Rydberg atom-based single photon detectors for dark matter axion searches

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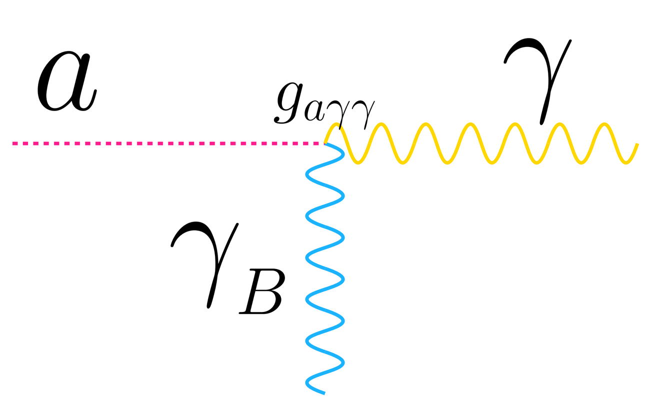
Axion Dark Matter



The QCD axion would solve both the dark matter problem and the Strong CP problem of *Quantum ChromoDynamics*. Haloscopes attempt to detect them through the *inverse Primakoff effect*, shown on the right.

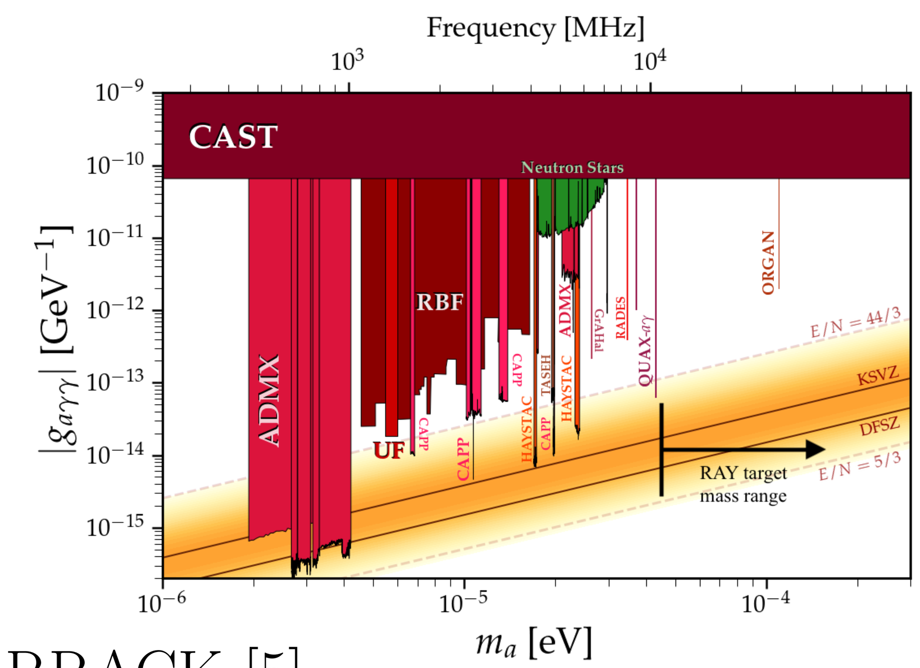
Single Photon Detection for Axion Searches

Scanning axion parameter space with a standard haloscope becomes intractable at high frequencies due to lower signal and increased quantum noise. Single-photon instrumentation has many benefits over the standard haloscope at higher masses [1]:

- Insensitive to phase; only limited by thermal / shot noise
- Can search at higher masses despite SNR relationship with cavity volume, as experimentally demonstrated in [2]
- Has already been demonstrated in a dark photon search [3]

Rydberg Atoms

Rydberg atoms have a high principal quantum number n and are useful for axion searches because they can have transition frequencies $> 40\ \mu$eV.



Right: Regions of the axion-photon interaction strength versus axion mass; QCD axion region is in yellow and haloscope exclusions are in red. Figure modified from [4].

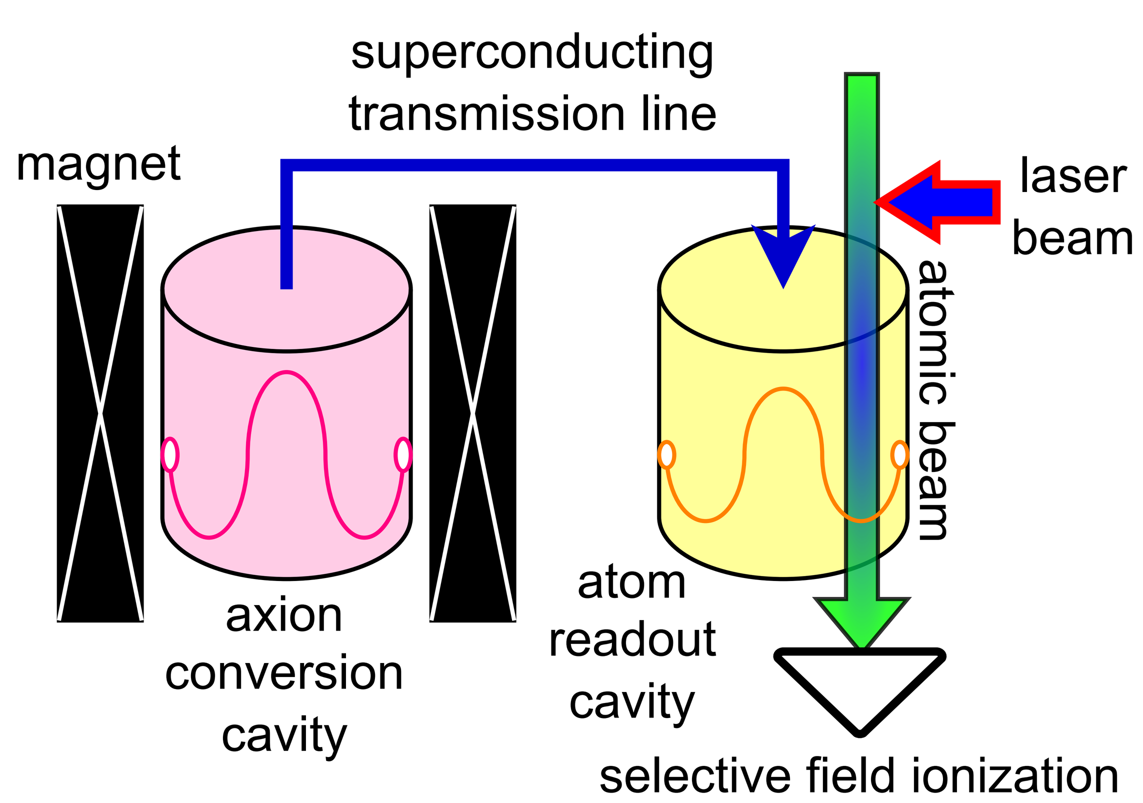
This technique was pioneered by CARRACK [5]. We are well-positioned to take it further:

- Advantages of measuring at higher frequencies:
  - Smaller cavity requires a smaller dilution refrigerator
  - Shorter Rydberg paths make R&D implementation easier
- Advantages of us doing it now:
  - Rydberg atoms are now being studied for quantum computing
  - New cavity design insulates Rydberg atoms from the Tesla-scale magnetic fields required for the axion-photon conversion
  - Experience translates from HAYSTAC collaboration

Rydberg-based Axion search at Yale (RAY)

Detection Scheme

We are building a haloscope setup with Rydberg atom-based single photon detectors.

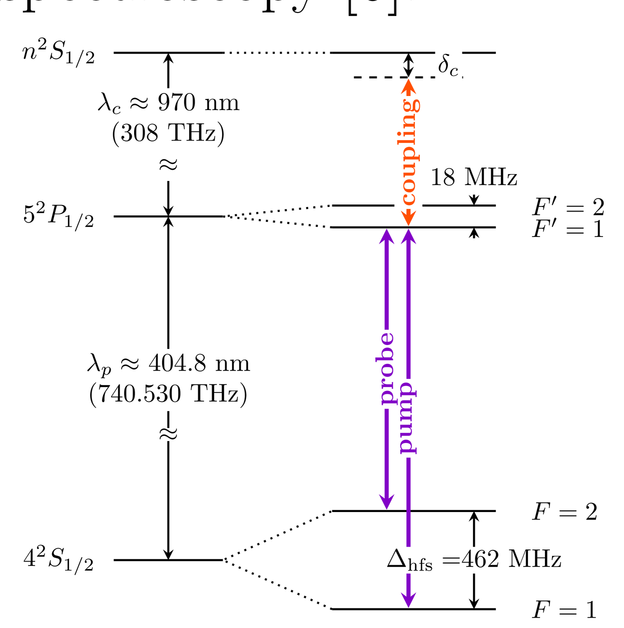


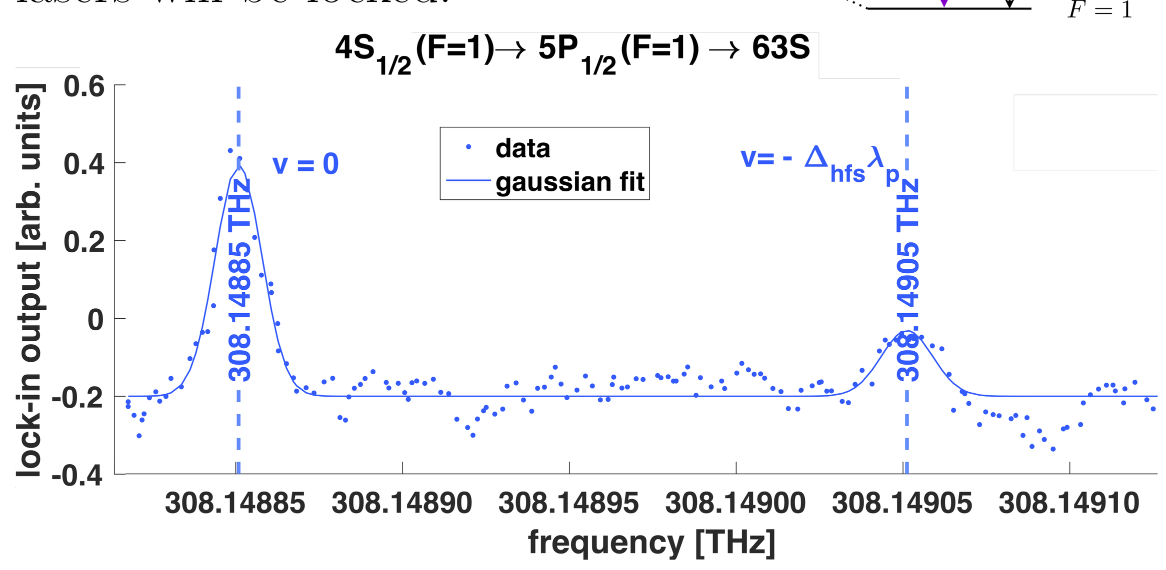
Above: A detection cavity is coupled to and locked in frequency with the conversion cavity.
Below: The system is cooled with a dilution refrigerator to reduce thermal noise.

Using ^{39}K Rydberg Atoms

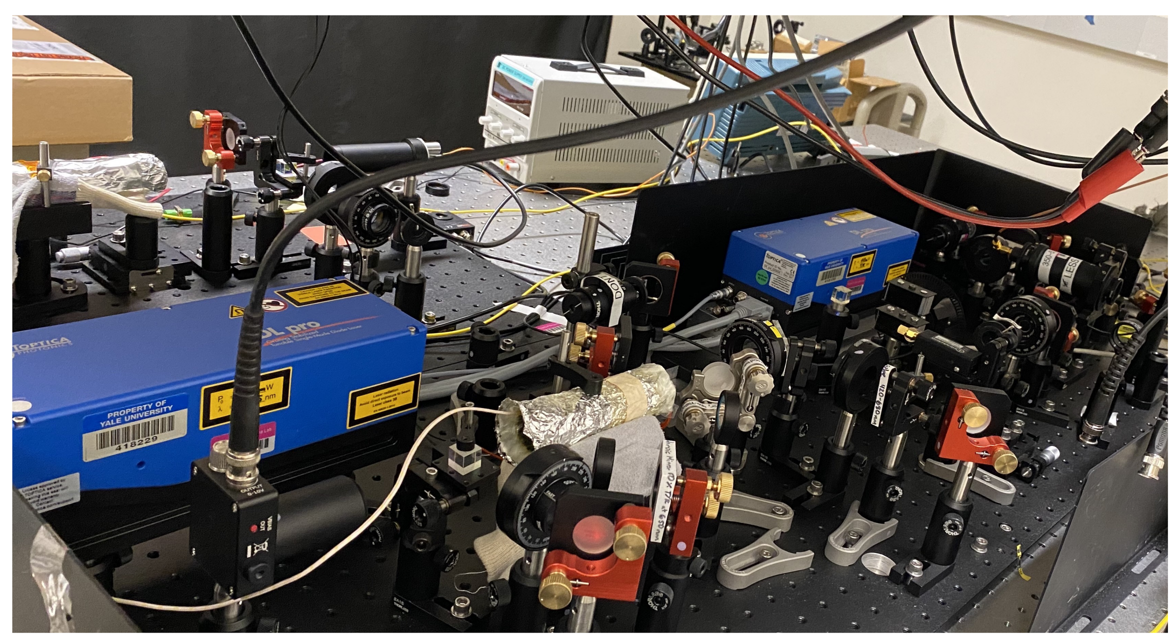
Our setup will use ^{39}K, which is less susceptible to Stark shift than the Rb used by CARRACK [5]. Rydberg transitions in ^{39}K were found with electromagnetically induced transparency (EIT) spectroscopy [6].

Right: Laser wavelengths used for EIT on a ^{39}K energy level diagram. **Below:** EIT signal measured for the $n = 63$ Rydberg level [6], to which the Rydberg excitation lasers will be locked.





Below: Our EIT setup. The two blue diode lasers are frequency-locked using spectroscopy, so that the ^{39}K atoms can be raised to the Rydberg state with a two-photon transition using a photon from each laser.



https://wlab.yale.edu/
https://maruyama-lab.yale.edu/
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References:

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[3] A. V. Dixit, S. Chakram, et al., "Searching for dark matter with a superconducting qubit", Phys. Rev. Lett. **126**, 141302 (2021).

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