Title: Looking for Low-Frequency Dark Matter in the Lab

Speakers: Saarik Kalia

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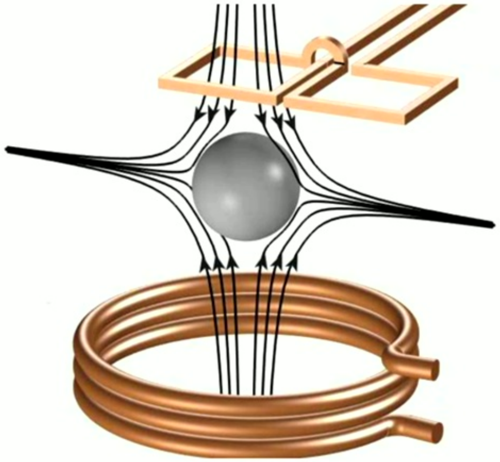
Abstract:

Dark photons and axions are exciting candidates for dark matter, which may be observable through their couplings to electromagnetism or electrons. While many experimental programs have been developed to explore the wide range of parameter space over which these candidates may exist, the mass range corresponding to frequencies below a kHz has been seldom probed by laboratory experiments. In this talk, I will discuss two ongoing efforts to probe this region of parameter space. Both rely on the ability of dark-photon or axion dark matter to source an oscillating magnetic field signal inside an experimental apparatus. In the first case, this magnetic field signal is detected by observing its effect on magnetically levitated (Maglev) systems. The oscillating magnetic field signal sourced by dark matter can drive translational motion of a levitated superconductor or rotational motion of a levitated ferromagnet. As mechanical resonators, Maglev systems are naturally sensitive to lower frequencies, making them well-suited detectors for sub-kHz dark matter candidates. In the second case, we instead consider Earth as the experimental apparatus. That is, we search directly for the oscillating magnetic field signal using unshielded magnetometers located across the Earth's surface. Not only does the signal strength receive an enhancement from the large size of the Earth, but it is also correlated between independent measurements at different locations. I will discuss the search for this signal in existing publicly available magnetometer data maintained by the SuperMAG collaboration, as well as an independent experimental effort, known as SNIPE Hunt, to measure this signal in the field. I will show that both Maglev systems and unshielded magnetometers have the potential to set the leading laboratory constraints on dark-photon and axion dark matter in the sub-kHz regime.

Looking for Low-Frequency Dark Matter in the Lab



Saarik Kalia

Perimeter Institute

Particle Physics Seminar

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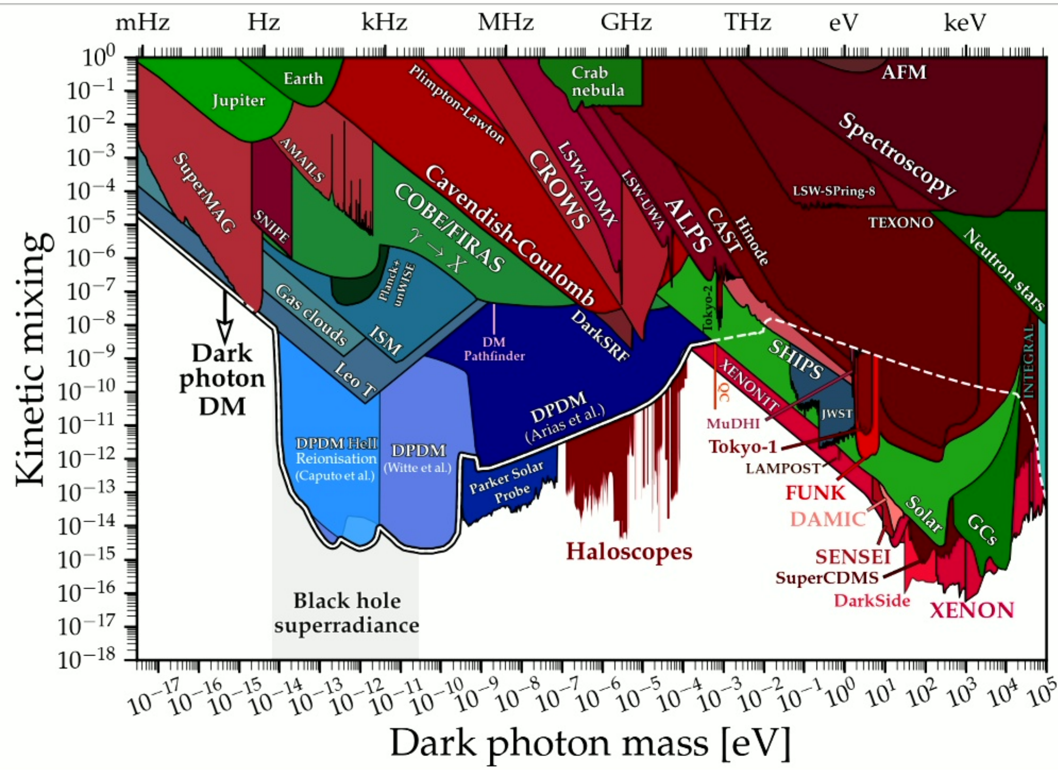
Based on arXiv:2310.18398, 2408.15330

and arXiv:2106.00022, 2108.08852, 2112.09620, 2306.11575, 2308.10931, 2408.16045

Introduction



[Caputo et al., Phys. Rev. D. **104,** 095029 (2021)]

Introduction

- Ultralight dark matter couplings:
  - Dark photon kinetic mixing
  - Axion-photon coupling
  - Axion-electron coupling
- Magnetic field signal inside experimental apparatus
- Hard to probe $f_{\mathrm{DM}} \lesssim \mathrm{kHz}\ (m_{\mathrm{DM}} \lesssim 10^{-12}\,\mathrm{eV})$
  - Most experiments utilize EM resonances → mechanical resonator: Maglev
  - Signal scales with size of apparatus → remove shield: Earth as apparatus

Outline

I. Ultralight Dark Matter

II. Magnetic Levitation

  a. Levitated Superconductors

  b. Levitated Ferromagnets

III. Unshielded Magnetometers

  a. SuperMAG

  b. SNIPE Hunt

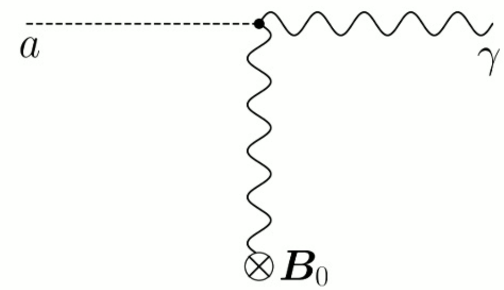
  c. SNIPE Hunt Curl

Kinetically mixed dark photon

- Low mass → high number density → classical/wavelike field
- Vector A'_μ with mass $m_{A'}$
- Non-relativistic
  - $\partial_\mu A'^\mu = 0 \implies A'_0 = 0$
  - $\boldsymbol{A}'$ constant in space
  - Oscillates with frequency $\omega = m_{A'}$
- Coupling to EM can be written as $\varepsilon m_{A'}^2 A'^\mu A_\mu$ [decouples as $m_{A'} \to 0$]
- Acts like effective current $J^\mu_{\text{eff}} = -\varepsilon m_{A'}^2 A'^\mu$ [same properties as A'_μ]

Axionlike particle

- Massive pseudoscalar a (oscillates with mass m_a)
- Axion-photon coupling $g_{a\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu}$
  - Effective current $\boldsymbol{J}_{\text{eff}} = i g_{a\gamma} m_a a \boldsymbol{B}_0$ → similar to dark photon
  - For levitated superconductor, trap can act as $\boldsymbol{B}_0$
  - For levitated ferromagnet, magnet can act as $\boldsymbol{B}_0$
  - For unshielded magnetometers, geomagnetic field acts as $\boldsymbol{B}_0$



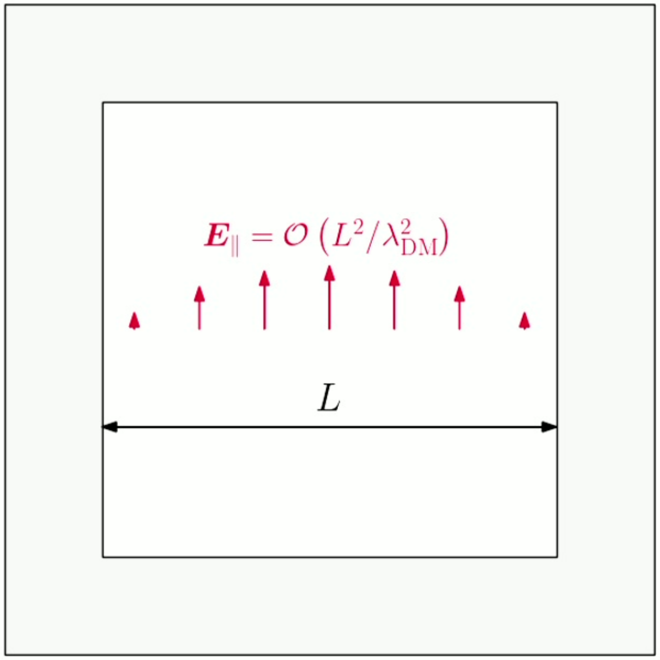
- Axion-electron coupling $\frac{g_{ae}}{2m_e} \partial_\mu a \bar{\psi}_e \gamma^\mu \gamma_5 \psi_e$
  - Causes precession of electron spins
  - Effective magnetic field $\boldsymbol{B}_{ae} = -\frac{g_{ae}}{e} \nabla a$

Dark-matter signal

- DPDM or axion-photon coupling can source

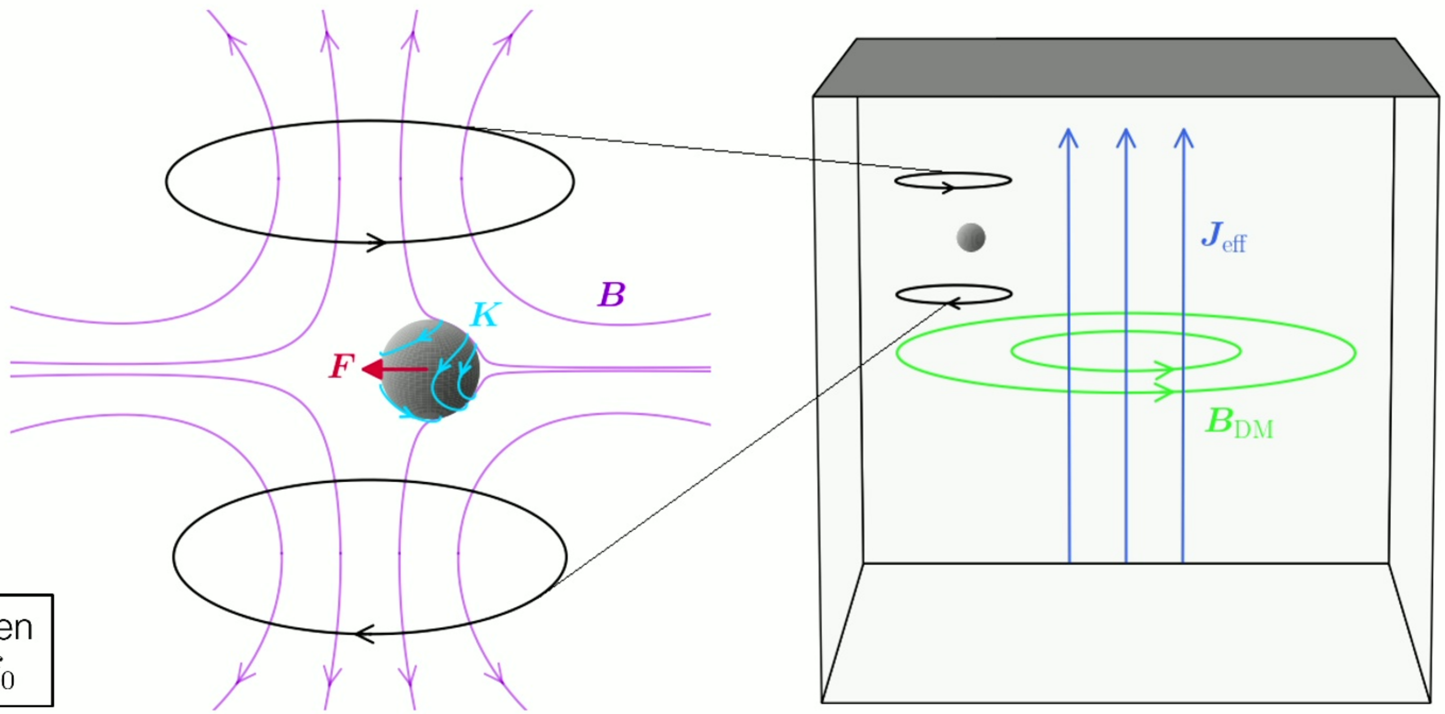
$$\nabla \times \boldsymbol{B} - \partial_t \boldsymbol{E} = \boldsymbol{J}_{\text{eff}}$$

- When $\lambda_{\text{DM}} \gg L$, then $\boldsymbol{E}$ negligible
  - $\boldsymbol{E}_{\|}$ vanishes at boundary
  - Can only grow on λ_{DM} length scales
  - Must be small in the interior
- Dominant signal is (oscillating) $\boldsymbol{B} \propto \boldsymbol{J}_{\text{eff}} \cdot L$



Magnetic Levitation

Levitated superconductors



Resonant when
$m_{\text{DM}} = 2\pi f_0$

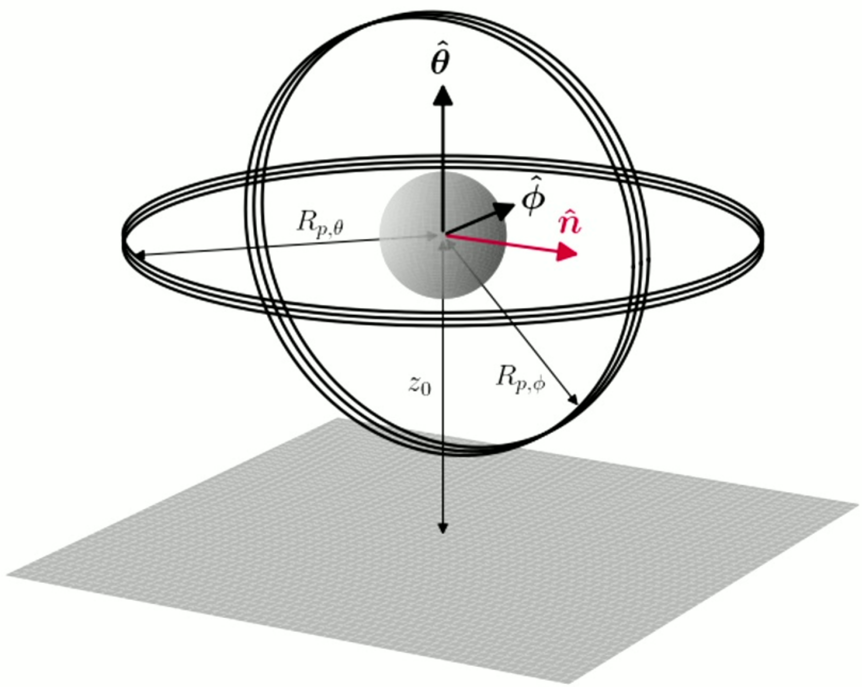
Superconductor parameters

Integration time: $1\,\mathrm{yr}$

Temperature: $10\,\mathrm{mK}$

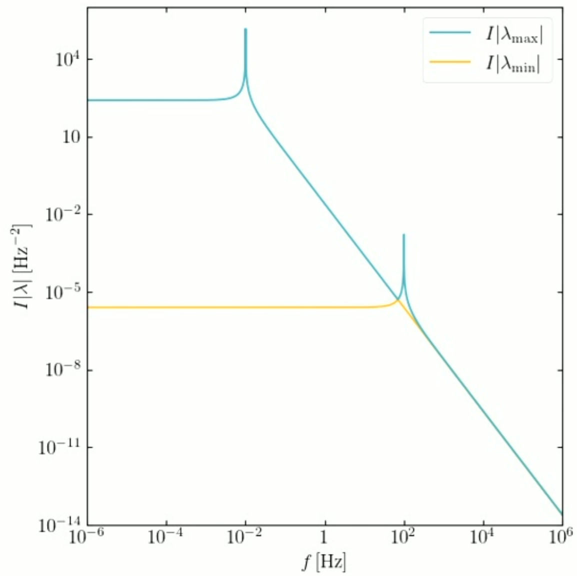
	Existing	Improved
Mass	$10\,\mu\mathrm{g}$	$1\,\mathrm{g}$
Density	$10\,\mathrm{g/cm^3}$	$0.1\,\mathrm{g/cm^3}$
Shield size	$10\,\mathrm{cm}$	$1\,\mathrm{m}$
Quality factor	10^7	10^{10}

Ferromagnet readout

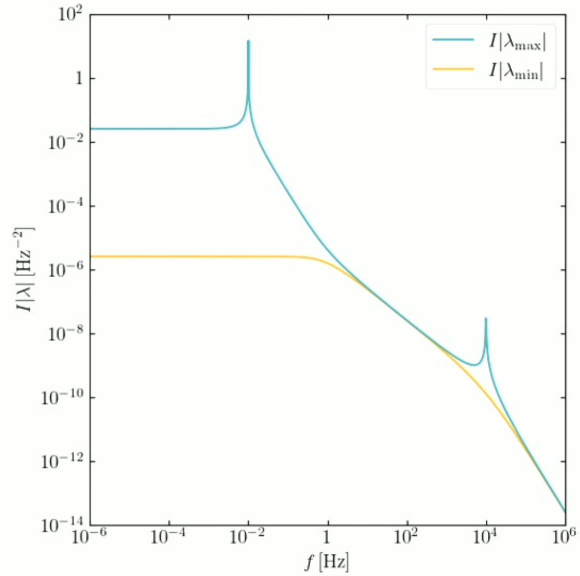


Mechanical susceptibility

$$\chi(\omega)^{-1} = I\left[-\omega^2\begin{pmatrix}1 & 0\\0 & 1\end{pmatrix} - i j_n \omega_I \omega \begin{pmatrix}0 & 1\\-1 & 0\end{pmatrix} + \omega_I \begin{pmatrix}v_{\theta\theta} & 0\\0 & v_{\phi\phi}\end{pmatrix}\right]$$



Partially Trapped ($v_{\theta\theta} \gg \omega_I \gg v_{\phi\phi}$)



Gyroscope ($\omega_I \gg v_{\theta\theta} \gg v_{\phi\phi}$)

Noise trade-off (cont.)

- If $S^{\mathrm{th}}_{BB,\alpha\alpha} < \sqrt{S^{\mathrm{imp}}_{BB,\alpha\alpha}(\omega = 0) \cdot S^{\mathrm{back}}_{BB,\alpha\alpha}}$ [or $\tilde{\eta}^{(\mathrm{res})} \leq \tilde{\eta}^{(\mathrm{broad})}$], then either:
  - Resonant detection: $\tilde{\eta}^{(\mathrm{res})} = \sqrt{\frac{4m\gamma T}{\kappa}}$
  - Broadband detection: $\tilde{\eta}^{(\mathrm{broad})} = \sqrt{m\omega_0}$
- Otherwise, can choose any $\tilde{\eta}^{(\mathrm{res})} \geq \tilde{\eta} \geq \left[\tilde{\eta}^{(\mathrm{broad})}\right]^2 / \tilde{\eta}^{(\mathrm{res})}$
  - Larger $\tilde{\eta}$ is better for higher frequencies

Sources of dissipation

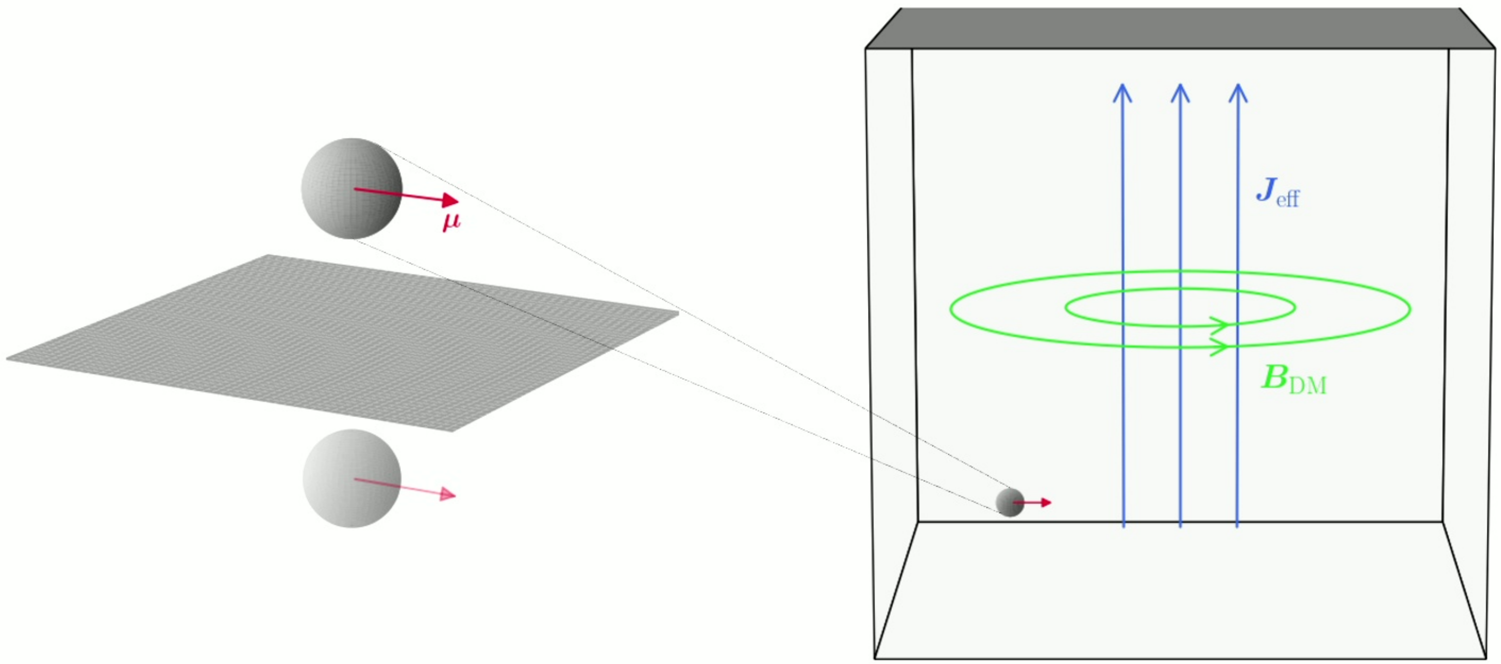
- Gas collisions:

$$\gamma \sim \frac{PA}{m\bar{v}_{\rm gas}} \sim 2\pi \cdot 10^{-8}\,{\rm Hz} \cdot \left(\frac{P}{10^{-7}\,{\rm Pa}}\right)\left(\frac{1\,{\rm g}}{m}\right)^{1/3} \cdot \left(\frac{0.1\,{\rm g/cm}^3}{\rho}\right)^{2/3} \sqrt{\left(\frac{m_{\rm gas}}{4\,{\rm Da}}\right)\left(\frac{10\,{\rm mK}}{T}\right)}$$

- Flux creep: movement of unpinned flux lines in type-II SC → use type-I SC

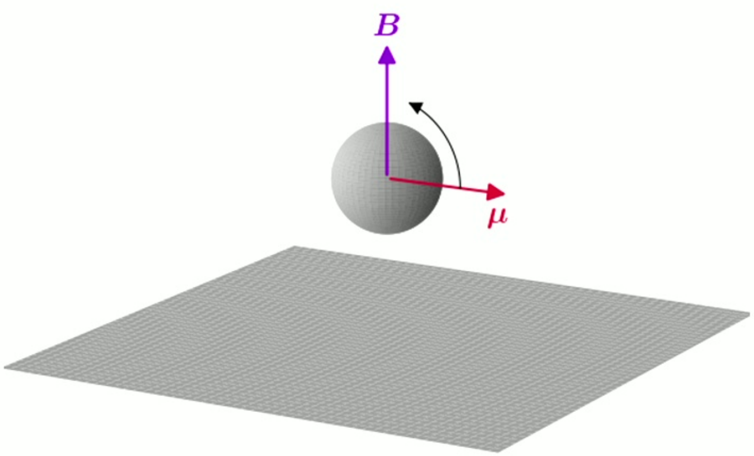
- Eddy current damping in nearby conductors → use only SCs and dielectrics

Levitated ferromagnets



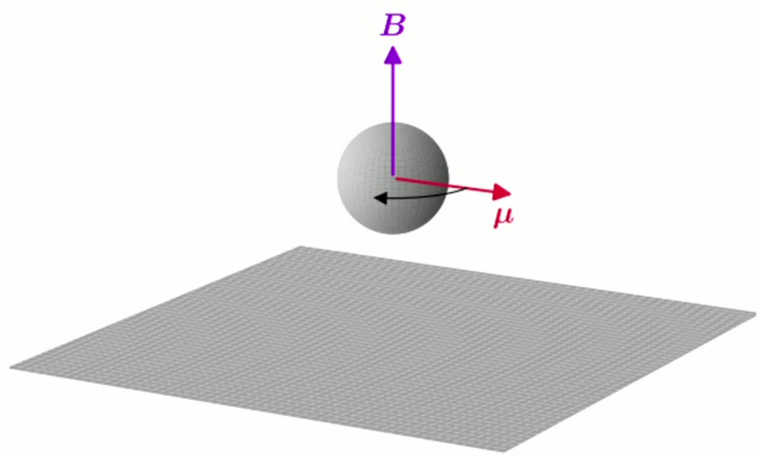
Ferromagnetic gyroscope

Libration (Compass)



$$I\Omega = L \gg S = N\hbar/2$$

Precession (Spin)



$$L \ll S$$

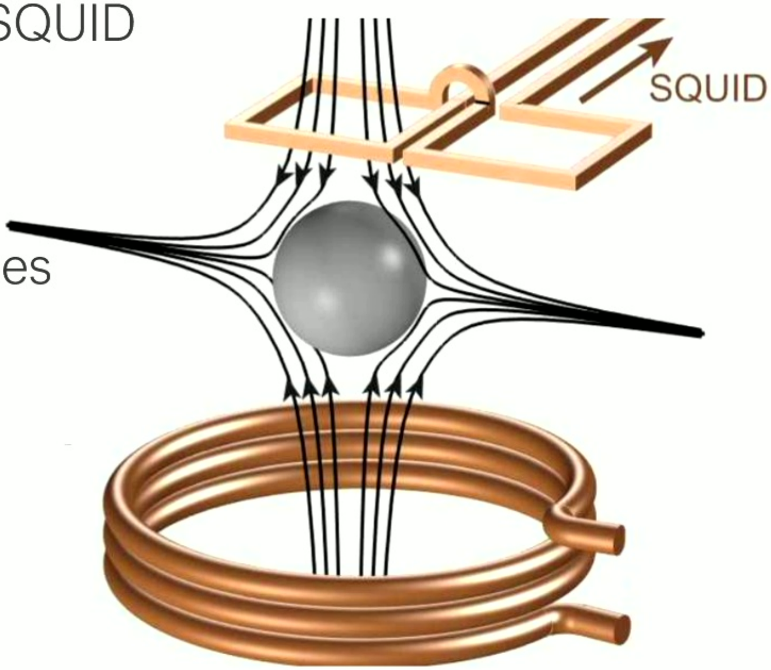
Effect of trapping potential

- Ferromagnet levitated in trapping potential $V(\boldsymbol{x}, \hat{\boldsymbol{n}})$, e.g.
  - Over superconductor $V \propto \frac{1+\cos^2\theta}{z^3}$
  - In freefall $V \approx 0$
- Resonances and behavior depend on angular trapping $v_{\alpha\alpha} \equiv \frac{2}{N\hbar}\partial_\alpha^2 V$:
  - Trapped ($v_{\alpha\alpha} \gg \omega_I$): only libration, resonances at $m_{\rm DM} = \sqrt{v_{\alpha\alpha}\omega_I}$
  - Gyroscope ($v_{\alpha\alpha} \ll \omega_I$): precession when $v_{\alpha\alpha} \ll m_{\rm DM} \ll \omega_I$, resonances at $m_{\rm DM} = \omega_I, \sqrt{v_{\theta\theta}v_{\phi\phi}}$

where $\omega_I = \frac{N\hbar}{2I}$

Readout

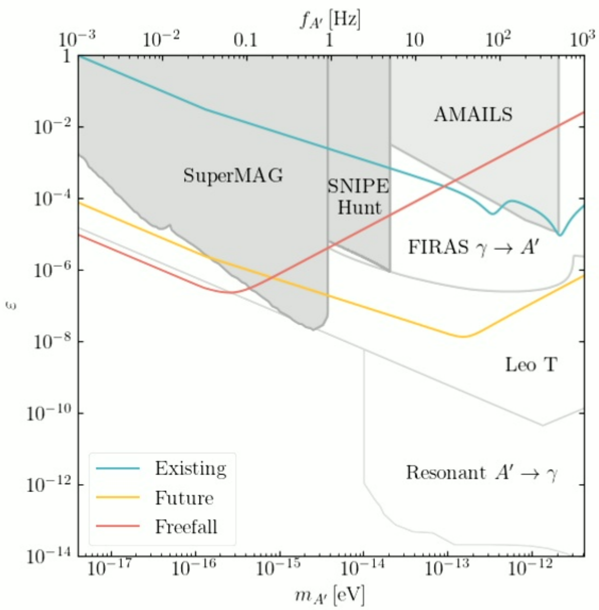
- Can readout with pickup loop connected to SQUID
- $\boldsymbol{B}_0$ has flux through pickup loop
- As levitated object moves/rotates, flux changes
- Changes in flux measured by SQUID
- If SQUID is tightly coupled, can back-react
  - Small coupling → resonant detection
  - Large coupling → broadband detection



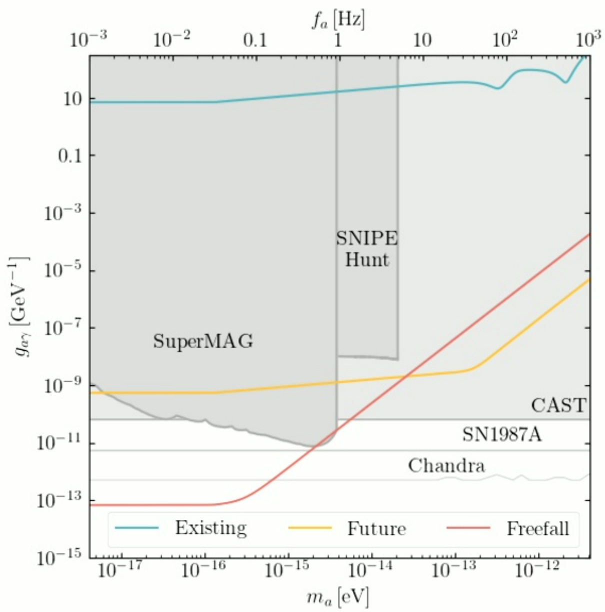
[Hofer et al., Phys. Rev. Lett. **131**, 043603 (2023)]

Ferromagnet sensitivities

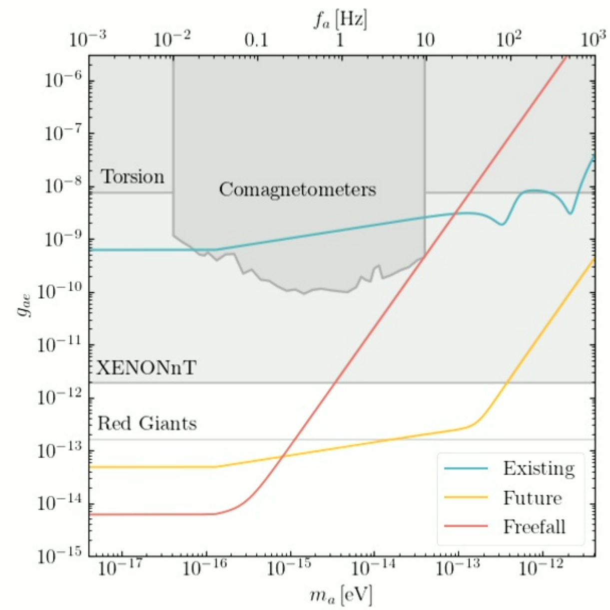
Dark photon



Axion-photon coupling

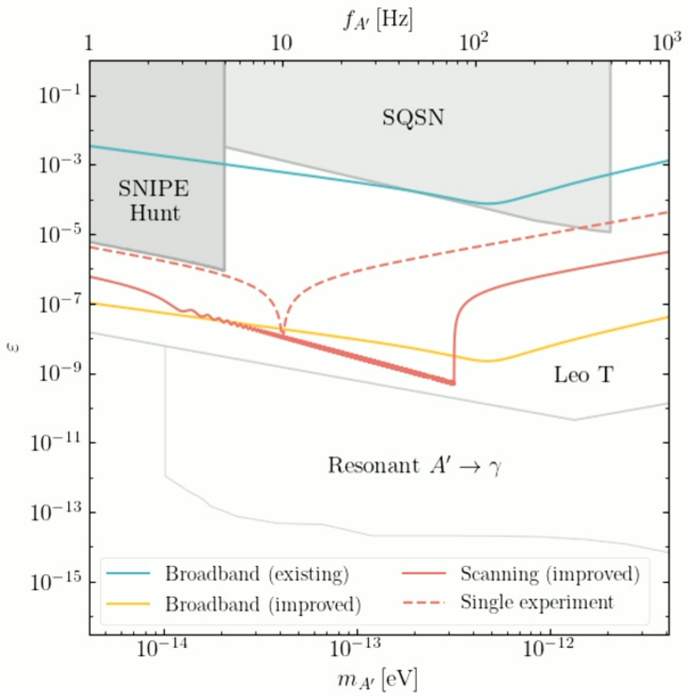


Axion-electron coupling

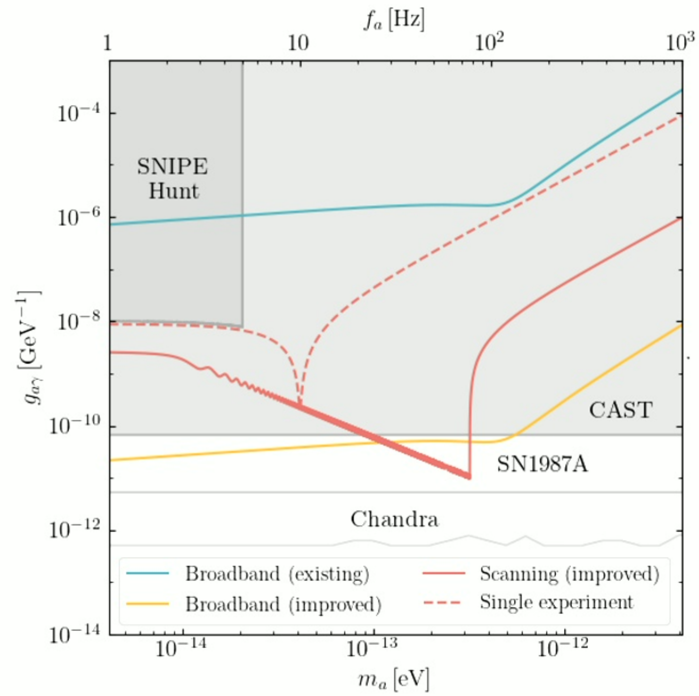


Superconductor sensitivities

Dark photon

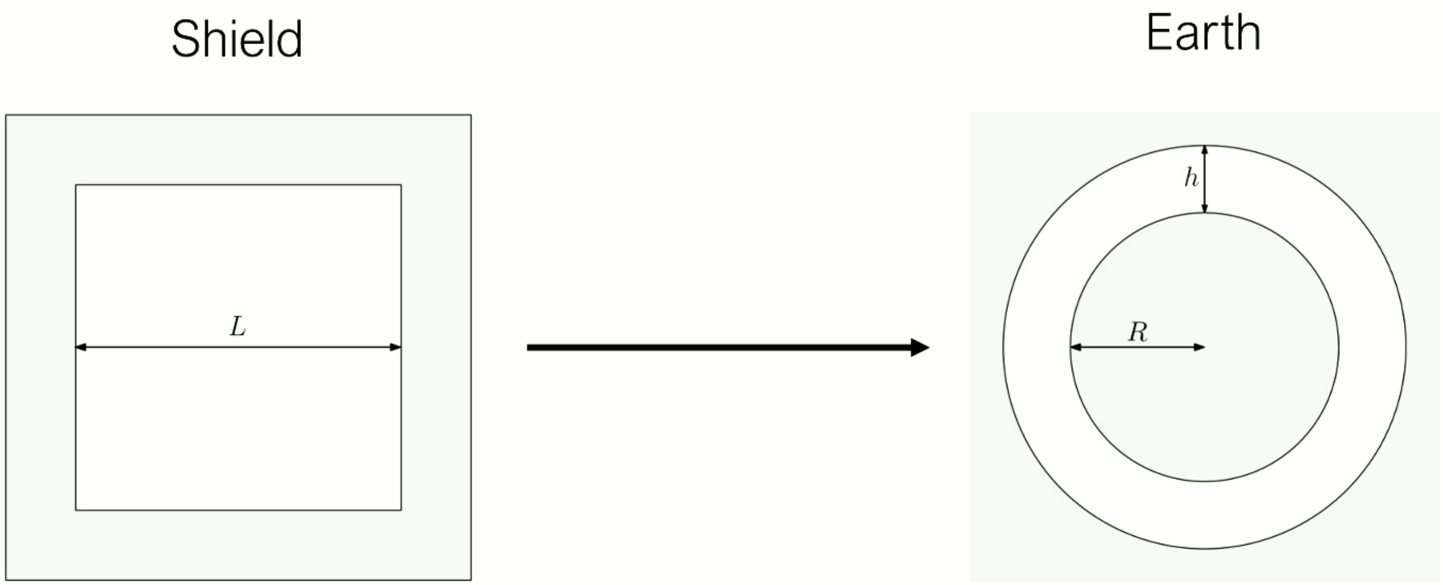


Axion-photon coupling



Unshielded Magnetometers

Earth as the apparatus



$\boldsymbol{B}$ scales with L

$\boldsymbol{B}$ scales with R

Magnetic field signal

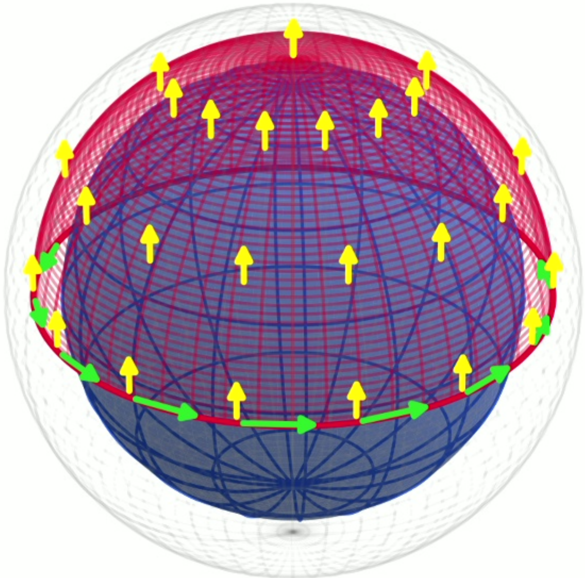
- Scales with R

$$BR \sim \oint \boldsymbol{B} \cdot d\ell = \iint \boldsymbol{J}_{\text{eff}} \cdot d\boldsymbol{A} \sim \boldsymbol{J}_{\text{eff}} \cdot R^2$$

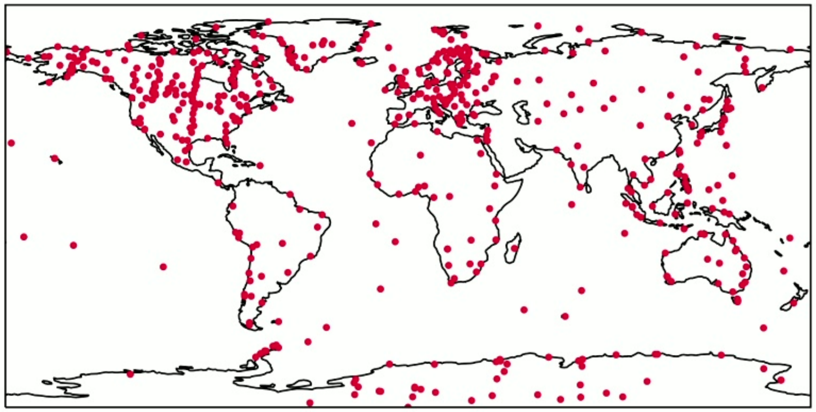
- Robust to boundary conditions (when $\lambda_{\text{DM}} \gg R$)

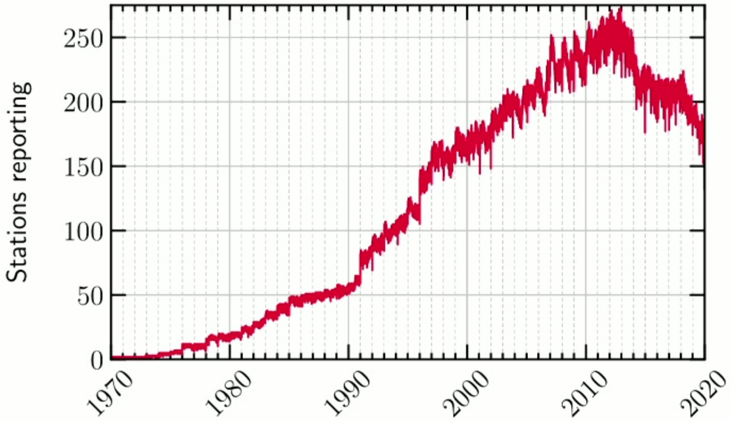
$$\nabla \times \boldsymbol{B} = \boldsymbol{J}_{\text{eff}} \implies \boldsymbol{B} = \boldsymbol{B}_{\text{sph}} + \text{curl-free}$$

Can project out curl-free part



Search in SuperMAG datasets





- 500+ ground-based magnetometers → leverage spatial coherence
- 50 years of data → leverage temporal coherence
- 1-minute resolution dataset → sensitive to $f_{\rm DM} \lesssim 10^{-2}\,{\rm Hz}$
- 1-second resolution dataset → sensitive to $f_{\rm DM} \leq {\rm Hz}$

SNIPE Hunt

- Search for Non-Interacting Particles Experimental Hunt
- Take our own data for $0.5\,\mathrm{Hz} \leq f_{\mathrm{DM}} \leq 5\,\mathrm{Hz}$
- Most noise is man-made → go to radio quiet area, e.g. state park
- Summer 2022 run
    - Collected data at three locations (CA, PA, OH) over 2.5 days
    - Magnetometer noise limited, but already leading lab constraints on dark photons!
- Stay tuned for Summer 2024 data (from five locations)!

SNIPE Hunt

SNIPEs and Where to Find Them

Rising fourth-year physics major Eduardo Castro Munoz and his mentor, Oberlin professor Jason Stalnaker, conducted summer research intended to shed light on a little-known facet of our universe. Along with fellow physics student Ehsan Nikfar, they took to the woods to capture information about dark photons, which could provide evidence supporting the existence of dark matter. All of which helps explain the study's playful acronym: the Search for Non-Interacting Photons Experiment, or SNIPE.

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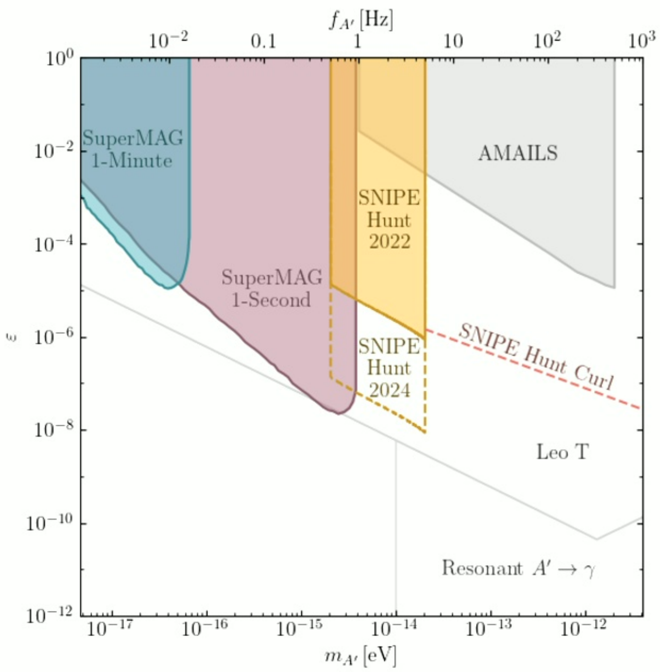
RESEARCH HIGHLIGHT | 30 November 2023

The hunt for dark-matter particles ventures into the wild

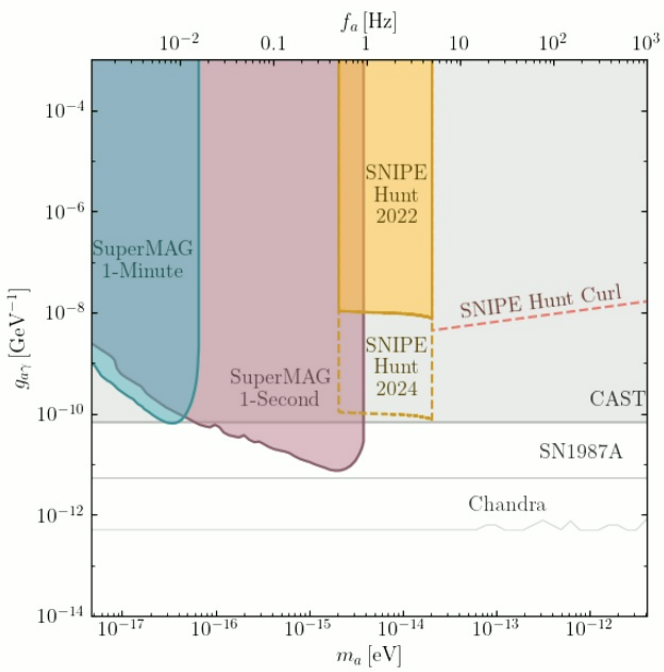
Sensors deployed at magnetically quiet rural sites looked for axions and 'hidden photons' – with no luck yet.

Existing and future limits

Dark photon



Axion



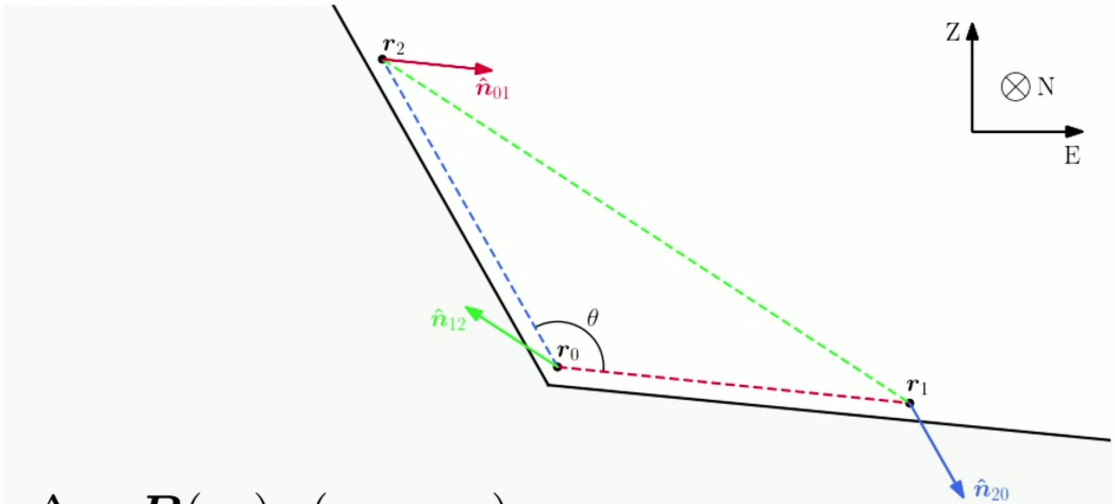
New technique above 5 Hz

- $\lambda_{\rm DM} \lesssim R$ → no robustness, environmental effects relevant
- Ex: Signal diverges at Schumann resonances $m_{\rm DM} R = \sqrt{\ell(\ell+1)}$
  - Predicted: 11 Hz, 18 Hz, 26 Hz…
  - Measured: 8 Hz, 14 Hz, 20 Hz…
  - Measured widths as low as 2 Hz
- Because the ground is a conductor, we still have $\boldsymbol{E}_{||} = 0$, so

$$(\nabla \times \boldsymbol{B})_{||} = \boldsymbol{J}_{\rm eff,||}$$

- We can measure $\nabla \times \boldsymbol{B}$ instead!
- No physical currents in lower atmosphere → background cancellation

Curl measurement scheme



$$\begin{aligned}\Delta = &\boldsymbol{B}(\boldsymbol{r}_0)\cdot(\boldsymbol{r}_2-\boldsymbol{r}_1)\\ &+\boldsymbol{B}(\boldsymbol{r}_1)\cdot(\boldsymbol{r}_0-\boldsymbol{r}_2)\\ &+\boldsymbol{B}(\boldsymbol{r}_2)\cdot(\boldsymbol{r}_1-\boldsymbol{r}_0)\end{aligned}$$

Noise sources

- Thermal: kicks from gas molecules
- Imprecision: flux noise → position
- Back-action: current noise → force
- Trade-off based on readout coupling
  - Resonant: back-action = thermal
  - Broadband: back-action = low-f imprecision