Recent ADMX Results from the DFSZ Frontier

Stockholm University / NORDITA

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University of Washington

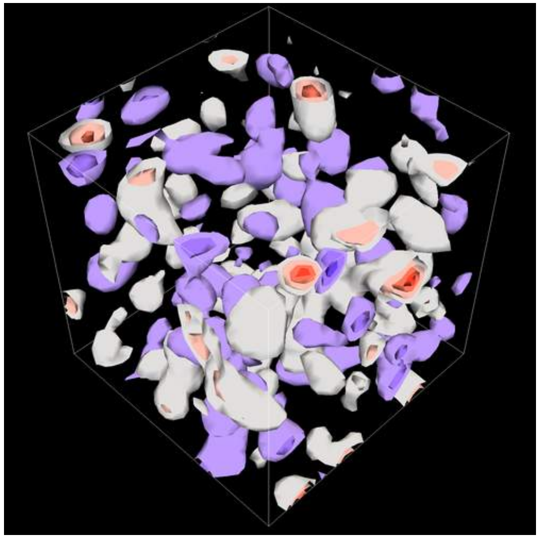
Talk Outline

(brief) QCD, dark matter and axions.
(brief) Why DFSZ couplings and why 1-100 μeV?
Description of ADMX.
Recent results, preliminary results & longer-term plans.
Beyond Gen 2 ADMX.
Conclusions.

The longstanding problem of CP violation

QCD is expected to violate CP.

e.g.,
CP-violating instantons from lattice QCD

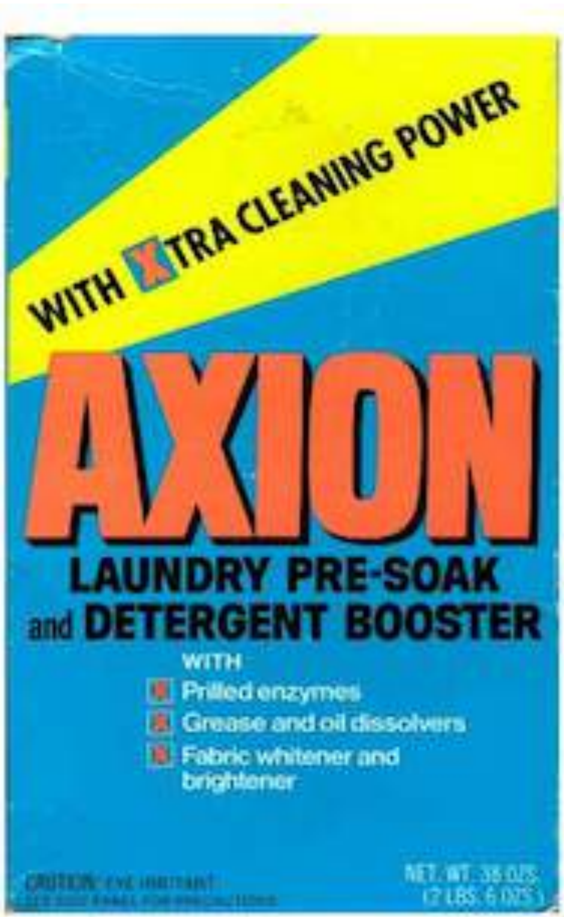


… so one expects a neutron EDM of order 10^{-16} e•cm.
But current bounds on the nEDM are of order 10^{-26} e•cm: the Strong CP Problem.

What to do? Introduce a new, spontaneously broken, axial U(1) symmetry. Yielding a new Higgs-like boson (the axion) and new terms in the QCD potential with a minimum where CP violation vanishes.

The axion shares quantum numbers with the π^0, so they mix and $m_a = m_\pi f_\pi / f_a$.

The axion “cleans up QCD”



(With apologies to Frank.)

“I named them after a laundry detergent since they clean up a problem with the axial current.”
2004 Frank Wilczek (Nobel lecture).

The longstanding problem of dark matter

ADMX
AXION DARK MATTER EXPERIMENT

FIRST ATTEMPT AT A THEORY OF THE ARRANGEMENT AND MOTION OF THE SIDEREAL SYSTEM[1]

By J. C. KAPTEYN[2]

ABSTRACT

First attempt at a general theory of the distribution of masses, forces, and velocities in the stellar system.—(1) *Distribution of stars.* Observations are fairly well represented, at least up to galactic lat. 70°, if we *assume that the equidensity surfaces are similar ellipsoids of revolution*, with axial ratio 5.1, and this enables us to compute quite readily (2) *the gravitational acceleration at various points due to such a system*, by summing up the effects of each of ten ellipsoidal shells, in terms of the acceleration due to the average star at a distance of a parsec. The *total number of stars* is taken as 47.4×10^9. (3) *Random and rotational velocities.* The nature of the equidensity surfaces is such that the stellar system cannot be in a steady state unless there is a general rotational motion around the galactic polar axis, in addition to a random motion analogous to the thermal agitation of a gas. In the neighborhood of the axis, however, there is no rotation, and the behavior is assumed to be like that of a gas at uniform temperature, but with a gravitational acceleration (G_η) decreasing with the distance ρ. Therefore the density Δ is assumed to obey the barometric law: $G_\eta = -\bar{w}^2(\delta\Delta/\delta\rho)/\Delta$; and taking the mean random velocity $\bar{u}$ as 10.3 km/sec., the author finds that (4) *the mean mass of the stars* decreases from 2.2 (sun = 1) for shell II to 1.4 for shell X (the outer shell), the average being close to 1.6, which is the value independently found for the average mass of both components of visual binaries. In the galactic plane the resultant acceleration—gravitational minus centrifugal—is again put equal to $-\bar{w}^2(\delta\Delta/\delta\rho)/\Delta$, $\bar{u}$ is taken to be constant and the average mass is assumed to decrease from shell to shell as in the direction of the pole. The angular velocities then come out such as to make the linear rotational velocities about constant and equal to 19.5 km/sec. beyond the third shell. If now we suppose that part of the stars are rotating one way and part the other, the relative velocity being 39 km/sec., we have a quantitative explanation of the phenomenon of star-streaming, where the relative velocity is also in the plane of the Milky Way and about 40 km/sec. It is incidentally suggested that when the theory is perfected it may be possible to determine *the amount of dark matter* from its gravitational effect. (5) The *chief defects of the theory* are: That the equidensity surfaces assumed do not agree with the actual surfaces, which tend to become spherical for the shorter distances; that the *position of the center of the system* is not the sun, as assumed, but is probably located at a point some 650 parsecs away in the direction galactic long. 77°, lat. −3°; that the average mass of the stars was assumed to be the same in all shells in deriving the formula for the variation of G_η with ρ on the basis of which the variation of average mass from shell to shell and the constancy of the rotational velocity were derived—hence either the assumption or the conclusions are wrong; and that no distinction has been made between stars of different types.

1. *Equidensity surfaces supposed to be similar ellipsoids.*—In *Mount Wilson Contribution* No. 188[3] a provisional derivation was given of the star-density in the stellar system. The question was there raised whether the inflection appearing near the pole in the

[1] *Contributions from the Mount Wilson Observatory*, No. 230.

[2] Research Associate of the Mount Wilson Observatory.

[3] *Astrophysical Journal*, 52, 23, 1920.

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Kapetyn 1922

as to the distribution of dark matter. It would appear from the comparison that the dark mass must be relatively more frequent near the galactic plane than far from it, but the data are too uncertain to derive numerical results. A similar conclusion was reached by KAPTEYN in the investigation quoted above.

Recognized by Oort 1932

… then Zwicky, Smith 1937 …

What is dark matter?

Not atoms
Not low mass stars
Not black holes
Not neutrinos

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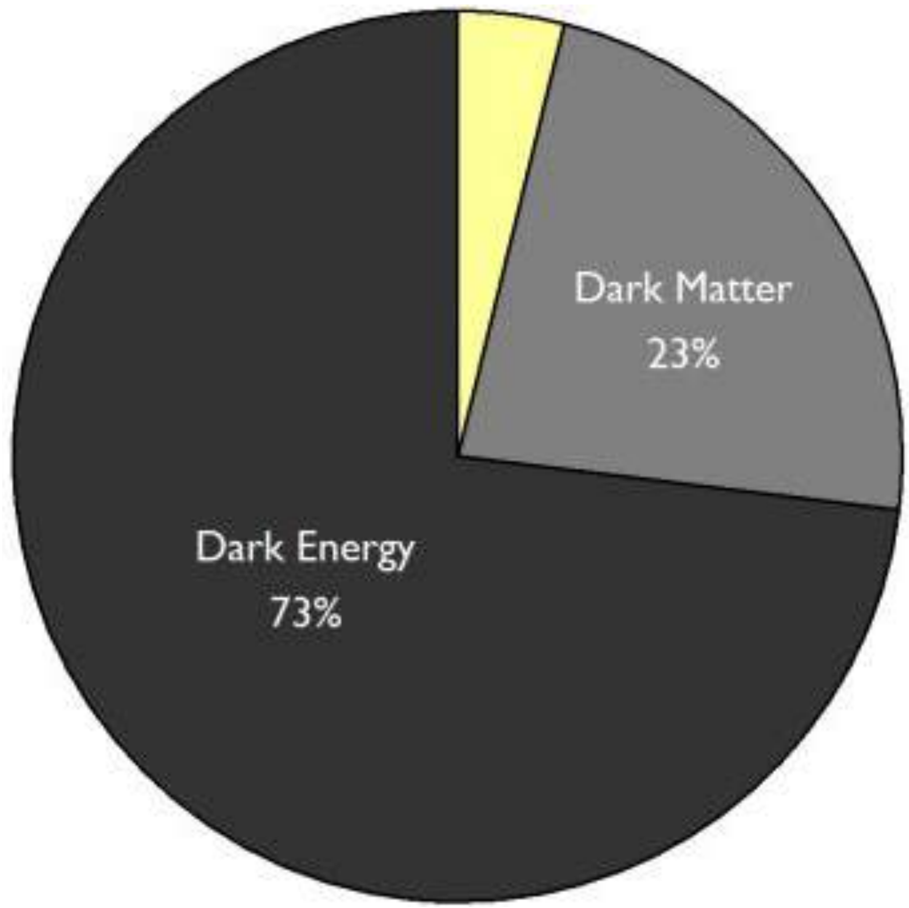
Not anything in the Standard Model

Two “known unknowns:”
WIMPS & axions



“Dark Energy” Wikipedia

Approximate dark-matter and dark-energy fractions of the universe

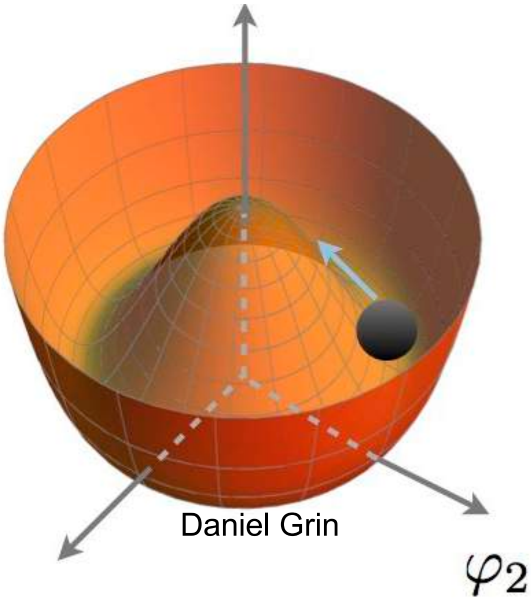
Axions and dark matter

As the Universe cools and the temperature falls to f_a, the new U(1) symmetry is broken and axions appear.

But the QCD potential is not likely close to the minimum, so the axion field then oscillates about the minimum.

There's energy in field oscillations (the dark matter), with contribution to closure density:

$$\frac{\Omega_a}{\Omega_c} = \left(\frac{f_a}{0.45\times 10^{12}\ GeV}\right)^{1.18} \theta^2$$

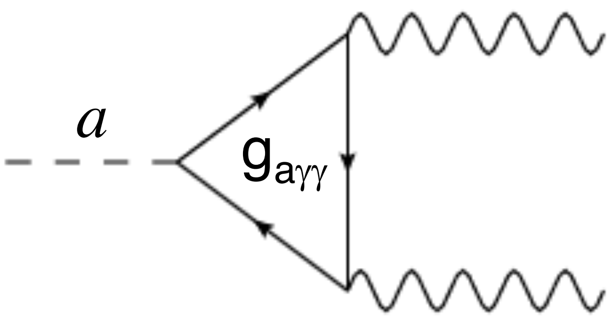


For $\Omega_a \approx \Omega_c$, $f_a \approx 10^{12} GeV$ and $m_a \approx$ 10's μeV for θ of order 1.
This probably isn't too far off; after all, the axion has the quantum numbers of the π^0 so this is what you get from dimensionality. You can work very hard to do better, but if your result deviates much from this, you're probably either injecting new physics or mighjt have made a mistake.

What's the axion coupling to normal matter and radiation?

In general, the coupling of axion to normal matter and radiation is hard to estimate; the new U(1) symmetry has unknown U(1) couplings.

However, estimates of the axion to two-photon coupling are much more robust:



This contains loops with color (N) and loops with electric charge (E). This process contains E and N as E/N: the U(1) charges at the axion vertex cancel with little model dependence.

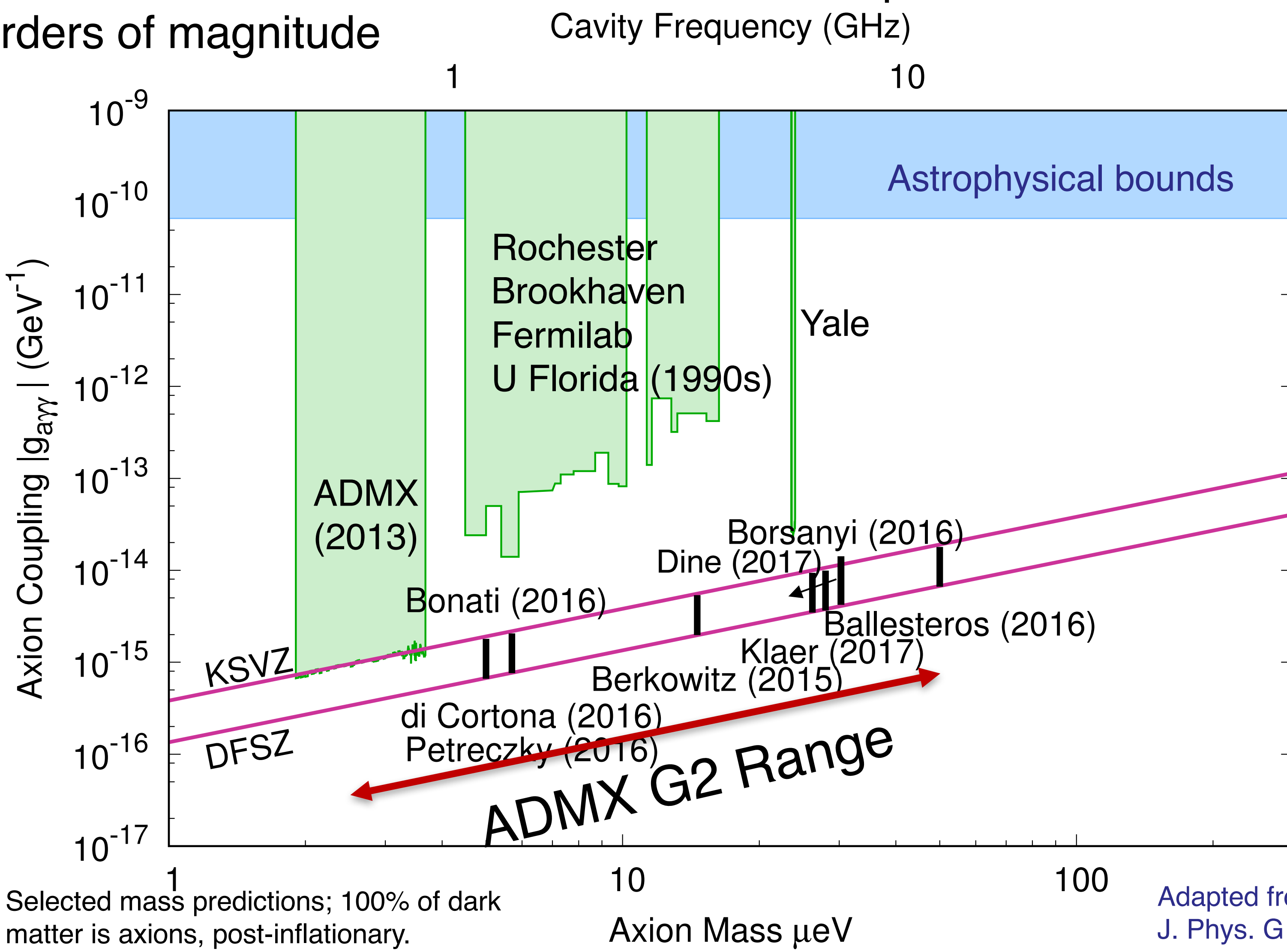
Two benchmark axion models:

"KSVZ": With ad hoc "hadronic" axion couplings: E=0; an early milestone model.
"DFSZ": 1/(E/N) = 3/8 from unification and $\sin^2\theta_w$=3/8. If your result deviates much from this, you're probably either injecting new physics or made a mistake.

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

Predictions of dark-matter axion mass

For axions to be most of the dark matter, the predictions fall within a few orders of magnitude



Selected mass predictions; 100% of dark matter is axions, post-inflationary.

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

Theoretical restlessness: Other masses and couplings for the QCD dark-matter axion?

Could DFSZ axions couple more strongly?
Which of unrenormalized $\sin^2\theta_w$=3/8 or unification do you give up? Or new physics?

Could axions be much heavier?
But limits from supernovae, white dwarfs, neutron stars in different channels.
Can all limits be far off from the dimensionality arguments, is new physics at play?

Could axions be much lighter?
Fine-tuning to counter suppression of light-axion production, or anthropic arguments?
New physics to control isocurvature fluctuations.
Fine-tuning the scale of inflation.
Even eventual problems with baryogenesis.

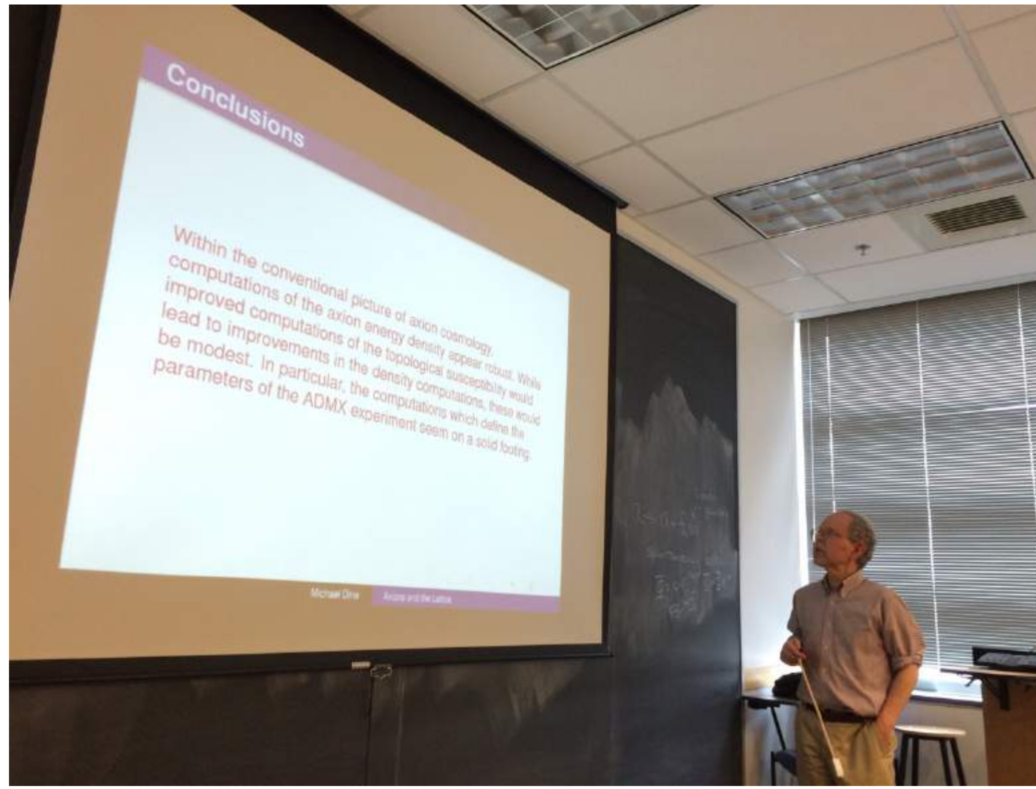
.
. etc. etc.
.

Very light axions require fine tuning, special scales, new physics or introduce new problems.

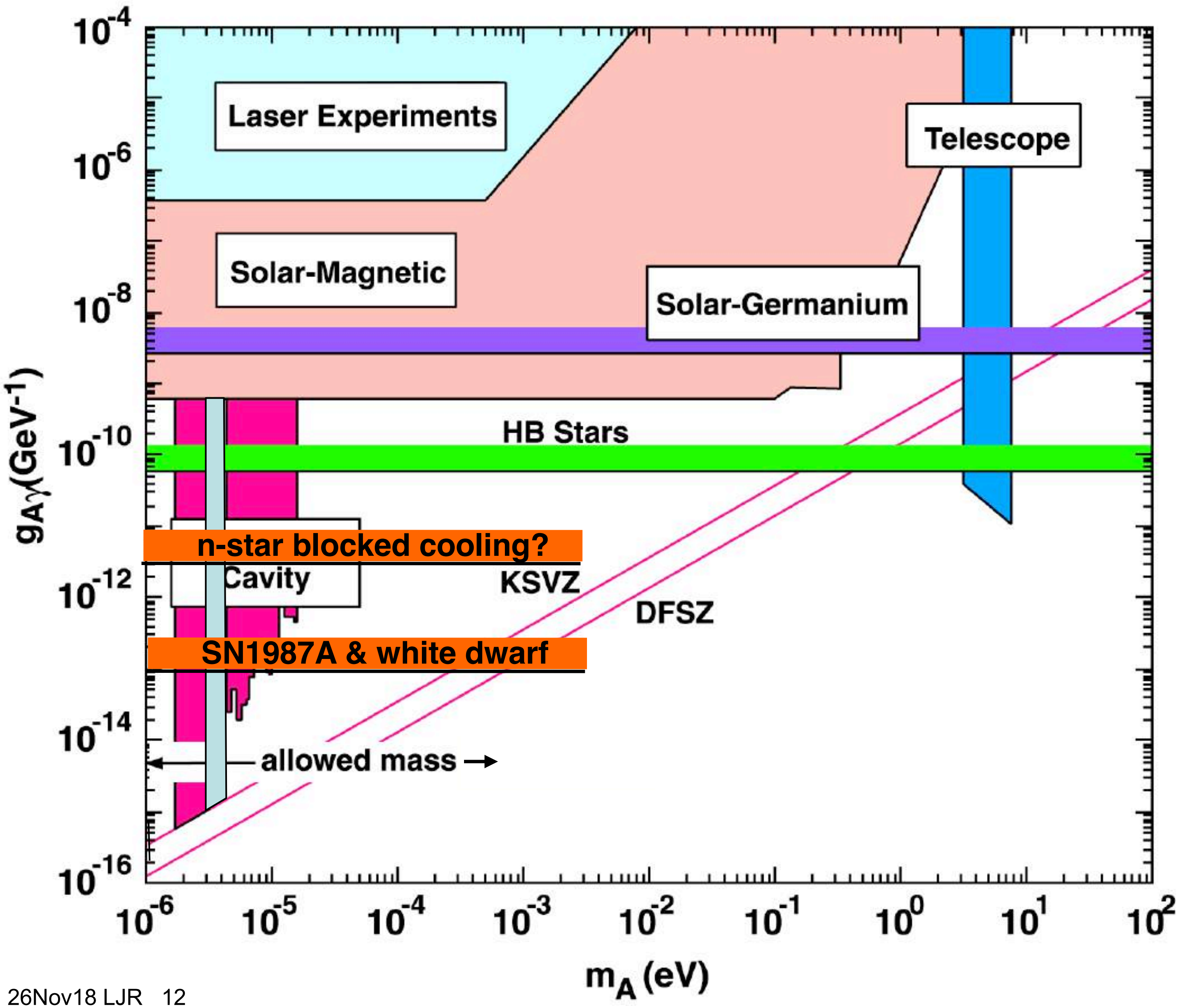
I'm sure we'll hear otherwise this week; we feel a credible QCD dark-matter axion detector should search in the general mass range 1-100 μeV and be sensitive to DFSZ axions.

1-100 μeV, DFSZ coupling: ADMX is searching in right place

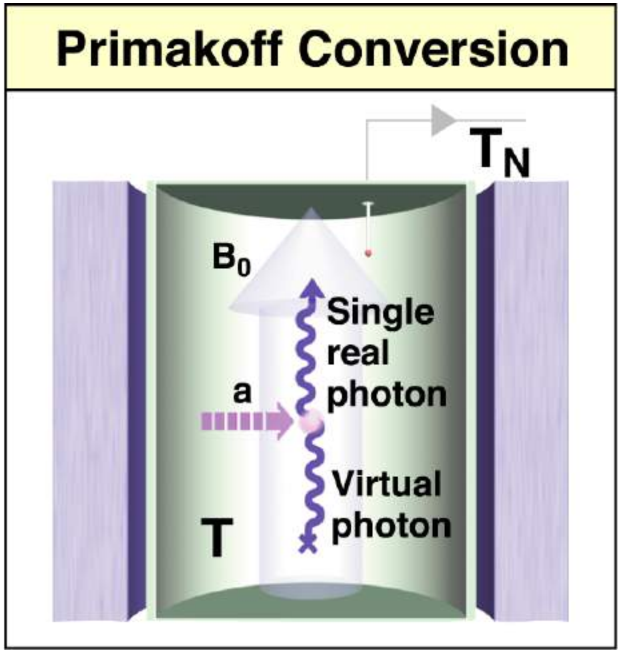
“… In particular, the computations which define the parameters of the ADMX experiment seem to be on a solid footing” – Michael Dine, 2017



Selected limits on dark-matter axion masses and couplings near the axion dark-matter "window"



Axion Haloscope: How to search for dark-matter axions



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

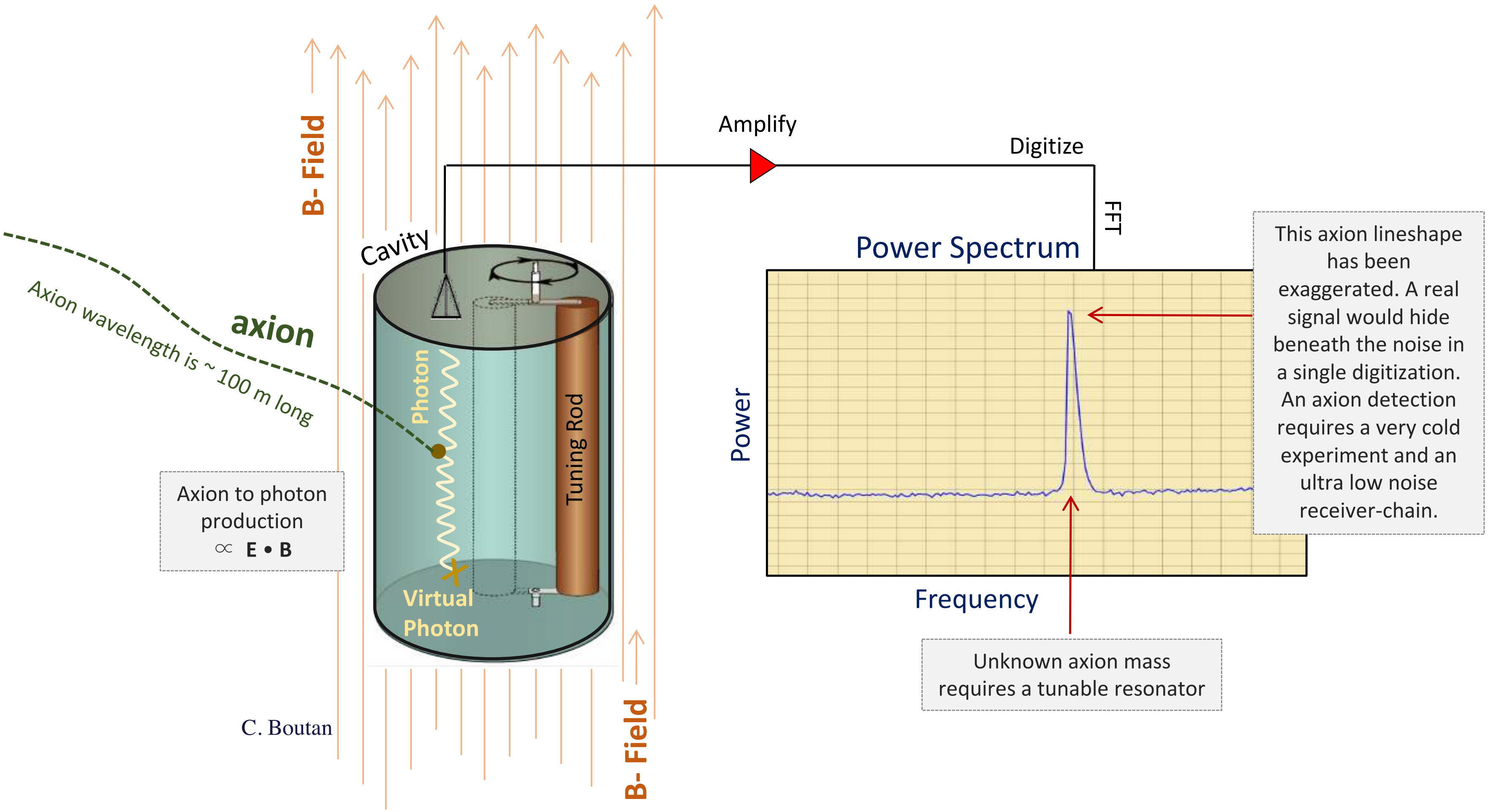
The conversion rate is enhanced if the photon's frequency corresponds to a cavity's resonant frequency. Sikivie PRL 51:1415 (1983)

Signal Proportional to
Cavity Volume
Magnetic Field
Cavity Q

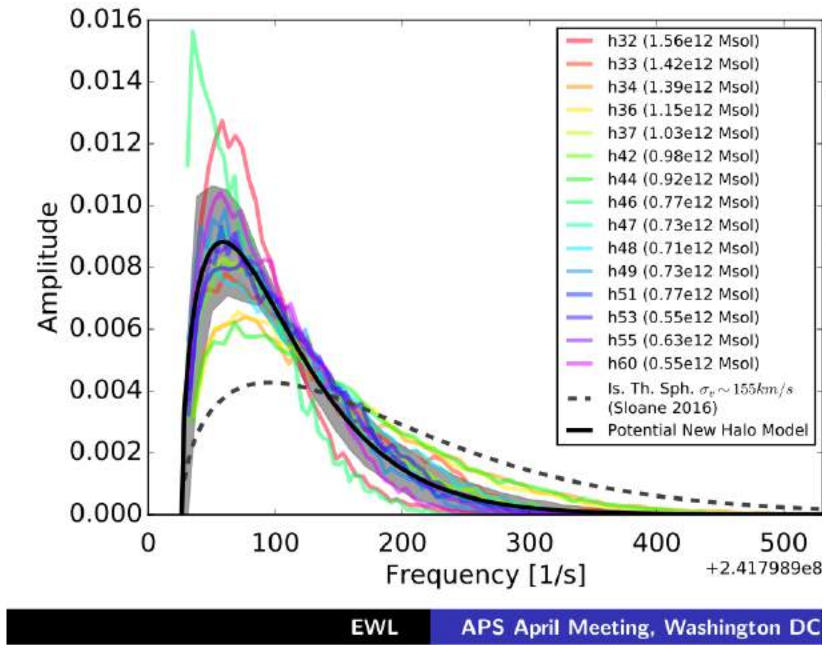
Noise Proportional to
Cavity Blackbody Radiation
Amplifier Noise

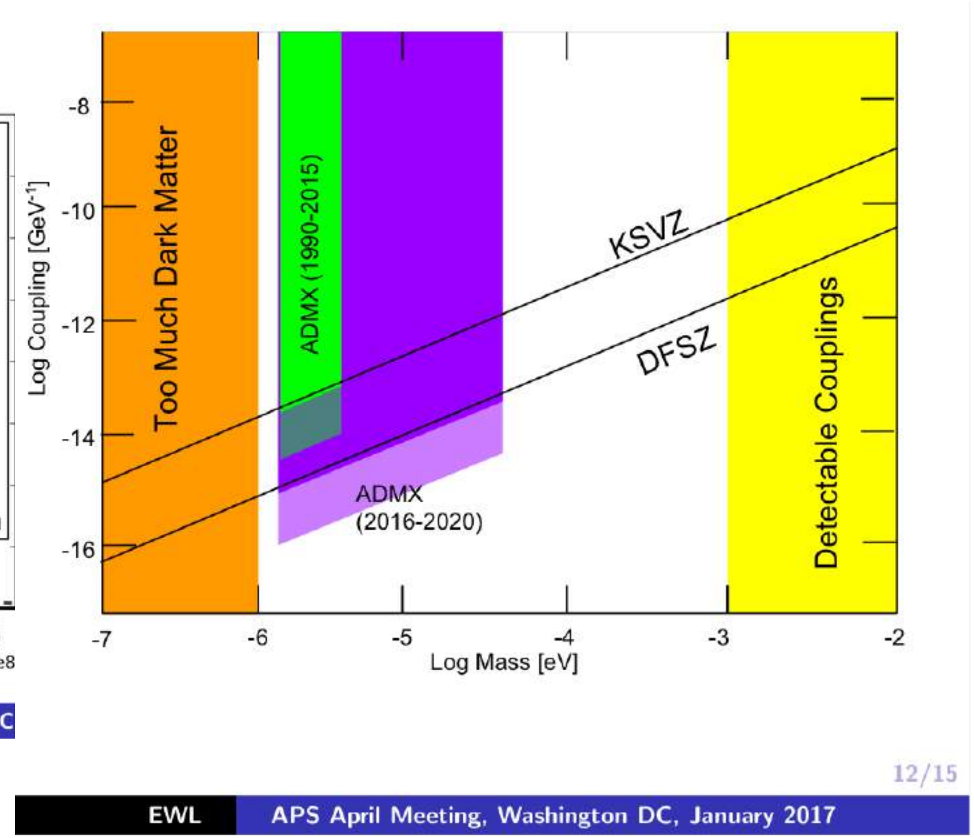
Principle of the Sikivie Axion Haloscope

The Axion Haloscope



What is the axion lineshape?





This is a very active line of research; the isothermal sphere is likely very conservative.

E.. Lentz, Ap. J (2017);

also see Nicib (2018) SDSS-GAIA.

A selected, brief history of ADMX

1983 Collaboration formed; the goal is the DFSZ axion, but technology not ready. Large magnet ordered.

1985 Magnet delivered. ADMX Gen 0: Transistor amplifiers, 1.2 K cooling.

1987 First PRL: KSVZ axion sensitivity.

2002 Complete scan at KSVZ sensitivity.

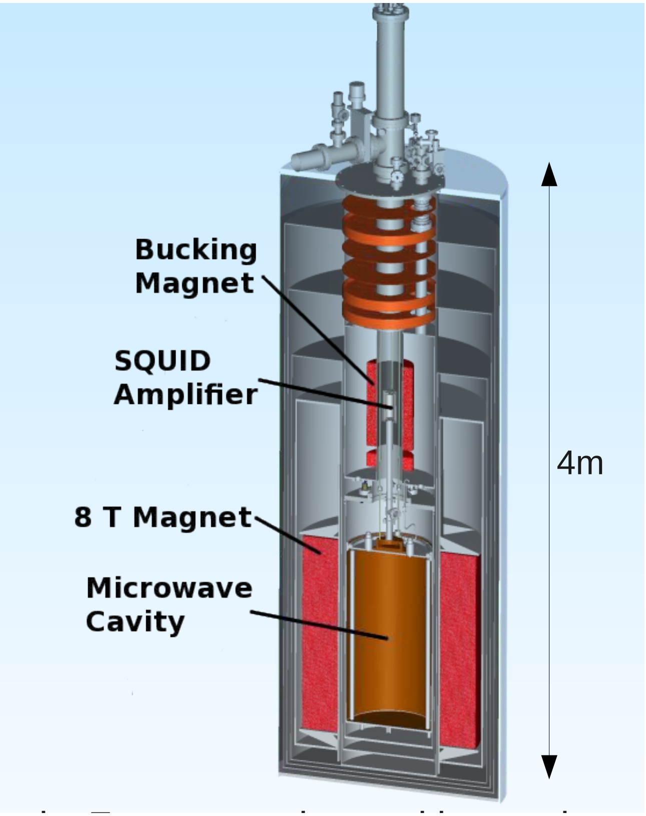
2002 Start development of quantum-limited amplifiers at microwave frequencies.

2008 Near quantum-limited SQUIDs demonstrated.

2017 ADMX-G2 First scan at DFSZ sensitivity

2018 First PRL at DFSZ sensitivity

… and ADMX G2 data-taking continues



The road to a DFSZ search is long…you don't just get a magnet and some SQUIDs and have an experiment.

ADMX: Axion Dark-Matter eXperiment
one of of three "Gen 2" dark-matter searches

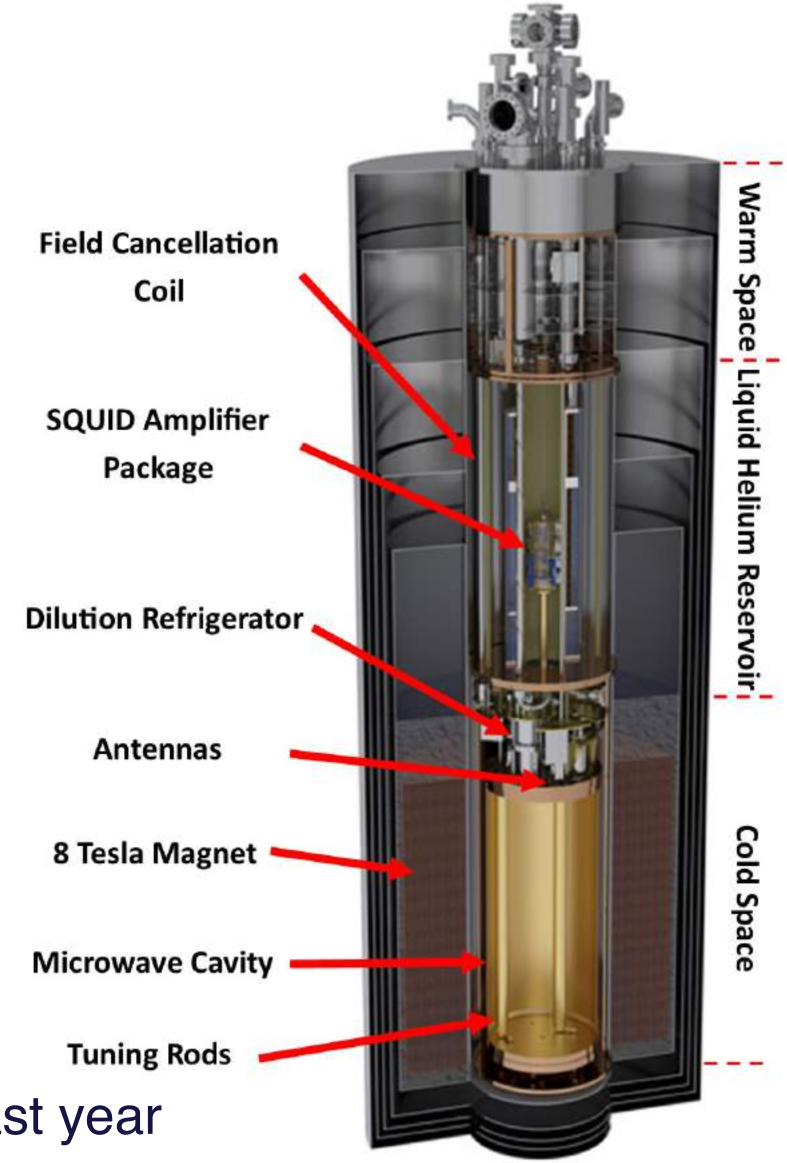
U. of Washington, LLNL, U. of Florida, U.C. Berkeley, National Radio Astronomy Observatory, U. of Virginia, Sheffield U., FNAL, LANL, PNNL, Washington U., U. of Goettingen, U of Western Australia (2019)

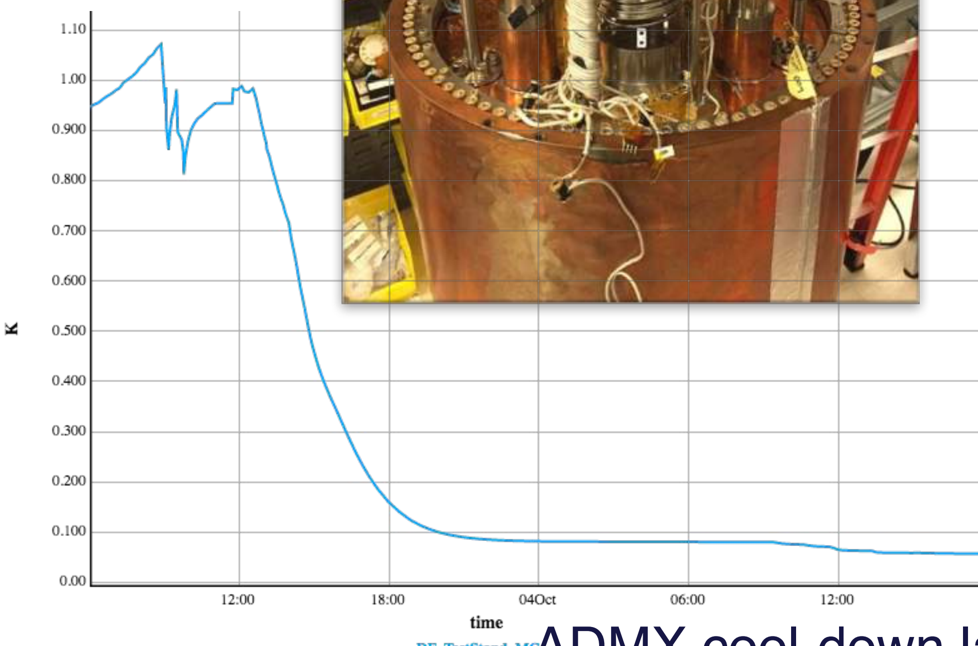
Three main search platforms:
ADMX-MC main-cavity
ADMX-SC "side car"
ADMX-PO "project Orpheus" (R&D)

ADMX Gen2 design

dilution refrigerator

insert, magnet, cryostat



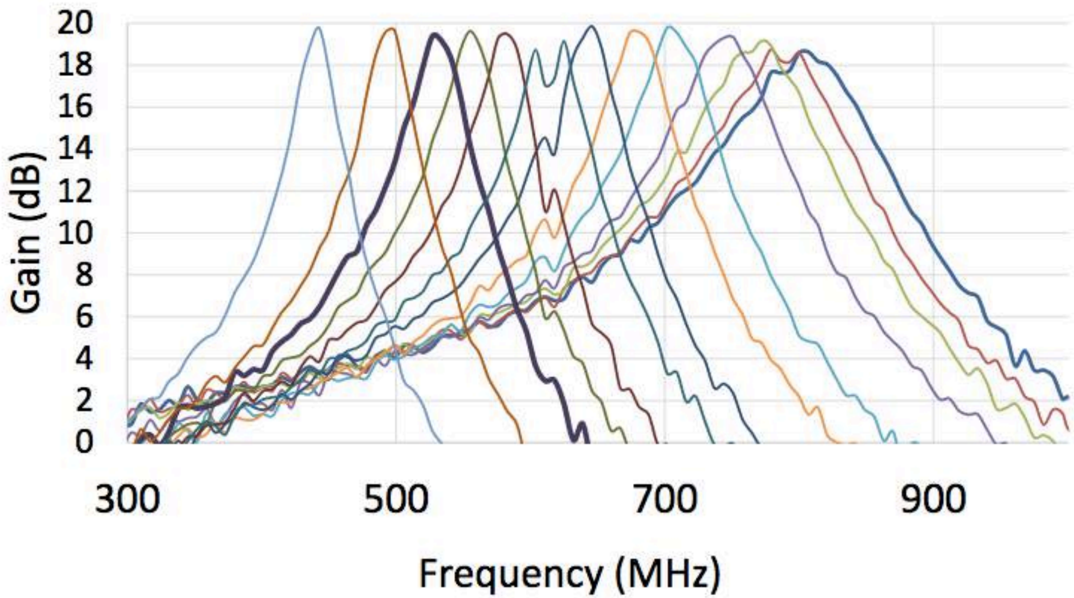


ADMX cool-down last year

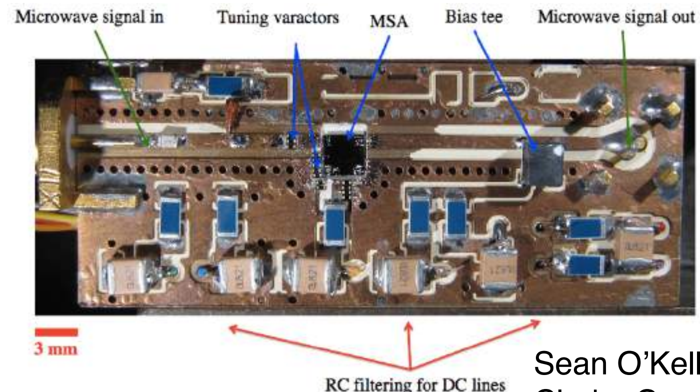
Quantum amplification

SQUID and JPA amplifiers operating near the quantum noise limit are key to ADMX's sensitivity.

MSA Varactor Tunability



ADMX Tunable MSA



Sean O'Kelley, Clarke Group, UC Berkeley

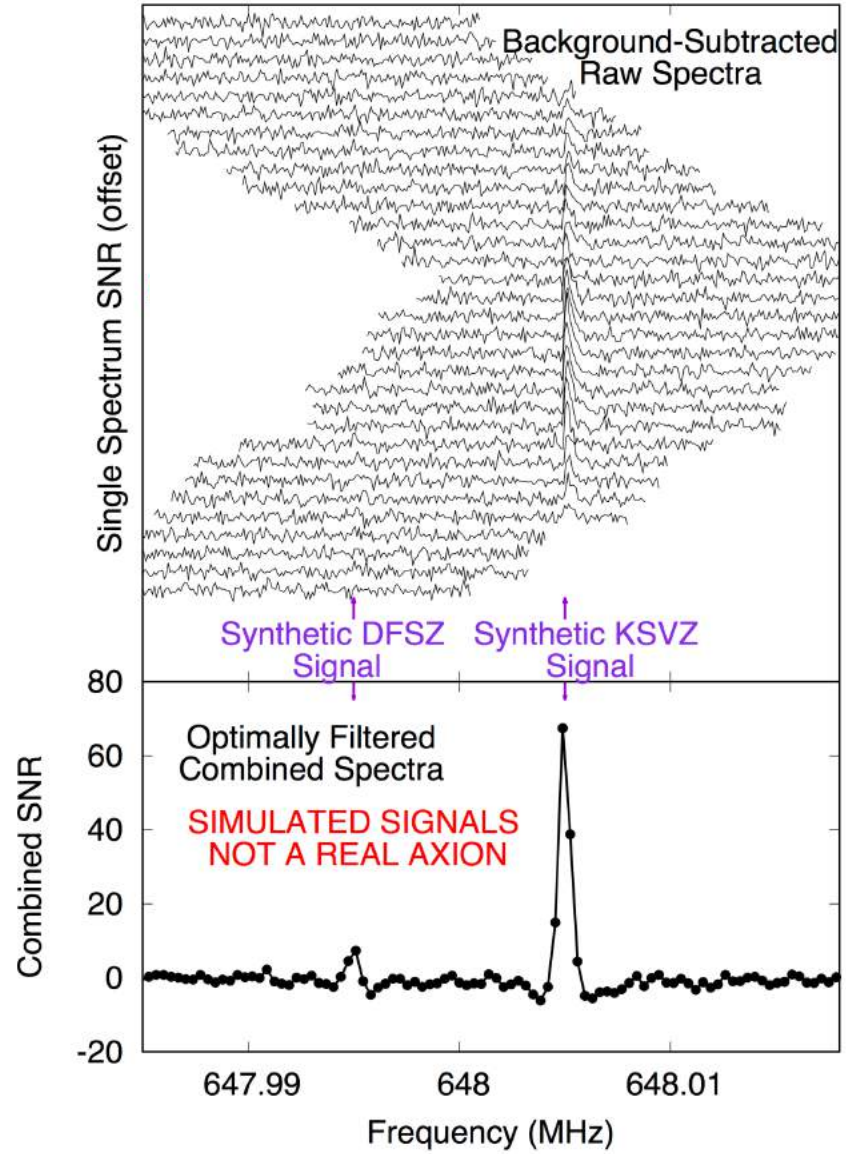
ADMX JPA

Yanjie Qiu, Siddiqi Group, UC Berkeley

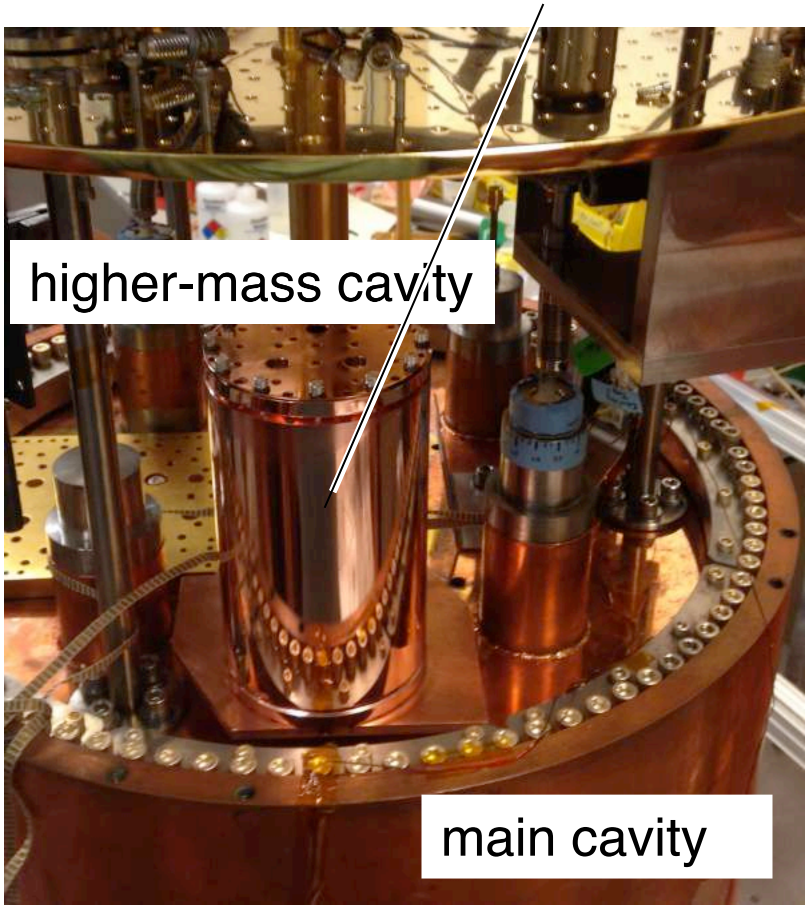
2nd Workshop of Microwave Cavities and Detectors for Axion Research

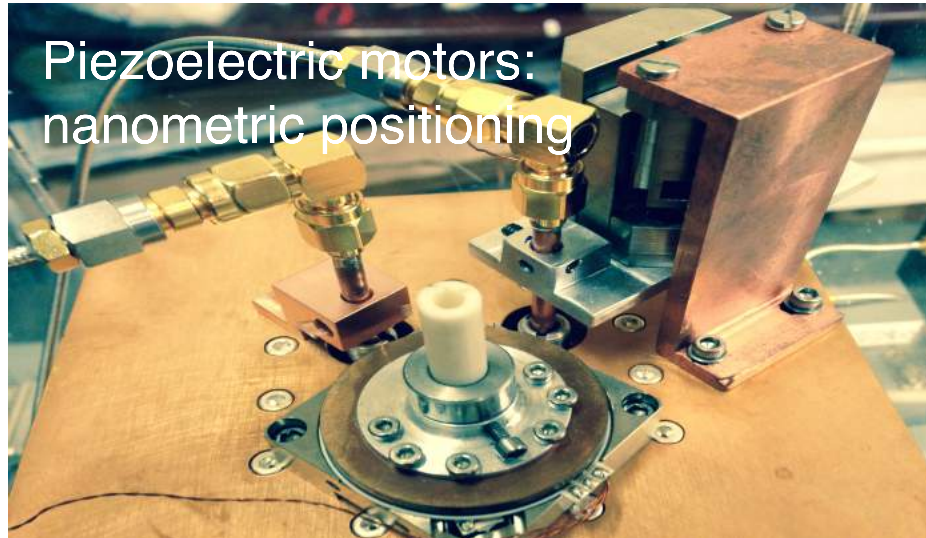
Experiment Operating Cadence

- The cavity frequency is scanned over a region until the desired SNR is achieved.
- We then examine the combined power spectrum for an excess.
- Excess power can be statistical fluctuations, synthetically injected signals, RF interference, or axions.
- Excess power regions are rescanned to see if they persist.
- Persistent candidates are subjected to a variety of confirmation tests: for example: magnet field changes or probing with other cavity modes; most are interference.
- We have blind hardware signal injection, so we always have candidates.

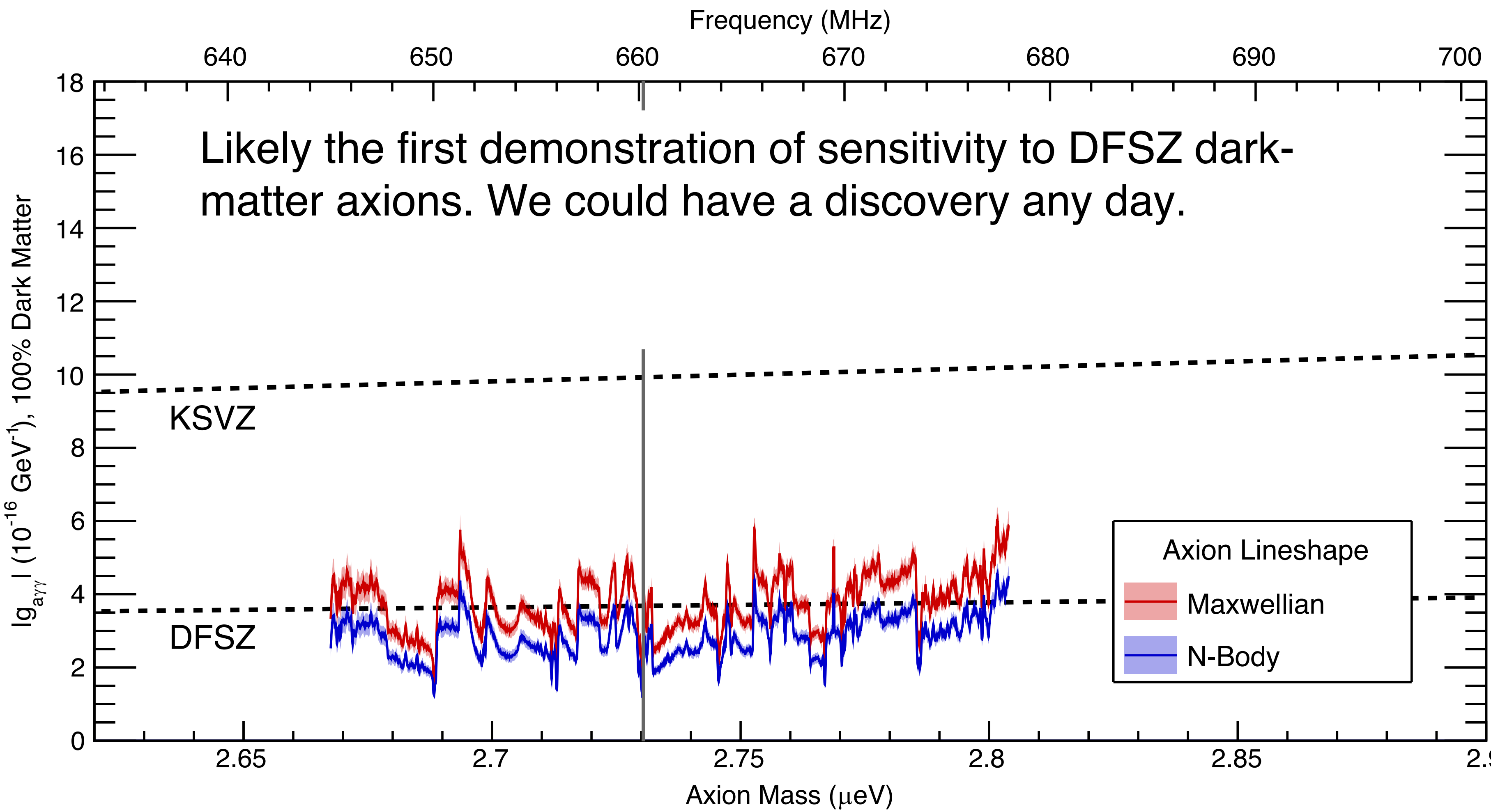


A high-frequency (high-mass) cavity operates in parallel ("side car")





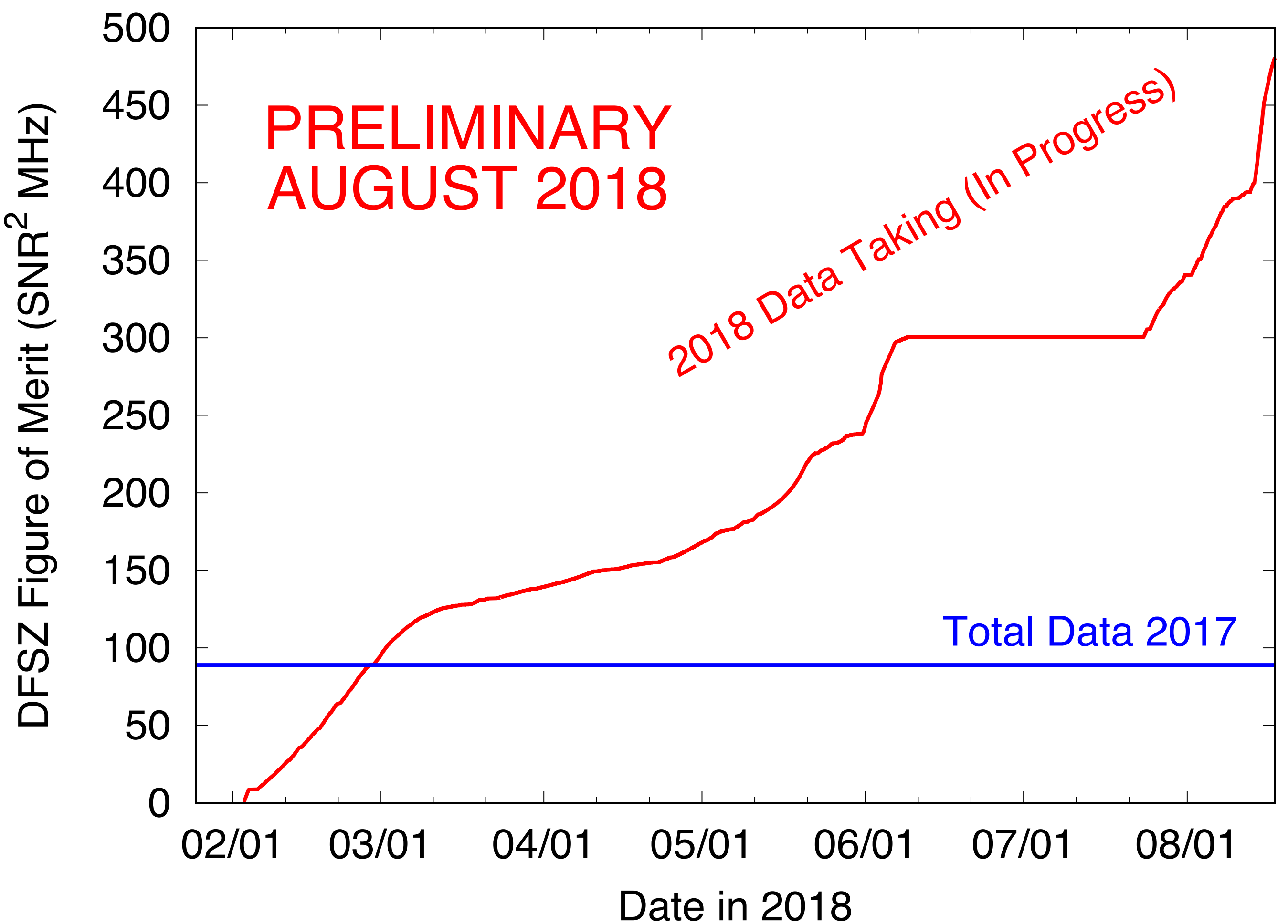
ADMX 2017 sensitivity



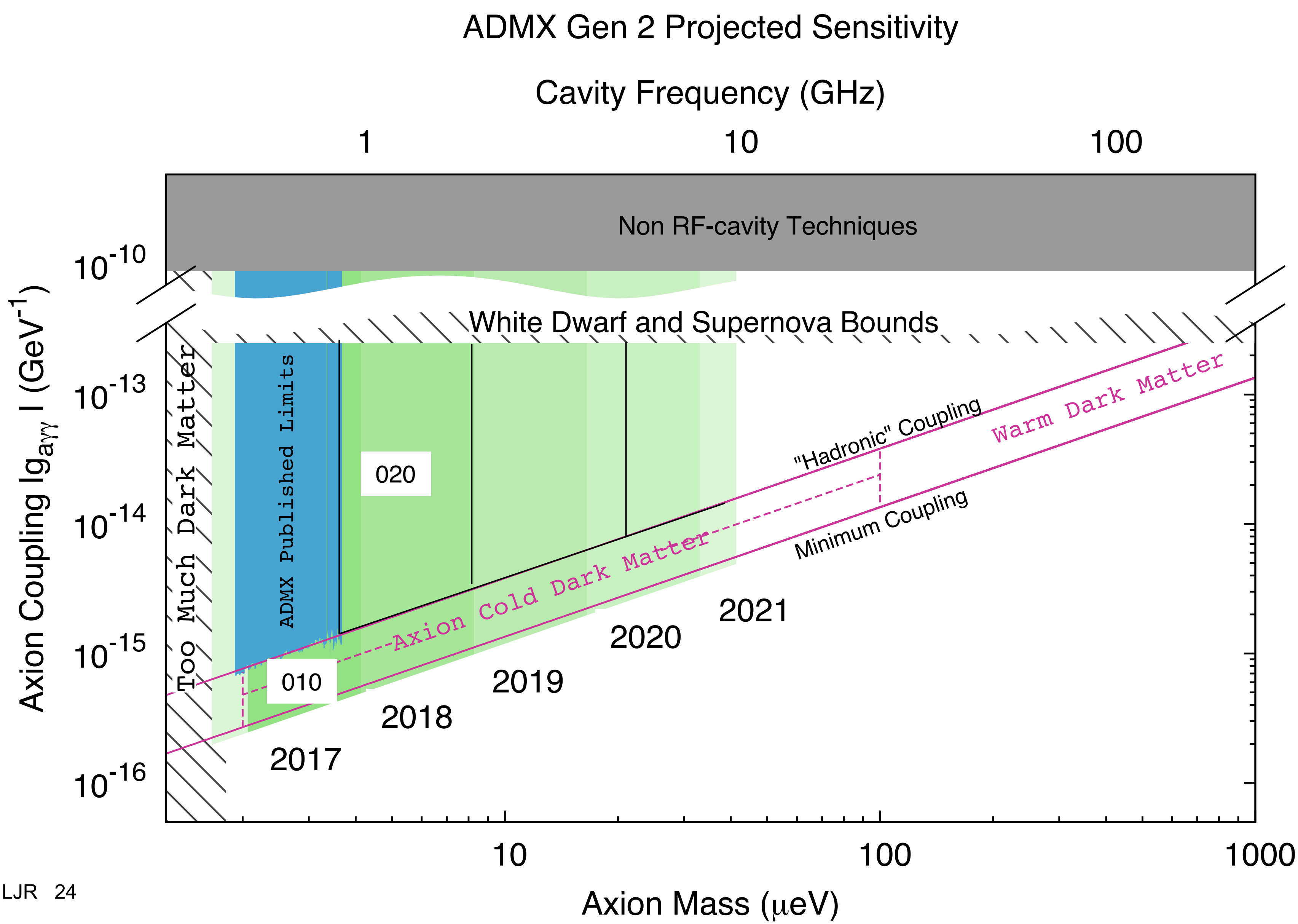
N. Du *et al.* (ADMX Collaboration), "Search for Invisible Axion Dark Matter with the Axion Dark Matter Experiment," Phys. Rev. Lett. **120**, 151301 (2018).

2018 Operations: Large "integrated luminosity"

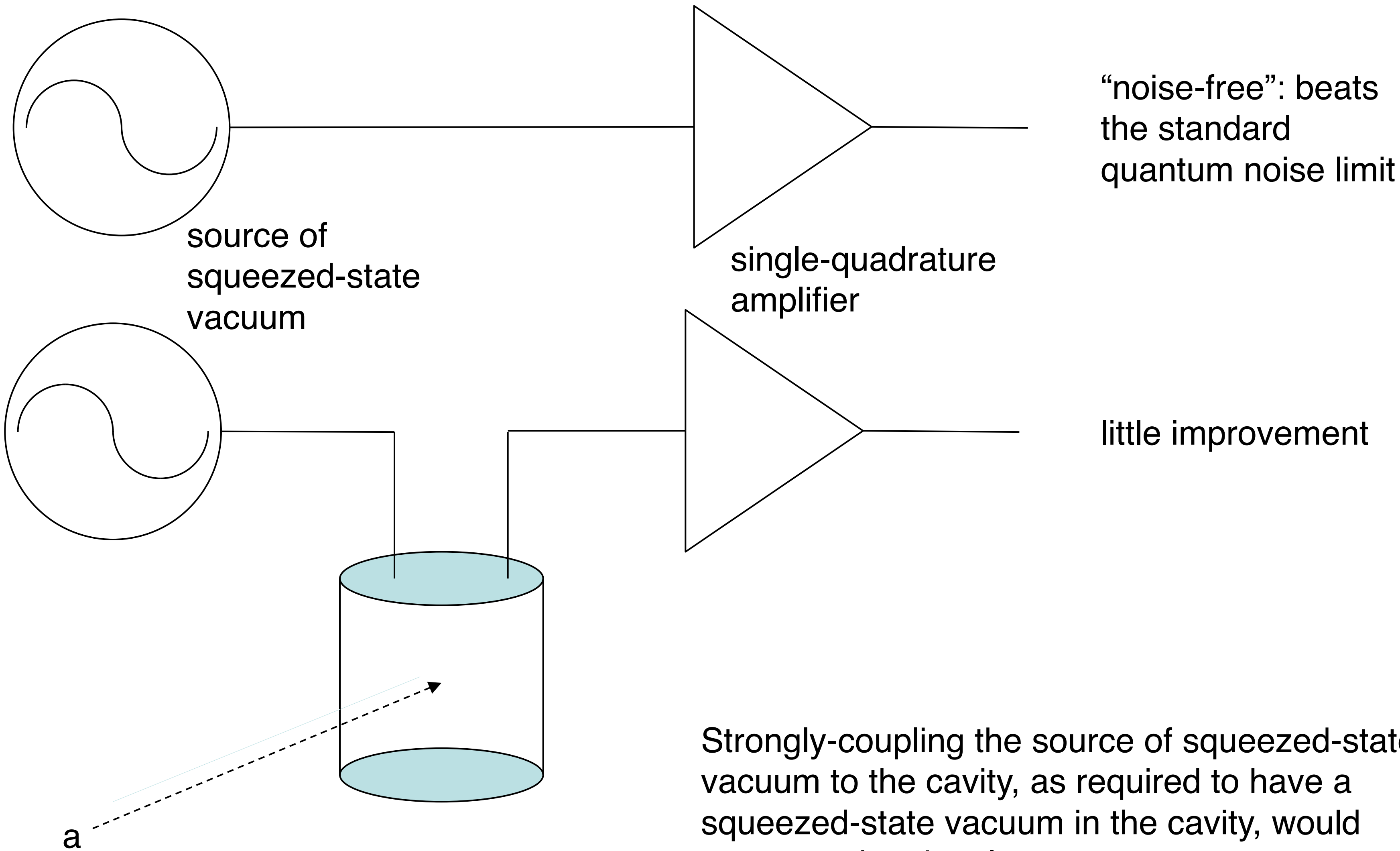
We acquired many times more data in 2018 than from our 2017 run. Analysis in progress (MC, SC, 010, 020).



ADMX Gen 2: Science prospects



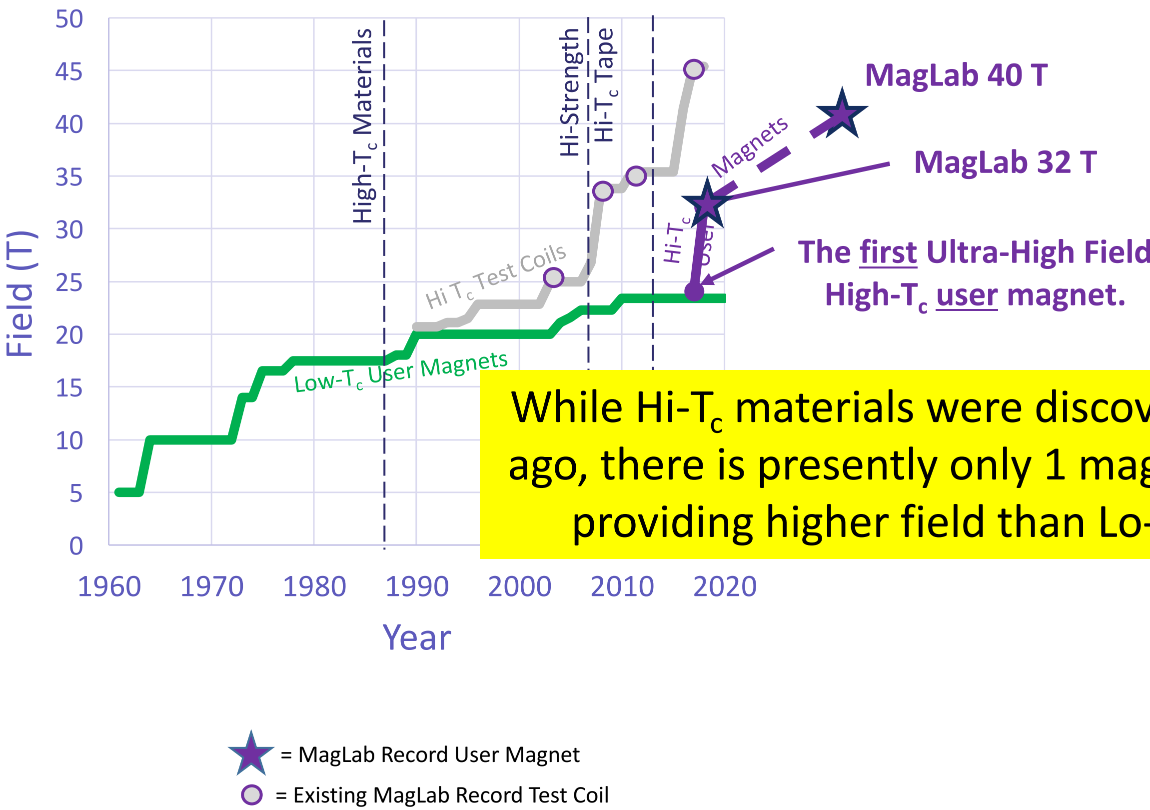
Beyond ADMX G2: Squeezed states?



Strongly-coupling the source of squeezed-state vacuum to the cavity, as required to have a squeezed-state vacuum in the cavity, would suppress the signal.

Beyond ADMX G2: High-field, large-bore magnet (1)?

The Development of Superconducting Solenoids



Hi Tc (HTS) materials were discovered in 1986.

Test coils using HTS materials were built by several groups during the 1990s. The fields reached were only slightly higher than those available from LTS materials.

In 2007 a hi-strength version of REBCO became available. Higher field test coils have now been built with this & other hi-strength

...net > 23.5 T using HTS is a ...agnet in Japan. Both this ... 32 T, 32 mm bore magnet are for condensed matter physics (CMP).

The MagLab now has funding to start a 40 T magnet project.

While Hi-T_c materials were discovered >30 years ago, there is presently only 1 magnet worldwide providing higher field than Lo-T_c magnets.

Mark Bird, NHMFL (2018)

Beyond ADMX G2: High-field, large-bore magnet (2)?

4 HTS Coil Technologies Being Developed for Ultra-High Field Applications

	Insulated REBCO	No-Insulation REBCO	Bi-2212	Bi-2223
Pros	Technology used in MagLab's 32 T, 34 mm magnet for CMP.	Very compact → low cost. MagLab test coil has reached 45.5 T (14.4 T inside 31.1 T resistive magnet).	MagLab has led >5x increase in current density which is now > I-REBCO. …nitiated Bi- …velopment …NMR.	Only magnet >23.5 T in routine service (24 T, 3 cm, Sendai, Japan). Consistent wire is produced in long lengths.
Cons	F… in 2015 & 2017, coils destroyed both times by quench. Bruker has missed several deadlines for 1.2 GHz (28.2 T) NMR magnets.	… published. 24 T, 3 cm bore magnet by SuNAM at CAPP has high resistance and does not operate. 3 coils of 30.5 T NMR magnet built by MIT were destroyed in quench in 2018.	…y strength and requires reaction at 900C after winding.	Wire has low current density, which results in larger magnets.

4 HTS Magnet Technologies being pursued worldwide.

None of them yet routinely provide field higher than LTS.

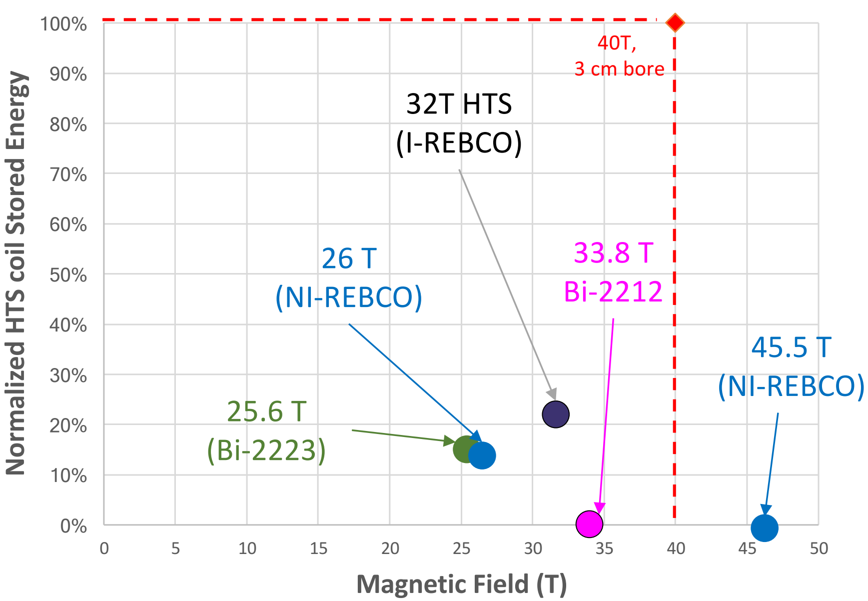
None of them yet have robust quench-protection strategies.

Table above only addresses magnets producing fields higher than those attainable by LTS materials.

Mark Bird, NHMFL (2018)

Beyond ADMX G2: High-field, large-bore magnet (3)?

Stored Energy: an Obstacle to Scaling Up



The MagLab is starting to develop a 40 T, 3 cm bore magnet for CMP. (Similar in size to 30 T, 10 cm bore.)

During a quench, the energy stored in the inductance of a supercodncuting magnet ($LI^2/2$) is converted into heat.

The HTS part of the 40 T will store more energy than any HTS coils to date.

No quench protection systems have yet been demonstrated that can be used at this energy scale.

Quench Damage

- MIT 30.5 T NMR NI-REBCO, destroyed 3 coils (2018).
- Riken 28 T, 2x I-REBCO coils destroyed (2015-2017).
- Tohoku University 25 T I-REBCO destroyed (2016).
- ***Numerous*** **other HTS test coils around the world have destroyed themselves.**

STORED ENERGY

- 1 MJ ~ 1 stick of dynamite.
- 20 T Oxford Instruments = 1-2 MJ.
- 40 T ~ 10 MJ.
- LHC at CERN = 11 GJ. Unprotected Quench Sept. 2008. Many magnets damaged.
- EDIPO = 16 MJ. Unprotected Quench May 2016. ~$15M magnet destroyed.

... and don't even mention the cost!

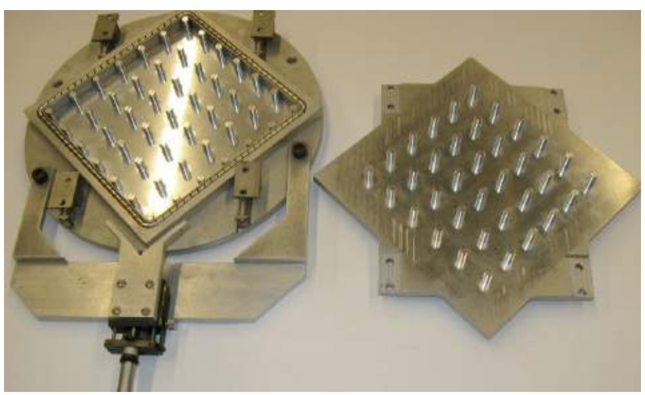
Mark Bird, NHMFL (2018)

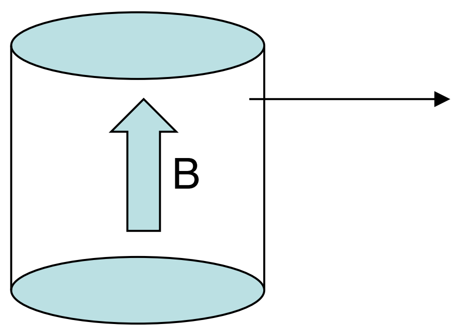
Beyond ADMX G2: Exotic cavities?

Sub-cavities. “Bulk” cavities subdivided into smaller sub-cavities for higher-frequency operation suffer from mode localization. As the number of sub-cavities increases, the required mechanical precision quickly becomes more stringent. In the cavity below, you can’t even measure the mode localization without distorting the fields.

Increase Q with superconductors? Due to the large magnetic field, this would be applied to the cavity side-walls. But you would need incredible parallelism of the field, any radial component would need to escape at the ends; it would instead penetrate the side-walls and destroy the Q.

The sub-volume of even a highly uniform magnet where this would work is a tiny fraction of the total magnetic volume. You would have better SNR by using the full volume at lower Q.





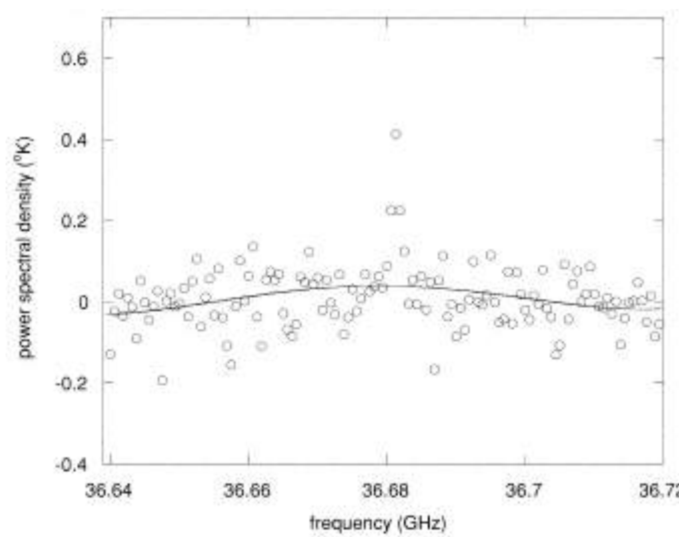
It’s energetically more favorable for the field to penetrate the side-wall than be “bunched” and escape at the ends.

Beyond ADMX G2: Project ADMX-Orpheus (I)

A ”hybrid” high-frequency search: Candidate lines from spontaneous halo decays are selected with a radio telescope. Those candidates are studied with a terrestrial detector.

ADMX did a pilot radio telescope search in the 1990’s. As the axion mass increases, so does the axion spontaneous decay rate. The signal is adequate, but the radio spectrum at 100 GHz and up is a picket fence of molecular lines, known and unknown. Almost all the time in the pilot experiment was spent evaluating candidate lines. (Is the line in common with other astrophysical halos at the apropriate red shift? Does the line have a reasonable angular spread or is it localized? Etc.).

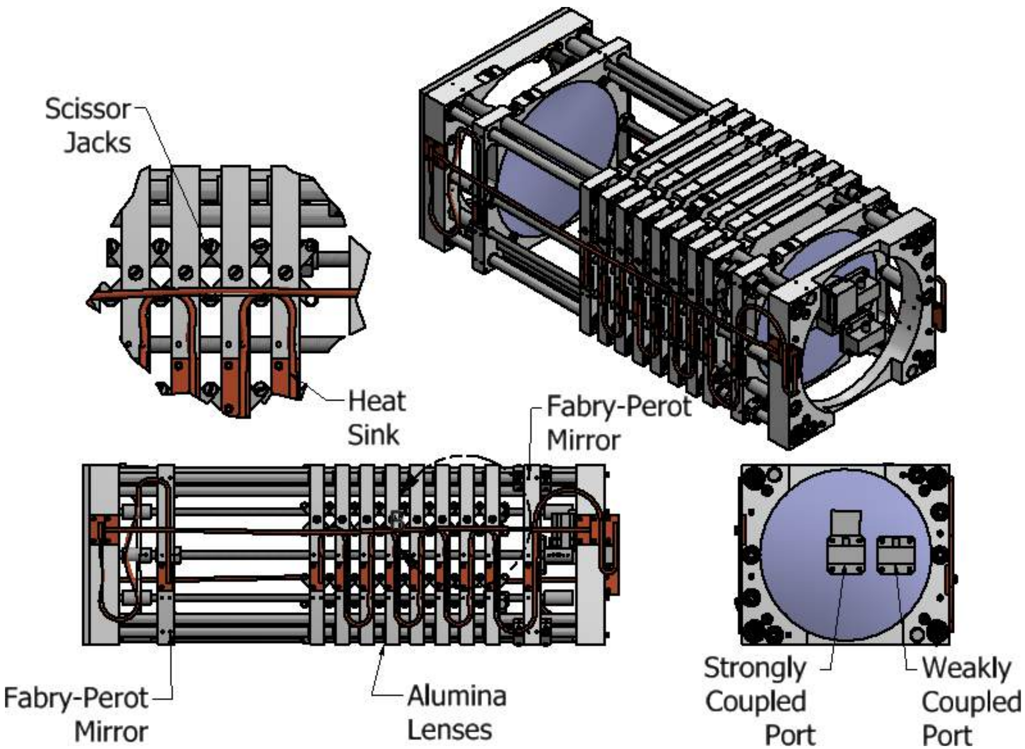
A terrestrial detector does not have adequate DFSZ SNR for selecting candidates and evaluating the candidates, but the SNR may be adequate for the later.

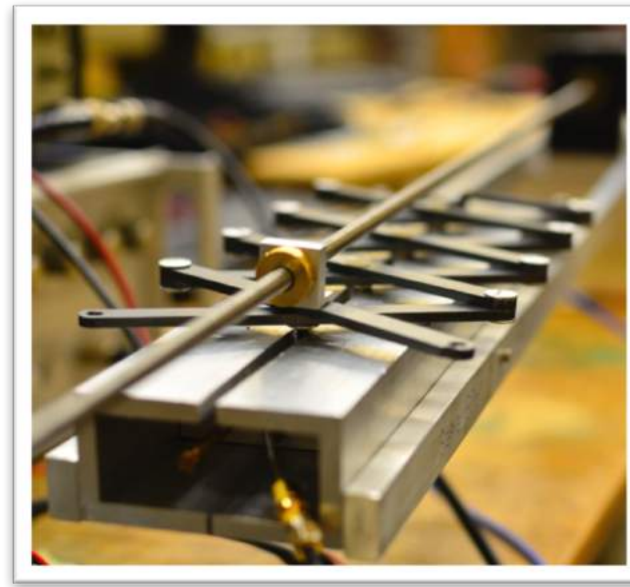


B. Blout et al., Ap. J. (2000)

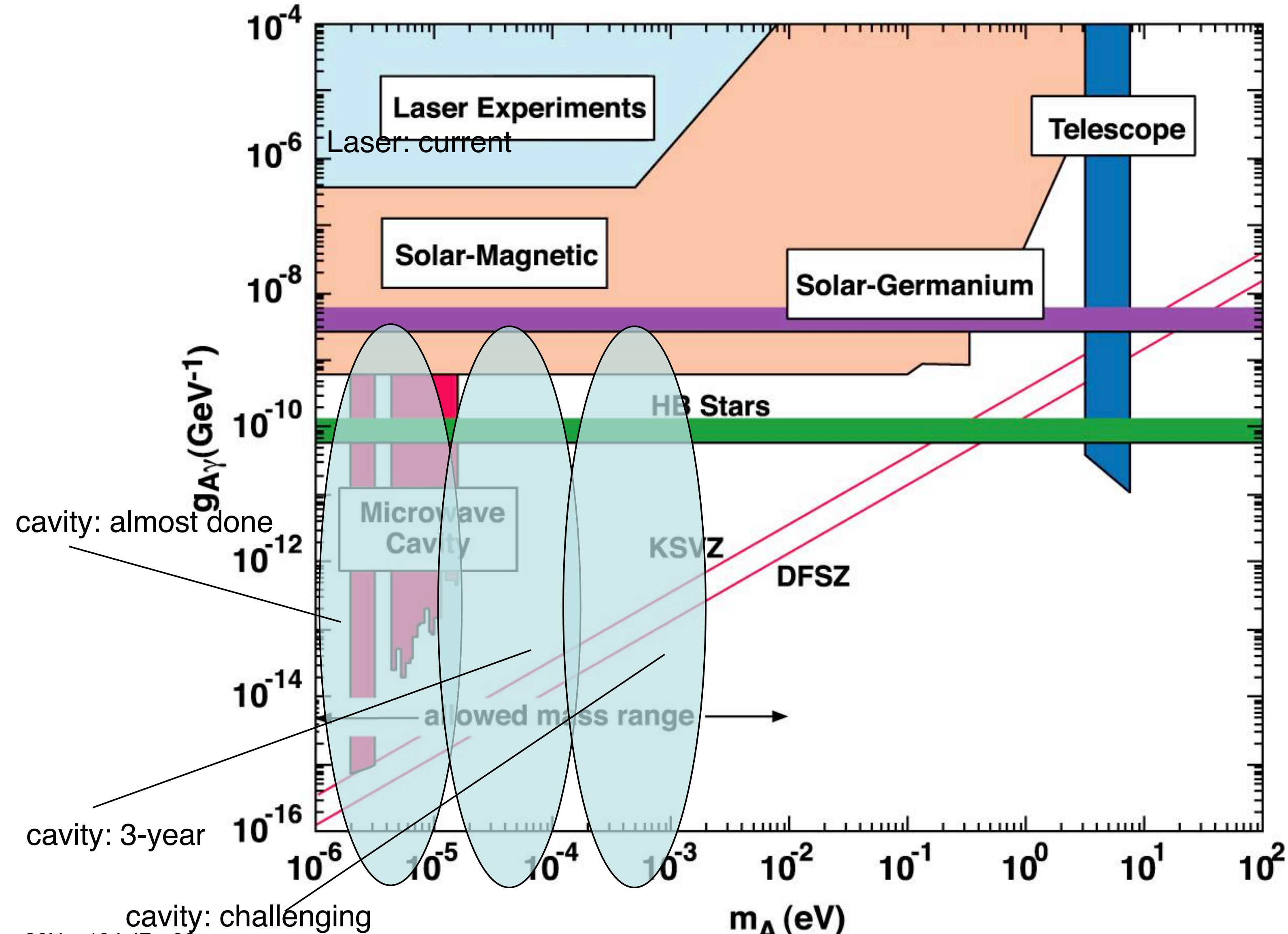
Beyond ADMX G2: Project ADMX-Orpheus (II)

ADMX-PO: A high-Q Fabry-Perot periodic structure with tunable dielectric periodicity. Operates at a high mode (high frequency).





Conclusions I: ADMX continues its scan



Conclusions II

Axions are a compelling dark matter candidate.

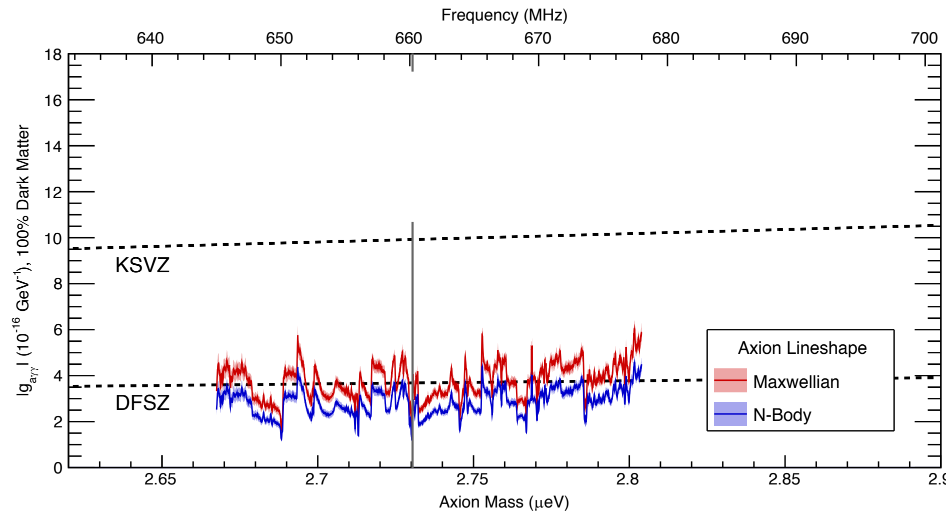
ADMX Gen 2 is aimed at a what we feel is the most plausible axion mass range.

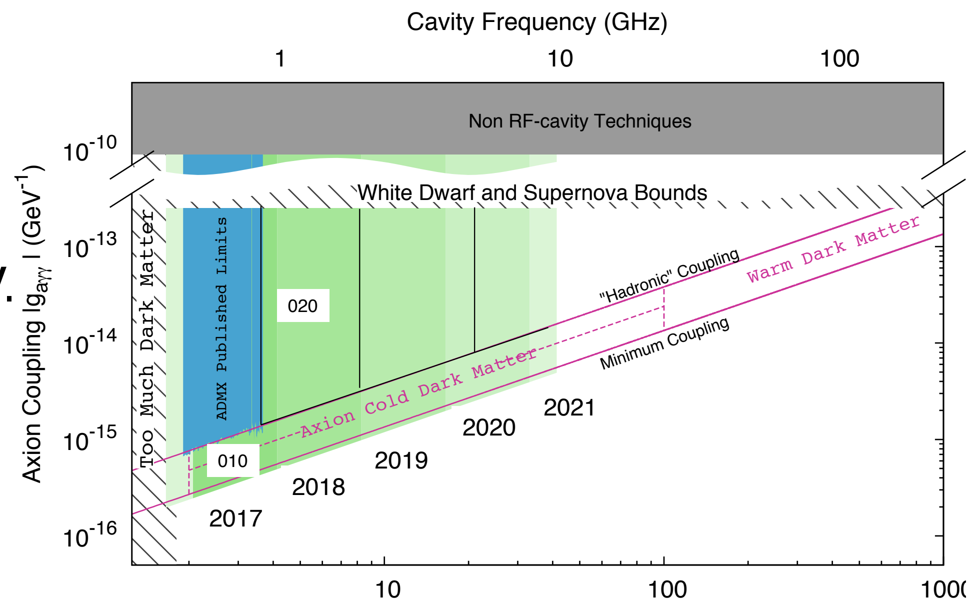
ADMX Gen 2 is operating with better-than sensitivity to the DFSZ axion.

… and ADMX Gen 2 is the only experiment sensitive to the DFSZ axion.

ADMX Gen 2 continues scanning upwards in mass with run-plan to 40 μeV.

ADMX-PO Beyond-Gen 2 program is in prototyping.





Thank you

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