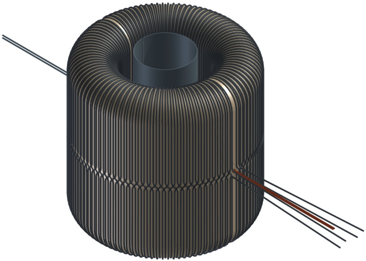
ABRACADABRA: Detecting axion dark matter

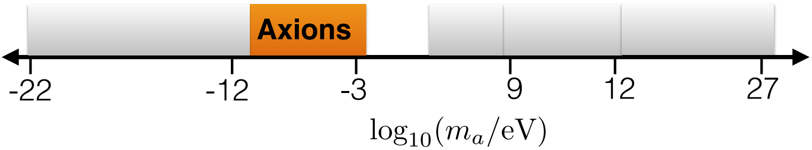


Ben Safdi

MIT / University of Michigan

*Y. Kahn, **B.S.**, J. Thaler, PRL 2016*

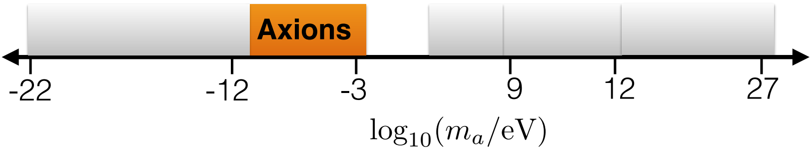
ABRA-10 cm collaboration



- Axion solves strong CP problem (neutron EDM)

$$\mathcal{L}_{\text{axion}} = -\frac{a}{f_a}\frac{g^2}{32\pi^2}G_{\mu\nu}\tilde{G}^{\mu\nu}$$

Peccei, Quinn 1977; Weinberg 1978; Wilczek 1978



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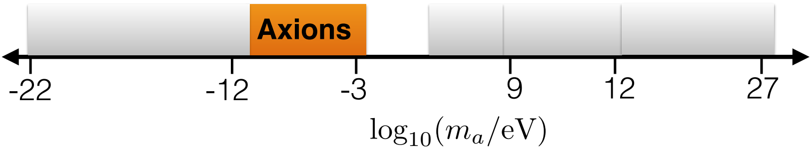

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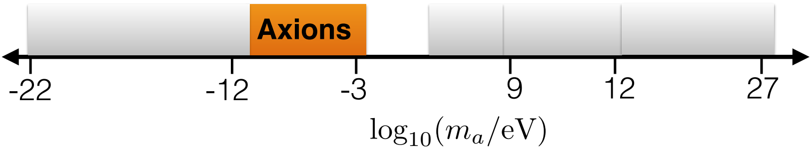

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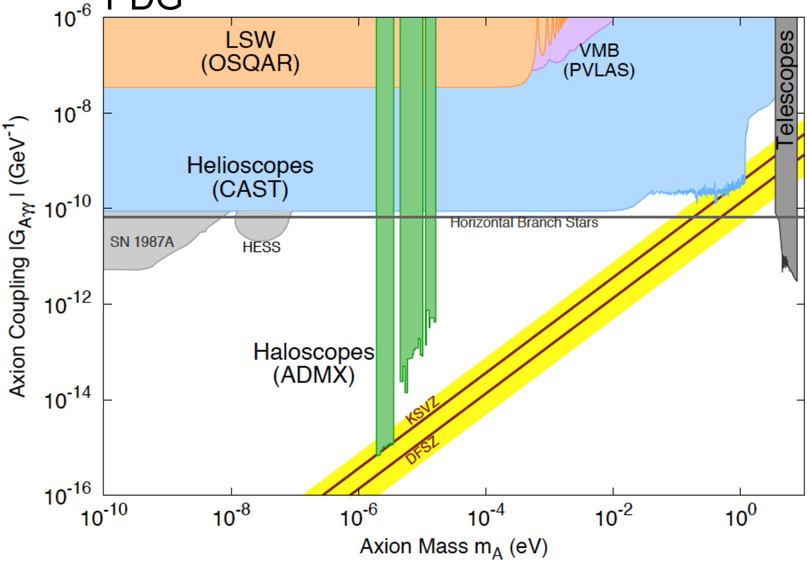
- Axion (field) can make up all of dark matter

Peccei, Quinn 1977; Weinberg 1978; Wilczek 1978

PDG



LSW
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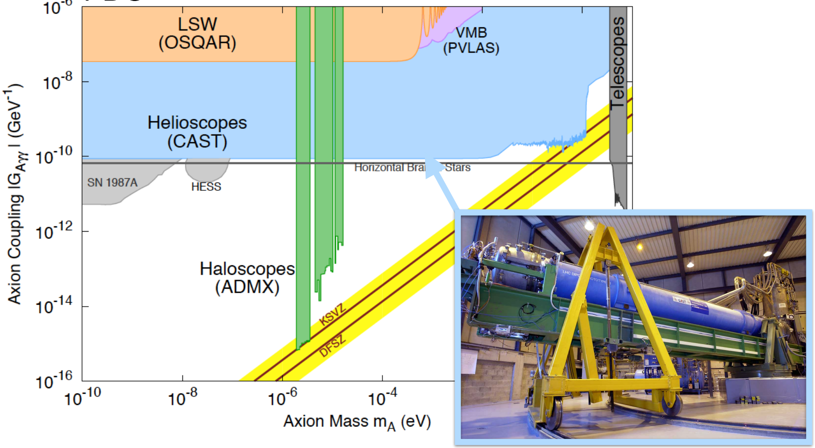
VMB
(PVLAS)
Telescopes
Helioscopes
(CAST)
Horizontal Branch Stars
SN 1987A
HESS
Haloscopes
(ADMX)
KSVZ
DFSZ
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
Axion Coupling $|G_{A\gamma\gamma}|$ (GeV^{-1})
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
Axion Mass m_A (eV)

PDG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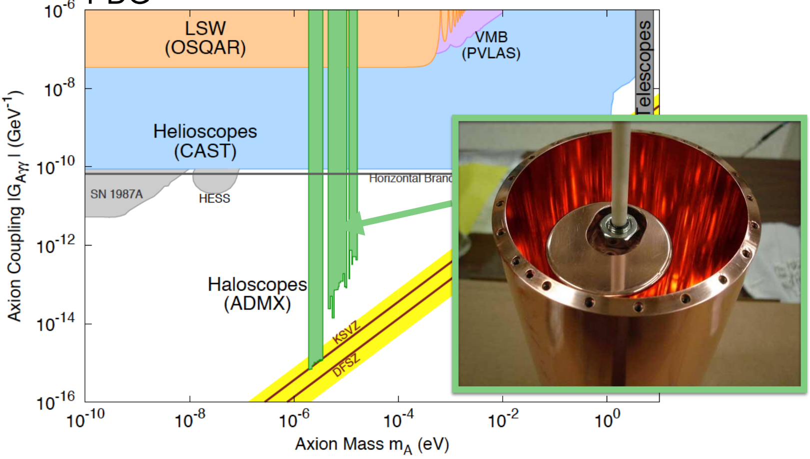

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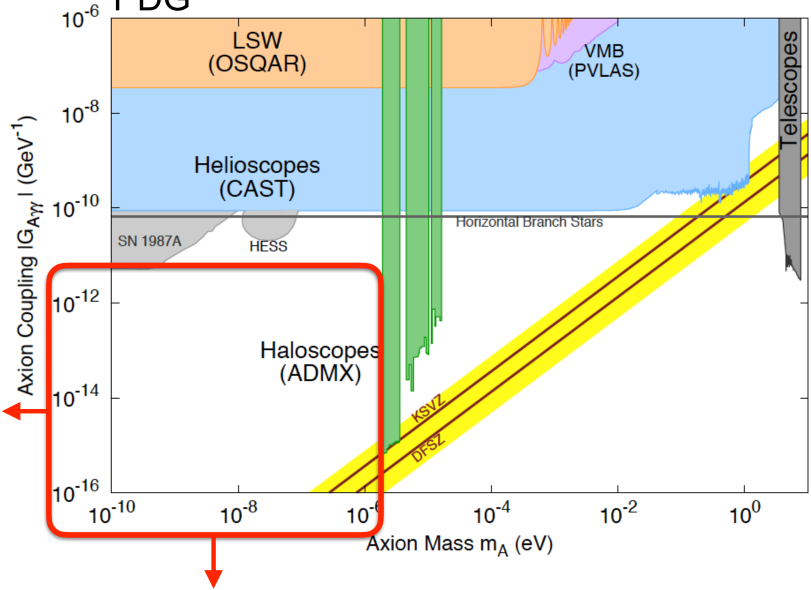

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Axion dark matter modifies Maxwell's equations

- Recall axions also couple to QED:

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- Magnetoquasistatic approximation: new electric current that follows $\mathbf{B}$-field lines

$$\nabla \times \mathbf{B} = g_{a\gamma\gamma} \mathbf{B} \frac{\partial a}{\partial t}$$

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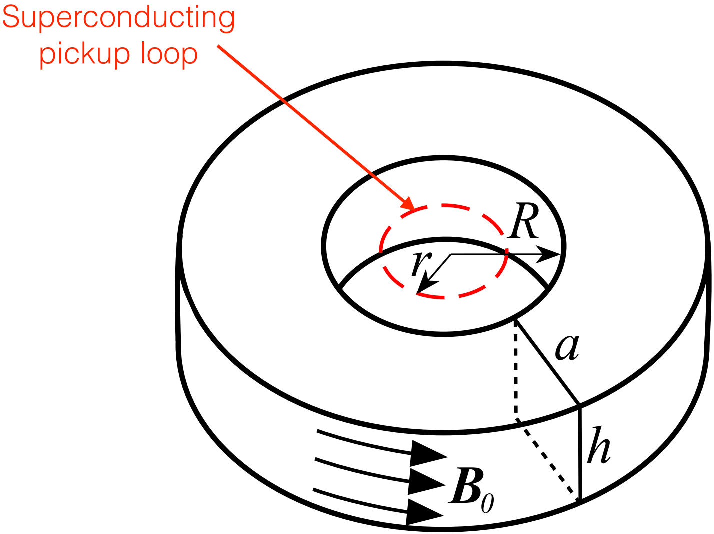
- Locally: $a(t) \approx a_0 \sin(m_a t)$ and $\frac{1}{2} m_a^2 {a_0}^2 = \rho_{\mathrm{DM}}$
- $\mathbf{J}_{\mathrm{eff}} = g_{a\gamma\gamma} \sqrt{2\,\rho_{\mathrm{DM}}} \mathbf{B} \sin(m_a t)$

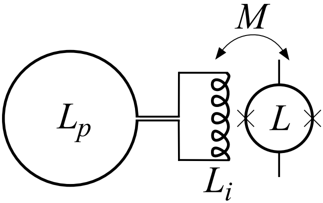
Axion dark matter generates magnetic flux

Y. Kahn, **B.S.**, J. Thaler, PRL 2016



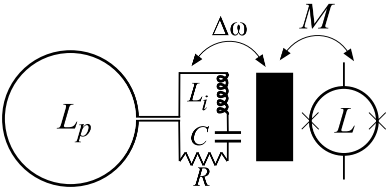
Two readout strategies

Broadband

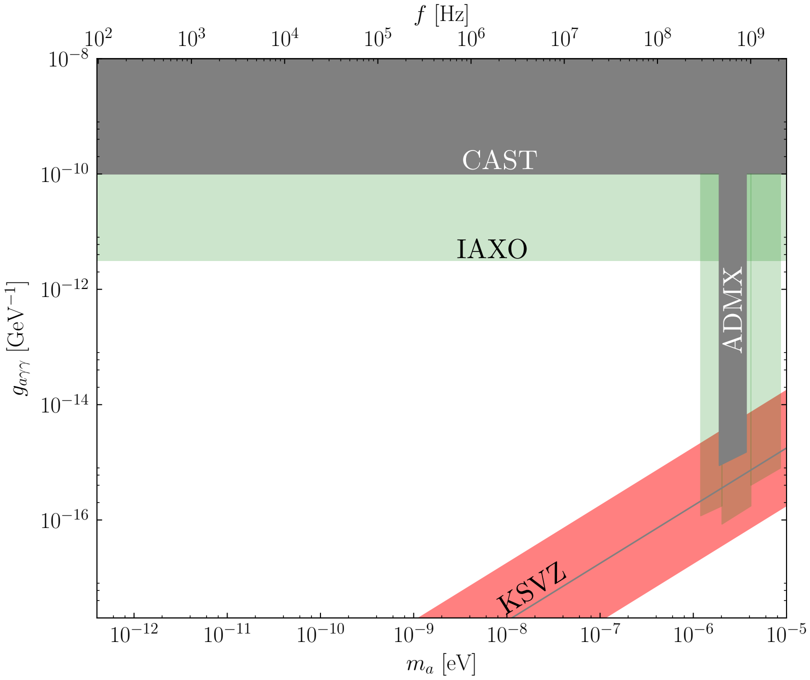


Better at low frequency

Resonant



Better at high frequency



f [Hz]
10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9
10^{-8} 10^{-10} 10^{-12} 10^{-14} 10^{-16}
$g_{a\gamma\gamma}$ [GeV^{-1}]
CAST
IAXO
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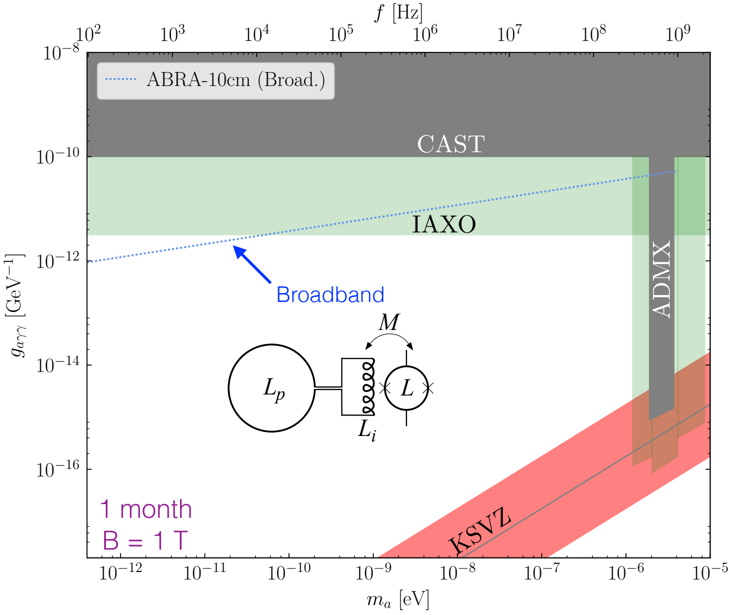
m_a [eV]

ABRA-10 cm (happening now!)



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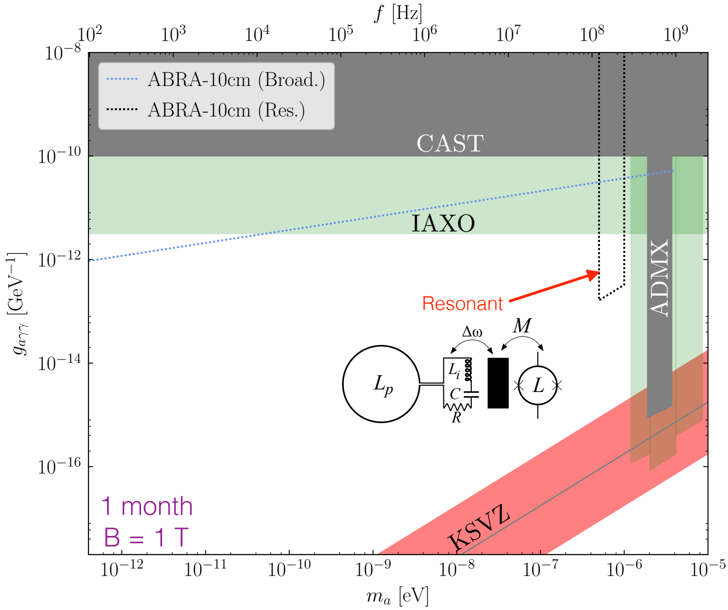
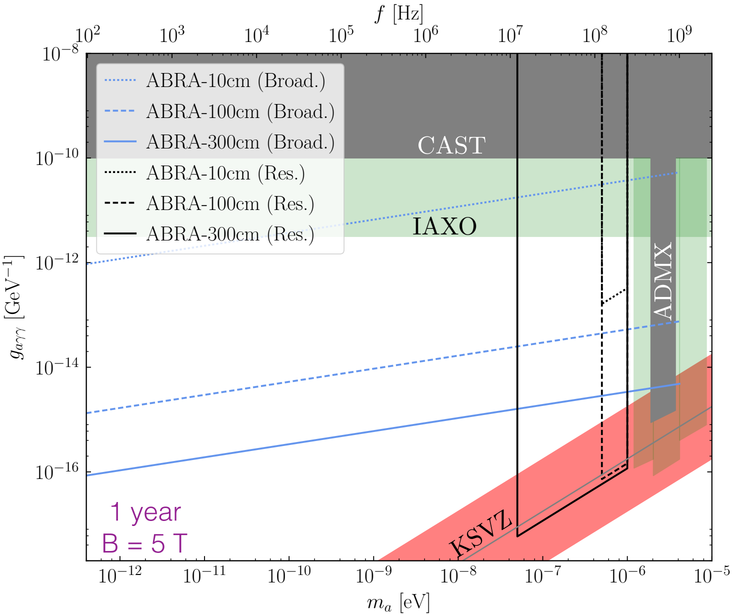


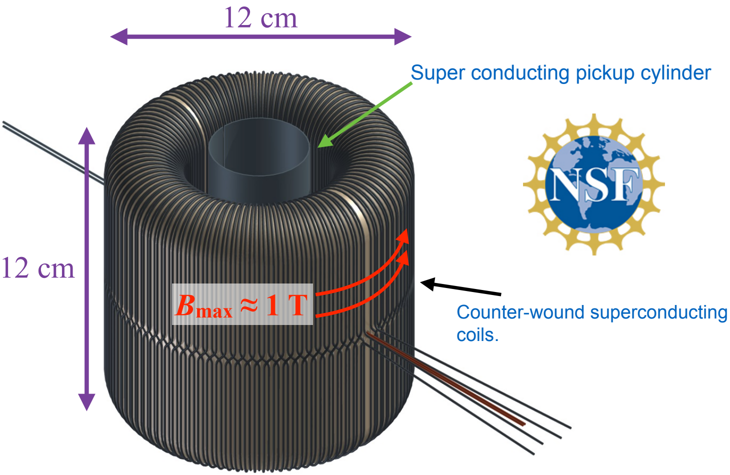
ABRA-Gen2


f [Hz]
10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9
10^{-8} 10^{-10} 10^{-12} 10^{-14} 10^{-16}
$g_{a\gamma\gamma}$ [GeV^{-1}]
ABRA-10cm (Broad.)
ABRA-100cm (Broad.)
ABRA-300cm (Broad.)
ABRA-10cm (Res.)
ABRA-100cm (Res.)
ABRA-300cm (Res.)
CAST
IAXO
ADMX
KSVZ
1 year
B = 5 T
10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5}
m_a [eV]

The MIT prototype: ABRACADABRA-10 cm

- ABRACADABRA: A Broadband/Resonant Approach to Cosmic Axion Detection with an Amplifying B-field Ring Apparatus
- People (LNS+CTP, PSFC, Princeton, UNC, UMich): Janet Conrad, Joe Formaggio, Sarah Heine, Reyco Henning, Yoni Kahn, Joe Minervini, Jonathan Ouellet, Kerstin Perez, Alexey Radovinsky, **B.S.**, Jesse Thaler, Daniel Winklehner, Lindley Winslow
- Funded by the NSF!

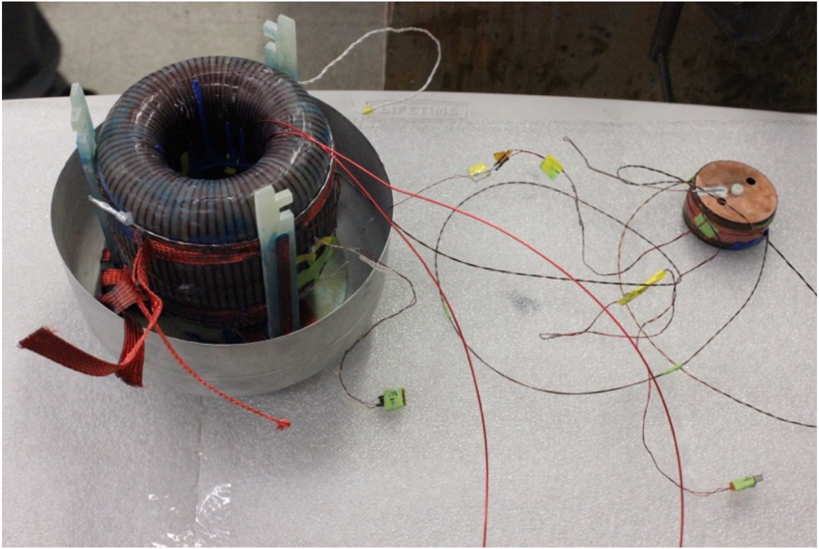
ABRACADABRA-10 cm at MIT



ABRA-10 cm


Jonathan Ouellet
(postdoc)
Lindley Winslow
(PI)
CALIFORNIA
CYCLING

ABRA-10 cm



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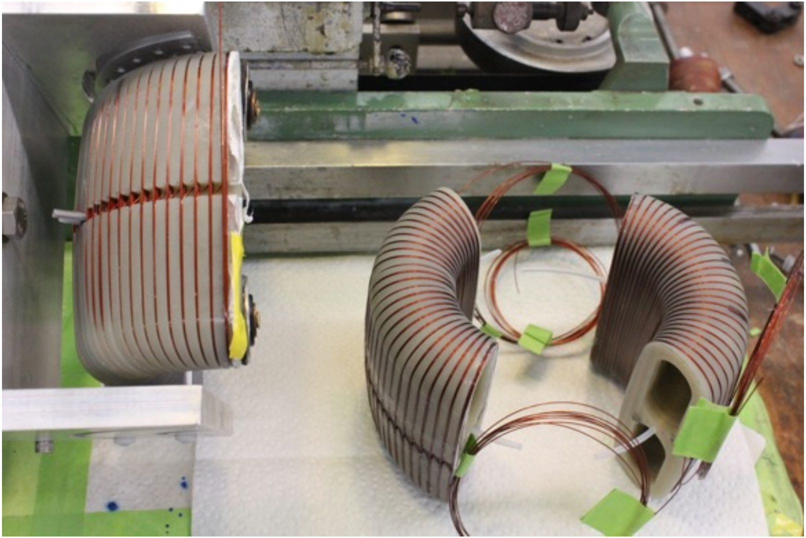


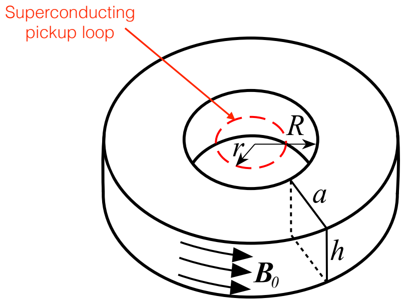
Light bosonic dark matter future

- MIT: ABRA-10 cm followed by ABRA-1 m ($B \sim 5$ T)
- Axions and light bosonic dark matter well motivated by strong-CP problem and high-scale physics (e.g., compactified string theory)
- New ideas to search for ultra-light scalars, dark-photons, etc. (laboratory experiments + astrophysics)
  - e.g., CASPEr experiment ($f_a \sim 10^{17} - 10^{19}$ GeV)
  - Black Hole superradiance ($f_a \sim 10^{17} - 10^{19}$ GeV)
  - Florida LC circuit ($f_a \sim 10^{15}$ GeV)
  - ADMX-HF ($f_a \sim 10^{11}$ GeV)
  - CMB (isocurvature + ΔN_{eff})
  - DM-radio (dark photons)

Questions?

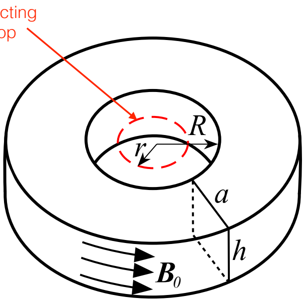
Axion backup

Axion dark matter generates magnetic flux



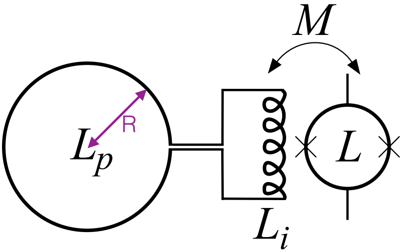
- Estimate B-field induced through pickup loop ($r = a = h = R$)

Axion dark matter generates magnetic flux



- Estimate B-field induced through pickup loop ($r = a = h = R$)
- Axion effective current: $I_{\text{eff}} \sim R^2 J_{\text{eff}}$
- $B \sim \frac{I_{\text{eff}}}{R} \sim R\, g_{a\gamma\gamma} \sqrt{2\,\rho_{\text{DM}}}\mathbf{B_0} \sin(m_a t)$
- $f_a = 10^{16}$ GeV, $\mathbf{B_0} \sim 5$ T, $R \sim 4$ m: $B \sim 10^{-22}$ T (KSVZ)

Broadband estimate



- Example from MRI application: (Myers et. al. 2007)
  - B-field sensitivity: $S_B^{1/2} \approx 6.4 \times 10^{-17}$ T/$\sqrt{\text{Hz}}$
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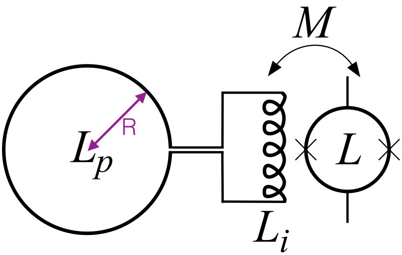

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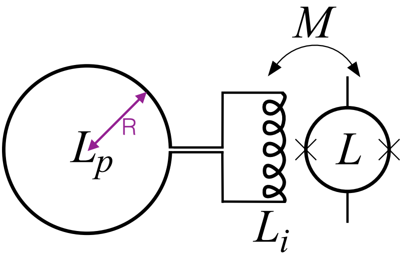

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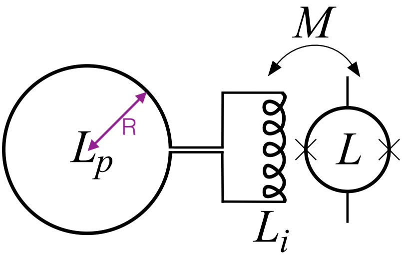

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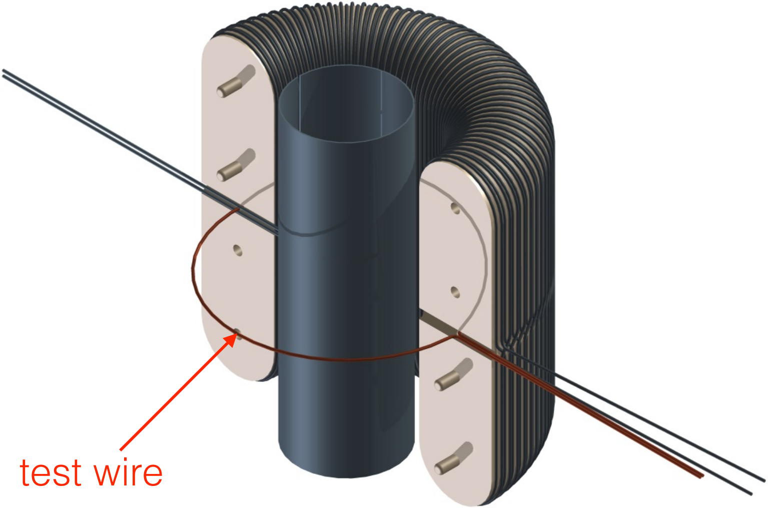
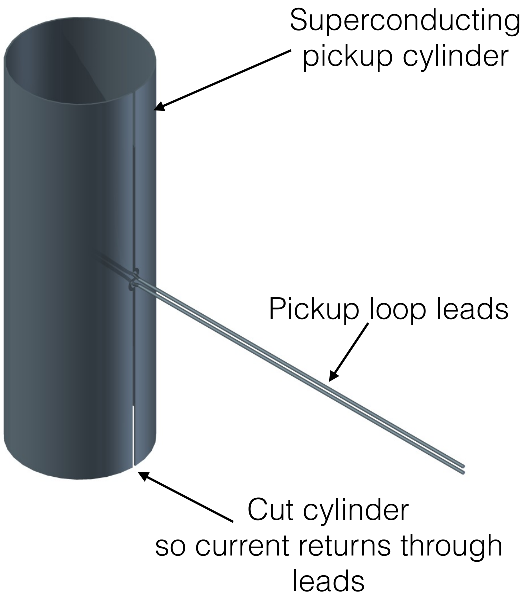
  - $S/N = 1$ for $B = S_B^{1/2}(t\tau)^{-1/4} \sim 10^{-22}$ T

ABRA-10 cm: vertical cut



ABRA-10 cm: pickup cylinder



Magnetic field sensitivity calculation

- $B(t) = B_0 \sin[\omega_0 t + \phi(t)] + B_n(t)$
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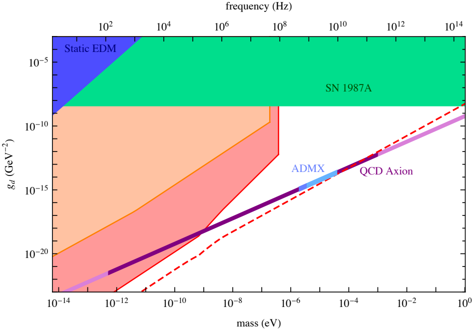
  - But, line-width is broad and can resolve $N = T/\tau$ different frequencies
  - $B^2 = S_B^{1/2}(\omega_0)/\tau/\sqrt{N} = S_B^{1/2}(\omega_0)/\sqrt{T\tau}$

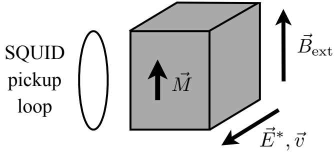
Complementary proposals for axion dark matter experiments

CASPEr: oscillating neutron EDM

$$\mathcal{L}_{\text{axion}} = -\left(\bar{\theta} + \frac{a}{f_a}\right)\frac{g^2}{32\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

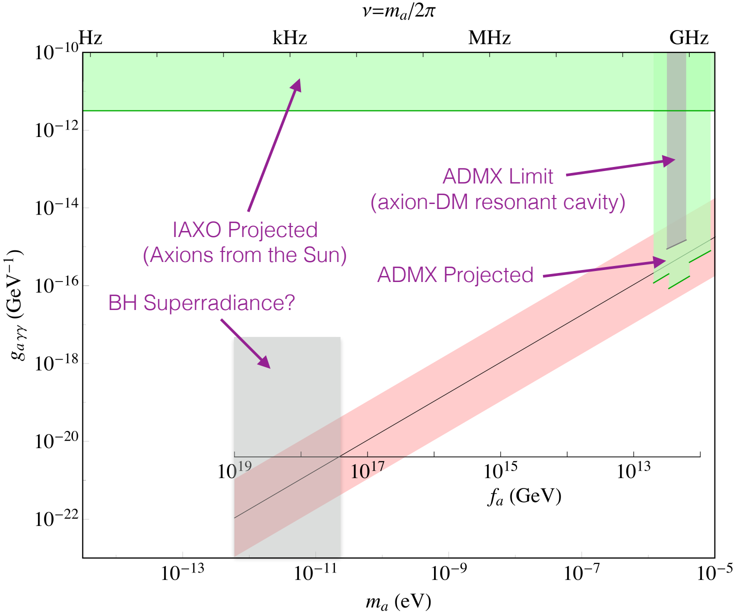
$$d_n(t) = g_d\, a(t)\,, \qquad g_d \approx \frac{2.4\times 10^{-16}\ \text{e}\cdot\text{cm}}{f_a}$$





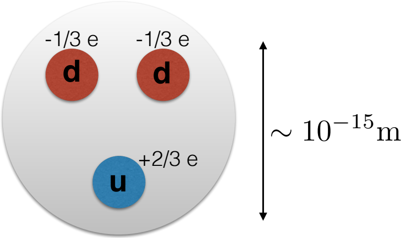
(Budker, Graham, Ledbetter, Rajendran, and Sushkov '13)

How can we probe axion dark matter?



e.g., Arvanitaki, Baryakhtar, Huang 2014

The strong CP problem (neutron EDM)



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  $|d_n| < 3 \times 10^{-26}$ e · cm

Peccei, Quinn 1977; Weinberg 1978; Wilczek 1978

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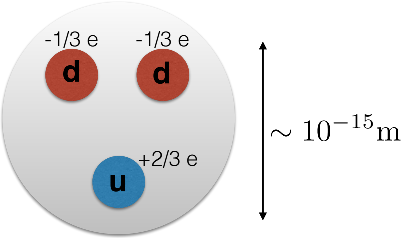

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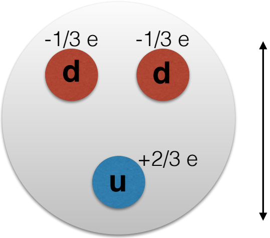

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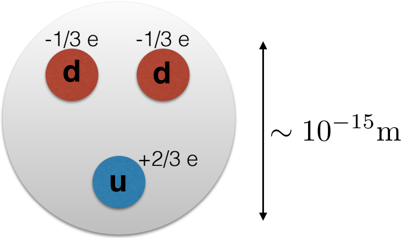

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