Time in Quantum Theory 2025

June 17th to 20th – Genoa, Italy

Abstracts

Talks

Mohammed Alkhateeb - University of Namur

Relativistic Quantum Field Theory Approach to Wavepacket Tunneling

Tunneling is one of the most intriguing quantum phenomena, underlying many important processes in nearly every area concerned by quantum physics. Recent literature, including theoretical works studying the tunneling of wave packets whose dynamics is governed by relativistic wave equations, and reports on experimental works using attoclocks, suggests that tunneling may exhibit superluminal effects. When considering the tunneling of relativistic wave packets, it is essential to account for the nonlinear effect of the creation of particle-antiparticle pairs due to vacuum excitation by the strong electromagnetic background an effect expected to be observed in the upcoming intense laser experiments. Accounting for pair creation necessitates a quantum field theoretical approach. We demonstrate using computational quantum field theory (CQFT) that microcausality ensures fully subluminal propagation, precluding any superluminal or instantaneous propagation behaviors. We illustrate this result by propagating strictly localized Dirac wave packets that tunnel through potential barriers and show that they always remain inside the light cone.

Alessio Avella - Istituto Nazionale di Ricerca Metrologica, Italy

Pseudo-Density Operator: from chronology violation to quantum dynamics via time domain teleportation

Recently, a novel quantum mechanical tool dubbed pseudo-density operator (PDO) has been introduced [1], allowing to treat spatial and temporal quantum correlations on an equal footing. Here we illustrate some results obtained by

applying PDOs to two different frameworks. First, we consider an entangled pair in which one of the qubits enters an open time-like curve (OTC). We show that, by exploiting PDOs, the causality issues can be solved without asking for a non-linear dynamics, usually required to avoid entanglement monogamy violation (EMV). By exploiting entangled photons, we simulate an OTC and provide quantum tomographic reconstruction of its PDO, showing how EMV would occur when describing such a scenario with traditional density operators [2]. The same approach is applied to chronology violation involving entangled particles falling into evaporating black holes [3]. Second, we illustrate how PDOs allow expressing quantum dynamical evolution as a sequence of teleportations in the temporal domain. This stems from the strict correspondence between spatial and temporal entanglement in quantum theory, here demonstrated by a multipartite violation of generalised temporal and spatial inequalities achieved with photonic qubits [4].

[1] J. F. Fitzsimons, et. al., Sci. Rep. 5, 18281 (2015).

[2] C. Marletto, et. al., Nat. Commun. 10, 182 (2019).

[3] C. Marletto, et al., Entropy 22, 228 (2020).

[4] C. Marletto, et al., Sci. Adv. 7, eabe4742 (2021).

Konstantin Beyer - Stevens Institute of Technology, Hoboken

A one-sided witness for quantum gravity

The non-unitary time evolution of a quantum system can be seen as arising from tracing out inaccessible environmental degrees of freedom of a larger system. The local dynamics are particularly intriguing when the environment exhibits memory effects. Such non-Markovian quantum dynamics can originate from both classical and quantum memory effects in the environment. However, recent findings show that dynamics driven by genuine quantum memory effects show unique signatures impossible with a purely classical memory [1]. Thus, measurements of local properties of an open system can probe and reveal the quantum nature of an otherwise inaccessible environment.

[1] C. Backer, K. Beyer, W. T. Strunz, Phys. Rev. Lett. 132, 060402 (2024)

[2] K. Beyer, M. S. Kim, I. Pikovski, in preparation

Alessandro Bisio - University of Pavia

Higher order maps in general physical theories

Sequential and concurrent models of classical and quantum computing, e.g. Turing machines and circuits, describe state changes over time. However, models like Lambda calculus use higher-order operations on functions and are not given in terms of a sequence of state transformations. Physically, this corresponds to transforming transformations, leading to Higher Order Quantum Theory. Here, channels become inputs, enabling second-order gates that map channels to channels. This extends recursively to a hierarchy of higher-order maps. We fully characterize "admissible" higher-order maps those consistent with quantum theory. Some maps fit a causal order and can be realized as quantum circuits with open slots. Others, like the quantum switch, exhibit indefinite causal order. We prove a result linking a maps functional description to its causal structure via no-signaling relations, based on the compositional structure of higher-order maps. Our approach extends beyond quantum theory. We developed a higher-order framework for quantum theory with indefinite input-output direction and classified its admissible higher-order maps. We also generalized our formalism to operational probabilistic theories by introducing contraction of systems, enhancing system connectivity and enabling the definition of higher-order maps. This contraction aligns with the existence of a Choi isomorphism, showing that a theory higher-order functionality stems from its native compositional structure.

Massimo Blasone - University of Salerno

Time-energy uncertainty relations for neutrino oscillations in quantum field theory

In the context of quantum field theory, I discuss flavor-energy uncertainty relations for neutrino oscillations. By identifying the nonconserved flavor charges with the "clock observables", one obtains the Mandelstam-Tamm version of time-energy uncertainty relations. In the ultrarelativistic limit, these relations yield the well-known condition for neutrino oscillations. The analogy among flavor states and unstable particles and a novel interpretation of our uncertainty relations, based on the unitary inequivalence of Fock spaces for flavor and massive neutrinos, are also discussed. Extension of these results to generic stationary curved spacetime is also presented. Finally, I discuss Leggett-Garg inequalities for neutrino oscillations in the quantum field theoretical setting.

Dario Cafasso - University of Naples Federico II

Gravitational time dilation from quantum interactions

Given a bipartite quantum system in an energy eigenstate, the dynamical description for one component can be derived via entanglement using the other component as a clock. This is the essence of the Page and Wootters mechanism. Moreover, if the clock is subject to a gravitational-like interaction, relative time evolution is then described by a time-dilated Schrodinger equation, in which the so-called redshift operator describes a purely quantum effect, analog to gravitational time-dilation. Here we adopt a nonperturbative approach and present a finite-dimensional generalization of this mechanism, expressing the quantum time-dilation effect as an effective interaction involving previously noninteracting system components. We name this a time-dilation induced interaction transfer (TiDIT) mechanism and discuss an example using two coupled spins as a quantum clock model. Our approach is suitable for implementations in current quantum technology and provides a new tool for exploring gravity at the intersection with quantum physics.

Esteban Castro, IQOQI Vienna

Measurement events relative to temporal quantum reference frames

The Page-Wootters formalism is a proposal for reconciling the background-dependent, quantum-mechanical notion of time with the background independence of general relativity. However, there has been much discussion regarding the physical meaning of the framework. In this work, we compare two consistent approaches to the Page-Wootters formalism to clarify the operational meaning of evolution and measurements with respect to a quantum temporal reference frame. The so-called "twirled observable" approach implements measurements as operators that are invariant with respect to the Hamiltonian constraint. The "purified measurement" approach instead models measurements dynamically by modifying the constraint itself. While both approaches agree in the limit of ideal clocks, a natural generalization of the purified measurement approach to the case of non-ideal, finite-resource clocks yields a radically different picture. We discuss the physical origin of this discrepancy and argue that they describe operationally distinct situations. Moreover, we show that, for non-ideal clocks, the purified measurement approach yields time non-local, non-unitary evolution and implies a fundamental limitation to the operational definition of the temporal order of events. Nevertheless, unitarity and definite temporal order can be restored if we assume that time is discrete.

Giovanni Chesi - University of Pavia

Time-frequency quantum key distribution with basis-dependent detection probability

Quantum Key Distribution (QKD) is a promising technology for secure communication. However, in certain contexts, there are still potential gaps between theoretical models and actual QKD implementations. A common assumption in security proofs is that the detection probability at the receiver, for a given input state, is independent of the measurement basis, which might not always be verified and could lead to security loopholes. This is the case of a mode-dependent detection efficiency mismatch, which could originate from an asymmetric coupling of the two measurement bases to the incoming mode. A notable example is the one of tailored light pulses prepared by the adversary to control which basis clicks in time-frequency QKD setups. We present a security proof for QKD protocols that does not rely on the above assumption and is thus applicable in scenarios with detection probability mismatches, even when induced by the adversary. Interestingly, our proof can extract positive key rates for setups vulnerable to large detection probability mismatches.

Alessandro Coppo - Istituto dei Sistemi Complessi & Università "La Sapienza" Roma

Black Holes as Quantum Clocks

Can black holes serve as fundamental timekeepers in the universe? In this talk, we explore the idea that black holes could be concretely identified with specific quantum systems exploiting entanglement to function as clocks for nearby test particles. We employ the Page and Wootters mechanism, combined with generalized coherent states, to realize the quantum-to-classical crossover of a bipartite quantum system in the large-N limit, showing that it can faithfully reproduce the classical dynamics of a test particle in the proximity of a Schwarzschild black hole. We then use the model to explore the quantum nature of black holes and their thermodynamics.

Nahuel Diaz - Los Alamos National Laboratory

From Quantum time to Quantum fields in spacetime: The Quantum Action approach

The problem of incorporating time within a fully quantum framework has recently attracted wide interest. However, the connection between "quantum time" formalisms and the well-established field of Quantum Field Theory (QFT) remains largely unexplored. In this presentation we review our recent progress in bridging the concept of quantum time with more traditional relativistic approaches to quantum mechanics (QM), and, in particular, with the Feynman space-time approaches based on Path Integrals (PI). After a brief introduction of the Page and Wootters (PaW) quantization of relativistic particles, we present a novel second quantization of this formalism. This method, non-equivalent to a direct application of the PaW formalism to QFT, reveals a remarkable connection with the PI formulation: the second-quantized universe operators of PaW are a quantum version of the actions of classical mechanics. Moreover, the trace of the exponential of the action becomes a PI when evaluated in field configurations in space-time, establishing a direct link to the PI formulation of QFT. As a result, a canonical and space-time formulation of QFT is obtained where the single particle field excitations are PaW states. The quantum action approach can be applied to general (interacting) theories, and to non-relativistic and finite systems as well.

Pablo Álvarez Domínguez - University Grenoble Alpes

Clock Precision Characterization in the Absence of Ideal Time References

The characterization of any physical device requires comparison against reference standards of known precision. In metrology, evaluating tolerance specifications typically demands reference instruments (e.g., a ruler) that are significantly more precise than the object being measured. This approach extends to timekeeping devices, where a clock's precision is conventionally determined by comparison with a more accurate reference. However, this methodology faces a fundamental challenge in quantum theory. While standard measurement frameworks assume the theoretical possibility of increasingly precise references, an ideal time reference frame is unattainable without infinite energy. This constraint prompts a critical question: can a collection of non-ideal clocks determine their own precision collectively without requiring an absolute time reference? This paper answers this question affirmatively, providing methods for quantifying clock accuracy without an ideal reference frame, including error bounds, when multiple copies are available. These copies need not be in-phase, and our approach accommodates external factors (manufacturing imperfections, environmental coupling, or time dilation) that alter their ticking frequencies. Beyond clock characterization, these methods enable precise measurements of sub-period time intervals and relativistic effects like time dilation, offering valuable tools for quantum metrology and fundamental physics research.

Moritz Epple - University of Bonn

A phenomenological approach to quantum gravity

If one accepts that the universe is fundamentally quantum, a quantum description of the universe, a quantum cosmology, ought to exist. However, such a description cannot ignore our own point of view and the fact that all of our knowledge is ultimately derived from human experience. In my talk I would like to present a phenomenological approach to quantum gravity that takes the irreducibility of human experience and the ensuing epistemic limitations of our inquiry into nature as its starting point. The approach is event-based and perspectival. On the one hand, it relies on the idea that events, besides their spatio-temporal characteristics, possess intrinsic qualitative properties and that these properties ultimately also account for the observables of physical systems. On the other hand, we propose an extension of the representation-transformation-invariance structure of general relativity to the realm of quantum mechanics by generalizing relativistic reference frames to perspectives on the whole universe, including the past, present and future.

Peter Evans - University of Queensland

Reading out a quantum clock: what does measurement mean for time?

A good clock is a physical dynamical system driven far from thermal equilibrium that maintains a stable and periodic oscillation, coupled to an auxiliary system that counts this oscillation. Stability arises from being driven to overcome friction, and so a good clock must be an open, nonlinear, dissipative physical system, and subject to noise, which renders the period of oscillation a stochastic variable. Atomic clocks, of the sort used to coordinate UTC, are classical: the low energy of microwave photons means that counting the ticks of a microwave oscillator requires measuring the electric field of the cavity, which can be described entirely classically. Thus, `reading out' the time on such a clock does not affect its operation or precision. In contrast, optical clocks employ lasers at optical frequencies, and since optical photon energy is much larger than room temperature thermal excitations, the quantum nature of an optical clock thus arises through the noise of counting the oscillations: the direct measurement of the electric field leads to phase noise arising purely from the Heisenberg uncertainty principle. In this talk we analyse the relationship between the oscillator and counter in both classical and quantum clocks, and the role played by measurement when reading out a clock. We consider in this context the possibility of coherent feedback in a quantum clock. We show that quantum clocks provide a neat illustration of the relational nature of time.

Samuel Fedida - University of Cambridge

Einstein causality of quantum measurements in the interaction picture

When quantum measurements are conducted over spacelike-separated regions of spacetime, a natural and commonly assumed physical postulate, called Einstein causality, asserts that they should commute. In this talk, we provide a generalisation to LÃ¼ders' rule Ã la Hellwig and Kraus in those globally hyperbolic spacetimes which allow unitarily equivalent Hilbert spaces to be defined along Cauchy hypersurfaces, thus relying on the existence of an interaction picture Ã la Tomonaga-Schwinger. One example where this is possible is in free scalar quantum field theory in 1+1-dimensional Minkowski spacetime. We show that under this rule, selective quantum measurements satisfy a state-independent anyonic commutation relation over spacelike-separated (pre)compact regions. We highlight that this propagates to positive operator-valued measures (POVMs), where the commutation is necessarily bosonic. Consequently, if there exists a POVM which is informationally complete across algebras of local observables, we prove that these algebras necessarily commute over spacelike-separated (pre)compact regions provided the state update rule holds. We finish by discussing the possibility of extending such results beyond the interaction picture.

Guilherme Fiusa - University of Rochester

Time and thermodynamics of stochastic excursions

Understanding thermodynamics beyond steady-state is crucial for characterizing energy fluctuations and dissipation in quantum systems, especially when time-dependent effects play a central role. We introduce stochastic excursions as a framework for analyzing thermodynamic processes that alternate between inactive and active phases, providing a natural way to track nonstationary behavior over time. An excursion begins with a transition into an active phase and ends upon returning to inactivity, providing a natural way to track nonstationary thermodynamic behavior. By incorporating counting variables, our approach extends beyond full counting statistics (FCS), enabling the study of finite-time fluctuations and trajectory-level thermodynamics. In the long-time limit, excursion statistics recover FCS results, while at finite times they reveal a fluctuation theorem of the exchange type, highlighting the importance of temporal ordering in quantum processes. To illustrate these ideas, we apply our framework to a three-qubit quantum absorption refrigerator, demonstrating how excursions distinguish heating, cooling, and idle cyclesâ€”elucidating time-dependent trade-offs between cooling capacity and precision. Our results offer new insights into the nonequilibrium thermodynamics of quantum trajectories, emphasizing the role of time in optimizing quantum heat engines and control strategies.

Joshua Foo - University of Waterloo

Quantum signatures of proper time in optical atomic clocks

Optical clocks based on atoms and ions probe relativistic effects with unprecedented sensitivity by resolving time dilation through frequency shifts. However, all measurements of time dilation so far are effectively classical, stemming from classical motion. Here we show that first tests of time dilation where the proper time is no longer a single classical parameter can be achieved with atomic clocks. We apply a Hamiltonian formalism to derive time dilation effects in atomic clocks from first principles, and show how second-order Doppler shifts due to the vacuum energy arise (vSODS). We then isolate the quantum-second-order-Doppler-shift (qSODS), a new effect for which a semiclassical description of proper time is insufficient, and which arises due to interference of relativistic effects in both time and length. We show that both vSODS and qSODS are within reach of near-future experiments with atomic ion clocks.

Sébastien Garmier - ETH Zurich

Poincare-Covariant Quantum Reference Frame Transformations in Linearised Quantum Gravity

Gravitationally-induced entanglement (GIE) and related proposed experiments are thought to provide valuable insight into the low-energy regime of (potentially quantum) gravity. In particular, it is believed that situations displaying a quantum superposition of masses would correspond to a superposition of spacetimes. However, this has not yet been described in detail, and we set out to do this by modelling such superpositions using linearised quantum gravity. Specifically, we consider a general linear and abelian quantum field theory sourced by semi-classical matter. We then develop procedures to firstly solve the quantum state of the field sourced by any such matter configurations, and secondly to PoincarÃ©-transform the field states. By promoting the source to a quantum reference frame (QRF), we can covariantly perform QRF transformations. Our framework is thus capable of describing the entirety of a GIE-type experiment microscopically. This includes transient parts, where quantum masses are moved in and out of spatial superposition. Thanks to QRF transformations, we can also analyse GIE-type experiments in the quantum rest frame of the involved matter, where the gravitational field becomes especially simple.

Karthik Hosapete Seshadri - ICTQT, University of Gdansk

Non-classical advantage in metrology using a system under coherently controlled unitary dynamics

Quantum metrology improves the estimation of an unknown parameter using optimal measurement scheme on the quantum system. With increase in optimality of measurement, an improvement in sensing the value of the unknown parameter is observed. Considering a qubit undergoing unitary temporal evolution, estimation of the period of evolution (I) is done given the information about the Hamiltonian (H). The method for garnering information about (I), is by maximizing the Fisher information. In the absence of information about the parameters of H, the optimality of this task reduces drastically. We overcome this limitation by initializing the system in a coherent state. The system and the probe then interact through an entangling unitary. The system is measured in the same coherent state as initialized. The measurement of the probe now results in the enhanced Fisher information about the period of evolution than could be gathered from the probe alone. Notably, this strategy doesn't involve any entangled probe states nor entangled measurements yet accounts for maximum Fisher information about the period of evolution. Comparison with other metrological protocols inspired from simulations of closed time-like curves is drawn.

Niyusha Hosseini - TU Wien

Time of arrival from Page and wooters formalism

The concept of time in quantum mechanics presents unique challenges, as time is not an observable in the conventional sense. We explore the construction of a time of arrival observable 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 observable 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.

Lionel Martellini - EDHEC

Time measurement distributions for quantum systems

While the Born rule gives the probability distribution X(t) of a position measurement at a fixed time t, there is no readily available rule in the standard formalism of quantum mechanics for obtaining the probability distribution of a time measurement T(x) at a fixed position x. In recent work (Beau and Martellini (PRA, 2024) and Beau et al. (PRA, 2024)), we have used a stochastic representation of the random variable T(x) to obtain explicit results about the time-of-arrival (TOA) distribution for continuous systems, Gaussian or otherwise. In this talk, we use this framework to present a set of new experimental predictions regarding the TOA distribution, as well as its mean and standard-deviation, for a free falling quantum particle starting from a Gaussian or from a superposed state. We also explain how to extend the analysis from continuous state space systems to discrete sate space systems, and discuss an application to time measurement distributions for spin systems.

Alex Matzkin - CNRS & CY Cergy-Paris University

Wavepacket tunneling is causal: a relativistic QFT approach

Recent results on electron tunneling across a potential barrier, inferred from experimental observations or obtained from theoretical models, have suggested superluminal or instantaneous barrier traversal times. We will argue, by linking the QFT property of microcausality to the wave-packet second quantized state that the tunneling dynamics is fully causal, precluding instantaneous or superluminal effects. This holds for regular or Klein tunneling across a standard or a supercritical potential: the transmitted wave packet remains in the causal envelope of the propagator, even when its average position lies ahead of the average position of the corresponding freely propagated wave packet. We will also present some numerical illustrations obtained by employing a space-time resolved QFT framework for Klein-Gordon and Dirac fields.

Florian Meier - Atominstitut, TU Wien

Clock precision is not limited by the second law of thermodynamics

Physical devices operating out of equilibrium are inherently affected by thermal fluctuations, limiting their operational precision. This issue is pronounced at microscopic and especially quantum scales and can only be mitigated by incurring additional entropy dissipation. Understanding this constraint is crucial for both fundamental physics and technological design. For instance, clocks are inherently governed by the second law of thermodynamics and need a thermodynamic flux towards equilibrium to measure time, which results in a minimum entropy dissipation per clock tick. Classical and quantum models and experiments often show a linear relationship between precision and dissipation, but the ultimate bounds on this relationship are unknown. In this talk I will present our recent theoretical discovery of a quantum many-body system that achieves clock precision scaling exponentially with entropy dissipation. This finding demonstrates that coherent quantum dynamics can surpass the traditional thermodynamic precision limits, showing clocks may not be fundamentally limited by the second law. Moreover, the system we find to exhibit this behavior is robust to imperfections and it is based on an extensible spin-chain model with nearest neighbor interactions, making it a particularly interesting candidate for experimental realization. We conclude the talk with an outlook on possible applications that quantum ticking clocks may have beyond foundational thermodynamic considerations.

Perola Milman - CNRS

Revisiting Quantum Optical States: Superselection Rules, Non-Classicality, and Quantum Advantage

Quantum optical states are typically represented in the quadrature basis, enabling intuitive descriptions of quasi-classical states and phase-space representations. Equivalently, states can be represented as superpositions of Fock states. However, within these representations, a general framework for understanding quantum advantage and classical simulability of quantum information encoded in field states remains lacking. Moreover, the mentioned approaches neglect the photon-number superselection rule and assumes an implicit phase reference. We adopt a representation that respects the superselection rule by encoding states in two orthogonal modes of the Fock basis. We show that this allows us to clarify key notions in quantum optics, including quantum universality, non-classicality, and classical simulability. First, we propose a method to classify quantum optical states based on their computational utility in a bosonic quantum computer. By mapping arbitrary bosonic states onto multiple single-photon modes, we identify how non-classicality emerges from their ability to enable quantum computations. Second, we provide a unified framework for quantum information encoding in quantum optics, bridging single-photon modal encoding with arbitrary continuous-variable schemes. We analyze the distinct roles of Gaussian and non-Gaussian operations and discuss how representations of quantum optical states in terms of modes or Fock states superposition are related.

Angela Rosy Morgillo - University of Pavia

Learning Time-Varying Quantum Lossy Channels

Time-varying quantum channels are essential for modeling realistic quantum systems with evolving noise properties. We consider Gaussian lossy channels varying from one use to another and we employ neural networks to classify, regress, and forecast the behavior of these channels from their Choi-JamioÅ‚kowski states. The networks surpasses 80% of accuracy in distinguishing between non-Markovian, Markovian, memoryless, compound, and deterministic channels. In regression tasks, the model accurately reconstructs the loss parameter sequences, and in forecasting, it predicts future values, with improved performance as the memory parameter approaches 1 for Markovian channels. These results demonstrate the potential of neural networks in characterizing and predicting the dynamics of quantum channels.

Nicola Pranzini - University of Helsinki

Gravitational quantum speed limit

While playing an important role in the foundations of quantum theory, Quantum Speed Limits (QSL) have no role in discussions about the search for quantum gravity. We fill this gap by analysing what QSL arises when superposing spherically symmetric masses in canonical quantum gravity. By this procedure, we find that the quantum mechanical Mandelstam-Tamm and Margolus-Levitin bounds can be improved by superposing a spherically symmetric, static and asymptotically flat spacetime between states with different ADM energies and mass densities. We discuss the feasibility and significance of measuring times via these superpositions.

Giuseppe Ragunì - Universidad de Murcia, Spain

Two-Time Relativistic Bohmian Model of Quantum Mechanics

Two-Time Relativistic Bohmian Model is a theory that takes seriously the Feynman's sum over history formulation of QM. The only way to avoid absurdity in assuming ubiquity of matter is to introduce a new and independent time variable (tau) with respect to which the particle is free to travel while the commonly time (t) does not flow. Nonlocality and apparent indeterminism of QM are explained by tau-motions, which, caused by a Bohmian-type potential, determine quantum uncertainties. In the model: (1) Zig-zag paths violating t-momentum conservation can be obtained by composition with tau-motions, converting into real physical trajectories. (2) The virtual, simultaneous, self-interactions of a particle predicted by standard QM and excellently verified in experiments, are interpreted as actually realized in tau-time. (3) The path integral extends to a limited volume: this could make it a properly mathematical object, unlike the original Feymnan formulation. (4) Observational wavefunction collapses are interpreted as destructive interference in tau-time and occur after every particle energy change; observation itself has no special role. (5) A relativistic anisotropy of the uncertainty principles is predicted, which could be tested in high-energy accelerators. (6) Tau-time fulfills the characteristics that some authors have suggested for a non-measurable intrinsic time providing the background structure of QM. The model is able to derive a Time-Energy Uncertainty Relation without ambiguity.

Enrico Rebufello - Istituto Nazionale di Ricerca Metrologica, Italy

Emergence of constructor-based irreversibility in quantum systems

The emergence of irreversibility from time symmetric physical laws is a central problem in contemporary physics. Here we present an innovative take on this topic adopting the recently proposed constructor theory framework [1,2], in which irreversibility is expressed as the requirement that a task is possible, while its inverse is not. We prove the compatibility of such constructor-based irreversibility with quantum theoryâ€™s time-reversal symmetric laws, using a dynamical model based on the universal quantum homogenizer. We also test the physical realizability of this model by means of an experimental demonstration exploiting high-quality single-photon qubits [3].

[1] D. Deutsch, Constructor theory, Synthese 190, 4331 (2013).

[2] D. Deutsch and C. Marletto, Constructor theory of information, Proc. R. Soc. A 471, 20140540 (2015).

[3] C. Marletto et al., Emergence of Constructor-Based Irreversibility in Quantum Systems: Theory and Experiment, Phys. Rev. Lett. 128, 080401 (2022)."

Simone Rijavec - Tel Aviv University

Conditions for Unitary Dynamics in Timeless Quantum Theory

The concept of time as an external parameter in conventional quantum theory clashes with the background-independent character of general relativity and suffers from several explanatory and technical issues, generally termed the "problem of time". A promising solution to this problem is to remove any appeal to an external time parameter and recover a notion of dynamics relative to some systems acting as clocks in an overall stationary quantum Universe. The resulting timeless quantum theory recovers the standard unitary evolution of physical systems when the clocks are isolated from the rest of the Universe but shows a non-unitary behavior when some types of clock interactions are present. In this talk, I will present some conditions on the Hamiltonian of the Universe that are sufficient for the relational dynamics to be unitary, and necessary in a looser sense. I will also give a physical interpretation of these conditions in terms of some properties of the clock.

Matthias Salzger - ICTQT

A decompositional framework for process theories in spacetime

Recent interest in quantum foundations has focused on incorporating ideas from general relativity and quantum gravity. However, many quantum information tools remain agnostic to the underlying spacetime. For instance, quantum circuits typically ignore the connectivity constraints imposed by physical qubits. In this work, we extend the framework of process theories to include a background causal structure arising from a fixed spacetime. We introduce the notion of process implementationsâ€”decompositions of a process. A process is then embeddable if and only if one of its implementations can be embedded in such a way that all the component processes are localized and all wires follow time-like paths. While conceptually simple, checking for embeddability is generally computationally intractable. We identify a canonical subset of implementations that determine both the embeddability of a process and the causal structures distinguishable in various process theories. Notably, we discover countably infinite "zigzag" causal structures beyond those typically considered. While these can be ignored in classical theory, they seem to be essential in quantum theory, as the quantum

CNOT gate can be implemented by all zigzag structures but not in a standard causal structure. These findings could be significant for quantum causal modeling and the study of novel quantum resources.

Amrapali Sen - International Centre for Theory of Quantum Technologies

Superluminal Quantum Reference Frames

The theory of relativity is generally assumed to impose a speed limit for all interactions. Particles cannot travel faster than the speed of light, nor can information. A standard argument for the impossibility of superluminal particles and superluminal observers say that they would allow for backwards-in-time signalling, thus causing causality paradoxes. However, Andrzej Dragan and Artur Ekert recently have argued that in a world with superluminal observers local determinism is impossible linking the two pillars of physics “quantum theory and relativity” suggesting that the latter serves as the foundation for the former. In this work, we extend the framework of quantum reference frames to incorporate superluminal Lorentz transformations (SpLT) and ensure consistency with a few fundamental laws of Physics. We examine an apparent paradox where particles acquire negative energies after undergoing a quantum SpLT and propose a resolution within this framework. We consider proposals for how thermodynamic quantities evolve under SpLT and argue that it is consistent with the second law of thermodynamics. Finally, we discuss Bell experiments under superluminal quantum reference frame transformations, and confirm conserved probabilities. These insights challenge conventional assumptions about superluminal theories but also represent the first work to integrate superluminal transformations within the framework of quantum reference frames.

Barbara Soda - Perimeter Institute

Emergence of (Space-)Time from Fluctuations

We use a result of Hawking and Gilkey to define a Euclidean path integral of gravity and matter which has the special property of being independent of the choice of basis in the space of fields. This property allows the path integral to also describe physical regimes that do not admit position bases. These physical regimes are pregeometric in the sense that they do not admit a mathematical representation of the physical degrees of freedom in terms of fields that live on a spacetime. In regimes in which a spacetime representation does emerge, the geometric properties of the emergent spacetime, such as its dimension and volume, depend on the balance of fermionic pressure and bosonic and gravitational pull. That balance depends, at any given energy scale, on the number of bosonic and fermionic species that contribute, which in turn depends on their masses. This yields an explicit mechanism by which the effective spacetime dimension can depend on the energy scale. In this talk I will present also new results on Lorentz signature and time.

Kyrylo Simonov - University of Vienna

Higher-order quantum theory with indefinite time direction: Framework and case study

Although quantum circuits are the most popular model of modern quantum computing, it is not the ultimate computational paradigm compatible with quantum mechanics. Indeed, in the last decade, a lot of effort has been put to develop more general higher-order models of quantum computing, which go beyond transformations of input quantum states, e.g., quantum combs. Discovery of quantum SWITCH, a supermap that puts quantum operations into a coherent superposition of their causal orders and cannot be deterministically reduced to a quantum circuit, has suggested a higher-order computation model without definite causal order of quantum operations based on transformations of quantum combs. On the other hand, while fundamental laws of physics do not depend on the direction of time, our everyday experience suggests an opposite observation, namely, time flows in the forward direction, from past to future. As it can be attributed to the way how an agent interacts with physical system, the possibility of interaction in backward direction, i.e., from future to past, has been questioned. This leads to a new class of supermaps, which relax the well-defined direction of time in a quantum operation, i.e., input-output direction. Such supermaps cannot be deterministically reduced to a quantum circuit, which implied a well-defined direction of propagation of a qubit. In this talk, we introduce a theoretical framework for description of supermaps of this kind and discuss its applications.

Michael Suleymanov - Bar-Ilan University, Israel

Uncertainty, Correlation, and Entanglement in QRF: Invariant Quantities and Frame-Dependent Measures

Viewing frames of reference as physical systems -- subject to the same quantum laws as the systems they describe -- is central to the relational approach in physics. Under the assumption that quantum mechanics universally governs all physical entities, this perspective naturally leads to the concept of quantum reference frames (QRFs). We investigate the perspective-dependence of position and momentum uncertainties, correlations, covariance matrices and entanglement within the QRF formalism. We show that the Robertson-Schrodinger uncertainty relations are frame-dependent, and so are correlations and variances which satisfy various constraints described as inequalities. However, the determinant of the total covariance matrix, linked to the uncertainty volume in phase space, as well as to a certain kind of entanglement entropy, remains invariant under changes of reference frame. These invariants suggest fundamental, robust measures of uncertainty and entanglement that persist despite changes in observational perspective, potentially inspiring dedicated quantum information protocols as well as further foundational studies.

Kristian Toccacelo - Technical University of Denmark (DTU)

Benchmarks for quantum communication via gravity

The question of whether gravity is fundamentally quantum has long eluded experimental verification. Recent experimental proposals, such as the Bose-Marletto-Vedral (BMV) experiment, rely on gravity-induced entanglement (GIE) as evidence of the underlying quantum nature of gravity. As such, these proposals assume the ability to prepare highly non-classical macroscopic states, which is a major hurdle to reach potential laboratory implementations. In this talk, we establish limitations and bounds on the transmission of quantum states between gravitationally interacting mechanical oscillators under different models of gravity.

This provides benchmarks that enable tests for quantum features of gravity that do not require the measurement of GIE and only require final measurements of a single subsystem. We discuss bounds for classical models based on local operations and classical communication when considering coherent-state alphabets, and we discuss the transfer of quantum squeezing for falsifying the Schrodinger-Newton model.

Alessandro Tosini - University of Pavia

Disentangling signalling and causal influence

The causal effects activated by a quantum interaction are studied, modelling the last one as a bipartite unitary channel. The two parties, say Alice and Bob, can use the channel to make signalling, namely to exchange messages. On the other hand, the most general form of causal influence includes also the possibility for Alice, via a local operation on her system, to modify Bob's correlations. The two effects are equivalent in the digital sense, they always occur together, but can differ in magnitude. We study the properties of two functions that quantify the signalling and the causal influence conveyed by an arbitrary unitary channel. The functions are proved to be continuous and monotonically increasing with respect to tensor product of channels. Monotonicity is instead disproved in the case of sequential composition. Signalling and causal influence are analytically computed for the quantum SWAP and CNOT gates, both in the single use scenario and in the n-parallel uses scenario. A finite gap has been found between signalling and causal influence for the quantum CNOT, thus proving the existence of extra causal effects that cannot be explained in terms of communication only. However, this gap disappears in the asymptotic limit of an infinite number of parallel uses, leaving room for asymptotic equivalence between signalling and causal influence.

Eyuri Wakakuwa - Nagoya University

Detecting post-Newtonian classical and quantum gravity via clock interferometry

Understanding physical phenomena at the intersection of quantum mechanics and general relativity remains one of the major challenges in modern physics.

Among various approaches, experimental tests have been proposed to investigate the dynamics of quantum systems in curved spacetime and to examine the quantum nature of gravity in the low-energy regime. However, most previous studies have considered only Newtonian gravity, leaving the post-Newtonian regime largely unexplored. Developing an experimental test to probe how gravitational and quantum mechanical effects interact in this regime would provide valuable insights into the physics bridging quantum mechanics and general relativity. In this study, we propose an experimental test to investigate how post-Newtonian gravity affects quantum systems and to examine its quantum nature. Specifically, we design two types of experiments: one using a quantum clock interferometry to detect the gravitational field generated by a rotating axisymmetric mass, and another leveraging this effect to generate gravity-mediated entanglement. Although the proposed experiments are extremely challenging to implement, they are suited for probing post-Newtonian gravity, as they are sensitive to the direction of the source mass rotation. Moreover, assuming the universality of gravitational redshift, our approach provides a potential means not only to test the quantumness of gravity but also to explore the possible quantum nature of spacetime itself.

Mischa Woods - ENS de Lyon, France & Inria

Quantum frequential computing: using quantum control & clocks to outperform conventional computers

An enduring challenge in computer science is reducing the runtime required to solve computational problems. Quantum computing has attracted significant attention due to its potential to deliver asymptotically faster solutions to certain problems compared to the best-known classical algorithms. This advantage is due to the quantum mechanical nature of the logical degrees of freedom. To date, it was unknown if permitting other parts of the computer to be quantum mechanical, rather than semi-classical, could yield runtime speed-ups as a function of resource utilization (e.g. power consumption or cooling requirements). In this work, we prove that when control mechanisms are implemented optimally using quantum technology, they can achieve a quadratic runtime speedup (with respect to power consumption or cooling rate) for any algorithm, relative to optimal classical or semi-classical control schemes. Moreover, we demonstrate that only a small fraction of the computers architecture needs to employ quantum control to realize this advantage, thereby significantly simplifying the design of future systems. The quantum speedup arises from an increase in gate frequency due to quantum properties of timekeeping. In particular, autonomous signal generation, detection & utilization. In current state-of-the-art designs, gate frequency is often limited by the coupling strength between components; notably, our approach achieves the speedup without requiring an increase in coupling strength.

Magdalini Zonnios - Trinity College Dublin

Memory-minimal quantum generation of stochastic processes

Stochastic processes abound in nature and accurately modeling them is essential across the quantitative sciences. They can be described by hidden Markov models (HMMs) or by their quantum extensions (QHMMs). These models explain and give rise to process outputs in terms of an observed system interacting with an unobserved memory. Although there are infinitely many models that can generate a given process, they can vary greatly in their memory requirements. It is therefore of great fundamental and practical importance to identify memory-minimal models. This task is complicated due to both the number of generating models, and the lack of invariant features that determine elements of the set. In general, it is forbiddingly difficult to ascertain that a given model is minimal. Addressing this challenge, we here identify spectral invariants of a process that can be calculated from any model that generates it. This allows us to determine strict bounds on the quantum generative complexity of the process -- its minimal memory requirement. We then show that the bound is raised quadratically when we restrict to classical operations. This is an entirely quantum-coherent effect, as we express precisely, using the resource theory of coherence. Finally, we demonstrate that the classical bound can be violated by quantum models.

Time in Quantum Theory 2025

June 17th to 20th – Genoa, Italy

Abstracts

Posters

Elia Sciama Bandel - University of Bristol

Exploring autonomous quantum clocks and their potential advantage

Quantum clocks, such as atomic clocks, are known to have advantages over classical ones. Autonomous quantum clocks are a relatively new addition to this realm. What makes them particularly interesting is the little external control they need. My research is currently focused on a minimal thermal clock model previously proposed. This consists of two qubits operating between macroscopic heat baths, extracting work from the heat flow and exerting it onto an external system, which works as a clock. I show that this particular model, for weak coupling regimes, is essentially classical and reproducible by stochastic models. However, the minimal thermal clock achieves a small coherent advantage, which hints that further improvements can be successful. I will also outline the future direction of these research, considering and characterising different thermodynamical systems used as clocks.

Matteo Cardi - University of Genoa

Measurement of the Unruh effect through extended quantum thermometers

The Unruh effect, predicting a thermal reservoir for accelerating systems, calls for a more refined understanding of measurement processes involving quantum systems as thermometers. Conventional models fail to account for the inherent spatial extent of the thermometer, ne- glecting the complexities associated with accelerated extended quantum systems. We propose a thermometer model incorporating a spin-1/2 particle where the spin acts as a temperature indicator, taking also into account the extended nature of the particle. This refined model demonstrates the ability to effectively measure the temperature under specific and realistic conditions, providing a unique value that essentially averages the local Unruh temperatures throughout the extended quantum system acting as the thermometer.

Carolina Moreira Ferrera - University of Bristol

Classical-to-quantum non-signalling boxes

Here we introduce the concept of classical input - quantum output (C-Q) non-signalling boxes, a generalisation of the classical input - classical output (C-C) non-signalling boxes. We argue that studying such objects leads to a better understanding of the relation between quantum nonlocality and non-locality beyond quantum mechanics. The main issue discussed in the paper is whether there exist 'genuine' C-Q boxes or all C-Q boxes can be built from objects already known, namely C-C boxes acting on pre-shared entangled quantum particles. We show that large classes of C-Q boxes are non-genuine. In particular, we show that all bi-partite C-Q boxes with outputs that are pure states are non-genuine. We also present various strategies for addressing the general problem, i.e. for multi-partite C-Q boxes which output mixed states, whose answer is still open. Finally, we show that even some very simple non-genuine C-Q boxes require large amounts of C-C nonlocal correlations in order to simulate them.

Milad Ghadimi - Technische Universitat Dresden

Temporal Dynamics and the Foundations of Quantum Theory: A Study on Time's Role in Quantum Processes

The concept of time in quantum theory challenges traditional understandings, intertwining with phenomena such as superposition, entanglement, and measurement. This study explores the dual role of time as both an external parameter and an emergent property in quantum systems. We investigate time in quantum mechanics, as time-energy uncertainty relations, and the impact of temporal correlations in quantum communication protocols. Additionally, the poster discusses recent developments in quantum clocks and synchronization and their implications for defining and measuring time at microscopic scales. This work aims to bridge the gap between theoretical insights and practical applications.

Fumio Hiroshima - Kyushu University

Analysis of time operators associated with 1D harmonic oscillator

A time operator T of 1D harmonic oscillator H is rigorously constructed. The angle operator, the Dirac phase operator and the so-called Galapon operator are examples of time operators. It is shown that CCR [H,T]=-i holds true on a dense domain in the sense of sesqui-linear forms, and an asymptotic behavior of T is investigated. A matrix representation of T and its analytic continuation are given. A classification of T's are also given. Finally the time evolution of T is investigated, and show the period.

Christos Karapoulitidis - Stevens Institute of Technology

Distinguishing Semi-Classical and Quantum Models of Proper Time with Atomic Clocks

Experiments such as atomic fountains or neutron interferometers measure how a quantum particle in a spatial superposition experiences a gravitational phase shift, as predicted by Schrödinger's equation with a Newtonian potential. Extending this scenario to include an internal clock degree of freedom for the particle enables to probe post-Newtonian effects due to differences in proper times. New phenomena such as gravitational decoherence can arise, which however are far from an experimental realization. Here we reinvestigate this scenario by considering joint observables of both the external and the clock degrees of freedom. We show that for entangled initial states, the system acquires a gravitationally induced phase shift that can rule out semiclassical models of an objective background time. An observation of this effect is in reach with current quantum technologies and will provide further insights into the quantum nature of gravitational effects on timekeeping systems.

Francisco Jara Lobo - University of Concepción

Testing alternative metric theories using Quantum state discrimination theory

This project aims to explore the possibility of distinguishing between space-time metric theories in terms of the post-Newtonian (PN) parameters through quantum state discrimination techniques, and therefore constitutes an instance of hypothesis testing. To determine the most suitable hypothesis, that is, which alternative theory is correct, we proposed an experiment. To perform this task, we employ massive particles with internal degrees of freedom that act as quantum clocks. We Will show a simple setup where is possible to distinguish between several theories in terms of the PN parameters and how Helstrom's bound depends on these parameters.

Michael Masters

Experimentally testing whether No-Signaling implies No-Supremacy

The Arrow of Time is a fact but remains unexplained by current time-symmetric physical theories (Coveney, 1992; Penrose 1998, 1994). It is well-established that time-symmetry leads to causal paradox and additional logical self-consistency axioms are required (Deutsch, 1991; Wheeler, 1945). A number of physical experiments have prompted formulations of various principles of logical self-consistency (Lloyd, 2011; Nimtz, 2011) including the No-Signaling theorem (Siegel, 2024). It is well-known that if a signal, even a single bit, could be sent instantaneously, it would enable computational supremacy (Aaronson, 2008). The specific degree of supremacy varies depending on the specific formulation of logical self-consistency (Lloyd, 2011), but in all cases, it appears too good to be true, and lends additional support to the various forms of No-Signaling conjectures (Hawking, 1992). Theoretical models of counter-factual computation propose that when no signal is sent, it might be possible to achieve computation from the fundamental requirement of logical self-consistency (Brun, 2003; Mitchison, 2001). This suggests an experimental paradigm focussed on probing computational power rather than signaling properties. The computation does not come from signaling but from the requirement of logical causal self-consistency leading to an information creation paradox so as to avoid disallowed paradoxes. I propose reviewing known setups which could experimentally test this.

Maciej Ogrodnik - University of Warsaw

Time-phase encoded quantum key distribution with resource-efficient time-resolved detection

The temporal degree of freedom is often employed in quantum key distribution (QKD) since time-bin encoding enables easy state preparation and measurement. Typically, the coherence of time-bin superpositions is verified by multi-arm interferometers in the case of high-dimensional encoding. Here we employ direct time-resolved detection for multidimensional time-bin superposition verification by means of the temporal Talbot effect. We report proof of principle high-dimensional time-phase BB84 QKD experiment using only one time-resolved single-photon detector per measurement basis. We show experimentally-obtained key rates for the two-dimensional and four-dimensional case, including in an urban fiber network. A comparison of the secret key rates obtained from two different security proofs displays security issues stemming from asymmetric detection efficiencies in the two bases due to the restriction of the time of arrival measurement. Our results contribute to the discussion of the benefits of high-dimensional encoding, highlight the impact of security analysis on the achievable QKD performance and show new detection capabilities using the high temporal resolution.

Ismael Lucas Paiva - University of Bristol

Unitarity, nonunitarity, and clock choices in the Page-Wootters framework

The Page-Wootters framework introduces a covariant observable for a physical system, allowing it to serve as a time reference clock to describe the dynamics of a system of interest. Within this framework, standard Schrodinger dynamics is recovered when the clock and system do not interact. However, interactions

generally lead to time-nonlocal and potentially nonunitary dynamics. We show that these effects stem from the standard choice of clock observables. Specifically, we present an example where a generalized clock observable yields unitary dynamics, while the standard choice results in nonunitarity. We then establish conditions on the joint state of the clock and system that allow for generalized clock observables that ensure unitarity. Finally, we outline a method to construct such observables when they exist.

Yifei Ren - Western University

The Epistemic Role of Time in Classical Equations of Motion in Light of Loop Quantum Gravity

The distinction between conventional and generally covariant formalisms in physics lies in their treatment of time. In conventional formalisms, time is treated as a preferred independent variable, guiding the evolution of physical systems. In contrast, generally covariant formalisms, such as those found in Loop Quantum Gravity (LQG), eschew a preferred time parameter and instead describe dynamics as the evolution of physical variables with respect to one another. This raises an important conceptual question: if time disappears from the fundamental formalism of LQG, what role did it serve in classical equations of motion?

Marco Rivera - University of Concepción

Probing Post-Newtonian Gravity with Entangled Quantum Clock Networks

Preliminary results demonstrate the capability of a network of quantum clocks to independently estimate the parameterized post-Newtonian (PPN) parameters Î^3 and Î^2, achieving significantly lower relative errors than possible with single-clock approaches, even those employing superposition states. This work theoretically investigates a distributed network of quantum clocks, leveraging their shared entanglement to enhance sensitivity to the gravitational effects described by the PPN formalism. We quantify the achievable precision in estimating Î^3 and Î^2 using both error propagation and Bayesian analysis of the clocks' readout. Our findings indicate an order of magnitude improvement in the relative error for both parameters. This enhanced precision opens new avenues for testing general relativity and exploring potential deviations from its predictions in the weak-field regime.

Bruna Sahdo - IQOQI Vienna

Adding and removing systems in QRFs

Can we define the reference frame of a system that is in a quantum superposition? If so, how would the world look like from this perspective? Recent works on quantum reference frames (QRFs) seek a quantum generalization of reference frame transformations to answer these questions. Apart of some notable exceptions, most of these works assume a global system in isolation, which is unrealistic both fundamentally and in practice. Understanding how to consistently add and remove subsystems in QRFs is not straightforward and leads to puzzles such as the paradox of the third particle. Here we approach this problem within the extra particle approach to QRF transformations, which is well suited to address such compositional questions. We define general rules for adding and removing new systems and identify the constraints on the states for doing so. We find that subsystems can only be added/removed according to standard quantum theory when the reference frame can be purified to a classical, sharply localized state. This suggests that there might be a notion of what it means to be classical/quantum in QRFs. Our formalism avoids the third particle paradox and its variations and sheds light on the connection between different frameworks for QRF transformations. It also provides a way to study fundamental limitations on measurability encoded in the extra particle, which can have consequences for operational descriptions of spacetime by non-ideal observers.

Armin Nikkhah Shirazi - University of Michigan

Time and Possibilities in Quantum Mechanics

If we start with Minkowski Spacetime and take the global limit c to 0 seriously, it yields a spacetime which is utterly unfamiliar to our intuitions, yet consistent and intelligible. In such a spacetime, motion in space is impossible and a novel coordinate transformation I call the time-Galilean transformation describes aging without motion. I argue that this transformation fits the role of unitary time evolution in quantum mechanics because a) quantum states can always be decomposed in terms of a superposition of stationary states (energy eigenstates), and b) quantum motion is fundamentally different from classical motion. I take this as evidence for a modal distinction between the classical and quantum worlds. I concretize this idea with the introduction of what I call the Heisenberg Interpretation, which interprets quantum states as a certain kind of pure physical possibility. The interpretation makes novel predictions with respect to the interface between quantum theory and Einstein's general relativity arising from the distinction between possibilities and actualities in spacetime.