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, QCD axion offers a solution of the strong CP problem

- Axions are generically wave-like with frequency $\omega_a = \frac{m_a c^2}{\hbar}$

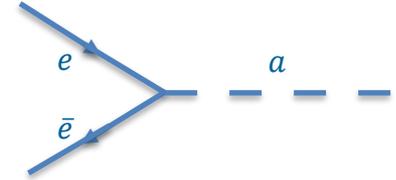$$a(t) \simeq \frac{\sqrt{\rho_{\text{DM}}}}{\omega_a} \cos(\omega_a t)$$

- Most of theoretically motivated QCD axion mass range corresponds to radio frequencies: $3\text{ kHz} - 300\text{ GHz}$

Axions as a Background Magnetic Field

- Axion-electron coupling

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

- 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

$$\left|\vec{B}_{ae}\right| = 2 \times 10^{-8} \text{ T} \times g_{ae} \sin(\omega_a t)$$
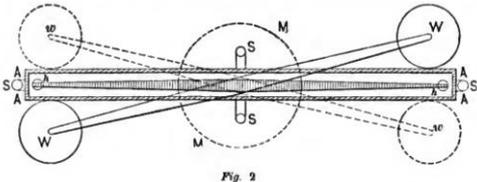
Axion Wind

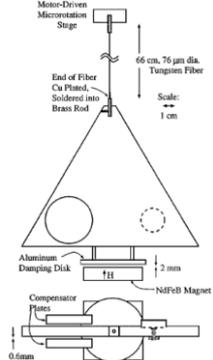Other spin magnetometry based axion searches: QUAX, CASPEr, …

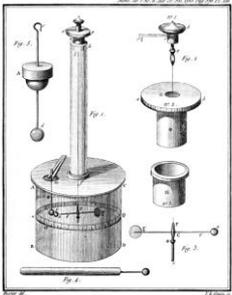# Mechanical Detection for Fundamental Physics

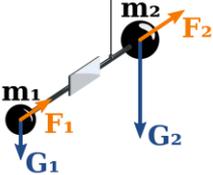Cavendish
Gravitational Force

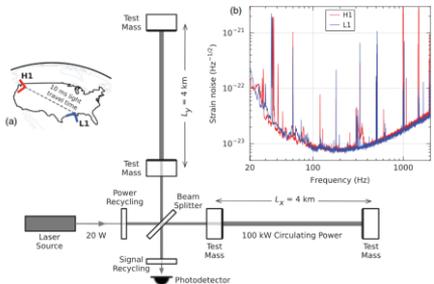1798

Casimir Force

1997

1785

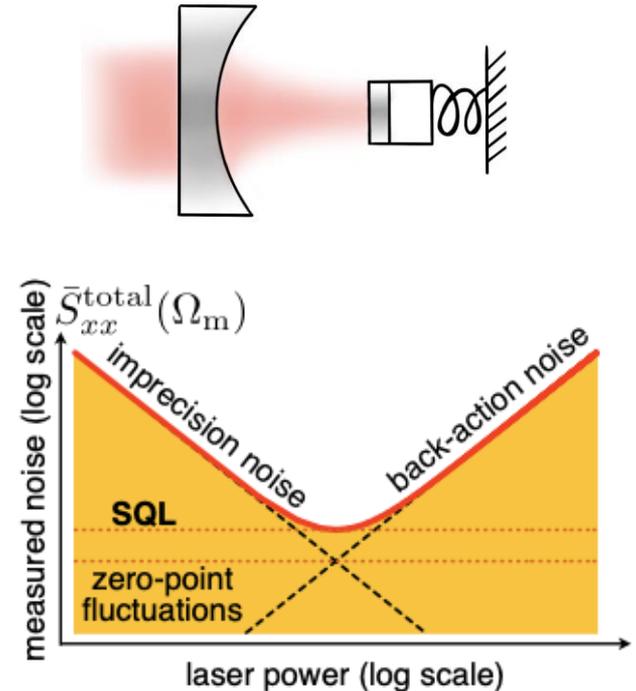Coulomb Force

1885

Eötvös
EP Test

2015

Gravitational
Waves (LIGO)

Mechanical Detection 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

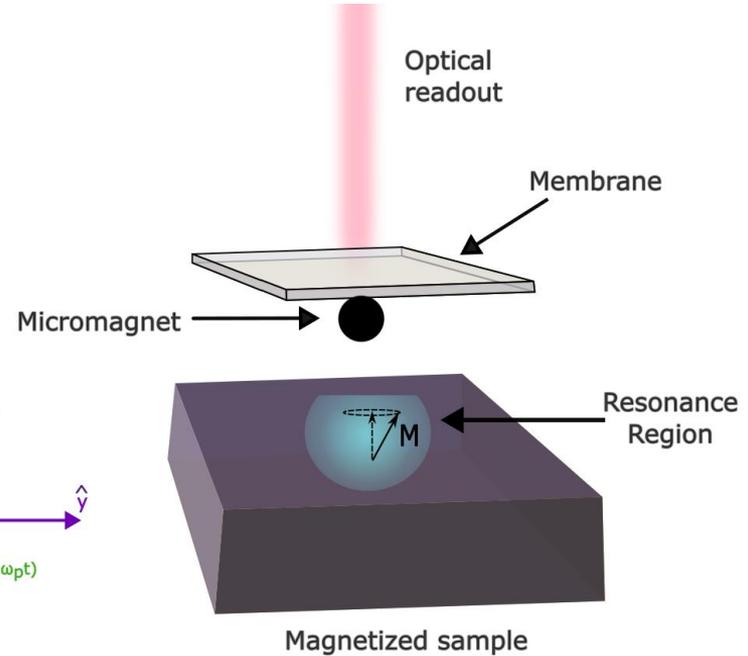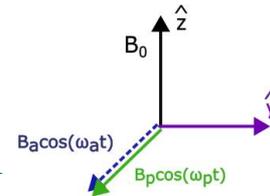Aspelmeyer, et al, Rev. Mod. Phys. 86, 1391 (2014)

Magnetic Resonance Force Microscopy

- Force on mechanical resonator from magnetized sample:

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

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

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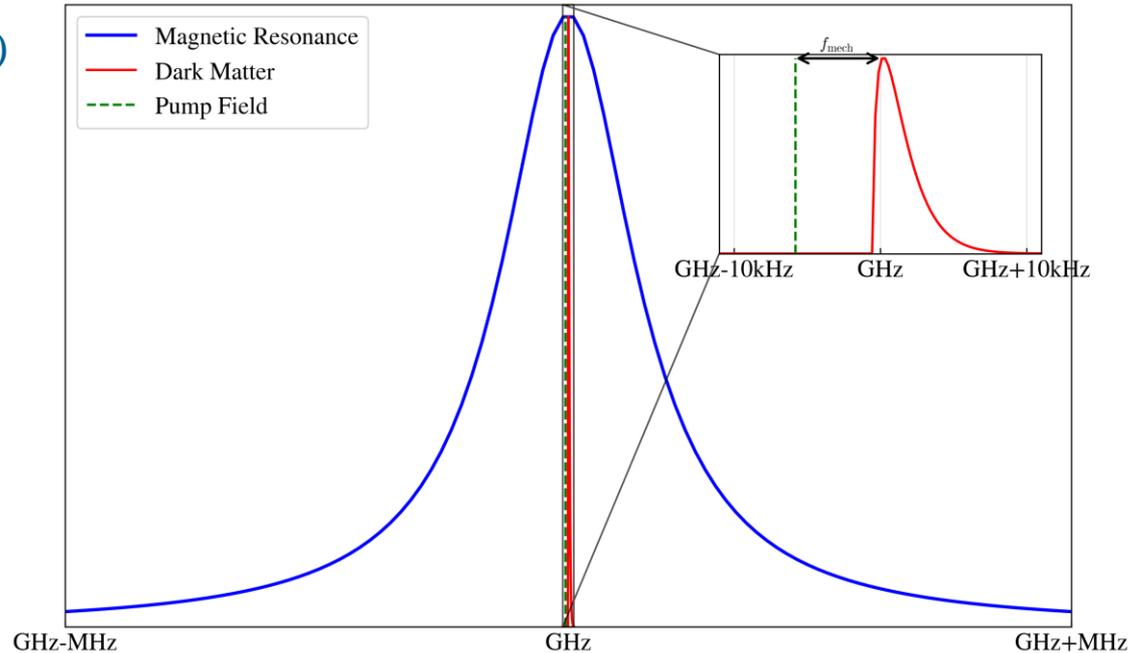 - Large number of spins resonating at ω_L

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

- Pump field: effective AM of axion signal

- Detection frequency:
$$\omega_D = \omega_a - \omega_p$$

- At mechanical resonance:
$$\omega_D = \omega_m$$

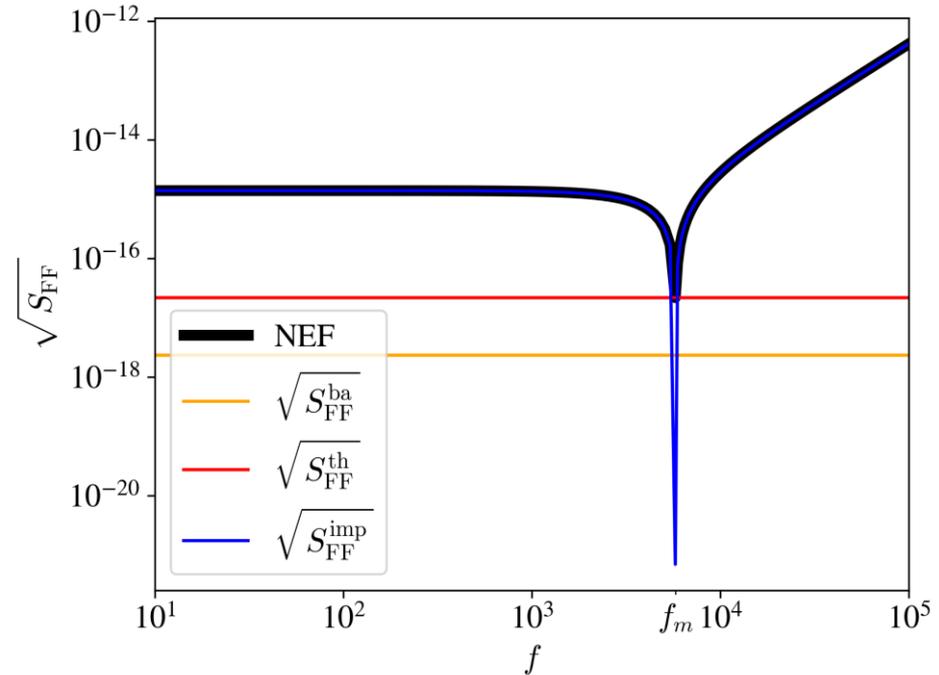Inspired by: QUAX Proposal 2015 [J. Phys.: Conf. Ser. 718 042051]

Force Noise

- Noise equivalent force:

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

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

$$S_{\text{FF}}^{\text{th}} = \frac{4 k_B T m_{\text{eff}} \omega_m}{Q}$$
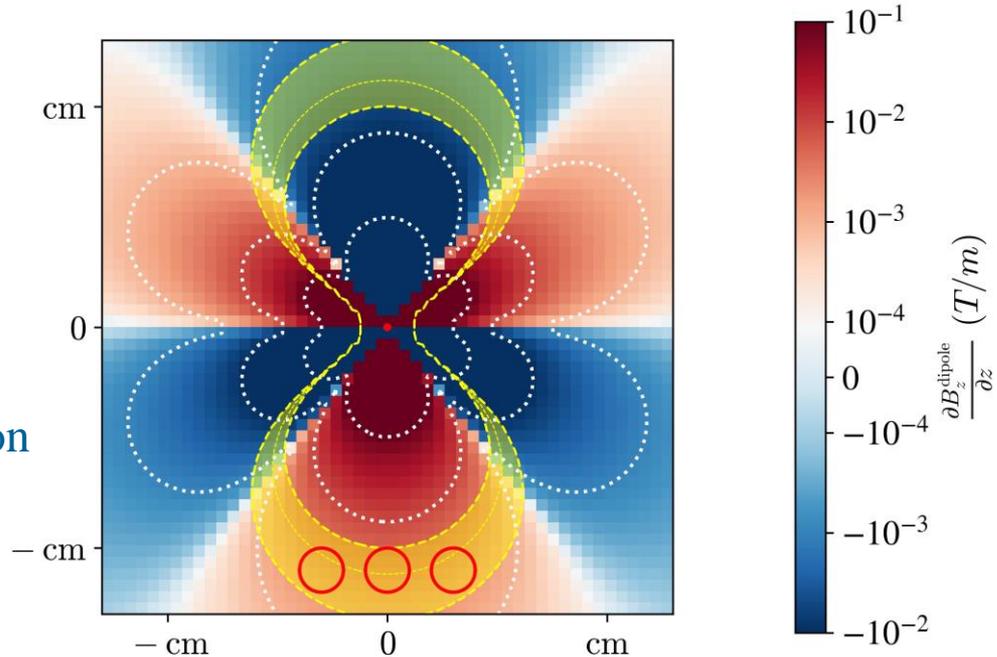
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Maximizing Number of Resonating Spins

- Magnetic resonance condition:

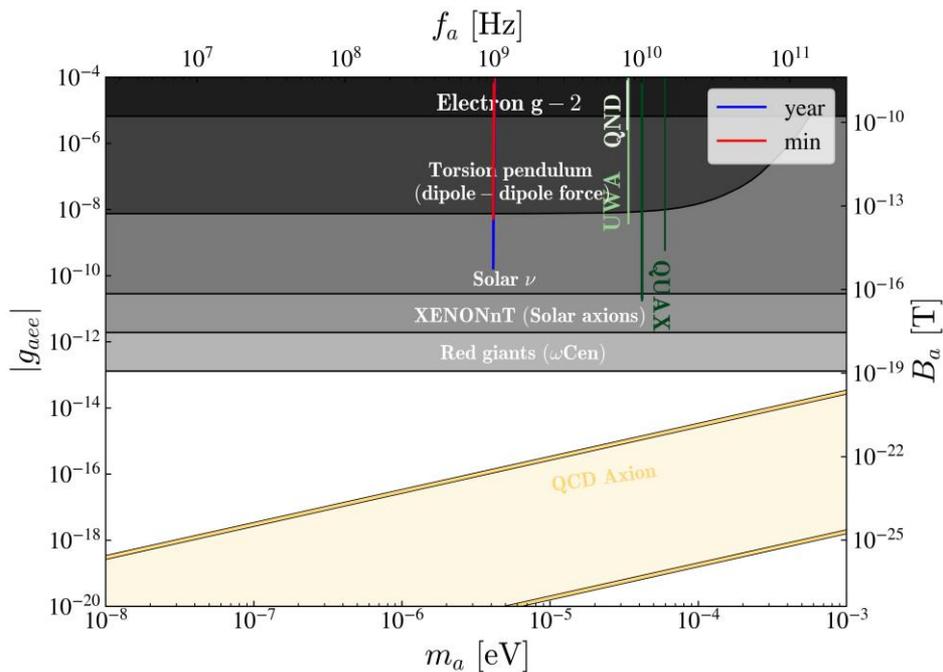$$\frac{\omega_L}{\gamma} = \sqrt{B_0^2 + B_z^2}$$

- 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
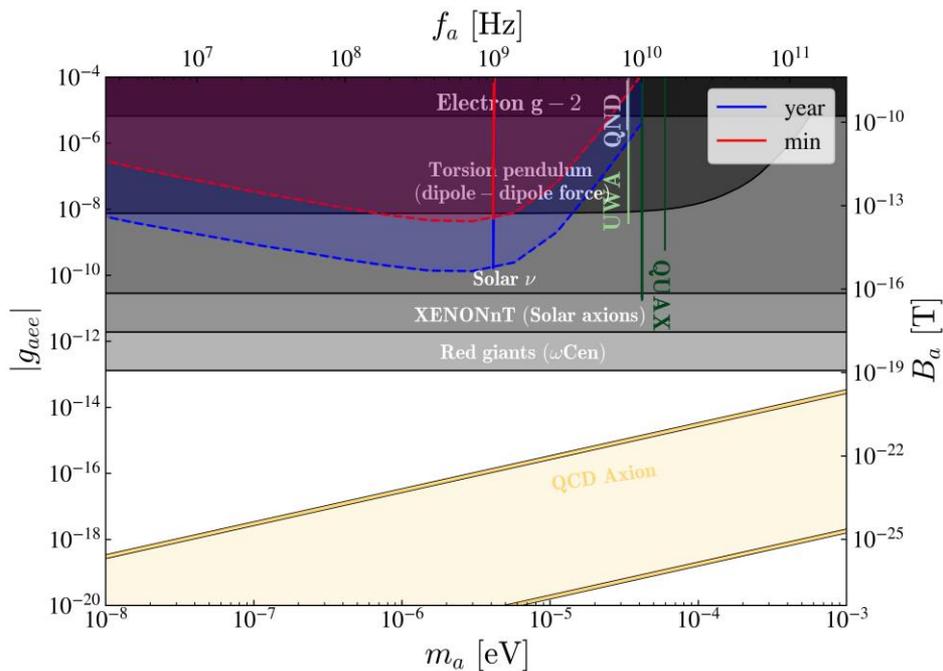
- Tune B_0 to find optimal value

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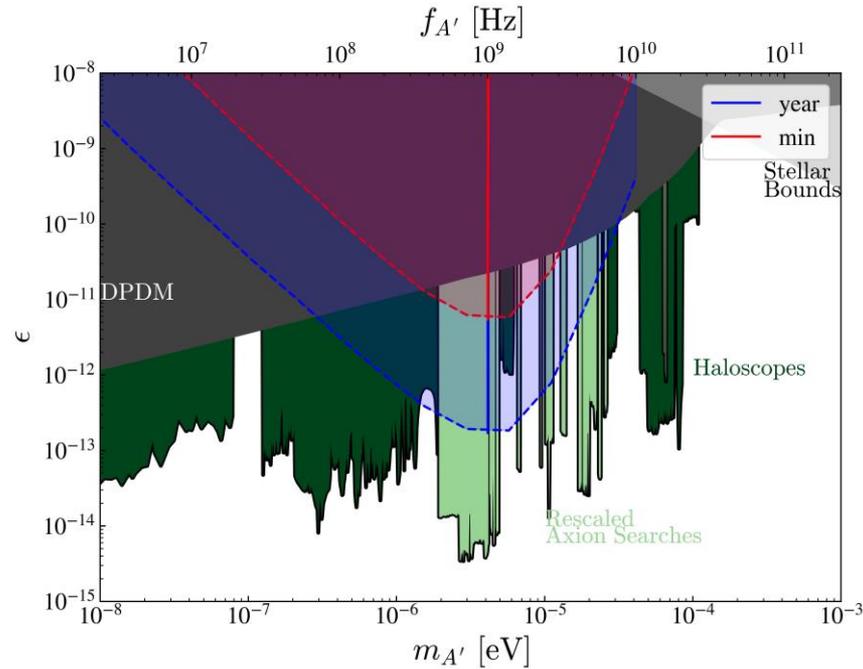
Axion-Electron Coupling

Axion-Electron Coupling

Dark Photon Kinetic Mixing Parameter

Conclusion

- Axion detection can be formulated as a magnetometery 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!