Searching for Dark Matter with the ADMX experiment

CPPM-Marseille Seminar

Nathan Woollett
On behalf of the ADMX collaboration

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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

- What’s an axion?
- How do we look for axions?
- Challenges of working with small signals.
- Results from the first run.
- Going forward.

Dark Matter

- Observations hint at the existence of a form of matter that we cannot see in our current detectors.
- Galaxy and star cluster rotation curves do not match what is expected from the observable matter distribution.
- Adding a non-interacting mass to the galaxy allows the theory to match observation. This mass is ‘dark matter’.

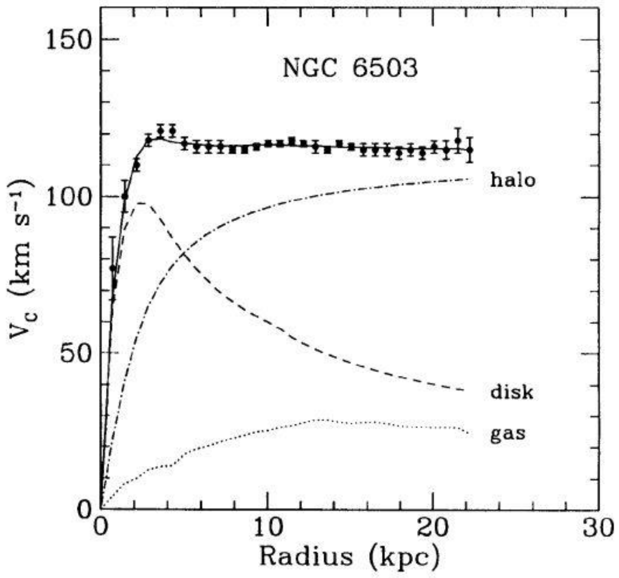
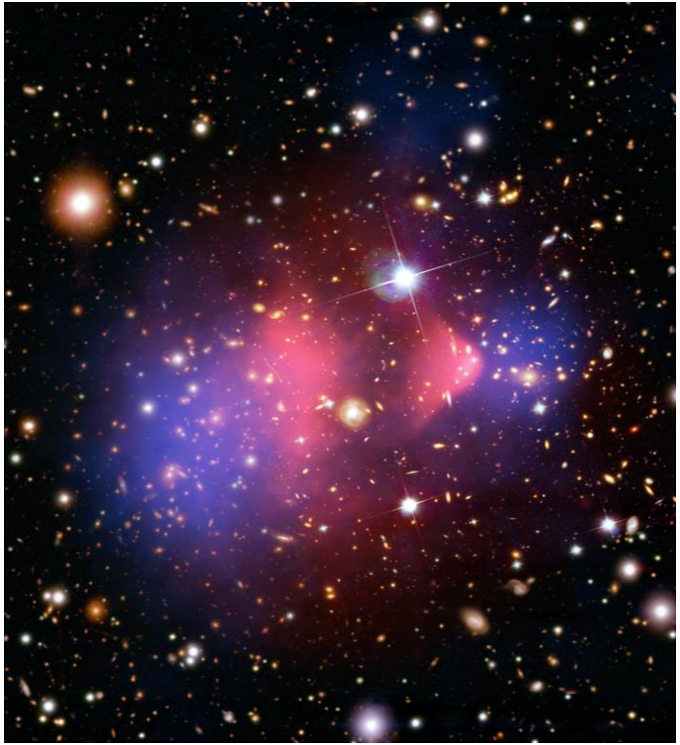


Image source: Katherine Freese, Caltech
https://ned.ipac.caltech.edu/level5/Sept17/Freese/Freese2.html

Dark Matter

- The Bullet Cluster is the result of two star clusters colliding.
- Gravitational lensing shows the majority of the cluster mass is separate from gaseous matter.
- Weakly interacting massive particles(WIMPs) have been a favored solution with candidates coming from theories such as super symmetry.
- With recent results from dedicated detectors and the LHC, WIMPs are now running out of places to hide.

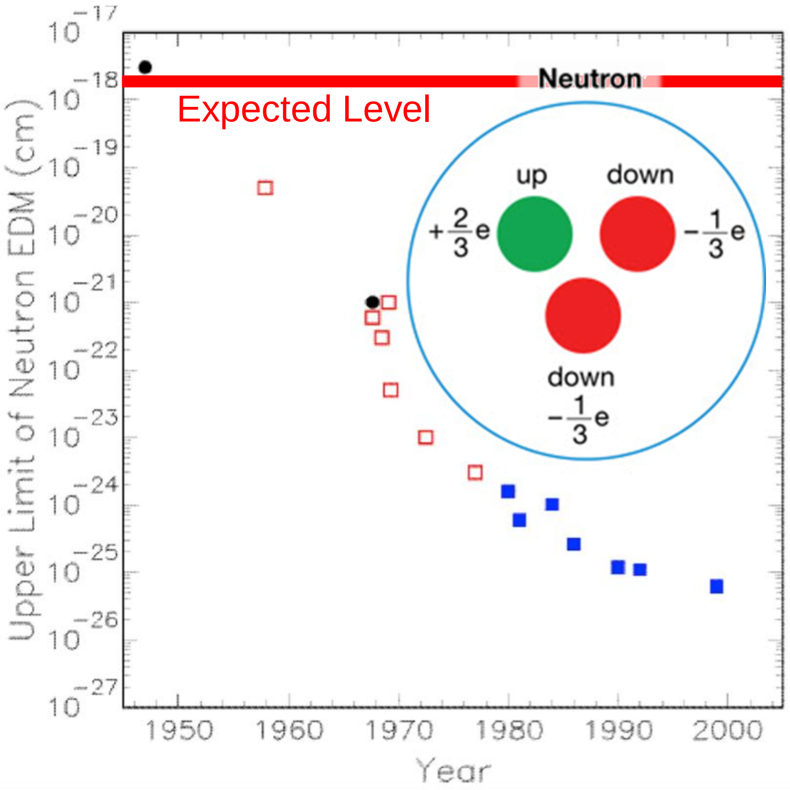


Strong CP Problem

QCD Lagrangian $$L_\theta = \theta \frac{g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu}$$

Neutron dipole moment $$d_n \approx \theta \, e \frac{m_q}{m_n^2}$$

- The strong force should be able to violate charge parity symmetry but appears not to.
- CP violation would lead to a neutron dipole moment of 10^{-18}e m.
- Experimental upper limits of the neutron dipole moment 10^{-28}e m.

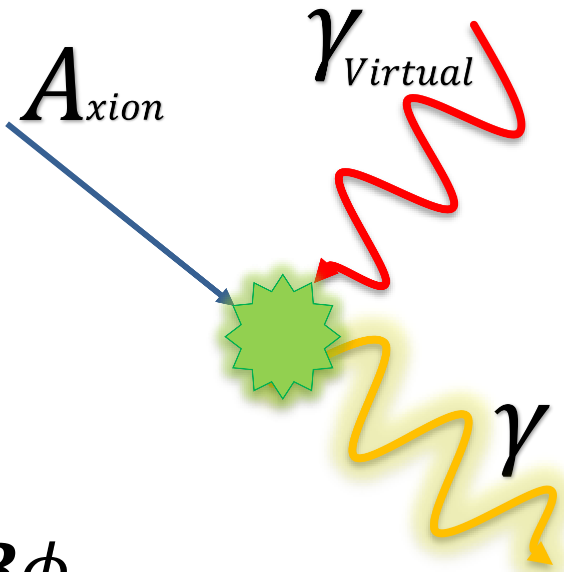


What are Axions?

- Peccei and Quinn introduced their solution to the strong CP Problem in 1977. It promotes the CP-violating term θ to be it's own dynamical field.

- As with other global fields, this also predicts an associated pseudo-scalar boson, the axion.

- The axion has a two photon interaction which is used for searches.



$g_{A\gamma\gamma}$ - Axion photon coupling

E – Electric field

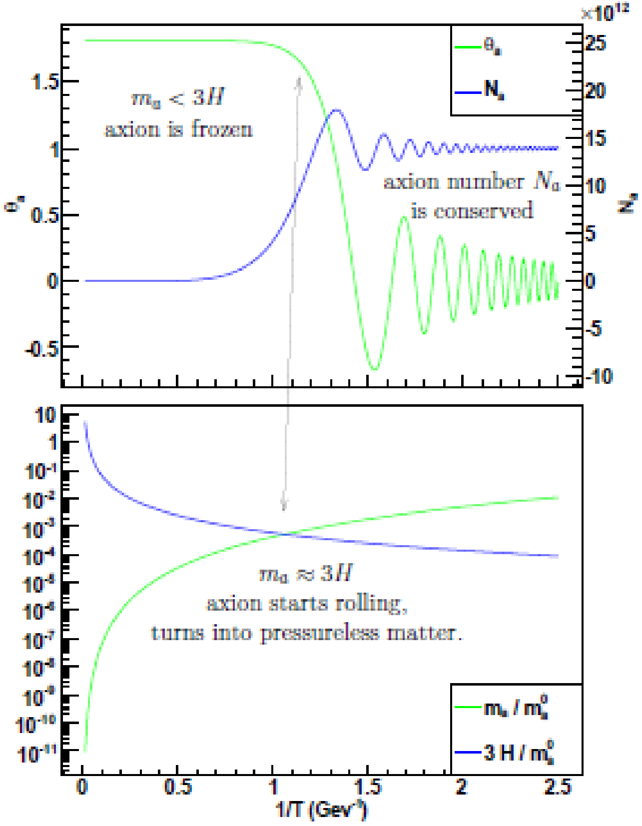
B – Magnetic field

ϕ_A – Axion Field

$$\mathcal{L}_{A\gamma\gamma} = -g_{A\gamma\gamma}\boldsymbol{E}\cdot\boldsymbol{B}\phi_A$$

Axion Dark Matter

- Axions are created non-thermally in the early universe via the misalignment mechanism.
- At high energies the axion is massless with the field value set at some initial value $\theta_a = \theta_a^0$
- Once the axion wavelength becomes comparable to the Hubble scale the axion mass becomes significant and the field starts to oscillate.
- The oscillations are damped and therefore the field approaches $\theta_a = 0$

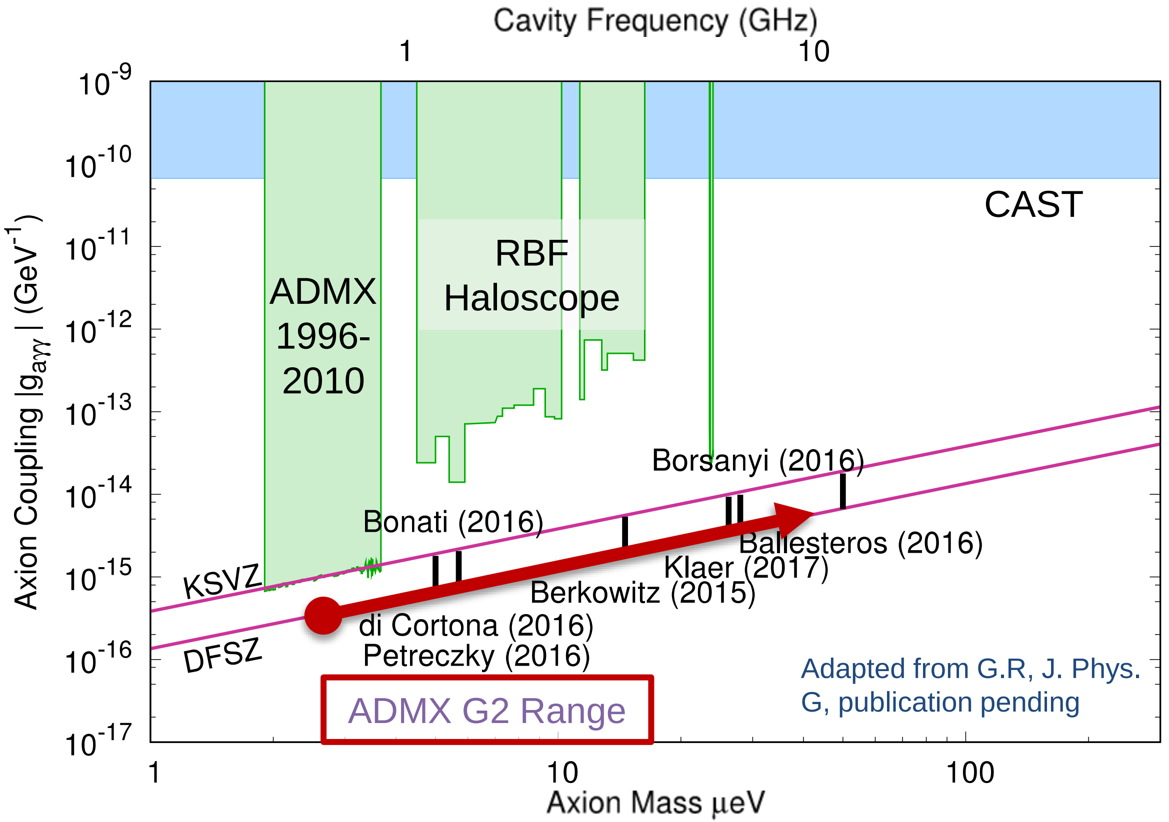


Axion cosmology revisited, Olivier Wantz and E. P. S. Shellard, Phys. Rev. D 82, 123508

Axion Dark Matter

- The misalignment mechanism results in a high number density of low mass particles with a small coupling to the SM.
- This provides the necessary conditions for structure formation in the universe.
- Due to the high number density, the particles can be easily represented as a classical field.
  - Wavelength of ~100m
  - Coherent over ~1000km

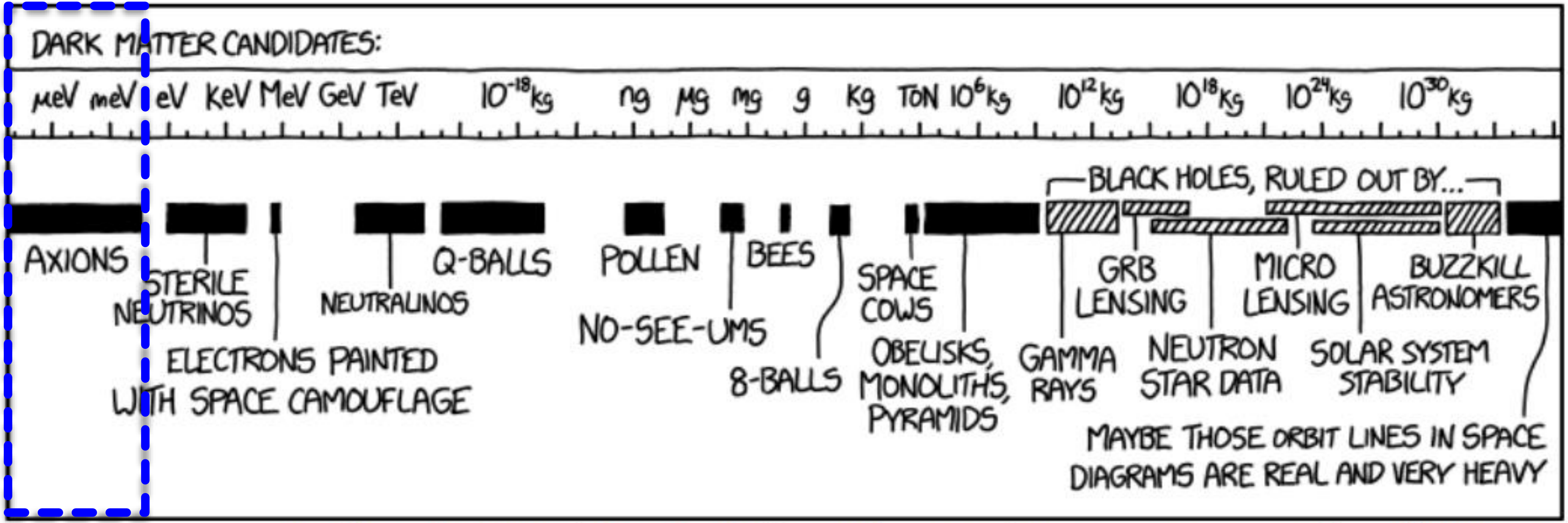
Parameter Landscape



Axions

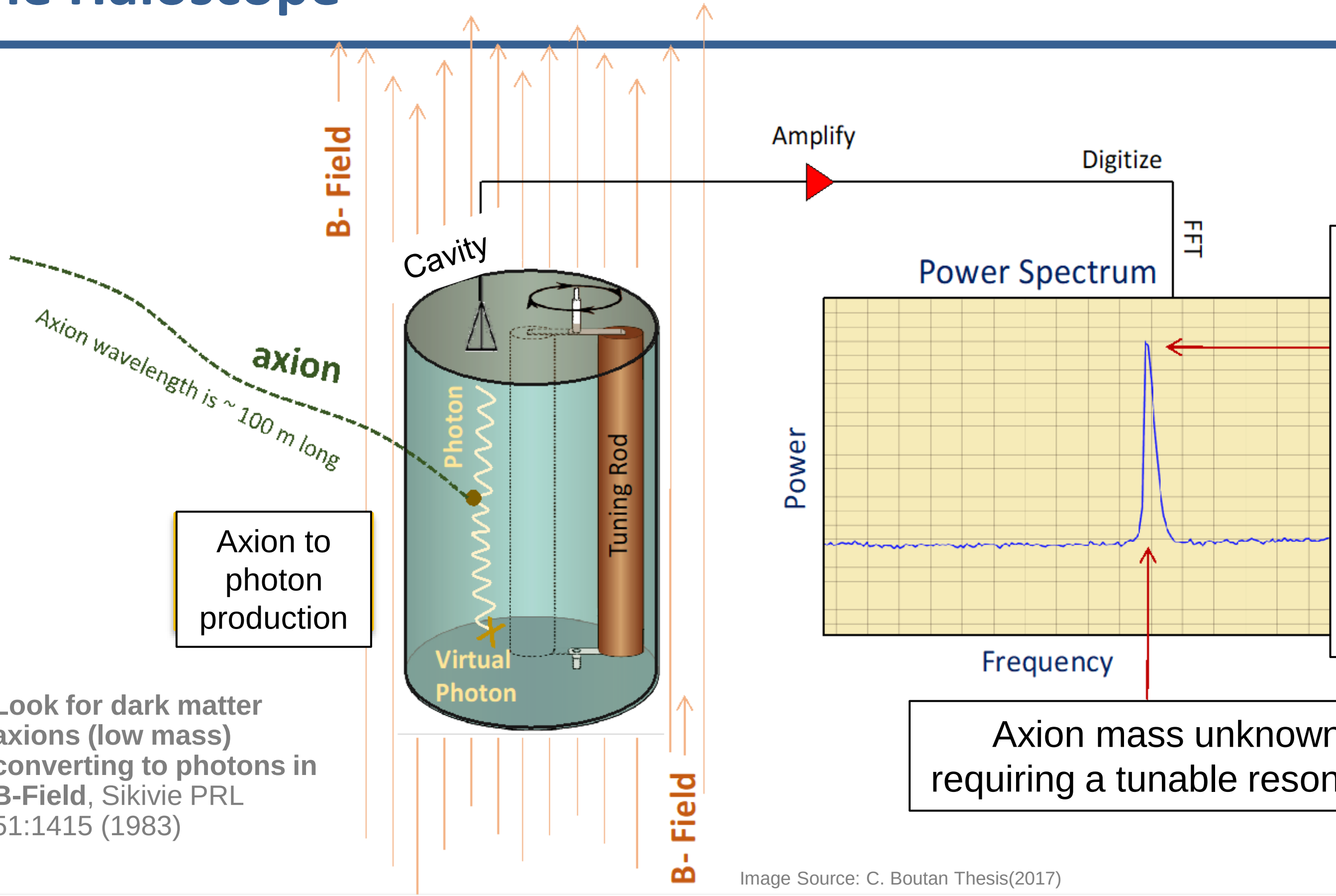
Motivation	General Properties
• Provides a natural solution to the strong CP problem. • In the 10^{-6}-10^{-2}eV range also provides a dark matter candidate.	• Light weakly coupled stable particle. • Fundamental pseudo-scalar particle.
Photon Coupling	**Mass and Couplings**
• Couples to two photons via a Primakoff conversion. • Magnetic fields facilitate the conversion from axion to photons.	Generically: $m_a \propto g_{aii} \propto 1/f_a$ $10^{-6} eV < m_a < 10^{-2} eV$

Axions Are Now Mainstream



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

The Haloscope



Axion to photon production

Exaggerated axion lineshape. Expected signal would be close to or within the noise

Axion mass unknown requiring a tunable resonator

Look for dark matter axions (low mass) converting to photons in B-Field, Sikivie PRL 51:1415 (1983)

Image Source: C. Boutan Thesis(2017)

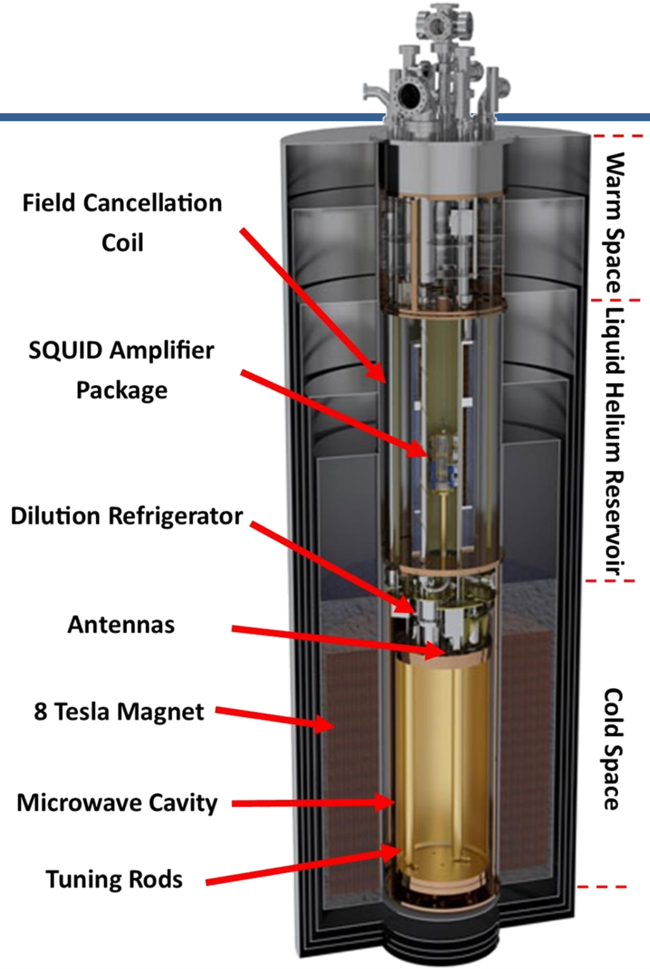
Power transfer from axion field to cavity field

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

Number of swings → cavity quality factor.

Narrowband cavity response → iterative scan through frequency space.

The ADMX Insert



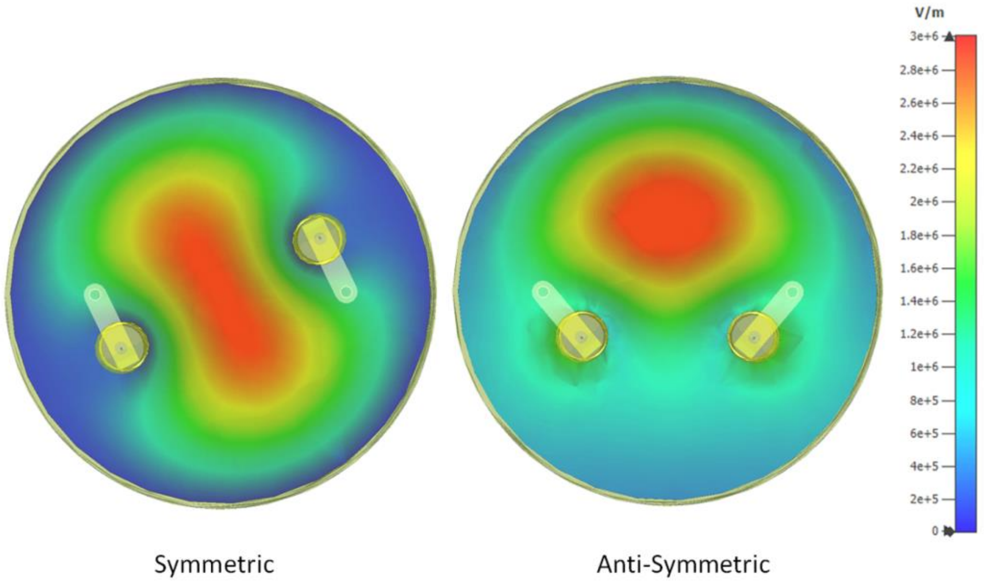
Run 1B Cavity, 2018

First time that we demonstrated filling in mode crossing regions <u>by moving the tuning rod to new configuration</u>

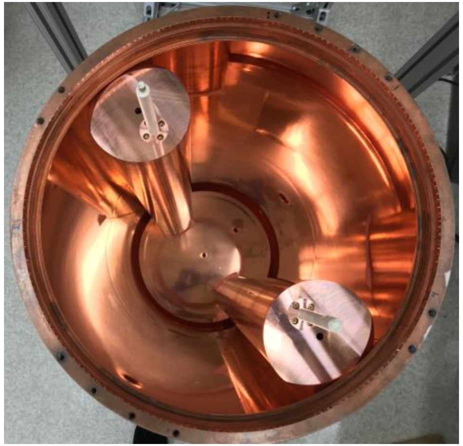
Example:
same frequency at
730 MHz

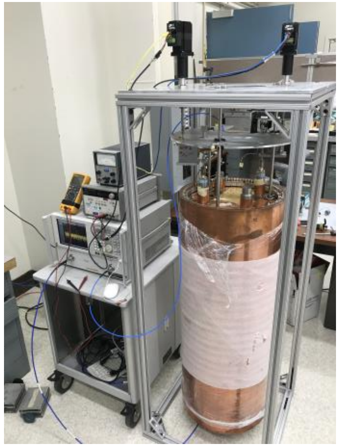
Mode crossing shifted

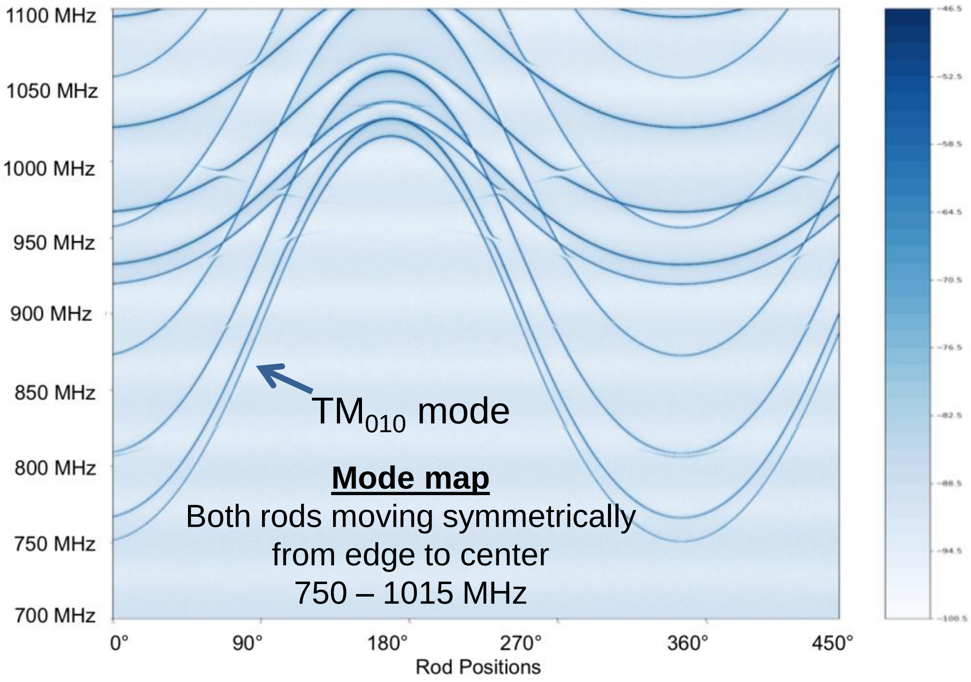
Form factor larger in
symmetric case (usual
running condition for 2 rods)



Run 1C Cavity, 2019-20







- New 4.5” tuning rods.
- Smaller total volume but higher Frequency range.
- Smaller end cap gaps resulting in narrower mode crossings.

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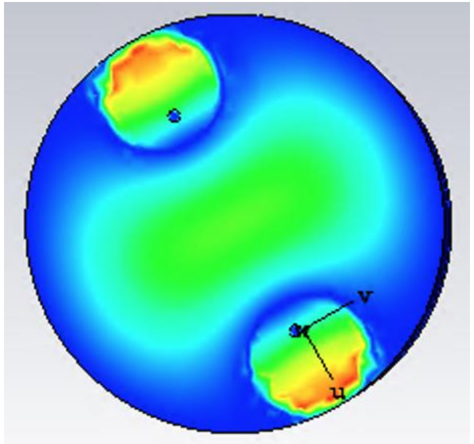

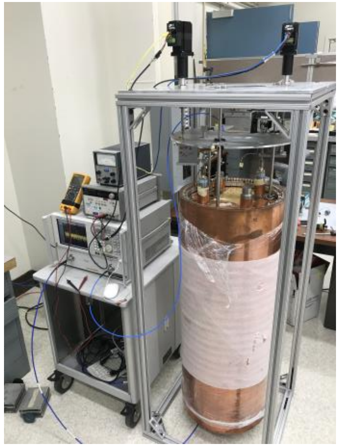

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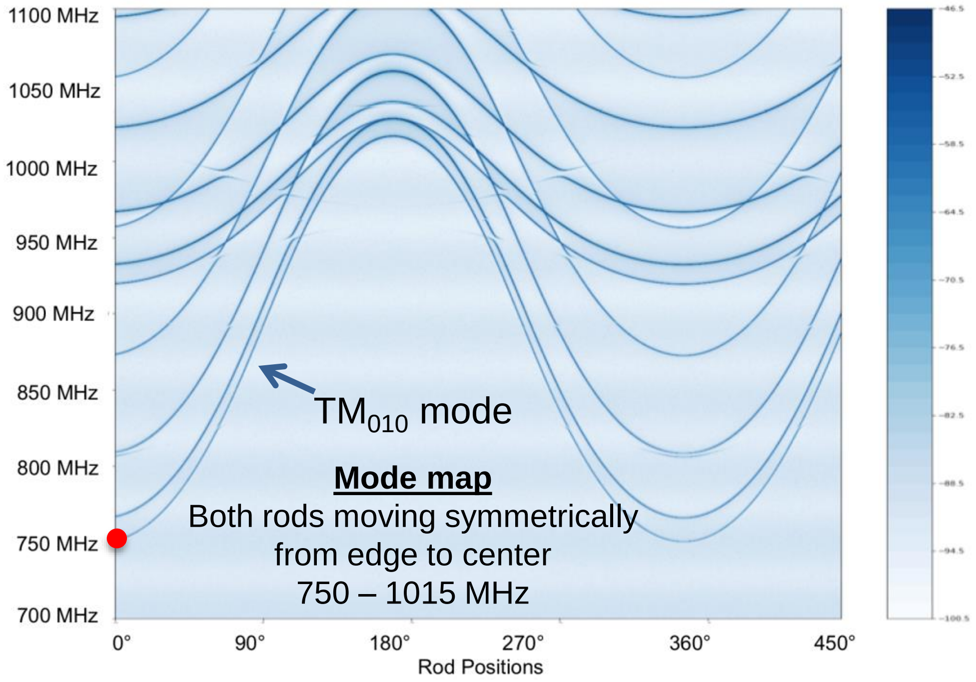

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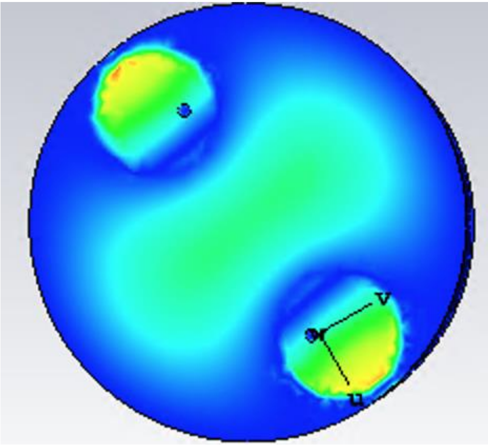

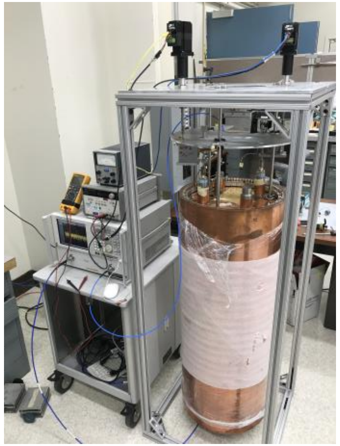

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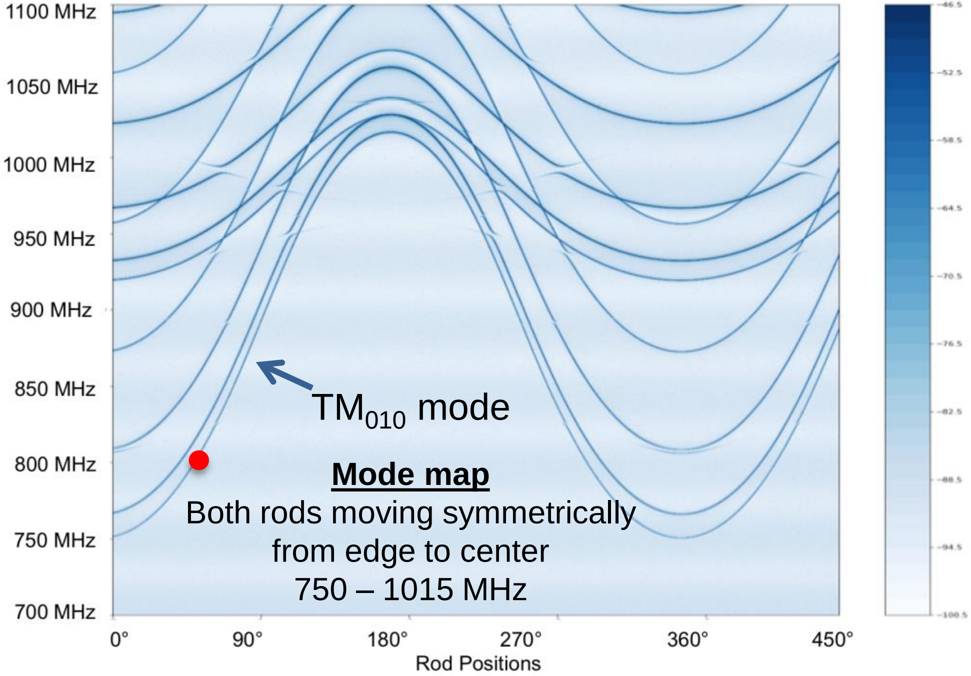

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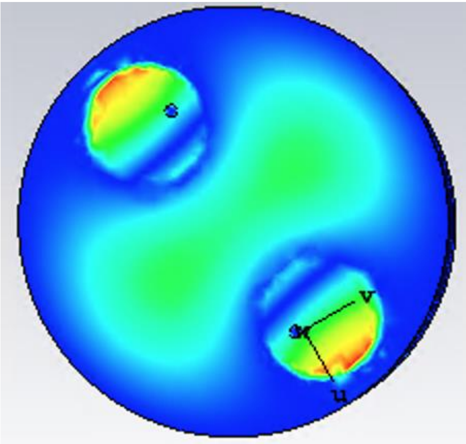

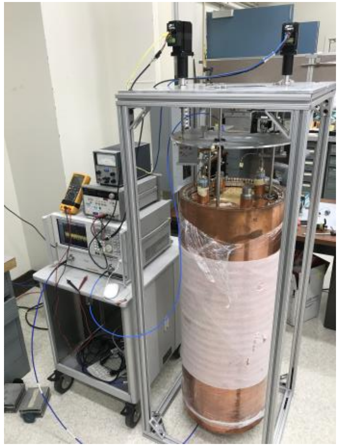

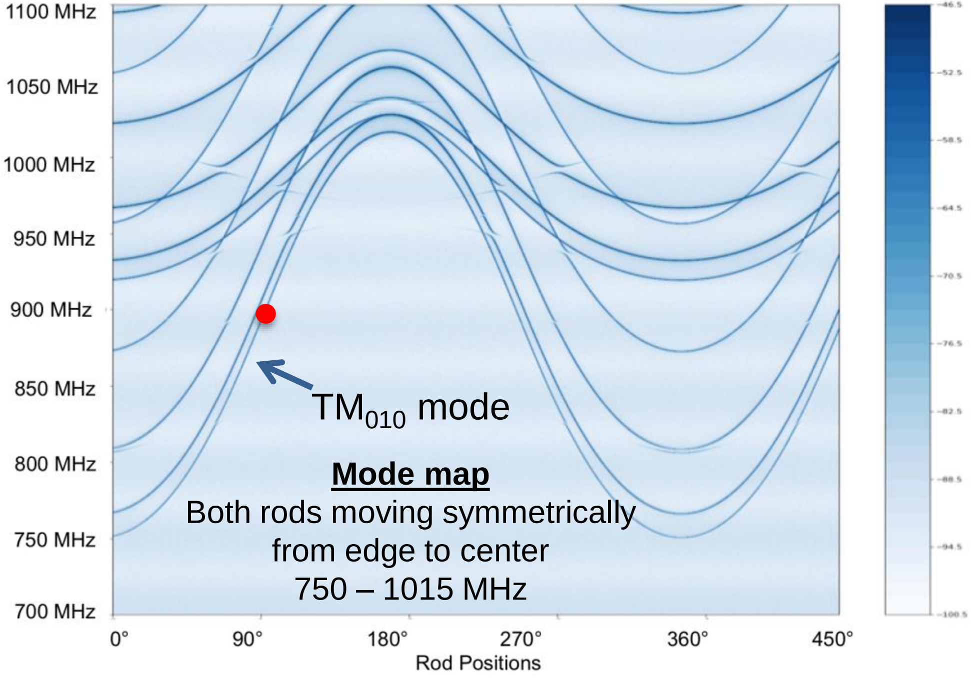

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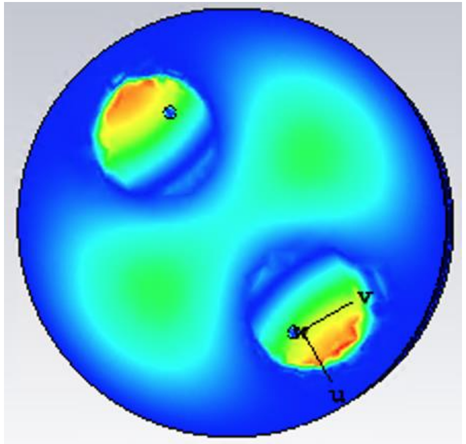

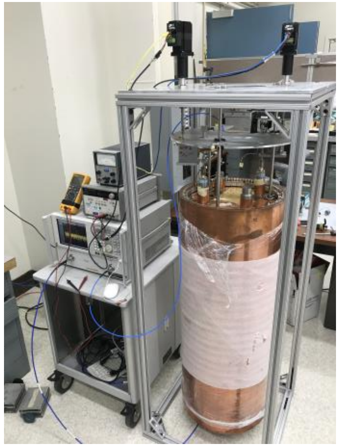

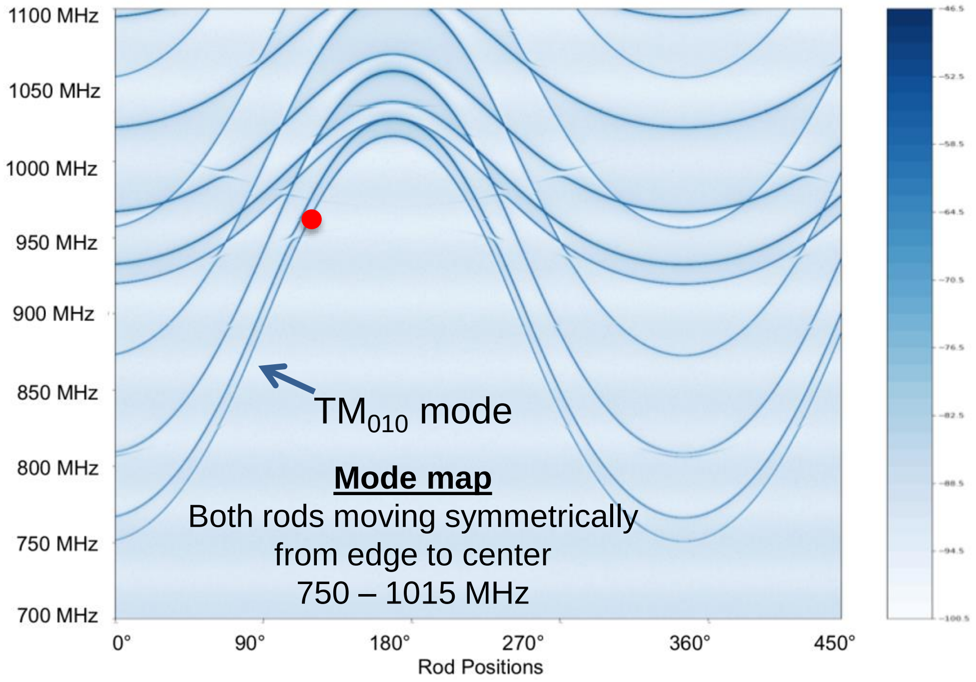

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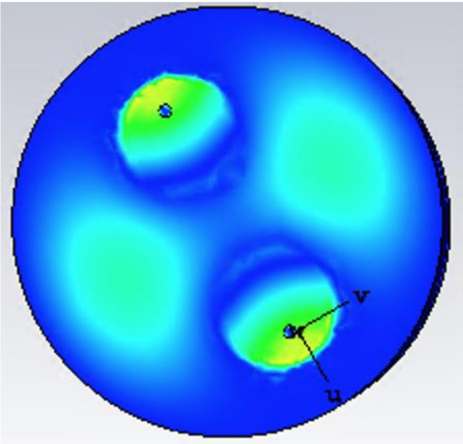

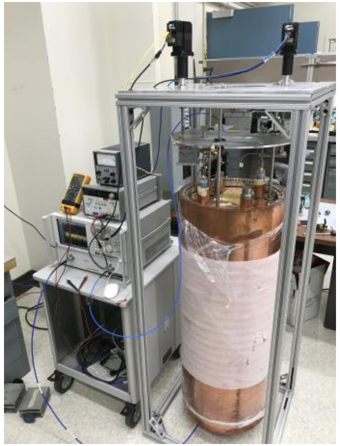

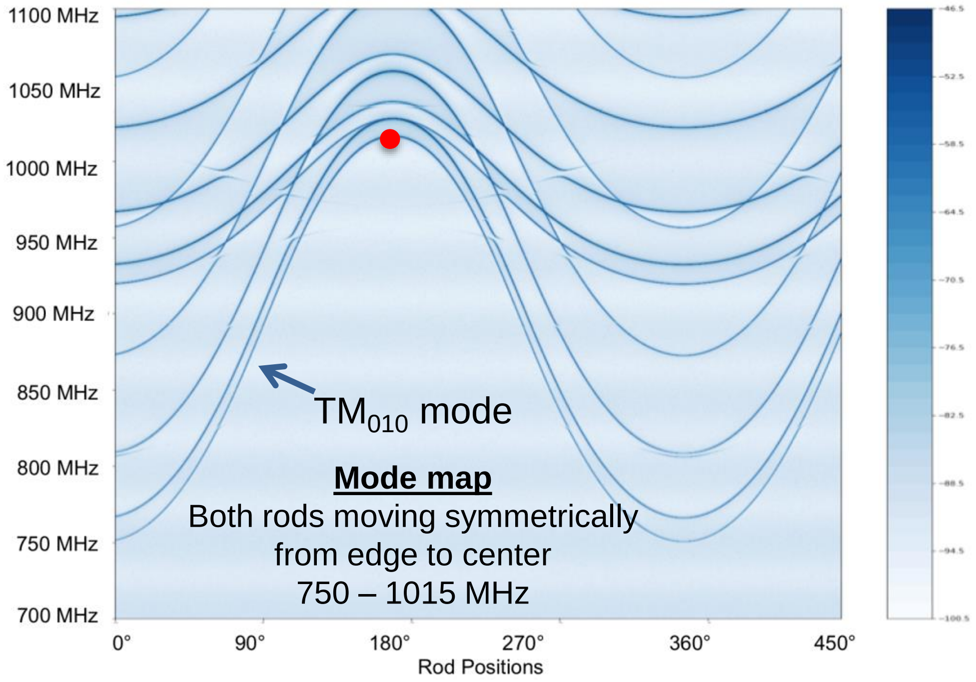

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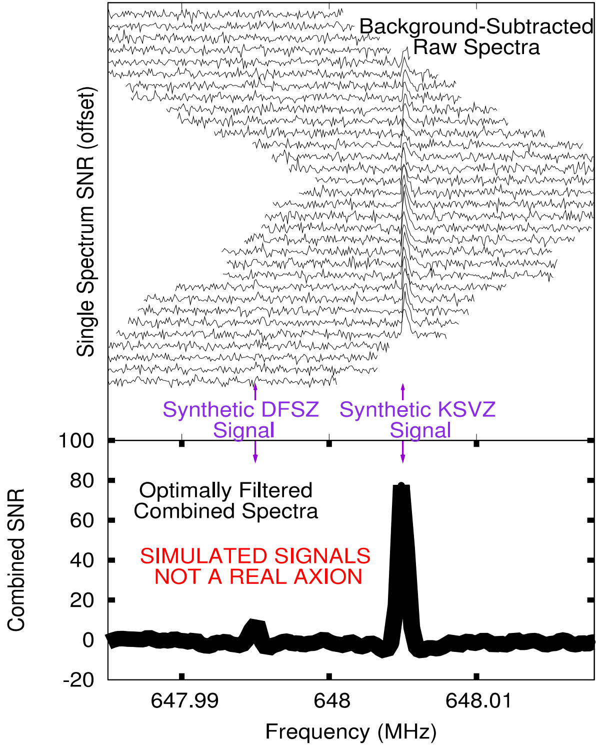
Finding a Signal



- To calibrate the detector a 'synthetic axion' signal could be injected into the cavity. This both verified the electronics and the analysis procedure.
- KSVZ axions produce a clear signal.
- DFSZ axions are not visible in the raw spectra but combining spectra over all observations reveals the peak.

Seeing a Signal

- 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.

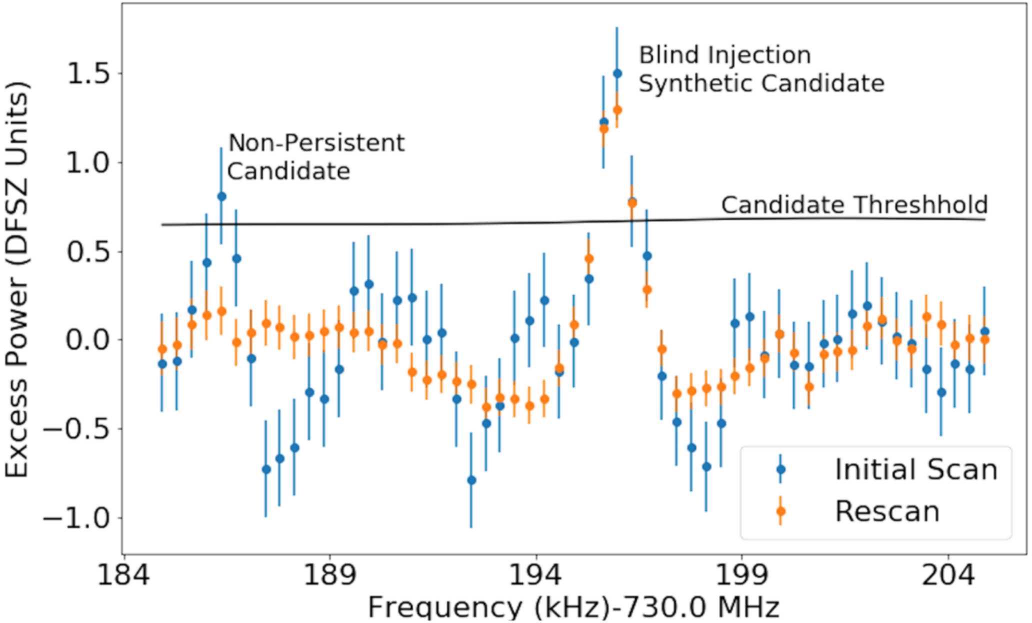


Figure provided by Gray Rybka (U. of Washington)

The Signal

- The signal to noise ratio is given by the Dickie Radiometer equation.

- Axion power is proportional to the cavity characteristics, the magnetic field and the resonant mode.

$$P_{\text{sig}} \propto B^2 \, V \, Q_{\text{cav}} \, C_{\text{mode}}$$

$$\frac{S}{N} = \frac{P_{\text{sig}}}{k_B \, T} \cdot \sqrt{\frac{t}{\Delta f}}$$

- Noise temperature is the sum of the thermal noise and amplifier noise.

$$T = T_{\text{phys}} + Tpre + \frac{T_{\text{postamp}}}{\text{Gain1}}$$

- Integration time depends on the experimental cadence.
  - Step size.
  - Operational frequency.
- Currently limited to the range of minutes.

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Experimental Cadence

1. The cavity frequency is scanned over a region until the desired SNR is achieved
2. We then examine the combined power spectrum for signs of excess
3. Excess power regions can be statistical fluctuations, synthetically injected signals, RF interference, or axions
4. Excess power regions are rescanned to see if they persist
5. Persistent candidates are subjected to confirmation tests

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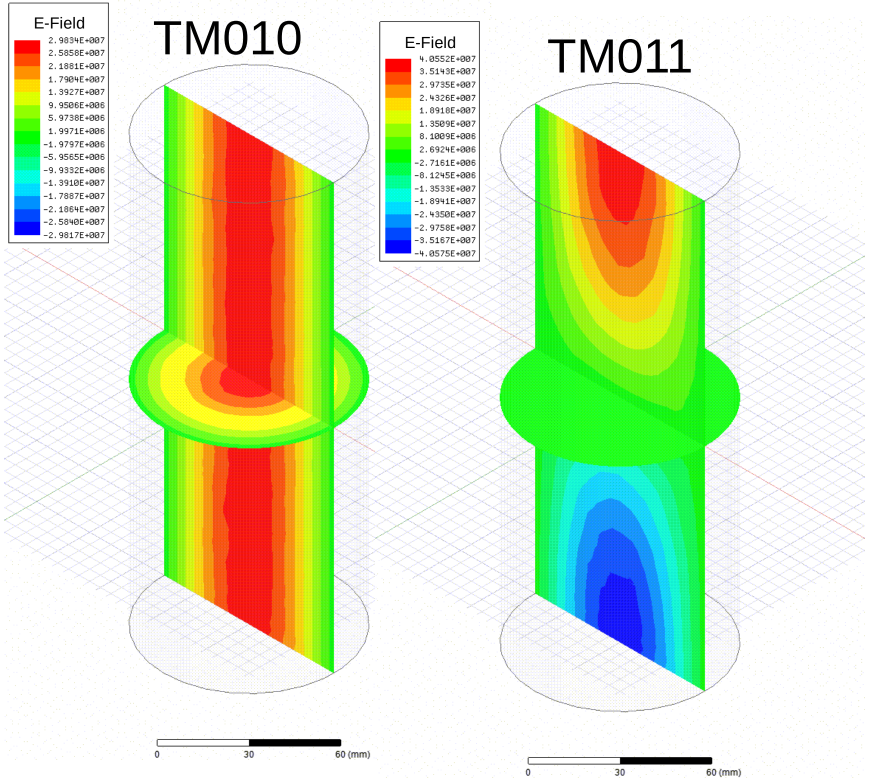
Cavity Form Factor

$$C_{\text{mode}} = \frac{\left(\int_V dV \ \ E \cdot B\right)^2}{V \ B^2 \int_V dV \ E^2}$$

- The cavity form factor is a function of the mode structure of the cavity.
- TM010 has the maximum form factor of ~0.7.
- The majority of modes have a negligible form factor.
- Due to the tuning rod ADMX typically achieves ~0.4



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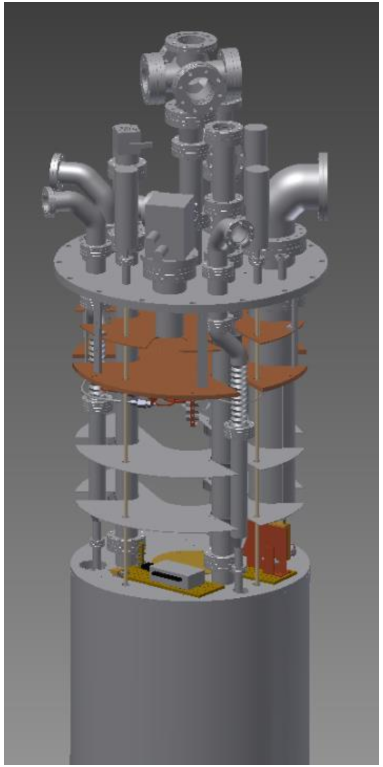
Cryogenics

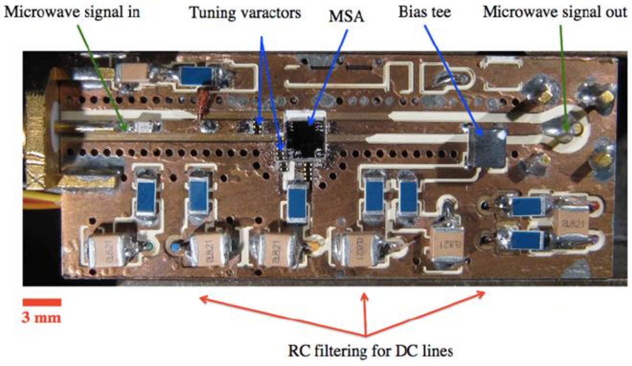
- Cryocooler
  - Actively cools baffle to 40K
  - First heatsinking stage
- Two 1K pots
  - Large 1K pot for the shielding, gearbox and electricals.
  - Small 1K pot for Dil Fridge
- Dil fridge was custom built by Janis Research Company
- 800 µW of cooling at 100 mK
- Cools the resonator and amplifiers.



Quantum RF electronics.

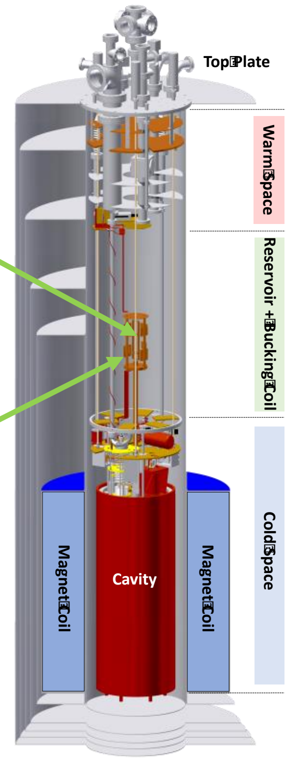
ADMX Tunable MSA

Sean O'Kelley, Clarke Group, UC Berkeley



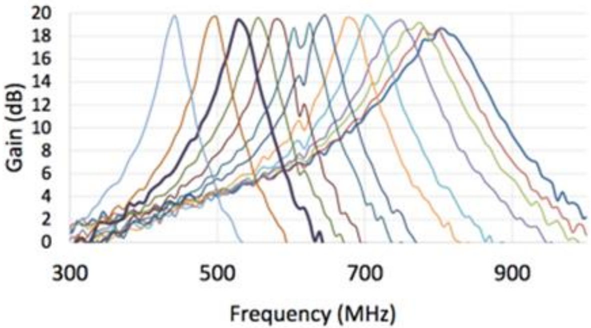
ADMX JPA

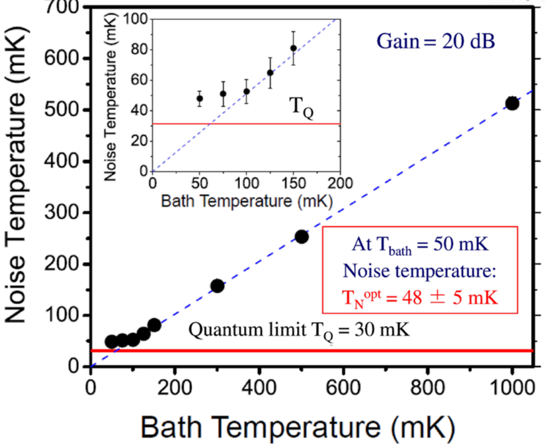
Yanjie Qiu, Siddiqi Group, UC Berkeley



Quantum RF electronics.

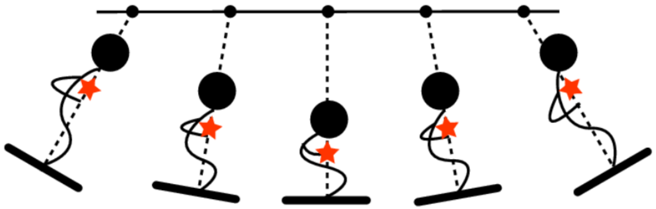
- The scan rate of ADMX is inversely proportional to the system noise squared. To achieve this, quantum limited amplifiers are used.
- Microstrip squid amplifiers(MSAs) are used for low frequency(0.5-2GHz) searches.
- The MSA works by having DC squid amplifiers attached to a microstrip resonator.
- Produced by the John Clarke Group at UC Berkley.



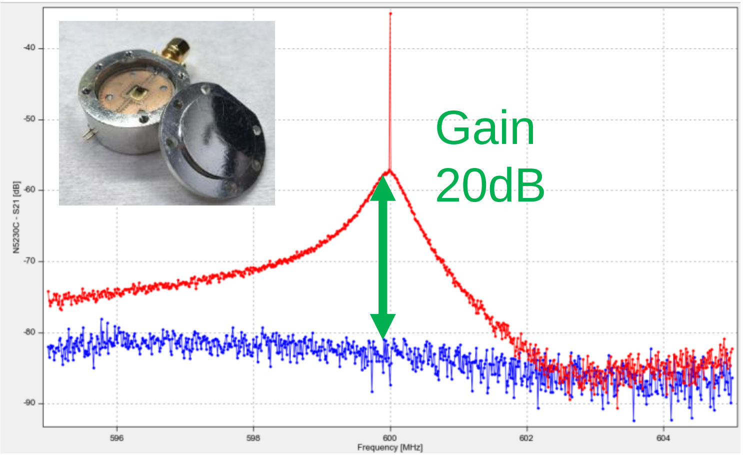


Quantum RF electronics.

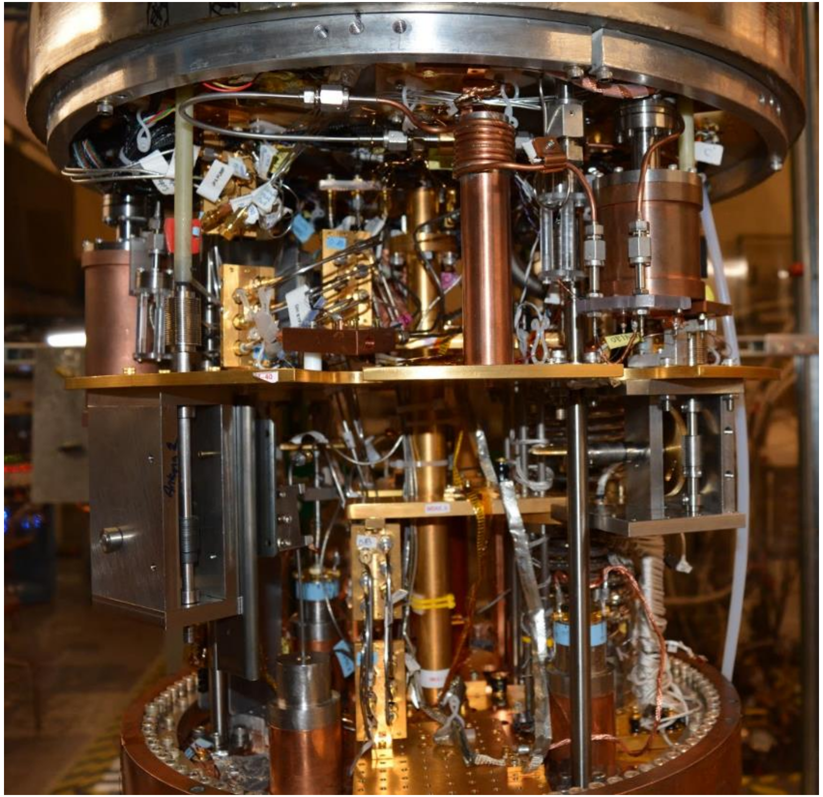
- For frequencies above 1GHz Josephson parametric amplifiers are more suitable.
- A pump tone is used to excite squid loops which in turn amplify the incoming signal.
- Produced by the Siddiqi Group at UC Berkeley
- Testing of the quantum electronics took place at Livermore before being shipped to the experiment.



Classic example of parametric amplification is a child on a swing



Complexity



ADMX Gen-2 2018 (run 1B)

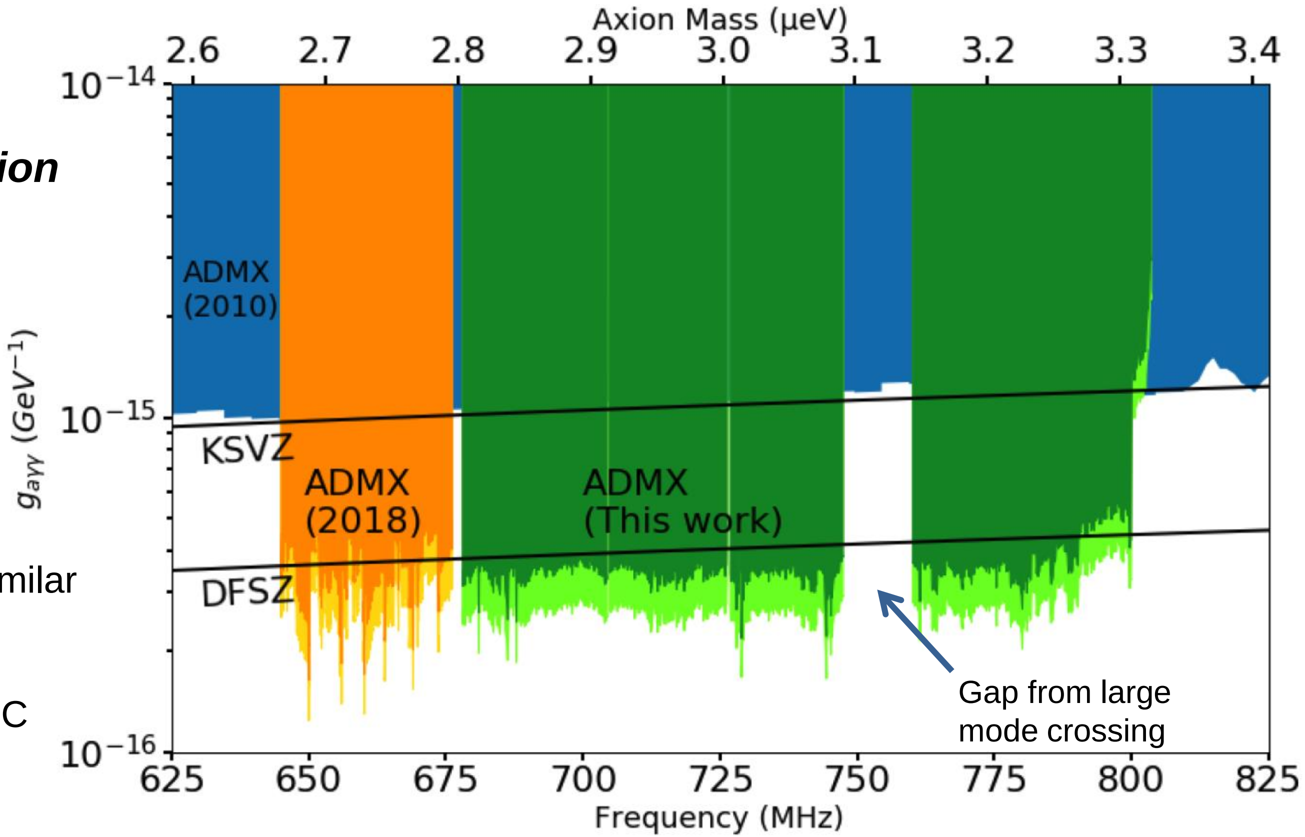
Extended Search for the Invisible Axion with the Axion Dark Matter Experiment
arxiv.org:1910.08638
Recently submitted to PRL

First run with JPA.

Operated: Jan-June 2018

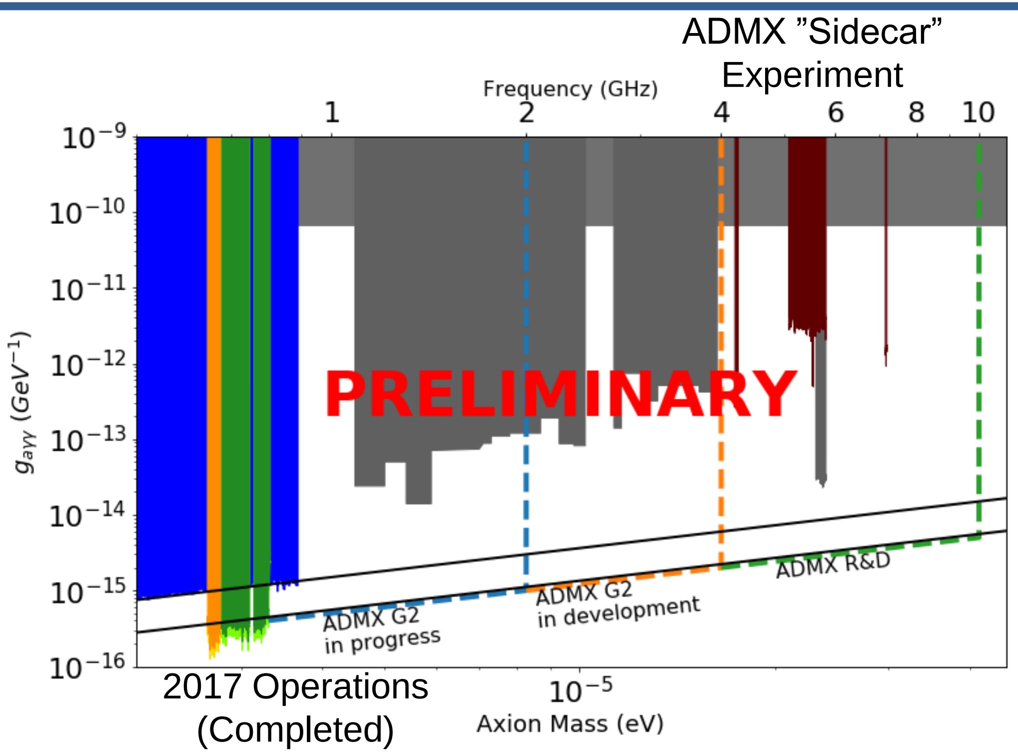
Collected ~ 3 times the data in similar 6 month run as 1A (MSA)

Concurrent development of run 1C hardware



Going forward

- Currently ADMX is scanning 700-890 MHz
- We anticipate faster frequency coverage in the future due to:
  - Higher magnetic field
  - More stable quantum electronics
  - Lower temperatures
  - Reduced engineering overheads.
- Speed up of ~6x



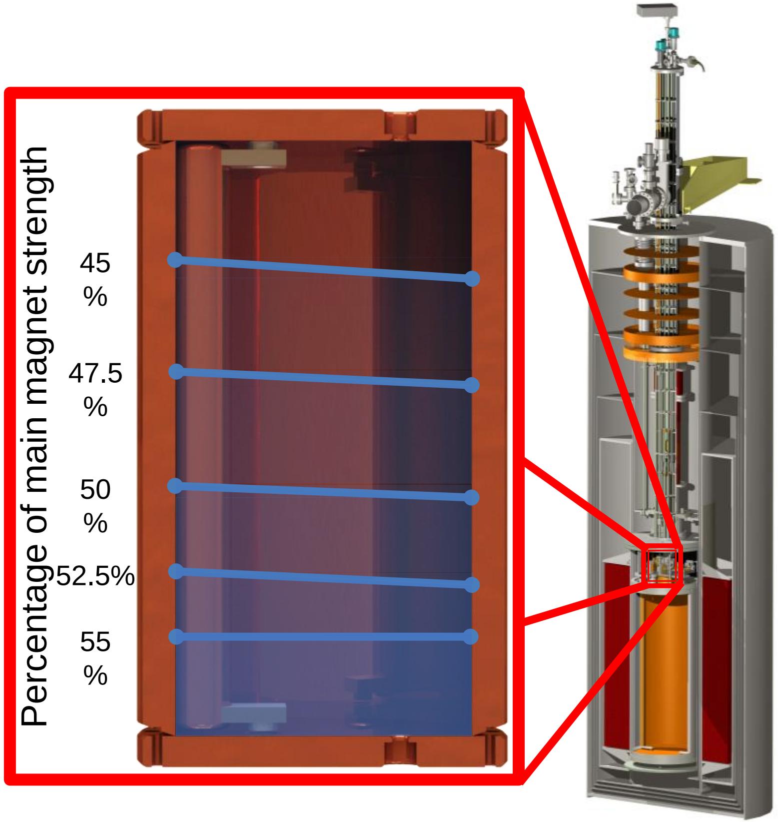
The ADMX Sidecar

The Sidecar cavity is an in-situ R&D platform which is testing components for future ADMX main cavity systems. The cavity sits inside the main cavity magnet field allowing the production of scientific data.

Key Test Objectives:

1. Motion control schemes.
2. High frequency amplification.
3. Frequency tuning mechanisms.
4. Cavity construction.

The Sidecar cavity is also being used to test resonant feedback techniques which could form the basis of future axions searches.



2018 Result

PHYSICAL REVIEW LETTERS **121,** 261302 (2018)

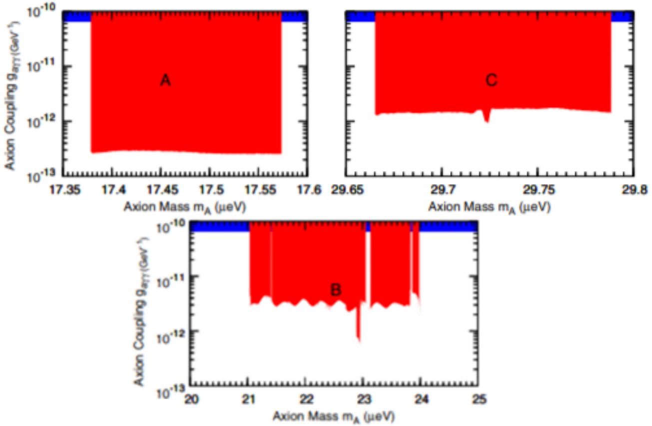
Piezoelectrically Tuned Multimode Cavity Search for Axion Dark Matter

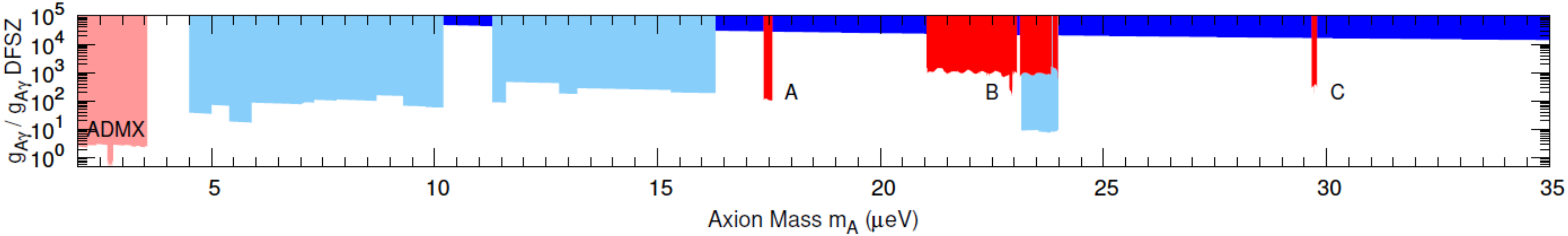
(ADMX Collaboration)

(Received 22 August 2018; published 28 December 2018)

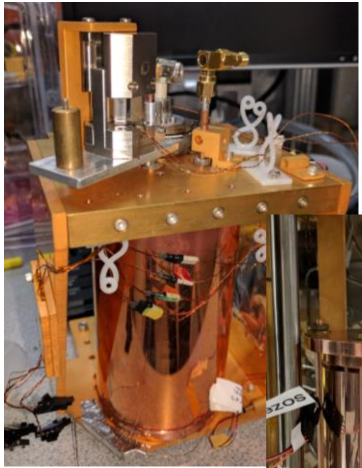
Sidecar ran in parallel with the main cavity during 2016 and 2017 taking data on both the TM010 and TM020 modes of the cavity.

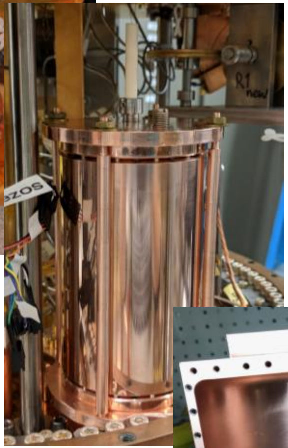
Run	A	B	C
Timeline	May 24–June 11 2017	Aug 9–Oct 4 2016	Feb 27–April 9 2017
Mode	TM_{010}	TM_{010}	TM_{020}
Freq (MHz)	4202–4249	5086–5799	7173–7203
Mass (μeV)	17.38–17.57	21.03–23.98	29.67–29.79
Usable spectra	11 *k*	32 *k*	24 *k*
B field (T)	3.11	0.78 (2.55[a])	3.11
Form factor	0.49	0.44–0.61	0.04–0.046
Q_L	6.2 *k*	2.2 *k*	2.3 *k*
T_{sys} (K)	7.0 ± 0.3	7.0 ± 0.3	7.1 ± 0.3





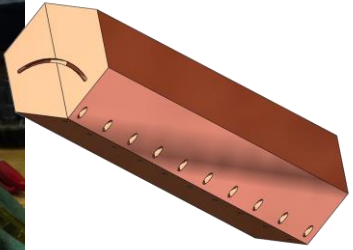
The Sidecar Cavity





The Cheese Block – A copper plated stainless steel cavity. With piezo actuators mounted directly to the cavity. A large thermal ballast prevents temperature changes due to actuator stepping.

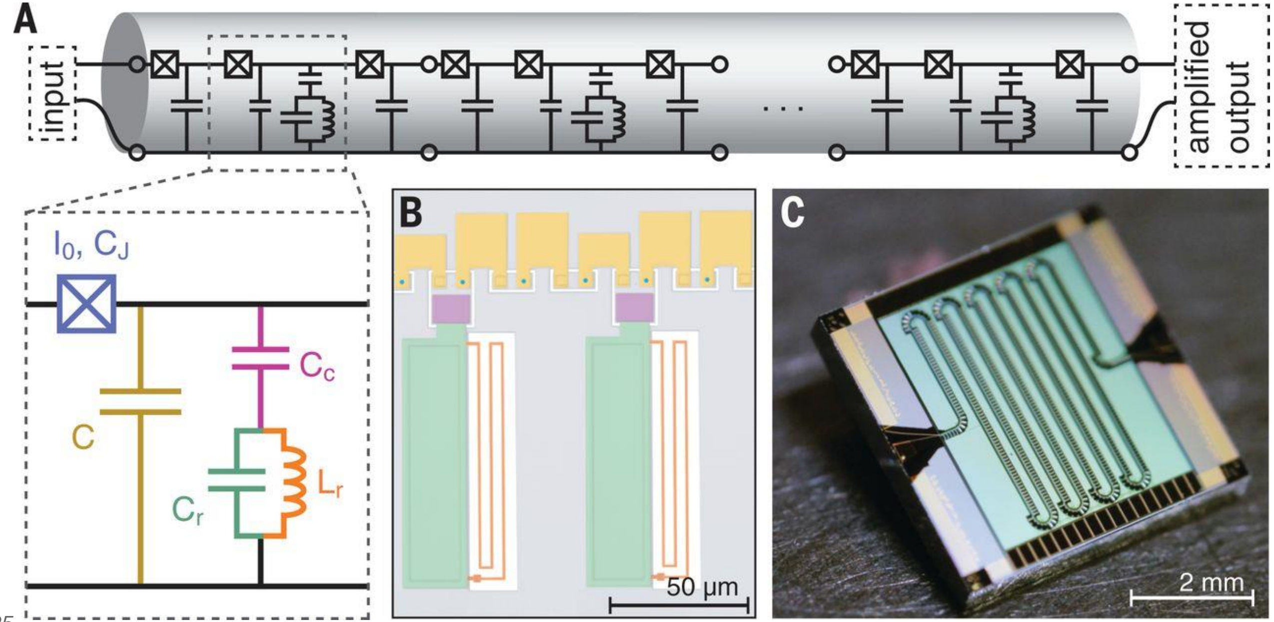
The Coke Can – Same cavity was used with a copper outer structure to ensure good thermal conduction. No thermal ballast needed as piezo actuators moving to the 1k stage. Change in piezo supplier lead to new mounts.



The Clamshell – A new cavity design comprising two half-shells formed from solid copper. Without the worry about thermal ballast or conduction the cavity has been enlarged to fill the usable space.

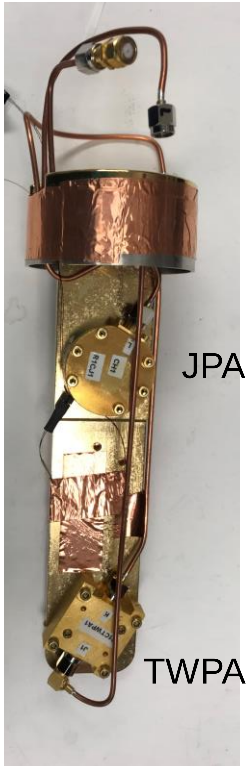
TWPA

Sidecar has run with a Low Noise Factory HEMT amplifier giving a noise temperature of 4±0.3K. To make significant exclusions this needs to be reduced, a travelling wave parametric amplifier will be used in the next run.



DOI: 10.1126/science.aaa8525

Motion Control for 2019

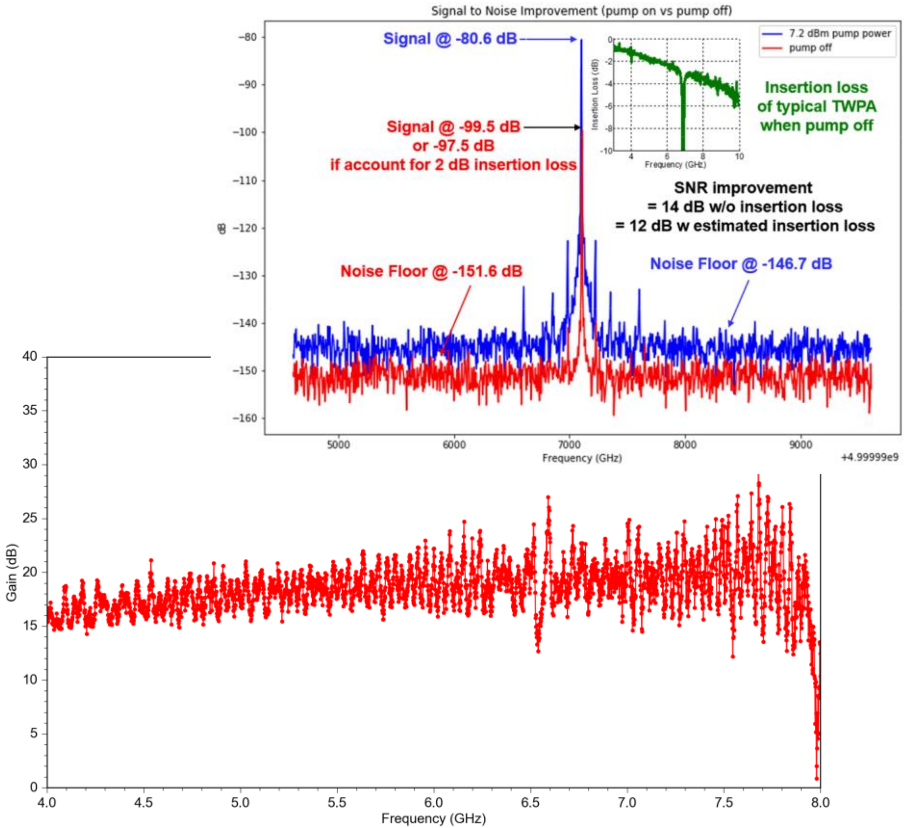


The sidecar TWPA was included in the new Squidedal and will run through 2019.

Gain:
- 26dB at 7GHz
- 16.5dB at 4.5GHz

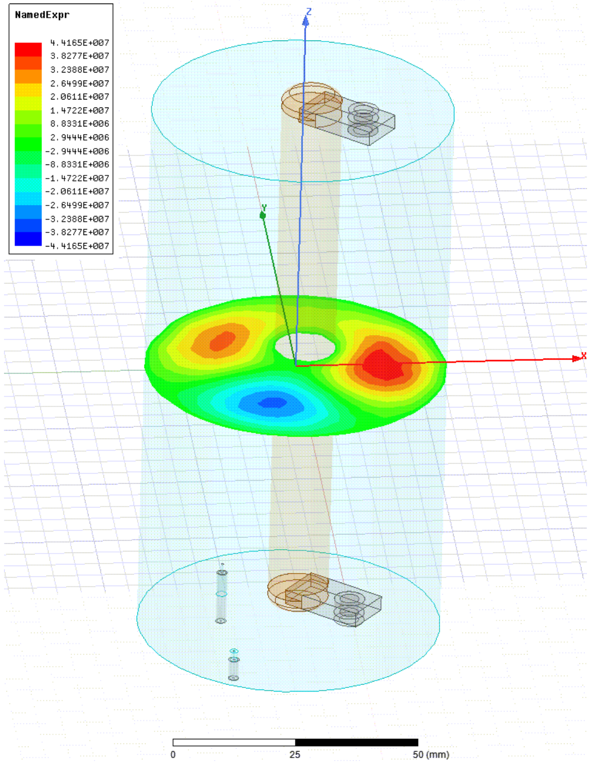
SNR improvement:
- 11dB(226mK) at 7GHz
- 12dB(159mK) at 4.5GHz

The reduction in noisse will lead to a significant speedup in scan speed.

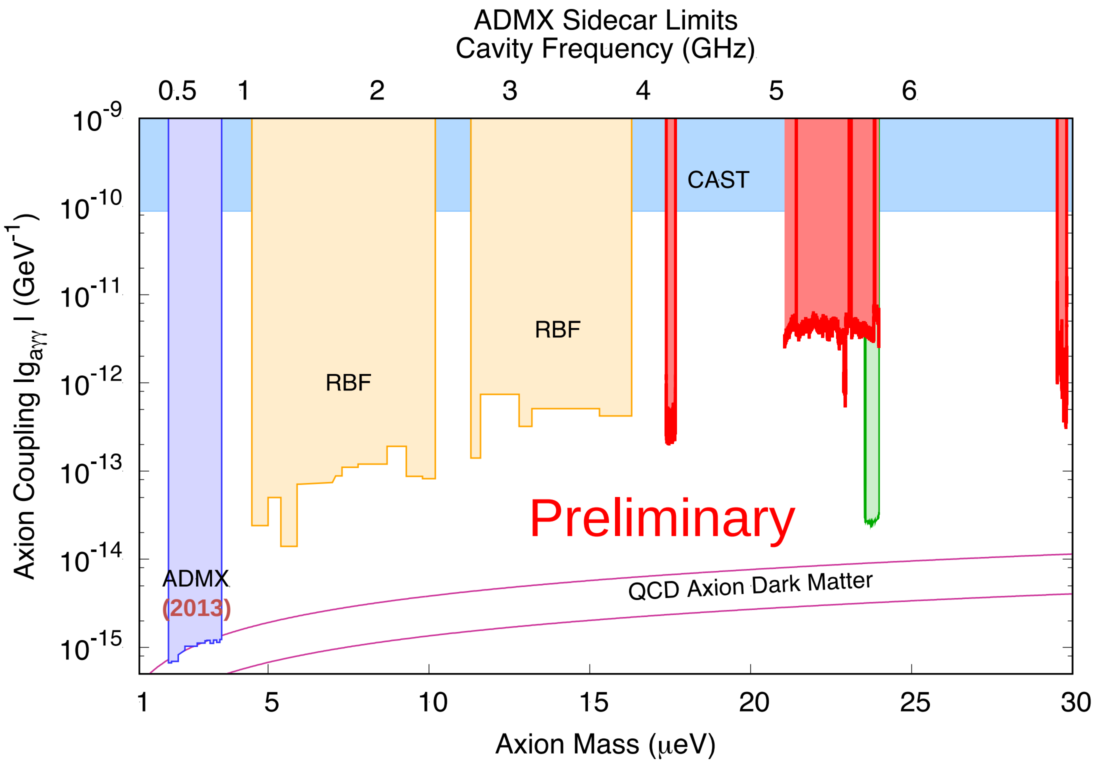


Higher Order Modes

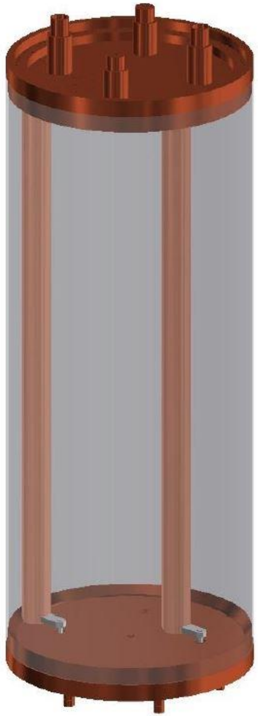
- Modes other than the TM010 have none zero form factors.
- The TM020 has a form factor of ~0.1.
- Testing operation using the Sidecar cavity.
- Extends the scannable range to 6.4-7.2GHz



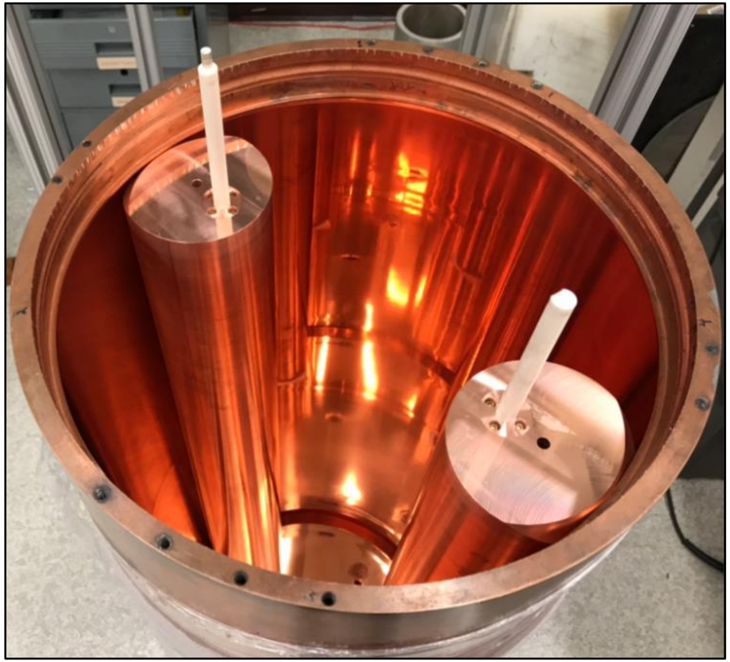
ADMX Sidecar Exclusion



ADMX Cavity Systems as we move up in frequency



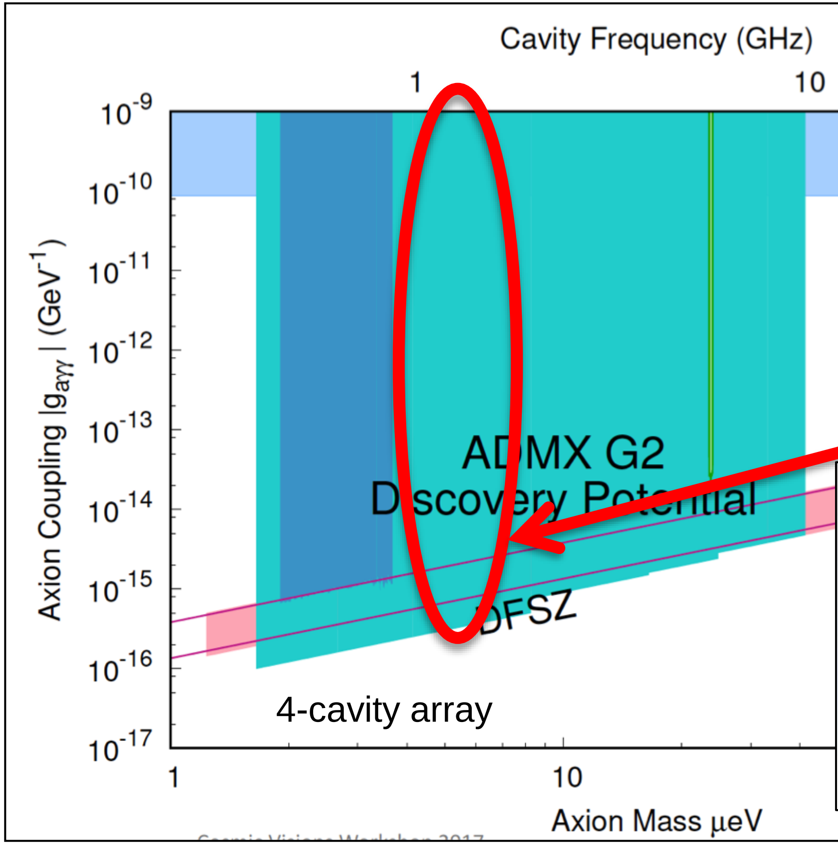
Cavity from run 1a & 1b
Two 2” diameter tuning rods
580 – 890 MHz



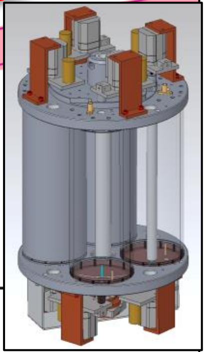
Cavity from run 1c & 1d
Larger 4.5” (then 6”) diameter tuning rods
780 – 1200 MHz
Tuning rods for run 1D soon

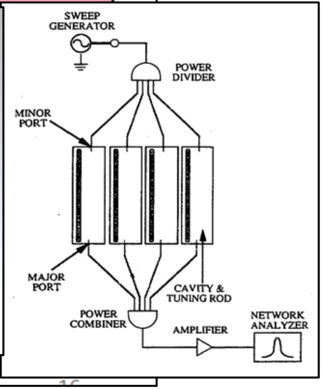
Cavity system for run 2a
4 cavity array
Sapphire (1200 – 1500 MHz)
Metal Rods (1500 – 2000 MHz)

ADMX Science Prospects (1-2 GHz)



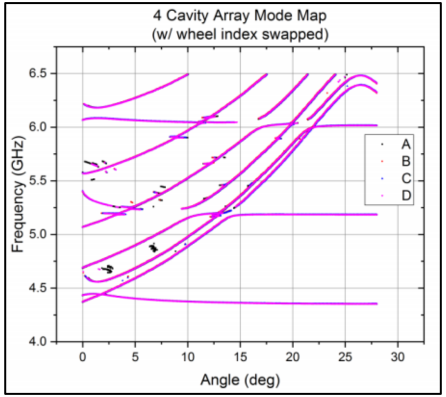
4-cavity array

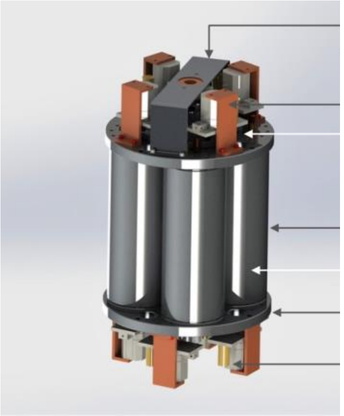




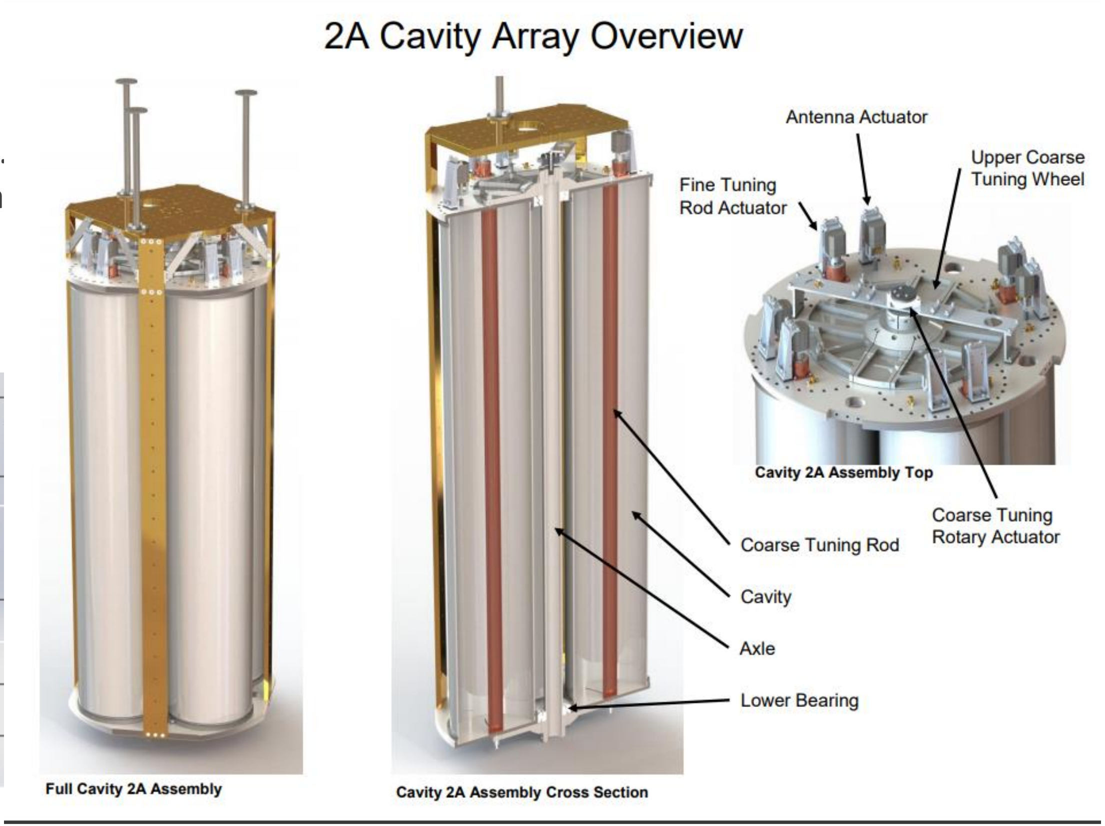
Current status of 4-cavity array (to 2 GHz)

- 4 – cavity array based on a common rotor
- All rods move at same time from edge to center
- Fine frequency tuning done by linear stages
- Piezoelectric drives for rotary and linear motion.
- Feedback locking scheme to ensure all cavities a the same frequency
- Aluminum prototype system constructed and tested at room temp at UFL





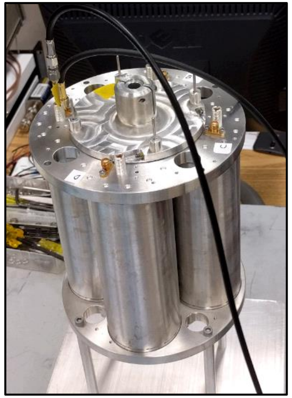
Prototype 4-cavity array



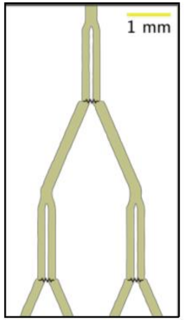
Current status of 4-cavity array (to 2 GHz)

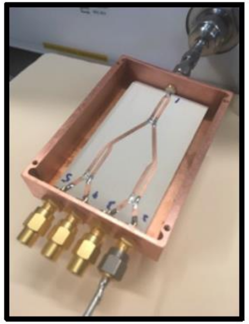
- Prototype 4-cavity array in FNAL 4K test-stand for cryo-testing

- Main Cavity Tubes built by Florida. Copper plating started at LLNL. Delivery to FNAL in new year for full systems testing.



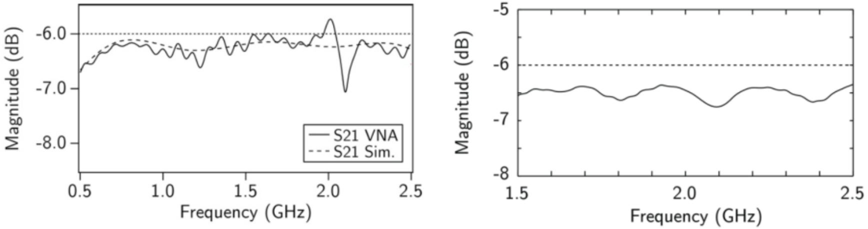
- 100 mK systems components testing being done at Washington U. St. Louis
  - Custom power-combiners
  - Updated SQUIDADEL
  - Circulator testing
  - Testing of Berkeley JPAs





Insertion loss

Room temperature   4 K / mK



Further-out G2 ADMX Program: New Magnet

The axion signal power goes as **V^2B^4**.

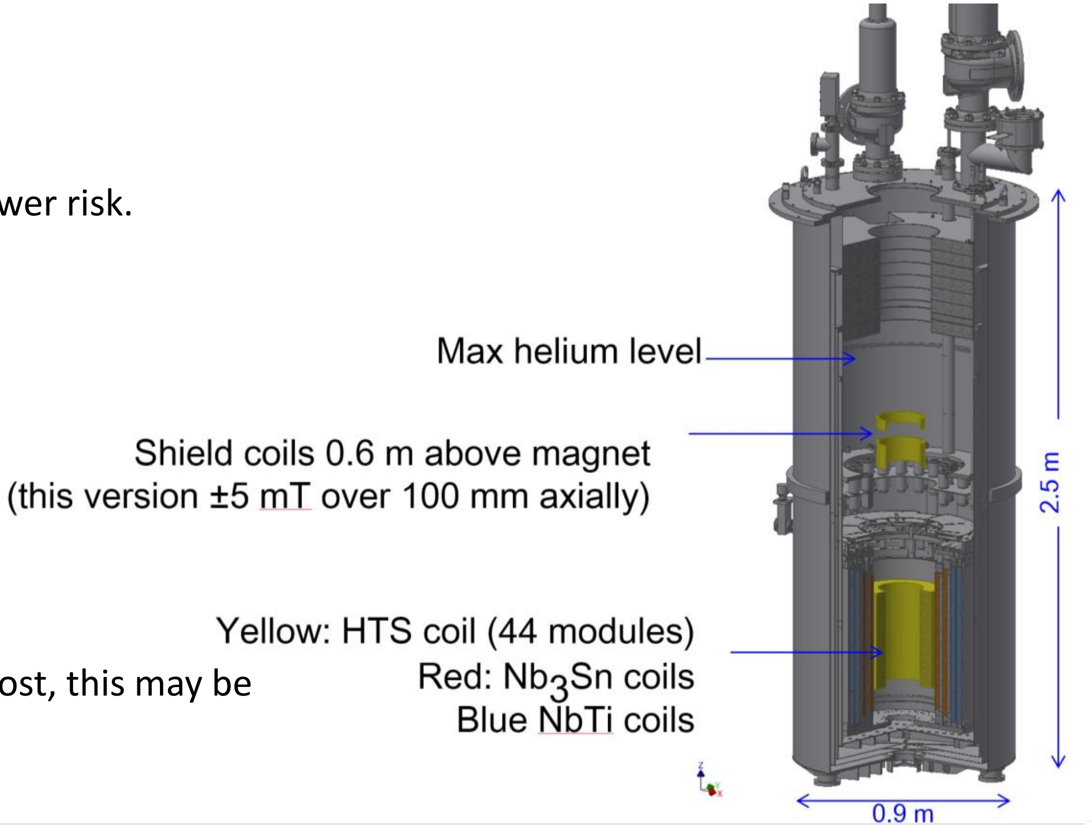
High-field (32 Tesla), smaller diameter.
DFSZ sensitivity at high mass with
many fewer parallel cavities, so much lower risk.

Design study by UF and FSU Magnet Lab
Funded by Heising-Simons Foundation.

Option for 2-4 GHz phase

Lower cavity cost and risk, but magnet procurement cost $5-10M.

In the tradeoffs of complexity, risk and cost, this may be very attractive.



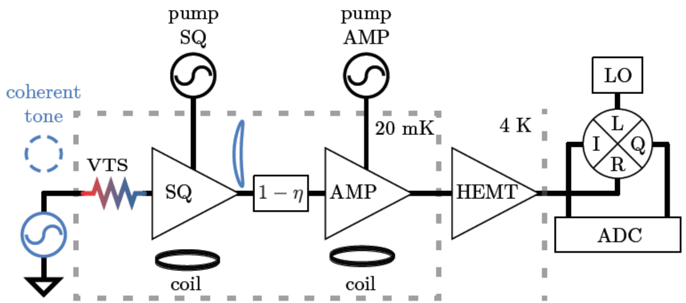
Getting beyond the standard quantum limit

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

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:

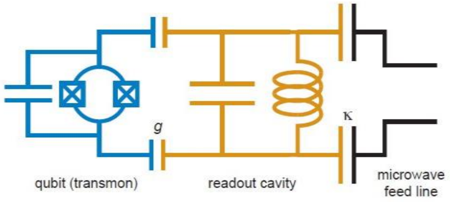
- Squeezed-vacuum state receiver (e.g., LIGO)
  - HAYSTAC haloscope (Yale) testing now.
  - Single-photon detectors (e.g. qubits, bolometers)

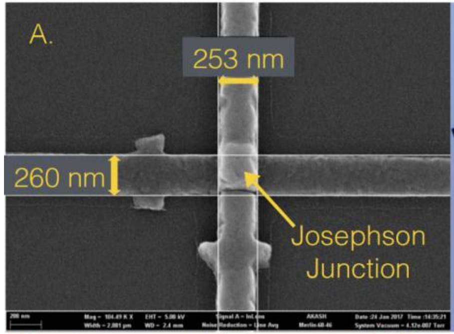


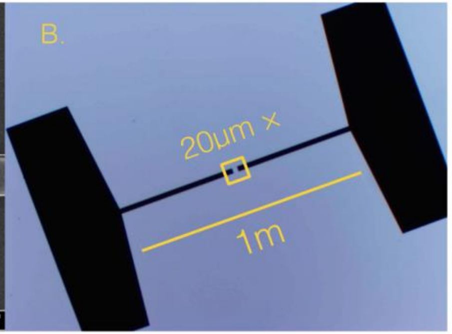
Transmon Qubits

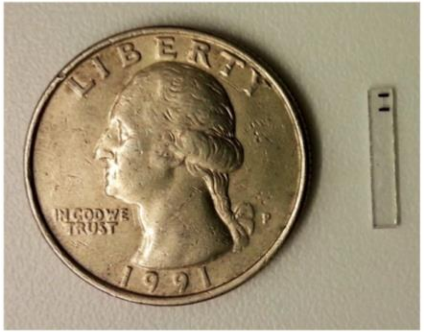
Transmon Qubit – single cooper pair box shunted with capacitor

Can tune the qubit frequency with flux through SQUID

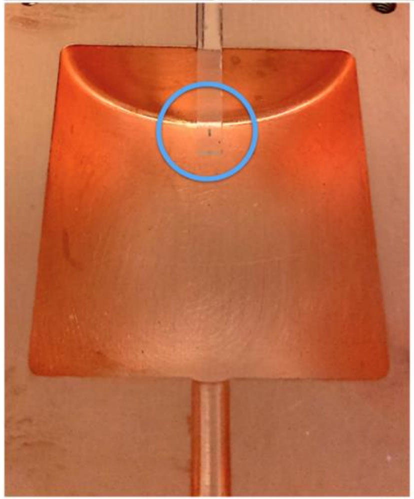


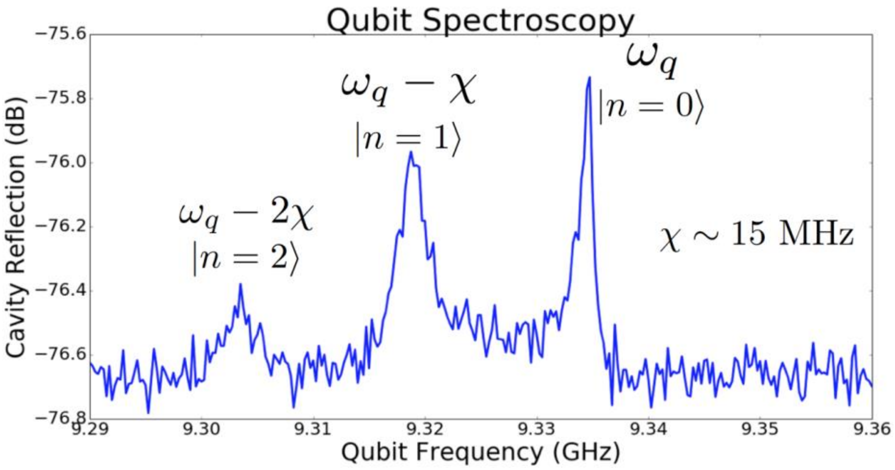






Example of device fabricated at U. of Chicago with FNAL
- Heising-Simons funded R&D (Aaron Chou @ FNAL)





Potential Scan Rate Speedup

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

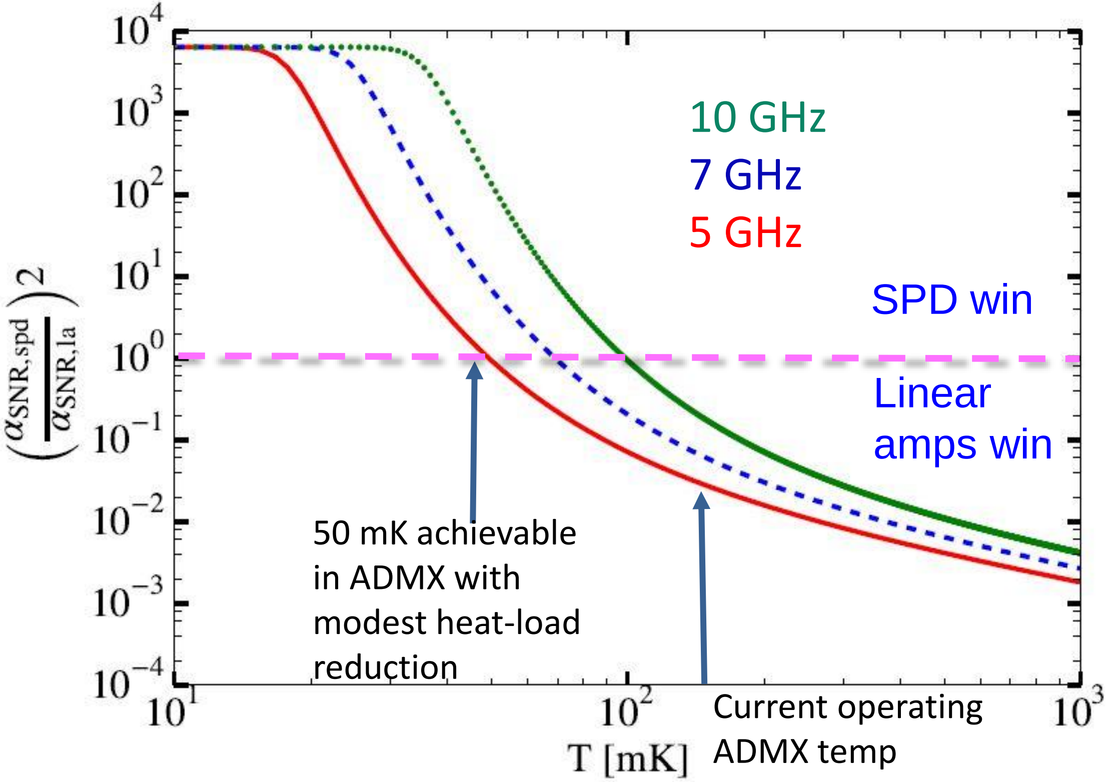
***Accelerating dark-matter axion searches with quantum measurement technology, arXiv:1607.02529v2, 19 July 2016**

Aim for 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 µW temp can go below 50 mK

Rich R&D program has begun
HEP-QIS grant FNAL, U. Chicago, UC Boulder & Yale.



ADMX Gen-2: 2019 operations and beyond

Search to extended from 780 – 1015 MHz (run 1C)

New JPA package

New Cavity Tuning Rods

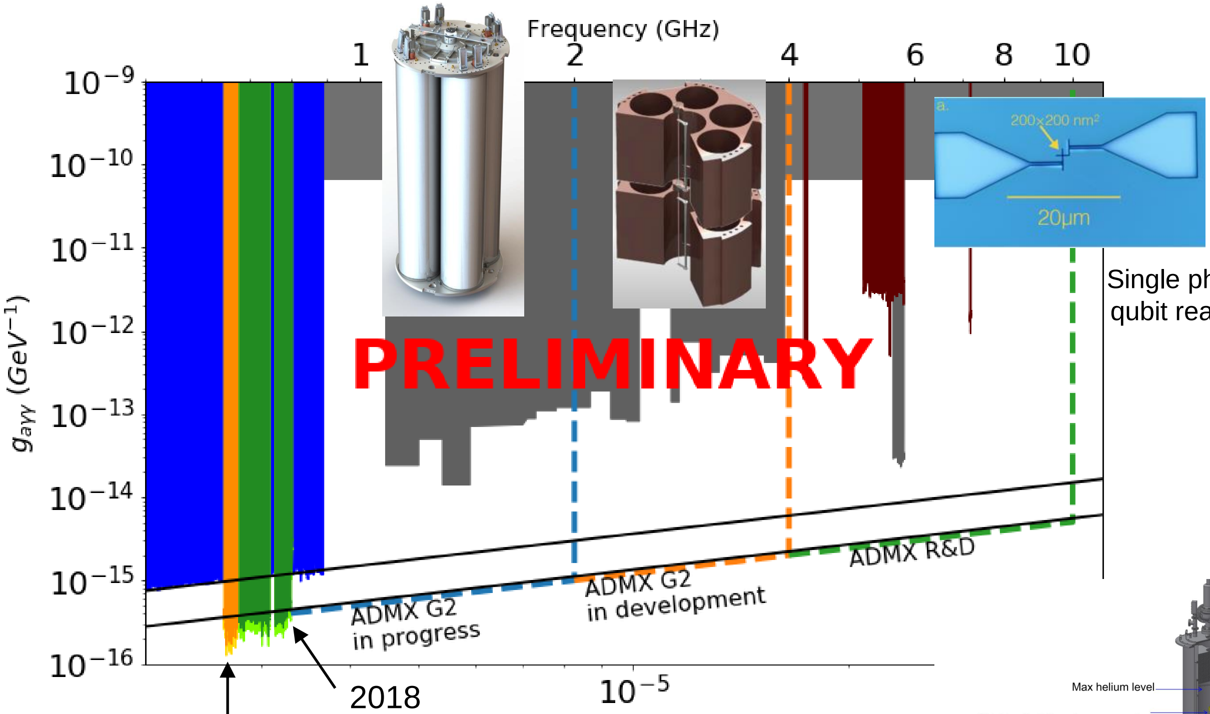
Multicavity systems

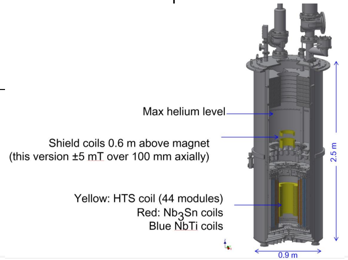
- Axions add coherently
- Noise adds incoherently
- √N improvement

Large Magnet system

Squeezing / Single Photon Counting

Axions may be around the corner!





Axions Beyond Gen 2

A workshop to explore the landscape of

QCD dark-matter axions

for 2021 and beyond

Date to be announced soon.

- Theory & phenomenological development of QCD dark-matter axions
- Astrophysical & laboratory searches
- Axions & cosmology

HEISING-SIMONS FOUNDATION

Workshop website: beyondgen2.npl.washington.edu

Workshop Coordinator: Ida Boeckstiegel imboxx@uw.edu

Local Organizing Committee: C. Boutan, G. Carosi, L. Rosenberg, G. Rybka, N. Woollett

Collaborating Institutions:
UW, UFL, PNNL
FNAL, UCB, LLNL
LANL, NRAO, WU, Sheffield

The ADMX collaboration gratefully acknowledges support from the US Dept. of Energy, High Energy Physics DE-SC0011665 & DE-SC0010280 & DE-AC52-07NA27344

Also support from PNNL and LLNL LDRD programs and R&D support from the Heising-Simons institute.

Lawrence Livermore National Laboratory