Spin-Based Magnetometers: An introduction

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CERN & Technion
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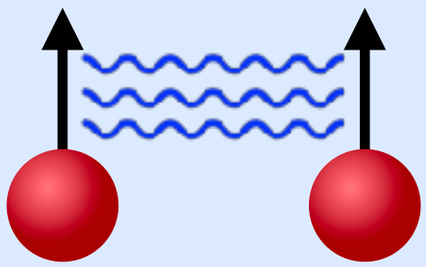
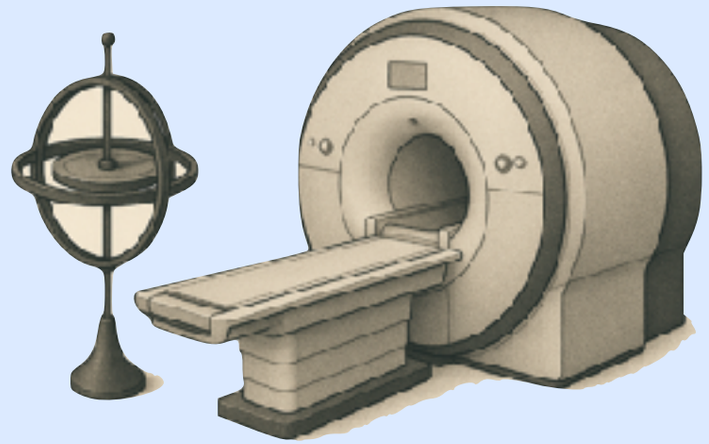
Prologue: Applications of Spin-Based-Systems

(1) Quantum Information



(2) Measuring “Real” Things



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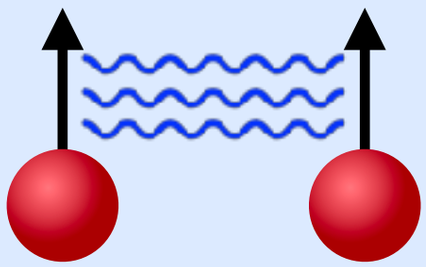

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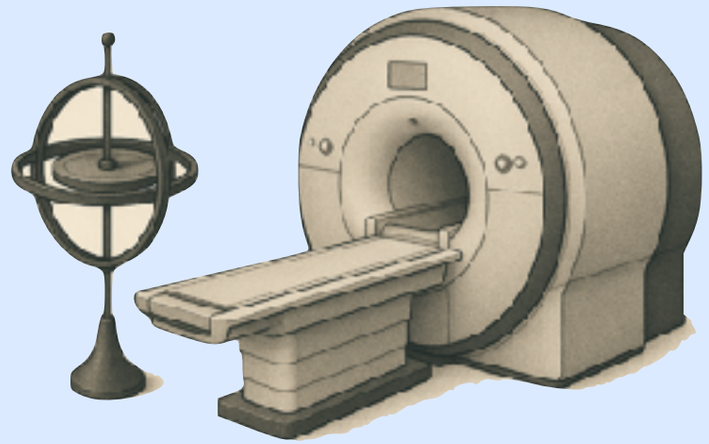

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- (more)

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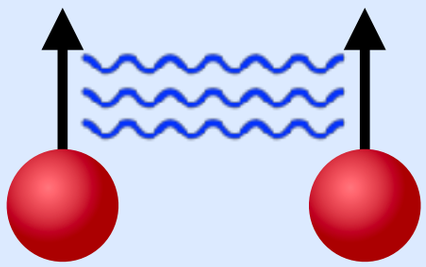

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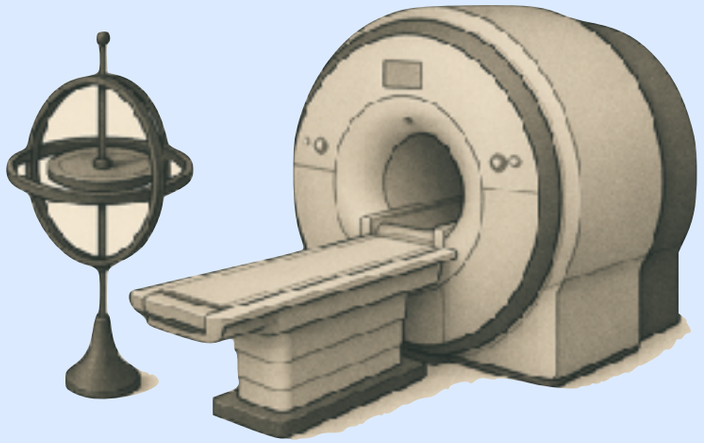

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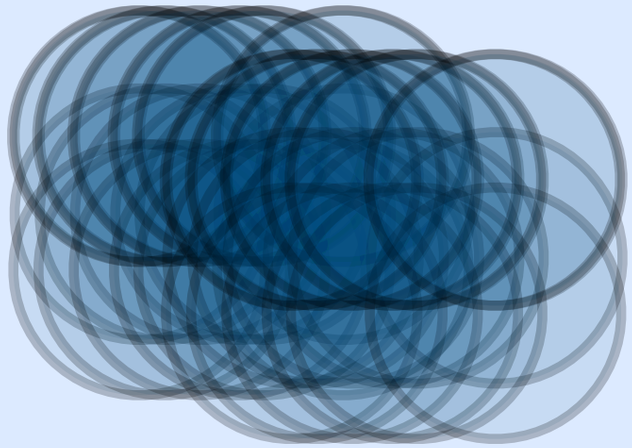

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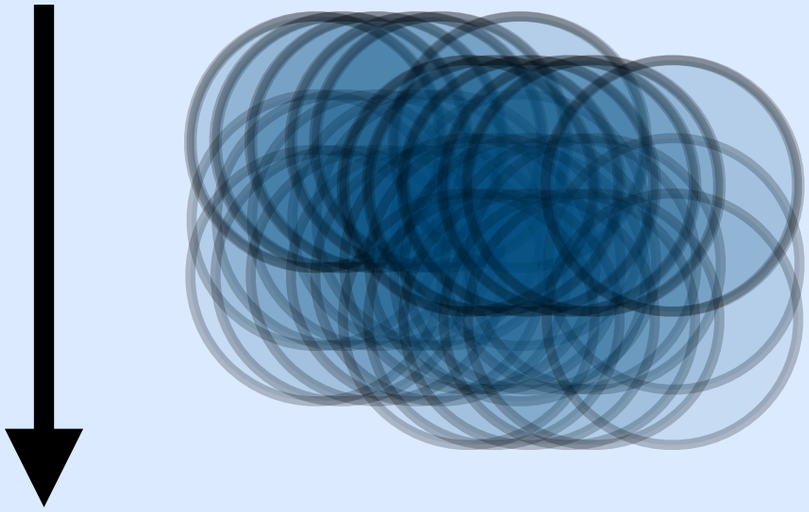

(overlapping particles)

$$a = a_0 \cos(E_{\rm DM} t - \vec{k}_{\rm DM} \vec{x}) \approx a_0 \cos(m_{\rm DM} t)$$

Ultralight DM behaves like classical plane-waves!

(Mass and frequency are used interchangeably)

Axion-Like Particles Interaction with spins

$$\mathscr{L} = g_{a\psi\psi}\partial_\mu a \cdot \bar{\psi}\gamma^\mu\gamma_5\psi \rightarrow H = -\ \vec{b}_{a-\psi} \cdot \vec{S}_\psi + \ldots$$

$$\text{For DM}: \vec{b}_{a-\psi} = g_{a\psi\psi}\sqrt{2\rho_a}\cos(m_a t) \cdot \vec{v}_{a-\psi}$$ [astro-ph/9501042]

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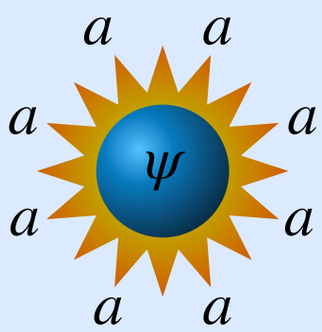

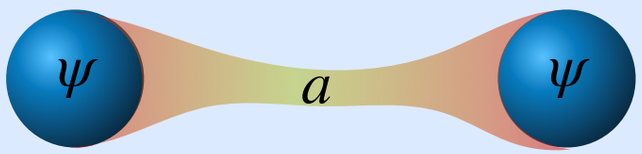

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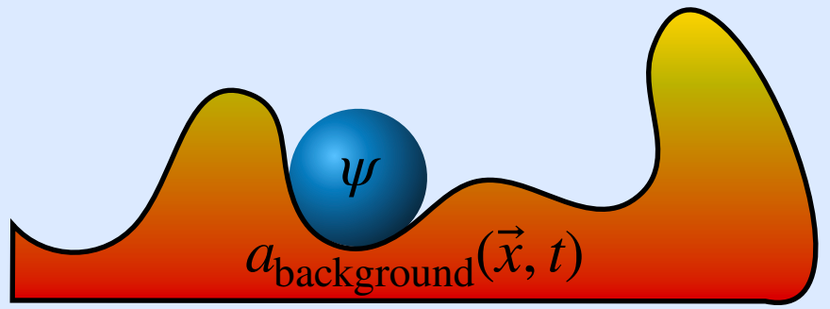

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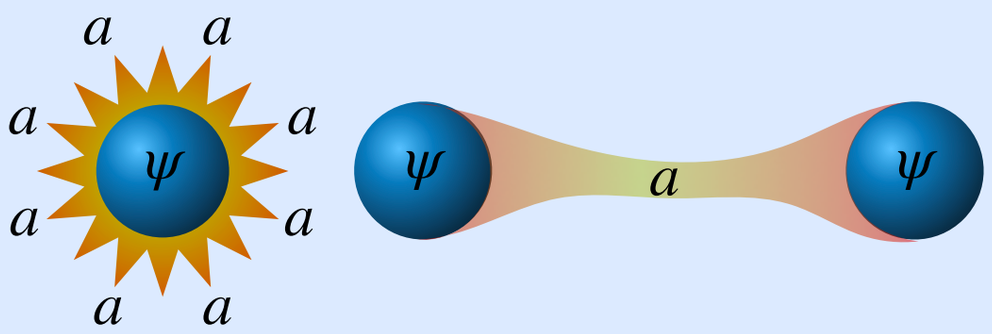

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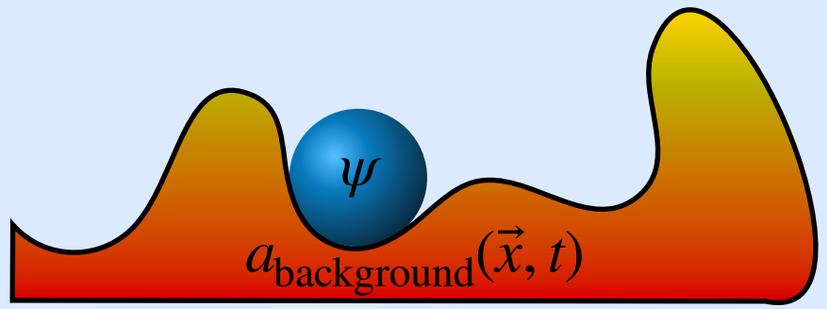

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$$(H_{zeeman} = -\gamma\vec{B}\vec{S})$$

Bloch Equations

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Describe the evolution of macroscopic spin systems

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$$\dot{\vec{S}} = \left(\gamma \vec{B} + \vec{b}\right) \times \vec{S}$$

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(generates transverse from longitudinal)

Decaying excitations

(causes stabilization)

Bloch Equations

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Pumping term: Creating macroscopic polarization
(generates a non-trivial steady state solution)

$$\dot{\vec{S}} = \left(\gamma\vec{B} + \vec{b}\right) \times \vec{S} - \Gamma\vec{S} + R\hat{z}$$

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Taking $S_z \gg S_x, S_y$, the $S_+ = S_x + iS_y$ equation is that of a damped driven harmonic oscillator, solved via a fourier transform,

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$$S_+(\omega = m_a) = \frac{b_\perp + \gamma B_\perp}{(\gamma B_z - m_a) + i\Gamma} S_z \quad \propto \frac{\text{signal} + \gamma \cdot \text{magnetic fields}}{\text{resonant detector with width}}$$

Giving us a linear resonant sensor.

Alternatively, one can measure the resonance frequency,

$\omega_L = \gamma B_z + b_z$.

Readout Schemes

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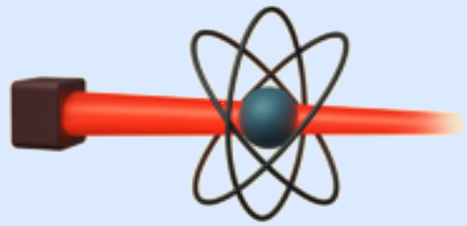
Optical: Using a laser beam, mostly through Faraday rotation, we can learn about the spin polarization



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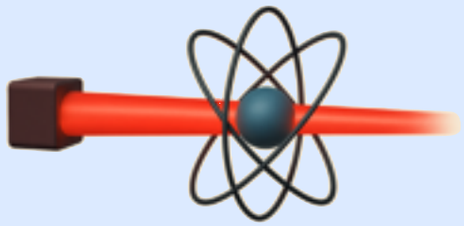
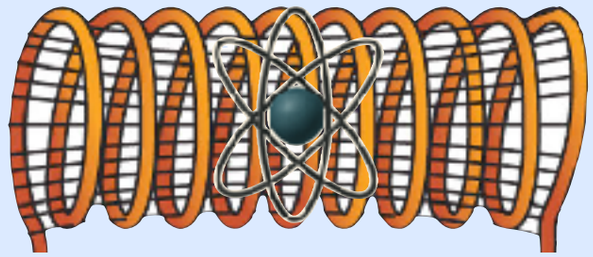


Auxillary magnetometer: a magnetometer measures the magnetization of the spin-sample:



Combined: One can use an optical magnetometer to read out a different magnetometer.

Fundamental Noise Sources

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Magnetic Noise:

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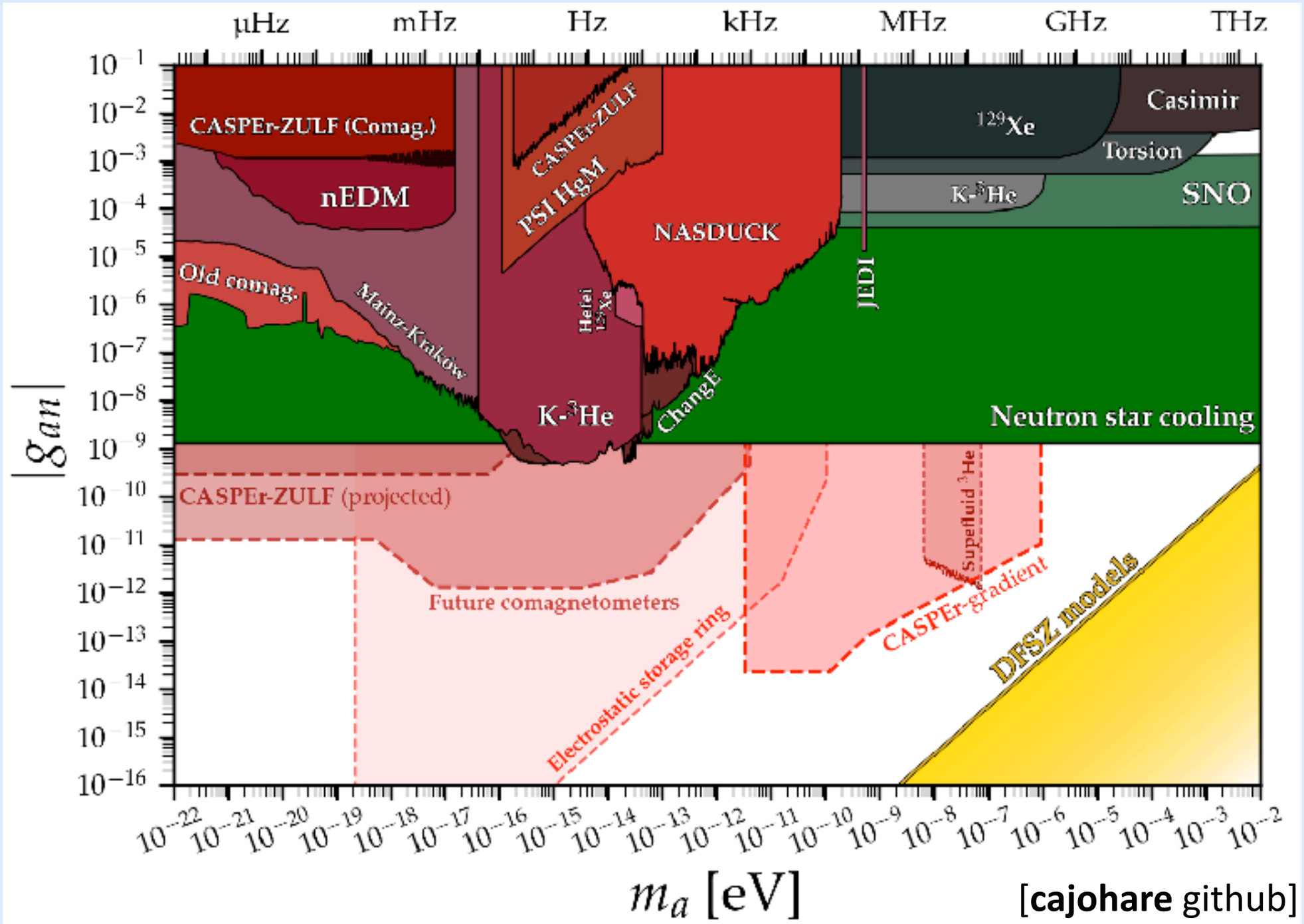
Atomic Shot Noise: Similar to the SQL, arises from measuring S_x in an S_z polarized system, with $[S_x, S_z] \neq 0$.

$$B_{\text{ASN}} \sim \frac{1}{\gamma S_z}\sqrt{\Gamma / N_{\text{spins}}}$$

Current Performances



[**cajohare** github]

Green=Astrophysical Constraints

Red Tinted Opaque Regions=Magnetometry Constraints

Red Shaded Regions = The Dreams of Theorists (Including Myself).

Other Regions=Terrestrial Non-DM Searches

Alkali-Noble Comagnetometer

(Currently) the most mature atomic magnetometer technology for BSM.

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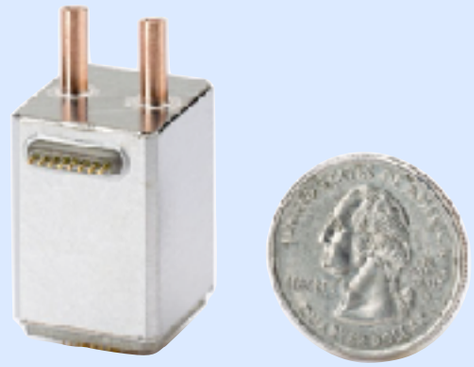

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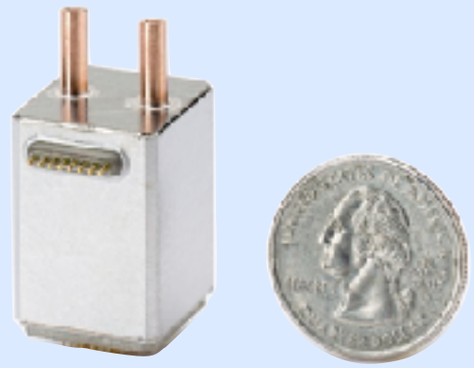

Hot vapor Alkali magnetometers are electron-based.
Dense nulcear-spin carrying Noble gasses have long lifetimes and low sensitivity to magnetic fields.

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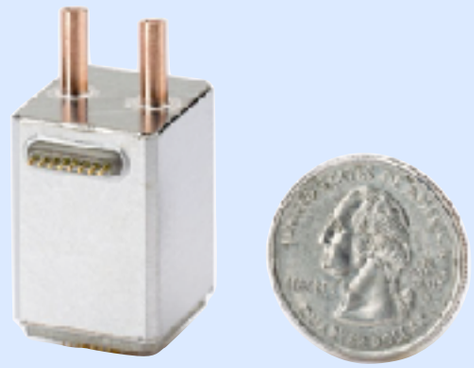

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Some examples of experiments using these are GNOME, ChangE, the Romalis Group, and…

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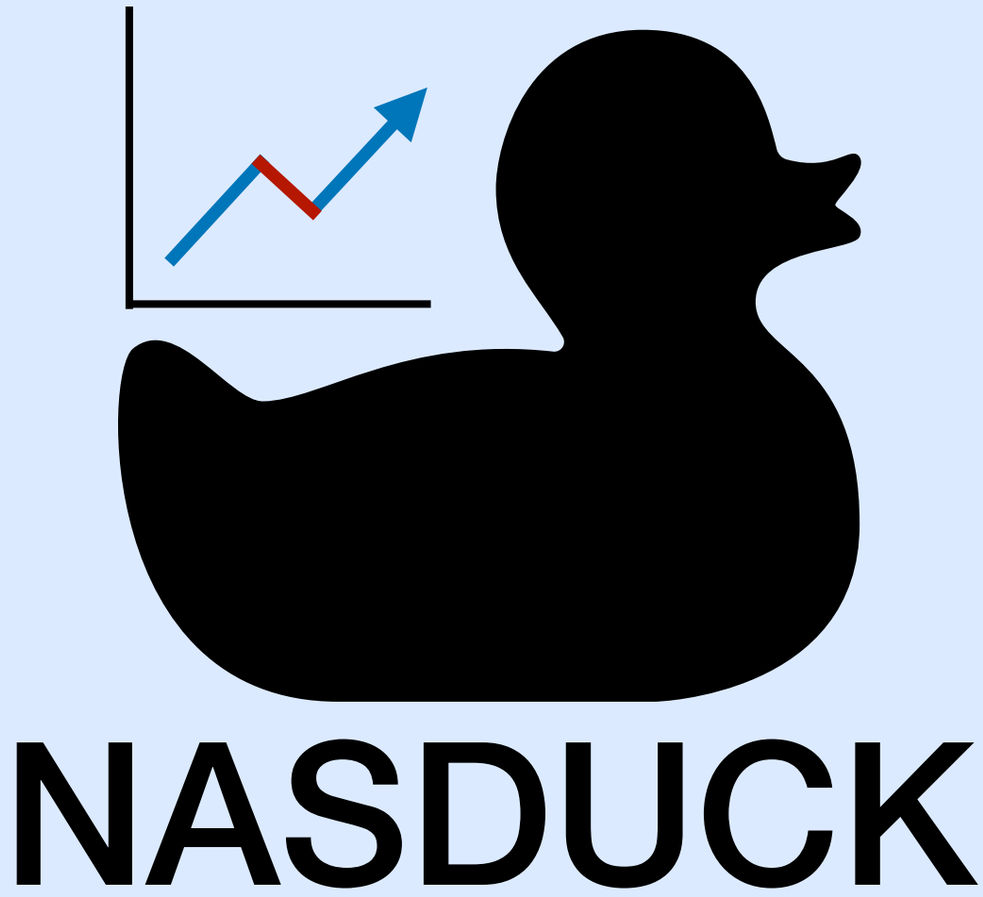

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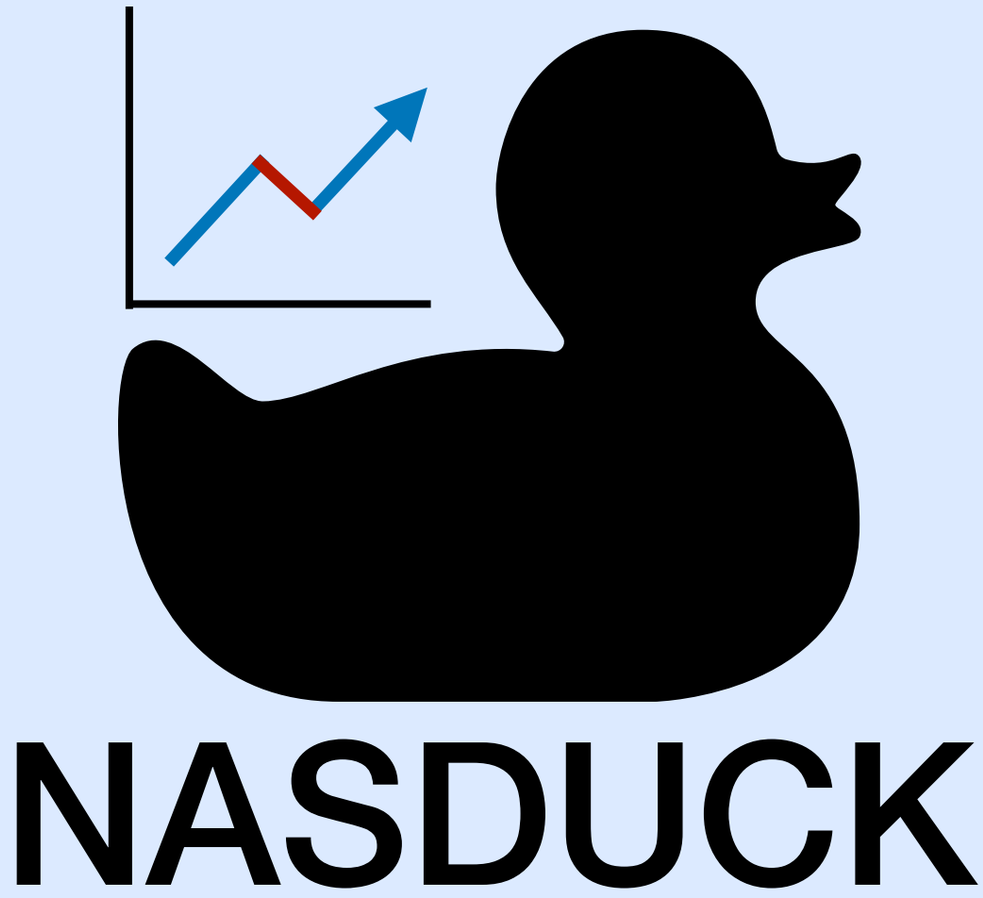

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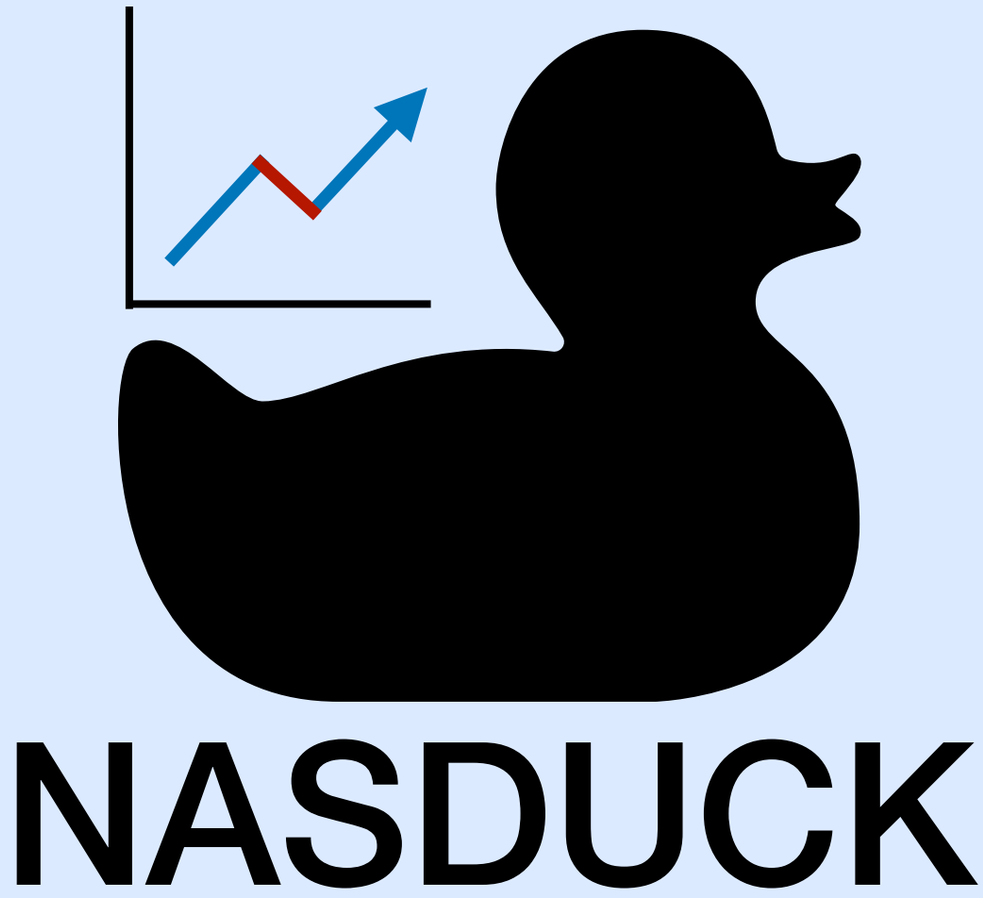

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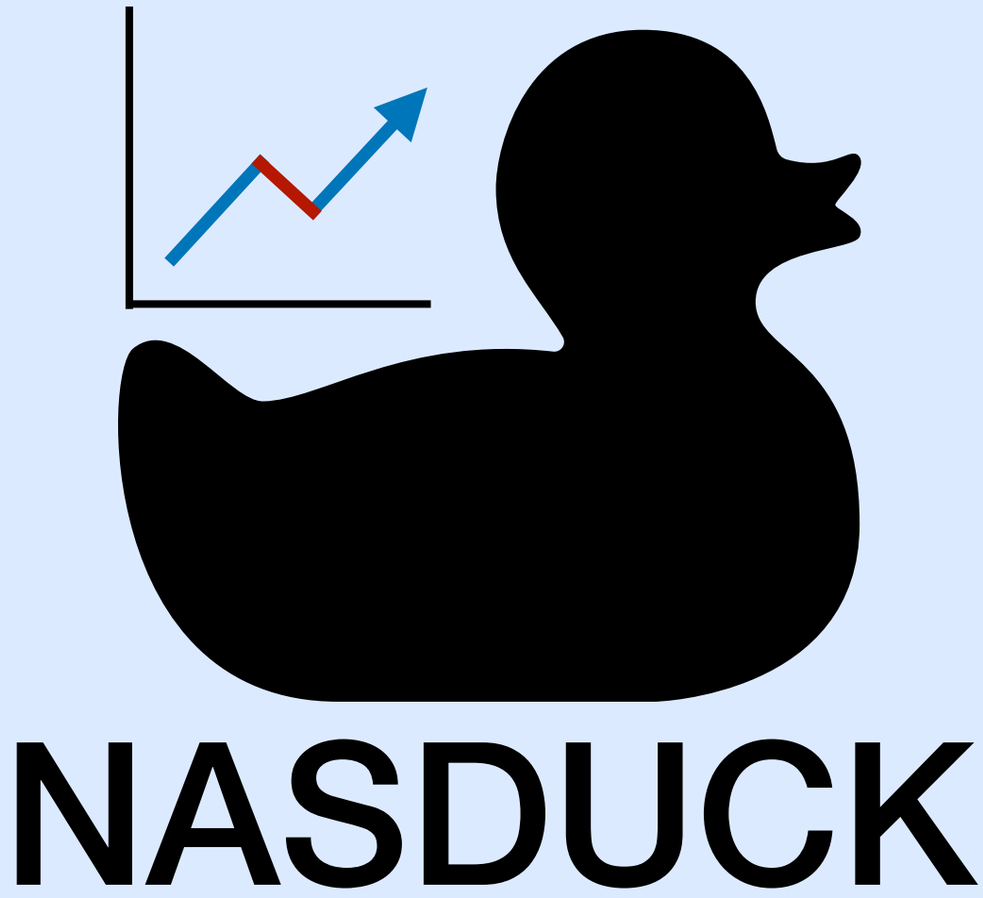

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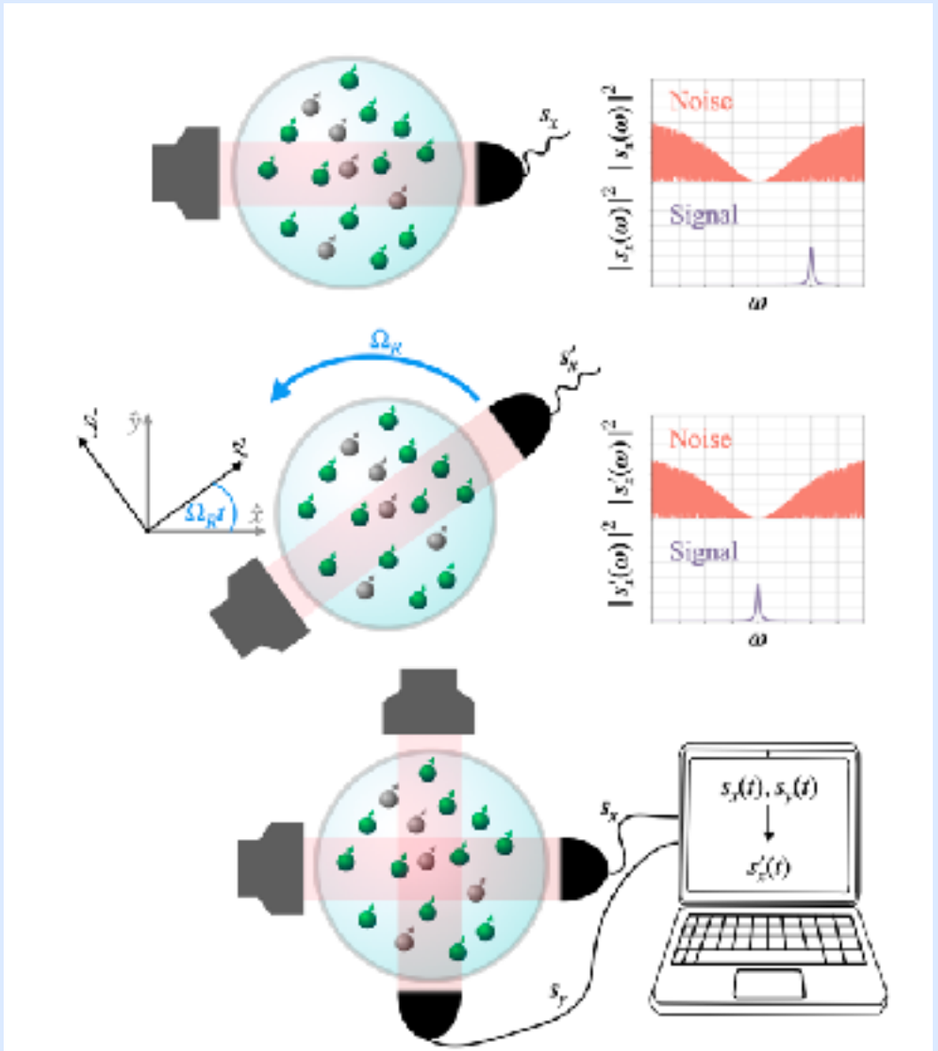
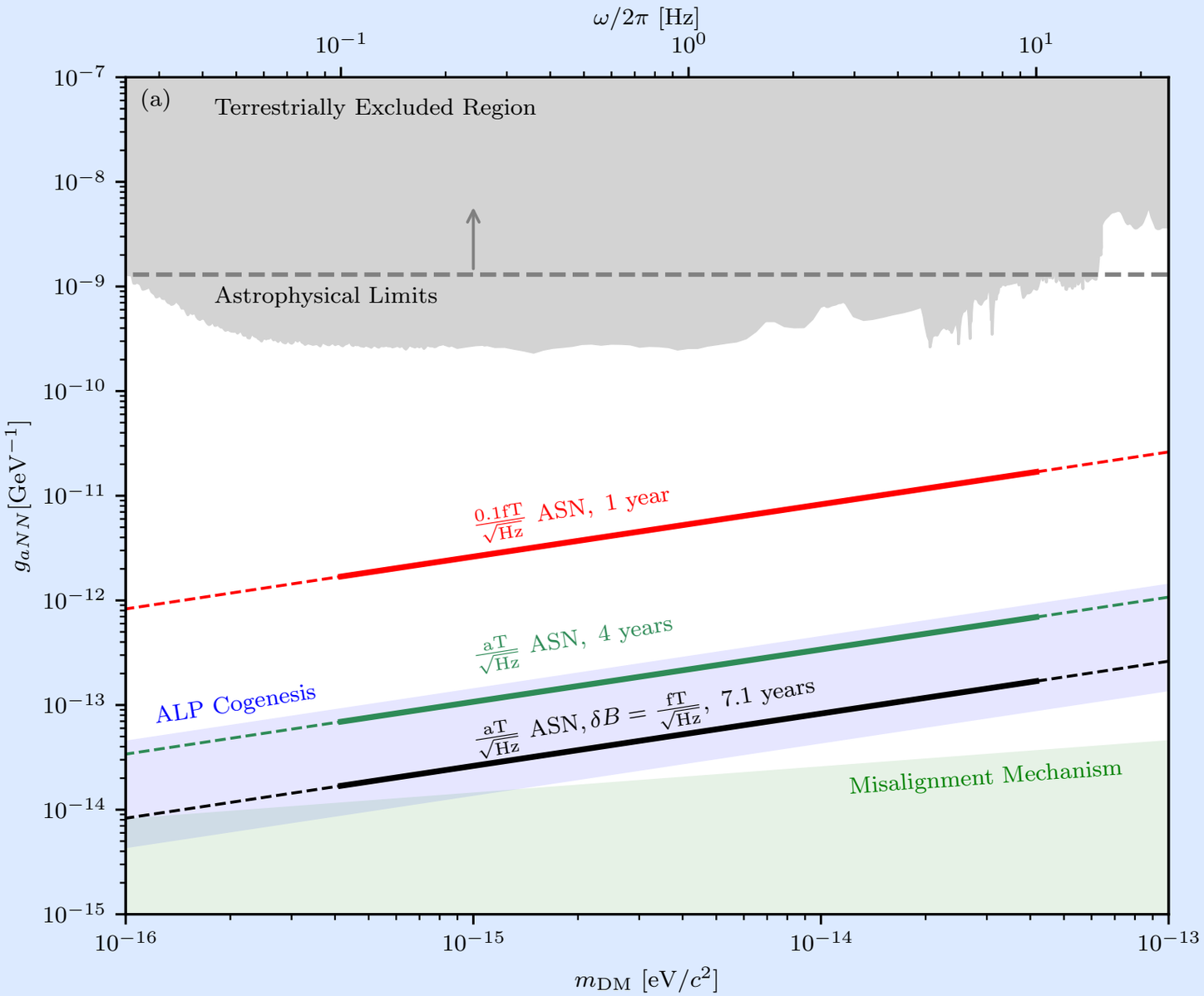
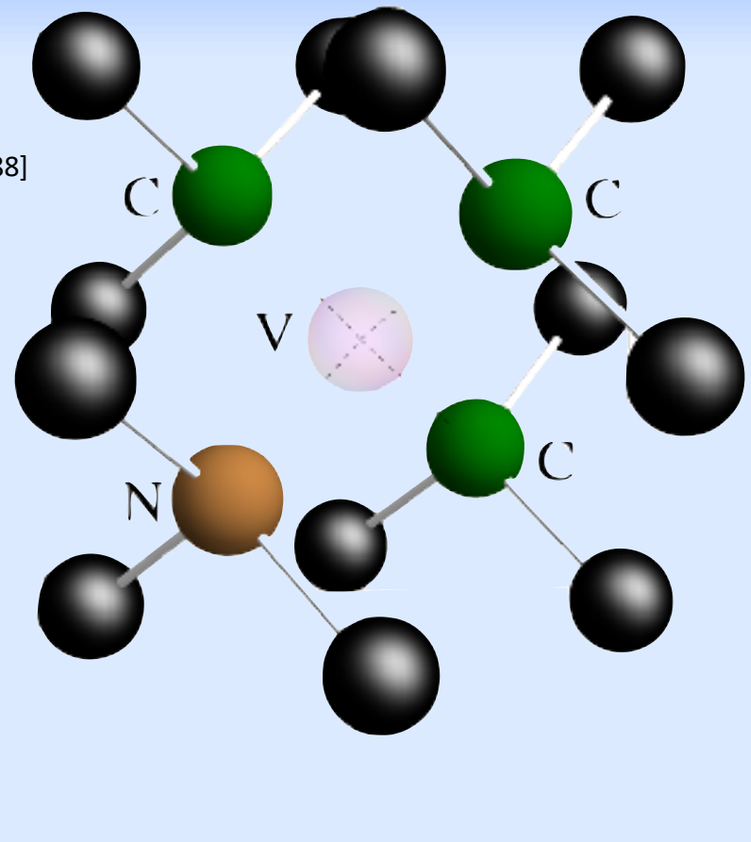
New Techniques are still being invented!





NV Centers

[1302.3288]



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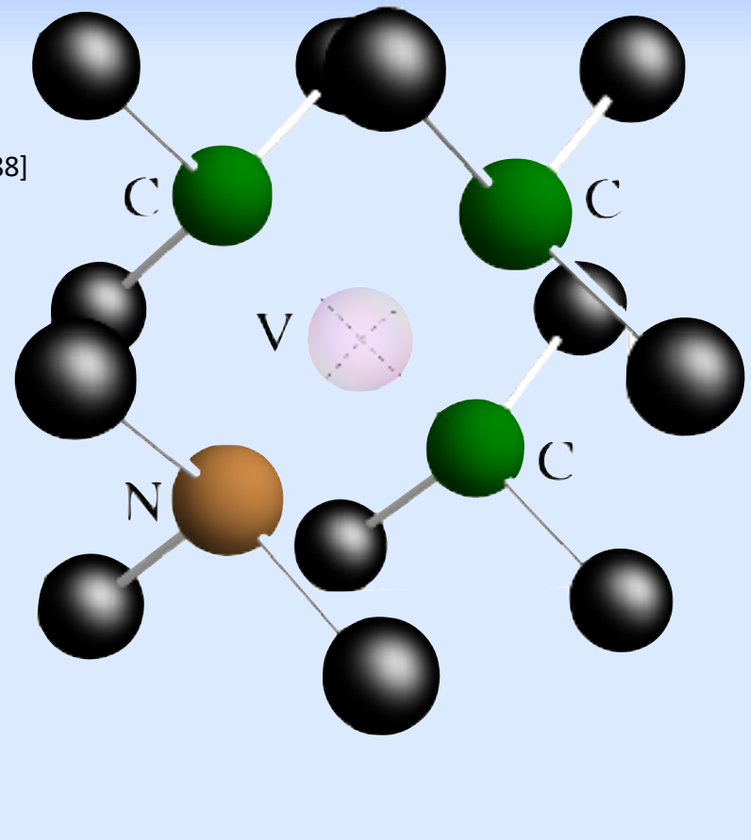

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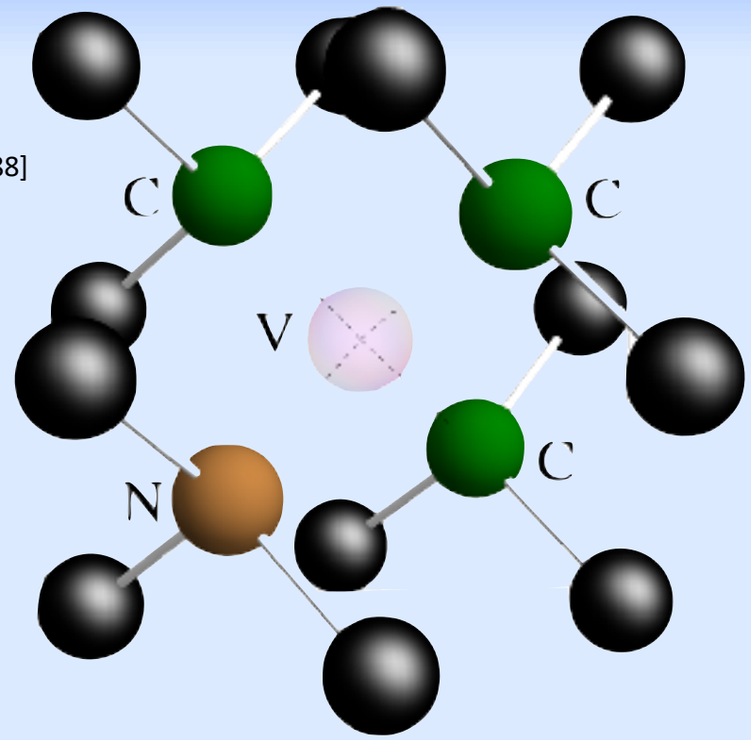

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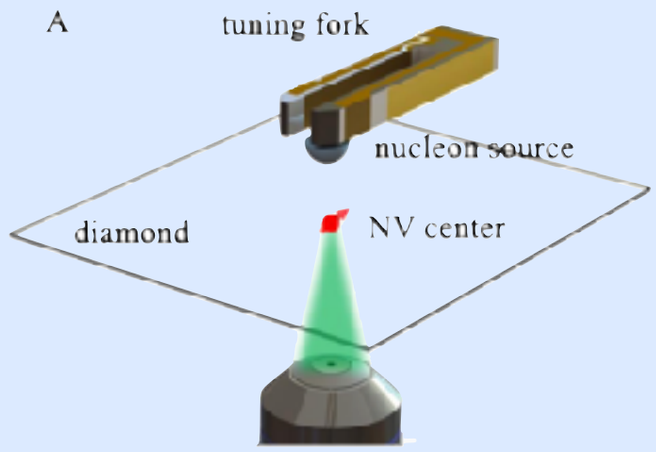
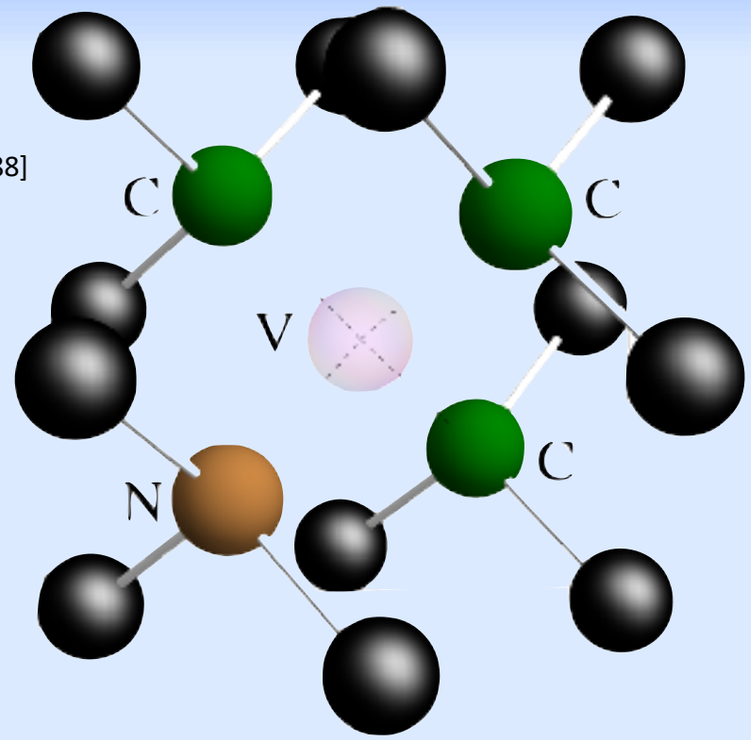
Conversely, for searching for short range interactions, their small size offers interesting possibilities [2010.15667]



NV Centers

[1302.3288]

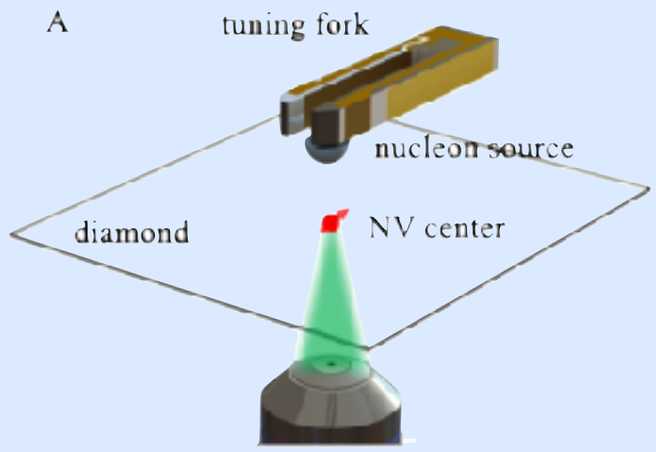


Nitrogen-Vacancy centers are defects in diamonds. The negatively charged defects are spin triplets, that can, unlike alkali magnetometers, be probed individually. They also have far larger bandwidth.

Because electron-interactions are relatively harder BSM targets, NV centers have not yet been used for Dark Matter searches (though proposals exist).

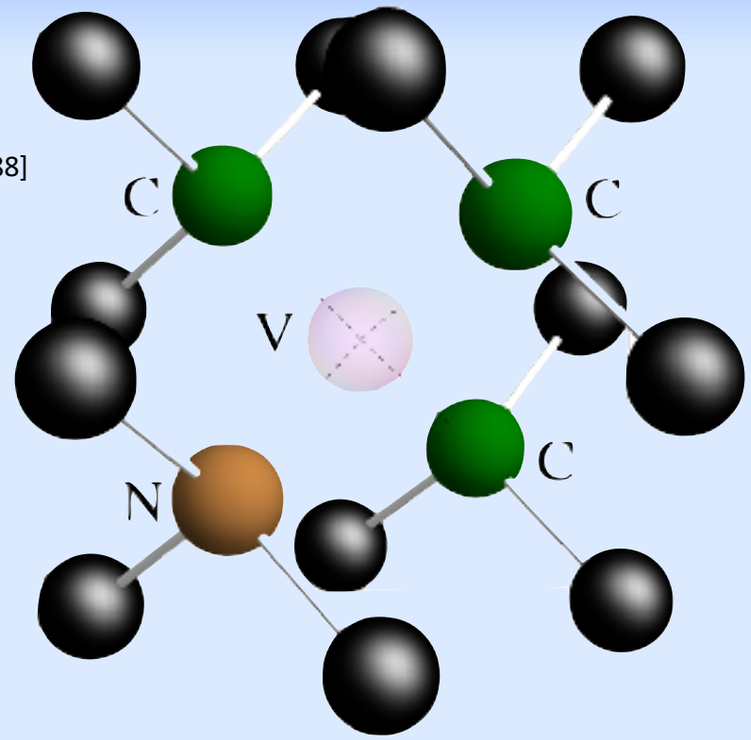
Conversely, for searching for short range interactions, their small size offers interesting possibilities [2010.15667]

Additionally, their individual spin nature offers interesting interferometry possibilites, that could probe some speculative quantum gravity models [2508.13662]



NV Centers

[1302.3288]



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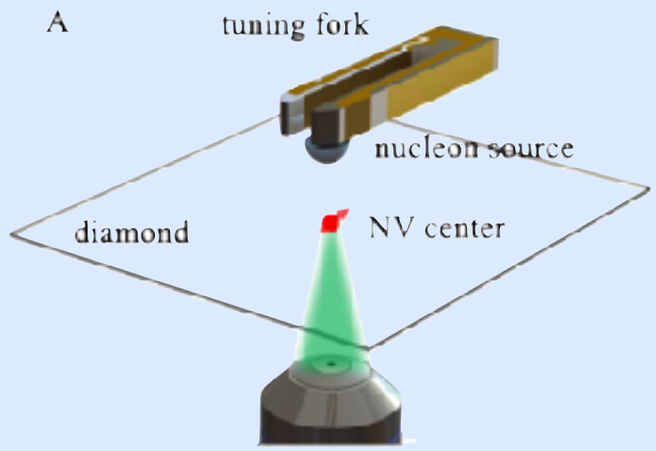

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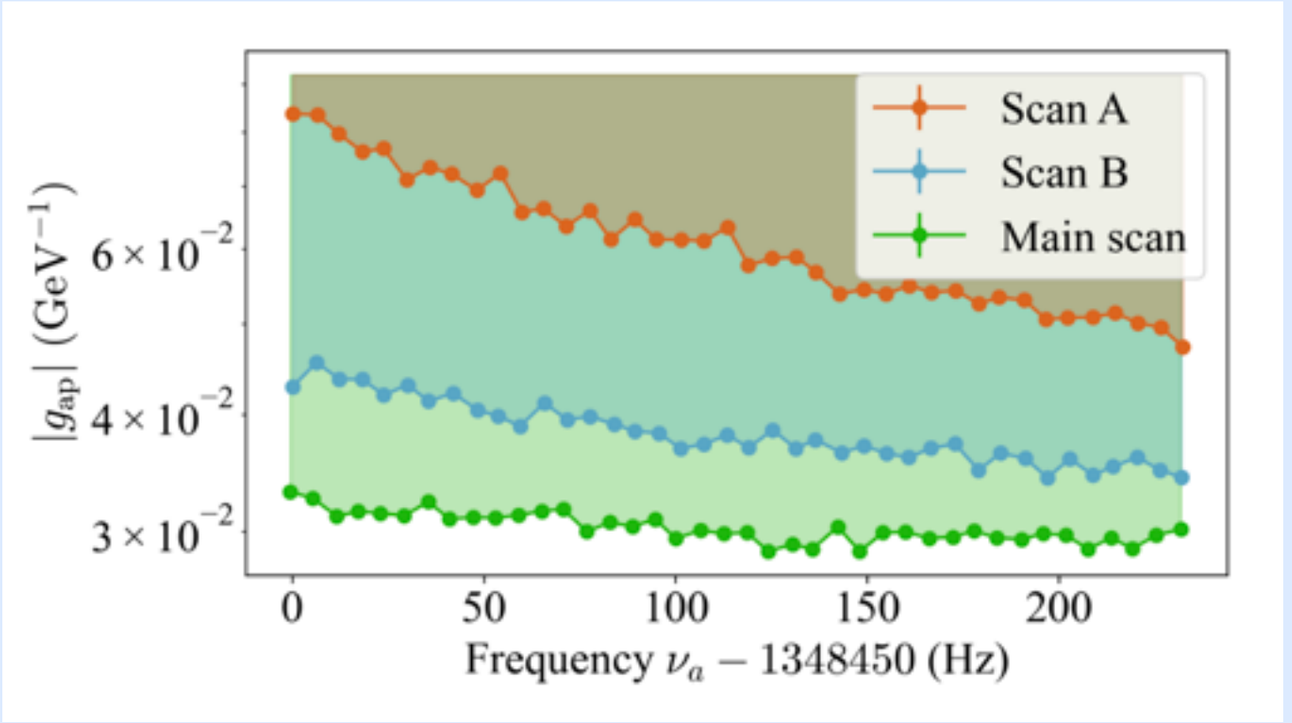
And discussions exist for SM-usages in LHC (talk to Michael)

Most famous spin-based BSM experiments: CASPEr

CASPEr is meant to probe axion-like particles, through two different efforts, CASPEr wind (led by Dmitry Budker), and CASPEr electric (led by Alex Sushkov).

CASPEr wind is a liquid Xenon experiment, measured by SQUIDs to high precision, recently, this was the focus of CASPEr



2504.16044

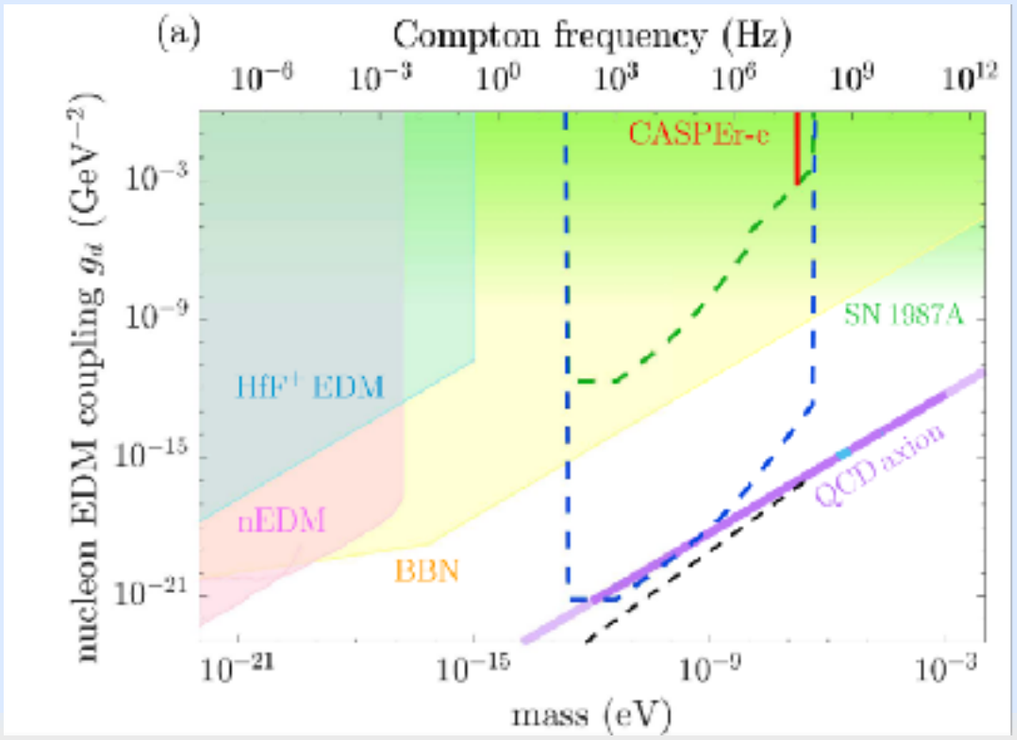
CASPEr Electric

CASPEr electric is one of the only methods that may measure low-mass QCD axions through their induced oscillating EDM.

It relies on crystals with large internal electric fields, and then the oscillating EDM would cause a tilt of magnetization,

$$M \sim M_z \cdot \frac{\epsilon_{\text{schiff}} E_{\text{eff}} T_2 g_d \sqrt{\rho_{\text{DM}}}}{m_a}$$

Where $\epsilon_{\text{schiff}} E_{\text{eff}}$ is the effective electric field multiplied by the schiff-suppression factor. The $1/m_a$ scaling is crucial:



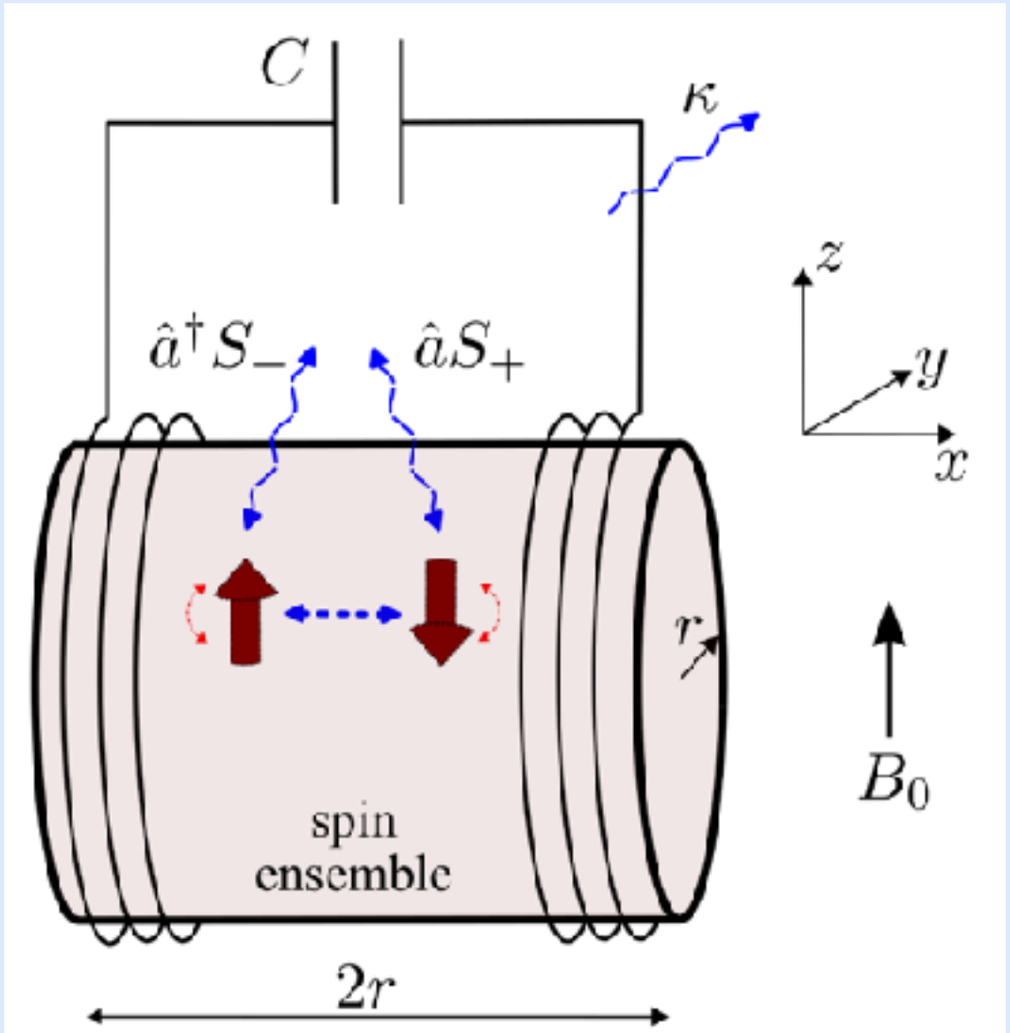
[D. Aybas et al., Phys. Rev. Lett. 126, 160505 (2021)]
[D. Aybas et al., Quant. Sci. Tech. (2021)]

Other Technologies

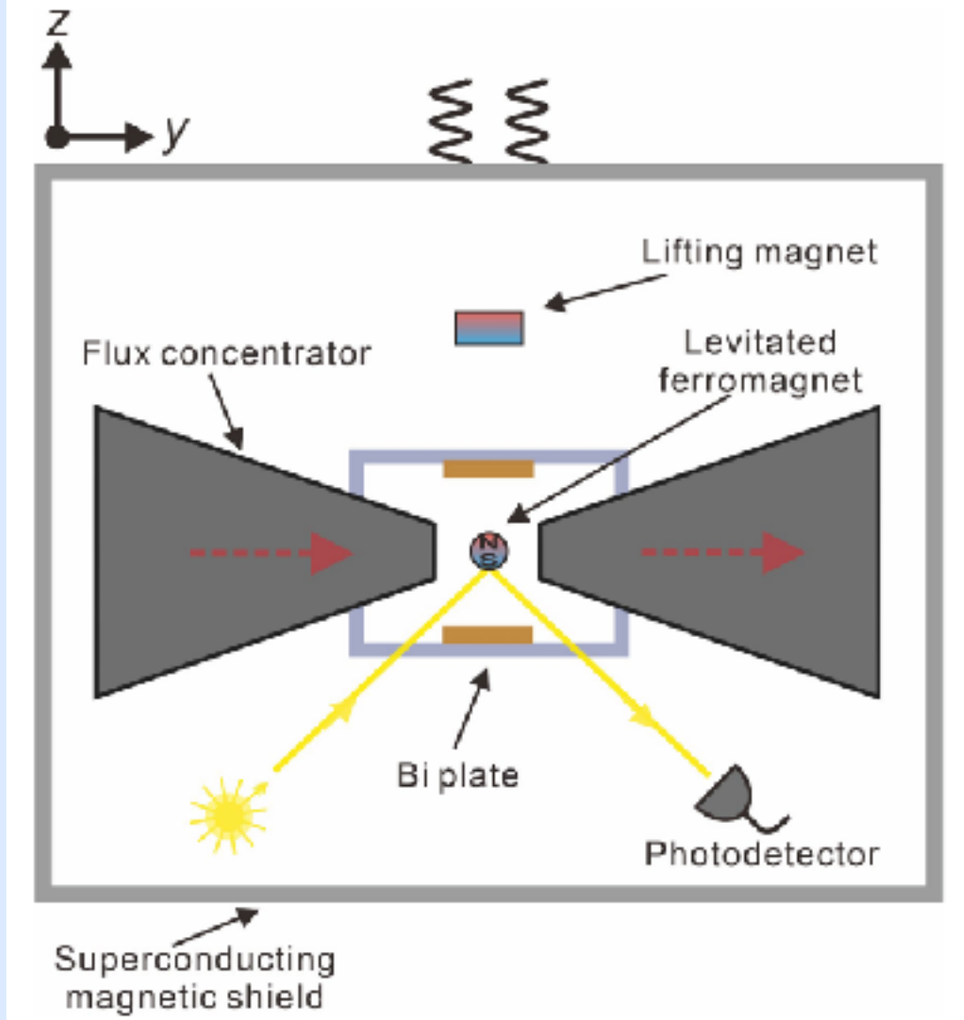
- Storage Rings: expected hold promise for low frequencies.
- Torsion Balance and the more futuristic levitated ferromagnets: use electron spins, and the torsion/rotation leads to very different systematics.
- Liquid He3: interesting phases can lead to different experimental regimes [2310.07791]
- More! (magnons, longitudinal magnetometry, cold atoms…)

Upgrades to Existing Technologies?

Squeezing Nuclear spins
[2502.14103, 2508.20520]

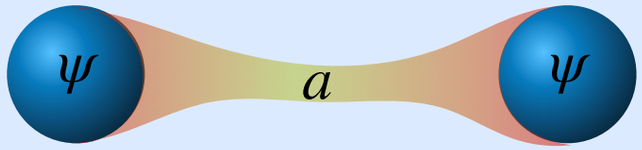


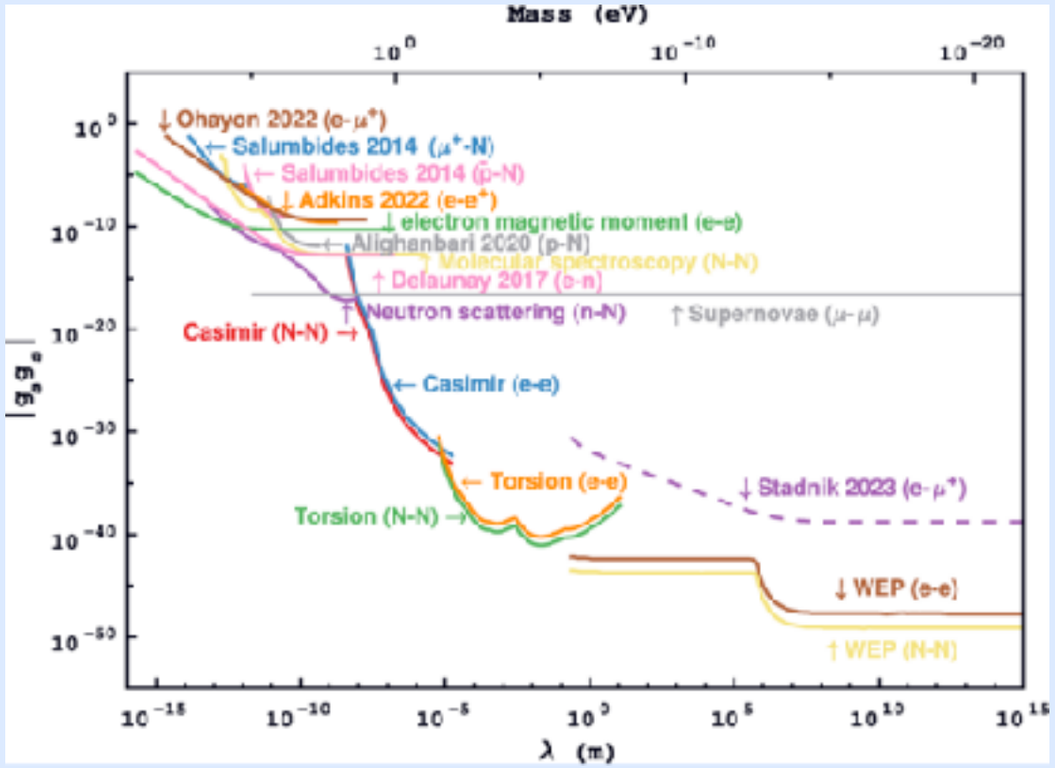
Flux concentrators
[2509.24553]



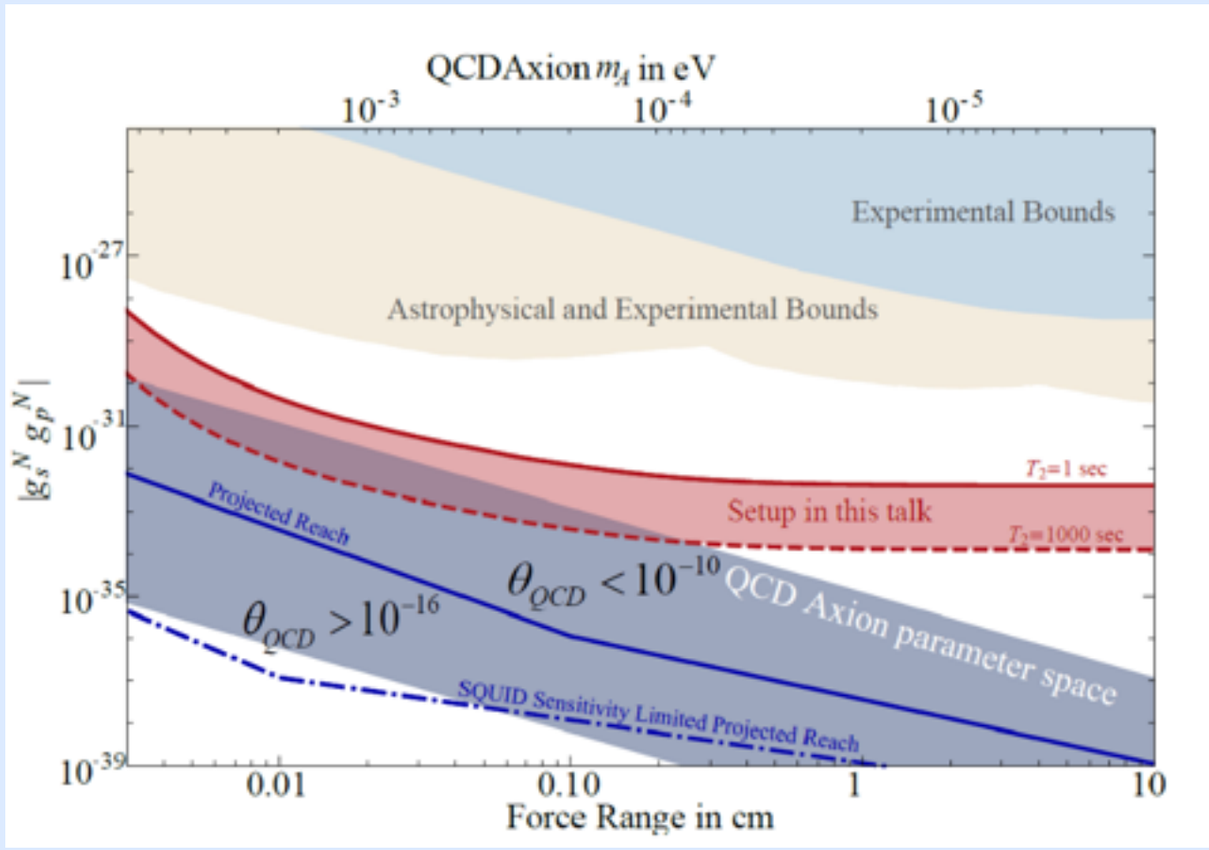
Aside: Long-Range Force Searches

In addition to DM, some of these spin-based sensors are used to search for new (mostly long-range) forces





[Cong 2025 review]



[ARIADNE experiment projections]

Summary

- Spin Based sensors have been growing in usage for BSM applications over the last decade.

- There’s many ambitious proposals out there already.

- And yet, the full set of possibilities has certainly not yet been fully explored.