Quantum Connections 2024

Quantum Sensing and Photonics in the Hunt for Dark Matter

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The idea that the visible universe was not all there was goes back nearly a century, but it took nearly half a century to put the existence of dark matter on a firm footing. In the subsequent half century, experiments of ever-increasing scale and sensitivity have been mounted to search for it, fruitlessly to date. Curiously, while it may be the predominant form of matter in the universe, it also may also represent the weakest interaction in nature, save for gravity. These four lectures are presented not only as an interlude to the main program, but because the search for dark matter is both a beneficiary and a driver of recent advances in quantum sensing and photonic materials. And indeed if ultralight dark matter, such as the axion, is discovered, it may itself represent a remarkable macroscopic quantum system that will teach us much about cosmology and open up undreamt of practical applications.

- Overall reference: *The Search for Ultralight Bosonic Dark Matter*, eds. D.F. Jackson Kimball, K. van Bibber, Springer (2021)

Session 1: The Evidence, Nature and Identity of Dark Matter

This first presentation will present the case for our conviction about dark matter, taking a historical perspective, what we know about its distribution and role in cosmology, limits on its mass, and a few of the leading candidates for its constitution. The scope for the remainder of the series will then narrow down to ultralight dark matter, the axion in particular, which owing to its very high occupation number can be treated as a classical field, setting the stage for how exquisitely sensitive searches are being carried out.

- General reference: *The Pool-Table Analogy with Axion Physics*, Pierre Sikivie, Physics Today, December 1996, p. 22

Session 2: The Axion in Particle Physics, Astrophysics and Cosmology

The axion emerged as a solution to a solution to the Strong-CP problem in particle physics, one of the last remaining loose ends in the Standard Model. This talk will explore its implications in particle physics and the cosmos, and the landscape of current experimental efforts, with the axion-photon coupling in particular giving rise to so many inspired schemes for detecting the axion. This lecture will conclude with an introduction to the microwave cavity searches and their variants.

- General reference: *Ultrasensitive Searches for the Axion*, K. van Bibber, L. Rosenberg, Physics Today, August 2006 p. 30

Session 3: Resonators, Photonic Band Gap structures, and Metamaterials

This is the first of two talks on the "business end" of a microwave cavity dark matter experiment. The multiple stringent requirements for microwave resonators will be presented, motivating the need for a new paradigm beyond conventional cavities at the very high frequencies corresponding to the post-inflation axion.

Session 4: Quantum amplifiers and receivers

The extraordinarily weak signal expected in these experiments, optimistically a yoctowatt, has spurred a revolution in quantum sensing in the gigahertz frequency range and beyond. These include quantum-limited amplifiers, squeezed state receivers to circumvent the Standard Quantum Limit of noise, more advanced schemes such as two-cavity entanglement and state exchange, Rydberg atom single-quantum detectors, and finally superconducting qubits.

- General reference: *Putting the Squeeze on the Axion*, K. van Bibber, K. Lehnert, A. Chou, Physics Today 72 (2019) 48
- Technical reference: *A Quantum-Enhanced Search for Dark Matter Axions*, K.M. Backes, et al., Nature 590 (2021) 238

Conclusion: The series will finish with a series of open questions for the conferees to think about and hopefully solve.