensions between quantum mechanical nonlocality and relativity theory are all connected to the problem of time in quantum mechanics and more specifically to the lack of a self-adjoint time operator. In my talk I want to present an interpretation of quantum mechanics that is based on an event-ontology and a branching theory of time according to which only events in the causal past of an observer are fixed and immutable (relative to that observer), whereas the events in the causal future and elsewhere are genuinely open (relative to that observer). Physical systems are defined as causal chains of events. Given the complementary structure of quantum observables, the ensuing interpretation is a hidden-variable theory that violates statistical independence and therefore implies the future-input dependence of quantum observables. This future-input dependence allows us to reconcile Bell-type correlations with relativistic causality in an arguably local way. Even though our interpretation does not offer a direct solution to the above mentioned problems with TOA-probabilities and particle localization, it does provide a general strategy to approach these issues.

6. **Carlos Frajuca:** DERIVATION OF A MAGNETIC CLOCK USING PAGE AND WOOTERS APPROACH

   In Quantum Mechanics time is an external parameter, not related with any observable of the system; referred to as "the problem of time" decreasing the capacity of Quantum Mechanics to describe some characteristics of the physical world. One promising proposal for resolving such a problem is treating time as a quantum observable that emerged from quantum interactions, this was some decades ago by Page and Wootters, and received the name of "Page and Wootters (PaW) mechanism". The author presents an implementation of such a procedure for defining time, making a description of an evolving system and its clock as entangled non-interacting systems, using Page and Wootters approach applied in a harmonic oscillator. The author studies how quantum dynamics transforms itself into a classical behavior. The description of this emerging behavior goes in the direction of the classical notion of time. Then it is possible to analyze the relations that characterize the system that appear between quantities and characteristics that characterize the clock.

7. **Niyusha Hosseini:** TIME OF ARRIVAL IN THE PAGE-WOOTERS FORMALISM

   The concept of time in quantum mechanics presents unique challenges, as time is not an observable in the conventional sense. This work explores the construction of a time of arrival operator within the framework of the Page-Wooters formalism, which treats time as an additional degree of freedom in a larger Hilbert space. By conditioning on a clock subsystem, we derive a time of arrival operator and investigate the resulting time of arrival probability distribution. We examine the necessary structure for the conditional Hilbert space and discuss the limitations of using single factor observables in deriving accurate probability distributions. Through comparative analysis with similar approaches, we evaluate the validity and applicability of the derived distribution. This study provides insights into the boundaries and potential applications of the Page-Wooters formalism in quantum mechanics, offering a deeper understanding of the nature of time and its measurement at the quantum level.

8. **Lorenzo Maccone:** GEOMETRIC EVENT-BASED (GEB) RELATIVISTIC QUANTUM MECHANICS

   We propose a special relativistic framework for quantum mechanics. It is based on introducing a Hilbert space for events. Events are taken as primitive notions (as customary in relativity), whereas quantum systems (e.g. fields and particles) are emergent in the form of joint probability amplitudes for position and time of events. Textbook relativistic quantum mechanics and quantum field theory can be recovered by dividing the event Hilbert spaces into space and time (a foliation) and then conditioning the event states onto the time part. Our theory satisfies the full Poincare' symmetry as a 'geometric' unitary transformation, and possesses observables for space (location of an event) and time (position in time of an event).

9. **Maik Reddiger:** ON A PROBABILISTIC APPROACH TO THE PROBLEM OF TIME: THE ONE-BODY BORN RULE IN CURVED SPACETIME

In this talk, I present a novel, probabilistic approach to the foundations of relativistic quantum theory. It is based on generalizing the quantum-mechanical Born rule for determining particle position probabilities to curved spacetime. As such it naturally translates the quantum mechanical conception of time to the general-relativistic setting. A principal motivator for this research has been to overcome mathematical and conceptual problems internal to quantum field theory (QFT). The approach presented can accommodate a wide array of dynamical models, does not rely on the symmetries of Minkowski spacetime, and respects the general principle of relativity.

As a first step, we considered the one-body case under the assumption of smoothness of the mathematical quantities involved. This is what I focus on in the presentation. The one-body case may be identified as a special case of the theory of the general-relativistic continuity equation. As in the non-relativistic analog theory, there are two distinct formulations of the theory, namely the Lagrangian and the Eulerian pictures. The main contribution of this work towards a resolution of the problem of time is the development of the Lagrangian picture in this general-relativistic setting. The Langrangian picture serves as a blueprint for the generalization to the many-body case and the most general case, for which the number of bodies itself is a random variable.

10. **Bruna Sahdo:** GRAVITATIONAL QUANTUM SWITCH ON A SUPERPOSITION OF SPHERICAL SHELLS

Since the beginning of its study, indefinite causality has been pointed out as an expected feature in quantum gravity. The quantum information tools used to model it, like process matrices, are seen as potentially important to understand quantum spacetime and its consequences. However, only a few works have really aimed at using these mathematical constructions to represent causal structures of quantum spacetime regions. In this work, we propose a thought experiment in a quantum gravity scenario that corresponds to a process in an operationally meaningful way: a gravitational quantum switch (GQS). In a quantum switch (QS), two agents named Alice and Bob apply local operations A and B on a system. The final state of the system derived from the switch process indicates that the order in which the operations are applied, A before B or B before A, is indefinite and can actually be interpreted as entangled with a control q-bit initially in a superposition. In a gravitational switch, spacetime itself acts as the control q-bit. Differently from other works, the spacetime we propose is composed of two massive spherical shells in a quantum superposition state of different radii. This type of spacetime is interesting because it behaves classically outside of the region where the shells are, allowing us to better account for the description by external observers and apply the hypotheses of the process formalism. The setup has unique characteristics that produce indefinite order between the two events no matter which local operations agents Alice and Bob choose to apply at them, in contrast with other proposals of QS and GQS. The universality for operations suggests that this case arises fundamentally as consequence of the spacetime quantum causal structure and that there is no straightforward way to simulate its operational properties in a non-quantum gravity scenario.

11. **Lodovico Scarpa:** OBSERVABLE THERMALIZATION IN ISOLATED QUANTUM SYSTEMS

I will present my research on the thermalization of observables in isolated quantum systems. Progress in this field is essential to understanding the emergence of irreversibility from the underlying unitary dynamics, as well as to determine the applicability and limitations of thermodynamics and statistical mechanics. Together with my collaborators, I have been developing a new approach called "Observable Thermalization", which is based on a maximum entropy principle. This framework has already led to genuinely novel predictions, including in Many-Body Localized systems. Moreover, we have been able to use it to determine the equilibrium value (diagonal ensemble) of observables without the need to know the energy eigenstates. We found strong numerical support for the framework's predictions for one-body and two-body observables in 7 different spin-1/2 XYZ-type 1D Hamiltonians (covering integrable to quantum chaotic) for 5 different initial states and with system sizes up to L=20. In particular, we are able to predict the equilibrium value of the whole eigenvalue probability distribution of one and two-body observables with a remarkable degree of accuracy. For one-body observables, the distance between the exact and predicted distributions is always less than 10^{-9}, while for two-body observables it is less than $10^{-3} in 90\%$ of cases. Our results mark significant progress towards a fully predictive theory of thermalization in isolated quantum systems and open interesting questions about observable-specific thermodynamic quantities.

12. **Nadja Simão Magalhães:** TIME AND SPACETIME AT THE QUANTUM LIMIT

From a macroscopic viewpoint time is a variable that allows the description of motion. In classical applications Newton's understanding of time is normally sufficient. In modern Physics the following phenomena make Newton's classical approach break down: motions at speeds close to the speed of light and interactions at the subatomic level. Both led to important mainstream theories, respectively: Einstein's theory of relativity and quantum mechanics. In Einstein's relativity a new approach to time was taken as the result of a limiting speed being assumed for free, massless objects in vacuum. The spacetime concept emerged associated to the gravitational field. Both Newton and Einstein did not discuss what time is. In previous works (e.g. [1]) I supported the view that time is an operational variable that quantifies the relevant physical property, namely motion. On the other hand, in quantum mechanics the use of time as an operator has been a historical struggle. Recently a proposal was presented to implement a procedure for defining time [2]. With this presentation I expect to foster a discussion on the nature of time and its role in the above theories, perhaps contributing to compatibilize quantum mechanics and general relativity.

[1] Magalhaes, N. S. "Motion, time and gravity". In "Spacetime Physics 1907 – 2017", eds. C. Duston and M. Holman. Minkowski Inst. Press, 2019.

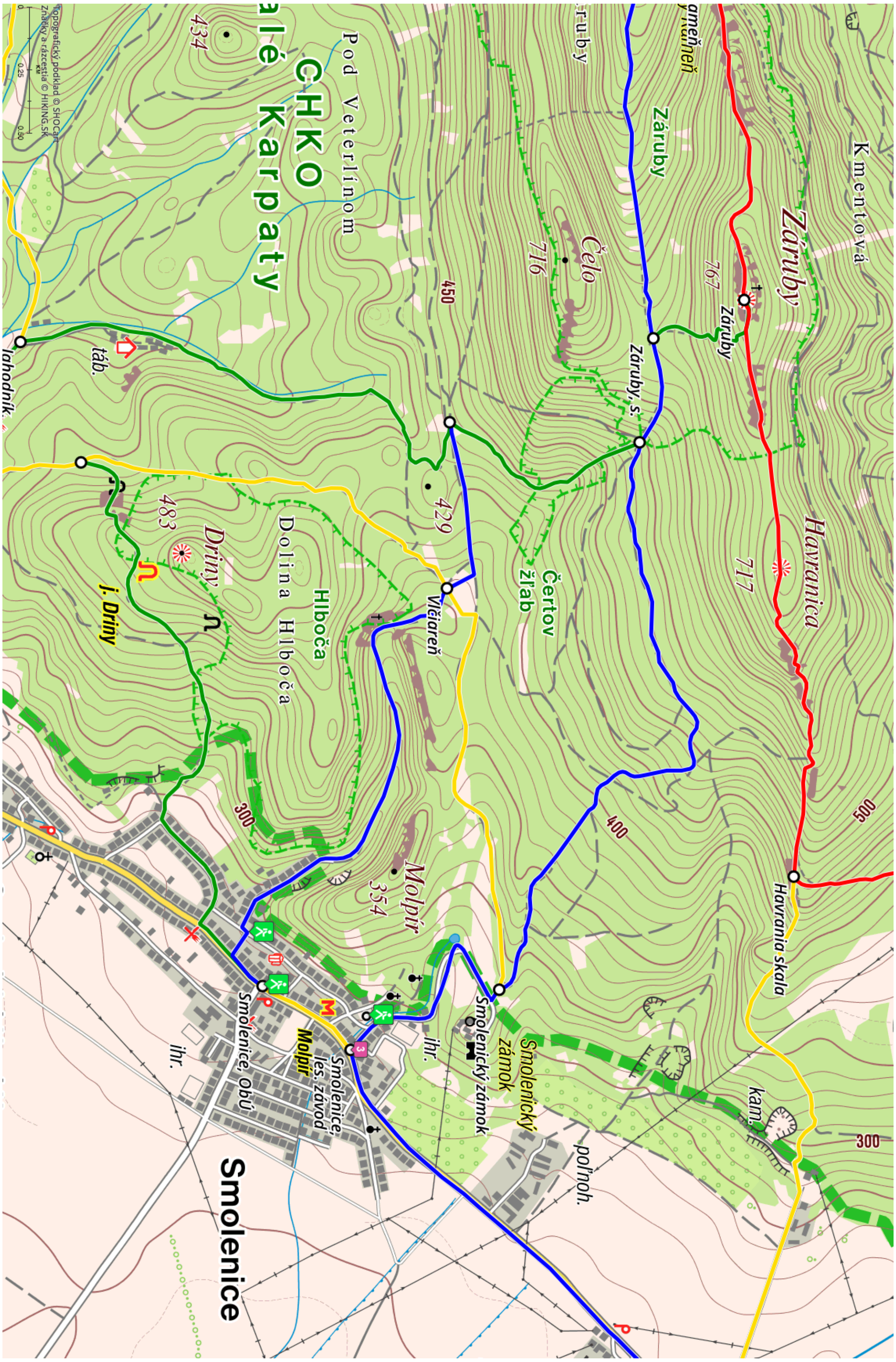
[2] Coppo, A.; Cuccoli, A.; Verrucchi, P. "Magnetic clock for a harmonic oscillator". Phys. Rev. A 109 (2024) 052212.

13. **Michael Suleymanov:** UNCERTAINTIES AND COVARIANCES IN THE FRAMEWORK OF SPATIOTEMPORAL QUANTUM REFERENCE FRAMES

The perspective-dependence of position and momentum uncertainties, as well as their correlations, is studied in the framework of nonrelativistic spatiotemporal quantum frames of reference [M. Suleymanov, I.L. Paiva, E. Cohen, Nonrelativistic spatiotemporal quantum reference frames, Phys. Rev. A 109, 032205 (2024)]. One of the results [M. Suleymanov, A. Carmi, E. Cohen, Uncertainties and covariances in the framework of spatiotemporal quantum reference frames, forthcoming] is that, even in the non-interacting case, the various correlations between observables are time-dependent, as opposed to the standard quantum mechanical case, due to the translation invariance constraint of the total system at the frame-neutral level. It also turns out that, when switching reference frames, the Heisenberg uncertainty relations of a certain particle described by different observers do not coincide in general. What is invariant for all observers, in the current framework, is the determinant of the frame-dependent covariance matrix [A. Carmi, E. Cohen, Relativistic independence bounds nonlocality, Sci. Adv. 5, eaav8370 (2019)]. A generalized version of uncertainty relations is obtained for the relational description that is affected by the correlations between all observables in a chosen frame.

14. **Patrick Wong:** QUANTUM SENSING FROM GRAVITY AS UNIVERSAL DEPHASING CHANNEL FOR QUBITS

We investigate the interaction of a transmon qubit with a classical gravitational field. Exploiting the generic phenomena of the gravitational redshift and Aharonov-Bohm phase, we show that entangled quantum states dephase with a universal rate. The gravitational phase shift is expressed in terms of a quantum computing noise channel. We give a measurement protocol based on a modified phase estimation algorithm which is linear in the phase drift, which is optimal for measuring the small phase that is acquired from the gravitation channel. Additionally, we propose qubit-based platforms as quantum sensors for precision gravitometers and mechanical strain gauges as an example of this phenomenon's utility. We estimate a sensitivity for measuring the local gravitational acceleration to be $\delta g/g$ 10^{-7}. This paper demonstrates that classical gravitation has a non-trivial influence on quantum computing hardware, and provides an illustration of how quantum computing hardware may be utilized for purposes other than computation. While we focus on superconducting qubits, we point the universal nature of gravitational phase effects for all quantum platforms.



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