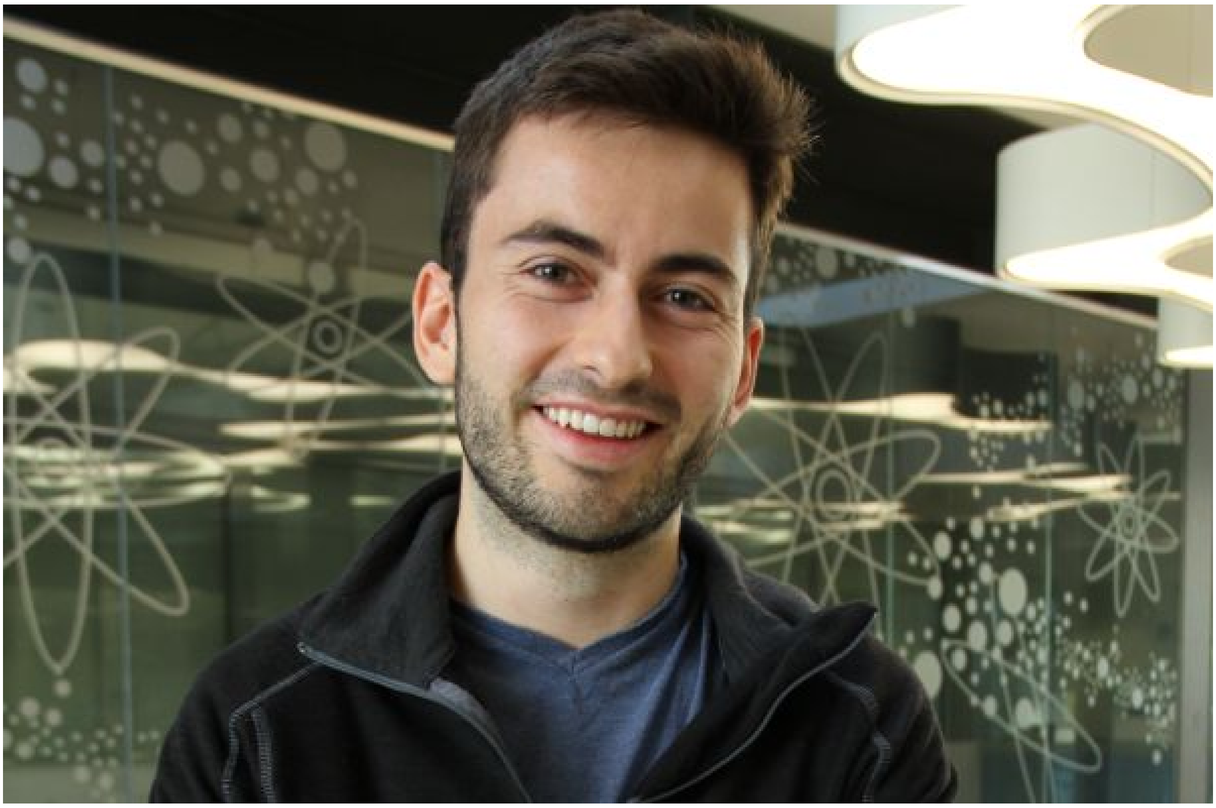

PhD THESIS DEFENSE: Synthetic quantum matter using atoms and light

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Atomic and optical physics are two fields closely connected by a shared range of energ scales, and the interactions between them. Atoms represent the most fundamenta components of matter, and interactions with electromagnetic fields are responsable fo many properties used to characterize a material, like the emission and absorption of radiatio by these systems. Over the last decades, this has allowed us to use light as a tool to acces and manipulate the internal states of atomic systems. Such a quantum control ha transformed atoms into one of the preferred platforms to explore fundamental science including Applications in quantum information, quantum metrology or, more recently, th realization of synthetic materials where light can induce interactions that would be difficult t find intrinsically in real materials

In the first part of this Thesis, we show how single atoms coupled to a cavity field can offe

unique opportunities as quantum optomechanical devices because of their small mass an 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 ar sufficient to shift the cavity resonance frequency by more than its linewidth. By couplin atomic motion to the narrow cavity-dressed atomic resonance, we theoretically observe tha the scattering properties of single photons can become highly entangled with the atomi wavefunction, even if the cavity linewidth is large. This leads to a per-photon motiona heating that is significantly larger than the single-photon recoil energy, as well a mechanically-induced oscillations that could be observed in the correlations o state-of-the-art cavity systems

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

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

Second, we introduce a set of experimental schemes where long-range interactions ar mediated by an additional bosonic species trapped in a commensurate optical lattice, both i 2D and 3D. In particular, we show that the interplay with cavity QED can lead to effectiv Coulomb-like repulsion, which opens the door to the analog simulation of quantum chemistr problems using ultracold fermionic atoms as simulated electrons. Apart from explaining th emergent mechanism, we provide operational conditions for the simulator, benchmark it wit simple atoms and molecules, and analyze how the continuous limit is approached fo increasing optical lattice sizes. Finally, we compare our results with those of the continuu limit, where conventional quantum chemistry methods can be evaluated and tested. I summary, our results show connections between different areas of theoretical an experimental physics where light-matter interaction can play a dominant role, and sugges how this can be harnessed to further advance our understanding of strongly correlate quantum matter

Thesis Directors: Prof Dr. Darrick Chang & Dr. Alejandro Gonzalez Tudela

Hosted by: Darrick Chang