Axion Search Summary

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Dark Matter @ LHC 2019 - Seattle

Why Axions?

The Strong CP Problem

Lack of neutron electron dipole moment
indicates strong force is CP invariant

edm<$3\cdot10^{-26}$ e-cm
Baker et al.
PRL 97 2006

How can the weak force be CP violating but the strong force remains CP invariant? O(10^{-10}) cancellation required

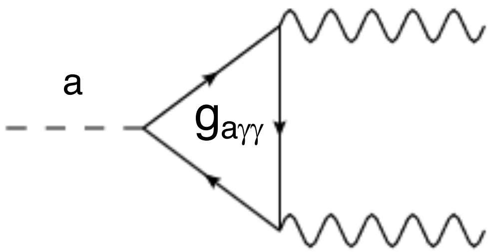
The Peccei-Quinn Solution

Add a dynamic field, spontaneously broken,
which cancels any strong CP violation -Peccei, Quinn

This results in a new pseudoscalar particle, the Axion
-Weinberg, Wilczek

The Axion

The Axion has the same quantum numbers as, and mixes with, the π_0.
This gives a fairly clear picture of how the axion couplings scale with axion mass.



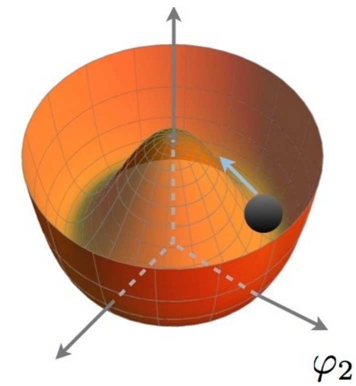
In the QCD axion particular the axion-photon coupling has very little model dependence. Benchmark models:

"KSVZ": Ad hoc "hadronic" axion couplings.
"DFSZ": Grand unification.

"DFSZ" is so compelling that a search needs sensitivity to DFSZ axions in order to be credible. Unfortunately, DFSZ couplings are almost x10 weaker than KSVZ.

Axions as Dark Matter

As the Universe cools and the temperature falls below the Peccei-Quinn symmetry breaking scale, the axion field begins oscillating about the new minimum.



Oscillation about the QCD minimum – *Daniel Grin*

The energy stored in this minimum is Dark Matter, and can be estimated to be at the ueV scale. Uncertainties are due to:

- Inflation scale (axion is a probe of inflation)
- Lattice QCD calculations of instantons
- Additional production mechanisms

The most reasonable assumptions yield a range of axions 1-100 ueV that could produce 100% dark matter.

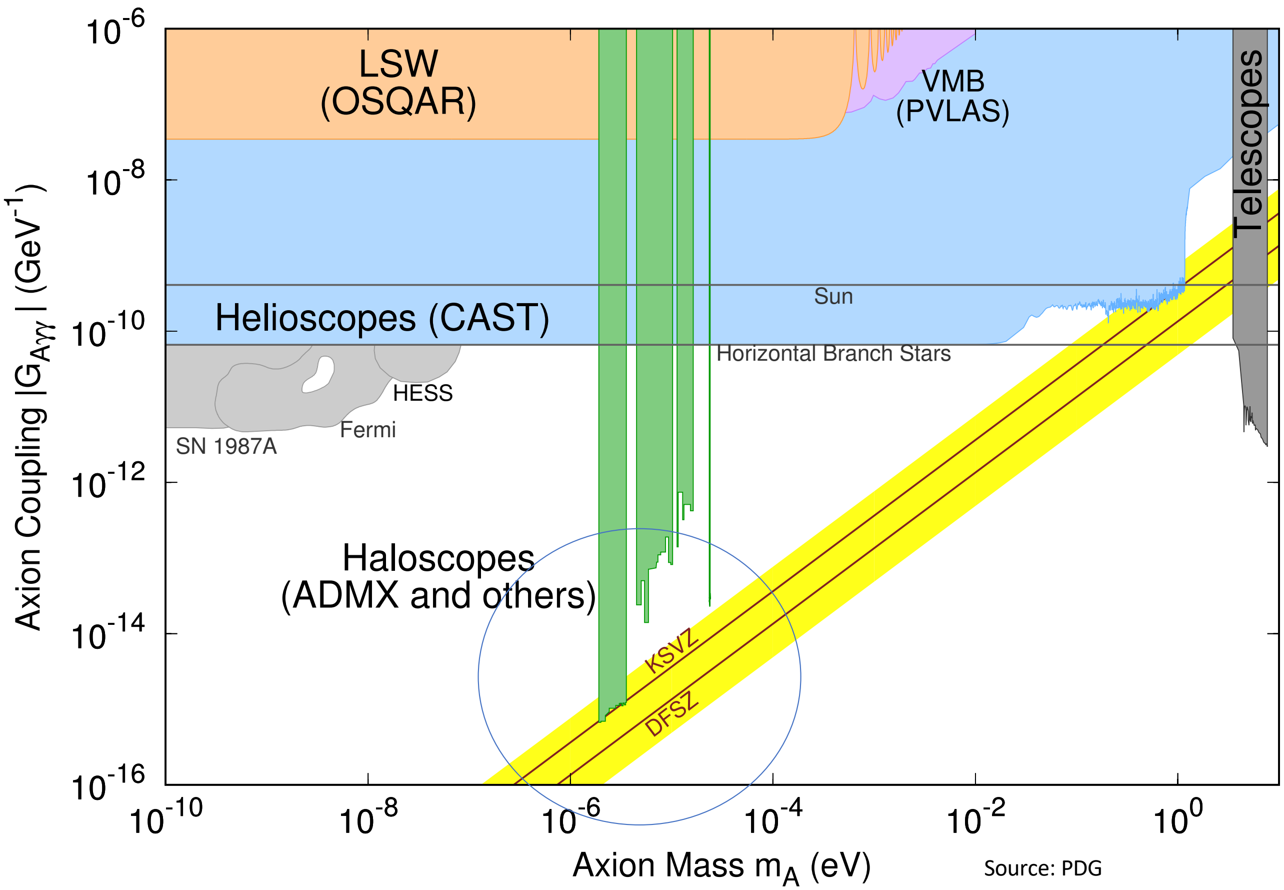
Axion Landscape

The classic axion-like particle experiments are:

Light Shining Through Walls:
Laser photon-axion mixing
E.g. old: OSQAR, ALPS
future: ALPS-II

Helioscopes:
Axions from the sun
E.g. old: CAST, Sumico
future: IAXO

Haloscopes:
Axion dark matter
E.g. old: ADMX, RBF
future: ADMX G2



Source: PDG

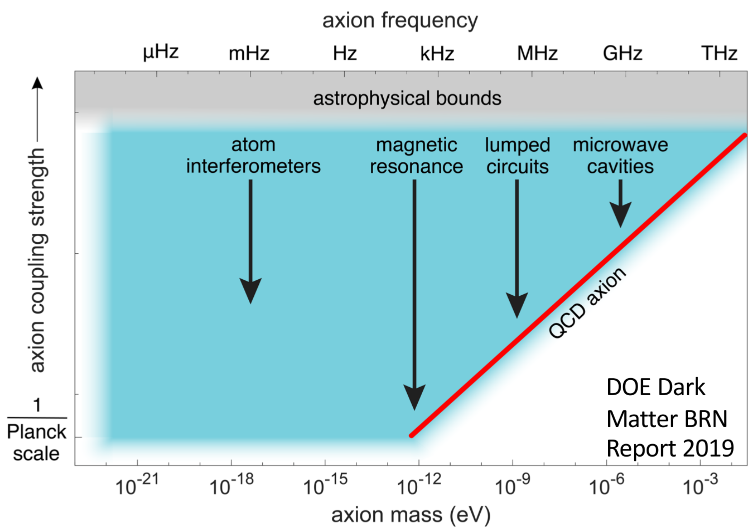
A Wide World of Axion-Like Particles (ALPs)

- The classic view of axion production in the early universe suggests QCD axions must be more than micro-eV to accommodate how much dark matter we see
- However, recently, there has been a lot of exciting work that permits axions to be much lighter or more strongly coupled
  - Removing the strong-CP requirement
  - Anthropic arguments
  - Preferred energy scales
  - Ties to inflation
  - Ties to dark energy
  - Other new physics
- This is a very active field

A Wide World of ALP Searches

There has been an explosion of search techniques being explored

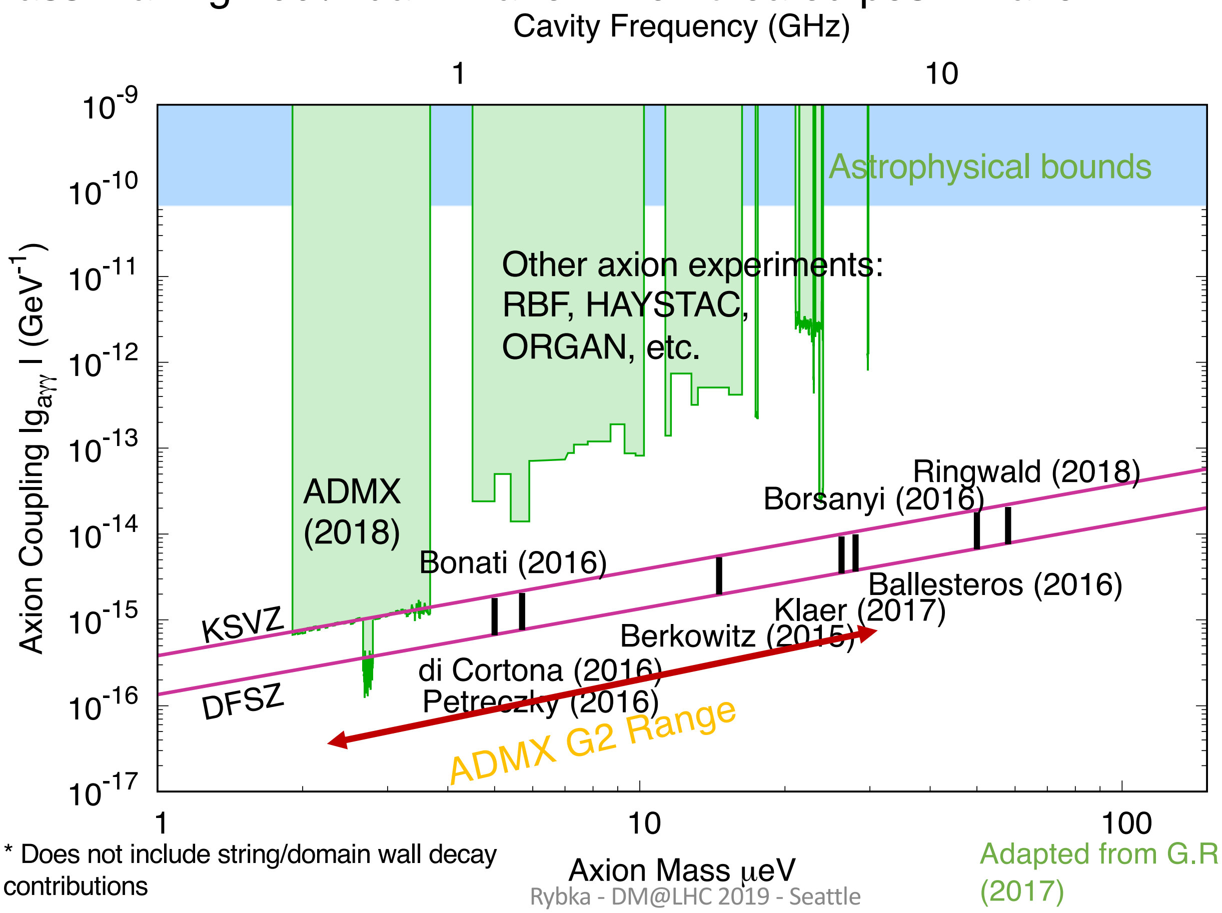
- Black hole superradiance (using LIGO) ~10^{-20} eV
- Time varying nuclear EDM (e.g. CASPER) 10^{-15}-10^{-8} eV
- Lumped circuit haloscopes (ABRACADABRA, DM Radio) 10^{-8} – 10^{-6} eV
- Frequency Metrology, Axion Radar, Atomic Interferometers etc.



These are in too early development to have sensitivity to the QCD axion, but the community is hopeful

The QCD Axion Dark Matter Sweet-Spot

Analytic and Lattice predictions for the "classical" QCD (PQWW) axion mass making 100% dark matter when created post-inflation

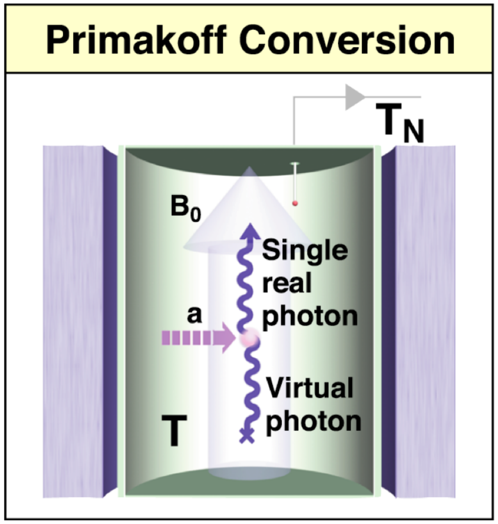


See also
Iwazaki arXiv:1810.07270
For a 7 ueV mass prediction

* Does not include string/domain wall decay contributions

Adapted from G.R, J. Phys. G (2017)

Axion Haloscope: How to search for Dark Matter Axions



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.

Sikivie PRL 51:1415 (1983)

Signal Proportional to

Cavity Volume
Magnetic Field
Cavity Q

Noise Proportional to

Cavity Blackbody Radiation
Amplifier Noise

ADMX "G2" Dark Matter Search
Goal: Find Dark Matter Axions

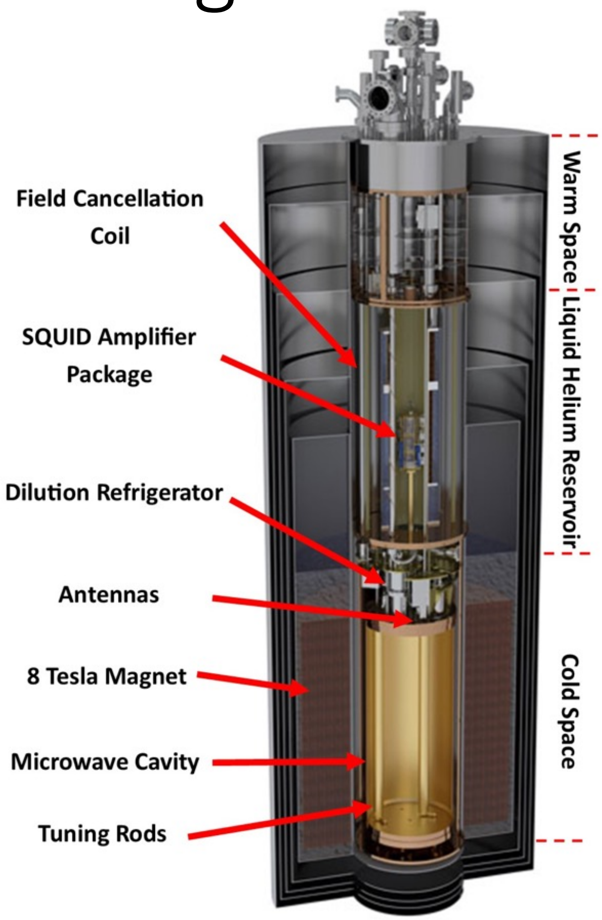
ADMX collaboration meeting, UW, December 2018

Collaborating Institutions:
UW, UFL, LLNL
FNAL, UCB, PNNL
LANL, NRAO, WU, UWA,
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 LLNL and PNNL LDRD programs
and R&D support the Heising-Simons institute

ADMX Design

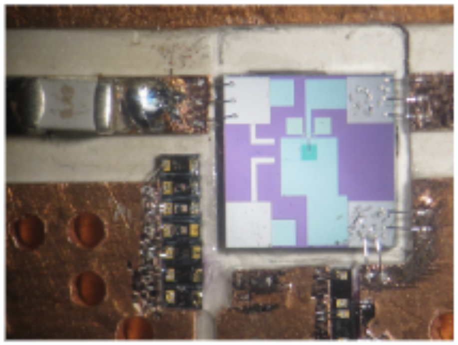


Key technologies:

-millikelvin cryogenics

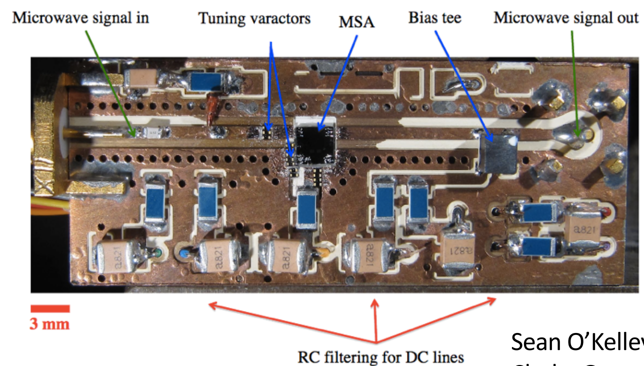
-ultralow noise quantum amplifiers

Quantum Amplifiers



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

ADMX Tunable MSA



Sean O'Kelley,
Clarke Group, UC
Berkeley

ADMX JPA

Yanjie Qiu,
Siddiqi Group,
UC Berkeley

- Enabling Technology!
- Superconducting Interference Device (SQUID) amplifiers
- Josephson Parametric Amplifiers (JPA)

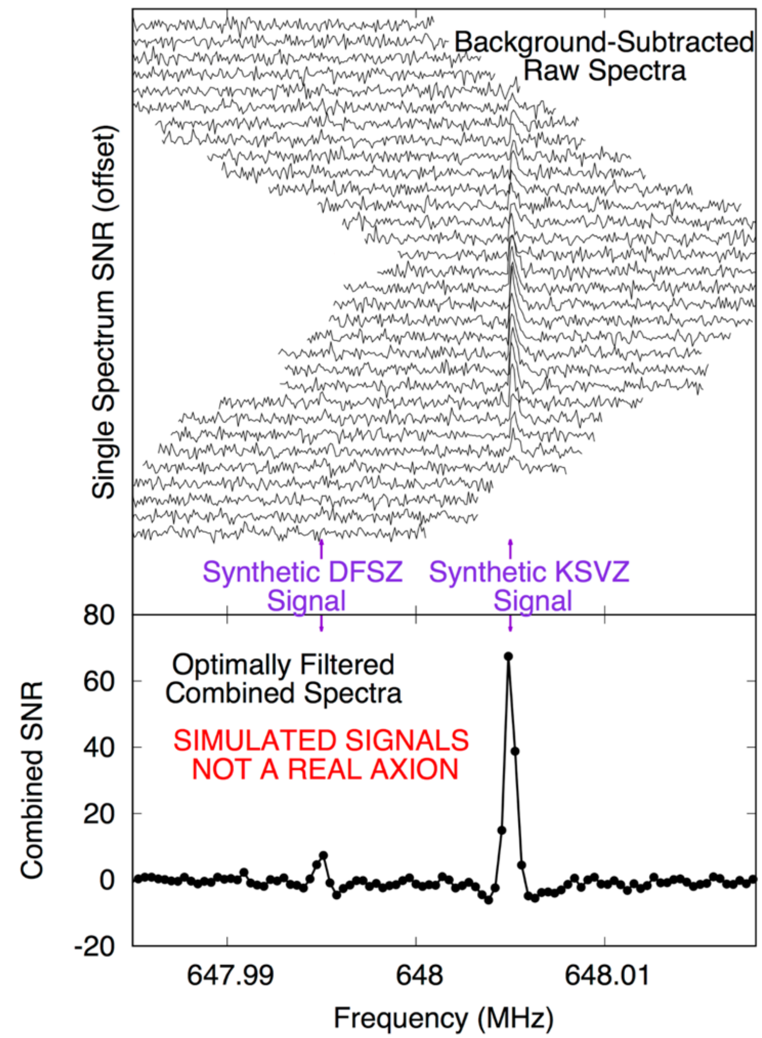
Scanning Technique

The cavity is scanned in few kHz steps with 100 seconds integration ime over the frequency range.

The power spectra are filtered for expected axion lineshapes

Multiple spectra are combined to reach our sensitivity. Candidate excesses are rescanned.

Transient candidates or candidates that do not follow cavity lineshape (RFI) can be vetoed.



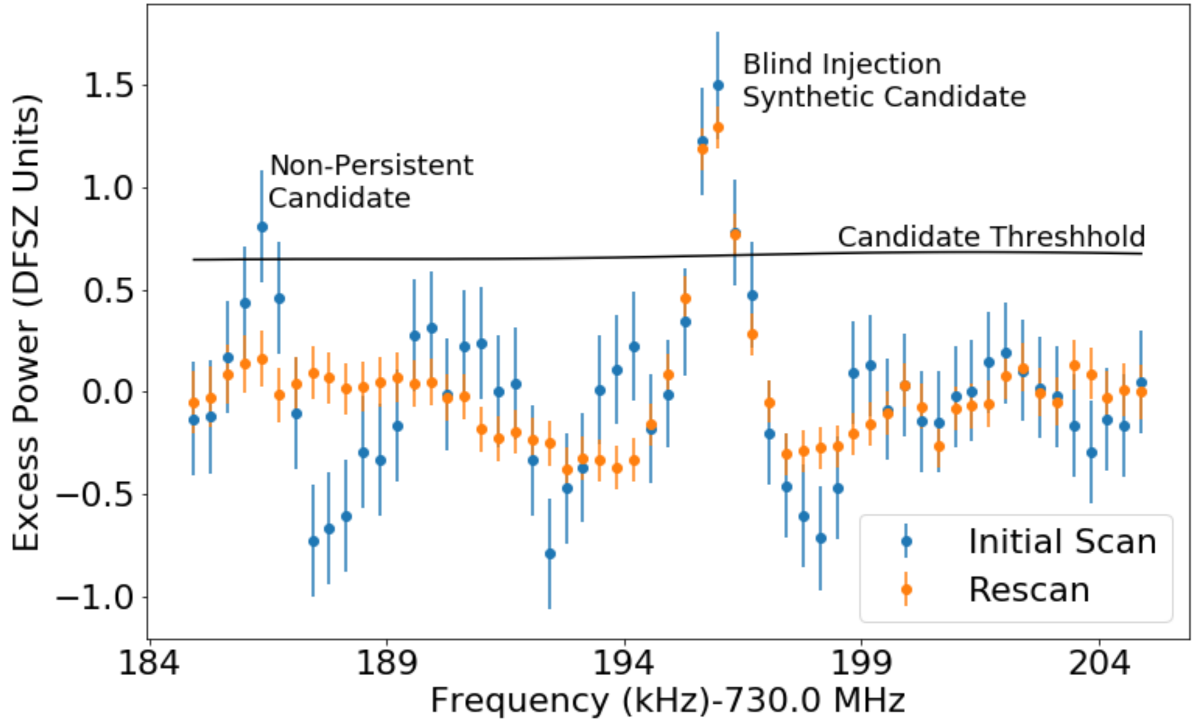
Synthetic Axion Signal Injection

Axion-shaped RF signal are periodically injected into the cavity, blind to the analysis.

Most signals are unblinded at the time of rescan to verify our detection efficiency.

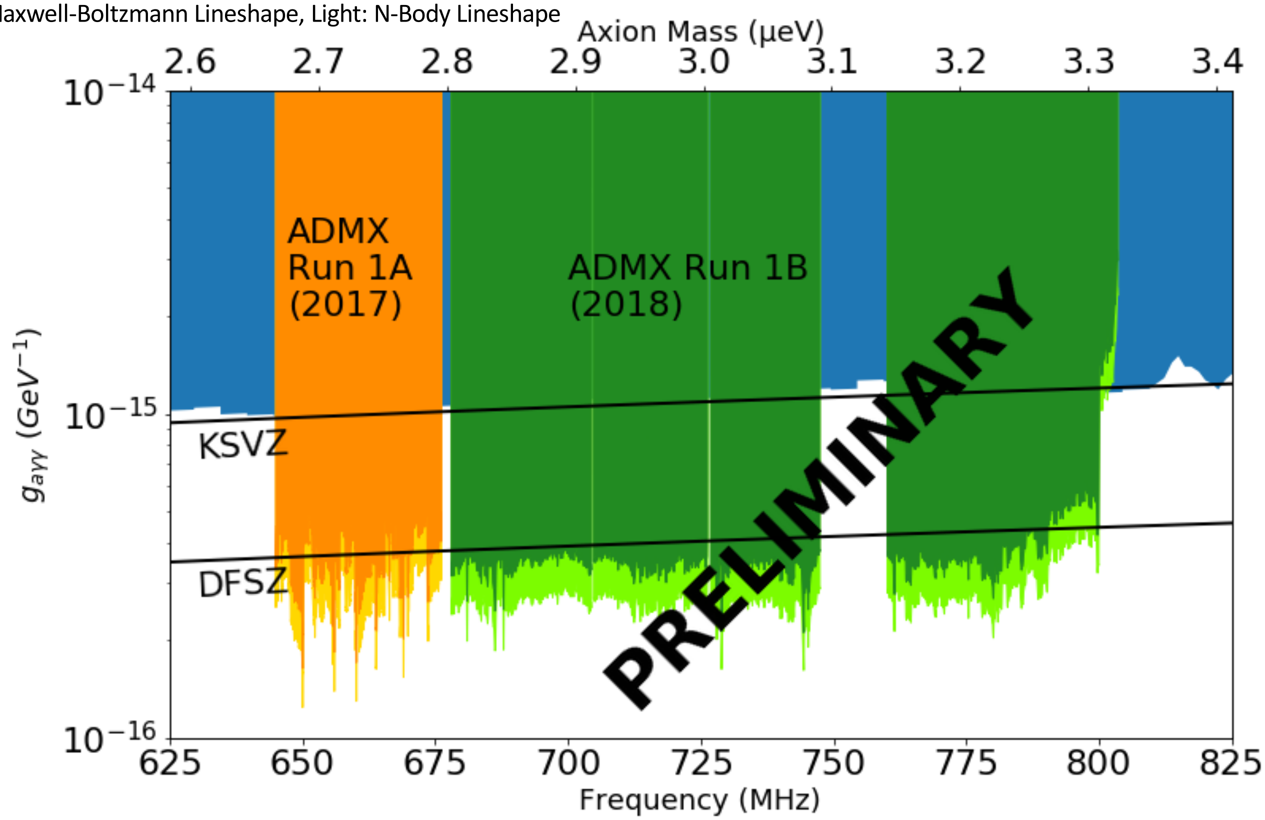
Some (like this one) are not unblinded until the decision to ramp the magnet down.

Note much more data is required in a rescan than during the initial scan.



Preliminary Sensitivity from 2018 Run

Dark: Maxwell-Boltzmann Lineshape, Light: N-Body Lineshape



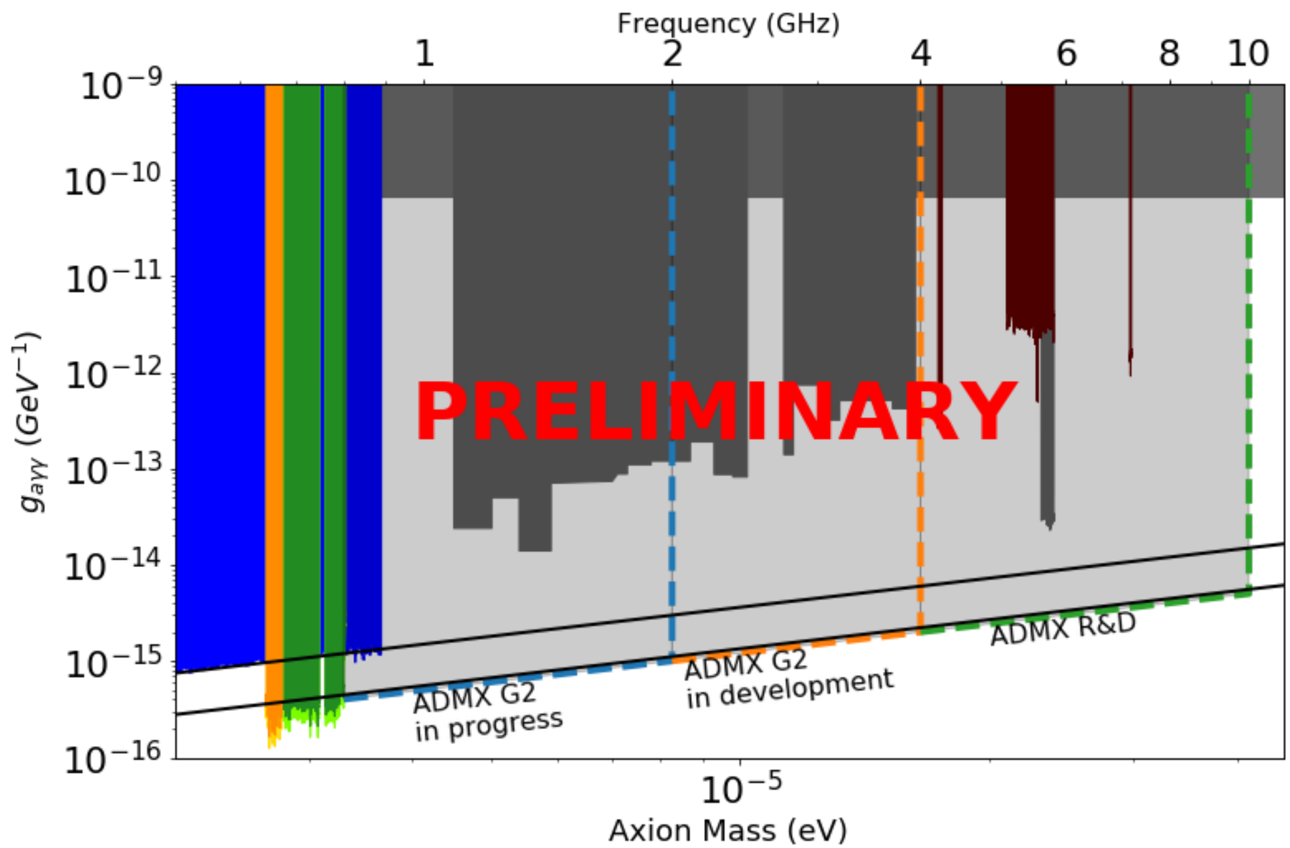
We estimate sensitivity to DFSZ dark matter axions between 2.8 and 3.3 ueV

This is four times as much mass range with much more even DFSZ coverage.

3 Gaps from mode crossings in cavity.

Paper in preparation!

Moving to Higher Frequencies



Why are higher frequencies more challenging?

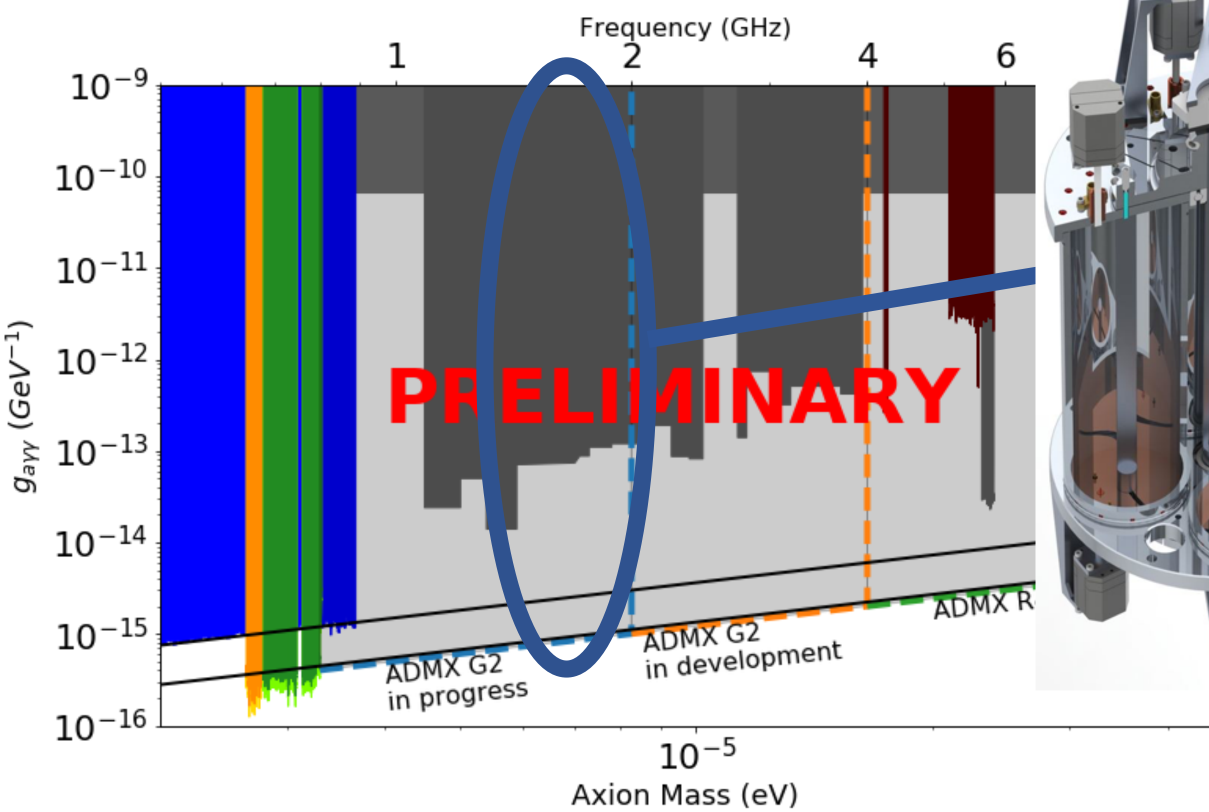
- Smaller resonator volume decreases signal
- Resonator Q worse at high frequencies
- Standard quantum limit increases noise

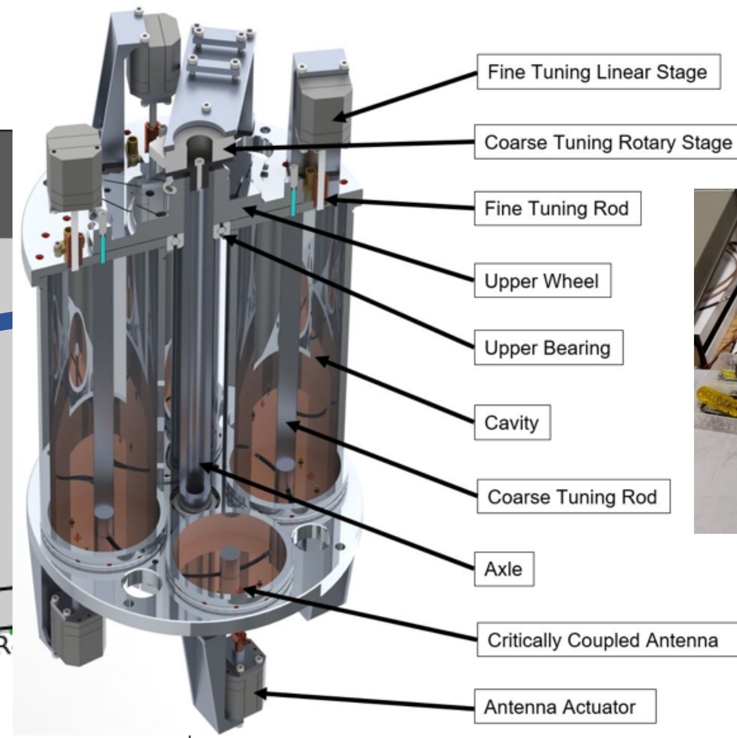
How will future Axion Experiments counter these?

- *More sophisticated, large volume resonators*
- *Sub-quantum limited amplifiers*
- Bigger magnets
- Field tolerant high-Q resonators

ADMX G2 – Multicavity Systems

Maintain detection volume at higher frequencies





Multicavity system 1-2 GHz
Prototype fabricated, tested

Conclusions

The axion is a compelling dark matter candidate

ADMX Gen 2 shows haloscopes are finally sensitive to the most compelling DFSZ axion model in the ideal dark matter axion mass range

We are scanning up in mass, more quickly each year. New technologies are enabling access to higher axion masses.

Discovery could come at any time!