

PhD thesis title:

Precision Measurements with Ultracold Matter-Wave Devices

Abstract:

Ultracold atoms provide a useful platform for quantum sensing, which through matter-wave interferometry enables precision measurements beyond classical limits. In realistic settings, interactions with the environment and intrinsic many-body dynamics play a crucial role in determining interferometric performance. This thesis investigates phase estimation and sensitivity limits in atom interferometers within the framework of open quantum systems. To this end we employ the two-mode model of the Bose–Einstein condensate in a double-well potential together with tools from quantum estimation theory like Fisher information and the Cramér–Rao bound to characterize the interferometric sensitivity. Within a Lindblad formalism, we analyze the impact of both particle-conserving and particle non-conserving noise on interferometric protocols. We identify the emergence of insensitivity points, evolution times at which phase estimation becomes impossible, and show that their location depends on system parameters but is independent of noise strength. While specific measurement strategies may suggest advantages for number-conserving processes, ultimate precision bounds reveal that particle non-conserving noise leads to lower achievable sensitivity. We further examine how the scaling of the system–environment coupling affects precision. By comparing models with and without Kac rescaling, we demonstrate that the commonly expected degradation from Heisenberg-limited to shot-noise-limited sensitivity is not universal. For linear coupling to a harmonic environment, extensivity-restoring rescaling can preserve Heisenberg scaling. Then we explored the modification of the interferometric protocol by substituting the usual unitary Beam-Splitter with a projective measurement induced splitting of the initial populations. Finally, we extend existing Sagnac interferometry schemes based on single atomic clocks to the regime of Bose–Einstein condensates. We analyze implementations relying on fully confined atoms and state-dependent transport, and quantify the impact of Bose-Einstein statistics and finite temperature on the sensitivity of such interferometric platforms.



## **Precision measurements with ultracold matter-wave devices**

### **PhD Candidate Žan Kokalj**

Supervisor: Andrea Trombettoni.

Dr. Kokalj presented his PhD thesis on quantum sensing with ultracold atoms, focusing on interferometric protocols in realistic settings where environmental effects and many-body dynamics play a crucial role. The work investigates phase estimation and sensitivity limits in atom interferometers within the framework of open quantum systems.

The candidate first discussed the two-mode model of a Bose–Einstein condensate in a double-well potential and reminded basic notion of quantum interferometry. Then he presented results for open quantum interferometers. Within a Lindblad formalism, both particle-conserving and particle non-conserving noise processes were analyzed, highlighting the emergence of insensitivity points, i.e. evolution times at which phase estimation becomes impossible. It was shown that their location depends on system parameters while remaining independent of noise strength. The analysis also demonstrated that, although specific measurement strategies may suggest advantages for number-conserving processes, the ultimate precision bounds indicate a more detrimental effect of particle non-conserving noise. The thesis further examined how the scaling of the system–environment coupling affects precision. By comparing models with and without Kac rescaling, the candidate showed that the commonly expected transition from Heisenberg-limited to shot-noise-limited sensitivity is not universal. In particular, for linear coupling to a harmonic environment, extensivity-restoring rescaling can preserve Heisenberg scaling. The candidate also explored modifications of the interferometric protocol, including a scheme based on projective measurement-induced splitting of the initial populations.

The quality of the presentation was good and the candidate presented in a sufficiently clear way the results obtained during the PhD. During the presentation, Dr. Kokalj showed very good knowledge of the topic, and he well replied 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    KOKALJ	NOME / NAME    ŽAN
CORSO DI DOTTORATO / PHD COURSE	CICLO / CYCLE
PHD IN PHYSICS	XXXVIII
SUPERVISORE (COGNOME, NOME) / SUPERVISOR (SURNAME, NAME)	
TROMBETTONI ANDREA	
CO-SUPERVISORE (EVENTUALE) (COGNOME, NOME) / CO-SUPERVISOR IF APPLICABLE (SURNAME, NAME)	

**BREVE RELAZIONE SULL'ATTIVITÀ DI RICERCA / CONCISE PROGRESS REPORT (RESEARCH ACTIVITIES)**  
(max 2500 caratteri, spazi esclusi/ max 2500 characters excluding blanks)

Over the course of my PhD, my research has focused on the theoretical and computational investigation of Bose–Einstein condensates, quantum interferometry and open quantum systems. The work combines numerical simulations with analytical techniques to understand and optimize interferometric protocols in realistic, noisy environments. In the beginning, I focused on understanding the underlying physics of the BEC through Gross–Pitaevskii equations, the interferometry protocols in a double-well system and employing numerical methods, like Runge–Kutta, enabling the study of BEC dynamics in various potential configurations. This led me to continue by investigating the role of interaction strength, evolution times, and measurement strategies, for example the impact of intermediate measurements on sensitivity. I also contributed to a collaboration on open quantum interferometers by extending analytical results to many-particle systems and studying noise within the Lindblad framework, which led to the paper “Insensitivity points and performance of open quantum interferometers under number-conserving & non-conserving Lindblad dynamics” [arXiv:2512.10559]. Then, I expanded this work by focusing on the scaling of interferometric sensitivity with particle number in the presence of dissipation and decoherence. Our results revealed a degradation of sensitivity with system size, even for weak noise, unless the noise parameter is appropriately rescaled with system size. This insight led to a deeper investigation of extensivity in Boson Josephson junctions and its implications for noisy interferometry. I applied quantum information tools such as Fisher information, Kraus operators, and completely positive maps, supported by simulations of Lindblad dynamics for various initial states and dissipation mechanisms. These were summarised in the paper “Effect of Energy Extensivity on the Performance of Open Quantum Interferometers” [arXiv:2511.22439]. I am currently focusing on a generalization of a Sagnac interferometry protocol with a single atom to the employment of a gas of bosons, to see a possible improvement in sensitivity when the temperature crosses the critical temperature for condensation.

ATTIVITÀ FORMATIVE / TRAINING ATTENDED BY THE PHD STUDENT			
TIPO / TYPE	TITOLO / TITLE	SEDE / LOCATION	PERIODO (DAL AL) / TIME PERIOD (FROM TO)
Corso/Seminario/Workshop/ Convegno/ Stage/Altro (specificare) – Course/Seminar/ Workshop/Conference/Stage/Other (specify)			

SUMMERSCHOOL	VDSP SUMMERACADEMY 2023 - MATTERWAVES	VIENNA, AUSTRIA	17/06/2023 - 28/06/2023
CONFERENCE	IQIS CONFERENCE 2023	TRIESTE, ITALY	18/09/2023 - 22/09/2023
SUMMERSCHOOL	MAW SCHOOL ON COMPUTATIONAL METHODS FOR ULTRACOLD QUANTUM MATTER	GRENOBLE, FRANCE	25/03/2024 - 29/03/2024
SUMMERSCHOOL & CONFERENCE	FOMO 2024 SUMMER SCHOOL & CONFERENCE	ARCHANES & CHANIA, CRETE, GREECE	02/09/2024 - 13/09/2024
CONFERENCE	First MAWI Conference on Quantum sensing for quantum technologies	TRIESTE, ITALY	18/02/2025 - 20/02/2025
CONFERENCE	FISMAT 2025	VENICE, ITALY	07/07/2025 - 11/07/2025
CONFERENCE	MAW STUDENT-LED MEETING ON QUANTUM TECHNOLOGY: FROM THEORY TO APPLICATIONS	ST. ANDREWS, SCOTLAND	14/07/2025 - 16/07/2025
COURSE	ADVANCED QUANTUM MECHANICS AND SELECTED APPLICATIONS FOR QUANTUM COMPUTATION	TRIESTE, ITALY	
COURSE	COMPLETE POSITIVITY IN QUANTUM INFORMATION	TRIESTE, ITALY	
COURSE	LOW TEMPERATURE PHYSICS: QUANTUM FLUIDS AND SUPERCONDUCTIVITY	TRIESTE, ITALY	
COURSE	INTRODUCTION TO BAYESIAN METHODS	TRIESTE, ITALY	

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

TIPO / TYPE	TITOLO / TITLE
<b>ATTIVITÀ TUTORIALI E DIDATTICO INTEGRATIVE SVOLTE / TUTORING ACTIVITIES</b>	/
<b>SEMINARI TENUTI DAL DOTTORANDO / SEMINARS HELD BY THE PHD STUDENT</b>	/
<b>PUBBLICAZIONI SCIENTIFICHE / SCIENTIFIC PUBLICATIONS</b>  riferimenti bibliografici completi delle pubblicazioni presenti nel catalogo ArTS / full bibliographic references of the publications submitted to the ArTS catalog	1.) EFFECT OF ENERGY EXTENSIVITY ON THE PERFORMANCE OF OPEN QUANTUM INTERFEROMETERS 2.) INSENSITIVITY POINTS AND PERFORMANCE OF OPEN QUANTUM INTERFEROMETERS UNDER NUMBER-CONSERVING & NON-CONSERVING LINDBLAD DYNAMICS 3.)

**PRESENTAZIONI A CONGRESSI,  
POSTER, ABSTRACT ETC /  
PRESENTATIONS AT CONFERENCES,  
POSTERS, ABSTRACTS,**

*se pubblicato, riportare i riferimenti  
bibliografici / if published provide full  
bibliographic references*

POSTER AT FOMO 2024

TALK AT FISMAT 2025

POSTER AT MAWI STUDENT-LED MEETING ON QUANTUM TECHNOLOGY, ST. ANDREWS

**Data compilazione /Date,**

29.3.2026

**Firma dottorando/PhD student's signature**



**Firma supervisore/Supervisor's signature**

