New Results from the Axion Dark Matter Experiment

CEA Saclay

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On behalf of the ADMX collaboration

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- 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’.

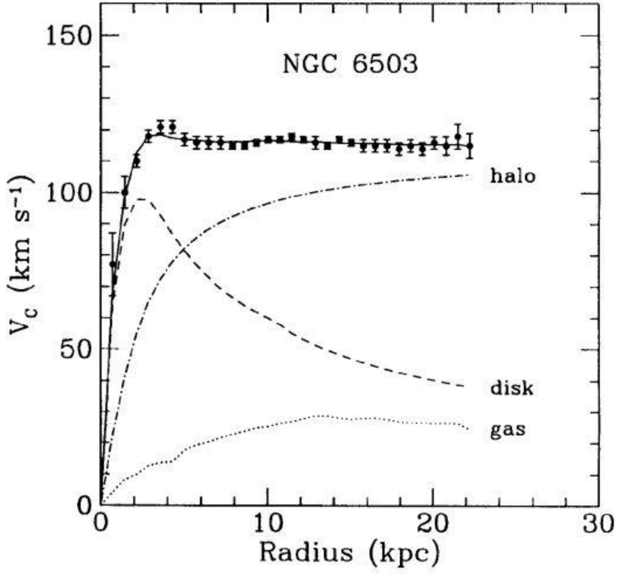
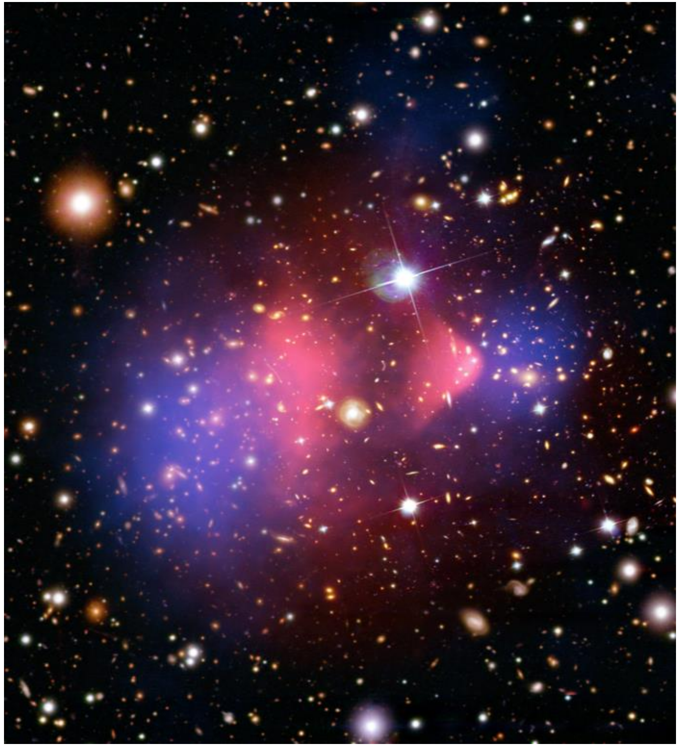


Image source: Katherine Freese, Caltech
https://ned.ipac.caltech.edu/level5/Sept17/Freese/Freese2.html

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.

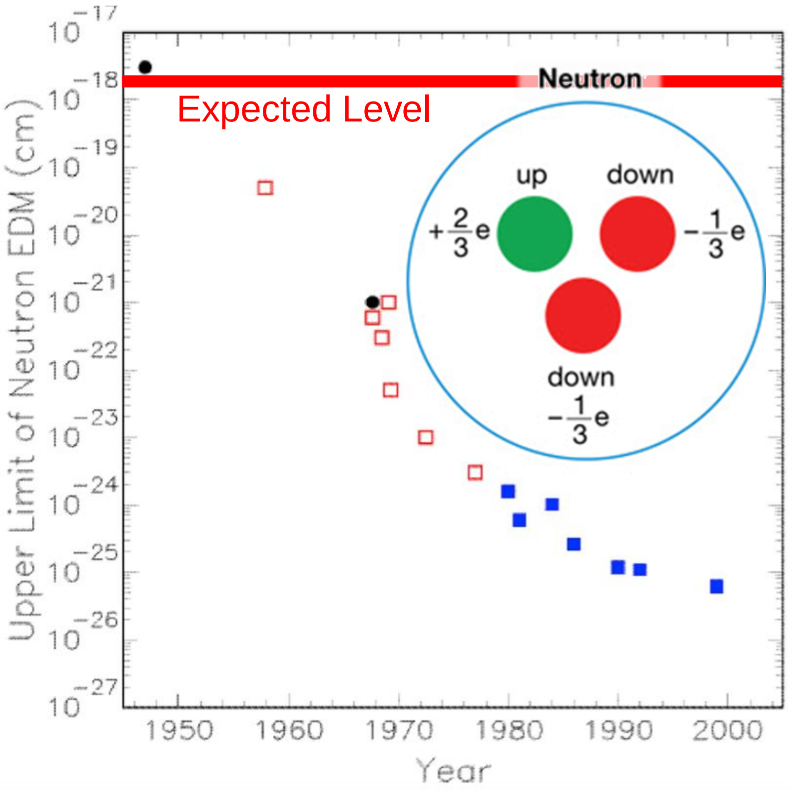


Strong CP Problem

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

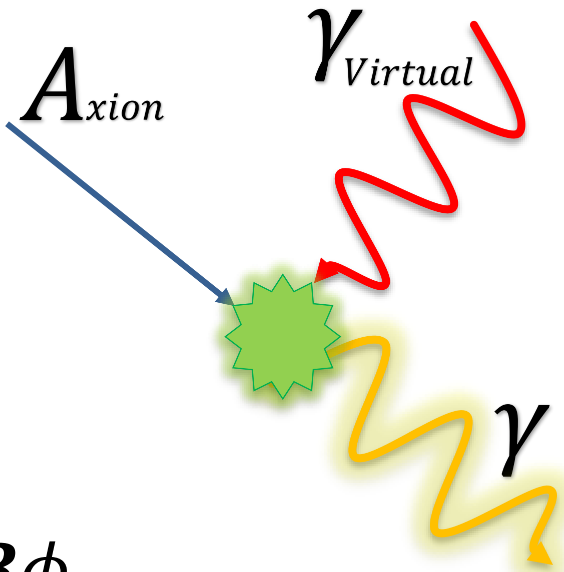
Neutron dipole moment $$d_n \approx \theta\, e \frac{m_q}{m_n^2}$$

- 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

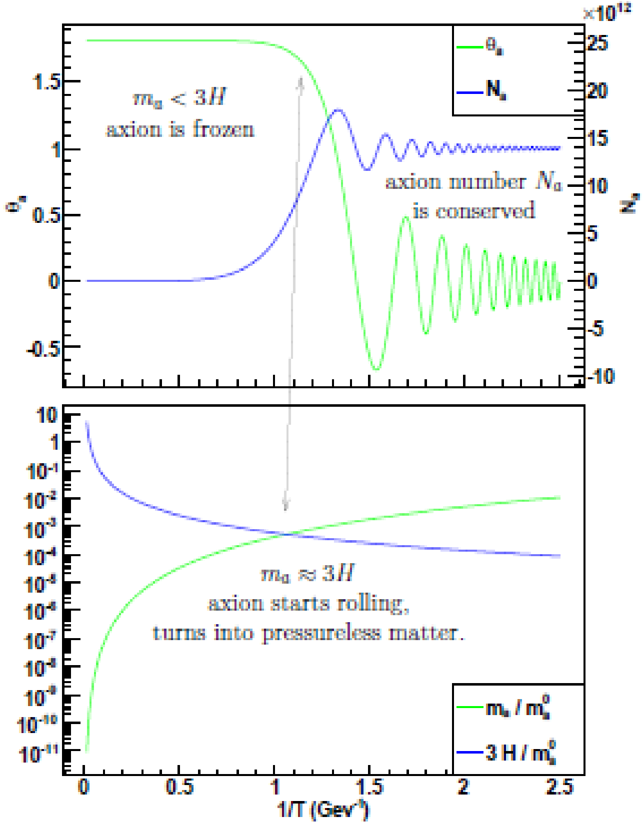
B – Magnetic field

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 $\theta_a = 0$

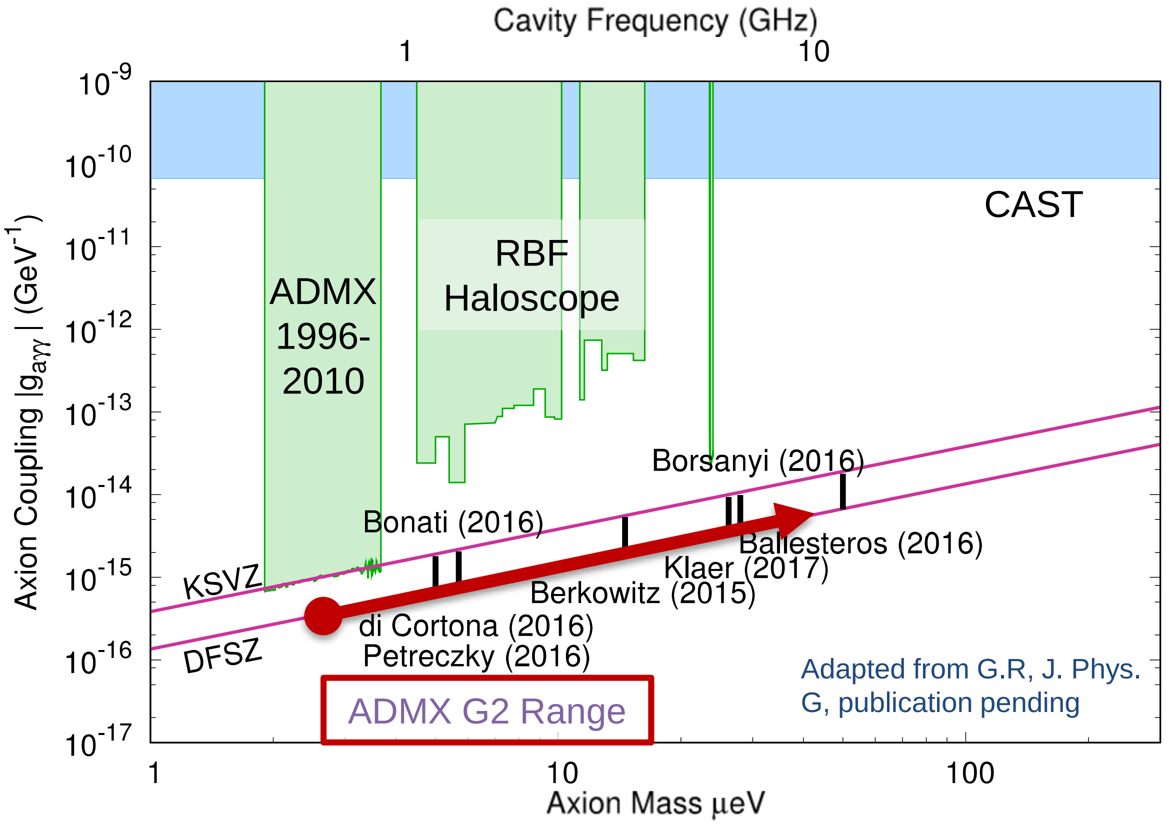


Axion cosmology revisited, Olivier Wantz and E. P. S. Shellard, Phys. Rev. D 82, 123508

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

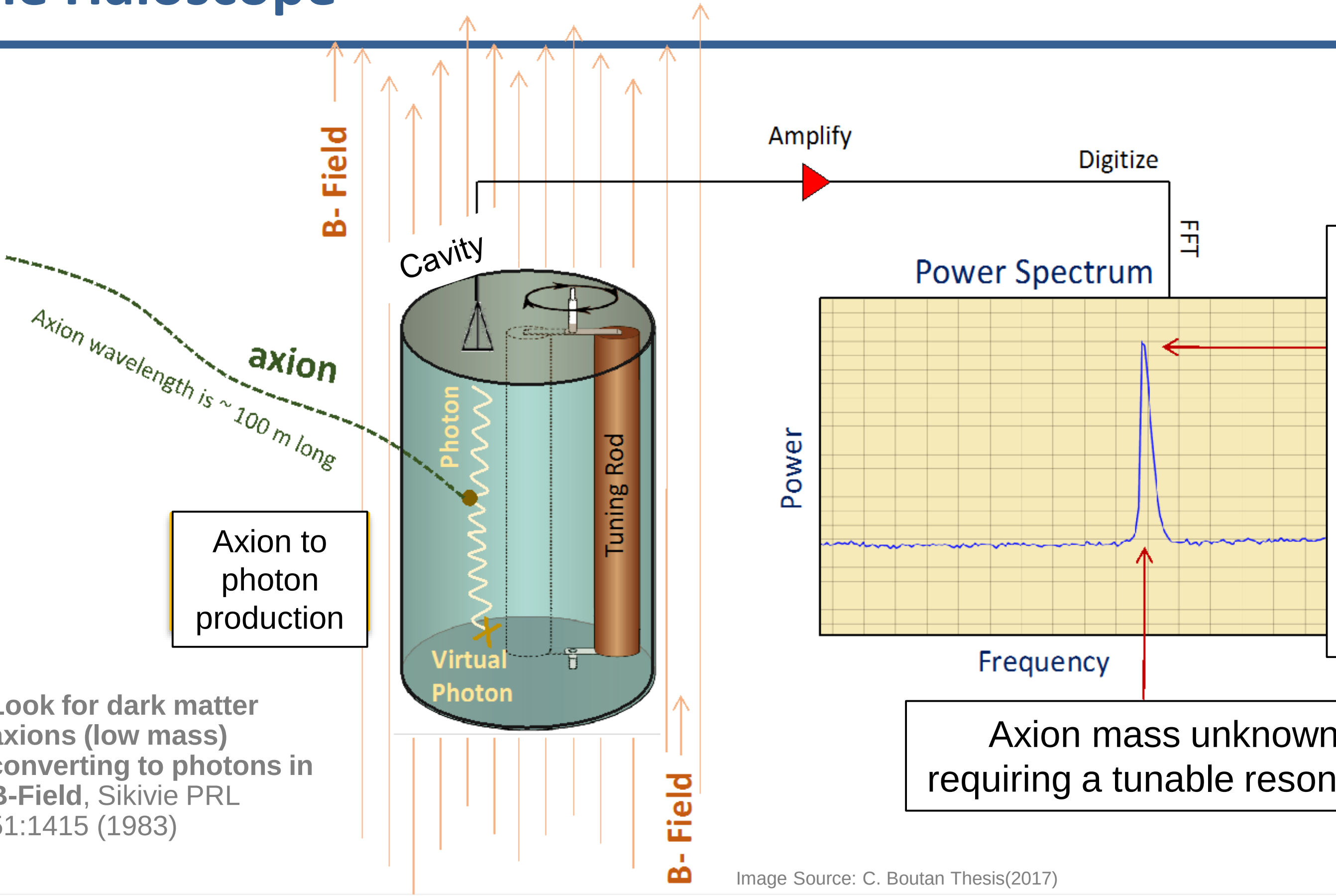
Parameter Landscape



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: $m_a \propto g_{aii} \propto 1/f_a$ $10^{-6} eV < m_a < 10^{-2} eV$

The Haloscope



Axion to photon production

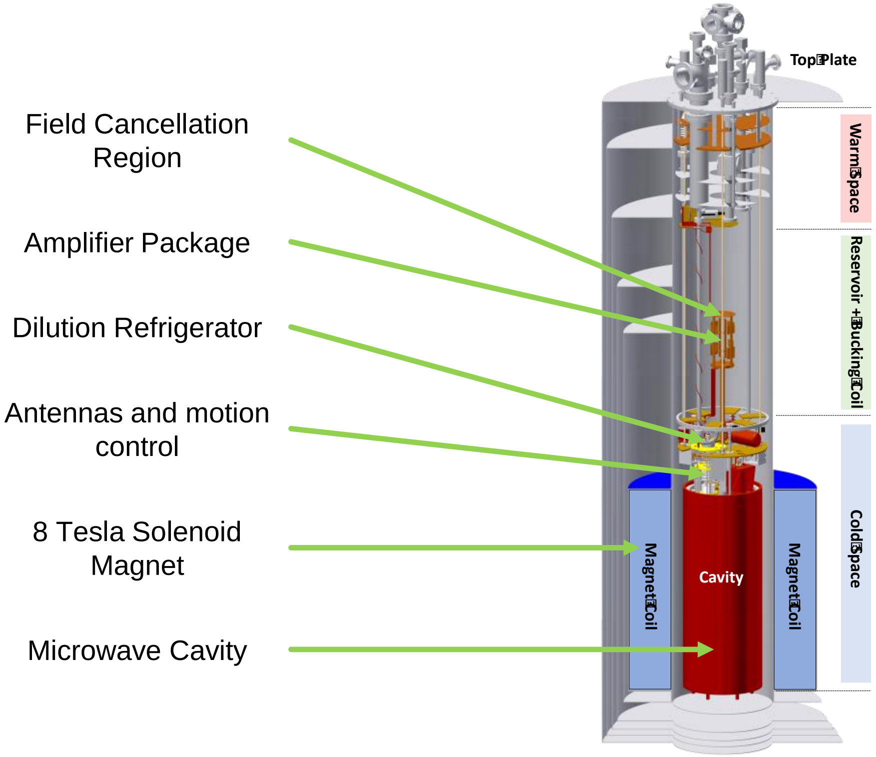
Exaggerated axion lineshape. Expected signal would be close to or within the noise

Axion mass unknown requiring a tunable resonator

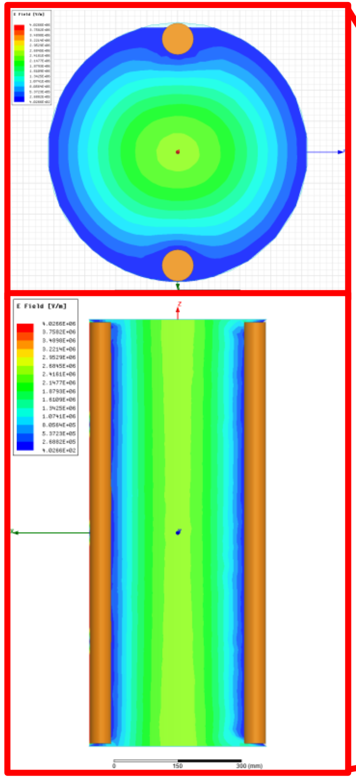
Look for dark matter axions (low mass) converting to photons in B-Field, Sikivie PRL 51:1415 (1983)

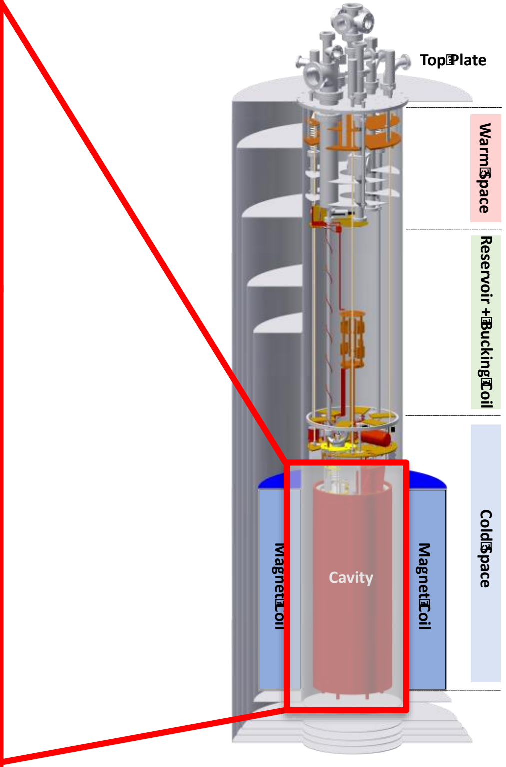
Image Source: C. Boutan Thesis(2017)

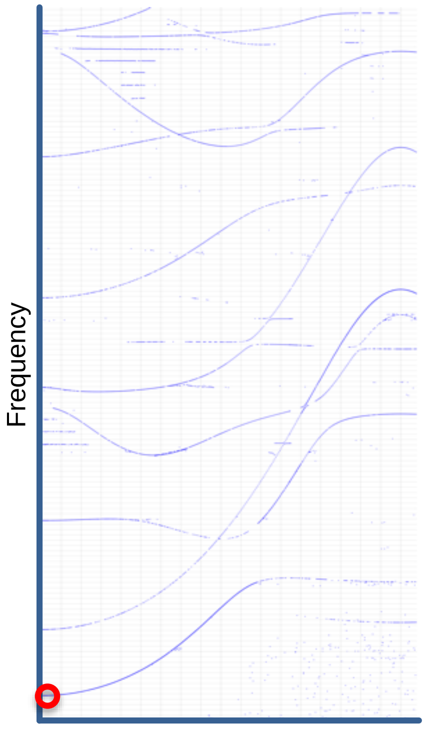
The ADMX


Field Cancellation Region
Amplifier Package
Dilution Refrigerator
Antennas and motion control
8 Tesla Solenoid Magnet
Microwave Cavity
Top Plate
Warm Space
Reservoir + Bucking Coil
Cold Space
Magnet Coil
Cavity
Magnet Coil

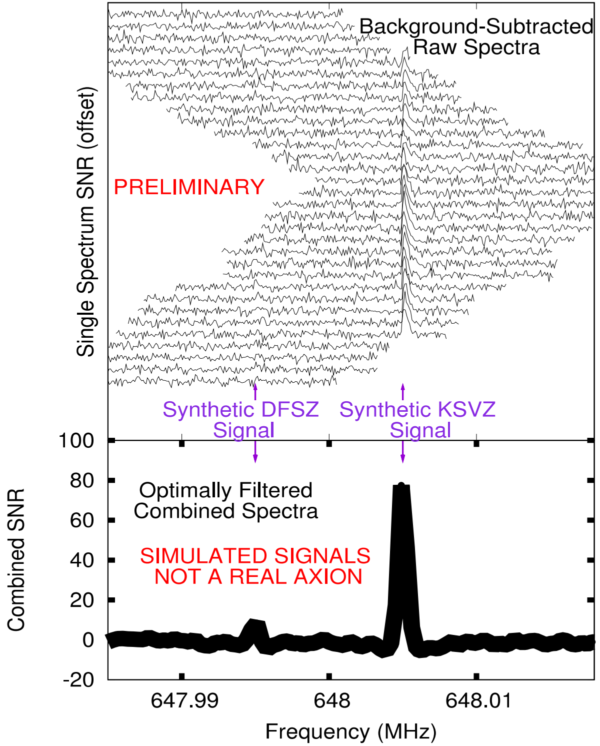
Scanning Masses







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.

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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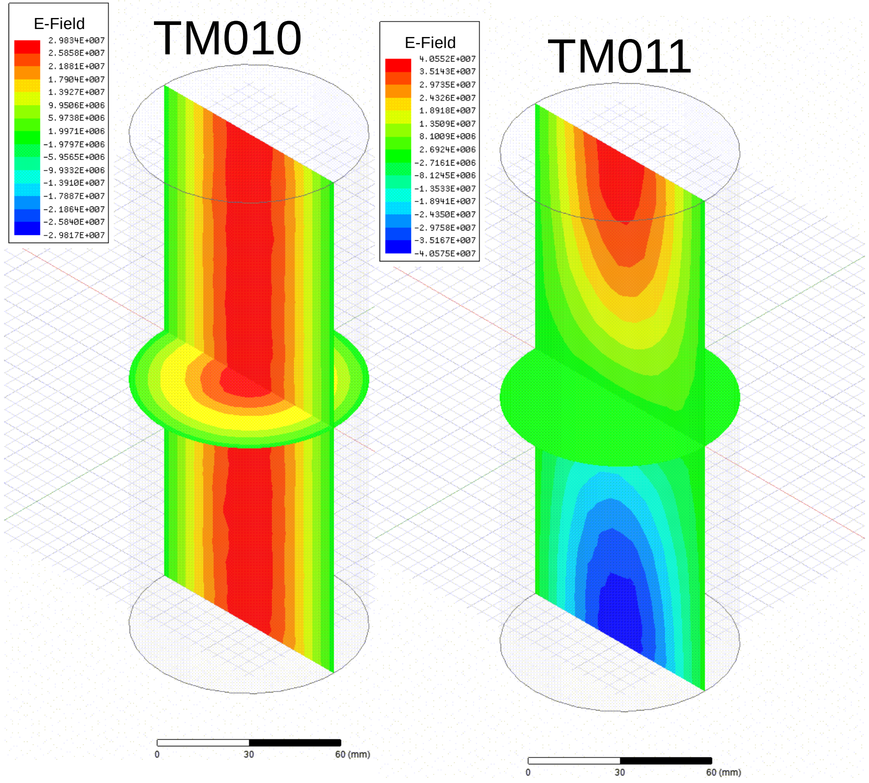
Cavity Form Factor

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

- 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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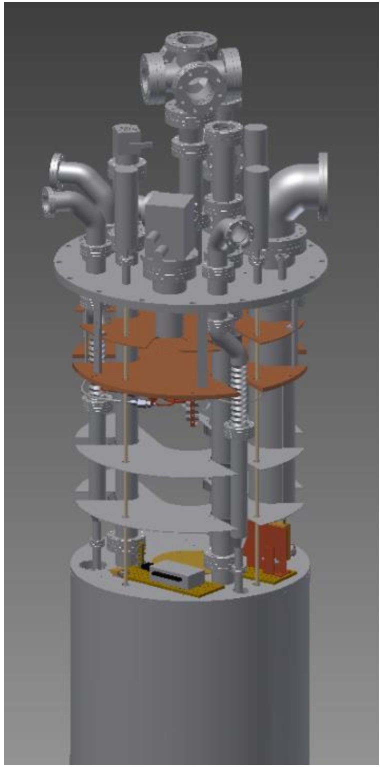
- Currently limited to the range of minutes.

Cryogenics

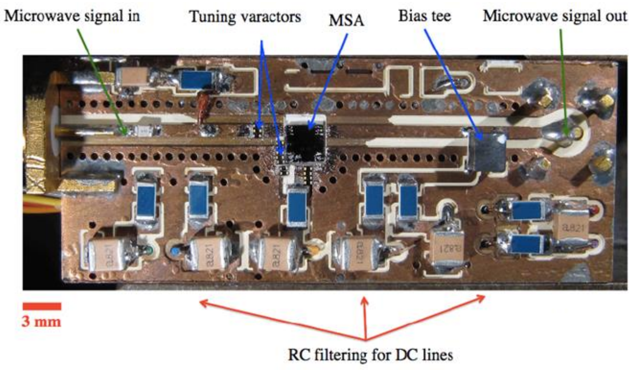
- Cryocooler
  - Actively cools baffle to 40K
  - First heatsinking stage
- Two 1K pots
  - Large 1K pot for the shielding, gearbox and electricals.
  - Small 1K pot for Dil Fridge
- Dil fridge was custom built by Janis Research Company
- 800 µW of cooling at 100 mK
- Cools the resonator and amplifiers.



Quantum RF electronics.

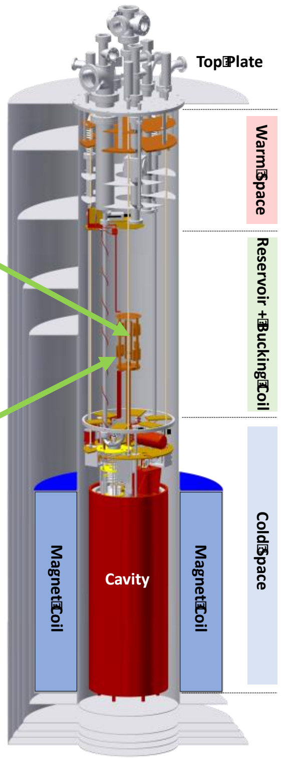
ADMX Tunable MSA

Sean O'Kelley, Clarke Group, UC Berkeley



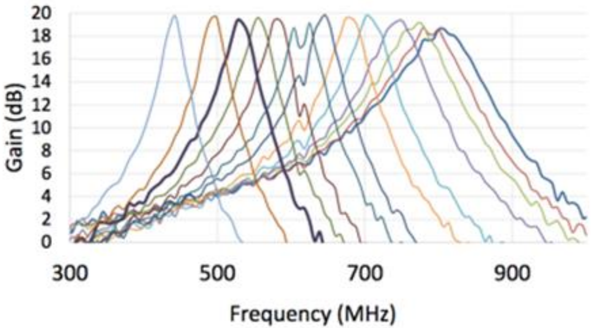
ADMX JPA

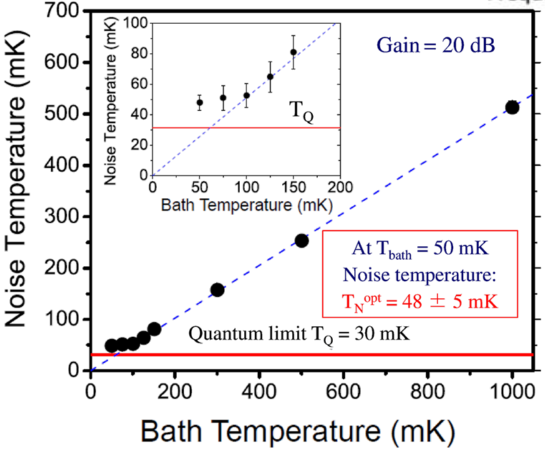
Yanjie Qiu, Siddiqi Group, UC Berkeley



Quantum RF electronics.

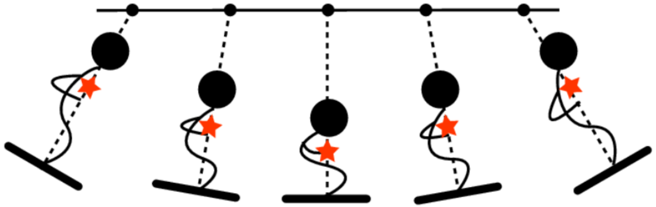
- The scan rate of ADMX is inversely proportional to the system noise squared. To achieve this, quantum limited amplifiers are used.
- Microstrip squid amplifiers(MSAs) are used for low frequency(0.5-2GHz) searches.
- The MSA works by having DC squid amplifiers attached to a microstrip resonator.
- Produced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



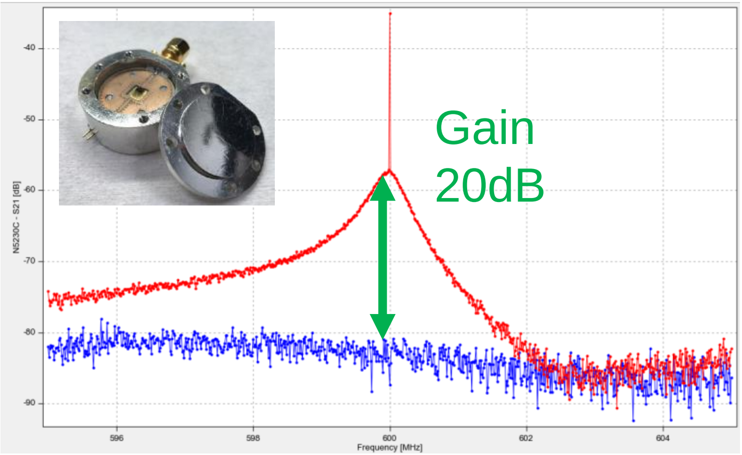


Quantum RF electronics.

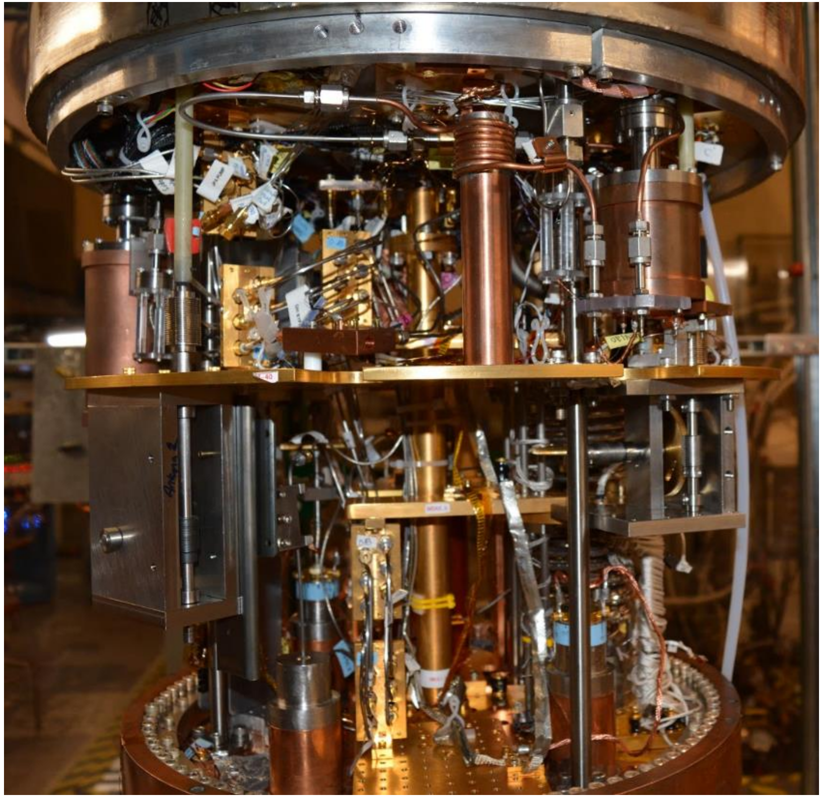
- For frequencies above 1GHz Josephson parametric amplifiers are more suitable.
- A pump tone is used to excite squid loops which in turn amplify the incoming signal.
- Produced by the Siddiqi Group at UC Berkeley
- Testing of the quantum electronics took place at Livermore before being shipped to the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



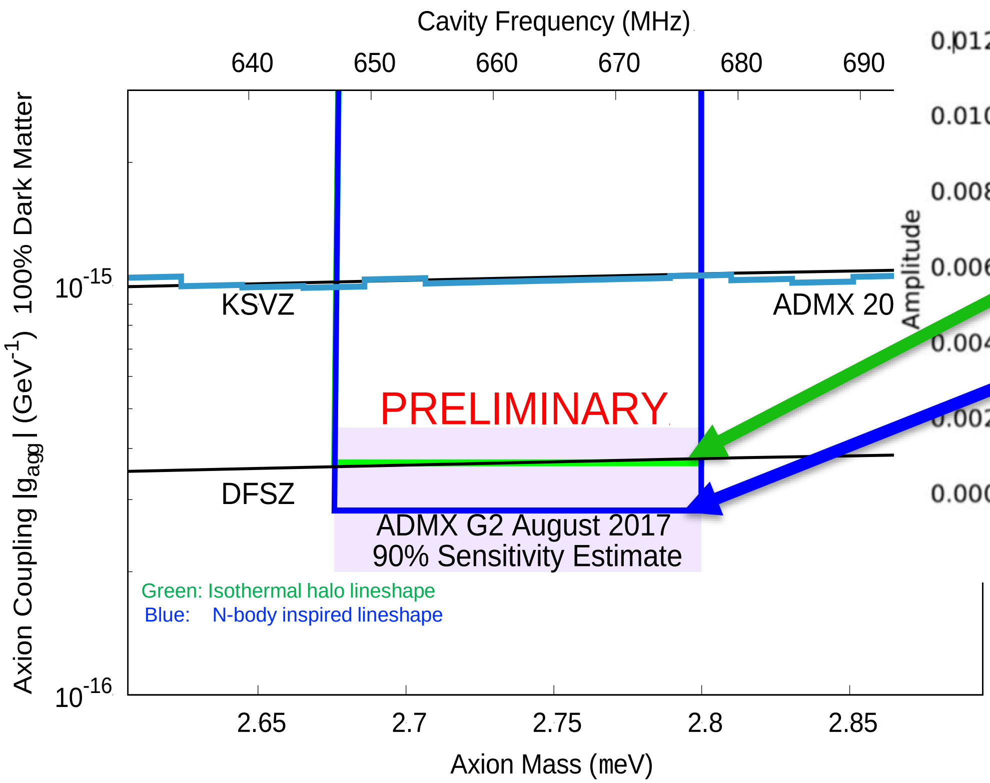
Classic example of parametric amplification is a child on a swing

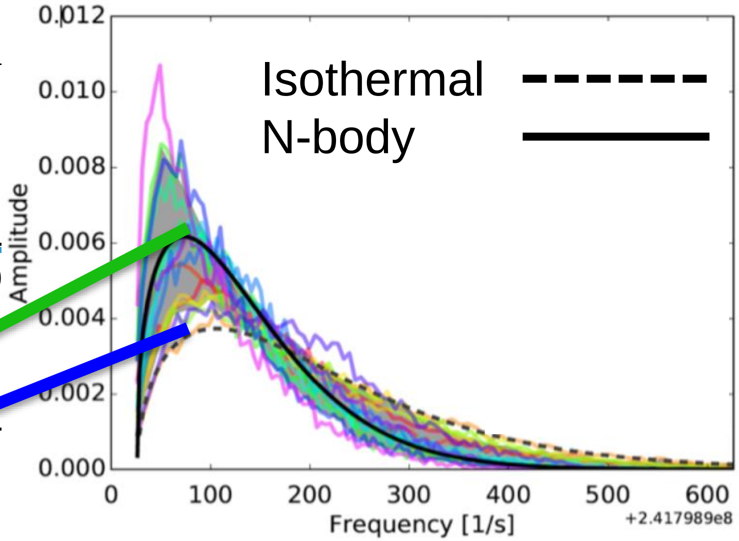


Complexity



First Results of Gen 2





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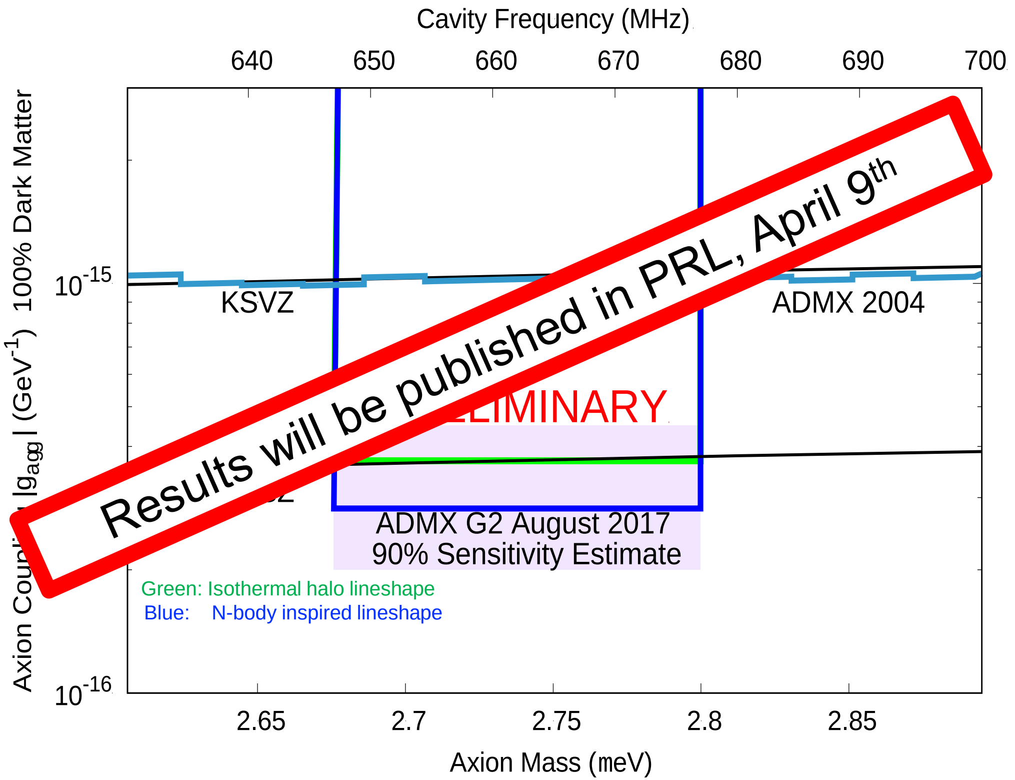
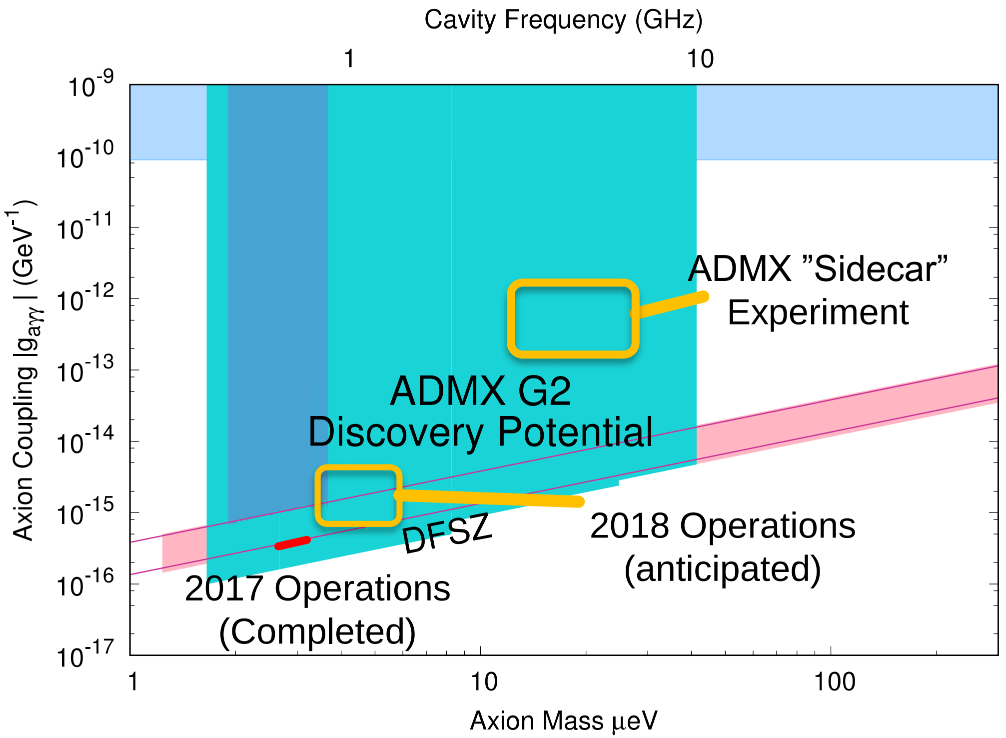


Going forward

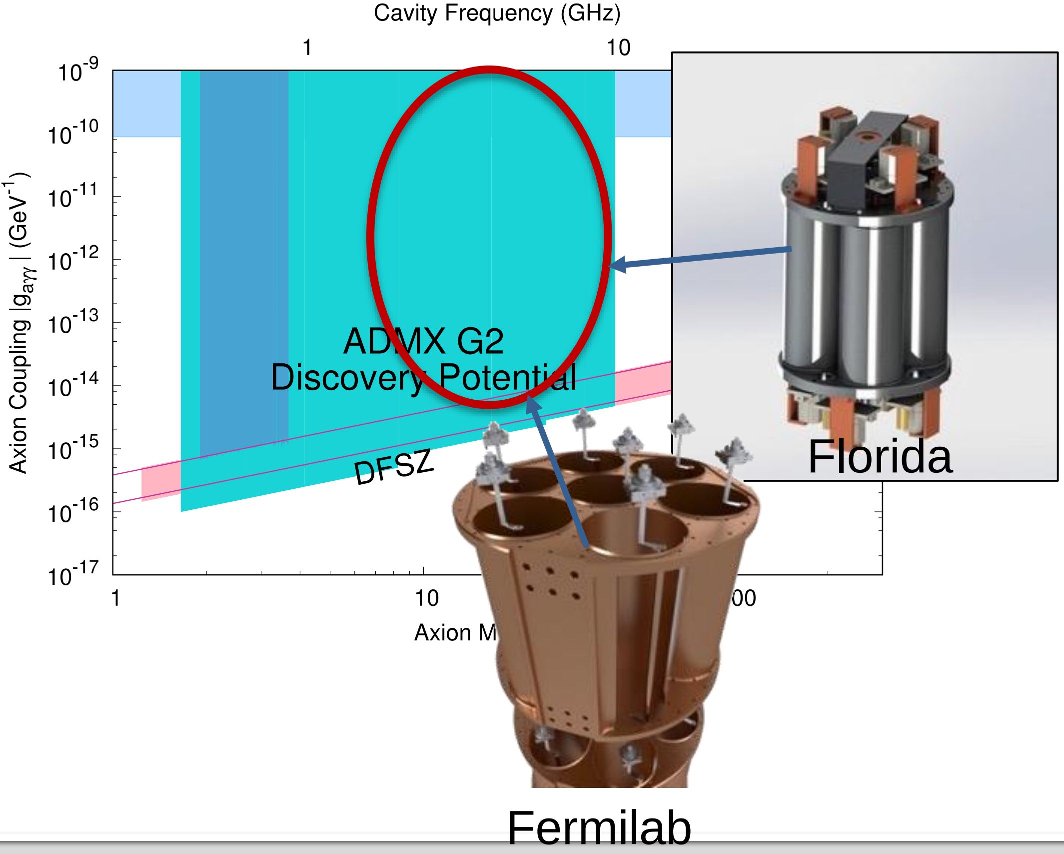
- Currently ADMX is scanning 700-890 MHz
- We anticipate faster frequency coverage in the future due to:
  - Higher magnetic field
  - More stable quantum electronics
  - Lower temperatures
  - Reduced engineering overheads.
- Speed up of ~6x



Going Forward

- Each cavity design has a finite frequency range.
- Beyond 1.5GHz the operational volume of a single cavity is prohibitive.

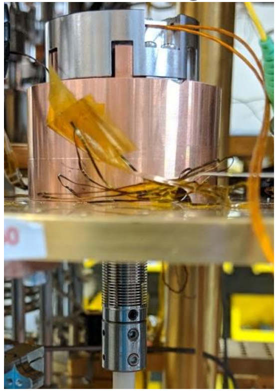
- New technical challenge: Tuning multiple cavities to the same frequency.



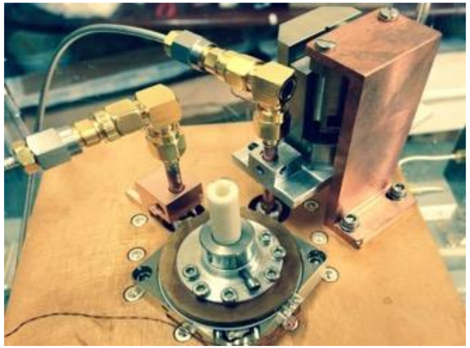
ADMX Sidecar

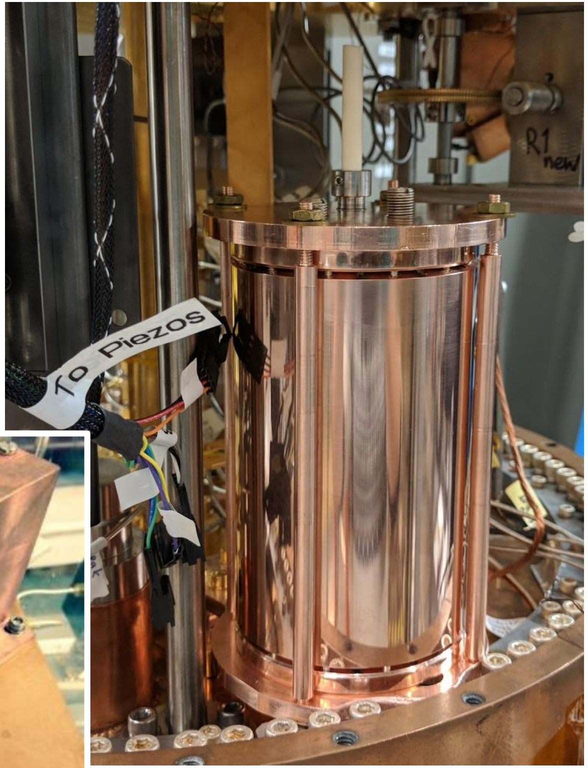
- Sidecar is a small cavity that lives above the main ADMX cavity.
- Operating range of 4-6GHz in the fundamental mode.
- Currently testing piezo actuators for motion control.
- Currently insensitive to QCD axions but still searching for ALPs.

Jensen Precision Engineering



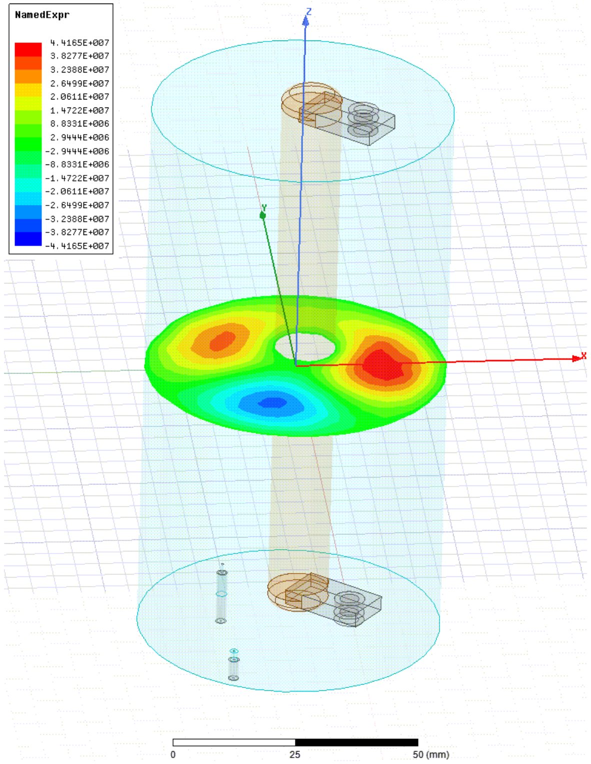
Attocube



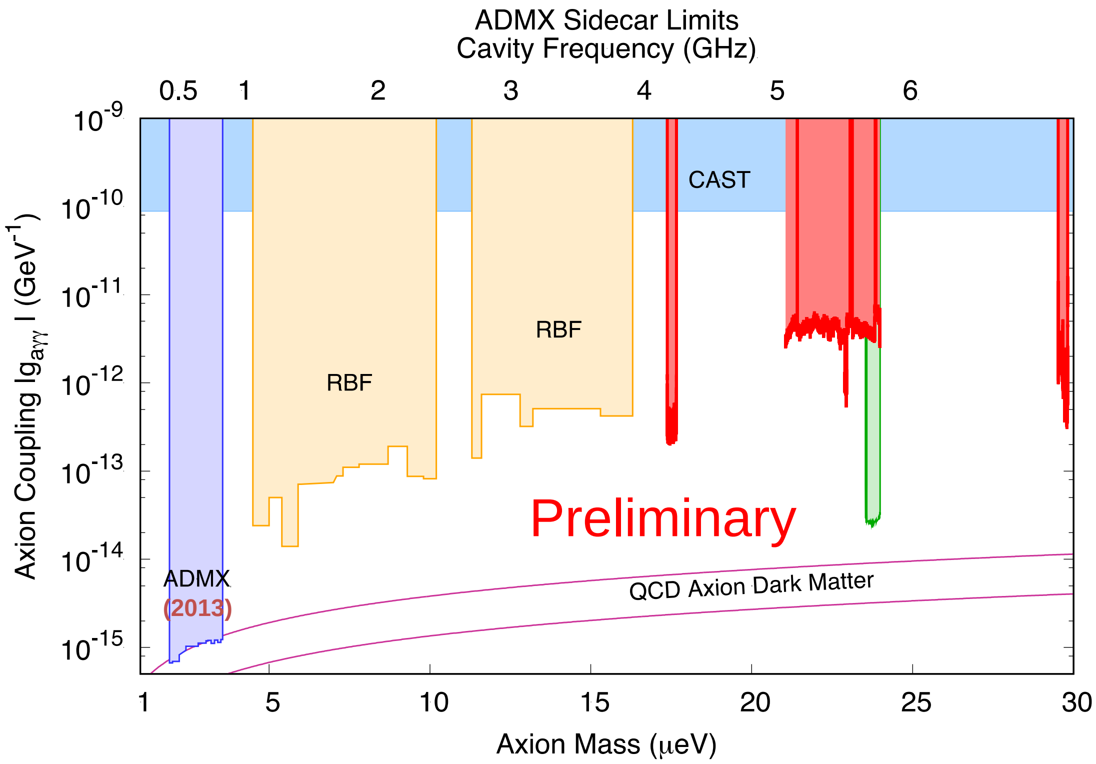


Higher Order Modes

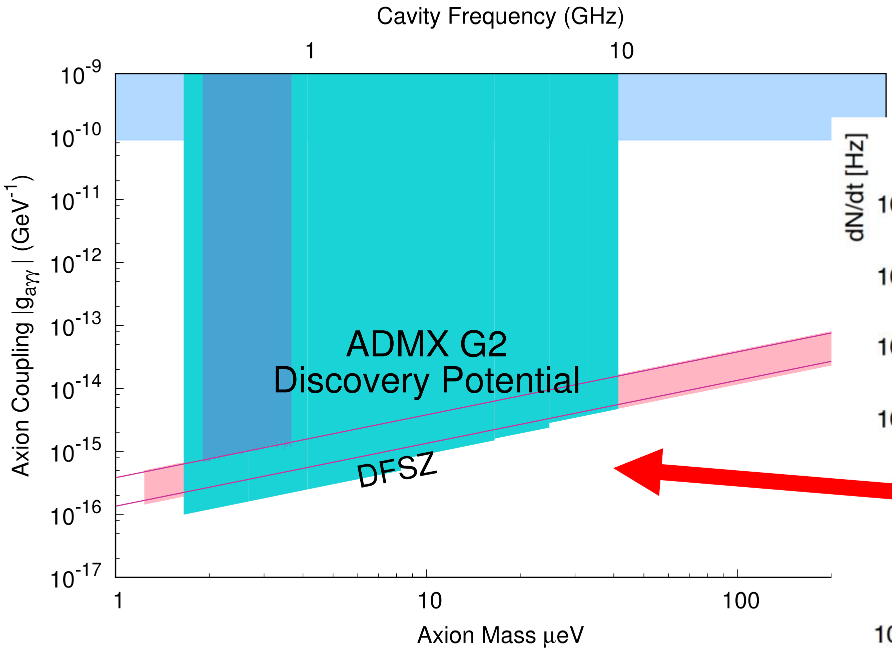
- Modes other than the TM010 have none zero form factors.
- The TM020 has a form factor of ~0.1.
- Testing operation using the Sidecar cavity.
- Extends the scannable range to 6.4-7.2GHz

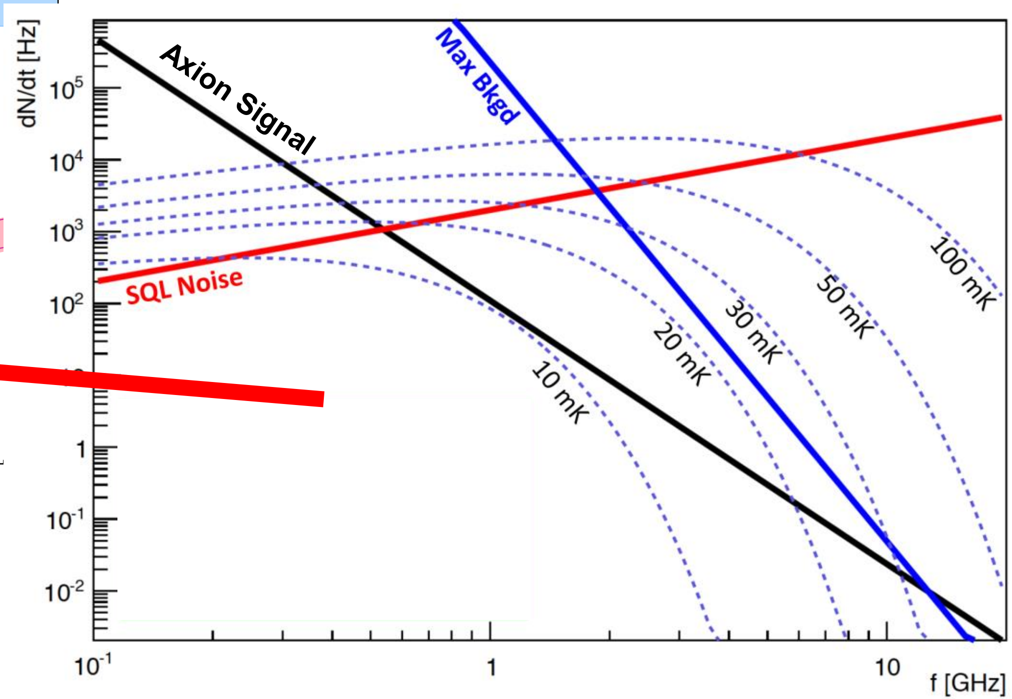


ADMX Sidecar Exclusion



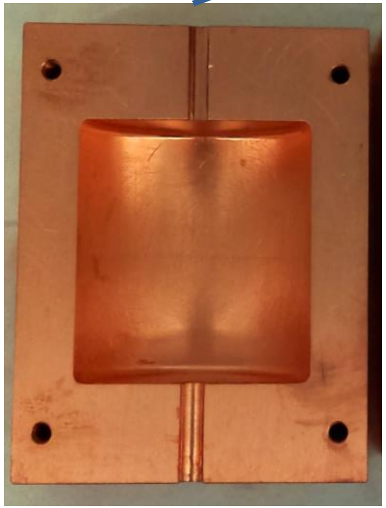
High Frequency Operations

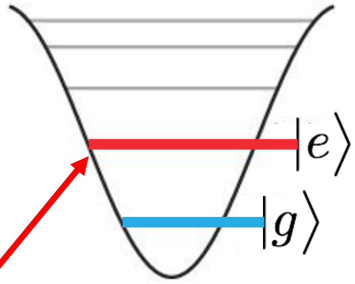




Cavity Readout Using Qubits

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



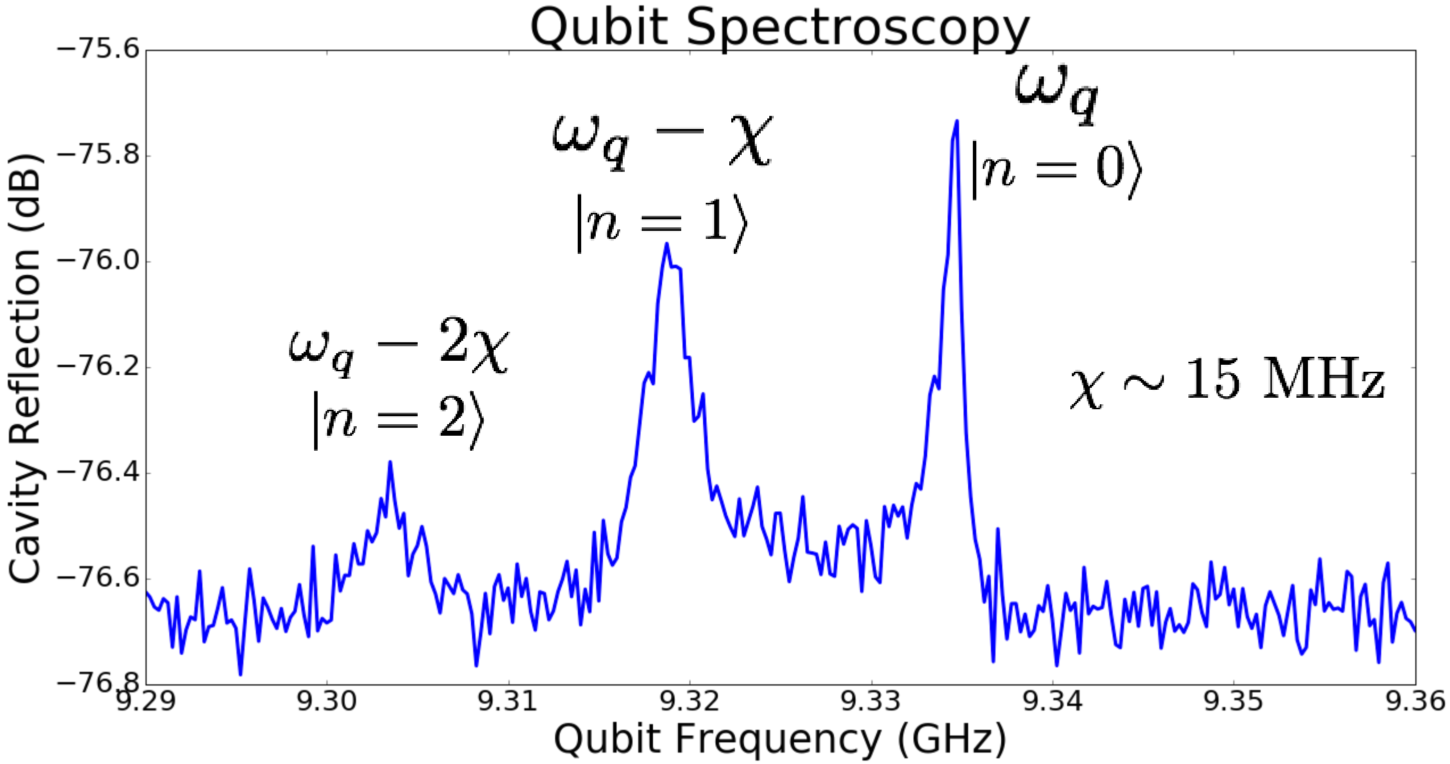


Cavity occupation shifts qubit transition

$$\omega_q = E_1 - E_0$$

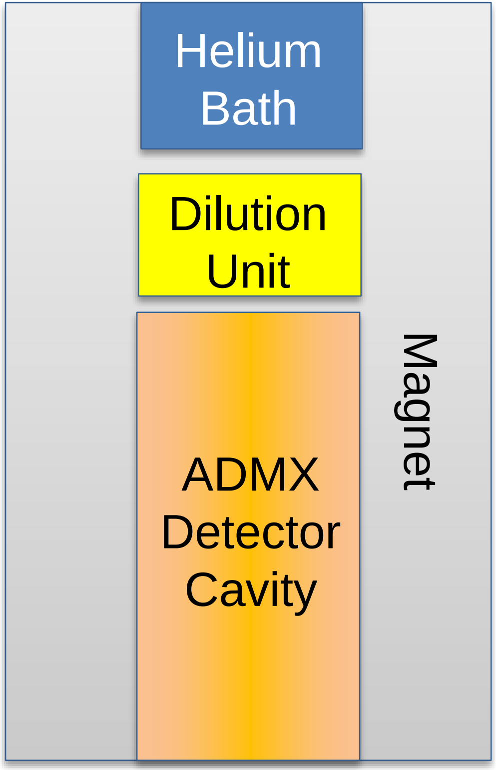
Work Performed in the Schuster Group at the University of Chicago.

Cavity Readout Using Qubits

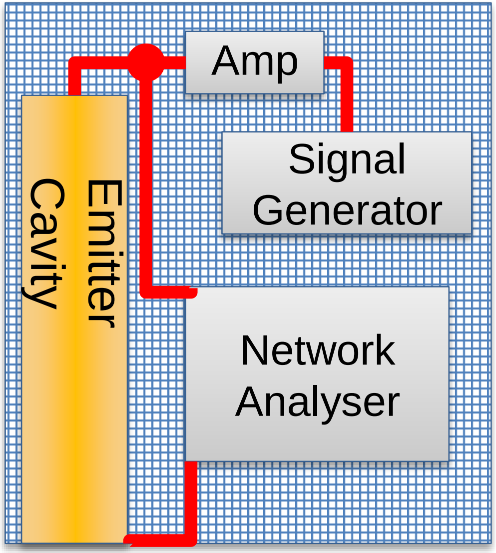


Diverse Dark Matter

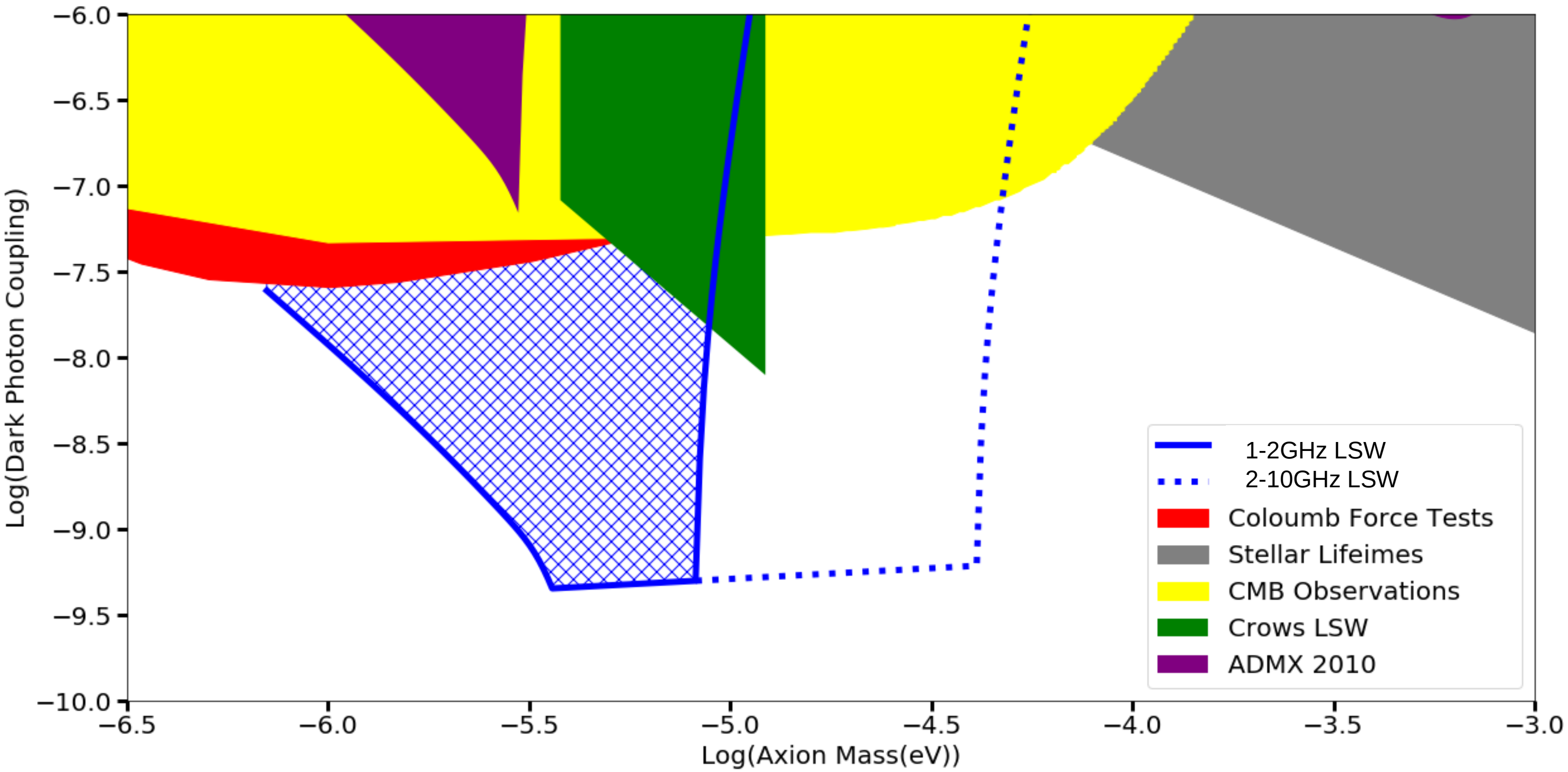
- Up until now we have assumed axions make up 100% of dark matter.
- Dark matter could be an entire ‘hidden sector’ reducing the available signal power.
- Light Shining through a Wall experiments overcome dark matter distribution by producing the species.
- Suffers a penalty of the coupling factor squared.



The Lamp-Ray Experiment



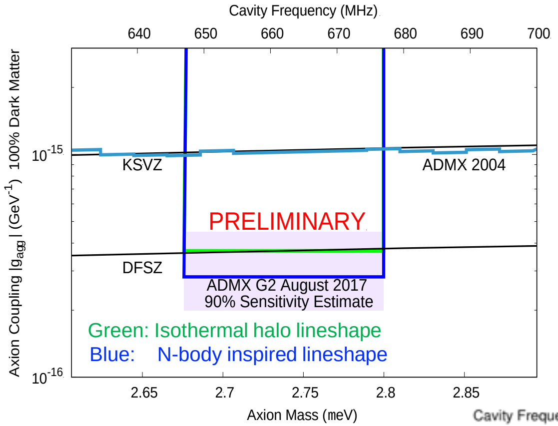
Diverse Dark Matter

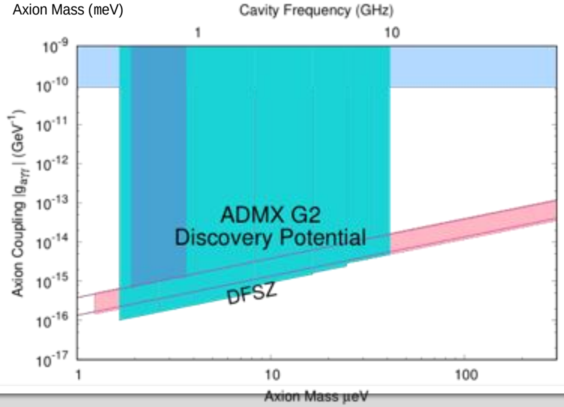


Conclusion

- Axions are well motivated additions to the standard model.
- ADMX Gen 2 has searched with sensitivity to the DFSZ axion over 2.7-2.8 ueV
- ADMX is the first and only experiment with DFSZ sensitivity in the ideal dark matter axion mass range
- Over the next 2 years ADMX will search for dark matter axions up to 8.2 ueV
- R&D currently taking place to enable searches up to 40 ueV

Watch this space…





ADMX G2 at U. Washington, Scientific American, 2015

Lawrence Livermore
National Laboratory

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.

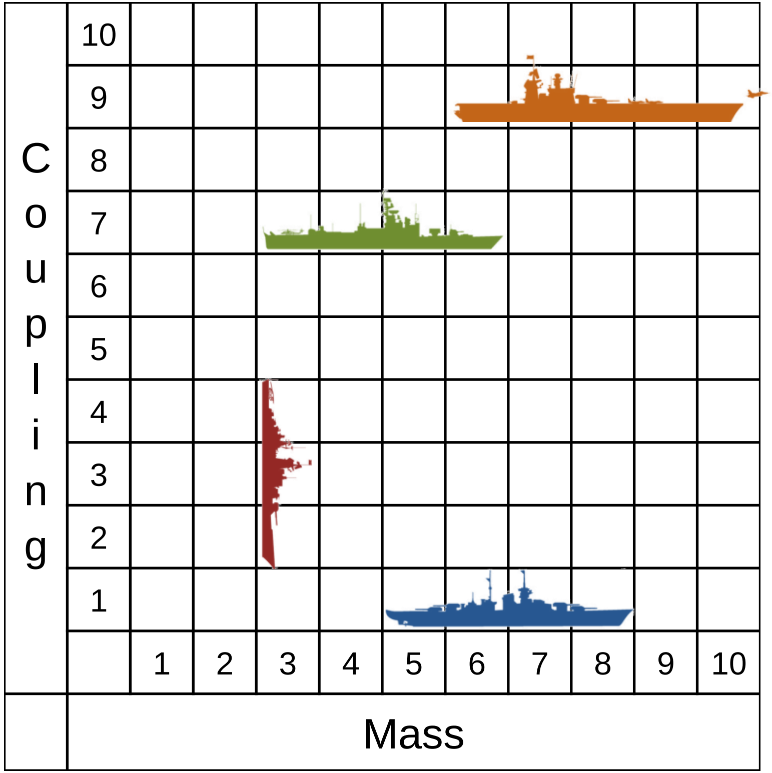
Power transfer increased by coherence between cavity E-field and axion field

Weak coupling -- takes many swings to fully transfer the wave amplitude.
Number of swings = cavity Quality factor.
Narrowband cavity response → iterative scan through frequency space.

Axion Hunting

Coupling	10										
	9										
	8										
	7										
	6										
	5										
	4										
	3										
	2										
	1										
		1	2	3	4	5	6	7	8	9	10
	Mass										

Axion Hunting



Axion Hunting