Wave-like Dark Matter and Axions

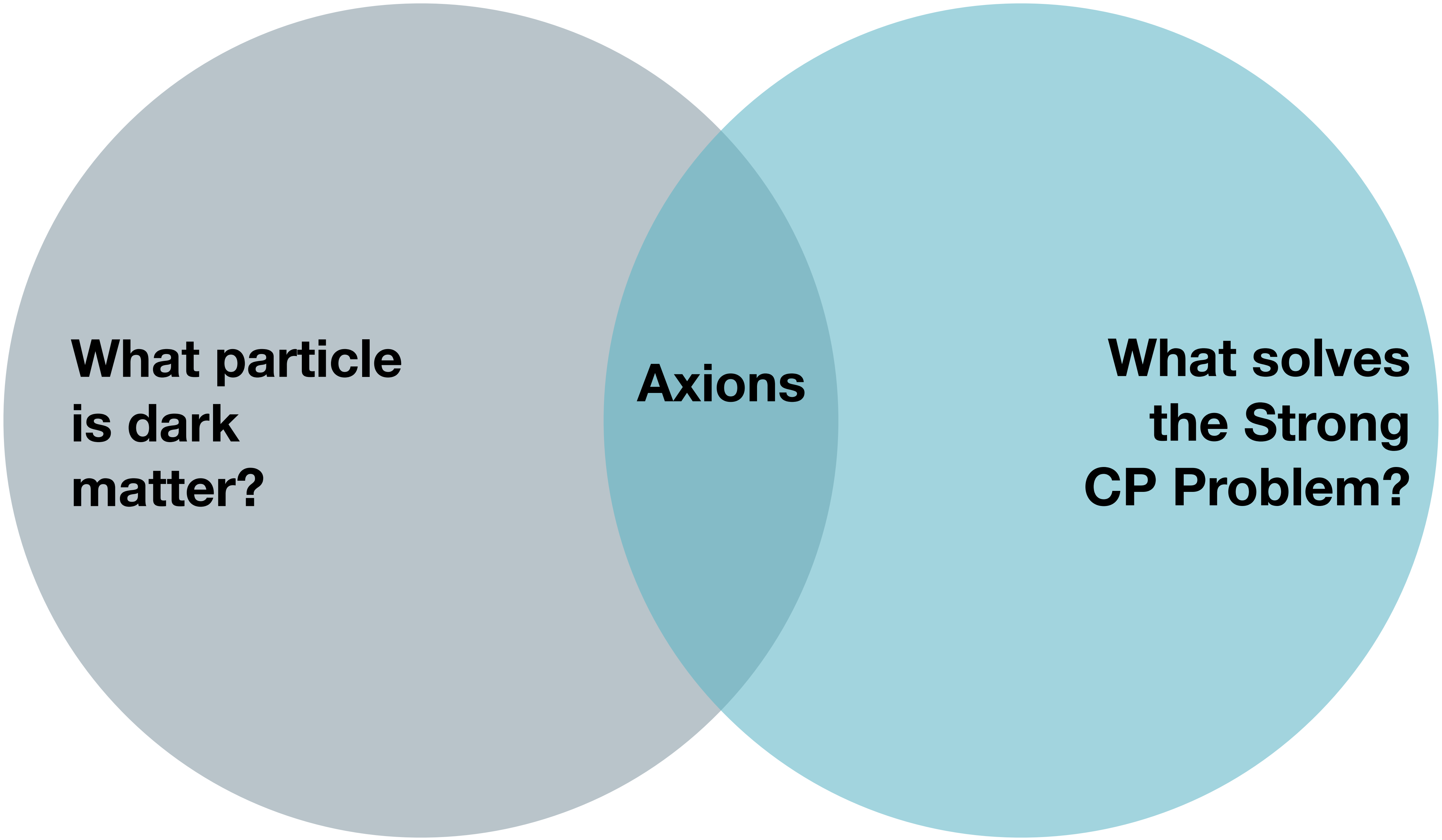
ICHEP Plenary Talk
August 04 2020

Chelsea Bartram
University of Washington

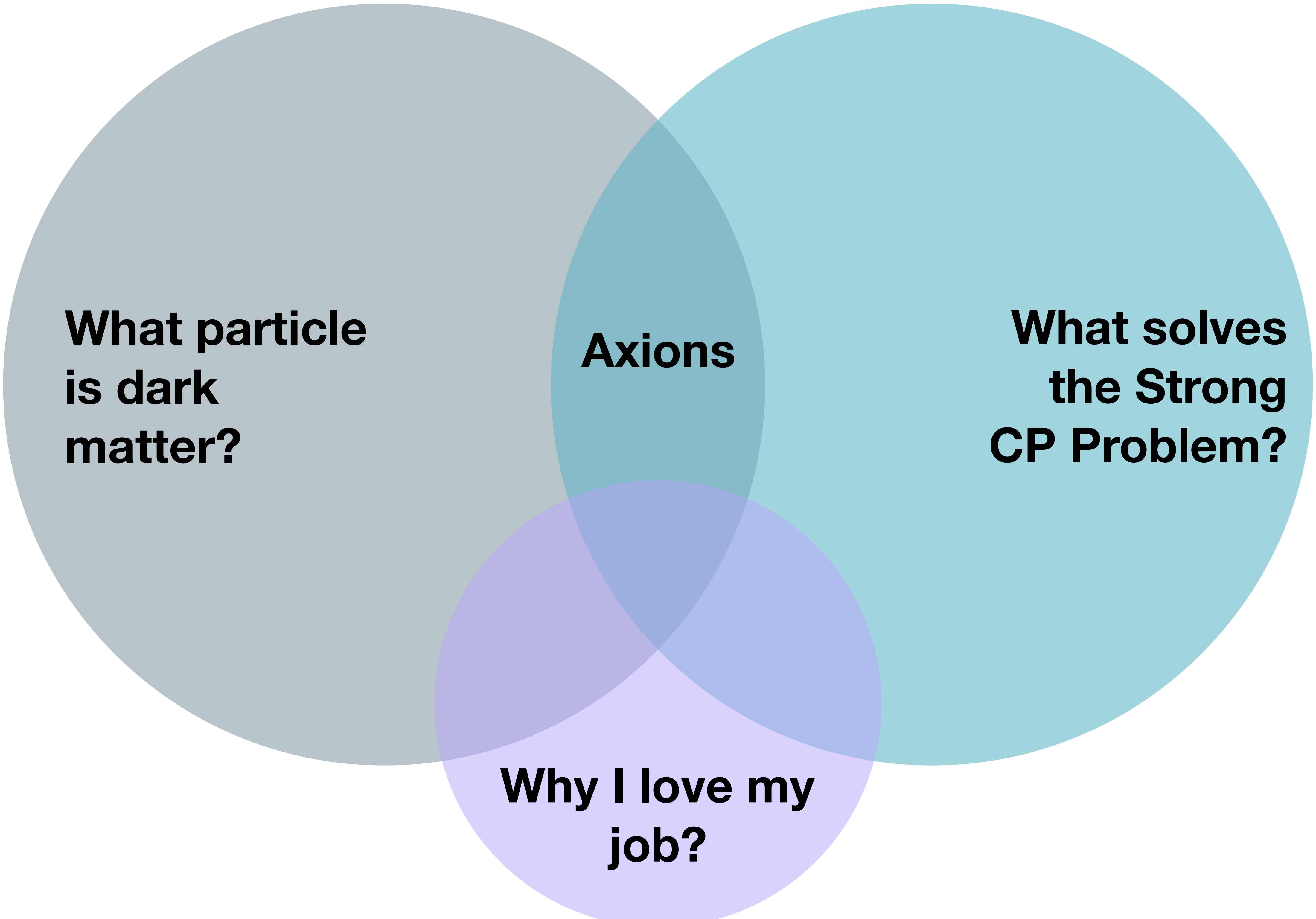
Exciting Ideas!

- Search idea using Migdal effect
- IAXO: Prospective Helioscope Experiment
- CAPP 8T: Haloscope Experiment
- Axion-like particle search with BABAR
- MADMAX experiment

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 $\longrightarrow$ 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

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

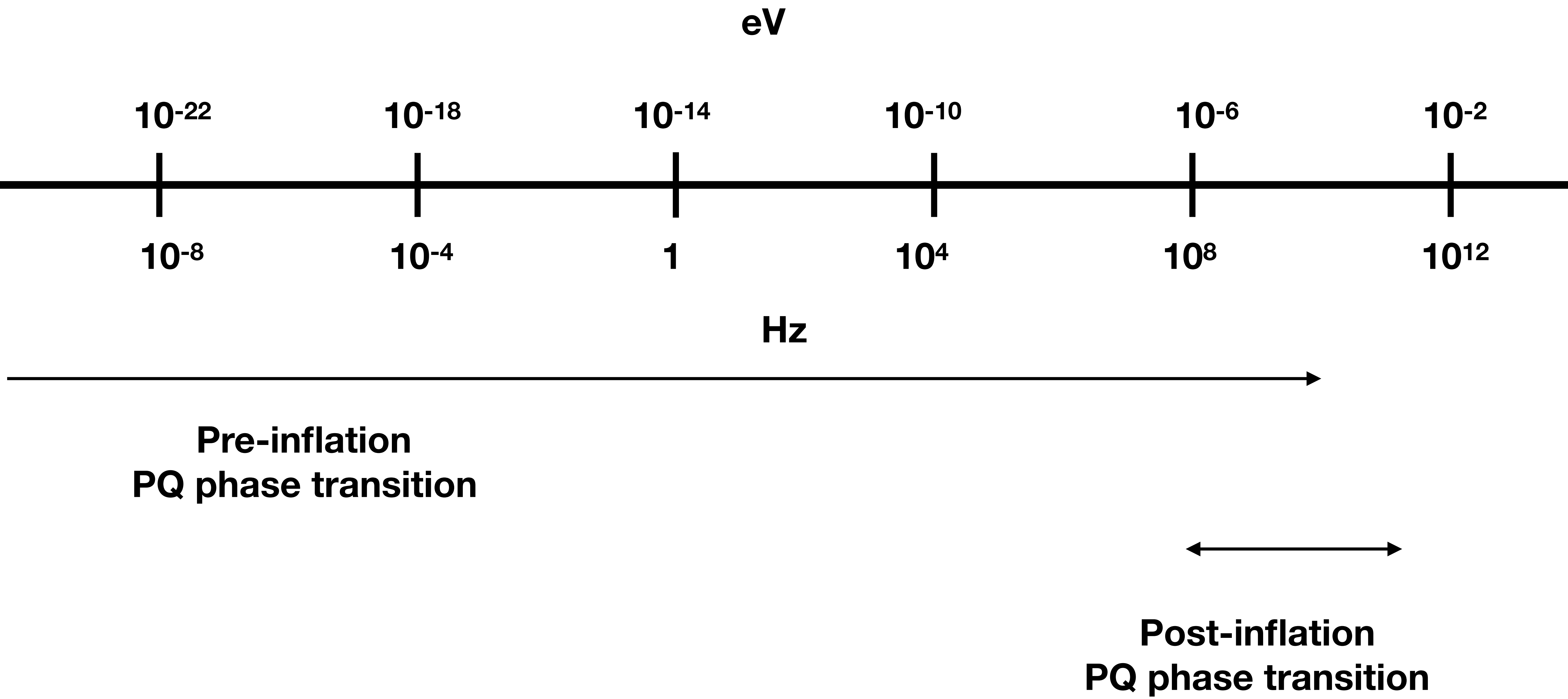
- Peccei-Quinn Solution to Strong CP Problem: Θ is now a dynamical variable which relaxes to zero at critical temperature.

- 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

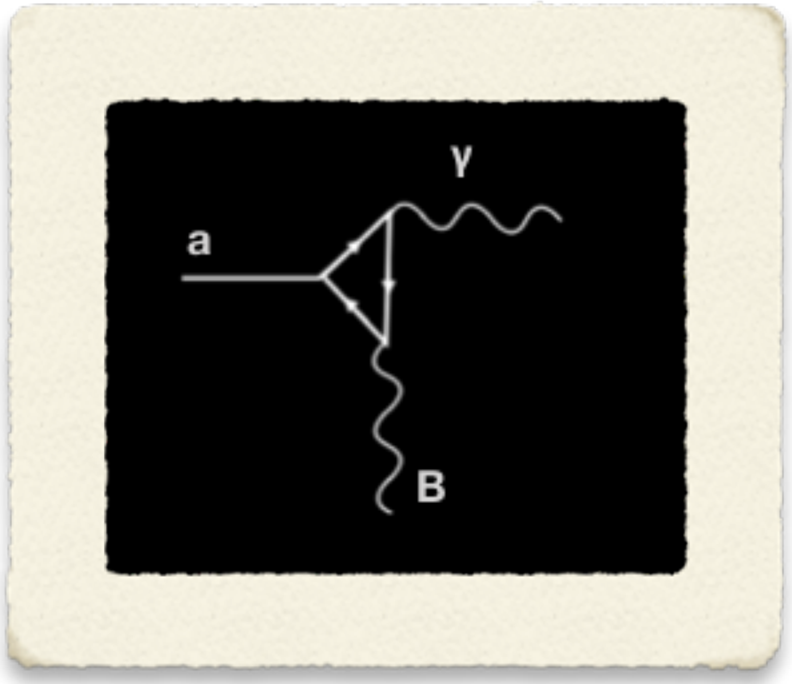
Upper bound set by SN1987A and white dwarf cooling time



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:

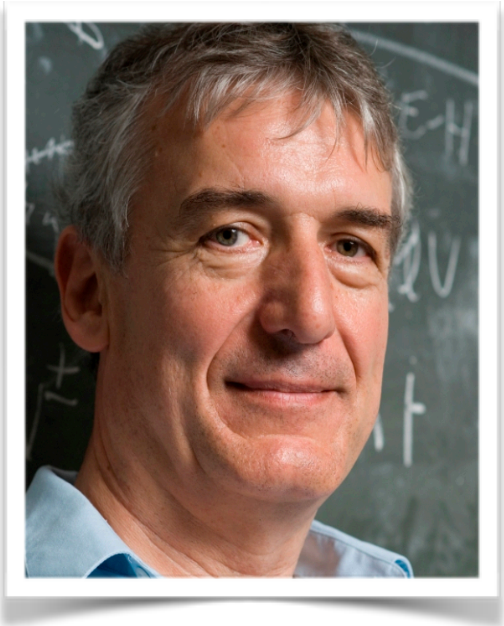
  - KSVZ (Kim-Shifman-Vainshtein-Zakharov):
    - couples to leptons
    - g_γ=0.97

  - DFSZ (Dine-Fischler-Srednicki-Zhitnitsky):
    - couples to quarks and leptons
    - g_γ=0.36

What is wave-like dark matter?

Calculate de Broglie wavelength of axions:

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



Wavelength of the Conversion Photon:
~several meters

New techniques needed here.

"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

Quantum Computing

Cryogenics

Microwave Electronics

High Magnetic Fields

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

Coupling to nucleon EDM

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

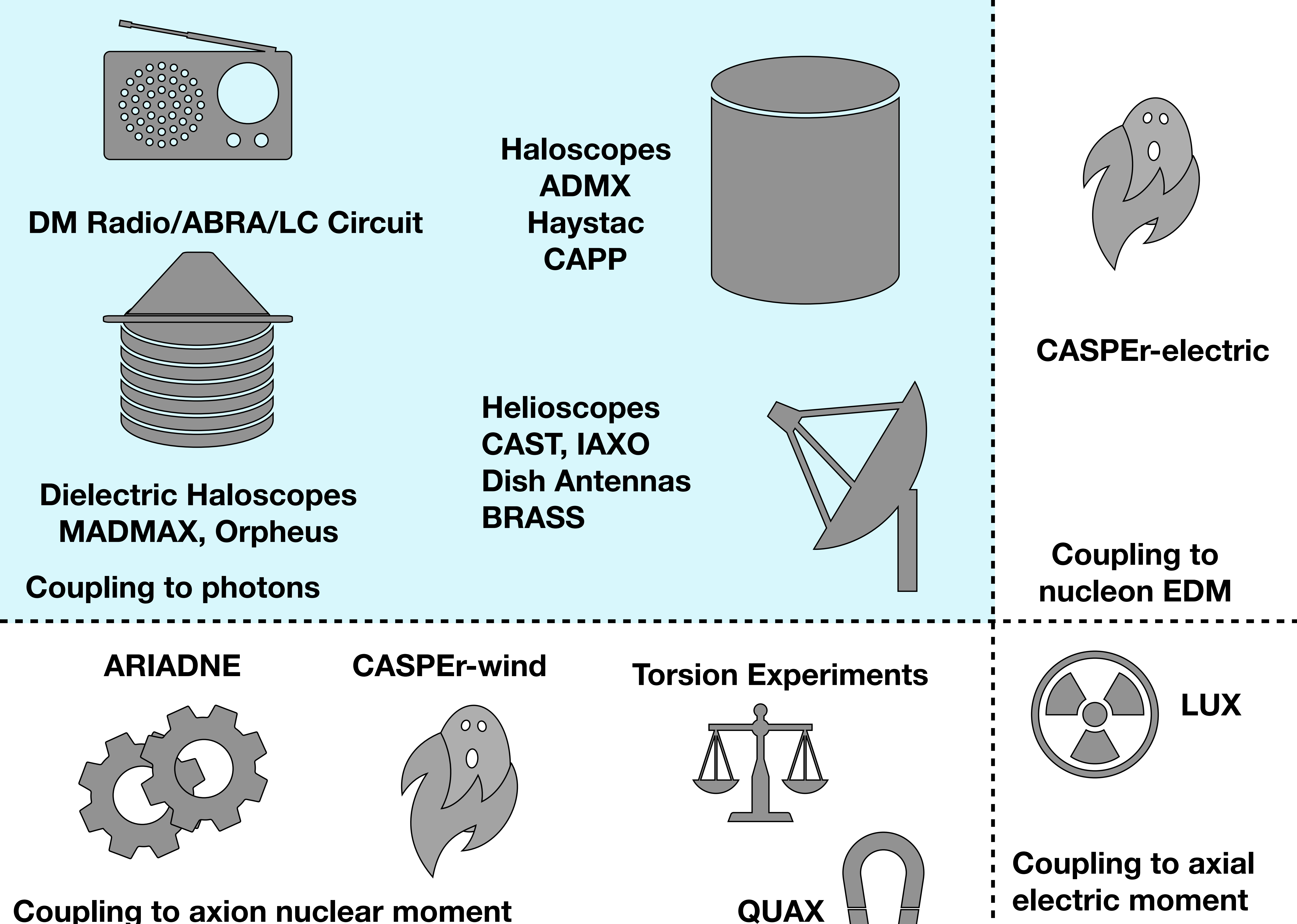
Coupling to axion nuclear moment

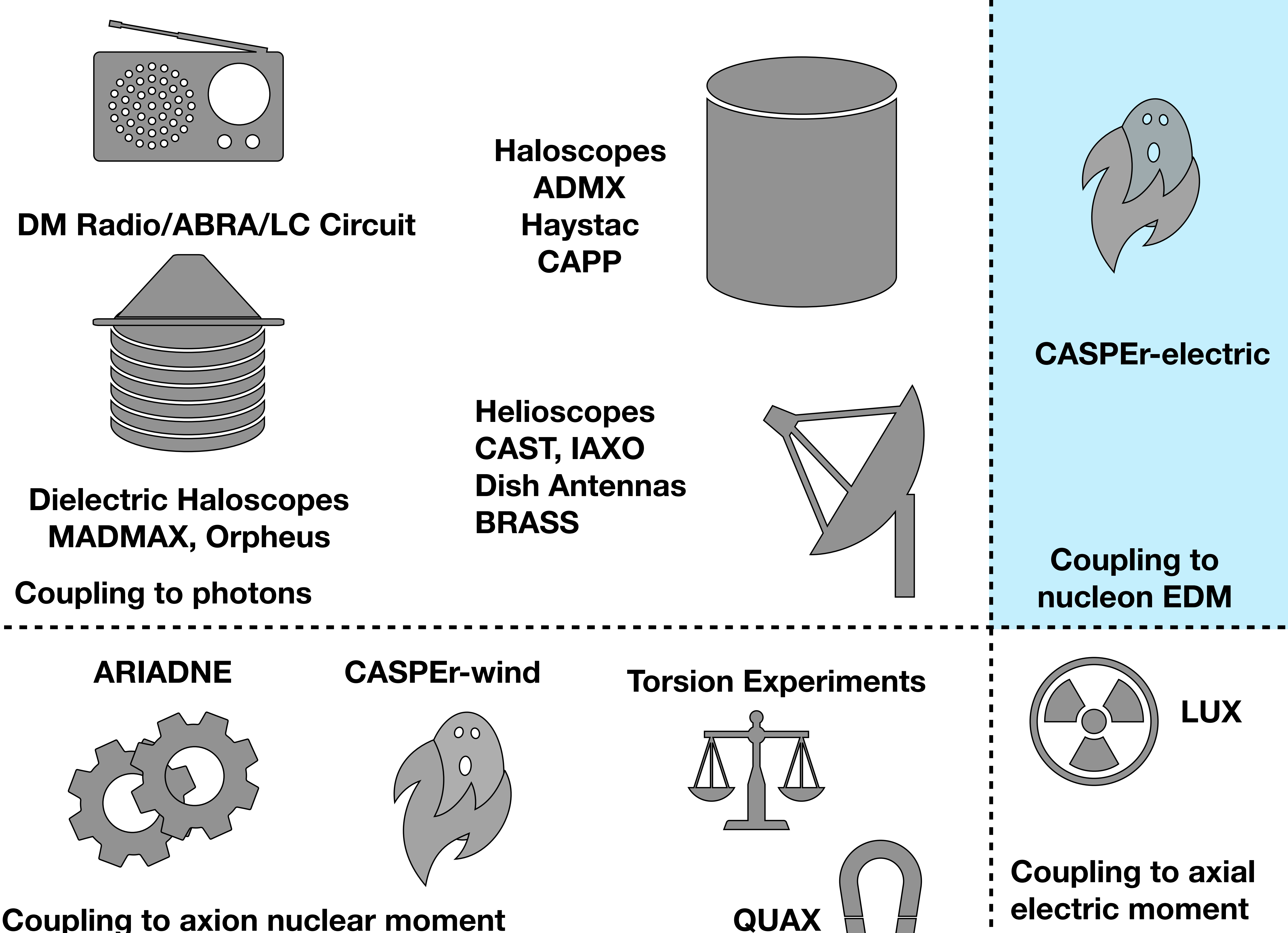
Creates for spin-dependent energy shifts/spin precession in fermions

Coupling to axial electron moment

Axioelectric effect, Analogous to photoelectric effect

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


DM Radio/ABRA/LC Circuit
Haloscopes
ADMX
Haystac
CAPP
CASPEr-electric
Helioscopes
CAST, IAXO
Dish Antennas
BRASS
Dielectric Haloscopes
MADMAX, Orpheus
Coupling to photons
Coupling to
nucleon EDM
ARIADNE
CASPEr-wind
Torsion Experiments
LUX
QUAX
Coupling to axion nuclear moment
Coupling to axial
electric moment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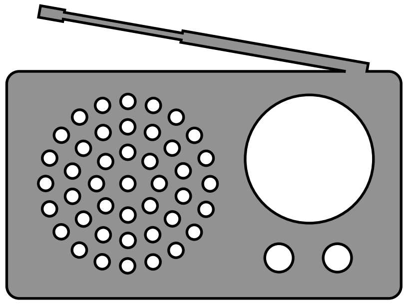
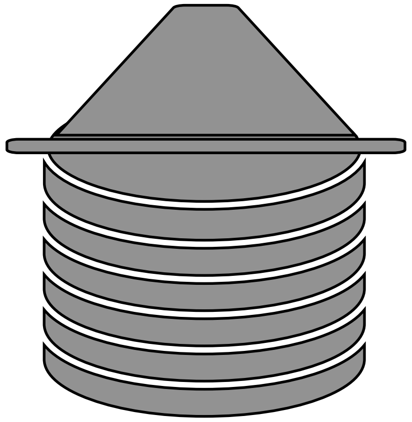


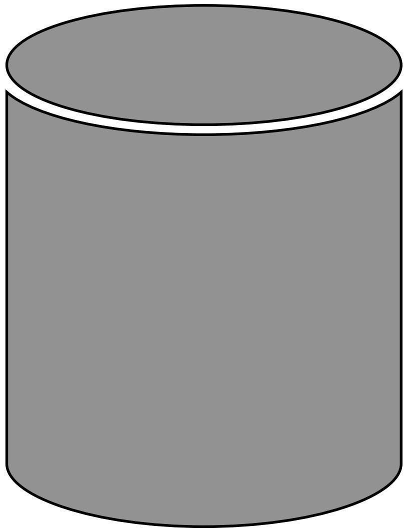
DM Radio/ABRA/LC Circuit



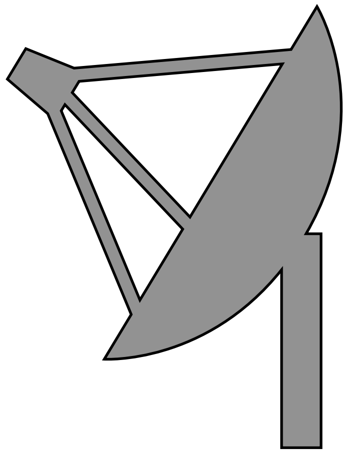
Dielectric Haloscopes
MADMAX, Orpheus

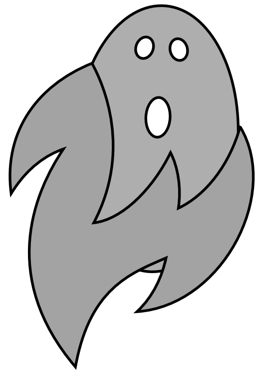
Coupling to photons

Haloscopes
ADMX
Haystac
CAPP



Helioscopes
CAST, IAXO
Dish Antennas
BRASS

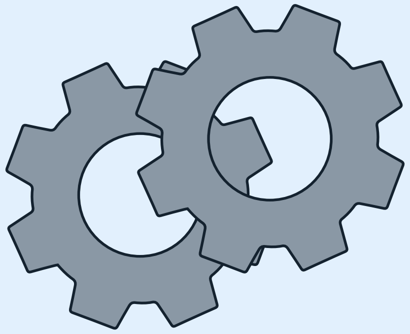




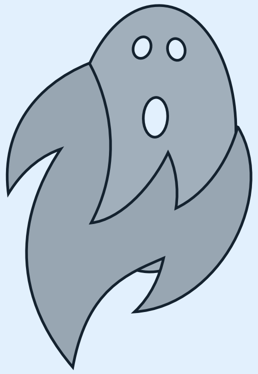
CASPEr-electric

Coupling to
nucleon EDM

ARIADNE

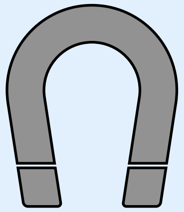


CASPEr-wind

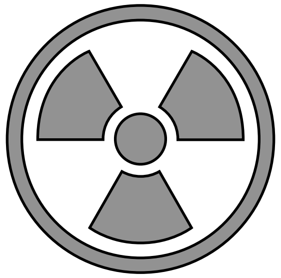


Torsion Experiments

QUAX

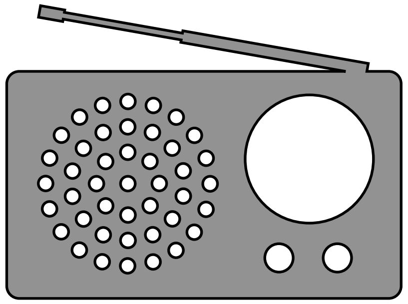


Coupling to axion nuclear moment



LUX

Coupling to axial
electric moment



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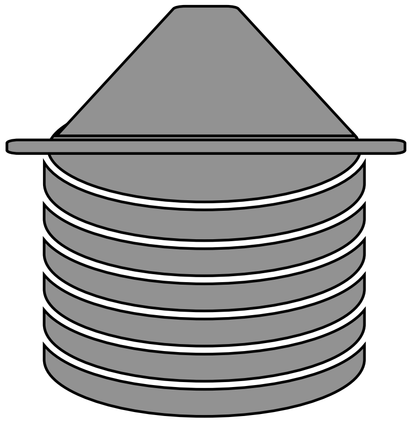
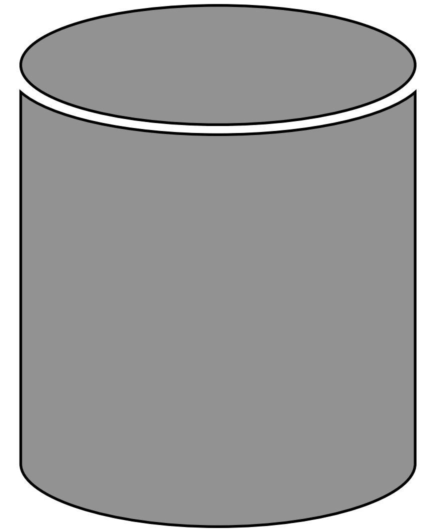


Dielectric Haloscopes
MADMAX, Orpheus

Haloscopes
ADMX
Haystac
CAPP



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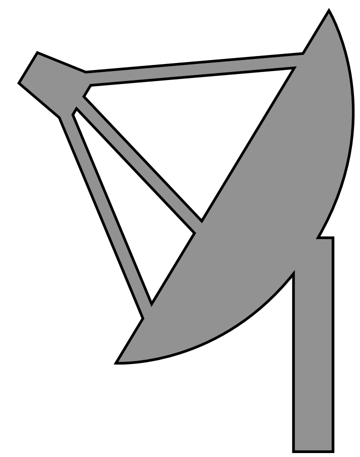
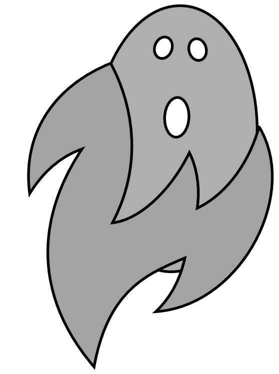


Coupling to photons



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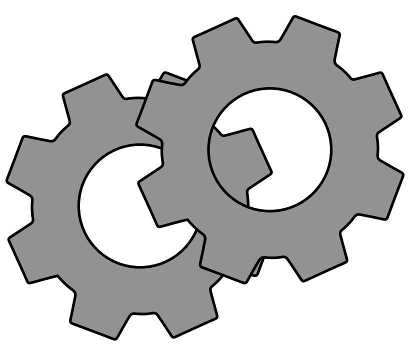
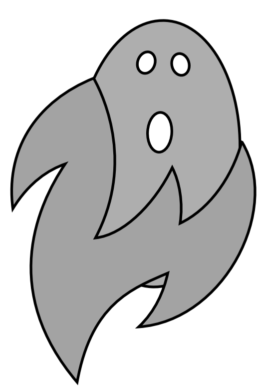


CASPEr-wind



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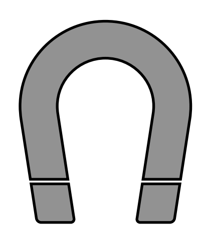
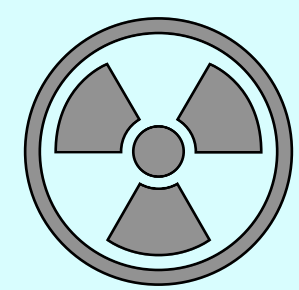


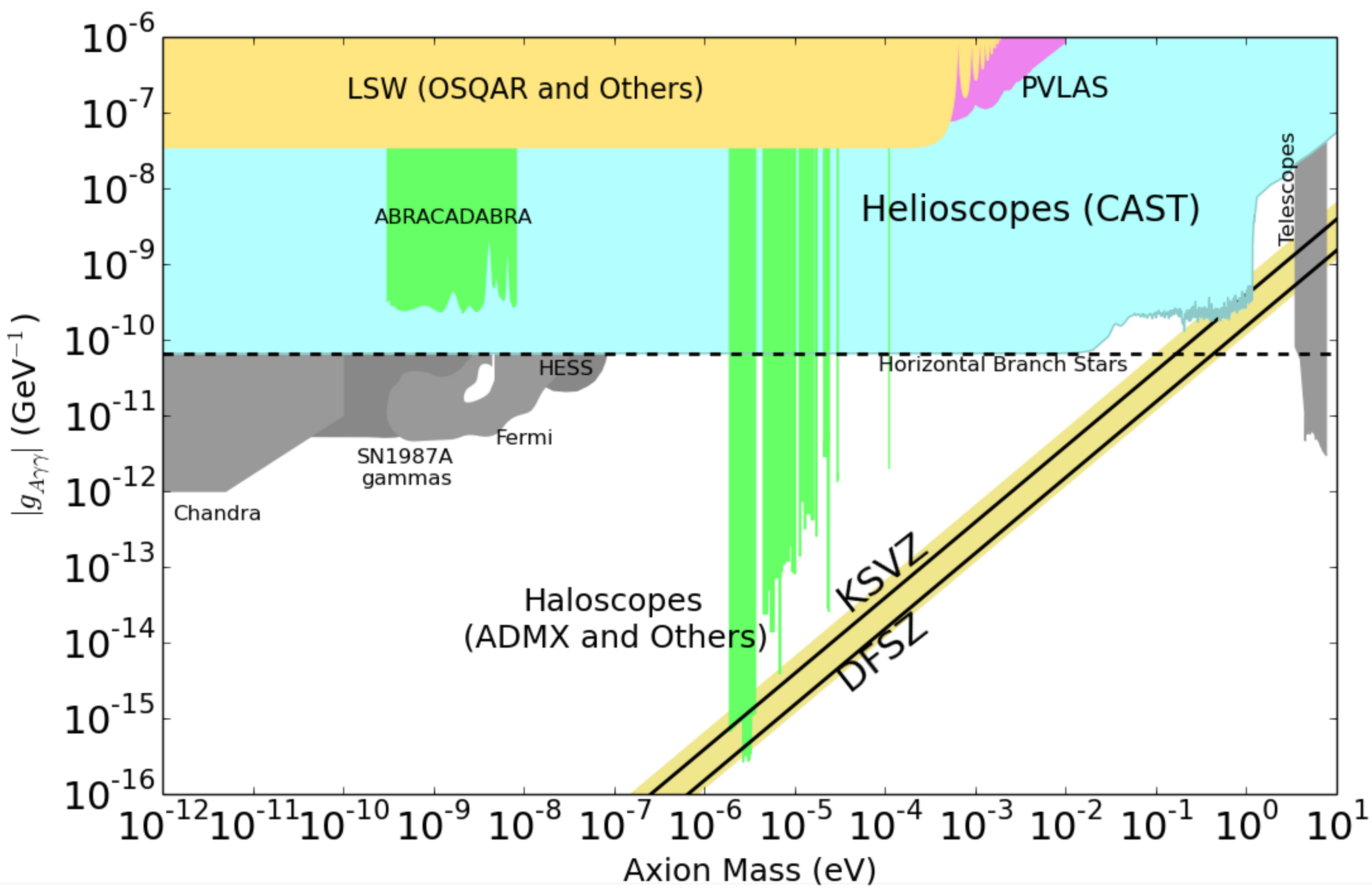
Coupling to axion nuclear moment



LUX

Coupling to axial
electric moment

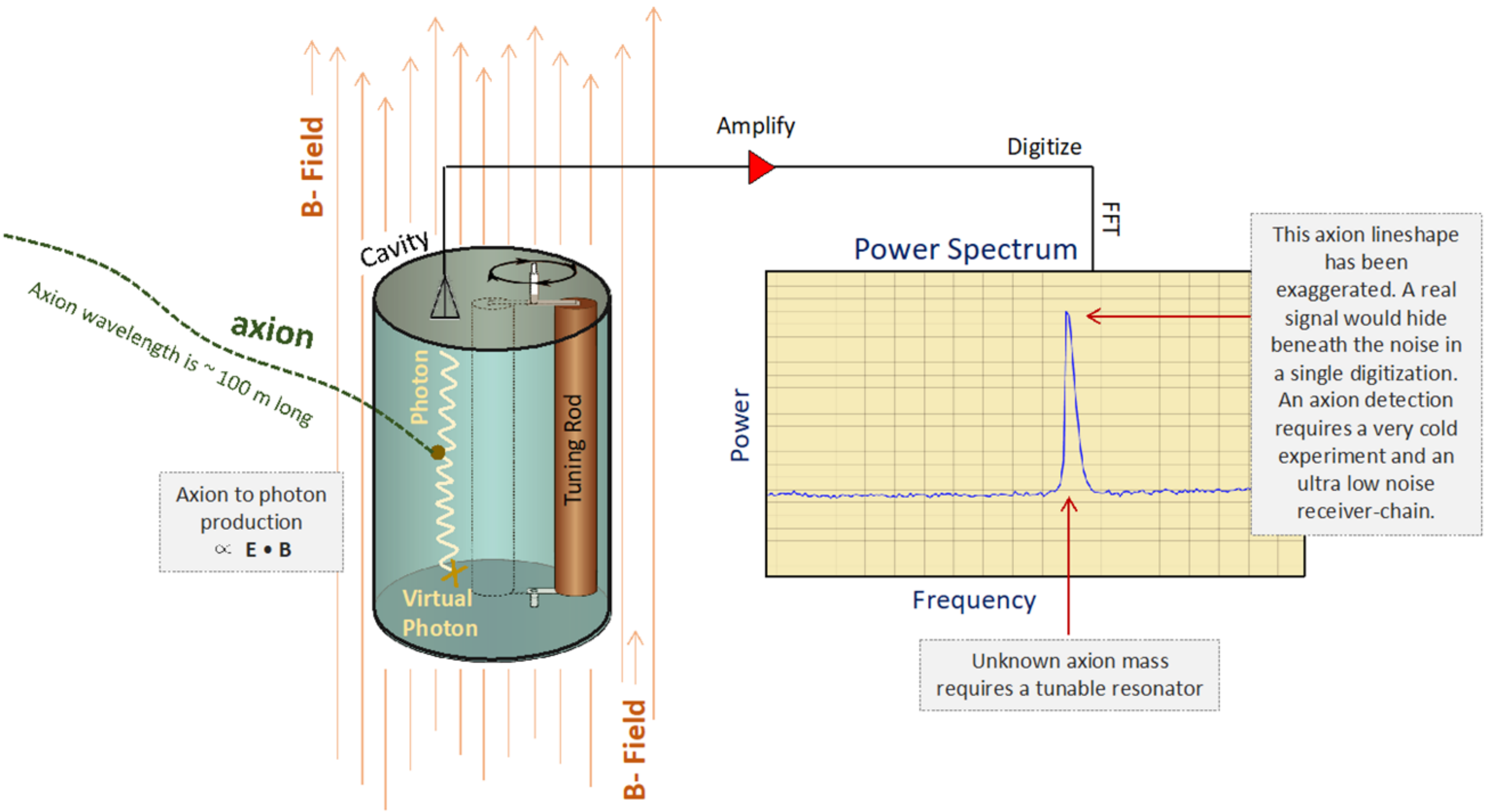
Axion-like Particles Exclusion Plot



Axion Haloscopes

All use microwave cavity in magnetic field

Relies on Inverse Primakoff effect and resonant enhancement of cavity



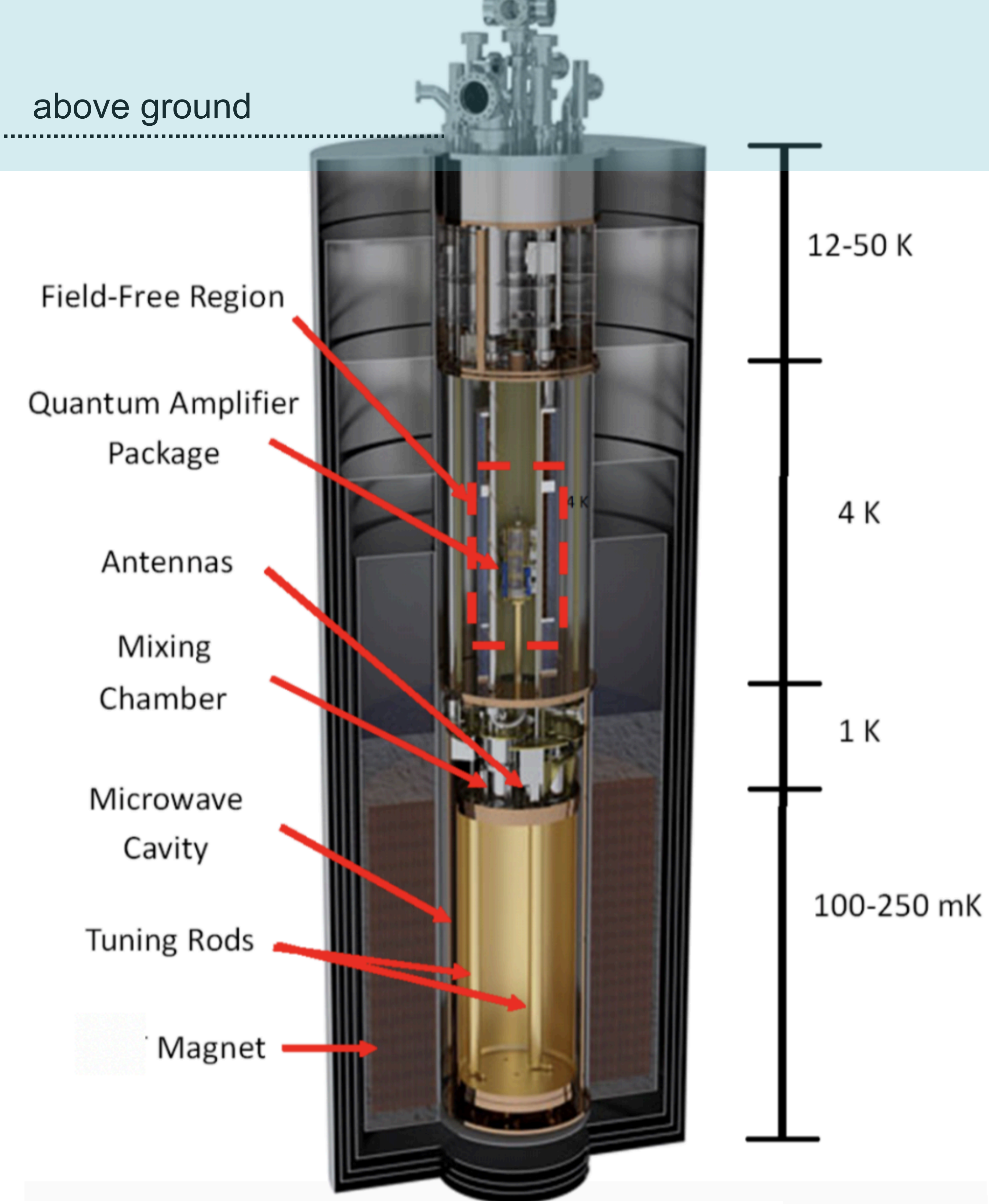
Scan Rate: Figure of Merit for Haloscope Search

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

Maximize	Can't Control	Minimize
• B Field • Volume • Quality Factor • Form Factor	• Frequency • Coupling • Dark Matter Density	• System noise: • Amplifier Noise • Physical Noise

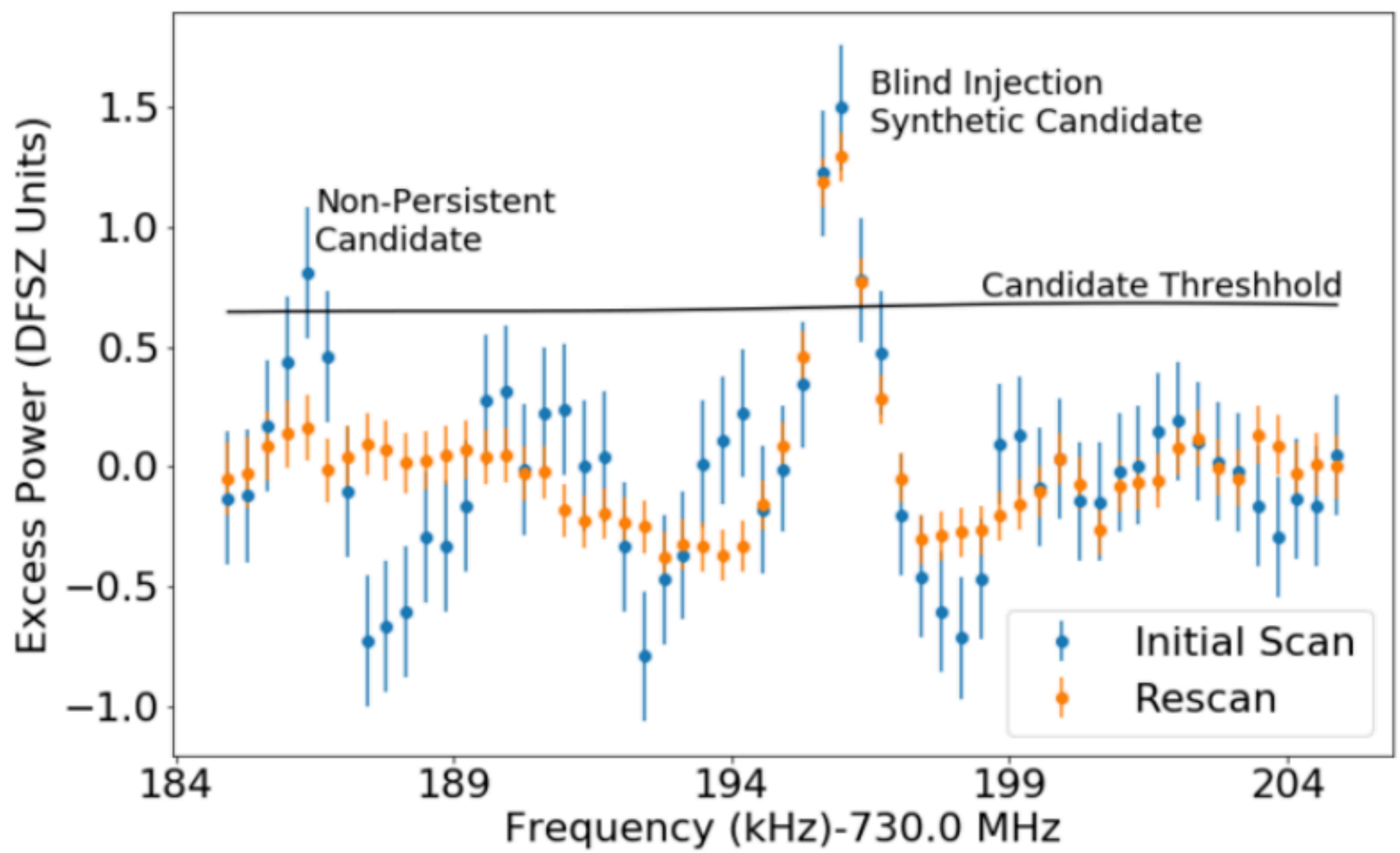
ADMX Haloscope

- 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

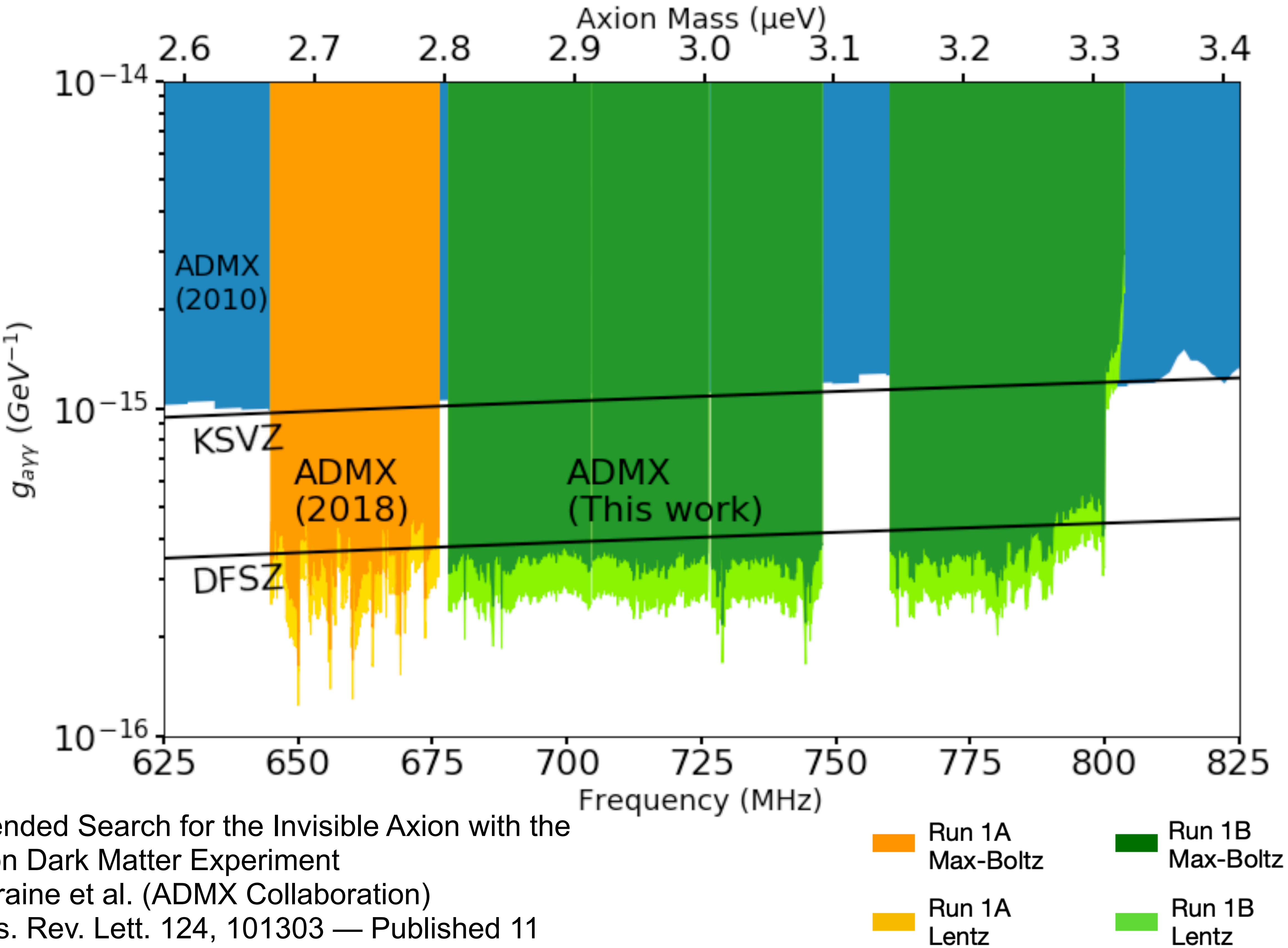


Hardware Synthetic Axion Injections

Excellent Confirmation of Ability To Detect DFSZ Axions!

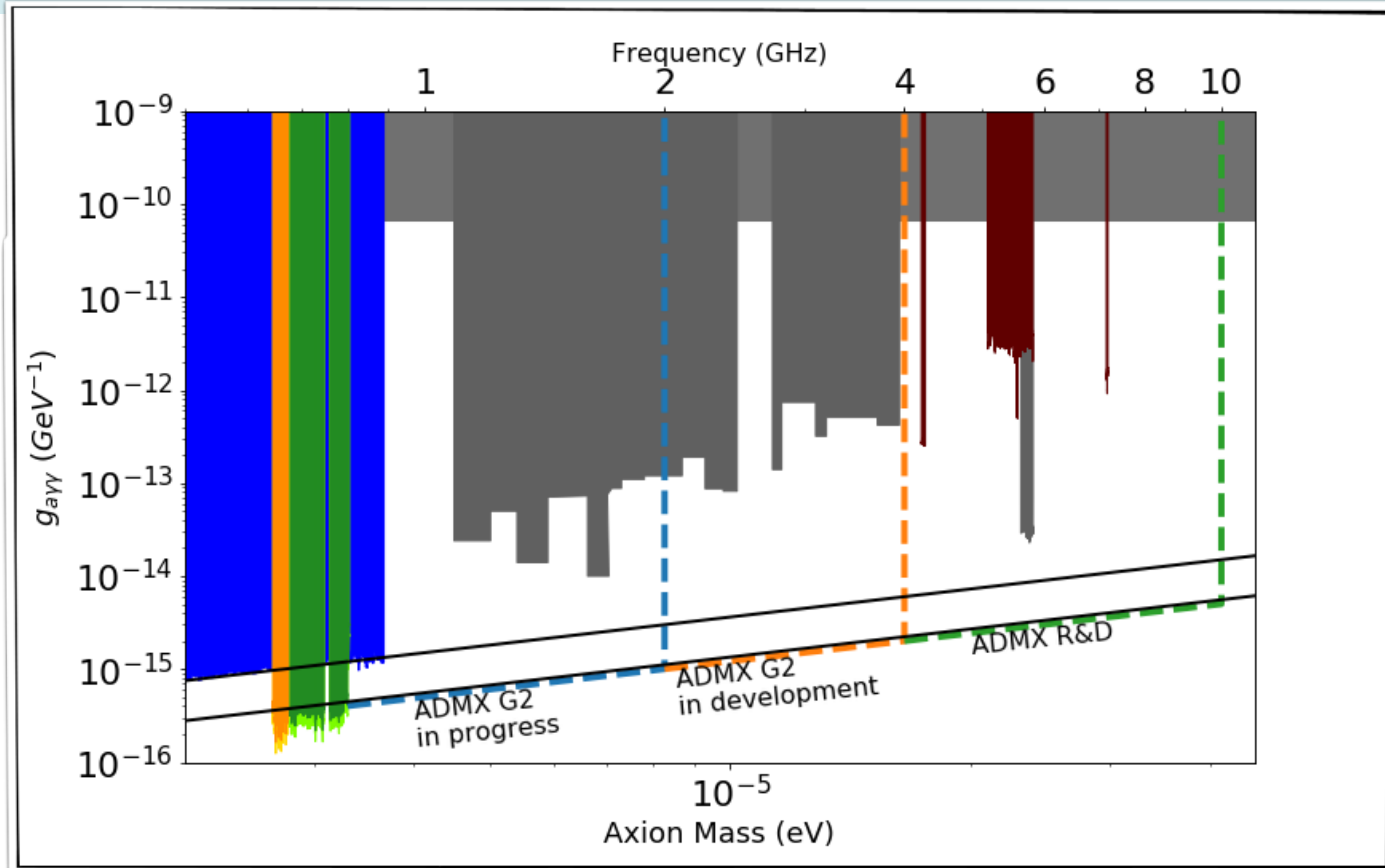


ADMX Limits



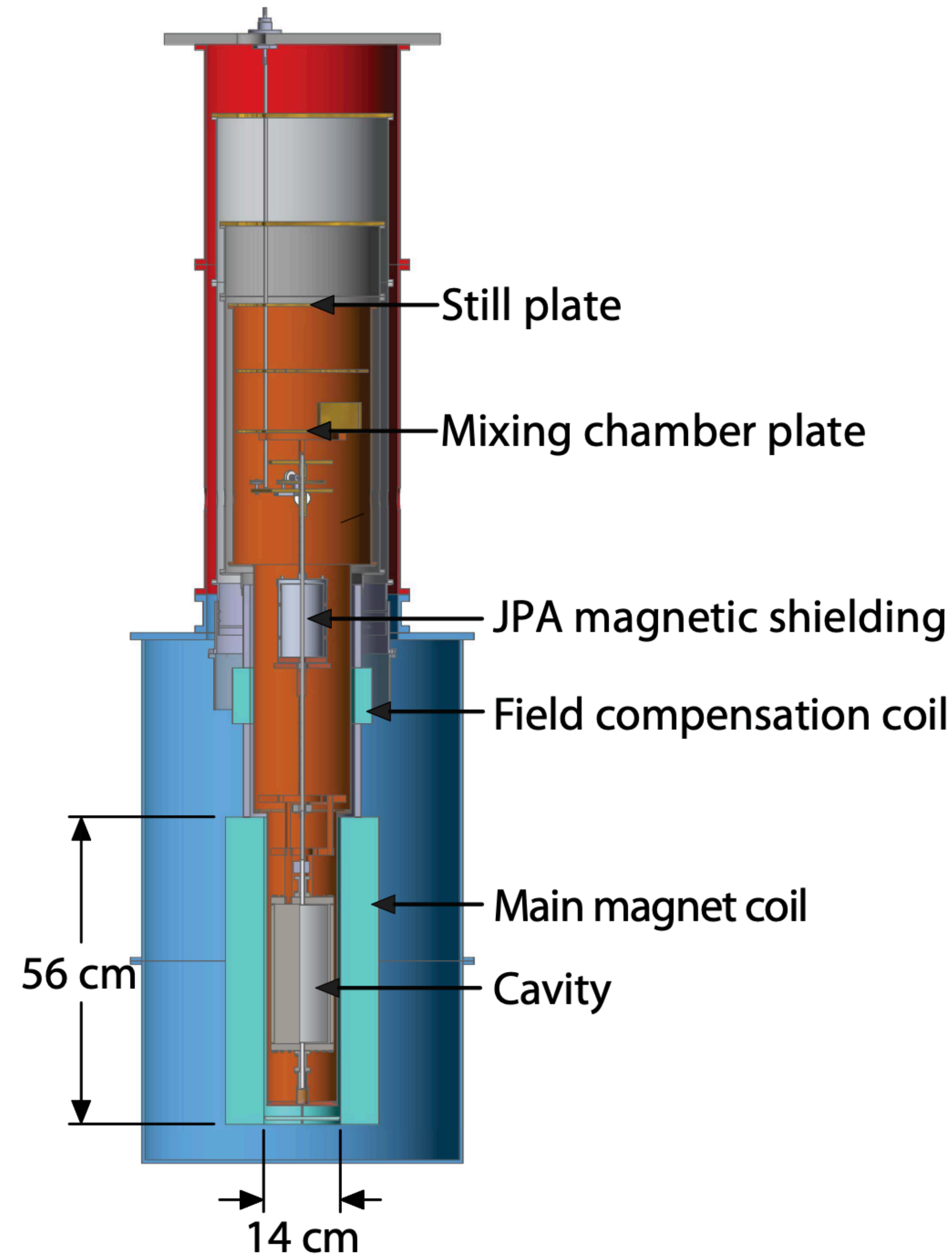
Extended Search for the Invisible Axion with the Axion Dark Matter Experiment
T. Braine et al. (ADMX Collaboration)
Phys. Rev. Lett. 124, 101303 — Published 11 March 2020

Projected ADMX Sensitivity



Haystac

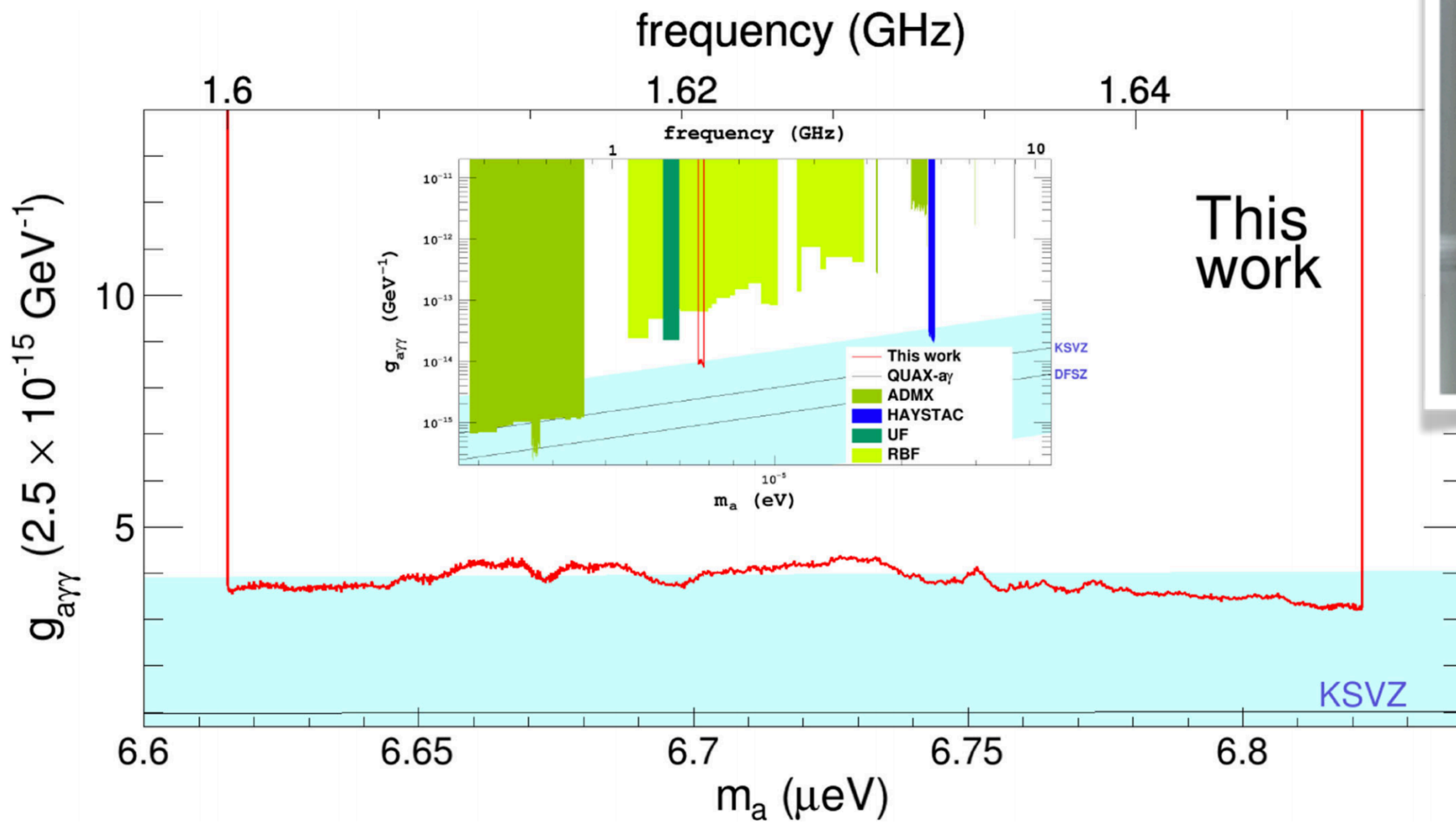
- Exploring higher frequency axions
- Using squeezed state receiver:
  - Phys. Rev. X 9, 021023 (2019)
- Exploring Bayesian techniques:
  - Phys. Rev. D 101, 123011 (2020)
- Pulse-tube dil fridge
- Phase 1 results complete
- Phase 2 underway



First Results from the Axion Haystac Search
Benjamin M. Brubaker

CAPP-8T

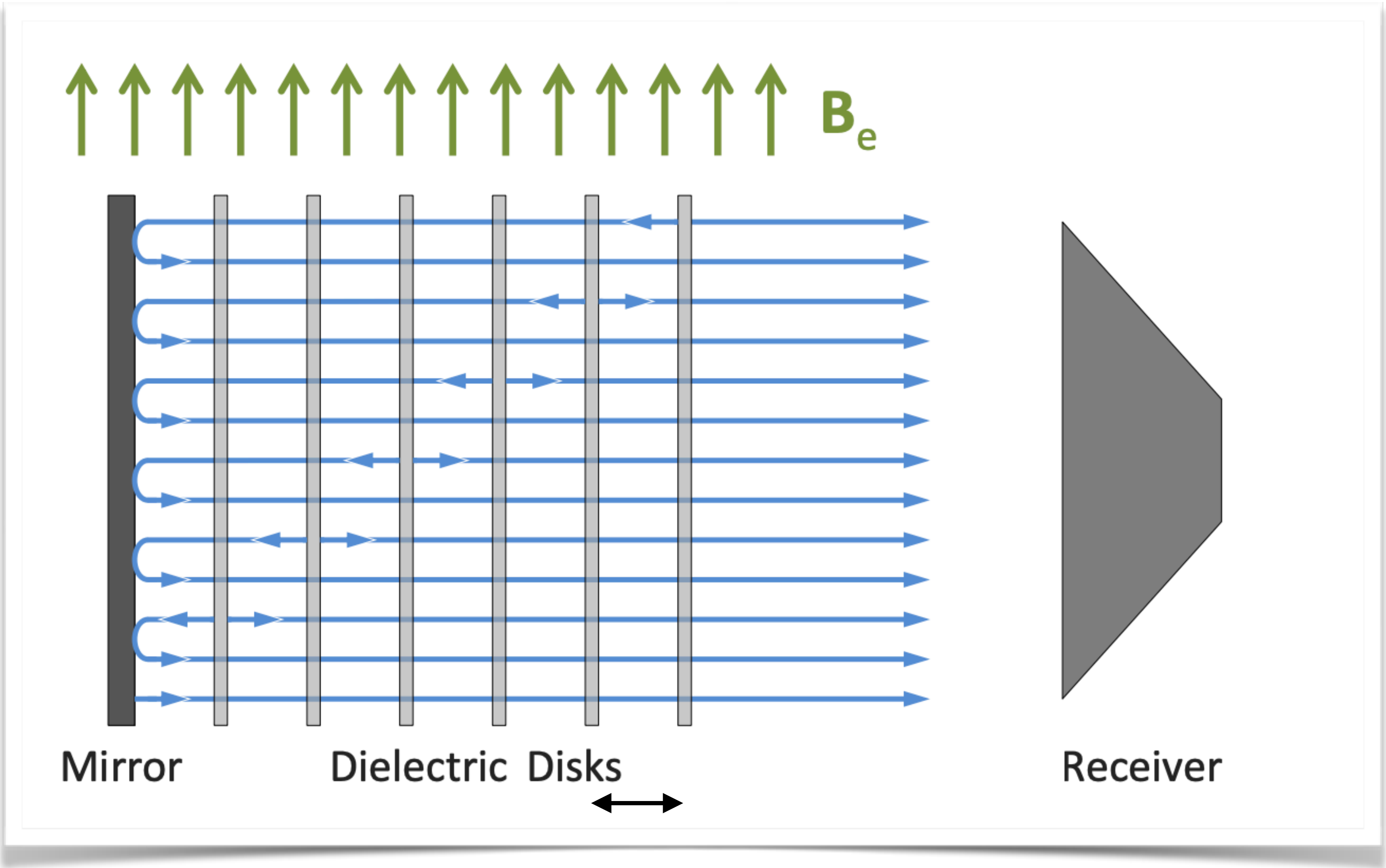
- Exploring frequency range near 6.62-7.04 μeV (1.6-1.7 GHz)



https://arxiv.org/abs/1910.11591

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



20 cm - 2 m

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

Power enhancement from EM waves emitted at the disk boundaries

Stefan Knirck and MADMAX interest group 2020 J. Phys.: Conf. Ser. 1342 012097

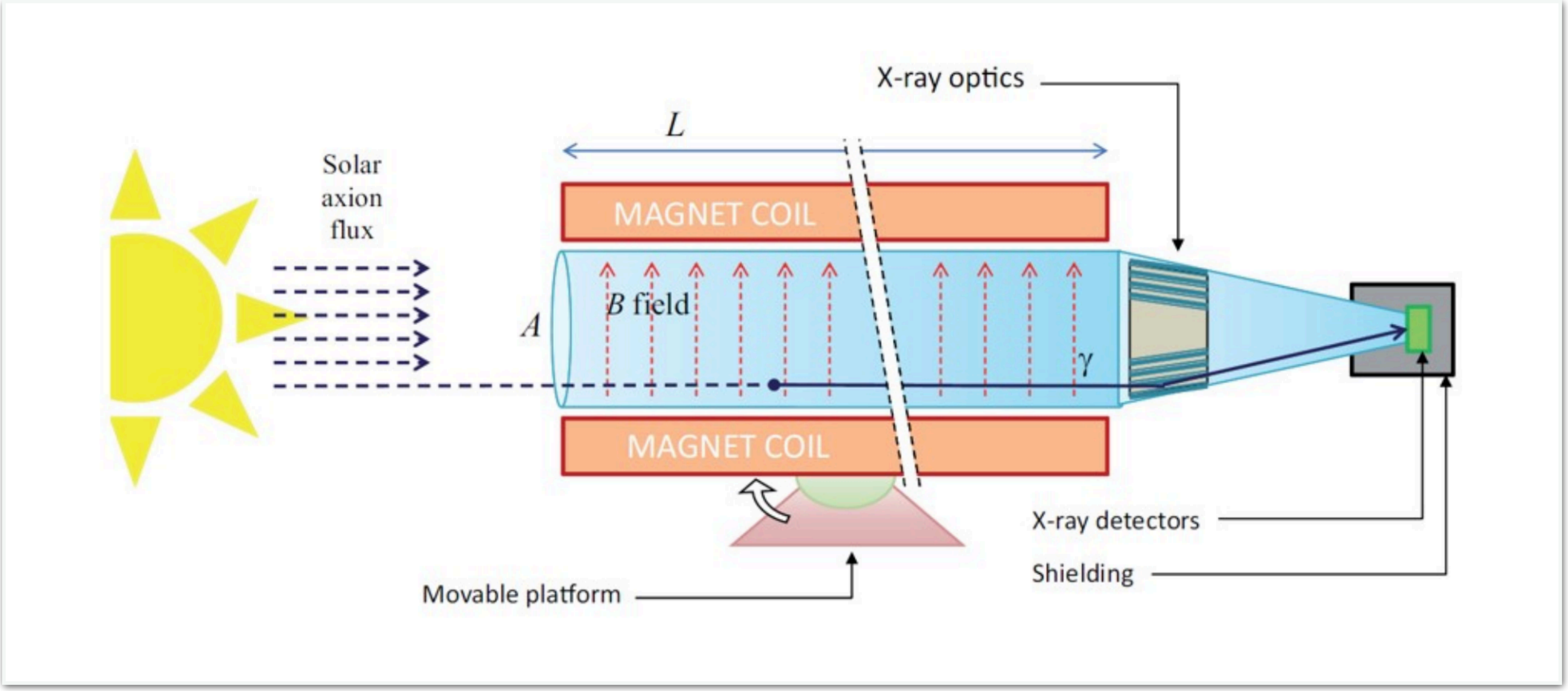
B. Majorovits and MADMAX interest groupt 2020 J. Phys.: Conf. Ser. 1342 012098

Helioscopes: IAXO

- Searching for axions/ALPs coming from the Sun

- IAXO requires stronger field and larger volume to improve sensitivity by a factor of 10 compared to its predecessor, CAST

- Goal: Reach axion masses up to 0.25 eV



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]()

Migdal Effect and Plasmons

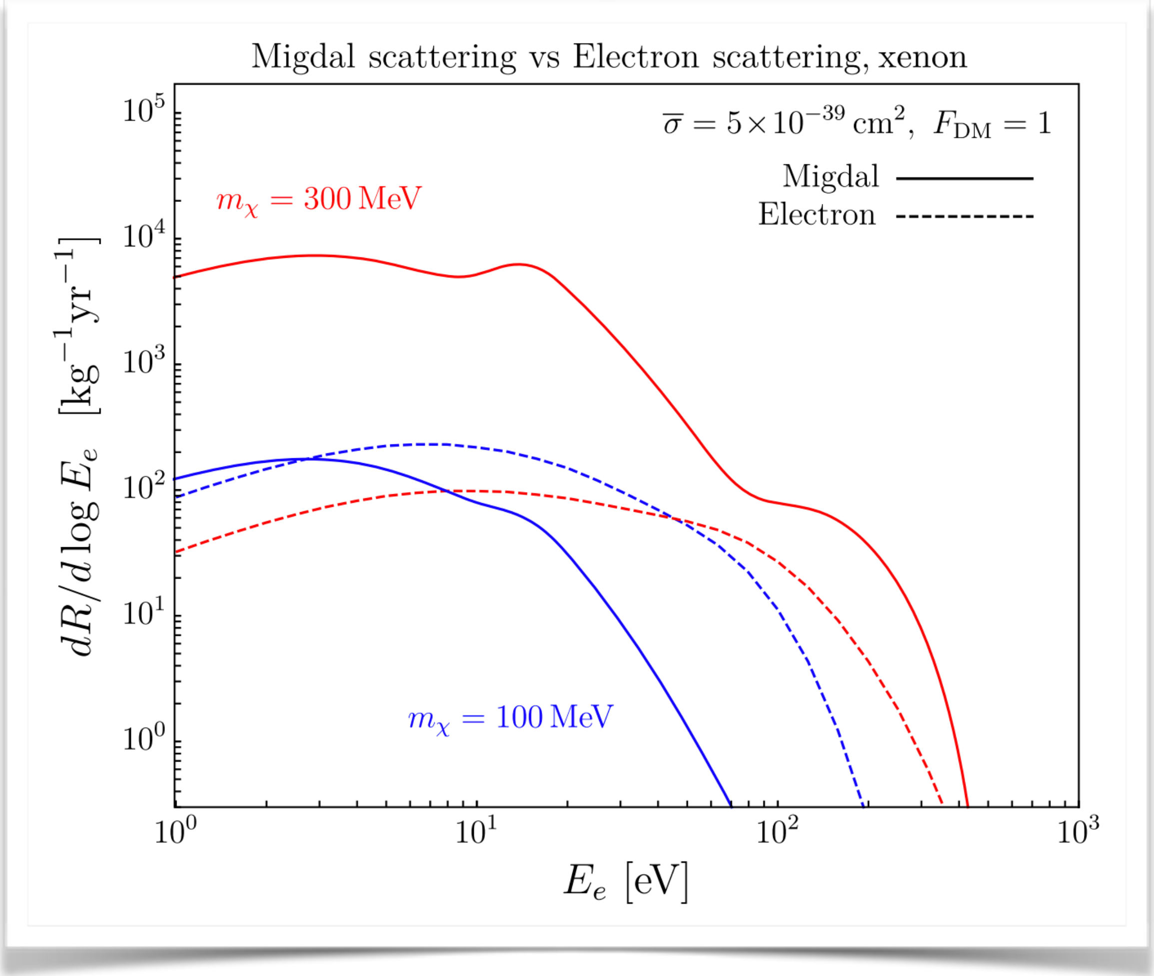
Migdal effect:

- Particle elastically scatters off nucleus—assumption that electron cloud follows immediately
- Not the reality—results in ionization and excitation of the atom

- Proposal to use this idea to search for dark matter in liquid noble as well as semiconductor detectors

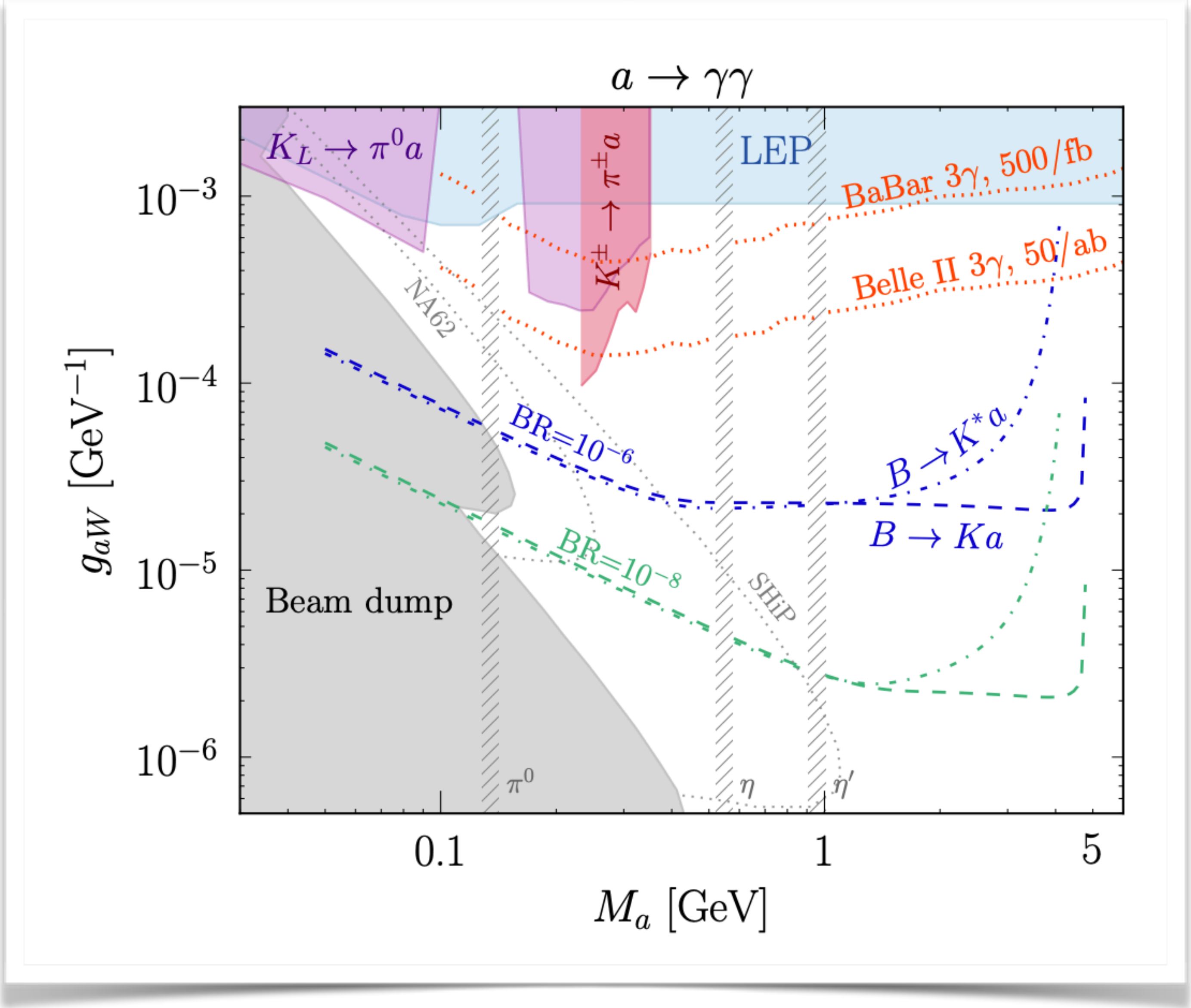
- Maybe we've already seen it….

Electron ionization via dark matter-electron scattering and the Migdal effect
Daniel Baxter, Yonatan Kahn, and Gordan Krnjaic
Phys. Rev. D 101, 076014 — Published 20 April 2020



Search for Axion-like particles with BABAR

- ALPs produced in flavor-changing neutral current (FCNC) processes
- Uses coupling to W± boson
- Electron-positron collider search for invisibly decaying ALPs



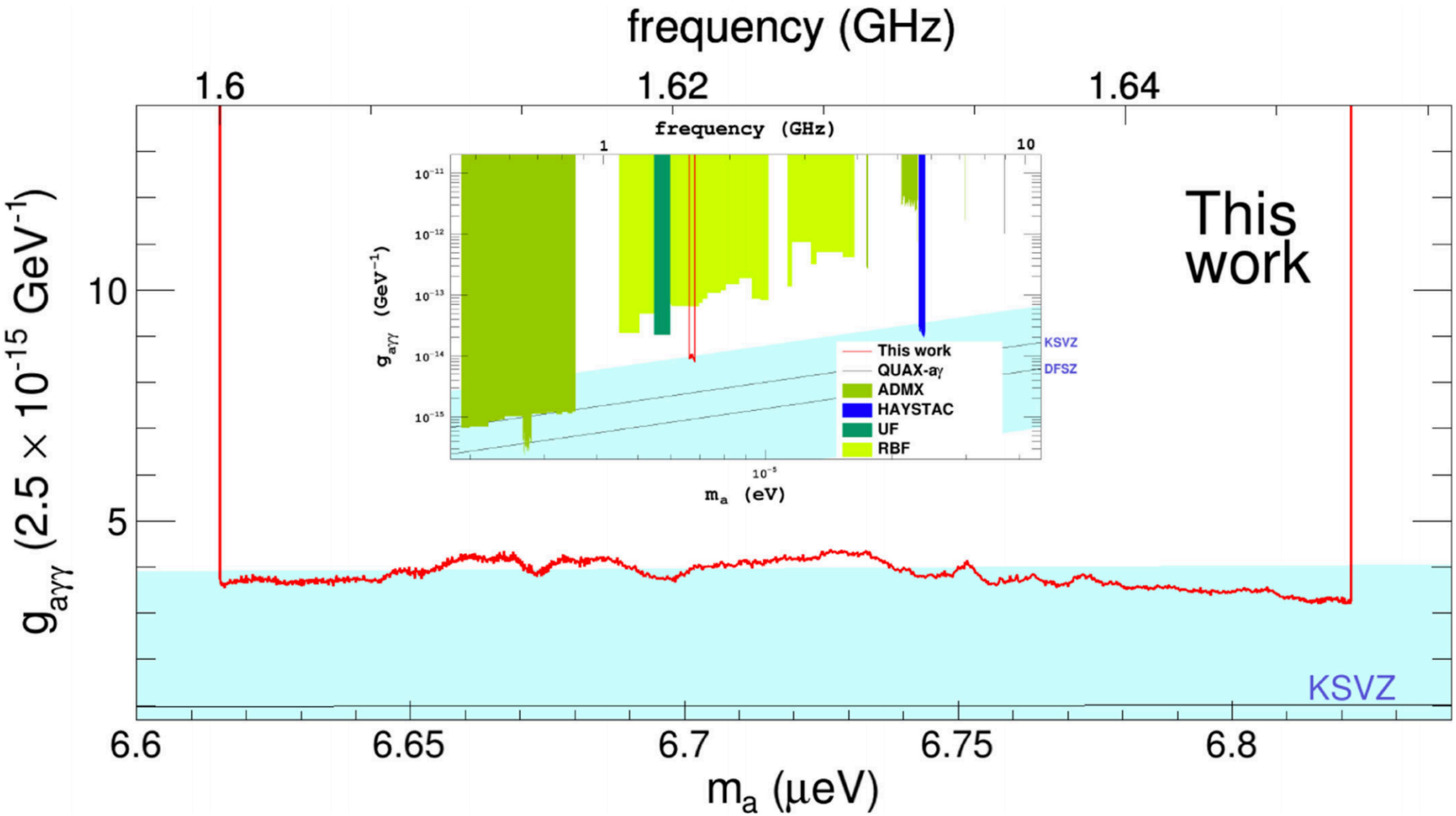
There is still uncovered territory here, but that’s all the time I have.

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!

CAPP: Latest results



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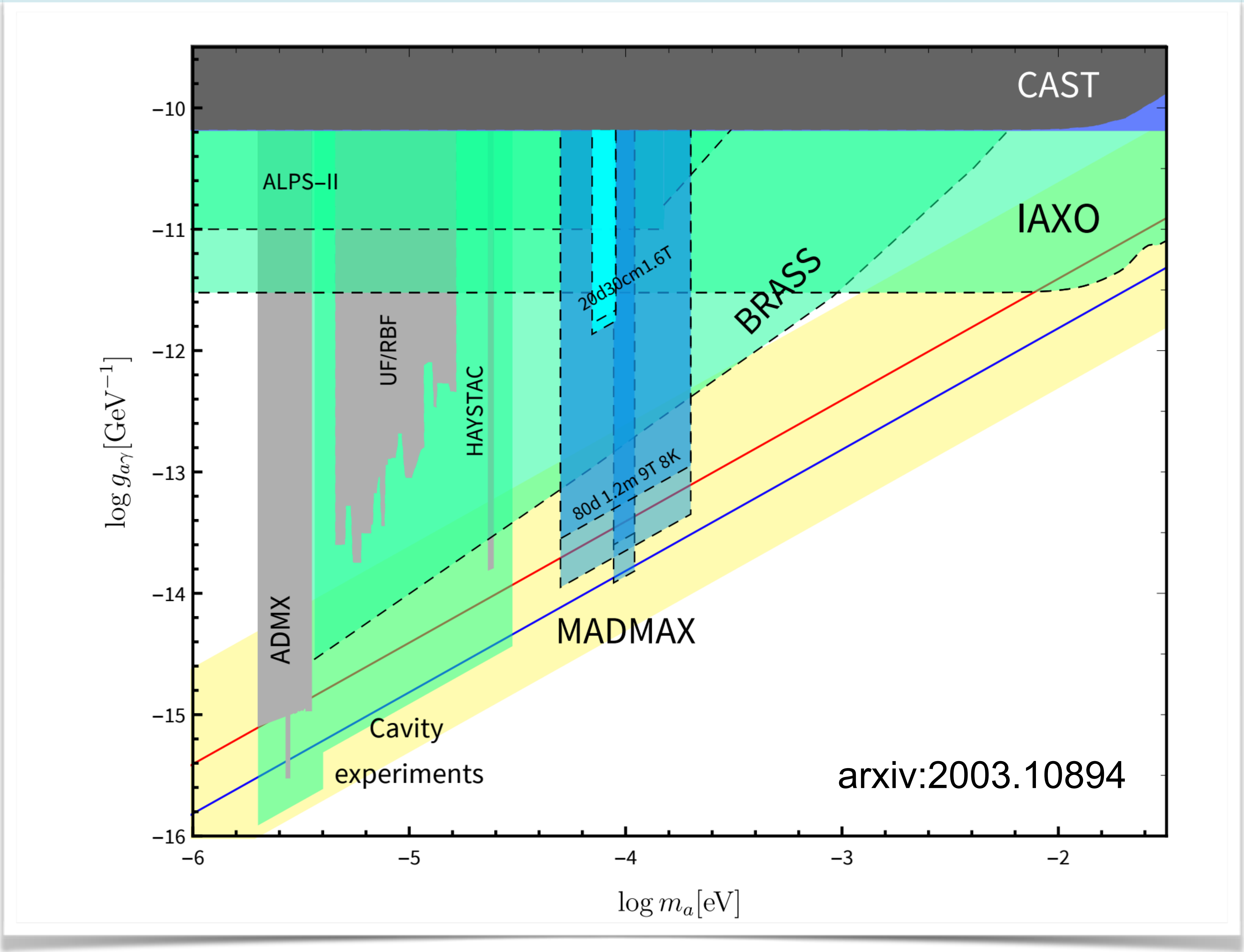
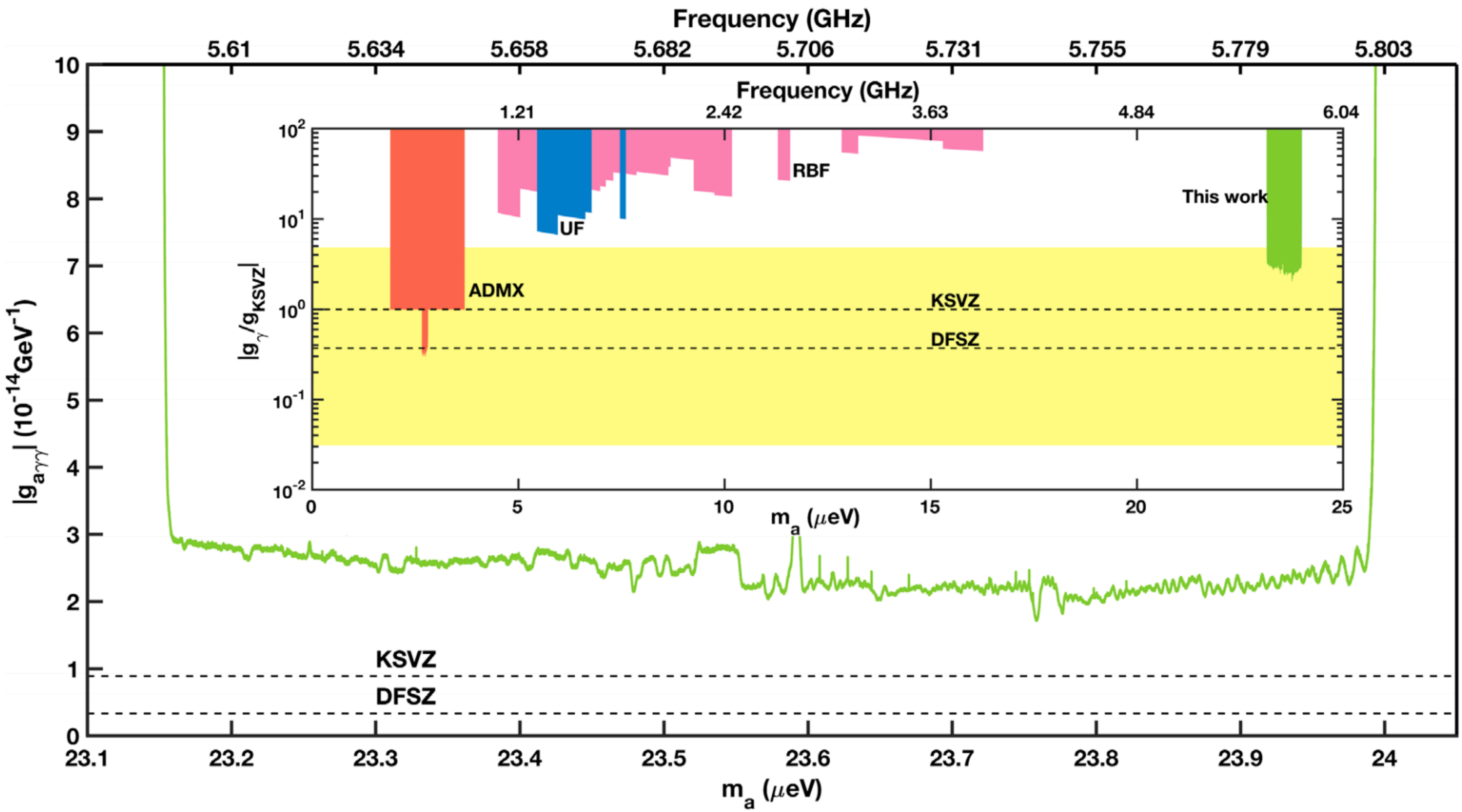
MADMAX: Prospective Sensitivity

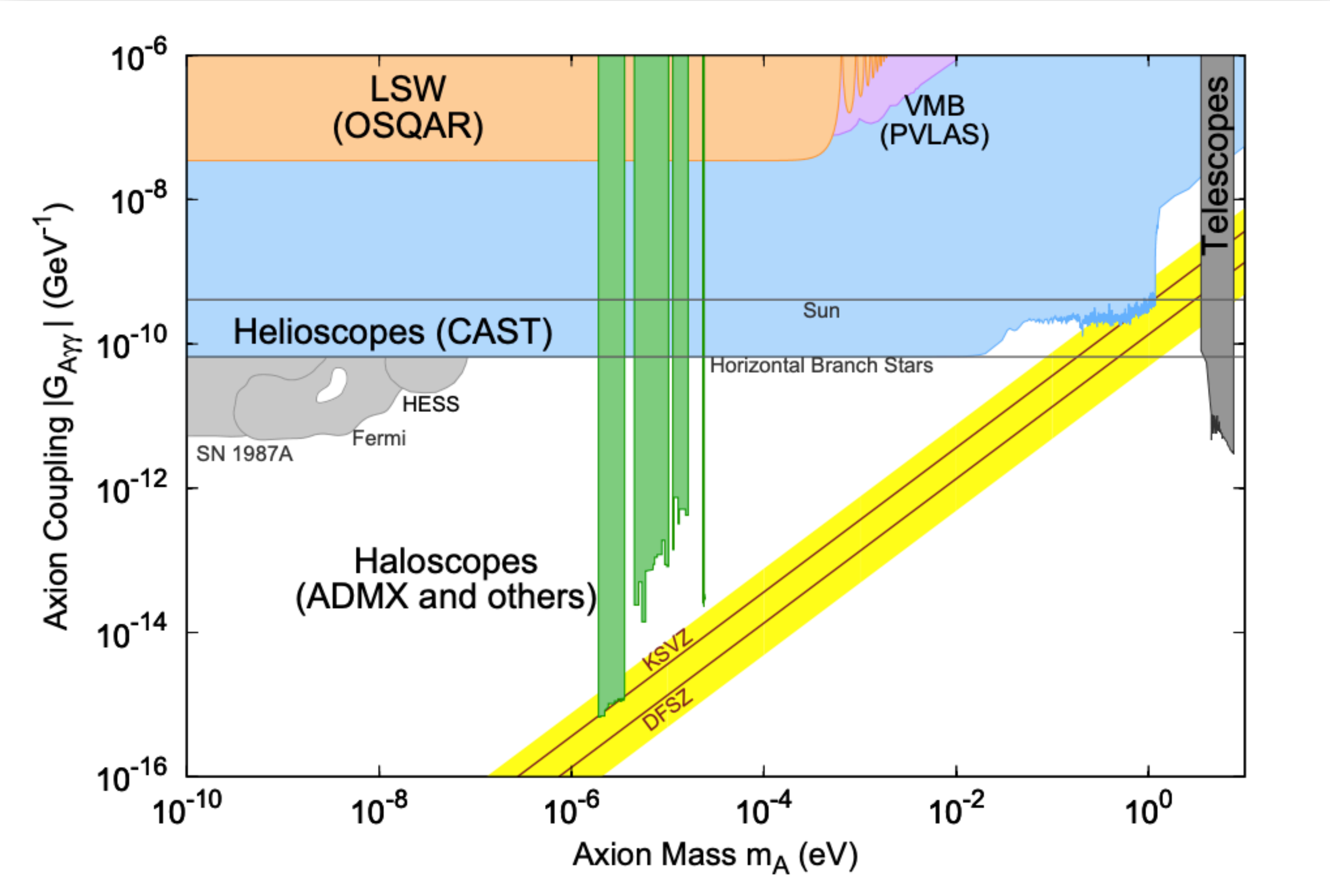


Haystac



Phase 1 results: Phys Rev D 97 092001 (2018)

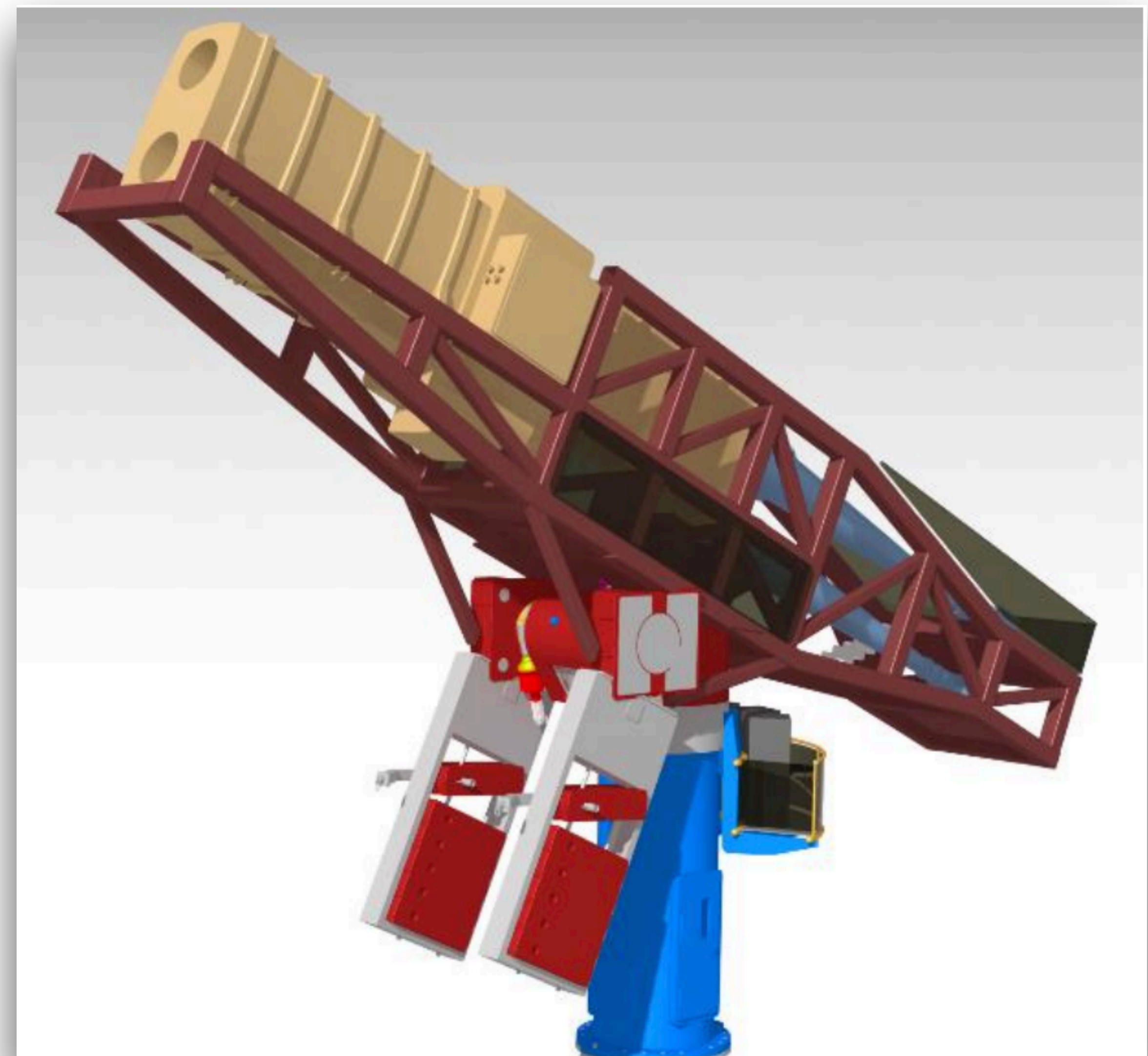
Axion-like Particles Exclusion Plot



PDG 2018

Baby-IAXO

Demonstration of feasibility for IAXO



- 2 10 m long flat racetrack coils with 0.8 m spacing with common coil configuration
- Average field of 2.1 T in the 2 700 mm detection bores

H F P Silva et al 2020 IOP Conf. Ser.: Mater. Sci. Eng. 755 012132