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Ultralight Axion Dark Matter Search using Optical Quantum Sensors

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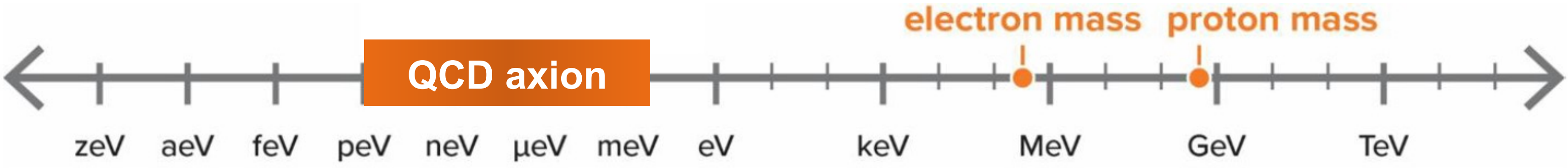
CPAD Workshop

SLAC

Dark Matter Mass Range

Dark matter mass:

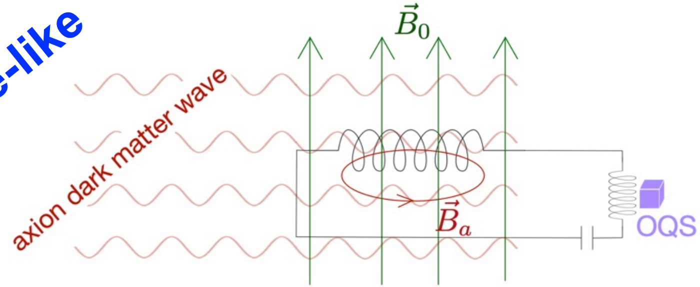


10^{-22} eV

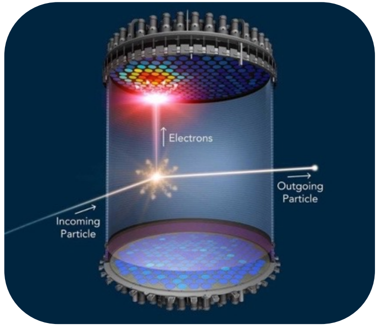
10^{12} eV

Different experimental methods

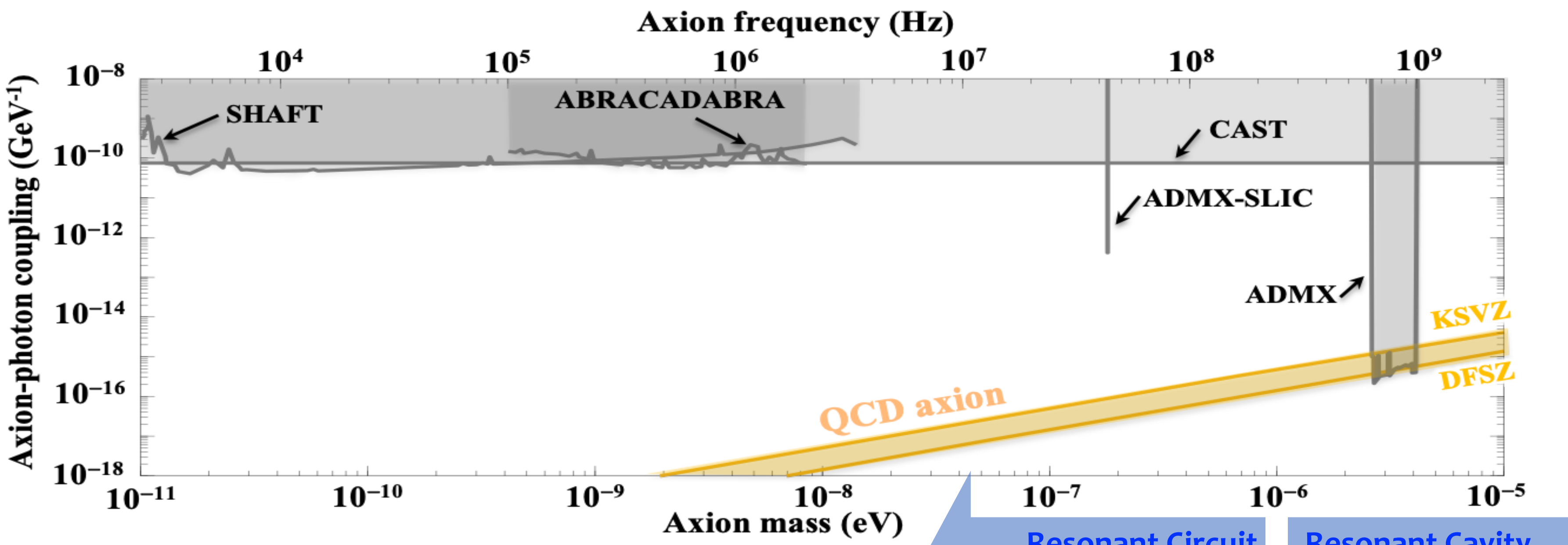
Wave-like



Particle-like



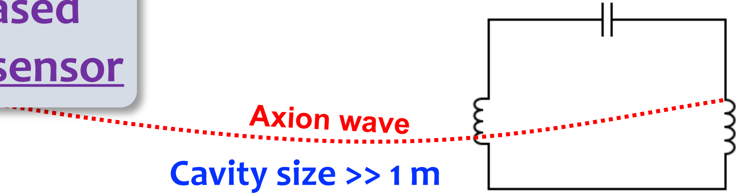
Axion Dark Matter Search



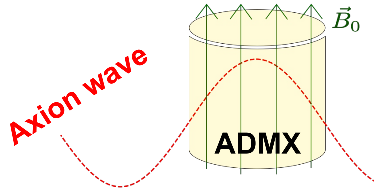
Resonant Circuit experiment

Resonant Cavity experiment

LANL axion search: New detection concept based on optical quantum sensor



Cavity size >> 1 m



Cavity size ~ 1 m

Publication

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Sensitivity of ultralight axion dark matter search with optical quantum sensors

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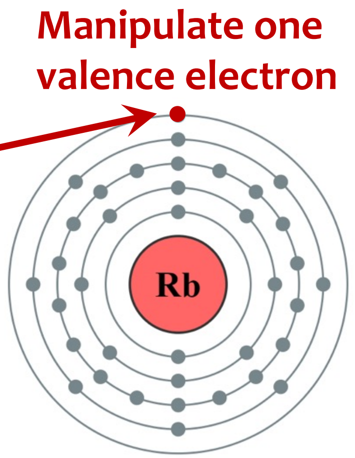
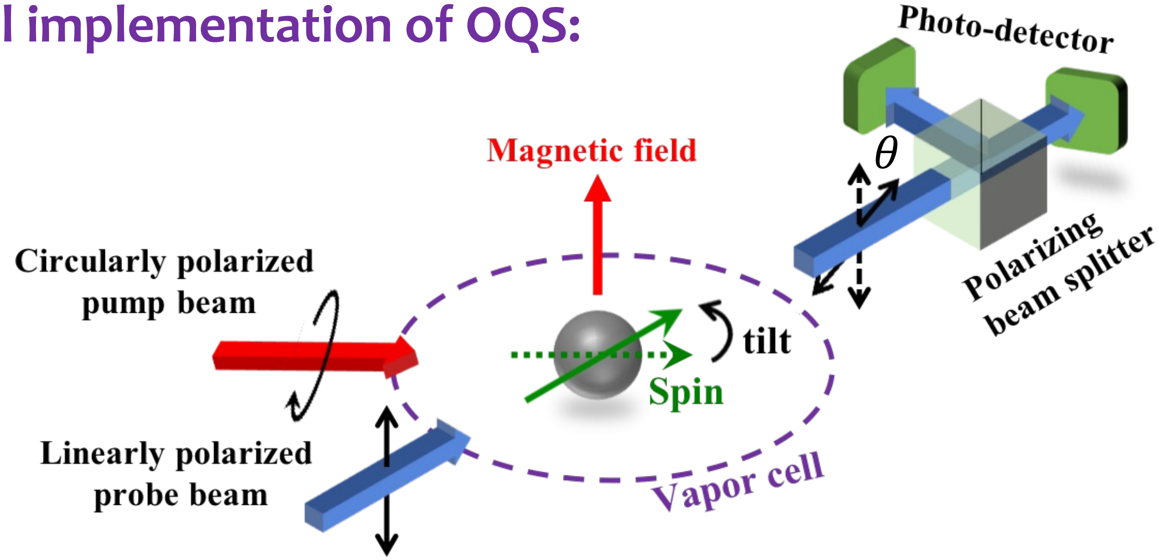
An optical quantum sensor (OQS) based on lasers and alkali-metal atoms is a sensitive ambient-temperature magnetometer that can be used in axion dark matter search with an inductor-capacitor (LC) circuit at kHz and MHz frequencies. We have previously investigated the sensitivity of an LC circuit-OQS axion detector to ultralight axion dark matter that could be achieved using a fT-noise OQS constructed in our lab. In this paper, we investigate the sensitivity that could be potentially reached by an OQS performing close to the fundamental quantum noise levels of 10 $\mathrm{aT}/\sqrt{\mathrm{Hz}}$. To take advantage of the quantum-limited OQS, the LC circuit has to be made of a superconductor and cooled to low temperature of a few K. After considering the intrinsic noise of the advanced axion detector and characterizing possible background noises, we estimate that such an experiment could probe benchmark QCD axion models in an unexplored mass range near 10 neV. Reaching such a high sensitivity is a difficult task, so we have conducted some preliminary experiments with a large-bore magnet and a prototype axion detector consisting of a room-temperature LC circuit and a commercial OQS unit. This paper describes the prototype experiment and its projected sensitivity to axions in detail.

Optical Quantum Sensor (OQS)

- Based on lasers (pumping and probing) and alkali-metal (Cs, Rb, K) vapor cells
- Manipulate electron spins for magnetic sensing

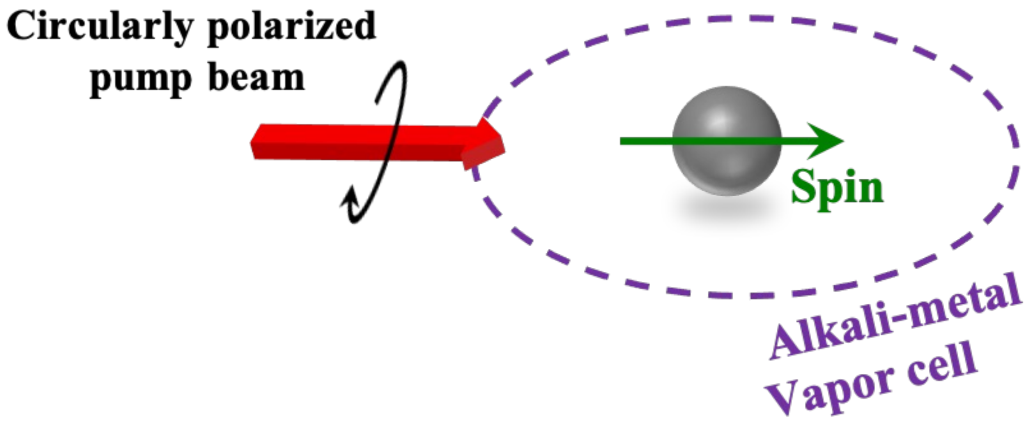


Typical implementation of OQS:



Optical Quantum Sensor

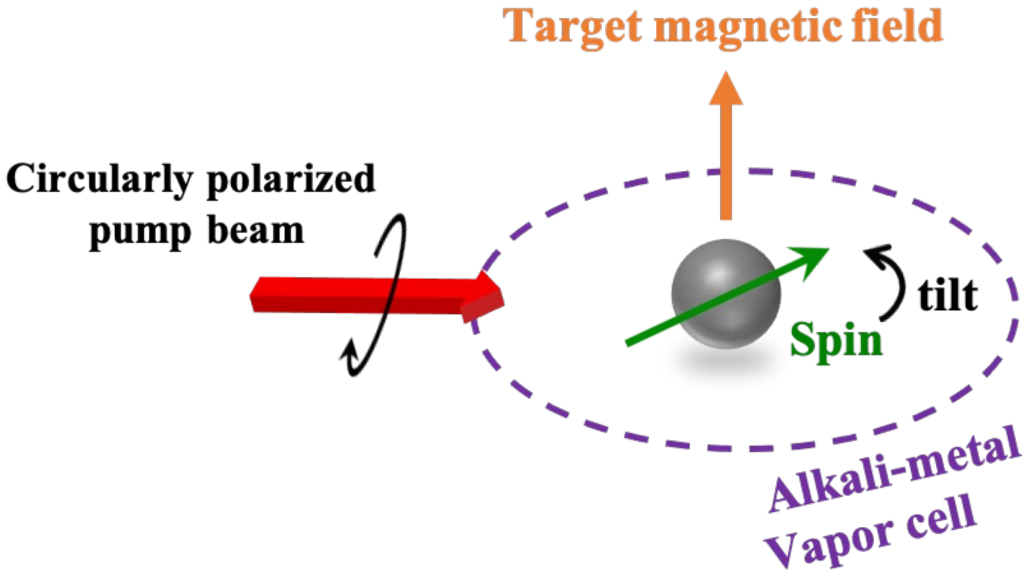
Pumping:



Polarize atomic spins

Optical Quantum Sensor

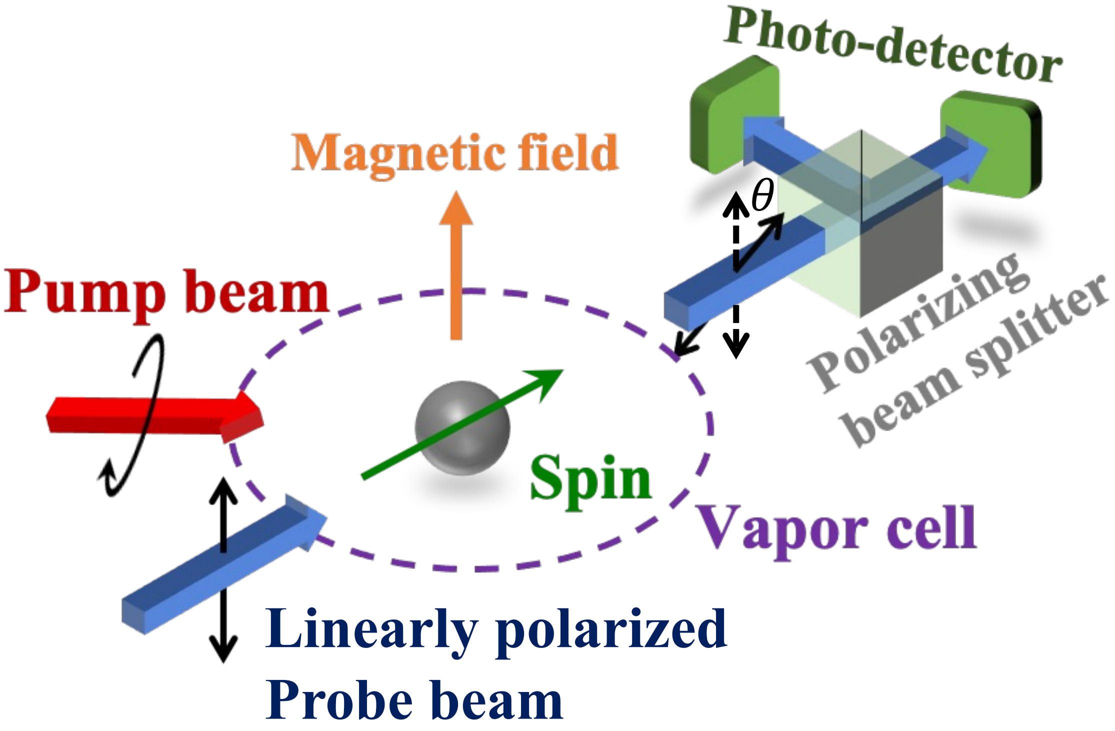
Spin tilt:



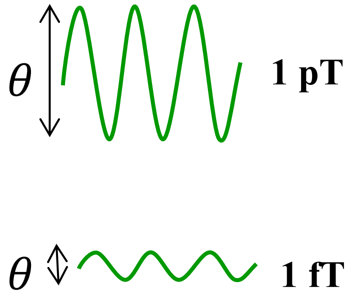
Spin tilt proportional to field strength

Optical Quantum Sensor (OQS)

Probing:



θ= light polarization rotation



Detect magnetic field with probe beam

Fundamental OQS Noise Limit

Fundamental quantum noise limit of OQS:

$$\delta B = \frac{1}{\gamma\sqrt{nV}}\sqrt{\frac{4}{T_2} + \frac{R_{pr}\mathrm{OD}}{32} + \frac{8}{R_{pr}\mathrm{OD}T_2^2\eta}}$$

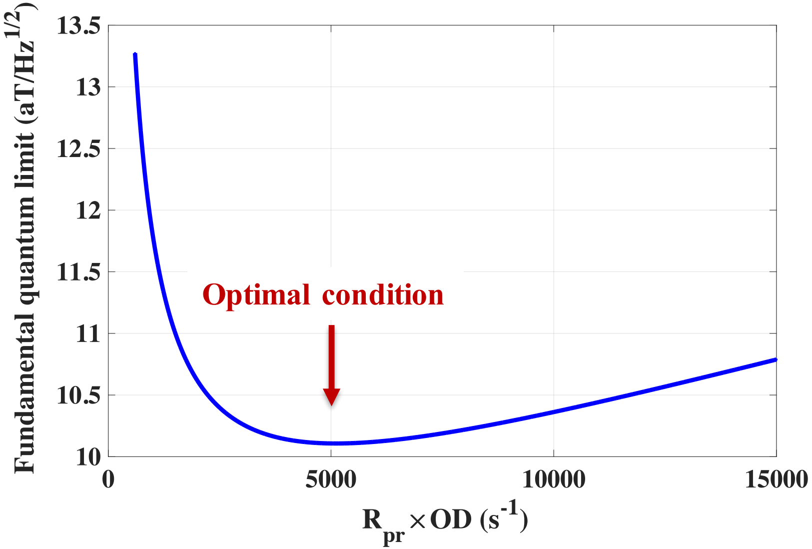
Spin projection noise

Light shift noise

Photon shot noise

γ = 7×10⁹ Hz/T, the gyromagnetic ratio of potassium (K) spins
n = 7×10¹³ cm⁻³, the density of K atoms
V = 100 cm³, the active measurement K cell volume
T_2 = 3.5 ms, the coherence time of K electron spins
η = 0.8, photodiode quantum efficiency in probe beam readout
R_{pr}: the absorption rate of photons from the probe beam
OD: the optical depth of the probe beam

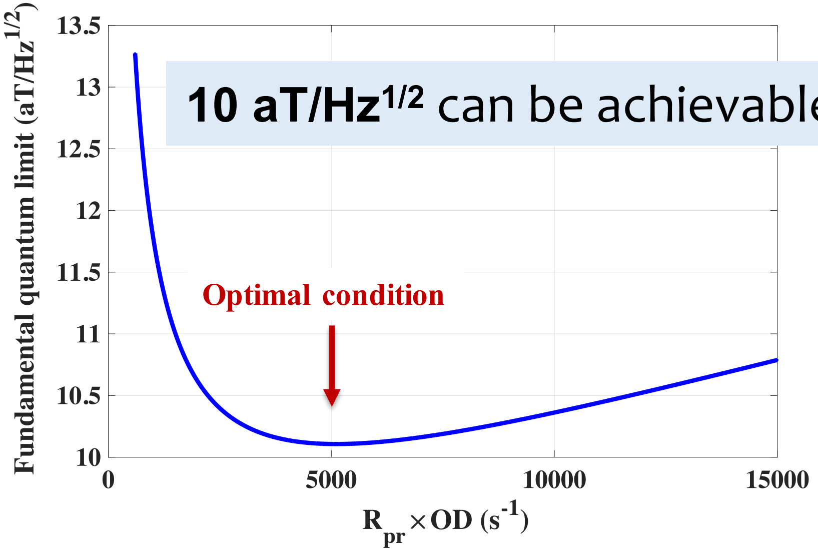
Estimation of fundamental quantum noise limit as a function of $R_{pr} \times$ OD (s^{-1}):



10 aT/Hz$^{1/2}$ can be achievable!

Optimal OQS parameters

Optimal parameters for the optimal condition: $R_{pr} \times$ OD = 5000 s^{-1}



10 aT/Hz$^{1/2}$ can be achievable!

$R_{pr} \times$ OD proportional to (1) probe laser power and (2) probe beam pass length

Optimal parameters
Probe laser power = 400 mW
Probe beam pass length = 10 cm

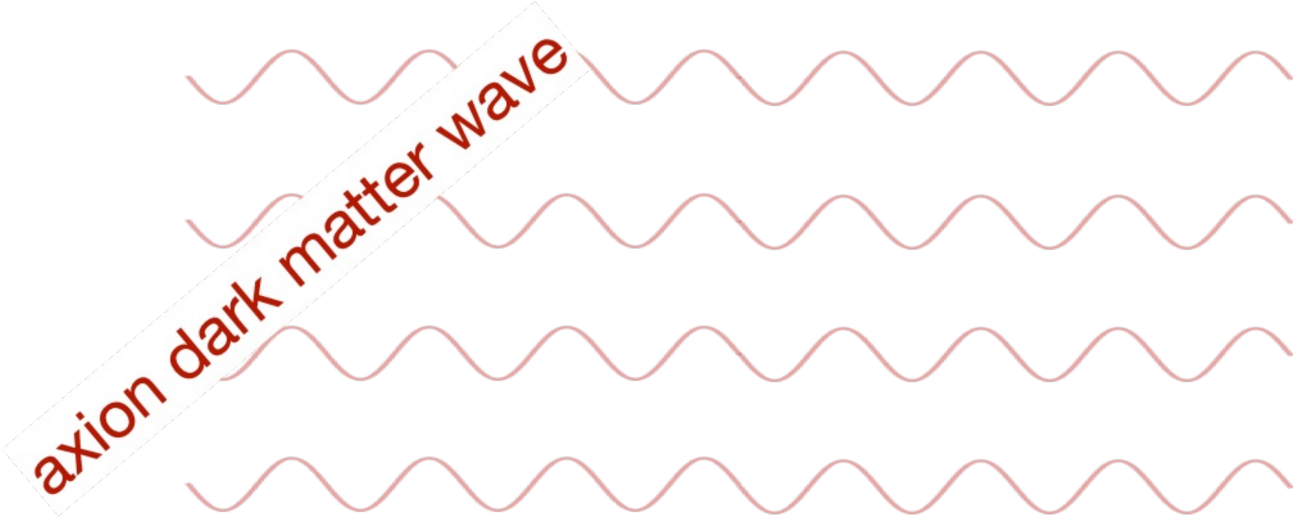
Current best OQS: 240 aT/Hz$^{1/2}$ at 423 kHz in the Rb cell volume of 96 cm^3

Lee, Sauer, Seltzer, Alem, Romalis, *Applied Physics Letters* 89, 214106 (2006)

Demonstrated with low probe laser power of 40 mW

LANL Axion Search: Target Signal

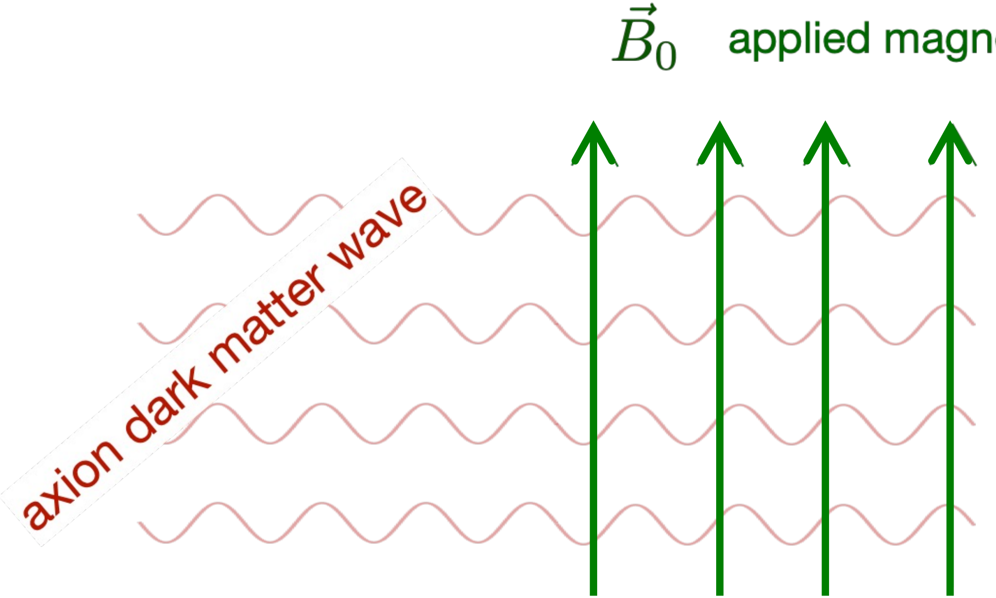
Axion dark matter is "wave-like": an oscillating field at a frequency of the axion mass (m_a) that permeates all of space



$$a(t) = a_0 \cos(m_a t)$$

LANL Axion Search: Target Signal

Axion dark matter is "wave-like": an oscillating field that permeates all of space and **interacts with the electromagnetic field**

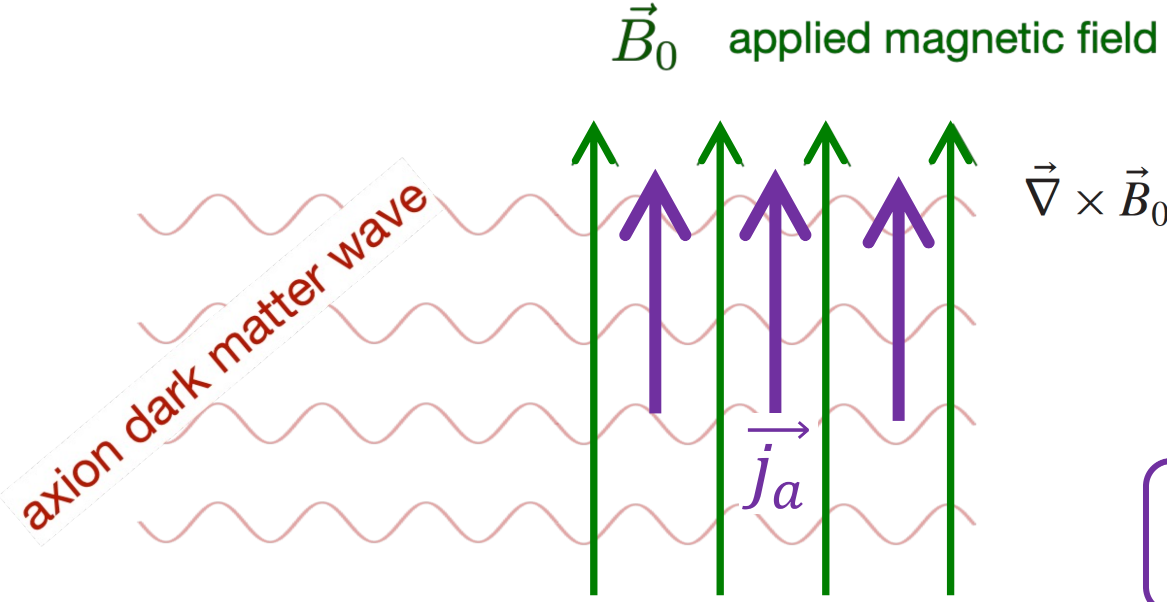


$$\vec{\nabla} \times \vec{B}_0 - \frac{\partial \vec{E}}{\partial t} = g\left(\vec{E} \times \vec{\nabla} a - \vec{B}_0 \frac{\partial a}{\partial t}\right) + \vec{j}_e$$

Axion-photon coupling

LANL Axion Search: Target Signal

Axion dark matter is "wave-like": an oscillating field that permeates all of space and **interacts with the electromagnetic field**



$$\vec{\nabla} \times \vec{B}_0 - \frac{\partial \vec{E}}{\partial t} = g\left(\vec{E} \times \vec{\nabla} a - \vec{B}_0 \frac{\partial a}{\partial t}\right) + \vec{j}_e$$

Axion-photon coupling

$$\vec{j}_a(t) = -g\vec{B}_0[da(t)/dt]$$

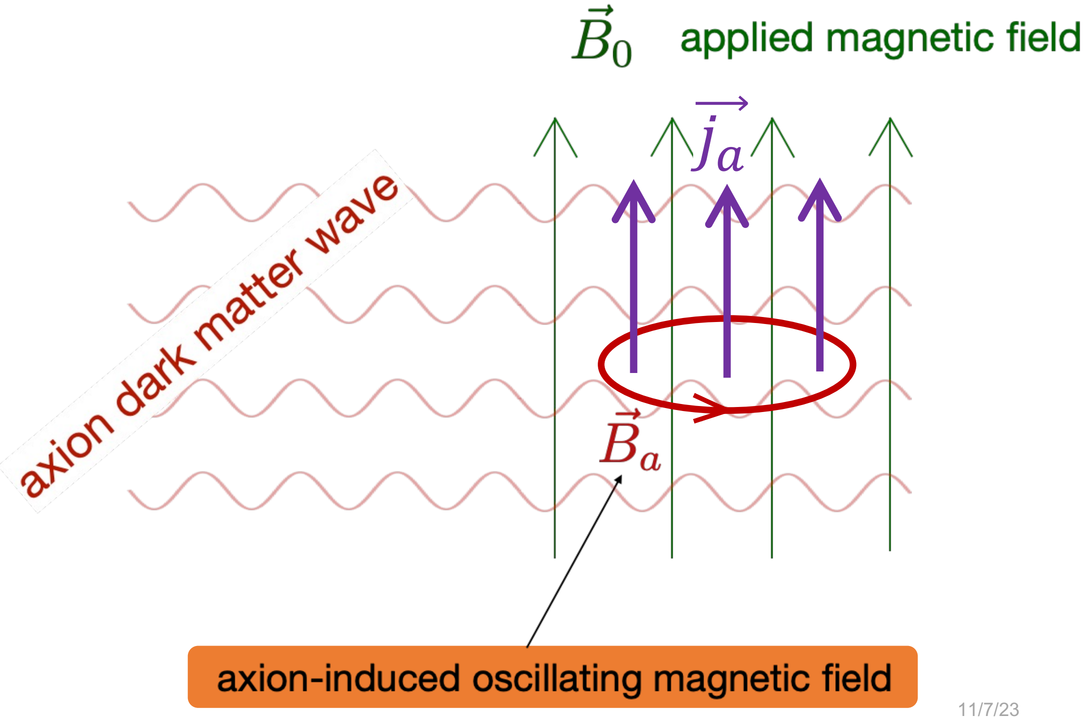
LANL Axion Search: Target Signal

Axion dark matter is "wave-like": an oscillating field that permeates all of space and interacts with the electromagnetic field

$$\vec{j}_a(t) = -g\vec{B}_0[da(t)/dt]$$

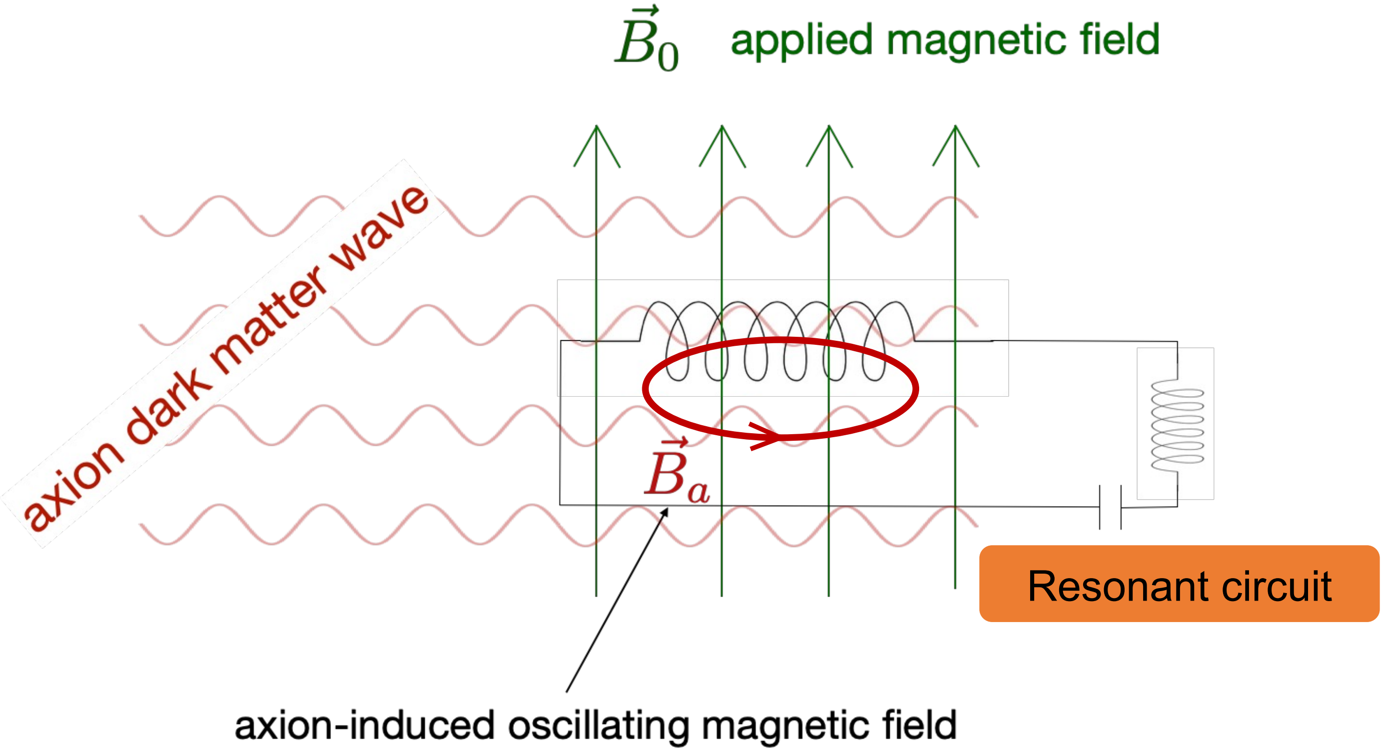
⇩

$$\vec{\nabla} \times \vec{B}_a = \vec{J}_a$$



LANL Axion Search: Target Signal

Axion dark matter is "wave-like": an oscillating field that permeates all of space and interacts with the electromagnetic field



LANL Axion Search: Target Signal

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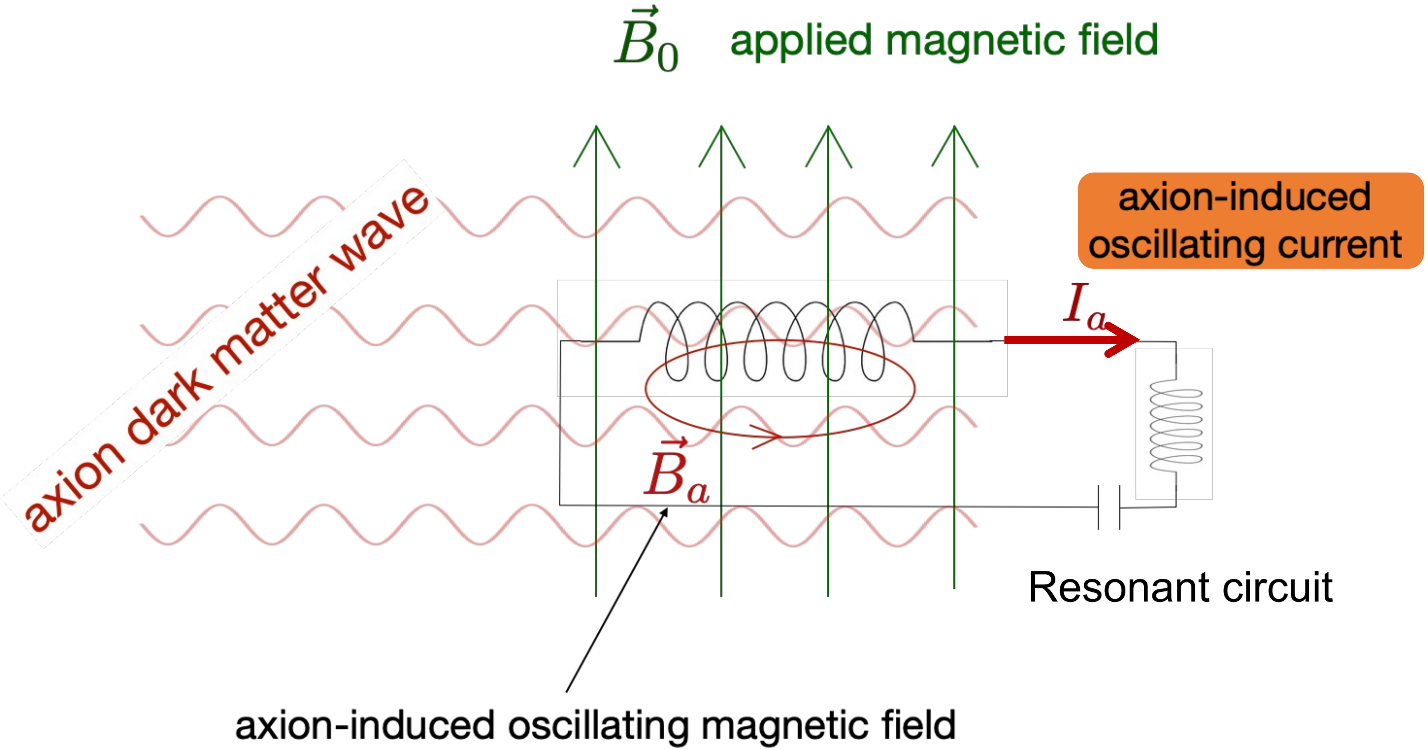
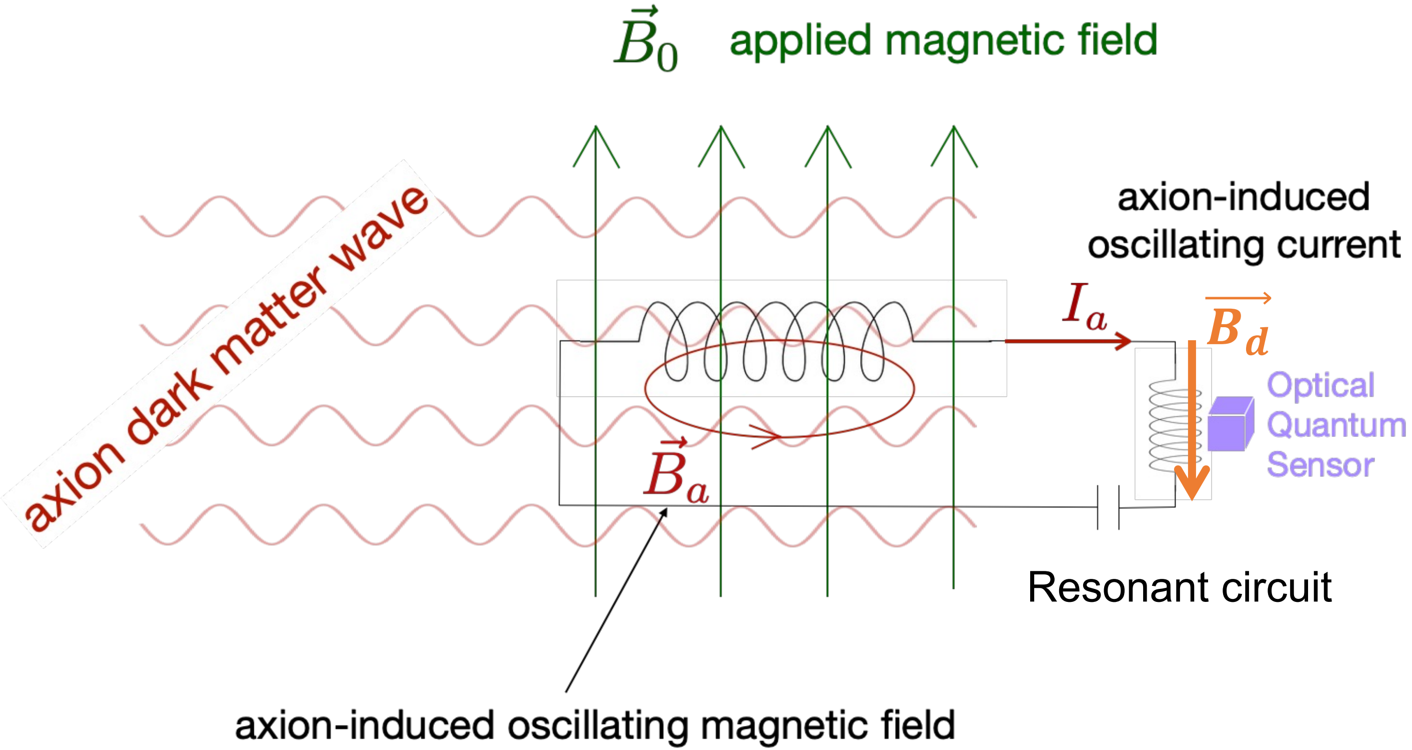
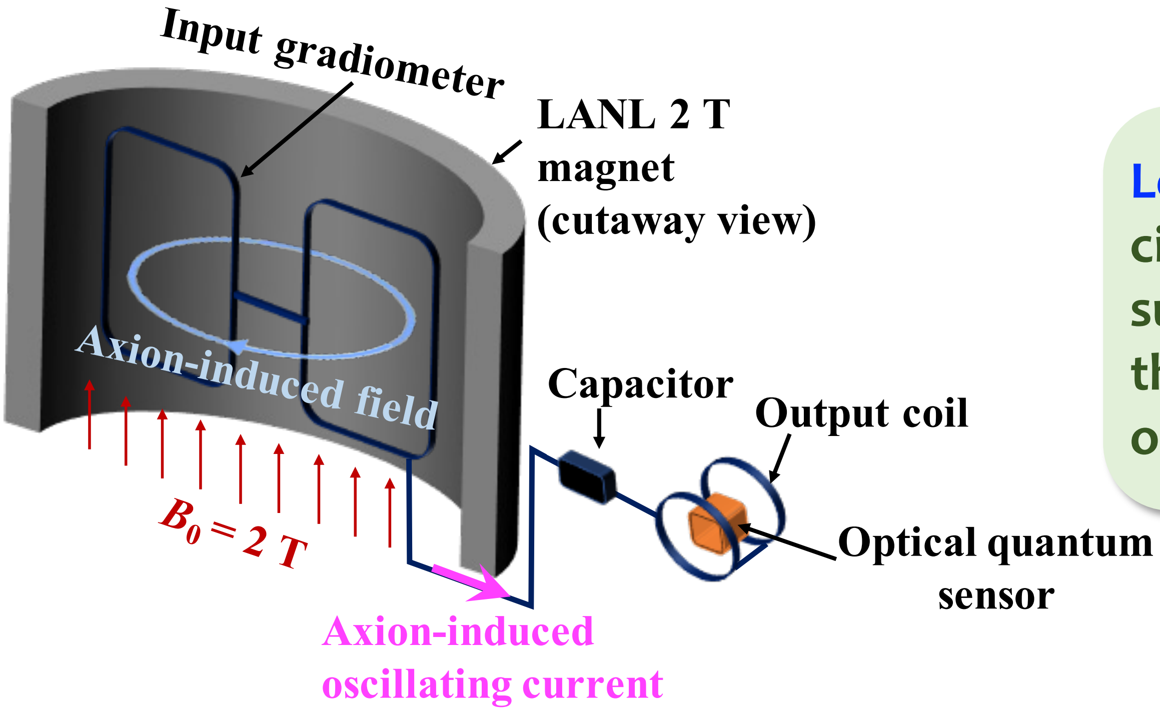


LANL Axion Search: Target Signal

Axion dark matter is "wave-like": an oscillating field that permeates all of space and interacts with the electromagnetic field



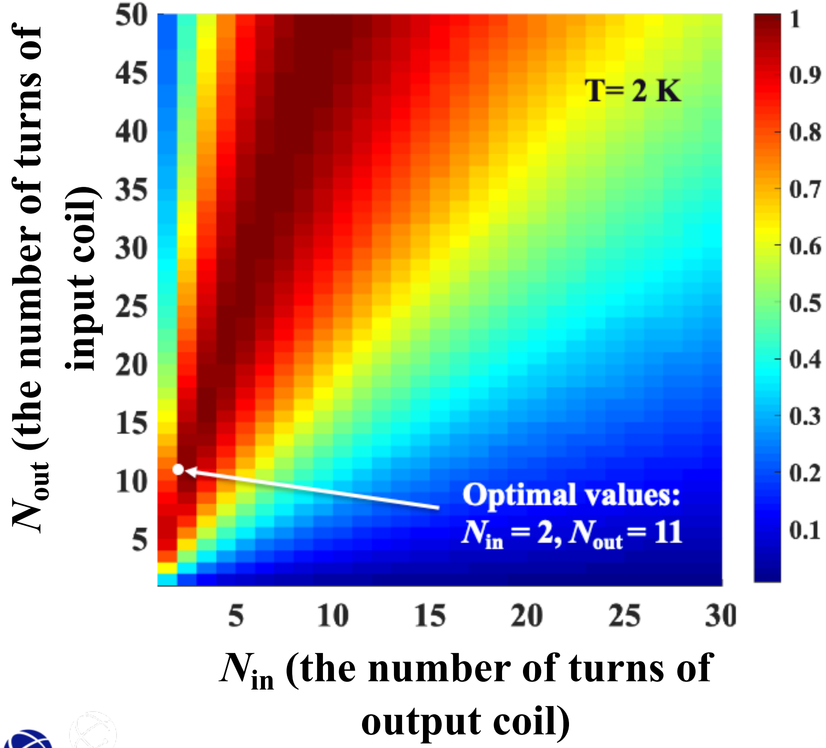
Experiment Layout



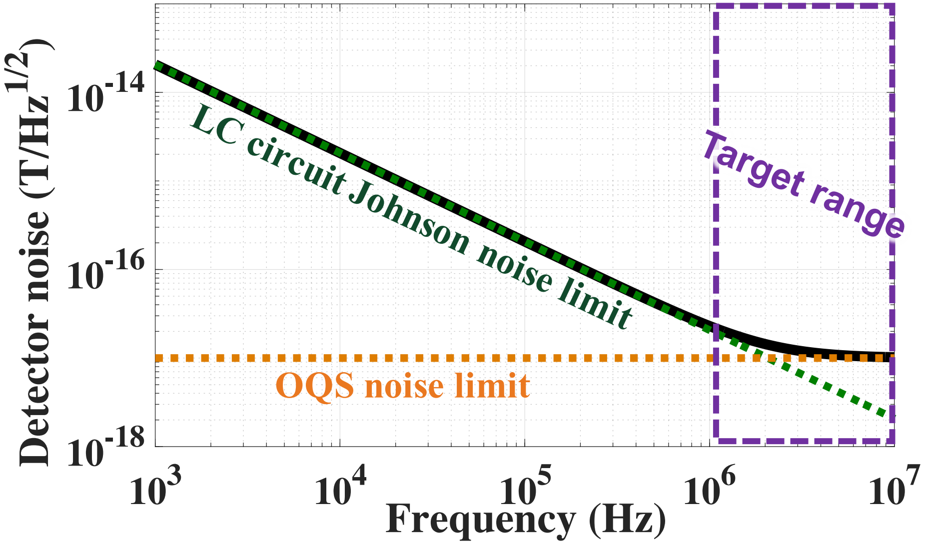
Low temperature resonant circuit made of pure superconducting wire + the quantum limited optical quantum sensor

Intrinsic Noise of Optimized Axion Detector

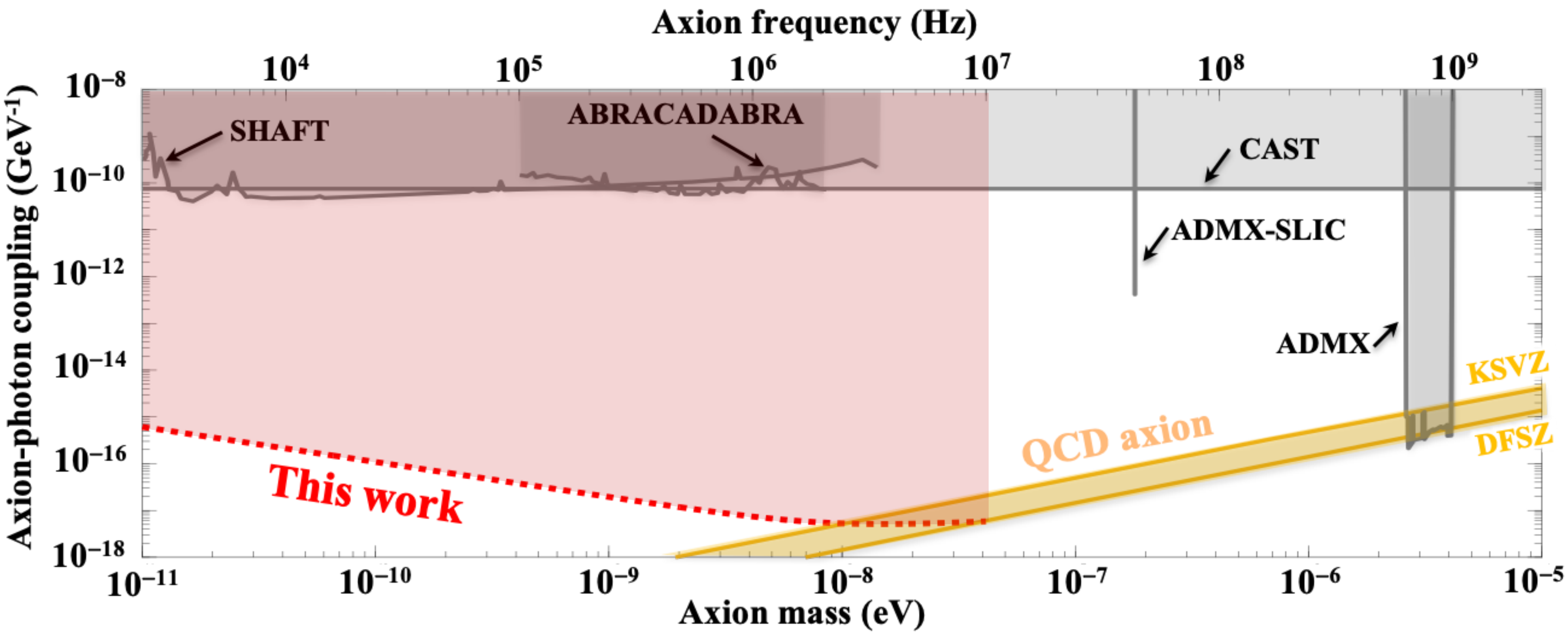
LC circuit optimization:



Intrinsic noise of LC circuit-OQS axion detector:

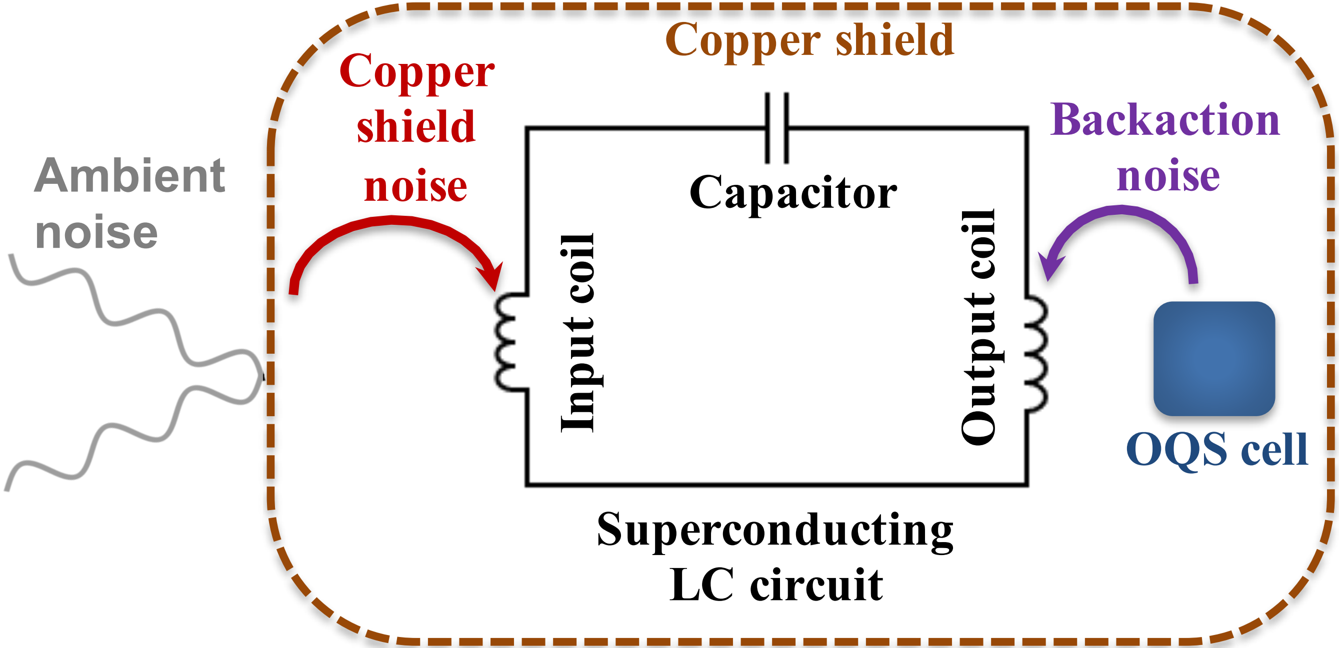


Projected Sensitivity of LANL Axion Searach



- **Unprecedented sensitivity** 7 orders of magnitude beyond the current limit
- Will probe a **completely unexplored axion mass range** near 10 neV

Background Noises

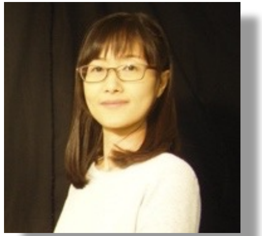


Background noises < Axion detector intrinsic noise

Research Team

Key investigators at Los Alamos National Laboratory:

Young Jin Kim



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Michael Malone

Thank you!