Axion Searches:

A New Wave of Dark Matter Experiments

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Massachusetts Institute of Technology

A Quick Aside as a Dark Matter Convener:

So many **Great Talks!**

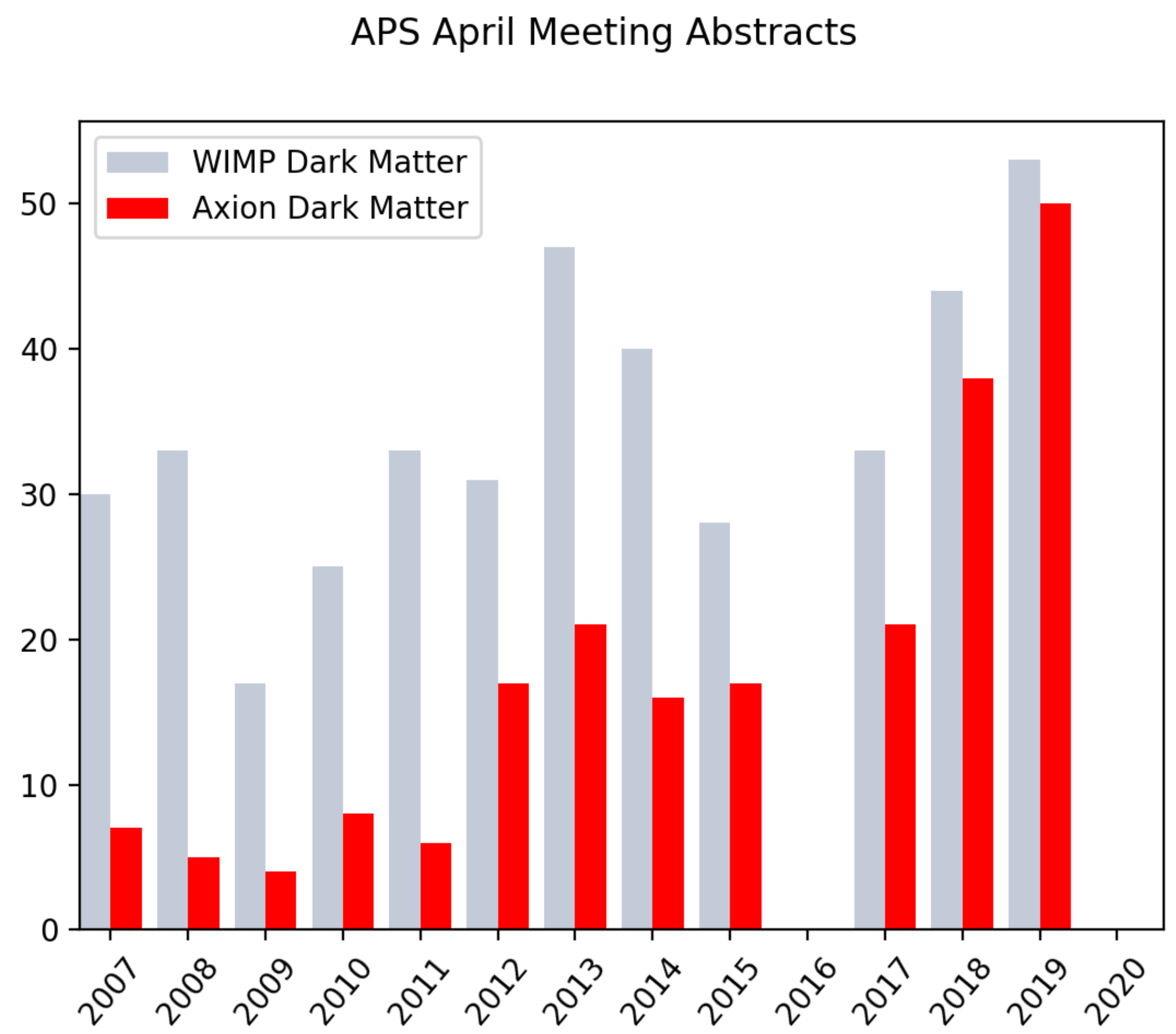
M - Dark Photons, Dark Matter and Galactic Dynamics, Theory

T - Indirect detection and the latest from direct WIMP searches

W - Axions and a special joint BSM session

Th - More ideas, theories and experiment!

Do you feel like you have been hearing a lot about axions lately?



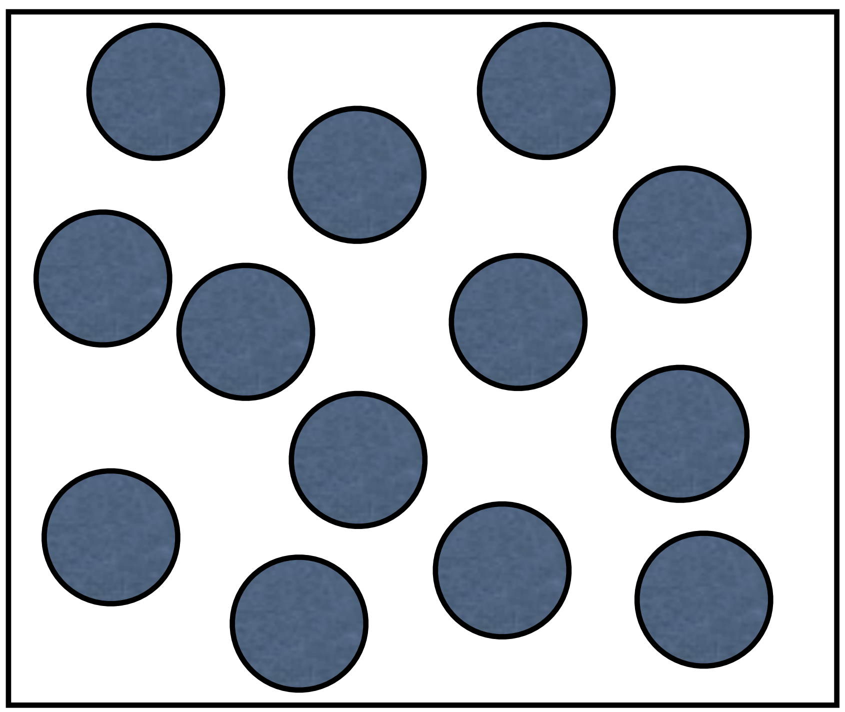
From: Jon Ouellet (MIT)

This has been fueled by:

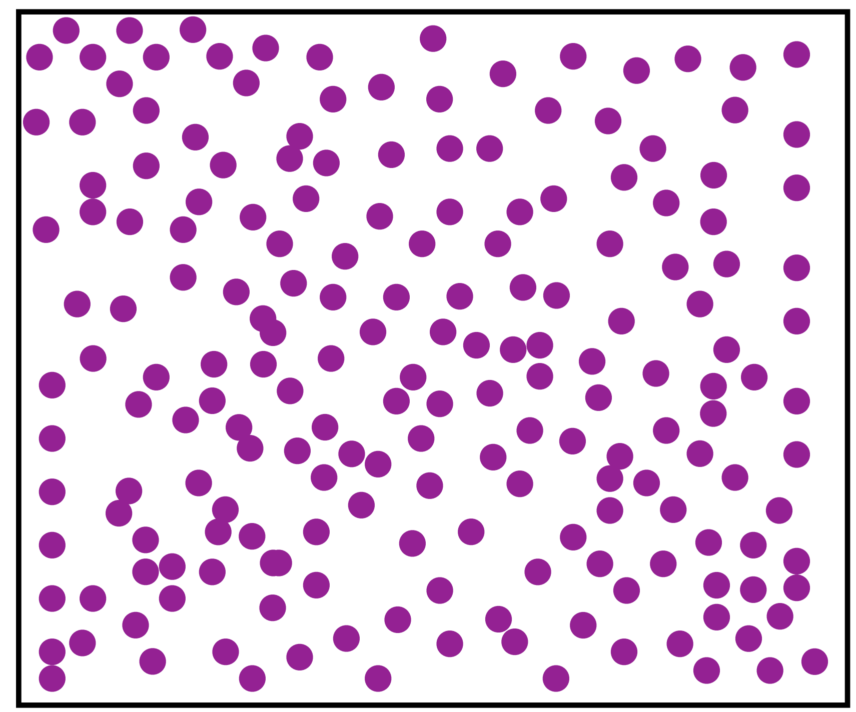
- Better understanding of cosmology
- New ideas
- New technology (cryogenics, quantum sensors, magnets, lasers ....)

Axions are different.

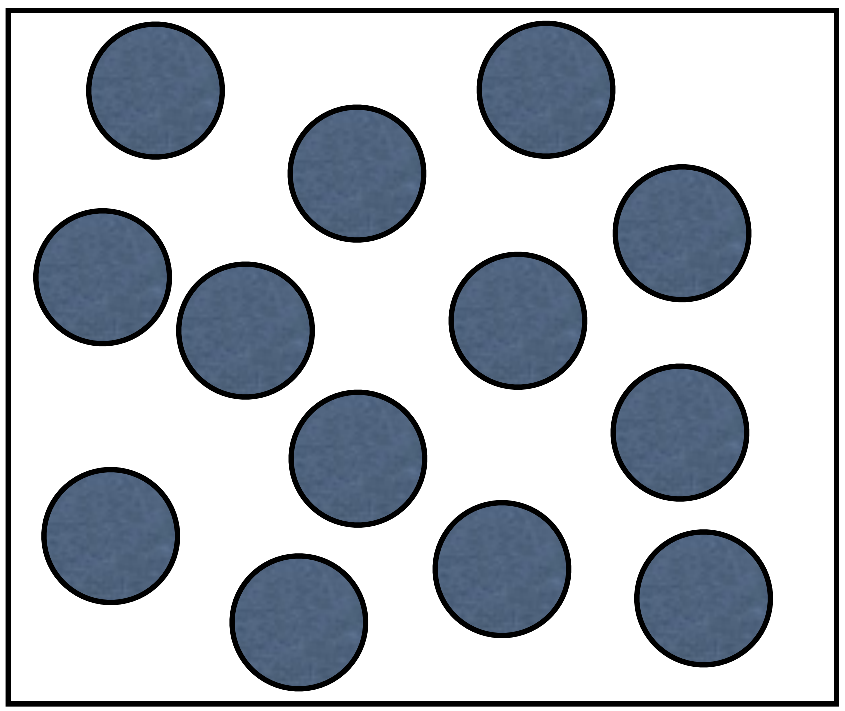
Heavy Dark Matter



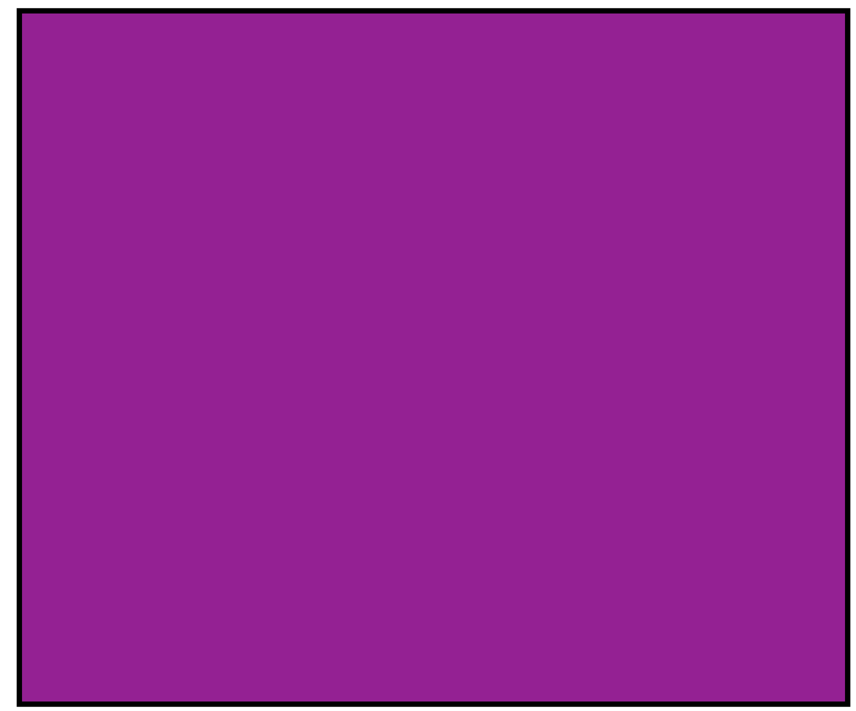
Axion Dark Matter

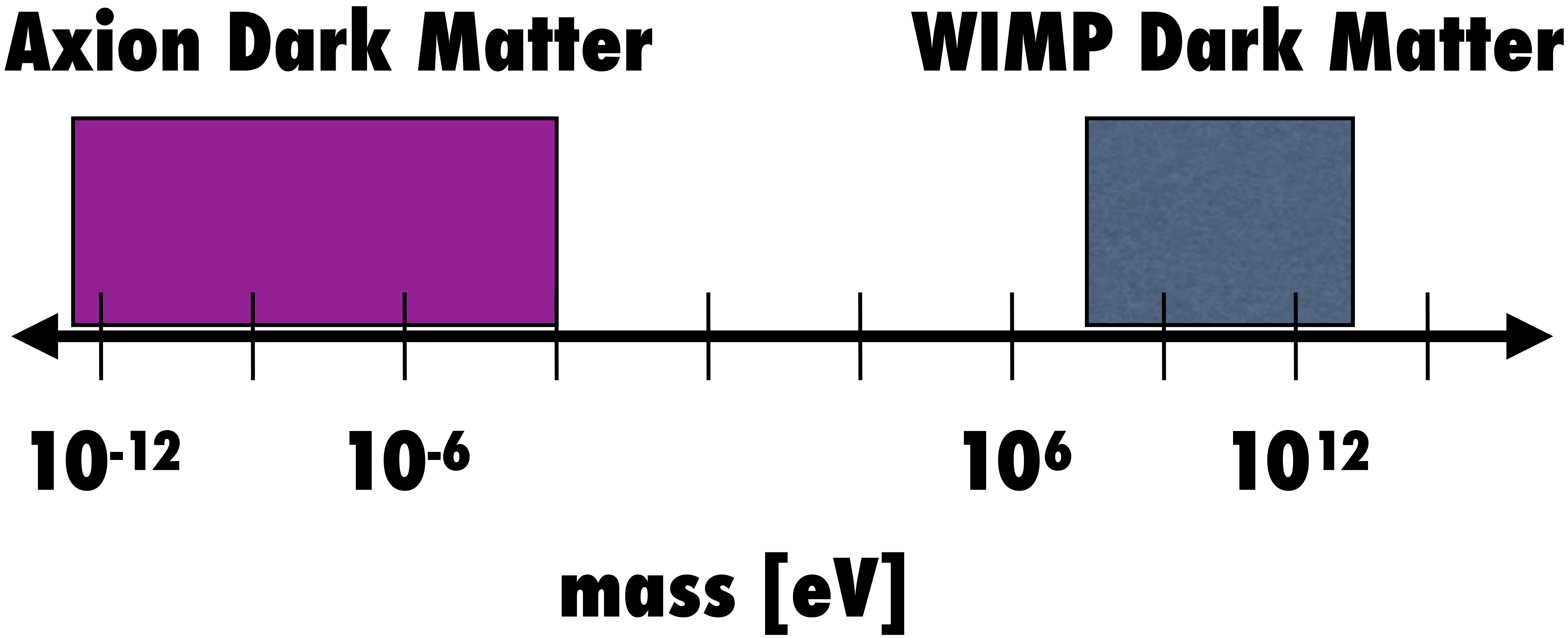


Heavy Dark Matter



Axion Dark Matter





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

… so we are really talking about wave dark matter.

Why axions?

CP Violation

We desperately want to observe more of it but why don't we see it in the strong interaction?

Some Details:

This is the CP violating term of the QCD Lagrangian.

$$\mathcal{L}_{\Theta} = -\bar{\Theta}\,(\alpha_s/8\pi)\,G^{\mu\nu a}\tilde{G}^{a}_{\mu\nu}$$

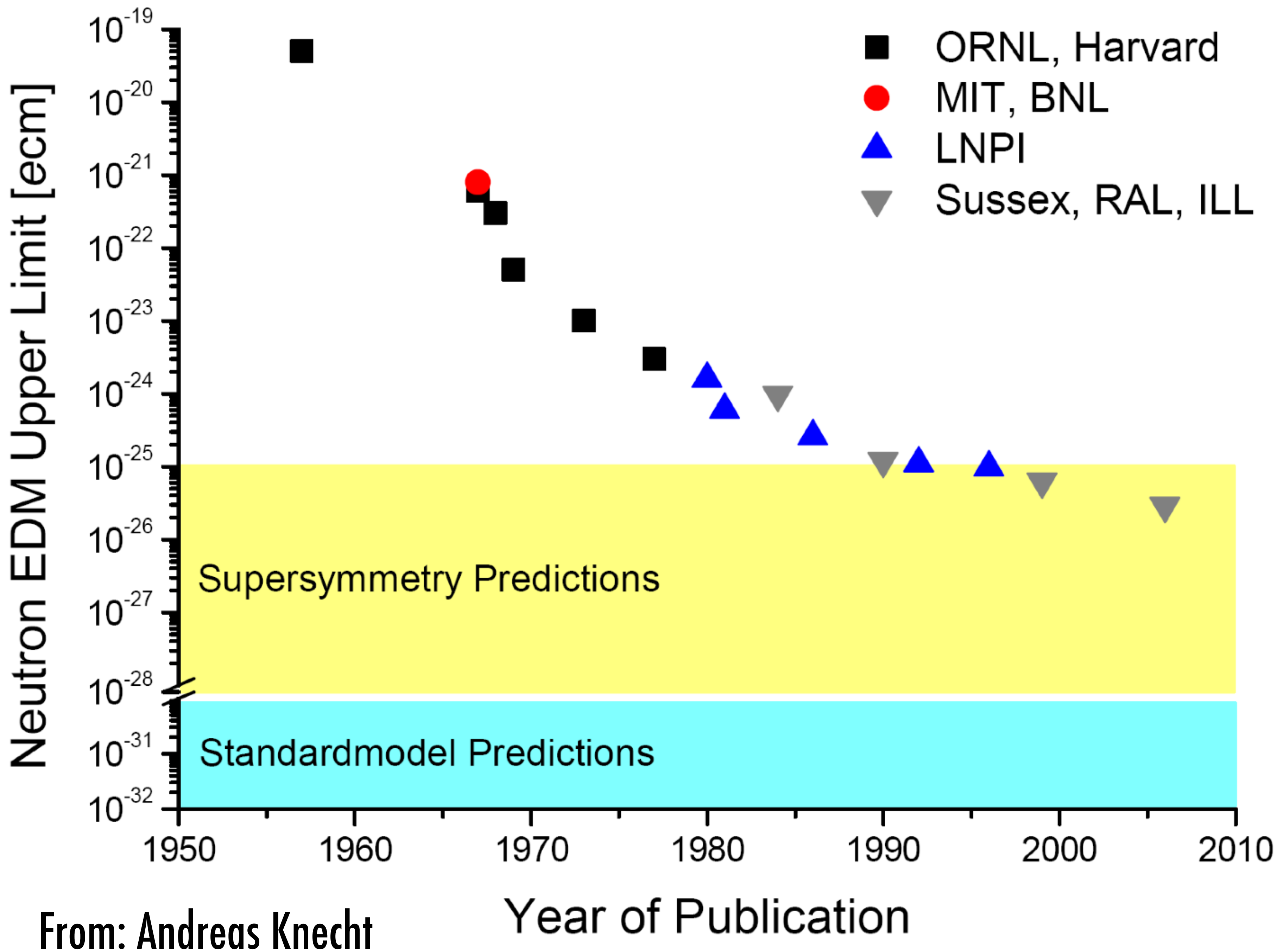
↑

Gluon field strength tensor

This term gives rise to an electric dipole moment of the neutron.

$$d_n \approx 3.6 \times 10^{-16}\bar{\Theta}\,[e\,cm]$$

The current limit: $|d_n| < 2.9 \times 10^{-26}\, e\, \mathrm{cm}$ (90% C.L.)



From: Andreas Knecht

This implies

$$\bar{\Theta} < 10^{-10}$$

That is small!!!

The Breaking of PQ Symmetry restores CP Symmetry!

Axion Field

$$\mathcal{L} = \left(\frac{\phi_A}{f_A} - \bar{\Theta}\right)\frac{\alpha_s}{8\pi} G^{\mu\nu a}\tilde{G}^a_{\mu\nu}$$

Symmetry breaking scale

$$m_a \sim 10^{-9}\,\mathrm{eV}\left(\frac{10^{16}\,\mathrm{GeV}}{f_a}\right)$$

mass of the axion

Dynamically sends Θ to zero!

The Breaking of PQ Symmetry restores CP Symmetry!

Axion Field

$$\mathcal{L} = \left(\frac{\phi_A}{f_A} - \bar{\Theta}\right)\frac{\alpha_s}{8\pi}G^{\mu\nu a}\tilde{G}^{a}_{\mu\nu}$$

Symmetry breaking scale

$$m_a \sim 10^{-9}\,\mathrm{eV}\left(\frac{10^{16}\,\mathrm{GeV}}{f_a}\right)$$

mass of the axion

and results in a new particle!

Kim-Shifman-Vainshtein-Zakharav (KSVZ) Axion

Introduces heavy quarks as well as the PQ scalar.

Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) Axion

Introduces additional Higgs field as well as the PQ scalar.

KSVZ and DFSZ:

These are the QCD axions.

ALPs:

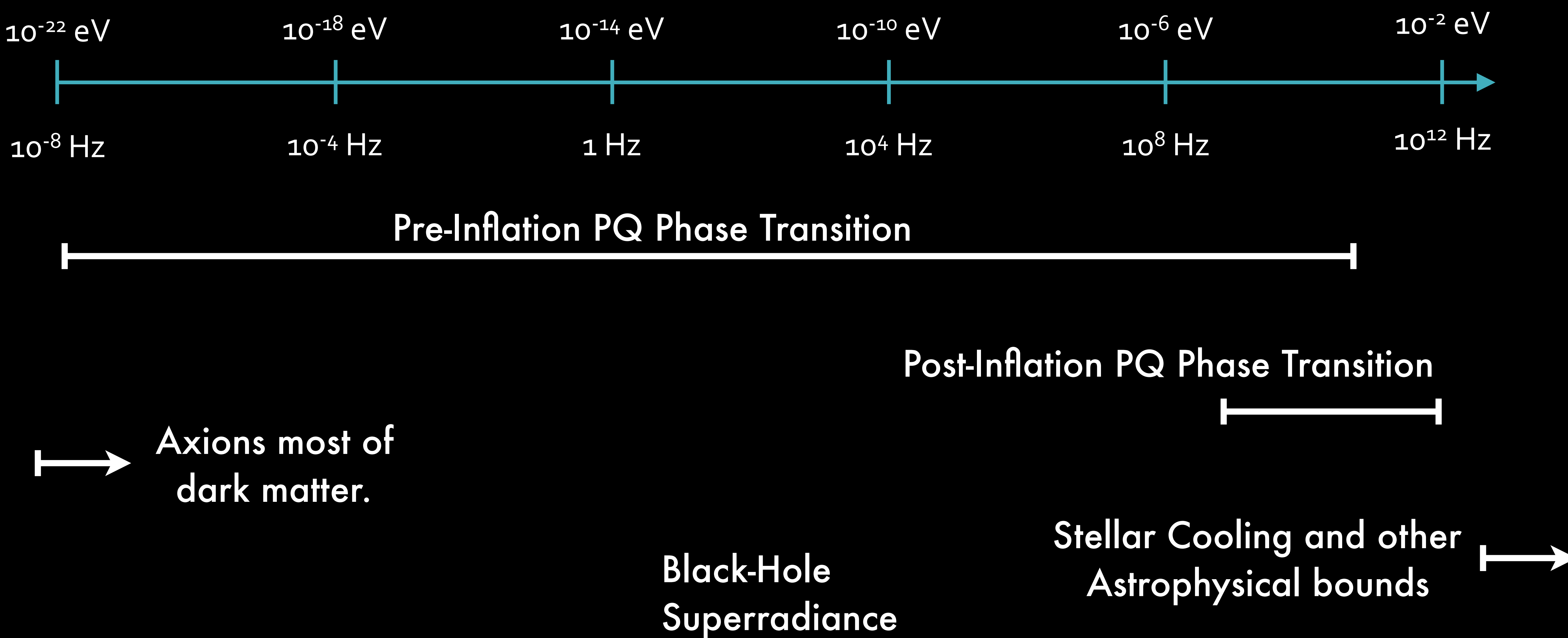
Axion-like particles made in many higher order theories.

Axions:

QCD axions + ALPs = axions.

What is the axion mass?

Theoretical Preferences



Adapted From: PDG Axion Review 2018

How do you detect them?

Axion-Standard Model Interactions

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

Coupling to Photons

Coupling to Nucleon EDM

Coupling to Axial Nuclear Moment

Coupling to Axial Electron Moment

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

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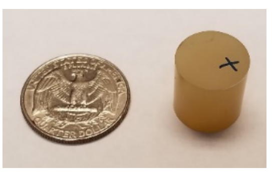
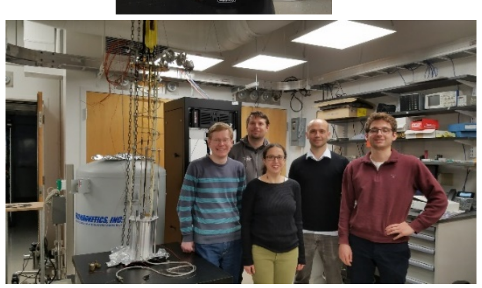
CASPEr-electric at Boston University

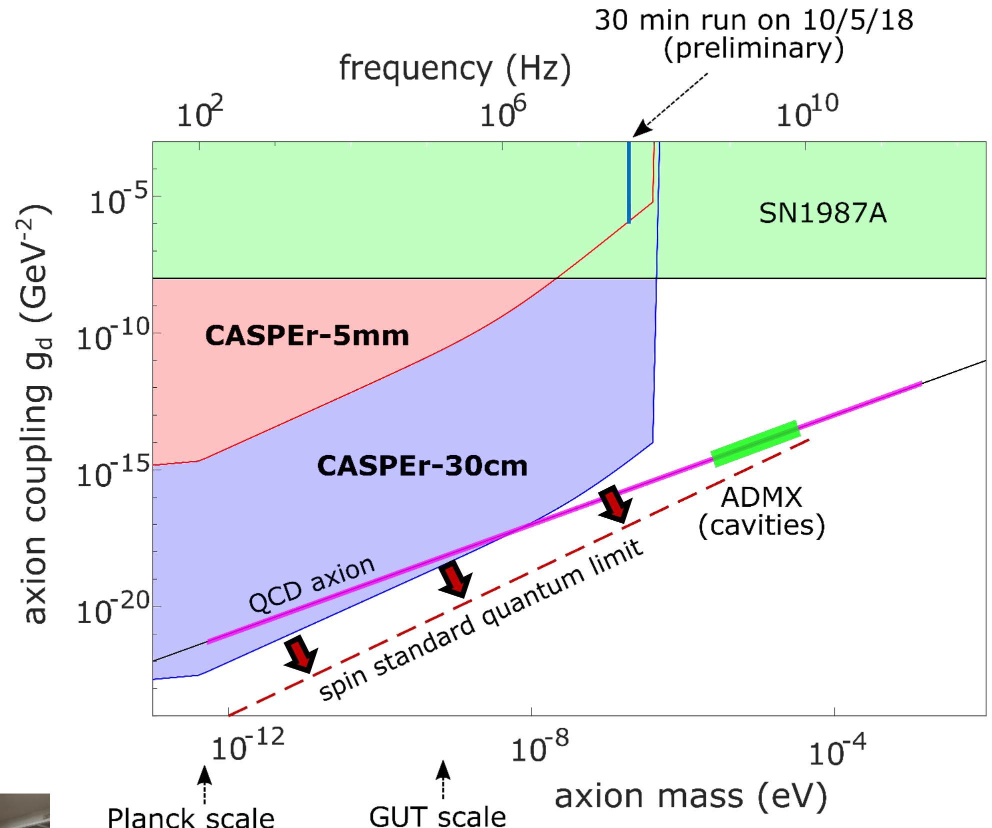
search for axion-gluon coupling → $\frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu}$

Deniz Aybas (Wed, 4:17pm):
Latest results from CASPEr-e

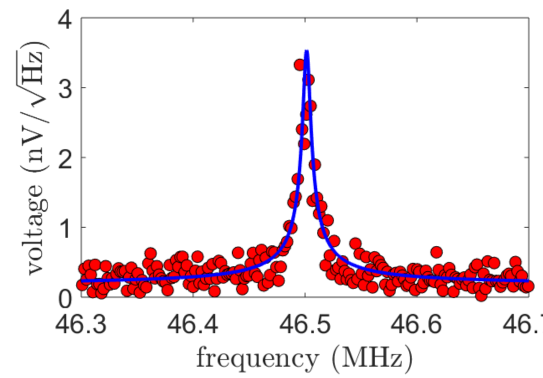
^{207}Pb nuclear spins in ferroelectric PMN-PT



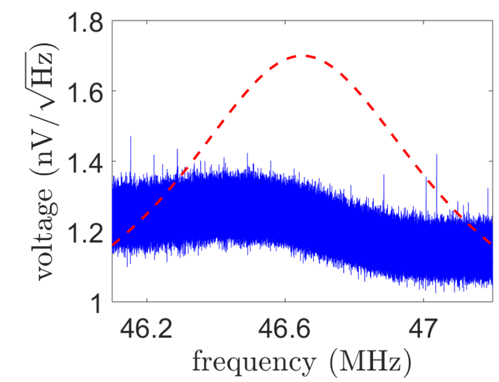




^{207}Pb NMR at 4 K

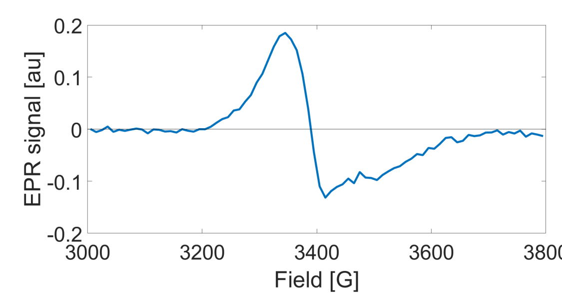


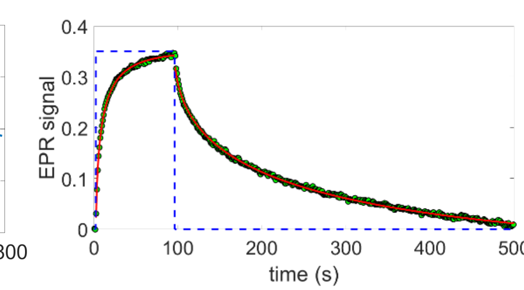
our first axion-sensitive measurements



Janos Adam (Wed, 4:34pm):
Enhancing axion search sensitivity using DNP

EPR of laser-induced paramagnetic centers in PMN-PT at 10 K





[*Phys. Rev. X* **4**, 021030 (2014)]

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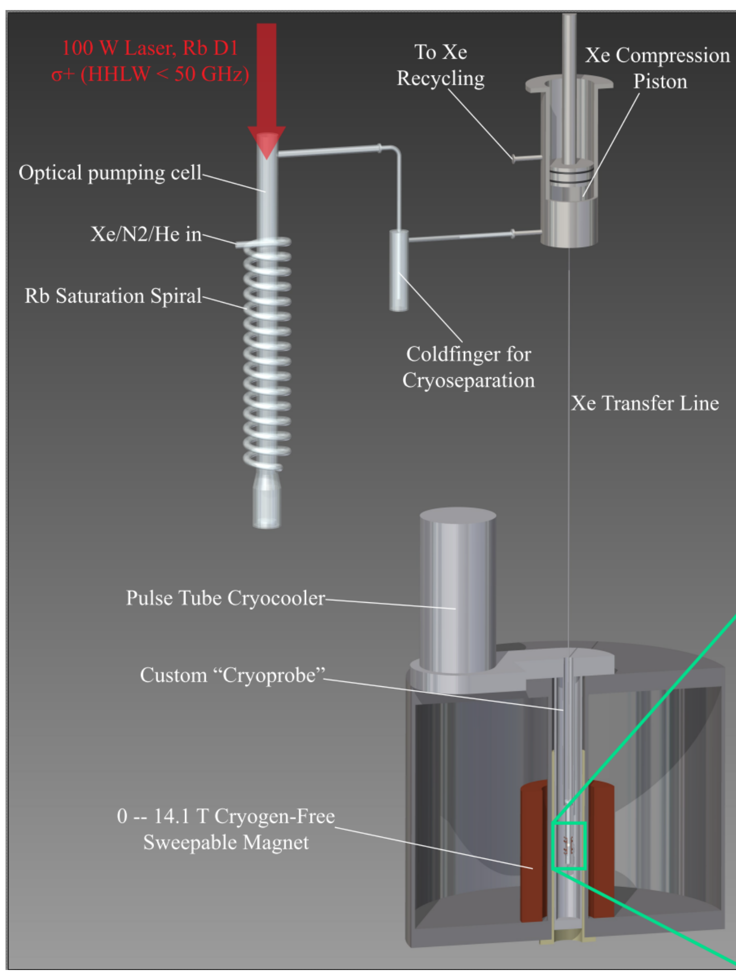
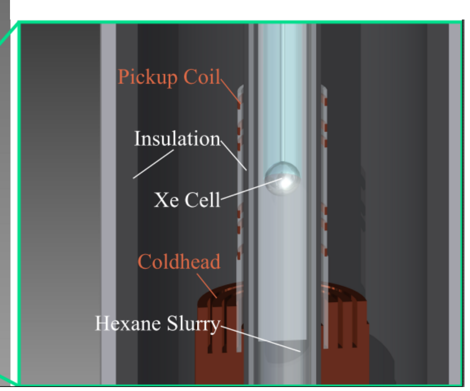
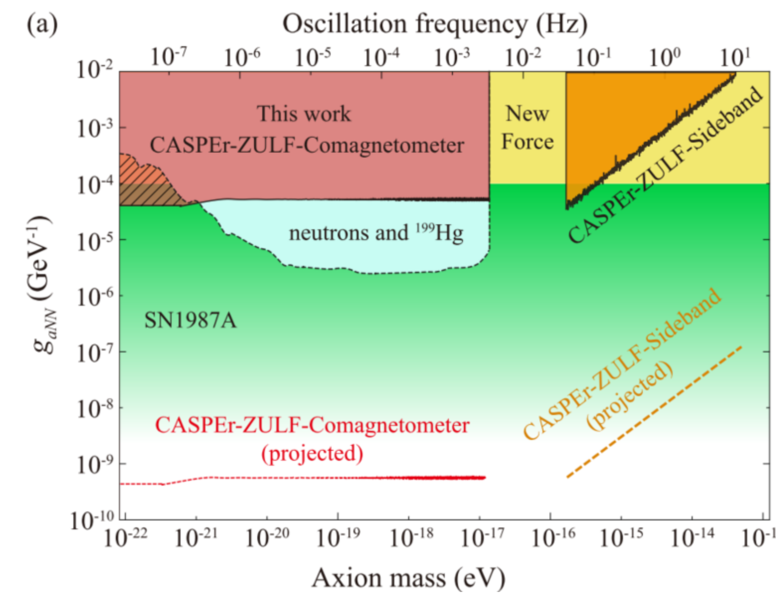
CASPEr-wind at Mainz

search for axion-wind coupling $\rightarrow \frac{\partial_\mu a}{f_a}\bar{\Psi}_f\gamma^\mu\gamma_5\Psi_f$

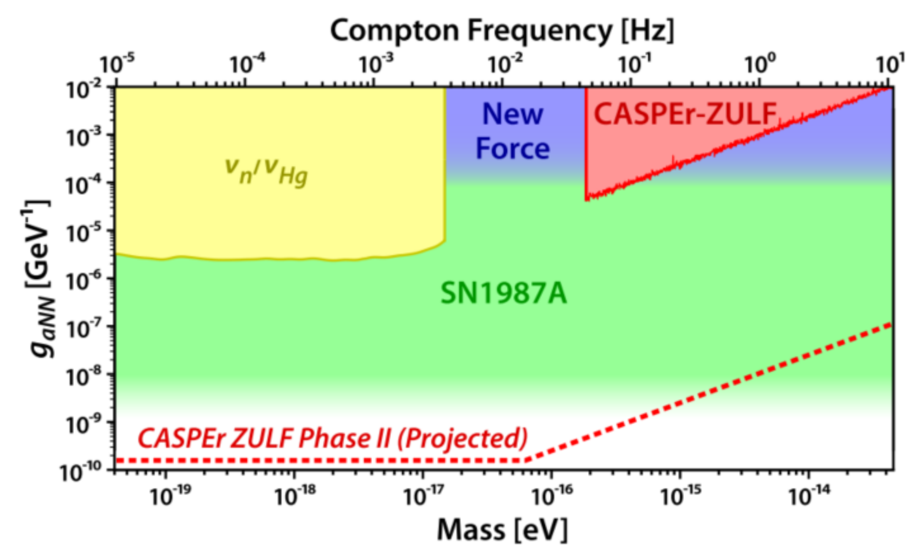



led by Dima Budker's group
(JGU Mainz & UC Berkeley)

Derek Kimball (CSUEB)



[*Phys. Rev. Lett.* **122**, 191302 (2019)]



[*arXiv:1902.04644*]

Axion-Standard Model Interactions

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Coupling to Photons

Coupling to Nucleon EDM

Coupling to Axial Nuclear Moment

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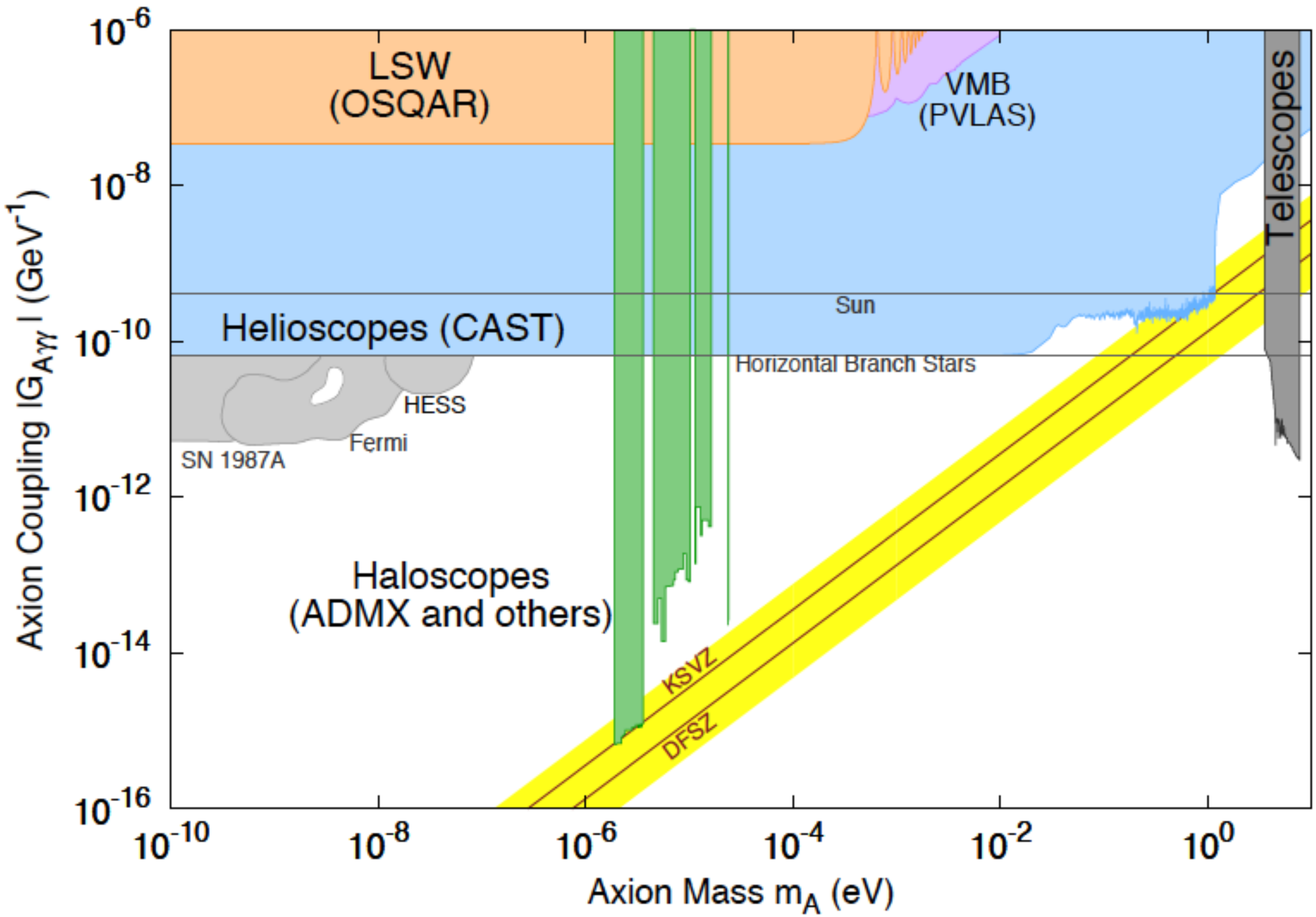
Adapted from Y. Kahn, See Graham and Rajendran, Phys.Rev. D88 (2013) 035023

The Summary of the Axion Photon Coupling



PDG - Axion Review 2018

Axions modify Maxwell's Equations!

$$\nabla \cdot E = -g_{a\gamma\gamma} B \cdot \nabla a$$

$$\nabla \cdot B = 0$$

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

$$\nabla \times B = \frac{\partial E}{\partial t} - g_{a\gamma\gamma}(E \times \nabla a - \frac{\partial a}{\partial t} B)$$

Modified Source-free Maxwell's Equations

Axions modify Maxwell's Equations!

$$\nabla \cdot E = -g_{a\gamma\gamma} B \cdot \nabla a$$

$$\nabla \cdot B = 0$$

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

$$\nabla \times B = \frac{\partial E}{\partial t} - g_{a\gamma\gamma}(E \times \nabla a - \frac{\partial a}{\partial t} B)$$

These terms are assumed to be small.

Axion-Photon Searches

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

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

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

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

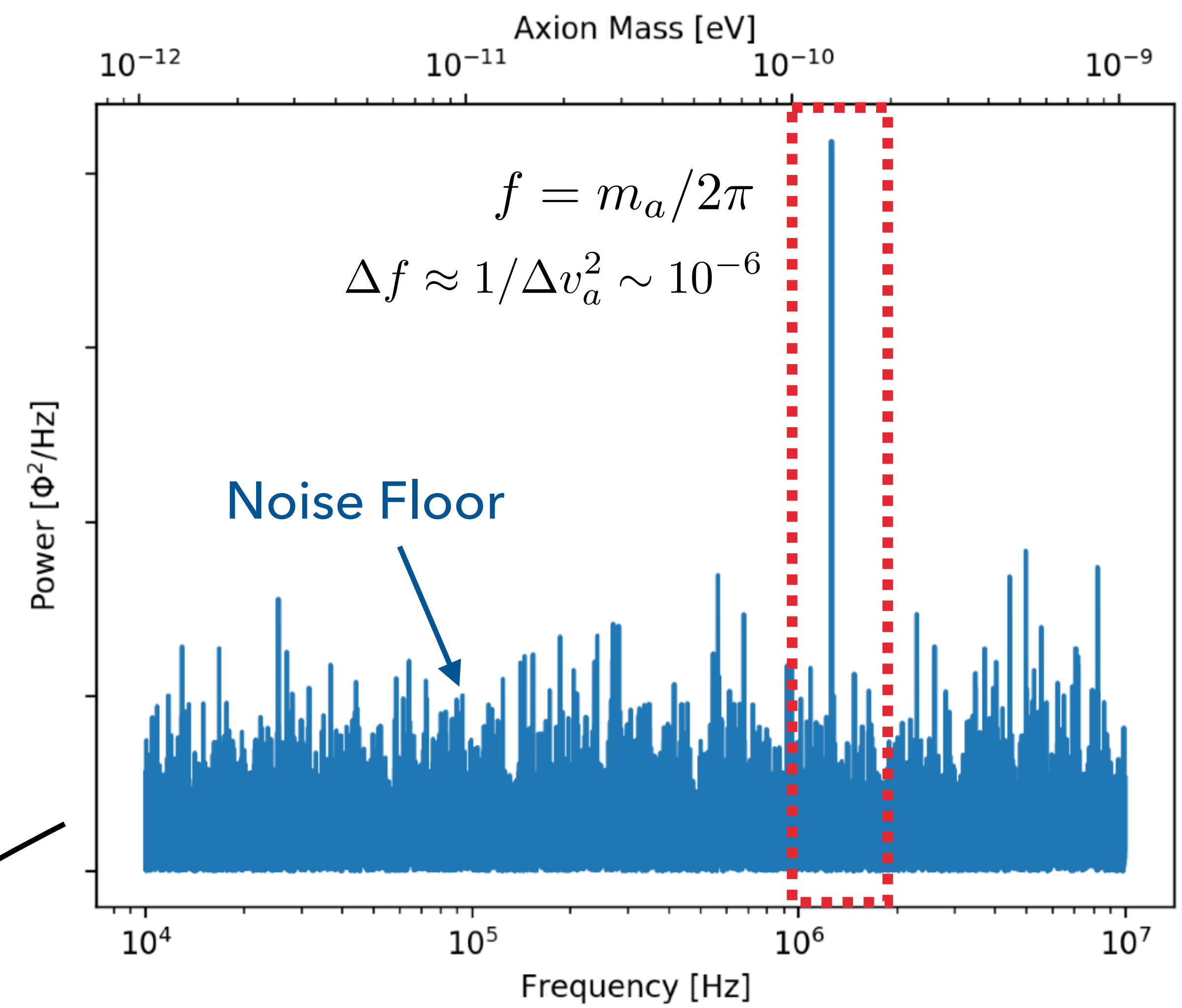
$$\cancel{\nabla \times \mathbf{B}_r} = \frac{\partial \mathbf{E}_r}{\partial t} + g_{a\gamma\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}$$

Radiation regime: $\lambda_{\text{Comp}} \ll R_{\text{exp}}$

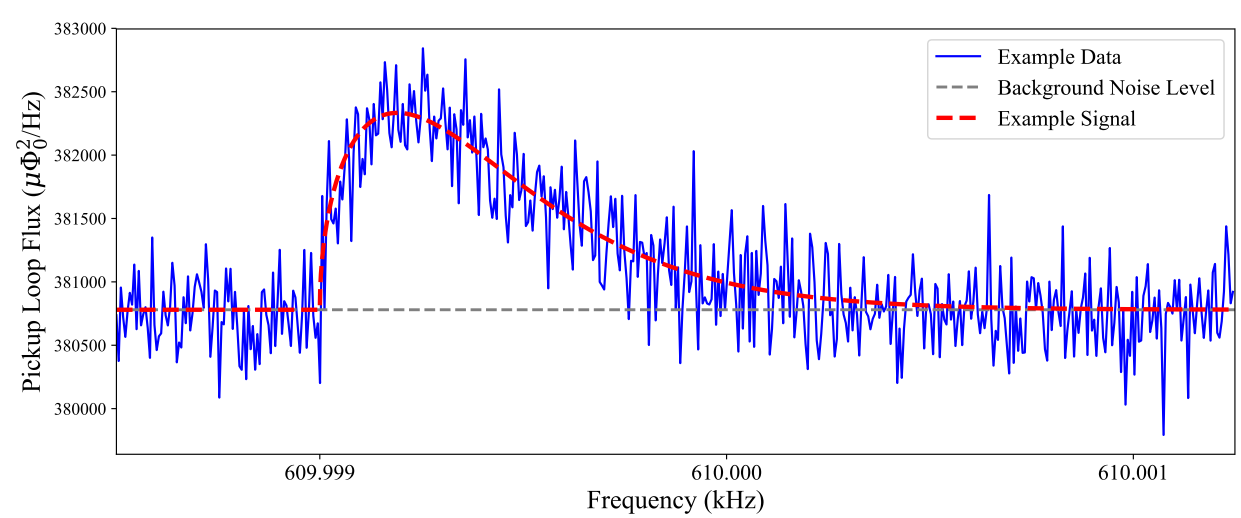
From: Yoni Kahn

We will be measuring a frequency!

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



ZOOM

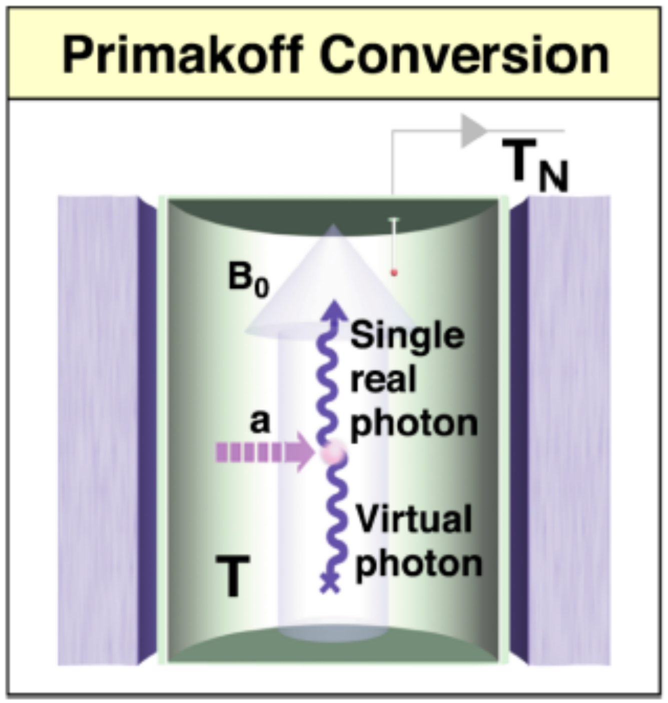


There is a characteristic line shape due to the halo velocity distribution.

Other neat features could show up here!

Starting with Cavities

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)

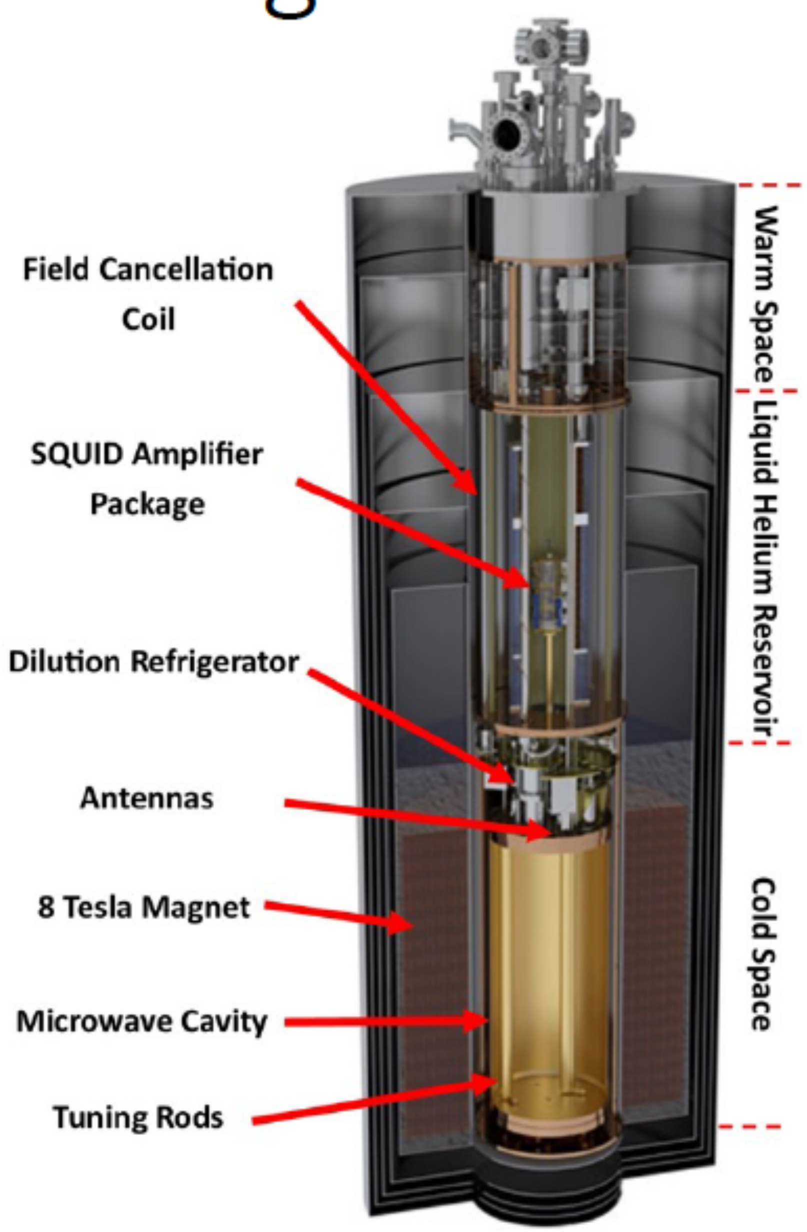
Signal Proportional to

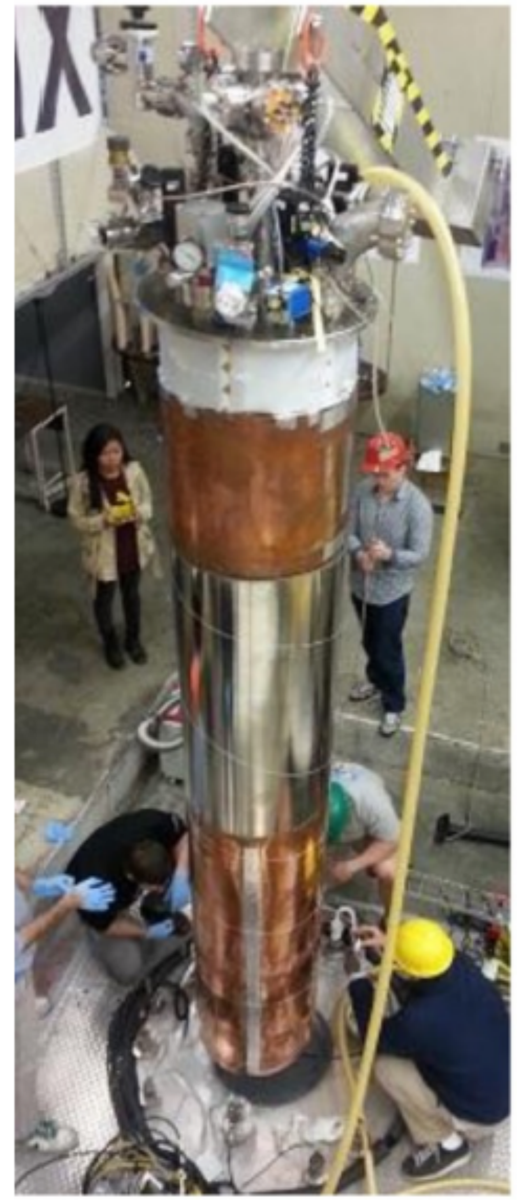
Cavity Volume
Magnetic Field
Cavity Q

Noise Proportional to

Cavity Blackbody Radiation
Amplifier Noise

ADMX Design





Key technologies:

-millikelvin cryogenics

-ultralow noise quantum amplifiers

ɌAS 2019

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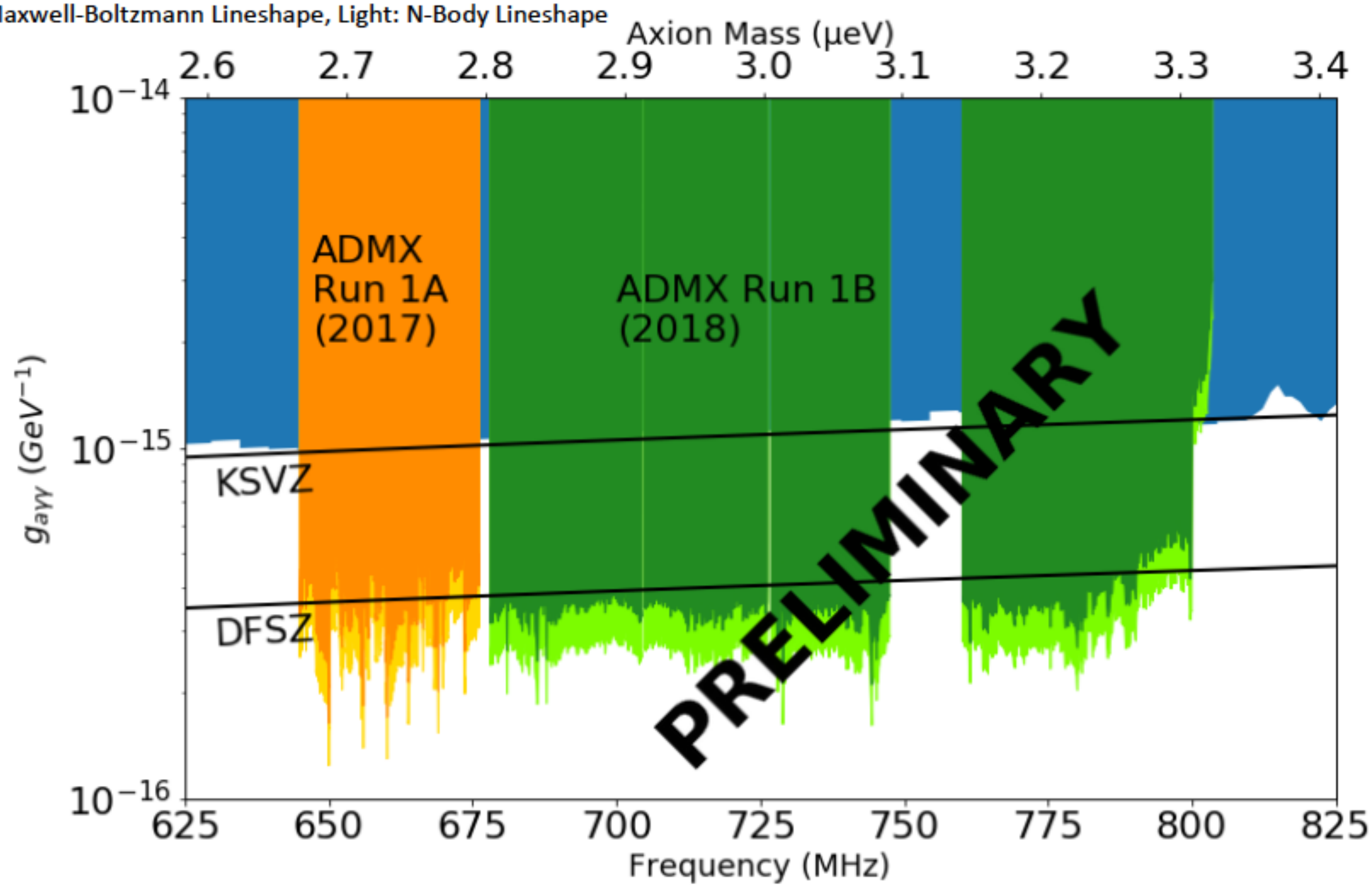
Preliminary Sensitivity from 2018 Run

Dark: Maxwell-Boltzmann Lineshape, Light: N-Body Lineshape



We estimate sensitivity to DFSZ dark matter axions between 2.8 and 3.3 ueV

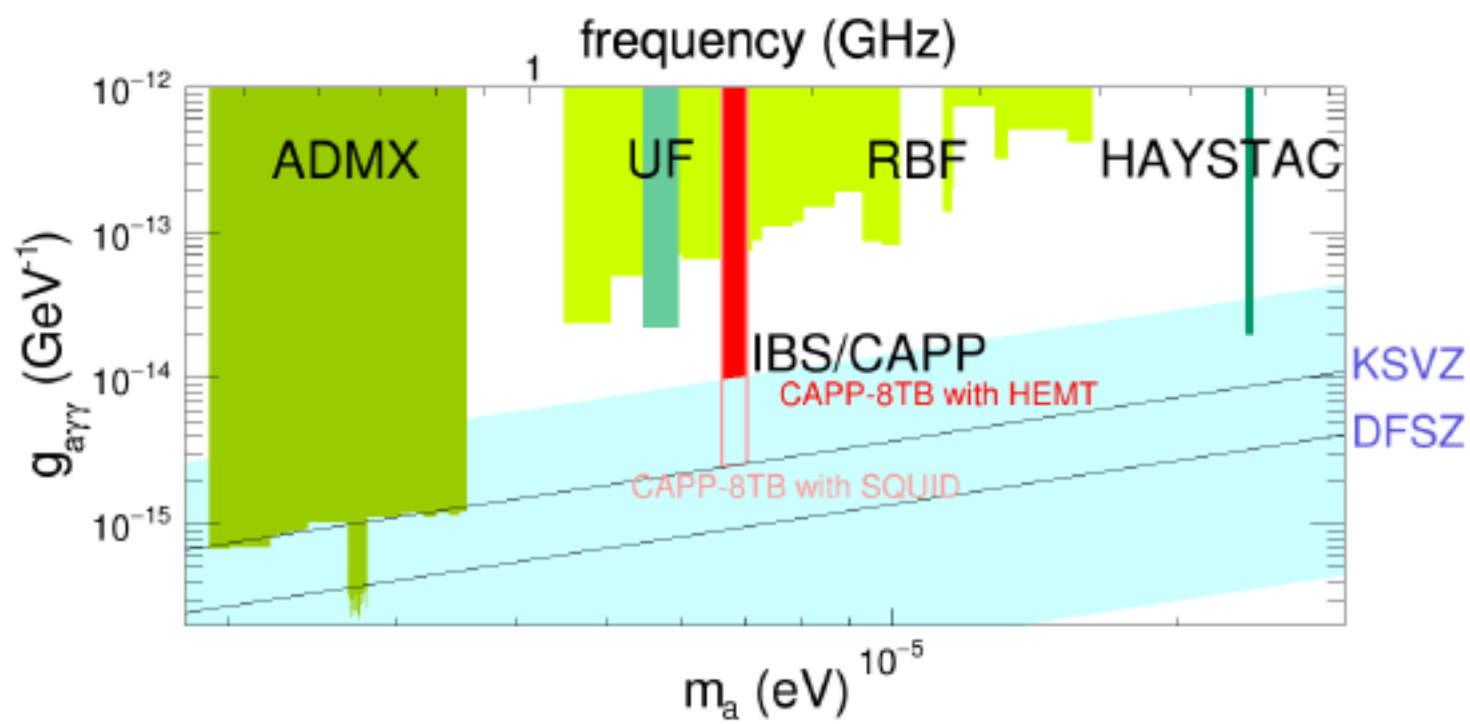
This is four times as much mass range with much more even DFSZ coverage.

3 Gaps from mode crossings in cavity.

Paper in preparation!

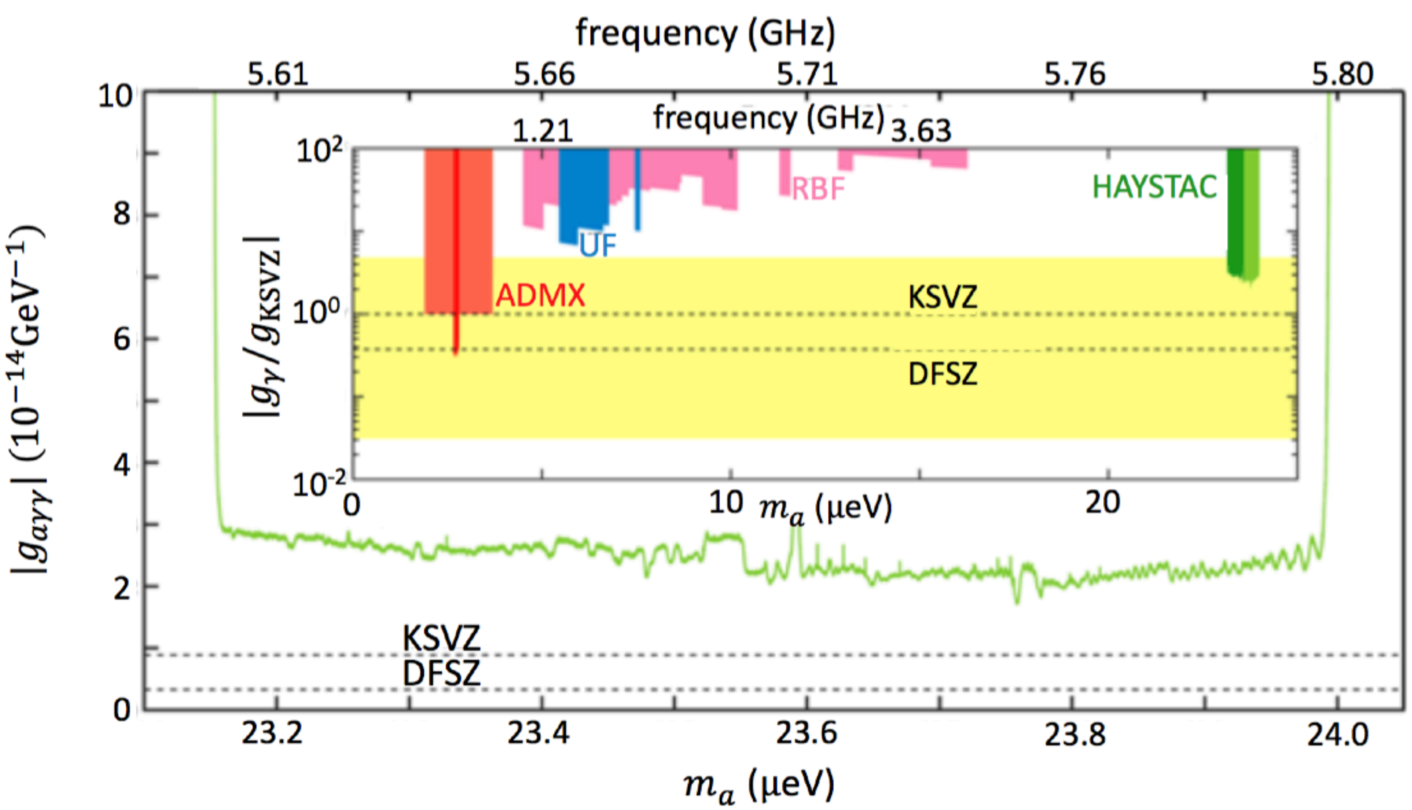
CAPP-8TB: Axion Haloscope for 6.62 - 7.04 μeV

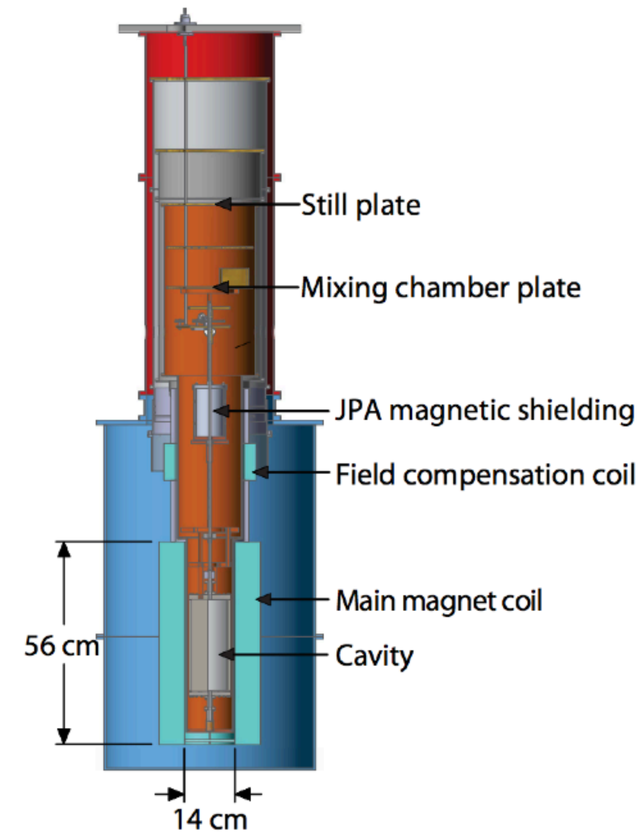
- CAPP-8TB is a dedicated experiment to search for axion dark matter in a mass range of 6.62 - 7.04 μeV (= 1.6 - 1.7 GHz in frequency domain)
  - External magnetic field: 7.3 T (avg.)
  - Resonant cavity physical temperature: 50 mK
  - System noise temperature: ~ 1 K
- 1st phase will touch QCD axion band with HEMT, 2nd phase will challenge KSVZ with quantum limit noise amplifiers

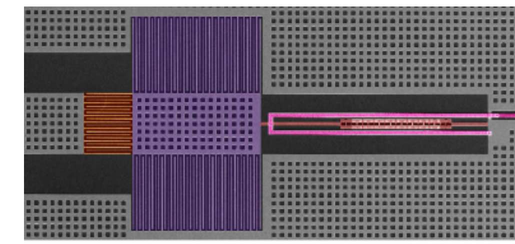


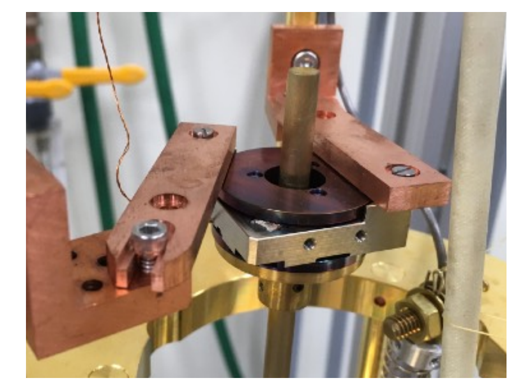
HAYSTAC Phase 1

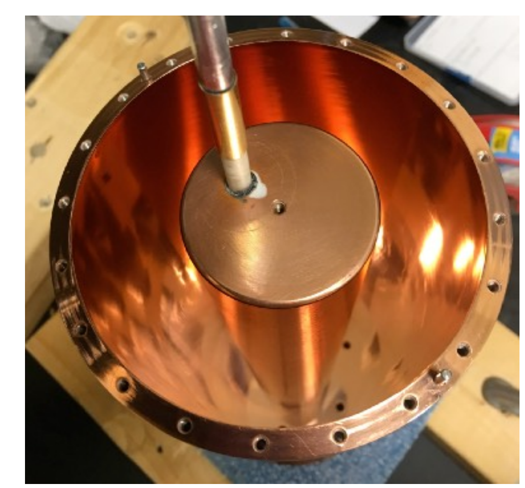
Zhong et al., PRD **97** 092001 (2018)
Brubaker et al., PRL **118** 061302 (2017)
S. Al Kenany et al., NIMA **854** 11 (2017)
2019 Tanaka Prize, B. Brubaker







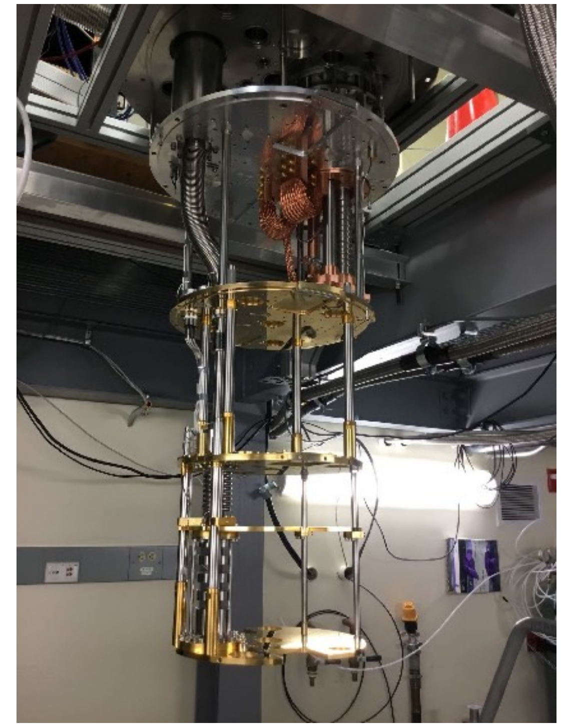




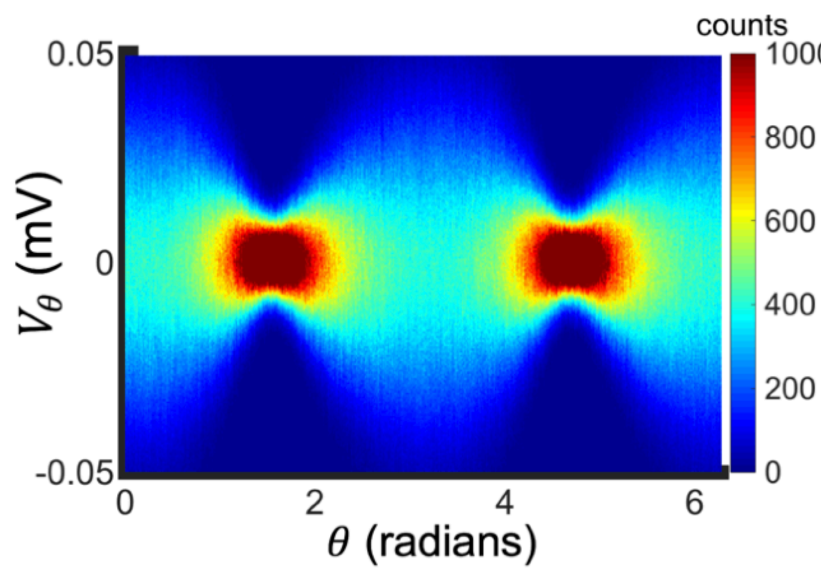
- Tc = 127 mK, B = 9T, Q_L ~ 10,000, near-quantum-limited JPA receiver, Attocube piezoelectric rotary motor for cavity tuning in dilution refrigerator
- Data taking 2016 – 2017
- First QCD axion search above 20 μeV
- Exclude $\left|g_\gamma\right| \geq 2.7 \left|g_\gamma^{\mathrm{KSVZ}}\right|$ for $23.15 \leq m_a \leq 24\ \mu$eV (5.6 - 5.8 GHz)

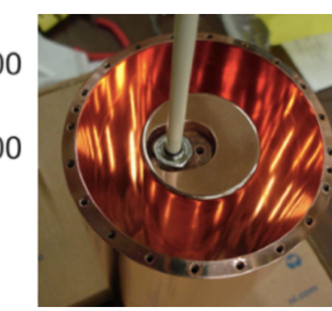
Haystac

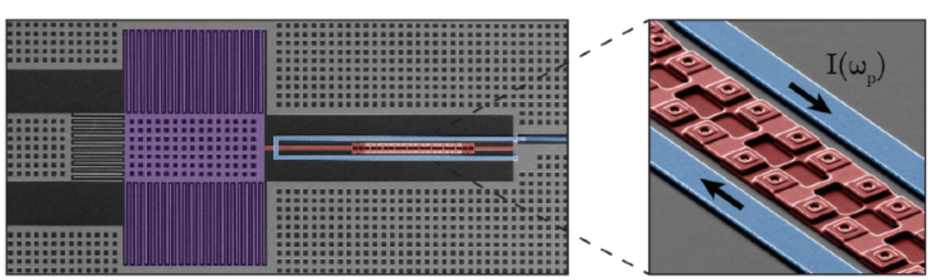
HAYSTAC Phase 2



- Commissioning underway
- New technology implementation & enhancements
  - "Squeezed-state" receiver to reduce noise below the quantum limit
    - scan rate increase expected > factor of 2
    - concept demonstrated in a stand-alone system [M. Malnou et al., Phys. Rev. Applied **9** 044023, 2018]
  - BlueFors dilution refrigerator, redesigned support structure
  - Better thermalization of tuning rod







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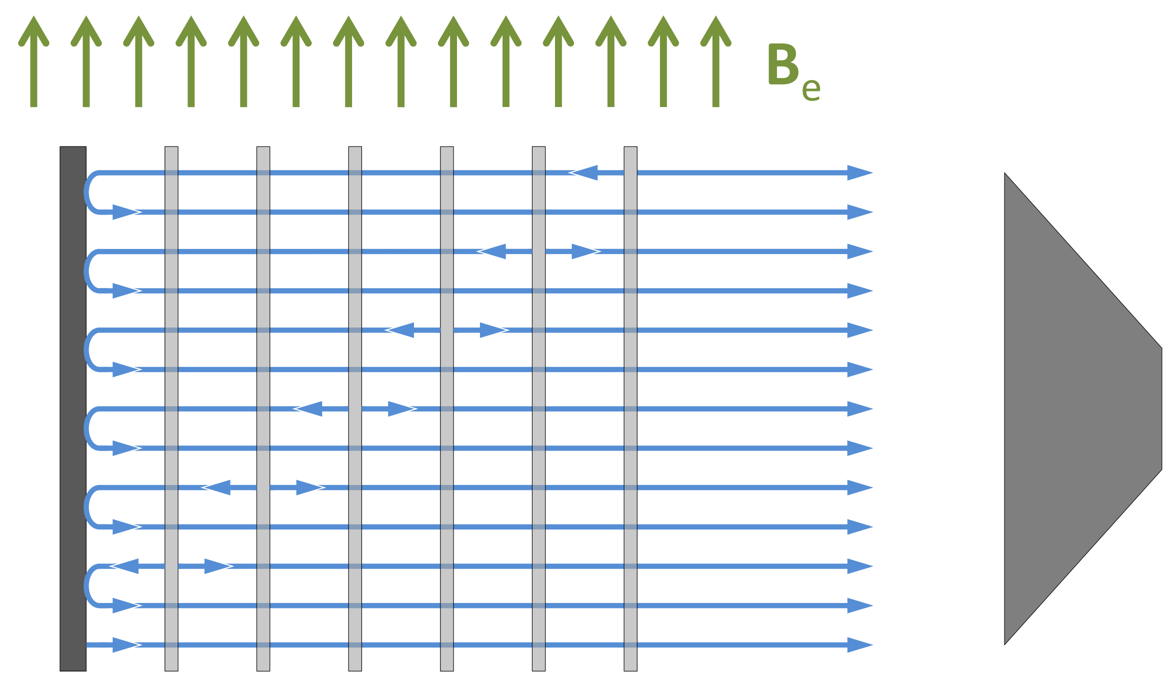
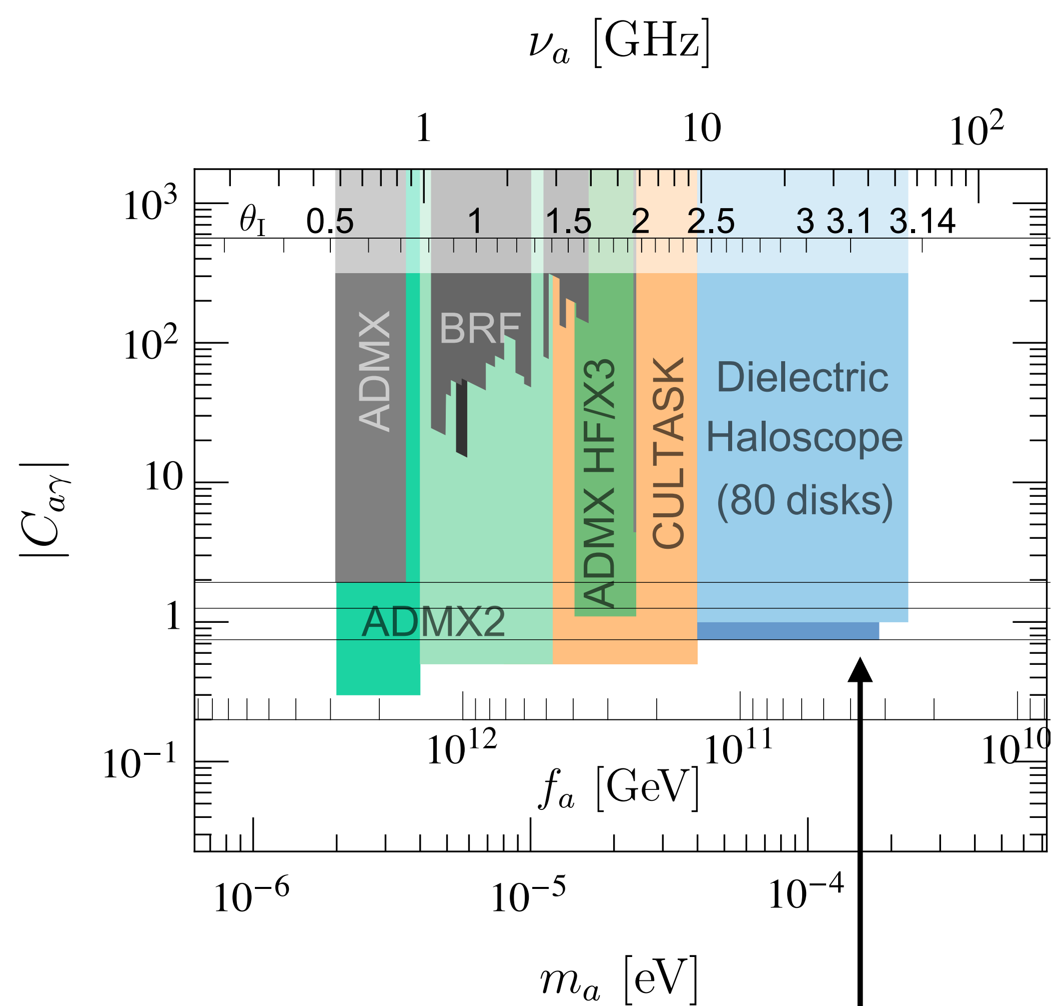
The Dielectric Haloscope: MADMAX

$\lambda_{\rm Comp} \ll R_{\rm exp}$





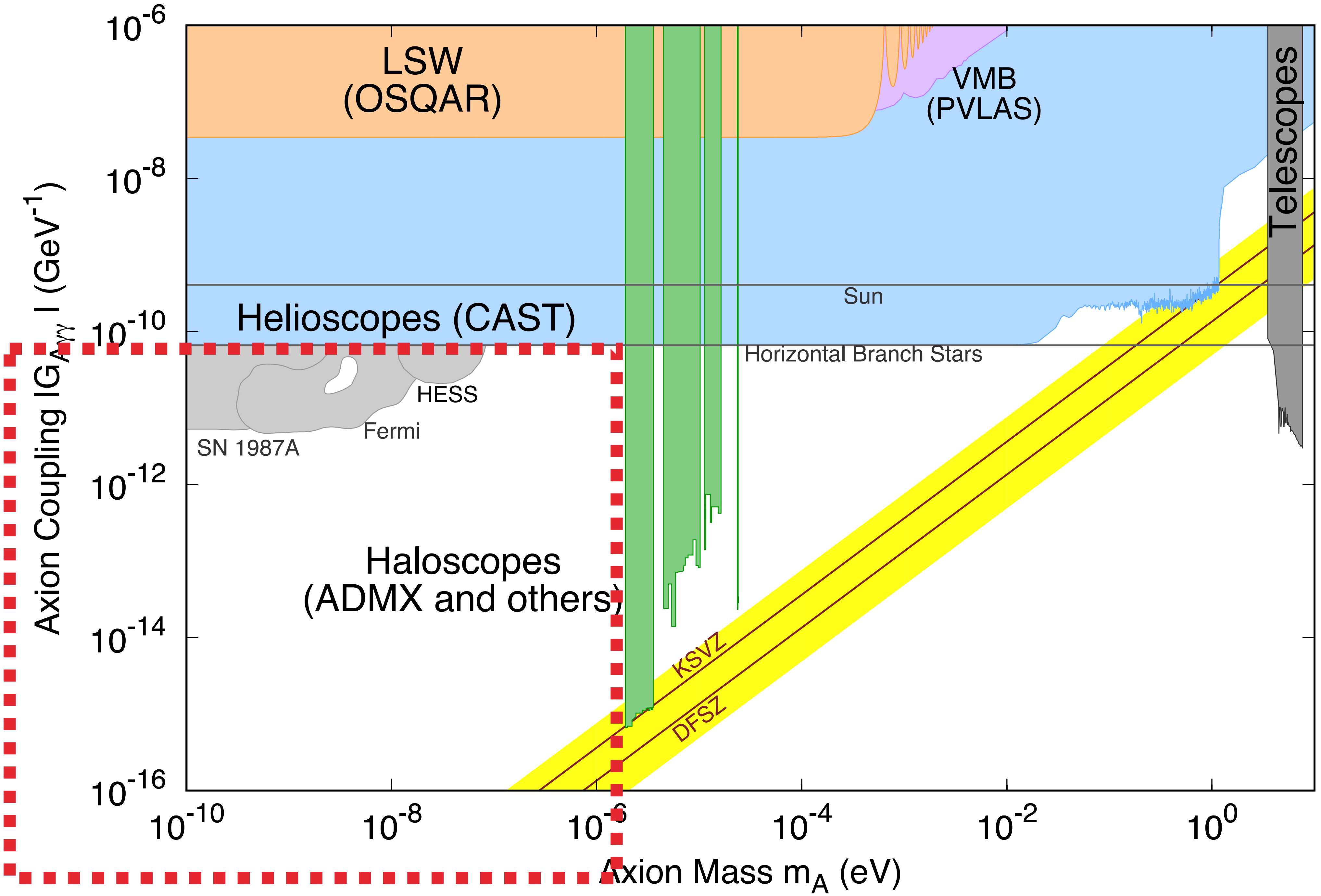
E+M boundary condition at interfaces forces radiation to cancel axion-induced **D**

Proposed Sensitivity

Now back to lower masses

The Lumped Element Parameter Space

$\lambda_{\mathrm{Comp}} \gg R_{\mathrm{exp}}$

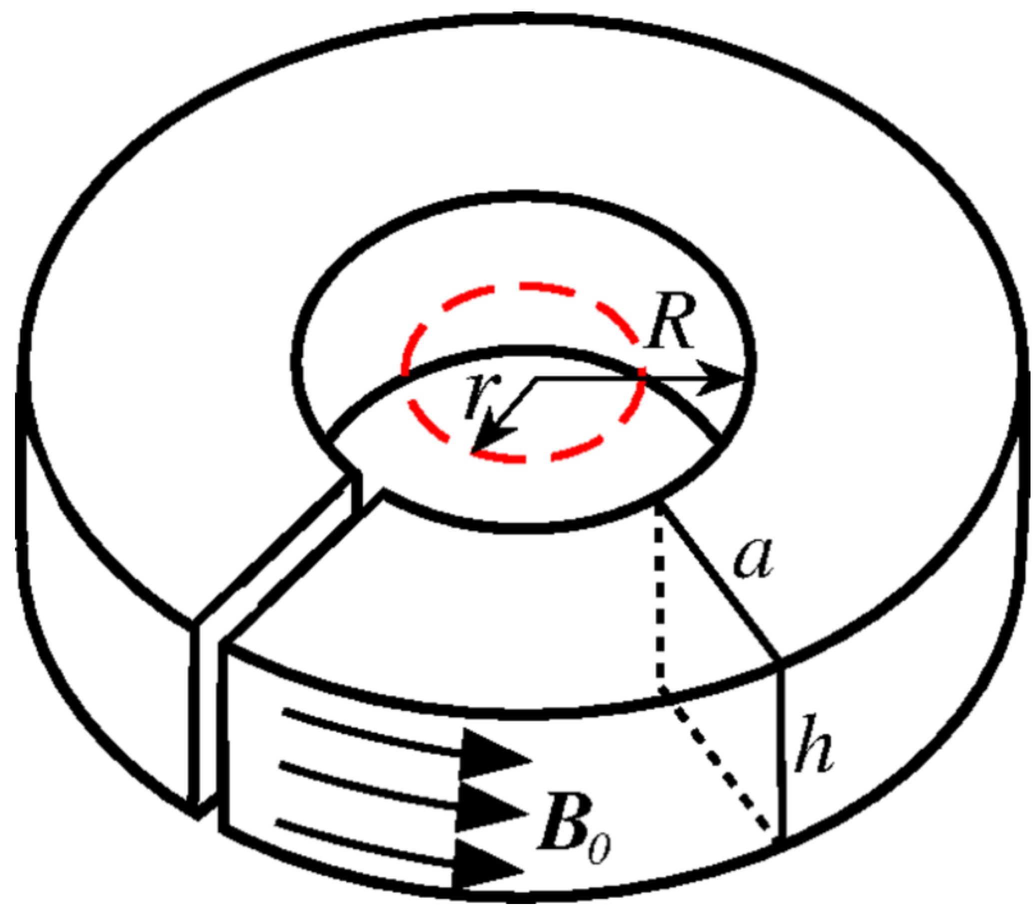


Sensitive to m_A between 10^{-14} to 10^{-6} eV, ~Hz to~GHz

This parameter space is particularly interesting because it corresponds to a GUT-scale axion.

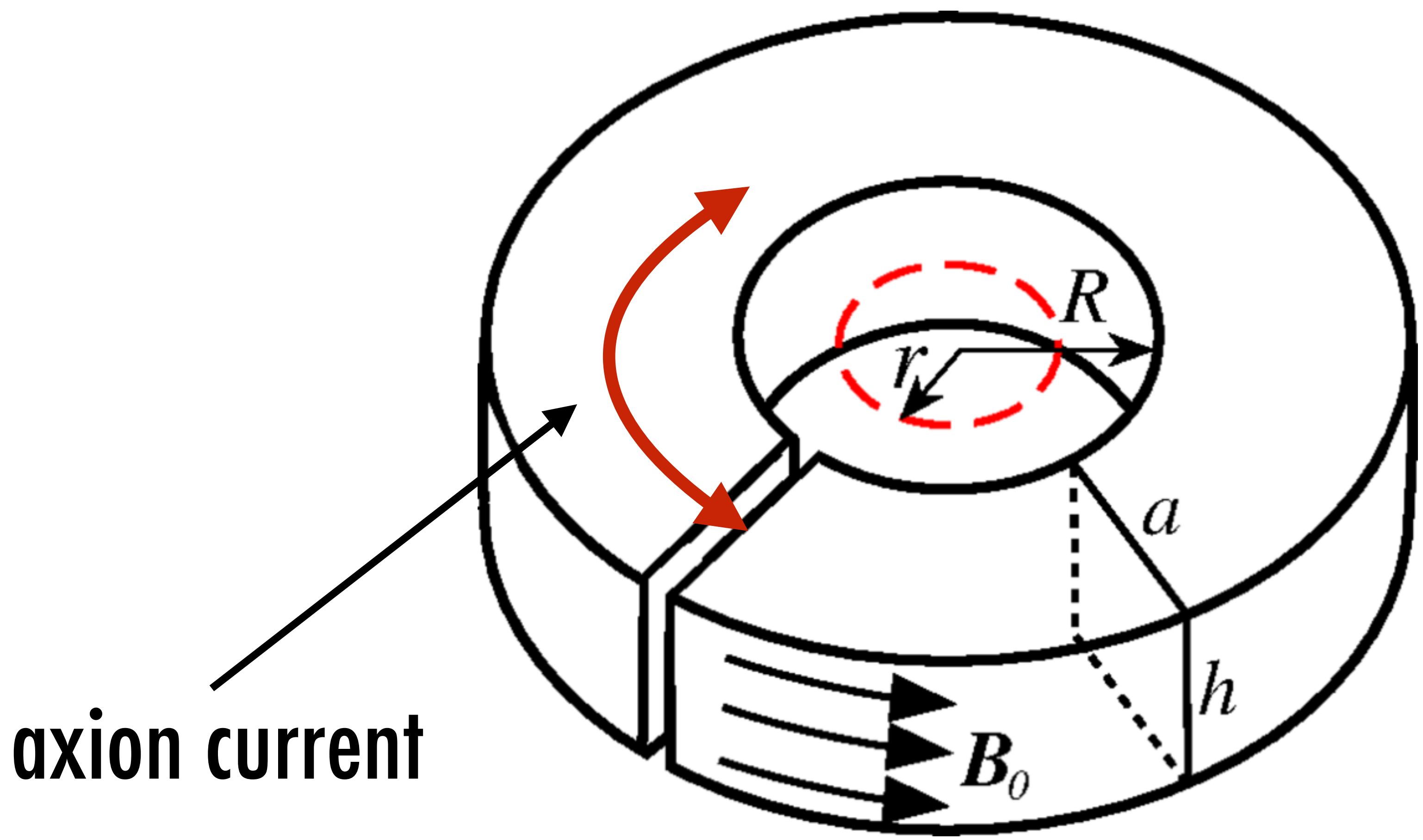
$$m_a \sim 10^{-9}\,\mathrm{eV}\left(\frac{10^{16}\,\mathrm{GeV}}{f_a}\right)$$

The cartoon experiment

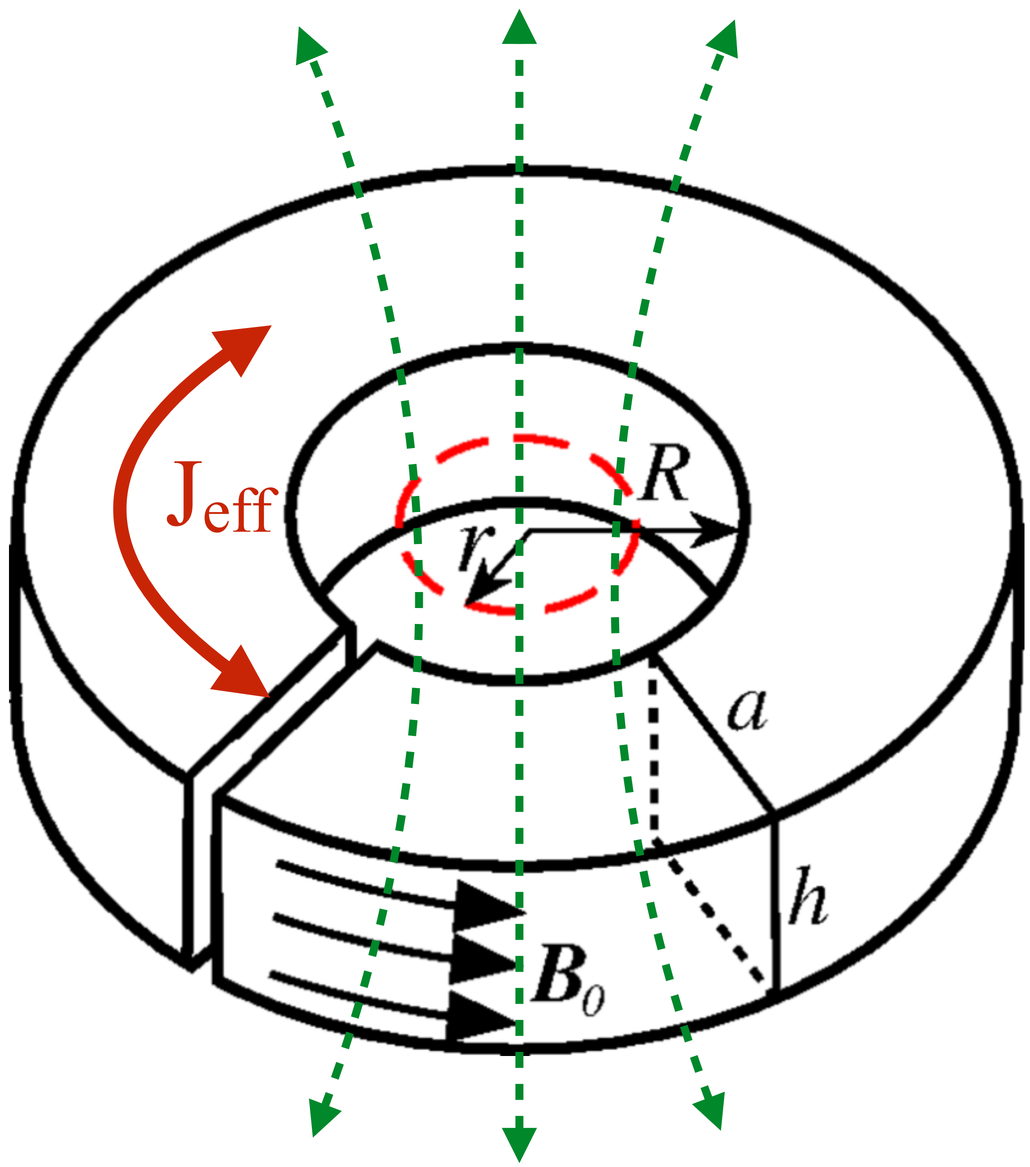


Based on Kahn, Safdi and Thaler, Phys.Rev.Lett. 117 (2016) no.14, 141801

The cartoon experiment

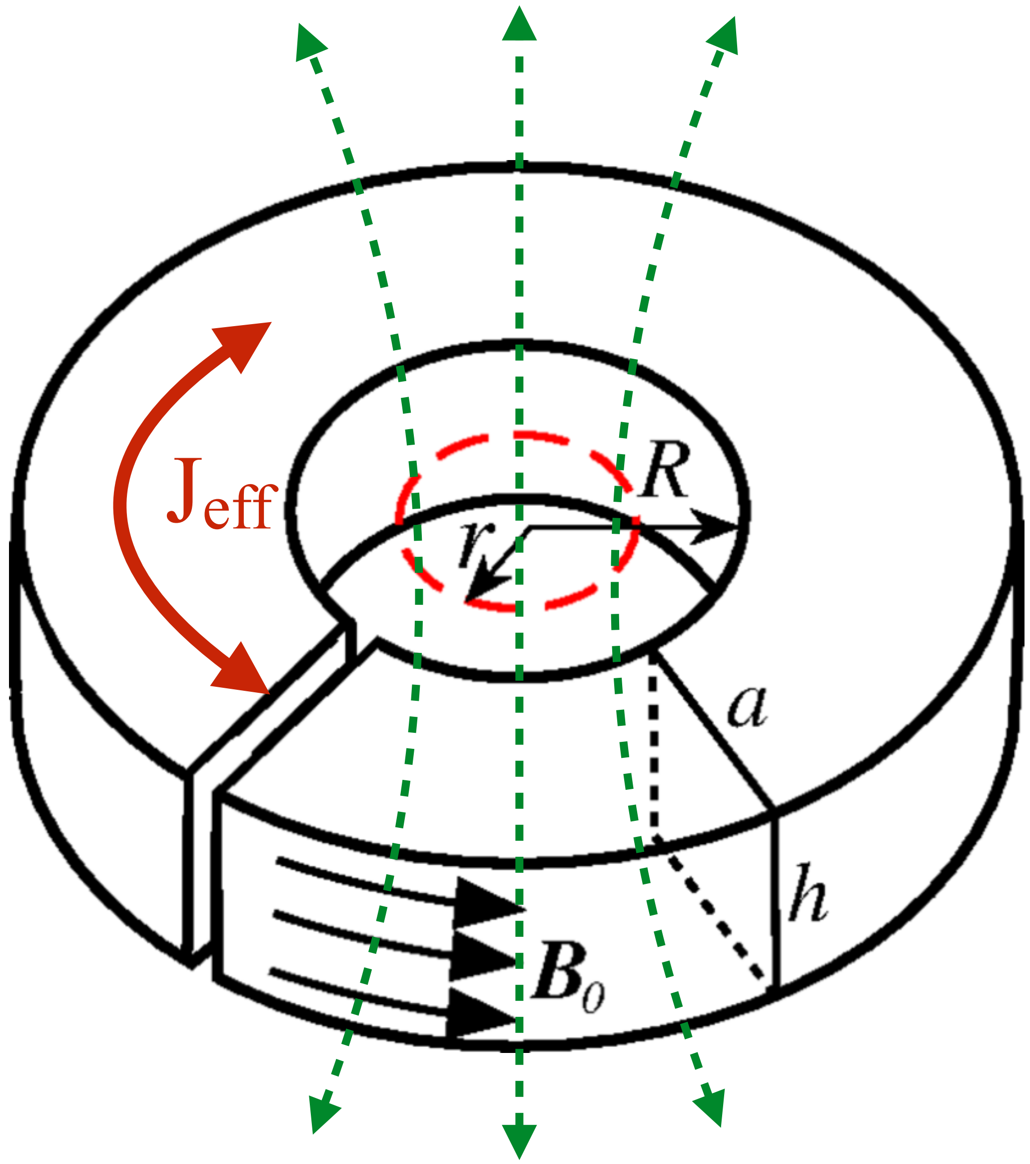


The cartoon experiment



Real Magnetic Field!

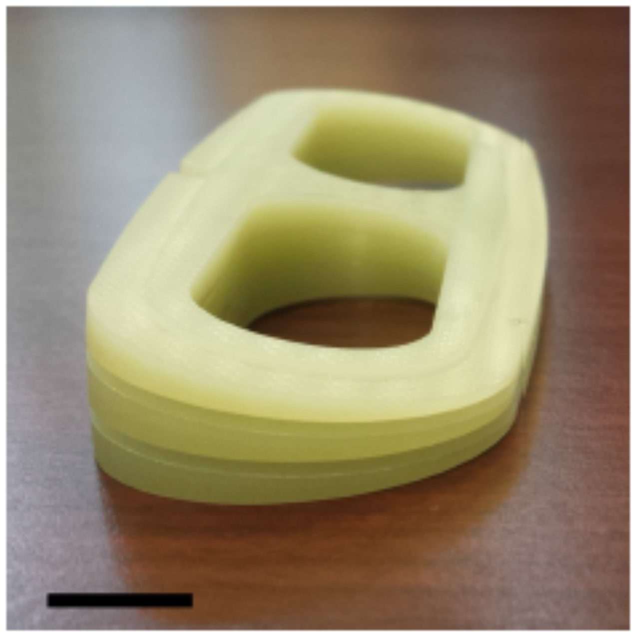
The cartoon experiment



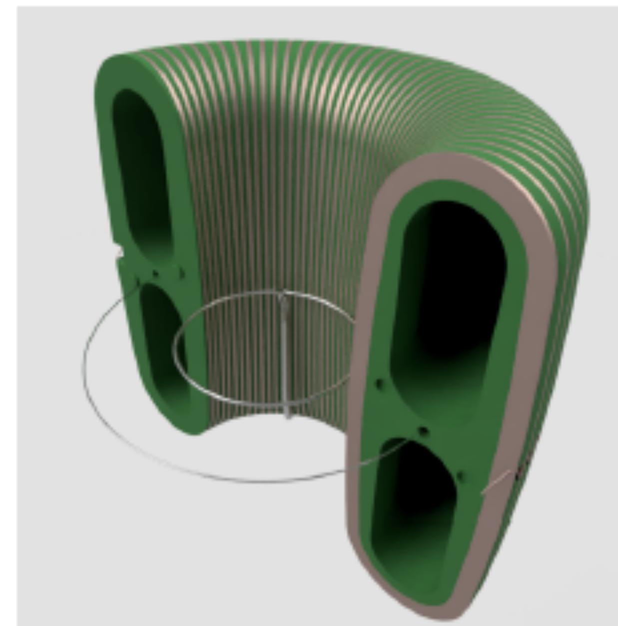
A real magnetic field induced in a zero field region.

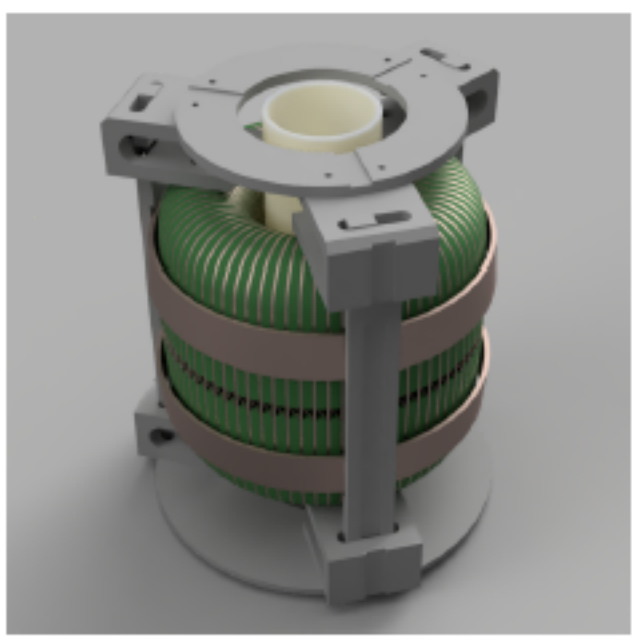
ABRACADABRA

Delrin Supports

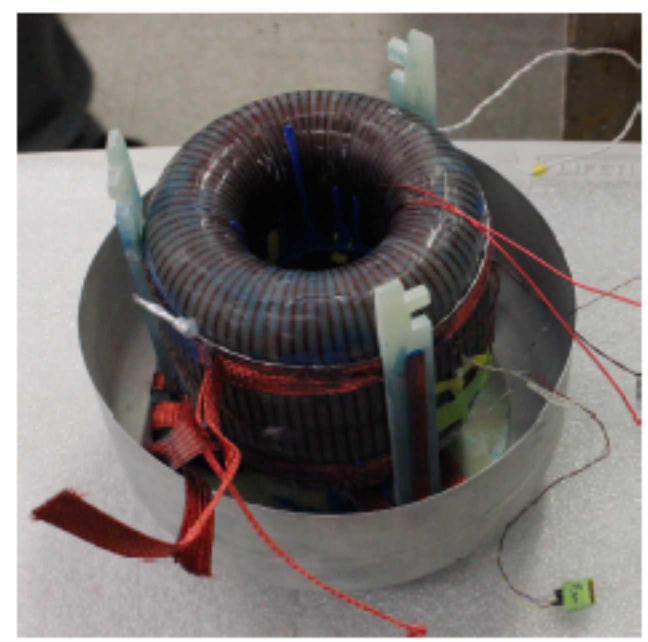


Pickup and Calibration Loops





Mechanical Design



Assembly in Progress

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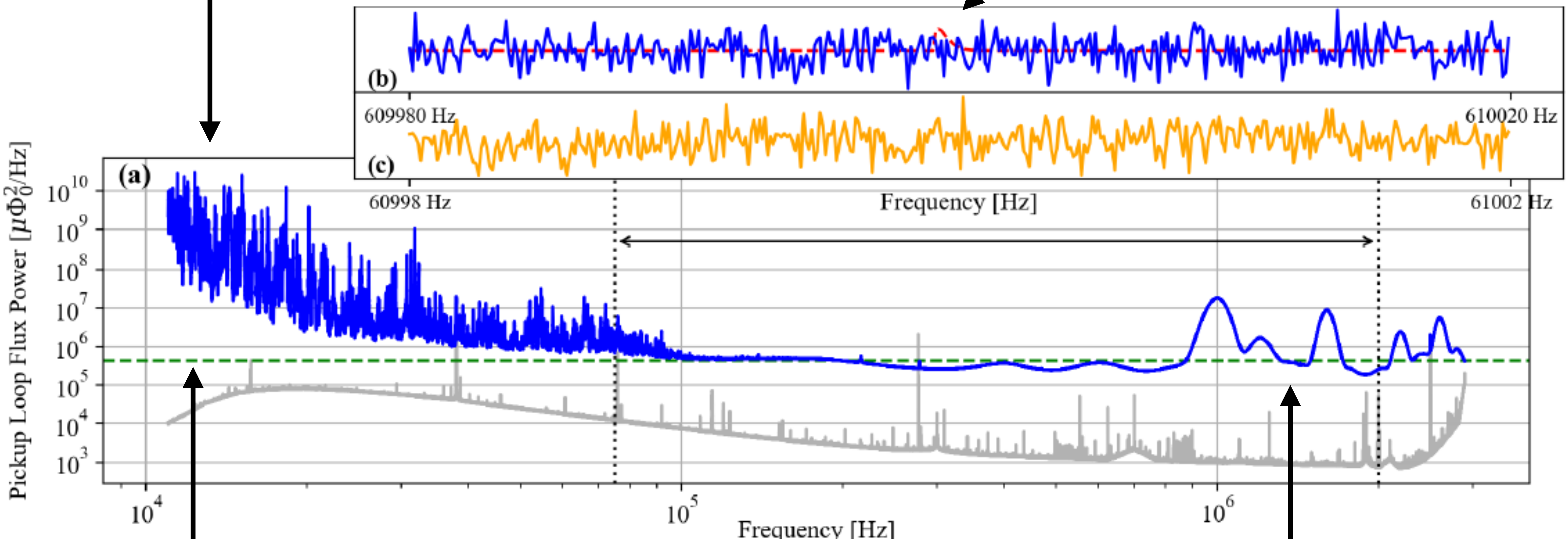
Physics Data

Mechanically cooled fridge so vibration dominate at low frequency.

Example signal



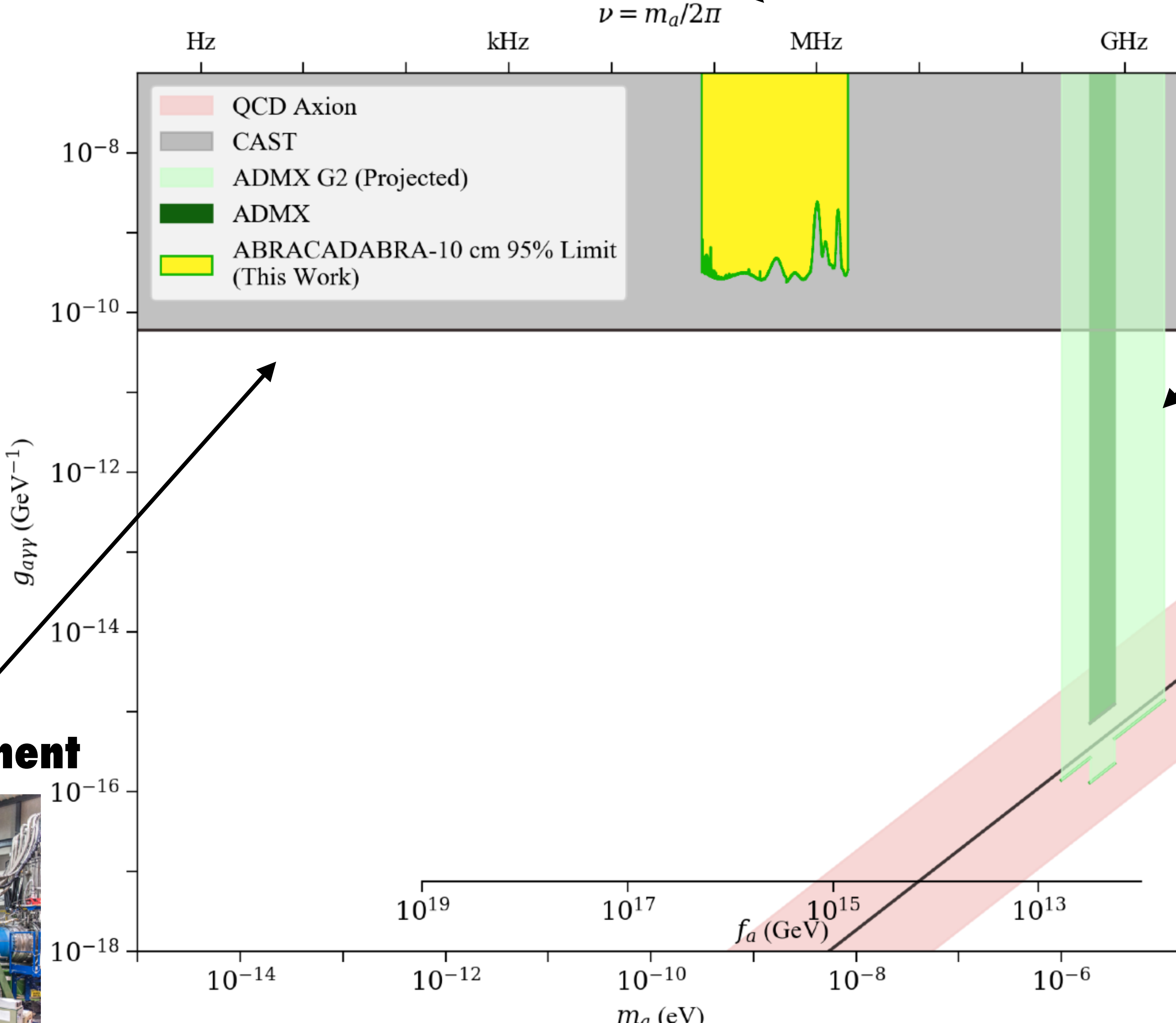
EM Shielding not as effective at high frequency or large sources.

SQUID Noise Floor!

Data taken from July 16, 2018 to August 14, 2018, continuous digitization and data transfer was a major accomplishment in itself!

ABRACADABRA

First direct search for axion dark matter below 1μeV, and we are just beginning!



ADMX

CAST
Solar Axion Experiment

ABRACADABRA

First Results October 2018!

Ouellet et al., Phys.Rev.Lett. 122 (2019) no.12, 121802

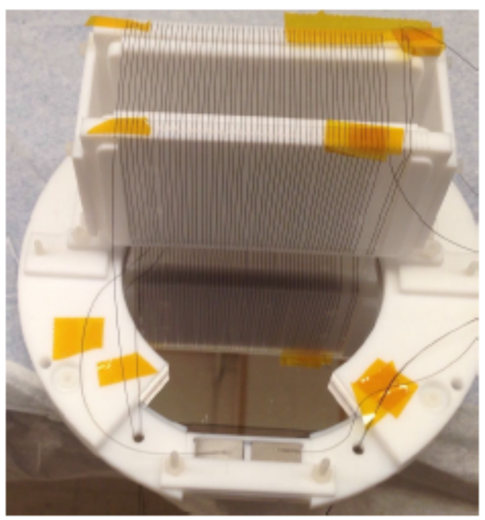
arXiv:1810.12257

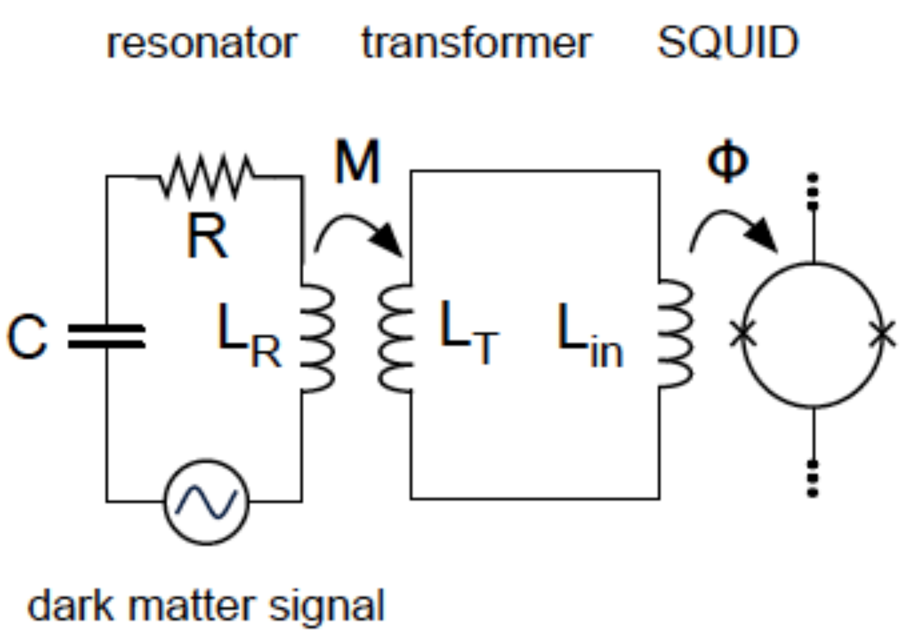
Long Technical Paper

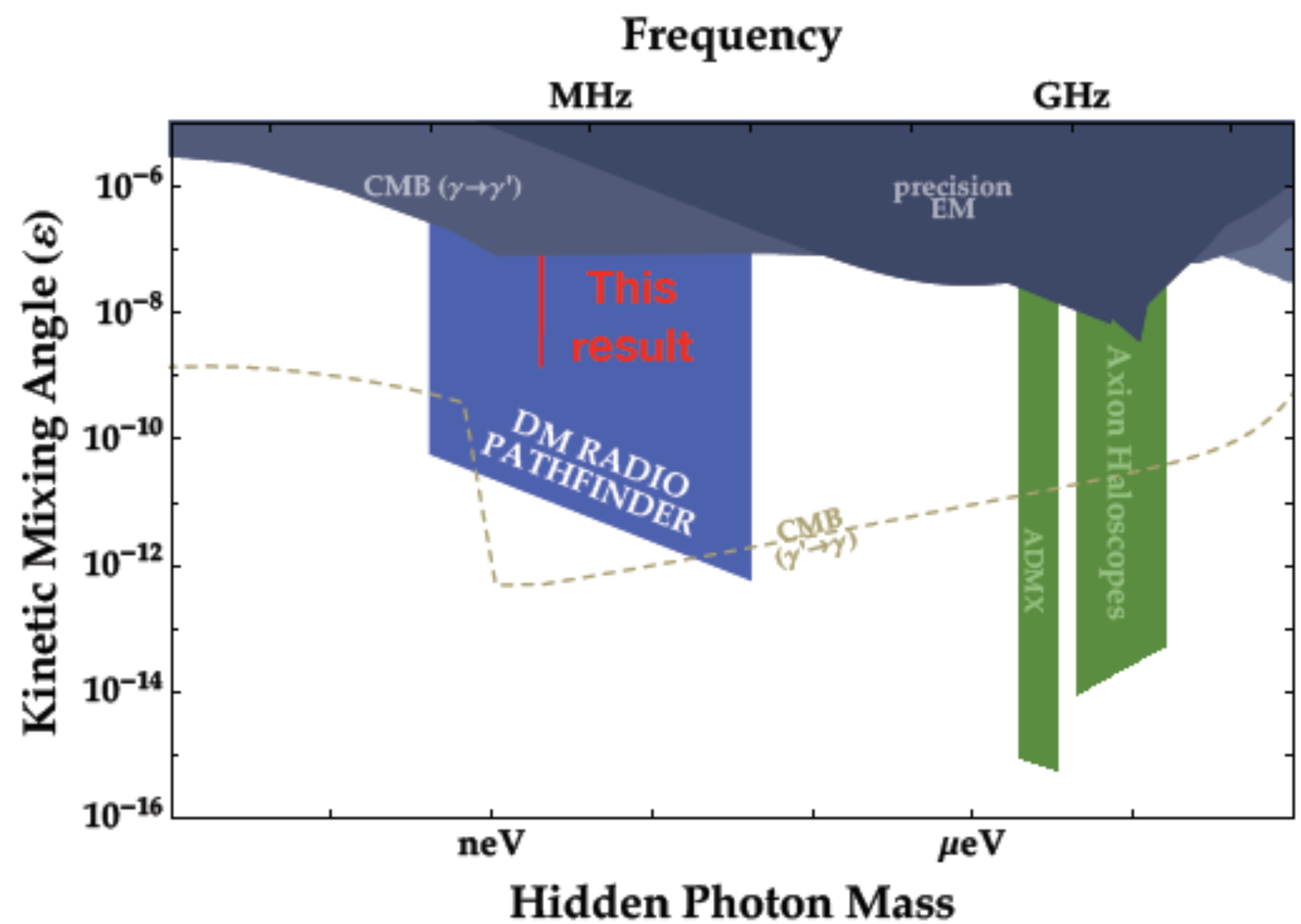
Ouellet et al., Phys.Rev. D99 (2019) no.5, 052012

arXiv:1901.10652

Hidden Photon Search Demonstrates Lumped Element Resonator





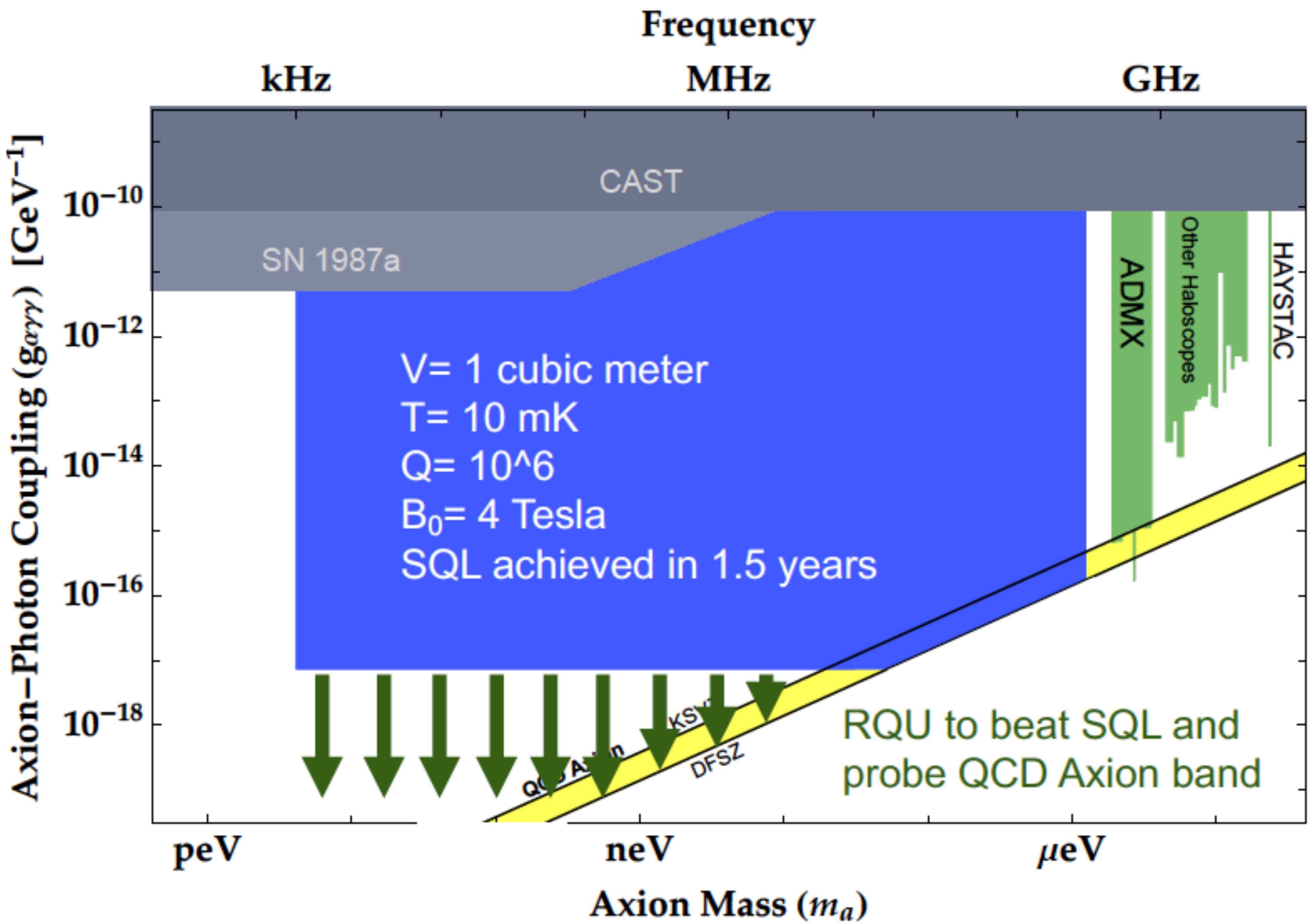


Now working towards DM Radio w/ a 50L magnet.

From arXiv:1906.08814

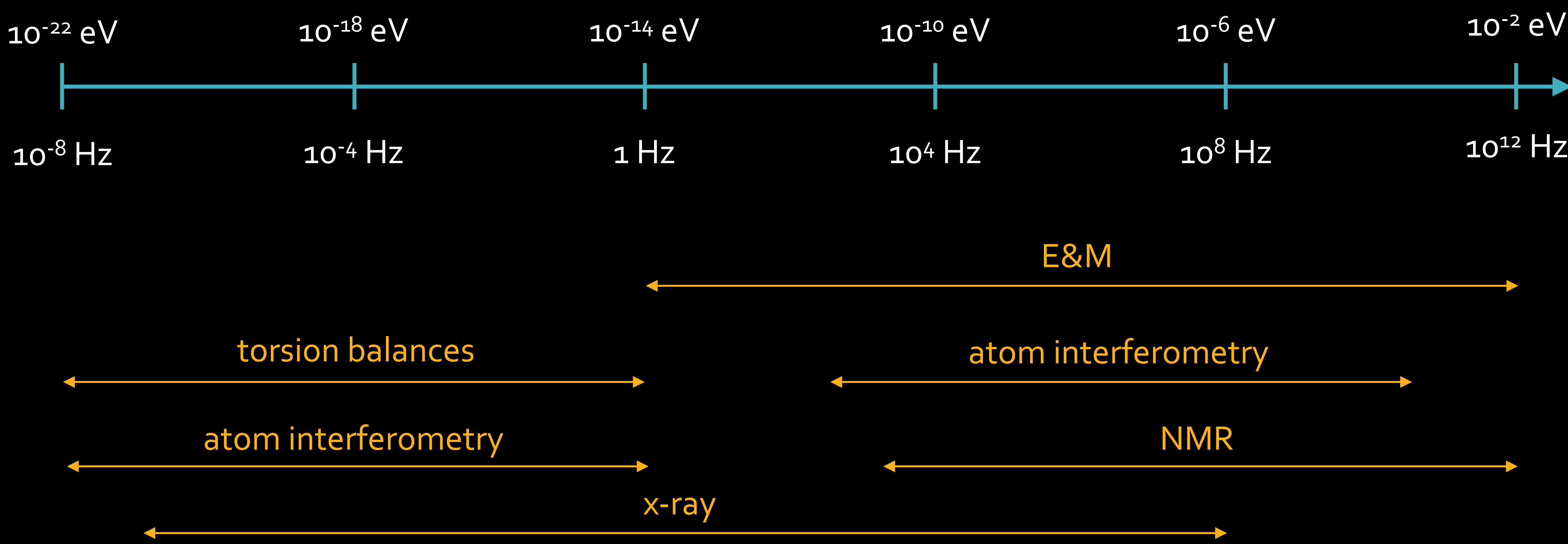
DARK MATTER RADIO + ABRACADABRA

The Future



From: D. Li @ LTD 2019

Summary of Techniques



Adapted From: U.S. Cosmic Visions, arXiv:1707.04591v1

There is so much I didn’t get to talk about!

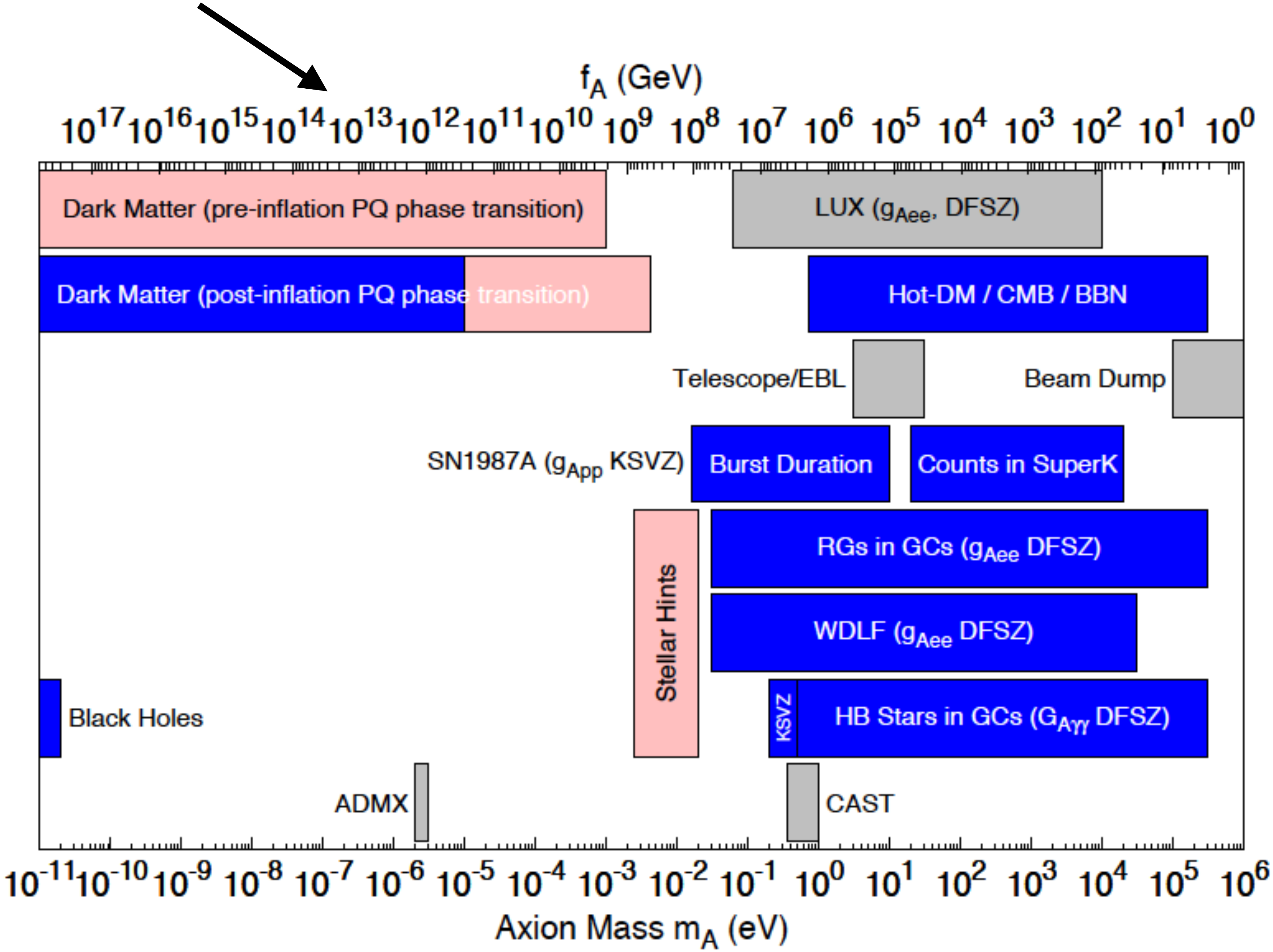
Summary

- We need dark matter.
- We need a QCD axion.
- Possibility of a discovery anywhere!
- Established experiments are reaching the QCD axion.
- New experiments coming online!

Thank you!

Back-Up

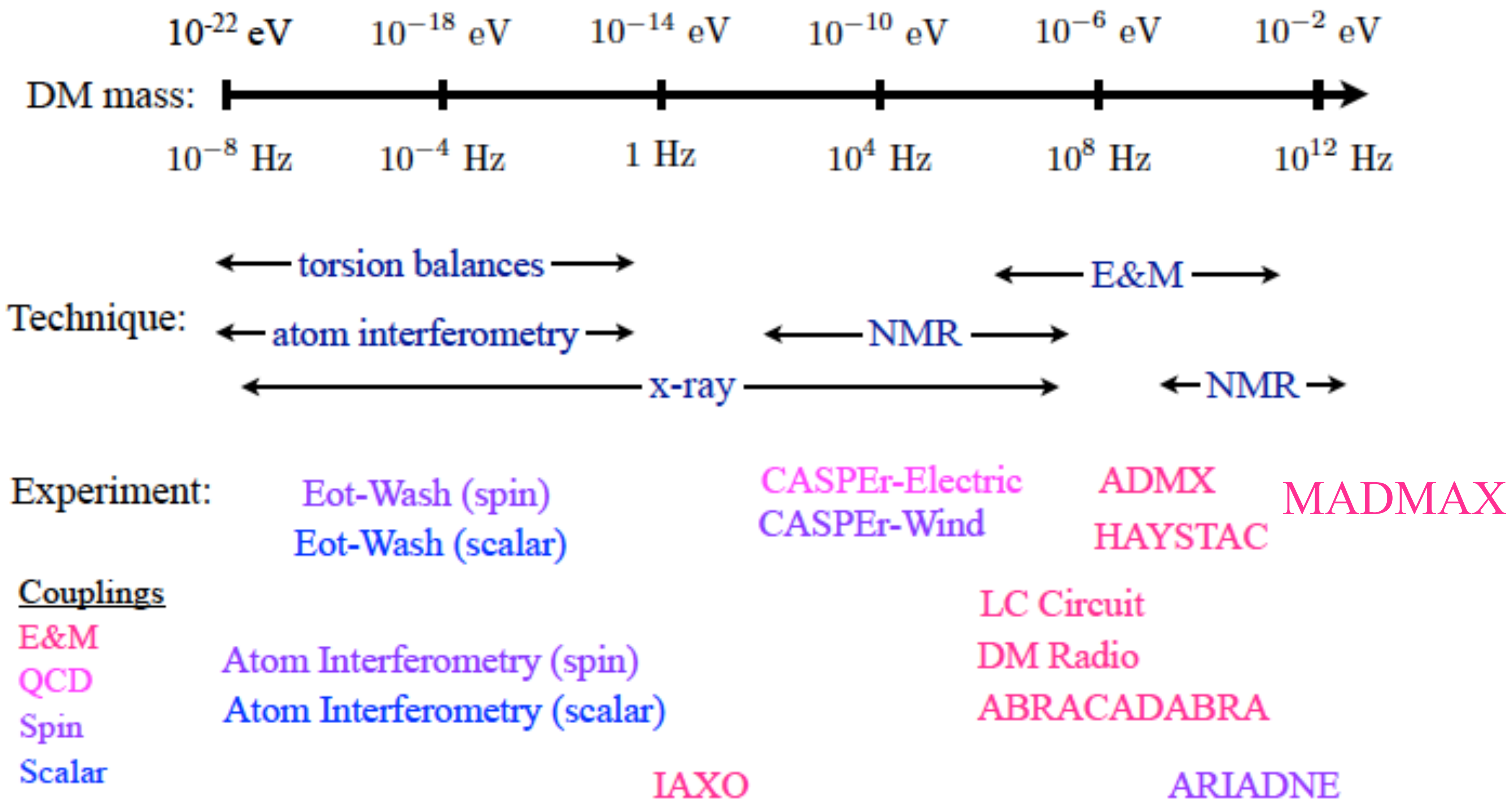
Theoretical Preferences in Pink



PDG - Axion Review 2018

There are some preferences but a lot of wiggle room!

The Summary of Axion Efforts



From: U.S. Cosmic Visions, arXiv:1707.04591v1