Axion Dark Matter: Experimental Overview

Axions Beyond Boundaries Workshop – 2023

Galileo Galilei Institute for Theoretical Physics

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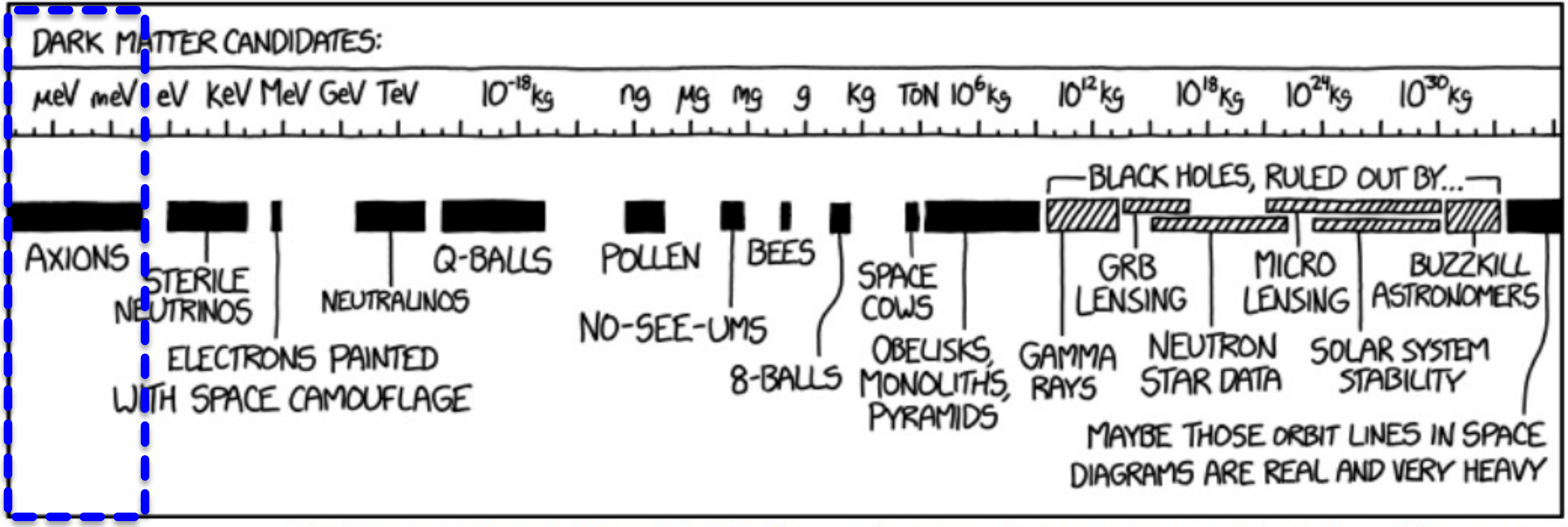
The Mass Range of Dark Matter Candidates

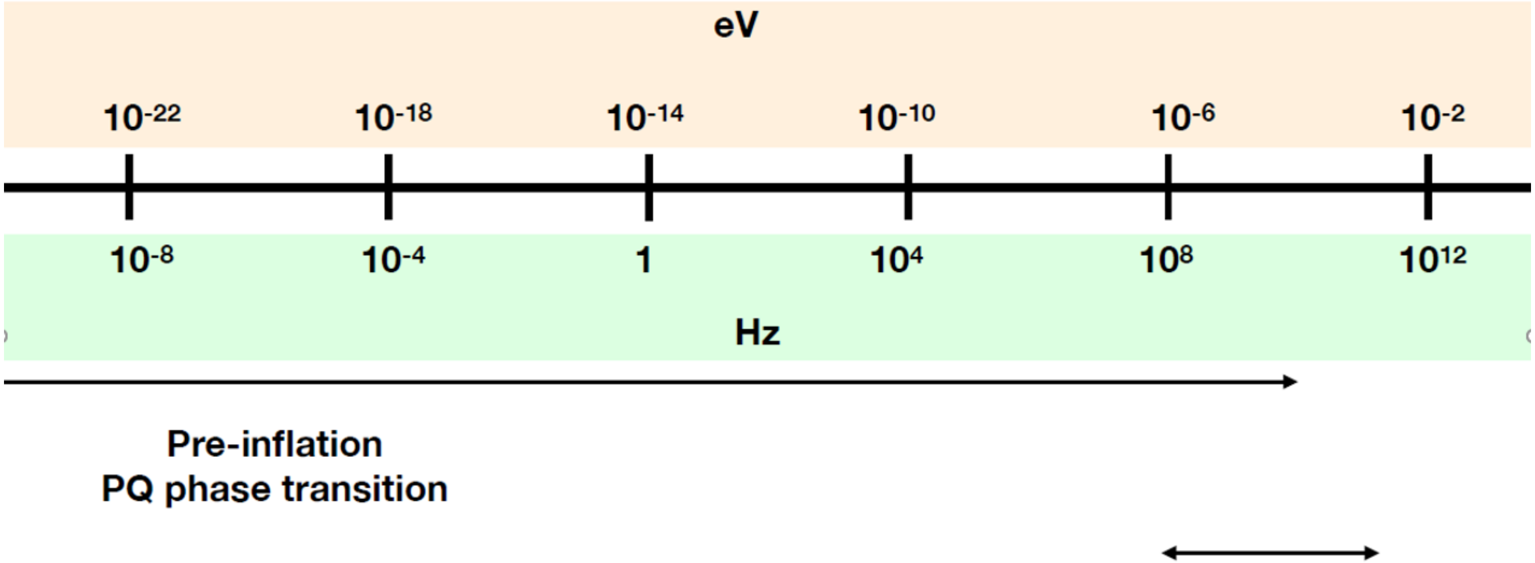


Credit to: **xkcd.com** (Aug. 20, 2018) "*A webcomic of romance, sarcasm, math, and language.*"

Axion mass range

Lower bound set by size of dark matter halo size of dwarf galaxies

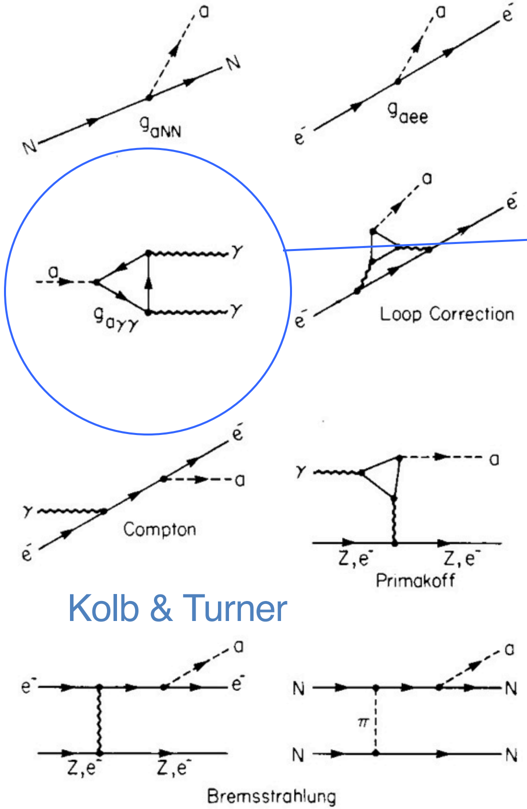
Upper bound set by SN1987A and white dwarf cooling time



Pre-inflation
PQ phase transition

Post-inflation
PQ phase transition

Axion Couplings



Kolb & Turner

General classes of couplings

Axion – Nucleon
Axion – Electron
Axion – Photon

$g_{a\gamma\gamma}$ is a process with small model uncertainty
Coupling used for haloscopes

Rate depends on "unification group" (the particles in the loops), ratio of u/d quark masses. The U(1) charges at the axion vertex cancel with little model dependence

$$g_{a\gamma\gamma} \sim \frac{\alpha}{f_{PQ}}\left(\frac{E}{N} - 1.95\right)$$

Axion Couplings

$$L = -\frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{i}{2}g_d a\bar{N}\sigma_{\mu\nu}\gamma_5 N F_{mu\nu} + g_{aNN}(\partial_\mu)\bar{N}\gamma^\mu\gamma_5 N + g_{aie}(\partial_\mu)\bar{e}\gamma^\mu\gamma_5 e$$

Coupling to photons

Coupling to nucleon EDM

Causes electric dipole moments (EDMs) in nuclei/atoms/molecules

Coupling to axion nuclear moment

Creates spin-dependent energy shifts/spin precession in fermions

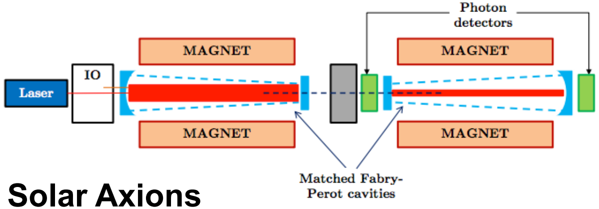
Coupling to axial electron moment

Axioelectric effect, Analogous to photoelectric effect

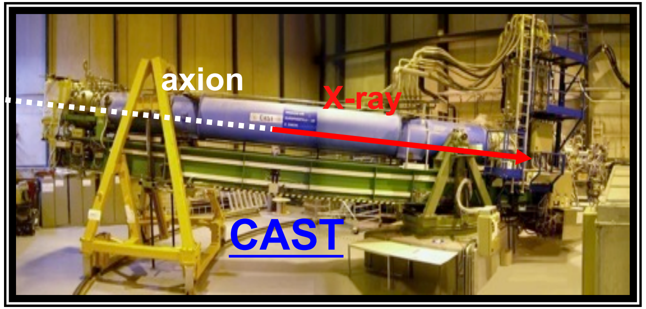
Adapted from L. Winslow DPF slide and Y. Kahn, See Graham and Rajendran, Phys.Rev. D88 (2013) 035023

Types of axion experiments typically fall in three categories

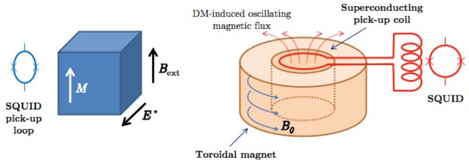
Laboratory Experiments: Lasers (light shining through walls) & 5th force experiments

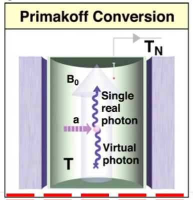


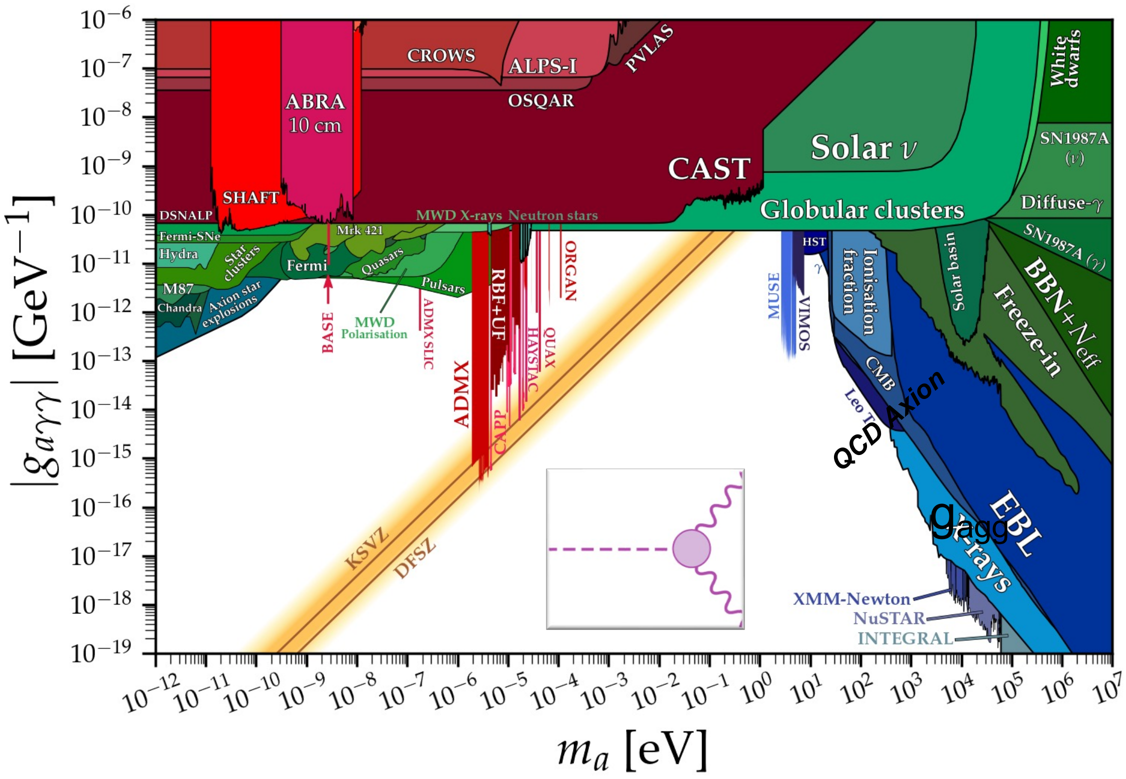
Solar Axions



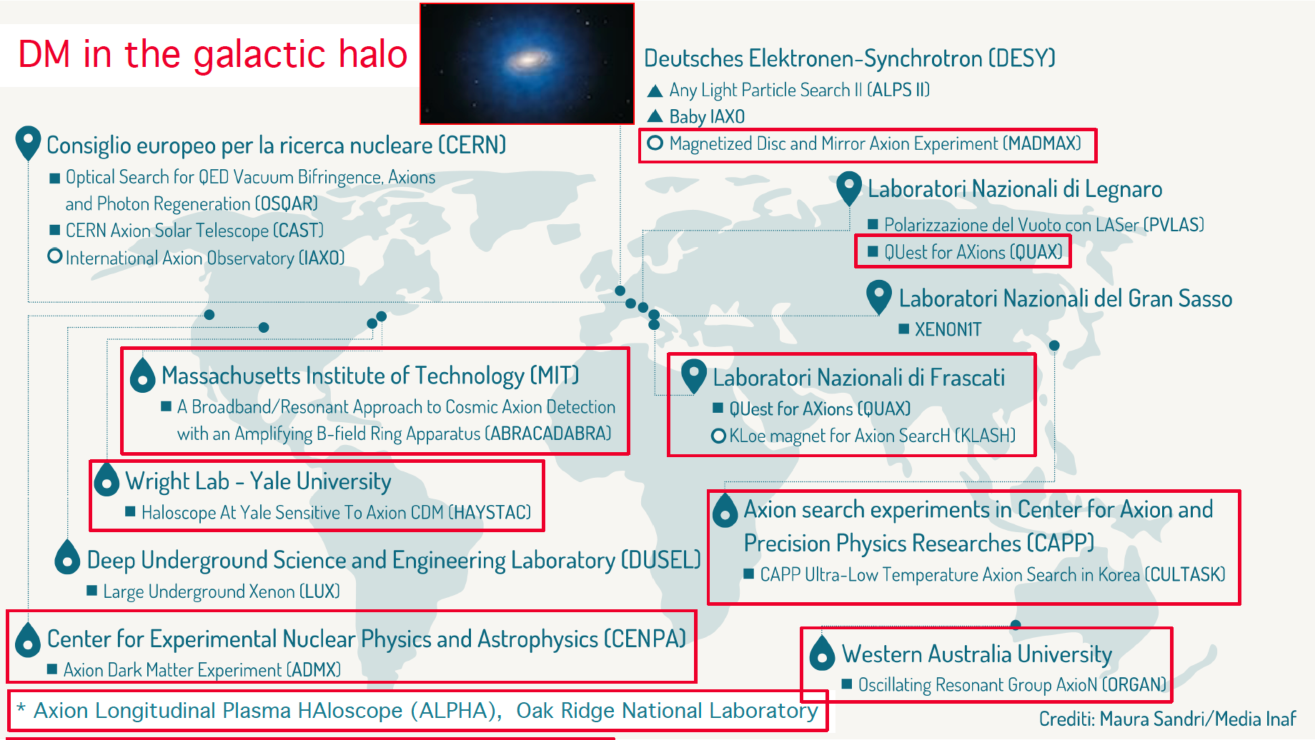
Axions from Dark Matter (Haloscopes, NMR, etc)







List of dark matter experiments & locations

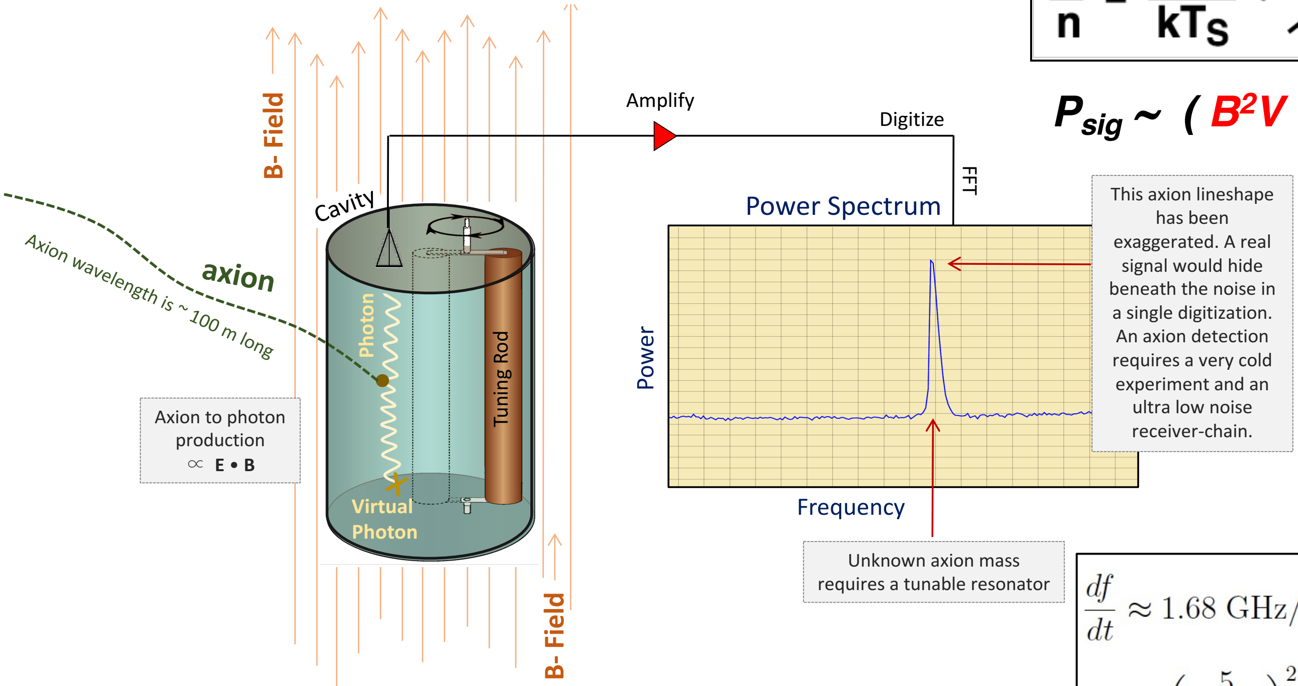


* Axion Longitudinal Plasma HAloscope (ALPHA), Oak Ridge National Laboratory

* Taiwan Axion Search Experiment with Haloscope (TASEH)

+ Cosmic Axion Spin Precession Experiment (CASPEr), Boston University and Mainz

Axion Dark Matter Searches: The Axion Haloscope Technique



$$\frac{s}{n} = \frac{P_{sig}}{kT_S} \cdot \sqrt{\frac{t}{\Delta\nu}}$$

$$P_{sig} \sim (B^2 V\, Q_{cav} C_{010})(g^2 m_a \rho_a) \sim 10^{-24}\ W$$

System noise temp.

$$T_S = T_{phys} + T_N$$

$$T_{Quant} \sim 48\ mK\ @\ 1\ GHz$$

t = Integration time limited to ~ 100 sec

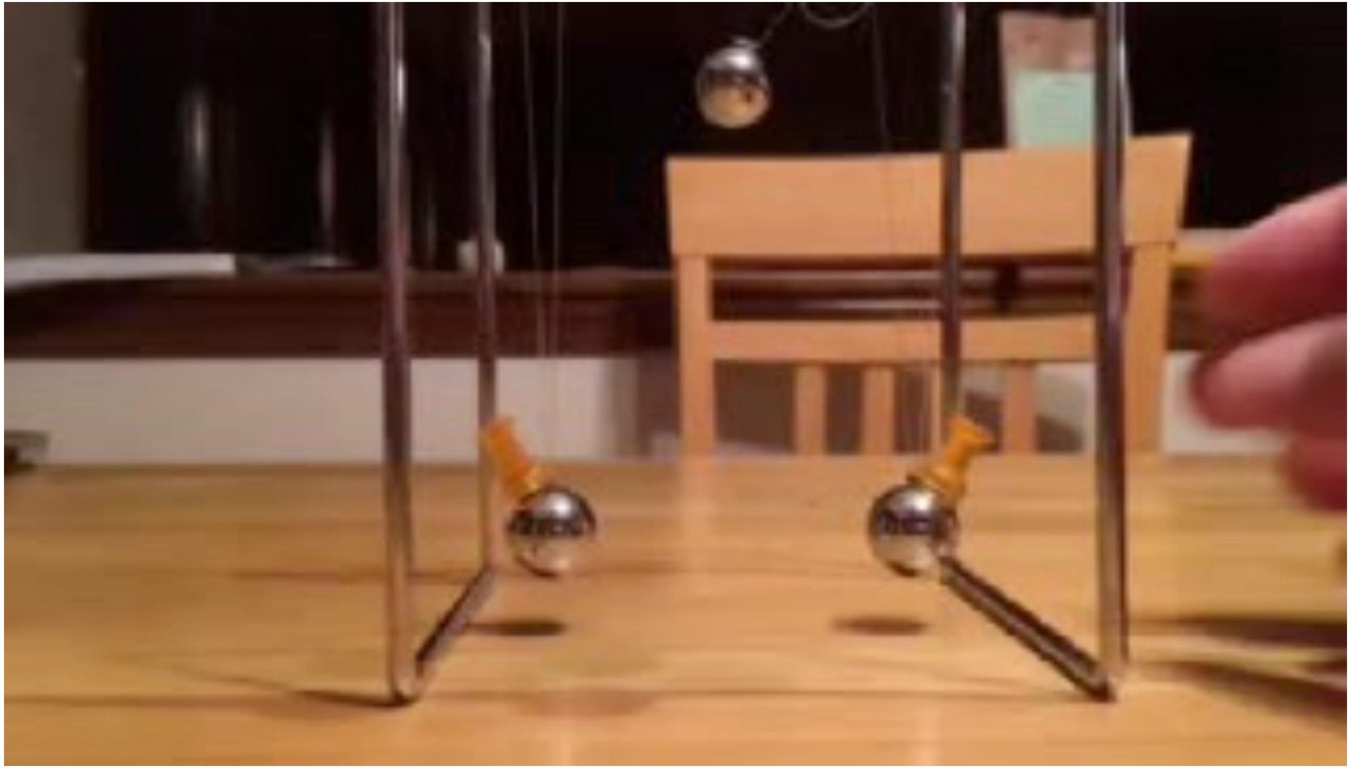
$$\frac{df}{dt} \approx 1.68\ \mathrm{GHz/year} \left(\frac{g_\gamma}{0.36}\right)^4 \left(\frac{f}{1\ \mathrm{GHz}}\right)^2 \left(\frac{\rho_0}{0.45\ \mathrm{GeV/cc}}\right)^2 \cdot \left(\frac{5}{SNR}\right)^2 \left(\frac{B_0}{8\ \mathrm{T}}\right)^4 \left(\frac{V}{100\mathrm{l}}\right)^2 \left(\frac{Q_L}{10^5}\right) \left(\frac{C_{010}}{0.5}\right)^2 \left(\frac{0.2\ K}{T_{sys}}\right)^2$$

Power transfer from axion field to cavity field

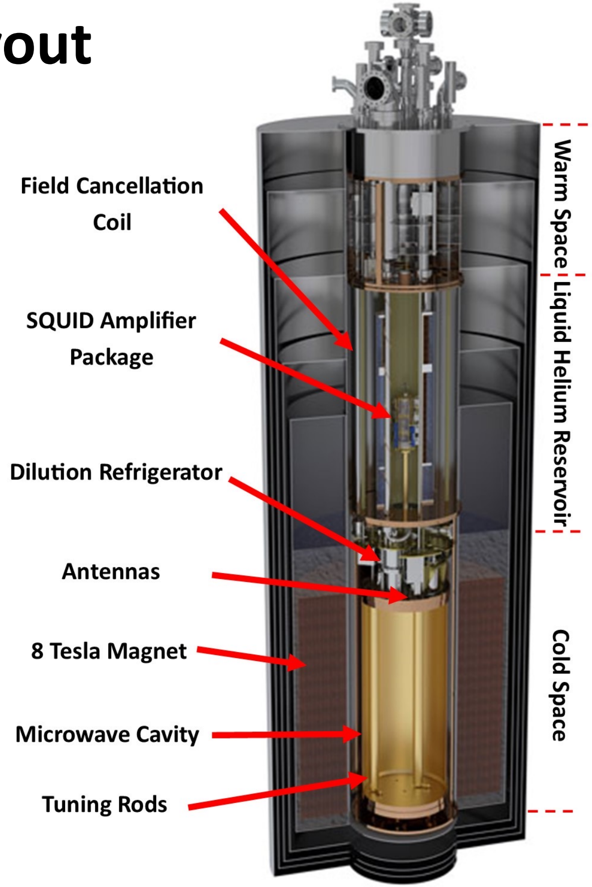
<u>Weak coupling</u>
Takes many swings to fully transfer the wave amplitude.

Number of swings is equivalent to cavity *Quality factor (Q)*.

Narrowband cavity response → iterative scan through frequency space.

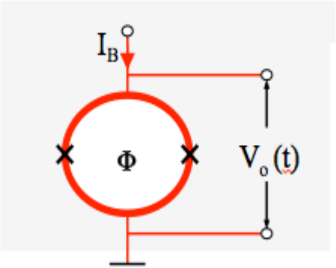


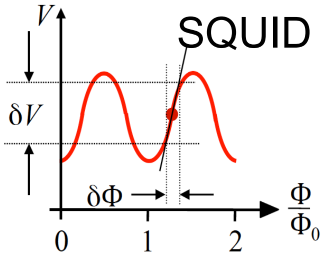
ADMX experimental layout

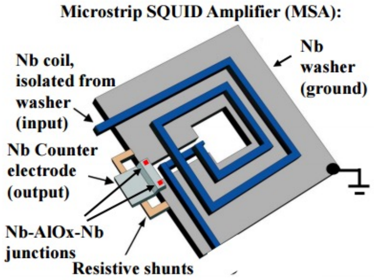


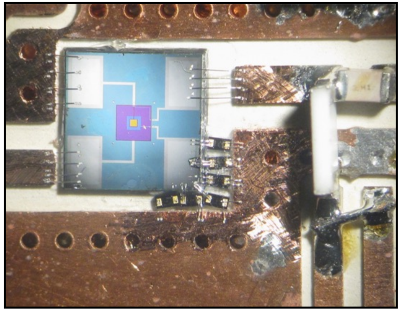
Enabling Technology: Microstrip SQUID Amplifier (MSA)

- Voltage biased SQUID loop
- Flux-to-Voltage Transducer

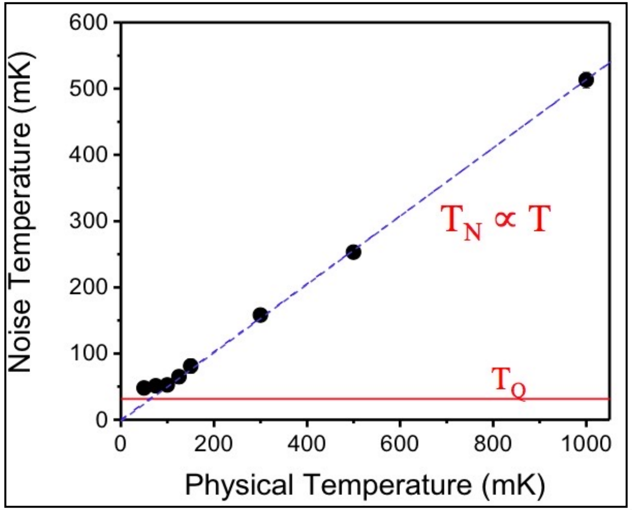


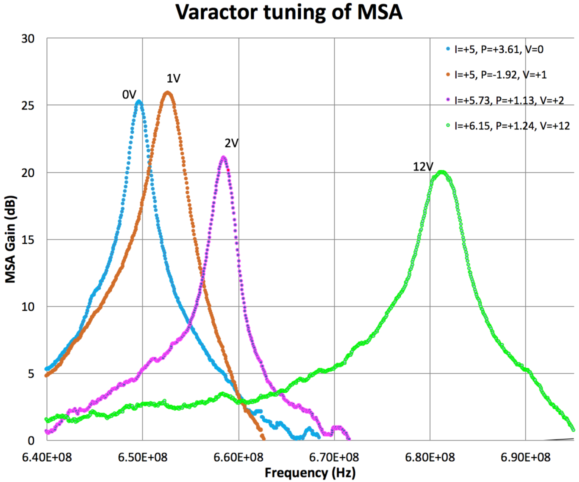






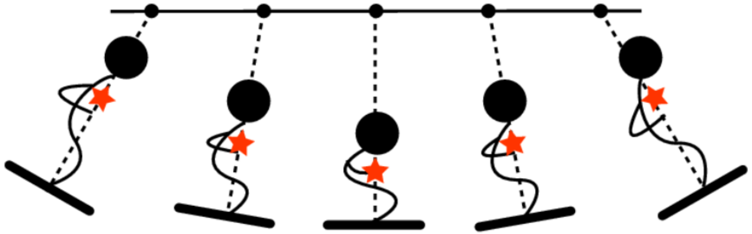
Prof. John Clarke



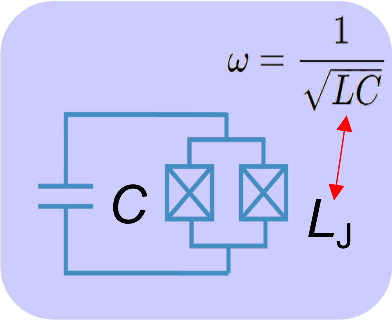


Josephson Parametric Amplifiers (JPAs)

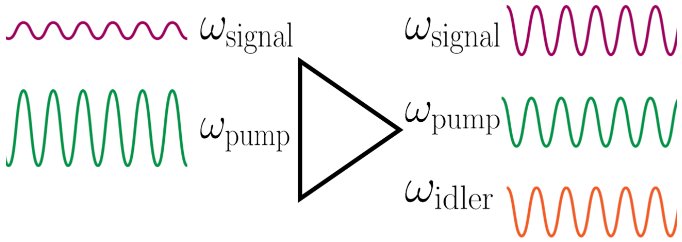
- JPA's provided by Irfan Siddiqi's group at UC Berkeley

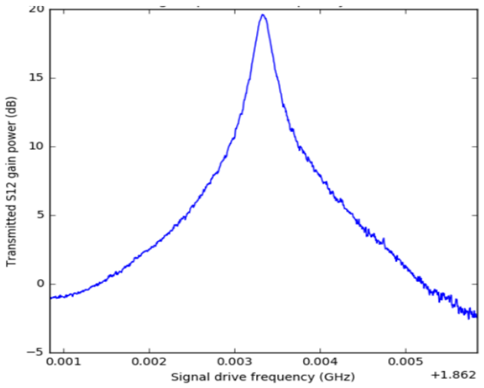


Classic example of parametric amplification is a child on a swing



Prof. Irfan Siddiqi





High gain achievable at JPA resonance.

- Anharmonicity leads to energy transfer from the pump tone to the signal tone.

*figures courtesy of Shahid Nawaz

Receiver Chain with MSA or a JPA

Injection of swept power & fake axions

Reflection to look at antenna coupling

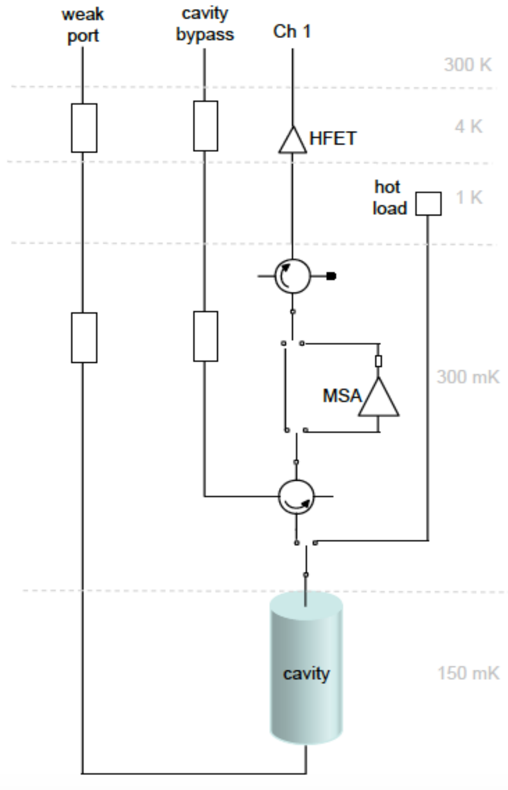
Hot / Cold load:
Measure system noise temperature by staring at thermal source with same microwave path

MSA is a two-port device

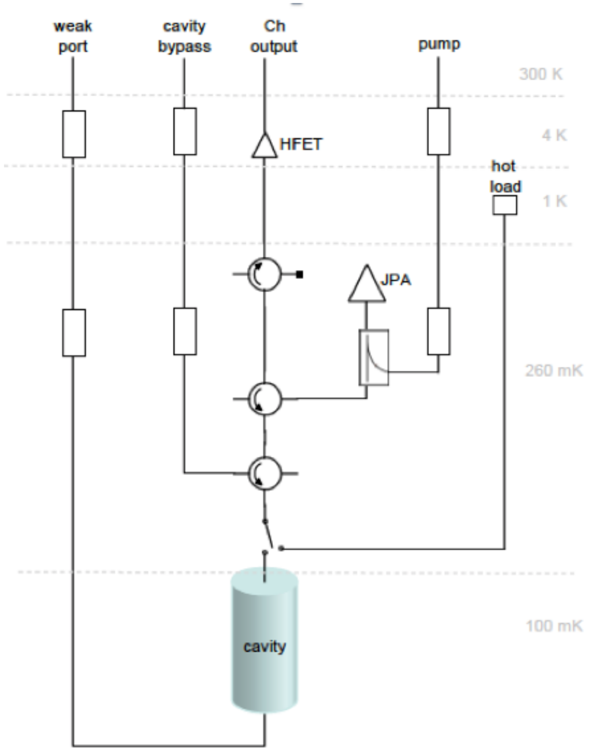
JPA operates in reflection mode

First ADMX operations used MSA

Transitioned to using JPAs & TWPA

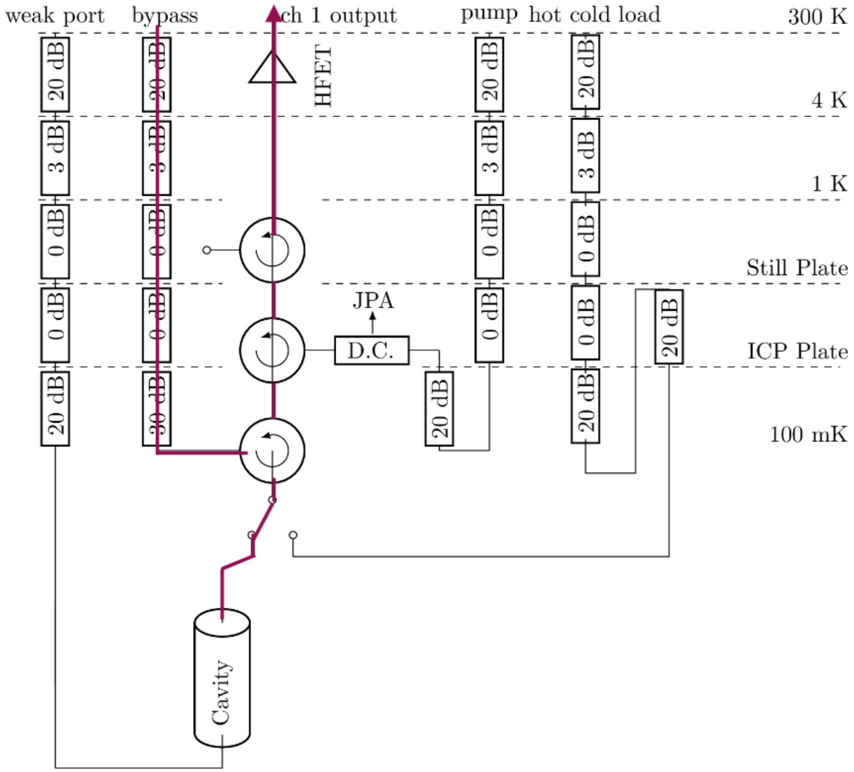


MSA signal layout

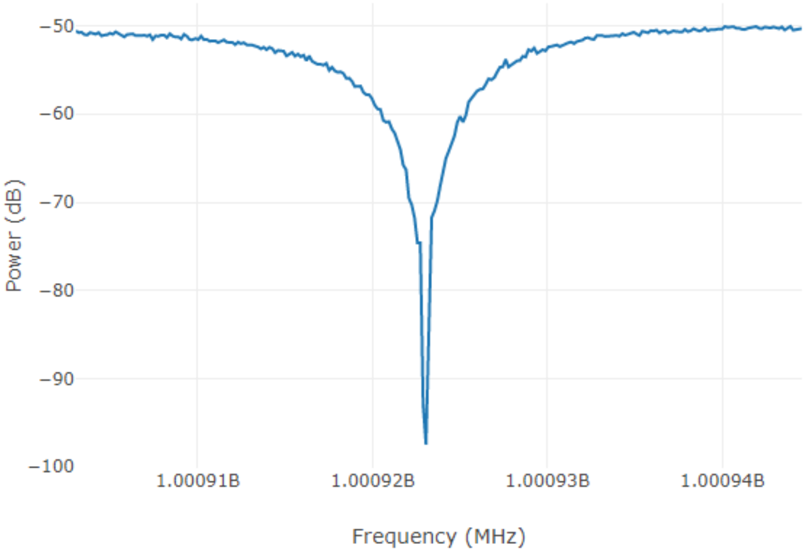


JPA signal layout

Modes of operations



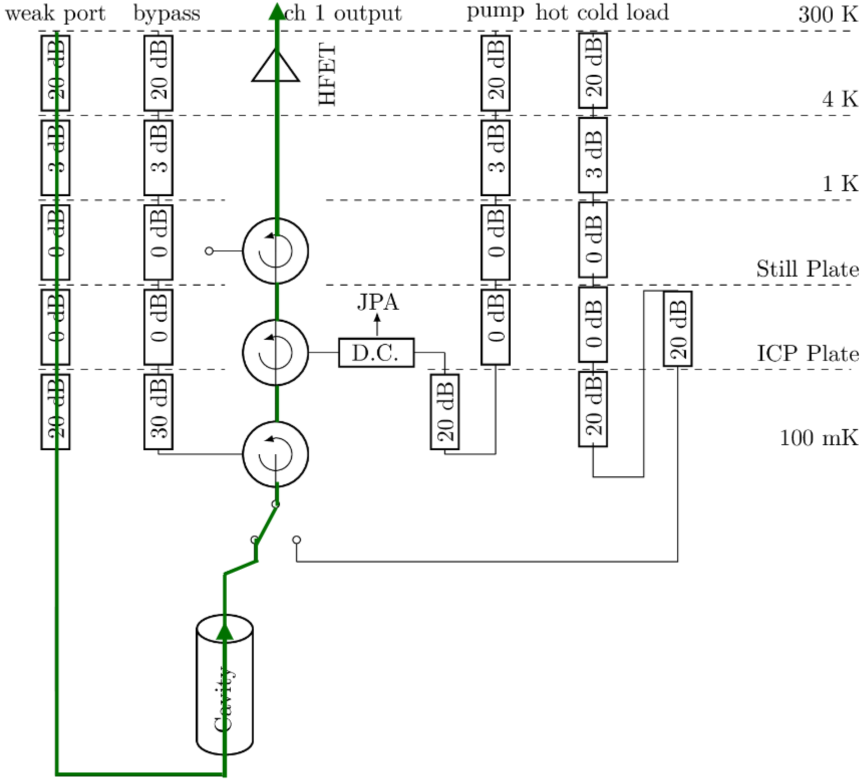
Reflection Measurements

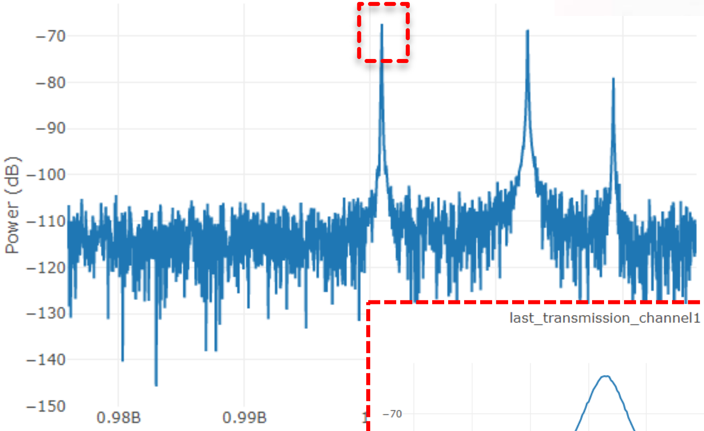


Gives antenna coupling

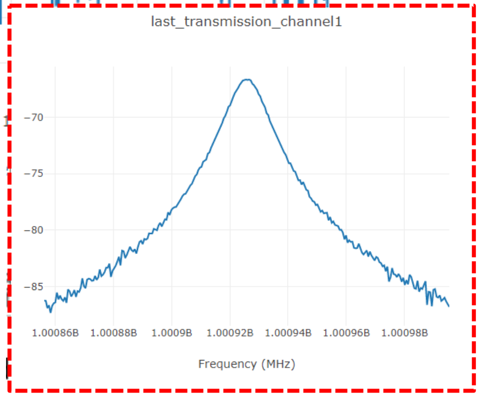
Needed to understand how much power comes from cavity

Modes of operations





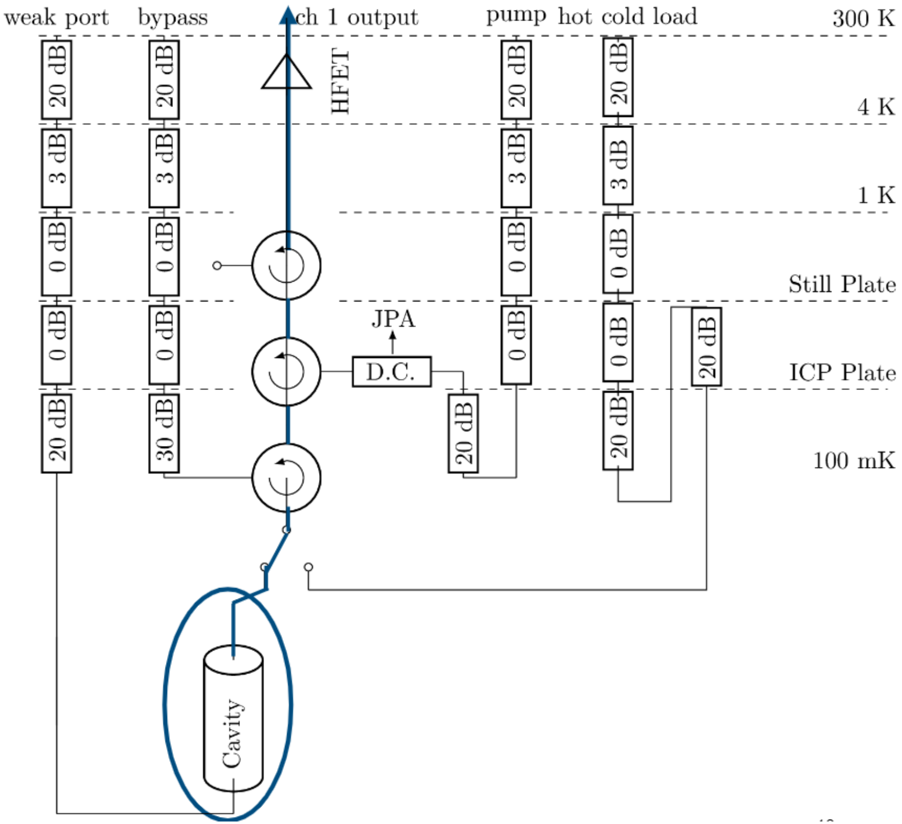
Transmission



Quality Factor & Frequency

Independent measure of resonance
Also used for synthetic axion injection (RF tones)

Modes of operations



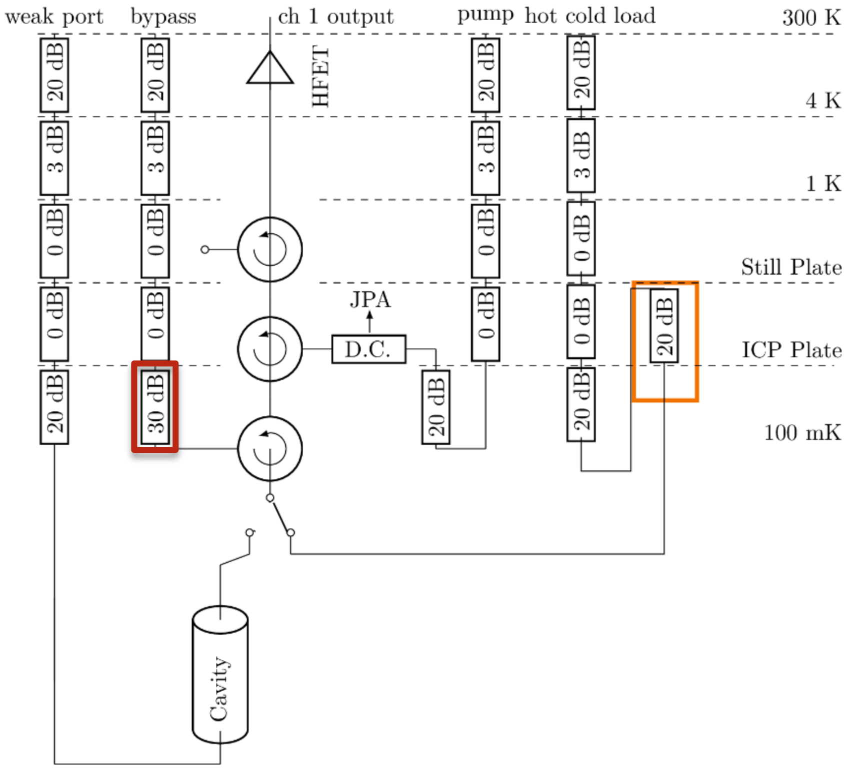
Data-Taking Mode

- Lowest attenuation on the output line
- Highest attenuation on the input lines
- Signal path in blue. Weak port is terminated unless SAG is being injected.

Majority of time spent here collecting data

*SAG: Synthetic Axion Generator

Modes of operations

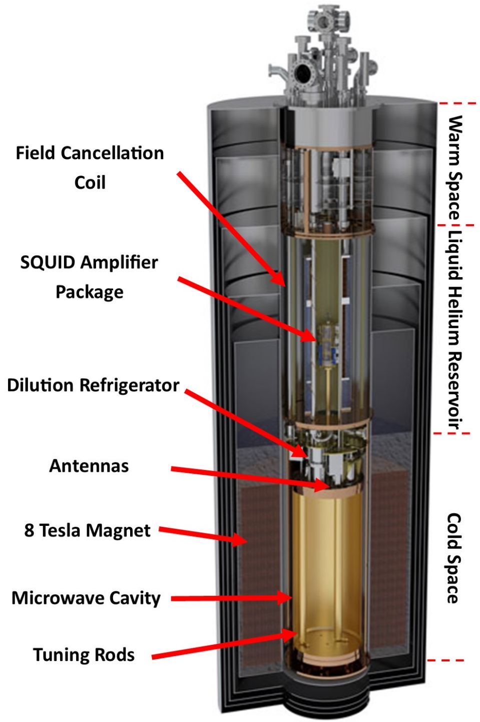


Noise Calibration Mode

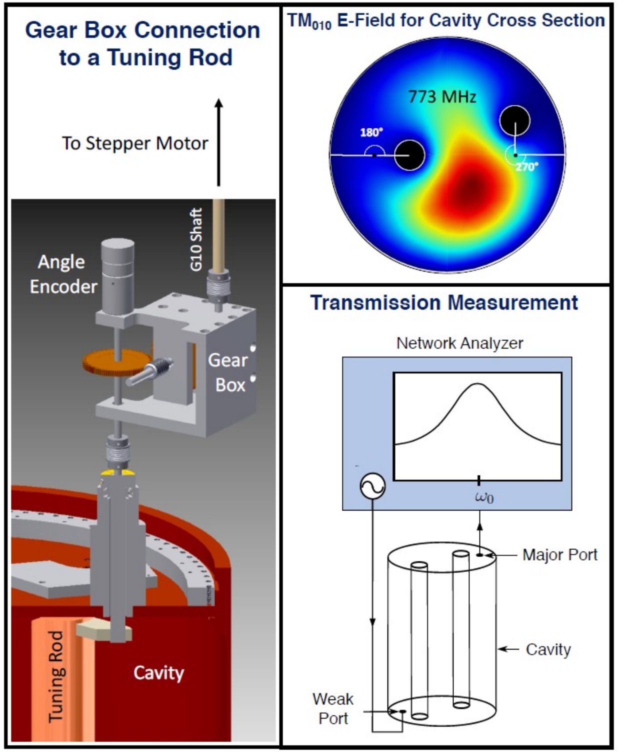
- Receiver chain provides means for measuring key RF parameters, such as quality factor
- Two types of noise measurement
- 1) Heating of the 'hot-load' via dc current (by design)
- 2) Heating of the quantum amplifier package via an RF switch

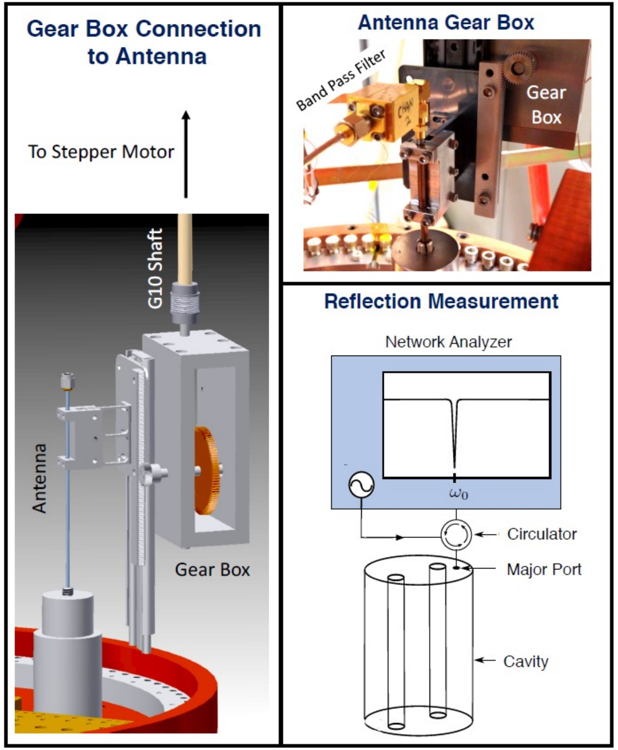
Performed semi-regularly (every few months)

ADMX Run 1C: Tuning & Coupling



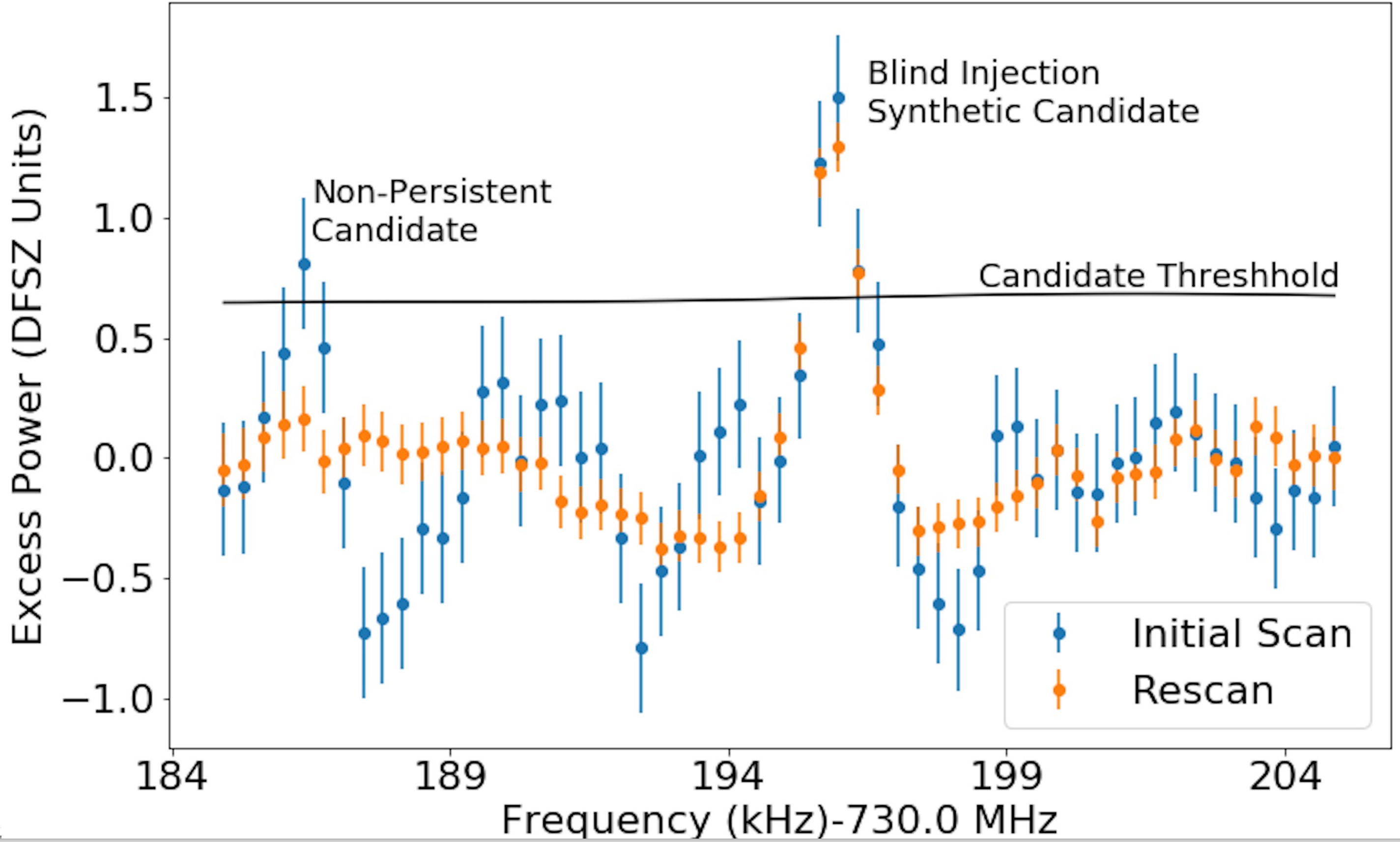
Cavity 1B



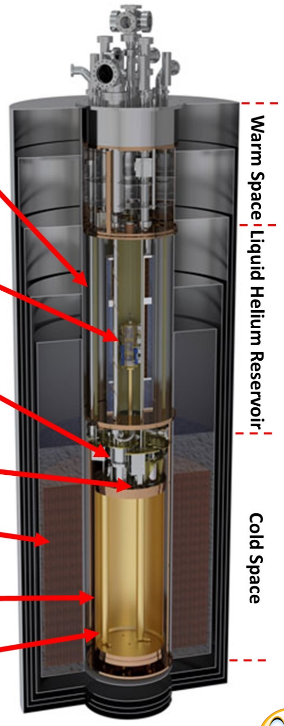


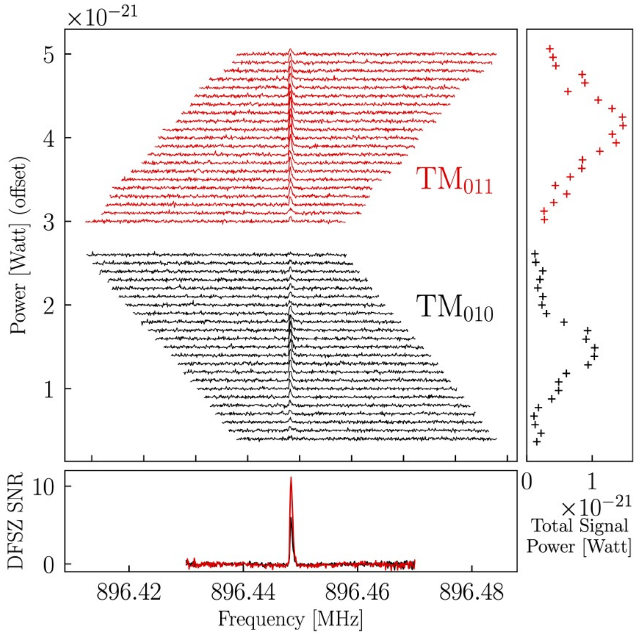
ADMX Gen-2 2018 (run 1B): Example Axion Candidates!

- Initial scan revealed 2 candidates above threshold.
- Subsequent rescan showed that there was one remaining candidate.
- Blind-injection team revealed it was a synthetic axion signal injected into the cavity.



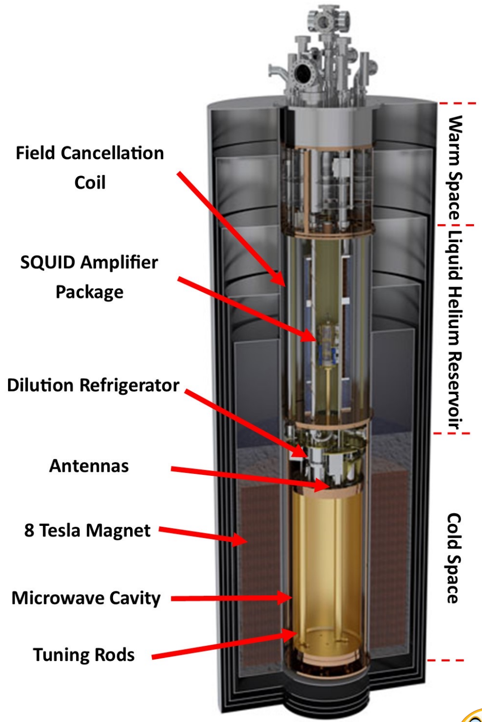
ADMX Run 1C: Persistent Signal at 896.45 MHz!

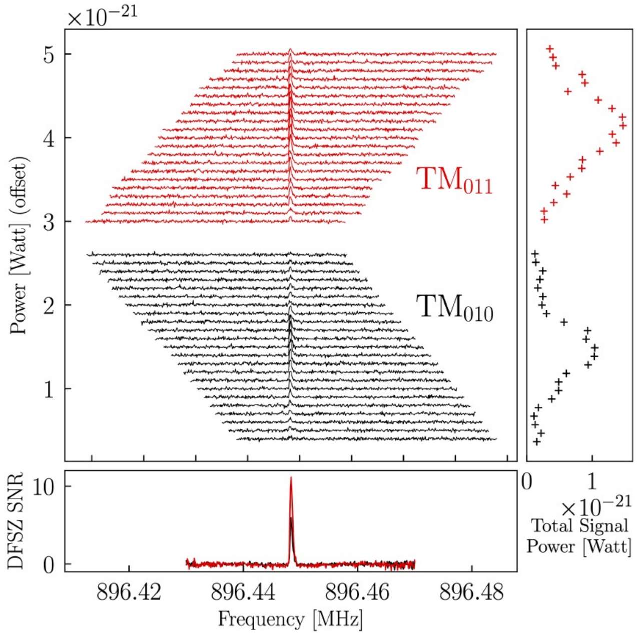


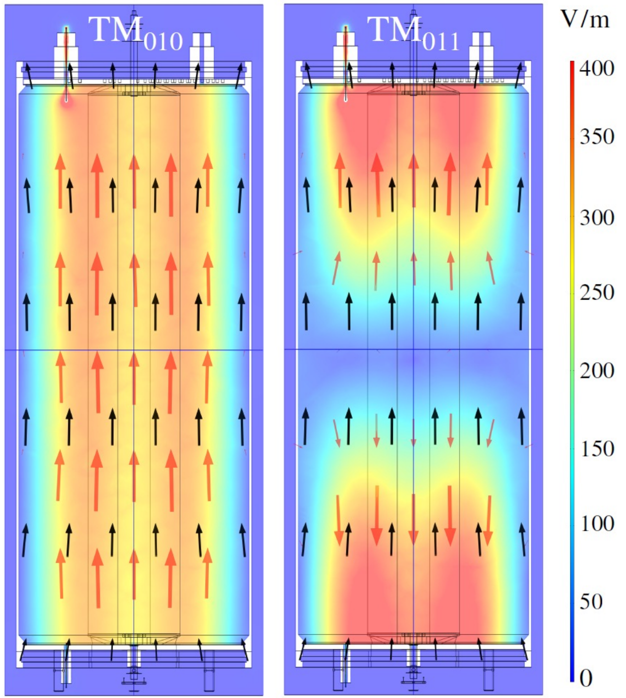


Signal had line-shape consistent with axion!
Power went away off resonance (not RFI)!

ADMX Run 1C: Persistent Signal at 896.45 MHz!







Signal had line-shape consistent with axion!
Power went away off resonance (not RFI)!

Seen in TM_{011} mode as well
Fake axion from Blind Injection team

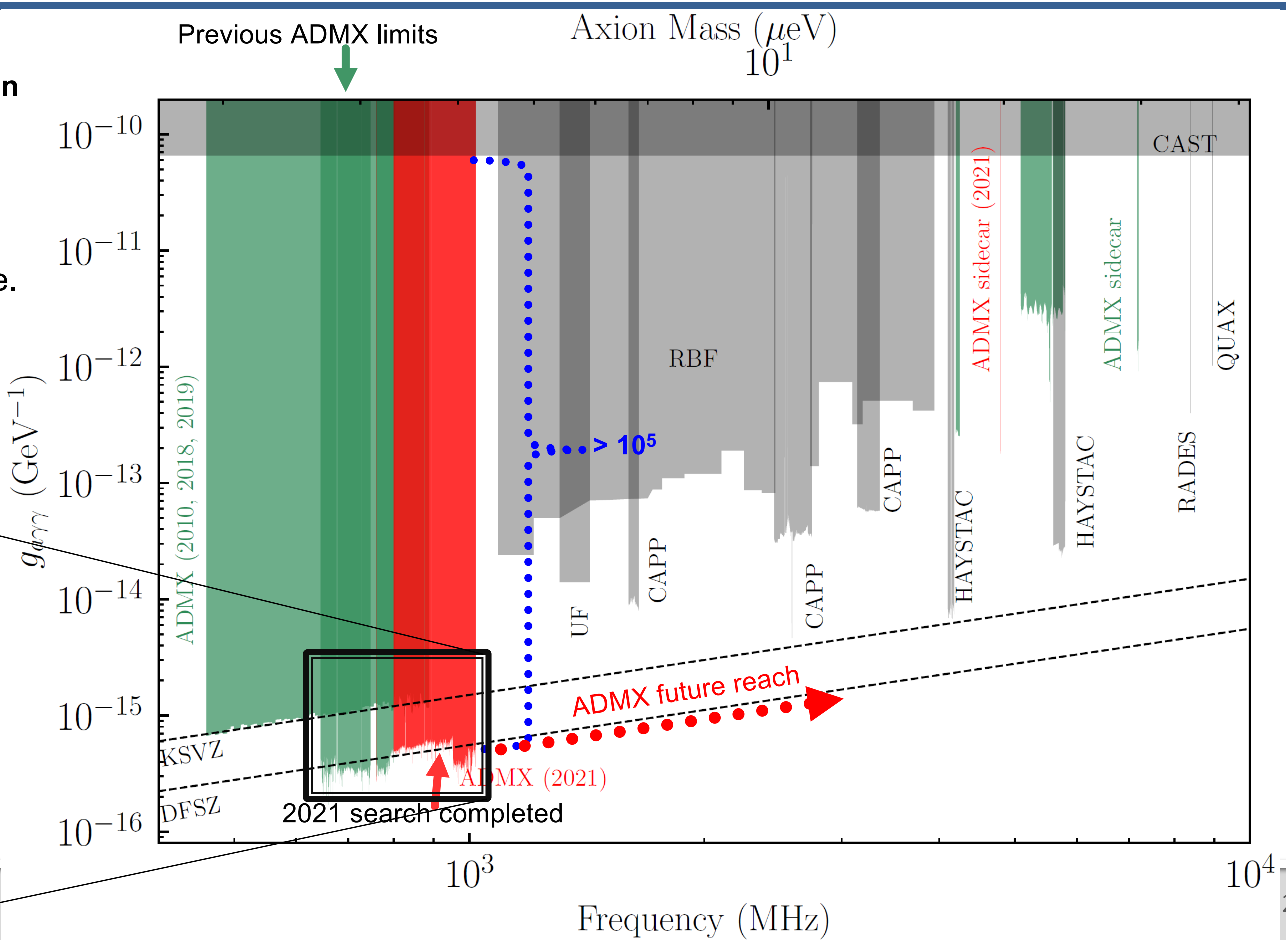
ADMX most recent published data covered new dark matter masses

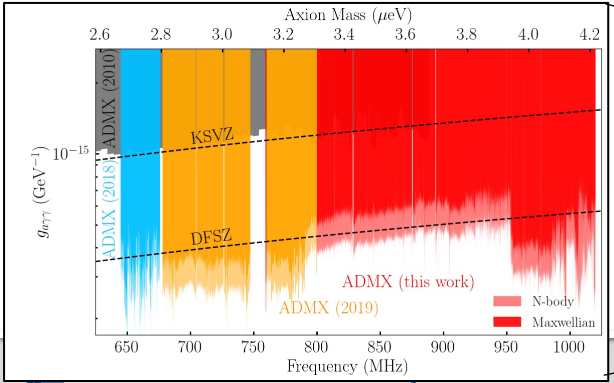
2019-2020 data run

Search for "Invisible" Axion Dark Matter in the 3.3-4.2 μeV Mass Range:
[Phys. Rev. Lett. **127**, 261803]

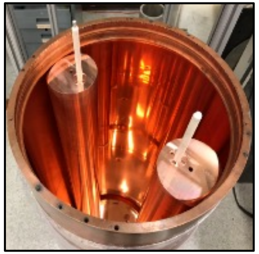
Includes mass range never explored by any dark matter haloscope search before.

Currently scanning with lower noise to reach DFSZ sensitivity

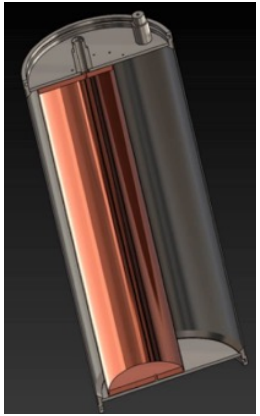




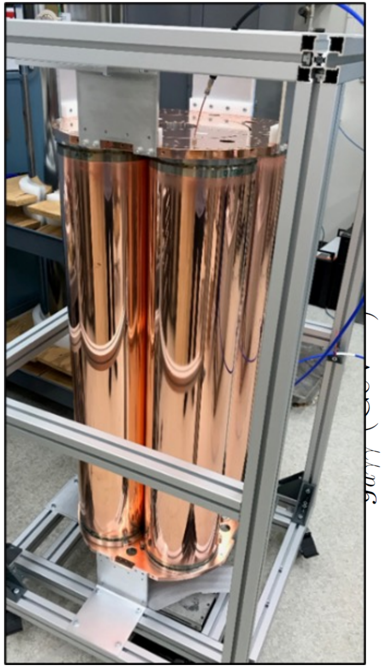
ADMX



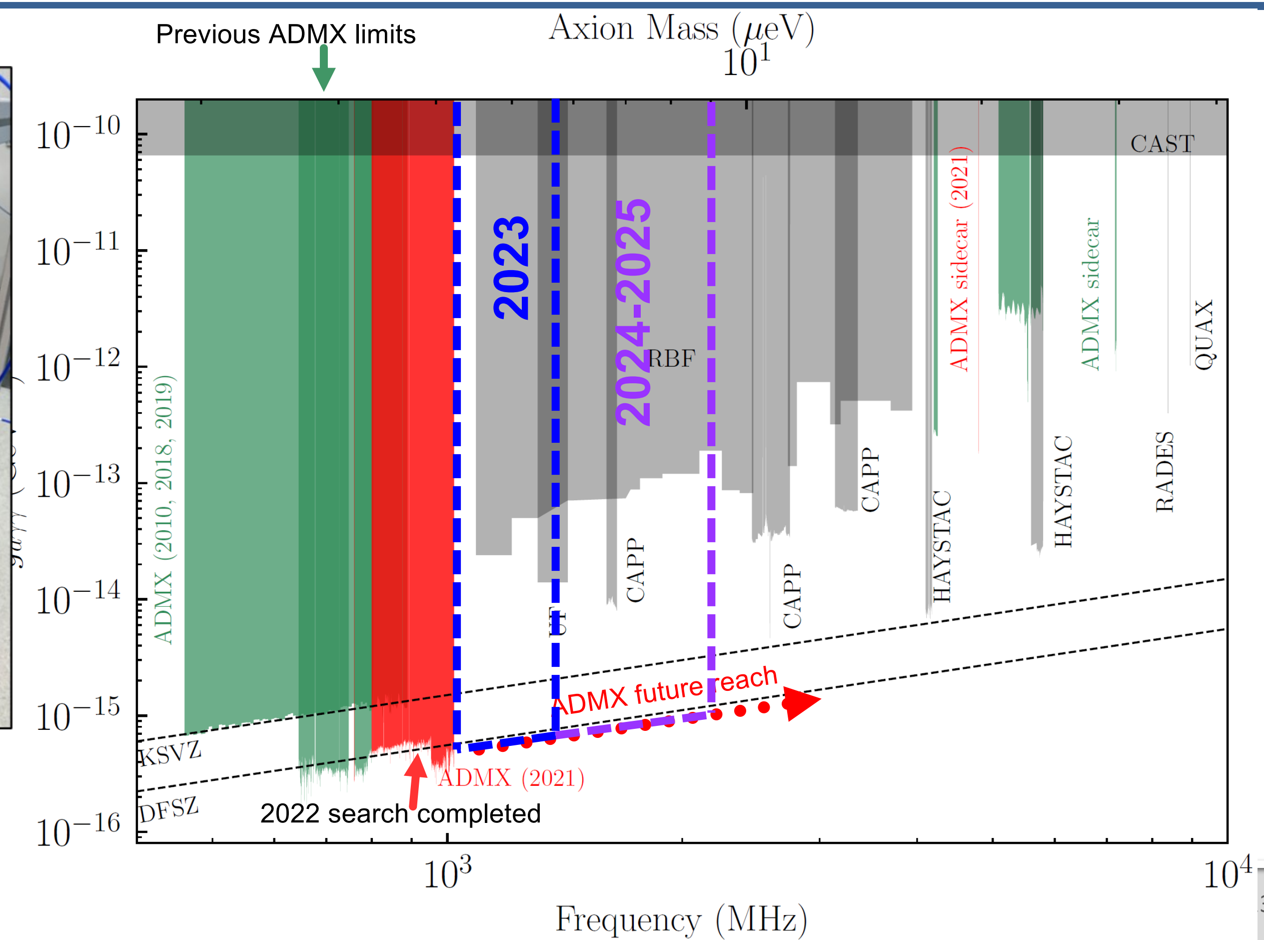
Cavity 1C
800-1020 MHz



Cavity 1D
1020 – 1400 MHz

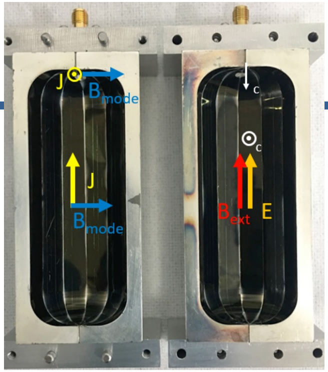


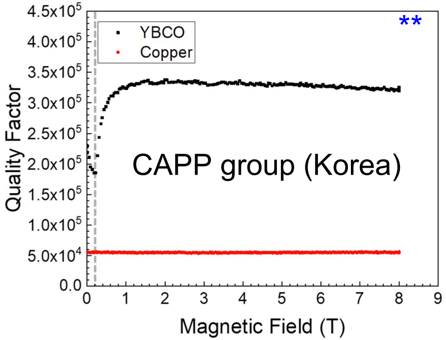
Cavity 2A (1400 - 1900 MHz)
2B (1900 – 2200 MHz)

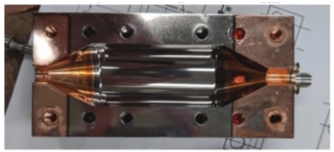


Quality Factor Enhancement

- Q_{Loaded} of copper ~ 40k below 4K for 2-4 GHz scale cavities.
- Superconducting cavities can have $Q > 10^{10}$ but become dissipative in high magnetic fields due to the dissipative flux vortices motion.
- Recent examples of cavities: NbTi in QUAX* and YBCO in CAPP**
- Not baseline but, if successful, **could be applied directly as coatings** to cavity inner surfaces to cut run-time and/or increase sensitivity.
- Current clamshell design allows no required change to mechanical design.



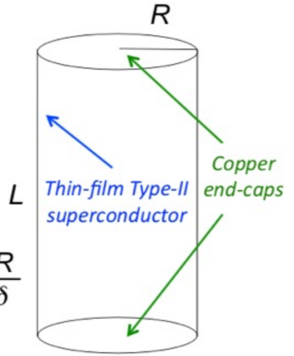


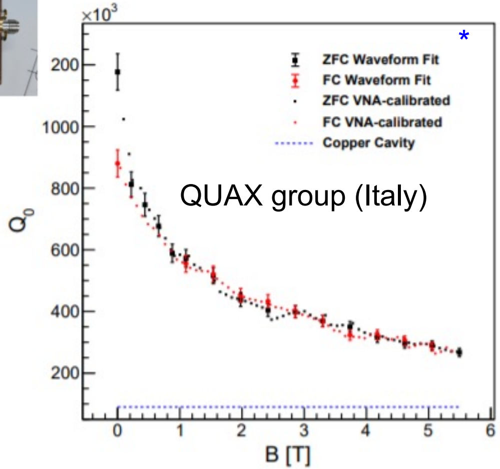


$$Q^{Copper} = \frac{L/R}{1 + L/R} \cdot \frac{R}{\delta}$$

$$\boxed{\frac{Q^{Hybrid}}{Q^{Copper}} = \left(1 + \frac{L}{R}\right)}$$

(a) $$Q^{Hybrid} = \frac{L/R}{1 + \cancelto{0}{L/R}} \cdot \frac{R}{\delta}$$





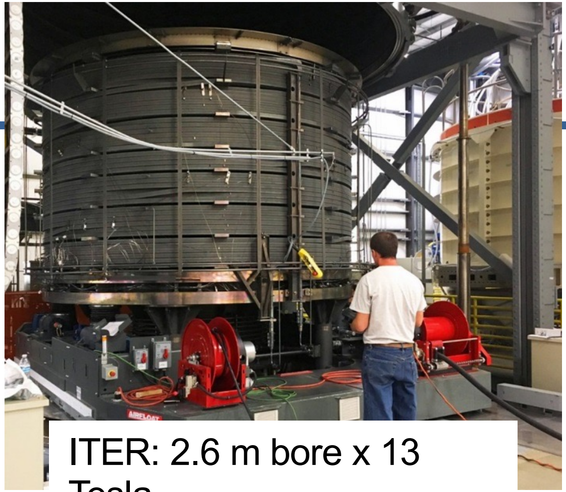
*10.1103/PhysRevD.99.101101 **arXiv:2103.14515v1

[1] 10.1103/PhysRevD.99.101101
QUAX experiment (NbTi coated cavity)

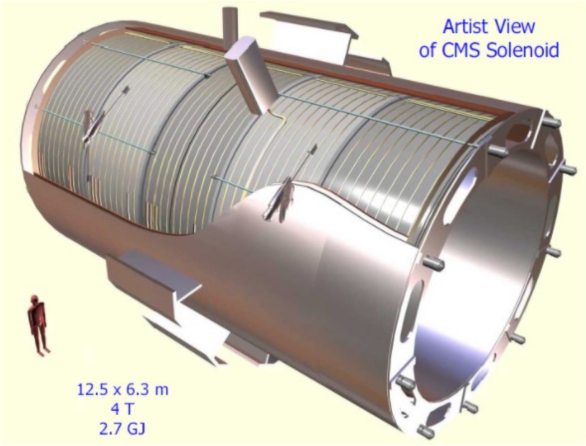
Large Solenoids

- The key metric is B^2V or stored energy
- ADMX is actually quite modest

B_0^2V (T^2m^3)	Magnet	Application/ Technology	Location	Field (T)	Bore (m)	Len (m)	Energy (MJ)	Cost ($M)
12000	*ITER CS*	*Fusion/Sn CICC*	*Cadarache*	*13*	*2.6*	*13*	*6400*	*>500*
5300	CMS	Detector/Ti SRC	CERN	3.8	6	13	2660	>458[1]
650	Tore Supra	Fusion/Ti Mono Ventilated	Cadarache	9	1.8	3	600	
430	*Iseult*	*MRI/Ti SRC*	*CEA*	*11.75*	*1*	*4*	*338*	
320	ITER CSMC	Fusion/Sn CICC	JAEA	13	1.1	2	640	>50[2]
290	*60 T out*	*HF/HTS CICC*	*MagLab*	*42*	*0.4*	*1.5*	*1100*	
250	*Magnex*	*MRI/Mono*	*Minnesota*	*10.5*	*0.88*	*3*	*286*	*7.8*
190	Magnex	MRI/Mono	Juelich	9.4	0.9	3	190	
70	45 T out	HF/Nb_3Sn CICC	MagLab	14	0.7	1	100	14
12	ADMX	Axion/NbTi mono	U Wash	7	0.5	1.1	14	0.4
5	900 MHz	NMR/Sn mono	MagLab	21.1	0.11	0.6	40	15



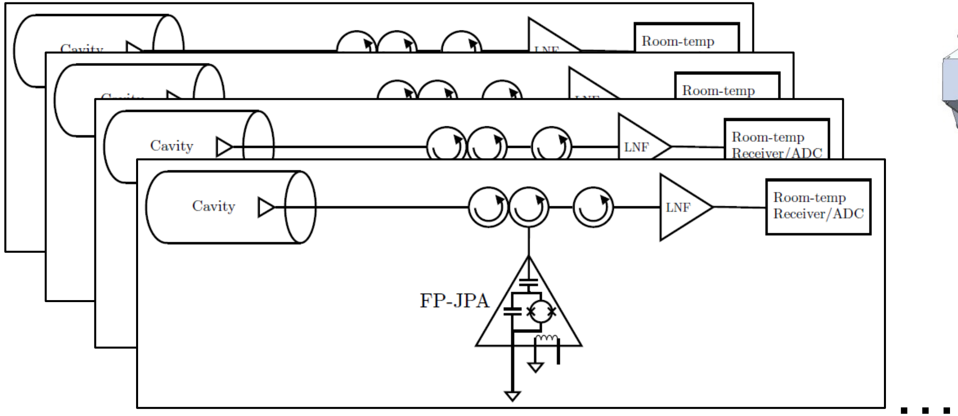
ITER: 2.6 m bore x 13 Tesla

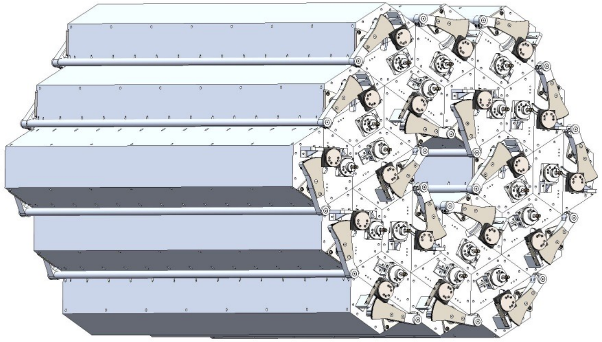


Compilation by Mark Bird, NHMFL

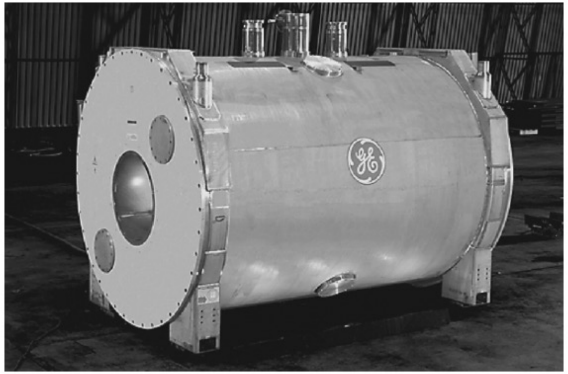
ADMX-Extended Frequency Range (ADMX-EFR)

- 18 cavities each instrumented with their own quantum amplifier chain and readout.
- In-phase amplitude combining digitally at room temperature.



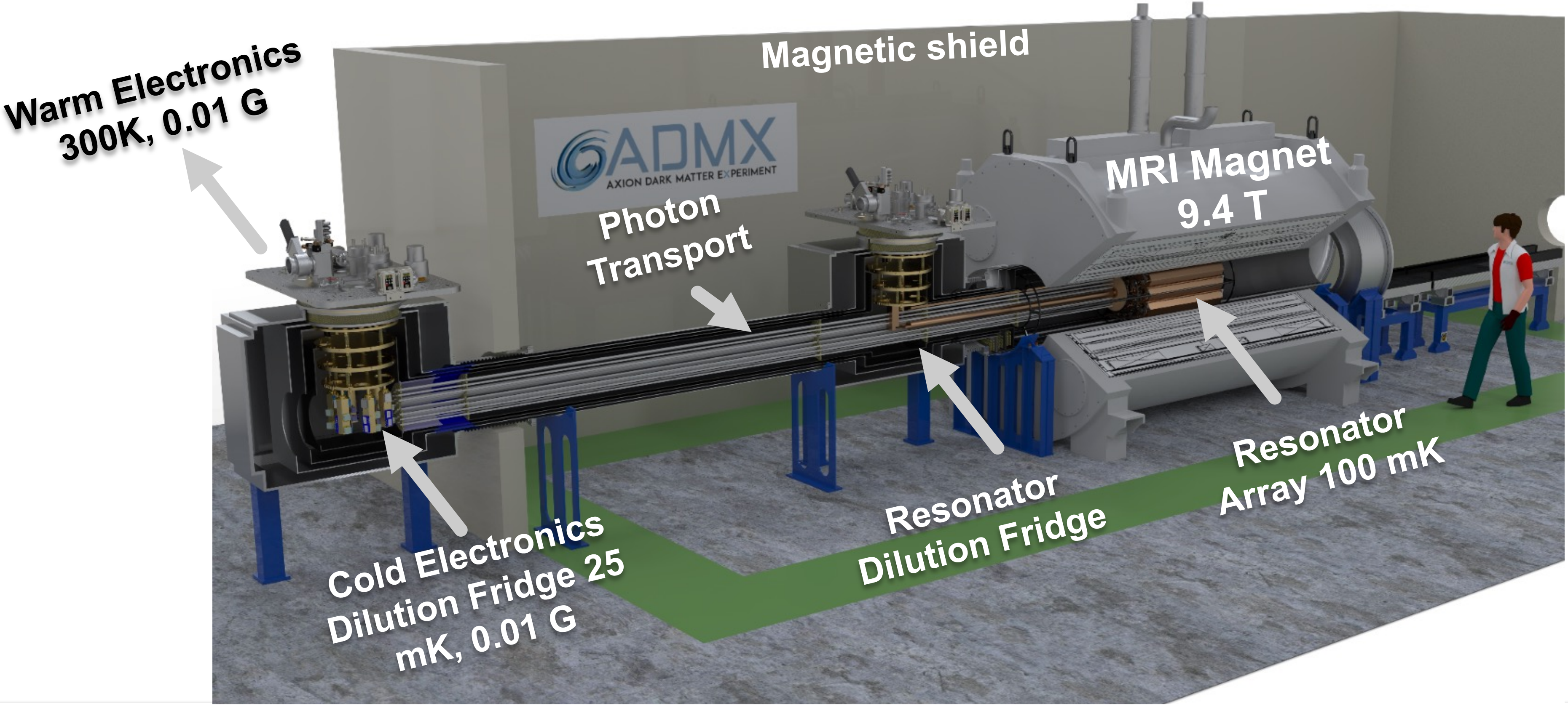


- Takes full advantage of coherence of axion signal relative to incoherent noise
- 18 x faster scanning than individual cavities
- Maximal flexibility, system repeatability and mass production.

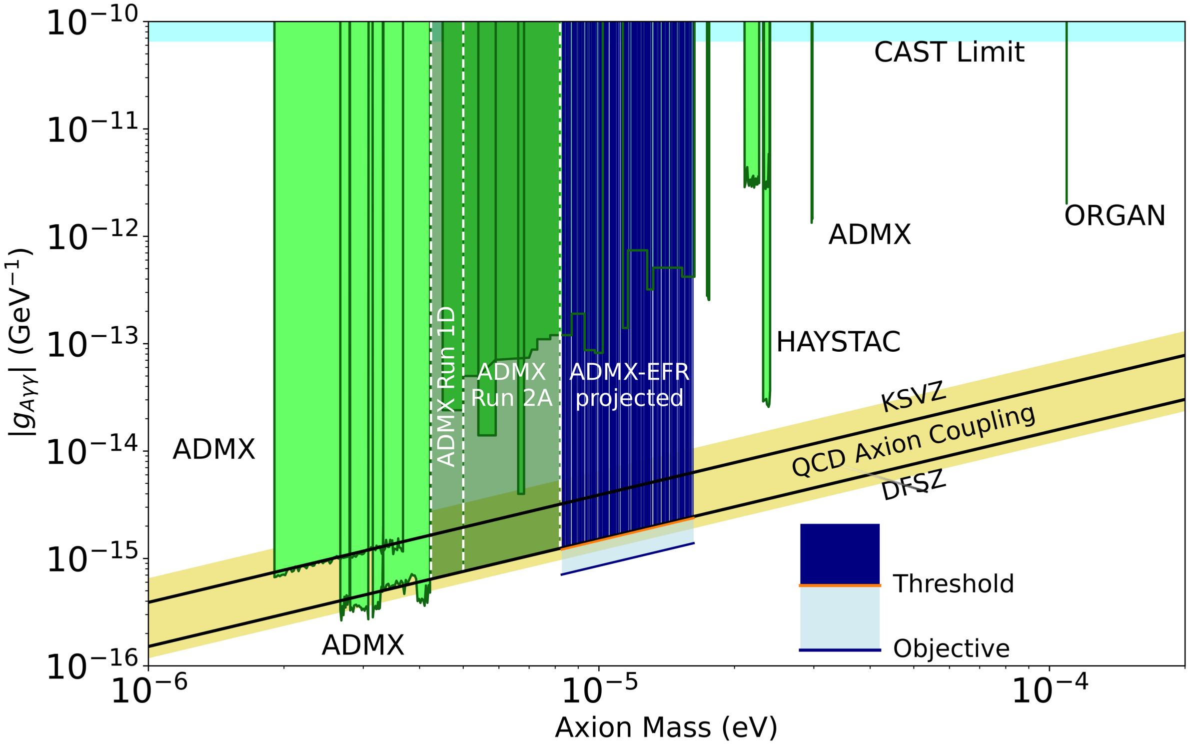


9.4 T 800 mm bore MRI magnet being moved to Fermilab

Overall ADMX-EFR System Layout



ADMX-EFR Operations: Run Times



total runtime:
3 years

Threshold:
skips mode crossings

Objective:
Includes mode crossings
Increased sensitivity reach

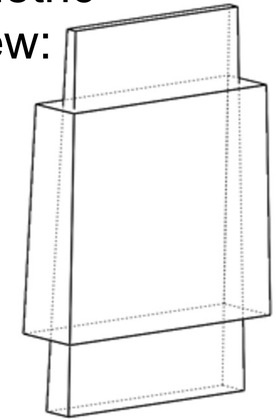
Anticipate 2 year construction FY25-FY26
Begin 3-year operations in FY27

Enhanced sensitivity / scan rate with superconducting cavities

The ADMX-VERA (Volume-Enhanced Resonant Axion) Experiment **decouples volume from resonant frequency:**

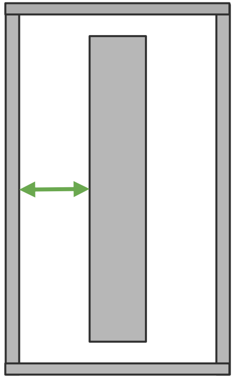
Typically for haloscopes, $\frac{\mathrm{d}\nu}{\mathrm{d}t} \sim V^2 \sim \nu^{-6}$

Isometric view:



The resonant cavity exists between an inner wedge and an outer shell.

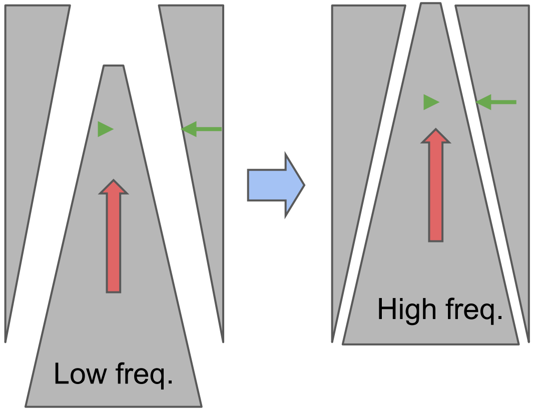
Top view:



Gap width sets TM_{010} frequency.

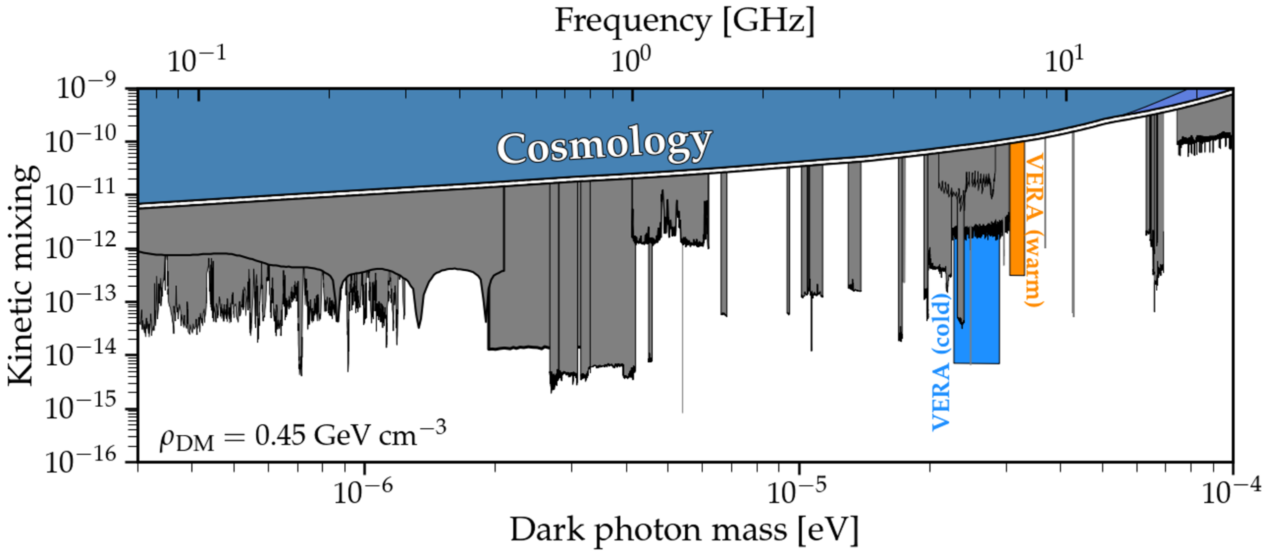
V can be scaled up by increasing length and height, keeping the gap the same.

Side view:

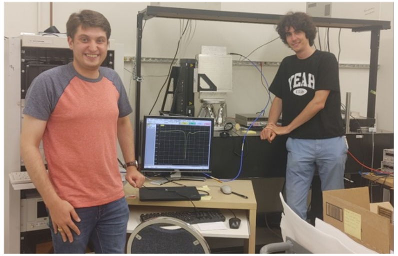


Gap width is tuned as the wedge moves vertically.

Compatible with solenoid *B* field.



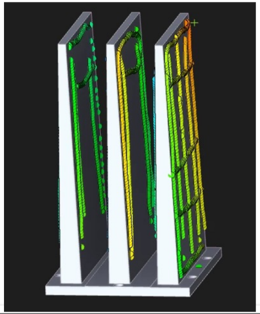
	Warm	Cold
f_0 (GHz)	7.4 – 8	5.5 – 7
V (L)	2.5	6
Q	5000	20000
T_{sys} (K)	300	0.4



Matt Withers and Taj Dyson, graduate students with the current warm dark photon haloscope.

Projected limits for the current warm run and planned cold run, 1 month of uptime.

Graduate student Sephora Ruppert is assembling a **"triple wedge" haloscope** using precision metrology.



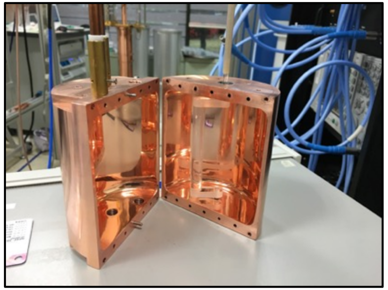
Extensions to the design such as this will make better use of the full magnet bore.

Slides provided by Taj Dyson

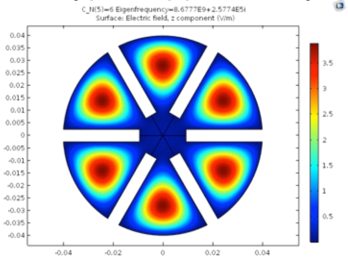
CAPP program (multiple systems)

Center for Axion and Precision Physics (CAPP) in South Korea

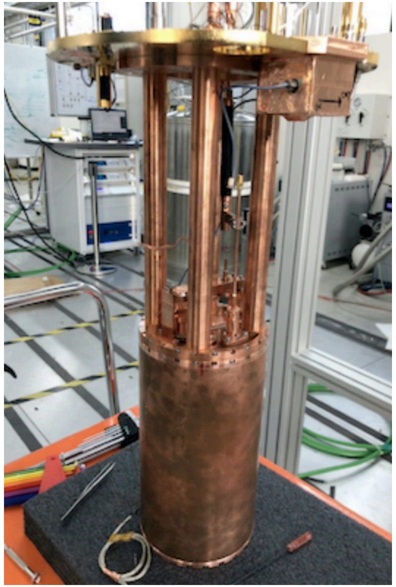
Multiple experimental efforts with new magnets and innovations such as superconducting cavities (YBCO)



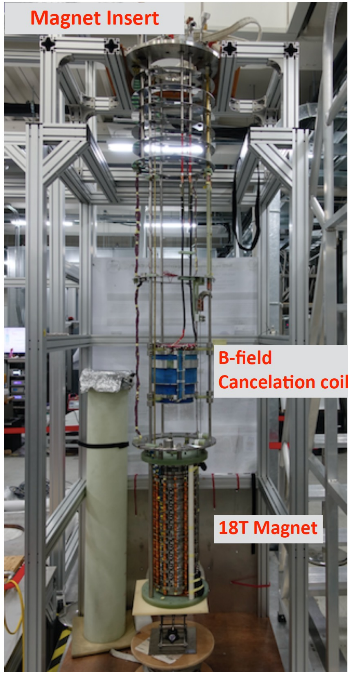
Prototype copper cavity



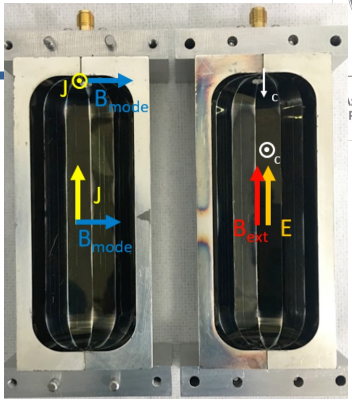
Multi-cell cavities



12 Tesla System

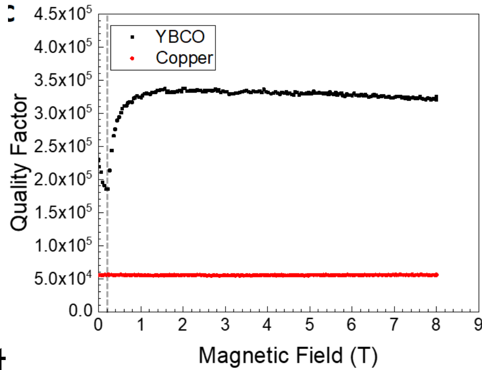


18 Tesla Magnet



YBCO superconducting cavity Demonstrated to 300k (and up)

[Phys. Rev. Applied **17**, L061005]



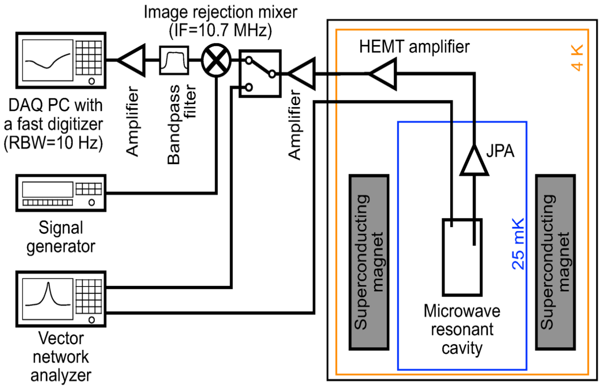
CAPP program (multiple systems)

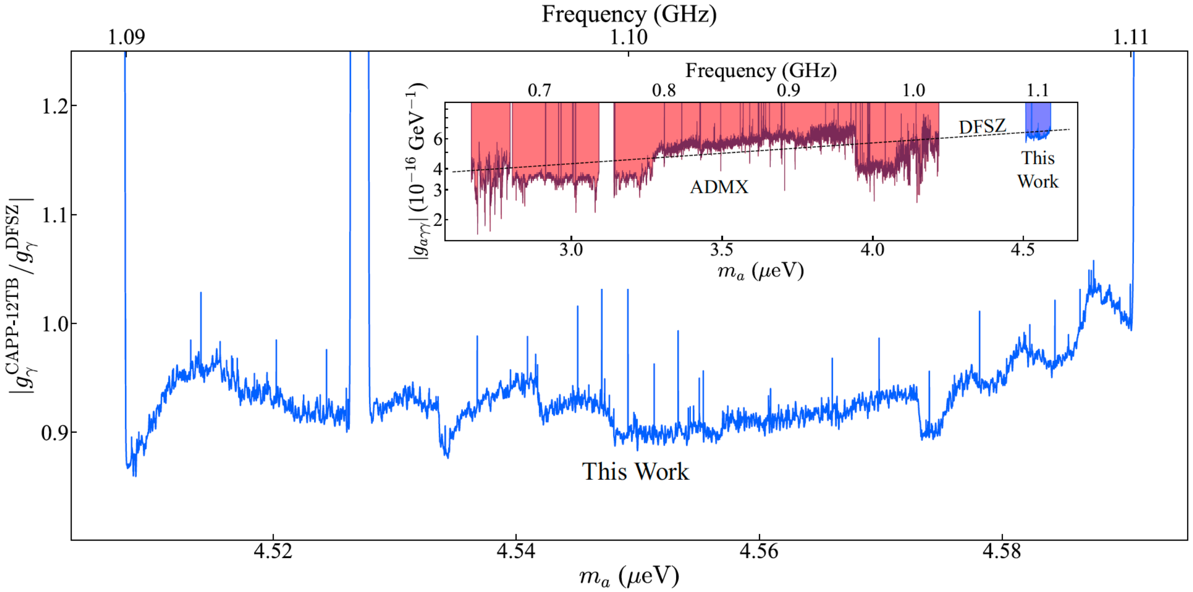
Recently demonstrated DFSZ sensitivity!
[Phys. Rev. Lett. **130**, 071002](#)

20 MHz scanned in this region
Anticipate scanning 1-2 GHz range in 2023

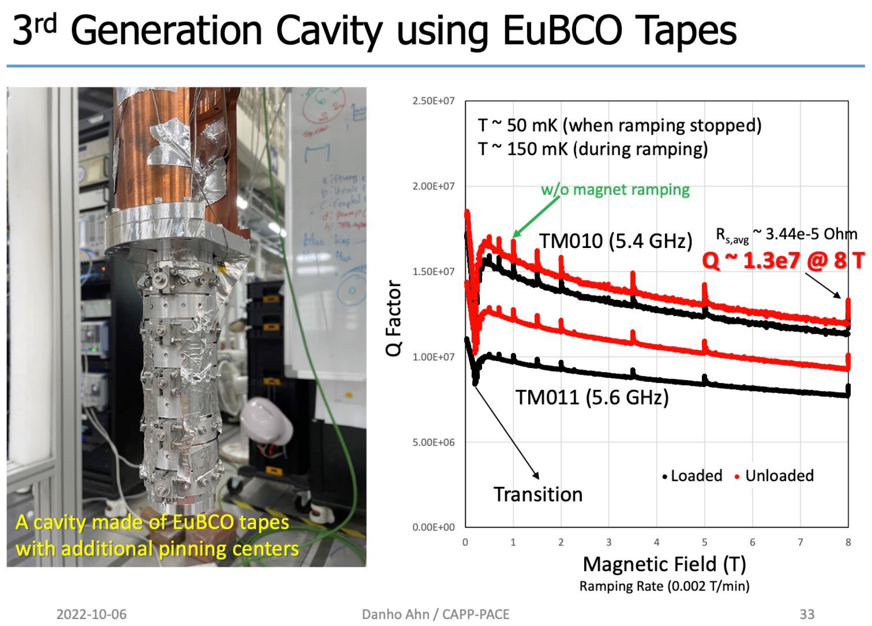
Center for Axion and Precision Physics Research

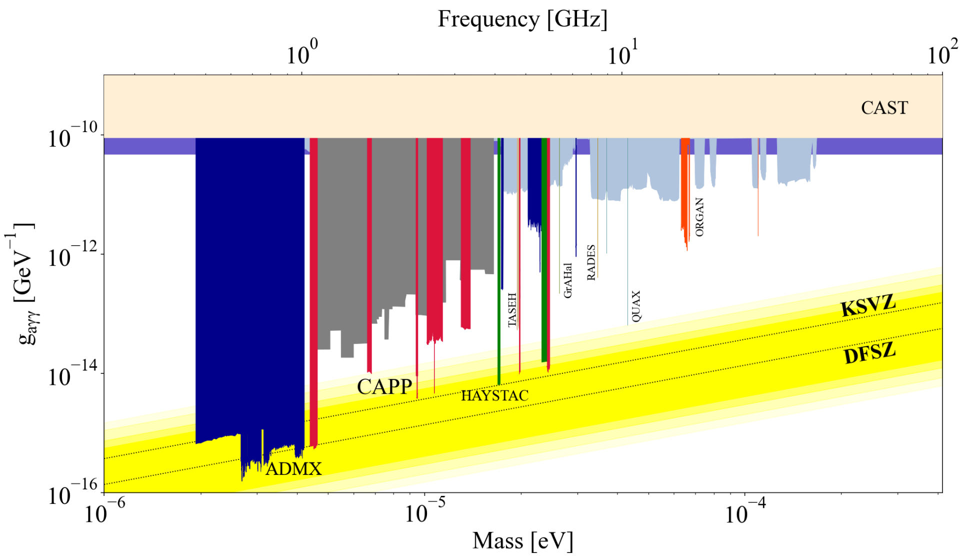
12-Tesla magnet (10.31 T averaged over cavity)
25 mK base temperature (system noise temp)





CAPP program (multiple systems)





Q ~ 13M demonstrated at 8 T!!!

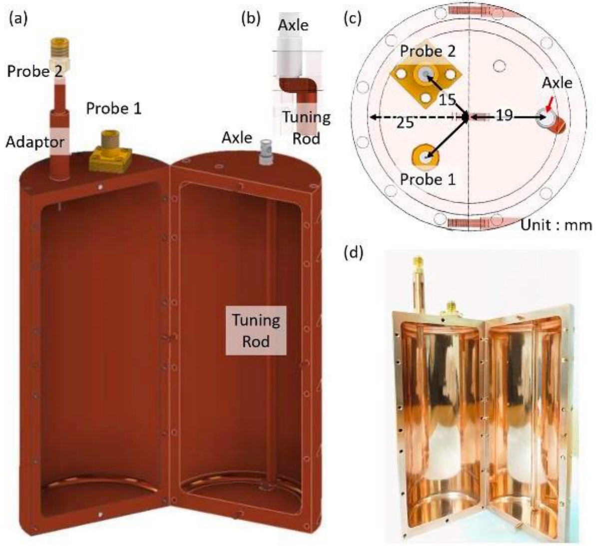
Planning to build 36-liter cavity for 12-T system

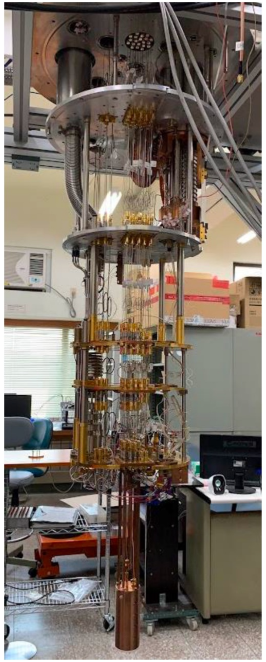
CAPP results in **red**. Multiple experiments planned over next decade.

Director Yannis Semertzidis presenting at GGI Conference next week

TASEH: Taiwan Axion Search Experiment with Haloscope

First results out last year
PHYS. REV. D 106, 052002 (2022)





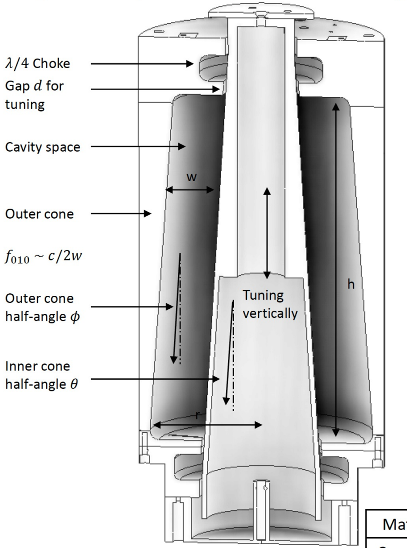
Existing cryostat and magnet in NCU

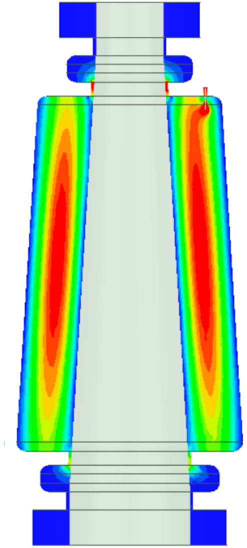
Bluefors DR:
- base: 27 mK

AMI magnet:
- field: 8 T
- bore: 6.8 mm

Future: Developing conical shell cavity system for higher frequencies (inspired by C. Kuo)

Design model (assisted by HFSS simulation)

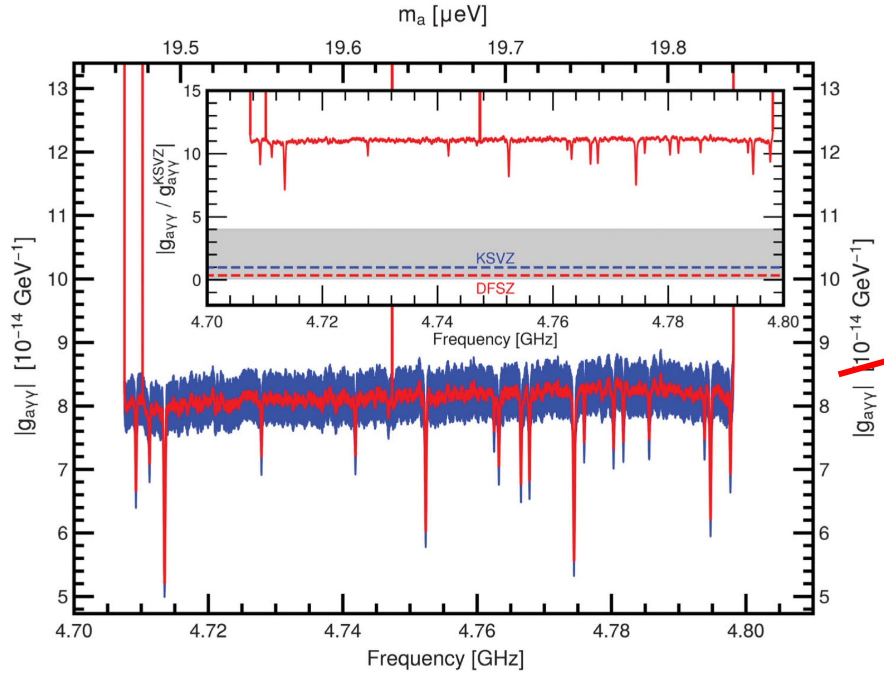


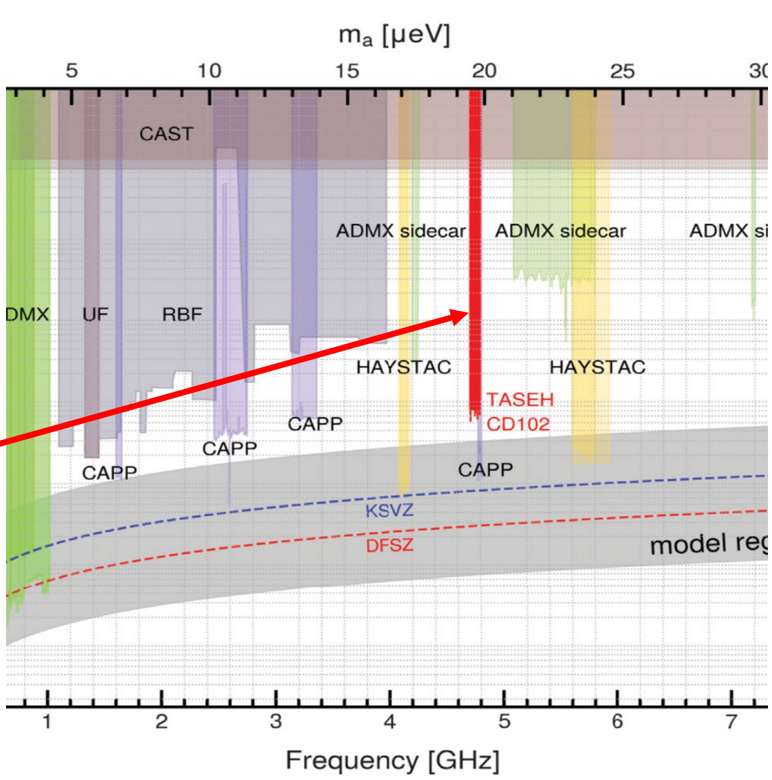


Targeting 4.75 GHz
223 MHz tunable range for 24 mm travel

TASEH: Taiwan Axion Search Experiment with Haloscope

First results out last year
PHYS. REV. D 106, 052002 (2022)





ORGAN: Oscillating Resonant Group AxioN Experiment

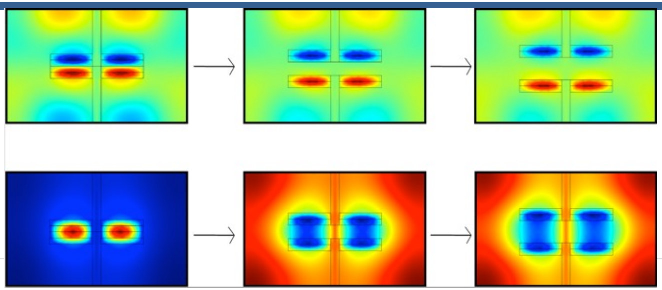
THE UNIVERSITY OF WESTERN AUSTRALIA

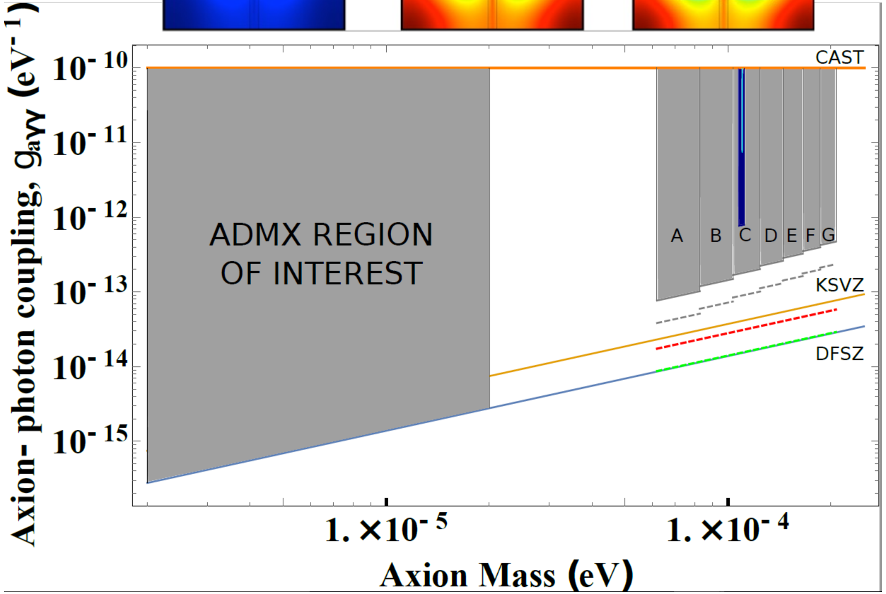
Exploring new cavity geometries and modes with sapphire disks.

Initial experiment aimed at 26-27 GHz.
Ultimate goal is to search 60-200 microeV

Phase 1
- targeted 1 GHz scans ~month(s) scale
- TM010 tuning rod
- HFET Amps

Phase 2
- wider scans with enhanced sensitivity, broken into 5 GHz chunks, ~year scale
- Novel resonators / better Q
- Better Amps / Readout





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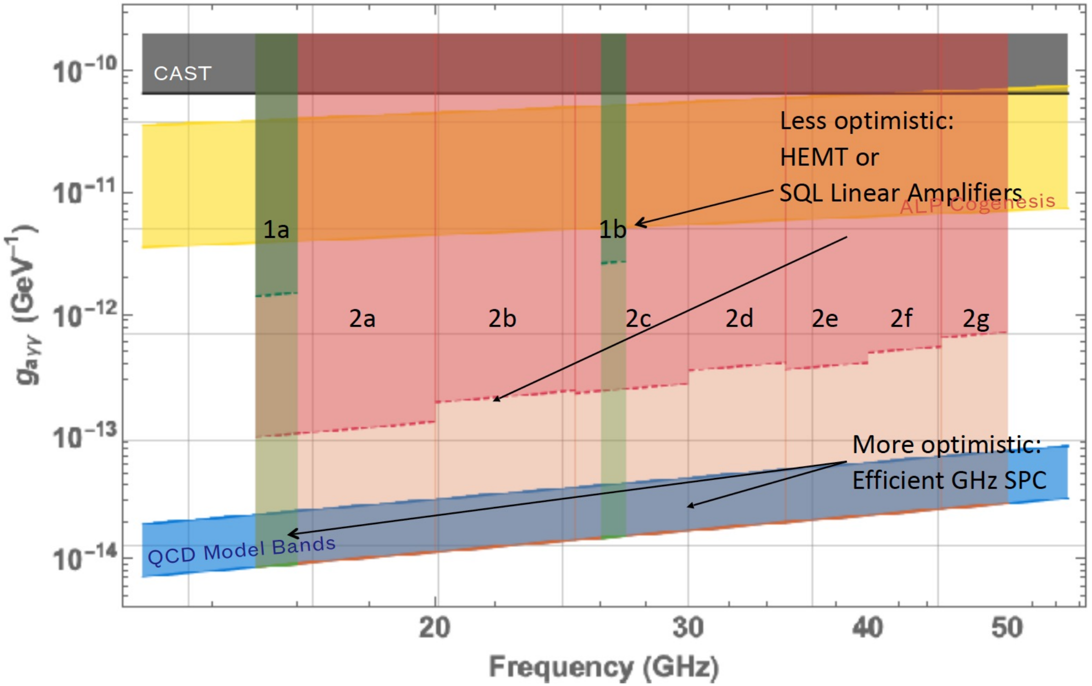
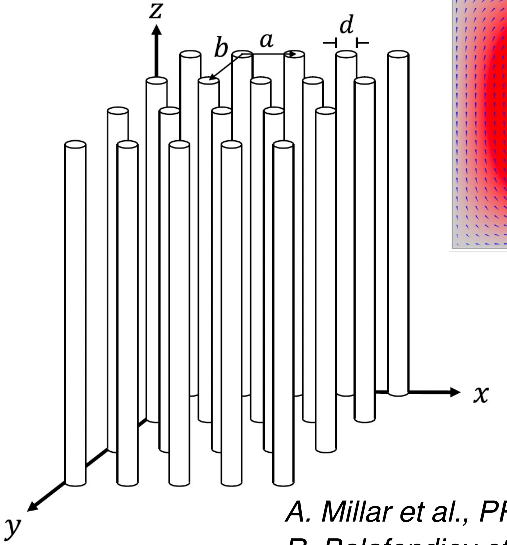
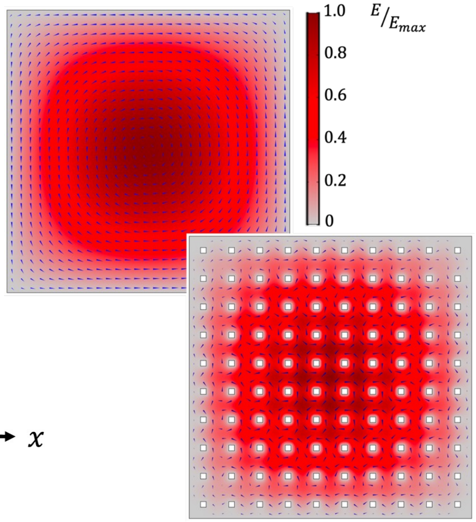


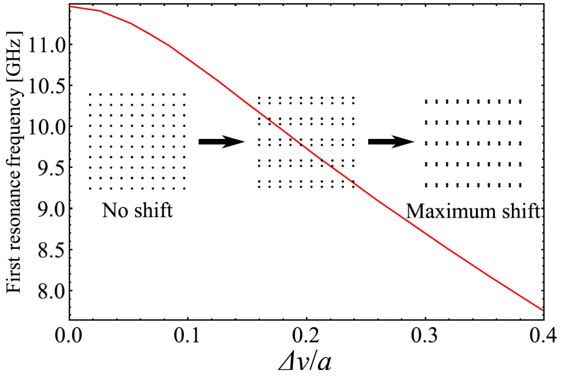
ALPHA: Axion Longitudinal Plasma Haloscope

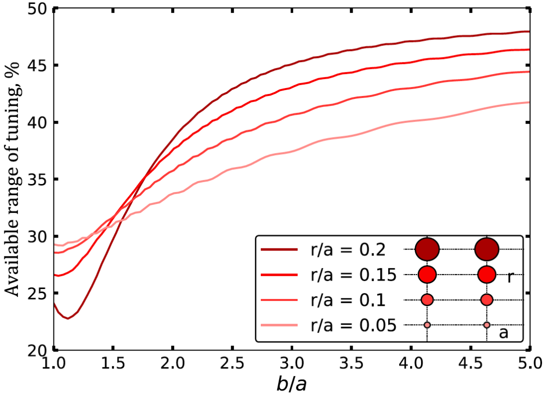
Concept: Instead of a closed cavity use a grid of wires as a metamaterial

[M. Lawson et al., PRL 123 (2019) 14, 141802]









A. Millar et al., PRD 107 (2023) 5, 055013
R. Balafendiev et al., PRB 106, 075106 (2022).
M.Wooten et al., Annalen der Physik (2022) 00479.

See previous talk today by Rustam Balafendiev

ALPHA: Axion Longitudinal Plasma Haloscope

Concept: Instead of a closed cavity use a grid of wires as a metamaterial

[M. Lawson et al., PRL 123 (2019) 14, 141802]

ALPHA PHASE I

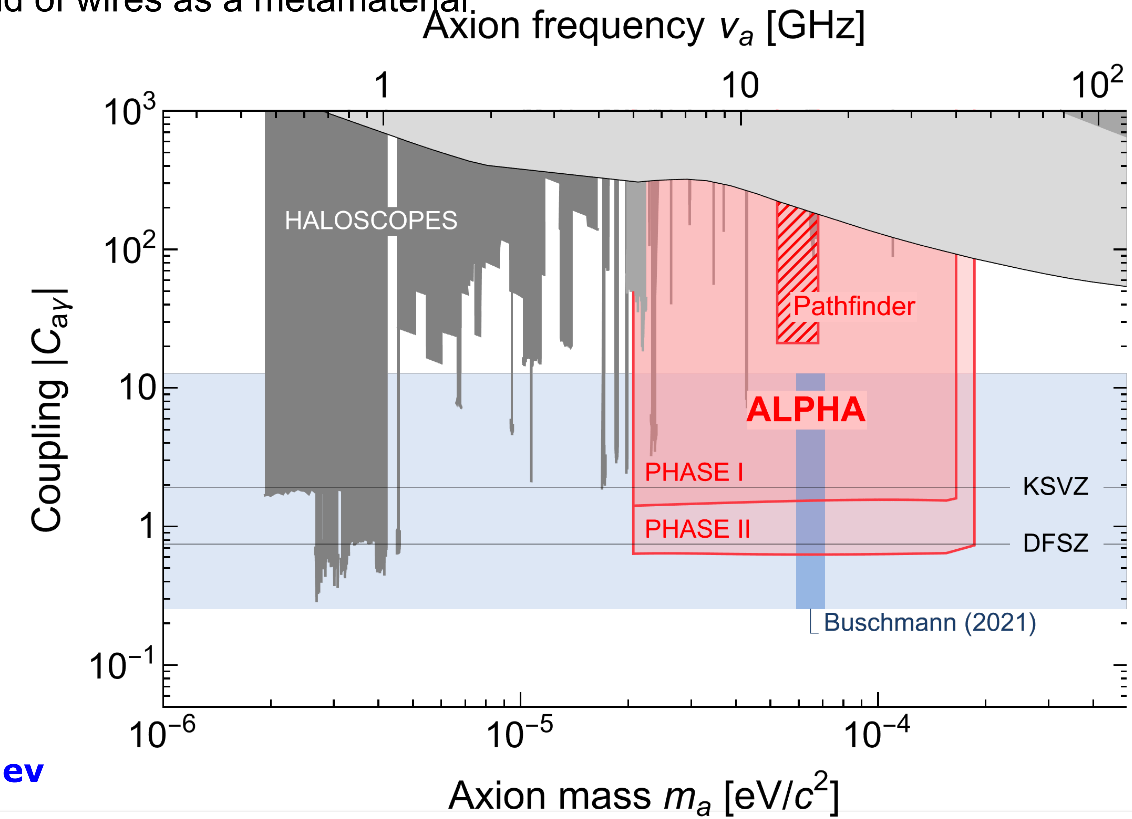
- *2 years run*
- *(5 - 40) GHz*
- *HEMT amplifiers*
- *Single scan*

ALPHA PHASE II

- *2 years run*
- *(5 - 45) GHz*
- *Quantum limited*
- *Single scan*

($Q \sim 10^4$, $B \sim 10$ T, $V \approx 0.3$ m^3)

See previous talk today by Rustam Balafendiev



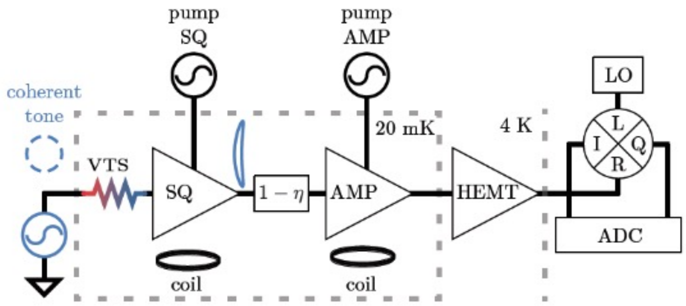
Challenge for higher frequency Haloscopes: Quantum limit

$$T_N > T_{SQL} \quad \text{where} \quad k_B T_{SQL} = h\nu$$

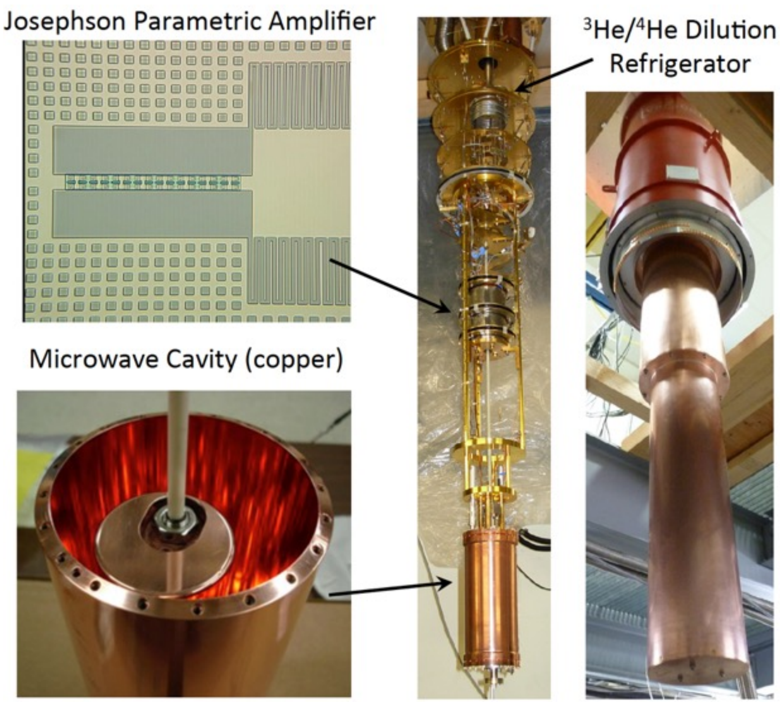
ν [GHz]	m_a [μeV]	T_{SQL} [mK]
0.5	2.1	24
5	20.7	240
20	82.8	960

The SQL can be evaded by:

- Squeezed-vacuum state receiver (e.g., LIGO)
  - HAYSTAC currently in the process of implementing
- Single-photon detectors (e.g. qubits, bolometers)



HAYSTAC experiment



9.4 Tesla magnet with 2-liter cavity

<u>Results</u>:

1. B. M. Brubaker et al., First Results from a Microwave Cavity Axion Search at 24 ueV, [arXiv:1610.02580]; [Phys. Rev. Lett. 118 061302 (2017)]

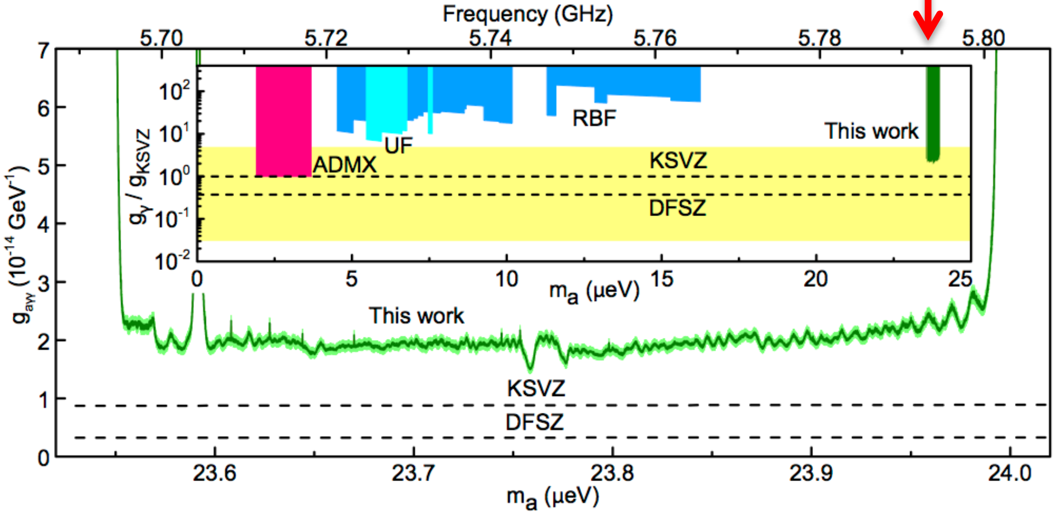
2. L. Zhong et al., Results from phase 1 of the HAYSTAC microwave cavity axion experiment, [arXiv:1803.03690]; [Phys. Rev. D **97** 092001 (2018)]

<u>Design details:</u>

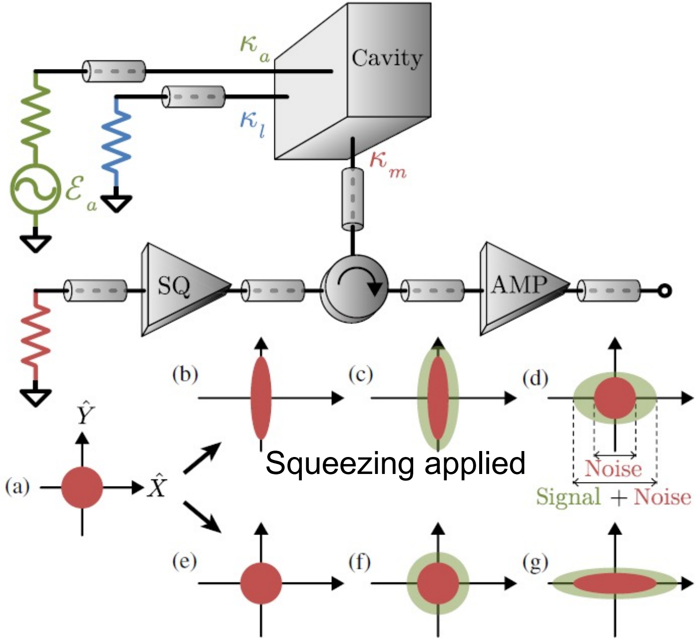
1. S. Al Kenany et al., Design and operational experience of a microwave cavity axion detector for the 20-100 ueV range, [arXiv:1611.07123]; [Nucl. Instrum. Meth. A 854 11 (2017)]

<u>Squeezing demonstration:</u>

1. M. Malnou et al., Squeezed vacuum used to accelerate the search for a weak classical signal, [arXiv:1809.06470]; [Phys. Rev. X 9, 021023 (2019)]

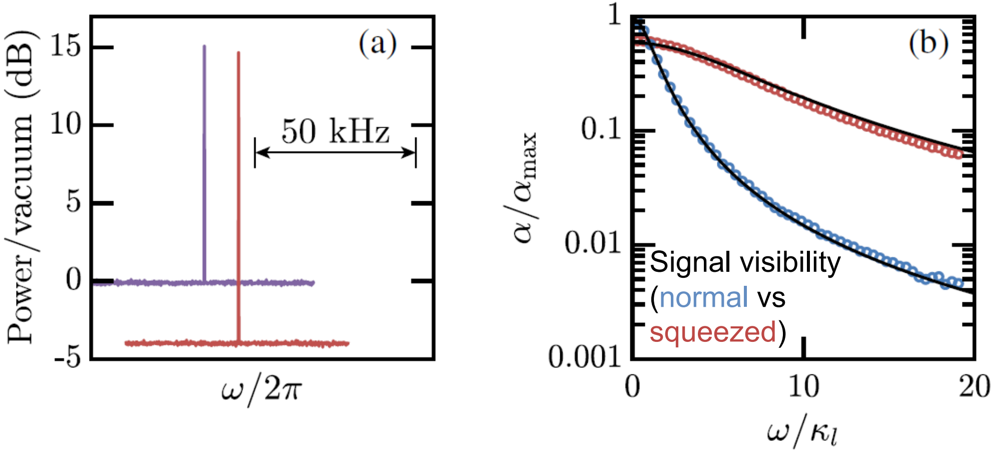


Squeezing the vacuum (HAYSTAC group)



Squeezed Vacuum Used to Accelerate the Search for a Weak Classical Signal

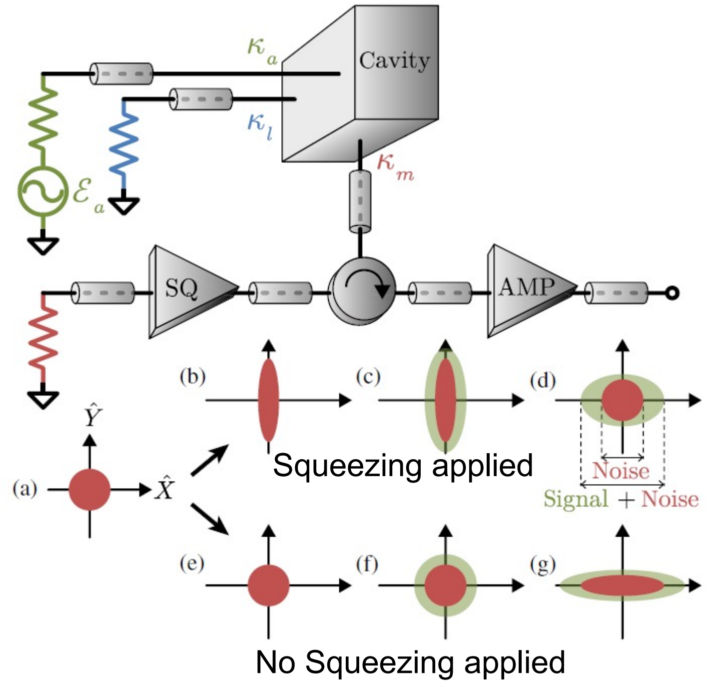
M. Malnou,[1,2,*,†] D. A. Palken,[1,2,†] B. M. Brubaker,[1,2] Leila R. Vale,[3] Gene C. Hilton,[3] and K. W. Lehnert[1,2]
[1]JILA, National Institute of Standards and Technology and the University of Colorado, Boulder, Colorado 80309, USA
[2]Department of Physics, University of Colorado, Boulder, Colorado 80309, USA
[3]National Institute of Standards and Technology, Boulder, Colorado 80305, USA



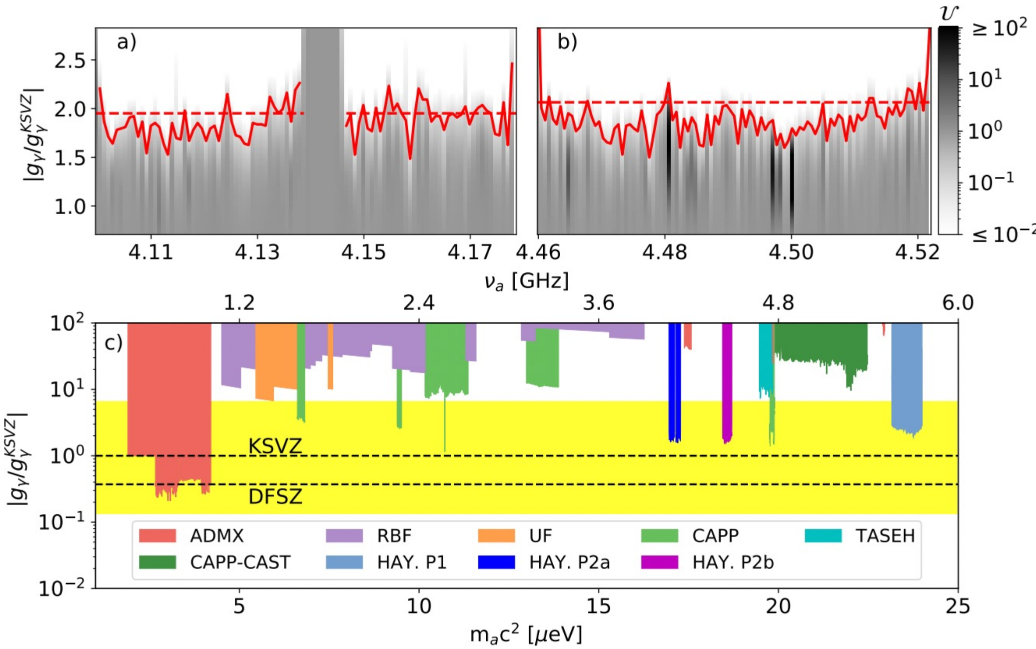
Figures from **Phys. Rev. X 9, 021023 – Published 3 May 2019**

Signal over background 1 MHz from cavity
Demonstrated axion search. **Factor of 2 in scan rate!**
New Results: https://arxiv.org/pdf/2301.09721.pdf

Squeezing the vacuum (HAYSTAC group)



Figures from **Phys. Rev. X 9, 021023 – Published 3 May 2019**

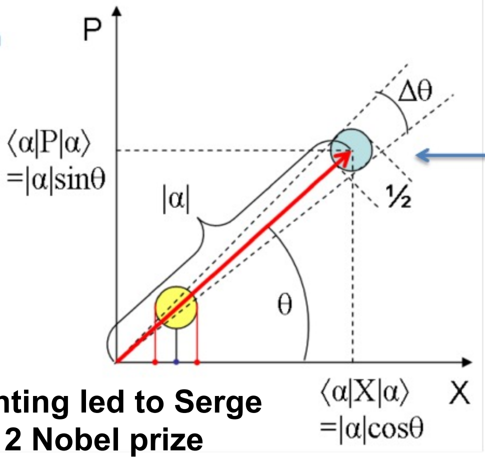


New Results: https://arxiv.org/pdf/2301.09721.pdf

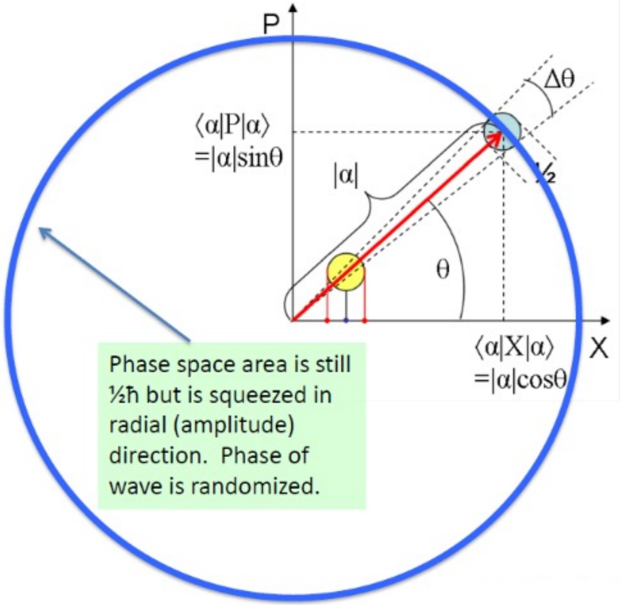
Paper on 2-mode squeezing (> 15 times increase) CEASEFIRE: https://arxiv.org/pdf/2107.04147.pdf

Photon Counting

Phasor representation of wave oscillator

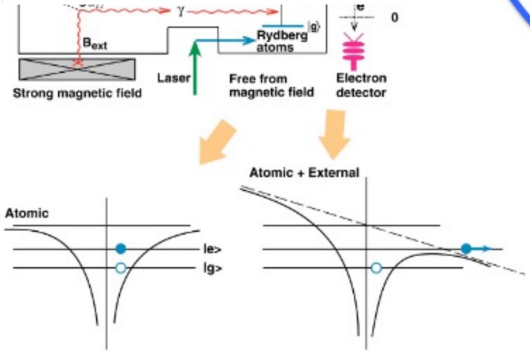


½ ħ= quantum of phase space area.
Simultaneous measurement of wave amplitude and phase gives irreducible zero-point noise in measurement.
(C.Caves, 1982)



Phase space area is still ½ħ but is squeezed in radial (amplitude) direction. Phase of wave is randomized.

Photon counting led to Serge Haroche 2012 Nobel prize



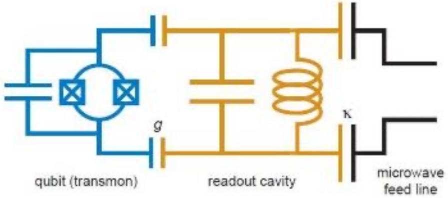
Initial attempt made using Rydberg Atoms in the late 1990s (CARRACK)

Updated version being investigated by Yale (Reina Maruyama)

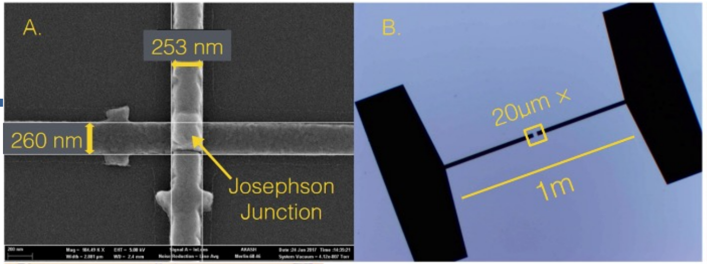
Transmon Qubits

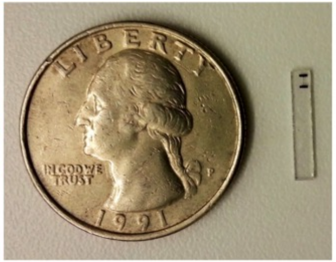
Transmon Qubit – single cooper pair box shunted with capacitor

Can tune the qubit frequency with flux through SQUID

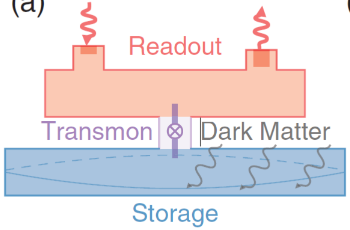


Example of device fabricated at U. of Chicago (Heising-Simons funded R&D)

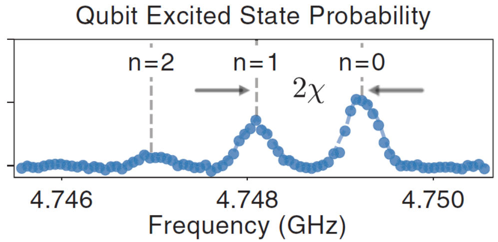


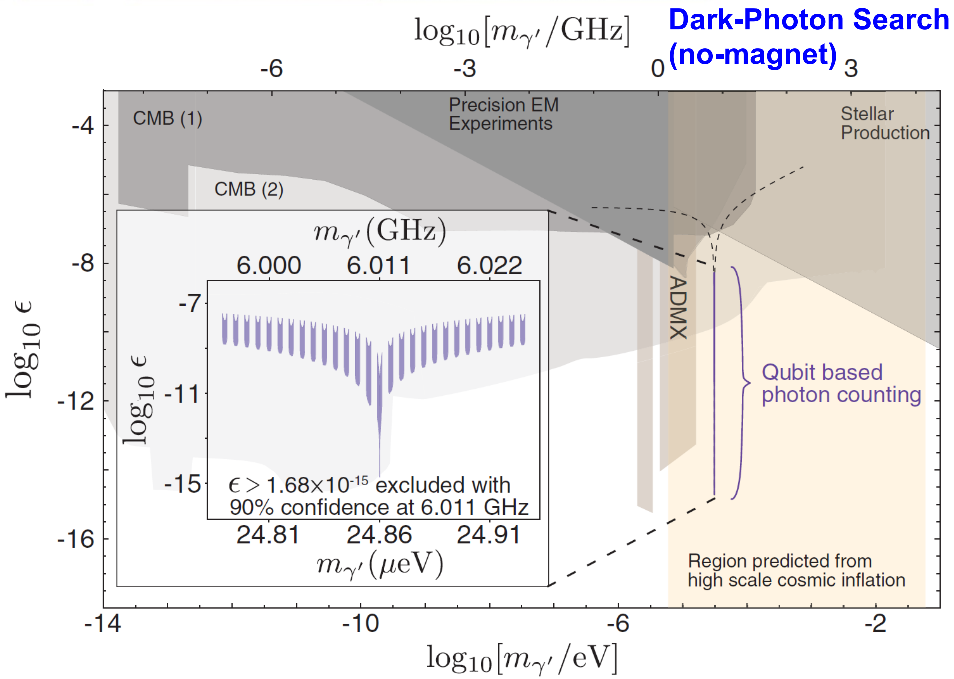


(a)



(b)





Searching for Dark Matter with a Superconducting Qubit: PRL 126, 141302 (2021)

Potential Scan Rate Speedup

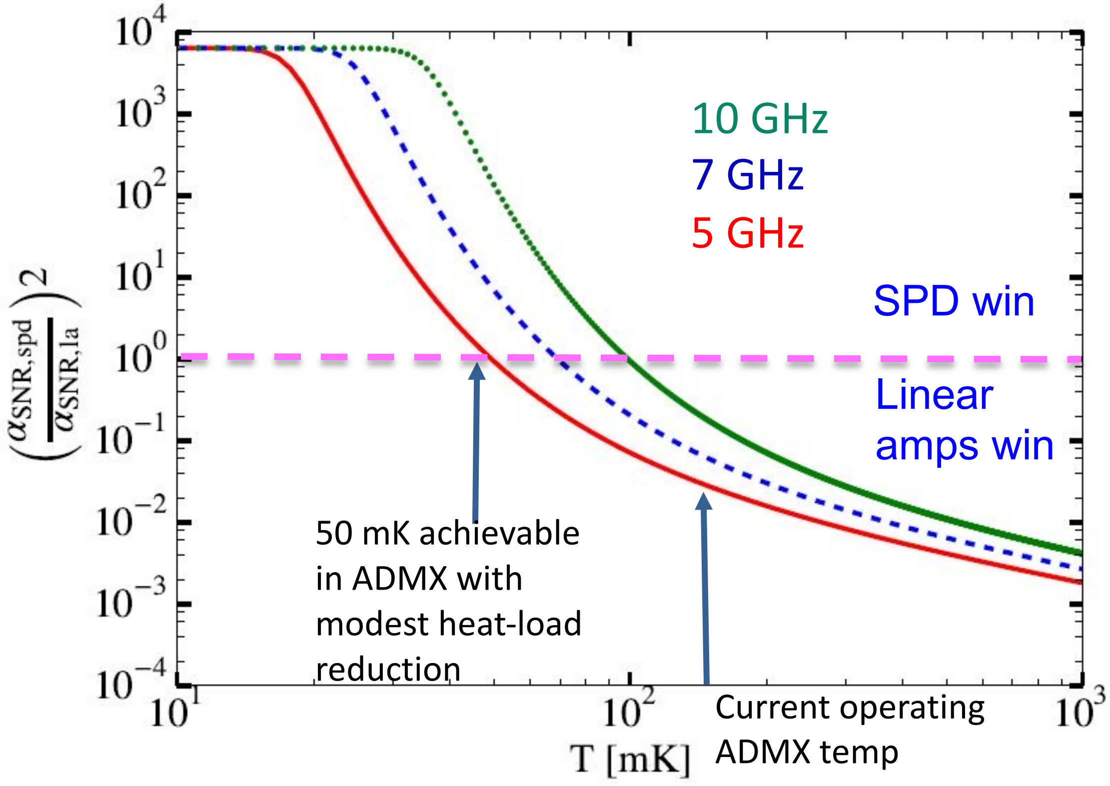
- Below are some estimates on relative to physical temperature for different frequencies

***Accelerating dark-matter axion searches with quantum measurement technology, arXiv:1607.02529v2, 19 July 2016**

Shot noise limit
Need at least 3 photons for detection

ADMX at 10 GHz produces ~ tens a minute.

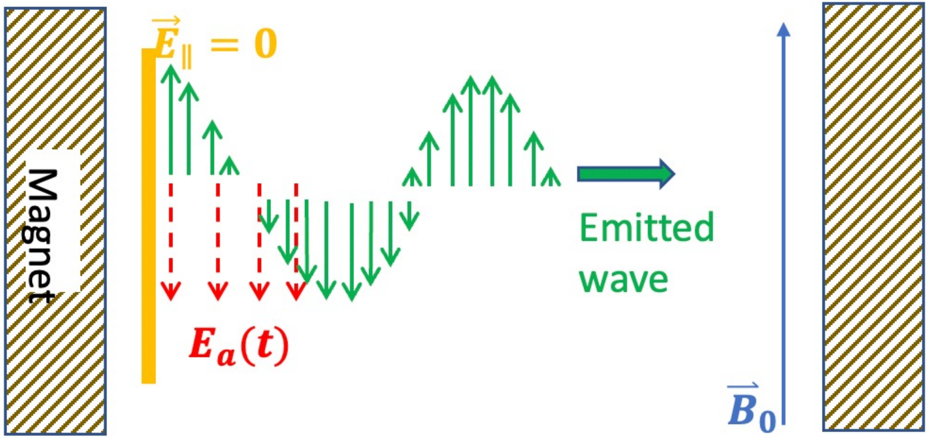
If we can get heat loads on ADMX DR down to < 120 uW temp can go below 50 mK



Axion-Induced Radiation from Conducting Surface in Magnetic Field

- Axions interact with a static magnetic field producing an oscillating parallel electric field in free space

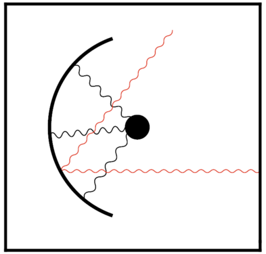
- A conducting surface in this field emits a plane wave perpendicular to surface.



- Radiated power is low:

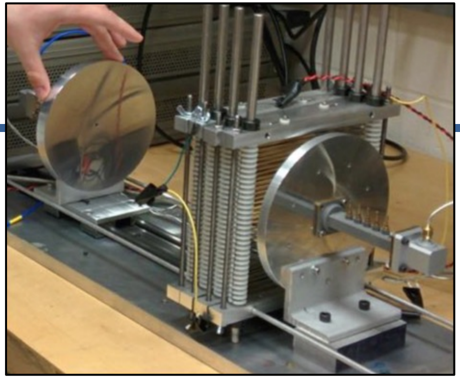
$$P_{signal} = 8.27 \cdot 10^{-26} W \cdot \left(\frac{A}{10\ m^2}\right)\left(\frac{B_{\parallel}}{10\ \text{Tesla}}\right)^2\left(\frac{\rho_{DM}}{0.3\ GeV/cm^3}\right)\left(\frac{g_{a\gamma\gamma}}{3.92 \cdot 10^{-16}\ GeV^{-1}}\right)^2\left(\frac{1\ \mu eV}{m_a}\right)^2$$

- No detector tuning is required.



"Dish Antenna" Horns, Jaeckel, Lindner, Lobanov, Redondo & Ringwald, 2012

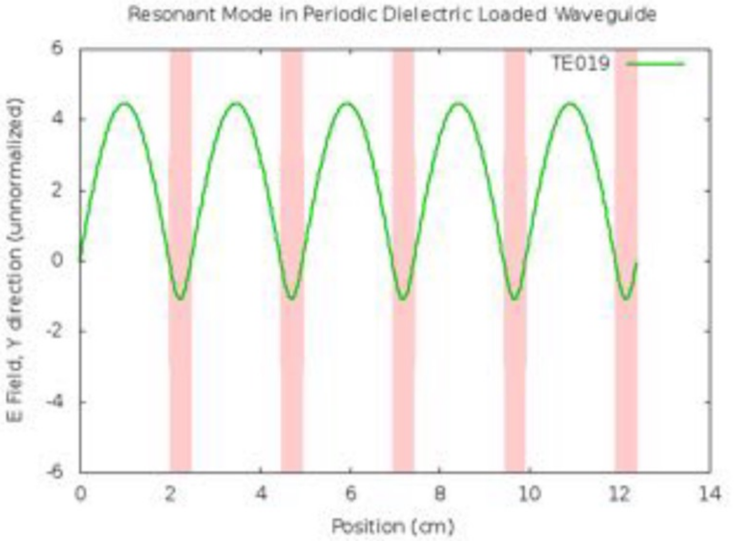
Open resonator design with dipole magnet

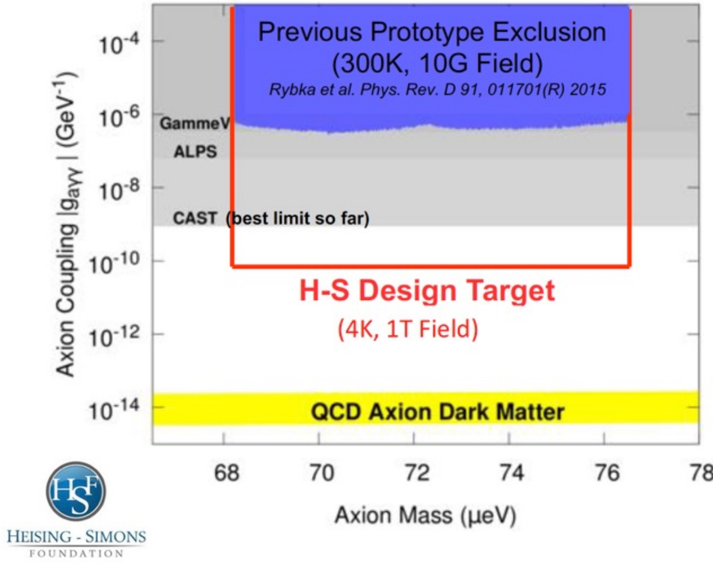


Orpheus Project (UW)

Open resonator would usually not couple to axion field (positive and negative E-fields cancel).

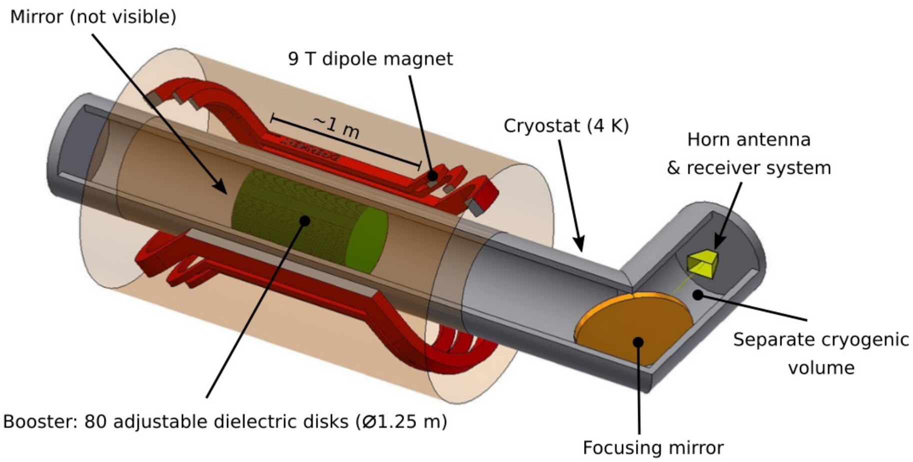
Manipulating modes with dielectrics or alternating the magnetic field leads to a net axion coupling.

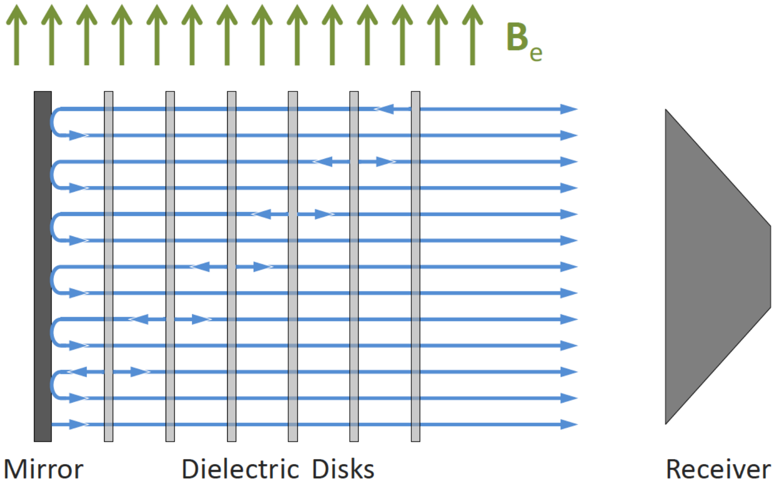




MADMAX: Magnetized Disc and Mirror Axion experiment

- Weak signal power at single interface boosted using a tunable stack of dielectric plates
- Aims to probe 40-400 µeV range (10-100 GHz)
- 10 T field & ~80 disks
- Currently in prototype phase with CERN dipole magnet



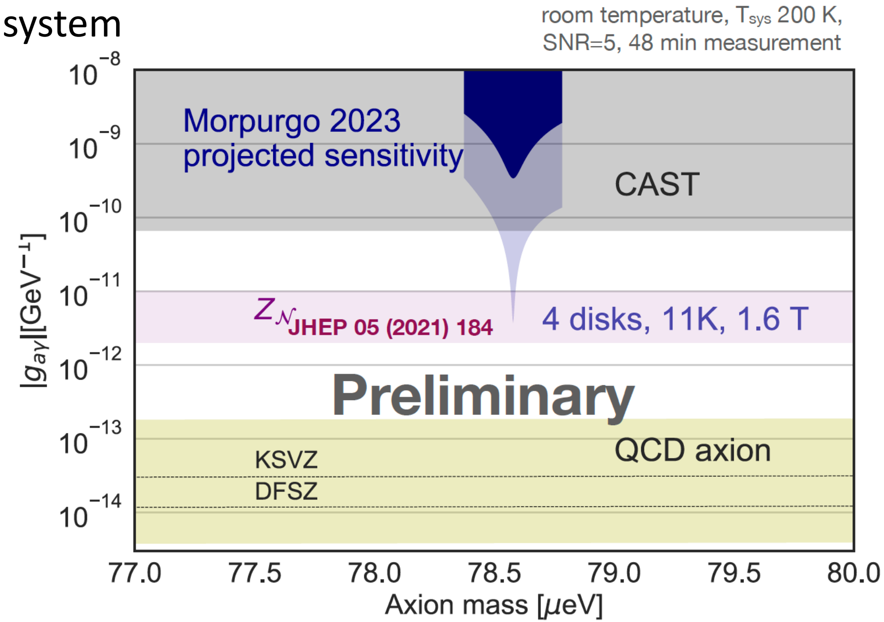


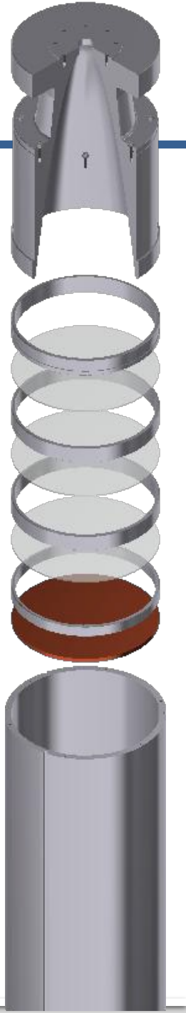
$$P/A = 2.2 \times 10^{-27}\,\mathrm{W\,m^{-2}} \left(\frac{B_e}{10\,\mathrm{T}}\right) C_{a\gamma}{}^2 \cdot \beta^2$$

β^2: power emitted by booster / power emitted by single mirror ($\epsilon = \infty$)

MADMAX: Magnetized Disc and Mirror **Axion** experiment

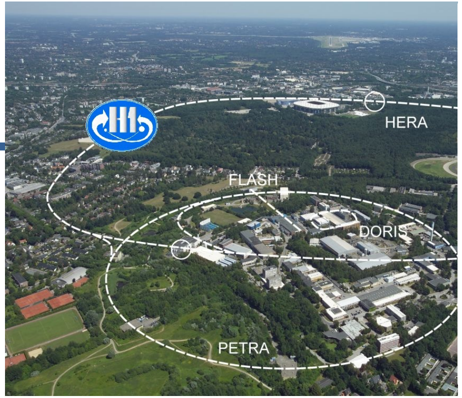
- CB-100 (Closed-Booster 100 mm)
- Initial test run in Morpurgo magnet at CERN (1.6 T)
- Boost factor validated ~ 700
- T_{sys} ~ 200 K ← planning to upgrade with 4K system

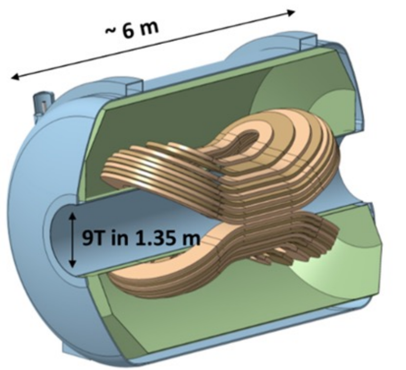


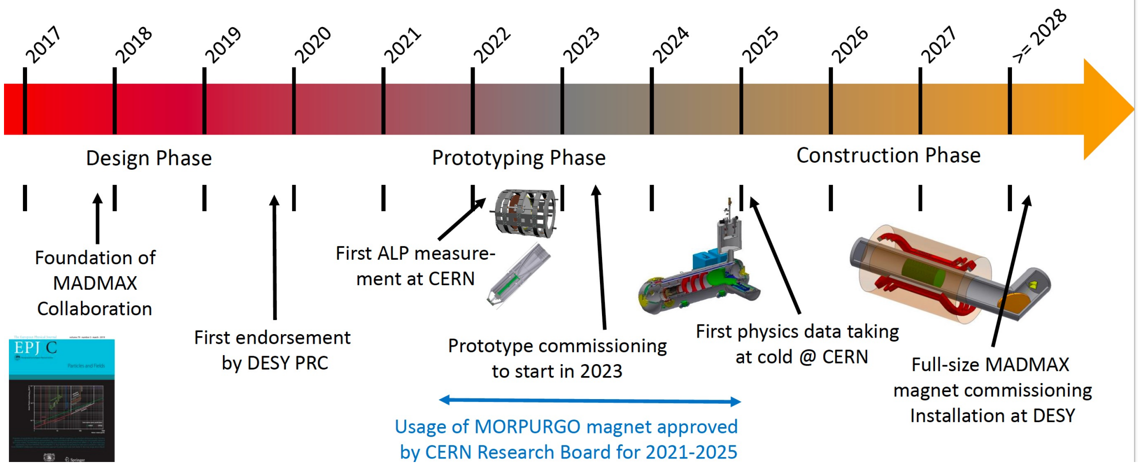


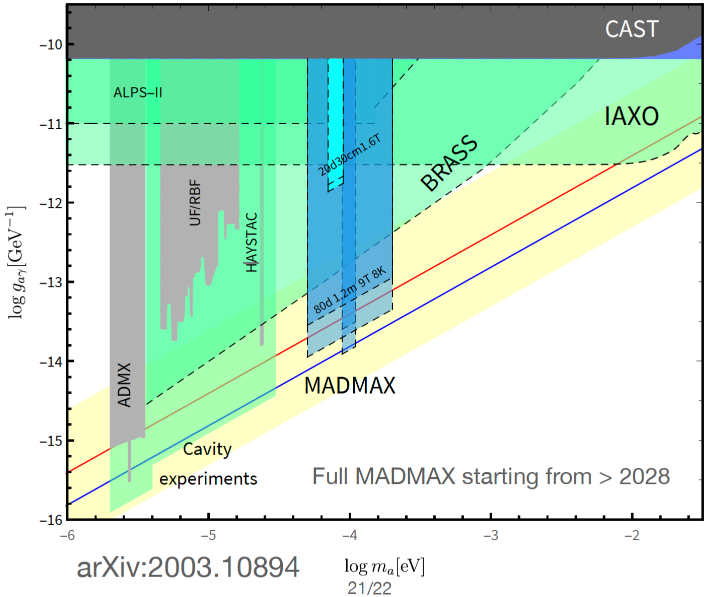
MADMAX: Overall plans

- Ultimate plans aim to construct 9T 1.35 m diameter dipole at DESY.
- Prototyping Phase now
- Ultimately construction & commissioning ~ 2028.



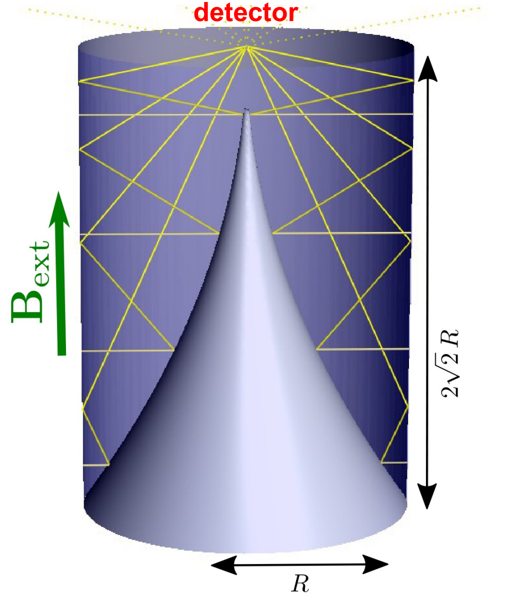






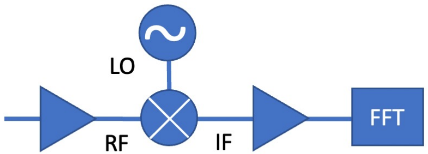
BREAD: Broadband Experiment for Axion Detection

- Fermilab led dish antenna concept with a twist.
- Uses cylindrical mirror in a solenoid and an internal parabolic mirror to focus axion signal onto a single detector area.



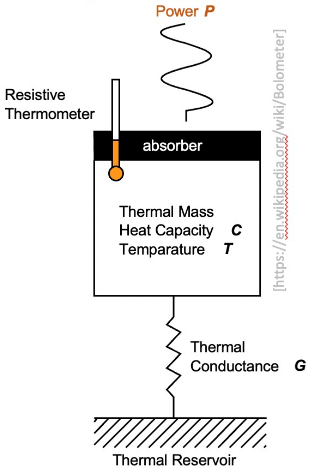
Pursuing various detection strategies

Heterodyne



- high resolution
- **Standard Quantum Limit (SQL):** $k_B\, T_{noise} = hf$

Bolometer



NEP ~ $10^{-20}\ W/\sqrt{Hz}$

Single Photon Counting

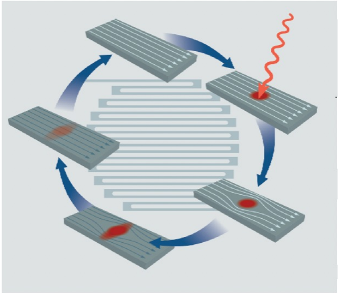


Fig.: Sae Woo Nam (NIST)

e.g., nanowire detectors

SNSPDs, KIDs, QCDs, …

down to ~ 1 photon/day

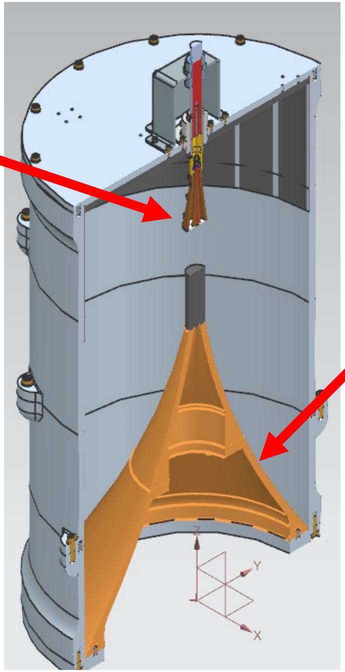
8

Proof of Concept Experiments: GigaBREAD and InfraBREAD

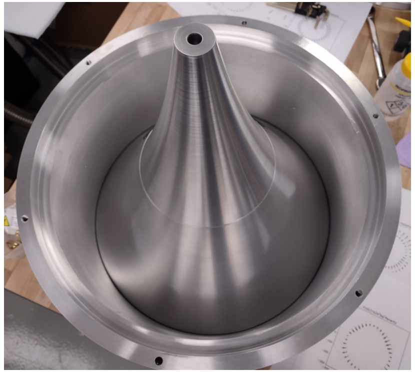
GigaBREAD: 10-20 GHz experiment with HEMT amplifier

Horn Antenna with Axial position adjustment

Room temperature

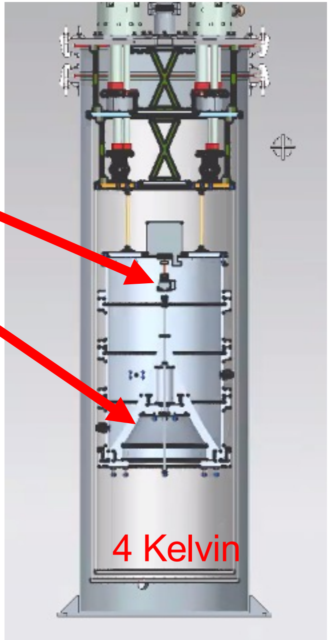


400 mm diameter Coaxial Dish



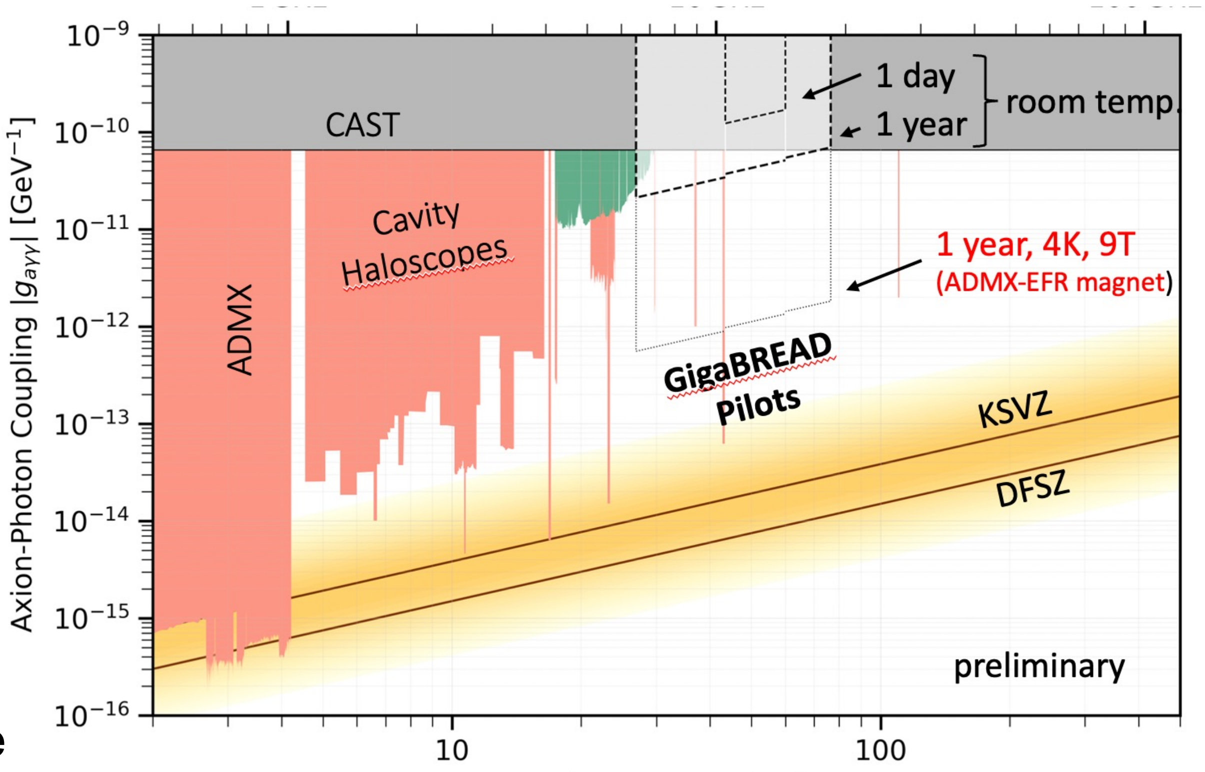
InfraBREAD: 300 THz experiment (~1 micron) with Superconducting Nanowire Detectors (SNSPDs)

SNSPD @ 800 mK



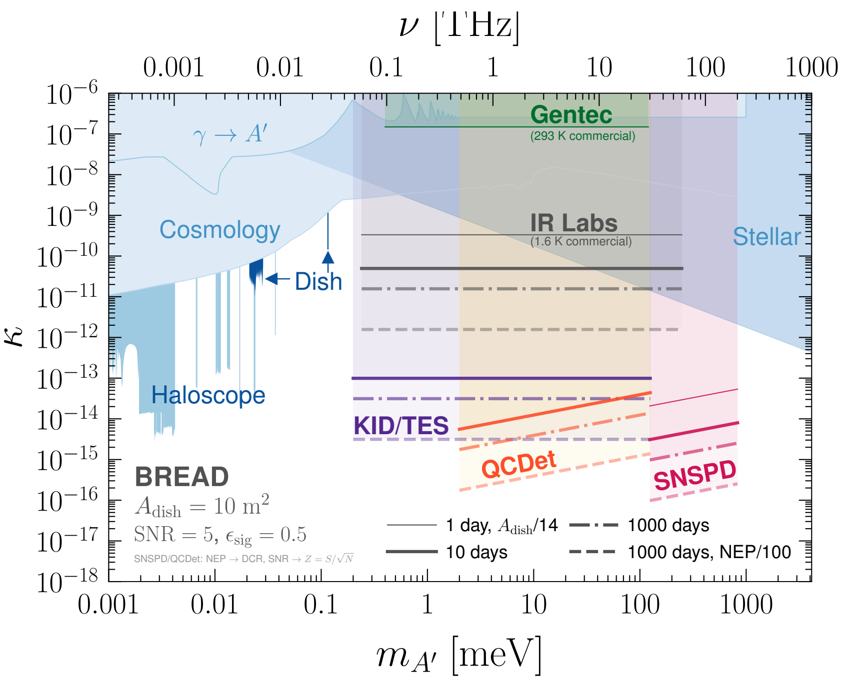
BREAD: Sensitivity projections

4 T MRI magnet at Argonne

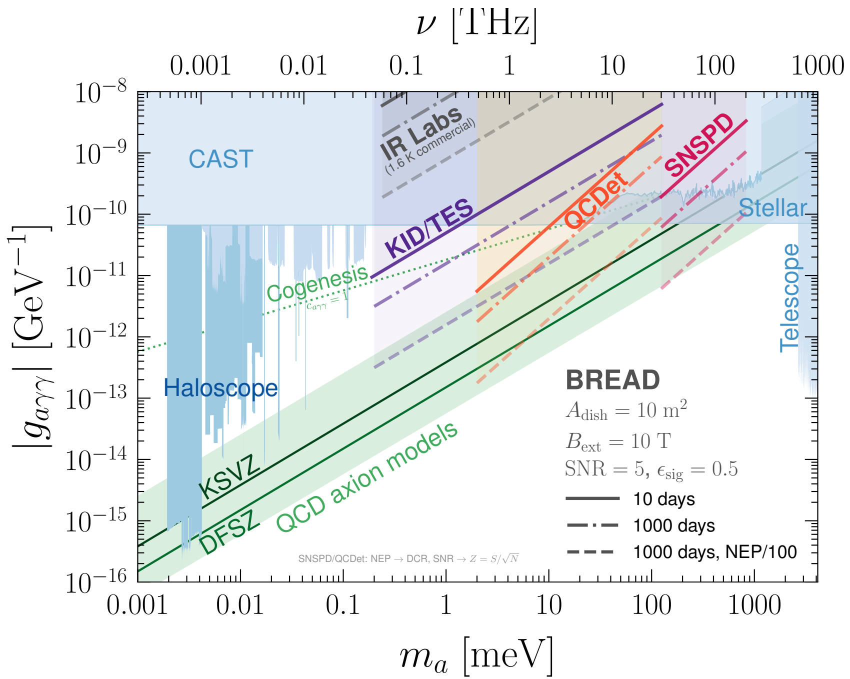


BREAD: Sensitivity projections

Dark Photons



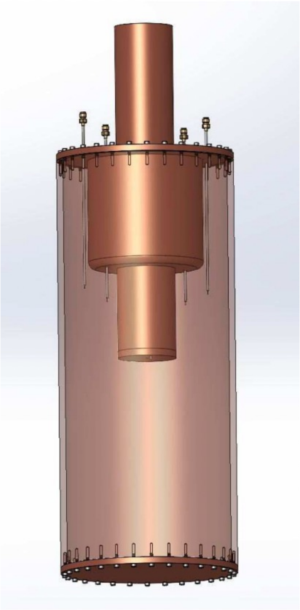
Axions

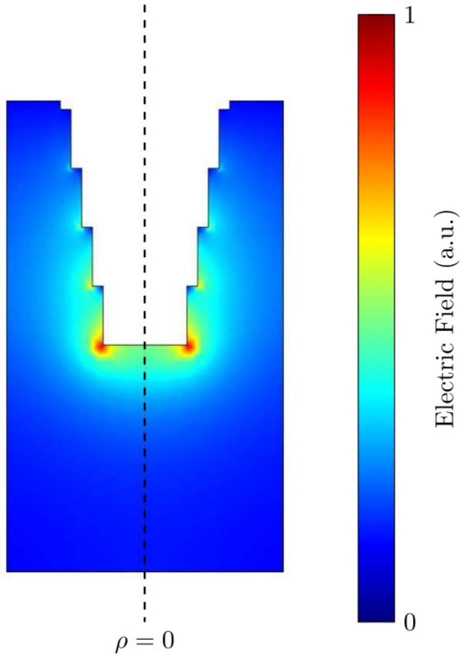


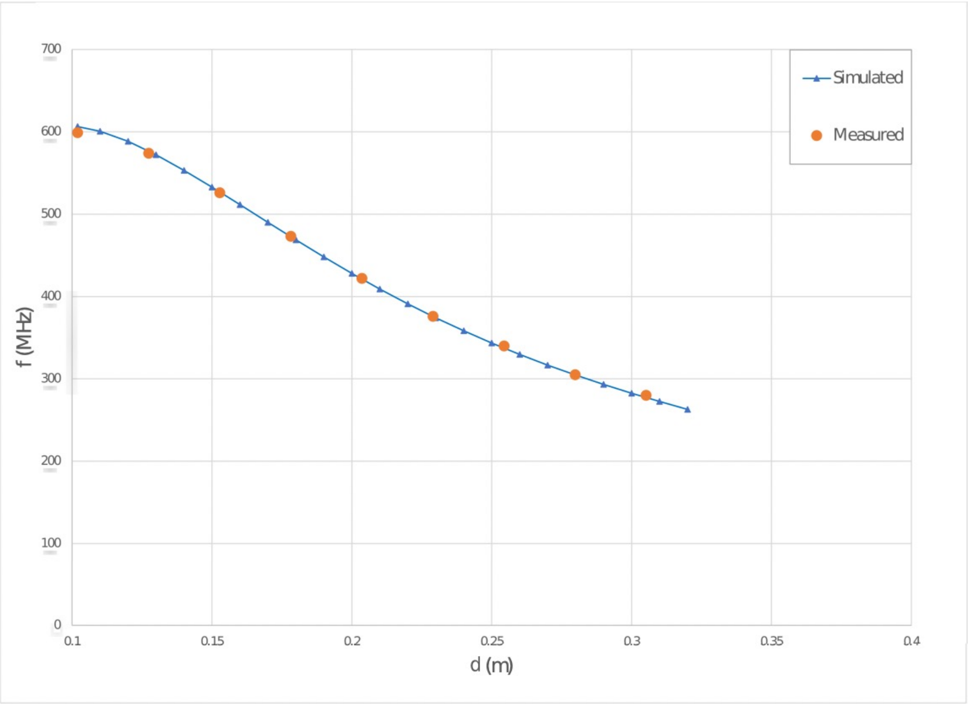
[Liu *et al*, BREAD collab., arXiv:2111.12103, PRL 128 (2022) 131801]

Going to lower masses (100-600 MHz): ADMX Reentrant Cavity

Recent paper: https://arxiv.org/pdf/2303.07116.pdf
Design led by U. of Florida group



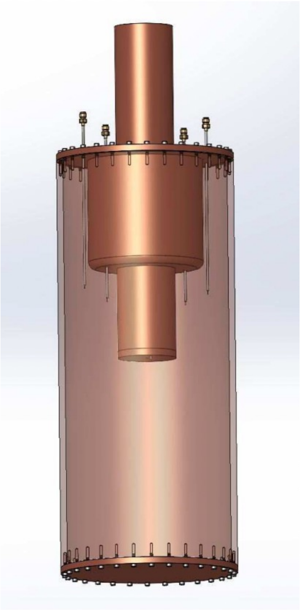


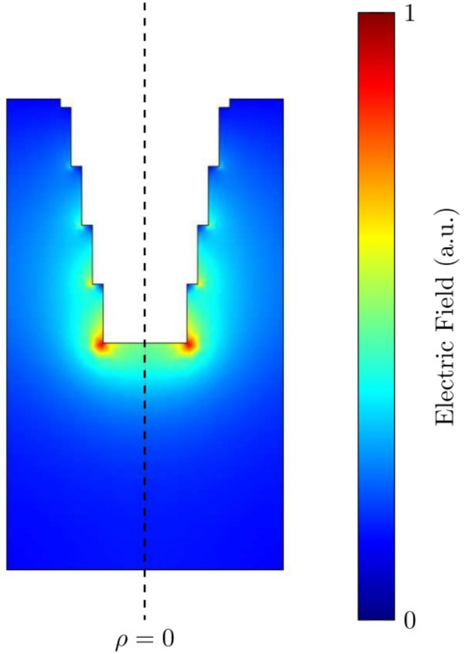


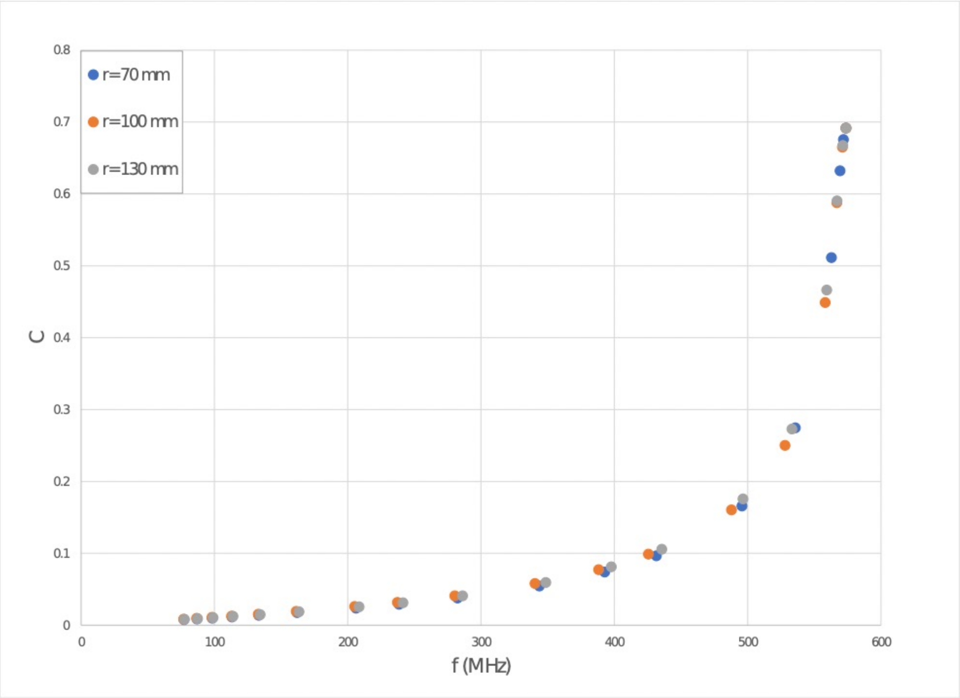
Frequency shift vs insertion

Going to lower masses (100-600 MHz): ADMX Reentrant Cavity

Recent paper: https://arxiv.org/pdf/2303.07116.pdf
Design led by U. of Florida group

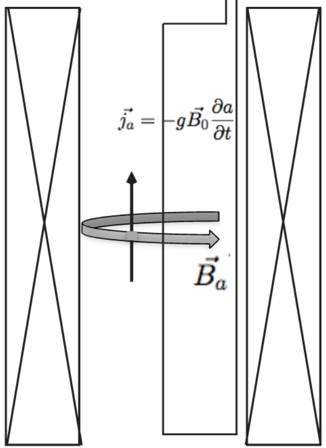


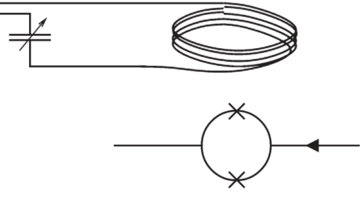




Form Factor drops at low frequency

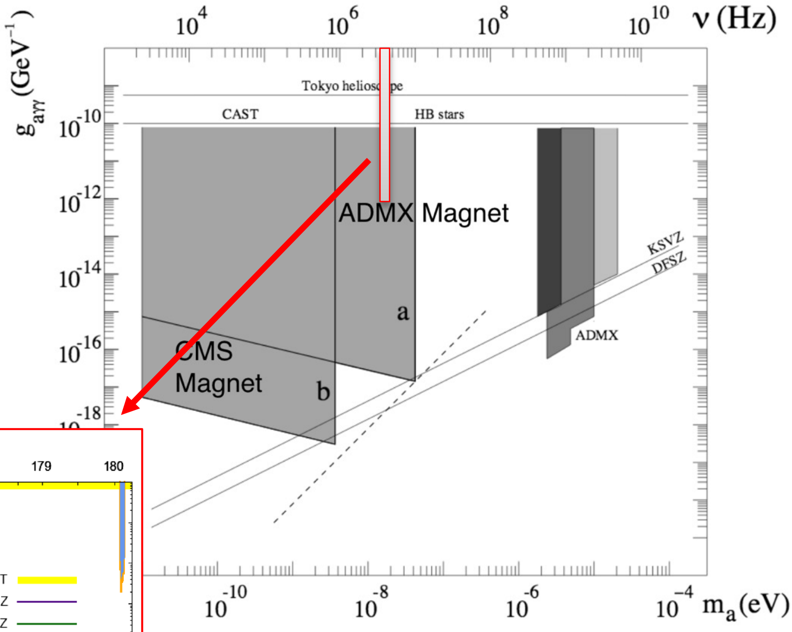
Going to lower masses (< 1 μeV): ADMX LC Circuit

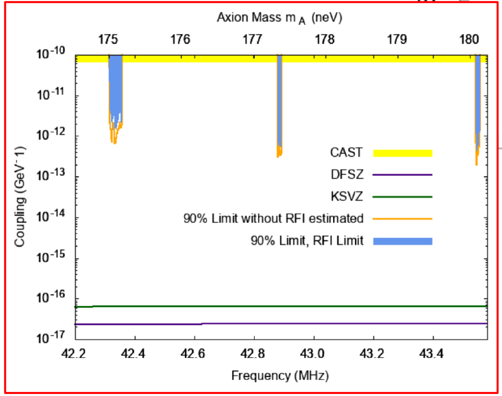




Proposal for Axion Dark Matter Detection Using an LC Circuit
PRL 112, 131301 (2014)

$$I = \frac{-\Phi_a}{L} = \frac{Q}{L} V_m g \frac{\partial a}{\partial t} B_0$$



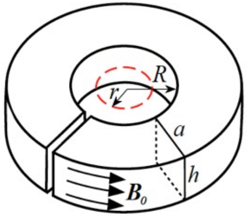


ADMX SLIC: Results from a Superconducting LC Circuit Investigating Cold Axions
N. Crisosto, P. Sikivie, N. S. Sullivan, D. B. Tanner, J. Yang, and G. Rybka
Phys. Rev. Lett. **124**, 241101 – Published 17 June 2020

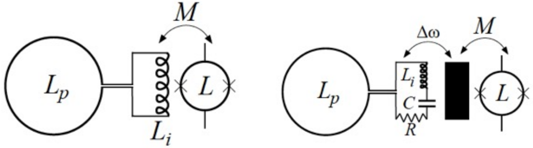
ABRACADABRA Experiment

A Broadband/Resonant Approach to Cosmic Axion Detection with an Amplifying B-field Ring Apparatus

Theory:



Toroidal geometry for zero-field detection



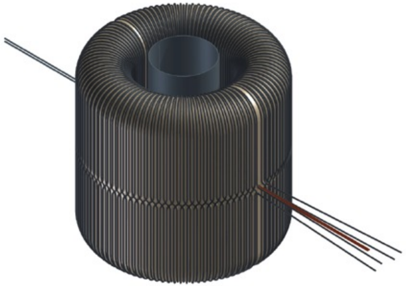
Interchangeable readout:
broadband (low freq.) or
resonant (high freq.)

Original Concept Paper:
Yoni Kahn, Ben Safdi, Jesse Thaler,
[Phys. Rev. Lett. **117**, 141801]

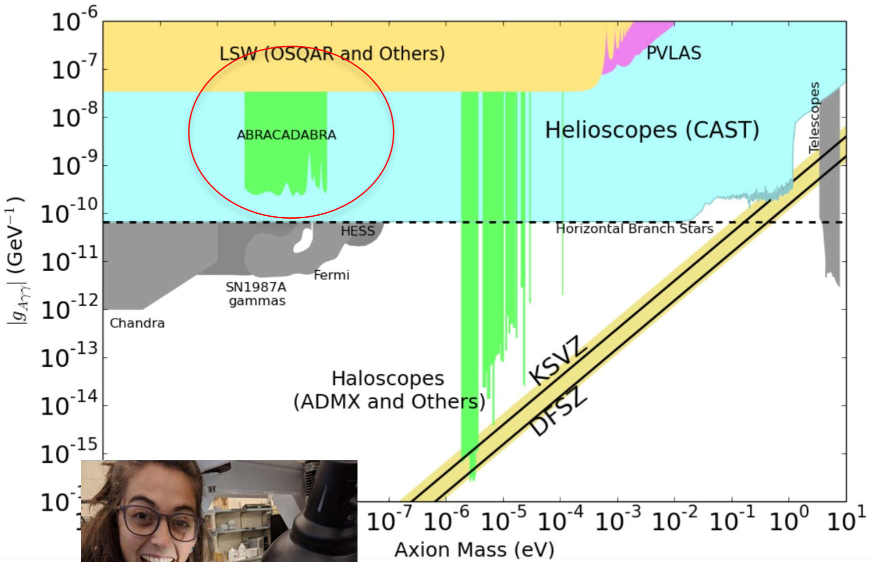
Experiment:

Prototype specs:

$R_{\rm in} = 3$ cm, $R_{\rm out} = 6$ cm, $h = 12$ cm,
$V = 680$ cm^3, $B_{\max} = 1$ T, $G = 0.085$



ABRA-10cm @ MIT



C. Salemi at MIT

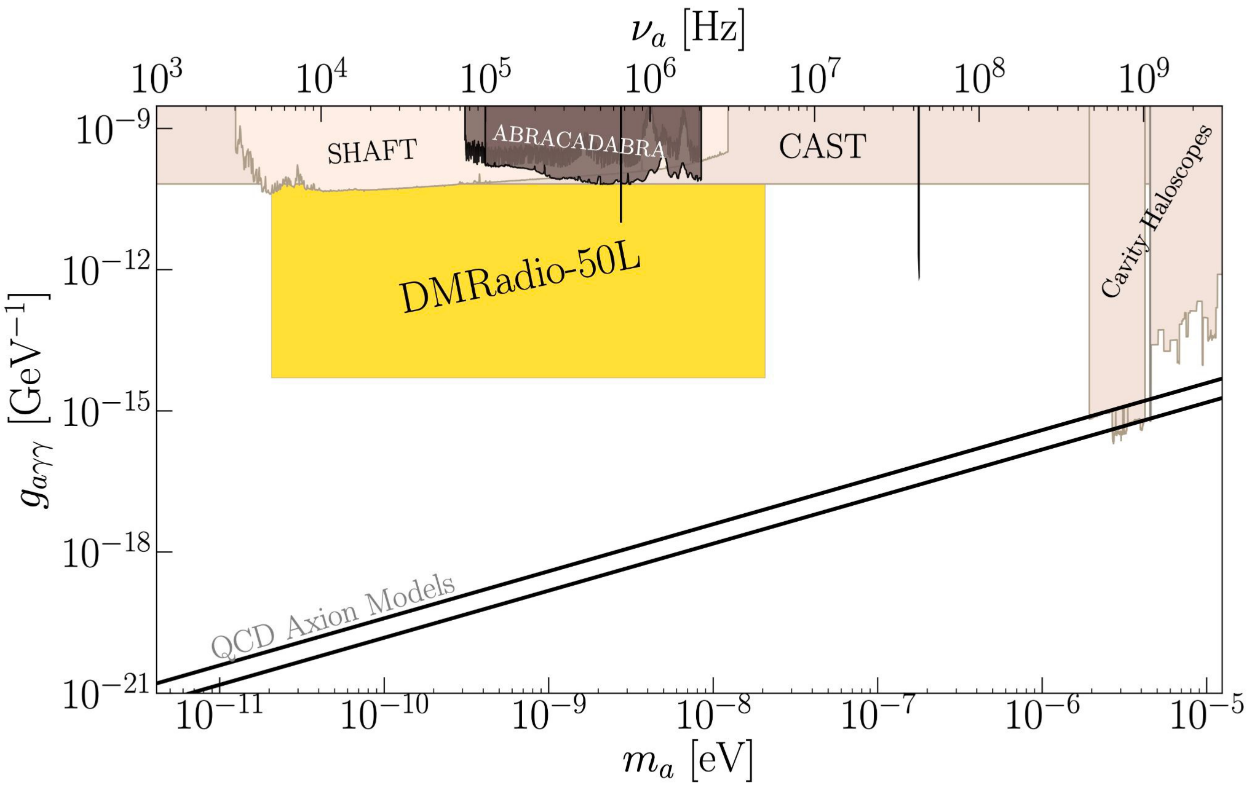
First Results
[2019: Phys. Rev. Lett. **122**, 121802]

[2021: Phys. Rev. Lett. **127**, 081801]

DMRadio (recent combined with ABRACADABRA Group)

DMRadio-50L

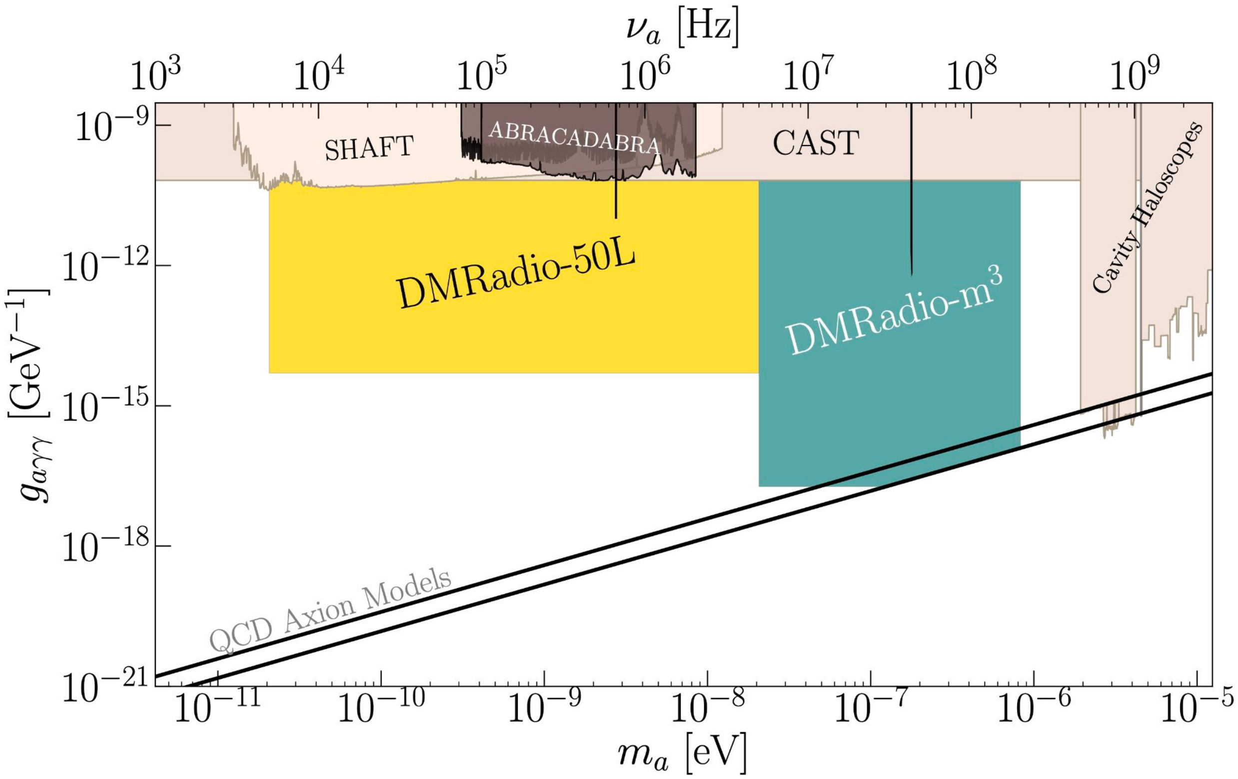
- 5 kHz – 5 MHz
- Quantum Sensor testbed



DMRadio (recent combined with ABRACADABRA Group)

DMRadio-50L
- 5 kHz – 5 MHz
- Quantum Sensor testbed

DMRadio-m3 (DOE DMNI)
- PRD 106 (2022): 103008
- Primary goal:
- DFSZ 30MHz – 200 MHz
- Secondary Goal
- KSVZ down to 10 MHz
- Extended Goal:
- QCD axion band to 5 MHz



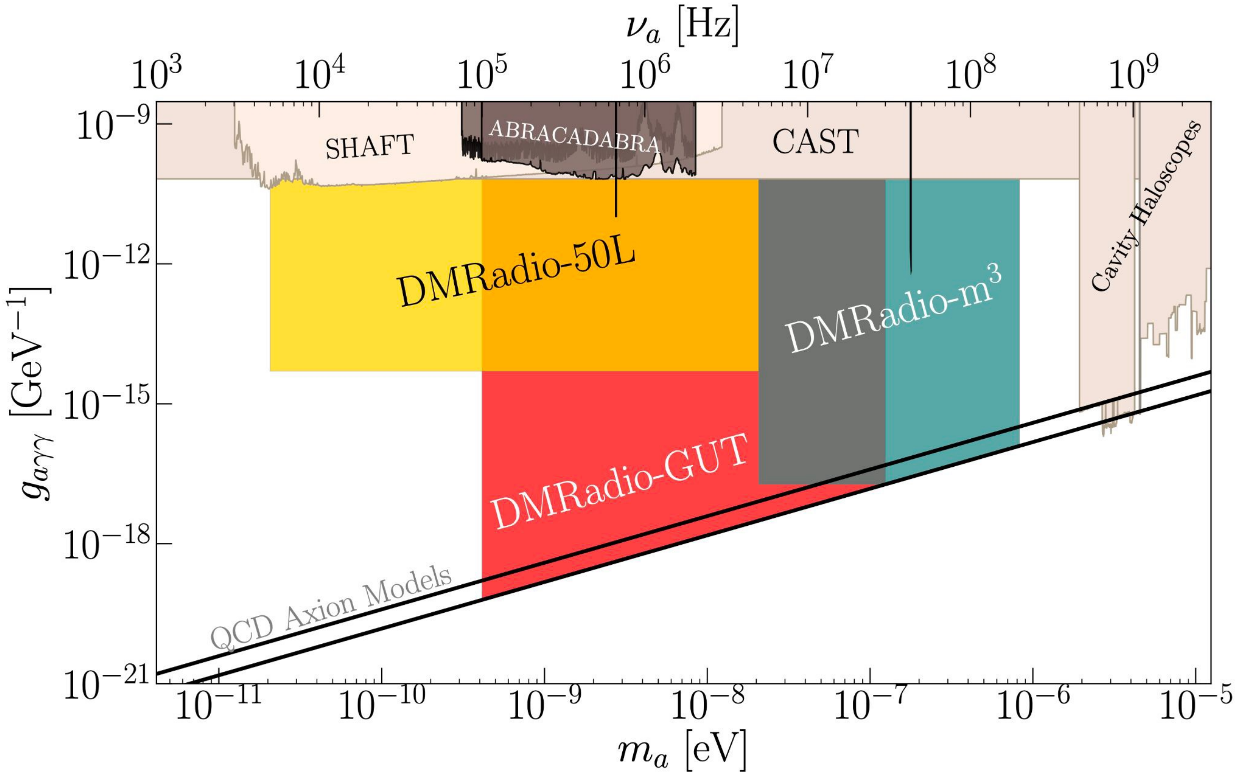
Slide credit: Maria Simanovskaia (UCLA DM 2023)

DMRadio (recent combined with ABRACADABRA Group)

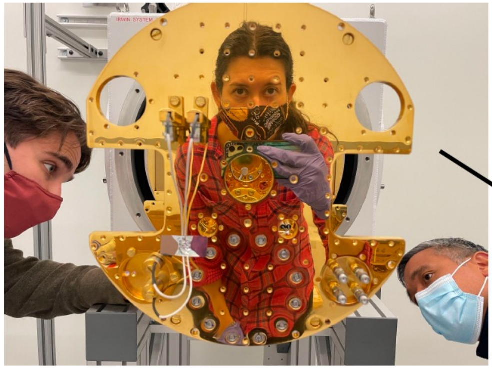
DMRadio-50L
- 5 kHz – 5 MHz
- Quantum Sensor testbed

DMRadio-m3 (DOE DMNI)
- PRD 106 (2022): 103008
- Primary goal:
- DFSZ 30MHz – 200 MHz
- Secondary Goal
- KSVZ down to 10 MHz
- Extended Goal:
- QCD axion band to 5 MHz

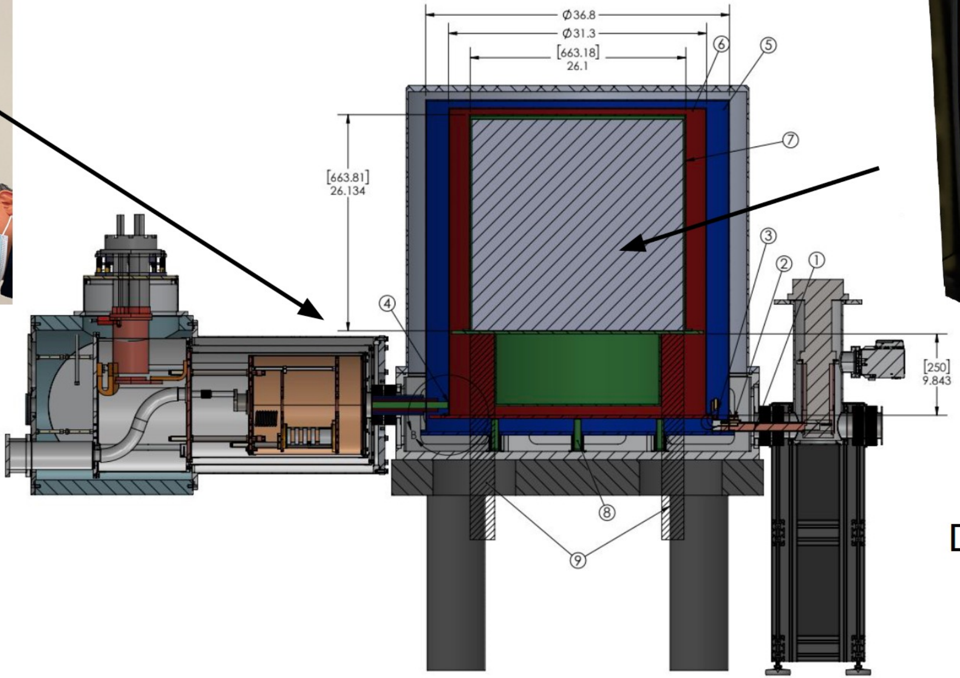
DMRadio-GUT
- PRD 106 (2022): 112003
- DFSZ 100 kHz – 30 MHz
- Next Gen Detector



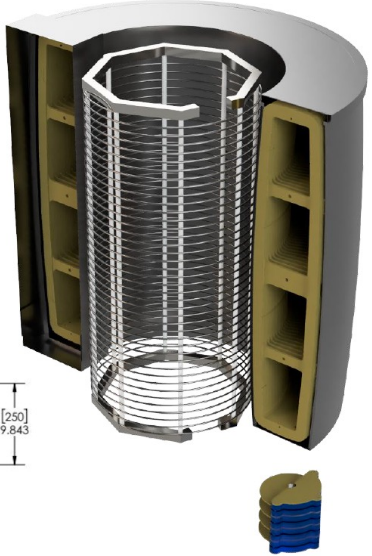
DMRadio-50L: under construction at Stanford



Working on the dilution refrigerator in the lab.



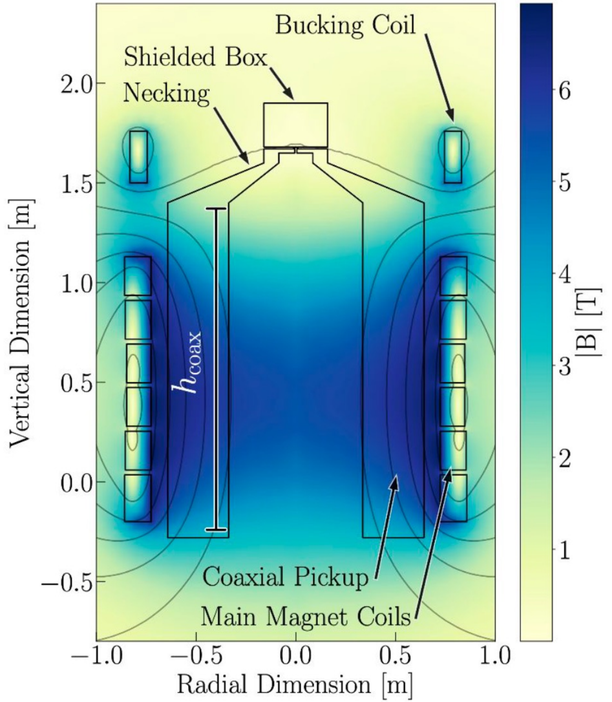
DMRadio-50L cryosystem CAD model.



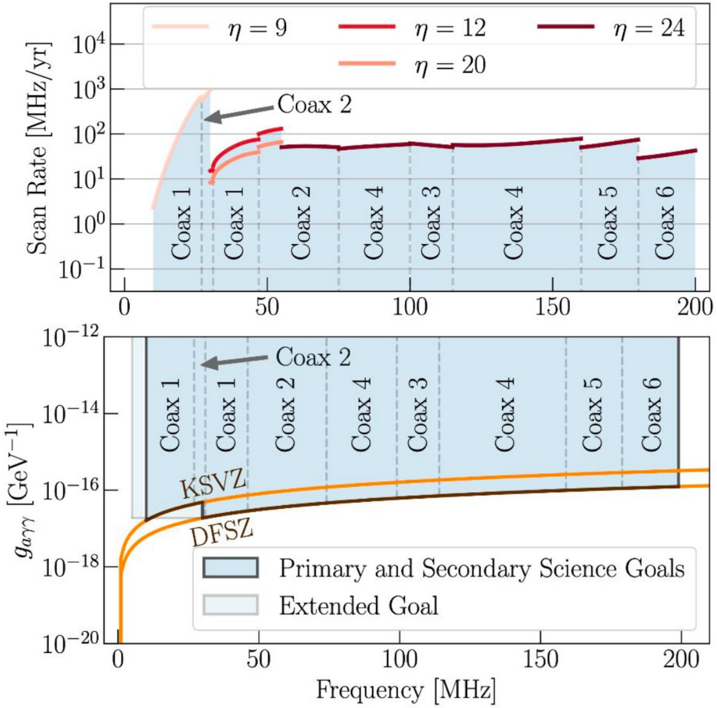
Detector and receiver CAD models.

Slide credit: Maria Simanovskaia (UCLA DM 2023)

DMRadio-m3: design to be completed in 2024



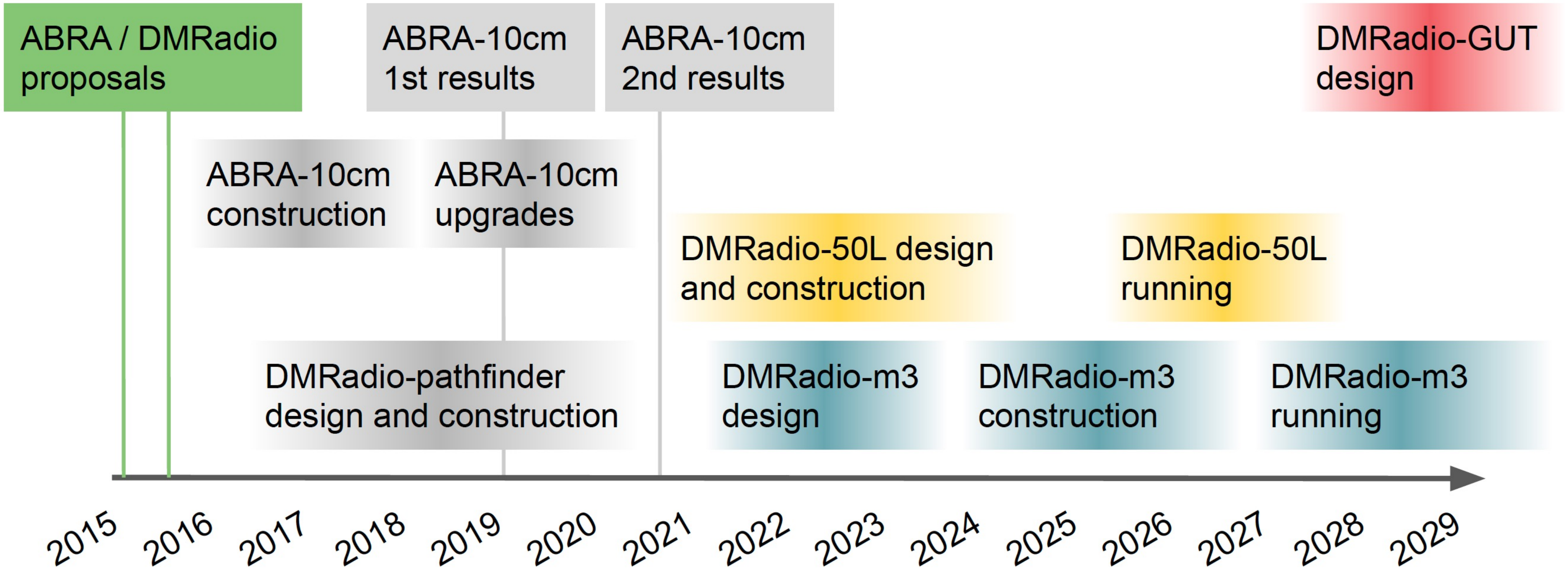
Coaxial cross section overlaid with simulation of the magnetic field.



Predicted scan rate and sensitivity across frequency range of interest.

Slide credit: Maria Simanovskaia (UCLA DM 2023)

DMRadio program schedule



Very low mass axions (neV) NMR based experiment: CASPEr

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

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

CASPEr Electric

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

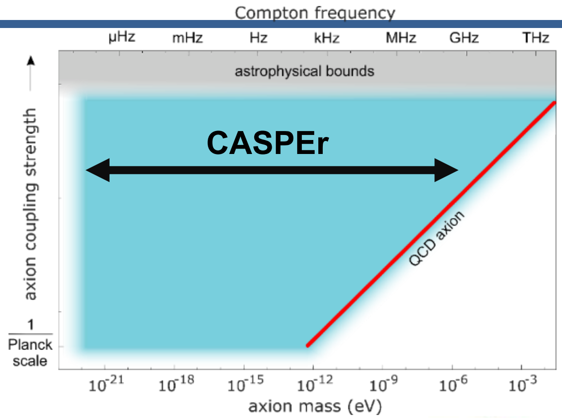
$$\frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$ ← Coupling to fermions

CASPEr Wind

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

CASPEr program

Boston University:
CASPEr-electric using spins in solids
→ sensitive to both $\mathcal{H}_{\mathrm{EDM}} = g_d a \boldsymbol{E}^* \cdot \boldsymbol{I}/I$
$\mathcal{H}_{aNN} = g_{aNN} \boldsymbol{\nabla} a \cdot \boldsymbol{I}$

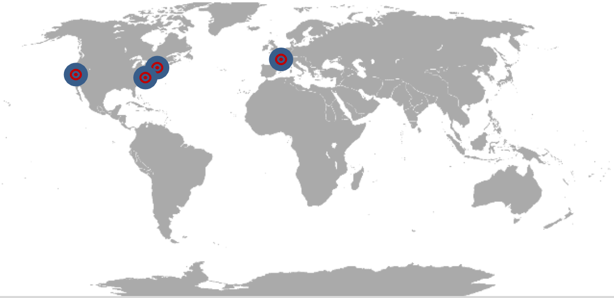



Mainz:
CASPEr-gradient using hyperpolarized liquids
→ sensitive to $\mathcal{H}_{aNN} = g_{aNN} \boldsymbol{\nabla} a \cdot \boldsymbol{I}$




Janos Adam
Stephen Kuenstner
Glenn Randall
Andrew Winter
Tanja Maric

Hendrik Bekker
Arne Wickenbrock
Yuzhe Zhang
John Blanchard
Deniz Aybas



HEISING - SIMONS FOUNDATION
erc
SIMONS FOUNDATION
HIM Helmholtz-Institut Mainz
GORDON AND BETTY MOORE FOUNDATION
Alfred P. Sloan FOUNDATION
Deutsche Forschungsgemeinschaft DFG

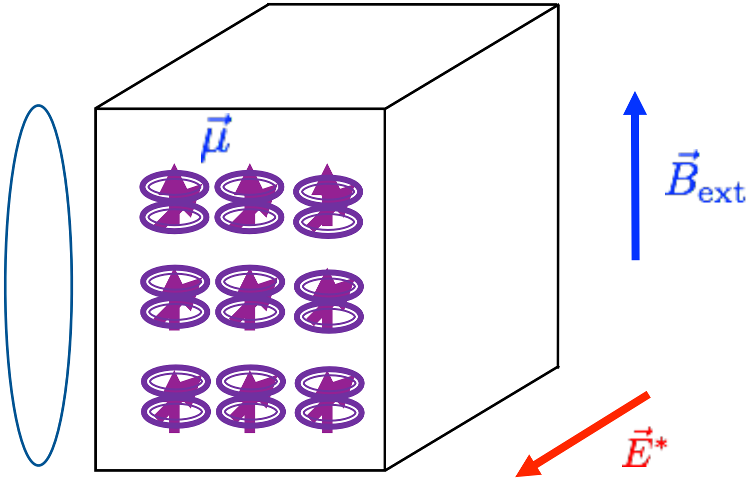
Dmitry Budker, Peter Graham, Derek Kimball, Surjeet Rajendran, Alex Sushkov.

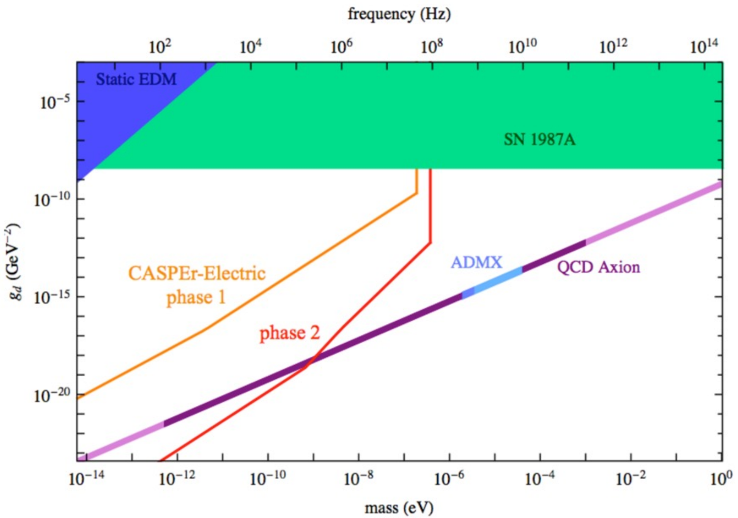
Slide adapted from **Alex Sushkov UCLA DM 2023**

CASPEr-Electric

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

Coupling to gluon field



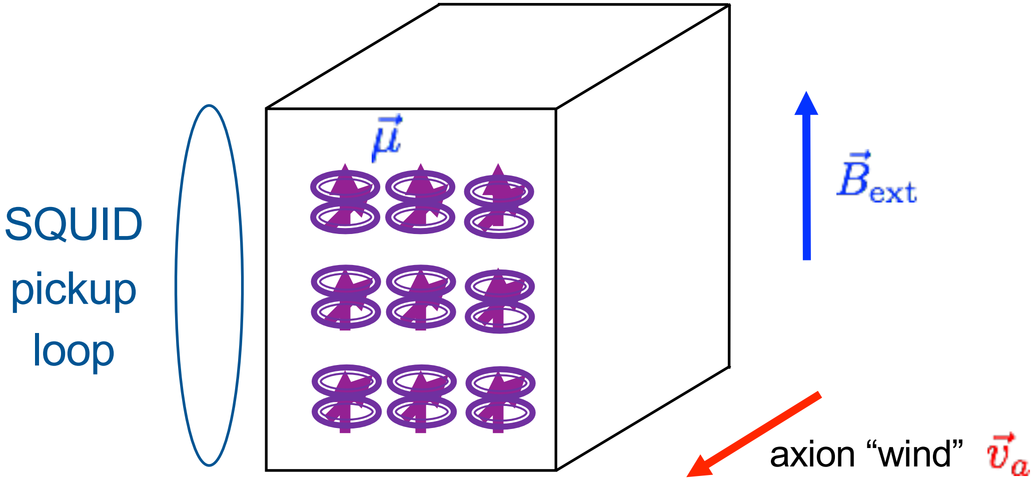


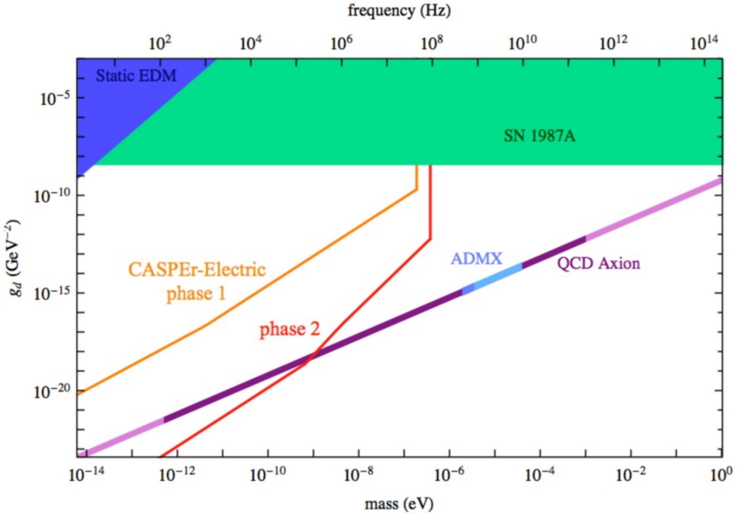
Larmor frequency = axion Compton frequency
➔ resonant enhancement.

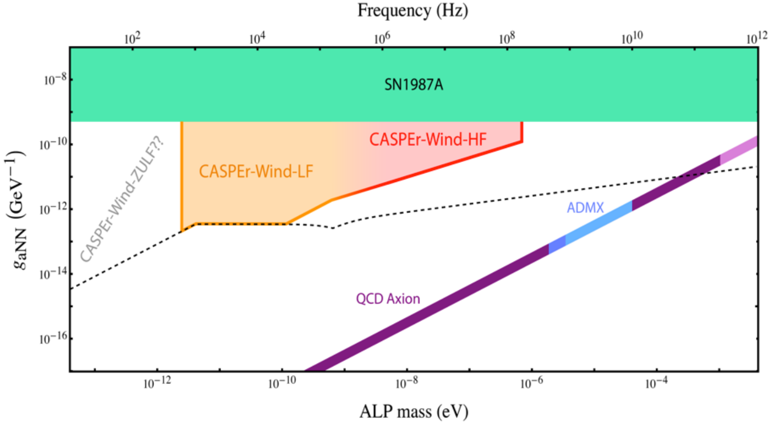
CASPEr-Wind

$$H_{\mathrm{wind}} \approx g_{aNN} \nabla a \cdot \boldsymbol{\sigma}_N \ .$$

Coupling to axion gradient







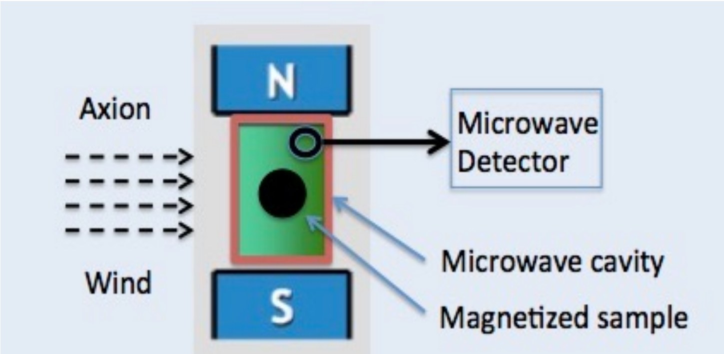
Larmor frequency = axion Compton frequency
➔ resonant enhancement.

Similar strategy for high mass axions (QUAX experiment)

- **Look for an axion "wind"** which acts as an **effective RF magnetic field on electron spin** via **electron-axion coupling**

- This axion induced RF excites **magnetic transition in a magnetized sample** (Larmor frequency) and produces a detectable signal

- The **QUAX** (QUest for AXion) experiment

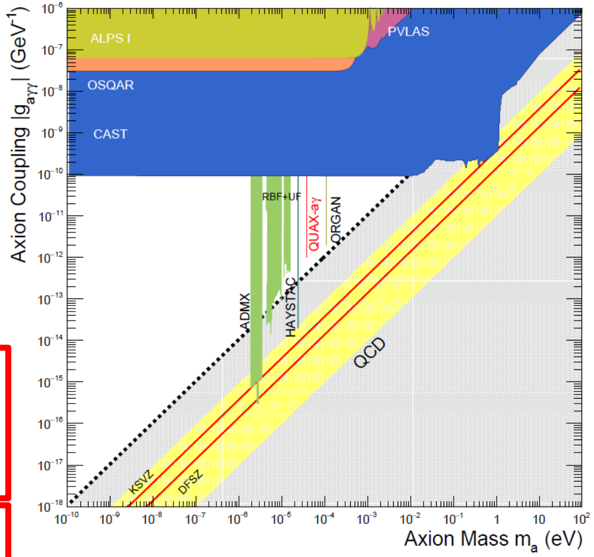


The effective magnetic field associated with the axion wind

$$B_a = \frac{g_p}{2e}\left(\frac{n_a h}{m_a c}\right)^{1/2} m_a v_E$$

$$B_a = 2.0 \cdot 10^{-22}\left(\frac{m_a}{200\,\mu\mathrm{eV}}\right) \quad \mathrm{T},$$

$$\frac{\omega_a}{2\pi} = 48\left(\frac{m_a}{200\,\mu\mathrm{eV}}\right) \quad \mathrm{GHz},$$

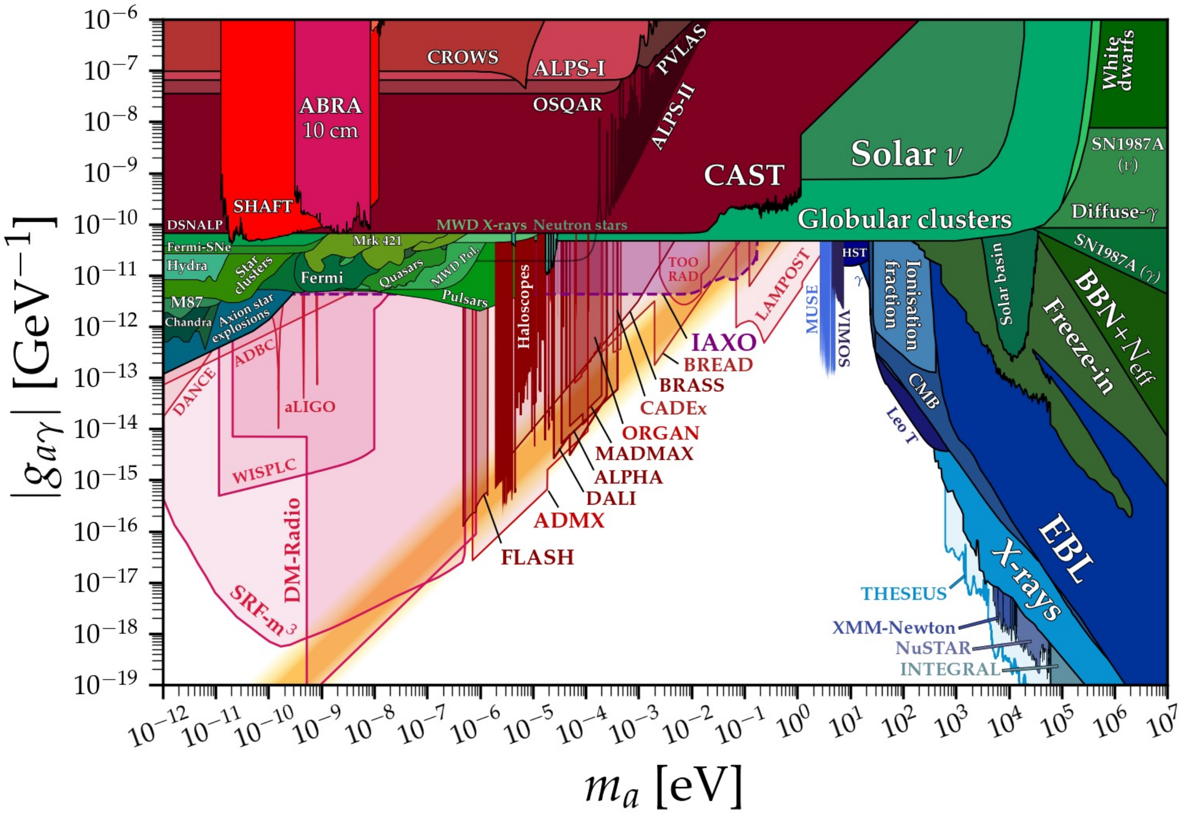


Phys. Rev. D 99, 101101(R)
Published 1 May 2019

- R. Barbieri et al., *Searching for galactic axions through magnetized media: The QUAX proposal* Phys. Dark Univ. **15,** 135 - 141 (2017)

Summary

- Axions solve the strong-CP problem and make a natural Cold Dark Matter candidate
- Dark Matter Detection techniques primarily rely on detection of a coherent signal
    - Current experiments are already near to (or beginning to evade) the quantum limit
    - Exciting experimental prospects and leveraging of quantum enabled technology
- **Potential for discovery (or ruling out large regions of parameter space) high over the next decade!**



Thank you

ADMX Collaboration

This work was supported by the U.S. Department of Energy through Grants No DE-SC0009800, No. DE-SC0009723, No. DE-SC0010296, No. DE-SC0010280, No. DE-SC0011665, No. DEFG02-97ER41029, No. DE-FG02-96ER40956, No. DEAC52- 07NA27344, No. DE-C03-76SF00098 and No. DE-SC0017987. Fermilab is a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02- 07CH11359. Additional support was provided by the Heising-Simons Foundation and by the Lawrence Livermore National Laboratory and Pacific Northwest National Laboratory LDRD offices.

Backup Slides

ADMX Collaboration

- Experiment formed in 1994 at LLNL
- Currently one of the 3 “Generation-2” Dark Matter Projects (along with LZ & SuperCDMS-SNOLAB)
- Now located at the U. of Washington

Sponsors

ADMX now DOE Gen 2 project

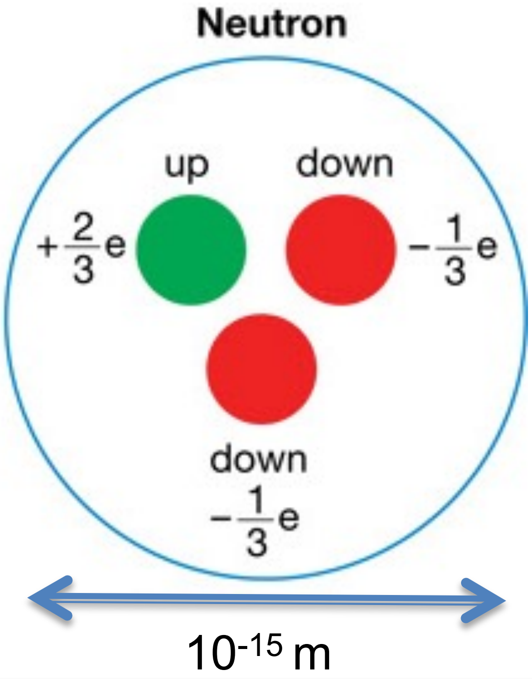
Primary sponsor

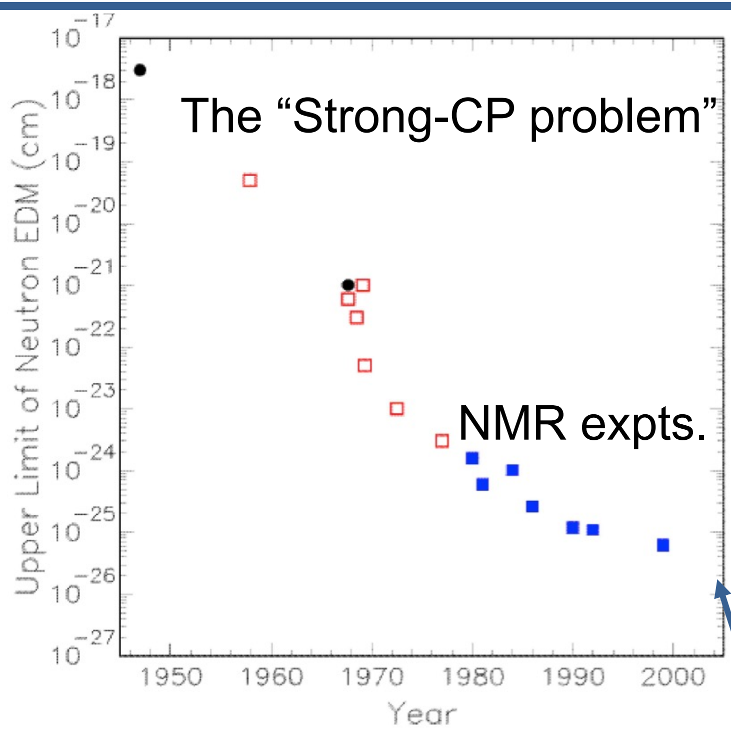
Supported by U.S. Department of Energy through Awards No. DE-SC0009723, No. DESC0010296, No. DE-SC0010280, No. DE-SC0010280, No. DE-FG02-97ER41029, No. DE-FG02-96ER40956, No. DE-AC52-07NA27344, and No. DE-C03- 76SF00098. Fermi Research Alliance, LLC under Grant No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics. Additional support was provided by the Heising-Simons Foundation and by the Laboratory Directed Research and Development offices of the Lawrence Livermore and Pacific Northwest National Laboratories

Another mystery of physics:

Why is the neutron electric dipole moment so small?

Naive estimate gives
$d_n \approx 10^{-16}$ e-cm



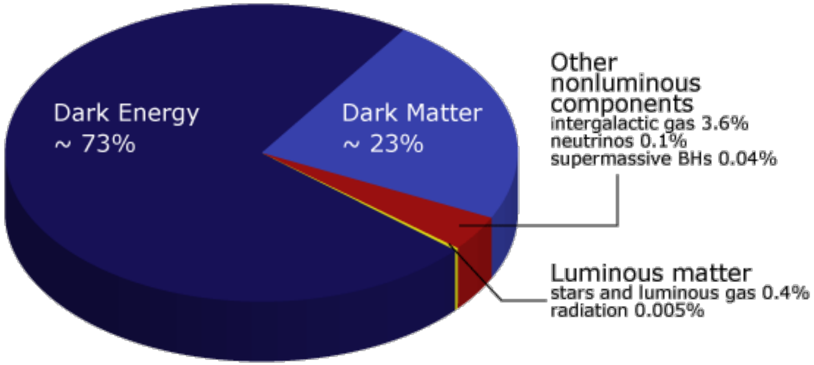


$$d_n = (0.0 \pm 1.1_{stat} \pm 0.2_{sys}) \times 10^{-26} e \cdot cm$$

C. Abel et al.
Phys. Rev. Lett. 124, 081803 — Published 28 February 2020

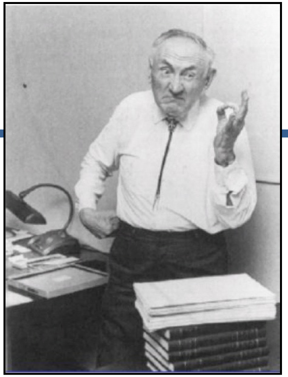
The Nature of Dark Matter

One of the premier unsolved mysteries in physics



1930s

Fritz Zwicky: noticed odd motion of member galaxies of the Coma Cluster

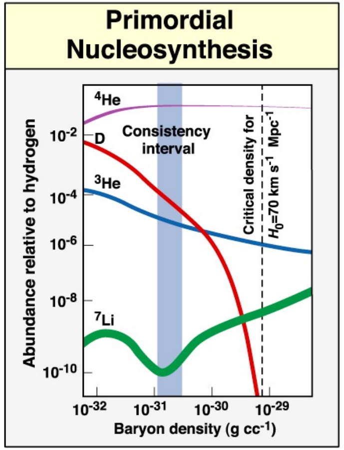


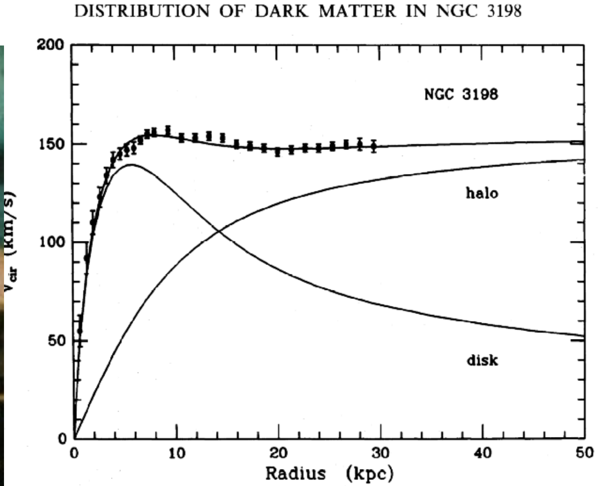
1980s

Vera Rubin: Galaxy rotation curves did not make sense without a large unseen mass

Additional DM Talks at this Summer School

- **Tim Tait (Theory), Tracy Slatyer (Indirect DM Exp), Jodi Cooley (WIMP DM Exp)**
- **Superconducting detectors: Kent Irwin (TES) & Zeeshan Ahmed (CMB)**





Peccei-Quinn Solution to the Strong-CP problem

- <u>Mystery of why the neutron doesn't have a measurable electric dipole</u>

- <u>Peccei & Quinn</u>: Postulated new U(1) symmetry that would be spontaneously broken.

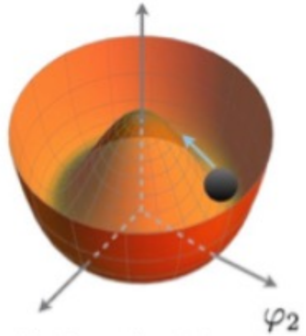
- <u>Weinberg & Wilczek</u>: A new Goldstone boson (dubbed the axion)

- Remnant axion vacuum expectation value nulls QCD CP violation.

- <u>Only free parameter</u>: Symmetry breaking scale (f_a)

"Invisble Axion": f_a >> Weak Scale (dark matter candidate)

- <u>Two general classes of models</u>
  - **KSVZ** [Kim (1979), Shifman, Vainshtein, Sakharov (1980)]:
    - *Couples to leptons*
  - **DFSZ** [Dine, Fischler, Srednicki (1981), Zhitnitsky (1980)]
    - *Couples to quarks & leptons*



Oscillation about the QCD minimum – *Daniel Grin*

Roberto Peccei
1942-2020

Helen Quinn

Steven Weinberg

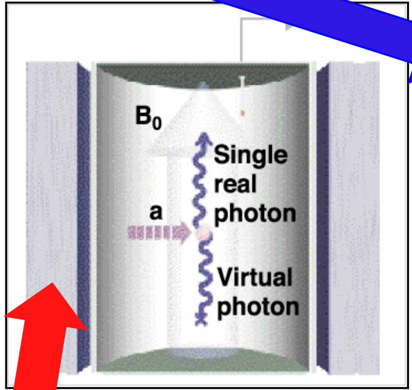
Frank Wilczek

Signal to noise dictates search strategy

$$\frac{s}{n} = \frac{P_{sig}}{kT_S} \cdot \sqrt{\frac{t}{\Delta\nu}}$$

Integration time limited to ~ 100 sec

** Dicke, 1946*



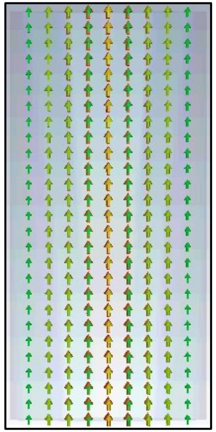
System noise temp.

$$T_S = T_{phys} + T_N$$

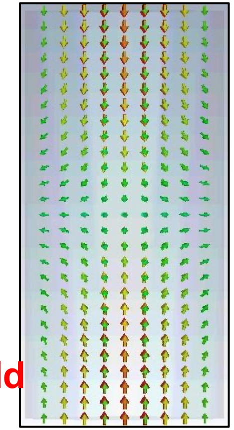
T_{Quant} *~ 48 mK @ 1 GHz*

Gen2: Dilution Fridge + Quantum-limited amps

TM_{010} mode
C_{010} ~ 0.69



TM_{011} mode
C_{011} ~ 0.0



B-field

$$P_{sig} \sim (B^2 V\, Q_{cav} C_{010})(g^2 m_a \rho_a)$$

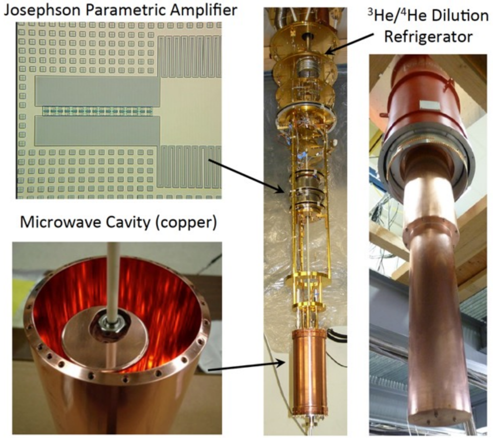
~ 10^{-23} *Watts for ADMX*

$$\frac{df}{dt} \approx 1.68\ \mathrm{GHz/year} \left(\frac{g_\gamma}{0.36}\right)^4 \left(\frac{f}{1\ \mathrm{GHz}}\right)^2 \left(\frac{\rho_0}{0.45\ \mathrm{GeV/cc}}\right)^2 \cdot \left(\frac{5}{SNR}\right)^2 \left(\frac{B_0}{8\ \mathrm{T}}\right)^4 \left(\frac{V}{100\mathrm{l}}\right)^2 \left(\frac{Q_L}{10^5}\right) \left(\frac{C_{010}}{0.5}\right)^2 \left(\frac{0.2\ K}{T_{sys}}\right)^2$$

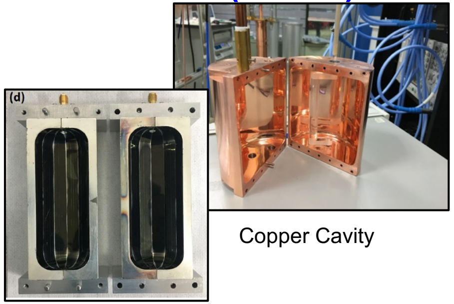
Additional Haloscopes Worldwide

Several other groups have started to take haloscope data
A variety of technological enhancements being explored:
- Novel Cavity Geometries
- Superconducting Cavities (B-field tolerant)
- Squeezed Amplifiers

HAYSTAC (NSF)



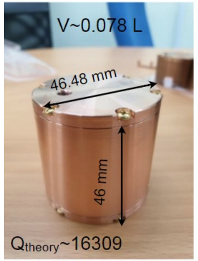
CAPP (Korea)



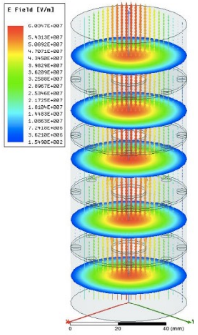
superconducting cavity (YBCO)

Copper Cavity

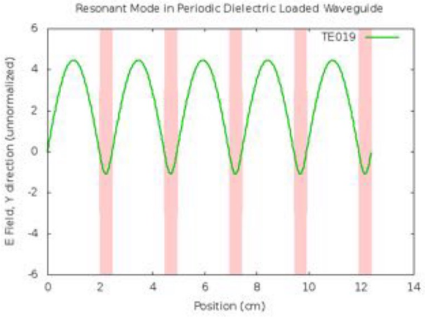
TASEH (Tawian)



Single-frequency cavity

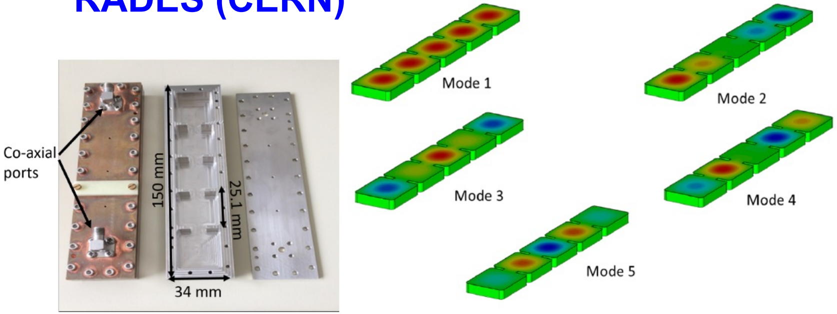

Periodic cavity

ORPHEUS (UW)



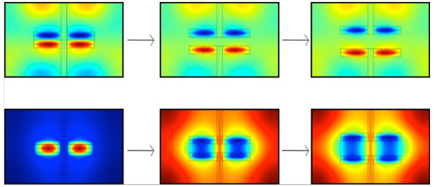
Sapphire loaded cavities can utilize higher order modes

RADES (CERN)



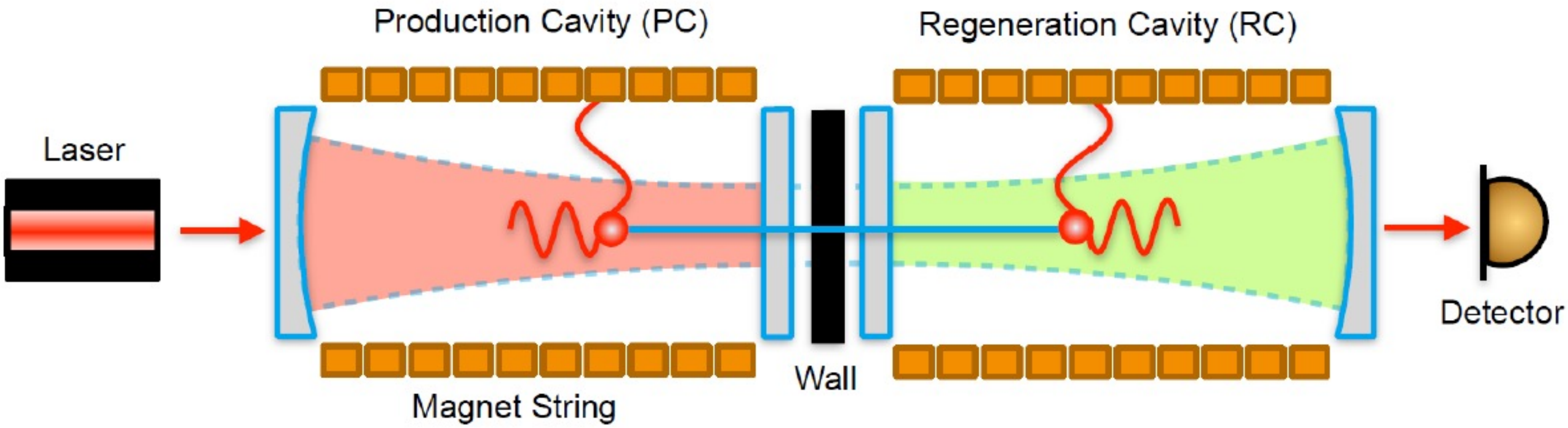
Uses CAST dipole

ORGAN (Australia)



Please see broader details in community whitepaper
https://arxiv.org/pdf/2203.14923.pdf

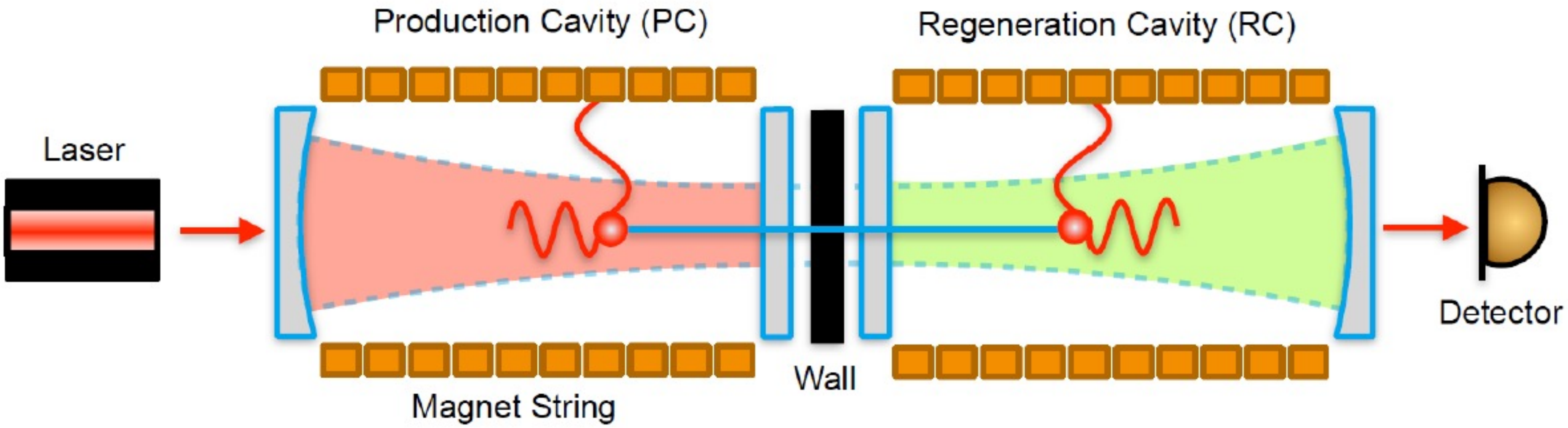
Laser searches for Axion-Like-Particles (ALPS-II experiment)



12+12 dipole magnets from the HERA proton accelerator

Production cavity and regeneration cavity, mode matched

Laser searches for Axion-Like-Particles (ALPS-II experiment)



$$P_{\gamma\to\phi\to\gamma} = \frac{1}{16}\cdot\mathcal{F}_{PC}\mathcal{F}_{RC}\cdot(g_{a\gamma\gamma}Bl)^4 = 6\cdot 10^{-38}\cdot\mathcal{F}_{PC}\mathcal{F}_{RC}\cdot\left(\frac{g_{a\gamma\gamma}}{10^{-10}GeV^{-1}}\frac{B}{1T}\frac{l}{10m}\right)^4$$

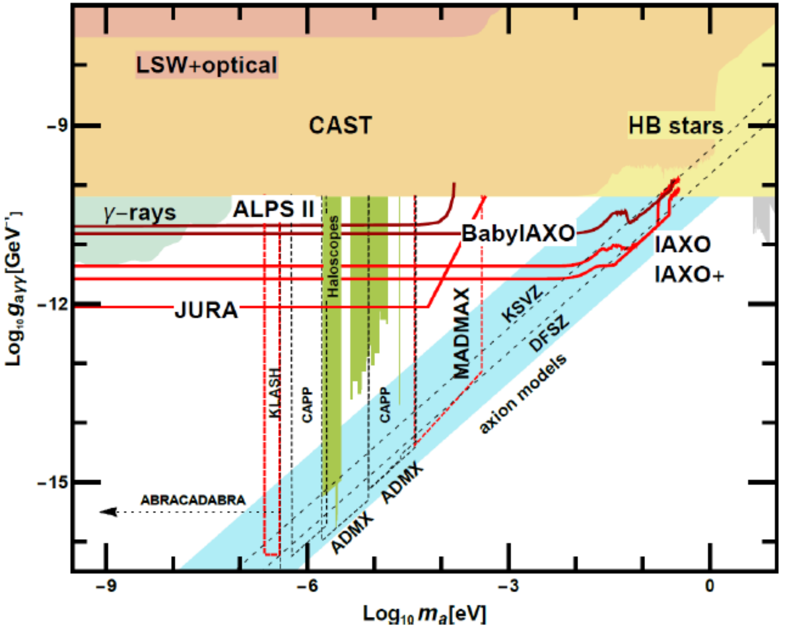
= 10^{-25} W (using 30 W cw laser) 5.000 40.000 0.2 5.3 10.56

Laser searches for Axion-Like-Particles (ALPS-II experiment)

JURA

- Magnetic field strength: 13 T
- Magnetic length: 426 m
- Light wavelength: 1064 nm
- Circulating light power: 2.5 MW
- Power built-up behind the wall: 10^5
- Detector sensitivity: 10^{-4} s^{-1}

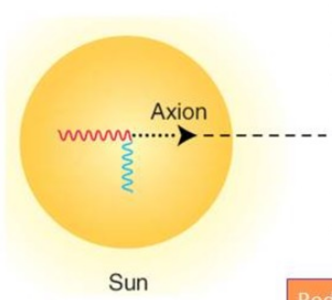
10 · ALPS II

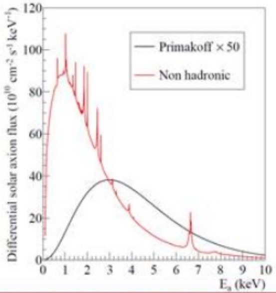


JURA could allow to probe for very lightweight ALPs in the laboratory even beyond the IAXO reach.
It would be a (costly) about 1km long apparatus.

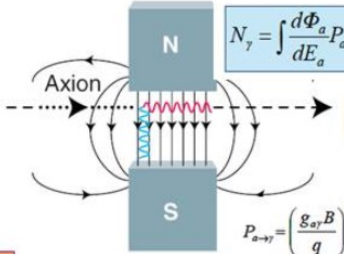
If ALPS II fulfills expectations, JURA should be feasible. Dipole magnet R&D is essential.

CAST (Cern Axion Solar Telescope)





Redondo JCAP 1312 008 (2013)

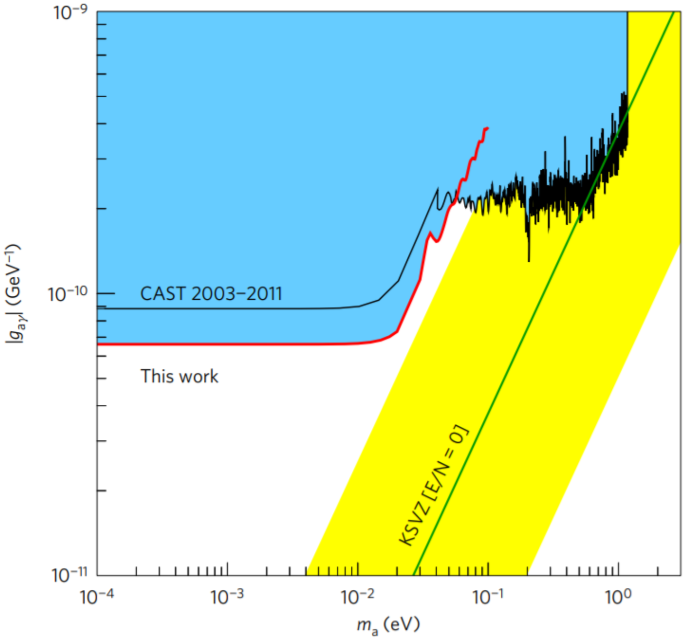


$$N_\gamma = \int \frac{d\Phi_a}{dE_a} P_{a\to\gamma} S\,t\,dE_a \;\propto\; g_{a\gamma}^4$$

$$P_{a\to\gamma} = \left(\frac{g_{a\gamma}B}{q}\right)^2 \sin^2\left(\frac{qL}{2}\right) \qquad q = \frac{m_a^2}{2E}$$

- Idea refined by K. van Bibber by using buffer gas to restore coherence over long magnetic field

Van Bibber et al. *Phys.Rev. D 39*:2089 (1989)



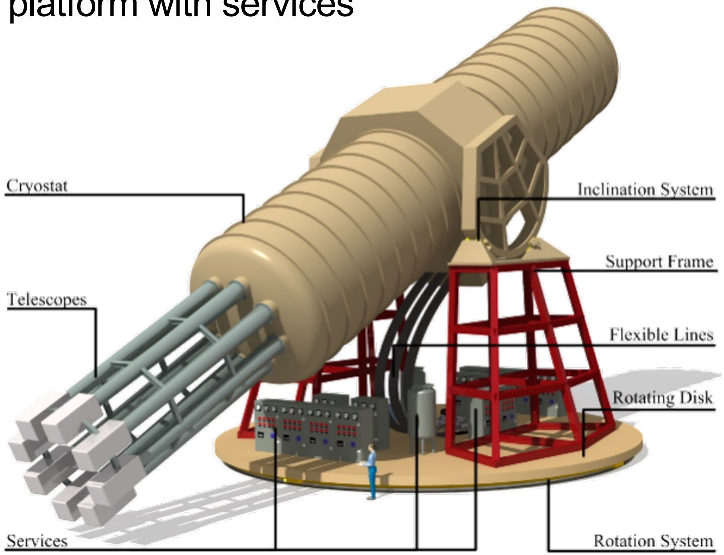
CAST best limits for relatively high mass (~eV) axions

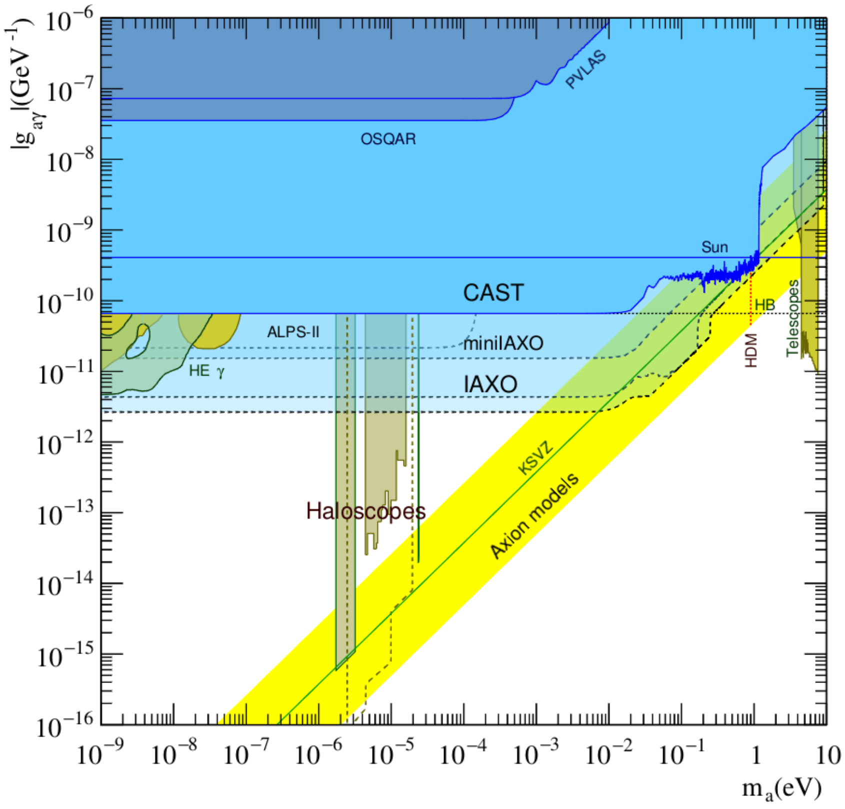
New CAST limit on the axion–photon interaction

CAST Collaboration *Nature Physics* **volume 13**, pages584–590(2017)

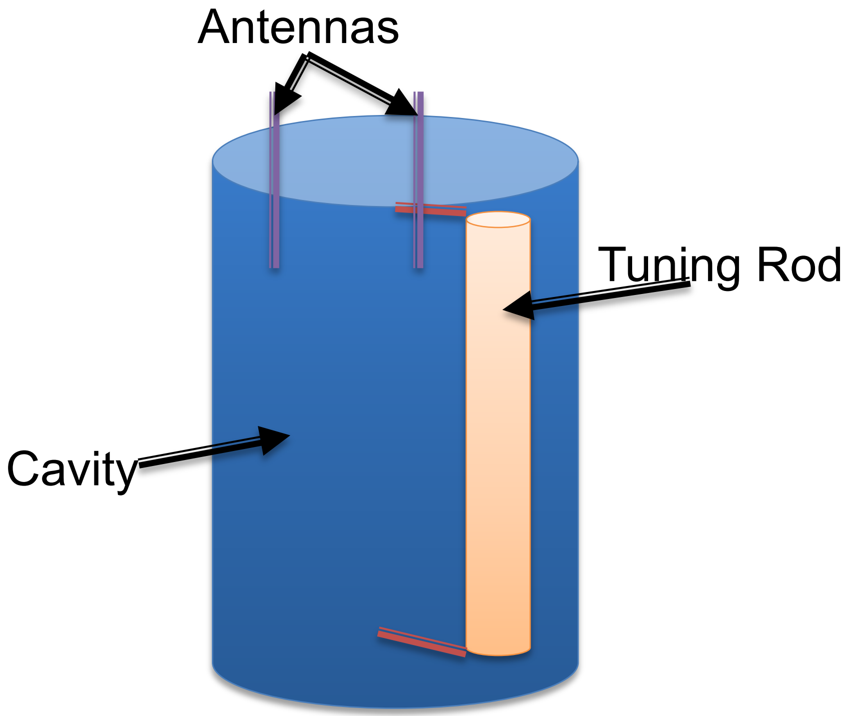
IAXO (International AXion Observatory)

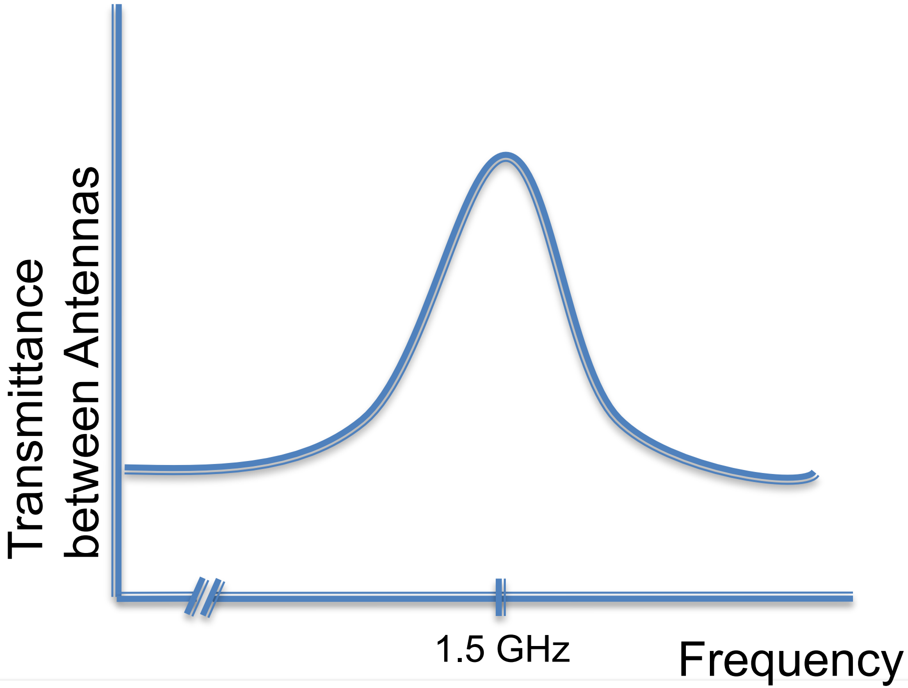
- Large toroidal 8-coil magnet L = ~20 m
- 8 bores: 600 mm diameter each
- 8 x-ray telescopes + 8 detection systems
- Rotating platform with services



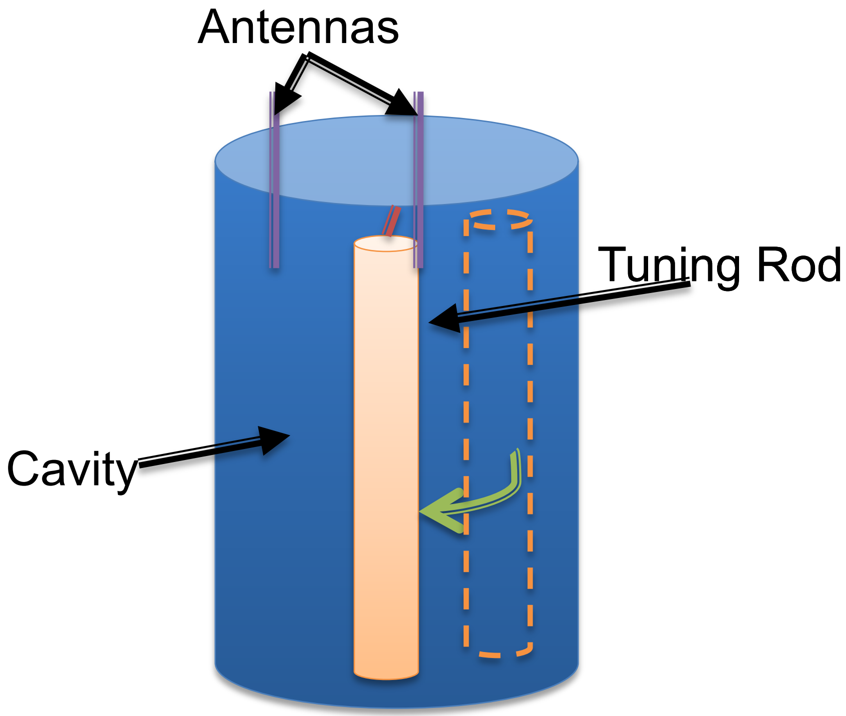


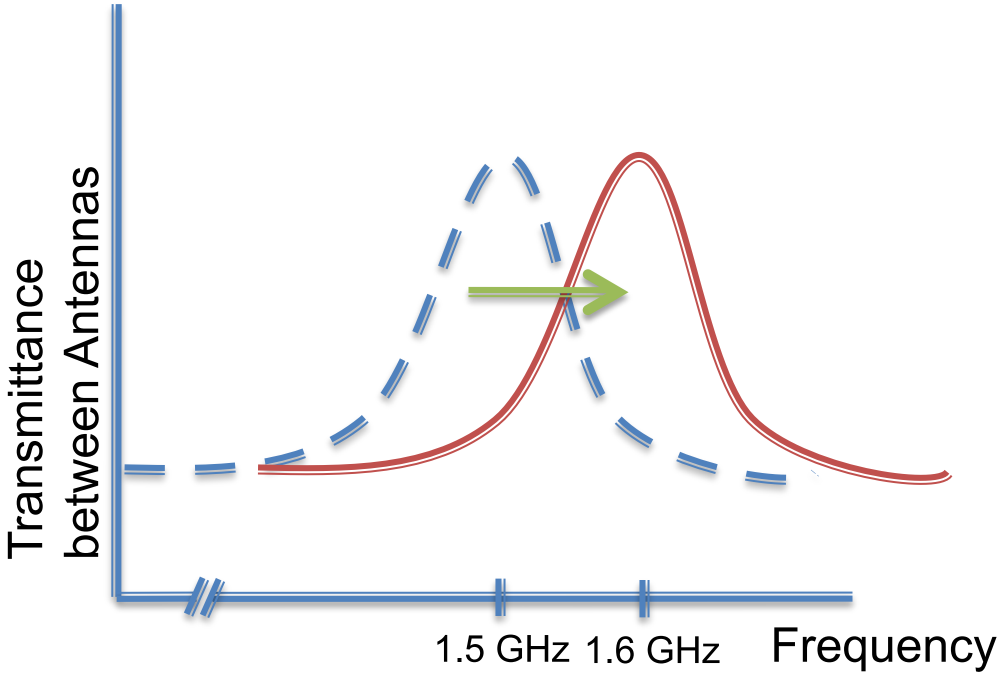
Microwave Cavity needs tunable resonance





Microwave Cavity needs tunable resonance





* LLNL sponsored HMC Clinic Final Presentation – 2010