Development of Optical Quantum Sensors for Ultralight Axion Dark Matter Detection

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Seattle, WA

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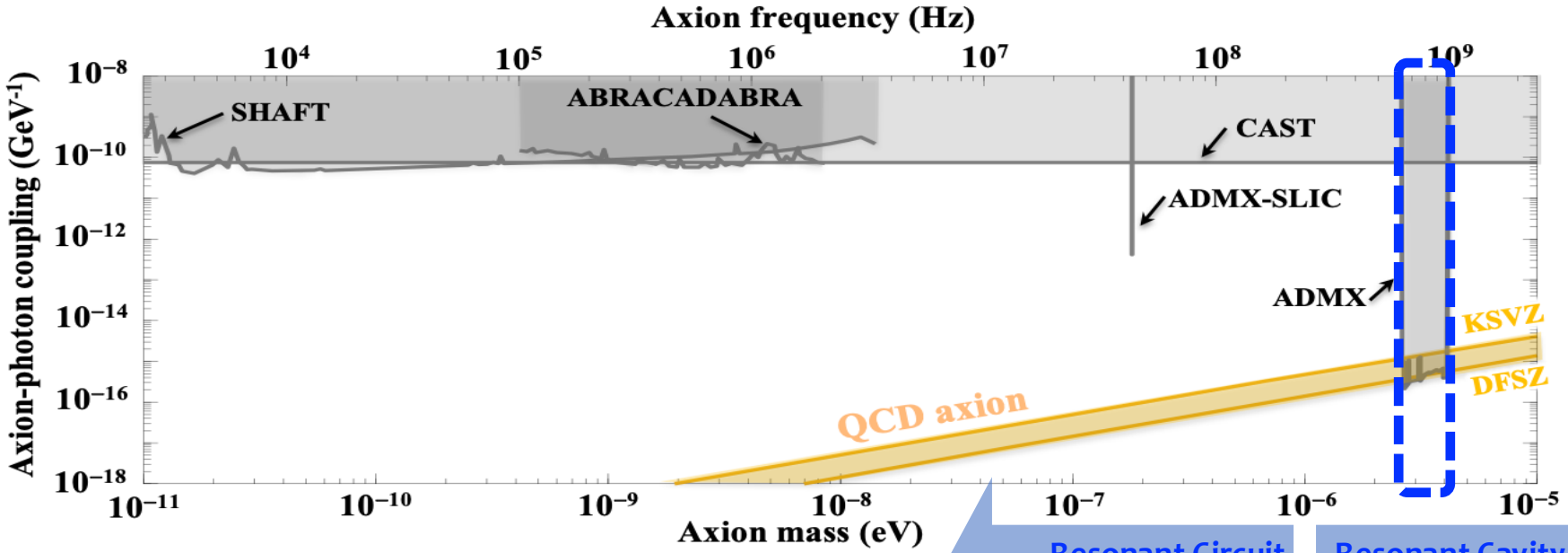
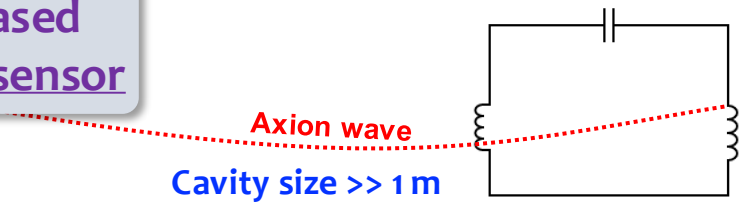
Axion Dark Matter Search



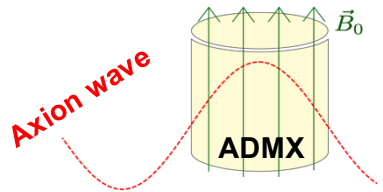
Resonant Circuit experiment

Resonant Cavity experiment

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



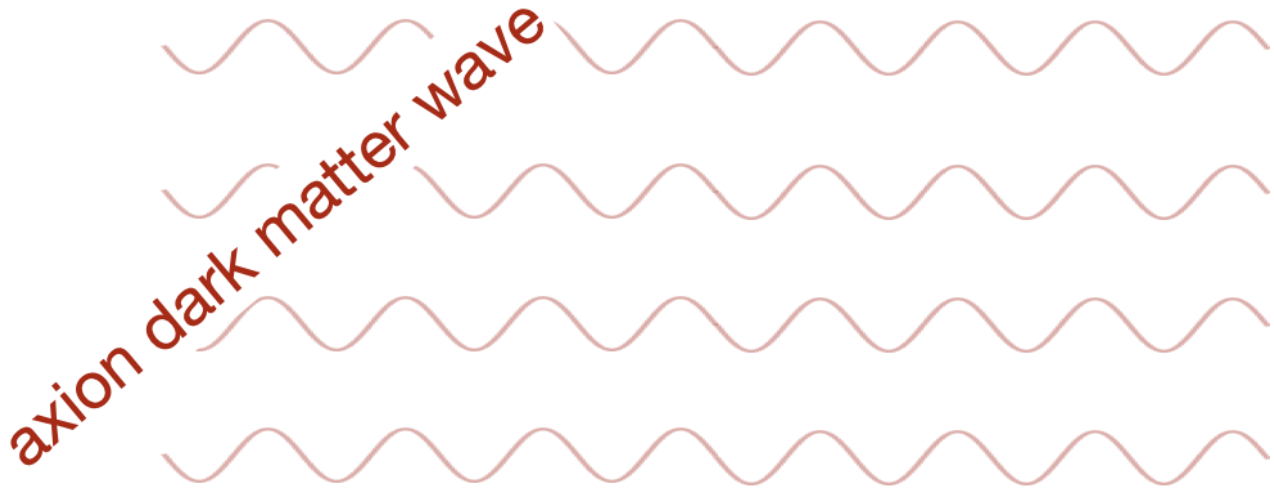
Cavity size >> 1 m



Cavity size ~ 1 m

LANL Axion Search: Target Signal

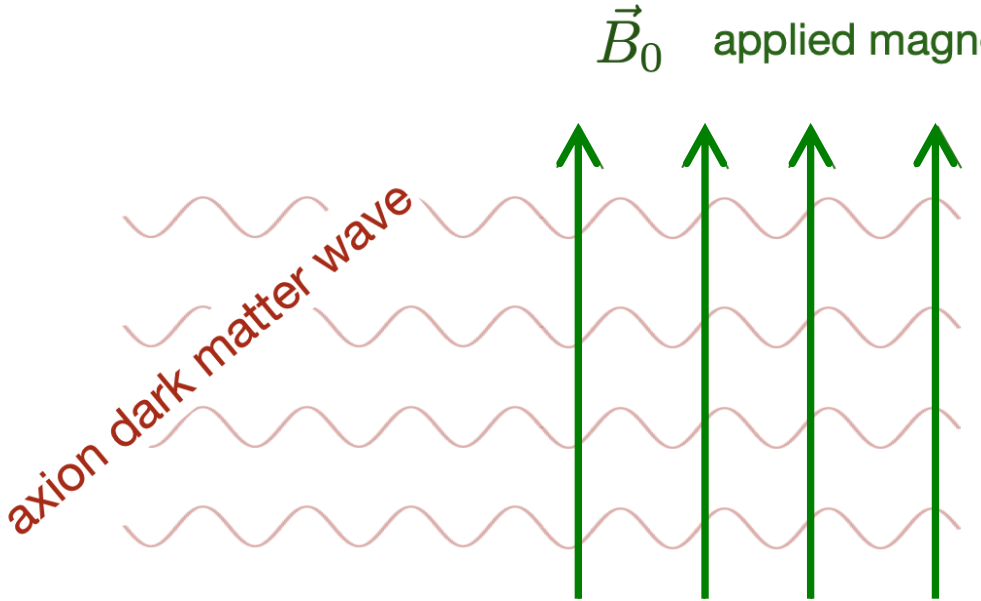
Axion dark matter is "wave-like": an oscillating field at a frequency of the axion mass (m_a) that permeates all of space



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

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

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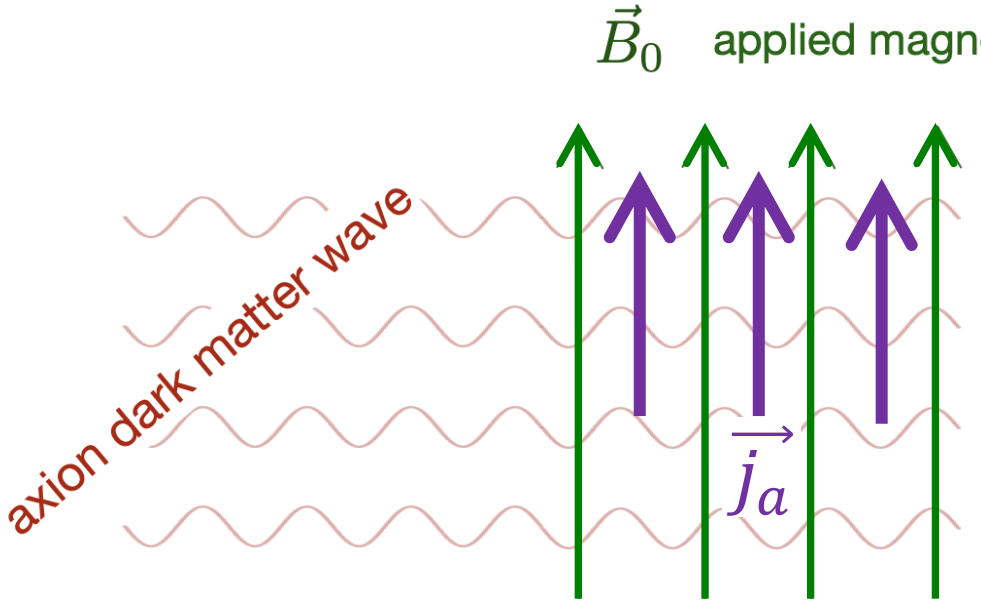

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Axion-photon coupling

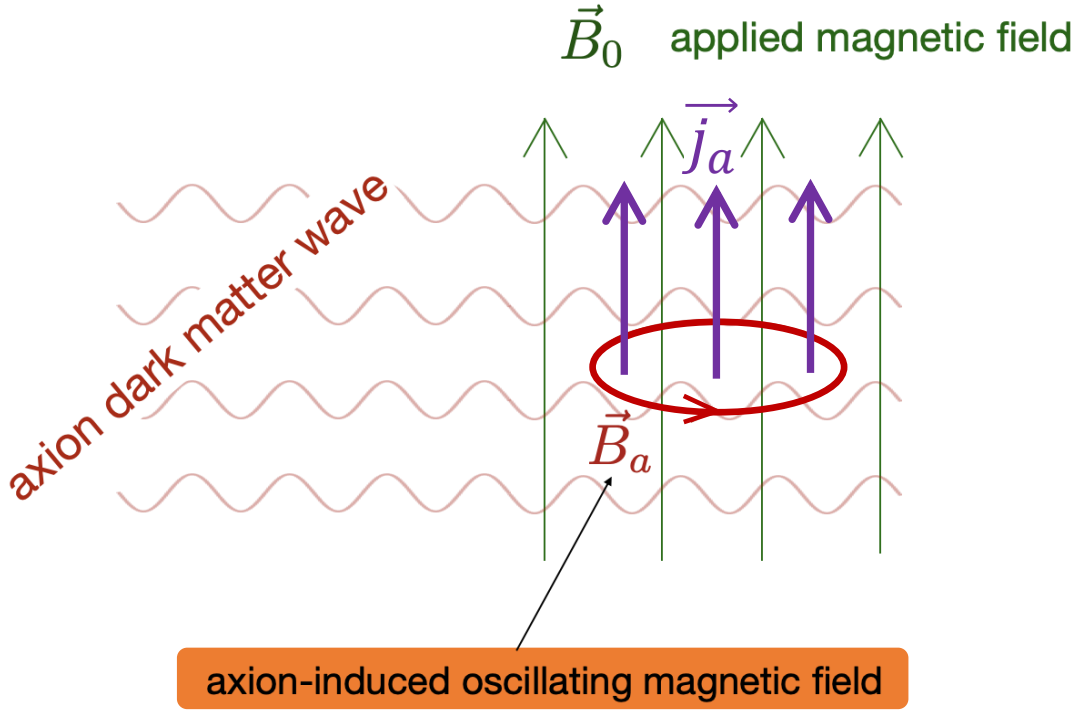
$$\vec{j}_a(t) = -g\vec{B}_0[da(t)/dt]$$

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

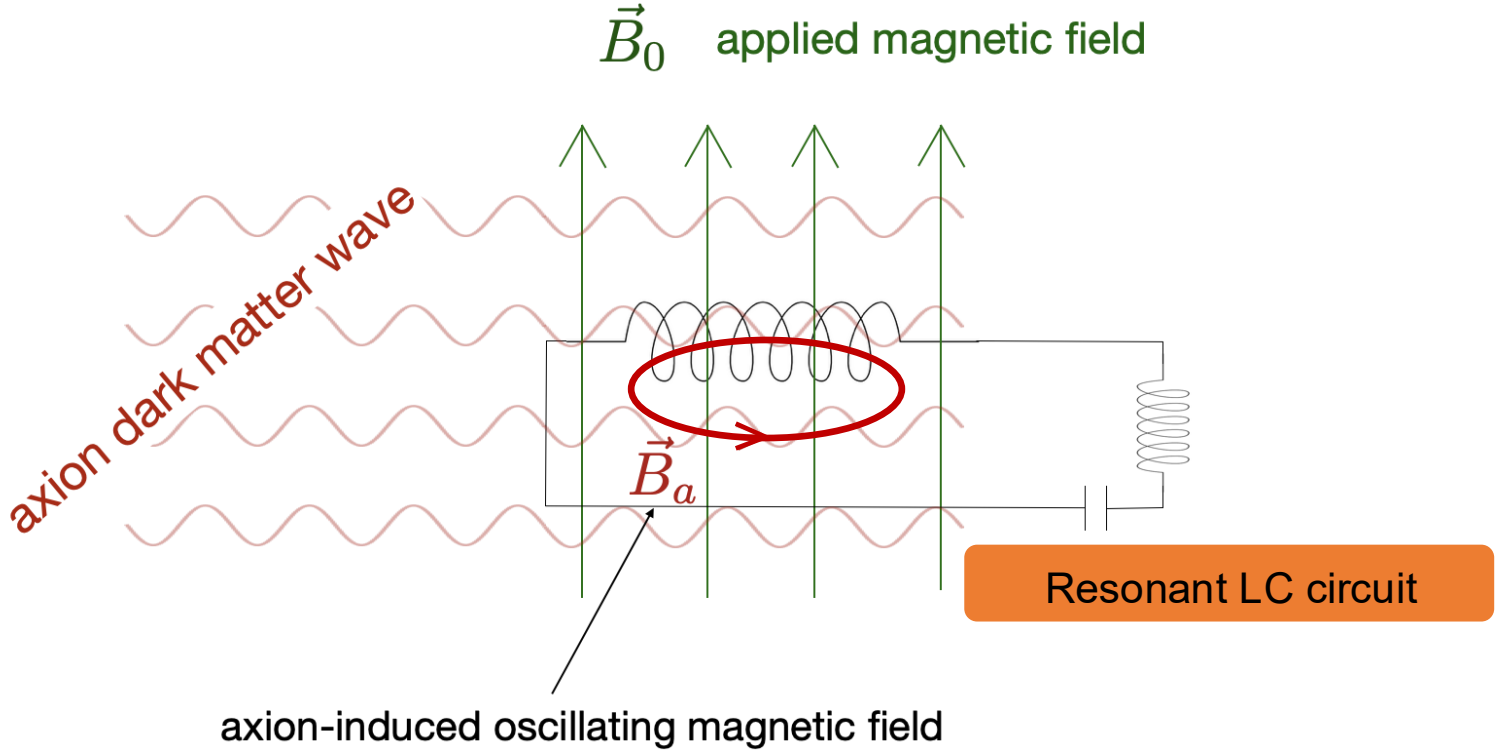
$$\vec{j}_a(t) = -g\vec{B}_0[da(t)/dt]$$

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



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



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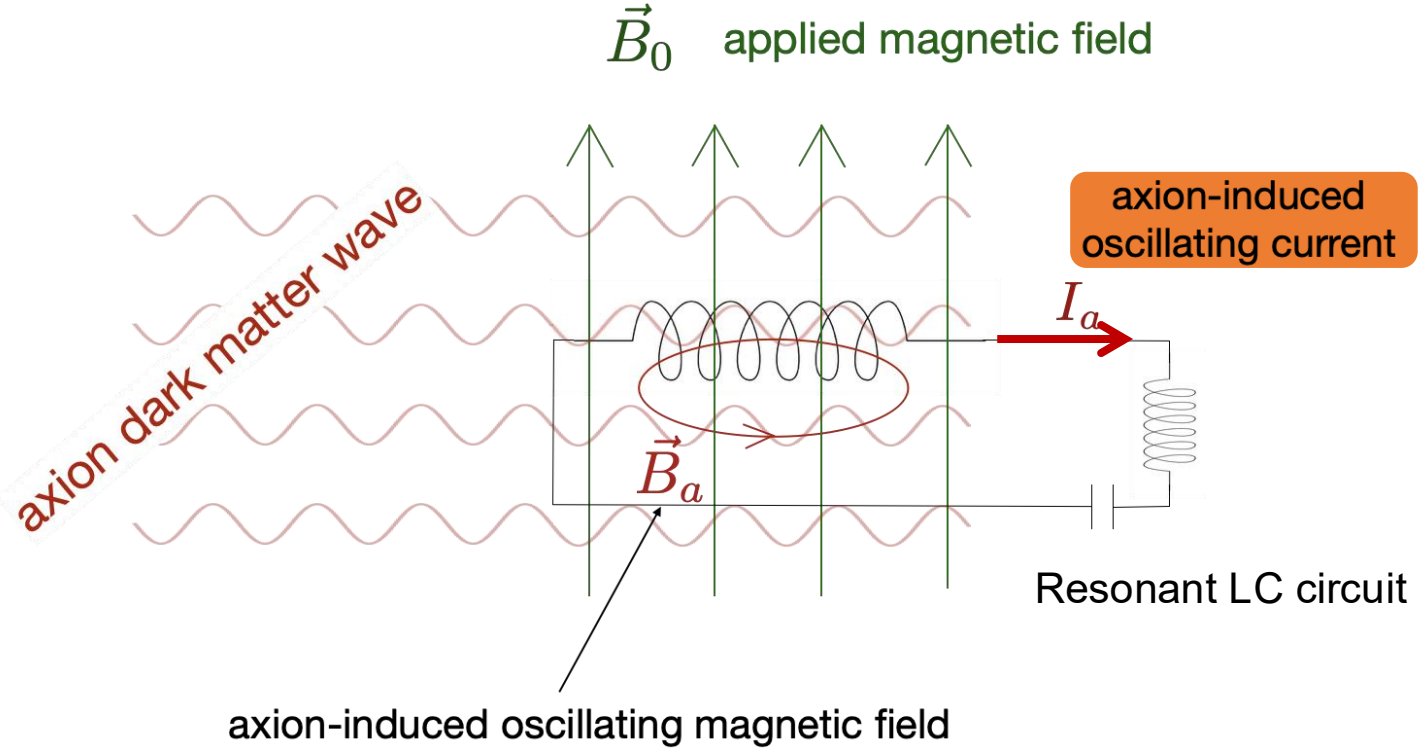

LANL Axion Search: Target Signal

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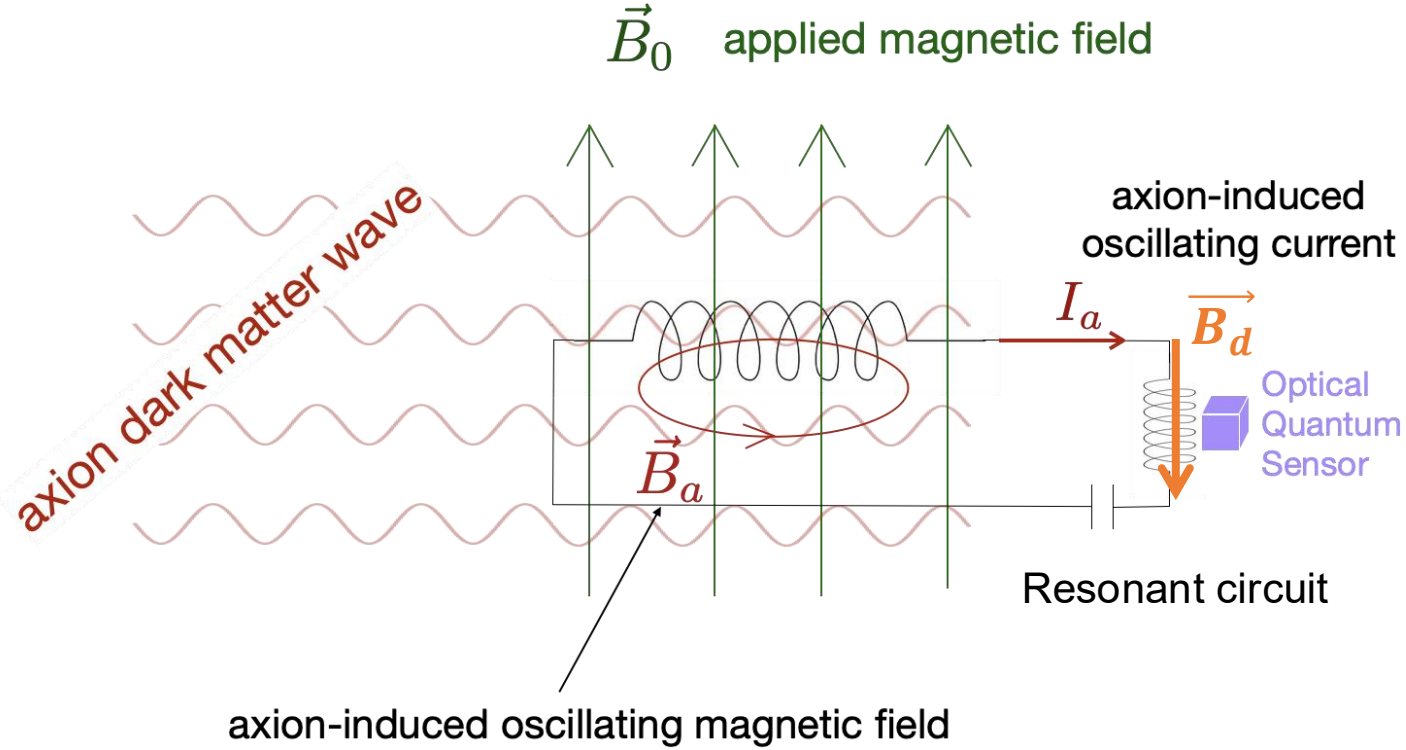
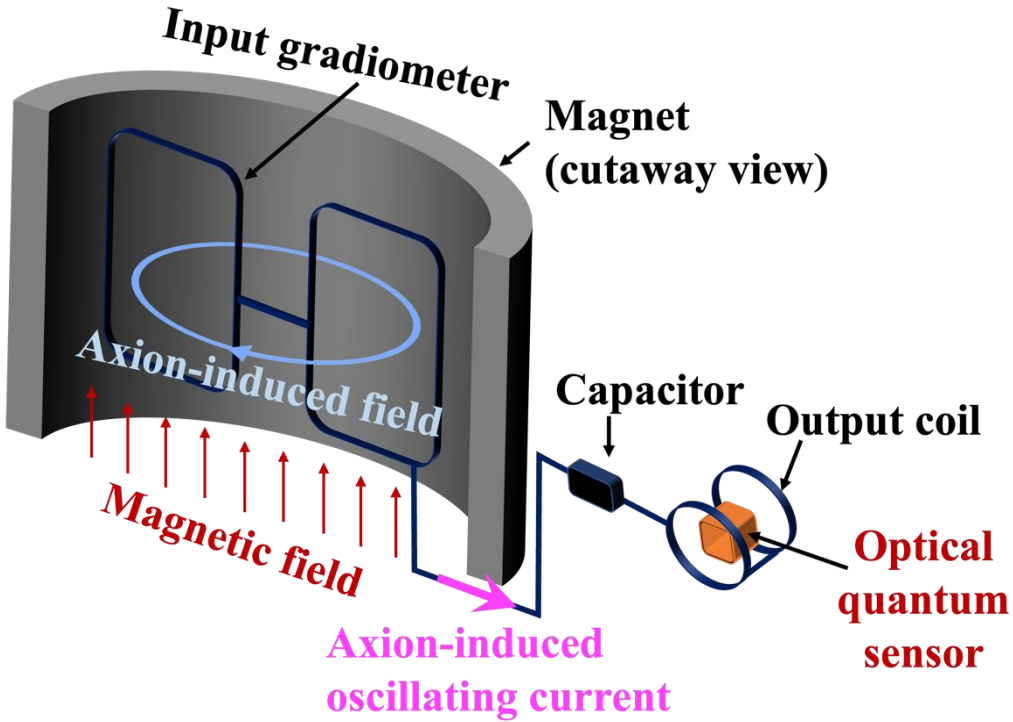


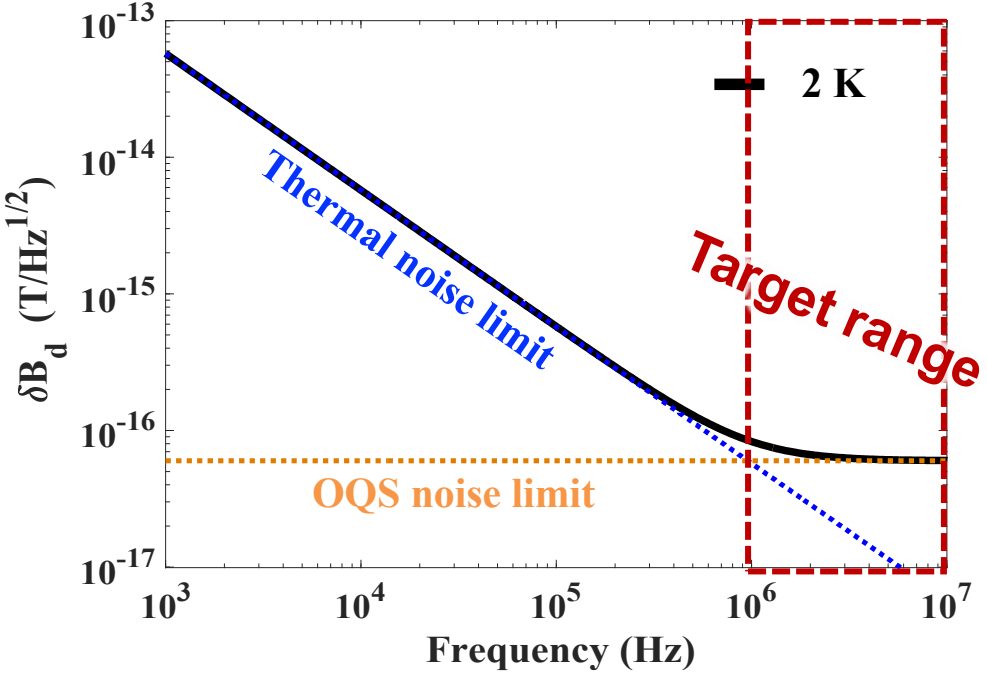
Experiment Layout



Key component:

- Low-temperature resonant circuit.
- Optical quantum sensor (OQS) with 60 aT field noise level.
- 7.5 T magnet (17 cm diameter, 40 cm length).

Intrinsic Noise of Optimized Axion Detector

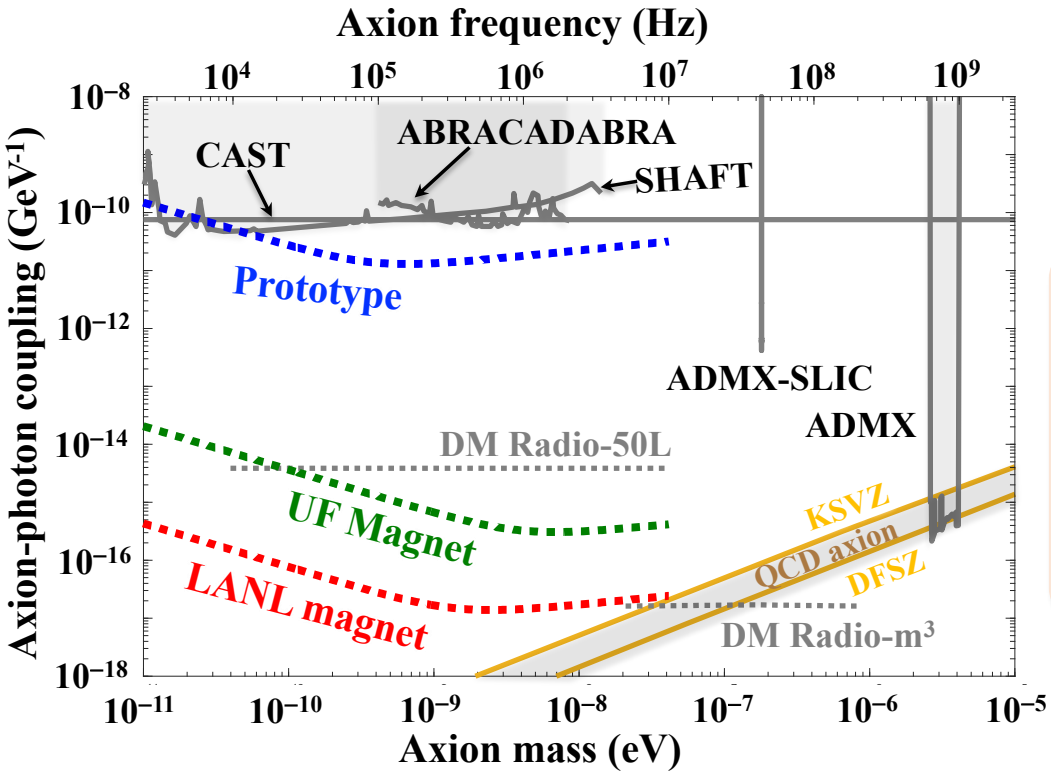


At MHz target frequency (i.e., 10 neV mass range), axion detector sensitivity is determined by optical quantum sensor noise

⇩

OQS noise reduction = key to success of the project!

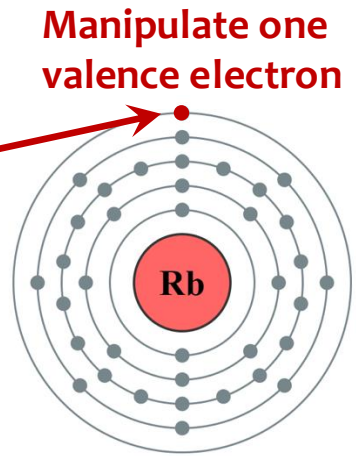
Projected Sensitivity to Axion Dark Matter



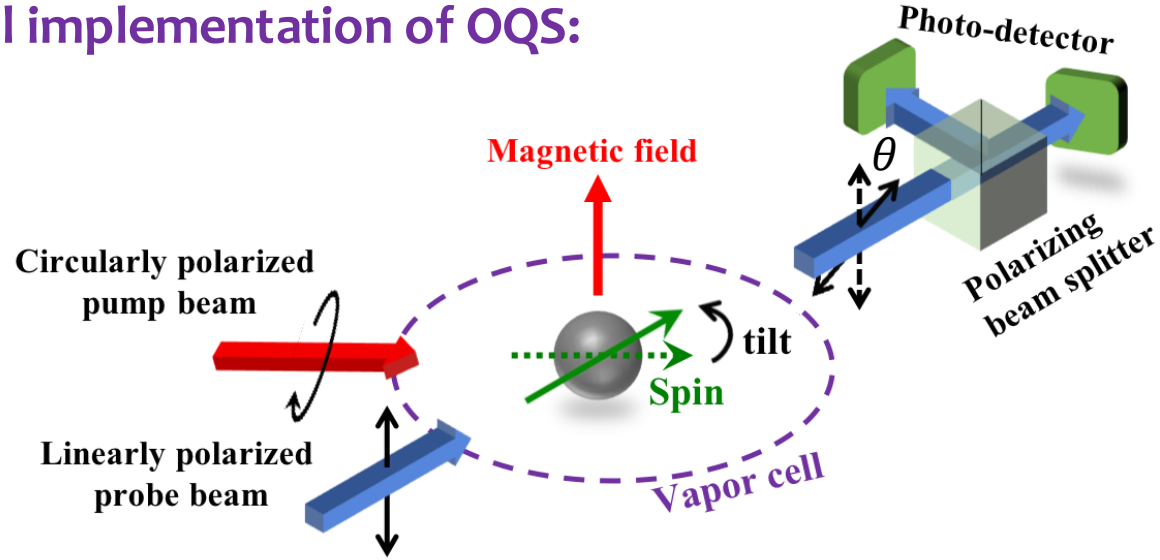
Unprecedented sensitivity 5-7 orders of magnitude beyond the current limit.

Optical Quantum Sensor (OQS)

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



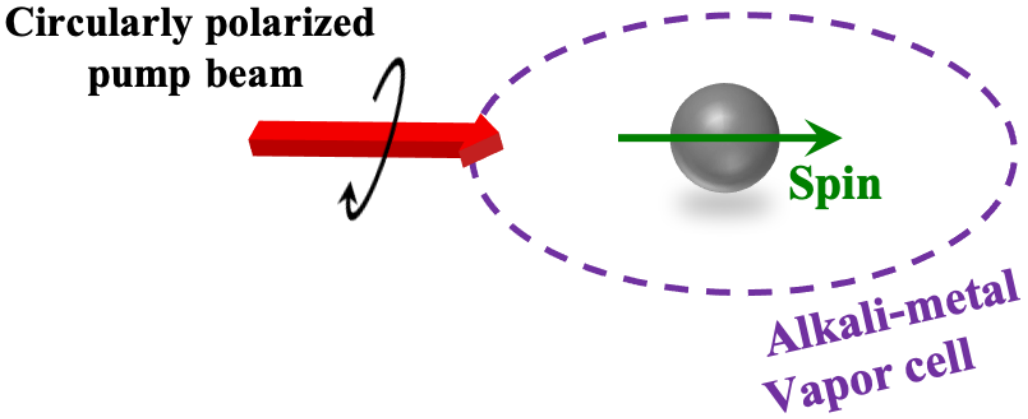
Typical implementation of OQS:



Cryogen-free sensor!

Optical Quantum Sensor (OQS)

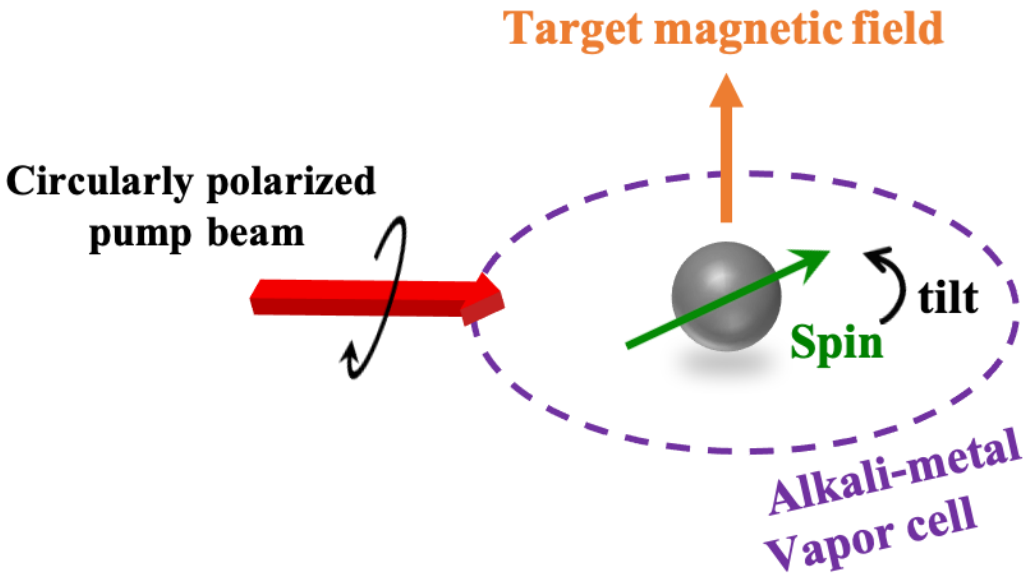
Optical Pumping:



Optically polarize atomic spins

Optical Quantum Sensor (OQS)

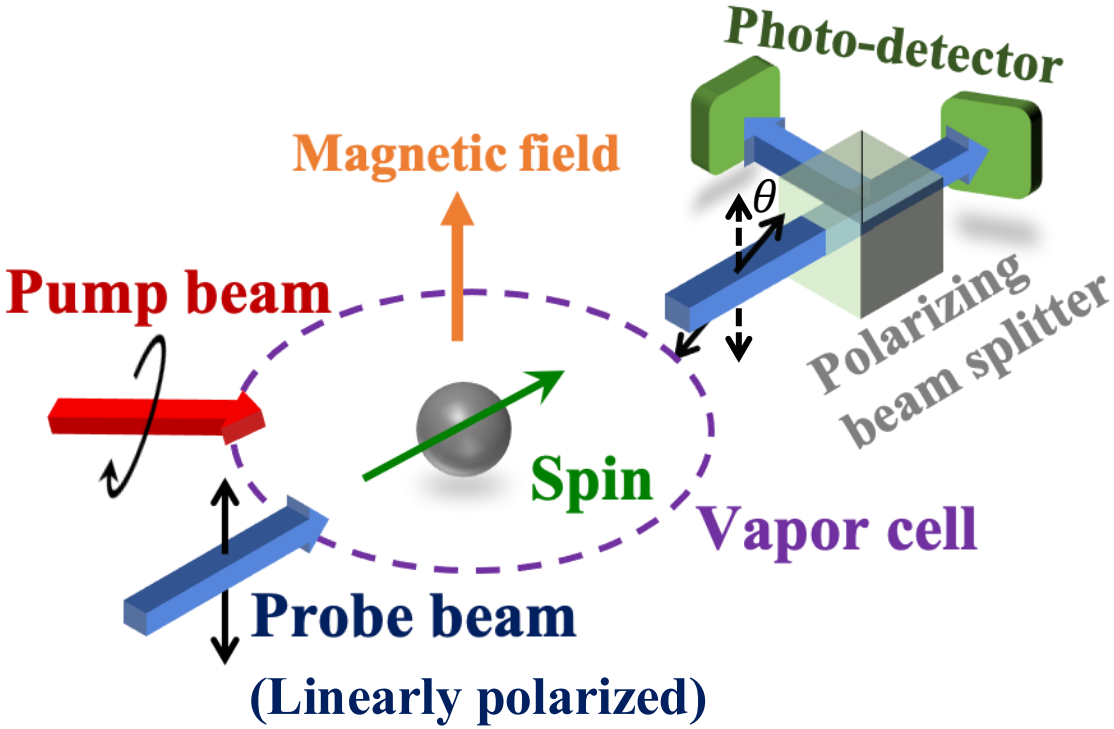
Spin tilt:



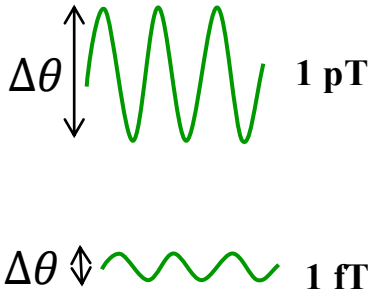
Spin tilt proportional to field strength

Optical Quantum Sensor (OQS)

Probing:



θ= light polarization rotation



Detect target magnetic field with probe beam (Faraday rotation)

Standard Quantum Noise Limit of OQS

Standard quantum noise limit of OQS:

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

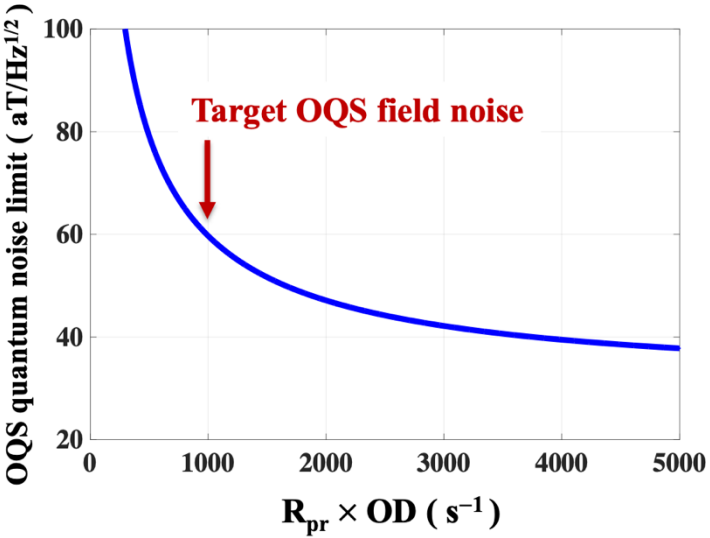
Spin projection noise

Light shift noise

Photon shot noise

$\gamma = 7\times10^9$ **Hz/T**, the gyromagnetic ratio of potassium (K) spins
$n = 7\times10^{13}$ **cm^{-3}**, the density of K atoms
$V = 43$ **cm^3**, the active measurement K cell volume
$T_2 = 0.8$ **ms**, the coherence time of K electron spins
$\eta = 0.8$, photodiode quantum efficiency in probe beam readout

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



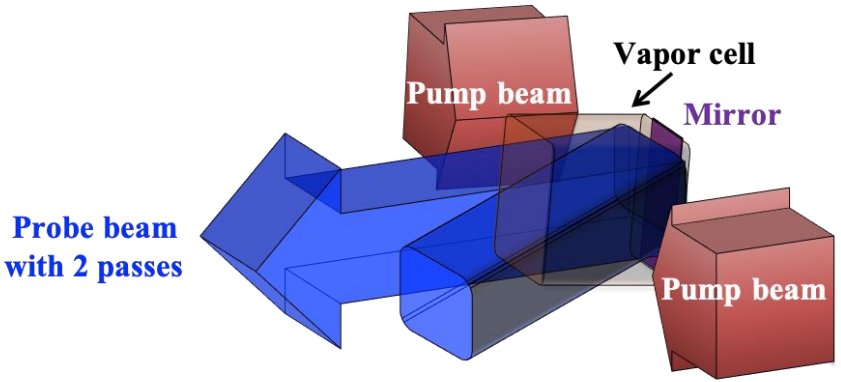
R_{pr}: Absorption rate of probe beam photons
OD: Optical depth of probe beam

Optimal OQS parameters

Optimal parameters for the target OQS noise: $R_{pr} \times OD = 1000\ s^{-1}$

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

Optimal parameters
Probe laser power = 360 mW
Probe beam pass length = 7 cm

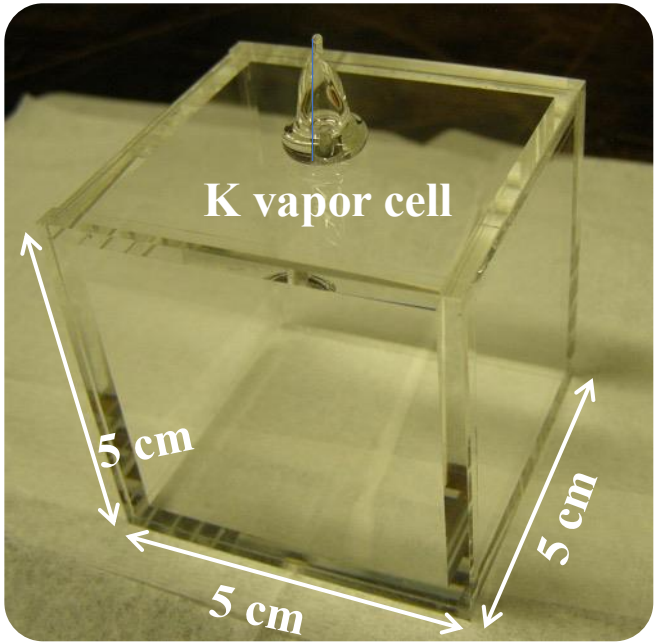


Current best OQS: 240 aT/Hz$^{1/2}$ at 423 kHz in the Rb cell volume of 96 cm^3

Romalis, Sauer, **Savukov**, Seltzer, Lee, U.S. Patent# 7521928B2 (2007)

Demonstrated with low probe laser power of 40 mW

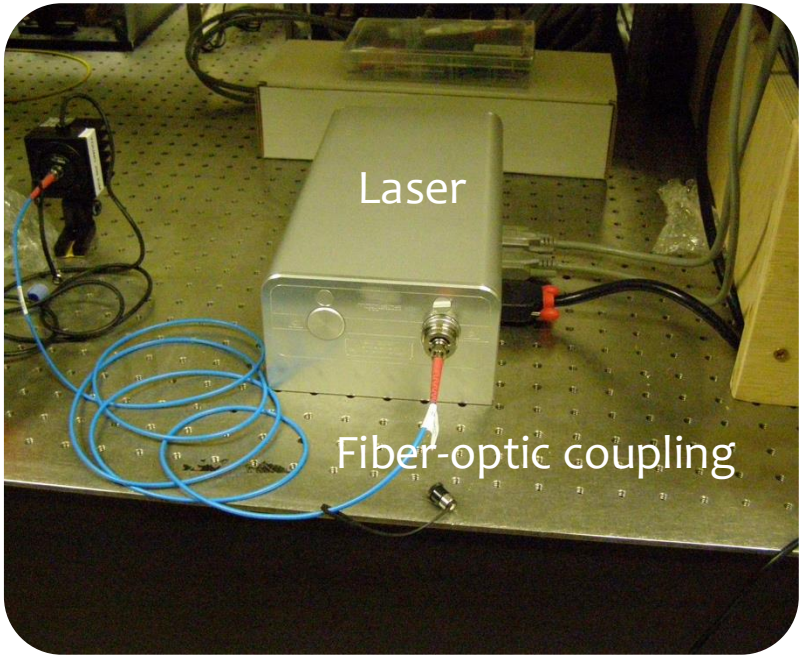
Key Element in OQS Development: Potassium Vapor Cell



- Cell material: Borosilicate glass
- Inner cell Size: $4\times4\times4\ cm^3$
- High optical quality
- Optimal pressure of gases:
  - 600 Torr helium
  - 100 Torr nitrogen

Key Element in OQS Development: Potassium Lasers

Two lasers for potassium OQS have been acquired



Pump laser wavelength : 770.0997 nm (sufficient for optical pumping)
Probe laser wavelength: 770.3917 nm (further adjustment required to improve OQS sensitivity)
Powers after fiber in both lasers: 1.427 W (close to laser specification)

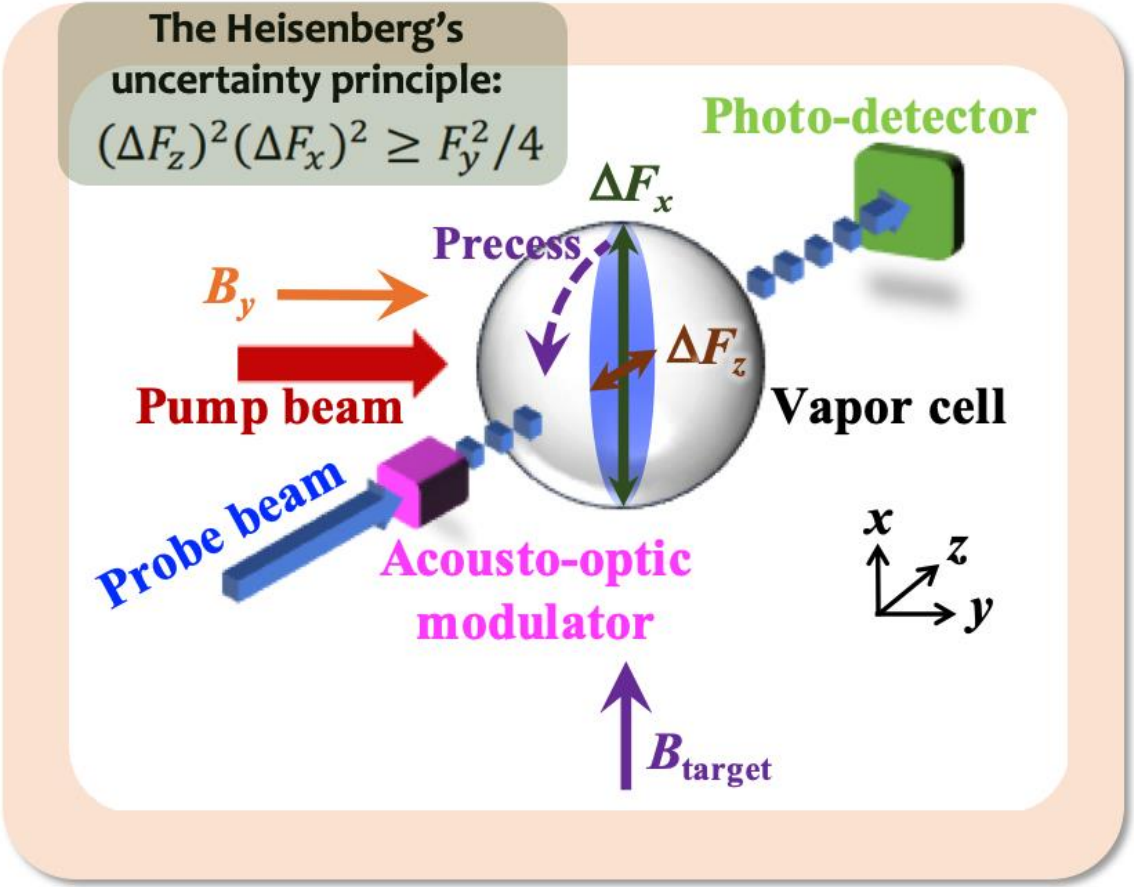
Spin Squeezing Method

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

To reduce spin noise

The Heisenberg's uncertainty principle:

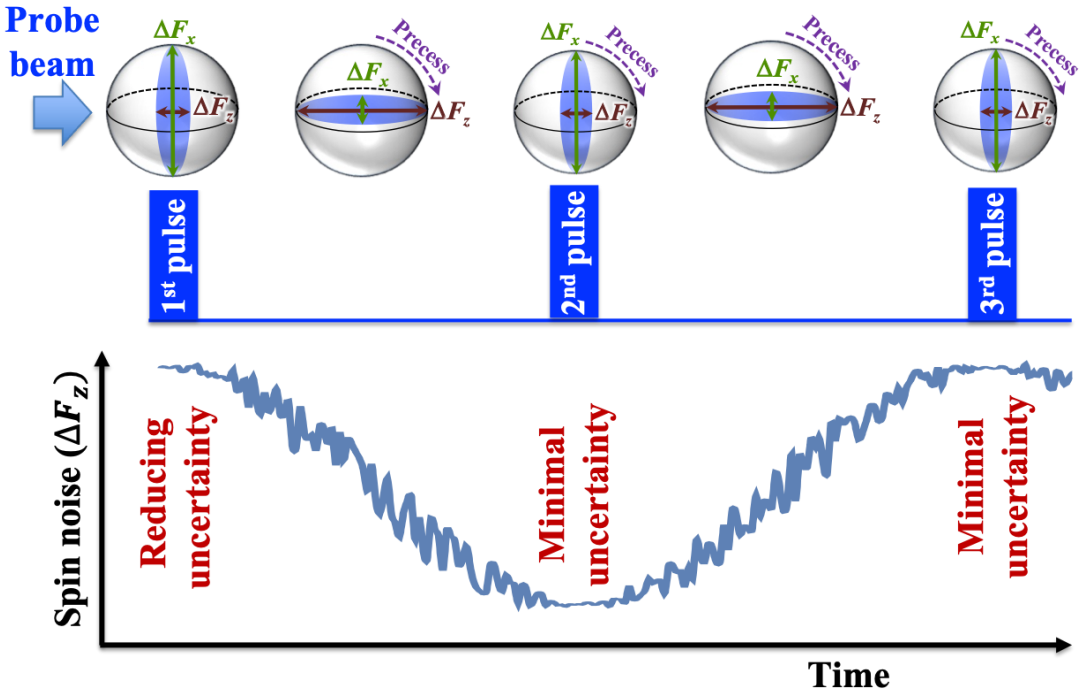
$$(\Delta F_z)^2(\Delta F_x)^2 \geq F_y^2/4$$



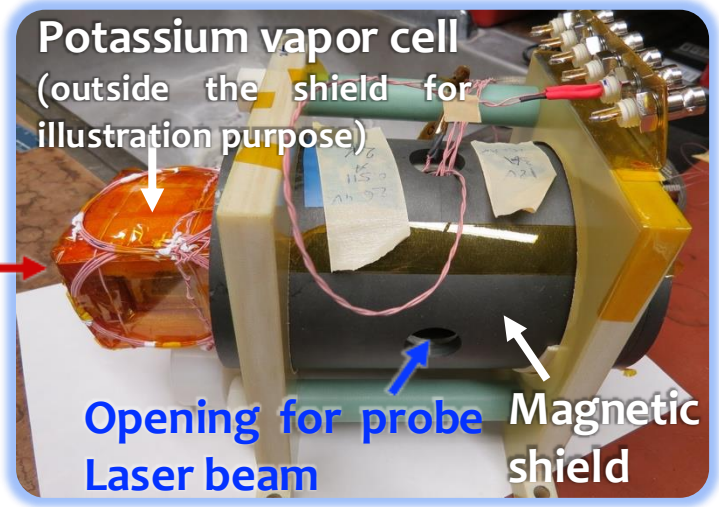
Spin Squeezing Method

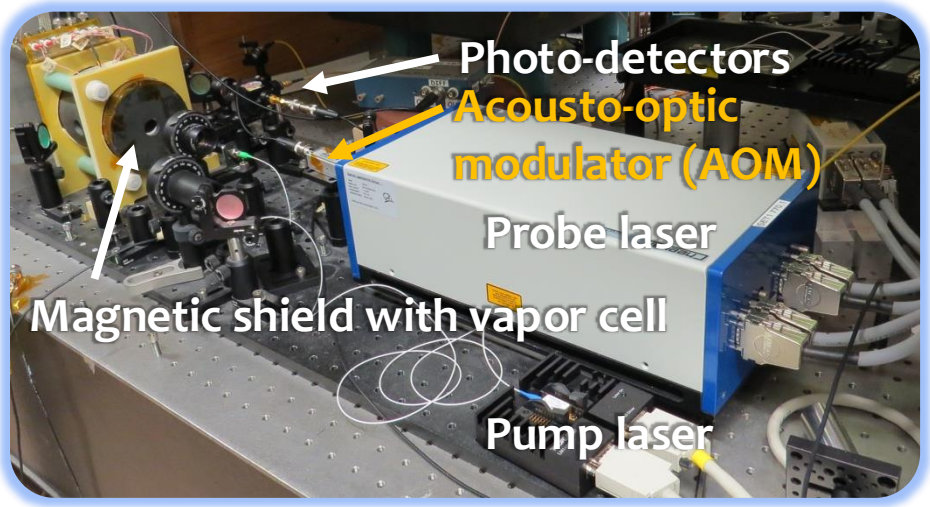
Probe beam pulsing for spin squeezing:

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



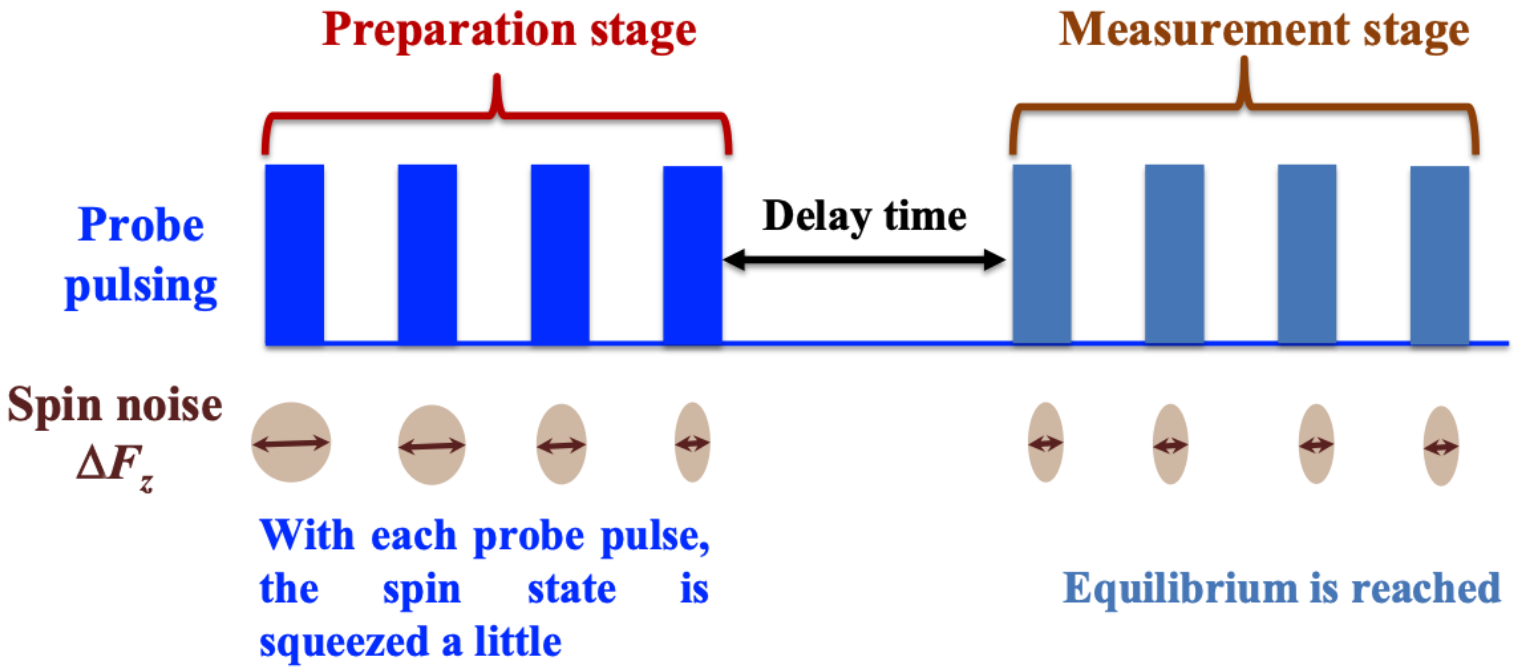
OQS Test Setup





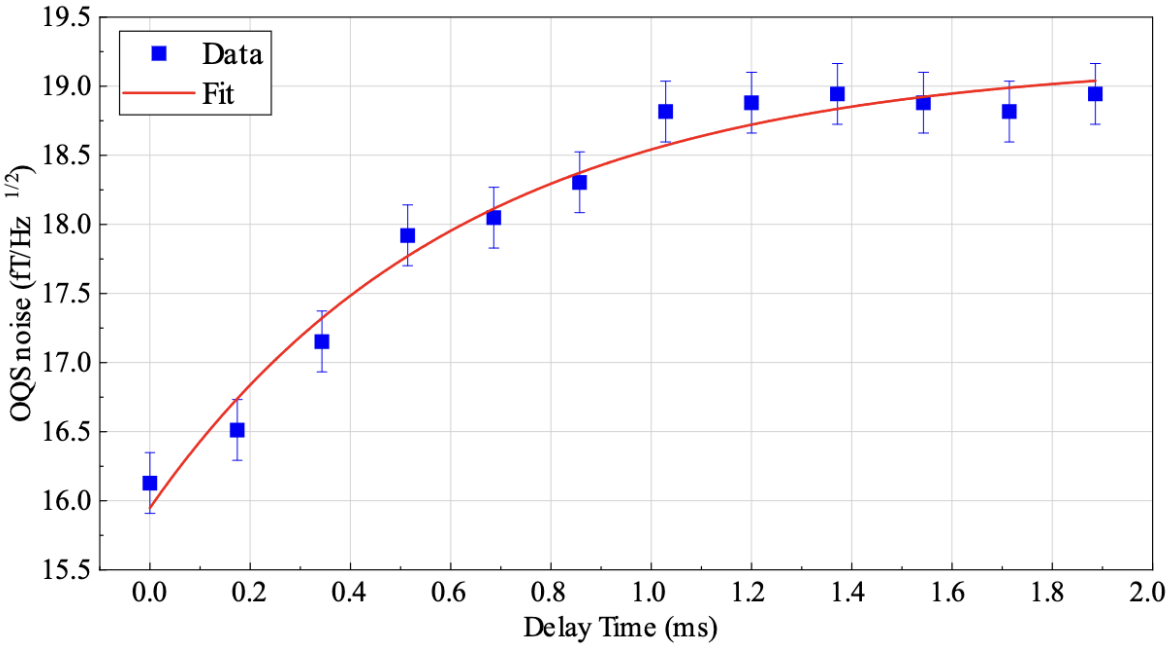
Built an OQS module based on a potassium vapor cell and stable lasers with measured OQS field noise at 10^{-15} T level

Protocol for Spin Squeezing Method



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

Correlated Spin Noise Measurement



Correlation Model:

$$N(\tau) = N_\infty - A\exp\left(-\frac{\tau}{\tau_c}\right)$$

Asymptotic noise:

$$N_\infty = (19.20 \pm 0.17)\ \mathrm{fT}/\sqrt{\mathrm{Hz}}$$

Correlated-noise reduction amplitude:

$$A = (3.25 \pm 0.18)\ \mathrm{fT}/\sqrt{\mathrm{Hz}}$$

Correlation decay time:

$$\tau_c = (0.62 \pm 0.10)\ \mathrm{ms}$$

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Article | Open access | Published: 06 October 2026

High-density optical quantum sensors with pulsed probe read-out for correlated spin-noise reduction

Igor Savukov & Young Jin Kim

Scientific Reports (2026) | Cite this article

Spin noise increases at longer delay time

Research Team

- **Key investigators at Los Alamos National Laboratory:**
  - **Young Jin Kim (PI), Leanne Duffy, Igor Savukov**
- **Key investigators : University of Florida**
  - **David Tanner, Neil Sullivan**

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U.S. Department of ENERGY | Office of Science

Thank you!