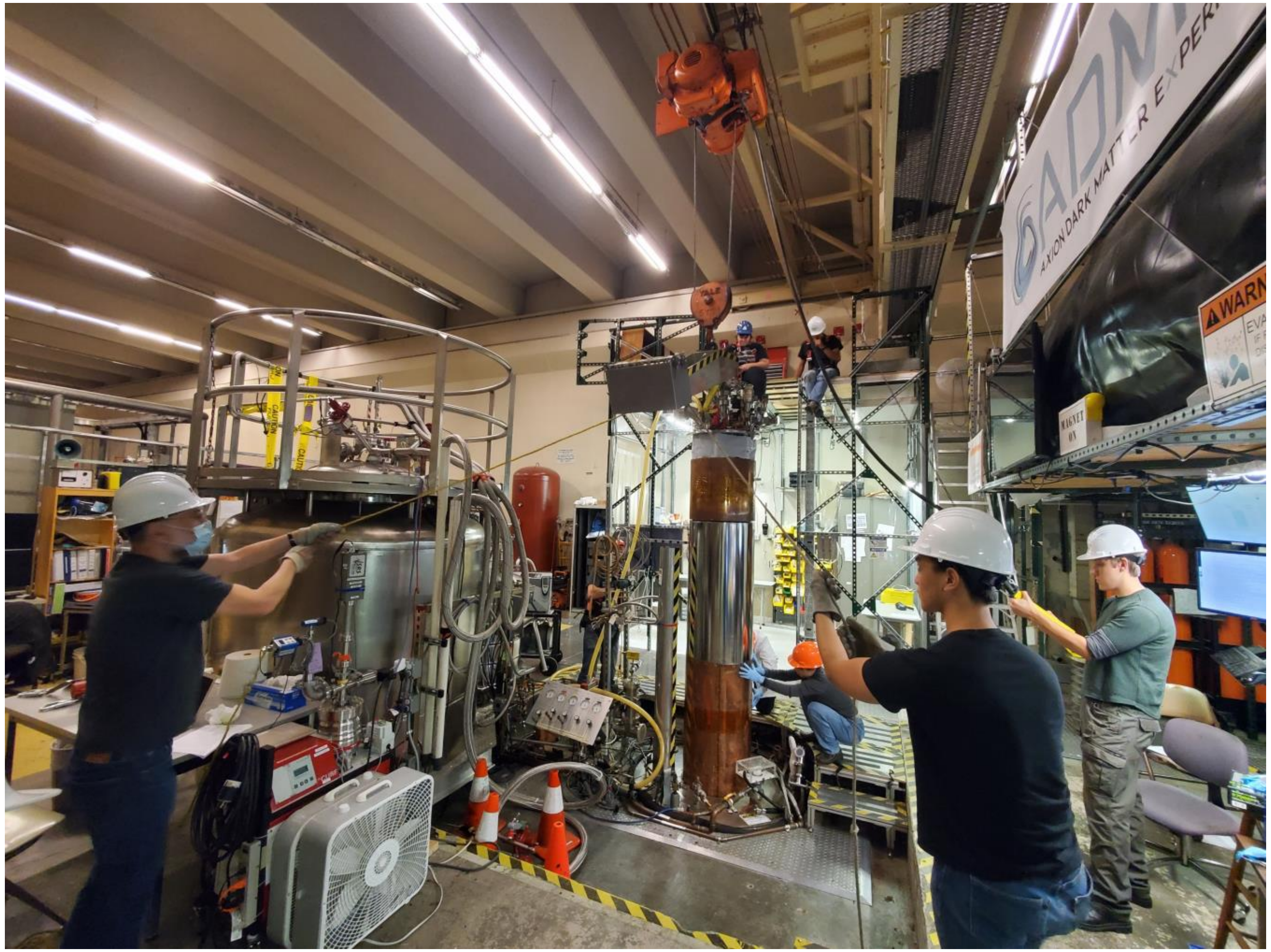
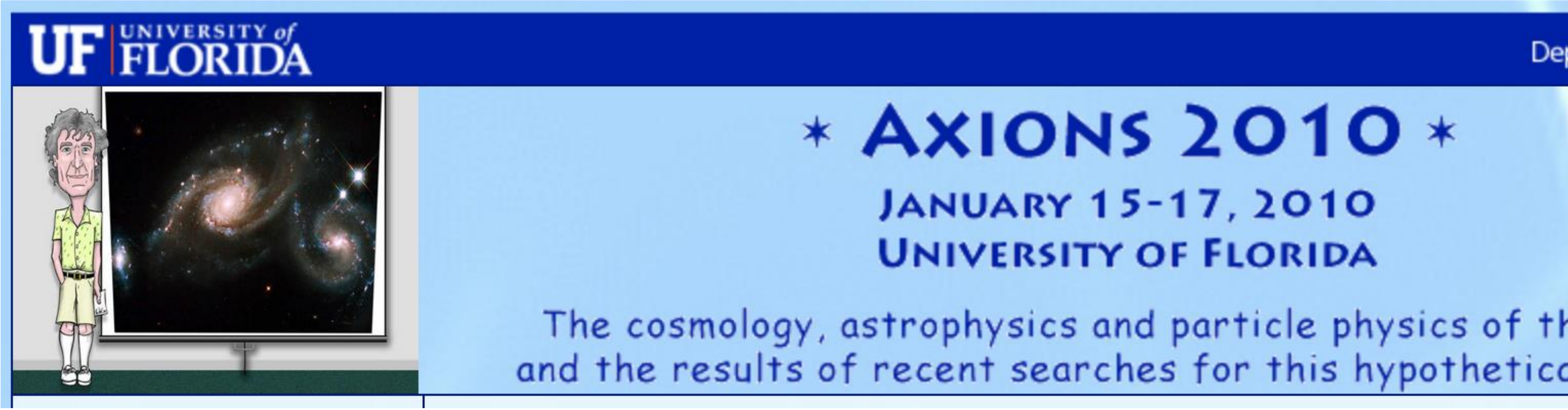
The Search for Axion Dark Matter



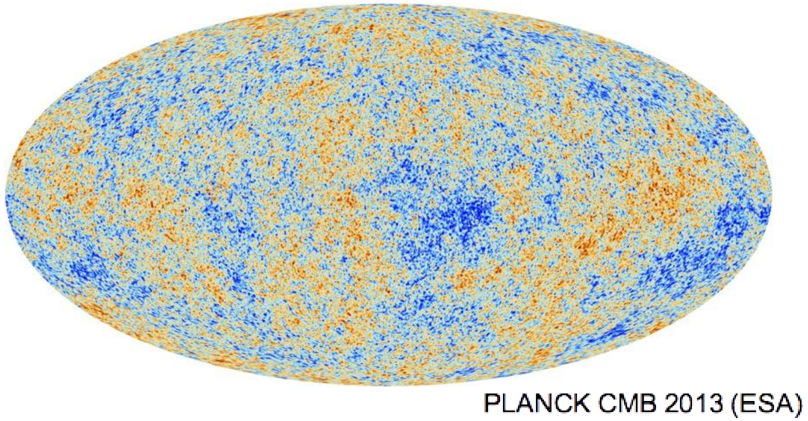
Gray Rybka – University of Washington

Axions 2024 U. Florida

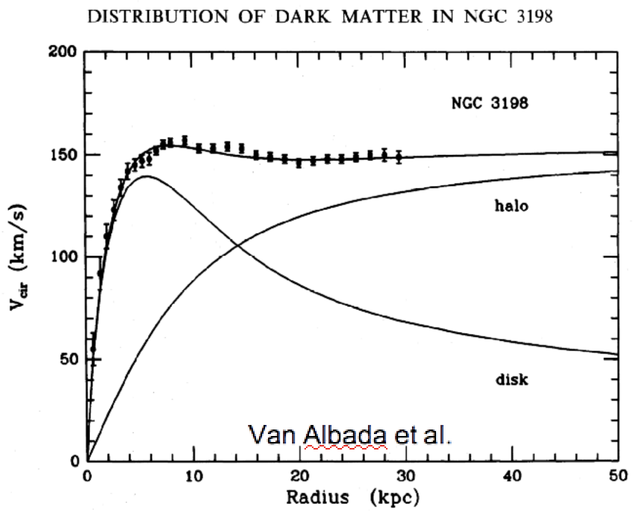


Proof that Pierre hasn't aged a day in the last 14 years!

Evidence for Dark Matter



Our Hubble Volume



Nearby Galaxies

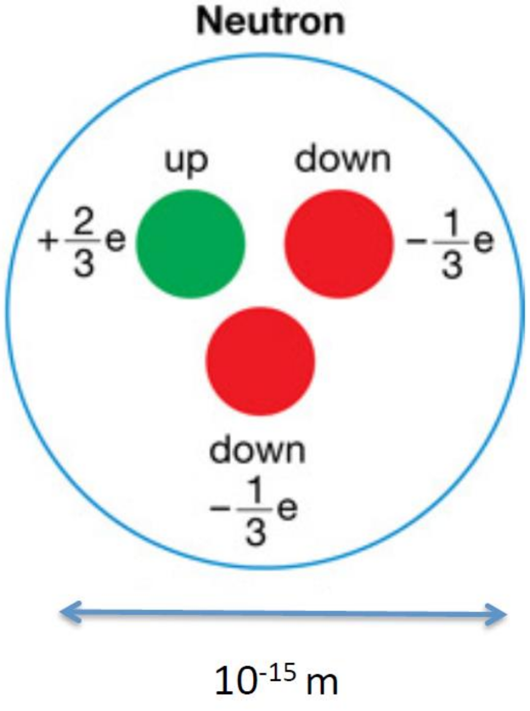
Galaxy Clusters

?

The Laboratory

The QCD Axion: Motivation

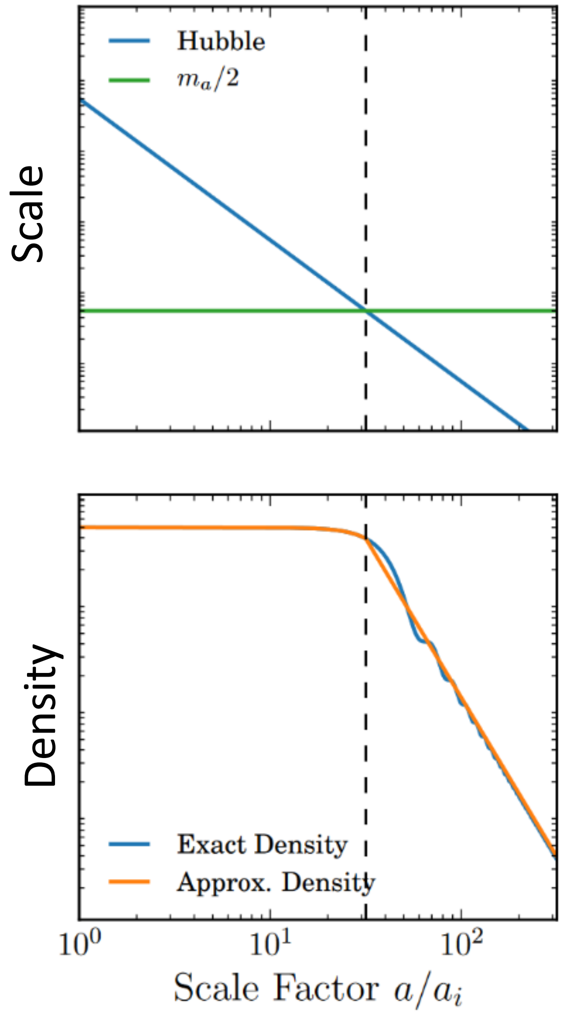
- QCD is naturally CP violating from phenomena like QCD-instantons
- One naively expects a neutron electric dipole moment of 10^{-16} e cm
- But nEDM is measured to be below $3\text{x}10^{-26}$ e cm *(Baker, 2006)*
- The best explanation? New U(1) axial symmetry, that when broken, cancels CP violation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



d = ~~10^{-16} e cm~~
< $3\text{x}10^{-26}$ 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

Axions as Dark Matter

- But you can’t detect them, can you?

The Sikivie Haloscope

VOLUME 51, NUMBER 16 PHYSICAL REVIEW LETTERS 17 OCTOBER 1983

Experimental Tests of the "Invisible" Axion

P. Sikivie
Physics Department, University of Florida, Gainesville, Florida 32611
(Received 13 July 1983)

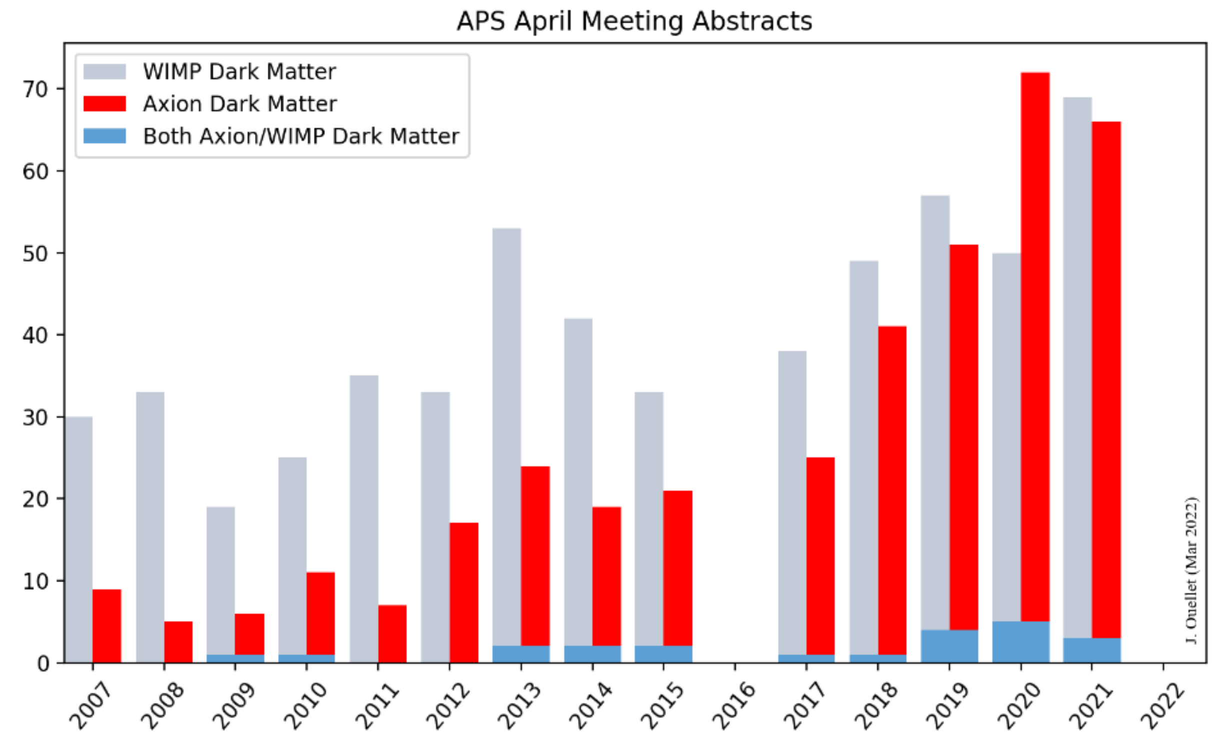
Experiments are proposed which address the question of the existence of the "invisible" axion for the whole allowed range of the axion decay constant. These experiments exploit the coupling of the axion to the electromagnetic field, axion emission by the sun, and/or the cosmological abundance and presumed clustering of axions in the halo of our galaxy.

PACS numbers: 14.80.Gt, 11.30.Er, 95.30.Cq

I had a great picture of Pierre applying a wrench to ADMX, but I've lost it. So here's a picture of Pierre deep in thought in a café on the beach in Greece

The Axion Community is Growing

Wrench joke aside, it took experimentalists a very long time to catch up with Pierre.



J. Ouellet

An example of the typical APS axion session back in 2008

2008 Annual Meeting of the Division of Nuclear Physics

Volume 53, Number 12

Thursday–Sunday, October 23–26, 2008; Oakland, California

Session Index

Show Abstracts

Session LG: Cosmology

Chair: Karl van Bibber, Lawrence Livermore National Laboratory
Room: *Jewett Ballroom C*

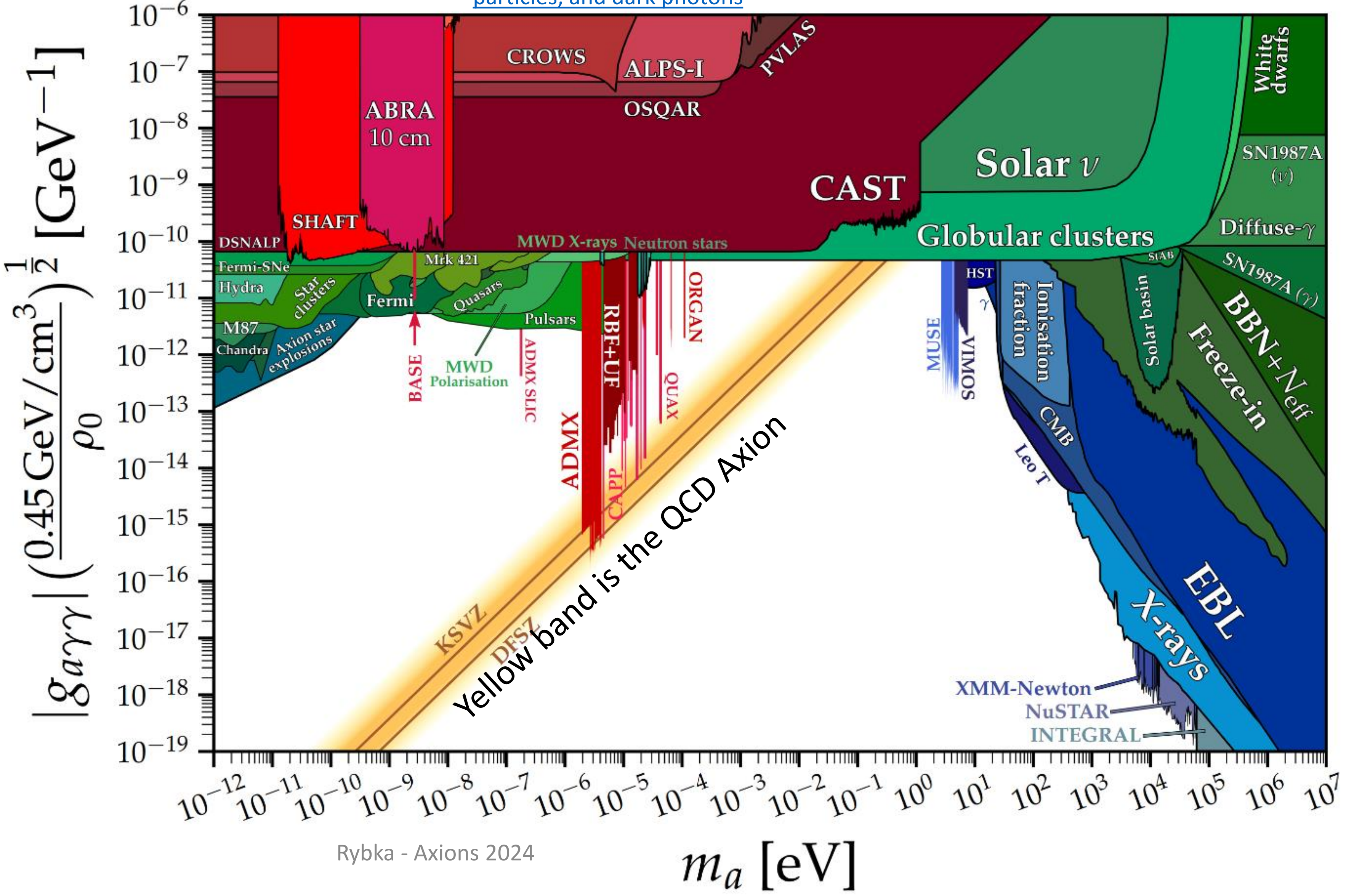
Sunday, October 26, 2008 8:30AM - 8:42AM	LG.00001: Limits on cold dark matter axions from the ADMX high resolution search Gray Rybka, Steven Asztalos, Richard Bradley, Gianpaolo Carosi, Michael Hotz, Jungseek Hwang, Darin Kinion, Leslie Rosenberg, Pierre Sikivie, David Tanner, Karl van Bibber Preview Abstract
Sunday, October 26, 2008 8:42AM - 8:54AM	LG.00002: Limits on thermally-distributed halo dark-matter axions from ADMX Gianpaolo Carosi, Steven Asztalos, Richard Bradley, Michael Hotz, Jungseek Hwang, Darin Kinion, Leslie Rosenberg, Gray Rybka, Pierre Sikivie, David Tanner, Karl van Bibber Preview Abstract
Sunday, October 26, 2008 8:54AM - 9:06AM	LG.00003: Overview, Technical Description and Future of the Axion Dark Matter eXperiment S. Asztalos, R. Bradley, G. Carosi, M. Hotz, J. Hwang, D. Kinion, L. Rosenberg, G. Rybka, P. Sikivie, D. Tanner, K. van Bibber Preview Abstract
Sunday, October 26, 2008 9:06AM - 9:18AM	LG.00004: Measuring the radiative width of the Hoyle state Jason Burke Preview Abstract
Sunday, October 26, 2008 9:18AM - 9:30AM	LG.00005: Astrophysical Data Transmission in Planck Units Shantilal Goradia Preview Abstract
Sunday, October 26, 2008 9:30AM - 9:42AM	LG.00006: The mass, energy, space and time system theory-MEST Dayong Cao Preview Abstract
Sunday, October 26, 2008 9:42AM - 9:54AM	LG.00007: Deeper Probing of the Fine-structure Constant Shantilal Goradia Preview Abstract
Sunday, October 26, 2008 9:54AM - 10:06AM	LG.00008: The mass, energy, space and time system of Wave, Particle and universe -MEST Dayong Cao

Axion Photon Bounds

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

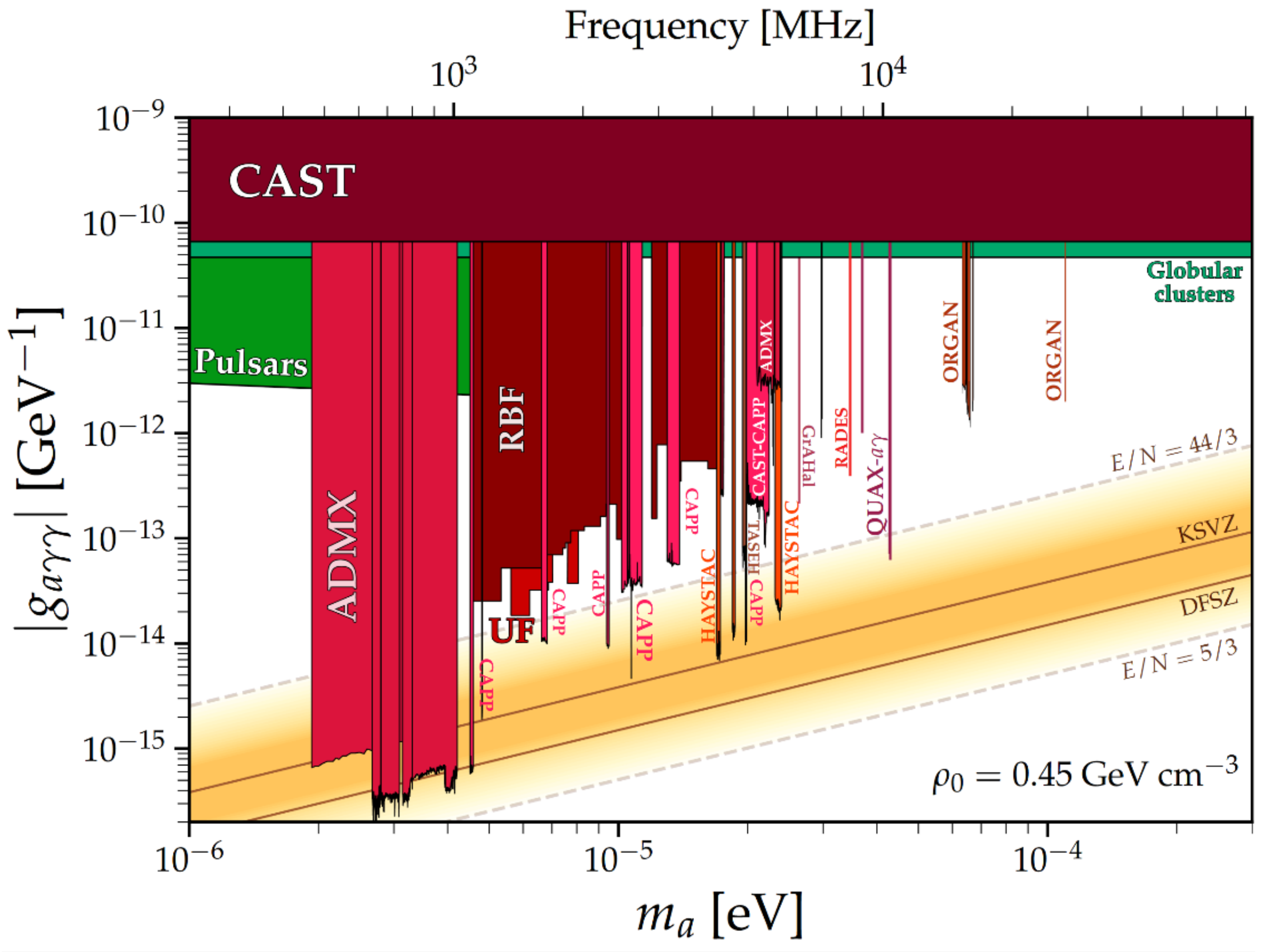
The yellow band is the QCD axion, white space is Axion-Like Particle (ALP) space

Note the significant astrophysical constraints on ALP parameters.



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”



ADMX Collaboration

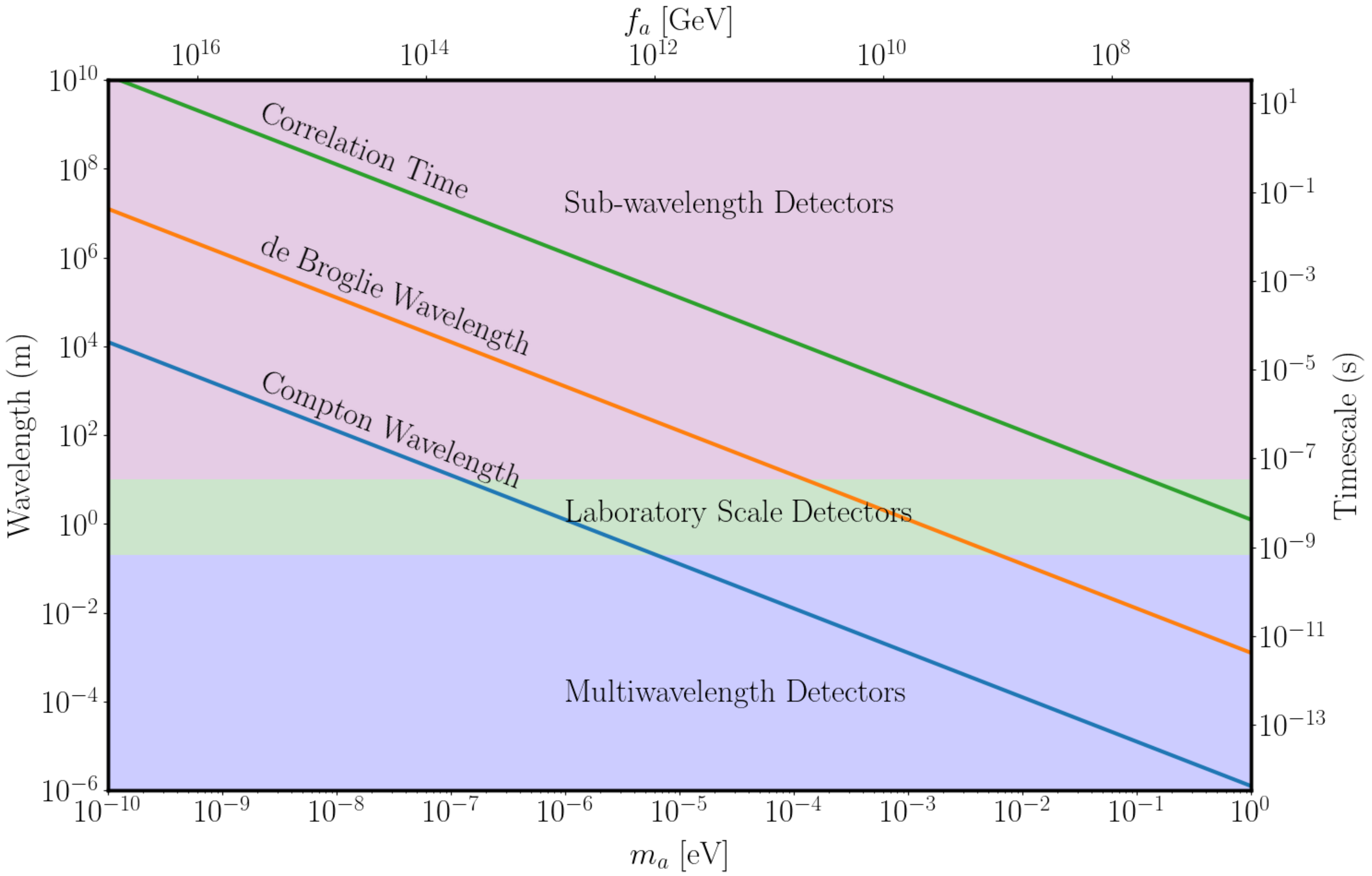
ADMX Collaboration meeting Jan 2023

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

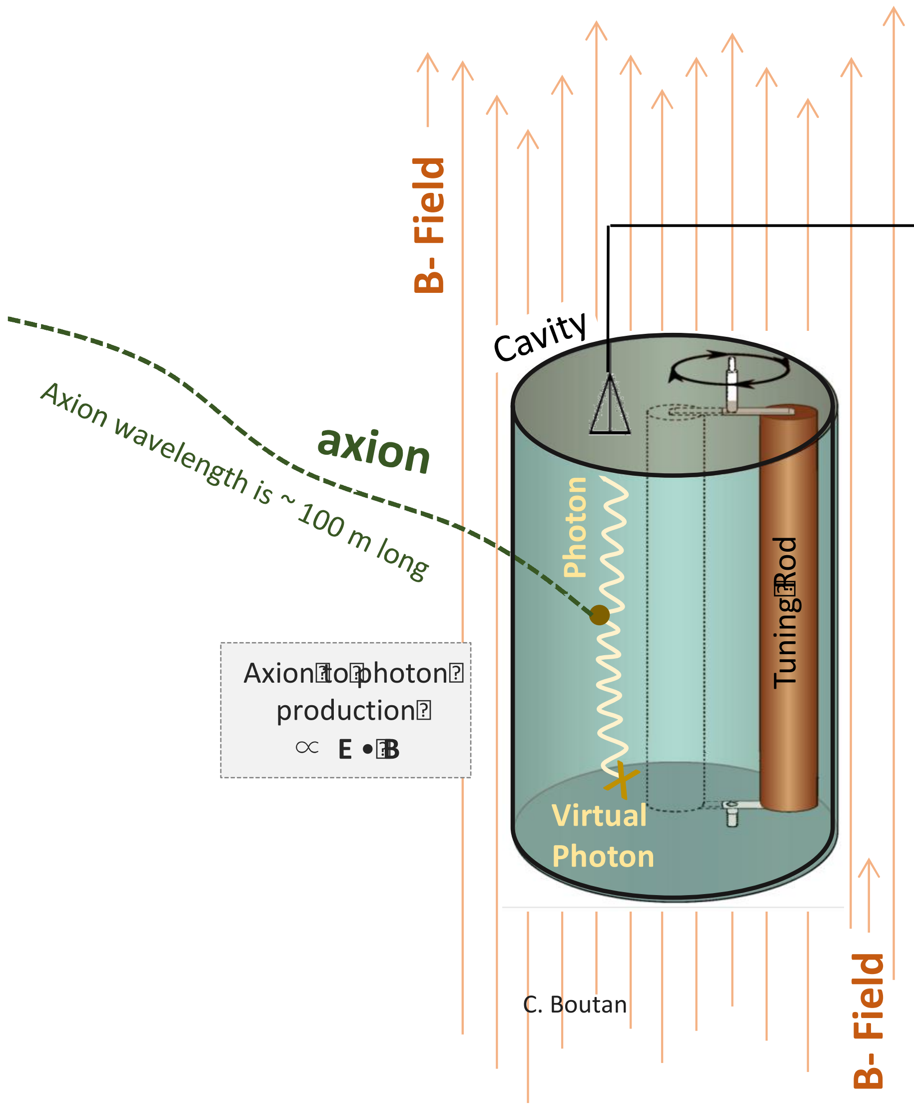
This work was supported by the U.S. Department of Energy through Grants No DE-SC0009800, No. DE-SC0009723, No. DE-SC0010296, No. DE-SC0010280, No. DE-SC0011665, No. DEFG02-97ER41029, No. DE-FG02-96ER40956, No. DEAC52-07NA27344, No. DE-C03-76SF00098 and No. DE-SC0017987. Fermilab is a U.S. Department 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

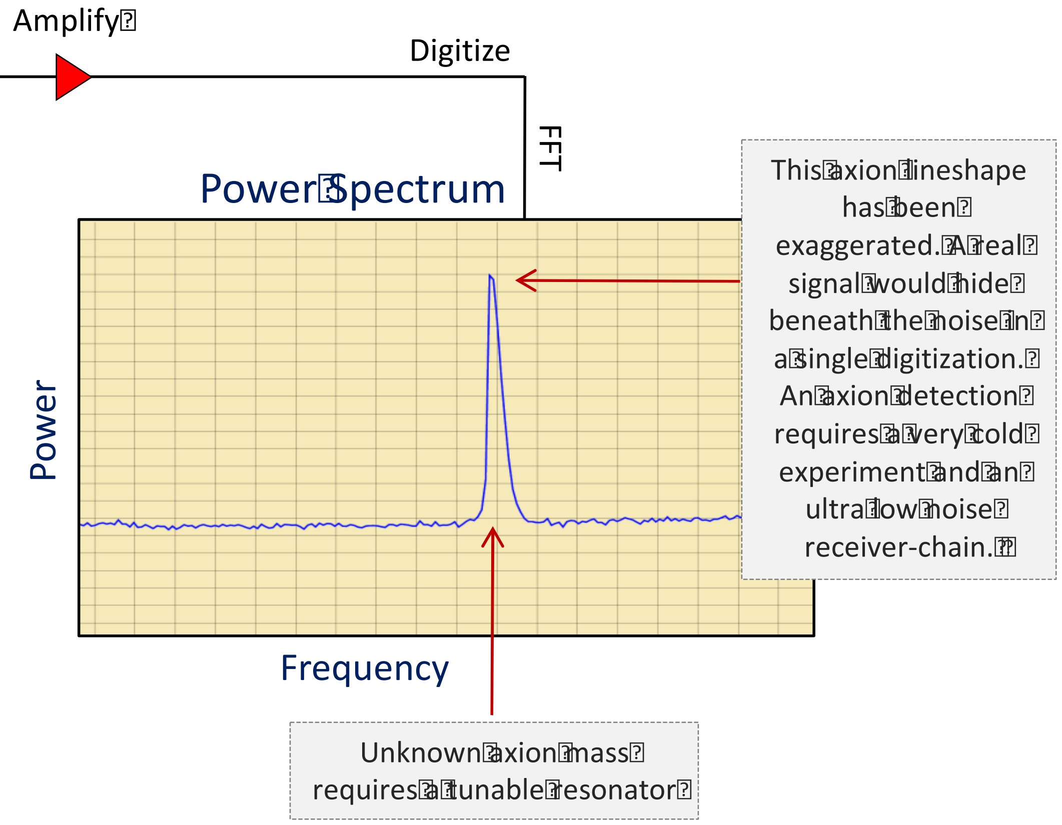
Axion Detector Length and Time Scales



Principle of the Sikivie Axion Haloscope

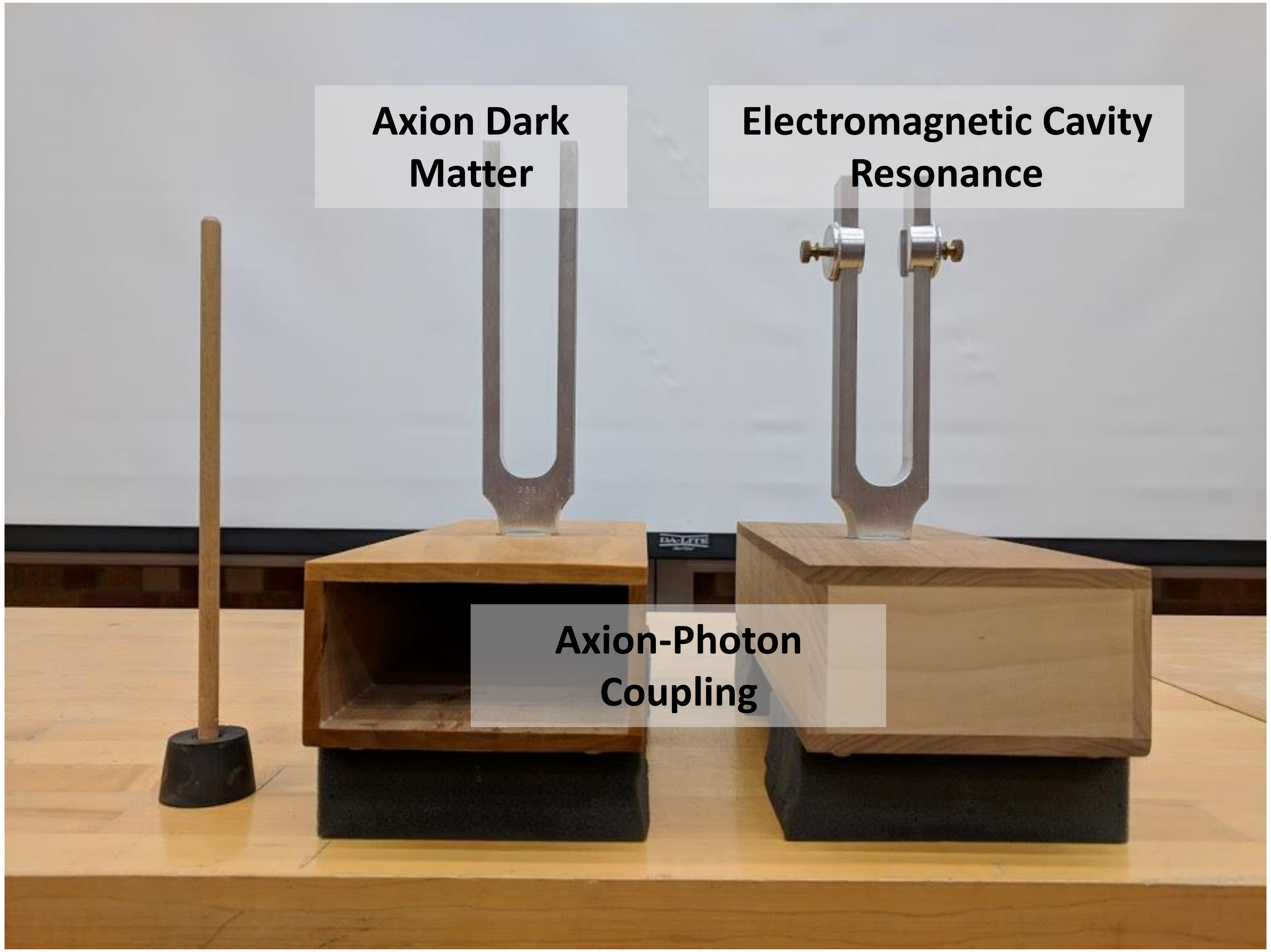
See P. Sikivie, PRL 51, 1415 (1983) for origin



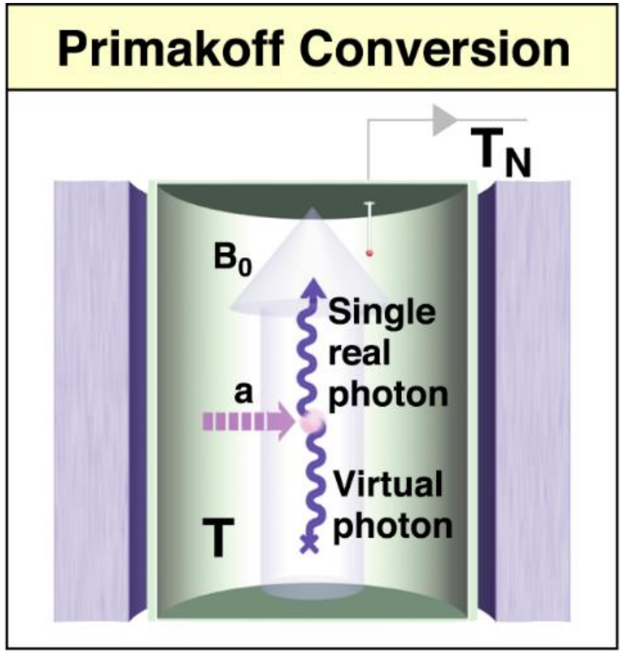


Axion Haloscope for my Intro Physics Class

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)

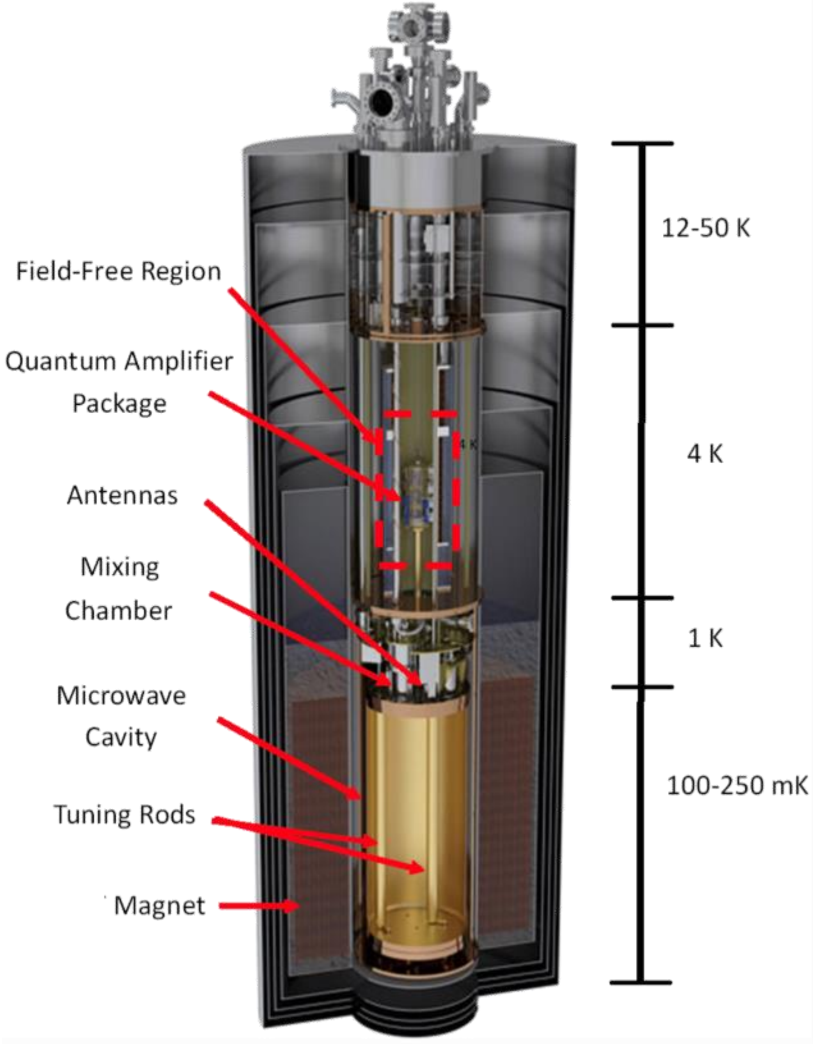
Signal Proportional to

Cavity Volume
Magnetic Field
Cavity Q

Noise Proportional to

Cavity Blackbody Radiation
Amplifier Noise

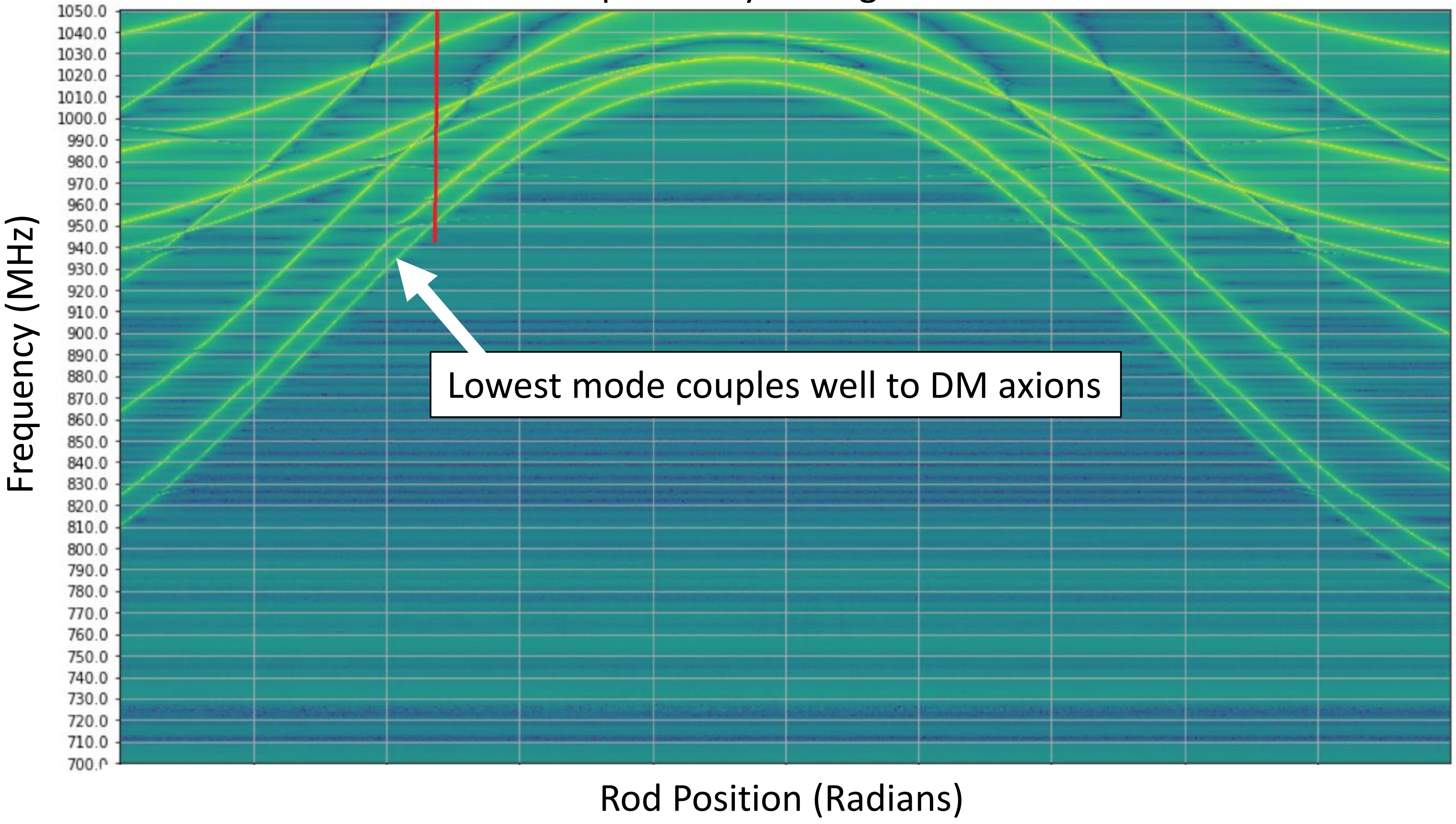
ADMX Design



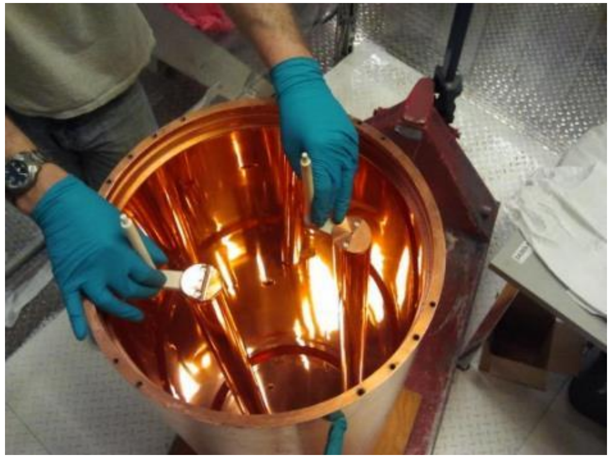
Field-Free Region
Quantum Amplifier Package
Antennas
Mixing Chamber
Microwave Cavity
Tuning Rods
Magnet
12-50 K
4 K
1 K
100-250 mK

Tuning ADMX

Example Cavity Tuning Curve



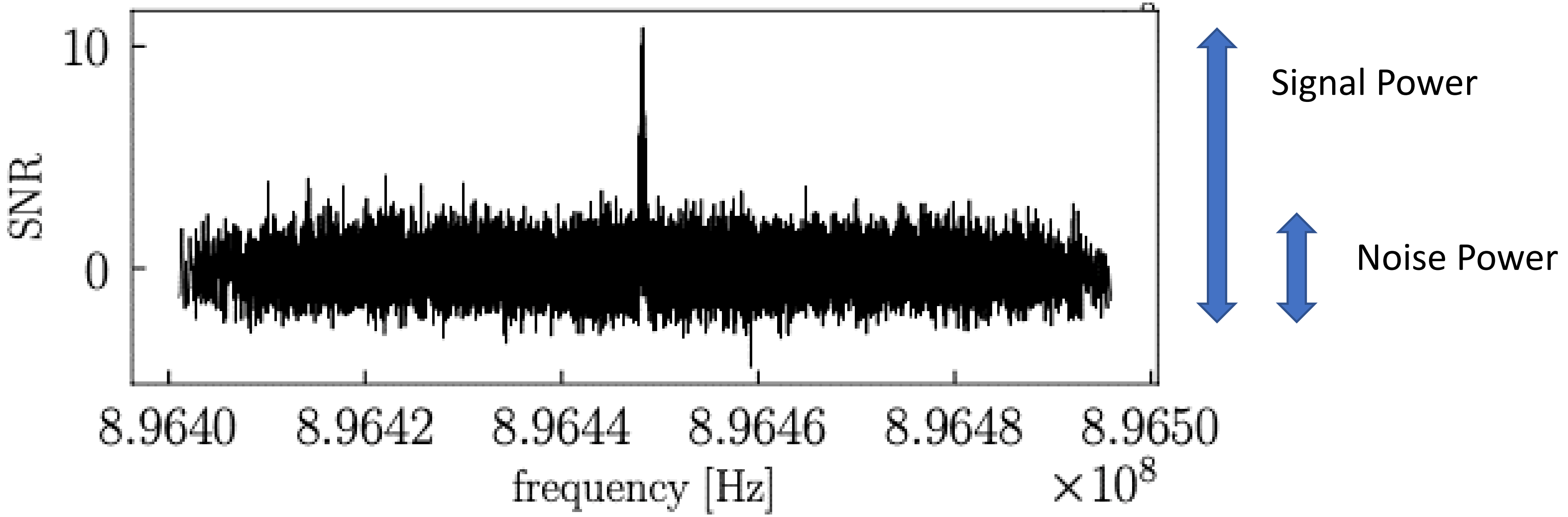
Tuning Rods within Cavity



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

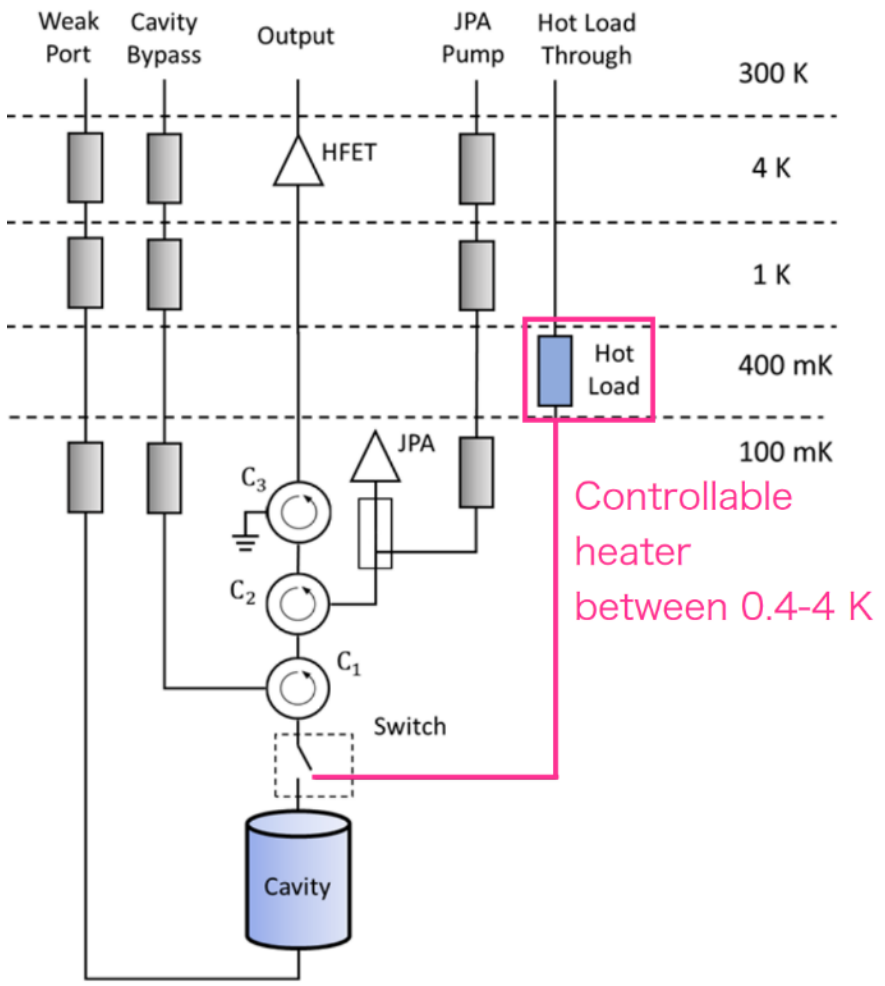


We need our noise to be much smaller than our signal to make a detection.

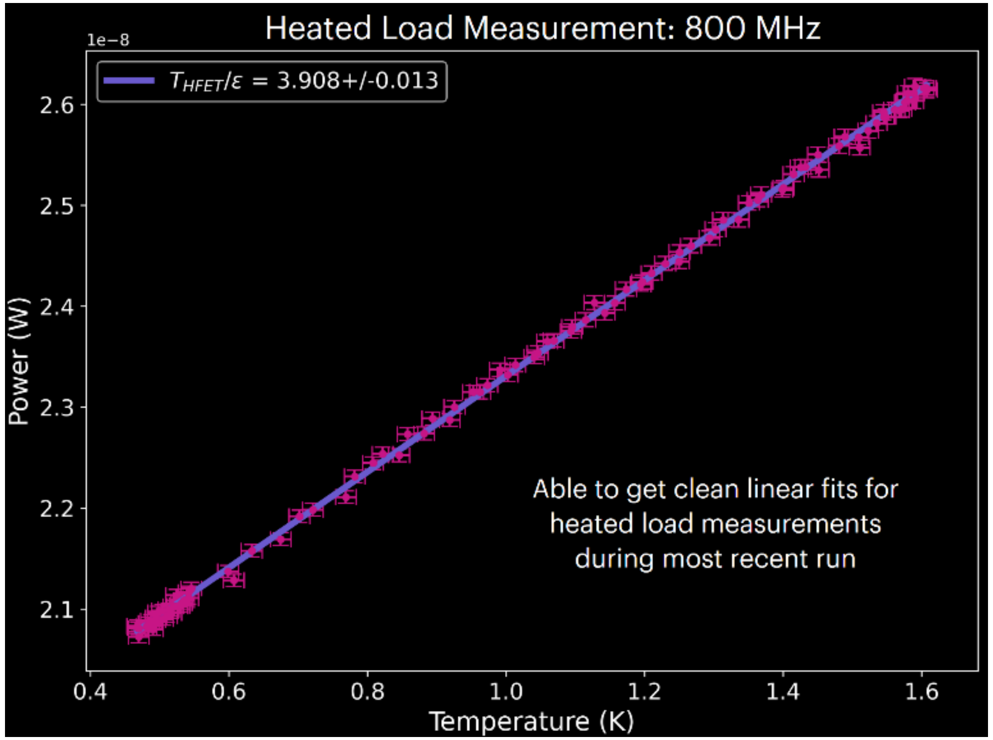
The noise is a thermal, and the slower we scan the smaller the uncertainty.

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.

ADMX Noise Calibration



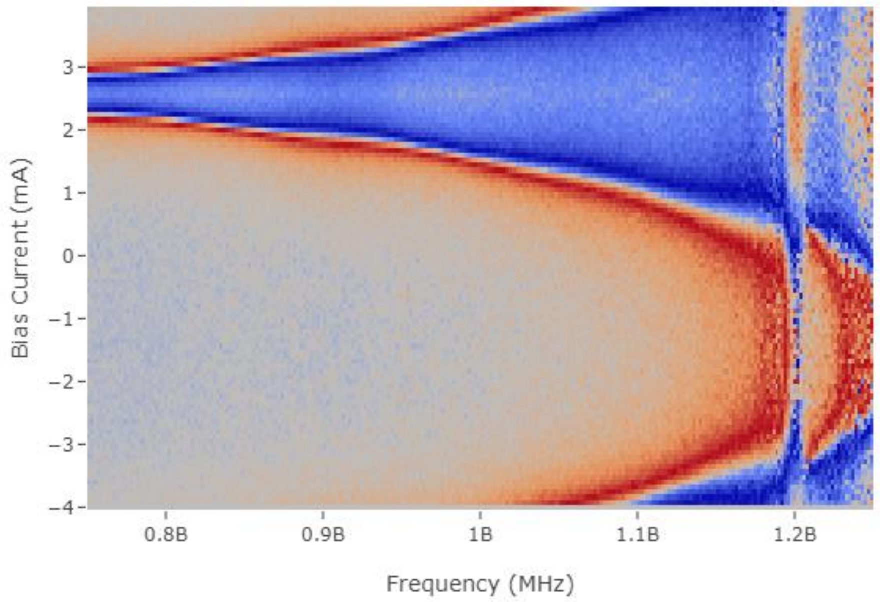
Our primary noise calibration comes from a temperature sensor

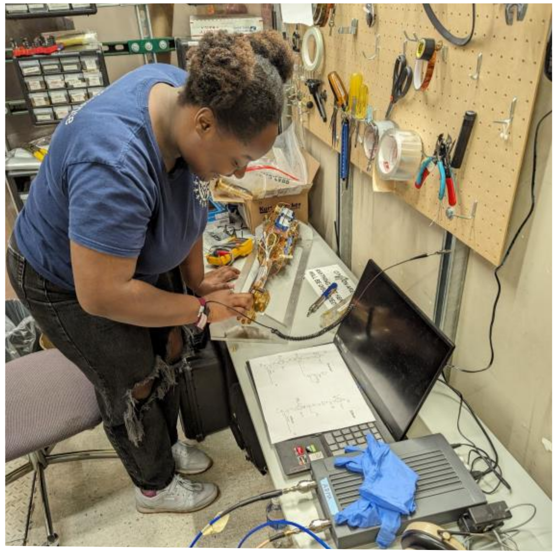


M. Guzzetti, APS April 2023

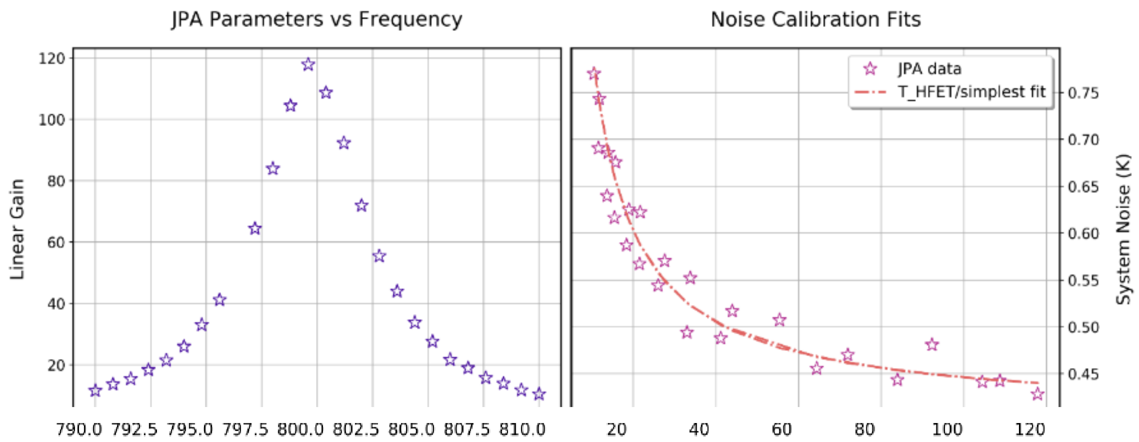
ADMX Noise Calibration

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



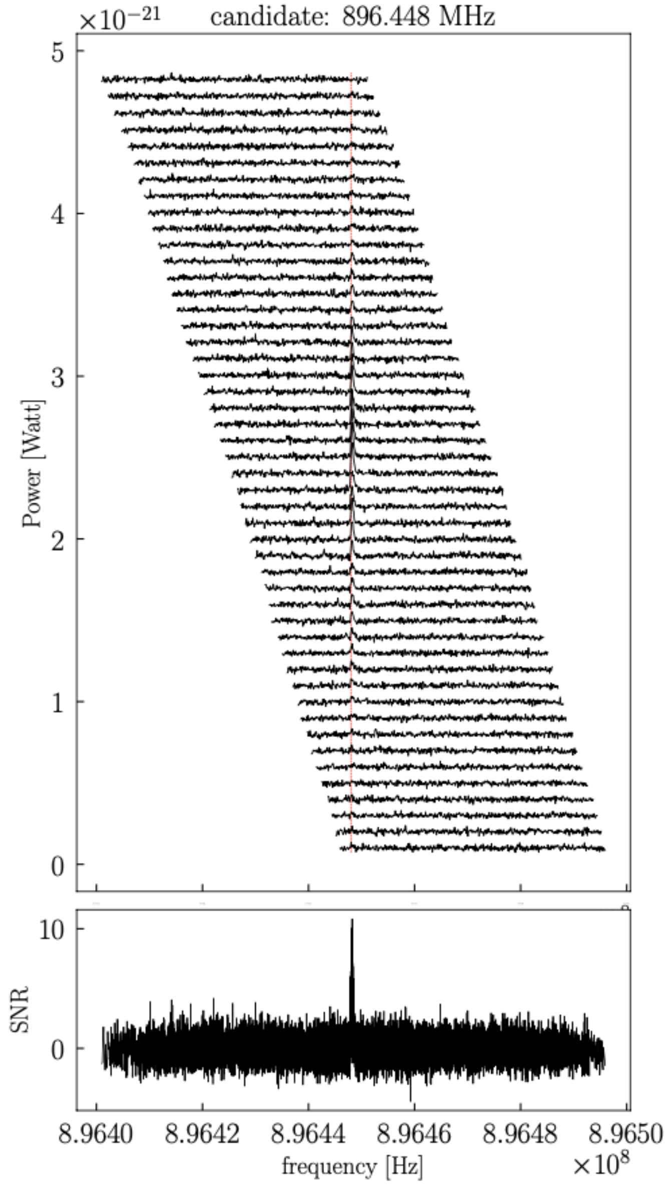


Warm testing of JPA electronics for ADMX Run1D



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

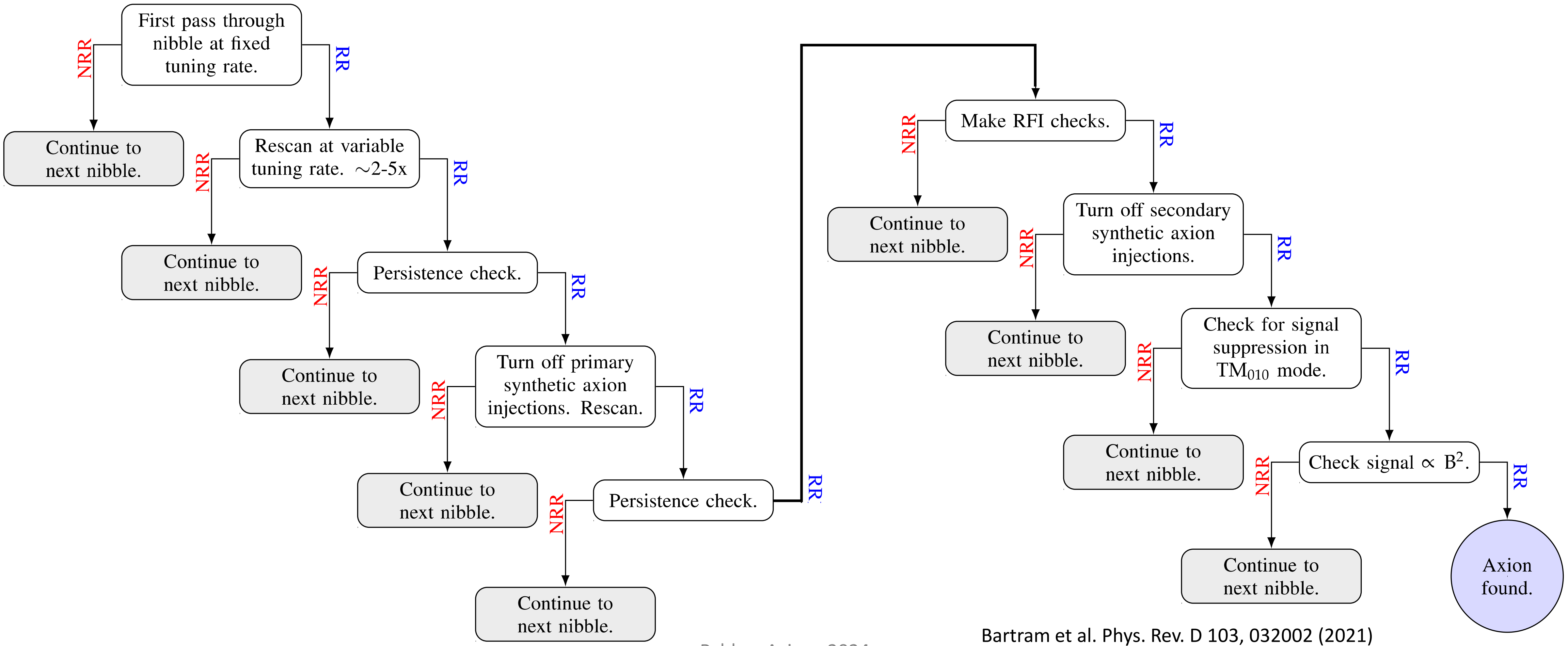


The cavity is tuned every 100 seconds, during which power spectra are taken. Overlapping power spectra are examined for the characteristic axion signal shape appearing on-resonance.

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

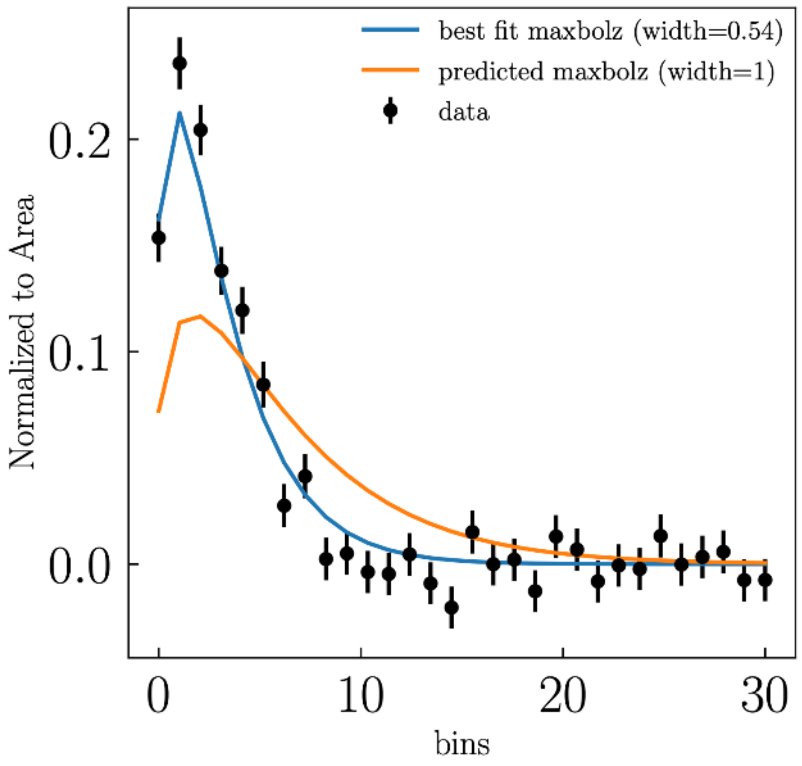
Data Taking Cadence

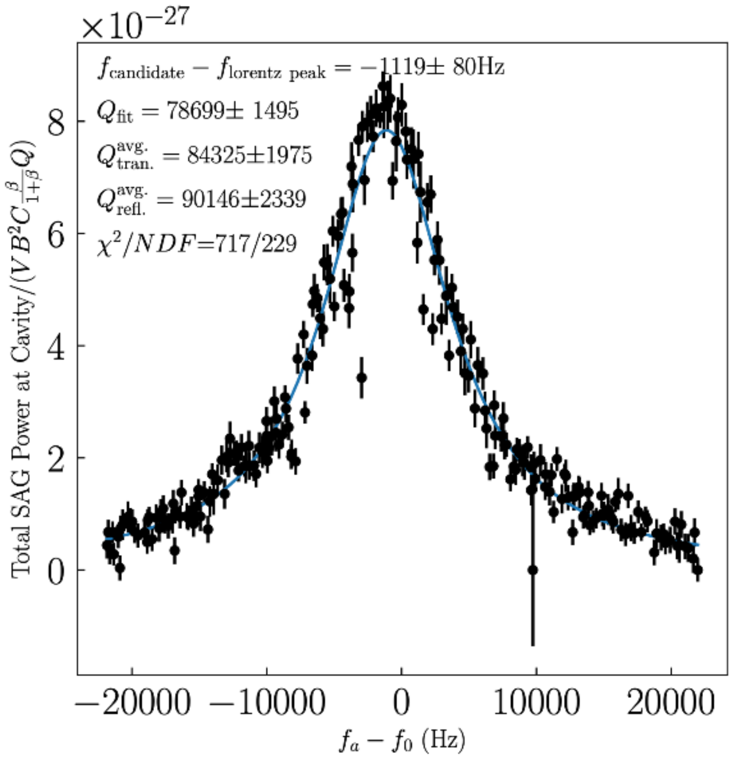
14 "nibbles" = ~ 10 MHz sweeps single scans: **range:** 50 kHz, **resolution:** 100Hz, **integration time:** 100s



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

Blind-Injection Synthetic Signal Detection



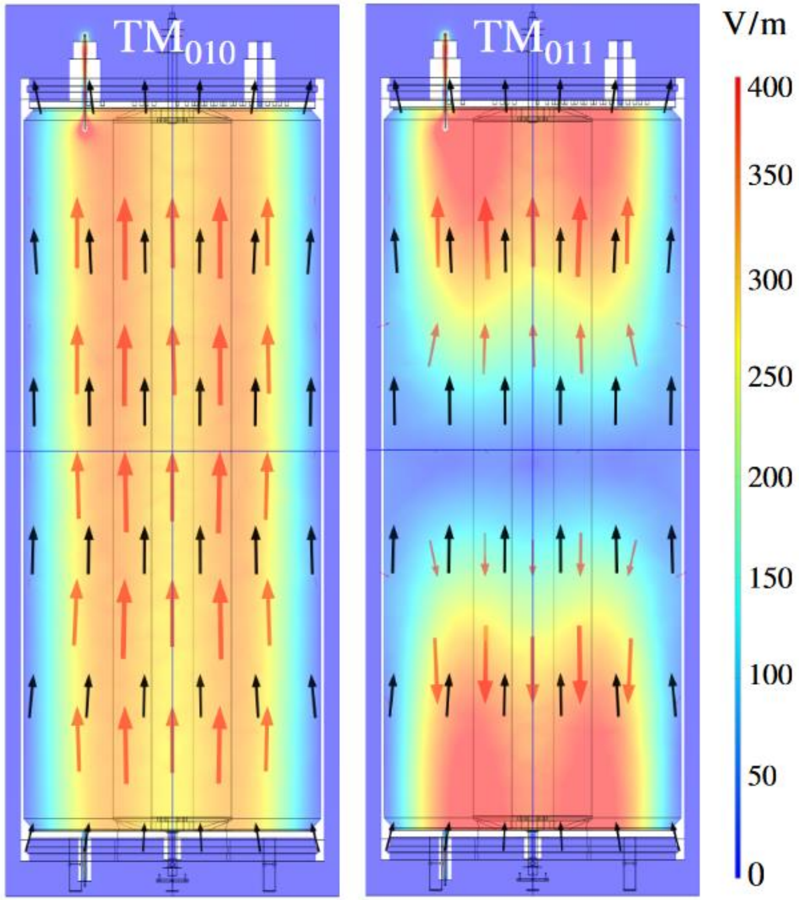


This signal sure looked like an axion. But before we began ramping the magnet down to be sure, we wanted to try looking at it from another mode.

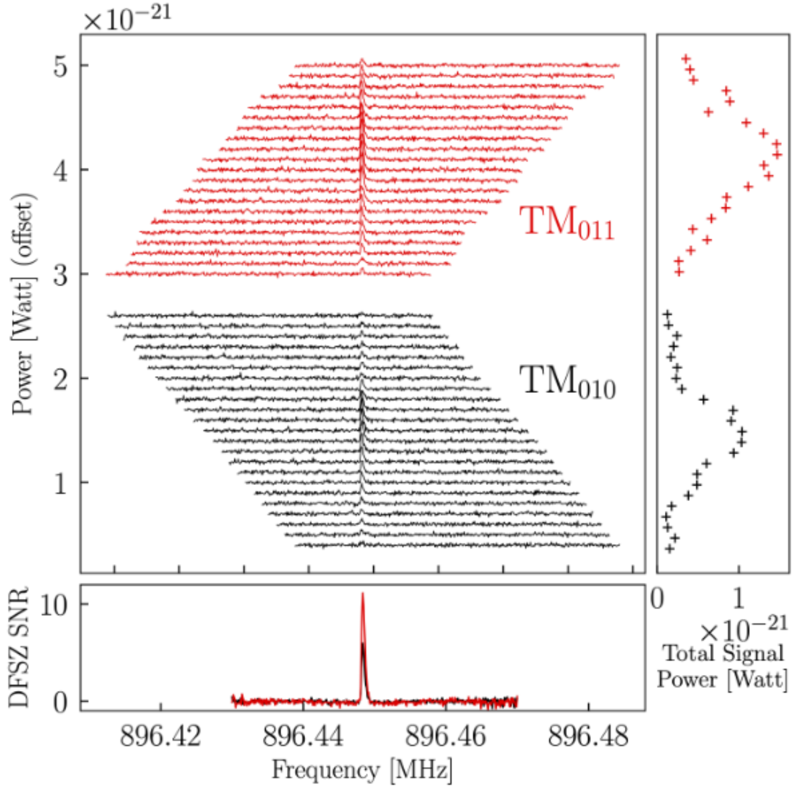
The lineshape was consistent with cosmological predictions

The signal was clearly coming from inside the cavity

Axions Couple to TM010 modes, not TM011



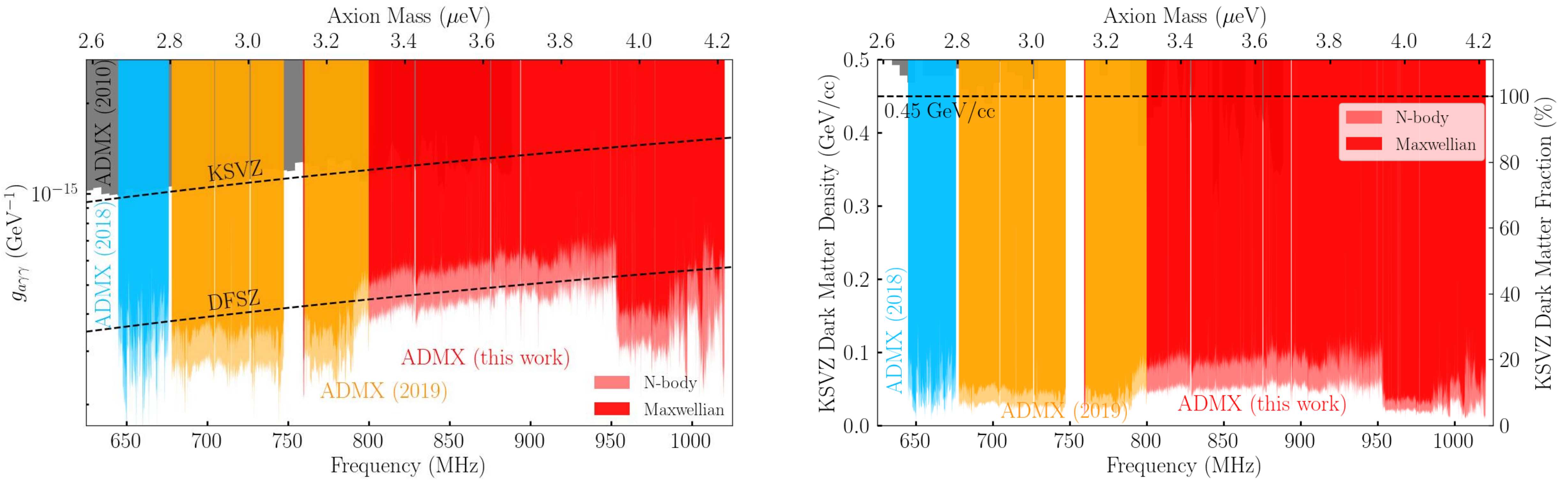
Overlap of axion field (black) and E&M mode field (red)



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

ADMX Recent Published Results

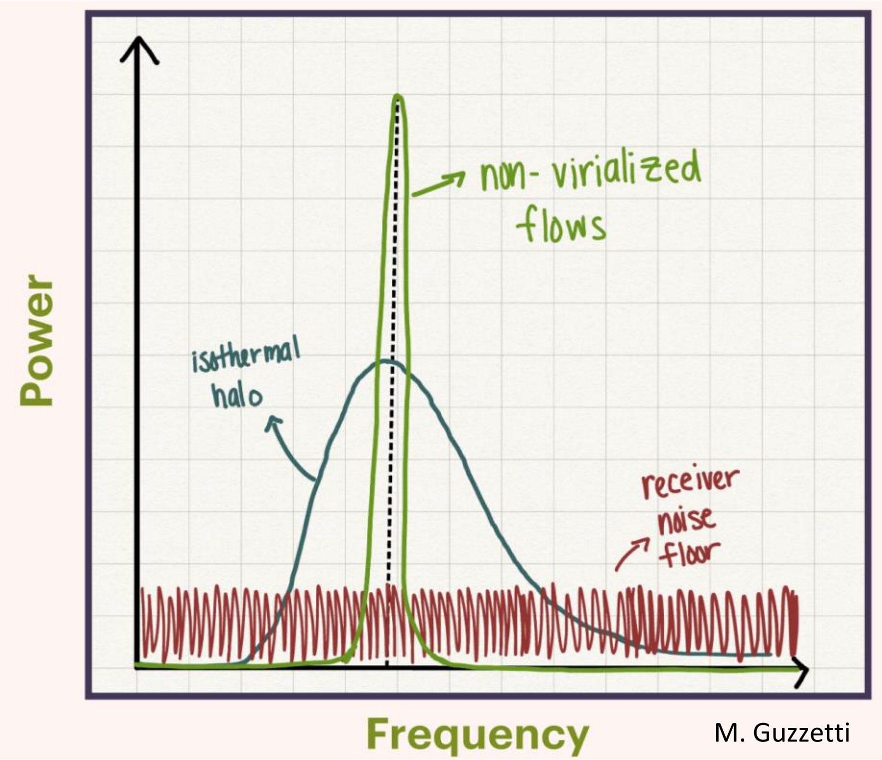
Excluded parameter space over the last 5 years



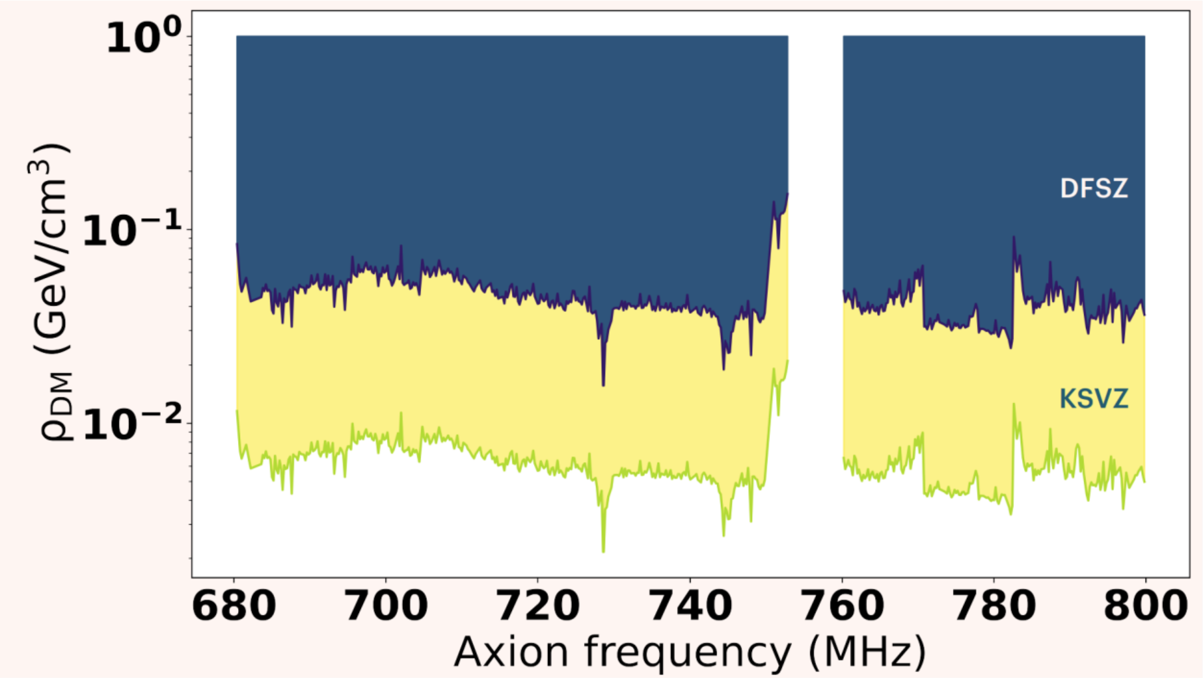
Bartram et al. PRL 127, 261803 (2021)

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



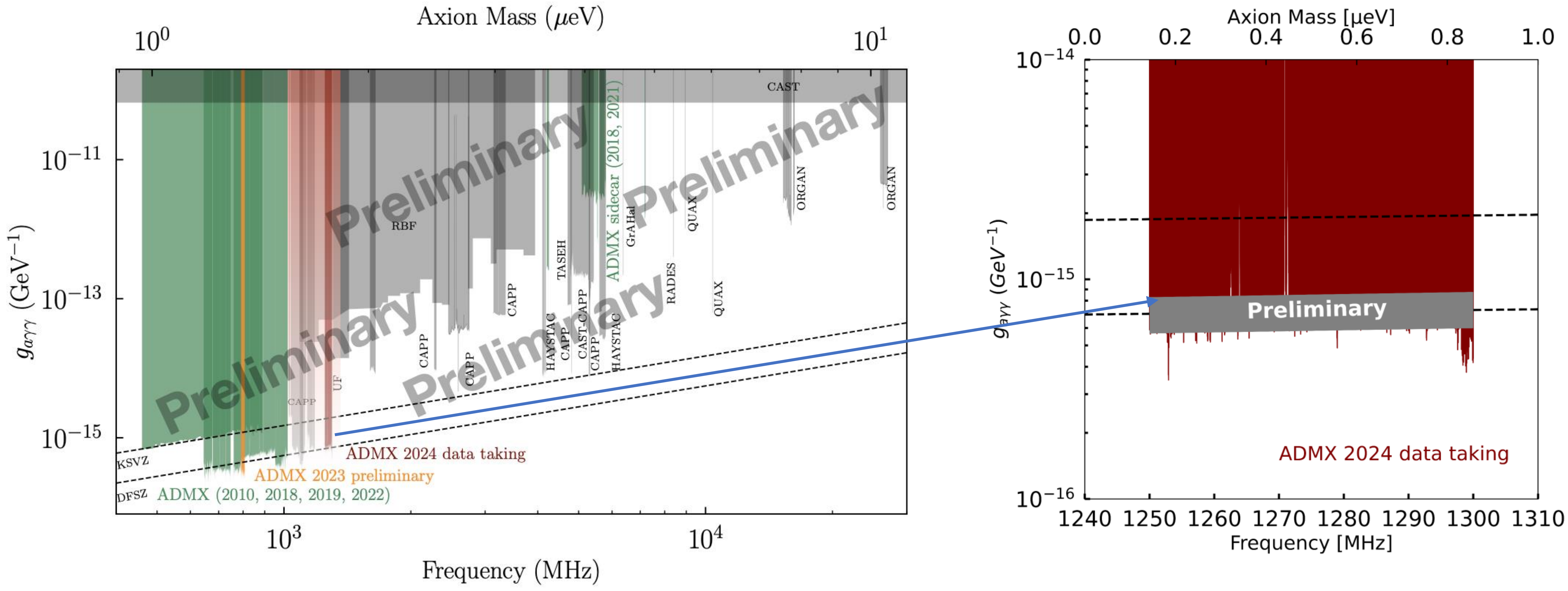
Nonvirialized “extra cold” dark matter produces a narrow signal with a measurable doppler shift



M. Guzzetti, General Exam

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

ADMX 2024 Preliminary Work



D. Zhang, April APS (2024)

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

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

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?