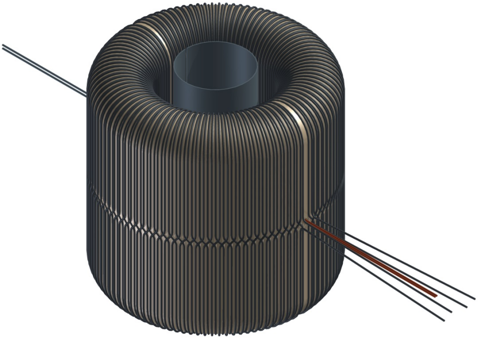
Cosmic Axion Detection with an Amplifying B-field Ring Apparatus



Ben Safdi
Massachusetts Institute of Technology

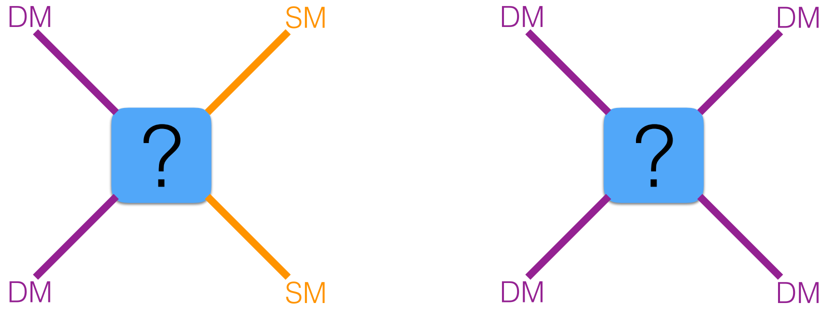
Two important facts to keep in mind in any dark matter talk
(at least, today)

Fact 1: we know a lot about dark matter

Fact 2: we know almost nothing about dark matter

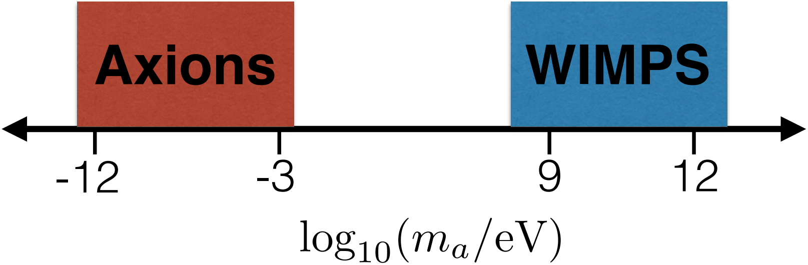
Fact 2: we know almost nothing about dark matter

- No evidence for non-gravitational interactions

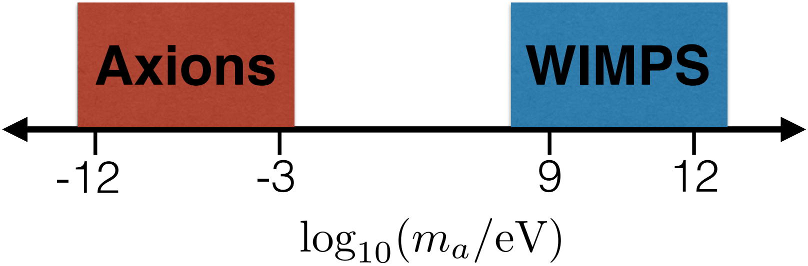


- No evidence for particular dark-matter mass

Over 20 orders of magnitude in DM mass!



Dark-matter: BSM physics exists



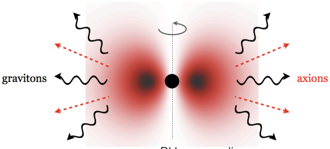
- Clear evidence that dark-matter (BSM physics) exists
- Well motivated dark-matter models (WIMPs, axions, . . .)

Dark matter models

Name	What is it?	Motivation
Axion	$\left(\bar{\theta} + \frac{a}{f_a}\right) G_{\mu\nu}\tilde{G}^{\mu\nu}$	Strong CP
Neutralino (WIMP)	$\tilde{B}, \tilde{W}_3, \tilde{H}_u, \tilde{H}_d$	Hierarchy Problem (why Higgs mass so light)

How can we probe axion dark matter?

Astrophysics

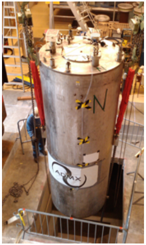


BH superradiance

Axion helioscope

CAST

Resonant cavity



ADMX

- Astrophysics/cosmology: stellar cooling, CMB, BBN (Phys. Lett. B. 2014: K. Blum, R. D'Agnolo,M. Lisanti,**B.S.**), superradiance
- Laboratory experiments: ADMX (resonant cavity), CAST (axion helioscope)
- New proposal: *PRL* 117, Sept. 2016 (Y. Kahn, **B.S.**, J. Thaler): A broadband approach to axion dark matter detection

Outline

- Axion particle physics (review)
- Axion cosmology (review and work in progress)
- ABRACADABRA: Cosmic axion detection (theory)
- ABRACADABRA-10 cm at MIT (experiment)

Why axions and what are they?

Strong CP: the other naturalness problem ($|\bar{\theta}| < 10^{-10}$)

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    - Axion can be dark matter

The axion solves the strong CP problem

$$\mathcal{L}_{\mathsf{QCD}}^{\mathcal{CP}} = -\frac{\theta\, g^2}{32\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu} - \sum_q \bar{q}\, m_q e^{-i\phi_q \gamma_5} q$$

- $U(1)_A$ anomaly: $\quad q \to e^{-i\alpha_q \gamma_5} q$

$$\theta \to \theta + 2\sum_q \alpha_q$$

- $U(1)_{\mathsf{A}}$ invariant: $\bar{\theta} \equiv \theta - \sum_q \phi_q$

Peccei, Quinn 1977; Weinberg 1978; Wilczek 1978

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- Measurement: $|\bar{\theta}| < 10^{-10}$
- No anthropic argument for why $\bar{\theta}$ is so small!

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

- QCD generates axion mass:

$$V(a) \approx \frac{1}{2} f_a^2 {m_a}^2 \left(\bar{\theta} + \frac{a}{f_a}\right)^2$$

$$m_a \approx \frac{f_\pi}{f_a} m_\pi \approx 10^{-9} \text{ eV} \left(\frac{10^{16} \text{ GeV}}{f_a}\right)$$

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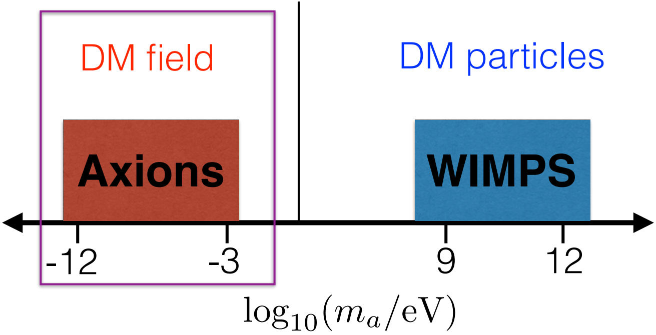
Axion dark matter is a classical field



- de Broglie wavelength: $\lambda_{dB} = \dfrac{2\pi}{p} \approx \dfrac{2\pi}{mv}$
  - Axion $(m = 10^{-9}$ eV): $\lambda_{dB} \approx 8 \times 10^3$ km
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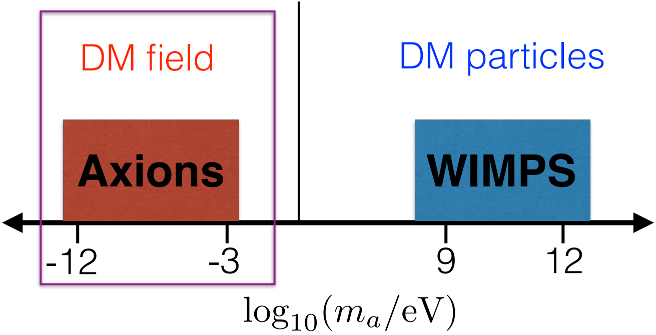

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- Local DM energy density: $\rho_{DM} \approx 0.4$ GeV/cm^3
- Local occupancy number: $\mathcal{N} \approx (\rho_{DM}/m) \times \lambda_{db}^3$
  - $\mathcal{N}_{\text{axion}} \approx 10^{44}$
  - $\mathcal{N}_{\text{WIMP}} \approx 10^{-36}$

The axion as dark matter ($f_a > H_I/2\pi$)

$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0 \qquad (H = T^2/m_{pl})$$

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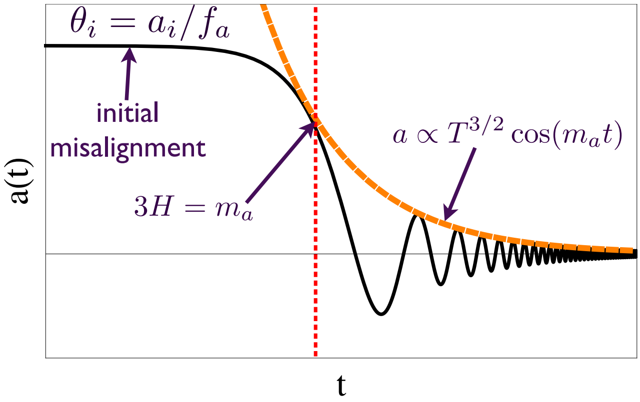

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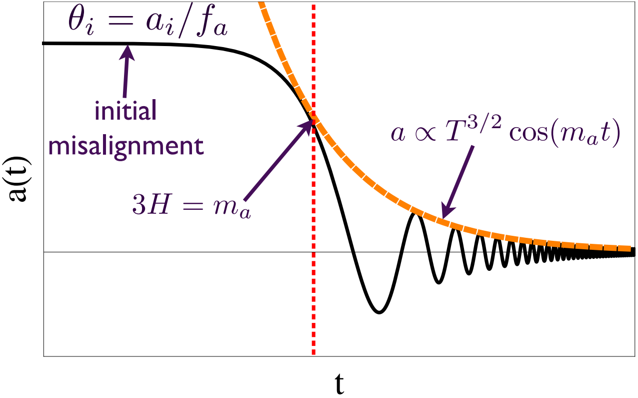

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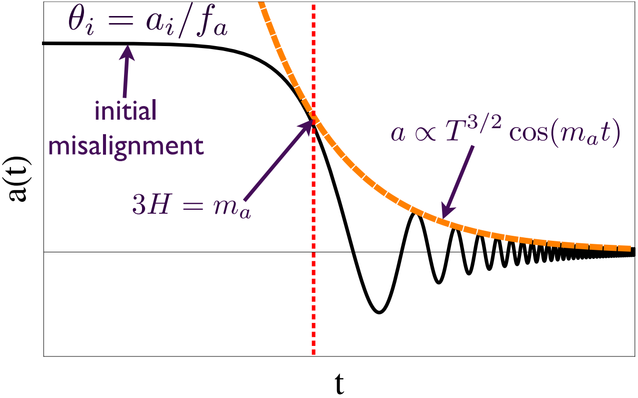

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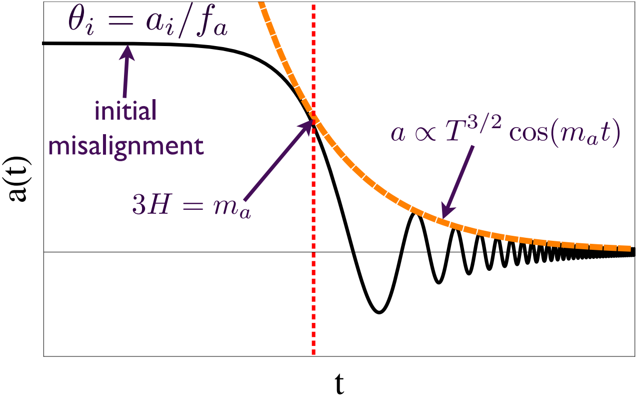

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- $f_a = 10^{16}$ GeV $\rightarrow |\theta_i| \lesssim 10^{-3} - 10^{-2}$ (e.g., Tegmark, Aguirre, Rees, Wilczek '05)

Is QCD damping relevant at small f_a?

Preliminary! In progress with Andrey Katz

$$\ddot{a} + (3H + \gamma_{\mathrm{QCD}})\dot{a} + m_a^2 a = 0$$

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- QCD Damping rate (McLerran et. al. 1990) :

$$\gamma_{\text{QCD}} = \frac{1}{f_a^2\, T} \int d^4x \langle \frac{\alpha_s}{4\pi} \text{tr}[G_{\mu\nu}\tilde{G}^{\mu\nu}(x)]\, \frac{\alpha_s}{4\pi} \text{tr}[G_{\mu\nu}\tilde{G}^{\mu\nu}(0)]\, \rangle_T$$

$$= \frac{\Gamma_{\text{sphaleron}}}{f_a^2 T}$$

$$\propto \text{(large coefficient)} \times \frac{T^3}{f_a^2}$$

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$$= \frac{\Gamma_{\text{sphaleron}}}{f_a^2 T}$$
$$\propto \text{(large coefficient)} \times \frac{T^3}{f_a^2}$$

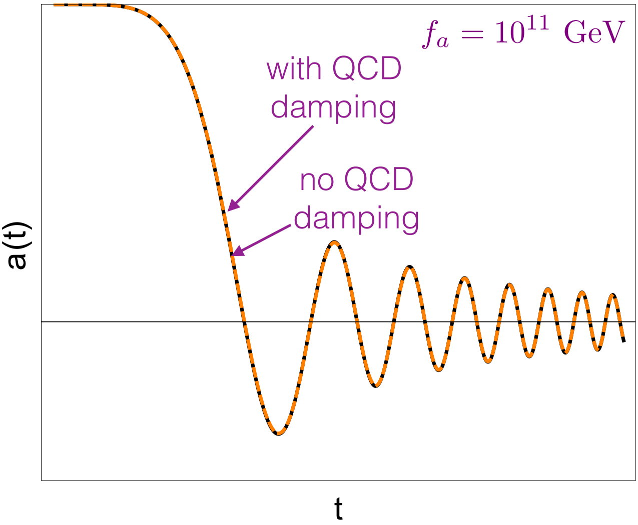
- Important if $\gamma_{\text{QCD}} \sim H$ at $T \sim 1$ GeV:

$$\frac{(1\ \text{GeV})^3}{f_a^2} \sim \frac{(1\ \text{GeV})^2}{10^{18}\ GeV}$$

- Important for $f_a \lesssim 10^{10}$ GeV (with the $\mathcal{O}(1)$ numbers)

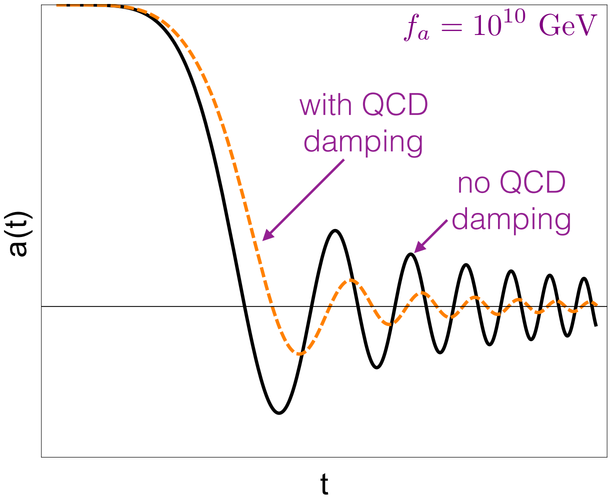
Is QCD damping relevant at small f_a?

Probably not if $f_a \gtrsim 10^{11}$ GeV



Is QCD damping relevant at small f_a?

Likely yes if $f_a \lesssim 10^{10}$ GeV



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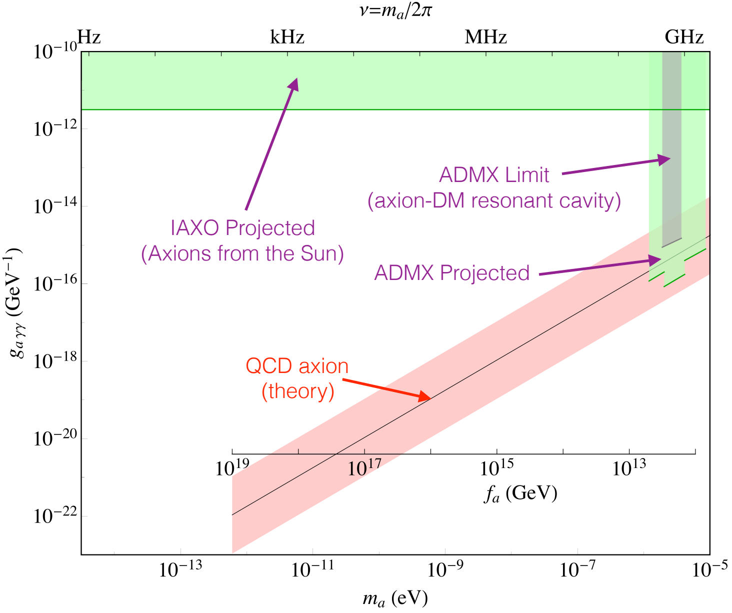
How can we probe axion dark matter?



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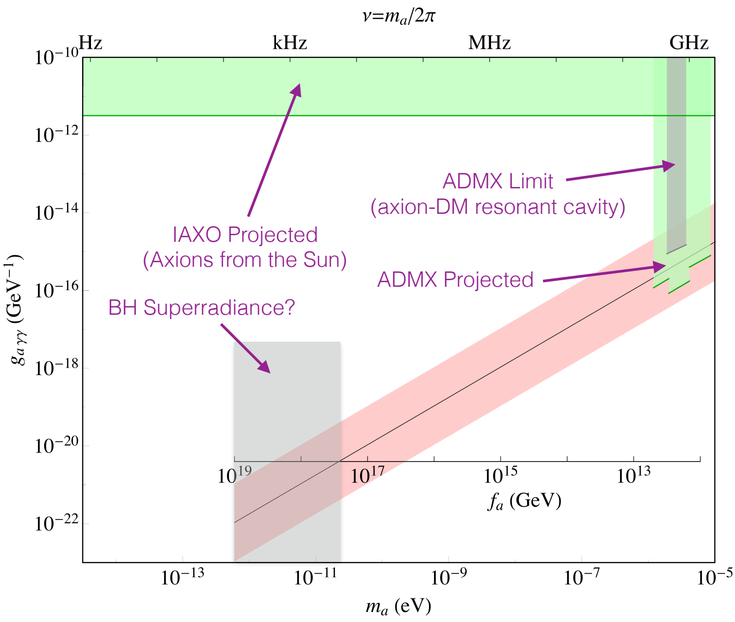

e.g., Arvanitaki, Baryakhtar, Huang 2014

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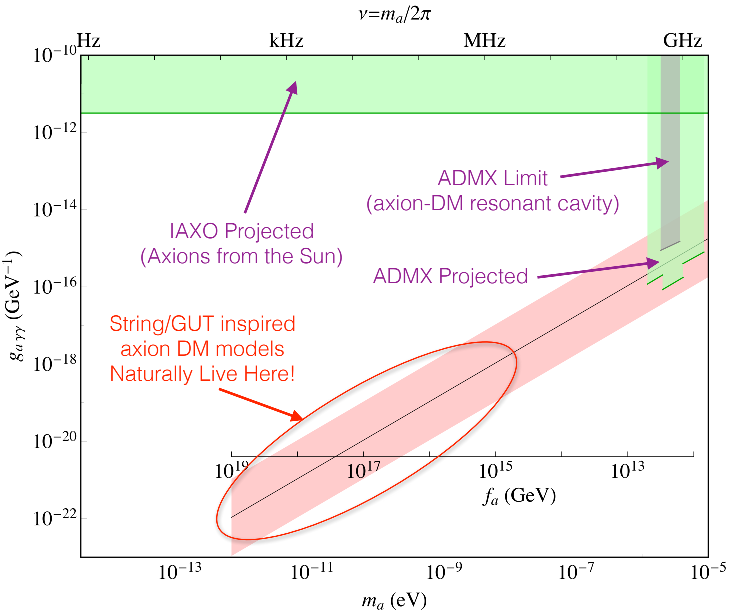

e.g., Svrcek, Witten 2006

Axion dark matter modifies Maxwell's equations

- Recall axions also couple to QED:

$$\mathcal{L} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} \qquad g_{a\gamma\gamma} \propto \frac{\alpha_{\text{EM}}}{f_a}$$

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

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

Scott Thomas and Blas Cabrera (2010), Sikivie et. al. (2013)

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

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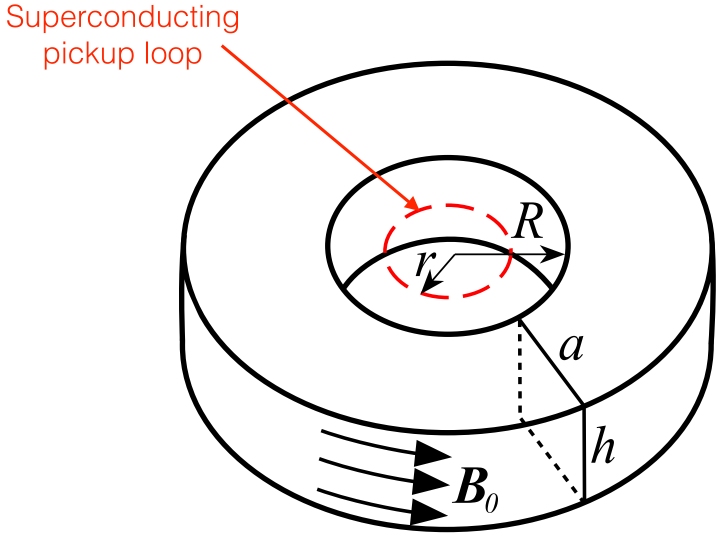
Axion dark matter generates magnetic flux



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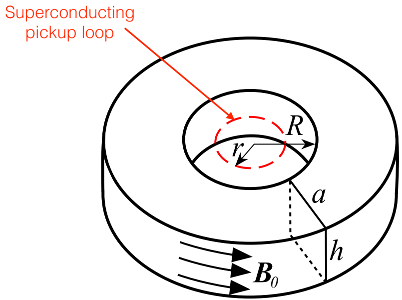

- Estimate B-field induced through pickup loop
  $(r = a = h = R)$

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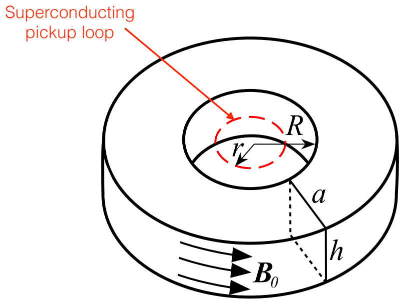
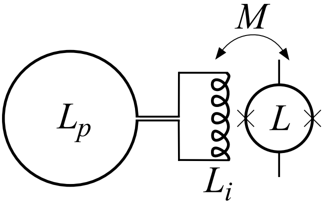


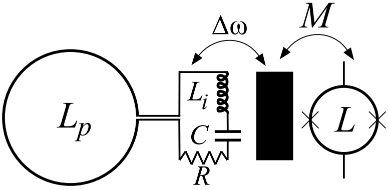
- Estimate B-field induced through pickup loop ($r = a = h = R$)
- Axion effective current: $I_{\text{eff}} \sim R^2 J_{\text{eff}}$
- $B \sim \frac{I_{\text{eff}}}{R} \sim R\, g_{a\gamma\gamma} \sqrt{2\,\rho_{\text{DM}}}\mathbf{B_0} \sin(m_a t)$
- $f_a = 10^{16}$ GeV, $\mathbf{B_0} \sim 5$ T, $R \sim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

Two readout strategies

Broadband



Resonant



Better at low frequency

Better at high frequency

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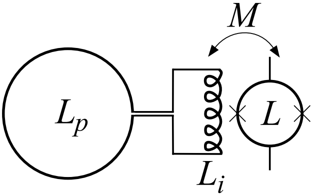

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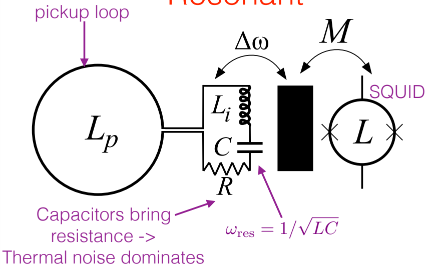

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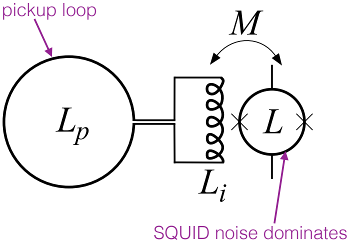

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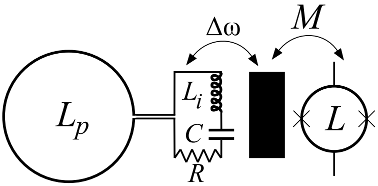

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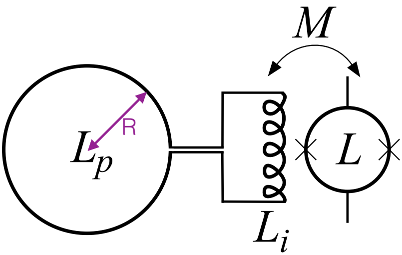
Broadband estimate



- Example from MRI application: (Myers et. al. 2007)
  - B-field sensitivity: $S_B^{1/2} \approx 6.4 \times 10^{-17}$ T/$\sqrt{\text{Hz}}$
  - $R \approx 3.3$ cm

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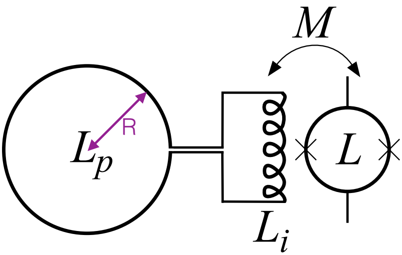

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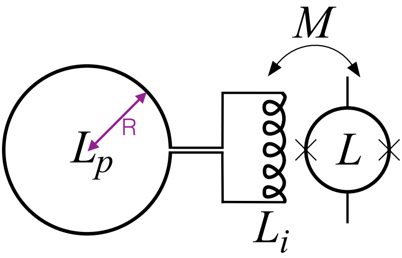
- Scale to $R \approx 4$ m
  - $S_B^{1/2} \approx 5 \times 10^{-20}$ T/$\sqrt{\text{Hz}}$

Broadband estimate



- Example from MRI application: (Myers et. al. 2007)
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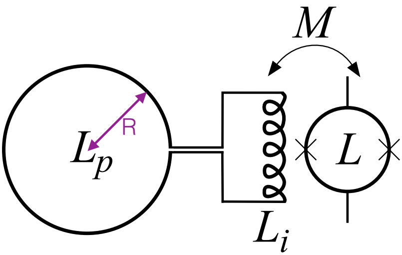

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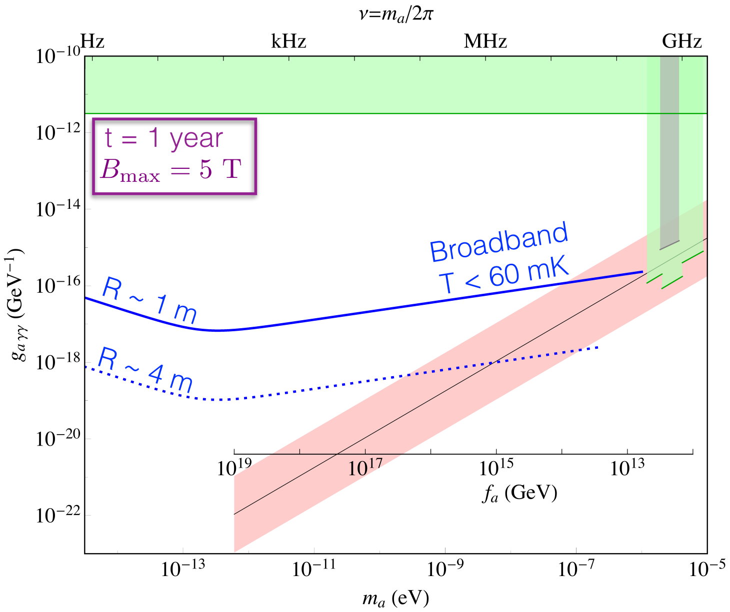
Axion dark matter projected reach



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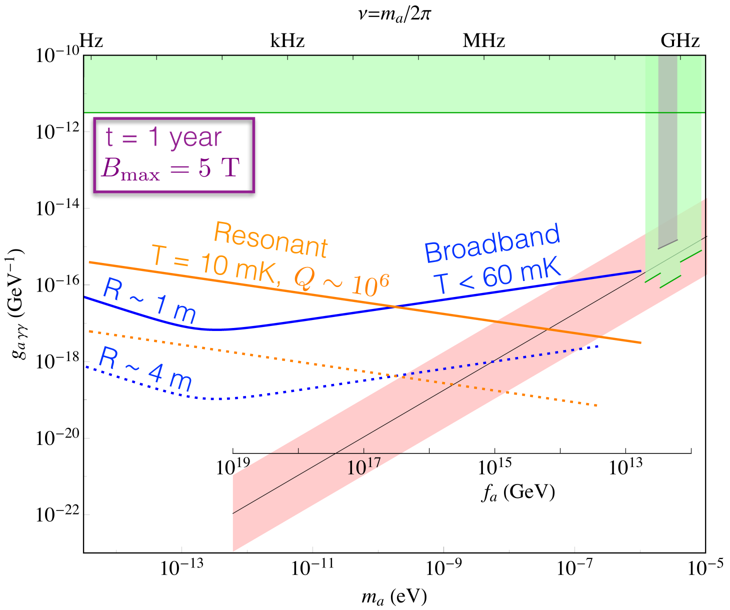

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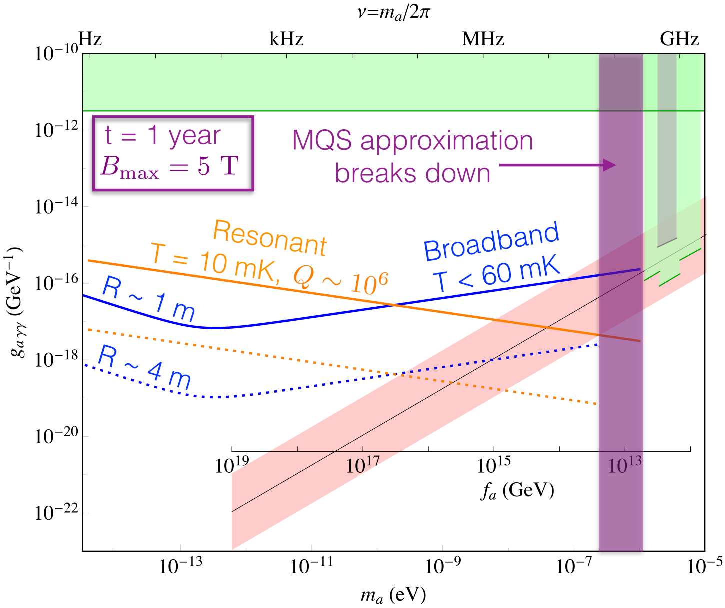

Outline

- Axion particle physics (review)
- Axion cosmology (review)
- ABRACADABRA: Cosmic axion detection (theory)
- ABRACADABRA-10 cm at MIT (experiment)

The MIT prototype: ABRACADABRA-10 cm

- ABRACADABRA: A Broadband/Resonant Approach to Cosmic Axion Detection with an Amplifying B-field Ring Apparatus
- Dimensions: 12×12 cm^2 ($R = 3$ cm, $h = 12$ cm), $B = 1$ T
- People (LNS+CTP, PSFC, +1 Princeton): Janet Conrad, Joe Formaggio, Sarah Heine, Yoni Kahn, Joe Minervini, **Jonathan Ouellet**, Kerstin Perez, Alexey Radovinsky, **B.S.**, Jesse Thaler, Daniel Winklehner, **Lindley Winslow**
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- Funded by the NSF (as of this week)

ABRACADABRA-10 cm

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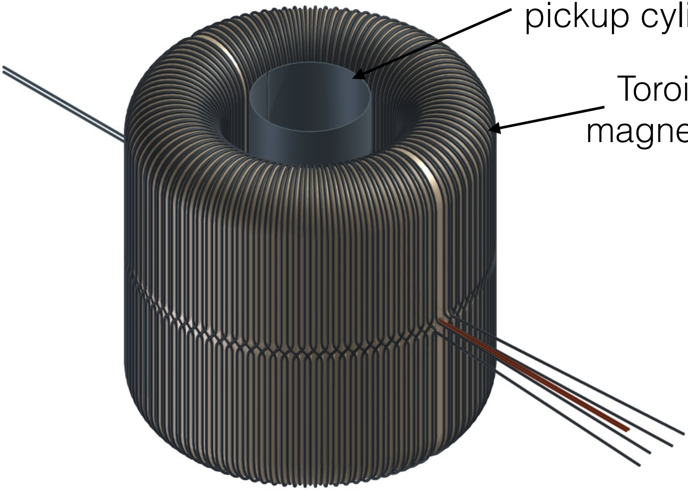
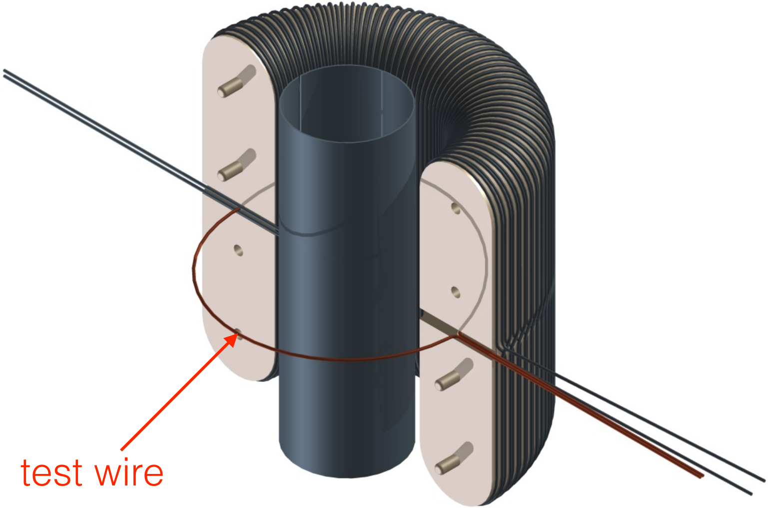
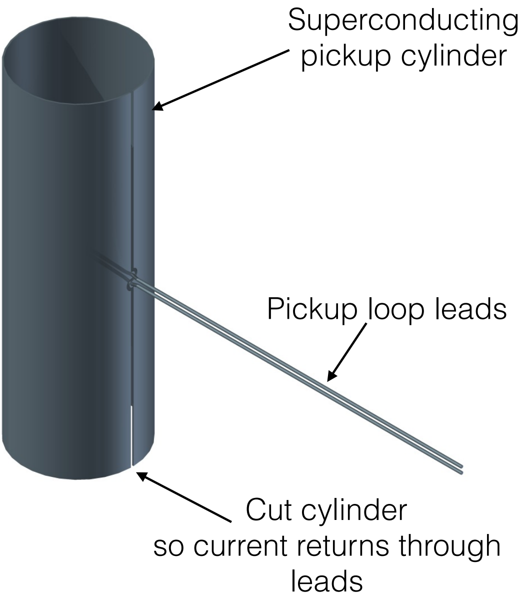


Thanks Daniel Winklehner for CAD model and slides.

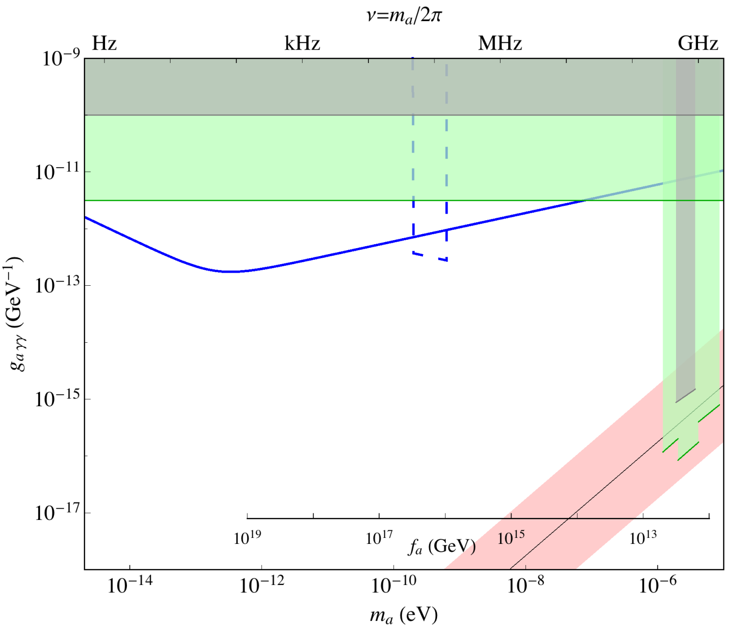
ABRA-10 cm: vertical cut



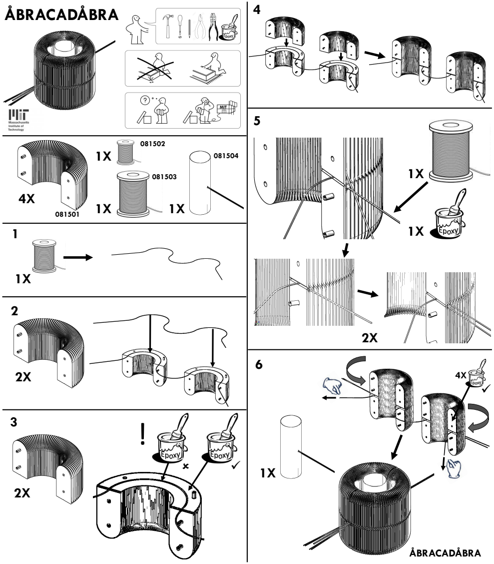
ABRA-10 cm: pickup cylinder



ABRA-10 cm: reach after 1 month



ÅBRACADÅBRA

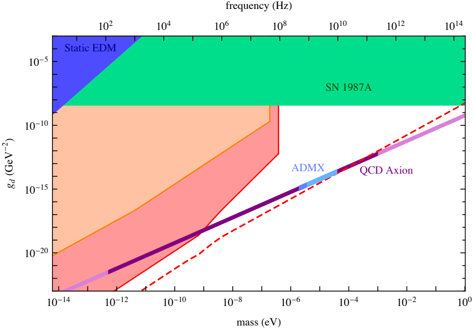


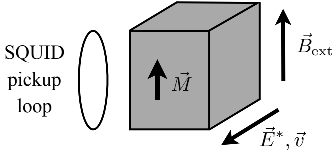
Complementary proposals for axion dark matter experiments

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)

Light bosonic dark matter future

- MIT: ABRA-10 cm followed by ABRA-1 m ($B \sim 10$ T)
- ABRA-1 m: multiple experiments at different locations
  - Preliminary discussions with Korean Center for Axion and Precision Physics (Yannis Semertzidis)
- Axions and light bosonic dark matter well motivated by high-scale physics (e.g., compactified string theory)
- Detection may provide window to high-scale physics (GUT scale, inflation, . . .)
- New ideas to search for ultra-light scalars, dark-photons, etc. (laboratory experiments + astrophysics)
  - e.g., CASPEr experiment
  - Black Hole superradiance

Questions?

Axion Backup Slides

Magnetic field sensitivity calculation

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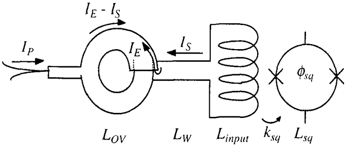
  - $B^2 = S_B^{1/2}(\omega_0)/\tau/\sqrt{N} = S_B^{1/2}(\omega_0)/\sqrt{T\tau}$

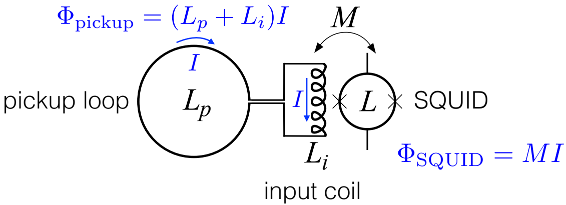
Broadband: detailed calculation

Cryogenic Current Comparator



Sese et. al., 1999

Axion DM: Broadband Readout



- $L_i \approx L_p$ and $M \approx \sqrt{L\, L_i}$

$$\Phi_{\text{SQUID}} \approx \frac{1}{2}\sqrt{\frac{L}{L_p}}\Phi_{\text{pickup}} \approx 0.01\Phi_{\text{pickup}}$$

CASPEr: BBN and tuning bounds

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

- QCD generates minimum m_a
- Effective operator changes neutron-proton mass difference in early universe (Phys. Lett. B. 2014: K. Blum, R. D'Agnolo, M. Lisanti, **B.S.**)