Searching for Axions with Magnetic Resonance Force Microscopes

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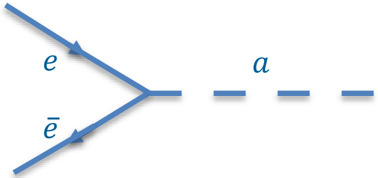
Axion Dark Matter

- Axions are a cosmologically well-motivated dark matter candidate
  - In particular, the QCD axion offers a solution of the strong CP problem
- Axions are generically wave-like with frequency $\omega_a = \frac{m_a c^2}{\hbar}$

$$a(t) \simeq \frac{\sqrt{\rho_{\mathrm{DM}}}}{\omega_a} \cos(\omega_a t)$$

- Most of theoretically motivated QCD axion mass range corresponds to radio frequencies: 3 kHz – 300 GHz
- Other ultralight dark matter candidates (scalars, dark photon) have similar phenomenology

Axions as a Background Magnetic Field



- Axion-electron coupling

$$\mathcal{L}_{ae} = g_{ae}\frac{\sqrt{\hbar^3 c}}{2m_e}(\partial_\mu a)(\bar{\psi}_e\gamma^\mu\gamma_5\psi_e)$$

- This coupling can be rewritten as Zeeman Hamiltonian inducing an effective magnetic field on electron spins

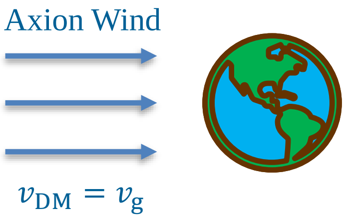
$$H_{ae} = -\gamma_e\vec{S}_e \cdot \vec{B}_{ae}$$

- The effective magnetic field is

$$B_{ae} = 2\times10^{-8}\ \mathrm{T}\times g_{ae}\sin(\omega_a t)$$

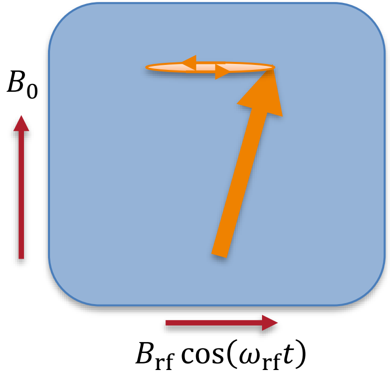
- Magnetic field sensitivity required to beat best current bounds

$$B_{ae} = 2\times10^{-16}\ \mathrm{T}\times\frac{g_{ae}}{7\times10^{-9}}\sin(\omega_a t)$$



Magnetic Resonance Based Dark Matter Detection

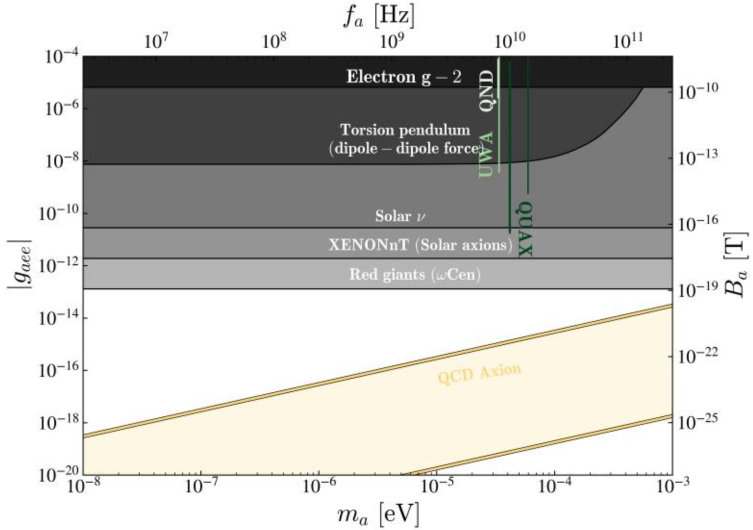
Magnetic Resonance



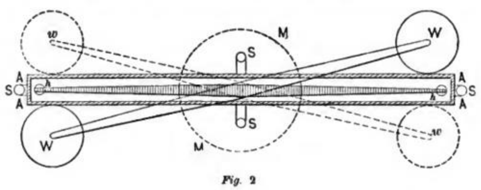
Larmor frequency
$\omega_L = \gamma B_0$
Resonance
$\omega_L = \omega_{\mathrm{rf}}$

Several Magnetic Resonance Dark Matter Searches including

- CASPEr
- QUAX
- …

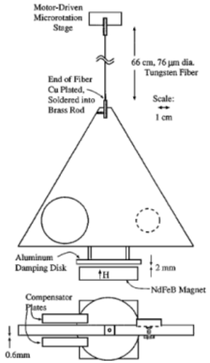


Mechanical Detection for Fundamental Physics



Cavendish
Gravitational Force

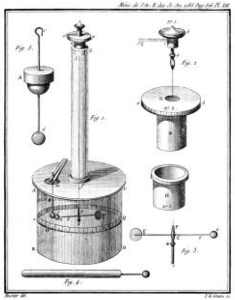
1798



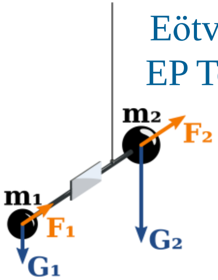
Casimir Force

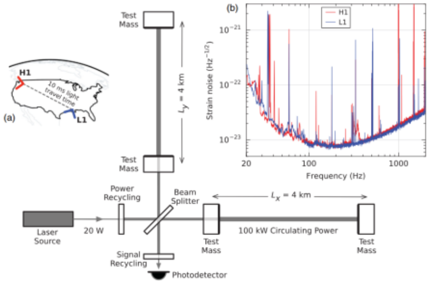
1997

1785
Coulomb Force



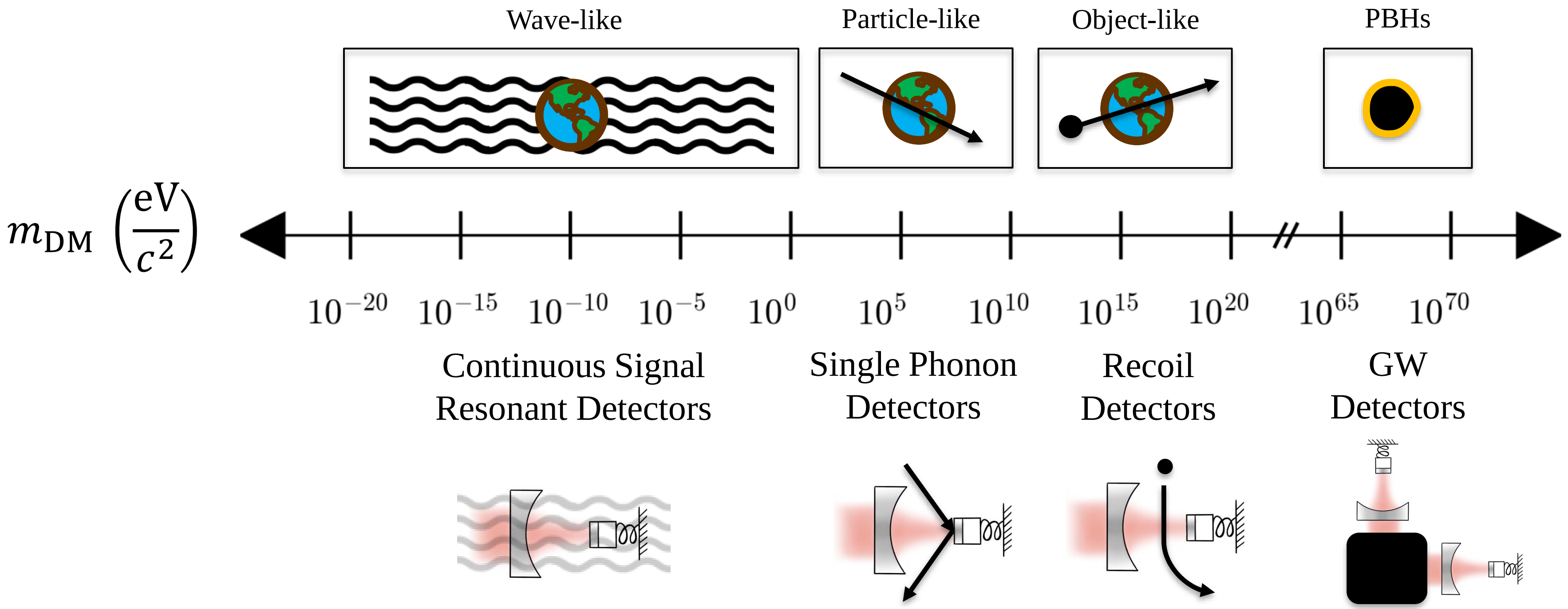
1885
Eötvös
EP Test





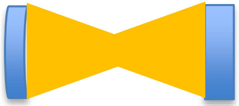
2015
Gravitational
Waves (LIGO)

Mechanical Detection for Dark Matter



Mechanical Detection for Ultralight Dark Matter

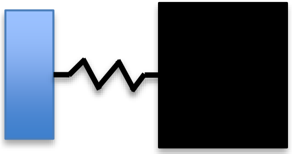
Cavities



- PRL 125, 201302 (2020)
- PRL 126, 051301 (2021)
- PRD 110, 043005 (2024)

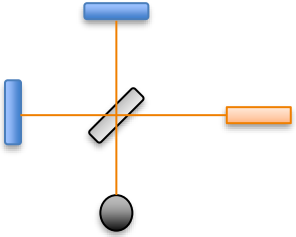
Resonant Mechanical Oscillators

- PRL 118, 021302 (2017)
- PRL 126, 071301 (2021)



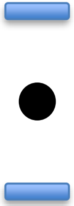
Interferometers

- Nature 600, 424-428 (2021)
- PRD 105, 063030 (2022)
- PRD 110, 042001 (2024)



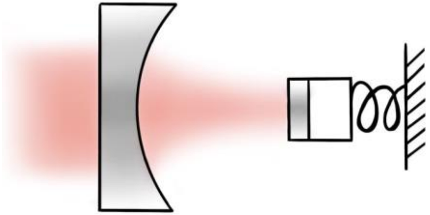
Levitated Sensors

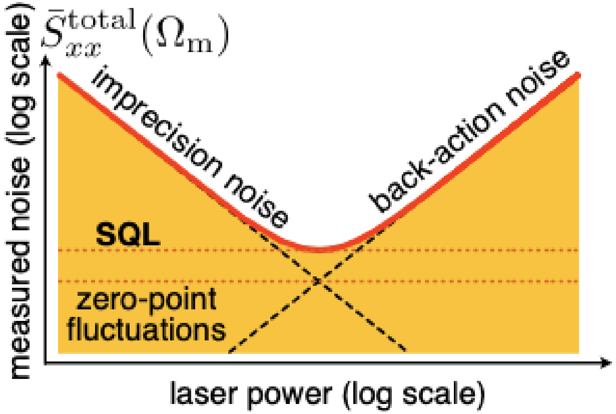
- PRL 134, 251001 (2025)



Mechanical Detection at SQL

- Modern state-of-the-art mechanical detectors can operate at the standard quantum limit (SQL) or beyond
- Low photon count: higher imprecision/shot noise due to quantum fluctuations
- High photon count: higher back action noise from radiation pressure
- Minimum readout noise happens at SQL





Aspelmeyer, et al, Rev. Mod. Phys. 86, 1391 (2014)

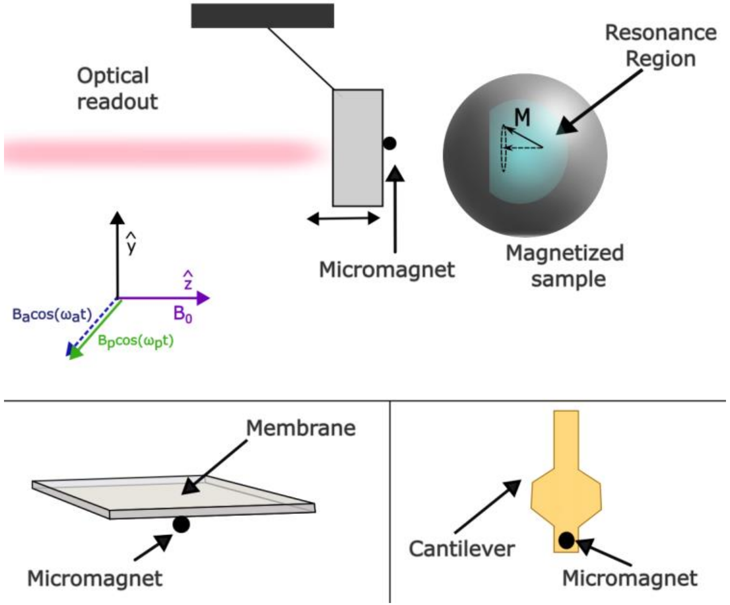
Magnetic Resonance Force Microscopy

- Force on mechanical resonator from magnetized sample:

$$F_z(t) = \int -[\vec{m}(\vec{r},t) \cdot \vec{\nabla}] B_z(\vec{r})\, dV$$

$$= -m_z(t) \int \frac{\partial B_z}{\partial z}\, dV$$

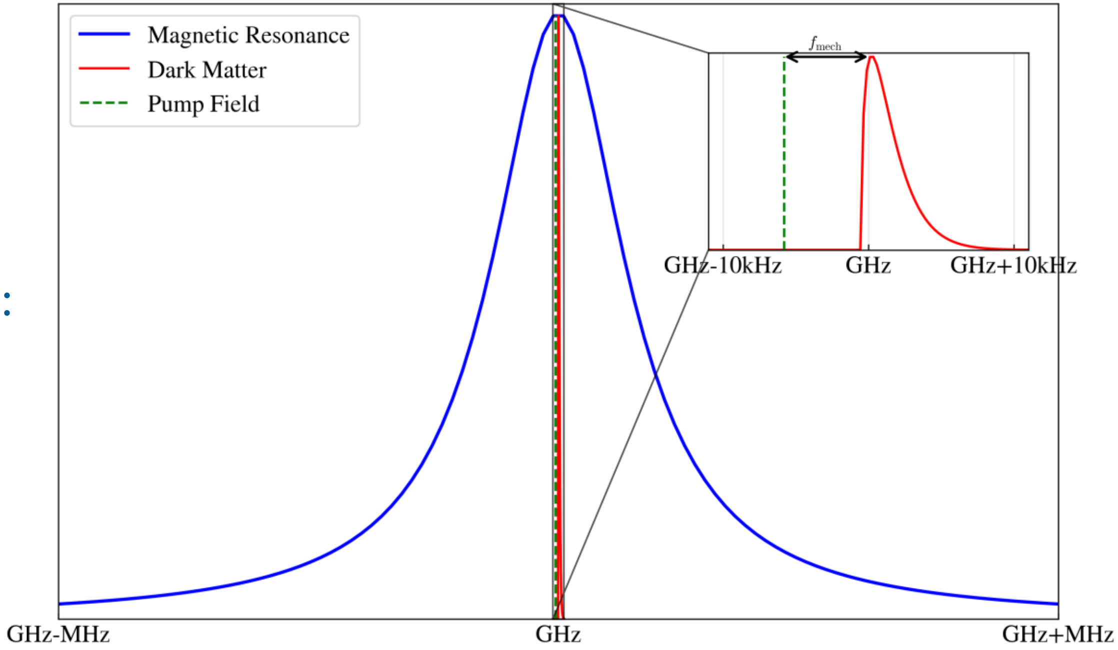
- We need:
  - Frequency link between mechanical ω_m and Larmor frequency ω_L
  - Low force noise at ω_m
  - Large number of spins resonating at ω_L



Sidles, et al, Rev. Mod. Phys., 67, 249 (1995)
Scozzaro, et al, J. Mag. Res., 271, 15 (2016)
Half, et al, Phys. Rev Appl., 15, L021001 (2021)

Frequency Down-Conversion Scheme

- Amplitude modulate (AM) axion signal to oscillate at ω_m
- Effective AM: Pump field
- Detection (beat) frequency:
  $$\omega_D = \omega_a - \omega_p$$
- At mechanical resonance:
  $$\omega_D = \omega_m$$
- Amplification: $B_p \gg B_a$



Inspired by: QUAX Proposal 2015 [J. Phys.: Conf. Ser. 718 042051]

Force Noise

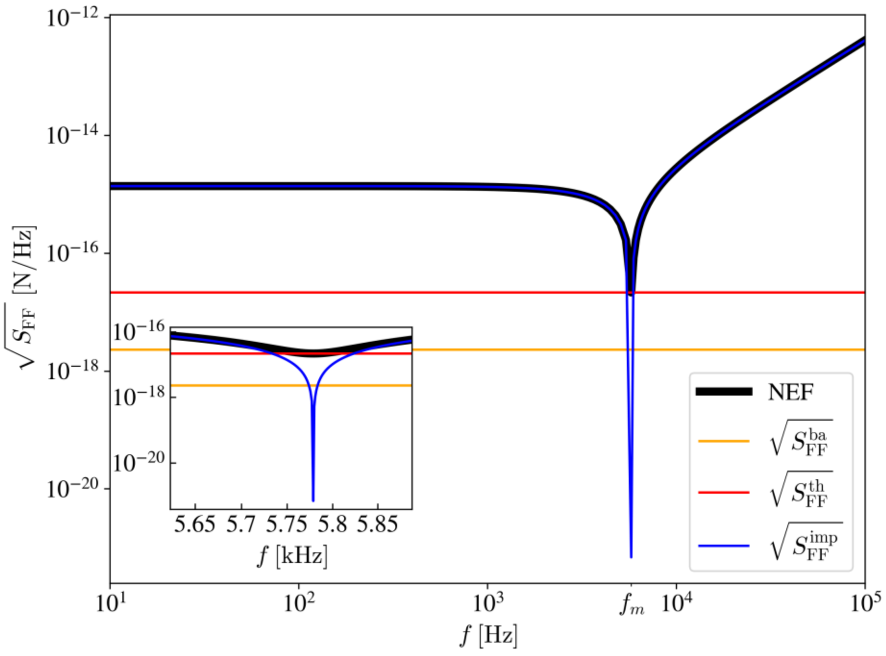
- Noise equivalent force [1]:

$$F = \left(\frac{3}{\sqrt{T_{\text{int}}}} + \frac{1}{(T_{\text{coh}}T_{\text{int}})^{1/4}}\right)\sqrt{2S_{\text{FF}}^{\text{noise}}}$$

- At mechanical resonance ($\omega = \omega_m$), thermal noise dominates:

$$S_{\text{FF}}^{\text{th}} = \frac{4k_B T m_{\text{eff}}\omega_m}{Q}$$

- Single run scans ~ 100 Hz region



[1] Manley, Stump, Petery, & Singh, Phys Rev D 108, 075008 (2023)

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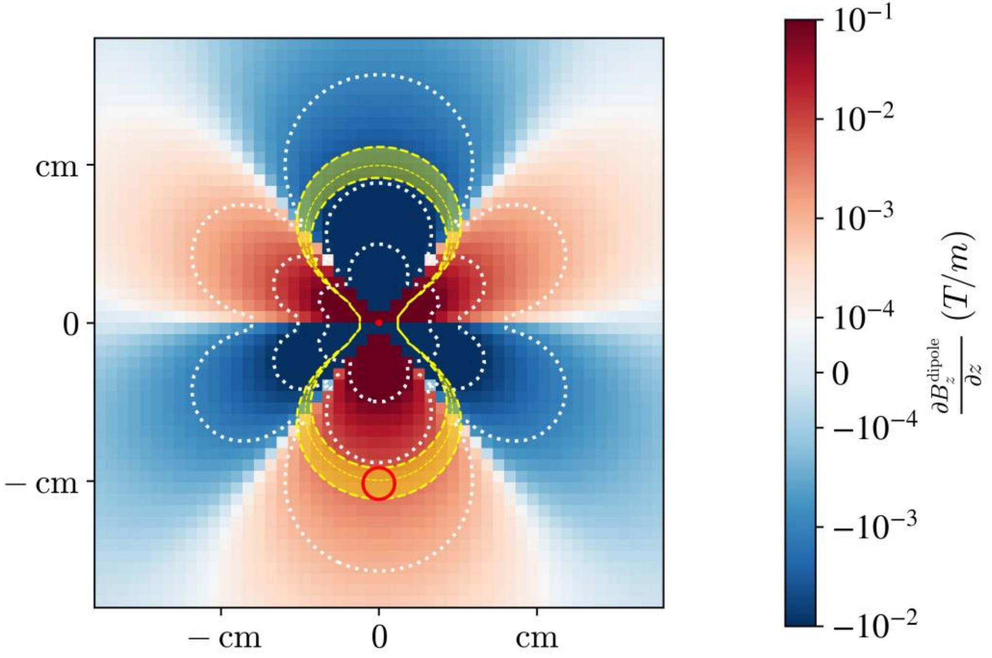
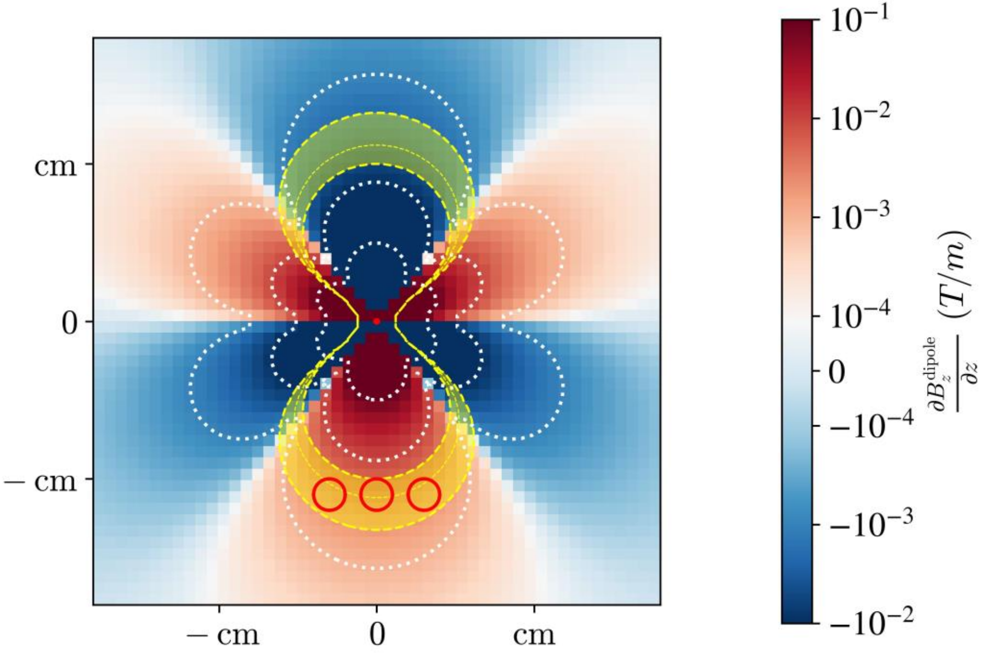
Maximizing Number of Resonating Spins

- Magnetic resonance condition:
$$\frac{\omega_L}{\gamma} = B_0 + B_z$$
- If $B_0 = 0$, small resonance slice near the micromagnet
  - Too few spins in resonance
- If $B_0 = \frac{\omega_L}{\gamma}$, large resonance region
  - Far away from micromagnet → smaller force
- Tune B_0 to find optimal value



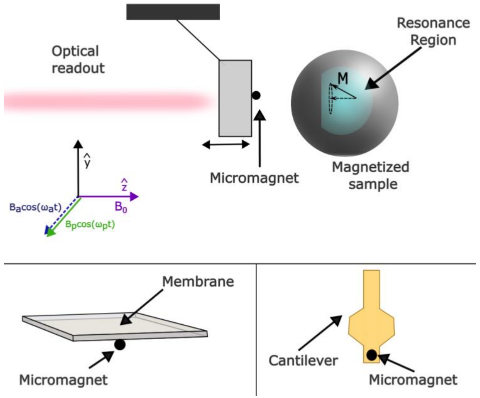
Maximizing Number of Resonating Spins

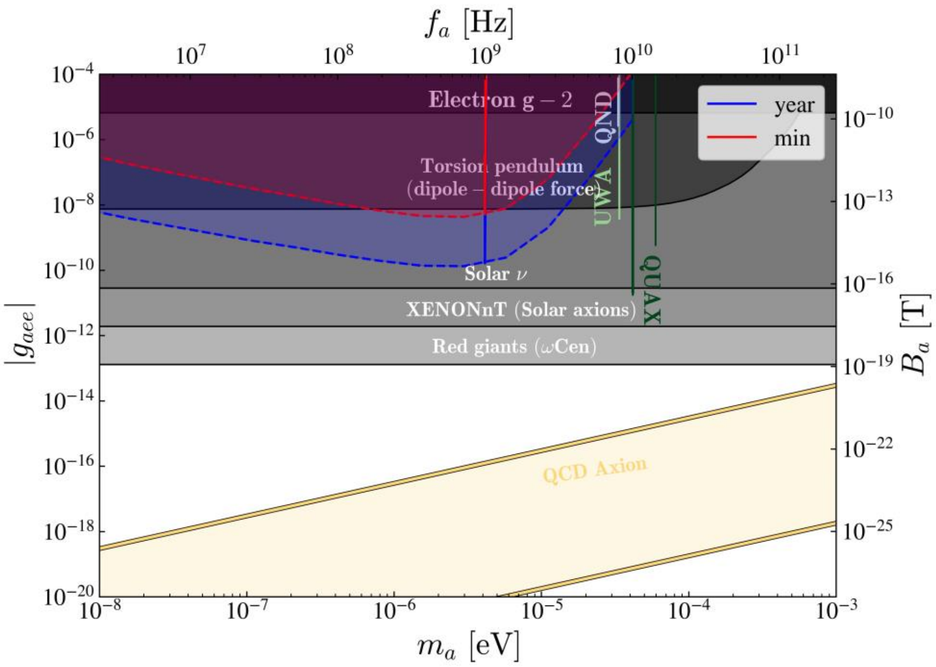
- Magnetic dipole radiation damping limits sample size
- Use multiple spheres
  - 9 in 3 × 3 grid
- Separate with opaque walls to avoid photon transfer
- Potential for more YIG spheres.
  - Limited by resources not technicalities.



10 YIG spheres: Crescini, et al. Phys. Rev. Lett. 124, 171801 (2020)

Axion-Electron Coupling





Parameters Used	
Temperature T	0.01 K
Laser Power P	10^{-6} W
Fabry-Perot Cavity	
Resonant Frequency ω_{cav}	1.77×10^{15} rad/s
Length L_{cav}	10^{-4} m
Finesse F_{cav}	200
Fe-Co Micromagnet	
Saturation Magnetization M_0	2.4 T
Radius R_{mag}	100 μm
Density ρ_{mag}	8.5 g/cm^3
Mass m_{mag}	36 μg
SiN Membrane	
Quality Factor Q_{m}	10^6
Spring Constant k_{m}	60 N/m
Density ρ_{m}	3.17 g/cm^3
Side Length	5 mm
Thickness	500 nm
Mass m_{m}	39.6 μg
Resonant Frequency ω_{m}	$2\pi \times 45$ kHz
YIG Sample	
Longitudinal Relaxation Time T_1	10^{-6} s
Transverse Relaxation Time T_2	10^{-6} s
Number density N_{sample}	2.1×10^{28} m^{-3}
Radius r_{sample}	1 mm

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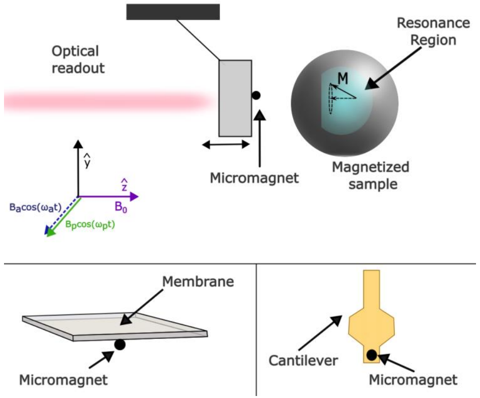
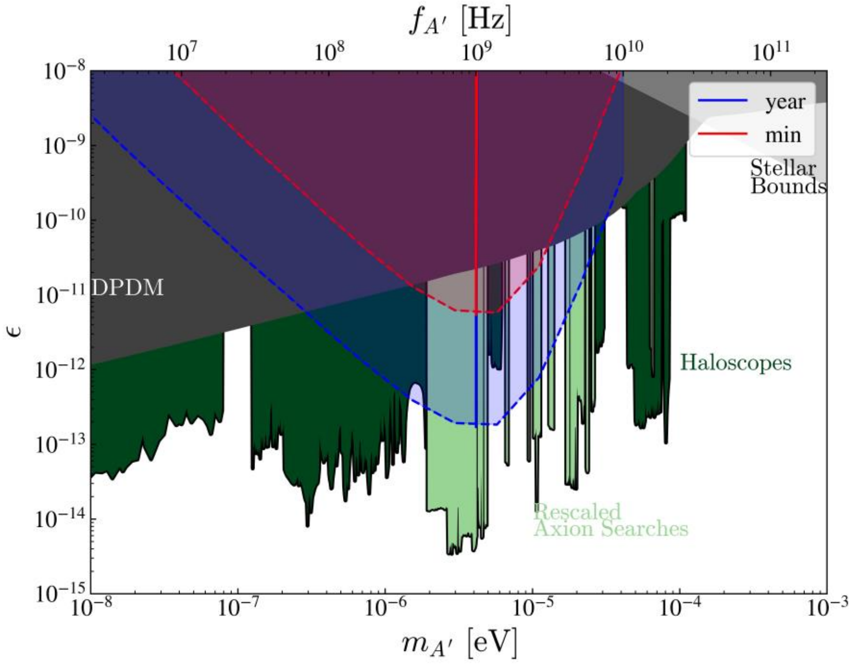
Dark Photon Kinetic Mixing Parameter





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Summary

- Axion detection can be formulated as a magnetometry problem
  - This approach completements conventional axion-photon searches
  - Ex: Axions induce effective magnetic field on fermions
- Mechanical detection for axion searches
  - MRFM based axion search beyond lab constraints with current technology
- Target axion mass/frequency can be tuned by scanning pump frequency ω_p
- Manuscript coming out soon!