Time and Clocks

781. WE-Heraeus-Seminar

27 Feb - 03 Mar 2023
at the Physikzentrum Bad Honnef/Germany

The WE-Heraeus Foundation supports research and education in science, especially in physics.
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Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 781. WE-Heraeus-Seminar:

"Time" and "clock" are ubiquitous notions that every physicist is working with, irrespectively of whether that work is experimental or theoretical in nature. In spite of that, the theoretical meanings as well as the operational realisations of these concepts are far from obvious and certainly not unique. A whole spectrum of shifts in, and losses of, interpretations occur in the transitions between classical mechanics, quantum mechanics, special-relativistic quantum-field theory, general relativity, and, finally, quantum gravity. As a result of this, issues arise that, up to this day, are the subject of challenging and often controversial debates. Recent developments in high-precision metrology partly help to resharpen but partly also refuel these controversies. Our seminar intends to bring together scientists from different disciplines in order to foster a productive dialogue on the problematic issues in connection with "time" and "clock". We specifically aim to characterise, in scientific terms, a common understanding of what the "problem of time" really entails.

Scientific Organizers:

Prof. Dr. Domenico Giulini	Leibniz Universität Hannover, Germany E-mail: giulini@itp.uni-hannover.de
Prof. Dr. Claus Lämmerzahl	University of Bremen (ZARM), Germany E-mail: claus.laemmerzahl@zarm.uni-bremen.de
Prof. Dr. Christian Pfeifer	University of Bremen (ZARM), Germany E-mail: christian.pfeifer@zarm.uni-bremen.de
Prof. Dr. Dennis Philipp	University of Bremen (ZARM), Germany E-mail: dennis.philipp@zarm.uni-bremen.de

Introduction

Administrative Organization:

Dr. Stefan Jorda
Martina Albert

Wilhelm und Else Heraeus-Stiftung
Kurt-Blaum-Platz 1
63450 Hanau, Germany

Phone +49 6181 92325-14
Fax +49 6181 92325-15
E-mail albert@we-heraeus-stiftung.de
Internet: www.we-heraeus-stiftung.de

Venue:

Physikzentrum
Hauptstrasse 5
53604 Bad Honnef, Germany

Conference Phone +49 2224 9010-120

Phone +49 2224 9010-113 or -114 or -117
Fax +49 2224 9010-130
E-mail gomer@pbh.de
Internetwww.pbh.de

Taxi Phone +49 2224 2222

Registration:

Martina Albert (WE-Heraeus Foundation)
at the Physikzentrum, reception office
Sunday (17:00 h – 21:00 h)
and Monday (08:00 – 12:30 h)

Program

Program

Sunday, 26 February 2023

17:00 – 21:00	**Registration**	
From 18:30	*BUFFETT SUPPER / Informal get together*	

Monday, 27 February 2023

08:00 – 08:45	*BREAKFAST*	
08:45 – 09:00	Organizers	**Welcome words**
09:00 – 10:00	Tanja Mehlstäubler	**Time in multi-ion systems**
10:00 – 11:00	Piet Schmidt	**Quantum engineering optical clocks**
11:00 – 11:30	*COFFEE BREAK*	
11:30 – 12:30	Emily Adlam	**Is There Causation in Fundamental Physics? New Insights from Process Matrices and Quantum Causal Modelling**
12:30 – 12:40	**Conference photo**	
12:40 – 14:00	*LUNCH*	

Program

Monday, 27 February 2023

14:00 – 15:00	Klaus Fredenhagen	**Time in quantum physics**
15:00 – 16:00	Julian Barbour	**Complexity as time**
16:00 – 16:30	*COFFEE BREAK*	
16:30 – 17:30	Carlo Rovelli (online)	**Quantum mechanics can be extended to general relativistic temporality**
17:30 – 17:45	Stefan Jorda (online)	**About the Wilhelm and Else Heraeus Foundation**
17:45 – 18:45	**Discussion Clocks**	
19:00	*HERAEUS DINNER at the Physikzentrum* *(cold and warm buffet, with complimentary drinks)*	

Program

Tuesday, 28 February 2023

08:00 – 09:00	*BREAKFAST*	
09:00 – 10:00	Claus Kiefer	**Origin of irreversibility in the Universe**
10:00 – 11:00	Martin Bojowald	**Time and clocks in extreme quantum regimes**
11:00 – 11:30	*COFFEE BREAK*	
11:30 – 12:30	Reinhard Werner	**Time observables in quantum mechanics**
12:30 – 14:00	*LUNCH*	
14:00 – 15:00	Fay Dowker	**Causal Set Quantum Gravity and the Hard Problem of Consciousness**
15:00 – 15:30	Sebastian Ulbricht	**Theoretical investigation of a cavity-clock operating in Earth's gravity**
15:30 – 16:00	**Poster-Flash-Talk Session**	
16:00 – 16:30	*COFFEE BREAK*	
16:30 – 18:30	**Poster Session**	
18:45 – 20:00	*DINNER*	
20:00	**Poster Session continued**	

Program

Wednesday, 1 March 2023

08:00 – 09:00	*BREAKFAST*	
09:00 – 10:00	Gérard Petit	**Atomic time, clocks, and clock comparisons in relativistic spacetime**
10:00 – 11:00	Sergei Klioner	**Time and Relativistic Reference Systems**
11:00 – 11:30	*COFFEE BREAK*	
11:30 – 12:30	Philip Schwartz	**Time in Newtonian physics from a spacetime perspective**
12:30 – 14:00	*LUNCH*	
14:00 – 18:30	**Excursion**	
18:45	*DINNER*	
20:00	**Evening Lecture** Claus Lämmerzahl	**The Unit(y) of Time**

Program

Thursday, 2 March 2023

08:00 – 09:00	*BREAKFAST*	
09:00 – 10:00	Eva Hackmann	**Time and Rotation**
10:00 – 11:00	Kristina Giesel	**Geometrical and matter clocks in quantum gravity models**
11:00 – 11:30	*COFFEE BREAK*	
11:30 – 12:30	**Networking / Discussion**	
12:30 – 14:00	*LUNCH*	
14:00 – 15:00	Volker Perlick	**Experimental characterisation of standard clocks**
15:00 – 16:00	Dennis Raetzel	**Geometry of physical dispersion relations**
16:00 – 16:30	*COFFEE BREAK*	
16:30 – 17:00	Ali Lezeik	**Quantum Clock Interferometry**
17:00 – 17:30	Akbar Shabanloui	**Application of optical clocks for unification of height systems and determination of temporal variations in the Earth's gravity field**
18:45	*DINNER*	
20:00	**Discussion**	

Program

Friday, 3 March 2023

08:00 – 09:00	*BREAKFAST*	
09:00 – 10:00	Philipp Hoehn	**Relational observables and microcausality in gravity**
10:00 – 11:00	Alexander R. H. Smith	**The Page-Wootters formalism and quantum time dilation**
11:00 – 11:30	*COFFEE BREAK*	
11:30 – 12:30	Manuel Hohmann	**How to (not) break local Lorentz invariance in gravity theory**
12:30 – 12:40	Organizers	**Poster Award and Closing Remarks**
12:40 – 14:00	*LUNCH*	

End of seminar and departure

Posters

Posters

Aroonkumar Beesham	**The concept of time and its units in ancient India**
Rogério Capobianco	**Spontaneous scalarization of self-gravitating magnetic fields**
Marian Cepok	**Entangled clock networks in gravity**
Leonardo Chataignier	**Beyond semiclassical time - dynamics and quantum diffeomorphism invariance**
Ruken Asya Ciftci	**Measurement of Time and Poincaré's Convoluted Position in the Theory of Special Relativity**
Daniel Derr	**Atom Interferometric Detection of Dark Matter**
M. Kemal Döner	**Gravitational decoherence from coherent matter-light interactions as a causal consistency requirement for gravity induced entanglement**
Max Joseph Fahn	**A gravitationally induced decoherence model in the relational formalism**
Ricardo Faleiro	**Connecting timelike and spacelike correlations in cooperation games**
Bennet Grützner	**Relativistic Perturbation Theory of Schwarzschild Geodesics**
Maria Jose Guzman Monsalve	**The premetric approach in teleparallel gravity**
Jan Hackstein	**Gravitational field recovery via inter-satellite redshift measurements**

Posters

Ekim T. Hanimeli	**General relativistic quantum clocks**
Olaf Hartwig	**LISA: a cutting edge time/frequency transfer measurement to detect gravitational waves**
Joost Hinrichs	**Compact rack-integrated UV laser system for a transportable Al+ quantum logic optical clock**
Huanchen Hu	**Gravity experiments in strong fields using pulsars as clocks**
Fernando Izaurieta	**Some Questions on the Problem of Time and Quantum Mechanics**
Fech Scen Khoo	**Quasinormal modes of Kerr-Newman black holes in slow rotation**
Timm Kielinski	**Optimal Ramsey Protocols in Ion Clocks**
Nadja Magalhaes	**Time, spacetime and quantum mechanics**
Giulia Maniccia	**WKB decomposition of classical and quantum gravitational degrees of freedom for the QFT-CS limit from Quantum Gravity**
Luca Marchetti	**Time and relationality from an emergent quantum gravity perspective**
Lucía Menéndez-Pidal	**Unitarity, singularity resolution, and clock choices in quantum cosmology**
Lisa Mickel	**Quantum gravity and cosmological perturbations: Effects of a modified Friedmann equation on the evolution of gauge-invariant perturbations**
Constantin Nauk	**Progress on PTB's transportable Al+ ion clock**

Posters

Manfred Niehus	**Clock synchronization through an optical quantum channel part of a free space QKD system**
Laxmipriya Pati	**Hamilton's equations in the (covariant) teleparallel equivalent of general relativity**
Nikola Paunković	**Distinguishing between definite and superposed causal orders**
Andrea Russo	**Quantum relational field theory**
Patrik Schach	**Tunneling of clocks**
Maja Scharnagel	**Ramsey interferometry with optimally twisted states and measurements**
Sebastian Schuster	**Relational Dynamics and Time Travel**
Sebastiano Segreto	**Extended GUP quantization of the FLRW Universe**
Harkirat Singh Sahota	**Quantum cosmology with fluid clock: Implications for the dressed metric approach**
Mritunjay Tyagi	**Entanglement entropy and the emergence of an arrow of time in Wheeler-DeWitt Quantum Cosmology**
Linda van Manen	**The effect of gravitational waves on an atom**
Tatevik Vardanyan	**Quantum-gravitational corrections in a closed universe**
Marko Vojinovic	**Operational verification of the existence of time and space**

Posters

Michael Werner	**Systematic description of matter wave interferometers using elastic scattering in weakly curved spacetimes**
Aneta Wojnar	**Matter and gravity**
Fabian Wolf	**Towards a molecular ion clock**
Emmanuel Zambrini Cruzeiro	**Quantum measurements, energy conservation and quantum clocks**

Abstracts of Lectures

(in alphabetical order)

Is There Causation in Fundamental Physics? New Insights from Process Matrices and Quantum Causal Modelling

Emily Adlam[1]

[1]*Rotman Institute, University of Western Ontario, Canada*

In this talk I set out to understand the significance of the process matrix formalism and the quantum causal modelling programme for ongoing disputes about the role of causation in fundamental physics. I argue that the process matrix programme has correctly identified a notion of 'causal order' which plays an important role in fundamental physics, but this notion is weaker than the common-sense conception of causation because it does not involve asymmetry. I argue that causal order plays an important role in grounding more familiar causal phenomena. Then I apply these conclusions to the causal modelling programme within quantum foundations, arguing that since no-signalling quantum correlations cannot exhibit causal order, they should not be analysed using classical causal models. This resolves an open question about how to interpret fine-tuning in classical causal models of no-signalling correlations. Finally I observe that a quantum generalization of causal modelling can play a similar functional role to standard causal reasoning, but I emphasize that this functional characterisation does not entail that quantum causal models offer novel explanations of quantum processes.

Complexity as time

Julian Barbour

Elimination from the N-body gravitational problem of all traces of the absolute elements that Newton introduced in dynamics together with adoption of the Newton gravitational potential made scale-invariant as both time and a measure of complexity reveals remarkable properties hidden in standard presentations. Time and structure become one and the same thing and Newton's theory of universal gravity, properly interpreted, is not one of a clockwork universe but a theory of creation. An arrow of time is a dynamical necessity, not something that needs to be explained by imposition of a special low-entropy condition in the past. Perhaps most intriguingly the Newtonian gravitational potential made scale-invariant through multiplication by the root-mean-square length exhibits purely classical quantum-like structures of the kind enforced by the Pauli exclusion principle and also indications of quantisation of lengths.

Time and clocks in extreme quantum regimes

M. Bojowald[1]

[1]Institute for Gravitation and the Cosmos, The Pennsylvania State University, University Park, PA 16802, USA

Time is usually represented in physical models as a mathematical parameter that does not exhibit interactions or dynamics of its own. However, fundamental theories such as general relativity and its possible quantum versions suggest a more physical role of space-time, and therefore of time. While low-curvature space-time phenomena can be described well by time as a simple coordinate, high-curvature and extreme quantum regimes may require new physical models of time. Examples are time extracted from an oscillating fundamental clock, which has been shown to imply enhanced decoherence and thereby an upper bound on the fundamental clock period, and new causal properties in models of quantum space-time at high curvature.

Causal Set Quantum Gravity and the Hard Problem of Consciousness

Fay Dowker

[1]*Imperial College, London, UK*
[2] *Perimeter Institute, Waterloo, Ontario, Canada*

In this talk I will develop Rafael D. Sorkin's heuristic that a partially ordered process of the birth of spacetime atoms in causal set quantum gravity can provide an objective physical correlate of our perception of time passing. I will argue that one cannot have an external, fully objective picture of the birth process because the order in which the spacetime atoms are born is a partial order. I propose that live experience in causal set theory is an internal ``view'' of the objective birth process in which events that are neural correlates of consciousness occur. In causal set theory, what ``breathes fire'' into a neural correlate of consciousness is that which breathes fire into the whole universe: the unceasing, partially ordered process of the birth of spacetime atoms.

References

[1] Fay Dowker https://arxiv.org/abs/2209.07653

Time in quantum physics

Klaus Fredenhagen

II. Institut für Theoretische Physik, Hamburg
Luruper Chaussee 149, 22761 Hamburg

An observable in the sense of a positive operator valued measure is constructed which characterises the time when a given event happens. It can be obtained by viewing the Schrödinger equation as a constraint.

References

R. Brunetti, K.Fredenhagen, Physical Review A66, 044101 (2002)
R. Brunetti, K. Fredenhagen. M. Hoge, Found. Phys. 40, 1368 (2010)

Geometrical and matter clocks in quantum gravity models

Kristina Giesel

Department Physik, Institut für Theoretische Physik III, Lehrstuhl für Quantengravitation, FAU Erlangen-Nürnberg, Erlangen, Germany
kristina.giesel@gravity.fau.de

Accessing the physical sector in models of quantum gravity is on the one hand a challenge, but on the other hand also an important step to be able to analyse and test such models. One way to complete the quantisation programme in loop quantum gravity is to choose so-called matter or geometric clocks for which Dirac observables can be constructed in the framework of the relational formalism. The quantisation step then consists in finding representations for the corresponding algebra of Dirac observables that allow one to quantise the dynamics as well. In this way, one obtains an observer-dependent quantum field theory. We will give a brief overview of the existing models and discuss their similarities and differences. Finally, we will discuss examples for investigating some physical properties of models formulated with a particular choice of clocks.

Time and Rotation

E. Hackmann

ZARM, University of Bremen, Germany

In the context of Special and General Relativity the presence of rotations have a peculiar influence on time. In Special Relativity the Sagnac effect prevents a consistent Einstein synchronisation of clocks in closed rings, and in General Relativity rotations introduce new effects on clocks, so called gravitomagnetic effects. We will discuss these effects in detail and also take a look on prospects to measure the gravitomagnetic clock effect with satellites orbiting the Earth.

How to (not) break local Lorentz invariance in gravity theory

Manuel Hohmann[1]

[1]*Laboratory of Theoretical Physics, Institute of Physics, University of Tartu, W. Ostwaldi 1, 50411 Tartu, Estonia*

Local Lorentz invariance is one of the crucial features of general relativity which allows relating the reference systems, and hence the clocks, of relatively moving observers. Several gravity theories are claimed to break local Lorentz invariance, including theories involving quantum corrections, modified dispersion relations, Finsler geometry and teleparallel gravity. I explain which of these correspond to an observable violation of local Lorentz invariance and which, despite their name, cannot be observed in nature, even if they are present in the theory.

References

[1] M. Hohmann, Int. J. Geom. Meth. Mod. Phys. **19, Supp. 1** 2240001 (2022) [arXiv:2112.15173 [gr-qc]].

[2] M. Hohmann, C. Pfeifer and N. Voicu, J. Math. Phys. **63** 032503 (2022) [arXiv:2106.14965 [math-ph].

Relational observables and microcausality in gravity

P. Höhn[1]

[1] *Okinawa Institute of Science and Technology, Onna, Japan*

The diffeomorphism gauge symmetry of generally covariant theories challenges traditional notions of locality and leads to the 'problem of time'. Relational observables constitute a way to address these challenges in both the classical and quantum theory. These are gauge-invariant observables that encode how some degrees of freedom localize and evolve relative to others. In this talk, I will summarize recent progress on constructing such observables and a relational form of time evolution. I will also discuss the interplay of relational observables with causal structure, especially whether they commute at spacelike separation and thus obey microcausality.

References

[1] C. Goeller, P. Höhn and J. Kirklin, arXiv:2206.01193 (2022)

[2] P. Höhn, A. Smith and M. Lock, Phys. Rev. D **104**, 066001 (2021)

[3] P. Höhn, A. Smith and M. Lock, Front. Phys. 9:587083 (2021)

[4] A.-C. de la Hamette, T. Galley, P. Höhn, L. Loveridge and M. Müller, arXiv:2110.13824 (2021)

Origin of irreversibility in the Universe

Claus Kiefer

University of Cologne, Institute for Theoretical Physics

I discuss whether the origin of the observed arrows of time can be derived from quantum cosmology. After a general discussion of the problem,
I address the concept of entropy in cosmology and give some numerical estimates. I then present a brief introduction into the formalism of quantum gravity that I use in the following analysis.
I investigate the possibility whether a natural boundary condition of low initial entropy can be imposed on the quantum gravitational state. A tentative scenario is discussed in which the observed arrows of time have their roots in this quantum state.

References

[1] C. Kiefer, AVS Quantum Science **4**, 015607 (2022); arXiv:2111.02137.
[2] H. D. Zeh, The Physical Basis of the Direction of Time, 5th ed. (Springer, Berlin, 2007).

Time and Relativistic Reference Systems

S. A. Klioner

Lohrmann Observatory, Technische Universität Dresden, 01062 Dresden, Germany

The review talk discusses the role of time in the modern astronomical relativistic reference systems used for precise modelling various physical phenomena in the Solar System. After a general introduction to the theory of relativistic reference systems such as Barycentric Celestial Reference System and Geocentric Celestial Reference System, we review the relativistic time scales used in astronomy, space science, geodesy and related disciplines. We will show how to the time scales and reference systems work for the relativistic models for some kinds of high-accuracy observations.

The Unit(y) of Time

Claus Lämmerzahl

University of Bremen, ZARM, Bremen, Germany

In this overview talk various definitions and realizations of time are considered and compared. These realizations are clocks based on kinematics and dynamics, on electromagnetic and gravitational interactions, on classical and quantum systems. Conditions are stated for which all these time scales coincide. Furthermore, the issue of the synchronization of clocks will be treated. Finally, the importance of the definition of time for the new Système International will be outlined.

Quantum Clock Interferometry

A. Lezeik[1], Klaus Zipfel[1], Mario Montero[1], Ernst Rasel[1], Christian Schubert[1,2], Dennis Schlippert[1]

[1]*Institut für Quantenoptik, Leibniz Universität Hannover, Germany*
[2]*Institut für Satellitengeodäsie und Inertialsensorik, Deutschen Zentrum für Luft- und Raumfahrt (DLR), Hannover, Germany*

Understanding the elapse of proper time in quantum regimes is crucial to the understanding of general relativity and quantum mechanics. A free falling atomic clock in a coherent spatial superposition raises the question as to how proper time evolves between the two superposition states, i.e. the quantum clock[1,2]. Quantum Clock Interferometry (QCI) is a series of experiments aiming to study the behaviour of the quantum clock in a gravitational field.

In this talk, we review the principles of QCI and give an overview of interferometry geometries that are sensitive to the proper time difference between the superposition states of the quantum clock due to gravitational redshift[3]. We discuss the possible implications to test the universality of gravitational redshift and the equivalence principle[4]. As the sensitivity of such an interferometer scales with the enclosed spacetime area of the quantum clock trajectory, this motivates long free fall times. This can be achieved through long baselines atom interferometers and atomic fountains such as the Very Long Baseline Atom Interferometry (VLBAI) facility in Hannover. We present the 16m facility, its controlled and well understood environment[5] and its ytterbium and rubidium atomic chambers[6] that work together to provide a platform for QCI experiments.

[1]: M Zych *et al* 2016 J. Phys*: Conf. Ser.* 723 012044
[2]: A. Roura *et al* 2021 Phys. Rev. D 104, 084001
[3]: F. Di Pumpo *et al* PRX Quantum 2, 040333
[4]: C. Ufrecht *et al* Phys. Rev. Research 2, 043240
[5]: A. Lezeik *et al* 2022 arXiv:2209.08886
[6]: E Wodey *et al* 2021 J. Phys. B: At. Mol. Opt. Phys. 54 035301

Time in multi-ion systems

T.E. Mehlstäubler
Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany
Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany

Trapped and laser-cooled ions allow for a high degree of control of atomic quantum systems. They are the basis for modern atomic clocks, quantum computers and quantum simulators. In our research we aim to use ion Coulomb crystals, i.e. many-body systems with complex dynamics, for precision spectroscopy. This paves the way to novel optical frequency standards with ultra-high stability and for applications such as relativistic geodesy and quantum simulators in which complex dynamics becomes accessible with atomic resolution. We will discuss the dynamics of trapped ion crystals and detail on the work on a multi-ion clocks. In particular, we will discuss aspect such as time dilation in such spatially extended complex quantum systems.

Experimental characterisation of standard clocks

Volker Perlick

University of Bremen, Germany

Standard clocks are defined in general relativity as clocks measuring proper time. The latter is defined, in turn, as a parametrisation of a worldline such that the corresponding tangent vector has unit length. In this talk I discuss a characterisation of standard clocks that uses light rays and freely falling particles as the tools. It fits very well in the axiomatic approach to general relativity of Ehlers, Pirani and Schild. I compare this characterisation with two other ones brought forward already in the 1960s by Marzke and Wheeler and by Kundt and Hoffmann, respectively. I also discuss in some detail to which alternative theories of gravity this characterisation can be generalized, with a special emphasis on Weyl geometry and on Finsler geometry.

Atomic time, clocks, and clock comparisons in relativistic spacetime

Gérard Petit[1]

[1]*Bureau International des Poids et Mesures, 92312 Sèvres, France*

Spacetime references that are used in the vicinity of the Earth and more generally in the Solar System are developed in the frame of the General Relativity theory. The International Astronomical Union passed two sets of Resolutions in 1991 and 2000, that explicitly define reference systems for the Earth (Geocentric Reference System) and for the Solar System (Barycentric Reference System) by providing the metric tensor and deriving transformation formulas between proper quantities and coordinates in the GRS and BRS, and between GRS and BRS coordinates.

The time coordinates in the GRS (Geocentric Coordinate Time TCG and Terrestrial Time TT) are presented. The relativistic formalism is applied in the geocentric system to solve practical problems encountered when using or comparing clocks in the vicinity of the Earth. These concern first the transformation between proper time and coordinate time for clocks on the Earth and in satellites (more specifically for GNSS); then the computation of the coordinate time of propagation of an electromagnetic signal in the vicinity of the Earth which is the basis of all clock comparison techniques, and in fact of all space geodesy techniques.

The lecture presents the main features of atomic timescales under the responsibility of the BIPM (TAI, UTC, UTCr and TT(BIPM)) which all provide realizations of the coordinate time TT. International Atomic Time TAI, from which UTC is derived, is generated on a monthly basis. TAI accuracy is provided by primary frequency standards (Cs fountains, based on the Cs transition presently defining the second) and by secondary frequency standards (mostly optical lattice clocks) operated in a number of time laboratories. Frequency standards also form the basis for TT(BIPM), the ultimate reference time coordinate produced by the BIPM.

Upcoming and future developments of time transfer techniques and atomic clocks are presented with their potential impact on atomic timescales. Particular emphasis is given to ultra-accurate optical clocks that are expected to provide a re-definition of the second in 2030. One main goal for the coming decades is to operate the technique of chronometric levelling, in which the comparison of accurate clocks placed at different locations on Earth provides a direct measurement of the difference in gravity potential, thus in height. A global network of optical clocks with a relative frequency accuracy of 10^{-18} could realize a global height reference with 1-centimeter consistency, if the clocks' frequencies can be remotely compared with the same accuracy. One can also imagine the most accurate clocks being placed in satellites in high orbit, far from the noisy Earth environment, to serve as a stable reference for terrestrial height systems and timescales.

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[1] Retired. Presently consultant for the BIPM Time Department.

Geometry of physical dispersion relations

D Rätzel[1], S Rivera, FP Schuller
[1]ZARM, Uni Bremen, Am Fallturm 2, 28359 Bremen

To serve as a dispersion relation, a cotangent bundle function must satisfy three simple algebraic properties. These conditions are derived from the inescapable physical requirements that local matter field dynamics must be predictive and allow for an observer-independent notion of positive energy. Possible modifications of the standard relativistic dispersion relation are thereby severely restricted. Dispersion relations passing the simple algebraic checks derived here correspond to physically admissible Finslerian refinements of Lorentzian geometry.

References

[1] D Rätzel, S Rivera, and FP Schuller, Phys. Rev. D 83, 044047

Quantum mechanics can be extended to general relativistic temporalisty

C Rovelli

Aix-Marseille University, CPT-CNRS, F-13288 Marseille, France.
Perimeter Institute, 31 Caroline Street N, Waterloo, N2L2Y5, Canada.
The Rotman Institute of Philosophy, 1151 Richmond St.N, London N6A5B7, Canada.

There is a persistent misunderstanding in the literature regarding the possibility of extending quantum theory to dynamical systems that do not have a canonical time, like General Relativity. This misunderstanding gives rise to ill-founded discussion about a pretended "problem of time" in quantum gravity. I show that, contrary to what often uncritically assumed, quantum theory can be extended to treat systems with a different temporal structure than non-relativistic quantum mechanics or conventional relativistic quantum field theory.

References

[1] C. Rovelli, Quantum Gravity, CUP 2004.
[2] F. Vidotto and C. Rovelli, Covariant Loop Quantum Gravity, CUP2015.

Quantum engineering optical clocks

Piet O. Schmidt
Physikalisch-Technische Bundesanstalt and
Leibniz University Hannover

Optical atomic clocks are with eighteen significant digits the most accurate measurement devices available to us. They are a highlight example of quantum technologies 2.0 which are characterized by exquisite quantum control over all degrees of freedom of atoms. Combined with world-record laser technology with millihertz linewidths and tens of seconds coherence times, fractional frequency uncertainties of a few 10^{-18} have been demonstrated in frequency comparisons of such clocks. In my contribution, I will describe the basic principle and building blocks of optical clocks, how they are compared and discuss some of the technological challenges [1] as well as fundamental aspects. In particular, I will show how quantum engineering techniques can overcome limitations in clocks concerning their systematic and statistical uncertainty [2], and how quantum algorithms [3,4] provide access to new clock species such as molecular [5,6] and highly charged [7,8] ions with fascinating applications for searches of new physics [9].

1. A. D. Ludlow, M. M. Boyd, J. Ye, E. Peik, and P. O. Schmidt, "Optical atomic clocks," Rev. Mod. Phys. **87**, 637–701 (2015).
2. N. Aharon, N. Spethmann, I. D. Leroux, P. O. Schmidt, and A. Retzker, "Robust optical clock transitions in trapped ions using dynamical decoupling," New J. Phys. **21**, 083040 (2019).
3. S. A. King, L. J. Spieß, P. Micke, A. Wilzewski, T. Leopold, J. R. Crespo López-Urrutia, and P. O. Schmidt, "Algorithmic Ground-State Cooling of Weakly Coupled Oscillators Using Quantum Logic," Phys. Rev. X **11**, 041049 (2021).
4. P. O. Schmidt, T. Rosenband, C. Langer, W. M. Itano, J. C. Bergquist, and D. J. Wineland, "Spectroscopy Using Quantum Logic," Science **309**, 749–752 (2005).
5. F. Wolf, Y. Wan, J. C. Heip, F. Gebert, C. Shi, and P. O. Schmidt, "Non-destructive state detection for quantum logic spectroscopy of molecular ions," Nature **530**, 457–460 (2016).
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Time in Newtonian physics from a spacetime perspective

P. K. Schwartz[1]

[1]*Institute for Theoretical Physics, Leibniz University Hannover, Appelstraße 2, 30167 Hannover, Germany*

Special and general relativity have both changed our perspective on the concept of time in a fundamental way. But even in 'non-relativistic' Newtonian physics, time is a concept deeper than it might appear to the naked eye.

In this talk, I will review the Newtonian concept of time—and, as a consequence, the concept of space—from a modern, spacetime-oriented point of view. This perspective particularly clarifies the relationship between Newtonian time on the one hand and special- or general-relativistic time on the other hand, showing how and in which sense the former arises from the latter in a Newtonian limit.

Application of optical clocks for unification of height systems and determination of temporal variations in the Earth's gravity field

Akbar Shabanloui, Asha Vincent, Hu Wu and Jürgen Müller
Institute of Geodesy, Leibniz University of Hannover, Hannover, Germany

The current generation of optical clocks has reached a fractional frequency uncertainty of 1.0×10^{-18} which corresponds to a gravitational potential change of 0.1 m^2/s^2 or 1 cm change in height. Those gravitational potential differences can be observed as gravitational redshift when comparing the frequencies of optical clocks. Optical clock networks show a great potential for height systems unification. To unify local/regional height systems, the offsets between different height systems and further discrepancies such as tilts along national levelling lines or in longitudinal and latitudinal directions can be detected using optical clock measurements. Furthermore, high-performance atomic clocks provide promising results in detecting gravitational potential variations due to different mass change processes such as present-day ice-mass loss in Greenland or groundwater changes in India. Large-scale mass variations might even be determined with precise optical clocks on-board of Low Earth Orbiters (LEOs) such as SLR-like (e.g. LAGEOS-1/2) or GRACE-like missions (e.g. the MAGIC constellation). To demonstrate the potential of space-borne clocks for the determination of temporal variations of the low-degree gravity field coefficients, various configurations of satellite orbits, i.e. at different altitudes (between 400 and 6000 km) and inclinations, as well as different values on the clock performance are considered. The optical clocks onboard LEOs have demonstrated promising results in estimation of the degree-2 coefficients.

Acknowledgements: This research was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy EXC 2123 QuantumFrontiers, Project-ID 390837967.

The Page-Wootters formalism and quantum time dilation

Alexander R. H. Smith

Department of Physics, Saint Anselm College, Manchester, NH USA,
Department of Physics and Astronomy, Dartmouth College, Hanover, NH USA

General relativity does not specify a preferred reference frame, and conservatively we should not expect that its quantization necessitates such background structure. However, this desire is incongruent with orthodox formulations of quantum theory which rely on a background time parameter or spacetime foliation external to the theory. Such considerations have led to the development of relational quantum dynamics and, in particular, the Page-Wootters formalism, which seeks to describe motion relative to a reference frame internal to a quantum theory that encompasses both the system of interest and employed reference frame.

I will begin by reviewing the modern formulation of the Page-Wootters formalism in terms of Hamiltonian constraints, generalized coherent states, and covariant time observables. I will then discuss Kuchar's criticism of the Page-Wootters formalism and its resolution by showing that the formalism is equivalent to formulations of dynamics in terms of relational Dirac observables (evolving constants of motion). This relational formalism will then be applied to the description of relativistic particles with internal clock degrees of freedom. A probabilistic notion of time dilation between such quantum clocks will be introduced and used to describe quantum corrections to their relative time dilation due to coherence in their external wave functions. This coherence leads to a novel interference effect that offers a new test of physics at the intersection of quantum mechanics and relativity.

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Theoretical investigation of a cavity-clock operating in Earth's gravity

S. Ulbricht[1,2] **and A. Surzhykov**[1,2]

[1]*Physikalisch–Technische Bundesanstalt, D–38116 Braunschweig, Germany*
[2]*Technische Universität Braunschweig, D–38106 Braunschweig, Germany*

In modern laser-cavity setups a relative frequency stability of $\delta\nu/\nu = 10^{-17}$ and beyond can be achieved. Thus, modern laser cavities operate in the same range of precision as atomic cesium clocks, constituting the "second" by providing our primary frequency standard. Based on Einstein's early works on special relativity, Lewis and Tolman proposed a simple model of a clock, consisting of a light ray bouncing back and forward between two comoving mirrors to visualize the effect of time dilation. We will pick up and extend this model to study the applicability of such a cavity-clock for tests of special and general relativity and discuss the concept of "the time" measured by such a clock device in the Earth's gravitational field. This investigation also gives rise to the analysis of the cavity internal light deflection effect and redshift properties of the laser light, initially entering the cavity. Finally, we will have a thought about the conceptional differences of timekeeping using either a cavity-clock or light emitted by an atomic clock transition.

Time observables in quantum mechanics

R.F. Werner

Quantum Information Group, Leibniz Universität Hannover, Germany

According to a famous argument by Pauli, a selfadjoint time operator canonically conjugate to the Hamiltonian cannot exist if the Hamiltonian is unbounded below. On the other hand, recording the time of a detector click is one of the most common measurement schemes in any lab. This discrepancy is mostly left unresolved in the textbook literature, but satisfactory approaches using positive operator valued measures as the basic notion of “observable” have long been developed. In the talk I review three options, varying in the degree of detail of detector description.

The overall statistics of an arrival time measurement is described by a covariant observable, but this takes into account the whole time evolution, and so there is no notion of putting “the same detector” in a different environment. The most detailed version is an explicit description of the coupling to a probe system with subsequent time measurement on the probe. This is usually very hard to get explicitly. A practical compromise relies on introducing absorptive terms in the Hamiltonian, so the dynamics becomes modified to a contraction semigroup [1]. The loss of normalization is then interpreted as arrival probability. The connection between these approaches is provided by scattering theory. Time-Energy uncertainty relations will be given in all three cases.

Time permitting, examples will be arrival at a point or at infinity, the role of contraction semigroups as no-event parts of Lindblad-type dynamical semigroups, the Hartmann effect in tunneling, and the full counting statistics of particle beams [2].

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Abstracts of Posters

(in alphabetical order)

The concept of time and its units in ancient India

A. Beesham[1,2]

[1]University of Zululand, KwaDlangezwa, South Africa
[2] Mangosuthu University of Technology, Umlazi, South Africa

A great deal of knowledge about time can be gleaned from ancient India, in particular, the Vedas, ancient Indian scripts. These scripts are very old, and there is no accepted idea of exactly how old they are. There an infinite series of births and deaths of the universe are described. Units of time ranging from a fraction of a second up to time scales of billions of years and beyond are discussed. We endeavour to describe these units of time and compare to our current units of time. It is very intriguing as to why people so long ago would define such small units of time when the atom had not even been discovered yet. What is the motive behind this? The time scales of the series of births and deaths of the universe are discussed. It is found that there is a great deal of similarity with our current accepted ideas of the universe. In this poster we try to unravel some of the mysteries of ancient Indian thoughts about time.

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Spontaneous scalarization of self-gravitating magnetic fields

Rogério Capobianco

University of Oldenburg, Institute of Physics, Oldenburg, Germany

The phenomenon known as Spontaneous Scalarization arises once a certain threshold in curvature is exceeded. It is triggered by an instability on the scalar field system that can lead to a stable scalarized solution. In this work, we show that an extended, self-gravitating system, which is static, cylindrically symmetric, and possesses electromagnetic fields, can undergo spontaneous scalarization. We demonstrate that a real massive scalar field condenses on the Melvin Magnetic Universe when introducing a non-minimal coupling between the scalar field and (a) the magnetic field, and (b) high-order curvature terms, respectively. We found that in both cases the solution exists on a finite interval of the coupling constant and solutions with a number of nodes, k, in the scalar field, exist. For case (a) we observe that the intervals of existence are mutually exclusive for different nodes.

Entangled clock networks in gravity

Marian Cepok

University of Bremen, ZARM, Bremen, Germany

We investigate the interplay of quantum entanglement and gravity in the context of optical clocks. In particular, we develop a theoretical basis for the description of networks of entangled atomic clocks in gravitational fields based on Newtonian Gravity. Entangled clock networks potentially improve time keeping stability beyond that of classically correlated clock networks as well as synchronisation between distant clocks. Therefore entanglement enhances comparability of clock frequencies, in turn promising higher accuracy e.g. for pairwise redshift measurements between clocks. Additionally, entangled clock networks provide means for testing our theoretical models of the gravity-quantum interface.

Beyond semiclassical time - dynamics and quantum diffeomorphism invariance

Leonardo Chataignier[1]

[1] *Dipartimento di Fisica e Astronomia, Università di Bologna, via Irnerio 46, 40126 Bologna, Italy*

We show that the usual Born–Oppenheimer type of approximation used in quantum gravity, in which a semiclassical time parameter emerges from a weak-coupling expansion of the Wheeler–DeWitt constraint, leads to a unitary theory at least up to the next-to-leading order in minisuperspace models. As there are no unitarity-violating terms, this settles the issue of unitarity at this order, which has been much debated in the literature. Furthermore, we also show that the conserved inner product is gauge-fixed in the sense that the measure is related to the Faddeev–Popov determinant associated with the choice of semiclassical time as a reparametrization gauge. This implies that the Born–Oppenheimer approach to the problem of time is, in fact, an instance of a relational quantum theory, in which transition amplitudes can be related to conditional probabilities. We comment on how this approach can be applied to computation of corrections to the usual power spectra of primordial perturbations and the anisotropies of the Cosmic Microwave Background radiation. Finally, we also relate this perturbative formalism to a non-perturbative definition of diffeomorphism-invariant relational observables, and we argue that time exists even beyond the semiclassical level, but it is entirely defined from the spectra of quantum operators.

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Measurement of Time and Poincaré's Convoluted Position in the Theory of Special Relativity

R. A. Ciftci[1]

[1]*Department of Physics, Middle East Technical University, Ankara, Turkey*

Poincaré and Einstein are thought to be simultaneous discoverers of special relativity. However, although he was one of the authors, Poincaré had a controversial position due to his critical attitude towards the theory. Stein (2021) explains Poincaré's attitude by claiming that he was deceived by a mistaken philosophy of science. This paper argues that Poincaré, on the contrary, had a well-working philosophical methodology, so he was much earlier in recognizing the problems of the theory, problems which Einstein also is known to admit later. The issues of the theory are that special relativity is a principle theory, and in relation to this, the theory needs measuring clocks and rods as elementary constituents.

Keywords: Special Relativity; measurement; time; clock hypothesis; conventionalism.

Atom Interferometric Detection of Dark Matter

<u>D. Derr</u>[1] and E. Giese[1]

[1]Technical University of Darmstadt, Department of Physics, Institute for Applied Physics, Schlossgartenstr. 7, D-64289 Darmstadt, Germany

Since the internal structure of atoms is possibly sensitive to dark matter (DM), atomic clocks may serve as suitable DM detectors. Additionally, atomic clocks provide a platform for detecting violations of the Einstein equivalence principle (EEP), e. g. universality of clock rates or universality of the gravitational redshift.

These features are not exclusive to atomic clocks, as atom interferometers can detect EEP violations as well, for example via gravimetry. In addition, atomic diffraction processes allow for driving internal transitions, which connects clocks and atom interferometers in a natural fashion.
Making use of the atom interferometer's internal (clock) transitions allows combining the clock's and the atom interferometer's susceptibility to DM in a single apparatus. Furthermore, the atoms' centre-of-mass motion is potentially affected by DM as well, making atom interferometers susceptible to DM even without internal transitions.

In this contribution we present a unified treatment of clocks and atom interferometers, in which relativistic effects, mass defects, and violation parameters (due to DM and EEP) are included. Based on this formalism, we investigate the leading-order effects for atom interferometers with and without internal transitions, as well as quantum clock interferometry. Consequently, different setups are analysed. Overall, we identify the effects of DM in atom interferometers and discuss the difference between the ones induced by the atom's clock properties and centre-of-mass effects.

Gravitational Decoherence from Coherent Matter-Light Interactions as a Causal Consistency Requirement for Gravity Induced Entanglement

M. Kemal Döner

Friedrich-Schiller-Universität Jena, Jena, Germany
E-mail: kemal.doner@uni-jena.de

Despite the lack of an established theory of quantum gravity, there is a widespread believe that, as far as low-energy physics is concerned, perturbative quantum gravity (i.e. the perturbative quantum field theoretical treatment of linearized Einstein gravity) provides an accurate model for the gravitational interactions of quantum matter. Many questions about these interactions can then be answered in direct analogy to the electrodynamical ones. For instance, the question “what is the gravitational field of a spatial superposition state of a massive particle” is immediately resolved by noticing that the particle-field system becomes entangled, precisely as for the electromagnetic interaction. This analogy holds for many proposed quantum gravitational effects, such as the recently suggested observation of entanglement induced by Newtonian forces, some gravitational decoherence effects, or thought experiments about the consistency of quantum gravity. In this paper, we will focus on these thought experiments by making use of matter-like interactions as a casual consistency requirement of gravity induced entanglement and create an adequate model for describing the situation.

A gravitationally induced decoherence model in the relational formalism

M. J. Fahn[1], **K. Giesel**[1], **and M. Kobler**[1]

[1]*Institute for Quantum Gravity, Theoretical Physics III,*
Friedrich-Alexander-Universität Erlangen-Nürnberg,
Staudtstr. 7, 91058 Erlangen, Germany

On the poster, the coupling of a scalar field to linearised gravity and the derivation of a relativistic gravitationally induced decoherence model using Ashtekar variables is presented. The model is formulated at the gauge invariant level using suitable geometrical clocks in the relational formalism, broadening existing gauge invariant formulations of decoherence models. For the construction of the Dirac observables the known observable map is extended by a kind of dual map where the role of clocks and constraints is interchanged. Also a second choice of geometrical clocks existing in the ADM literature is discussed which in the end enables the comparison of the final equation using either of the set of clocks. After the application of a reduced phase space quantisation on Fock space, the final master equation is derived choosing a Gibbs state for the gravitational environment and using the projection operator technique. The resulting master equation is not automatically of Lindblad type, a starting point sometimes assumed for phenomenological models, but still involves a residual time dependence at the level of the effective operators in the master equation due to the form of the correlation functions that are expressed in terms of thermal Wightman functions.

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The poster is based on work in

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Connecting timelike and spacelike correlations in cooperation games

Lorenzo Catani[1] , Ricardo Faleiro[2] , Pierre-Emmanuel Emeriau [3]

Shane Mansfield [3] , and Anna Pappa [1]

1−Electrical Engineering and Computer Science Department, Technische Universitat Berlin, 10587 Berlin, Germany

2− Instituto de Telecomunicações, 049-001, Lisboa, Portugal

3− Quandela, 7 Rue Léonard de Vinci, 91300 Massy, France

In this work we focus on two classes of games: XOR nonlocal games and XOR* sequential games. XOR games have been widely studied in the literature of nonlocal games, where it is known that quantum correlations originating from spacelike separated measurements perform better than their classical counterparts. We introduce XOR* games as a natural analogue to XOR games, within a setup where a single resource system is subjected to timelike ordered sequence of operations and a final measurement. We prove, using the diagrammatic language of process theories, that under certain assumptions the optimal classical and quantum correlations arising in both scenarios are equivalent, and consequently that the corresponding classical (Bell) and quantum (Tsirelson) bounds of some XOR games are identical to that of their dual XOR* version, and vice-versa.

One main assumption in the theorem is that the timelike correlations in the XOR* games are restricted to those originated from reversible/unitary operations. However, this does not affect the generality of the theorem in terms of assessing the maximum quantum-classical advantage gap.

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Relativistic Perturbation Theory of Schwarzschild Geodesics

Bennet Grützner

29. Januar 2023

Abstract For the classical Kepler solutions of the two body problem, the pertubation theory is given by the Gauß equations. These describe the perturbated orbit by giving time dependence to the orbital elements, therefore giving osculation orbits.

In this paper, this concept is applied to the general relativity by taking the Schwarzschild geodesics as a starting point. A mathematical theory is constructed to obtain generalized Gauß equations in a non-euclidian geometry. This mathematical theory is then applied to generate the generalized Gauß equations for the Schwarzschild geodesics. Some challenges stemming from the more complex nature of the Weierstrass $\wp$ function are discussed, especially with regards to the mean anomaly M_0.

The premetric approach in teleparallel gravity

M.J. Guzmán[1]

[1]*Institute of Physics, University of Tartu, Tartu, Estonia*

The field equations of some theories can be written in the premetric approach, which consists in a formulation of a physical theory that prescinds from the metric tensor as the fundamental variable, and relates a field strength and an excitation field through a constitutive law where the metric enters only through a constitutive tensor. A consequence of the premetric approach is the division of universal constants into two classes. Surprisingly, gravity can be written in this approach, but only through its teleparallel equivalent, and it has been used in the literature for reinterpreting the Lagrangian and developing the Hamiltonian formulation of this theory. It is an interesting, but still open question, if the premetric approach and its downplay of the metric tensor could shed some light in the definition and attributes of time in gravitation. We will summarize this approach and present its applications in teleparallel gravity and possible prospects.

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Gravitational field recovery via inter-satellite redshift measurements

J. P. Hackstein[1], E. Hackmann[1], D. Philipp[1] and C. Lämmerzahl[1]

[1]Center of Applied Space Technology and Microgravity, Bremen, Germany
E-mail: jan.hackstein@zarm.uni-bremen.de

Satellite gravimetry is commonly used to monitor global changes in the Earth system. First experiments in terrestrial gravimetry already employ high-precision atomic clocks to measure physical heights. In relativistic gravity, a frequency comparison of two clocks is susceptible to changes in the clocks' positions in the gravity field and their relative velocity. Therefore, clocks constitute ideal tools to investigate the Earth's gravity field. Equipping Earth-orbiting satellites with clocks and comparing their frequencies to clocks on terrestrial ground stations allows for global and continuous measurements. However, one important obstacle for Earth-satellite chronometry is the low measurement accuracy of the satellite's velocity, which enters into the redshift via the Doppler effect. We present an alternative approach based on the framework of general relativity with velocity measurements between satellites instead of from ground stations. Considering an idealised satellite setup in the Schwarzschild spacetime, pairwise redshift measurements between satellites equipped with clocks are used to recover the gravitational field's monopole moment. We investigate whether or not only relative observables between satellites suffice to recover the complete information of the gravitational field. This method promises higher accuracy for gravity field recovery by improving control over the Doppler effect. Results and error estimates of this simplified setup are compared with conventional Earth-satellite measurements and next steps to generalise this approach are specified.

General relativistic quantum clocks

Ekim T. Hanimeli

Universität Bremen, ZARM, Bremen, Germany

The effects of gravity on quantum clocks has lately been an active field of investigation in order to probe various effects in the interface between gravity and quantum physics. In many of these studies clocks are defined as systems evolving in superposition of two states in a Newtonian potential, with the gravitational effects are given by coupling between the center-of-mass and clock degrees-of-freedom. While these studies lead to some interesting results, they usually require many physical properties to be included by hand. In this context, an alternative approach would be to formulate quantum clocks from first principles in a way consistent with general relativity, resulting in a more general understanding of inertial and gravitational effects on quantum clocks, without any ad hoc assumptions. Here, we present some aspects of this problem, including an overview on some of the existing studies on quantum clocks.

LISA: a cutting edge time/frequency transfer measurement to detect gravitational waves

<u>O. Hartwig</u>[1], **A. Hees**[1], **M. Lilley**[1], **P. Wolf**[1]

[1] *SYRTE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, LNE, 61 avenue de l'Observatoire 75014 Paris, France*

The Laser Interferometer Space Antenna (LISA) will observe gravitational waves (GWs) in the mHz frequency range and is expected to answer a large number of important scientific questions in various areas of astrophysics, cosmology and fundamental physics. LISAs measurement principle relies on interferometrically tracking the relative distance between free-falling test-masses separated by 2.5 million km with a precision of $10\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$. This corresponds to less than $10\,\mu\mathrm{cycle}/\sqrt{\mathrm{Hz}}$ phase noise on the measurement of the optical carrier down to mHz Fourier frequencies or, equivalently, a modified Allen deviation of better than 10^{-22} in fractional frequency after $100\,\mathrm{s}$ integration of the frequency measurement of the incoming laser signal with respect to the local one.

This performance is only achieved in the final interferometric observables for LISA, which are constructed in post-processing using a technique called time-delay interferometry (TDI) that will suppress otherwise overwhelming laser frequency noise by more than 8 orders of magnitude. The input data to TDI are heterodyne interferometric beatnotes in the MHz range, which are recorded on each of the three satellites in comparison to a local clock. No existing space-qualified clocks are precise enough to perform this frequency measurement at the required $\mu\mathrm{cycle}/\sqrt{\mathrm{Hz}}$ precision, which is why LISA will include additional clock-tone modulations on the laser beams to measure relative instrumental clock errors at $50\,\mathrm{fs}/\sqrt{\mathrm{Hz}}$ precision and compensate for them in post-processing.

I will present a unified approach to correct both laser and clock noise in the same processing step, and discuss how these noise reduction steps are embedded into the overall LISA data processing pipeline to produce the final observables from which GWs can be extracted. This work is based on a recent publication [1].

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Compact rack-integrated UV laser system for a transportable Al^+ quantum logic optical clock

Joost Hinrichs[1,2], **Stephan Hannig**[1,3], **Benjamin Kraus**[1,3], **Constantin Nauk**[1], **and Piet O. Schmidt**[1,2,3]

[1] Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany
[2] Leibniz Universität Hannover, 30167 Hannover, Germany
[3] DLR-Institute for Satellite Geodesy and Inertial Sensing, 30167 Hannover, Germany

Optical atomic clocks currently provide the most precise frequency standards. For side-by-side comparisons or applications in relativistic geodesy, transportable and robust setups with lowest possible uncertainties are necessary. The feature of transportability requires a highly-stable, compact and automatized implementation.
For our transportable $^{27}Al^+$ clock all components, including optics and the vacuum chamber, will be integrated into conventional 19 in-racks. As one part of the clock apparatus we present a compact design of the Al^+ logic laser emitting at 267 nm to drive the $^1S_0 \leftrightarrow {}^3P_1$ transition. The system consists of a fibre laser operating at 1068 nm and two frequency doubling cavities to generate the required UV output for the logic transition. The complete optical setup is housed in one rack-integrated aluminium drawer. We present the setup and characterize its efficiency and long-term stability.

Gravity experiments in strong fields using pulsars as clocks

H. Hu[1], M. Kramer[1,2], N. Wex[1], D. J. Champion[1]

[1] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
[2] Jodrell Bank Centre for Astrophysics, The University of Manchester, Oxford Road, Manchester M13 9PL, UK

Pulsars are precise cosmic clocks, some of which can rival the stability of the best atomic clocks on long timescales. In addition, pulsars are strongly self-gravitating bodies, and pulsars in binary systems provide excellent testbeds for gravity experiments in the strong-field regime. Timing the pulses from pulsar itself enables precise measurements of a wide range of relativistic effects, such as orbital precession, time dilation, Shapiro delay, and orbital period decay due to gravitational wave damping. In particular, the Double Pulsar system PSR J0737-3039A/B enables measurements of these effects with unprecedented precision, all of which GR has passed with flying colors. Based on 3-yr MeerKAT observations of PSR J0737-3039A, we further investigate the next-to-leading-order (NLO) signal propagation effects, including the retardation effect due to the movement of pulsar B and the deflection of the signal of pulsar A by the gravitational field of pulsar B. In addition, future observations with MeerKAT and the SKA promise to provide one of the first measurements of the moment of inertia of a neutron star, hence an important complementary constraint on the equation of state of dense matter. Finally, other prospects for future observations of the Double Pulsar are also demonstrated, such as potential measurements of lensing, moment of inertia (and consequently equation of state of dense matter), frame-dragging, and NLO gravitational wave damping.

Some Questions on the Problem of Time and Quantum Mechanics

F. Izaurieta [1]

[1]*Department of Physics, Universidad de Concepción, Concepción, Chile*

Some considerations on whether a quantum observer could induce a relativistic quantum-mechanical time operator through a superposition of Märzke-Wheeler foliations.

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Quasinormal modes of Kerr-Newman black holes in slow rotation

F. S. Khoo

Institute of Physics, University of Oldenburg, D-26111 Oldenburg, Germany

We consider Kerr-Newman black holes in slow rotation up to second order in rotation. We present the results of the respective quasinormal modes for three types of family: gravitational, electromagnetic, and (minimally coupled) scalar fundamental modes. We find that the modes resulted from our slow-rotation approximation agree well with the previous results for full rotation, up to 50 - 60% of the extremal angular momentum.

Optimal Ramsey Protocols in Ion Clocks

T. Kielinski [1] **and K. Hammerer** [1,2]

[1] *Institute for Theoretical Physics, Appelstraße 2, 30167 Hannover, Germany*
[2] *Institute for Gravitational Physics (Albert-Einstein-Institute), Callinstraße 28, 30167 Hannover, Germany*
E-mail: timm.kielinski@itp.uni-hannover.de

Enhancement of clock stability beyond the classical limit can be accomplished by introducing entanglement between the atoms. In particular, one-axis-twisting (OAT) interactions receive much attention since they give enhanced sensitivity by generating squeezed spin states or echo protocols and can be reliably implemented in several experimental setups. In local (frequentist) phase estimation, the sensitivity is characterized using tools as the Fisher information and is limited by the Cramér Rao bound. However, laser noise limits the clock stability and therefore frequency fluctuations during the clock operation have to be considered. To accomplish for the finite prior information, Bayesian phase estimation is applied representing the trade-off between reduction in quantum projection noise (QPN) and the coherence time limit (CTL) of the laser. This work aims to optimize the stability of ion clocks building on a variational class of Ramsey protocols. Theoretical predictions are validated by numerical simulations of the full feedback loop of an atomic clock. The main limitation is imposed by fringe hops, especially in the presence of dead time.

"Time and Clocks", Bad Honnef, Feb. 27 – Mar, 3, 2023

Poster summary, by **Nadja S. Magalhaes**

Title:

Time, spacetime and quantum mechanics

Abstract:

At a macroscopic level, time is a variable used to aid in the description of motion. In classical applications, Newton's understanding of time is adopted in all areas of Physics. Modern Physics involves two limits in which Newton's classical approach breaks down: motions at speeds close to the speed of light and interactions at the subatomic level. These approaches led to the present mainstream theories at those limits, respectively: Einstein's theory of relativity and quantum mechanics. In Einstein's relativity a new approach to time had to be taken, as a limiting speed was assumed for free, massless objects in vacuum, yielding to the spacetime concept that eventually was associated to the gravitational field. In quantum mechanics, the use of time as an operator has been a historical struggle. In this presentation I intend to foster a discussion on the role of time in these two theories, hoping to contribute to the compatibilization between general relativity and quantum mechanics.

WKB decomposition of classical and quantum gravitational degrees of freedom for the QFT-CS limit from Quantum Gravity

G. Maniccia[1,2] **and G. Montani**[3,1] **and S. Antonini**[4]

[1] *Physics Department, "La Sapienza" University of Rome, P.le A. Moro 5, 00185 Roma, Italy*
[2] *INFN Section of Rome, P.le A. Moro 5, 00185 Roma, Italy*
[3] *ENEA, FNS Department, C.R. Frascati, Via E. Fermi 45, 00044 Frascati (Roma), Italy*
[4] *Maryland Center for Fundamental Physics, University of Maryland, College Park, MD 20742, USA*

We construct the proper low energy limit of quantum field theory in curved spacetime (QFT-CS) from the full quantum gravity-matter system, re-evaluating previous works [1,2] from which we outline four emerging shortcomings. To address these points, we formalize the quasi-classical gravitational sector via two intrinsically different components, namely a classical background (here a vacuum diagonal Bianchi I universe) and small quantum corrections to it, in the form of tensor perturbations corresponding to the two graviton degrees of freedom, while the quantum matter sector is expressed in the form of a test scalar field. By implementing a Born-Oppenheimer separation of the full wave functional, we consider the gravitons as "slow" quantum components, whereas matter has a "fast" quantum character [3]. The evolution of the system is then analyzed via a WKB expansion in a Planckian parameter up to the first order. The functional Schrödinger equation governing the quantum matter dynamics is recovered after averaging over quantum gravitational effects, provided that a condition is imposed on the gravitons' wave functional. Such a requirement fixes the gravitons' dynamics and is shown to be equivalent to the purely gravitational Wheeler-DeWitt (WDW) constraint that was implemented in previous approaches. The two main accomplishments of the present work are, on the one hand, the clarification that QFT-CS can be recovered in the low energy limit of the full quantum gravity-matter theory via an averaging procedure, and, on the other, the a posteriori justification of implementing the gravitational WDW equation on the "slow" wave functional, rather than assuming its validity a priori.

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Time and relationality from an emergent quantum gravity perspective

L. Marchetti[1]

[1]University of New Brunswick,
Department of Mathematics and Statistics,
Fredericton, NB, Canada

The relational approach to the problem of time takes an entirely new dimension in quantum gravity contexts in which continuum notions as spacetime and geometry are understood as emergent. We argue that, in this case, the relational strategy is best realized at an approximate and effective level, after suitable coarse-graining and only in terms of special quantum states. Importantly, we also show a concrete realization of such effective relational dynamics in the context of a cosmological application of the tensorial group field theory formalism for quantum gravity.

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Unitarity, singularity resolution, and clock choices in quantum cosmology

S. Gielen[1] **and** **L. Menéndez-Pidal**[2]

[1]School of Mathematics and Statistics, University of Sheffield, Sheffield, United Kingdom
[2] Physics faculty, Complutense University, Madrid, Spain
Email: lumene02@ucm.es

The problem of time has many nuances. Particularly, in minisuperspaces, the Wheeler—DeWitt equation does yield to a well defined notion of evolution. To allow for non static dynamics, one is very often tempted to use a dynamical variable of the system as an internal clock. However, this choice is not unambiguous. In the works [1-3], we study a minisuperspace universe with three quantum clock candidates: a geometrical clock directly related to the scale factor, and two matter degrees of freedom, one coming from a perfect fluid and a free massless scalar field. We see that each choice leads to a different quantum theory. Requiring unitary evolution in each quantum theory results in different dynamics, and consequently not all theories resolve the initial big bang singularity. We highlight the special rôle of unitarity and we show how the supposedly clock neutral Dirac quantisation approach also exhibits similar ambiguities.

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Quantum gravity and cosmological perturbations:

Effects of a modified Friedmann equation on the evolution of gauge-invariant perturbations

S. Gielen[1] and L. Mickel[1]

[1]*University of Sheffield, Sheffield, UK*

We investigate what conclusions can be drawn about alterations to the evolution of cosmological perturbations from a modified Friedmann equation alone. Modified Friedmann equations arise in many quantum gravity scenarios (such as loop quantum cosmology (LQC) or group field theory (GFT)) from the evolution of the expectation value of the volume operator with respect to a relational clock given by a massless scalar field. We derive generalized perturbation equations in the separate universe framework to study the behaviour of large scale perturbations. For a certain class of modified Friedmann equations the conservation laws from general relativity continue to hold, whereas for more general models, this is not the case. As an example for the latter, we compare the evolution of perturbations as obtained from the relational quantum framework of a simple GFT bounce scenario to that given by the generalized perturbation equations and find agreement up to second order effects.

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Progress on PTB's transportable Al^+ ion clock

<u>Constantin Nauk</u>[1], Benjamin Kraus[1,2], Joost Hinrichs[1,3], Simone Callegari[1], Stephan Hannig[1,2] and Piet O. Schmidt[1,2,3]

[1]Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany
[2]DLR-Institute for Satellite Geodesy and Inertial Sensing, 30167 Hannover, Germany
[3]Leibniz Universität Hannover, Institut für Quantenoptik, 30167 Hannover, Germany

Optical atomic clocks achieve fractional systematic and statistical frequency uncertainties on the order of 10^{-18} [1,2]. This enables novel applications, such as height measurements in relativistic geodesy with ∼ 1 cm resolution for earth monitoring [3]. Towards this goal, we set up a transportable clock based on the $^1S_0 \rightarrow {}^3P_0$ transition in $^{27}Al^+$. A co-trapped $^{40}Ca^+$ ion allows state detection and cooling via quantum logic spectroscopy [4] and sympathetic cooling.
We unveil the design and the current status of the transportable apparatus and review the recent development of the laser systems. In particular, we present the clock laser setup emitting at 267.4 nm based on single-pass frequency-quadrupling which allows un-interrupted phase stabilization of the complete path to a fractional frequency uncertainty at a level of well below 10^{-16} at one second. Furthermore, we show the clock laser fundamental frequency stabilized to a transportable clock cavity to reach a fractional frequency uncertainty of 5×10^{-16} at one second.

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Time and Clocks workshop,
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Poster abstract

Clock synchronization through an optical quantum channel part of a free space QKD system

Authors:
Manfred Niehus et.al.
Lisbon Polytechnical School of Engineering & Instituto de Telecomunicações,
Lisboa, Portugal

Precision clocked free-space optical (FSO) links typically require laser links to transmit time-frequency between spatially distant sites to synchronize the times. Precision synchronization is also 'key' in the quantum channel of a high performance free space quantum key distribution system. Recently a method for time-frequency transmission over an optical quantum channel was proposed that does not rely on a classical laser link neither on related network linkage beyond the direct quantum link: the synchronization is based on the transmitted qubits and does hence not need additional hardware, which is a significant driver for installations and deployment.

We consider a model system of an efficient QKD three-state BB84 prepare-and-measure protocol with decoy states, and analyse two related approaches, one that uses a cross-correlation algorithm aiming for low computational complexity, and another one that relies on an a Bayesian probabilistic algorithm. We compare these two promising approaches with regard to computational complexity and speed, as well as robustness towards high channel losses and atmospheric turbulence

Simulation and experimental results will be discussed.

Hamilton's equations in the (covariant) teleparallel equivalent of general relativity

Laxmipriya Pati

University of Tartu, Theoretical Physics, Tartu, Estonia

We present Hamilton's equations for the teleparallel equivalent of general relativity (TEGR), which is a reformulation of general relativity based on a curvatureless, metric compatible, and torsionful connection. For this, we consider the Hamiltonian for TEGR obtained through the vector, antisymmetric, symmetric and trace-free, and trace irreducible decomposition of the phase space variables. We present the Hamiltonian for TEGR in the covariant formalism for the first time in the literature, by considering a spin connection depending on Lorentz matrices. We introduce the mathematical formalism necessary to compute Hamilton's equations in both Weitzenbock gauge and covariant formulation, where for the latter we must introduce new fields: Lorentz matrices and their associated momenta. We also derive explicit relations between the conjugate momenta of the tetrad and the conjugate momenta for the metric that are traditionally defined in GR, which are important to compare both formalisms.

Distinguishing between definite and superposed causal orders

R. Faleiro[1], N. Paunković[1,2] and M. Vojinović[3]

[1] Instituto de Telecomunicações, Portugal
[2] Departamento de Matemática, Instituto Superior Técnico, Universidade de Lisboa, Portugal
[3] Institute of Physics, University of Belgrade, Serbia

We analyse optical realisations of the quantum switch using 4 and 3 spacetime events in classical spacetimes with fixed causal orders, and the realisation of a gravitational switch with only 2 spacetime events that features superpositions of different gravitational field configurations and their respective causal orders. We construct an observable that can distinguish between the quantum switch realisations in classical spacetimes, and gravitational switch implementations in superposed spacetimes. Also, we analyse the single-particle two-way communication protocol recently introduced by del Santo and Dakić, showing that the interaction with the vacuum should be treated as an operation, on equal footing with all other interactions. This way, precisely from the operational point of view, we argue in favour of the spacetime causal description. Finally, we present a protocol that features quantum-mechanical closed timelike curves in the presence of superposed gravitational fields, which do not require exotic spacetime topology.

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Quantum relational field theory

Andrea Russo

University College London, Physics and Astronomy, London, UK

Scalar field theory is formulated on an extended phase space that includes a dynamical description of an embedded hypersurface on which instantaneous states of the field may be defined. This extended phase space is quantised via the Dirac prescription and physical states of the theory are used to define conditional wave functionals of the field relative to an embedding of the real line into 1+1 dimensional Minkowski space, analogous to the conditional state that appears in the Page-Wootters formalism. It is shown that this conditional wave functional satisfies the Schwinger-Tomonaga equation, demonstrating that this manifestly relational formulation is equivalent to standard quantum field theory in this setting.

Tunneling of clocks

P. Schach[1] **and E. Giese**[1]

[1]*Technical University of Darmstadt, Department of Physics, Institute for Applied Physics, Schlossgartenstr. 7, D-64289, Darmstadt, Germany*

Contrary to classical particles, quantum physics allows tunneling of atoms through classically forbidden regions. In first quantized systems, the dynamics of a quantum particle is governed by the Schrödinger equation, effectively a wave equation that allows for tunneling. In this sense, the tunneling process is inherently related to the wave property of matter in quantum mechanics, analogous to evanescent light waves in classical physics. Since matter waves can be composed of bound systems like atoms, they may possess internal degrees of freedom that lead to an internal structure. As they are quantum particles, a superposition of several internal states is possible. Such a superposition constitutes the basis of atomic clocks, which measure time through phase differences between both internal states. Because their phase difference is affected by the motion of the atom in external potentials, it is natural that it is also affected by the tunneling process itself. Consequently, the measured phase difference gives insights into the tunneling process and, in particular, may assign a time period associated with tunneling. Different approaches of such tunneling times have been at the focus of research in recent years.

Detached from these debates, we study theoretically in our contribution the phase difference of tunneled clocks in various differential measurements. In addition, we take relativistic effects into account, such as different masses due to different internal energies during the center-of-mass motion as well as when tunneling through classically forbidden regions. We investigate the information contained in the phase difference of tunneled clocks and relate it to a time scale.

Ramsey interferometry with optimally twisted states and measurements

M. S. Scharnagl[1] and K. Hammerer[1,2]

[1]*Institute for Theoretical Physics, Appelstraße 2, 30167 Hannover, Germany*
[2]*Institute for Gravitational Physics (Albert-Einstein-Institute), Callinstraße 38, 30167 Hannover, Germany*
Email: maja.scharnagl@itp.uni-hannover.de

We consider a variational class of generalized Ramsey protocols with two one-axis-twisting (OAT) operations, one before and one after the phase imprint, for which we optimize the direction of the signal imprint, the direction of the second OAT interaction and the measurement direction via a numerical routine for global optimization of constrained parameters. In doing so, we distinguish between protocols whose signal from spin projection measurements exhibits a symmetric or anti-symmetric dependence on the phase to be measured. We find that the Quantum Fisher Information, which bounds the sensitivity achievable with a one-axis-twisted input state, can be saturated in our variational class of protocols for nearly all initial squeezing strengths. Therefore, the generalized Ramsey protocols considered here allow us to reduce quantum projection noise in comparison to the standard Ramsey protocol considerably.

Relational Dynamics and Time Travel

A. Alonso Serrano[1], J. Santiago[2], S. Schuster[3], and M. Visser[4]

[1]Max-Planck-Institut für Gravitationsphysik, Potsdam, Germany
[2] Section of Astrophysics, Astronomy and Mechanics, Aristotle University of Thessaloniki, Thessaloniki, Greece
[3] Ústav teoretické fyziky, Univerzita Karlova, Prague, Czech Republic
[4] School of Mathematics and Statistics, Victoria University of Wellington, Wellington, New Zealand

The Hamiltonian constraint of general relativity is often described as a fundamental problem for theories of quantum gravity and our usual understanding of dynamics therein: As time does not explicitly appear, theories of quantum gravity have to face the so-called “problem of time”. In recent years, older attempts of resolving this tension through relational dynamics, for example, the Page-Wootters formalism [1], have seen a resurgence and received a lot of attention, culminating in a more unified understanding of different approaches [2]. Classically, time-travel is ruled out (or at the very least contra-indicated) for a long list of reasons. Nevertheless, it often rears its head when assumptions of general relativity have to be relaxed, and it can often provide for tests and new perspectives on better-behaved physics. In this project, we attempt to answer what happens when an emergent notion of time in a quantum system meets the concept of time travel. We study what this can tell us as to how to even define time travel with only relational dynamics, and what new or improved limitations can be formulated through this point of view.

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Extended GUP quantization of the FLRW Universe

Sebastiano Segreto[1] **and Giovanni Montani**[1,2]

[1] *Physics Department, 'Sapienza' University of Rome, P.le Aldo Moro 5, Rome, 00185, Italy*

[2] *ENEA, FSN-FUSPHY-TSM R.C. Frascati, Via E. Fermi 45, Frascati, 00044, Italy*

We analyze the extended GUP theory deriving from the modified uncertainty principle in agreement with the string low energy limit, which is the most general formulation satisfying the Jacobi identity [1], [2]. By means of functional analysis, we first show how a natural formulation of the theory in an infinite momentum space does not lead to the appearance of a nonzero minimal uncertainty in position. Then, we construct a truncated formulation of the theory in momentum space, proving that only in this case we can recover the desired feature of an emerging nonzero minimal uncertainty in position, which - as usual in these theories - can be interpreted as a phenomenological manifestation of cut-off physics effects.

Finally, after a complete characterization of both quantization schemes, we apply them to the FLRW Universe, discussing the model's behavior in different sets of variables.

The obtained results, on the one hand, can shed light on which generalizations of the GUP theory are more coherent with the string low energy limit, in view of the existence of a minimum length deriving from a minimal uncertainty in position, on the other, they can elucidate the consequences of the implementation of these models at the cosmological level.

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Quantum cosmology with fluid clock: Implications for the dressed metric approach

Harkirat Singh Sahota[1] **and Kinjalk Lochan**[1]

[1] *Indian Institute of Science Education and Research, Mohali, India*

The canonical quantization scheme for general relativity is riddled with issues related to a proper definition of observables in a theory with time reparametrization invariance, which leads to the ‘problem of time’ in quantum gravity. For a de-parameterizable model, e.g. a flat-FLRW model with perfect fluid, we tackle this problem following Kuchař's proposal of perennials and observables. Fixing the gauge at the classical level by choosing the fluid degree of freedom as the clock, we quantize the Hamiltonian system and demonstrate that the quantum model is singularity-free, following DeWitt's criteria. We write the phase space expressions for the observables of interest, e.g., Hubble parameter and curvature invariants. Their behavior is studied in the quantum model by writing Hermitian operators that correspond to these observables. Since, these observables are in product form of the phase space variables, they suffer from operator ordering ambiguity. A wave packet is constructed representing a bouncing universe tunneling from the collapsing branch to the expanding branch. The expectation values of the geometric observables are computed with this wave packet, which remain finite at the classical singularity, thereby signaling the robustness of DeWitt's criteria. Moreover, the operator ordering ambiguity is shown to be relevant only near the singularity. We compare the observables for the quantum-corrected spacetime described by a dressed metric with their quantum expectations and check the viability of the dressed-metric approach. The dressed metric approach captures the essence of the full quantum treatment in the case of the dust dominated universe, whereas it receives significant contributions for the dark energy dominated universe. Although the issue of singularity gets resolved, within this clock choice the dressed metric approach might not capture the essential quantum features of geometry at hand.

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Entanglement entropy and the emergence of an arrow of time in Wheeler-DeWitt Quantum Cosmology

Mritunjay Tyagi[1]

[1]*Institut für Theoretische Physik, Köln, Germany*

Roger Penrose's Weyl curvature hypothesis can be extended to the quantum regime, where 'past singularities' have to be replaced by 'regions of small enough scale factors' in the configuration space of the wave function of the universe. At a fundamental level the justification for the quantum version of the Weyl Curvature hypothesis is expected to come from a full quantum theory of gravity : quantum geometrodynamics. Here we consider a *timeless* Wheeler-DeWitt equation to understand the generation of arrow of time by studying a toy model of the universe (for a small scale factor, i.e. early universe) which has two scalar fields. We calculate the linear (entanglement) entropy and show that it increases with the scale factor and hence the WKB time introduced in the semiclassical approximation to Wheeler-DeWitt equation. This forms the basis of an arrow of time in our universe and can help understand the origin of irreversibility in the universe as will be discussed further in the talk by Prof. Dr. Claus Kiefer.

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The effect of gravitational waves on an atom

Linda van Manen

FSU Jena, Theoretical physics institute, Jena, Germany

Experiments in quantum optics and atom interferometry have achieved great accuracy over recent years. Consequently, relativistic contributions from gravitational waves may be measurable, and a proper description for interactions between particles and electromagnetic fields including these contributions is needed. In this poster presentation I will discuss corrections from gravitational waves to the Hamiltonian, which describe the coupling between matter and the internal electromagnetic field of an atom. In particular I will focus on the coupling between center-of-mass and internal degrees of freedom. Furthermore, I will motivate possible applications to a test of quantum gravity by searching for graviton noise. This test was proposed in Phys. Rev. D 104, 046021 (2021).

Quantum-gravitational corrections in a closed universe

Tatevik Vardanyan

University of Cologne, Institute of Theoretical Physics, Köln, Germany

We study the quantum-gravitational corrections to the power spectrum of gauge-invariant inflationary scalar perturbations in a closed model of a universe. We consider canonical quantum gravity as an approach to quantize gravity. This leads to the Wheeler-DeWitt equation, which has been studied applying a semi-classical Born–Oppenheimer type of approximation. At the corresponding orders of approximation, we recover both the uncorrected and quantum-gravitationally corrected Schrödinger equations for the perturbation modes. Via these, we calculate the power spectrum for the slow-roll regime and correspondingly the modified power spectrum (including the quantum-gravitational correction term). The results are compared to the power spectra for the flat model of the universe. For the uncorrected spectrum, we find that at the largest scales the spectrum for the closed case is suppressed compared to the flat case. Regarding the corrected power spectra, for both cases, we get suppression of spectra for the large scales.

Operational verification of the existence of time and space

N. Paunković[1] and M. Vojinović[2]

[1] Instituto de Telecomunicações and Departamento de Matemática, Instituto Superior Técnico, Universidade de Lisboa, Portugal
[2] Institute of Physics, University of Belgrade, Serbia

Individual points of spacetime are not observable, due to the diffeomorphism symmetry. One is then often tempted to make a more general claim that the whole spacetime manifold is an unobservable entity. The purpose of this work is to scrutinize that claim, and demonstrate that time and space have additional properties, which are simultaneously both observable and diffeomorphism-invariant – specifically, the dimension and topology. Thus, we argue that the observation of these properties grants time and space their objective, physical existence, despite unobservability of individual points. This stands in sharp contrast with the relational point of view that there is no spacetime and that "fields live on fields".

To that end, we propose a gedanken-experiment to operationally observe the dimension and topology of a manifold. Using that, we argue that real-world observables always display correlations reflecting an underlying structure of a 4-dimensional manifold, which we call spacetime, and that its topology is simply connected on the scales that can be tested. Both D=4 and simply connected topology are intrinsic properties of the observed experimental signal, since in principle we could have obtained a different set of correlations.

Given any tentative theoretical model of physics which explicitly does not assume the existence of any underlying spacetime manifold (in line with the relational point of view), the challenge for that model is to deduce from its first principles that there exist some very peculiar correlations between the observables, describing their dynamics "as if they were fields living on a manifold" with a specific dimension and topology (so-called "strong emergence" of spacetime). In particular, any viable model ought to give rise to the result D=4 purely from the interactions between the fields in the model. However, so far no such model has ever been constructed, and until one is, we can argue that time and space are notions that objectively exist in their own right, as part of our physical reality.

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Systematic description of matter wave interferometers using elastic scattering in weakly curved spacetimes

Michael Werner[1] and Klemens Hammerer[1]

[1]*Institut für theoretische Physik and Institut für Gravitationsphysik (Albert-Einstein-Institut), Hannover, Germany*

We present a systematic approach to calculate all relativistic phase shift effects in Bragg-type light-pulse matter wave interferometer (MWI) experiments up to (and including) order $\mathcal{O}(c^{-2})$, placed in a weak gravitational field. The whole analysis is derived from first principles and even admits test of General Relativity (GR) apart from the usual Einstein Equivalence Principle (EEP) tests, consisting of universality of free fall (UFF) and local position invariance (LPI) deviations, by using the more general „parameterized post-Newtonian" (PPN) formalism. We collect general phase shift formulas for a variety of well-known MWI schemes and present how modern experimental setups could measure PPN induced deviations from GR without the use of macroscopic test masses. This procedure should be seen as a way to easily calculate certain phase contributions, without having to redo all relativistic calculations in new MWI setups and come up with possibly new measurement strategies.

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Matter and gravity

Aneta Wojnar[1]

[1]Complutense U., Madrid, Spain

I will briefly present the recent works related to effects of modified gravity on particular matter properties, such as Fermi gas [1], specific heats and cooling processes [2-4].

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Towards a molecular ion clock

F. Wolf[1], T. Rehmert[1], M. Zawierucha[1], P.O. Schmidt[1,2]

[1]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
[2] Institut für Quantenoptik, Leibniz Universität Hannover, Germany

We are currently setting up an experimental apparatus for the investigation of molecular ions. The main goal of the experiment is the construction of a single-ion molecular clock based on a vibrational overtone transition to probe for new physics effects such as a possible variation of fundamental constants. For this purpose, we are implementing quantum logic spectroscopy that was already successfully used for the aluminum optical clock [1] and the first clock based on highly charged ion [2]. We plan to implement a modified version of the classical quantum logic spectroscopy by using optical forces from bichromatic Raman interactions on the molecular ion, that allow to entangle the internal state of the molecule with the motional state [3]. The motional state is shared between the molecule and a co-trapped atomic ion and can therefore be used as a bus to transfer information from one ion to the other. Detection of the motional excitation on the atomic ion will allow us to infer the molecules internal state [4].
As we move toward the molecular clock, we are also investigating new techniques for time and frequency metrology. We have developed a quantum metrological measurement method based on Fock states and demonstrated frequency measurements below the standard quantum limit [5].
On my poster I will show the status of the molecular clock and present some ideas for experiments with trapped atomic and molecular ions in the context of time and frequency measurements.

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Quantum measurements, energy conservation and quantum clocks

N. Gisin[1,2] and E. Zambrini Cruzeiro[3]

[1] *Group of Applied Physics, University of Geneva, 1211 Geneva 4, Switzerland*
[2] *Constructor University, Geneva, Switzerland*
[3] *Instituto de Telecomunicações, 1049-001 Lisbon, Portugal*

A spin chain extending from Alice to Bob with nearest neighbors interactions, initially in its ground state, is considered. Assuming that Bob measures the last spin of the chain, the energy of the spin chain has to increase, at least on average, due to the measurement disturbance. Presumably, the energy is provided by Bob's measurement apparatus. Assuming that, simultaneously to Bob's measurement, Alice measures the first spin, it is shown that either energy is not conserved, – implausible – or the projection postulate doesn't apply, and that there is signalling. An explicit measurement model shows that energy is conserved (as expected), that the spin chain energy increase is not provided by the measurement apparatus(es), but instead by the clock, that the projection postulate is not always valid – illustrating the Wigner–Araki–Yanase (WAY) theorem – and that there is signalling, indeed.