



## Congratulations to New ICFO PhD Graduate

Dr Javier Argüello Luengo graduated with a thesis entitled 'Synthetic quantum matter using atoms and light'.

October 21, 2022

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We congratulate Dr Javier Argüello Luengo who defended his thesis today in ICFO's auditorium

Dr Argüello Luengo obtained his MSc in Theoretical Physics from the University of Waterloo in Canada before coming to ICFO as a PhD 'la Caixa' Foundation Fellow in the Theoretical Quantum-Nano Photonics group led by ICREA Prof Darrick Chang. His thesis entitled 'Synthetic quantum matter using atoms and light' was supervised by Prof Dr Darrick Chang and Dr Alejandro Gonzalez Tudel

### **ABSTRACT:**

Atomic and optical physics are two fields closely connected by a shared range of energy scales, and the interactions between them. Atoms represent the most fundamental

components of matter, and interactions with electromagnetic fields are responsible for many properties used to characterize a material, like the emission and absorption of radiation by these systems. Over the last decades, this has allowed us to use light as a tool to access and manipulate the internal states of atomic systems. Such a quantum control has transformed atoms into one of the preferred platforms to explore fundamental science including Applications in quantum information, quantum metrology or, more recently, the realization of synthetic materials where light can induce interactions that would be difficult to find intrinsically in real materials

In the first part of this Thesis, we show how single atoms coupled to a cavity field can offer unique opportunities as quantum optomechanical devices because of their small mass and a strong interaction with light. In particular, we focus on the "single-photon strong coupling" regime, where motional displacements on the order of the zero-point uncertainty are sufficient to shift the cavity resonance frequency by more than its linewidth. By coupling atomic motion to the narrow cavity-dressed atomic resonance, we theoretically observe that the scattering properties of single photons can become highly entangled with the atomic wavefunction, even if the cavity linewidth is large. This leads to a per-photon motion-induced heating that is significantly larger than the single-photon recoil energy, as well as mechanically-induced oscillations that could be observed in the correlations of a state-of-the-art cavity system

In the second part of the Thesis, we investigate how synthetic materials built using light can be harnessed as quantum simulators, defeating the limitations that classical computers face in the exploration of quantum phenomena. We particularly focus on ultracold atomic mixtures trapped in optical lattices, where atom-mediated long-range interactions can provide an enabling tool in the simulation of relevant problems in condensed matter and quantum chemistry

First, we show that fermionic atoms in an ultracold gas can act as a mediator, giving rise to effective long-range RKKY interactions among other neutral atoms trapped in an optical lattice. We further propose several experimental knobs to tune these interactions, which are characterized by the density and dimensionality of the gas and are accessible in current experimental platforms. We also show that these knobs open up the exploration of new frustrated regimes where symmetry-protected topological phases and chiral spin liquids emerge

Second, we introduce a set of experimental schemes where long-range interactions are mediated by an additional bosonic species trapped in a commensurate optical lattice, both in 2D and 3D. In particular, we show that the interplay with cavity QED can lead to effective Coulomb-like repulsion, which opens the door to the analog simulation of quantum chemistry problems using ultracold fermionic atoms as simulated electrons. Apart from explaining the emergent mechanism, we provide operational conditions for the simulator, benchmark it with simple atoms and molecules, and analyze how the continuous limit is approached

r increasing optical lattice sizes. Finally, we compare our results with those of the continuum limit, where conventional quantum chemistry methods can be evaluated and tested. In summary, our results show connections between different areas of theoretical and experimental physics where light-matter interaction can play a dominant role, and suggest how this can be harnessed to further advance our understanding of strongly correlated quantum matter.

**Thesis Committee:**

Prof. Dr. Maciej Lewenstein, ICF

Prof. Dr. Diego Porras Torre, Consejo Superior de Investigaciones Científicas

Dr. Johannes Maximilian Feist, Universidad Autónoma de Madrid



Thesis Committee