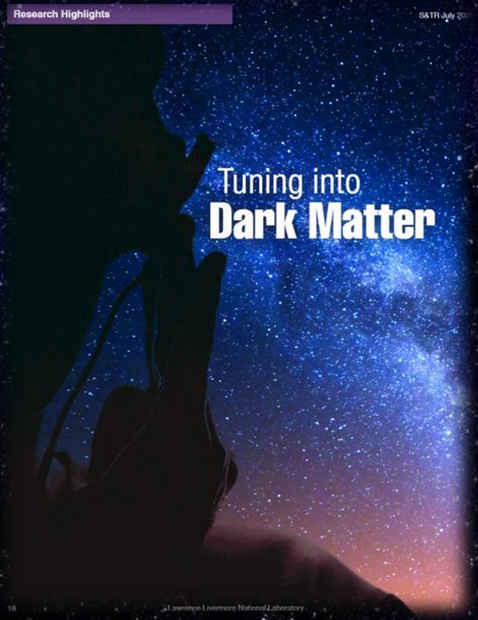
Tuning in to Axion Dark Matter with the ADMX Experiment

Feb 11th, 2021



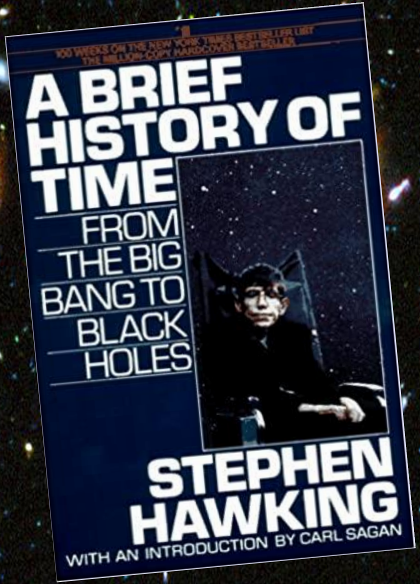
PRISMA+ Centre of Excellence
Johannes Gutenberg University Mainz

Gianpaolo Carosi
November 15th, 2023

LLNL-PRES-856462

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

My primary interest: Explaining how our physical reality works
(This is why I get up in the morning)

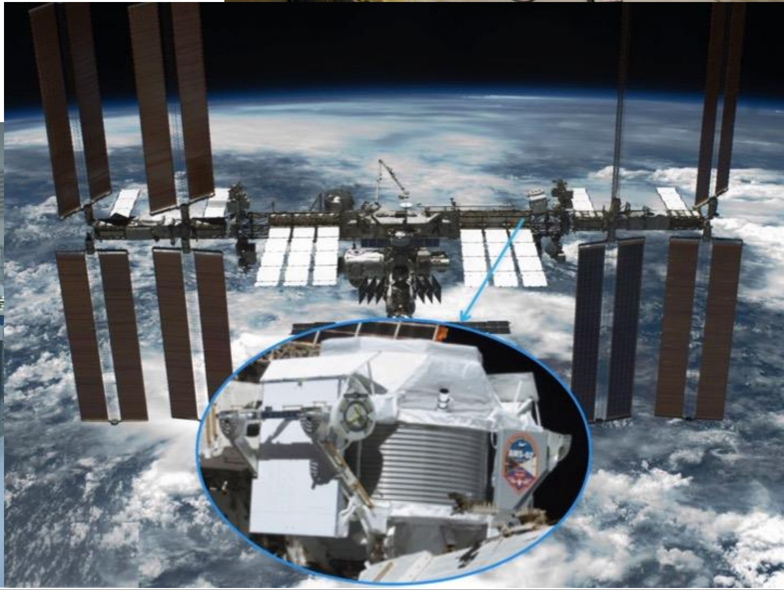


Nourished by a steady diet of scientific fact and fiction growing up

Always wanted to do something with space

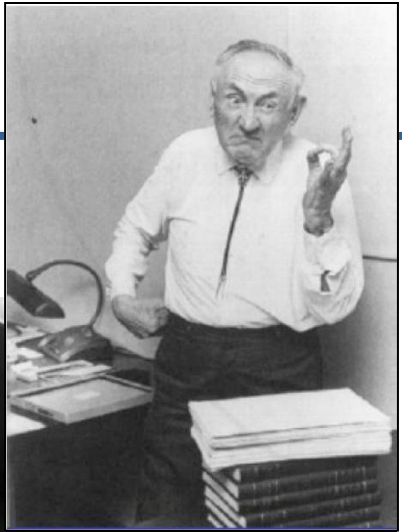
Harvey Mudd College (B.S. in Physics) 2000
JPL Table Mountain Facility (HMC/Pomona 1-m telescope)
JPL Keck Telescope Interferometer
(landed a summer job before graduate school)

MIT (Ph.D in Physics) 2006
AMS-02 Experiment (Cosmic Rays)



The Nature of Dark Matter

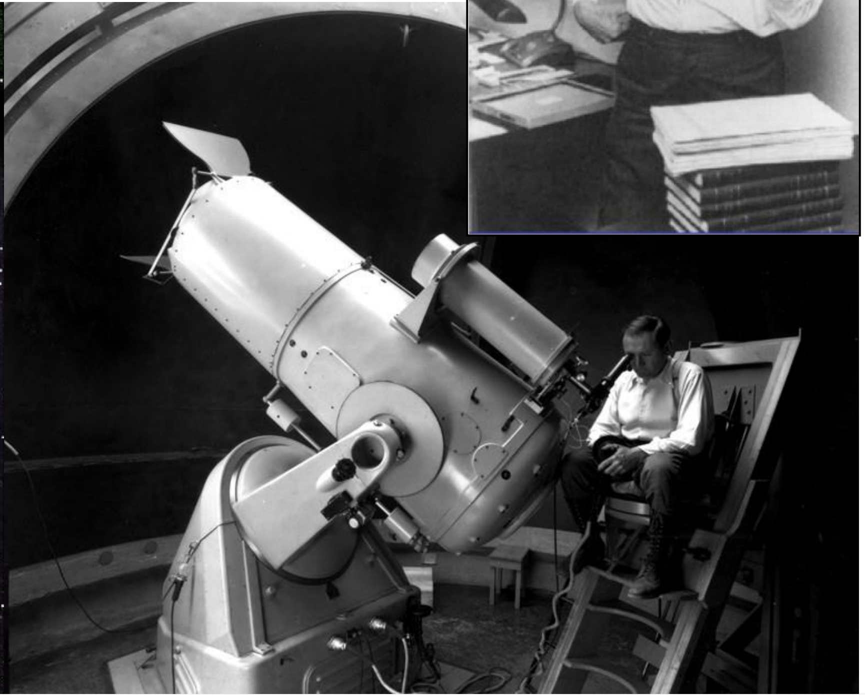
One of the premier unsolved mysteries in physics



1930s

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

Everything moving far too quickly to be held in the gravity well of system.
System should have broken up!



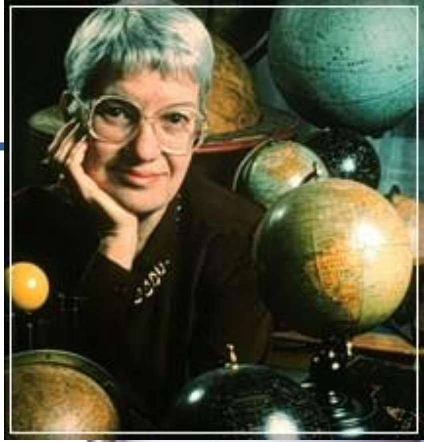
The Nature of Dark Matter

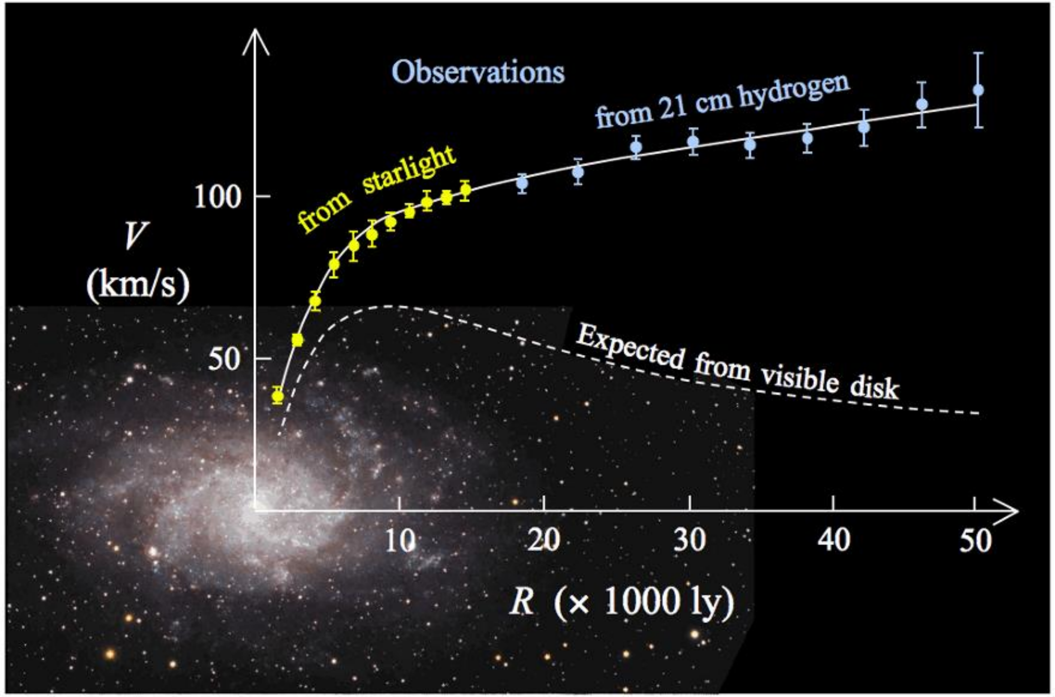
One of the premier unsolved mysteries in physics

1980s

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

Performed systematic surveys… put the issue of dark matter at the forefront of physics & cosmology





The Nature of Dark Matter

One of the premier unsolved mysteries in physics

Additional indirect evidence continues to build

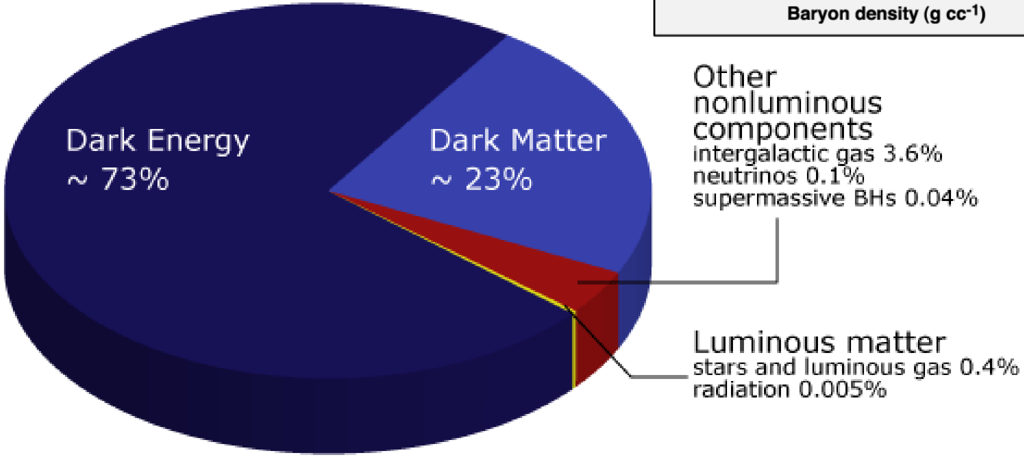
Bullet cluster

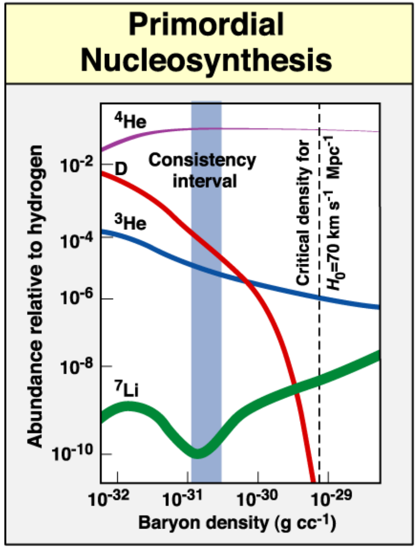
X-ray imaging (hot gas) and Gravitational Imaging (majority gravitating mass) shows separation after collision

Primordial Nucleosynthesis: Ratios of Hydrogen, Helium, Lithium limit number atoms in the universe.

It has to be something else!!!

Neutrinos are close but don't cut it (to small a fraction).

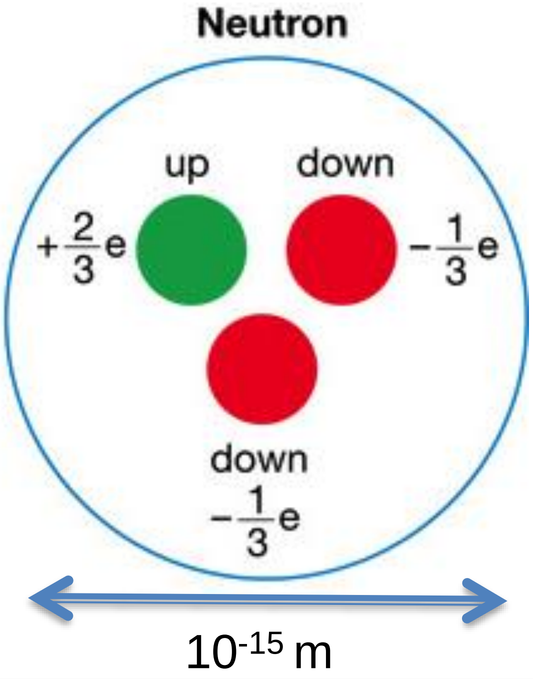


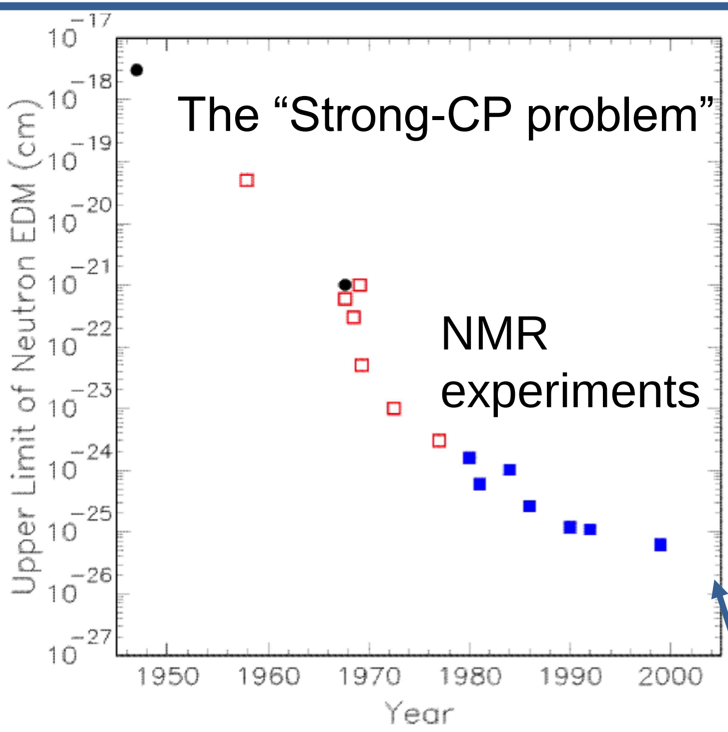


Meanwhile… another mystery of physics:

Why is the neutron electric dipole moment so small?

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





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

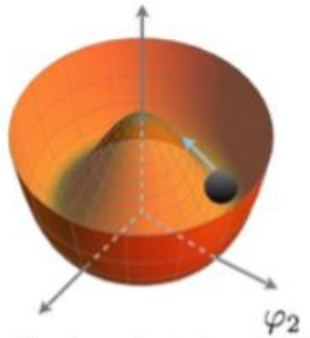
C. Abel et al.
Phys. Rev. Lett. 124, 081803 — Published 28 February 2020

Peccei-Quinn Solution to the Strong-CP problem

- <u>**Something conserved implies a Symmetry**</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)

- 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*



Oscillation about the QCD minimum – *Daniel Grin*

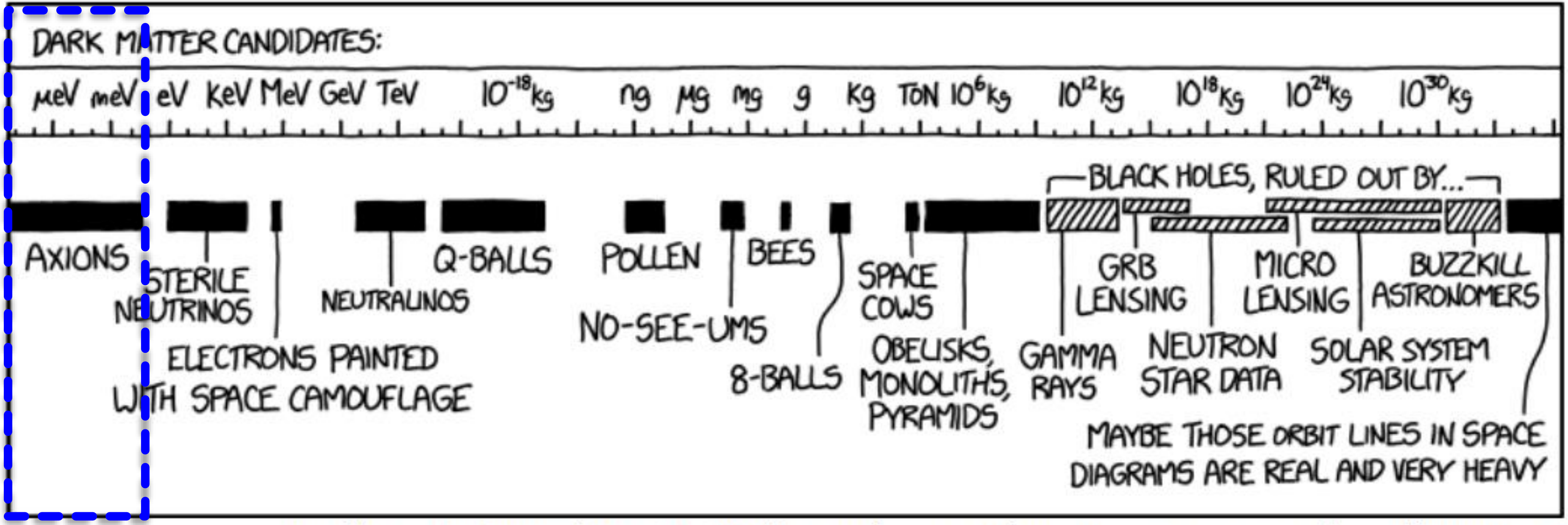
Roberto Peccei
1942-2020

Helen Quinn

Steven Weinberg

Frank Wilczek

The Mass Range of Dark Matter Candidates

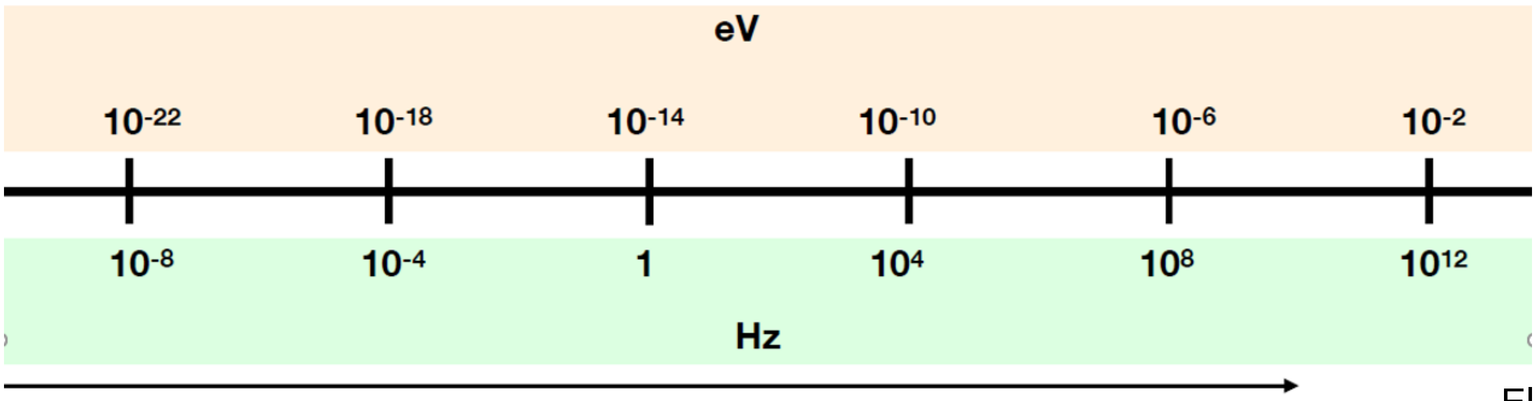


Credit to: **xkcd.com** (Aug. 20, 2018) "*A webcomic of romance, sarcasm, math, and language.*"

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



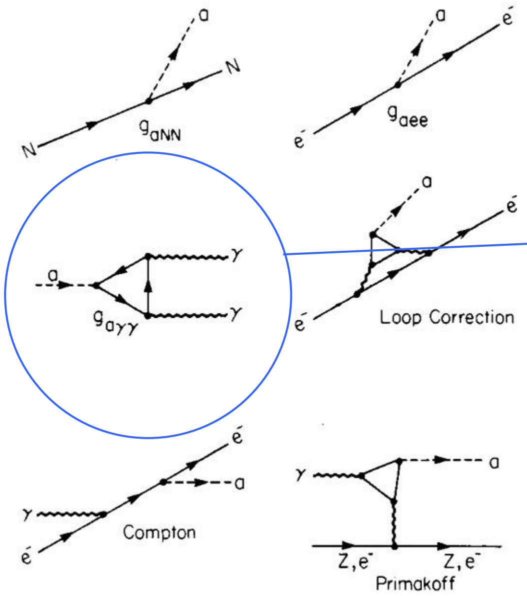
Pre-inflation
PQ phase transition

Electrons
0.5 GeV

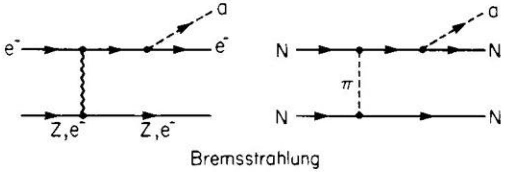
Protons/Neutrons
938/340 GeV

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

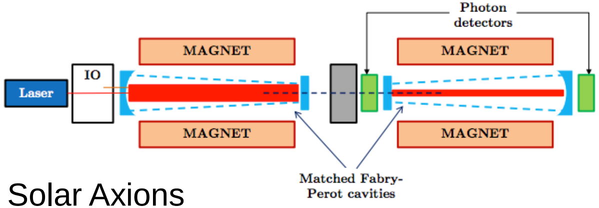
Rate depends on "unification group" (the particles in the loops), ratio of u/d quark masses. The U(1) charges at the axion vertex cancel with little model dependence

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

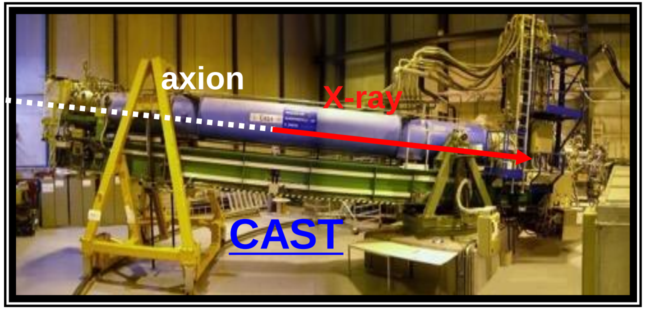
Types of axion experiments

Pierre Sikivie
PRL 51:1415 (1983)

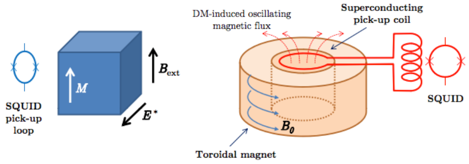
Laboratory Experiments: Lasers (light shining through walls) & 5th force experiments

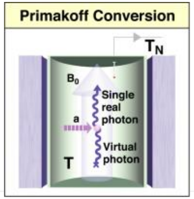


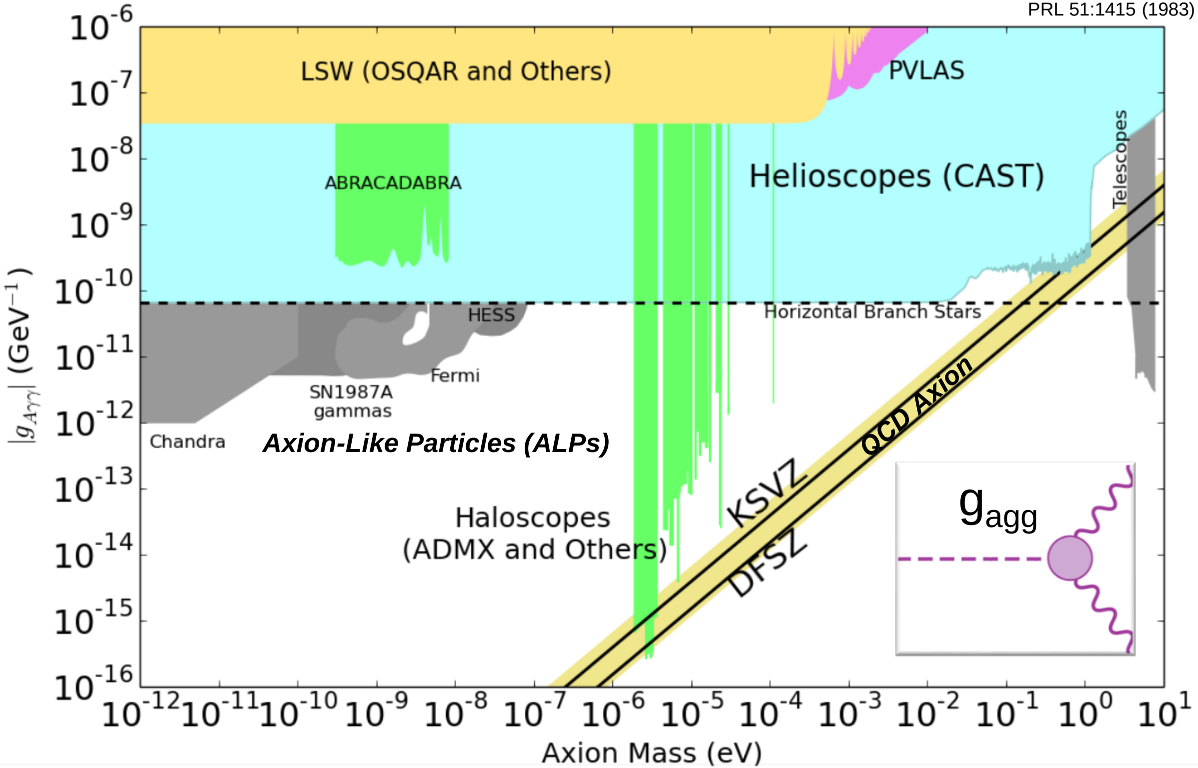
Solar Axions



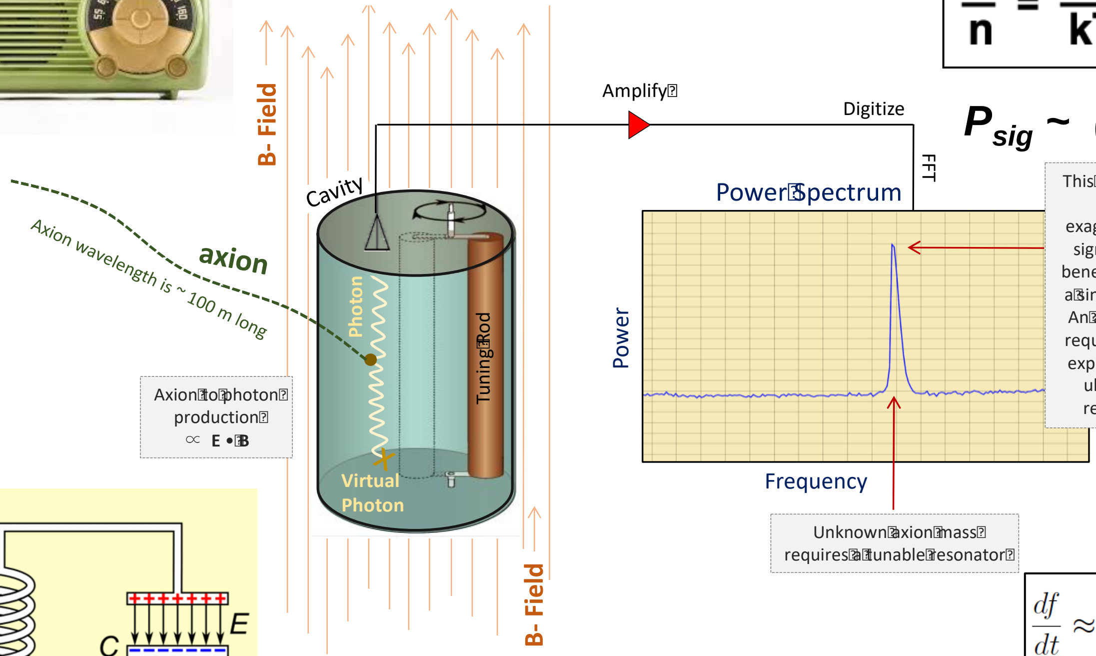
Axions from Dark Matter (Haloscopes, NMR, etc)

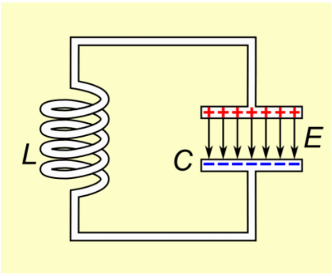






Axion Dark Matter Searches: The Haloscope Technique





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

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

System noise temp.

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

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

t = Integration time limited to ~ 100 sec

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

Power transfer from axion field to cavity field

<ins>Weak coupling</ins>
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.

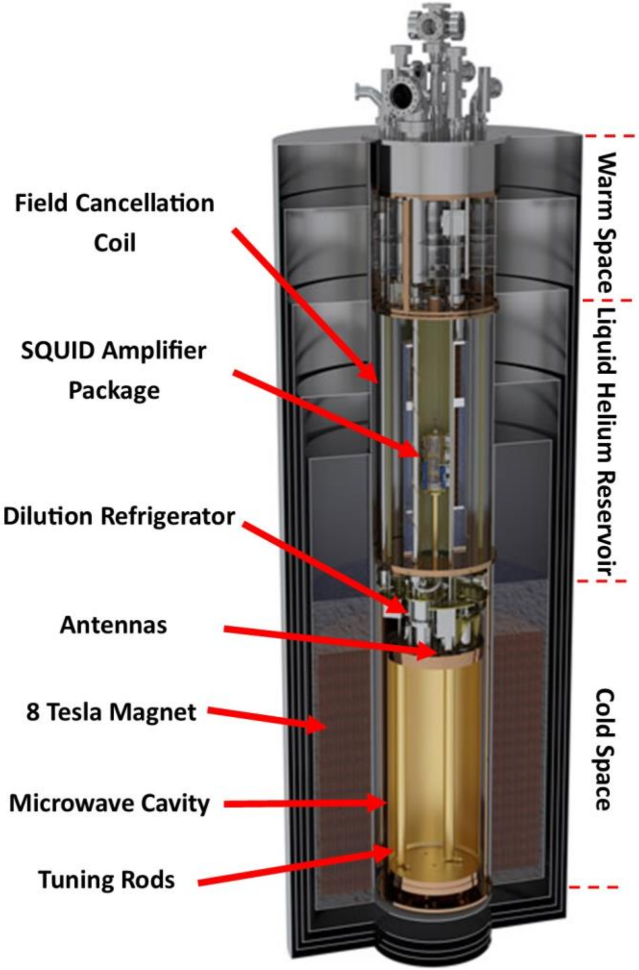
*Slide from Aaron Chou (FNAL)

ADMX started at LLNL

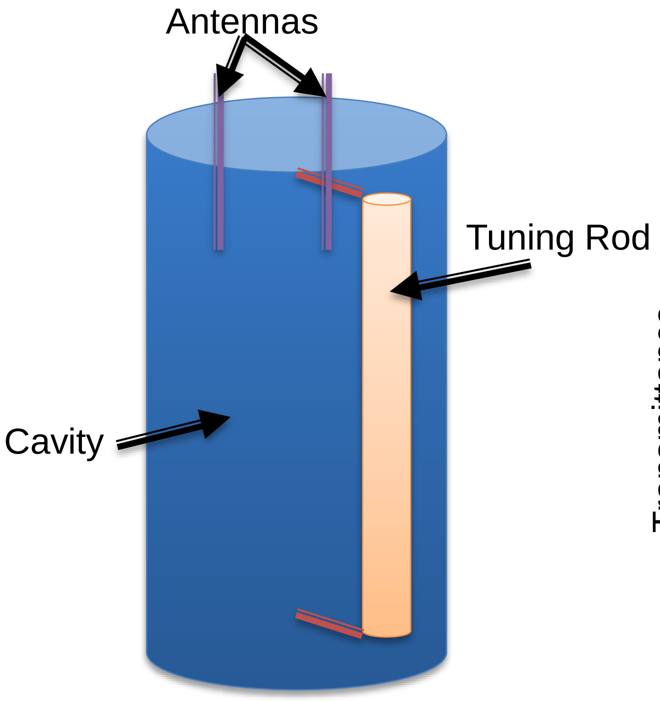
- Built off pioneering experiments at U. of Florida and Rochester/Brookhaven/Fermilab in late 1980s
- ADMX started with the purchase of large (8T 60-cm bore) Solenoid from Wang NMR (located in Livermore over by Costco). 16 MJ of stored energy (220 amps)
- Installed in the early 1990s and took data there with continuous upgrades until 2010. System then moved to the University of Washington

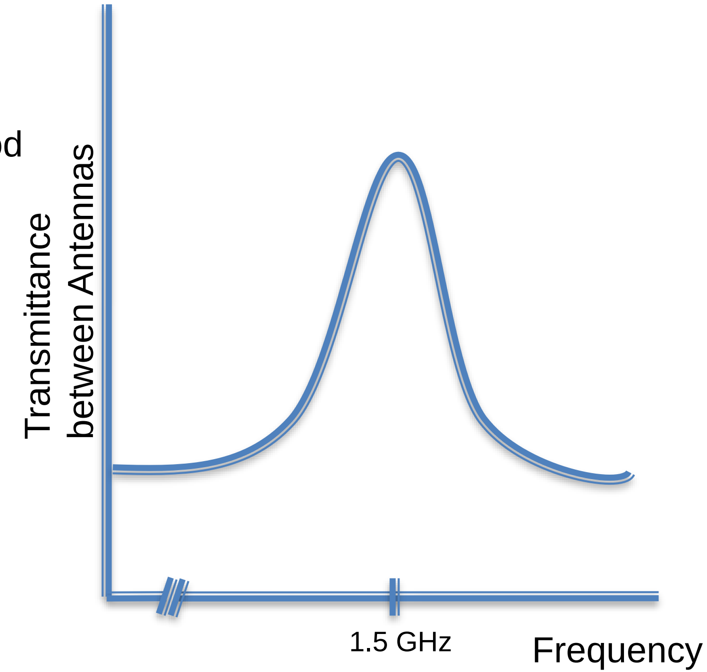
I joined as postdoc in 2006

ADMX experiment



Microwave Cavity needs tunable resonance





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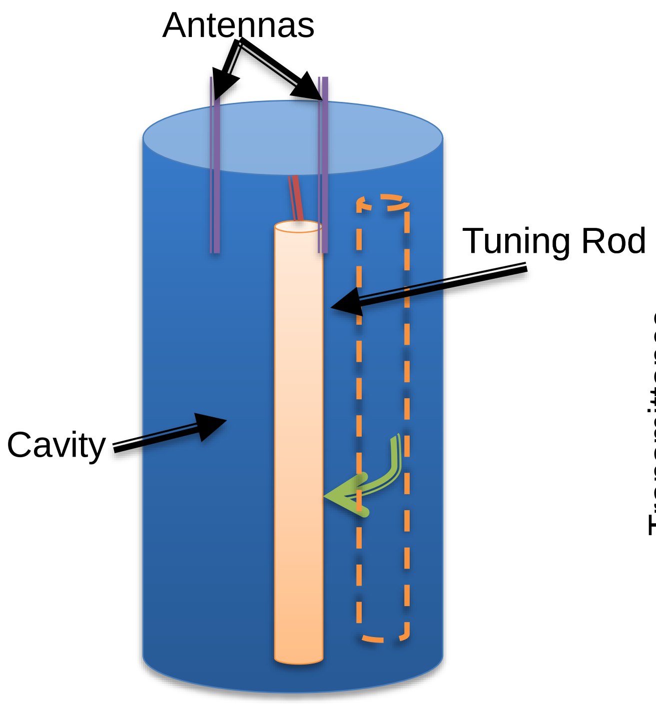
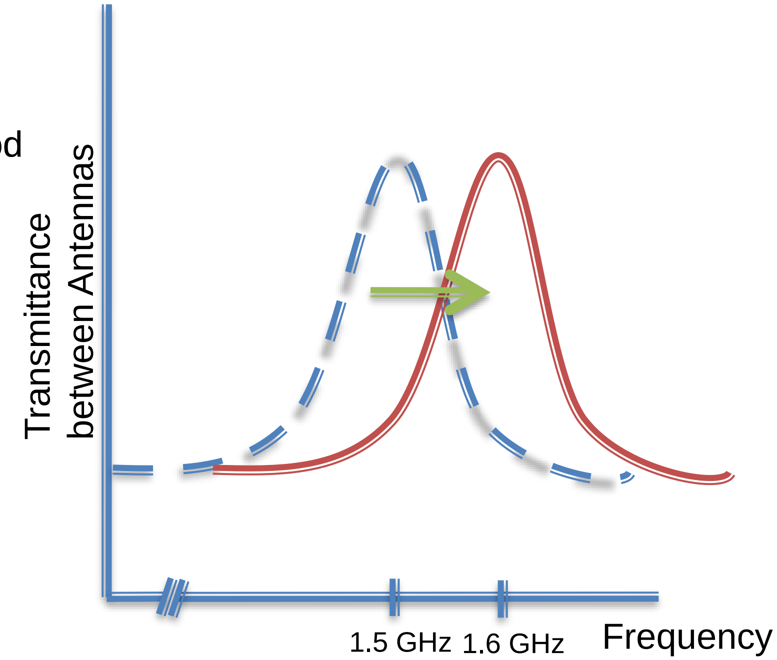
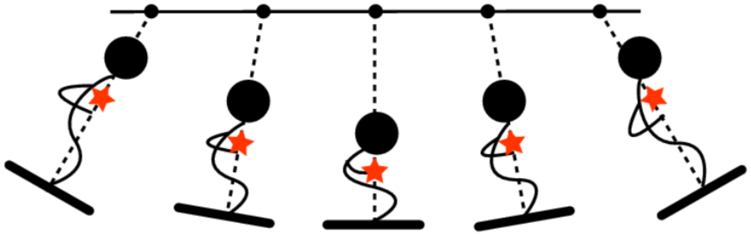




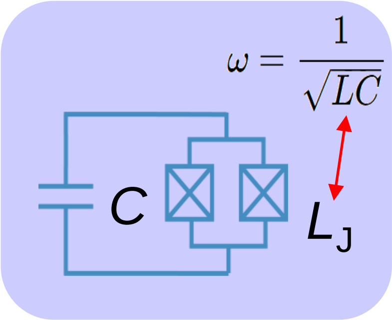
* LLNL sponsored HMC Clinic Final Presentation – 2010

Josephson Parametric Amplifiers (JPAs)

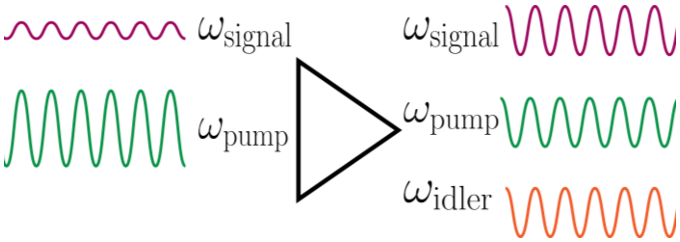
- JPA's provided by Irfan Siddiqi's group at UC Berkeley



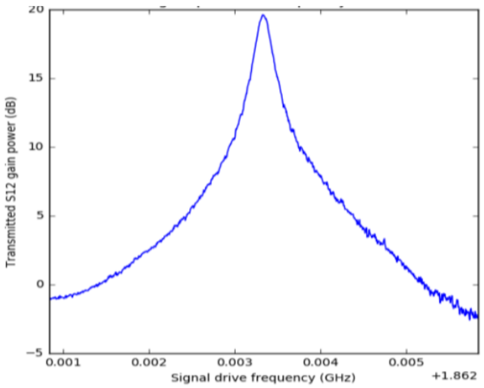
Classic example of parametric amplification is a child on a swing



Prof. Irfan Siddiqi



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

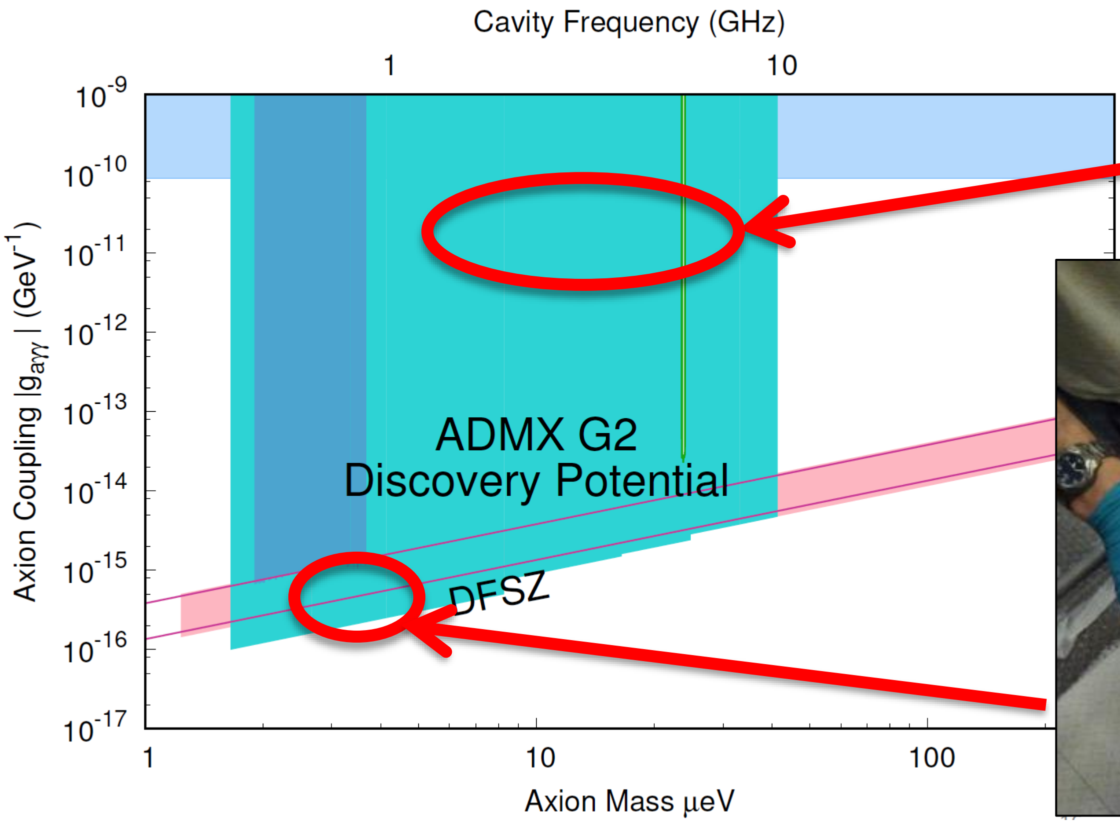


High gain achievable at JPA resonance.

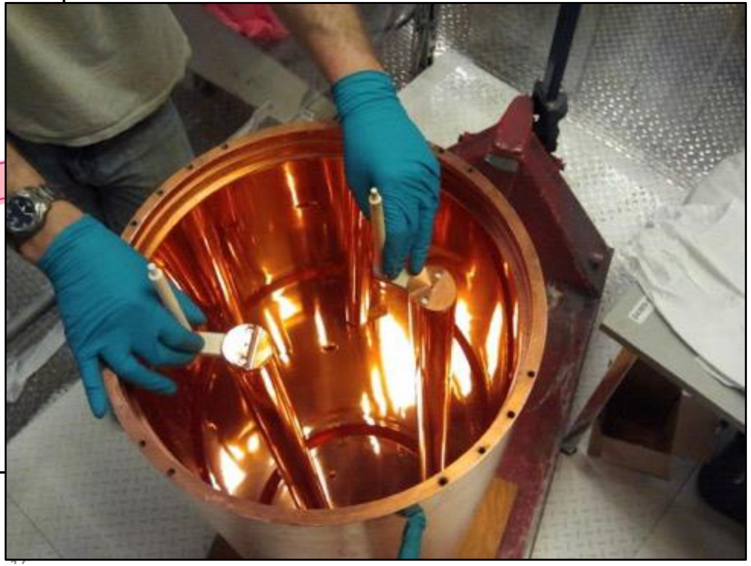
Run 1B and beyond

*figures courtesy of Shahid Nawaz

ADMX Gen-2: Main Cavity & Sidecar Cavity

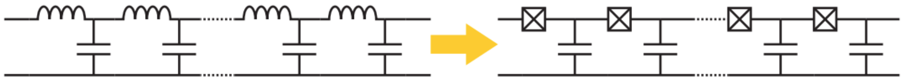


Sidecar cavity



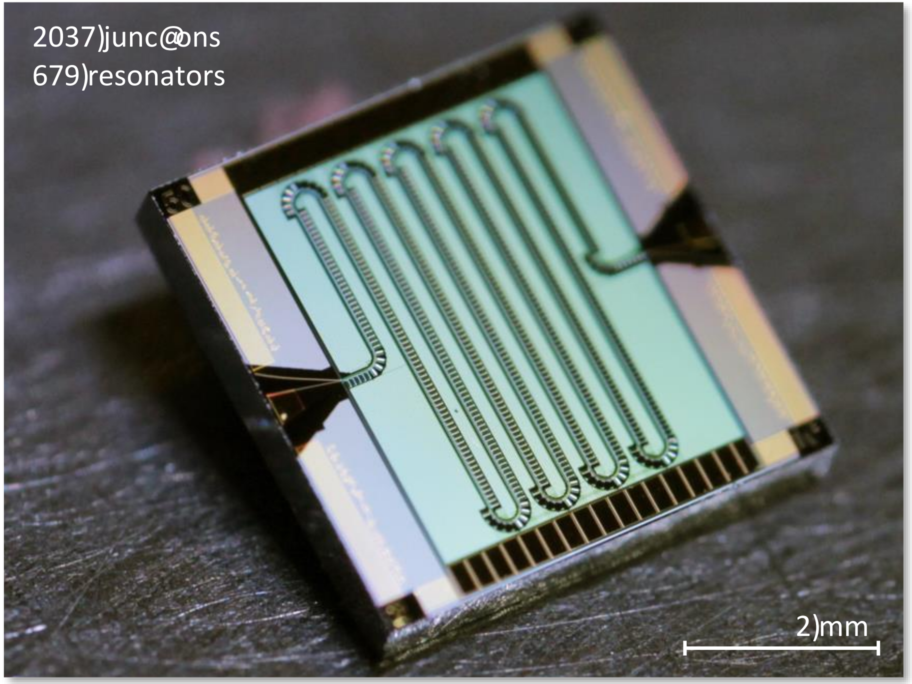
New Traveling Wave Parametric Amplifier (TWPA)

- Use long array of junctions. Phase match with pump (now directional 2-port device)

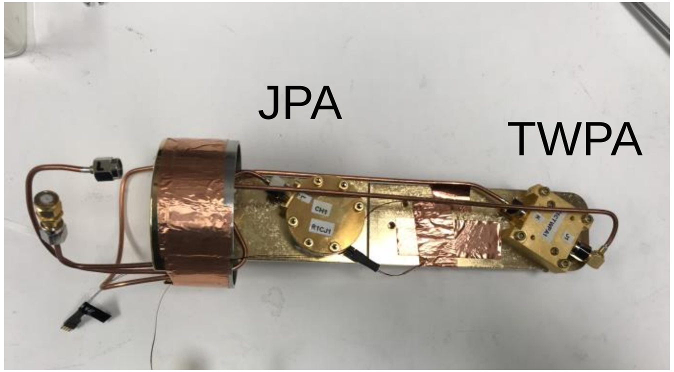


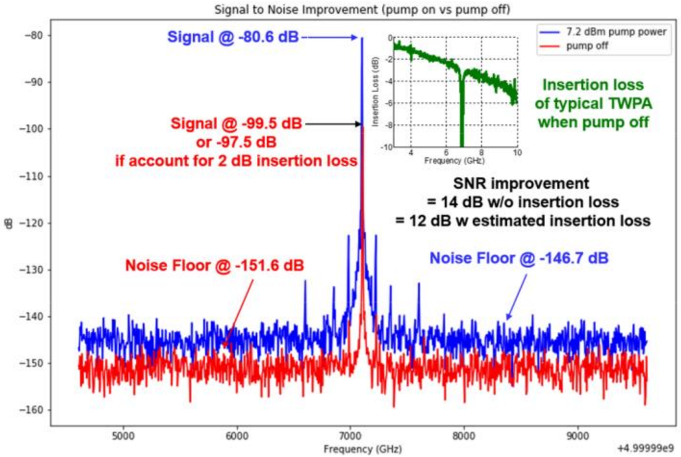
Broadband amplifier

- Potentially useful for frequency multiplexed axion searches (large # of cavities with complimentary frequency coverage).
- Provided to ADMX by Lincoln Lab
- Test on Sidecar cavity system

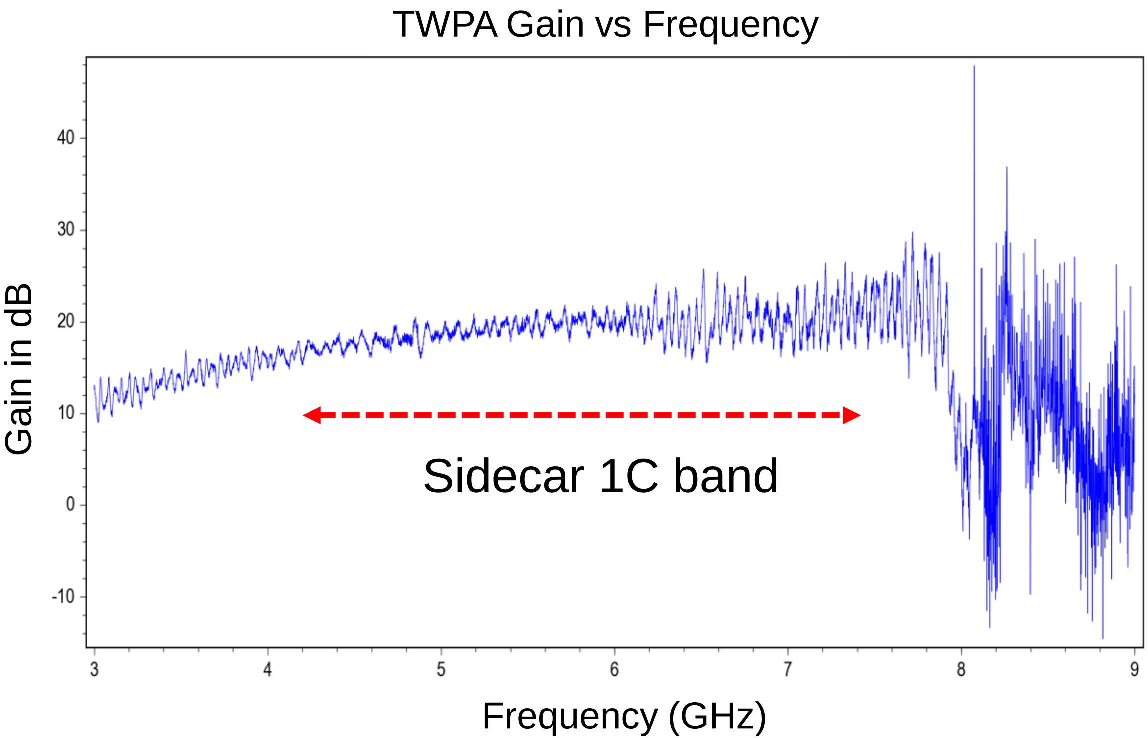


Traveling Wave Parametric Amplifier (TWPA)

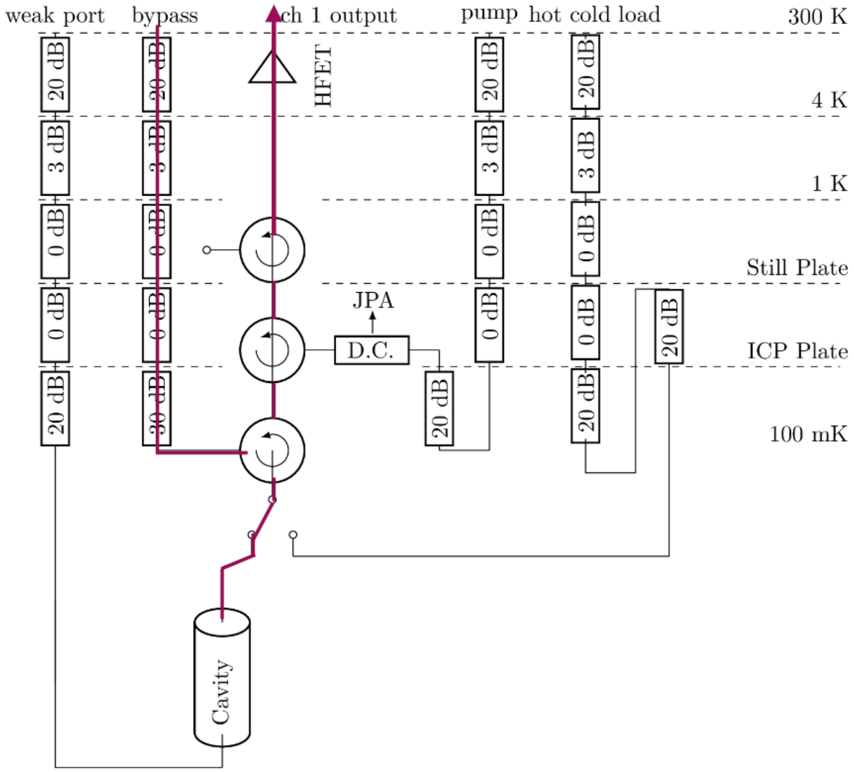




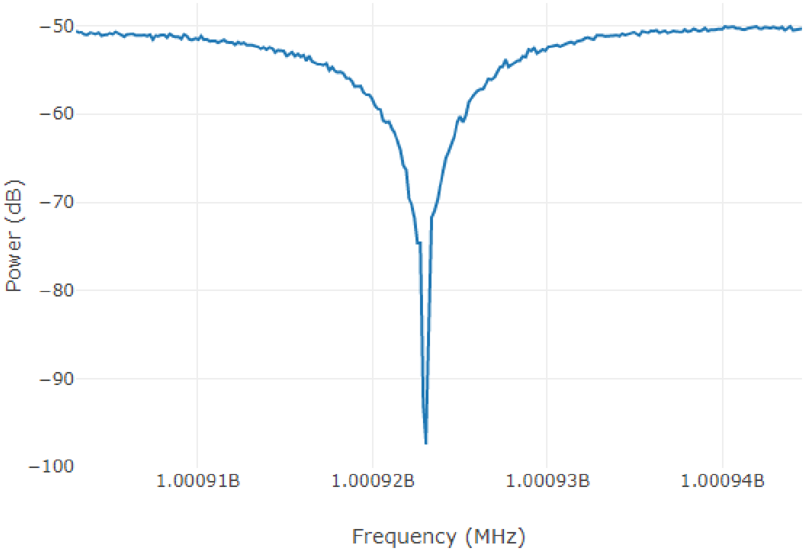
Packaged in the same paddle as the JPA



Modes of operations



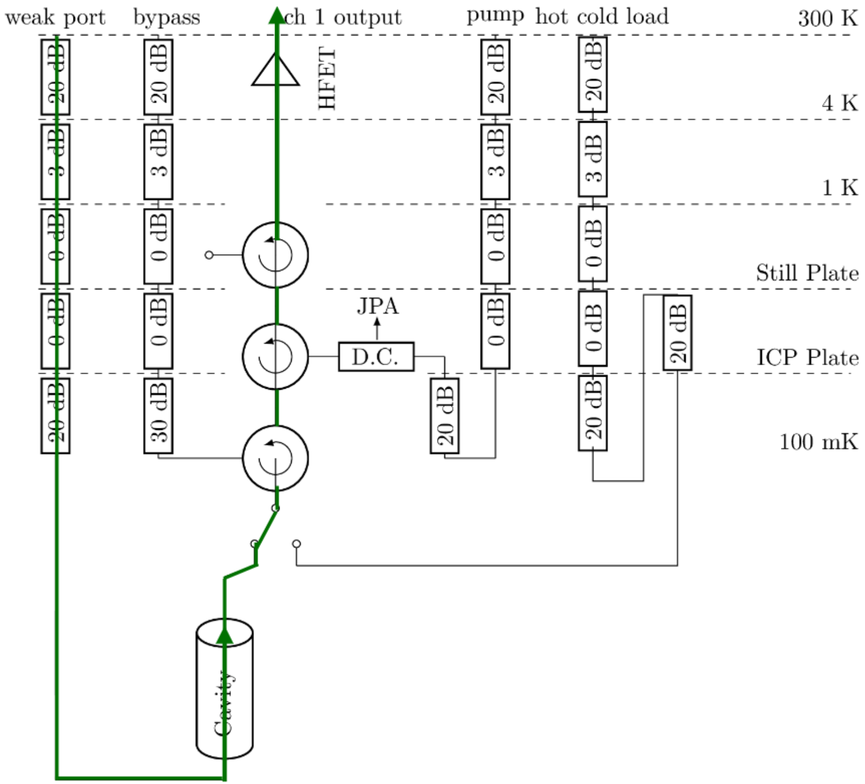
Reflection Measurements

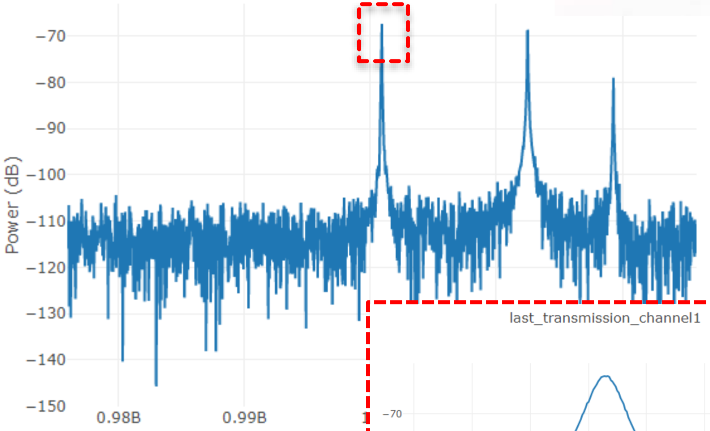


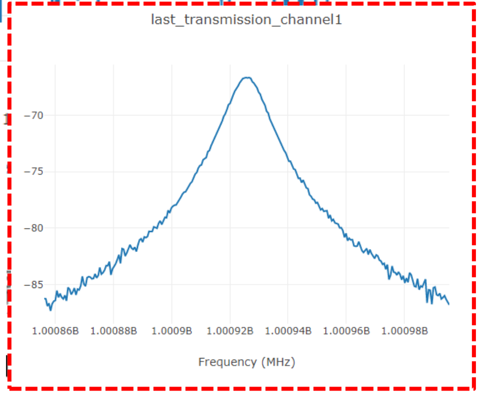
Gives antenna coupling

Needed to understand how much power comes from cavity

Modes of operations







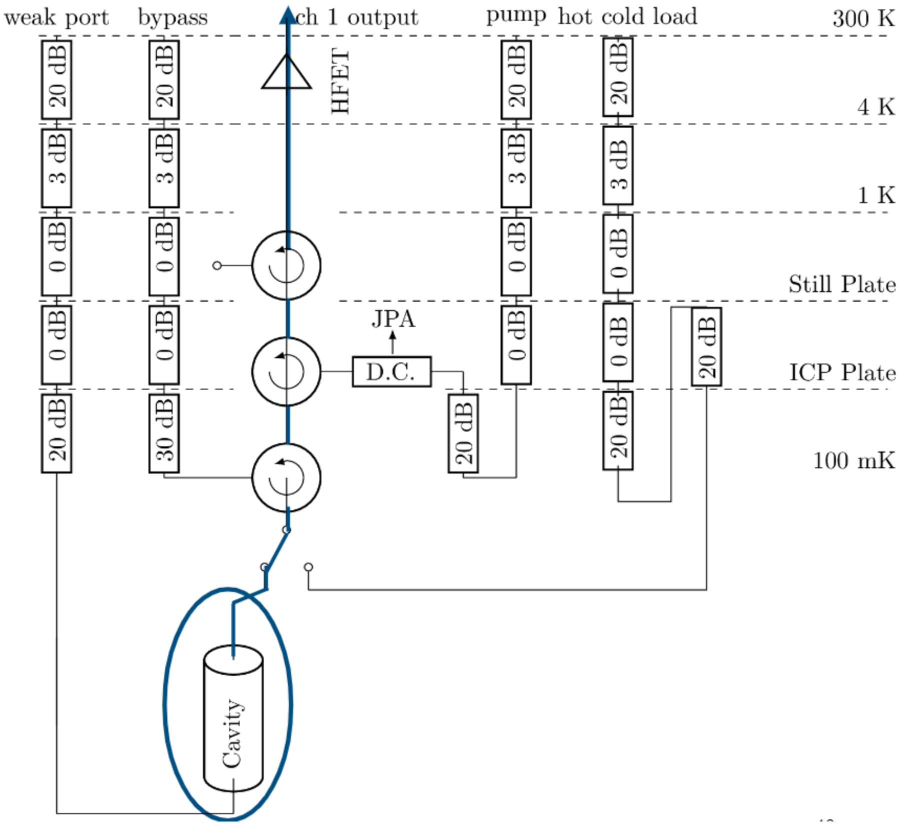
Transmission

Quality Factor & Frequency

Independent measure of resonance

Also used for synthetic axion injection (RF tones)

Modes of operations



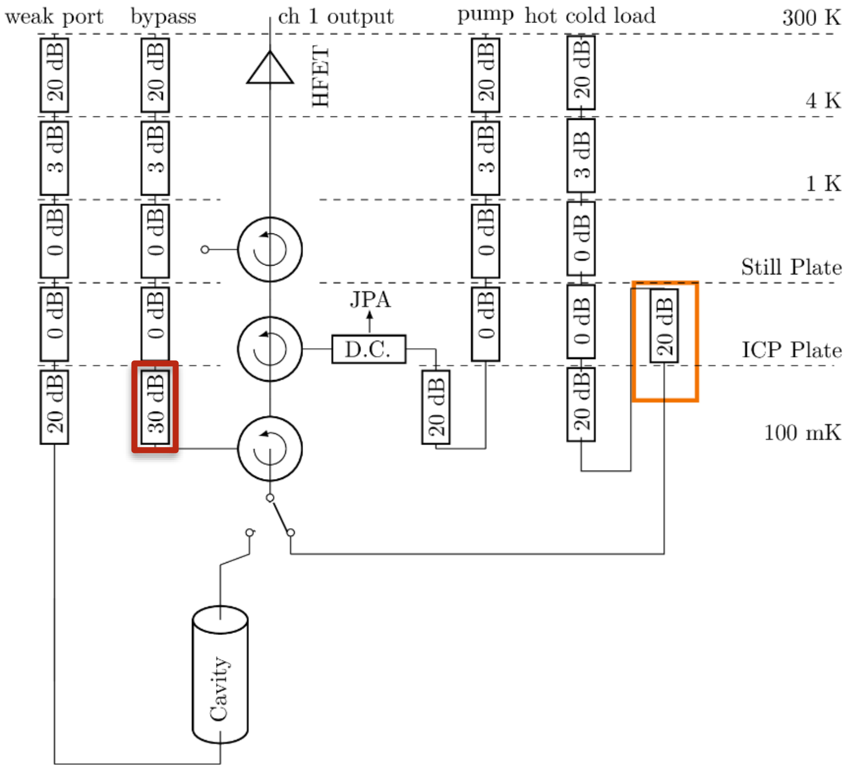
Data-Taking Mode

- 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

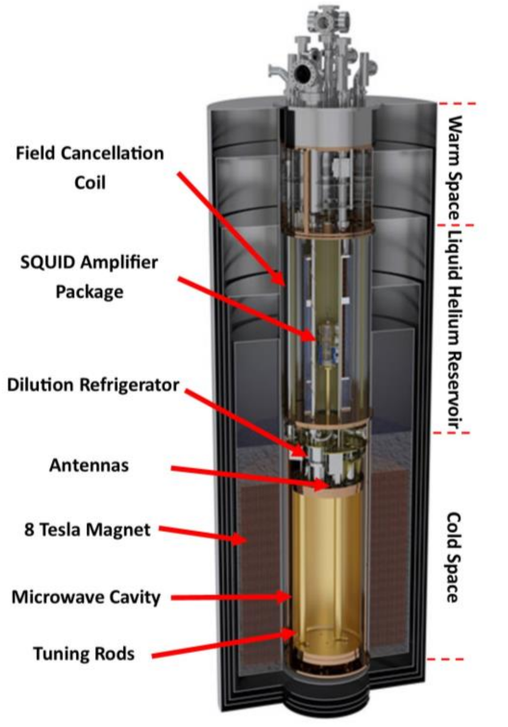


Noise Calibration Mode

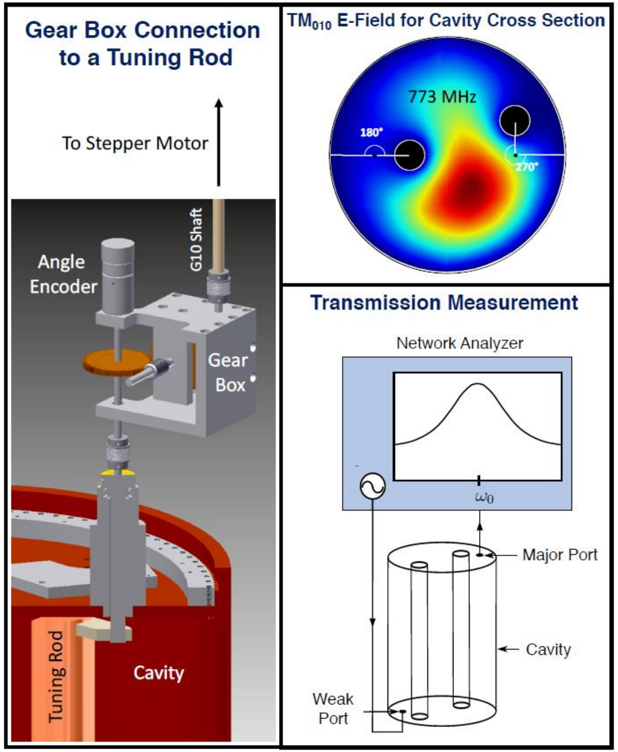
- Receiver chain provides means for measuring key RF parameters, such as quality factor
- Two types of noise measurement
- 1) Heating of the 'hot-load' via dc current (by design)
- 2) Heating of the quantum amplifier package via an RF switch

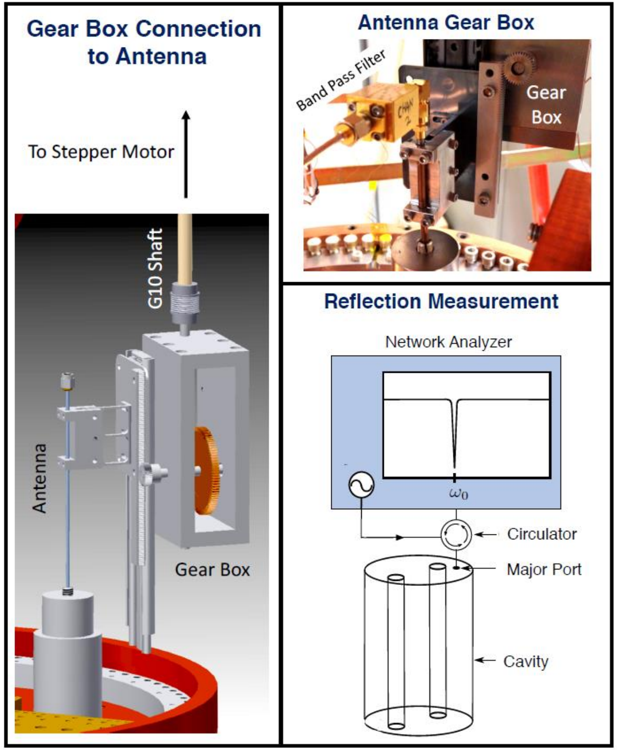
Performed semi-regularly (every few months)

ADMX Run 1C: Tuning & Coupling

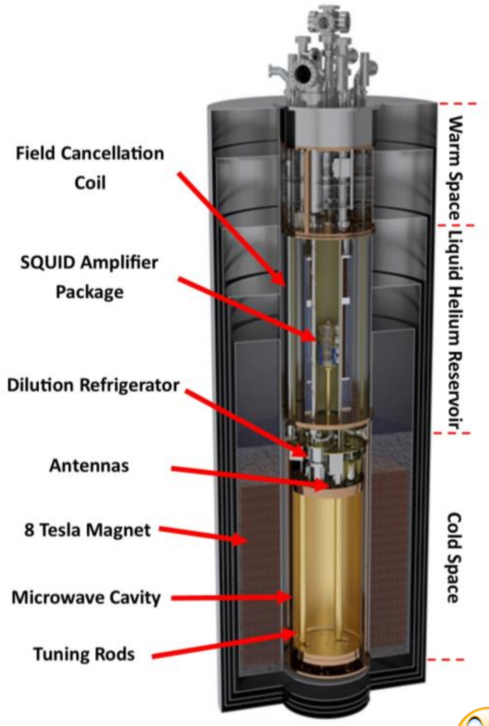


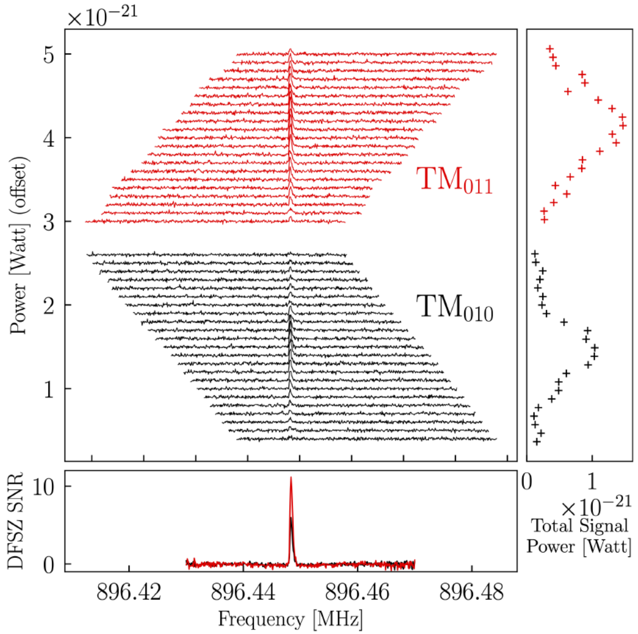
Cavity 1B





ADMX 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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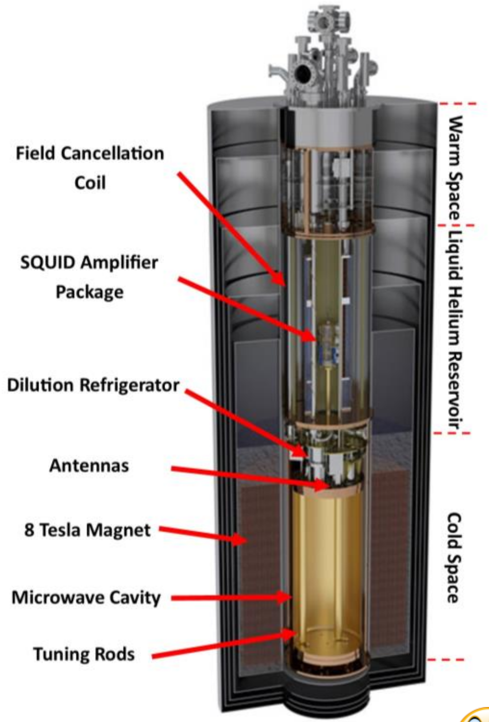
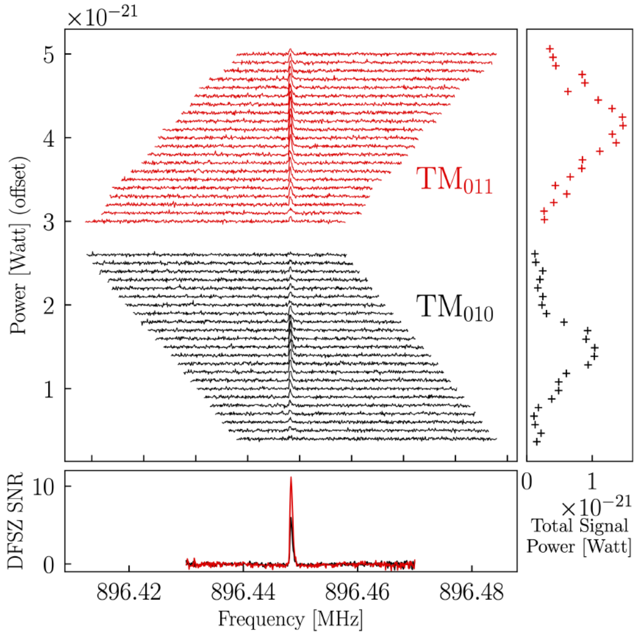
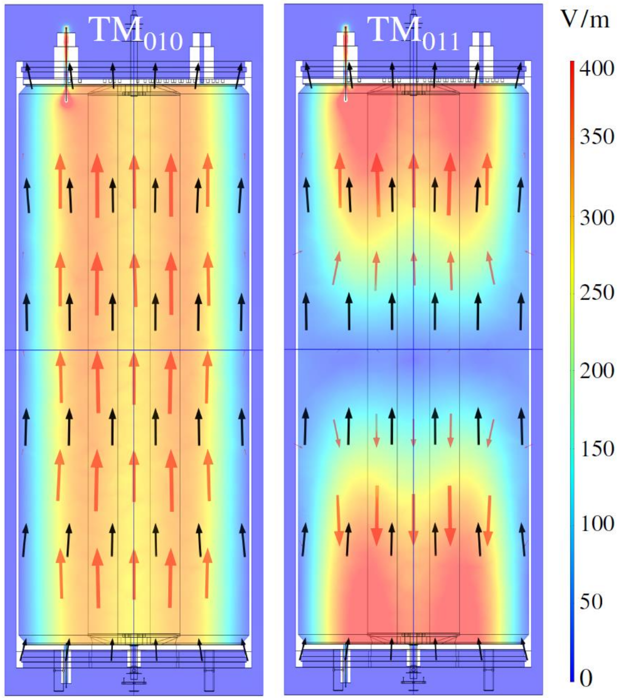




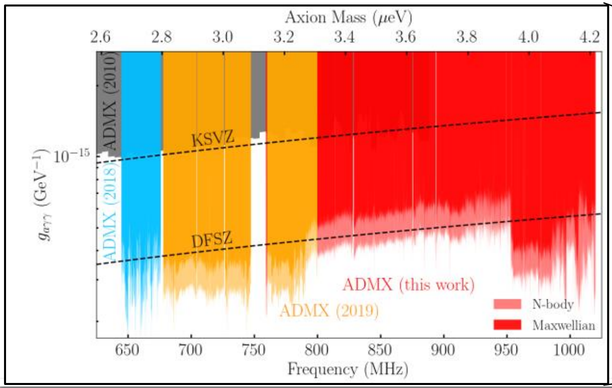


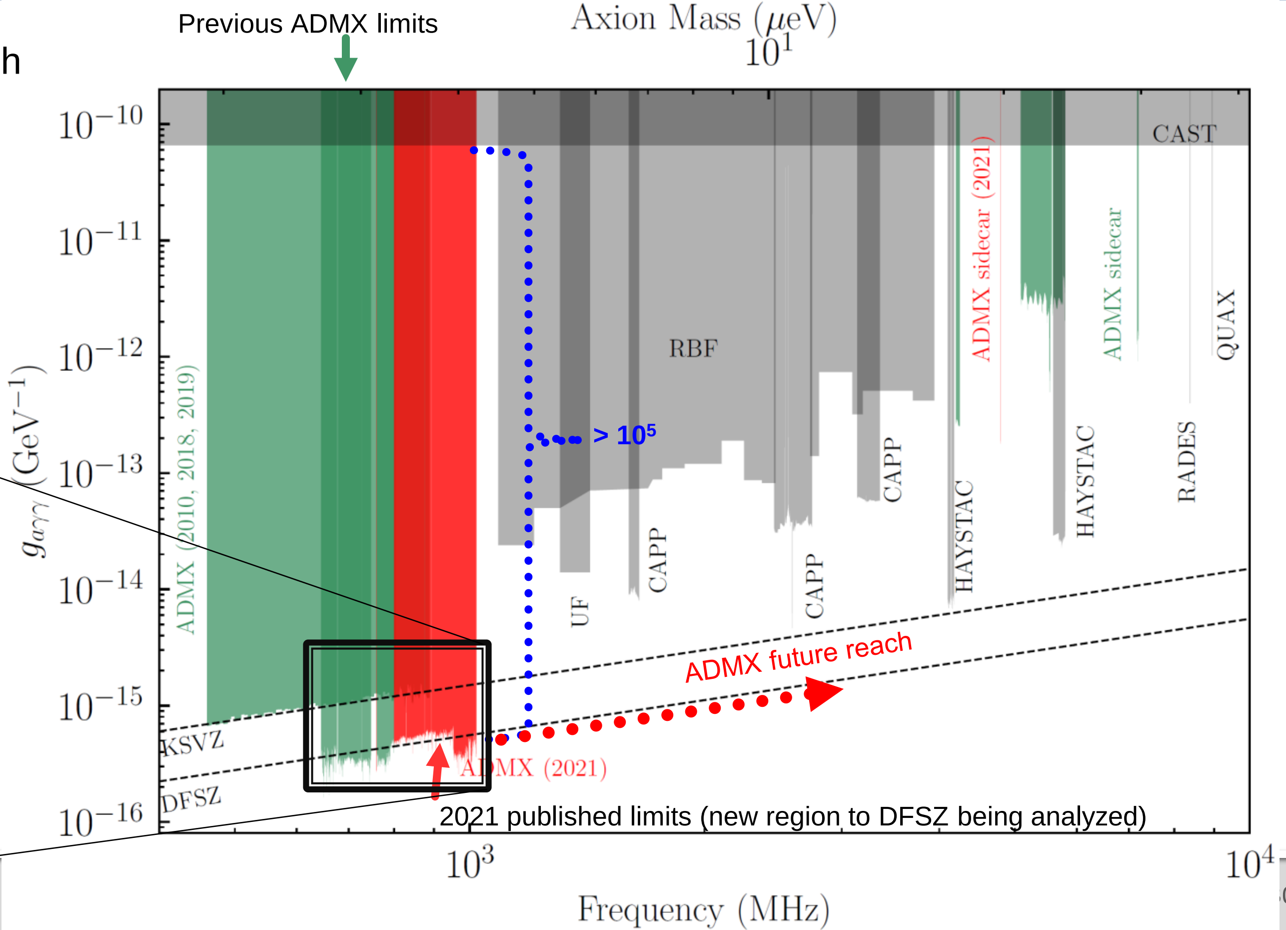
Signal had line-shape consistent with axion!
Power went away off resonance (not RFI)!

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

ADMX-G2 results and near term plans

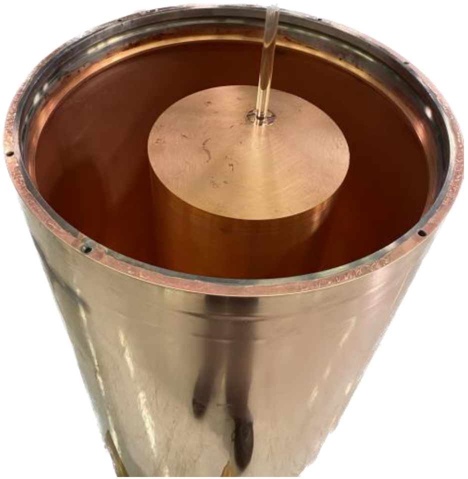
- Operations in phases that match the cavity tunable bandwidths
- Previous runs with sets of two tuning rods (runs 1A, 1B, 1C)

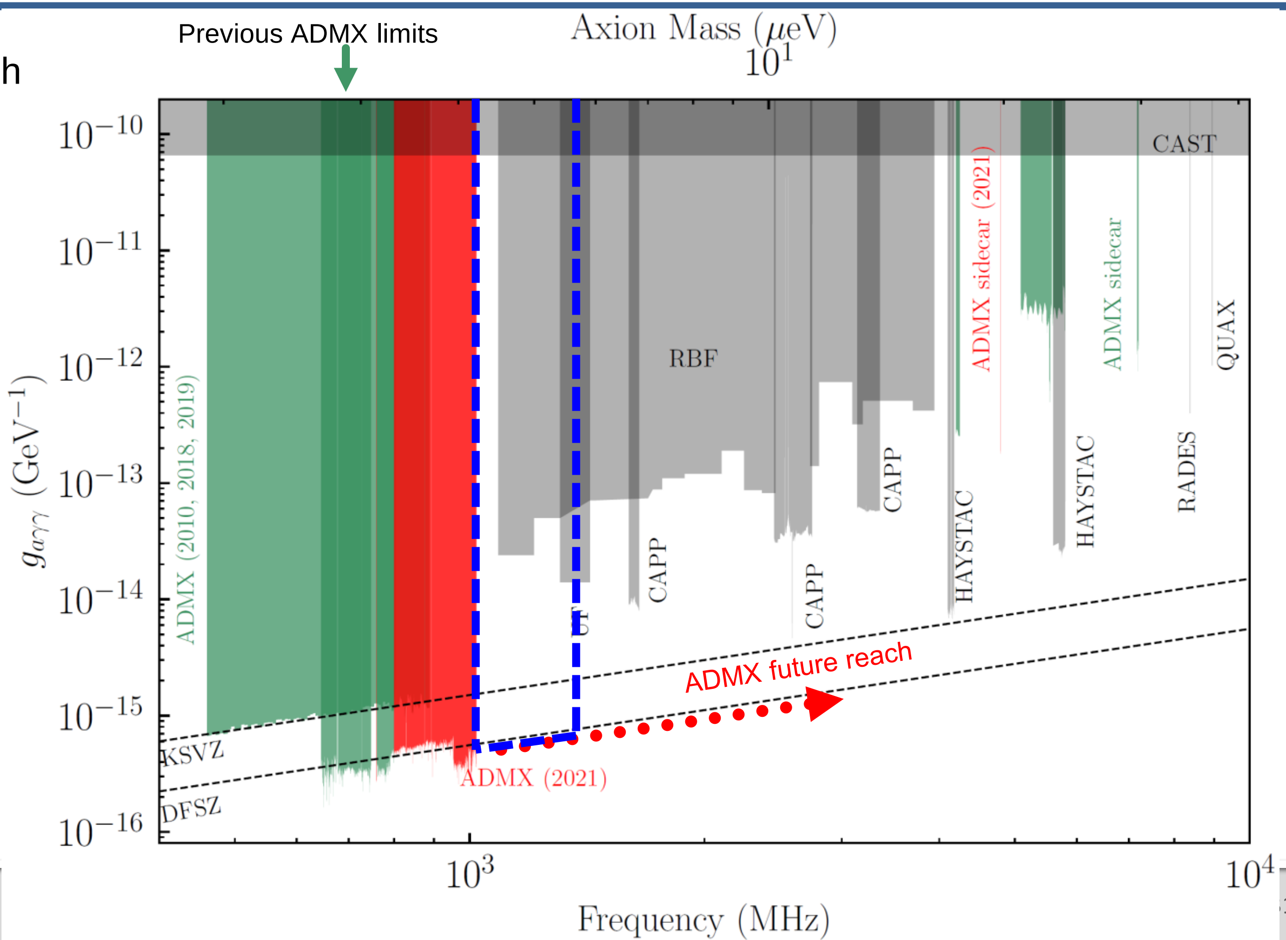




ADMX-G2 results and near term plans

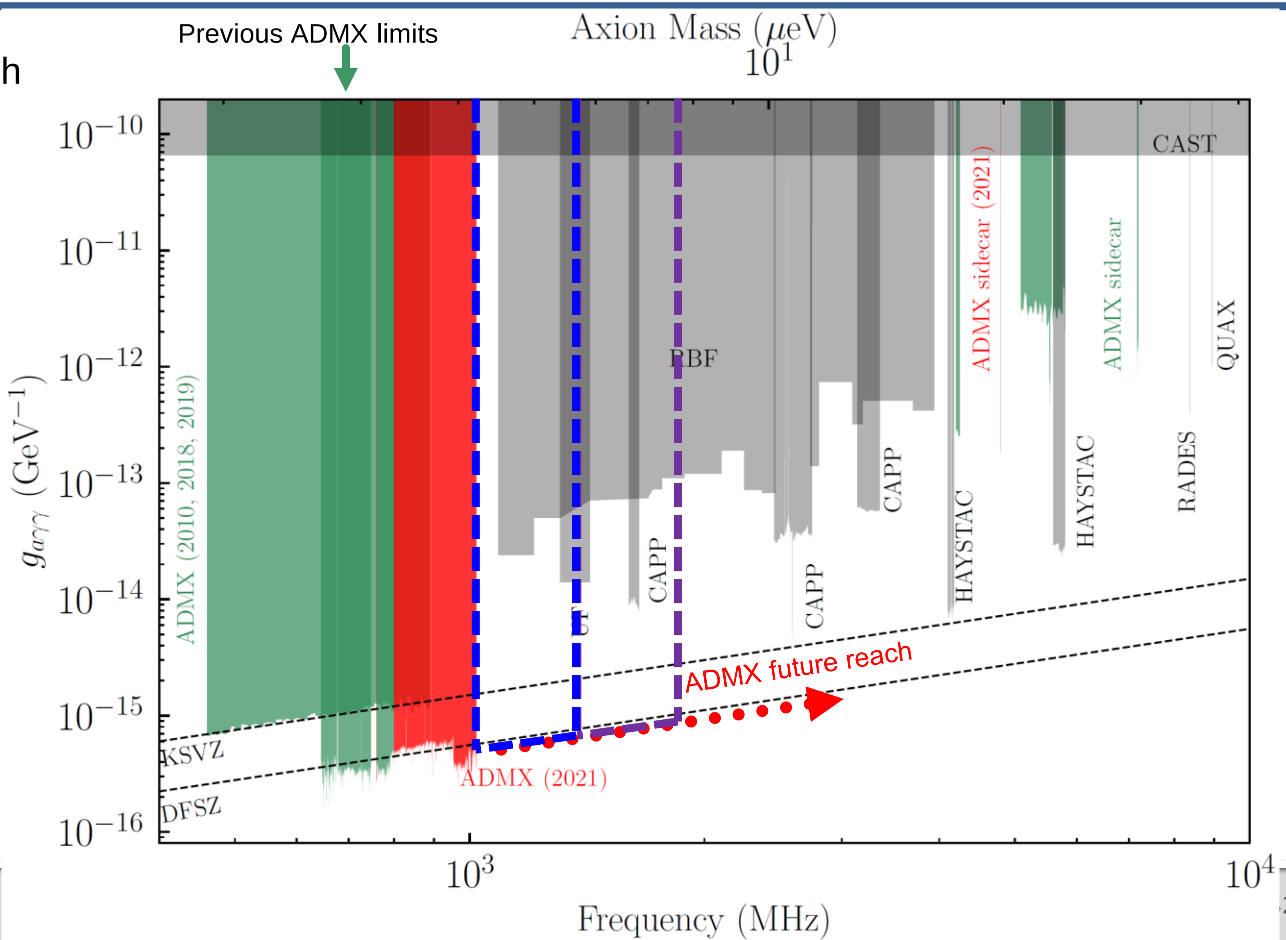
- Operations in phases that match the cavity tunable bandwidths
- Previous runs with sets of two tuning rods (runs 1A, 1B, 1C)
- Upcoming 1D (single rod) 1-1.4 GHz





ADMX-G2 results and near term plans

- Operations in phases that match the cavity tunable bandwidths
- Previous runs with sets of two tuning rods (runs 1A, 1B, 1C)
- Upcoming 1D (single rod) 1-1.4 GHz
- Switch to frequency locked 4-cavity array for 1.4-1.9 GHz



ADMX-Extended Frequency Range (2-4 GHz)

DOE HEP sponsored *Dark Matter New Initiative* project

Picks up where ADMX-G2 ends (~1.9 GHz)

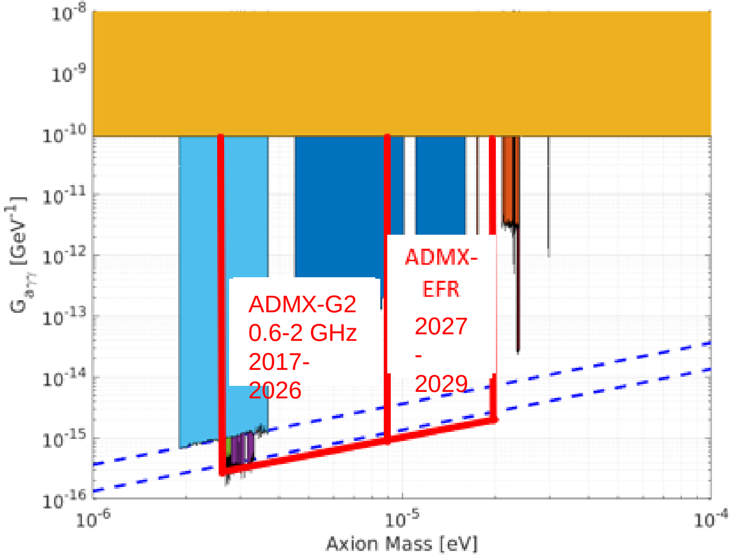
Currently in Design and Prototyping Phase

Aiming for construction start FY25. Aimed to be installed at Fermilab!

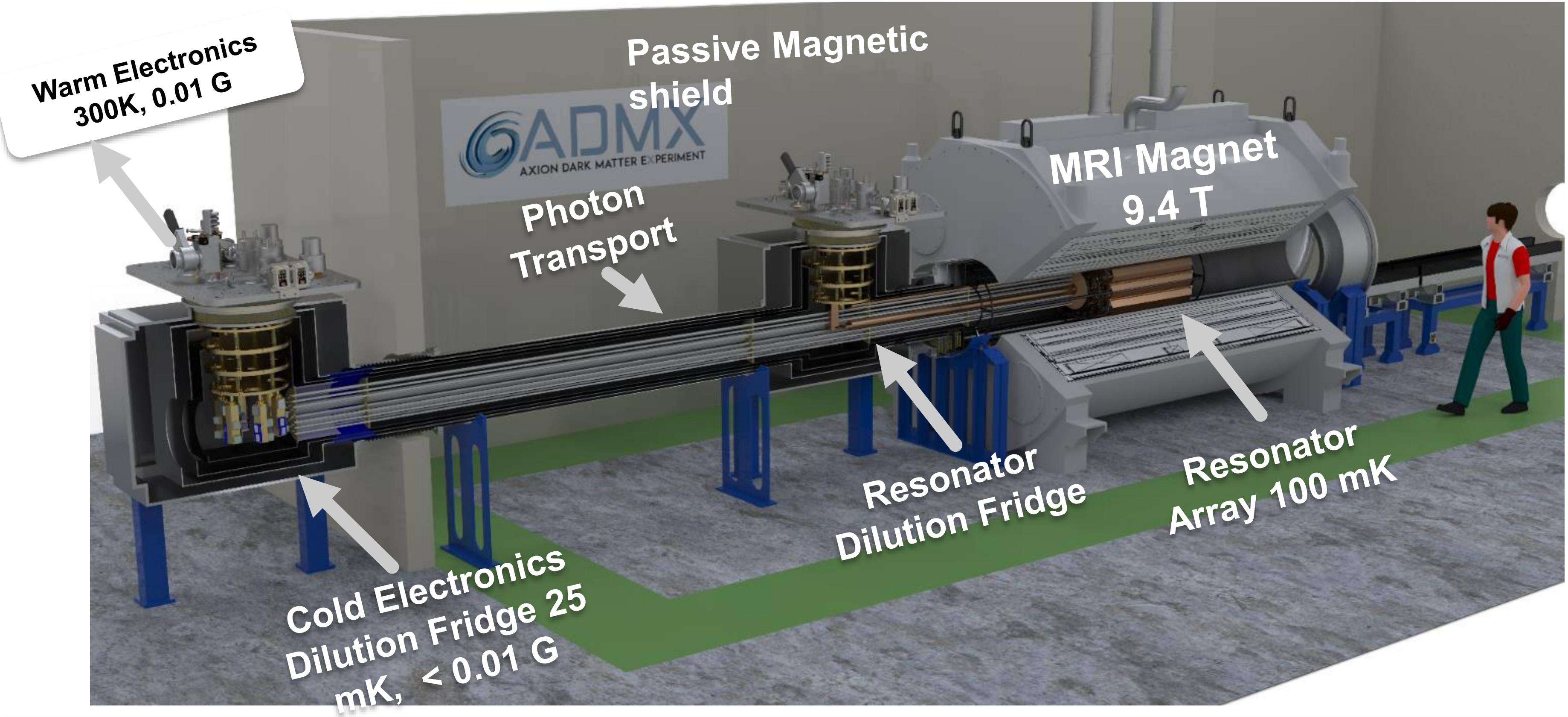
New MRI magnet being acquired
(9.4 T – 800 mm bore)
> 8x stored energy of ADMX-G2

	ADMX-G2 Magnet	ADMX-EFR Magnet
Peak Field	7.6 T	9.4 T
Bore diameter	530 mm	800 mm
Magnet length	1117 mm	3100 mm
Cryostat diameter	1295 mm	2580 mm
Stored Energy	16.5 MJ	140 MJ
Weight	6 tons	45 tons
Helium consumption	3 liters/ hour	0.35 liters/hour
Current	204 Amps	220 Amps
Persistent current	No	Yes
Orientation	Vertical	Horizontal
Manufacturer	Wang NMR	GE Medical Systems
Manufacture date	1993	2003

9.4 T 800 mm bore MRI magnet

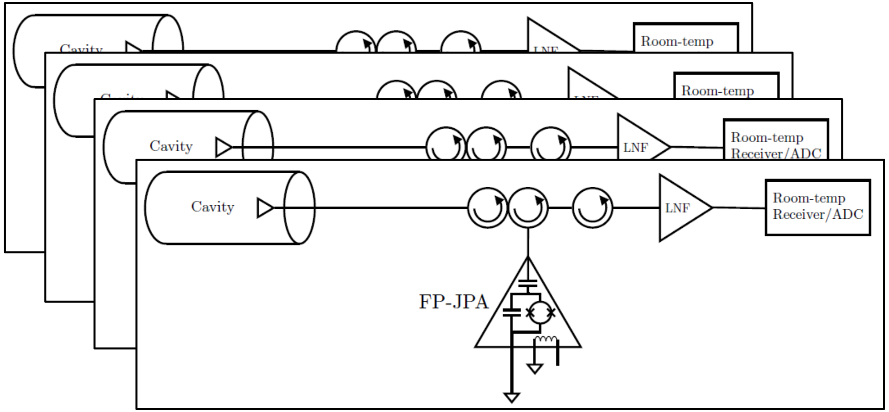


ADMX-Extended Frequency Range



Overall System Concept

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



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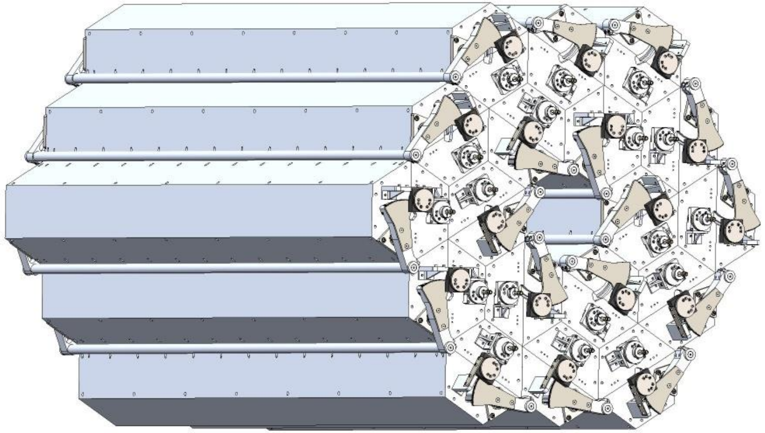
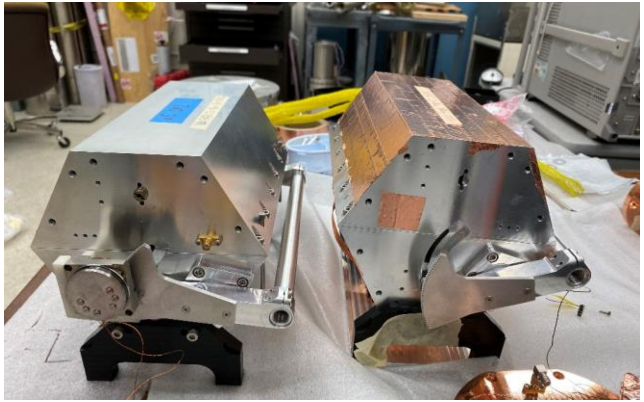
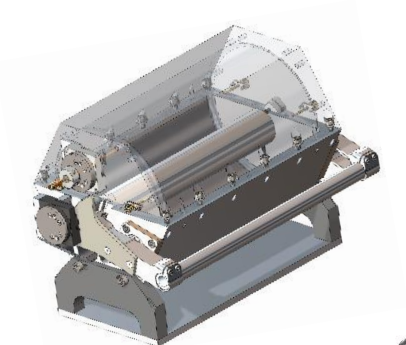


- Takes full advantage of coherence of axion signal relative to incoherent noise
  - SNR goes as √N cavities coherently combined.
  - Scan rate goes as $SNR^2 \sim N$. Factor of 18 x faster scanning than non-locked individual cavities
- Maximal flexibility, system repeatability and mass production

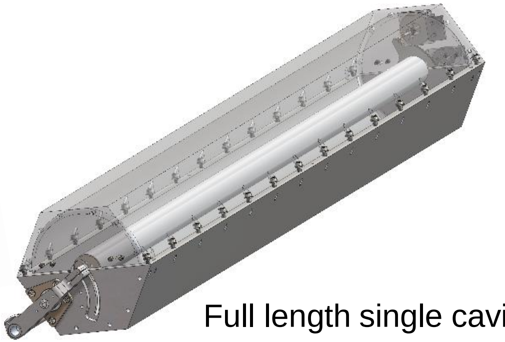
Resonator Design currently clamshell cavity

- Current baseline cavity cell is ~1 m long copper cavities with copper tuning rods.
- Two sets of tuning rods diameters (2-3 & 3-4 GHz with same clamshells)
- Piezoelectric actuators for frequency tuning & antenna coupling

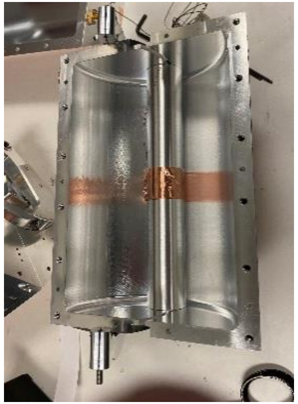




Scale length single cavity cell (~ ¼ m long)



Full length single cavity cell (~ 1m long)

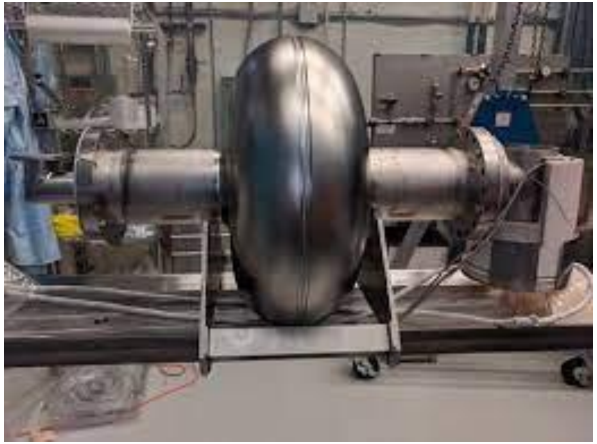


Tuning rod wired for thermal time-constant studies of sapphire axles

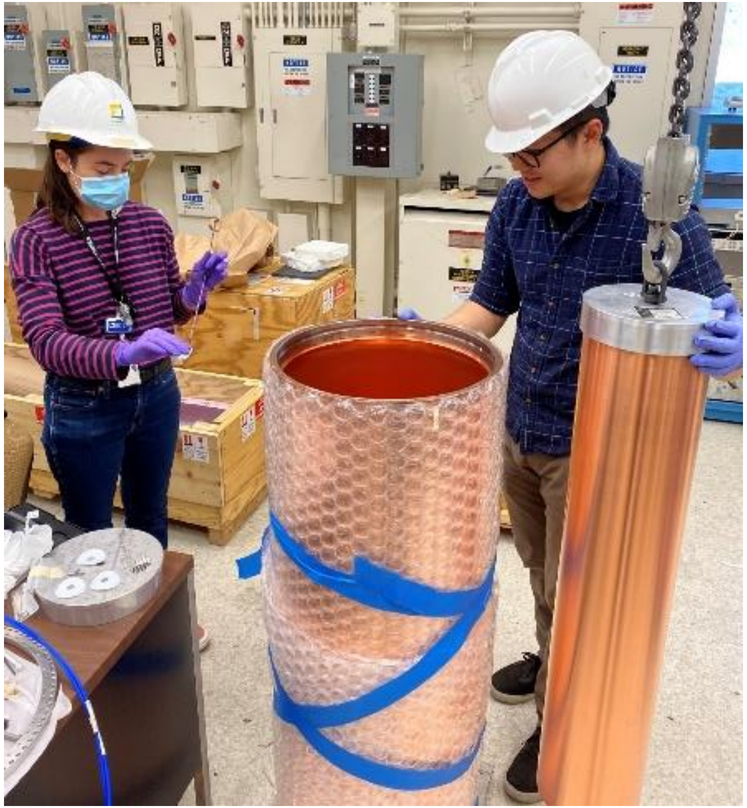
Postdoc Nick Du mounting scale length prototypes in dilution refrigerator

What about using superconductors for cavities?

- Extremely low RF resistance is ideal for high Q resonators
- Standard for accelerator cavities with typical $\boldsymbol{Q_0 \cong 10^{10}}$ **in zero magnetic field**
- ADMX Copper cavities, $\boldsymbol{Q_0 \cong 10^4 - 10^5}$
- **Axion $\mathbf{Q_a > 10^6}$**



Accelerator Cavity. Image credit: Fermilab SQMS



ADMX Copper Cavity (Run 1D)

The Challenge for ADMX SRF cavities

- **Meissner Effect:** the expulsion of magnetic field upon super-conduction (Below critical fields B_{c1} , B_{c2} in Type II SCs)

- **Problem:** SRF cavity quality factor quickly degrades in external magnetic fields due to breakdown of Meissner Effect
  - Development of vortices' or fluxons with magnetic field (normal regions) in Type II Superconductors
  - Magnetic vortices' motion drive up the surface resistance.
  - **Maximal loss for surfaces perpendicular to magnetic field** with greatest Lorentz forces (end caps) on the fluxons.

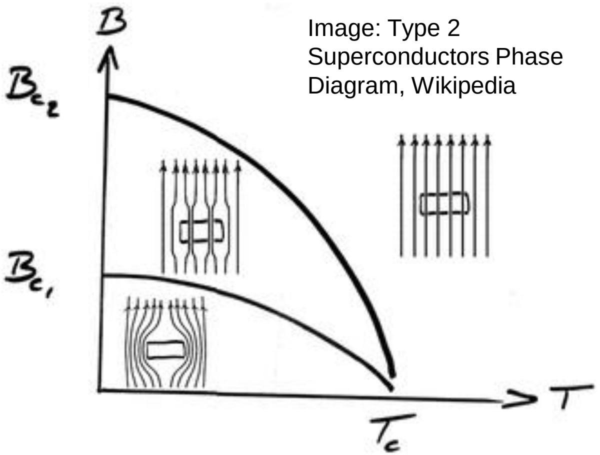
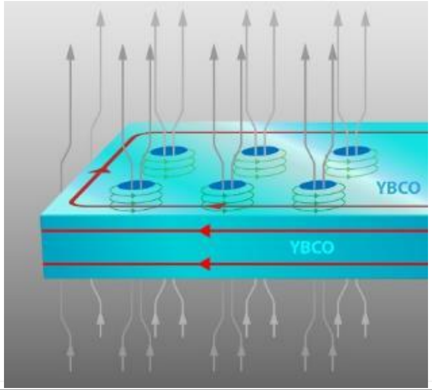
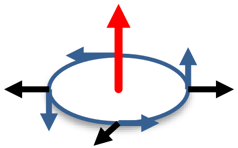


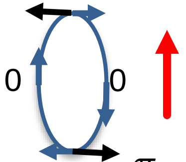
Image: Type 2 Superconductors Phase Diagram, Wikipedia



$$\vec{F} = \vec{I} \times \vec{B}$$



$$\overrightarrow{F_{\perp}} = |I||B| \sin\frac{\pi}{2} = |I||B|$$



$$\overrightarrow{F_{\parallel}} = IB\,(\sin 0 + \sin\frac{\pi}{2}(\hat{r} - \hat{r})) \approx 0$$

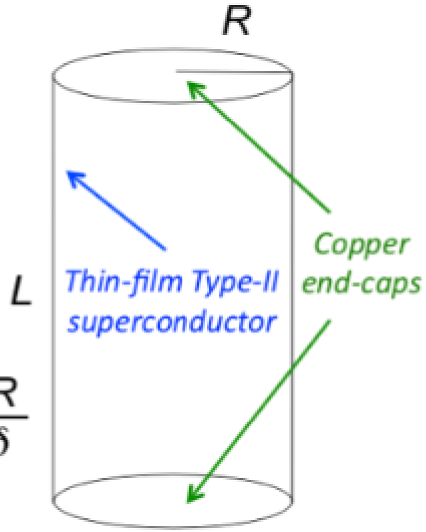
Possible Solution: Hybrid Material Cavity

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

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

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

Wall contribution goes to zero

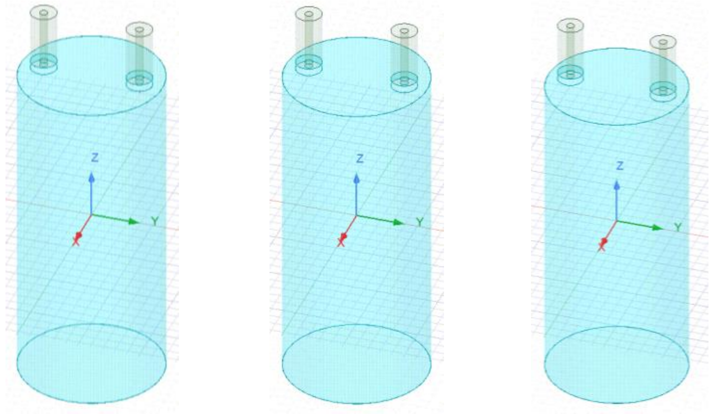


- Since vortex losses are minimal for surfaces parallel to field, only coating the walls of the cavity cuts out most dissipative part

- For an empty cavity, Q of the TM_{010} mode improves by a factor of $(1 + {}^{L}/_{R})$ when the barrel is coated with a thin-film superconductor.

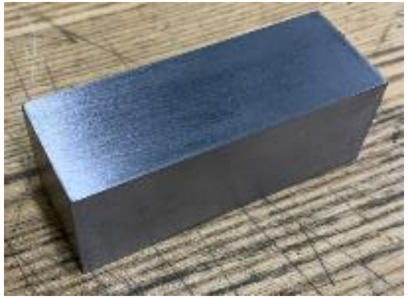
Test Cavity Geometries:
Multi-mode Measurements with NbTi Clamshell

- Cavity machined out of NbTi Square stock
- Looked at first 3 TM modes Q
- HFSS simulations of the cavity structure yields the geometric factor estimate for each mode and sub-surface
- This over-constrained problem allows us to calculate the wall vs. endcap resistance



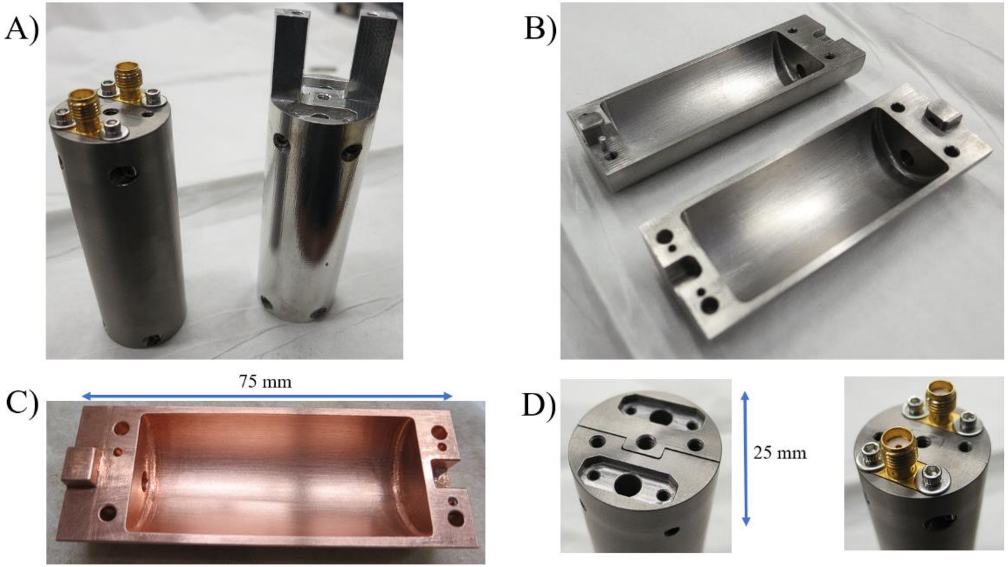
TM_{010} $f_0 = 9.95GHz$ TM_{011} $f_0 = 10.37GHz$ TM_{012} $f_0 = 11.47GHz$

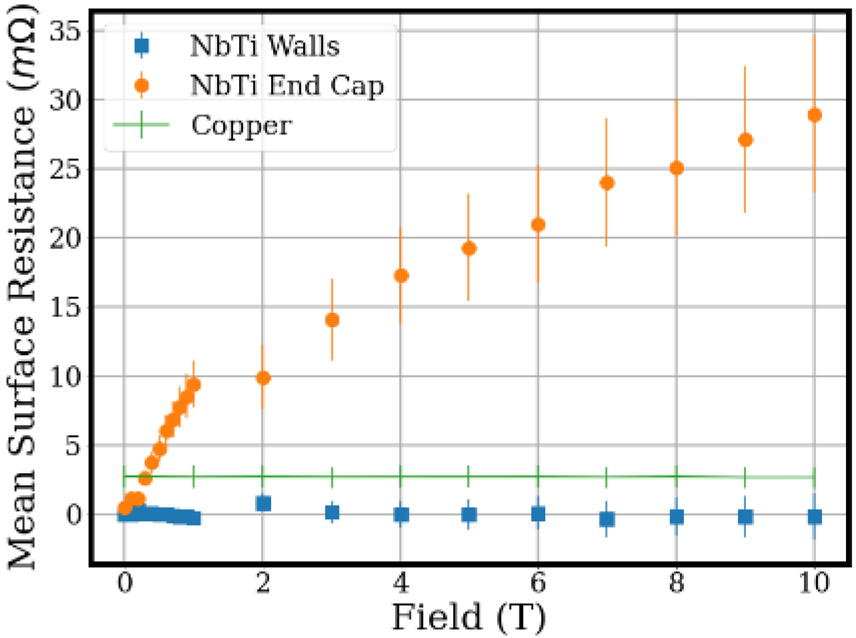
Geometric Factor (Ω)	TM_{010}	TM_{011}	TM_{012}
Walls	448	464	512
Top End Cap	4060	2194	2407
Bottom End Cap	4375	2173	237
Total End Caps	2106	1092	1195



NbTi Clamshell Cavity RF losses in Field: endcaps vs walls

- Applied method to show the endcap degradation in a Bulk NbTi clamshell cavity
- NbTi: $B_{c2} > 14\ T$, $T_c \cong 8.3\ K$
- Thesis work of UW grad student Tom Braine





T. Braine et al. Multi-mode analysis of surface losses in a superconducting microwave resonator in high magnetic fields. *Rev Sci Instrum* 1 March 2023; 94 (3): 033102. https://doi.org/10.1063/5.0122296

Simulations allow calculation of Geometric Factors

Q ~ Geometric Factor / Surface loss (Rs)

Rs_{Cu} = 2.9 mOhm at cryogenic temps

Q_{total} ~ 3e2 Ohm/2.9 mOhm
Q_{total} ~ 10^5 (all Copper Cavity)

Rs: Walls & Rods << lids

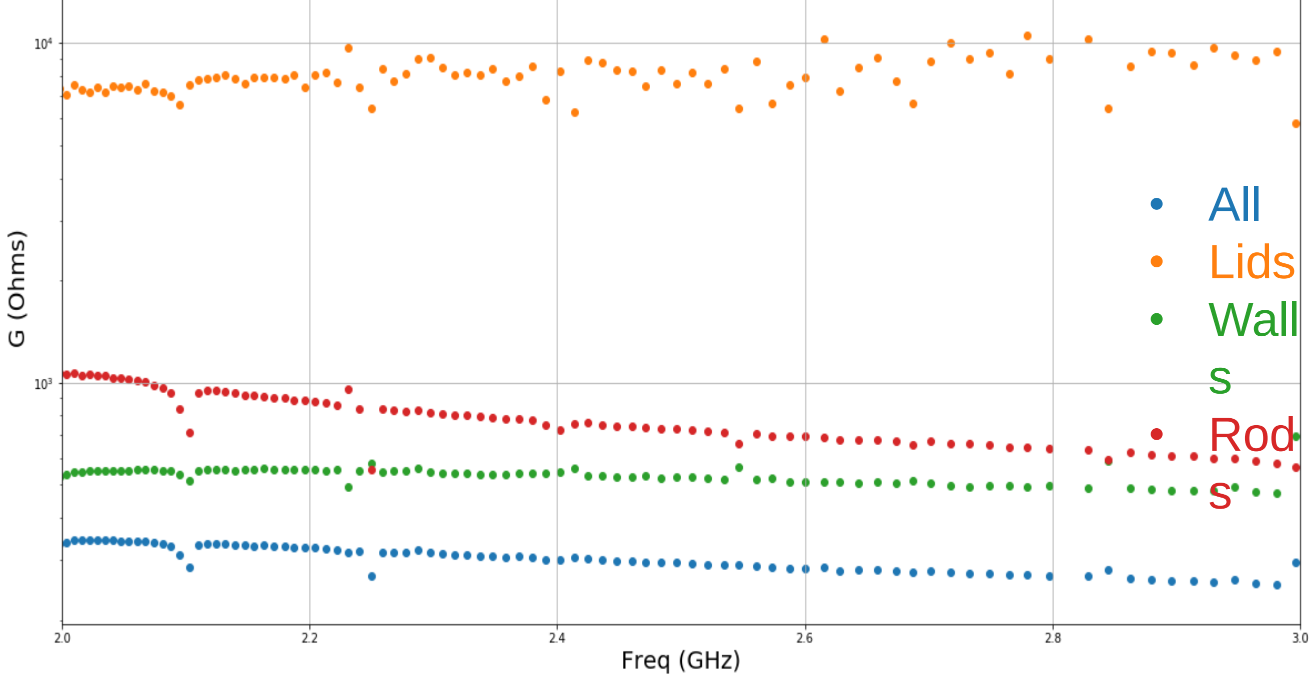
Eliminating Wall & Rod contributions due to parallel field and assuming losses dominated by copper endcaps

Q_{lids} ~ 8e3/2.9 mOhm

Q ~ 2.75e6 (x 27.5 higher Q)
Optimalization of shape of endcaps will likely allow lower RF losses (higher Q)

Need to maintain high form-factor & minimize number of mode-crossings

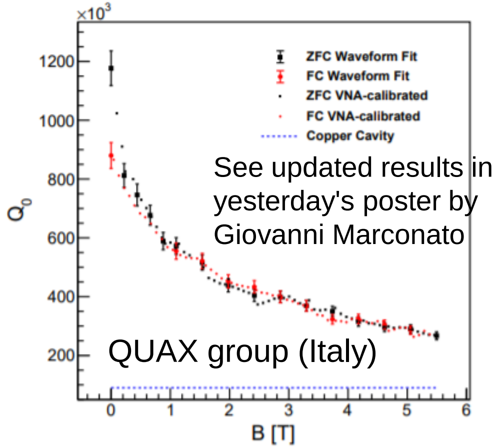
ADMX-EFR Geometric Factors as function of frequency (current design)

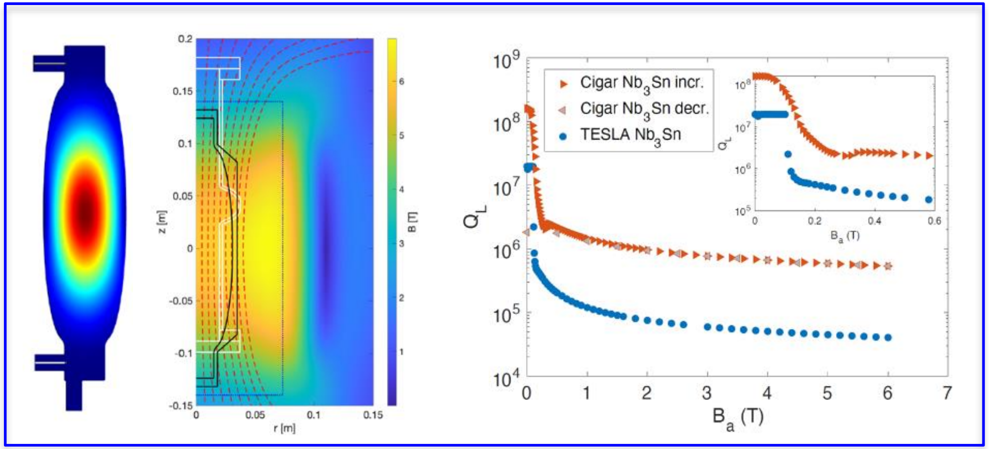


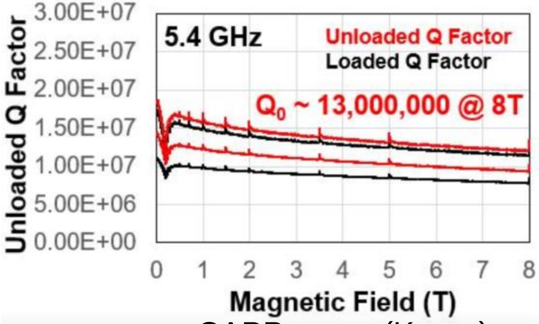
B-field tolerant SRF cavity development worldwide

Worldwide there has been excellent progress on field-tolerant SRF cavities for axion searches
3 potential materials (NbTi, Nb3Sn, and YBCO)

- **NbTi** sputtered cavities as inspired by QUAX group
- **Nb3Sn on Niobium led by SQMS** (Sam Posen & Anna Grasselino)
- **Nb3Sn on Copper** collaboration with Florida Statue U. (Lance Cooley)
- **HTC (EuBCO+APC)** superconducting cavities CAPP







CAPP group (Korea)

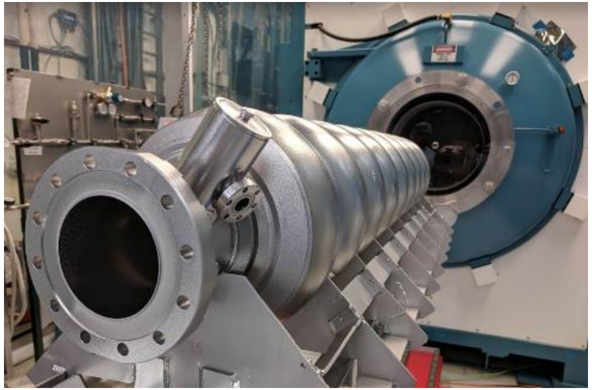
Recent SQMS results with Nb3Sn

Near term ‘Hybrid’-SRF ADMX Sidecar (Installing now)

- Sidecar is a ‘test’-bed for new axion tech atop the main experiment cavity
- Copper clamshell design with piezo-actuated rotor and TWPA readout
- Tuning rod is hollow Nb with a Nb_3Sn coating. (1.75” Diameter) from SQMS!

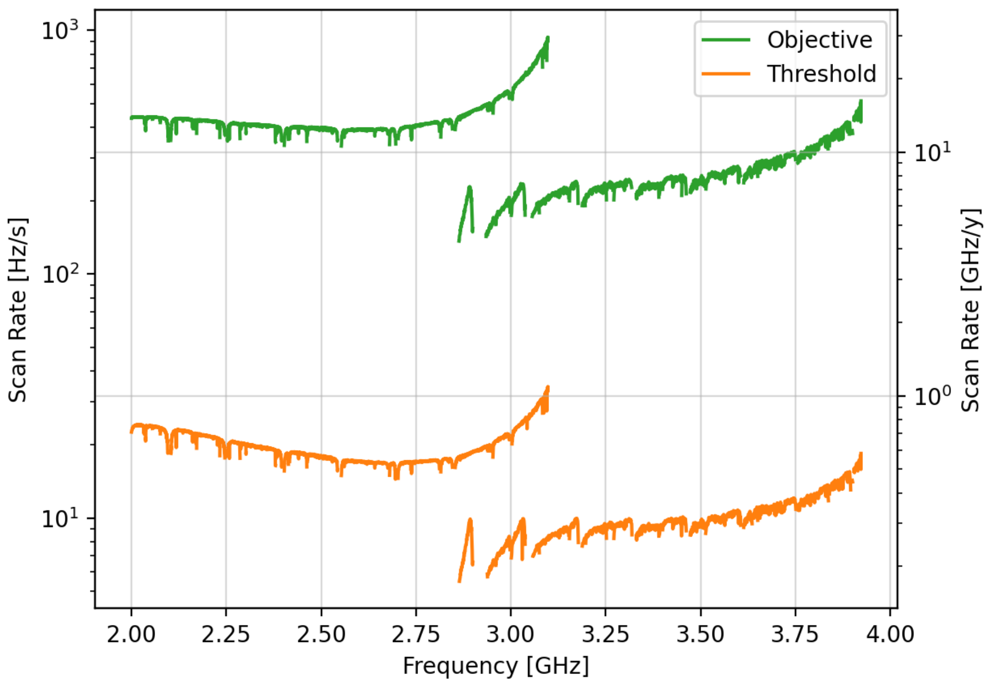
Copper Cavity Produced by U. Sheffield.

Nb3Sn Tuning Rod from SQMS



Fermilab Nb3Sn coating furnace with 9-cell cavity

ADMX-EFR Run Times Estimates

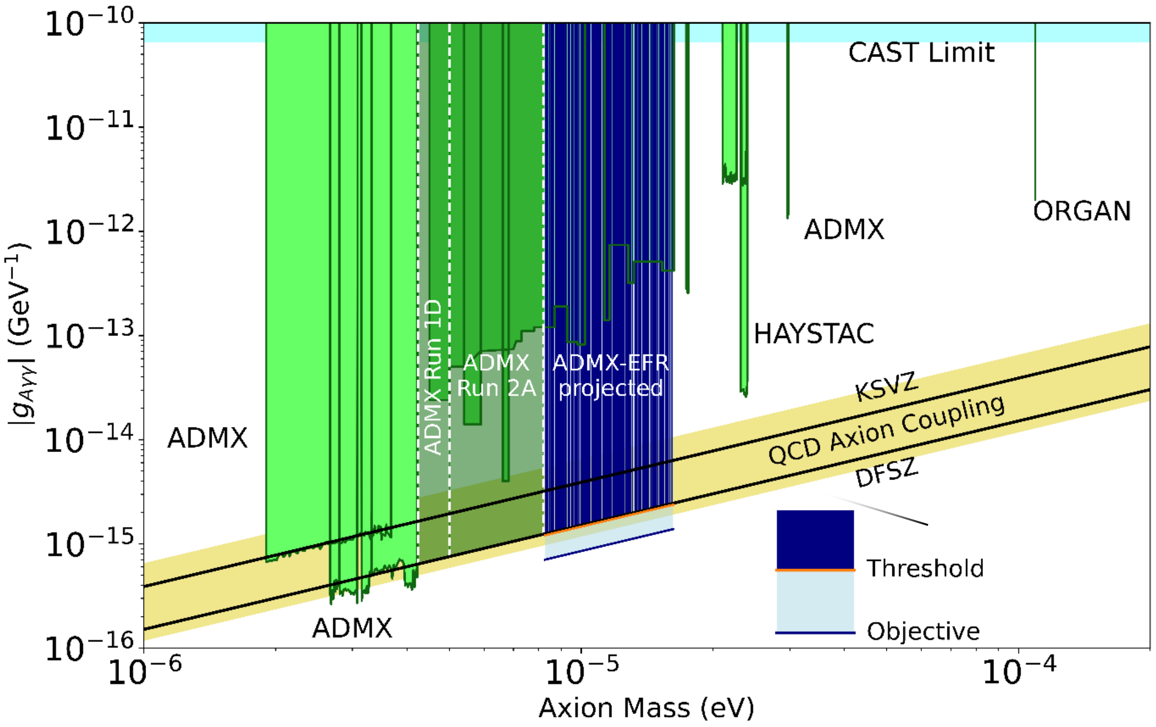


Parameter	Unit	Threshold	Objective
Cavity system full tuning range	GHz	2-4	2-4
Magnetic Field Average	Tesla	9.1	9.4
N Cavities		16	18
Volume per cavity	Liters	12.1/10.4	
Cavity Q_0 at 4 GHz *		54,000	180,000
Cavity TM010 form factor *		-5%	0.4-0.5
Maximum Cavity Physical Temperature	mK	100	100
Maximum Electronics Physical Temperature	mK	25	25
JPA Noise Temperature at 4 GHz *	mK	200	200
JPA Gain	dB	15	21
JPA Tuning range/ Circulator Bandwidth	GHz	0.5	1
Insertion loss (cavity to JPA, max)	dB	2	2
System Noise Temperature at 4 GHz *	mK	500	440
Amplifier squeezing speed up factor		1	1.4
Cavity locking error	% BW	15	5
Power combining efficiency	%	95%	99%
Time Fraction Initial Scan	%	21	28

Instantaneous scan rate to be updated as results of prototyping become clearer.
3 cavity configuration (0.99, 1.00 and 1.005 m) allows to fill in mode-crossings.

Skipped (Mode Crossings)
$\sim (10 \pm 3)\%$

ADMX-EFR Run Times Estimates



total runtime:
3 years

Threshold:
Q ~ Copper Cavity
skips mode crossings

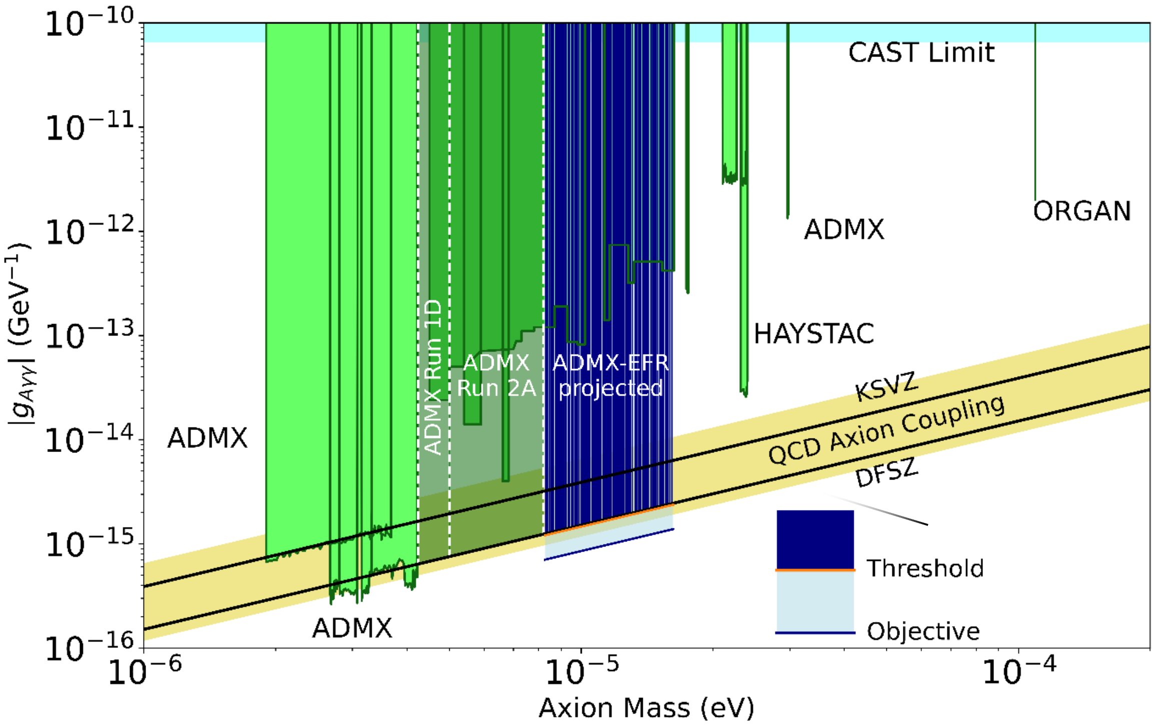
Objective:
Q ~ 3 x Q Copper Cavity
Includes mode crossings

Q > 27 x Q_{copper} would allow same DFSZ experiment with only 4 cavities (save cost)

Could run 2-3 GHz & 3-4 GHz simultaneously

Could drive down < DFSZ sensitivity (or <

ADMX-EFR Run Times Estimates



total runtime:
3 years

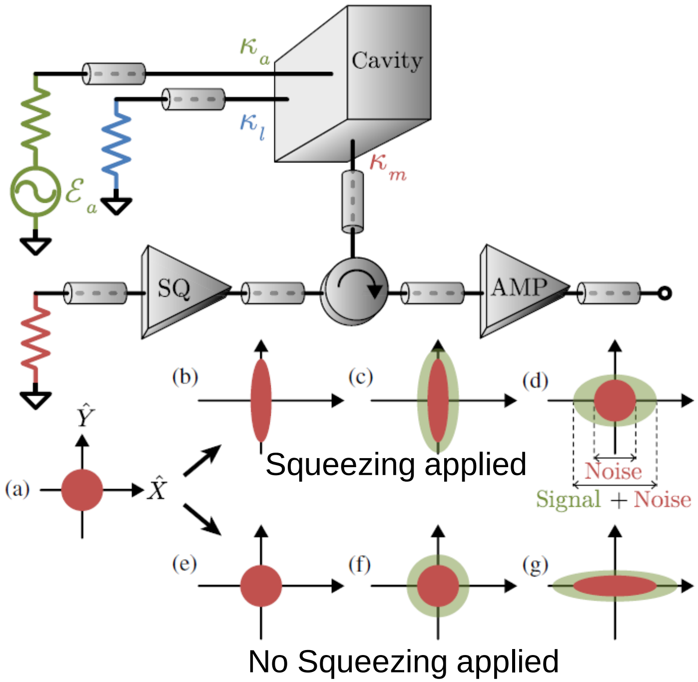
Threshold:
Q ~ Copper Cavity
skips mode crossings

Objective:
Q ~ 3 x Q Copper Cavity
Includes mode crossings

Recently joined the SQMS quantum center at Fermilab.

Prototypes in process of being tested

Squeezing the vacuum (HAYSTAC group)



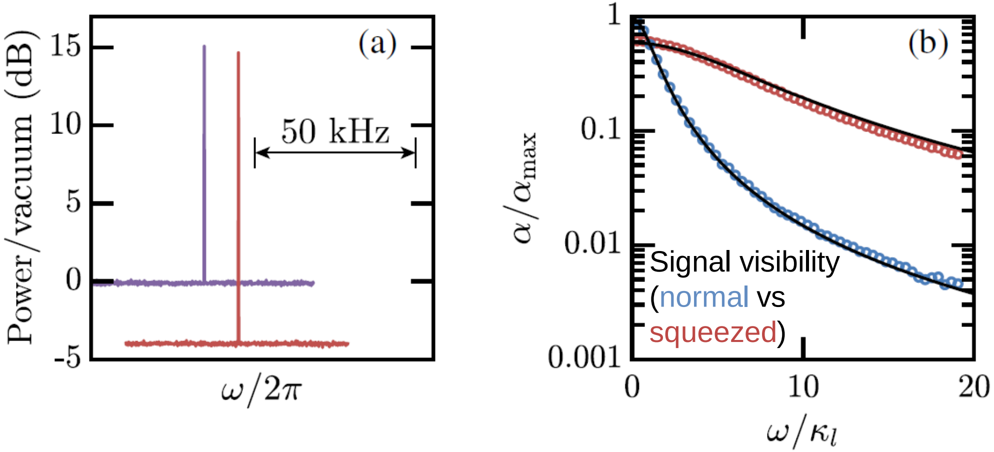
Squeezed Vacuum Used to Accelerate the Search for a Weak Classical Signal

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*

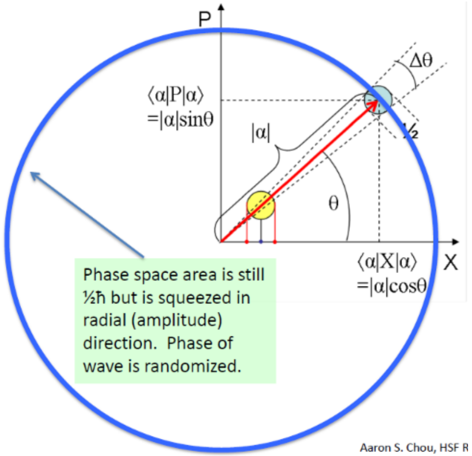


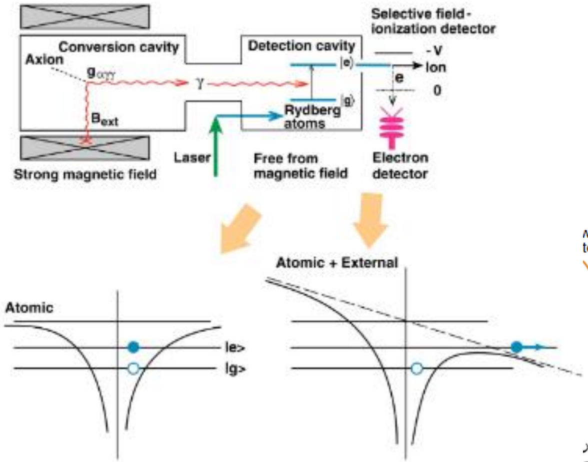
Signal over background 1 MHz from cavity

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)





Photon counting led to Serge Haroche 2012 Nobel prize

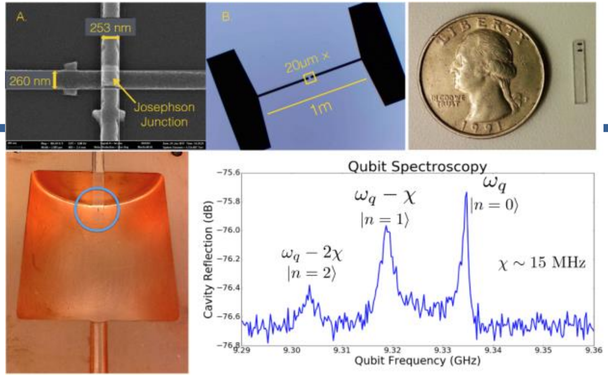
Initial attempt made using Rydberg Atoms in the late 1990s (CARRACK)

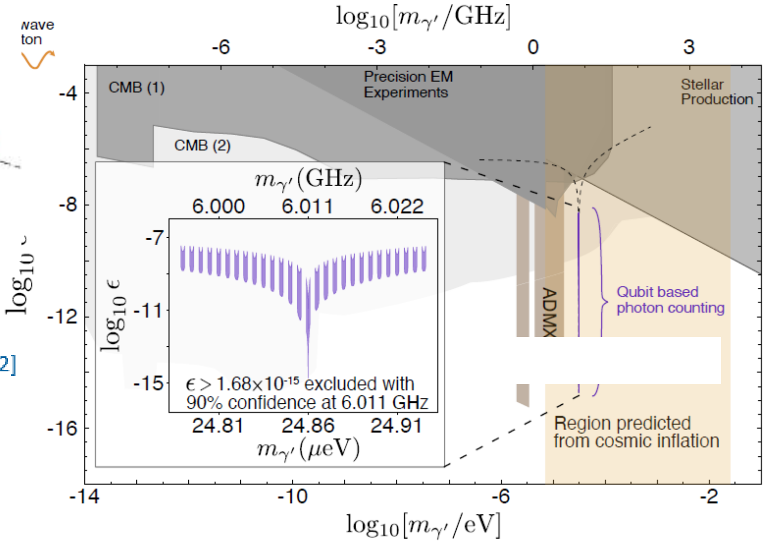
Updated version being investigated by Yale (RAY)

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!)

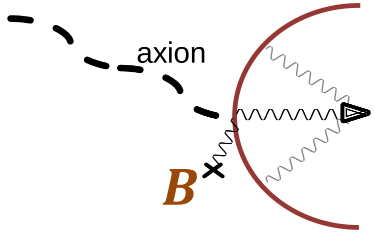




Hidden sector photon demonstration

Dish Antenna Type Experiments (Broadband)

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



MADMAX (Max Planck Institute)

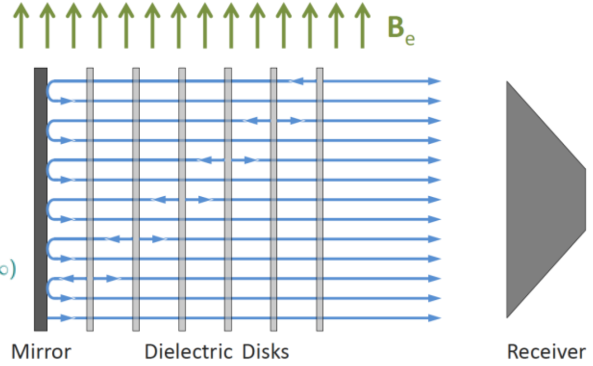
Will probe 40-400 μeV range (10-100 GHz)

10 T field & ~80 disks

Prototype phase using dipole magnet at CERN

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

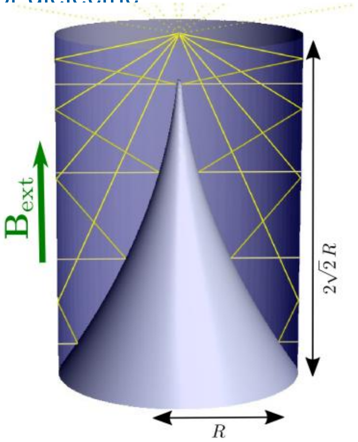
β^2: power emitted by booster / power emitted by single mirror ($\epsilon = \infty$)

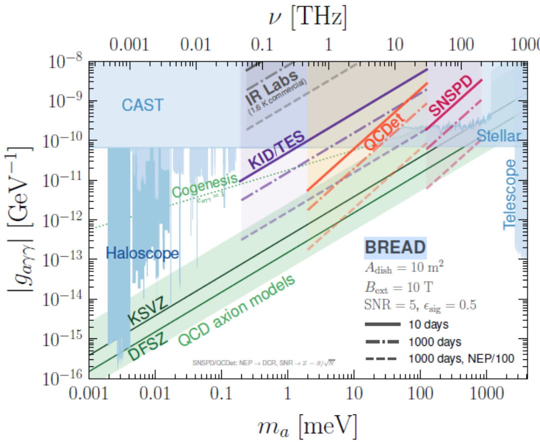


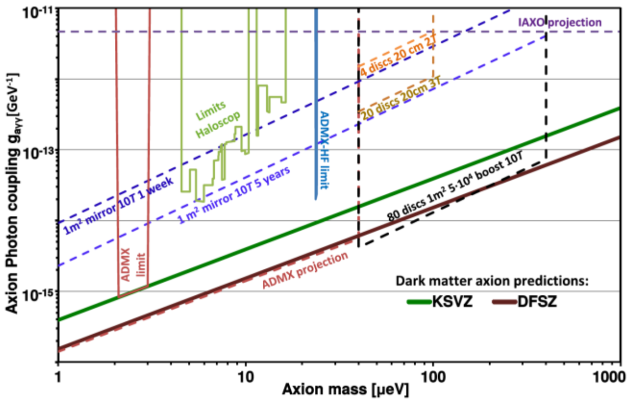
Similar production concept as microwave cavities. Magnetic field allows axions to convert to photons near a surface such as a mirror or dielectric

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

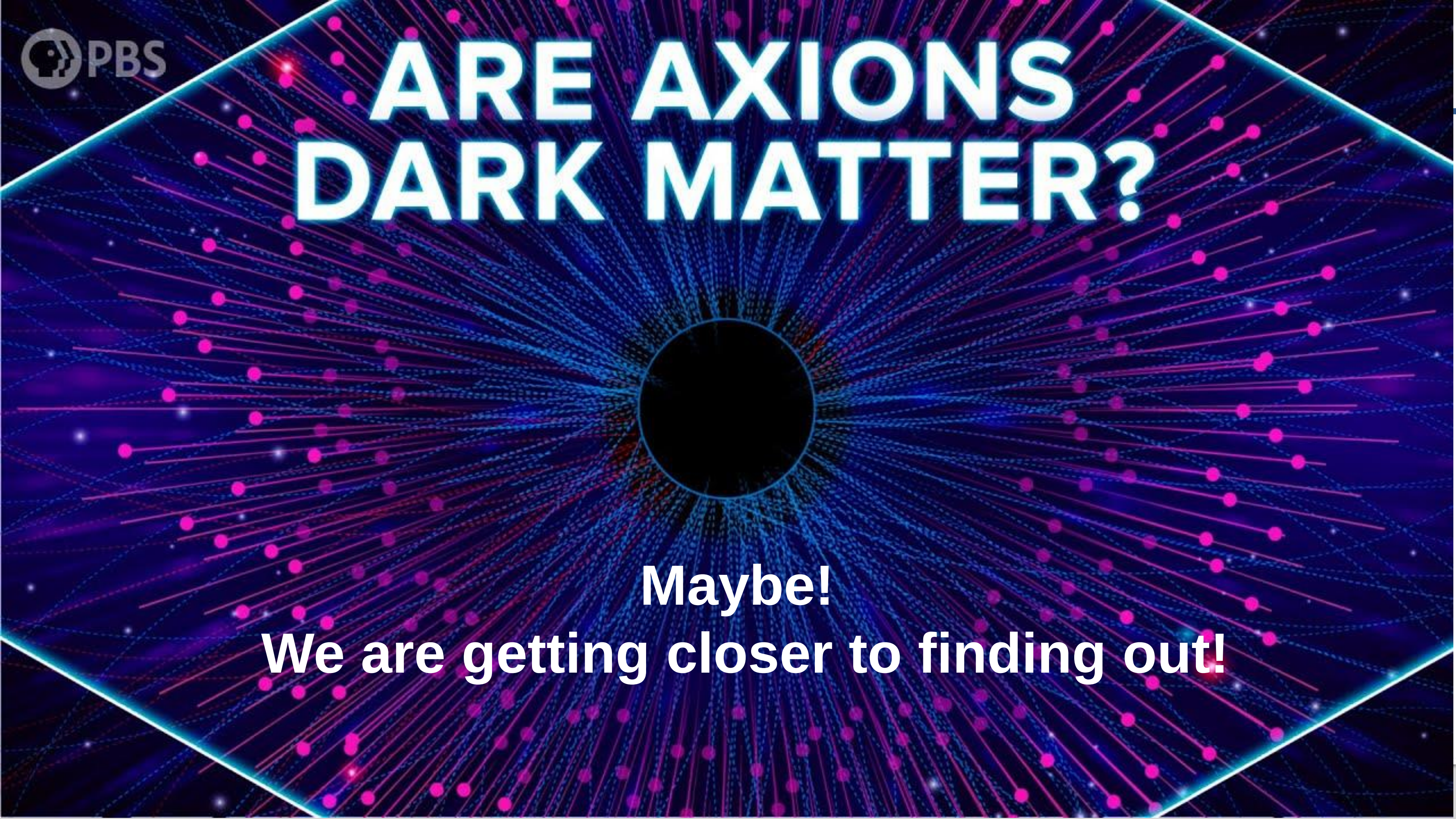
Variety of detectors that could be employed
- -superconducting nanowires
- -quantum cap. detectors
- -KID/TES







BREAD (Fermilab)



Maybe!

We are getting closer to finding out!

Thank You!

Acknowledgements:
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.

ADMX
AXION DARK MATTER EXPERIMENT
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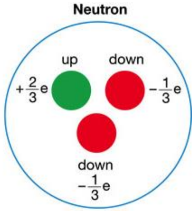
University of Florida
Berkeley University of California
Washington University in St. Louis
Los Alamos National Laboratory
SLAC
Pacific Northwest National Laboratory
The University Of Sheffield
The University of Western Australia
Heising-Simons Foundation

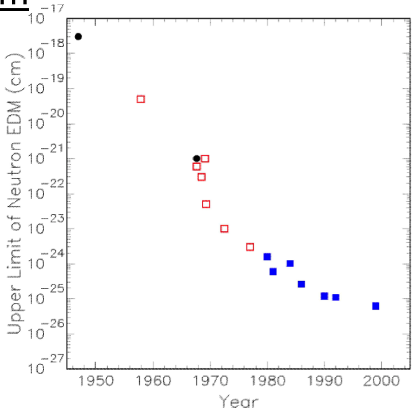
Backup

Axions: A solution to two major mysteries in physics and cosmology

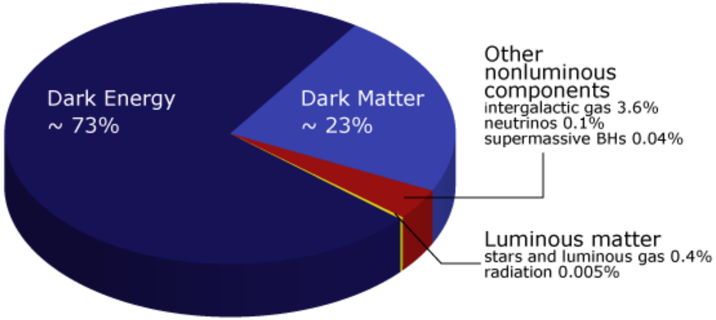
Strong-CP problem

Strange absence of measurable neutron electric dipole moment

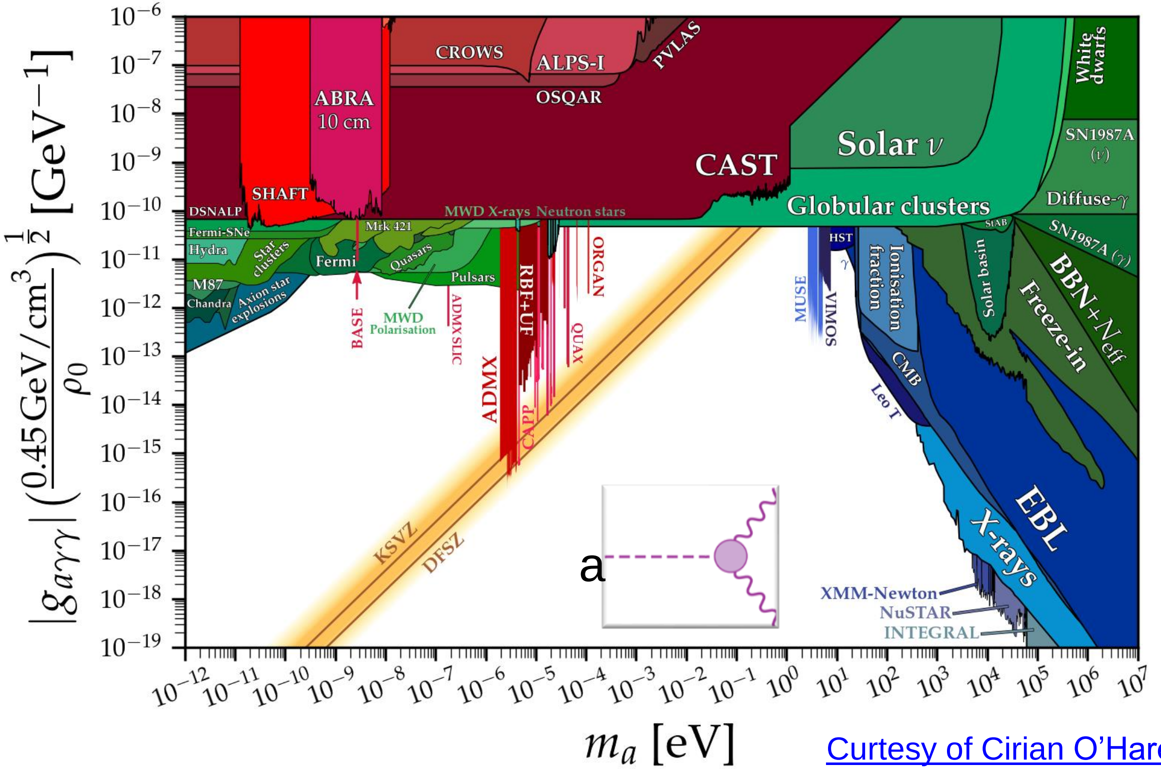




Dark Matter



Axion coupling to two photons a key detection technique



Curtesy of Cirian O'Hare