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Highly Sensitive Optical Quantum Sensors

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January 22, 2025

International Conference on Quantum Technologies for High-Energy Physics

CERN

U.S. DEPARTMENT OF
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High Energy Physics

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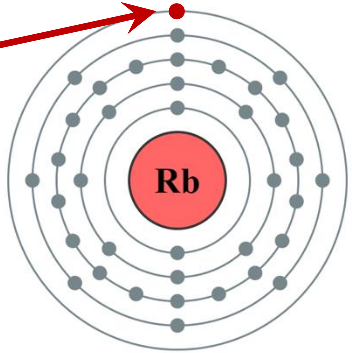
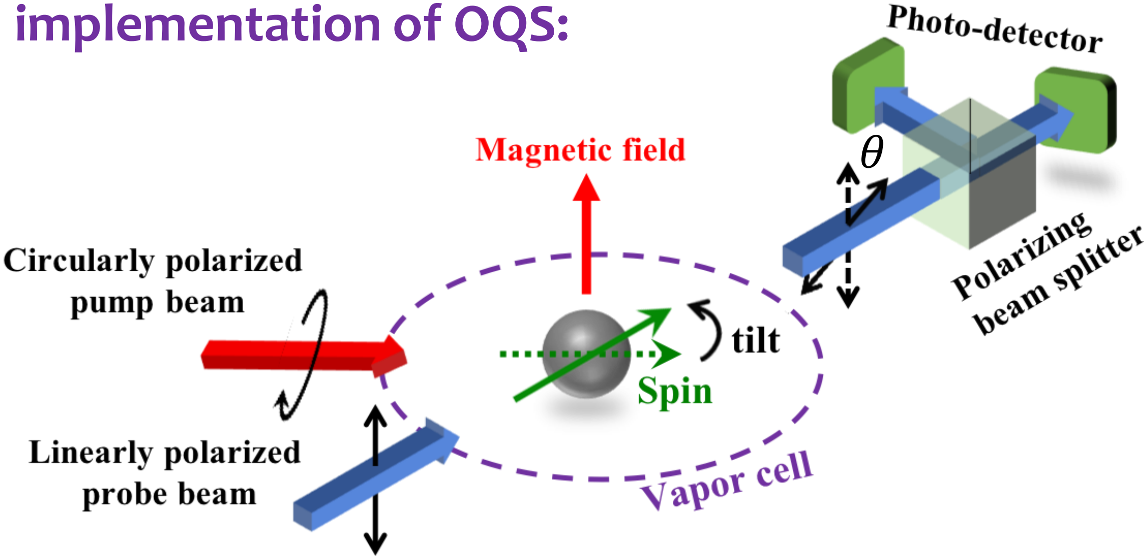
Optical Quantum Sensor (OQS)

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


Manipulate one valence electron

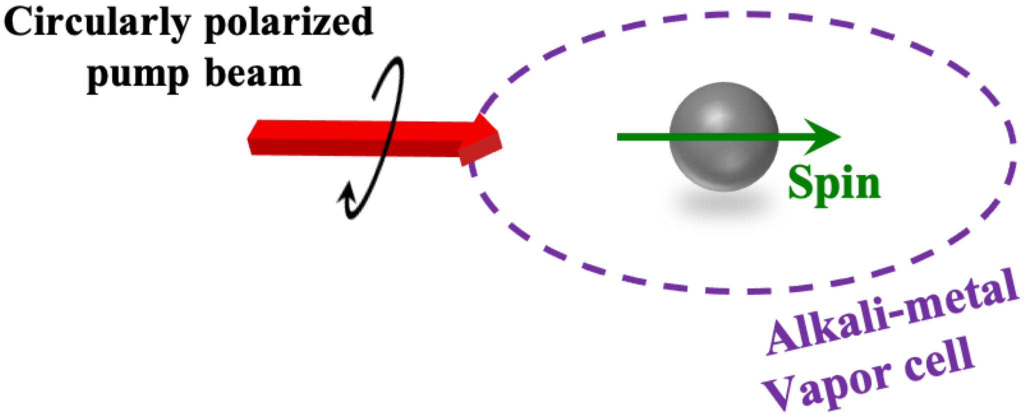
Typical implementation of OQS:



Cryogen-free sensor!

Optical Quantum Sensor (OQS)

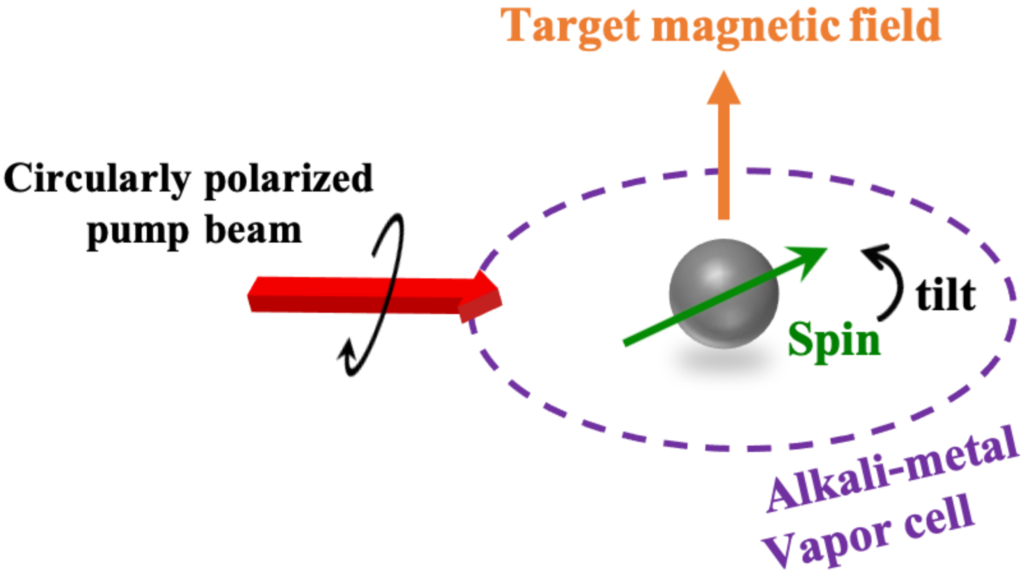
Pumping:



Polarize atomic spins

Optical Quantum Sensor (OQS)

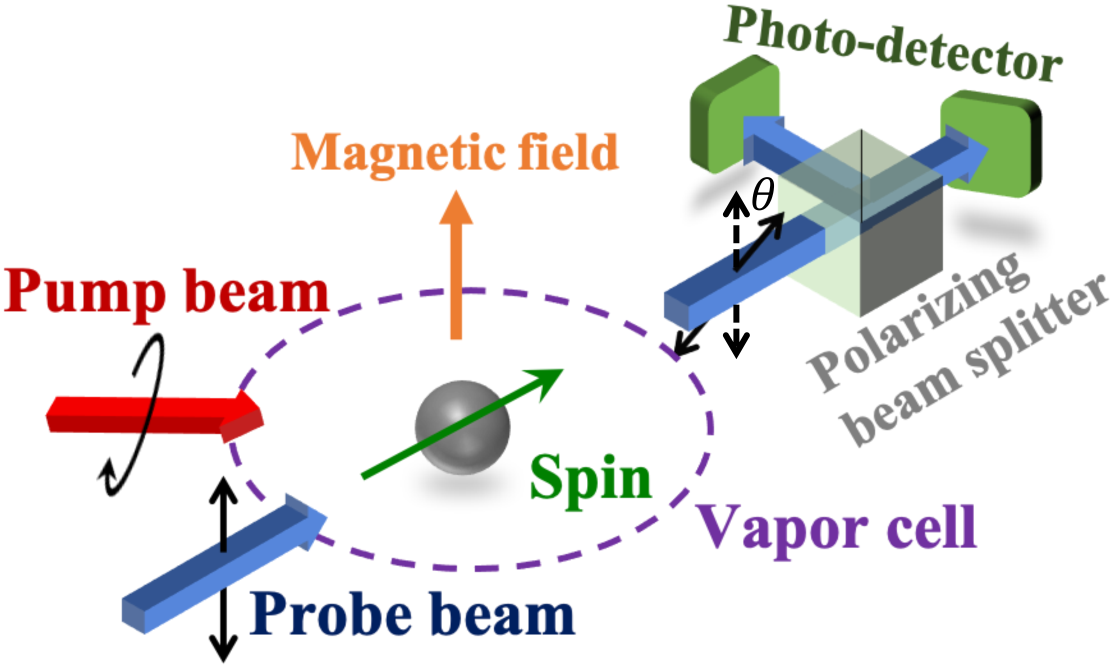
Spin tilt:



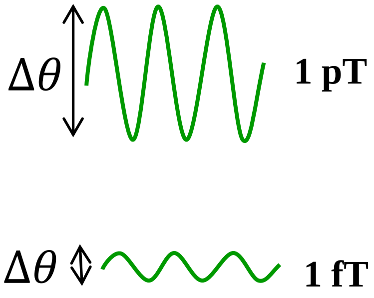
Spin tilt proportional to field strength

Optical Quantum Sensor (OQS)

Probing:



θ= light polarization rotation



Detect magnetic field with probe beam

OQS Noise Limit

Fundamental quantum noise limit:

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

Spin noise

Light shift noise

Photon shot noise

γ = gyromagnetic ratio of alkali-metal atoms

n = density of alkali-metal atoms

V = active measurement vapor cell volume

T_2 = coherence time of electron spins

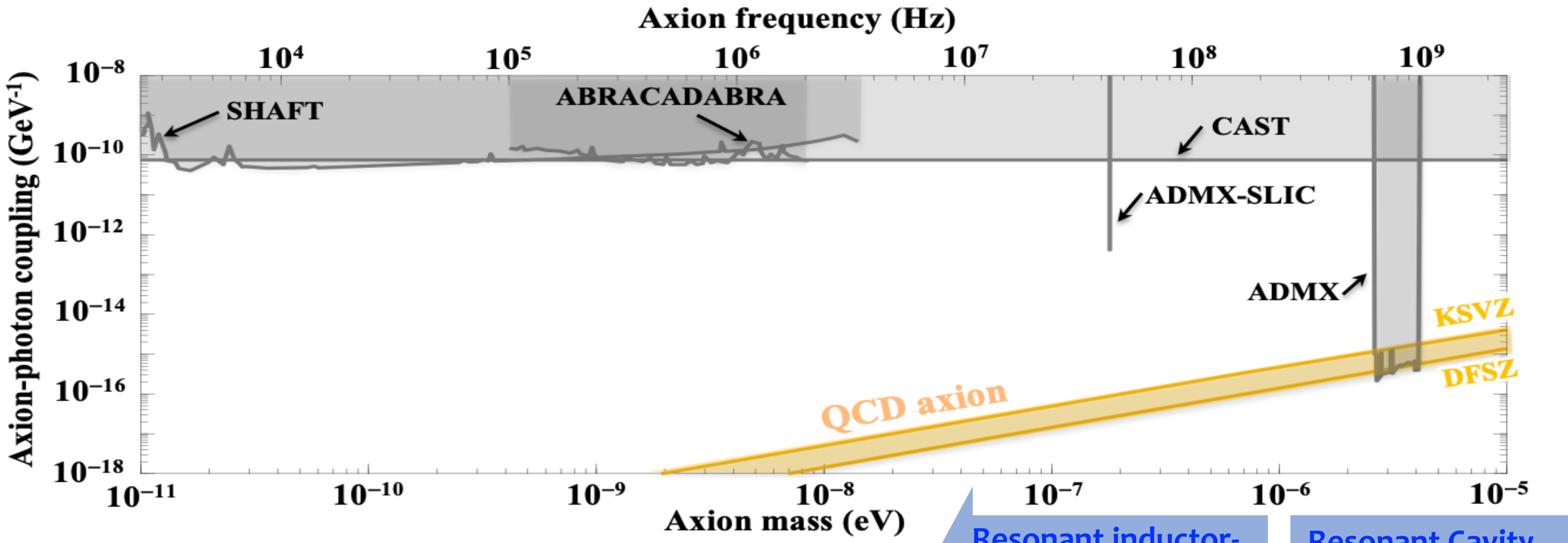
η = photodiode quantum efficiency in probe beam readout

R_{pr} = absorption rate of probe beam photons

OD = optical depth of the probe beam

Fundamental quantum limit	**10 aT/Hz$^{1/2}$** in the cell volume of 200 cm^3 at > kHz
Current best OQS sensitivity	**240 aT/Hz$^{1/2}$** at 423 kHz in the cell volume of 96 cm^3 Romalis, Sauer, Savukov, Seltzer, Lee, U.S. Patent# 7521928B2 (2007)

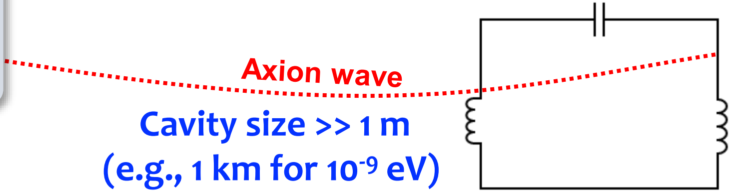
Application: Ultralight Axion Dark Matter Search



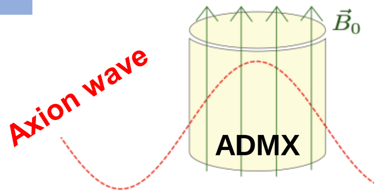
Resonant inductor-capacitor (LC) circuit experiment

Resonant Cavity experiment

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



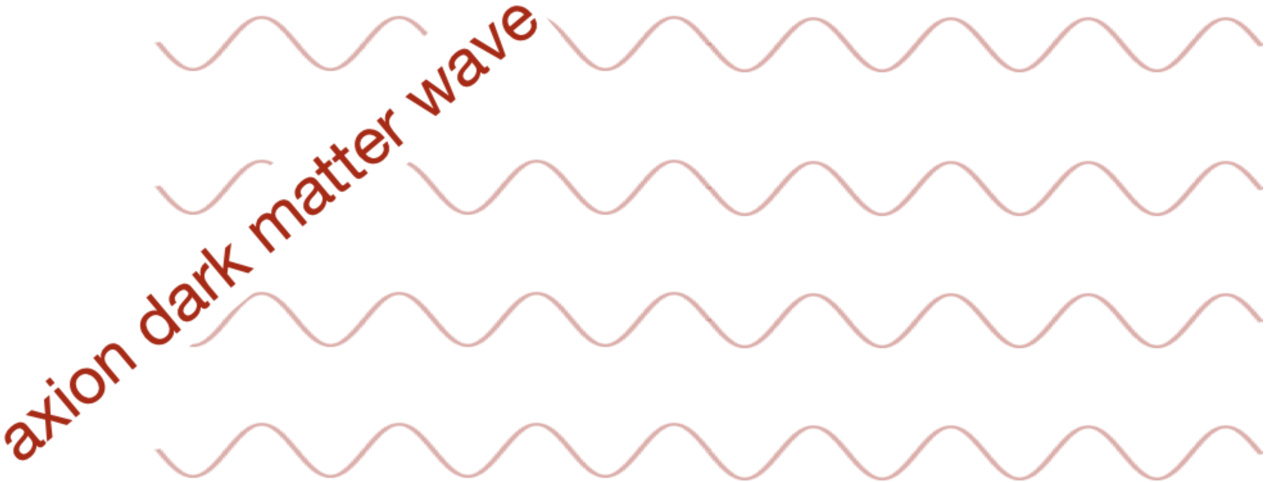
Cavity size >> 1 m
(e.g., 1 km for 10^{-9} eV)



Cavity size ~ 1 m for ~10^{-6} eV

LANL Axion Search: Target Signal

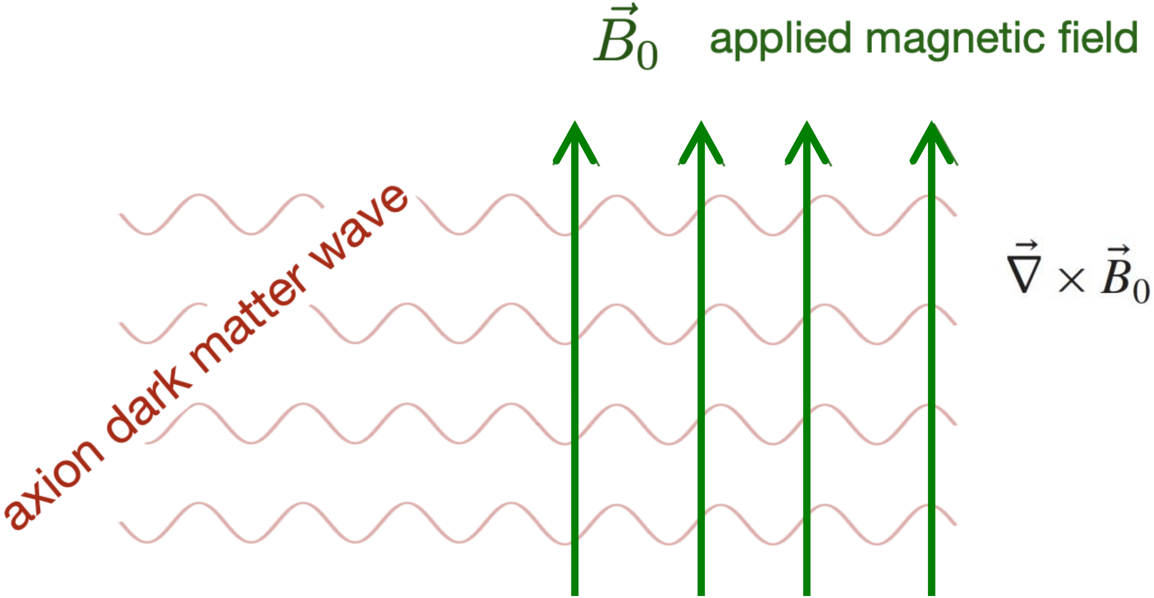
Axion dark matter is "wave-like": an oscillating field at a frequency of the axion mass (m_a) that permeates all of space



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

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**

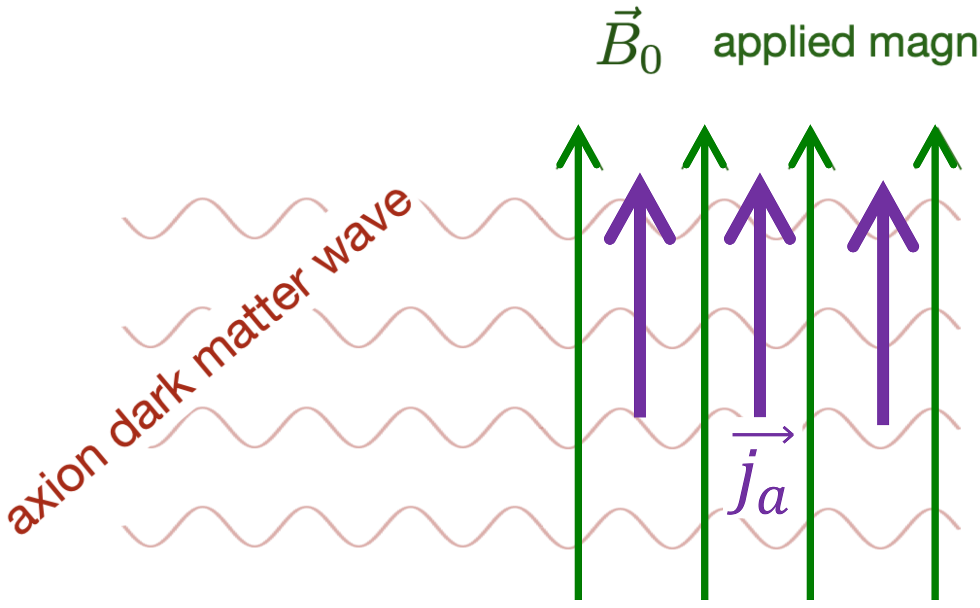


$$\vec{\nabla}\times\vec{B}_0-\frac{\partial\vec{E}}{\partial t}=\boxed{g\left(\vec{E}\times\vec{\nabla}a-\vec{B}_0\frac{\partial a}{\partial t}\right)}+\vec{j}_e$$

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**



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

Axion-photon coupling

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

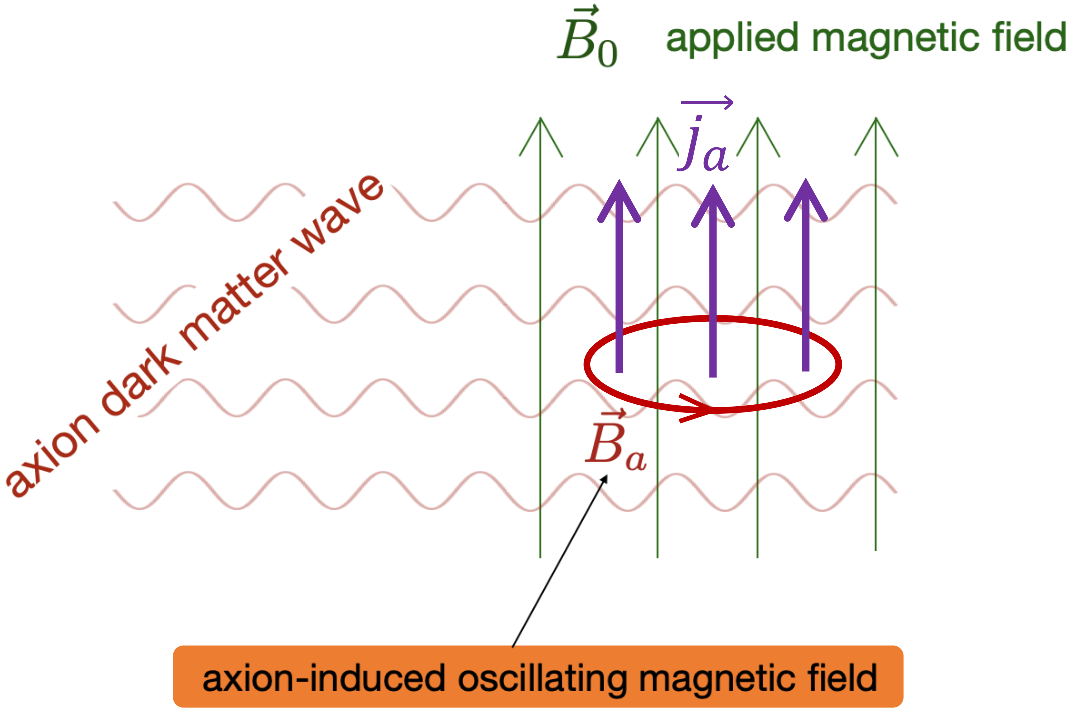
LANL Axion Search: Target Signal

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

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

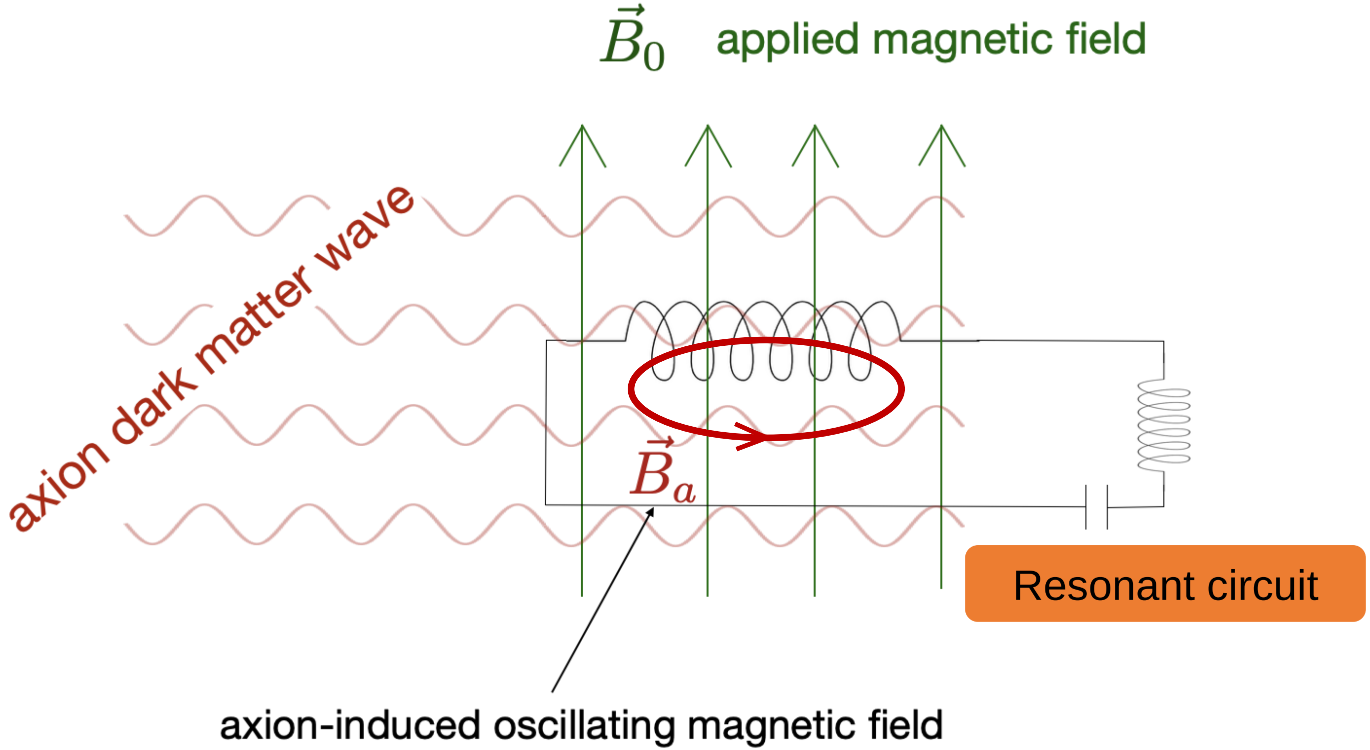
$$\Downarrow$$

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



LANL Axion Search: Target Signal

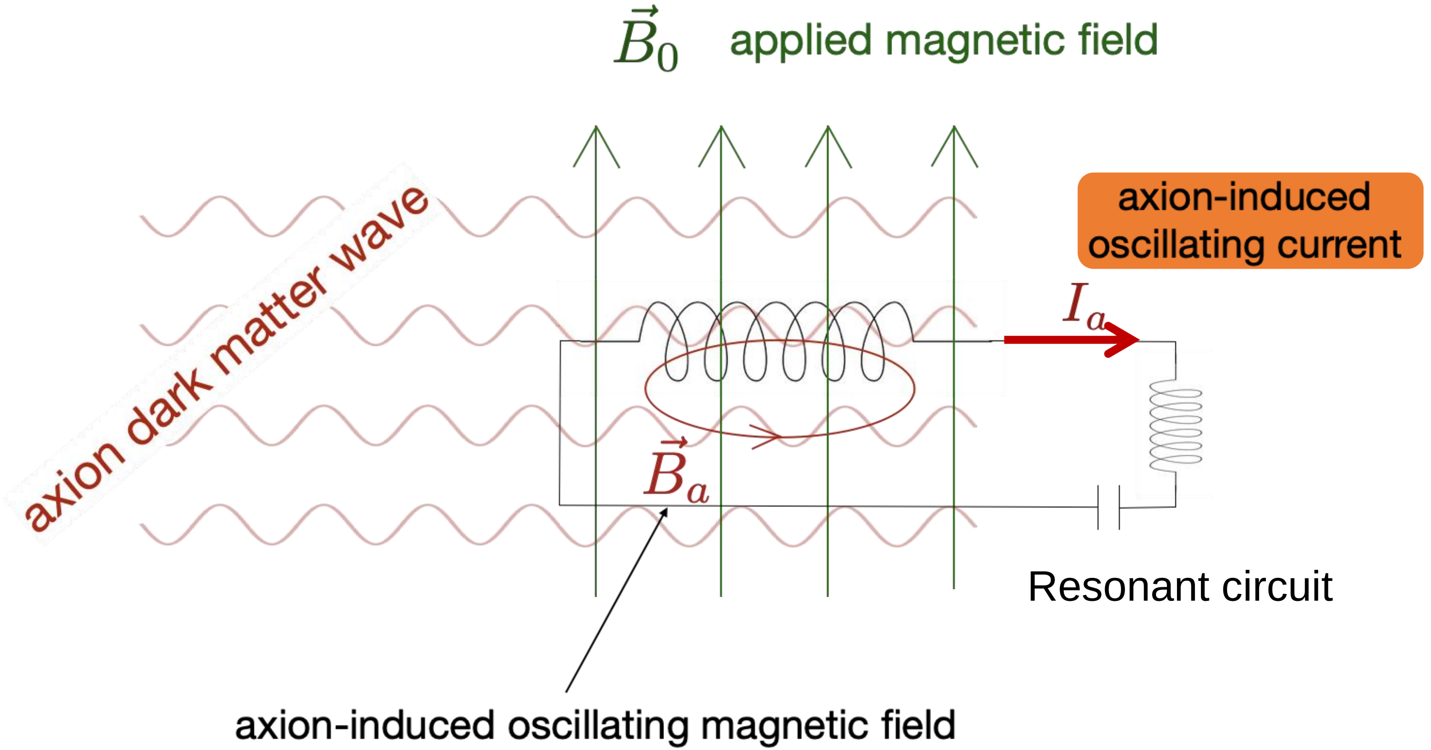
Axion dark matter is “wave-like”: an oscillating field that permeates all of space and interacts with the electromagnetic field



Resonant circuit

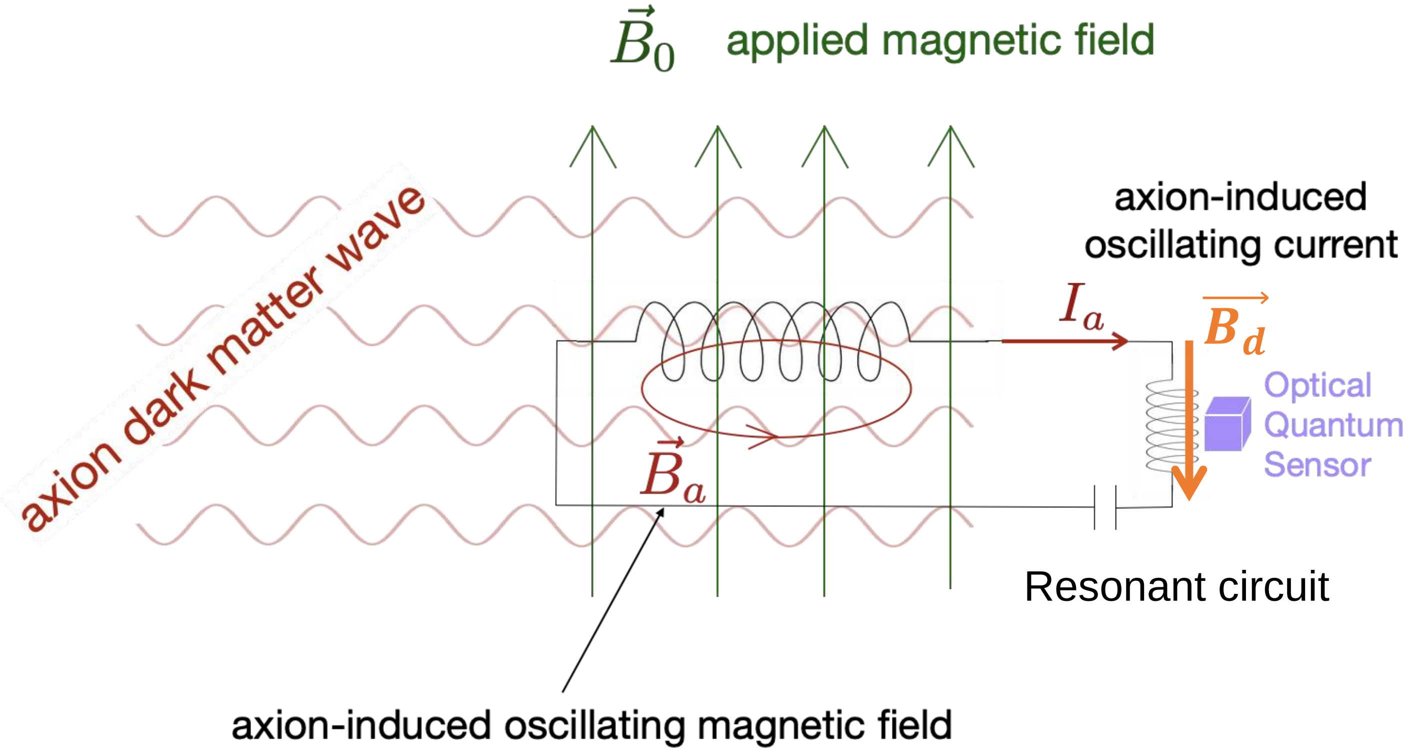
LANL Axion Search: Target Signal

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

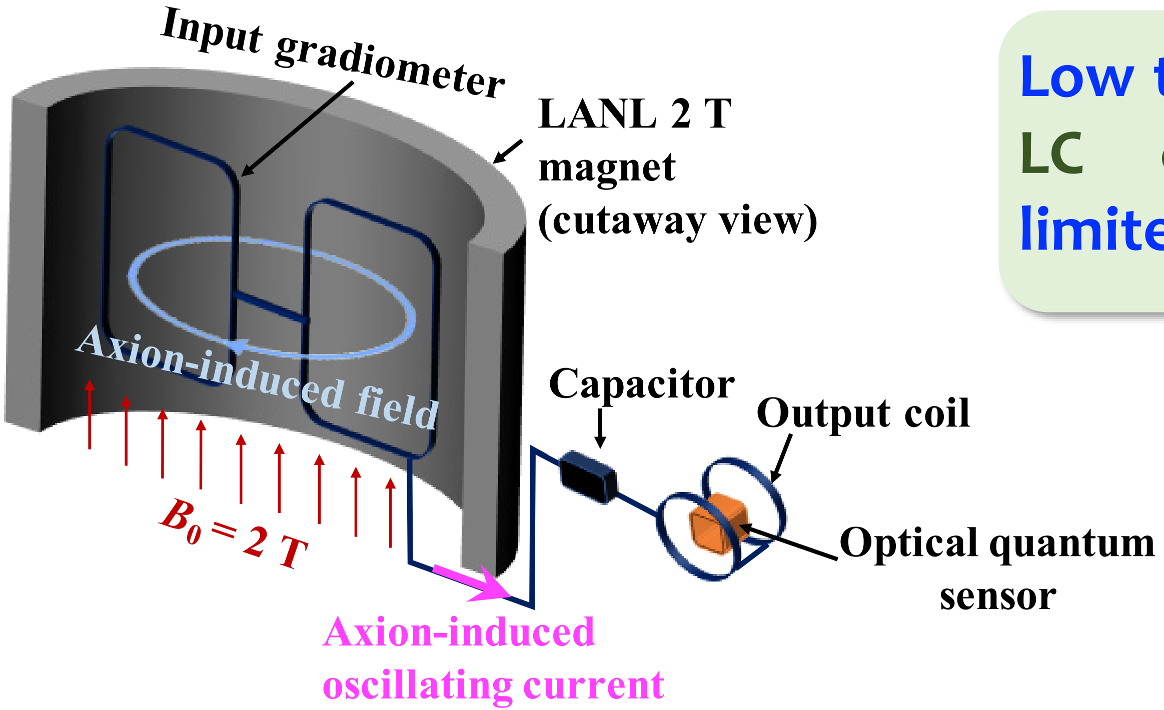


LANL Axion Search: Target Signal

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



LANL Experiment Layout



Low temperature resonant LC circuit + quantum limited (10 aT/Hz$^{1/2}$) OQS

Publication

PHYSICAL REVIEW D **108**, 052007 (2023)

Sensitivity of ultralight axion dark matter search with optical quantum sensors

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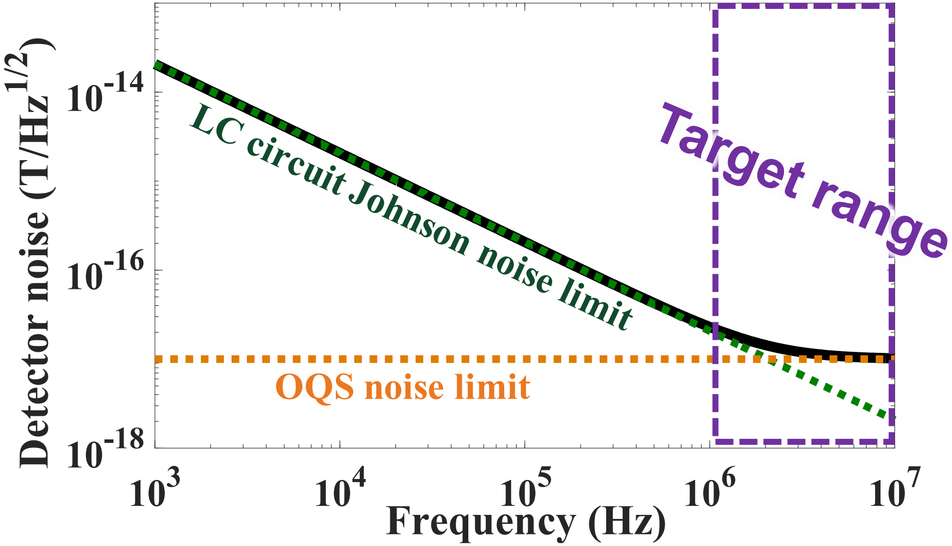
(Received 10 April 2023; accepted 14 August 2023; published 12 September 2023)

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.

Intrinsic Noise of Optimized Axion Detector

Intrinsic noise of LANL LC circuit-OQS axion detector:

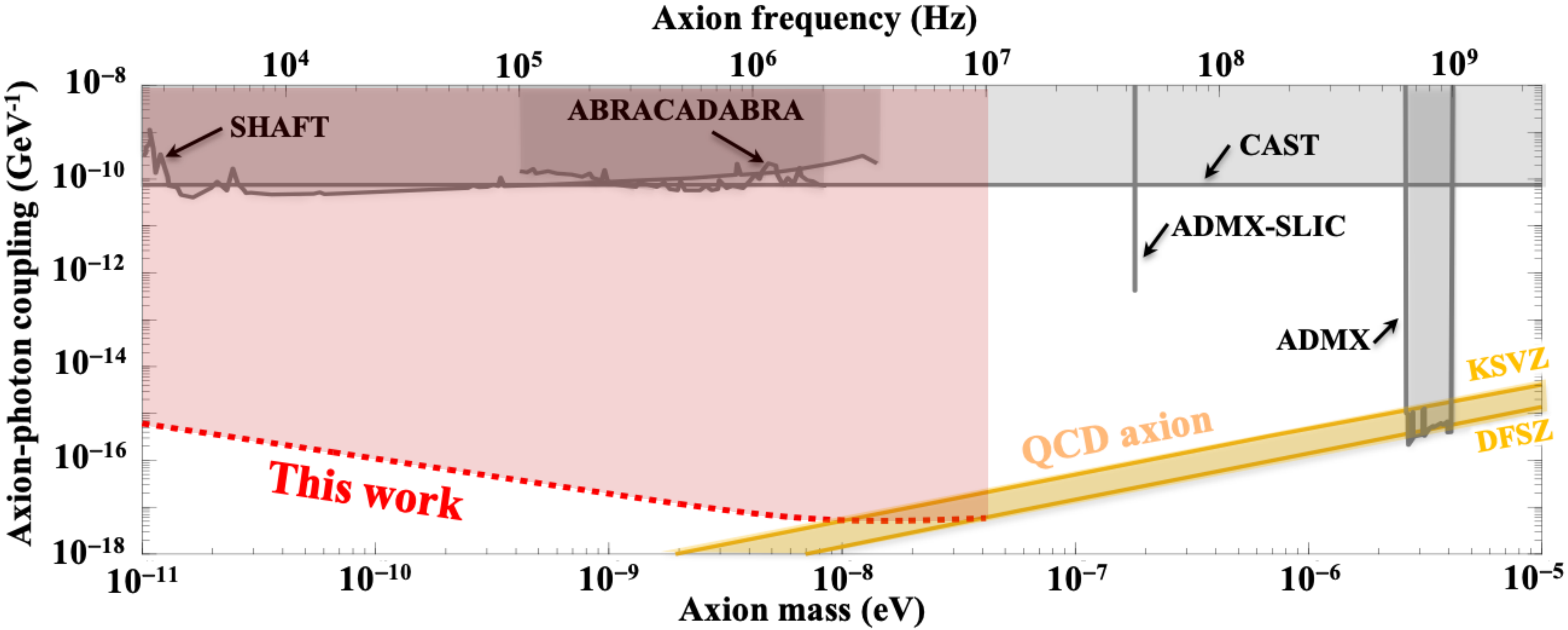


At MHz target frequency (i.e., neV mass range), axion detector sensitivity is determined by optical quantum sensor noise

⬇

OQS noise reduction = key to success of the project!

Projected Sensitivity of LANL Axion Search

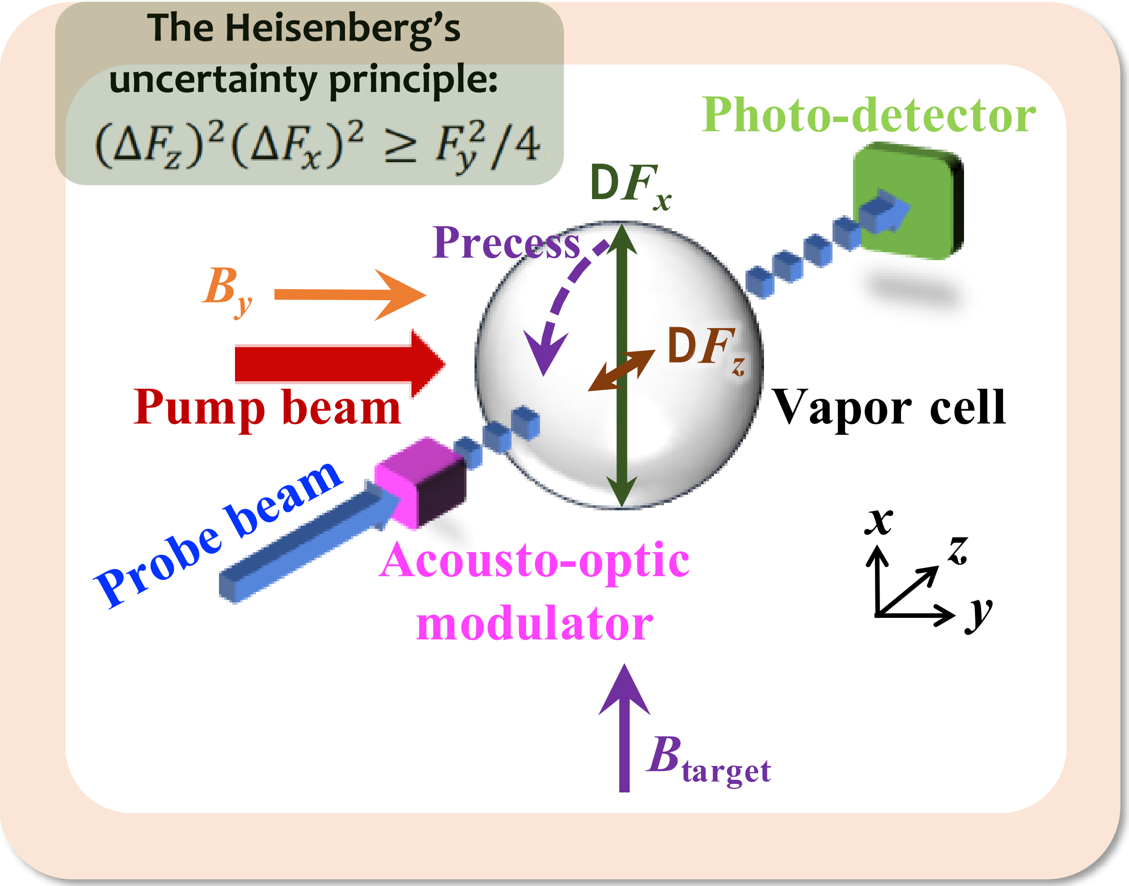


- **Unprecedented sensitivity** 7 orders of magnitude beyond the current limit
- Will probe a **completely unexplored axion mass range** near 10 neV

Spin Squeezing Method

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

To reduce spin noise



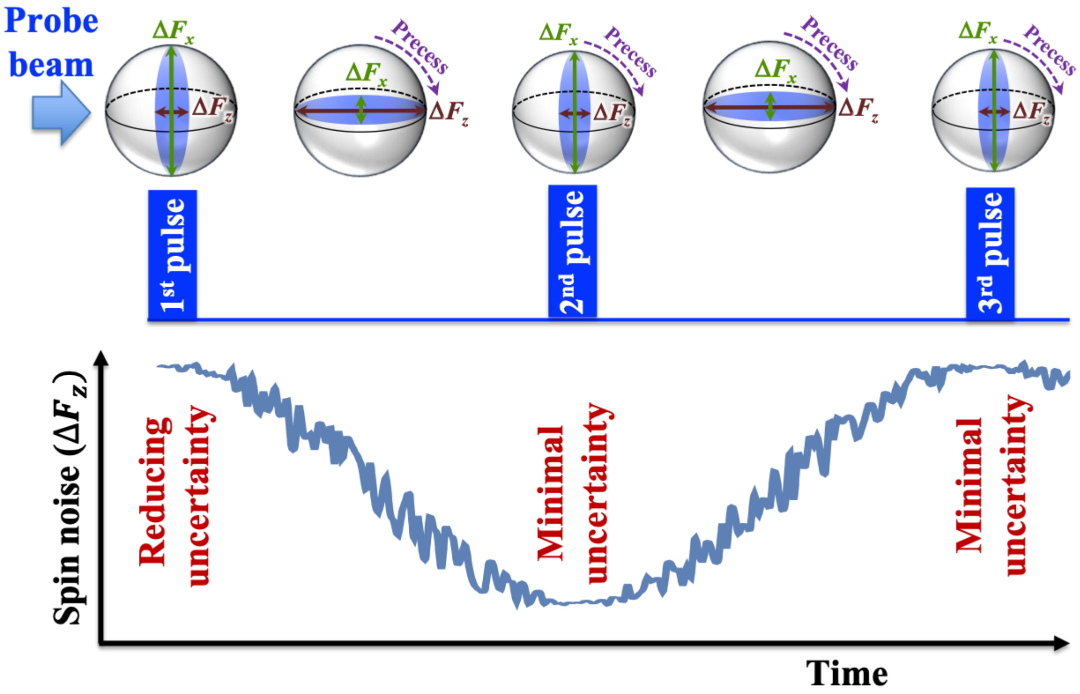
The Heisenberg's uncertainty principle:

$(\Delta F_z)^2(\Delta F_x)^2 \geq F_y^2/4$

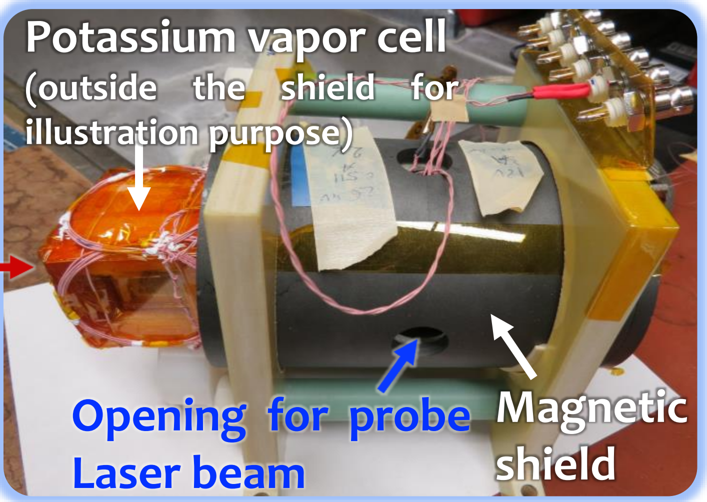
Spin Squeezing Method

Probe pulsing for spin squeezing:

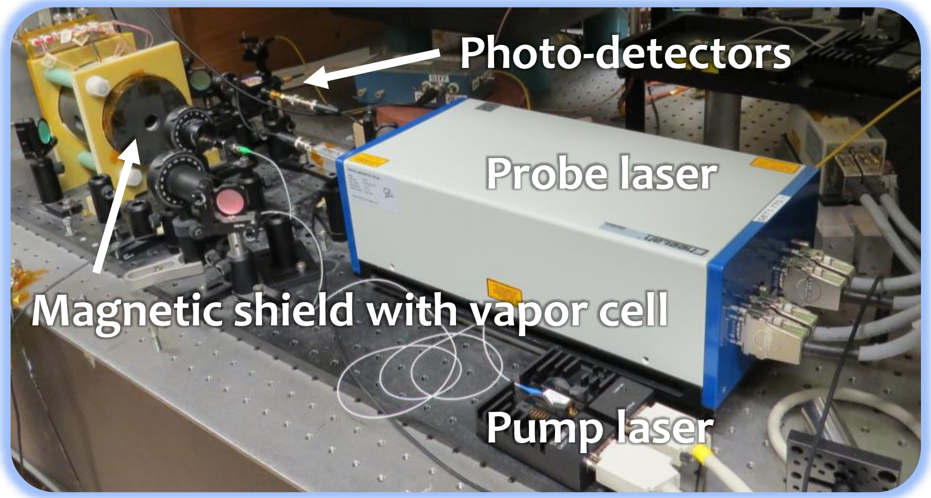
- The first pulse squeezes spins
- Subsequent pulses readout spin states when the uncertainty is minimal



OQS Setup

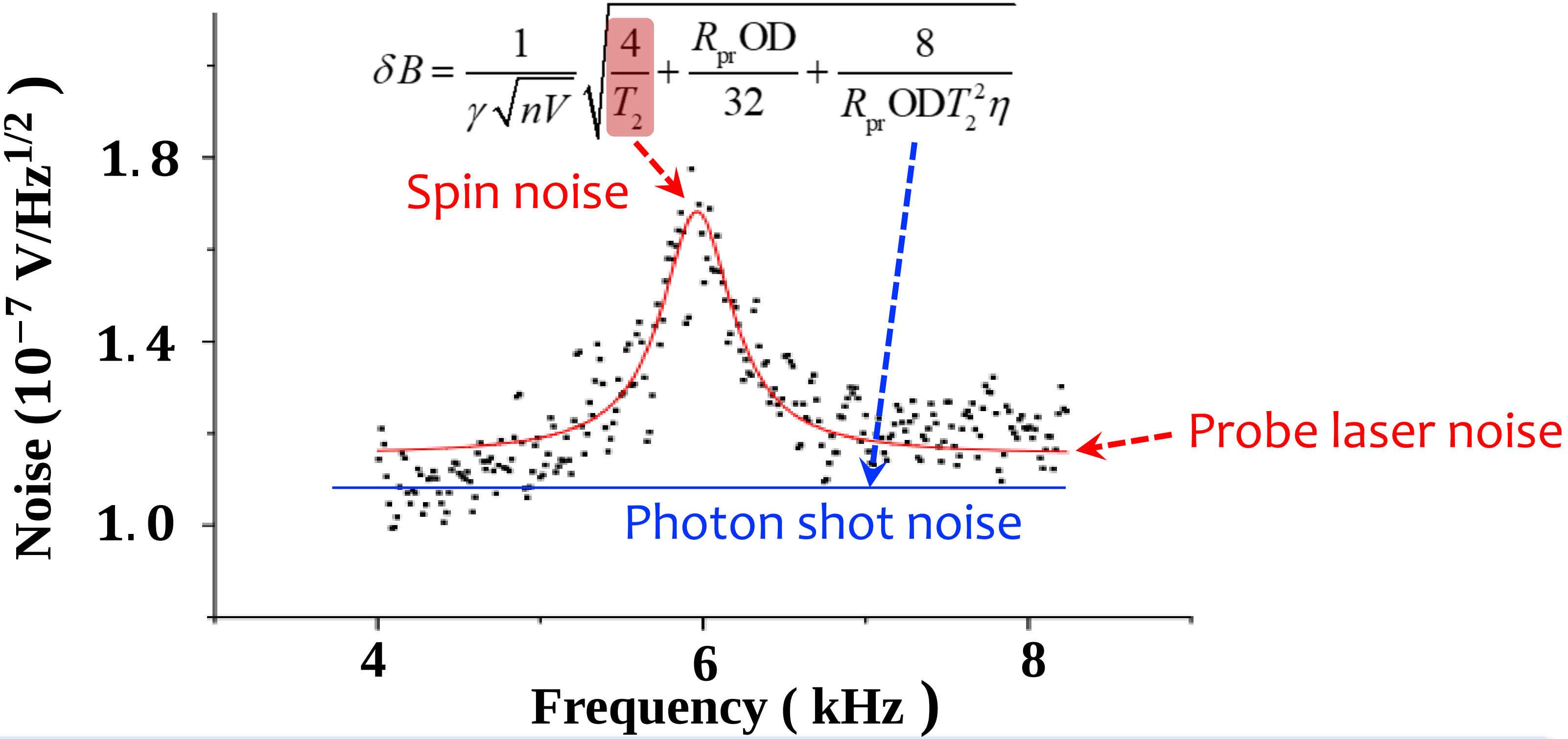


Pump Laser beam



Built an OQS module based on a potassium vapor cell and stable lasers with measured OQS field noise at 10^{-15} T level

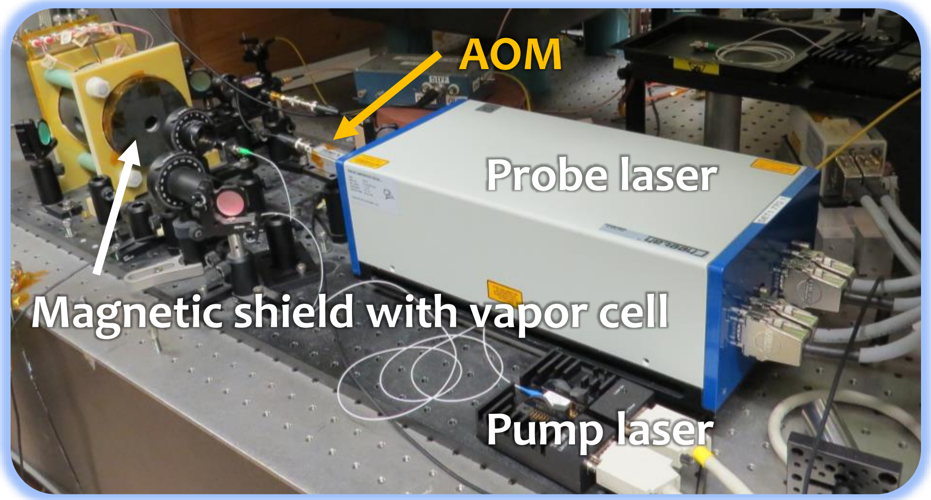
Spin Noise Measurement

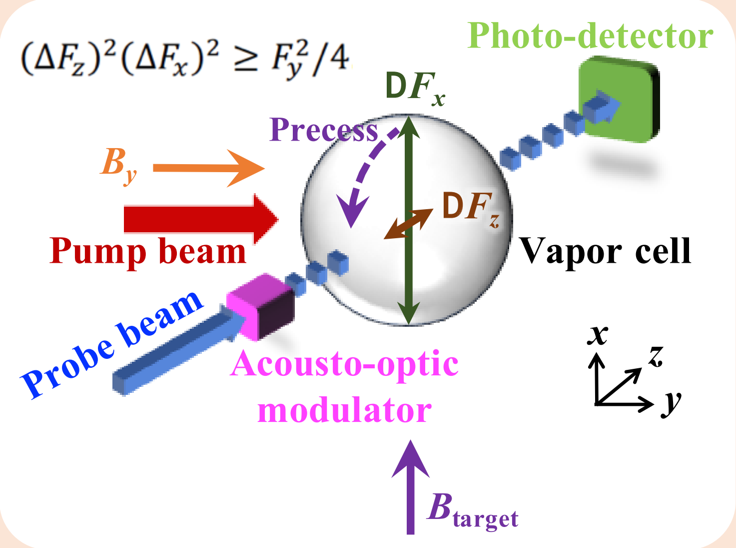


$$\delta B = \frac{1}{\gamma\sqrt{nV}}\sqrt{\frac{4}{T_2}+\frac{R_{\mathrm{pr}}\mathrm{OD}}{32}+\frac{8}{R_{\mathrm{pr}}\mathrm{OD}T_2^2\eta}}$$

Measured the spin noise term (resonant bump) with continuous probe (i.e., without spin squeezing)

Spin Squeezing with Acousto-optic Modulator (AOM)

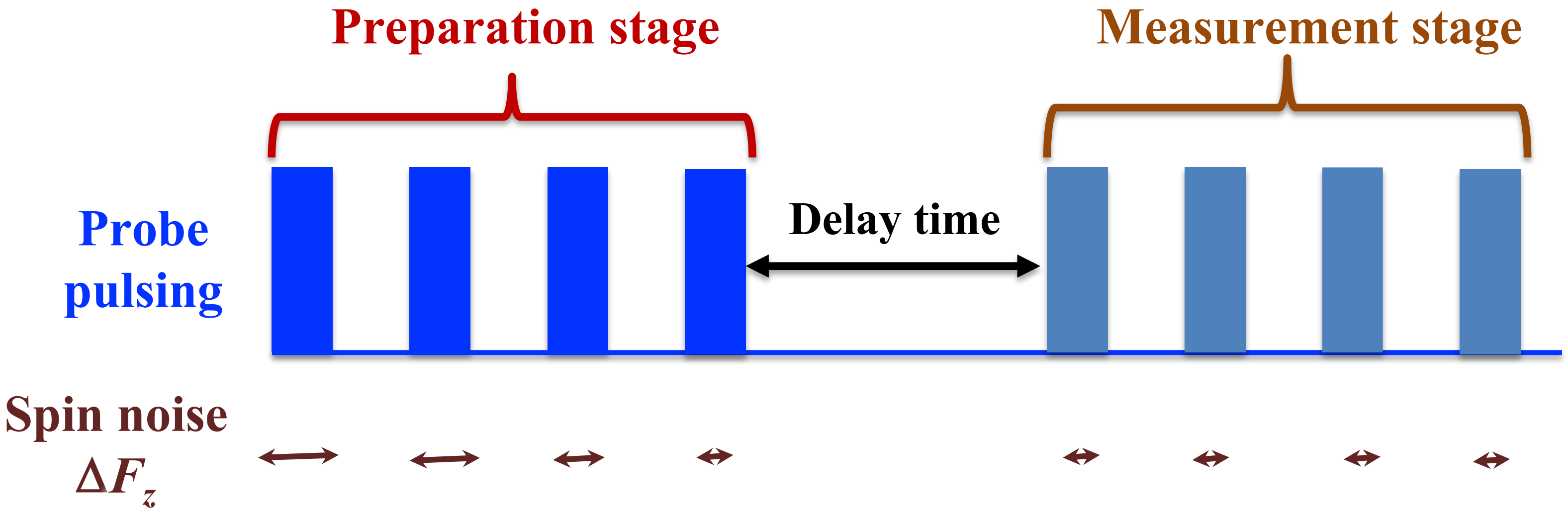




$$(\Delta F_z)^2(\Delta F_x)^2 \geq F_y^2/4$$

We added an AOM between the probe beam and the vapor cell for probe pulsing.

Protocol for Spin Squeezing



Preparation stage

Measurement stage

Probe pulsing

Delay time

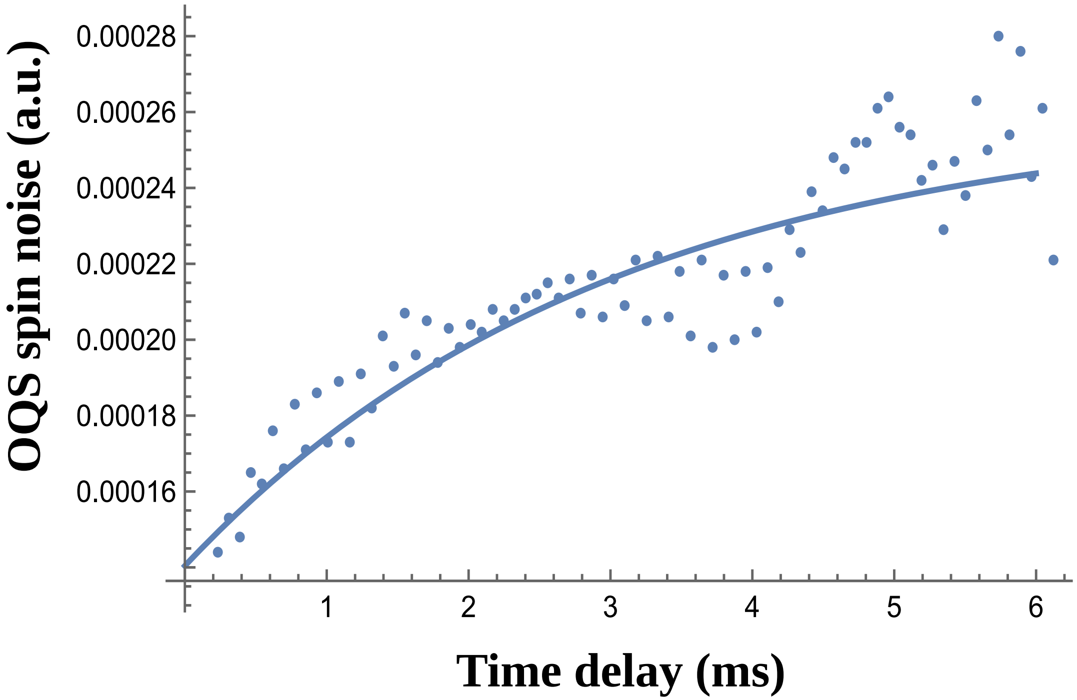
Spin noise ΔF_z

With each probe pulse, the spin state is squeezed a little

Equilibrium is reached

- During the delay time, the spin state is un-squeezed.
- Spin noise in measurement state depends on the delay time.

Preliminary Spin Squeezing Verification



- **Spin noise increases at longer delay time (preliminary Verification of spin squeezing effect!)**
- **Data fluctuation due to ambient magnetic noise**

Research Team

Key investigators at Los Alamos National Laboratory:

Young Jin Kim **Leanne Duffy** **Igor Savukov**

Axion search using OQS recently selected for a QuantISED 2.0 award (Quantum Information Science Enabled Discoveries in High Energy Physics)!

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Thank you!

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