Direct Experimental Searches for Ultralight Dark Sectors

(Heavily biased toward haloscope searches for QCD axion dark matter)

Dark Interactions 2024, Vancouver, BC

Gray Rybka – University of Washington

Wave-like Dark Matter Candidates

Wave-like Definition: Mass < 1 eV

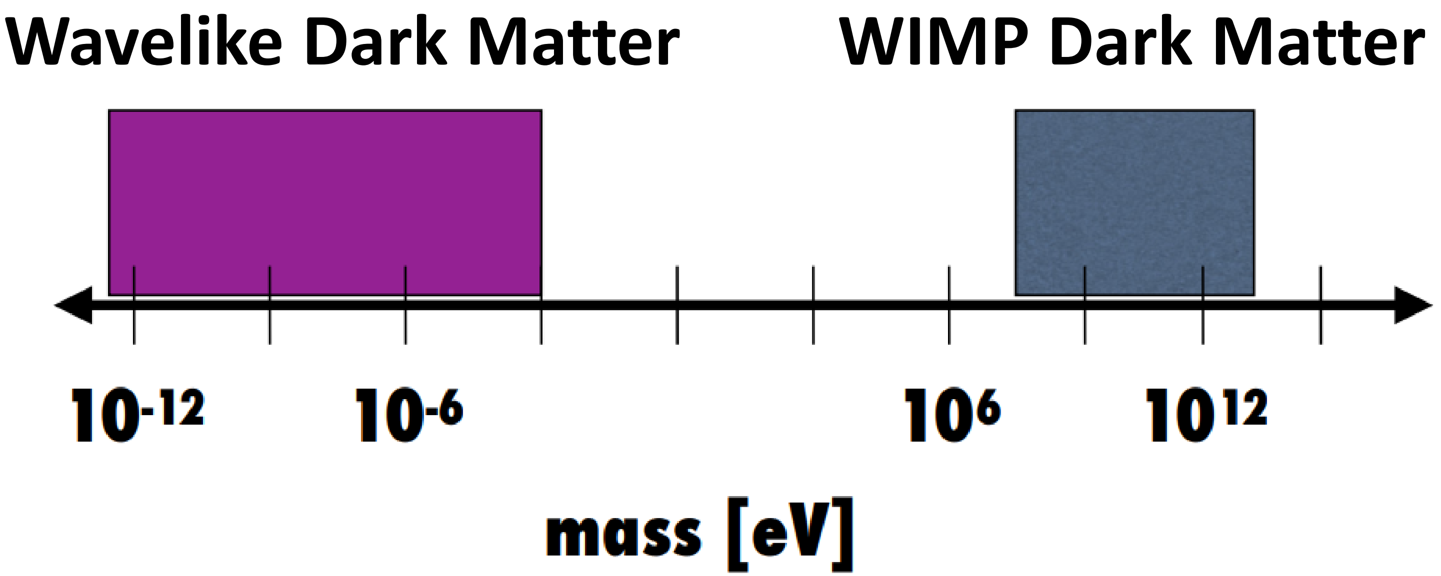
Broad Candidate Categories:

- 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.*



de Broglie Wavelength - $\lambda_{dB} \approx \frac{2\pi}{mv}$

Occupancy Number - $N \approx \frac{\rho_{DM}}{m} \lambda_{dB}^3$

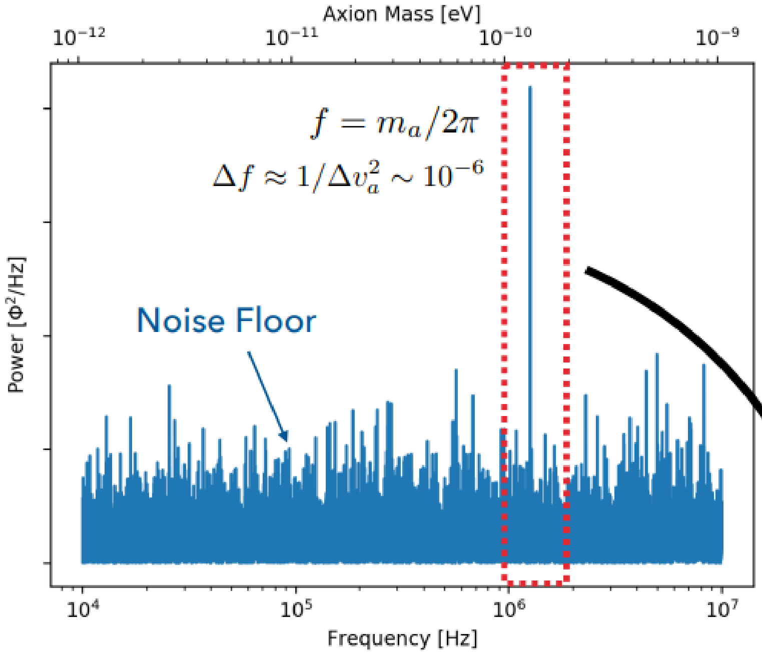
- Axion ($m \sim 10^{-9}$ eV): $\lambda_{dB} \sim 10^4$ km with $N \sim 10^{44}$
- WIMP ($m \sim 100$ GeV): $\lambda_{dB} \sim 10^{-16}$ km with $N \sim 10^{-36}$

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

Adapted from B. Safdi

To Measure a Wave: Measure Frequency

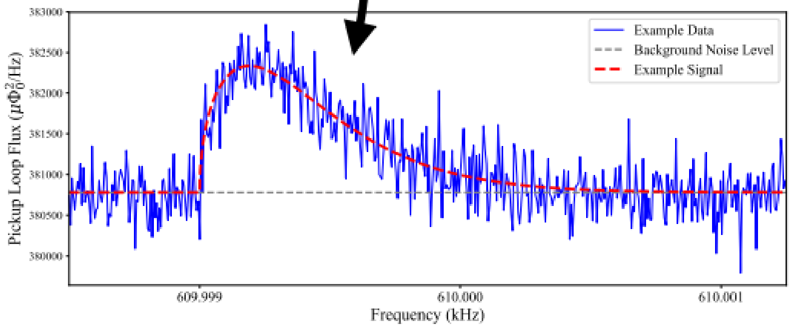
$$a(t) = a_o \sin(m_a t)$$



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

ZOOM

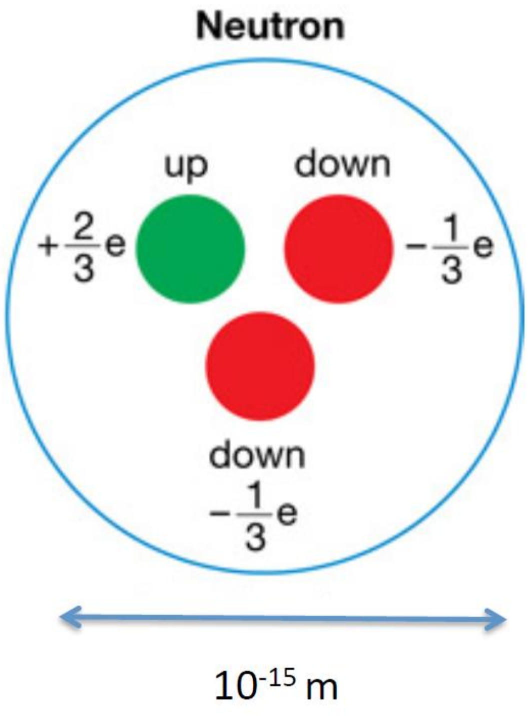
There is a characteristic line shape due to the halo velocity distribution. Features within the halo could show up here!



CF2: Wave-like Dark Matter 10

The QCD Axion: Motivation

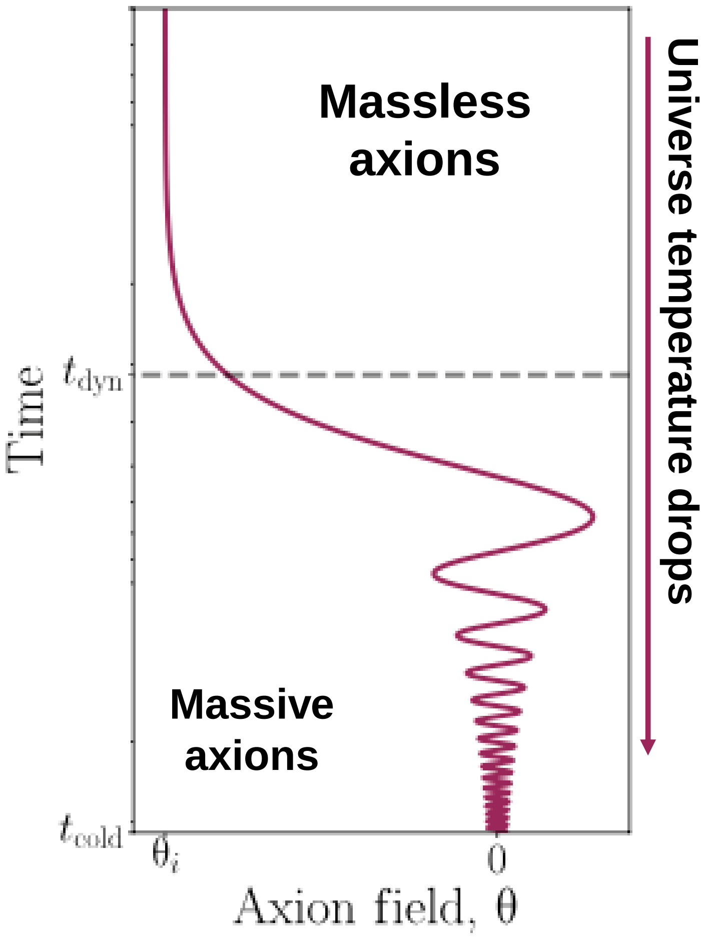
- QCD is naturally CP violating from phenomena like QCD-instantons
- One naively expects a neutron electric dipole moment of 10^{-16} e cm
- But nEDM is measured to be below 3×10^{-26} e cm *(Baker, 2006)*
- The best explanation? New U(1) axial symmetry, that when broken, cancels CP violation in the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

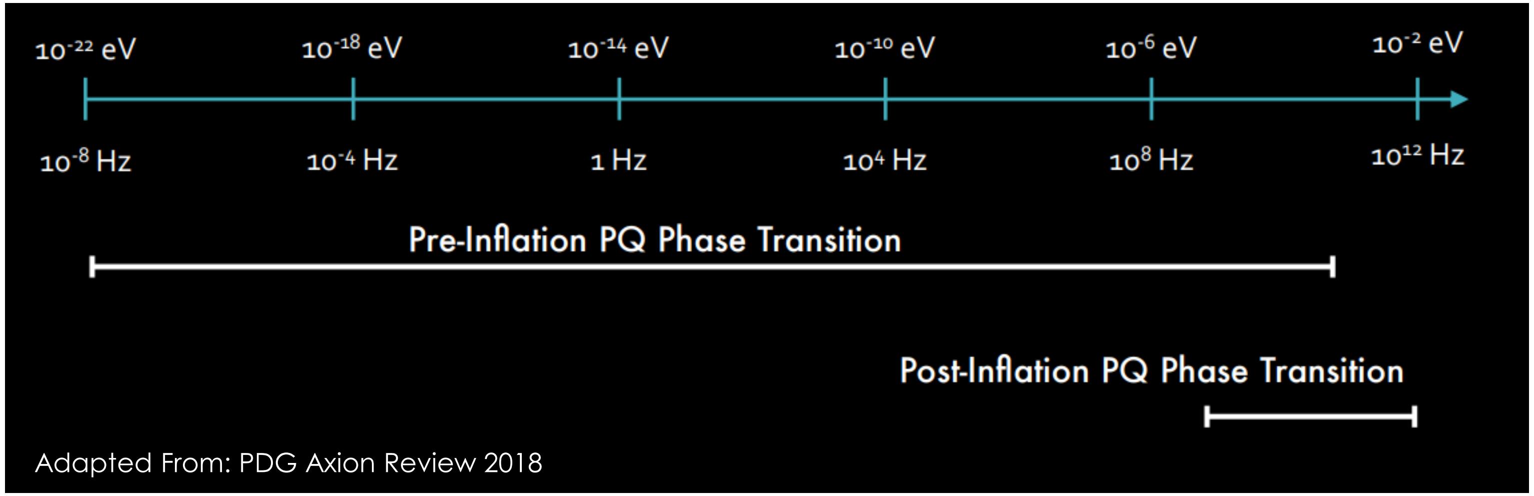
- Axions are produced athermally
  - Misalignment Mechanism – Phase transition in the early universe leaves energy in the axion field which behaves as dark matter
  - String/Defect Decay – Energy in topological defects radiates as cold axions
- In both cases axions are produced cold and in quantities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



Francesca Chadha-Day, John Ellis, David J. E. Marsh, sciadv.abj3618

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



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

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

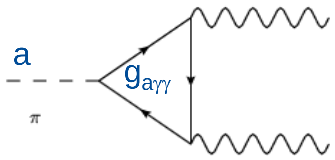
Coupling to Axial Nuclear Moment

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

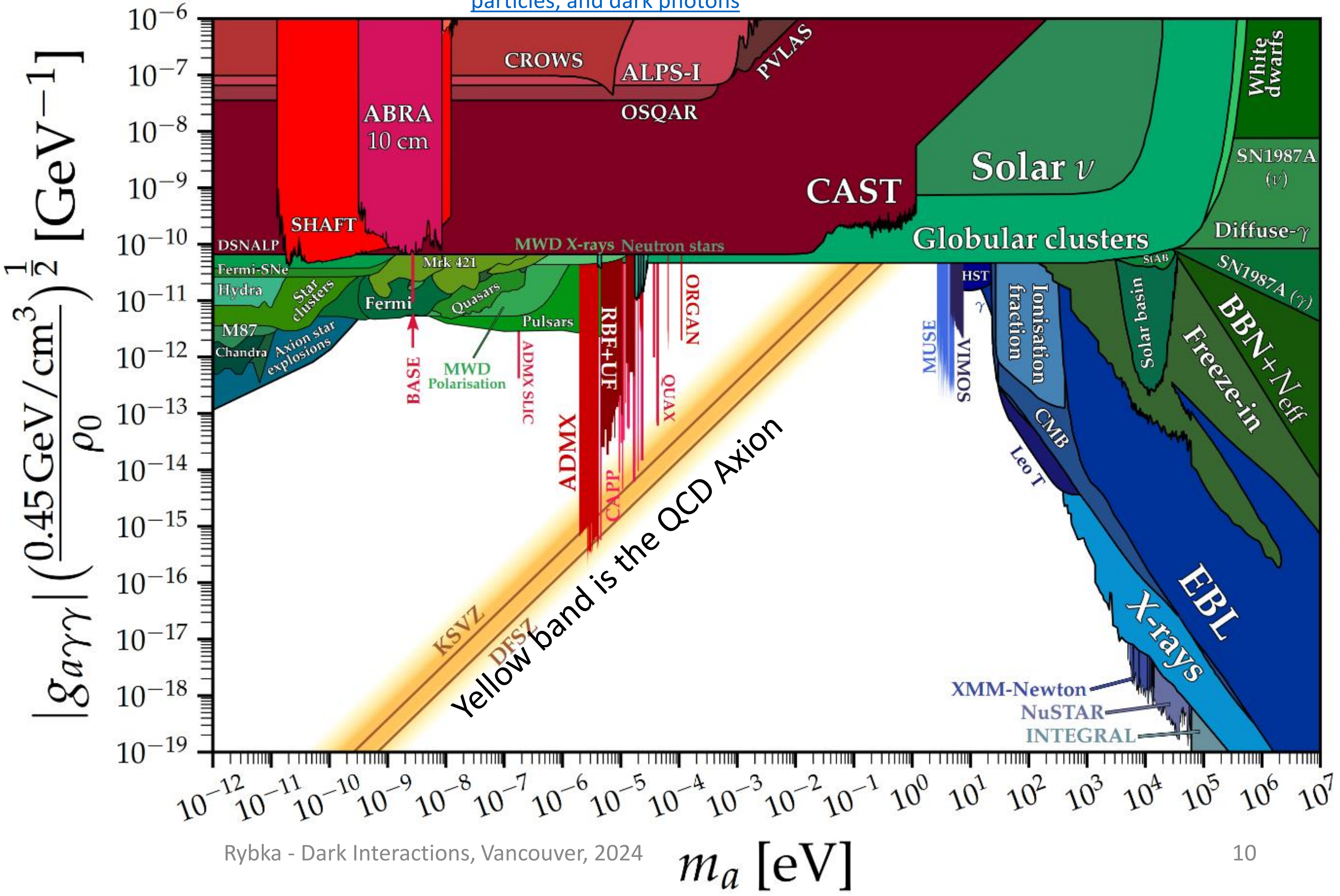
Adapted from Y. Kahn, See also Graham and Rajendran, Phys.Rev. D88 (2013) 035023

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.



Apologies for the Omissions

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

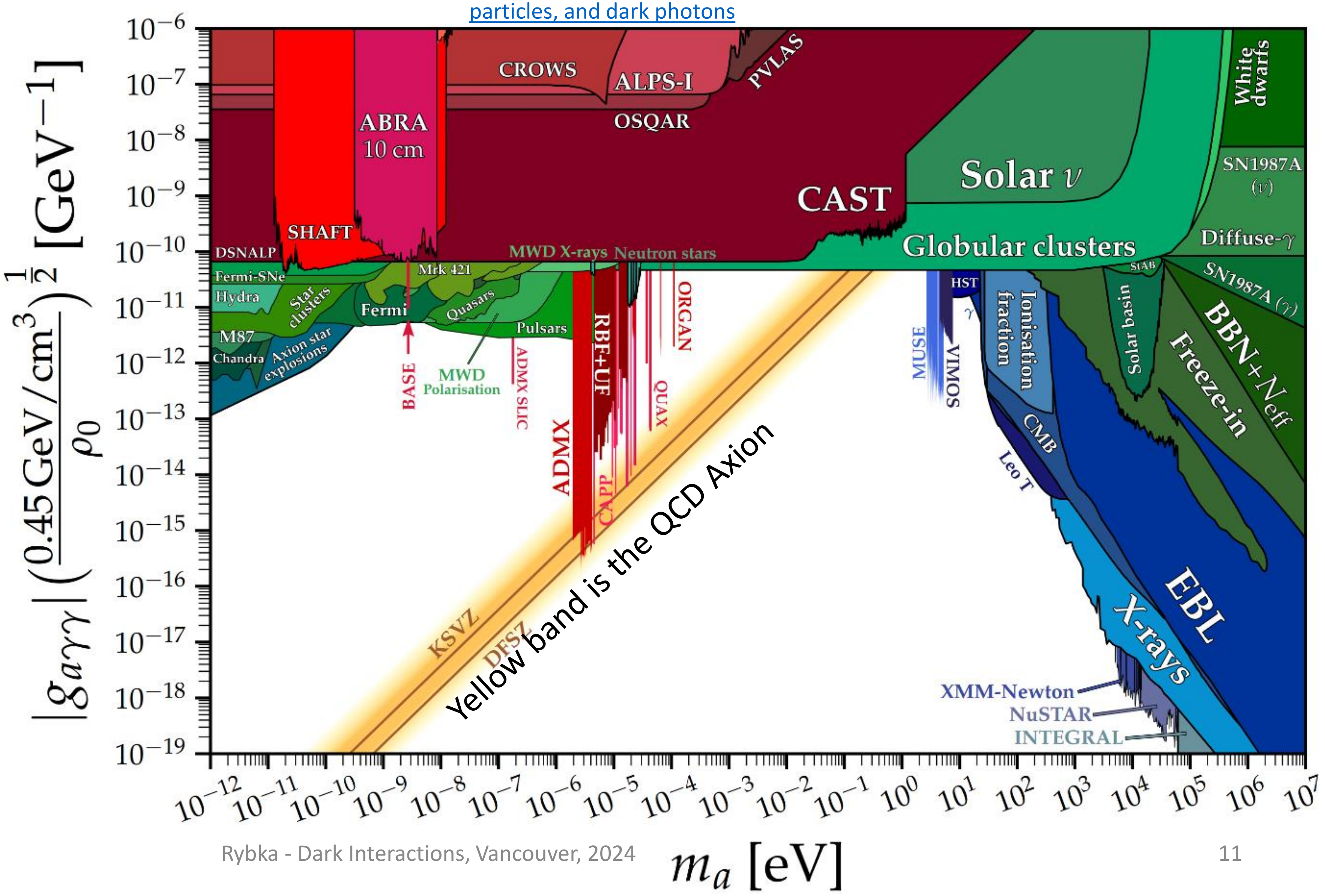
I'm not mentioning indirect searches for ultralight dark sectors

-Astrophysical Limits

-Helioscopes (CAST, IAXO)

-Laser experiments (ALPS, etc)

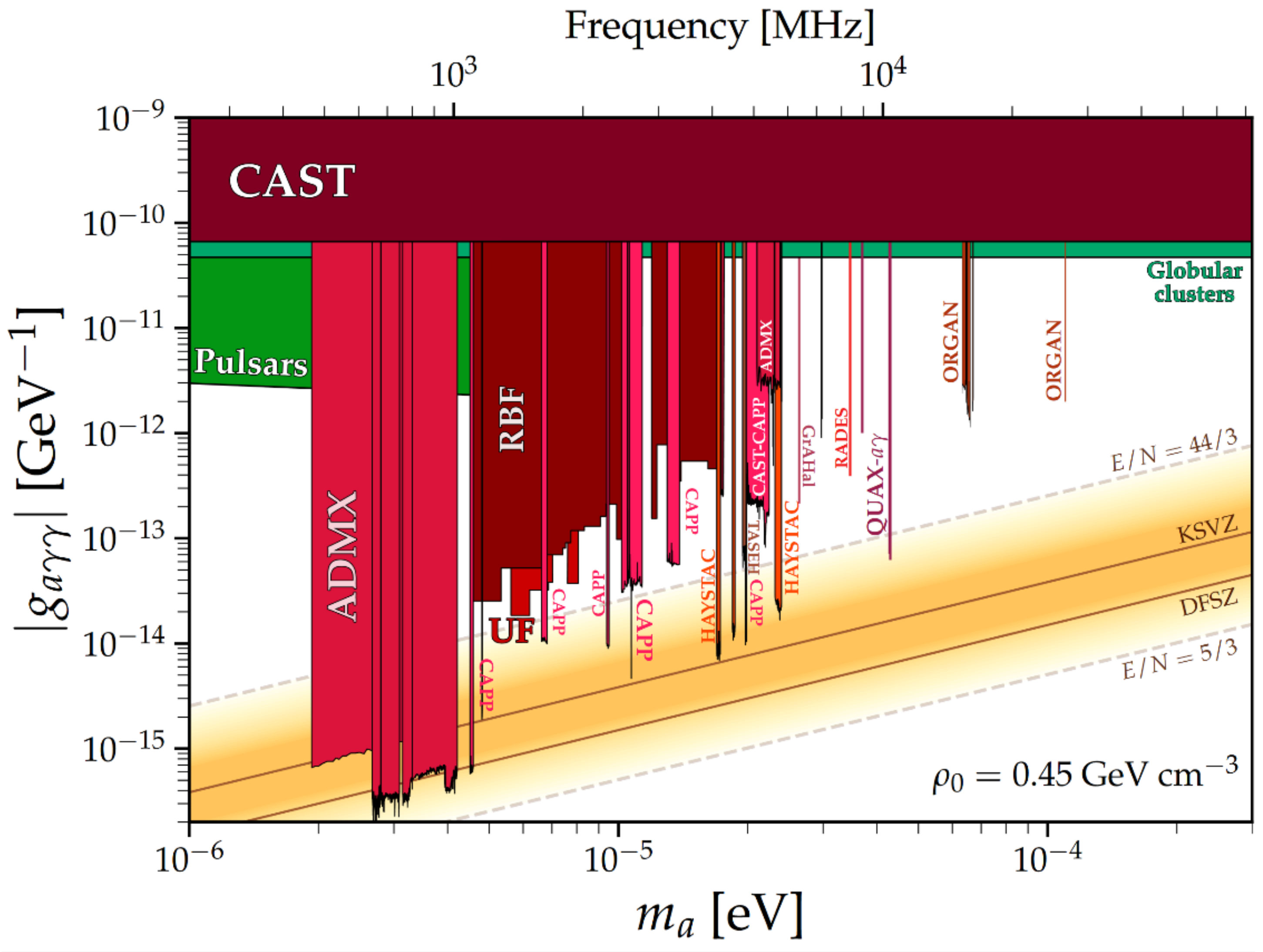
-Short range force experiments (Torsion pendula, ARIADNE)



Axion Photon Bounds, Zoomed In

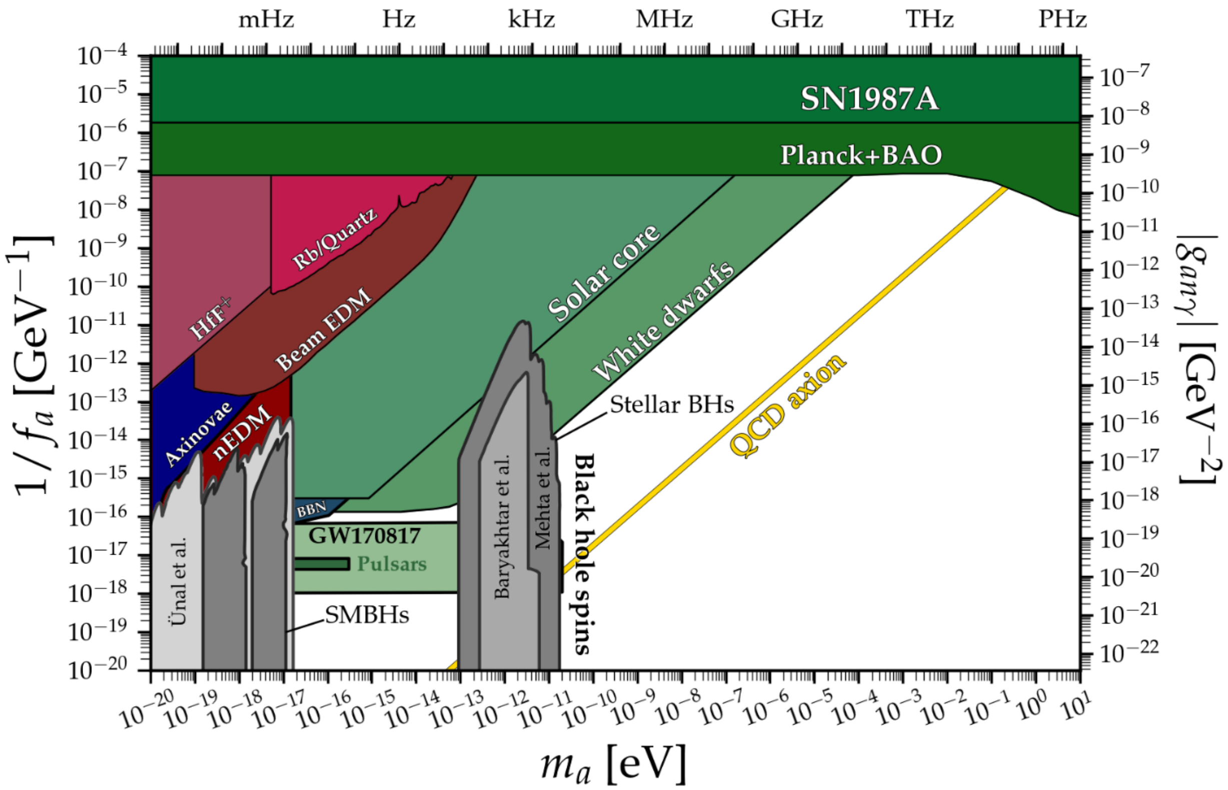
- KSVZ and DFSZ are benchmark axion coupling models.

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

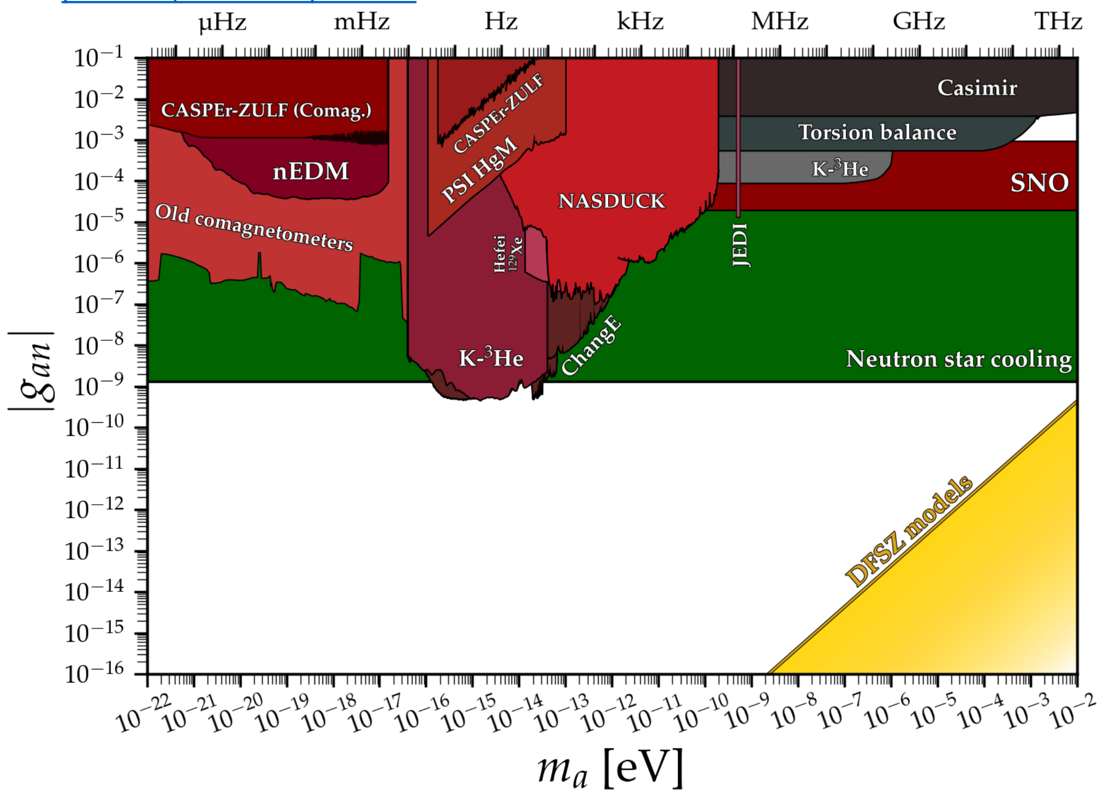


A few more example axion bounds

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



Less coupling dependent bounds

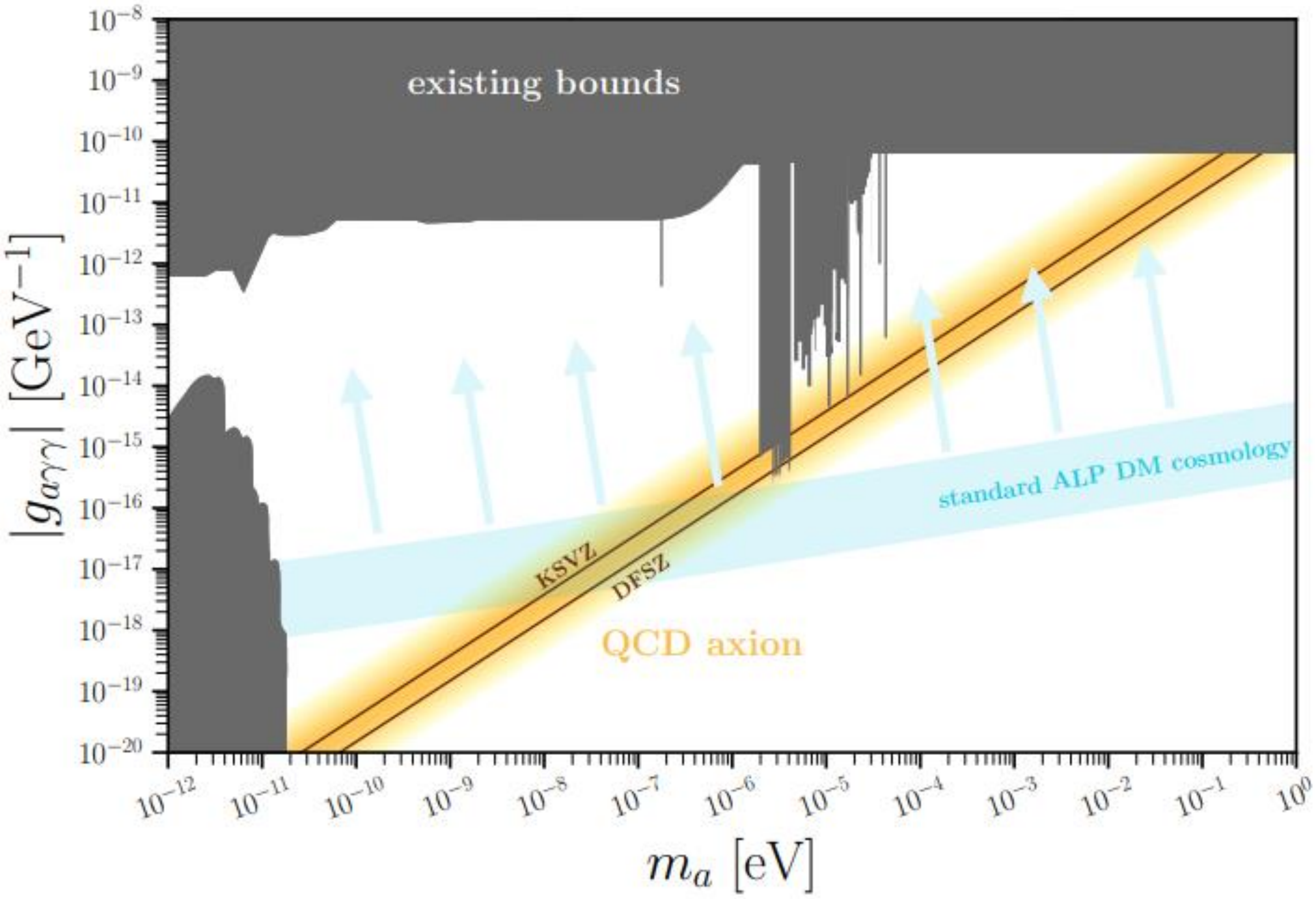


Axion-neutron bounds

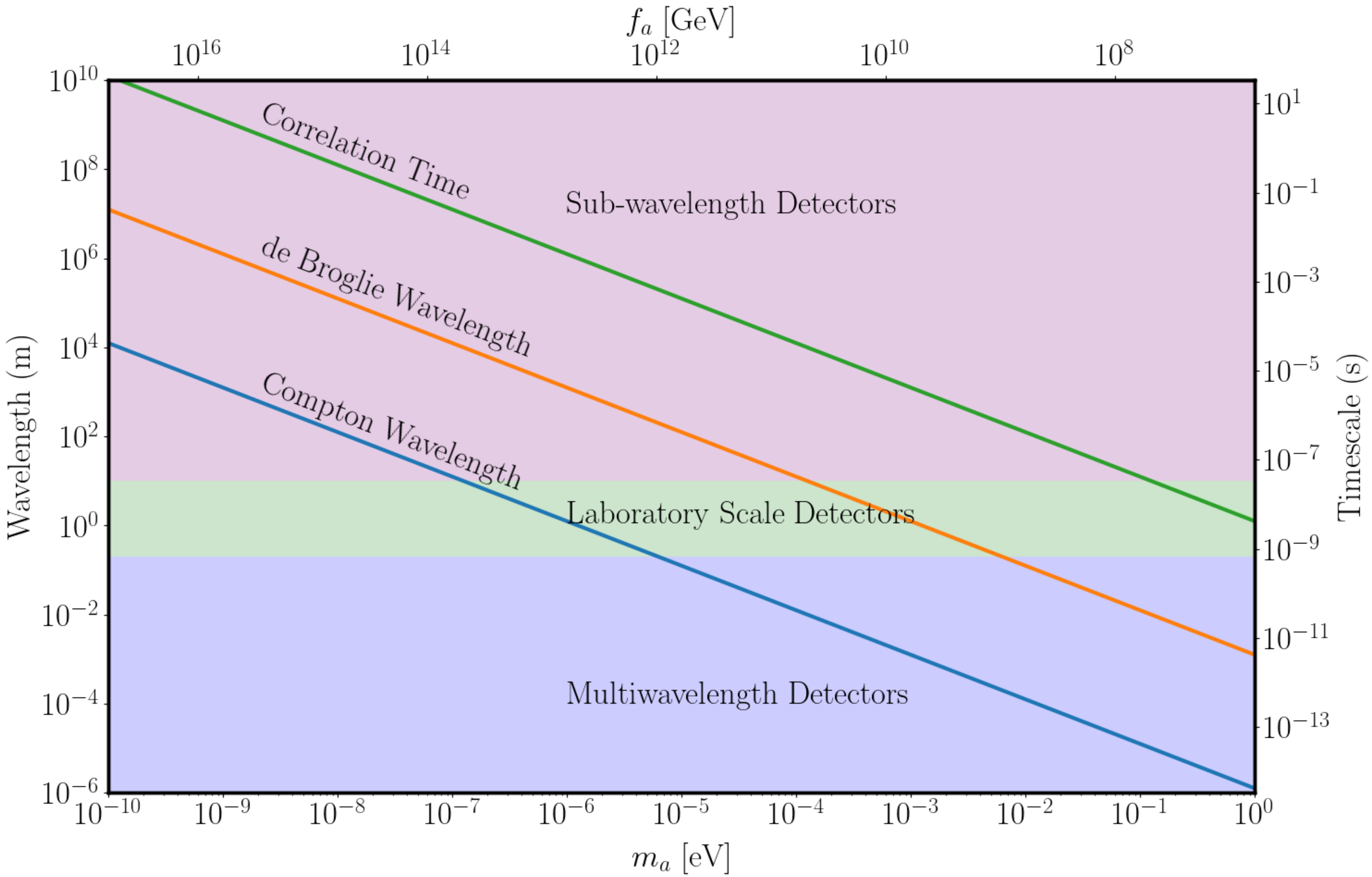
ALPs

- Axion-like particles may no longer fall on the QCD mass/coupling line
- But there are still theoretical preferences from the misalignment mechanism
- The same experimental techniques should be sensitive to ALP dark matter

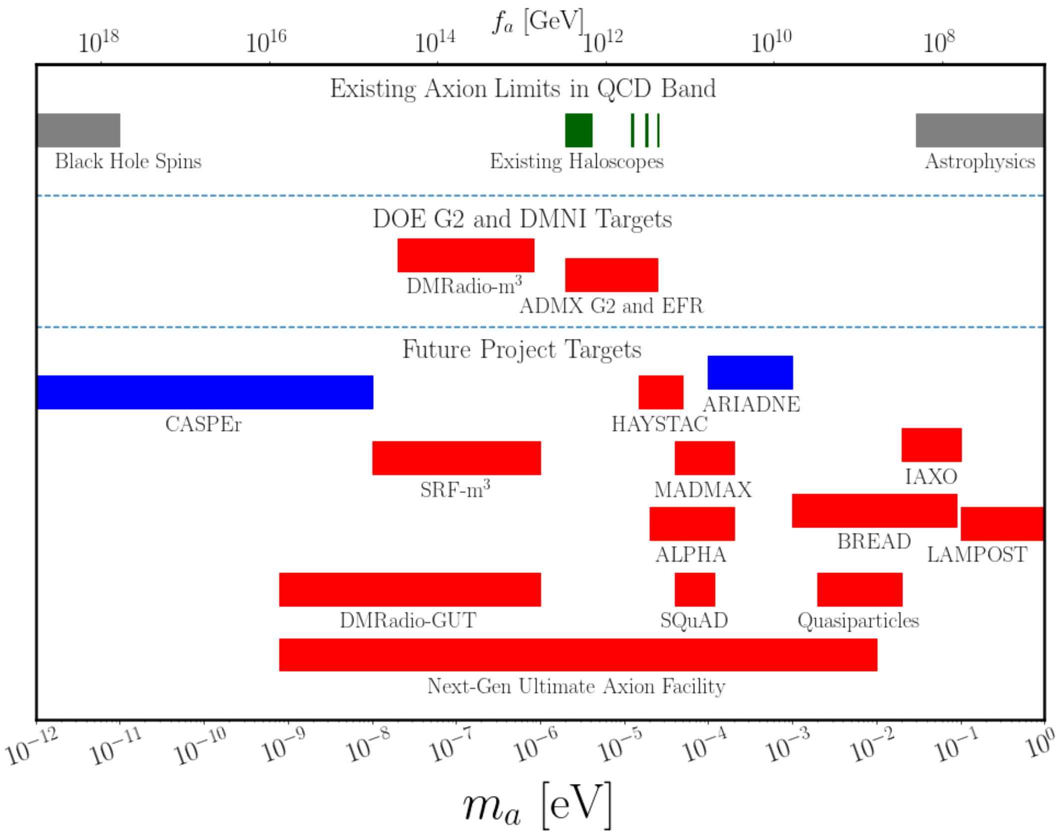
A. Berlin and others



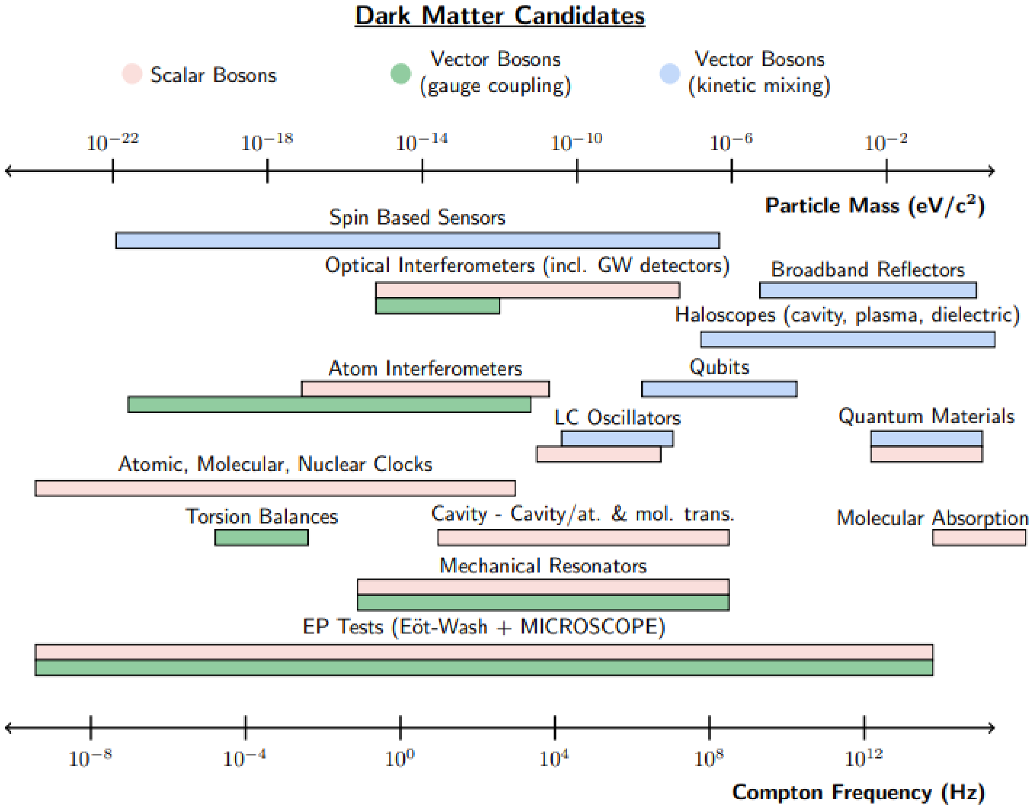
Axion Detector Length and Time Scales



Existing and Planned Axion and ALP searches in the US – (circa 2022)



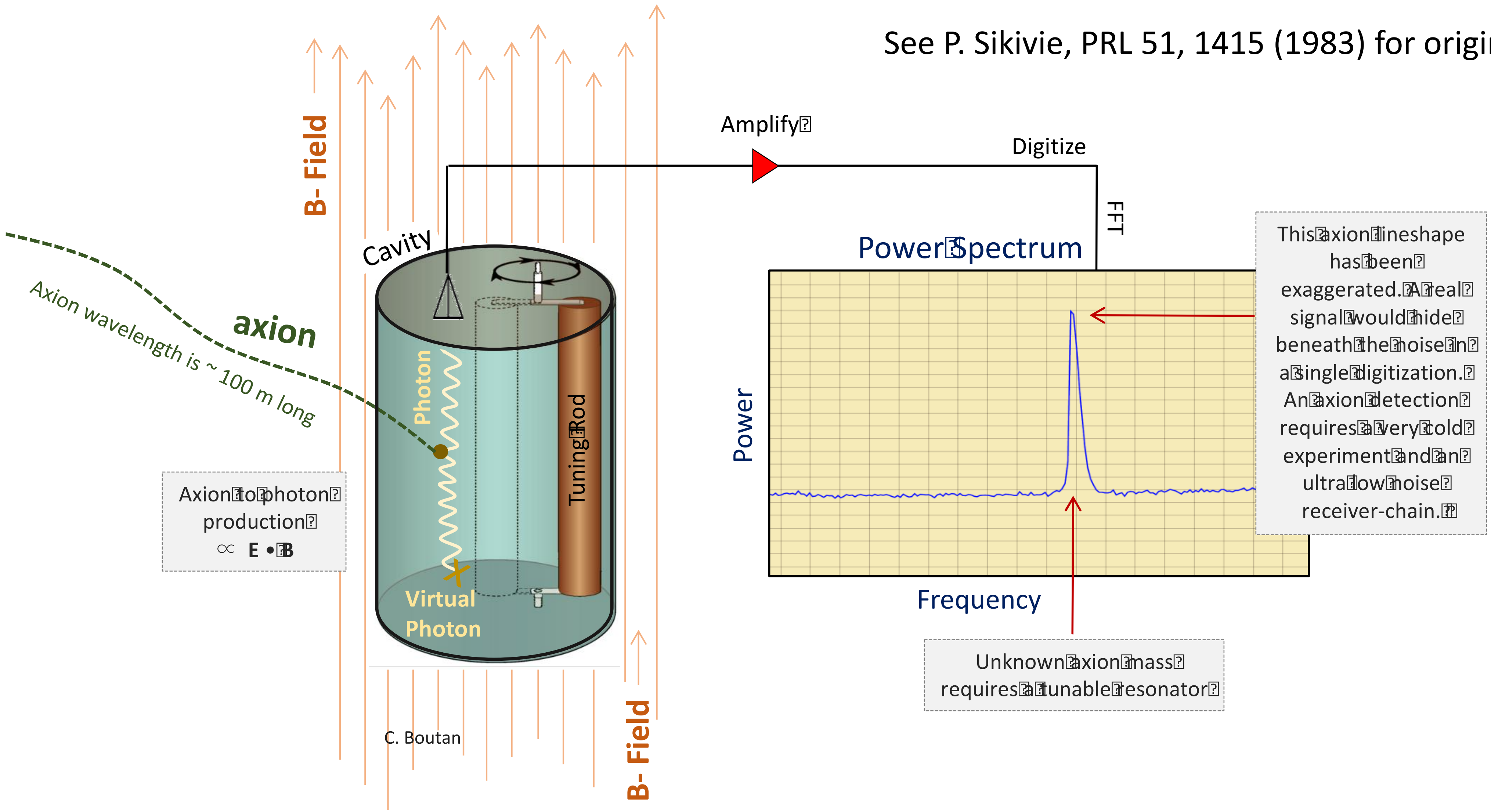
Axions, specifically



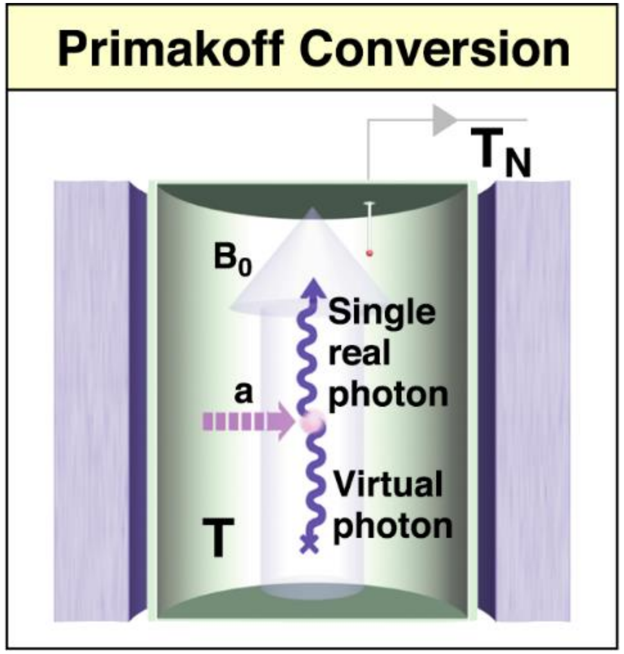
Others

Principle of the Sikivie Axion Haloscope

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



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

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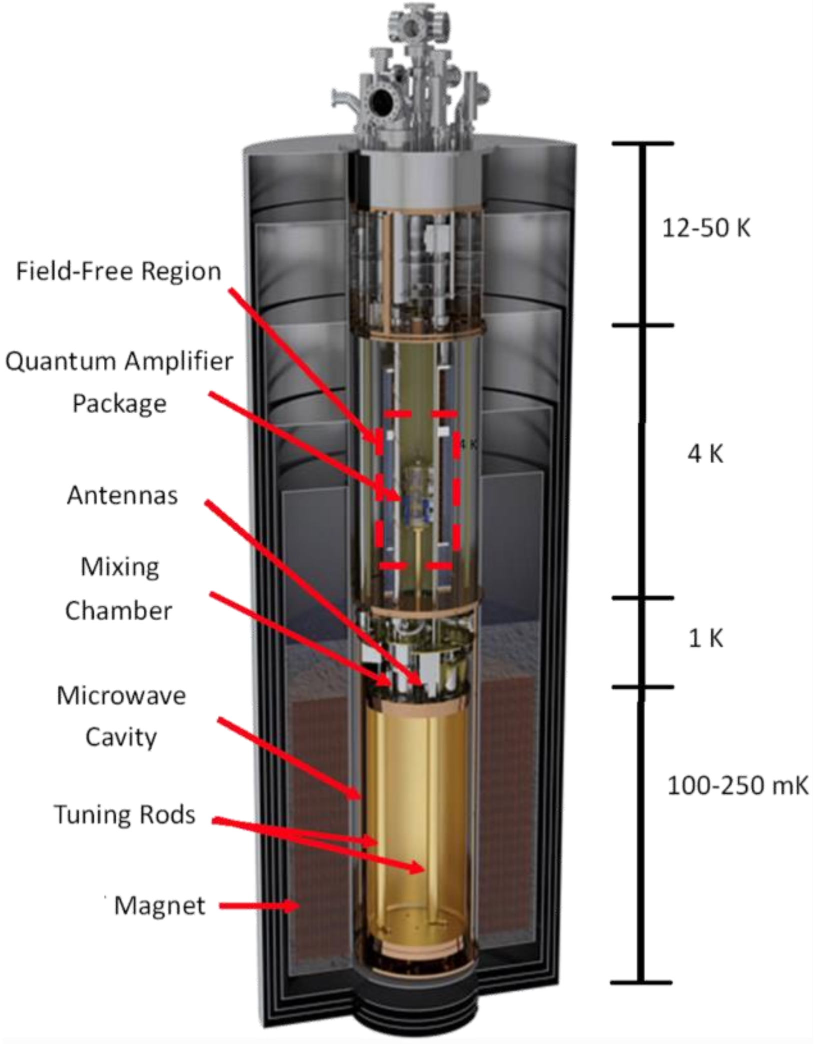
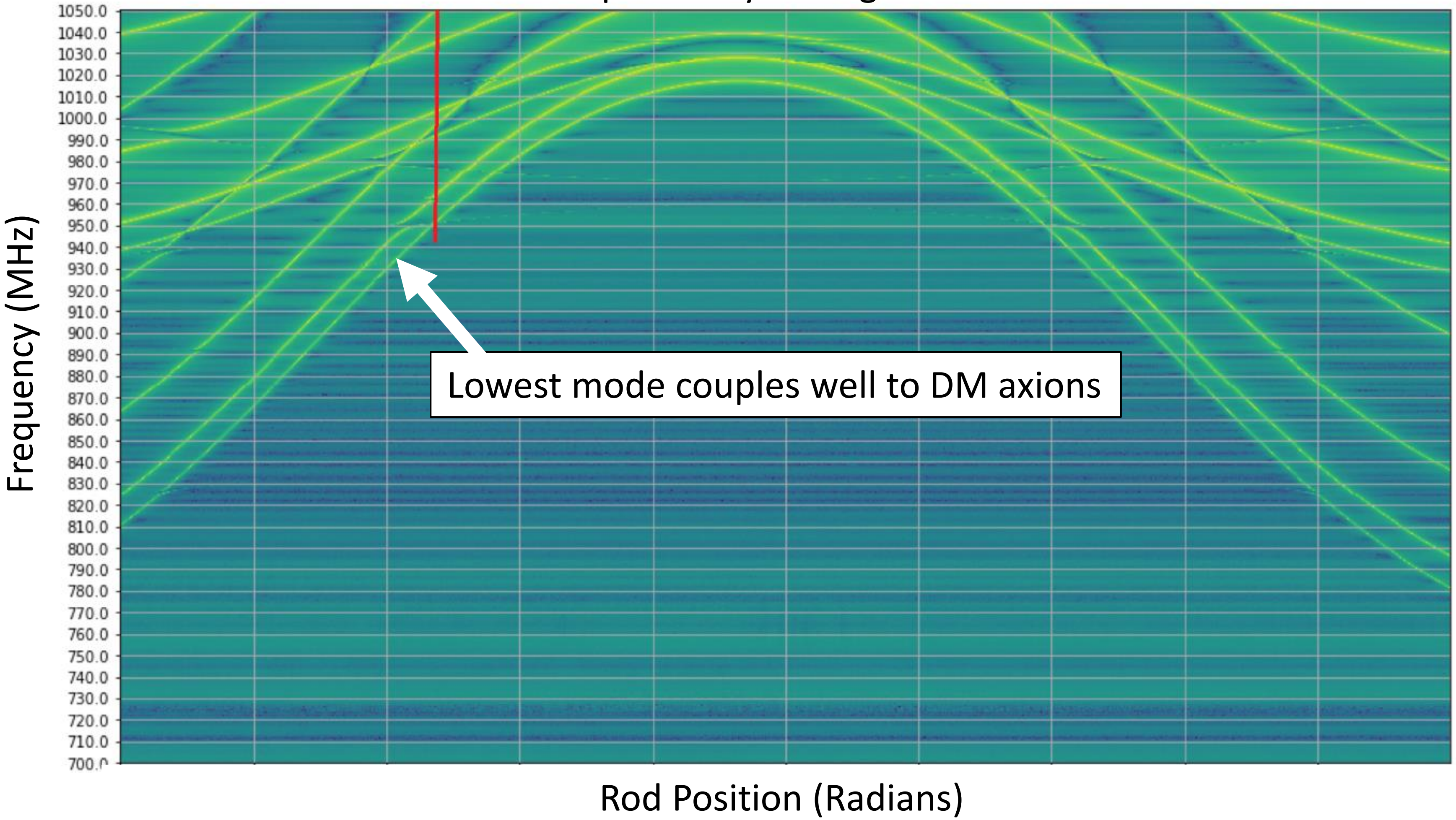
ADMX Design

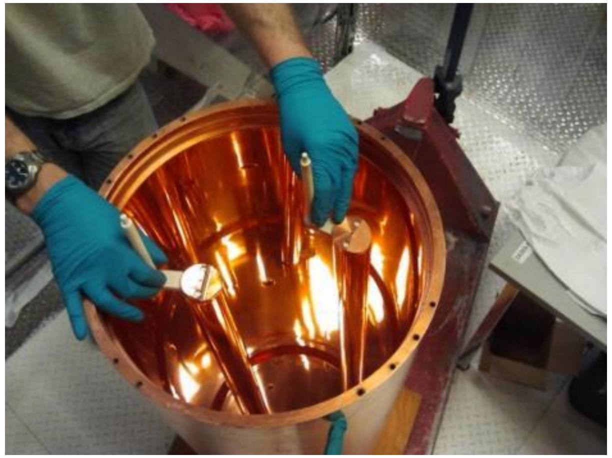

Field-Free Region
Quantum Amplifier Package
Antennas
Mixing Chamber
Microwave Cavity
Tuning Rods
Magnet
12-50 K
4 K
1 K
100-250 mK

Tuning ADMX

Example Cavity Tuning Curve



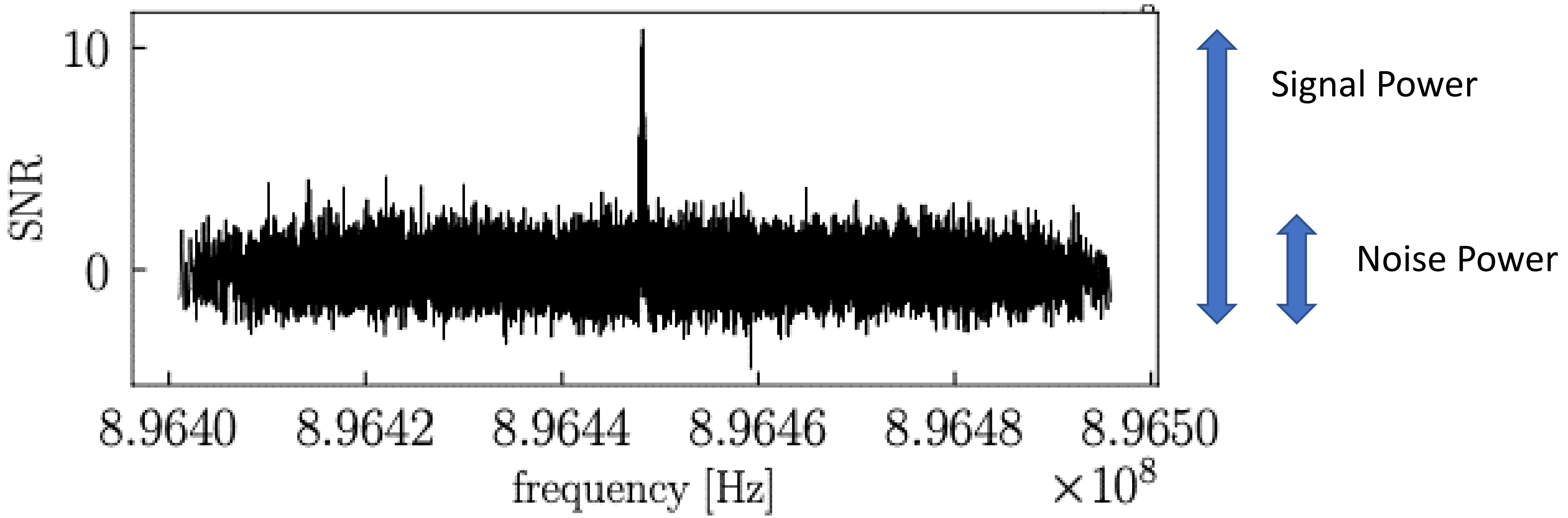
Tuning Rods within Cavity



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

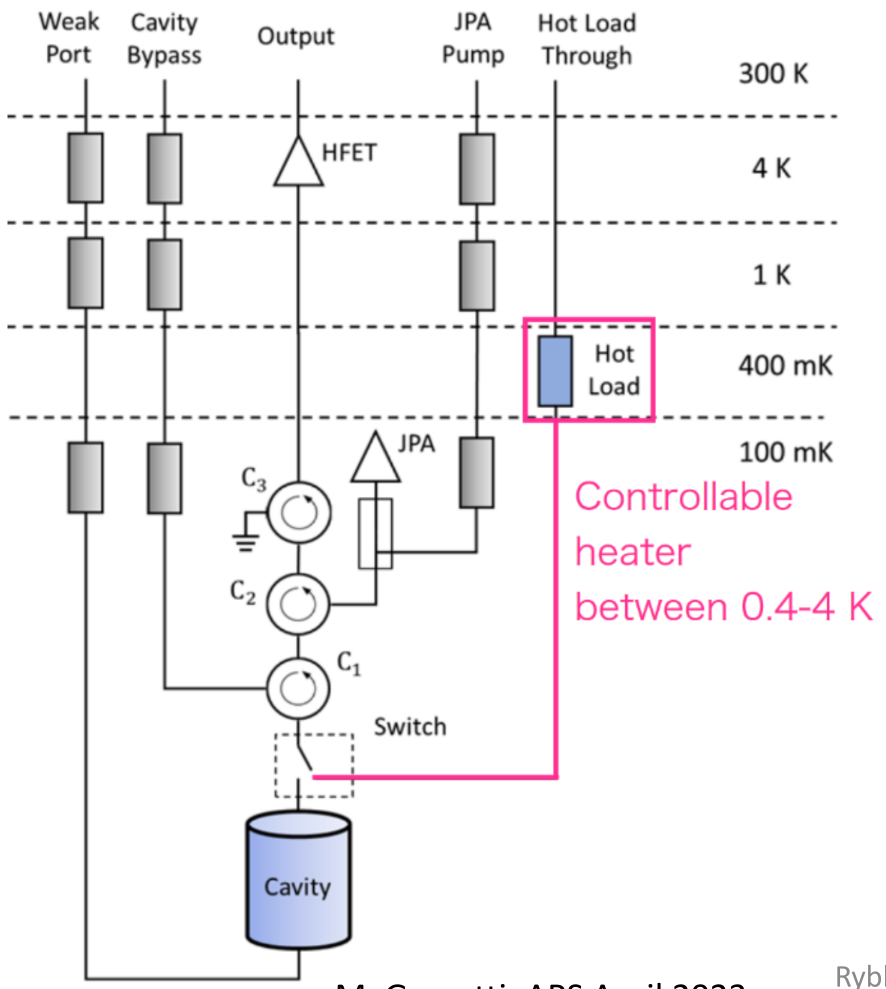


We need our noise to be much smaller than our signal to make a detection.

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

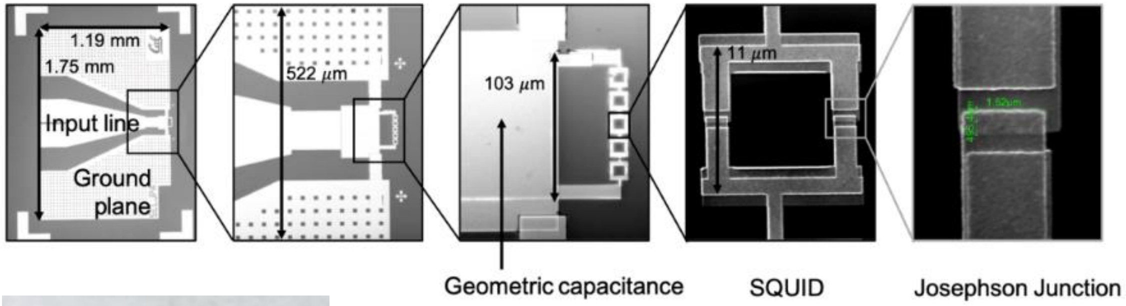
We must carefully calibrate the noise of our system – to understand our sensitivity, we must understand the temperatures of the components, the signal loss in the cables, and the performance of the amplifiers.

Minimizing Noise



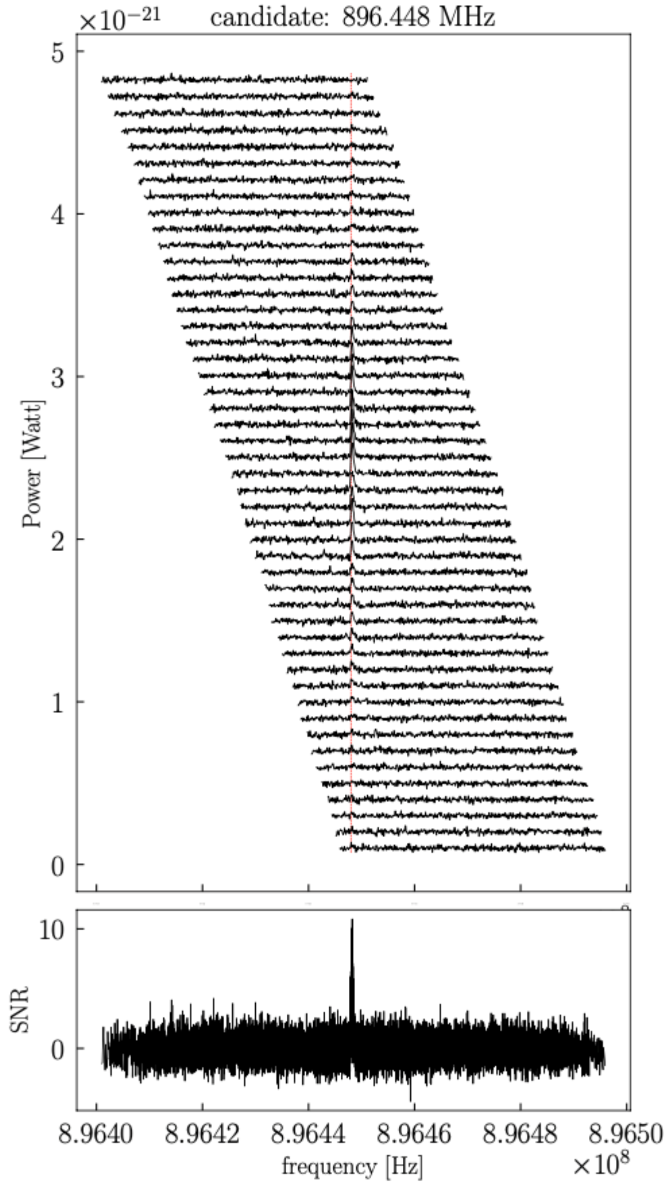
M. Guzzetti, APS April 2023

Noise is minimized by cooling to millikelvin temperatures and using superconducting amplifiers operating at or near the standard quantum limit



JPA provided by Siddiq Group at UC Berkeley

ADMX Operations

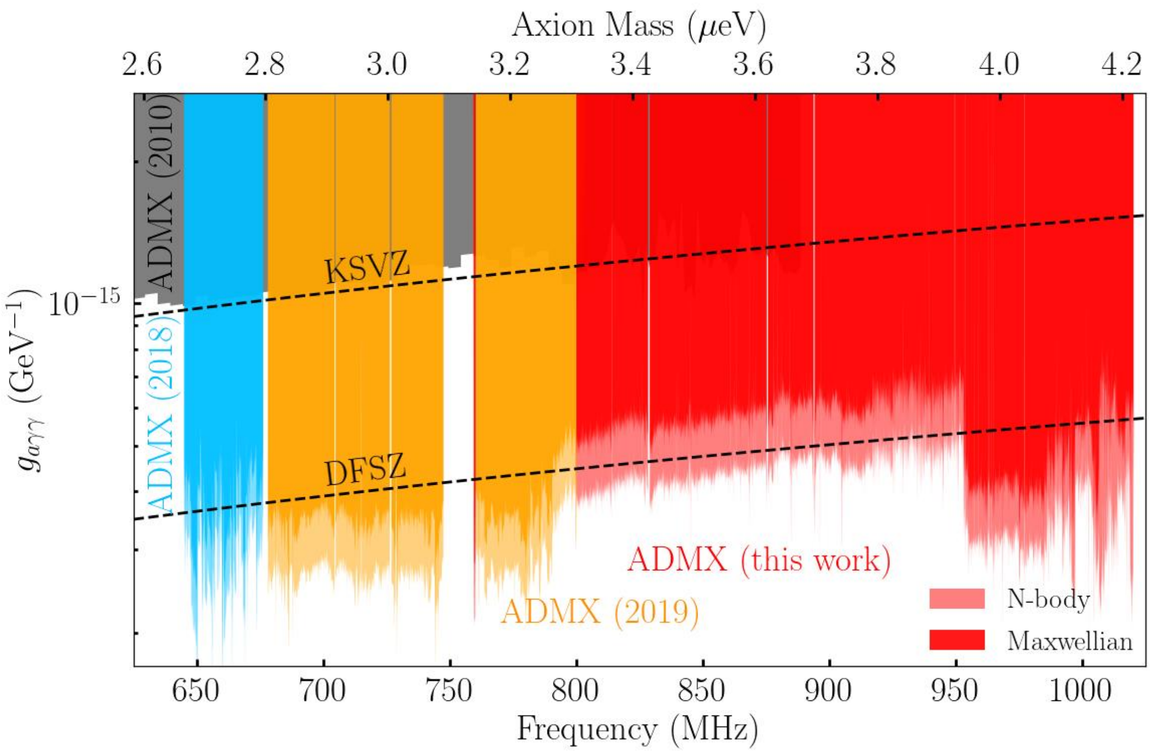


The cavity is tuned every 100 seconds, during which power spectra are taken. Overlapping power spectra are examined for the characteristic axion signal shape appearing on-resonance.

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

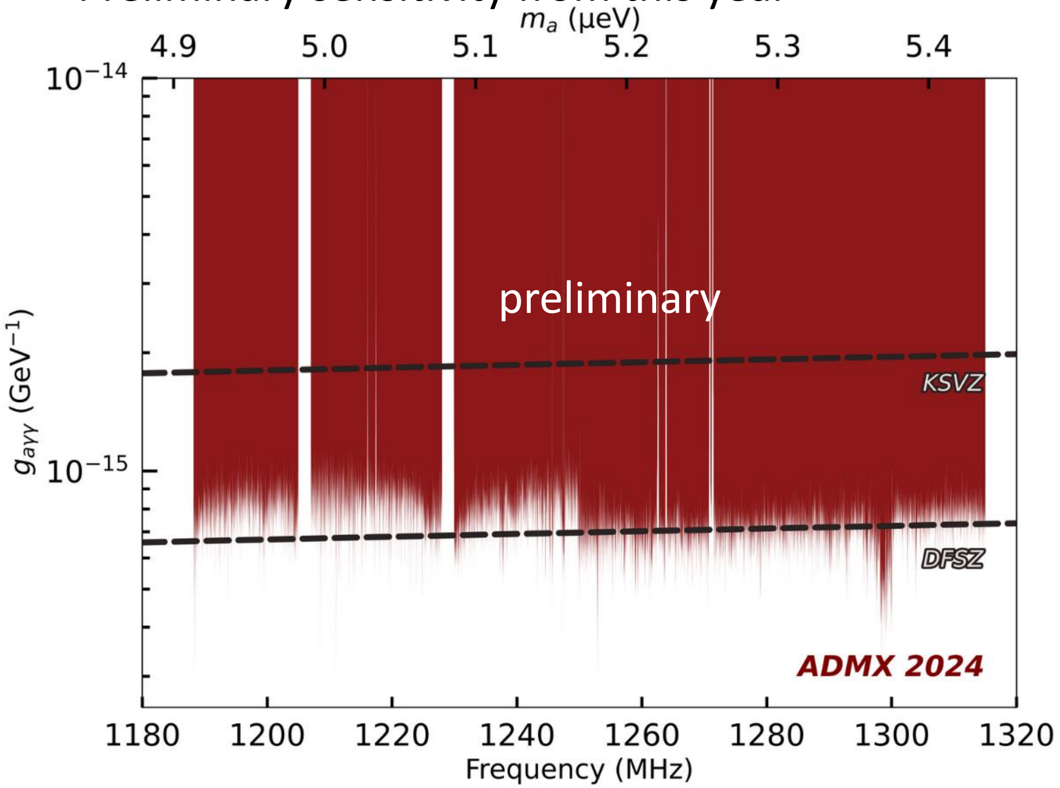
ADMX Recent Results

Excluded parameter space over the last 5 years



Bartram et al. PRL 127, 261803 (2021)

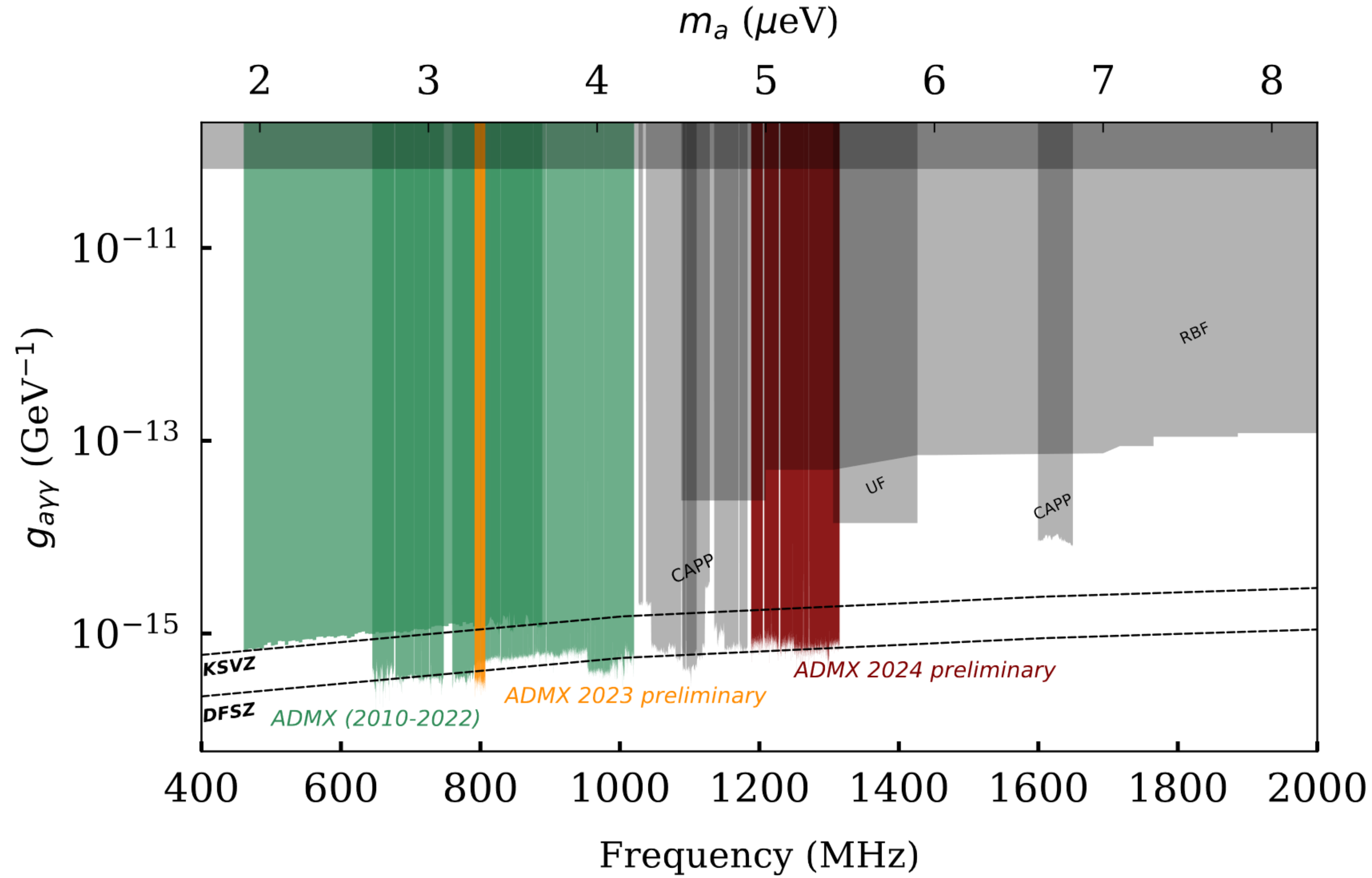
Preliminary sensitivity from this year



M. Guzzetti, Patras Workshop 2024

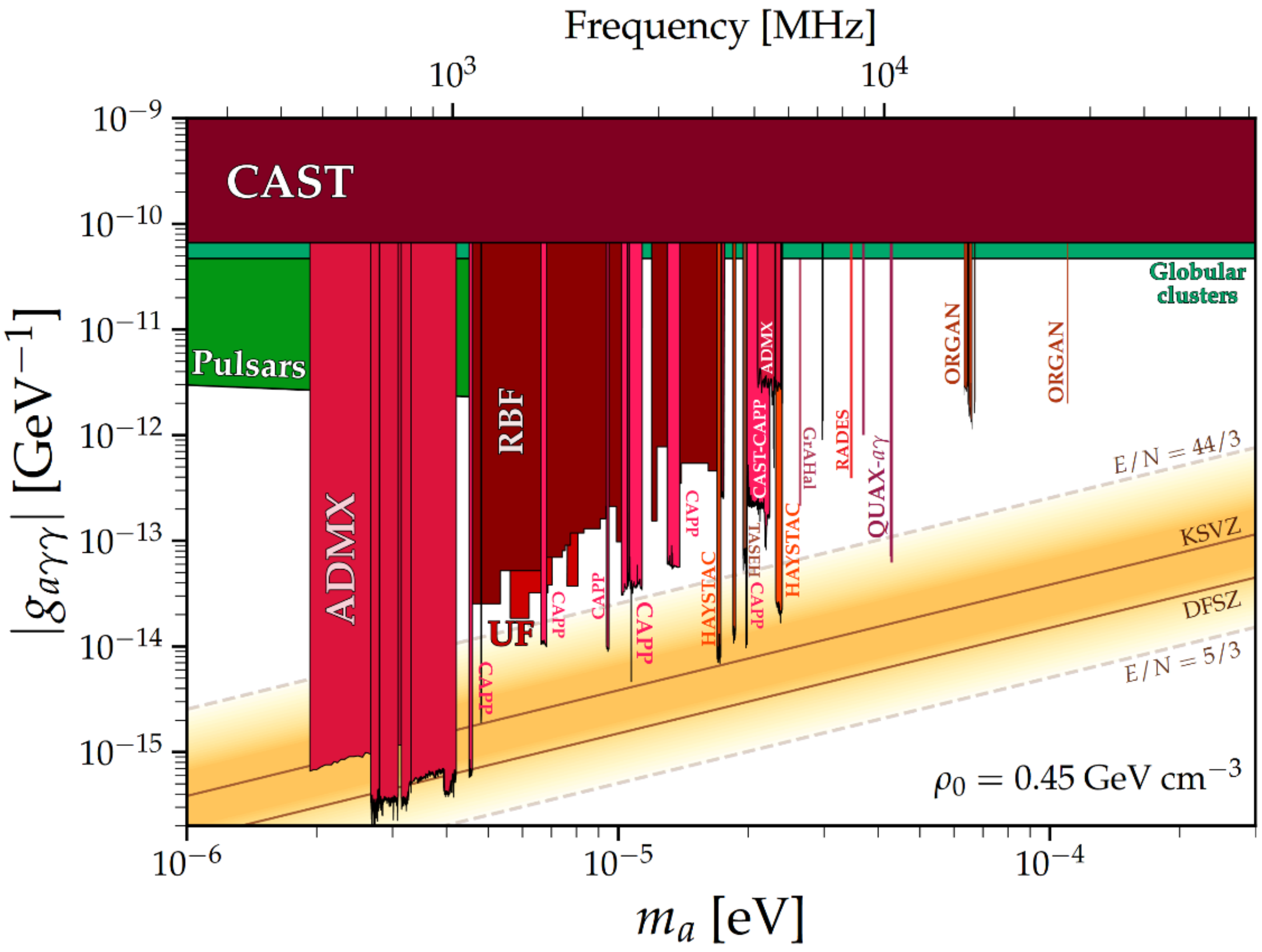
We are sensitive to DFSZ or near-DFSZ axions at nominal dark matter densities, and KSVZ axions at fractional dark matter densities.

ADMX Results in broader context



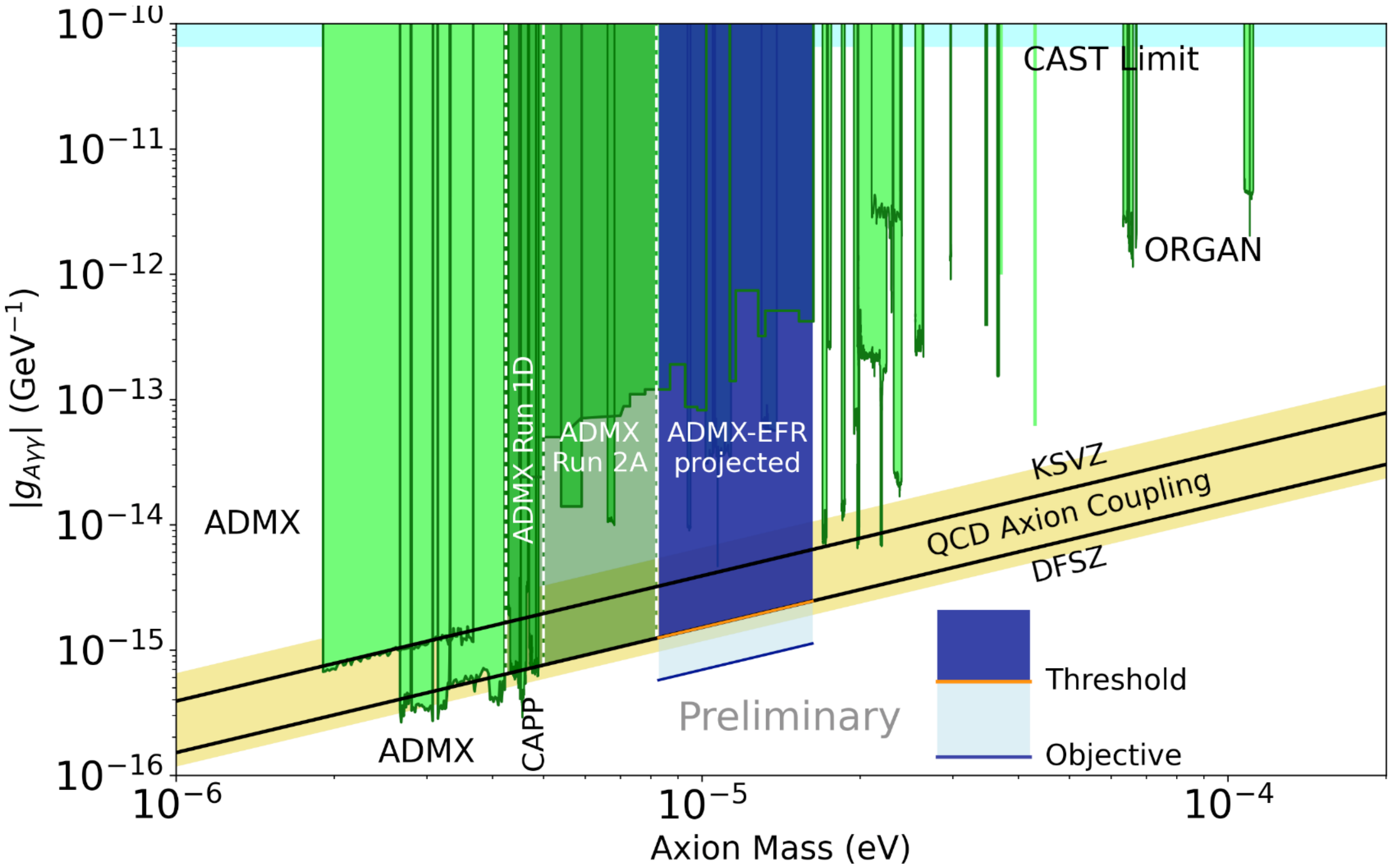
Other Operating Haloscopes

- 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!



ADMX: Future Plans

- Warning – from here on out, no plot is real! (they are projections)



ADMX EFR

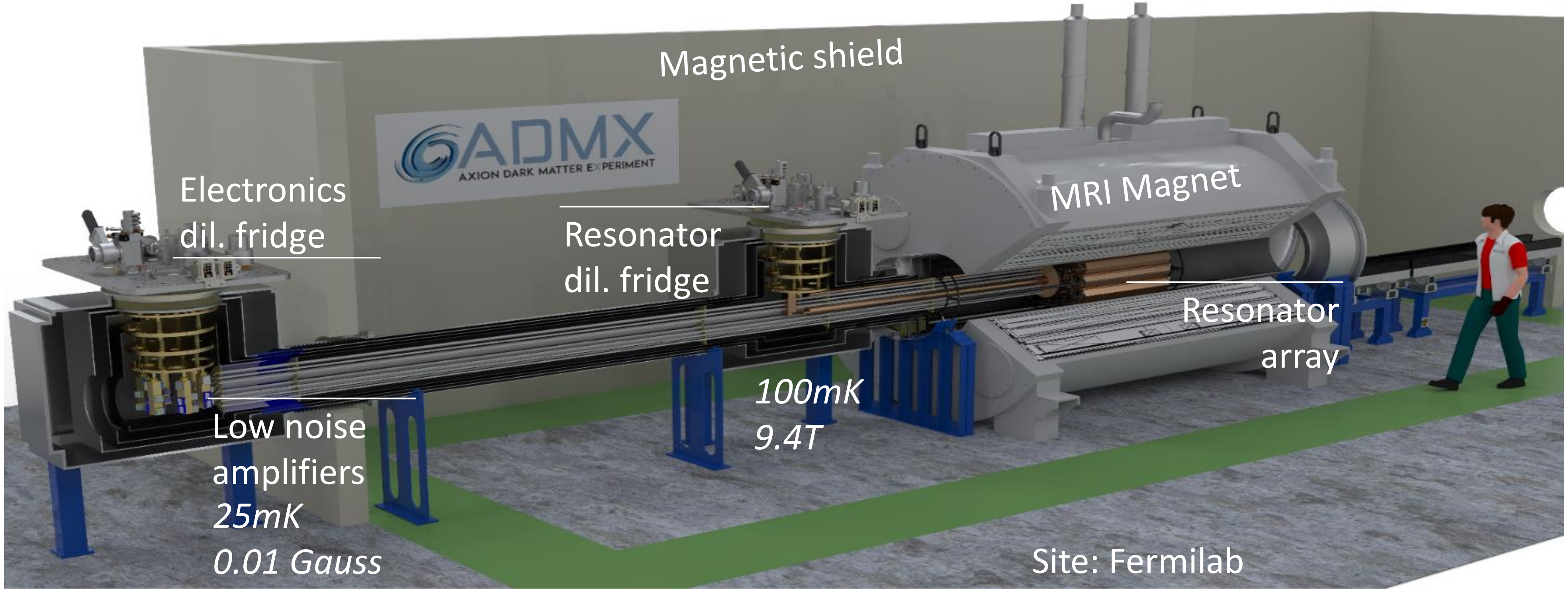
New Site

New Magnet

New Design

ADMX-EFR

- Incorporate technologies as they mature for a continuous scan sensitive to DFSZ axions at 2GHz and up
- Magnet is already deployed at Fermilab
- Opportunity for a “Dark Wave Laboratory”



The Future of Haloscopes

At higher frequencies, axion haloscopes suffer from unfavorable

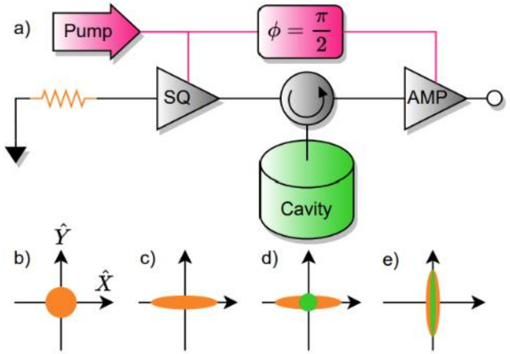
-Volume scaling
-Resonator Q scaling
-Standard Quartum Limit noise scaling

A thorough search up to 10 GHz+ will require

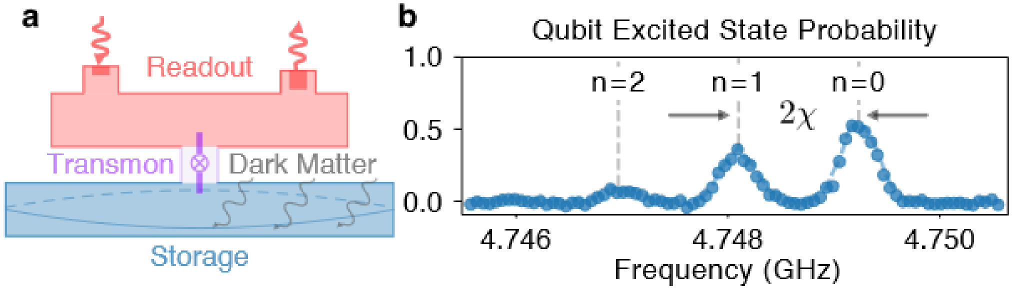
- Sophisticated, high-Q Resonators
  read out by
- Sub-quantum limit detectors
  inside of
- Large, high-field magnets
  located at
- Dedicated Facilities
  operated by
- Larger Collaborations

Exciting Emerging Haloscope Technologies

- Beyond SQL detectors.



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

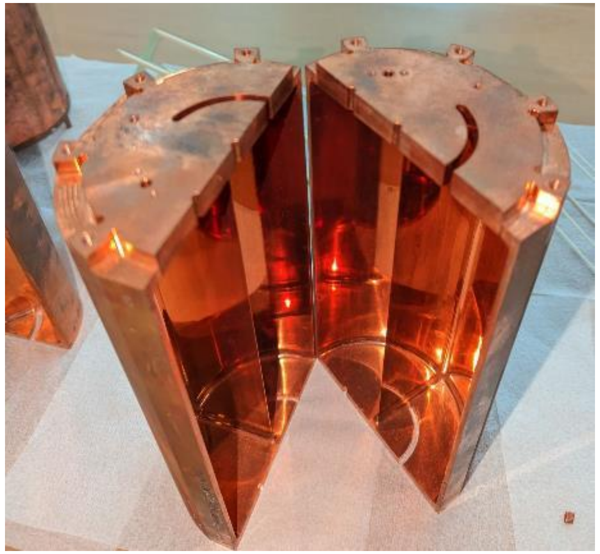


Qubit Based photon counting for sensitivity below the standard quantum limit (A. Dixit, PRL 126, 141302 (2021))

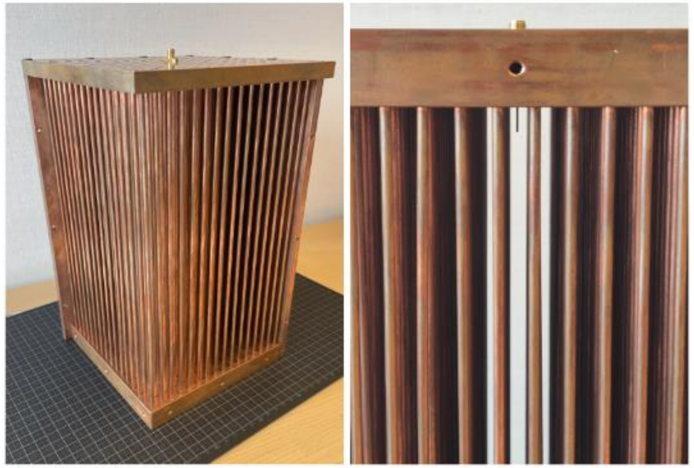
See also: CEASEFIRE – Wurtz et al. PRX 2,040350 (2021)
RAY – R. Maruyama, Patras 2024

Exciting Emerging Haloscope Technologies

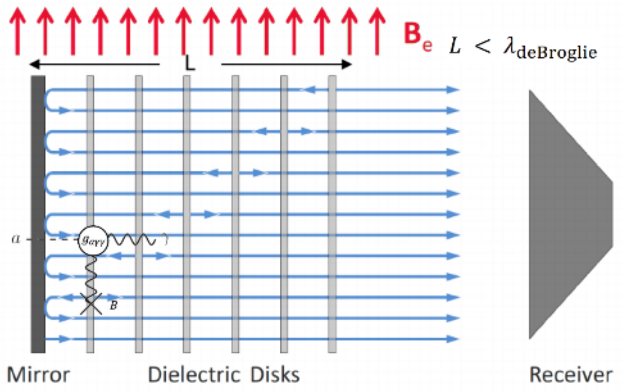
- Dividing single cavities or metamaterial structures captures similar volume gains to multiple cavities



"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)

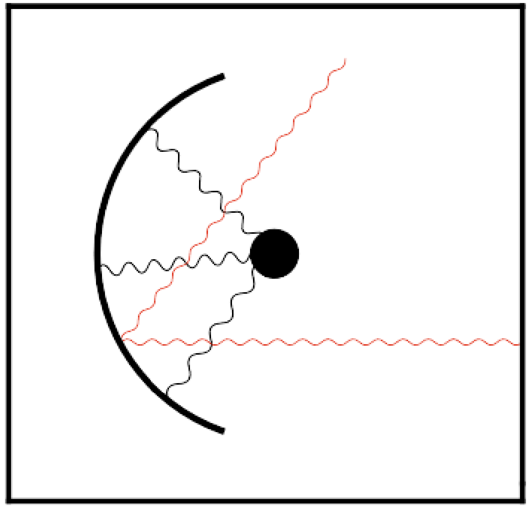


MADMAX Design
E. Garutti, Patras 2023

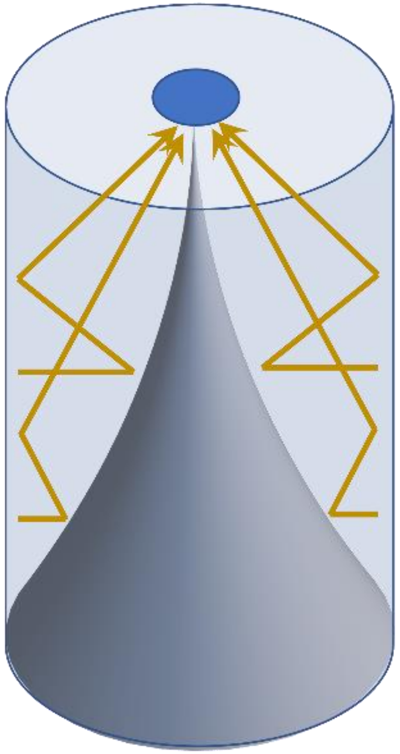
See also:
LAMPOST

Sophisticated Resonators – Nonresonant Systems

- Nonresonant systems sacrifice sensitivity for broad frequency coverage



Horns et al. JCAP04(2013)

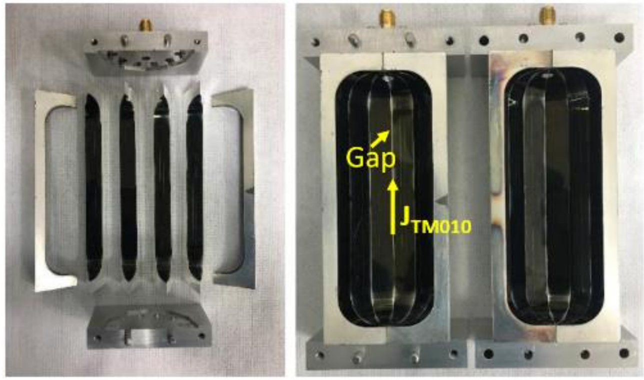


BREAD detector design
S. Knirck, Patras 2023

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, photo taken by me last Monday

Low-frequency resonators

- Non-cavity electromagnetic resonators can access lower masses

$$\nabla \times \mathbf{B}_r = \cancel{\frac{\partial \mathbf{E}_r}{\partial t}} + \underbrace{g_{a\gamma\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}}_{\mathbf{J}_{\text{eff}}}$$

Quasistatic regime: $\lambda_{\text{Comp}} \gg R_{\text{exp}}$

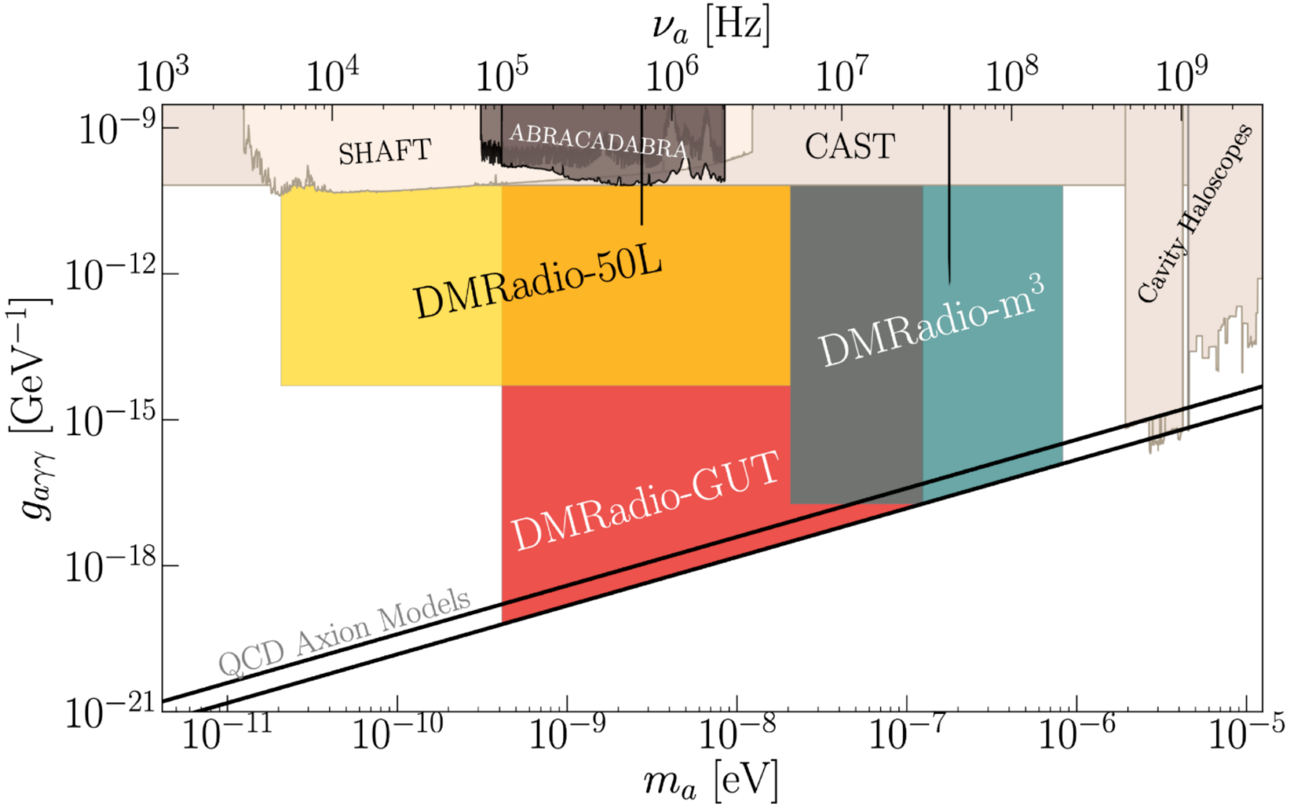
Below 1 ueV

$$\underbrace{\nabla \times \mathbf{B}_r} = \frac{\partial \mathbf{E}_r}{\partial t} + g_{a\gamma\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}$$

Cavity regime: $\lambda_{\text{Comp}} \sim R_{\text{exp}}$

1 ueV – 1 meV

Example:
ABRACADBRA – completed
SHAFT - completed
DMRadio – in preparation
(Brouwer et al. PRD 106 (2022))



DMRadio long-term sensitivity targets

Axion Electron/Nucleon Coupling Experiments

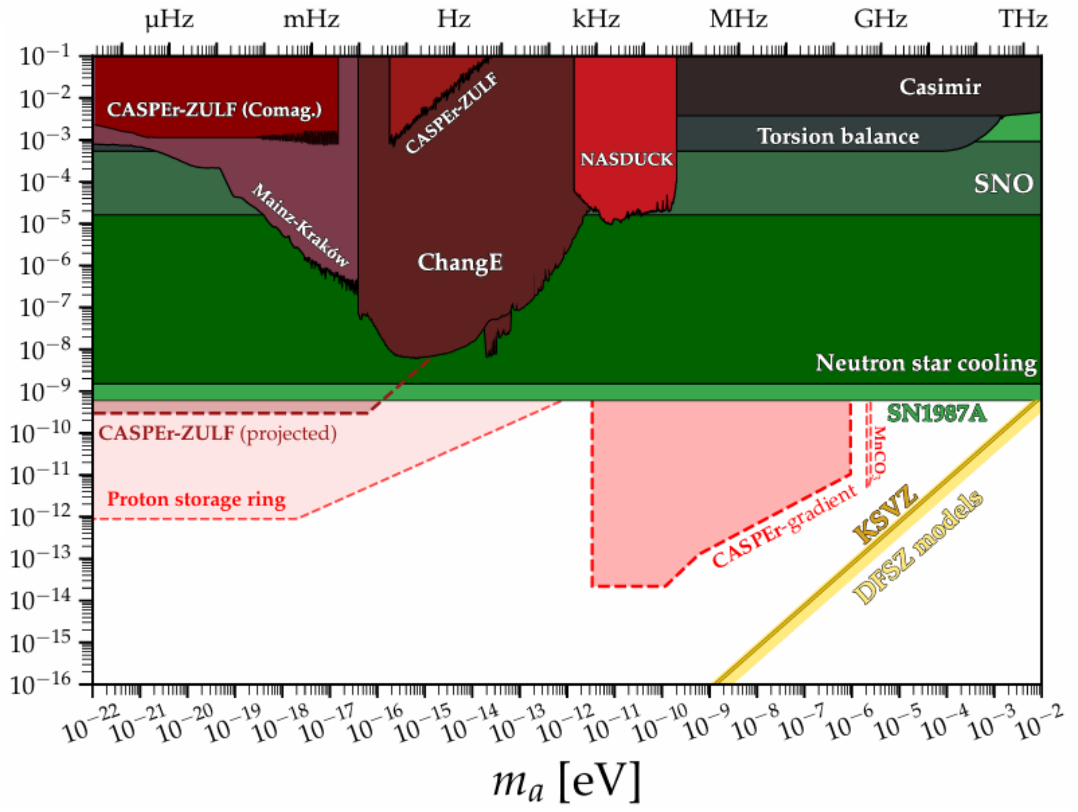
$$\mathcal{L} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{i}{2} g_d a \bar{N}\sigma_{\mu\nu}\gamma_5 N F_{\mu\nu} + g_{aNN}(\partial_\mu)\bar{N}\gamma^\mu\gamma_5 N + g_{aee}(\partial_\mu)\bar{e}\gamma^\mu\gamma_5 e$$

Coupling to Photons

Coupling to Nucleon EDM

Coupling to Axial Nuclear Moment

Coupling to Axial Electron Moment



These lead to NMR-style effects that can be targeted by experiments.

Example: Some future projections of the CASPER group for axion-nucleon couplings (M. Unni – Patras 2024)

There are subtle differences between electron/nucleon/dipole moment coupling to axion field magnitude or gradients. They are all model dependent.

Experiments have many orders of magnitude to go, but are making good progress.

Conclusions

- Much of the theoretically preferred ultralight dark matter is accessible experimentally (with enough work)
- Haloscopes (e.g., ADMX) are leading the way and could make a discovery at any time
- New technologies are enabling broader and more powerful searches, accelerating towards the goal of discovery