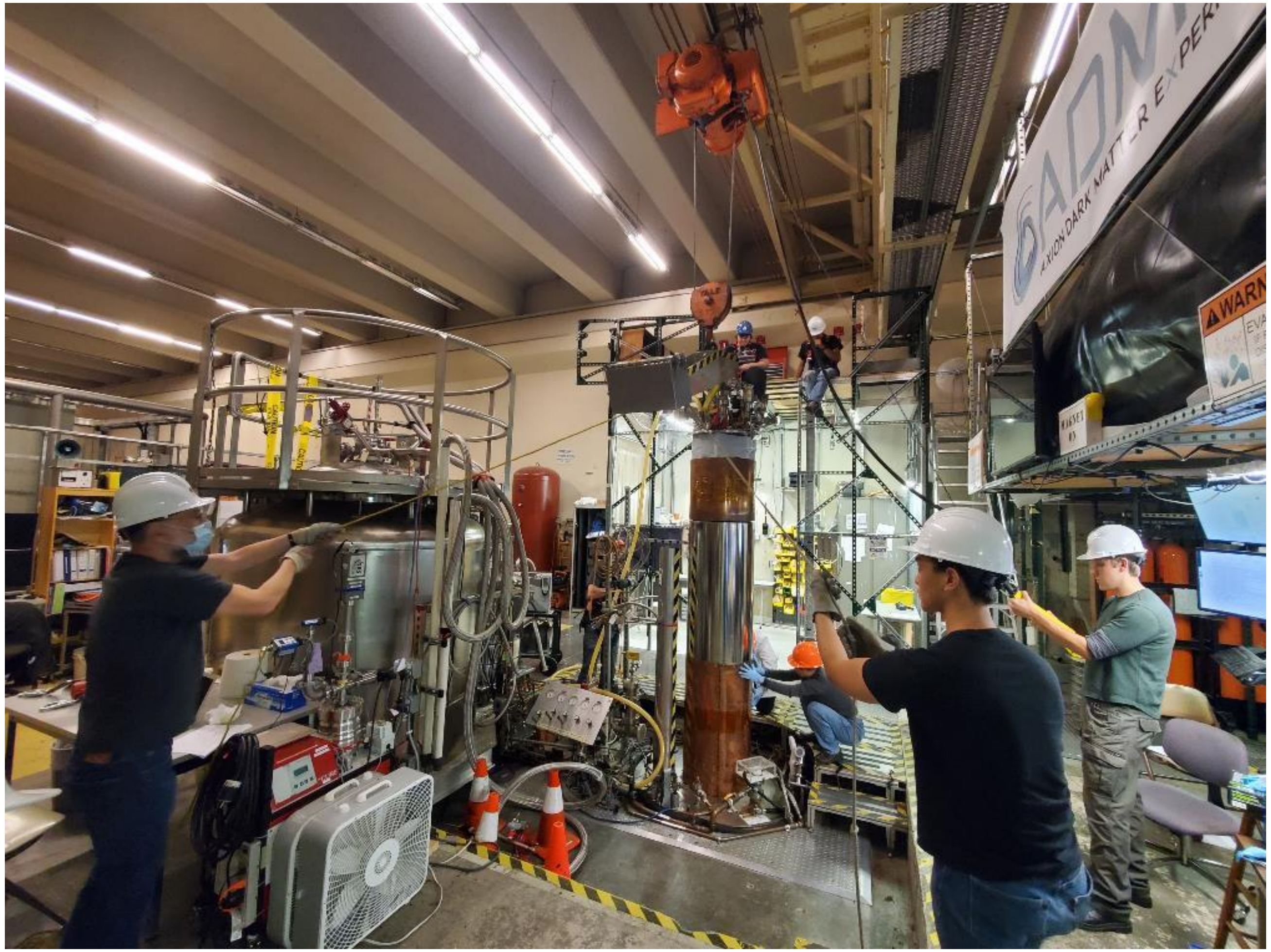
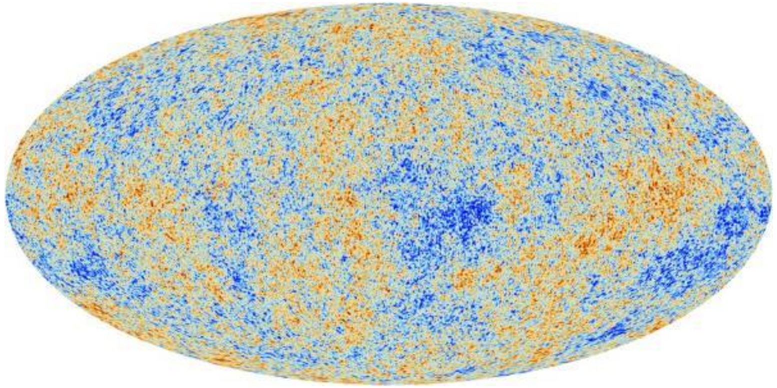
The Search for Axion Dark Matter



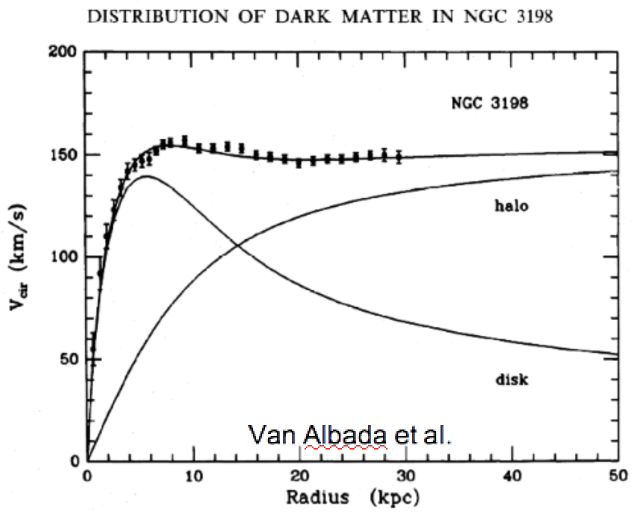
Gray Rybka – University of Washington

REU Seminar- 7/7/2024

Evidence for Dark Matter


PLANCK CMB 2013 (ESA)

Our Hubble Volume



Van Albada et al.

Nearby Galaxies


Composite: NASA, Markevitch etal., Clowe et al.

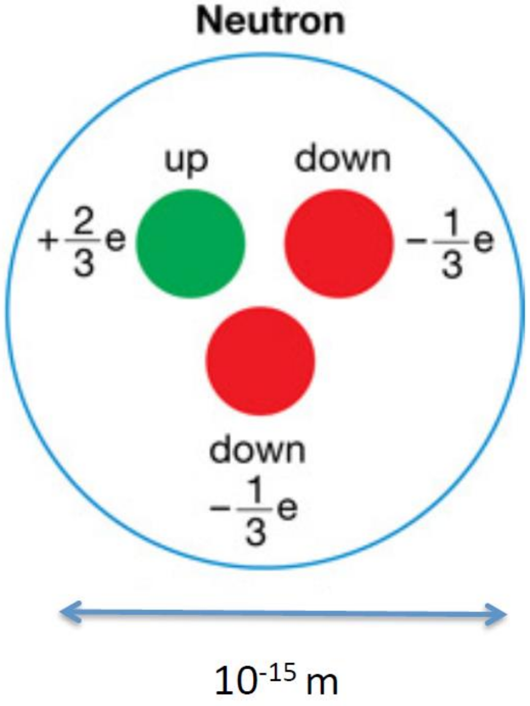
Galaxy Clusters

?

The Laboratory

The QCD Axion: Motivation

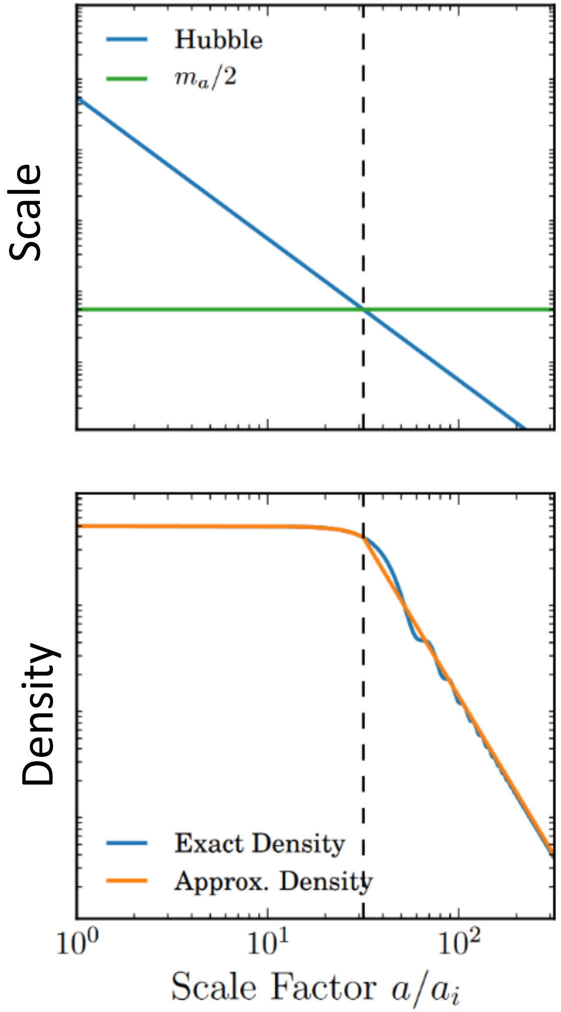
- QCD is naturally CP violating from phenomena like QCD-instantons
- One naively expects a neutron electric dipole moment of 10^{-16} e cm
- But nEDM is measured to be below 3×10^{-26} e cm *(Baker, 2006)*
- The best explanation? New U(1) axial symmetry, that when broken, cancels CP violation in the strong sector *(Peccei, Quinn, 1977)*
- Consequence: New particle, called the axion *(Weinberg, Wilczek, 1978)*



d = ~~10^{-16} e cm~~
< 3×10^{-26} e cm

Axions as Dark Matter

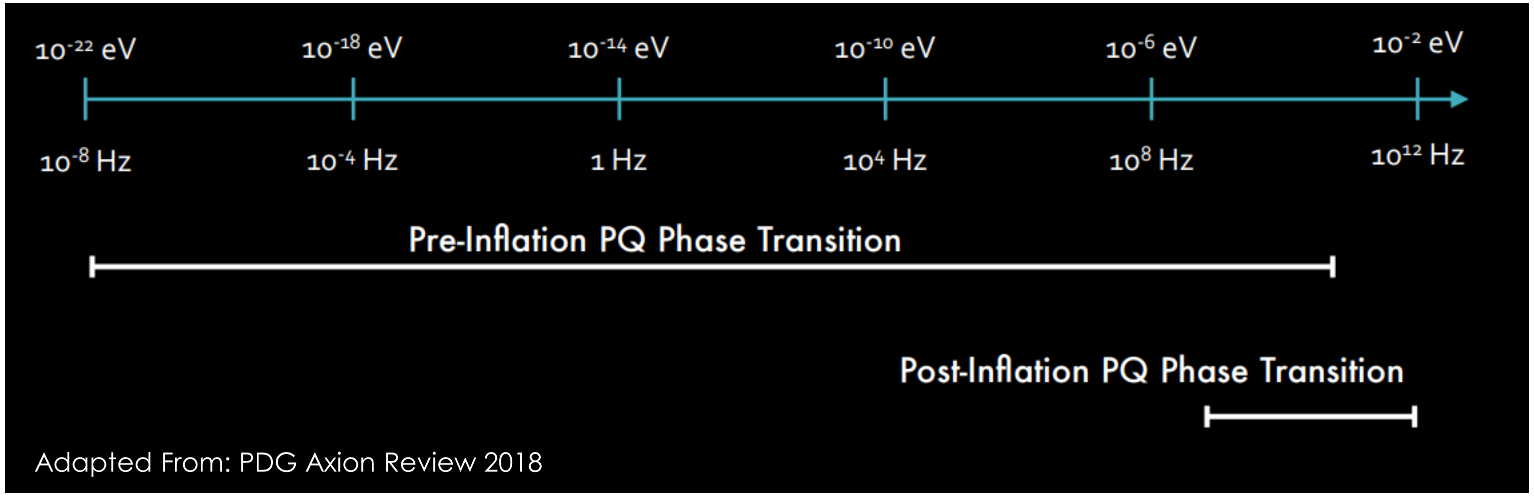
- Axions are produced athermally
  - Misalignment Mechanism – Phase transition in the early universe leaves energy in the axion field which behaves as dark matter
  - String/Defect Decay – Energy in topological defects radiates as cold axions
- In both cases axions are produced cold and in quantities sufficient to make up some or all of dark matter
- Perfect knowledge of QCD, cosmology, and inflation could, in principle, predict the axion mass that yields the amount of dark matter we have today



Adapted from D. Marsh, "Axion Cosmology" arXiv:1510.07633

Theoretical Preferences on Scale

- In general, things that happen before the end of inflation could produce dark matter with any axion mass, but after inflation favors 1ueV and above

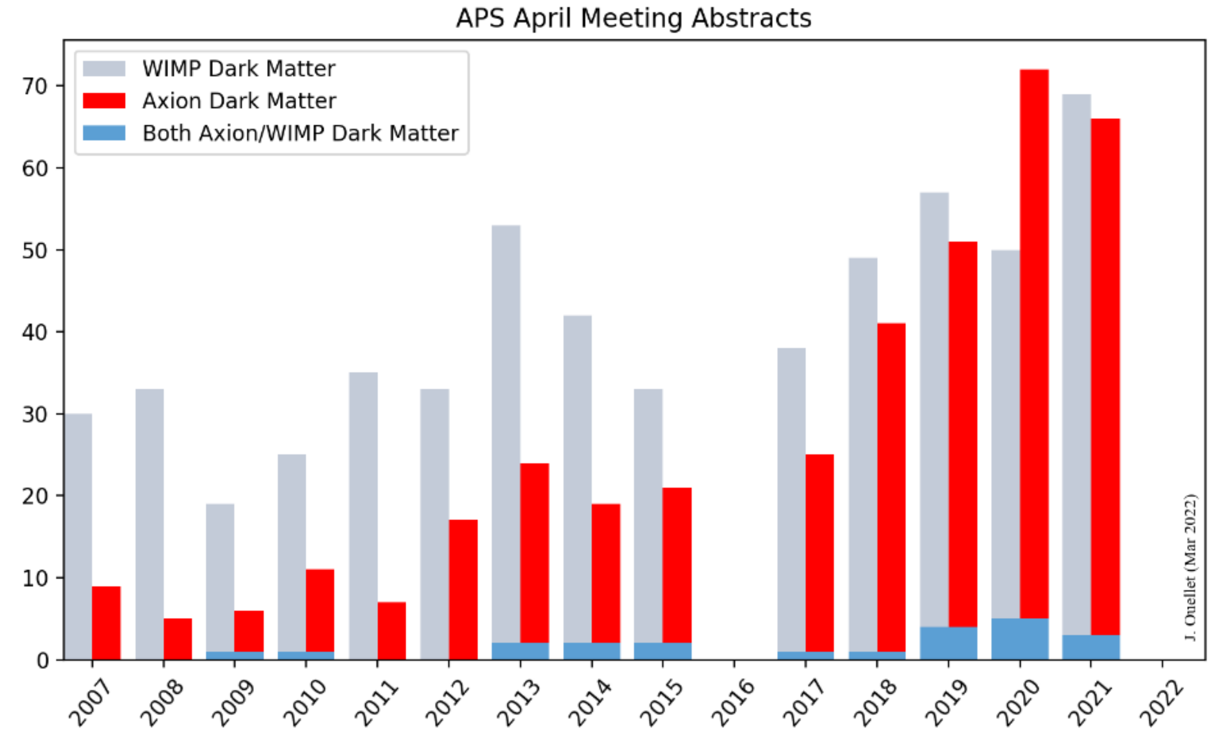


Adapted From: PDG Axion Review 2018

- Above 1 micro-eV, axions may have been produced after inflation

The Axion Community is Growing

With advancements in cryogenics, magnet and quantum sensing coupled with better theoretical understanding of the cosmology of wave-like dark matter, the community has grown quickly.



J. Ouellet

Snowmass Community Whitepapers

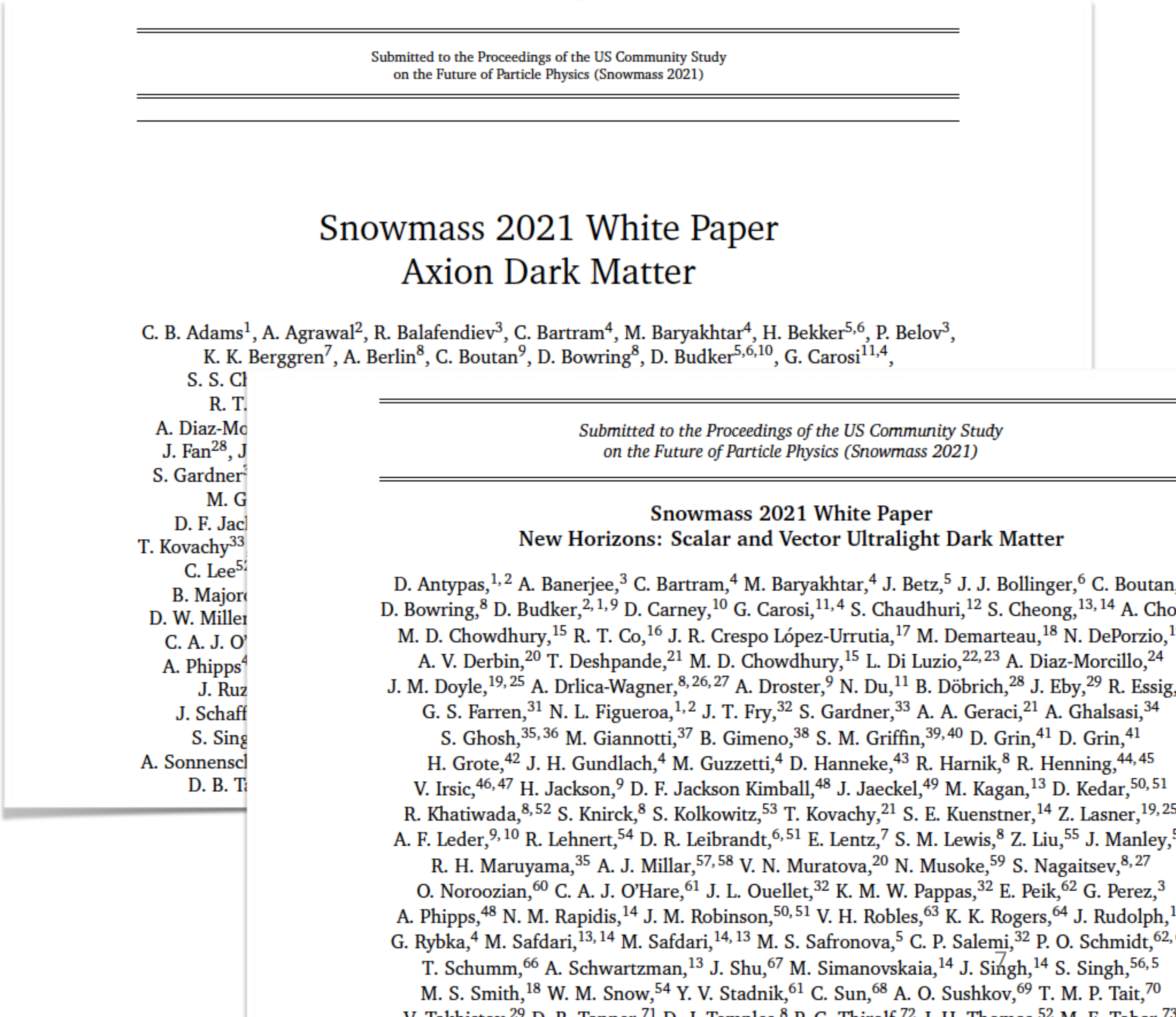
The community road map, theory, cosmology, and experimental details are presented in our two community white papers.

Axion Dark Matter
arXiv:2203.14923

Editors: J. Jaeckel, G. Rybka, L. Winslow

New Horizons:
Scalar and Vector Ultralight Dark Matter
arXiv:2203.14915

Editors: M. Safronova and S. Singh



Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Snowmass 2021 White Paper
Axion Dark Matter

C. B. Adams[1], A. Agrawal[2], R. Balafendiev[3], C. Bartram[4], M. Baryakhtar[4], H. Bekker[5,6], P. Belov[3],
K. K. Berggren[7], A. Berlin[8], C. Boutan[9], D. Bowring[8], D. Budker[5,6,10], G. Carosi[11,4],
S. S. Cl
R. T.
A. Diaz-Mo
J. Fan[28], J
S. Gardner
M. G
D. F. Jacl
T. Kovachy[33]
C. Lee
B. Major
D. W. Miller
C. A. J. O'
A. Phipps
J. Ruz
J. Schaff
S. Sing
A. Sonnenscl
D. B. T

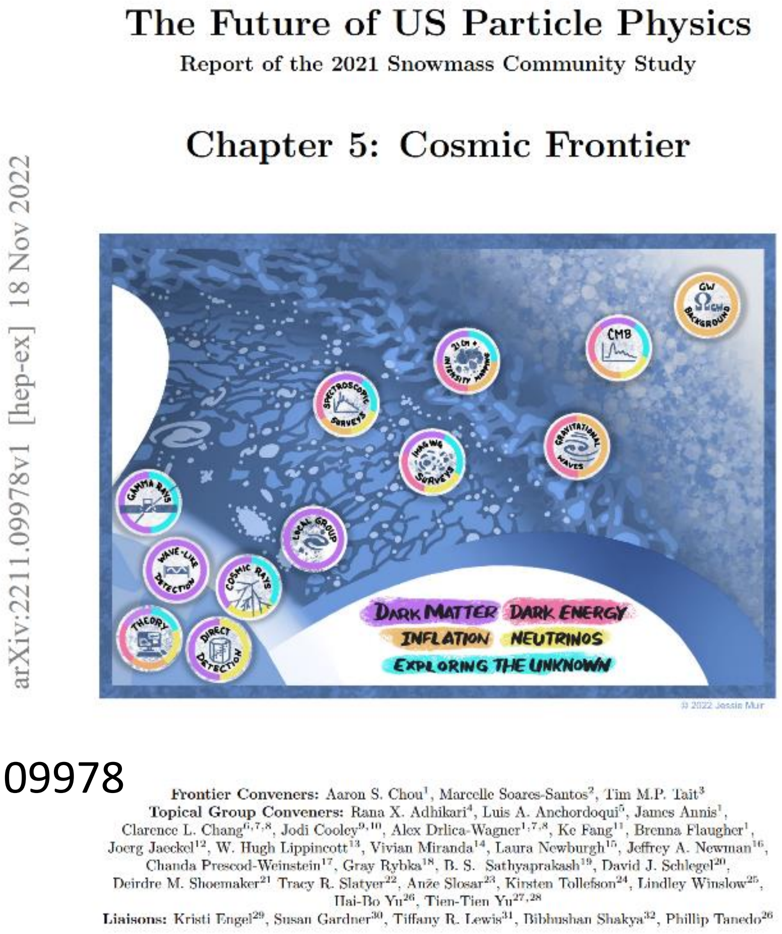
Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Snowmass 2021 White Paper
New Horizons: Scalar and Vector Ultralight Dark Matter

D. Antypas,[1,2] A. Banerjee,[3] C. Bartram,[4] M. Baryakhtar,[4] J. Betz,[5] J. J. Bollinger,[6] C. Boutan,
D. Bowring,[8] D. Budker,[2,1,9] D. Carney,[10] G. Carosi,[11,4] S. Chaudhuri,[12] S. Cheong,[13,14] A. Cho
M. D. Chowdhury,[15] R. T. Co,[16] J. R. Crespo López-Urrutia,[17] M. Demarteau,[18] N. DePorzio,
A. V. Derbin,[20] T. Deshpande,[21] M. D. Chowdhury,[15] L. Di Luzio,[22,23] A. Diaz-Morcillo,[24]
J. M. Doyle,[19,25] A. Drlica-Wagner,[8,26,27] A. Droster,[9] N. Du,[11] B. Döbrich,[28] J. Eby,[29] R. Essig,
G. S. Farren,[31] N. L. Figueroa,[1,2] J. T. Fry,[32] S. Gardner,[33] A. A. Geraci,[21] A. Ghalsasi,[34]
S. Ghosh,[35,36] M. Giannotti,[37] B. Gimeno,[38] S. M. Griffin,[39,40] D. Grin,[41] D. Grin,[41]
H. Grote,[42] J. H. Gundlach,[4] M. Guzzetti,[4] D. Hanneke,[43] R. Harnik,[8] R. Henning,[44,45]
V. Irsic,[46,47] H. Jackson,[9] D. F. Jackson Kimball,[48] J. Jaeckel,[49] M. Kagan,[13] D. Kedar,[50,51]
R. Khatiwada,[8,52] S. Knirck,[8] S. Kolkowitz,[53] T. Kovachy,[21] S. E. Kuenstner,[14] Z. Lasner,
A. F. Leder,[9,10] R. Lehnert,[54] D. R. Leibrandt,[6,51] E. Lentz,[7] S. M. Lewis,[8] Z. Liu,[55] J. Manley,
R. H. Maruyama,[35] A. J. Millar,[57,58] V. N. Muratova,[20] N. Musoke,[59] S. Nagaitsev,[8,27]
O. Noroozian,[60] C. A. J. O'Hare,[61] J. L. Ouellet,[32] K. M. W. Pappas,[32] E. Peik,[62] G. Perez,[3]
A. Phipps,[48] N. M. Rapidis,[14] J. M. Robinson,[50,51] V. H. Robles,[63] K. K. Rogers,[64] J. Rudolph,
G. Rybka,[4] M. Safdari,[13,14] M. Safdari,[14,13] M. S. Safronova,[5] C. P. Salemi,[32] P. O. Schmidt,
T. Schumm,[66] A. Schwartzman,[13] J. Shu,[67] M. Simanovskaia,[14] J. Singh,[14] S. Singh,[56,5]
M. S. Smith,[18] W. M. Snow,[54] Y. V. Stadnik,[61] C. Sun,[68] A. O. Sushkov,[69] T. M. P. Tait,[70]

Snowmass Cosmic Frontier Report – Main Message

- **Direct detection of axion dark matter**: A portfolio of axion dark matter search experiments enabled by new quantum sensing technologies will "delve deep" in searches for the ultraweak QCD axion signal in most of its predicted band. The Dark Matter New Initiatives (DMNI) has identified promising small projects to explore wide swaths of the parameter space.



The Future of US Particle Physics

Report of the 2021 Snowmass Community Study

Chapter 5: Cosmic Frontier

arXiv:2211.09978v1 [hep-ex] 18 Nov 2022

Frontier Conveners: Aaron S. Chou[1], Marcelle Soares-Santos[2], Tim M.P. Tait[3]
Topical Group Conveners: Rana X. Adhikari[4], Luis A. Anchordoqui[5], James Annis[1], Clarence L. Chang[6,7,8], Jodi Cooley[9,10], Alex Drlica-Wagner[1,7,8], Ke Fang[11], Brenna Flaugher[1], Joerg Jaeckel[12], W. Hugh Lippincott[13], Vivian Miranda[14], Laura Newburgh[15], Jeffrey A. Newman[16], Chanda Prescod-Weinstein[17], Gray Rybka[18], B. S. Sathyaprakash[19], David J. Schlegel[20], Deirdre M. Shoemaker[21] Tracy R. Slatyer[22], Anže Slosar[23], Kirsten Tollefson[24], Lindley Winslow[25], Hai-Bo Yu[26], Tien-Tien Yu[27,28]
Liaisons: Kristi Engel[29], Susan Gardner[30], Tiffany R. Lewis[31], Bibhushan Shakya[32], Phillip Tanedo[26]

2211.09978

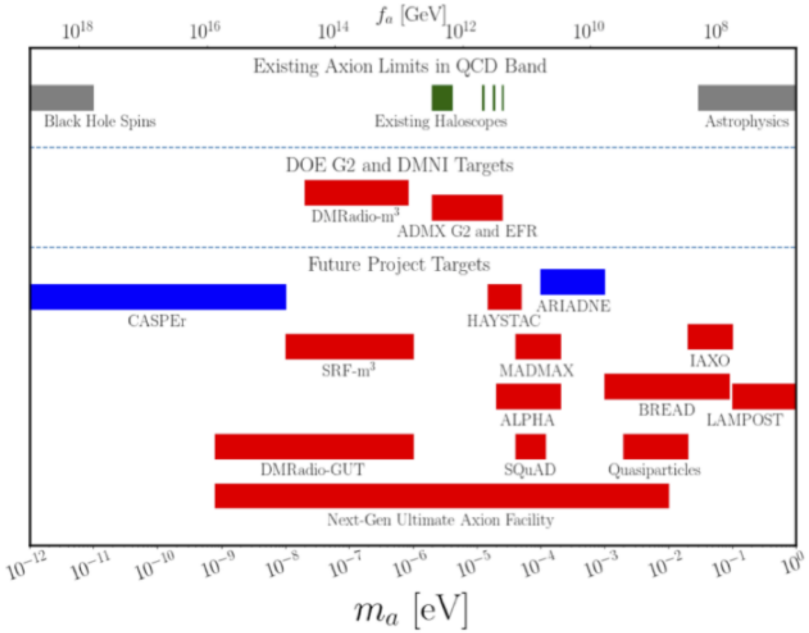


Figure 5-13. *A high priority target is the QCD axion which solves the strong CP problem as well as the origin of the dark matter. The QCD axion model makes testable predictions for the interaction strengths as a function of mass, providing useful benchmarks. This plot shows a suite of ongoing and future experiments which will test the QCD model by providing broad coverage of axion mass regions at the predicted coupling strengths to photons (red) and gluons (blue). From the CF2 report [2].*

Detecting Axions

$$\mathcal{L} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{i}{2} g_d a \bar{N}\sigma_{\mu\nu}\gamma_5 N F_{\mu\nu} + g_{aNN}(\partial_\mu)\bar{N}\gamma^\mu\gamma_5 N + g_{aee}(\partial_\mu)\bar{e}\gamma^\mu\gamma_5 e$$

Coupling to Photons

Coupling to Nucleon EDM

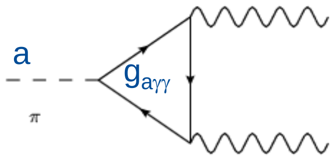
Coupling to Axial Nuclear Moment

Coupling to Axial Electron Moment

Adapted from Y. Kahn, See also Graham and Rajendran, Phys.Rev. D88 (2013) 035023

Detecting Axions

$$\mathcal{L} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{i}{2} g_d a \bar{N}\sigma_{\mu\nu}\gamma_5 N F_{\mu\nu} + g_{aNN}(\partial_\mu)\bar{N}\gamma^\mu\gamma_5 N + g_{aee}(\partial_\mu)\bar{e}\gamma^\mu\gamma_5 e$$



Coupling to Photons

Clean experimental signal
Well developed techniques
Ripe for incorporating quantum sensing techniques

Coupling to Nucleon EDM

Coupling to Axial Nuclear Moment

Promising experimental techniques under development

Coupling to Axial Electron Moment

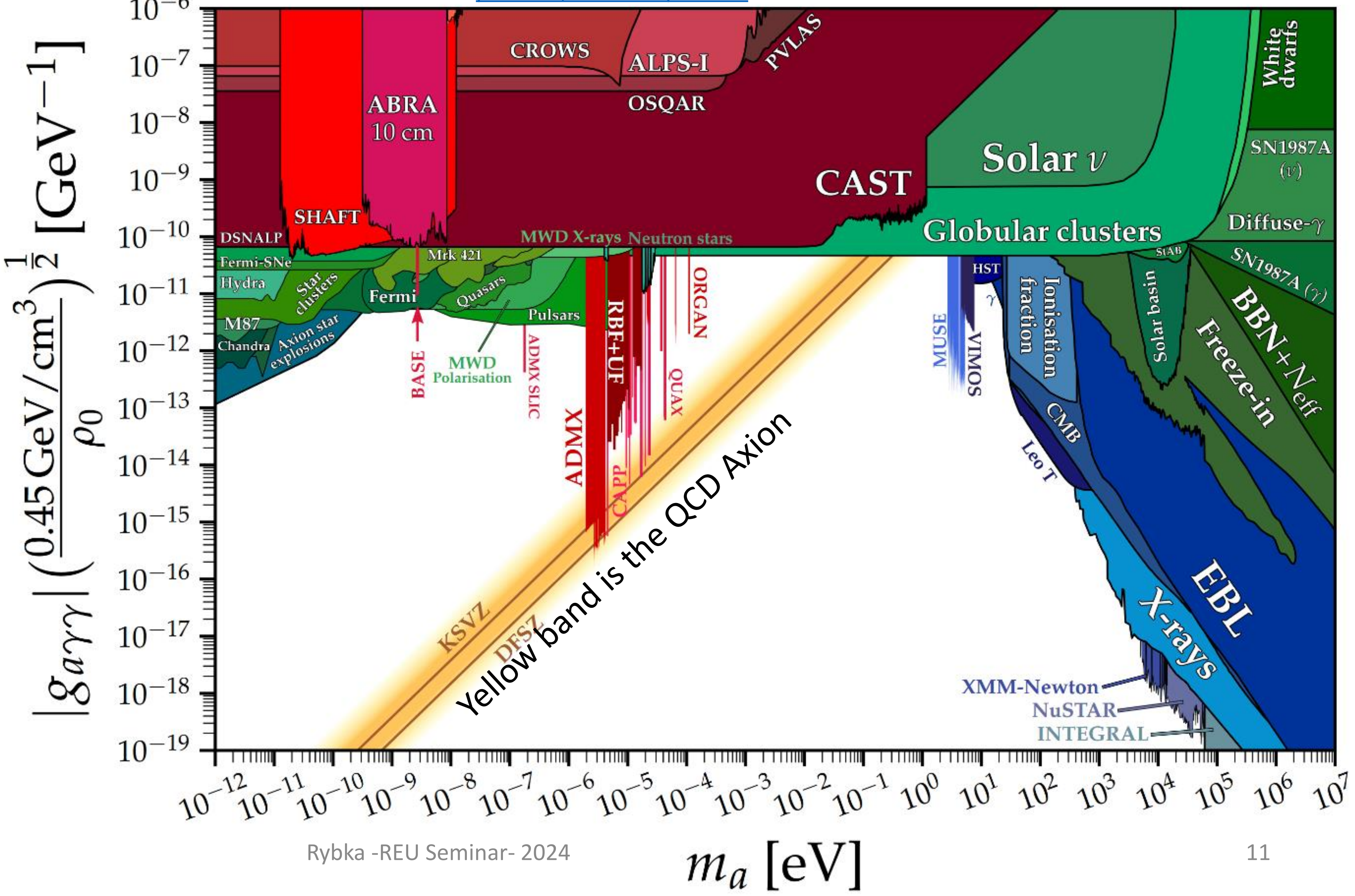
Adapted from Y. Kahn, See also Graham and Rajendran, Phys.Rev. D88 (2013) 035023

Axion Photon Bounds

[GitHub - cajohare/AxionLimits: Data, plots and code for constraints on axions, axion-like particles, and dark photons]

The yellow band is the QCD axion, white space is Axion-Like Particle (ALP) space

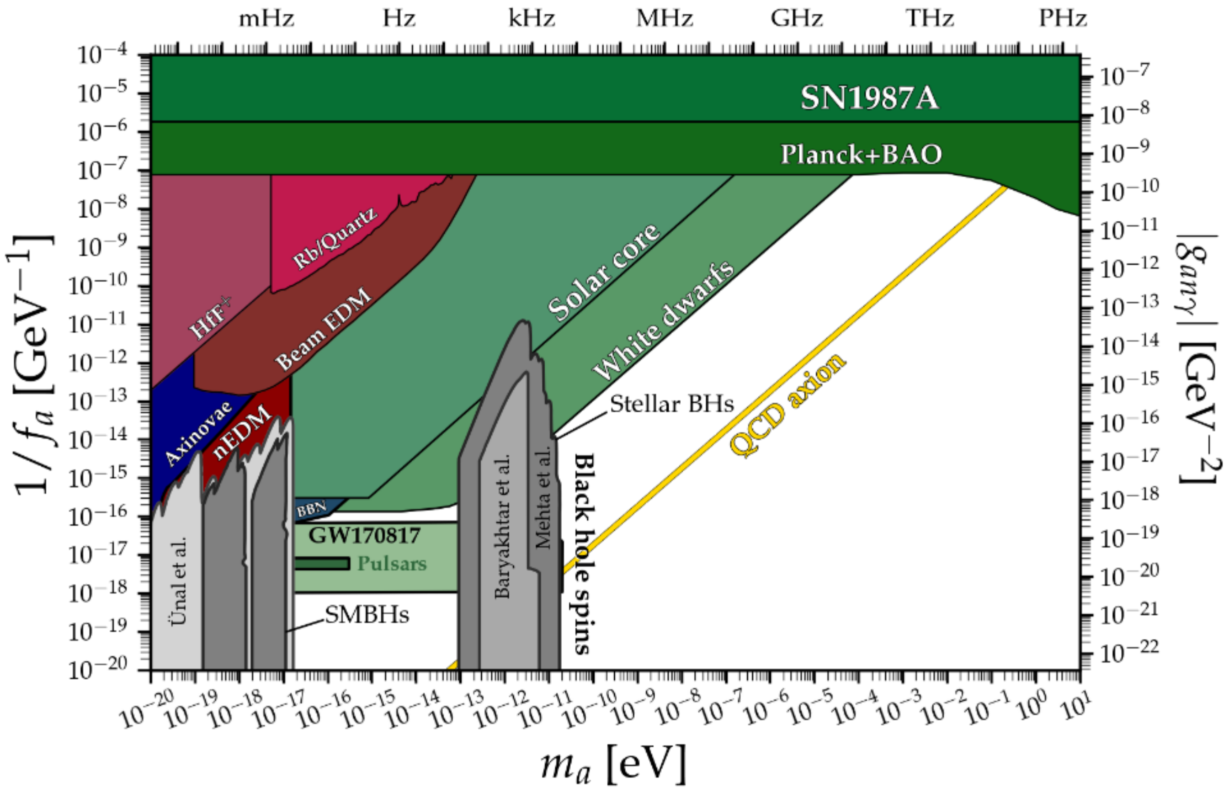
Note the significant astrophysical constraints on ALP parameters.



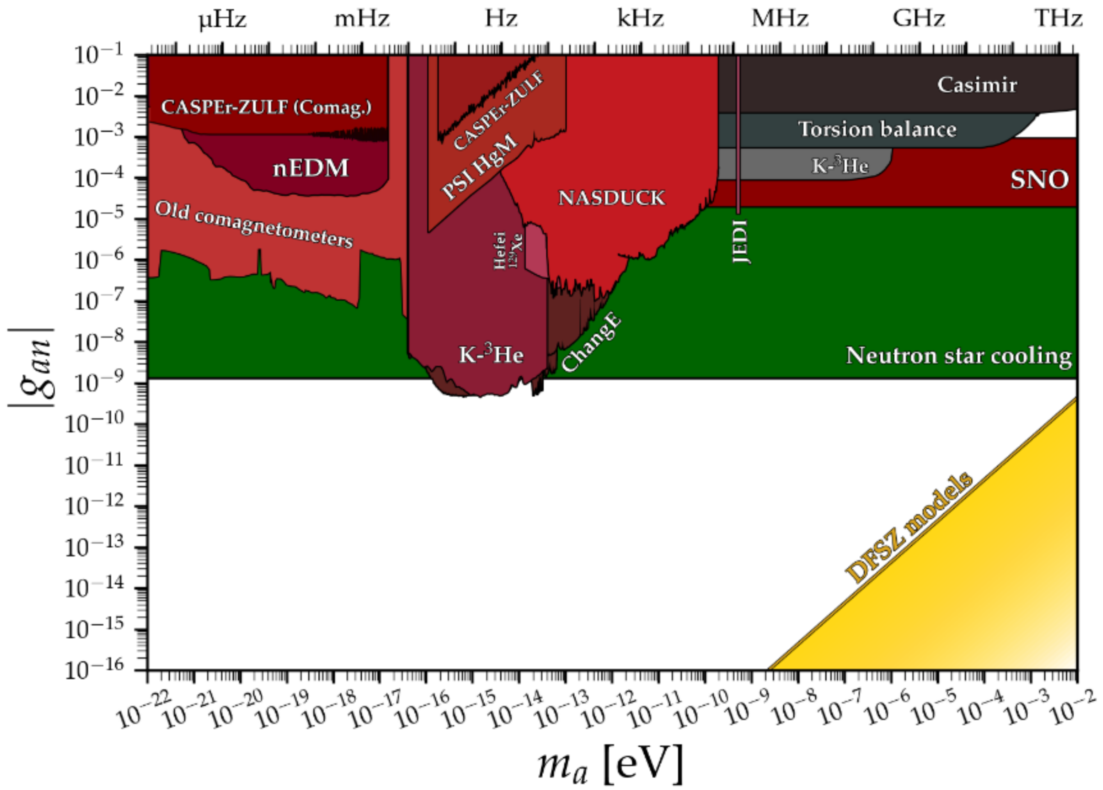
Yellow band is the QCD Axion

A few more example axion bounds

[GitHub - cajohare/AxionLimits: Data, plots and code for constraints on axions, axion-like particles, and dark photons]()

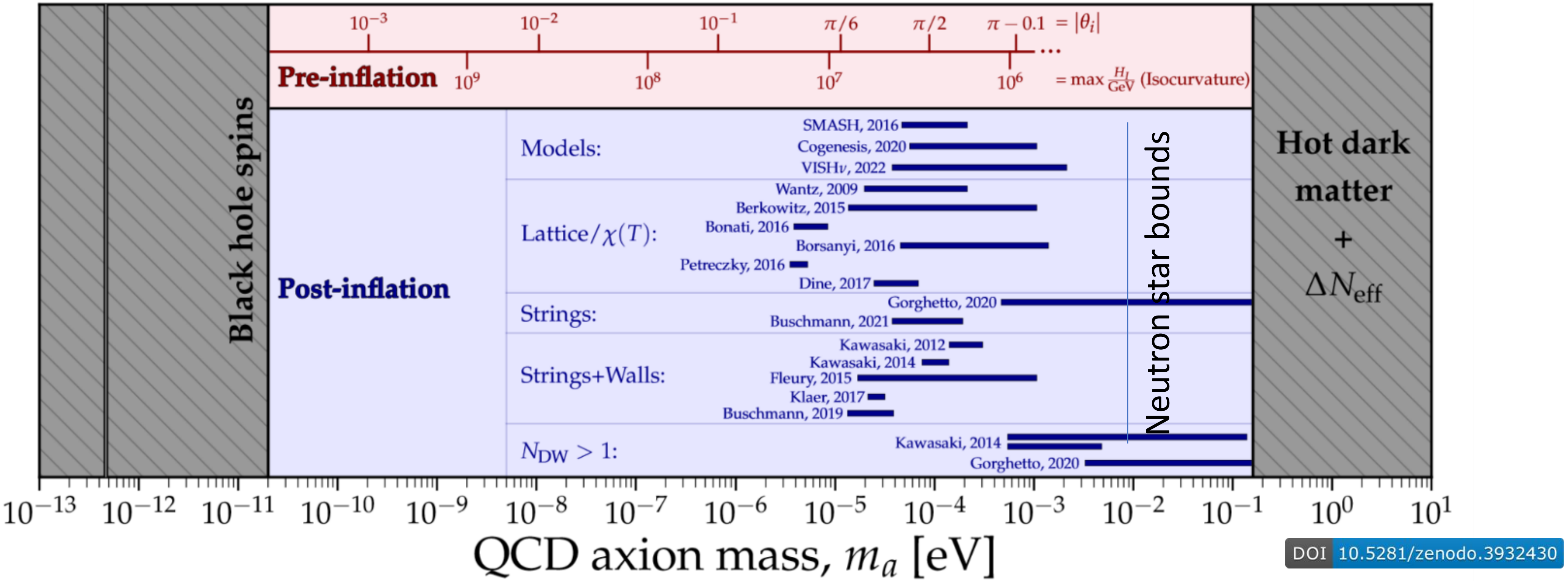


Less coupling dependent bounds



Axion-neutron bounds

Deeper Theoretical Preferences

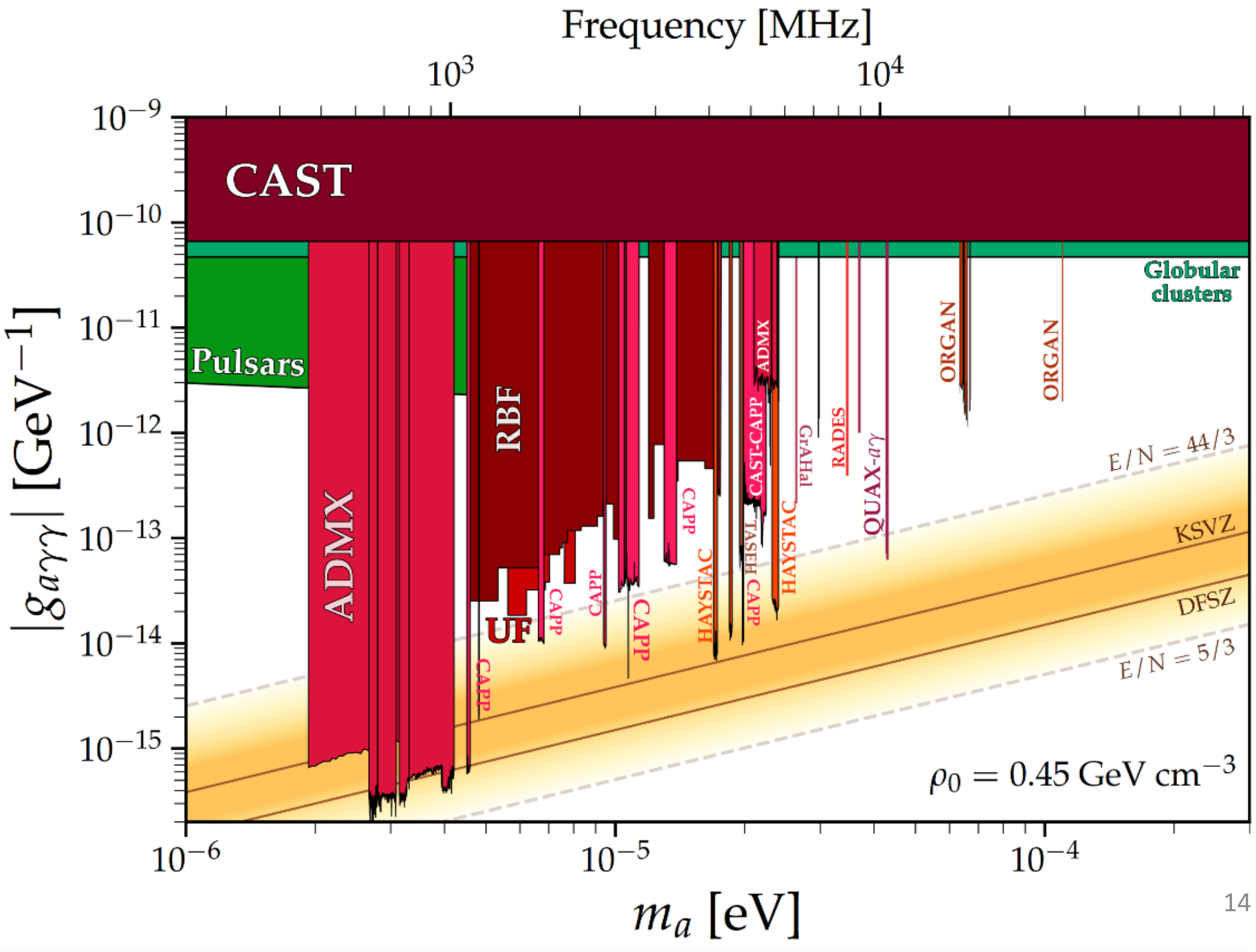


There is both model dependence and genuine disagreement in calculations about the axion mass that produces 100% dark matter density today – it is up to experimentalists do a comprehensive search

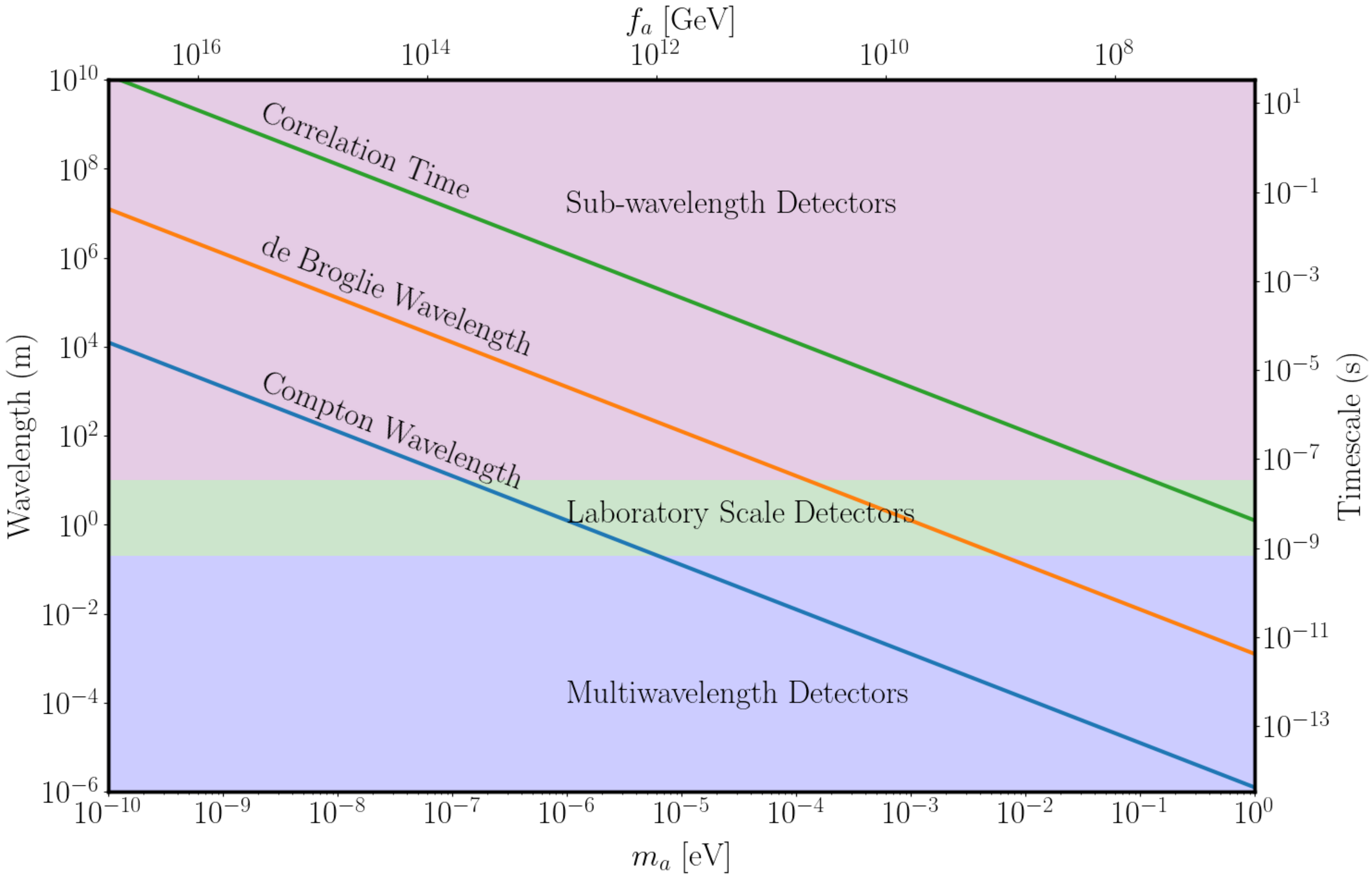
Axion Photon Bounds, Zoomed In

- KSVZ and DFSZ are benchmark axion coupling models.

- The class of experiments probing QCD axion parameters is the “Axion Haloscope”



Axion Detector Length and Time Scales



Maxwell’s Equations with an Axion Field

The Axion-Photon coupling can be interpreted classically as a small perturbation to Maxwell’s equations:

$$\nabla \cdot E = \rho - g_{a\gamma\gamma} B \cdot \nabla a$$

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

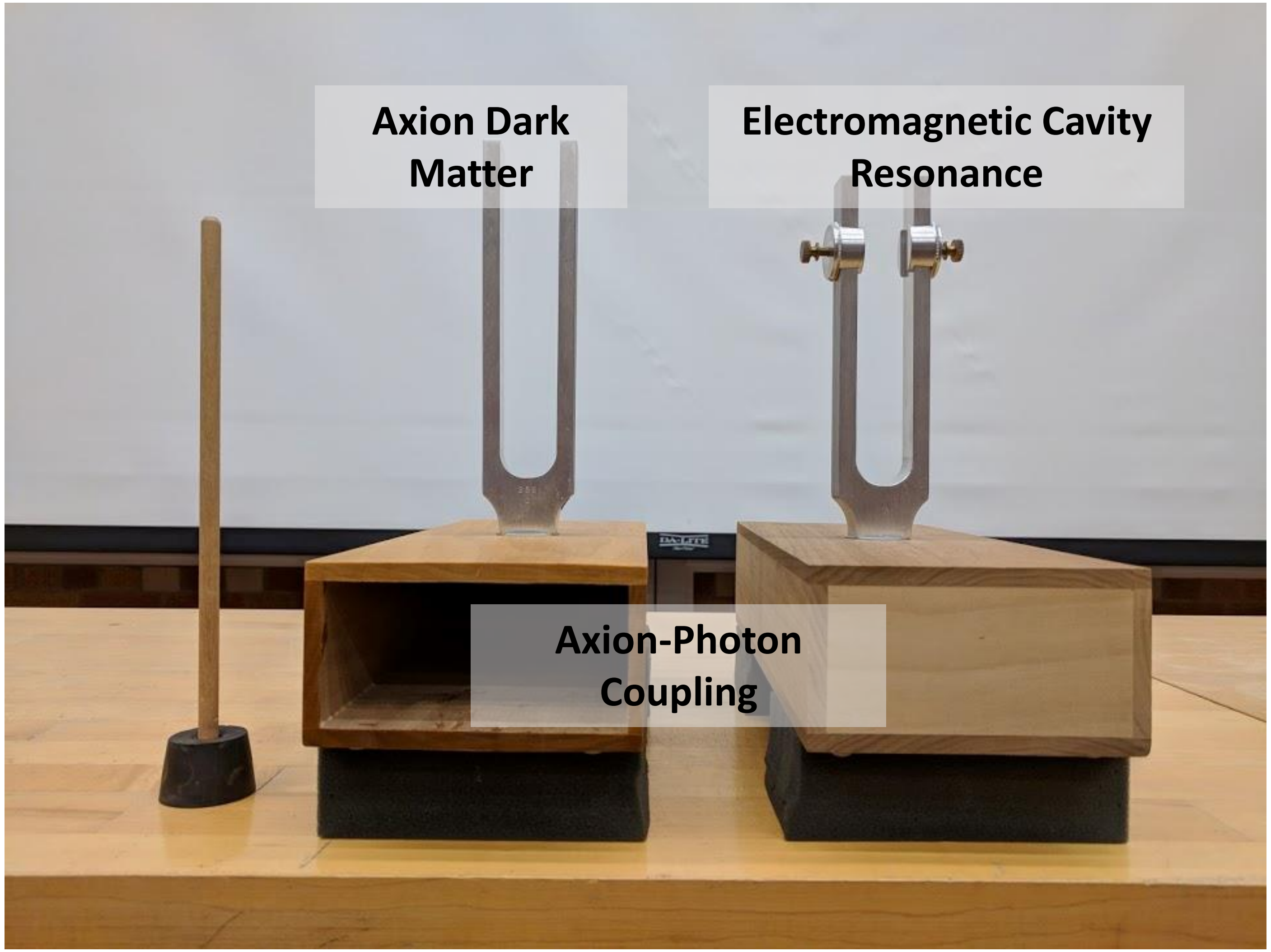
$$\nabla \times B = \frac{\partial E}{\partial t} + J - g_{a\gamma\gamma} (\mathrm{E} \times \nabla a - B \frac{\partial a}{\partial t})$$

$$\nabla \cdot B = 0$$

In particular, an axion field in a strong magnetic field radiates photons like a very weakly coupled antenna!

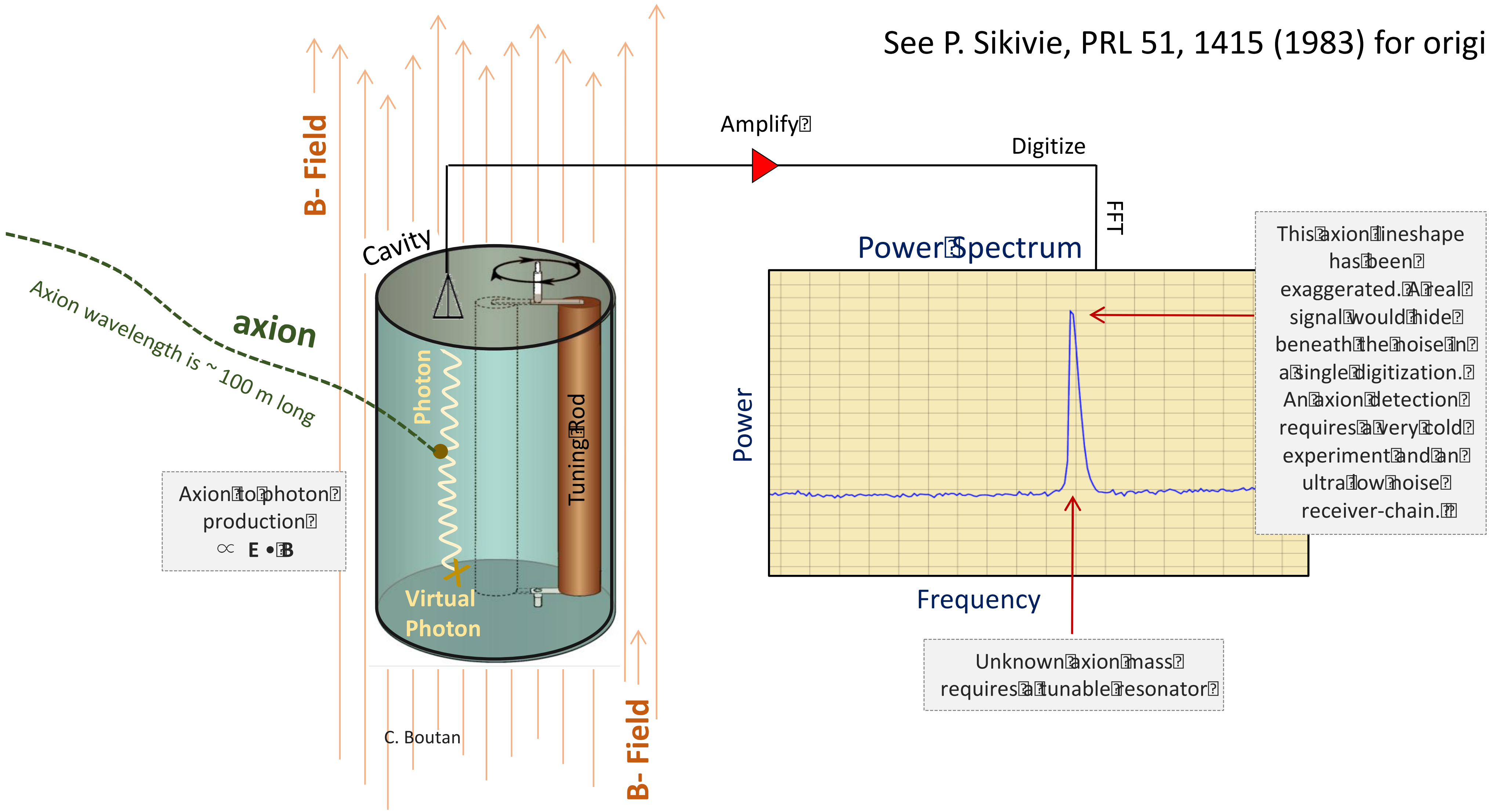
Axion Haloscope for my Intro Physics Class

Axion Haloscope for my Intro Physics Class



Principle of the Sikivie Axion Haloscope

See P. Sikivie, PRL 51, 1415 (1983) for origin

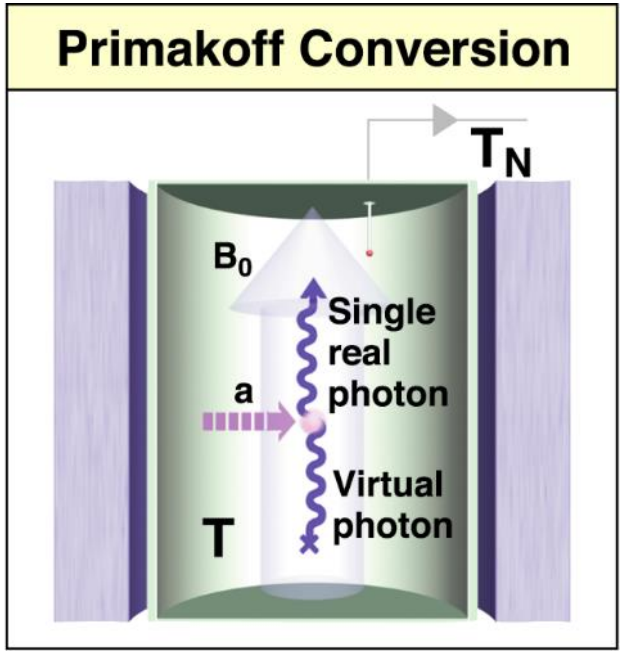


Axion to photon production
∝ **E • B**

This axion lineshape has been exaggerated. A real signal would hide beneath the noise in a single digitization. An axion detection requires a very cold experiment and an ultra low noise receiver-chain.

Unknown axion mass requires a tunable resonator

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 Collaboration

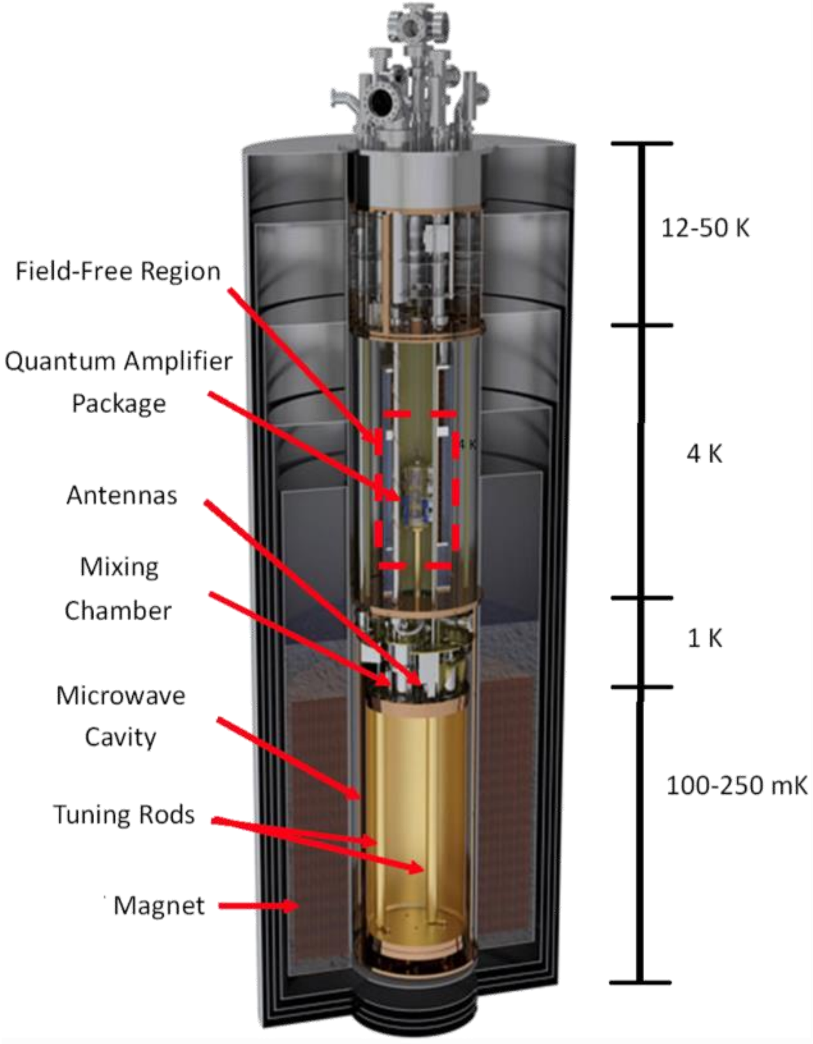
ADMX Collaboration meeting Jan 2023

Collaborating Institutions:

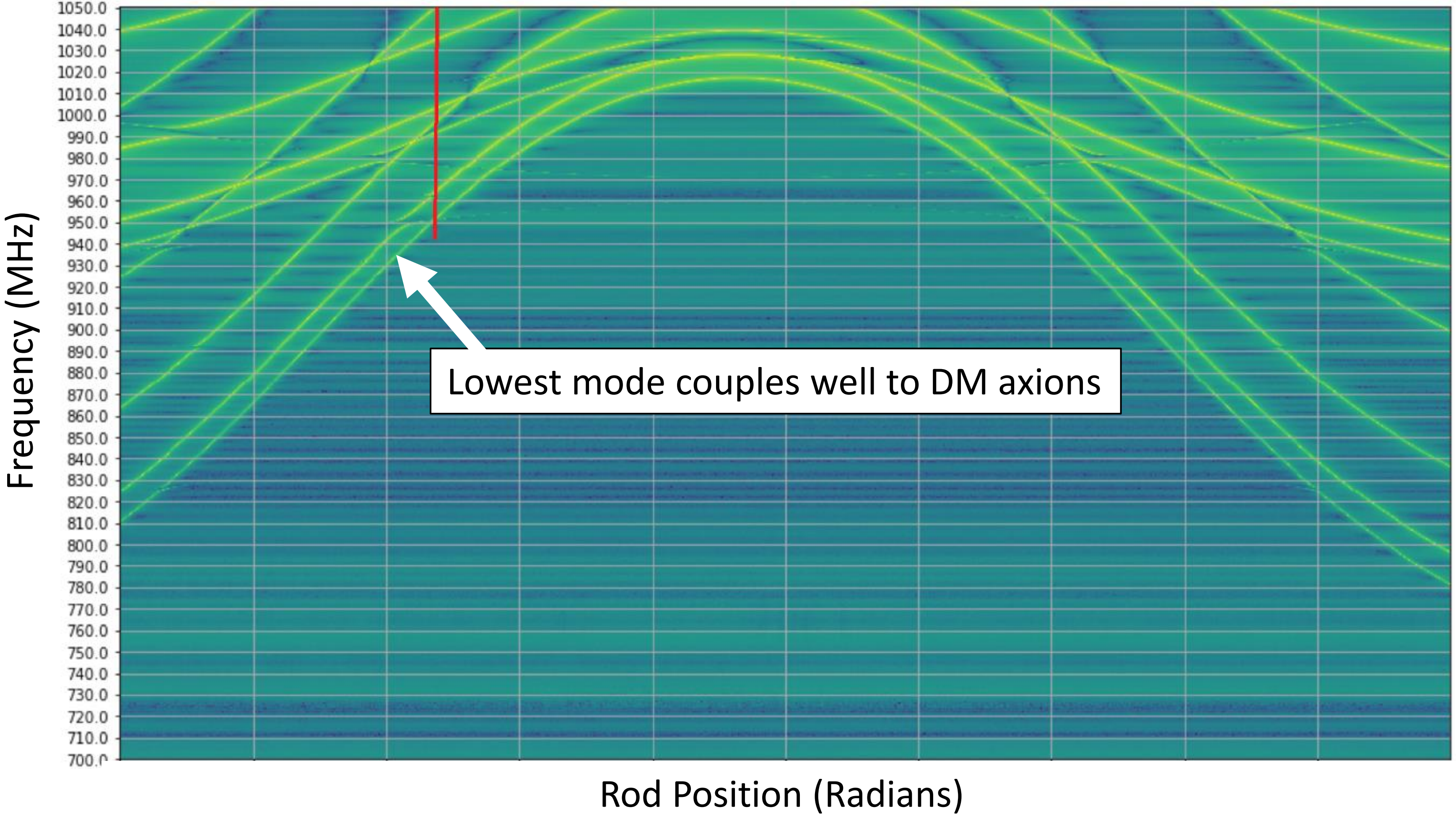
University of Washington
Washington University St. Louis
University of Western Australia
University of Florida
University of Sheffield
University of Western Australia
Stanford University / SLAC
UC Berkeley
Fermilab
Pacific Northwest National Laboratory
Lawrence Livermore National Laboratory
Los Alamos National Laboratory

This work was supported by the U.S. Department of Energy through Grants No DE-SC0009800, No. DE-SC0009723, No. DE-SC0010296, No. DE-SC0010280, No. DE-SC0011665, No. DEFG02-97ER41029, No. DE-FG02-96ER40956, No. DEAC52-07NA27344, No. DE-C03-76SF00098 and No. DE-SC0017987. Fermilab is a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359. Pacific Northwest National Laboratory is a multi-program national laboratory operated for the U.S. DOE by Battelle Memorial Institute under Contract No. DE-AC05-76RL01830.Additional support was provided by the Heising-Simons Foundation, and NSF Grant PHY-2208847

ADMX Design

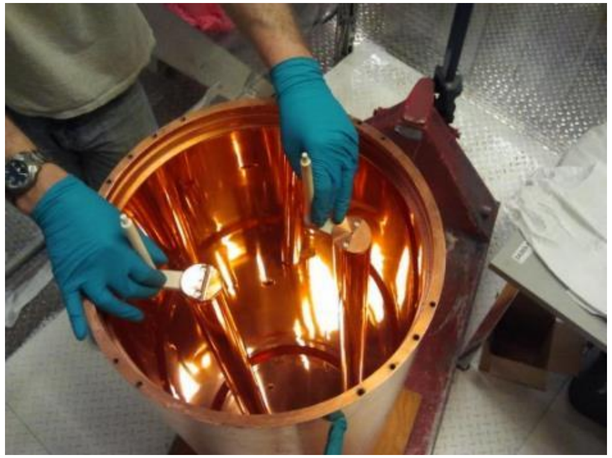

Field-Free Region
Quantum Amplifier Package
Antennas
Mixing Chamber
Microwave Cavity
Tuning Rods
Magnet
12-50 K
4 K
1 K
100-250 mK

Tuning ADMX


Example Cavity Tuning Curve

Lowest mode couples well to DM axions

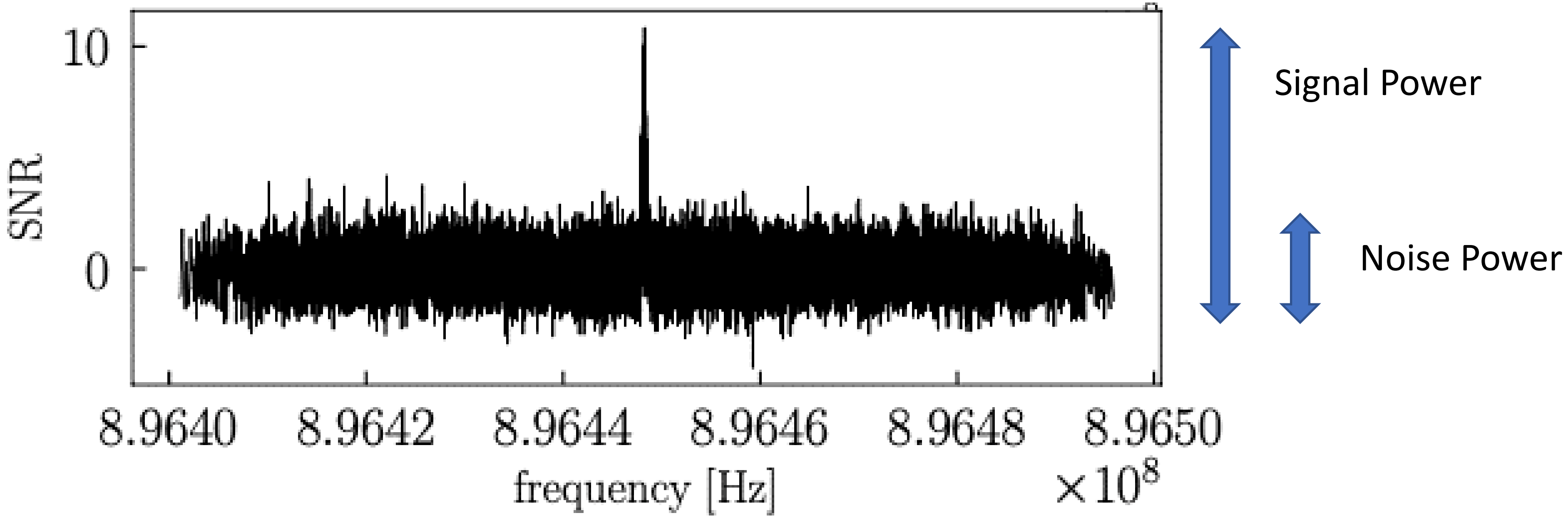
Tuning Rods within Cavity



We are only sensitive to axions within ~10 kHz of the cavity’s fundamental mode.

We tune this frequency mechanically by moving rods within the cylinder.

The Importance of Noise

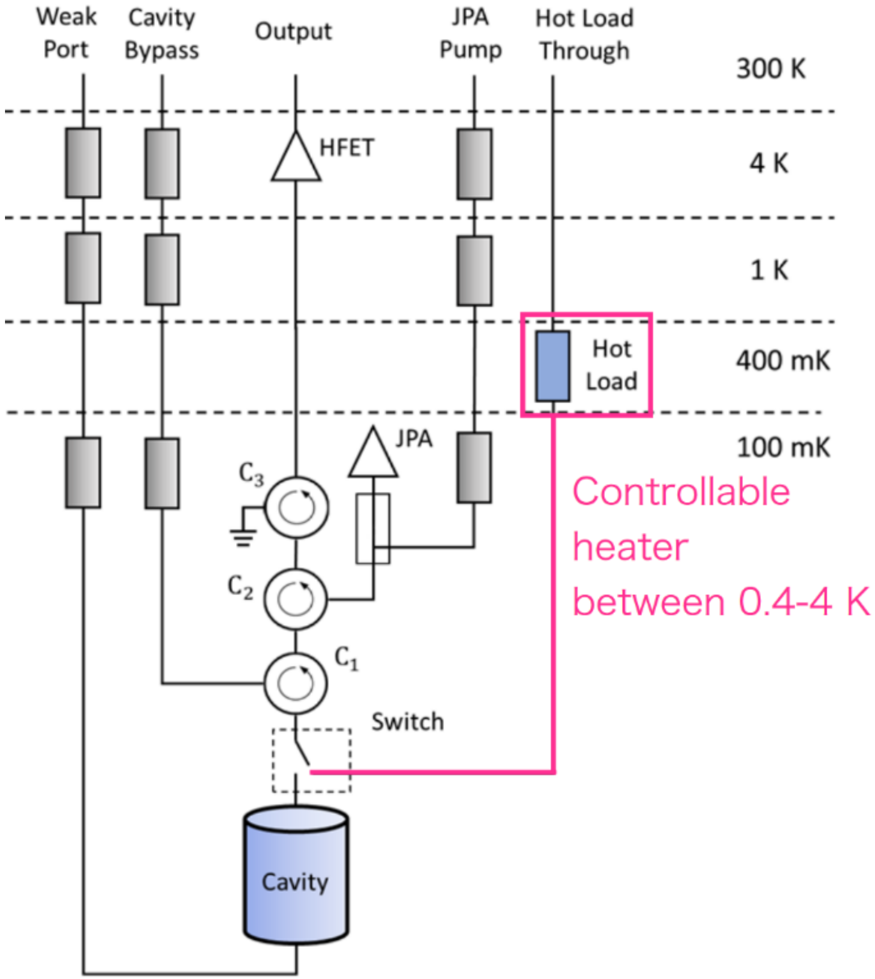


We need our noise to be much smaller than our signal to make a detection.

The noise is a thermal, and the slower we scan the smaller the uncertainty.

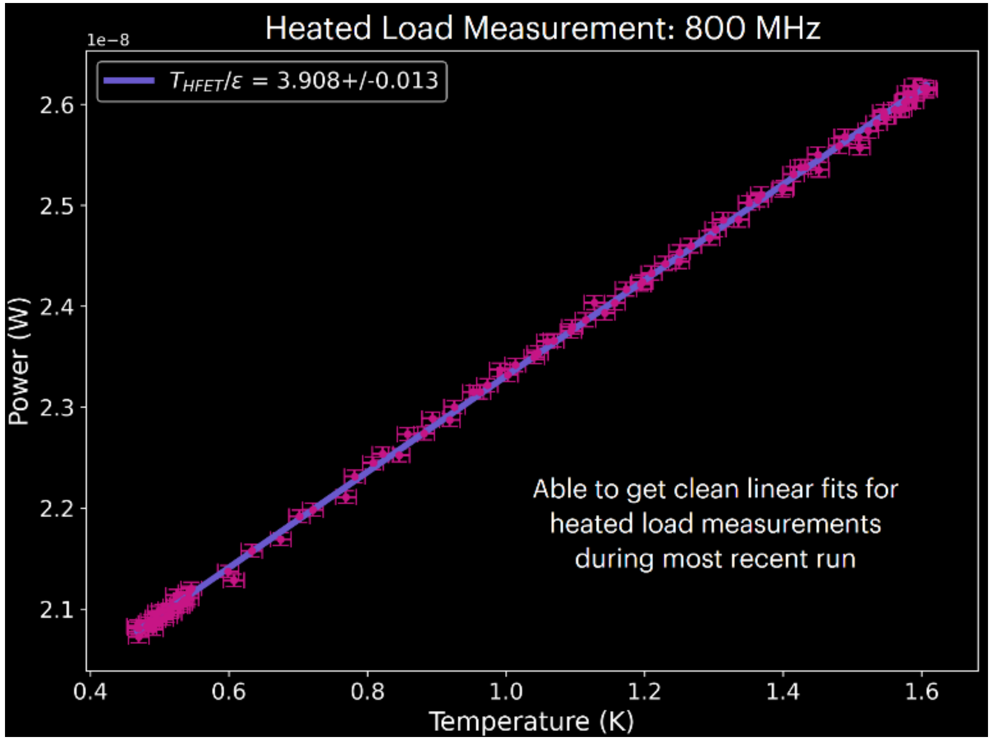
We must carefully calibrate the noise of our system – to understand our sensitivity, we must understand the temperatures of the components, the signal loss in the cables, and the performance of the amplifiers.

ADMX Noise Calibration



Controllable heater between 0.4-4 K

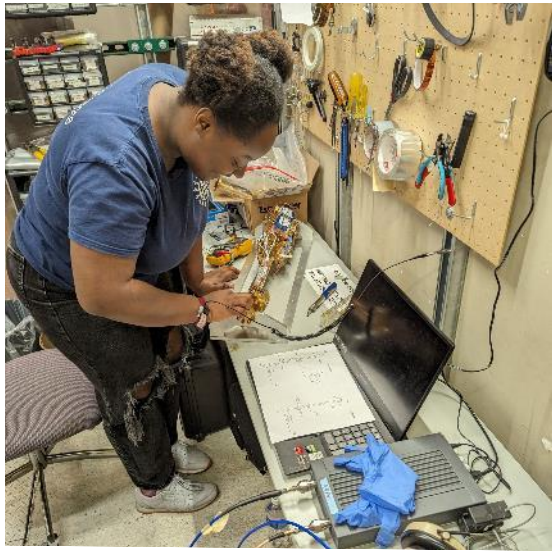
Our primary noise calibration comes from a temperature sensor



Able to get clean linear fits for heated load measurements during most recent run

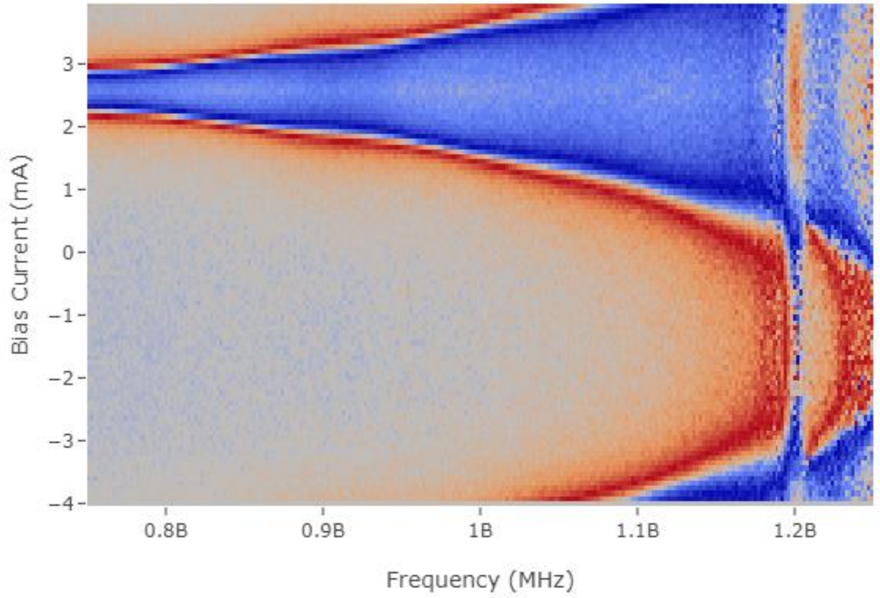
M. Guzzetti, APS April 2023

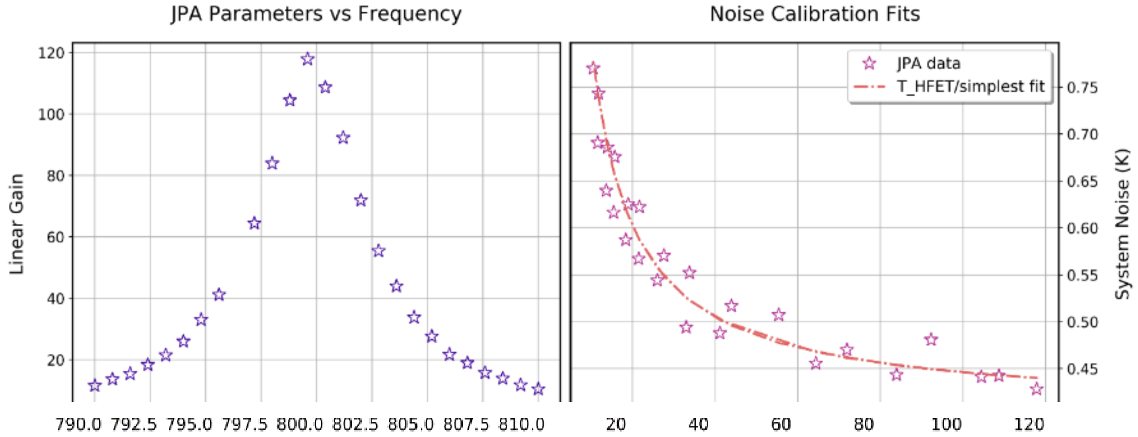
ADMX Noise Calibration



Warm testing of JPA electronics for ADMX Run1D

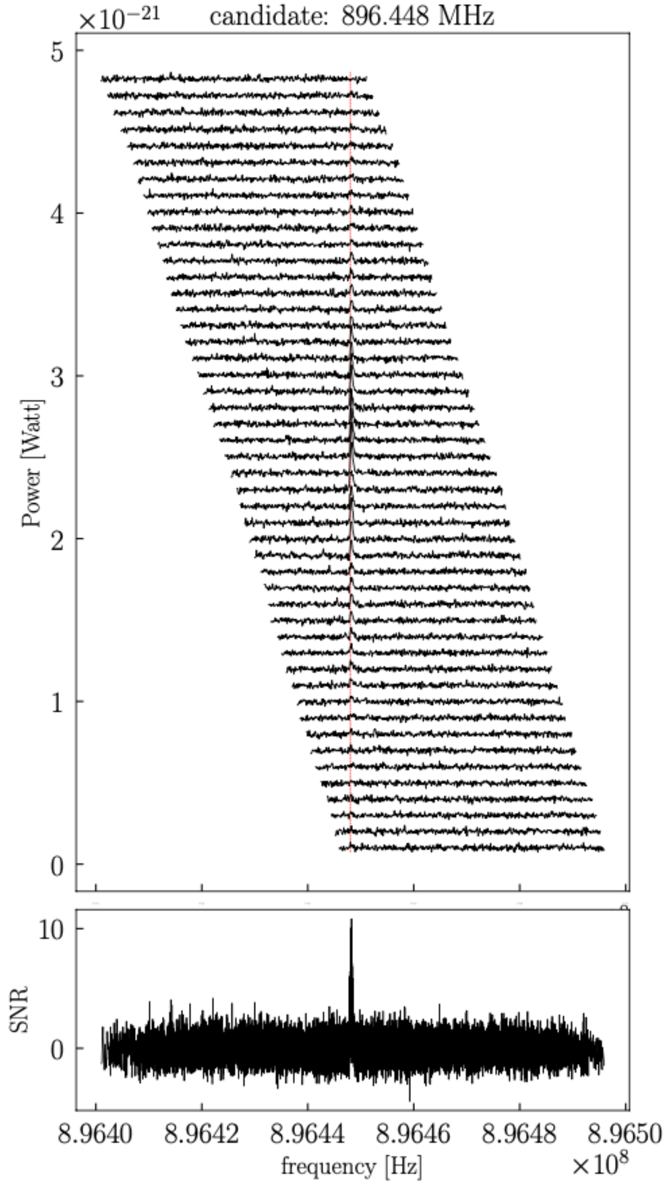
Our first-stage amplifier is a narrow-band JPA (Josephson Parametric Amplifier). It must be tuned to match the cavity.





JPA Added noise is calibrated by comparing powers and transmissions with the JPA powered and unpowered. We have a few photons of extra noise beyond the standard quantum limit.

ADMX Operations

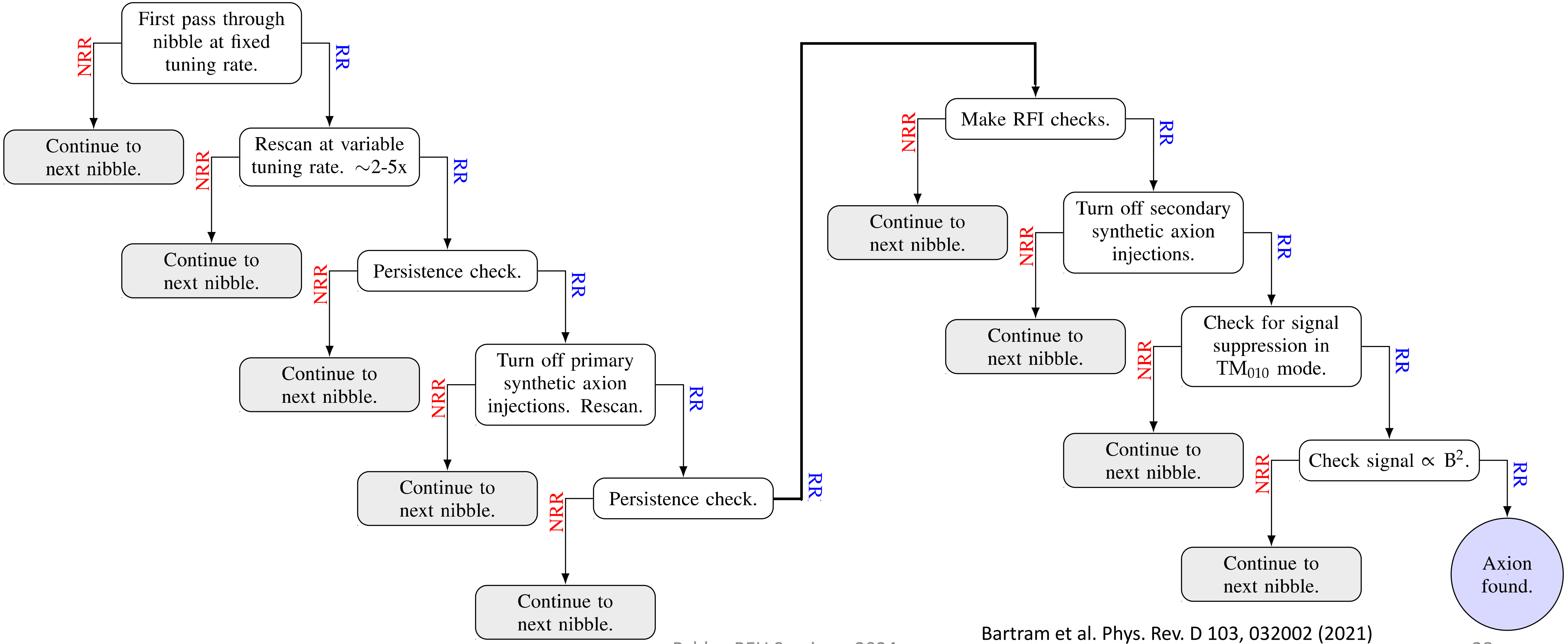


The cavity is tuned every 100 seconds, during which power spectra are taken. Overlapping power spectra are examined for the characteristic axion signal shape appearing on-resonance.

The picture on the left shows how an axion signal would appear in the data. This is a synthetic signal.

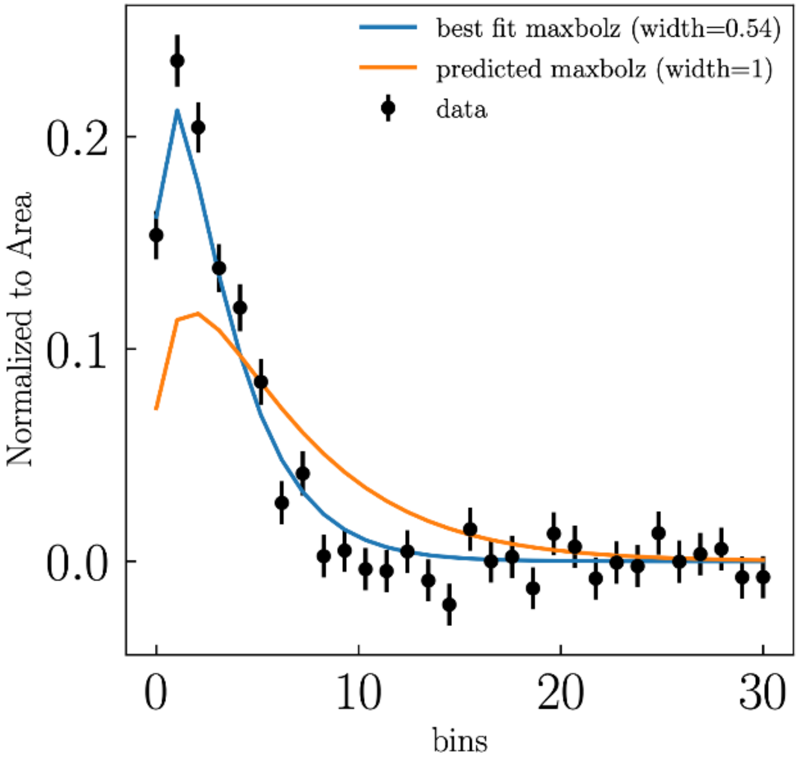
Data Taking Cadence

14 "nibbles" = $\sim$ 10 MHz sweeps single scans: **range:** 50 kHz, **resolution:** 100Hz, **integration time:** 100s

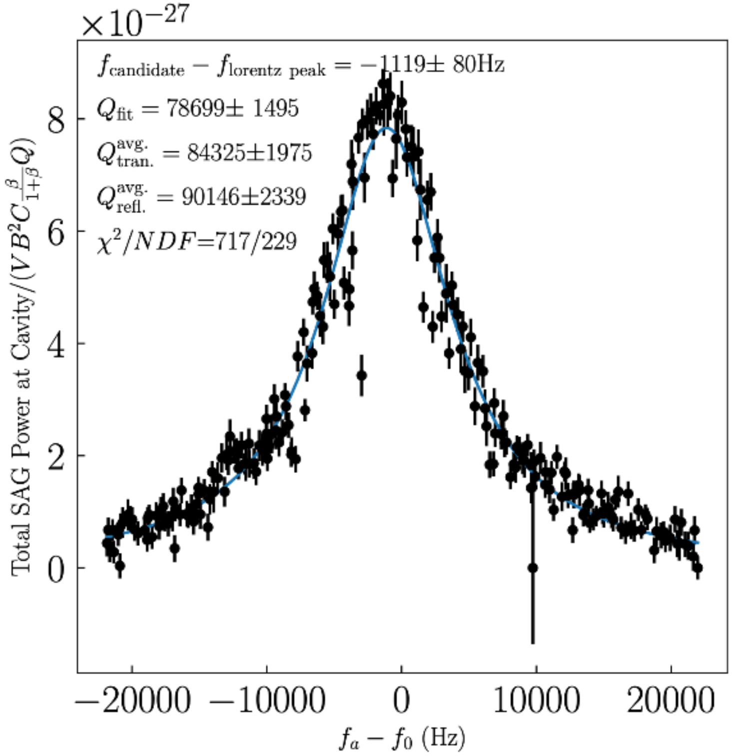


Bartram et al. Phys. Rev. D 103, 032002 (2021)

Blind-Injection Synthetic Signal Detection



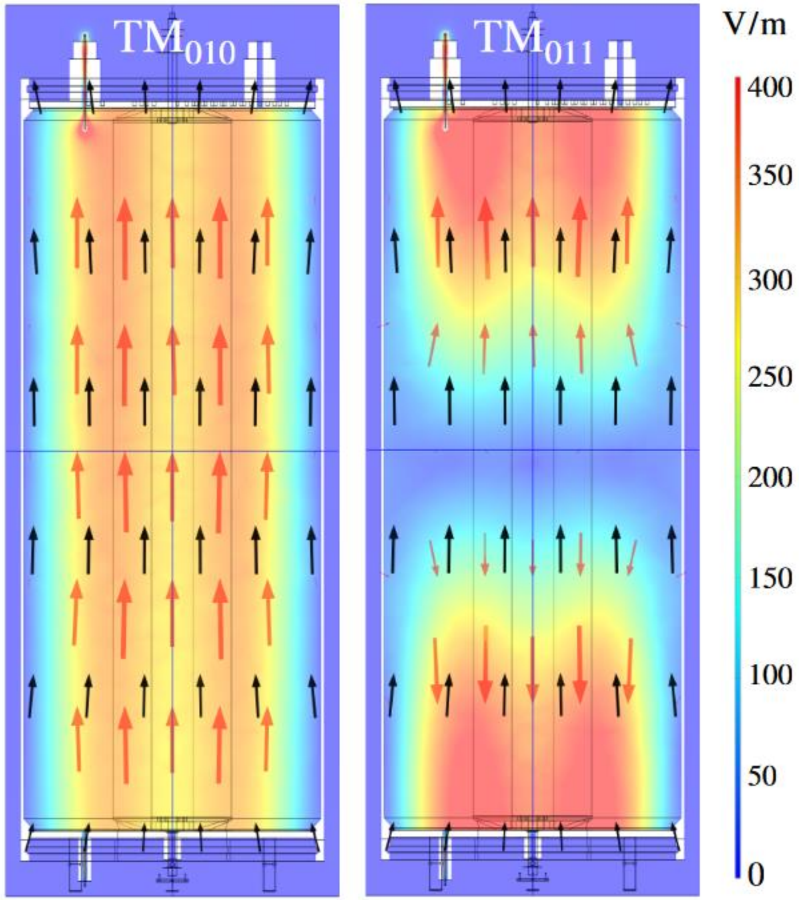
The lineshape was consistent with cosmological predictions

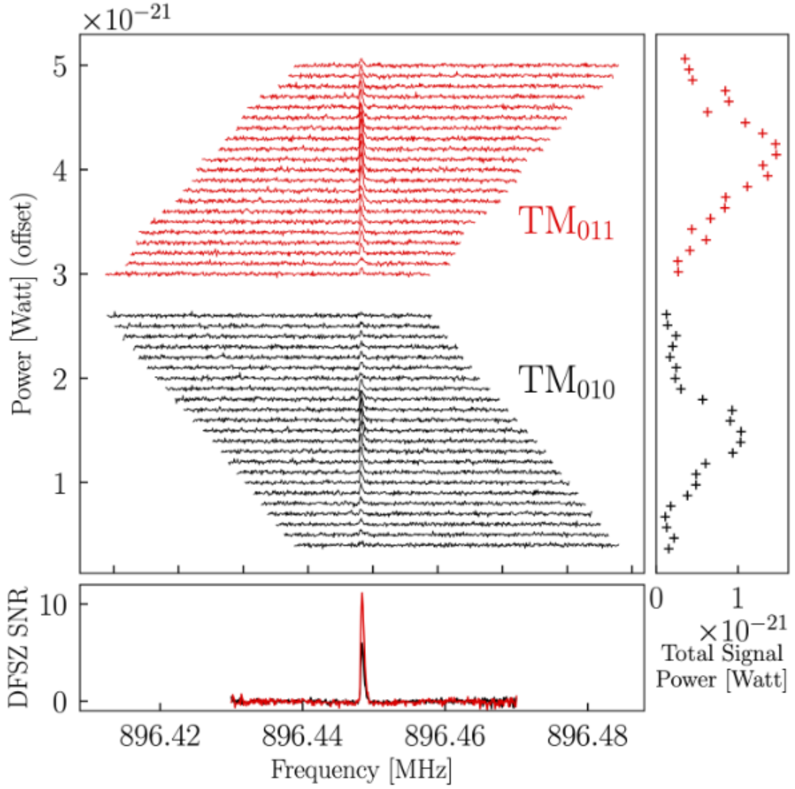


The signal was clearly coming from inside the cavity

This signal sure looked like an axion. But before we began ramping the magnet down to be sure, we wanted to try looking at it from another mode.

Axions Couple to TM010 modes, not TM011



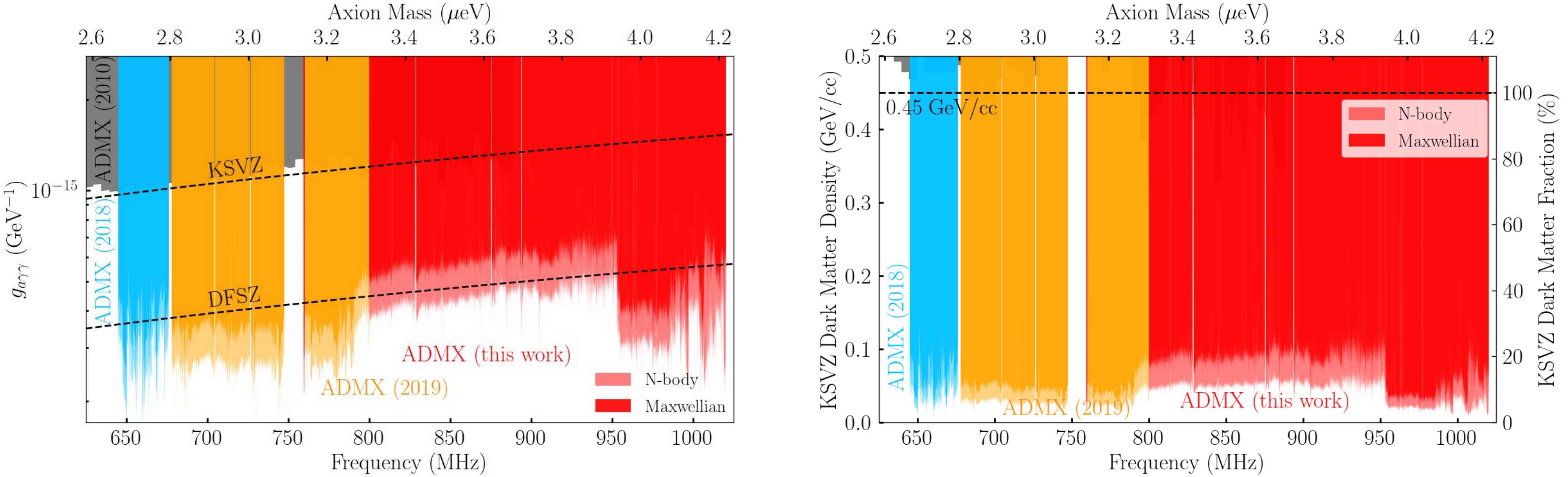


Overlap of axion field (black)
and E&M mode field (red)

This signal appeared in both modes,
and was thus clearly not an axion.

ADMX Recent Published Results

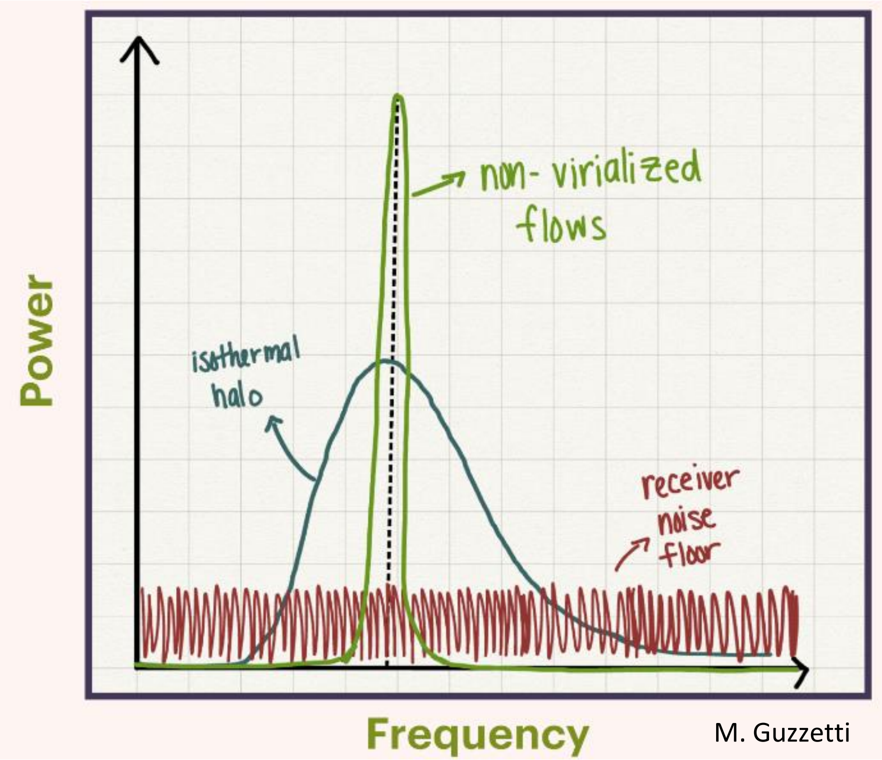
Excluded parameter space over the last 5 years



Bartram et al. PRL 127, 261803 (2021)

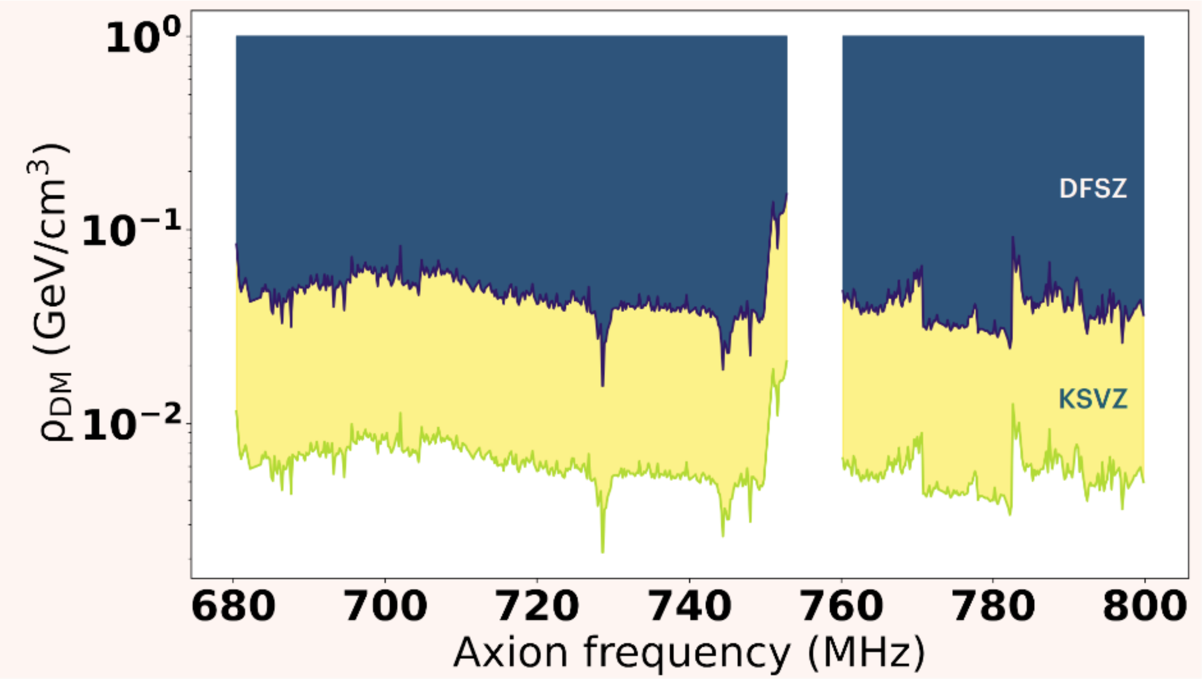
We are sensitive to DFSZ or near-DFSZ axions at nominal dark matter densities, and KSVZ axions at fractional dark matter densities.

ADMX High-Resolution Results



M. Guzzetti

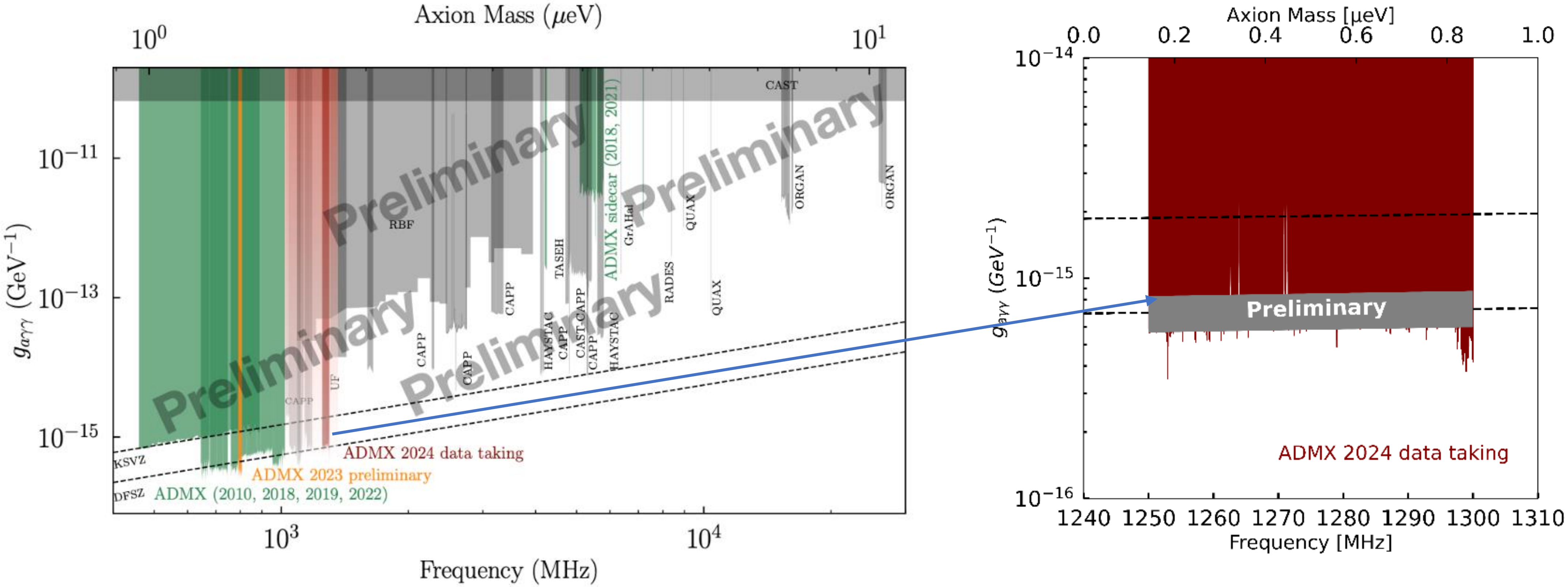
Nonvirialized “extra cold” dark matter produces a narrow signal with a measurable doppler shift



M. Guzzetti, General Exam

A high-resolution analysis to search for narrowband signals puts limits on dark matter axion flow densities

ADMX Upcoming Results

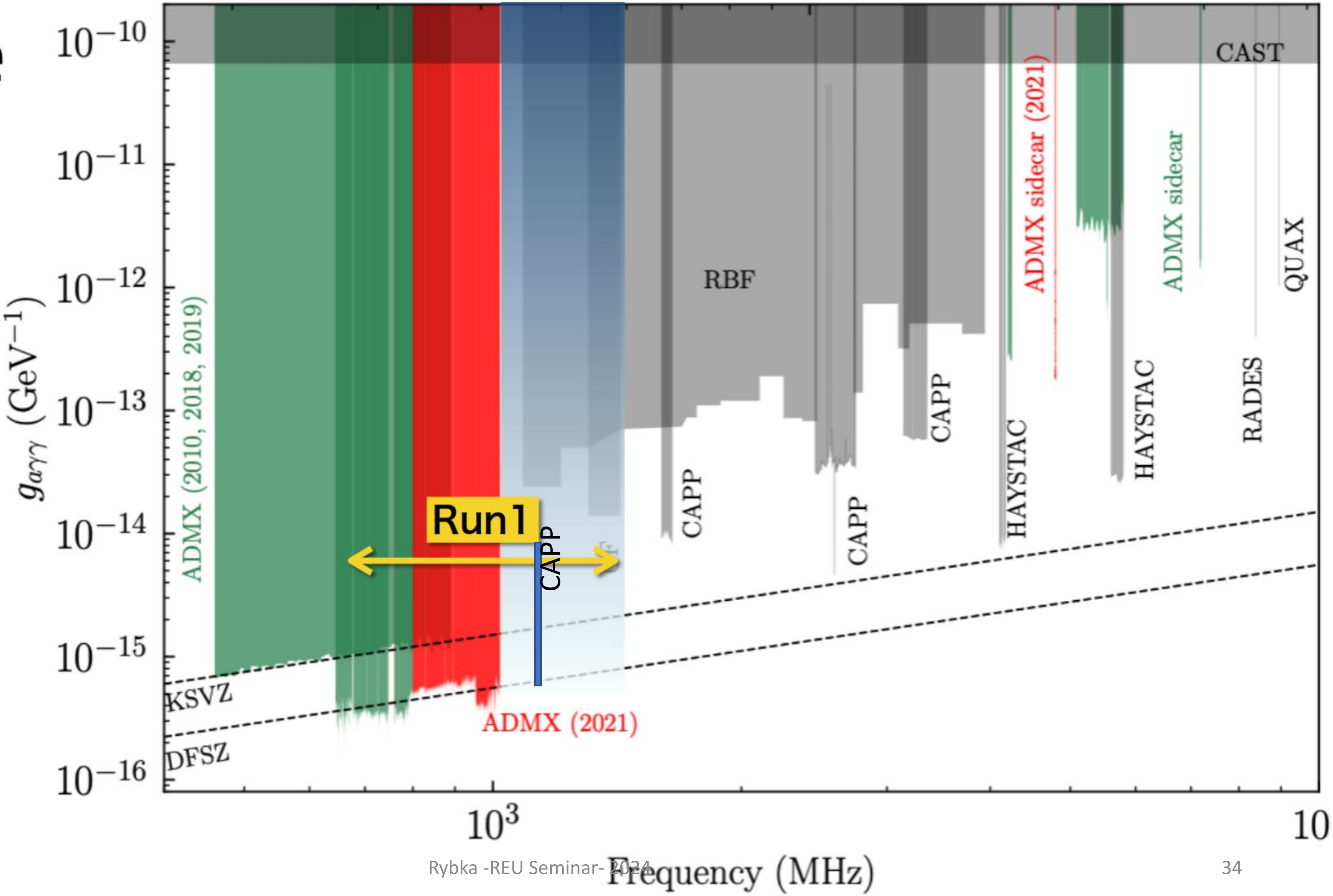


D. Zhang, April APS (2024)

Exploring new parameter space: Preliminary sensitivity in the 1.3 GHz range

Future Plans

Bigger tuning rod



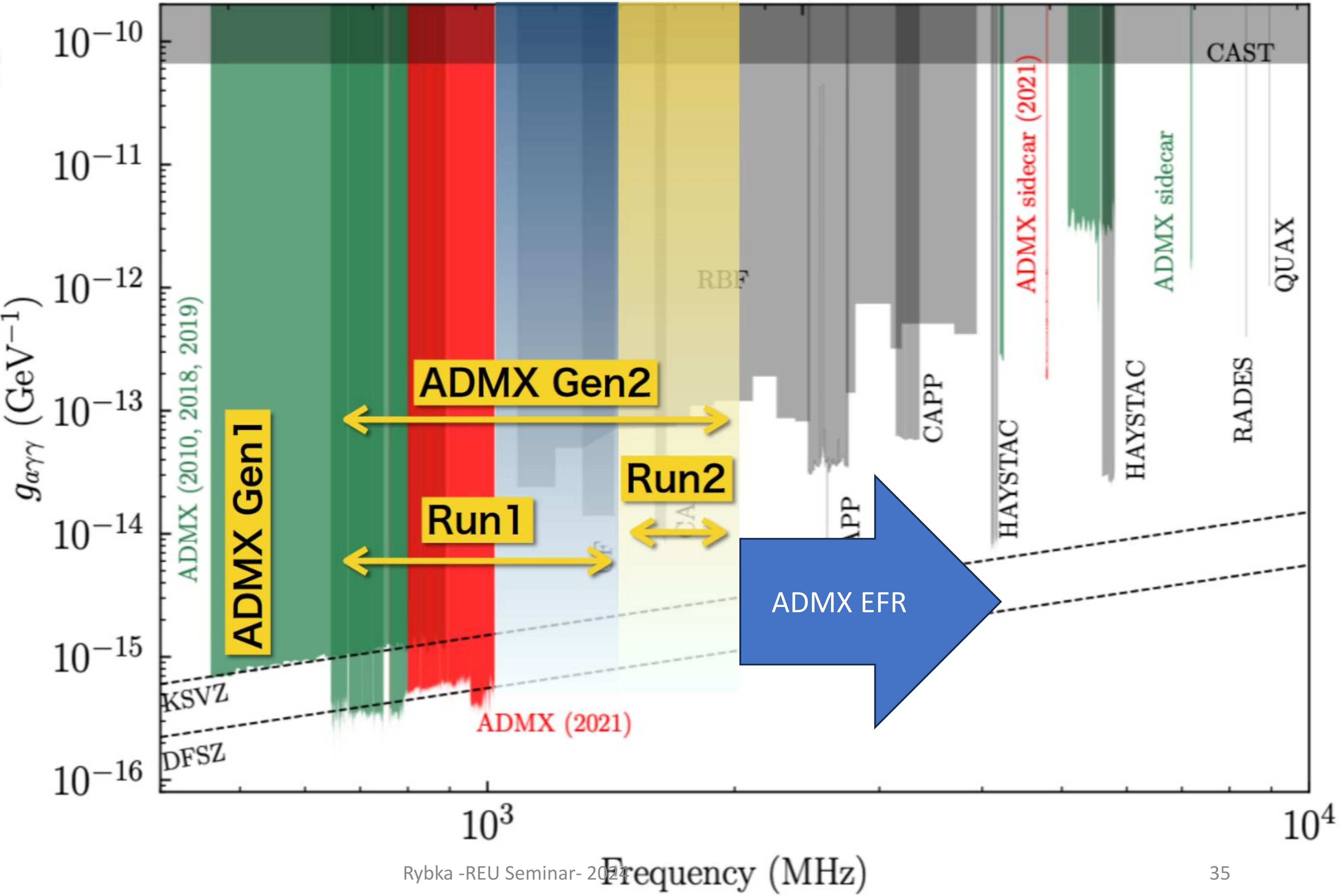
Further Plans

ADMX EFR

New Site

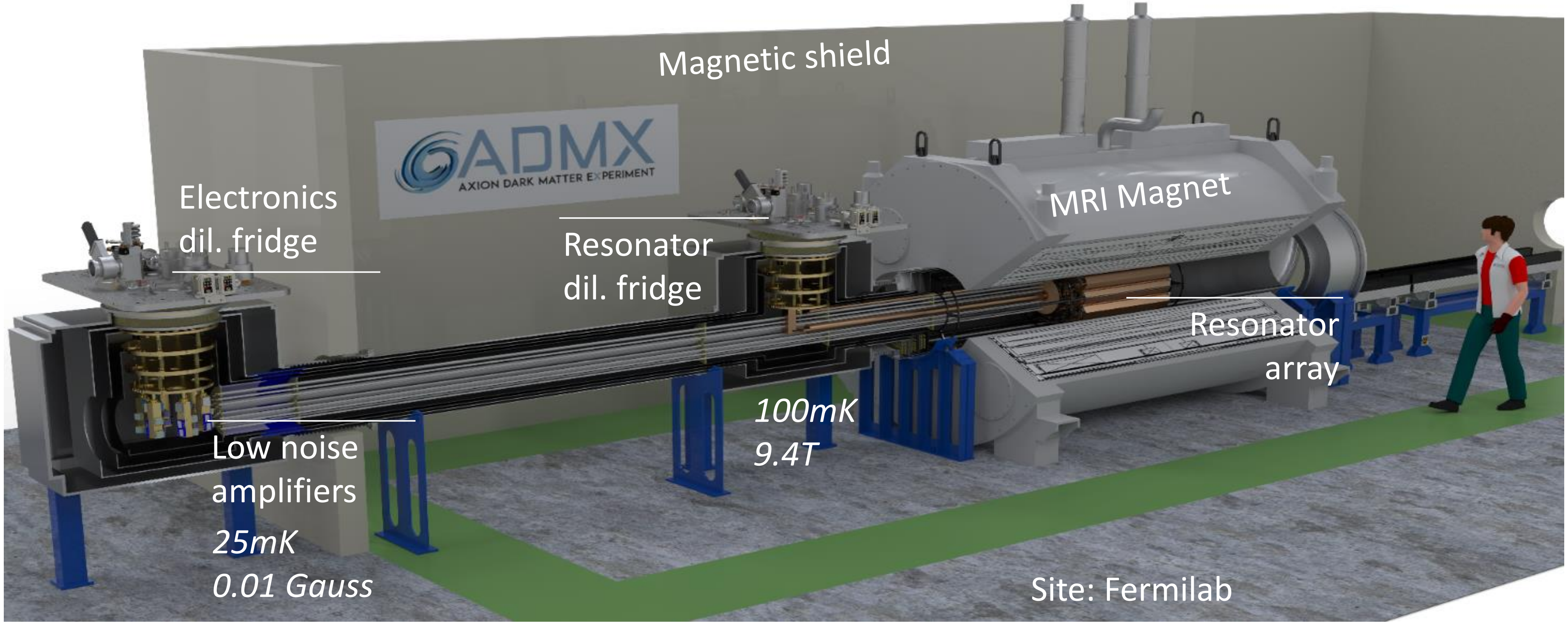
New Magnet

New Design



ADMX-EFR

- Incorporate technologies as they mature for a continuous scan sensitive to DFSZ axions at 2GHz and up



The Future of Haloscopes

At higher frequencies, axion haloscopes suffer from unfavorable

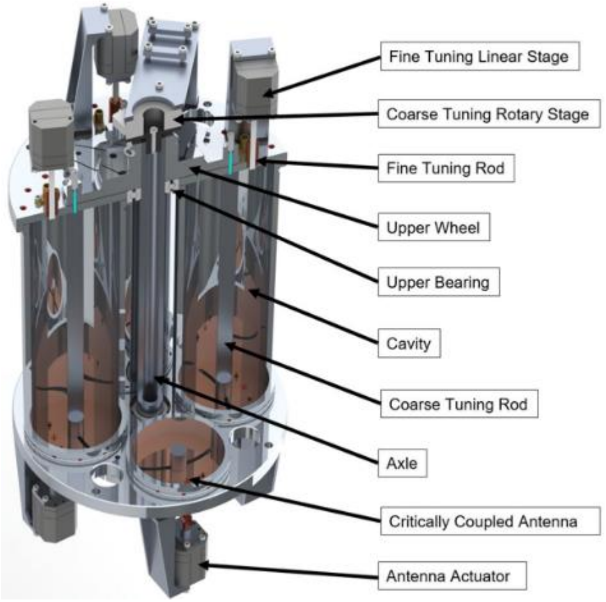
-Volume scaling
-Resonator Q scaling
-Standard Quartum Limit noise scaling

A thorough search up to 10 GHz+ will require

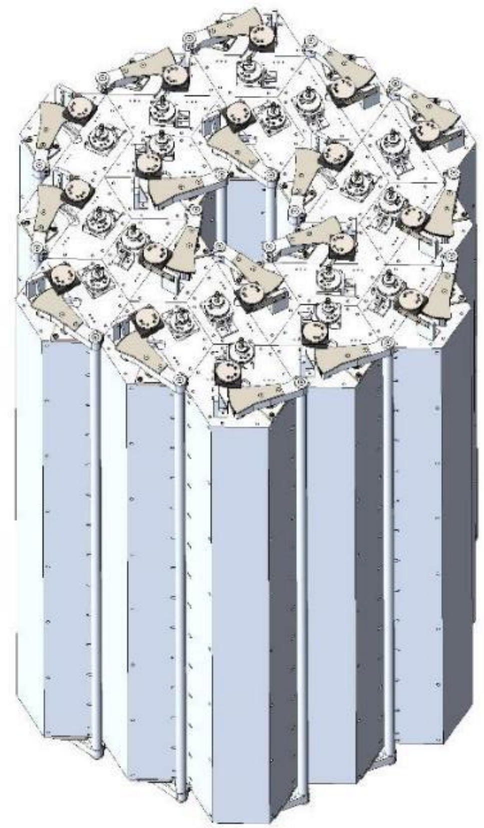
- Sophisticated, high-Q Resonators
  read out by
- Sub-quantum limit detectors
  inside of
- Large, high-field magnets
  located at
- Dedicated Facilities
  operated by
- Larger Collaborations

Sophisticated Resonators – Multicavity Systems

- Multiple haloscope cavities, combined in a phase-aware way scale SNR by number of cavities



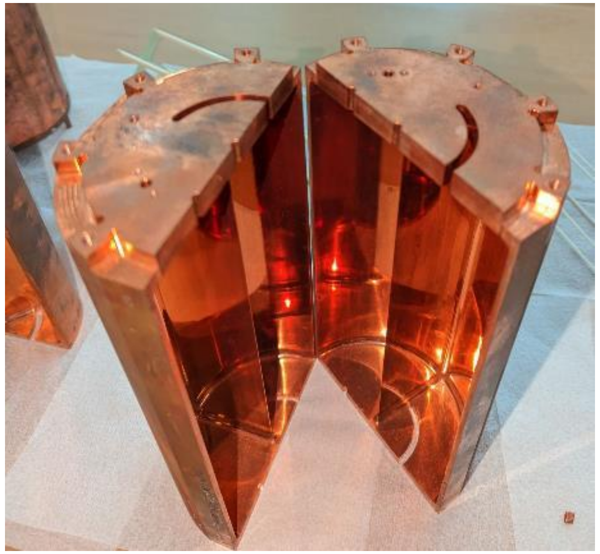
ADMX 2GHz
4-Cavity array



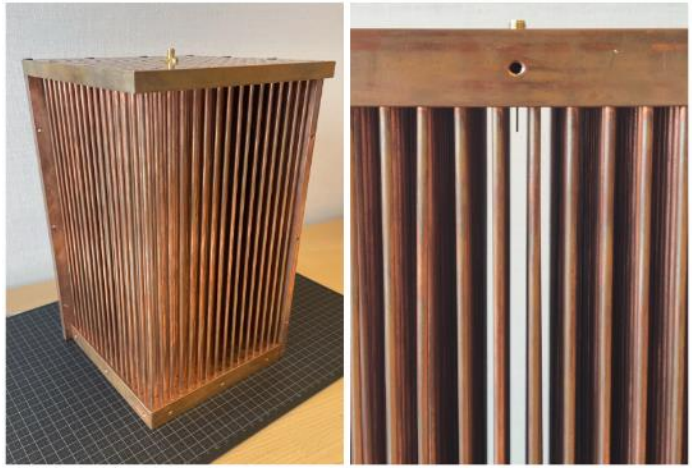
ADMX EFR 4GHz
Multicavity
design

Sophisticated Resonators – Multiwavelength Cavities

- Dividing single cavities or metamaterial structures captures similar volume gains to multiple cavities



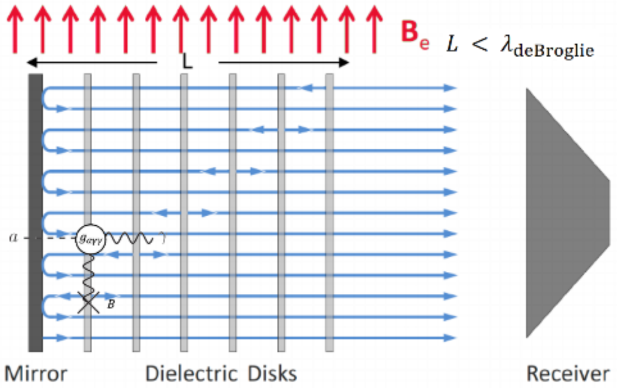
"Pizza" Cavity is divided into subregions and read out coherently.
S. Youn, CAPP (2023)



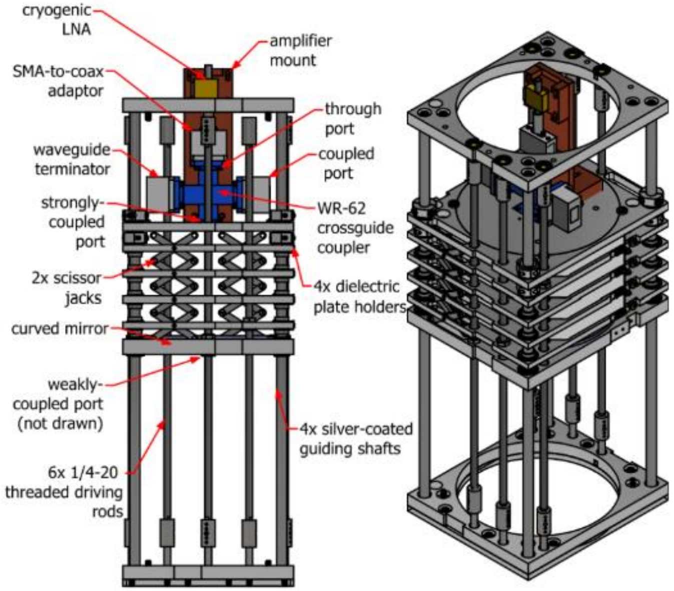
Multiple periodic conductors allow the ALPHA "Plasma Haloscope" to have a multiwavelength volume
A. Millar Phys. Rev. D. 107 055103 (2023)

Sophisticated Resonators –Multiwavelength Dielectric Cavities

- Dielectrics can also be used to make multiwavelength cavities



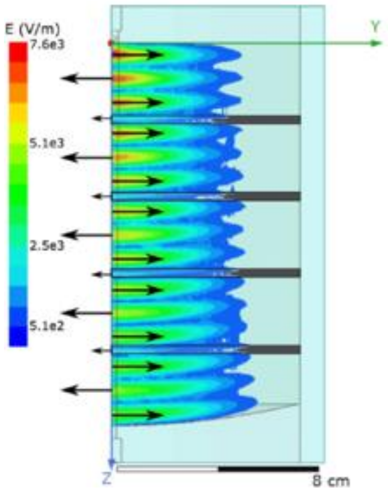
MADMAX Design
E. Garutti, Patras 2023

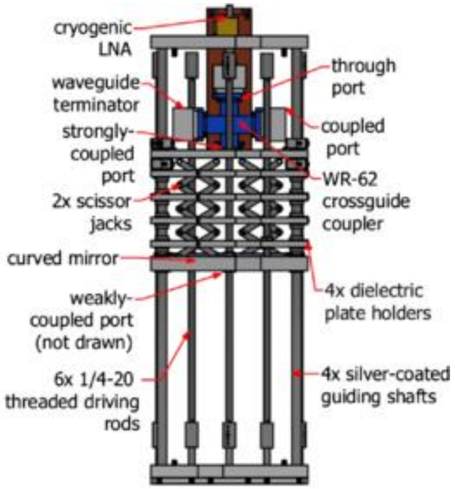


ADMX-Orpheus Design
R. Cervantes, Phys. Rev. D 106, 102002 (2022)

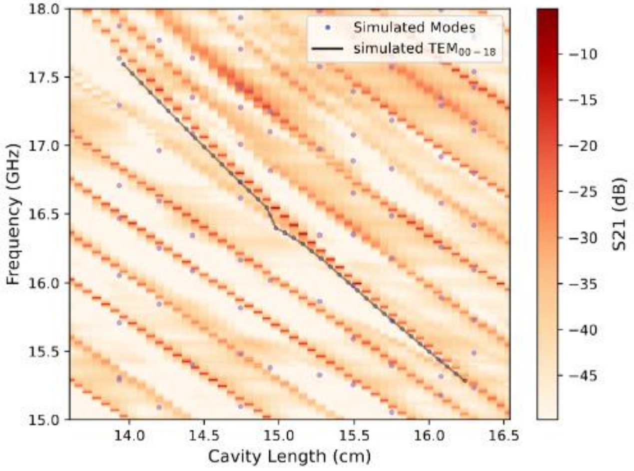
ADMX-VERA wedge-cavity design
T. Dyson, Patras 2023

Example: ADMX-Orpheus

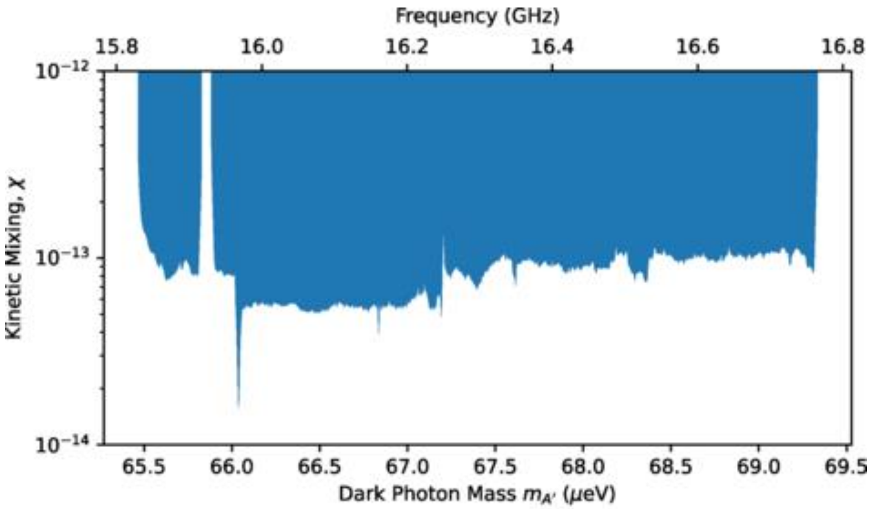


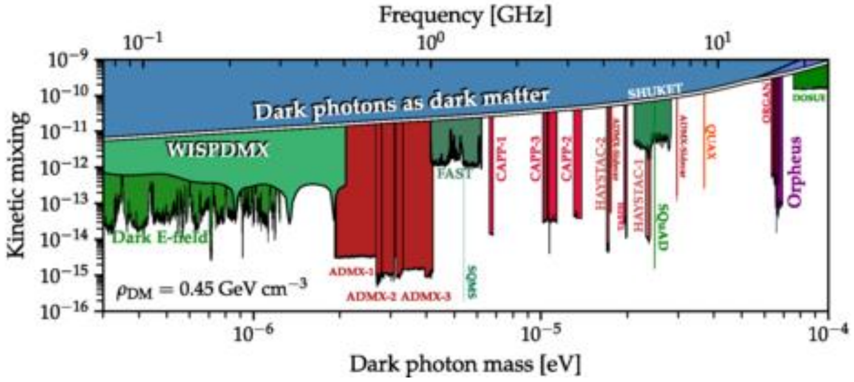


multiwavelength



tunable



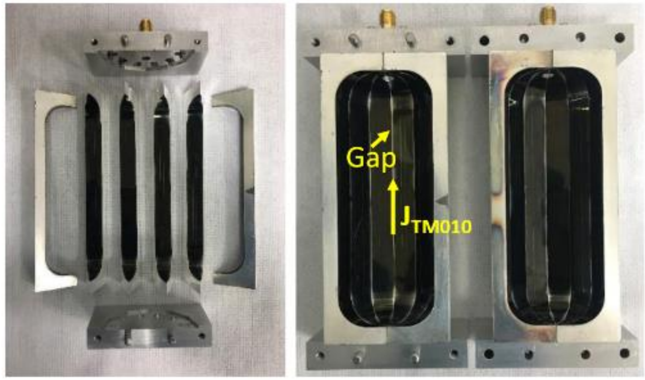


New limits on hidden photons:
Cervantes et al. Phys. Rev. Lett. 129, 201301 (2022)

Sophisticated Resonators – High-Q Resonators

- One thought a pipe dream, groups are developing the capability to run superconducting magnets in multi-Tesla fields

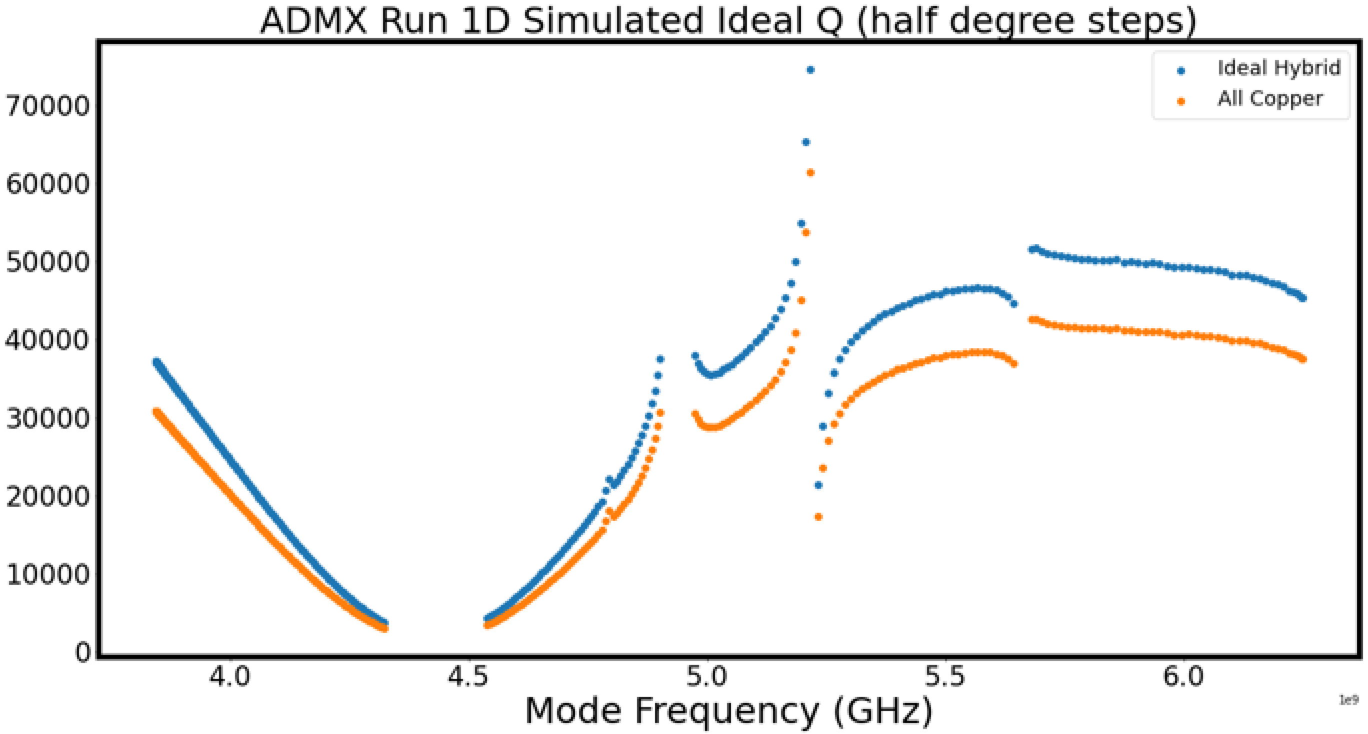
SQMS at Fermilab reports a Q of 10^6 with NbSn
-R. Cervantes, Patras 2023



CAPP reports a Q of 10^7 with high-Tc Superconductor
-D. Ahn, Patras 2023

Test NbSn tuning rod (from SQMS) being installed in ADMX “sidecar” system
-T. Braine 2023

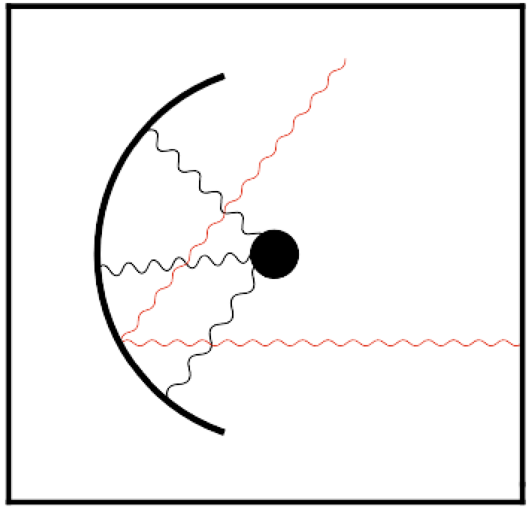
Example: ADMX-Sidecar



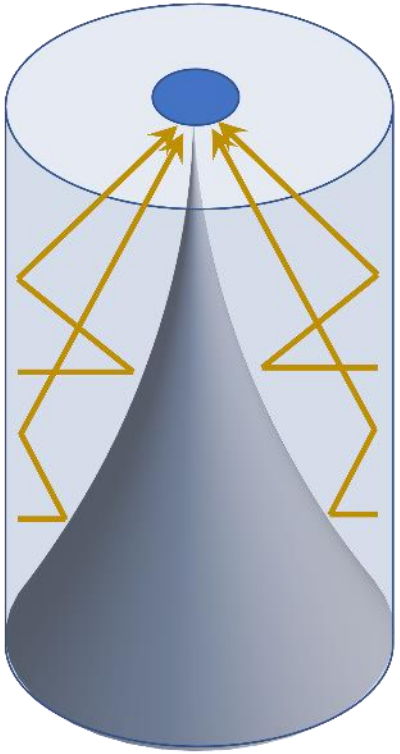
UW Grad student installs a superconducting tuning rod in ADMX-Sidecar. Expected improvement in scan speed – 20%. Testing underway.

Sophisticated Resonators – Nonresonant Systems

- Nonresonant systems sacrifice sensitivity for broad frequency coverage



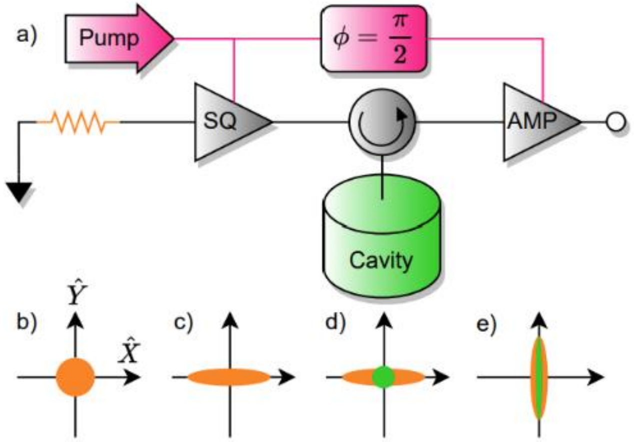
Horns et al. JCAP04(2013)



BREAD detector design
S. Knirck, Patras 2023

Detectors - Squeezing

- The standard quantum noise limit scales with frequency (~30 mK/GHz), so higher frequency axion searches will be adversely impacted
- Squeezing sacrifices phase information for lower amplifier noise, translating to higher scan speeds

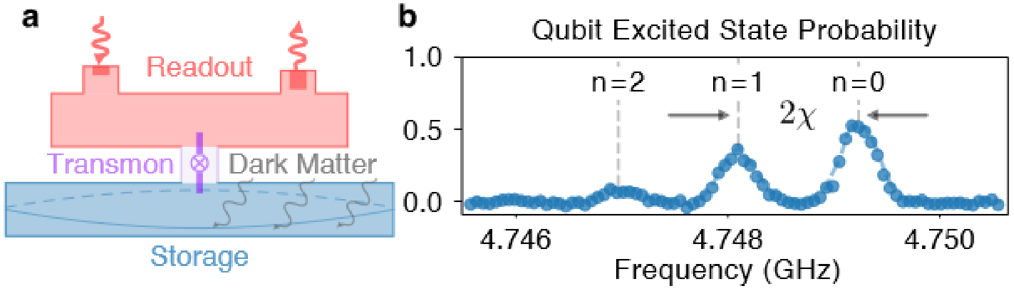


Squeezed noise setup used in
HAYSTAC experiment
Jewell et al. 2301.09721 (2023)

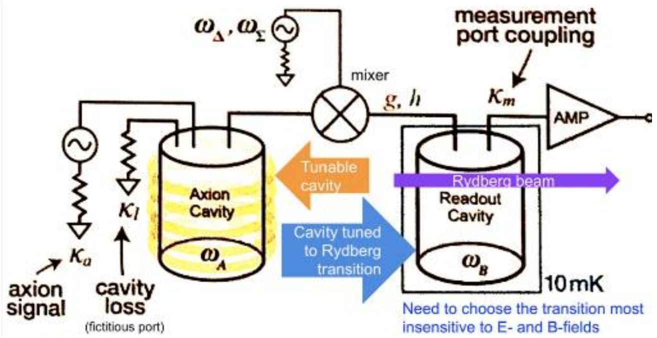
See also CEASEFIRE – Wurtz et al. PRX 2,040350 (2021)

Detectors – Photon Counting

- Single photon counting with a ‘microwave phototube’ will push noise below the standard quantum limit – coupling to cavities is a challenge.

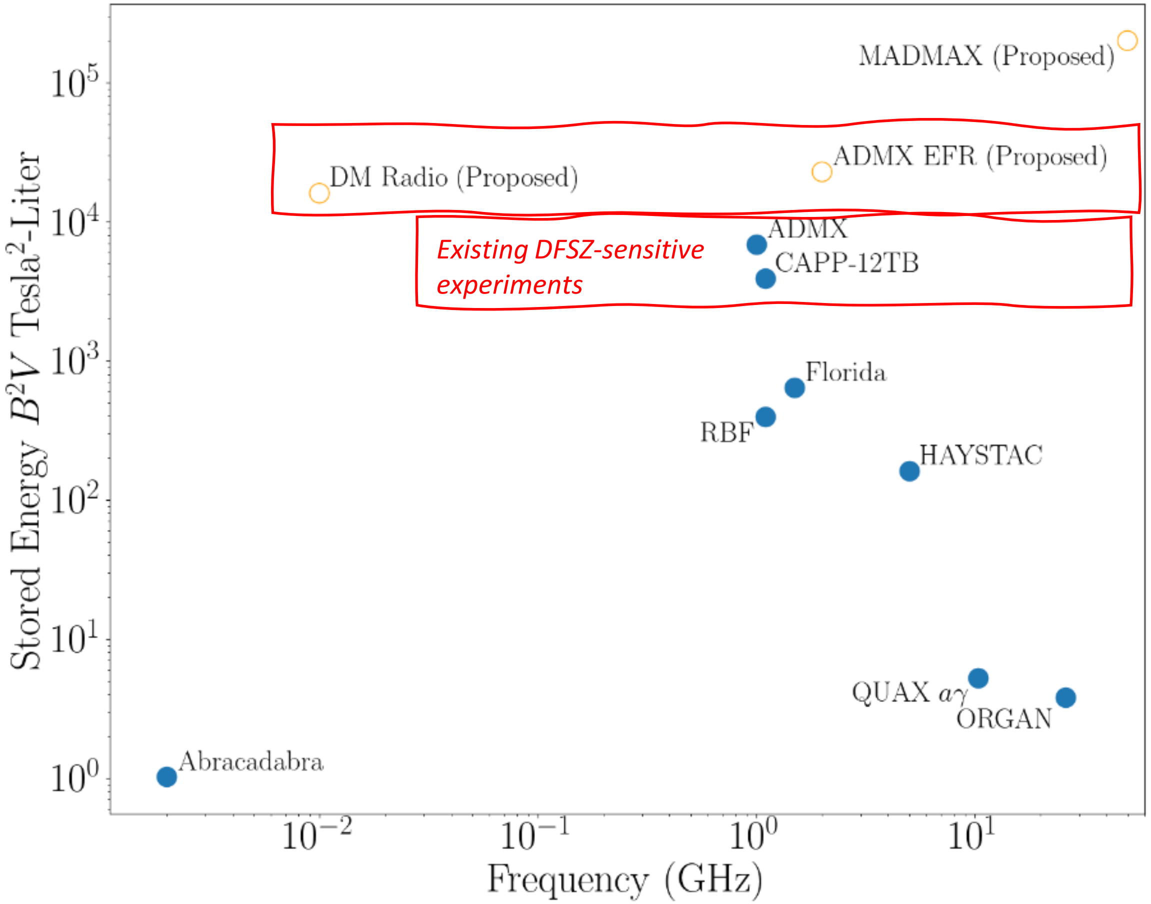


Qubit Based photon counting for sensitivity below the standard quantum limit (A. Dixit, PRL 126, 141302 (2021))



Rydberg atoms can be used as microwave photon counters (R. Maruyama – Aspen 2022)

Haloscope Magnet Development



Axion sensitivity scales as magnet stored energy.

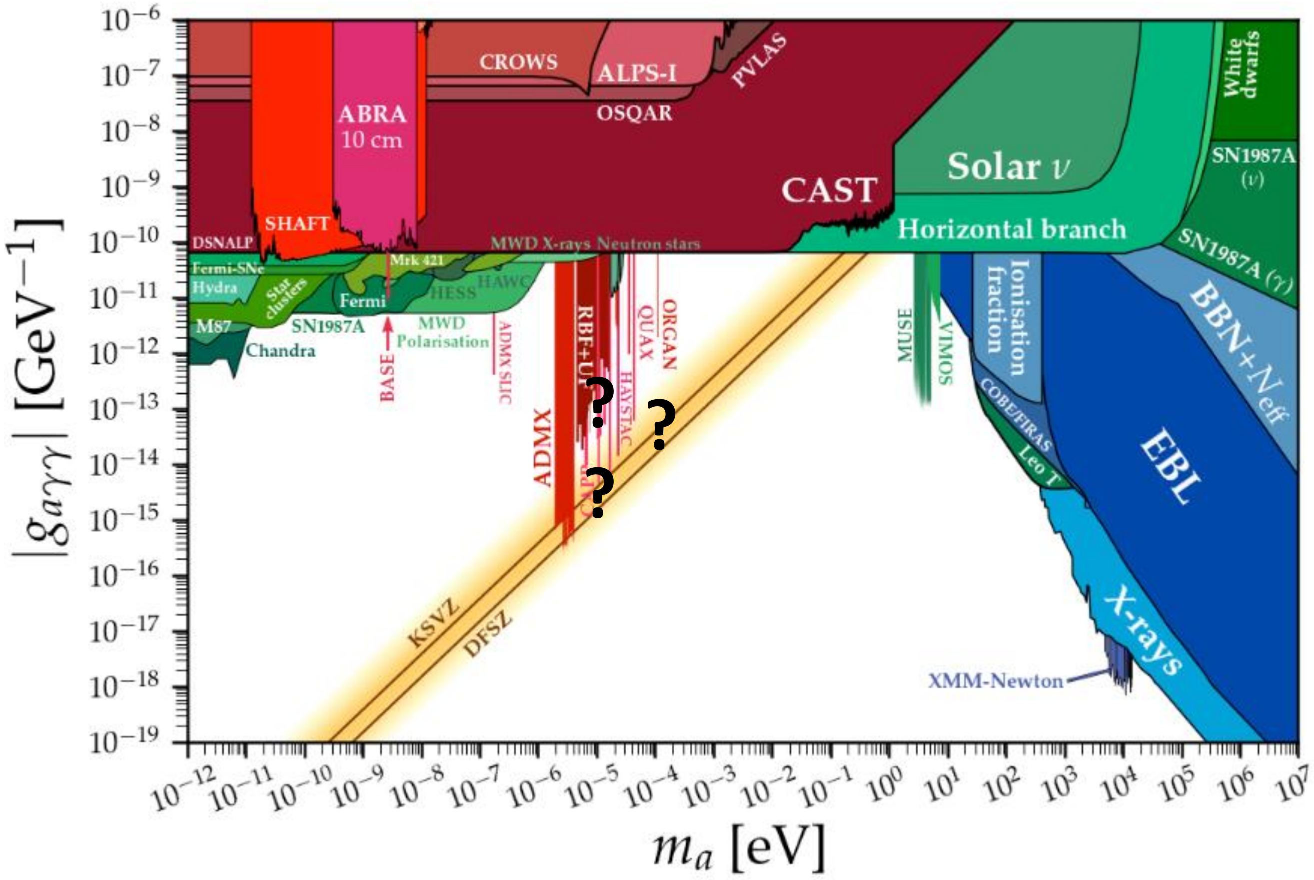
Magnets are large, expensive, and critical for most axion search techniques. They are also potentially usable at different frequency ranges with very different detector styles.

A user facility with large stored energy magnets would be of use to the wavelike dark matter community.

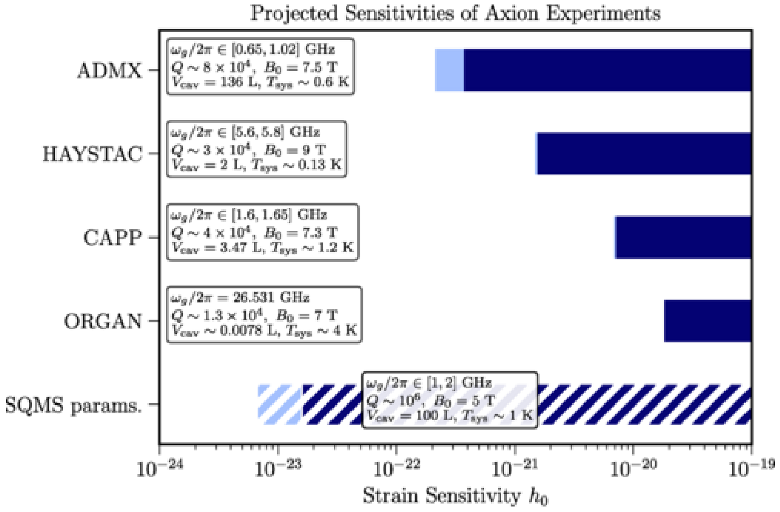
Many techniques share engineering requirements in cryogenics and quantum sensing. Shared engineering resources would make for a more efficient axion program.

Consequences of Discovery

- Mass probes physics during or just after inflation
- Model predicts new Higgs sector or heavy quarks – possible accelerator signatures
- Lineshape probes local dark matter astrophysics
- Points the way to electron/nucleon coupling experiments – is it really the QCD axion?



Aside – Gravitational waves with ADMX – a work in progress

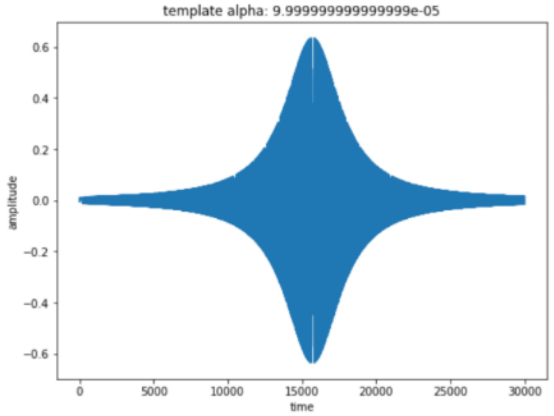


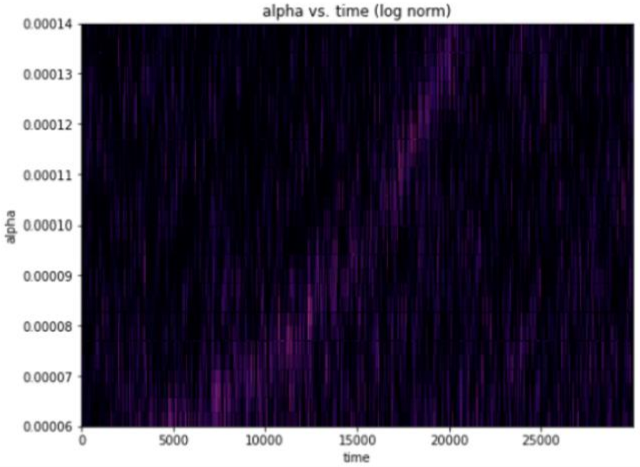
Gravity wave conversion in axion haloscope cavity and projected sensitivities

Berlin et al. Phys. Rev. D 105, 116011 (2022)

Simulated black hole inspiral signal in ADMX

Work by UW undergraduates Shaun Lee, Henry Su, and grad David Liu



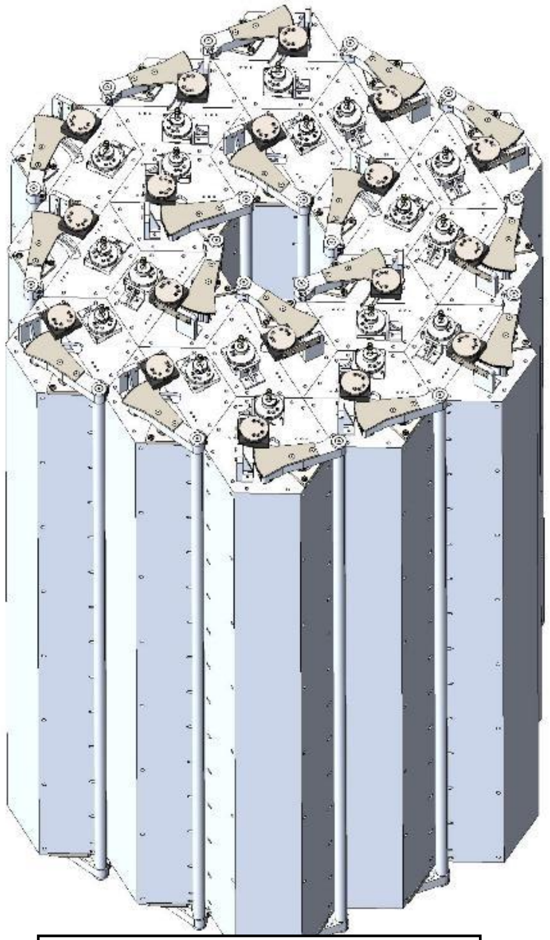


Summary

- In the past few years, QCD Axion Dark Matter experiments have transitioned from an “instrument development” phase to a “discovery phase”.
- ADMX is operating with the hope of a discovery over an increasingly wider frequency range. ADMX-EFR is in preparation to reach even higher.
- Emerging technologies have great potential to improve axion haloscopes
- We are scaling up axion experiments to make the discovery a reality.

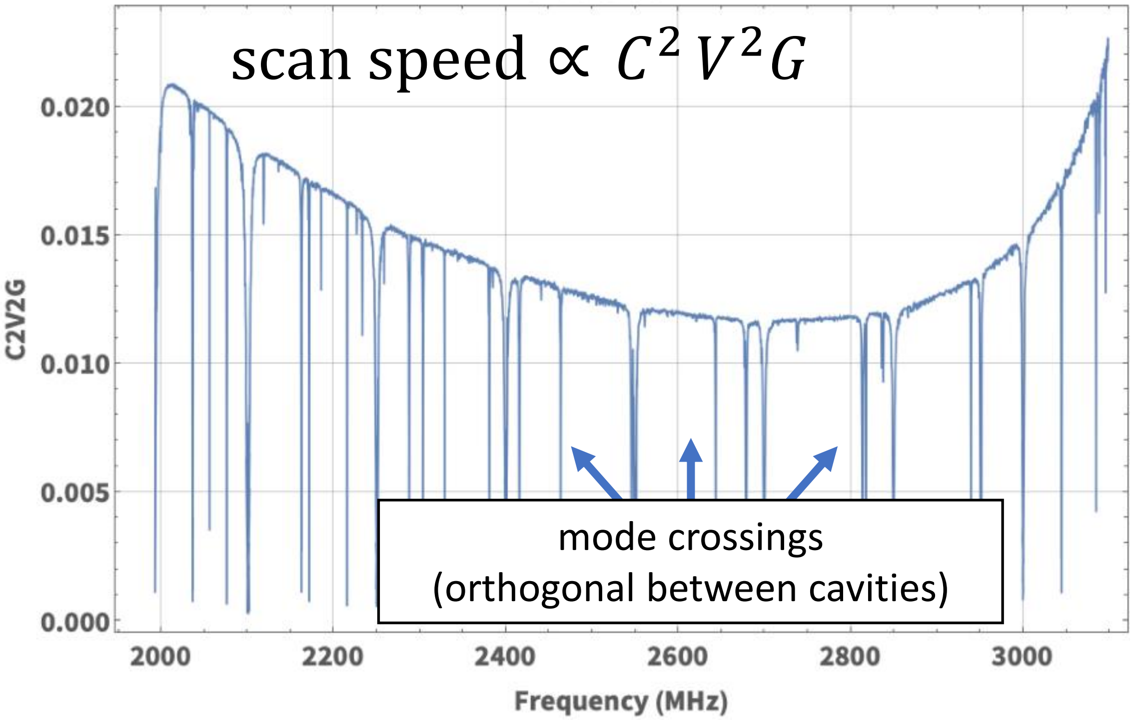
Back-up slides follow

ADMX-EFR: More Cavities



18 cavity array

Simulations:

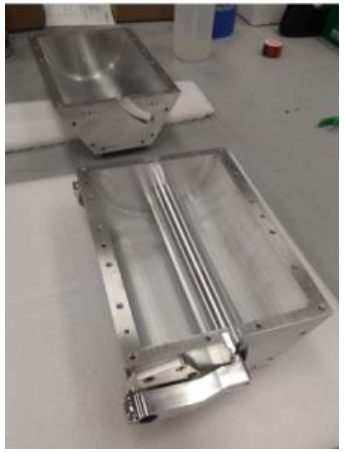


mode crossings
(orthogonal between cavities)

$Q_0 \sim 60{,}000$ (predicted, cryogenic)

$V \sim 250\ \ell$

First Prototypes:

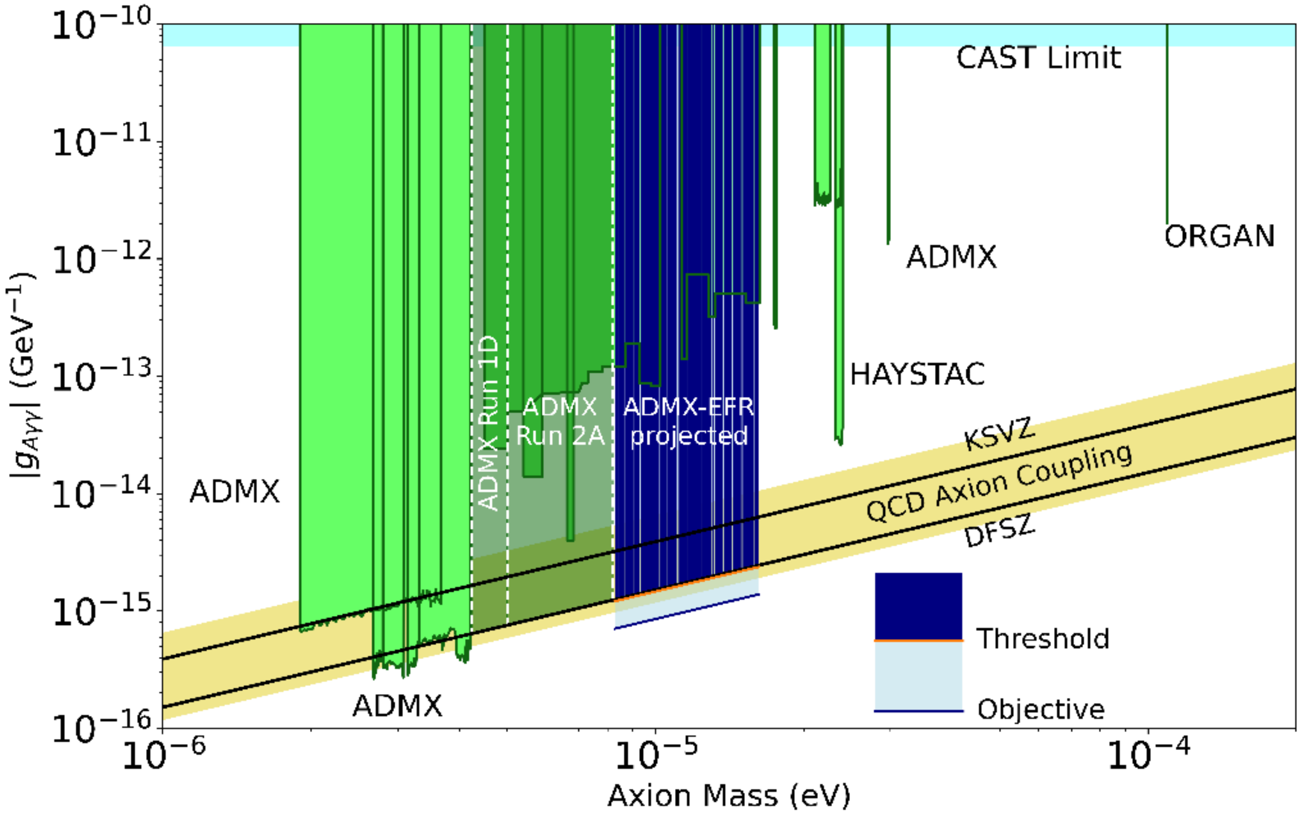


Other interesting thinking about axions

Axions may for clumps or 'minihalos' at solar-system or smaller scales (1). This makes direct detection more challenging, but may allow parametric conversion, greatly enhancing signal (2,3)

1) Hogan and Rees, Phys. Lett. B 50 (1994) 769
2) M. Hertzberg and E. D. Schiappacasse JCAP11(2018)004
3) G. Rybka, K. Ruffin, *in preparation*

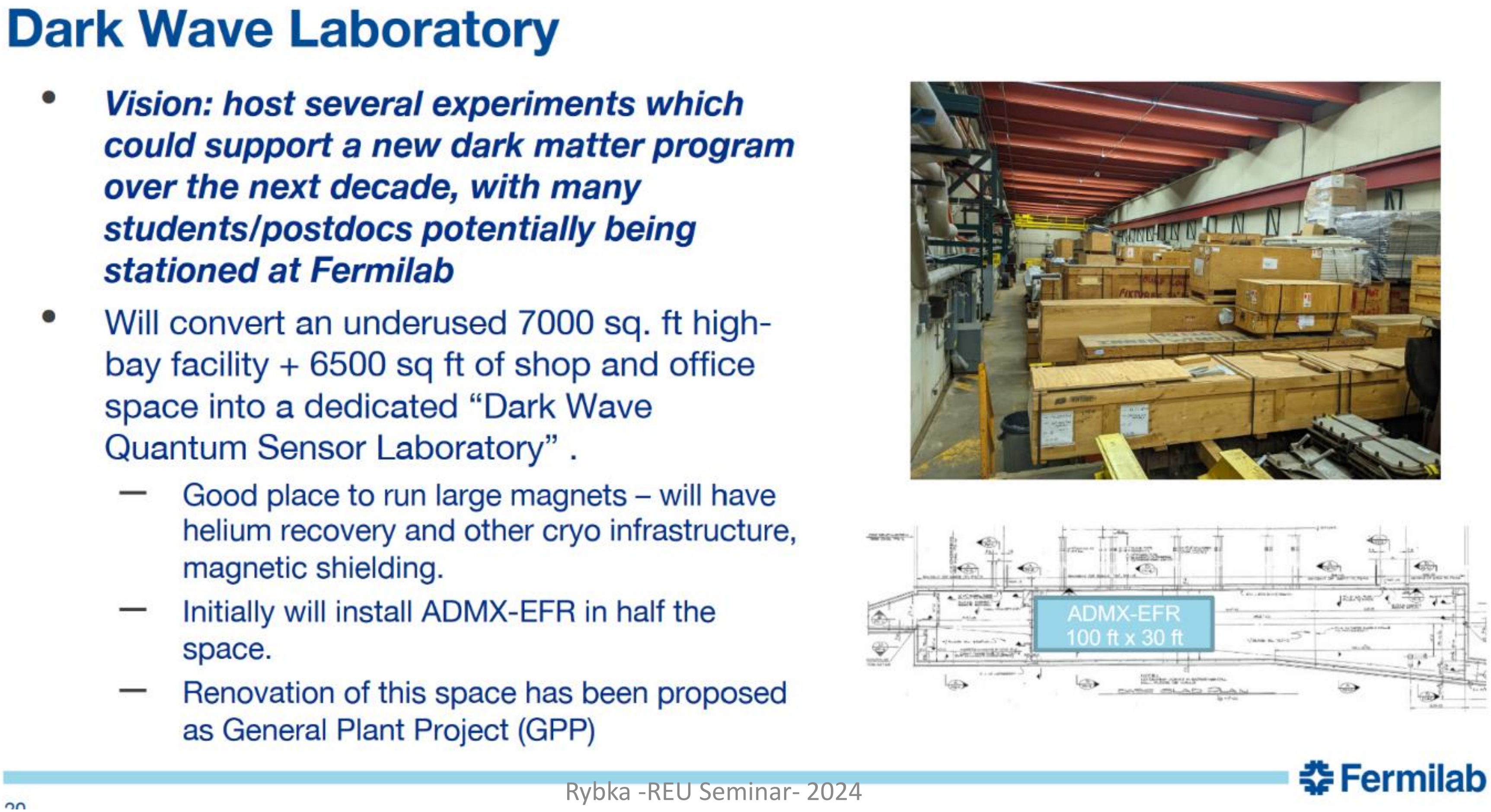
EFR Initial Target



- Continuous coverage at DFSZ up to 4 GHz to start

Beyond ADMX-EFR

We have visions of a larger multipurpose axion facility at FNAL – We may reach out to potential collaborators or users if the idea gains traction.



Dark Wave Laboratory

- ***Vision: host several experiments which could support a new dark matter program over the next decade, with many students/postdocs potentially being stationed at Fermilab***
- Will convert an underused 7000 sq. ft high-bay facility + 6500 sq ft of shop and office space into a dedicated “Dark Wave Quantum Sensor Laboratory” .
  - Good place to run large magnets – will have helium recovery and other cryo infrastructure, magnetic shielding.
  - Initially will install ADMX-EFR in half the space.
  - Renovation of this space has been proposed as General Plant Project (GPP)

Other Operating Haloscopes

- DFSZ searches from ADMX and CAPP
- KSVZ or near-KSVZ searches from HAYSTAC and TASEH
- Plus a host of small scale operating prototypes and planned haloscope experiments!