New Axion-Induced Effects in Mechanical Quantum Sensors

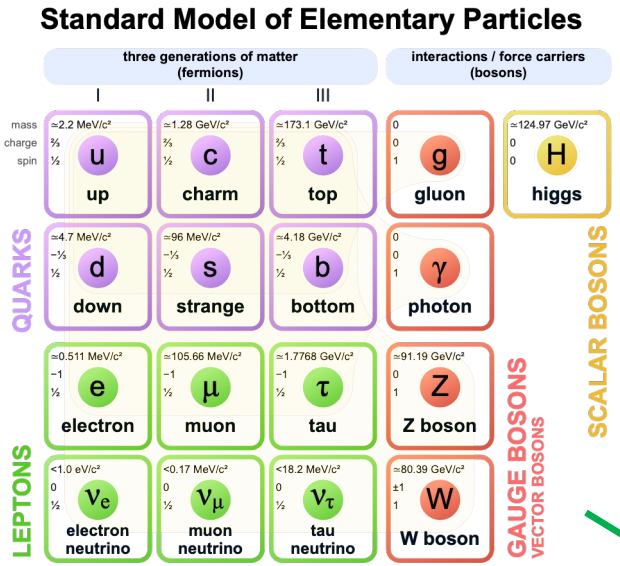
Felix Yu (JGU Mainz)
with Louis Hamaide (JGU Mainz, Humboldt Research Fellow)
Based on arXiv:2611.soon

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Cluster of Excellence PRISMA++ Precision Physics, Fundamental Interactions and Structure of Matter

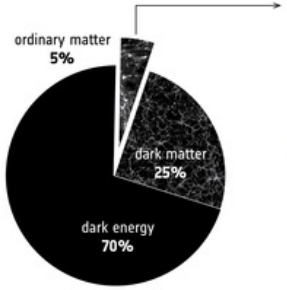
DISCRETE 2026, U. Cornelius, Bratislava
November 14, 2026

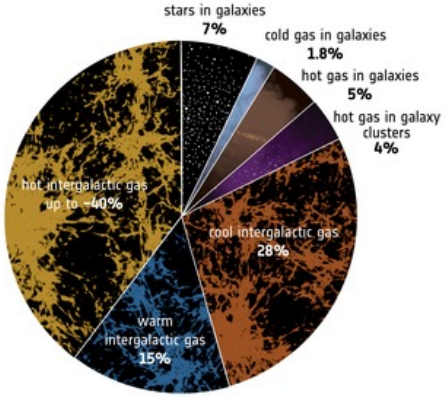
With the **SM** now **complete**, we are on a global hunt for **New Physics**



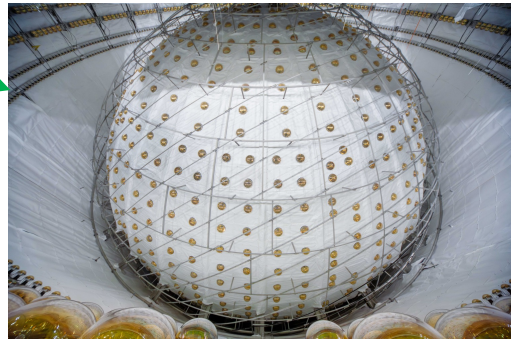
+ many more

DM, DE





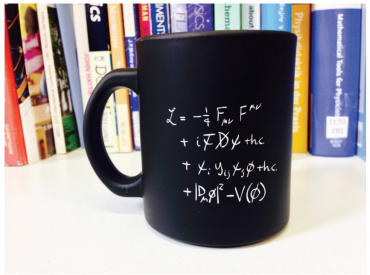
Origin of vs



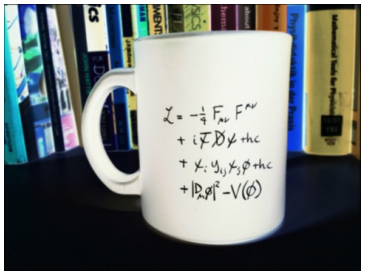
Baryon asymmetry

New particles, new interactions





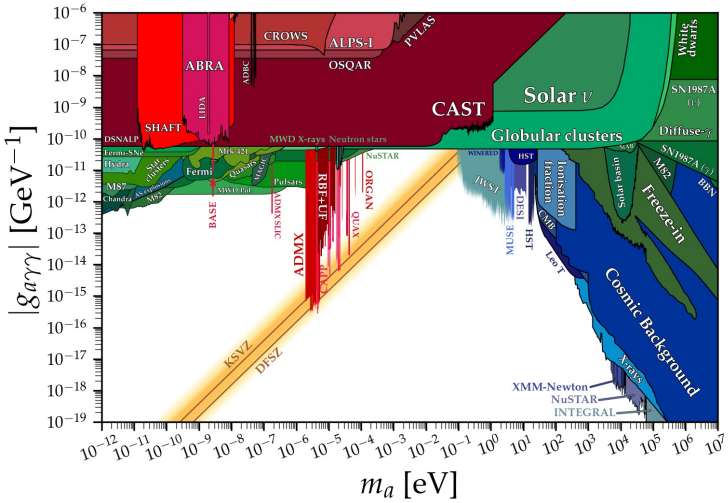
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Axions and axion-like particles (ALPs) are prime candidates for BSM "tabletop" experiments

Motivations include connections to strong CP*, **, ULDM candidates, generic predictions from moduli spaces

Today's main question: How to design search strategies and propose experiments covering the orders of magnitude in possible couplings and masses?

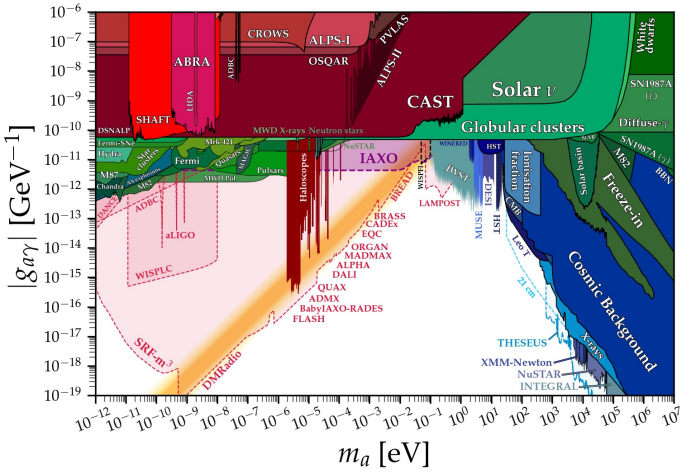


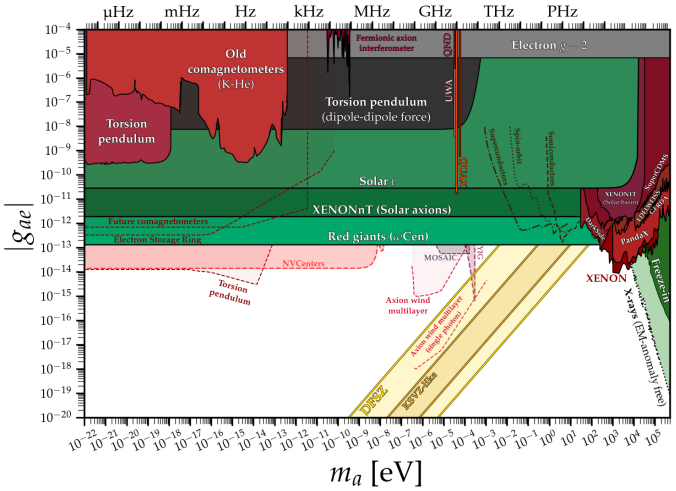
C. O'Hare, AxionLimits

*Non-vanilla models: Kivel, Laux, FY, JHEP 11 (2022) 088, [2207.08740]; Elahi, et. al. PRD 108 (2023) 3, [2301.08760]

**But also see Ai, Cruz, Garbrecht, Tamarit, Phys. Lett. B 822 (2021) 136616, [2001.07152]; upcoming talk by Björn Garbrecht

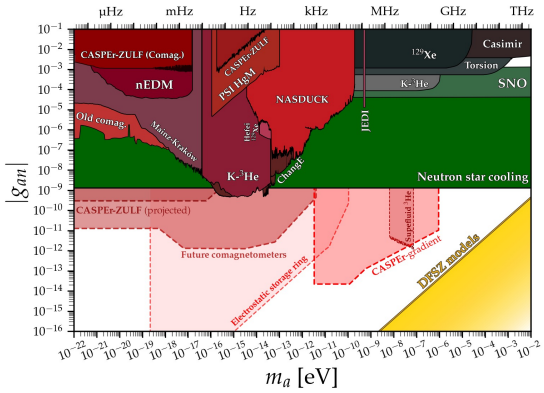
Relevant for all possible effective couplings

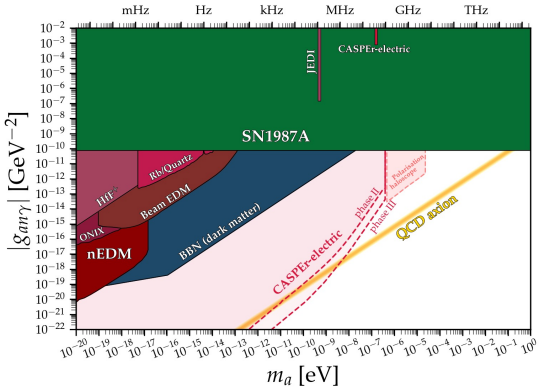


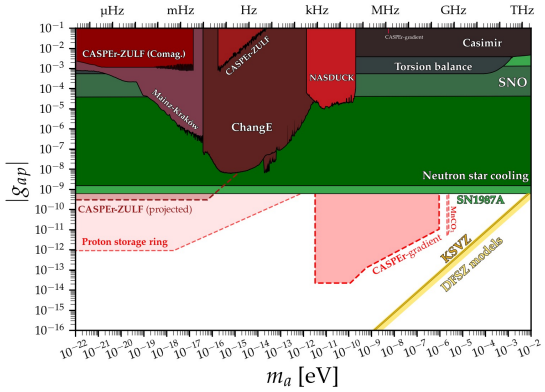


Remark: Relic abundance assumptions not equally required or assumed

C. O'Hare, AxionLimits







Rapid advancements in quantum sensors have impressive future sensitivity reach

Can new ideas and technologies provide even better reach?

Axion/ALP Lagrangian

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \sum_{f=e,p,n}\left(\overline{\psi}_f\, i\not{D}\,\psi_f + m_f\overline{\psi}_f\psi_f\right) + \frac{1}{2}\left(\partial_\mu a\right)^2 - \frac{1}{2}m_a^2 a^2$$
$$+ \sum_{f=e,p,n}\left(g_f\,\partial_\mu a\,\overline{\psi}_f\,\gamma^\mu\gamma^5\psi_f\right) - i\frac{g_d}{2}\sum_{f=p,n}\left(a\overline{\psi}_f\,\sigma_{\mu\nu}\gamma^5\psi_f F^{\mu\nu}\right) + g_{a\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}$$

Work at effective scale with electrons, protons, neutrons, and photons as relevant SM dofs

Main signal: probe the ambient DM background via effects on quantum sensors (devices with very low noise thresholds)

Number occupancy for ULDM is very high, given ρ ~ 0.4 GeV/cm^3 and v_{DM} ~ 10^{-3}

$$n = \frac{\rho_{\rm DM}}{m_a^4 v_a^3} \sim 10^{15}\left(\frac{1\ \text{meV}}{m_a}\right)^4$$

Focus on mechanical quantum sensors to do “direct detection” at the ULDM level

- *Mechanical* = think classical forces and torques
- *Quantum* = think noise approaching standard quantum limit (SQL)

The background axion classical field, via couplings to spins of electrons/protons/neutrons, imparts momentum transfer to a macroscopic sensor (μg scale)

- As a result, the (trapped) sensor will experience COM translational motion and rotational motion – idealized harmonic oscillator
- The time-dependent axion field $a(t) = a_0 \cos(m_a t)$ dictates a “driving” force or torque that can be coherently constructive

Microscopic Lagrangian to macroscopic Hamiltonian

Construct the appropriate effective EOM for the macroscopic sensor from the relativistic Lagrangian via two main steps

Non-relativistic fermion expansion (Foldy-Wouthuysen transformation)

Foldy, Wouthuysen, Phys. Rev. 78 (1950)

$$H_{\rm int} \simeq \frac{g_f}{2m_f}\left\{\partial_t a,\, \vec{P}\cdot\vec{\sigma}\right\} - g_f\left(\vec{\nabla}a\cdot\vec{\sigma} + \frac{1}{4m_f^2}\left(\left\{\vec{P}^{\,2},\, \vec{\sigma}\cdot\vec{\nabla}a\right\} - 2(\vec{P}\cdot\vec{\nabla}a)(\vec{P}\cdot\vec{\sigma})\right)\right)$$

$$- g_d\, a\,\vec{\sigma}\cdot\vec{E} - g_d\,\frac{a}{2m_f}\vec{\sigma}\cdot\left(\vec{B}\times\vec{P} - \vec{P}\times\vec{B}\right)\,, \qquad \vec{P} = \vec{p} - q_{\rm eff}\vec{A}$$

Linearity assumption for the quantum sensor Hamiltonian (leading effect of the many-body quantum system)

$$\vec{x} = \frac{1}{N_f}\sum_i \vec{x}_i \qquad \vec{p} = \sum_i \vec{p}_i \qquad \vec{\sigma} = \sum_i P_f\,\vec{\sigma}_i = P_f N_f\,\vec{\sigma}_f$$

Axion-induced effects in EOMs

Translate less-studied fermion/EDM axion couplings into mechanical observables

Torques

- Ferromagnetic spins are locked to the lattice
- Axion wind generates an oscillating torque and angular motion

Forces

- In paramagnetic systems, spatial polarization gradients turn axion-spin interactions into translational forces

Frequency shifts

- Axion interaction acts as a time-dependent spring constant, shifting the mechanical resonance frequency

Consider one coupling at a time and calculate each EOM

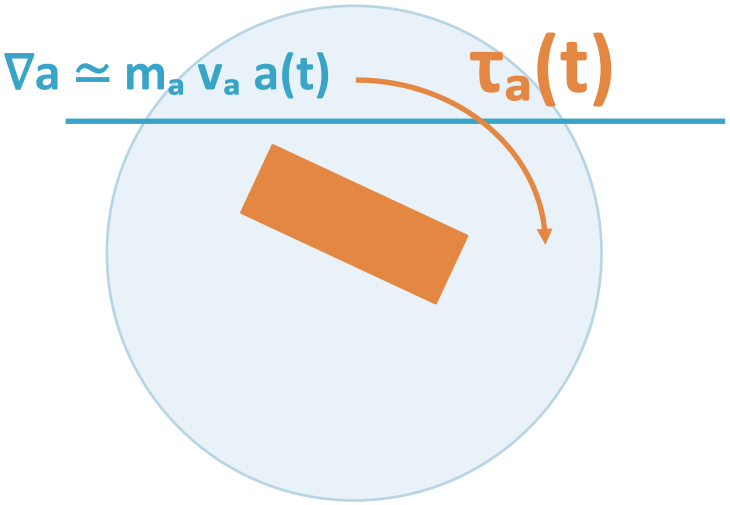
Axion wind can *torque* a ferromagnet

$$-g_f \left(\vec{\nabla} a \cdot \vec{\sigma}\right) \text{-induced effects} - \text{ferromagnets}$$

Sensor angular orientation (magnetization) experiences an oscillating wiggle

$$I\ddot{\theta} + I\gamma_\theta \dot{\theta} + I\Omega_\theta^2 \theta + g_e PN m_a v_a a(t)\, \sigma_x(t) \sin\theta = \tau_N(t) \ ,$$

$$\tau_a(t) = g_e PN m_a v_a a(t) \sigma_x$$



Consider one coupling at a time and calculate each EOM

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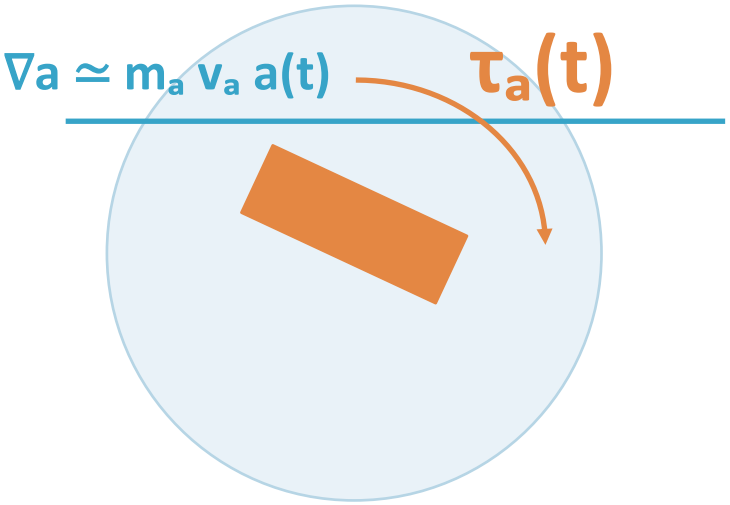
$$\tau_a(t) = g_e P N m_a v_a a(t) \sigma_x$$

Homodyne vs. heterodyne

If the axion frequency is too slow, we can flip the magnetization to *heterodyne* the signal

Allows access to the axion signal even if we are not on resonance

$$\Omega_\pm = \Omega_\theta \pm \omega_a$$



Axion-induced effects in EOMs – forces

Can also study EOM of center of mass motion

$$-g_f \left(\vec{\nabla} a \cdot \vec{\sigma}\right)\text{-induced effects – paramagnetic materials}$$

Here, we can employ a large polarization gradient of spins to enhance the axion signal

$$m\ddot{x} + m\gamma\dot{x} + m\Omega^2 x + g_f m_a v_a a(t)\sigma_x(\vec{x}(t))\frac{\partial P(\vec{x}(t))}{\partial x}N = F_N(t)$$

$$F_a(t) = g_f m_a v_a a(t)\sigma_x(\vec{x}(t))\frac{\partial P(\vec{x}(t))}{\partial x}N$$

Axion-induced effects in EOMs – EDMs

Study the COM motion for the EDM coupling

$$g_d\, a(t)\, \vec{\sigma} \cdot \vec{E}\text{-}induced\ effects$$

Corresponding EOM also scales with polarization gradient

$$m\ddot{x} + m\gamma\dot{x} + m\Omega^2 x + g_d\, N \frac{\partial}{\partial x}\left(a(\vec{x},t) P(\vec{x}) \vec{\sigma}(\vec{x}) \cdot \vec{E}\right) = F_N(t)$$

$$F_a(t) = \frac{g_d}{2} N a(t) \sigma_x(t) E_x \frac{\partial P(\vec{x}(t))}{\partial x}$$

Resulting signal power expression

$$S^a_{\mathrm{FF}}(\omega) = \frac{F_a^2(\omega_a)}{\max(\gamma, m_a v_a^2)}$$

Power comparison between signal and noise

As usual, study power spectrum of signal + noise in Fourier space

Integrate power ratios within giving frequency range dictated by integration time

$$\mathrm{SNR}_\tau(\omega_a, T_{\mathrm{coh}}) \equiv \frac{\sqrt{\int_{\delta\omega} S^a_{\tau\tau}(\omega) d\omega}}{\sqrt{\int_{\delta\omega} S^N_{\tau\tau}(\omega) d\omega}} \simeq \frac{\tau_a(\omega_a)}{\sqrt{S^N_{\tau\tau}(\omega_a)/T_{\mathrm{coh}}}}$$

$$\mathrm{SNR}_{\mathrm{F}}(\omega_a, T_{\mathrm{coh}}) \equiv \frac{\sqrt{\int_{\delta\omega} S^a_{\mathrm{FF}}(\omega) d\omega}}{\sqrt{\int_{\delta\omega} S^N_{\mathrm{FF}}(\omega) d\omega}} \simeq \frac{\mathrm{F}_a(\omega_a)}{\sqrt{S^N_{\mathrm{FF}}(\omega_a)/T_{\mathrm{coh}}}}$$

$$\delta\omega = 1/T_{\mathrm{int}}$$

$$N_T \equiv T_{\mathrm{int}}/T_{\mathrm{coh}} > 1$$

Simplify integrals by assuming “top-hat” signal response, adjust integration time to be 50 coherence times (axion-mass dependent)

Relevant frequency band depends on resonant quality factor or signal width (in frequency units)

$$\delta\omega \leq 1/T_{\mathrm{coh}} = \max(\gamma, m_a v_a^2) \qquad Q^{-1} = \gamma/\Omega \ll 1$$

On-resonance SQL vs. off-resonance SQL

When we are on-resonance, the signal only lives in a narrow bandwidth of γ and the **noise** power is lower

$$S^N_{\mathrm{FF}}(\omega_a) = m\gamma\,\omega_a \qquad S^N_{\tau\tau}(\omega) \simeq I\gamma\Omega \qquad \Omega = \omega_a$$

A wide axion scan therefore requires many narrow frequency bins

If we are off-resonance SQL, then there is a higher noise power

$$S^N_{\mathrm{FF}}(\omega_a) = m\omega_a^2 \qquad S^N_{\tau\tau}(\omega) \simeq I\omega^2$$

But it is broadband and highly tunable for a trapped sensor

Thus, broadband off-resonance SQL is a competitive baseline (given the orders of magnitude of coverage necessary)

For terrestrial experiments, are limited by the seismic noise, so adopt

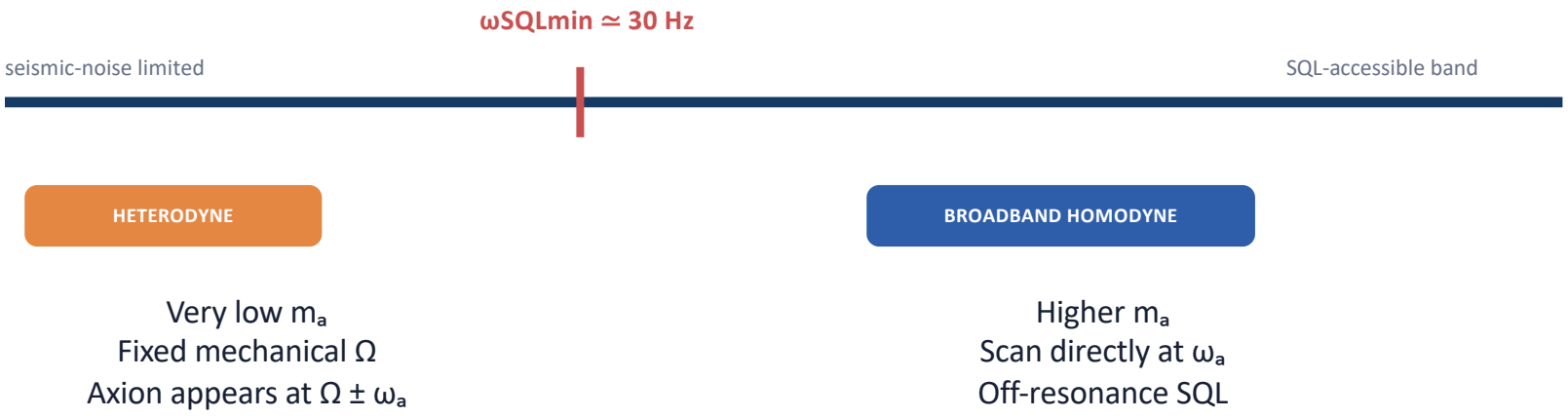
$$\omega^{\mathrm{min}}_{\mathrm{SQL}} \simeq 30\ \mathrm{Hz}$$

On-resonance SQL vs. off-resonance SQL

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For terrestrial experiments, are limited by the seismic noise, so adopt

$$\omega_{\rm SQL}^{\rm min} \simeq 30 \text{ Hz}$$



Optimal sensor design corresponds to each coupling and must account for engineering challenges (traps, thermal considerations, phonon absorption and heat dissipation, etc.)

Electron coupling

Ferromagnetic sensor

Large electron polarization
Torque readout is natural
Magnetization flipping enables heterodyne searches

Heating / Curie temperature matters

Proton coupling

Paramagnetic sensor

External B-field polarizes nuclear spins
Spatial polarization gradients generate forces

Cryogenic operation can increase polarization

EDM coupling

NMR-active / ferroelectric material

Internal E-field plus proton polarization
Mechanical cooling to ~10 mK prioritized

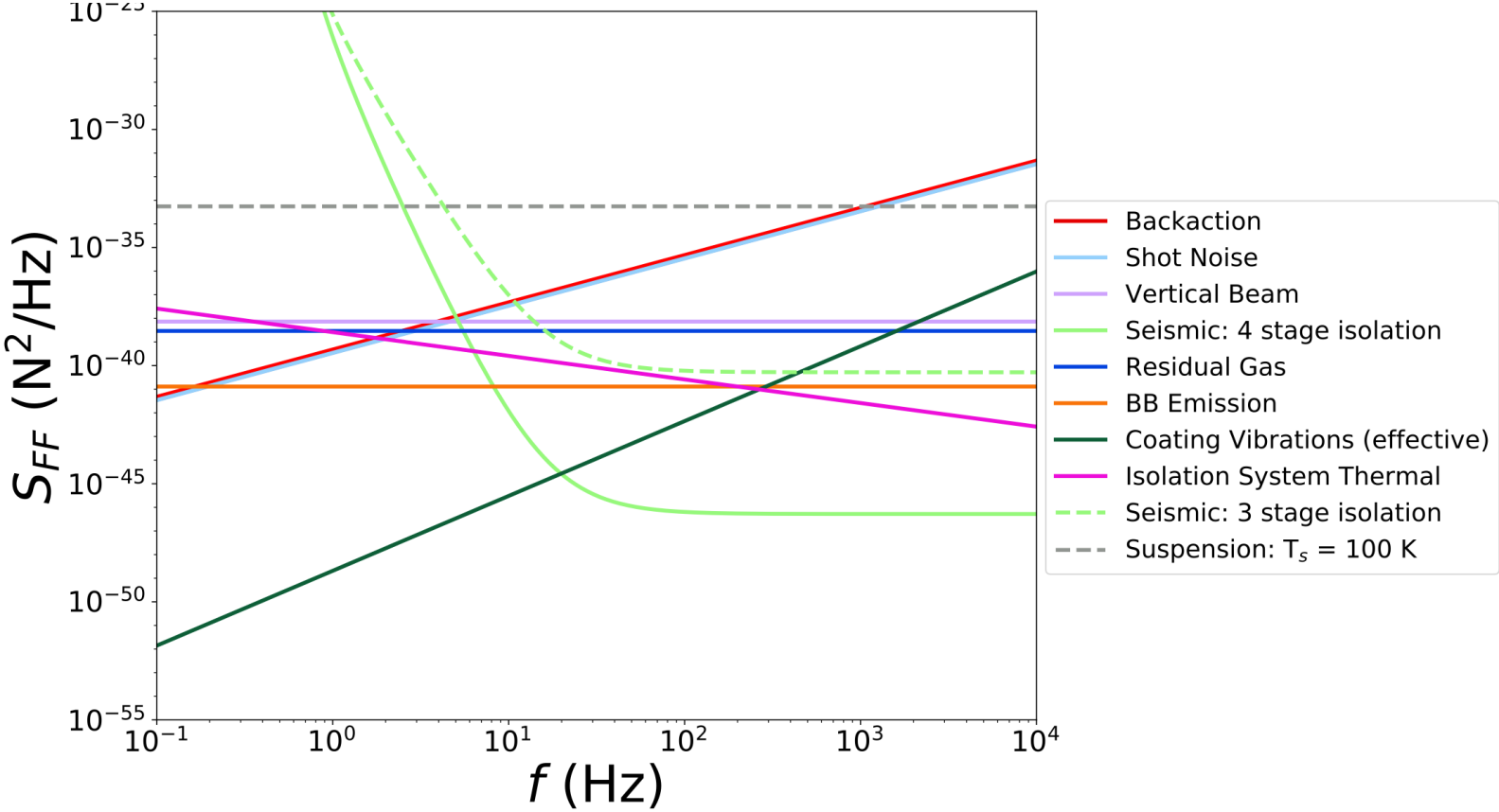
Force and frequency-shift channels

Systematic treatment of noises in analogy with the MOLeQuTE proposal

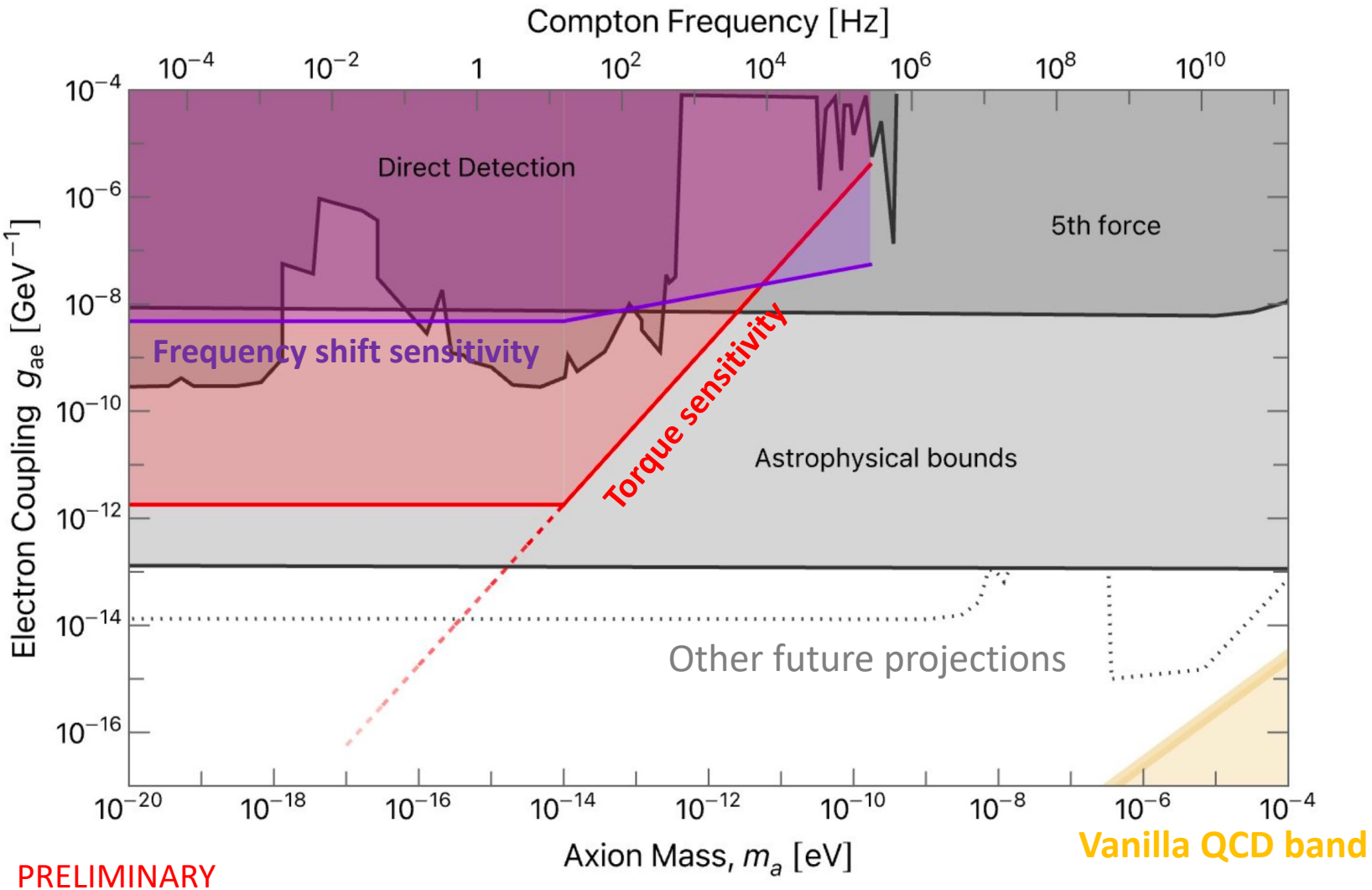
Phys. Rev. Res. **8** (2026) 4, 043086 [2512.00166]

Searching for Ultralight Dark Matter with MOLeQuTE: a Massive Optically Levitated Quantum Tabletop Experiment

Louis Hamaide,[1,2,*] Hannah Banks,[3,4] Peter Barker,[5] and Andrew A. Geraci[6]

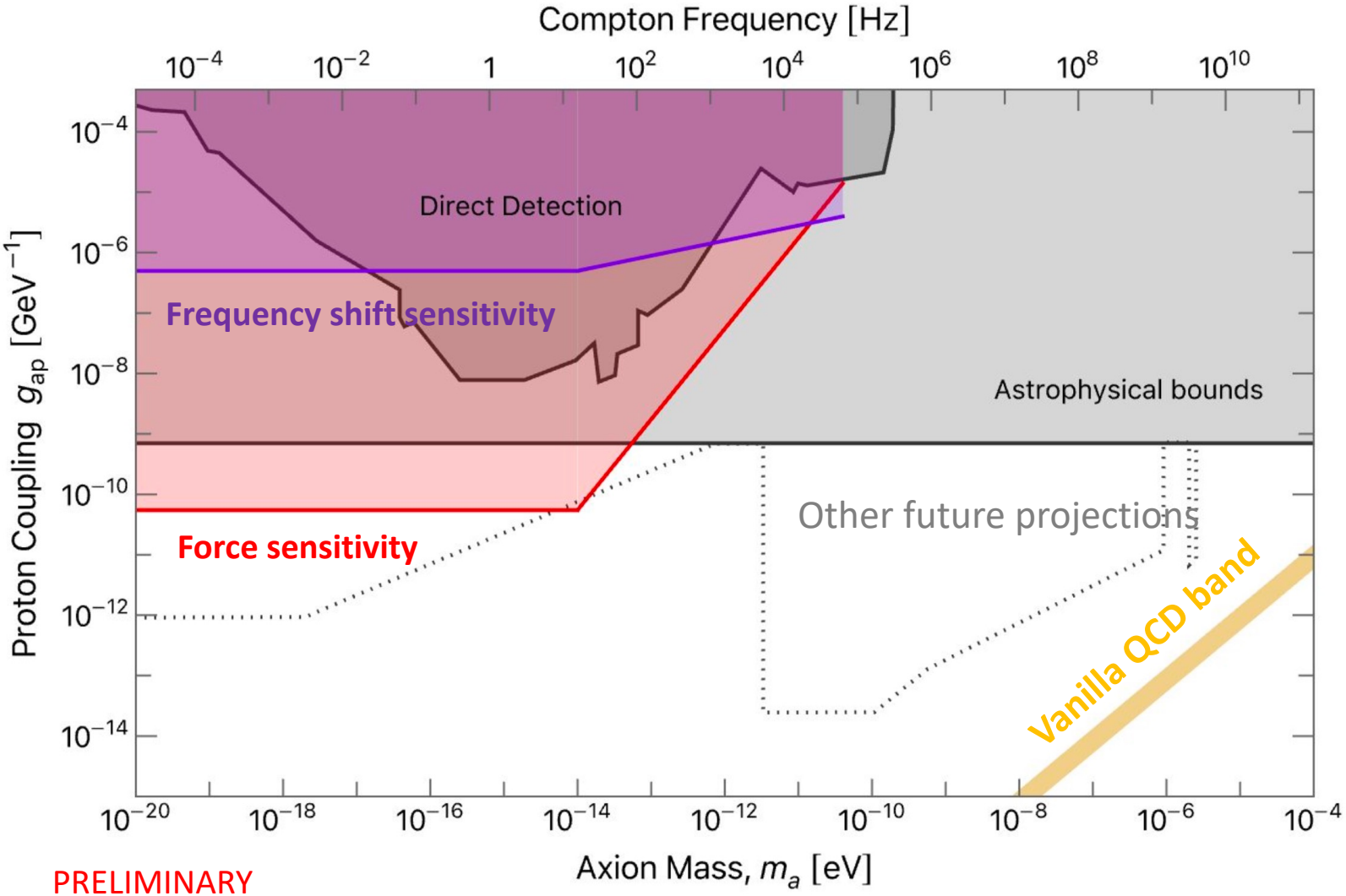


Electron Coupling projections



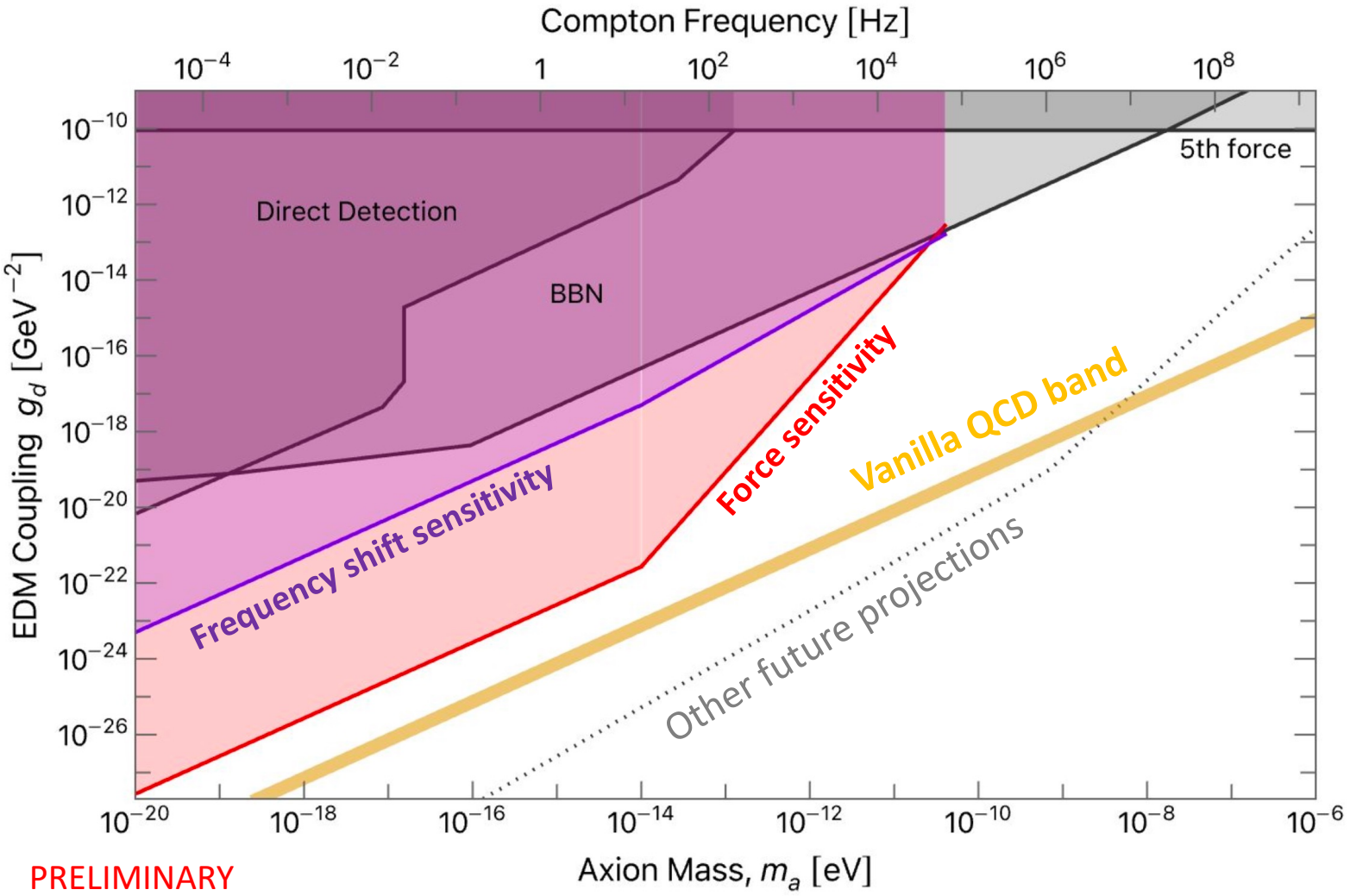
PRELIMINARY

Proton Coupling projections



PRELIMINARY

EDM Coupling projections



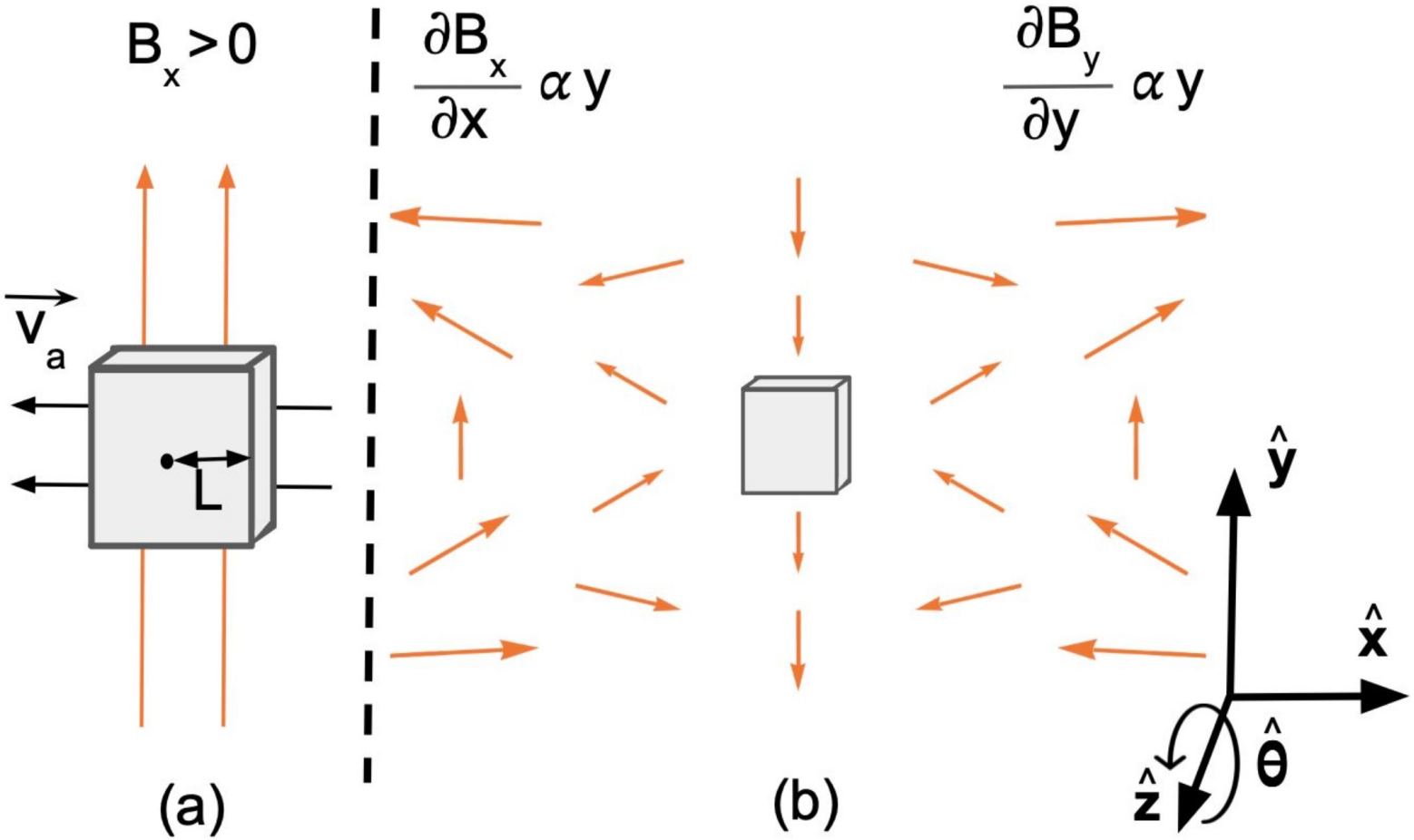
PRELIMINARY

Conclusion and outlook

We can achieve broadband sensitivity to several axion couplings using mechanical quantum sensors and a mix of homodyne and heterodyne search strategies

Further improvements on noises are also possible (space-based quantum sensors, material optimization to avoid heating)

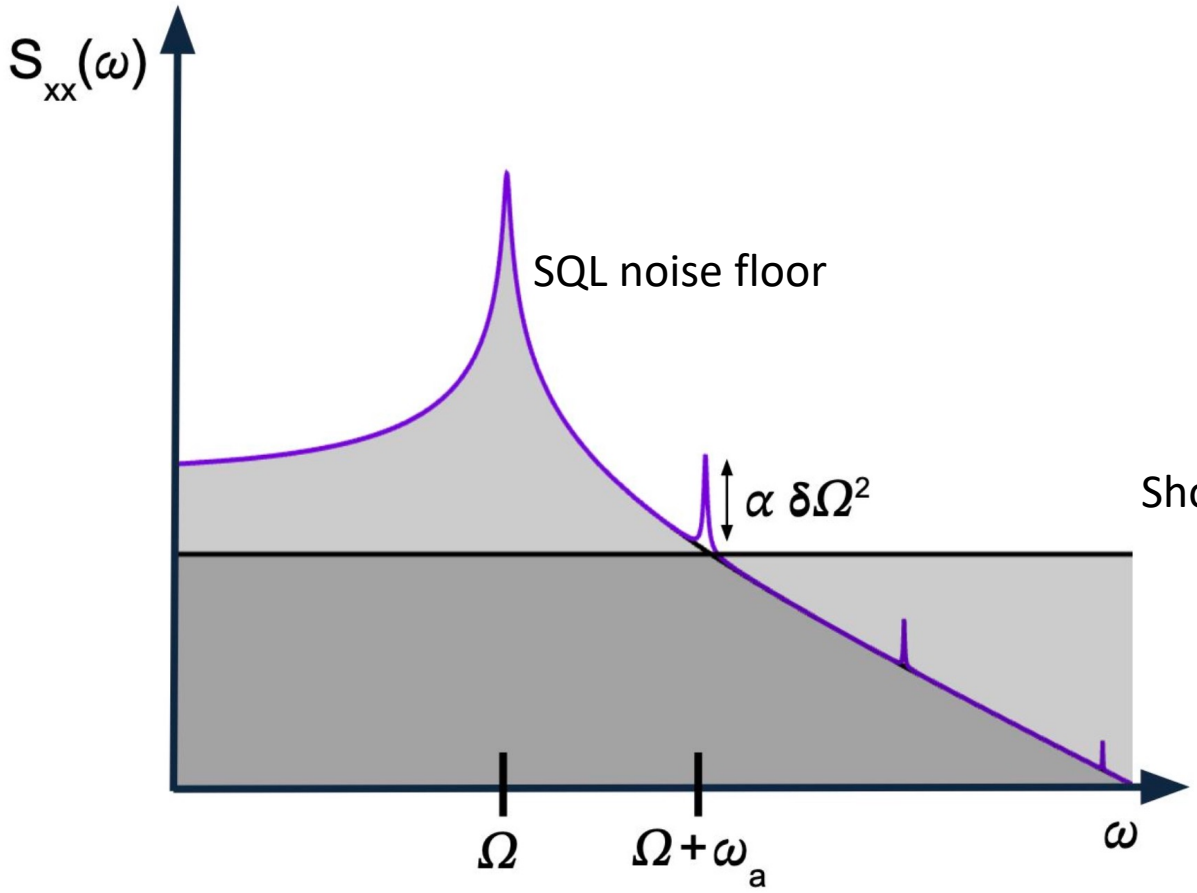
Quantum noise 3D projections and trapping



Signal response for frequency shifts

Experimenter-defined challenge to adjust mechanical frequency Ω

Focus on $\omega_a > \gamma$



Axion-induced effects in EOMs – more terms in Hamiltonian

Similar story for other couplings

$$\frac{g_f}{m}\partial_t a\,(\vec{p}\cdot\vec{\sigma})\text{-}induced\ effects\ -\ paramagnetic\ materials$$

Becomes subleading because of extra velocity suppression

$$m\ddot{x} + m\gamma\dot{x} + m\Omega^2 x - g_f m_a N a(t) v_y(t)\sigma_x(\vec{x}(t))\frac{\partial P(\vec{x}(t))}{\partial y} + \mathcal{O}(m_a^2) = F_N(t)$$

$$F_a(t) = g_f m_a a(t) N v_y \sigma_y(\vec{x}(t))\frac{\partial P(\vec{x}(t))}{\partial x}$$