Axion Detection Experiments

PPC 2022: XV International Conference on Interconnections between Particle Physics & Cosmology

Gianpaolo Carosi
June 6th, 2022

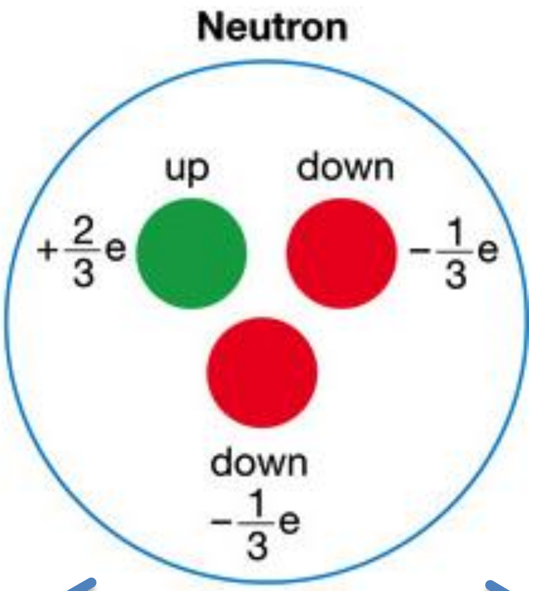
Rare Event Detection

LLNL-PRES-835851
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

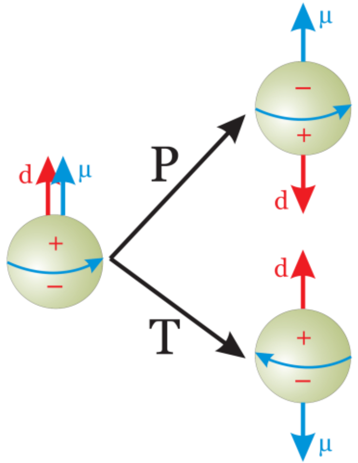
Lawrence Livermore National Laboratory

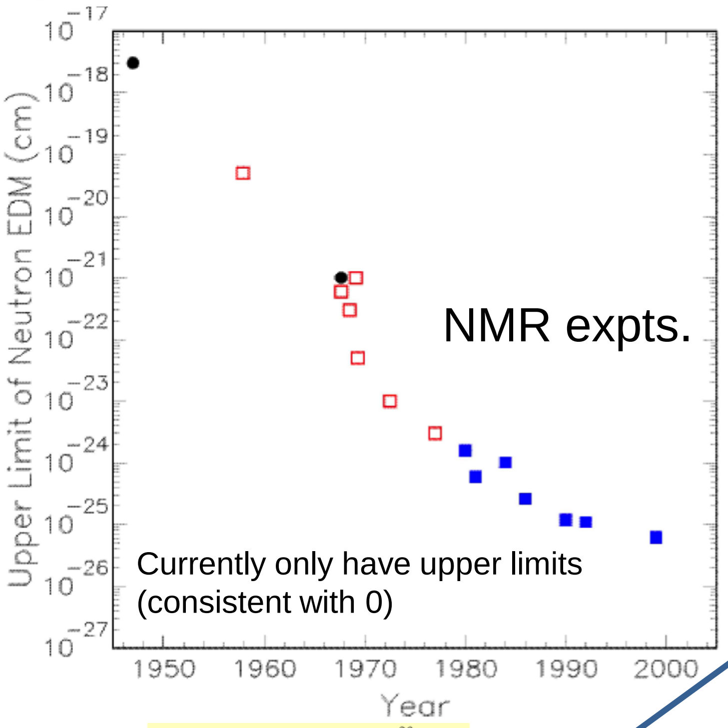
The Strong-CP problem:
or the conspicuous absence of the neutron electric dipole moment!

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



10^{-15} m



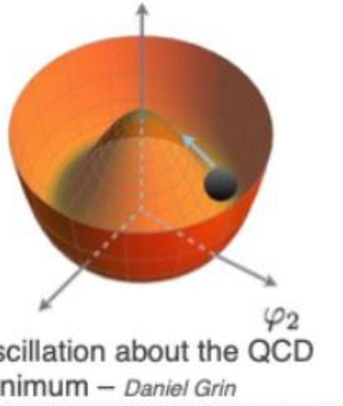


$d_n = (0.0 \pm 1.1_{stat} \pm 0.2_{sys}) \times 10^{-26}$ e·cm

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

Peccei-Quinn Solution to the Strong-CP problem

- Mystery of why the neutron doesn't have a measurable electric dipole
- Peccei & Quinn: Postulated new U(1) symmetry that would be spontaneously broken.
- Weinberg & Wilczek: A new Goldstone boson (dubbed the axion)
- Remnant axion vacuum expectation value nulls QCD CP violation.
- Only free parameter: Symmetry breaking scale (f_a)



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

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

Roberto Peccei
1942-2020

Helen Quinn

Steven Weinberg
1933-2021

Frank Wilczek

Axion Couplings

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

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

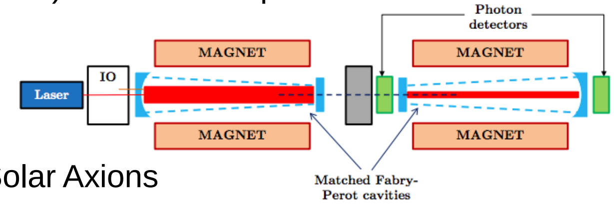
Adapted from L. Winslow DPF slide and Y. Kahn, See Graham and Rajendran, Phys.Rev. D88 (2013) 035023

Types of axion experiments

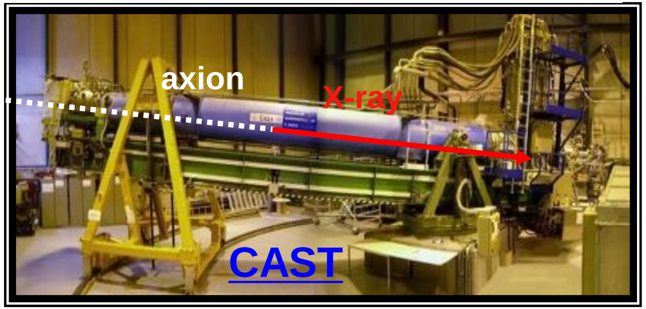
Snowmass 2021 White Paper
Axion Dark Matter

J. Jaeckel[1], G. Rybka[2], L. Winslow[3], and the Wave-like Dark Matter Community [4]

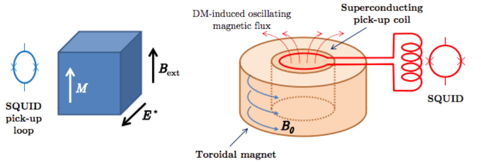
Laboratory Experiments: Lasers (light shining through walls) & 5th force experiments

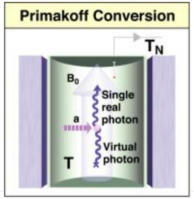


Solar Axions

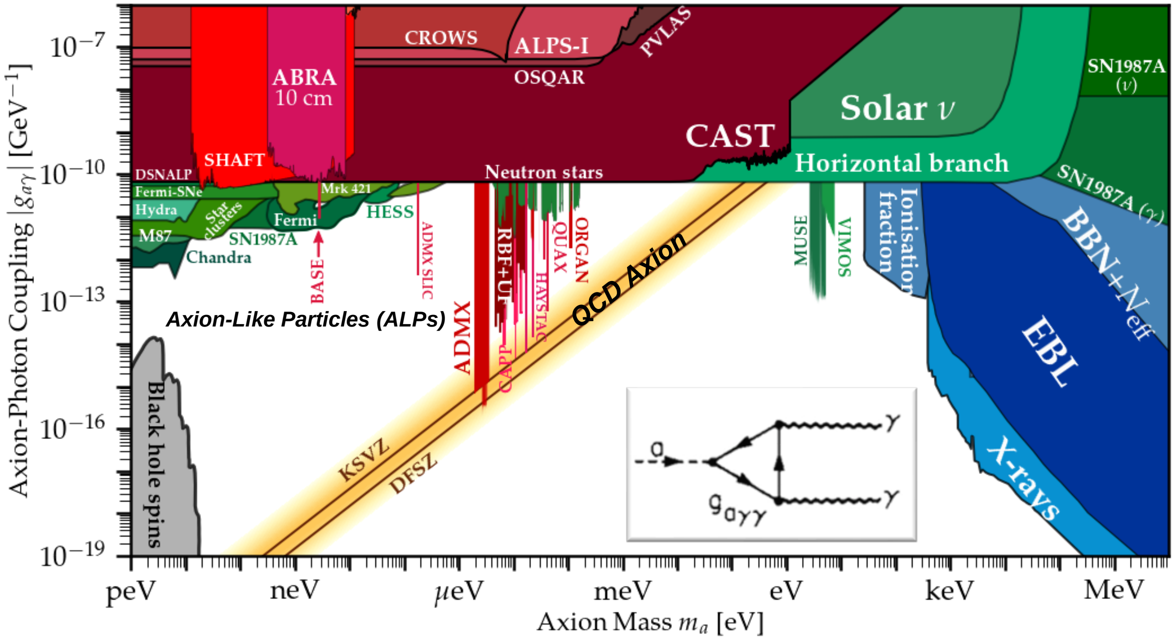


Axions from Dark Matter (Haloscopes, NMR, etc)

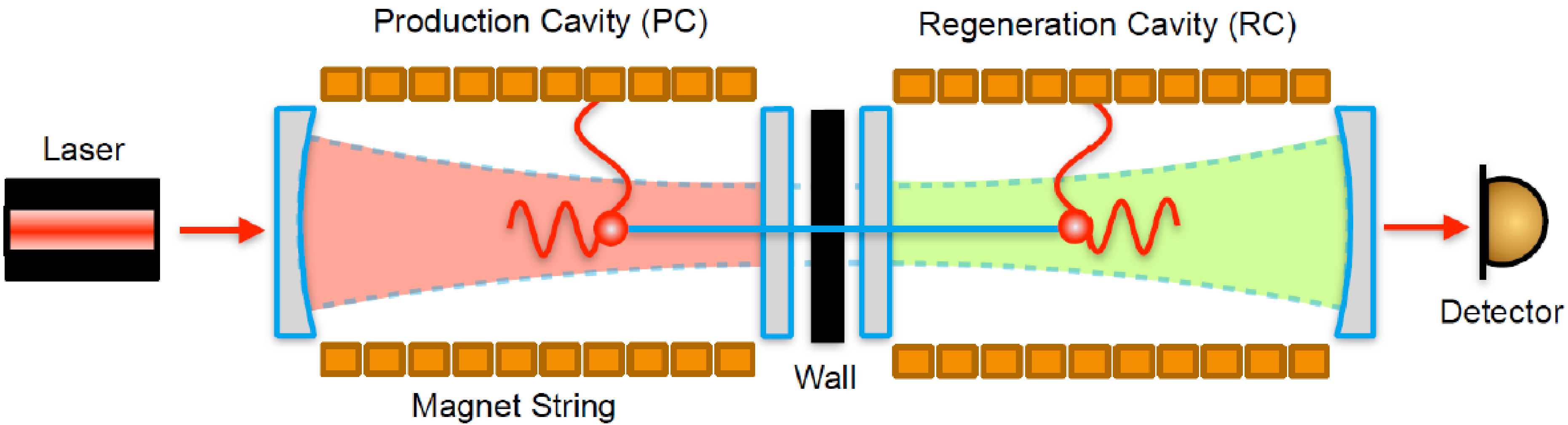




Please see broader details in community whitepaper
https://arxiv.org/pdf/2203.14923.pdf



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

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

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

ALPS-II experiment: Current Status at DESY

Status June 2022:

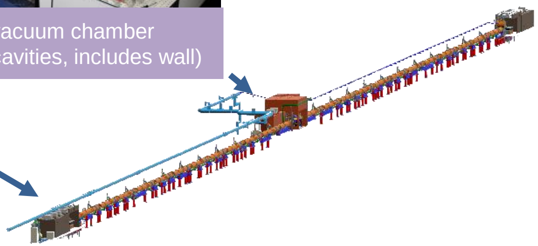
- Magnet string and infrastructure completed.
  - October 2020:
    last magnets (23 and 24) installed
  - December 2021:
    magnet string cooled down to 4.2 K
  - March 2022:
    test operation of magnet string at full current

- **Optics installation and commissioning progressing now.**
  - April 2021:
    start of optics installation.
  - June 2021:
    lock of 250 m cavity (whole exp., no wall)
    characterize noise.
  - May 2022:
    installation of optics in the
    central vacuum chamber.
  - May 2022:
    lock of regeneration cavity.

- **November 2022:**
  early science run (without production cavity).
- **1st quarter 2023:**
  science run with the full optical system.

central vacuum chamber
(match both cavities, includes wall)

high power laser light injection

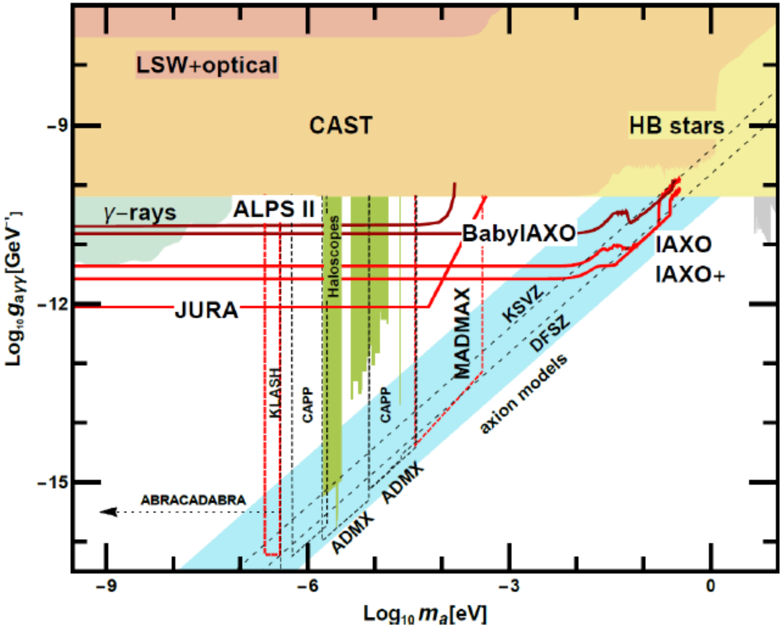


Beyon ALPS-II experiment

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}

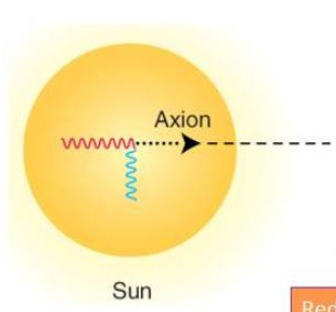
(13 T and 426 m: 10 · ALPS II)

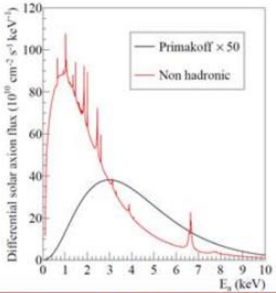


JURA could allow to probe for very lightweight ALPs in the laboratory even beyond the IAXO reach.
It would be a (costly) about 1km long apparatus.

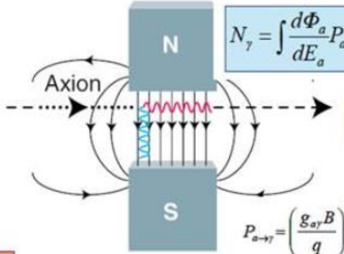
If ALPS II fulfills expectations, JURA should be feasible. Dipole magnet R&D is essential.

CAST (Cern Axion Solar Telescope)





Redondo JCAP 1312 008 (2013)

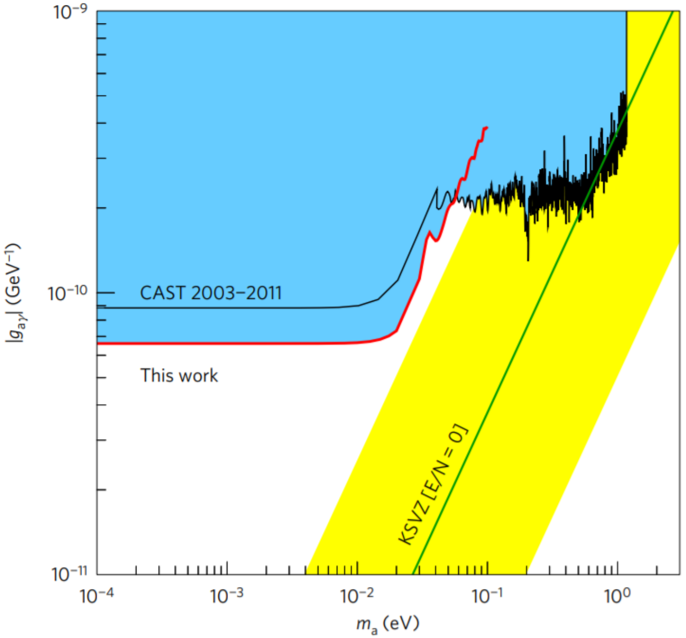


$$N_\gamma = \int \frac{d\Phi_a}{dE_a} P_{a\to\gamma} S\, t\, dE_a \quad \propto \quad g_{a\gamma}^4$$

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

- 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

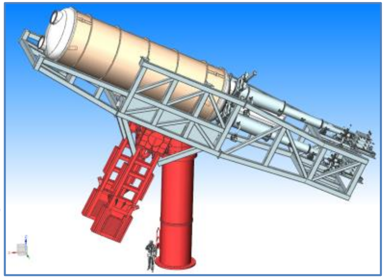
CAST Collaboration *Nature Physics* **volume 13**, pages584–590(2017)

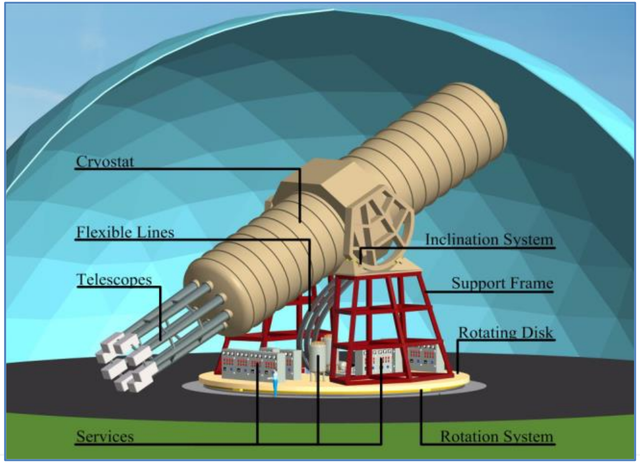
IAXO (International AXion Observatory)

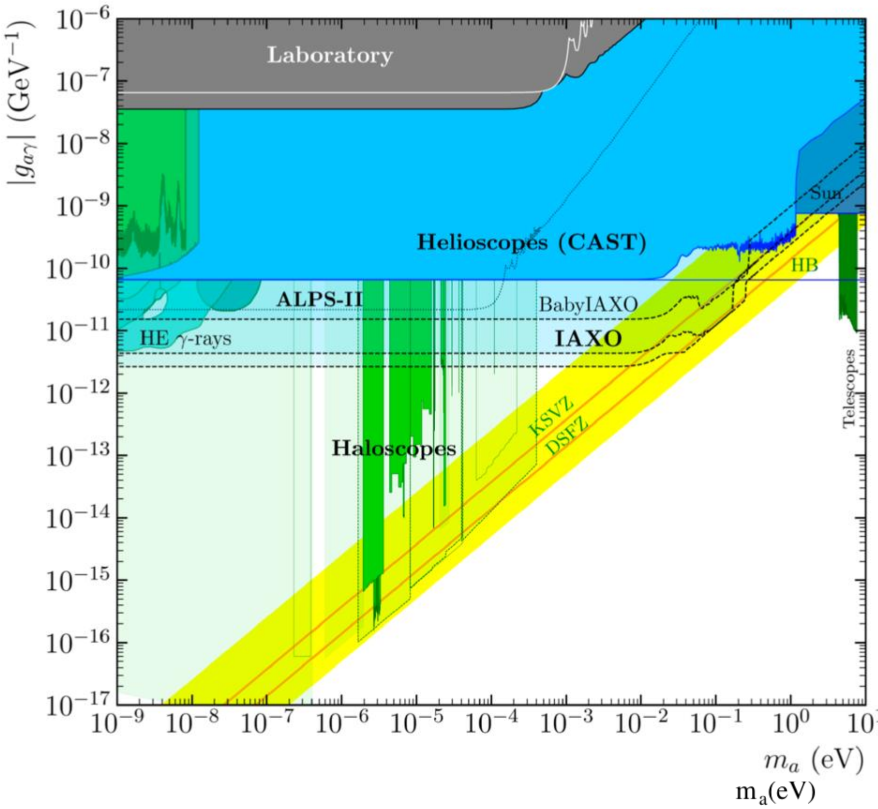
- Large toroidal 8-coil magnet L = 20 m
- 8 bores: 600 mm diameter each
- 8 x-ray telescopes + 8 detection systems
- Rotating Platform
- Currently supported at DESY, Germany

- Near term work on BabyIAXO demonstrator
  - Anticipated data taking in 2024

- Full IAXO expected 2030s





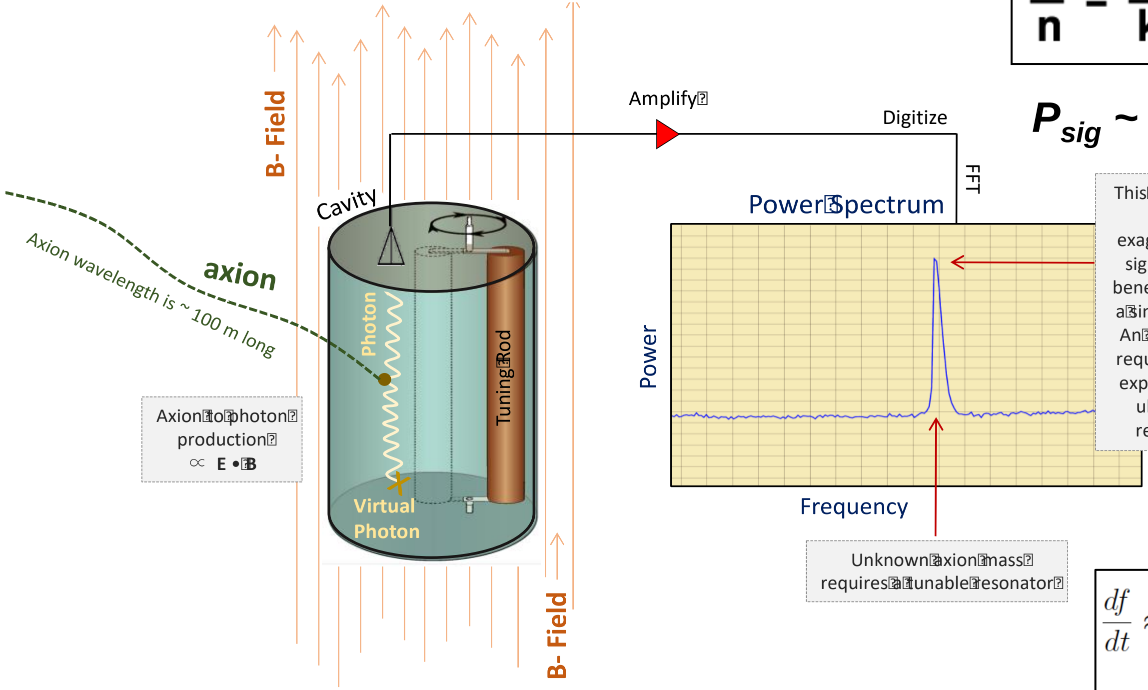


Axion Dark Matter Searches: The Axion Haloscope Technique

Pierre Sikivie
PRL 51:1415 (1983)

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

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



System noise temp.

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

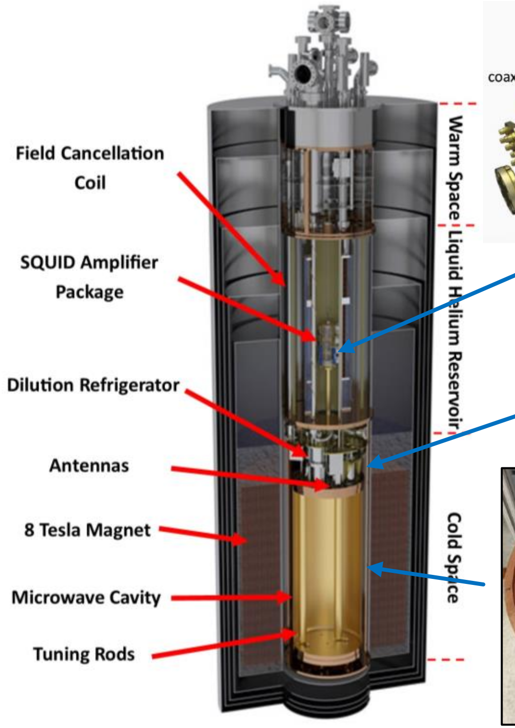
$$T_{Quant} \sim 48\ mK\ @\ 1\ GHz$$

t = Integration time limited to ~ 100 sec

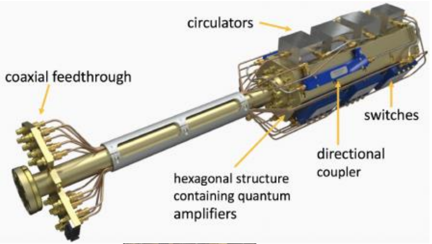
$$\frac{df}{dt} \approx 1.68\ \mathrm{GHz/year} \left(\frac{g_\gamma}{0.36}\right)^4 \left(\frac{f}{1\ \mathrm{GHz}}\right)^2 \left(\frac{\rho_0}{0.45\ \mathrm{GeV/cc}}\right)^2 \cdot \left(\frac{5}{SNR}\right)^2 \left(\frac{B_0}{8\ \mathrm{T}}\right)^4 \left(\frac{V}{100\mathrm{l}}\right)^2 \left(\frac{Q_L}{10^5}\right)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

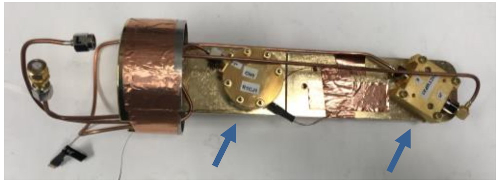
ADMX Experimental Layout

[WUSTL group leads our Quantum Electronics efforts!]



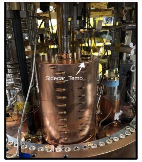
Cavity 1B



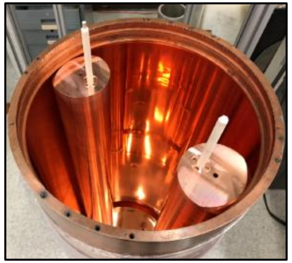


JPA)

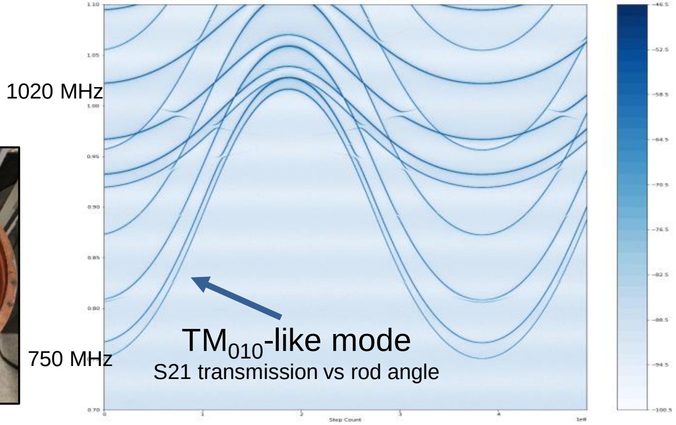
TWPA



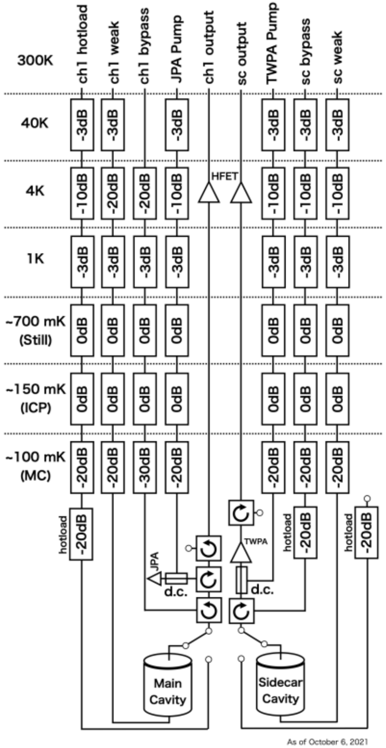
Sidecar



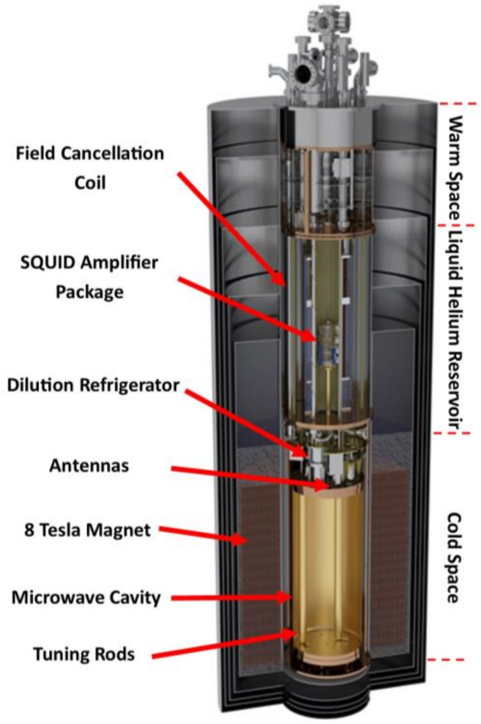
Cavity 1C

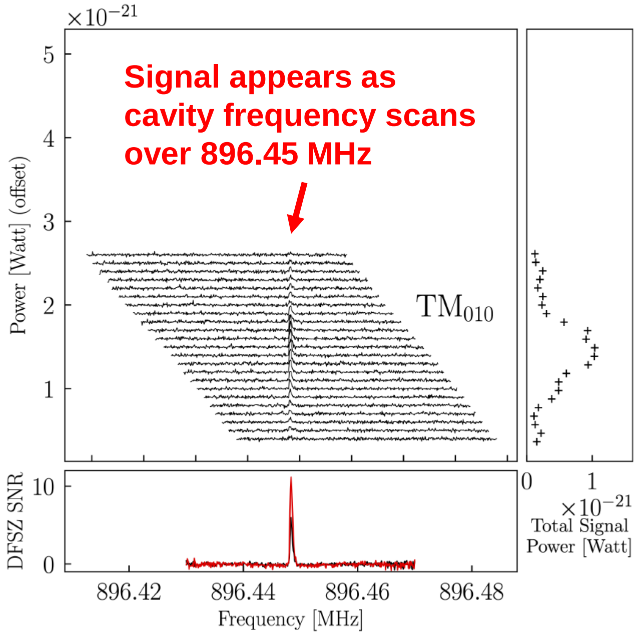


Cavity 1C Mode Map



ADMX Run 1C: Persistent Signal at 896.45 MHz!





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

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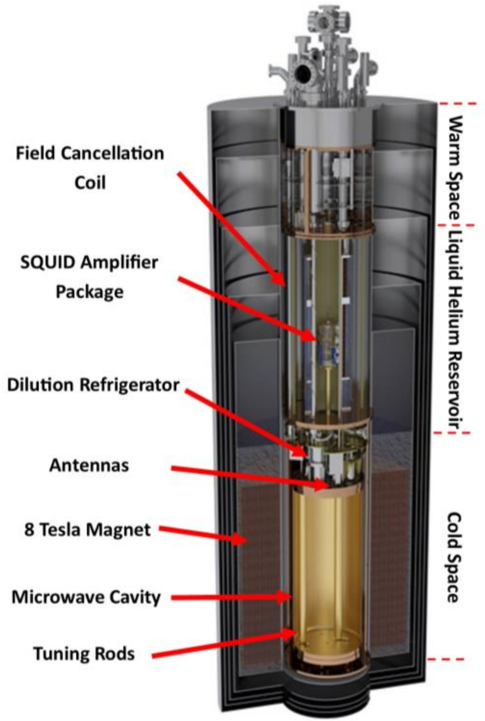

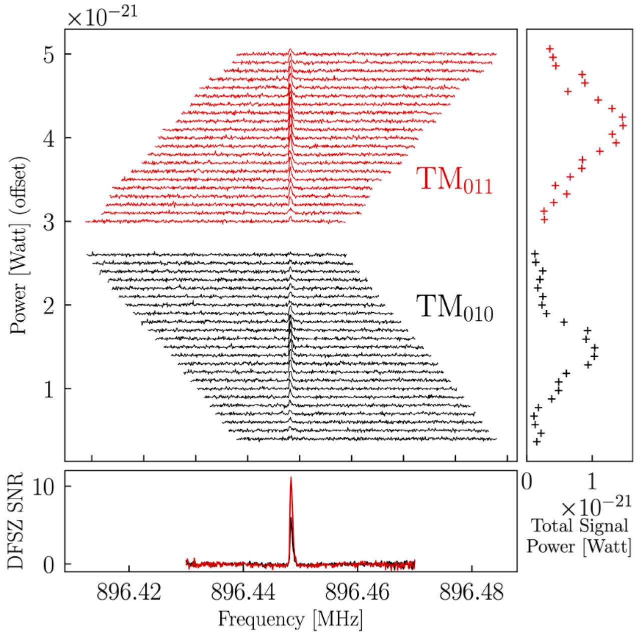

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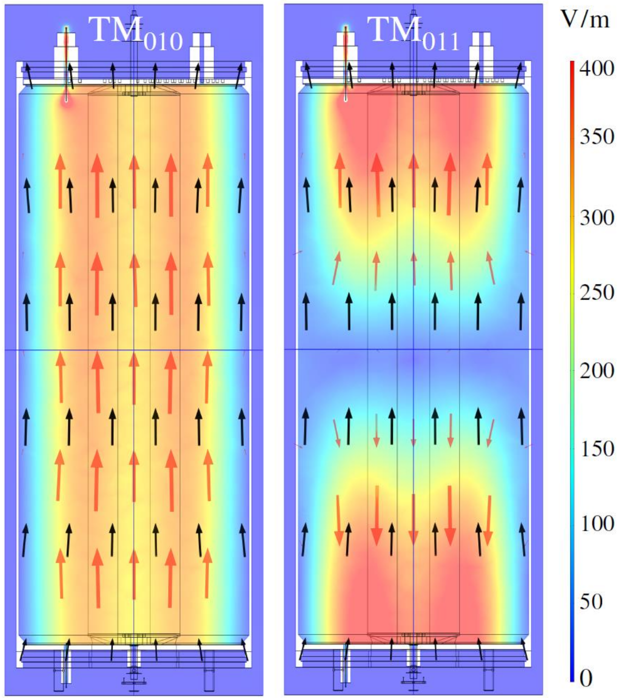


Seen in TM_{011} mode as well
Fake axion from Blind Injection team

ADMX latest data run covers new dark matter mass range

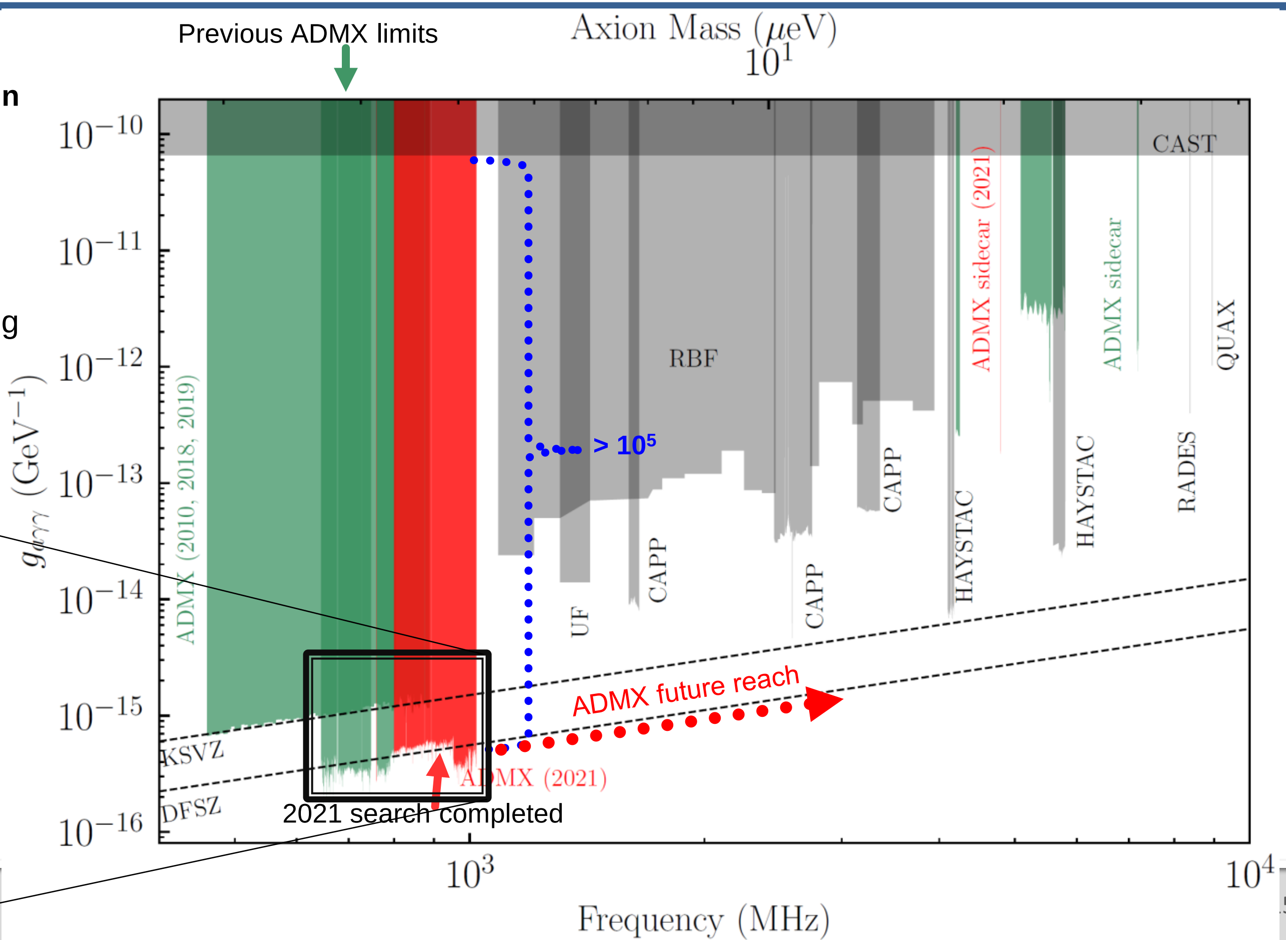
2019-2020 data run

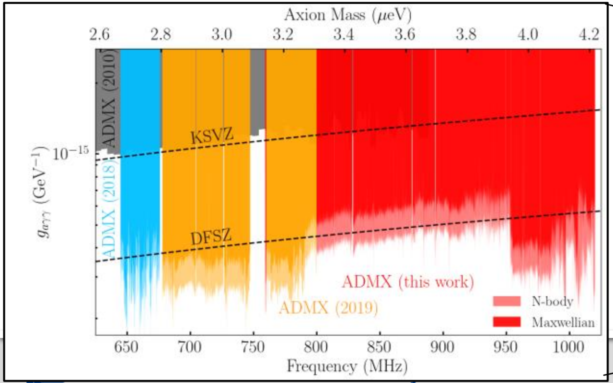
Search for "Invisible" Axion Dark Matter in the 3.3-4.2 μeV Mass Range:

Includes mass range never explored by any dark matter haloscope before

Planning to complete run 1C at DFSZ sensitivity by Fall 2022 (required repairing vacuum leak… testing as we speak)

Run 1D (1-1.4 GHz) and Run 2A (1.4-1.9 GHz) to follow soon after



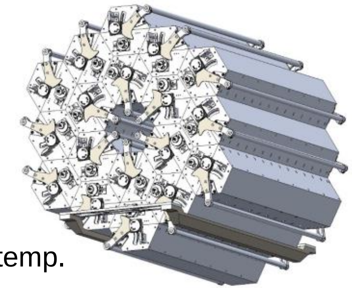


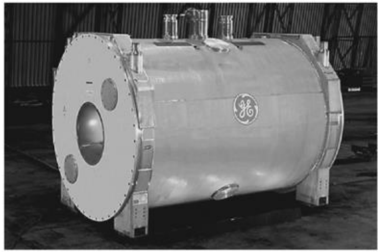
ADMX Extended Frequency Range (ADMX-EFR)

Dark Matter New Initiative: ADMX 2-4 GHz project
- Explores axion mass range from 8.3-16.5 μeV to DFSZ
- Picks up where ADMX-G2 ends (~2 GHz)

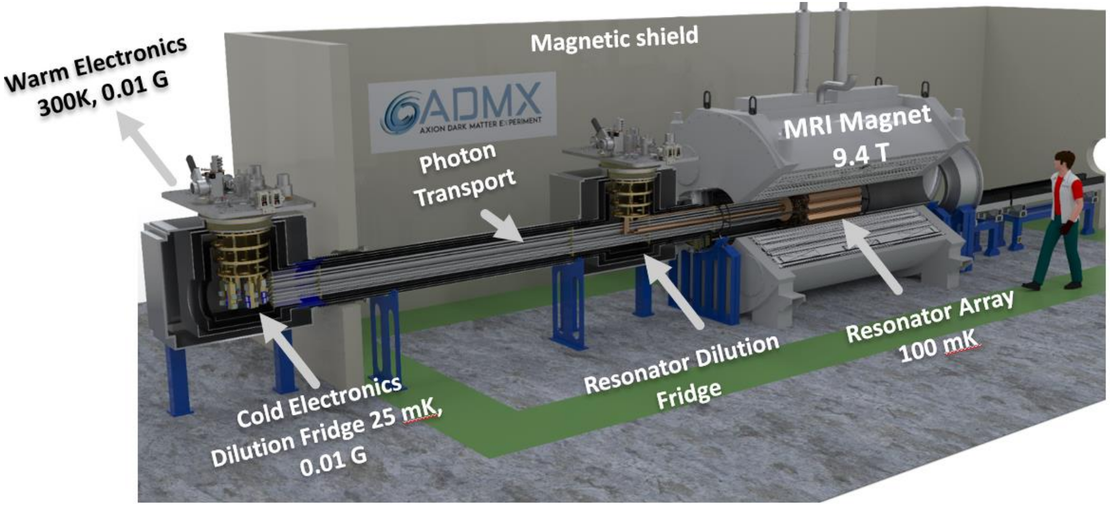
Currently in Design Phase: Built around new 800 mm bore 9.4 T MRI magnet being acquired by Fermilab
Aiming to be ready for construction start in FY24 (anticipate data taking in FY27)

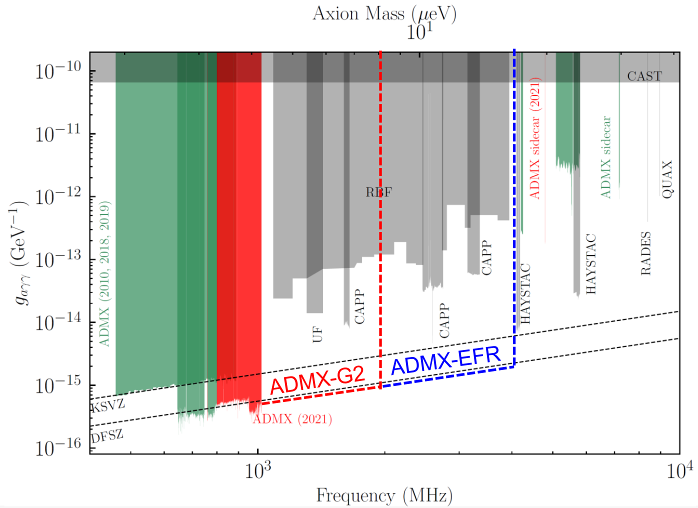
- 18 cavity array.
- Each has own JPA.
- In-phase voltage combining at room-temp.





9.4 T 800 mm bore MRI magnet





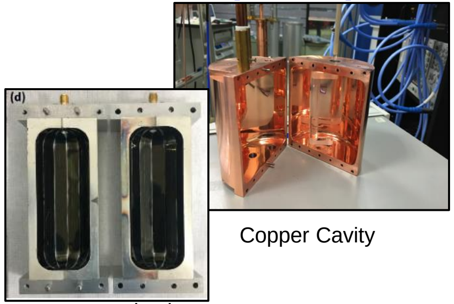
Additional Haloscopes Worldwide

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

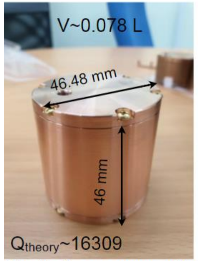
CAPP (Korea)



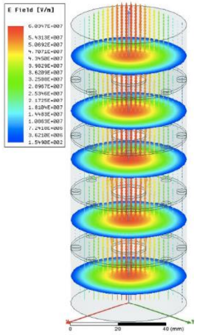
Copper Cavity

superconducting cavity (YBCO)

TASEH (Tawian)

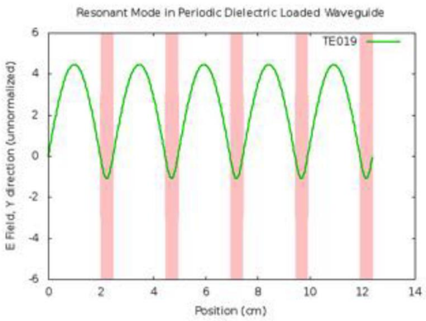


Single-frequency cavity



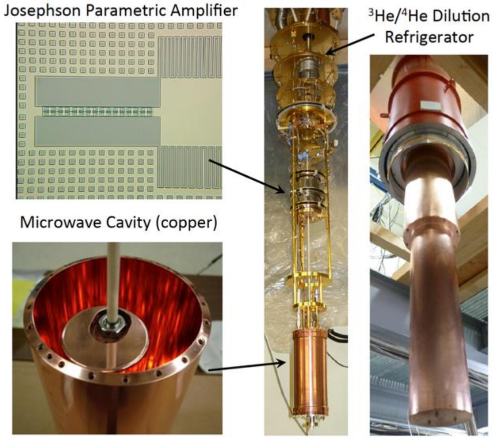
Periodic cavity

ORPHEUS (UW)

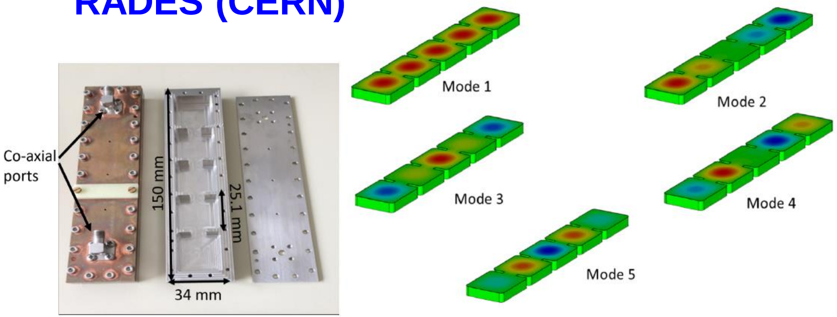


Sapphire loaded cavities can utilize higher order modes

HAYSTAC (NSF)

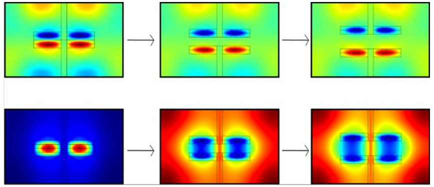


RADES (CERN)



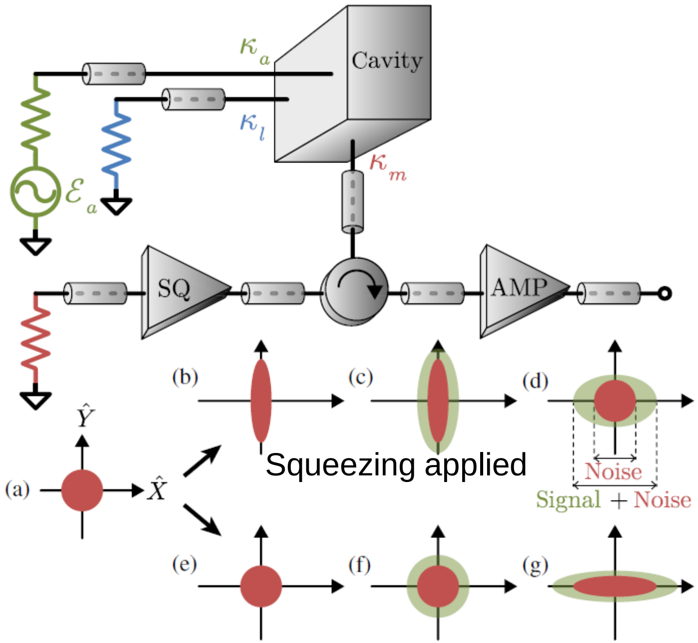
Uses CAST dipole

ORGAN (Australia)



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

Squeezing the vacuum (HAYSTAC group)



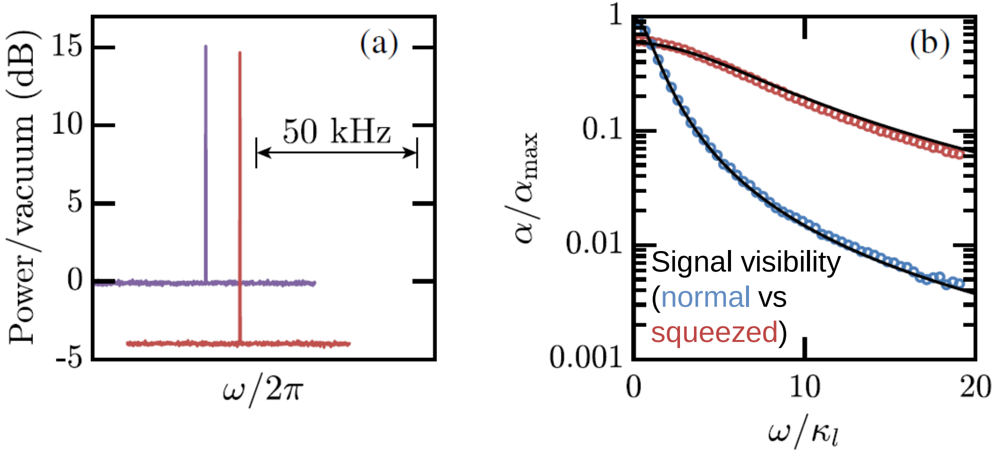
Squeezed Vacuum Used to Accelerate the Search for a Weak Classical Signal

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*

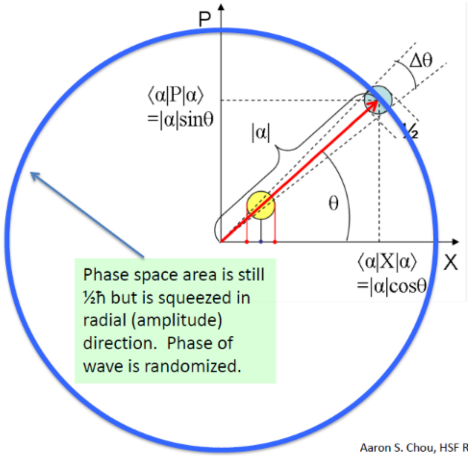


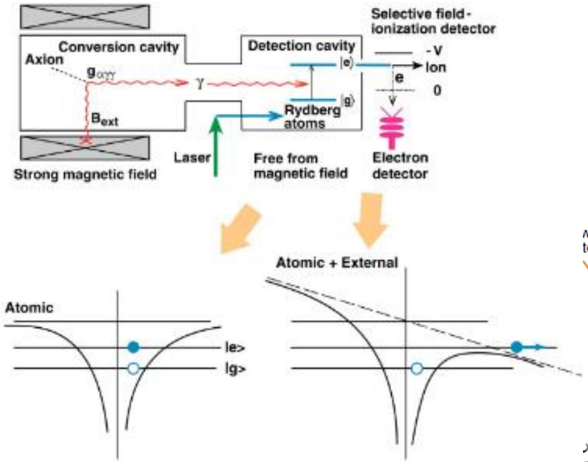
Signal over background 1 MHz from cavity

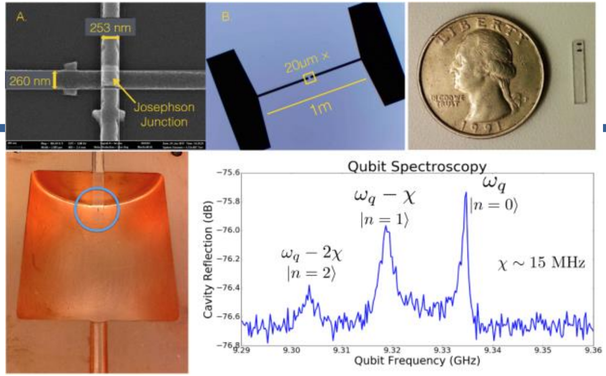
Demonstrated in lab. **Factor of 2.5 increased scan rate!**

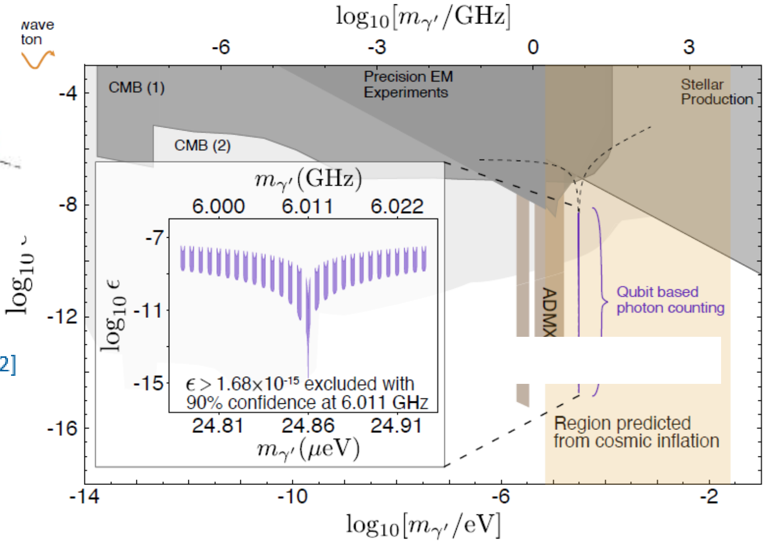
Figures from **Phys. Rev. X 9, 021023 – Published 3 May 2019**

Photon Counting (qubits, rydberg atoms)









Hidden sector photon demonstration

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 (RAY)

Non-Destructive Qubit Readout: [A. V. Dixit *et al*, PRL 126, 141302]

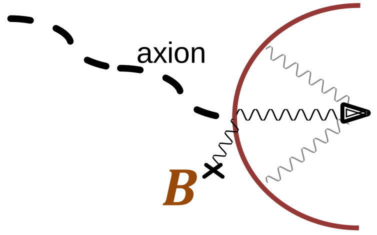
$$\mathcal{H} = \omega_c a^\dagger a + \tfrac{1}{2}(\omega_q + 2\chi a^\dagger a)\sigma_z$$

cavity — Qubit — Interaction (commutes with cavity/Qubit!)

QuantiSED project led by Aaron Chou

Dish Antenna Type Experiments (Broadband)

[Horns *et al.*, JCAP 04 (2013) 016]

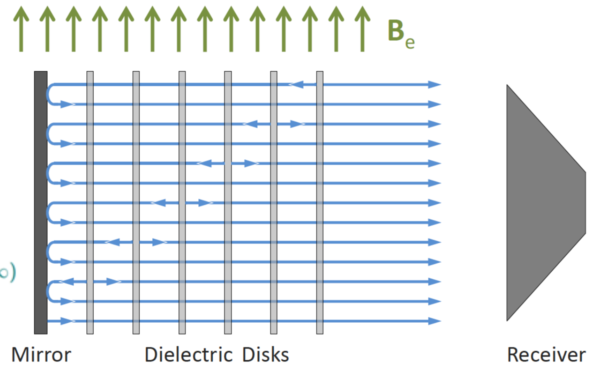


MADMAX (Max Planck Institute)

Will probe 40-400 μeV range (10-100 GHz)
10 T field & ~80 disks
Prototype phase using dipole magnet at CERN

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

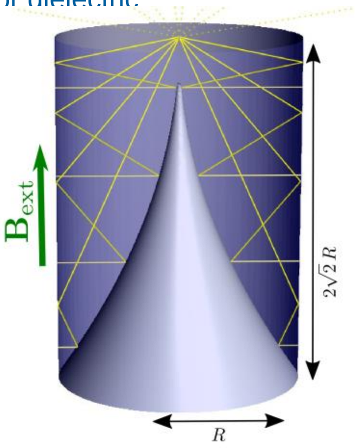
β^2: power emitted by booster / power emitted by single mirror ($\epsilon = \infty$)

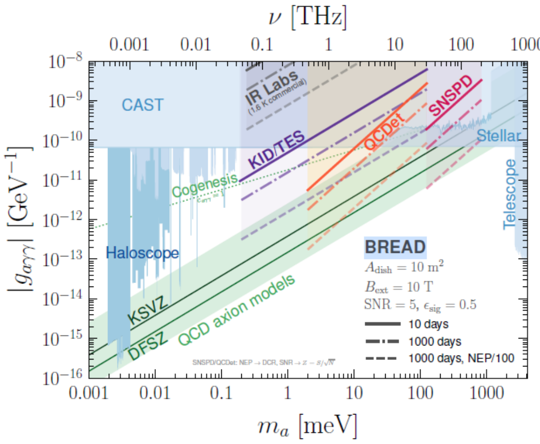


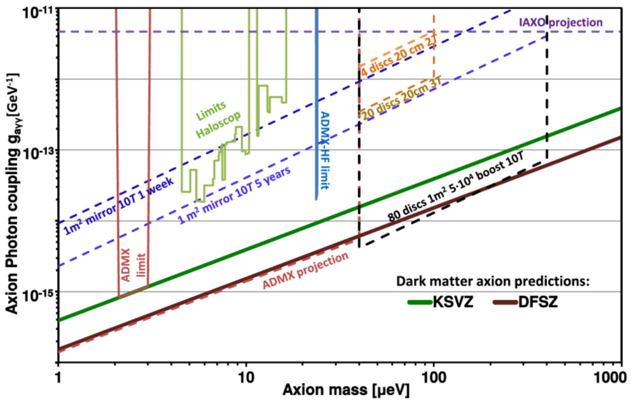
Similar production concept as microwave cavities. Magnetic field allows axions to convert to photons near a surface such as a mirror or dielectric

Does not use high resonance of a cavity (broadband searches)

Variety of detectors that could be employed
-superconducting nanowires
-quantum cap. detectors
-KID/TES



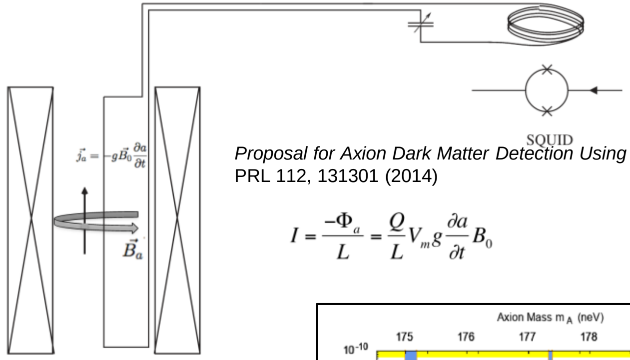




BREAD (Fermilab)

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

For axions with Compton wavelengths > size of the experiment move to lumped-elements as opposed to resonant cavities.

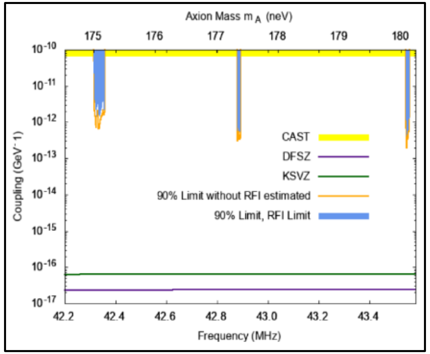


Proposal for Axion Dark Matter Detection Using an LC Circu
PRL 112, 131301 (2014)

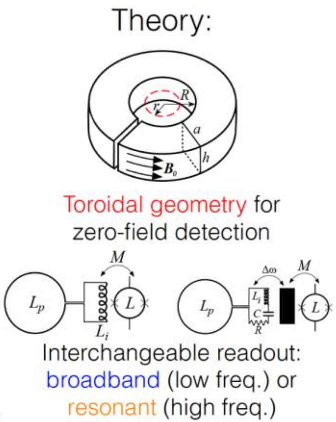
$$I = \frac{-\Phi_a}{L} = \frac{Q}{L} V_m g \frac{\partial a}{\partial t} B_0$$

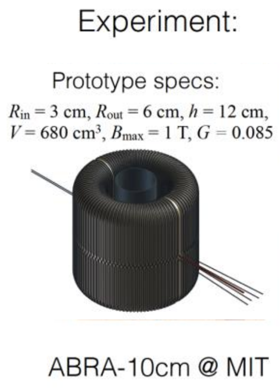
ADMX-SLIC

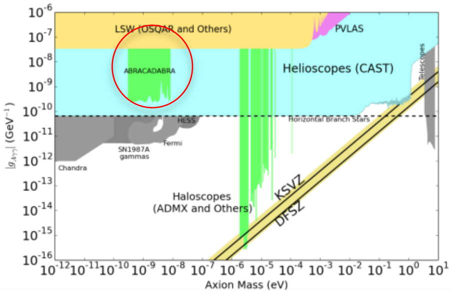
ADMX SLIC: Results from a Superconducting LC Circuit Investigating Cold Axions
N. Crisosto, P. Sikivie, N. S. Sullivan, D. B. Tanner, J. Yang, and G. Rybka
Phys. Rev. Lett. **124**, 241101 – Published 17 June 2020



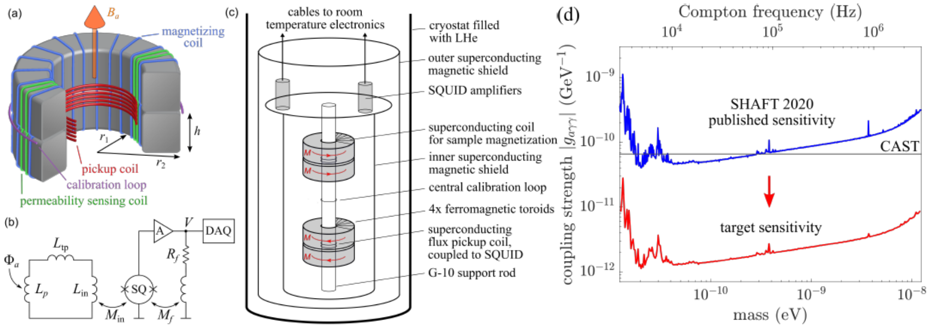
ABRACADABRA







SHAFT Experiment: Enhanced with Ferromagnet

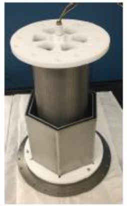


DM Radio
(collaboration with ABRA as part of Dark Matter New Initiative Program)

DM Radio Pathfinder

Status: In testing / operation

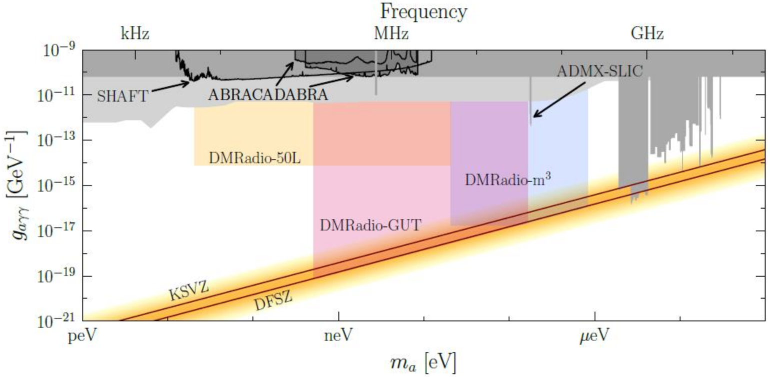
- 0.67 L, no magnet
- Q~200,000 now
- 4 K
- Hidden photon science
- DC SQUID



DM Radio-Quantum
DM Radio-50L

Status: In construction

- ~0.5 T, 50 L magnet
- Dilution refrigerator
- ALP science
- Platform for quantum sensors



3-year DMRadio-50L prototype
5-year DMRadio-m3 (Dark Matter New Initiative)
5-year DMRadio-GUT

Dark Matter Radio Cubic Meter (DMRadio-m^3)

Status: R&D funded under DOE Dark Matter New Initiatives call

- Brings together both DM Radio and ABRACADABRA teams
- QCD axion over 5 MHz – 200 MHz (20neV-0.8 μeV)
- ~4T, ~m^3 magnet
- Dilution refrigerator

Low-frequency DC SQUIDs have noise much higher than quantum-limit

Can apply phase sensitive techniques to evade quantum back-action (DOE QuantISED program)

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

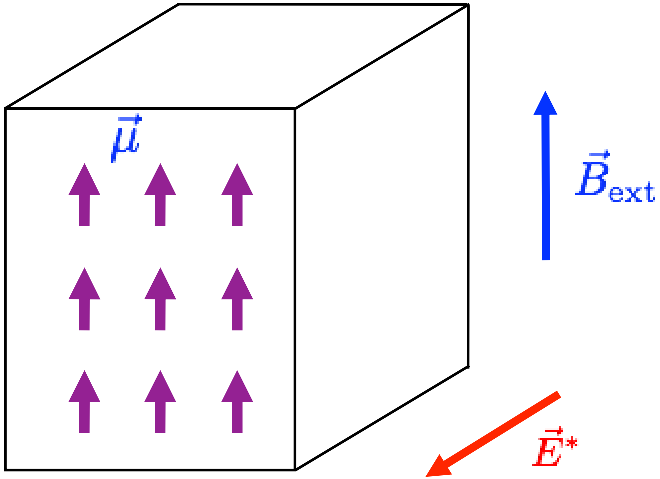
CASPEr Wind

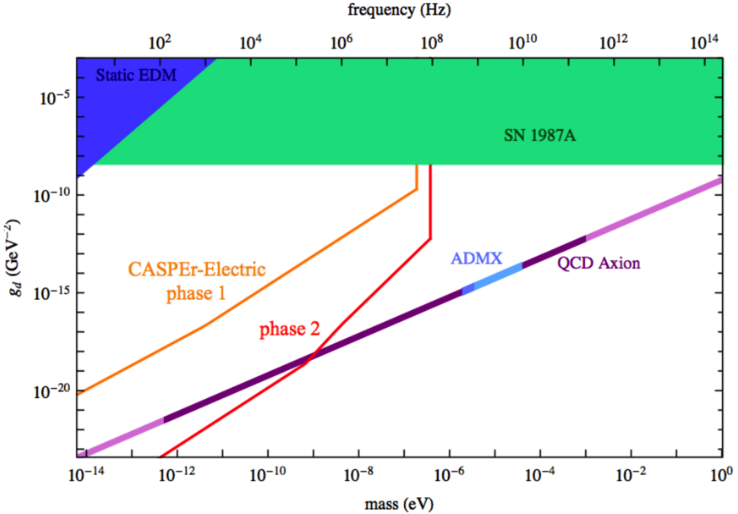
Graham PW, Rajendran S. Phys. Rev. D88:035023 (2013)

CASPEr-Electric

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

Coupling to gluon field

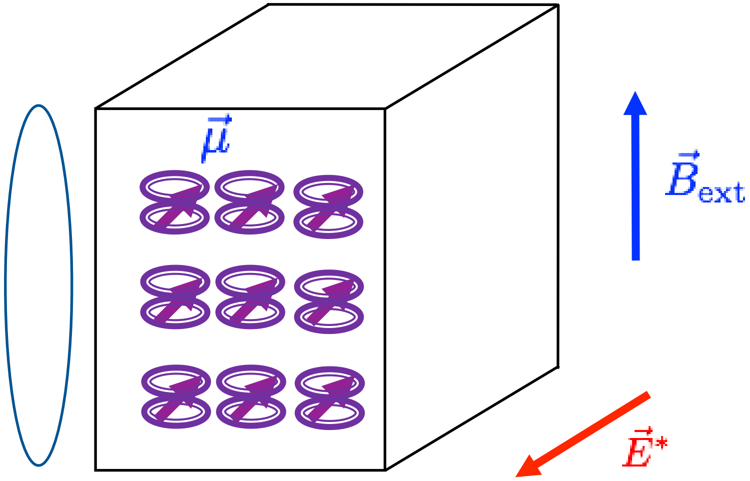


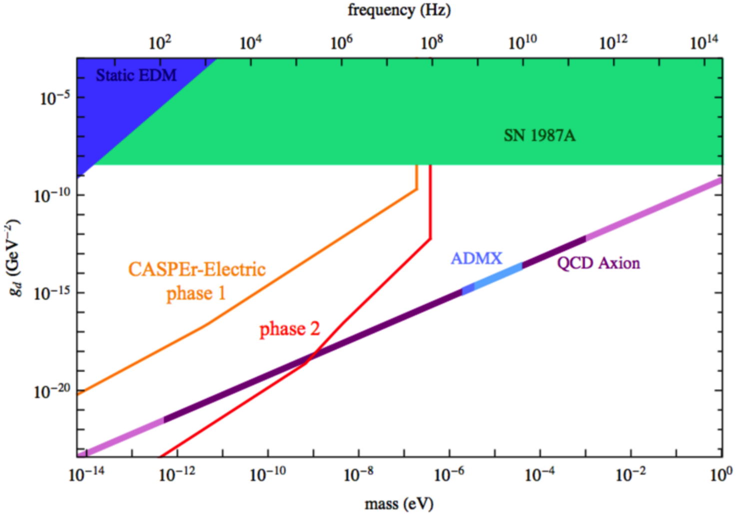


Start with material in an external B-field

CASPEr-Electric

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

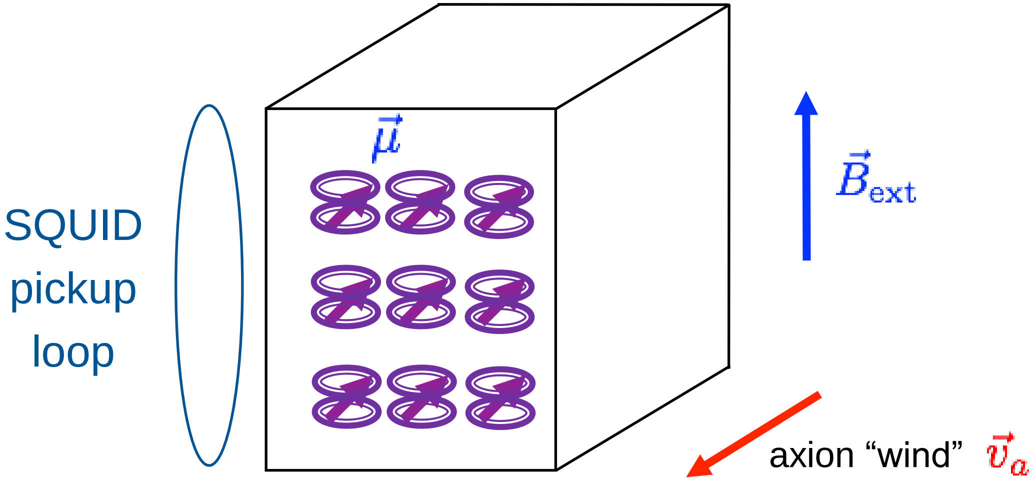


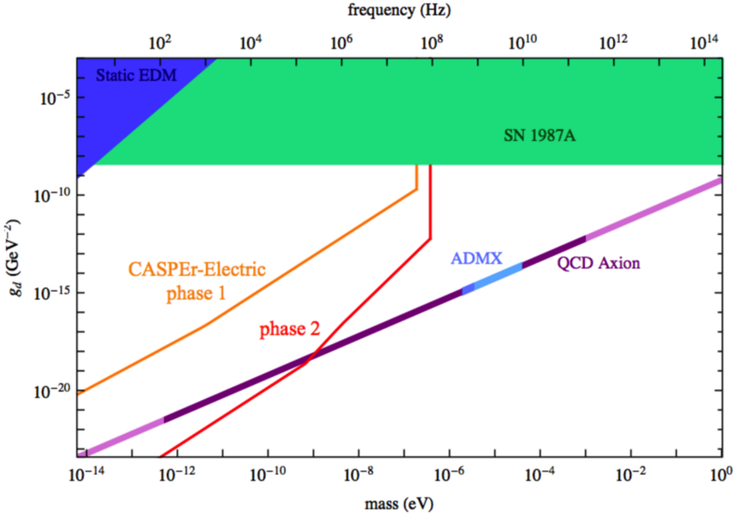


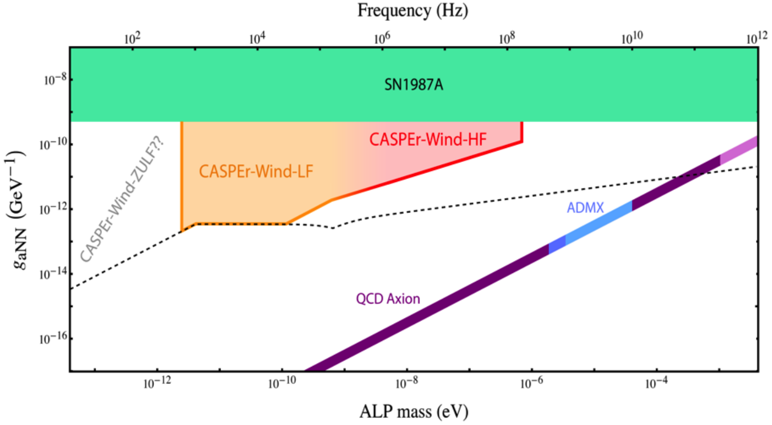
Larmor frequency = axion Compton frequency
➔ resonant enhancement.

CASPEr-Wind

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



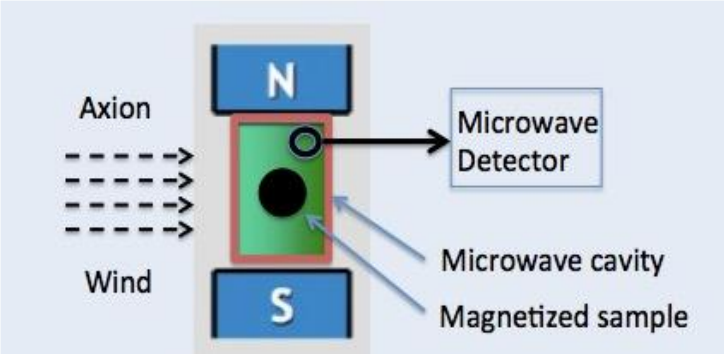




Larmor frequency = axion Compton frequency
➔ resonant enhancement.

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



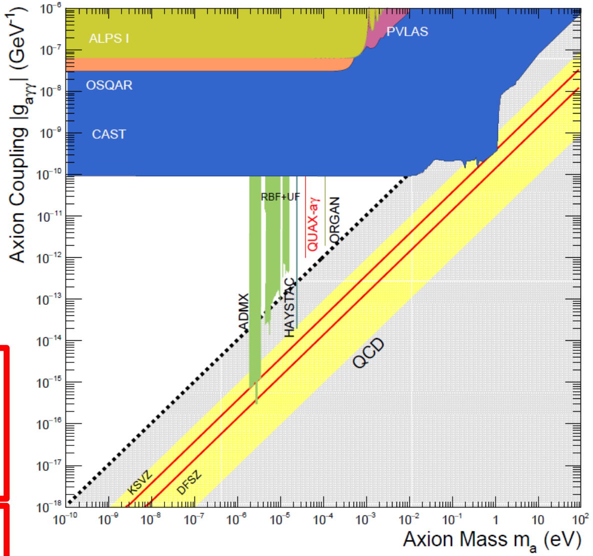
- R. Barbieri et al., *Searching for galactic axions through magnetized media: The QUAX proposal* Phys. Dark Univ. **15,** 135 - 141 (2017)

The effective magnetic field associated with the axion wind

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

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

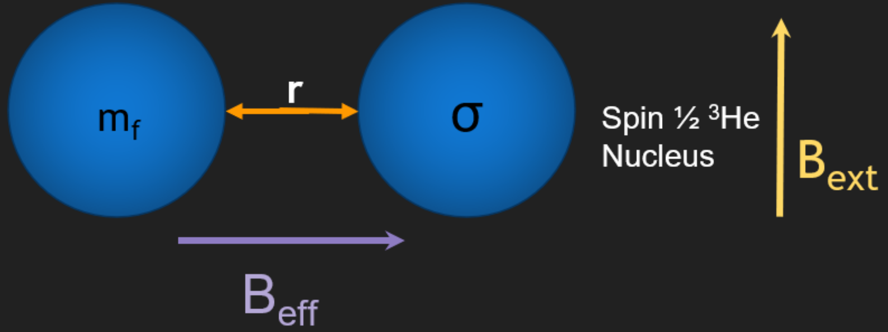
$$\frac{\omega_a}{2\pi} = 48 \left(\frac{m_a}{200\,\mu\mathrm{eV}}\right) \quad \mathrm{GHz},$$



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

5^{th} force searches (axions as a force mediator)

NMR for detection



$$U = \mu \cdot B_{\text{ext}}$$

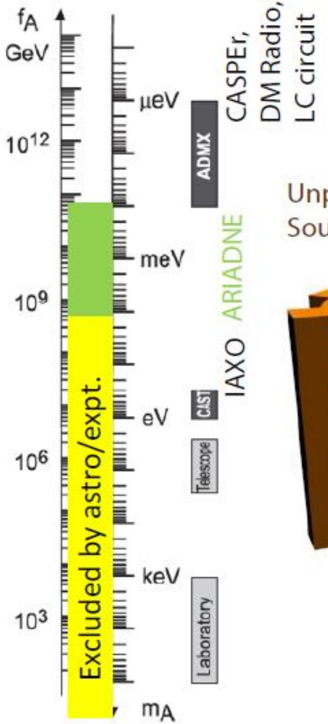
$$\omega = \frac{2\mu_N \cdot B_{\text{ext}}}{\hbar}$$

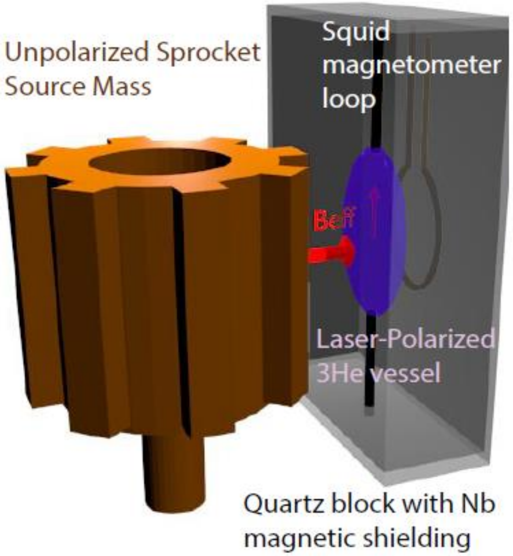
$$B_{eff} = B_{\perp}\cos(\omega t)$$

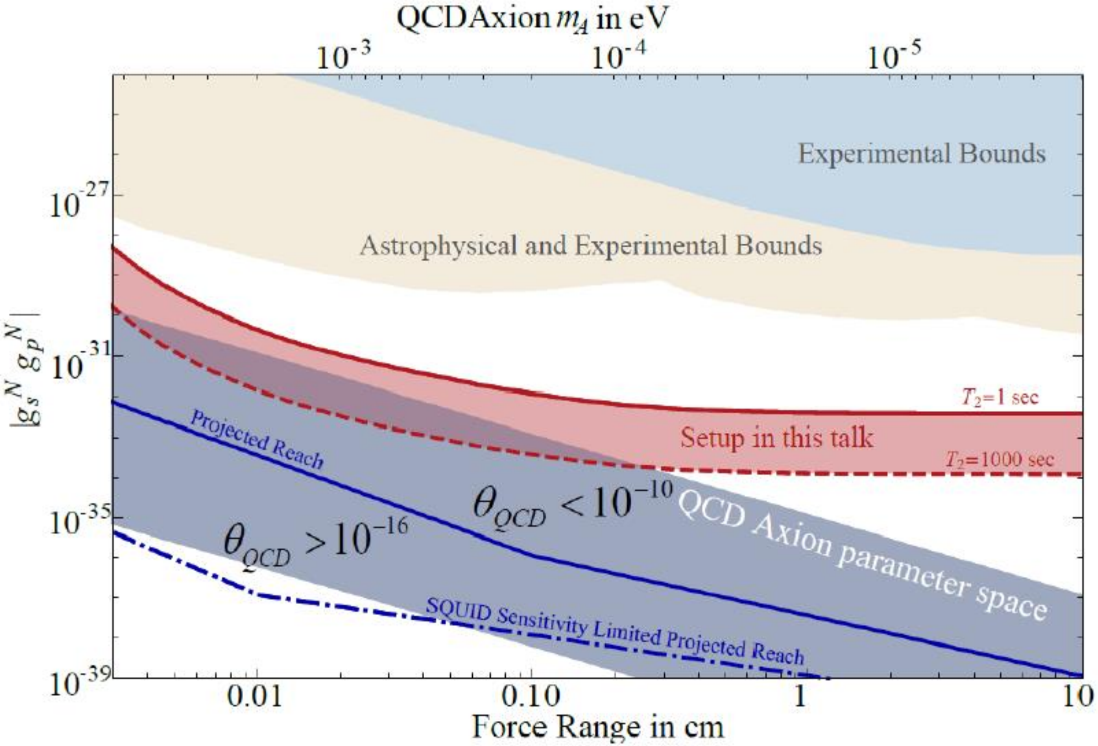
- Time varying B_{eff} drives spin precession
- This produces a transverse magnetization
- Magnetization can be detected using a SQUID

A. Arvanitaki and A. Geraci, Phys. Rev. Lett. 113, 161801 (2014)

5th force searches: ARIADNE Experiment



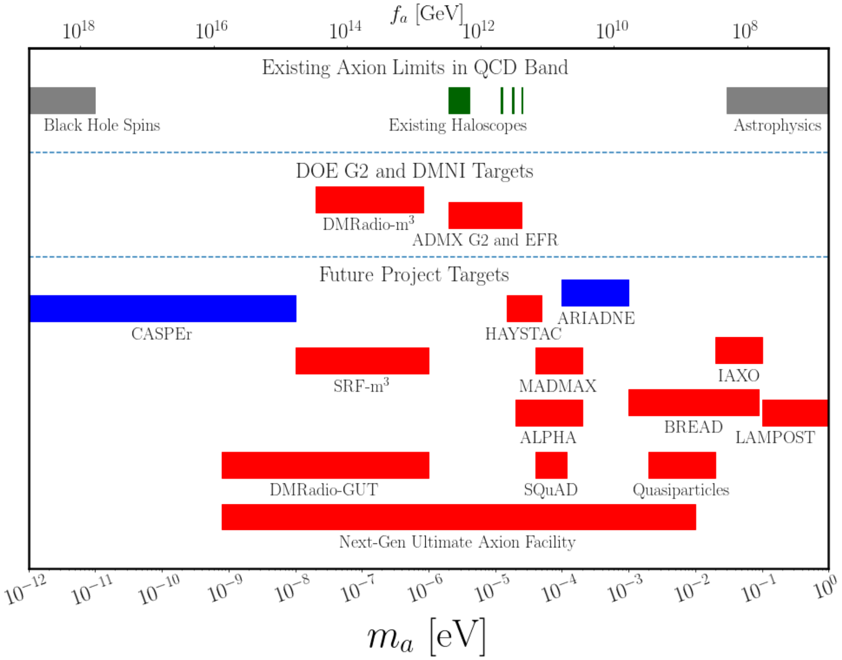




Summary

- Axions solve the strong-CP problem and make a natural Cold Dark Matter candidate

- There is a broad set of detection strategies
    - Generate and then detect axions in the lab (or sense their force mediation)
    - Detect axions generated from the sun
    - Directly detect axion dark matter



- 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

- 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

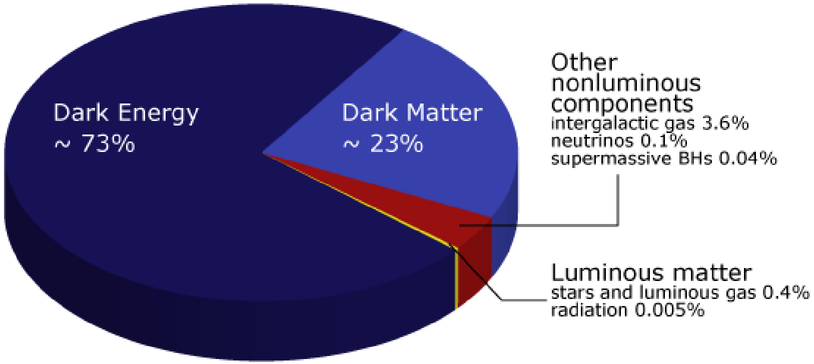
Primary sponsor

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

Backups

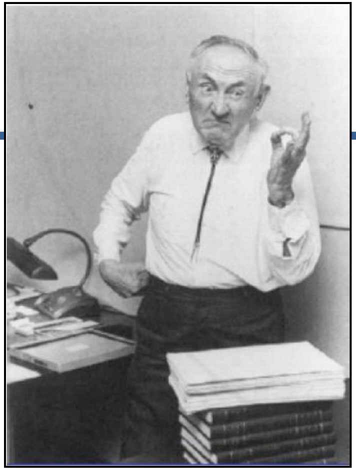
The Nature of Dark Matter

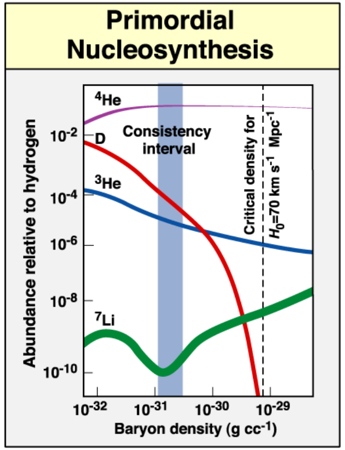
One of the premier unsolved mysteries in physics

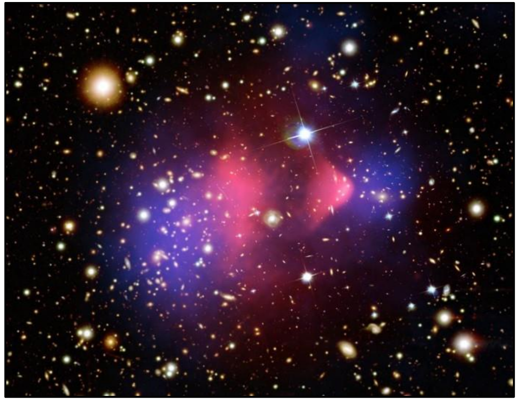


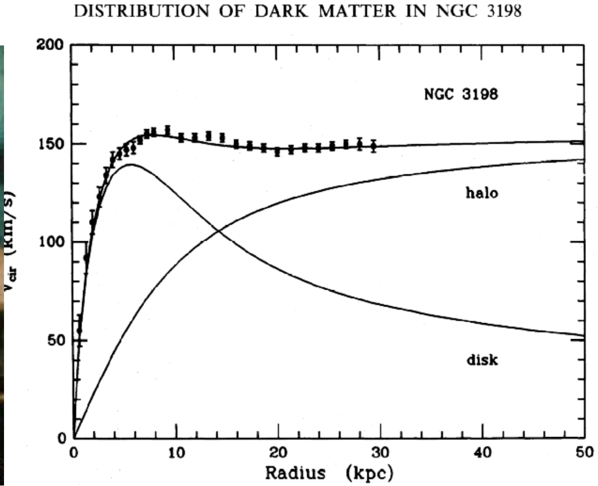
1930s
Fritz Zwicky: noticed odd motion of member galaxies of the Coma Cluster

1980s
Vera Rubin: Galaxy rotation curves did not make sense without a large unseen mass

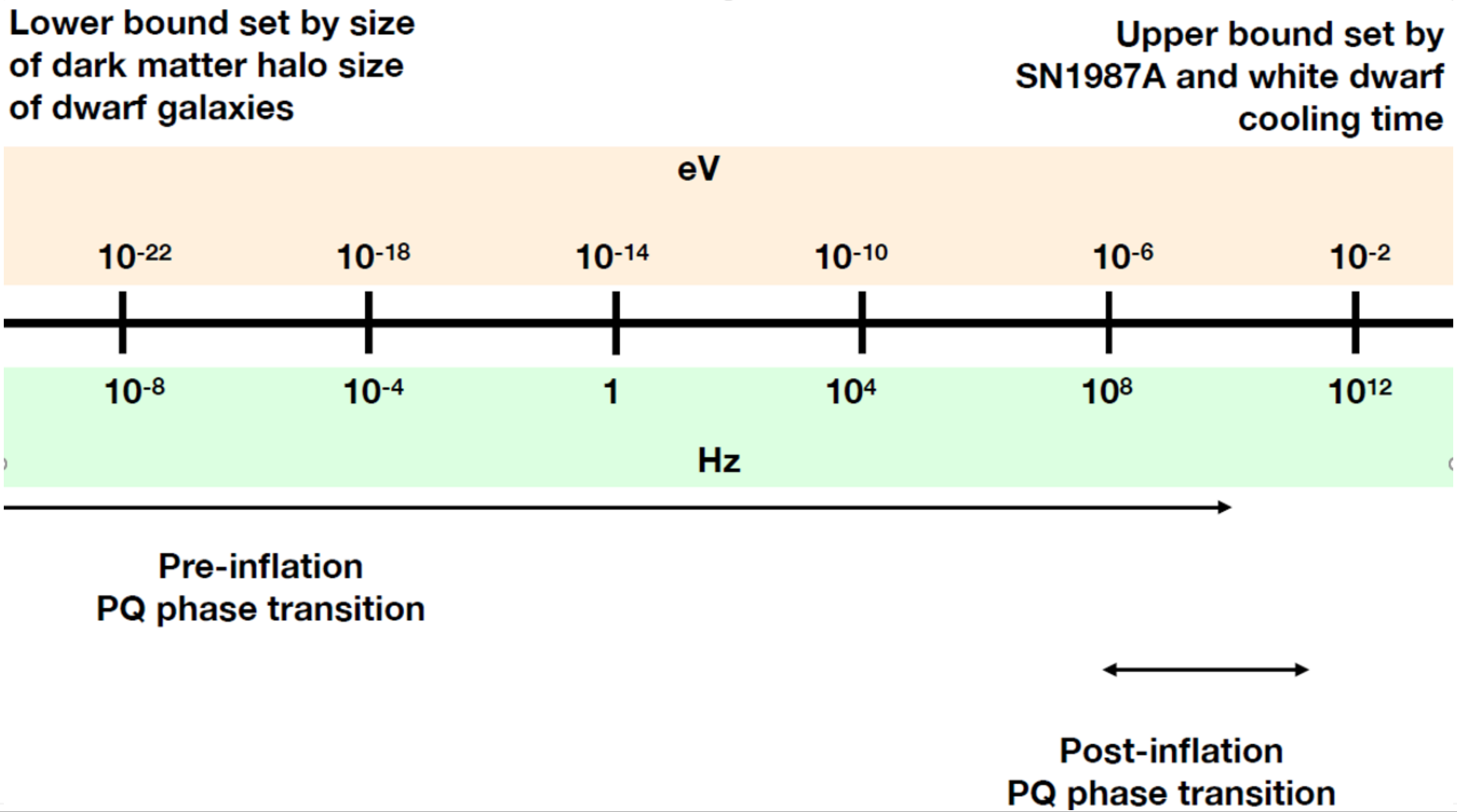






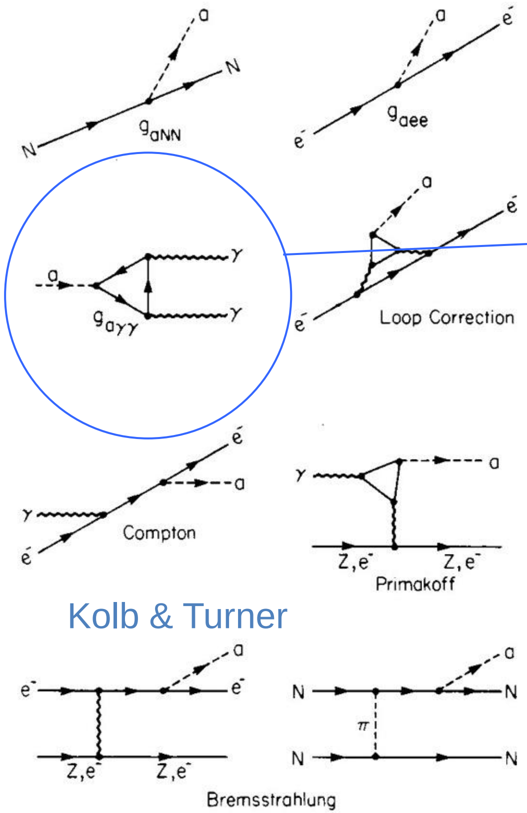


Axion mass range



Adapted from Lindley Winslow DPF slide

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

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

Power transfer from axion field to cavity field

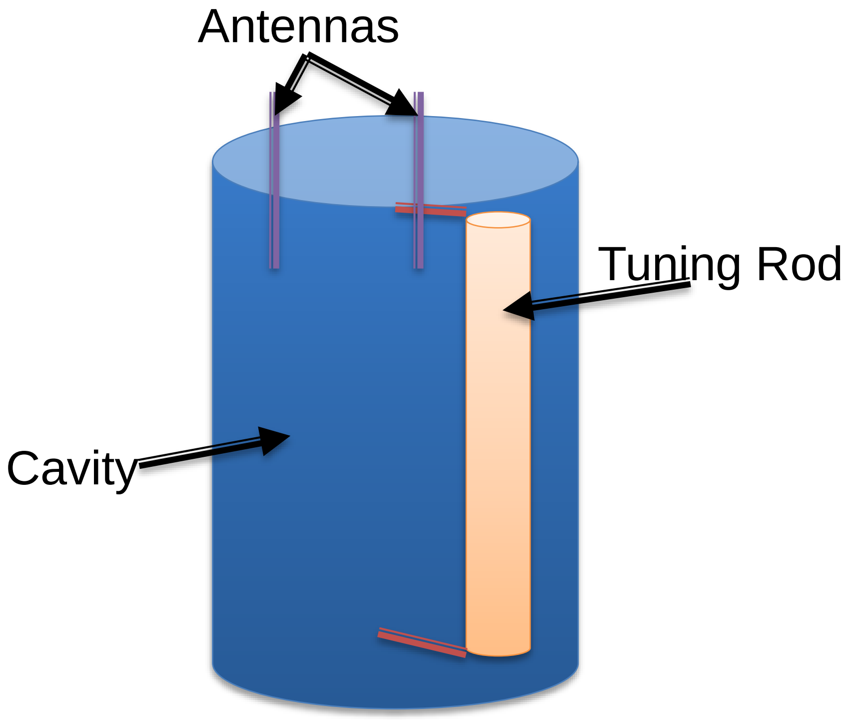
<u>Weak coupling</u>
Takes many swings to fully transfer the wave amplitude.

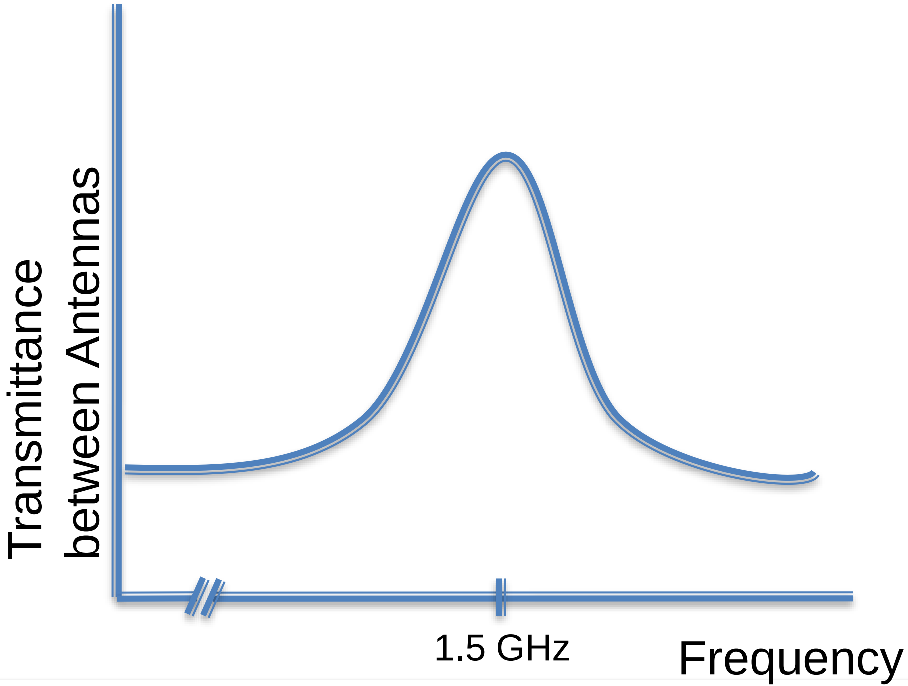
Number of swings is equivalent to cavity *Quality factor (Q)*.

Narrowband cavity response → iterative scan through frequency space.

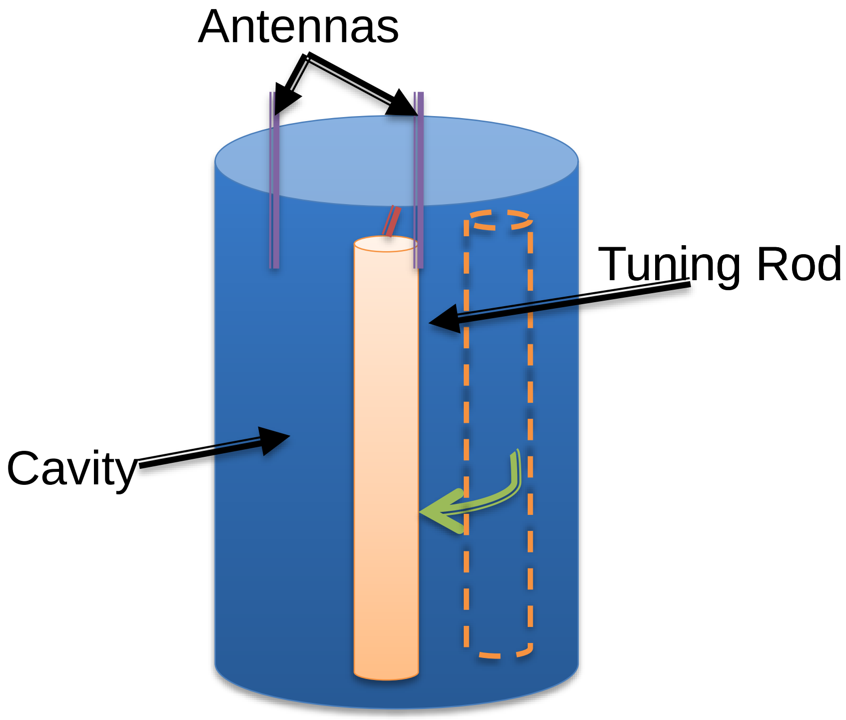
*Slide from Aaron Chou (FNAL)

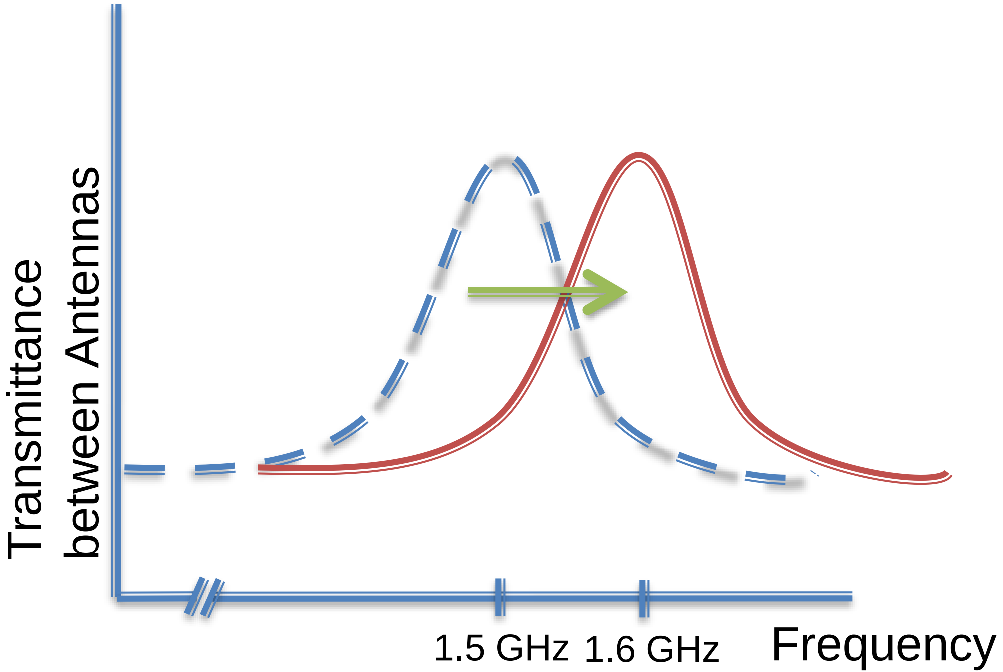
Microwave Cavity needs tunable resonance





Microwave Cavity needs tunable resonance



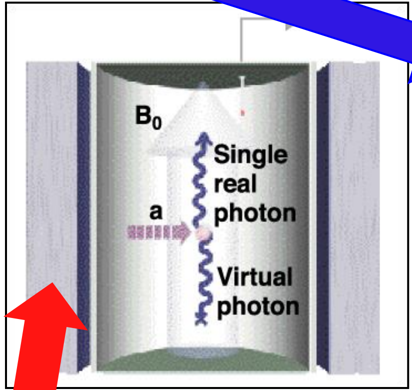


Signal to noise dictates search strategy

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

Integration time limited to ~ 100 sec

* *Dicke, 1946*



System noise temp.

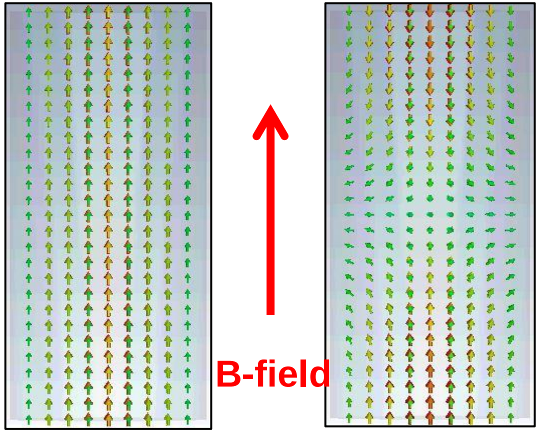
$T_S = T_{phys} + T_N$

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

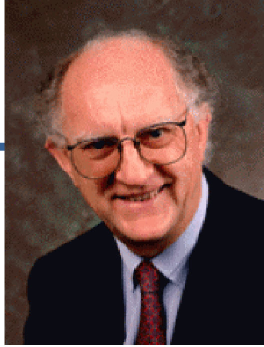


P_{sig} ~ $(B^2V\, Q_{cav} C_{010})(g^2 m_a \rho_a)$

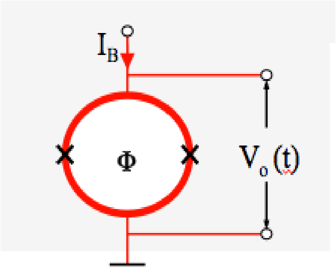
~ 10^{-23} Watts for ADMX

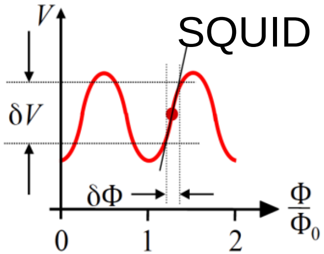
$$\frac{df}{dt} \approx 1.68\ \text{GHz/year} \left(\frac{g_\gamma}{0.36}\right)^4 \left(\frac{f}{1\ \text{GHz}}\right)^2 \left(\frac{\rho_0}{0.45\ \text{GeV/cc}}\right)^2 \cdot \left(\frac{5}{SNR}\right)^2 \left(\frac{B_0}{8\ \text{T}}\right)^4 \left(\frac{V}{100\text{l}}\right)^2 \left(\frac{Q_L}{10^5}\right)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

Enabling Technology: Microstrip SQUID Amplifier (MSA)

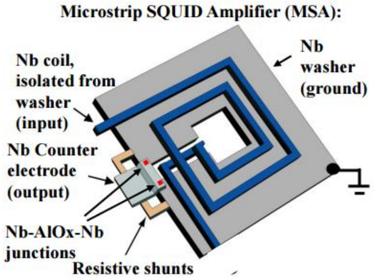

Prof. John Clarke

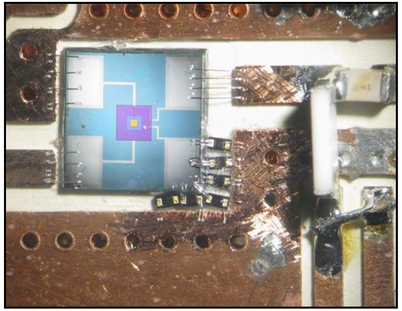
- Voltage biased SQUID loop
- Flux-to-Voltage Transducer

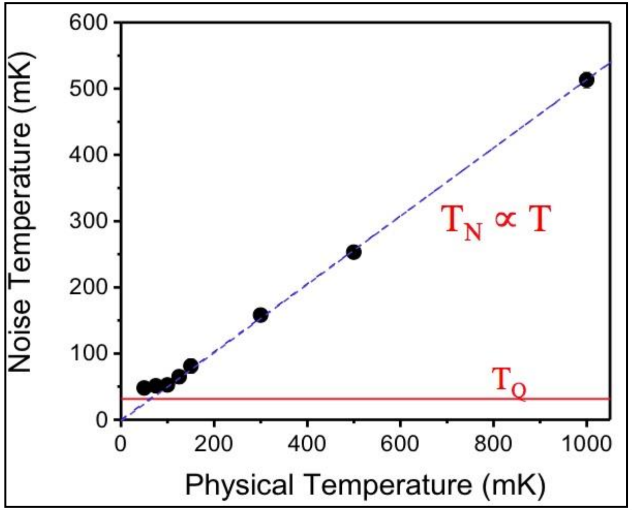


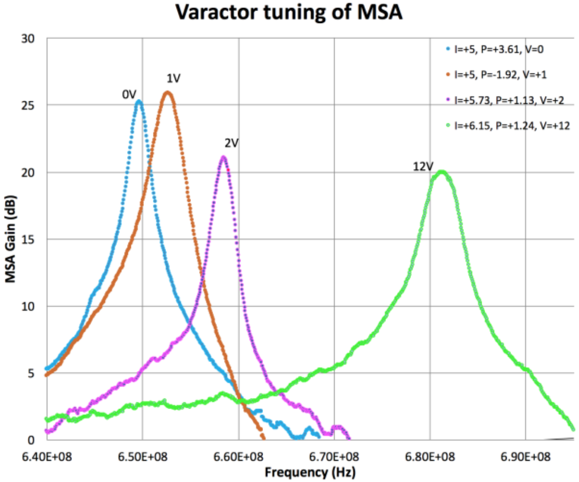


SQUID Φ vs. V





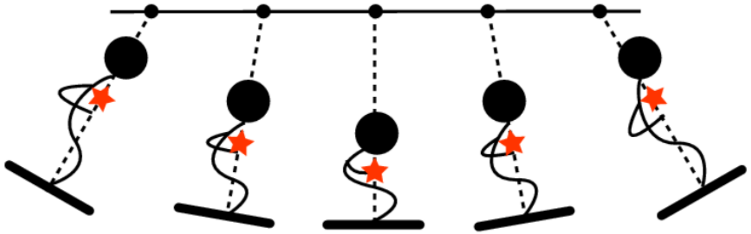




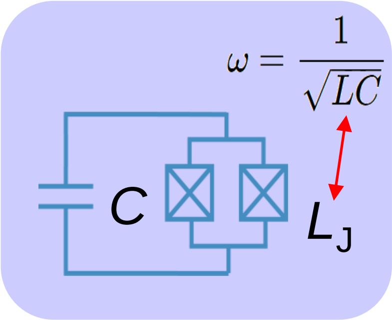
See talk from Kent Irwin (TES) last week

Josephson Parametric Amplifiers (JPAs)

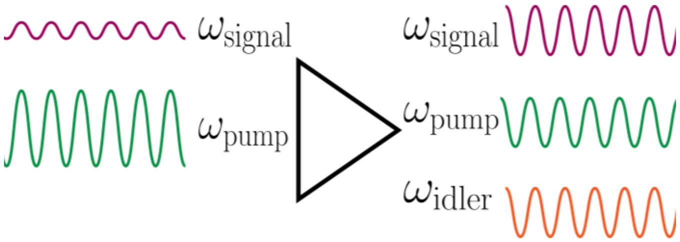
- JPA's provided by Irfan Siddiqi's group at UC Berkeley

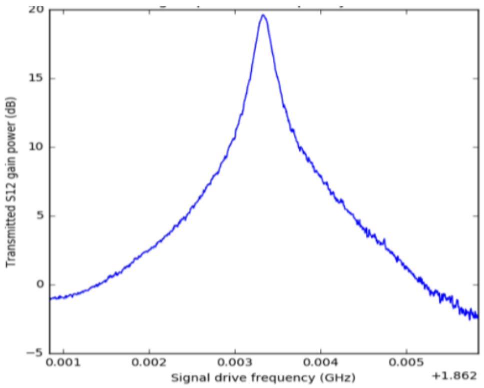


Classic example of parametric amplification is a child on a swing



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

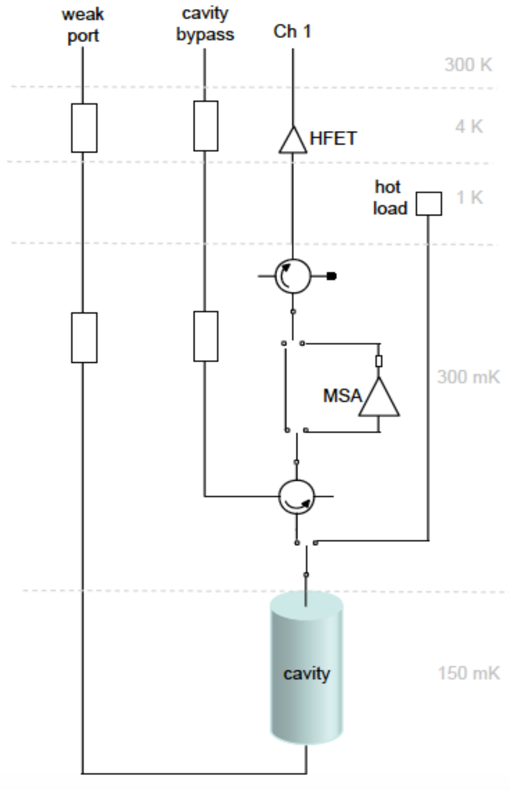
Hot / Cold load:
Measure system noise temperature by staring at thermal source with same microwave path

MSA is a two-port device

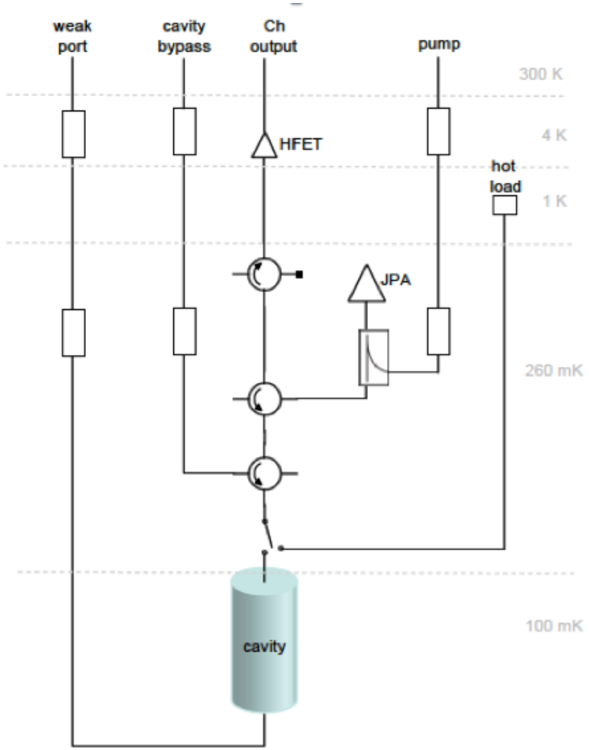
JPA operates in reflection mode

First ADMX operations used MSA

Recently transitioned to using JPAs

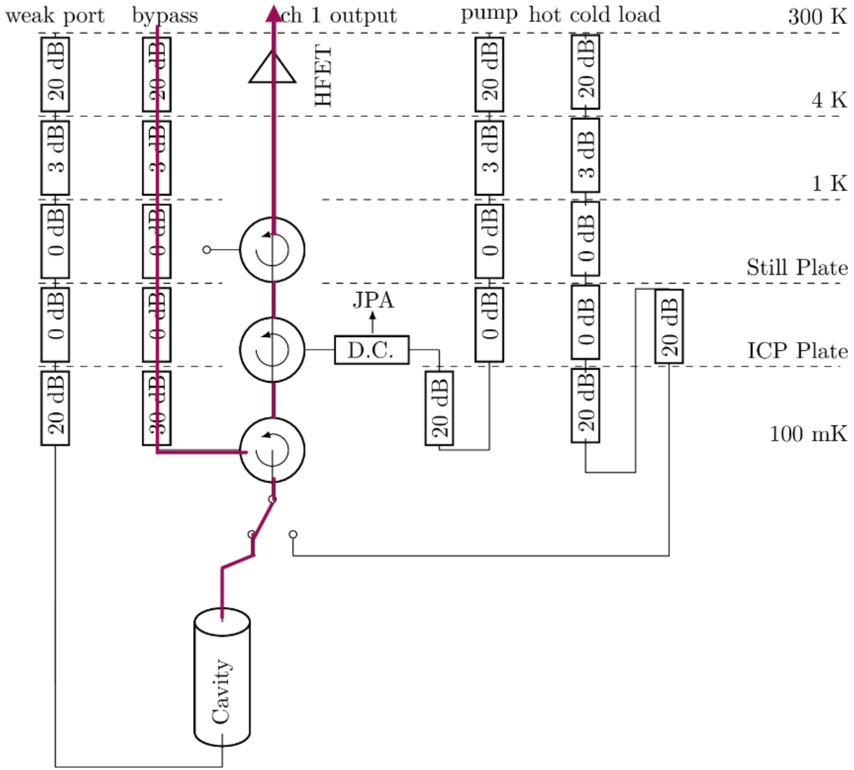


MSA signal layout

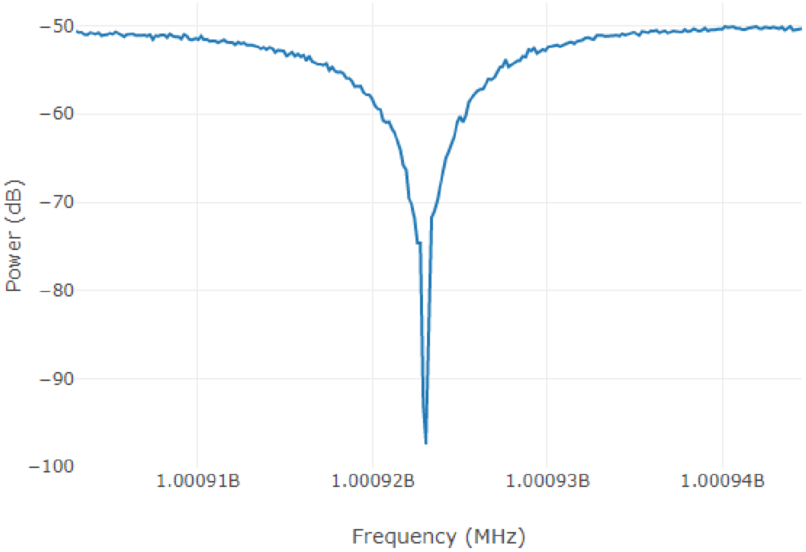


JPA signal layout

Modes of operations



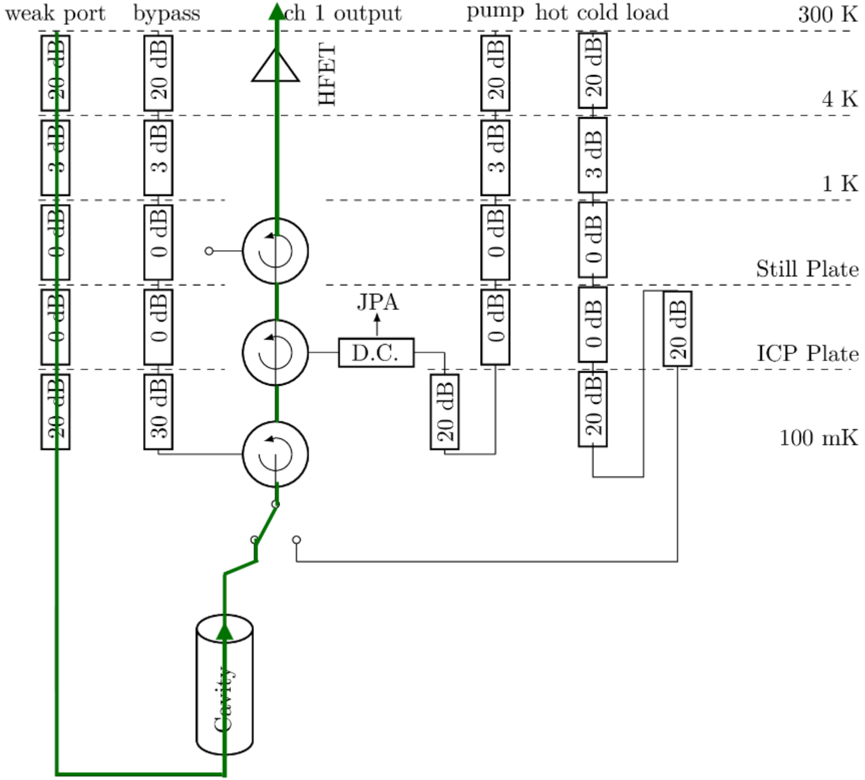
Reflection Measurements

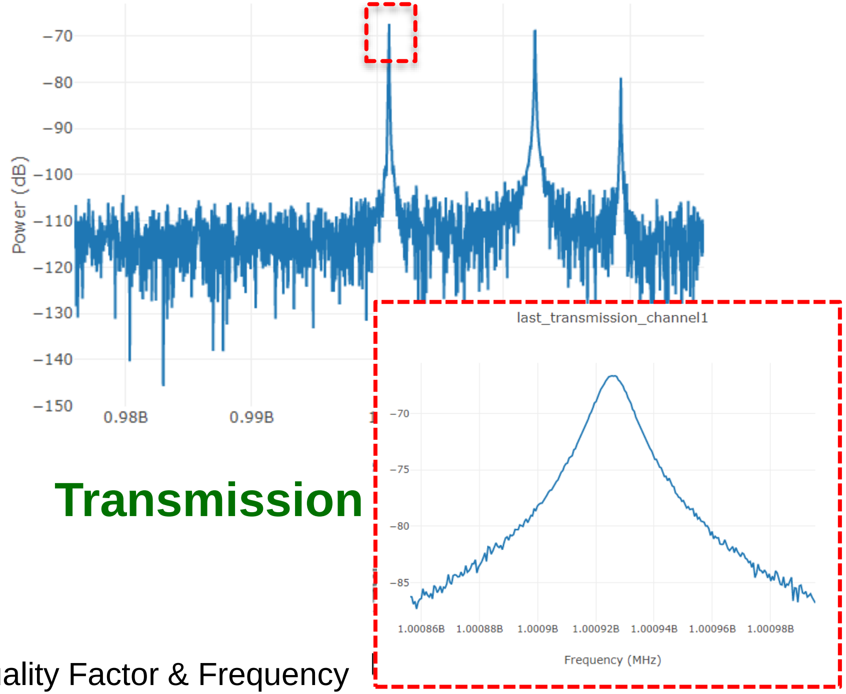


Gives antenna coupling

Needed to understand how much power comes from cavity

Modes of operations



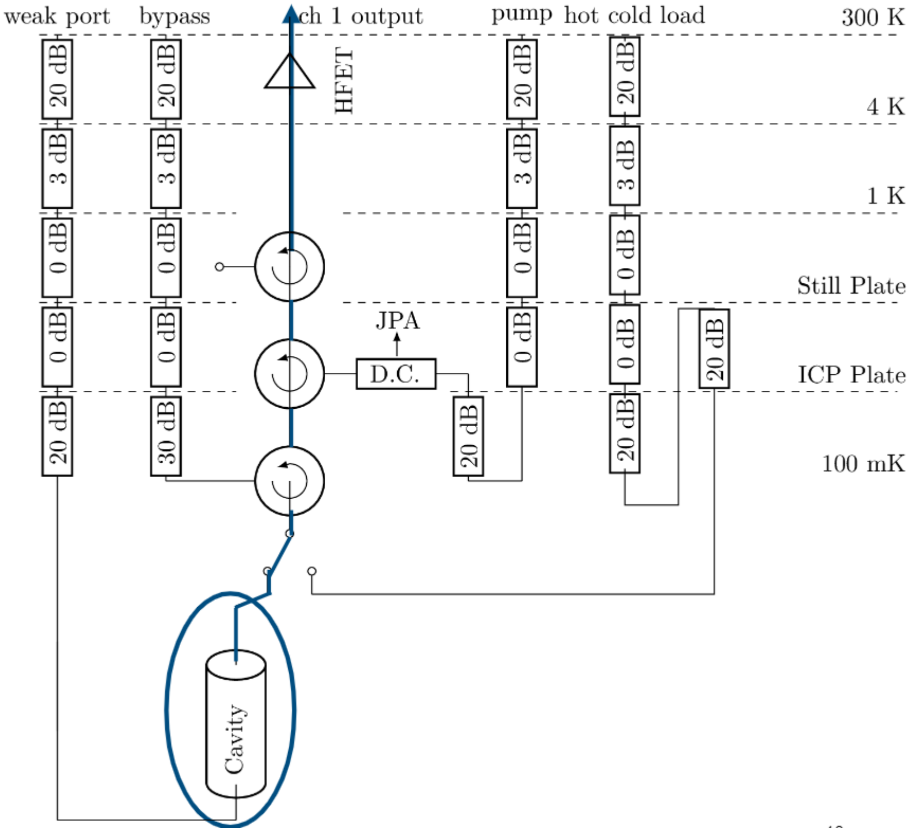


Transmission

Quality Factor & Frequency

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

Modes of operations



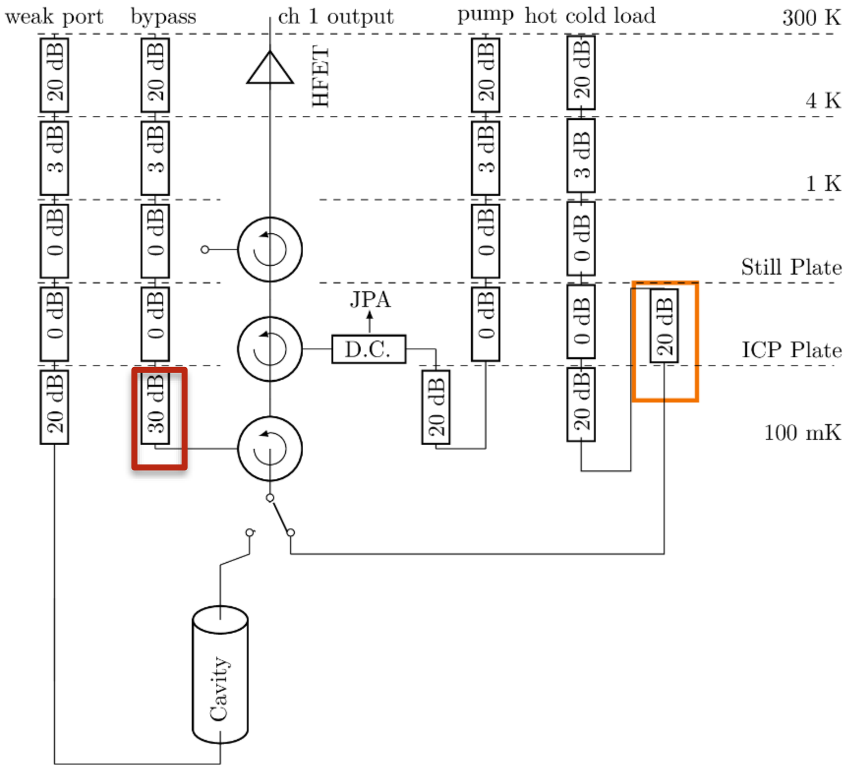
Data-Taking Mode

- 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 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.

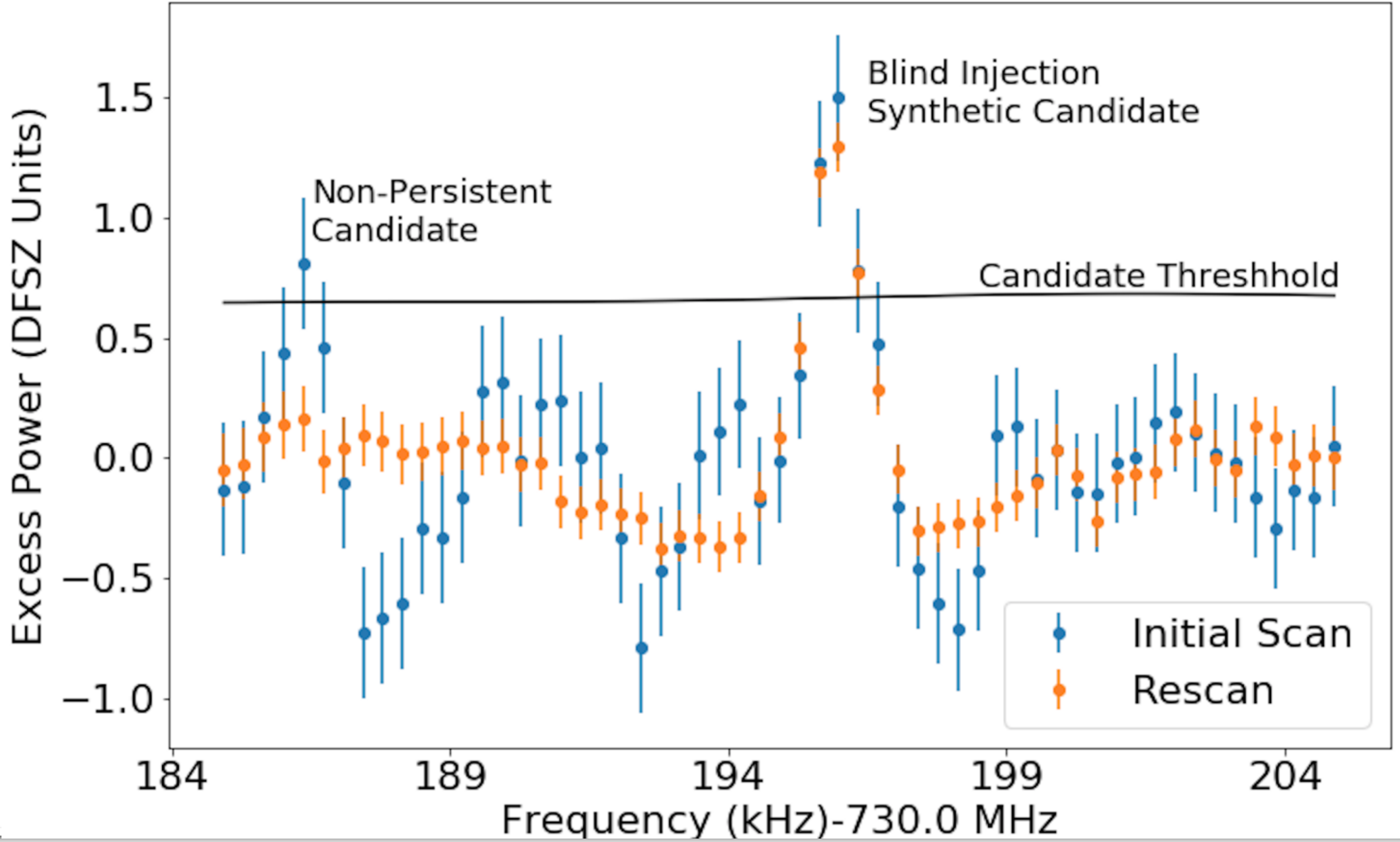
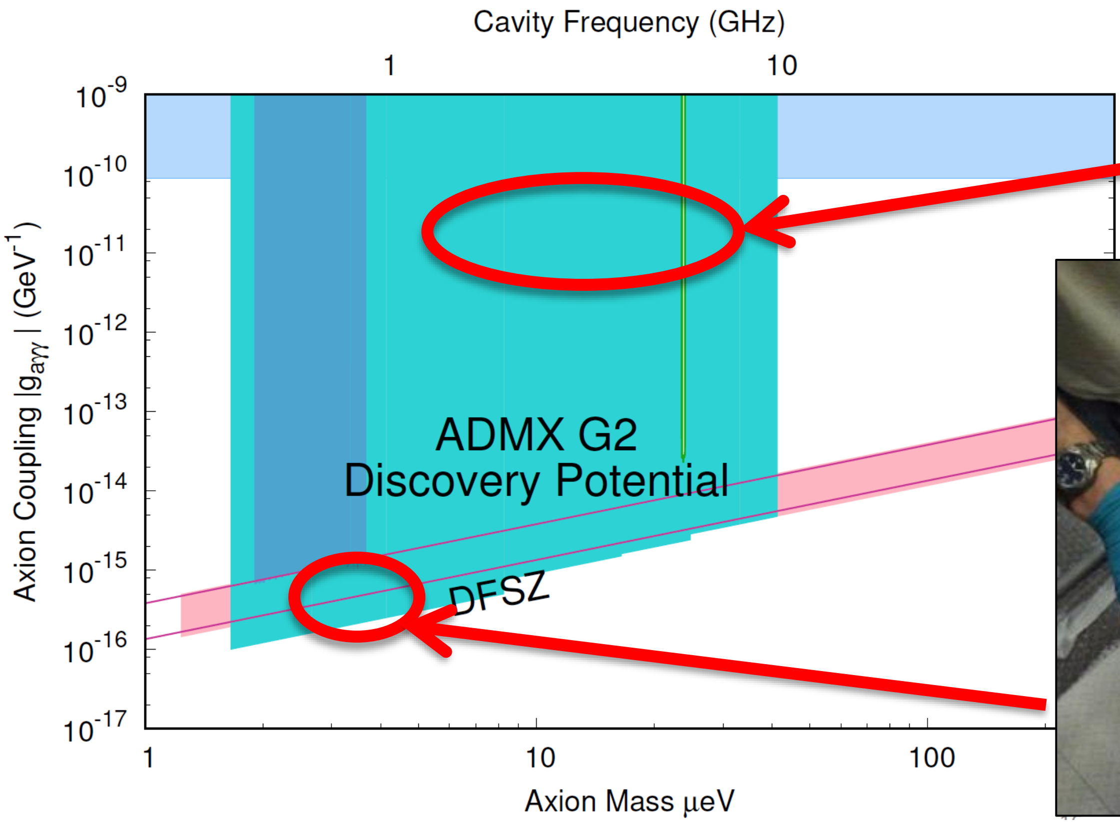
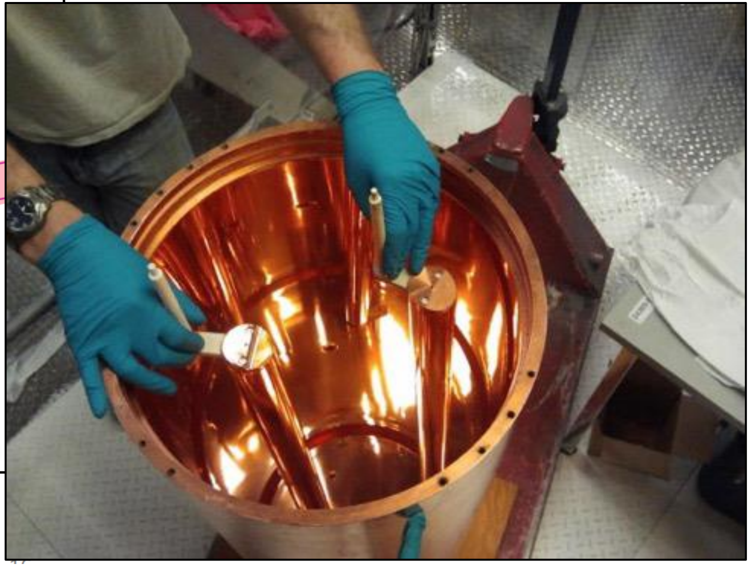


Figure provided by Gray Rybka (U. of Washington)

ADMX Gen-2: Main Cavity & Sidecar Cavity



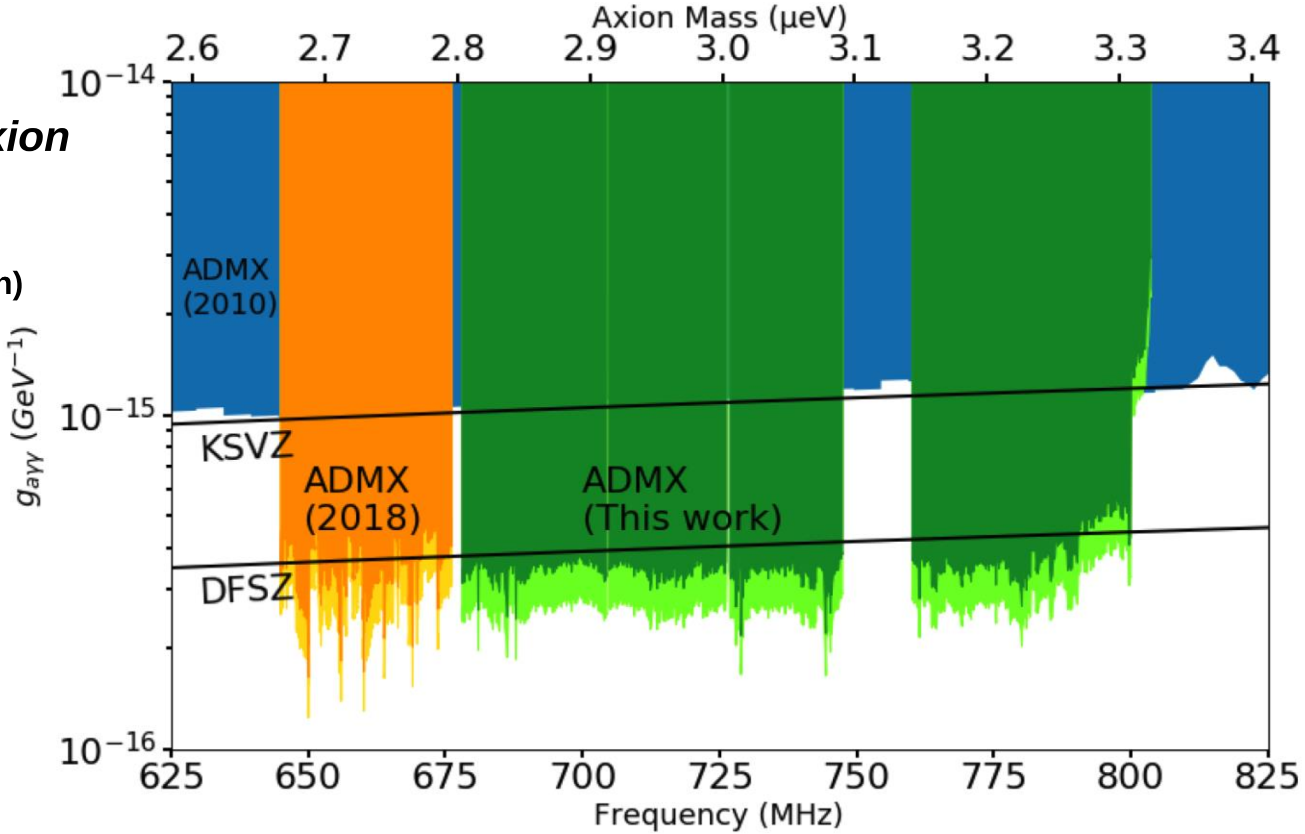
Sidecar cavity



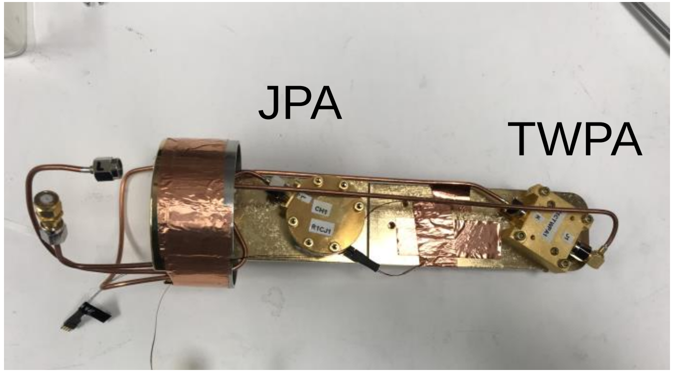
ADMX Gen-2: 2018 operations (run 1B)

Extended Search for the Invisible Axion with the Axion Dark Matter Experiment

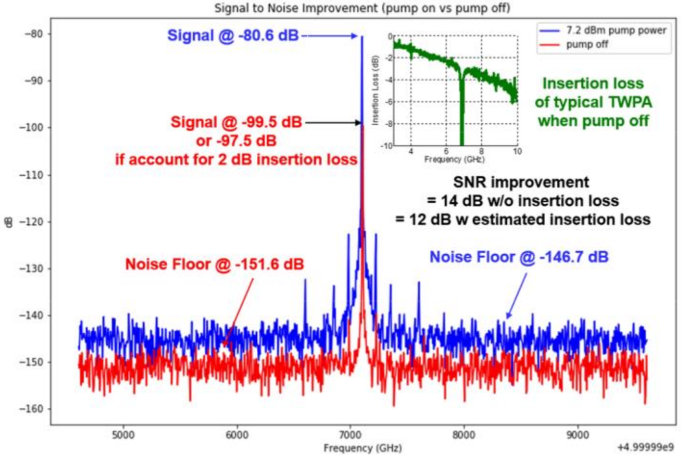
T. Braine et al. (ADMX Collaboration)
Phys. Rev. Lett. 124, 101303
Published 11 March 2020



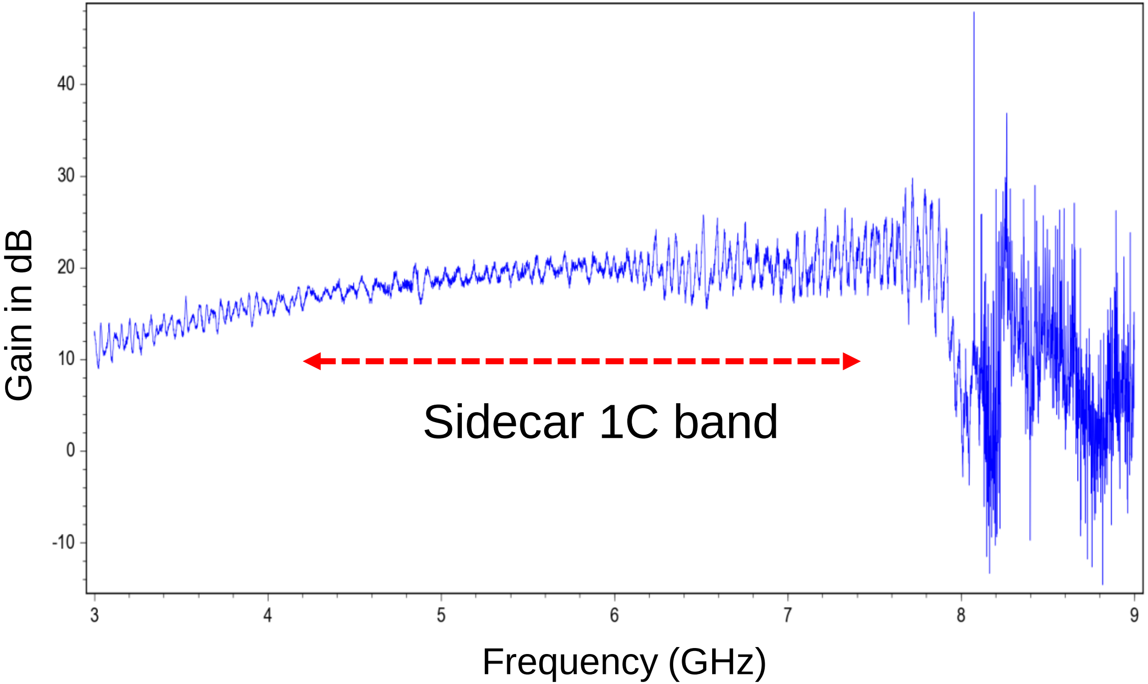
Traveling Wave Parametric Amplifier (TWPA)



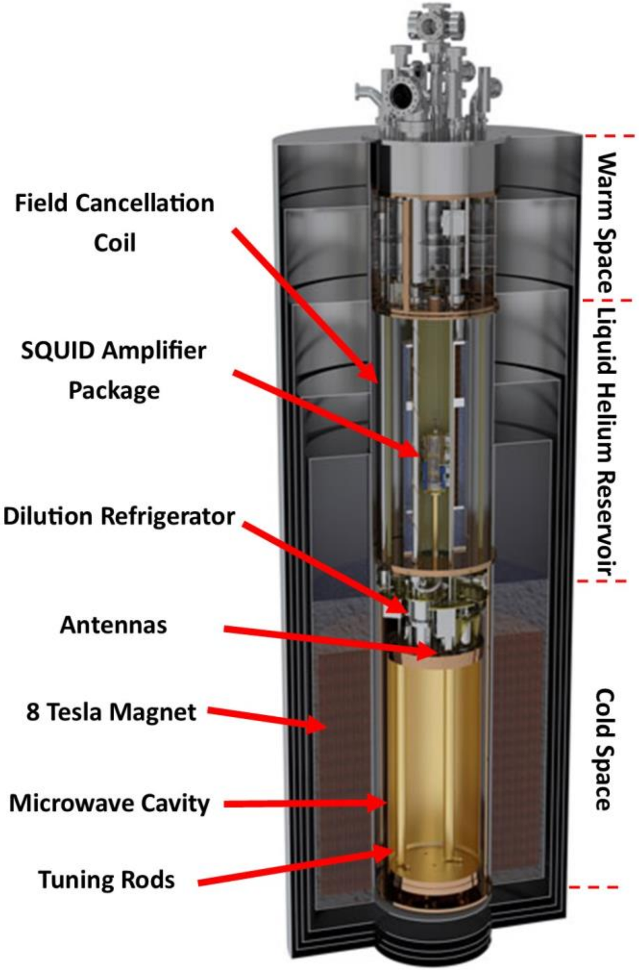
Packaged in the same paddle as the JPA



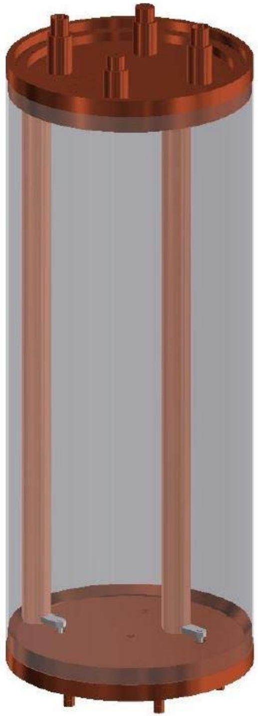
TWPA Gain vs Frequency



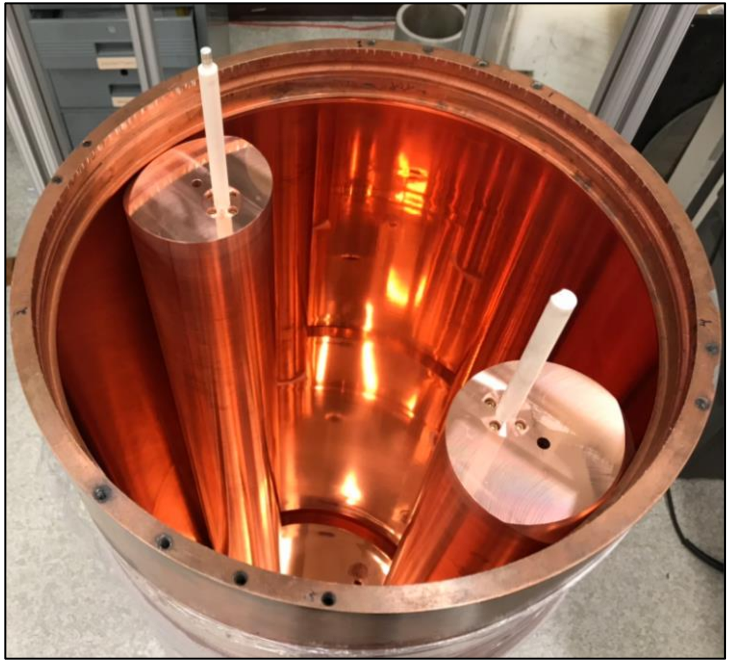
ADMX experiment



ADMX Cavity Systems as we move up in frequency



Cavity from run 1a & 1b
Two 2” diameter tuning rods
580 – 890 MHz



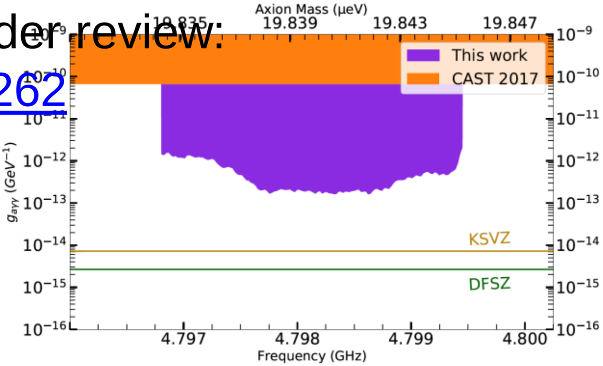
Cavity from run 1c & 1d
Larger 4.5” (then 6”) diameter tuning rods
780 – 1200 MHz
Tuning rods for run 1D soon

Cavity system for run 2a
4 cavity array
Sapphire (1200 – 1500 MHz)
Metal Rods (1500 – 2000 MHz)

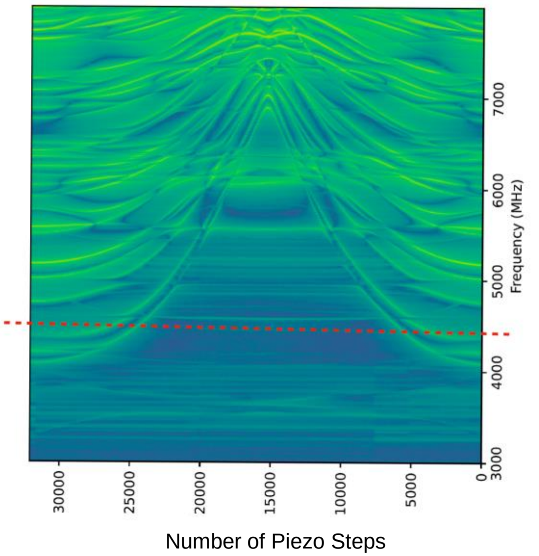
ADMX: Run 1C Sidecar

Sidecar Initial Publication under review:

https://arxiv.org/abs/2110.10262



Tuning rod is set to start at 4.4 GHz

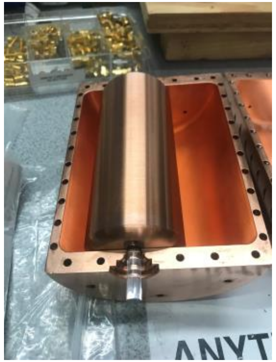


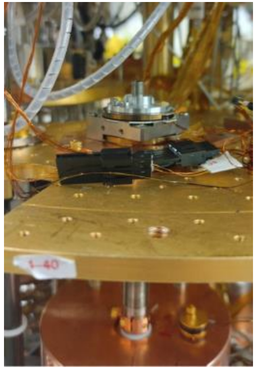
Had some issues last run

1. Stuck Tuning Rod
2. Broken input cable (no transmission)

Upgrades Made

1. All copper tuning rod
   a. Welded Cu tube vs solid Cu-coated SS (1/2 the weight)
2. Lowered resistance for piezos
3. New smaller bearings (slip fit)
4. New Copper Thermal Clamp
5. Sapphire axles vs Alumina
   a. Higher thermal conduction





Attocube Rotor on 1K plate

Other Haloscopes recently coming online

THE UNIVERSITY OF WESTERN AUSTRALIA

ORGAN experiment

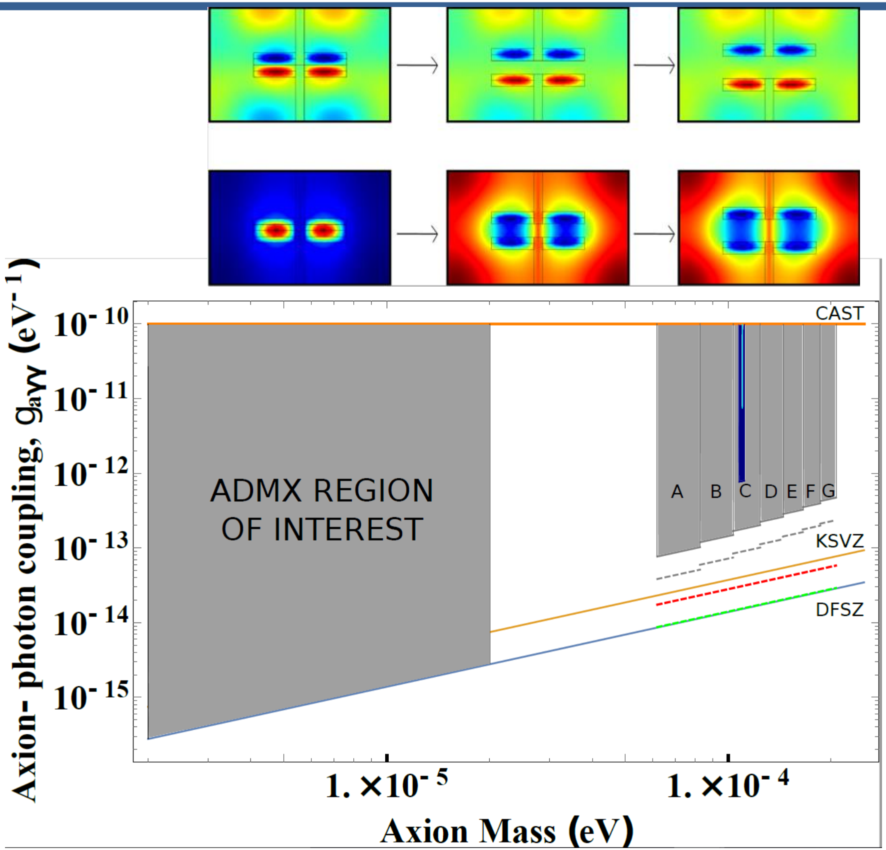
Oscillating Resonant Group AxioN Experiment
(U. of Western Australia)

Exploring new cavity geometries and modes with sapphire disks.

Initial experiments aimed at 26-27 GHz.

Runs A→G are the 2018-2025 runs, with 14 T magnet and SQL Amps

Dashed lines rely on success of squeezed state amplifiers and magnet upgraded to 28 T



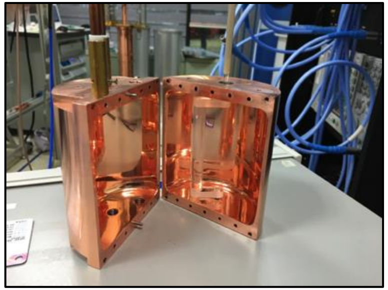
Figures from CAPP Patras 2017

Other Haloscopes recently coming online

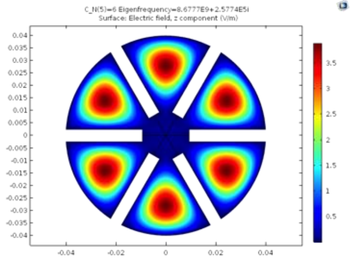
CAPP
Center for Axion and Precision Physics Research

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

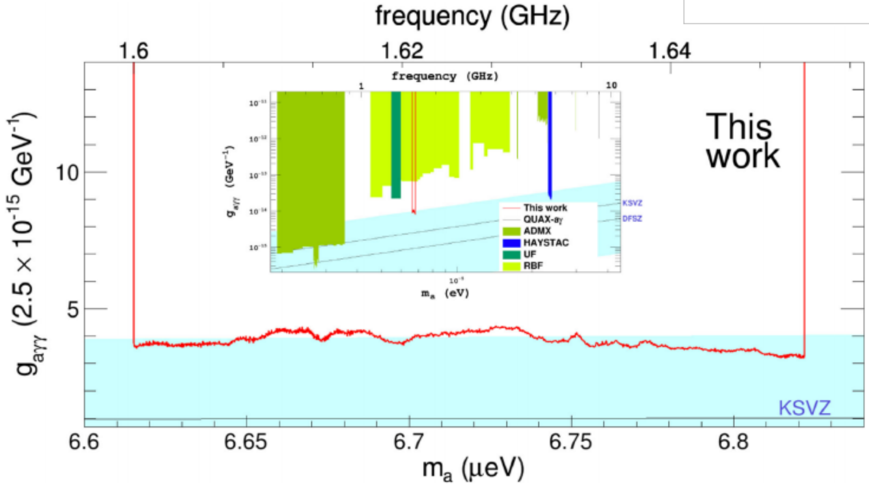
Bring online multiple experimental efforts over the next few years including microwave cavity searches (CULTASK, Toroid & multi-cell cavities)



Prototype copper cavity

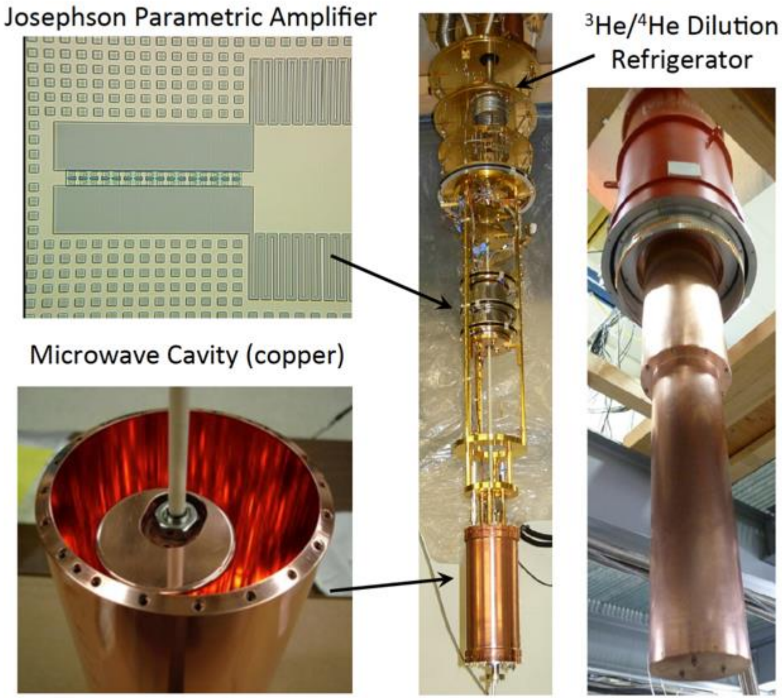


Multi-cell cavities



Axion Dark Matter Search around 6.7 μeV
S. Lee, S. Ahn, J. Choi, B. R. Ko, Y. K. Semertzidis
Phys. Rev. Lett. 124, 101802 —Published 13 March 2020

HAYSTAC experiment



9.4 Tesla magnet with 2-liter cavity

Results:

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)

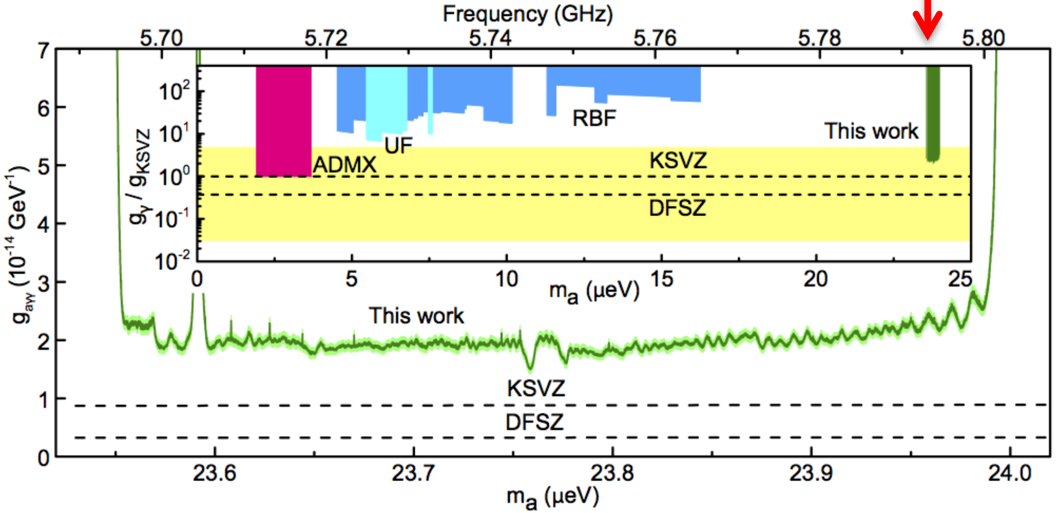
2. L. Zhong et al., Results from phase 1 of the HAYSTAC microwave cavity axion experiment, arXiv:1803.03690; Phys. Rev. D **97** 092001 (2018)

Design details:

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)

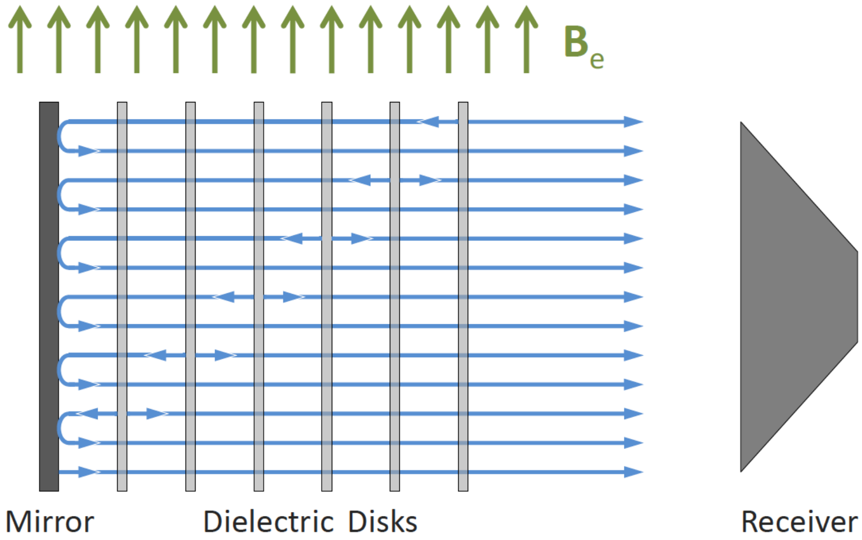
Squeezing demonstration:

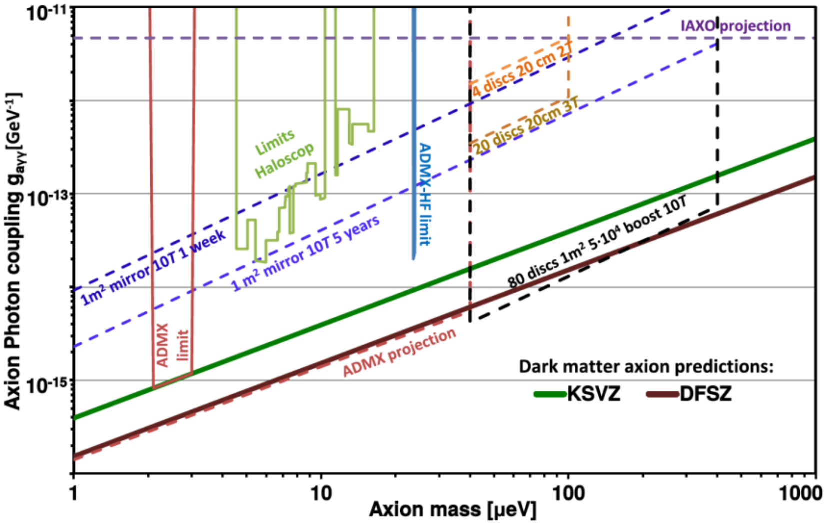
1. M. Malnou et al., Squeezed vacuum used to accelerate the search for a weak classical signal, arXiv:1809.06470; Phys. Rev. X 9, 021023 (2019)



Broadband design with dipole magnet: MADMAX

- Multiple dielectrics can constructively interfere as axions emit from surfaces





Will probe 40-400 μeV range (10-100 GHz)
10 T field & ~80 disks
<u>Prototype phase using dipole magnet at CERN</u>

B. Majorovits and MADMAX interest group 2020 J. Phys.: Conf. Ser. 1342 012098
Stefan Knirck and MADMAX interest group 2020 J. Phys.: Conf. Ser. 1342 012097
Status Report: https://arxiv.org/abs/1901.07401

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

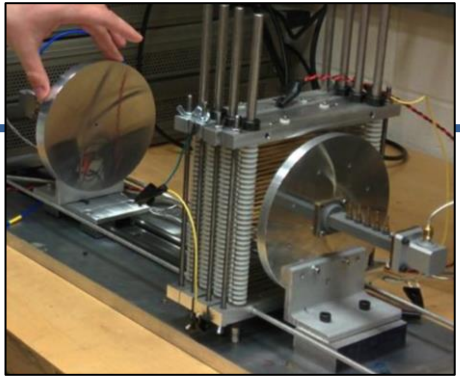
β^2: power emitted by booster / power emitted by single mirror ($\epsilon = \infty$)

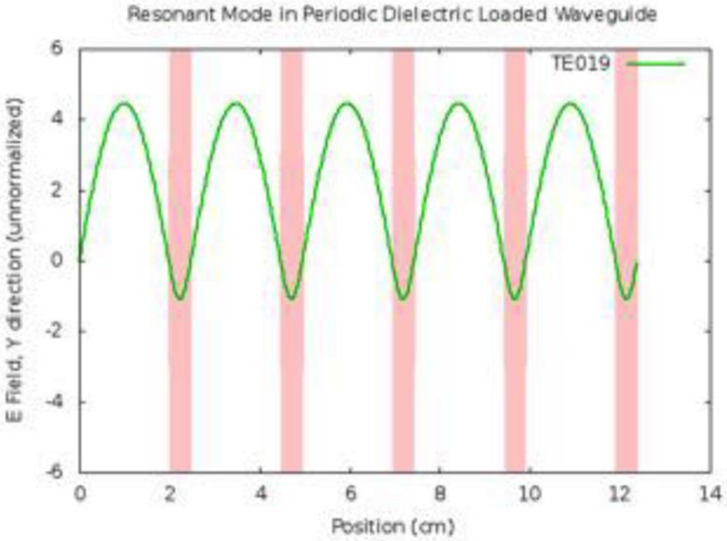
Open resonator design with dipole magnet

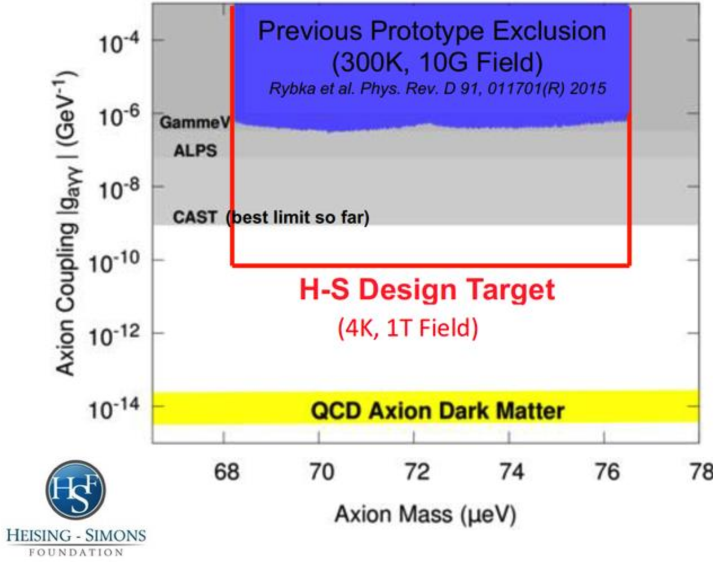
Orpheus Project (UW)

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.







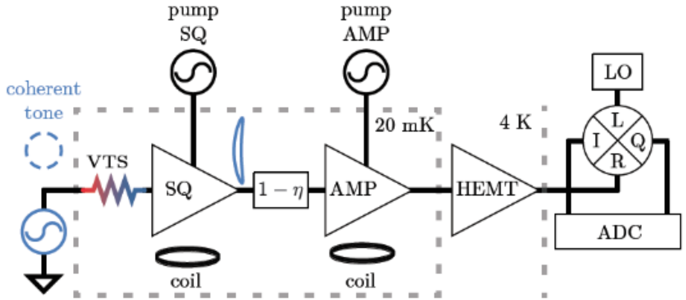
Quantum limit begins to dominate above 2 GHz.

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

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)



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