Journal Club – Quantum and Gravity Foundations

Tuesdays, 3:00pm Stockholm time

Place [Hybrid]:NORDITA Large lunch room (level 6 in Hus 3)

Zoom: https://stockholmuniversity.zoom.us/j/61469822588

Please add your name to volunteer at one of the dates below. The volunteer should give a short overview of the paper, but the main goal is to have discussions between all attendants about the topics covered. Thus please make sure to read the paper before participating. The volunteer can choose the paper to be discussed from the list below or add a new paper to the list.
If you have other paper suggestions, please e-mail them to us (magdalena.zych@fysik.su.se, igor.pikovski@fysik.su.se, fabio.costa@su.se).

Date	Volunteer to give the overview	Paper to be discussed
30 Sept 2025	Magdalena Zych	*Observation of the quantum equivalence principle for matter-waves* Or Dobkowski, Barak Trok, Peter Skakunenko, Yonathan Japha, David Groswasser, Maxim Efremov, Chiara Marletto, Ivette Fuentes, Roger Penrose, Vlatko Vedral, Wolfgang P. Schleich, Ron Folman https://arxiv.org/abs/2502.14535
7 October 2025	Navdeep Arya	*Quantum Mechanics of Gravitational Waves* Maulik Parikh, Frank Wilczek, and George Zahariade DOI: https://doi.org/10.1103/PhysRevLett.127.081602
21 October 2025	Sebastian Schuster	*Spectrum of Hawking radiation and the Huygens principle"* Hirosi Ooguri, https://journals.aps.org/prd/abstract/10.1103/PhysRevD.33.3573
28 October 2025	Jerzy Paczos	*Phonon creation by gravitational waves* Carlos Sabín, David Edward Bruschi, Mehdi Ahmadi and Ivette Fuentes New J. Phys. 16 085003 (2014) *https://iopscience.iop.org/article/10.1088/1367-2630/16/8/085003*
4 November	Navdeep Arya	*Stimulated Emission or Absorption of Gravitons by Light* Ralf Schützhold

		Phys. Rev. Lett. **135**, 171501 – 2025 https://doi.org/10.1103/xd97-c6d7
11 November	Germain Tobar	Wave-particle duality in the measurement of gravitational radiation Hudson A. Loughlin, Germain Tobar, Evan D. Hall, Vivishek Sudhir https://arxiv.org/abs/2504.03527
18 November 2025	Niklas E. Önne	“Classical theories of gravity produce entanglement” https://www.nature.com/articles/s41586-025-09595-7
25 November 2025	No JC	NoQIP workshop
2 December 2025	Sara Butler	“Path integrals for classical-quantum dynamics“ https://arxiv.org/abs/2301.04677
9th December 2025	Josh	Diosi-Penrose model of classical gravity predicts gravitationally induced entanglement https://doi.org/10.1103/PhysRevD.111.L121101

Possible papers to be discussed (if you volunteer for giving a brief overview, please choose one and indicate above):

24	*“Two-slit diffraction with highly charged particles: Niels Bohr's consistency argument that the electromagnetic field must be quantized”* by Gordon Baym and Tomoki Ozawa We analyze Niels Bohr's proposed two-slit interference experiment with highly charged particles which argues that the consistency of elementary quantum mechanics requires that the electromagnetic field must be quantized. In the experiment a particle's path through the slits is determined by measuring the Coulomb field that it produces at large distances; under these conditions the interference pattern must be suppressed. The key is that, as the particle's trajectory is bent in diffraction by the slits, it must radiate and the radiation must carry away phase information. Thus, the radiation field must be a quantized dynamical degree of freedom. However, if one similarly tries to determine the path of a massive particle through an interferometer by measuring the Newtonian

	gravitational potential the particle produces, the interference pattern would have to be finer than the Planck length and thus indiscernible. Unlike for the electromagnetic field, Bohr's argument does not imply that the gravitational field must be quantized.
23	*[related papers diff. groups]* *Quantitative Nonclassicality of Mediated Interactions* Ray Ganardi, Ekta Panwar, Mahasweta Pandit, Bianka Woloncewicz, and Tomasz Paterek PRX Quantum **5**, 010318 – **Published 6 February, 2024** DOI: https://doi.org/10.1103/PRXQuantum.5.010318 *Witnessing nonclassicality beyond quantum theory* Chiara Marletto and Vlatko Vedral Phys. Rev. D **102**, 086012 – **Published 16 October, 2020** DOI: https://doi.org/10.1103/PhysRevD.102.086012
22	*"Stimulated Emission or Absorption of Gravitons by Light"* by Ralf Schützhold We study the exchange of energy between gravitational and electromagnetic waves in an extended Mach-Zehnder or Sagnac type geometry that is analogous to an "optical Weber bar." In the presence of a gravitational wave (such as the ones measured by the Laser Interferometer Gravitational Wave Observatory), we find that it should be possible to observe (via interference or beating effects after a delay line) signatures of stimulated emission or absorption of gravitons with present-day technology. Apart from marking the transition from passively observing to actively manipulating such a natural phenomenon, this could also be used as a complementary detection scheme. Nonclassical photon states may improve the sensitivity and might even allow us to test certain quantum aspects of the gravitational field.
21	*"Enhancing Gravitational Interaction between Quantum Systems by a Massive Mediator"* by Julen S. Pedernales, Kirill Streltsov, and Martin B. Plenio In 1957 Feynman suggested that the quantum or classical character of gravity may be assessed by testing the gravitational interaction due to source masses in superposition. However, in all proposed experimental realizations using matter-wave interferometry, the extreme weakness of this interaction requires pure initial states with extreme squeezing to achieve measurable effects of nonclassical interaction for reasonable experiment durations. In practice, the systems that can be prepared in such nonclassical states are limited to small masses, which in turn limits the strength of their interaction. Here we address this key challenge—the weakness of gravitational interaction—by using a massive body as an amplifying mediator of gravitational interaction between two test

	systems. Our analysis shows that this results in an effective interaction between the two test systems that grows with the mass of the mediator, is independent of its initial state and, therefore, its temperature. This greatly reduces the requirement on the mass and degree of delocalization of the test systems and, while still highly challenging, brings experiments on gravitational source masses a step closer to reality.
20	*"Unruh effect and Takagi's statistics inversion in strained graphene"* by Anshuman Bhardwaj, Daniel E. Sheehy https://journals.aps.org/prb/abstract/10.1103/PhysRevB.107.224310 Abstract: "We present a theoretical study of how a spatially varying quasiparticle velocity in honeycomb lattices, achievable using strained graphene or in engineered cold-atom optical lattices that have a spatial dependence to the local tunneling amplitude, can yield the Rindler Hamiltonian embodying an observer accelerating in Minkowski space-time. Within this setup, a sudden switch on of the spatially varying tunneling (or strain) yields a spontaneous production of electron-hole pairs, an analog version of the Unruh effect characterized by the Unruh temperature. We discuss how this thermal behavior, along with Takagi's statistics inversion, can manifest themselves in photoemission and scanning tunneling microscopy experiments. We also calculate the average electronic conductivity and find that it grows linearly with frequency ω. Finally, we find that the total system energy at zero environment temperature looks like Planck's blackbody result for photons due to the aforementioned statistics inversion, whereas for an initial thermally excited state of fermions, the total internal energy undergoes stimulated particle reduction."
19	"*Testing the Quantumness of Gravity without Entanglement*" https://doi.org/10.1103/PhysRevX.14.021022 Given a unitary evolution U on a multipartite quantum system and an ensemble of initial states, how well can Ube simulated by local operations and classical communication (LOCC) on that ensemble? We answer this question by establishing a general, efficiently computable upper bound on the maximal LOCC simulation fidelity—what we call an "LOCC inequality." We then apply our findings to the fundamental setting where U implements a quantum Newtonian Hamiltonian over a gravitationally interacting system. Violation of our LOCC inequality can rule out the LOCCness of the underlying evolution, thereby establishing the nonclassicality of the gravitational dynamics, which can no longer be explained by a local classical field. As a prominent application of this scheme we study systems of quantum harmonic oscillators initialized in coherent states following a normal distribution and interacting via Newtonian gravity, and discuss a possible physical implementation with torsion pendula. One of our main technical contributions is the analytical calculation of the above LOCC inequality for this family of systems. As opposed to existing tests based on the detection of gravitationally mediated entanglement, our proposal works with coherent states alone, and thus it does not require the generation of largely delocalized states of motion nor the detection of entanglement, which is never created at any point in the process.

18	*“Polariton Fluids as Quantum Field Theory Simulators on Tailored Curved Spacetimes”* by Kévin Falque, Adrià Delhom, Quentin Glorieux, Elisabeth Giacobino, Alberto Bramati, Maxime J Jacquet https://journals.aps.org/prl/abstract/10.1103/t5dh-rx6w Abstract: “Quantum field theory (QFT) in curved spacetimes predicts the amplification of field excitations and the occurrence of classical and quantum correlations, as in the Hawking effect for example. This raises interest in experiments in which the curvature of spacetime can be controlled and amplification measured, as in fluids going from subsonic to supersonic speeds where acoustic excitations are effectively trapped inside an acoustic horizon. Quantum fluctuations of the acoustic field are predicted to yield entangled emission across the horizon, as in black holes. Here, we introduce such a QFT simulator in a one-dimensional polaritonic fluid of light. We demonstrate the unique tunability of our system by engineering smooth and steep horizons, which respectively have quasithermal, but weak, and strong Hawking radiation. We measure the spectrum on either side of the horizon and evidence the excitation of negative energy waves in fluids of light for the first time. Notably, we explicitly show that, beyond phononic excitations as in other systems, our simulator also supports excitations with a massive, relativistic dispersion. In the future, quantum optics techniques offer the possibility to measure entanglement in unexplored regimes, giving insight in this outstanding prediction of relativistic QFT.”
17	*“Spectrum of Hawking radiation and the Huygens principle"* by Hirosi Ooguri https://journals.aps.org/prd/abstract/10.1103/PhysRevD.33.3573 Abstract: “It has been established that the Minkowski vacuum observed by a uniformly accelerating detector can be equivalently described by a canonical ensemble of states. However, recent calculations have revealed that in a spacetime of odd dimensions free massless scalar particles are detected with the Fermi-Dirac distribution instead of the Planck one. The purpose of this paper is to solve this apparent puzzle. It is concluded that the cause of this phenomenon is the lack of the Huygens principle in odd dimensions: the expectation value of the commutator of massless fields does not vanish in the timelike region. The case of a spinor field is treated equally. Other spacetimes, de Sitter space and Schwarzschild space, are also discussed.”
16	“Probing Curved Spacetime with a Distributed Atomic Processor Clock” Jacob P. Covey, Igor Pikovski, and Johannes Borregaard http://dx.doi.org/10.1103/q188-b1cr abstract: Quantum dynamics on curved spacetime has never been directly probed beyond the Newtonian limit. Although we can describe such dynamics theoretically, experiments would provide empirical evidence that quantum theory holds even in this extreme limit. The practical challenge is the minute spacetime curvature difference over the length scale of the typical extent of quantum effects. Here, we propose a quantum network of alkaline earth (like) atomic processors for constructing a distributed quantum state that is sensitive to the differential proper time between its constituent atomic processor nodes, implementing a quantum observable that is affected by post-Newtonian curved spacetime. Conceptually, we propose to delocalize one clock between three locations by encoding the presence or absence of a clock into the state of the local

15	atoms. By separating three atomic nodes over approximately kilometer-scale elevation differences and distributing one clock between them via a W state, we demonstrate that the curvature of spacetime is manifest in the interference of the three different proper times that give rise to three distinct beat notes in our nonlocal observable. We further demonstrate that N-atom entanglement within each node enhances the interrogation bandwidth by a factor of N. We discuss how our proposed system can probe new facets of fundamental physics, such as the linearity, unitarity, and probabilistic nature of quantum theory on curved spacetime. Our protocol combines several recent advances with neutral atom and trapped ions to realize a novel quantum probe of gravity uniquely enabled by quantum networks.
15	"Diffeomorphism-invariant observables and their nonlocal algebra" W.Donnelly, S.Giddings https://doi.org/10.1103/PhysRevD.93.024030 abstract: Gauge-invariant observables for quantum gravity are described, with explicit constructions given primarily to leading order in Newton's constant, analogous to and extending constructions first given by Dirac in quantum electrodynamics. These can be thought of as operators that create a particle, together with its inseparable gravitational field, and reduce to usual field operators of quantum field theory in the weak-gravity limit; they include both Wilson-line operators, and those creating a Coulombic field configuration. We also describe operators creating the field of a particle in motion; as in the electromagnetic case, these are expected to help address infrared problems. An important characteristic of the quantum theory of gravity is the algebra of its observables. We show that the commutators of the simple observables of this paper are nonlocal, with nonlocality becoming significant in strong field regions, as predicted previously on general grounds.
14	"Observation of the quantum equivalence principle for matter-waves" at al and Ron Folman https://doi.org/10.48550/arXiv.2502.14535 abstract: Einstein's general theory of relativity is based on the principle of equivalence - in essence, dating back to Galileo - which asserts that, locally, the effect of a gravitational field is equivalent to that of an accelerating reference frame, so that the local gravitational field is eliminated in a freely-falling frame. Einstein's theory enables this principle to extend to a global description of relativistic space-time, at the expense of allowing space-time to become curved, realising a consistent frame-independent description of nature at the classical level. Einstein's theory has been confirmed to great accuracy for astrophysical bodies. However, in the quantum domain the equivalence principle has been predicted to take a unique form involving a gauge phase that is observable if the wavefunction - fundamental to quantum descriptions - allows an object to interfere with itself after being simultaneously at rest in two differently accelerating frames, one being the laboratory (Newtonian) frame and the other in the freely-falling (Einsteinian) frame. To measure this gauge phase we realise a novel cold-atom interferometer in which one wave packet stays static in the laboratory frame while the other is in free fall. We follow the relative-phase evolution of the wave packets in the two frames, confirming the equivalence principle in the quantum domain. Our observation is yet another fundamental test of the interface between quantum theory and gravity. The new interferometer also opens the door for further probing of the latter interface, as well as to searches for new physics comment: from Peter Asenbaum and Chris Overstreet https://doi.org/10.48550/arXiv.2504.15409

13	”Quantum Mechanics of Gravitational Waves” Maulik Parikh, Frank Wilczek, and George Zahariade DOI: https://doi.org/10.1103/PhysRevLett.127.081602 related publications: winning essay for GRF “The noise of gravitons” https://doi.org/10.1142/S0218271820420018 technical companion: “Signatures of the quantization of gravity at gravitational wave detectors” https://doi.org/10.1103/PhysRevD.104.046021
12	“Revisiting the algebraic structure of the generalized uncertainty principle” Fadel, Maggiore, arXiv:2112.09034 https://arxiv.org/abs/2112.09034 *A recent paper on the GUP: Generalized uncertainty principle, a speculative model incorporating the “minimal length” through changes in the Heisenberg uncertainty principle. This paper is on theory, there are experimental proposals to test for such models in table-top experiments.*
11	“Path integrals for classical-quantum dynamics“ https://arxiv.org/abs/2301.04677 *A hybrid classical-quantum description to incorporate gravity (as a speculative model) [more developed version of* “A post-quantum theory of classical gravity?” Jonathan Oppenheim, https://arxiv.org/abs/1811.03116]
10	“Non-gaussianity as a signature of a quantum theory of gravity”; Howl, Vedral, Naik, Christodoulou, Rovelli, Iyer (2021). https://doi.org/10.1103/PRXQuantum.2.010325 *Proposal to test quantum gravity signatures, or violations of mean field theory, in a BEC system through preparation of Gaussian states that evolve into non-Gaussian states.*
9	“Gravity and quantum mechanics”; Penrose (1992) *https://inspirehep.net/files/14c36edf8fa8670ff9123527338ca927* *This is the only reference where Penrose writes down a formula for quantifying the difference of two spacetimes at given moment as the "weak field gravitational symplectic integral". This paper would be an add-on to “On gravity's role in quantum state reduction - Penrose” which we discussed last year. Deals with Penrose’s proposal of wavefunction collapse.*
8	“Loss of coherence of matter-wave interferometer from fluctuating graviton bath”; Toros,

	Mazumdar & Bose. https://arxiv.org/abs/2008.08609 (2020). *Decoherence of matter waves to due background gravitons.*
7	"*Scrambling Time and Causal Structure of the Photon Sphere of a Schwarzschild Black Hole", Peter Shor, https://arxiv.org/abs/1807.04363* *Discussion of the difference between scrambling and entanglement*
6	"Measurement of Gravitational Coupling between Millimeter-Sized Masses"; Westphal et al. https://www.nature.com/articles/s41586-021-03250-7 (2021). *Experiment testing the mutual gravitational interaction between two opto-mechanical systems at millimeter scales.*
5	"A no-summoning theorem in relativistic quantum theory"; Kent. Quantum Inf Process 12, 1023–1032 (2013) https://doi.org/10.1007/s11128-012-0431-6 . *A quantum information protocol that intrinsically relies on special relativity*
4	"On Formalisms and Interpretations" Baumann, Wolf (2018). https://quantum-journal.org/papers/q-2018-10-15-99/ *An introduction to "Wigner's friend", and good overview of interpretations.*
3	"The necessity of quantizing the gravitational field"; Eppley & Hannah (1977).. https://doi.org/10.1007/BF00715241 *Classic paper on the price to pay when coupling a classical system to a quantum system. We discussed it before but good to revisit for new participants.*
2	"*Observation of a gravitational Aharonov-Bohm effect"* *Chris Overstreet, Peter Asenbaum, Joseph Curti, Minjeong Kim, and Mark A. Kasevich* *Science 375 226 (2022)* *https://www.science.org/doi/10.1126/science.abl7152*
1	*"Einstein A and B coefficients for a black hole"* Jacob D. Bekenstein and Amnon Meisels Phys. Rev. D 15, 2775 (1977)

	https://journals.aps.org/prd/pdf/10.1103/PhysRevD.15.2775

Internal papers, of interest but less priority(better to have a neutral perspective):

i.	"Minimum uncertainty states for free particles with quantized mass-energy" Wood & Zych, Phys. Rev. Research 3, 013049 (2021) https://journals.aps.org/prresearch/abstract/10.1103/PhysRevResearch.3.013049 *Follow-up on time-dilation induced entanglement due to internal composition of particles. This paper shows how composite particles require new states that do not delocalize, since the internal Hamiltonian contributes to the dynamics through its time-dilation induced coupling to position and momentum.*
ii.	"Reversible dynamics with closed time-like curves and freedom of choice"; Tobar & Costa. Class. Quantum Grav. 37 205011 (2020), https://arxiv.org/abs/2001.02511 *Theory paper (quite abstract) on closed time-like curves and a mathematical formulation that allows for arbitrary local operations without causing inconsistencies. Paper has caused quite some buzz in the media.*
iii.	"Quantum test of the equivalence principle for atoms in coherent superposition of internal energy states", Rosi et al. *Nature Communications* 8, 15529 (2017); https://www.nature.com/articles/ncomms15529 *Experiment on possible violations of a quantum version of the equivalence principle*
iv.	"Detecting single gravitons with quantum sensing", Tobar, Manikandan, Beitel, Pikovski. arXiv:2308.15440 (2023). *Theory paper on graviton absorption and emission of massive resonators, shows how to detect single gravitons through massive quantum systems and continuous quantum measurement of internal energy.*

old meetings

Date	Volunteer to give the overview	Paper to be discussed
Sep 19, 2023	Magdalena Zych	Asenbaum et al Phase Shift in an Atom Interferometer due to Spacetime Curvature across its Wave Function Phys. Rev. Lett. 118, 183602 – Published 1 May 2017
Sep 26, 2023	Fabio Costa	"The necessity of quantizing the gravitational field"; Eppley & Hannah (1977).. https://doi.org/10.1007/BF00715241 *Classic paper on the price to pay when coupling a classical system to a quantum system. We discussed it before but good to revisit for new participants.*
Oct 03, 2023		
Oct 10, 2023	Germain Tobar	*Any consistent coupling between classical gravity and quantum matter is fundamentally irreversible* *https://arxiv.org/abs/2301.10261*
Oct 17, 2023	none	Conference - 15 years of Oskar Klein Centre https://indico.fysik.su.se/event/8274/contributions/
Oct 24, 2023	Vasileios Fragkos	"Strongly incoherent gravity" https://arxiv.org/pdf/2301.08378.pdf
Oct 31, 2023	Joshua Foo	*"Hilbert space representation of the minimal length uncertainty relation"* Kempf, Mangano, Mann, Phys. Rev. D **52**, 110 (1995) https://doi.org/10.1103/PhysRevD.52.1108

Nov 07, 2023	Erik Aurell	The Mukhanov-Bekenstein theory
Nov 14, 2023	Robert Jonsson	T. Jacobson, “Entanglement Equilibrium and the Einstein Equation,” *Physical Review Letters*, vol. 116, no. 20, May 2016, doi: 10.1103/PhysRevLett.116.201101. or https://arxiv.org/abs/1505.04753
Nov 21, 2023	Evan Gale	M.-O. Renou, D. Trillo, M. Weilenmann, T. P. Le, A. Tavakoli, N. Gisin, A. Acín, and M. Navascués, *Quantum Theory Based on Real Numbers Can Be Experimentally Falsified*, Nature **600**, 625 (2021).
Nov 28, 2023	Sreenath Manikandan	Frauchinger, Renner *Nature Communications* volume 9, Article number: 3711 (2018) https://www.nature.com/articles/s41467-018-05739-8
Dec 05, 2023	Fabio Costa	Michael Redhead “More ado about nothing“ Foundations of Physics volume 25, pages 123–137 (1995) https://link.springer.com/article/10.1007/BF02054660
Dec 12, 2023	Alessio Belfiglio	Rafael D. Sorkin *Impossible Measurements on Quantum Fields* In “Directions in General Relativity”: Proceedings of the 1993 International Symposium, Maryland, Vol. 2: Papers in honor of Dieter Brill, pages 293-305, Bei-Lok Hu and T.A. Jacobson editors, (Cambridge University Press, 1993) https://arxiv.org/abs/gr-qc/9302018
Dec 19, 2023 – Jan 2, 204	**End of Year Break!**	
Feb 13 2024	Magdalen Zych	S. J. Summers and R. Werner, “Bell’s inequalities and quantum field theory, I: General setting,” *J. Math. Phys.* 28, 2440 (1987) S. J. Summers and R. Werner, “Bell’s inequalities and quantum field theory. II. Bell’s inequalities are maximally violated in the vacuum *J. Math. Phys.* 28, 2448–2456 (1987)

Feb 27 2024	Navdeep Arya	“*Observation of a gravitational Aharonov-Bohm effect” Chris Overstreet, Peter Asenbaum, Joseph Curti, Minjeong Kim, and Mark A. Kasevich Science 375 226 (2022)* https://www.science.org/doi/10.1126/science.abl7152
March 5 2024	Jerzy Paczos	*Quantum mechanics and the covariance of physical laws in quantum reference frames* by Flaminia Giacomini, Esteban Castro-Ruiz, and Časlav Brukner. *Nat Commun* **10**, 494 (2019) https://doi.org/10.1038/s41467-018-08155-0
March 12 2024	Magdalena Zych	*Inference of gravitational field superposition from quantum measurements,* Overstreet at al PRD 108, 084038 (2023) https://journals.aps.org/prd/abstract/10.1103/PhysRevD.108.084038
March 19 2024	–	visit of Dr Natalia Móller – seminar “**Indefinite temporal order on a superposition of spherical shells”** Móller, Sahdo, Yokomizo, Quantum 8, 1248 (2024) **Wednesday 20/03, 10:30am in A3:1003**, https://uqz.zoom.us/j/82173900083
March 26 2024	Gui Franzmann	Sections 1 and 2 of Chris Fewster, *The split property for quantum field theories in flat and curved spacetimes* https://arxiv.org/abs/1601.06936v2
April 2 2024	Gui Franzmann	“Why Einstein did not believe that general relativity geometrizes gravity”, Dennis Lehmkuhl, *Studies in History and Philosophy of Modern Physics* **46** (2014) 316–326 https://doi.org/10.1016/j.shpsb.2013.08.002
April 9 2024	Joshua Foo	“Quantum clocks observe classical and quantum time dilation” Alexander RH Smith, Mehdi Ahmadi https://www.nature.com/articles/s41467-020-18264-4
April 23 2024	Germain Tobar	Analogue gravity on a superconducting chip https://arxiv.org/abs/2003.00382

April 30 2024	no meeting - Valborg	
May 7 2024	Jerzy Paczos	*Bremsstrahlung and and zero-energy Rindler photons*Higuchi, G. E. A. Matsas, and D. Sudarsky https://journals.aps.org/prd/abstract/10.1103/PhysRevD.45.R3308