New Results from the Axion Dark Matter Experiment

Rencontres de Moriond

Nathan Woollett
On behalf of the ADMX collaboration

March 14, 2018

LLNL-PRES-747684
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

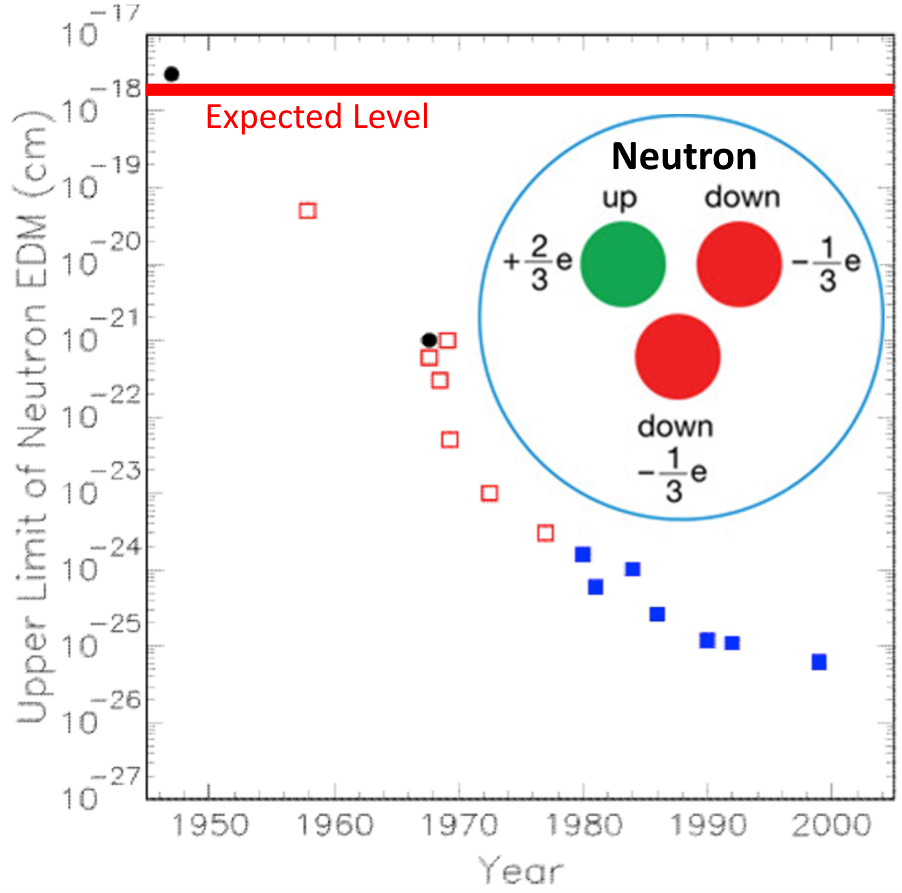
Lawrence Livermore National Laboratory

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 cm.
- Experimental upper limits of the neutron dipole moment 10^{-28}e cm.

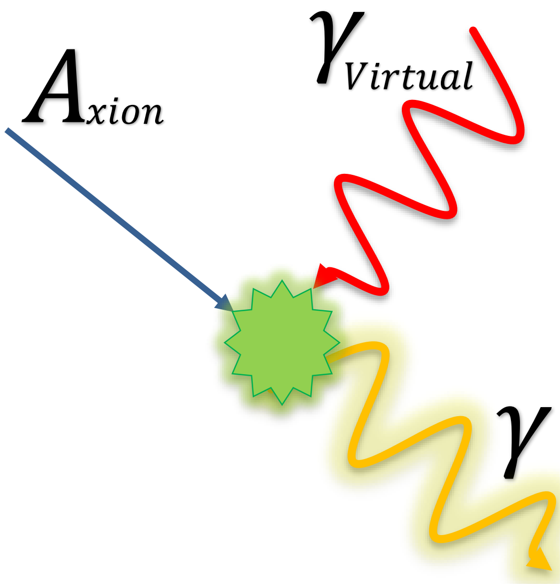


Strong CP Problem

- 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.

- The additional field has an associated pseudo-goldstone boson, the axion.

- The axion has a two boson interaction and is therefore searched via a two photon interaction.



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

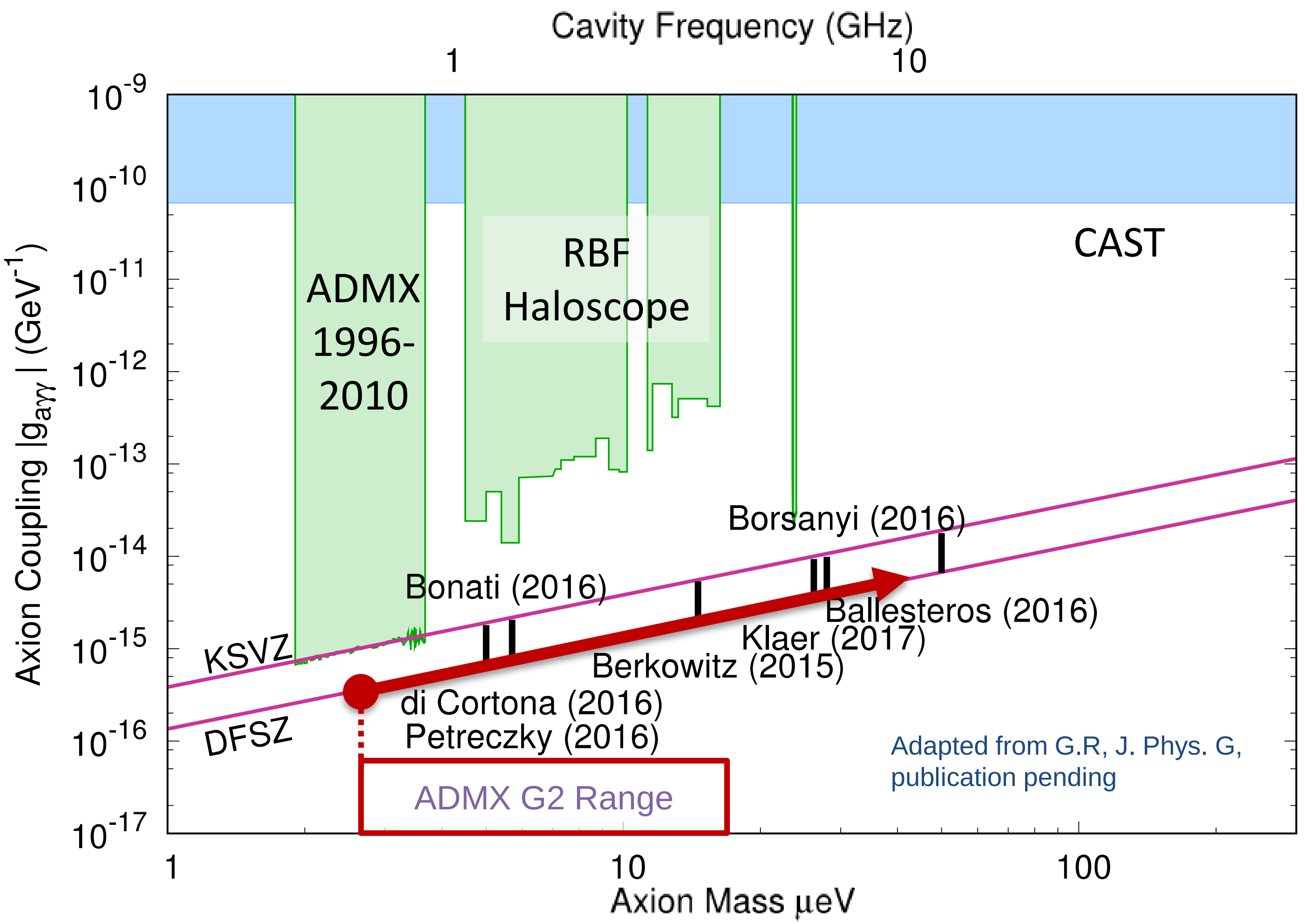
$g_{A\gamma\gamma}$ - Axion photon coupling

E – Electric field

B – Magnetic field

ϕ_A – Axion Field

Axion Parameter Space



Axion Summary

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.	• Low mass. • Weakly coupled to Standard Model. • 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: $m_a \propto g_{aii} \propto 1/f_a$ $10^{-6} eV < m_a < 10^{-2} eV$

Haloscopes

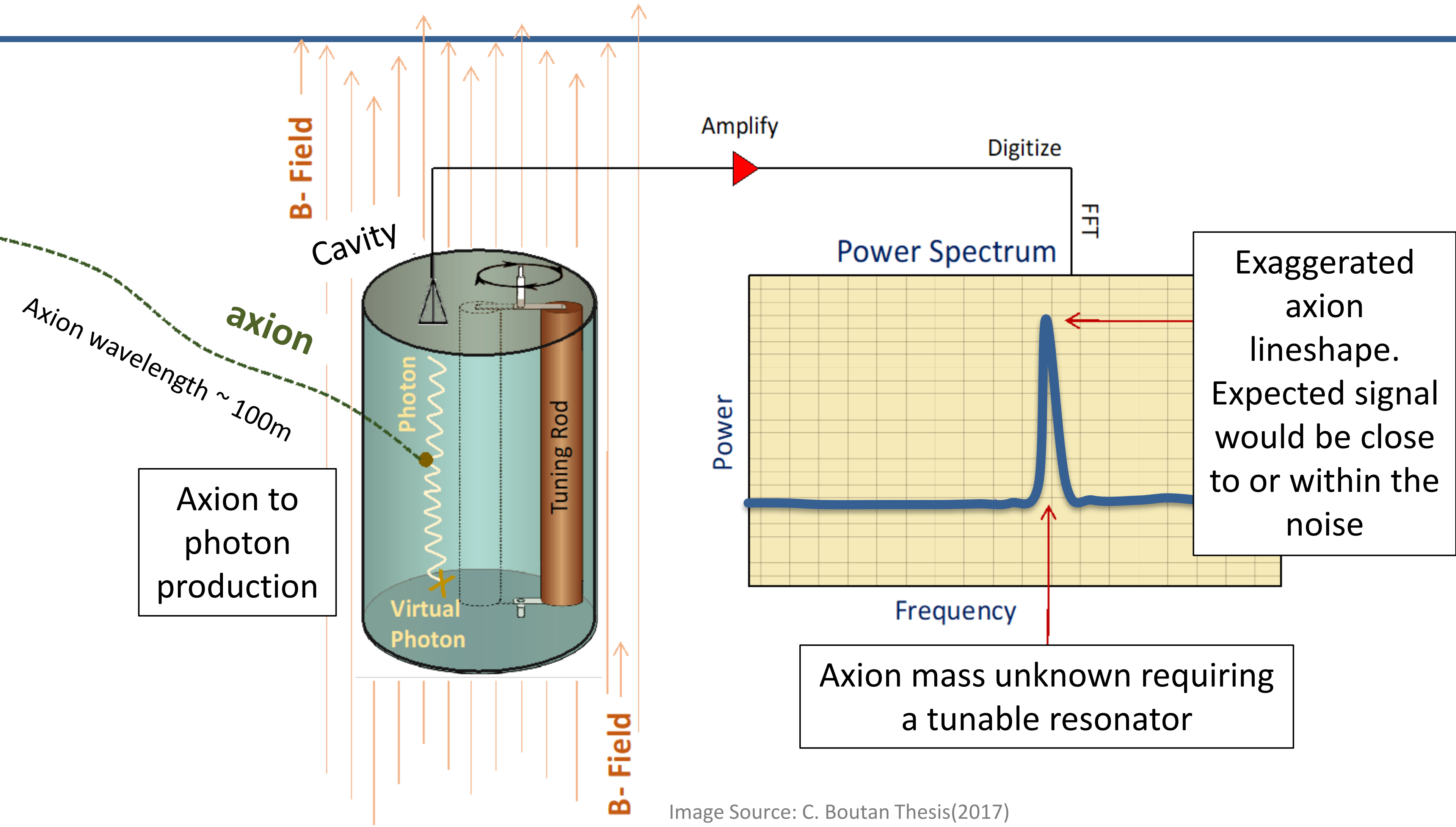
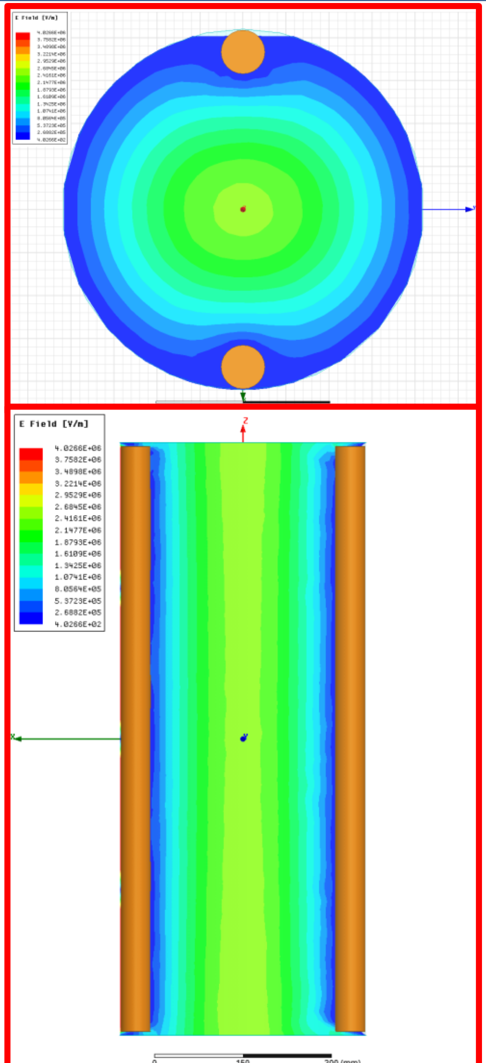
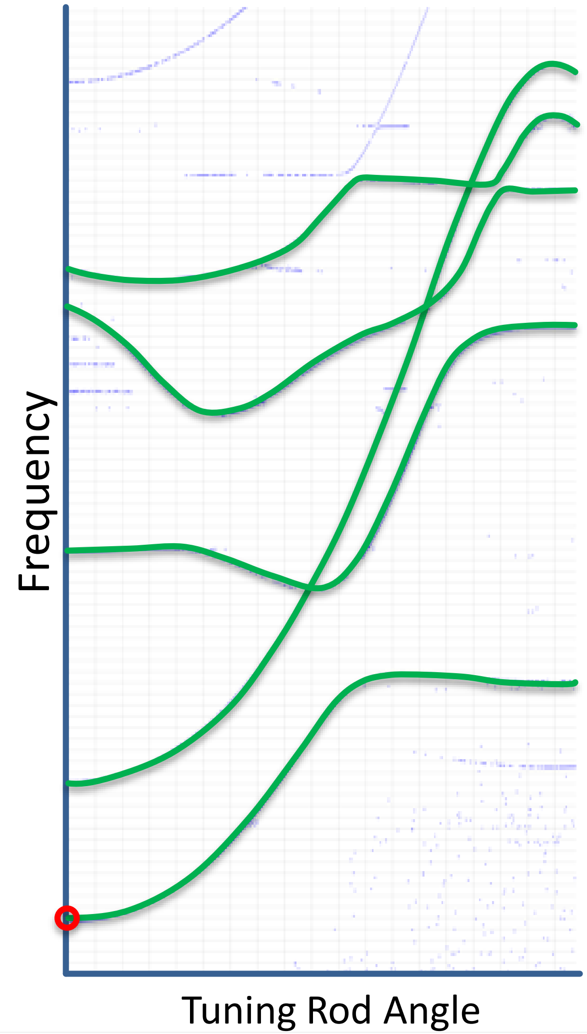


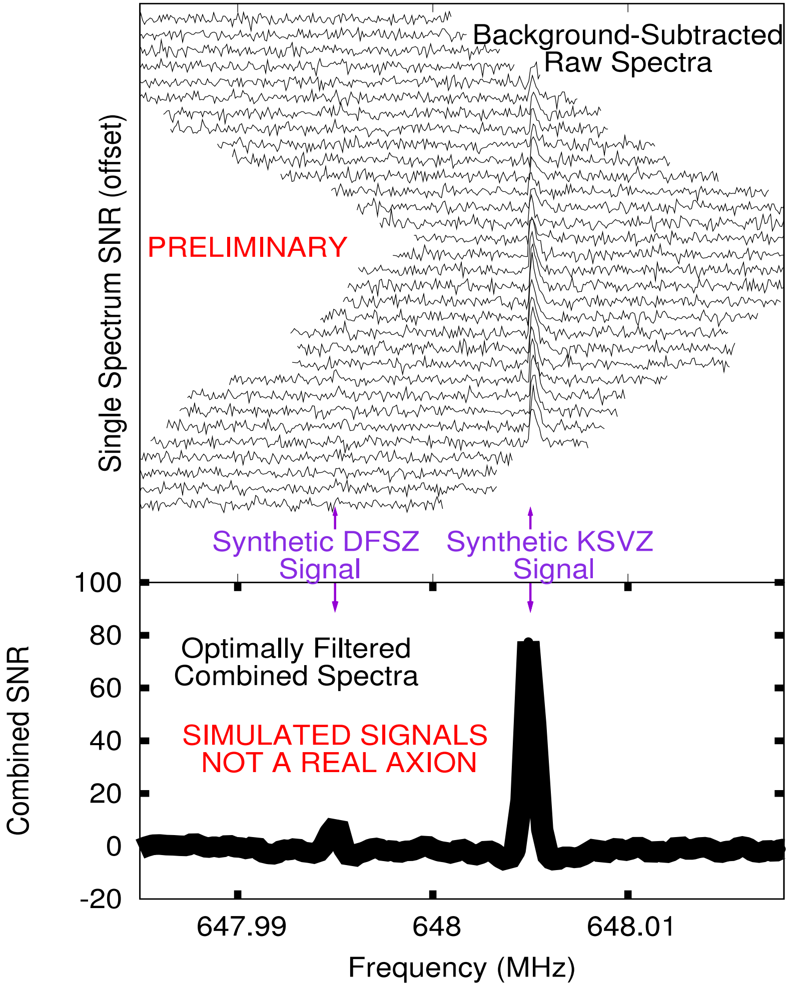
Image Source: C. Boutan Thesis(2017)

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.

Signal Strength

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

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

- Integration time depends on the experimental cadence.
- Set by step size and operational frequency.
  - Currently limited to the range of minutes.

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

$$T = T_{\text{phys}} + Tamp + \frac{T_{\text{postamp}}}{\text{Gain}amp}$$

- Axion power is proportional to:
  - Cavity characteristics
  - Magnetic field
  - resonant mode

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

Signal Strength

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

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

- Integration time depends on the experimental cadence.
- Set by step size and operational frequency.
  - Currently limited to the range of minutes.

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

$$T = T_{\text{phys}} + Tamp + \frac{T_{\text{postamp}}}{\text{Gain}amp}$$

- Axion power is proportional to:
  - Cavity characteristics
  - Magnetic field
  - resonant mode

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

Signal Strength

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

- Integration time depends on the experimental cadence.
- Set by step size and operational frequency.
  - Currently limited to the range of minutes.

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

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

$$T = T_{\text{phys}} + T amp + \frac{T_{\text{postamp}}}{\text{Gain}amp}$$

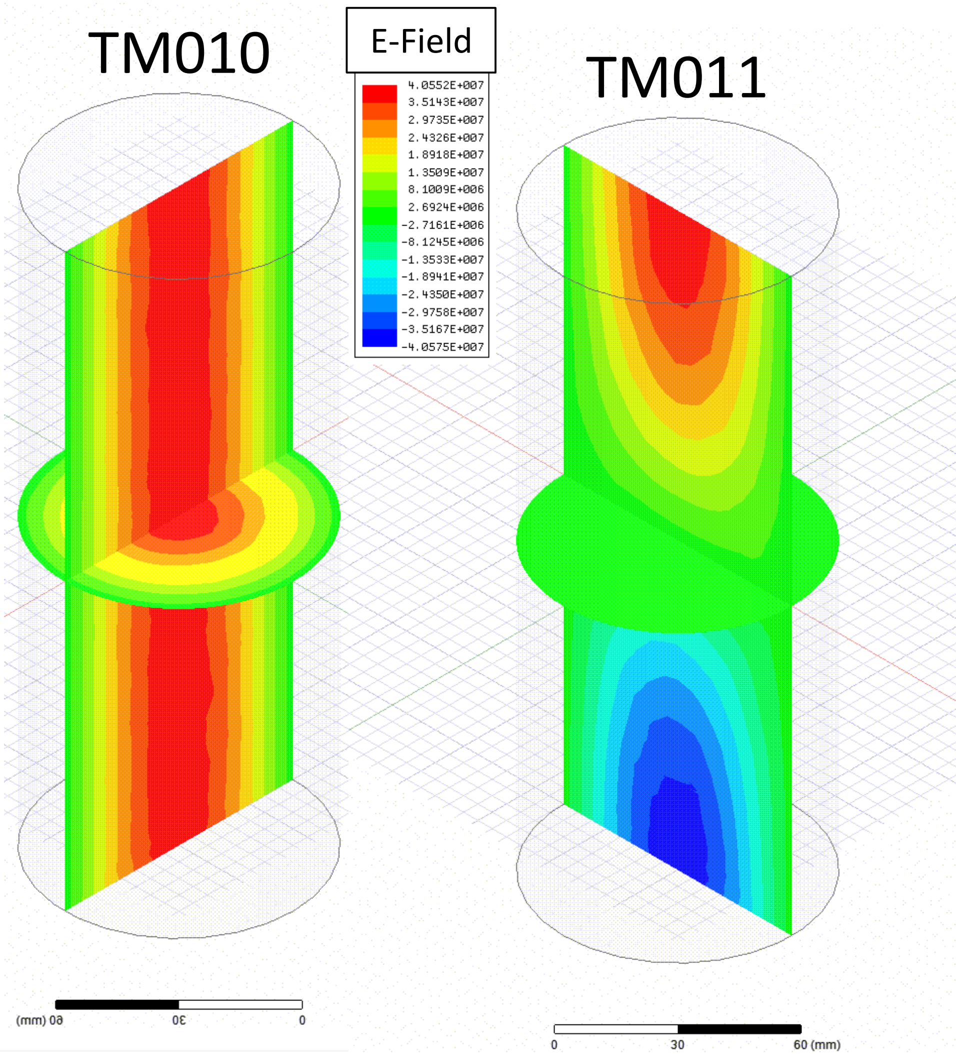
- Axion power is proportional to:
  - Cavity characteristics
  - Magnetic field
  - resonant mode

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

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



Signal Strength

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

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

- Integration time depends on the experimental cadence.
- Set by step size and operational frequency.
  - Currently limited to the range of minutes.

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

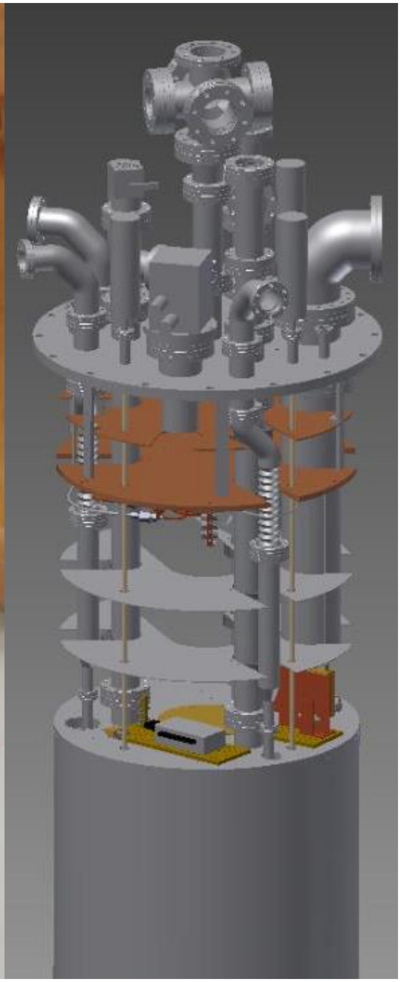
$$T = T_{\mathrm{phys}} + T_{\mathrm{amp}} + \frac{T_{\mathrm{postamp}}}{Gain_{\mathrm{amp}}}$$

- Axion power is proportional to:
  - Cavity characteristics
  - Magnetic field
  - resonant mode

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

Cryogenics

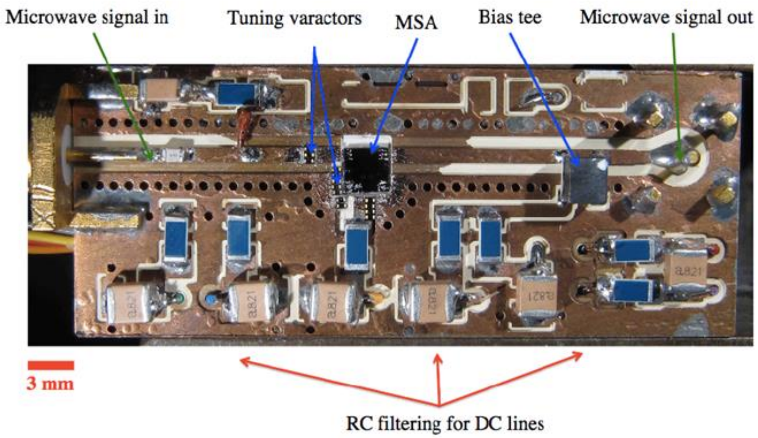
- Cryocooler
  - Actively cools upper stage to 40K.
  - First heatsinking stage.
- LHe Bath to cool secondary magnet
- Two 1K pots
  - Large 1K pot for the shielding, gearbox and electricals.
  - Small 1K pot for Dil Fridge
- Dil fridge was custom built by Janis Research Company
  - 800 µW of cooling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

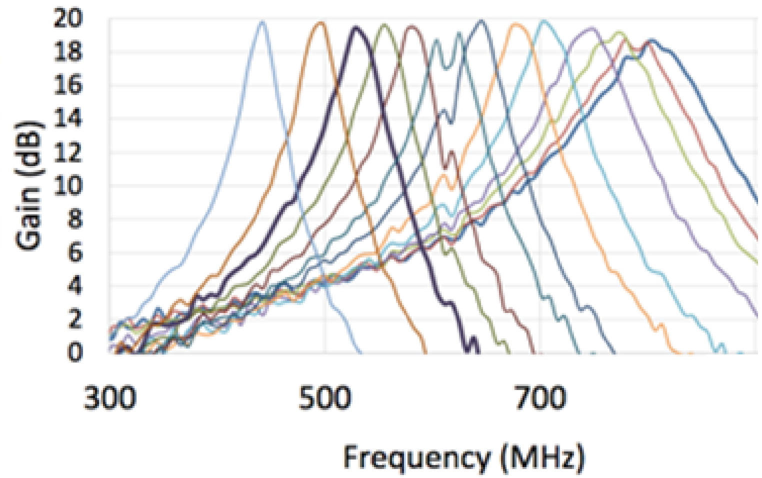


Quantum Amplifiers

ADMX Tunable MSA

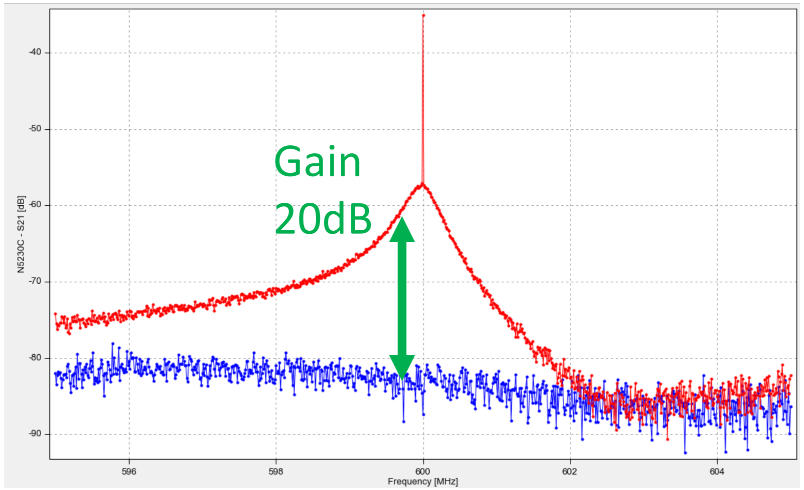
Sean O'Kelley, Clarke Group, UC Berkeley



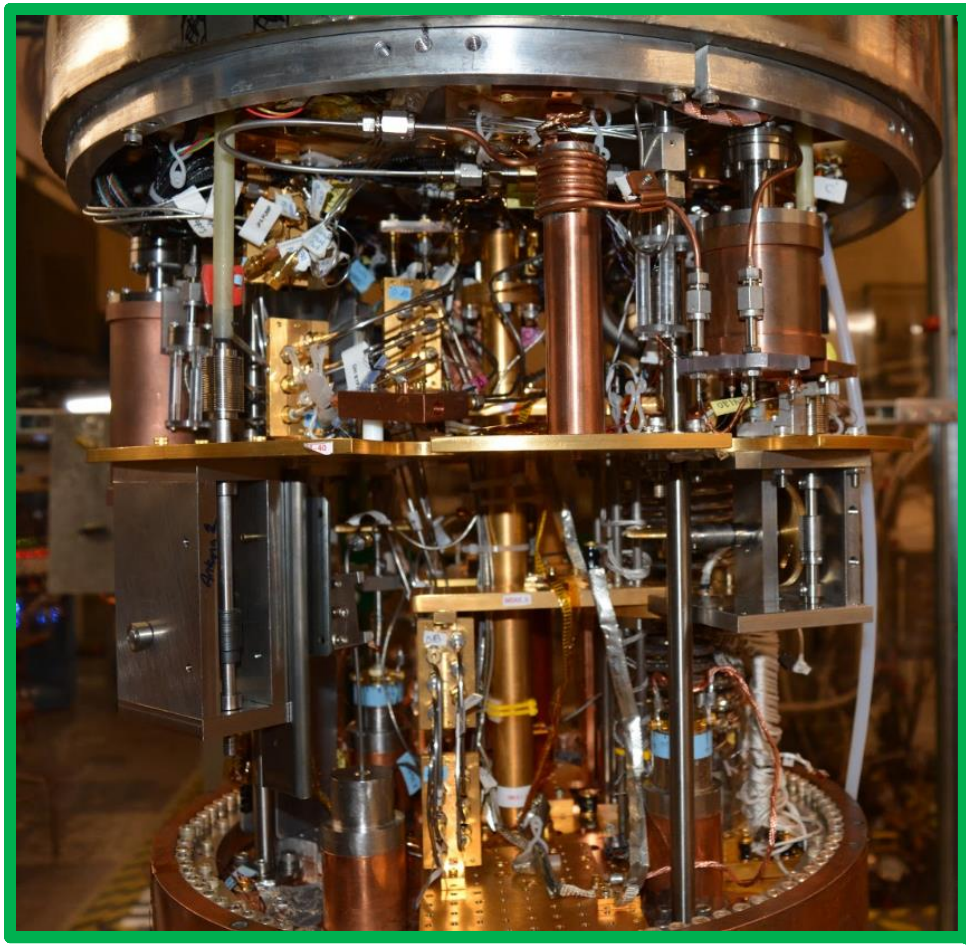


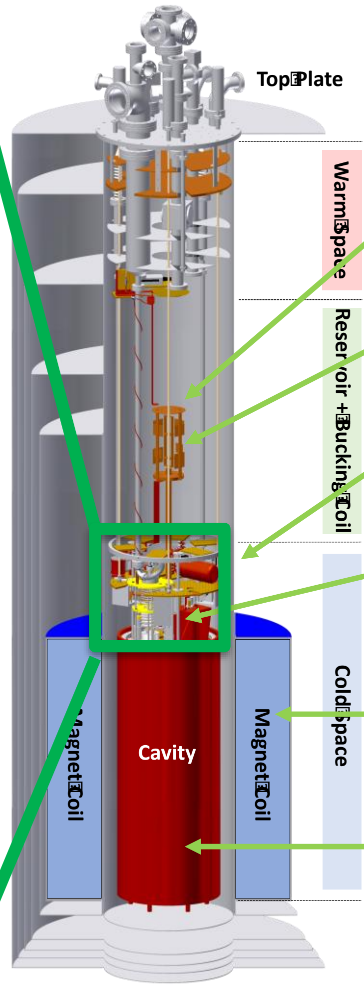
ADMX JPA

Yanjie Qiu, Siddiqi Group, UC Berkeley



Complexity





Field Cancellation Region

Amplifier Package

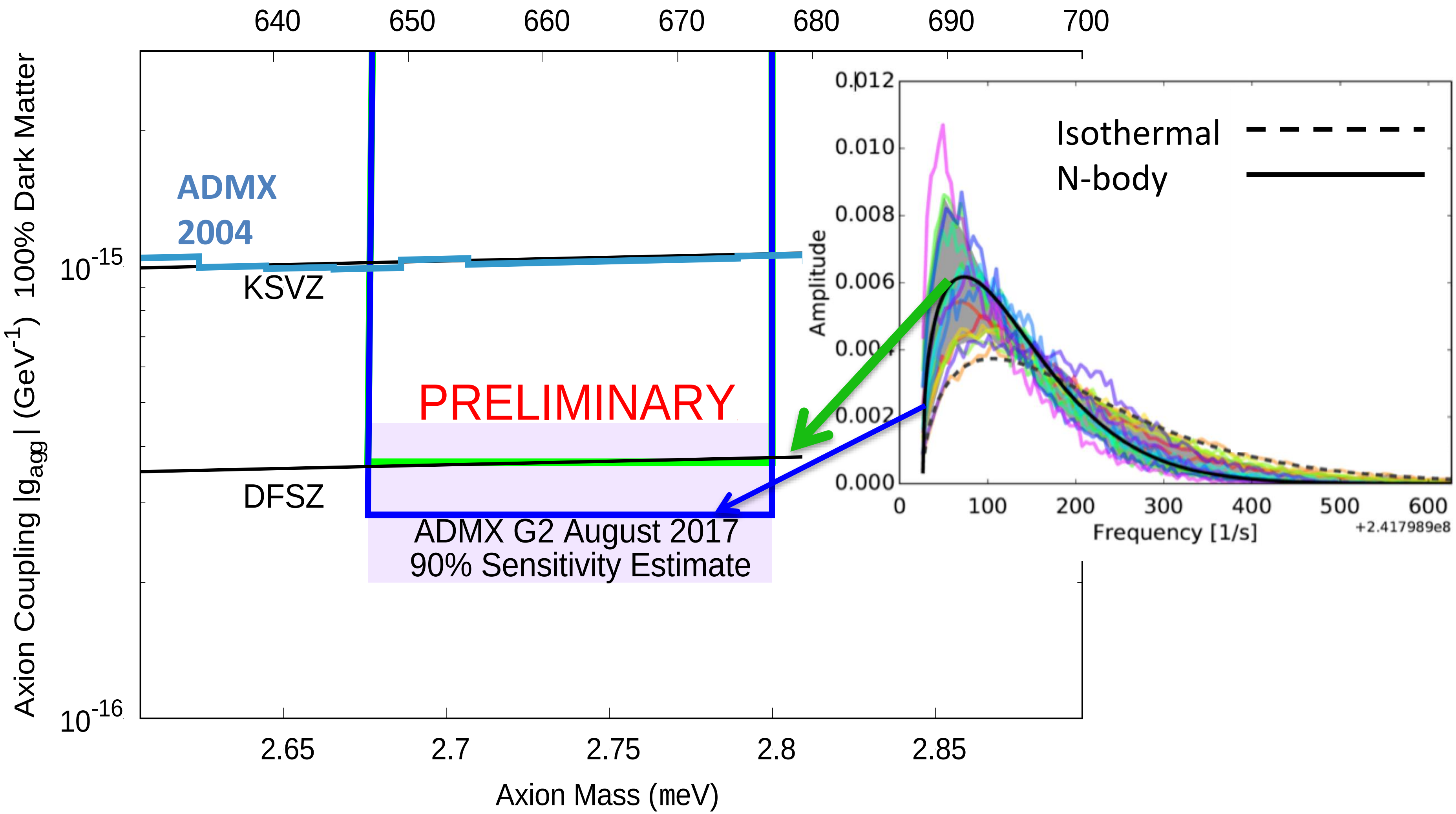
Dilution Refrigerator

Antennas and motion control

8 Tesla Solenoid Magnet

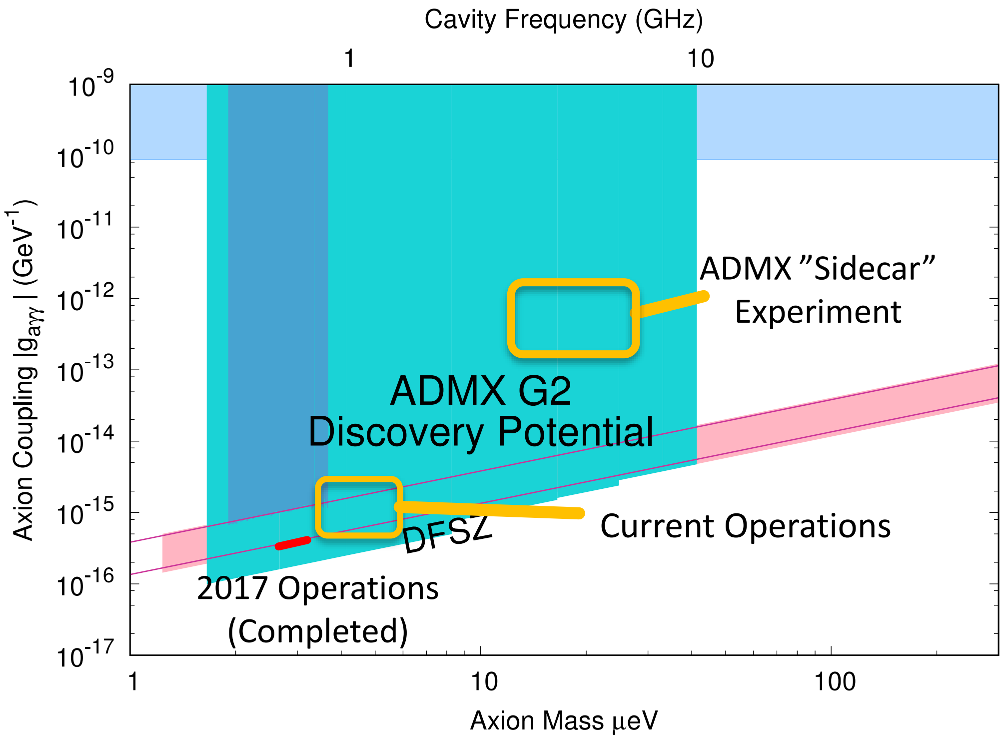
Microwave Cavity

Gen 2 Results



Going Forward

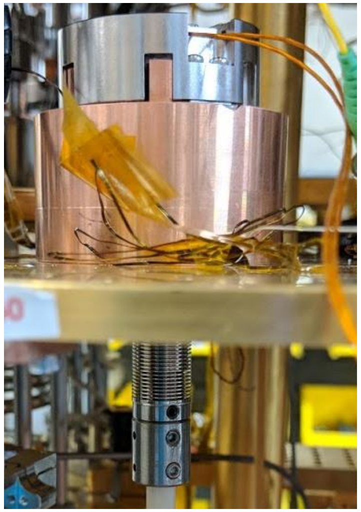
- Currently ADMX is scanning 700-890 MHz
- We anticipate faster frequency coverage in the future due to:
  - Higher magnetic field
  - More stable quantum electronics
  - Lower temperatures
  - Reduced engineering overheads.
- Speed up of ~6x



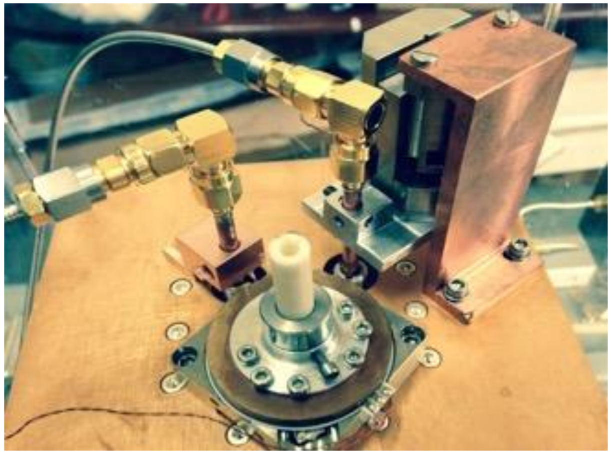
The ADMX Sidecar

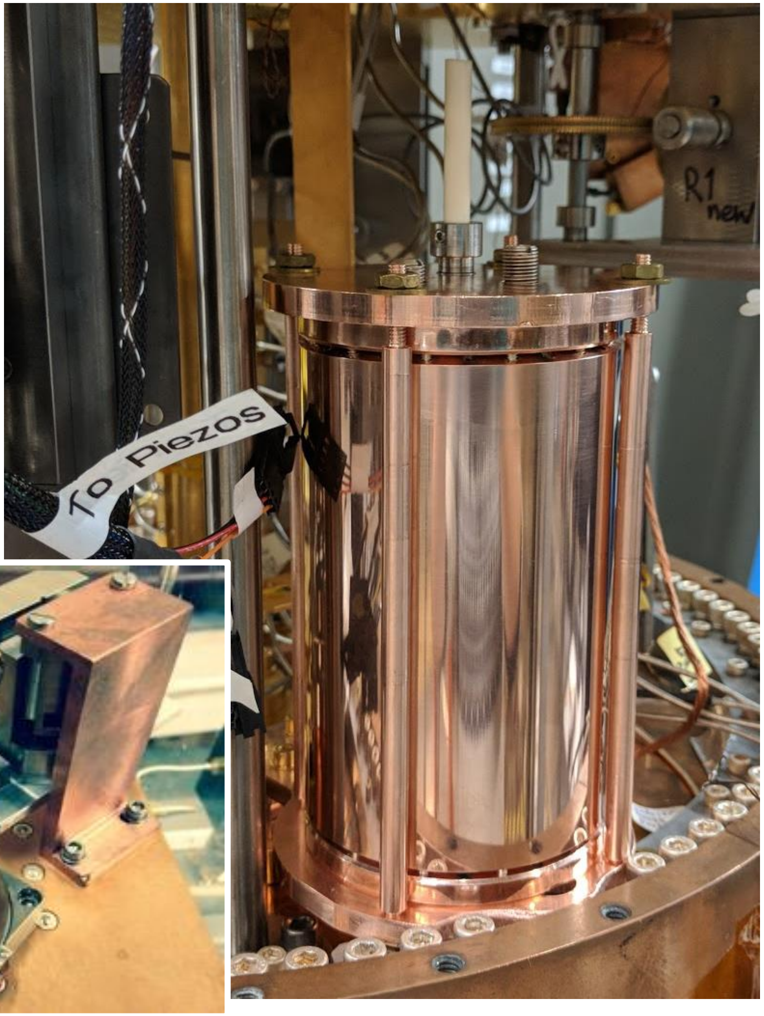
- Sidecar is a small cavity that lives above the main ADMX cavity.
- Operating range of 4-6GHz in the fundamental mode.
- Currently testing piezo actuators for motion control.
- Testing data taking in TM020 Mode.
- Currently insensitive to QCD axions but still searching for ALPs.

Jensen Precision Engineering

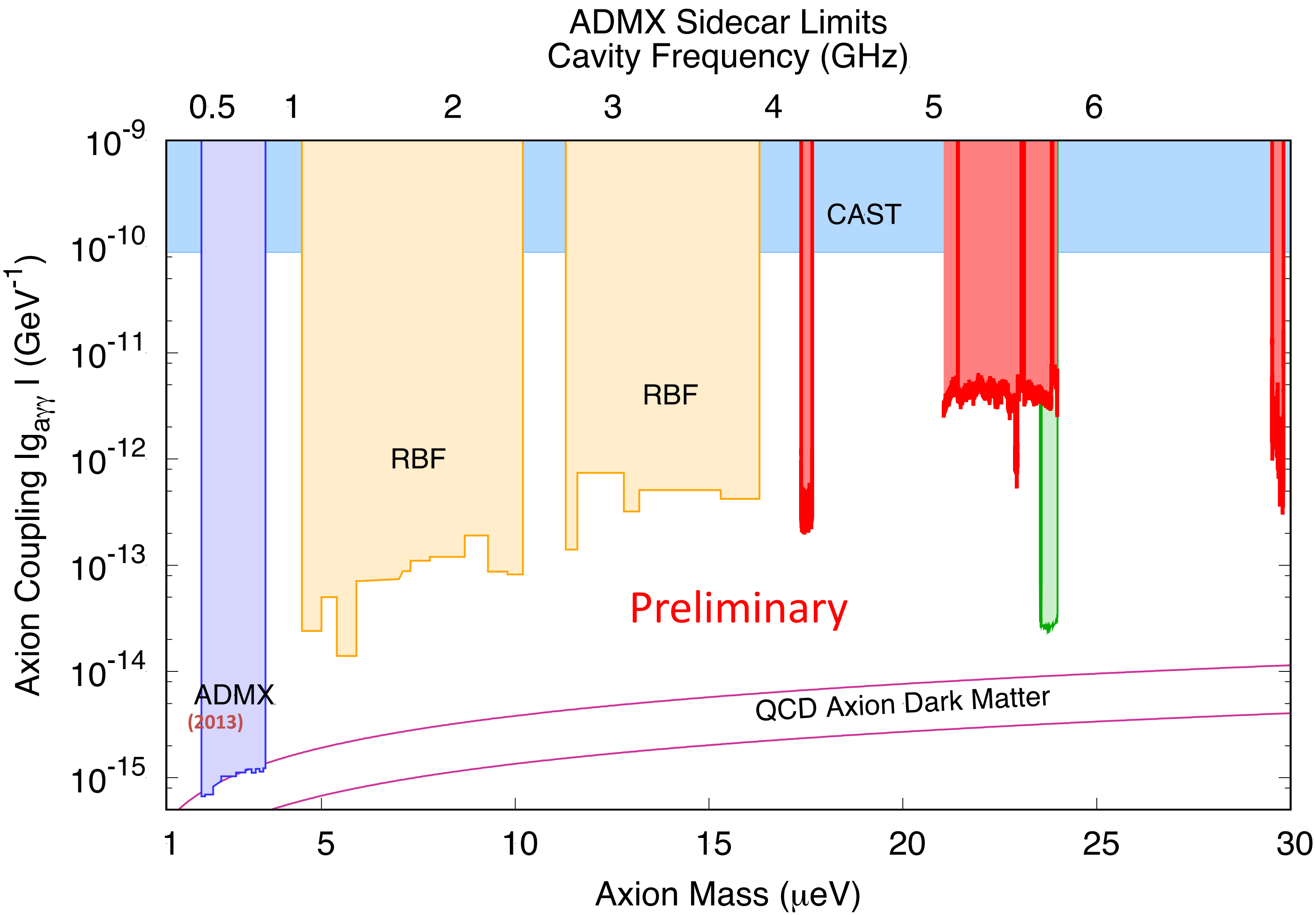


Attocube



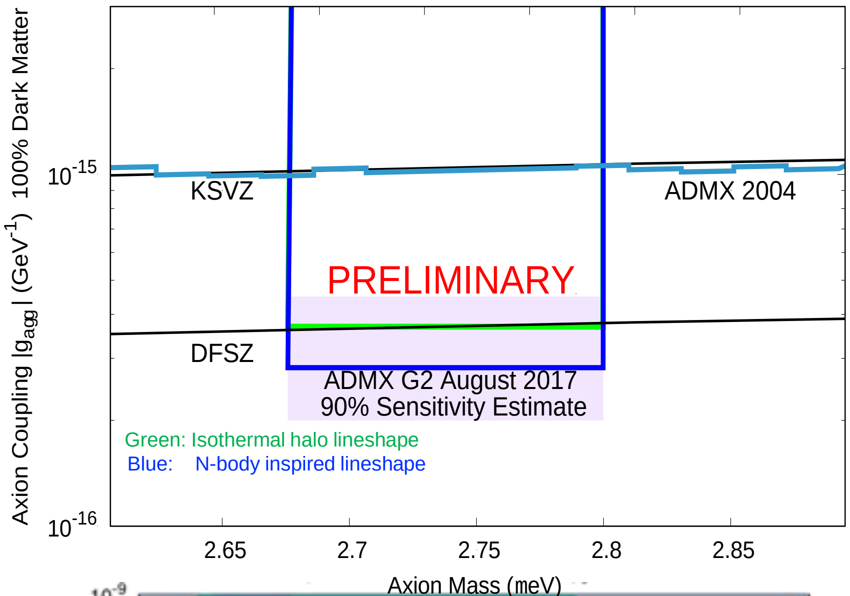


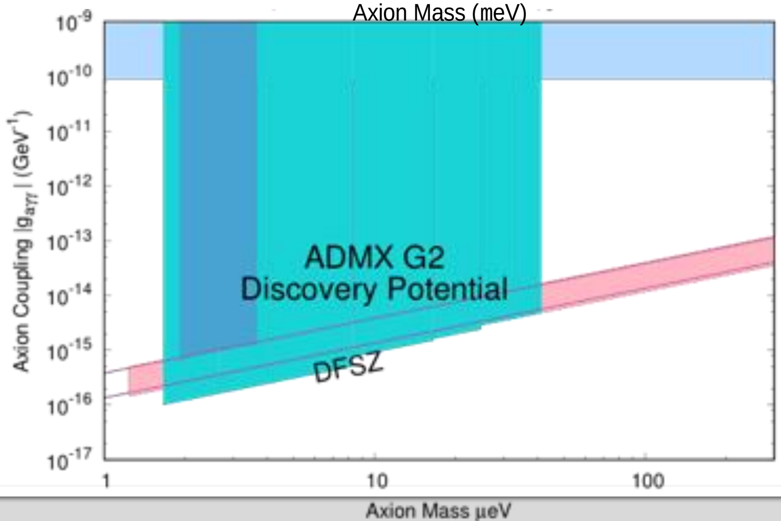
Sidecar Exclusions



Conclusions

- 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





ADMX G2 at U. Washington, Scientific American, 2015

Lawrence Livermore National Laboratory

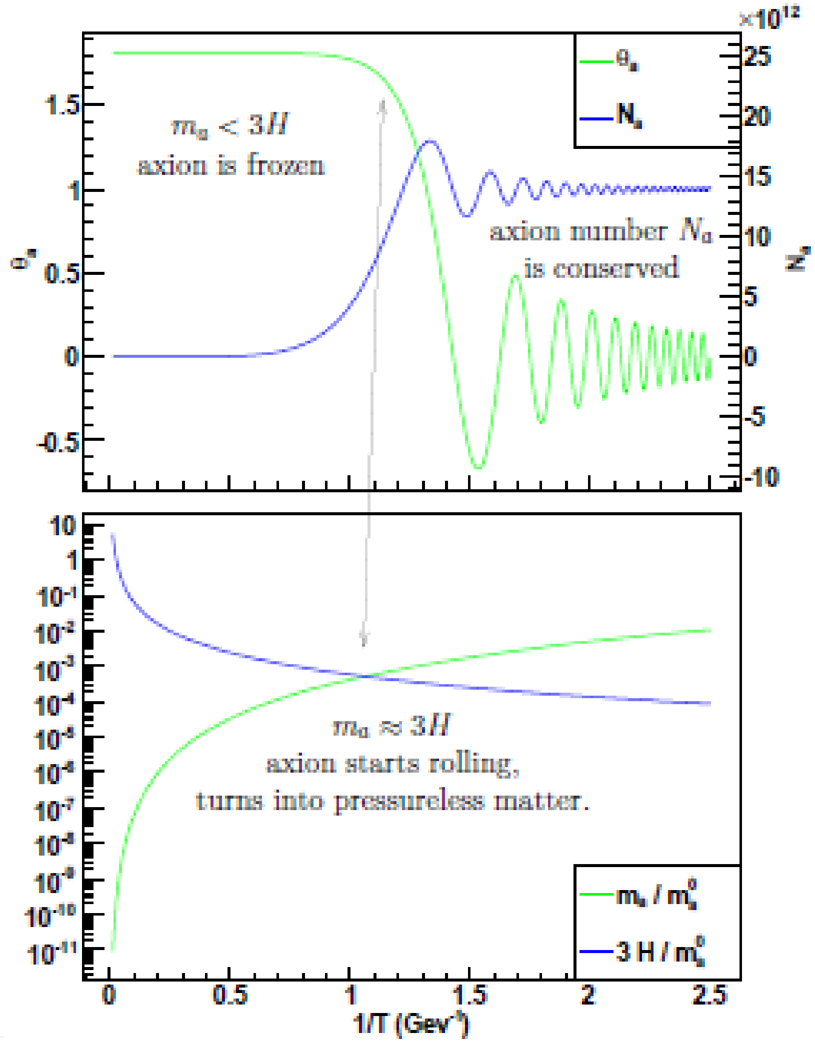
Collaborating Institutions:
UW, UFL, PNNL
FNAL, UCB, LLNL
LANL, NRAO, WU, Sheffield

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.

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

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’.

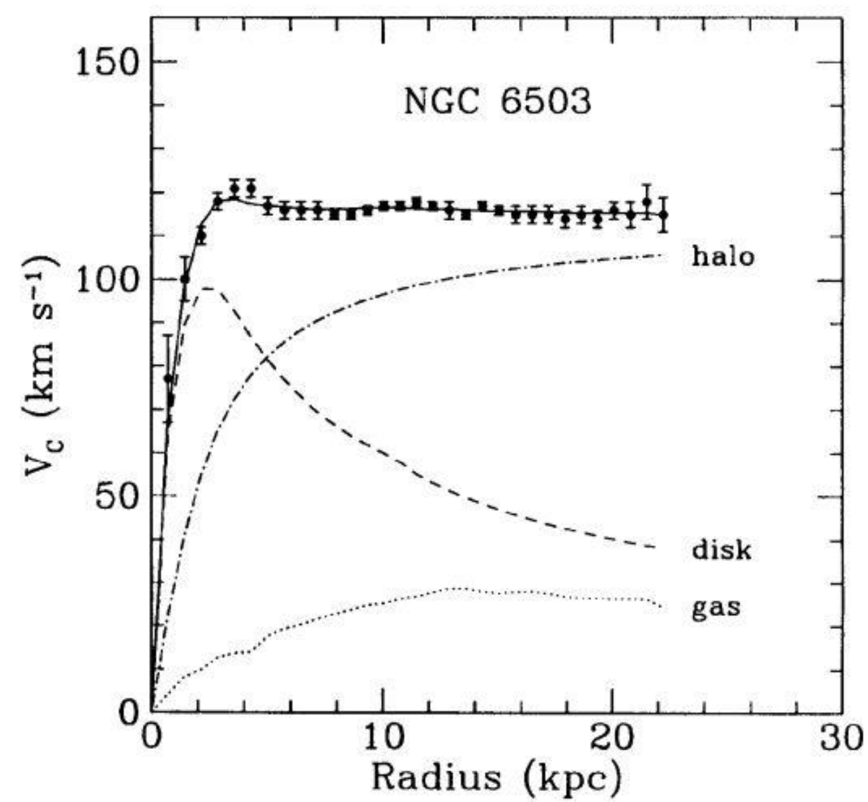


Image source: Katherine Freese, Caltech
https://ned.ipac.caltech.edu/level5/Sept17/Freese/Freese2.html