THE UNIVERSITY OF WESTERN AUSTRALIA

FACULTY OF SCIENCE

Axion / WISP Experiments at UWA

Perth, Australia

MICHAEL TOBAR, STEPHEN PARKER, BEN MCALLISTER, EUGENE IVANOV

11th Patras Workshop on Axions, WIMPs and WISPs
June 23rd, 2015
University of Zaragoz, Spain

Axion / WISP Experiments at UWA

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eQus
ARC CENTRE OF EXCELLENCE FOR ENGINEERED QUANTUM SYSTEMS

- **Core membership**
- Michael Tobar
- Eugene Ivanov
- John McFerran
- Sascha Schediwy
- Daniel Creedon
- Stephen Parker
- Maxim Goryachev
- Leandro de Paula

- **Postgraduate students**
- Romain Bara-Maillet
- Jeremy Bourhill
- Nikita Kostylev
- Natalia Carvalho
- Akhter Hoissan
- David Gozzard
- Ben McAllister

Research Programs

Precision Measurement with frequency, time or phase.

1) Clocks, Oscillators, low noise detection

2) ACES Mission

3) Fundamental Physics Tests

ARC Centre of Excellence in Engineered Quantum Systems

1) Spins in solids (dressed states of photons and spins)

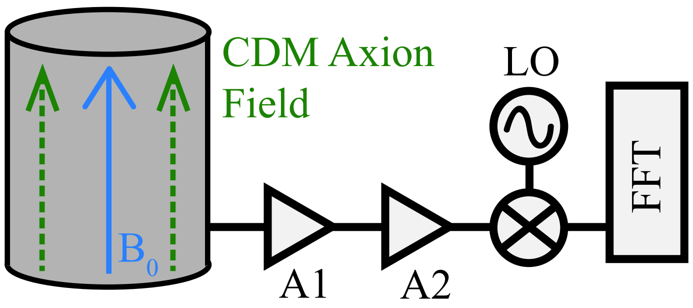
2) Opto-Mechanics -> Macroscopic Mass at the quantum limit

3) Low noise quantum limited readouts

Current Projects in Time and Frequency

- Key Technology
  - Yb Lattice Clock (ACES)
  - Cryogenic Sapphire Oscillator (CSO) -> 10^{-17}
  - Microwave Interferometry: Low Phase Noise Oscillators and Phase Detection
  - High-Q Cavities -> transducers -> Special designs
- Test on Fundamental Physics
  - Lorentz Invariance (CSO, BAW, short range gravity)
  - Dark Sector Detection (Axion, Paraphoton)
  - Variation of Fundamental Constants
  - ACES Ground Station

The Axion Haloscope – Quick Recap & Overview



$$P_A = \left(\frac{g_\gamma \alpha}{\pi f_A}\right)^2 \rho_A V B_0^2 C \min(Q_L, Q_A)$$

ρ_a – Axion density
m_a – Axion mass
B_0 – Magnetic field strength
V – Cavity volume
C – Form factor (E.B overlap)
Q – Cavity quality factor (or axion Q)

Cavity enables resonant enhancement of converted photon signal. Measure power to constrain axion-2photon coupling.

Advantages:

Excellent sensitivity (real discovery potential)
Can reveal some astrophysics
Relatively cheap

Disadvantages:

Not broadband (relatively narrow search range)
Major technological challenges for higher masses.

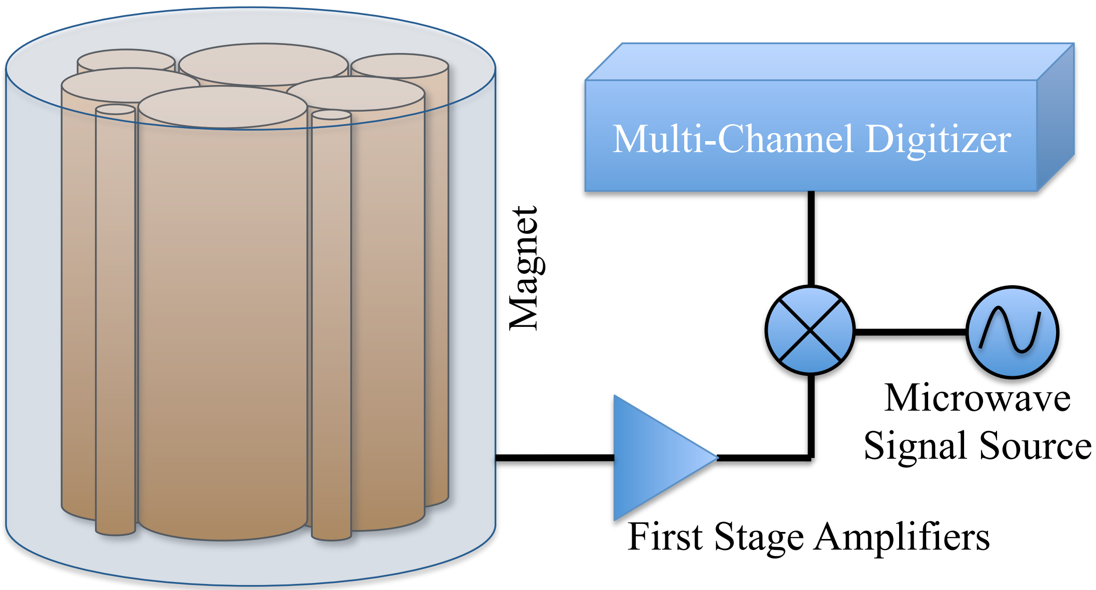
ORGAN: The concept
(Funding Request Australian Research Council, ADMX PIs)

Act as stepping-stone to see if we can scale up to undertake search over larger mass range?

E.G. Can we be generating real "science" data right now by just using an array of cavities looking at different frequencies?

Compensate for loss in volume at High frequencies by looking at Multiple frequencies simultaneously.

1st Step this year
Check candidate 110 μeV signal via different method of detection.
(Use equipment already in the lab)



Prospects for CDM-Axion Haloscope Searches

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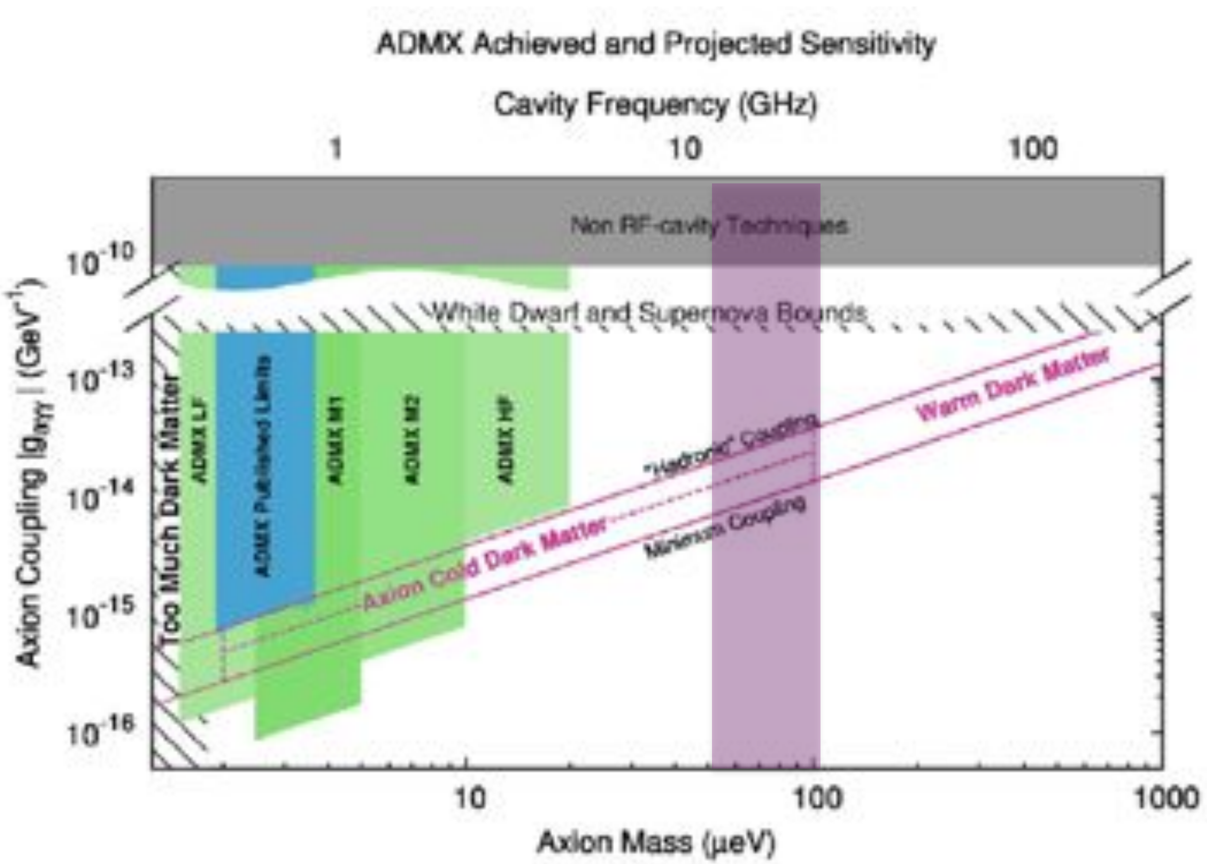


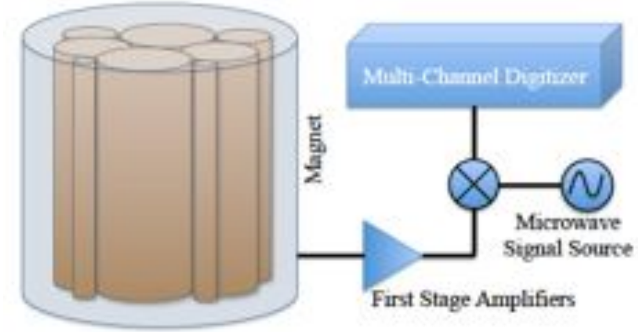
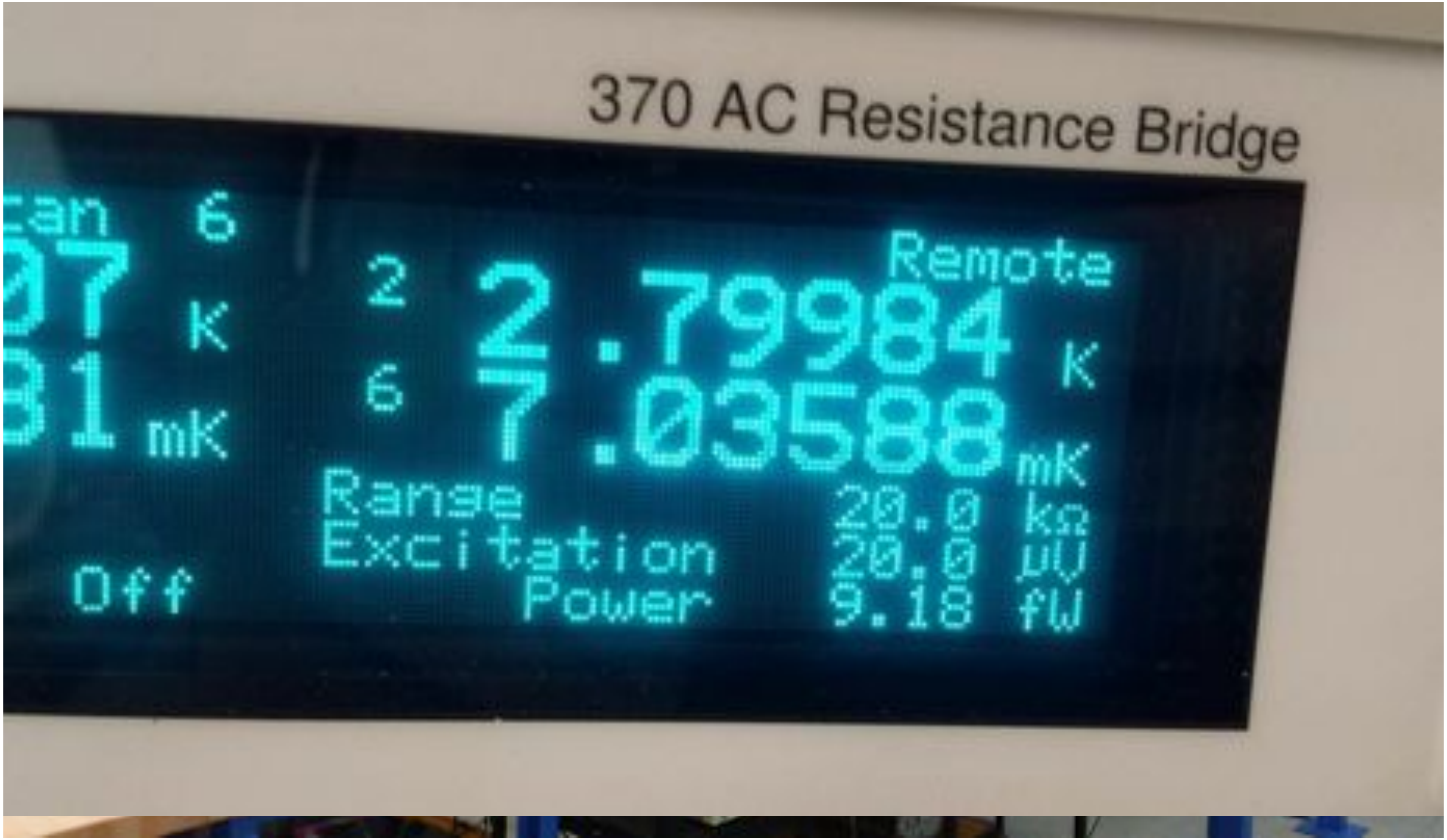


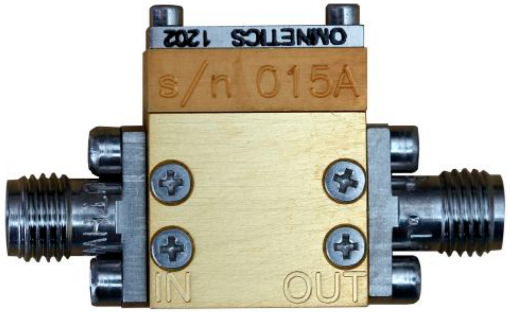
Figure 3: *Sketch of the ORGAN detector. The cavities, magnet and first stage amplifiers are cryogenic; a microwave signal source is used to mix the spectrums down so they can be sampled by the digitizer.*

micrOwave Resonator Group Axion coNverter (ORGAN)

We (UWA) are well positioned to search in the 10 – 40 GHz region


370 AC Resistance Bridge
Remote
2 2.79984 K
6 7.03588 mK
Range 20.0 kΩ
Excitation 20.0 μV
Power 9.18 fW
Off

Equipment…



Best “off-the-shelf” immediate amplifier solution

Lownoisefactory, noise temp ~10 K @ 26 GHz.

Look at alternatives after first experiment…

7 T Magnet (10 cm bore)

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Axion

From Wikipedia, the free encyclopedia

For other uses, see Axion (disambiguation).

The **axion** is a 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.

Possible detection [edit]

Axions may have been detected through irregularities in X-ray emission due to interaction of the Earth's magnetic field with radiation streaming from the Sun. Studying 15 years of data by the European Space Agency's XMM-Newton observatory, a research group at Leicester University noticed a seasonal variation for which no conventional explanation could be found. One potential explanation for the variation, described as "plausible" by the senior author of the paper, was X-rays produced by axions from the Sun's core.[29]

A term analogous to the one that must be added to Maxwell's equations[30] also appears in recent theoretical models for topological insulators.[31] This term leads to several interesting predicted properties at the interface between topological and normal insulators.[32] In this situation the field θ describes something very different from its use in high-energy physics.[32] In 2013, Christian Beck suggested that axions might be detectable in Josephson junctions; and in 2014, he argued that a signature, consistent with a mass ~110μeV, had in fact been observed in several preexisting experiments.[33]

Axion Detection?

PRL 111, 231801 (2013) PHYSICAL REVIEW LETTERS week ending 6 DECEMBER 2013

Possible Resonance Effect of Axionic Dark Matter in Josephson Junctions

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(Received 17 September 2013; published 2 December 2013)

We provide theoretical arguments that dark-matter axions from the galactic halo that pass through Earth may generate a small observable signal in resonant S/N/S Josephson junctions. The corresponding interaction process is based on the uniqueness of the gauge-invariant axion Josephson phase angle modulo 2π and is predicted to produce a small Shapiro steplike feature without externally applied microwave radiation when the Josephson frequency resonates with the axion mass. A resonance signal of so far unknown origin observed by C. Hoffmann *et al.* [Phys. Rev. B **70**, 180503(R) (2004)] is consistent with our theory and can be interpreted in terms of an axion mass $m_a c^2 = 0.11$ meV and a local galactic axionic dark-matter density of $0.05\ \mathrm{GeV/cm^3}$. We discuss future experimental checks to confirm the dark-matter nature of the observed signal.

DOI: 10.1103/PhysRevLett.111.231801 PACS numbers: 14.80.Va, 74.45.+c, 95.35.+d

A 110 μeV (26.6 GHz) Axion Haloscope Search

Claim that multiple J-J experiments observe anomalous Shapiro steps that are consistent with being caused by axions with mass M_a = 110 +/- 2 μeV.

Should be checked via independent dedicated experiment. Relatively narrow mass-range means Haloscope could be appropriate method.

BUT Need to check for local galactic axion density of $\rho_a \sim 0.05$ GeV/cm^3 (compared to the usual assumption of ~ 0.45 GeV/cm^3)

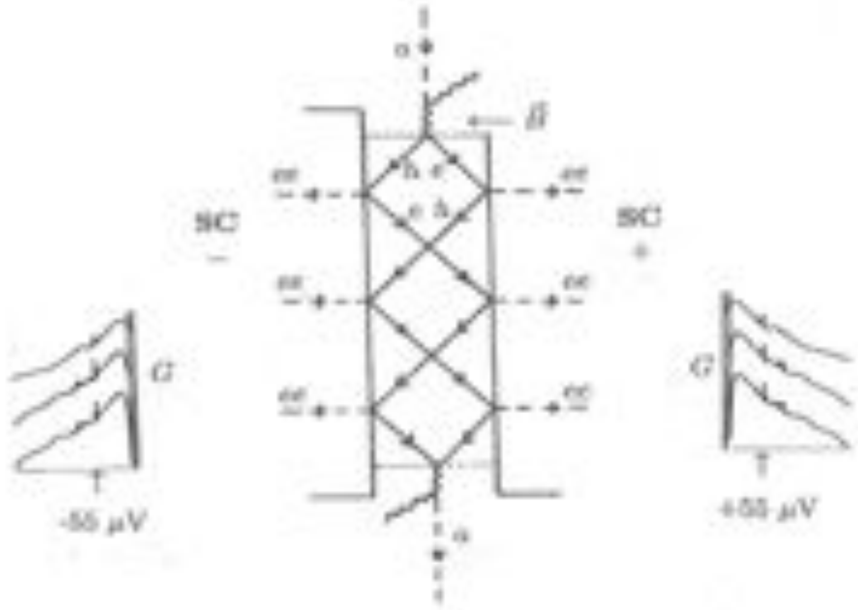
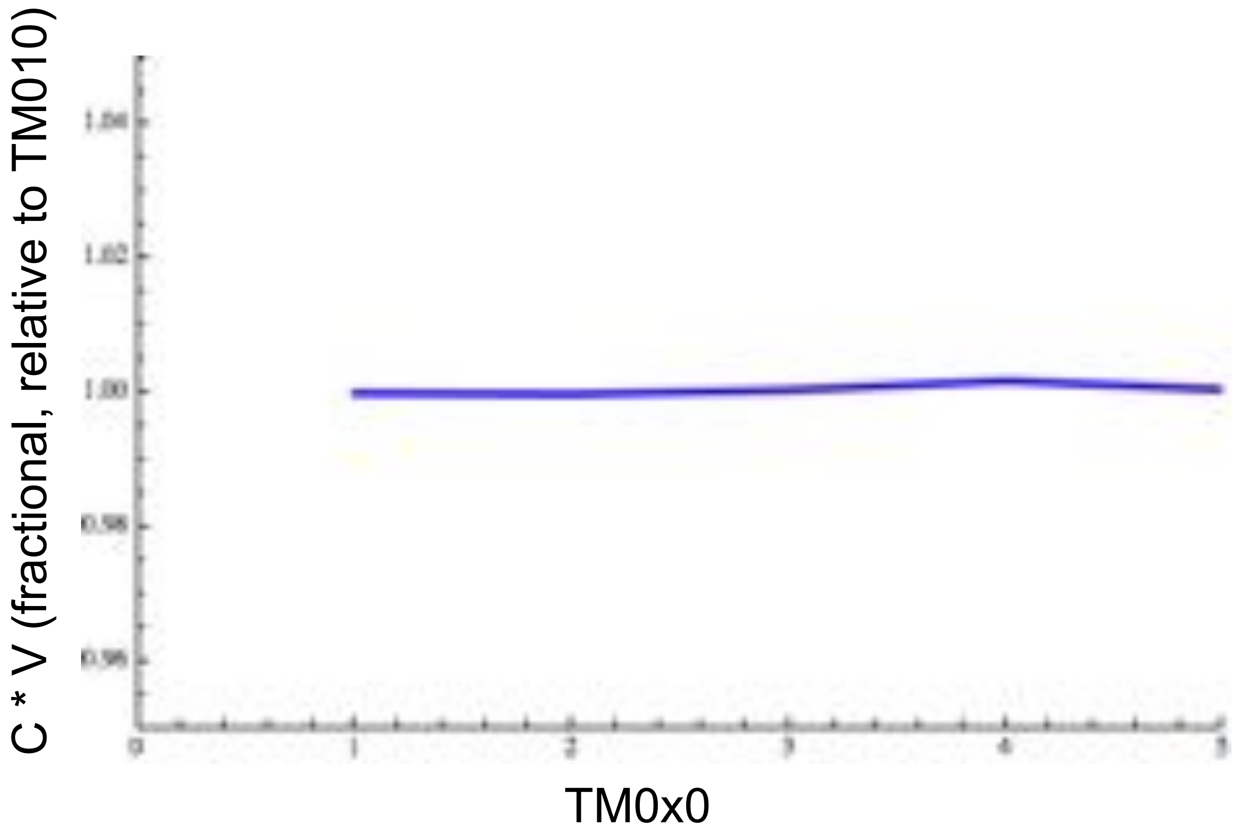


FIG. 2: Axion triggering the transport of n Cooper pairs ee in an S/N/S junction by multiple Andreev reflections, here shown for the example $n = 3$. The dotted line corresponds to the normal metal surface. The left and right insets show the shape of the differential conductance curve $G(V)$ as measured by Hoffmann et al. [12] for $T = 0.9K, 0.5K, 0.1K$ (top to bottom), with a peak occuring at $\pm 0.055mV$.

Need 80 days -> 1 cavity to cover M_a = 110 +/- 2 μeV (maybe use two?)

Cavity design

TM0x0 mode family provides best overlap for E.B
Note that product of form factor * volume is ~constant for TM0x0 modes



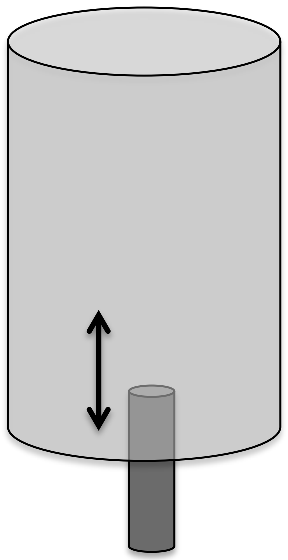
At such high frequencies using a higher order mode (i.e. larger cavity) has practical advantages.

For TM020, a 2cm diameter gives 26.6 GHz

Cavity Tuning

Would require 3 – 4% tuning range to "check" the full range of possible masses.

Want a simple tuning solution that can be implemented on a physically small cavity in cryogenic environment. Thankfully small range reduces complications related to mode crossings etc.



One approach is to perturb field slightly via 1-d insertion of small post

Cavity Tuning

Simple copper test cavity

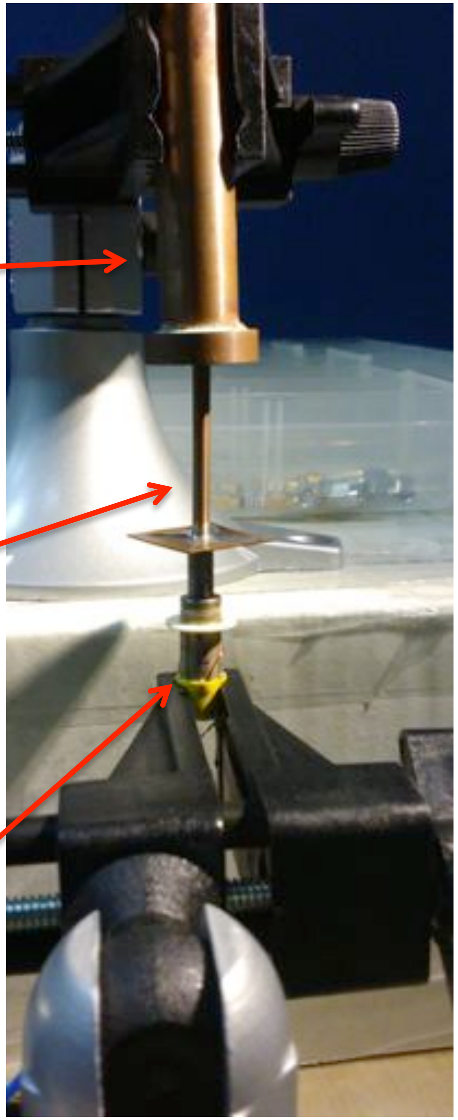
On the bench testing indicates can tune ~50 MHz for relative post insertion of 10% of cavity length.

Currently checking via simulations (field deformation etc.) and preparing for a prototype cavity to test cryogenically.

Need to arrive at trade-off between complex design and just swapping out cavities.

Post

“Squiggle” motor. Compact, operates cryogenically



Forecast

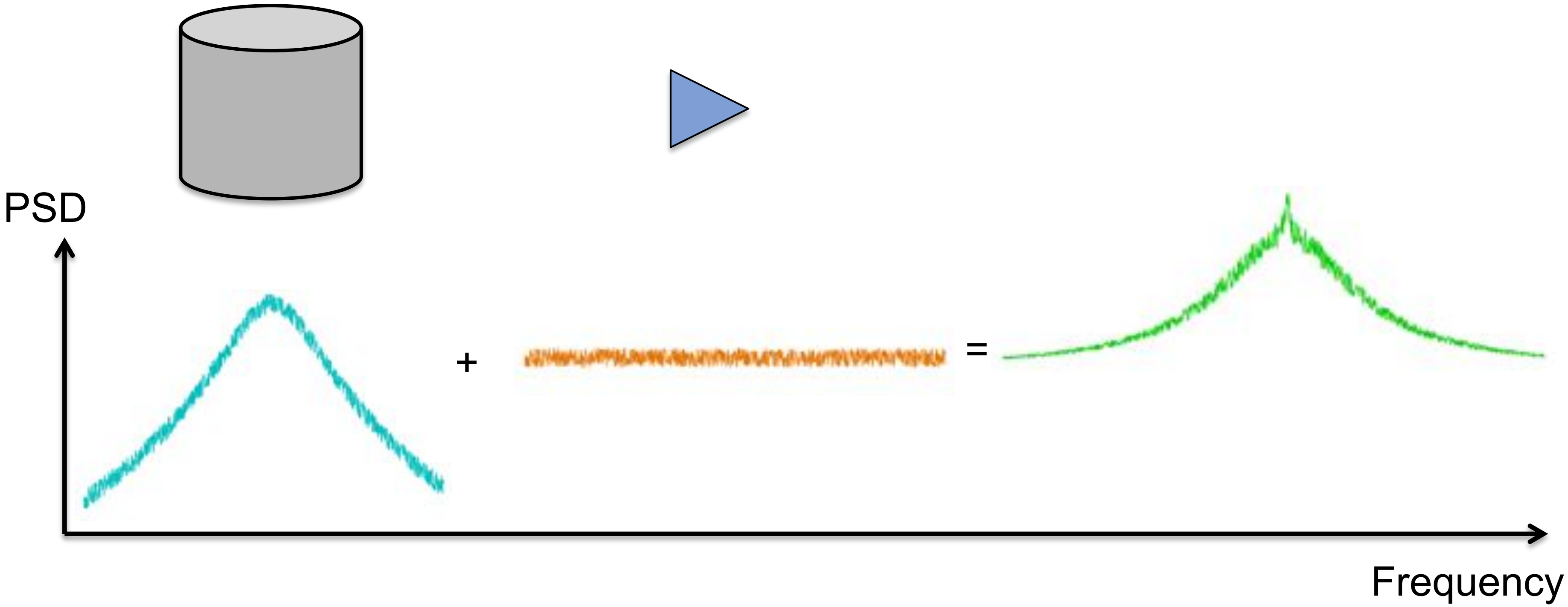
Beck's supposed 110 μeV signal doesn't assume a KSVZ or DFSZ model (g_γ cancels, f_a and ρ_a remain)

To test for KSVZ axions with local density of 0.05 GeV/cm^3 using modest assumptions (Q~10^4, total noise temp~10 K), a single cavity of ~2cm diameter, 10 cm length would take ~80 days total measurement time to cover the full mass range given (110 +/- 2 μeV = 26.6 +/- 0.5 GHz).

With an array of 6 cavities of similar properties, could test for DFSZ axions with local density of 0.45 GeV/cm^3 over 83 – 124 μeV (20 – 30 GHz) with a measurement time of ~110 days.

Noise - Overview

Cavity thermal noise + Amplifier noise = measurement system noise



Can we use techniques from precision measurement community to improve experiment?

Cross-Correlation

Compute the cross-spectrum of two signals
Uncorrelated signals are rejected
Correlated signals are retained

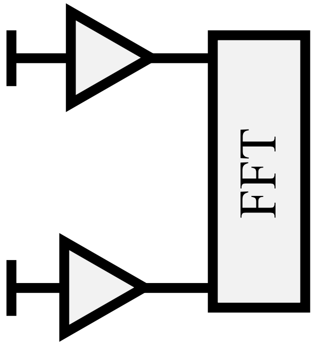
$$S_{ab}(f) = F\left(\lim_{\theta\to\infty}\frac{1}{\theta}\int_{\theta} a(t)b^*(t-\tau)d\tau\right)$$

$$S_{ab}(f) = \langle A(f)B^*(f)\rangle$$

Implemented in hardware, two channels sampled simultaneously with cross-spectrum computed “on-the-fly”

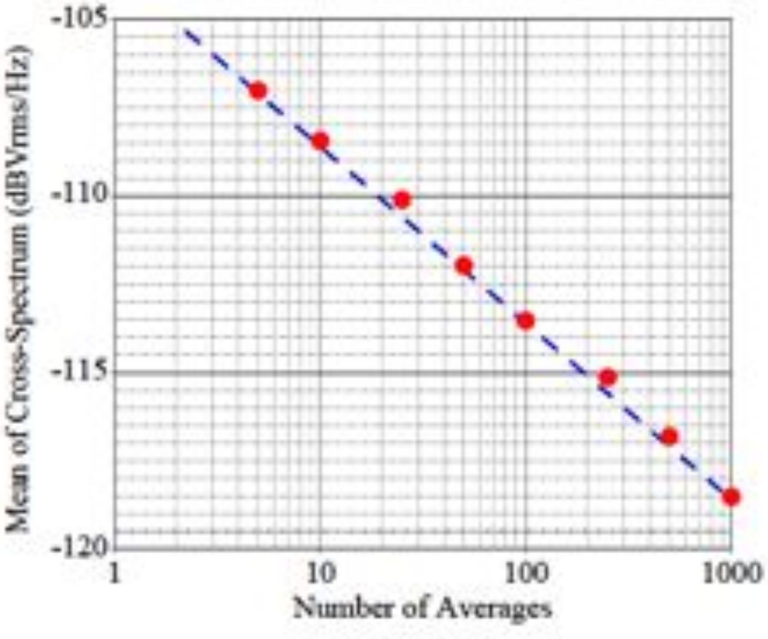
Important: No additional measurement time required compared to just measuring a single channel.

Rejection of uncorrelated noise



Fundamental: Uncorrelated noise rejected from cross-spectrum at rate 1 / sqrt(2m)

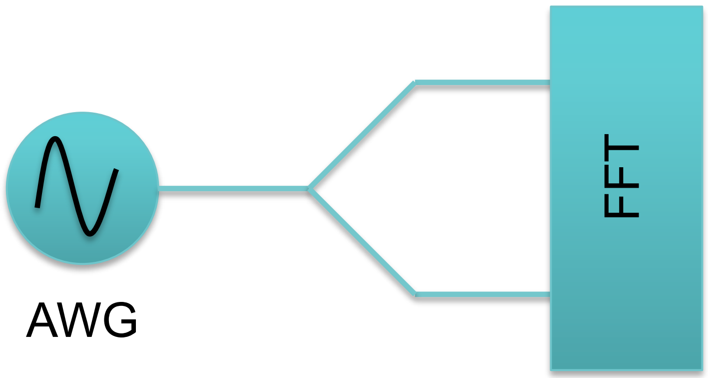
E.G. Two amplifiers with inputs terminated with 50 ohm loads.



Mean of cross-spectrum of voltage fluctuations reduces with sqrt(2m) compared to single channel.

Typically factor of 2 lost as correlated signal is power-split between two channels.

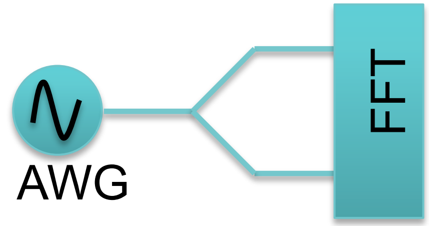
Cross-spectrum retains correlated signals regardless of “size”

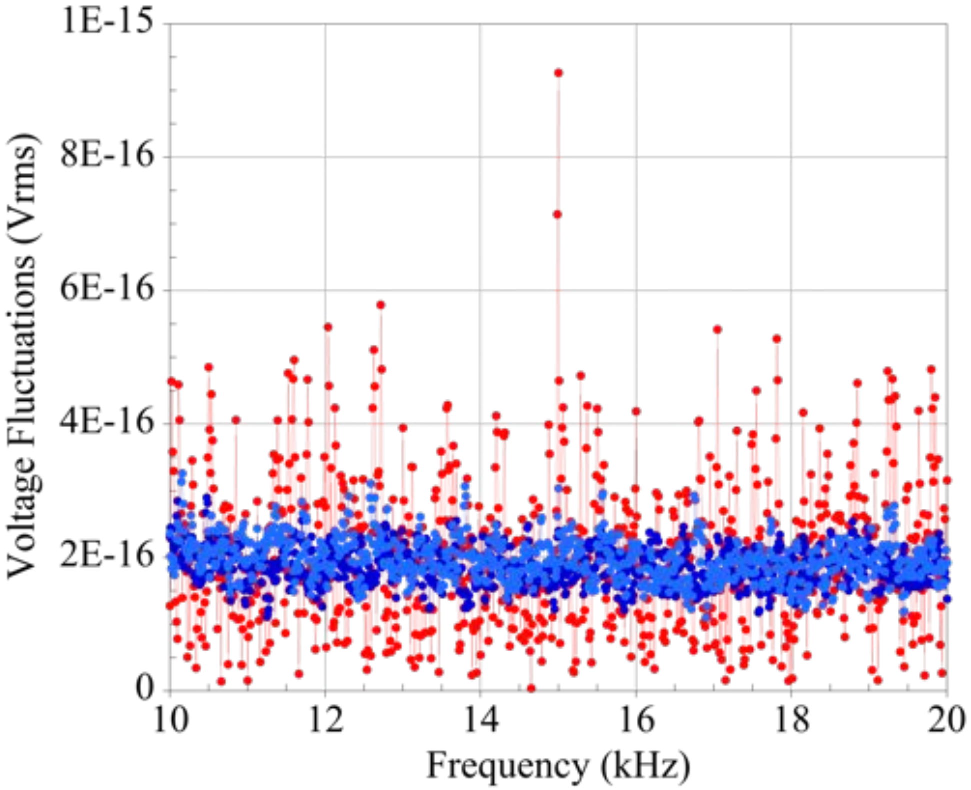


Small amplitude 15 kHz sinewave split and recorded on two channels.

Cross-spectrum retains correlated signals regardless of "size"

Single channels in blue
Cross-spectrum in red
(moved to overlap mean with single channel)





40 averages, 800 point spectrum

For single channels the ratio of 15 kHz signal to standard deviation (or uncertainty) of measurement is < 2.

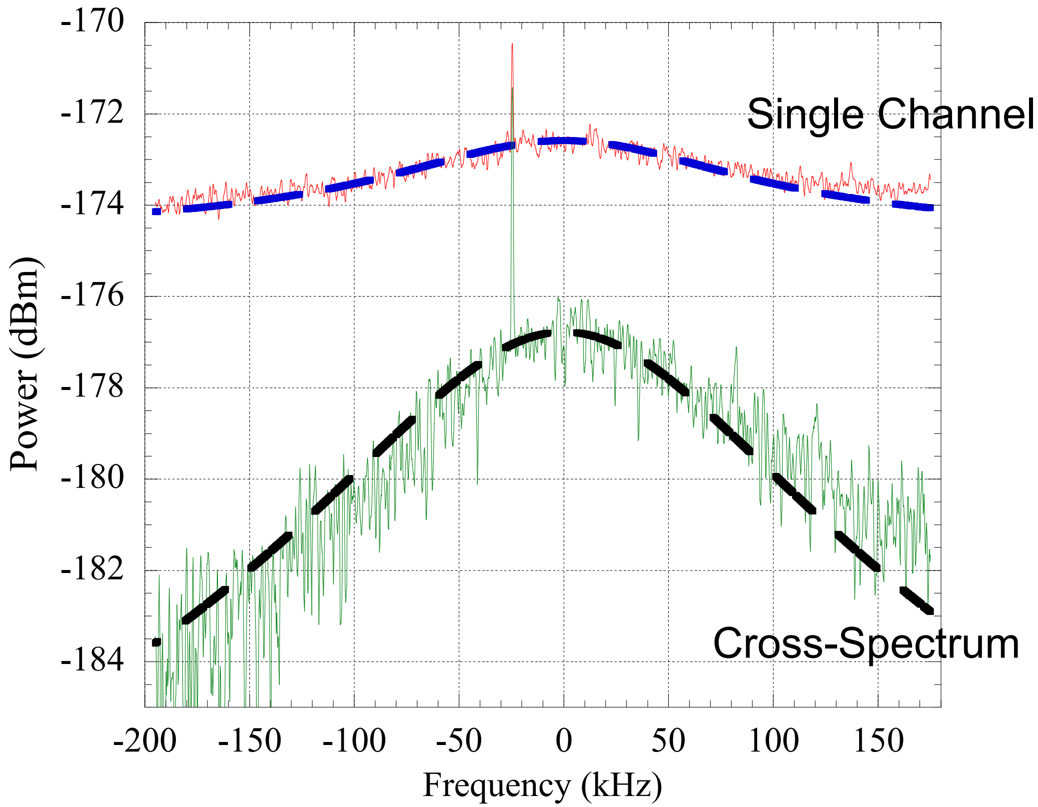
Same ratio for cross-spectrum is ~9.

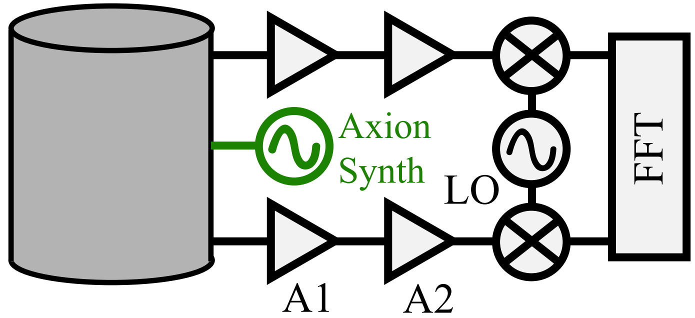
Cross-correlation can be applied to Haloscope style experiments to…

- Reduce noise contributions in hardware instead of during analysis / post-processing
- Power-sum cavities that have relatively large spatial separation – would be useful for applying scrutiny to any serious axion candidate signal
- Can also be applied to Light Shining through a Wall style experiments

Cross-Correlation Measurement Technique 1

Performing 2-channel measurements and computing the cross spectrum allows us to reject uncorrelated sources of noise



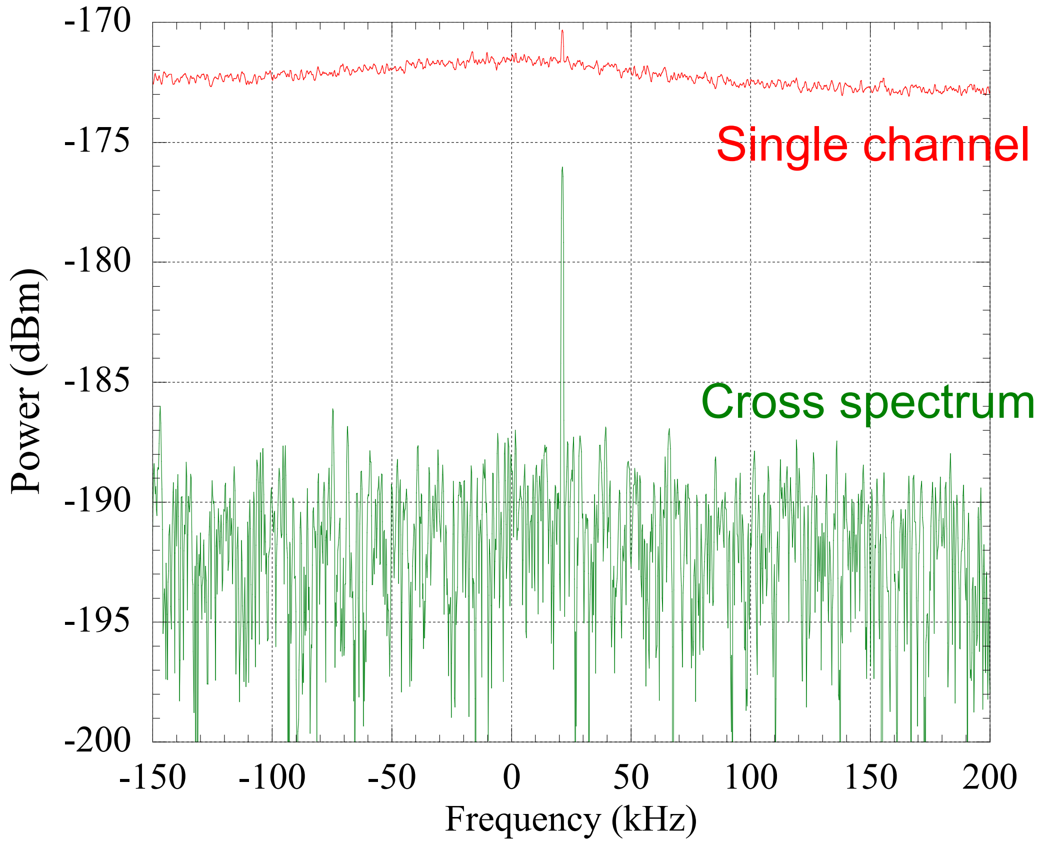


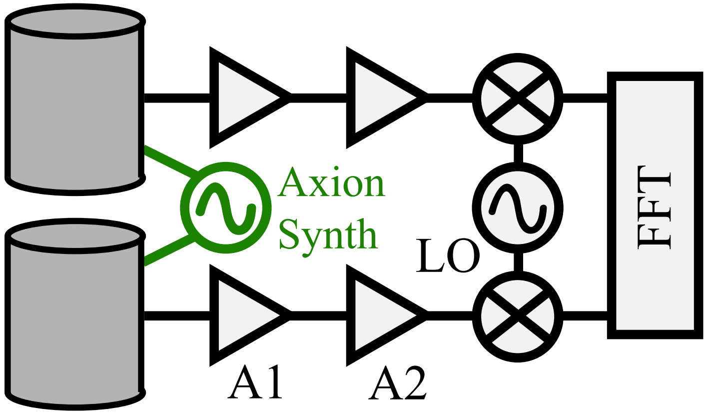
Axion signal simulated via synthesizer

Contribution of broadband amplifier noise to total system noise has been reduced by factor ~100.

Effectively eliminated relative to remaining thermal cavity noise.

Cross-Correlation Measurement Technique 2





Reduction of cavity noise and amplifier noise contributions

Can be used to “power-sum” cavities that are spatially well separated.

Types of Cavities: Couple to Spins

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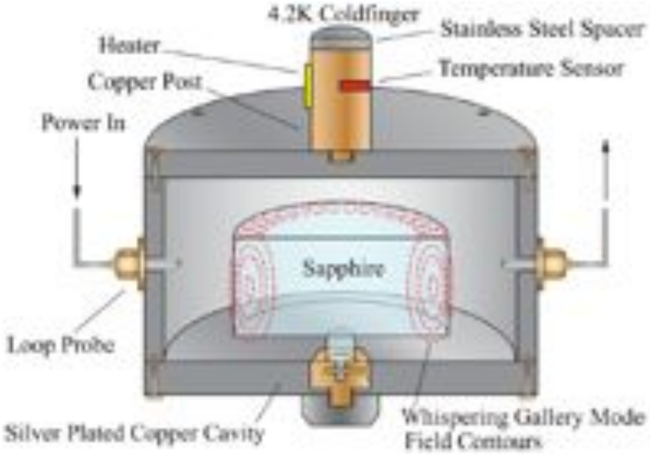
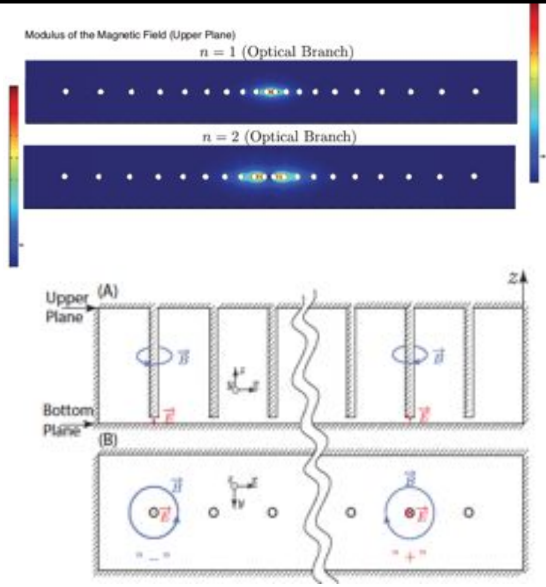
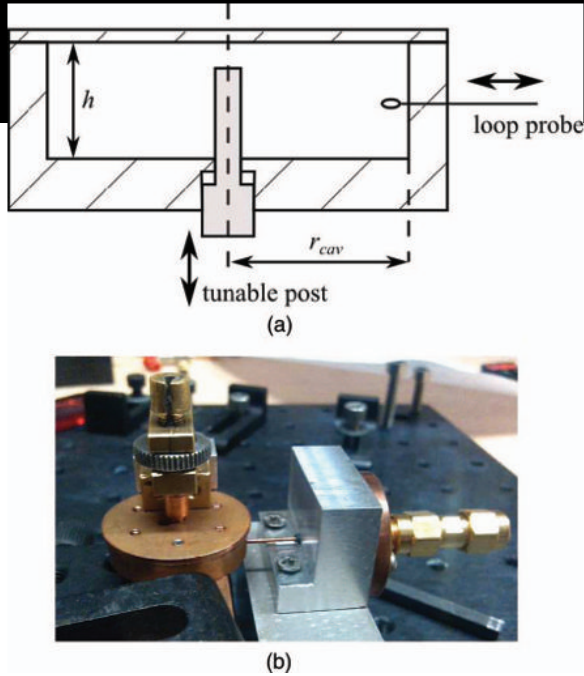
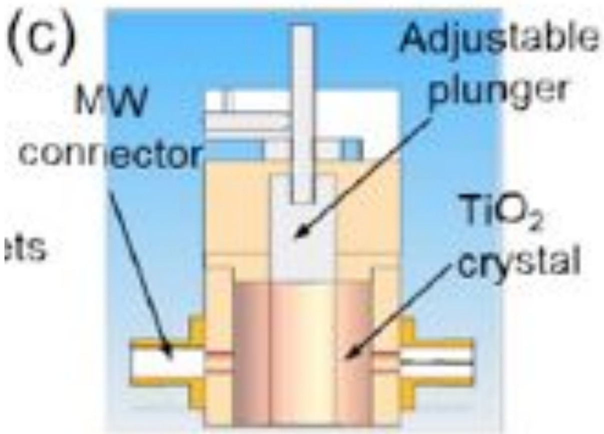
WG Modes



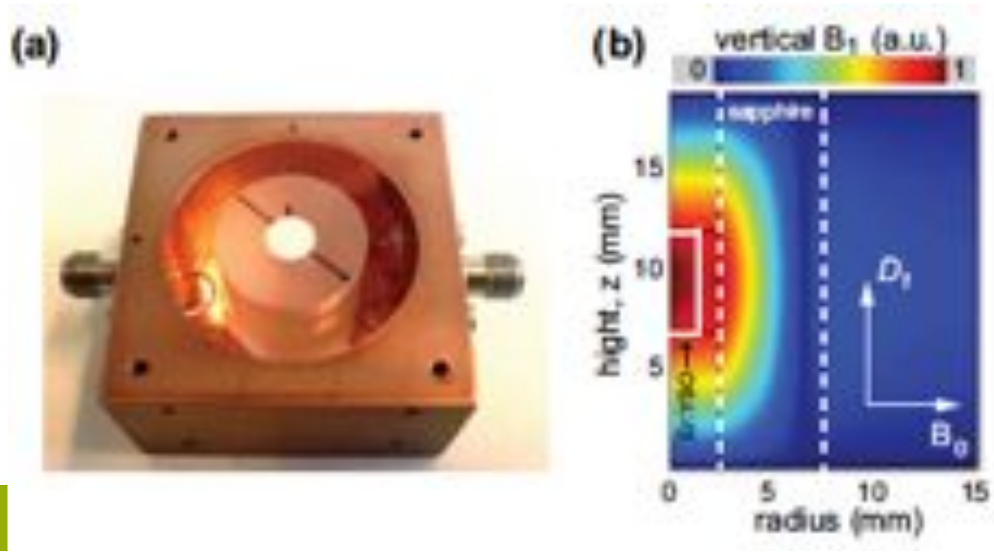
Reentrant Lattice







TE Cylindrical modes



arXiv:1408.2905 [quant-ph] PHYSICAL REVIEW APPLIED **2,** 054002 (2014)

High-Cooperativity Cavity QED with Magnons at Microwave Frequencies

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(Received 25 July 2014; revised manuscript received 10 October 2014; published 5 November 2014)

The 3D Split-Ring Cavity Lattice: A New Metastructure for Engineering Arrays of Coupled Microwave Harmonic Oscillators

arXiv:1408.3228 [physics.ins-det]

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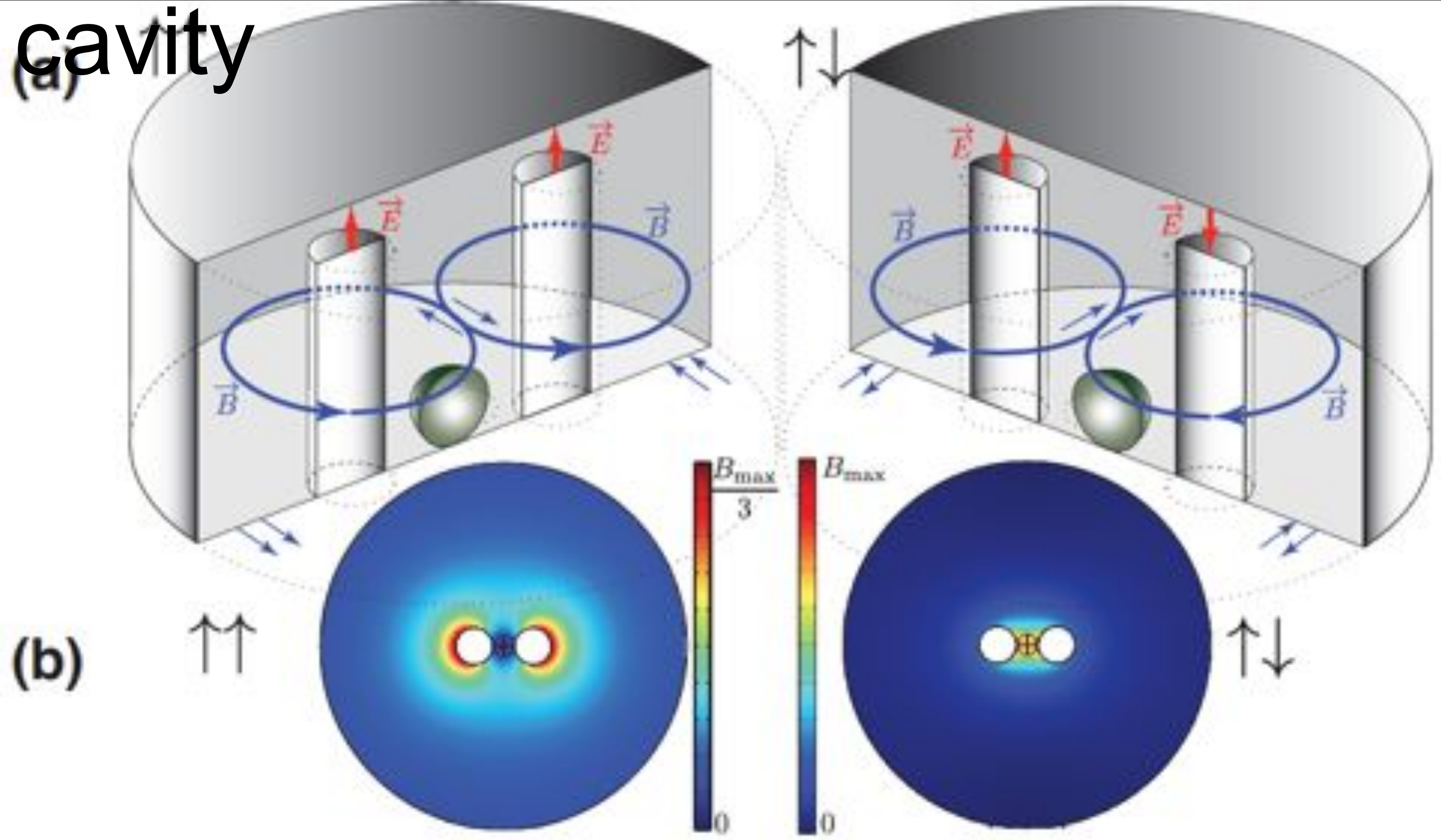
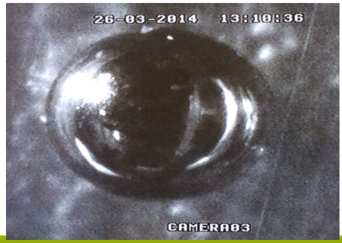
Goryachev and Tobar, 2014, Patent, PNo. AU2014,903,143

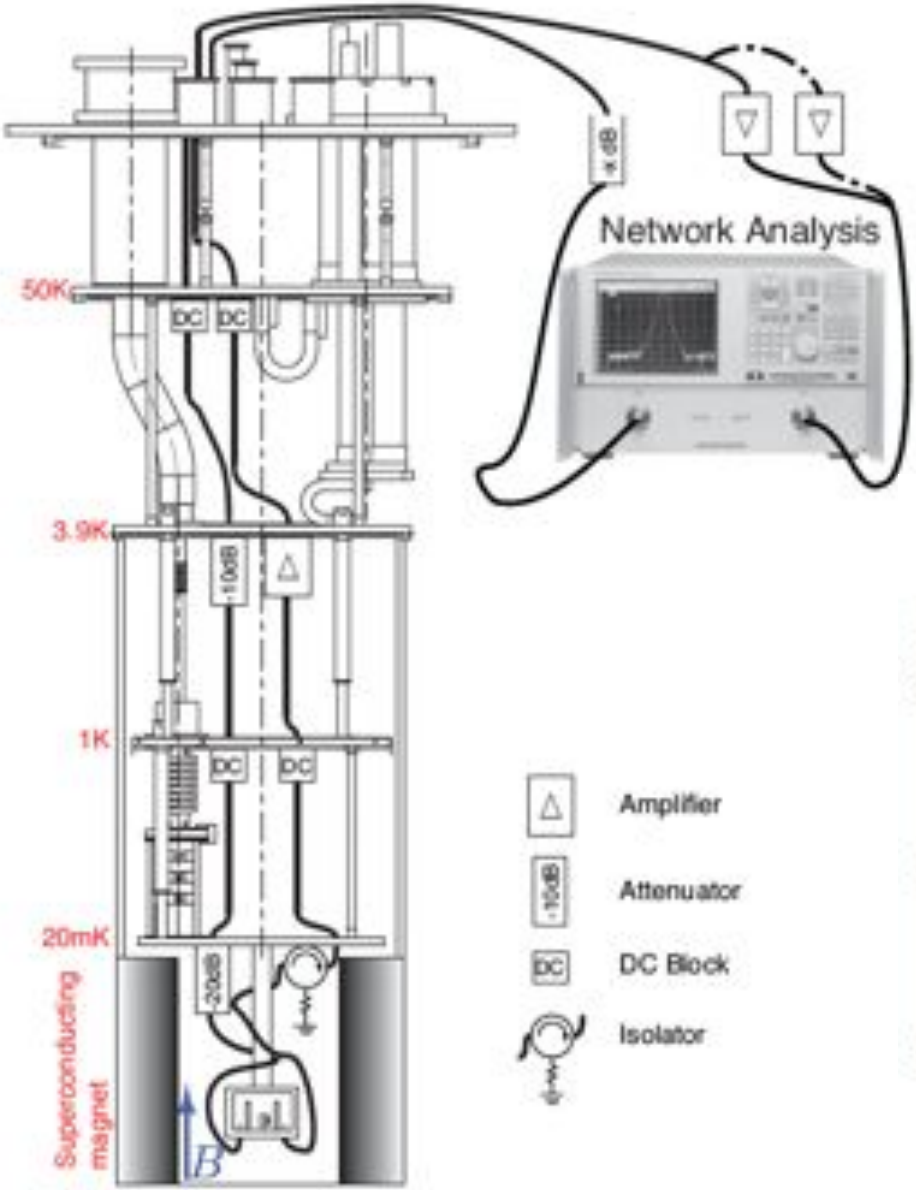
cavity

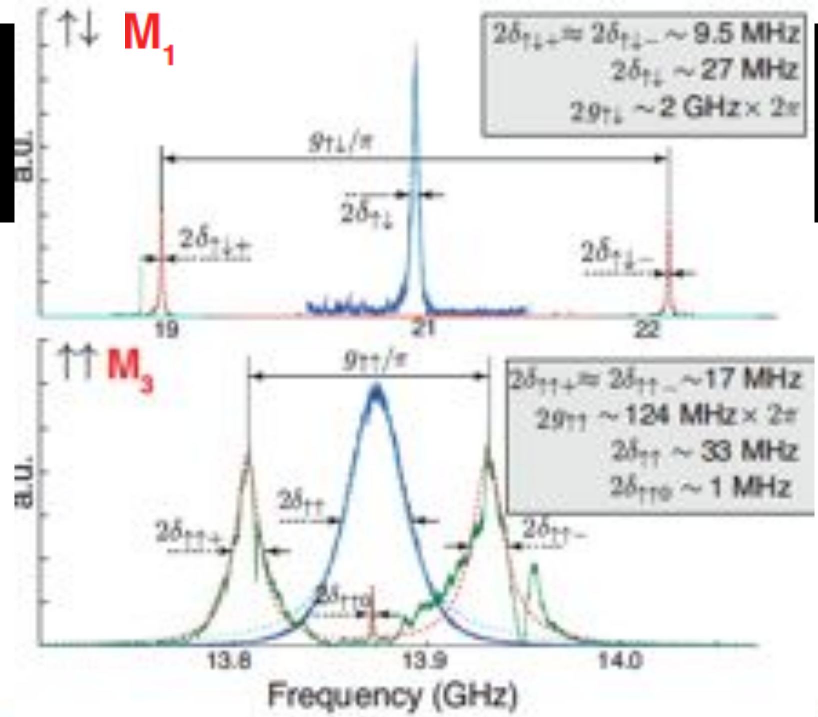


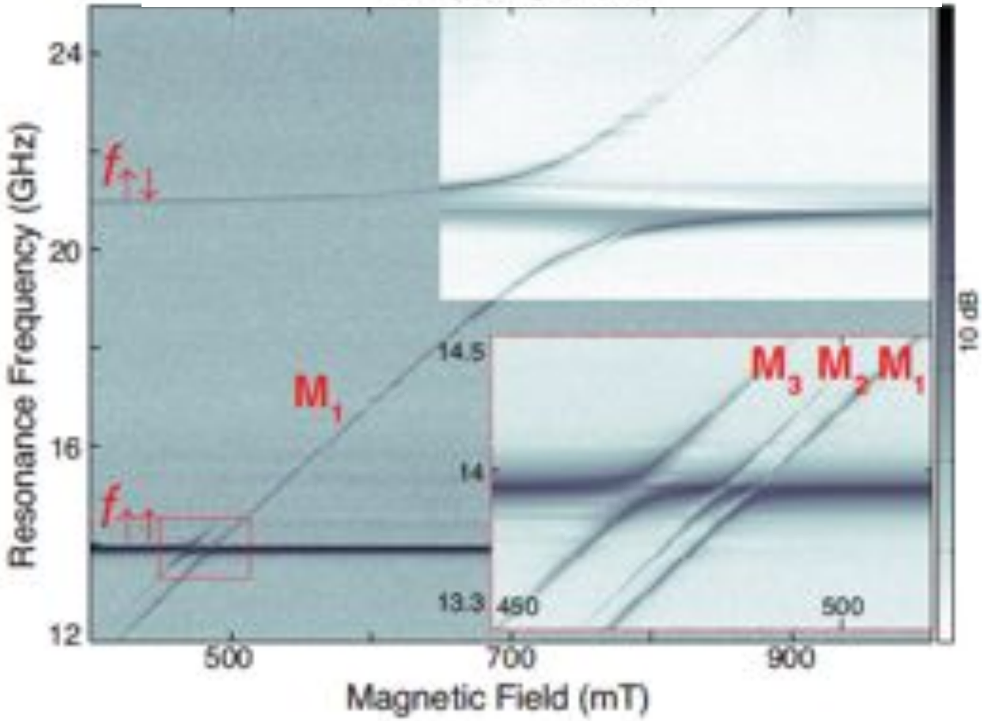
Dark Mode

Bright Mode




Network Analysis
50K
3.9K
1K
20mK
Superconducting magnet
DC
-10dB
-20dB
B
Amplifier
Attenuator
DC Block
Isolator


↑↓ M1
2δ↑↓+ ≈ 2δ↑↓− ~ 9.5 MHz
2δ↑↓ ~ 27 MHz
2g↑↓ ~ 2 GHz × 2π
a.u.
19
21
22
↑↑ M3
2δ↑↑+ ≈ 2δ↑↑− ~17 MHz
2g↑↑ ~ 124 MHz × 2π
2δ↑↑ ~ 33 MHz
2δ↑↑0 ~ 1 MHz
a.u.
13.8
13.9
14.0
Frequency (GHz)


Resonance Frequency (GHz)
24
20
16
12
M1
M3 M2 M1
14.5
14
13.3
480
500
700
900
10 dB
Magnetic Field (mT)

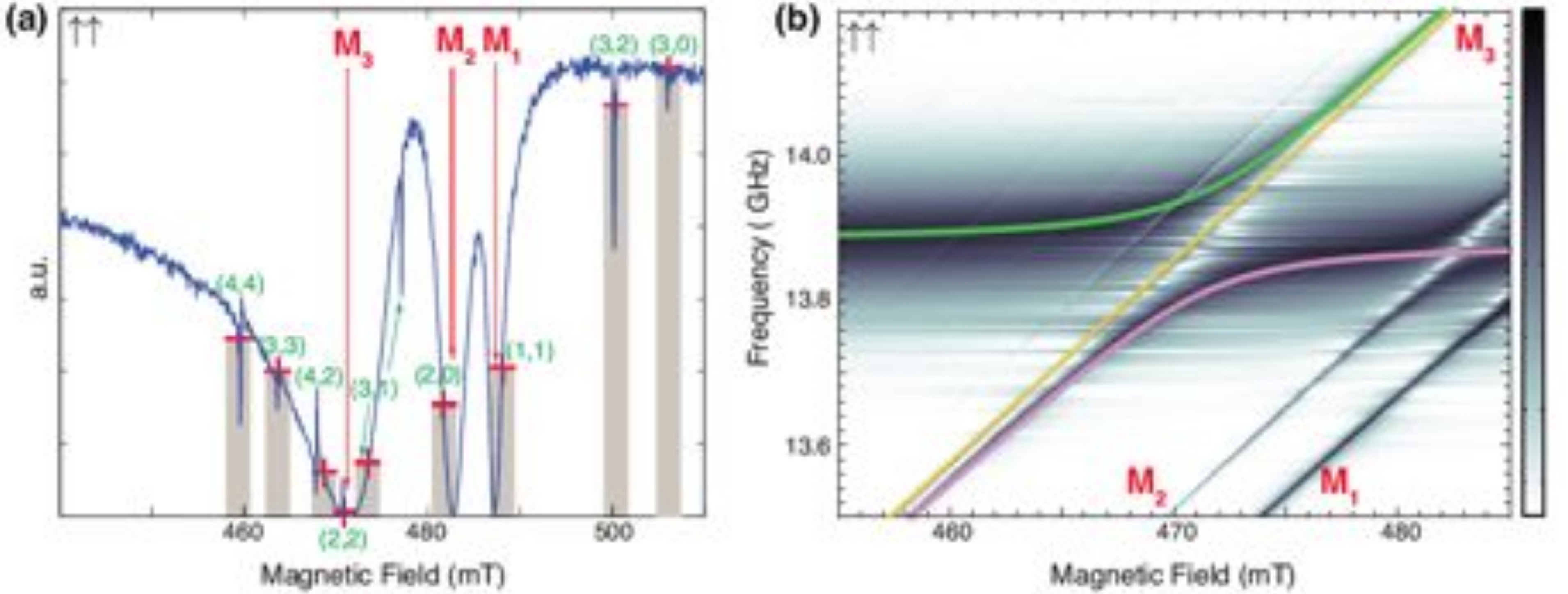
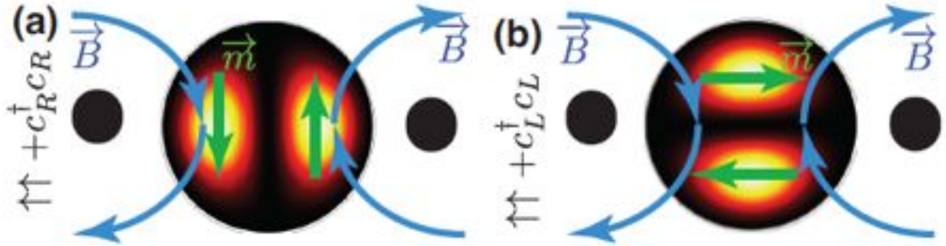


Figure 5: (a) Magnon modes observed near the dark cavity mode ↑↑ at $f_{\uparrow\uparrow}$. Shaded areas are theoretical predictions for magnon modes of order (n, m), (b) interaction between the magnon doublet M_3 and the dark cavity mode. Avoided crossings between photon and magnon modes are observed as transmission dips. The solid curves show the three-mode interaction model.

spin cooperativities $\frac{g_{\uparrow x}^2}{(\pi)^2 \gamma_M \gamma_{\uparrow x}}$

dark and bright

1.6×10^3 and 1.3×10^5



RAPID COMMUNICATIONS

PHYSICAL REVIEW B 91, 140408(R) (2015)

Strong coupling between $P1$ diamond impurity centers and a three-dimensional lumped photonic microwave cavity

Daniel L. Creedon,[1] Jean-Michel Le Floch,[1] Maxim Goryachev,[1] Warrick G. Farr,[1] Stefania Castelletto,[2] and Michael E. Tobar[1,*]

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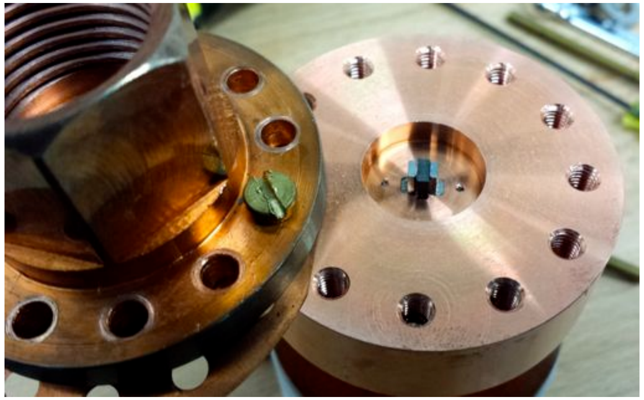
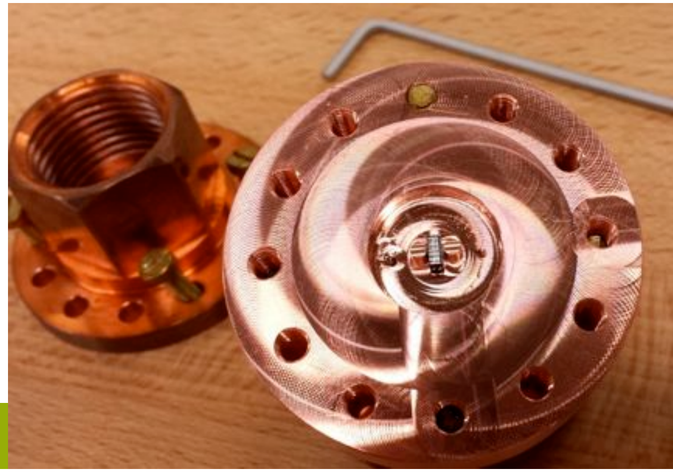
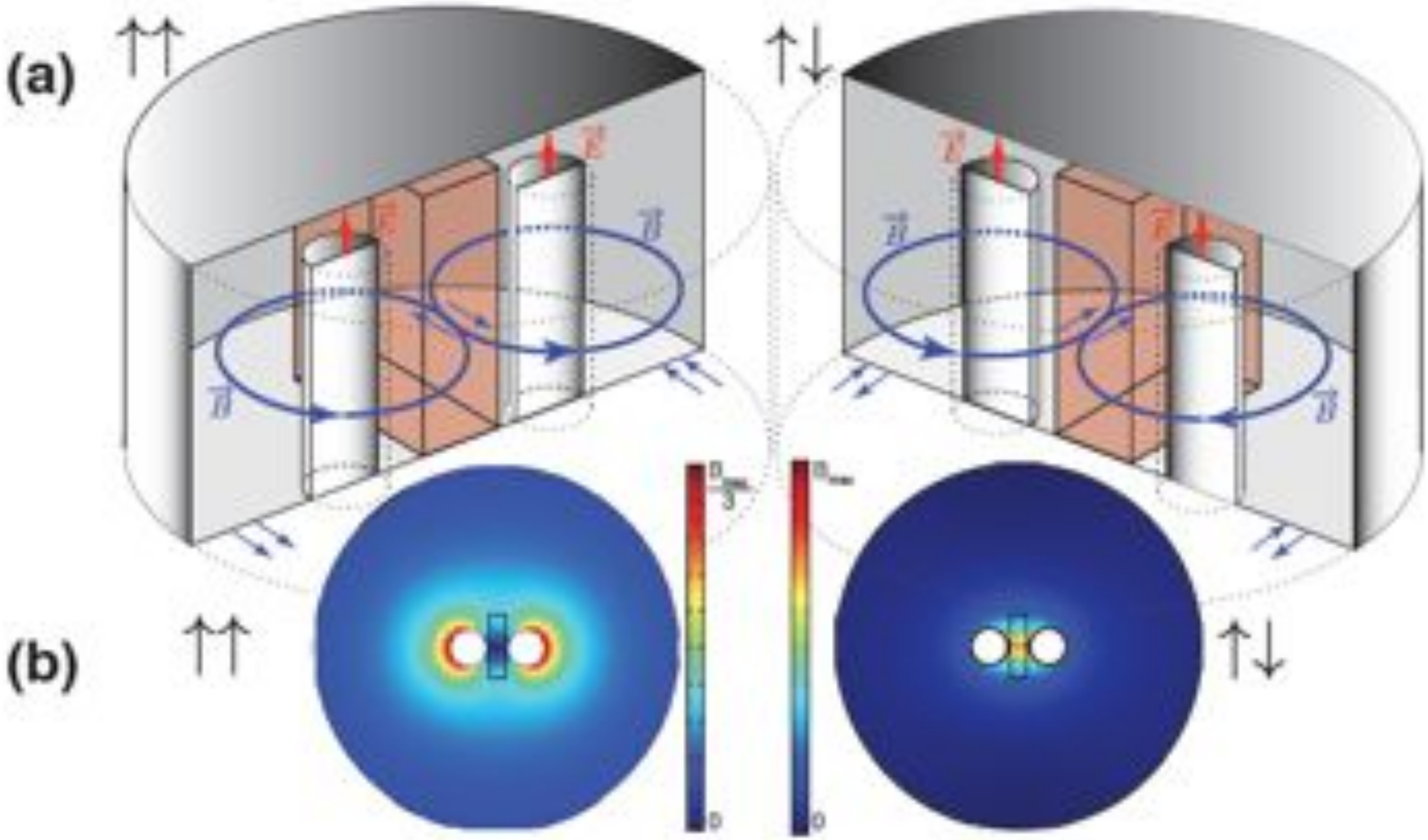




(to be submitted soon)


(a)
↑↑
↑↓
(b)
↑↑
↑↓

Strongly Couple to P1 Centres

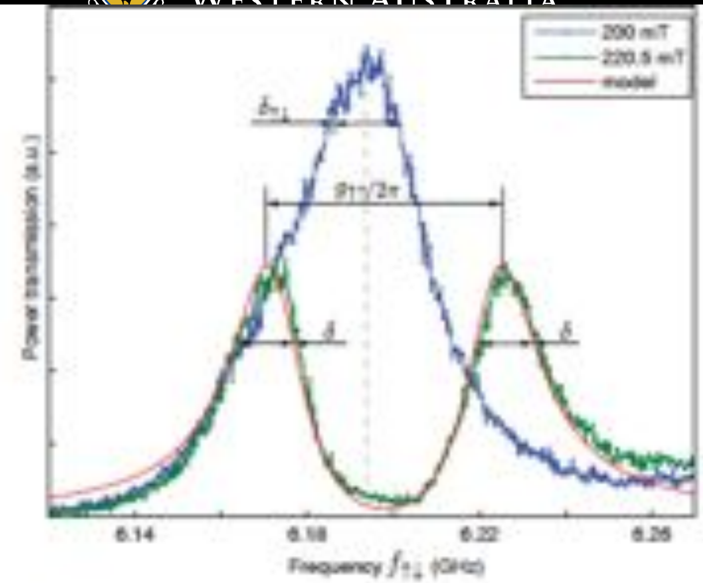
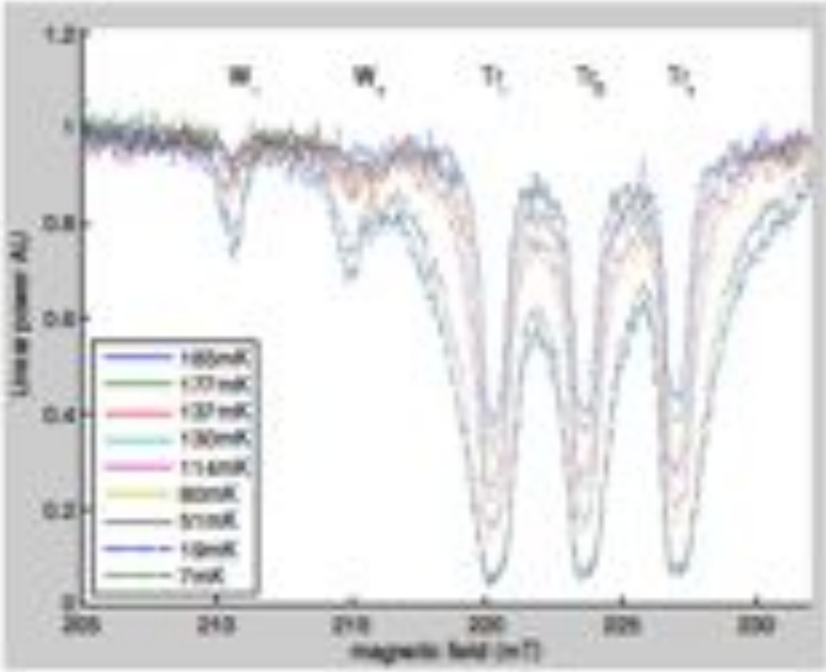
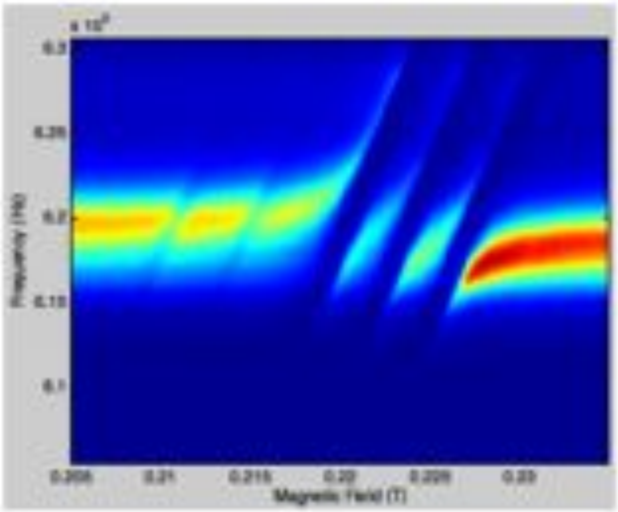
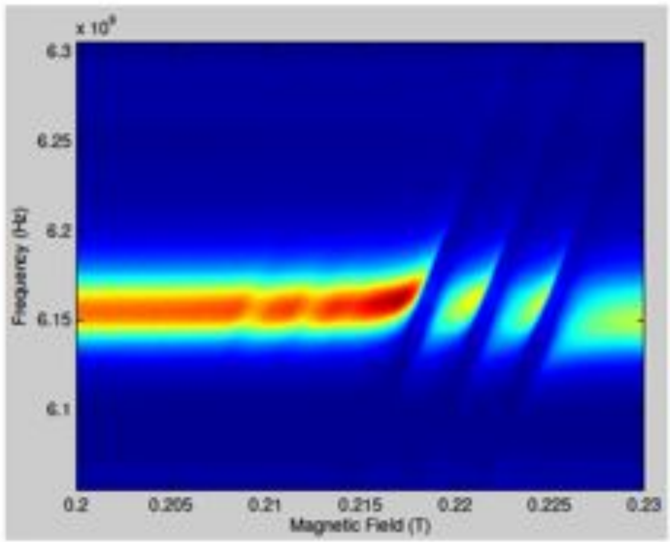


FIG. 3: Demonstration of strong coupling between P1 energy levels in diamond and the bright cavity mode. Slices through Figure 2 at 220 mT and 220.5 mT are shown.







PHYSICAL REVIEW B 88, 224426 (2013)

Ultrasensitive microwave spectroscopy of paramagnetic impurities in sapphire crystals at millikelvin temperatures

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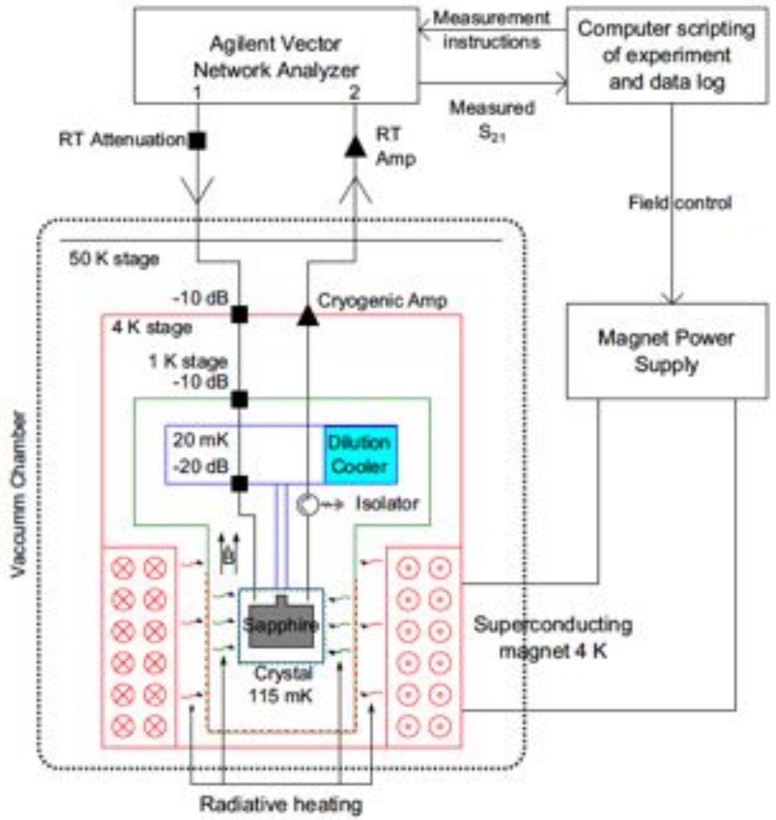

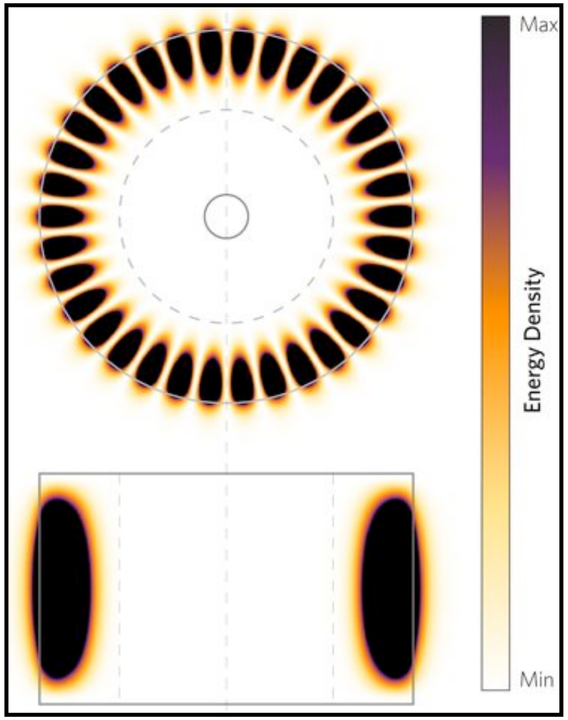

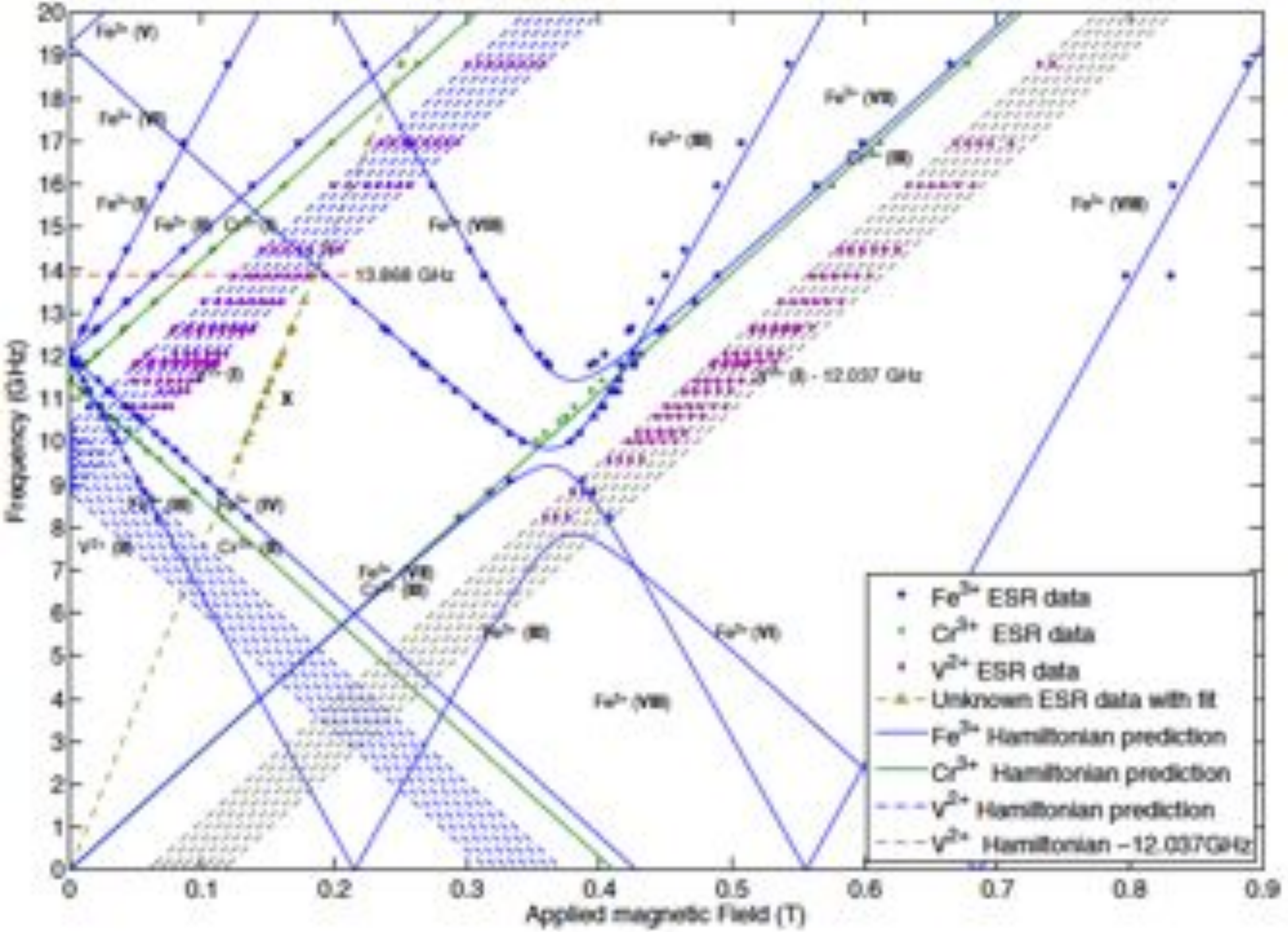

Frequency (GHz)
Applied magnetic Field (T)
13.868 GHz
Fe3+ ESR data
Cr3+ ESR data
V2+ ESR data
Unknown ESR data with fit
Fe3+ Hamiltonian prediction
Cr3+ Hamiltonian prediction
V2+ Hamiltonian prediction
V2+ Hamiltonian −12.037GHz

APPLIED PHYSICS LETTERS 106, 232401 (2015)

Discovery of iron group impurity ion spin states in single crystal Y_2SiO_5 with strong coupling to whispering gallery photons

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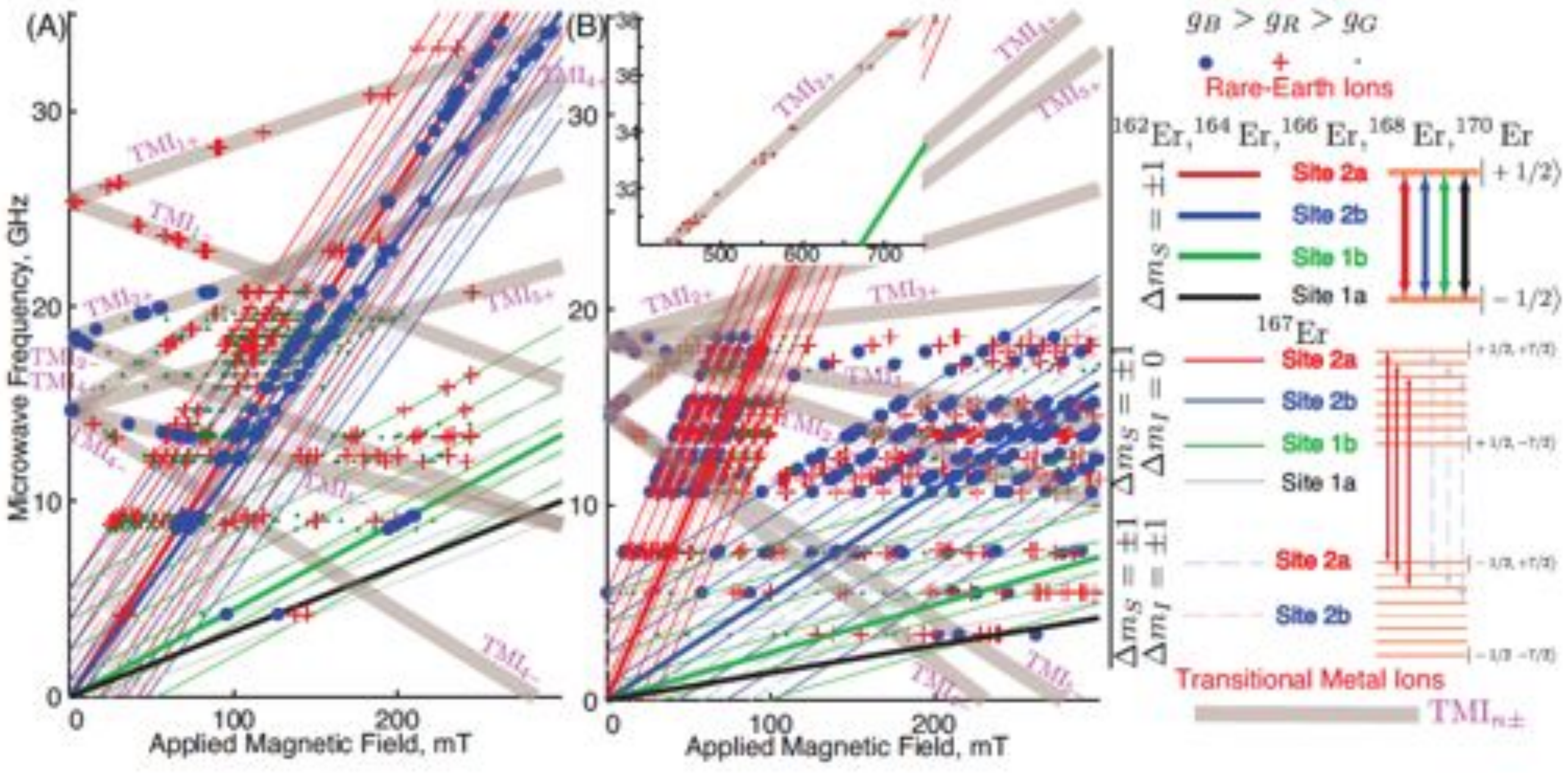

RAPID COMMUNICATIONS

PHYSICAL REVIEW B 90, 100404(R) (2014)

Three-dimensional cavity quantum electrodynamics with a rare-earth spin ensemble

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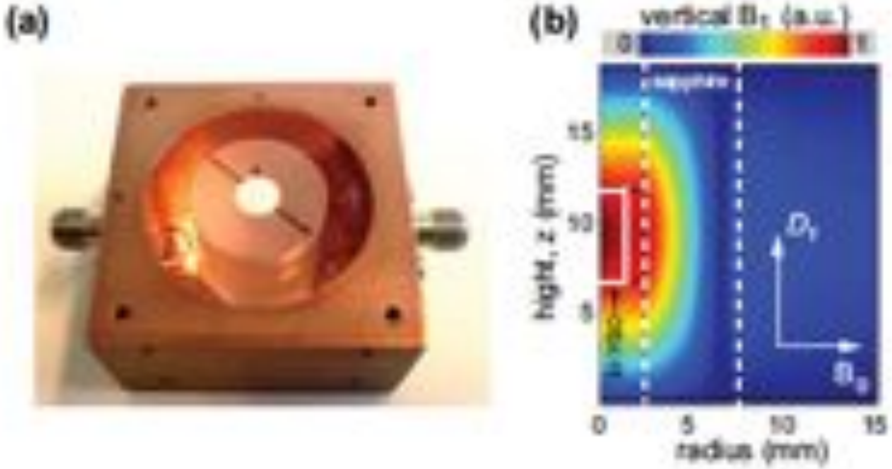

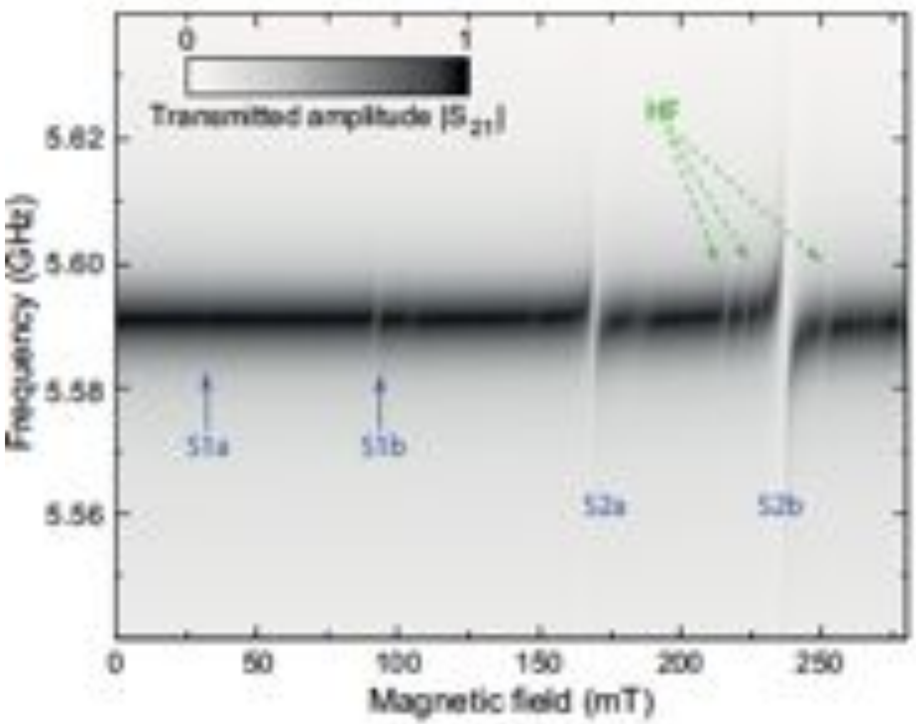

FIG. 1. (Color online) (a) Picture of the 3D hybrid quantum system. The Er:YSO crystal of $3 \times 3.5 \times 5$ mm^3 size is placed inside the sapphire loaded copper resonator. The external magnetic field is applied in the direction perpendicular to the symmetry axis of the cylindrical cavity. (b) Dimensions of the experiment, orientation of the crystal and simulation of the oscillating magnetic field component B_1 of the TE_{011} mode along the symmetry axis of the cavity.

Summary & Outlook

- Experiment in progress to check claim of axion signal at 110 μeV.
- Possible future expansion to look over wider mass range (Funding Request)
- Cross-correlation measurement techniques can be used in haloscope and LSW style experiments to help study any serious candidate signals
- Paramagnetic and Ferrimagnetic expertise to test Axions?