Signatures of quantum and classical gravity on non-relativistic quantum systems

Abstract. Understanding the interplay between gravitational phenomena and quantum mechanics is one of the greatest challenges of contemporary physics. Indeed, the theoretical difficulties in merging the theories are exasperated by the lack of experimental data. Recently, a lot of effort has been devoted to investigating whether, within non-relativistic and weak-field limits, some facets of gravity at the interface with quantum physics could be experimentally tested. This thesis focuses on identifying signatures of gravitational effects on quantum systems in this regime, following two complementary directions.

The first half of the thesis explores the effects of a quantized gravitational field when treated as an environment. The established claim in the literature is that gravitational environments induce decoherence in the kinetic-energy basis. It is shown that these result is affected by ambiguities both in the open quantum system (OQS) analysis and the general relativistic one. The first issue is not specific to gravity but concerns the OQS treatment of Lagrangians that differ by a total derivative. While such Lagrangians are equivalent for closed systems, they can lead to inequivalent reduced dynamics, because they induce different partitions of the Hilbert space between system and environment. From the General Relativistic side the standard result is undermined by an inadequate choice of coordinates which does not take into account the metric role played by the gravitational field. These issues are resolved by adopting an appropriate Lagrangian and reformulating the analysis in Fermi normal coordinates. This formulation provides an operationally well-defined analysis of gravitational decoherence and it predicts decoherence in position rather than in kinetic energy basis.

The second half instead explores the possibility that gravity may not be quantized at all and the consequences such an assumption necessarily entails. Two approaches are followed: one information theoretical, based on the notion of LOCC channel, and one dynamical, based on hybrid theories.

It is customarily assumed that a classical gravitational interaction, whatever its details, must induce an LOCC channel between quantum systems: in particular it cannot entangle previously separable quantum masses. This logic is the foundation of tabletop experiments on gravitationally induced entanglement (GIE) as evidence for the quantization of gravity. Such experiments, however, are outside the scope of present-day technology as they require the control of spatial superpositions of mesoscopic masses. However, alternative routes can be pursued. We show that a LOCC gravitational interaction cannot remain deterministic when coupled consistently to quantum matter, but must be random and induce diffusion in the motion of quantum systems. These diffusive effects can be quantitatively lower bounded and probed in non-interferometric experiments, thereby avoiding the main obstacles faced by entanglement-based tests.

Finally, hybrid classical-quantum theories of gravity are analysed in the context of the GIE proposals. These theories couple classical degrees of freedom of gravity to quantum matter, but their structure is not dictated by the notion of LOCC and is instead constructed using the tools of quantum measurement and feedback. We show that such models can generate entanglement between two masses even though gravity is described by classical degrees of freedom, and trace the root of this to some unavoidable non-locality of the models. Nevertheless, a comparison between the entanglement generated in the Tilloy-Diósi model and that generated by the standard Newtonian potential shows that entanglement detection should still quantitatively discriminate quantum gravity from hybrid theories.

UNIVERSITÀ DEGLI STUDI DI TRIESTE

Signatures of gravity on non-relativistic quantum systems

PhD Candidate Oliviero Angeli

Supervisor: Angelo Bassi.

Dr. Angeli presented his research on how near-future tabletop experiments could help determine whether gravity should be understood as a genuinely quantum interaction or as an effectively classical one. It emphasized that this question is more subtle than it first appears, because some hybrid classical-quantum descriptions can reproduce features that look quantum, including entanglement-like effects, but only by introducing hidden nonlocal elements rather than a truly local classical mediation. This means that observing such effects would not automatically settle the issue unless the underlying mechanism is carefully identified. The presentation also showed that these experiments could set much stronger constraints on such alternative descriptions. A second part focused on a different and potentially more accessible signature: if gravity were classical, it should unavoidably generate a small amount of noise or diffusion in the motion of quantum systems.

The presentation highlighted the conceptual depth of the problem, the increasing experimental realism of testing the quantum nature of gravity, and the very good quality of the results achieved by the PhD candidate. It was well organized and clear, and presented fluently. Dr. Angeli demonstrated a high degree of awareness of the subject and replied convincingly to the questions which were posed.

The committee recommends admitting him to the final presentation.

The Committee
Angelo Bassi
Federico Becca
Ugo Marzolino
Thomas Schäfer
Andrea Trombettoni

DOTTORANDO / *PHD STUDENT*	
COGNOME / *SURNAME* ANGELI	**NOME / *NAME*** OLIVIERO
CORSO DI DOTTORATO / *PHD COURSE*	**CICLO / *CYCLE***
FISICA	XXXVIII
SUPERVISORE (COGNOME, NOME) / *SUPERVISOR (SURNAME, NAME)*	
BASSI ANGELO	
CO-SUPERVISORE (EVENTUALE) (COGNOME, NOME) / CO-*SUPERVISOR IF APPLICABLE (SURNAME, NAME)*	
BENATTI FABIO	

BREVE RELAZIONE SULL'ATTIVITÀ DI RICERCA / *CONCISE PROGRESS REPORT (RESEARCH ACTIVITIES)*

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The PhD research focused on identifying signatures of gravitational effects on quantum systems. Two directions were pursued: applying open-quantum-system tools to study gravitational environments, and investigating models of classical gravity coupled to quantum matter.

i. **Open dynamics for fundamental interactions**: Decoherence induced by fundamental interactions, like QED and linearized quantum gravity, is of great interest: however different works in the literature arrive at substantially different conclusions in regard to the decoherence basis.

The differences are rooted in the fact Lagrangians that differ by a total derivative, although equivalent for a closed system, may lead to inequivalent reduced dynamics. This is due to the different system-environment splits which emerge when quantizing such Lagangians. This analysis led to the identification of a criterion to choose, operationally, the most adequate system-environment partition which, for QED, yields a master equation of the Caldeira-Leggett form [2].

Then the treatment of open linearized quantum gravity was scrutinized [4]. The standard result in the literature is that a gravitational environment induces decoherence in the kinetic-energy basis. This claim was shown to suffer from both general relativistic ambiguities, in the choice of coordinates, and open-quantum-system ones, in the choice of observables. These ambiguities were removed by formulating the problem in Fermi normal coordinates and choosing the appropriate Lagrangian according to our analysis in [2]. The work thus provides an operationally well-defined description of gravitational decoherence, and predicts decoherence in position rather than kinetic energy.

ii. **Classical gravity signatures**: Tabletop experiments have been proposed to assess the nature of gravity (classical vs quantum) by measuring its ability to entangle quantum systems. This experiments, however, are still unfeasible since they require the control of delocalized states of mesoscopic masses.

This prompted a search for alternative routes to test the non-classicality of gravity. In Ref. [3] it is proved that a classical gravitational interaction cannot remain purely deterministic and must induce diffusion in the motion of quantum systems. This diffusive effect – which was quantitatively lower bounded – can be tested via non-interferometric experiments, bypassing the major technological hurdle of the entanglement tests.

Finally, hybrid classical-quantum models of gravity were analysed against the gravitationally induced entanglement proposals. In [1] it is proved that some hybrid models can generate entanglement between two masses despite describing gravity with classical degrees of freedom, because of an unavoidable underlying non-locality. A comparison of the entanglement generated in the Tilloy–Diósi model and by the standard Newton potential, shows that entanglement detection should still quantitatively discriminate quantum gravity from hybrid theories [1].

ATTIVITÀ FORMATIVE / *TRAINING ATTENDED BY THE PHD STUDENT*

TIPO / *TYPE* Corso/Seminario/Workshop/ Convegno/Stage/Altro (specificare) – *Course/Seminar/Workshop/Conference/Stage/ Other (specify)*	**TITOLO / *TITLE***	**SEDE / *LOCATION***	***PERIODO (DAL AL)* / TIME PERIOD (FROM TO)**
PHD COURSE	ADVANCED GENERAL RELATIVITY AND QFT IN CURVED SPACETIME	SISSA TRIESTE, ITALY	SPRING 2023
PHD COURSE	COMPLETE POSITIVITY IN QUANTUM INFORMATION	UNIVERSITY OF TRIESTE, TRIESTE, ITALY	FALL 2023
PHD COURSE	LOW TEMPERATURE PHYSICS: QUANTUM FLUIDS AND SUPERCONDUCTIVITY	UNIVERSITY OF TRIESTE, TRIESTE, ITALY	FALL 2023
PHD COURSE	DECOHERENCE IN OPEN QUANTUM SYSTEMS	UNIVERSITY OF TRIESTE, TRIESTE, ITALY	SPRING 2024
SCHOOL	INTERFACING GRAVITY AND QUANTUM PHYSICS – VCQ AND TURIS SUMMER SCHOOL 2024	VIENNA UNIVERSITY, VIENNA, AUSTRIA	2.9.2024 – 6.9.2024
SCHOOL	FUNDAMENTAL PROBLEMS IN QUANTUM PHYSICS 2024	UNIVERSITY OF TRIESTE, TRIESTE, ITALY	10.9.2024 – 12.9.2024
SCHOOL	FUNDAMENTAL PROBLEMS IN QUANTUM PHYSICS 2025	UNIVERSITY OF TRIESTE, TRIESTE, ITALY	17.6.2025 – 19.6.2025

SCHOOL	SCHOOL OF QUANTUM FOUNDATIONS: SPEAKABLE AND UNSPEAKABLE	UNIVERSITY OF SPLIT, SPLIT, CROATIA	18.8.2025 – 28.8.2025
WORKSHOP	A LOOK AT THE INTERFACE BETWEEN GRAVITY AND QUANTUM THEORY – 2023	CALALZO DI CADORE (BL), ITALY	11.7.2023 – 13.7.2023
WORKSHOP	QUANTUM SENSING AND FUNDAMENTAL PHYSICS WITH LEVITATED MECHANICAL SYSTEMS	ECT* - EUROPEAN CENTER FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS, TRENTO, ITALY	31.7.2023 – 3.8.2023
WORKSHOP	A LOOK AT THE INTERFACE BETWEEN GRAVITY AND QUANTUM THEORY – 2024	SAN VITO DI CADORE (BL), ITALY	2.7.2024 – 4.7.2024
CONFERENCE	PAFT24 - QUANTUM GRAVITY AND INFORMATION	VIETRI SUL MARE (SA)	24.3.2024 – 27.3.2024
CONFERENCE	14TH ANNUAL CONFERENCE ON RELATIVISTIC QUANTUM INFORMATION (NORTH)	CHARLES UNIVERSITY, PRAGUE, CZECH REPUBLIC	5.8.2024 – 9.8.2024
CONFERENCE	"QUANTUM 2025" FROM FOUNDATIONS OF QUANTUM MECHANICS TO QUANTUM INFORMATION AND QUANTUM METROLOGY & SENSING	UNIVERSITY OF TORINO TORINO, ITALY	18.5.2025 – 24.5.2025
CONFERENCE	FROM PUZZLES TO NEW INSIGHTS IN FUNDAMENTAL PHYSICS	CAMPAGNA (SA), ITALY	23.6.2025 – 27.6.2025
CONFERENCE	BRIDGING HIGH AND LOW ENERGIES IN SEARCH OF QUANTUM GRAVITY 2025 (BRIDGEQG 2025)	LABORATOIRE DE PHYSIQUE NUCLÉAIRE ET DES HAUTES ÉNERGIES (LPNHE), PARIS, FRANCE	7.7.2025 – 10.7.2025
SHORT TIME VISIT	SCIENTIFIC VISIT	UNIVERSITY OF PALERMO, PALERMO, ITALY	17.3.2026 – 19.3.2026

ATTIVITÀ DI DIDATTICA E DI RICERCA / *TEACHING AND RESEARCH ACTIVITIES HELD BY THE PHD STUDENT*

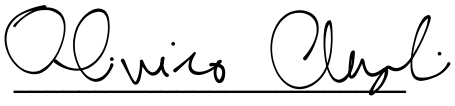
TIPO / *TYPE*	**TITOLO / *TITLE***
ATTIVITÀ TUTORIALI E DIDATTICO INTEGRATIVE SVOLTE / *TUTORING ACTIVITIES*	TUTOR AT "SCHOOL OF QUANTUM FOUNDATIONS: SPEAKABLE AND UNSPEAKABLE"
SEMINARI TENUTI DAL DOTTORANDO / *SEMINARS HELD BY THE PHD STUDENT*	SEMINAR "SIGNATURES OF CLASSICAL GRAVITY ON QUANTUM SYSTEMS", DEPARMENT OF PHYSICS, UNIVERSITY OF PALERMO, 18.3.2026
PUBBLICAZIONI SCIENTIFICHE / *SCIENTIFIC PUBLICATIONS* riferimenti bibliografici completi delle	[1]. **O. ANGELI**, M. CARLESSO "*ENTANGLEMENT IN MARKOVIAN HYBRID CLASSICAL-QUANTUM THEORIES OF GRAVITY*". PHYSICAL REVIEW D, 2025, 112.2: 024047. https://doi.org/10.1103/jzht-fbwt

pubblicazioni presenti nel catalogo ArTS / *full bibliographic references of the publications submitted to the ArTS catalog*	[2]. A. GUNDHI, **O. ANGELI**, A. BASSI. "*FROM EQUIVALENT LAGRANGIANS TO INEQUIVALENT OPEN QUANTUM SYSTEM DYNAMICS*." PHYSICAL REVIEW RESEARCH 8.1 (2026): 013133. https://doi.org/10.1103/4rpx-zj2x [3]. **O.ANGELI**, S. DONADI, G. DI BARTOLOMEO, J.L.G. REYES, A. BASSI "*PROBING THE QUANTUM NATURE OF GRAVITY THROUGH CLASSICAL DIFFUSION*." submitted for publication, arXiv preprint: https://arxiv.org/2501.13030 [4]. **O.ANGELI**, A.GUNDHI, A. BASSI "*GRAVITATIONAL DECOHERENCE*.", manuscript in preparation.
PRESENTAZIONI A CONGRESSI, POSTER, ABSTRACT ETC / *PRESENTATIONS AT CONFERENCES, POSTERS,* ABSTRACTS, se pubblicato, riportare i riferimenti bibliografici / *if published provide full bibliographic references*	I. **POSTER** "*POSITIVITY AND ENTANGLEMENT IN HYBRID MODELS F GRAVITY*" – QUANTUM 2025" FROM FOUNDATIONS OF QUANTUM MECHANICS TO QUANTUM INFORMATION AND QUANTUM METROLOGY & SENSING, 2025 II. **POSTER** "*PROBING THE NATURE OF GRAVITY THROUGH DIFFUSION*" – FROM PUZZLES TO NEW INSIGHTS IN FUNDAMENTAL PHYSICS, 2025 III. **CONTRIBUTED TALK** "*THE NOISE OF GRAVITATIONAL WAVES*" – A LOOK AT THE INTERFACE BETWEEN GRAVITY AND QUANTUM THEORY – 2023, IV. **CONTRIBUTED TALK** "*A FUNDAMENTAL AMBIGUITY IN OPEN QUANTUM SYSTEMS*" – A LOOK AT THE INTERFACE BETWEEN GRAVITY AND QUANTUM THEORY – 2024, V. **CONTRIBUTED TALK** "*AMBIGUITIES IN OPEN QUANTUM SYSTEMS*" – FUNDAMENTAL PROBLEMS IN QUANTUM PHYSICS 2024 VI. **CONTRIBUTED TALK** "*PROBING THE NATURE OF GRAVITY VIA DIFFUSION*" – A LOOK AT THE INTERFACE BETWEEN GRAVITY AND QUANTUM THEORY – 2025, VII. **CONTRIBUTED TALK** "*ENTANGLEMENT IN HYBRID CLASSIAL-QUANTUM MODELS OF GRAVITY*"– FUNDAMENTAL PROBLEMS IN QUANTUM PHYSICS 2025 VIII. **CONTRIBUTED TALK** "*PROBING THE NATURE OF GRAVITY VIA DIFFUSION*" – BRIDGING HIGH AND LOW ENERGIES IN SEARCH OF QUANTUM GRAVITY 2025 (BRIDGEQG 2025)

Data compilazione /*Date,*

1/4/2026

Firma dottorando/*PhD student's signature*



Firma supervisore/*Supervisor's signature*