Axion Dark Matter Direct Detection

A Strategy For the US Wavelike Dark Matter Program

Gray Rybka – University of Washington
2/20/2023
P5 Town Hall, Berkeley, CA

Charge and Scope Creep

- Charge: “give a presentation on the status of ADMX and discuss future expansion to DMRadio and ADMX-EFR”
- My scope creep: “give a presentation on the status of ADMX and a plan for the Wavelike Dark Matter community for the next decade”

Many slides are from Lindley Winslow and other members of the Wavelike Dark Matter community
Mistakes are entirely my own

Wave-like Dark Matter Candidates

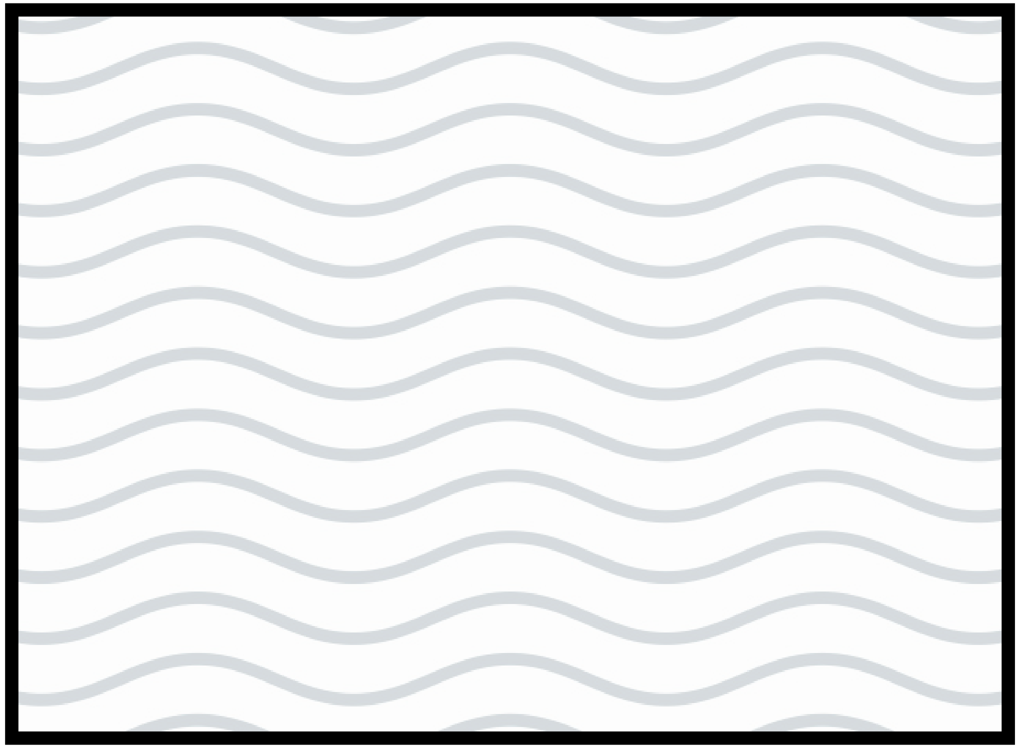
Wave-like Definition: Mass < 1 eV

Broad Candidate Categories:

- Pseudo-scalar*
- Scalar
- Vector

Production: Athermal production (misalignment).

Detection: Coherent interaction of the wave with the detector. Resonant amplification often key.



**The most famous candidate in this group is the QCD axion.*

Community Whitepapers

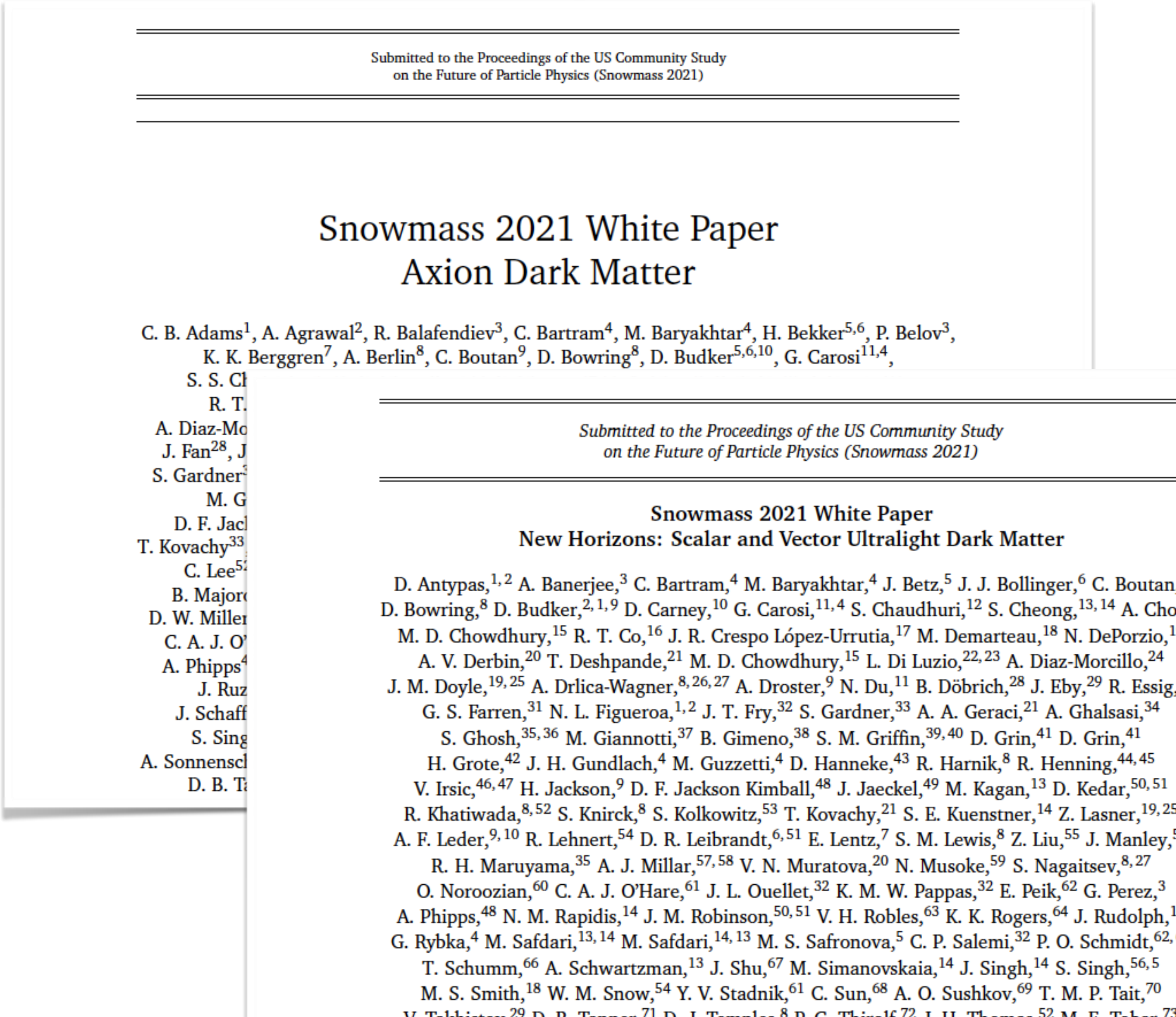
The community road map, theory, cosmology, and experimental details are presented in our two community white papers.

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)

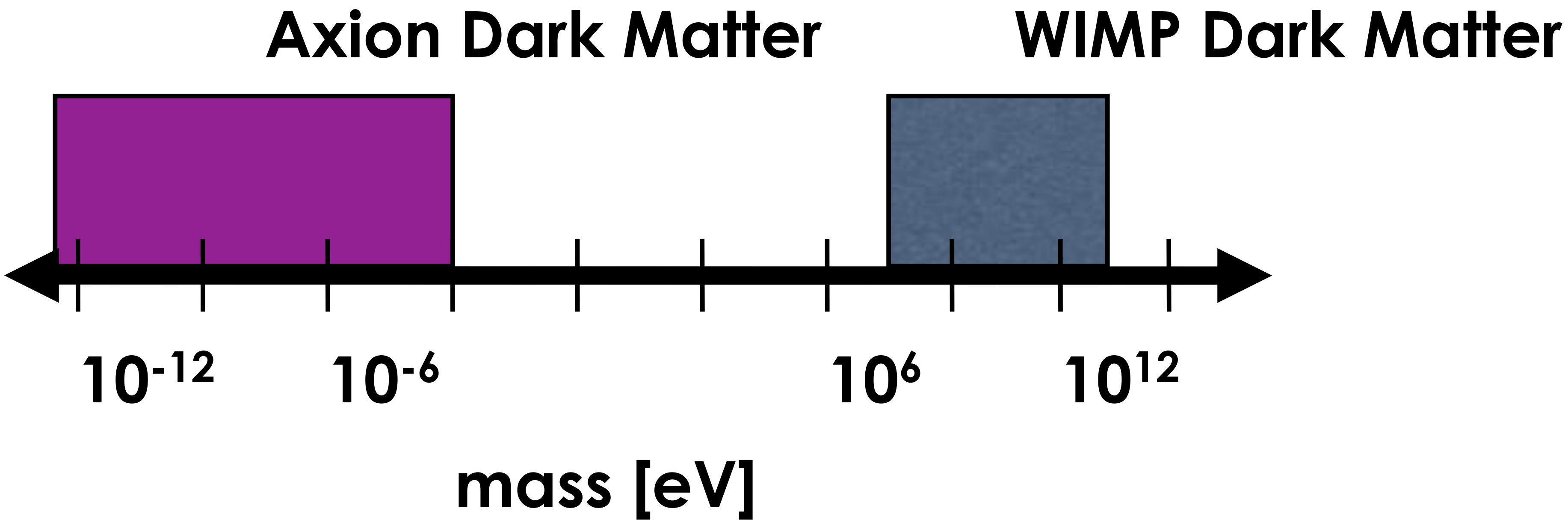
Snowmass 2021 White Paper
Axion Dark Matter

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. Ch
R. T.
A. Diaz-Mo
J. Fan[28], J
S. Gardner
M. G
D. F. Jacl
T. Kovachy[33]
C. Lee[5
B. Major
D. W. Miller
C. A. J. O'
A. Phipps[4
J. Ruz
J. Schaff
S. Sing
A. Sonnenscl
D. B. Ta

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,[19,25]
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,[62,
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]



de Broglie Wavelength - $\lambda_{dB} \approx \frac{2\pi}{mv}$ Occupancy Number - $N \approx \frac{\rho_{DM}}{m} \lambda_{dB}^3$

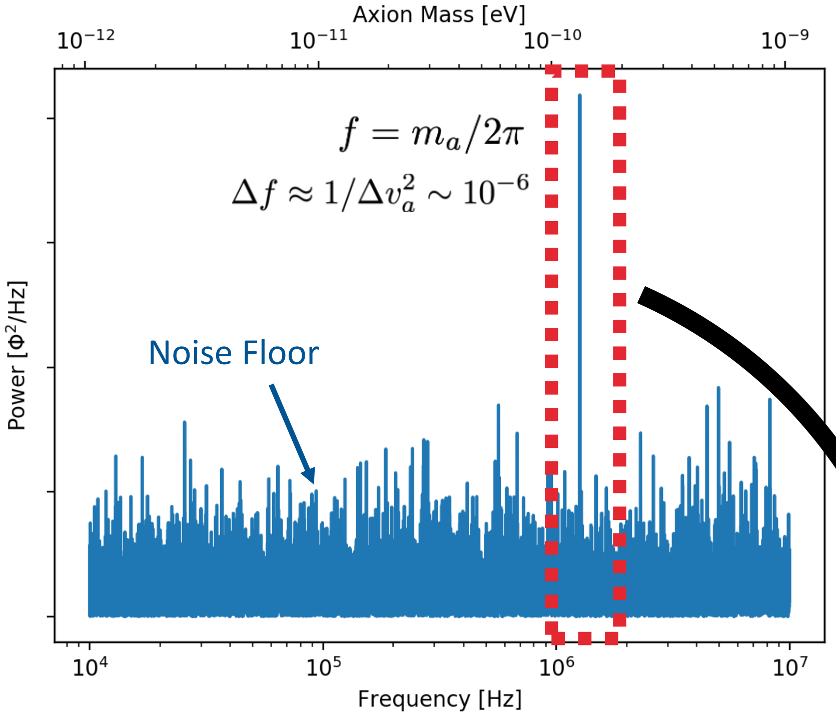
- Axion ($m \sim 10^{-9}$ eV): $\lambda_{dB} \sim 10^4$ km with $N \sim 10^{44}$
- WIMP ($m \sim 100$ GeV): $\lambda_{dB} \sim 10^{-16}$ km with $N \sim 10^{-36}$

where $\rho_{DM} = 0.4$ GeV/cm^3

Adapted from B. Safdi

To Measure a Wave: Measure Frequency

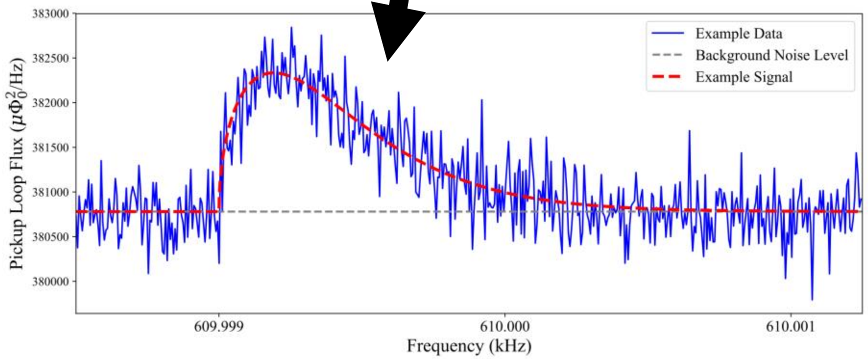
$$a(t) = a_o \sin\left(m_a t\right)$$



Note: the measurement of wave dark matter is inherently a quantum measurement.

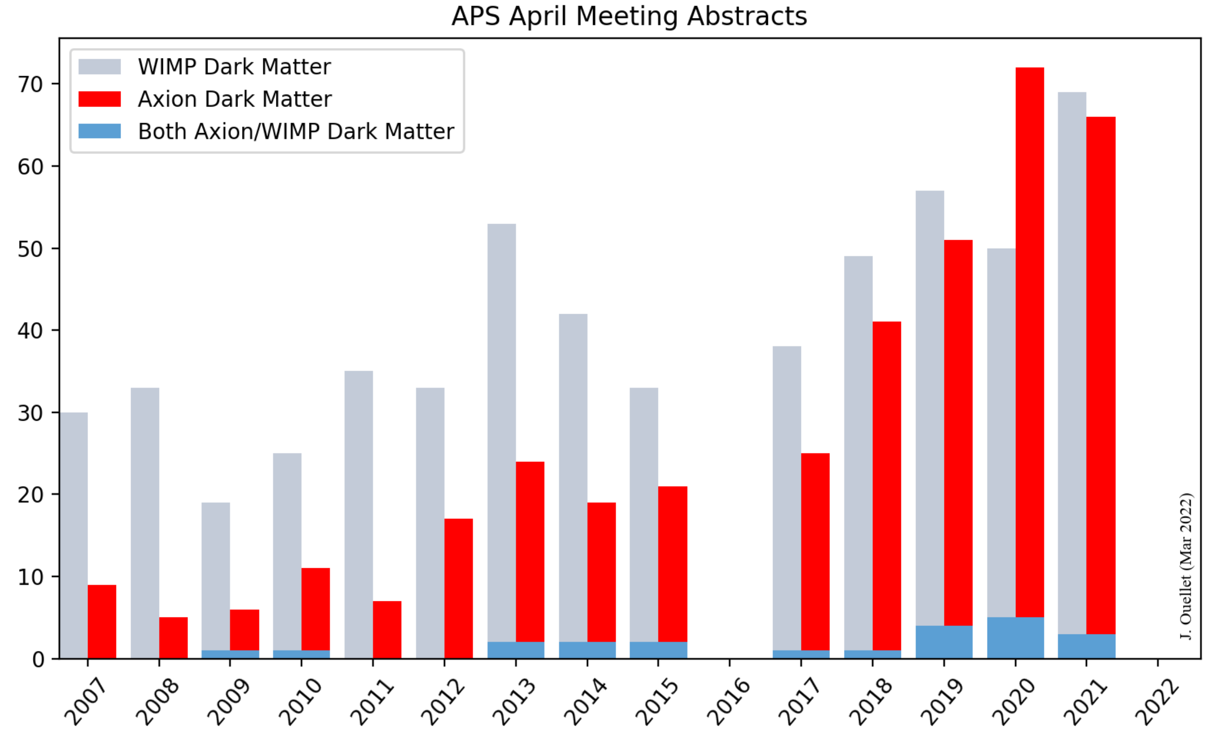
ZOOM

There is a characteristic line shape due to the halo velocity distribution. Features within the halo could show up here!



Growing Community

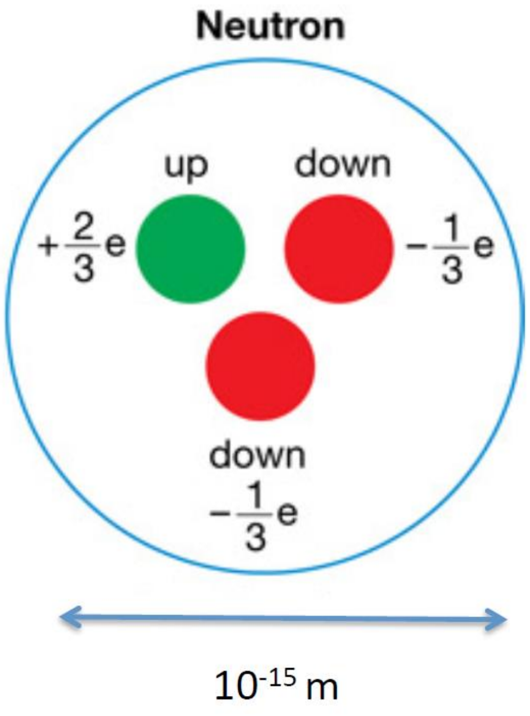
With advancements in cryogenics, magnet and quantum sensing coupled with better theoretical understanding of the cosmology of wave-like dark matter, the community has grown quickly.



J. Ouellet

The QCD Axion: Motivation

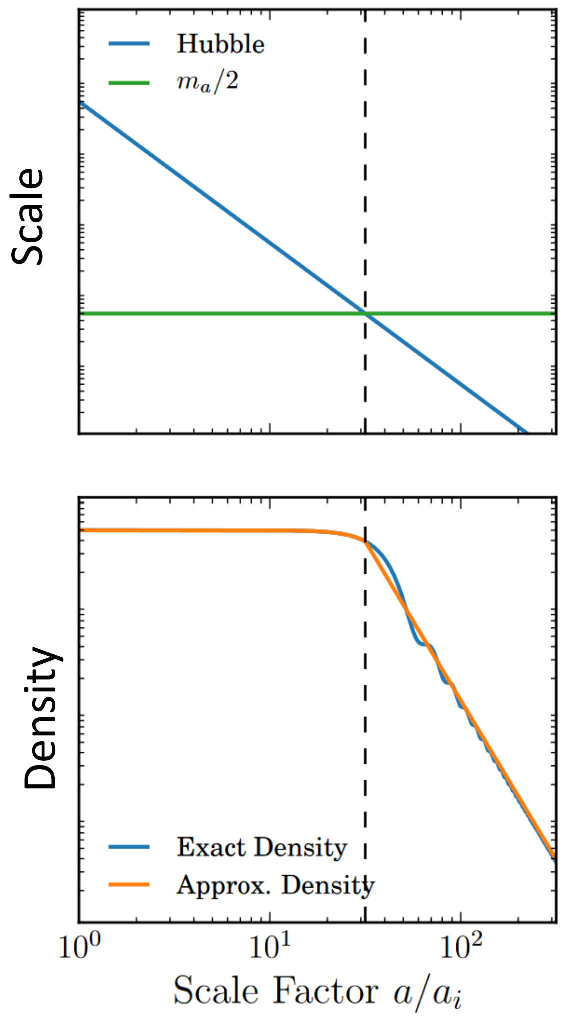
- QCD is naturally CP violating from phenomena like QCD-instantons
- One naively expects a neutron electric dipole moment of 10^{-16} e cm
- But nEDM is measured to be below 3×10^{-26} e cm *(Baker, 2006)*
- The best explanation? New U(1) axial symmetry, that when broken, cancels CP violation in the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

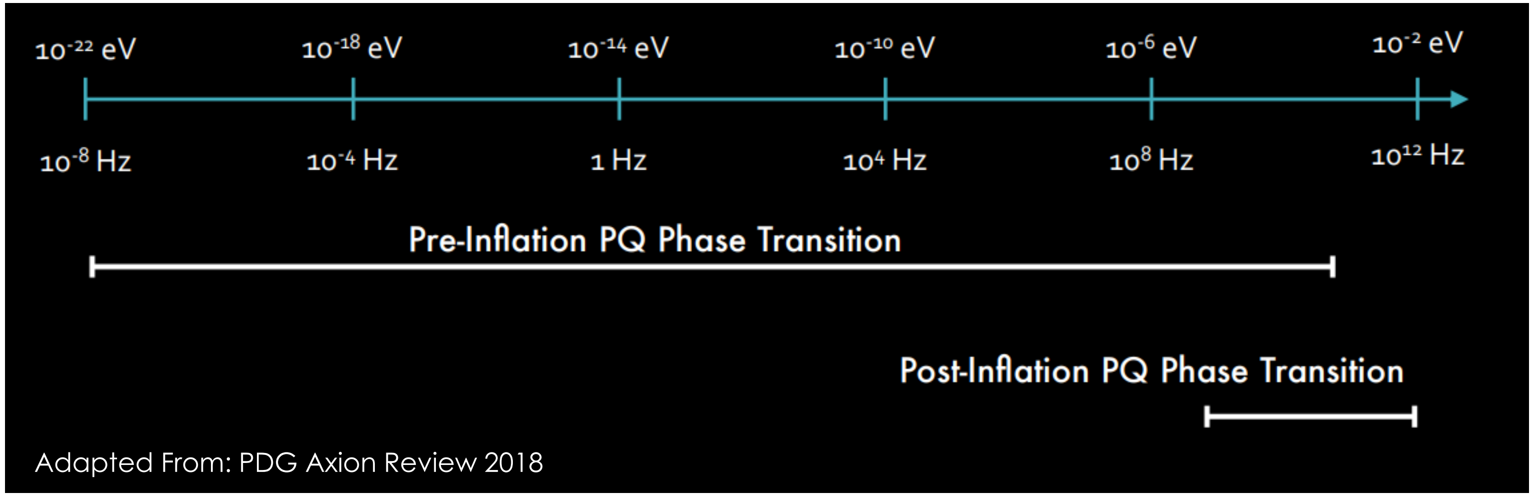
- Axions are produced athermally
  - Misalignment Mechanism – Phase transition in the early universe leaves energy in the axion field which behaves as dark matter
  - String/Defect Decay – Energy in topological defects radiates as cold axions
- In both cases axions are produced cold and in quantities 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



- Conclusions:
  - "look under the lamp post" - pursue techniques that are sensitive to QCD dark matter at any scale
  - "build brighter lamps" – push to develop techniques at every scale!

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

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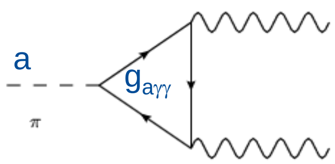


Coupling to Photons

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

Coupling to Nucleon EDM

Coupling to Axial Nuclear Moment

Coupling to Axial Electron Moment

Promising experimental techniques under development

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

Axion Photon Bounds

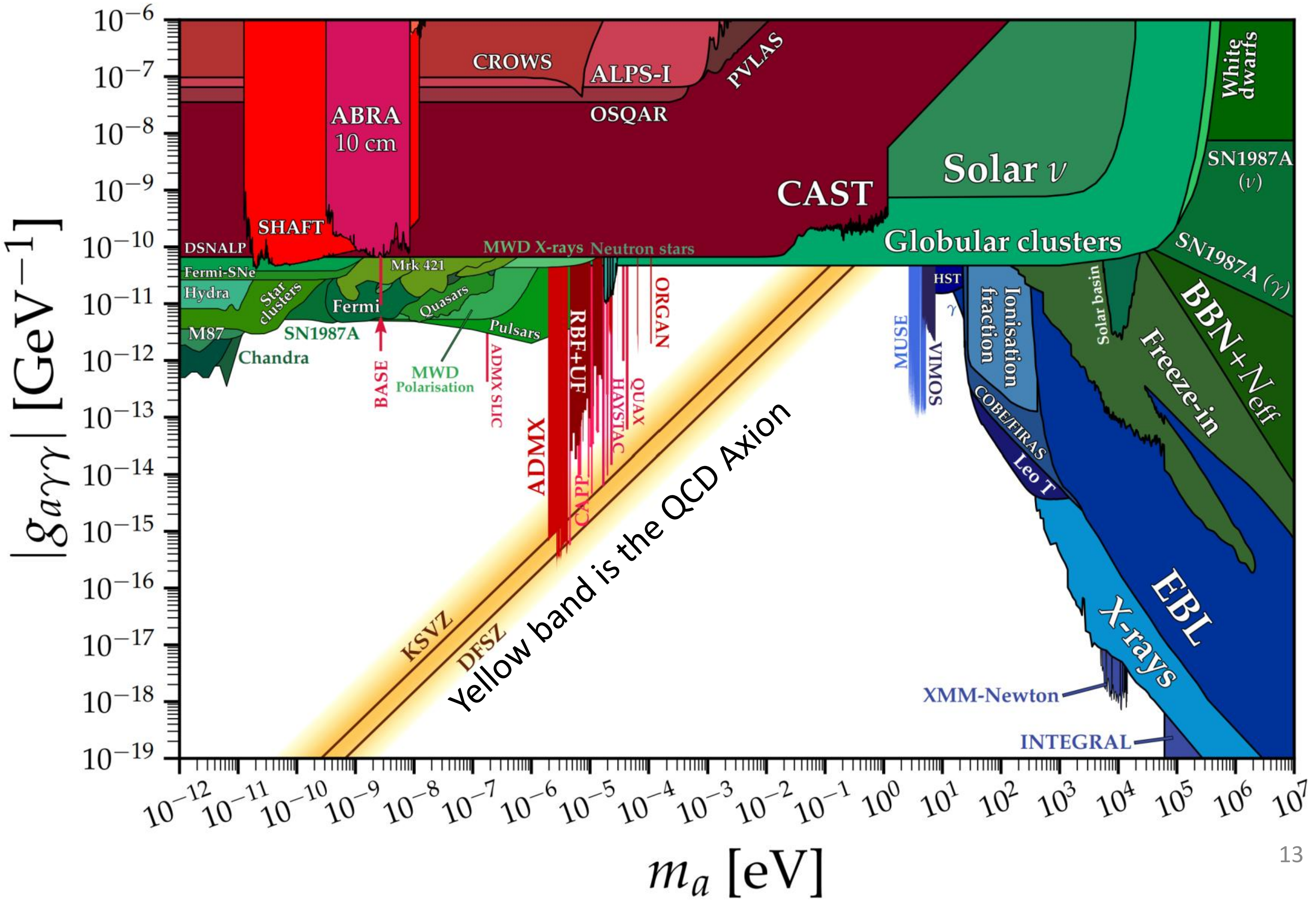
[GitHub - cajohare/AxionLimits: Data, plots and code for constraints on axions, axion-like particles, and dark photons]

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

Note the significant astrophysical constraints on ALP parameters.

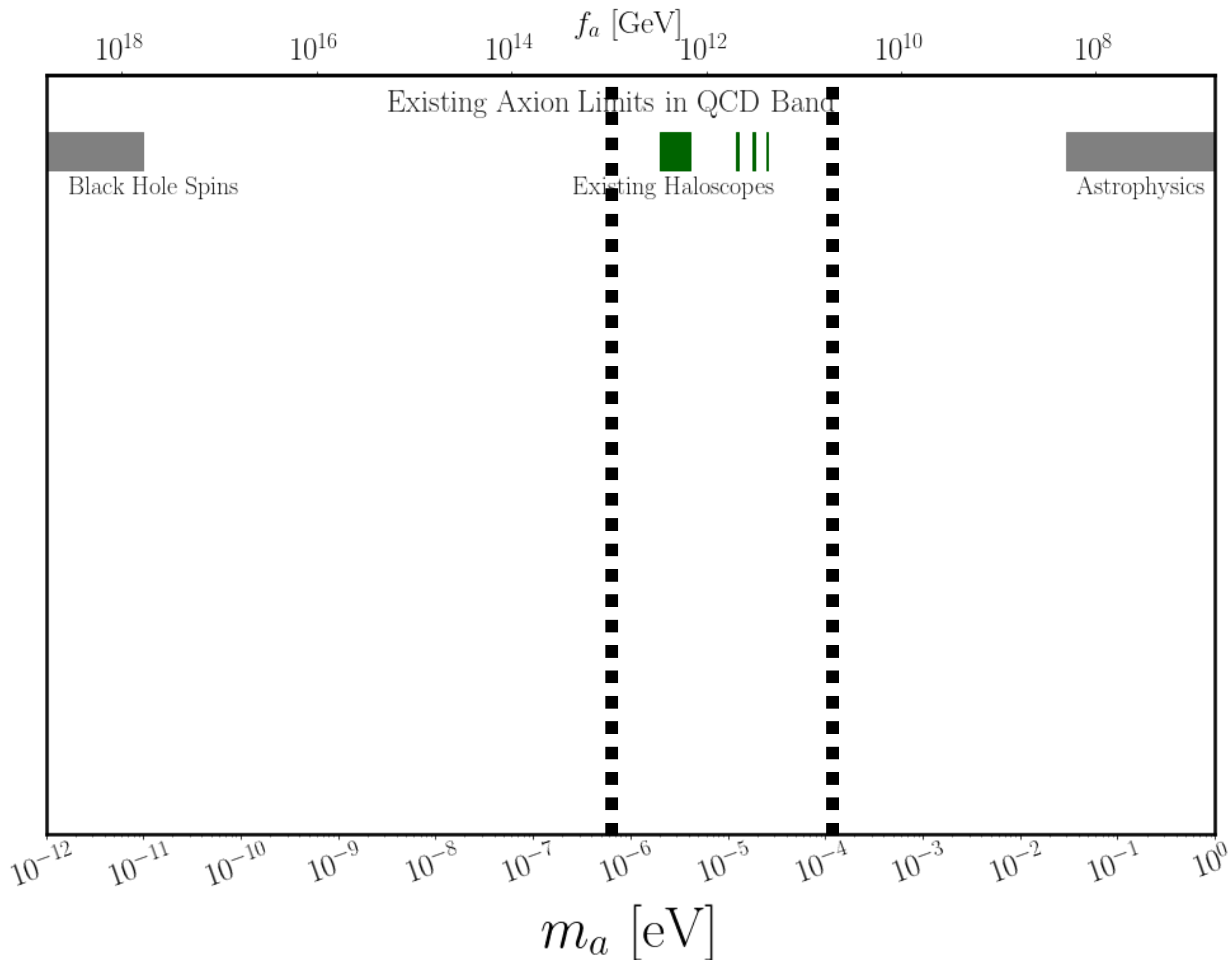
The haloscope technique is reaching into the QCD axion parameter space for μeV masses

Axions as low as 10^{-22} eV could be dark matter, but constraints are minimal so far (exception: black hole superradiance)



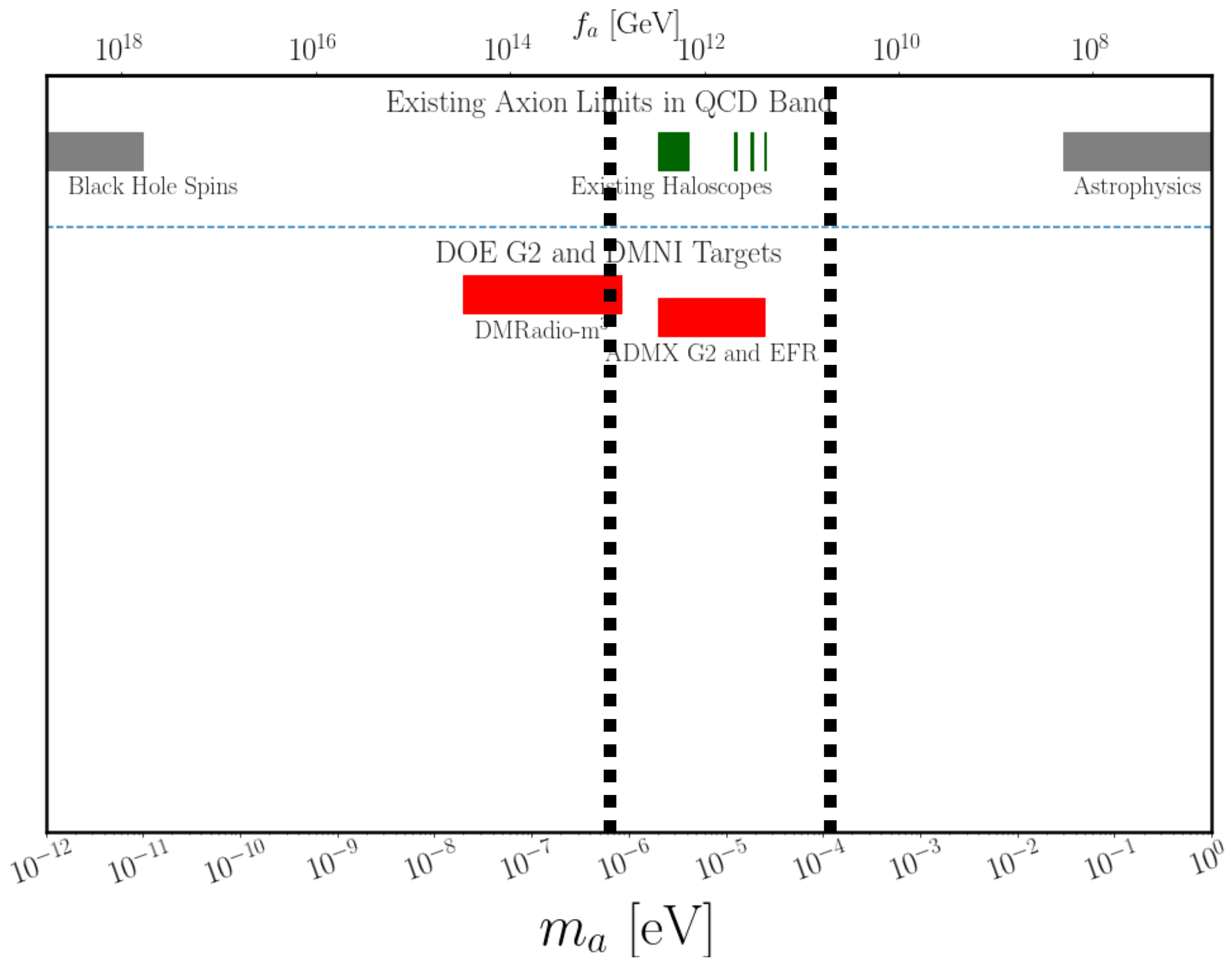
Status: Current

- ADMX G2 has reached DFSZ in some parameter space.
- CAPP has recently reached DFSZ over a small parameter space as well
- Other haloscopes, such as HAYSTAC have begun touching the upper part of the QCD band



Dark Matter New Initiatives (DMNI)

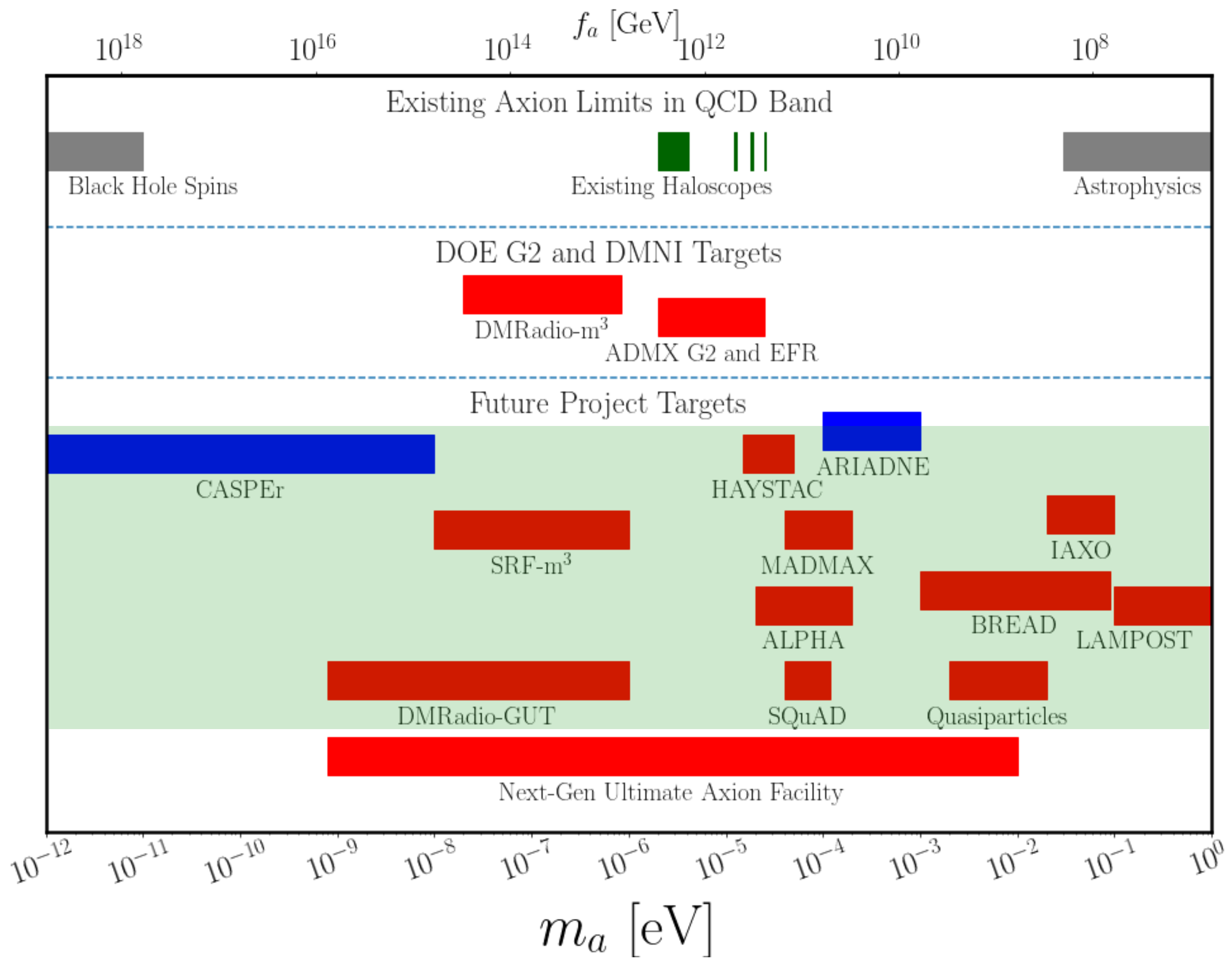
- The BRN for Dark Matter New Initiatives and subsequent call for proposals was very successful.
- DMRadio-m3 and ADMX-EFR are preparing project execution plans and are poised to make significant inroads into the QCD axion parameter space.



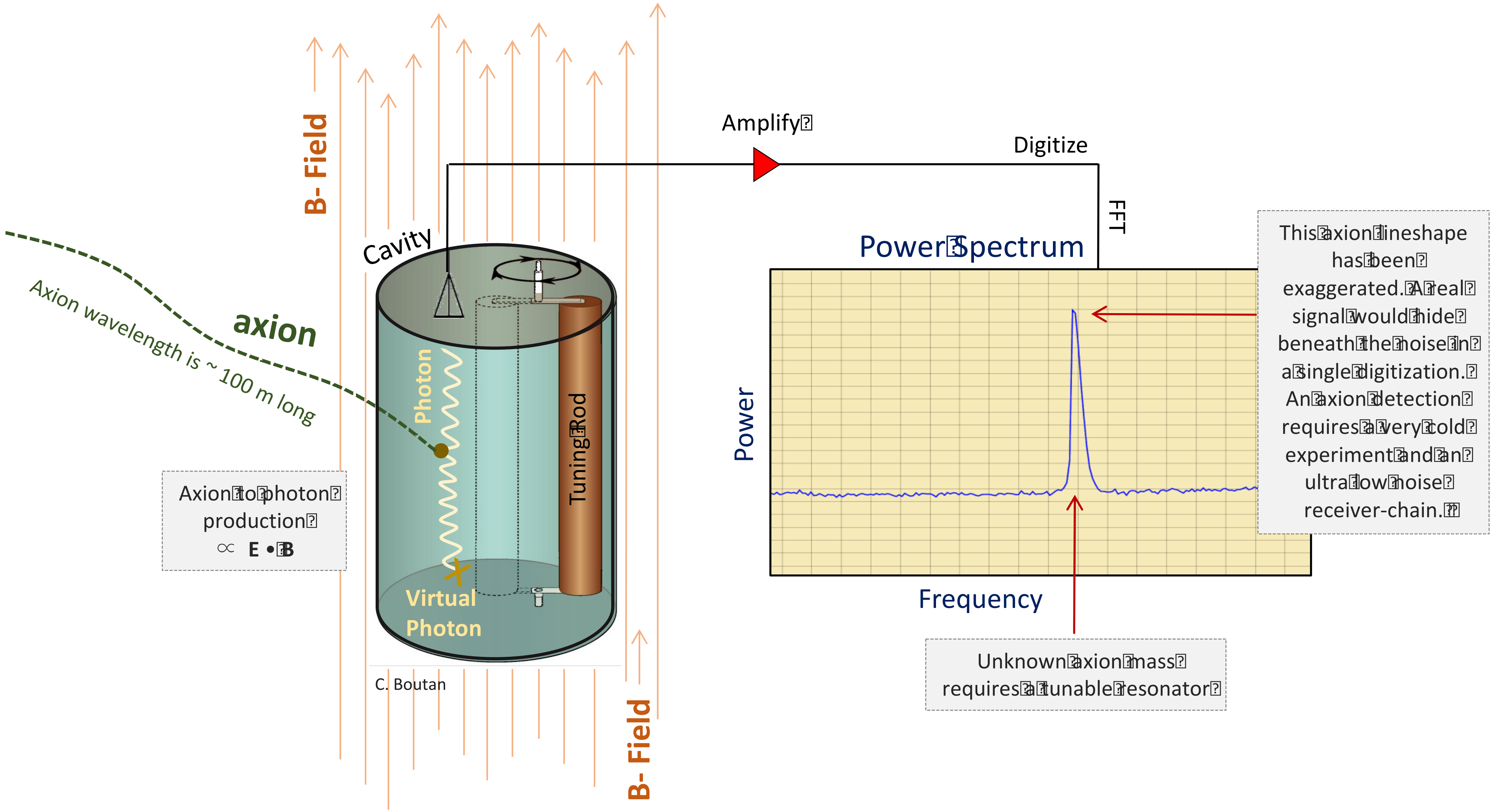
Demonstrator and R&D Programs

Many efforts focused on:

- Cavity geometry
- Beyond the Standard Quantum Limit (BSQL) Enabled Readout
- Couplings beyond axion-photon



The Axion Haloscope



ADMX Collaboration – Goal: Find the Axion

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

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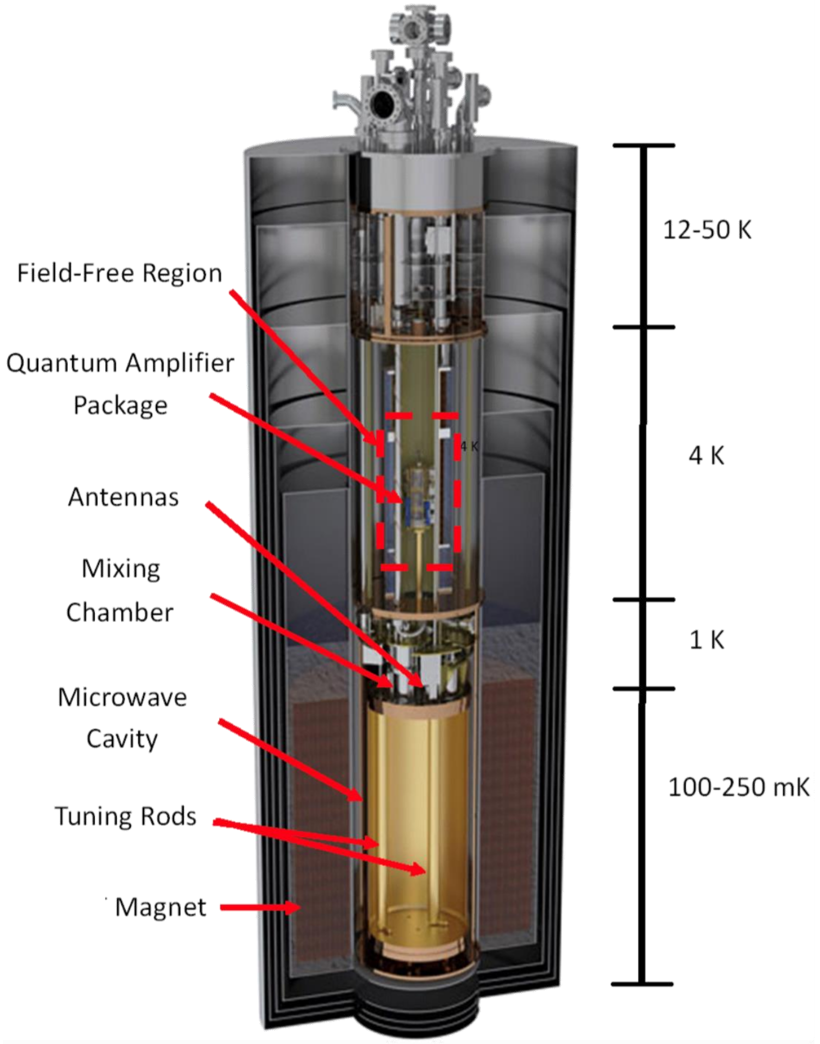
ADMX Design

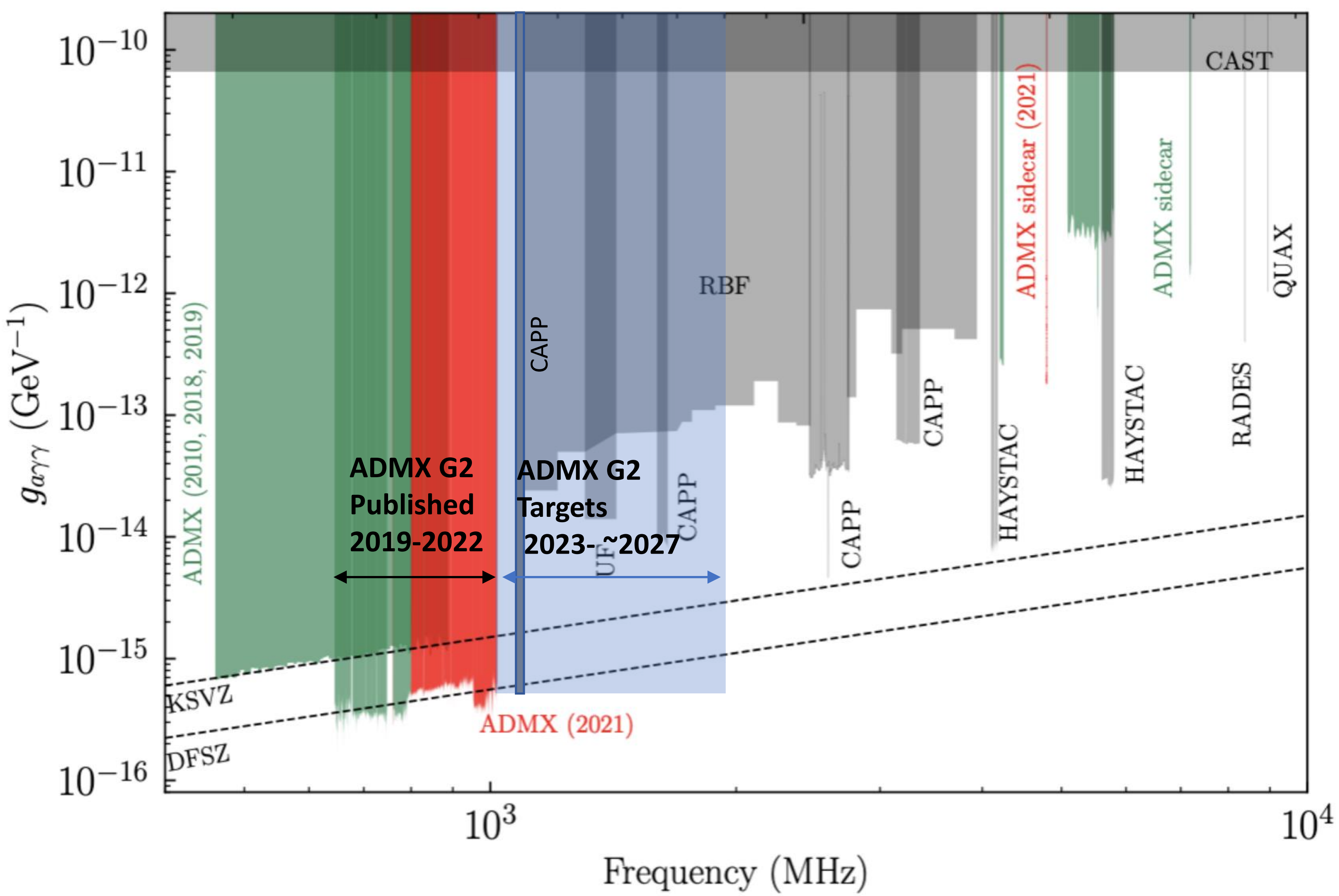
ADMX utilizes an 8 Tesla large-bore magnet, millikelvin cryogenics, and Josephson Parametric Amplifiers operating near the quantum limit to search for dark matter QCD axions in the 2 to 8 μeV range with sensitivity to the DFSZ coupling.



ADMX "G2" Results and Plans

ADMX has scanned 650-1020 GHz at or near DFSZ sensitivity

Over the next few years, ADMX will continue to scan up to 2 GHz



ADMX EFR

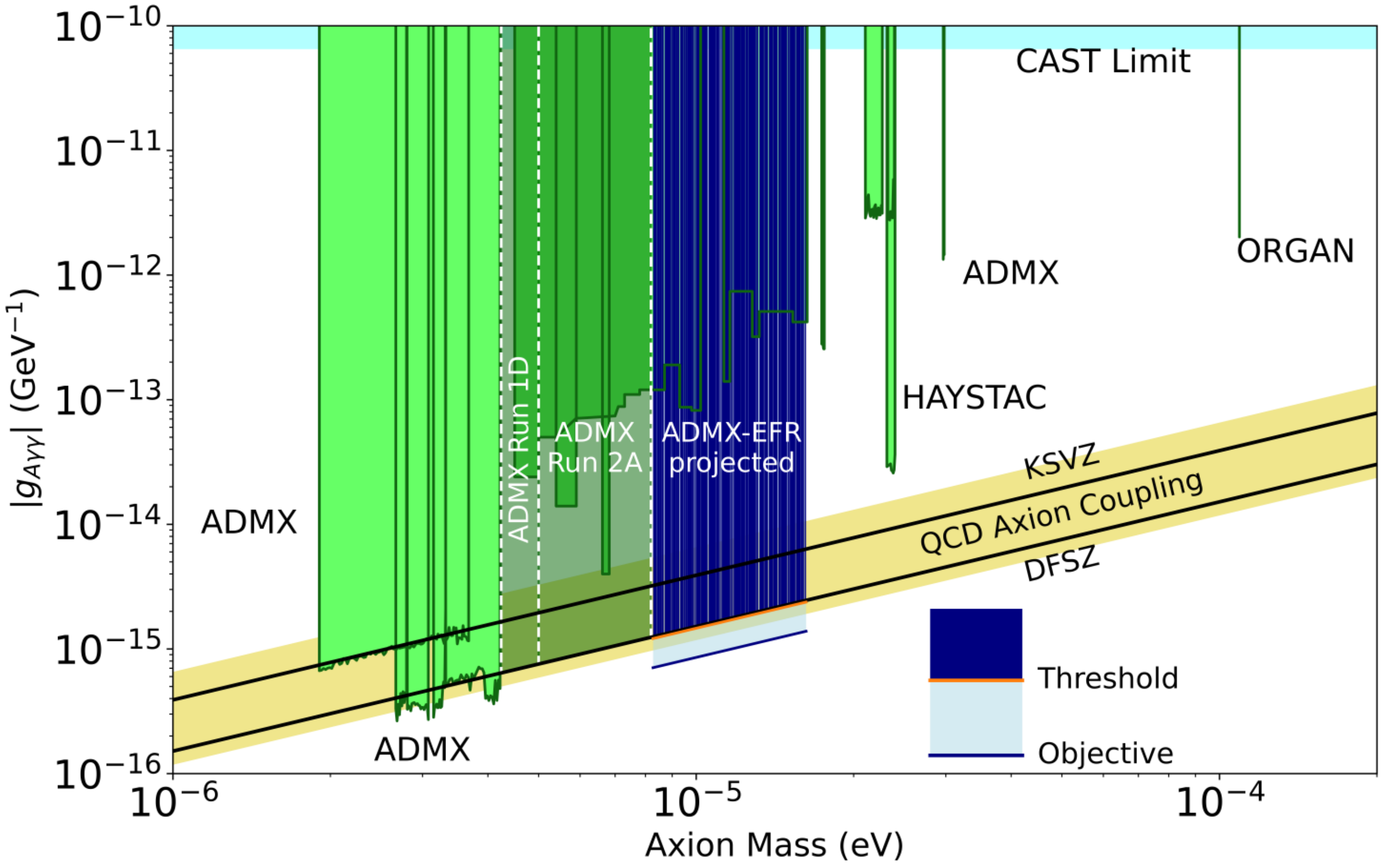
Searching for axions above 1μeV

ADMX EFR will utilize the same technology as ADMX G2 but with a larger magnet, lower temperatures, and improved quantum electronics, and a new site at Fermi National Laboratory

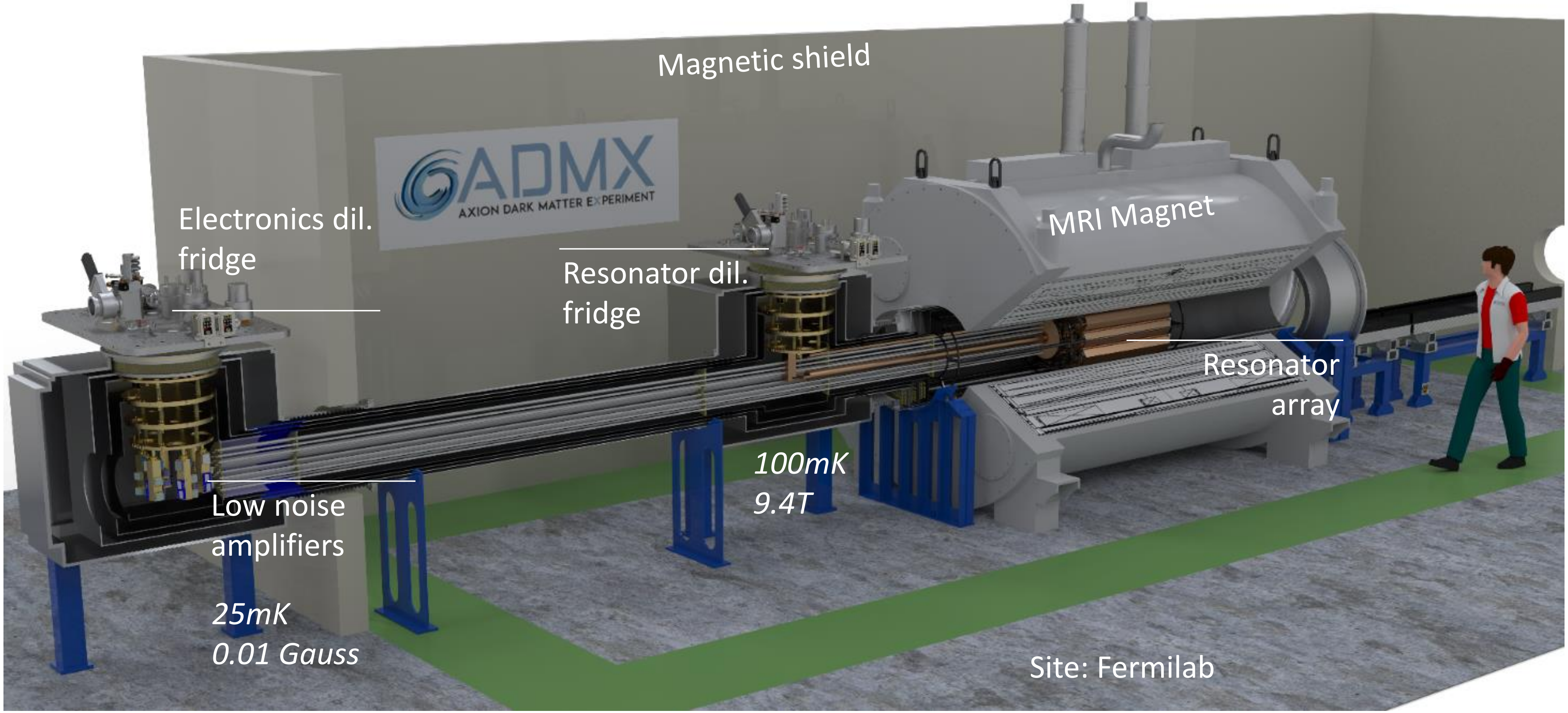
ADMX Extended Frequency Range (EFR) Goals

- ADMX EFR will search for QCD Axion Dark Matter in the well-motivated region above 1 ueV, starting where ADMX left off

- The first operations target 2-4 GHz with expectations to reach higher in future phases.



ADMX EFR Design



$\sim 5 \times$ scan speed of current ADMX

ADMX EFR Cost and Schedule

- Construction
  - 19 M$ FY24 through FY27 (assuming FY24 start)
  - Main magnet exists and has been procured (though not at FNAL yet)
- Operations
  - 5 years at 2M$/year to hit initial goals 2-4 GHz
  - Opportunity to increase frequency coverage with resonator R&D
  - Opportunity to increase scan speed with detector quantum sensing R&D

Magnet: 9.4 T, 80cm bore
at University of Illinois Chicago

Prototype resonator cell

The DMRadio Program

Searching for axions below 1μeV

U.S. DEPARTMENT OF ENERGY

SLAC NATIONAL ACCELERATOR LABORATORY

DMRadio Science Goals

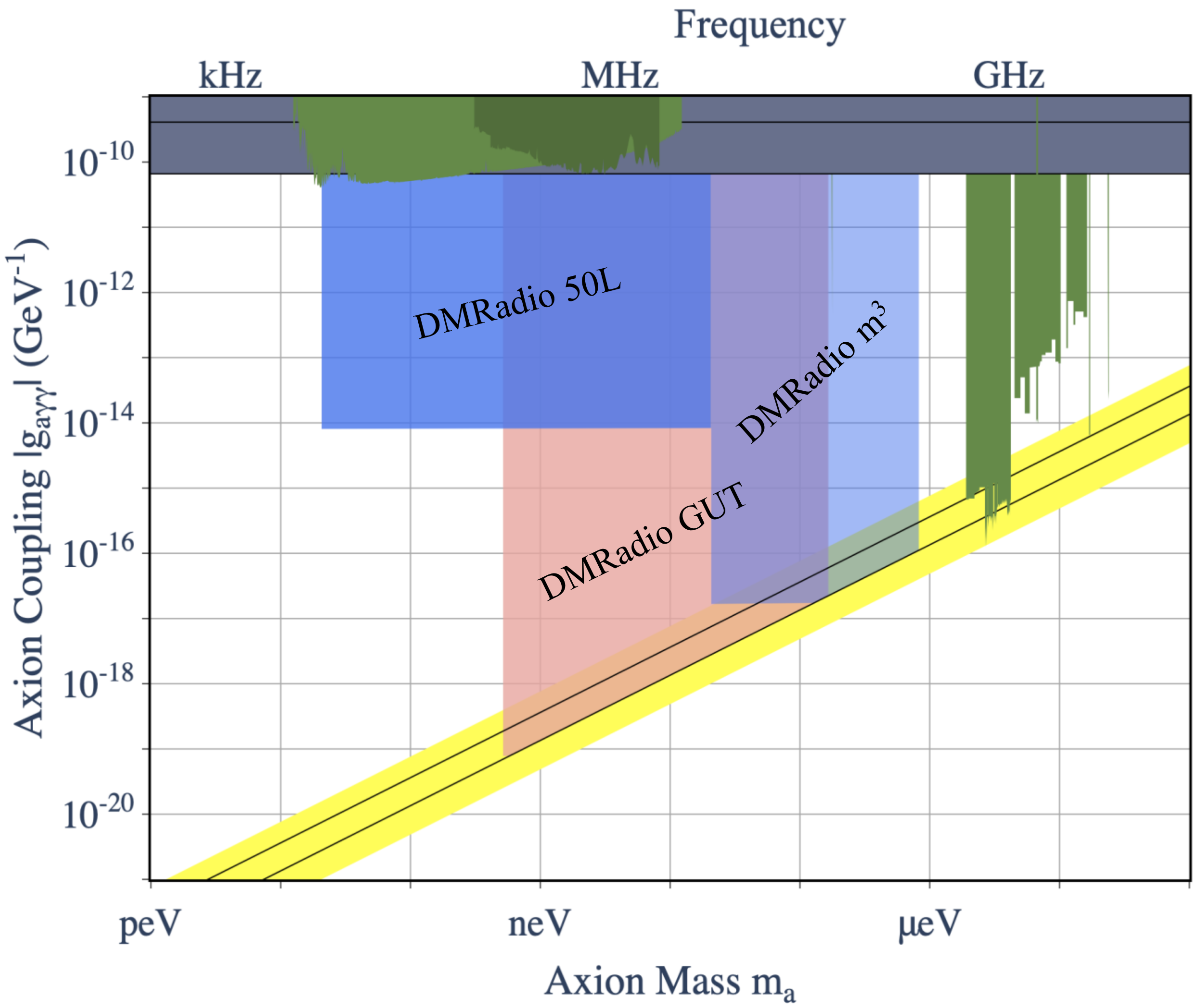
The DMRadio is a program to definitively search for the QCD axion below 1 μeV.

DMRadio-50L is an ALP search and a quantum testbed.

DMRadio-m3 is the DMNI Project:
Probing two favored QCD axion models:
KSVZ (top black line), DFSZ (bottom black line)

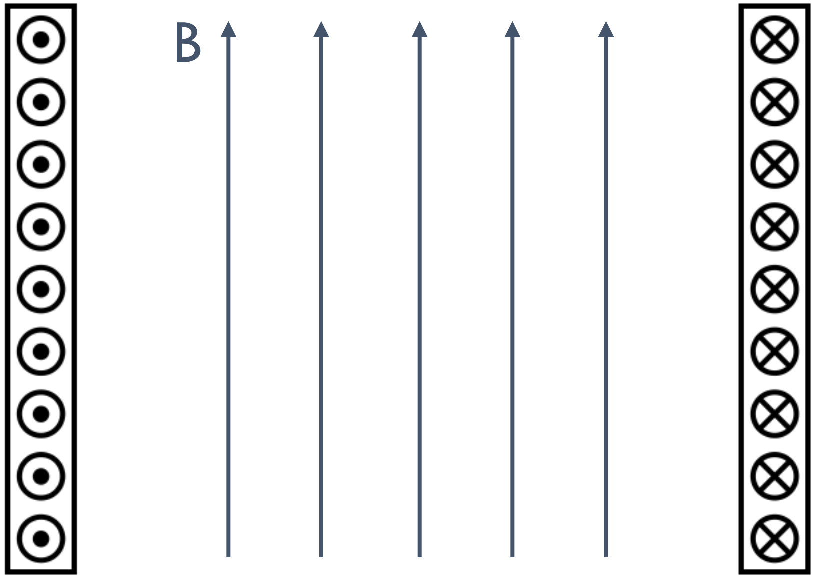
- Primary science goal: DFSZ 30-200 MHz
- Secondary science goal: KSVZ down to 10 MHz
- QCD band sensitivity down to 5 MHz

DMRadio-GUT is an ambitious next generation search for neV-scale axions.



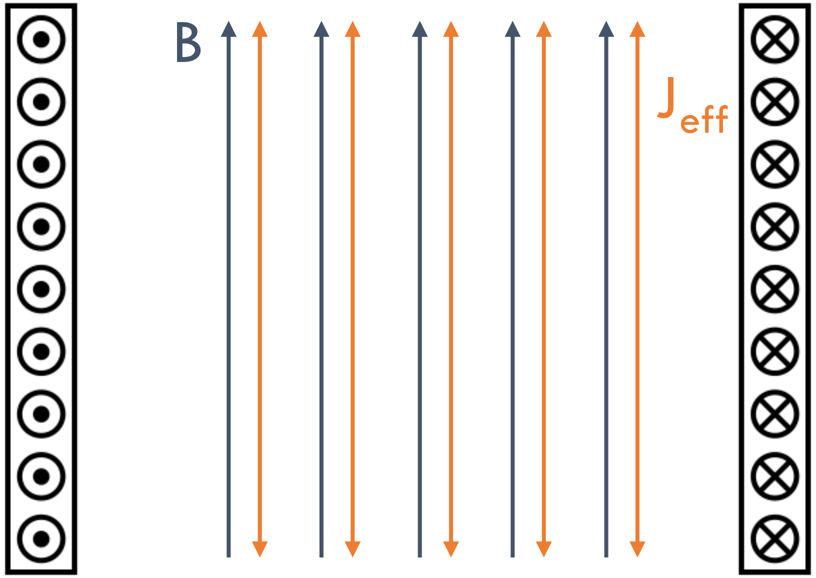
DMRadio-m^3: How it works!

Coupling to low frequency axion signals is different below the cavity regime.



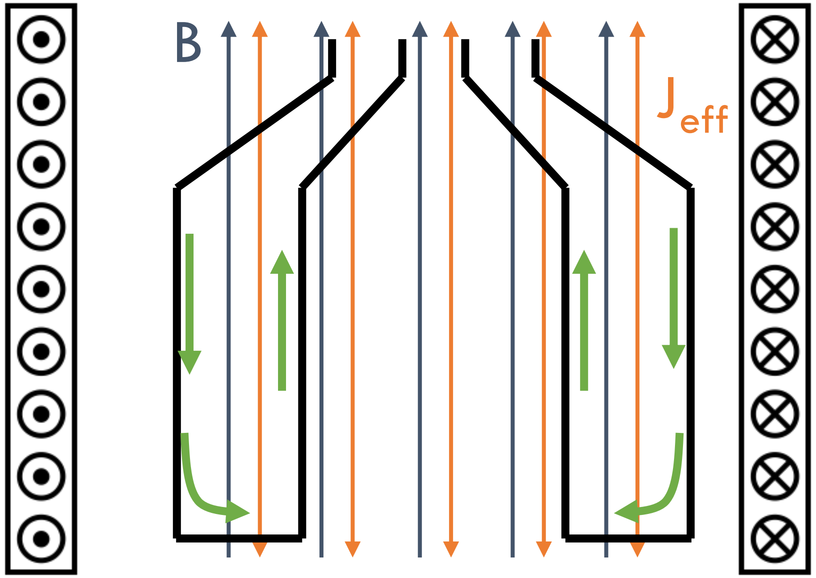
Low Frequency – Lumped Element Searches

Coupling to low frequency axion signals is different below the cavity regime.



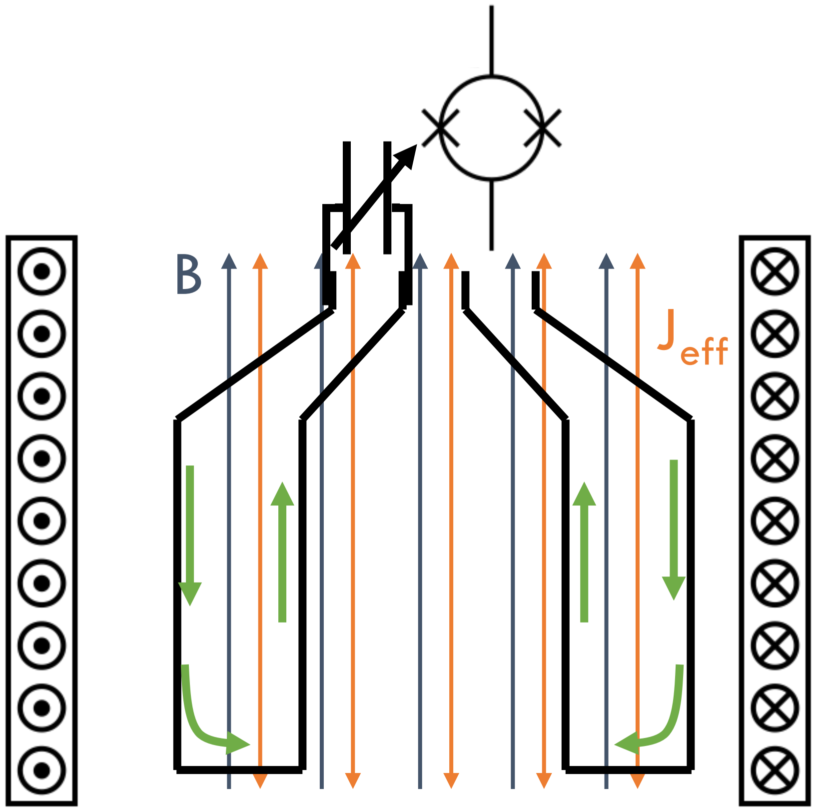
Low Frequency – Lumped Element Searches

A COAX Structure is inserted into the high field region.

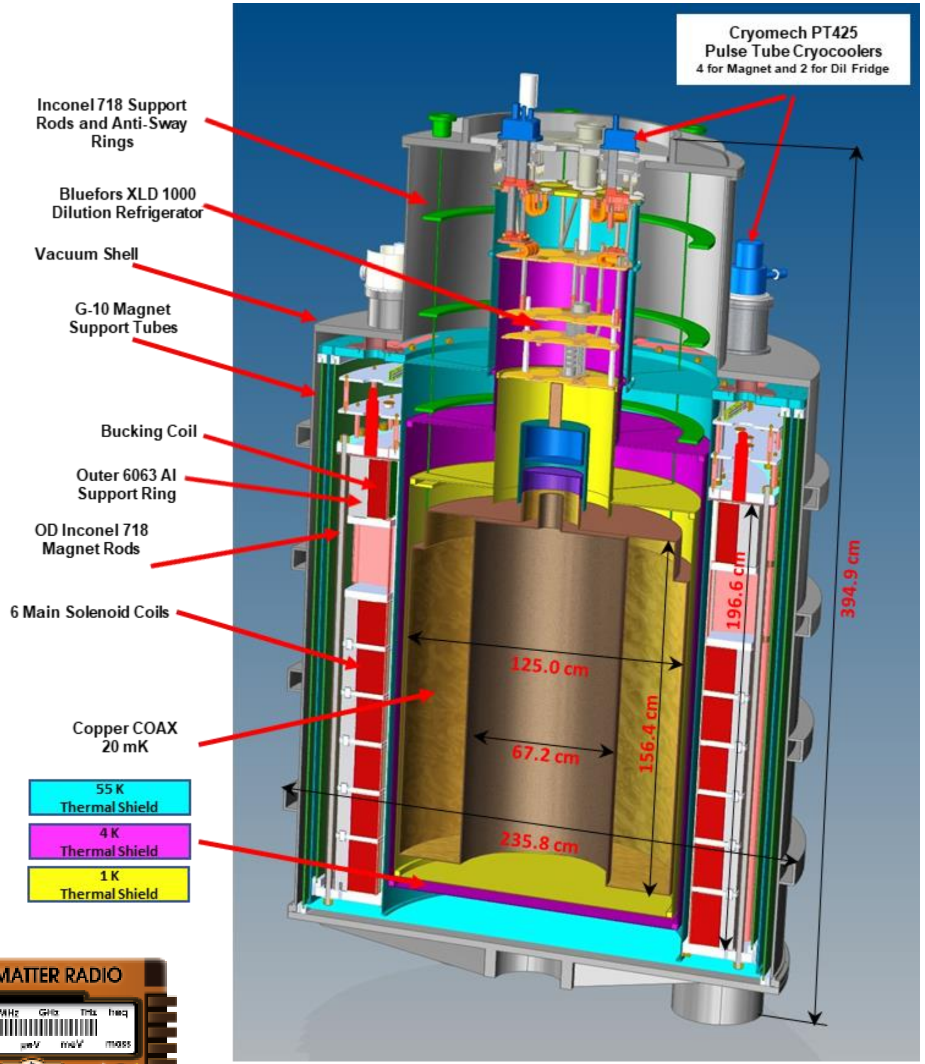


Low Frequency – Lumped Element Searches

The induced signal on the COAX is coupled to the readout SQUID.



Mature Design, Cost, and Schedule



- The design of DMRadio-m^3 is nearing maturity, including an engineering study of the magnet.
- The experiment's total cost fits well within the DMNI program's guidance of ~$20M.
- The construction timeline is 3 years, driven by the construction of the magnet.
- A set of six COAX's will be used as part of the science scan.

The DMRadio Scientific Collaboration

SLAC National Accelerator Laboratory

H.M. Cho, W. Craddock, D. Li, W.J. Wisniewski

Department of Physics, Stanford University

J. Corbin, P.W. Graham, **K. D. Irwin**, F. Kadribasic, S. Kuenstner, N. Rapidis, M. Simanovskaia, J. Singh, E. C. van Assendelft, K. Wells

Laboratory of Nuclear Science, Massachusetts Institute of Technology

J.W. Foster, J. Fry, J. L. Ouellet, K.M.W. Pappas, C.P. Salemi, **L. Winslow**

Department of Physics and Astronomy, University of North Carolina, Chapel Hill

R. Henning

Department of Physics, University of Illinois, Urbana-Champagne

Y. Kahn

Department of Physics, Santa Clara University

B. A. Young

Department of Nuclear Engineering, University of California, Berkeley

A. Droster, A. Keller, A. F. Leder, K. van Bibber, M. Wooten

Department of Physics, University of California, Berkeley

B. R. Safdi

Accelerator Technology & Applied Physics Division,

Lawrence Berkeley National Lab

L. Brouwer

California State University, East Bay

A. Phipps

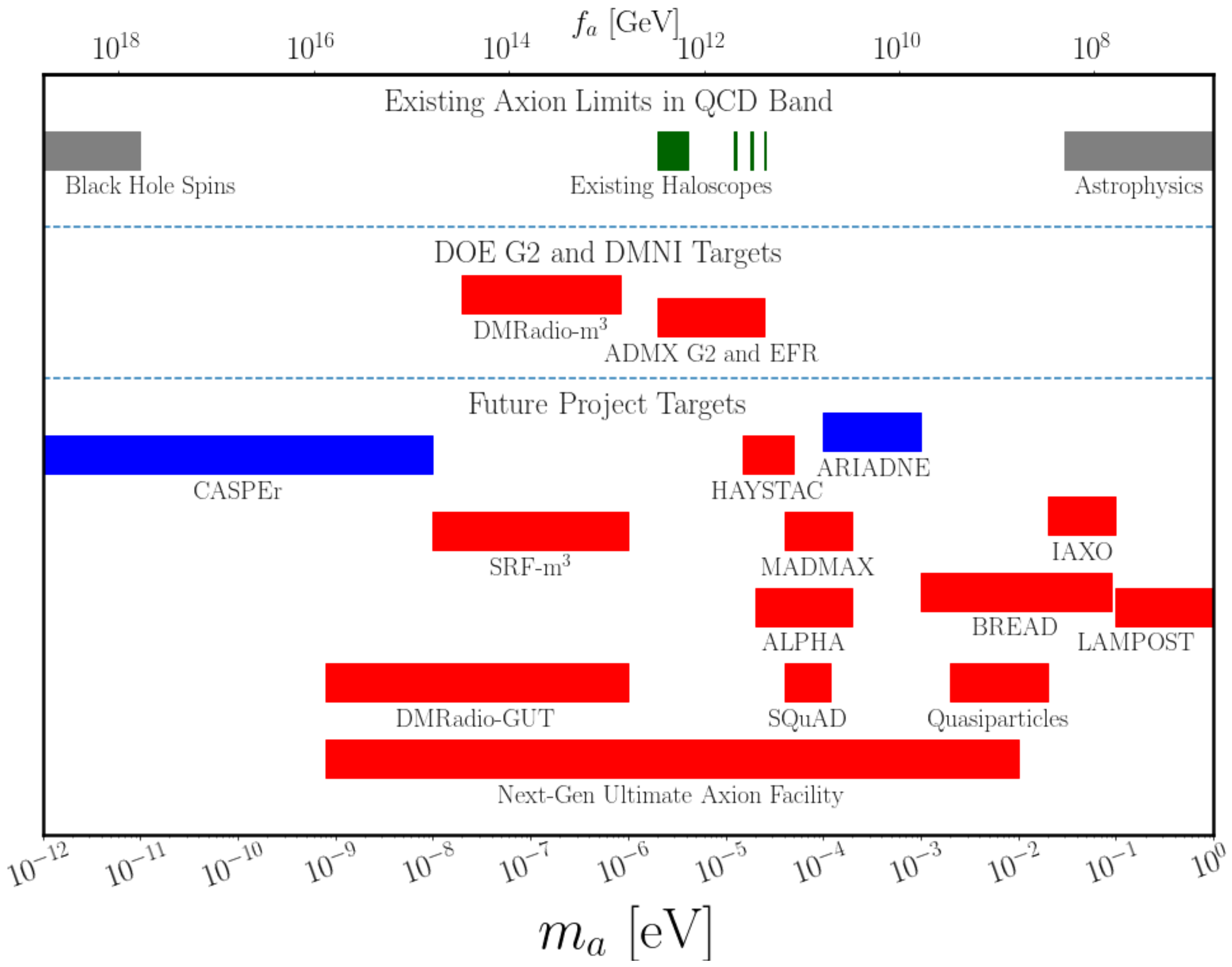
Department of Physics, Princeton University, Princeton

S. Chaudhuri, R. Kolevatov

Project Director: K. Irwin, Collaboration Spokesperson: L. Winslow

Program for Developing Ideas

- ADMX and DMRadio are only the first steps in an exhaustive search for Wavelike Dark Matter
- Many ideas and small groups need R&D support to become small projects with QCD axion sensitivity
- The DMNI process was successful at this
- Suggestion – a few million per year for development with a small (~10 M$) project start every 3 years



Example Projects

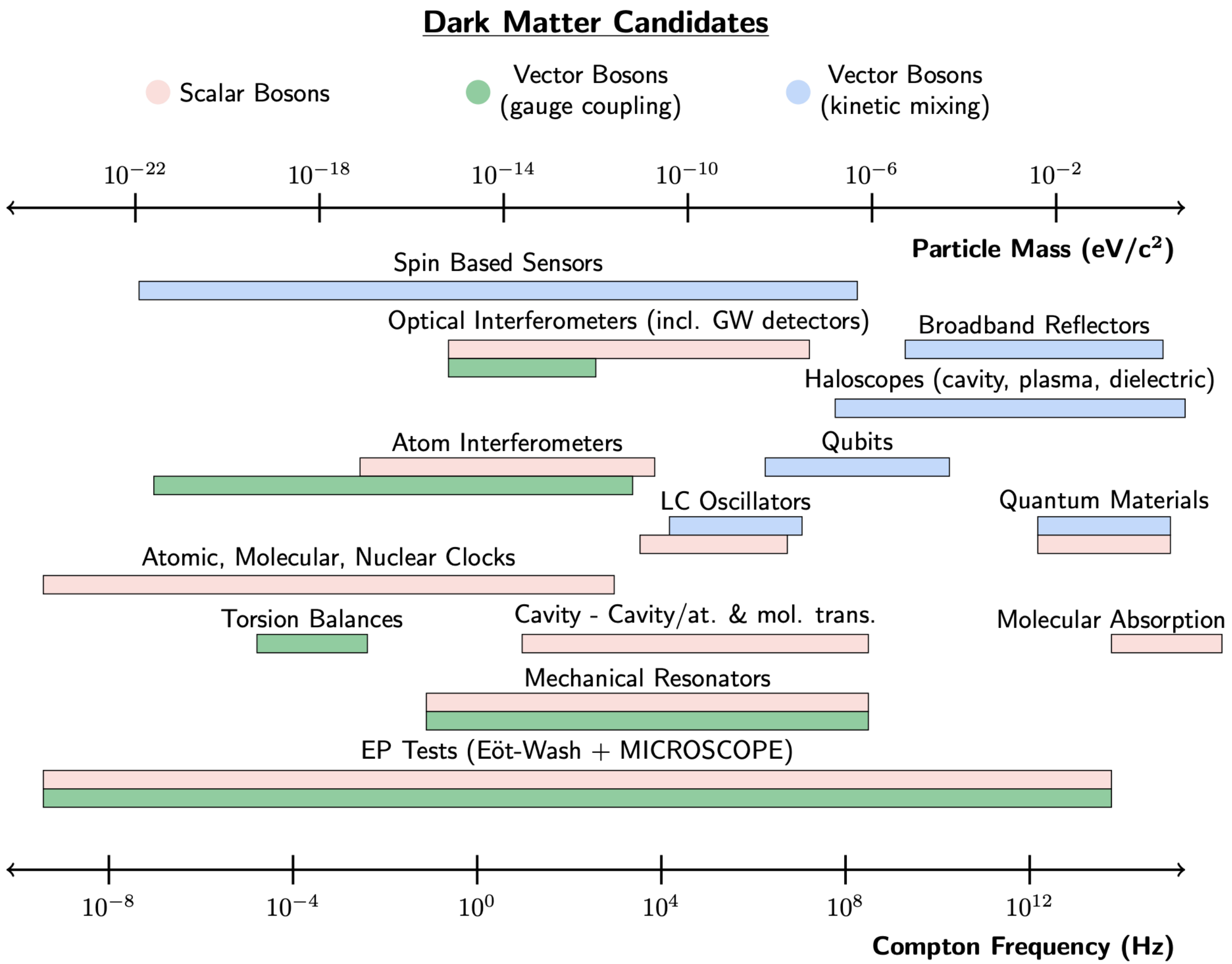
(An incomplete listing)

- RF Squeezed State (HAYSTAC)
- Superconducting cavities (SRF)
- Low-frequency NMR (CASPEr)
- Compact Reflectors (MADMAX, BREAD, LAMPPOST)
- Short Range Force + NMR (ARIADNE)
- Solar Axion Detection (IAXO)

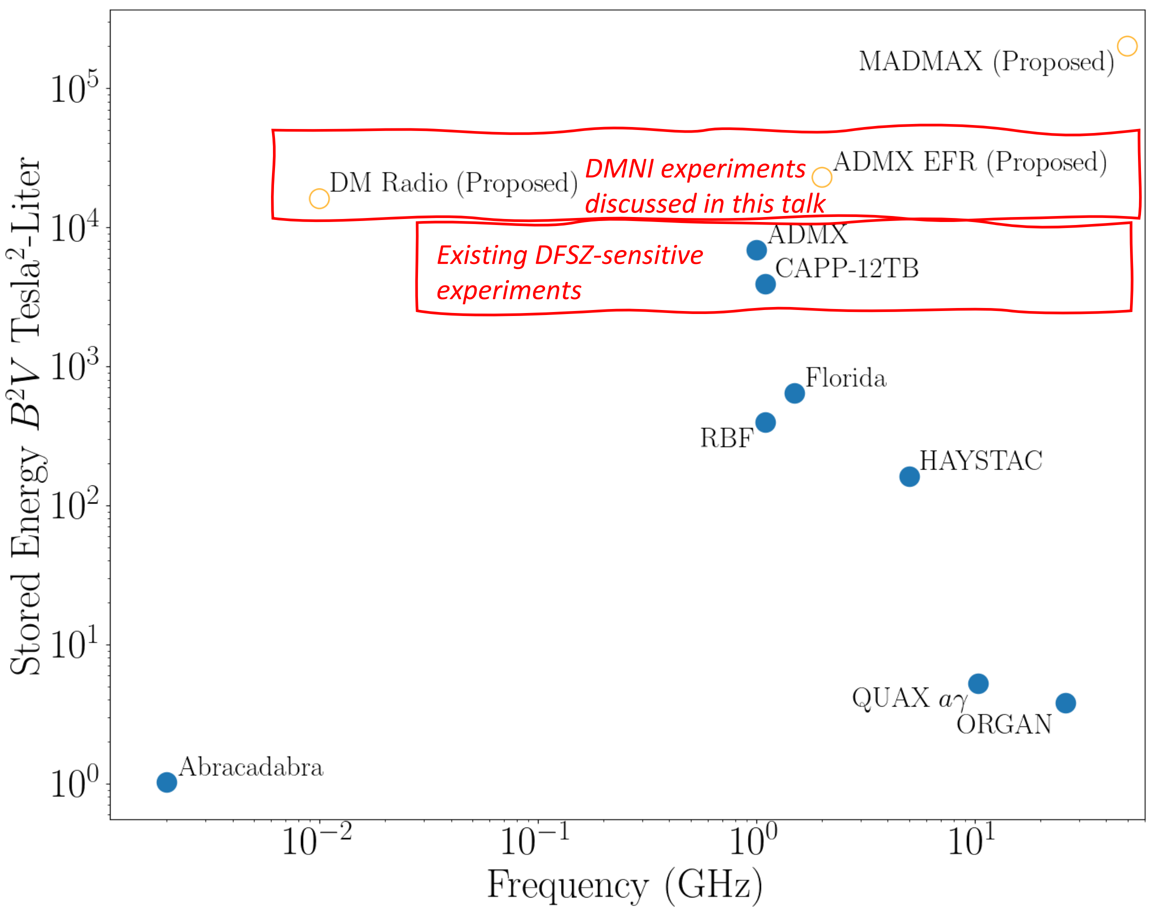
Example Projects – Scalar and Vector DM

Signals:
- Precession of nuclear spins
- Time variation in fundamental constants
- New short range forces
- Equivalence Principle violations
- Many opportunities to incorporate AMO and Quantum Sensing techniques

What is needed:
- Theory support to understand consequences of WLDM for experiments
- Support to develop these techniques into projects



The Utility of an Axion/WLDM Center



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.

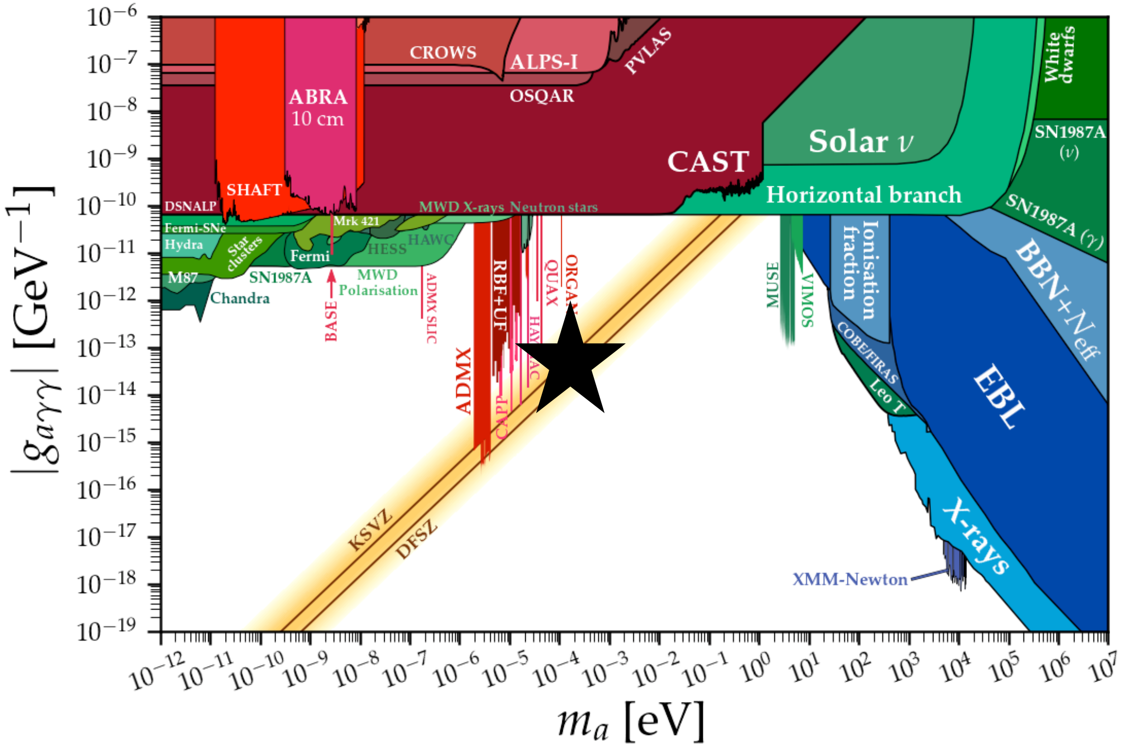
A user facility with large stored energy magnets would be of use to the wavelike dark matter community.

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

Any national laboratory with an axion center would become the focus of US wavelike dark matter efforts.

Consequence of Discovery

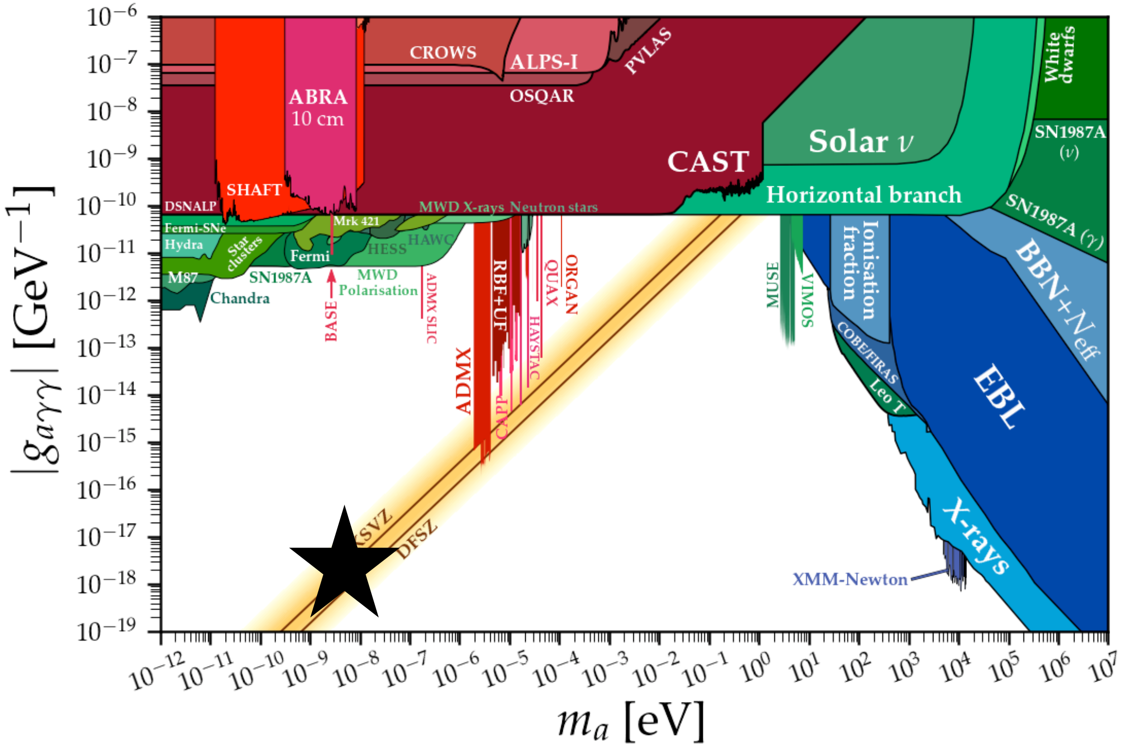
- This is a QCD axion that was created after inflation.
- Predicts expanded Higgs sector or additional quarks.
- Tests of the nuclear and electron couplings would be needed.
- Line shape explores halo structure.



https://cajohare.github.io/AxionLimits/docs/ap.html

Consequence of Discovery

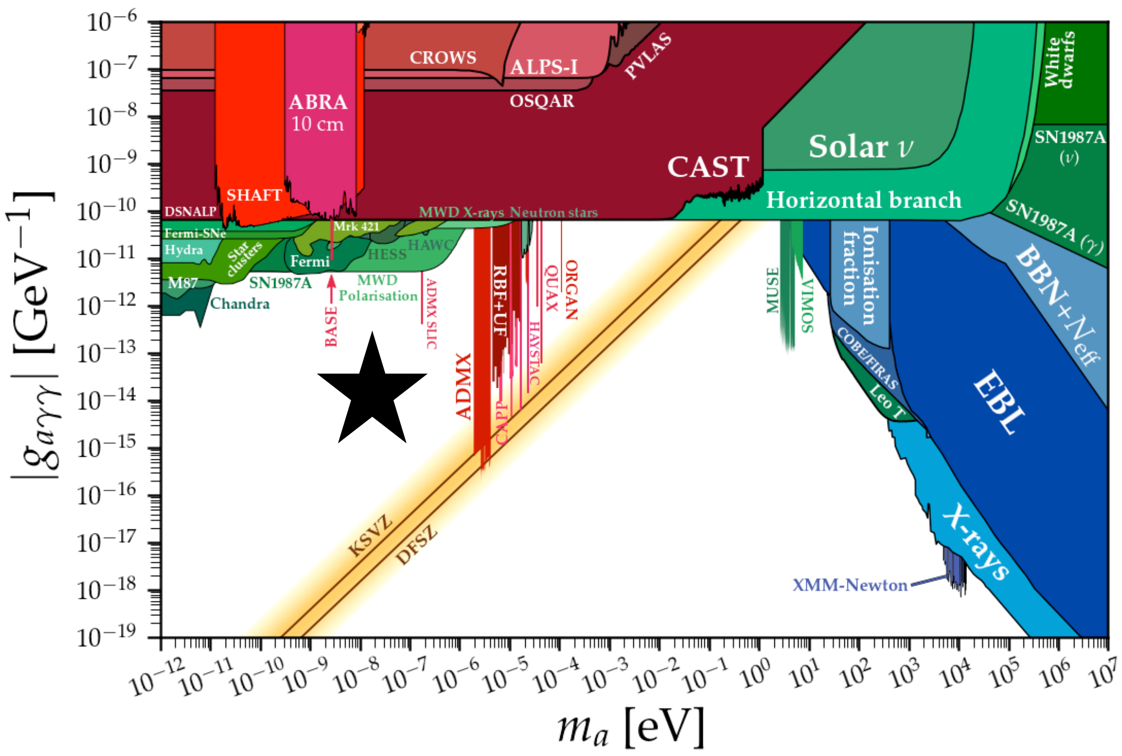
- This is a QCD axion that was created before inflation.
- GUT-scale axion clear proof of new physics at this scale.
- Predicts expanded Higgs sector or additional quarks.
- Possible affect on CMB signatures.
- Tests of the nuclear and electron couplings would be needed.
- Line shape explores halo structure.



https://cajohare.github.io/AxionLimits/docs/ap.html

Consequence of Discovery

- This is an axion-like particle (ALP)
- Proof of higher order theory.
- Possible signatures in accelerator-based experiments.
- Tests of the nuclear and electron couplings would be needed.
- Line shape explores halo structure.



https://cajohare.github.io/AxionLimits/docs/ap.html

Summary and Conclusions

- There is growing interest in Wavelike Dark Matter and technological advancements now allow us to build sensitive experiments
- The QCD axion is the flagship model of WLDM, but not the only one
- Haloscope experiments (ADMX-EFR and DMRadio) have an excellent chance of discovery and should be supported immediately
- A program to support R&D on upcoming techniques for Axion, Scalar, and Vector dark matter searches and associated quantum sensing technology should be initiated – a center dedicated to this would be useful
- Consequences of a discovery extend beyond dark matter and will point the way to expand the Standard Model