Wave-like Dark Matter and Axions

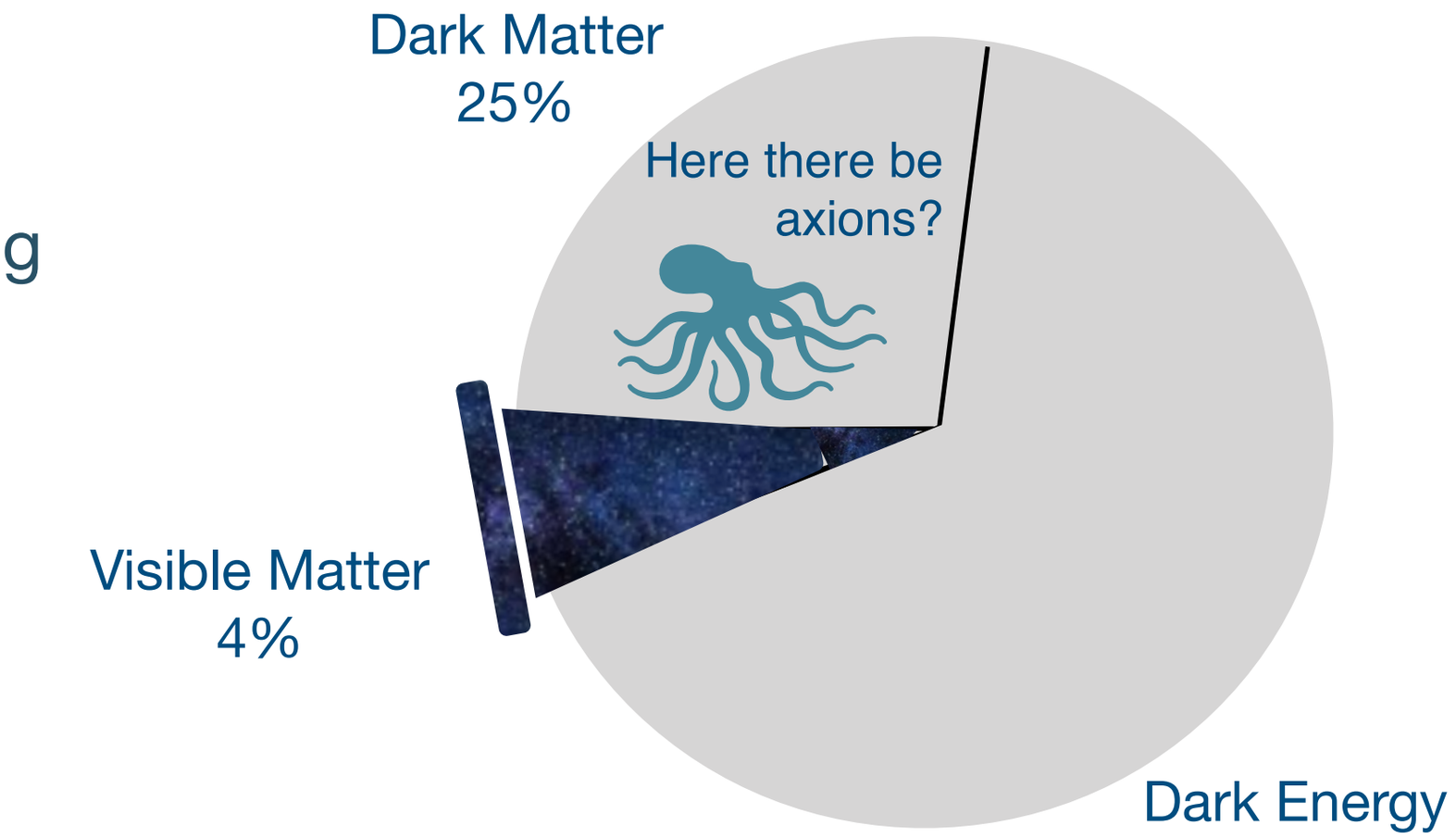
ICHEP Plenary Talk
August 04 2020
Chelsea Bartram
University of Washington

Axions and wave-like dark matter

Indirect astrophysical observations indicate 85% of the total matter composition of the universe is unknown!

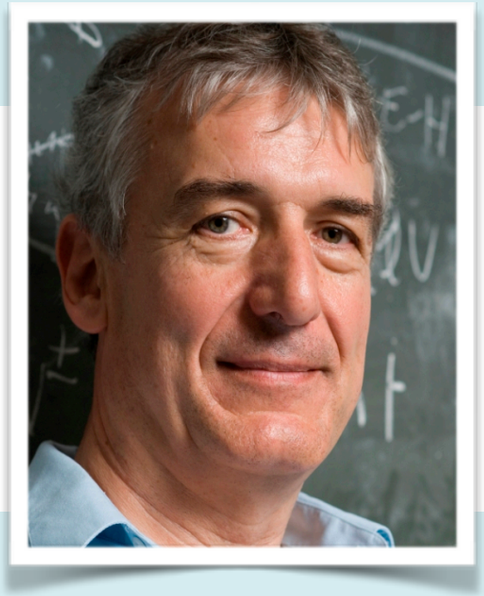
Dark Matter thought to be:

- Cold (non-relativistic)
- Feebly (non) interacting
- Very stable
- Non-baryonic



What is wave-like dark matter?

$$a(\vec{x},t) = \frac{\sqrt{(2\rho_{DM})}}{m_a}\cos\left(m_a t + \mathcal{O}(\nu_{DM})\vec{x}\right)$$



ρ_{DM}: dark matter density
m_a: axion mass

Calculate de Broglie wavelength of axions:

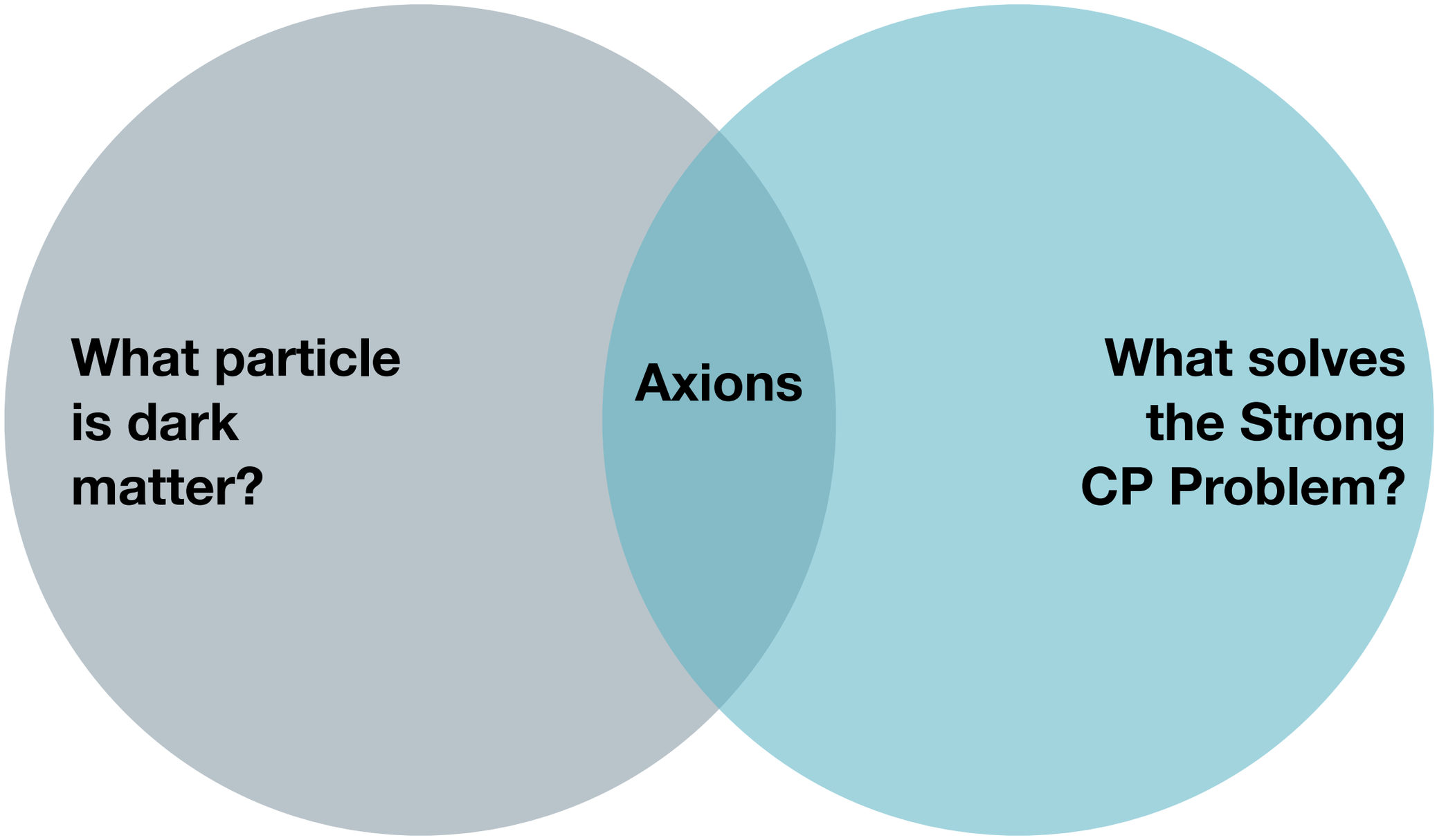
$$\lambda \approx \frac{2\pi}{mv} \approx 100\text{s of m}$$

Wavelength of the Conversion Photon: ~meter

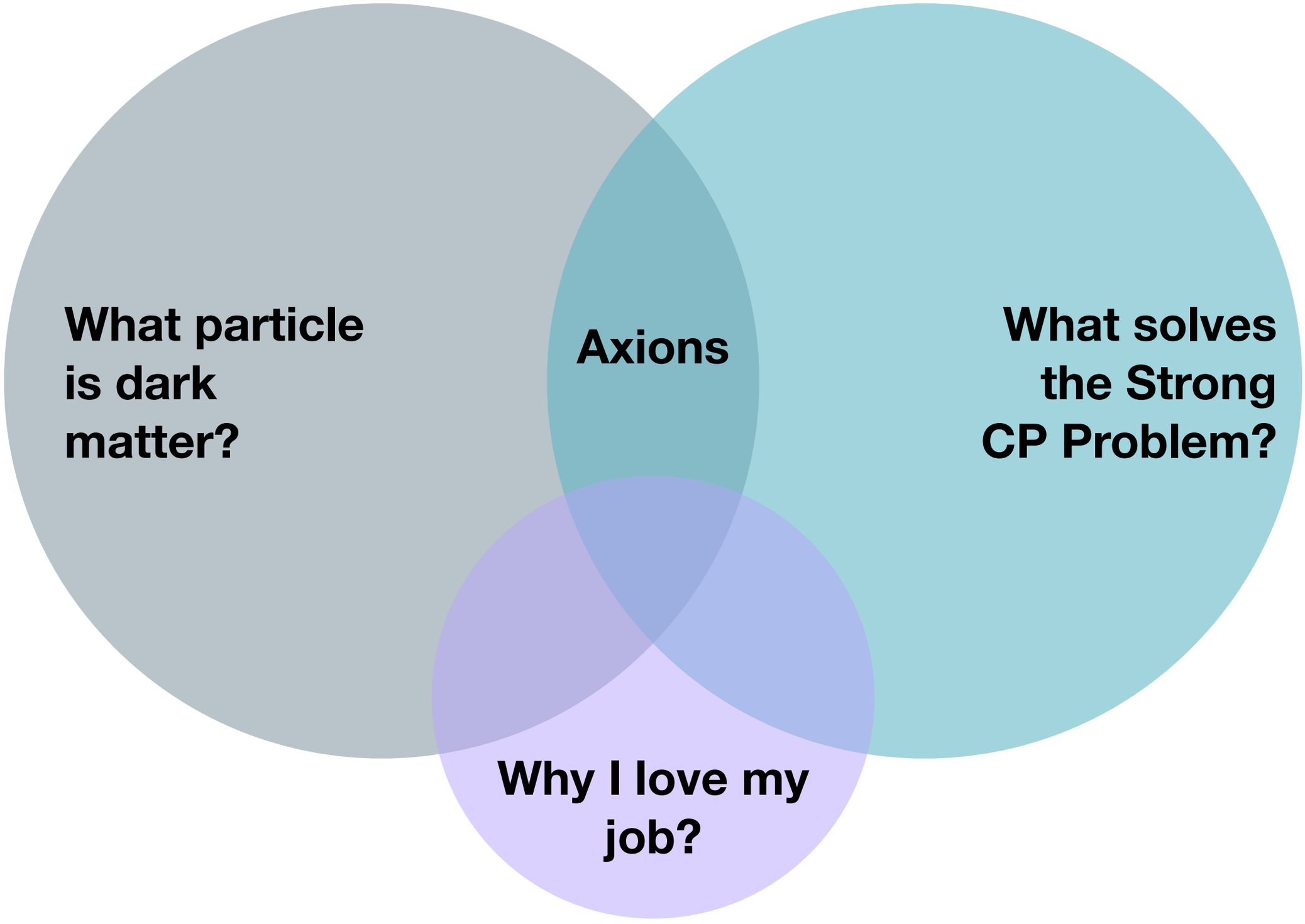
“The axion had been declared invisible”, says theorist Pierre Sikivie. “[I said], let me just calculate how invisible they truly are.”

https://spectrum.ieee.org/aerospace/astrophysics/the-hunt-for-the-invisible-axion

Axions: Good Multi-Taskers
Solve two problems at once!



Ok, maybe three…



Axions and Strong CP Problem

Strong Interactions -should- violate CP due to term in QCD Lagrangian

$$L_\theta = \frac{g^2}{32\pi^2}\theta_{QCD}F_a^{\mu\nu}\tilde{F}_{\mu\nu a}$$

CP-violation in strong interactions ⟶ Neutron EDM

- New limit on neutron EDM published this year!

- After many years searching: Still no neutron EDM!

$$\mathrm{d_n} = (0.0 \pm 1.1_{\mathrm{stat}} \pm 0.2_{\mathrm{sys}}) \times 10^{-26}\,\mathrm{e{\cdot}cm}$$

C. Abel et al.
Phys. Rev. Lett. 124, 081803 — Published 28 February 2020

Axions and Strong CP Problem

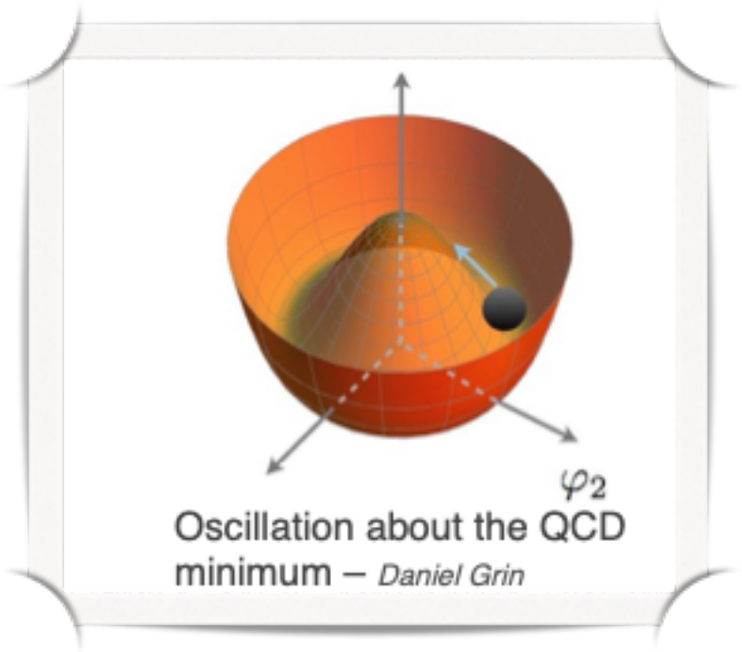
$$L_\theta = \frac{g^2}{32\pi^2}\theta_{QCD}F_a^{\mu\nu}\tilde{F}_{\mu\nu a}$$

Helen Quinn

Roberto Peccei
1942-2020

- Peccei-Quinn Solution to Strong CP Problem: Θ is now a dynamical variable which relaxes to zero at critical temperature.

- PQ Mechanism predicts a pseudo scalar boson which is the axion! (Weinberg, Wilçek)



Theoretical Constraints

Lower bound set by size of dark matter halo size of dwarf galaxies

Upper bound set by SN1987A and white dwarf cooling time

eV

10^{-22} 10^{-18} 10^{-14} 10^{-10} 10^{-6} 10^{-2}

10^{-8} 10^{-4} 1 10^{4} 10^{8} 10^{12}

Hz

Pre-inflation
PQ phase transition

Post-inflation
PQ phase transition

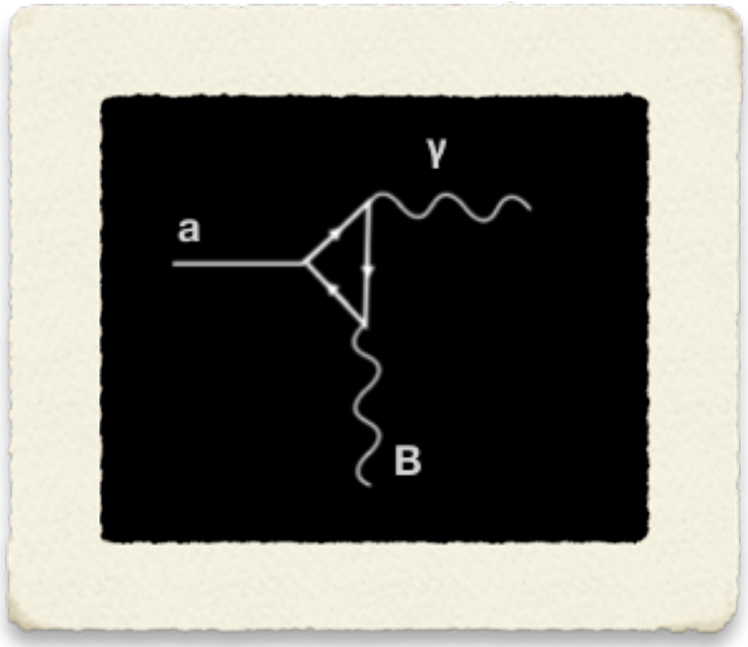
PDG https://arxiv.org/pdf/1710.05413.pdf

Adaptation of L. Winslow DPF Slide

Types of Axions

QCD axion:

- 1-100 μeV
- Two classes of models:
  - KSVZ (Kim-Shifman-Vainshtein-Zakharov):
    - couples to leptons
    - g_γ=0.97
  - DFSZ (Dine-Fischler-Srednicki-Zhitnitsky):
    - couples to quarks and leptons
    - g_γ=0.36



Detection Methods Depend on Axion Interactions

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

Coupling to photons

Causes electric dipole moments (EDMs) in nuclei/atoms/ molecules

Coupling to nucleon EDM

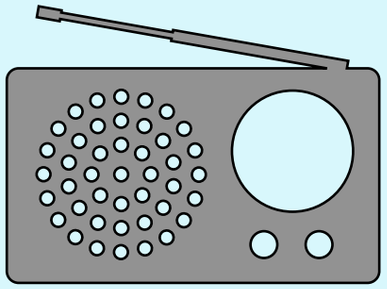
Coupling to axion nuclear moment

Creates spin-dependent energy shifts/spin precession in fermions

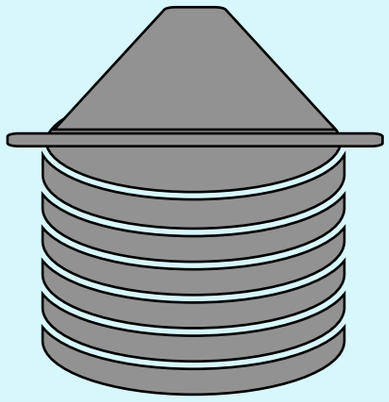
Coupling to axial electron moment

Axioelectric effect, Analogous to photoelectric effect

Adapted from L. Winslow DPF slide and Y. Kahn, See Graham and Rajendran, Phys.Rev. D88 (2013) 035023



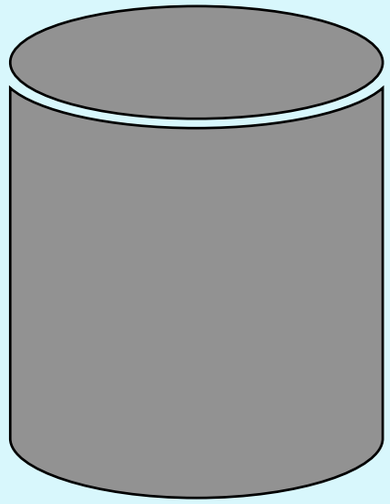
DM Radio/ABRA/LC Circuit



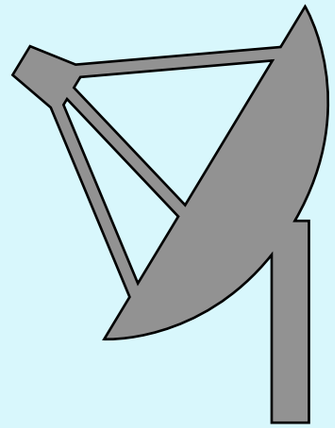
Dielectric Haloscopes
MADMAX, Orpheus

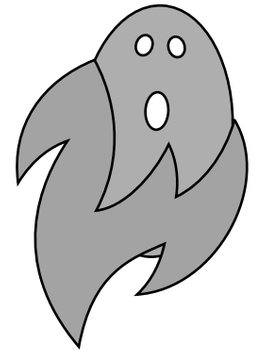
Coupling to photons

Haloscopes
ADMX
Haystac
CAPP-8TB



Helioscopes
CAST, IAXO
Dish Antennas
BRASS

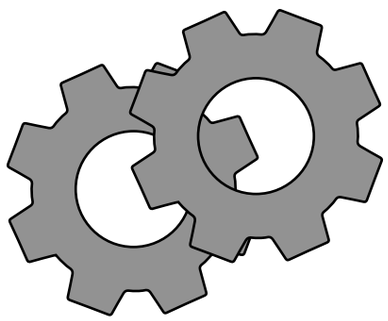




CASPEr-electric

Coupling to nucleon EDM

ARIADNE



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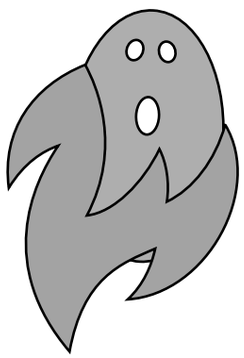
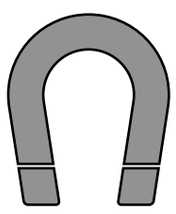
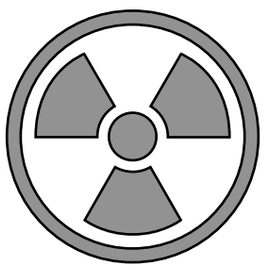


Coupling to axion nuclear moment

Torsion Experiments

QUAX

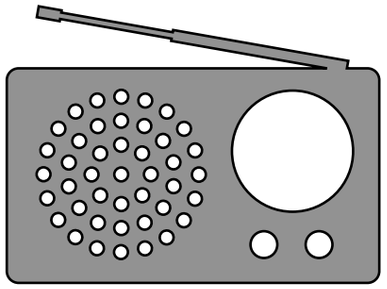




LUX

XENON1T

Coupling to axial electric moment



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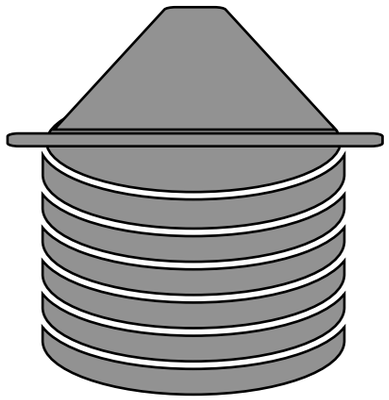

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MADMAX, Orpheus

Coupling to photons

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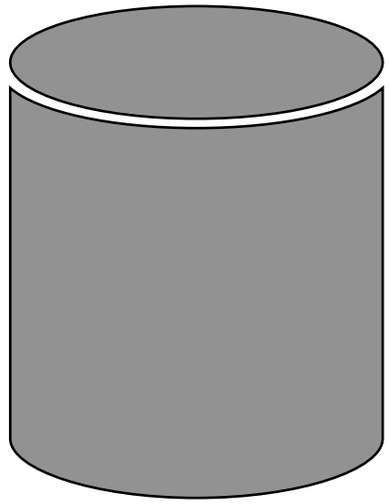

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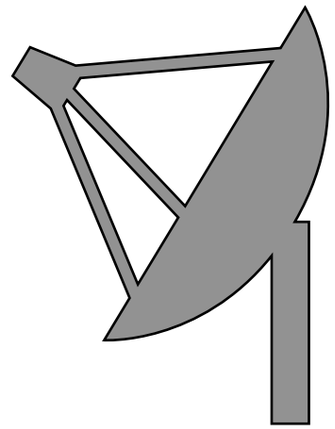
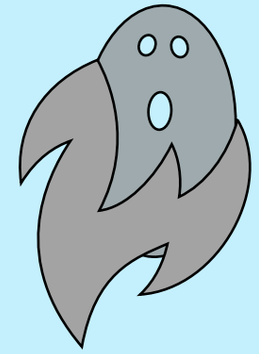
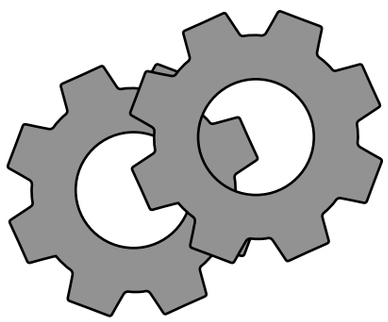




CASPEr-electric

Coupling to nucleon EDM

ARIADNE



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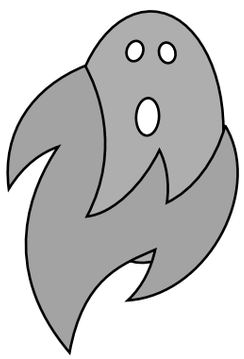

Coupling to axion nuclear moment

Torsion Experiments

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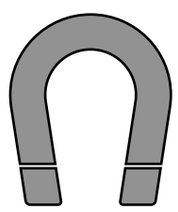
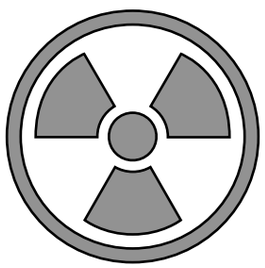
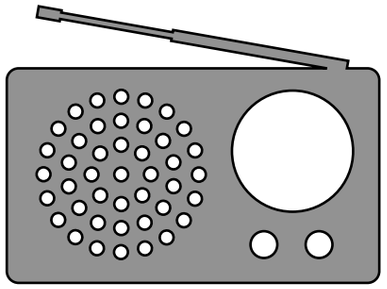




LUX

XENON1T

Coupling to axial electric moment



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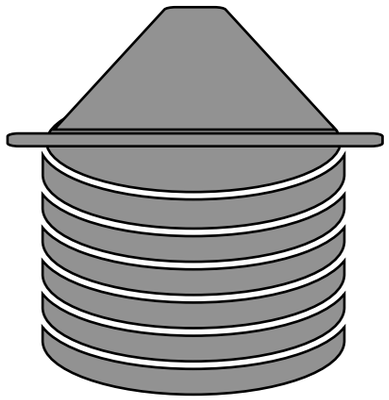

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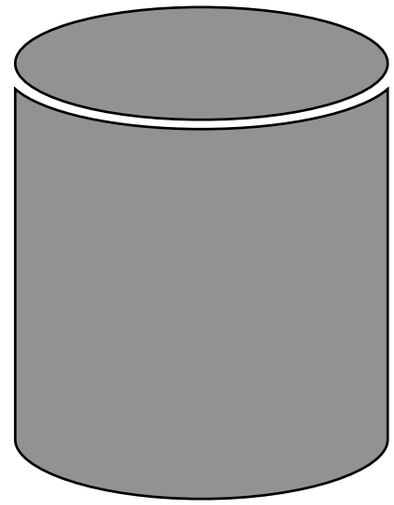

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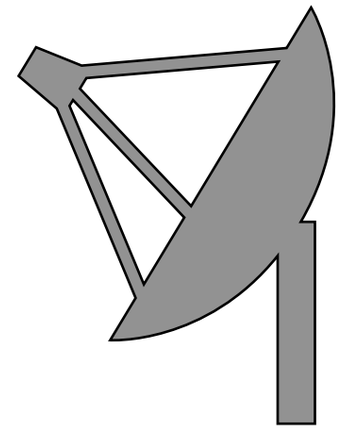

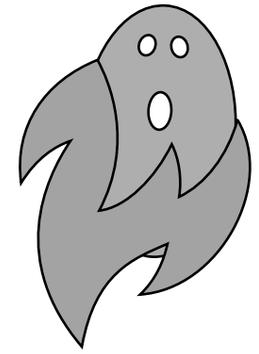

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Coupling to nucleon EDM

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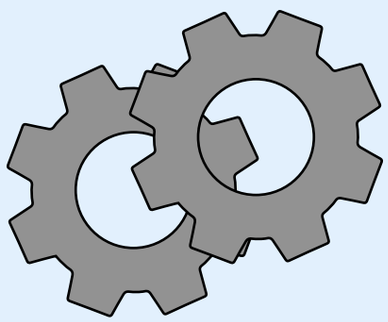

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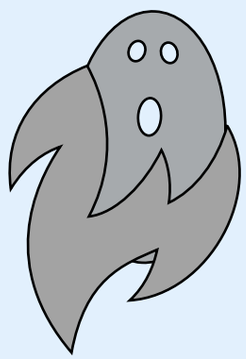
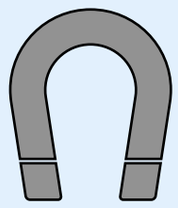


Coupling to axion nuclear moment

Torsion Experiments



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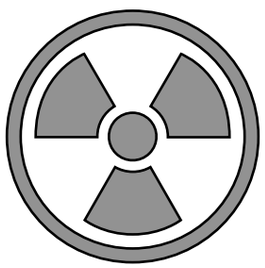
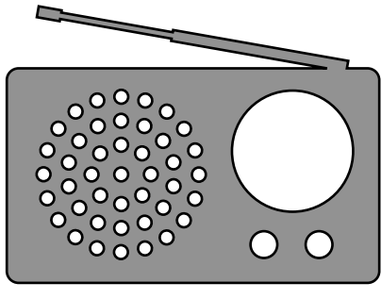


LUX

XENON1T

Coupling to axial electric moment



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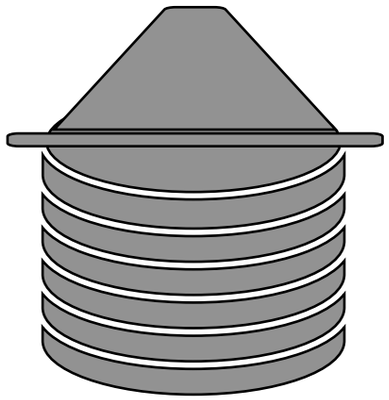

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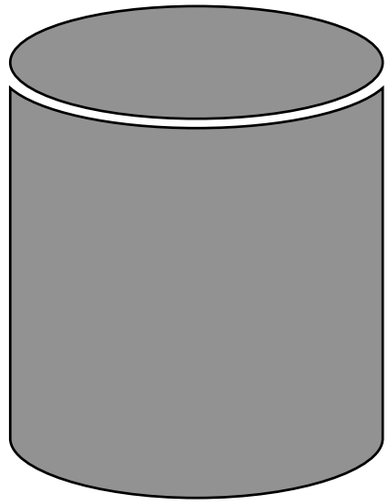

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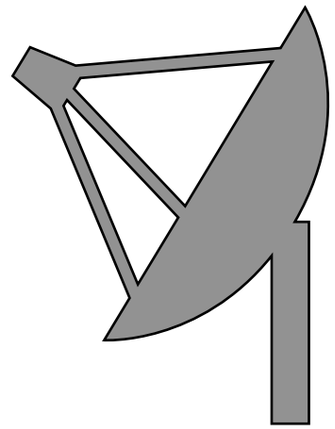

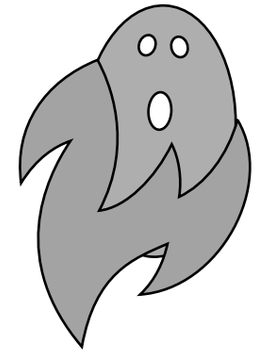

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Coupling to nucleon EDM

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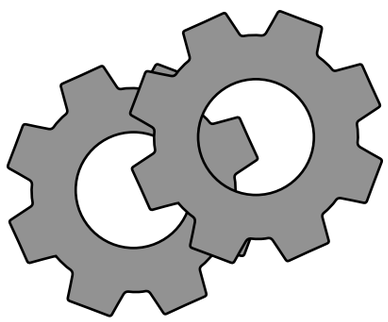
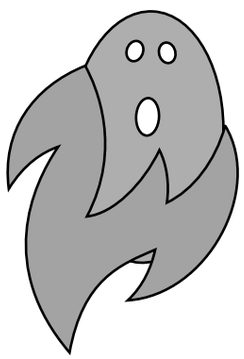


CASPEr-wind



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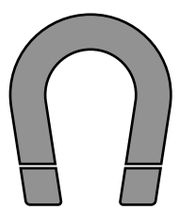
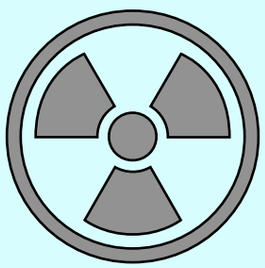




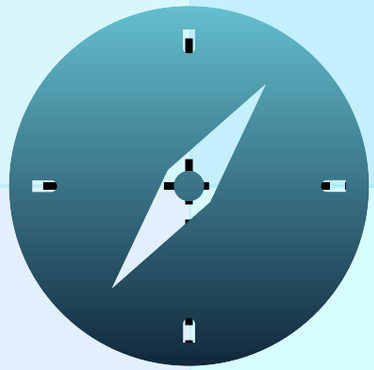
LUX

XENON1T

Coupling to axial electric moment

Quantum Computing

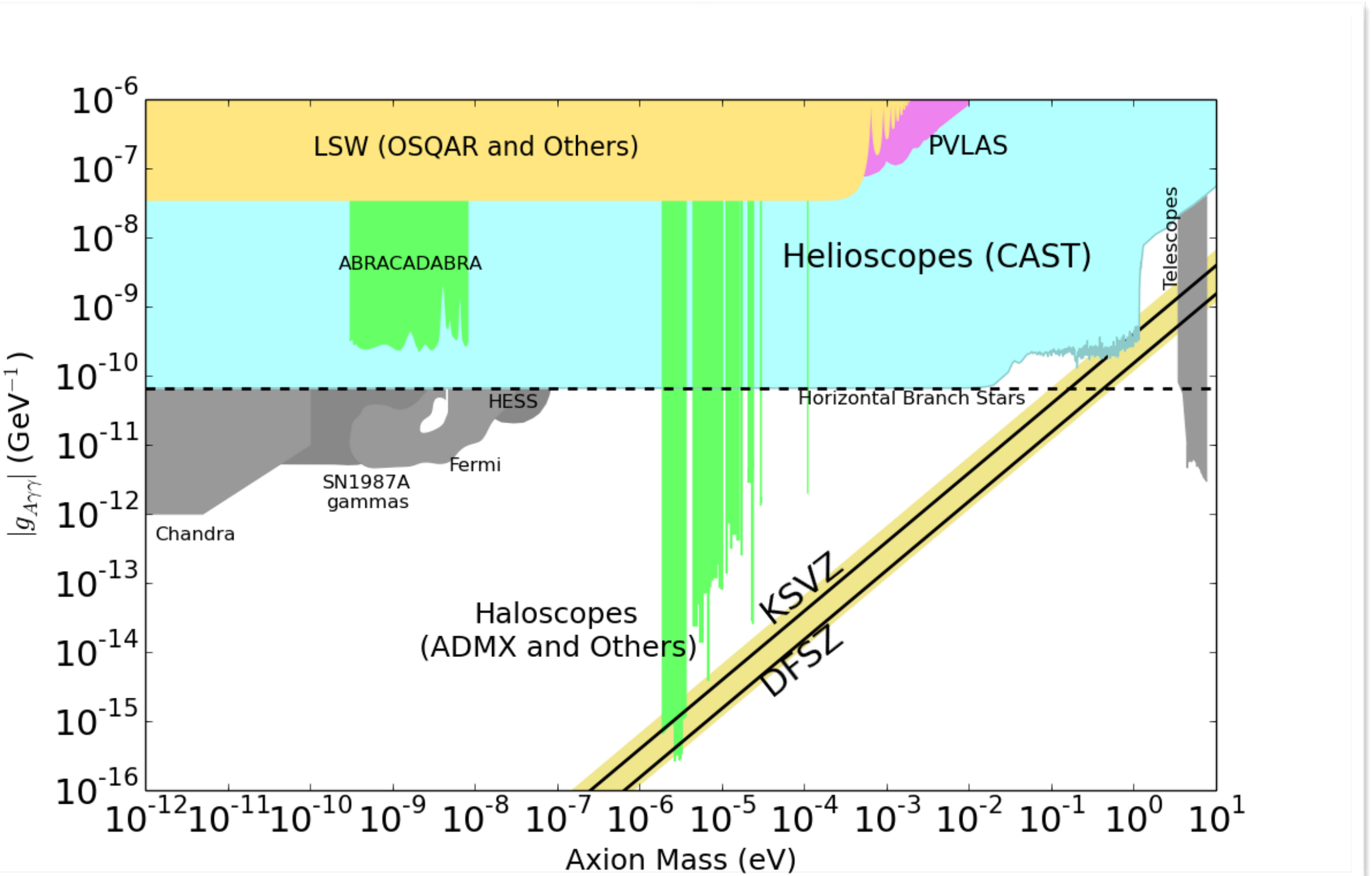
Cryogenics



Microwave Electronics

High Magnetic Fields

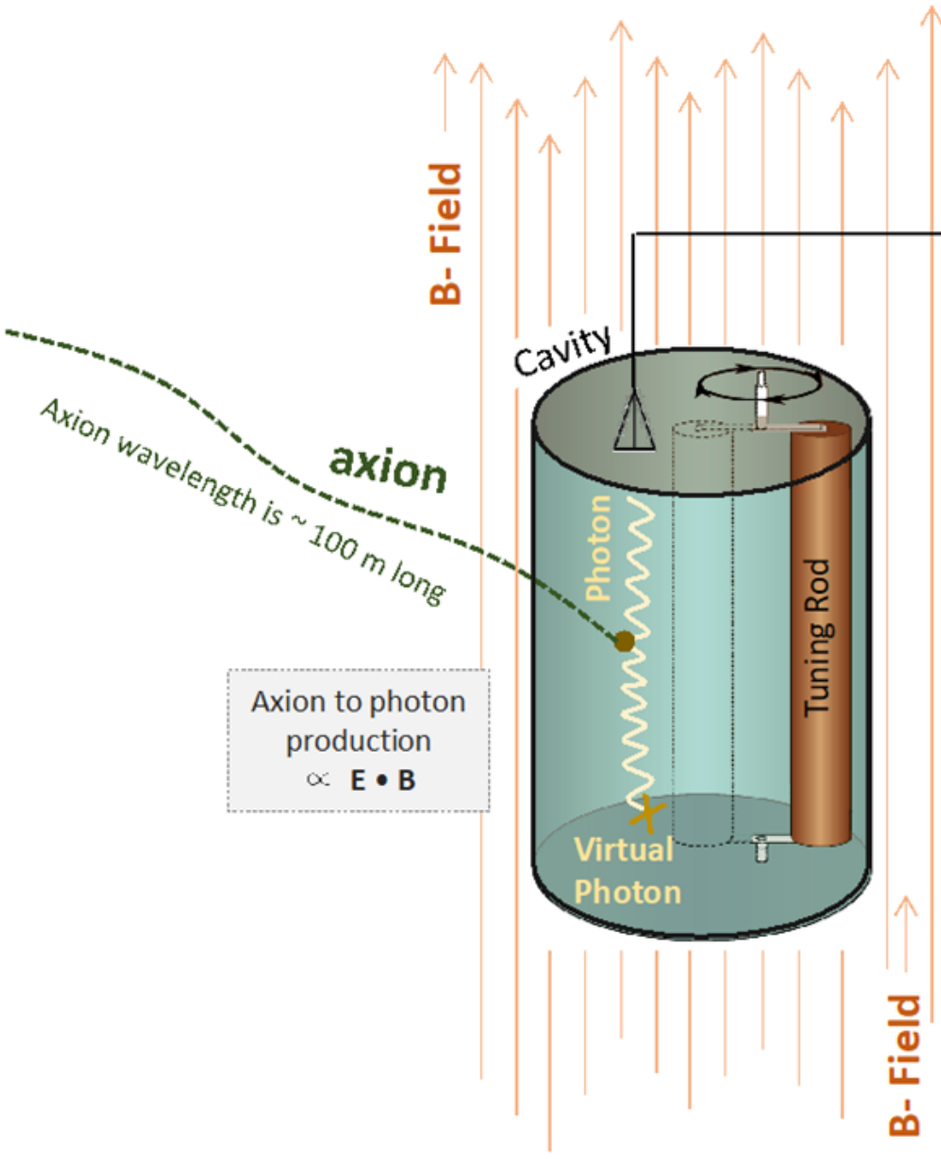
Axion-like Particles Exclusion Plot

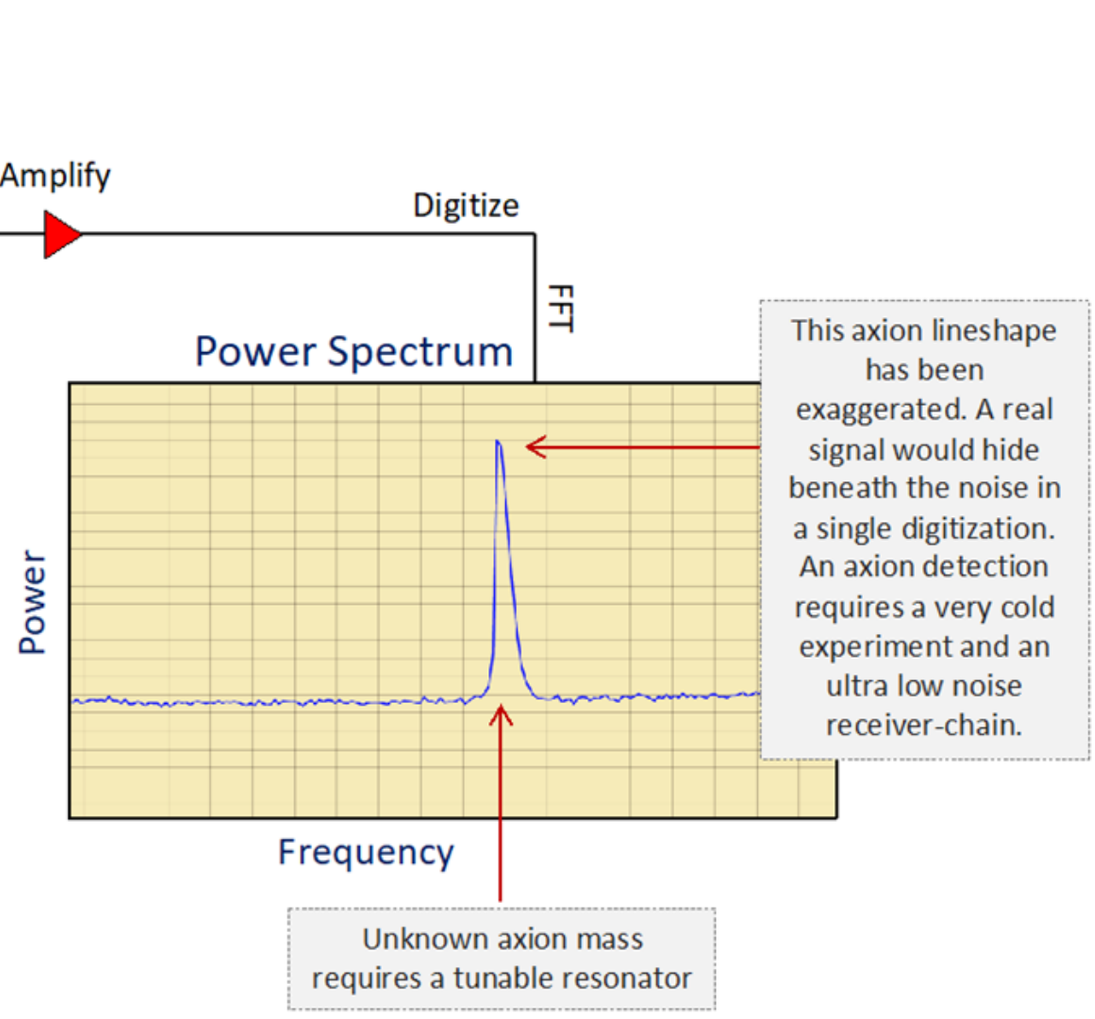


Axion Haloscopes

All use microwave cavity in magnetic field

Relies on inverse Primakoff effect and resonant enhancement of cavity





Scan Rate: Figure of Merit for Haloscope Search

$$\frac{df}{dt} \approx 1.68 \frac{\mathrm{GHz}}{\mathrm{yr}} \left(\frac{g_\gamma}{0.36}\right)^4 \left(\frac{f}{1\ \mathrm{GHz}}\right)^2 \left(\frac{\rho_o}{0.45\ \mathrm{GeV/cc}}\right)^2 \left(\frac{5}{\mathrm{SNR}}\right)^2 \left(\frac{B_0}{8}\right)^4 \left(\frac{V}{100\ \mathrm{l}}\right)^2 \left(\frac{Q_L}{10^5}\right) \left(\frac{C_{010}}{0.5}\right)^2 \left(\frac{0.2}{T_{sys}}\right)^2$$

Maximize

- B Field
- Volume
- Quality Factor
- Form Factor

Can't Control

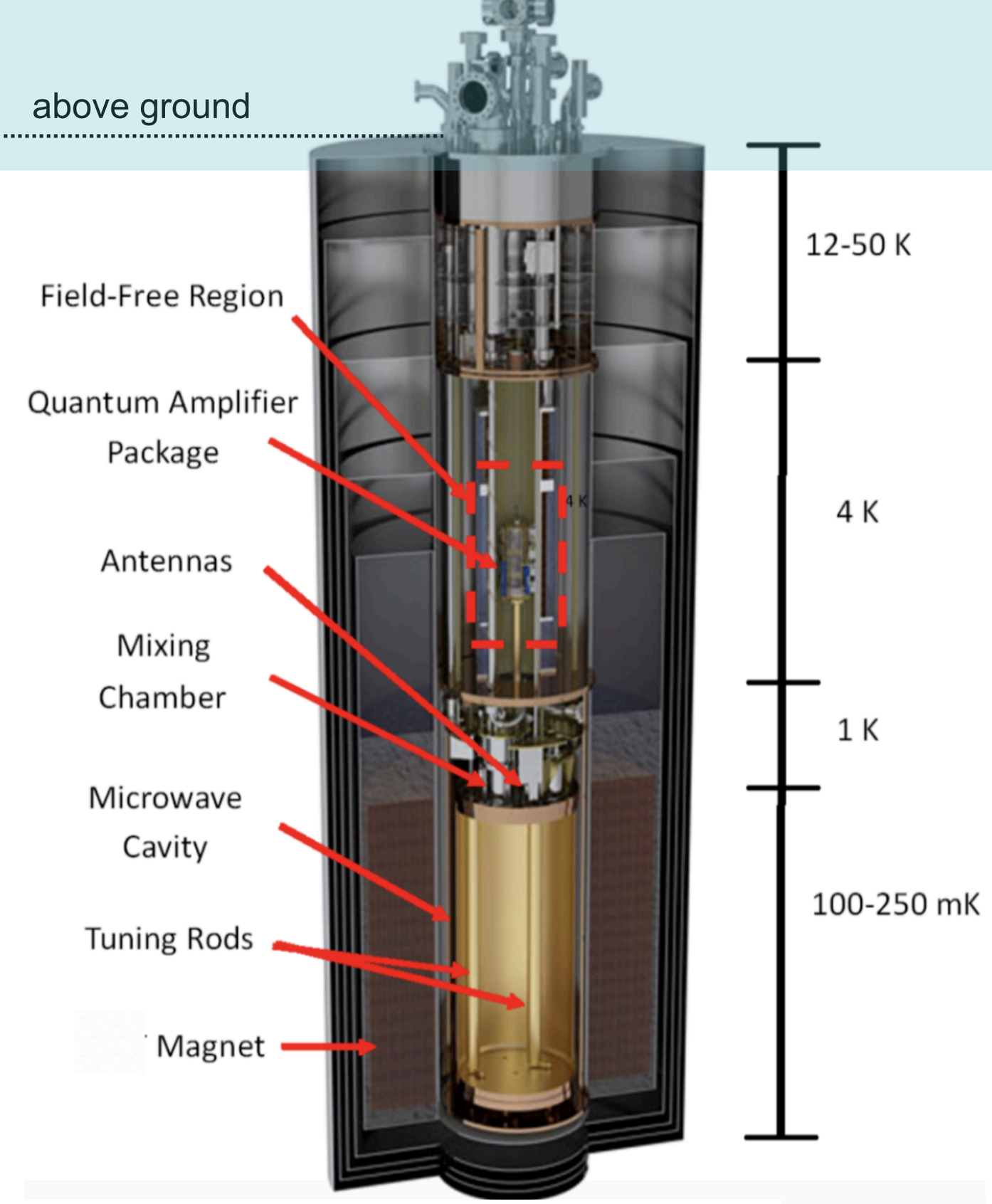
- Frequency
- Coupling
- Dark Matter Density

Minimize

- System noise:
- Amplifier Noise
- Physical Noise

ADMX Haloscope

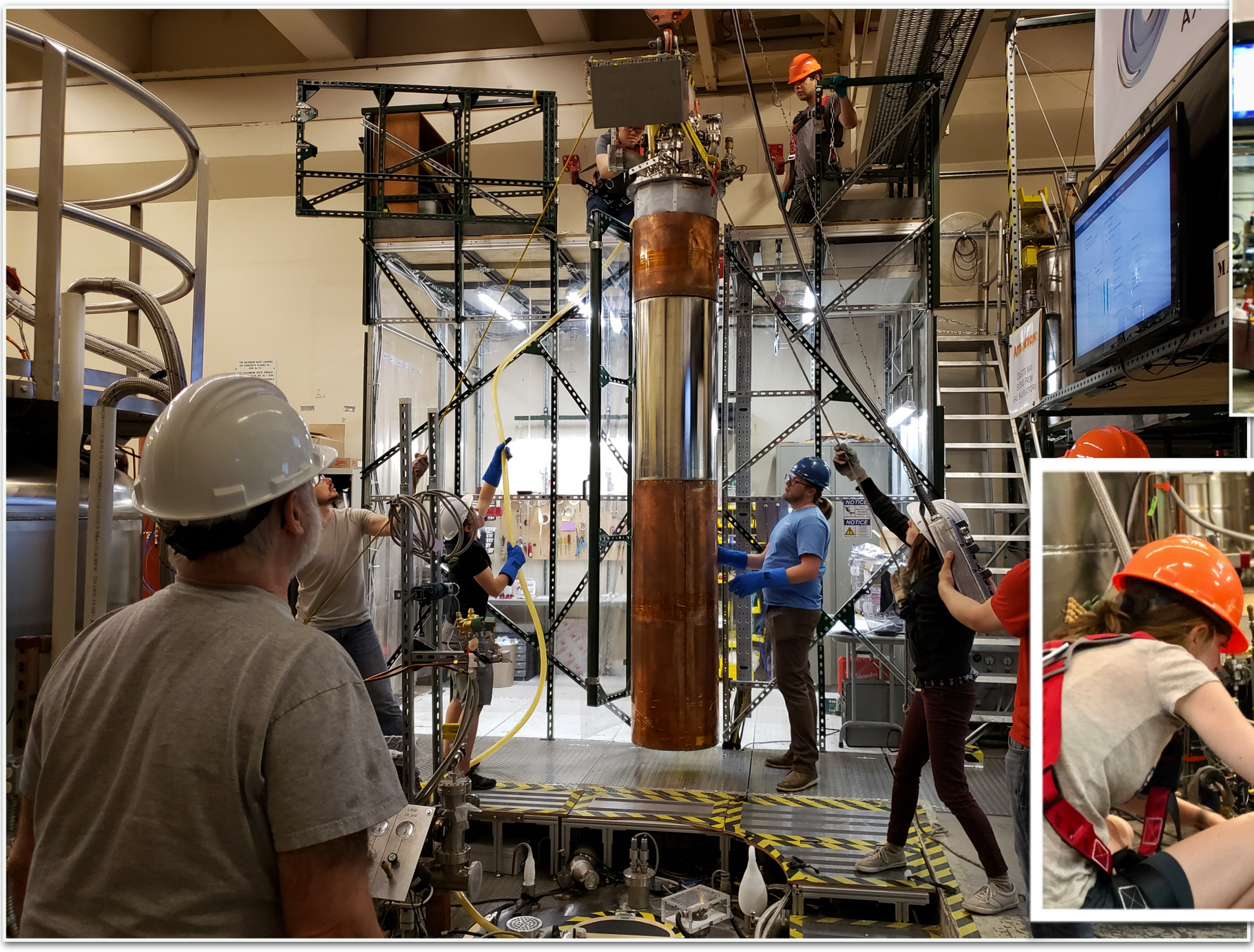
- Dil Fridge: Reaches ~100 mK
- Superconducting magnet: ~can reach up to 8 T
- Quantum electronics: Josephson Parametric Amplifier (JPA)
- Field cancellation coil
- Microwave cavity and electronics



Axion Dark Matter eXperiment collaboration

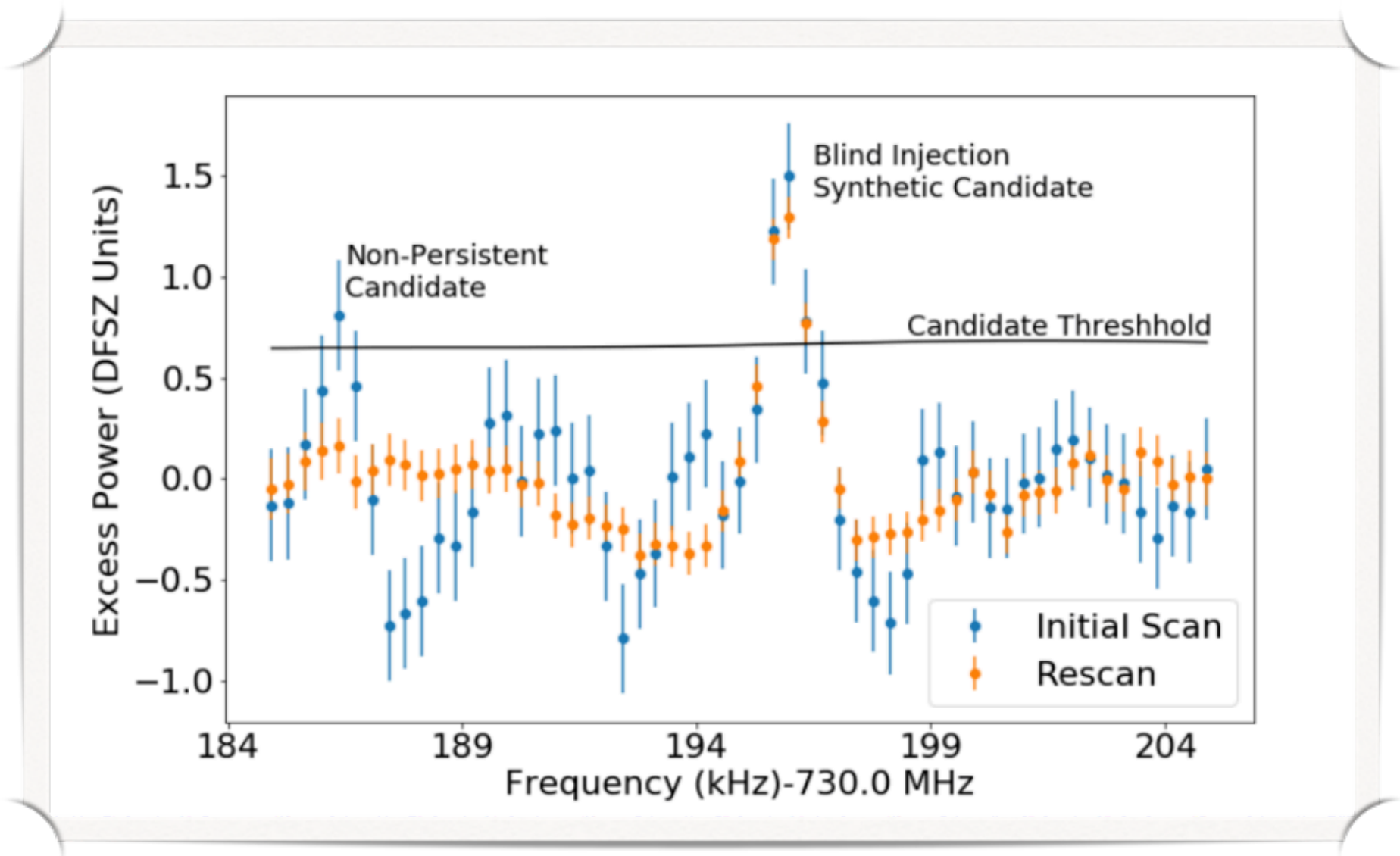
This work was supported by the U.S. Department of Energy through Grants No DE-SC0009800, No. DE-SC0009723, No. DE-SC0010296, No. DE-SC0010280, No. DE-SC0011665, No. DEFG02-97ER41029, No. DE-FG02-96ER40956, No. DEAC52-07NA27344, No. DE-C03-76SF00098 and No. DE-SC0017987. Fermilab is a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359. Additional support was provided by the Heising-Simons Foundation and by the Lawrence Livermore National Laboratory and Pacific Northwest National Laboratory LDRD offices.

ADMX Rigging Operation

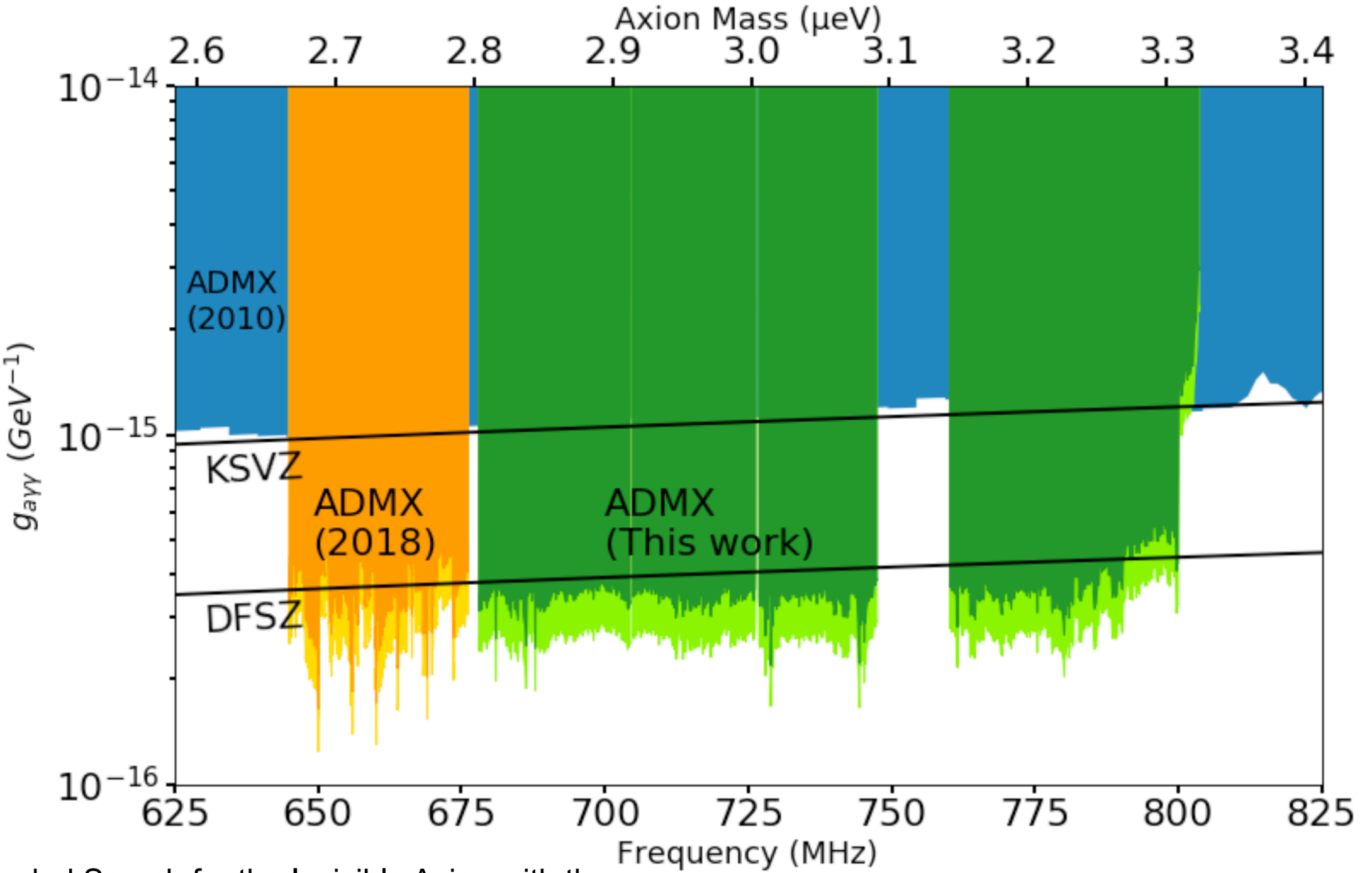


Hardware Synthetic Axion Injections

Excellent Confirmation of Ability To Detect DFSZ Axions!

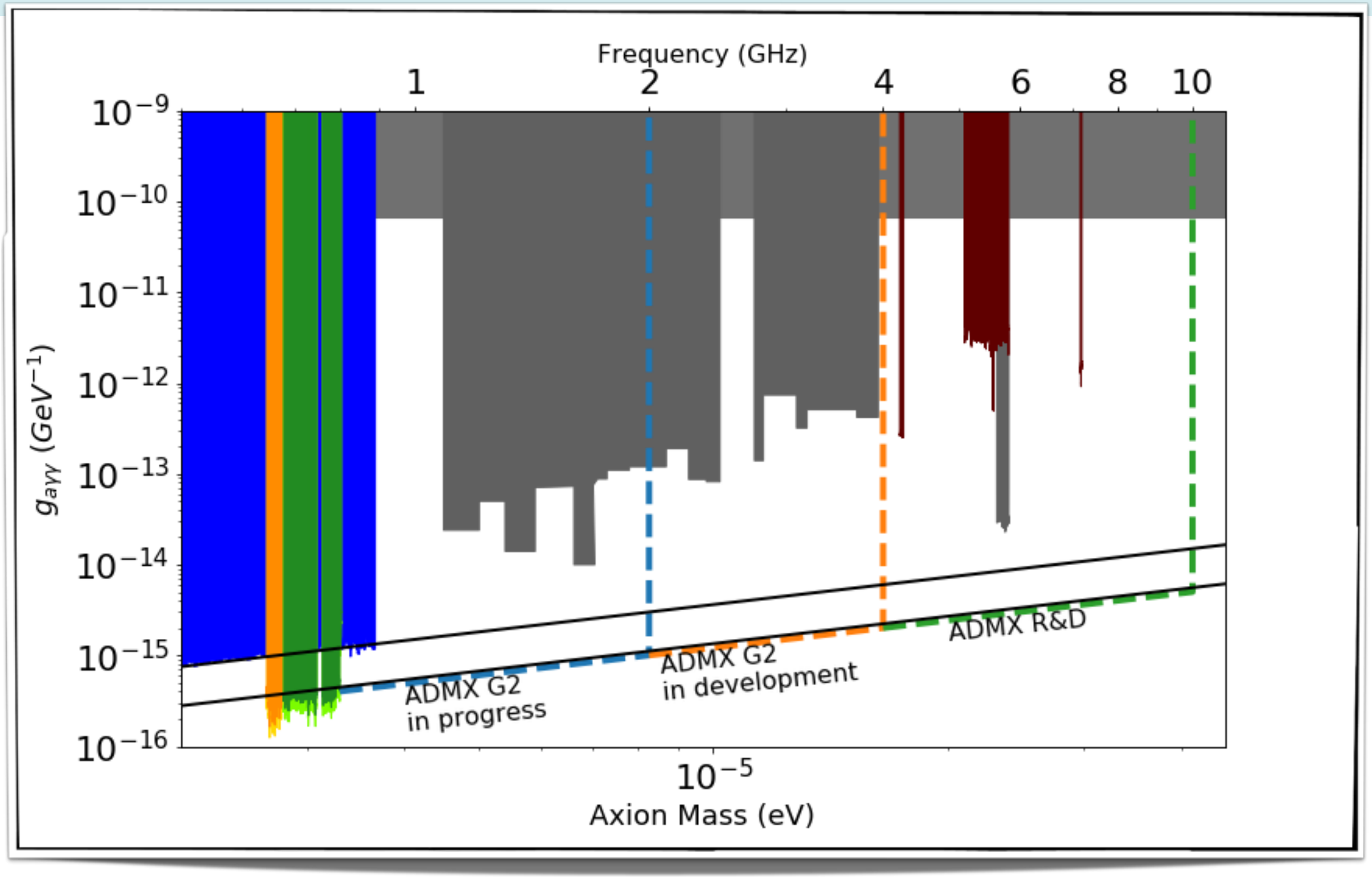


ADMX Limits

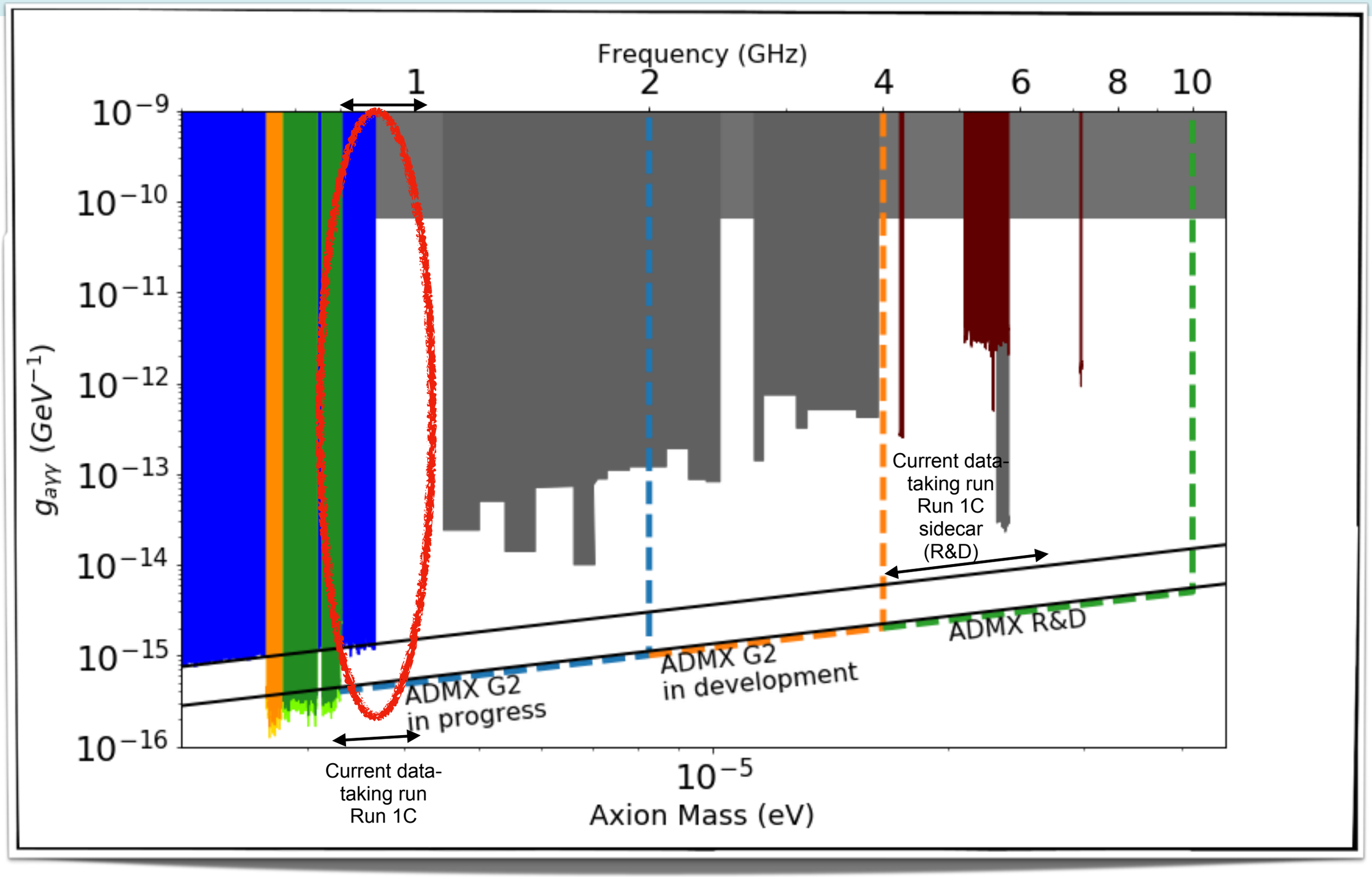


Extended Search for the Invisible Axion with the Axion Dark Matter Experiment
T. Braine et al. (ADMX Collaboration)
Phys. Rev. Lett. 124, 101303 — Published 11 March 2020

Projected ADMX Sensitivity

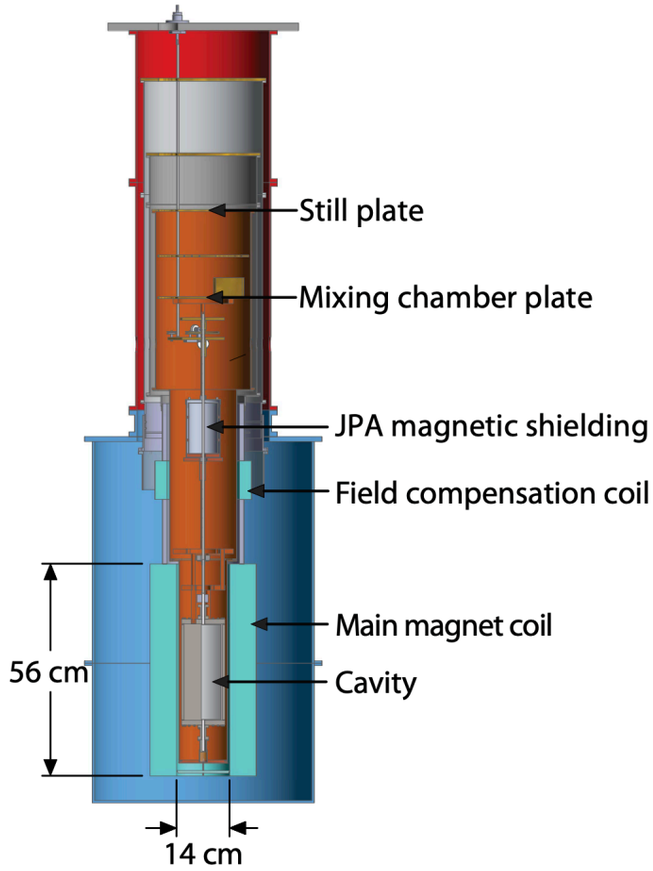


Projected ADMX Sensitivity

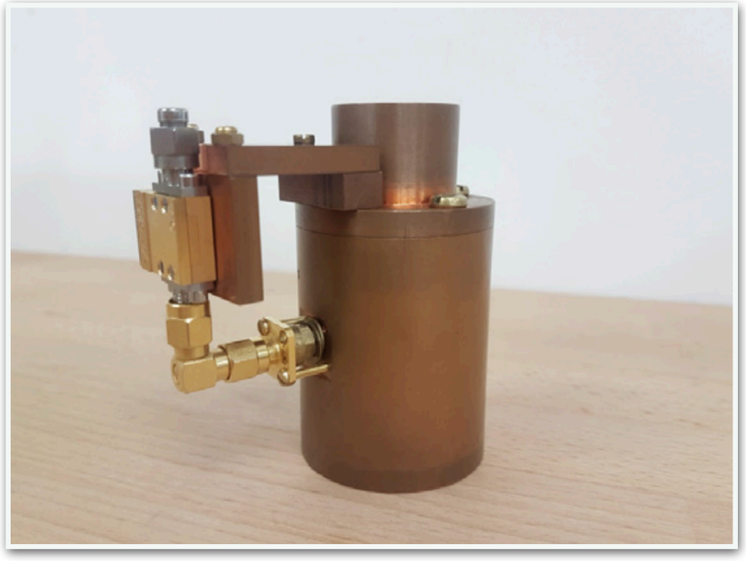


Other haloscopes

- Haystac: Yale
  - Exploring higher frequency axions
  - Using squeezed state receiver:
  - Phys. Rev. X 9, 021023 (2019)
  - Exploring Bayesian techniques:
  - Phys. Rev. D 101, 123011 (2020)
  - Phase 1 results complete
  - Phase 2 underway

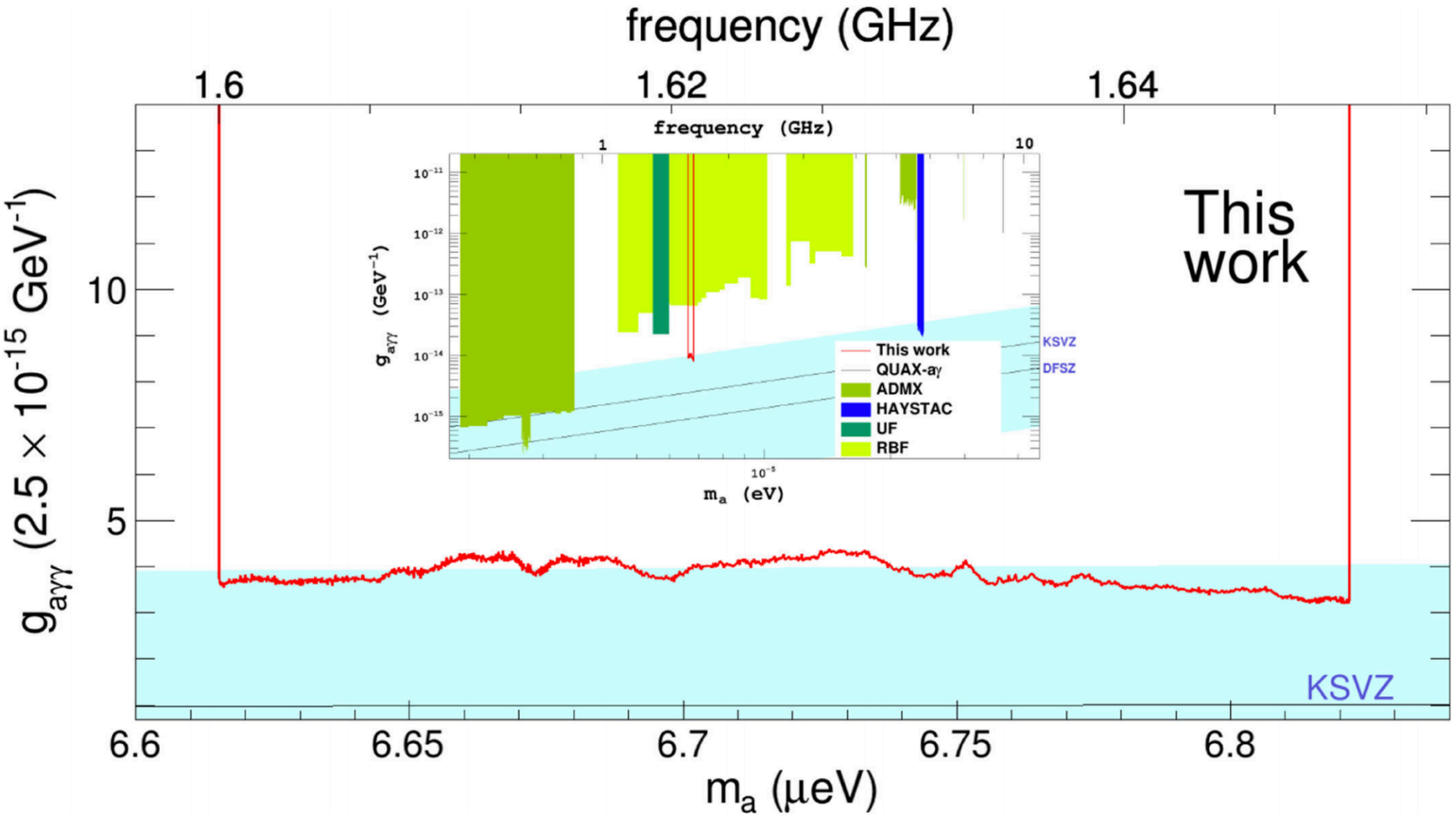


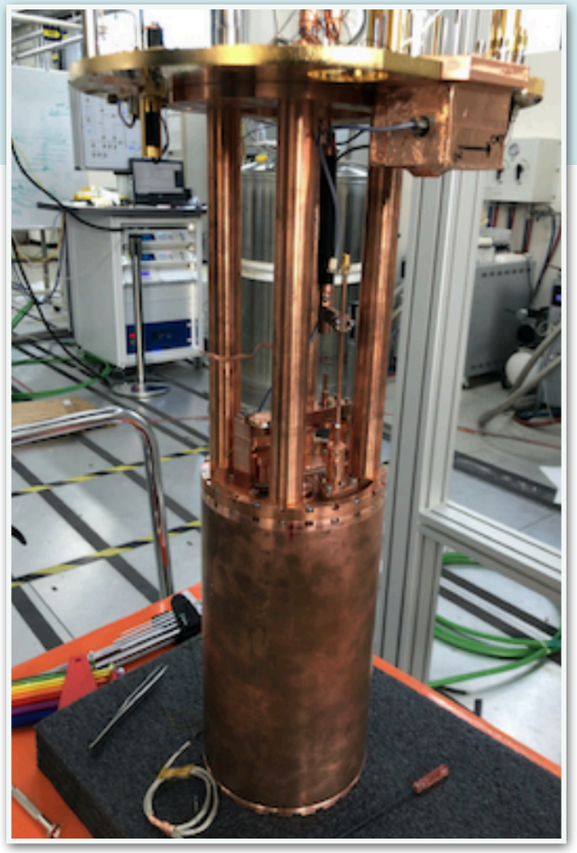
- ORGAN: University of Western Australia
  - Higher frequencies 26.6 ~GHz (110 ueV)
  - Physics of the Dark Universe, Volume 18, December 2017, Pages 67-72



CAPP-8TB

- Exploring frequency range near 6.62-6.82 μeV (1.6-1.65 GHz)



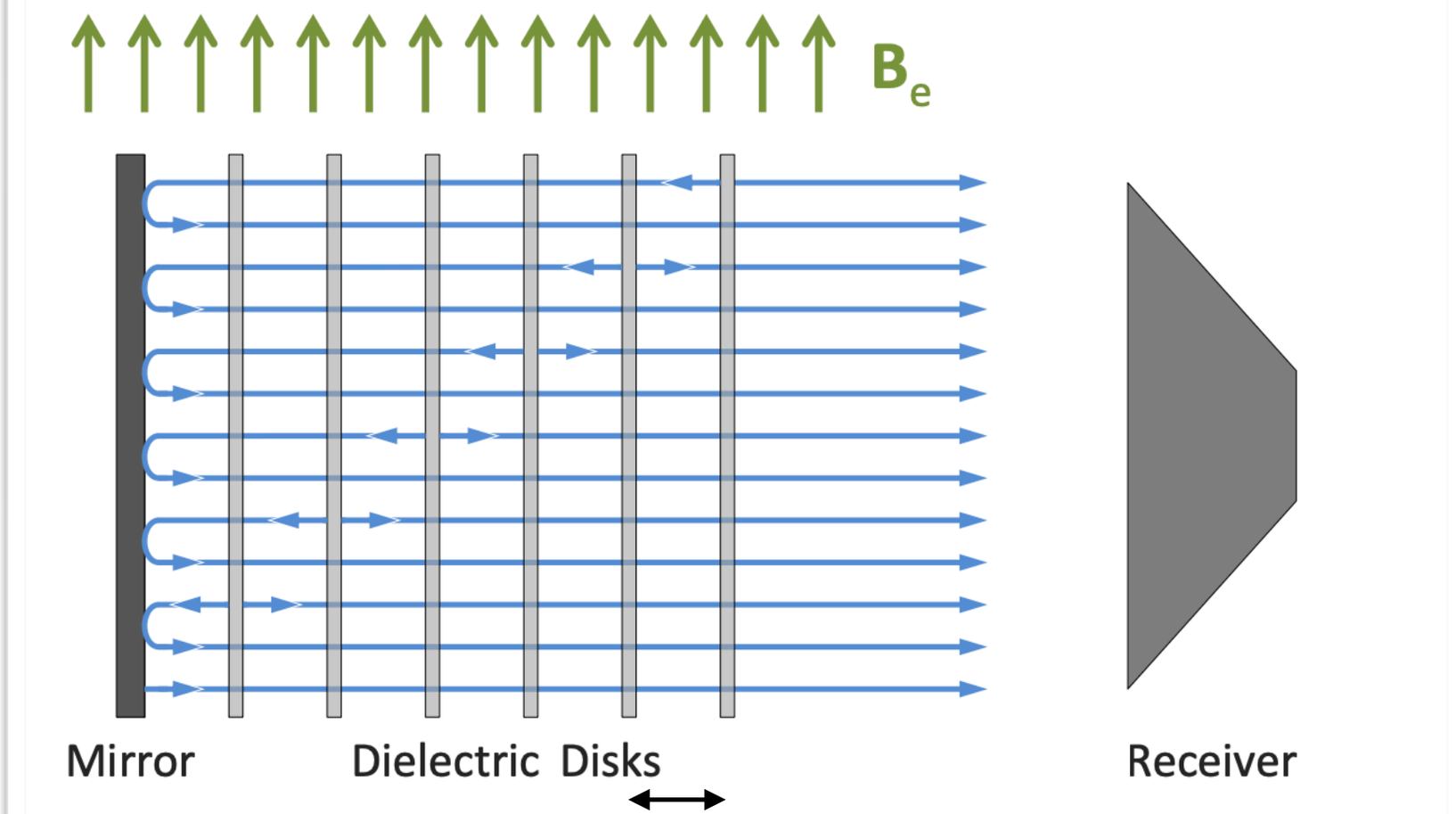


New technical paper

https://arxiv.org/pdf/2007.07468.pdf

Axion Dark Matter Search around 6.7 μeV
S. Lee, S. Ahn, J. Choi, B. R. Ko, Y. K. Semertzidis
Phys. Rev. Lett. 124, 101802 —Published 13 March 2020

Dielectric Haloscopes: MADMAX



- Will probe 40-400 μeV range (10-100 GHz)
- 10 T field
- ~80 disks
- Prototype phase using dipole magnet at CERN
- Status Report:

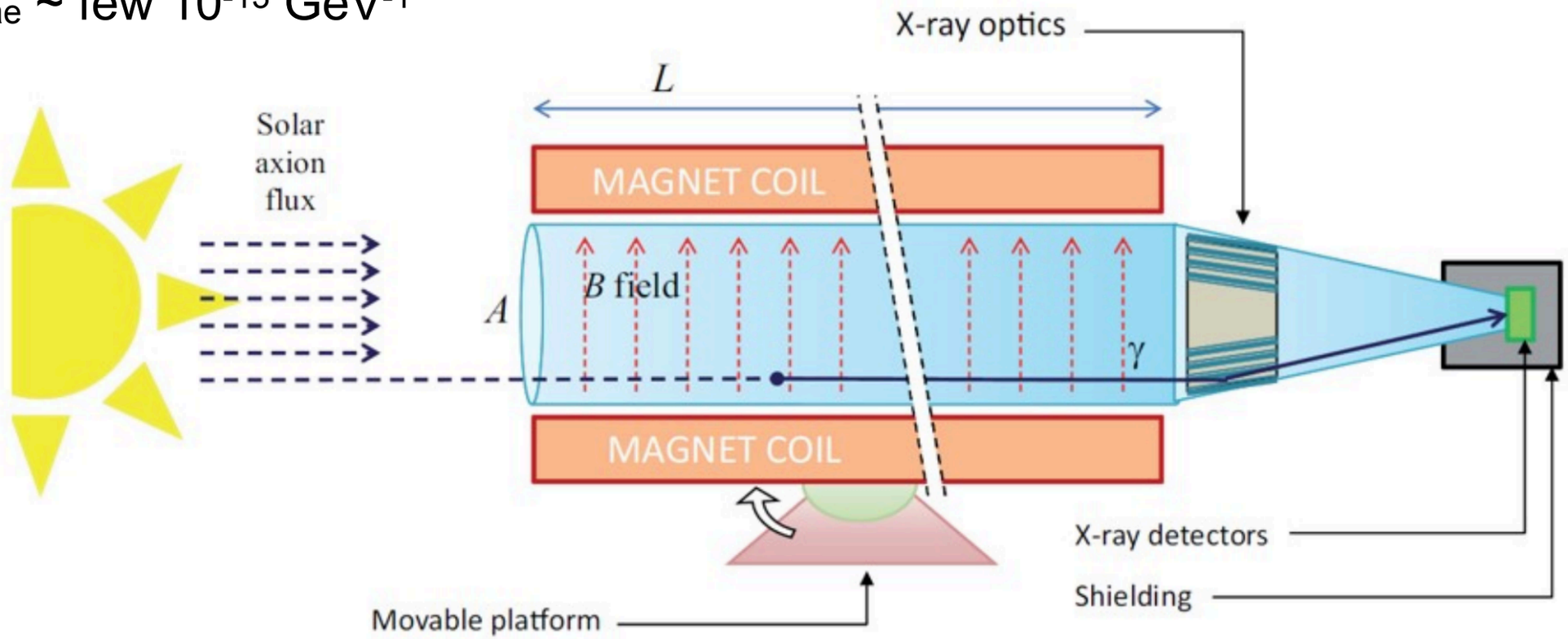
https://arxiv.org/abs/1901.07401

Power enhancement from EM waves emitted at the disk boundaries

Stefan Knirck and MADMAX interest group 2020 J. Phys.: Conf. Ser. 1342 012097
B. Majorovits and MADMAX interest groupt 2020 J. Phys.: Conf. Ser. 1342 012098

Helioscopes: IAXO

- Searching for axions/ALPs coming from the Sun
- IAXO requires stronger field and larger volume to improve sensitivity compared to its predecessor, CAST
- IAXO will probe unexplored ALP space https://arxiv.org/pdf/1904.09155.pdf
  - $g_{a\gamma}$ ~ few 10^{-12} GeV^{-1}
  - g_{ae} ~ few 10^{-13} GeV^{-1}



Conceptual design of the International Axion Observatory (IAXO)
E Armengauda, F T Avignoneb, M Betzc, P Braxd, P Bruna, G Cantatoree, J M Carmonaf, G P Carosig, F Caspersc, S Caspih
Published 12 May 2014 • © CERN 2014 for the benefit of the IAXO collaboration.
Journal of Instrumentation, Volume 9, May 2014

There is still uncovered territory here, but that’s all the time I have.

Thank you!

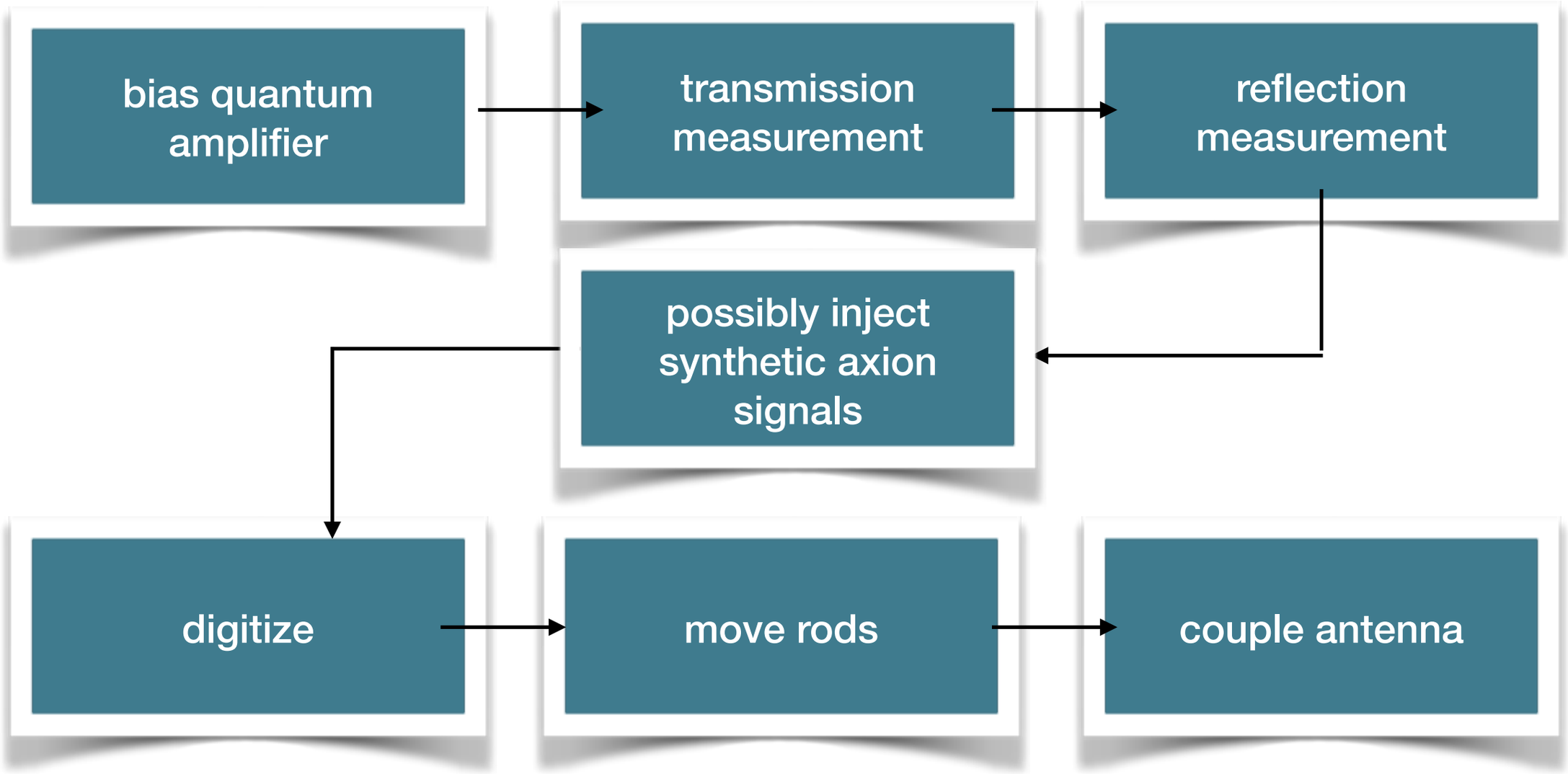
Conclusions

- Wave-like dark matter and axions are uncharted territory.

- Progress is being made, especially for the QCD axions, and even at DFSZ sensitivity!

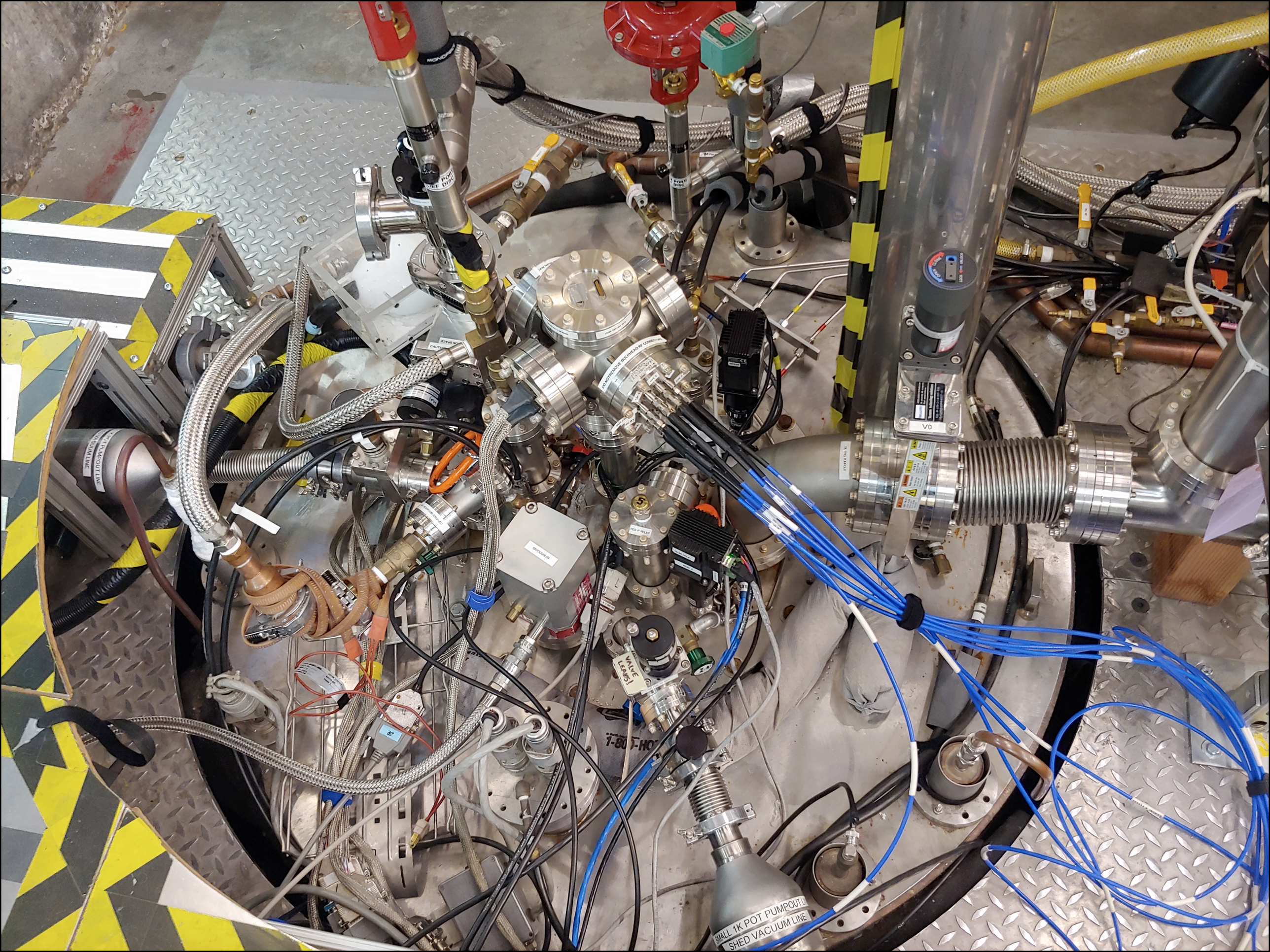
- Real possibility of discovery around the corner!

ADMX: Full Run Cadence

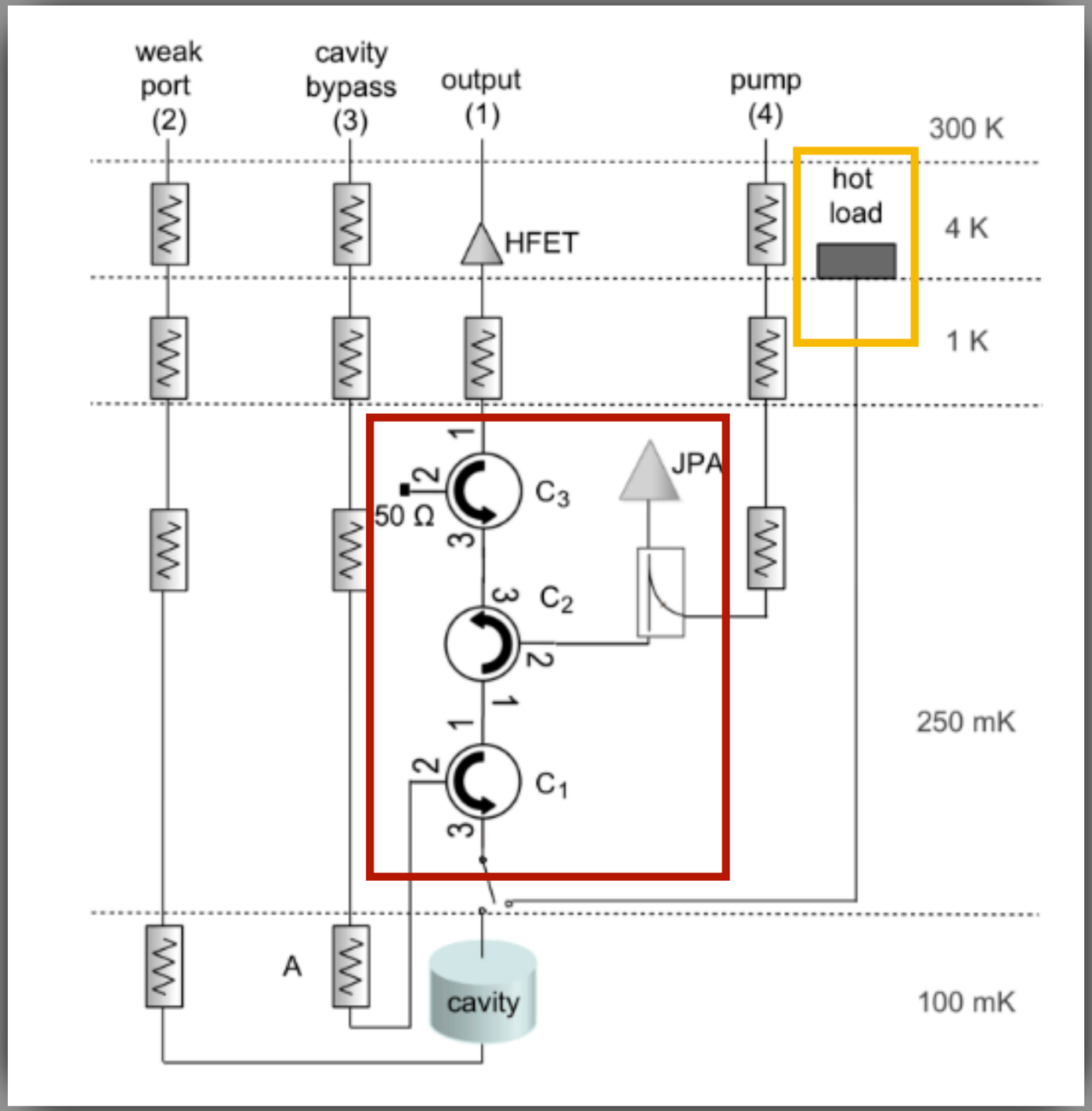


Data-taking operations:

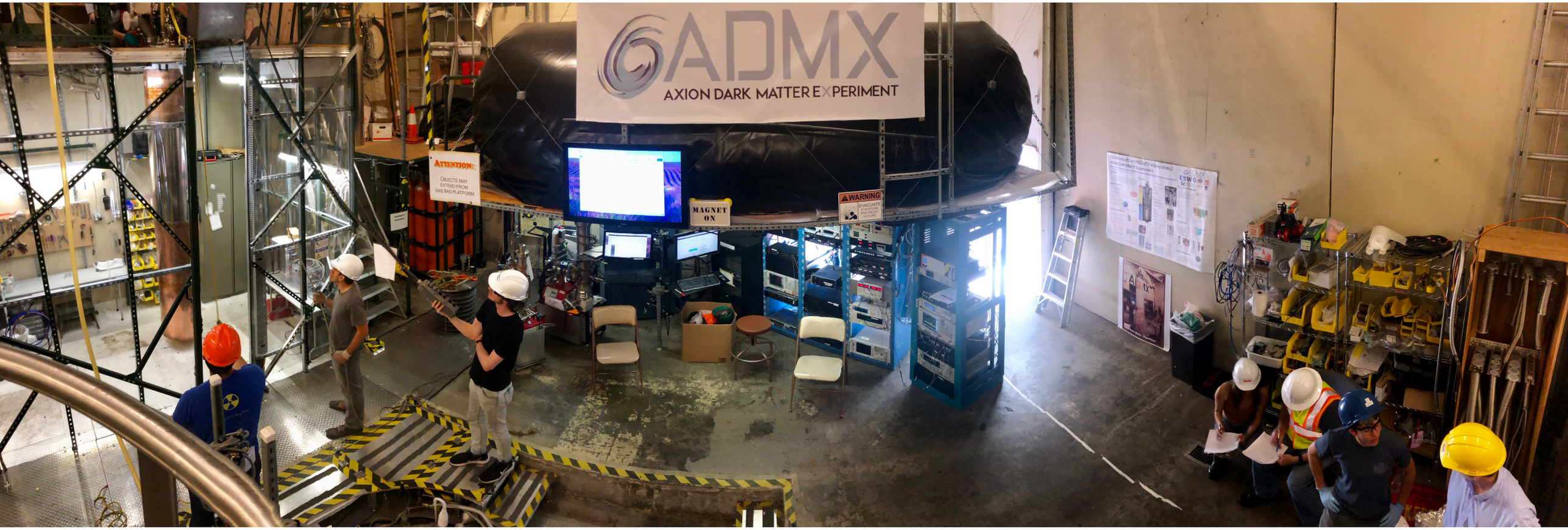
- 1st pass through—determine if we rescan
- Interrupted by noise temperature measurements
- 2nd pass through to achieve necessary sensitivity, or rescan candidates


SMALL 1K POT PUMPOUT LINE
SHED VACUUM LINE
VALVE LEAKS
V0

How the ADMX Receiver Chain Informs the Analysis



- Receiver chain provides means for measuring key RF parameters, such as quality factor
- Two types of noise measurement
- 1) Heating of the 'hot-load' via dc current (by design)
- 2) Heating of the quantum amplifier package via an RF switch (by creative impulse when the switch refused to flip)


ADMX
AXION DARK MATTER EXPERIMENT
ATTENTION
OBJECTS MAY EXTEND FROM GAS BAG PLATFORM
MAGNET ON
WARNING