Exciting Times for Axion Dark Matter

Gray Rybka, University of Washington

Double Beta Decay and Underground Physics
Osaka
November 2016

Outline

The field of axions is exciting and rapidly growing

Contents of this Talk:

A Brief Theoretical Introduction to Axion Dark Matter

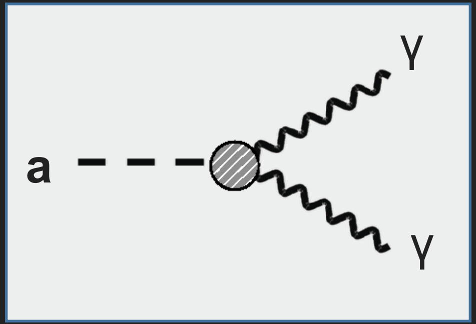
A Whirlwind Tour of Some Axion Searches

Highlights of the ADMX Axion Dark Matter Search

Axion Motivation

The Strong CP Problem

Neutron electric dipole moment is much smaller than expected (see more talks this session) Lack of neutron electric dipole moment indicates strong force is CP invariant. $O(10^{-10})$ cancellation required in relevant terms



Same properties as π^0, scaled by mass

The Peccei-Quinn Solution

Add a dynamic field, spontaneously broken, which cancels strong CP violation

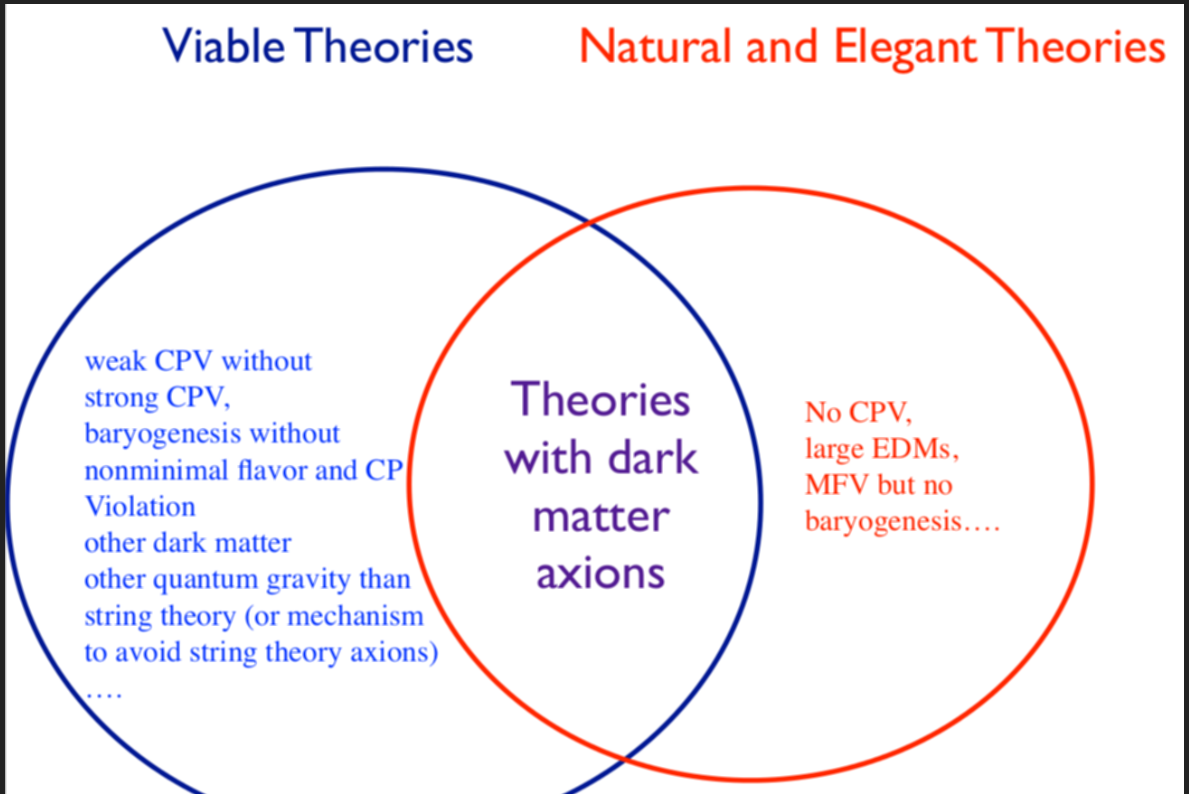
This results in a new pseudoscalar particle, the axion

Weinberg, Wilczek

Axions as Dark Matter – Motivation

"If they exist at all, axions would be copiously produced in the early universe. They provide an excellent candidate to compose the dark matter that astronomers have observed but not yet identified. Ingenious, challenging experiments are being mounted to detect axions, either as a cosmic background or through their effects. Within 100 years—and possibly much sooner—they should succeed."

Frank Wilczek, Physics Today April 2016



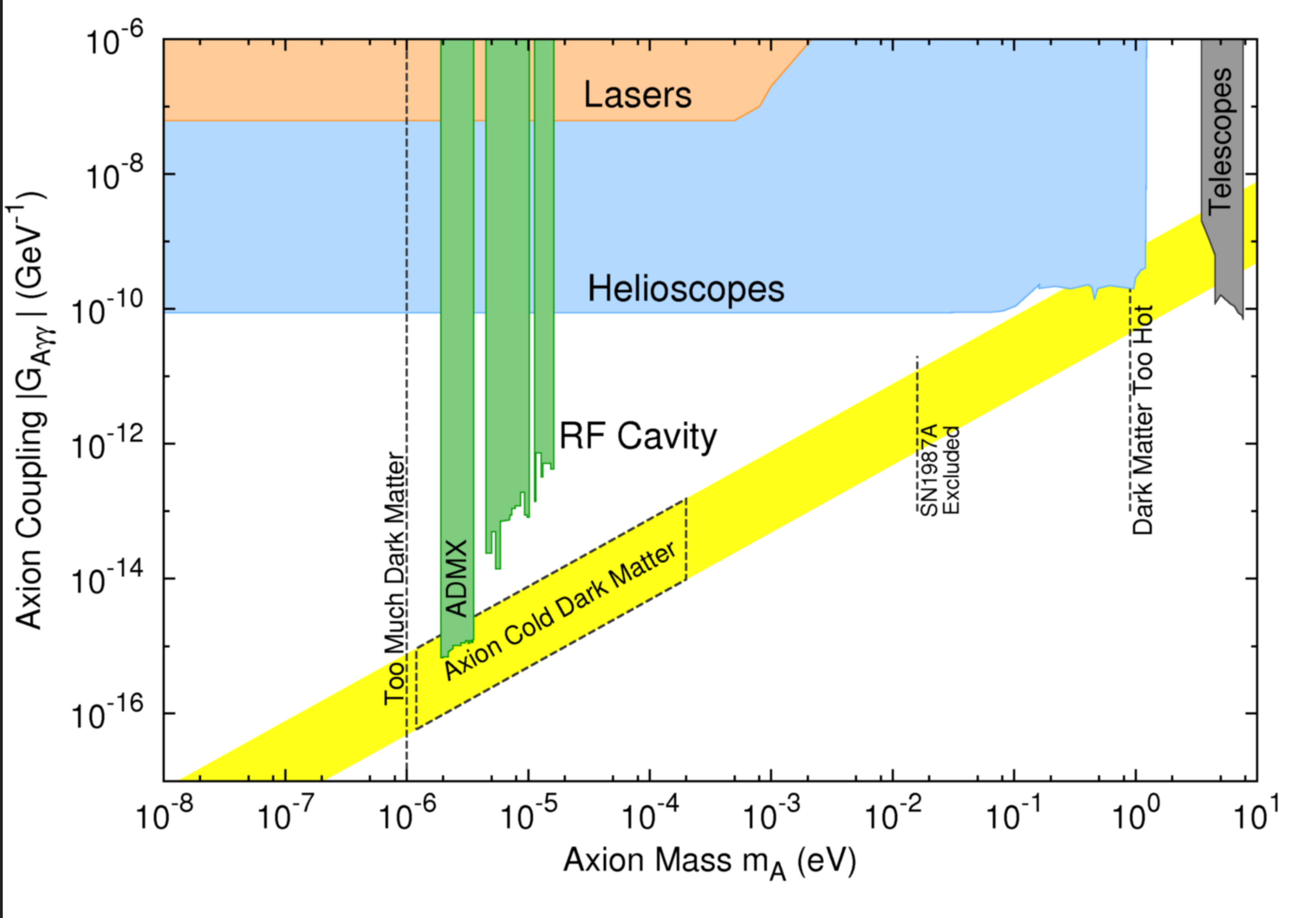
Source: Ann Nelson, Vistas in Axion Physics 2012

Axion Dark Matter Properties

Axions would be produced in the early universe via the misalignment mechanism, and possible more exotic mechanisms (string or domain wall decay)

A first pass calculation suggests axions with masses in the ueV to meV could produce all of the cold dark matter

Note the mass-coupling ratio is constrained by the requirement axions solve the strong CP problem



Theoretical Developments

- Axion Like Particles – The misalignment mechanism works for other light scalars, pseudoscalars, and vectors which are worth looking for. (for example Phys Rev. D. 29 (2009) 15014)

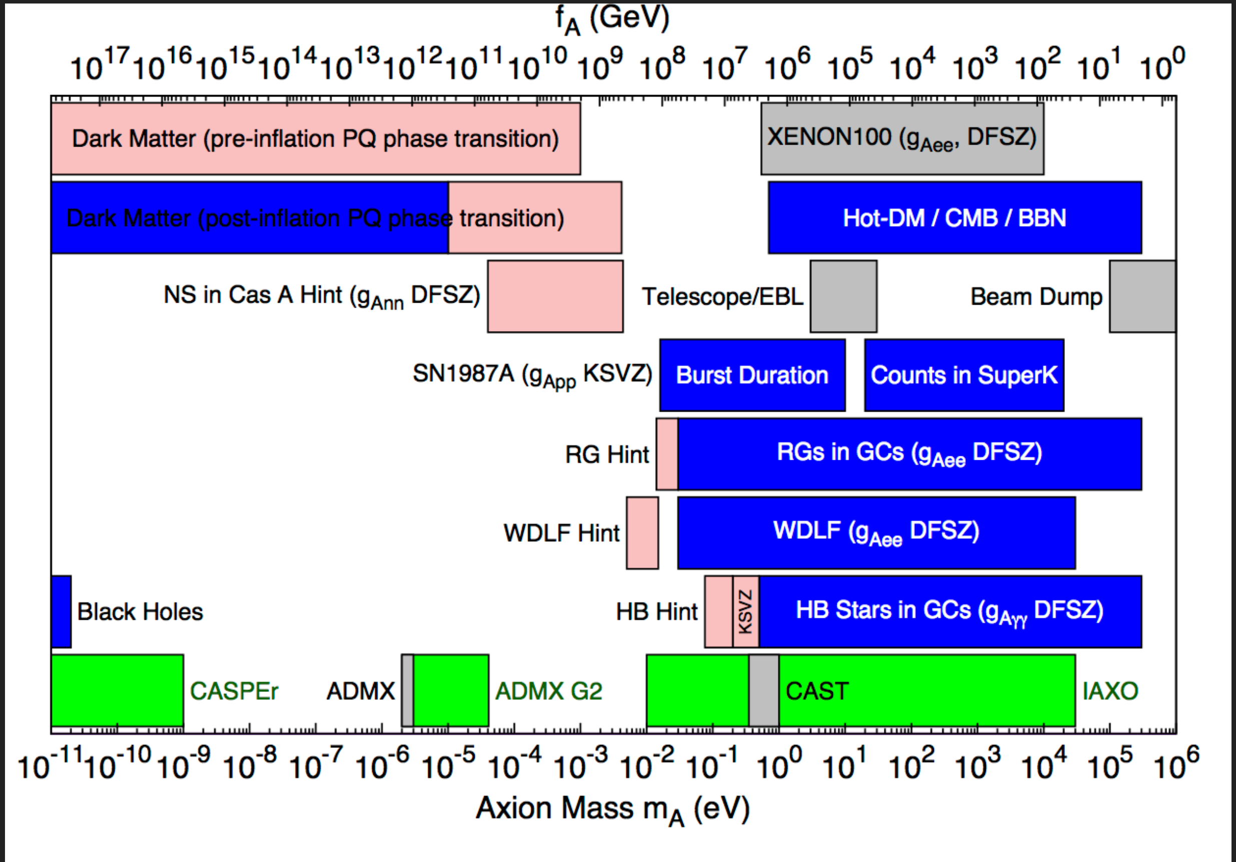
- Anthropic Axion Window – Axions created before inflation may evade the "too much dark matter" bound (for example (for example Phys Rev D. 88 (2013) 035023)

- Improved Axion Mass Predictions – Lattice QCD and understanding of axion creation story yield improved (conflicting) axion mass predictions (for example arXiv 1610:01639)

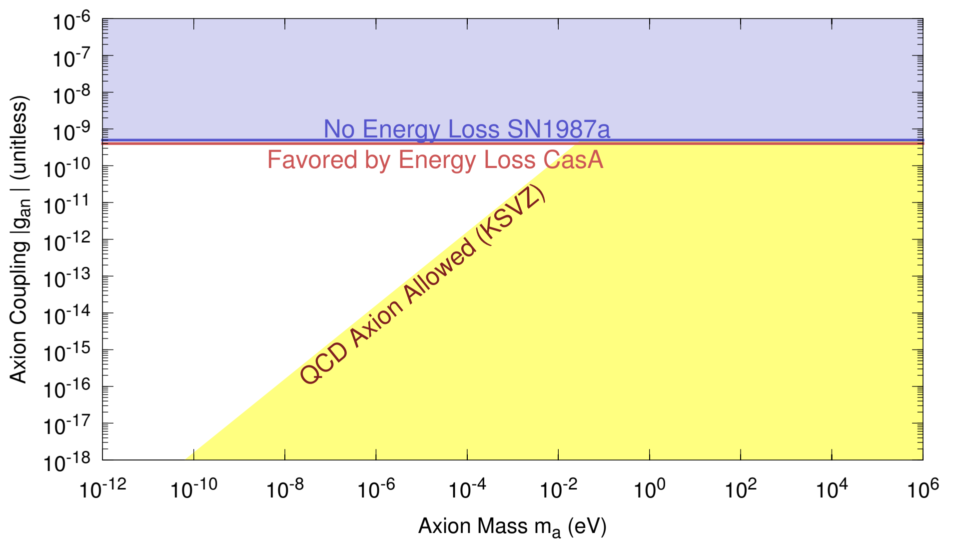
- Clear message: We should be looking for axions!

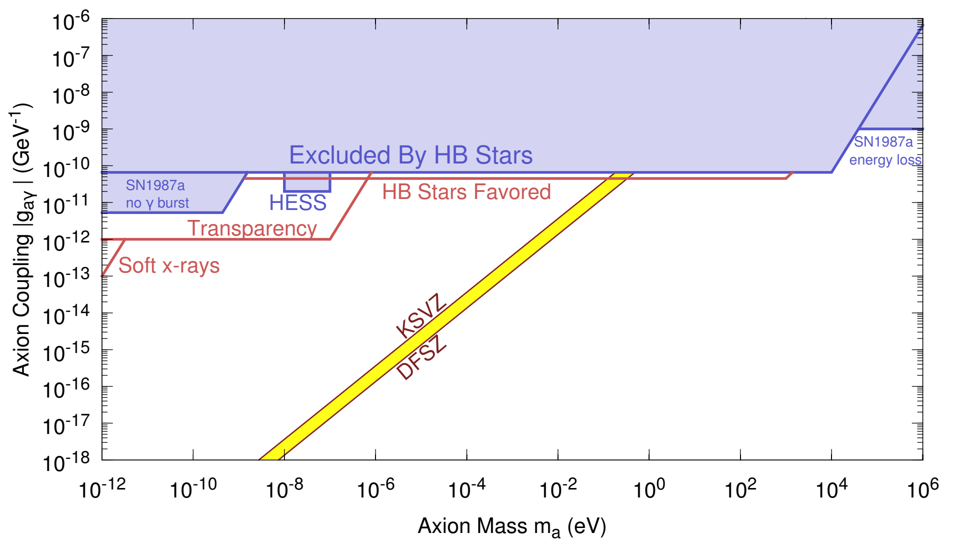
Astrophysical Constraints

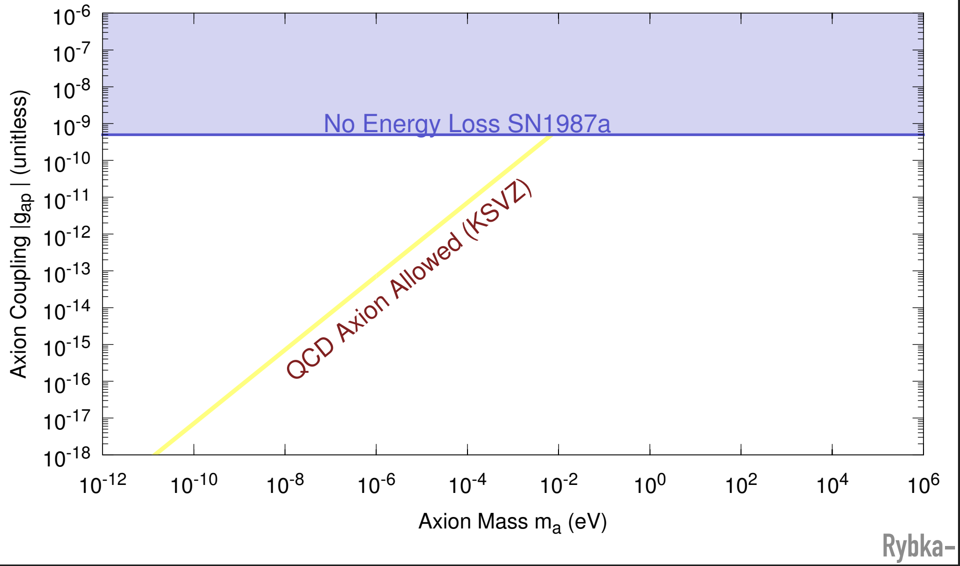
- Axions are an energy loss mechanism from stars
  - Altering Helium Burning Stars Evolution
  - Altering Supernova Explosions
  - Increasing Cooling Rate of White Dwarfs
- Axions can cause anomalous transparency in the interstellar medium
- Axions can spin down black holes

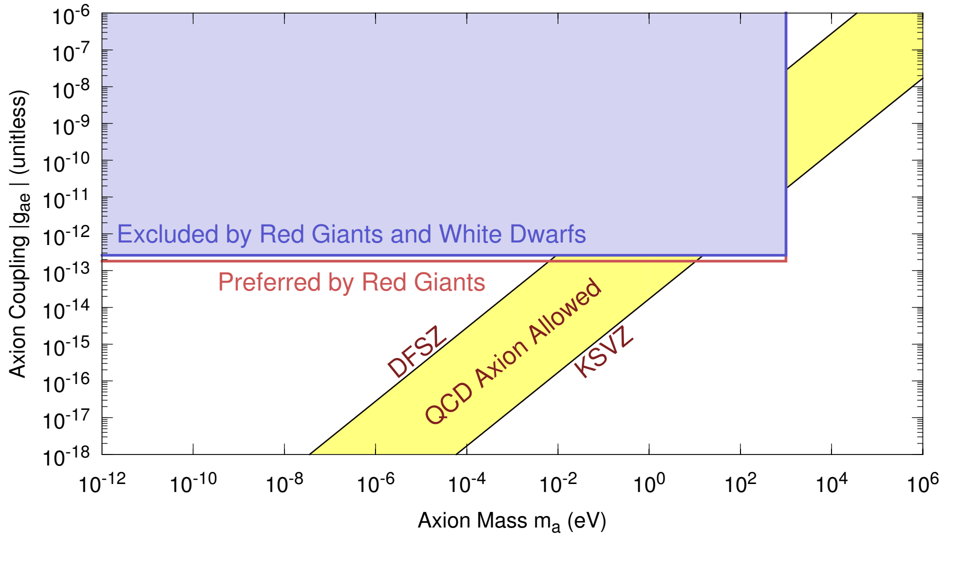


Astrophysical Constraints

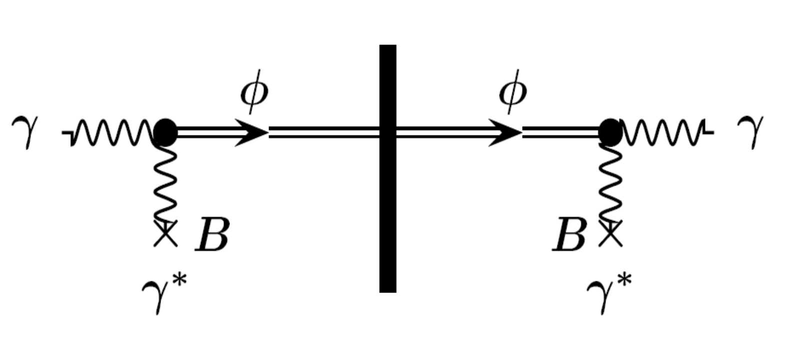




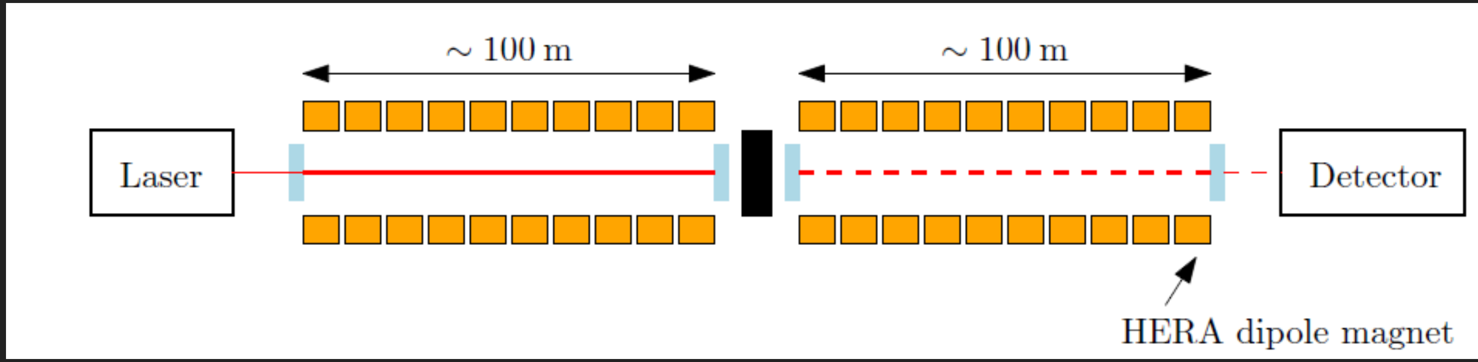




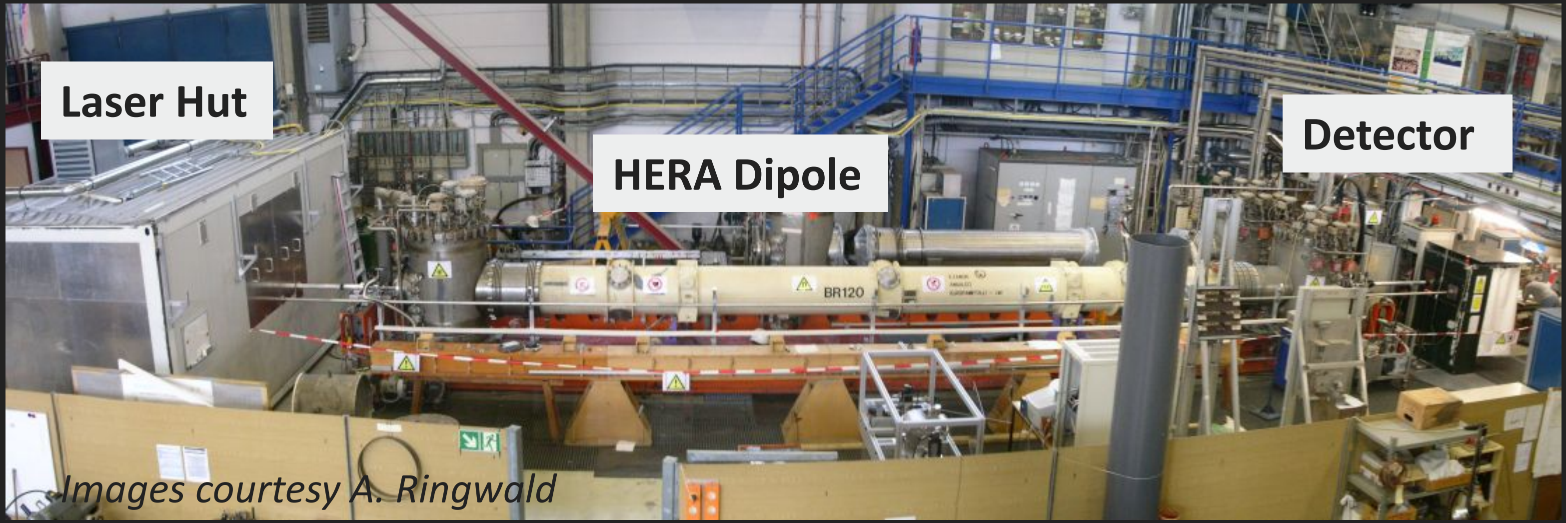
Light Shining Through Walls Experiments



Photon-Axion-Photon conversion



Implemented with lasers, dipole magnets. Resonant enhancement possible

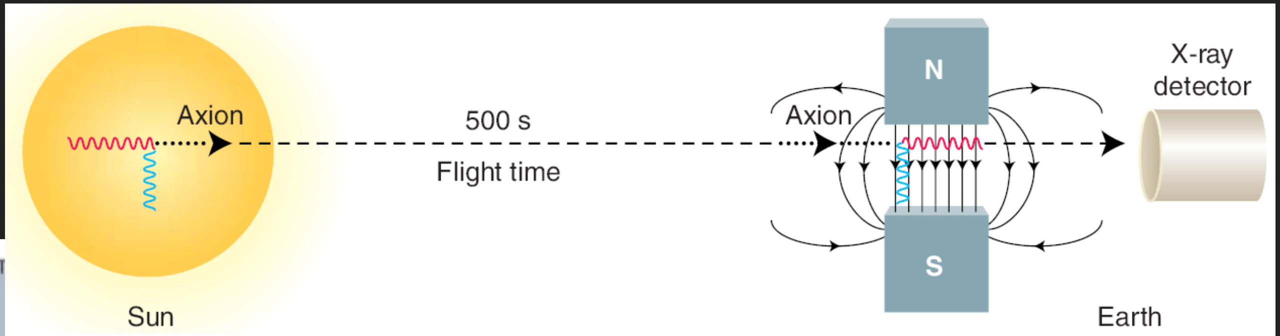


Images courtesy A. Ringwald

Example: ALPs (completed) and ALPS-II at DESY.

Projected sensitivity competitive with astrophysical bounds. Primary target is axion-like particles

Solar Axion Experiments



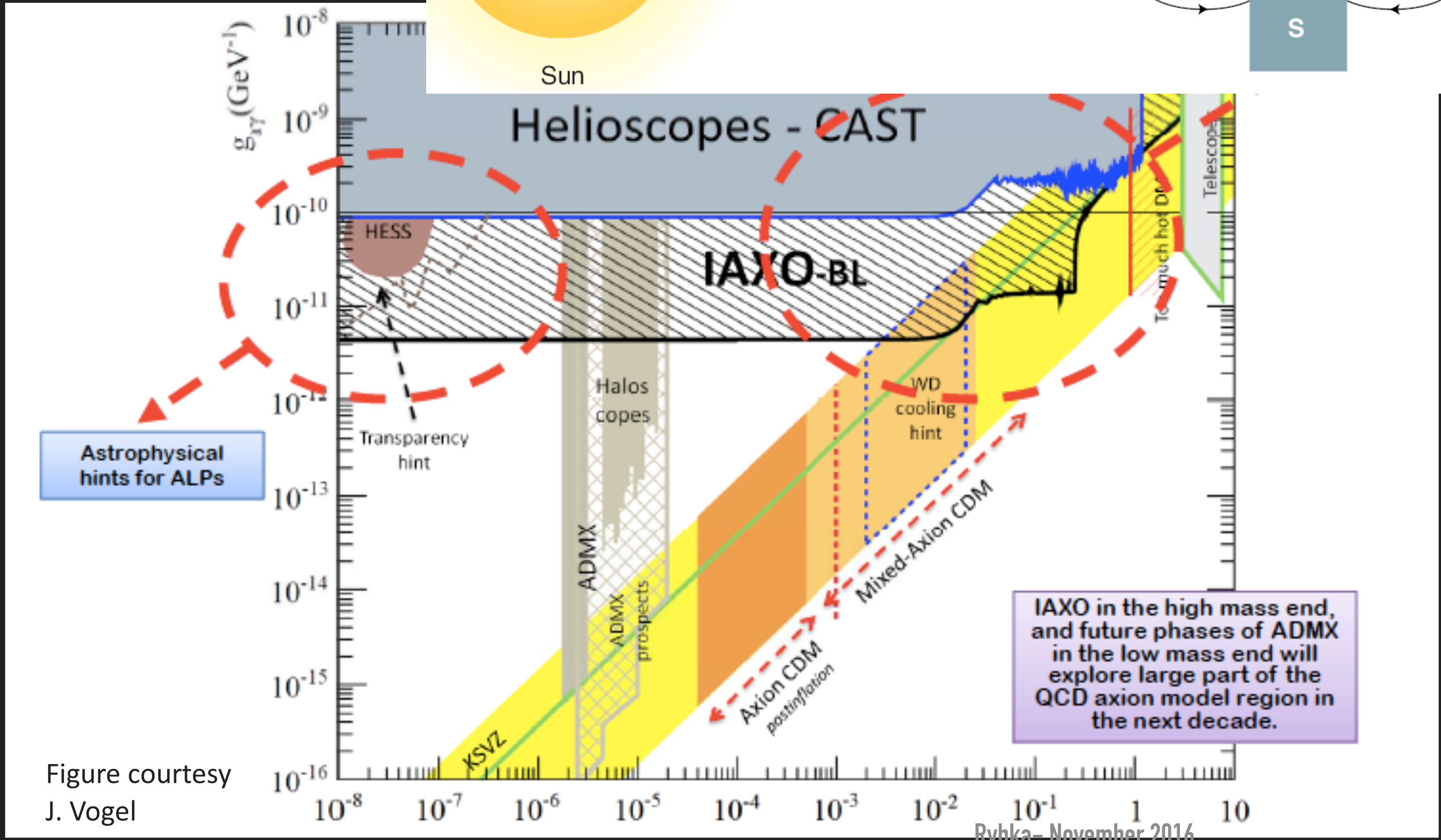
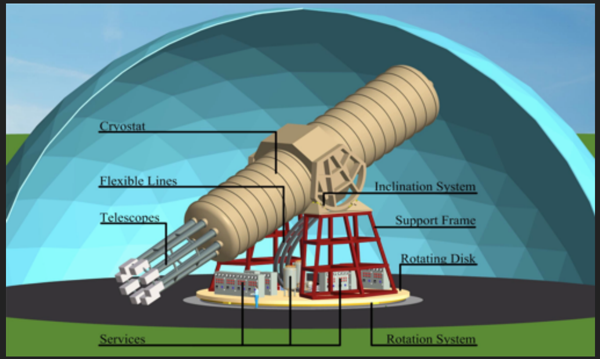


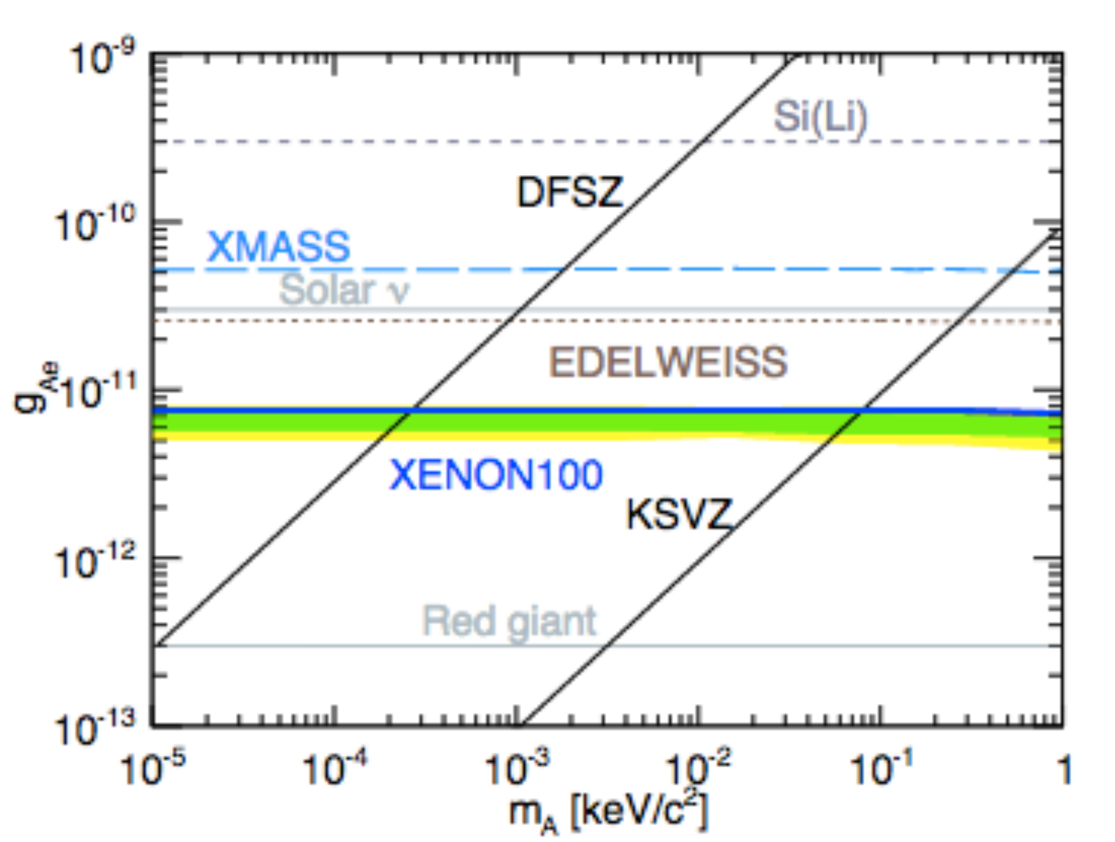
Figure courtesy J. Vogel

Existing helioscopes:
Sumico/Tokyo Axion Helioscope
CAST (pictured below)

Proposed Helioscope: IAXO



WIMP (and DBD) Detectors for Solar Axion Searches



Example axion-electron coupling limits from Aprile et al. PRD 90, 062009 (2014)

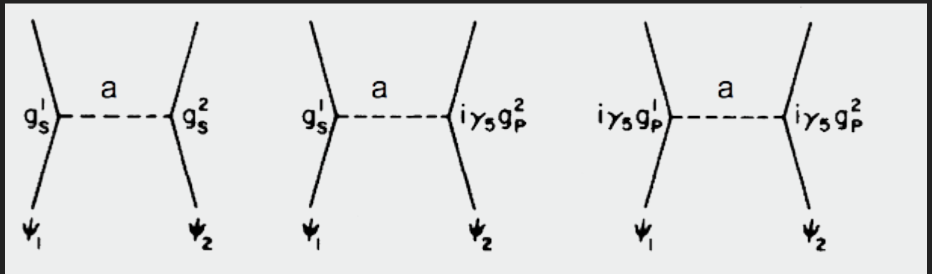
Nuclear recoil experiments are sensitive to solar axions, with sensitivities approaching helioscopes, excluding QCD axions above the ~eV scale

They are also sensitive to dark matter axions with keV scale masses through electron recoils

Germanium Double Beta Decay experiment may also be sensitive to solar axions at similar couplings

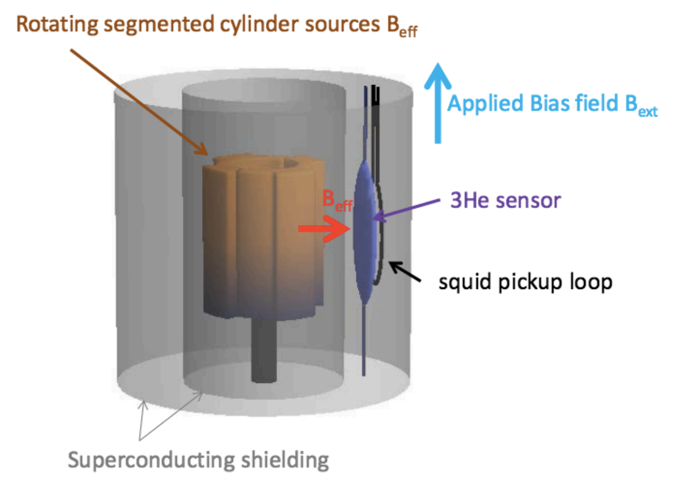
Axion-Mediated Force Experiments

- Axions would mediate a 5th force

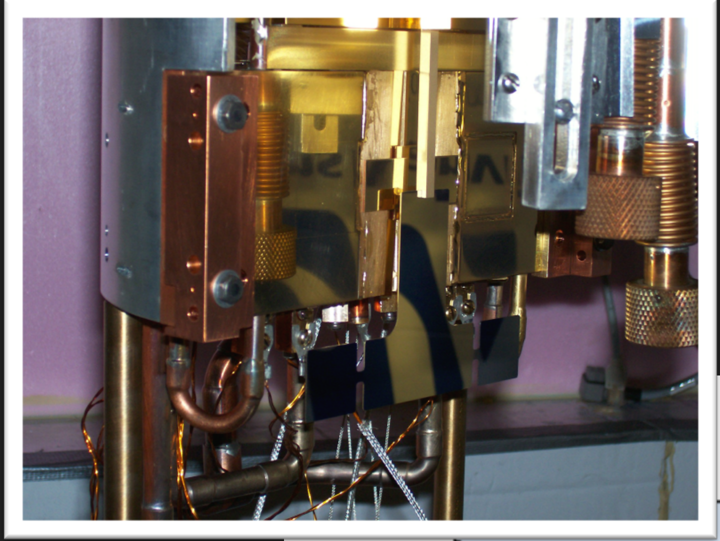


Moody & Wilczek, 1984

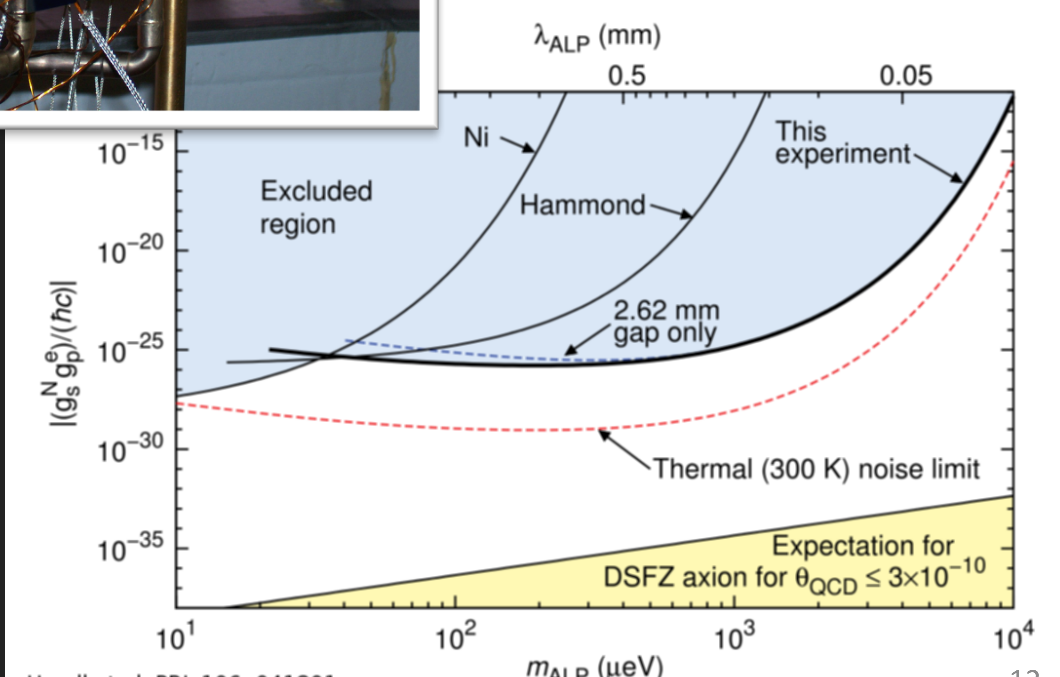
- Current bounds are far from QCD couplings
- New ideas may probe meV scale axions



Ariadne NMR Concept
Arvanitaki and Geraci *Phys. Rev. Lett.* 113, 161801 (2014)



Torsion pendula experiments at University of Washington

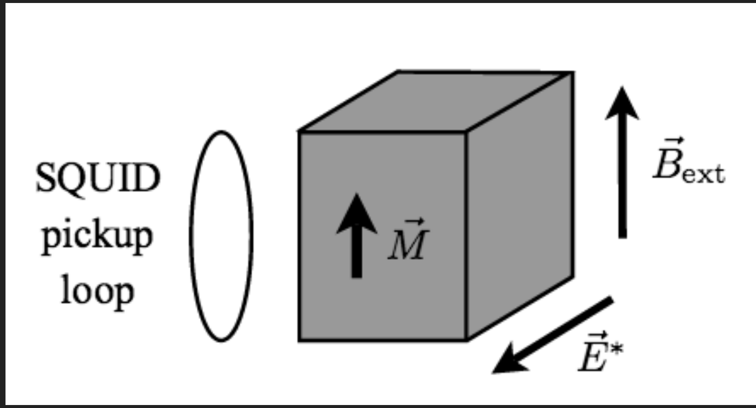


Hoedl et al. PRL 106, 041801

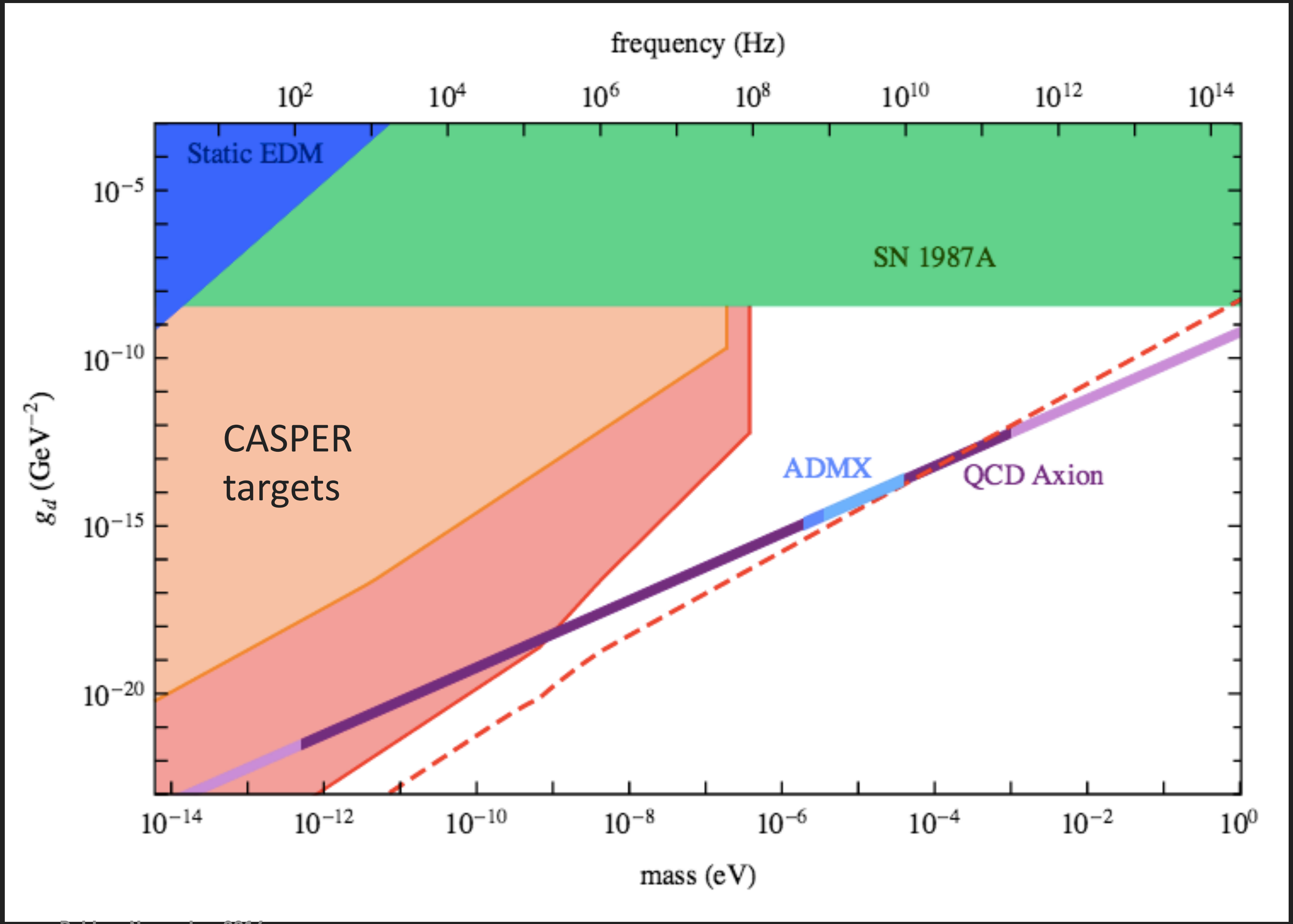
NMR to Detect Axion Dark Matter

Dark matter axions would induce an oscillating electric dipole moment in some atoms

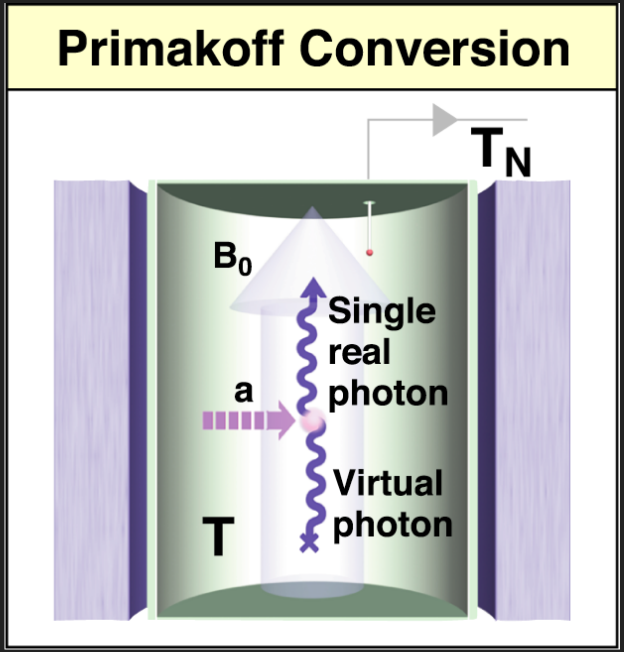
Could be detected if made resonant with Larmor frequency of NMR sample



See: Graham & Rajendran
PRD 88, 035024 (2013)



Axion Haloscopes



Dark Matter Axions will convert to photons in a magnetic field.

The conversion rate is enhanced if the photon's frequency corresponds to a cavity's resonant frequency.

See Sikivie, Phys. Rev. Lett. 1983

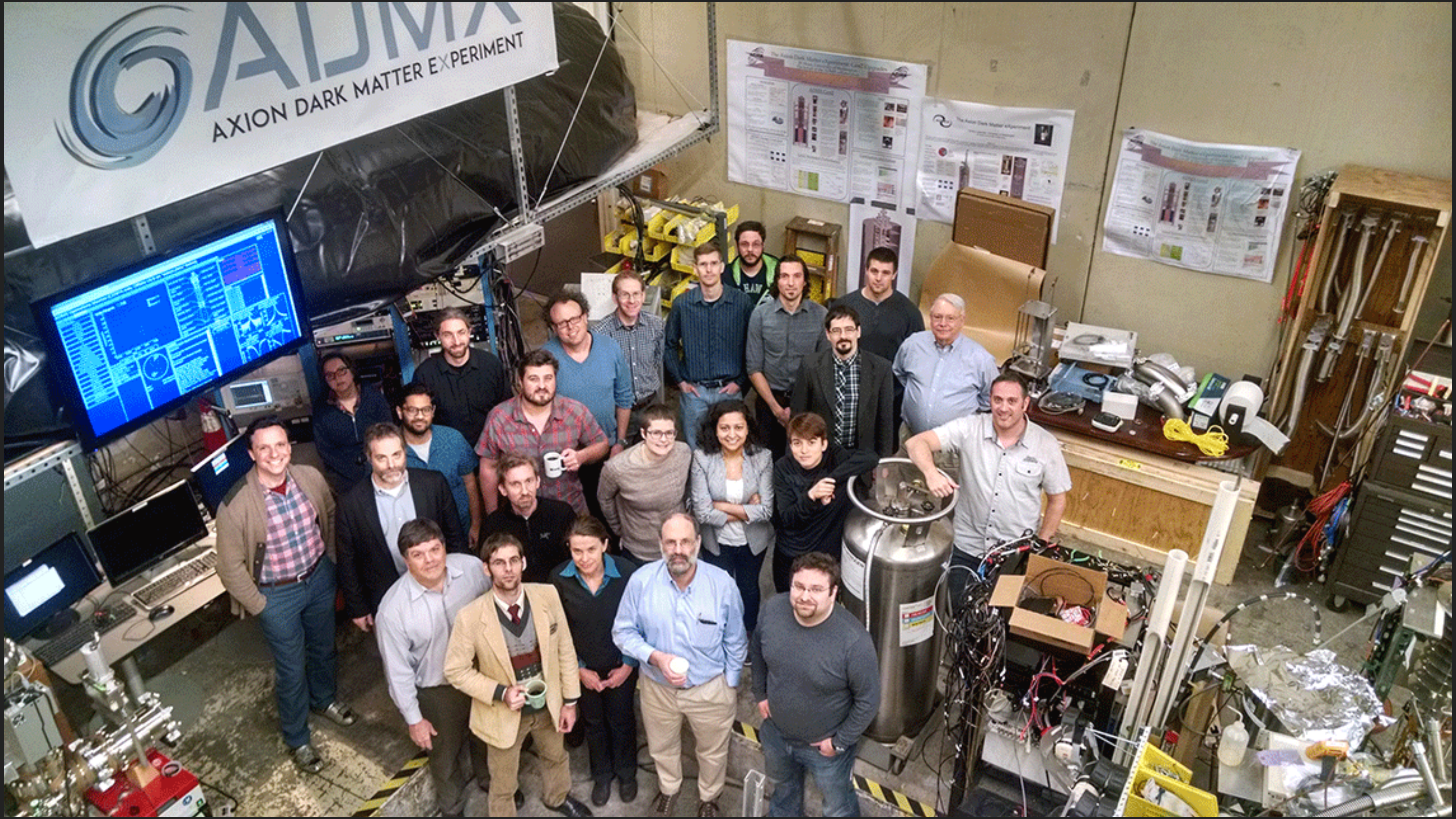
Increase Signal

Cavity Volume
Magnetic Field
Cavity Q

Noise Sources

Cavity Blackbody Radiation
Amplifier Noise

The Axion Dark Matter Experiment: ADMX



ADMX "G2" Dark Matter Search

Collaboration Members:
UW, UFL, LLNL
FNAL, LLNL, UCB
PNNL, LANL, NRAO

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

ADMX Design

Field Cancellation Coil

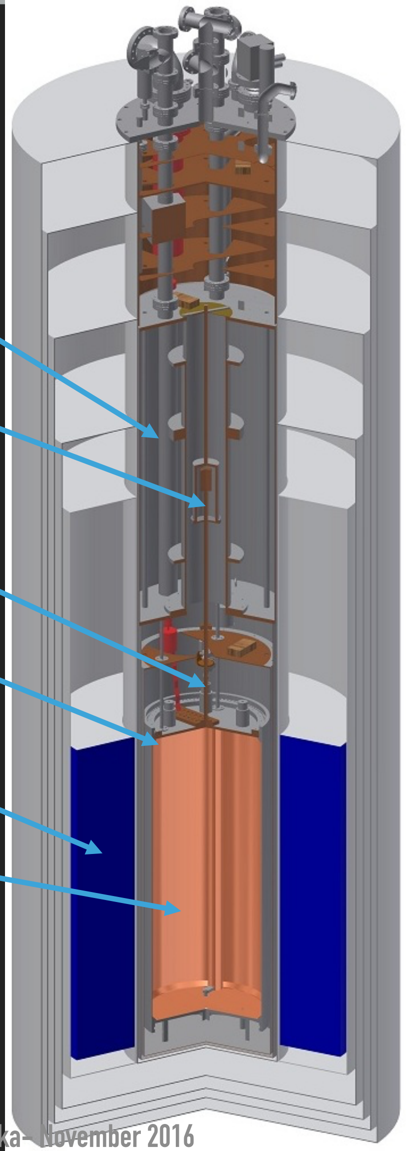
SQUID Amplifier Package

Dilution Refrigerator

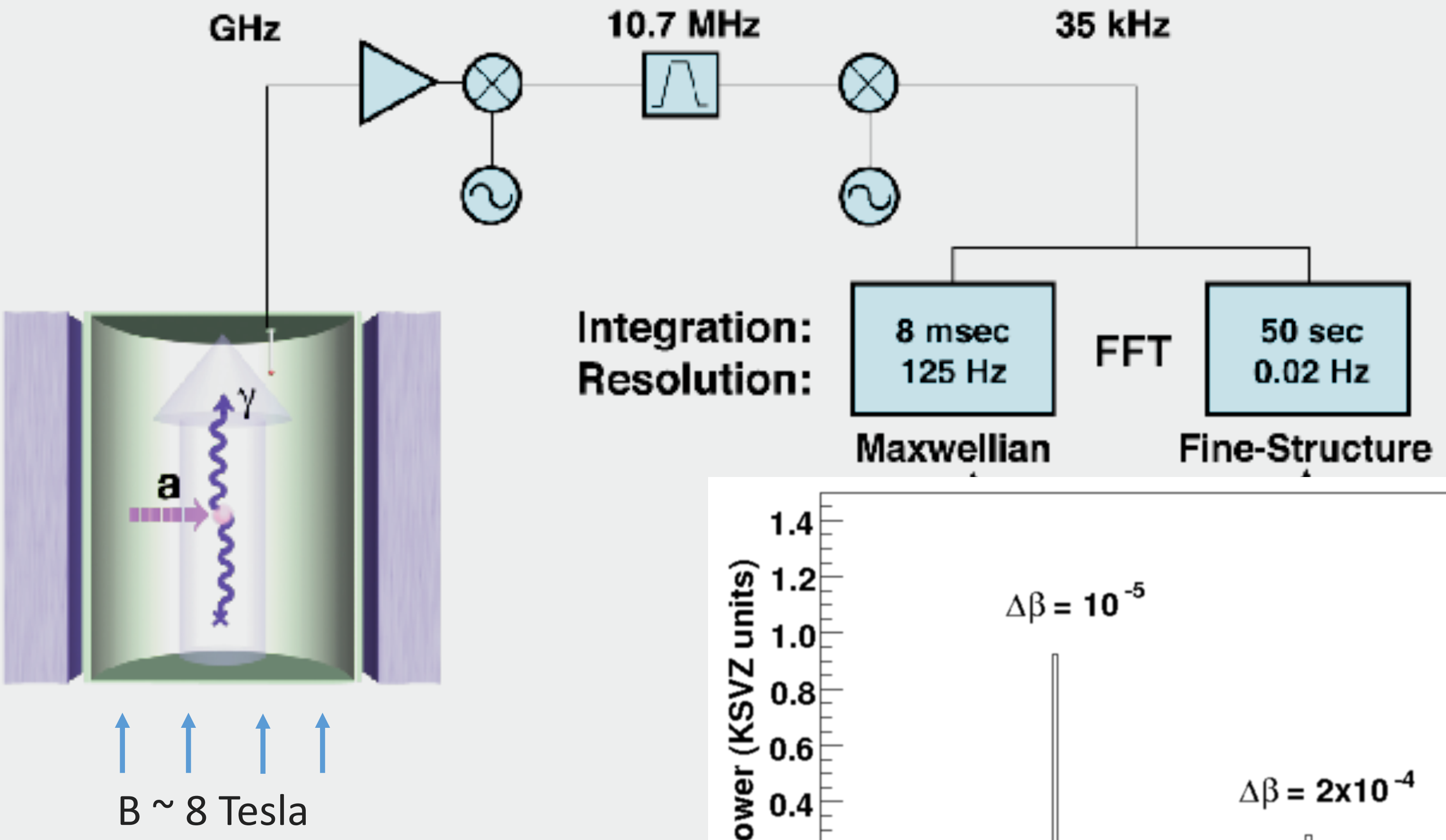
Antennas

8 Tesla Solenoid Magnet

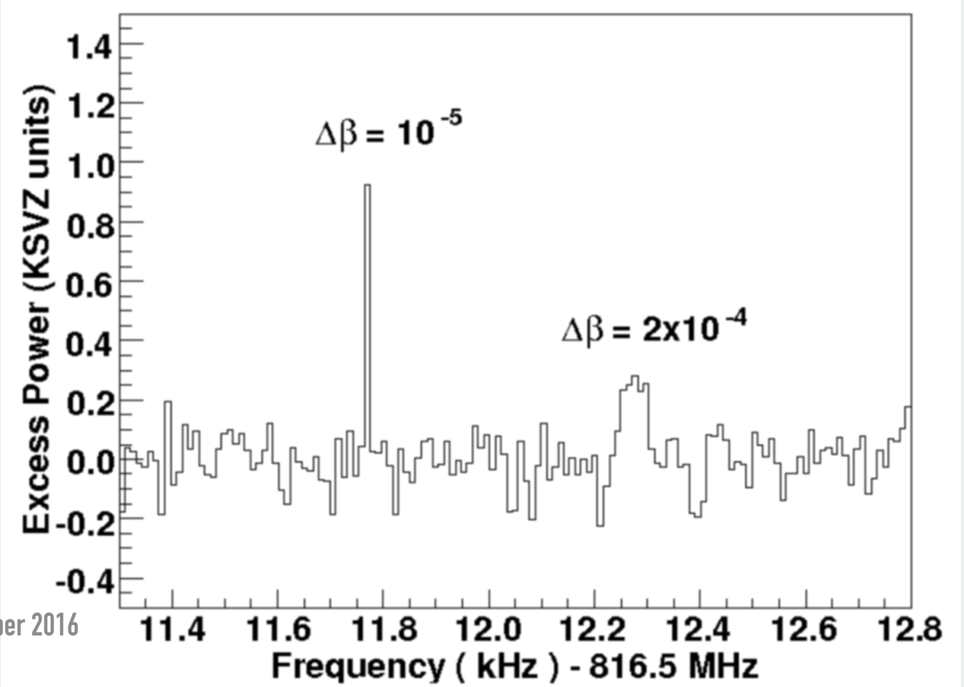
Microwave Cavity



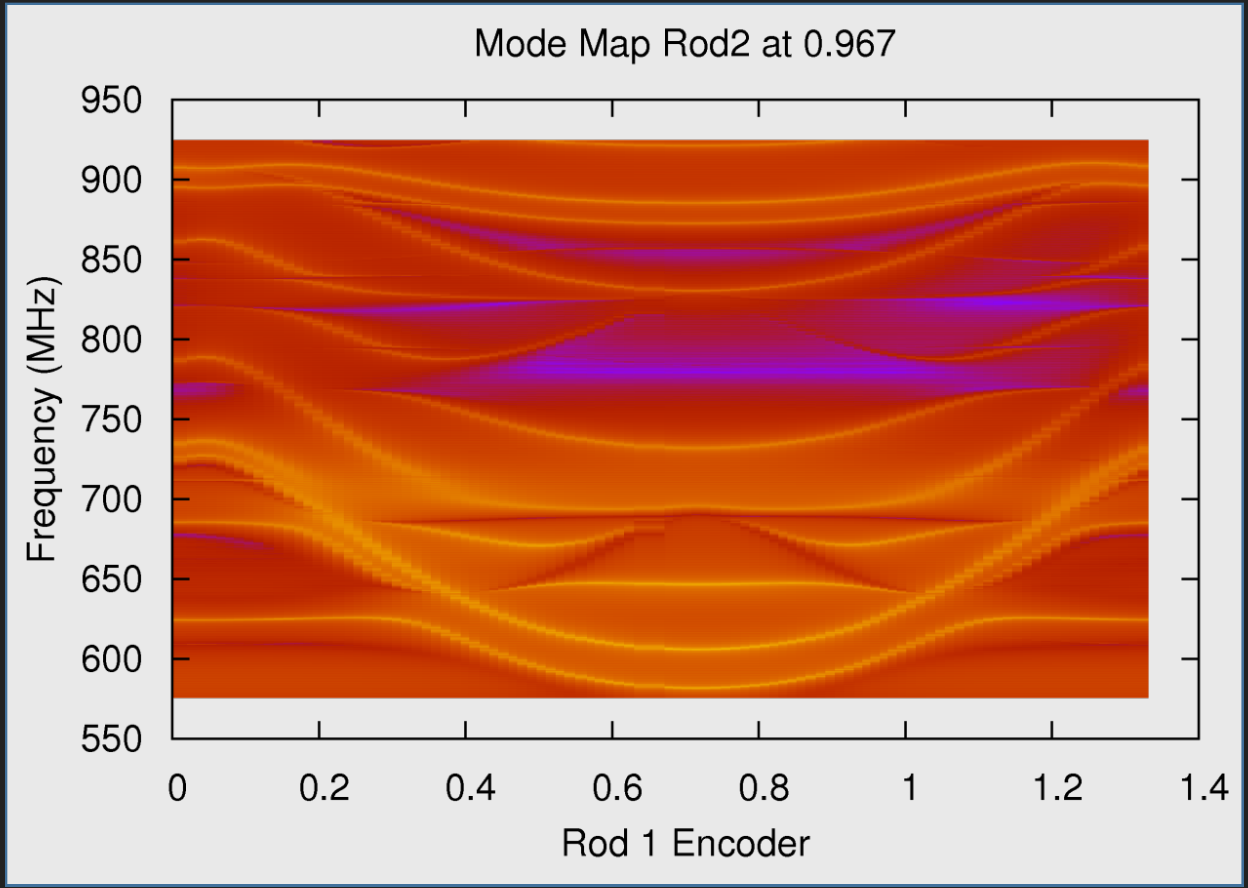
ADMX Receiver

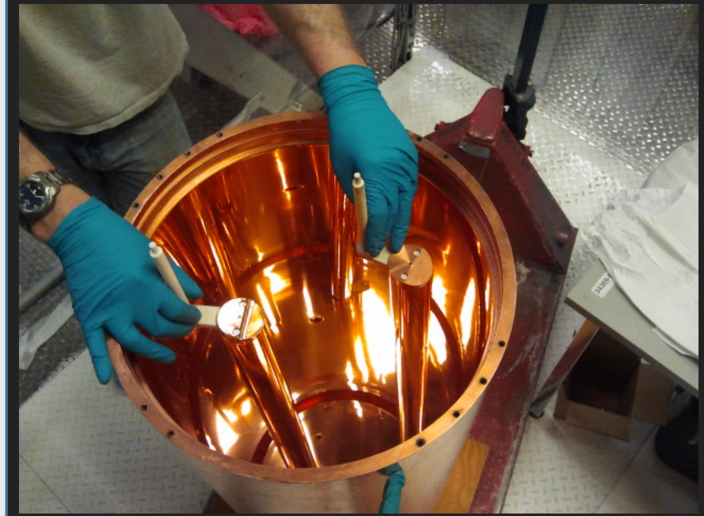


Axions convert to microwave photons (GHz), which are amplified, mixed to (MHz) frequencies and digitized

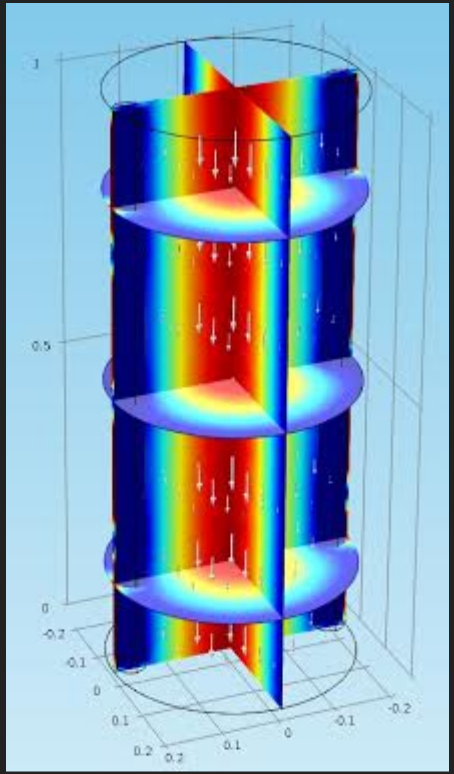


Tuning Resonant Frequency



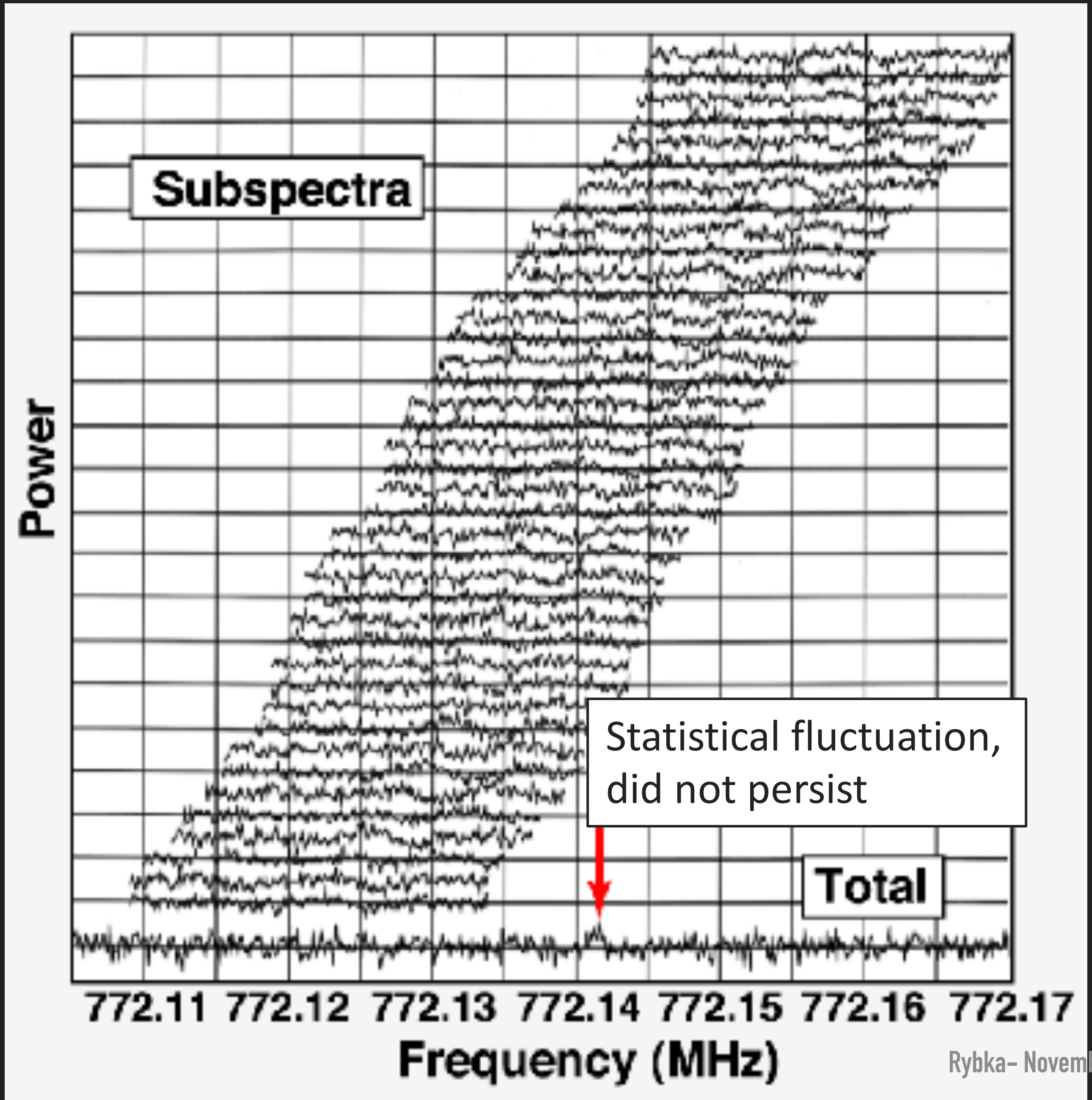


Rods in Microwave Cavity



Field Simulation

Axion Search Strategy



Power spectrum is recorded for each rod position

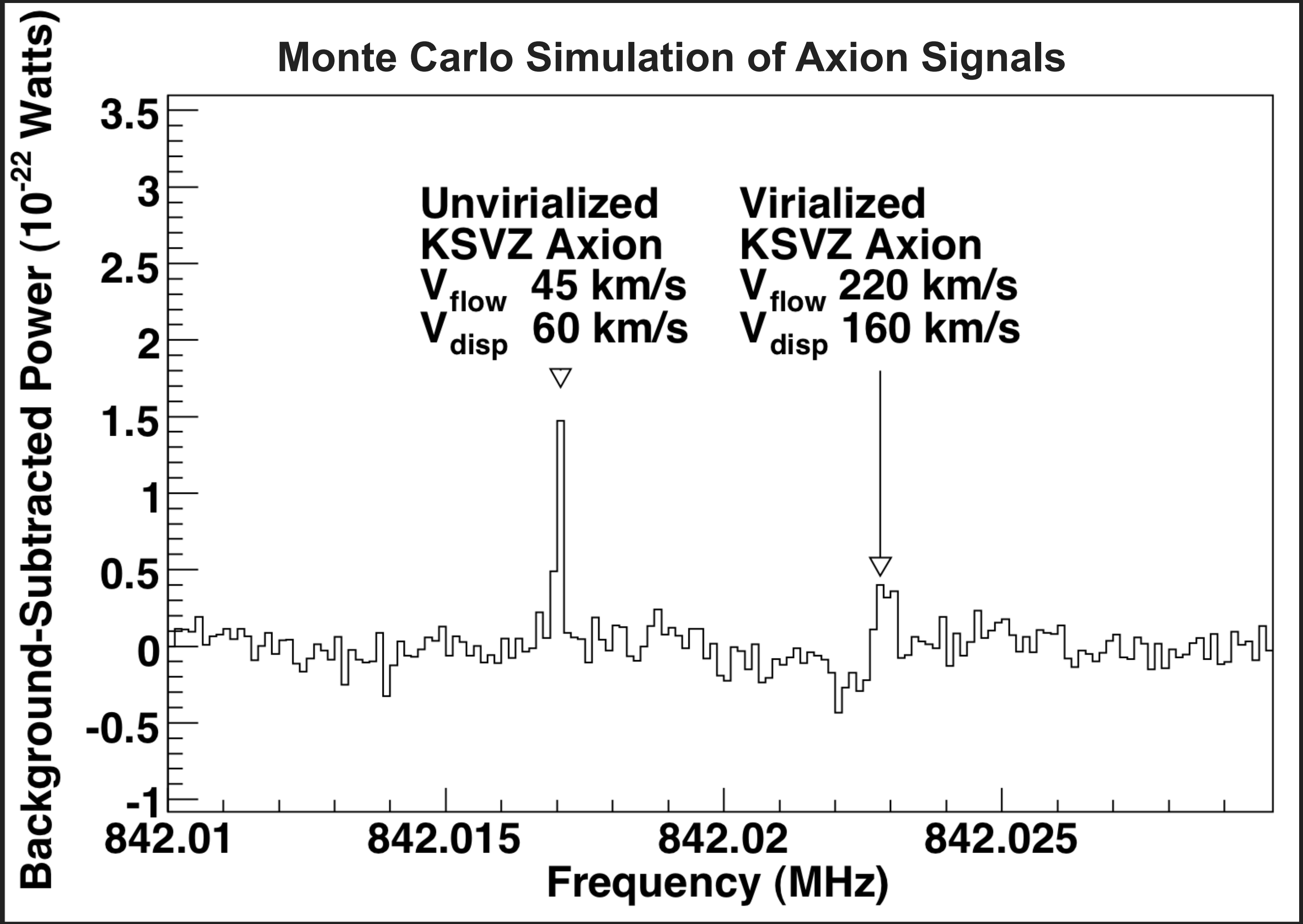
Axion signal would appear as excess power at a certain frequency

Regions with excess power are revisited: statistical fluctuations decrease in significance

External RF interference (rare) will occur independent of magnetic field

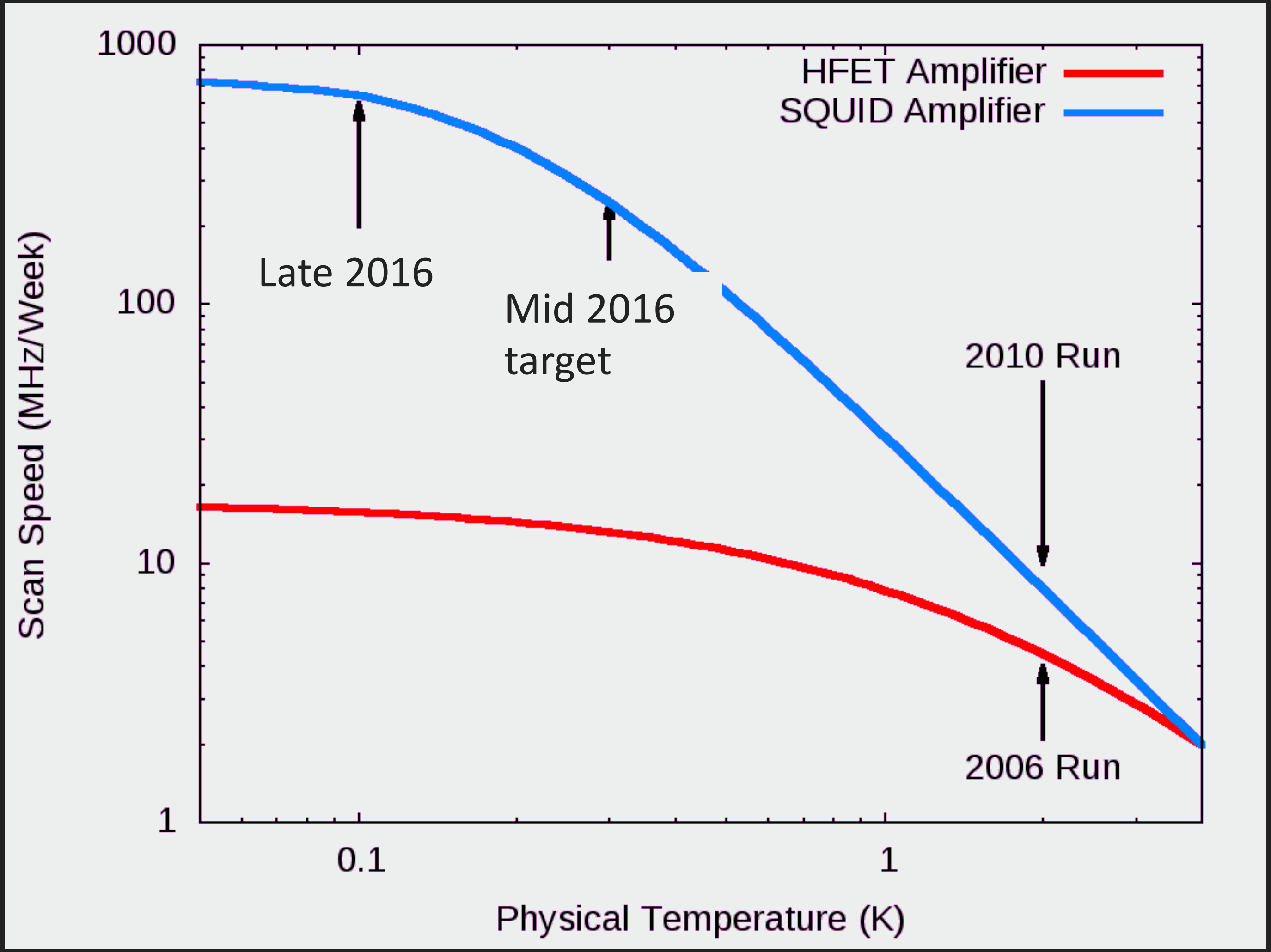
To date, no signal candidate has persisted

Predicted Axion Signal



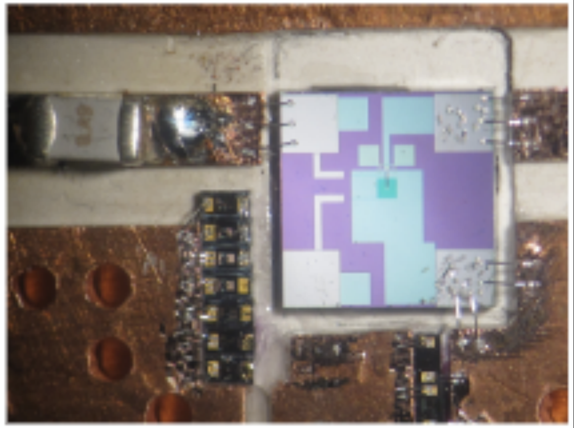
Key Technology – Millikelvin Refrigerator

Dilution Refrigerator installed above ADMX Cavity

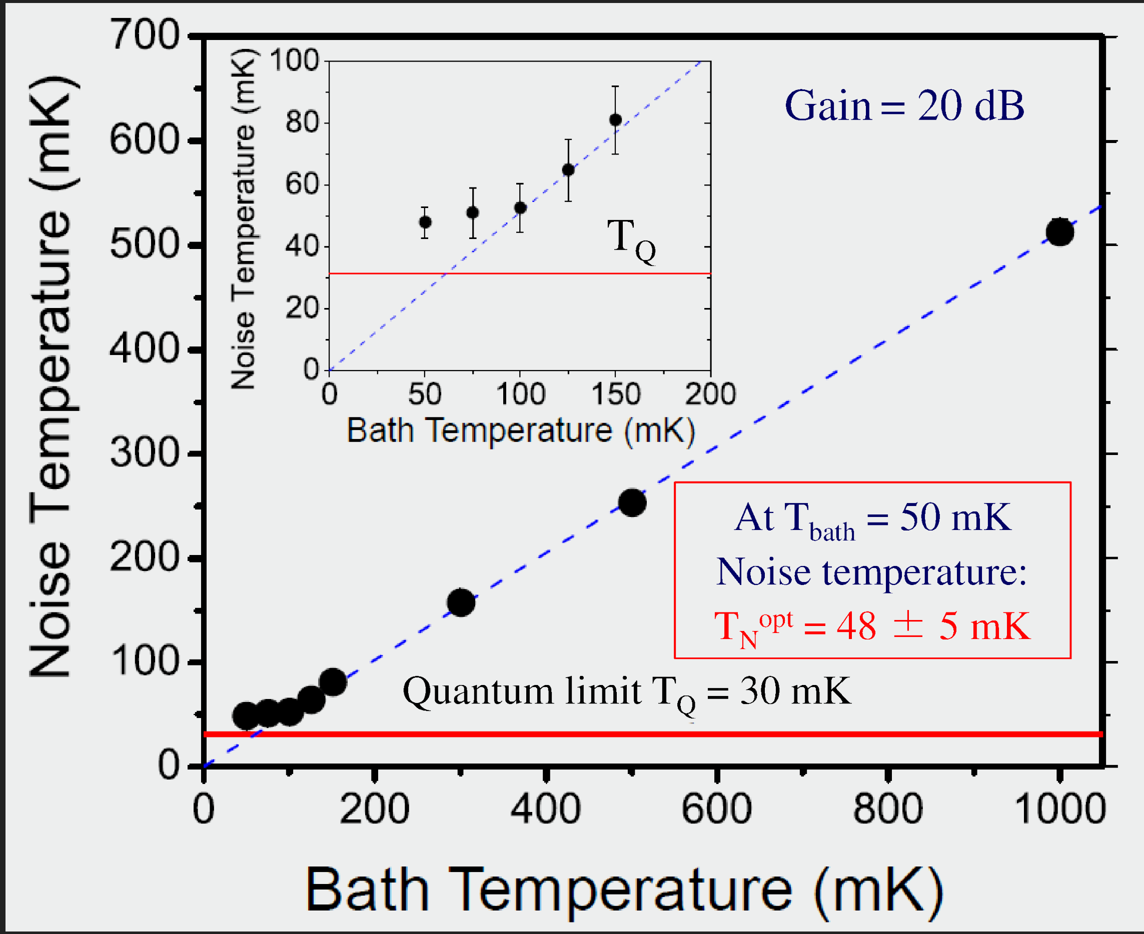


Key Technology: Quantum Limited Amplifiers

Superconducting amplifiers like SQUIDs and JPAs operate at the standard quantum limit: minimum noise added to signal



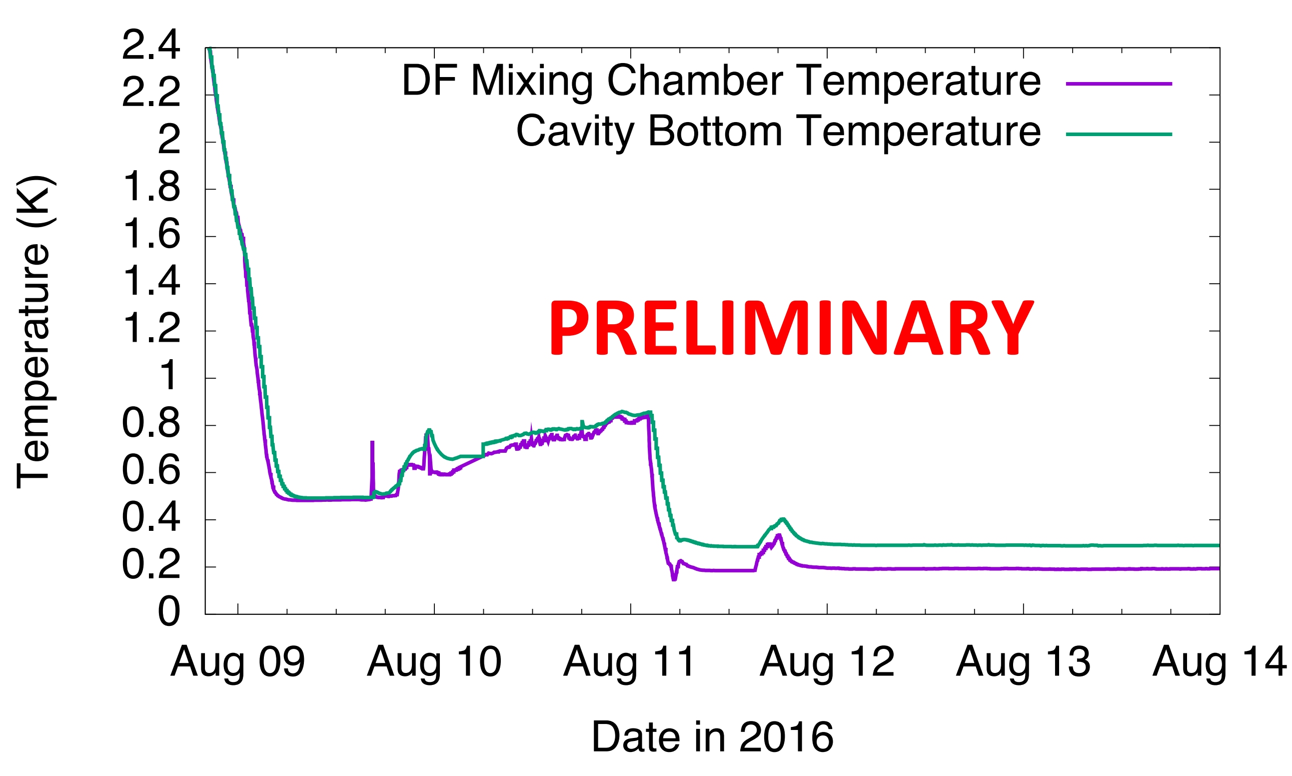
Niobium SQUID amplifier made by Sean O'Kelley Clarke Lab, Berkeley



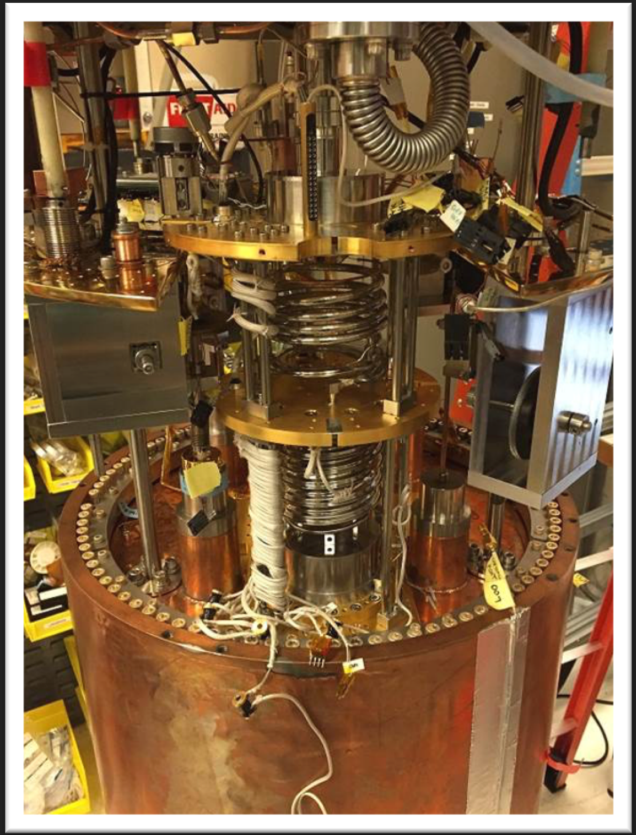
ADMX Current Status

- Previous versions of ADMX have demonstrated sensitivity to optimistically coupled axions over a narrow mass range
- ADMX G2 designed to search pessimistically coulped axion dark matter in the 0.5 to 10 GHz range over the next 5 years
- 2016-2017 Phase: 3 Channels operating ~700 MHz, 2 GHz, 5 GHz
- Experiment underwent cold commissioning during the summer
  - Preliminary measurements indicate 700 MHz and 5 GHz channels fit for science data
- Data acquired during Data taking/Commissioning Run in August-September under analysis
- Experimental insert warm, undergoing optimization
- Resume data taking early next year

Operating Parameters



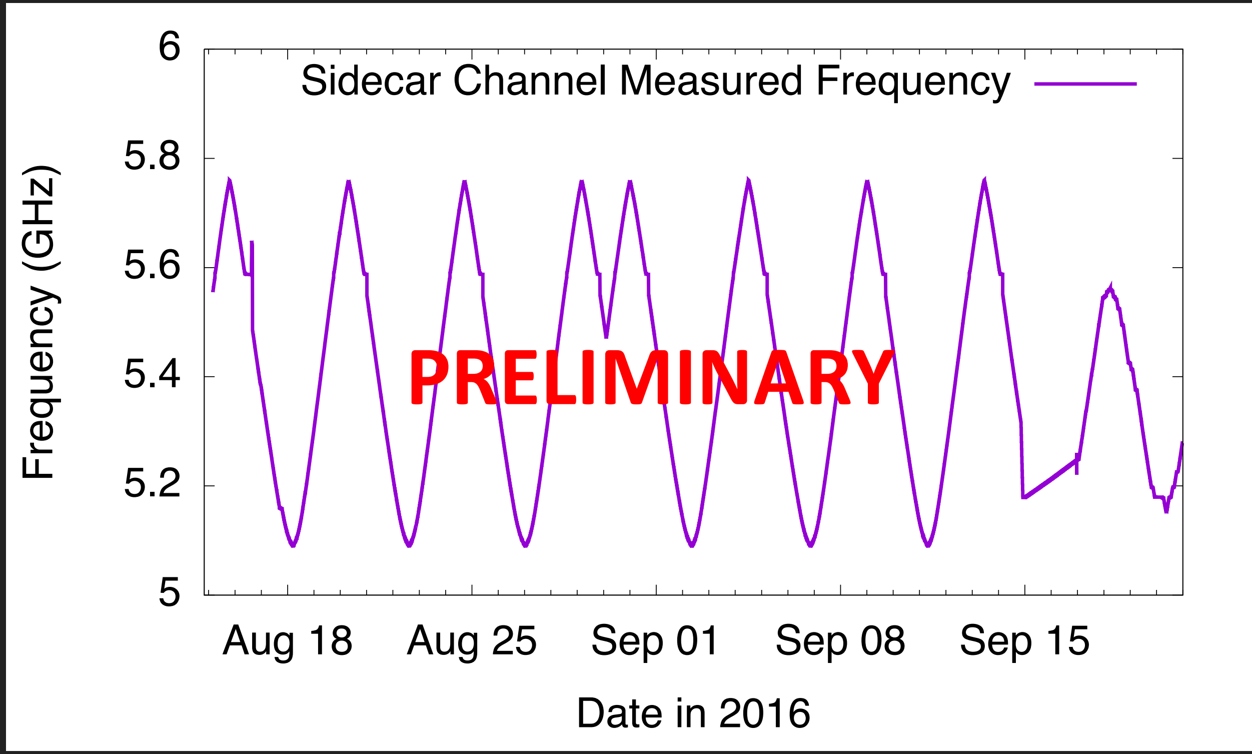
Temperatures during fridge cooldown
Temperatures held steady around 200 mK
for over a month



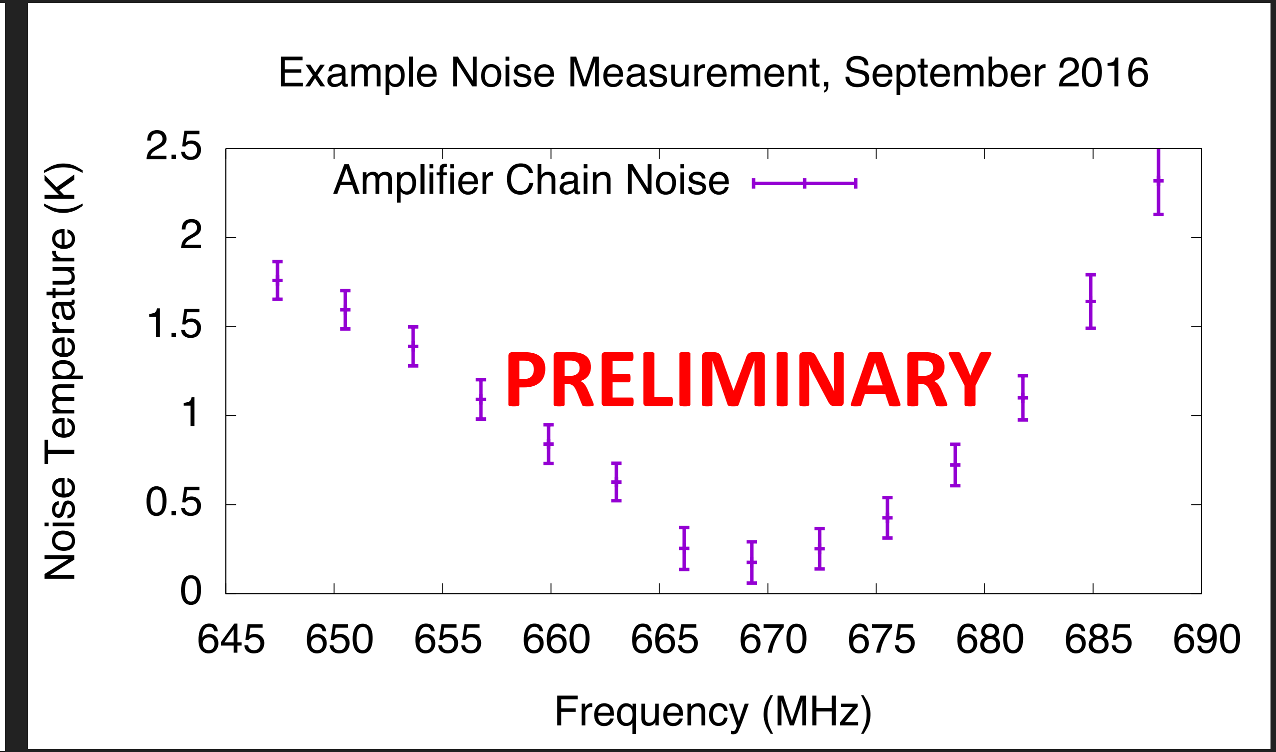
Dilution refrigerator installed above cavity

Early ADMX Data

Data around 700 MHz and 5 GHz undergoing analysis

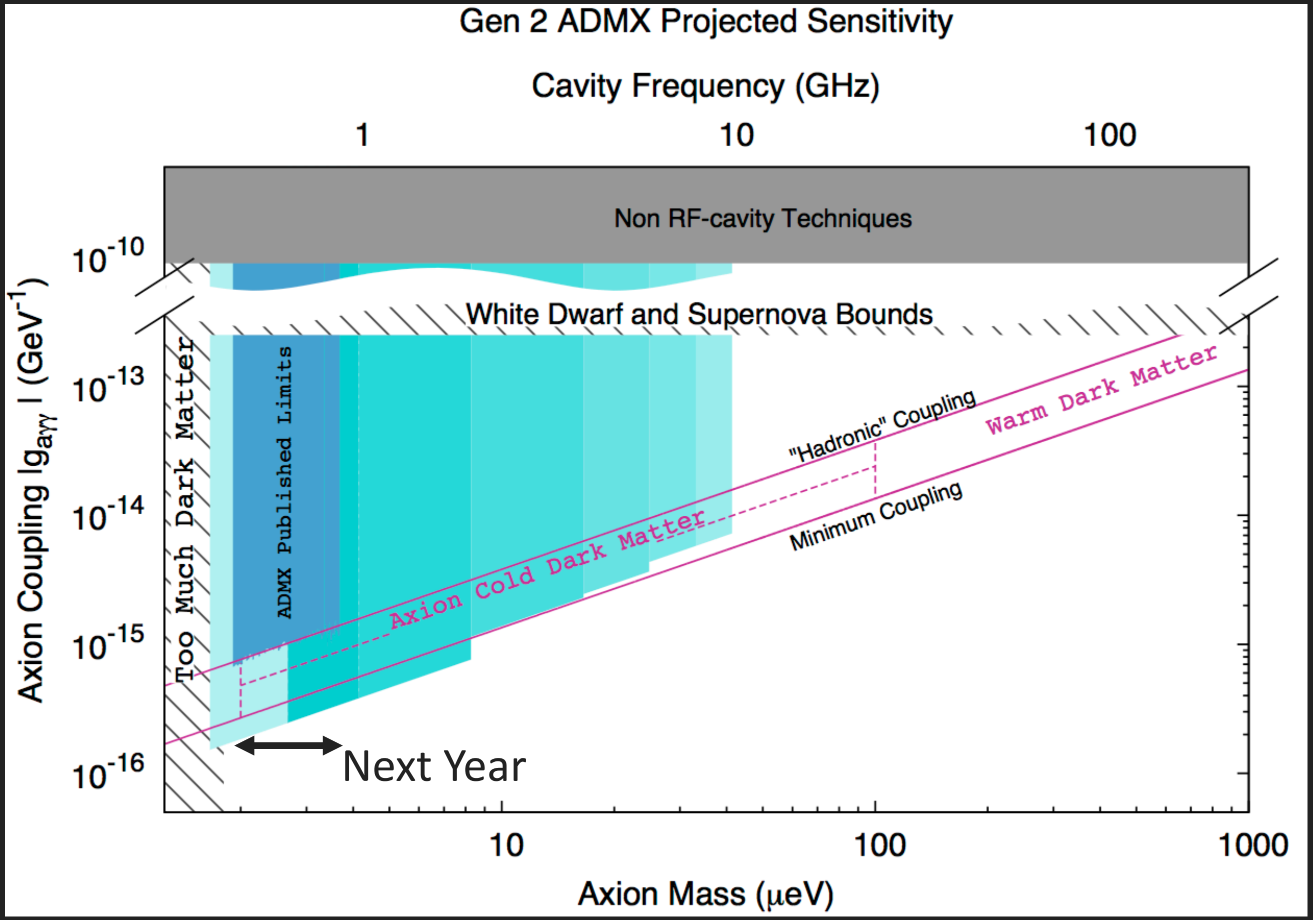


Scanning (and rescanning) around 5 GHz



700 MHz channel RF chain noise measurement with MSA tuned optimally to 670 MHz. Shows sub-Kelvin noise temperature

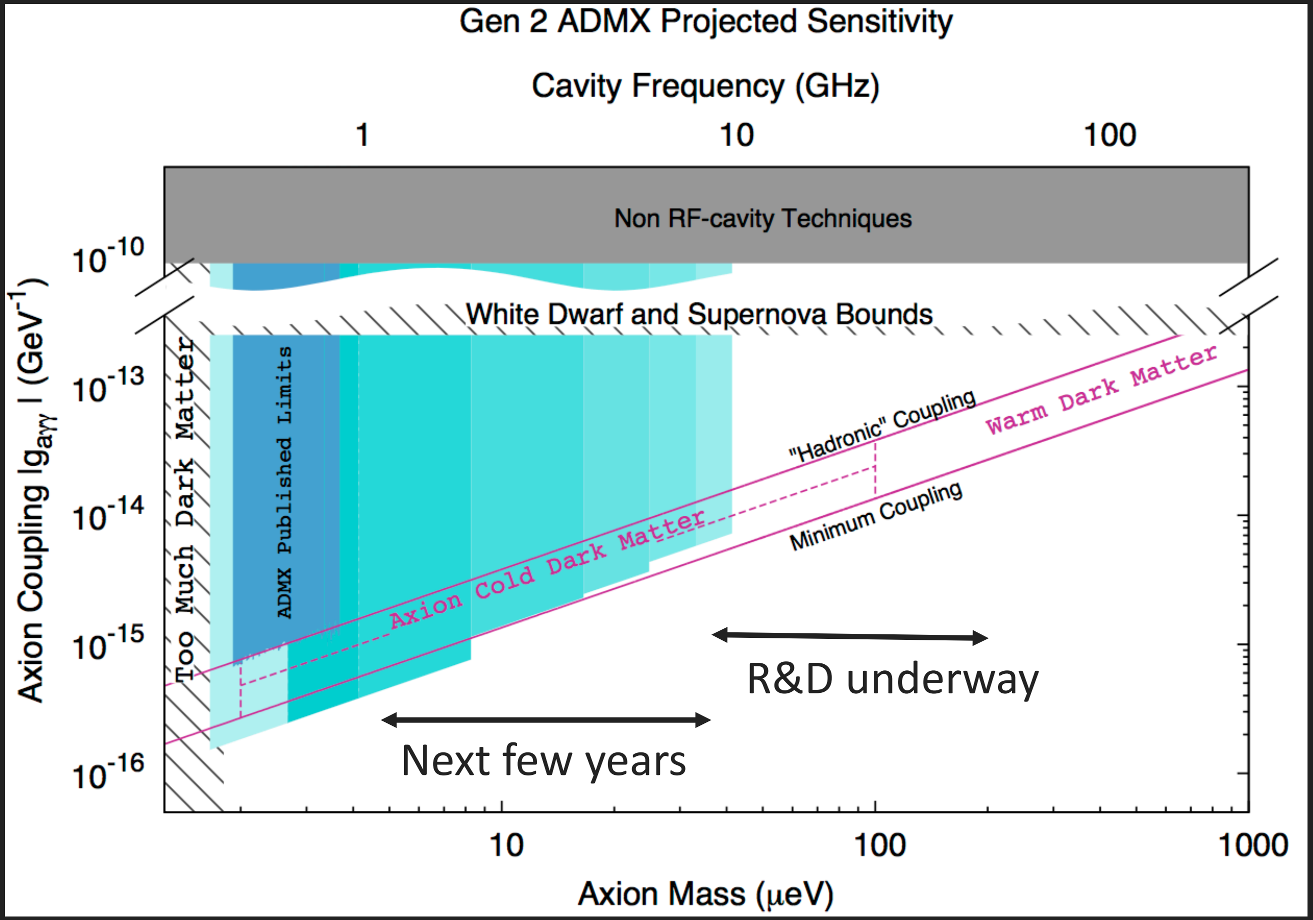
ADMX G2 Projected Sensitivity – Next Year

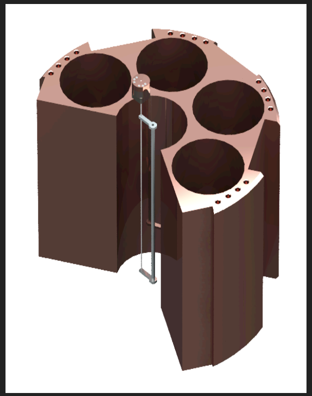


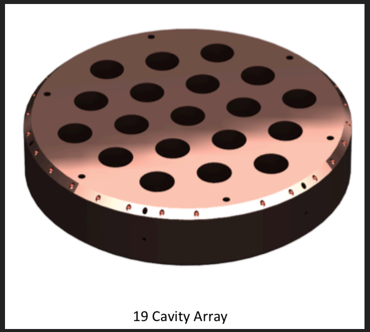
ADMX G2 will scan for 500 MHz-1 GHz in 2016-2017 using a single cavity

Sensitive to even pessimistically coupled axion dark matter

ADMX G2 Projected Sensitivity





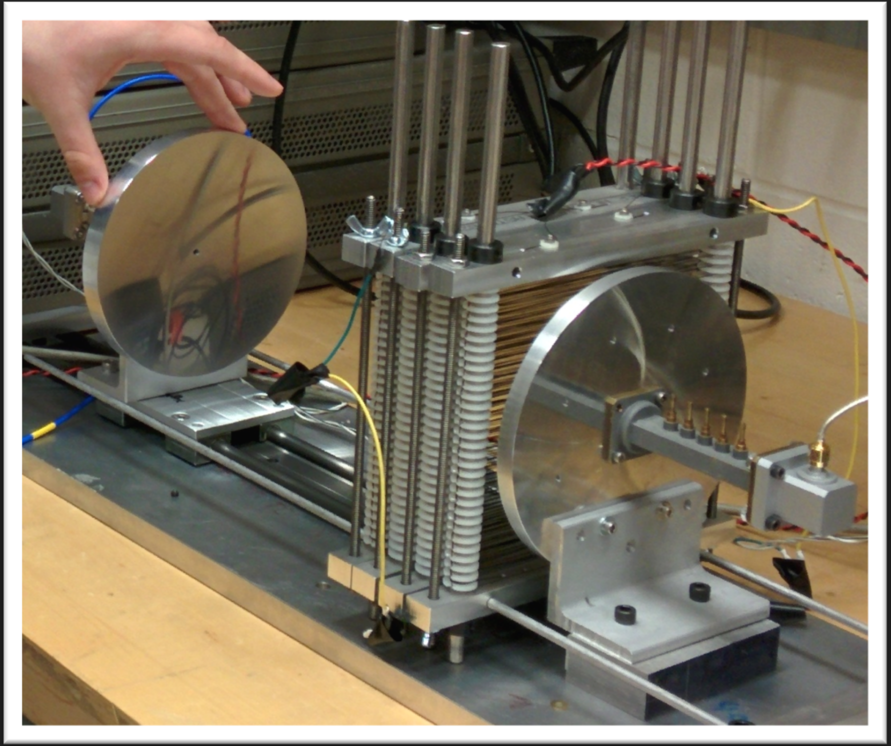


ADMX G2 will scan 500 MHz – 10 GHz in the next 5 years using cavity arrays

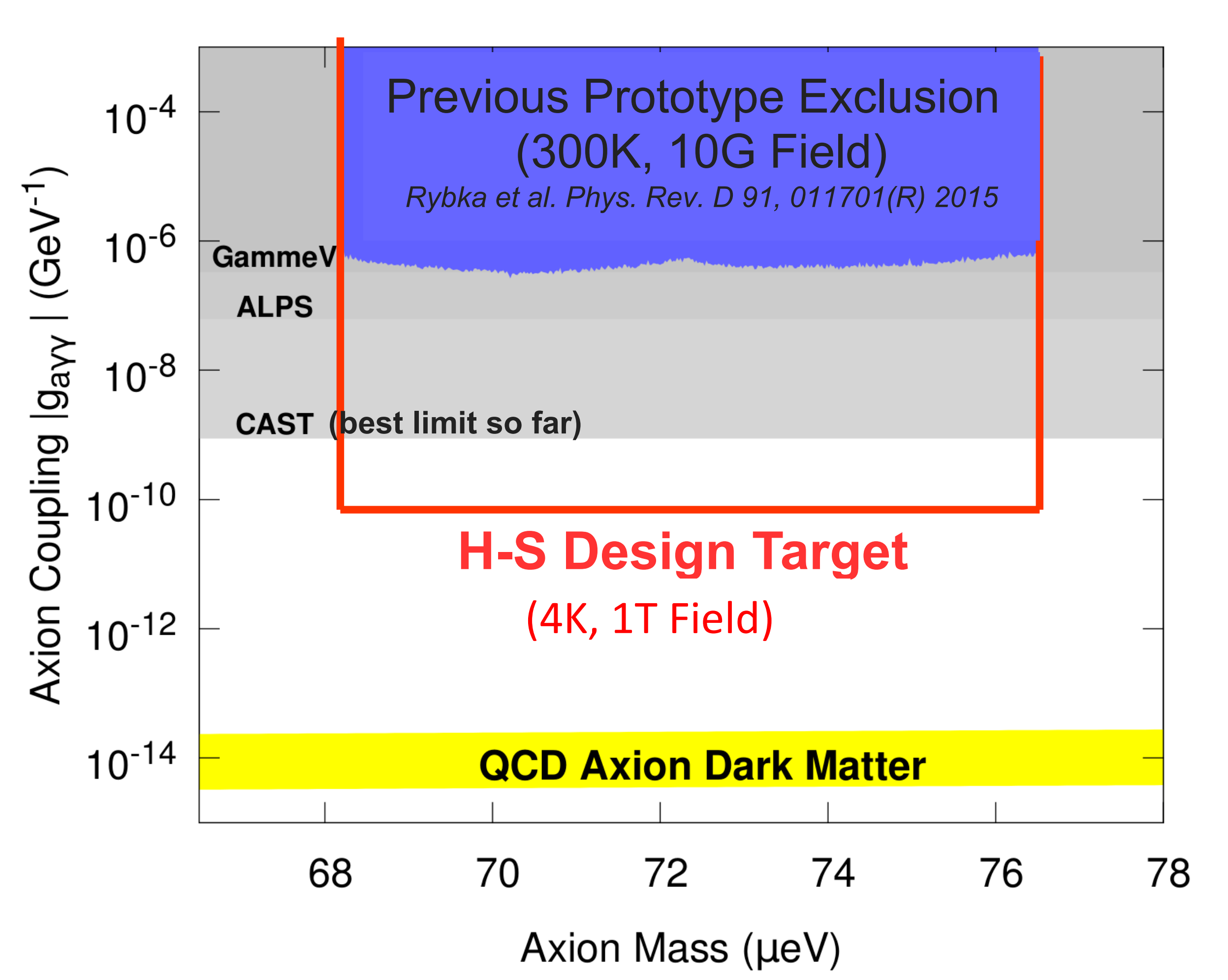
Excellent chance of discovery!

Plus R&D into higher frequencies…

ADMX R&D High Frequency Resonators



Multiwavelength resonators may allow access to higher frequencies



ADMX R&D: Single Photon Detection

Single photon counting allows sensitivity below the standard quantum limit. Work underway at FNAL/U. Chicago

Qbit pattern for single photon counting

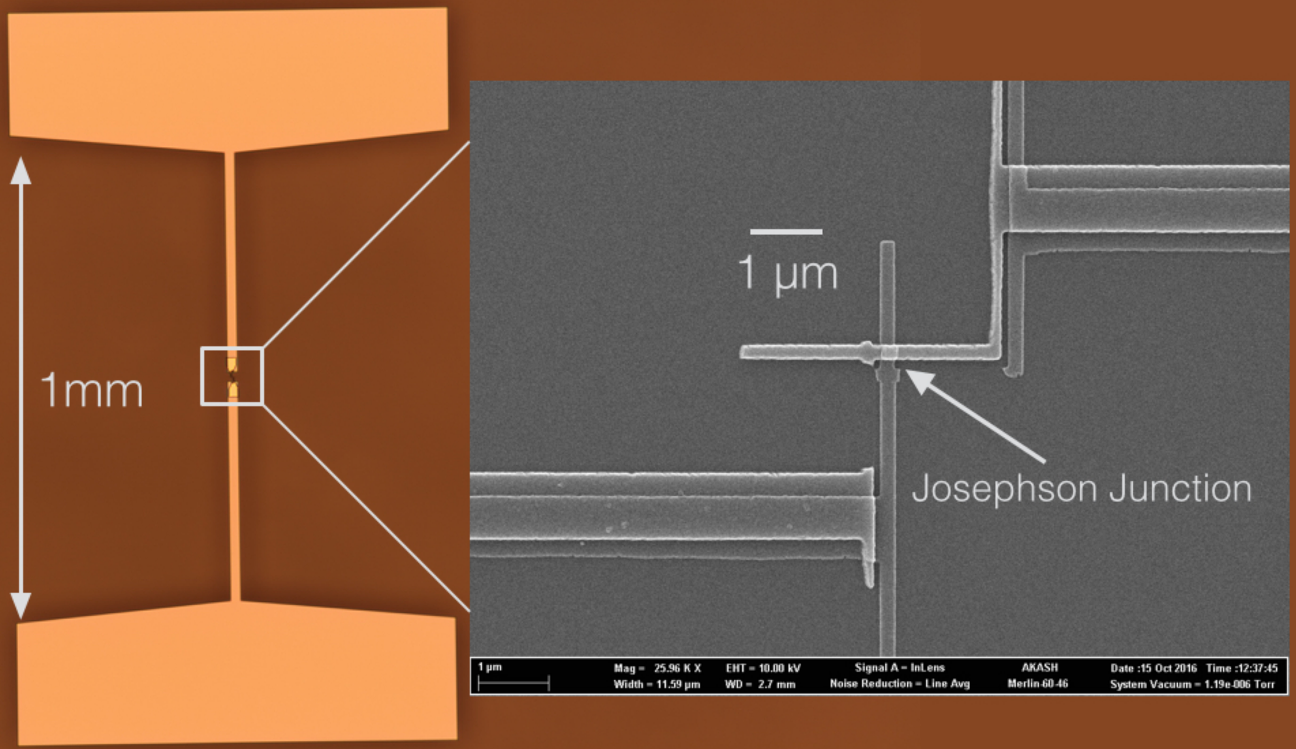
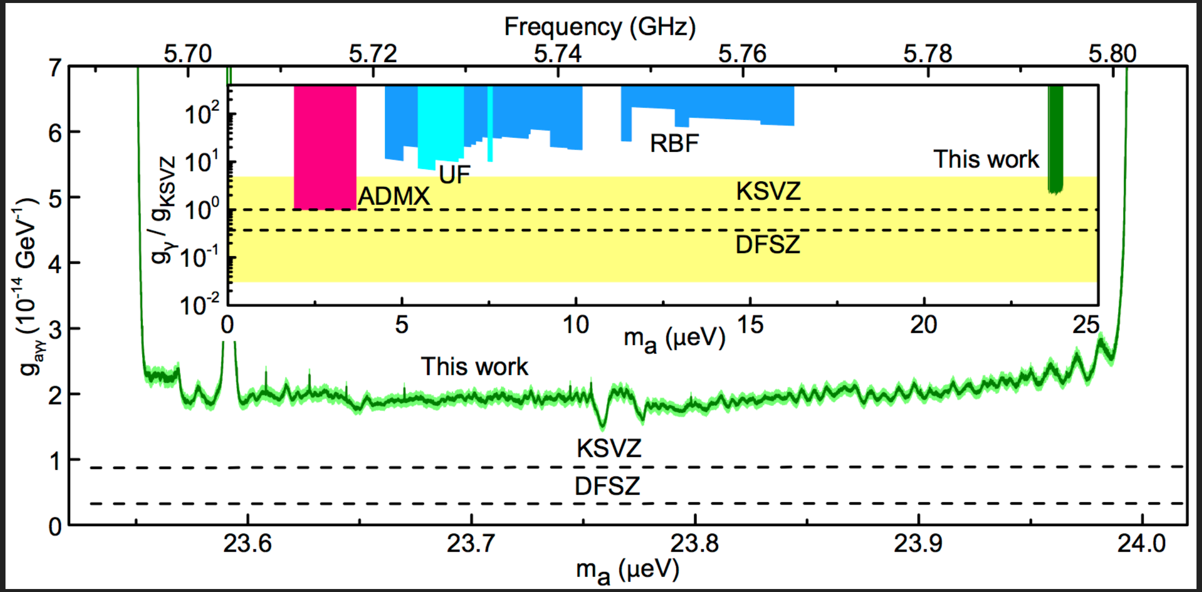


Image courtesy A. Dixit

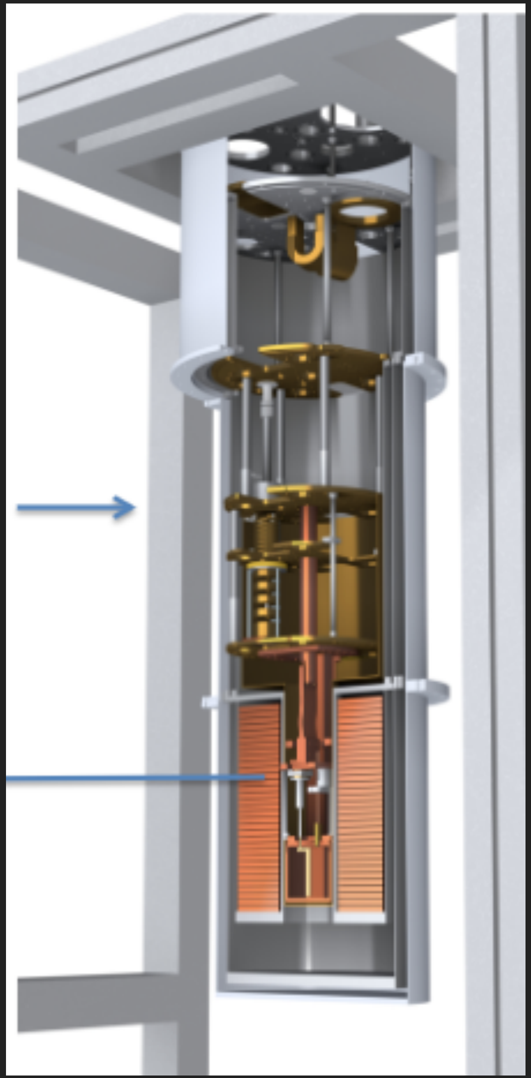
Haloscope R&D: Other Paths

Work at Yale to test "hybrid" superconducting cavities and squeezed-state electronics (eXtreme Axion Experiment)



Recent results from Yale microwave cavity, arXiv:1610:02580

Ultra-low temperatures and aluminum cavity work with CULTASK, at CAPP in Korea



Conclusion I – An Exciting Time for Axion Dark Matter

- The Axion is a compelling dark matter candidate
  - The axion is still the best way to solve the strong CP Problem
  - Theoretical interest in axion physics continues to grow
  - Even in some SUSY models, axions are the majority of dark matter

Axion Dark Matter Theory is Exciting!

- The best Axion Dark Matter parameter space is just about to be explored
  - Experiments underway have good discovery potential
  - Promising R&D to access corners of parameter space
  - QCD axions may be found or experimentally ruled out

Axion Dark Matter Expoeriments are Exciting!

Conclusions II – The Hunt for Dark Matter Axions is On

Exciting parameter space is being covered in the next few years

R&D is underway to cover remaining parameter space in the future