Searching for New Physics with Precision Low Temperature Experiments
Michael Tobar
https://arxiv.org/a/tobar_m_1.html
Frequency and Quantum Metrology Research Group at UWA

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Searching For new Physics
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• Unsolved problems in Physics
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• Unsolved problems in Physics
  – Dark Matter (search for dark sector particles)
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  – Spins (search spin interaction with axions)
Outline

• Some Tools for Precision Measurements
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  • Phonon-Cavities -> Matter Sector ; Speed of Phonon; Tests of Quantum Gravity (Pavel Bushev)
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Precision measurement =>
Phase, Frequency, Energy, Time
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Technology: High-Q -> Narrow Line Width Systems:
Low Noise Techniques Classical and Quantum (SQL)
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New Tests of Fundamental Physics
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Resonator/Oscillator/Clock Zoo
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Photons

LC-circuits

Metallic Cavities

Dielectric Cavities
Resonator/Oscillator/Clock Zoo

Photons
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Phonons
- SAW
- BAW
- Structures
Resonator/Oscillator/Clock Zoo

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Magnons
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- Spin-Torque

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Atoms
- Hyperfine transitions
- Electron transitions
- Nuclear transitions

Other:
- Photons
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- Metallic Cavities
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Resonator/Oscillator/Clock Zoo

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- Cesium
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Cesium
- Hyperfine splitting of the 6s electron level
- Electron transitions

Thorium
- Nuclear transitions

Equus
Australian Research Council Centre of Excellence for Engineered Quantum Systems
Searching for Dark Matter

- Dark Energy: 71.4%
- Dark Matter: 24%

Diagram showing the distribution of energy and matter components in the Milky Way, with a focus on the dark matter halo.
Candidates for Dark Matter

Dark Sector Candidates, Anomalies, and Search Techniques

- QCD Axion
- Ultralight Dark Matter
- Pre-Inflationary Axion
- Post-Inflationary Axion
- Hidden Sector Dark Matter
- Hidden Thermal Relics / WIMPless DM
- Asymmetric DM
- Freeze-In DM
- SIMPs / ELDERS
- Beryllium-8
- Muon g-2
- Small-Scale Structure

Small Experiments: Coherent Field Searches, Direct Detection, Nuclear and Atomic Physics, Accelerators

Microlensing


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Best Candidate the Axion Solves Strong CP Problem Created in early universe
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Candidates for Dark Matter

Best Candidate the Axion
Solves Strong CP Problem
Created in early universe

Supersymmetry
WIMP Miracle

ARC Centre of Excellence for Dark Matter Particle Physics

SHORT LISTED BY
Australian Government
Australian Research Council

The University of Melbourne | The University of Adelaide | The University of Sydney | The University of Western Australia | The Australian National University | Swinburne University
PROJECT ID: CE200100008

First Investigator: Prof Elisabetta Barberio

Admin Org: The University of Melbourne

Total number of sheets contained in this Proposal: 435
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![Graph of Axion and WIMP-like DM](image)
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![Energy Scale Diagram](image)

**Total number of sheets contained in this proposal:**

- **10^-21 eV**
- **eV**
- **MeV**
- **GeV**
- **TeV**
- **PeV**
Detection of Ultra-Light (sub-eV) Dark Matter
Weakly Interacting Sub-eV Particles (WISPs)
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- Exploiting physical effects to search for coherent field effects of dark matter ranging from $10^{-22}$-1 eV, including QCD axions
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Detection of Ultra-Light (sub-eV) Dark Matter Weakly Interacting Sub-eV Particles (WISPs)

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• Precision Low Energy Experiments

  • Spin-0 non-trivial gauge field configurations: String Axiverse

  • Spin-1 non-trivial gauge field configurations: String Photiverse

  • Fields that determine the shape and size of extra dimensions as well as values of fundamental constants: Dilatons, Moduli, Radion
Are Quantum Technologies Useful for Detecting Dark Matter?
Are Quantum Technologies Useful for Detecting Dark Matter?????????

1 hertz [Hz] = 4.13566553853599x10^{-15} electron-volt [eV]
Are Quantum Technologies Useful for Detecting Dark Matter????????

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Quantum Technologies: JPA SQUID etc.
SEARCH FOR THE QCD AXION AS DARK MATTER
QCD: Why is the neutron electric dipole moment so small?

*from Aaron Chou (FNAL)
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\text{-}cm

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

This leads to the "Strong CP Problem": Where did QCD CP violation go?
Peccei-Quinn Solution to Strong CP Problem
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Roberto Peccei  Helen Quinn
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- Two general classes of models
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- Two general classes of models
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Peccei-Quinn Solution to Strong CP Problem

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  - DFSZ [Dine, Fischler, Srednicki (1981), Zhitnitsky (1980)]
Coupling to electromagnetic field

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

Coupling to gluon field

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

CASPEr Electric


Coupling to fermions

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

CASPEr Wind

Coupling to electromagnetic field
\[ \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu} \]

Coupling to gluon field
\[ \frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu} \]

CASPER Electric

Coupling to fermions
\[ \frac{\partial \mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f \]

CASPER Wind

\[ \mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - J^\mu A_\mu + \frac{1}{2} \partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 - \frac{g_a \gamma}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} a, \]
THE AXION MUST EXIST!!!!
THE AXION MUST EXIST!!!!
THE AXION MUST EXIST!!!!

TO CLEAN UP THE STRONG CP PROBLEM JUST AS IMPORTANT AS THE HIGGS!? 
THE AXION MUST EXIST!!!!

TO CLEAN UP THE STRONG CP PROBLEM
JUST AS IMPORTANT AS THE HIGGS!?  
MANY THEORIES PREDICT AXIONS CREATED
BEFORE, DURING OR AFTER INFLATION!!  ->
DARK MATTER CANDIDATE DUE TO WEAK
INTERACTION WITH SM PARTICLES
The Axion Haloscope Technique
The Axion Haloscope Technique

Pierre Sikivie
The Axion Haloscope Technique

Axion wavelength is ~100 m long

Axion to photon production $\propto E \cdot B$

This axion lineshape has been exaggerated. A real signal would hide beneath the noise in a single digitization. An axion detection requires a very cold experiment and an ultra-low noise receiver-chain.

Unknown axion mass requires a tunable resonator
The Axion Haloscope Technique

Axion

Coupling

Detected photon

$g_{a\gamma\gamma}$
The Axion Haloscope Technique

From an external DC magnetic field

Axion

Coupling

Detected photon

Virtual photon

From an external DC magnetic field

\( g_{a\gamma\gamma} \)
From an external DC magnetic field

Virtual photon

Axion

Detected photon

Coupling

$g_{a\gamma\gamma}$

From an external DC magnetic field

Resonant cavity

The Axion Haloscope Technique
The Axion Haloscope Technique

\[ \mathcal{L} \propto a g_{a\gamma\gamma} \hat{E}_{\text{cavity}} \cdot \hat{B}_{\text{ext}} \]

Lagrangian gives effective strength

Axion

Detected photon

Coupling

Virtual photon

From an external DC magnetic field

Resonant cavity
From an external DC magnetic field

Virtual photon

Axion

Detected photon

Resonant cavity

Lagrangian gives effective strength

\[ \mathcal{L} \propto a g_{a\gamma\gamma} \vec{E}_{\text{cavity}} \cdot \vec{B}_{\text{ext}} \]

• Power from the cavity is

\[
P = 4 \cdot 10^{-22} \text{ W} \left( \frac{V}{200 \ell} \right) \left( \frac{B_0}{8 \text{ Tesla}} \right)^2 C_{nl} \left( \frac{g_{\gamma}}{0.97} \right)^2 \left( \frac{\rho_a}{0.5 \cdot 10^{-24} \text{ g/cm}^3} \right) \left( \frac{m_a}{1 \text{ GHz}} \right) \left( \frac{\min(Q_L, Q_a)}{1 \times 10^5} \right)
\]
From an external DC magnetic field

Virtual photon

Lagrangian gives effective strength

Axion

Detected photon

Coupling

g_{\alpha\gamma}

Virtual photon

From an external DC magnetic field

Resonant cavity

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\]

- \( C_{nl} \) is form factor,
The Axion Haloscope Technique

From an external DC magnetic field

Virtual photon

Axion

Detected photon

Resonant cavity

Coupling

The Axion Haloscope Technique

Lagrangian gives effective strength

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The Axion Haloscope Technique

Lagrangian gives effective strength

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• \( C_{nl} \) is form factor,
• \( \rho_a \) is the halo density, \( m_a \) the axion mass, and
• \( Q_L \sim 70000(\text{GHz}/f)^{2/3} \) (ASE); \( Q_a \sim 10^6 \) are quality factors
The Axion Haloscope Technique

\[ L \propto a g_{a\gamma\gamma} \mathbf{E}_{\text{cavity}} \cdot \mathbf{B}_{\text{ext}} \]

Lagrangian gives effective strength

- **Power from the cavity is**

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From an external DC magnetic field

Virtual photon

Axion

Detected photon

Coupling

The Axion Haloscope Technique

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- \( g_{\gamma} \sim 0.97 \) (KSVZ); \( g_{\gamma} \sim 0.36 \) (DFSZ) are coupling strengths
- We use DFSZ; look for \( \sim 10^{-22} \) Watts power
ADMX Collaboration

- Experiment formed in 1994 at LLNL
- Currently one of the 3 “Generation-2” Dark Matter Projects
- Now located at the U. of Washington

**Sponsors**
ADMX now DOE Gen 2 project
ADMX Collaboration

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Sponsors
ADMX now DOE Gen 2 project

Primary sponsor
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Sponsors
ADMX now DOE Gen 2 project

Primary sponsor

UWA Joined Officially in January 2019
Searching for Axion Dark Matter with ADMX G2

ADMX Experiment, CENPA
University of Washington
ADMX experiment
The ORGAN Experiment:
The ORGAN Experiment:

McGillivary Organ at UWA
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McGillivary Organ
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McGillivary Organ at UWA
Australia's National Centre for Engineering Quantum Systems
Australia's National Centre for Engineering Quantum Systems

UWA lab $350,000 / year 14 years!
Axion Research Program at UWA

Australia's National Centre for Engineering Quantum Systems

COLLABORATING INSTITUTIONS

THE UNIVERSITY OF WESTERN AUSTRALIA
THE UNIVERSITY OF SYDNEY
THE UNIVERSITY OF QUEENSLAND AUSTRALIA
MACQUARIE UNIVERSITY
AUSRTALIAN NATIONAL UNIVERSITY

Australian Government
Australian Research Council

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Other Funding For Axion Dark Matter at UWA
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<table>
<thead>
<tr>
<th>Grant Number</th>
<th>Project Title</th>
<th>PI</th>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>LE180100042</td>
<td>Australian Dark Matter Detector for High Mass Axions</td>
<td>Prof Michael Tobar</td>
<td>The University of Western Australia</td>
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Other Funding For Axion Dark Matter at UWA

Funded Biggest BlueFors DilFridge 14 T Magnet: Arrive June 2019 ~ $900,000
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Precision low energy experiments to search for new physics. This project aims to give experimental answers to long existing theoretical questions about the origins and nature of dark matter. Dark matter is a fundamental component of the universe, yet the nature of its composition is still unknown. There is growing evidence that dark matter is comprised of low mass and weakly interacting particles. By developing ultra-precise measurement tools and new techniques, this project aims to perform a stringent and comprehensive new laboratory search for ultra-light dark matter particles, over likely mass ranges not yet searched. The knowledge gained will provide economic benefits through commercialisation and stimulation of new research and development, and to defence through applications in radar, communications and sensing.
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Funded:
- $530,000      Gray Rybka ADMX, Frank Wilczek, Membership of ADMX
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- $15,000

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Analytic and Lattice predictions for the “classical” QCD (PQWW) axion mass making 100% dark matter, created post-inflation

* Does not include string/domain wall decay contributions

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ORGAN SEARCHES HIGHER MASS

Axion Mass (eV)

Axion-photon coupling, $g_{a\gamma}$ (GeV$^{-1}$)

ALPs DM CANDIDATES

UF

RBF

QCD Axions DM Candidates

QCD Axions DM Candidates

KSVZ

DFSZ

QCD Axions DM Candidates

ADMX

CAST

ORGAN 14 T

ORGAN 28 T

ORGAN 14 T + Low Q Noise

ORGAN 28 T + Low Q Noise

HAYSTAC
ORGAN SEARCHES HIGHER MASS

Axion-photonic coupling, $g_{\text{av}}$ (GeV$^{-1}$)

Axion Mass (eV)

ALPs DM CANDIDATES

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Axion Search at UWA
Any idea where we should start?
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Any idea where we should start?

Group introduces six new particles to standard model to solve five enduring problems

Feb 2017

Five problems of particle physics and cosmology solved in one stroke

Guillermo Ballesteros 1, Javier Redondo 2-3, Andreas Ringwald 4, Tamarit Carlos

1 IPHT - Institut de Physique Théorique - UMR CNRS 3681
2 Universidad Zaragoza [Zaragoza]
3 MPI-P - Max-Planck-Institut für Physik
4 DESY - Deutsches Elektronen-Synchrotron [Hamburg]
Axion Search at UWA
Any idea where we should start?

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February 20, 2017 by Bob Yrka

Standard Model-Axion-Seesaw-Higgs Portal Inflation. Five problems of particle physics and cosmology solved in one stroke
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SMASH theory predicted range
ORGAN CONCEPT
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- High frequency/high mass axion haloscope
ORGAN CONCEPT

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- Oscillating Resonant Group AxioN Experiment
ORGAN CONCEPT

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- Designed to probe promising high mass window
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Multiple cylindrical resonators to scan over multiple frequencies
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Multiple cylindrical resonators to scan over multiple frequencies
FIRST STEP
Oscillating Resonator Group AxioN
Pathfinder Project
FIRST STEP
Oscillating Resonator Group AxioN PathfInder ProjEct

Start with 1 cavity borrow equipment from other projects…

1) Check Detection Claim
2) Show proof of concept at higher masses
3) Test novel noise reduction and signal enhancing techniques
FIRST STEP
Oscillating Resonator Group AxioN
Pathfinder Project

ORGAN PIPE

Start with 1 cavity borrow equipment from other projects…

1) Check Detection Claim
2) Show proof of concept at higher masses
3) Test novel noise reduction and signal enhancing techniques
Magnet & readout

7 T Magnet (10 cm bore)

LNF Cryo HEMTS
~10 K Noise temp (15 – 29 GHz)
Need to develop JPA’s at high frequency

2-channel digitizer
Keysight U5303A

Stephen.Parker@uwa.edu.au
Magnet & readout

7 T Magnet (10 cm bore)

LNF Cryo HEMTS
~10 K Noise temp (15 – 29 GHz)
Need to develop JPA’s at high frequency

2-channel digitizer
Keysight U5303A

VSA
SYNTH
HEMT AMPS
T~295 K

B = 7T
T=4 K
TM020 Mode
f = 26.531 GHz

Stephen.Parker@uwa.edu.au
First run complete

$\text{TM}_{020}$ mode

sampling frequency of the digitizer is 1GHz, the 26.54GHz
First Path finding Run Reported with strategy for Improvements

The ORGAN experiment: An axion haloscope above 15 GHz
Ben T. McAllister a,*, Graeme Flower a, Eugene N. Ivanov b, Maxim Goryachev a, Jeremy Bourhill a, Michael E. Tobar a

a ARC Centre of Excellence for Engineered Quantum Systems, School of Physics, The University of Western Australia, Crawley 6009, Australia
b School of Physics, The University of Western Australia, Crawley 6009, Australia

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ABSTRACT
We present first results and future plans for the Oscillating Resonant Group Axion (ORGAN) experiment, a microwave cavity axion haloscope situated in Perth, Western Australia designed to probe for high mass axions motivated by several theoretical models. The first stage focuses around 26.6 GHz in order to directly test a claimed result, which suggests axions exist at the corresponding mass of 110 μeV. Later stages will move to a wider scan range of 15–50 GHz (62–207 μeV). We present the results of the pathfinding run, which sets a limit on $g_{aγγ}$ of $2.02 \times 10^{-12}$ eV$^{-1}$ at 26.531 GHz, or 110 μeV, in a span of 2.5 neV (shaped by the Lorentzian resonance) with 90% confidence. Furthermore, we outline the current design and future strategies to eventually attain the sensitivity to search for well known axion models over the wider mass range.
Traditional Haloscope cavity design

Typically Low order modes are used as they have more in phase field

Top Down view of $E_z$ field over tuning range
Traditional Haloscope cavity design

- Consider traditional haloscope design

Typically Low order modes are used as they have more in phase field

Top Down view of $E_z$ field over tuning range
Typically Low order modes are used as they have more in phase field.

Consider traditional haloscope design.

Top Down view of $E_z$ field over tuning range.
Consider traditional haloscope design

Past investigation shows $TM_{020}$ mode is best for our purposes

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Past investigation shows $\text{TM}_{020}$ mode is best for our purposes

By moving the rod radially the mode is perturbed, shifting the frequency

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Past investigation shows \( \text{TM}_{020} \) mode is best for our purposes

By moving the rod radially the mode is perturbed, shifting the frequency

Low form factors, rod reduces geometry factor

Typically Low order modes are used as they have more in phase field

Top Down view of \( E_z \) field over tuning range
Tunable Supermode Dielectric Resonators for Axion Dark-Matter Haloscopes

Ben T. McAllister,¹,* Graeme Flower,¹ Lucas E. Tobar,¹,² and Michael E. Tobar¹,*

¹ARC Centre of Excellence for Engineered Quantum Systems, School of Physics,
The University of Western Australia, Crawley 6009, Australia
²Department of Electrical and Computer Systems Engineering, Monash University,
Clayton 3800, Australia

(Received 16 June 2017; revised manuscript received 19 September 2017; published 26 January 2018)

We present frequency-tuning mechanisms for dielectric resonators, which undergo “supermode” interactions as they tune. The tunable schemes are based on dielectric materials strategically placed inside traditional cylindrical resonant cavities, necessarily operating in transverse-magnetic modes for use in axion haloscopes. The first technique is based on multiple dielectric disks with radii smaller than that of the cavity. The second scheme relies on hollow dielectric cylinders similar to a Bragg resonator, but with a different location and dimension. Specifically, we engineer a significant increase in form factor for the TM_{030} mode utilizing a variation of a distributed Bragg reflector resonator. Additionally, we demonstrate an application of traditional distributed Bragg reflectors in TM modes which may be applied to a haloscope. Theoretical and experimental results are presented showing an increase in Q factor and tunability due to the supermode effect. The TM_{030} ring-resonator mode offers a between 1 and 2-order-of-magnitude improvement in axion sensitivity over current conventional cavity systems and will be employed in the forthcoming ORGAN experiment.

DOI: 10.1103/PhysRevApplied.9.014028

arXiv:1705.06028 [physics.ins-det]
Tunable Supermode Dielectric Resonators for Axion Dark-Matter Haloscopes

Ben T. McAllister,¹,* Graeme Flower,¹ Lucas E. Tobar,¹,² and Michael E. Tobar¹,†
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Axion-Bragg Resonator

• We can tune this structure, similar to the disk structure
• Axial “supermodes”
• TM030 and TM031 modes
Axion Mass (eV)

Axion-Photon Coupling, $g_{\gamma A}$ (GeV$^{-1}$)

ALPs DM CANDIDATES

UF

RBF

ADMX

KSVZ

DFSZ

QCD Axions DM Candidates

CAST

ORGAN 14 T

ORGAN 28 T

ORGAN 14 T + Low Q Noise

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HAYSTAC

ORGAN

QCD Axions DM Candidates

Axion Mass (eV)
New Grant Success for Other Dark Matter Experiments

Precision Low Energy Experiments to Search for New Physics
New Grant Success for Other Dark Matter Experiments

Precision Low Energy Experiments to Search for New Physics

Search for Scalar particles with phonons
(Resonant GW Detectors)

Fig. 4. Scalar field limits, with mass $m_\phi$ and corresponding DM oscillation frequency on the bottom and top horizontal axes, and couplings of the electron mass modulus ($d_7 = d_{me}$) and electromagnetic gauge modulus ($d_1 = d_e$) on the vertical axis. [51] Possible limits for this experiment are labeled quartz.
New Grant Success for Other Dark Matter Experiments

Precision Low Energy Experiments to Search for New Physics

Search for Scalar particles with phonons (Resonant GW Detectors)

Search for Spin 0 Bosons (axions) interaction with spins

Fig. 2 Ultra-strong coupling of magnons to cavity photons [15].

\[ \text{Fig. 4. Scalar field limits, with mass } m_\phi \text{ and corresponding DM oscillation frequency on the bottom and top horizontal axes, and couplings of the electron mass modulus } (d_e = d_{me}) \text{ and electromagnetic gauge modulus } (d_t = d_e) \text{ on the vertical axis. [51] Possible limits for this experiment are labeled quartz.} \]
New Grant Success for Other Dark Matter Experiments

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Dual-Mode Oscillator coupled to axions
3D lumped LC resonators as low mass axion haloscopes

Ben T. McAllister,* Stephen R. Parker, and Michael E. Tobar†

ARC Centre of Excellence for Engineered Quantum Systems, School of Physics,
The University of Western Australia, 35 Stirling Highway, Crawley 6009, Western Australia, Australia
(Received 18 May 2016; published 11 August 2016)

FIG. 6. Predicted axion-photon coupling exclusion limits for the reentrant cavity designs, using the assumptions outlined in the main text (RC). Current and future bounds from ADMX and CAST are shown for comparison, along with the predicted exclusion limits for magnetometer experiments (MM) presented in Ref. [21].
**Frequency Metrology for Paraphoton (Dark photon) Dark Matter search**

New alternative to Light Shining through a Wall

**PHYSICAL REVIEW D 87, 115008 (2013)**

**Hidden sector photon coupling of resonant cavities**

Stephen R. Parker,1,* Gray Rybka,2 and Michael E. Tobar1

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Many beyond the standard model theories introduce light paraphotons, a hypothetical spin-1 field that kinetically mixes with photons. Microwave cavity experiments have traditionally searched for paraphotons via transmission of power from an actively driven cavity to a passive receiver cavity, with the two cavities separated by a barrier that is impenetrable to photons. We extend this measurement technique to account for two-way coupling between the cavities and show that the presence of a paraphoton field can alter the resonant frequencies of the coupled cavity pair. We propose an experiment that exploits this effect and uses measurements of a cavity’s resonant frequency to constrain the paraphoton-photon mixing parameter $\chi$. We show that such an experiment can improve the sensitivity to $\chi$ over existing experiments for paraphoton masses less than the resonant frequency of the cavity, and that it can eliminate some of the most common systematics for resonant cavity experiments.

**coupled mode system**

$$\omega_{\pm} \approx \omega_0 \left(1 - \frac{x^2}{2}\left(1 + \frac{1}{2Q_1Q_2} + \frac{x^2}{4} + \frac{m^2_{y}\chi^2}{\omega_0^2} - \frac{m^4_{y}\chi^2G_S}{\omega_0^4}\right) \pm \left(\frac{1}{Q_1Q_2} + x^2 + \frac{2m^2_{y}\chi^2}{\omega_0^2} - \frac{2m^4_{y}\chi^2G_S}{\omega_0^4} + \frac{m^8_{y}\chi^4G^4}{\omega_0^8}\right)^{\frac{1}{2}}\right),$$

Paraphoton coupling to the 2nd cavity modulate resonance frequency
Axion Detection with Precision Frequency

Maxim Goryachev,¹ Ben McAllister,¹ and Michael E. Tobar¹, a)

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(Dated: 27 June 2018)

We investigate a new class of galactic halo axion detection techniques based on precision frequency and phase metrology. Employing equations of axion electrodynamics, it is demonstrated how a dual mode cavity exhibits linear mode-mode coupling mediated by the axion upconversion and axion downconversion processes. The approach demonstrates phase sensitivity with an ability to detect axion phase with respect to externally pumped signals. Axion signal to phase spectral density conversion is calculated for open and closed loop detection schemes. The fundamental limits of the proposed approach come from the precision of frequency and environment control electronics, rather than fundamental thermal fluctuations allowing for table-top experiments approaching state-of-the-art cryogenic axion searches in sensitivity. Practical realisations are considered, including a TE-TM mode pair in a cylindrical cavity resonator and two orthogonally polarised modes in a Fabry-Pérot cavity.
Axion Detection with Precision Frequency Metrology

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Theoretical Sensitivity Limits

Sensitivity of the loop oscillator experiment

**Axion UpConversion**
\[ \omega_a = \omega_2 - \omega_1 \]
\[ H_U = \hbar g_{\text{eff}} \xi_- (a^* c_1 c_2^\dagger - a c_1^\dagger c_2) \]

- allows optical search at microwaves and mm-wave

**Axion DownConversion**
\[ \omega_a = \omega_2 + \omega_1 \]
\[ H_D = \hbar g_{\text{eff}} \xi_+ (a c_1^\dagger c_2^\dagger - a^* c_1 c_2) \]

- allows mm-wave search at microwave

\[ \log_{10}(m_a/1\text{eV}) \]
\[ \log_{10}(g_{\text{ann}}/1\text{GeV}) \]

Frequency (Hz)

- Cryogenic DownConversion
- Cryogenic UpConversion
- RT DownConversion
- RT UpConversion

Maxim Goryachev, Ben McAllister, Michael Tobar, 2018
Operation of a ferromagnetic Axion haloscope at $m_a = 58 \mu eV$

\[ P_{in} = B_a \frac{dM}{df} V_s = 4\pi \gamma \mu_B f_a B_a^2 \tau_{\text{min}} n_s V_s \]

\[ \mathcal{L} = \bar{\psi}(x)(i\hbar \gamma^\mu \partial_\mu - mc)\psi(x) - ig_{aee} a(x)\psi(x)\gamma_5 \psi(x) \]

\[ \mathbf{B}_a = \frac{g_{aee}}{2e} \nabla a \]

\[ \mathbf{B}_a = \frac{g_{aee}}{2e} \frac{m_a v_a}{\hbar} a_0 \sin(\omega_a t - \frac{m_a v_a x}{\hbar}) \hat{x} \]
Axion Wind Detection with an Improved Ferromagnetic Haloscope

Graeme Flower, Jeremy Bourhill, Maxim Goryachev, and Michael E. Tobar
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(Dated: 6 December 2018)

With the axion being a prime candidate for dark matter, there has been some recent interest in direct detection through a so-called ‘Ferromagnetic haloscope.’ Such devices exploit the coupling between axions and electrons in the form of collective spin excitations of magnetic materials with readout through a microwave cavity. Here, we present a new, more general, theoretical treatment of such experiments in a Hamiltonian framework with coupled magnons and photons. In particular, this opens up the possibility of operating this experiment in the dispersive regime which allows easy searching of the axion mass parameter space. This experiment is implemented in a cryogenic setup, and initial results are presented setting first laboratory limits on the axion-electron coupling strength of $g_{aee} > 3.7 \times 10^{-9}$ in the range $33.79 \mu$eV < $m_a$ < $33.94 \mu$eV with 95% confidence. Future improvements and requirements to reach the DFSZ axion model are further discussed.

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

Photons  Magnons  Interaction

Magnon-Cavity Polariton
Cavity: Magnon-Cavity Polariton
First results

**White Dwarf Cooling**

- DFSZ model
- Centred at 8.2GHz

36MHz in 6 MHz blocks from 8hrs of averages

3MHz static range 7x6hrs of averages

- Centred at 14GHz
Local Lorentz Invariance

- Local Lorentz symmetry
  - Two kinds of transformations: Rotations and Boosts

Rotations (3)

Boosts (3)

- Experimental outcomes are the same when the apparatus undergoes (local) Lorentz transformations
General framework for studying Lorentz violation

**Standard-Model Extension (SME)**
(Developed by Kostelecký and collaborators in the 90s)

- **Basic Idea:**
  - **General Relativity** + **Standard Model** + **All possible forms of Lorentz violation**
  - Background fields interacting with known matter

**SME** - effective field theory with lagrangian:

\[ \mathcal{L}_{SME} = \mathcal{L}_{GR} + \mathcal{L}_{SM} + \mathcal{L}_{LV} + \ldots \]

- **Usual GR lagrangian**
- **Usual SM fields**
- **All possible Lorentz-violating terms constructed from SM & GR fields and background coefficients**
Tested Across Many Different Particle Sectors

-> Photon

http://www.physics.indiana.edu/~kostelec/
Tested Across Many Different Particle Sectors
-> Photon
-> Matter (neutron, proton, electron, neutrino..)

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Experiment: Resonators

Cylindrical Sapphire crystal

Superconducting Niobium Cavity

Operate the E8,1,1 mode
Frequency ~ 10GHz
Q ~ 1 x 10^8
Direct terrestrial test of Lorentz symmetry in electrodynamics to $10^{-18}$

Moritz Nagel$^{1,*}$, Stephen R. Parker$^{2,*}$, Evgeny V. Kovalchuk$^{1}$, Paul L. Stanwix$^{2}$, John G. Hartnett$^{2,3}$, Eugene N. Ivanov$^{2}$, Achim Peters$^{1}$ & Michael E. Tobar$^{2}$

Figure: Graph showing data points from 1880 to 2020, with a legend indicating interferometer tests and cavity tests. The graph includes a marker labeled "This work".

Table 1: Bounds on non-birefringent photon-sector coefficients of the minimal SME.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Bound (Error)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_{e}^{X,Y}$</td>
<td>- 0.7 (1.6)</td>
</tr>
<tr>
<td>$\kappa_{e}^{X,Z}$</td>
<td>- 5.5 (4.0)</td>
</tr>
<tr>
<td>$\kappa_{e}^{Y,Z}$</td>
<td>- 1.9 (3.2)</td>
</tr>
<tr>
<td>$\kappa_{e}^{X,Z} - \kappa_{e}^{Y,Y}$</td>
<td>- 1.5 (3.4)</td>
</tr>
<tr>
<td>$\kappa_{e}^{Z,Z}$</td>
<td>- 286 (279)</td>
</tr>
<tr>
<td>$\kappa_{o}^{X,Y}$</td>
<td>- 3.0 (3.4)</td>
</tr>
<tr>
<td>$\kappa_{o}^{X,Z}$</td>
<td>- 0.2 (1.7)</td>
</tr>
<tr>
<td>$\kappa_{o}^{Y,Z}$</td>
<td>- 2.0 (1.6)</td>
</tr>
<tr>
<td>$\kappa_{tr}$</td>
<td>- 6.0 (4.0)</td>
</tr>
</tbody>
</table>

SME, standard model extension. Errors are standard 1σ of statistical origin. Values for $\kappa_{e}^{\pm}$ are given in $10^{-16}$, $\kappa_{o}^{\pm}$ in $10^{-14}$ and $\kappa_{tr}$ in $10^{-10}$. 
Acoustic Tests of Lorentz Symmetry Using Quartz Oscillators

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Michael Hohensee
Lawrence Livermore National Laboratory, Livermore, California 94550, USA

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(Received 8 December 2014; revised manuscript received 6 July 2015; published 24 February 2016)

We propose and demonstrate a test of Lorentz symmetry based on new, compact, and reliable quartz oscillator technology. Violations of Lorentz invariance in the matter and photon sector of the standard model extension generate anisotropies in particles’ inertial masses and the elastic constants of solids, giving rise to measurable anisotropies in the resonance frequencies of acoustic modes in solids. A first realization of such a “phonon-sector” test of Lorentz symmetry using room-temperature stress-compensated-cut crystals yields 120 h of data at a frequency resolution of $2.4 \times 10^{-15}$ and a limit of $\tilde{c}_Q = (-1.8 \pm 2.2) \times 10^{-14}$ GeV on the most weakly constrained neutron-sector $c$ coefficient of the standard model extension. Future experiments with cryogenic oscillators promise significant improvements in accuracy, opening up the potential for improved limits on Lorentz violation in the neutron, proton, electron, and photon sector.

DOI: 10.1103/PhysRevX.6.011018

Subject Areas: Acoustics, Atomic and Molecular Physics, Electronics
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Next Generation of Phonon Tests of Lorentz Invariance Using Quartz BAW Resonators

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PLL mixer

Delay line: $\Delta \phi \sim 76$ deg at 5 MHz

Attenuator

Power combiner

LNA (1.3 dB NF)

10 dB coupler

Isolation/booster amplifier

PLL loop filter

Mixer of readout system
Phase Noise Spectrum of 5 MHz Oscilloquartz oscillator

### Phase noise (BW = 1 Hz) Options

<table>
<thead>
<tr>
<th>Frequencies</th>
<th>5 MHz</th>
<th>10 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard/Option L</td>
<td>Standard/Option L</td>
<td>Standard/Option L</td>
</tr>
<tr>
<td>Phase noise 1 Hz</td>
<td>-125 dBc</td>
<td>-130 dBc</td>
</tr>
<tr>
<td>10 Hz</td>
<td>-145 dBc</td>
<td>-145 dBc</td>
</tr>
<tr>
<td>100 Hz</td>
<td>-153 dBc</td>
<td>-153 dBc</td>
</tr>
<tr>
<td>1'000 Hz</td>
<td>-156 dBc</td>
<td>-156 dBc</td>
</tr>
<tr>
<td>10'000 Hz</td>
<td>-156 dBc</td>
<td>-156 dBc</td>
</tr>
</tbody>
</table>
Rotating Bulk Acoustic Wave Oscillators
Rotating Quartz Oscillators
Rotating Quartz Oscillators
Rotating Quartz Oscillators
Cooling/Damping Massive Objects (phonons) to the Ground State (need high-Q)
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Cooling/Damping Massive Objects (phonons) to the Ground State (need high-Q)

Quartz: Piezoelectric
Cooling/Damping Massive Objects (phonons) to the Ground State (need high-Q)

Sapphire: Parametric

Quartz: Piezoelectric
Quartz Phonon Trapping Technology

Tabletop experiment could detect gravitational waves
Oct 17, 2014  10 comments
Tiny device could beat LIGO to detecting ripples in space-time, say physicists.

Acoustic analog of optical Fabry-Pérot:

Features:
- phonon wavelengths $\sim 8 - 1000 \, \mu m$ ($f \to 1 \, GHz$),
- (quasi)-longitudinal and (quasi)-transverse polarizations,
- effective phonon trapping (BVA-technology),
- extremely long acoustic phonon life times ($Q \to 10^{10}$)...
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Phonons in BAW Resonators

- HIGH-Q PHONON MODES 20mK $Q_{xf} \sim 10^{18}$
Observation of the fundamental Nyquist noise limit in an ultra-high $Q$-factor cryogenic bulk acoustic wave cavity

Maxim Goryachev,¹,a) Eugene N. Ivanov,¹ Frank van Kann,² Serge Galliou,³ and Michael E. Tobar¹
¹ARC Centre of Excellence for Engineered Quantum Systems, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia
²School of Physics, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia
³Department of Time and Frequency, FEMTO-ST Institute, ENSMM, 26 Chemin de l’Épitaphe, 25000 Besançon, France

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Thermal Nyquist noise fluctuations of high-$Q$ bulk acoustic wave cavities have been observed at cryogenic temperatures with a DC superconducting quantum interference device amplifier. High $Q$ modes with bandwidths of few tens of milliHz produce thermal fluctuations with a signal-to-noise ratio of up to 23 dB. The estimated effective temperature from the Nyquist noise is in good agreement with the physical temperature of the device, confirming the validity of the equivalent circuit model and the non-existence of any excess resonator self-noise. The measurements also confirm that the quality factor remains extremely high ($Q > 10^8$ at low order overtones) for very weak (thermal) system motion at low temperatures, when compared to values measured with relatively strong external excitation. This result represents an enabling step towards operating such a high-$Q$ acoustic device at the standard quantum limit. © 2014 AIP Publishing LLC.

[http://dx.doi.org/10.1063/1.4898813]
Resonator with Squid Output
Resonator with Squid Output

DC SQUID in a copper holder to be attached to the “cold finger” of the pulse-tube cryocooler
Resonator with Squid Output

DC SQUID in a copper holder to be attached to the “cold finger” of the pulse-tube cryocooler.
Resonator with Squid Output

DC SQUID in a copper holder to be attached to the “cold finger” of the pulse-tube cryocooler

Calibration: Use resistors instead of resonators -
> Derive SQUID transimpedance $\sim 1.2 \, \text{M}\Omega$
Calculate Mode Temperature
Calculate Mode Temperature

(i) Measurements of the SQUID voltage noise  
(ii) Estimation of the RMS current through resonator (known SQUID impedance from calibration)  
(iii) Calculation of power dissipated in resonator for evaluation of mode temperature.
Calculate Mode Temperature

(i) Measurements of the SQUID voltage noise
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FIG. 2. Results of noise measurements for $C_{3,0,0}$, $A_{3,0,0}$, $B_{5,0,0}$, and $A_{5,0,0}$. The latter is measured using the downconversion as shown in the inset.
Calculate Mode Temperature

(i) Measurements of the SQUID voltage noise
(ii) Estimation of the RMS current through resonator (known SQUID impedance from calibration)
(iii) Calculation of power dissipated in resonator for evaluation of mode temperature.
• Most of our resonators are identical 5MHz SC cut. -> do not have good modes around 300MHz where the mode density is sparse.

• 5MHz AT cut crystal (we have only one) has a good mode around this frequency, to be measured soon (varactor?), close to Ground State.
System is a sensitive GW Detector
System is a sensitive GW Detector

Quartz
Mass = Gram Scale
Q = $10^9$
f = 5 MHz to 700 MHz
T = 15 mK
System is a sensitive GW Detector

Old Resonant Bar Detector

Mass = 1.5 tonne
Q = 10^7
F = 710 Hz
T = 5 K

Quartz
Mass = Gram Scale
Q = 10^9
f = 5 MHz to 700 MHz
T = 15 mK
System is a sensitive GW Detector (PRD)
Gravitational wave detection with high frequency phonon trapping acoustic cavities

Maxim Goryachev and Michael E. Tobar*

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(Received 25 September 2014; published 24 November 2014)

There are a number of theoretical predictions for astrophysical and cosmological objects, which emit high frequency (10^6 – 10^9 Hz) gravitational waves (GW) or contribute somehow to the stochastic high frequency GW background. Here we propose a new sensitive detector in this frequency band, which is based on existing cryogenic ultrahigh quality factor quartz bulk acoustic wave cavity technology, coupled to near-quantum-limited SQUID amplifiers at 20 mK. We show that spectral strain sensitivities reaching 10^{-22} per \sqrt{Hz} per mode is possible, which in principle can cover the frequency range with multiple (>100) modes with quality factors varying between 10^6 and 10^{10}, allowing wide bandwidth detection. Due to its compactness and well-established manufacturing process, the system is easily scalable into arrays and distributed networks that can also impact the overall sensitivity and introduce coincidence analysis to ensure no false detections.

DOI: 10.1103/PhysRevD.90.102005

PACS numbers: 04.80.Nn, 95.55.Ym
System is a sensitive GW Detector (PRD)

FIG. 5: Normalised the single sided power spectral density of the strain sensitivity for various OTs of the longitudinal mode of two acoustical cavities at 4K and 20mK.
The Sound of Dark Matter: Searching for Light Scalars with Resonant-Mass Detectors

Asimina Arvanitaki,1, * Savas Dimopoulos,2, † and Ken Van Tilburg2, ‡

1Perimeter Institute for Theoretical Physics, Waterloo, Ontario, N2L 2Y5, Canada
2Stanford Institute for Theoretical Physics, Stanford University, Stanford, CA 94305, USA
(Dated: August 11, 2015)

The fine structure constant and the electron mass in string theory are determined by the values of scalar fields called moduli. If the dark matter takes on the form of such a light modulus, it oscillates with a frequency equal to its mass and an amplitude determined by the local dark matter density. This translates into an oscillation of the size of a solid that can be observed by resonant-mass antennae. Existing and proposed resonant-mass detectors can probe dark matter moduli with frequencies between 1 kHz and 1 GHz, with much better sensitivity than force measurements.
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FIG. 1. Scalar field parameter space, with mass $m_\phi$ and corresponding DM oscillation frequency $f_\phi = m_\phi/2\pi$ on the bottom and top horizontal axes, and couplings of both an electron mass modulus ($d_e = d_{m_e}$) and electromagnetic gauge modulus ($d_e = d_e$) on the vertical axis. Natural parameter space for a 10 TeV cutoff is depicted by the green regions, while the other regions represent 95% CL limits from fifth-force tests ("5F", gray), equivalence-principle tests ("EP", orange), atomic spectroscopy in dysprosium ("Dy", purple), and low-frequency terrestrial seismology ("Earth", black). The blue curve shows the projected SNR = 1 reach of a proposed resonant-mass detector—a copper-silicon (Cu-Si) sphere 30 cm in radius—after 1.6 y of integration time, while the red curve shows the reach for the current AURIGA detector with 8 y of recasted data. Rough estimates of the 1-year reach of a proposed DUAL detector (pink) and several harmonics of two piezoelectric quartz resonators (gold points) are also shown.
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(Dated: August 11, 2015)

The fine structure constant and the electron mass in string theory are determined by the values of scalar fields called moduli. If the dark matter takes on the form of such a light modulus, it oscillates with a frequency equal to its mass and an amplitude determined by the local dark matter density. This translates into an oscillation of the size of a solid that can be observed by resonant-mass antennae. Existing and proposed resonant-mass detectors can probe dark matter moduli with frequencies between 1 kHz and 1 GHz, with much better sensitivity than force measurements.

FIG. 1. Scalar field parameter space, with mass $m_\phi$ and corresponding DM oscillation frequency $f_\phi = m_\phi / 2\pi$ on the bottom and top horizontal axes, and couplings of both an electron mass modulus ($d_e = d_{me}$) and electromagnetic gauge modulus ($d_e = d_\phi$) on the vertical axis. Natural parameter space for a 10 TeV cutoff is depicted by the green regions, while the other regions represent 95\% CL limits from fifth-force tests ("5F", gray), equivalence-principle tests ("EP", orange), atomic spectroscopy in dysprosium ("Dy", purple), and low-frequency terrestrial seismology ("Earth", black). The blue curve shows the projected SNR = 1 reach of a proposed resonant-mass detector—a copper-silicon (Cu-Si) sphere 30 cm in radius—after 1.6 y of integration time, while the red curve shows the reach for the current AURIGA detector with 8 y of recasted data. Rough estimates of the 1-year reach of a proposed DUAL detector (pink) and several harmonics of two piezoelectric quartz resonators (gold points) are also shown.
Quantum Gravity

Theoretically proposed modification:

\[ [x, p] = i\hbar \sqrt{1 + 2\eta_0 \frac{(p/c)^2 + m^2}{M_p^2}} \]

Gravity correction to the Heisenberg principle

\[ \Delta x \Delta p = \frac{\hbar}{2} \left( 1 + \frac{\beta_0}{M_p^2} \Delta p^2 \right) \]

Forbidden by quantum gravity proposals

\[ \delta x \delta p = \hbar \left( \frac{\Delta x_{\text{min}}}{\Delta x} \right)^2 \]
\[ \Delta x \Delta p > \frac{\hbar}{2} \left[ 1 + \beta_0 \left( \frac{\Delta p}{M_p c} \right)^2 \right] \]
THE END
High-Q and Novel Cavity Structures for Photon-Spin Strong Coupling and testing Fundamental Physics
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WG Modes
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TE + TM Cylindrical modes
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TE + TM Cylindrical modes
• High frequency region has physically understood processes of generation of GWs
  – thermal gravitational radiation from stars
  – Radiation from low mass primordial black holes
  – gravitational modes of plasma flows
• Tests for many emerging theories predicting GW radiation at such frequencies.
  – stochastic sources in the early Universe
  – GW background from quintessential inflation
  – cosmic strings
  – Dilation
  – pre-big bang scenarios
  – Superinflation in loop quantum gravity
  – Postinflationary phase transitions
  – parametric resonance at the end of inflation or preheating
  – braneworld black holes associated with extra dimensions
  – clouds of axions (super radiance)
  – quark nuggets
  – One hypothetical source (due to the Galactic center shadow brane) comes within the sensitivity of the proposed single detector