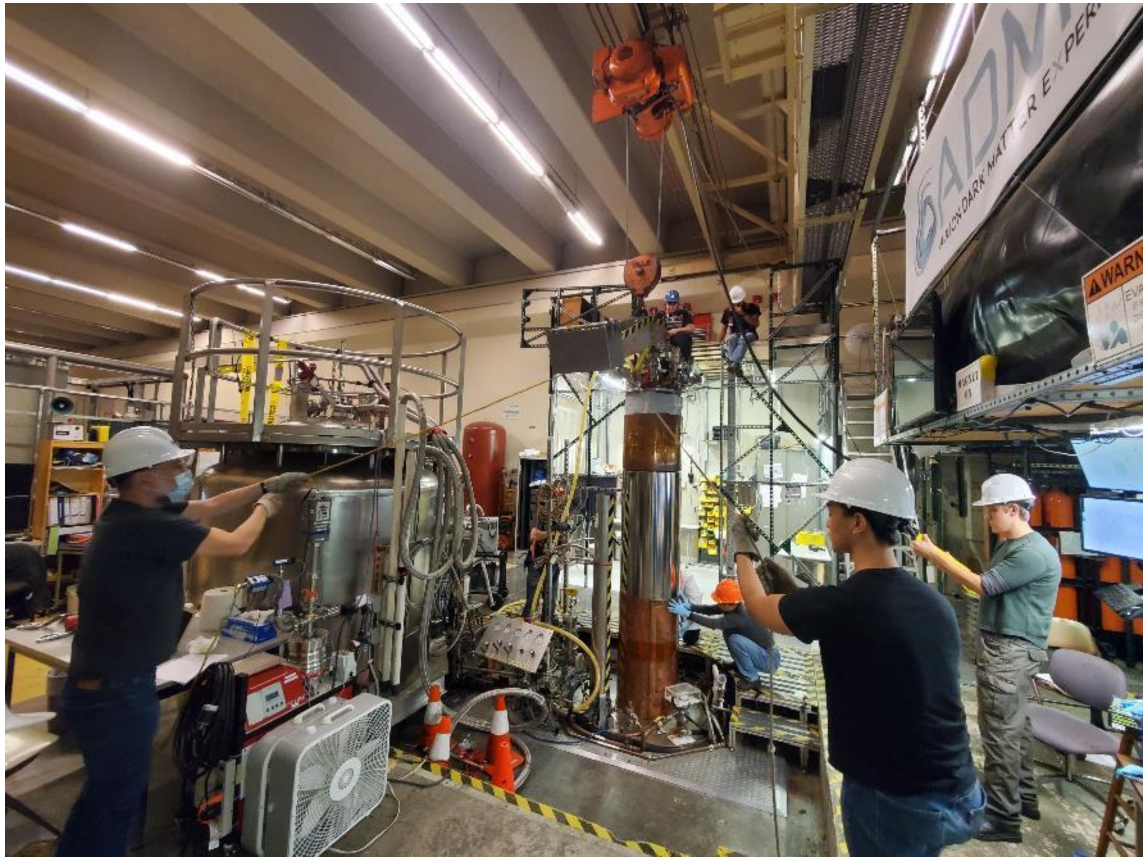
An Update on ADMX's axion dark matter search

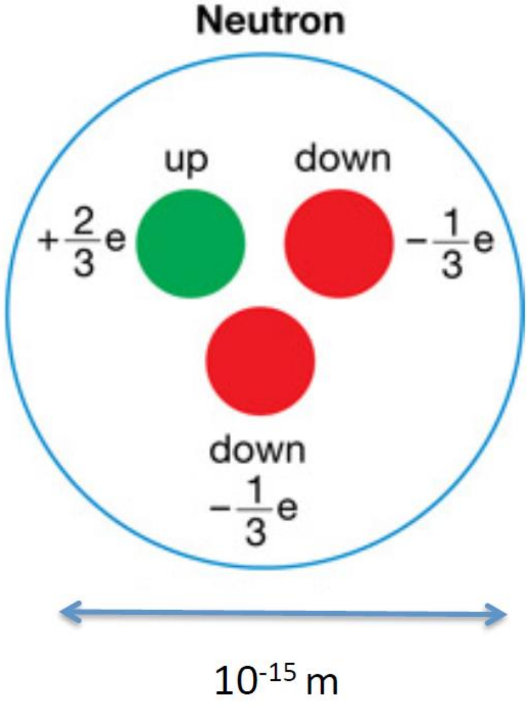


PPP15 2024
October 21
Taipei, Taiwan

Gray Rybka
University of Washington

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)*

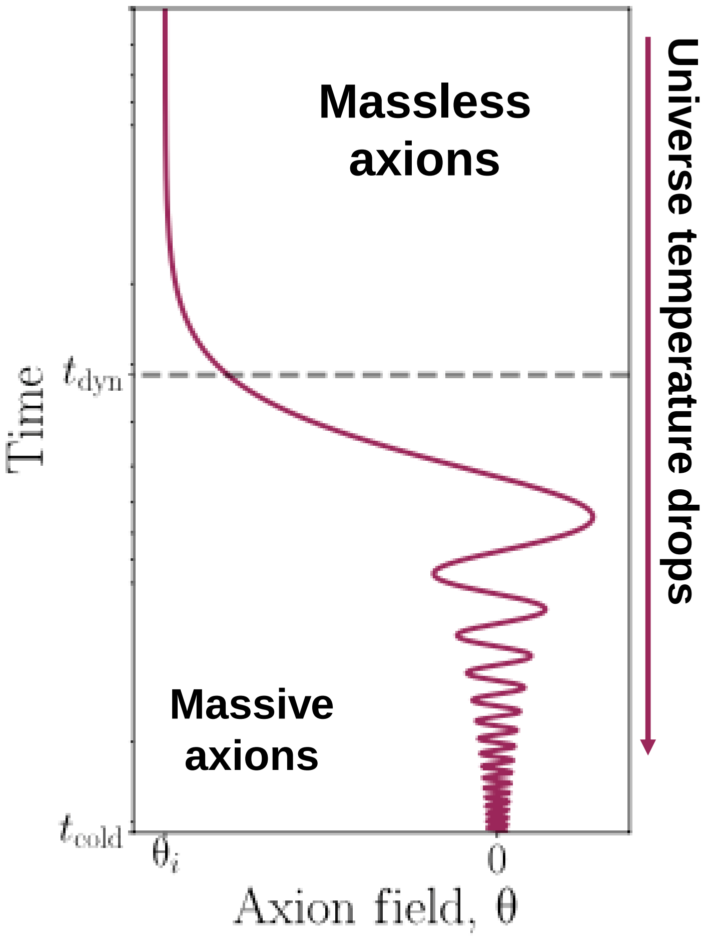


d = ~~10^{-16} e cm~~

$< 3\times10^{-26}$ e cm

Axions as Dark Matter

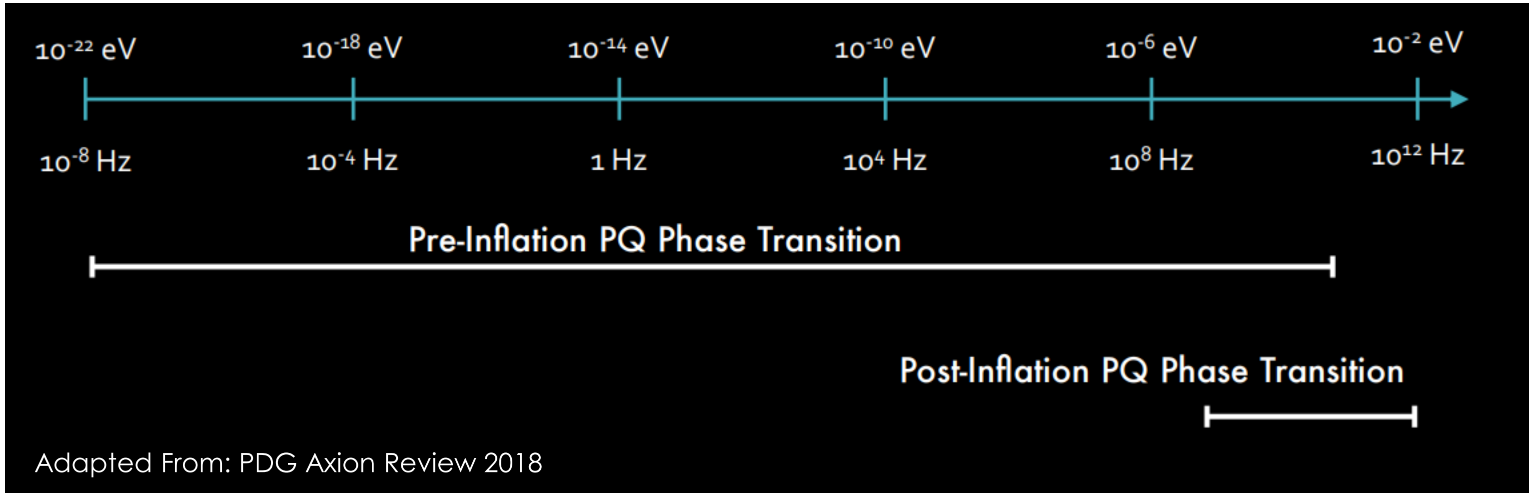
- Axions are produced athermally
  - Misalignment Mechanism – Phase transition in the early universe leaves energy in the axion field which behaves as dark matter
  - String/Defect Decay – Energy in topological defects radiates as cold axions
- In both cases axions are produced cold and in quantities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

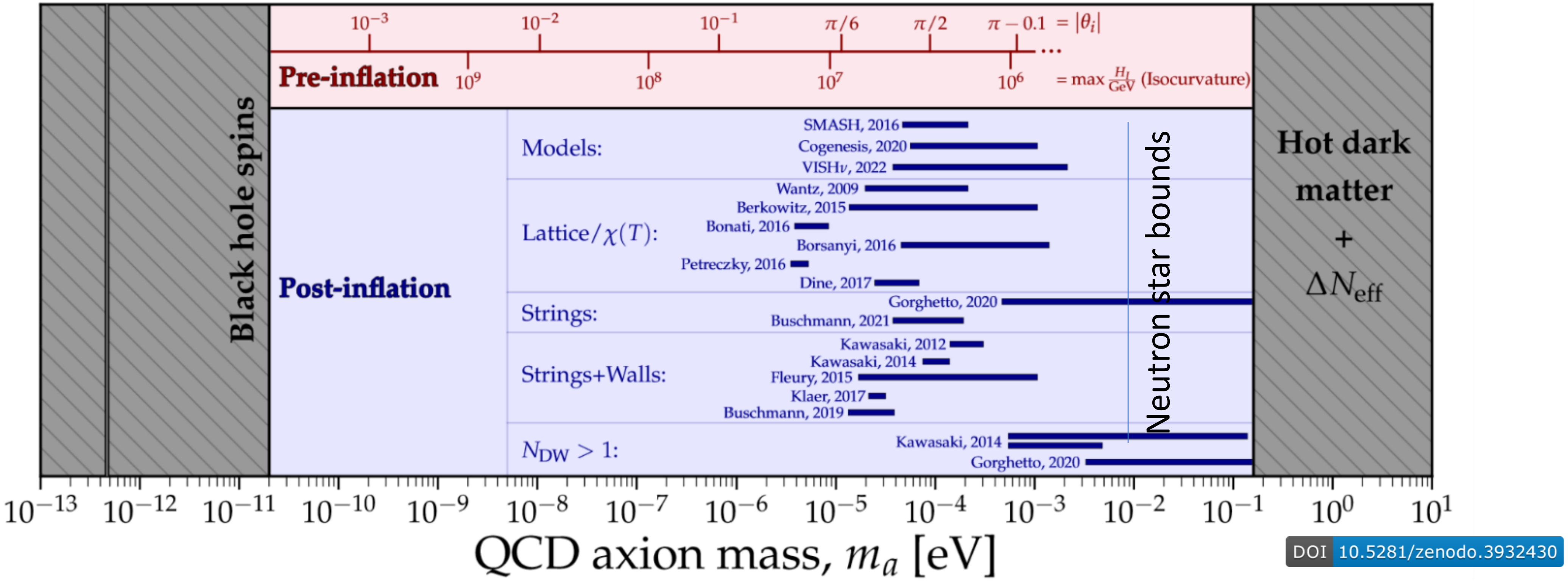
- In general, things that happen before the end of inflation could produce dark matter with any axion mass, but after inflation favors 1ueV and above



Adapted From: PDG Axion Review 2018

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

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

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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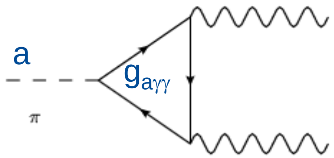


Coupling to Photons

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

Coupling to Nucleon EDM

Coupling to Axial Nuclear Moment

Promising experimental techniques under development

Coupling to Axial Electron Moment

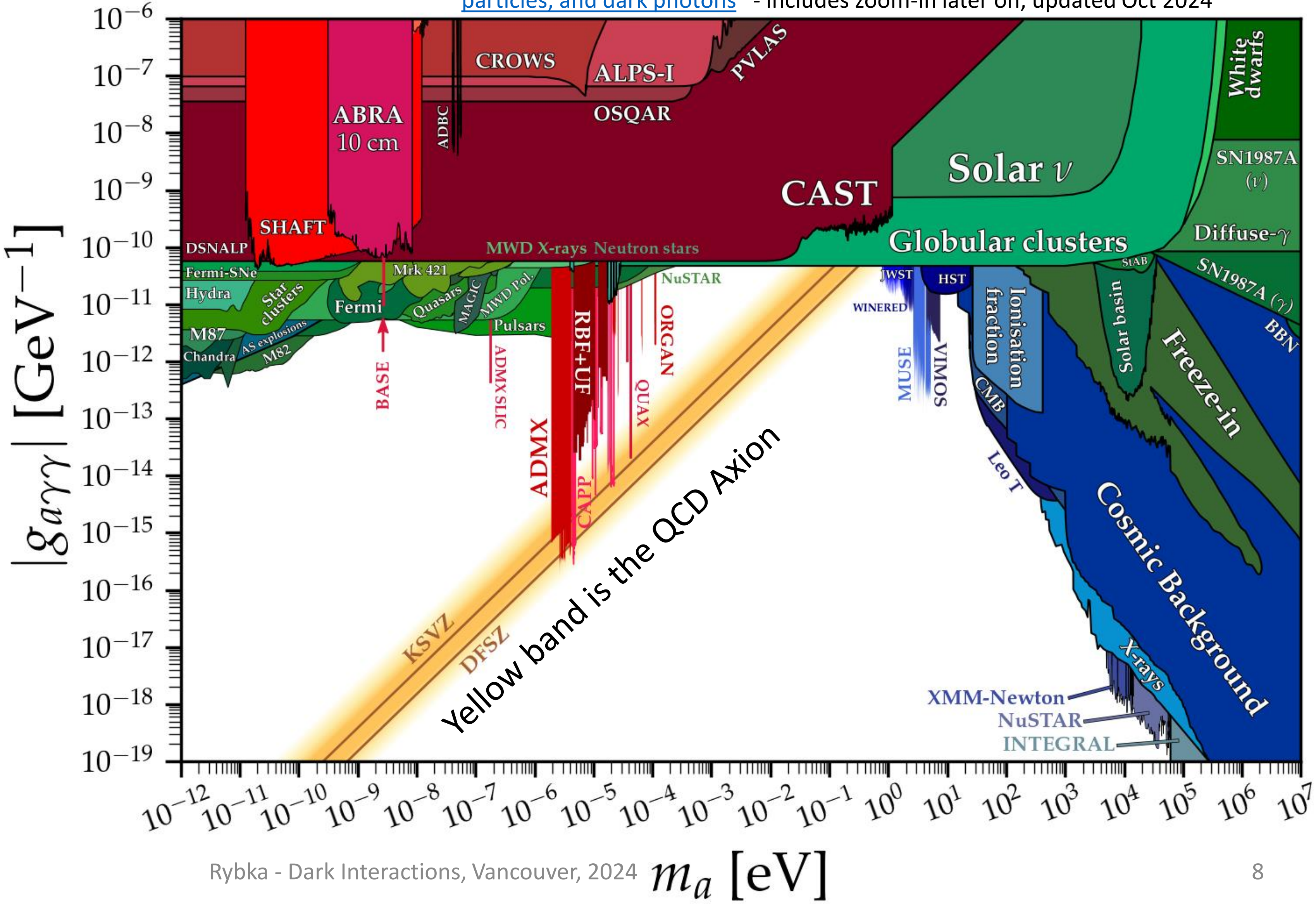
Adapted from Y. Kahn, See also Graham and Rajendran, Phys.Rev. D88 (2013) 035023

Axion Photon Bounds

[GitHub - cajohare/AxionLimits: Data, plots and code for constraints on axions, axion-like particles, and dark photons](https://github.com/cajohare/AxionLimits) - includes zoom-in later on, updated Oct 2024

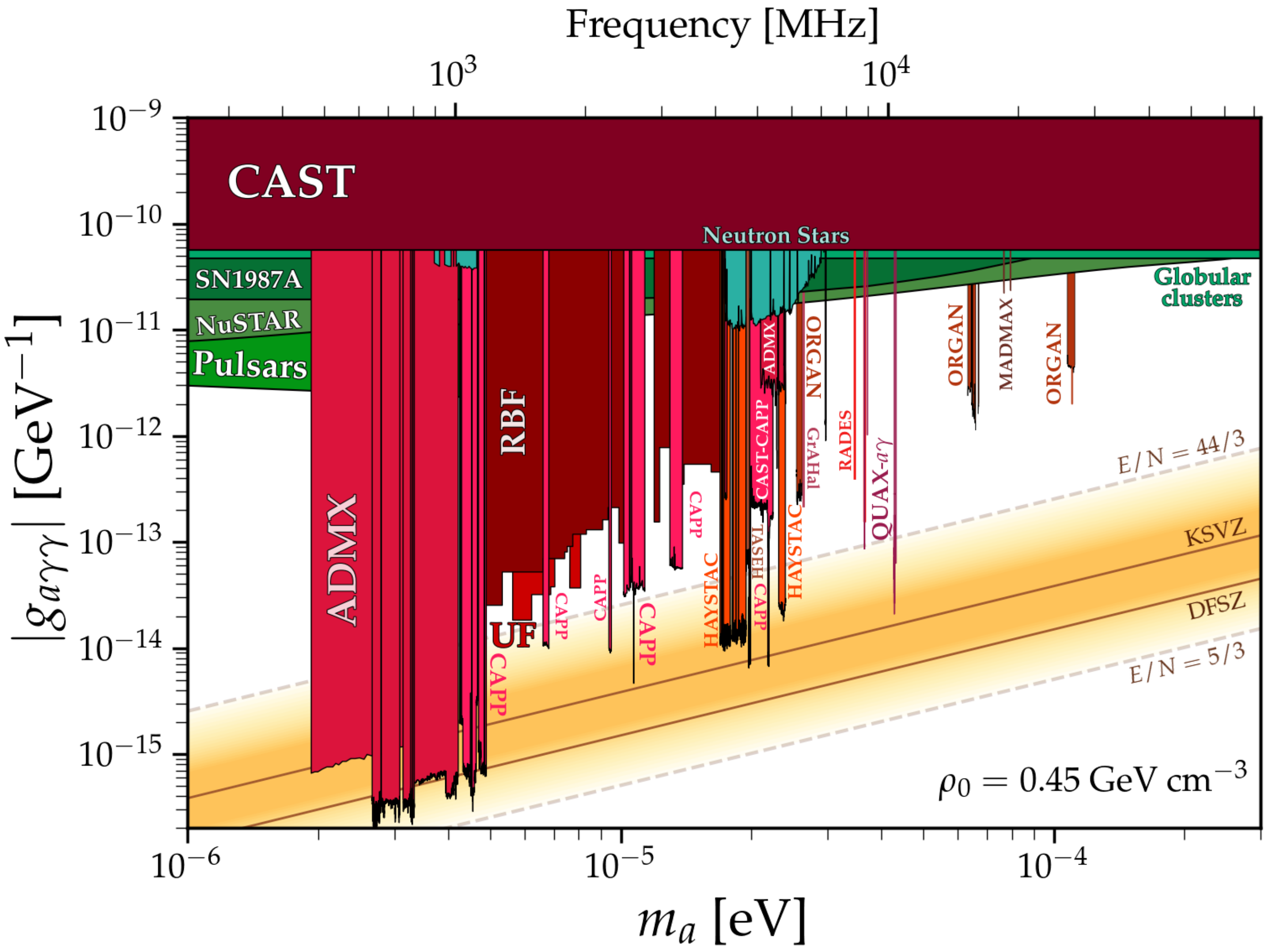
The yellow band is the QCD axion, white space is Axion-Like Particle (ALP) space

Note the significant astrophysical constraints on ALP parameters.

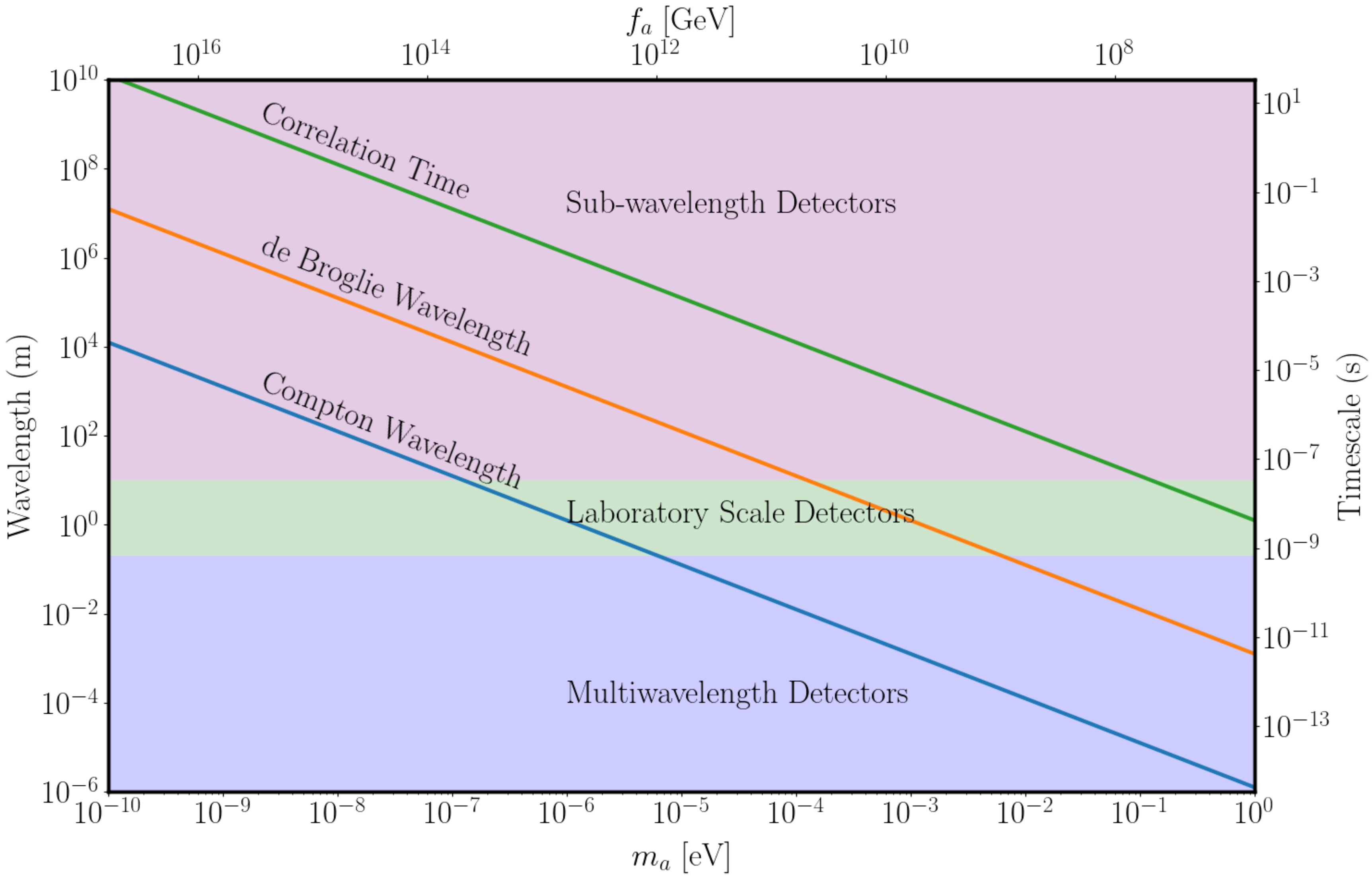


Axion Photon Bounds, Zoomed In

- KSVZ and DFSZ are benchmark axion coupling models.
- The class of experiments probing QCD axion parameters is the "Axion Haloscope"

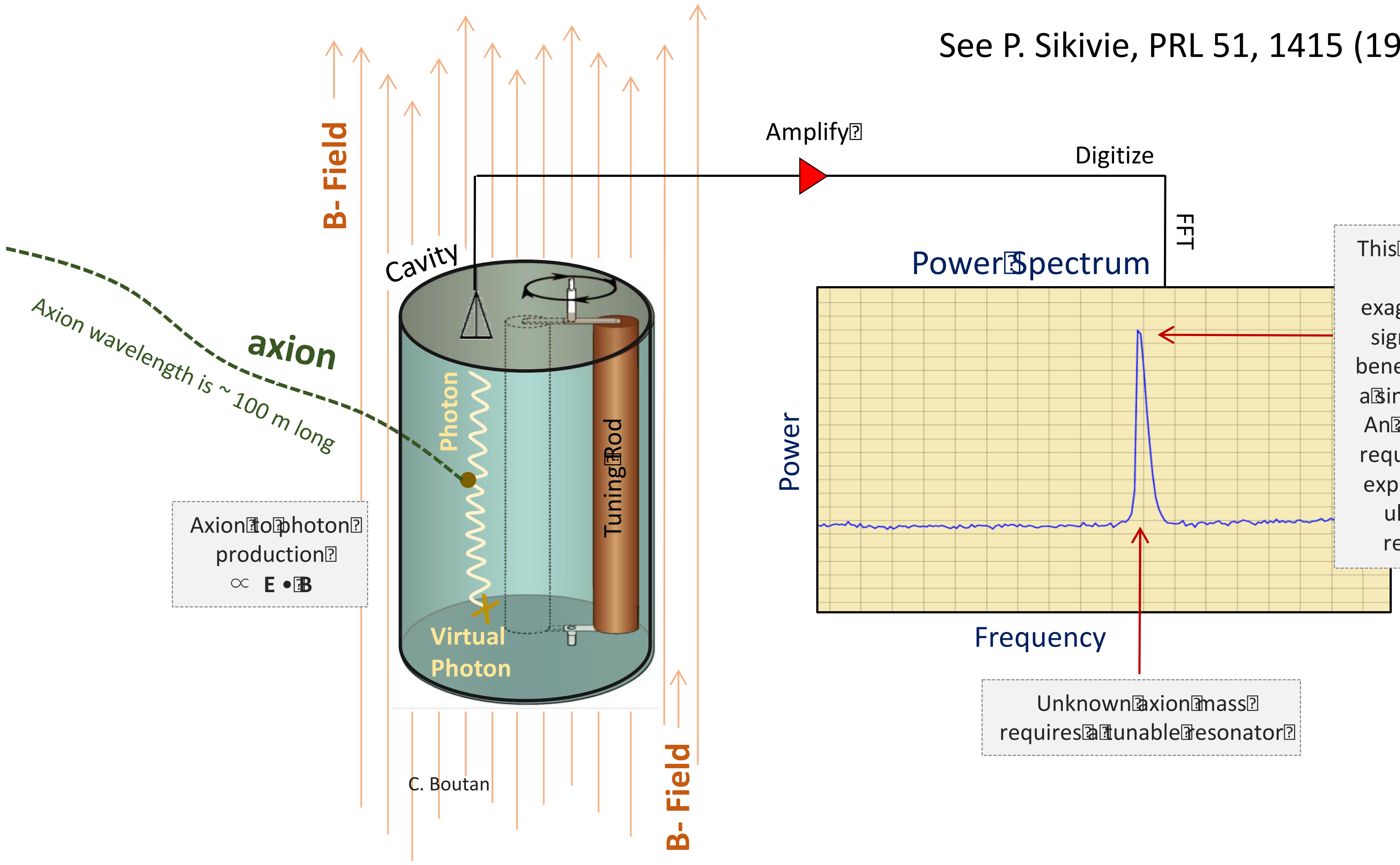


Axion Detector Length and Time Scales



Principle of the Sikivie Axion Haloscope

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



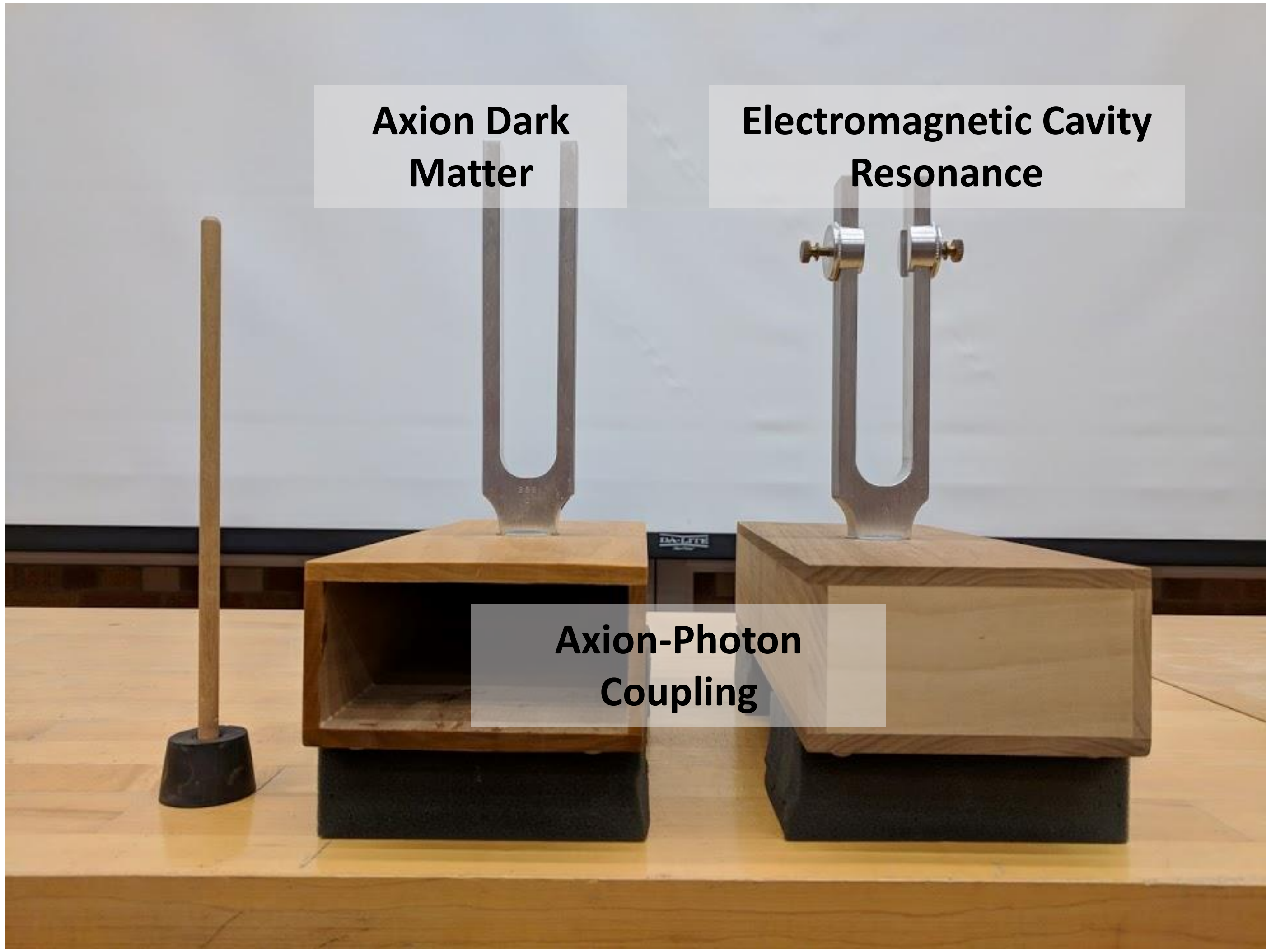
Axion to photon production $\propto$ **E • B**

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.

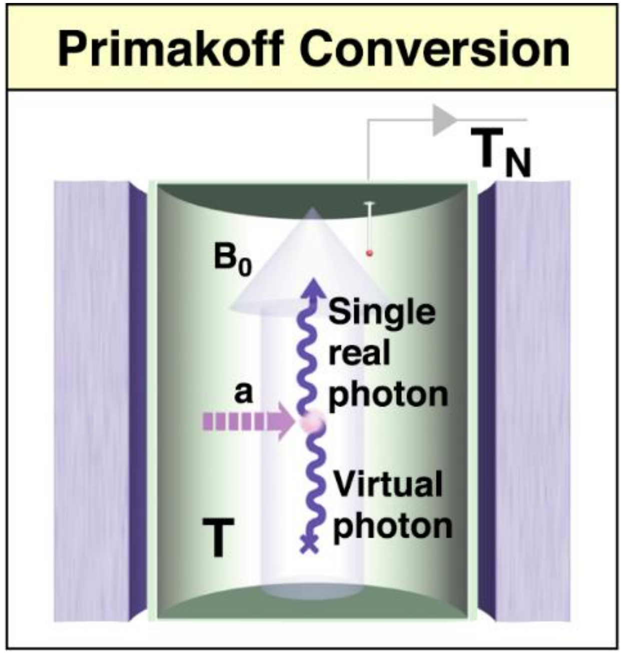
Unknown axion mass requires a tunable resonator

Axion Haloscope for my Intro Physics Class

Axion Haloscope for my Intro Physics Class



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	Noise Proportional to
Cavity Volume	Cavity Blackbody Radiation
Magnetic Field	Amplifier Noise
Cavity Q	

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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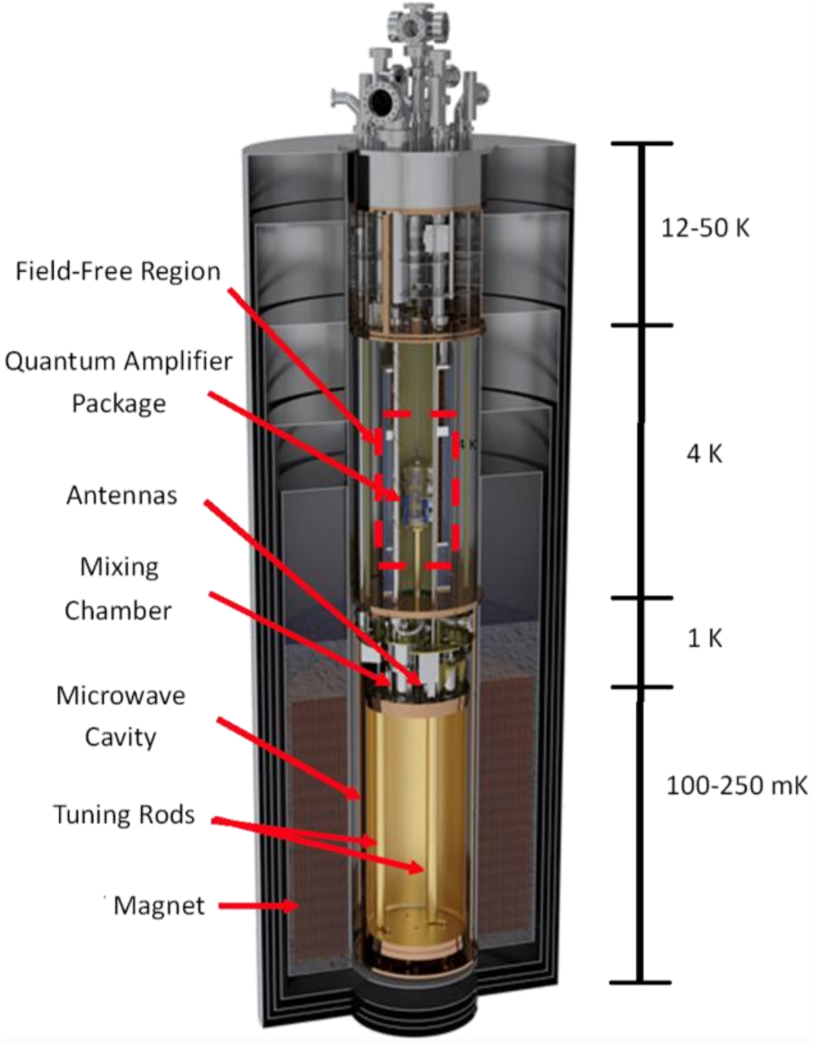
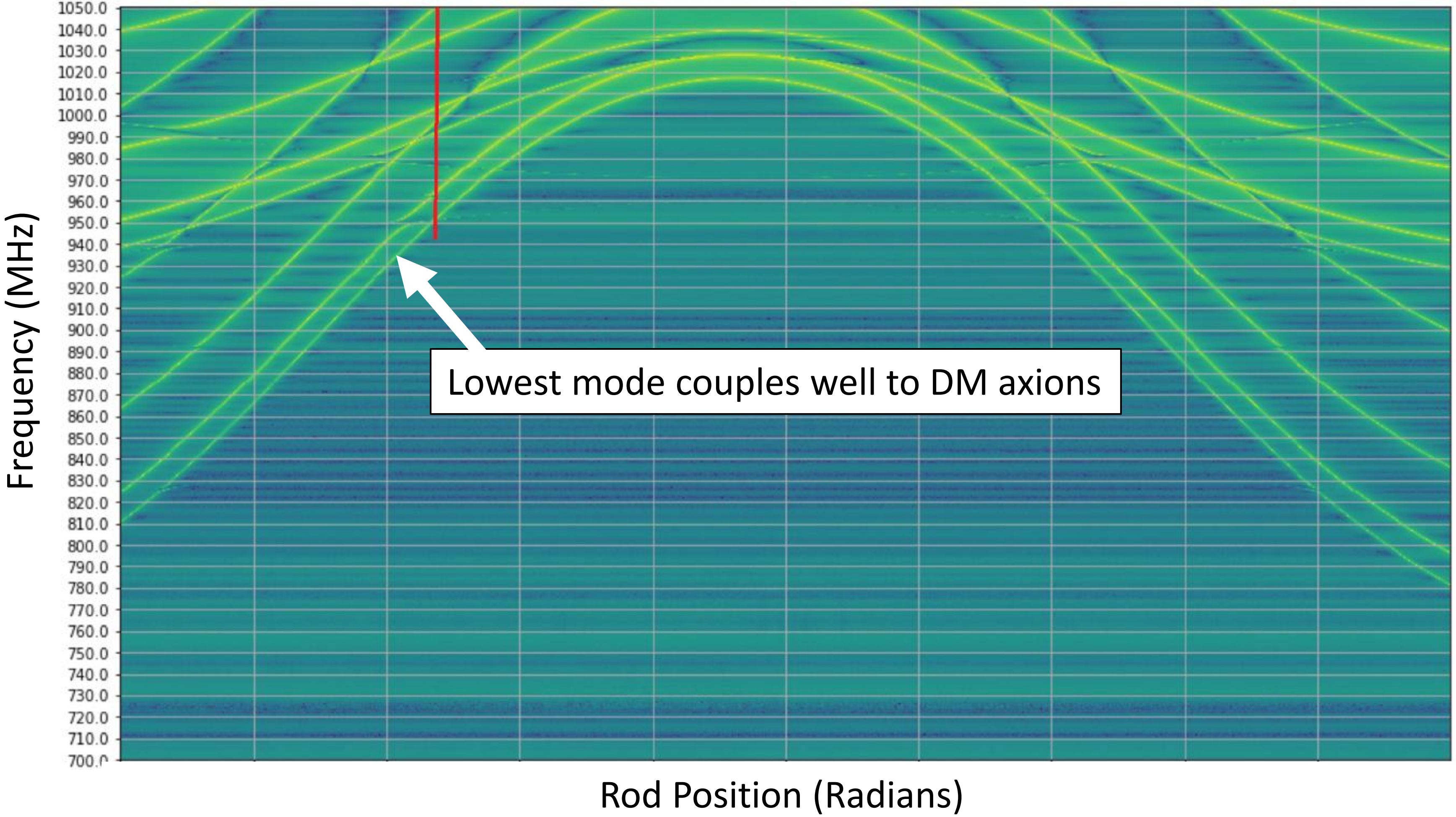
ADMX Design

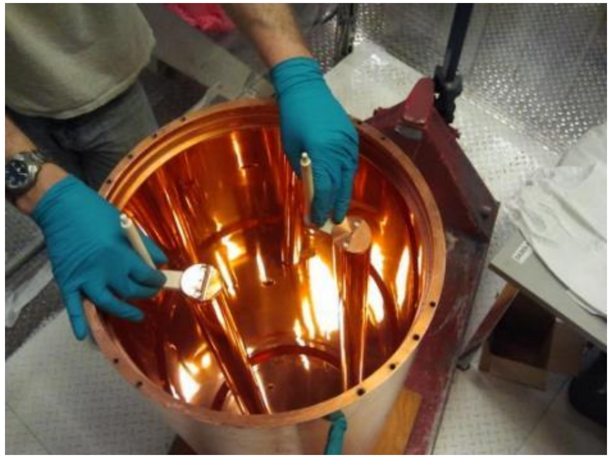

Field-Free Region
Quantum Amplifier Package
Antennas
Mixing Chamber
Microwave Cavity
Tuning Rods
Magnet
12-50 K
4 K
1 K
100-250 mK

Tuning ADMX


Example Cavity Tuning Curve

Lowest mode couples well to DM axions

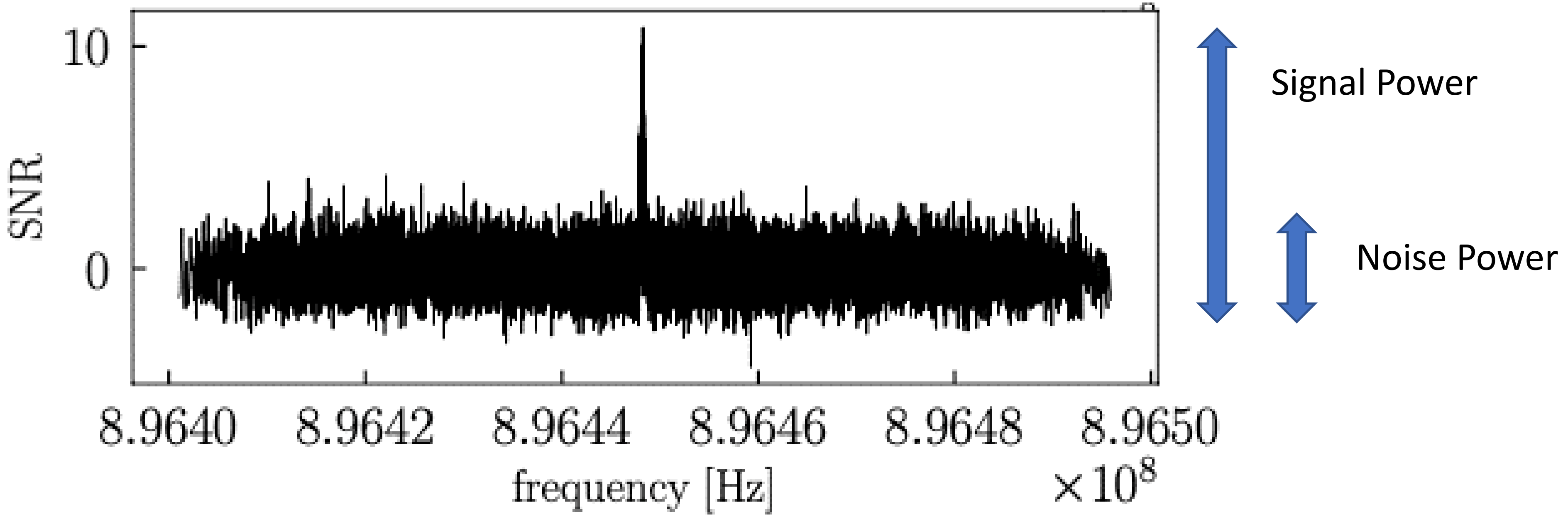
Tuning Rods within Cavity



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

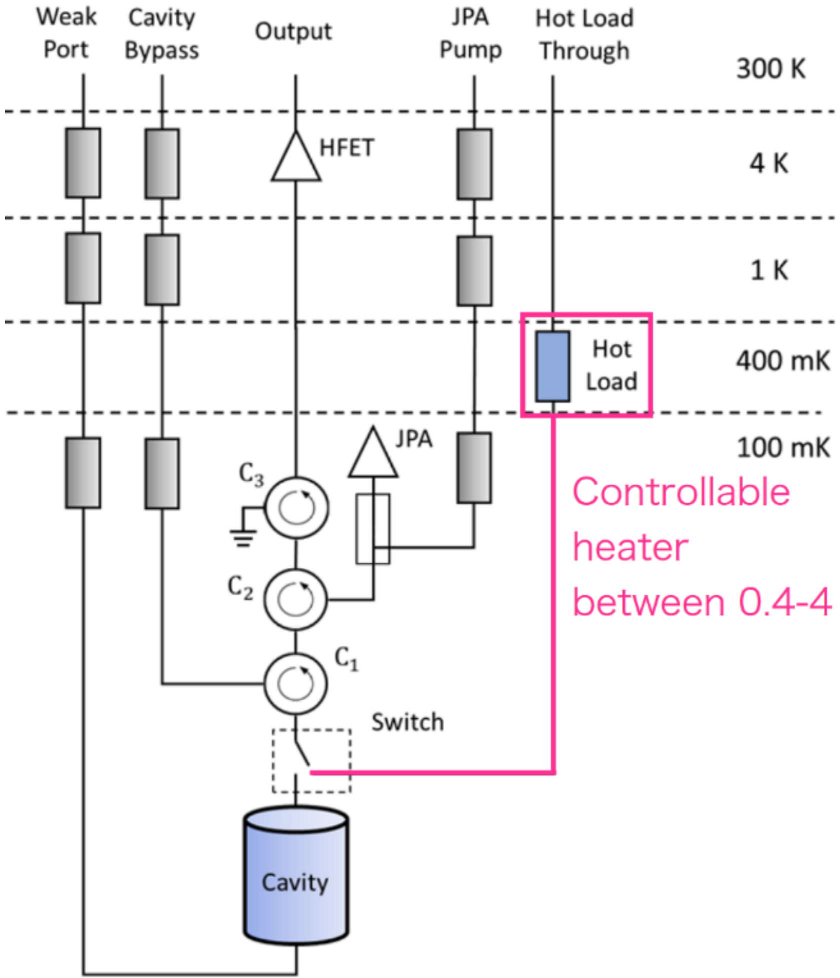


We need our noise to be much smaller than our signal to make a detection.

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.

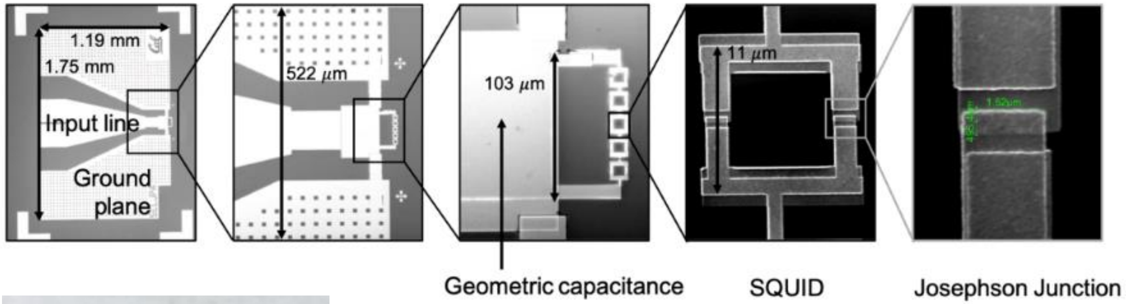
Minimizing Noise



Controllable heater between 0.4-4 K

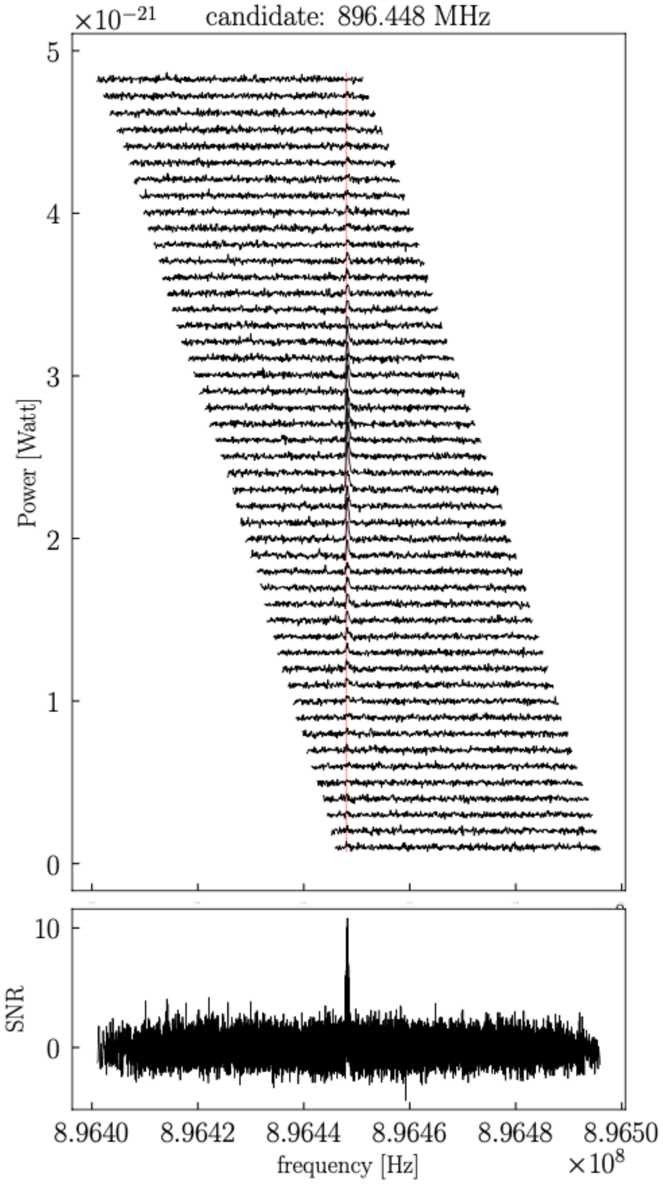
M. Guzzetti, APS April 2023

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

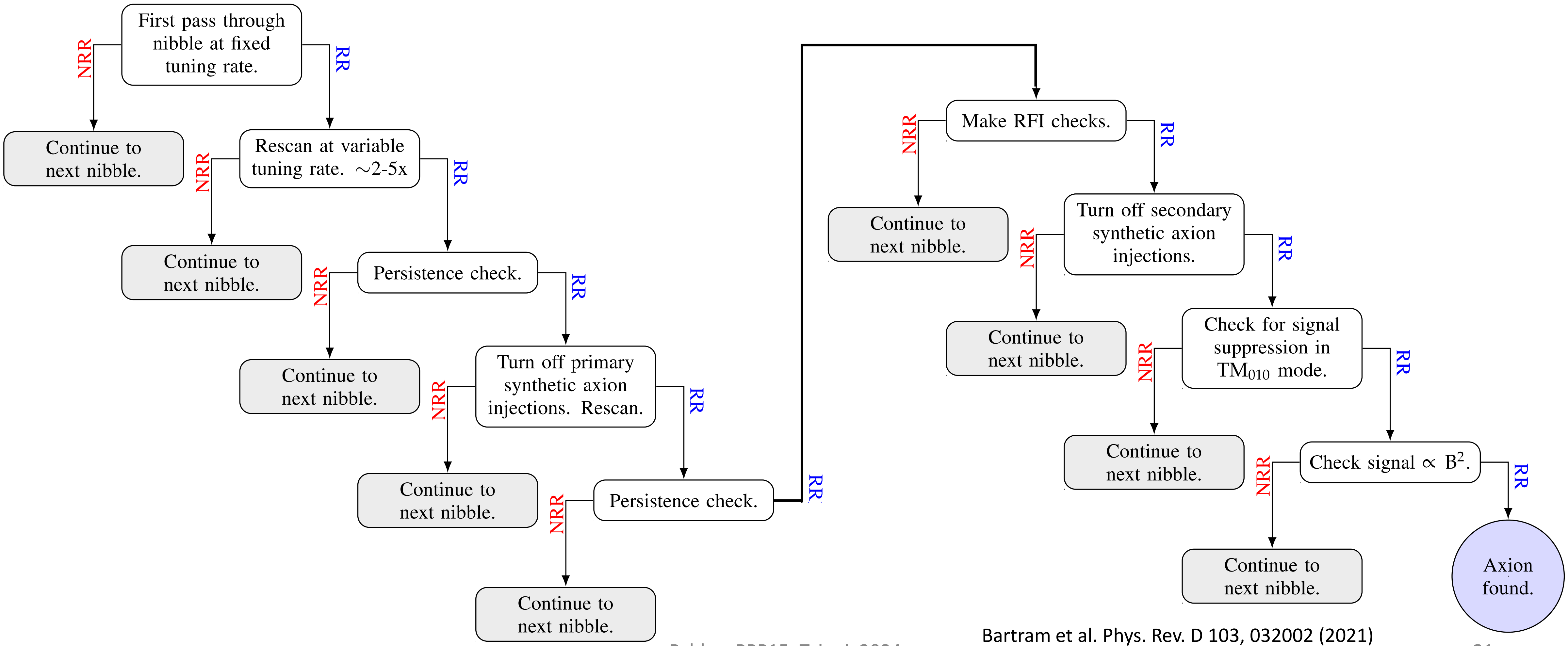


The cavity is tuned every 100 seconds, during which power spectra are taken. Overlapping power spectra are examined for the characteristic axion signal shape appearing on-resonance.

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

Data Taking Cadence

14 “nibbles” = ~ 10 MHz sweeps single scans: **range:** 50 kHz, **resolution:** 100Hz, **integration time:** 100s



First pass through nibble at fixed tuning rate.

NRR

Continue to next nibble.

RR

Rescan at variable tuning rate. ~2-5x

NRR

Continue to next nibble.

RR

Persistence check.

NRR

Continue to next nibble.

RR

Turn off primary synthetic axion injections. Rescan.

NRR

Continue to next nibble.

RR

Persistence check.

NRR

Continue to next nibble.

RR

Make RFI checks.

NRR

Continue to next nibble.

RR

Turn off secondary synthetic axion injections.

NRR

Continue to next nibble.

RR

Check for signal suppression in TM_{010} mode.

NRR

Continue to next nibble.

RR

Check signal $\propto B^2$.

NRR

Continue to next nibble.

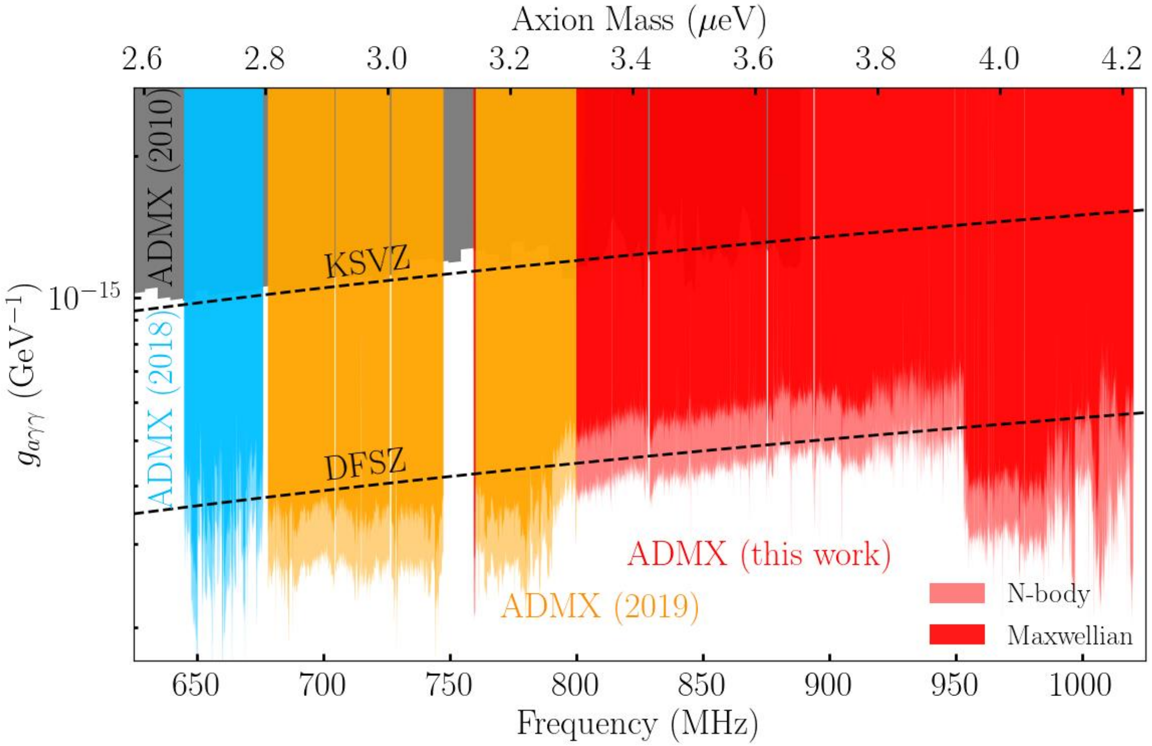
RR

Axion found.

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

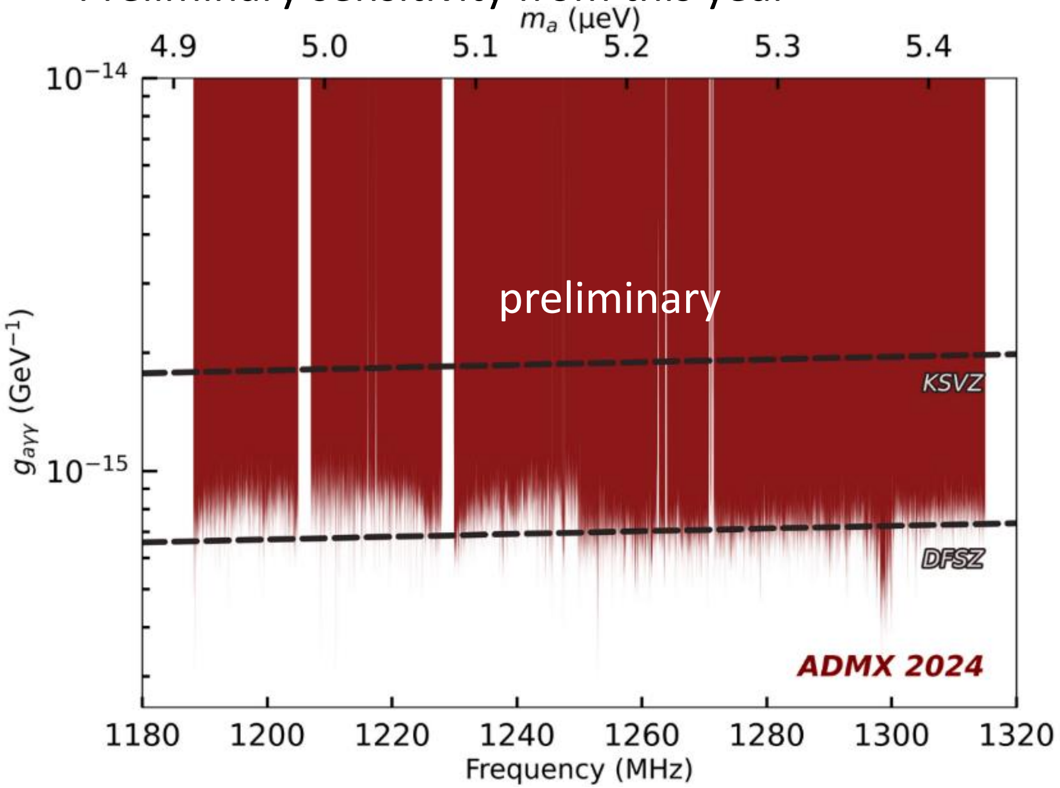
ADMX Recent Results

Excluded parameter space over the last 5 years



Bartram et al. PRL 127, 261803 (2021)

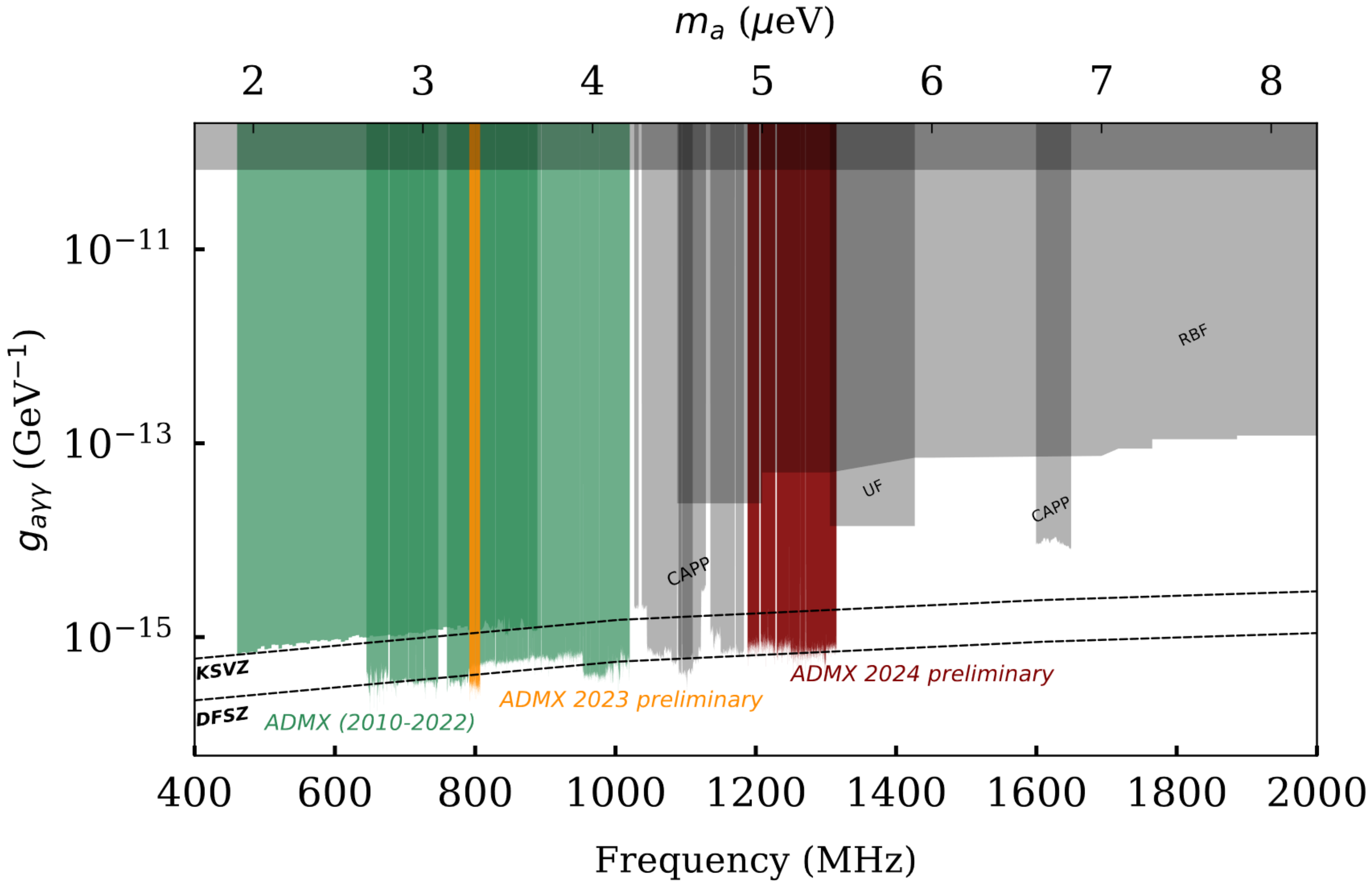
Preliminary sensitivity from this year



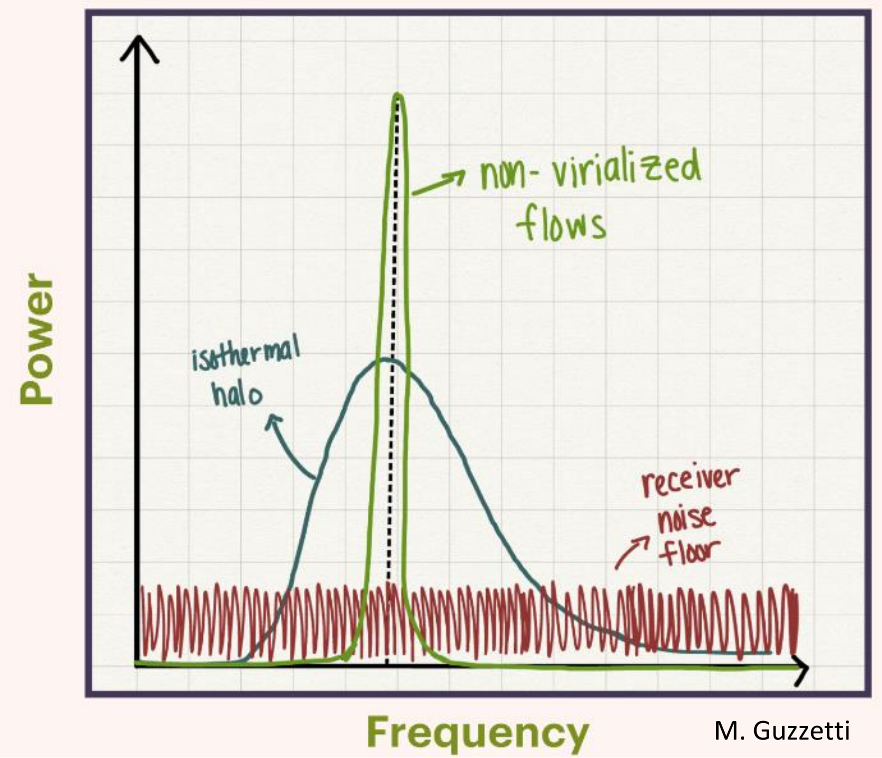
M. Guzzetti, Patras Workshop 2024

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

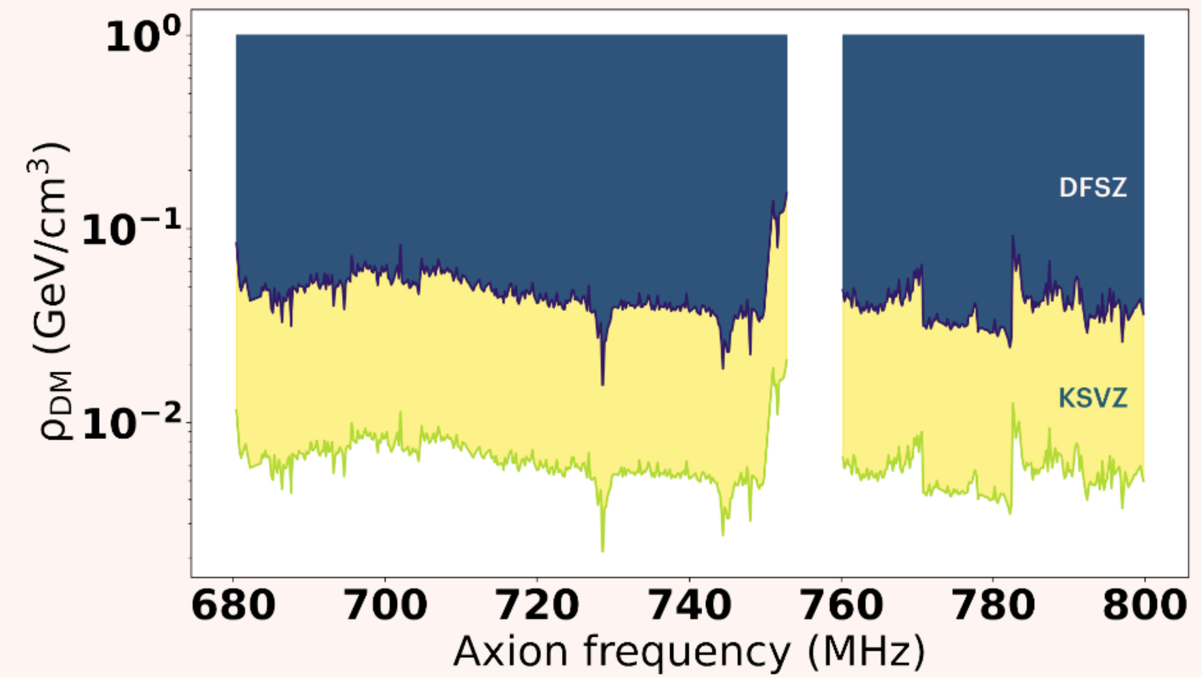


ADMX High-Resolution Results



M. Guzzetti

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

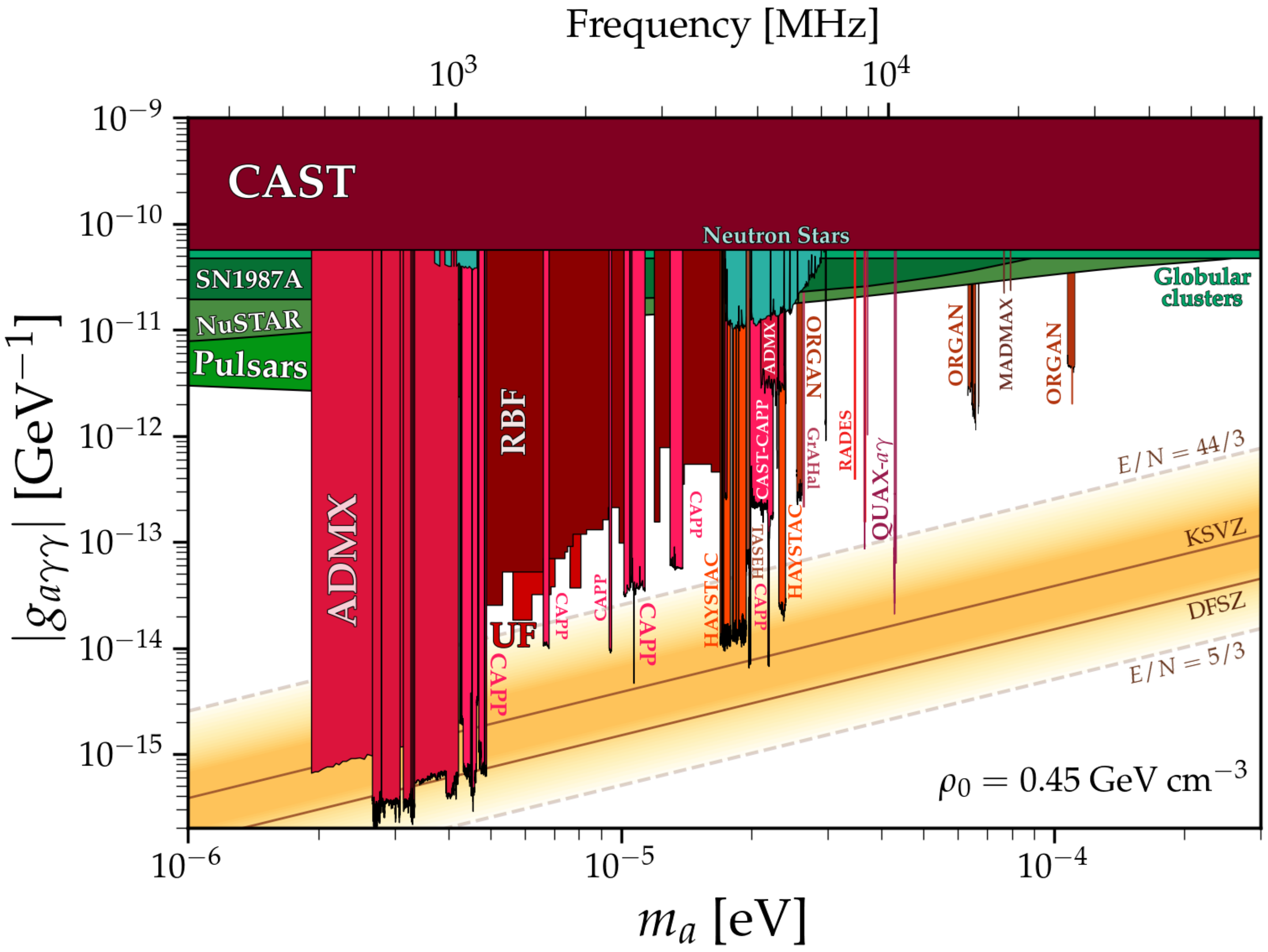


M. Guzzetti, General Exam

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

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

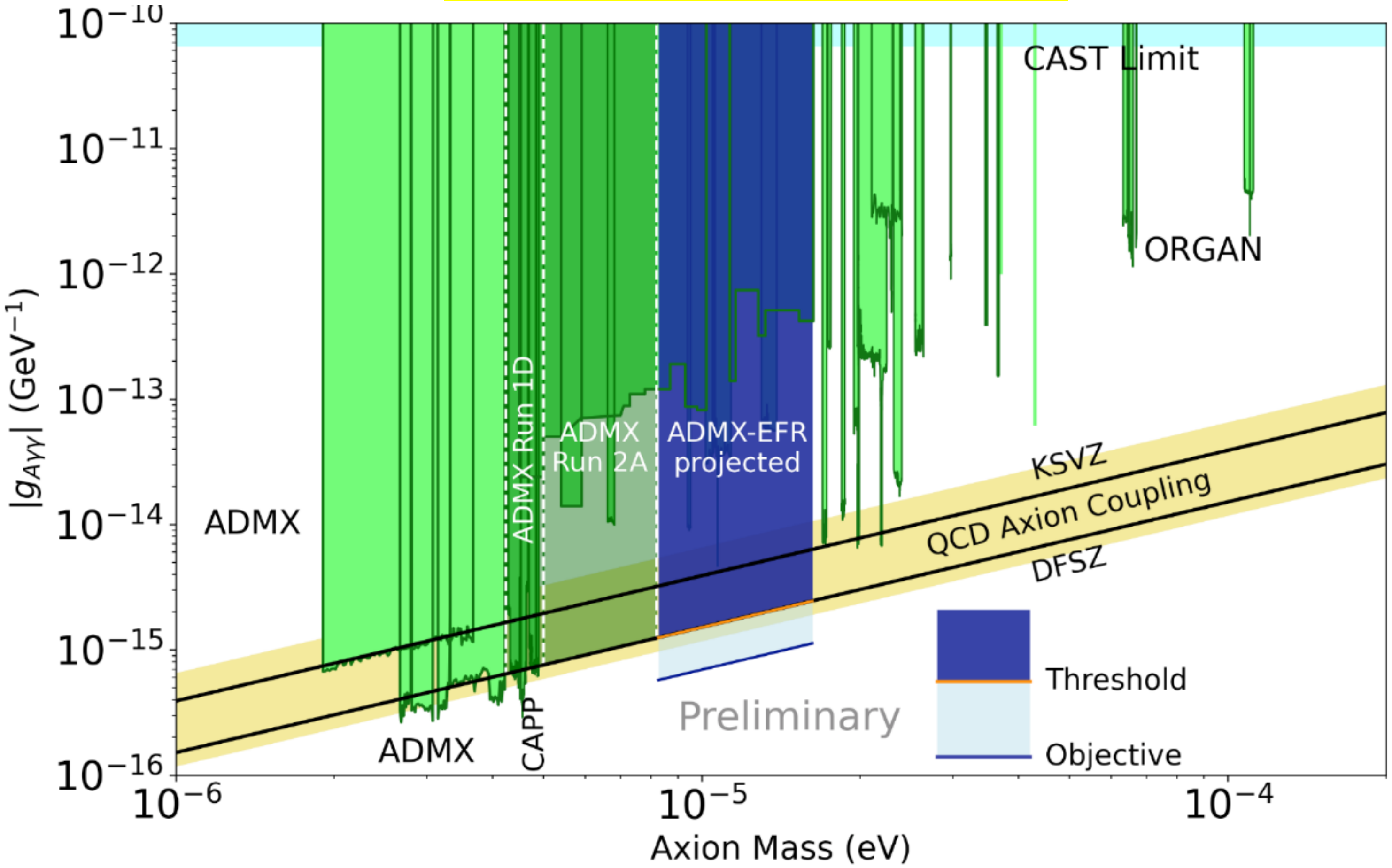
ADMX EFR

New Site

New Magnet

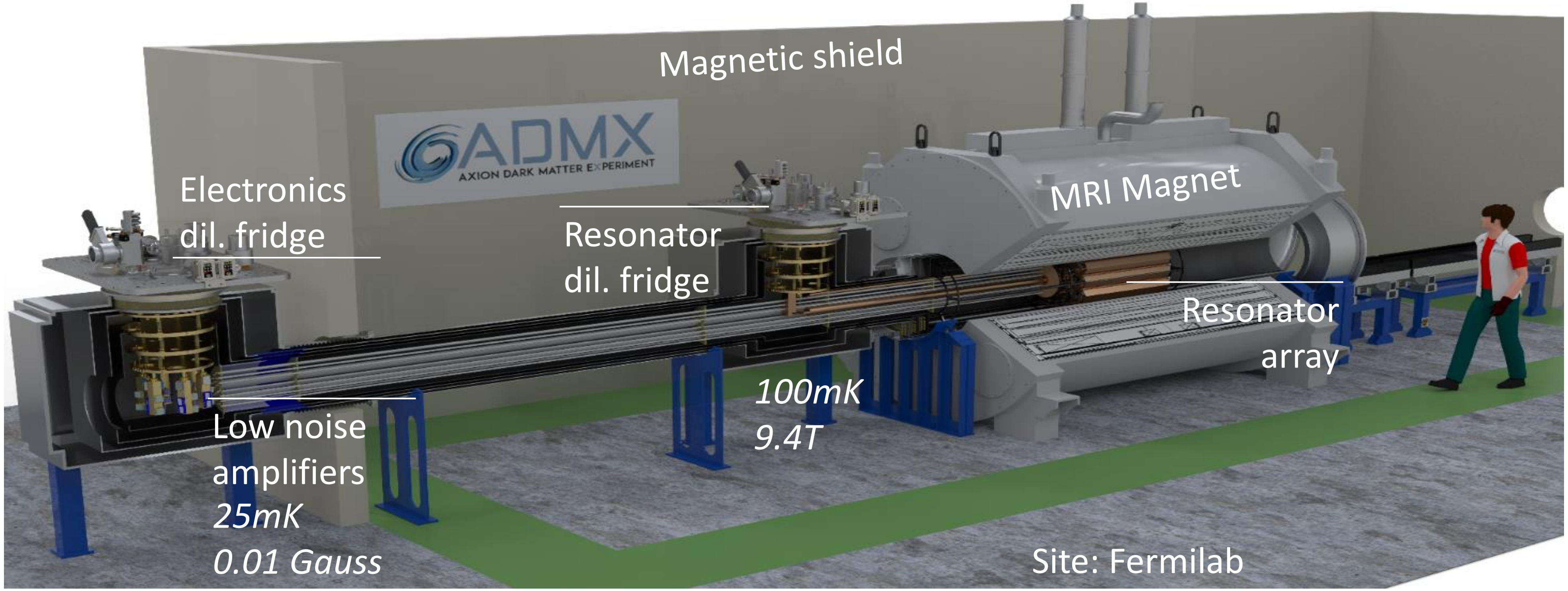
New Design

Sensitivity Projections



ADMX-EFR

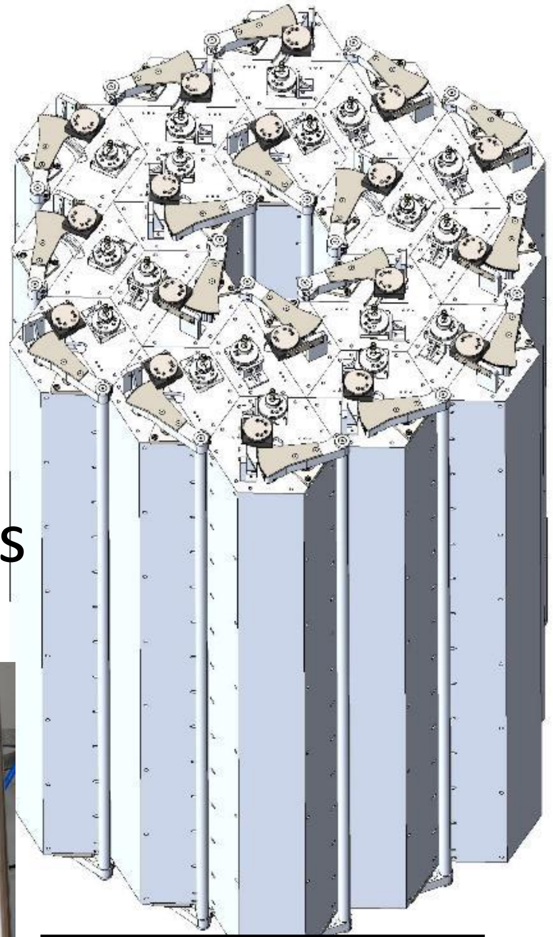
- Incorporate technologies as they mature for a continuous scan sensitive to DFSZ axions at 2GHz and up
- Magnet is already deployed at Fermilab
- Opportunity for a “Dark Wave Laboratory”



Status of ADMX EFR

Magnet has been delivered to Fermilab June 26, 2025

Resonator array designed; prototypes constructed



18 cavity array

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

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