# **CI Michael Tobar:** Dark Matter Direct Detection Subprogram b): Axion and Weakly Interacting Slim (or Sub eV) Particles (WISPs)

# CI Michael Tobar: Dark Matter Direct Detection Subprogram b): Axion and Weakly Interacting Slim (or Sub eV) Particles (WISPs)

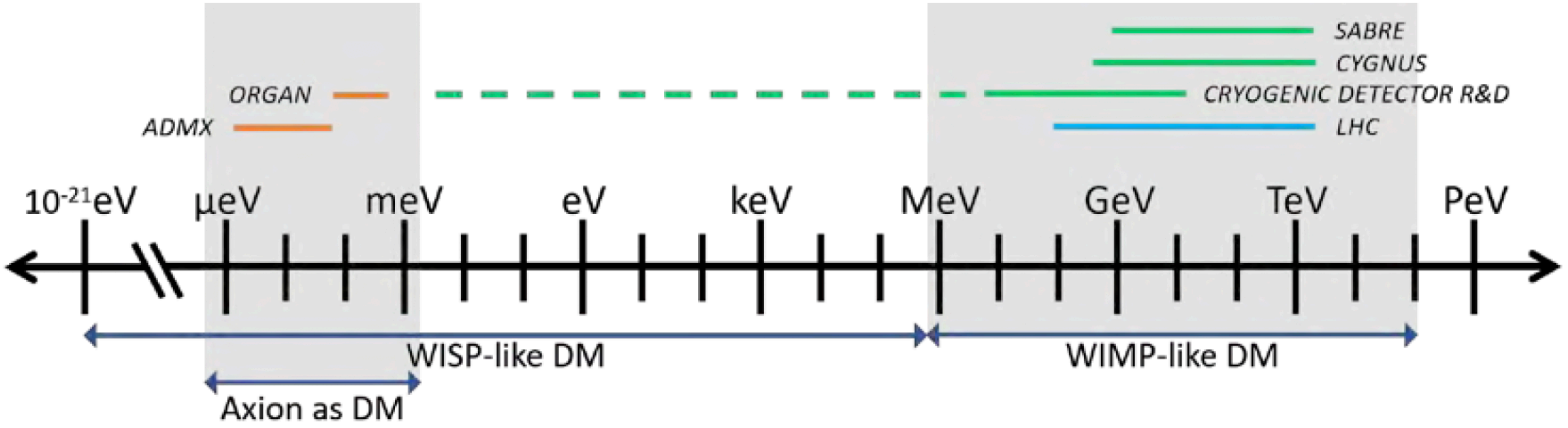


*Figure 4: Dark matter mass ranges to be searched in Centre WIMP and WISP direct detection experiments and the LHC Program.*

**SNOWMASS COSMIC FRONTIER: CF2 WAVE LIKE DARK MATTER**

https://snowmass21.org/cosmic/start

# **CI Michael Tobar:** Dark Matter Direct Detection Subprogram b): Axion and Weakly Interacting Slim (or Sub eV) Particles (WISPs)

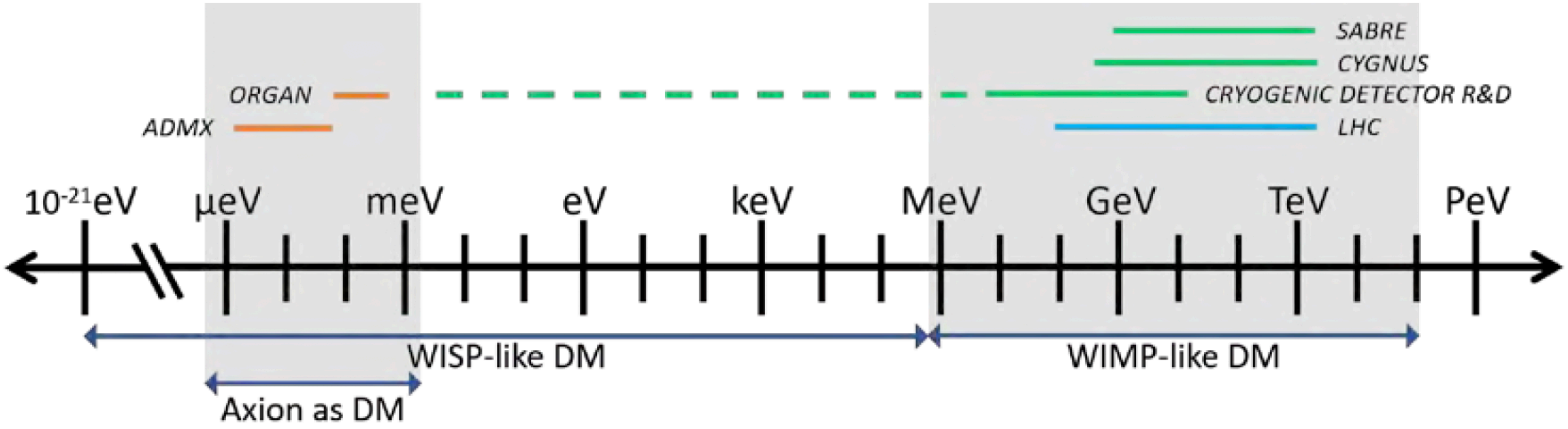


*Figure 4: Dark matter mass ranges to be searched in Centre WIMP and WISP direct detection experiments and the LHC Program.*

**SNOWMASS COSMIC FRONTIER: CF2 WAVE LIKE DARK MATTER**

https://snowmass21.org/cosmic/start

- Low-mass bosonic dark matter ->

# CI Michael Tobar: Dark Matter Direct Detection Subprogram b): Axion and Weakly Interacting Slim (or Sub eV) Particles (WISPs)

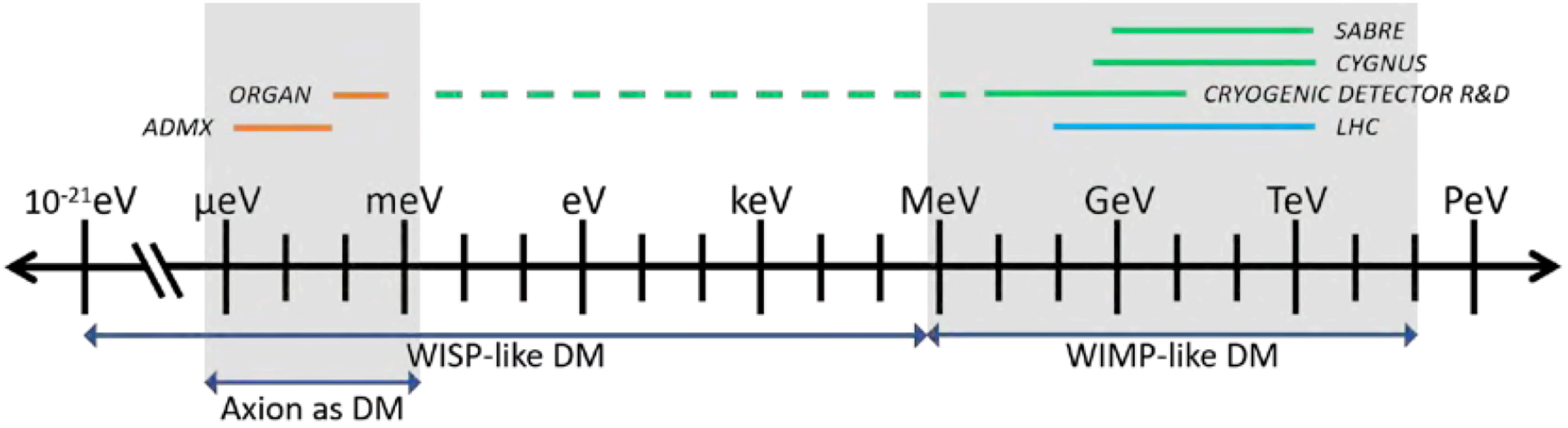


*Figure 4: Dark matter mass ranges to be searched in Centre WIMP and WISP direct detection experiments and the LHC Program.*

**SNOWMASS COSMIC FRONTIER: CF2 WAVE LIKE DARK MATTER**

https://snowmass21.org/cosmic/start

- Low-mass bosonic dark matter ->
- Appears in experiments coherently via wave phenomena rather than as individual quanta.

# CI Michael Tobar: Dark Matter Direct Detection Subprogram b): Axion and Weakly Interacting Slim (or Sub eV) Particles (WISPs)

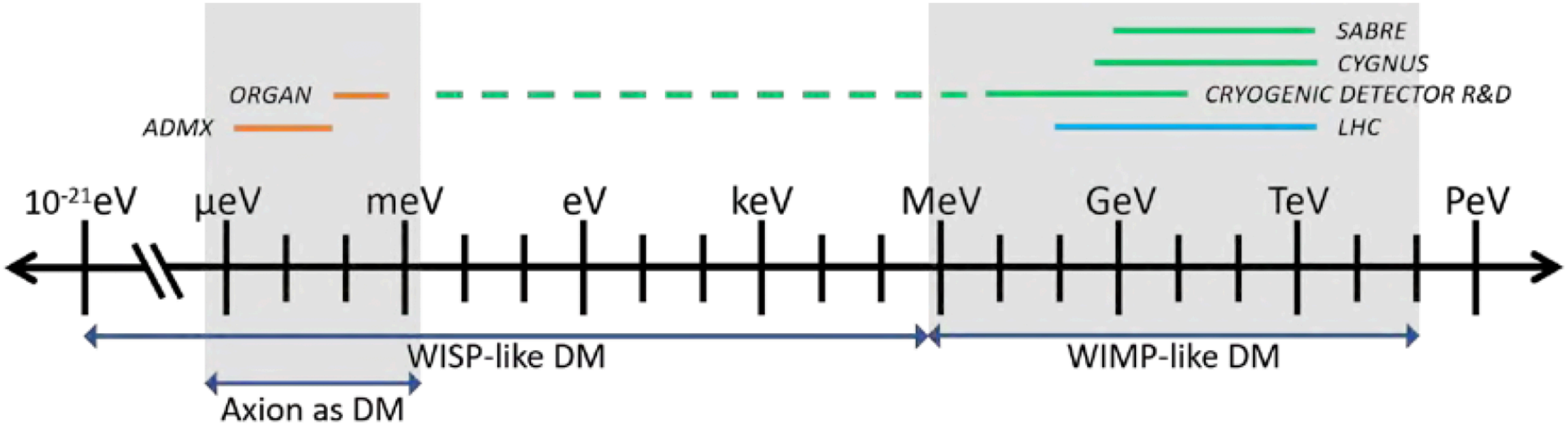


*Figure 4: Dark matter mass ranges to be searched in Centre WIMP and WISP direct detection experiments and the LHC Program.*

**SNOWMASS COSMIC FRONTIER: CF2 WAVE LIKE DARK MATTER**

https://snowmass21.org/cosmic/start

- Low-mass bosonic dark matter ->
- Appears in experiments coherently via wave phenomena rather than as individual quanta.
  - QCD axion and more general axions (Axion Like Particles)

# **CI Michael Tobar:** Dark Matter Direct Detection Subprogram b): Axion and Weakly Interacting Slim (or Sub eV) Particles (WISPs)

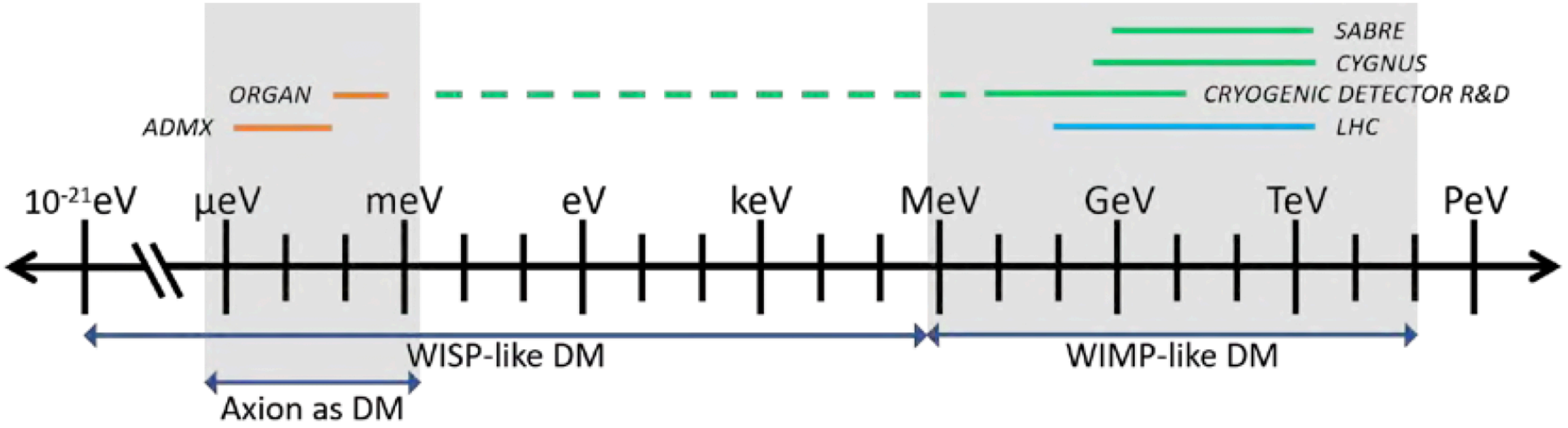


*Figure 4: Dark matter mass ranges to be searched in Centre WIMP and WISP direct detection experiments and the LHC Program.*

**SNOWMASS COSMIC FRONTIER: CF2 WAVE LIKE DARK MATTER**

https://snowmass21.org/cosmic/start

- Low-mass bosonic dark matter ->
- Appears in experiments coherently via wave phenomena rather than as individual quanta.
  - QCD axion and more general axions (Axion Like Particles)
  - Dark photons

# **CI Michael Tobar:** Dark Matter Direct Detection Subprogram b): Axion and Weakly Interacting Slim (or Sub eV) Particles (WISPs)

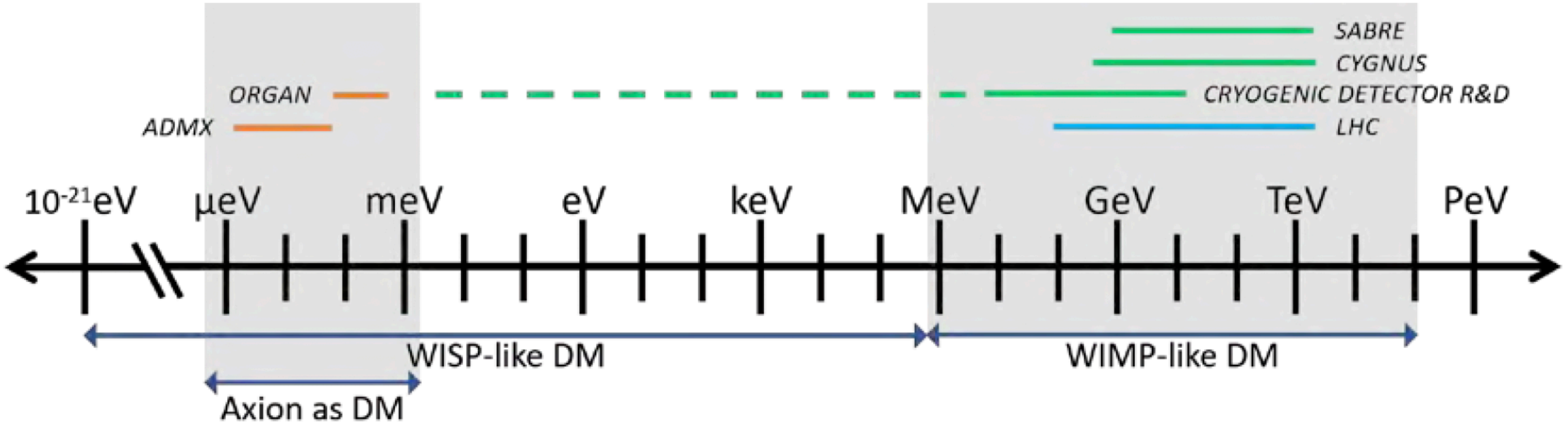


*Figure 4: Dark matter mass ranges to be searched in Centre WIMP and WISP direct detection experiments and the LHC Program.*

**SNOWMASS COSMIC FRONTIER: CF2 WAVE LIKE DARK MATTER**

https://snowmass21.org/cosmic/start

- Low-mass bosonic dark matter ->
- Appears in experiments coherently via wave phenomena rather than as individual quanta.
  - QCD axion and more general axions (Axion Like Particles)
  - Dark photons
  - Scalar dark matter (i.e. Dilaton)

# **CI Michael Tobar:** Dark Matter Direct Detection Subprogram b): Axion and Weakly Interacting Slim (or Sub eV) Particles (WISPs)

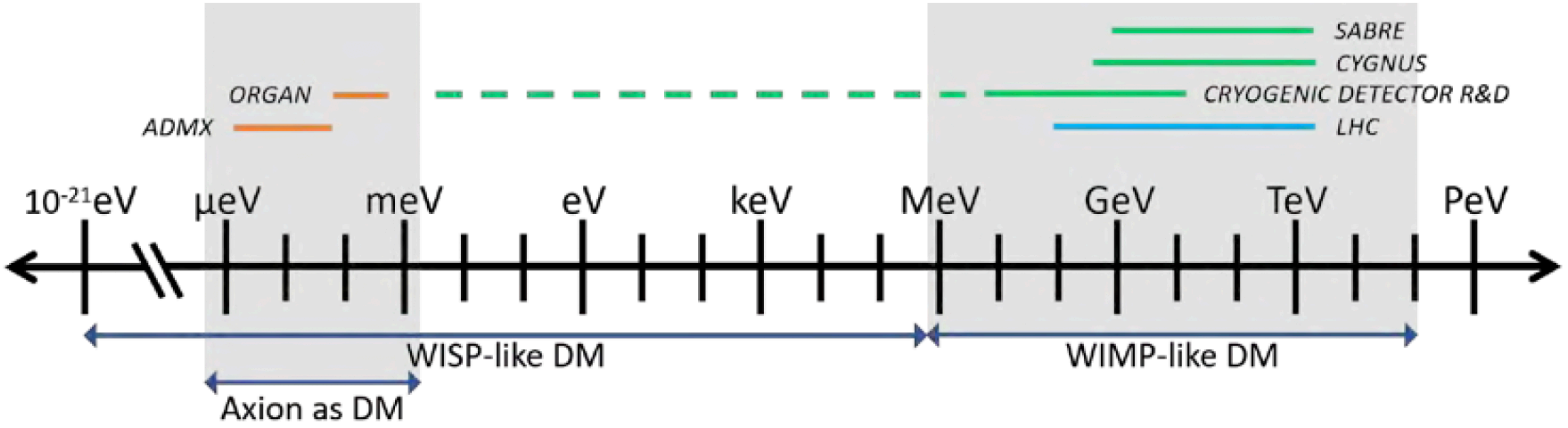


*Figure 4: Dark matter mass ranges to be searched in Centre WIMP and WISP direct detection experiments and the LHC Program.*

**SNOWMASS COSMIC FRONTIER: CF2 WAVE LIKE DARK MATTER**

https://snowmass21.org/cosmic/start

- Low-mass bosonic dark matter ->
- Appears in experiments coherently via wave phenomena rather than as individual quanta.
  - QCD axion and more general axions (Axion Like Particles)
  - Dark photons
  - Scalar dark matter (i.e. Dilaton)
- Current experimental techniques ->

# **CI Michael Tobar:** Dark Matter Direct Detection Subprogram b): Axion and Weakly Interacting Slim (or Sub eV) Particles (WISPs)

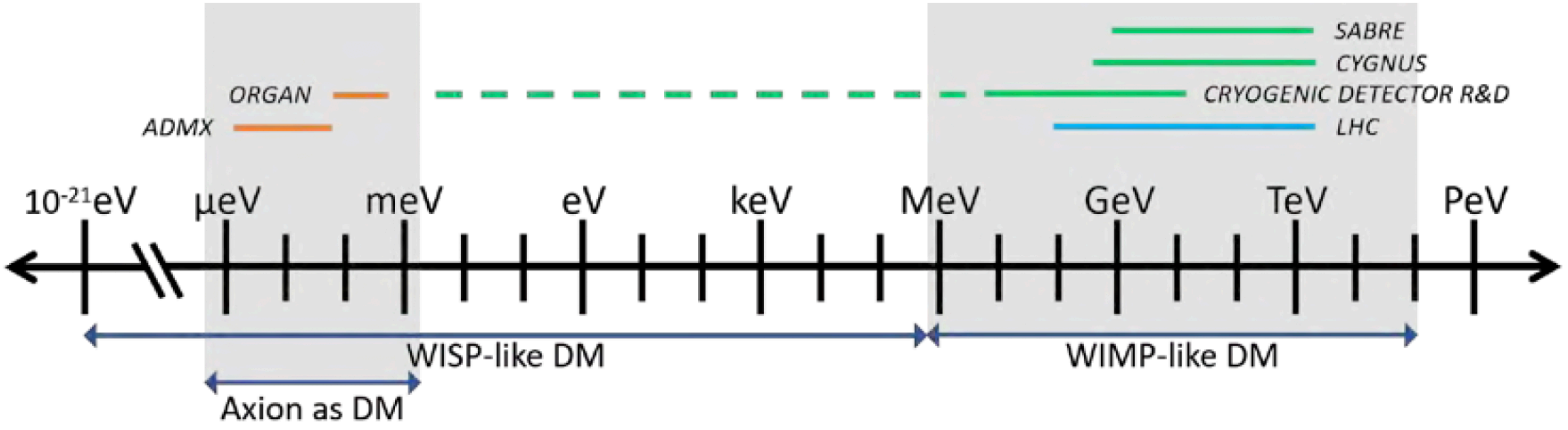


*Figure 4: Dark matter mass ranges to be searched in Centre WIMP and WISP direct detection experiments and the LHC Program.*

**SNOWMASS COSMIC FRONTIER: CF2  WAVE LIKE DARK MATTER**

https://snowmass21.org/cosmic/start

- Low-mass bosonic dark matter ->
- Appears in experiments coherently via wave phenomena rather than as individual quanta.
  - QCD axion and more general axions (Axion Like Particles)
  - Dark photons
  - Scalar dark matter (i.e. Dilaton)
- Current experimental techniques ->
  - Broadband and resonant searches via cavities, circuit oscillators, NMR etc.

# CI Michael Tobar: Dark Matter Direct Detection Subprogram b): Axion and Weakly Interacting Slim (or Sub eV) Particles (WISPs)

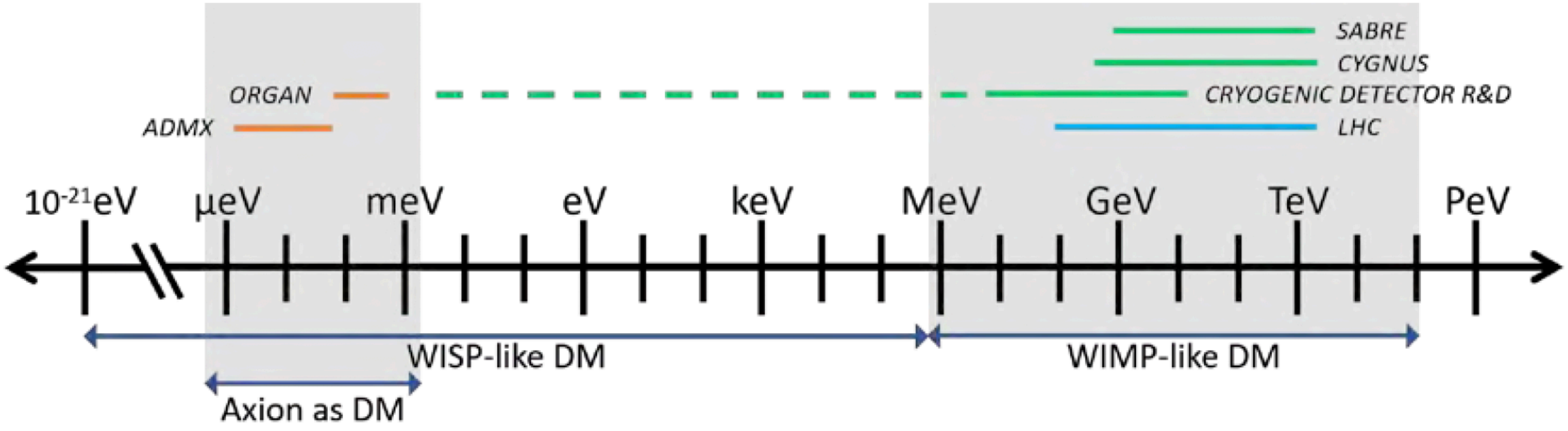


*Figure 4: Dark matter mass ranges to be searched in Centre WIMP and WISP direct detection experiments and the LHC Program.*

**SNOWMASS COSMIC FRONTIER: CF2 WAVE LIKE DARK MATTER**

https://snowmass21.org/cosmic/start

- Low-mass bosonic dark matter ->
- Appears in experiments coherently via wave phenomena rather than as individual quanta.
  - QCD axion and more general axions (Axion Like Particles)
  - Dark photons
  - Scalar dark matter (i.e. Dilaton)
- Current experimental techniques ->
  - Broadband and resonant searches via cavities, circuit oscillators, NMR etc.
  - Utilizes low noise readout with quantum sensing and amplification technologies.

# Research Plans as in Application

# Research Plans as in Application

(1) Axion Dark Matter eXperiment (ADMX) Project run by Fermilab, run out of Seattle at Washington University. UWA Officially a group member since 2019. PI Gray Rybka

# Research Plans as in Application

(1) Axion Dark Matter eXperiment (ADMX) Project run by Fermilab, run out of Seattle at Washington University. UWA Officially a group member since 2019. PI Gray Rybka

(2) Oscillating Resonant Group AxioN experiment (ORGAN). The first Axion experiment at UWA, will test Axion Cogenesis in 2021, arXiv:2006.04809 [hep-ph]

# Research Plans as in Application

(1) Axion Dark Matter eXperiment (ADMX) Project run by Fermilab, run out of Seattle at Washington University. UWA Officially a group member since 2019. PI Gray Rybka

(2) Oscillating Resonant Group AxioN experiment (ORGAN). The first Axion experiment at UWA, will test Axion Cogenesis in 2021, arXiv:2006.04809 [hep-ph]

(3) Searches for axions through coupling with electron spins; Magnon-Cavity UWA

# Research Plans as in Application

(1) Axion Dark Matter eXperiment (ADMX) Project run by Fermilab, run out of Seattle at Washington University. UWA Officially a group member since 2019. PI Gray Rybka

(2) Oscillating Resonant Group AxioN experiment (ORGAN). The first Axion experiment at UWA, will test Axion Cogenesis in 2021, arXiv:2006.04809 [hep-ph]

(3) Searches for axions through coupling with electron spins; Magnon-Cavity UWA

(4) Low mass detectors for axions with LCR Circuits, ADMX-SLIC (Superconducting Lc-circuit Investigating Cold axions) UF (Sikivie and Tanner) and Broadband Electrical Action Sensing Technique (BEAST) UWA

# Research Plans as in Application

(1) Axion Dark Matter eXperiment (ADMX) Project run by Fermilab, run out of Seattle at Washington University. UWA Officially a group member since 2019. PI Gray Rybka

(2) Oscillating Resonant Group AxioN experiment (ORGAN). The first Axion experiment at UWA, will test Axion Cogenesis in 2021, arXiv:2006.04809 [hep-ph]

(3) Searches for axions through coupling with electron spins; Magnon-Cavity UWA

(4) Low mass detectors for axions with LCR Circuits, ADMX-SLIC (Superconducting Lc-circuit Investigating Cold axions) UF (Sikivie and Tanner) and Broadband Electrical Action Sensing Technique (BEAST) UWA

(5) AC Halloscope with Low Noise Oscillators (UPconversion Loop Oscillator Axion Detector (UPLOAD) UWA

# Research Plans as in Application

(1) Axion Dark Matter eXperiment (ADMX) Project run by Fermilab, run out of Seattle at Washington University. UWA Officially a group member since 2019. PI Gray Rybka

(2) Oscillating Resonant Group AxioN experiment (ORGAN). The first Axion experiment at UWA, will test Axion Cogenesis in 2021, arXiv:2006.04809 [hep-ph]

(3) Searches for axions through coupling with electron spins; Magnon-Cavity UWA

(4) Low mass detectors for axions with LCR Circuits, ADMX-SLIC (Superconducting Lc-circuit Investigating Cold axions) UF (Sikivie and Tanner) and Broadband Electrical Action Sensing Technique (BEAST) UWA

(5) AC Halloscope with Low Noise Oscillators (UPconversion Loop Oscillator Axion Detector (UPLOAD) UWA

(6) **Light Scalar Dark Matter** (Dilaton) Clock Comparisons, Acoustic Detectors UWA

# Centre Involvement

THE UNIVERSITY *of* ADELAIDE

Australian Government
Department of Defence
Defence Science and Technology Group

Australian Government
ANSTO

Australian National University

THE UNIVERSITY OF MELBOURNE

SWIN BUR NE
SWINBURNE UNIVERSITY OF TECHNOLOGY

THE UNIVERSITY OF SYDNEY

THE UNIVERSITY OF WESTERN AUSTRALIA

INFN

KAIST
1971
KOREA ADVANCED INSTITUTE OF SCIENCE AND TECHNOLOGY
한국과학기술원

Massachusetts Institute of Technology

PRINCETON UNIVERSITY

上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

Stockholm University

UNI FREIBURG

UNIVERSITEIT VAN AMSTERDAM

The University Of Sheffield.

UNIVERSITY *of* WASHINGTON

# Centre Involvement

THE UNIVERSITY of ADELAIDE

Australian Government
Department of Defence
Defence Science and Technology Group

Australian Government
ANSTO

Australian National University

THE UNIVERSITY OF MELBOURNE

SWINBURNE
SWINBURNE UNIVERSITY OF TECHNOLOGY

THE UNIVERSITY OF SYDNEY

UWA

THE UNIVERSITY OF WESTERN AUSTRALIA

INFN

KAIST
KOREA ADVANCED INSTITUTE OF SCIENCE AND TECHNOLOGY
1971

Massachusetts Institute of Technology

PRINCETON UNIVERSITY

上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

Stockholm University

UNI FREIBURG

UNIVERSITEIT VAN AMSTERDAM

The University Of Sheffield.

UNIVERSITY of WASHINGTON

# Centre Involvement

THE UNIVERSITY of ADELAIDE

Australian Government
Department of Defence
Defence Science and Technology Group

Australian Government
ANSTO

**Paul Altin**

Australian National University

THE UNIVERSITY OF MELBOURNE

SWINBURNE
SWINBURNE UNIVERSITY OF TECHNOLOGY

THE UNIVERSITY OF SYDNEY

**UWA**

THE UNIVERSITY OF WESTERN AUSTRALIA

INFN

KAIST
1971
KOREA ADVANCED INSTITUTE OF SCIENCE AND TECHNOLOGY
한국과학기술원

Massachusetts Institute of Technology

PRINCETON UNIVERSITY

上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

Stockholm University

UNI FREIBURG

UNIVERSITEIT VAN AMSTERDAM

The University Of Sheffield.

UNIVERSITY of WASHINGTON

# Centre Involvement

**Paul Altin**

THE UNIVERSITY of ADELAIDE

Australian Government
Department of Defence
Defence Science and Technology Group

Australian Government
ANSTO

Australian National University

THE UNIVERSITY OF MELBOURNE

SWIN BUR NE
SWINBURNE UNIVERSITY OF TECHNOLOGY

**UWA**

THE UNIVERSITY OF SYDNEY

THE UNIVERSITY OF WESTERN AUSTRALIA

INFN

KAIST
1971

Massachusetts Institute of Technology

PRINCETON UNIVERSITY

上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

Stockholm University

UNI FREIBURG

UNIVERSITEIT VAN AMSTERDAM

The University Of Sheffield.

UNIVERSITY of WASHINGTON

**ADMX Collaboration**

# Centre Involvement

THE UNIVERSITY of ADELAIDE

Australian Government
Department of Defence
Defence Science and Technology Group

Australian Government
ANSTO

**Paul Altin**

Australian National University

THE UNIVERSITY OF MELBOURNE

SWINBURNE UNIVERSITY OF TECHNOLOGY

**UWA**

THE UNIVERSITY OF SYDNEY

THE UNIVERSITY OF WESTERN AUSTRALIA

INFN

KOREA ADVANCED INSTITUTE OF SCIENCE AND TECHNOLOGY
KAIST
1971

Massachusetts Institute of Technology

PRINCETON UNIVERSITY

上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

Stockholm University

UNI FREIBURG

UNIVERSITEIT VAN AMSTERDAM

The University Of Sheffield.

**Ed Daw**

UNIVERSITY of WASHINGTON

**ADMX Collaboration**

# Centre Involvement

**Paul Altin**

THE UNIVERSITY *of* ADELAIDE

Australian Government
Department of Defence
Defence Science and
Technology Group

Australian Government
ANSTO

Australian
National
University

THE UNIVERSITY OF
MELBOURNE

SWIN
BUR
NE
SWINBURNE
UNIVERSITY OF
TECHNOLOGY

**UWA**

THE UNIVERSITY OF
SYDNEY

SEEK WISDOM
THE UNIVERSITY OF
WESTERN
AUSTRALIA

INFN

KOREA ADVANCED INSTITUTE OF SCIENCE AND TECHNOLOGY
KAIST
1971
한국과학기술원

Massachusetts
Institute of
Technology

PRINCETON
UNIVERSITY

上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

Stockholm
University

UNI
FREIBURG

UNIVERSITEIT
VAN AMSTERDAM

The
University
Of
Sheffield.

W
UNIVERSITY *of*
WASHINGTON

**Wilczek Group**

**Ed Daw**

**ADMX Collaboration**

# Centre Involvement

THE UNIVERSITY of ADELAIDE

Australian Government
Department of Defence
Defence Science and Technology Group

Australian Government
ANSTO

**Paul Altin**

Australian National University

THE UNIVERSITY OF MELBOURNE

SWINBURNE UNIVERSITY OF TECHNOLOGY

THE UNIVERSITY OF SYDNEY

**UWA**

THE UNIVERSITY OF WESTERN AUSTRALIA

INFN

KAIST 1971

Massachusetts Institute of Technology

PRINCETON UNIVERSITY

上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

Stockholm University

**Wilczek Group**

UNI FREIBURG

UNIVERSITEIT VAN AMSTERDAM

The University Of Sheffield.

**Ed Daw**

UNIVERSITY of WASHINGTON

**ADMX Collaboration**

- Room for more input from Centre Nodes, to join ORGAN Collaboration?

# Centre Involvement

**Paul Altin**

THE UNIVERSITY of ADELAIDE

Australian Government
Department of Defence
Defence Science and Technology Group

Australian Government
ANSTO

Australian National University

THE UNIVERSITY OF MELBOURNE

SWINBURNE UNIVERSITY OF TECHNOLOGY

**UWA**

THE UNIVERSITY OF SYDNEY

THE UNIVERSITY OF WESTERN AUSTRALIA

INFN

KAIST
1971

Massachusetts Institute of Technology

PRINCETON UNIVERSITY

上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

Stockholm University

UNI FREIBURG

UNIVERSITEIT VAN AMSTERDAM

The University Of Sheffield.

UNIVERSITY of WASHINGTON

**Wilczek Group**

**Ed Daw**

**ADMX Collaboration**

- Room for more input from Centre Nodes, to join ORGAN Collaboration?
- For example, application -> 3-year PDRA -> kickstart WISP program at Adelaide with UWA
Supported by the SA government in the form of $100,000/year?

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

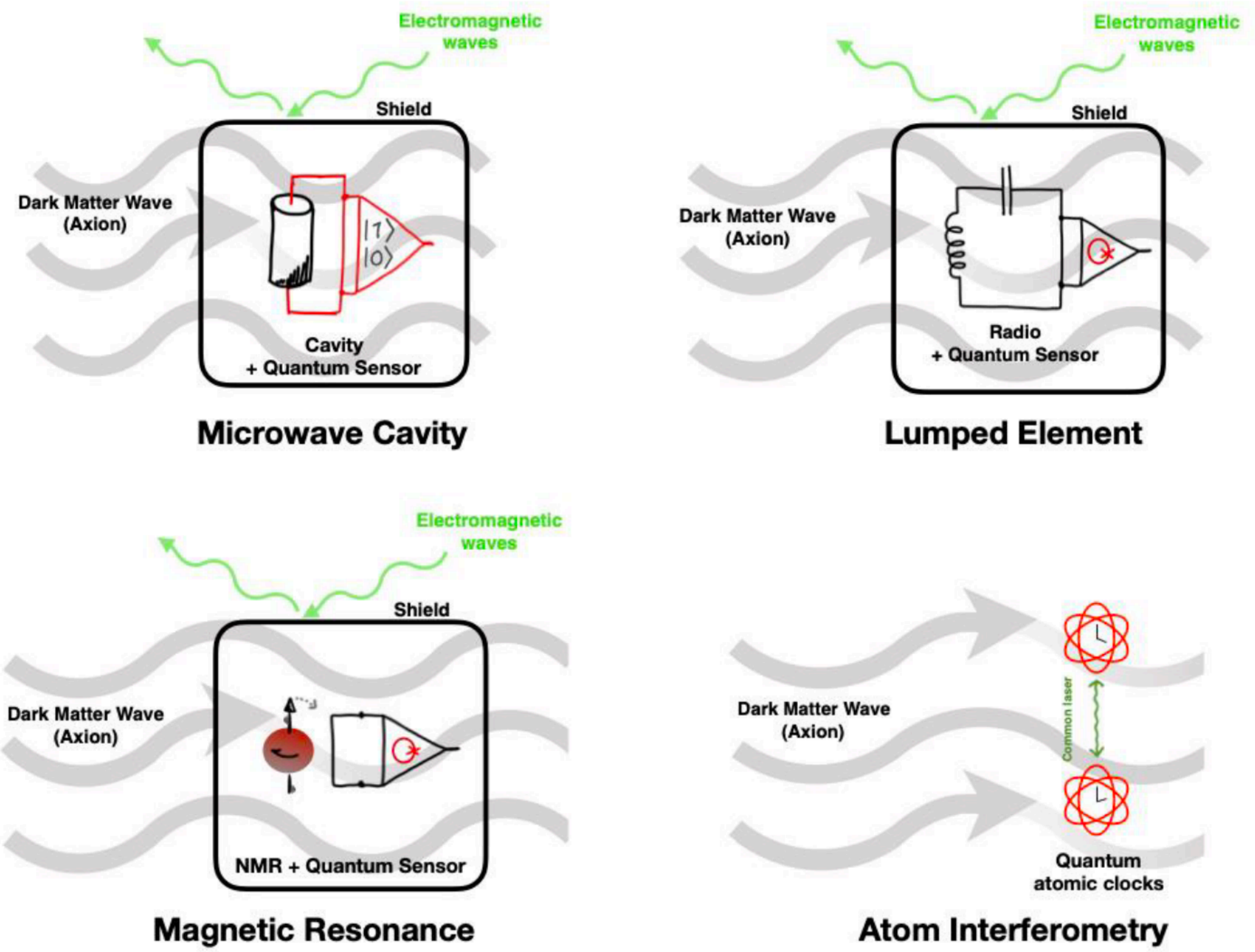
# QUANTUM TECHNOLOGIES AND DARK MATTER RESEARCH LAB

EQUS Australian Research Council Centre of Excellence for Engineered Quantum Systems

https://www.qdmlab.com/

# Generic Experiment

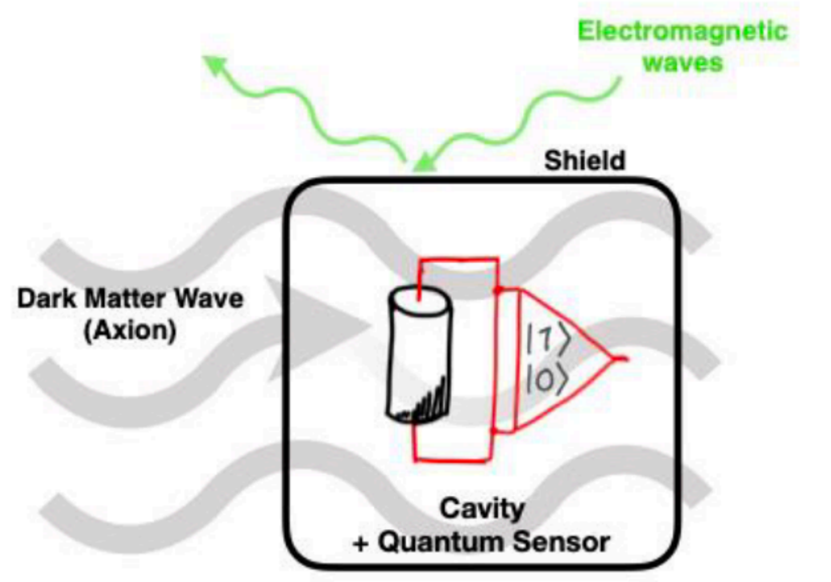
Wave like Dark Matter surrounds us



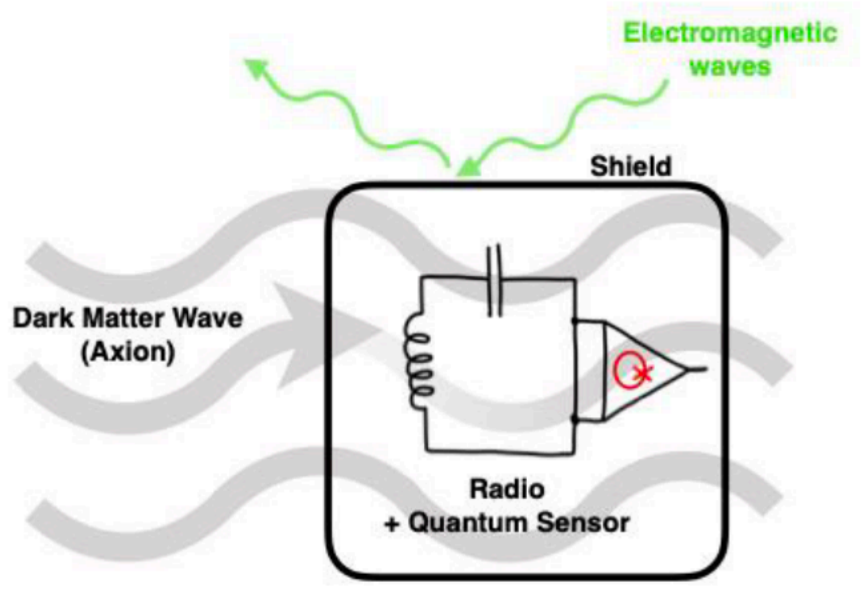
Design Physics Package:

# Generic Experiment

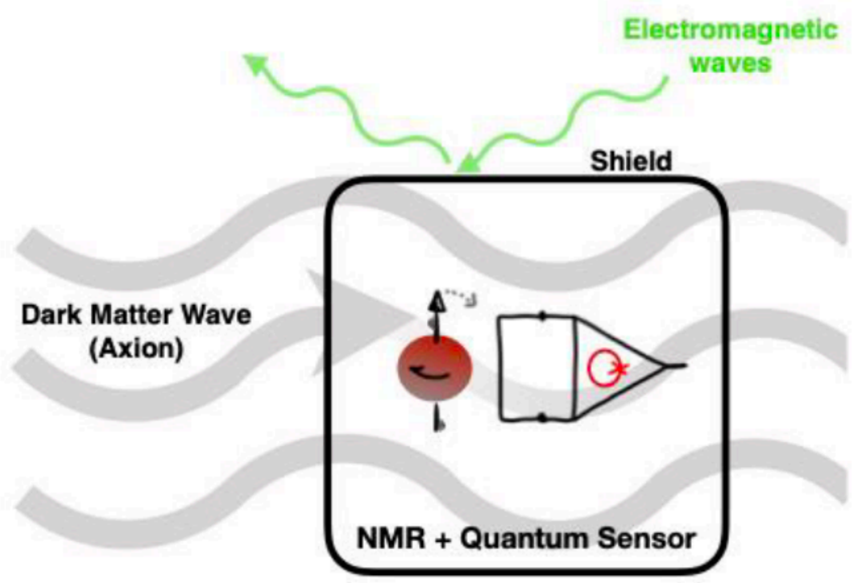
Wave like Dark Matter surrounds us



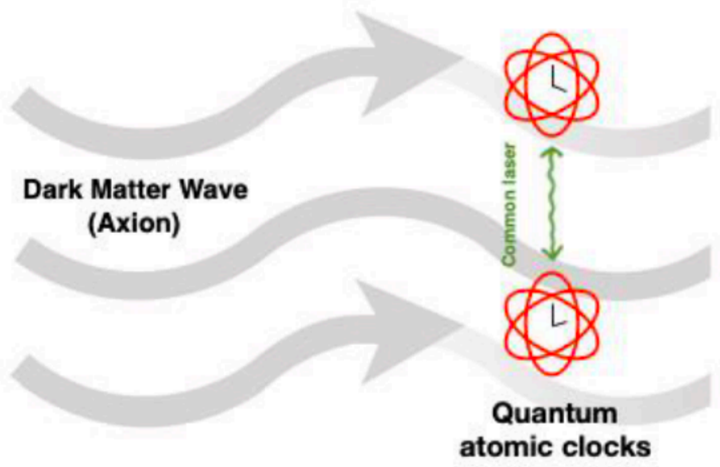
**Microwave Cavity**



**Lumped Element**



**Magnetic Resonance**



**Atom Interferometry**

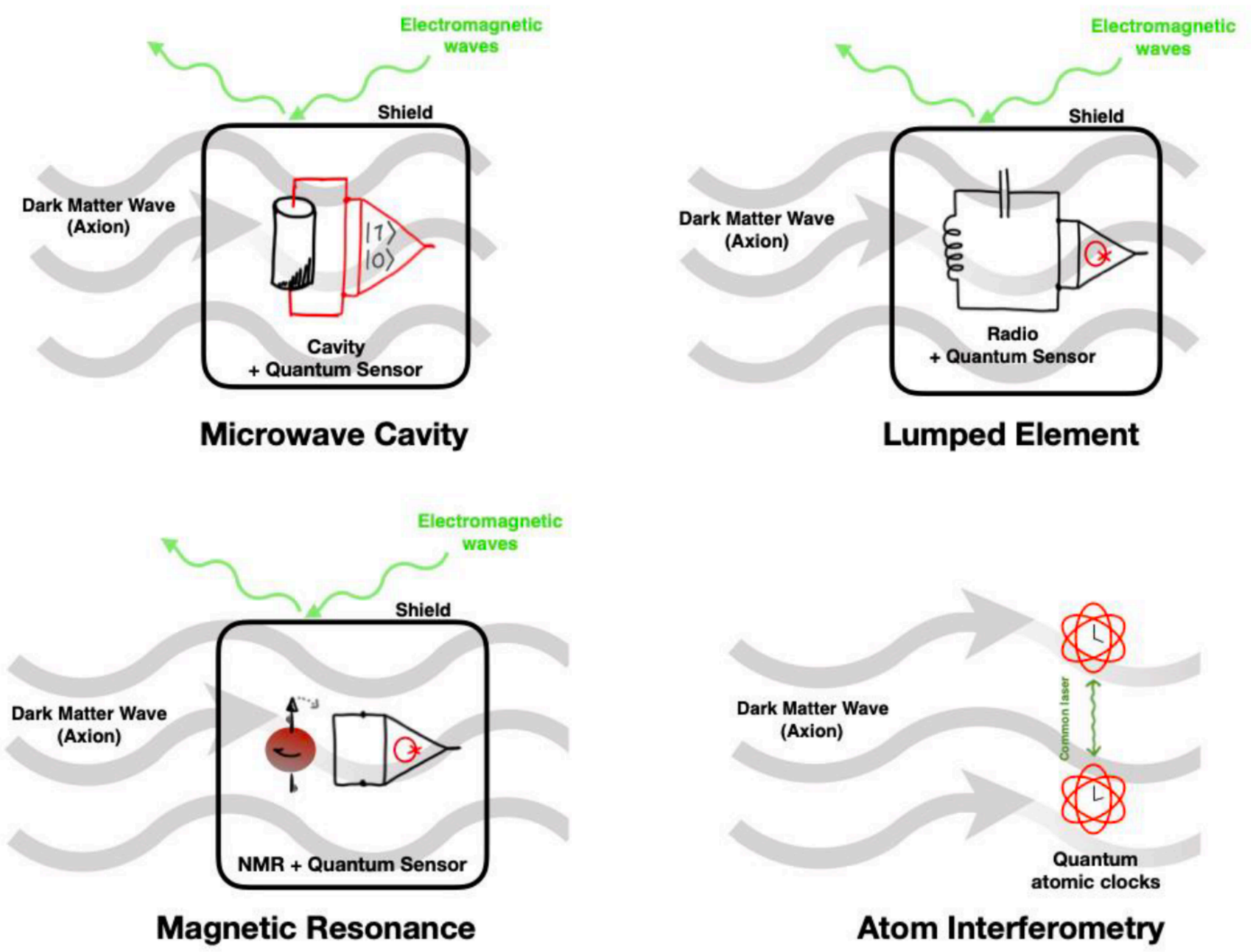
## Design Physics Package:

-> Sensitive to the type of Dark Matter of Interest

-> Axion, Dilaton etc.

# Generic Experiment

Wave like Dark Matter surrounds us



Design Physics Package:

-> Sensitive to the type of Dark Matter of Interest

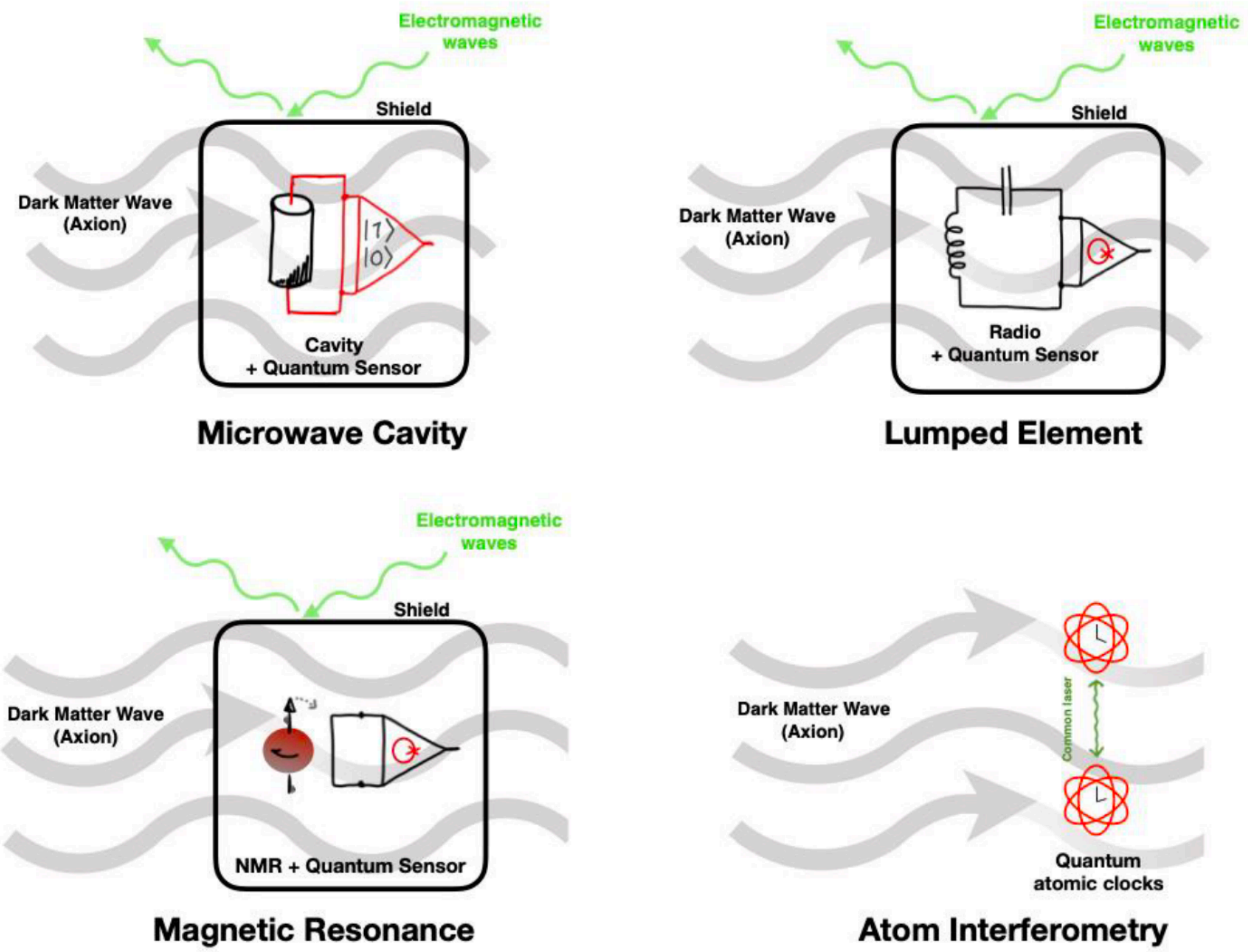
-> Axion, Dilaton etc.

-> Theory interacts with Experiment: How Dark Matter interacts with Standard Model Particles, Optimise Signal

# Generic Experiment

Wave like Dark Matter surrounds us

Design Readout with Lowest Noise Possible:
Optimize Noise



Microwave Cavity

Lumped Element

Magnetic Resonance

Atom Interferometry

Design Physics Package:

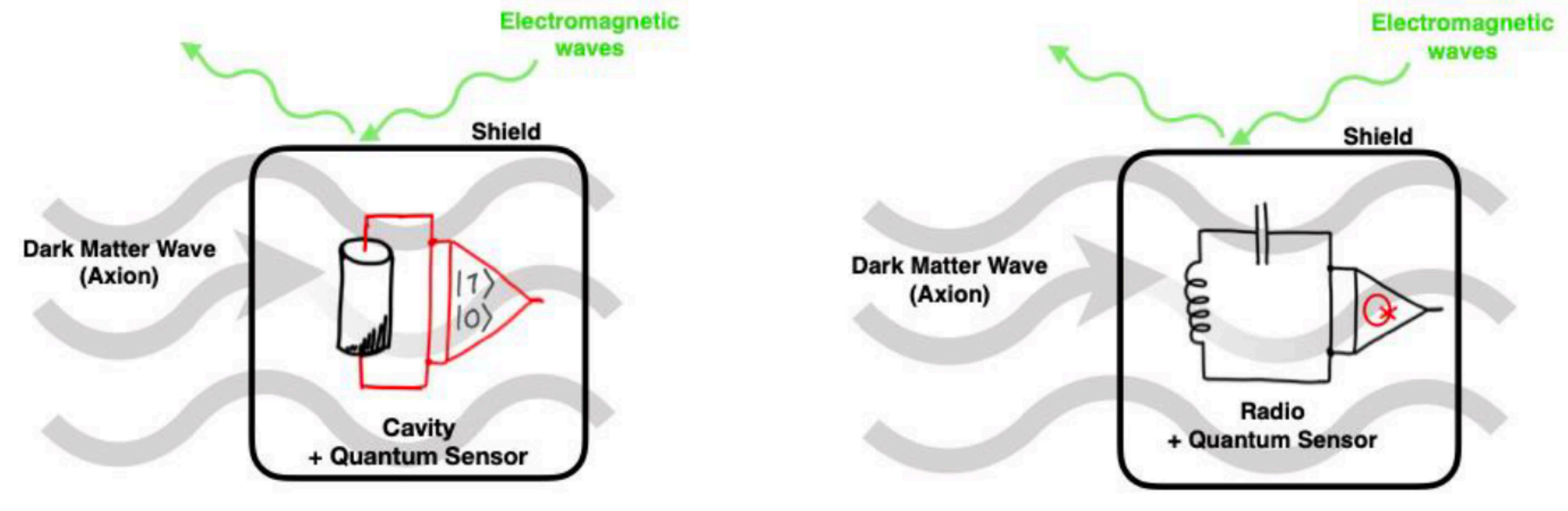
-> Sensitive to the type of Dark Matter of Interest

-> Axion, Dilaton etc.

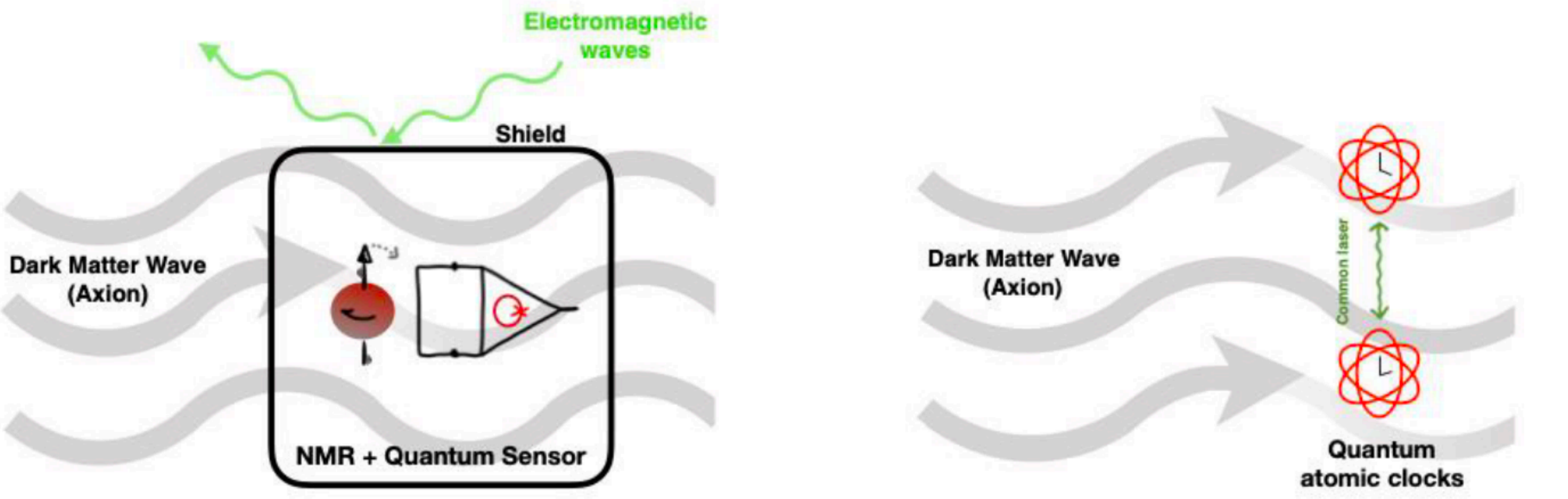
-> Theory interacts with Experiment: How Dark Matter interacts with Standard Model Particles, Optimise Signal

# Generic Experiment

Wave like Dark Matter surrounds us



**Microwave Cavity** **Lumped Element**



**Magnetic Resonance** **Atom Interferometry**

## Design Readout with Lowest Noise Possible: Optimize Noise

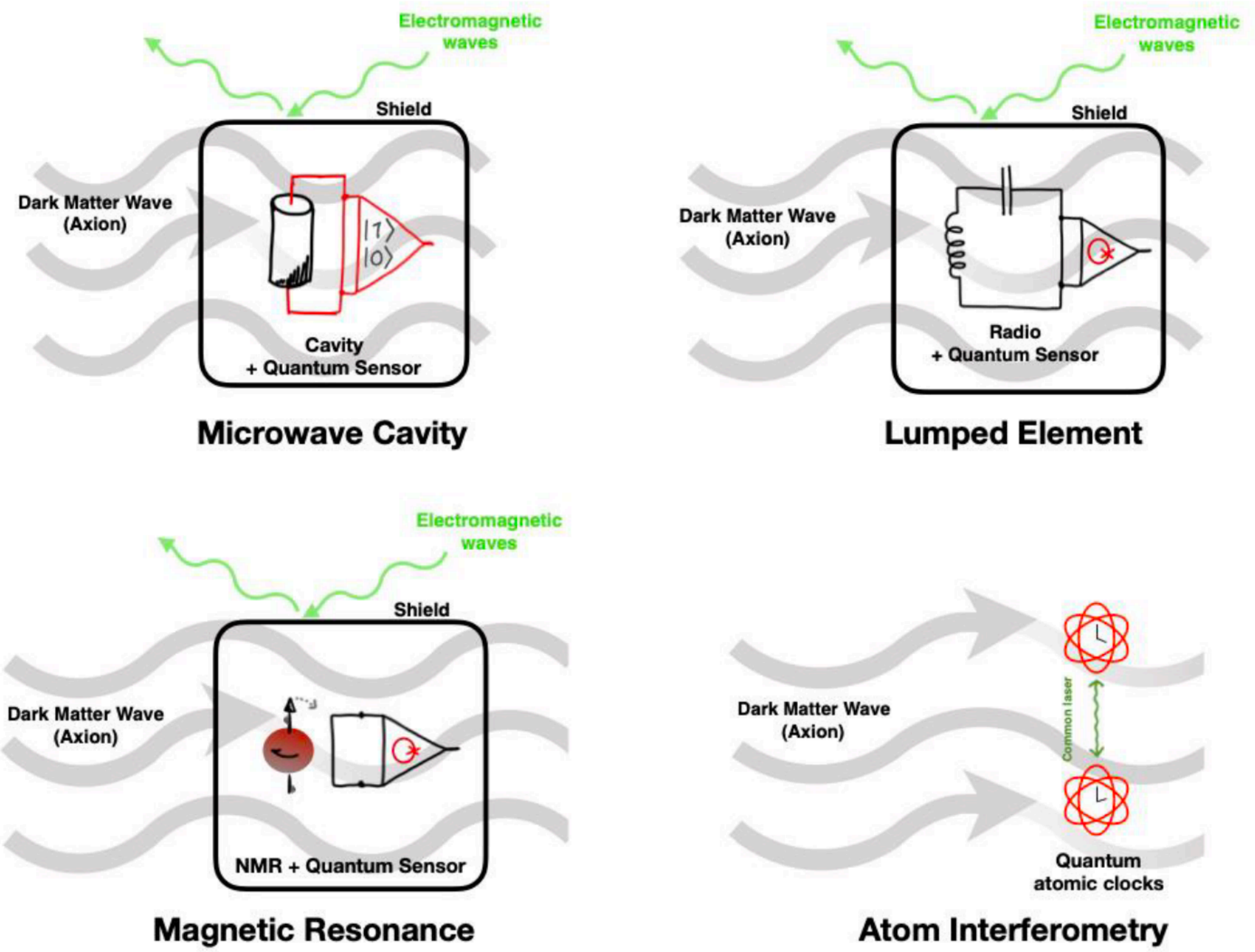
Precision Microwaves
Precision Optics
Precision RF
Precision Acoustics
Precision Spin ESR, NMR
Precision Hybrid Quantum Systems
Magnon/Photon
Phonon/Photon

## Design Physics Package:

-> Sensitive to the type of Dark Matter of Interest
-> Axion, Dilaton etc.
-> Theory interacts with Experiment: How Dark Matter interacts with Standard Model Particles, Optimise Signal

# Generic Experiment

Wave like Dark Matter surrounds us



## Design Readout with Lowest Noise Possible: Optimize Noise

Precision Microwaves
Precision Optics
Precision RF
Precision Acoustics
Precision Spin ESR, NMR
Precision Hybrid Quantum Systems
Magnon/Photon
Phonon/Photon

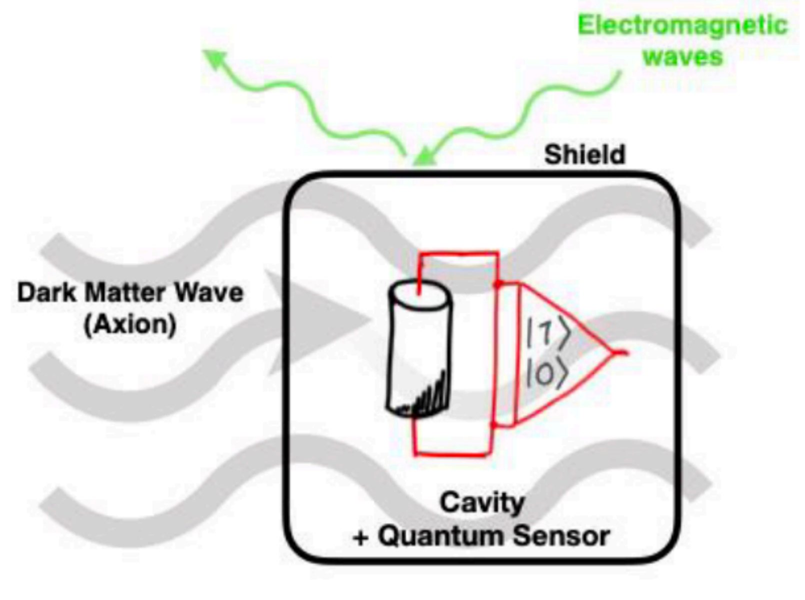
Low Noise Quantum Limit

## Design Physics Package:

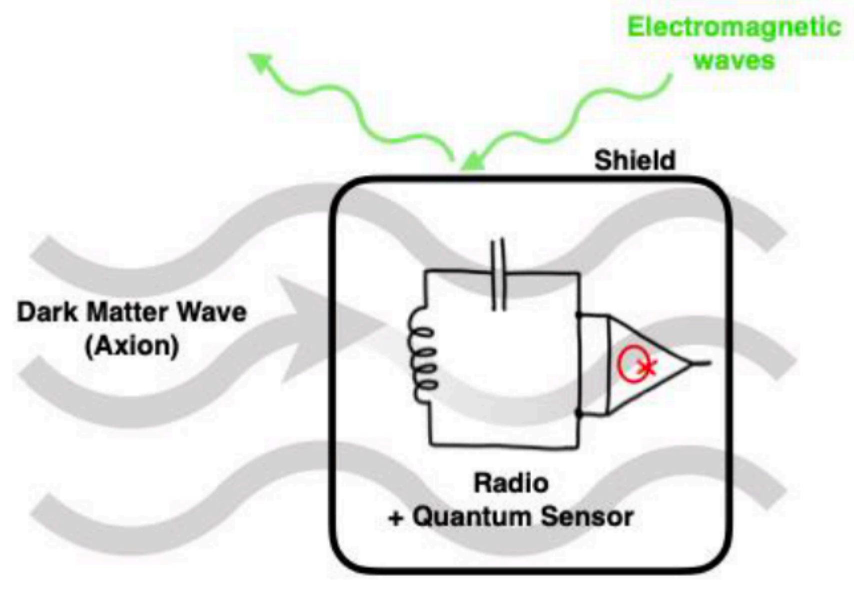
-> Sensitive to the type of Dark Matter of Interest
-> Axion, Dilaton etc.
-> Theory interacts with Experiment: How Dark Matter interacts with Standard Model Particles, Optimise Signal

# Generic Experiment

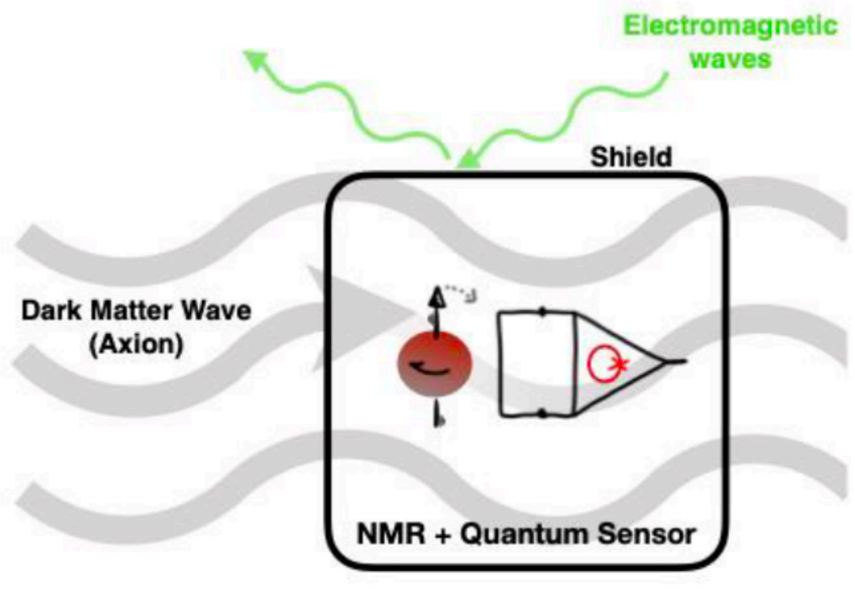
Wave like Dark Matter surrounds us



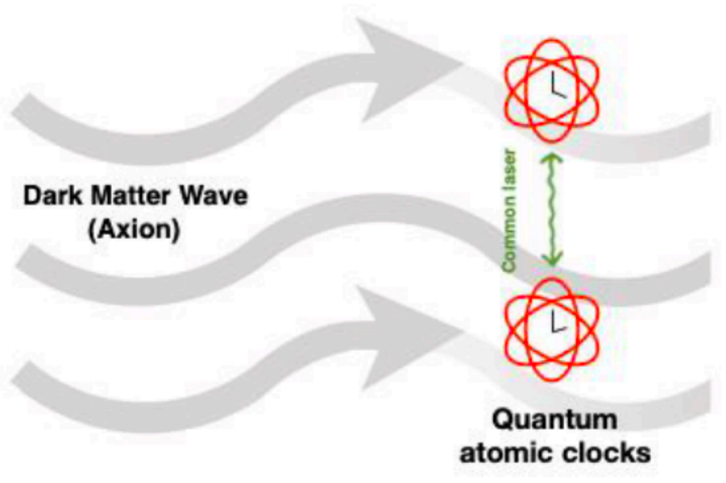
Microwave Cavity



Lumped Element



Magnetic Resonance



Atom Interferometry

## Design Readout with Lowest Noise Possible: Optimize Noise

Precision Microwaves
Precision Optics
Precision RF
Precision Acoustics
Precision Spin ESR, NMR
Precision Hybrid Quantum Systems
Magnon/Photon
Phonon/Photon

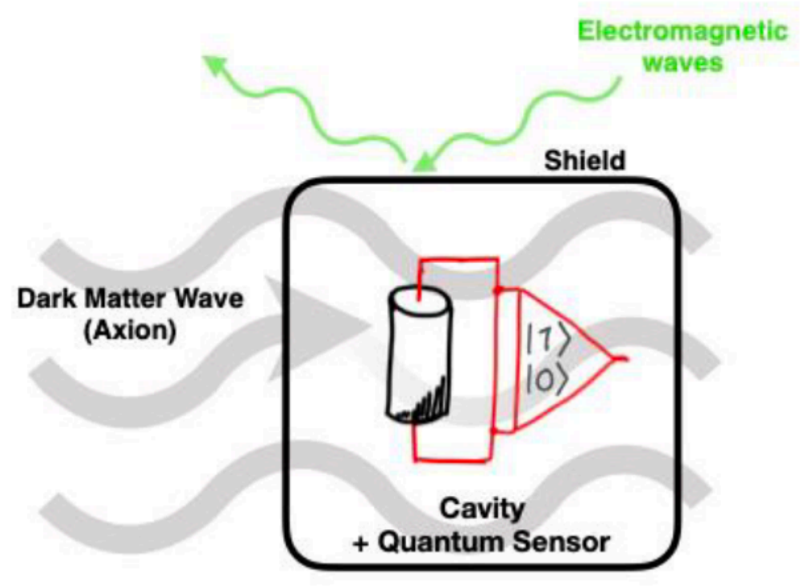
Low Noise Quantum Limit
Quantum metrology to surpass

## Design Physics Package:

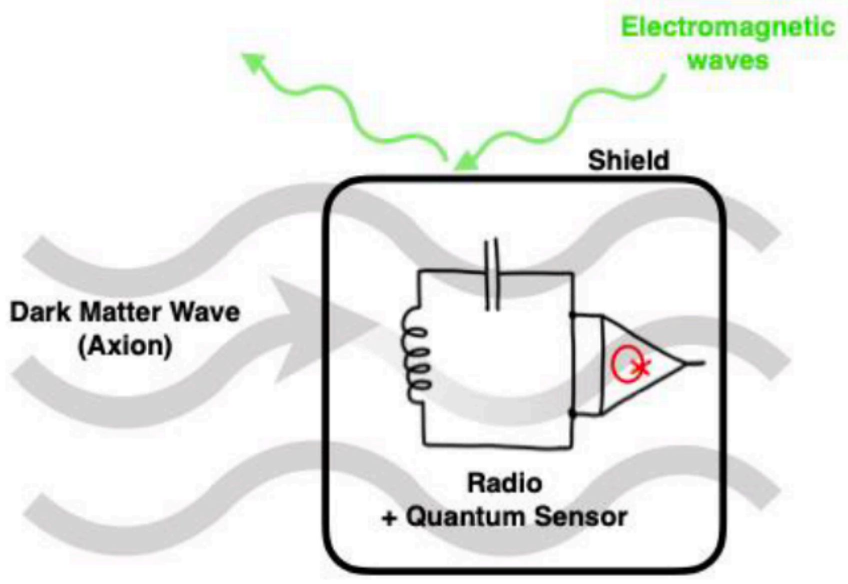
-> Sensitive to the type of Dark Matter of Interest
-> Axion, Dilaton etc.
-> Theory interacts with Experiment: How Dark Matter interacts with Standard Model Particles, Optimise Signal

# Generic Experiment

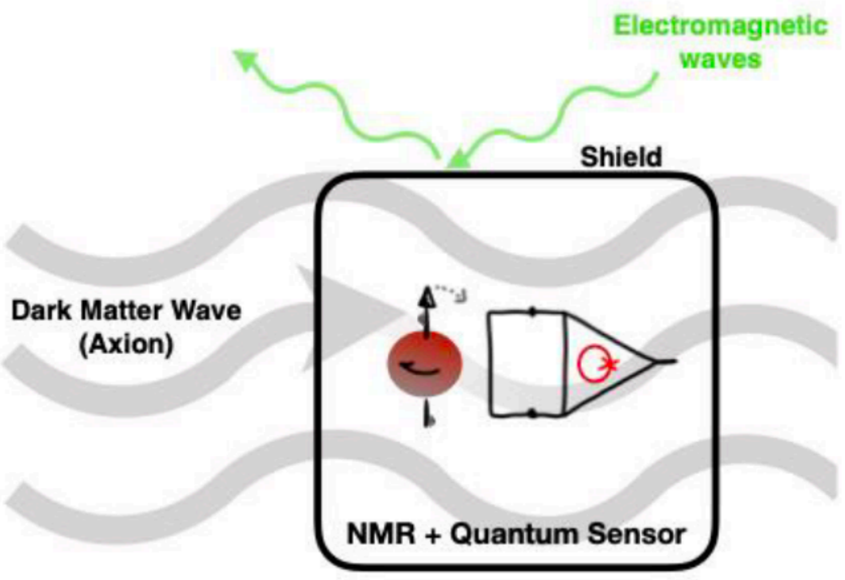
Wave like Dark Matter surrounds us



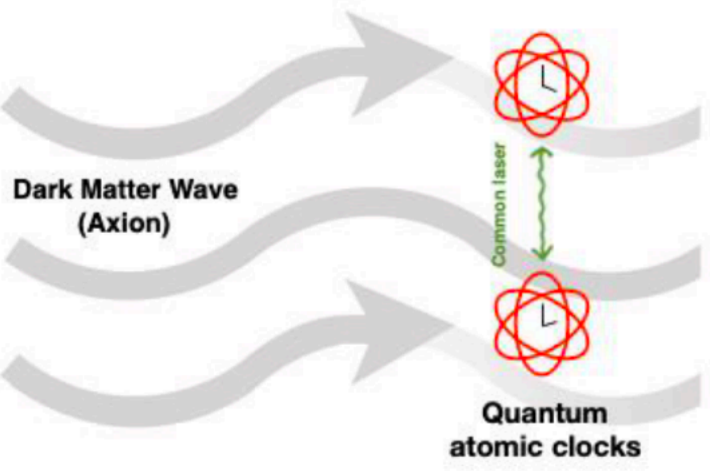
**Microwave Cavity**



**Lumped Element**



**Magnetic Resonance**



**Atom Interferometry**

## Design Physics Package:

-> Sensitive to the type of Dark Matter of Interest

-> Axion, Dilaton etc.

-> Theory interacts with Experiment: How Dark Matter interacts with Standard Model Particles, Optimise Signal

## Design Readout with Lowest Noise Possible: Optimize Noise

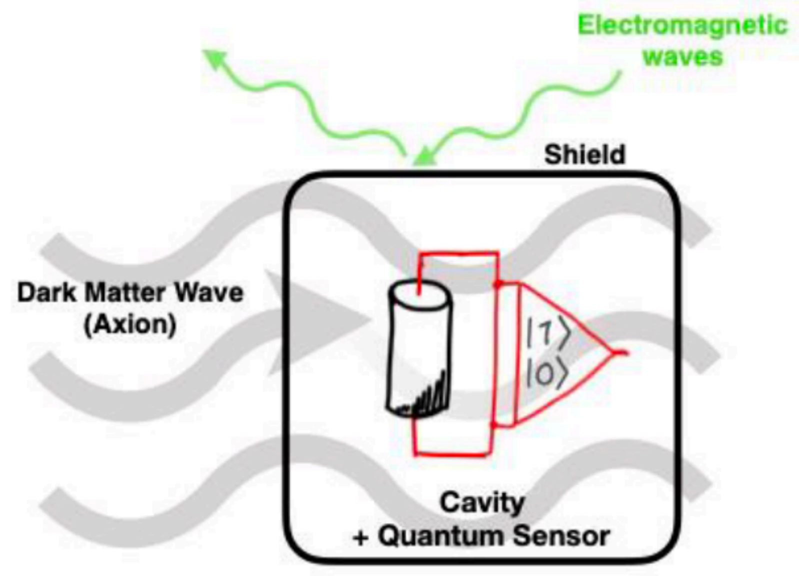
Precision Microwaves
Precision Optics
Precision RF
Precision Acoustics
Precision Spin ESR, NMR
Precision Hybrid Quantum Systems
Magnon/Photon
Phonon/Photon

Low Noise Quantum Limit
Quantum metrology to surpass

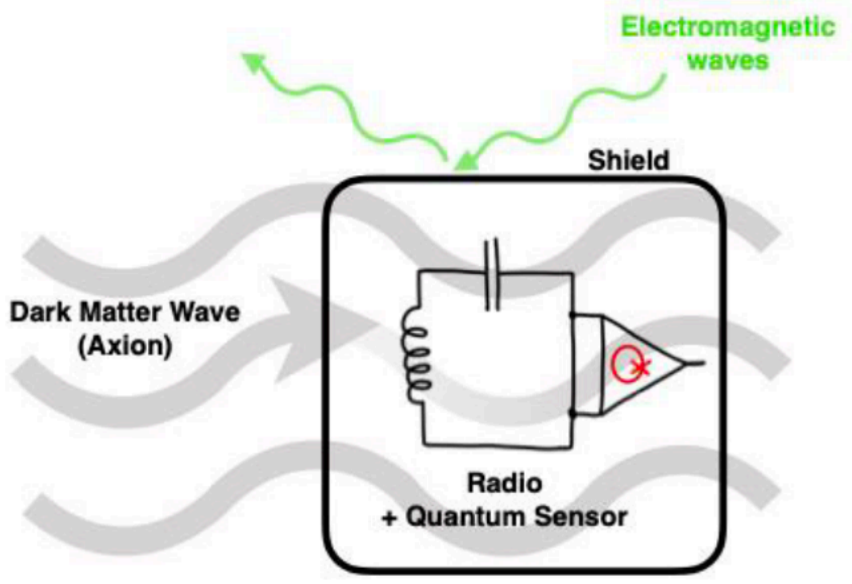
Eg. Photon Counter at Microwaves

# Generic Experiment

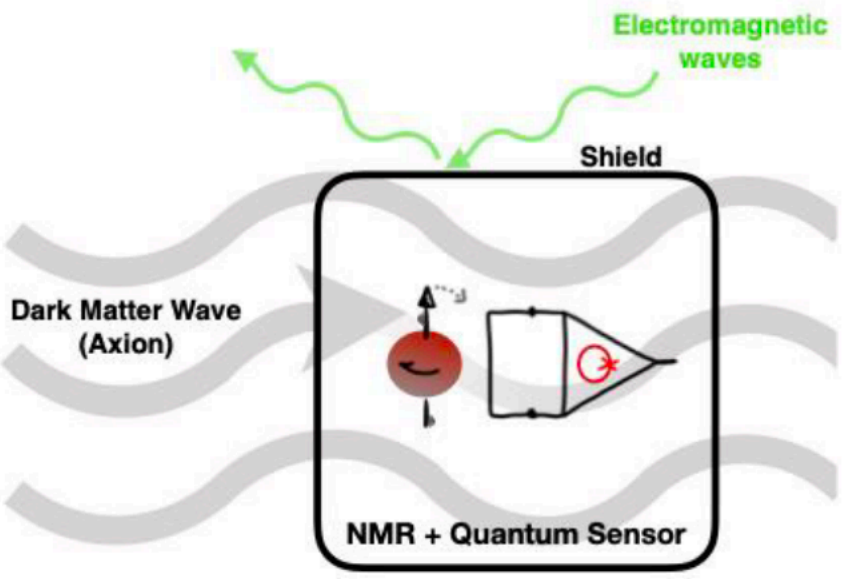
Wave like Dark Matter surrounds us



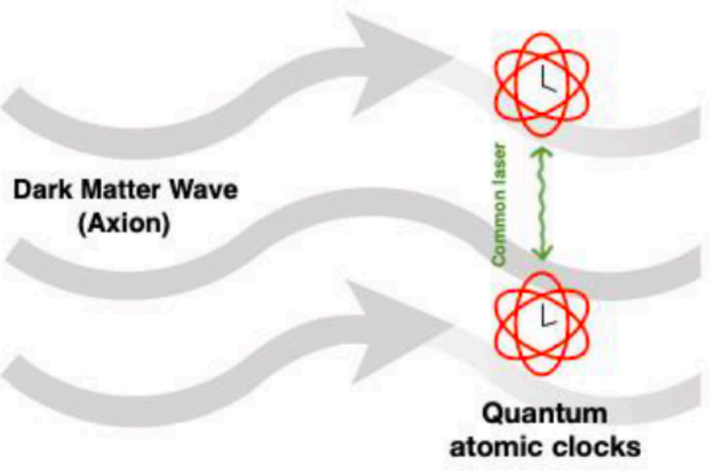
**Microwave Cavity**



**Lumped Element**



**Magnetic Resonance**



**Atom Interferometry**

Design Physics Package:
-> Sensitive to the type of Dark Matter of Interest
-> Axion, Dilaton etc.
-> Theory interacts with Experiment: How Dark Matter interacts with Standard Model Particles, Optimise Signal

## Design Readout with Lowest Noise Possible: Optimize Noise

Precision Microwaves
Precision Optics
Precision RF
Precision Acoustics
Precision Spin ESR, NMR
Precision Hybrid Quantum Systems
Magnon/Photon
Phonon/Photon

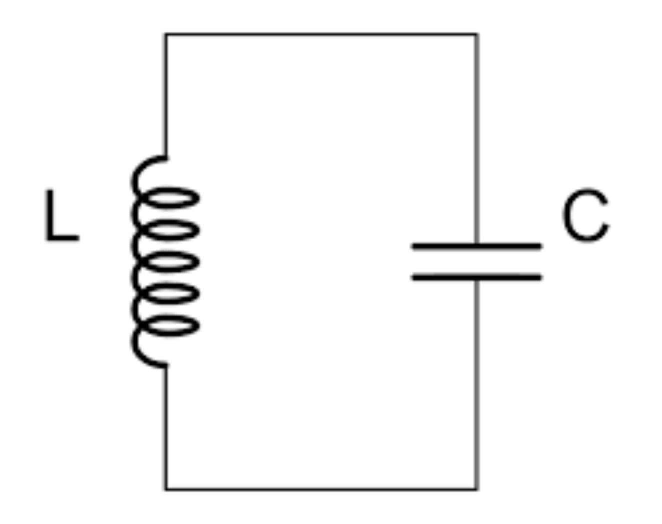
Low Noise Quantum Limit
Quantum metrology to surpass

Eg. Photon Counter at Microwaves

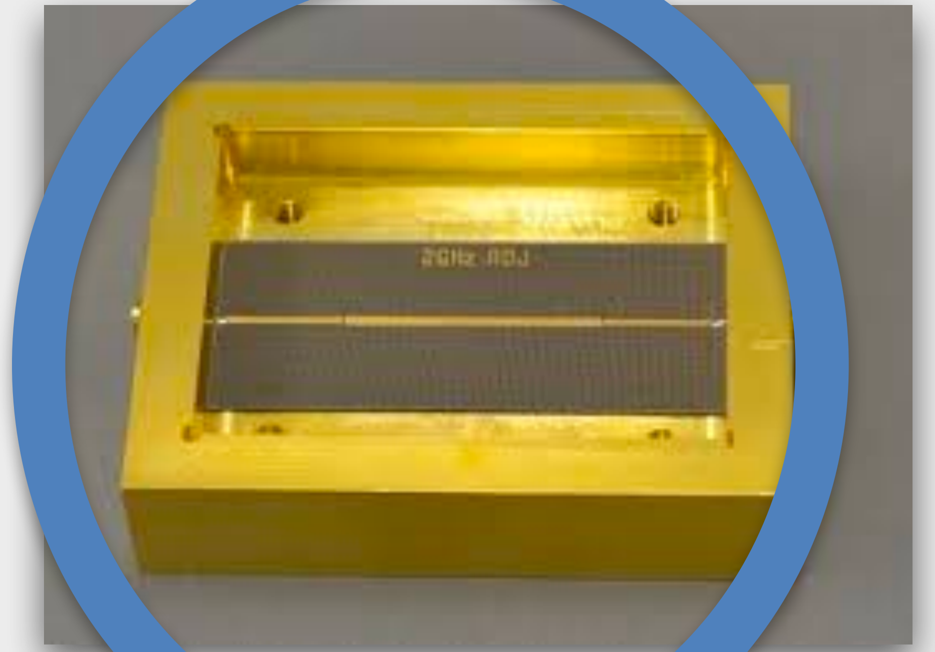
Signal To Noise Ratio (SNR) Capable of Detecting known Dark Matter Density?

# Resonator/Oscillator/Clock Zoo

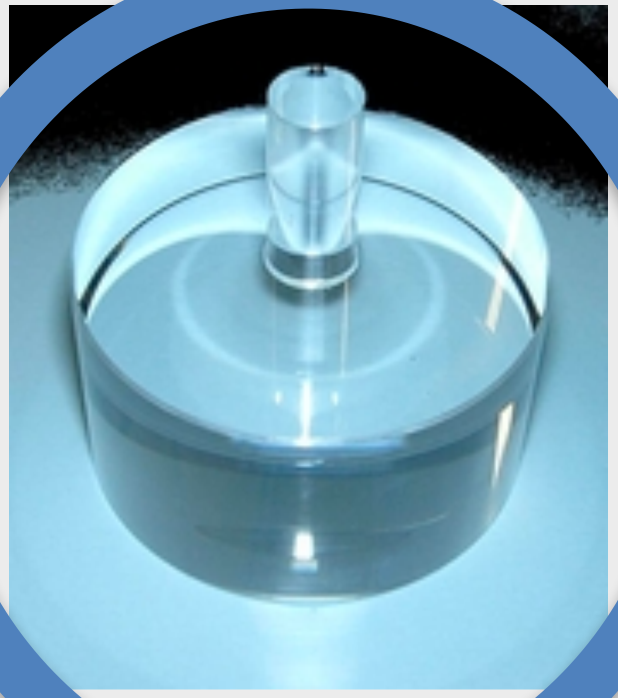
## Photons



LC circuits



Metallic Cavities



Dielectric Cavities

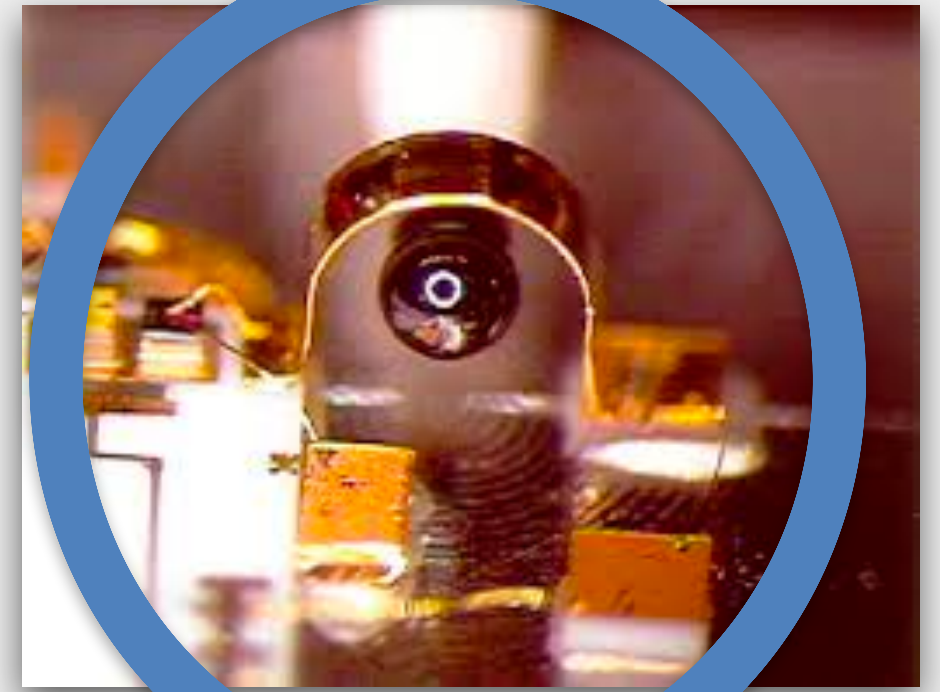
## Phonons

SAW

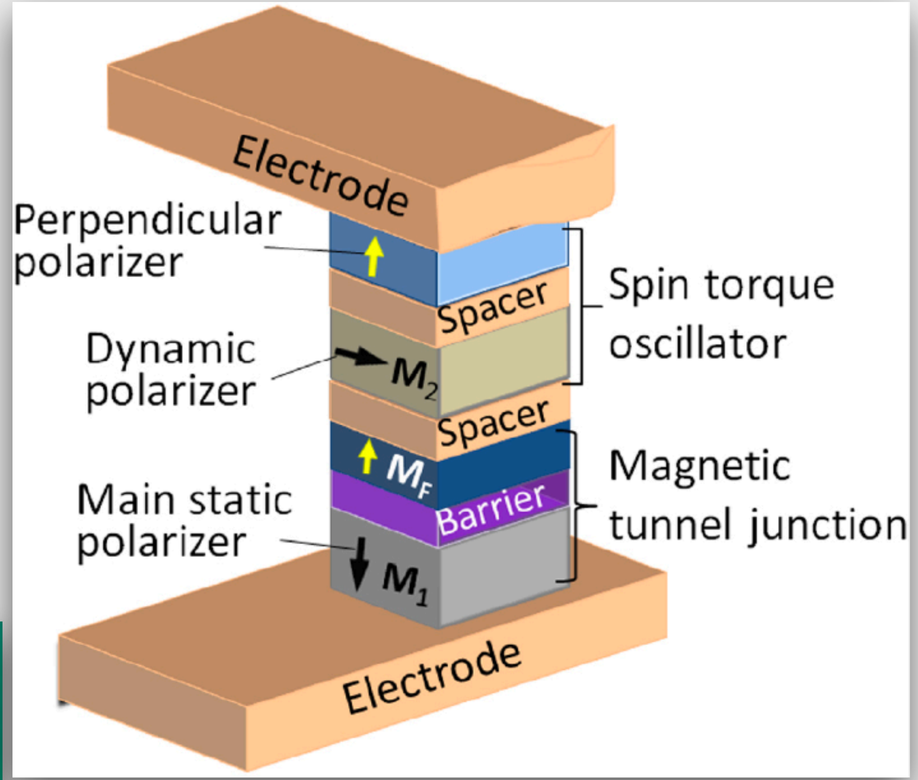
BAW

Structures

## Magnons



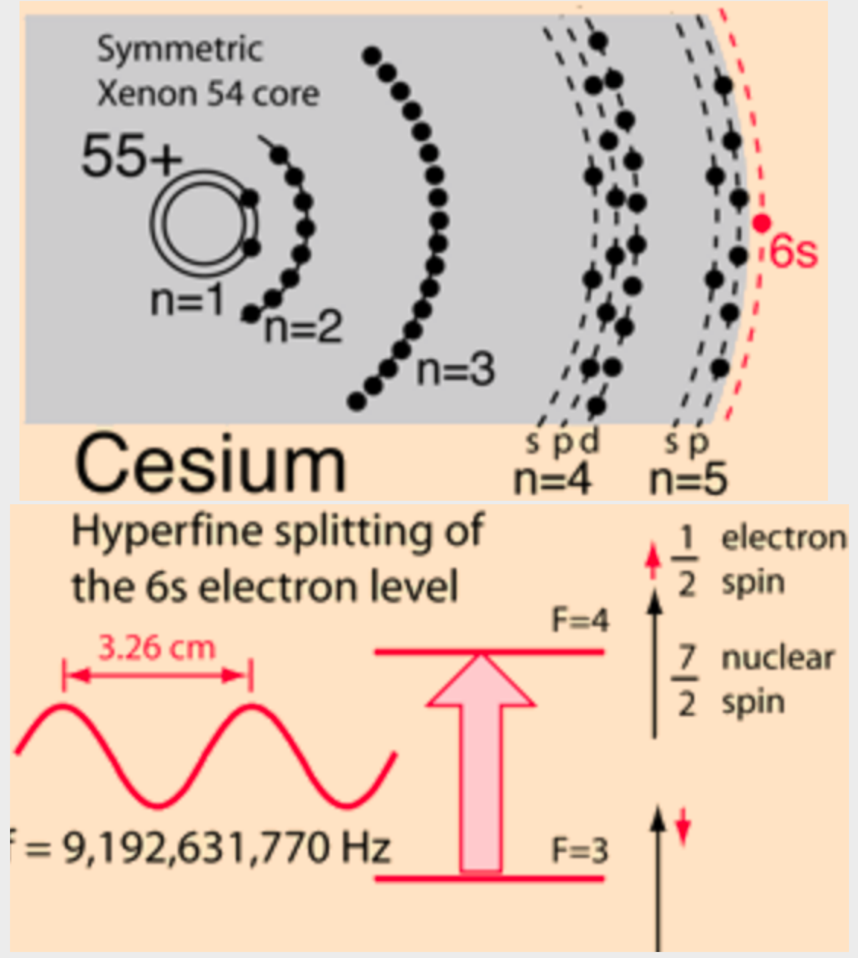
Bulk



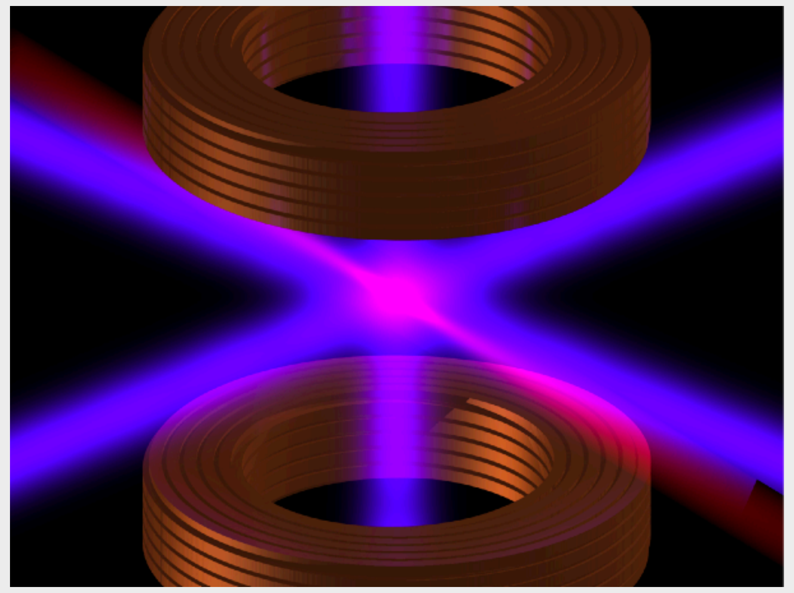
Spin-Torque

EQUS
Australian Research Council
Centre of Excellence for
Engineered Quantum Systems

## Atoms



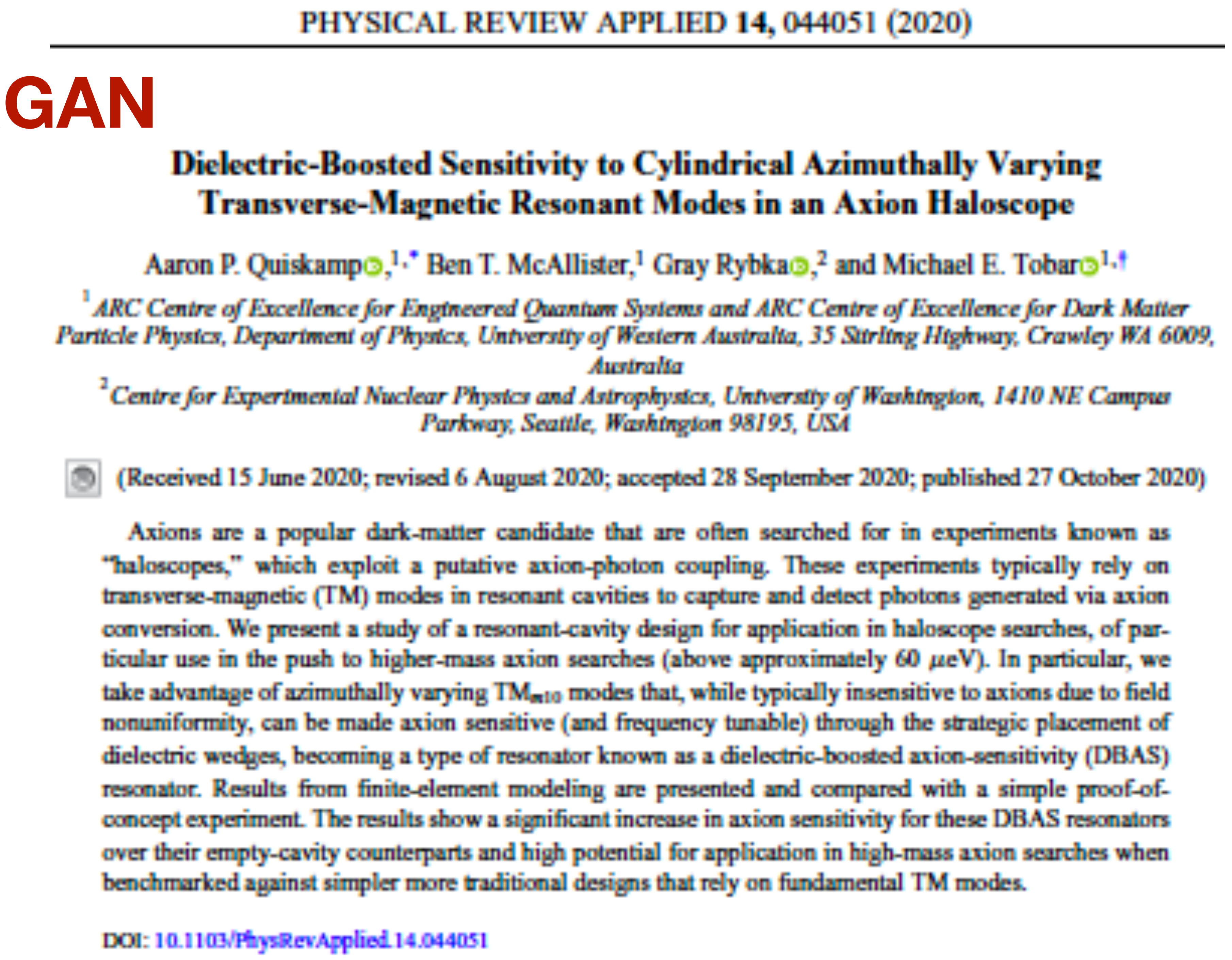
Hyperfine transitions



Electron transitions

Nuclear transitions

## (2) ORGAN



PHYSICAL REVIEW APPLIED **14,** 044051 (2020)

### Dielectric-Boosted Sensitivity to Cylindrical Azimuthally Varying Transverse-Magnetic Resonant Modes in an Axion Haloscope

Aaron P. Quiskamp,[1,*] Ben T. McAllister,[1] Gray Rybka,[2] and Michael E. Tobar[1,†]

[1] *ARC Centre of Excellence for Engineered Quantum Systems and ARC Centre of Excellence for Dark Matter Particle Physics, Department of Physics, University of Western Australia, 35 Stirling Highway, Crawley WA 6009, Australia*

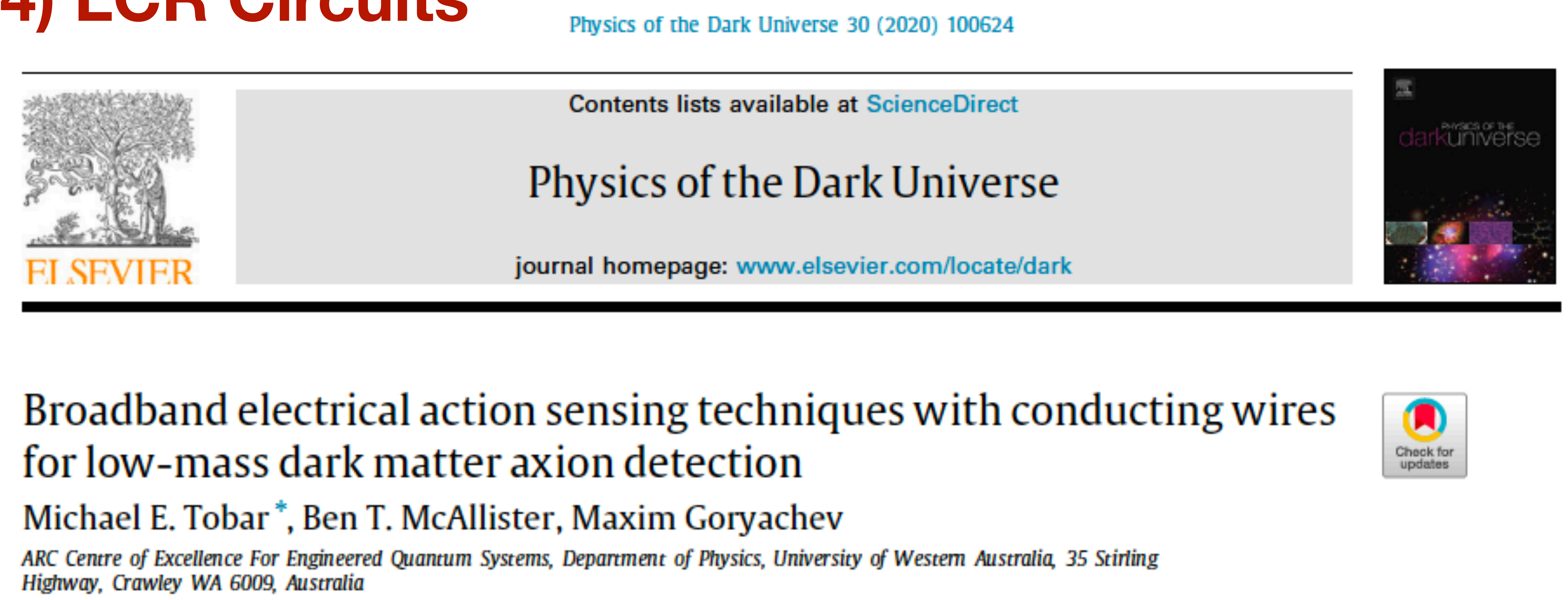
[2] *Centre for Experimental Nuclear Physics and Astrophysics, University of Washington, 1410 NE Campus Parkway, Seattle, Washington 98195, USA*

(Received 15 June 2020; revised 6 August 2020; accepted 28 September 2020; published 27 October 2020)

Axions are a popular dark-matter candidate that are often searched for in experiments known as "haloscopes," which exploit a putative axion-photon coupling. These experiments typically rely on transverse-magnetic (TM) modes in resonant cavities to capture and detect photons generated via axion conversion. We present a study of a resonant-cavity design for application in haloscope searches, of particular use in the push to higher-mass axion searches (above approximately 60 $\mu$eV). In particular, we take advantage of azimuthally varying $\text{TM}_{m10}$ modes that, while typically insensitive to axions due to field nonuniformity, can be made axion sensitive (and frequency tunable) through the strategic placement of dielectric wedges, becoming a type of resonator known as a dielectric-boosted axion-sensitivity (DBAS) resonator. Results from finite-element modeling are presented and compared with a simple proof-of-concept experiment. The results show a significant increase in axion sensitivity for these DBAS resonators over their empty-cavity counterparts and high potential for application in high-mass axion searches when benchmarked against simpler more traditional designs that rely on fundamental TM modes.

DOI: 10.1103/PhysRevApplied.14.044051

## (4) LCR Circuits



Physics of the Dark Universe 30 (2020) 100624

Contents lists available at ScienceDirect

Physics of the Dark Universe

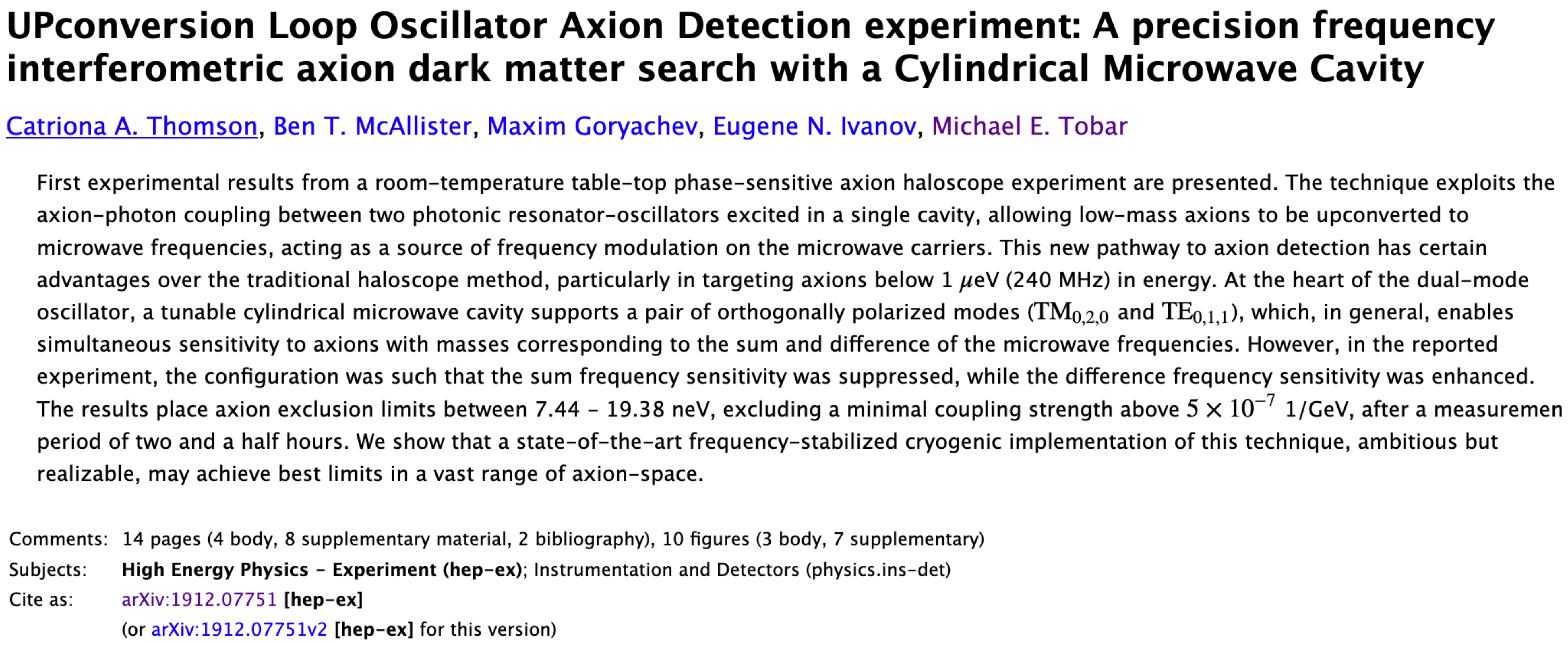
journal homepage: www.elsevier.com/locate/dark

### Broadband electrical action sensing techniques with conducting wires for low-mass dark matter axion detection

Michael E. Tobar *, Ben T. McAllister, Maxim Goryachev

*ARC Centre of Excellence For Engineered Quantum Systems, Department of Physics, University of Western Australia, 35 Stirling Highway, Crawley WA 6009, Australia*

## (5) UPLOAD



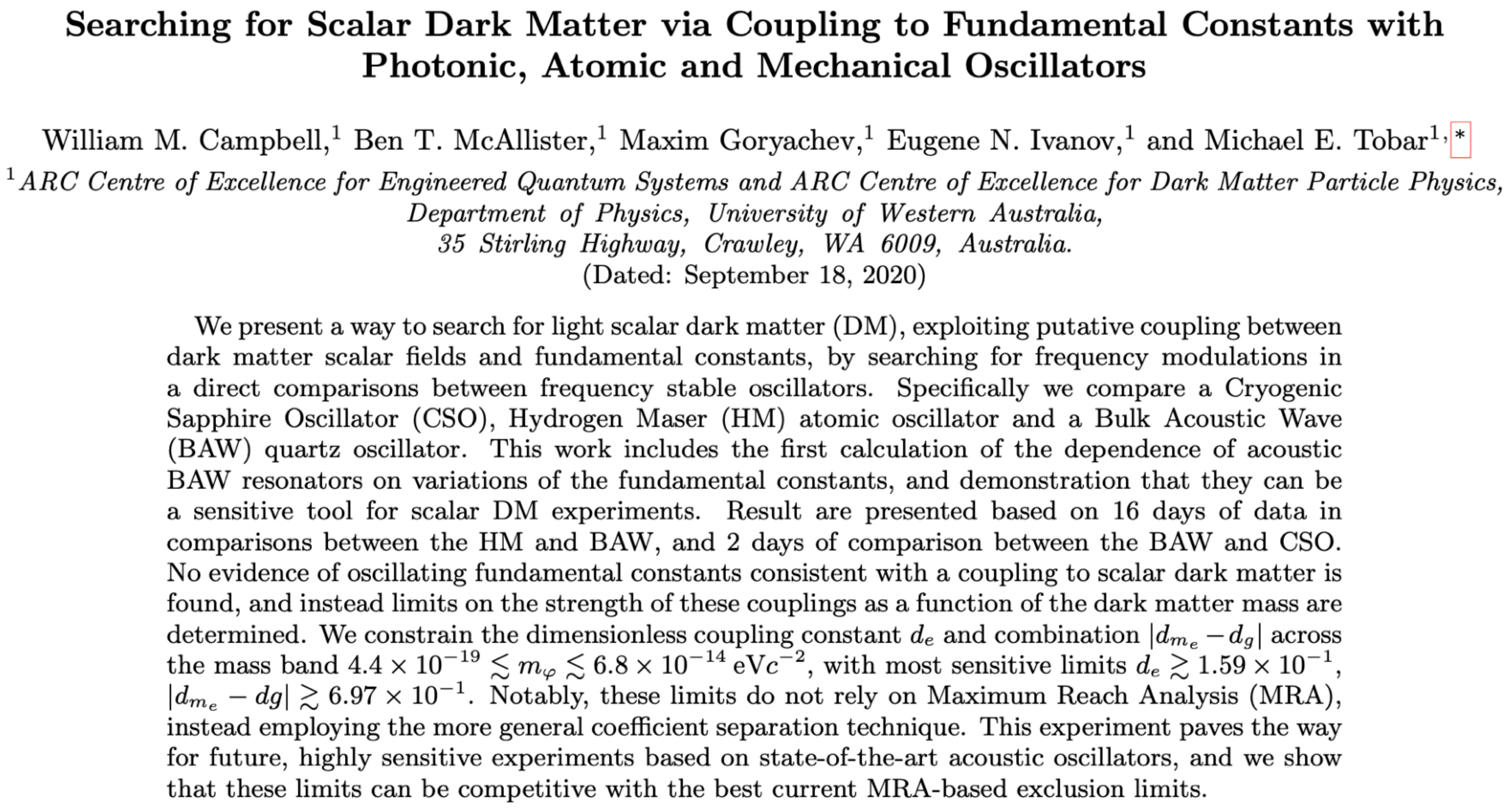
### UPconversion Loop Oscillator Axion Detection experiment: A precision frequency interferometric axion dark matter search with a Cylindrical Microwave Cavity

Catriona A. Thomson, Ben T. McAllister, Maxim Goryachev, Eugene N. Ivanov, Michael E. Tobar

First experimental results from a room-temperature table-top phase-sensitive axion haloscope experiment are presented. The technique exploits the axion-photon coupling between two photonic resonator-oscillators excited in a single cavity, allowing low-mass axions to be upconverted to microwave frequencies, acting as a source of frequency modulation on the microwave carriers. This new pathway to axion detection has certain advantages over the traditional haloscope method, particularly in targeting axions below 1 $\mu$eV (240 MHz) in energy. At the heart of the dual-mode oscillator, a tunable cylindrical microwave cavity supports a pair of orthogonally polarized modes ($\text{TM}_{0,2,0}$ and $\text{TE}_{0,1,1}$), which, in general, enables simultaneous sensitivity to axions with masses corresponding to the sum and difference of the microwave frequencies. However, in the reported experiment, the configuration was such that the sum frequency sensitivity was suppressed, while the difference frequency sensitivity was enhanced. The results place axion exclusion limits between 7.44 – 19.38 neV, excluding a minimal coupling strength above $5 \times 10^{-7}$ 1/GeV, after a measuremen period of two and a half hours. We show that a state-of-the-art frequency-stabilized cryogenic implementation of this technique, ambitious but realizable, may achieve best limits in a vast range of axion-space.

Comments: 14 pages (4 body, 8 supplementary material, 2 bibliography), 10 figures (3 body, 7 supplementary)
Subjects: **High Energy Physics - Experiment (hep-ex)**; Instrumentation and Detectors (physics.ins-det)
Cite as: arXiv:1912.07751 **[hep-ex]**
(or arXiv:1912.07751v2 **[hep-ex]** for this version)

## (6) SCALAR DARK MATTRR



### Searching for Scalar Dark Matter via Coupling to Fundamental Constants with Photonic, Atomic and Mechanical Oscillators

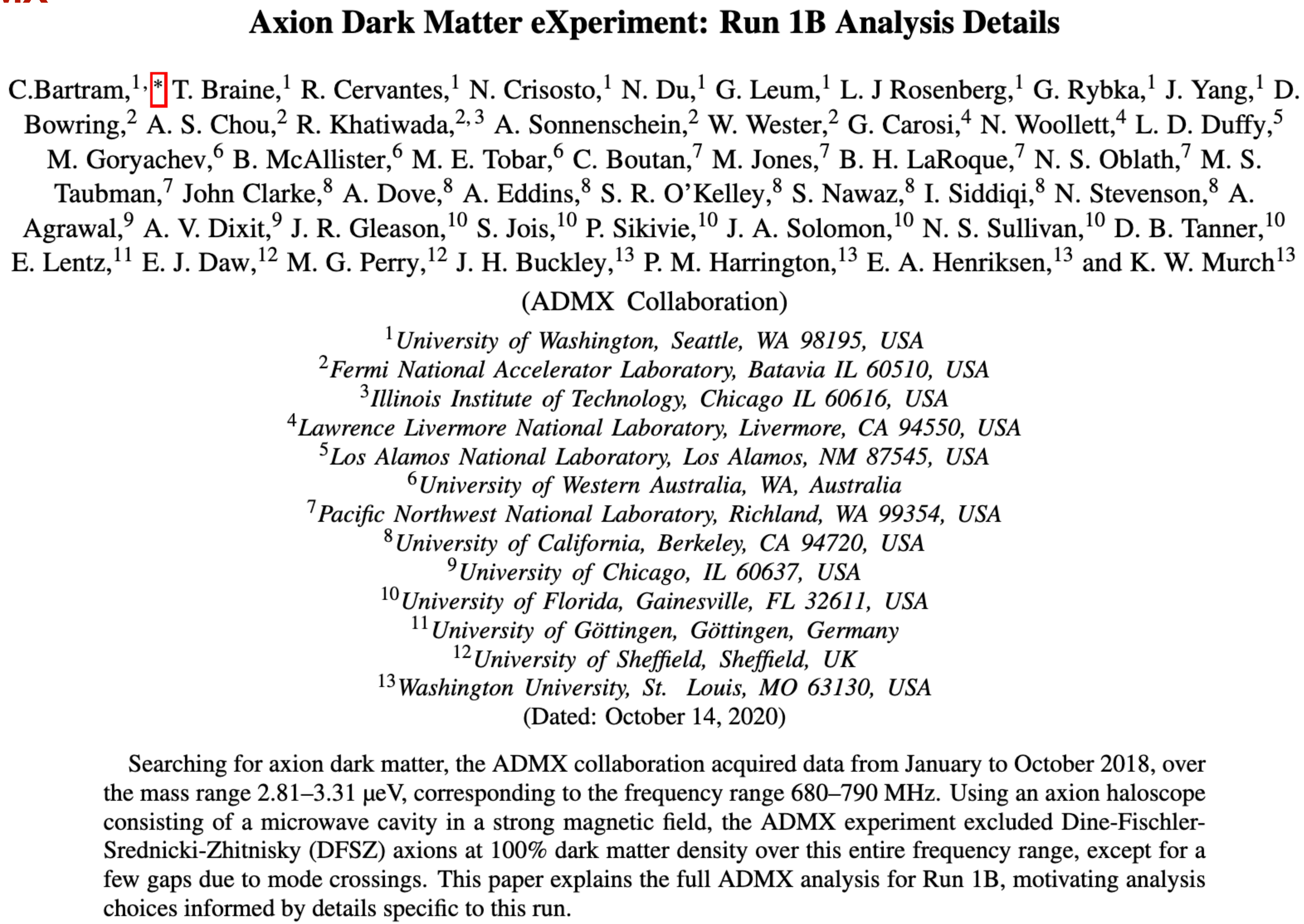
William M. Campbell,[1] Ben T. McAllister,[1] Maxim Goryachev,[1] Eugene N. Ivanov,[1] and Michael E. Tobar[1,*]

[1] *ARC Centre of Excellence for Engineered Quantum Systems and ARC Centre of Excellence for Dark Matter Particle Physics, Department of Physics, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia.*

(Dated: September 18, 2020)

We present a way to search for light scalar dark matter (DM), exploiting putative coupling between dark matter scalar fields and fundamental constants, by searching for frequency modulations in a direct comparisons between frequency stable oscillators. Specifically we compare a Cryogenic Sapphire Oscillator (CSO), Hydrogen Maser (HM) atomic oscillator and a Bulk Acoustic Wave (BAW) quartz oscillator. This work includes the first calculation of the dependence of acoustic BAW resonators on variations of the fundamental constants, and demonstration that they can be a sensitive tool for scalar DM experiments. Result are presented based on 16 days of data in comparisons between the HM and BAW, and 2 days of comparison between the BAW and CSO. No evidence of oscillating fundamental constants consistent with a coupling to scalar dark matter is found, and instead limits on the strength of these couplings as a function of the dark matter mass are determined. We constrain the dimensionless coupling constant $d_e$ and combination $|d_{m_e} - d_g|$ across the mass band $4.4 \times 10^{-19} \lesssim m_\varphi \lesssim 6.8 \times 10^{-14}\,\text{eVc}^{-2}$, with most sensitive limits $d_e \gtrsim 1.59 \times 10^{-1}$, $|d_{m_e} - dg| \gtrsim 6.97 \times 10^{-1}$. Notably, these limits do not rely on Maximum Reach Analysis (MRA), instead employing the more general coefficient separation technique. This experiment paves the way for future, highly sensitive experiments based on state-of-the-art acoustic oscillators, and we show that these limits can be competitive with the best current MRA-based exclusion limits.

# (1) ADMX



## Axion Dark Matter eXperiment: Run 1B Analysis Details

C.Bartram,[1,*] T. Braine,[1] R. Cervantes,[1] N. Crisosto,[1] N. Du,[1] G. Leum,[1] L. J Rosenberg,[1] G. Rybka,[1] J. Yang,[1] D. Bowring,[2] A. S. Chou,[2] R. Khatiwada,[2,3] A. Sonnenschein,[2] W. Wester,[2] G. Carosi,[4] N. Woollett,[4] L. D. Duffy,[5] M. Goryachev,[6] B. McAllister,[6] M. E. Tobar,[6] C. Boutan,[7] M. Jones,[7] B. H. LaRoque,[7] N. S. Oblath,[7] M. S. Taubman,[7] John Clarke,[8] A. Dove,[8] A. Eddins,[8] S. R. O'Kelley,[8] S. Nawaz,[8] I. Siddiqi,[8] N. Stevenson,[8] A. Agrawal,[9] A. V. Dixit,[9] J. R. Gleason,[10] S. Jois,[10] P. Sikivie,[10] J. A. Solomon,[10] N. S. Sullivan,[10] D. B. Tanner,[10] E. Lentz,[11] E. J. Daw,[12] M. G. Perry,[12] J. H. Buckley,[13] P. M. Harrington,[13] E. A. Henriksen,[13] and K. W. Murch[13]

(ADMX Collaboration)

[1]*University of Washington, Seattle, WA 98195, USA*
[2]*Fermi National Accelerator Laboratory, Batavia IL 60510, USA*
[3]*Illinois Institute of Technology, Chicago IL 60616, USA*
[4]*Lawrence Livermore National Laboratory, Livermore, CA 94550, USA*
[5]*Los Alamos National Laboratory, Los Alamos, NM 87545, USA*
[6]*University of Western Australia, WA, Australia*
[7]*Pacific Northwest National Laboratory, Richland, WA 99354, USA*
[8]*University of California, Berkeley, CA 94720, USA*
[9]*University of Chicago, IL 60637, USA*
[10]*University of Florida, Gainesville, FL 32611, USA*
[11]*University of Göttingen, Göttingen, Germany*
[12]*University of Sheffield, Sheffield, UK*
[13]*Washington University, St. Louis, MO 63130, USA*

(Dated: October 14, 2020)

Searching for axion dark matter, the ADMX collaboration acquired data from January to October 2018, over the mass range 2.81–3.31 µeV, corresponding to the frequency range 680–790 MHz. Using an axion haloscope consisting of a microwave cavity in a strong magnetic field, the ADMX experiment excluded Dine-Fischler-Srednicki-Zhitnisky (DFSZ) axions at 100% dark matter density over this entire frequency range, except for a few gaps due to mode crossings. This paper explains the full ADMX analysis for Run 1B, motivating analysis choices informed by details specific to this run.

(3) MAGNON

# Cavity-Magnon Polariton Axion Detection Experiment

This experiment can distinguish Axion models, if ever detected we will make a dedicated experiment

arXiv:1811.09348v3 [physics.ins-det]

$g_{aee} > 3.7 \times 10^{-9}$ in the range $33.79\ \mu\text{eV} < m_a < 33.94\ \mu\text{eV}$ with 95% confidence

$$\frac{H}{\hbar} = \omega_c a^\dagger a + \omega_m b^\dagger b + g_{cm}(a^\dagger + a)(b^\dagger + b)$$

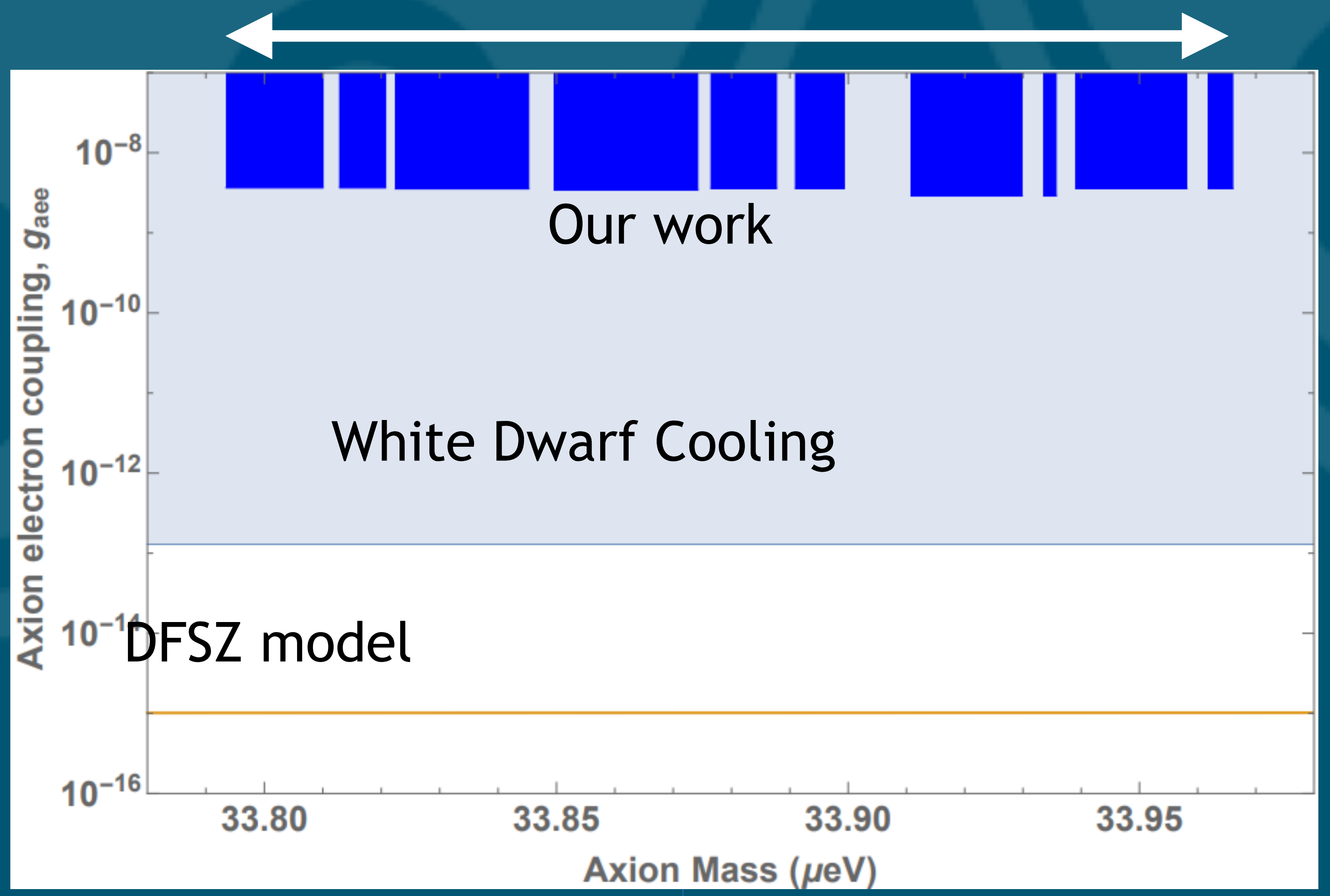
Photons

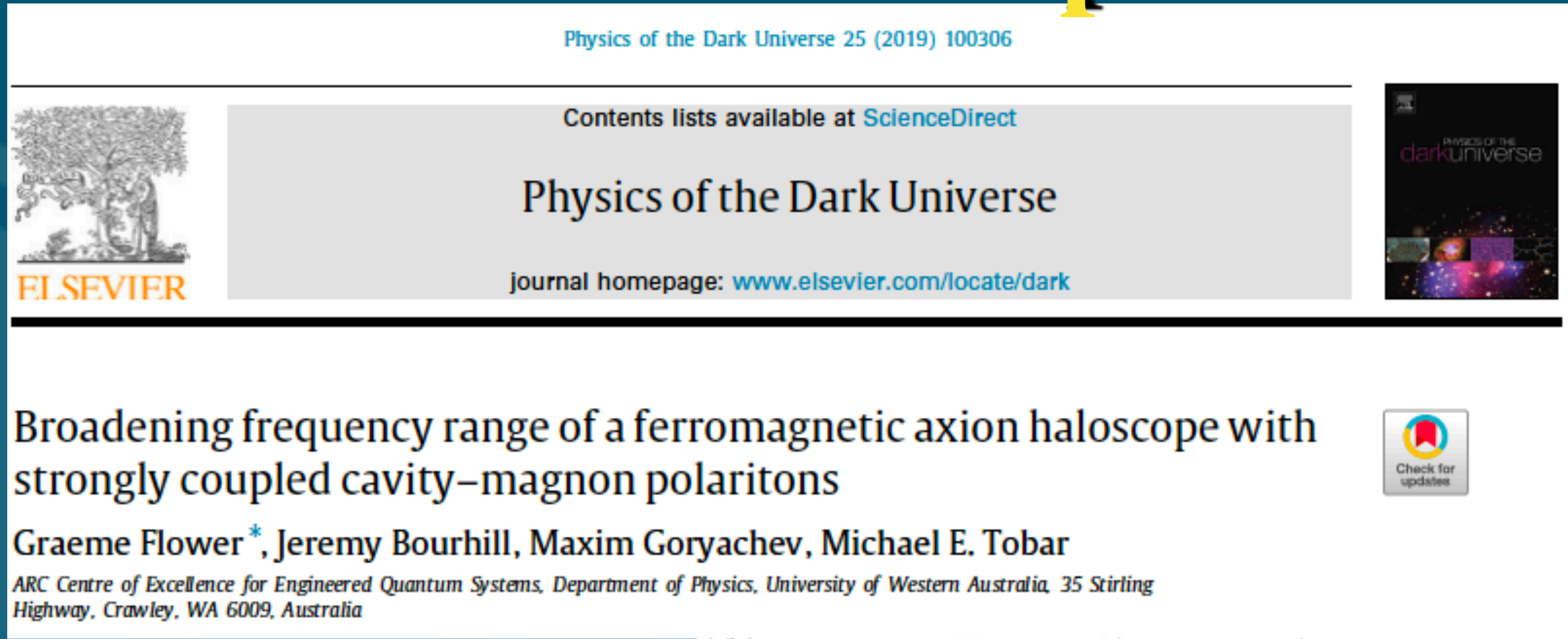
Magnons

Interaction

36MHz in 6 MHz blocks from 8hrs of averages

Centred at 8.2GHz





Physics of the Dark Universe 25 (2019) 100306

ELSEVIER

Contents lists available at ScienceDirect

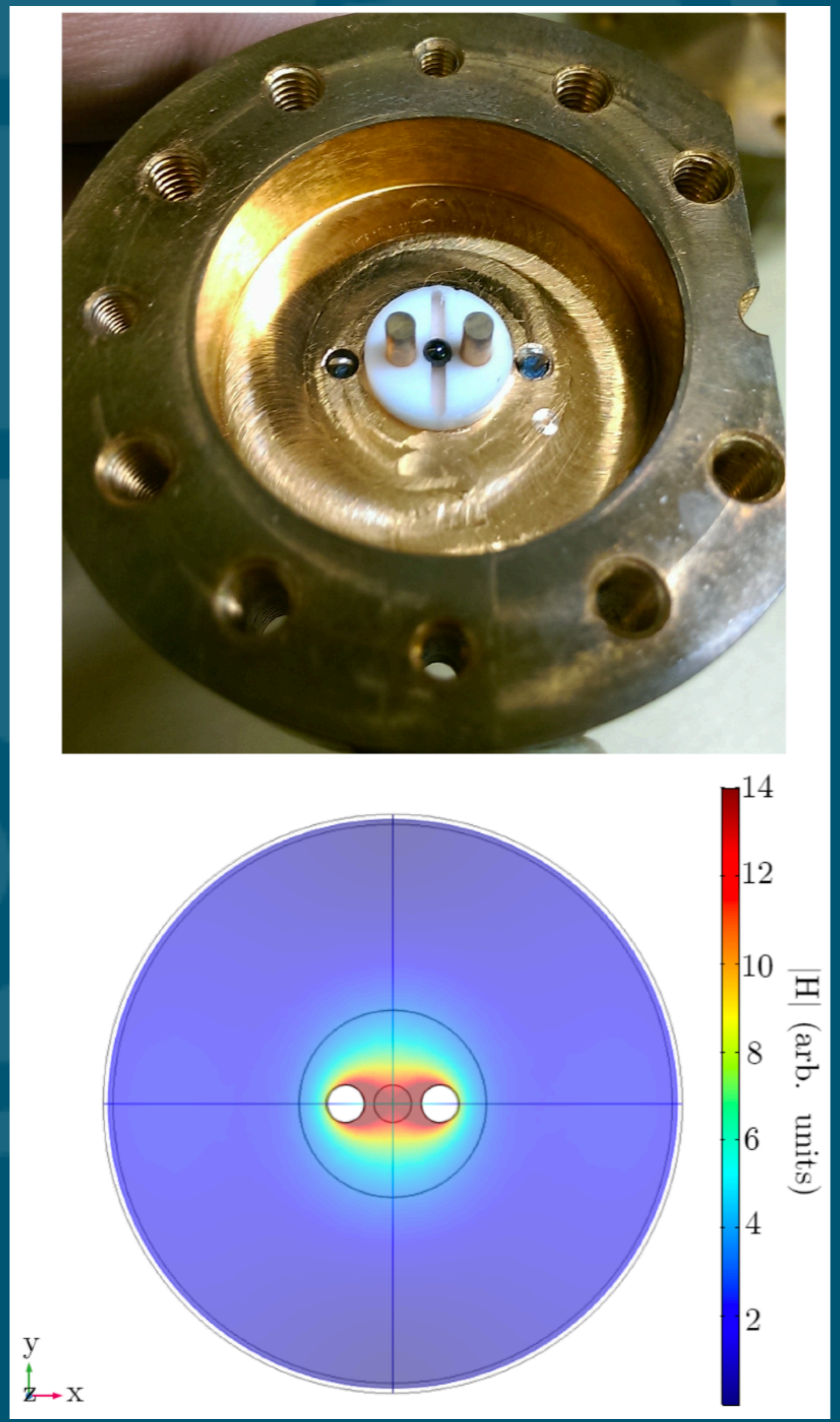
Physics of the Dark Universe

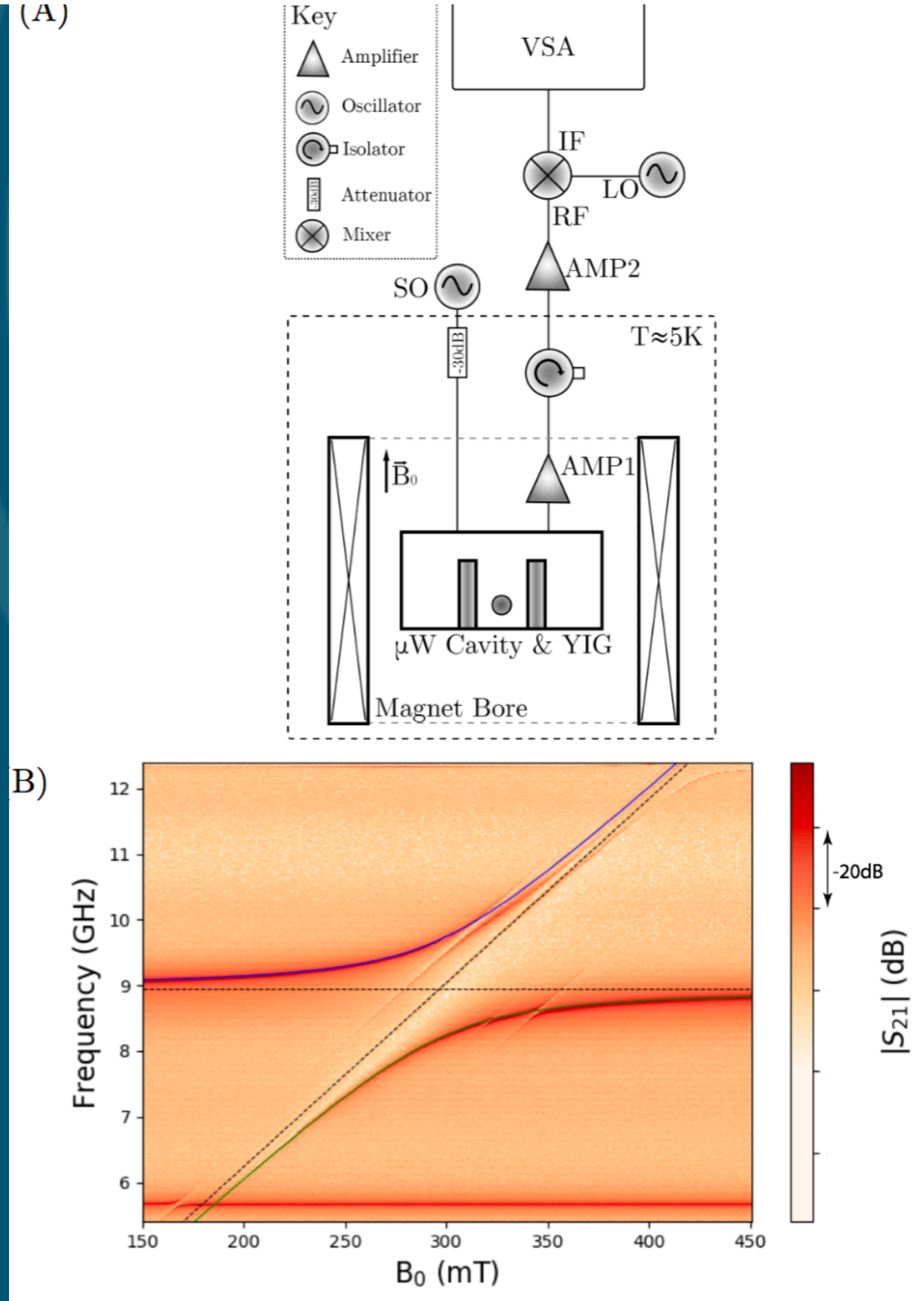
journal homepage: www.elsevier.com/locate/dark

## Broadening frequency range of a ferromagnetic axion haloscope with strongly coupled cavity–magnon polaritons

Graeme Flower*, Jeremy Bourhill, Maxim Goryachev, Michael E. Tobar

ARC Centre of Excellence for Engineered Quantum Systems, Department of Physics, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia





# What is an Axion and Why Should it Exist?

# What is an Axion and Why Should it Exist?

Hypothetical elementary particle postulated by the Peccei–Quinn theory in 1977 to resolve the strong CP problem in quantum chromodynamics (QCD).

# What is an Axion and Why Should it Exist?

Hypothetical elementary particle postulated by the Peccei–Quinn theory in 1977 to resolve the strong CP problem in quantum chromodynamics (QCD).

If axions exist and have low mass within a specific range, they are of interest as a possible component of cold dark matter.

# What is an Axion and Why Should it Exist?

Hypothetical elementary particle postulated by the Peccei–Quinn theory in 1977 to resolve the strong CP problem in quantum chromodynamics (QCD).

If axions exist and have low mass within a specific range, they are of interest as a possible component of cold dark matter.

**Science News** *from research organizations*

**'Axion' particle solves three mysteries of the universe**

*Date:* March 10, 2020

*Source:* University of Michigan

*Summary:* A hypothetical particle called the axion could solve one of physics' great mysteries: the excess of matter over antimatter, or why we're here at all.

# What is an Axion and Why Should it Exist?

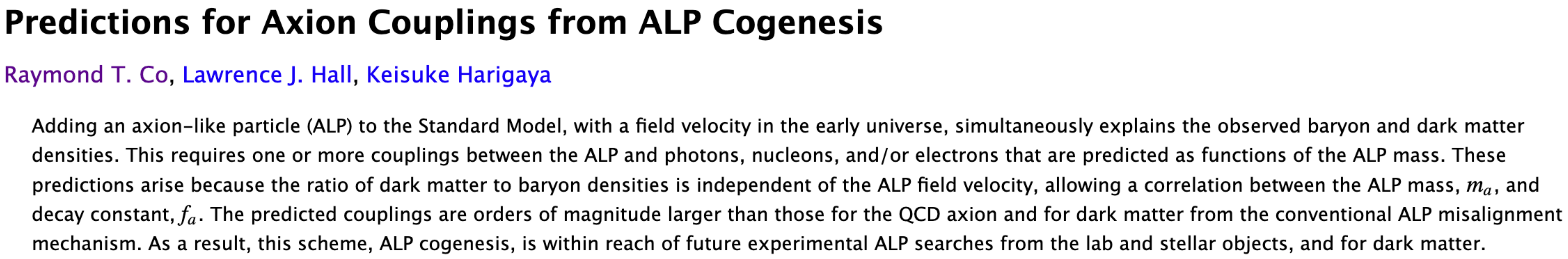
Hypothetical elementary particle postulated by the Peccei–Quinn theory in 1977 to resolve the strong CP problem in quantum chromodynamics (QCD).

If axions exist and have low mass within a specific range, they are of interest as a possible component of cold dark matter.

**Science News** *from research organizations*

## 'Axion' particle solves three mysteries of the universe

| | |
|---|---|
| *Date:* | March 10, 2020 |
| *Source:* | University of Michigan |
| *Summary:* | A hypothetical particle called the axion could solve one of physics' great mysteries: the excess of matter over antimatter, or why we're here at all. |



## Predictions for Axion Couplings from ALP Cogenesis

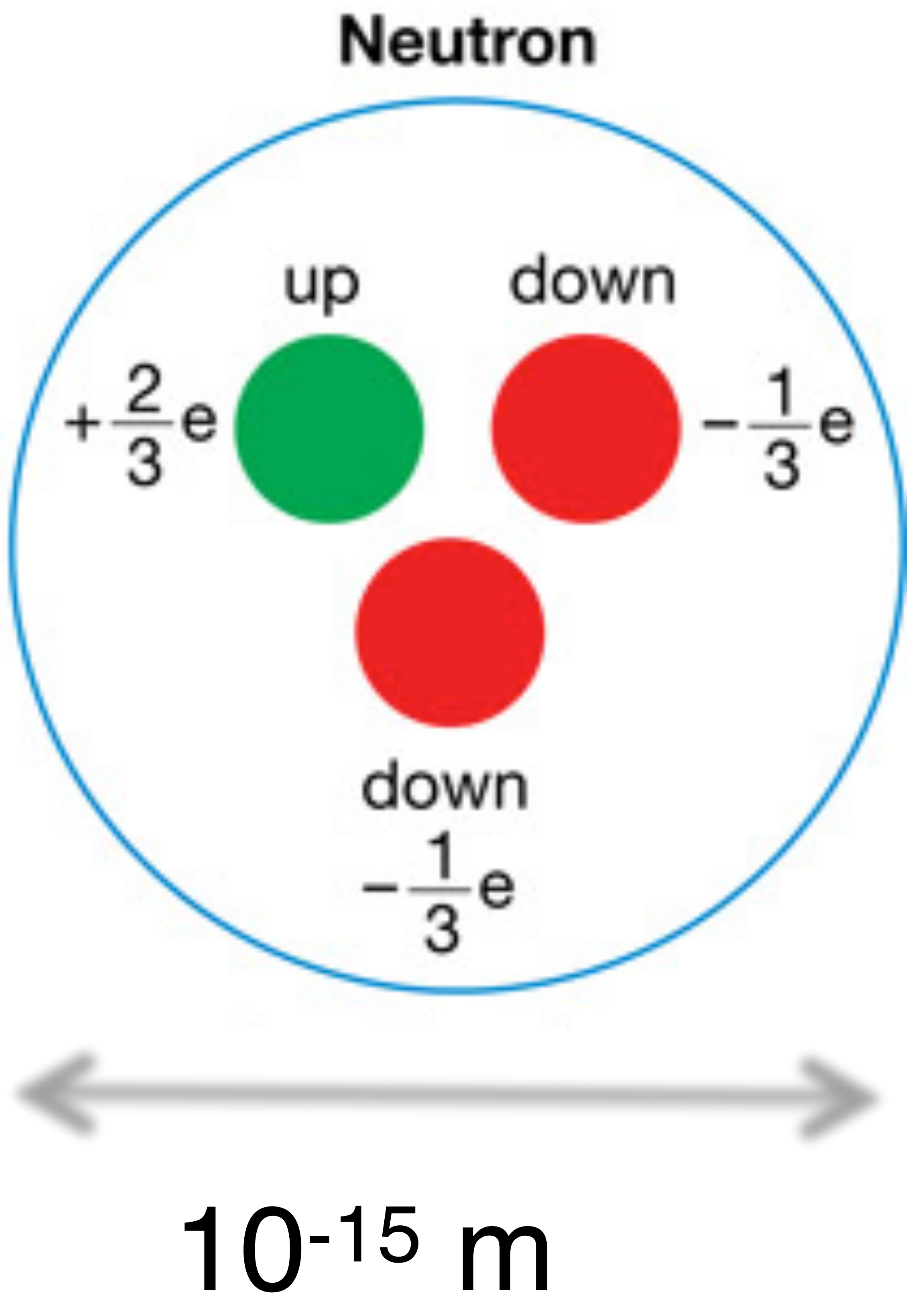
Raymond T. Co, Lawrence J. Hall, Keisuke Harigaya

Adding an axion-like particle (ALP) to the Standard Model, with a field velocity in the early universe, simultaneously explains the observed baryon and dark matter densities. This requires one or more couplings between the ALP and photons, nucleons, and/or electrons that are predicted as functions of the ALP mass. These predictions arise because the ratio of dark matter to baryon densities is independent of the ALP field velocity, allowing a correlation between the ALP mass, $m_a$, and decay constant, $f_a$. The predicted couplings are orders of magnitude larger than those for the QCD axion and for dark matter from the conventional ALP misalignment mechanism. As a result, this scheme, ALP cogenesis, is within reach of future experimental ALP searches from the lab and stellar objects, and for dark matter.

# QCD: Why is the neutron electric dipole moment so small?

*from Aaron Chou (FNAL)

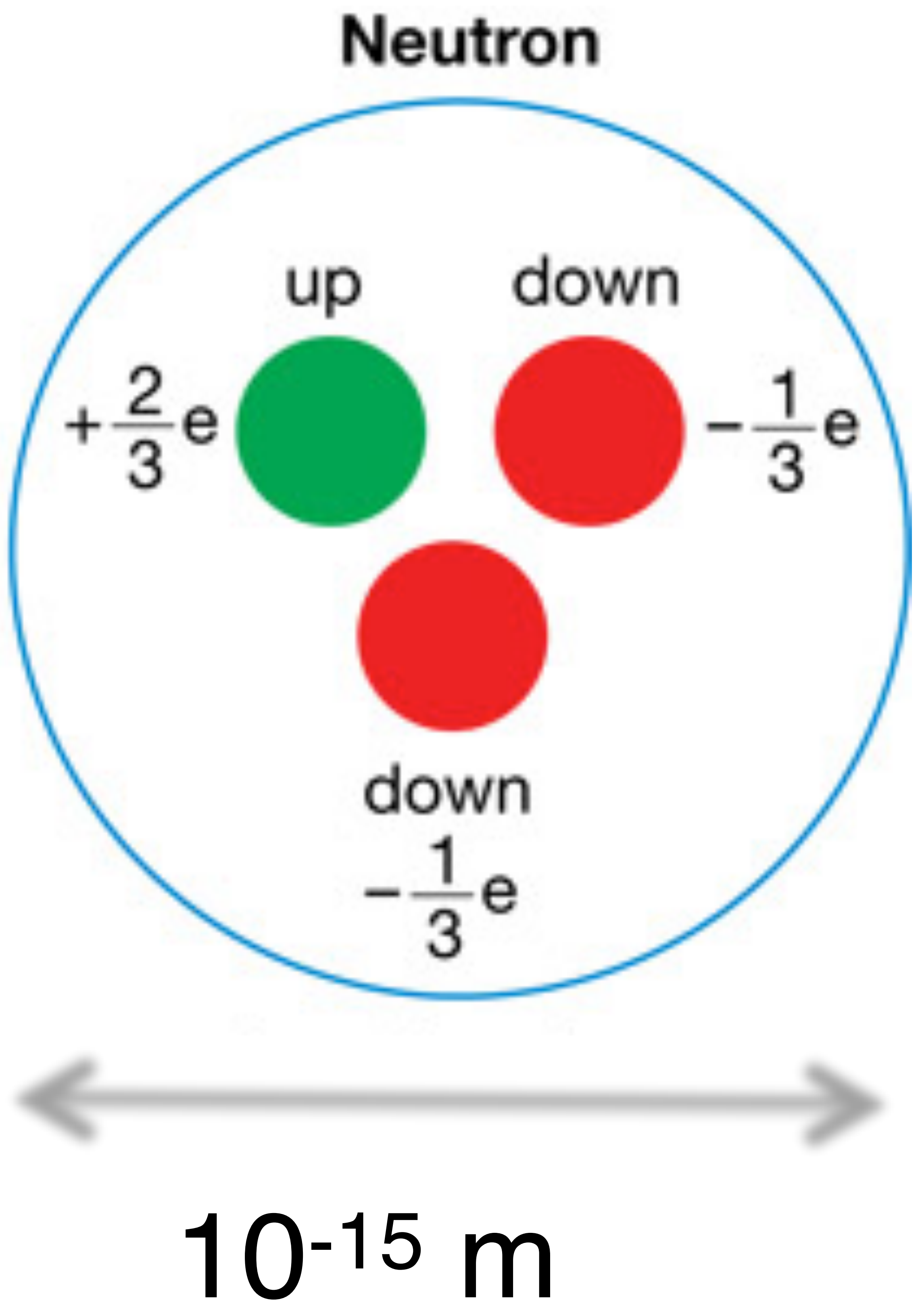
Quarks should give a charge distribution
Naive estimate gives $d_n \approx 10^{-16}$ e-cm

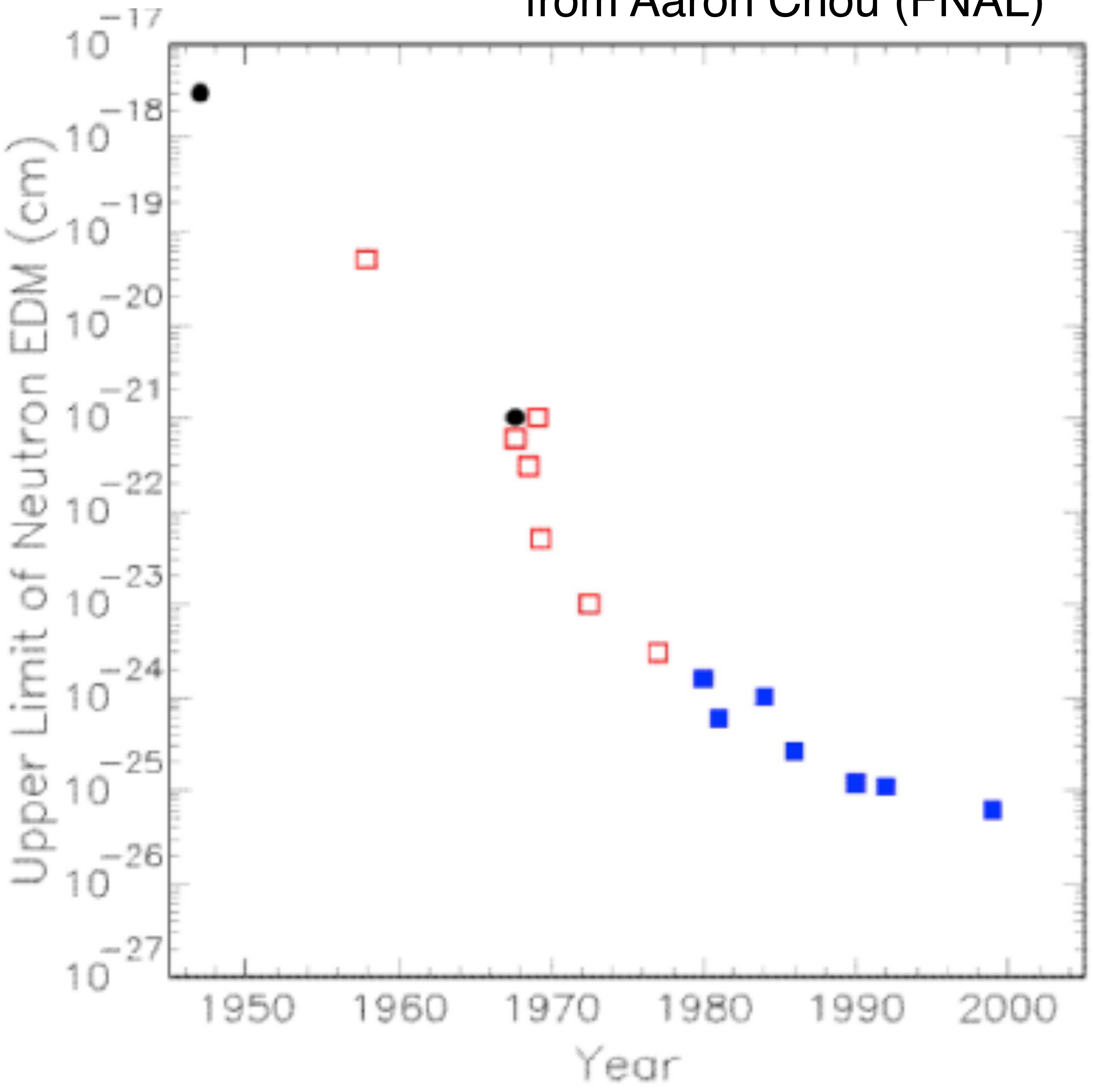


# QCD: Why is the neutron electric dipole moment so small?

*from Aaron Chou (FNAL)

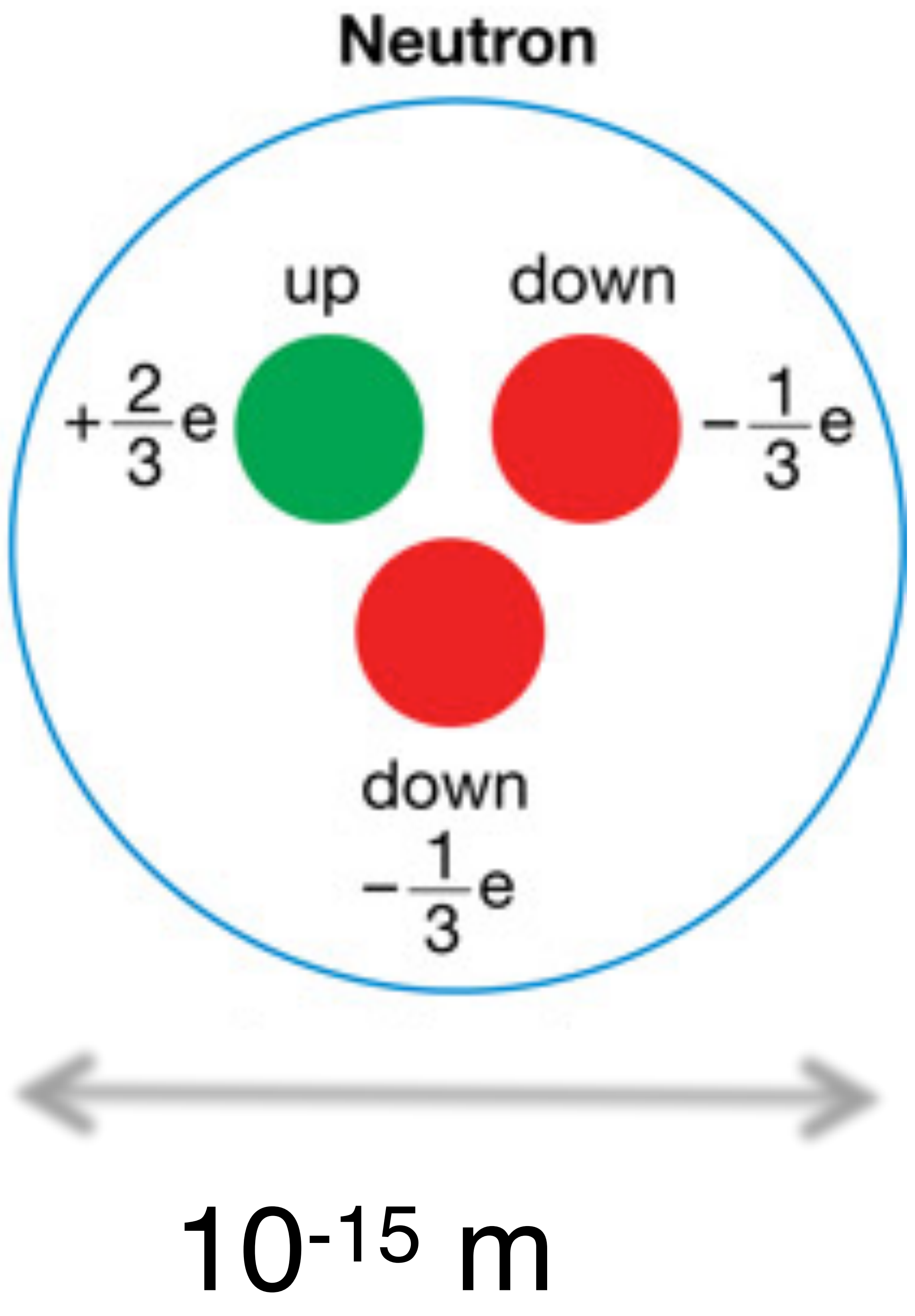
Quarks should give a charge distribution
Naive estimate gives $d_n \approx 10^{-16}$ e-cm



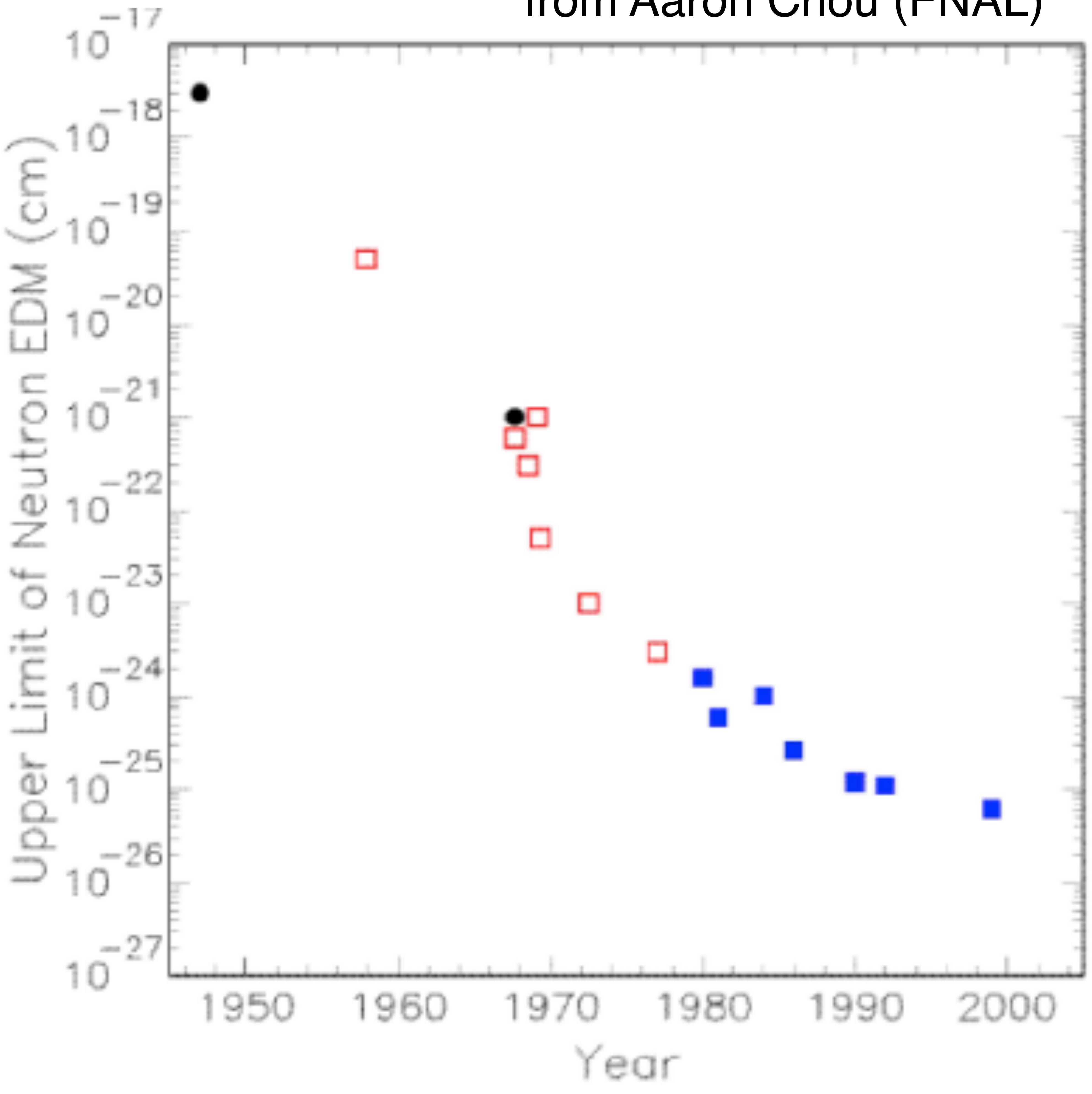


# QCD: Why is the neutron electric dipole moment so small?

Quarks should give a charge distribution
Naive estimate gives $d_n \approx 10^{-16}$ e-cm



*from Aaron Chou (FNAL)



This leads to the "**Strong CP Problem**": Where did QCD CP violation go?

$$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Coupling to electromagnetic field

$$\frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

Coupling to gluon field

**CASPEr Electric**

Budker D, et al. Phys. Rev. X4:021030 (2014)

**UWA: Hybrid Magnon-Photon Experiment**

$$\frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$

Coupling to fermions

**CASPEr Wind**

Graham PW, Rajendran S. Phys. Rev. D88:035023 (2013)

$$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu} \longleftarrow$$

Coupling to electromagnetic field

$$\frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu} \longleftarrow$$

Coupling to gluon field

**CASPEr Electric**

Budker D, et al. Phys. Rev. X4:021030 (2014)

**UWA: Hybrid Magnon-Photon Experiment**

$$\frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f \longleftarrow$$

Coupling to fermions

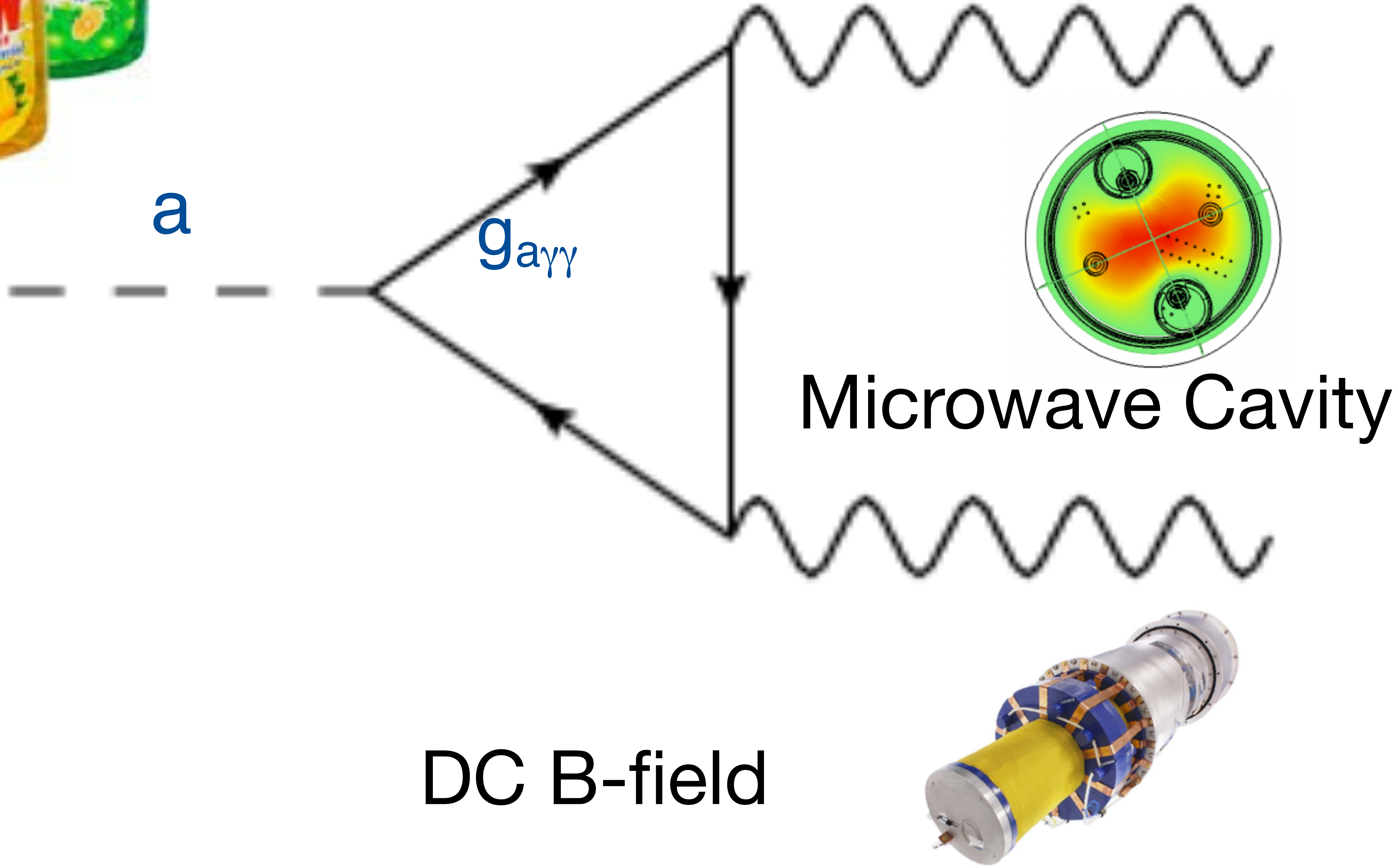
**CASPEr Wind**

Graham PW, Rajendran S. Phys. Rev. D88:035023 (2013)

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - J^\mu A_\mu + \frac{1}{2} \partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 - \boxed{\frac{g_{a\gamma}}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} a,}$$

# Axion-Photon Coupling to Search for Axion

# Axion-Photon Coupling to Search for Axion

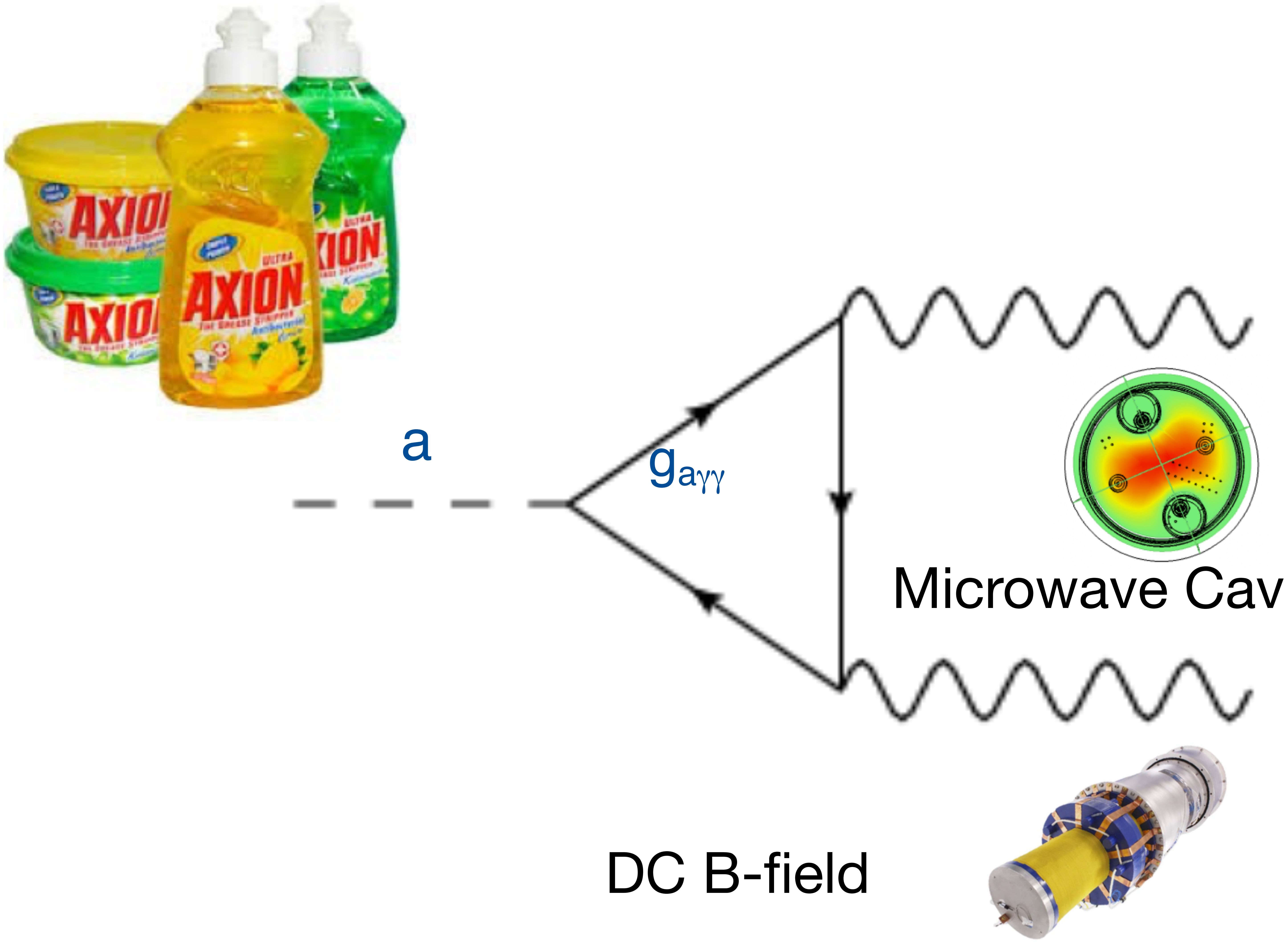


# Axion-Photon Coupling to Search for Axion

## The Axion Haloscope Technique

$$\mathscr{L} \propto a g_{a\gamma\gamma} \overrightarrow{E}_{cavity} \bullet \overrightarrow{B}_{ext}$$

Lagrangian gives effective strength

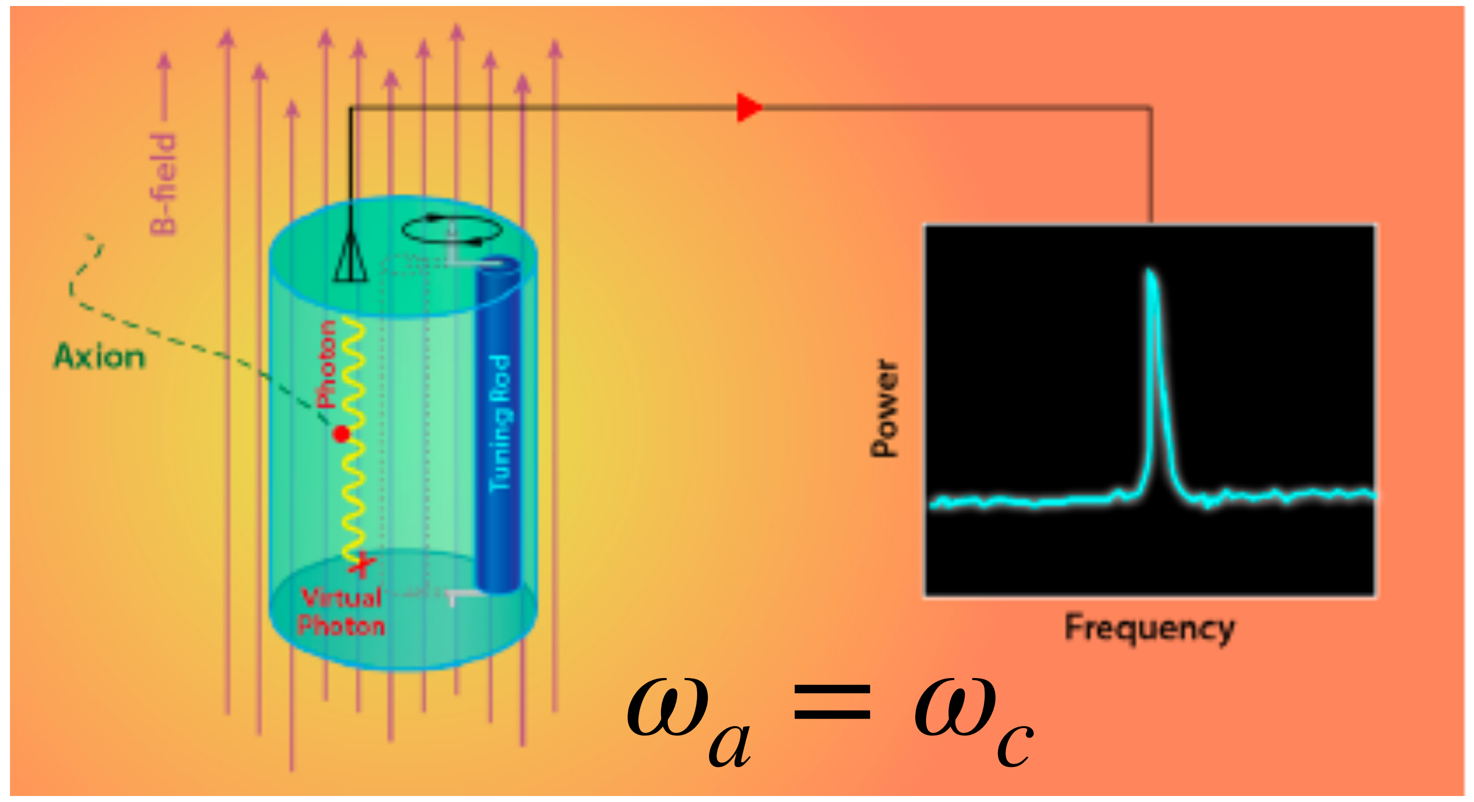


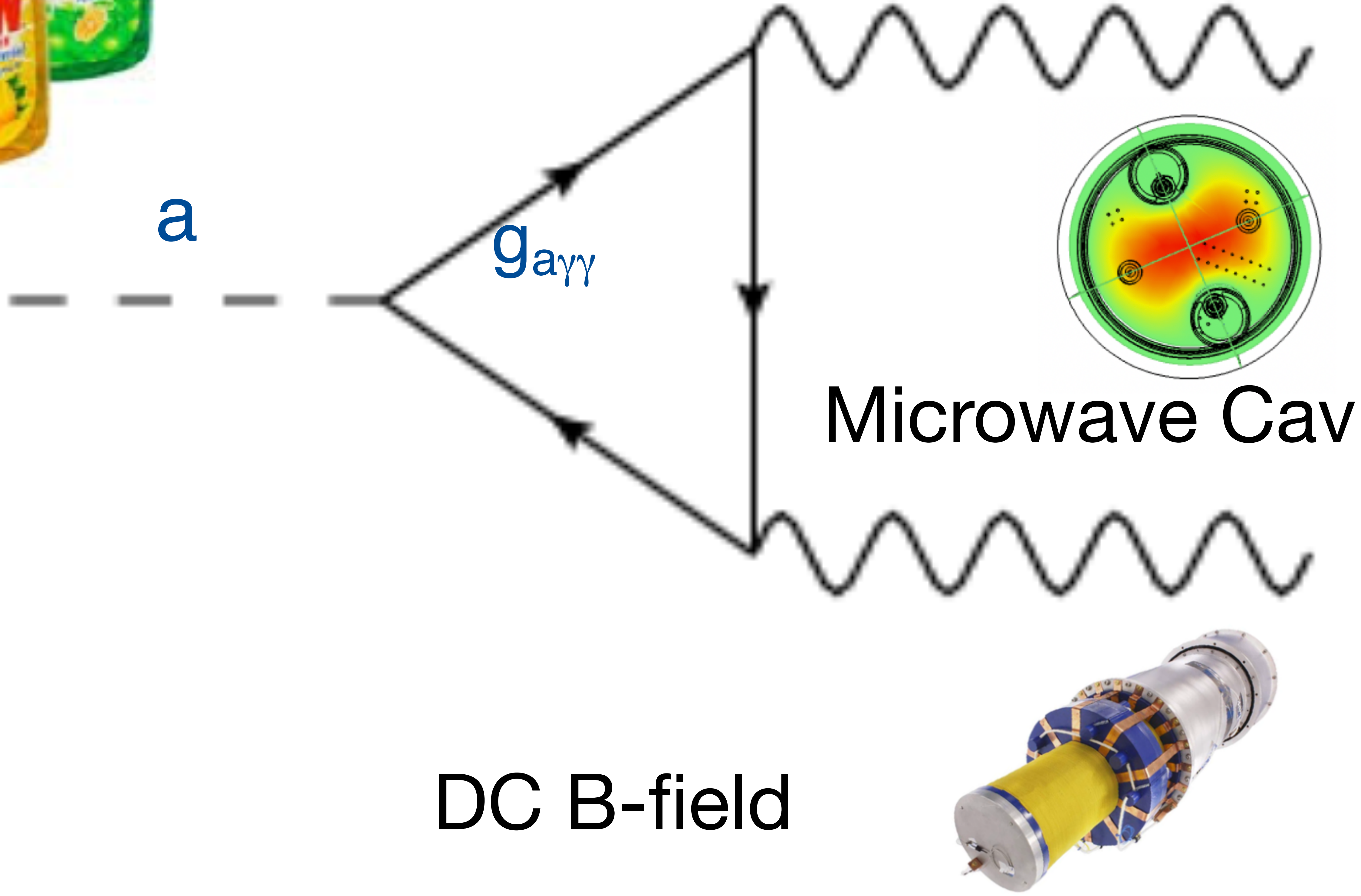
# Axion-Photon Coupling to Search for Axion

## The Axion Haloscope Technique

$$\mathscr{L} \propto a g_{a\gamma\gamma} \overrightarrow{E}_{cavity} \bullet \overrightarrow{B}_{ext}$$

Lagrangian gives effective strength





Microwave Cavity

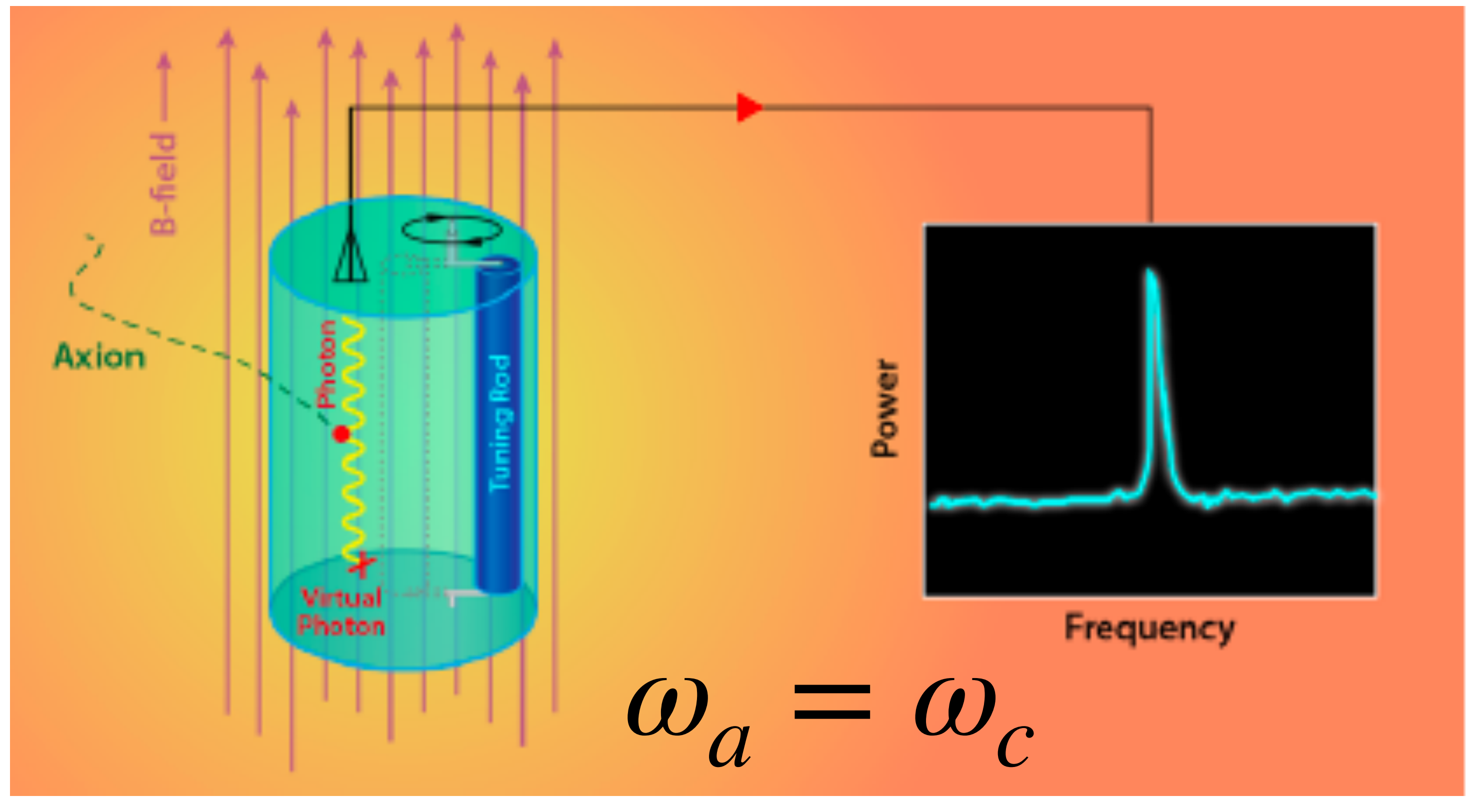
DC B-field

# Axion-Photon Coupling to Search for Axion

The Axion Haloscope Technique

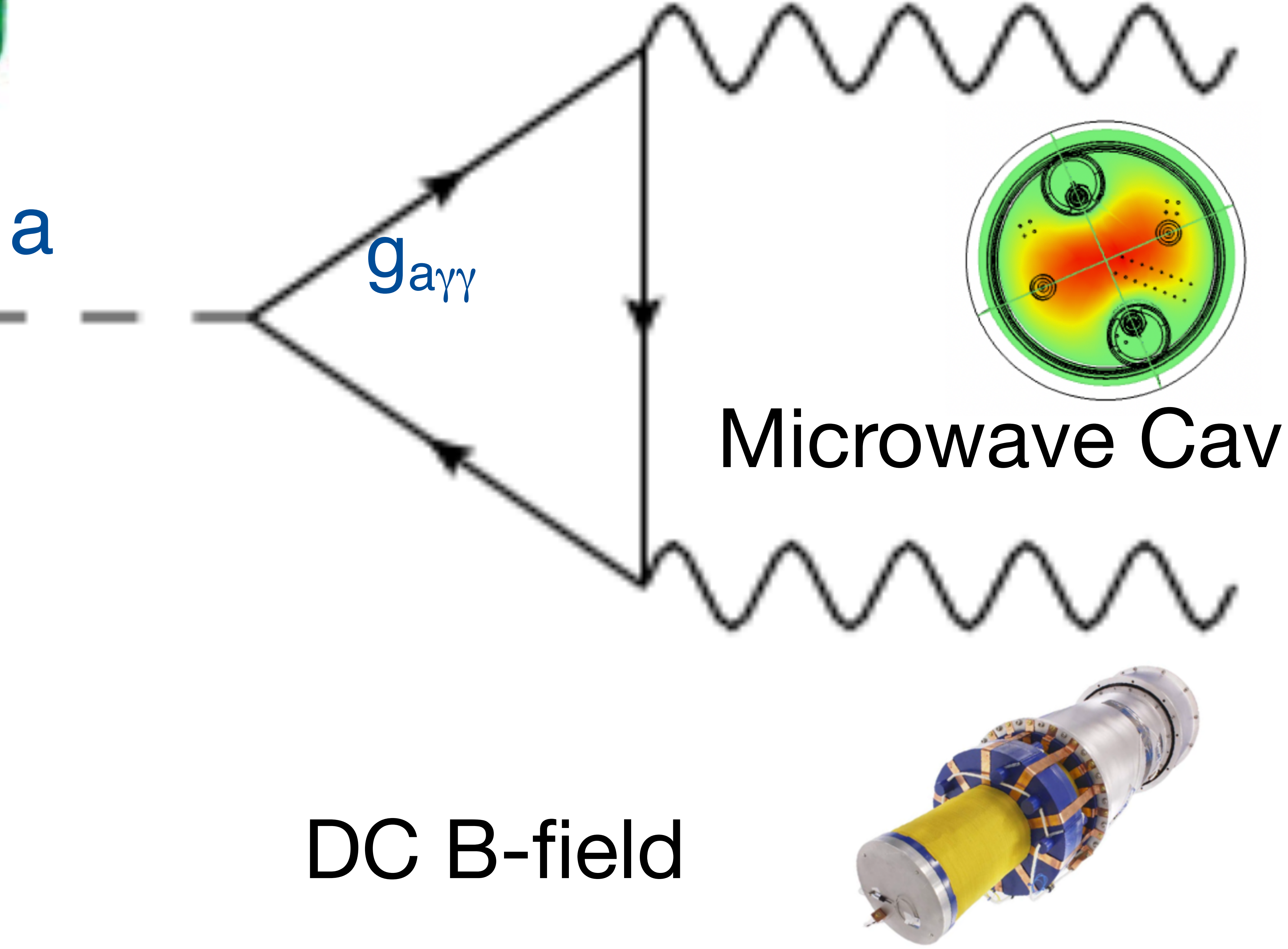
$$\mathscr{L} \propto a g_{a\gamma\gamma} \overrightarrow{E}_{cavity} \bullet \overrightarrow{B}_{ext}$$

Lagrangian gives effective strength



$$\omega_a = \omega_c$$

The AC Axion Haloscope Technique



Microwave Cavity

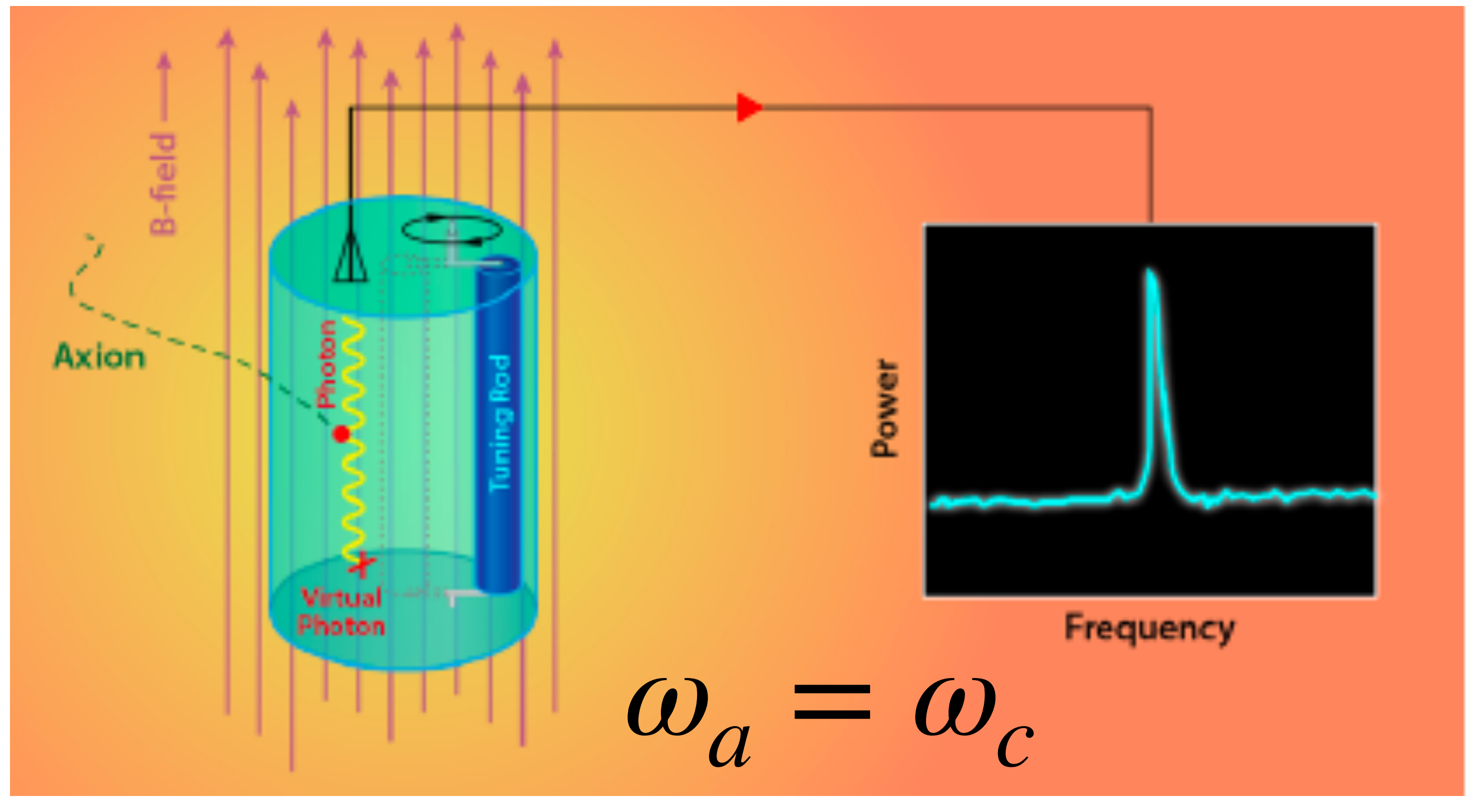
DC B-field

# Axion-Photon Coupling to Search for Axion

The Axion Haloscope Technique

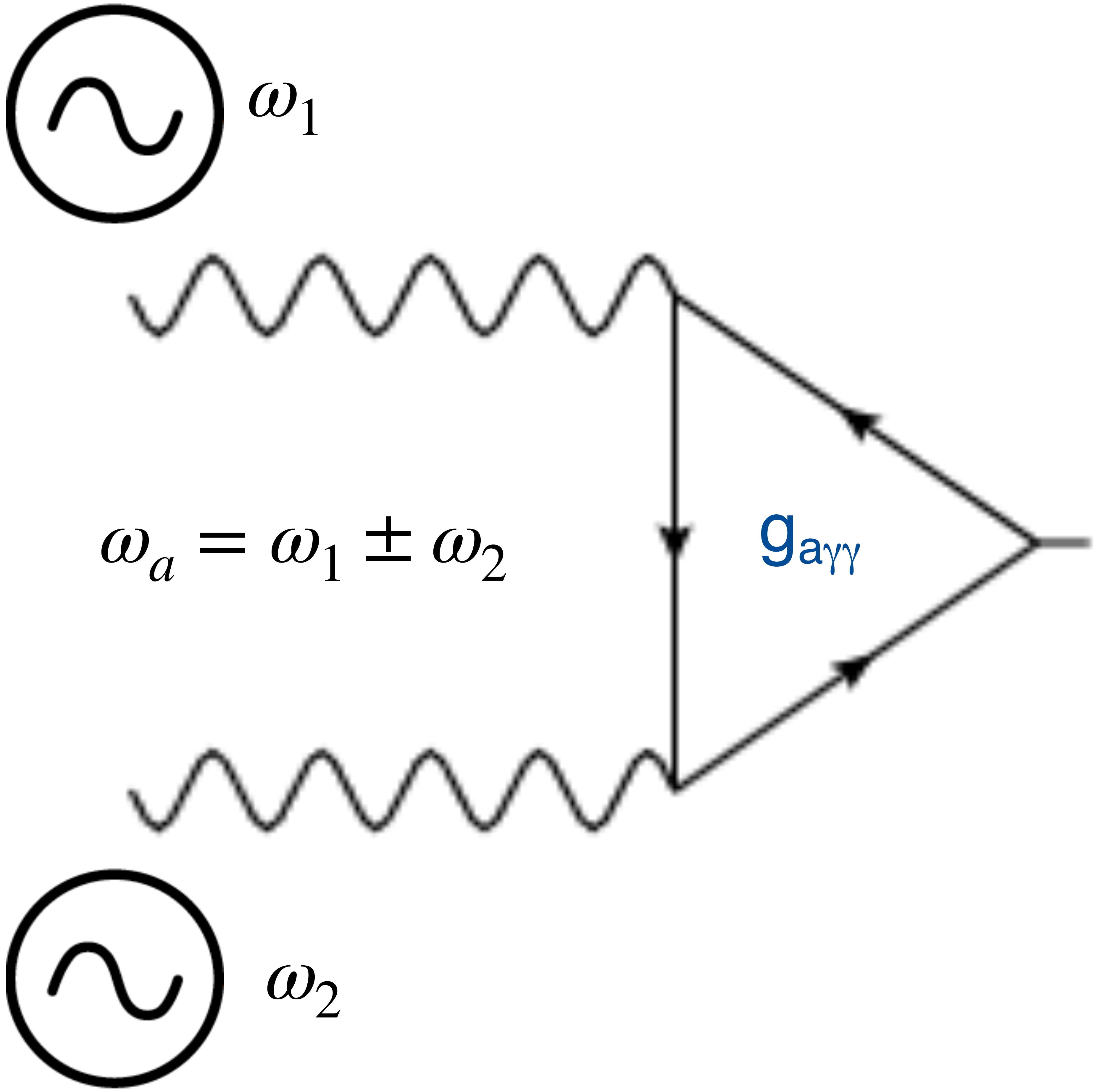
$$\mathscr{L} \propto a g_{a\gamma\gamma} \overrightarrow{E}_{cavity} \bullet \overrightarrow{B}_{ext}$$

Lagrangian gives effective strength

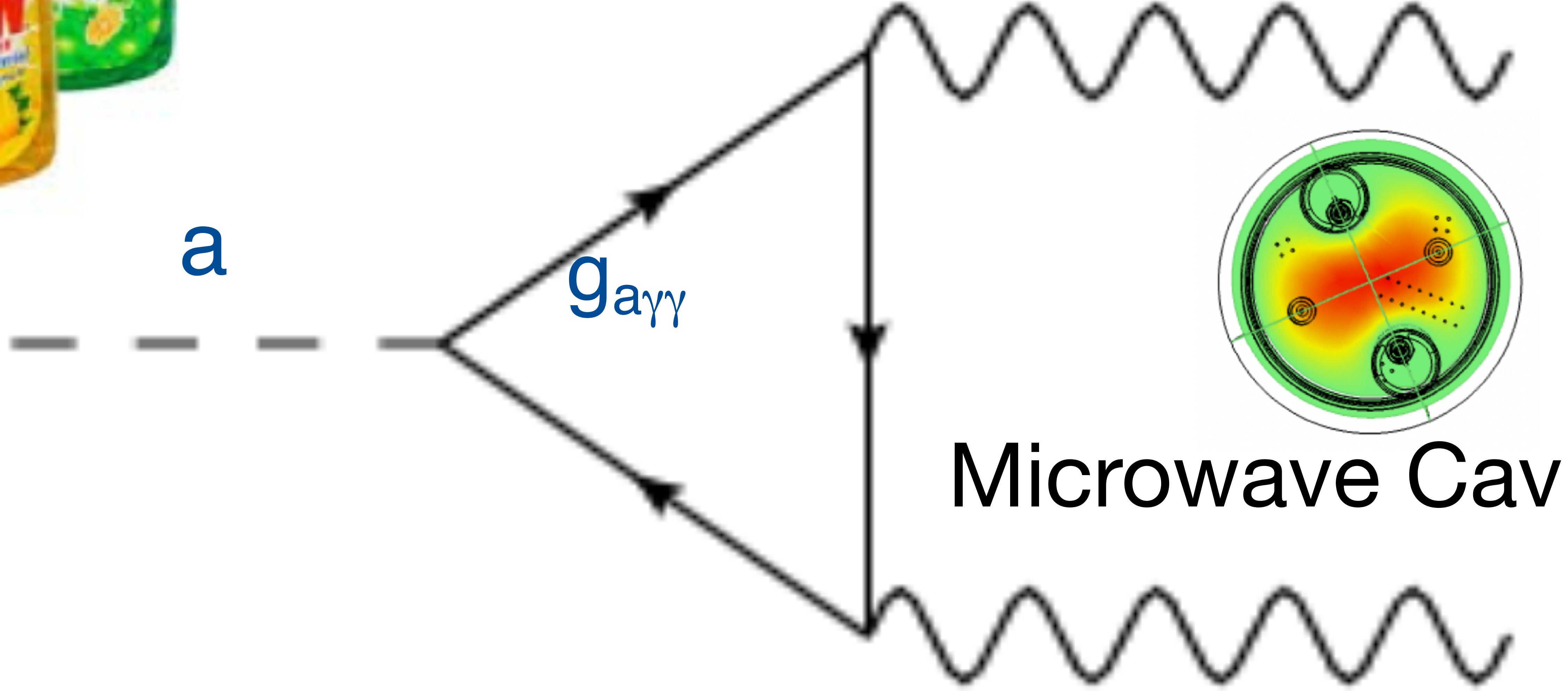


$\omega_a = \omega_c$

The AC Axion Haloscope Technique

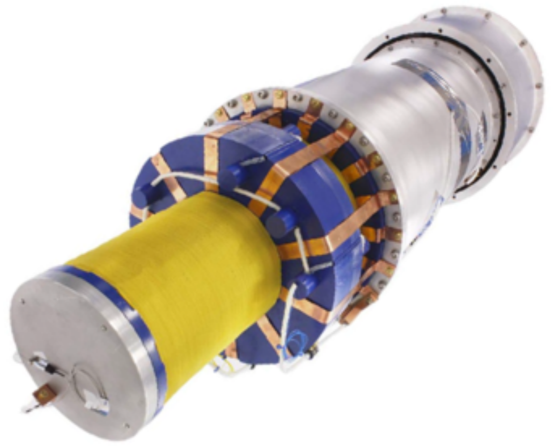


$\omega_a = \omega_1 \pm \omega_2$



Microwave Cavity

DC B-field



# Dark Matter Axion Virialization

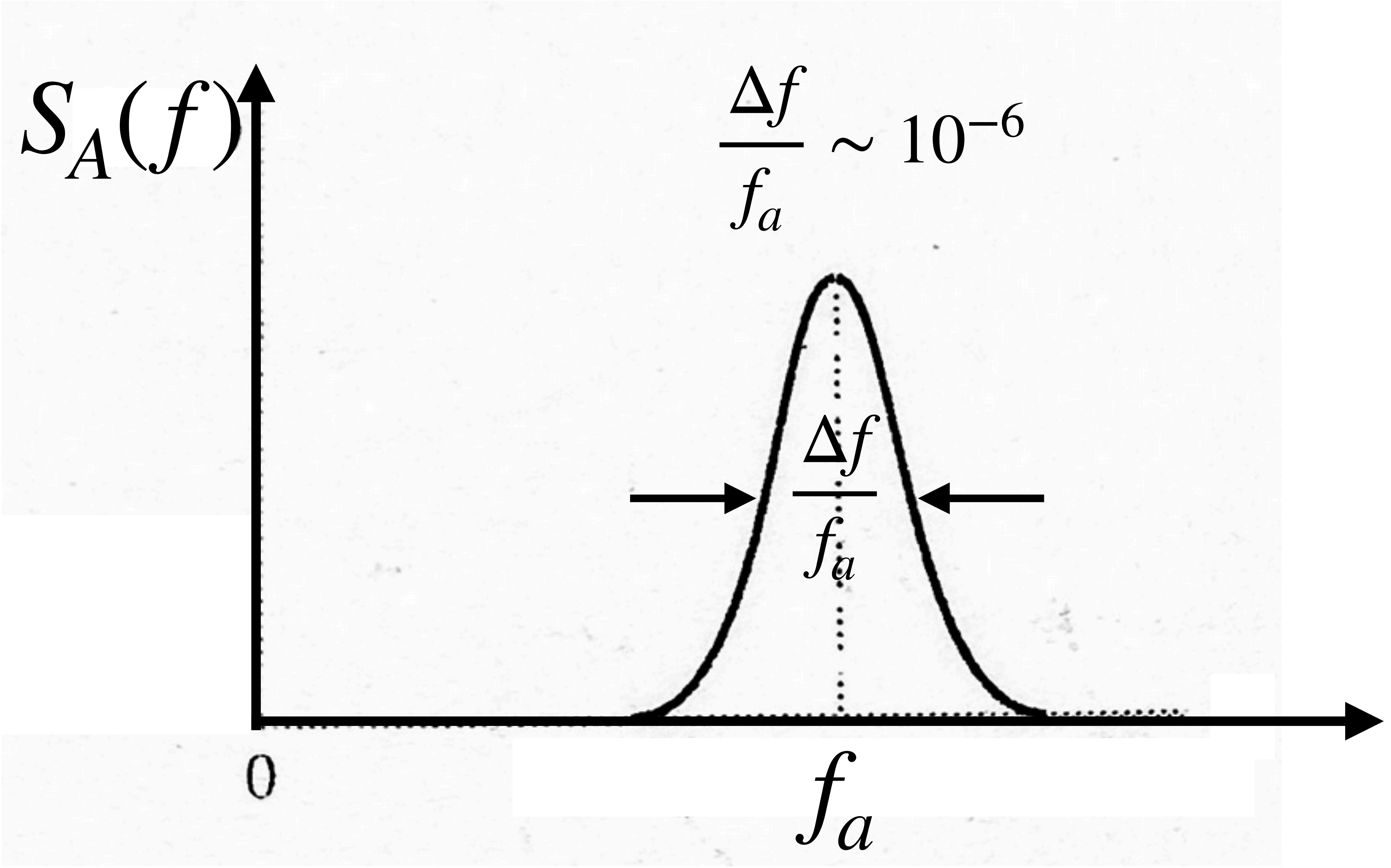
- Virialization of dark matter halo -> Dissipative effect that converts the kinetic energy of collapse into random motions.

- If no virialization the dark matter axion is coherent. $a(t) = a_0 Sin(\omega_a t + \phi)$

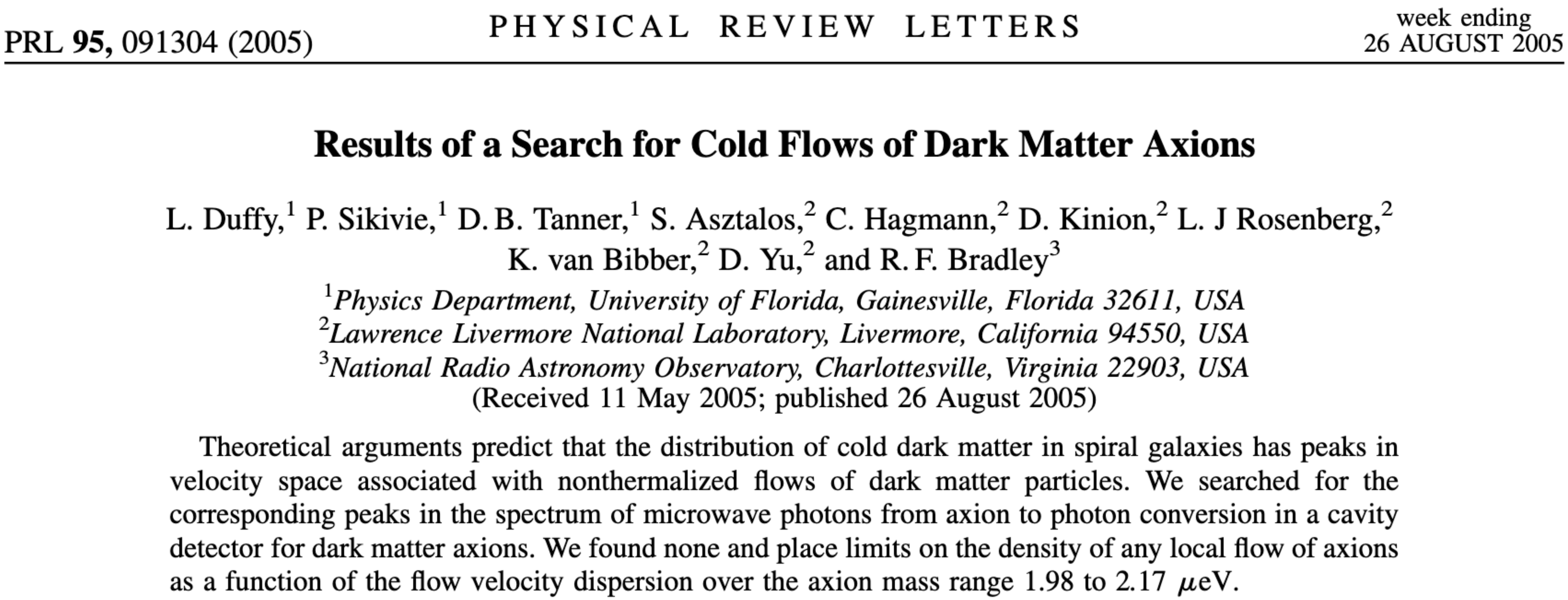
- Otherwise, model as a Narrow Band noise source, as a Spectral Density with a Bandwidth.

# Dark Matter Axion Virialization

- Virialization of dark matter halo -> Dissipative effect that converts the kinetic energy of collapse into random motions.
- If no virialization the dark matter axion is coherent. $a(t) = a_0 Sin(\omega_a t + \phi)$
- Otherwise, model as a Narrow Band noise source, as a Spectral Density with a Bandwidth.



# Possible Cold Flows Not Virialized



PRL **95,** 091304 (2005) PHYSICAL REVIEW LETTERS week ending
26 AUGUST 2005

## Results of a Search for Cold Flows of Dark Matter Axions

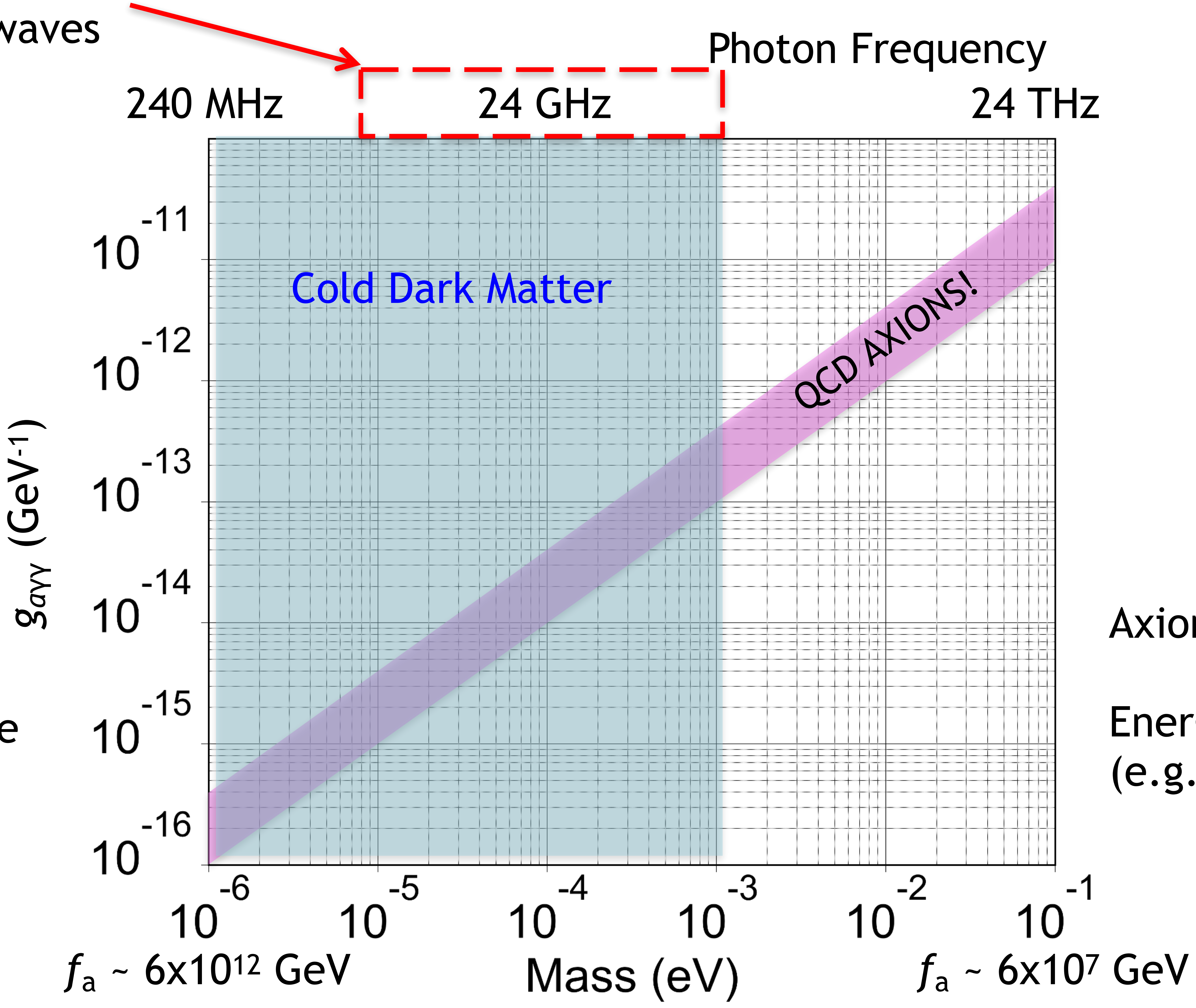
L. Duffy,[1] P. Sikivie,[1] D. B. Tanner,[1] S. Asztalos,[2] C. Hagmann,[2] D. Kinion,[2] L. J Rosenberg,[2]
K. van Bibber,[2] D. Yu,[2] and R. F. Bradley[3]
[1]*Physics Department, University of Florida, Gainesville, Florida 32611, USA*
[2]*Lawrence Livermore National Laboratory, Livermore, California 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 $\mu$eV.

# Axion Mass / Photon Coupling

Microwaves
& mm-waves

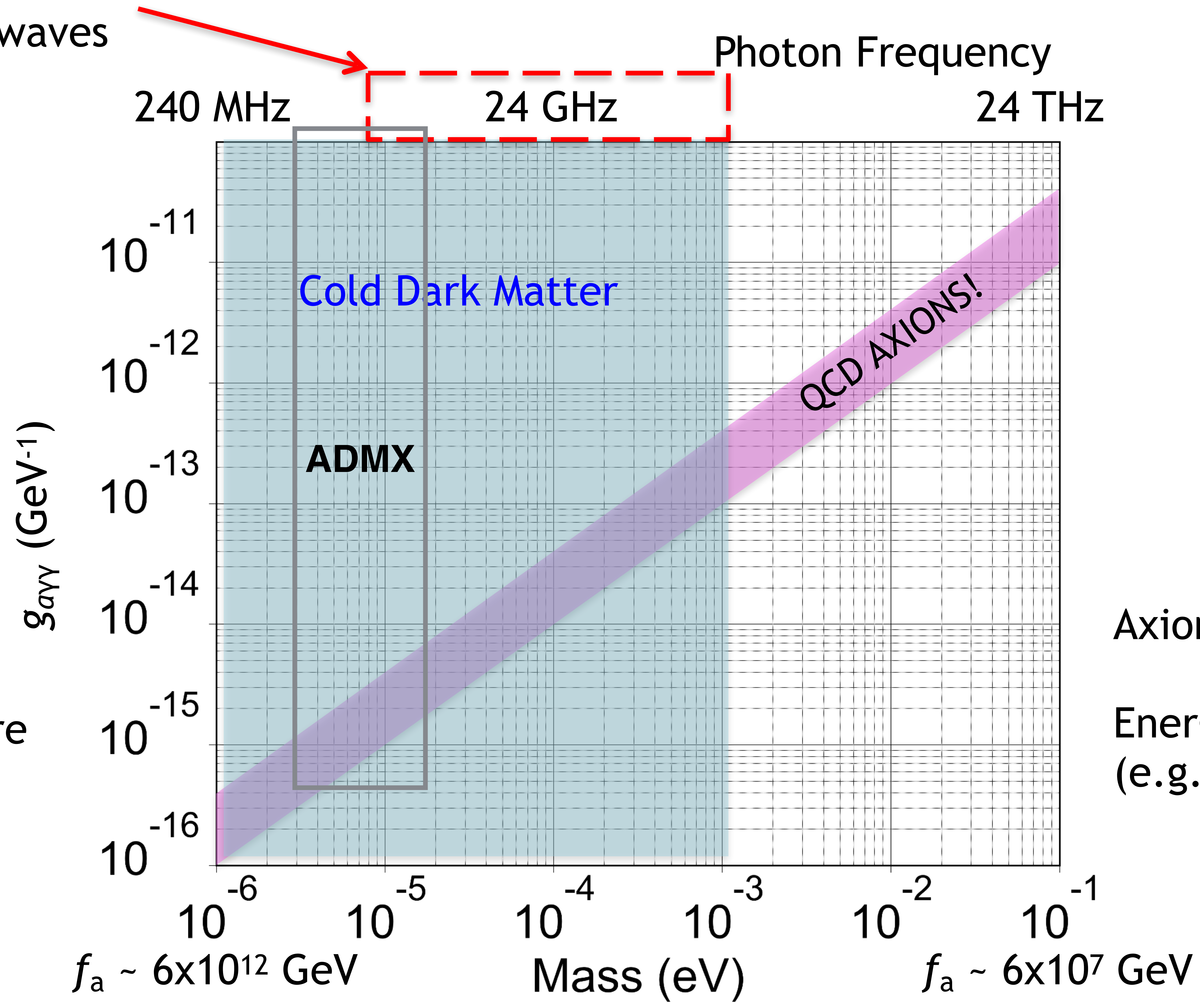


Overclosure

Axion decay

Energy loss
(e.g. SN1987A)

# Axion Mass / Photon Coupling



Microwaves
& mm-waves

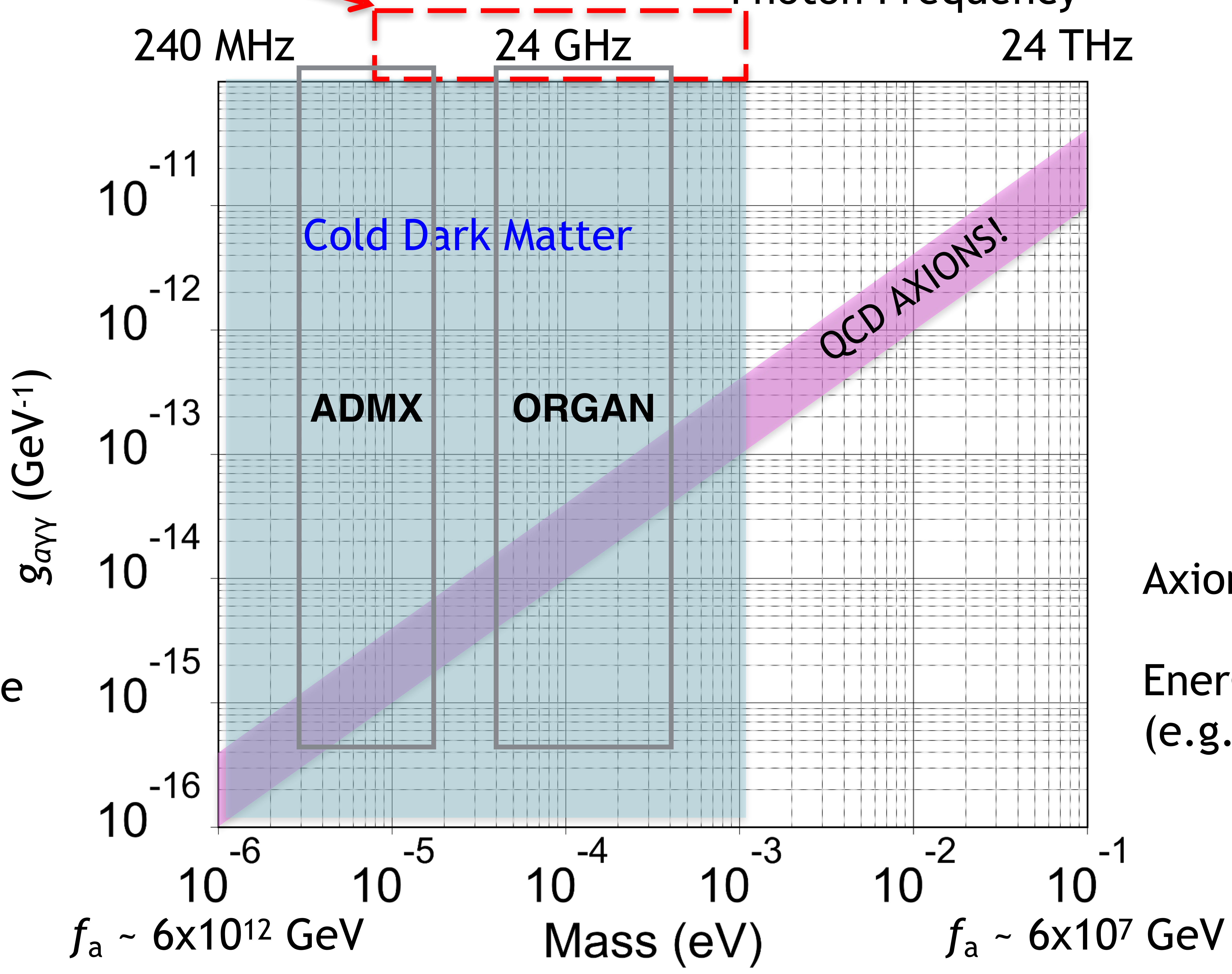
Overclosure

Axion decay

Energy loss
(e.g. SN1987A)

# Axion Mass / Photon Coupling

Microwaves
& mm-waves



Overclosure

Axion decay

Energy loss
(e.g. SN1987A)

# Major Experiments: Summary

| **Program** | **2019** | **2020** | **2021** | **2022** | **2023** | **2024** | **2025** | **2026 2027** |
|---|---|---|---|---|---|---|---|---|
| **WISP Direct Detection** | ADMX Run 1b, 1c, 2A, 2B | 🟩 | 🟩 | | | | | |
| | ADMX Upgrade, 8-16 $\mu$eV | | **Design/Proto** | **Construct** | 🟩 | 🟩 | 🟩 | 🟩 |
| | ORGAN | **Design/Proto** | 🟩 | 🟩 | | | | |
| | ORGAN Upgrade | | **Design/Proto** | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |

- ORGAN nearly ready for first run

# Major Experiments: Summary

| **Program** | **2019** | **2020** | **2021** | **2022** | **2023** | **2024** | **2025** | **2026 2027** |
|---|---|---|---|---|---|---|---|---|
| **WISP Direct Detection** | ADMX Run 1b, 1c, 2A, 2B | 🟩 | 🟩 | | | | | |
| | ADMX Upgrade, 8-16 $\mu$eV | | **Design/Proto** | **Construct** | 🟩 | 🟩 | 🟩 | 🟩 |
| | ORGAN | **Design/Proto** | 🟩 | 🟩 | | | | |
| | ORGAN Upgrade | | **Design/Proto** | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |

- ORGAN nearly ready for first run
- ADMX: Gen 2, 0.6-2 GHz or 2.5-8.3 micro eV mass (Approved to run to 2022 USA Financial Year)

# Major Experiments: Summary

| **Program** | **2019** | **2020** | **2021** | **2022** | **2023** | **2024** | **2025** | **2026** | **2027** |
|---|---|---|---|---|---|---|---|---|---|
| **WISP Direct Detection** | ADMX Run 1b, 1c, 2A, 2B | 🟩 | 🟩 | | | | | | |
| | ADMX Upgrade, 8-16 $\mu$eV | | **Design/Proto** | **Construct** | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| | ORGAN | **Design/Proto** | 🟩 | 🟩 | | | | | |
| | ORGAN Upgrade | | **Design/Proto** | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |

- ORGAN nearly ready for first run
- ADMX: Gen 2, 0.6-2 GHz or 2.5-8.3 micro eV mass (Approved to run to 2022 USA Financial Year)
  - Run 1a: 2016-2017
  - Run 1b: 2018 (Some data analysis still ongoing)
  - Run 1c: 2020 to reach 1030 MHz (Current run)
  - Run 1D: 1030-1200 MHz
  - Run 2A: 1200-1500 MHz and 2B 1500-2000 MHz

# Major Experiments: Summary

| **Program** | **2019** | **2020** | **2021** | **2022** | **2023** | **2024** | **2025** | **2026 2027** |
|---|---|---|---|---|---|---|---|---|
| **WISP Direct Detection** | ADMX Run 1b, 1c, 2A, 2B | 🟩 | 🟩 | | | | | |
| | ADMX Upgrade, 8-16 $\mu$eV | | **Design/Proto** | **Construct** | 🟩 | 🟩 | 🟩 | 🟩 |
| | ORGAN | **Design/Proto** | 🟩 | 🟩 | | | | |
| | ORGAN Upgrade | | **Design/Proto** | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |

- ORGAN nearly ready for first run
- ADMX: Gen 2, 0.6-2 GHz or 2.5-8.3 micro eV mass (Approved to run to 2022 USA Financial Year)
    - Run 1a: 2016-2017
    - Run 1b: 2018 (Some data analysis still ongoing)
    - Run 1c: 2020 to reach 1030 MHz (Current run)
    - Run 1D: 1030-1200 MHz
    - Run 2A: 1200-1500 MHz and 2B 1500-2000 MHz
- ADMX Gen 2, 2-4 GHz or 8.3-16.4 micro eV mass (Approved to run to 2022 USA Financial Year)
    - Run A: 2-3 GHz
    - Run B: 3-4 GHz

# ADMX Extended Frequency Range

May 26, 2019

FOA Number: DE-FOA-0002112
DOE/SC Program Office: **High Energy Physics (HEP)**
DOE/SC Program Office Technical Contact: **Dr. Kathleen Turner**
Research Track: **Track 1, PRD #3**
PAMS LOI Tracking Number: LOI-0000025690

**Principal Investigator:**

**Dr. Andrew Sonnenschein, 630-840-2883**, sonnenschein@fnal.gov
Institution: **Fermi National Accelerator Laboratory**
Administrative Point of Contact: **Hema Ramamoorthi, 630-840-6723**, hema@fnal.gov

**Co-PIs:**

**Professor James Buckley,** Washington University, St. Louis. buckley@wustl.edu
**Dr. Gianpaolo Carosi,** Lawrence Livermore National Laboratory. carosi2@llnl.gov
**Professor Kater Murch,** Washington University, St. Louis. murch@physics.wustl.edu
**Dr. Noah S. Oblath,** Pacific Northwest National Laboratory. noah.oblath@pnnl.gov
**Professor Leslie Rosenberg,** University of Washington. ljrosenberg@uw.edu
**Professor Gray Rybka,** University of Washington. grybka@uw.edu
**Professor David Tanner,** University of Florida. tanner@phys.ufl.edu

**Senior Personnel:**

**University of Washington:** Dr. Chelsea Bartram, Dr. Nicole Crisosto, Dr. Jihee Yang
**Los Alamos National Laboratory:** Dr. Leanne Duffy
**University of California, Berkeley:** Professor John Clarke, Professor Irfan Siddiqi
**Lawrence Livermore National Laboratory:** Dr. Nathan Woollett
**Pacific Northwest National Laboratory:** Dr. Christian Boutan, Dr. Benjamin LaRoque
**University of Florida:** Professor Neil Sullivan
**Washington University, St. Louis:** Professor Erik Henriksen
**Fermi National Accelerator Laboratory:** Dr. Daniel Bowring, Dr. Aaron Chou, Dr. Rakshya Khatiwada, Dr. William Wester
**University of Western Australia:** Professor Michael Tobar

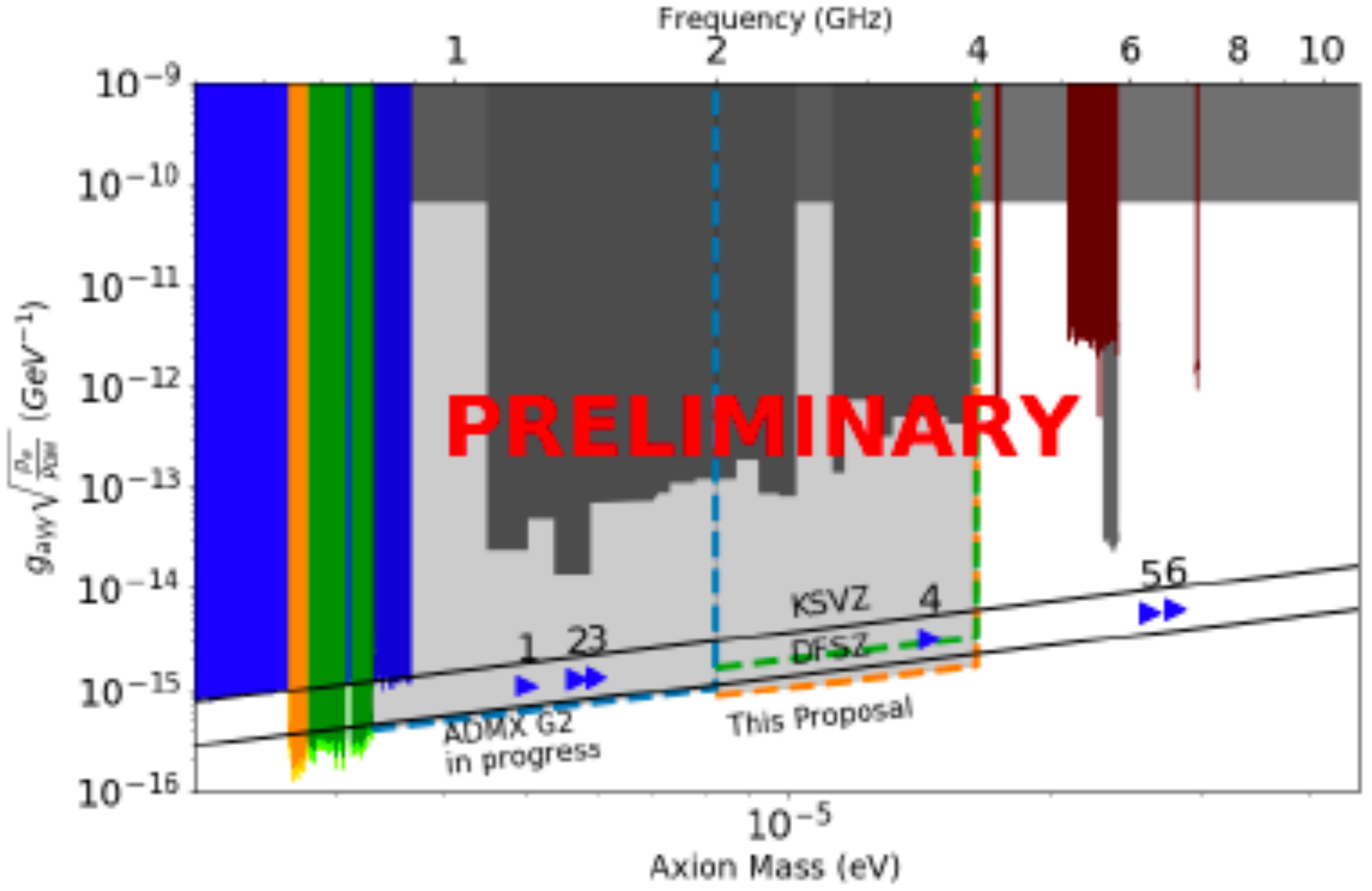
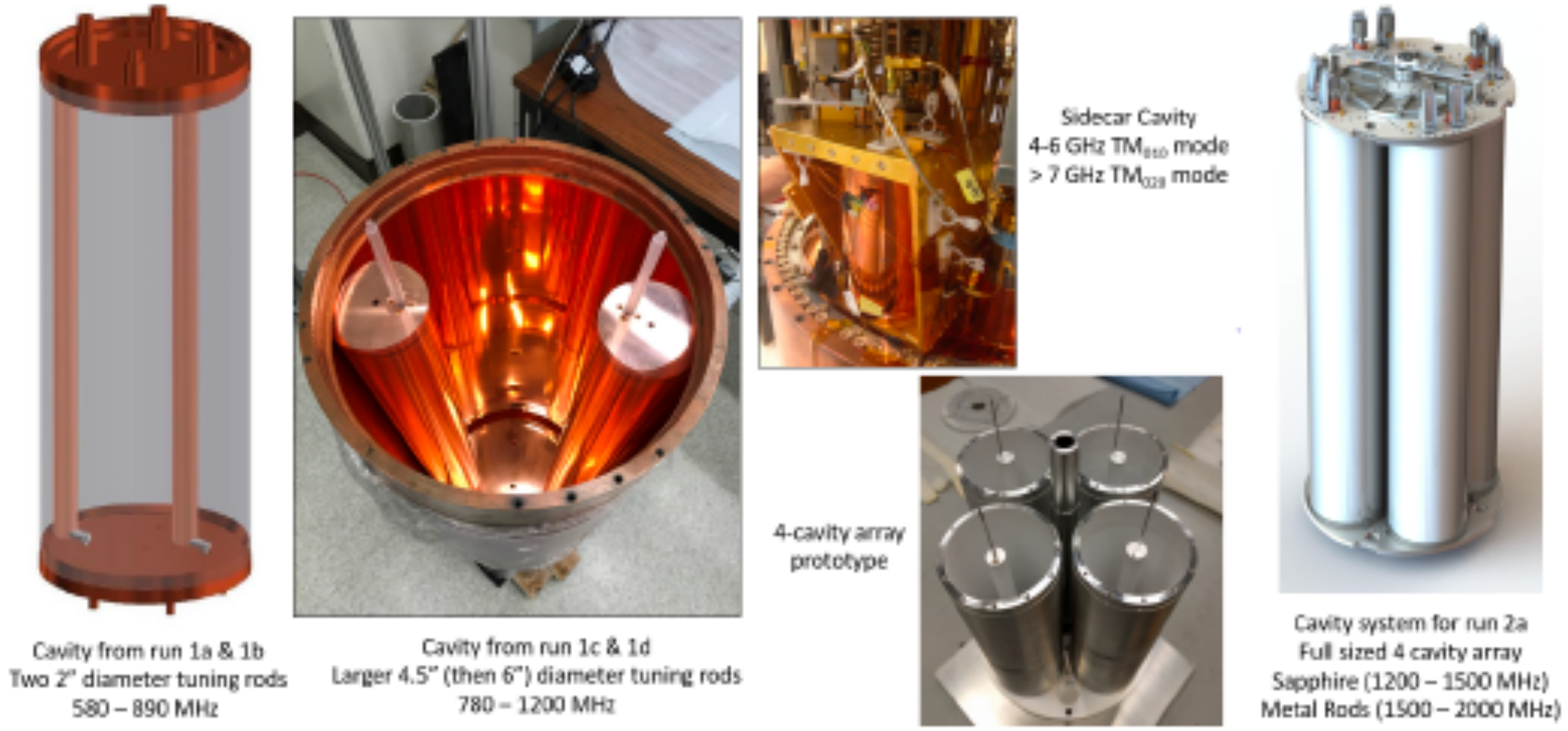


**Figure 3:** Axion coupling and mass parameter space showing regions covered by previous experiments, current ADMX G2 operations, and this proposal. Recent axion mass lower bound predictions are also shown numbered as follows: 1: Bonati (2016), 2: di Cortona (2016) 3: Petreczky (2016), 4: Berkowitz (2015), 5: Klaer (2017), 6: Borsanyi (2016)



Cavity from run 1a & 1b
Two 2" diameter tuning rods
580 – 890 MHz

Cavity from run 1c & 1d
Larger 4.5" (then 6") diameter tuning rods
780 – 1200 MHz

Cavity system for run 2a
Full sized 4 cavity array
Sapphire (1200 – 1500 MHz)
Metal Rods (1500 – 2000 MHz)

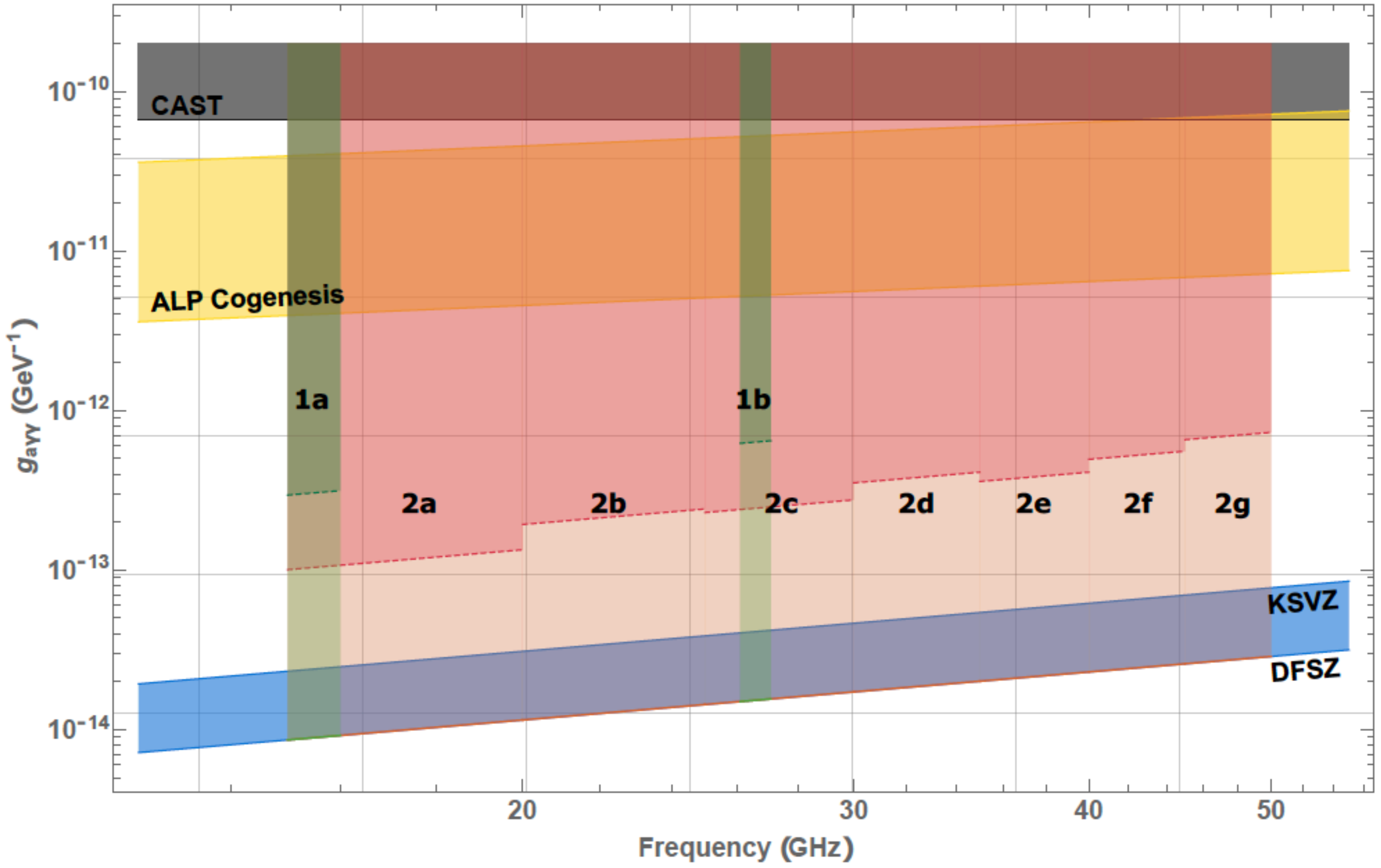
**Figure 6:** Set of currently deployed and planned cavities for the ADMX Gen 2 program that operates to 2 GHz. The Sidecar cavity system represents our in-situ testbed cavity system that will be the baseline unit for our 14 cavity array.

# ORGAN

## ORGAN: A summary

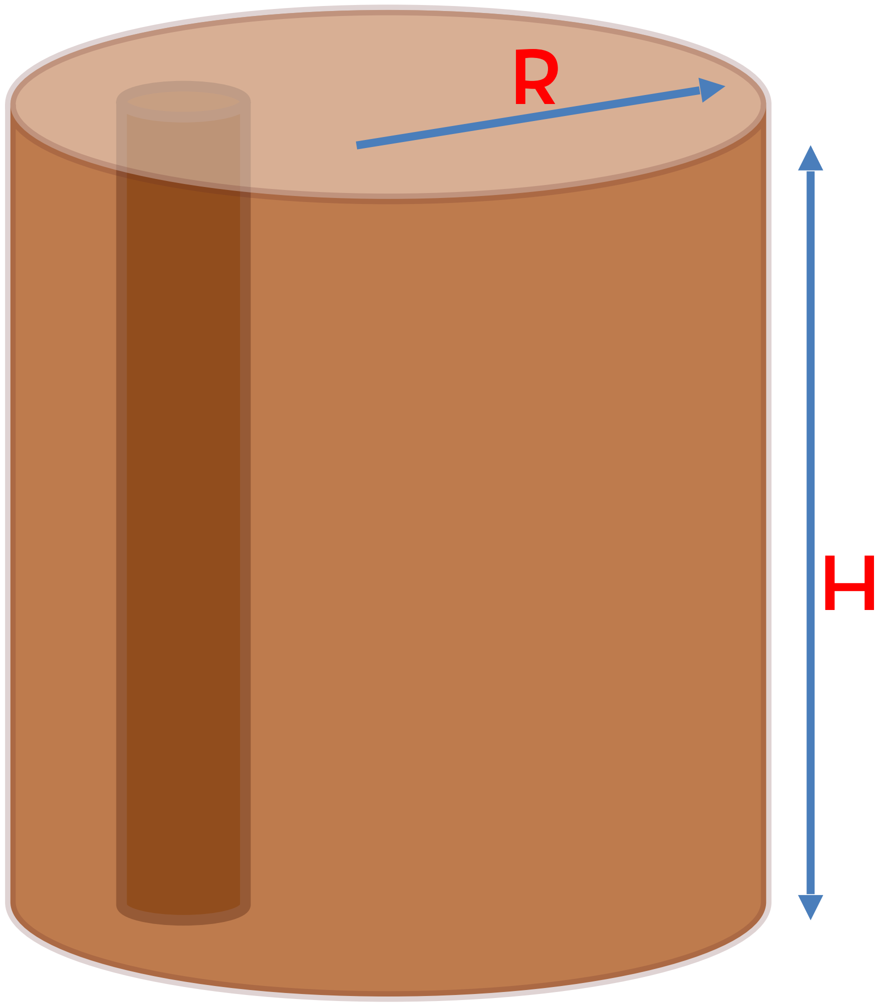
THE UNIVERSITY OF WESTERN AUSTRALIA

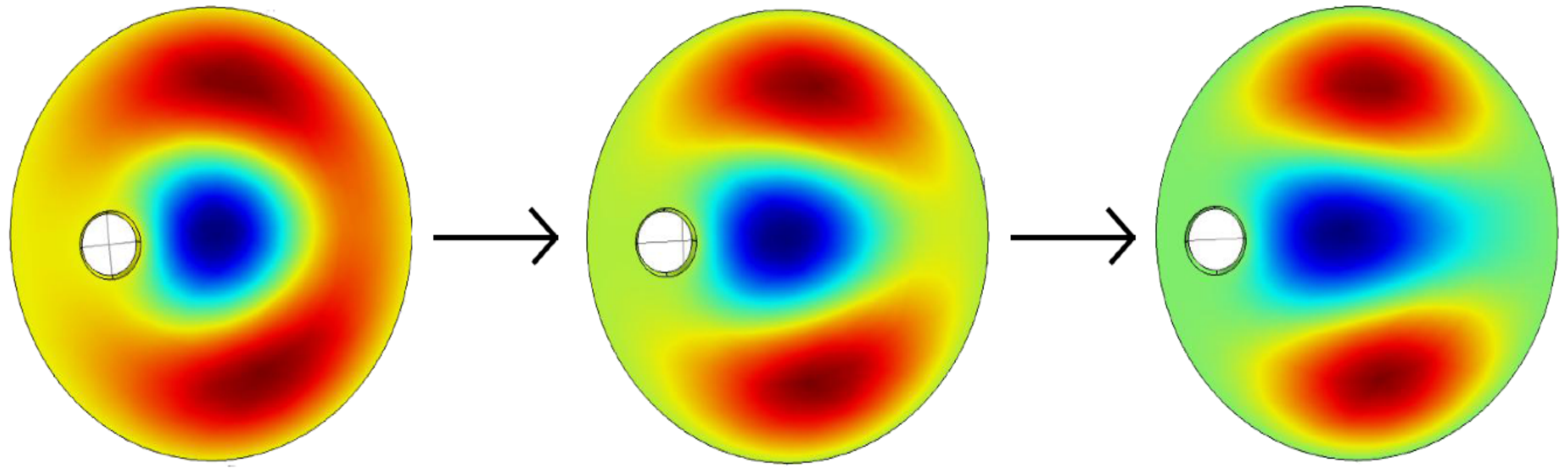
- High frequency haloscope at UWA (>15 GHz)
- Multi-stage project:
  - Narrow searches around 15-16 GHz, and 26-27 GHz (Phase I)
  - Wider scan at high frequencies: 15-50 GHz (Phase II)
- Pathfinder experiment already complete
- Funding for future acquired
- Ready to scale up and detect some axions
- Other complementary axion dark matter searches in development at UWA



- Phase 1, Darker green HEMT-based amplifiers, and $TM_{010}$, tuning rod-based resonators, form factor of 0.4, loaded Q of 30,000.
- Upgrade Lighter green -> Photon Counter, form factor of 0.45, a loaded quality factor of 50,000, and 50% greater volume
- Phase 2, Darker red quantum limited linear amplifiers (2-4 cavities) Quantum limited
- Lighter red, single photon counter

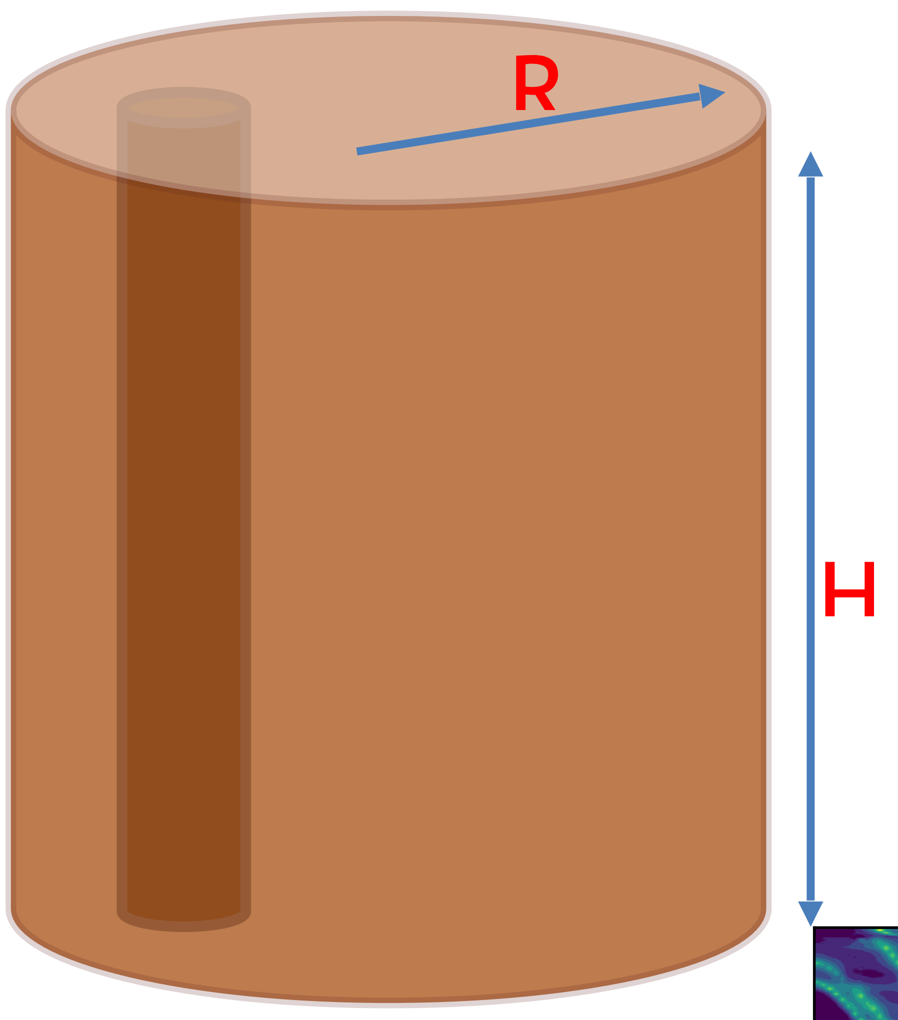
# FIRST CAVITY DESIGN: Standard

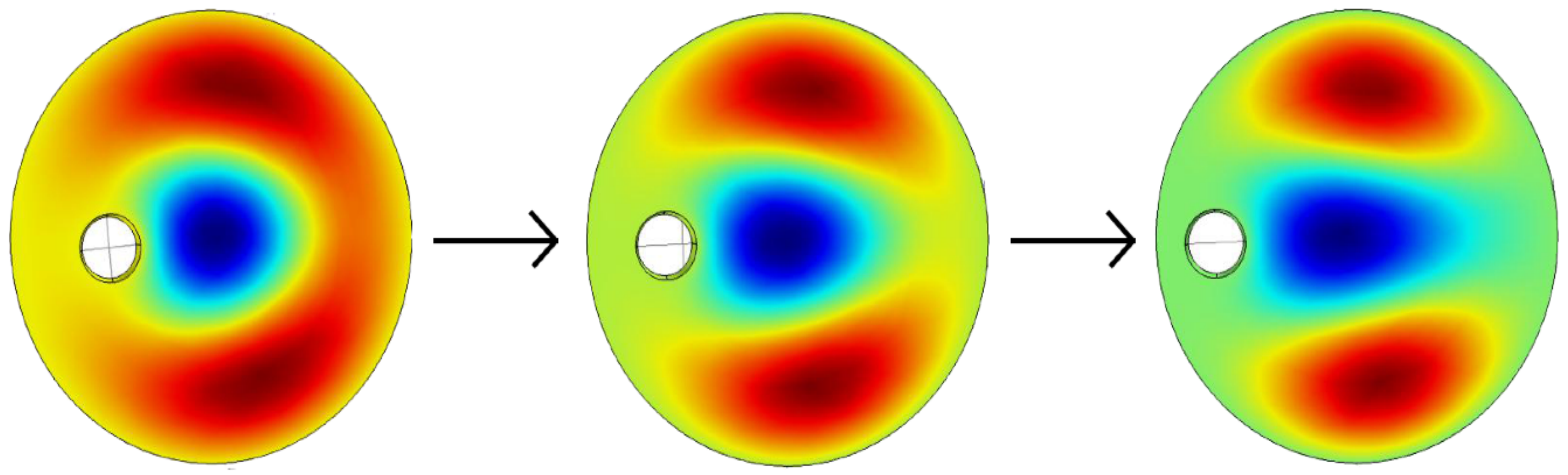




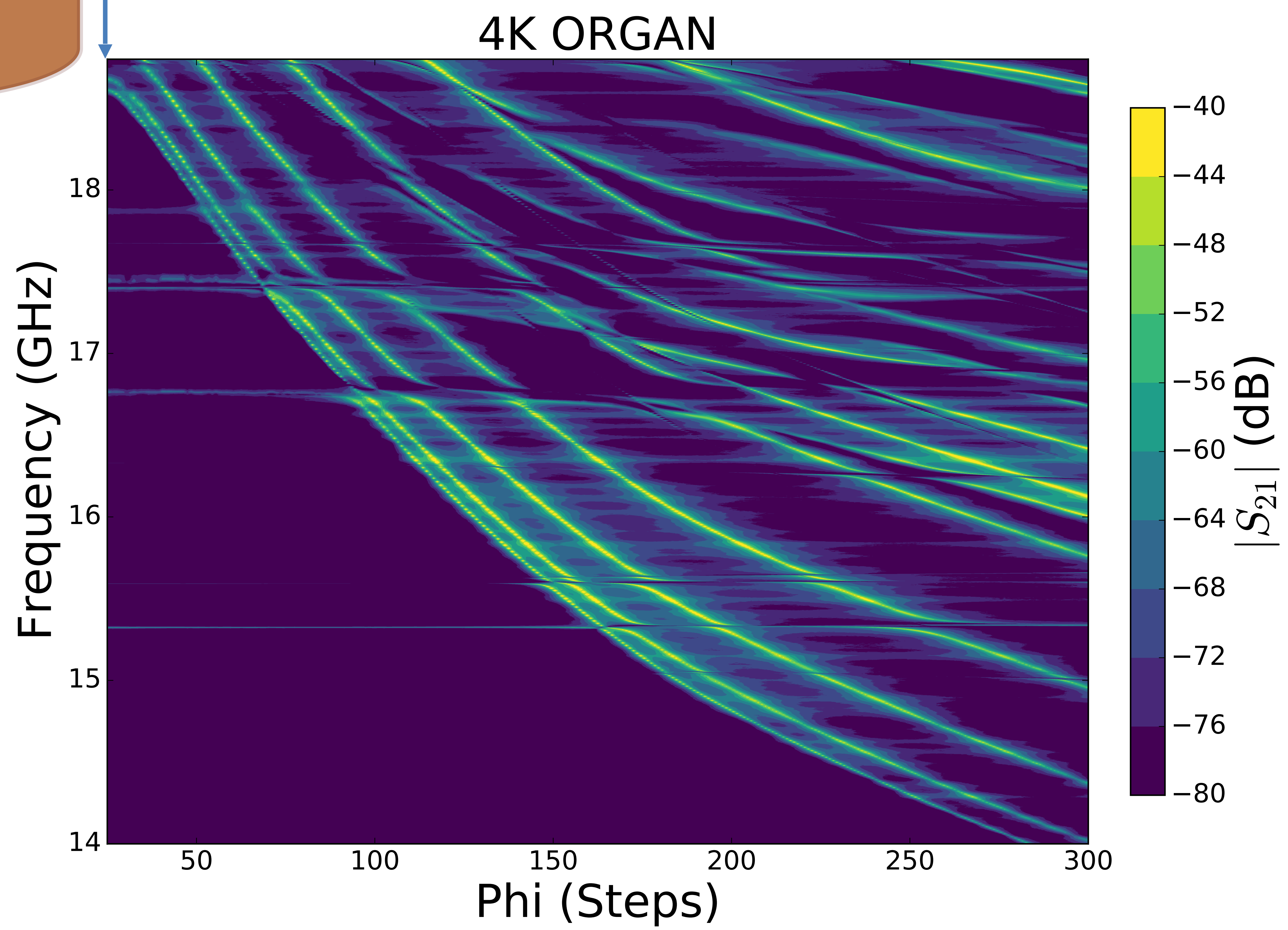
Top Down view of $E_z$ field over tuning range

# FIRST CAVITY DESIGN: Standard

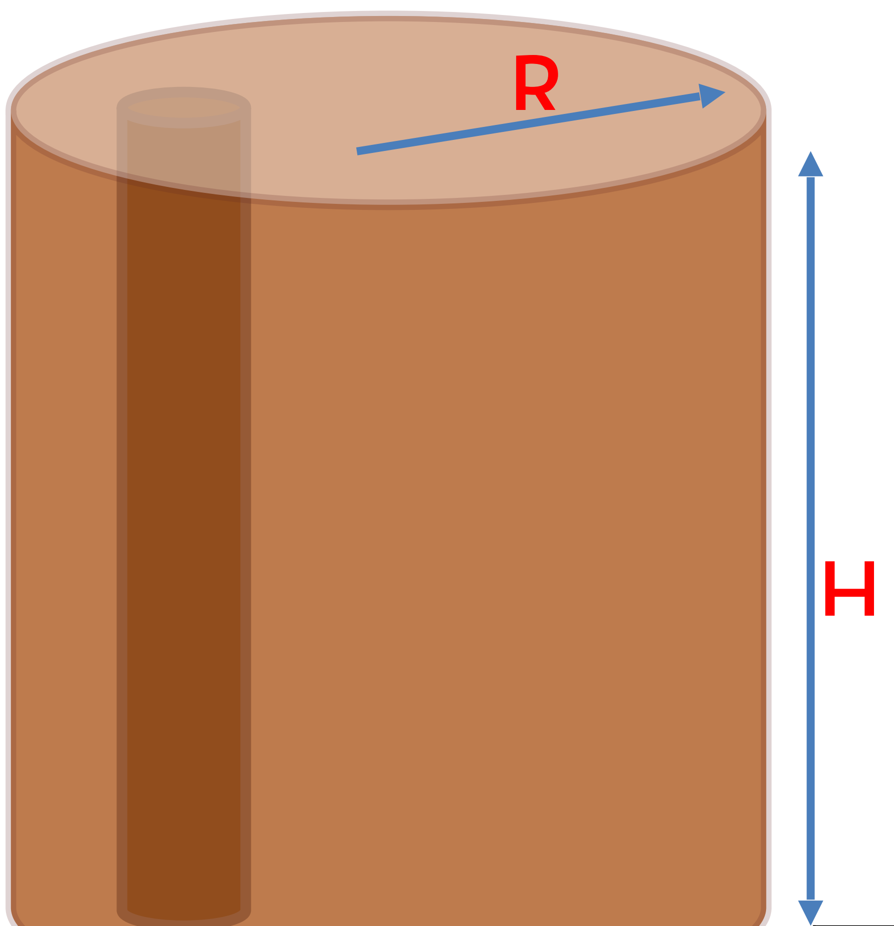


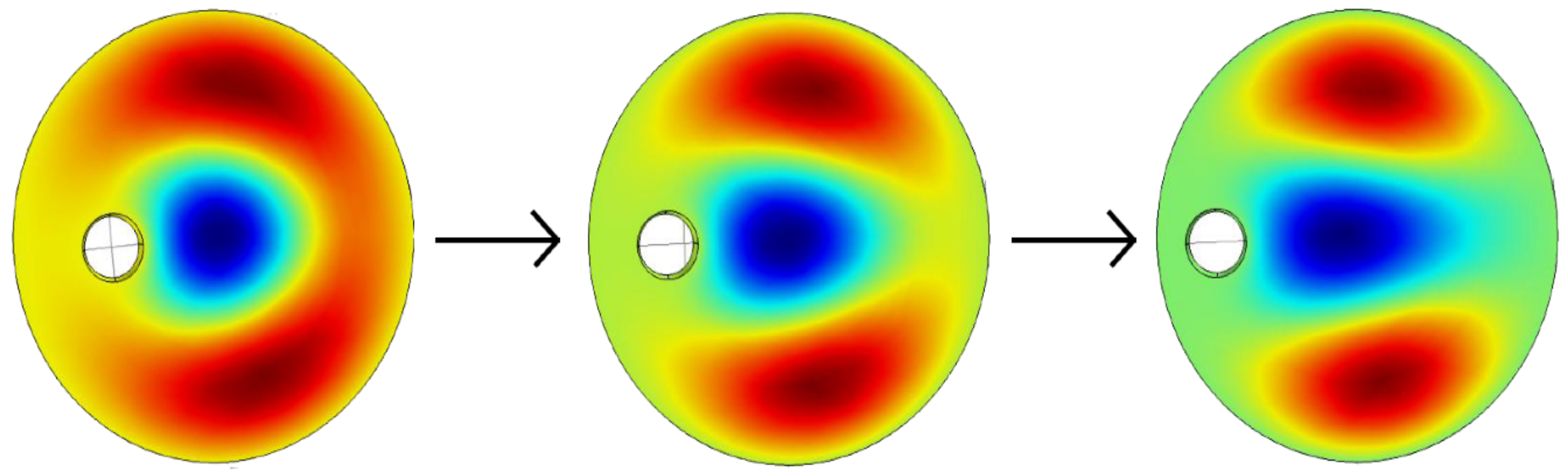


Top Down view of $E_z$ field over tuning range



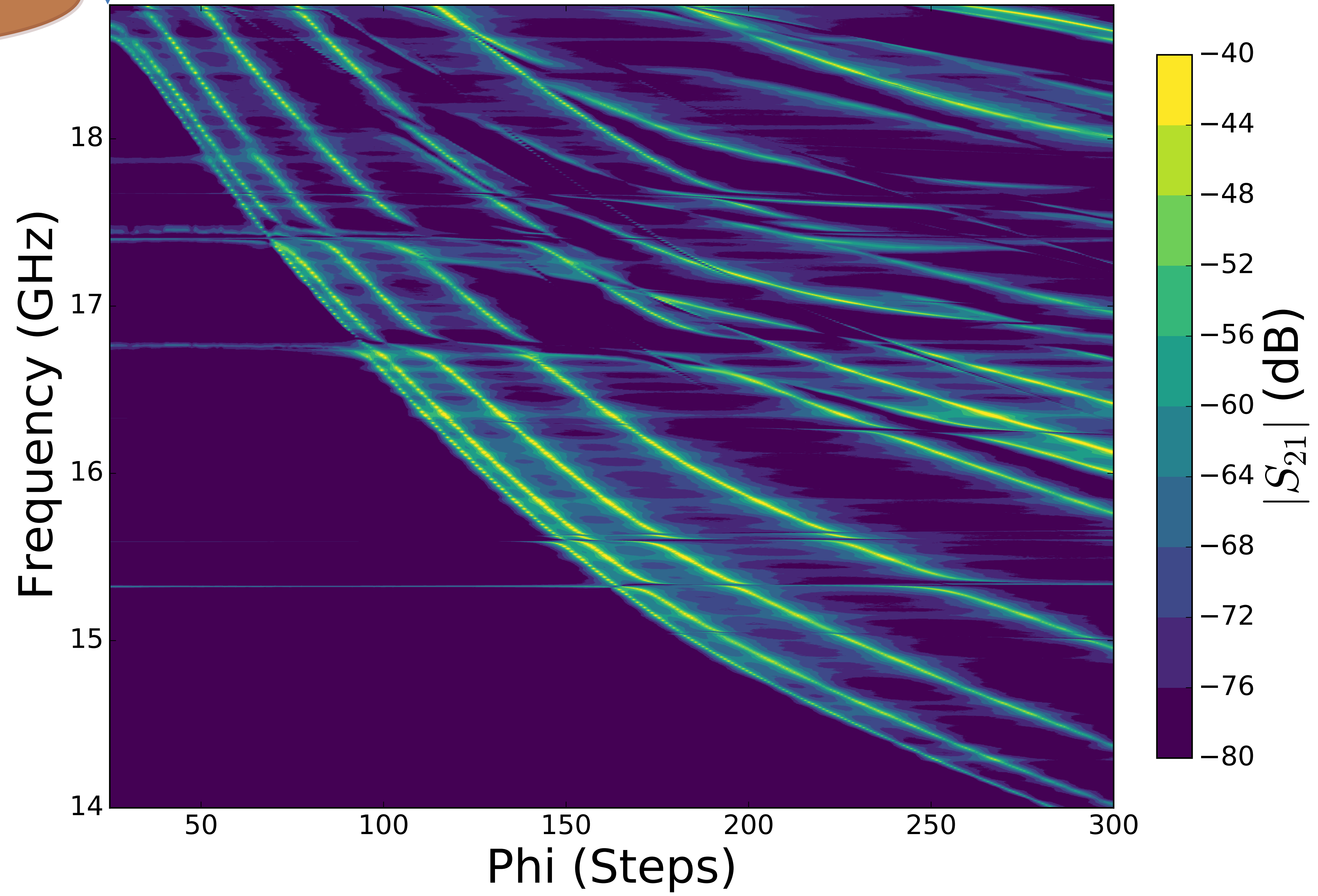
# FIRST CAVITY DESIGN: Standard

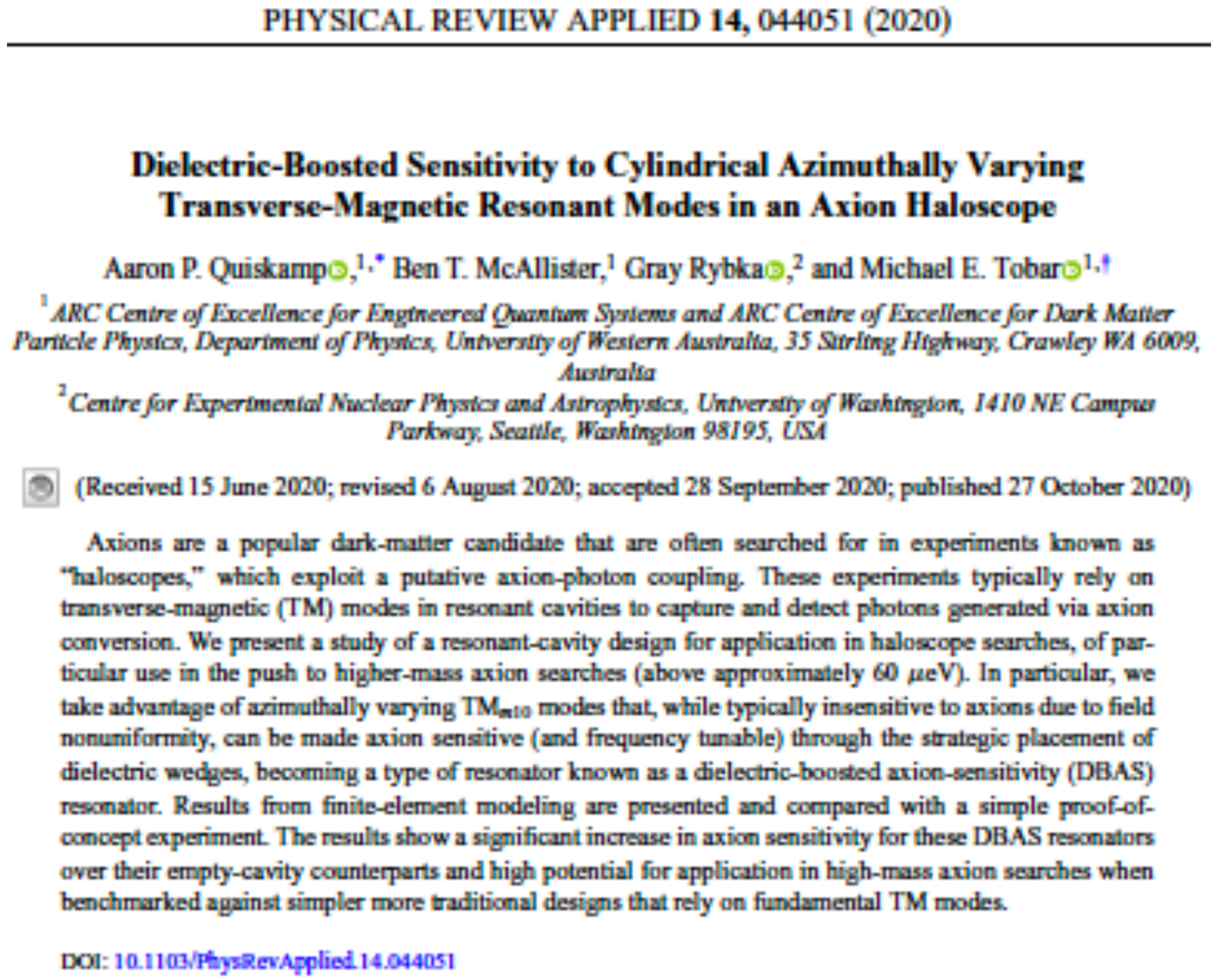




Top Down view of $E_z$ field over tuning range

4K ORGAN





PHYSICAL REVIEW APPLIED **14,** 044051 (2020)

**Dielectric-Boosted Sensitivity to Cylindrical Azimuthally Varying Transverse-Magnetic Resonant Modes in an Axion Haloscope**

Aaron P. Quiskamp,[1,*] Ben T. McAllister,[1] Gray Rybka,[2] and Michael E. Tobar[1,†]

[1] *ARC Centre of Excellence for Engineered Quantum Systems and ARC Centre of Excellence for Dark Matter Particle Physics, Department of Physics, University of Western Australia, 35 Stirling Highway, Crawley WA 6009, Australia*

[2] *Centre for Experimental Nuclear Physics and Astrophysics, University of Washington, 1410 NE Campus Parkway, Seattle, Washington 98195, USA*

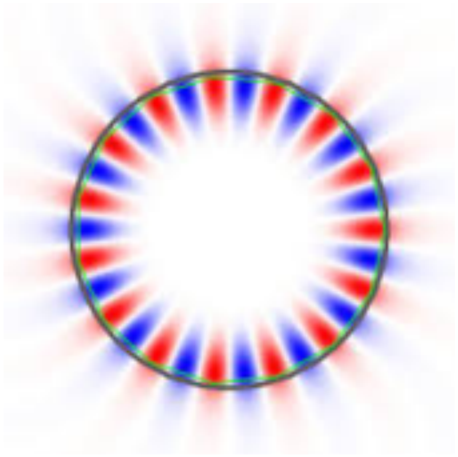
(Received 15 June 2020; revised 6 August 2020; accepted 28 September 2020; published 27 October 2020)

Axions are a popular dark-matter candidate that are often searched for in experiments known as "haloscopes," which exploit a putative axion-photon coupling. These experiments typically rely on transverse-magnetic (TM) modes in resonant cavities to capture and detect photons generated via axion conversion. We present a study of a resonant-cavity design for application in haloscope searches, of particular use in the push to higher-mass axion searches (above approximately 60 $\mu$eV). In particular, we take advantage of azimuthally varying $TM_{m10}$ modes that, while typically insensitive to axions due to field nonuniformity, can be made axion sensitive (and frequency tunable) through the strategic placement of dielectric wedges, becoming a type of resonator known as a dielectric-boosted axion-sensitivity (DBAS) resonator. Results from finite-element modeling are presented and compared with a simple proof-of-concept experiment. The results show a significant increase in axion sensitivity for these DBAS resonators over their empty-cavity counterparts and high potential for application in high-mass axion searches when benchmarked against simpler more traditional designs that rely on fundamental TM modes.

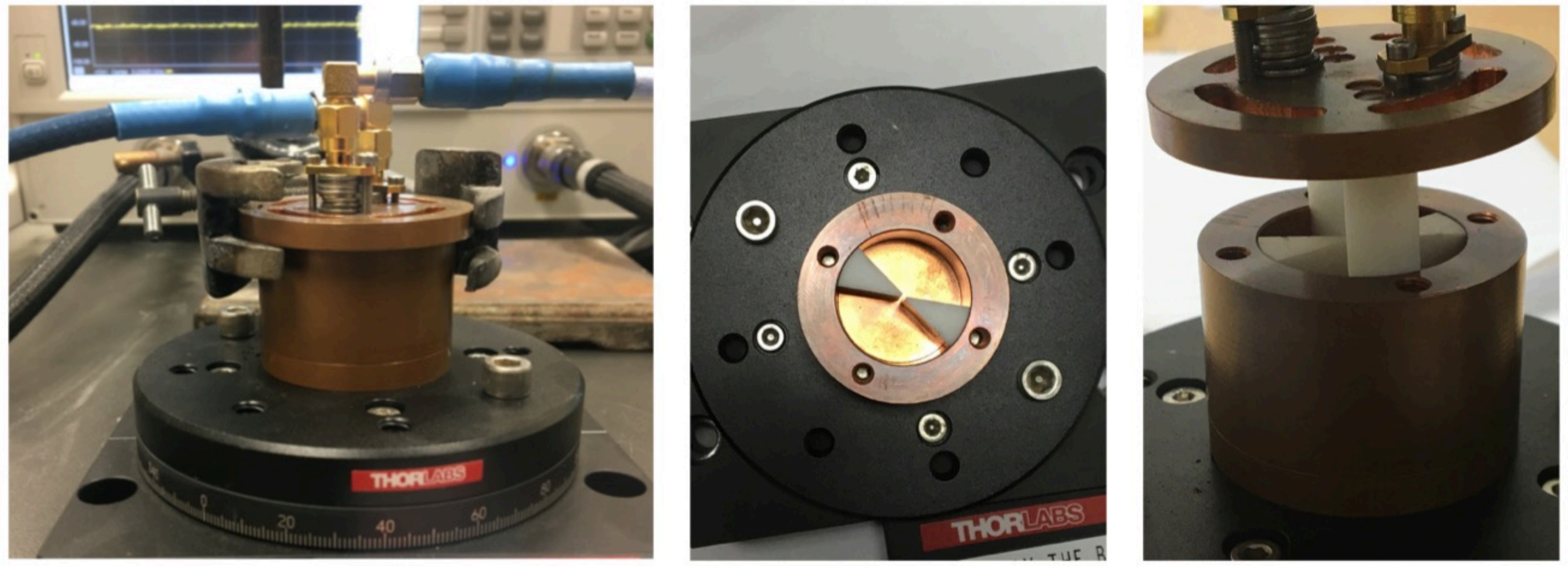
DOI: 10.1103/PhysRevApplied.14.044051

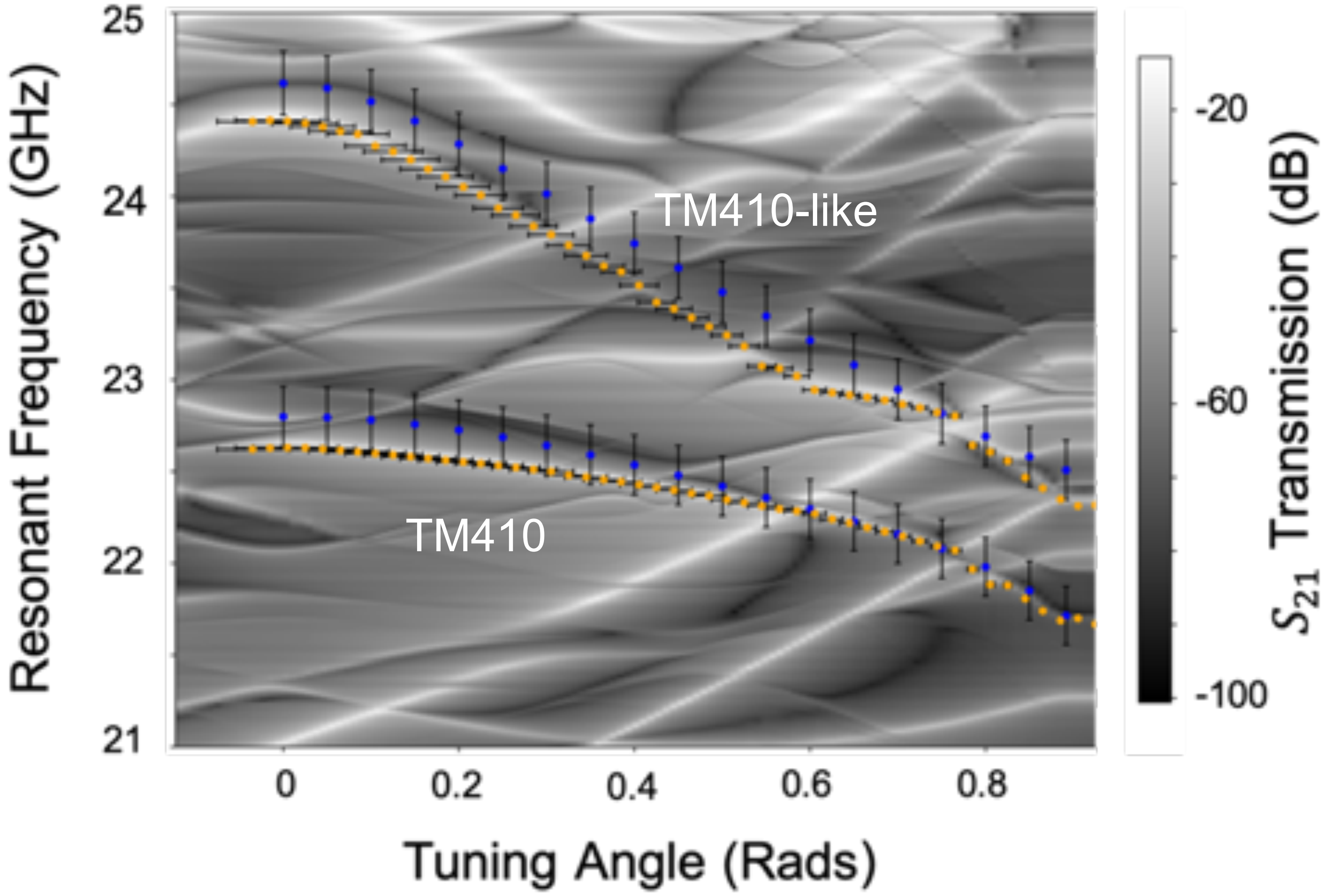
# NEXT CAVITY DESIGN: New Concept

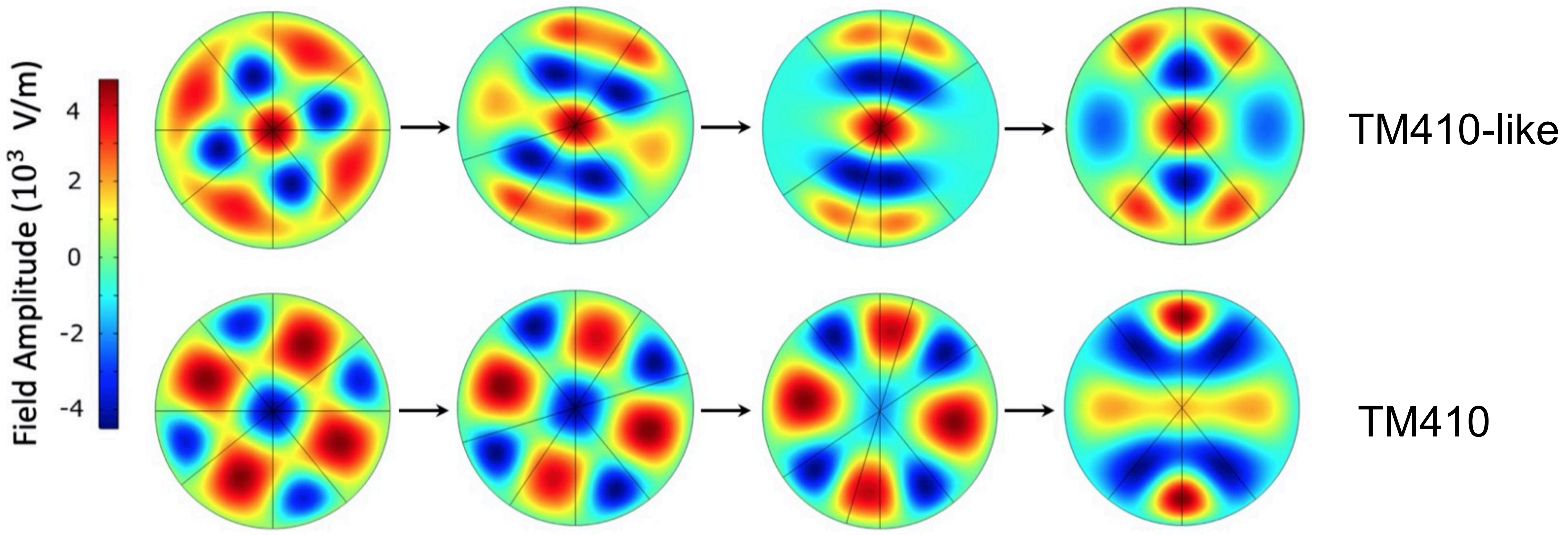
## Dielectric Wedge Resonator



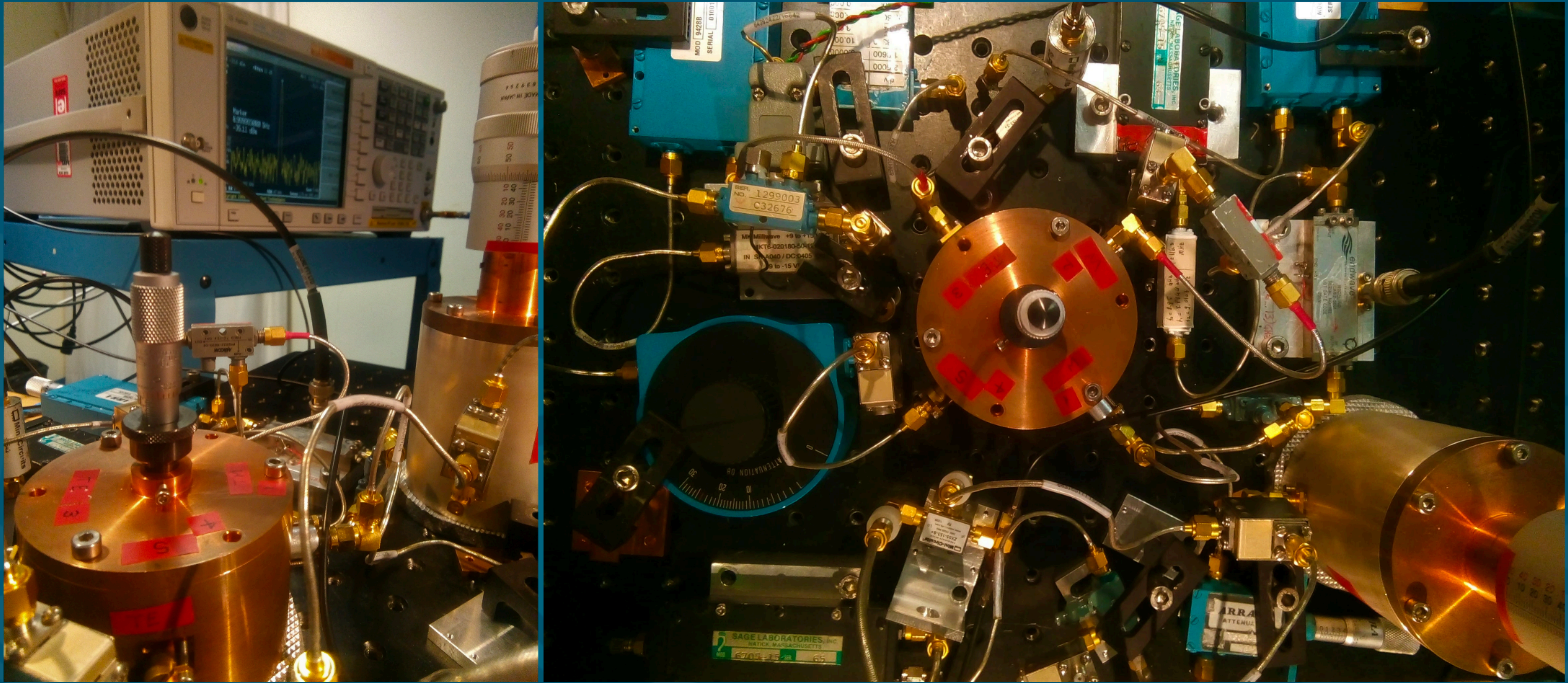
- Add dielectrics in alternate field lobes → boost form factor
- Design with Sapphire, Large Improvement in Sensitivity
- Tested with Teflon







# UPLOAD



THE UNIVERSITY OF
WESTERN
AUSTRALIA

ARC CENTRE OF EXCELLENCE FOR
DARK
MATTER

EQUS
Australian Research Council
Centre of Excellence for
Engineered Quantum Systems

# Schematic of the Experimental Setup

Axion Search via Dual-Mode Oscillator

Pump Oscillator

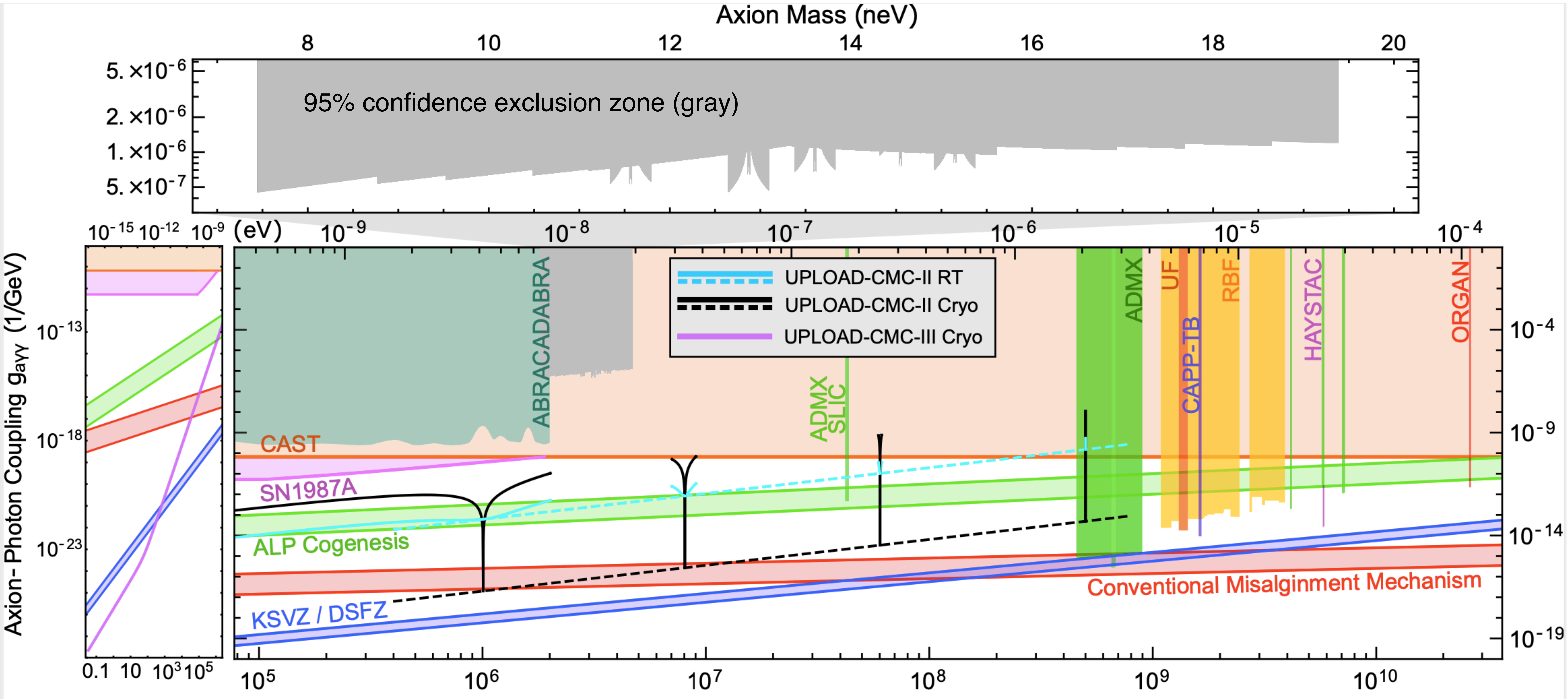
Read out Oscillator

Measure Frequency Noise

**Frequency Counter**
**Keysight 53230A**

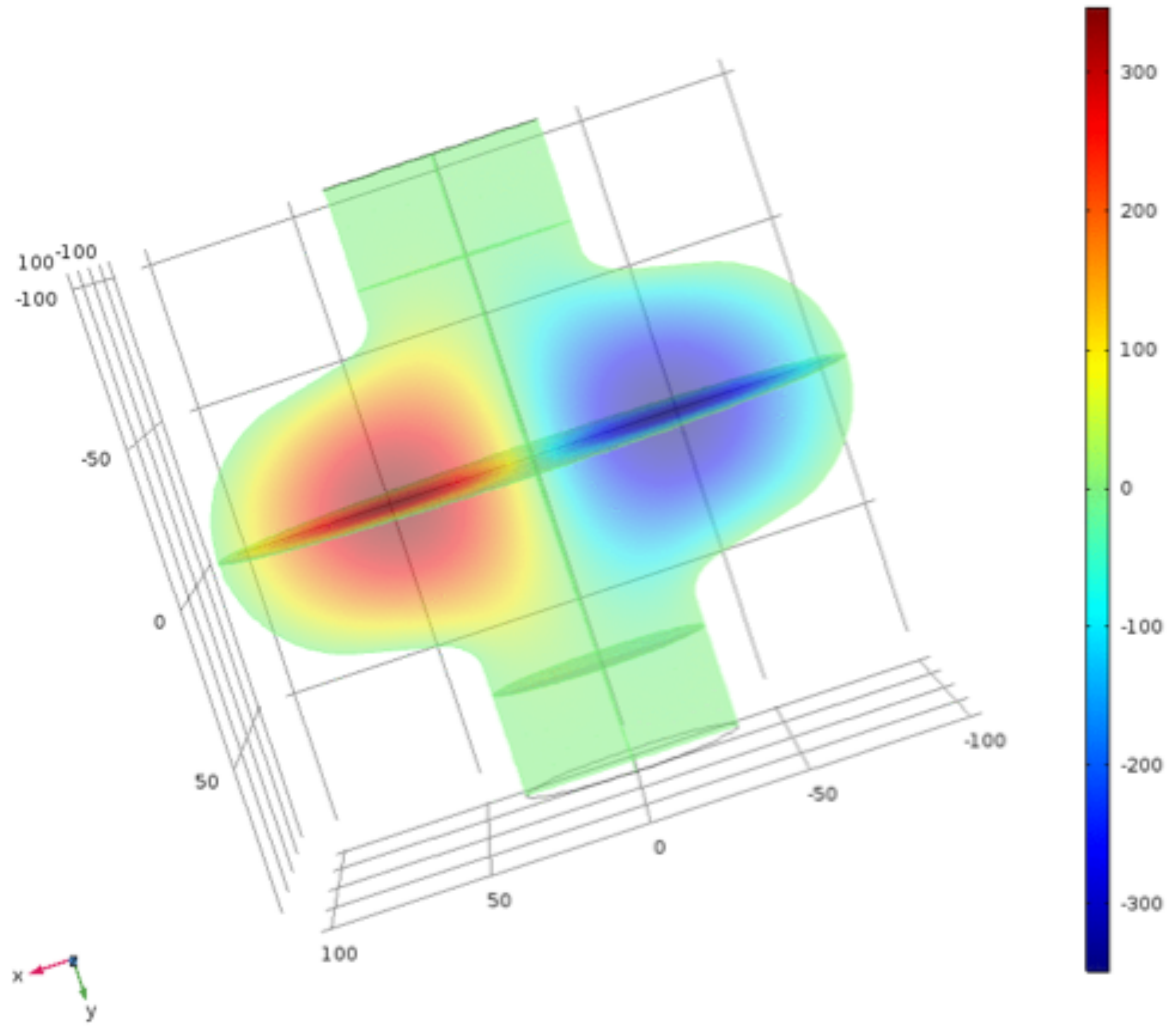
**VSA (FFT)**
**HP89410A**

**Oscilloscope**
**Keysight DSOX2012A**

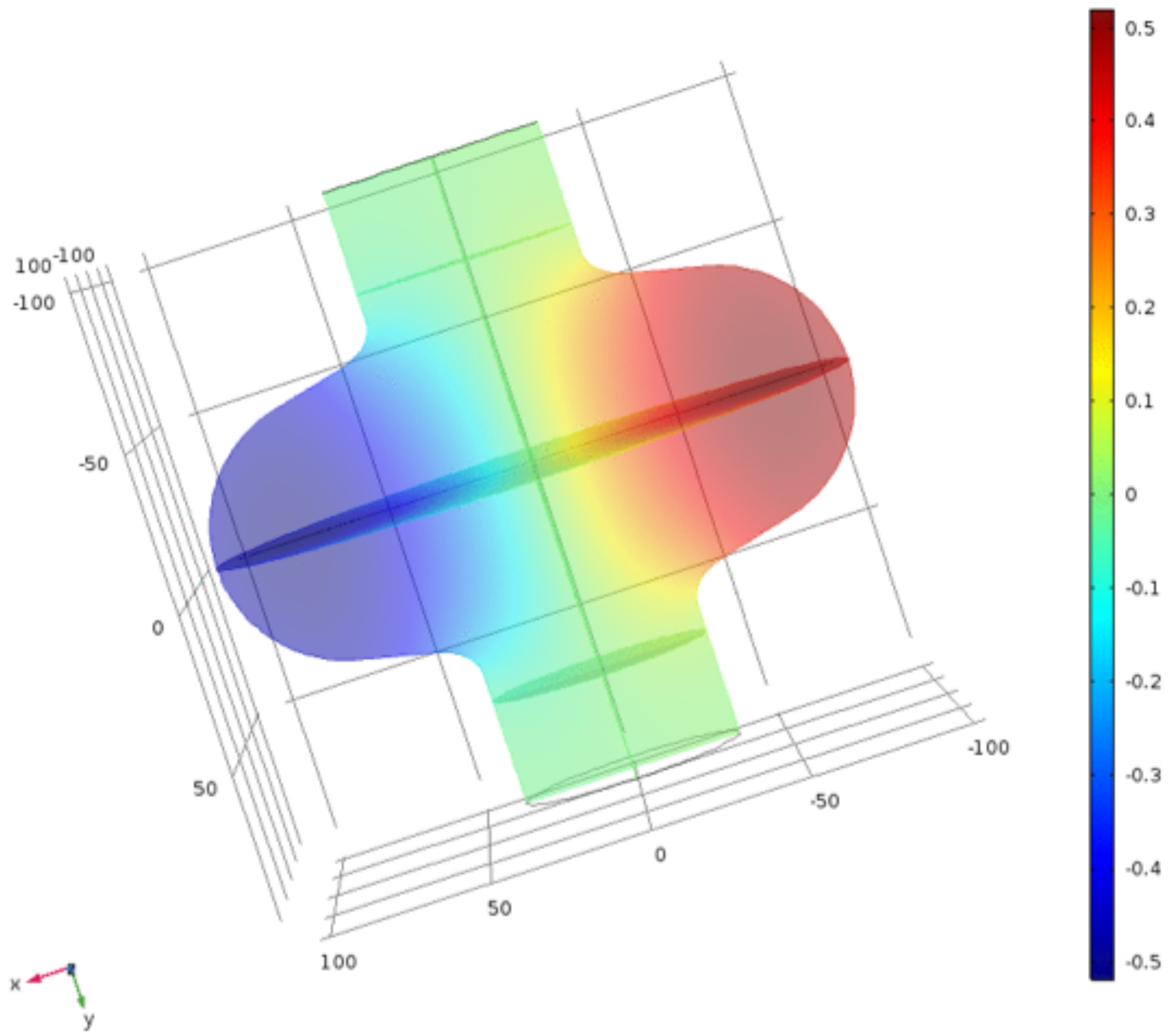

Axion Mass (neV)
8
10
12
14
16
18
20
5. ×10^-6
2. ×10^-6
1. ×10^-6
5. ×10^-7
95% confidence exclusion zone (gray)
10^-15
10^-12
10^-9
(eV)
10^-9
10^-8
10^-7
10^-6
10^-5
10^-4
Axion- Photon Coupling g_aγγ (1/GeV)
10^-13
10^-18
10^-23
0.1
10
10^3
10^5
ABRACADABRA
CAST
SN1987A
ALP Cogenesis
KSVZ / DSFZ
ADMX SLIC
ADMX
UF
CAPP-TB
RBF
HAYSTAC
ORGAN
Conventional Misalginment Mechanism
UPLOAD-CMC-II RT
UPLOAD-CMC-II Cryo
UPLOAD-CMC-III Cryo
10^-4
10^-9
10^-14
10^-19
10^5
10^6
10^7
10^8
10^9
10^10

# Nb Tesla Cavities

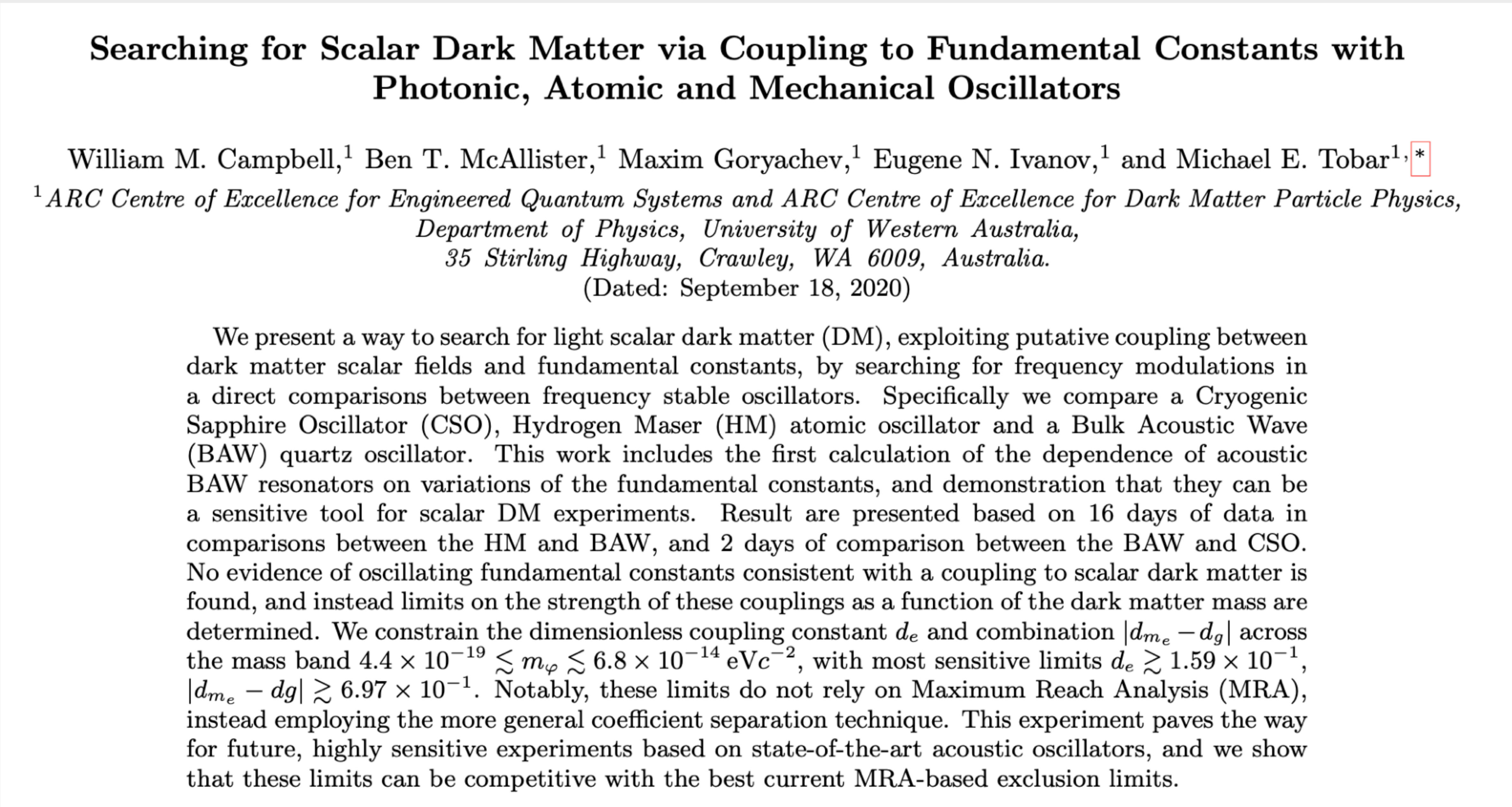
TE 011 MODE, 2.5 GHz



TM 010 MODE, 1.3 GHz



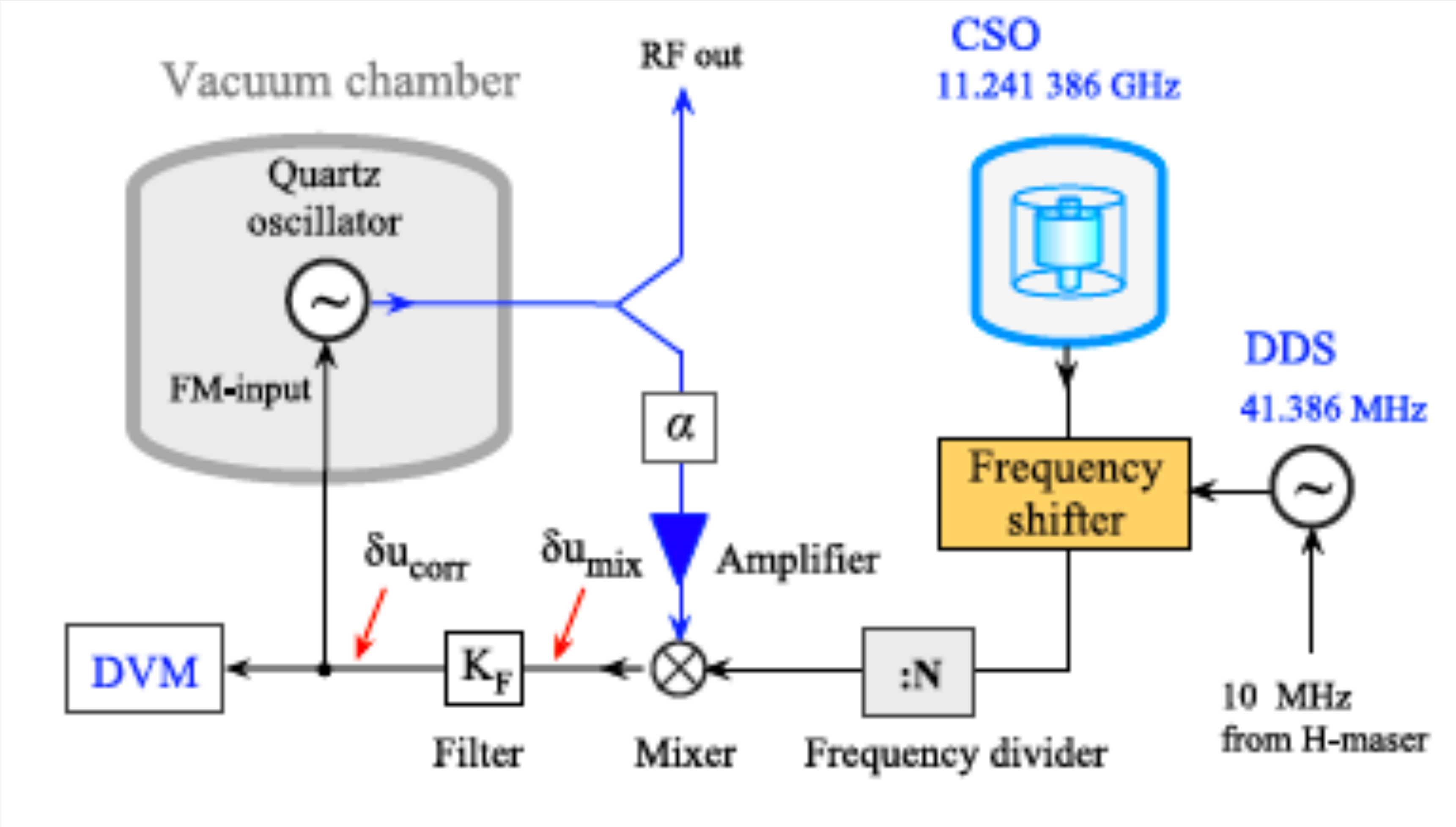
We would like to gain interest from Fermilab to collaborate on this project and add to the LOI

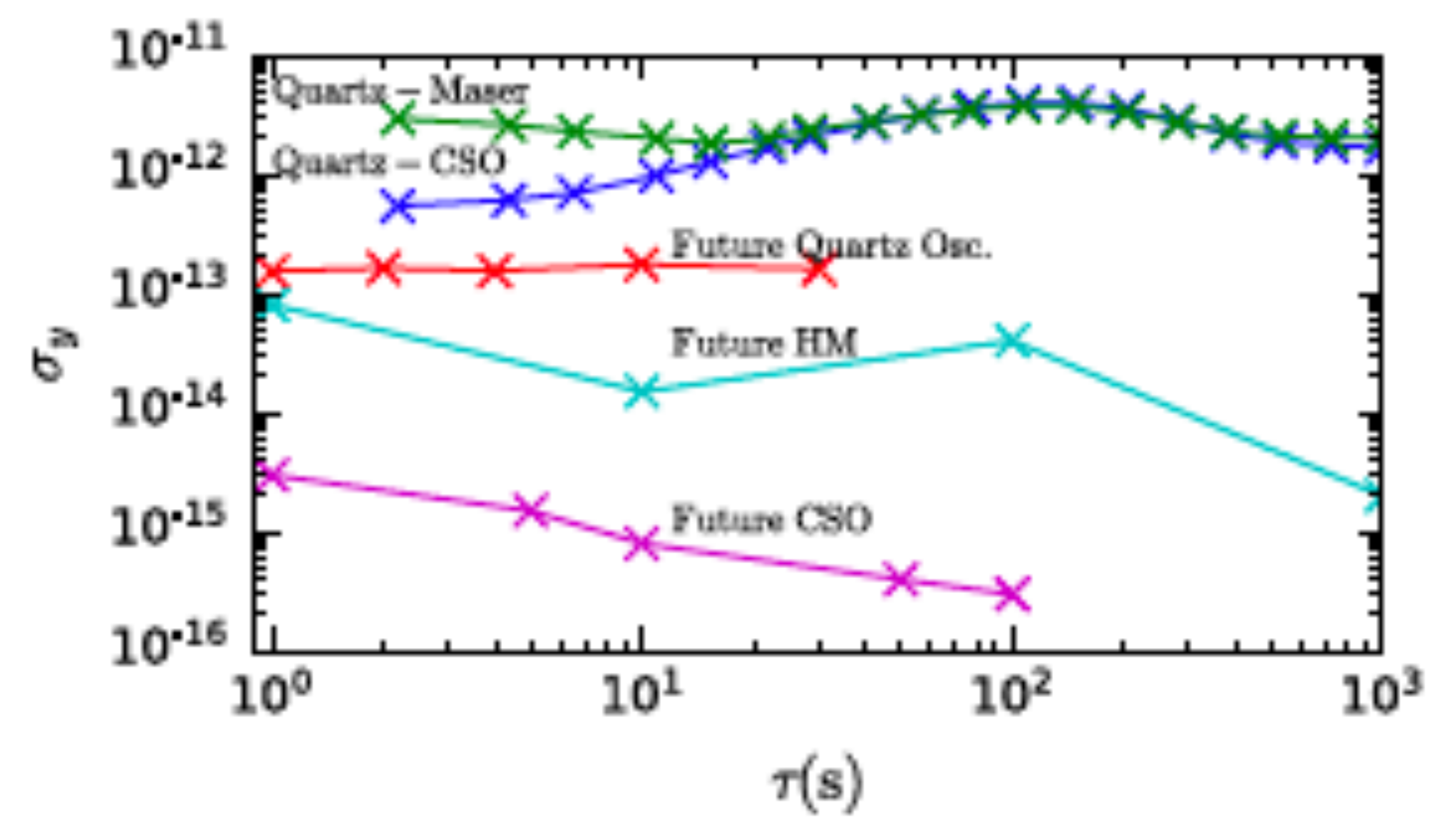


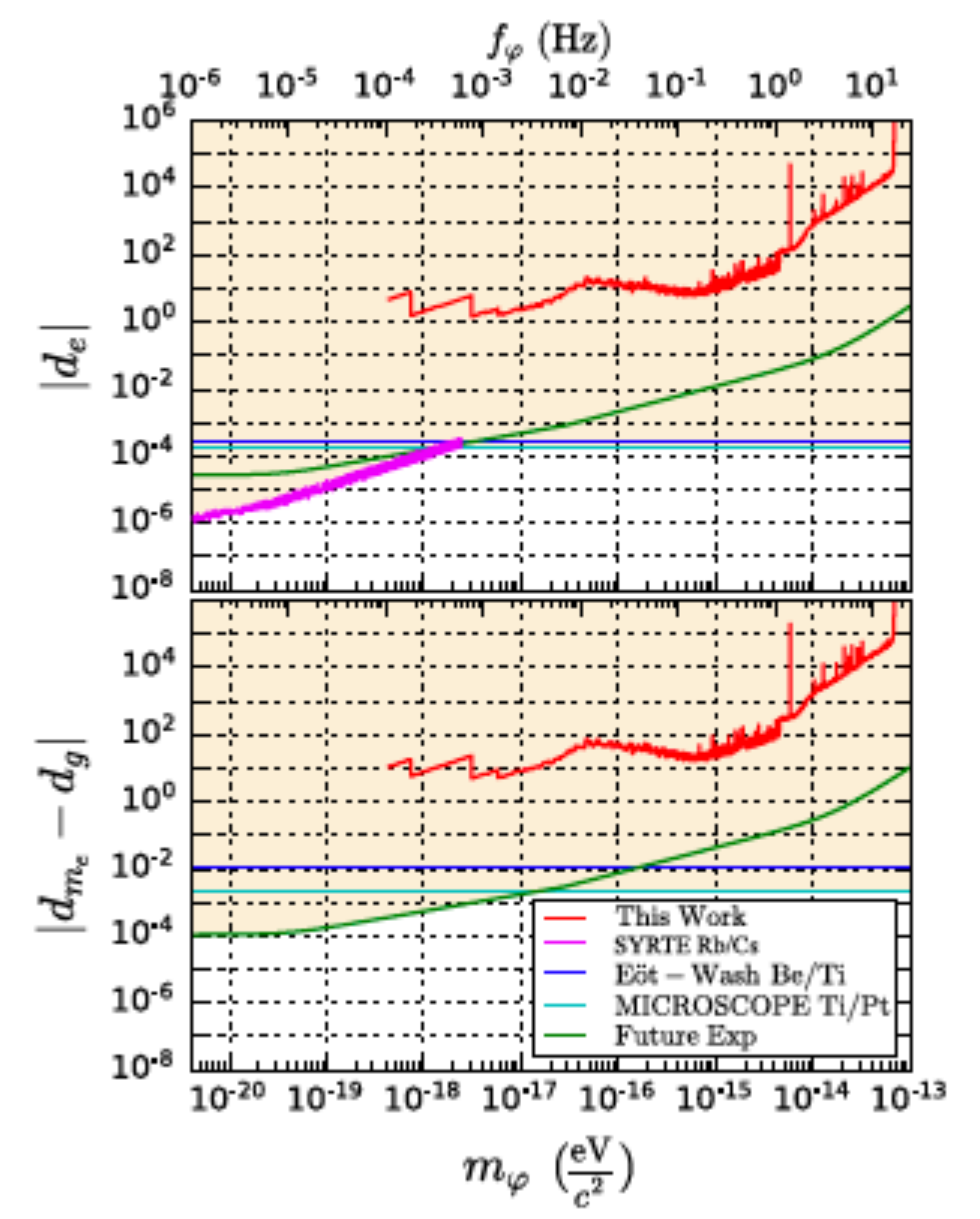
# Searching for Scalar Dark Matter via Coupling to Fundamental Constants with Photonic, Atomic and Mechanical Oscillators

William M. Campbell,[1] Ben T. McAllister,[1] Maxim Goryachev,[1] Eugene N. Ivanov,[1] and Michael E. Tobar[1,*]
[1] *ARC Centre of Excellence for Engineered Quantum Systems and ARC Centre of Excellence for Dark Matter Particle Physics,*
*Department of Physics, University of Western Australia,*
*35 Stirling Highway, Crawley, WA 6009, Australia.*
(Dated: September 18, 2020)

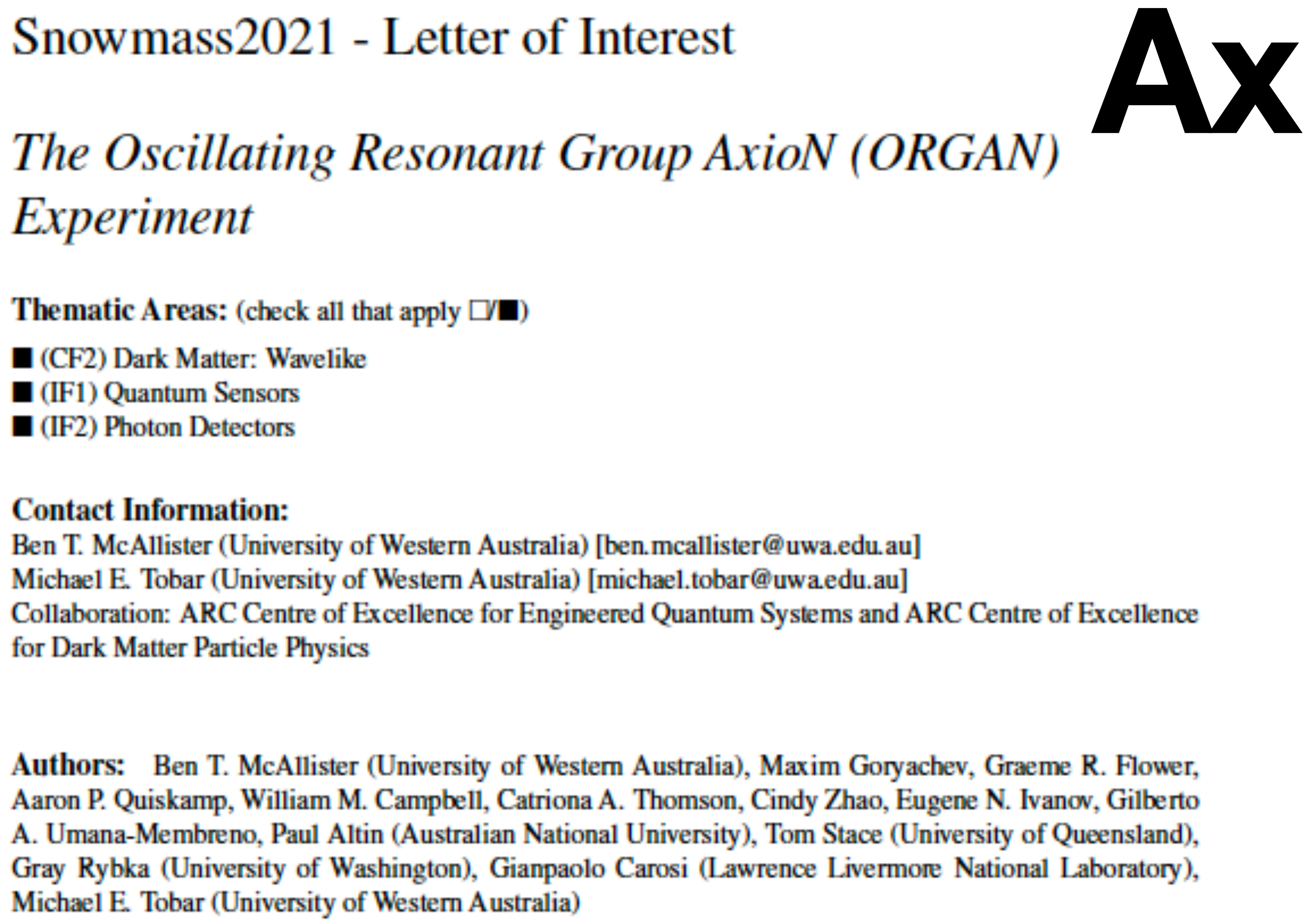
We present a way to search for light scalar dark matter (DM), exploiting putative coupling between dark matter scalar fields and fundamental constants, by searching for frequency modulations in a direct comparisons between frequency stable oscillators. Specifically we compare a Cryogenic Sapphire Oscillator (CSO), Hydrogen Maser (HM) atomic oscillator and a Bulk Acoustic Wave (BAW) quartz oscillator. This work includes the first calculation of the dependence of acoustic BAW resonators on variations of the fundamental constants, and demonstration that they can be a sensitive tool for scalar DM experiments. Result are presented based on 16 days of data in comparisons between the HM and BAW, and 2 days of comparison between the BAW and CSO. No evidence of oscillating fundamental constants consistent with a coupling to scalar dark matter is found, and instead limits on the strength of these couplings as a function of the dark matter mass are determined. We constrain the dimensionless coupling constant $d_e$ and combination $|d_{m_e} - d_g|$ across the mass band $4.4 \times 10^{-19} \lesssim m_\varphi \lesssim 6.8 \times 10^{-14}$ eVc$^{-2}$, with most sensitive limits $d_e \gtrsim 1.59 \times 10^{-1}$, $|d_{m_e} - dg| \gtrsim 6.97 \times 10^{-1}$. Notably, these limits do not rely on Maximum Reach Analysis (MRA), instead employing the more general coefficient separation technique. This experiment paves the way for future, highly sensitive experiments based on state-of-the-art acoustic oscillators, and we show that these limits can be competitive with the best current MRA-based exclusion limits.







# Axions: Letters of Interest: SNOWMASS



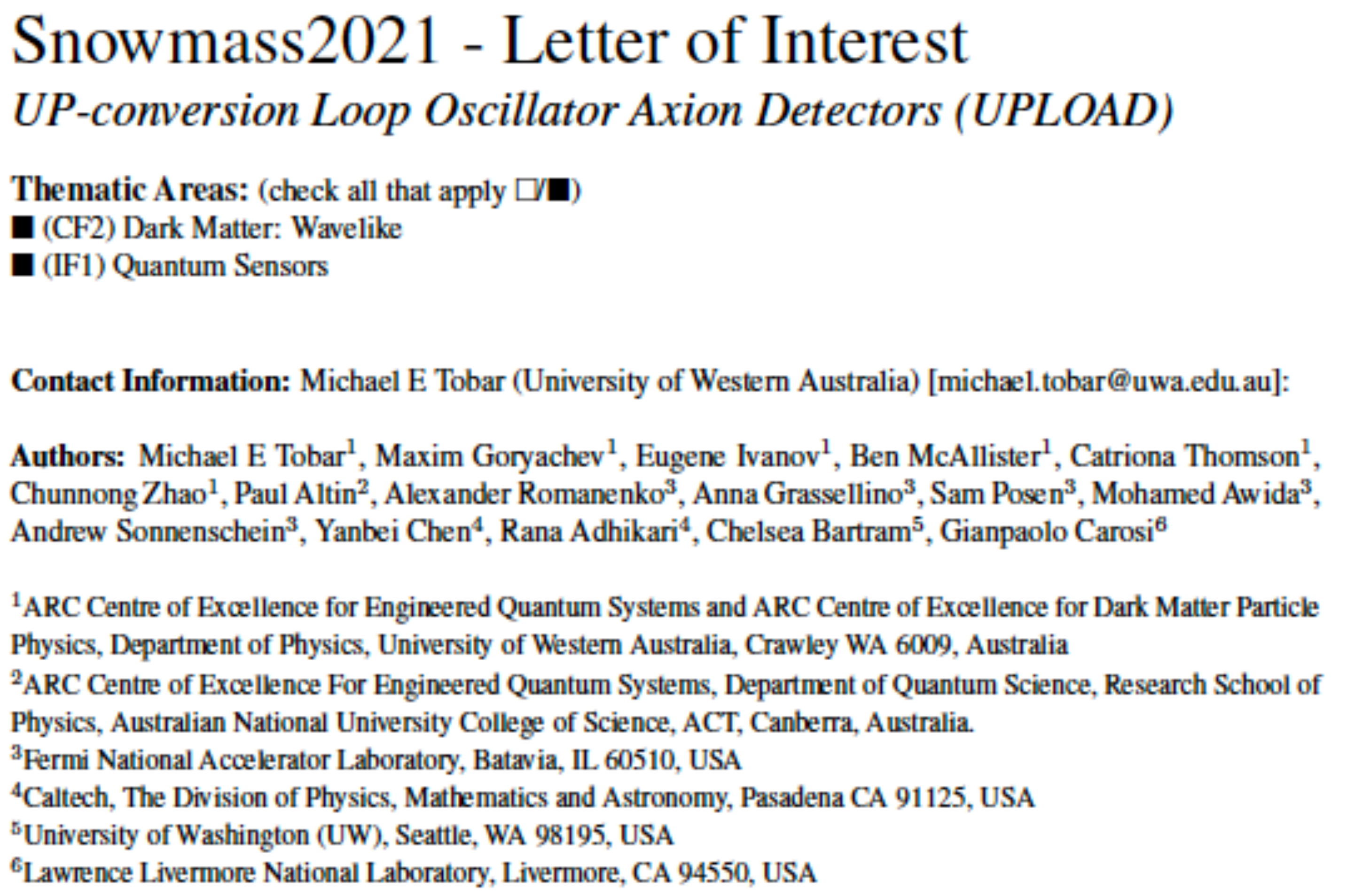
Snowmass2021 - Letter of Interest

## *The Oscillating Resonant Group AxioN (ORGAN) Experiment*

**Thematic Areas:** (check all that apply ☐/■)
■ (CF2) Dark Matter: Wavelike
■ (IF1) Quantum Sensors
■ (IF2) Photon Detectors

**Contact Information:**
Ben T. McAllister (University of Western Australia) [ben.mcallister@uwa.edu.au]
Michael E. Tobar (University of Western Australia) [michael.tobar@uwa.edu.au]
Collaboration: ARC Centre of Excellence for Engineered Quantum Systems and ARC Centre of Excellence for Dark Matter Particle Physics

**Authors:** Ben T. McAllister (University of Western Australia), Maxim Goryachev, Graeme R. Flower, Aaron P. Quiskamp, William M. Campbell, Catriona A. Thomson, Cindy Zhao, Eugene N. Ivanov, Gilberto A. Umana-Membreno, Paul Altin (Australian National University), Tom Stace (University of Queensland), Gray Rybka (University of Washington), Gianpaolo Carosi (Lawrence Livermore National Laboratory), Michael E. Tobar (University of Western Australia)



Snowmass2021 - Letter of Interest

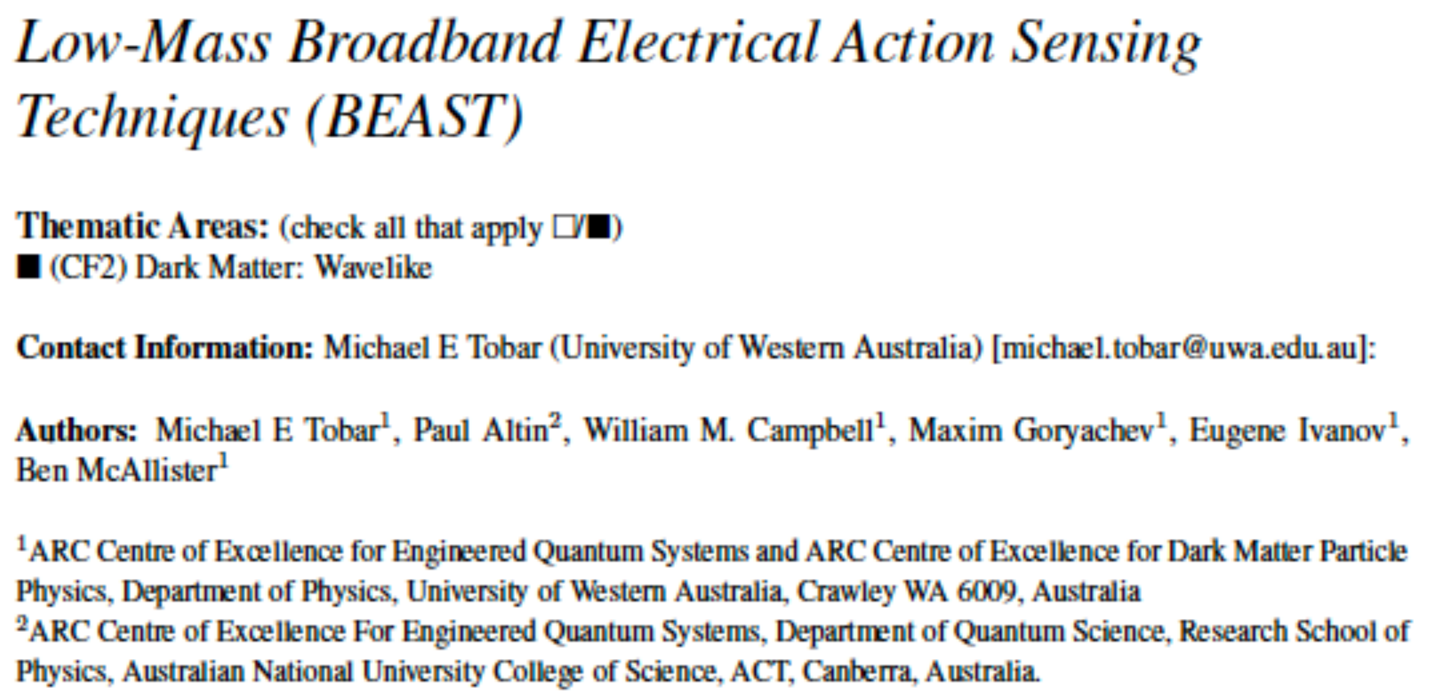
## *UP-conversion Loop Oscillator Axion Detectors (UPLOAD)*

**Thematic Areas:** (check all that apply ☐/■)
■ (CF2) Dark Matter: Wavelike
■ (IF1) Quantum Sensors

**Contact Information:** Michael E Tobar (University of Western Australia) [michael.tobar@uwa.edu.au]:

**Authors:** Michael E Tobar[1], Maxim Goryachev[1], Eugene Ivanov[1], Ben McAllister[1], Catriona Thomson[1], Chunnong Zhao[1], Paul Altin[2], Alexander Romanenko[3], Anna Grassellino[3], Sam Posen[3], Mohamed Awida[3], Andrew Sonnenschein[3], Yanbei Chen[4], Rana Adhikari[4], Chelsea Bartram[5], Gianpaolo Carosi[6]

[1]ARC Centre of Excellence for Engineered Quantum Systems and ARC Centre of Excellence for Dark Matter Particle Physics, Department of Physics, University of Western Australia, Crawley WA 6009, Australia
[2]ARC Centre of Excellence For Engineered Quantum Systems, Department of Quantum Science, Research School of Physics, Australian National University College of Science, ACT, Canberra, Australia.
[3]Fermi National Accelerator Laboratory, Batavia, IL 60510, USA
[4]Caltech, The Division of Physics, Mathematics and Astronomy, Pasadena CA 91125, USA
[5]University of Washington (UW), Seattle, WA 98195, USA
[6]Lawrence Livermore National Laboratory, Livermore, CA 94550, USA



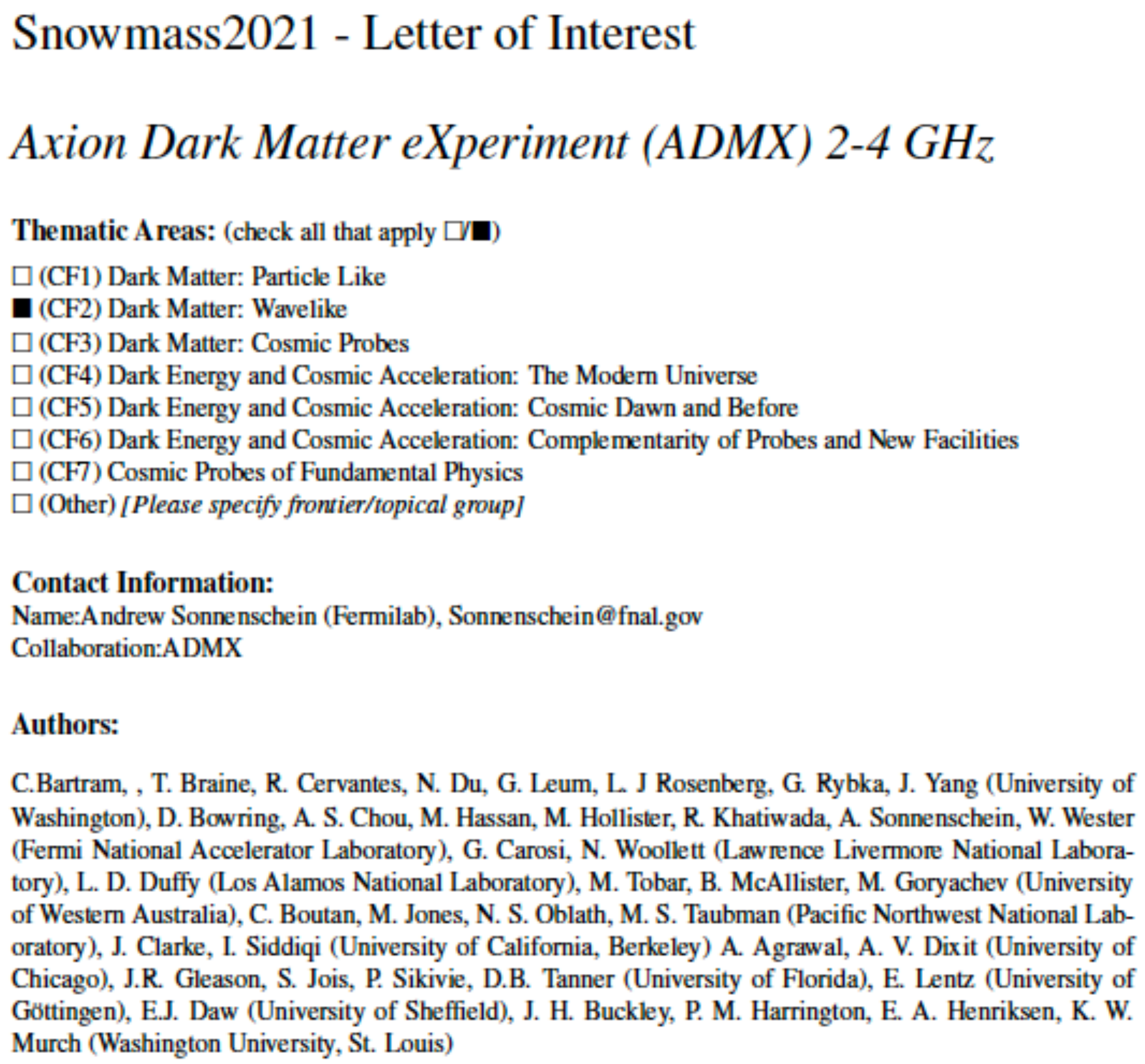
## *Low-Mass Broadband Electrical Action Sensing Techniques (BEAST)*

**Thematic Areas:** (check all that apply ☐/■)
■ (CF2) Dark Matter: Wavelike

**Contact Information:** Michael E Tobar (University of Western Australia) [michael.tobar@uwa.edu.au]:

**Authors:** Michael E Tobar[1], Paul Altin[2], William M. Campbell[1], Maxim Goryachev[1], Eugene Ivanov[1], Ben McAllister[1]

[1]ARC Centre of Excellence for Engineered Quantum Systems and ARC Centre of Excellence for Dark Matter Particle Physics, Department of Physics, University of Western Australia, Crawley WA 6009, Australia
[2]ARC Centre of Excellence For Engineered Quantum Systems, Department of Quantum Science, Research School of Physics, Australian National University College of Science, ACT, Canberra, Australia.



Snowmass2021 - Letter of Interest

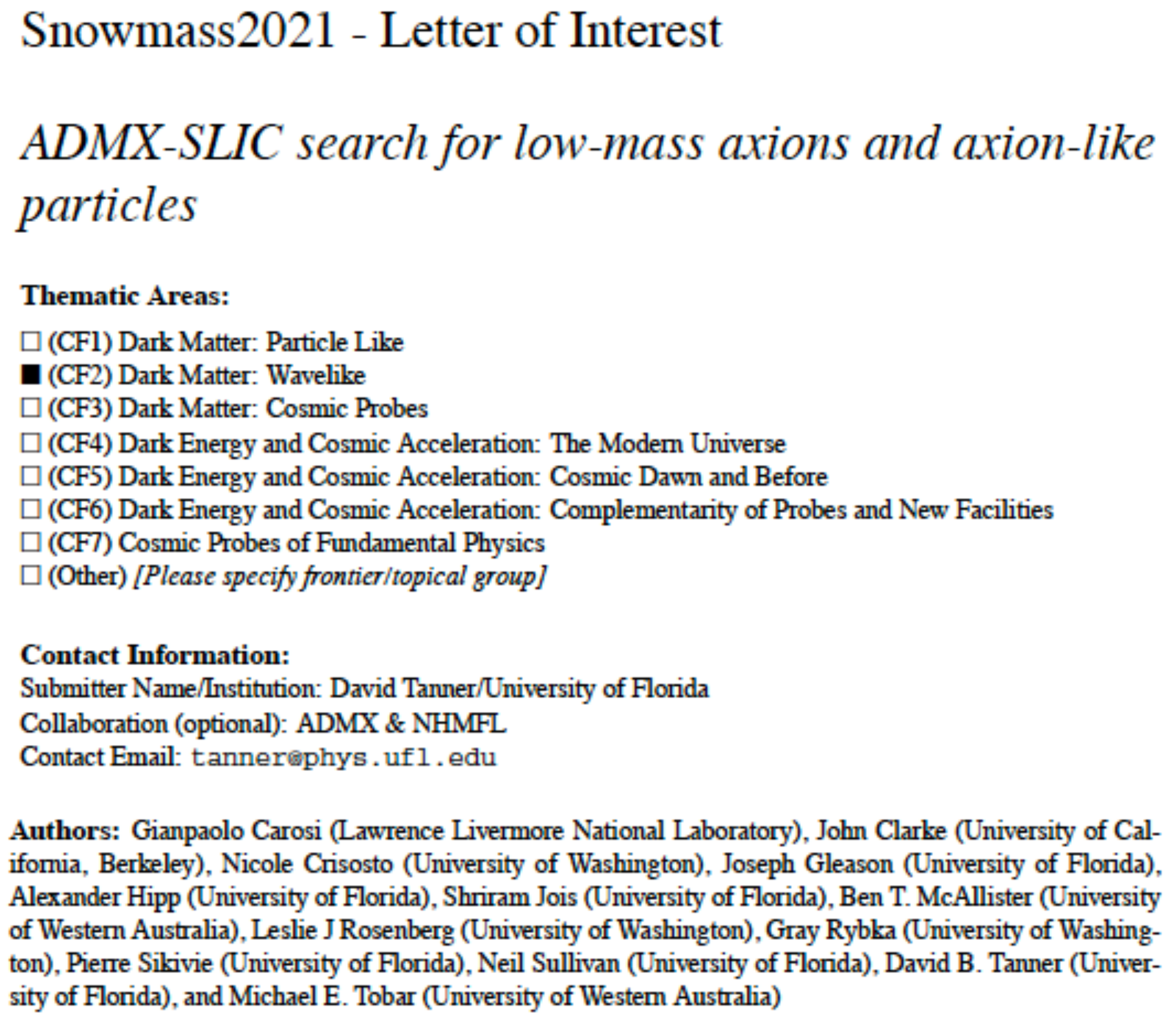
## *Axion Dark Matter eXperiment (ADMX) 2-4 GHz*

**Thematic Areas:** (check all that apply ☐/■)
☐ (CF1) Dark Matter: Particle Like
■ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
☐ (CF7) Cosmic Probes of Fundamental Physics
☐ (Other) *[Please specify frontier/topical group]*

**Contact Information:**
Name:Andrew Sonnenschein (Fermilab), Sonnenschein@fnal.gov
Collaboration:ADMX

**Authors:**

C.Bartram, , T. Braine, R. Cervantes, N. Du, G. Leum, L. J Rosenberg, G. Rybka, J. Yang (University of Washington), D. Bowring, A. S. Chou, M. Hassan, M. Hollister, R. Khatiwada, A. Sonnenschein, W. Wester (Fermi National Accelerator Laboratory), G. Carosi, N. Woollett (Lawrence Livermore National Laboratory), L. D. Duffy (Los Alamos National Laboratory), M. Tobar, B. McAllister, M. Goryachev (University of Western Australia), C. Boutan, M. Jones, N. S. Oblath, M. S. Taubman (Pacific Northwest National Laboratory), J. Clarke, I. Siddiqi (University of California, Berkeley) A. Agrawal, A. V. Dixit (University of Chicago), J.R. Gleason, S. Jois, P. Sikivie, D.B. Tanner (University of Florida), E. Lentz (University of Göttingen), E.J. Daw (University of Sheffield), J. H. Buckley, P. M. Harrington, E. A. Henriksen, K. W. Murch (Washington University, St. Louis)



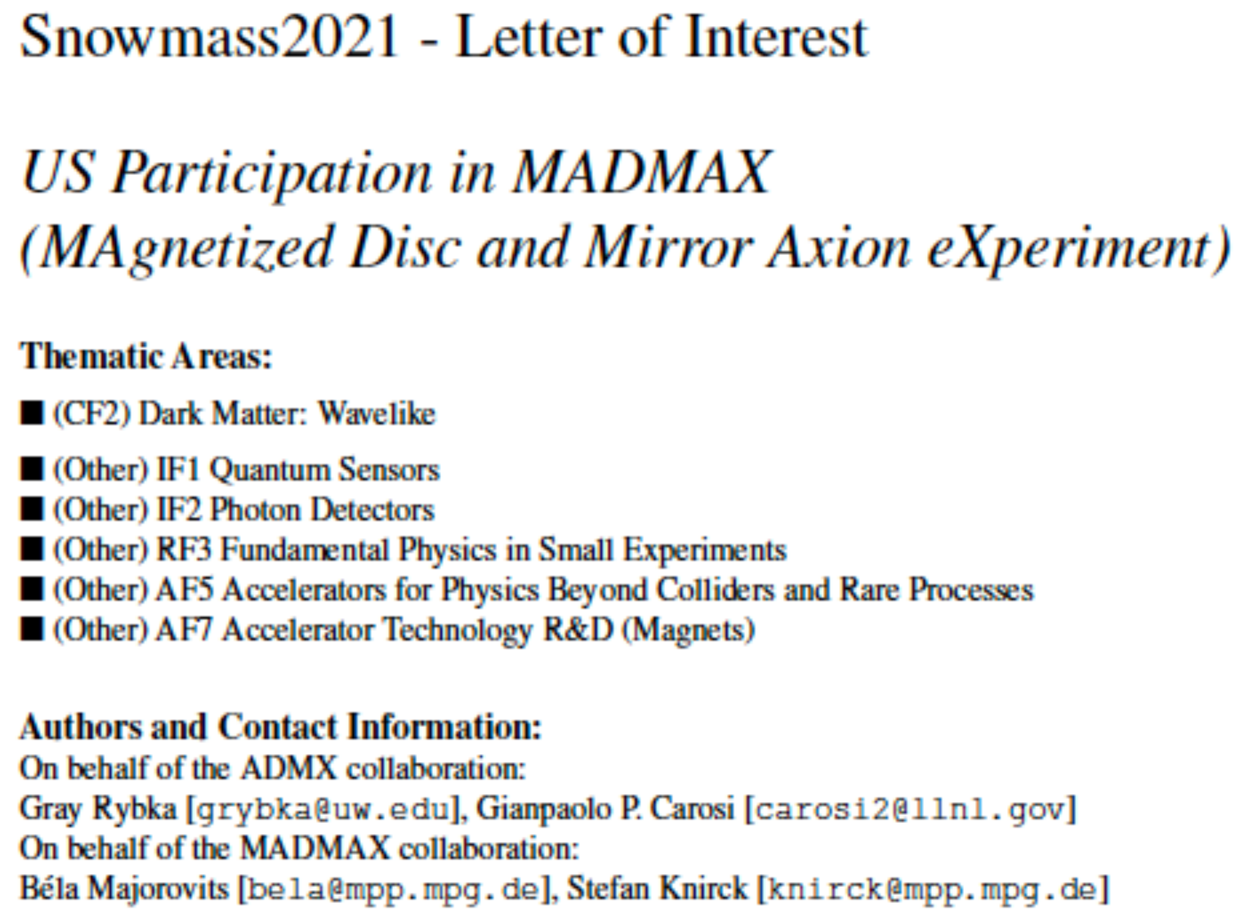
Snowmass2021 - Letter of Interest

## *ADMX-SLIC search for low-mass axions and axion-like particles*

**Thematic Areas:**
☐ (CF1) Dark Matter: Particle Like
■ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
☐ (CF7) Cosmic Probes of Fundamental Physics
☐ (Other) *[Please specify frontier/topical group]*

**Contact Information:**
Submitter Name/Institution: David Tanner/University of Florida
Collaboration (optional): ADMX & NHMFL
Contact Email: `tanner@phys.ufl.edu`

**Authors:** Gianpaolo Carosi (Lawrence Livermore National Laboratory), John Clarke (University of California, Berkeley), Nicole Crisosto (University of Washington), Joseph Gleason (University of Florida), Alexander Hipp (University of Florida), Shriram Jois (University of Florida), Ben T. McAllister (University of Western Australia), Leslie J Rosenberg (University of Washington), Gray Rybka (University of Washington), Pierre Sikivie (University of Florida), Neil Sullivan (University of Florida), David B. Tanner (University of Florida), and Michael E. Tobar (University of Western Australia)



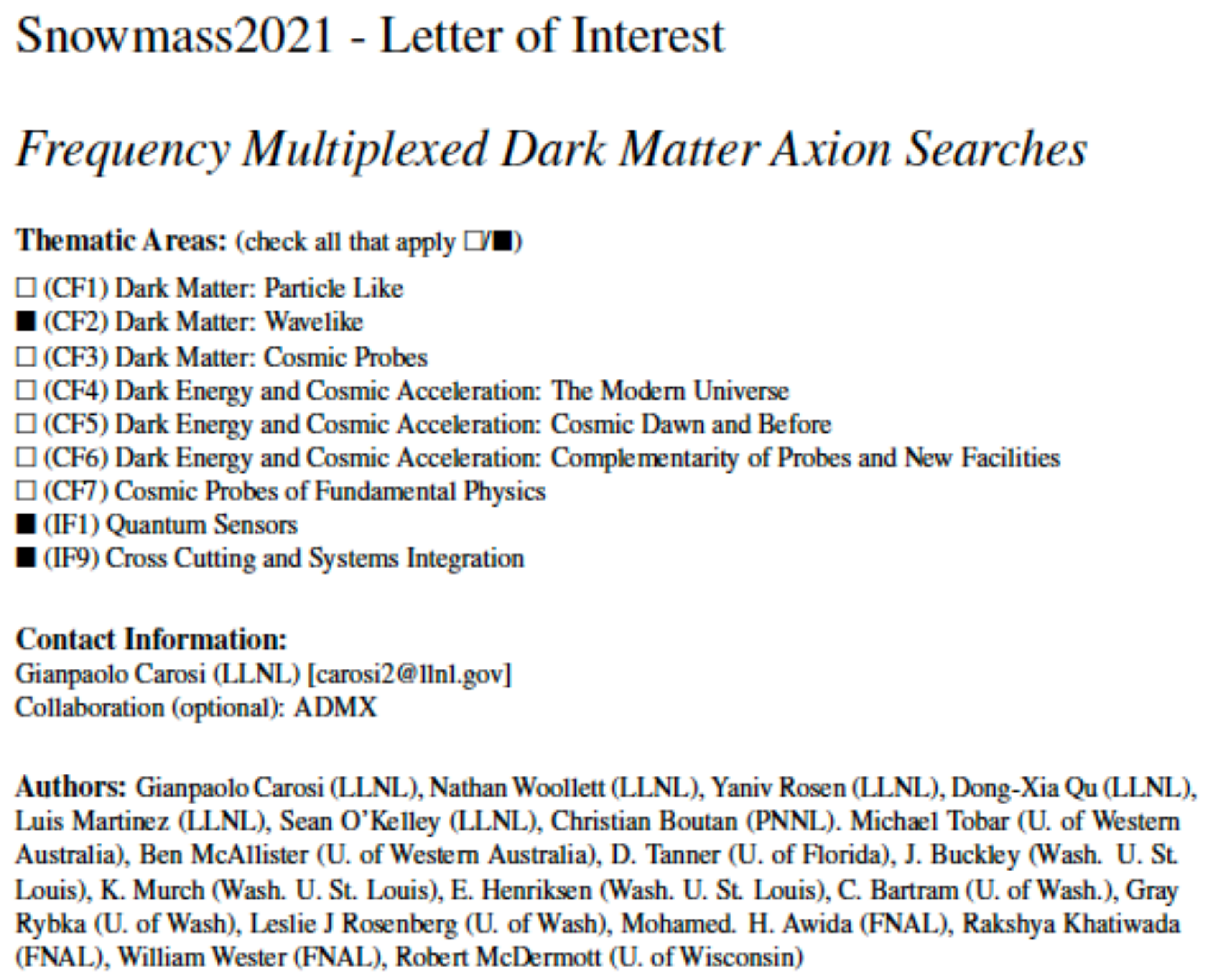
Snowmass2021 - Letter of Interest

## *US Participation in MADMAX (MAgnetized Disc and Mirror Axion eXperiment)*

**Thematic Areas:**
■ (CF2) Dark Matter: Wavelike

■ (Other) IF1 Quantum Sensors
■ (Other) IF2 Photon Detectors
■ (Other) RF3 Fundamental Physics in Small Experiments
■ (Other) AF5 Accelerators for Physics Beyond Colliders and Rare Processes
■ (Other) AF7 Accelerator Technology R&D (Magnets)

**Authors and Contact Information:**
On behalf of the ADMX collaboration:
Gray Rybka [`grybka@uw.edu`], Gianpaolo P. Carosi [`carosi2@llnl.gov`]
On behalf of the MADMAX collaboration:
Béla Majorovits [`bela@mpp.mpg.de`], Stefan Knirck [`knirck@mpp.mpg.de`]



Snowmass2021 - Letter of Interest

## *Frequency Multiplexed Dark Matter Axion Searches*

**Thematic Areas:** (check all that apply ☐/■)
☐ (CF1) Dark Matter: Particle Like
■ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
☐ (CF7) Cosmic Probes of Fundamental Physics
■ (IF1) Quantum Sensors
■ (IF9) Cross Cutting and Systems Integration

**Contact Information:**
Gianpaolo Carosi (LLNL) [carosi2@llnl.gov]
Collaboration (optional): ADMX

**Authors:** Gianpaolo Carosi (LLNL), Nathan Woollett (LLNL), Yaniv Rosen (LLNL), Dong-Xia Qu (LLNL), Luis Martinez (LLNL), Sean O'Kelley (LLNL), Christian Boutan (PNNL). Michael Tobar (U. of Western Australia), Ben McAllister (U. of Western Australia), D. Tanner (U. of Florida), J. Buckley (Wash. U. St. Louis), K. Murch (Wash. U. St. Louis), E. Henriksen (Wash. U. St. Louis), C. Bartram (U. of Wash.), Gray Rybka (U. of Wash), Leslie J Rosenberg (U. of Wash), Mohamed. H. Awida (FNAL), Rakshya Khatiwada (FNAL), William Wester (FNAL), Robert McDermott (U. of Wisconsin)