Australian Axion Dark Matter Detector

The ORGAN Experiment

THE UNIVERSITY OF WESTERN AUSTRALIA

eQus
ARC CENTRE OF EXCELLENCE FOR ENGINEERED QUANTUM SYSTEMS

Michael Tobar

Frequency and Quantum Metrology Group, School of Physics, University of Western Australia

ARC Centre of Excellence for Engineered Quantum Systems

Australian Axion Dark Matter Haloscope

The University of Western Australia

eQus — ARC Centre of Excellence for Engineered Quantum Systems

- **Core membership**
- Michael Tobar
- Eugene Ivanov
- John McFerran
- Alexey Veryaskin
- Sascha Schediwy
- Stephen Parker
- Maxim Goryachev
- Jeremy Bourhill

- **Research students**
- Nikita Kostylev
- Natalia Carvalho
- Akhter Hoissan
- David Gozzard
- Ben McAllister
- Justin Kruger

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)

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

1) Low noise quantum limited readouts

POPULAR DARK MATTER CANDIDATES: WISP or WIMP?

- Classic WIMP Searches: Expensive i.e. LHC
- WISP Searches: Cheaper Precision Low Energy Experiments
- Axion: Highly Motivated: ADMX Washington Seattle tune High-Q RF cavity (Radio receiver on steroids)
- -> ADMX mass range 2-20 μeV
- -> UWA: Search new mass ranges never searched before on the budget of an ARC grant (mass range 50-200 μeV)
- -> Funded for research and development through ARC Centre of Excellence in Engineered Quantum Systems
- -> Need Infrastructure, Dedicated Dil Fridge at Large Magnet (14 Tesla)

ORGAN Collaboration: EQuS2 funded

Tobar, Ivanov, Goryachev: Built prototype already, expert in precision test of fundamental physics using microwaves

Arkady Fedorov, Warwick Bowen, Michael Drinkwater: quantum Josephson Parametric Amplifier technology to enable improvement in sensitivity beyond the quantum limit, i.e. squeezing techniques and QND.

Tom Volz: Techniques to beat the quantum limit:
Jason Twamly, Gavin Brennan: Develop models that could lead the infrastructure to be implemented for more sensitively.

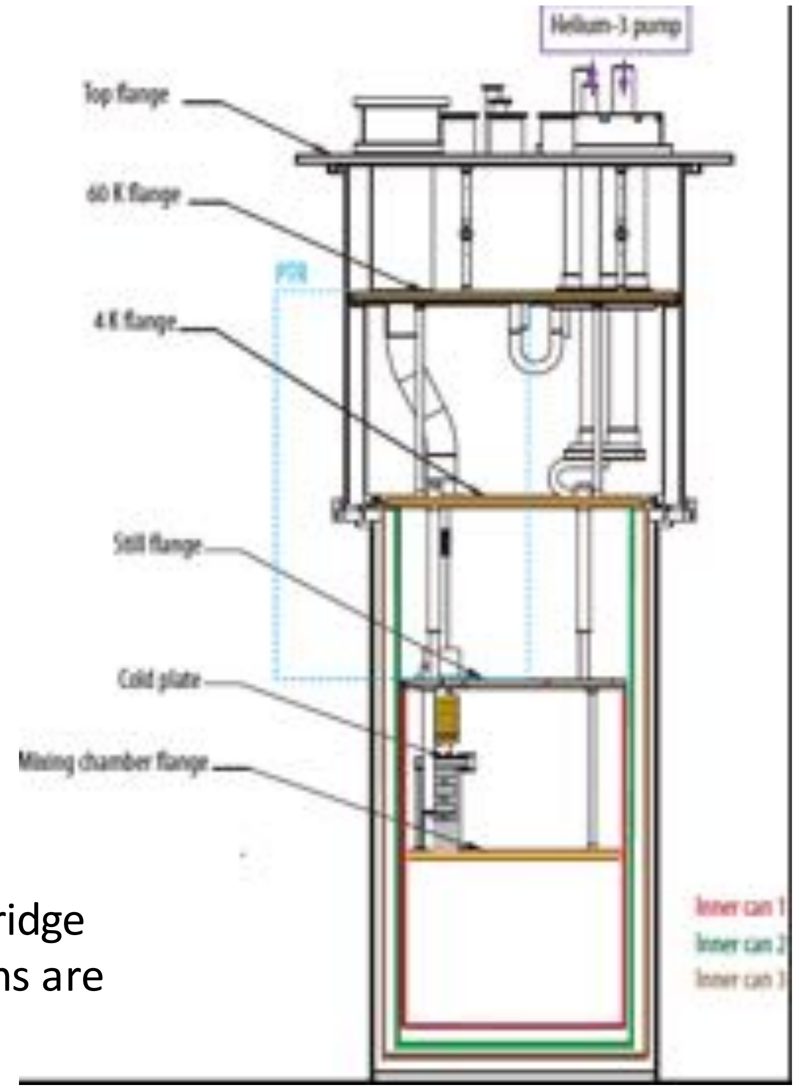
Andrew Doherty, David Reilly Develop mK cryogenically cooled HEMT amplifiers with UWA: Develop models that could lead the infrastructure to be implemented more sensitively.

Paul Altin Daniel Shaddock: Data analysis with FPGAs, huge problem! Speed of data collection essential for large scans. Liquid Instruments technology to be used.

Lief Grant to gain infrastructure necessary to test well known Axion models

14 T Magnet (6 cm bore)

Currently we have 7 T magnet, and borrowing Dil Fridge From other projects. For serious attempt these items are essential



Dedicated dilution Fridge

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Axion

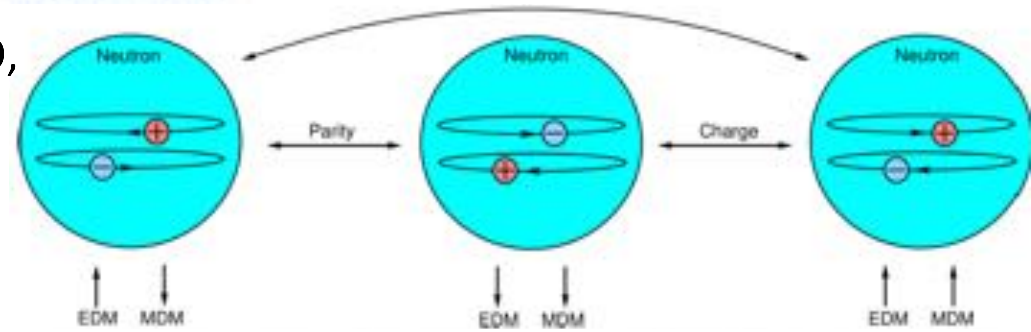
From Wikipedia, the free encyclopedia

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.

Effective periodic strong CP violating term, Θ, appears as a Standard Model input

- Expect $\bar{\theta}$ to be order 1
- Manifested as neutron EDM of 10^{-16} e cm
- Experiments limit neutron EDM < 3 * 10^{-26} e cm
- 10^{10} discrepancy!



No neutron EDM so no violation, Θ->0, why?

-> promote to a field (Axion)

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]

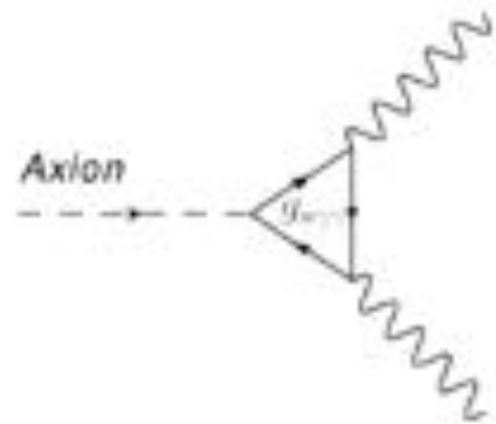
A term analogous to the one that must be added to Maxwell's equations[30] also appears in recent theoretical models for topological insulators.[31] This term leads to several interesting predicted properties at the interface between topological and normal insulators.[32] In this situation the field θ 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]

Peccei-Quinn solution

- Introduces new hidden $U(1)_{PQ}$ symmetry
- Broken at f_a scale
  - Symmetry breaking forces $\overline{\theta}$ to zero
  - Generates new boson: the axion
    - Weinberg and Wilczek

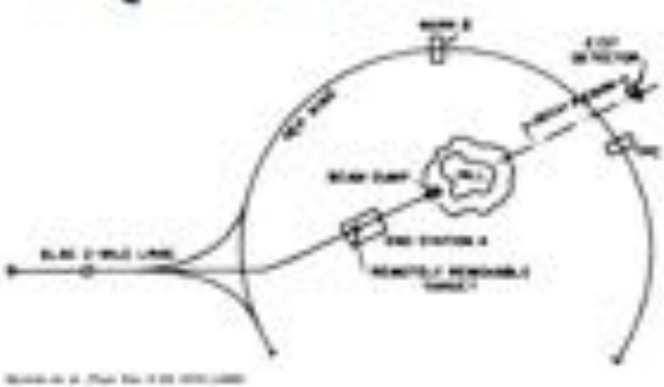
$$m_a \approx \frac{0.01GeV^2}{f_a}$$

$$g_{a\gamma\gamma} \approx \frac{0.01}{f_a}$$



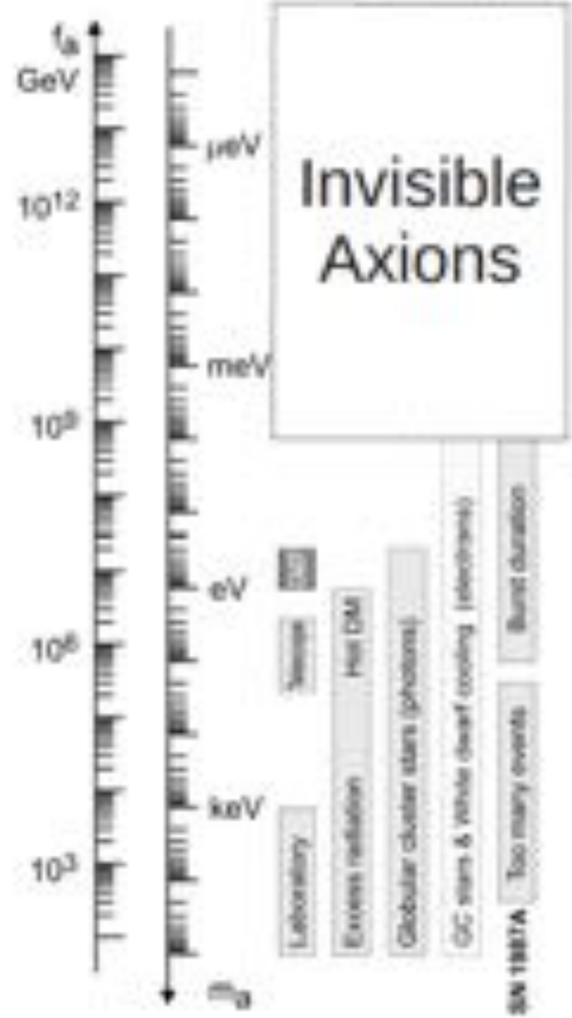
The PQWW Axion

- f_a associated with Weak scale (~200 GeV)
- Axion mass expected to be 1 keV to 10 MeV
- Not detected in beam dump searches: no PQWW axion



Non-PQWW Axions

- New f_a scale physics detaches PQ mechanism from the Weak scale
- Two benchmark models:
  - "Hadronic" KSVZ model
    - Stronger coupled to photons
  - "Leptonic" DFSZ model
    - Weaker coupling to photons



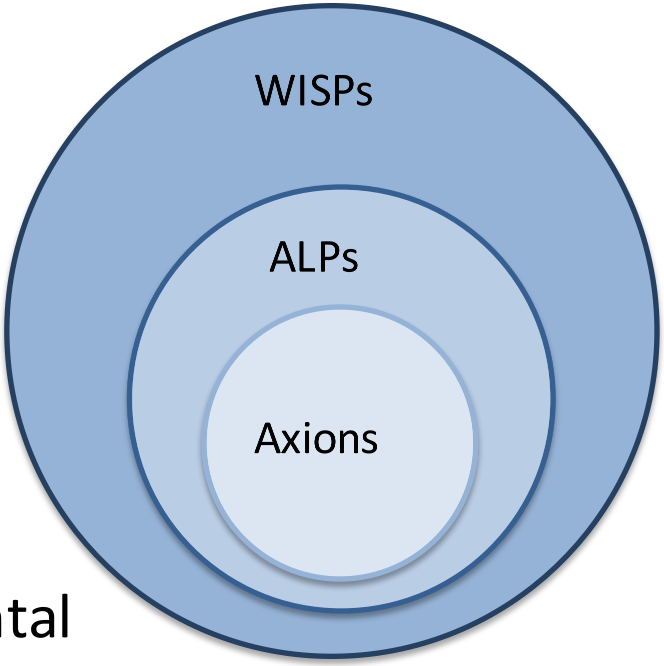
Axions and WISPs

Weakly **I**nteracting **S**lim **P**articles

Axion **L**ike **P**articles

Slim = sub-eV

Axions constituting our local galactic halo would have huge number density ~10^{14} cm^{-3}



Weakly interacting, small mass,
so offers compelling solutions to:

Dark Matter (i.e. Axions, hidden photons)
Dark Energy (i.e. Chameleons)

Low energy scale dictates precision experimental approach (i.e. don't need a particle collider)

WISP searches are *complementary* to WIMP searches

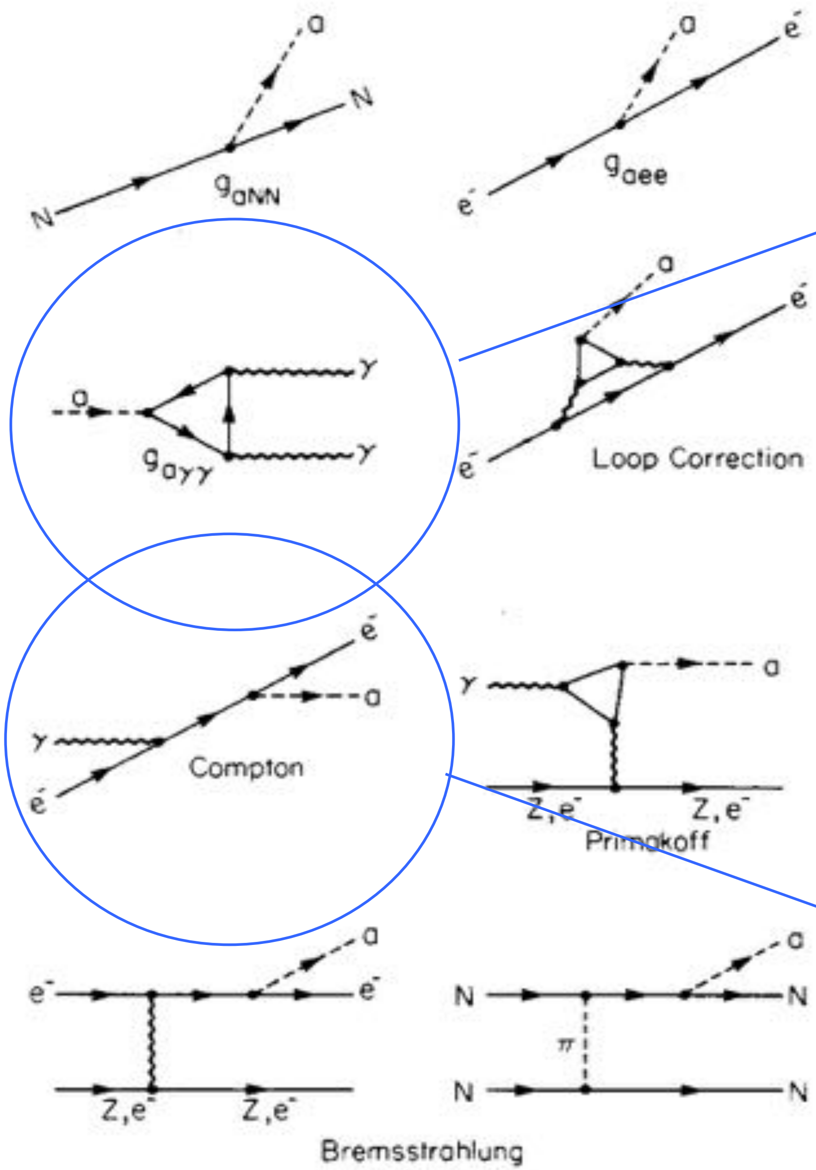
More Theoretical Motivations

- Any theory with both supersymmetry and field-dependent gauge couplings has axions.
- This is always true of string compactifications: 'string theory has no free parameters: all is dynamical'.
- Conclusion: every gauge field in every string compactification has an associated axion.

- Axion masses depend sensitively on non-perturbative effects and may take a wide range of values.

Joseph Conlon (Oxford University)
Patras Axions/WIMPs/WISPS Meeting, Durham
July 13, 2009

Selected Axion couplings & the important two-photon coupling



A process with small model uncertainty
Exploited in certain terrestrial searches
Easily calculable

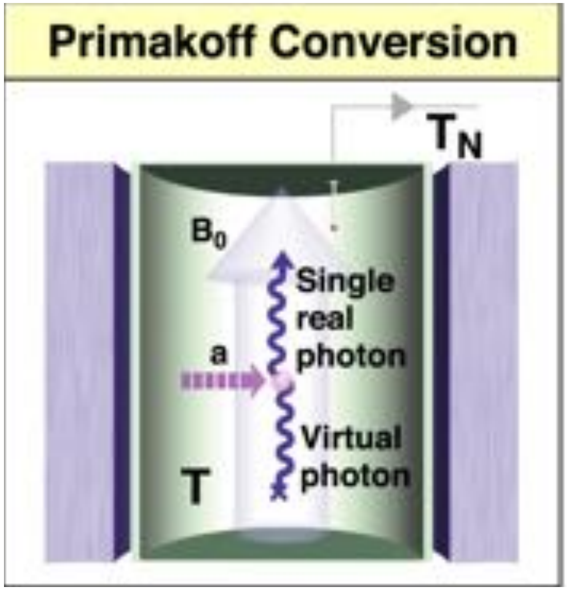
In contrast:
A process with large model uncertainty
Can occur, e.g., in the Sun
Contains unknown $U(1)_{PQ}$ charge of electron

Pierre Sikivie's RF-cavity idea (1983): Axion and electromagnetic fields exchange energy: WISP-Photon Coupling

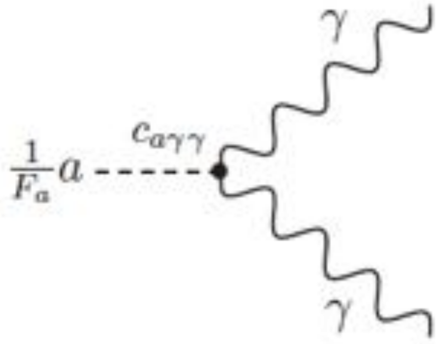
WISP-photon coupling provides very important experimental and observational access (with minimal model dependence).

$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma}\, a F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma}\, a \vec{E}\cdot\vec{B}$$

$$\frac{\partial\left(\mathbf{E}^2/2\right)}{\partial t} - \mathbf{E}\cdot\left(\nabla\times\mathbf{B}\right) = g_{a\gamma}\dot{a}\left(\mathbf{E}\cdot\mathbf{B}\right)$$



For example, the axion couples to 2 photons:



B field can act as 2nd virtual photon to induce axion-photon conversion

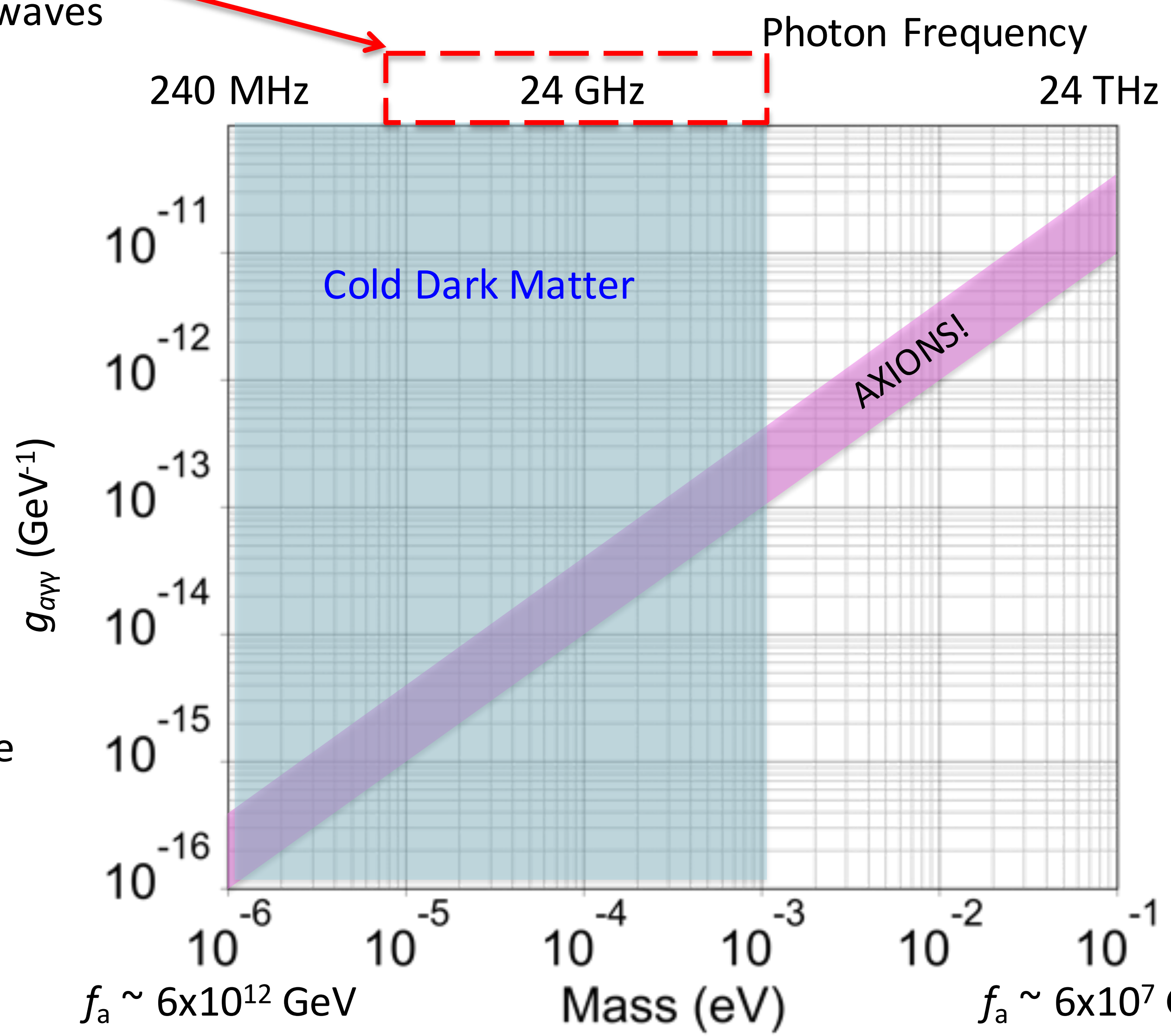
Axion mass dictates photon frequency

Want to test / bound $g_{a\gamma\gamma}$

What values of f_a make sense for axion dark matter?

Axion Mass / Photon Coupling

Microwaves
& mm-waves



Overclosure

Axion decay

Energy loss
(e.g. SN1987A)

Axion Dark Matter eXperiment (ADMX) and ADMX-High Frequency collaboration

Lawrence Livermore National Laboratory – ADMX began here in the mid-1990s.

Gianpaolo Carosi, Darrell Carter, Jaime Ruz Armendariz

University of Washington – main experiment moved here in 2010.

Leslie Rosenberg, Gray Rybka, Michael Hotz, Andrew Wagner, Doug Will, Dmitry Lyapustin, Christian Boutan, Jim Sloan, Ana Malagon, Rich Ottens, Hannah LeTourneau, Cliff Plesha

University of Florida

David Tanner, Pierre Sikivie, Neil Sullivan, Jeff Hoskins, Jungseek Hwang, Catlin Martin, Ian Stern, Nicole Crisosto

National Radio Astronomy Observatory

Richard Bradley

University of California, Berkeley

Karl van Bibber,Tim Shokair, John Clarke, Jaben Root, John Norton, Ben Clemens, Maria Simanovskaia, Kelly Backes, Isabella Urdinaran

Fermilab (recently joined)

Aaron Chou, Will Wester, Andrew Sonnenschein, Swapan Chatopadhyay

Sheffield University

Edward Daw

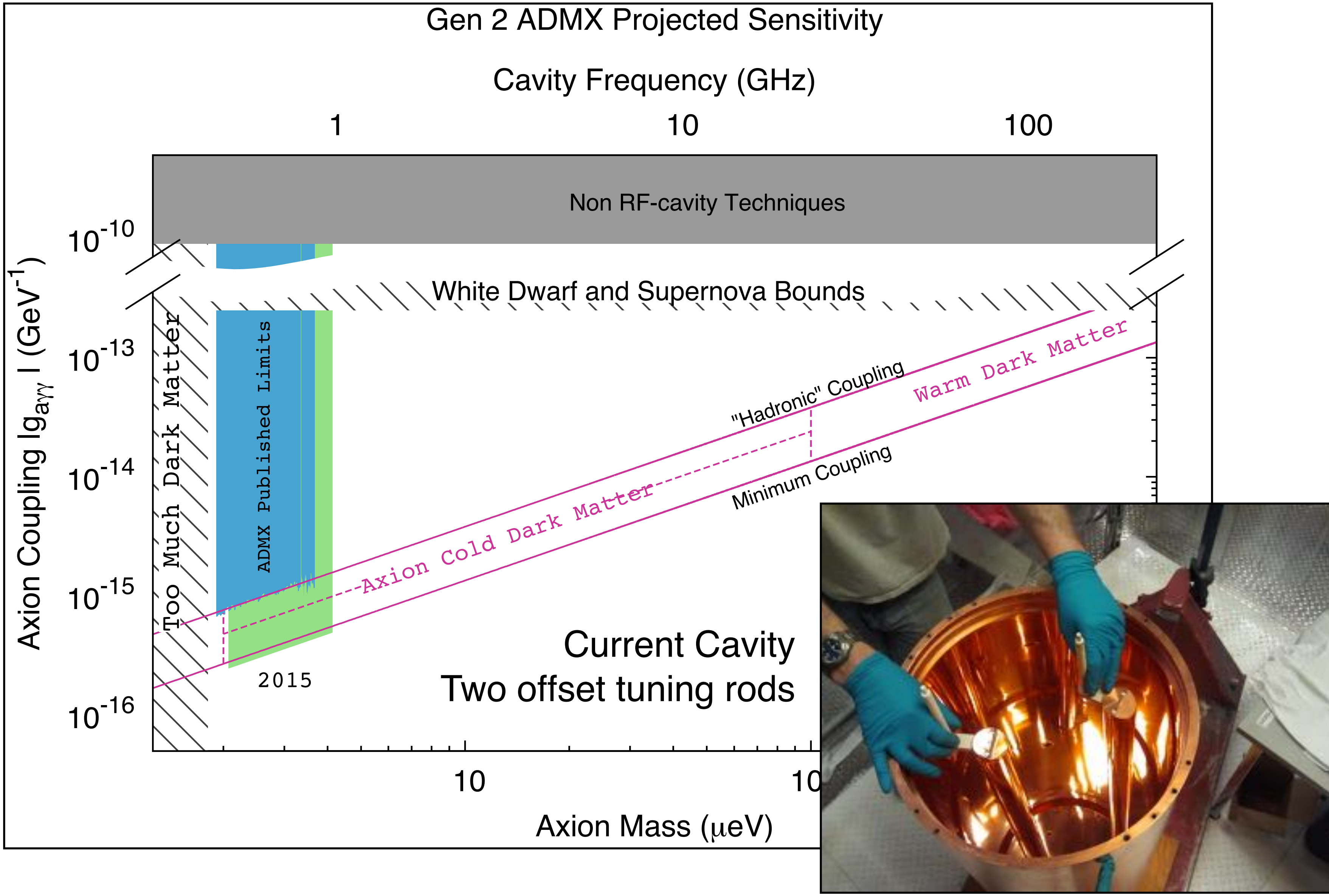
Yale University (ADMX-HF - NSF sponsored)

Steve Lamoreaux, Yulia Gurevich, Ben Brubaker, Sidney Cahn

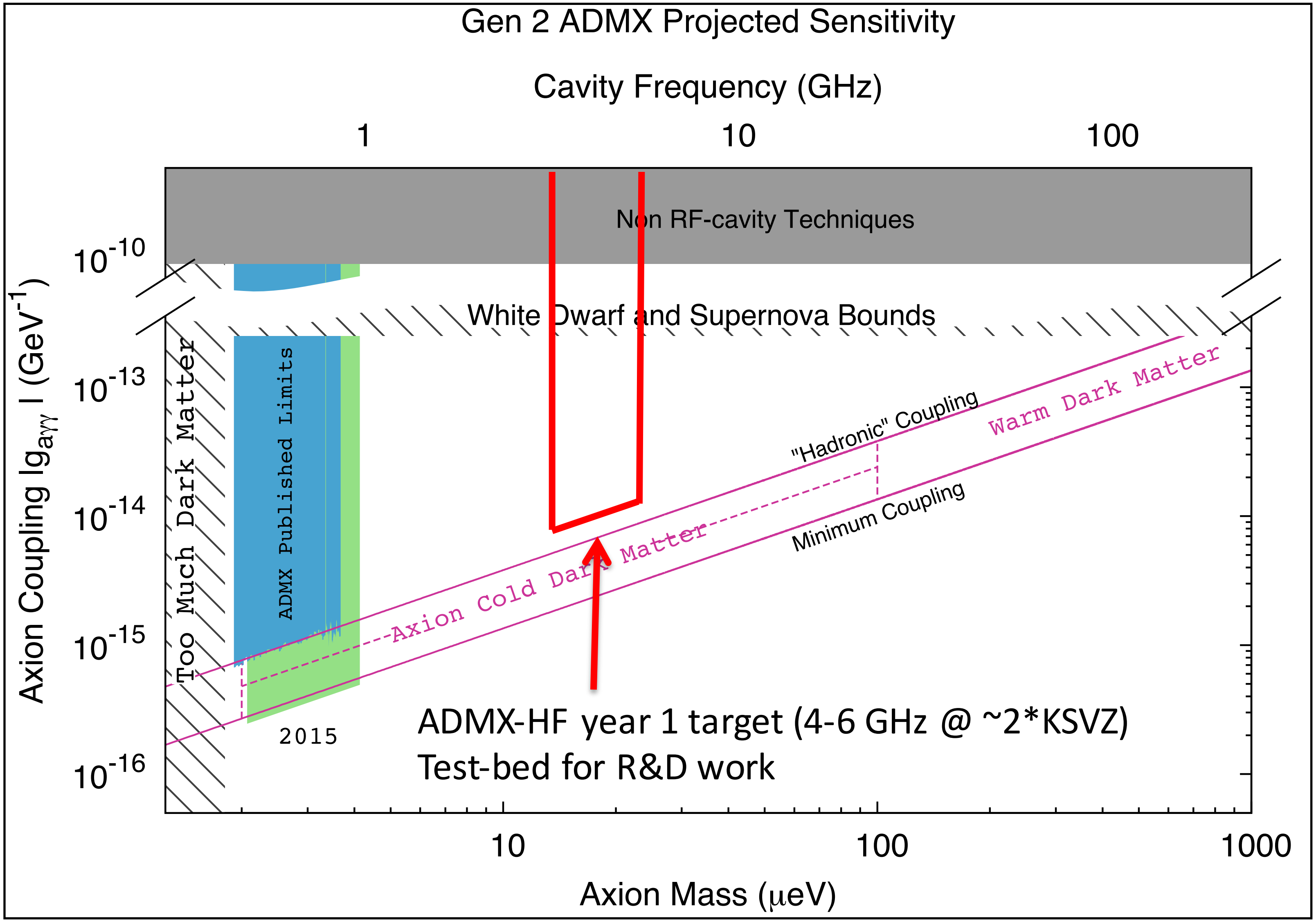
University of Colorado (ADMX-HF – NSF sponsored)

Konrad Lenhert, Memhet Ali, Dan Palken

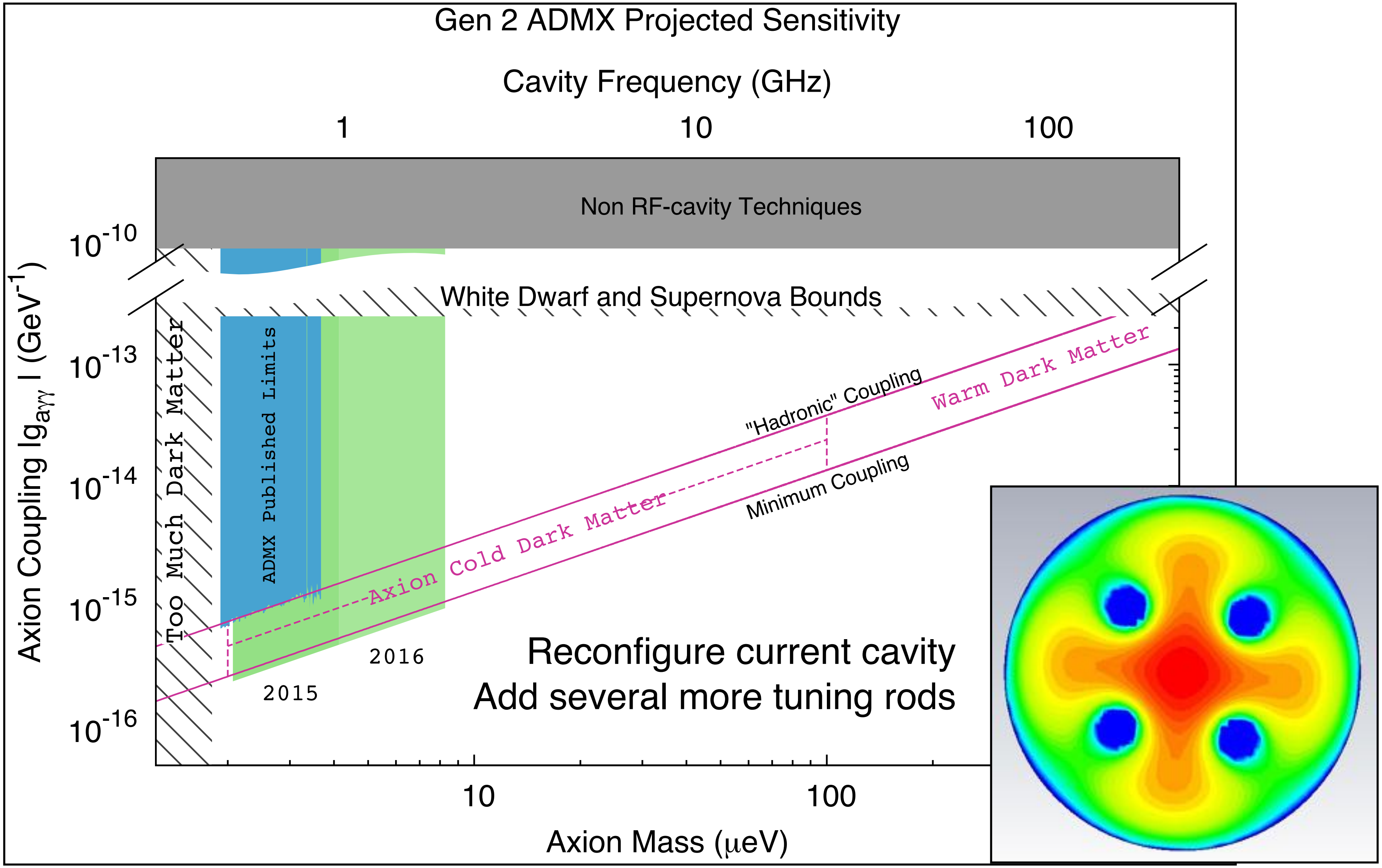
ADMX Gen 2 Science Prospects: Year 1 (0.5 – 1 GHz)



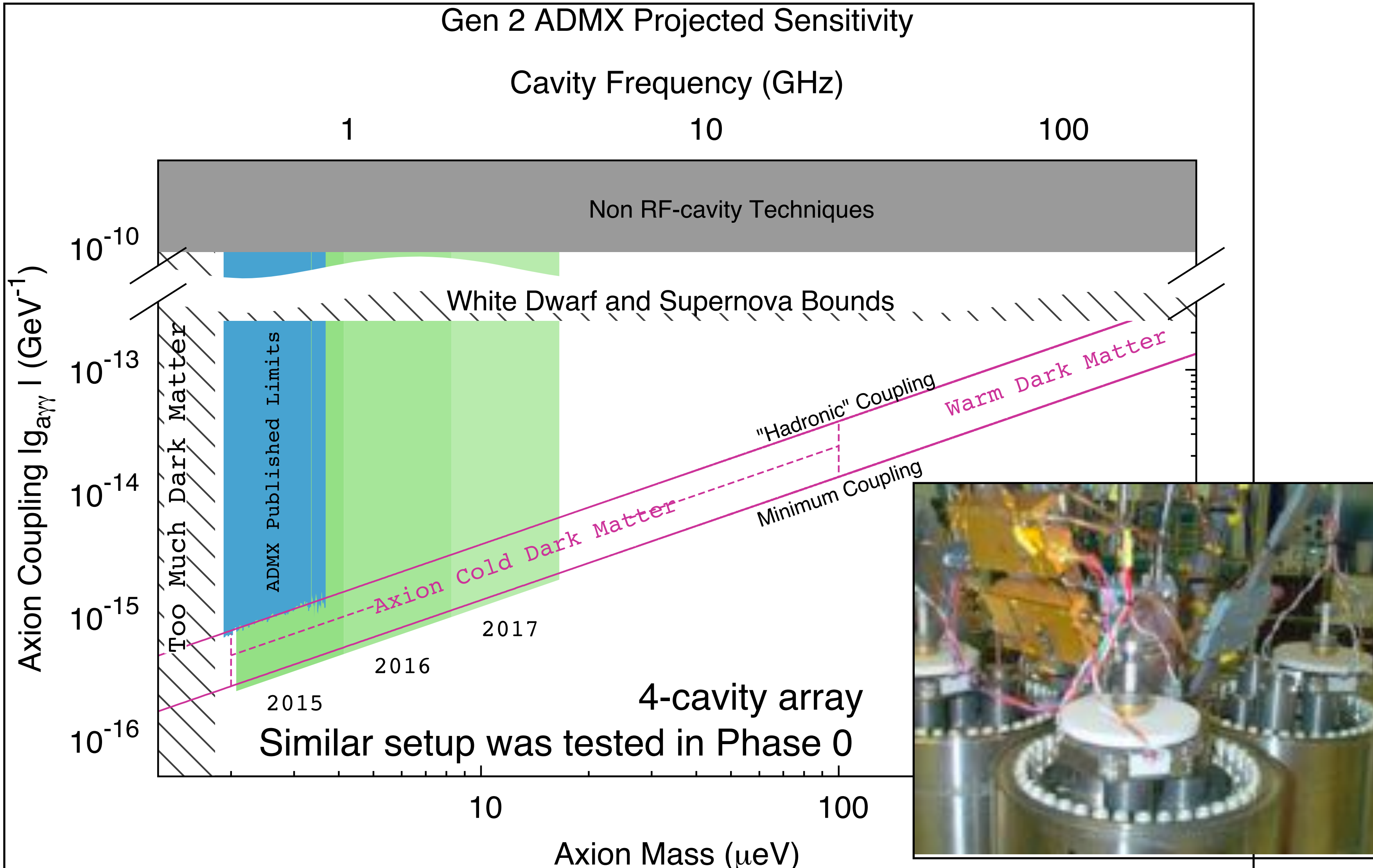
ADMX Gen 2 Science Prospects: Year 1 (0.5 – 1 GHz)



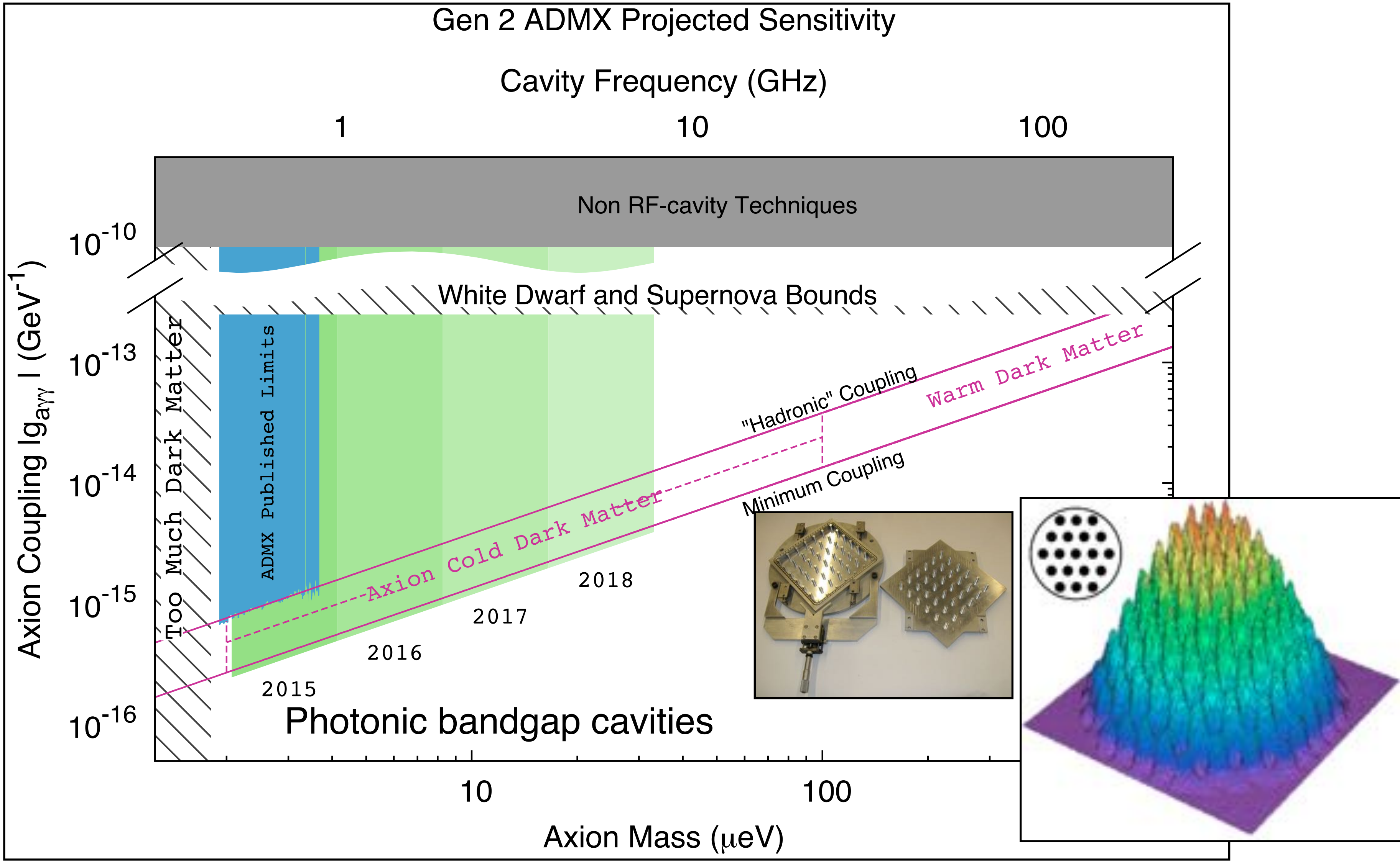
ADMX Gen 2 Science Prospects: Year 2 (1 – 2 GHz)



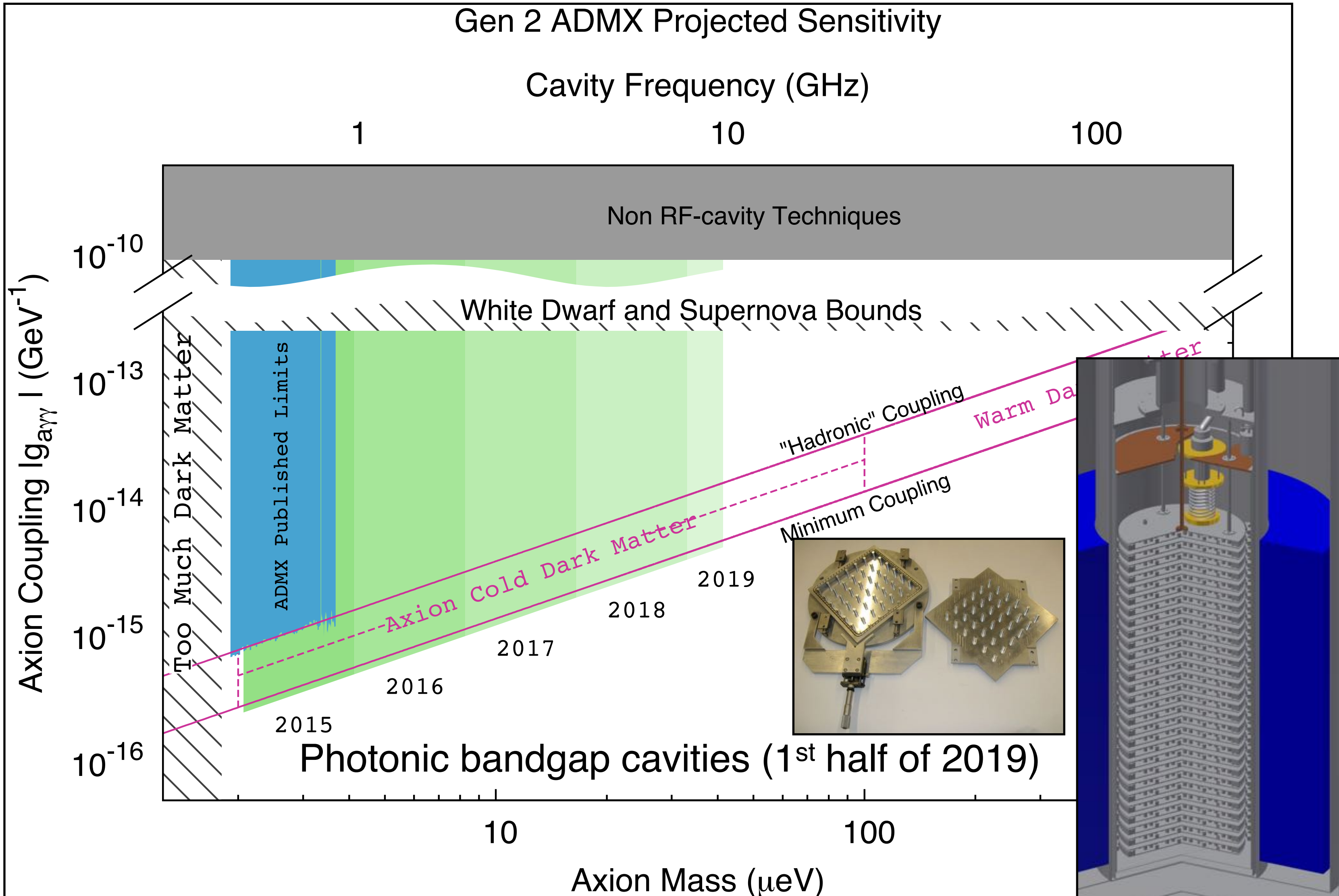
ADMX Gen 2 Science Prospects: Year 3 (2 – 4 GHz)



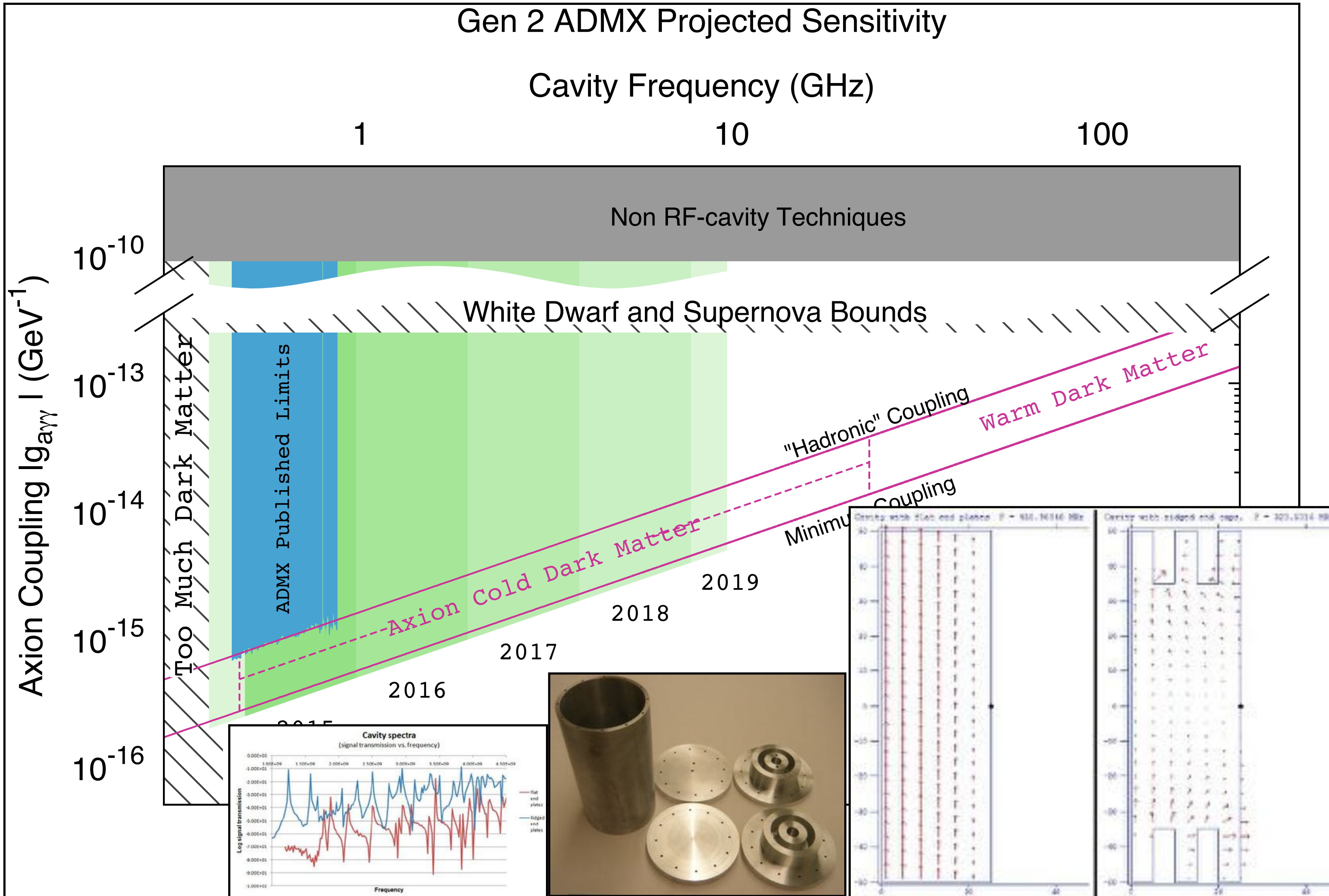
ADMX Gen 2 Science Prospects: Year 4 (4 – 8 GHz)



ADMX Gen 2 Science Prospects: Year 5 (8 – 10 GHz)

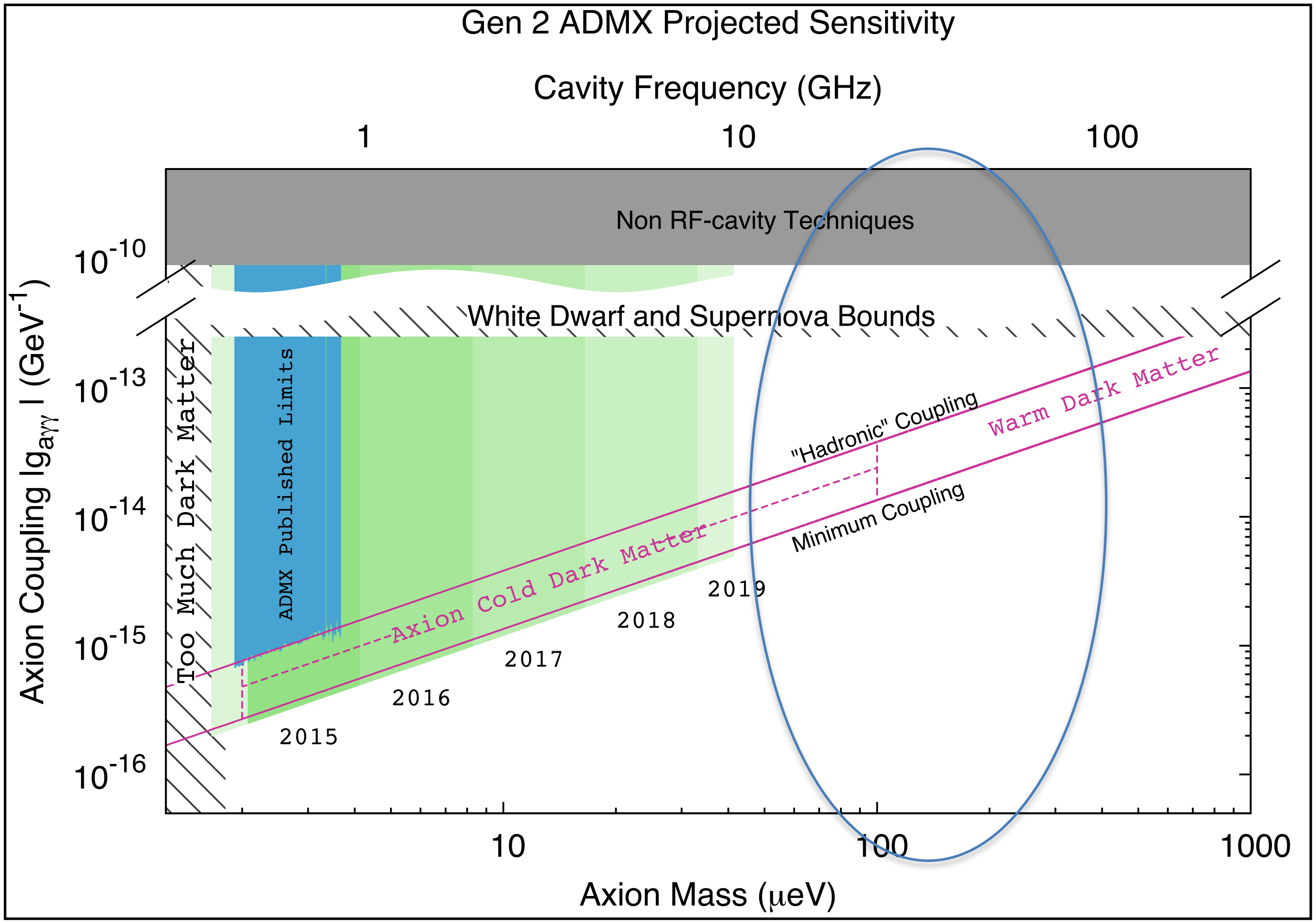


ADMX Gen 2 Science Prospects: Year 5 (< 0.5 GHz)



Slow-wave cavity
(2nd half of 2019)

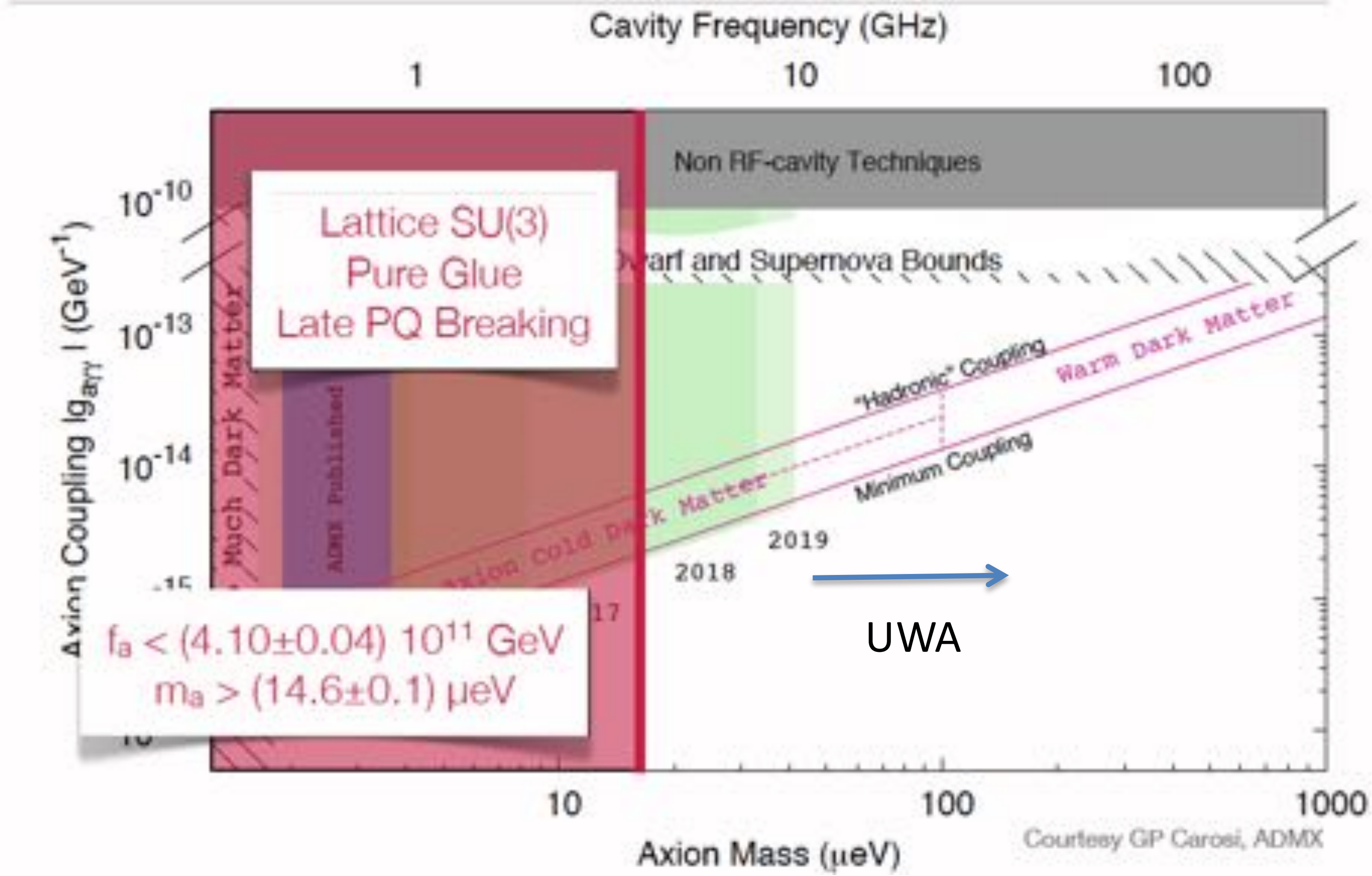
We propose high frequency cavity axion searches not currently under investigation (support from ADMX)



What frequencies are we best at measuring at UWA……

Phys. Rev. D92.034507 - E. Berkowitz, M. Buchoff, E. Rinaldi arXiv:1505.07455

The Over-Closure Bound As It Stands Today



Caveats -> Assumes PQ breaking occurs after inflation, study pure Yang-Mills (gluons only) and not yet full QCD. So still important to test low mass

High Frequency Haloscope Design

- High frequency haloscope at UWA (~26 GHz), known as **ORGAN**
- Multi-stage project:
  - Direct test of Beck result
  - Wider scan at high frequency
  - Novel resonators
- Designing a haloscope at high frequency is difficult
- TM Mode frequency inversely proportional to cavity size

→ **Lower volume**
→ **Lower sensitivity**
→ **Lossier material**

- **Quantum noise limit increases**
- Harder to tune, and couple to modes

Signal strength

- Power from the cavity is

$$P = 4 \cdot 10^{-22}\ \mathrm{W} \left(\frac{V}{200\ \ell}\right) \left(\frac{B_0}{8\ \mathrm{Tesla}}\right)^2 C_{nl} \left(\frac{g_\gamma}{0.97}\right)^2 \cdot \left(\frac{\rho_\mathrm{a}}{0.5 \cdot 10^{-24}\ \mathrm{g/cm^3}}\right) \left(\frac{m_\mathrm{a}}{1\ \mathrm{GHz}}\right) \left(\frac{\min(Q_\mathrm{L}, Q_\mathrm{a})}{1 \times 10^5}\right)$$

- Where C_{nl} is form factor, ρ_a is the halo density, m_a the axion mass, and
- $Q_L \sim 70000(\mathrm{GHz}/f)^{2/3}$ (ASE); $Q_a \sim 10^6$ are quality factors
- $g_\gamma \sim 0.97$ (KSVZ); $g_\gamma \sim 0.36$ (DFSZ) are coupling strengths
- We use DFSZ; look for $\sim 10^{-22}$ Watts power

Microwave Cavity Parameters to consider

- Maximize Volume inside B-Field
  - Axion conversion power goes as B^2V.
- Maximize Form Factor: $$C_{lmn} = \frac{|\int_V d^3x \vec{E}_\omega \cdot \vec{B}_0|^2}{B_0^2 V \int_V d^3x \epsilon |\vec{E}_\omega|^2}$$
- Maximize Quality Factor = freq/Δfreq (up to $Q_a \sim 10^6$)
- Tunability = must be able to shift resonant frequency over an appreciable range to scan axion masses.
- Ability to distinguish that you are on the correct mode (one that couples to axions)

Optimization of Axion Haloscope Cavity

$$P_a = \left(\frac{g_\gamma \alpha}{\pi f_a}\right)^2 \frac{\rho_a}{m_a} V B_0^2 QC,$$

Define CVG

$$G = \frac{\omega \mu_0 \int \left|\vec{H}\right|^2 dV_c}{\int \left|\vec{H}\right|^2 dS_c} = Q \times R_s.$$

$$C_{\text{EM}} = \frac{C_E + C_B}{2}$$

$$CVG = \left(\frac{|\int dV_c \vec{E}_c \cdot \vec{\hat{z}}|^2}{2\int dV_c |E_c|^2} + \frac{\frac{\omega_a^2}{c^2}|\int dV_c \frac{r}{2}\vec{B}_c \cdot \vec{\hat{\phi}}|^2}{2\int dV_c |B_c|^2}\right) \times \frac{\omega \mu_0 \int |\vec{H}|^2 dV_c}{\int |\vec{H}|^2 dS_c}.$$

$$C_E = \frac{|\int dV_c \vec{E}_c \cdot \vec{\hat{z}}|^2}{2V_c \int dV_c \epsilon_r |E_c|^2}$$

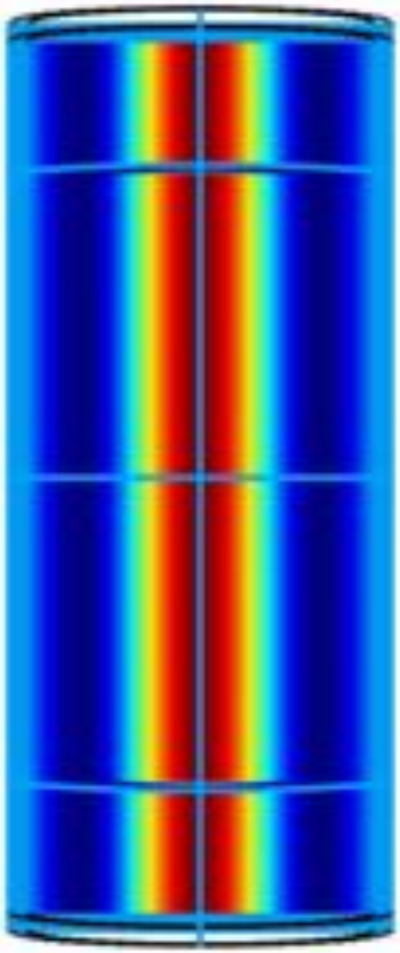
$$C_B = \frac{\frac{\omega_a^2}{c^2}|\int dV_c \frac{r}{2}\vec{B}_c \cdot \vec{\hat{\phi}}|^2}{2V_c \int dV_c \frac{1}{\mu_r}|B_c|^2}$$

(Always equal, good to calculate both to check complicated structures)

McAllister, Parker, Tobar PRL 117, 159901 (2016)

ORGAN

- Cavity dimensions:
  - ~1 cm radius
  - ~5 cm length
- TM_{020} Mode frequency ~26.5 GHz
- First "path-finding run" complete
  - Stationary frequency, single cavity
  - Traditional HEMT amplification
  - 4 K
  - 7 T
  - Commercial FFT
- Successful test of entire system, ready for tunable run
- Scale up sensitivity



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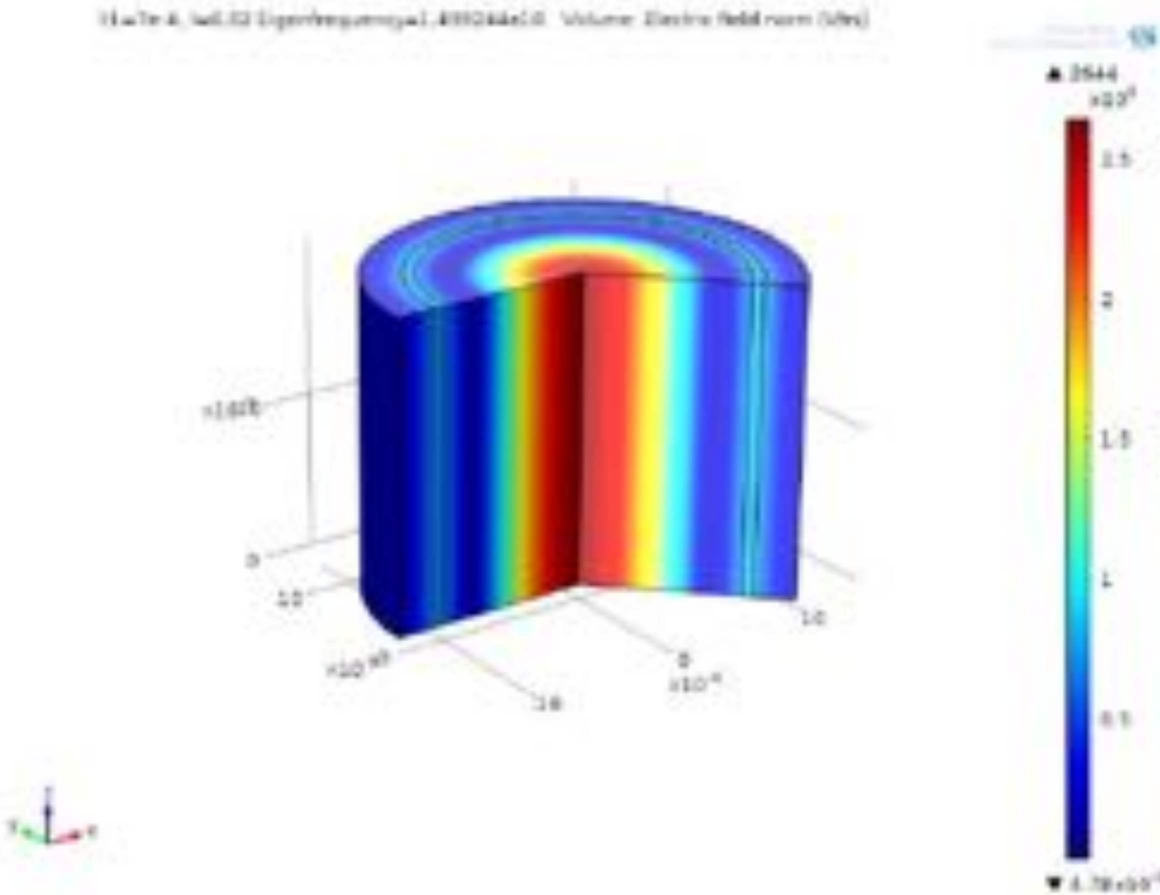
Bragg Resonators

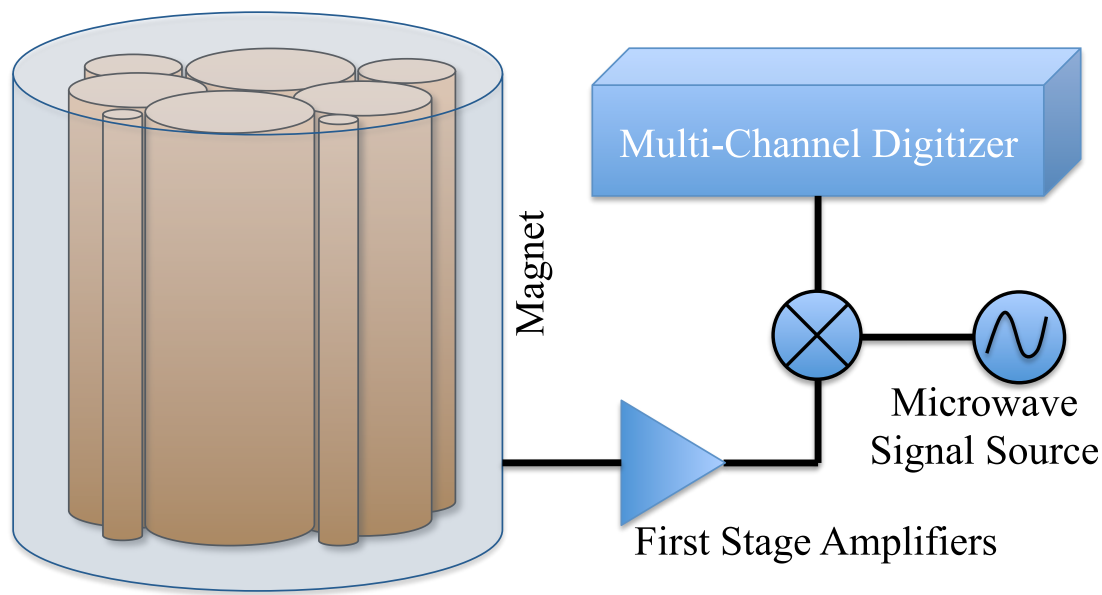
- Dielectric walls in cavity
- Air gap
- Confine modes, virtual boundary conditions
- Improve Q factor



THE ORGAN CONCEPT

Brute force solution: Compensate for loss in volume at high frequencies by looking at multiple frequencies simultaneously (Like an Organ!).

Alternative to power-summing at one frequency and dealing with keeping all the cavities frequency-tuned / locked



ORGAN

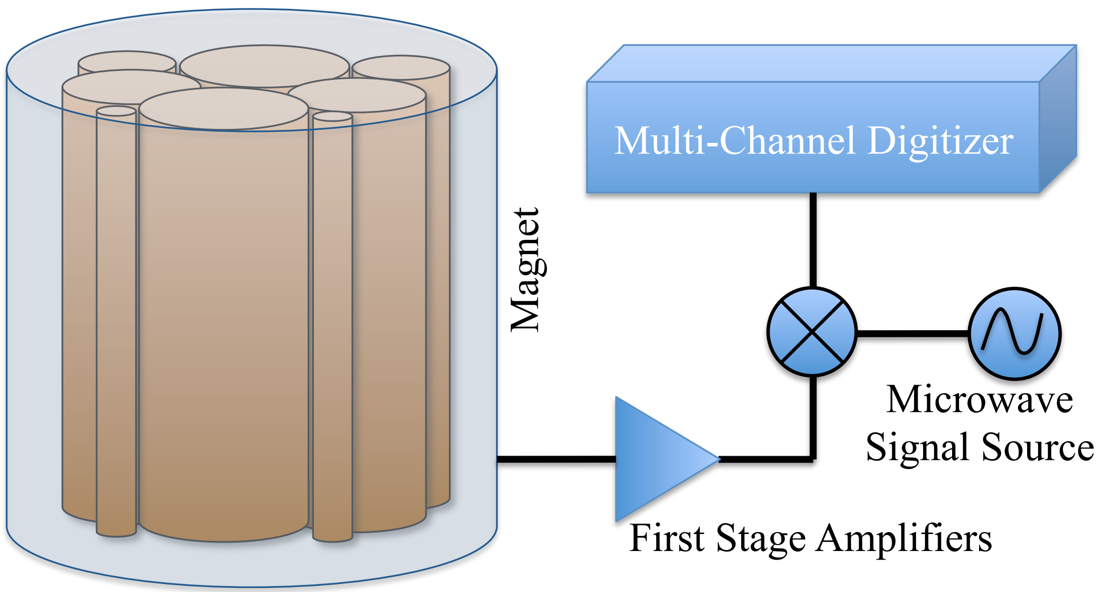
Oscillating **R**esonator **G**roup **A**xion co**N**vertor: Australian consortium
Project funded by the ARC CoE for Engineered Quantum Systems

-> ARC LIEF Application 14 Tesla Magnet (~ B^2) plus dedicated Dil Fridge for multiple year operation etc.

Oscillating **R**esonator **G**roup **A**xion co**N**vertor **P**athf**I**nder **P**roj**E**ct (ORGAN PIPE)

Start with 1 cavity…

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



Motivation for high frequency haloscope

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- Beck result: potential signal of axions at **~26.6 GHz (~10^-4 eV)**
- Higher frequency than typical haloscopes….or easily accessible
- Considered a spurious result by many
- Beck's hypothesis:
Shapiro step-like features in Josephson Junctions could be as a result of axions

Possible resonance effect of axionic dark matter in Josephson junctions

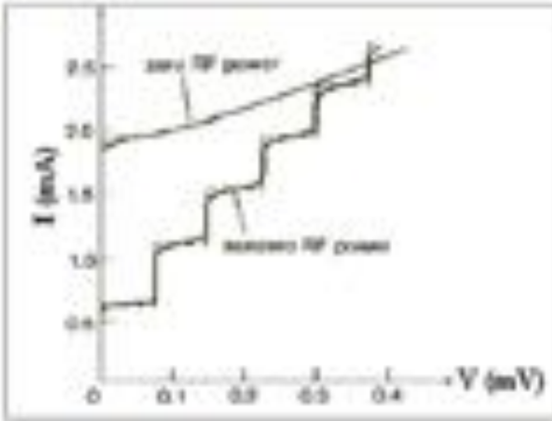
Christian Beck
Isaac Newton Institute for Mathematical Sciences, University of Cambridge, 20 Clarkson Road, Cambridge CB3 0EH, UK, and School of Mathematical Sciences, Queen Mary University of London, Mile End Road, London E1 4NS, UK

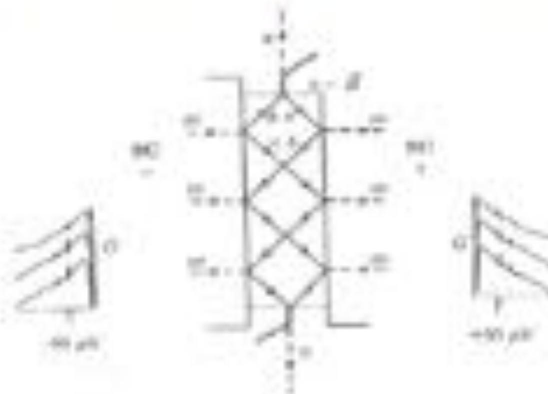
We provide theoretical arguments that dark matter axions from the galactic halo that pass through the earth may generate a small observable signal in resonant S/N/S Josephson junctions. The corresponding interaction process is based on uniqueness of the gauge-invariant axion Josephson phase angle modulo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

- DOI: http://dx.doi.org/10.1103/PhysRevLett.111.231801
- **No direct test of this candidate signal has been performed – seems like as good a place as any to start looking**

Motivation for high frequency haloscope

- Shapiro step-like features observed in experiments [C. Homann et al. PRB 70, 180503(R) (2004)]





Beck's Proposal: Axion entering WL region, transport of excess Cooper pairs

C. Hoffmann, F. Lefloch, M. Sanquer, B. Pannetier, Phys. Rev. B 70, 180503(R) (2004) [arXiv:cond-mat/0409723]
T.E. Golikova et al., Phys. Rev. B 86, 064416 (2012) [arXiv:1202.5460]
L. He, J. Wang, M.H.W. Chan, arXiv:1107.0061
M.-H. Bae, R.C. Dinsmore, M. Sahu, H.-J. Lee, A. Bezryadin Phys. Rev. B 77, 144501 (2008)

ORGAN PIPE
A 110 μeV (26.6 GHz) Axion Haloscope Search

First experiment 80 days ->
1 cavity to cover M_a = 110 +/- 2 μeV or
26.6 +/- 0.5 GHz
(maybe use two cavities to reduce scan time?)

Increase field 7-14 Tesla -> sensitivity increase x 4,
Search time reduced by 16,
Huge benefit (5 days!)

Equipment – Dilution Fridges from other projects has allowed proof of concept of Australian path finder test

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Magnet & readout

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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

First run complete

TM_{020} mode

sampling frequency of the digitizer is 1GHz, the 26.54GHz

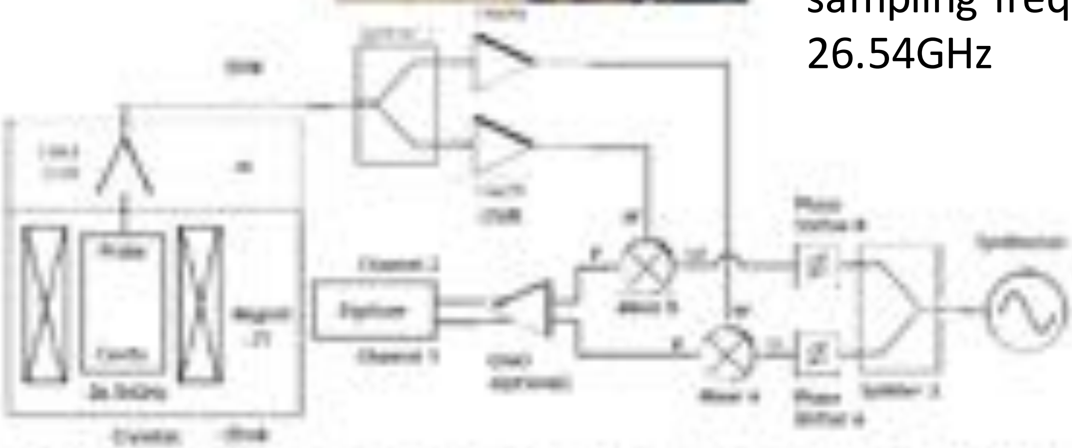
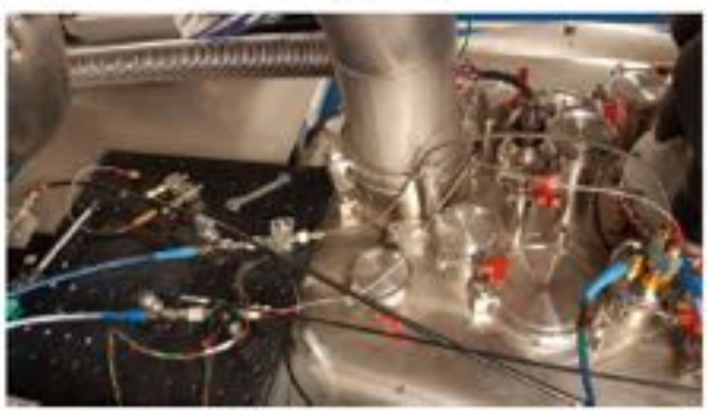
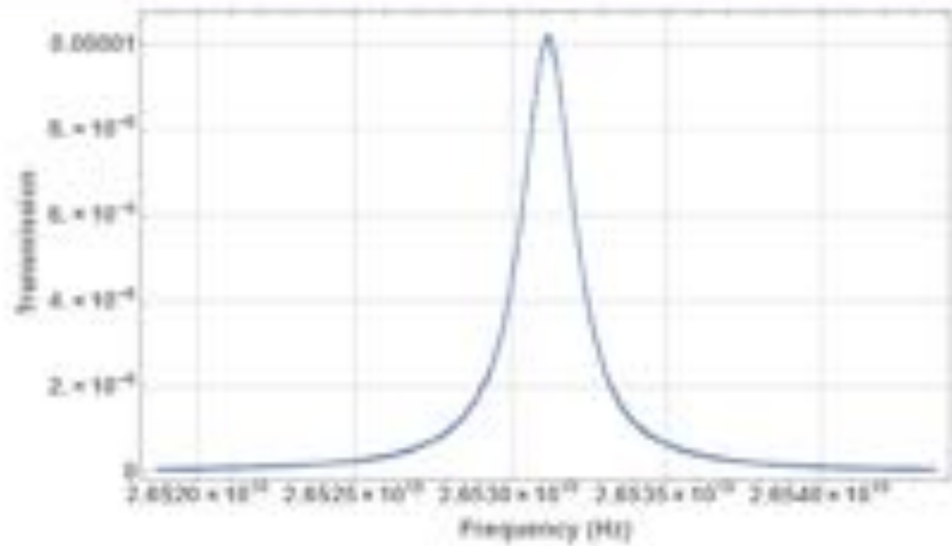
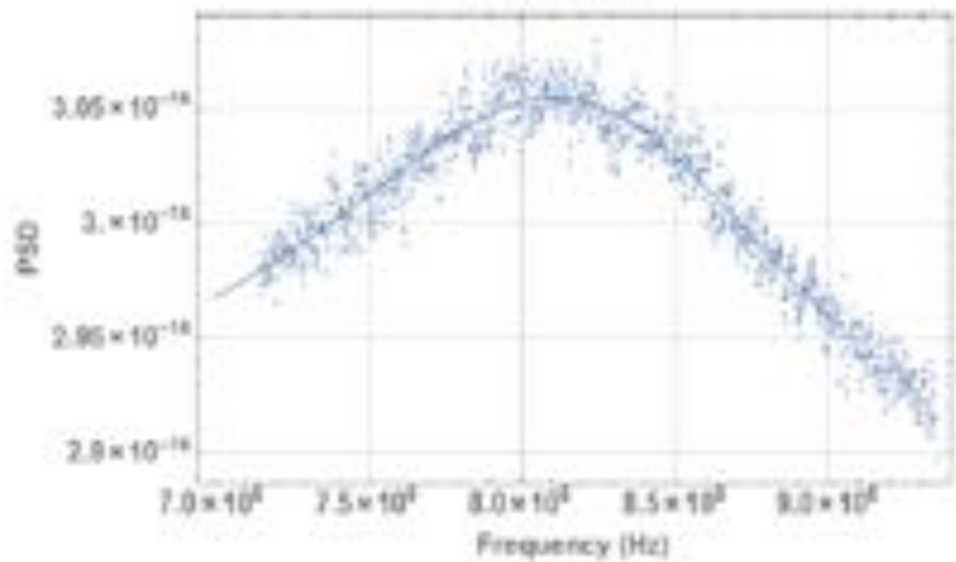


Figure 3.1: ORGAN configuration. The copper microwave cavity being used in the initial experiment (top) and a current ORGAN hardware diagram (bottom).



ORGAN





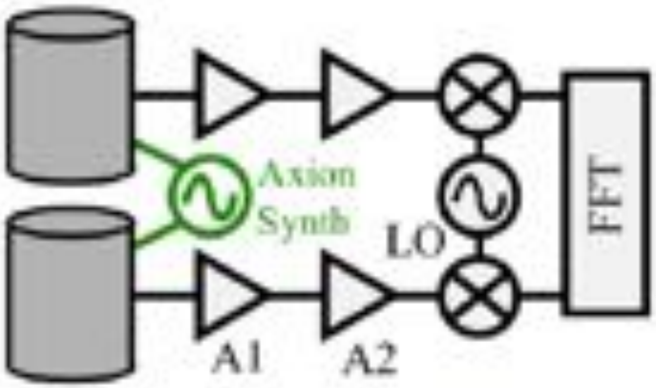
Now Some Ways to Improve SNR

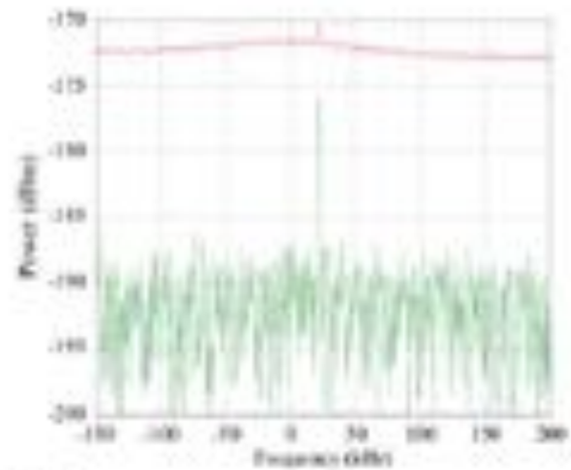
Cross-correlation techniques

- High frequency cavities very small

→ Would like to combine multiple cavities

- Cross-correlation measurements are two-channel measurements which reject uncorrelated noise sources





- Cross-correlate signals from two cavities

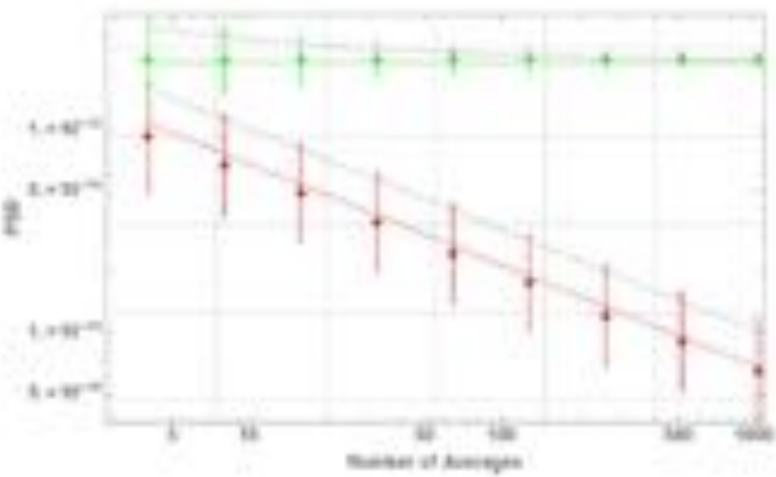
→ Reject the uncorrelated thermal cavity noise and amplifier noise
→ Retain correlated axion signal

Cross-correlation techniques

- Define SNR as signal divided by spread of background noise, for purpose of scheme comparison

- With cross-correlation spread (standard deviation) of background noise goes down proportional to $\frac{1}{2\sqrt{n}}$

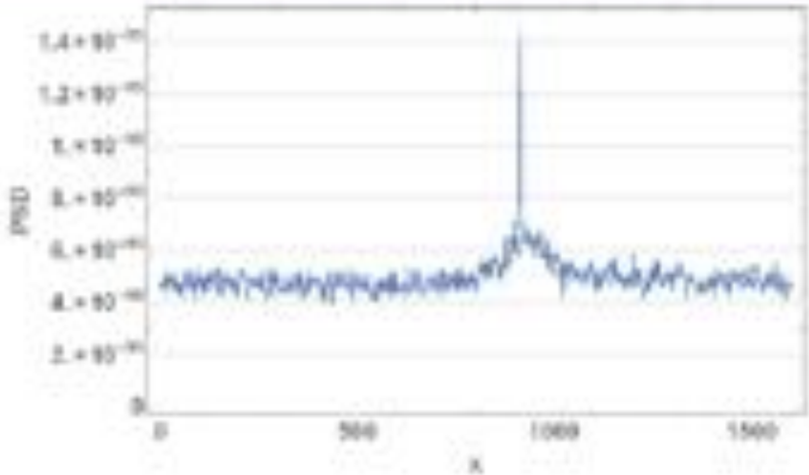
- Compared with $\frac{1}{\sqrt{n}}$ for single channel

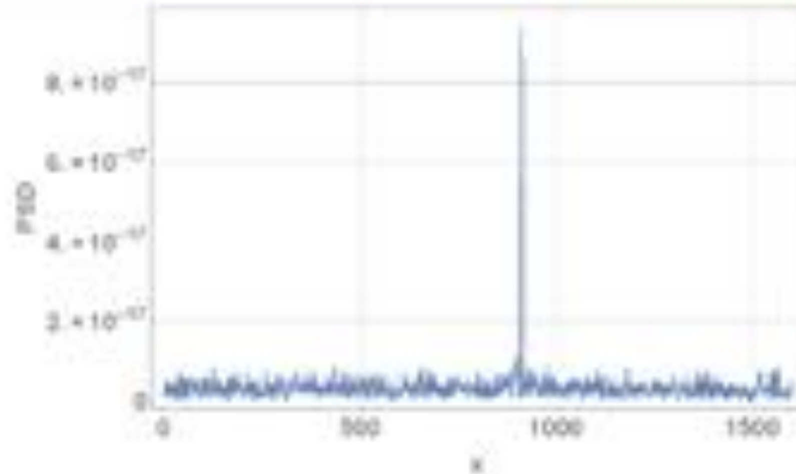


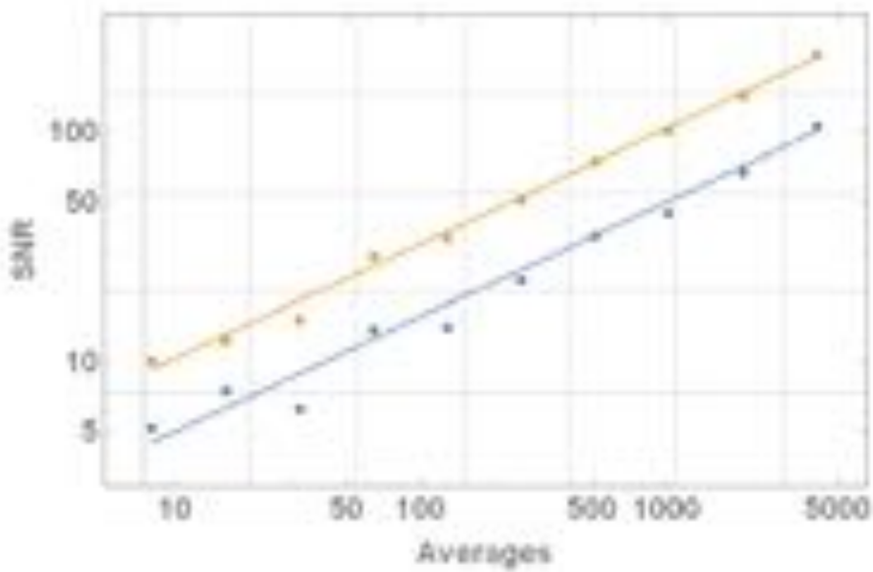
- Factor of 2 reduction in background spread, same improvement as doubling signal power by combining two cavities

- Downside: need two readouts, amps etc

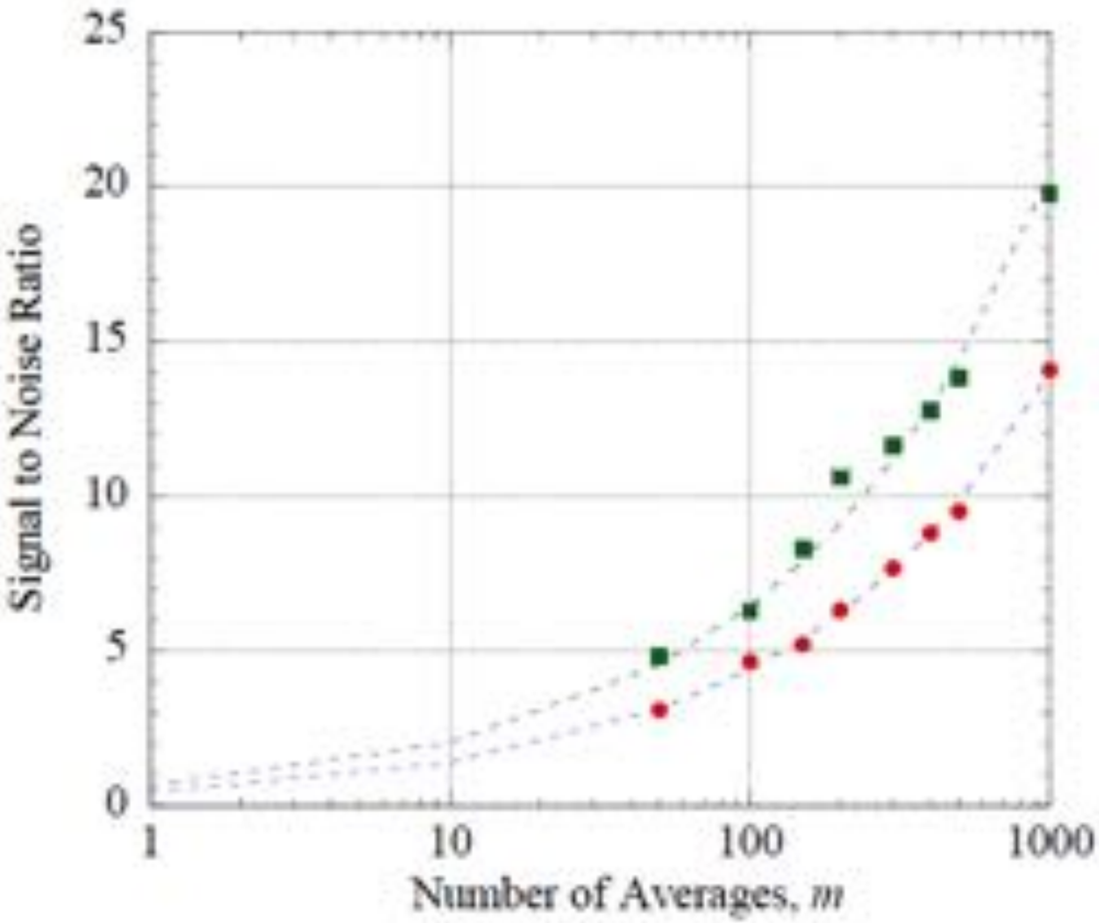
Cross-correlation techniques







Cross-correlating two cavities – measurements



Fit to data points:

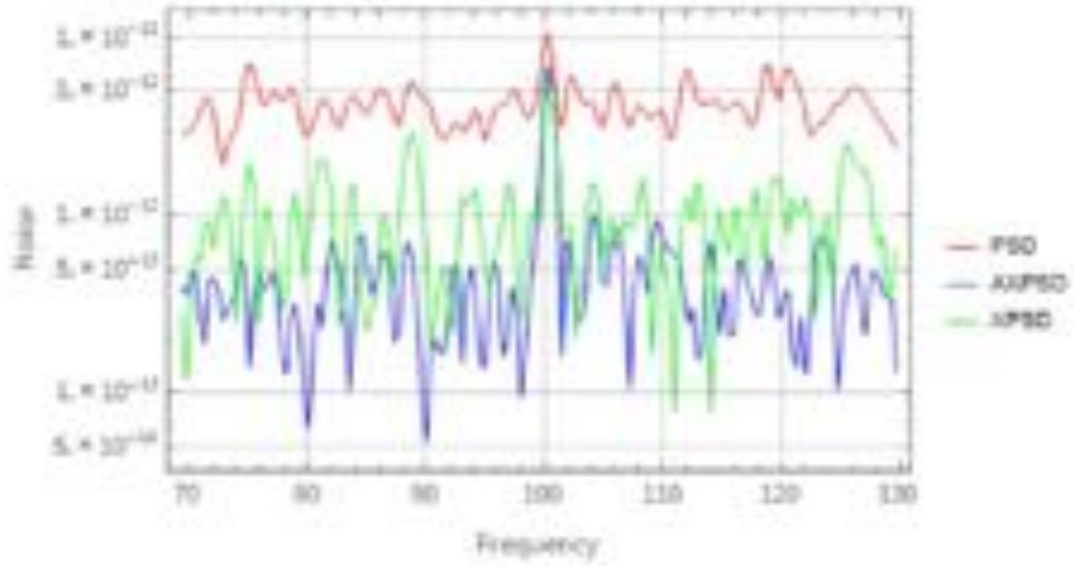
Single-channel = 0.44*rt(m)

Cross-spectrum = 0.46*rt(2m)

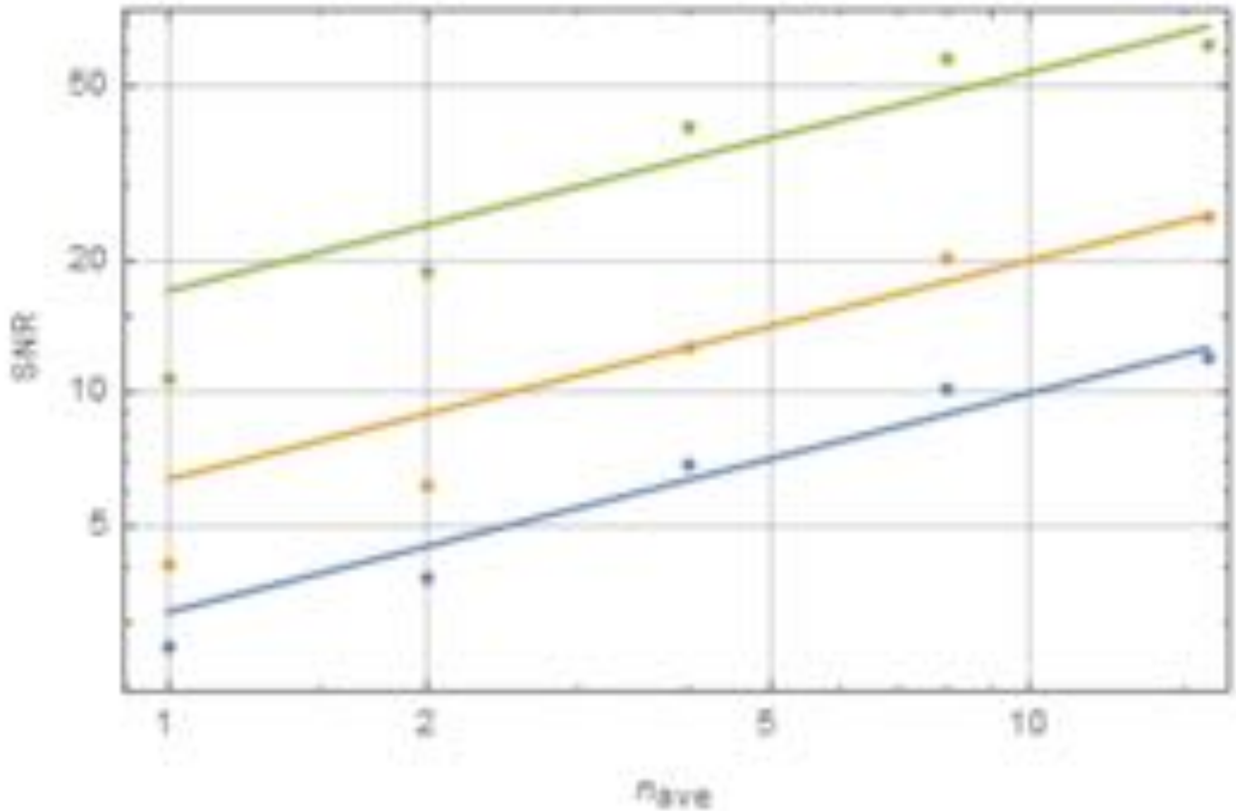
Starting SNRs are “small” (less than 1)

Cross-correlation techniques

- Real benefit achieved when synchronizing larger numbers of cavities
- Can compute "averaged cross spectrum"
- For n cavities we can compute n(n-1)/2 independent cross spectra
- Averaging these cross-spectra produces a new spectrum
→ WISP signal of interest retained
→ Mean of thermal noise reduced
→ Standard deviation of thermal noise reduced
- Achieve $2 \cdot \sqrt{n\,(n-1)/2}$ reduction in spread of background noise, compared with n from power combining

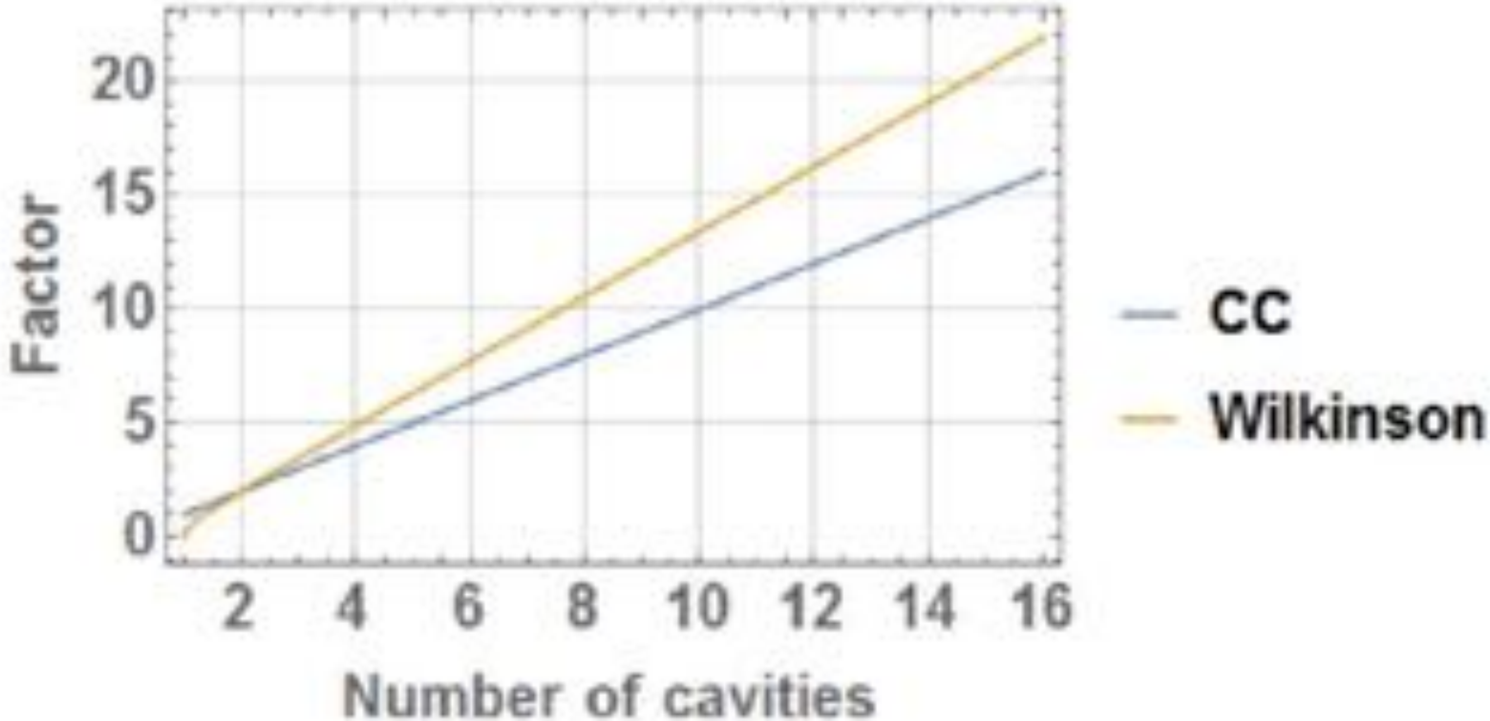


Cross-correlation techniques



Cross-correlation techniques

- **This is not magic or free → We have a tonne more data/readouts, this is all post-processing**
- We need n readouts, rather than one
- n digitization channels
- n times as much data
- Equivalent to averaging a Wilkinson system for longer in terms of data, but we do it simultaneously



Cross-correlation techniques

- Synchronizing 4+ cavities is a long term goal of ORGAN
- **Cross-correlation has other uses than increasing SNR:**
  - Power summation of multiple cavities is difficult
  - Cavities need to be inside same system, in phase
  - CC measurements can be performed with cavities spatially well separated
  - Characterize WISP signals e.g. coherence length
- **See arXiv:1510.05775v2** for more information on these techniques, update forthcoming

Circumventing quantum noise in axion dark matter searches

<u>ADMX-HF team</u>

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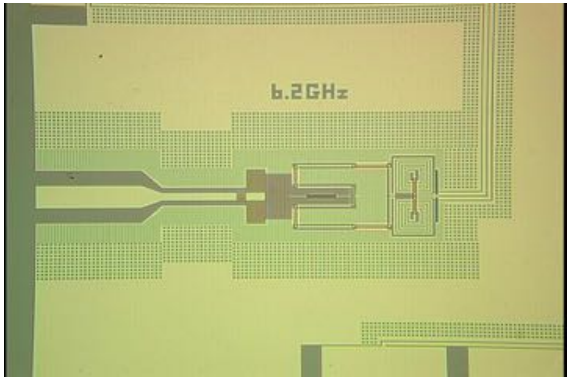

Future of search

- ARC CoE funding for 7 years, can scale up experiment
- ARC Centre of Excellence for Engineered Quantum Systems (EQuS) – Consortium
- Need 14 T magnet and dedicated dilution fridge
- Multiple cavity search
- Quantum or near-quantum limited amplification (JPAs, NQL HEMTs)
- Other areas we are exploring:
  - Signal processing techniques FPGAs with ANU and Liquid Instruments
  - Methods to increase Q factor (superconductivity, 3D printing, Bragg resonators)

THE END