Master in Photonics – "PHOTONICS BCN"
Master ERASMUS Mundus "EuroPhotonics"

MASTER THESIS PROPOSAL

Dates: April 2025 – July or September 2025

Laboratory: Atomic Quantum Optics (Mitchell group)
Institution: ICFO
City, Country: Barcelona, Spain

Title of the master thesis: Toward a Bose-Einstein condensate dark-matter detector

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Keywords: Quantum sensing, atomic physics, quantum optics

Summary of the subject (maximum 1 page):

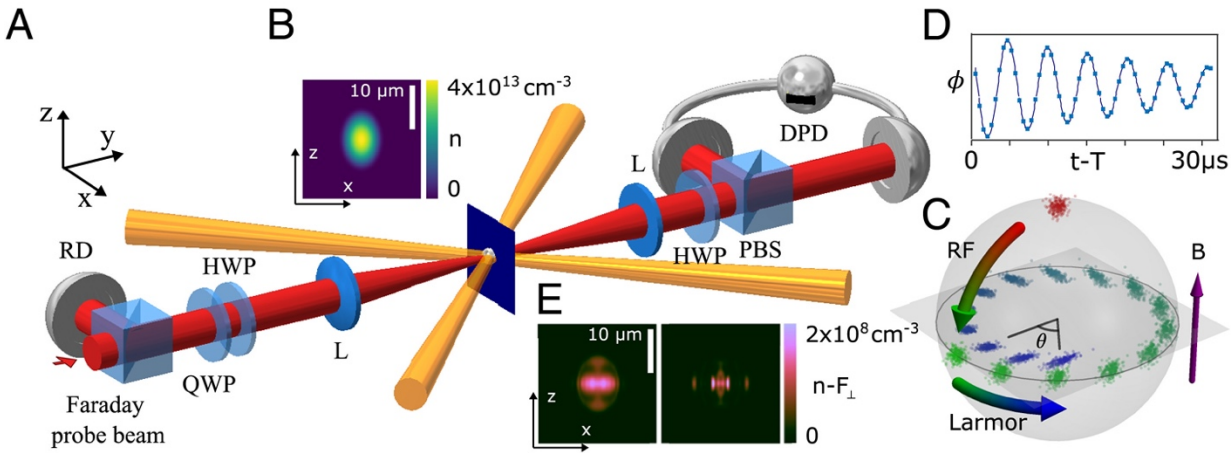
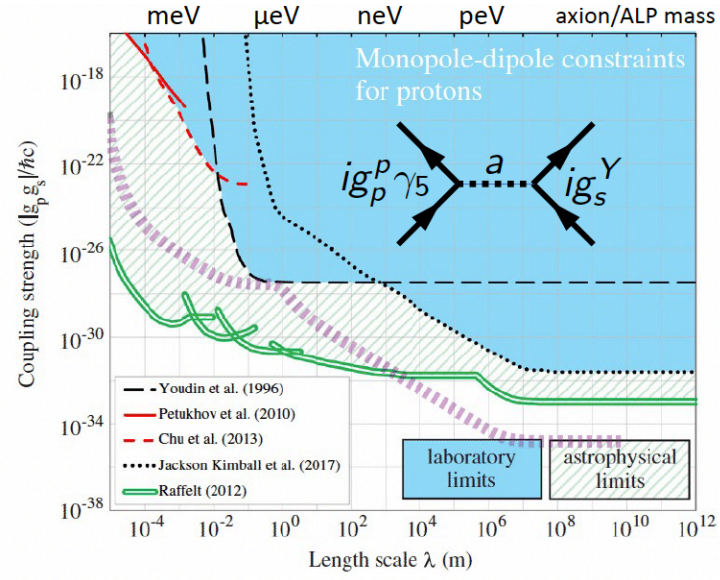


Figure 1 *BEC magnetic field sensor. (A) Experimental schematic: crossed, far-off-resonance beams (orange) are used to produce and hold a spinor condensate. A near-resonance probe*

*beam (red) is used to make nondestructive Faraday rotation measurements of the collective spin **F**. (B) Computed density* n *of the prepared SBEC in the* x–z *plane (dark square in schematic). (C) Evolution of the collective spin statistical distribution during the sensing protocol (not to scale): the atoms are spin polarized parallel to the field direction, with the collective spin **F** statistically distributed as shown by red dots, limited by spin projection noise and atom number uncertainty. (D) Readout: during the final few precession cycles the spin component* F_y *is detected by Faraday rotation. (E) Spatial distribution of the polarization density, obtained from 3 + 1D Gross–Pitaevskii equation simulations.*

Brief introduction: A Bose-Einstein condensate (BEC) is ultra-cold matter with extraordinary spatial coherence. We recently demonstrated that this spatial coherence implies also extraordinary spin coherence [1], making a spinor-BEC the most sensitive detector of magnetic fields ever [2]. Our goal now is to use this capability to search for new spin-dependent forces that (if they exist) would signal the existence of the axion, a hypothetical particle and leading candidate for the missing "dark matter" of the universe [3].



Predicted sensitivity (purple dashed line) for 1 week of acquisition. Adapted from Safronova et al. RMP 2018

Figure 2 Predicated sensitivity of the spinor BEC to axion-mediated monopole-dipole forces acting on the proton.

Possible masters projects:

1) (experimental) construction and testing of magnetic field compensation system, optically-detected microwave spectroscopy and control of BEC spin degrees of freedom.
2) (theoretical) quantum optical calculation and simulation of BEC spin dynamics, design of optimal protocols for detection of axion-mediated spin-dependent forces

Additional information:

* Required skills: Experimental experience is desirable but not absolutely required. Hard working, good knowledge of optics, quantum optics and laser principles.

[1] S. Palacios, S. Coop, P. Gomez, T. Vanderbruggen, Y. N. M. de Escobar, M. Jasperse, and M. W. Mitchell, *Multi-second magnetic coherence in a single domain spinor Bose–Einstein condensate*, New Journal of Physics **20**, 053008 (2018).
[2] S. Palacios Alvarez, P. Gomez, S. Coop, R. Zamora-Zamora, C. Mazzinghi, and M. W. Mitchell, *Single-Domain Bose Condensate Magnetometer Achieves Energy Resolution per Bandwidth below ħ*, PNAS **119**, (2022).
[3] P. Gomez, F. Martin, C. Mazzinghi, D. Benedicto Orenes, S. Palacios, and M. W. Mitchell, *Bose-Einstein Condensate Comagnetometer*, Phys. Rev. Lett. **124**, 170401 (2020).