THE UNIVERSITY OF WESTERN AUSTRALIA

FACULTY OF SCIENCE

AXIONS & WISPS

STEPHEN PARKER

2nd Joint CoEPP-CAASTRO Workshop
September 28 – 30, 2014
Great Western, Victoria

Talk Outline

- Frequency & Quantum Metrology Group at UWA
- Basic background / theory for axions and hidden sector photons
- Photon-based experimental searches + bounds
- Focus on resonant cavity “Haloscope” experiments for CDM axions
- Work at UWA: Past, Present, Future

A Few Useful Review Articles:

J.E. Kim & G. Carosi, *Axions and the strong CP problem*, Rev. Mod. Phys., **82**(1), 557 – 601, 2010.
M. Kuster et al. (Eds.), *Axions: Theory, Cosmology, and Experimental Searches*, Lect. Notes Phys. 741 (Springer), 2008.
P. Arias et al., *WISPy Cold Dark Matter*, arXiv:1201.5902, 2012.

Frequency & Quantum Metrology Research Group

ARC CENTRE OF EXCELLENCE FOR ENGINEERED QUANTUM SYSTEMS

~ 3 staff, 6 postdocs, 8 students

Hosts node of ARC CoE EQuS

Many areas of research from fundamental to applied:

Cryogenic Sapphire Oscillator
Tests of Lorentz Symmetry & fundamental constants
Ytterbium Lattice Clock for ACES mission
Material characterization
Frequency sources, synthesis, measurement
Low noise microwaves + millimetrewaves

…and lab based searches for WISPs!

Core WISP team: Stephen Parker, Ben McAllister,
Eugene Ivanov, Mike Tobar

Axions, ALPs and WISPs

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

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

Slim = sub-eV

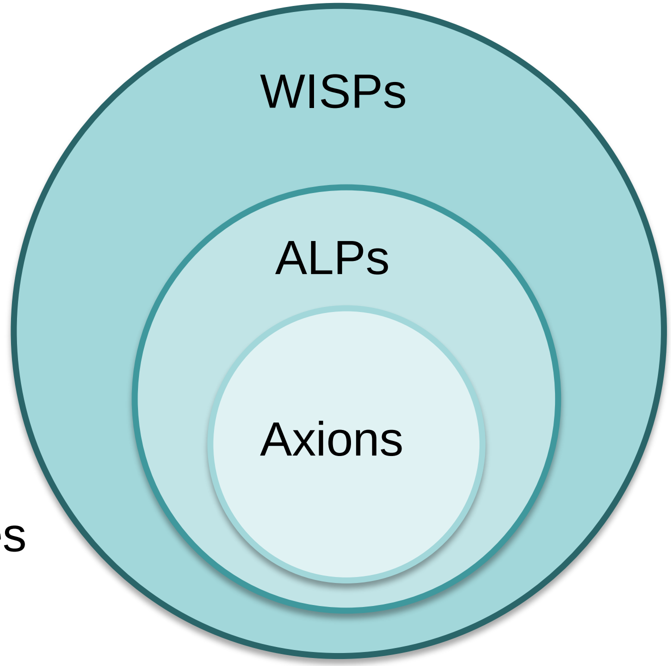
Origins in particle physics (see: strong CP problem, extensions to Standard Model) but become pretty handy elsewhere

Can be formulated as:

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

Low energy scale dictates experimental approach

WISP searches are *complementary* to WIMP searches



The Axion – Origins in Particle Physics

CP violating term in QCD Lagrangian implies neutron electric dipole moment: $d_n \simeq \frac{e\,\theta\, m_q}{m_N^2}$

But measurements place constraint: $\theta \lesssim 10^{-9}$

Why is the neutron electric dipole moment (and thus θ) so small?

This is the **Strong CP Problem**.

“Best” solution: Introduce the $U(1)_{PQ}$ symmetry. This symmetry breaks at some energy scale (f_a); the associated (pseudo) Goldstone boson is the **axion**, which acts as a dynamical CP-conserving field.

Coupling to quarks and gluons gives the axion mass: $0.6 \text{ eV} \, \frac{10^7 \text{ GeV}}{f_a}$

Coupling with QCD / SM / ED particles/fields also suppressed by f_a

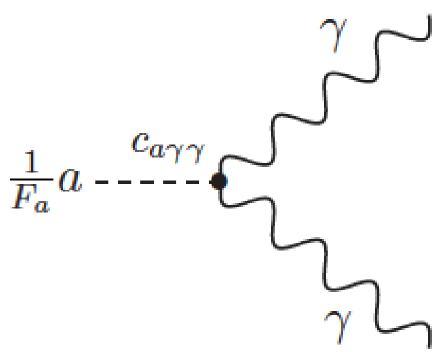
Weakly interacting, small mass particle: **WISP Dark Matter Candidate**.

Axion / Photon Coupling

Axion-2 photon coupling provides very important experimental and observational access (with minimal model dependence).

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

$g_\gamma \sim O(1)$



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

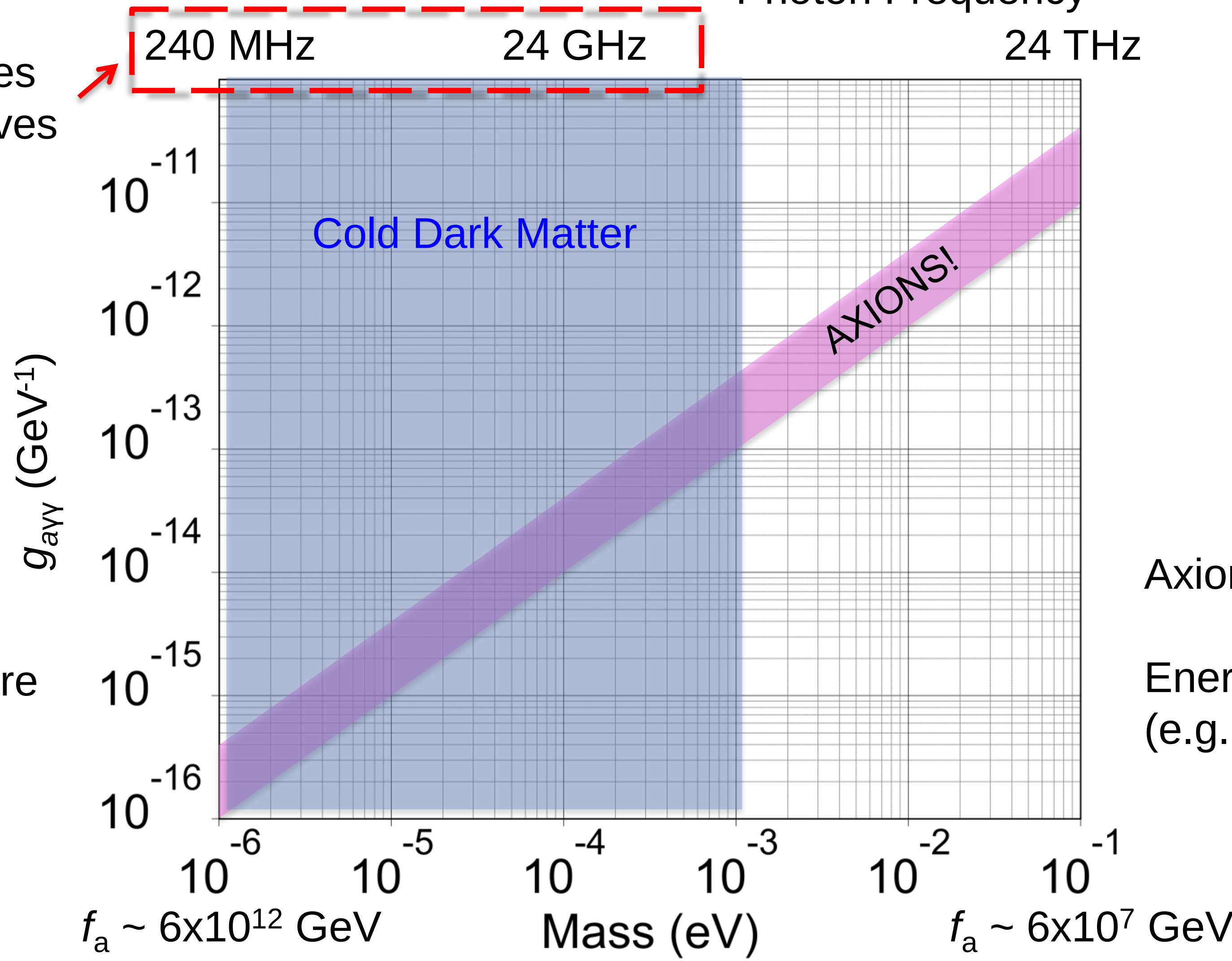
Axion mass dictates photon frequency

Want to test / bound $g_{a\gamma\gamma}$
What values of f_a make sense for axion dark matter?

Axion Mass / Photon Coupling

Photon Frequency

Microwaves
& mm-waves



Overclosure

Axion decay

Energy loss
(e.g. SN1987A)

BICEP2 and Others Hints…

PRL **113,** 011802 (2014) PHYSICAL REVIEW LETTERS week ending 4 JULY 2014

Axion Cold Dark Matter in View of BICEP2 Results

$m_a = (71 \pm 2\ \mu\text{eV})$

$m_\text{a} = 82.2 \pm 1.1\ \mu\text{eV}$

PHYSICAL REVIEW D **90,** 043534 (2014)

Axion cold dark matter: Status after Planck and BICEP2

$m_\text{a} = 63.7 \pm 1.2\ \mu\text{eV}$

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

$m_\text{a} = 76.6 \pm 2.6\ \mu\text{eV}$

Possible Resonance Effect of Axionic Dark Matter in Josephson Junctions

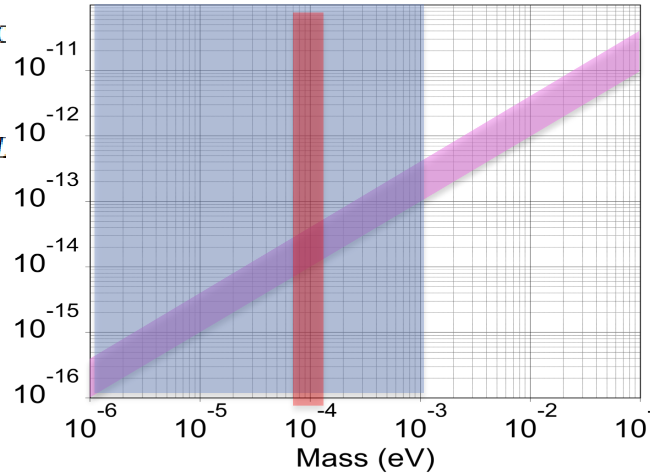
$(110 \pm 2)\ \mu\text{eV}$

Axion mass estimates from resonant Josephson junc

Christian Beck

Queen Mary University of London, School of Mathematical Sciences, Mile End Road, L

There's some (dubious) smoke, but will we find a fire?



Just Briefly: Hidden Sector Photons

Different SM extensions introduce “hidden sectors” of particles due to addition of extra symmetries.

Addition of extra U(1) symmetry interacts very weakly via kinetic mixing of the gauge bosons.

Consequence: Photon – Hidden Sector Photon oscillations

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \boxed{\frac{1}{2}\chi F^{\mu\nu}B_{\mu\nu}} + \frac{1}{2}\left(\frac{c}{\hbar}m_{\gamma'}\right)^2 B^{\mu}B_{\mu}$$

Broad range of allowable mass and coupling strength.

Can be formulated as WISP Dark Matter

Experimentalist’s approach: It’s like an axion but without the need for a magnetic field.

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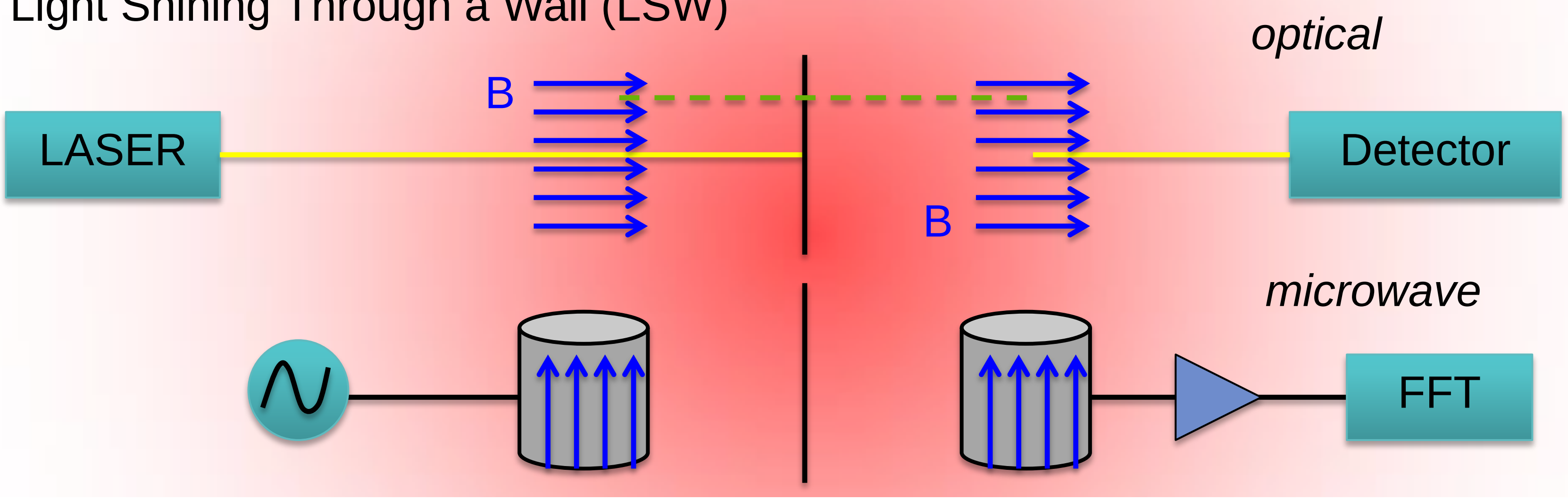
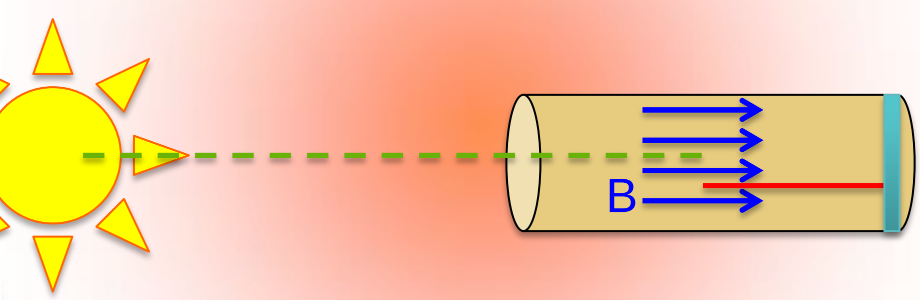
Some Types of Experiments Using Photons

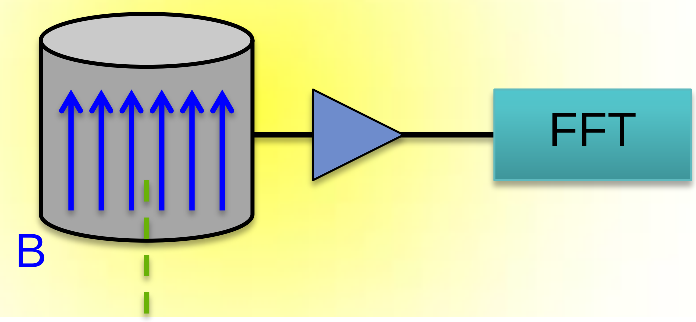
Light Shining Through a Wall (LSW)



Helioscope



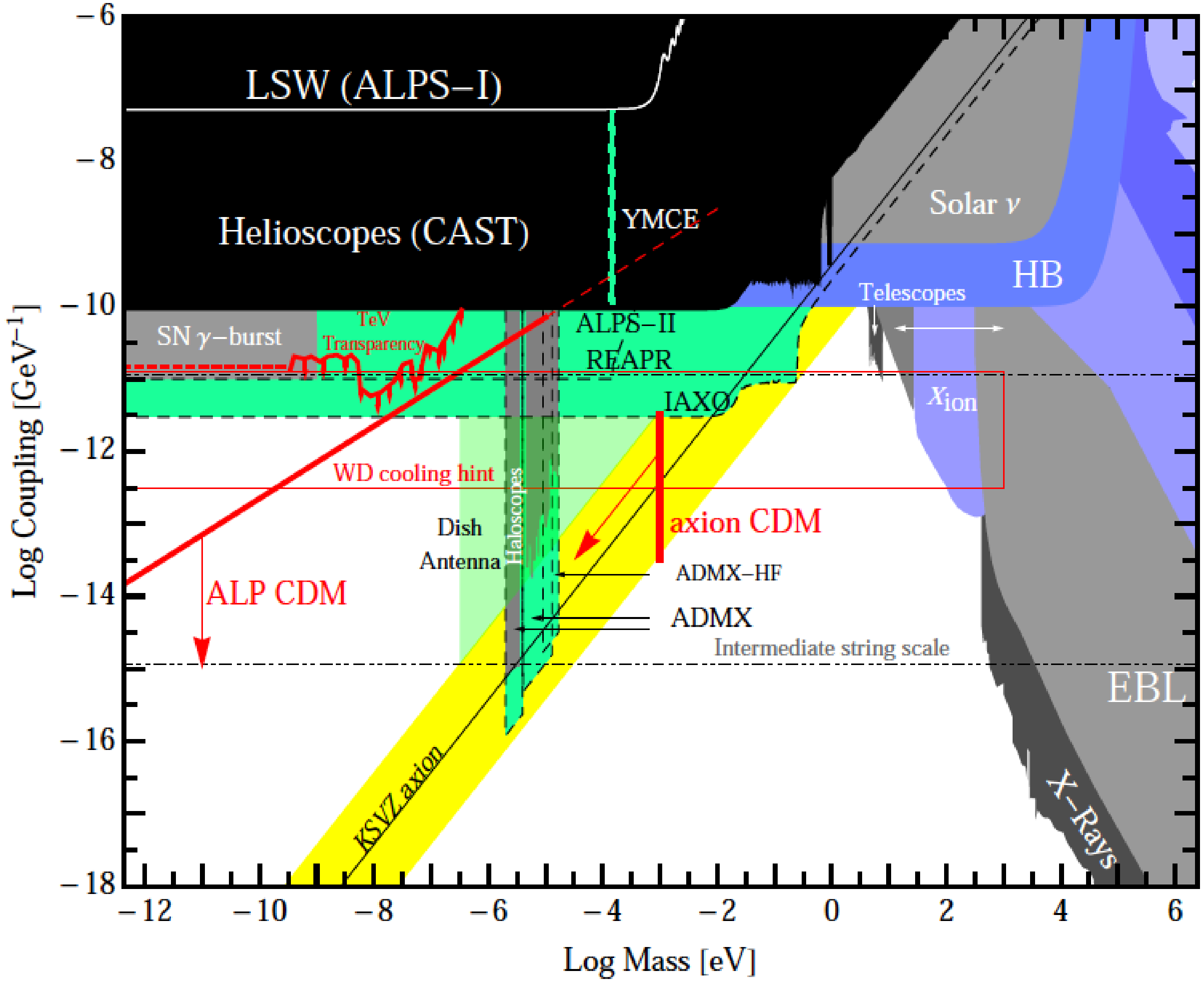
Haloscope



Types of Experiments

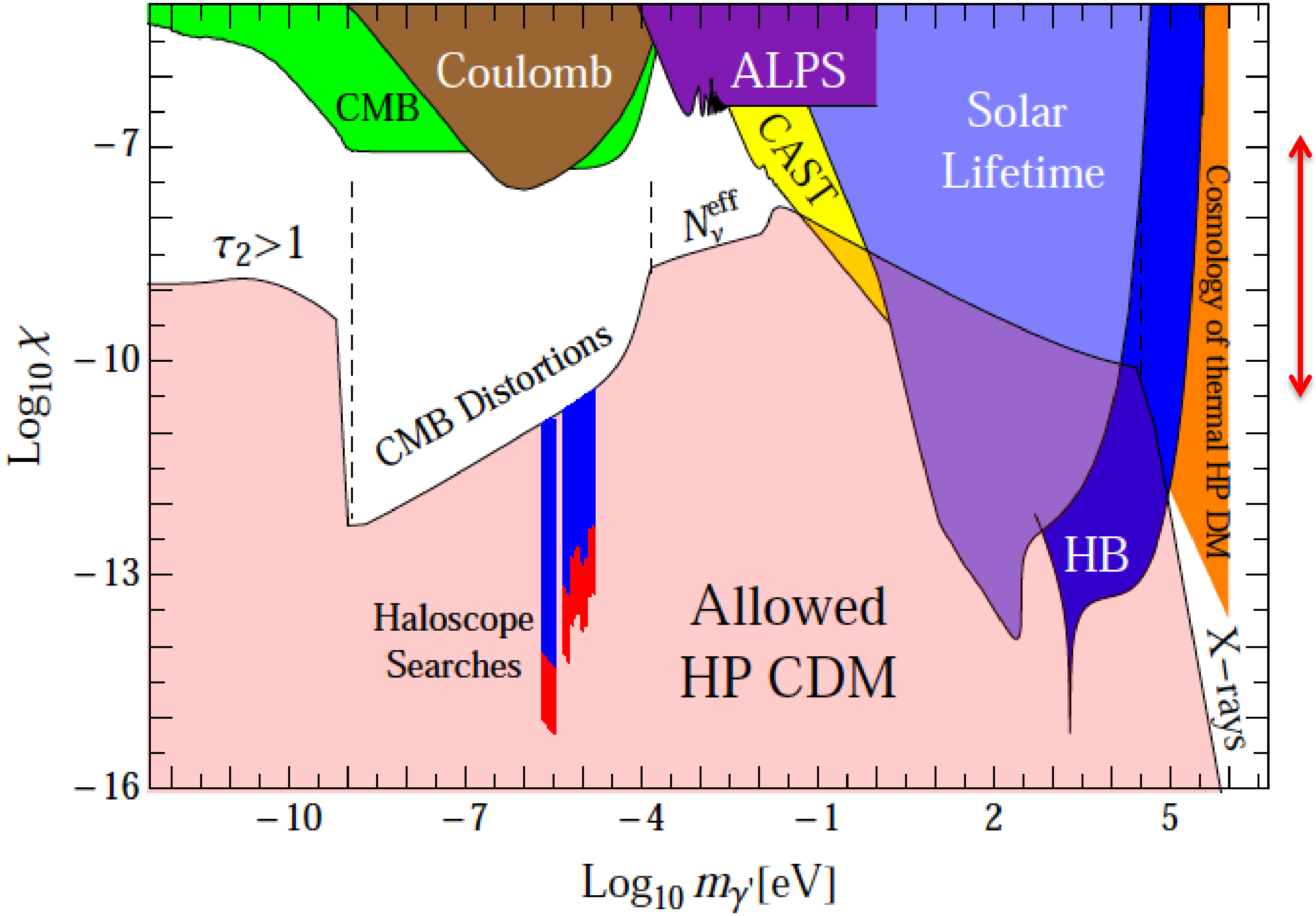
Lab Generation / Detection	Solar Generation / Detection	Dark Matter Detection
Light Shining Through a Wall	Helioscope	Haloscope
Optical		
OSQAR (CERN) ALPS/ALPS-II (DESY) GammeV/REAPR (Fermilab)	CAST (CERN) TSHIPS (DESY)	 WISPDMX (DESY)
Microwave	Sumico (Tokyo) IAXO	
ADMX (UW) CROWS (CERN) UWA Yale		ADMX (UW) ADMX-HF (Yale) CAPP (IBS/KAIST) UWA… (Acronym TBA)

Axion / ALP Exclusion Plot



G. Carosi et al., Probing the axion-photon coupling: phenomenological and experimental perspectives. A snowmass white paper, arXiv: 1309.7035, 2013.

Hidden Sector Photon Exclusion Plot



Jump in sensitivity due to difference between LSW and Haloscopes

i.e. convert once vs convert twice

P. Arias et al., WISPy Cold Dark Matter, arXiv:1201.5902v2, 2012.

The Axion Haloscope

Precision microwave – millimetre wave measurements to constrain axion-photon coupling

Advantages:

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

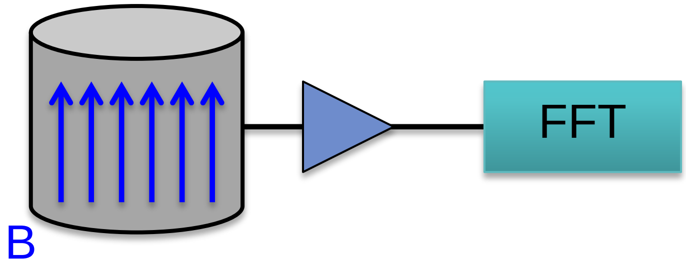
Disadvantages:

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

…challenges we can overcome!

ADMX @ University of Washington
http://www.phys.washington.edu/groups/admx/home.html

The Axion Haloscope



Cavity enables resonant enhancement of converted photon signal

$$P_{Sig} = g_{a\gamma\gamma}^2 \left(\frac{\rho_a}{m_a}\right) B_0^2 VCQ$$

Expected signal (power in Watts)

ρ_a – Axion density (~0.3 GeV/cm^3)
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)

Measure power to constrain axion-photon coupling.

C – the form factor

Recall - Dot product of E and B for axion-2 photon conversion:

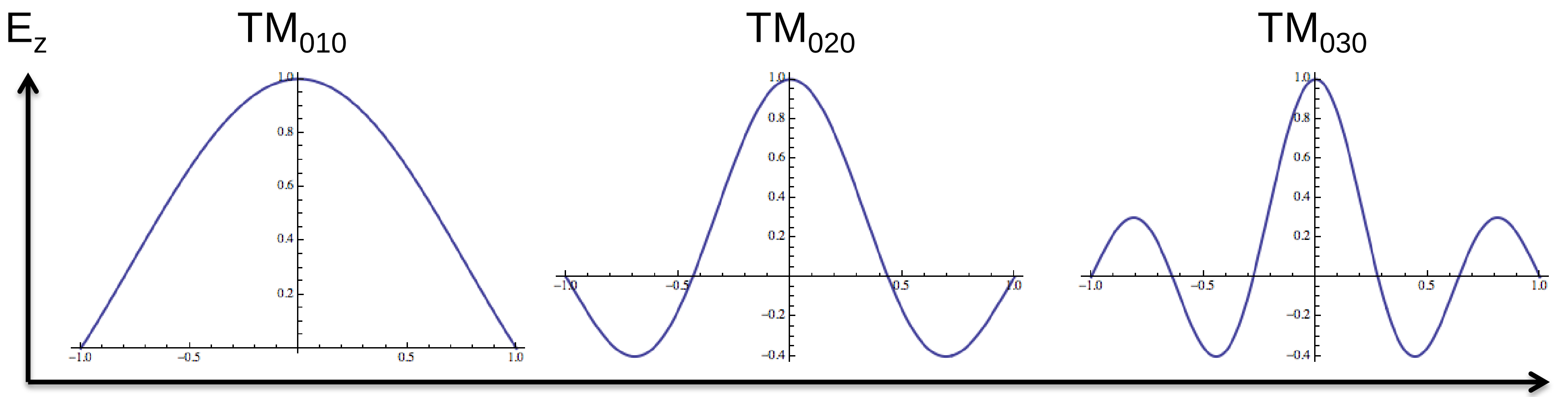
$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma}\, a F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma}\, a\, \vec{E}\cdot\vec{B}$$

$$C = \frac{|\int_V d^3x \mathbf{E}_\omega \cdot \mathbf{B}_0|^2}{\mathbf{B}_0^2 V \int_V d^3x \epsilon |\mathbf{E}_\omega|^2}$$

C, the form factor, provides value between 0 and 1 describing how much of E and B overlap in the cavity

Good choice is the TM_{0x0} mode family:

Frequency scales with 1/r



C ~ 0.69

C ~ 0.13

C ~ 0.05

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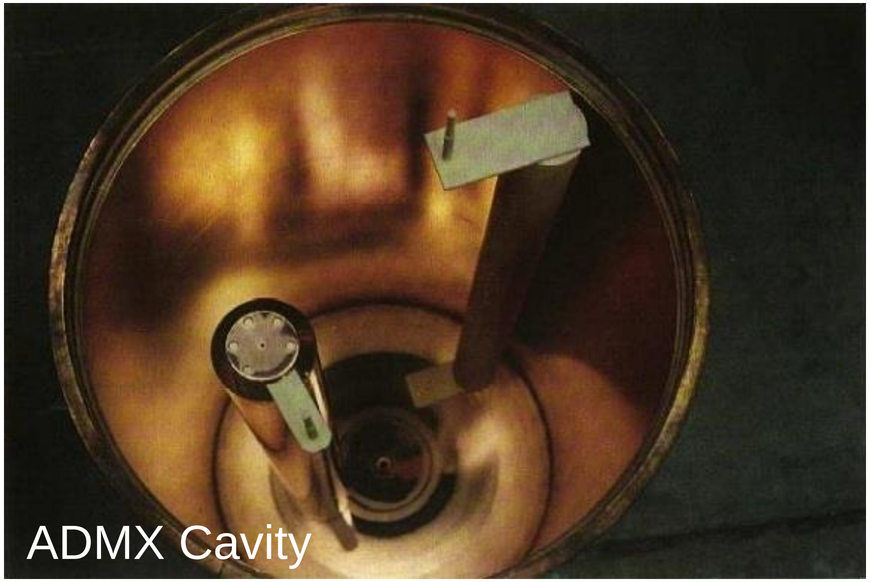
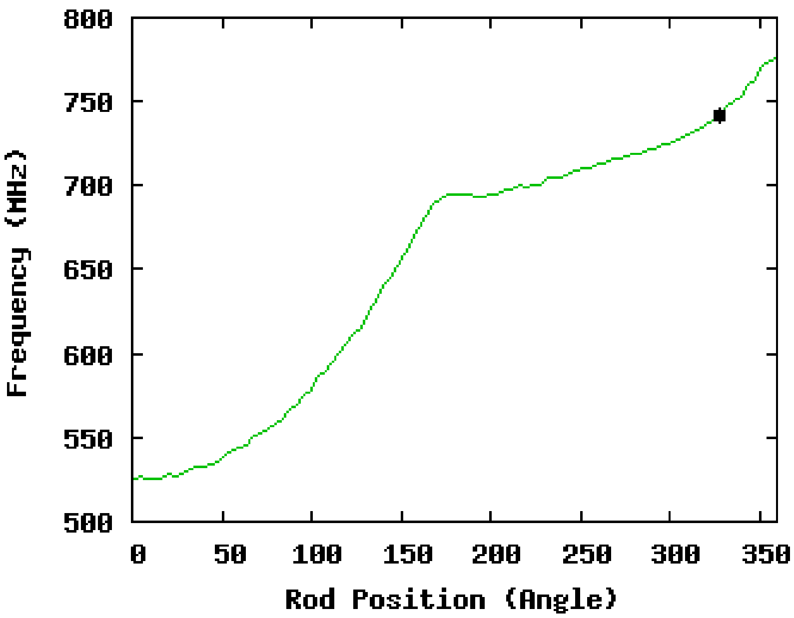
Cavity Frequency Tuning

Want to scan over a large region of parameter space

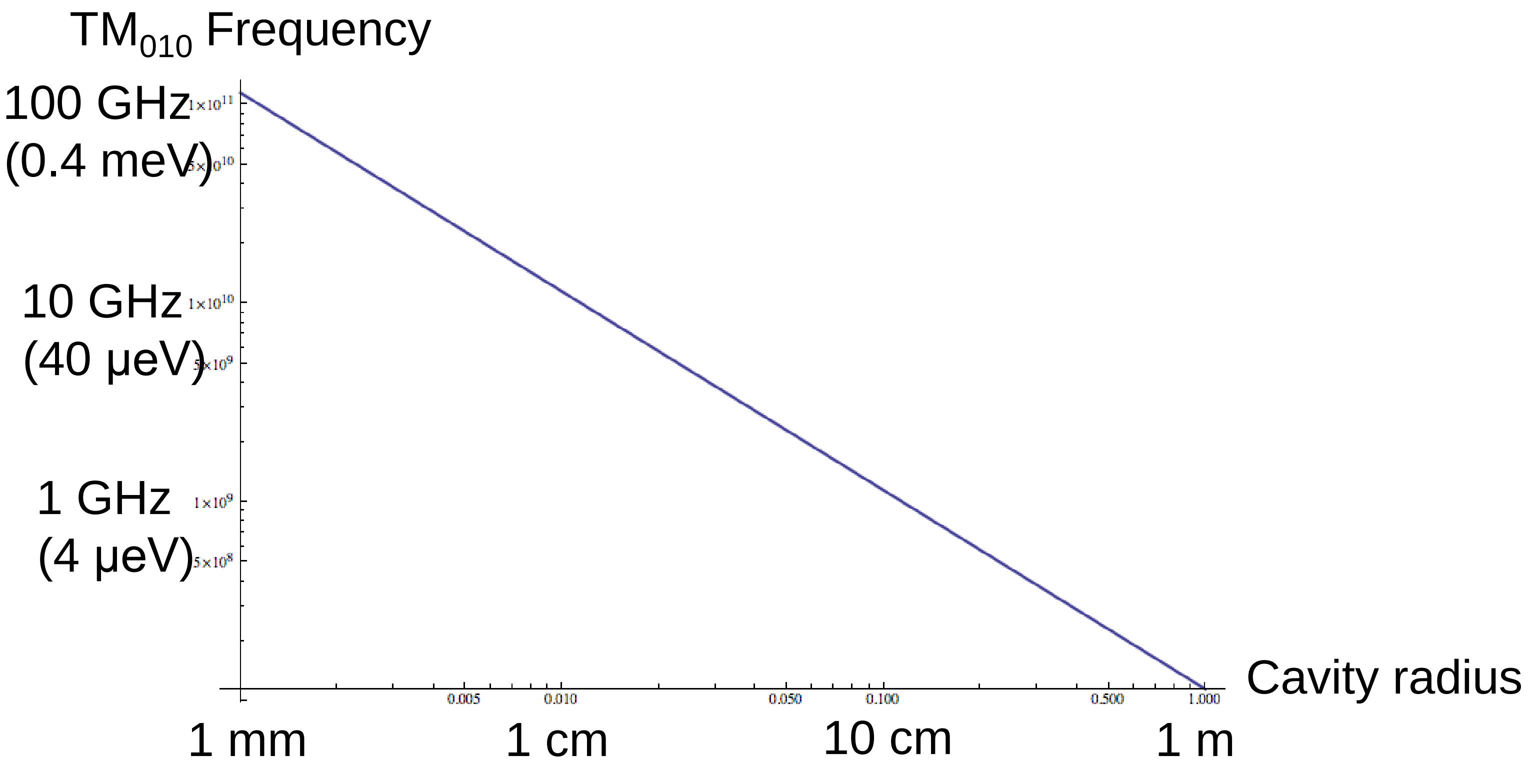
Hard to adjust radius of the cavity on-the-fly…

One approach: perturb the field structure.

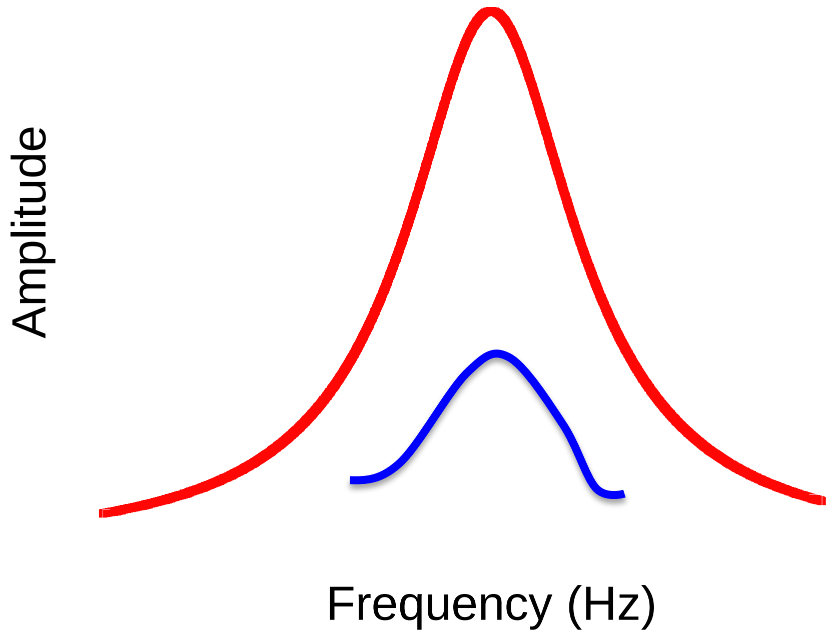




V – cavity volume



Q – Quality factor



$$P_{Sig} = g_{a\gamma\gamma}^2 \left(\frac{\rho_a}{m_a}\right) B_0^2 V C Q$$

Q is actually minimum of cavity Q or "axion Q"

$$E_a = m_a c^2 + \frac{1}{2} m_a c^2 \beta^2$$

$$\beta \approx 10^{-3}$$

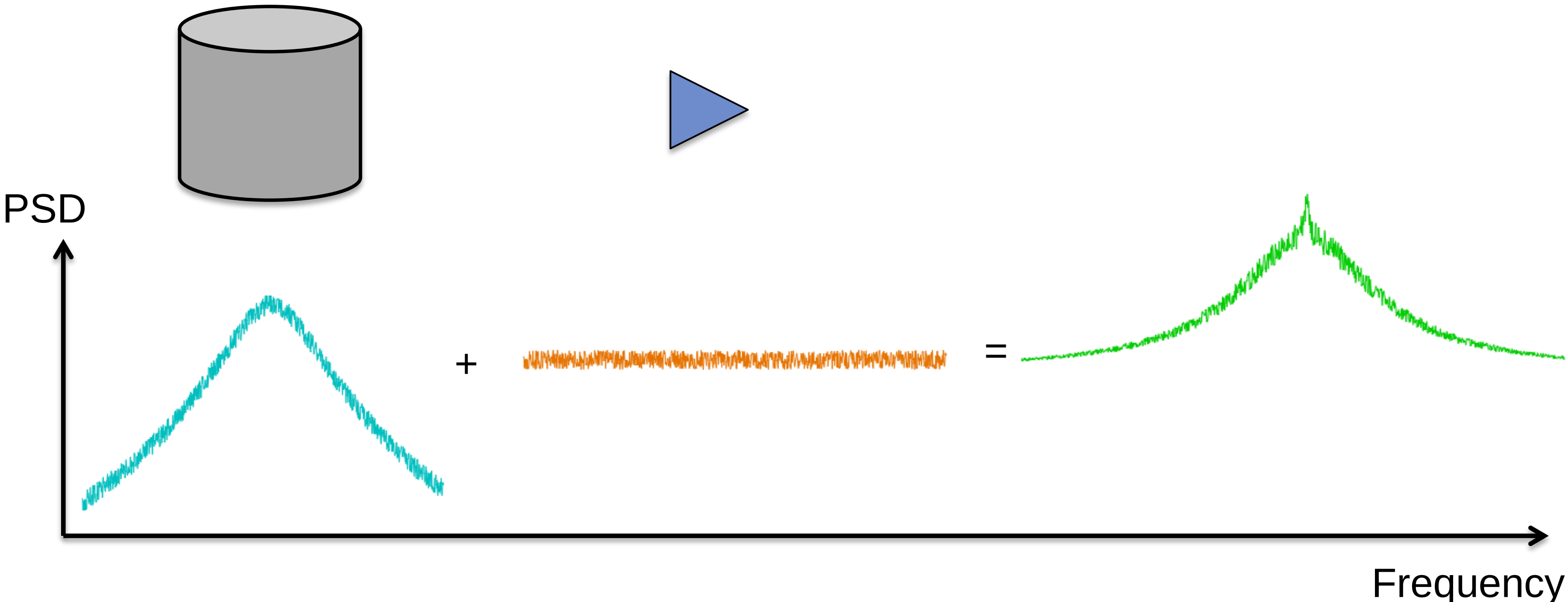
Implies "axion Q" ~ 10^6

Other assumptions do allow for lower dispersion (higher Q) axions.

Also need to consider Doppler shifting / daily modulation

Noise

Cavity thermal noise + Amplifier noise = measurement system noise



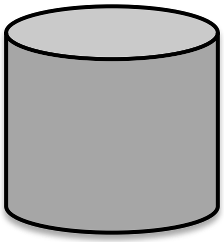
$$\mathrm{SNR} = \frac{P}{k_B T_N}\sqrt{\frac{t}{b}}$$

t = integration time
b = bandwidth

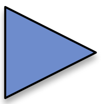
Sit and wait until you reach desired SNR

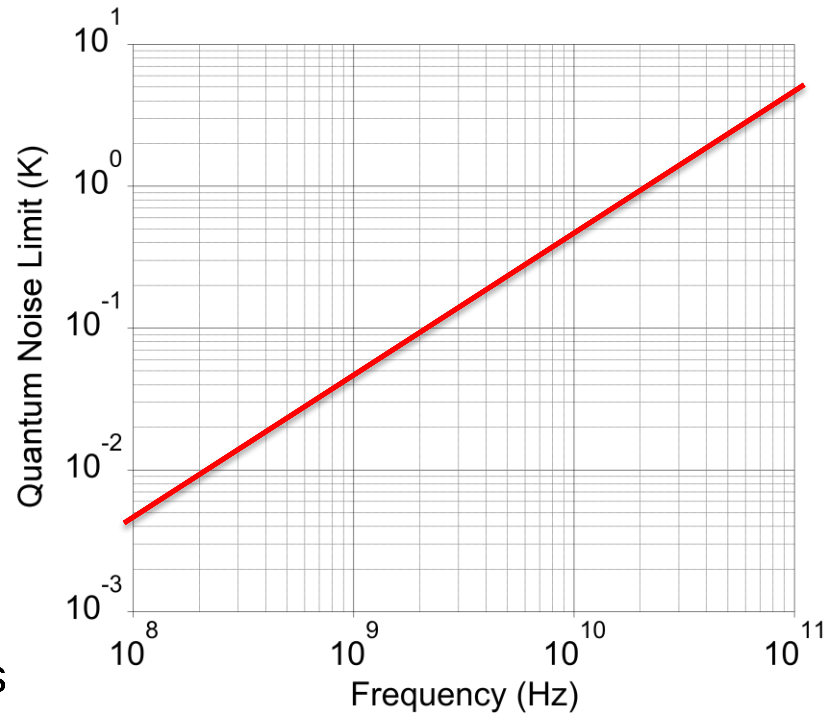
Dealing With Noise

Cavity thermal noise



Amplifier noise





Physical cooling:

Liquid helium ~ 4.2 K
Dilution fridge < 100 mK

Physical cooling
Amplifier technologies

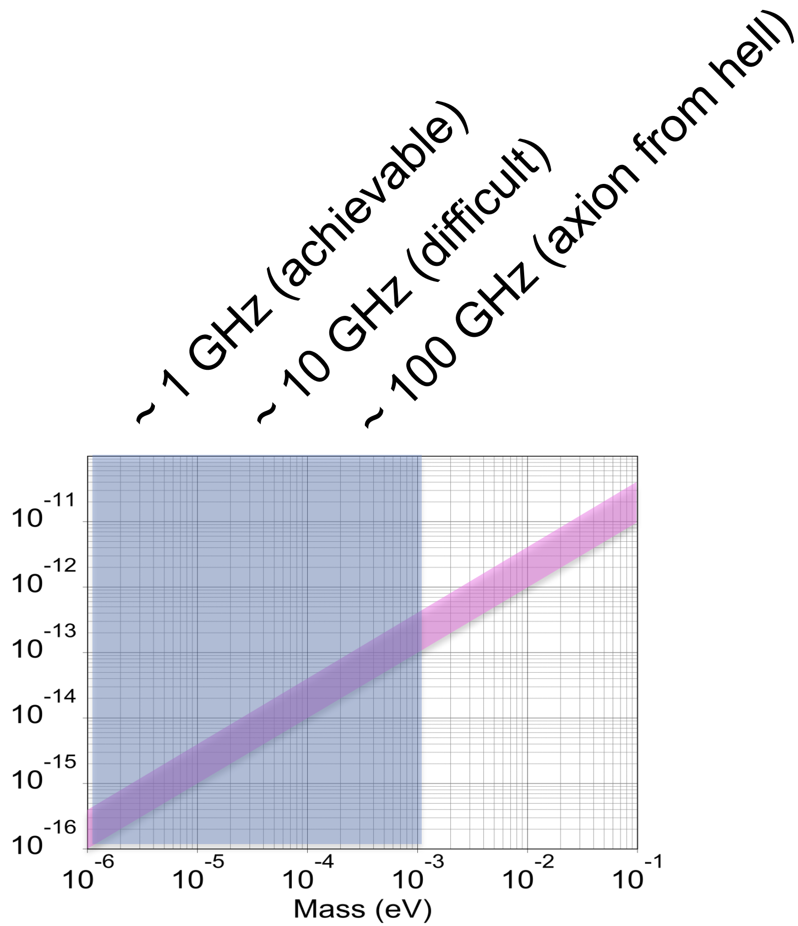
HEMT ~ O(1-10) K
SQUID ~ near quantum
JPA ~ near quantum

Also: new measurement schemes to improve SNR (current research at UWA)

Probing higher axion masses with haloscopes

Many things conspire against us:

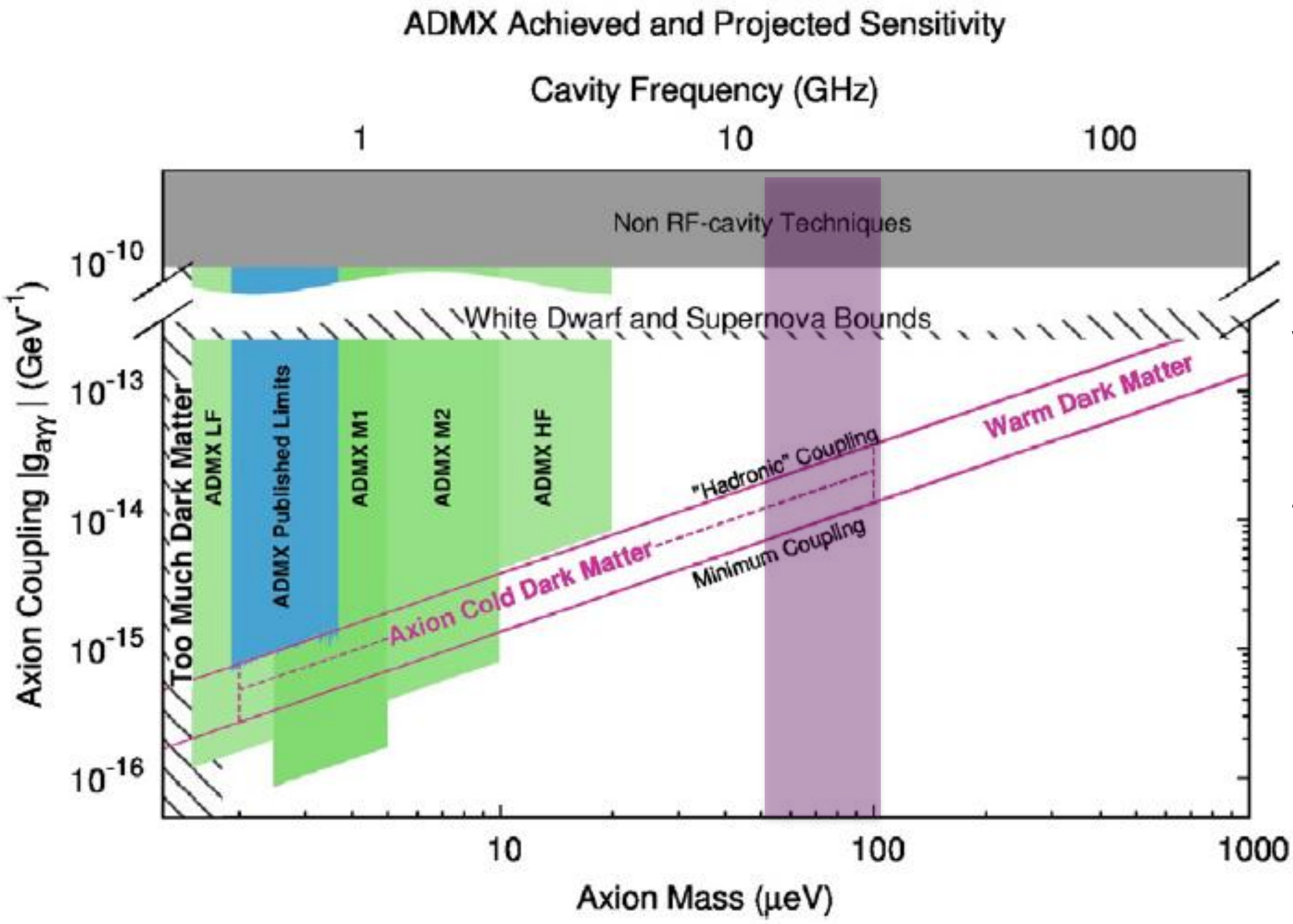
Smaller volume
Lower Q
Higher system noise



Areas of research being pursued:

Stronger magnetic field (very expensive)
Hybrid superconducting cavities
Different cavity structures and designs
Different amplifier technologies

Prospects for CDM-Axion Haloscope Searches



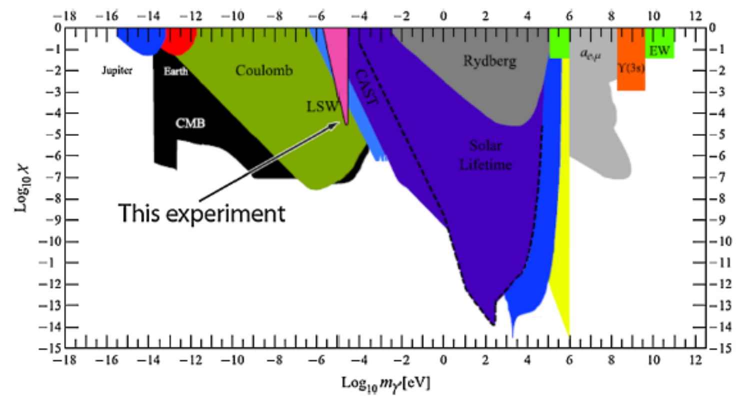
We (UWA) are well positioned to immediately search in the 15 – 40 GHz region

UWA – Past Work (Hidden Sector Photons LSW Experiments)

PHYSICAL REVIEW D 82, 052003 (2010)

Microwave cavity light shining through a wall optimization and experiment

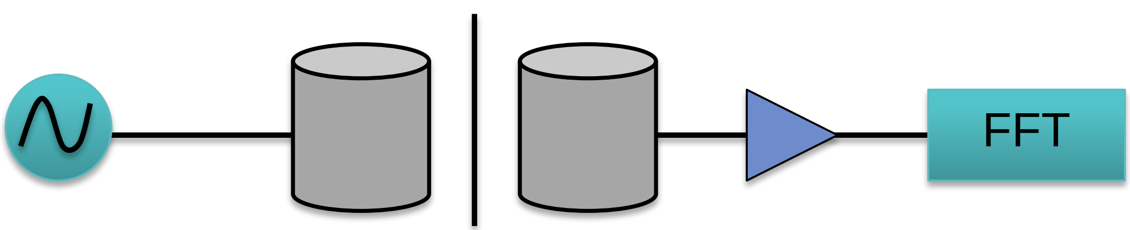
Rhys G. Povey,* John G. Hartnett, and Michael E. Tobar
School of Physics, University of Western Australia, WA 6009 Australia
(Received 29 June 2010; published 24 September 2010)

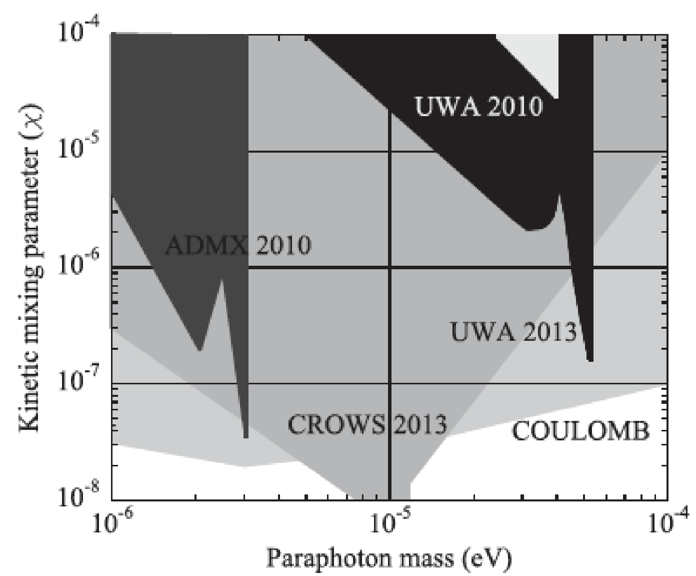


PHYSICAL REVIEW D 88, 112004 (2013)

Cryogenic resonant microwave cavity searches for hidden sector photons

Stephen R. Parker,[1,*] John G. Hartnett,[1,2] Rhys G. Povey,[1,3] and Michael E. Tobar[1]
[1]*School of Physics, The University of Western Australia, Crawley 6009, Australia*
[2]*Institute of Photonics and Advanced Sensing, School of Chemistry and Physics, University of Adelaide, Adelaide 5005, Australia*
[3]*Department of Physics, University of Chicago, Chicago, Illinois 60637, USA*
(Received 15 October 2013; published 3 December 2013)





UWA – Past Work (HSPs)

PHYSICAL REVIEW D 84, 055023 (2011)

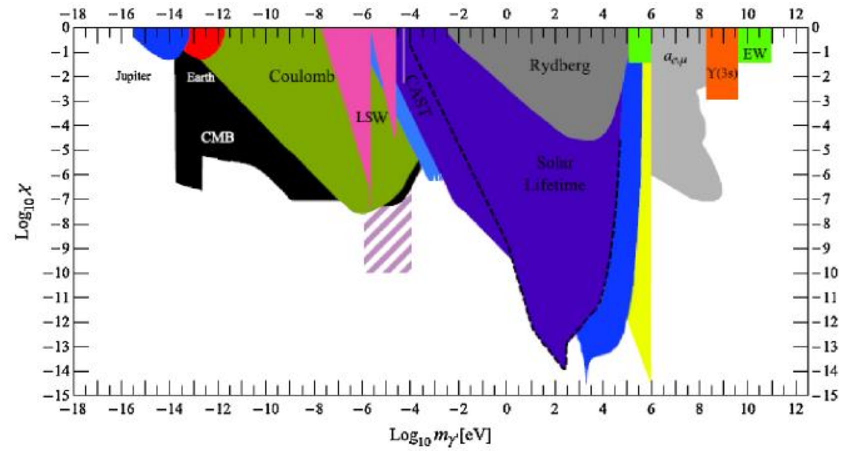
Microwave cavity hidden sector photon threshold crossing

Rhys G. Povey,* John G. Hartnett, and Michael E. Tobar
School of Physics, University of Western Australia, Western Australia 6009, Australia
(Received 31 May 2011; published 27 September 2011)

PHYSICAL REVIEW D 87, 115008 (2013)

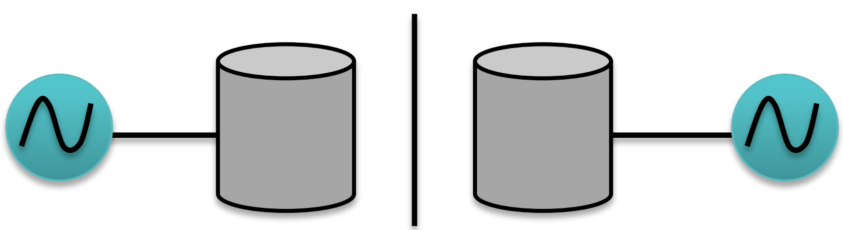
Hidden sector photon coupling of resonant cavities

Stephen R. Parker,[1,*] Gray Rybka,[2] and Michael E. Tobar[1]
[1]*School of Physics, The University of Western Australia, Crawley 6009, Australia*
[2]*University of Washington, Seattle, Washington 98195, USA*
(Received 25 April 2013; published 7 June 2013)



Exchange of HSPs between cavities leads to coupling, hence they will resonate at normal mode.

Frequency shift proportional to HSP-Photon kinetic mixing parameter.



Classical analogy: two spring-mass systems coupled via third weak spring

UWA – Present Work

New measurement scheme to improve SNR of Haloscope experiments

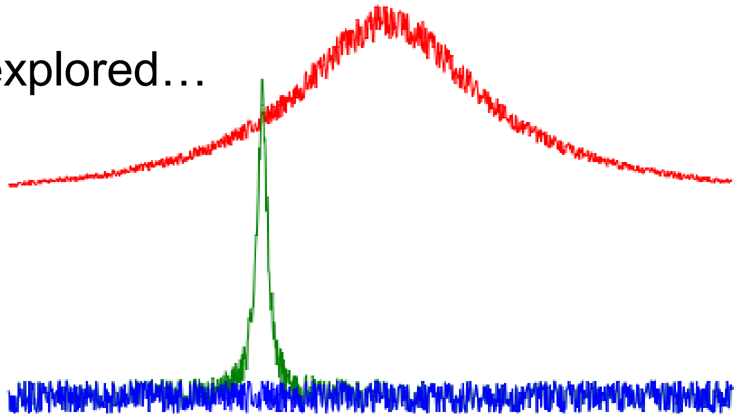
Novel application of precision microwave measurement techniques

Conversely: Increases scanning speed to reach desired SNR

Effectively increases the mass range that standard Haloscope can practically cover

Experimental work finished, manuscript under preparation.

Other ideas for new experimental schemes being explored…



UWA – Future Work

Axion search in the 10 – 40 GHz region*, enabled by new measurement scheme

26 GHz (0.11 meV) prototype experiment first up

Improved LSW Hidden Sector Photon searches

Further development of new schemes and ideas…

*pending funding (as always).

Summary

Axions (and WISPs) are compelling dark matter candidates

Haloscope experiments currently probing viable parameter space

More groups are joining the search with good prospects of covering all CDM QCD axion possibilities.

A Few Useful Review Articles:

J.E. Kim & G. Carosi, *Axions and the strong CP problem*, Rev. Mod. Phys., **82**(1), 557 – 601, 2010.
M. Kuster et al. (Eds.), *Axions: Theory, Cosmology, and Experimental Searches*, Lect. Notes Phys. 741 (Springer), 2008.
P. Arias et al., *WISPy Cold Dark Matter*, arXiv:1201.5902v2, 2012.