Ultralight Dark Matter Detection with Levitated Superconductors

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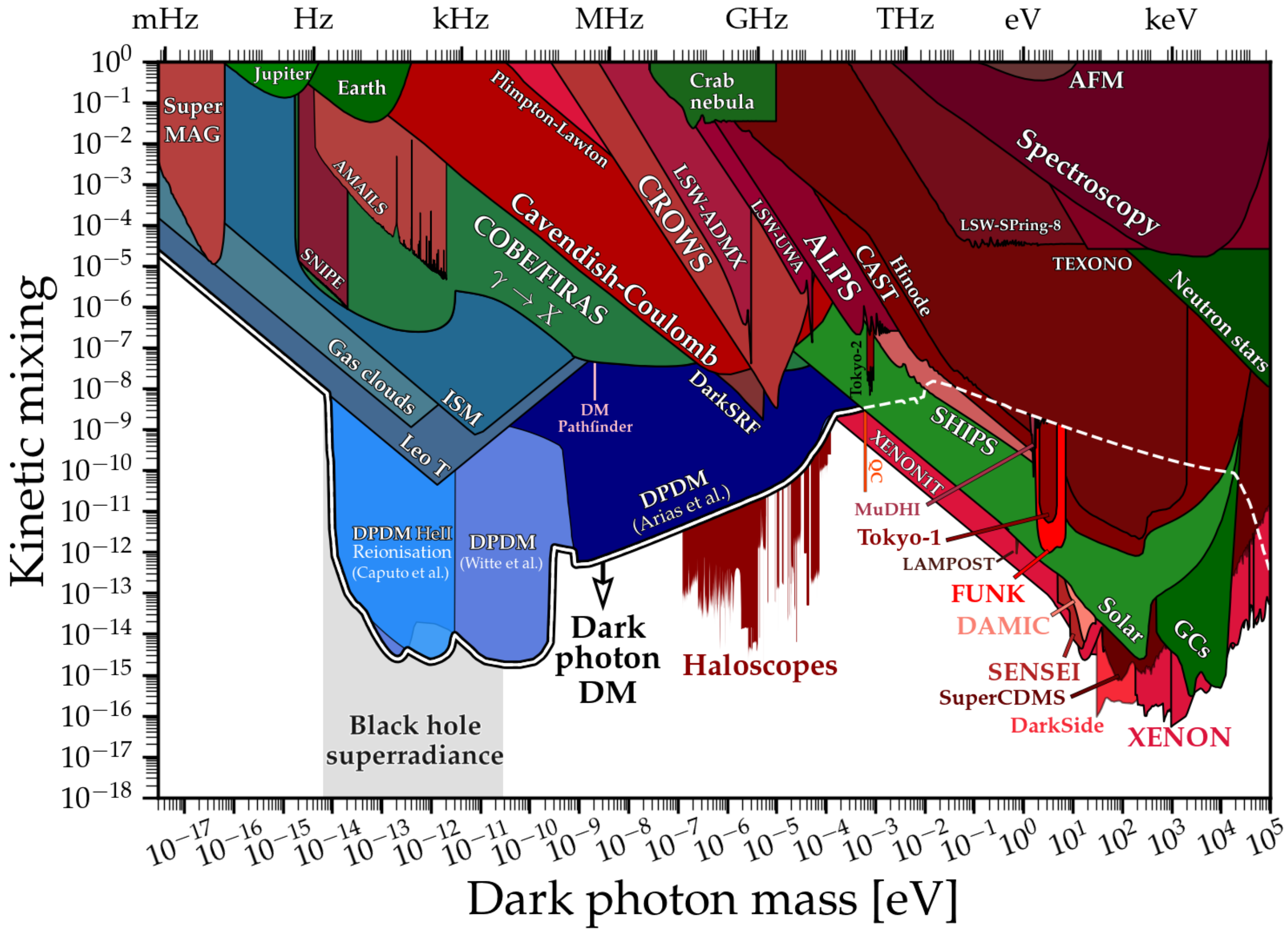
Based on arXiv:231X.XXXXX

Introduction



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

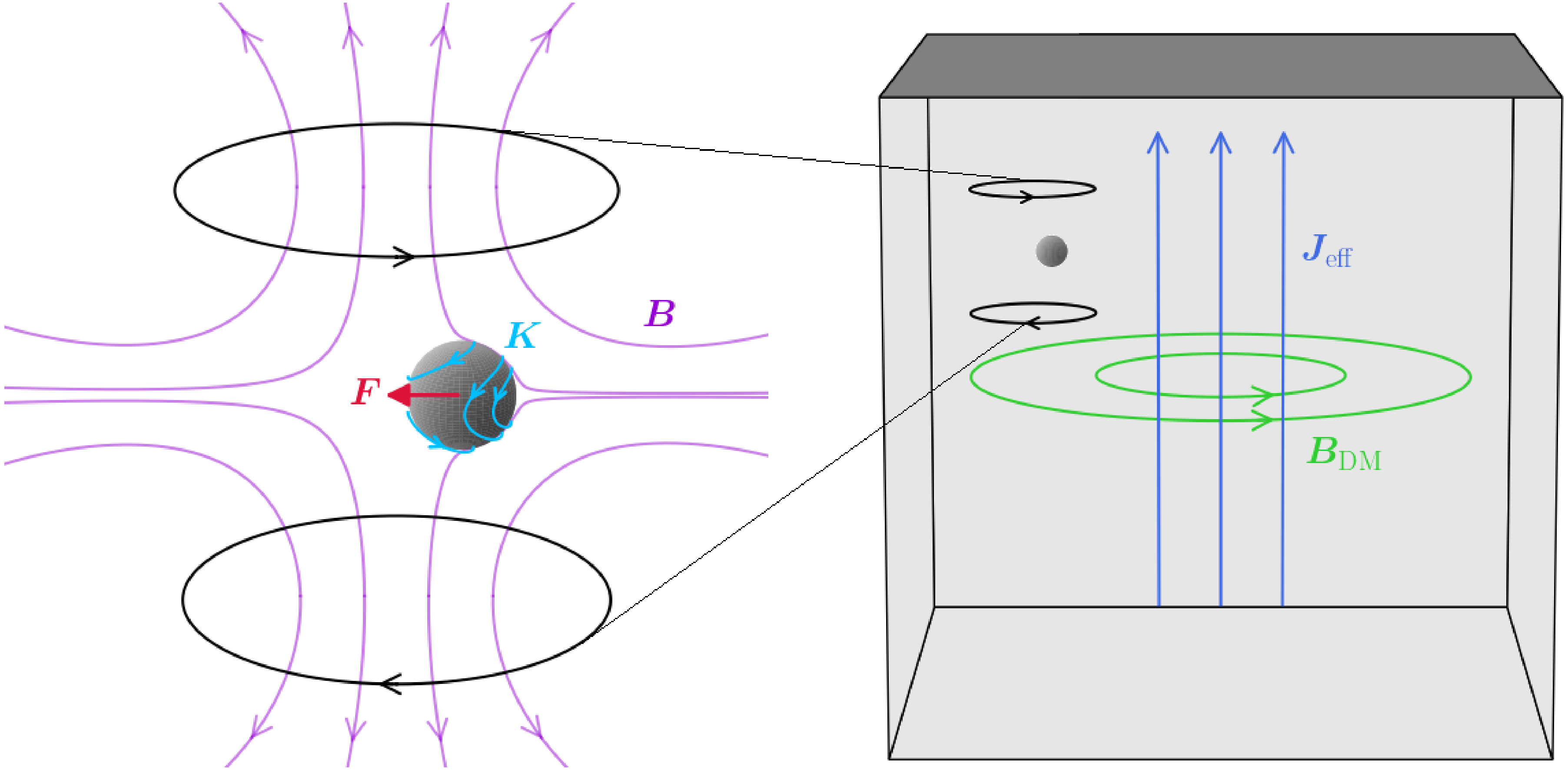
Introduction

- Ultralight dark matter coupled to EM:
  - Kinetically mixed dark photon
  - Axionlike particle
- Magnetic field signal inside experimental apparatus
- Most experiments utilize EM resonances → $f_{\mathrm{DM}} \gtrsim \mathrm{kHz}\ (m_{\mathrm{DM}} \gtrsim 10^{-12}\,\mathrm{eV})$
- Can use mechanical resonance for lower frequencies
- Mechanical system + sensitive to magnetic fields → magnetic levitation

Outline

- Levitated superconductors
- Dark matter signal
- Noise sources
- Sensitivity

Levitated superconductors



Levitated superconductors

- Surface currents screen external magnetic field
- Magnetic field exerts force on currents → net restoring force

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- Harmonic oscillator w/ trapping frequency

$$f_0 \sim \partial B/\sqrt{\rho}$$

- DM magnetic field signal will drive this oscillator

Dark matter candidates

- Dark photon: massive vector A'^{μ}
  - Non-relativistic → $\mathbf{A}'$ uniform in space, oscillates with frequency $m_{A'}$
  - Coupled to EM via $\varepsilon m_{A'}^2 A'^{\mu} A_{\mu}$

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- Axion: massive pseudoscalar a
  - Coupled to EM via $g_{a\gamma} a F \tilde{F}$ → $\mathbf{J}_{\text{eff}} = i g_{a\gamma} m_a a \mathbf{B}_0$
  - Trap can act as $\mathbf{B}_0$!

Dark matter signal

- Dark-photon or axion DM can source EM fields

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- When λ_{DM} larger than apparatus, $\mathbf{E}$ negligible → only $\mathbf{B}$ signal
- Oscillating $\mathbf{B}$ perturbs equilibrium → superconductor oscillates position
- Resonant if $m_{\text{DM}} \approx 2\pi f_0$

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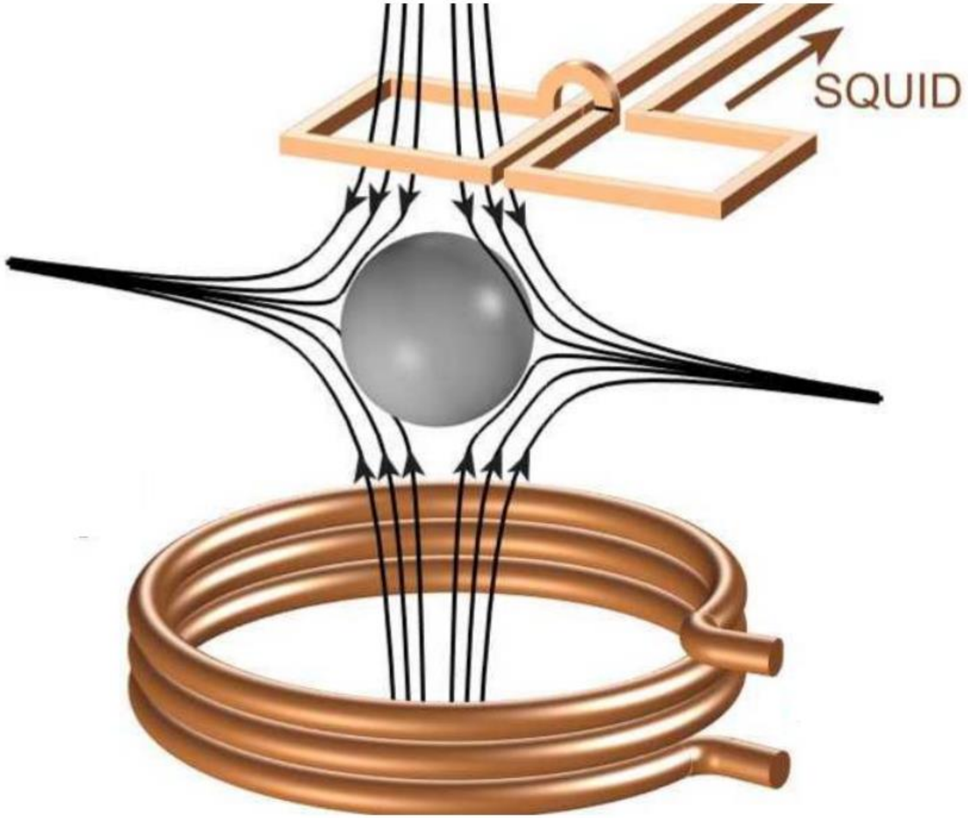
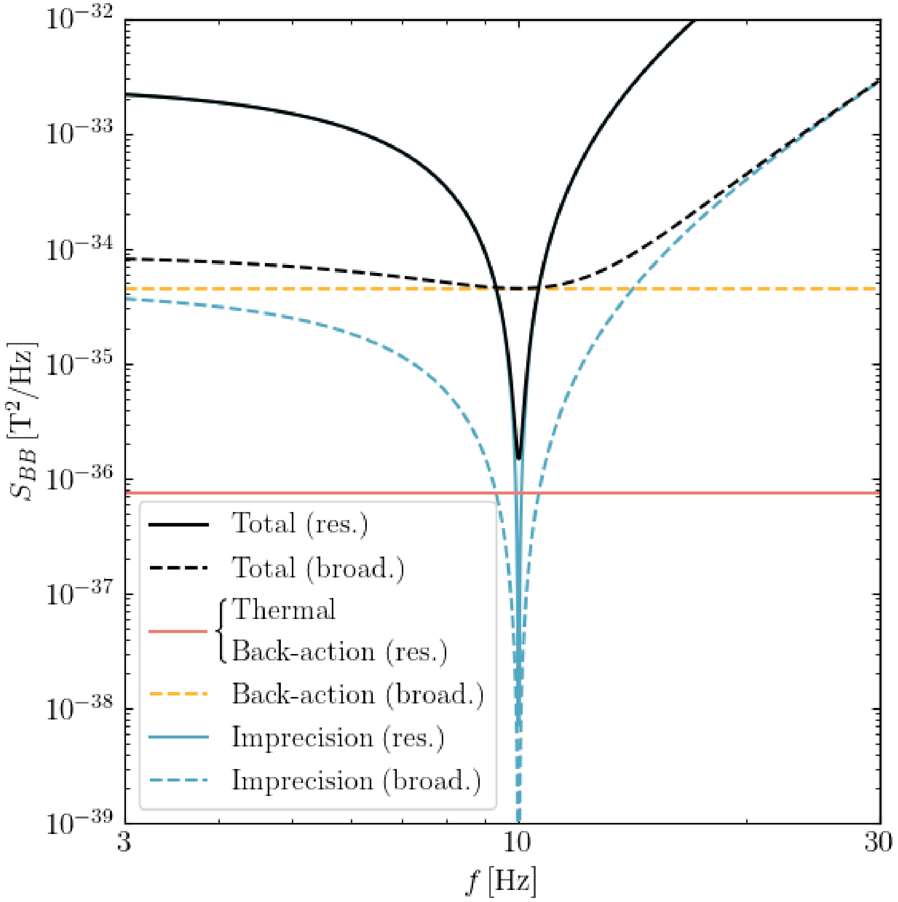
- Back-action: current noise → force
- Trade-off based on readout coupling



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

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

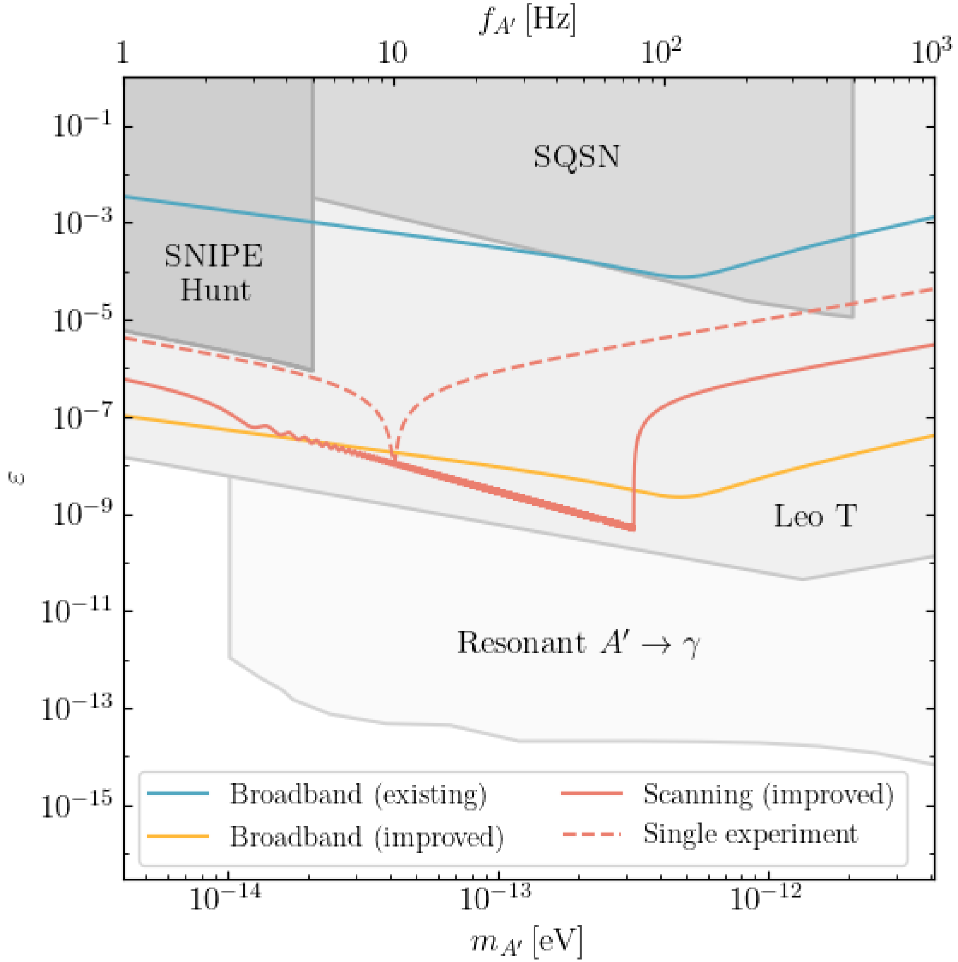


Dark photon sensitivity

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}

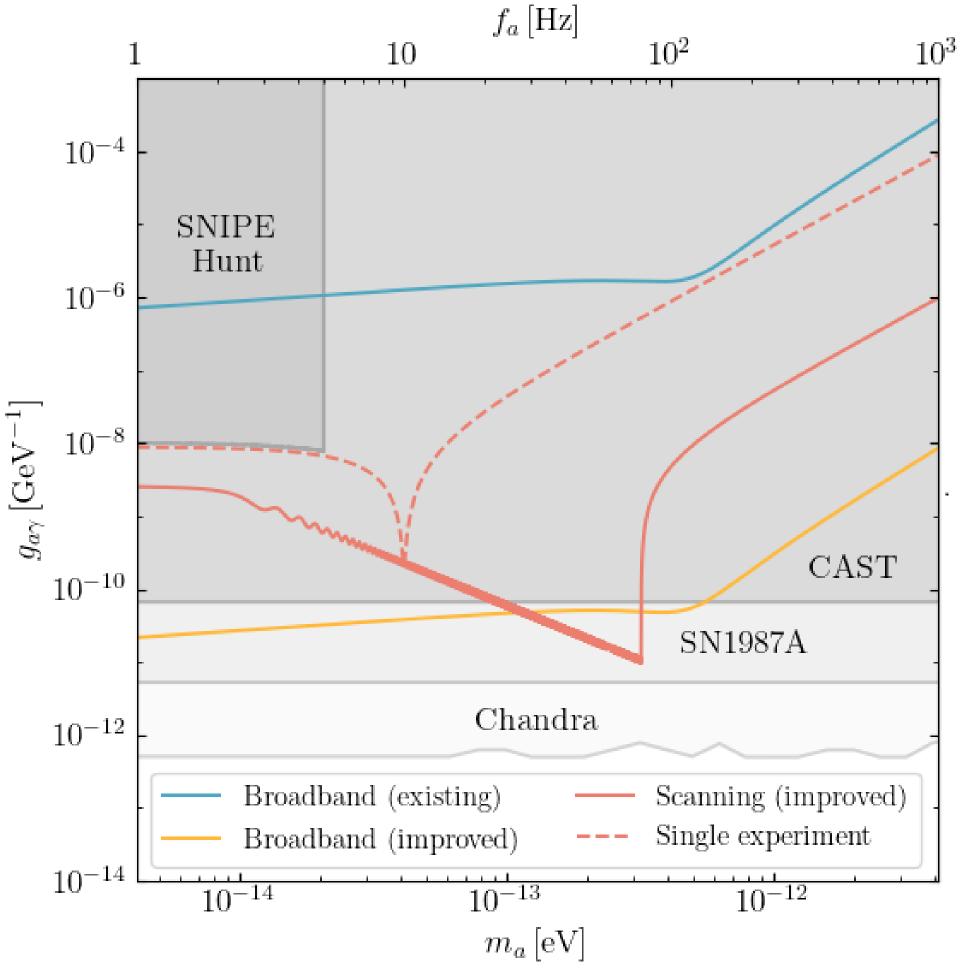


Axion sensitivity

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}



Conclusion

- Levitated superconductors can probe ultralight DM with $m_{\mathrm{DM}} \lesssim 10^{-12}\,\mathrm{eV}$
- Superconductor settles at center of quadrupole trap
- Ultralight DM sources magnetic field → perturbs equilibrium
- Resonant and broadband schemes
- Existing setups already comparable to DPDM experiments
- Dedicated setup can be leading laboratory probe of ultralight DM

Backup Slides

Physical considerations

- Vertical displacement:

$$\Delta z = \frac{g}{4\pi^2 f_z^2} \sim 3\,\mathrm{cm} \cdot \left(\frac{3\,\mathrm{Hz}}{f_z}\right)^2$$

- Maximum magnetic field:

$$B_{\mathrm{max}} \sim b_0 \mathcal{R} \sim 80\,\mathrm{mT} \cdot \left(\frac{m}{1\,\mathrm{g}}\right)^{1/3} \left(\frac{\rho}{0.1\,\mathrm{g/cm^3}}\right)^{1/6} \left(\frac{f_0}{100\,\mathrm{Hz}}\right)$$

- Pb and Ta have critical fields of $\sim 80\,\mathrm{mT}$

Sources of dissipation

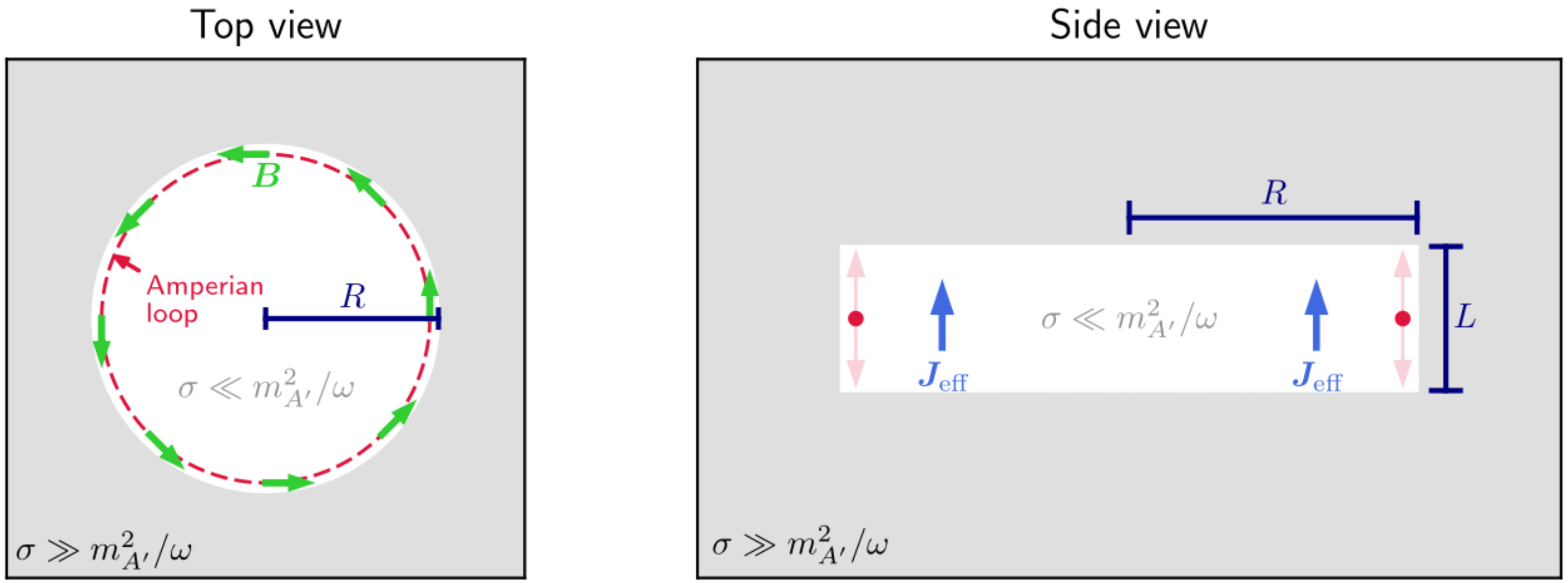
- Gas collisions:

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

- 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

DPDM magnetic field signal



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

Noise trade-off

- Imprecision and back-action noise determined by coupling η:

$$S_{BB}^{\text{imp}} = \frac{2\rho S_{\phi\phi}}{3m^2\omega_0^2\eta^2|\chi(\omega)|^2} \qquad S_{BB}^{\text{back}} = \frac{2\rho\eta^2 S_{JJ}}{3m^2\omega_0^2}$$

- Flux and current noise satisfy uncertainty relation $\sqrt{S_{\phi\phi}S_{JJ}} = \kappa \geq 1$
- Can define $\tilde{\eta} = \eta\sqrt[4]{\frac{S_{JJ}}{S_{\phi\phi}}}$, so that

$$S_{BB}^{\text{imp}} = \frac{2\rho\kappa}{3m^2\omega_0^2} \cdot \tilde{\eta}^{-2}|\chi(\omega)|^{-2} \qquad S_{BB}^{\text{back}} = \frac{2\rho\kappa}{3m^2\omega_0^2} \cdot \tilde{\eta}^2$$

Signal-to-noise ratio

- Coherent:

$$\mathrm{SNR} = \frac{B_{\mathrm{DM}}^2}{S_{BB}^{\mathrm{tot}}/t_{\mathrm{int}}}$$

- Incoherent:

$$\mathrm{SNR} = \frac{B_{\mathrm{DM}}^2}{S_{BB}^{\mathrm{tot}}/t_{\mathrm{coh}}} \cdot \sqrt{\frac{t_{\mathrm{int}}}{t_{\mathrm{coh}}}}$$

- Multiple scans:

$$\mathrm{SNR}^2 = \sum_i \mathrm{SNR}_i^2$$

Bandwidth

- Bandwidth defined by:

$$S_{BB}^{\text{tot}}\left(\omega_0+\frac{\delta\omega}{2}\right)=2S_{BB}^{\text{tot}}(\omega_0)$$

- For resonant coupling,

$$\delta\omega=\frac{4\sqrt{2}\gamma T}{\kappa\omega_0}\sim 2\pi\cdot 0.2\,\mathrm{Hz}\left(\frac{\gamma}{2\pi\cdot 10^{-8}\,\mathrm{Hz}}\right)\cdot\left(\frac{T}{10\,\mathrm{mK}}\right)\left(\frac{5}{\kappa}\right)\left(\frac{10\,\mathrm{Hz}}{f_0}\right)$$

- Total scan takes

$$\sum_i t_{\text{int},i}=\frac{\kappa\pi}{2\sqrt{2}\gamma T v_{\text{DM}}^2}\Delta\omega\sim 1\,\mathrm{yr}\left(\frac{\kappa}{5}\right)\left(\frac{2\pi\cdot 10^{-8}\,\mathrm{Hz}}{\gamma}\right)\cdot\left(\frac{10\,\mathrm{mK}}{T}\right)\left(\frac{\Delta f}{74\,\mathrm{Hz}}\right)$$