Optical Quantum Sensors for Light Axion Detection

Leanne Duffy

Axions 2024
April 26, 2024

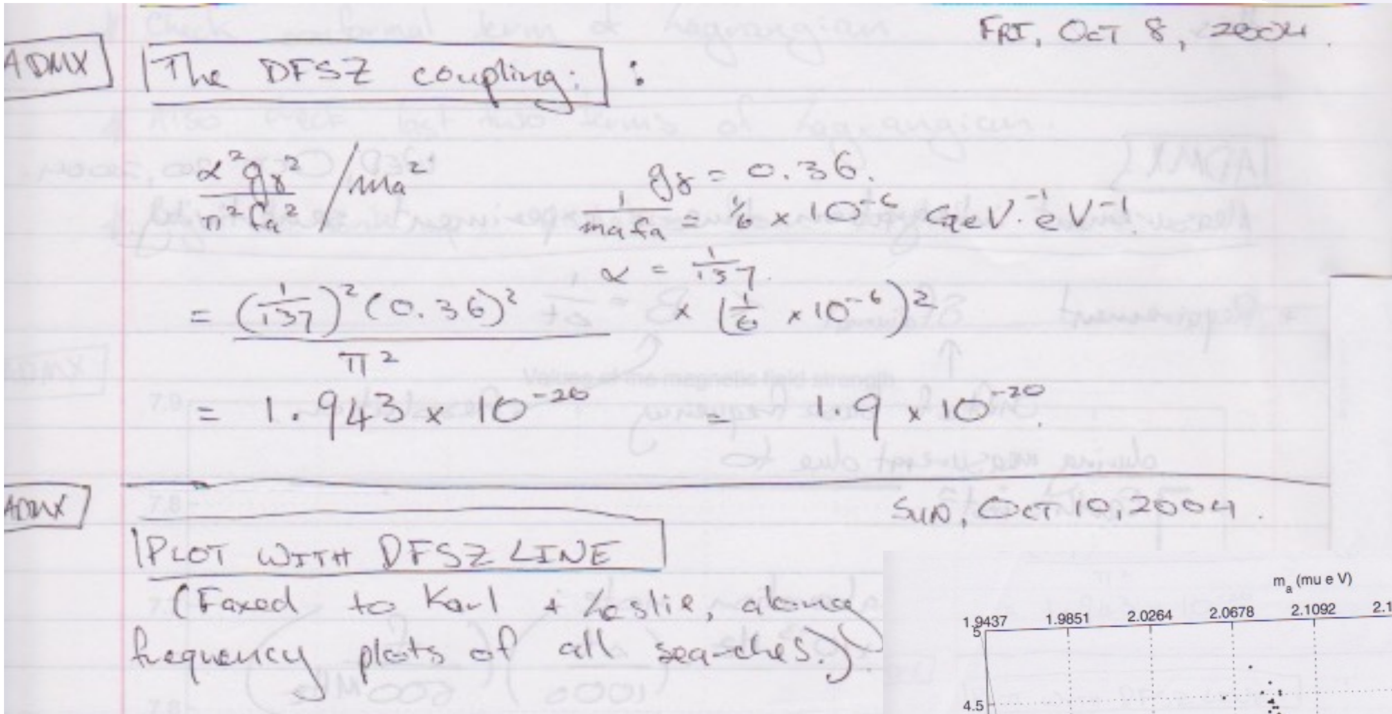
LA-UR-24-23951

How time flies..

- Started working with Pierre Sikivie as a UF grad student in summer of 2002.
- Pierre proposed a “short” project analysing High Resolution data for ADMX..

Los Alamos NATIONAL LABORATORY

ADMX High Resolution Search, 2004 version



ADMX

The DFSZ coupling:

FRI, OCT 8, 2004.

$$\frac{\alpha^2 g_\gamma^2}{\pi^2 f_a^2} \Big/ m_a^2 \qquad g_\gamma = 0.36. \qquad \frac{1}{m_a f_a} = \tfrac{1}{6} \times 10^{-6}\ \mathrm{GeV}^{-1}\cdot\mathrm{eV}^{-1} \qquad \alpha = \tfrac{1}{137}$$

$$= \frac{\left(\frac{1}{137}\right)^2 (0.36)^2}{\pi^2} \times \left(\tfrac{1}{6} \times 10^{-6}\right)^2$$

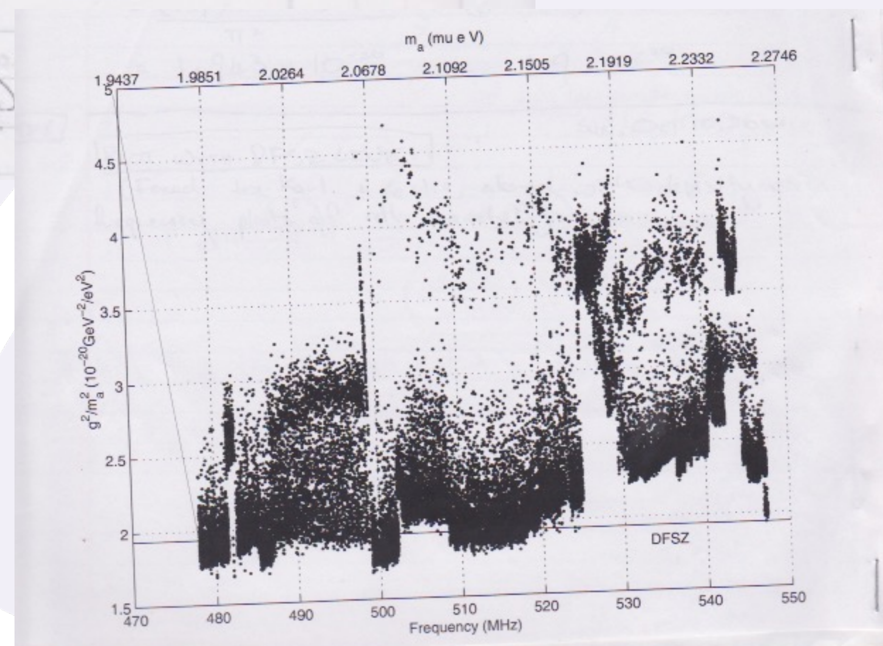
$$= 1.943 \times 10^{-20} \approx 1.9 \times 10^{-20}.$$

ADMX

SUN, OCT 10, 2004.

PLOT WITH DFSZ LINE

(Faxed to Karl + Leslie, along frequency plots of all searches.)



The short project ends..

.. In 2006.

HIGH RESOLUTION SEARCH FOR DARK MATTER AXIONS IN MILKY WAY HALO SUBSTRUCTURE

By

LEANNE DELMA DUFFY

A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

2006

Los Alamos
NATIONAL LABORATORY

Results of a Search for Cold Flows of Dark Matter Axions

L. Duffy,[1] P. Sikivie,[1] D. B. Tanner,[1] S. Asztalos,[2] C. Hagmann,[2] D. Kinion,[2] L. J Rosenberg,[2] K. van Bibber,[2] D. Yu,[2] and R. F. Bradley[3]

[1]*Physics Department, University of Florida, Gainesville, Florida 32611, USA*
[2]*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
[3]*National Radio Astronomy Observatory, Charlottesville, Virginia 22903, USA*

(Received 11 May 2005; published 26 August 2005)

Theoretical arguments predict that the distribution of cold dark matter in spiral galaxies has peaks in velocity space associated with nonthermalized flows of dark matter particles. We searched for the corresponding peaks in the spectrum of microwave photons from axion to photon conversion in a cavity detector for dark matter axions. We found none and place limits on the density of any local flow of axions as a function of the flow velocity dispersion over the axion mass range 1.98 to 2.17 μeV.

PHYSICAL REVIEW D **74**, 012006 (2006)

High resolution search for dark-matter axions

L. D. Duffy, P. Sikivie,* and D. B. Tanner
Department of Physics, University of Florida, Gainesville, Florida 32611, USA

S. J. Asztalos, C. Hagmann, D. Kinion, L. J Rosenberg, K. van Bibber, and D. B. Yu†
Lawrence Livermore National Laboratory, Livermore, California 94550, USA

R. F. Bradley
National Radio Astronomy Observatory, Charlottesville, Virginia 22903, USA
(Received 4 March 2006; published 25 July 2006)

We have performed a high resolution search for galactic halo axions in cold flows using a microwave cavity detector. The analysis procedure and other details of this search are described. No axion signal was found in the mass range 1.98–2.17 μeV. We place upper limits on the density of axions in local discrete flows based on this result.

Caustic Ring Model

Later:

PHYSICAL REVIEW D **78,** 063508 (2008)

Caustic ring model of the Milky Way halo

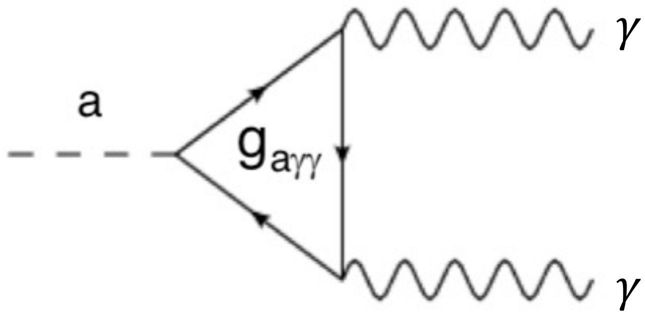
L. D. Duffy[1,*] and P. Sikivie[2,+]

[1]*Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[2]*University of Florida, Gainesville, Florida 32611, USA*
(Received 30 May 2008; published 5 September 2008)

But this is Axions 2024!

Axion-Electromagnetic Interaction

- Axion-EM interaction:

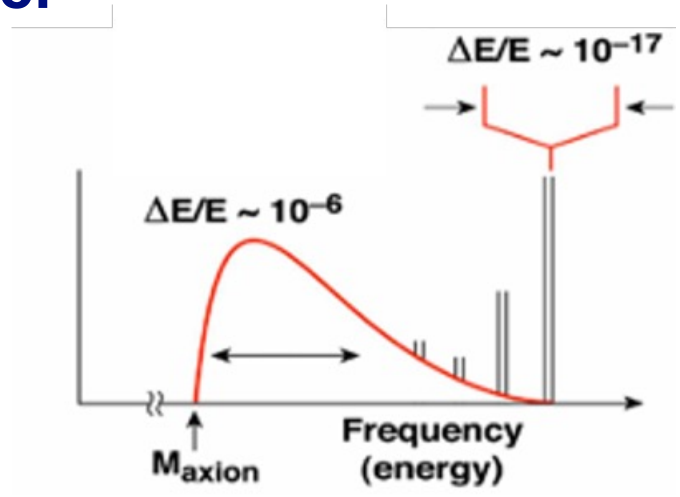


- $g_{a\gamma\gamma}$ is weak and model dependent. QCD axion models:
    - KSVZ: hadronic axion couplings
    - DFSZ: grand unification, weaker couplings than KSVZ
- Weak couplings also make an excellent dark matter candidate!

Axions as Dark Matter

- Signal expectation:

$$\hbar\omega = m_a c^2 + \frac{1}{2} m_a v^2$$



Mass unknown

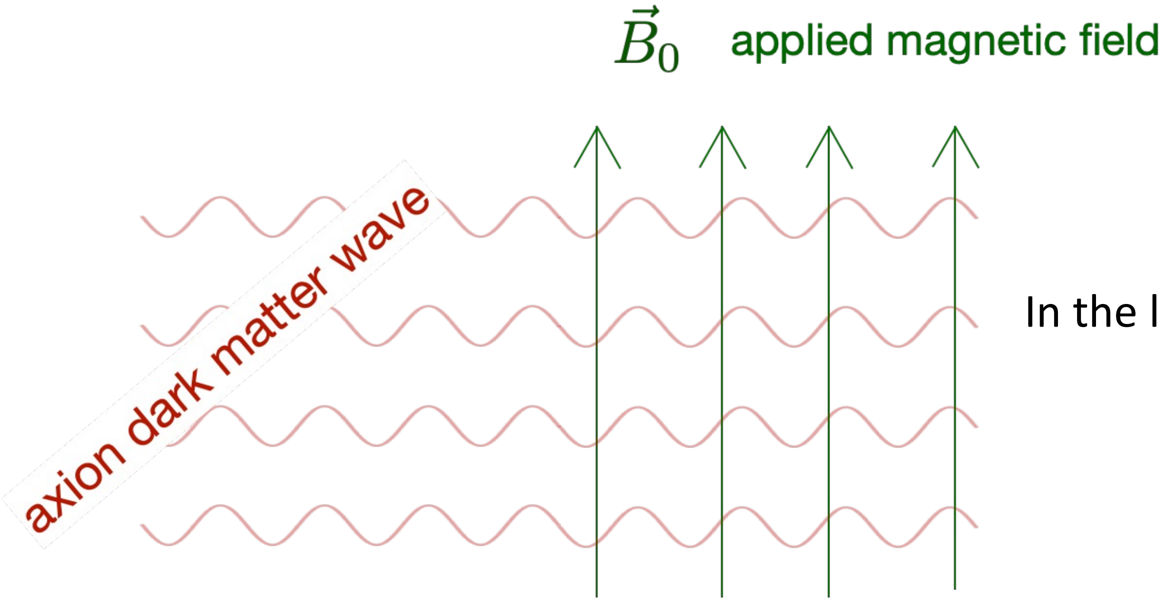
↓

Tune!

- We don't know the mass - need the ability to tune the frequency
- The signal is small – need to amplify

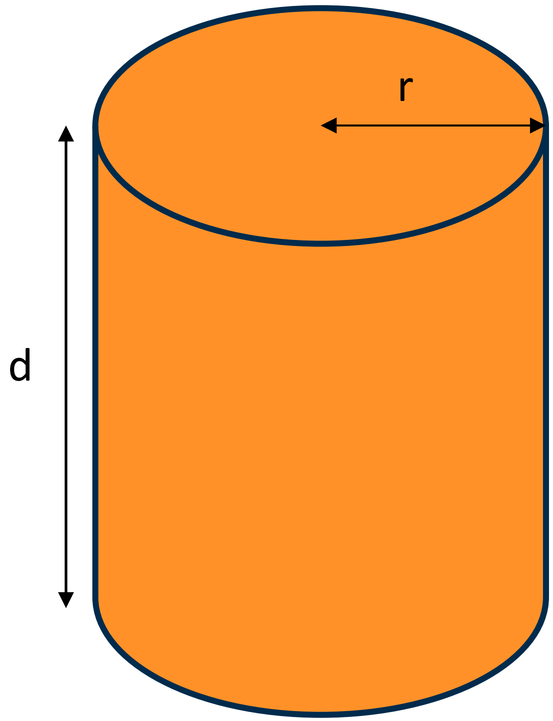
Target Signal

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



In the laboratory

Frequency Range for Cavities



- Power:

$$P_a \propto \rho_a B^2 V m_a$$

- Frequency (~TM_{010} cylindrical cavity):

$$f_{010} = \frac{2.405}{2\pi\sqrt{\mu\epsilon}}\frac{1}{r}$$

- Roughly r ~ 1 m gives a minimum f ~ 300 MHz

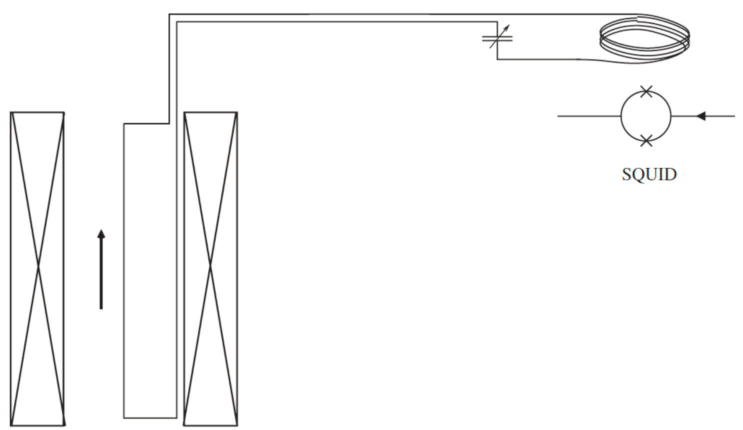
LC Circuit Proposal

PRL **112,** 131301 (2014) PHYSICAL REVIEW LETTERS week ending 4 APRIL 2014

Proposal for Axion Dark Matter Detection Using an *LC* Circuit

P. Sikivie, N. Sullivan, and D. B. Tanner
Department of Physics, University of Florida, Gainesville, Florida 32611, USA
(Received 31 October 2013; revised manuscript received 22 January 2014; published 31 March 2014)

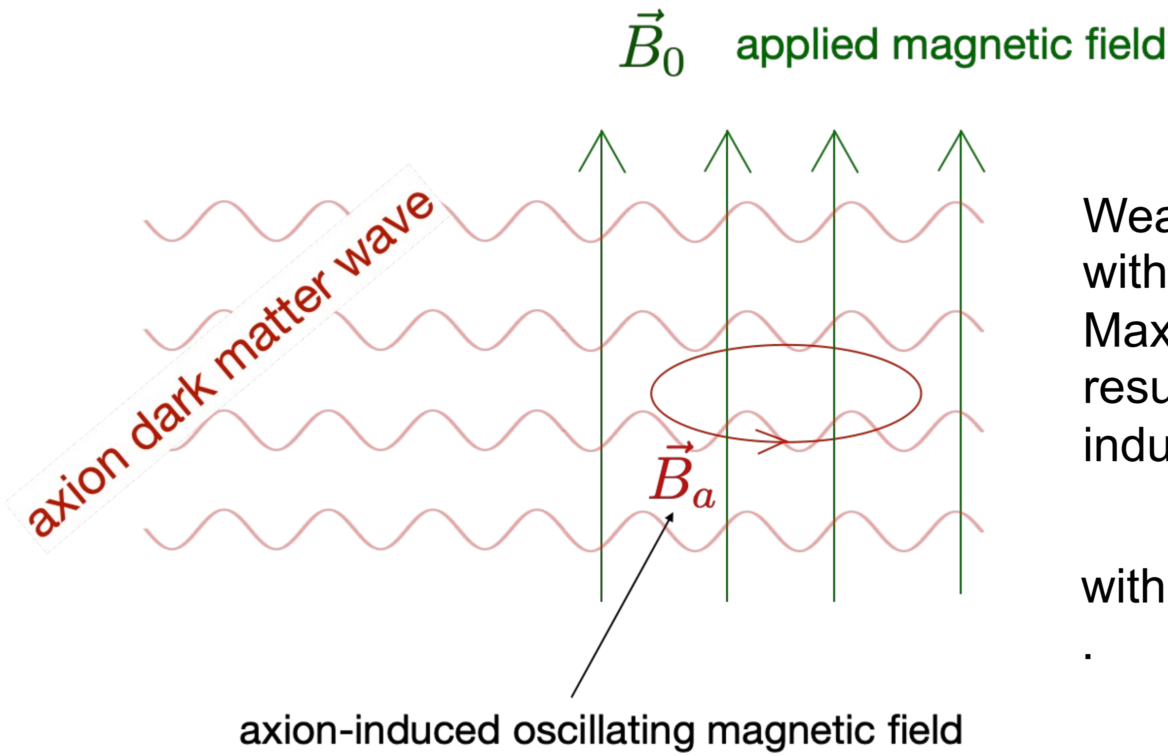
We show that dark matter axions cause an oscillating electric current to flow along magnetic field lines. The oscillating current induced in a strong magnetic field $\vec{B}_0$ produces a small magnetic field $\vec{B}_a$. We propose to amplify and detect $\vec{B}_a$ using a cooled *LC* circuit and a very sensitive magnetometer. This appears to be a suitable approach to searching for axion dark matter in the 10^{-7} to 10^{-9} eV mass range.



DM Radio
ABRACADABRA
ADMX SLIC

Target Signal

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



Weak axion interaction with EM fields modifies Maxwell's equations, and results in an axion-induced magnetic field:

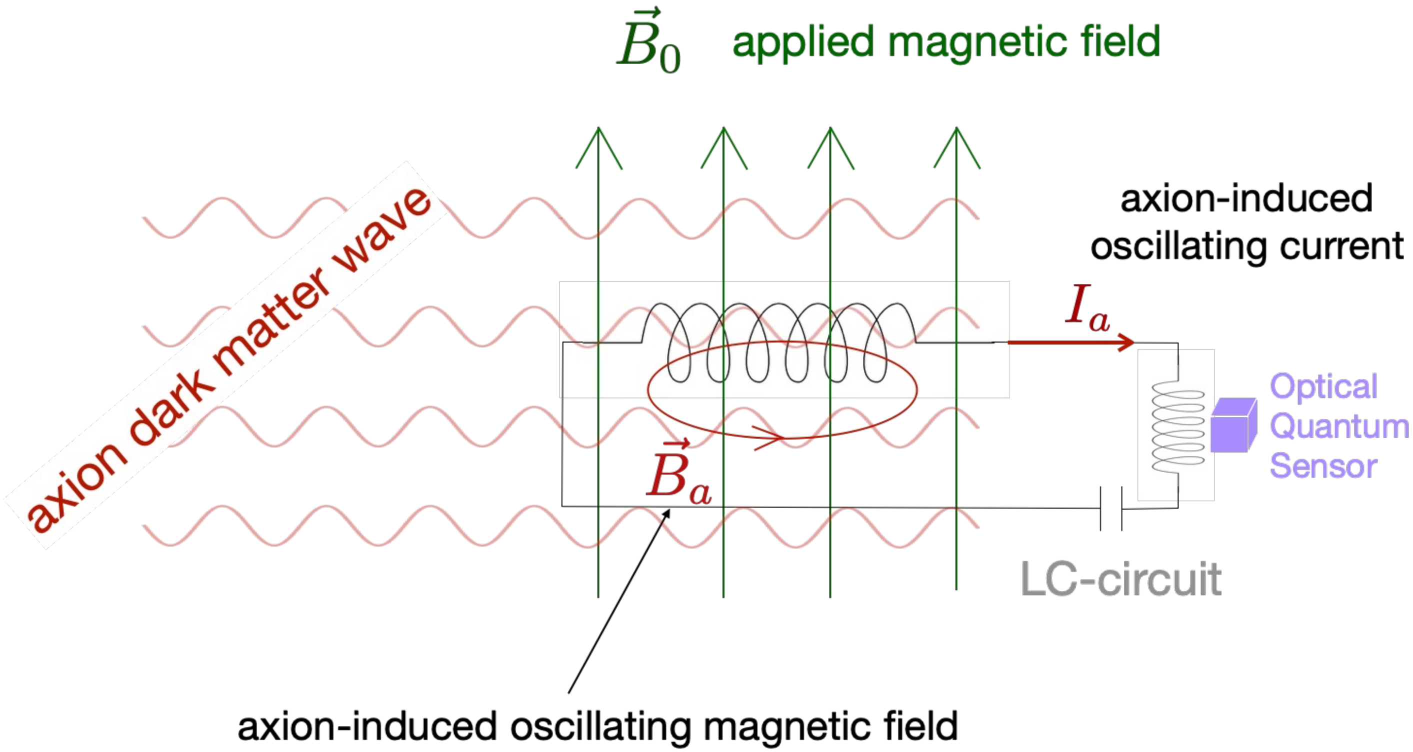
$$\vec{\nabla}\times\vec{B}_a=-g\vec{B}_0\frac{da}{dt}$$

with frequency $h\nu \cong m_a c^2$

.

Target Signal

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

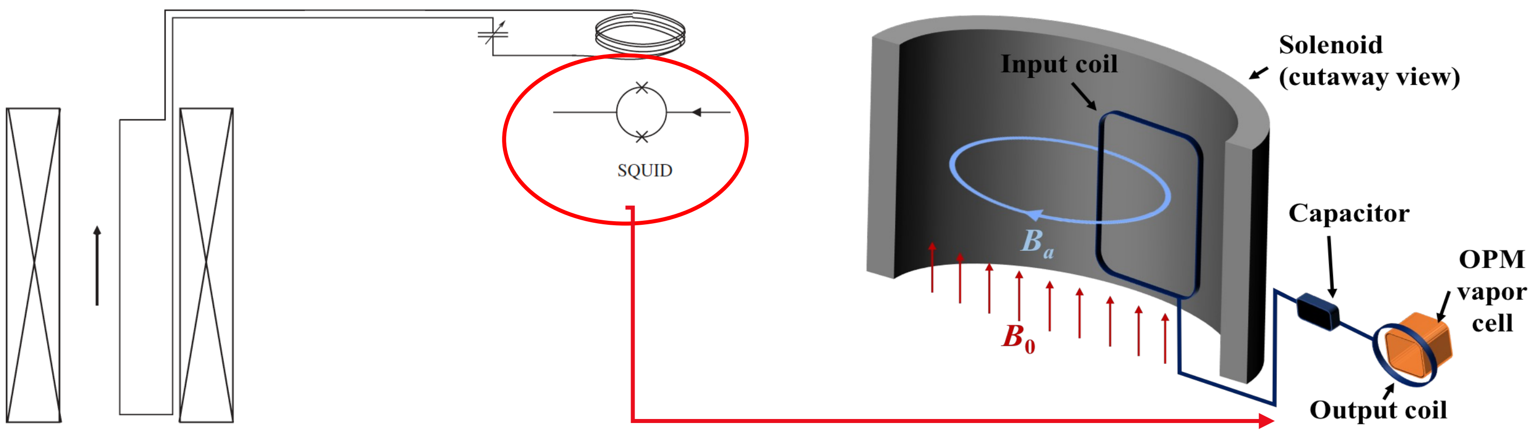


Resonant search for axion dark matter

PHYSICAL REVIEW D **97,** 072011 (2018)

Sensitivity of proposed search for axion-induced magnetic field using optically pumped magnetometers

P.-H. Chu,[*] L. D. Duffy,[†] Y. J. Kim,[‡] and I. M. Savukov
Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

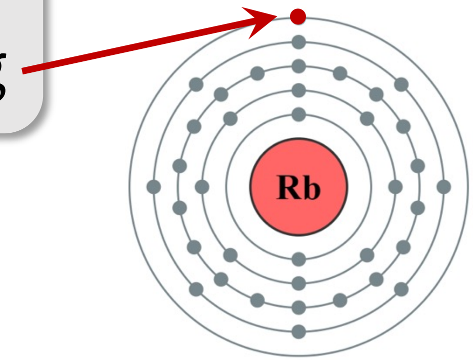


Axion dark matter detection with an LC circuit and an OPM. The axion-induced magnetic field, B_a, is perpendicular to the applied magnetic field, B_0, and is amplified by the LC circuit. The OPM sensitively detects the field from the output coil.

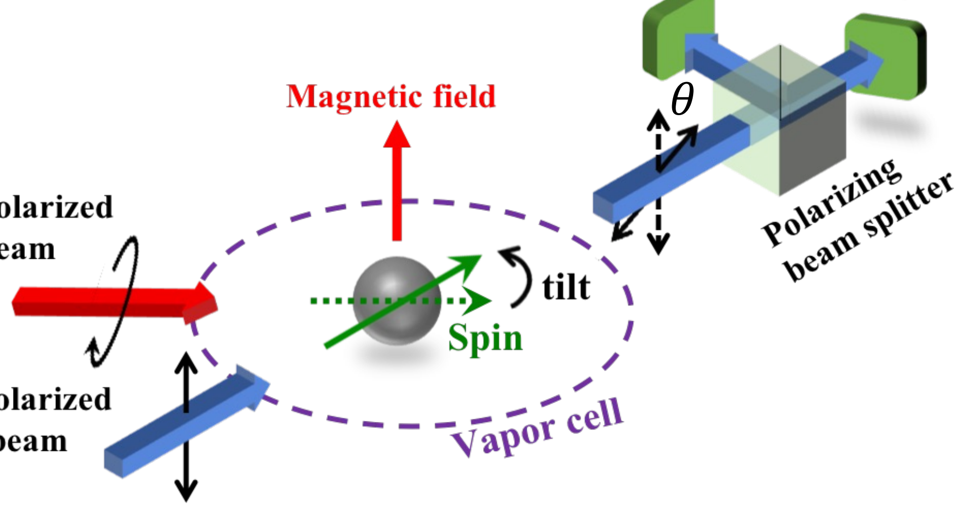
Optical Quantum Sensor

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

Manipulate one valence electron

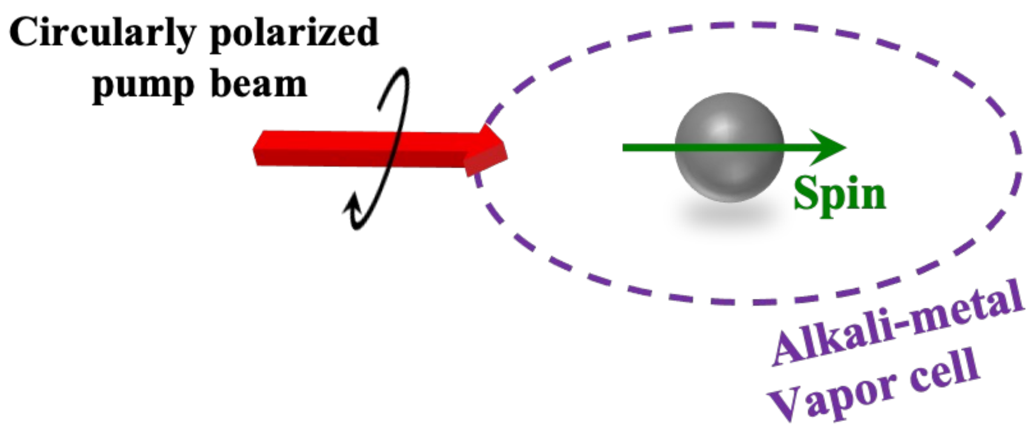


Typical implementation of OQS:



Optical Quantum Sensor

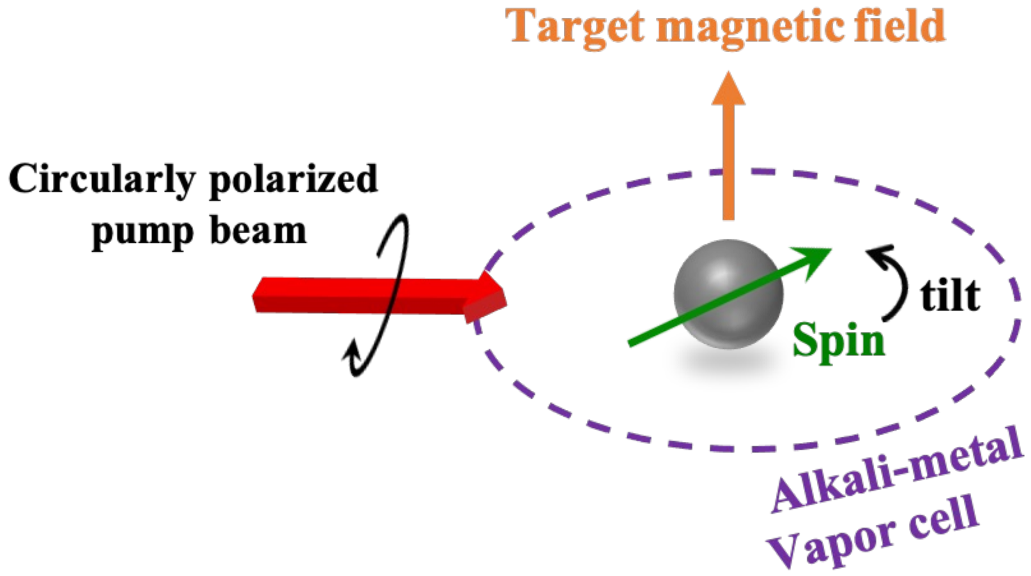
Pumping:



Polarize atomic spins

Optical Quantum Sensor

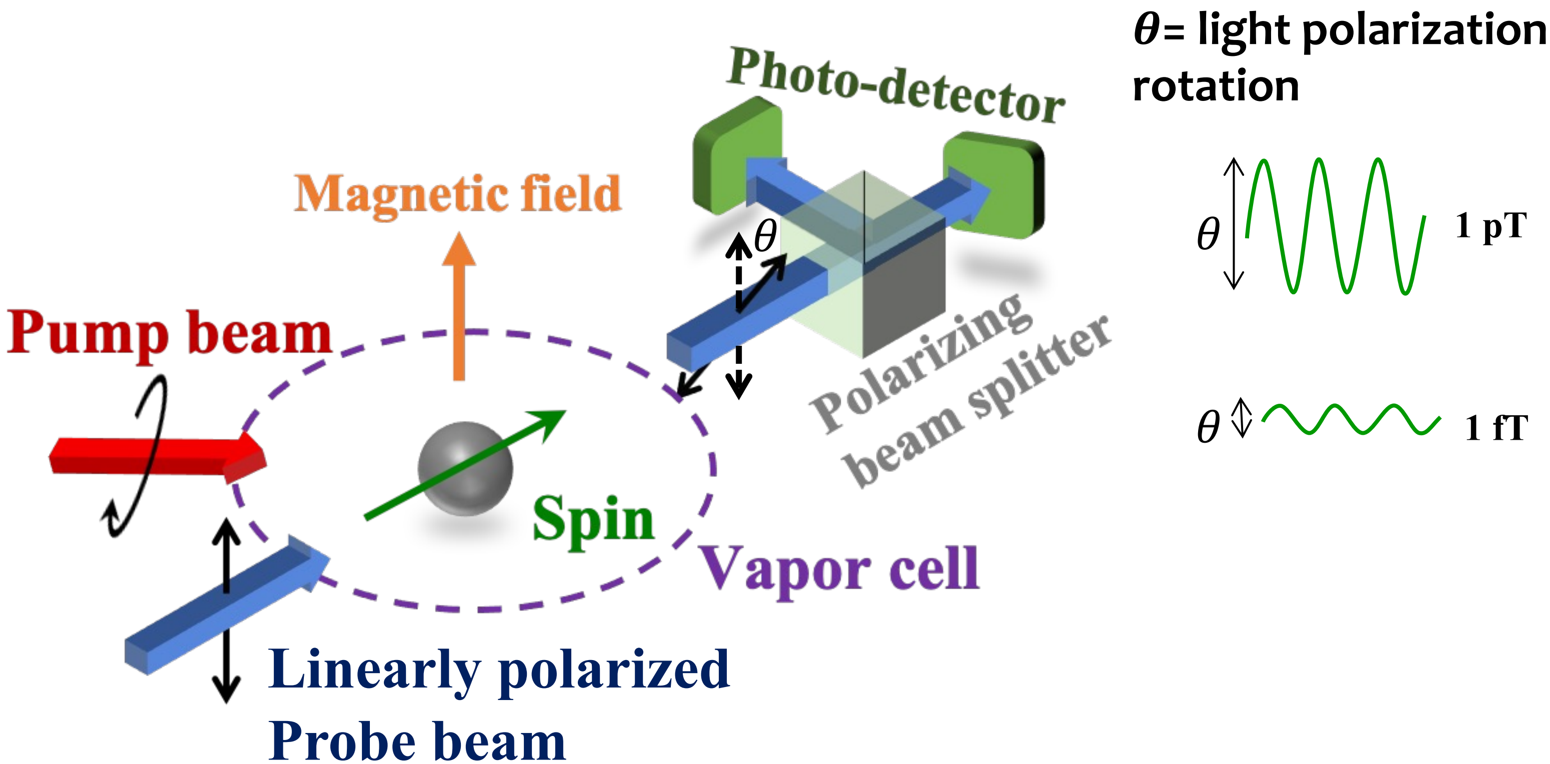
Spin tilt:



Spin tilt proportional to field strength

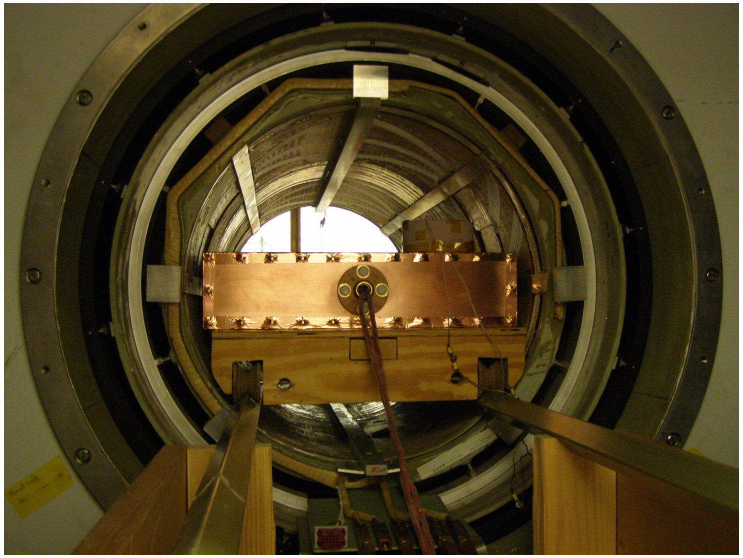
Optical Quantum Sensor

Probing:



Detect magnetic field with probe beam

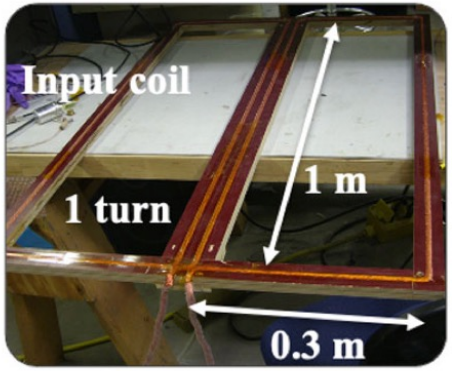
Prototype Development



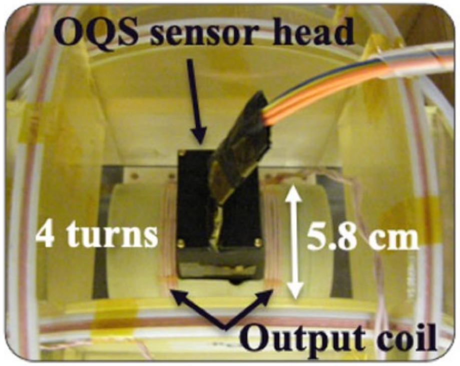
Pickup in MRI magnet bore

- Operates at room temperature
- Tunable

Pickup coil

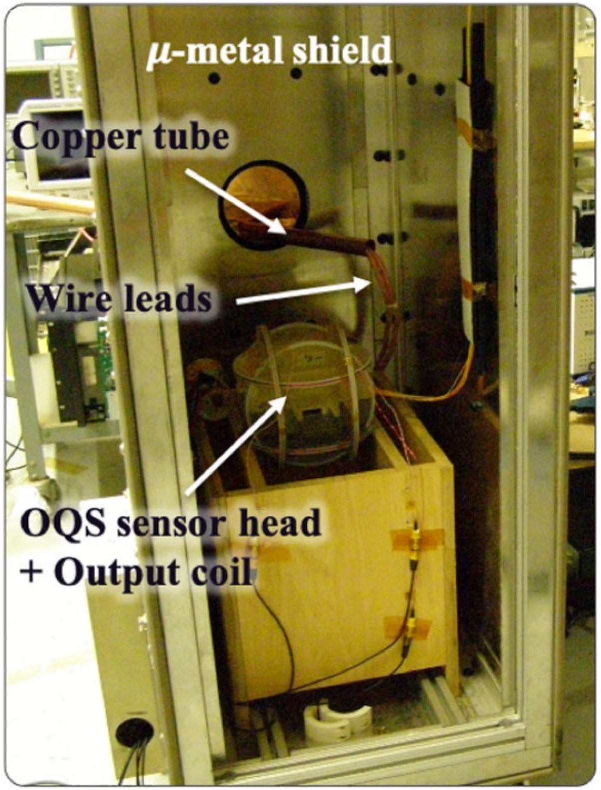


(a)

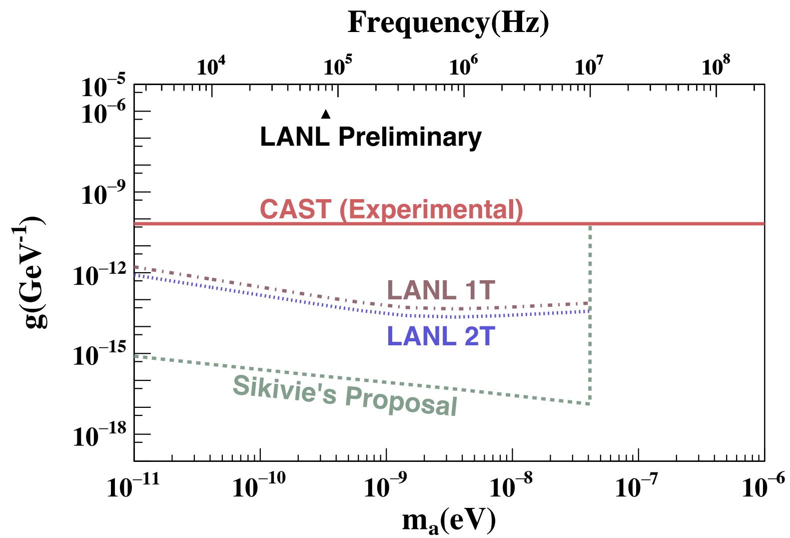


Output coil

Commercial OQS



Prototype Development



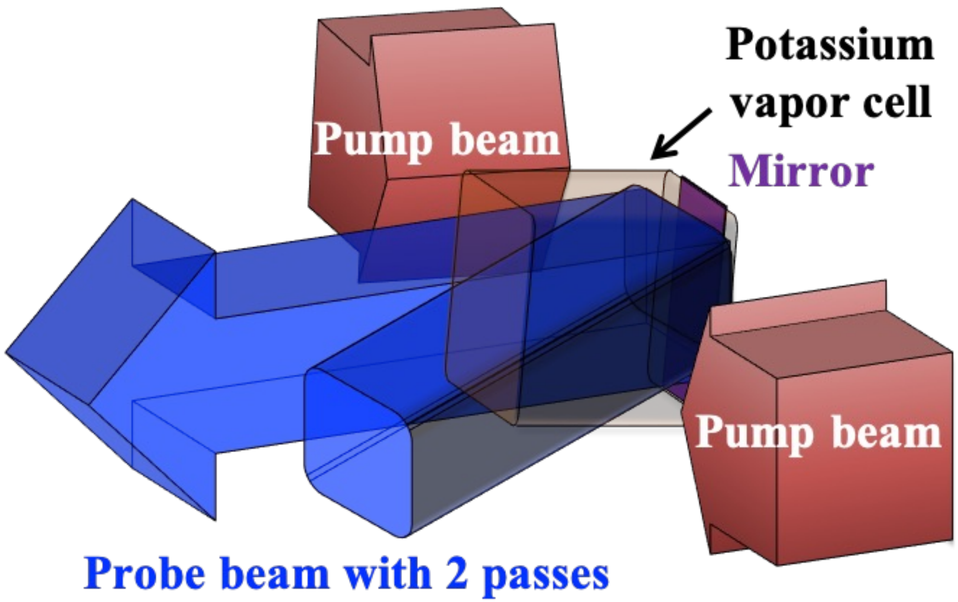
- COVID-19, national LHe supply crisis..
- Prototype used commercial OQS system
- Sensitivity was determined by the OQS noise, which led to..

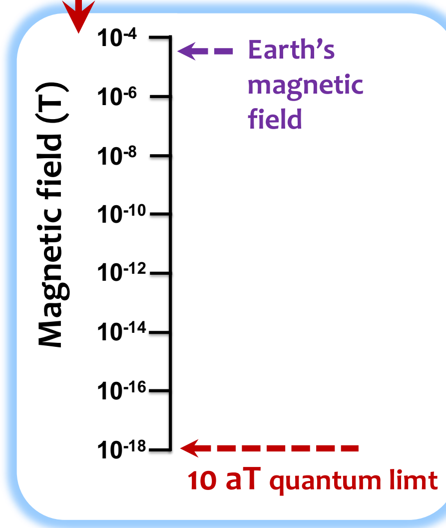
- Magnetometer development with **aT/Hz$^{1/2}$** sensitivity was successfully funded (20210254ER, "Most Sensitive Optical Quantum Sensor", PI: Young Jin Kim, with Igor Savukov). This magnetometer has broad applications, but was motivated to design the most sensitive LC axion search.

What sensitivity could we achieve with a quantum limited sensor?

The Most Sensitive Optical Quantum Sensor

Novel approaches to reach the quantum noise limit (**10 aT/Hz$^{1/2}$**):





Longer probe beam path length
→ lower noise (higher sensitivity)

Highly uniform pumping
→ lower noise (higher sensitivity)

Beyond the quantum limit: spin sqeezing could further reduce the noise
(DOE HEP Seedling funding FY 23-25)

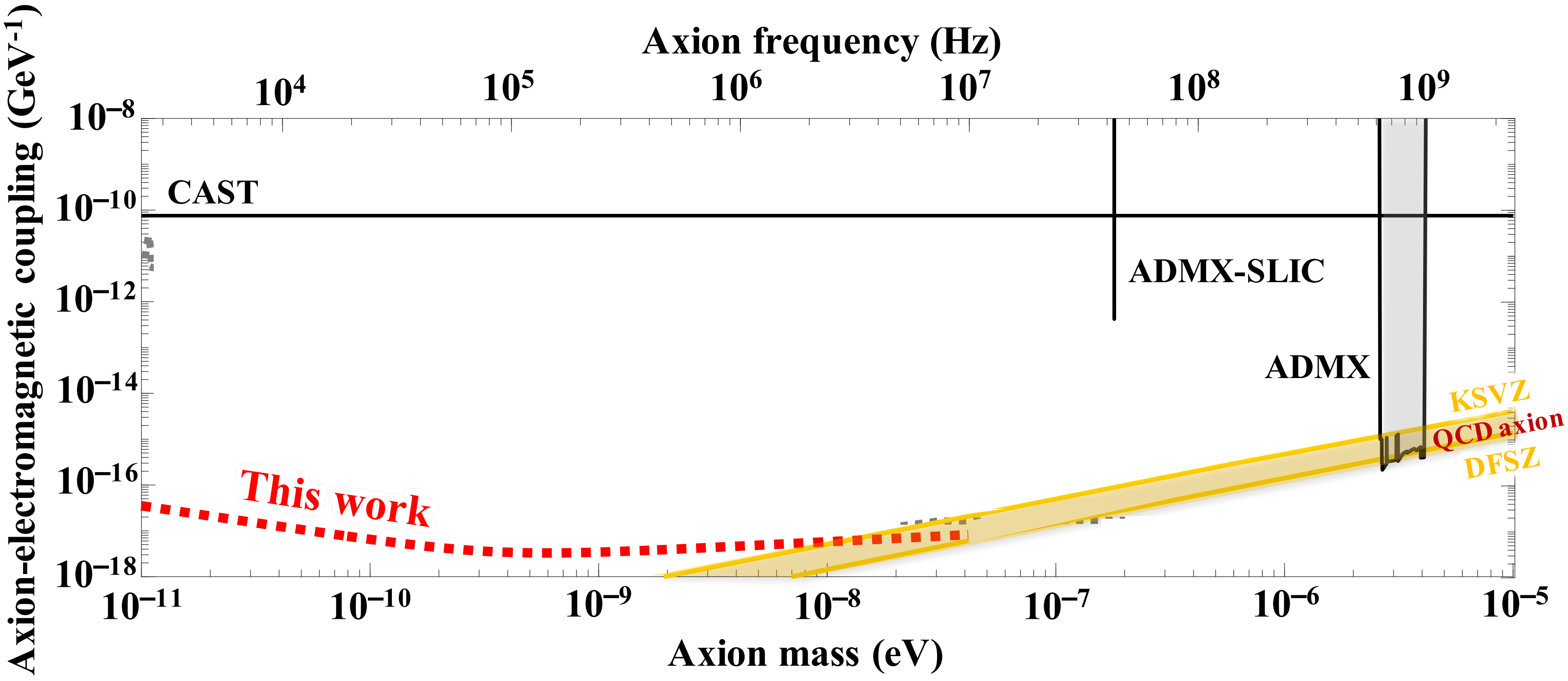
LC Circuit with Quantum Limited OQS

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

Sensitivity of ultralight axion dark matter search with optical quantum sensors

Young Jin Kim,* Leanne Duffy,† Igor Savukov,‡ and Ping-Han Chu
Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, New Mexico 87545, USA

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



Final thoughts

- The axion interaction with electromagnetism, and unknown mass, leads to the use of tunable EM resonators for search and detection.
  - Above ~300 MHz: RF cavity/haloscope receiver
  - Below ~100 MHz: LC circuit receiver
- Searches below 100 MHz are being developed. If successfully developed, a quantum limited OQS could provide a sensitive magnetometer, that is both tunable and operates at room temperature.
- The LC circuit idea has driven OQS development at LANL. While motivated by axion searches, this technology has broader impact for wide applications in sensitive magnetic field detection.

Acknowledgements: Thanks to Young Jin Kim of MPA-Q at LANL for borrowed slides!