Search for high-mass axion from exotic spin dependent interactions ARIADNE

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On behalf of ARIADNE collaboration

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TAU meeting
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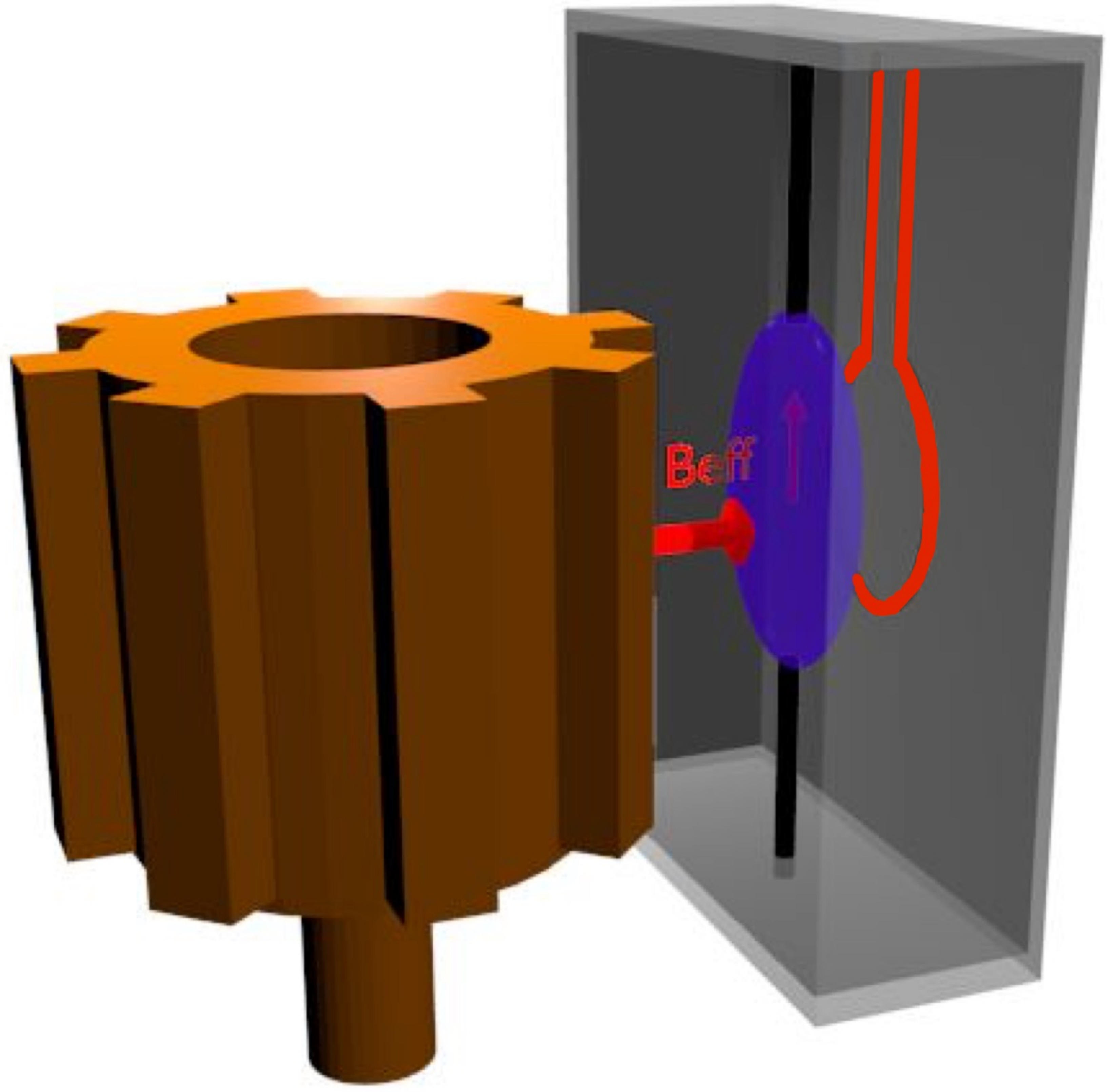
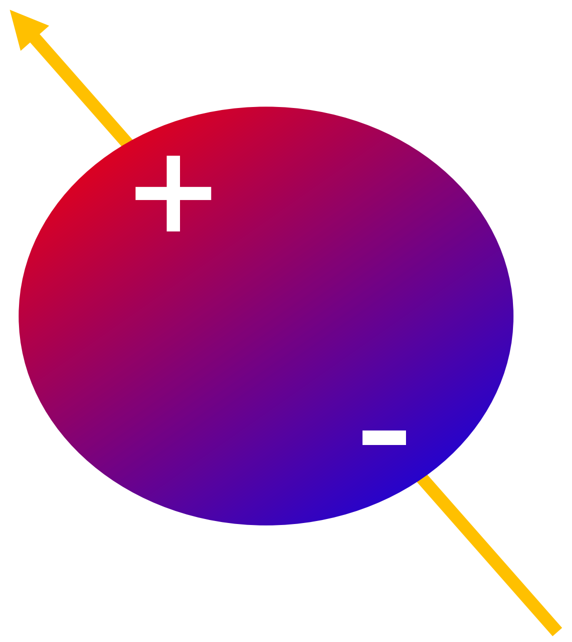


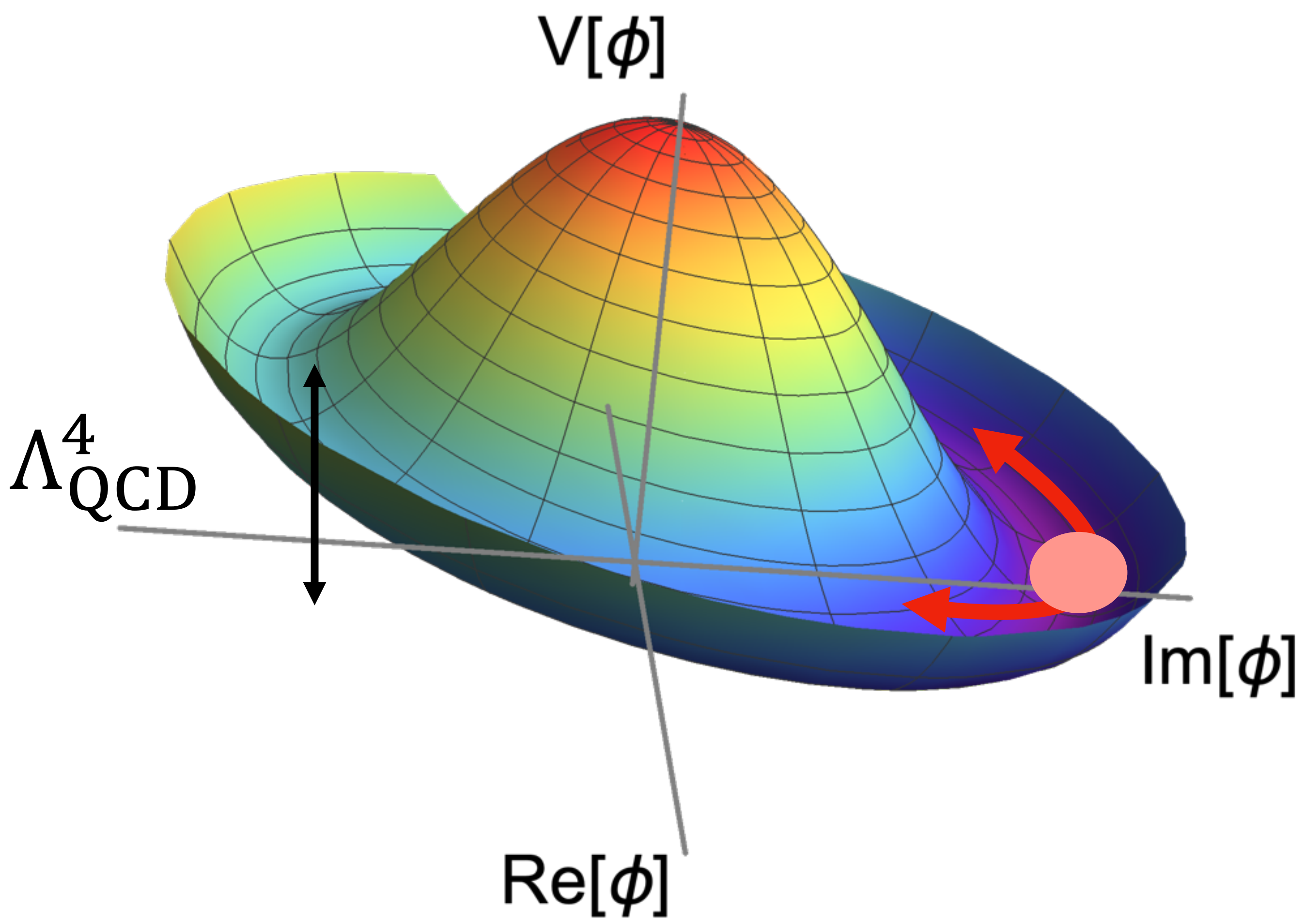
Fig from A. Arvanitaki and A. A. Geraci. Physical Review Letters, 113(16):161801, 2014

Strong CP problem and Axion

- **Neutron Electric Dipole Moment (nEDM):** $d_n = 3\times10^{-16}\bar{\theta}_{QCD}\ \mathrm{e\cdot cm}$
  - Expect: $\bar{\theta}_{QCD} \approx O(1)$
  - nEDM $d_n < 1.8\times10^{-26}\ \mathrm{e\cdot cm}:\ \bar{\theta}_{QCD} < 10^{-10}$ [1]
  - Unnatural small $\bar{\theta}_{QCD}$: Strong CP problem



- Peccei-Quinn proposed global $U(1)_{PQ}$ symmetry to solve the Strong CP problem [2],
  - Minimizing solution is $\theta_{\text{eff}} \equiv \bar{\theta}_{QCD} + \frac{\langle a\rangle}{f_a} = 0$



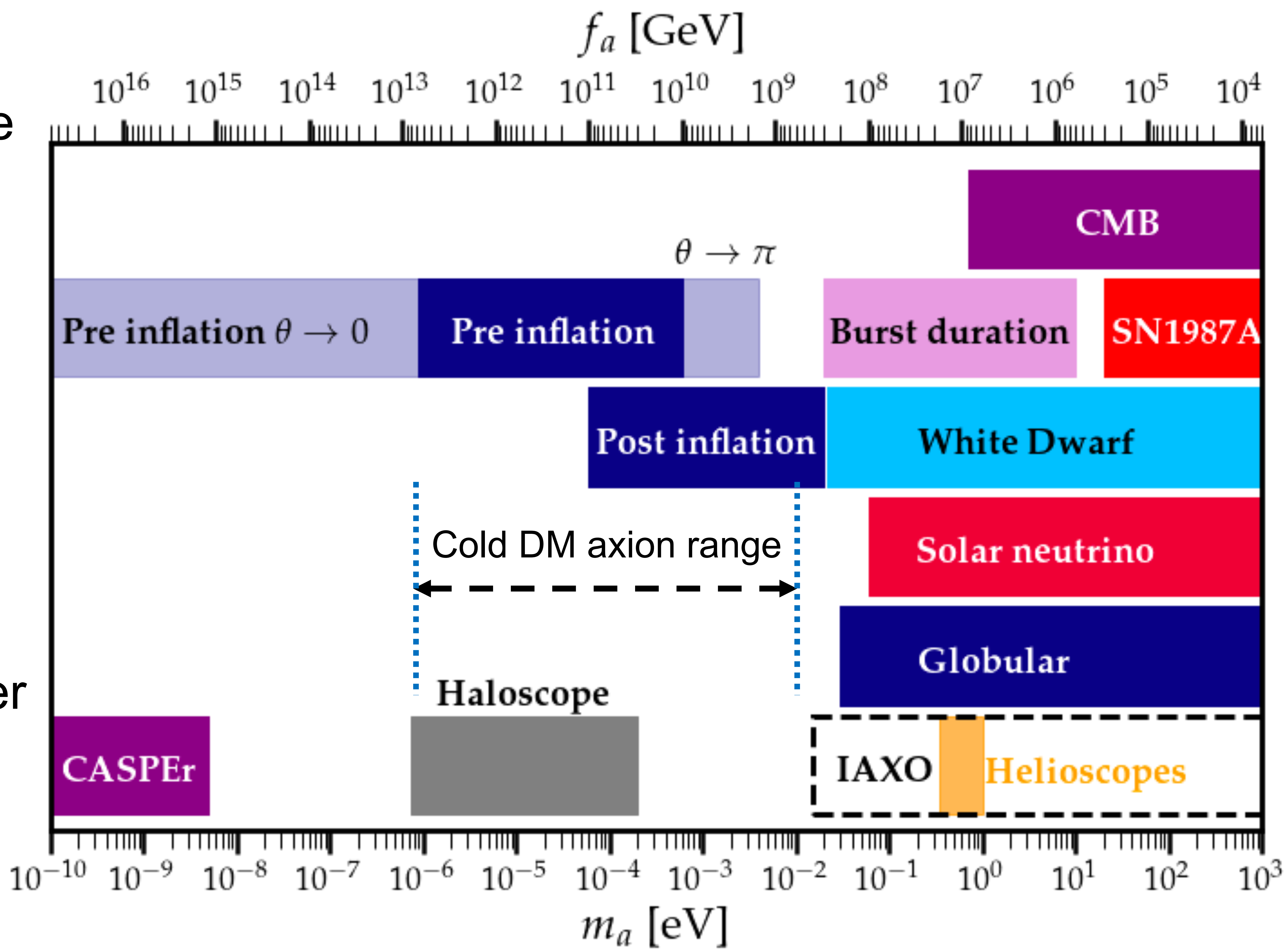
- An additional CP violating source (e.g CKM phase of EW CP violation) shifts the minimum to $\theta_{\text{eff}} \neq 0$! [3]

$\bar{\theta}_{QCD} \equiv \theta_{QCD} + \mathrm{Det}(\mathrm{Arg}\, M_q)$

[1] C. Abel *et al* ., Phys. Rev. Lett., 124:081803, 2020.
[2] R. D. Peccei and H. R. Quinn, Phys. Rev. Lett., 38:1440–1443, 1977.
[3] J. E. Moody and F. Wilczek, Physical Review, 30:130–138, 1984.

Axion parameter space

- Axion could be a **cold dark matter** candidate
- Favored mass range for dark matter axion :
  - $1\mu\text{eV} \lesssim \text{m}_\text{a} \lesssim 10\text{meV}$ [1,2]
- Haloscope searches can cover mass range $1\mu\text{eV} \lesssim \text{m}_\text{a} \lesssim 0.1\text{meV}$,
  - Relies on dark matter axion density
- $0.1\ \text{meV} \lesssim \text{m}_\text{a} \lesssim 10\ \text{meV}$ range needs another methods for axion search

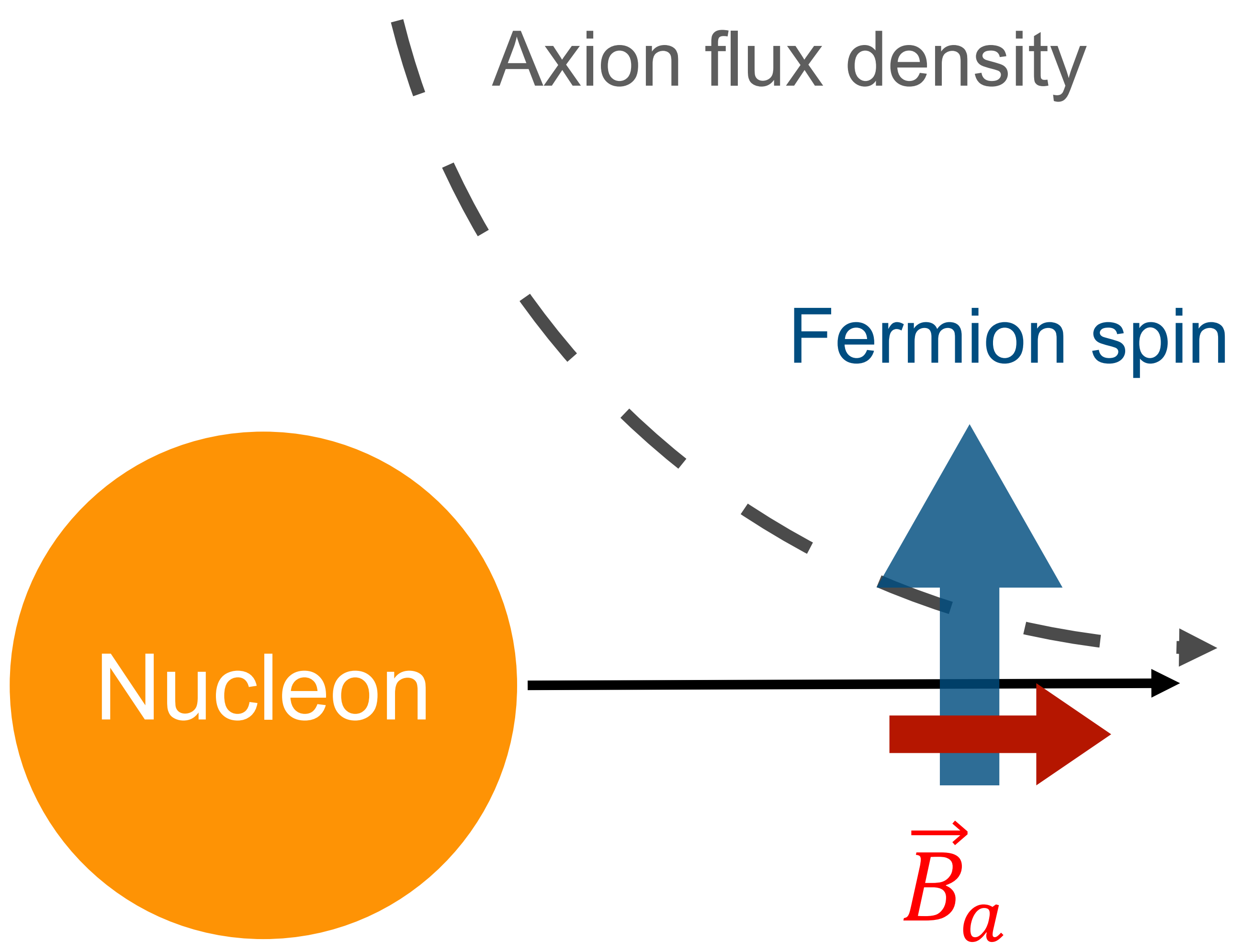


[1] C. Hagmann and P. Sikivie, Nucl. Phys. B363(1):247–280, 1991.
[2] G. Raffelt and D. Seckel. Phys. Rev. Lett., 60:1793– 1796,1988.

Fig from: Rouven Essig et al. arXiv:1311.0029. 2013.

Axion mediated interaction

- Axion can interact with SM fermions [1]
- Axion interactions can be categorized into two parts
  - CP odd: $L_s = g_s a\, \bar{\psi}\psi$
    - Additional CP violation θ_{CP} required, $g_s \sim \theta_{CP}/f_a$ [1,2]
  - CP even: $L_p = g_p \partial_\mu a\, \bar{\psi}\gamma^\mu \gamma_5 \psi$
    - Fermion spin couples to gradient of axion field



$$V(r) = \frac{\hbar g_s g_p}{8\pi m_f c}(\vec{\sigma}\cdot\hat{r})\left(\frac{2\pi}{\lambda_a r} + \frac{1}{r^2}\right) e^{-2\pi r/\lambda_a} \equiv \vec{\mu}\cdot\vec{B}_a$$

- In non-relativistic limit, the axion mediated interaction acts as a fictitious magnetic field on fermion spin
- The sensible interaction scale depends on the axion Compton wavelength λ_a

$\lambda_a/2\pi = 1mm$: 0.2 meV

[1] J. E. Moody and F. Wilczek, Phys. Rev. D 30, 130, 1984
[2] M. Pospelov, Phys. Rev. D, 58:097703, 1998.,

Axion Resonant InterAction DetectioN Experiment

- Search for axion using the monopole-dipole interaction between unpolarized mass and polarized fermion.
- No axion dark matter assumption is necessary
- Potential to probe broad axion mass range with single measurement:

$$0.1\text{meV} \lesssim m_a \lesssim 10\text{meV}$$

- **Potential to reach the QCD axion parameter space**
- **Strong correlation with nucleon EDM in the axion mass range**

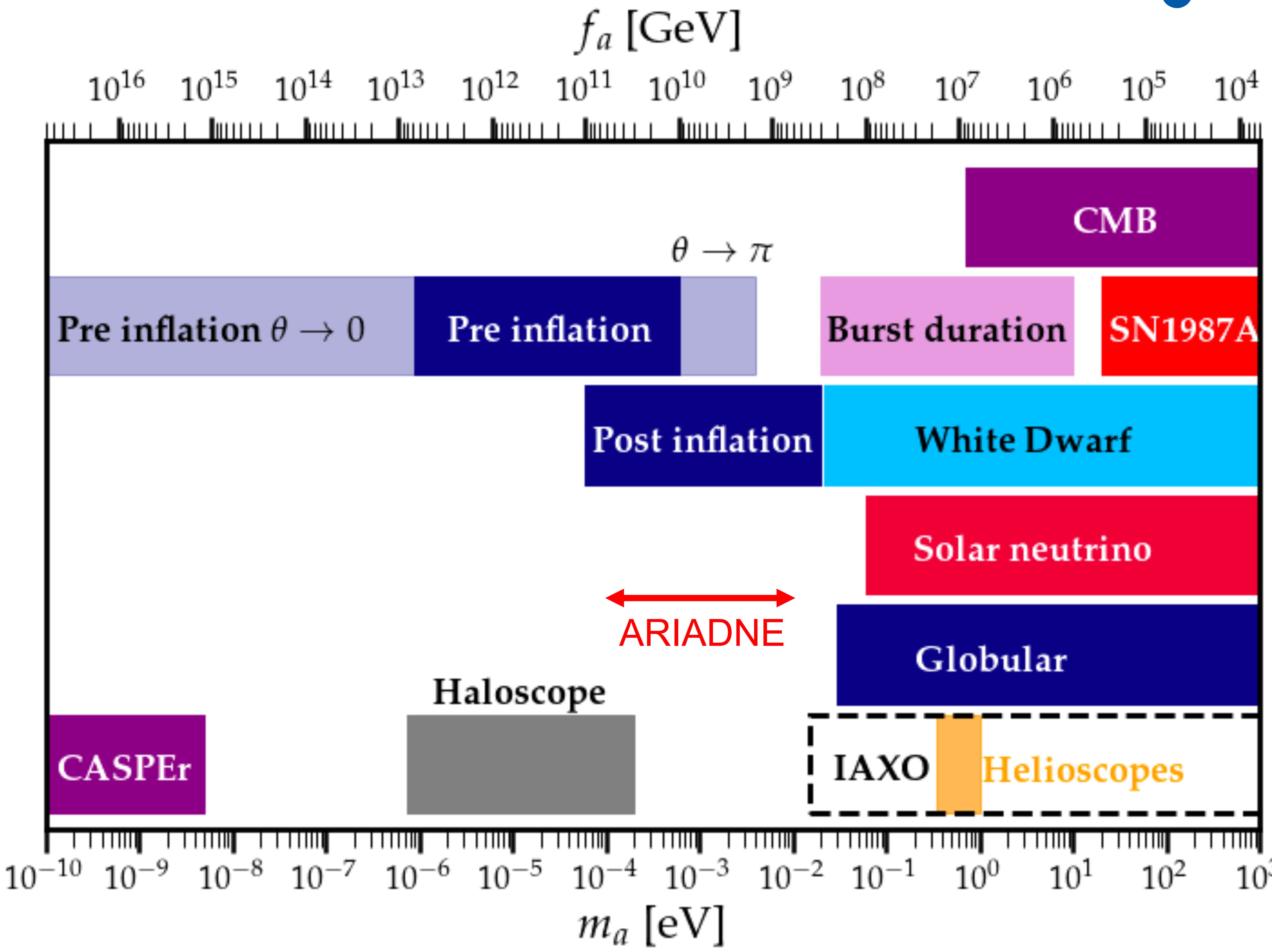


Fig from: Rouven Essig et al. arXiv:1311.0029. 2013.

ARIADNE - Schematic

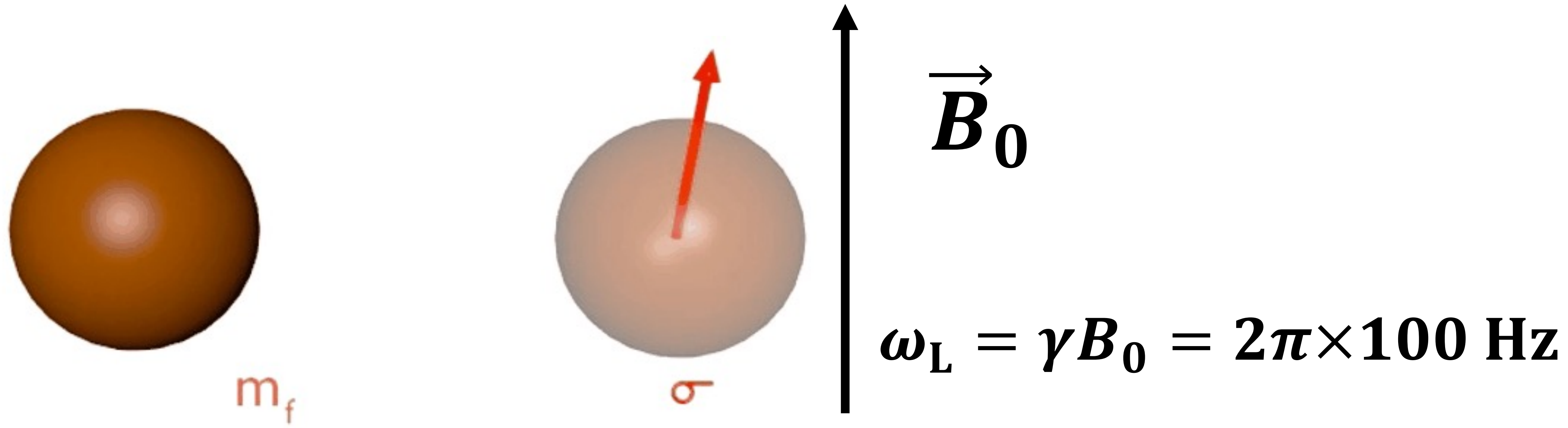
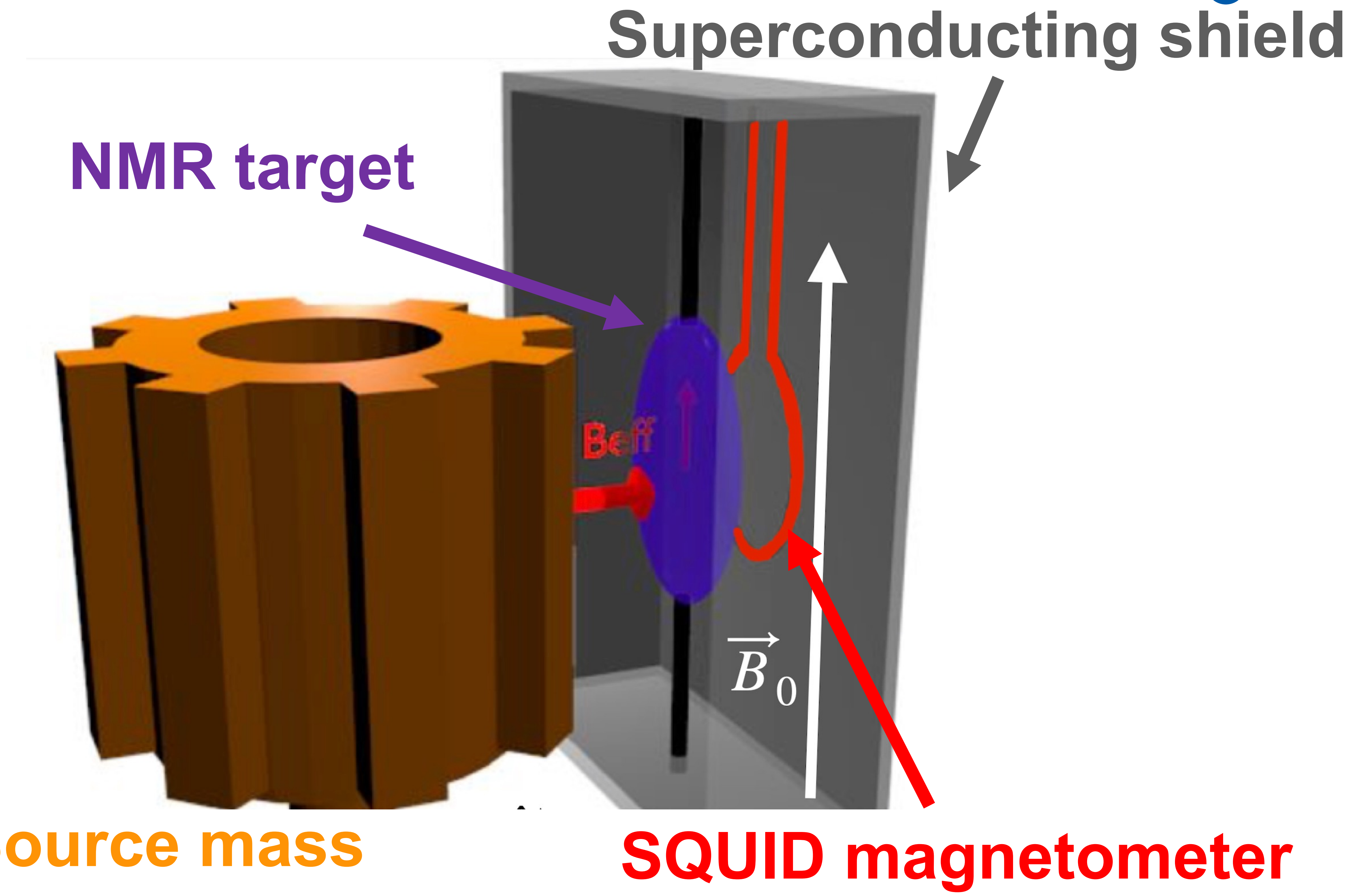


Figure from A.A. Geraci presentation

- Fictitious magnetic field B_{eff}:

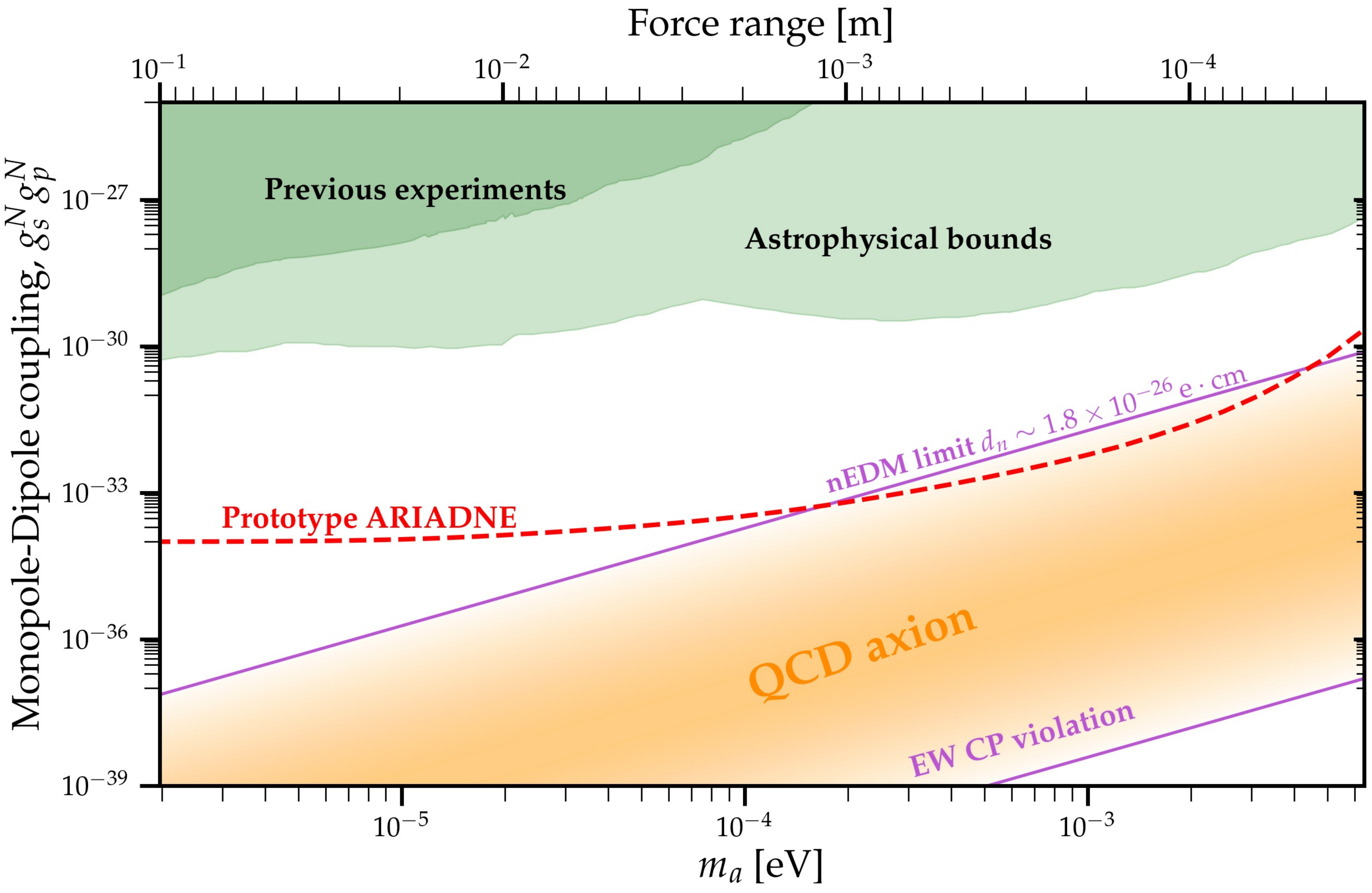
$$\vec{B}_{\text{eff}} = \frac{\hbar g_s g_p}{8\pi\gamma_p M_p}(\vec{\sigma}\cdot\hat{r})\left(\frac{2\pi}{\lambda_a r}+\frac{1}{r^2}\right)e^{-2\pi r/\lambda_a}\hat{r}$$

- Distance modulation → B_{eff} oscillation
- Spin system resonantly enhance B_{eff}
- It is not governed by Maxwell's equations
- Tungsten: Source mass, ^{3}He: NMR target



1. Nuclear Magnetic Resonance
2. High sensitive SQUID magnetometer
3. Superconducting shield

ARIADNE – projected sensitivity



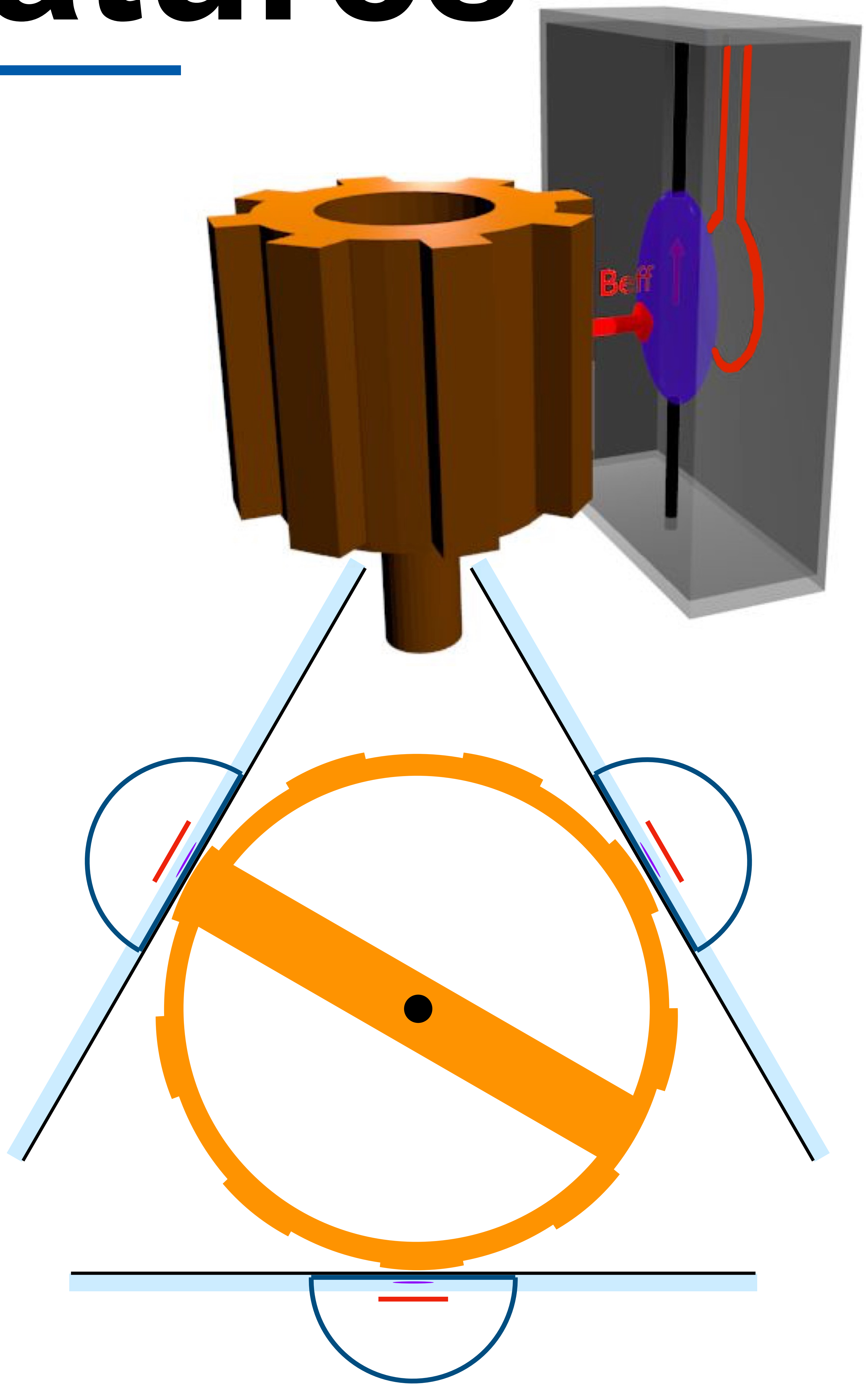
*Integration time: 10^6 s

[1] C. Abel *et al* ., Phys. Rev. Lett., 124:081803, 2020.
[2] Georgi, H., and L. Randall, 1986, Nucl. Phys. B276, 241.

- Experimentally allowed QCD axion:
  - Upper limit: nEDM [1]
  - Lower limit: EW CP violation [2]
- Prototype ARIADNE:
  - NMR target: Polarized ^{3}He gas
  - Constraints by quantum fluctuation of NMR target
  - $0.1\text{meV} \lesssim m_a \lesssim 4\text{meV}$
- Sensitivity does not rely on axion density in dark matter

Improved design features

- **Vibration-hardened SQUID based detector**
  - Detector is placed under external magnetic field with external vibrational noises: need to remove
- **Performance of thin film superconducting magnetic shield**
  - Thin superconductor film deposited on quartz
- **Source mass optimization**
  - Sensitivity dependence on amplitude of B_{eff} modulation

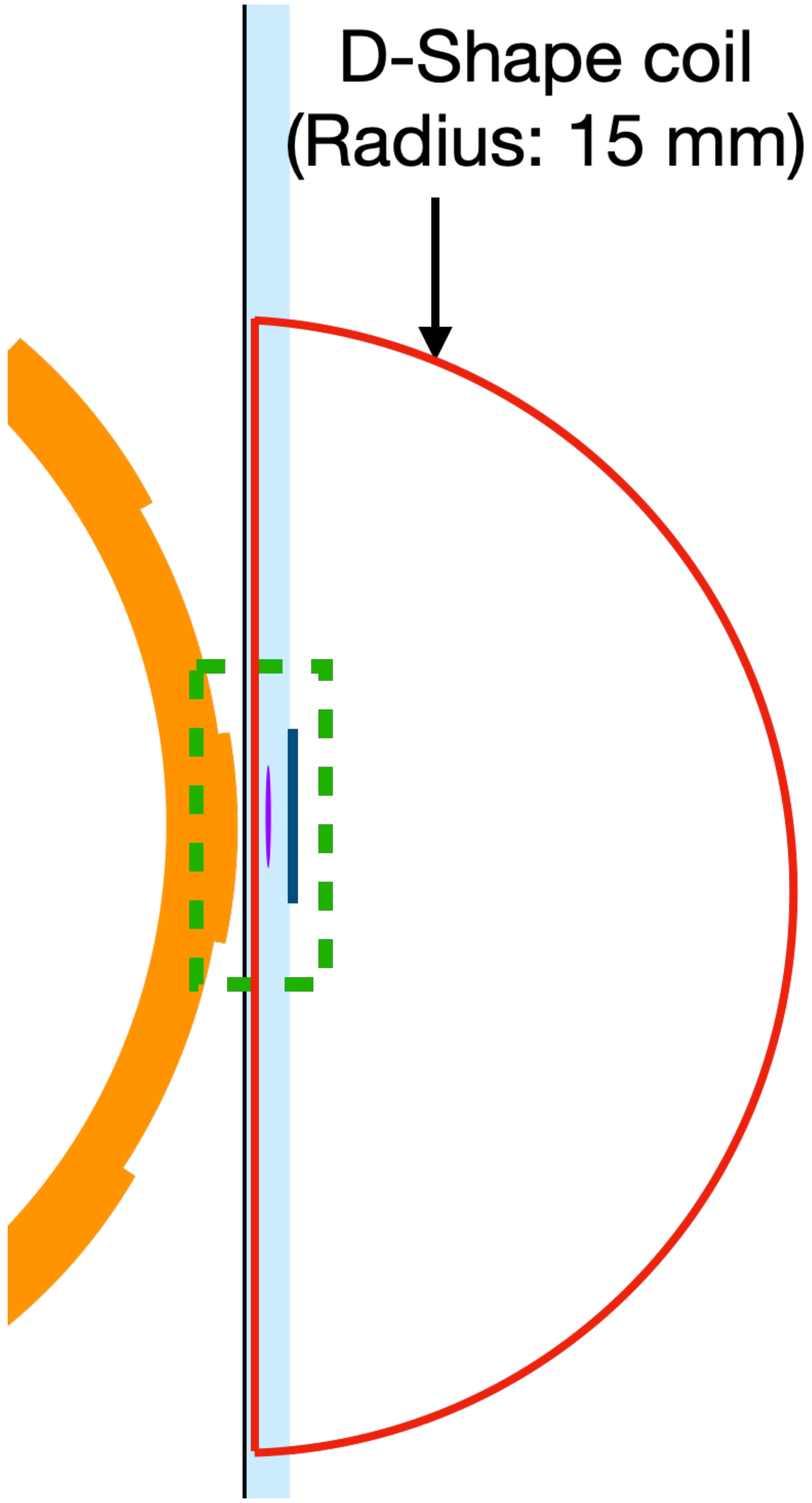


Vibration-hardened SQUID based detector

Thin film superconducting magnetic shield

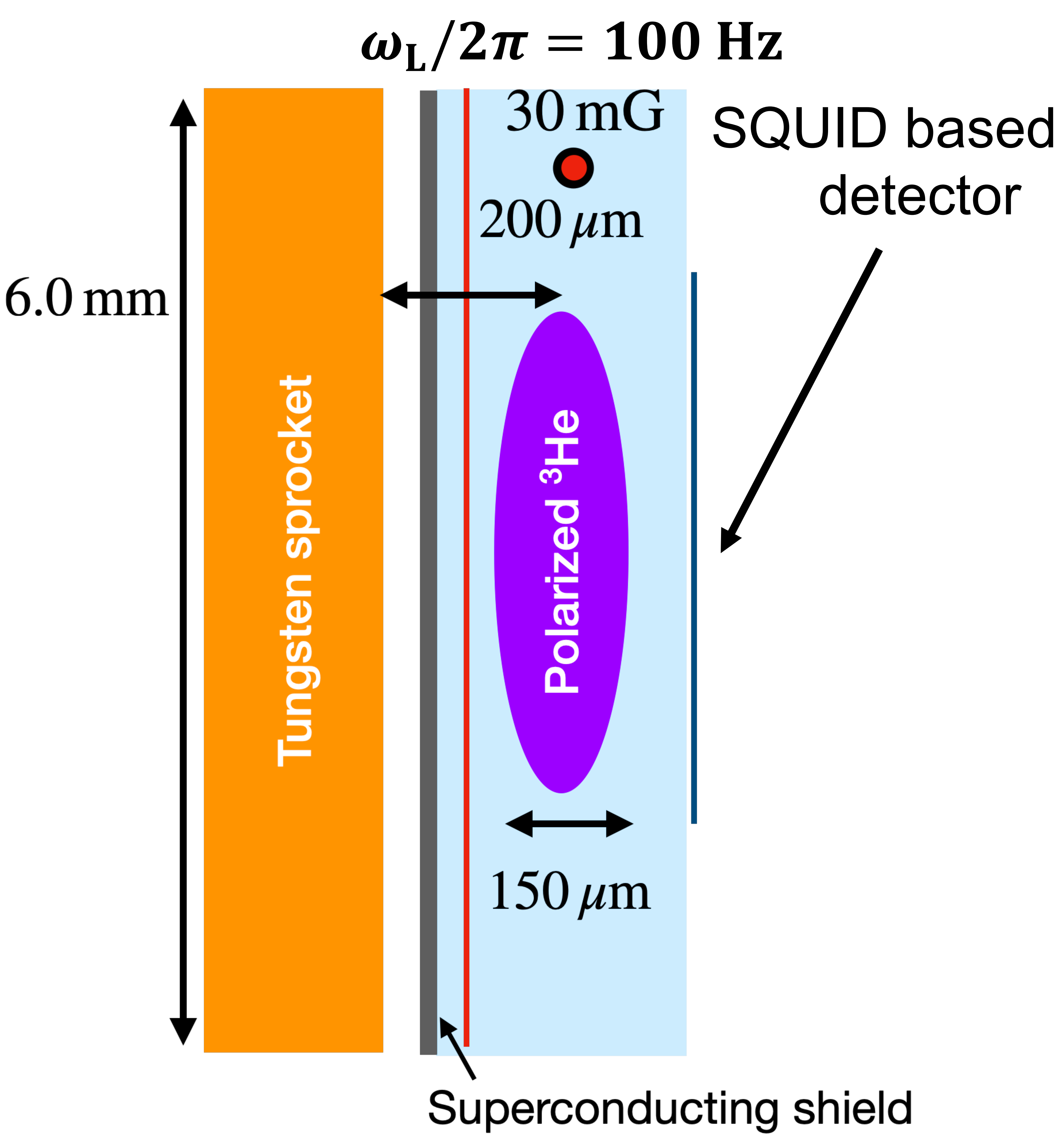
Source mass optimization

Issue with magnetometer

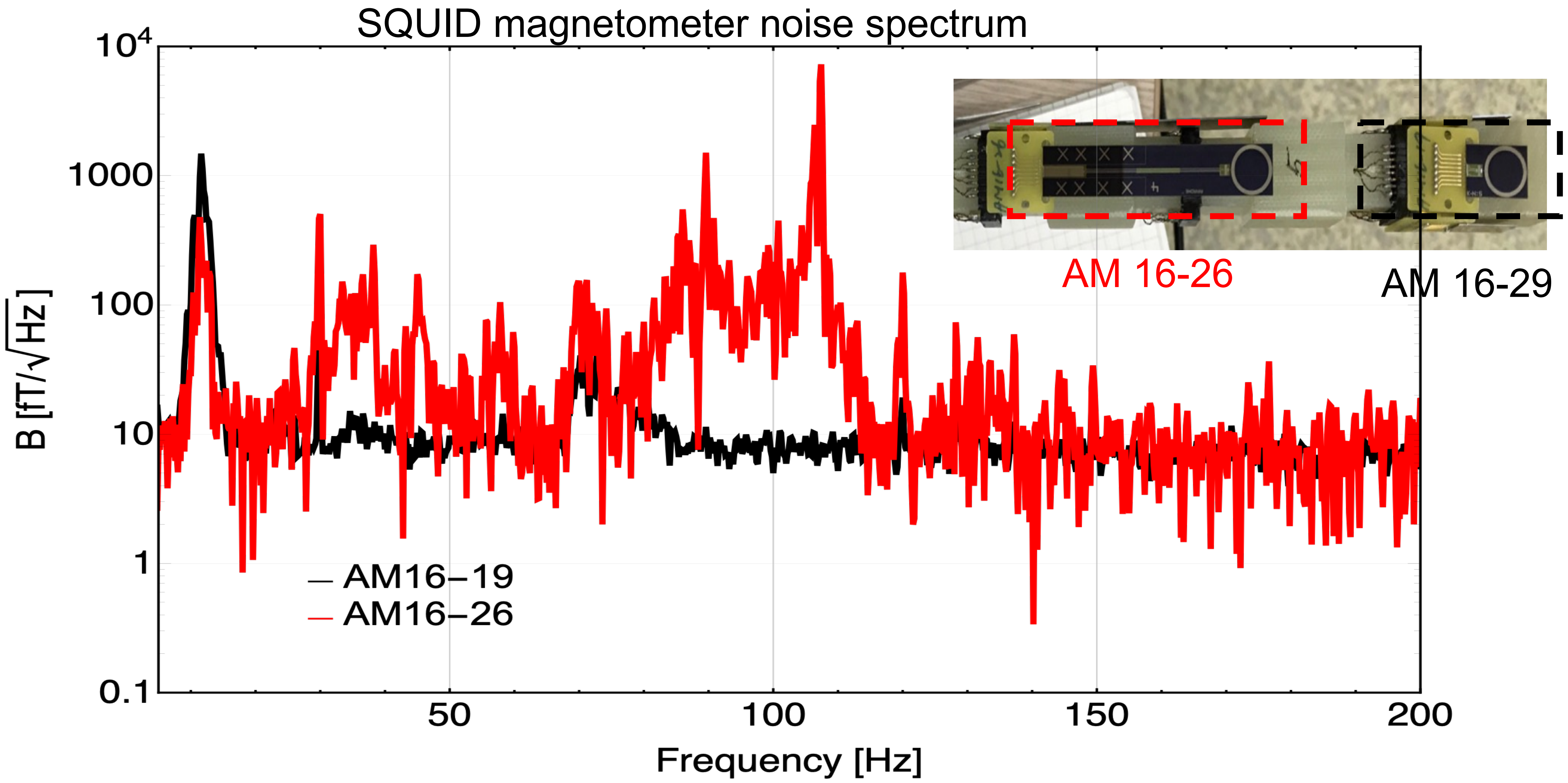


SQUID needs to be quite near 100Hz

Issue with magnetometer

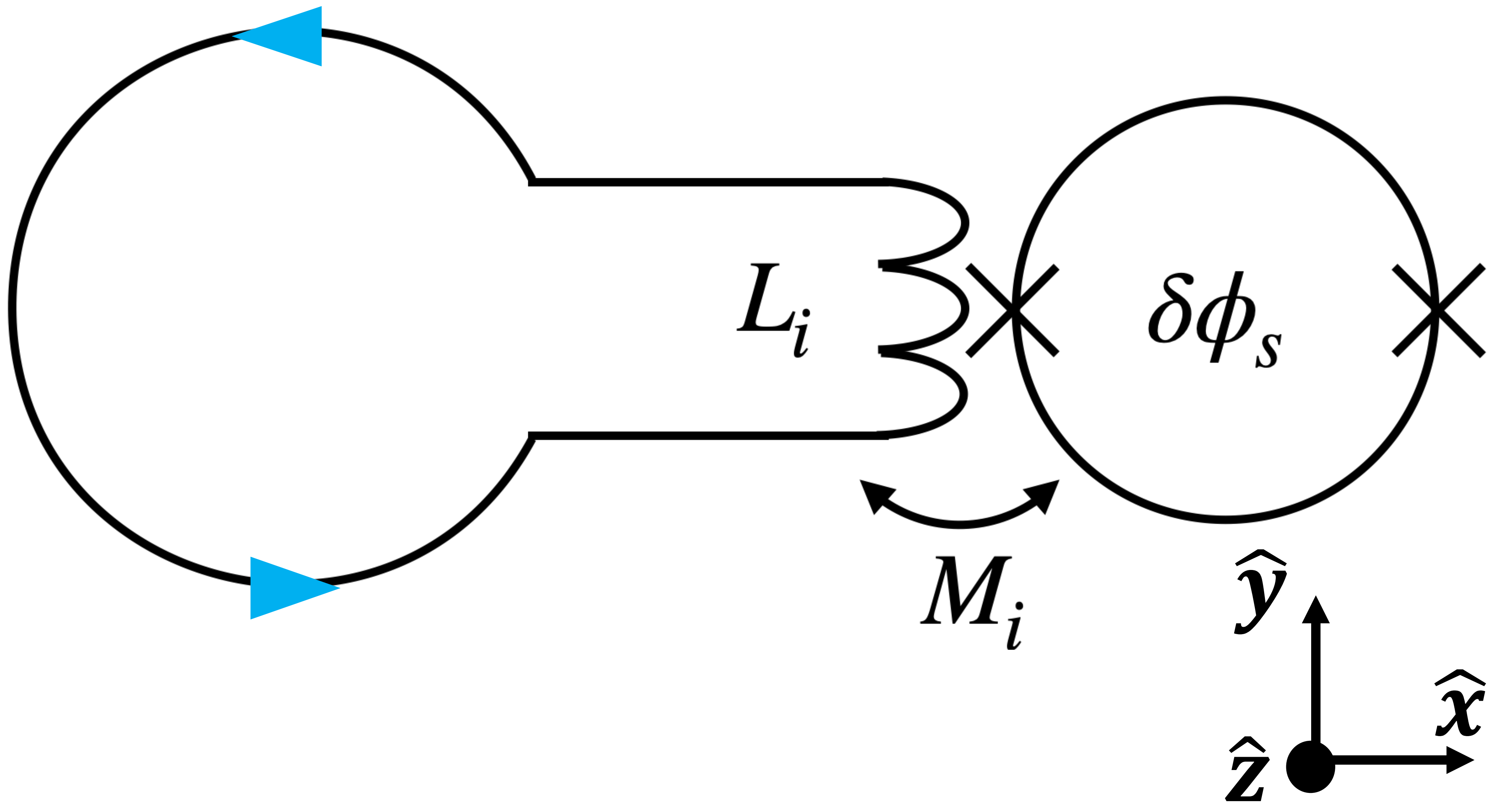


Detector needs to be quite near 100Hz

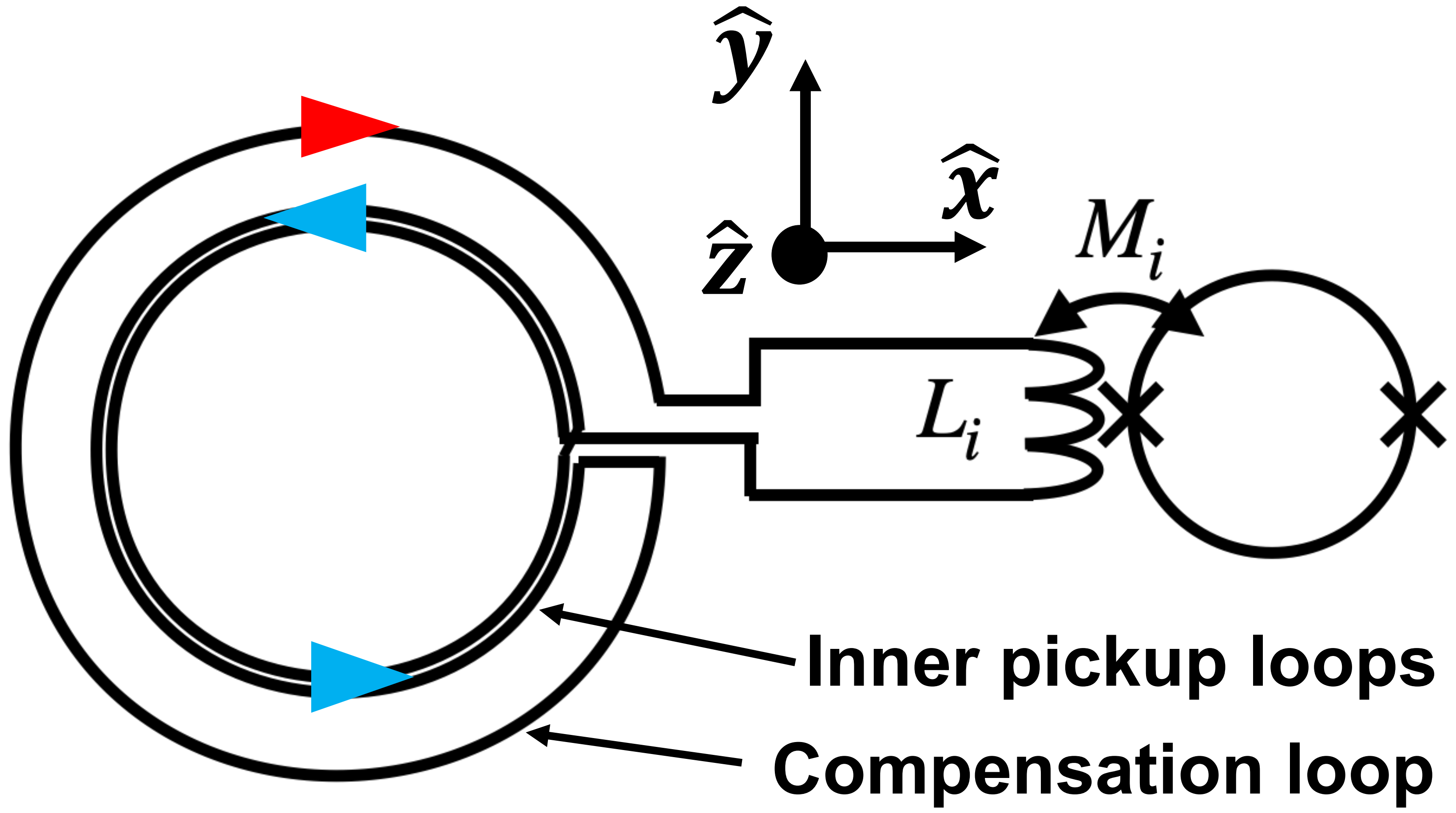


- **Measured noise inside magnetic shielded room with lead shield**
- Current magnetometer design⟹ **Vibration issue**

Magnetometer vs. gradiometer

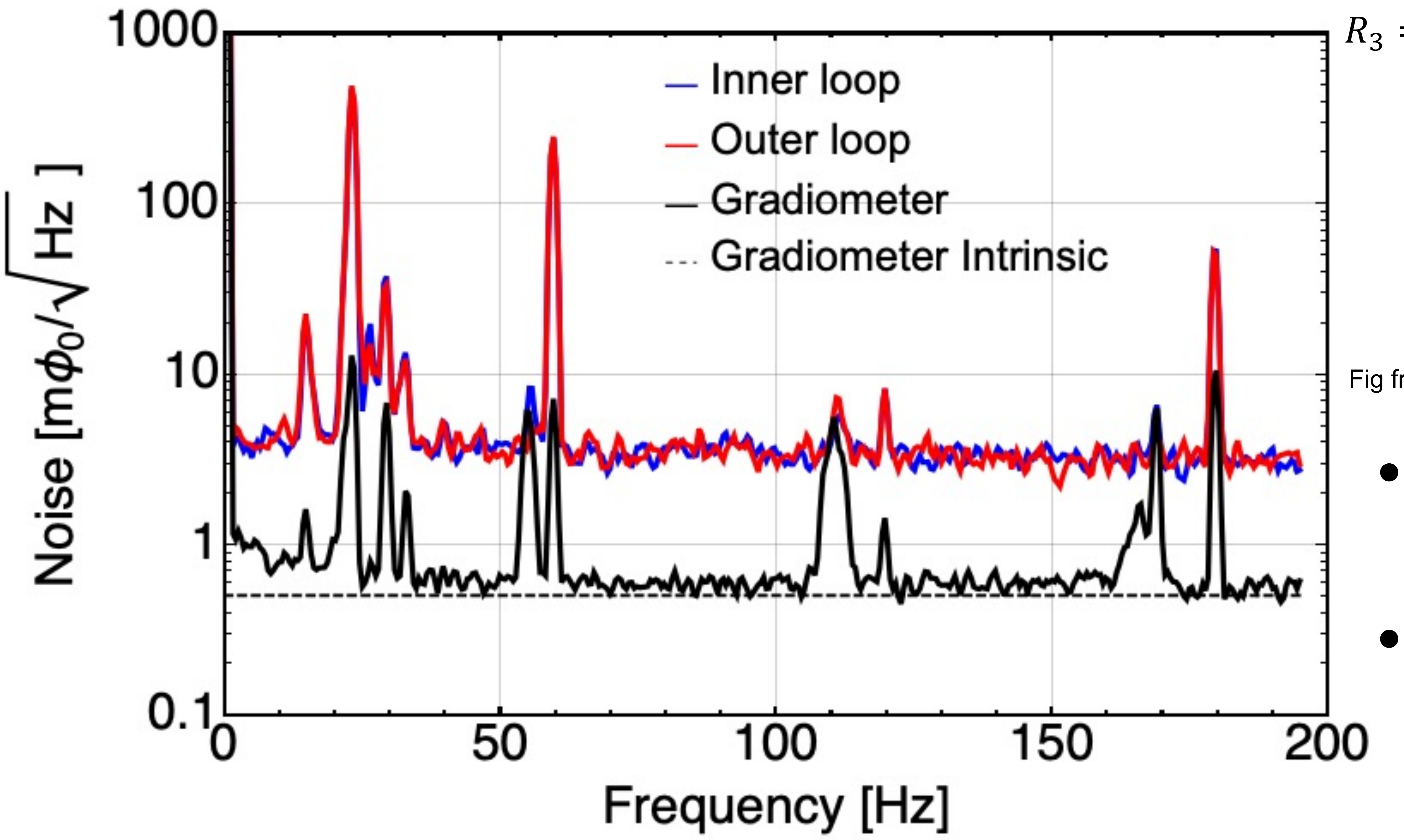


- Magnetometer
- Composed of single pickup loop
- Low intrinsic noise
- **High sensitive to vibration noise**



- Second order coaxial planar gradiometer
- Composed of two inner pickup loops and compensation loop
- High balance level (10^{-6})
- **Sensitive to local dipole source**

Noise vs. gradiometer



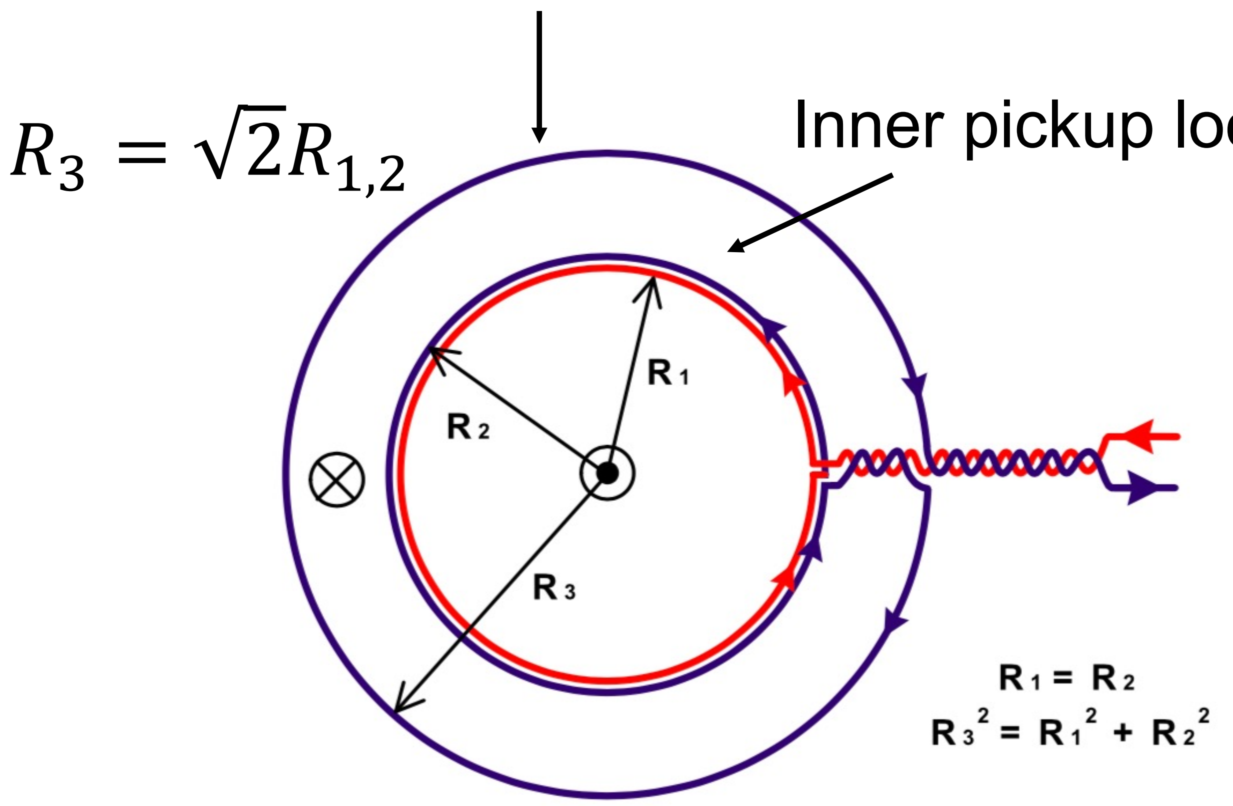
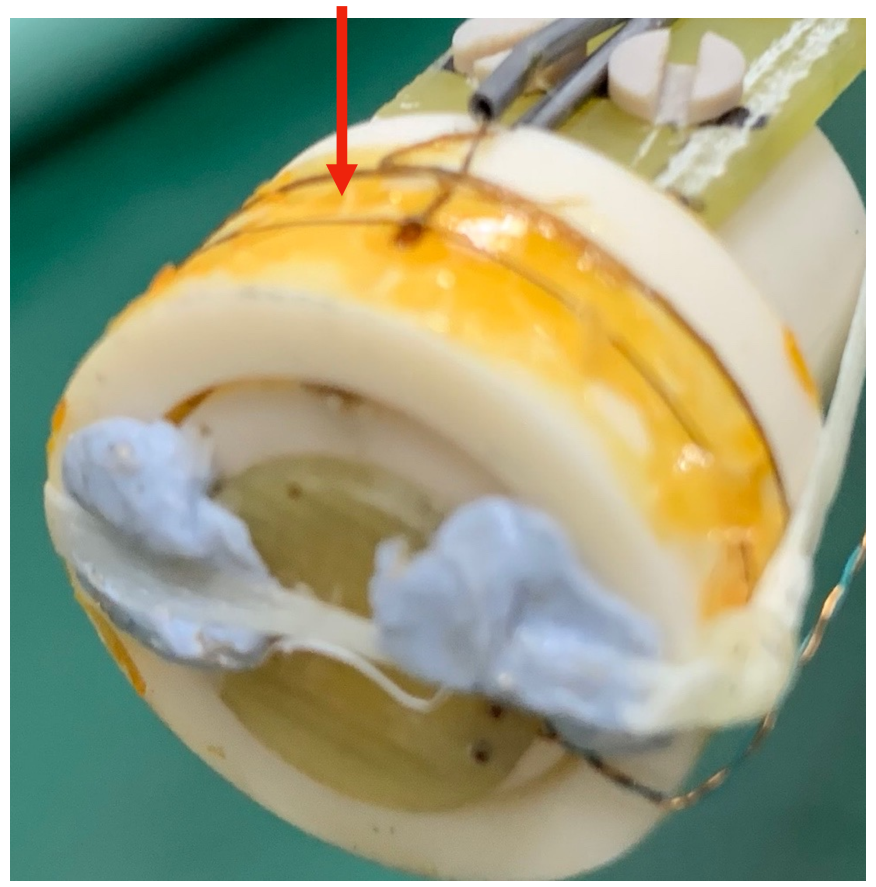


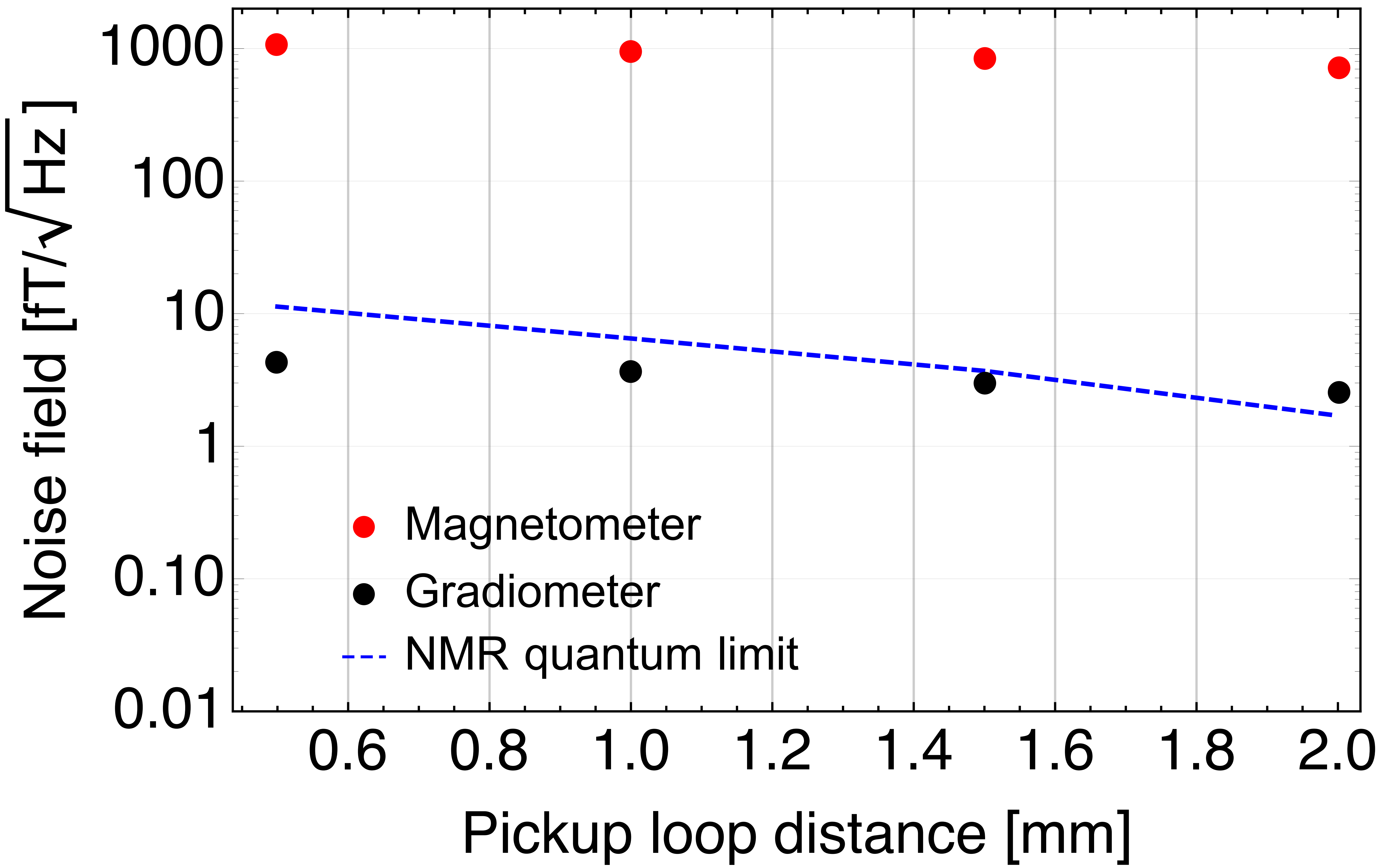
Fig from Y. J. Kim, et al. Physical Review D, 91(10):102004, 2015.

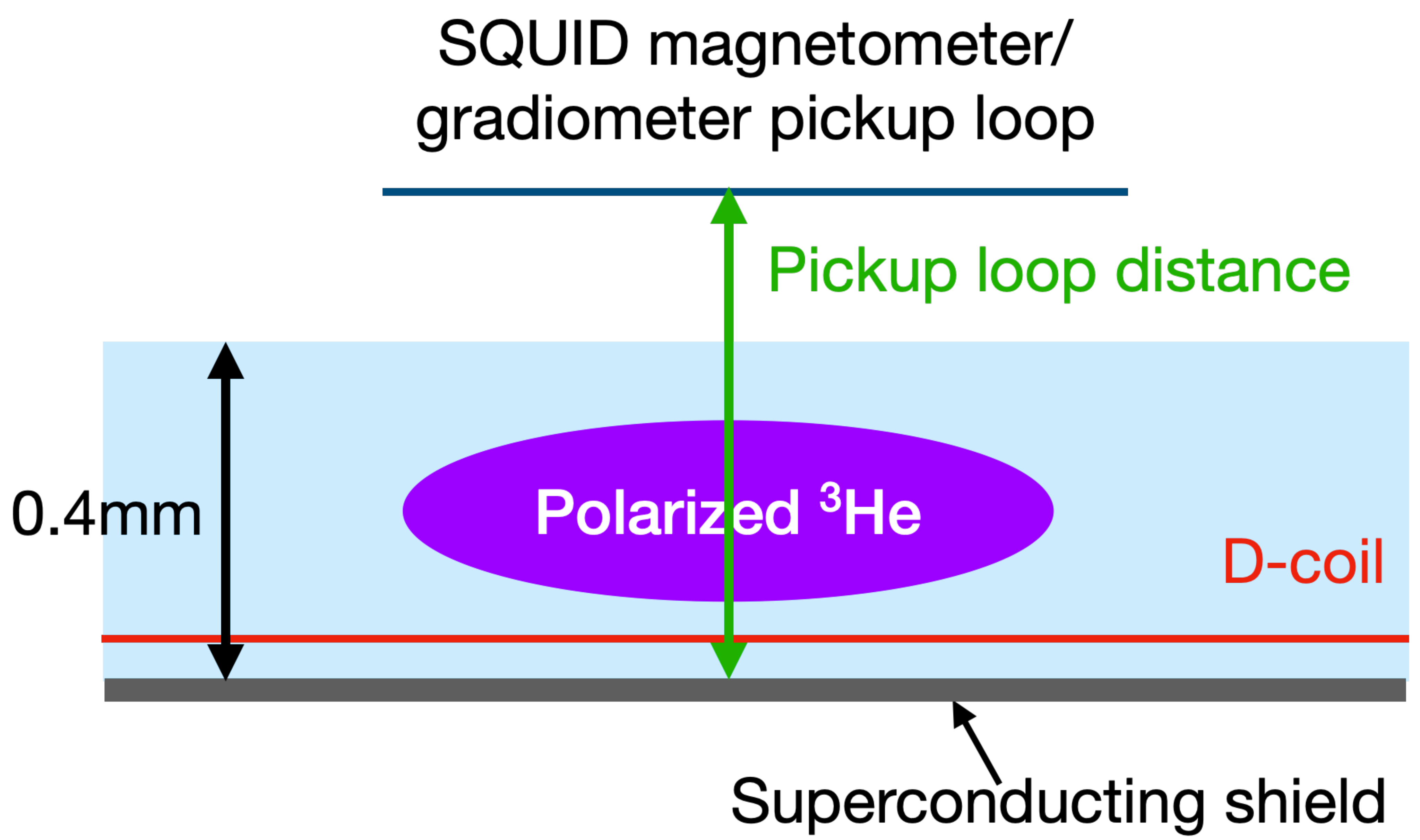
Outer coil (Compensation)



- Gradiometer: two SQUID magnetometers and electric compensation circuit
- Gradiometer:
  - Low and flat noise figure near 100Hz
  - Less sensitive to vibration

Optimization of gradiometer





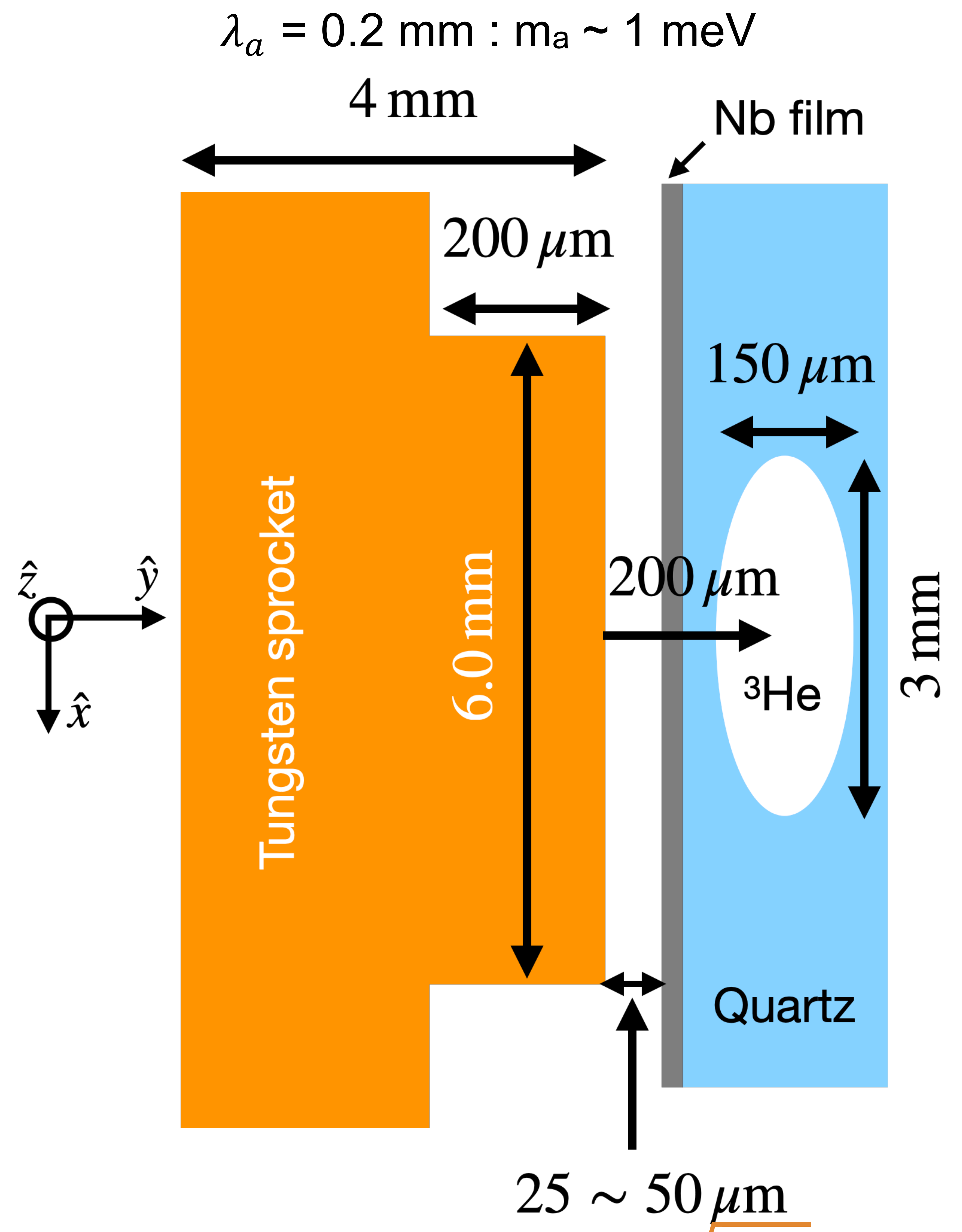
- Vibration level: $1\mathrm{nm}/\sqrt{\mathrm{Hz}}$
- Spin induced quantum noise: $\mathbf{10\ fT/\sqrt{Hz}}$
- Gradiometer intrinsic noise: $\mathbf{3fT/\sqrt{Hz}}$
- This gradiometer will be used in ARIADNE

Vibration-hardened SQUID based detector

Thin film superconducting magnetic shield

Source mass optimization

Superconducting thin-film magnetic shield



Johnson noise ~ $1\text{pT}/\sqrt{\text{Hz}}$

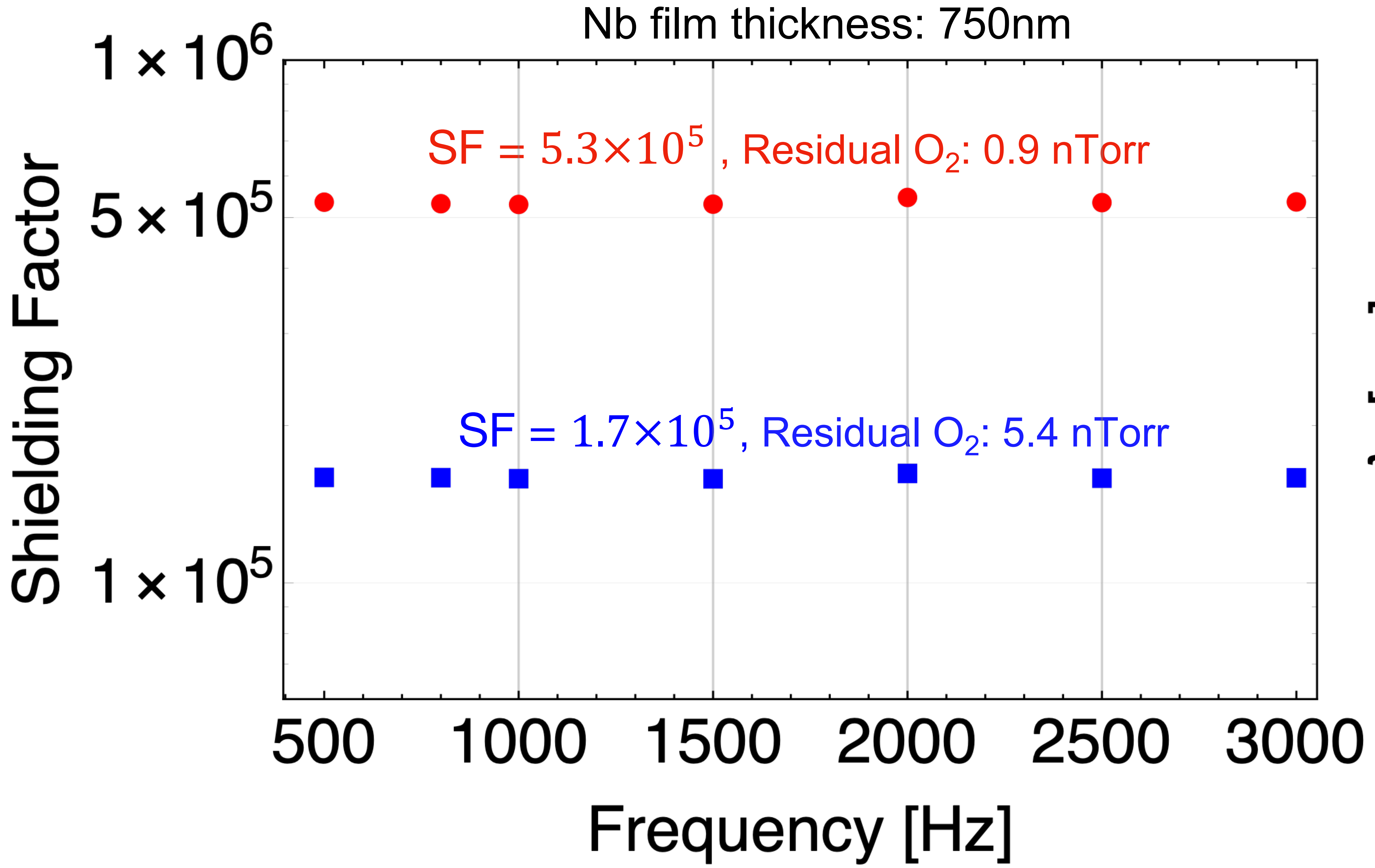
- Superconducting (SC) thin film shield reduces external magnetic noise (e.g: Johnson noise)
- Required noise level :

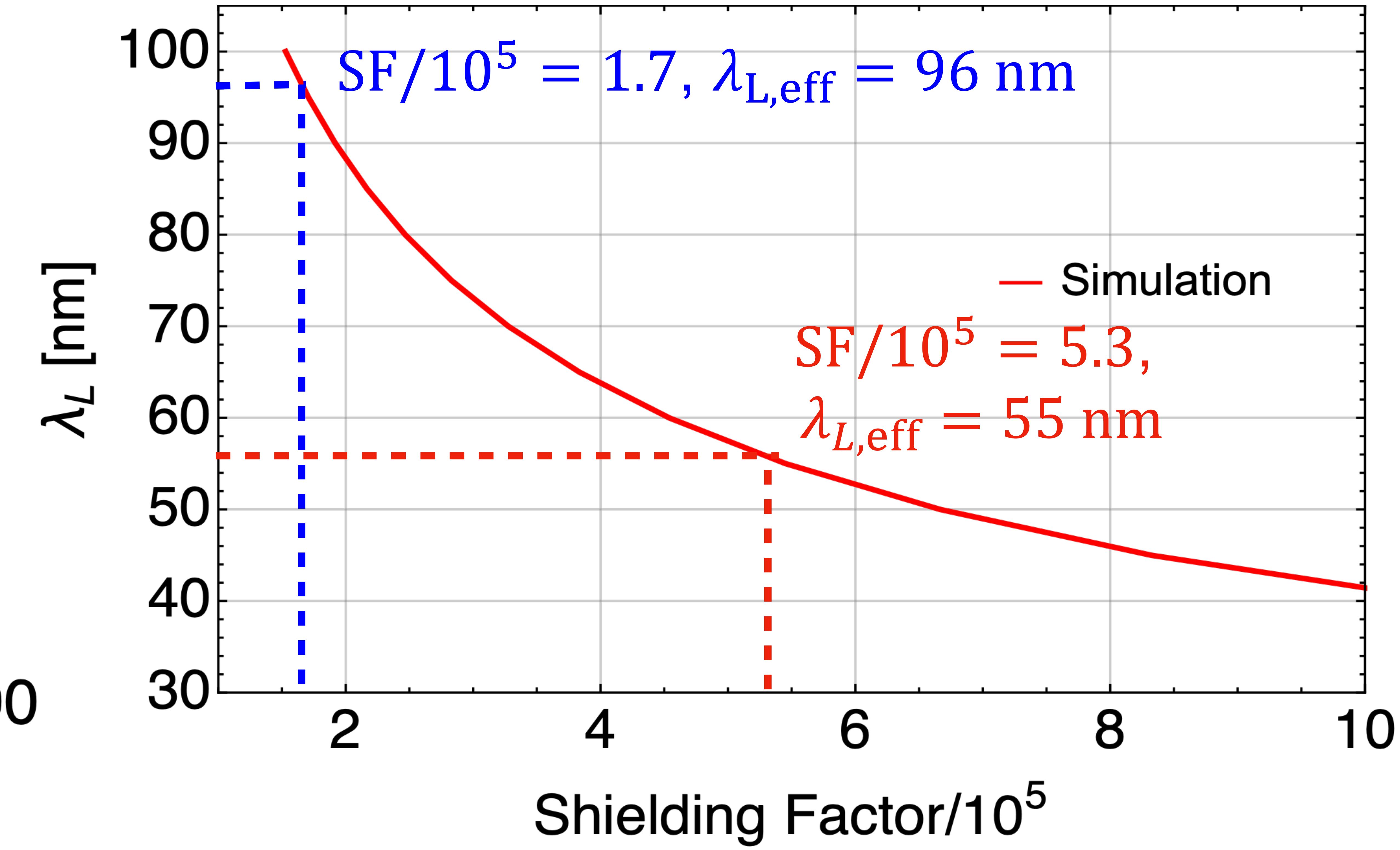
$$\delta B_{\text{min}} \leq \delta B_{\text{spin}} \approx 3\times10^{-19}\text{T}/\sqrt{\text{Hz}}$$

  - **Shielding factor (SF) >** 5×10^6
- **SC film deposited on quartz substrate**
- **SC film thickness** $\lesssim 10\mu m$
- Evaluate the quality of thin films on **quartz** by measuring SFs.

H. Fosbinder-Elkins, Y. Kim *et al.*, Quantum Science and Technology, 2021.

Shielding factor vs Film thickness





- SF of two Nb film samples fabricated under different condition

Pure Nb: $\lambda_L(4K) \approx 40\text{nm}$ (BCS), ξ_0/l: Purity parameter

$$\lambda_{L,\text{eff}} = \lambda_{\text{pure}}(T)\sqrt{1+\xi_0/l}$$

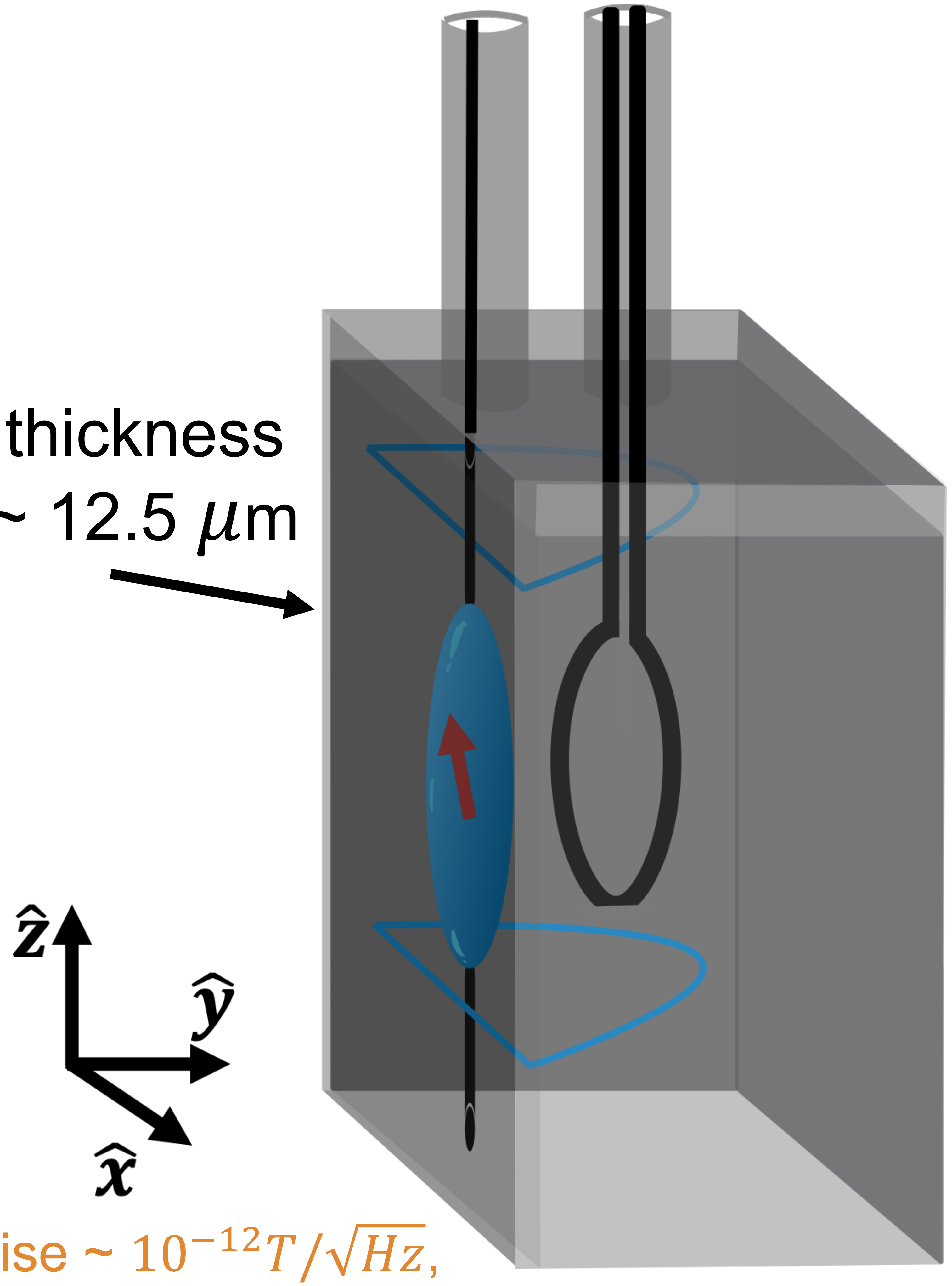
Quartz tube size: OD: 14 mm, Height: 150mm

Coherence length (ξ_0): 39 nm, Electron mean free path (l)

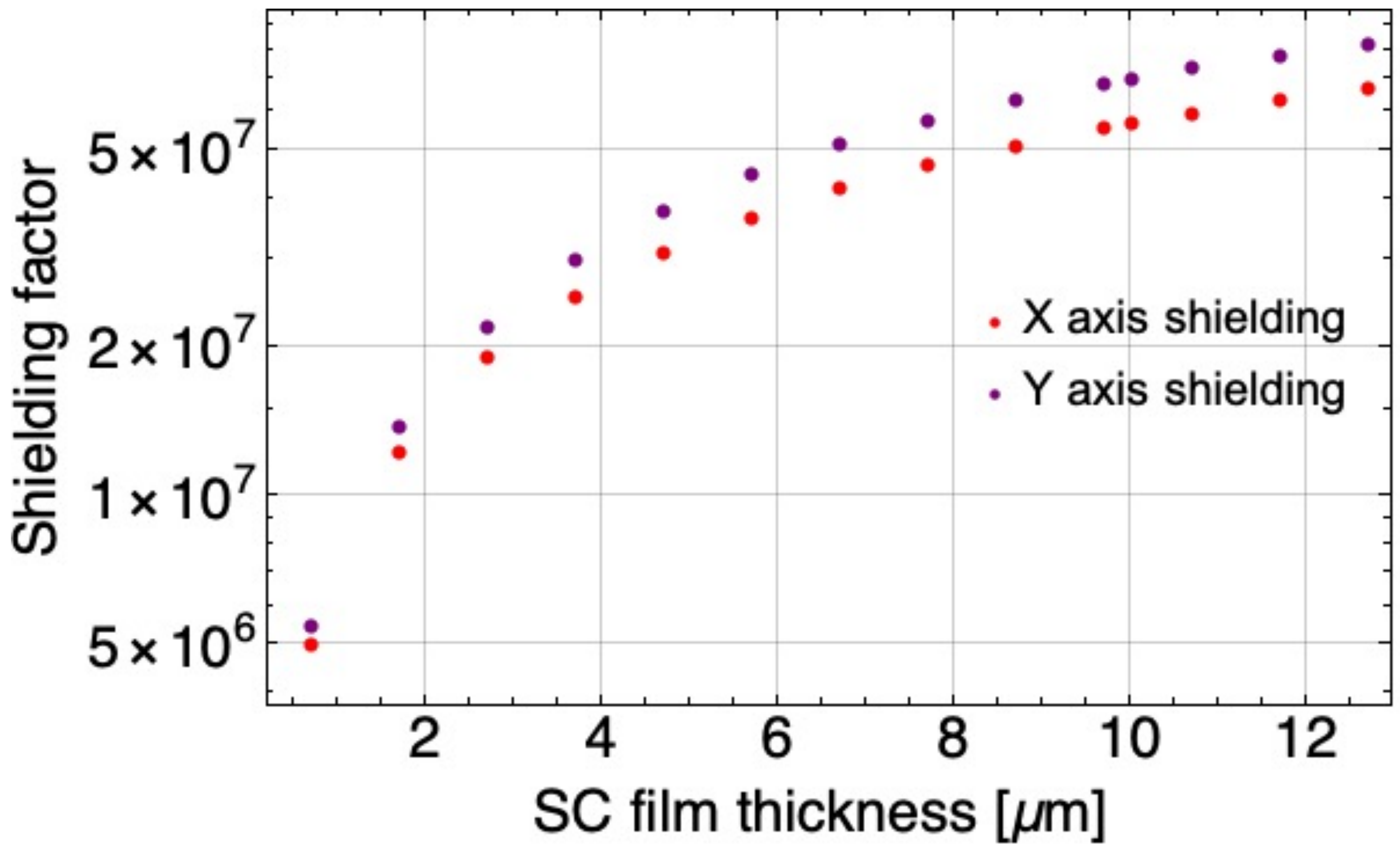
H. Fosbinder-Elkins, Y. Kim *et al.*, Quantum Science and Technology, 2021.

Shielding factor vs Film thickness

SC film thickness
0.7 μm ~ 12.5 μm



Johnson noise ~ $10^{-12} T/\sqrt{Hz}$,
Spin quantum limit ~ $10^{-19}\ T/\sqrt{Hz}$



- Estimate shielding factor with change of film thickness with Nb film quality $\lambda_L^{est.} = 55\text{nm}$,
- Shielding factor > $5{\times}10^6$ for thickness > $1\mu m$

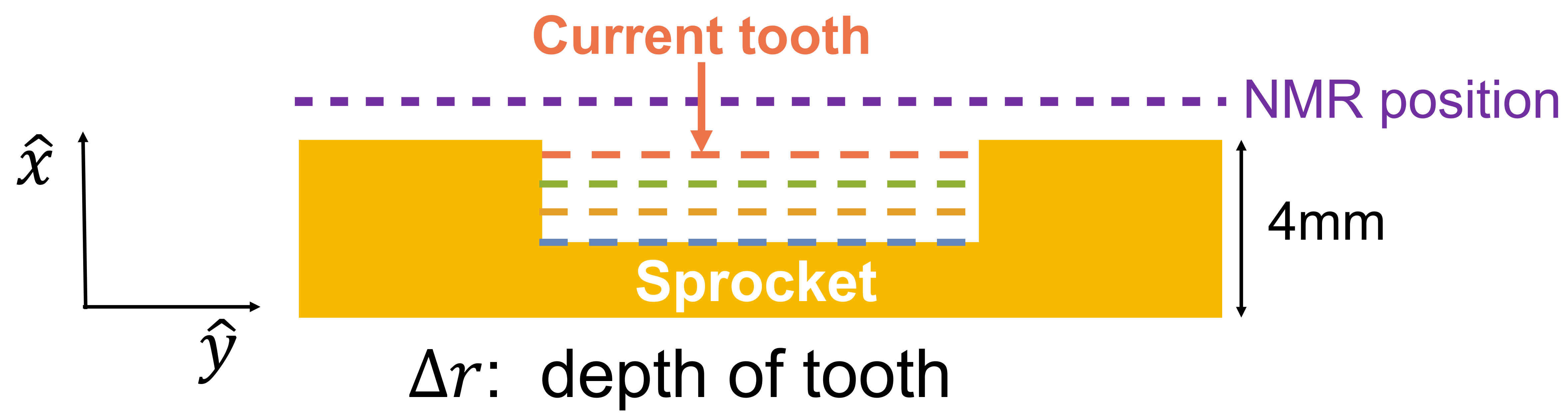
Vibration-hardened SQUID based detector

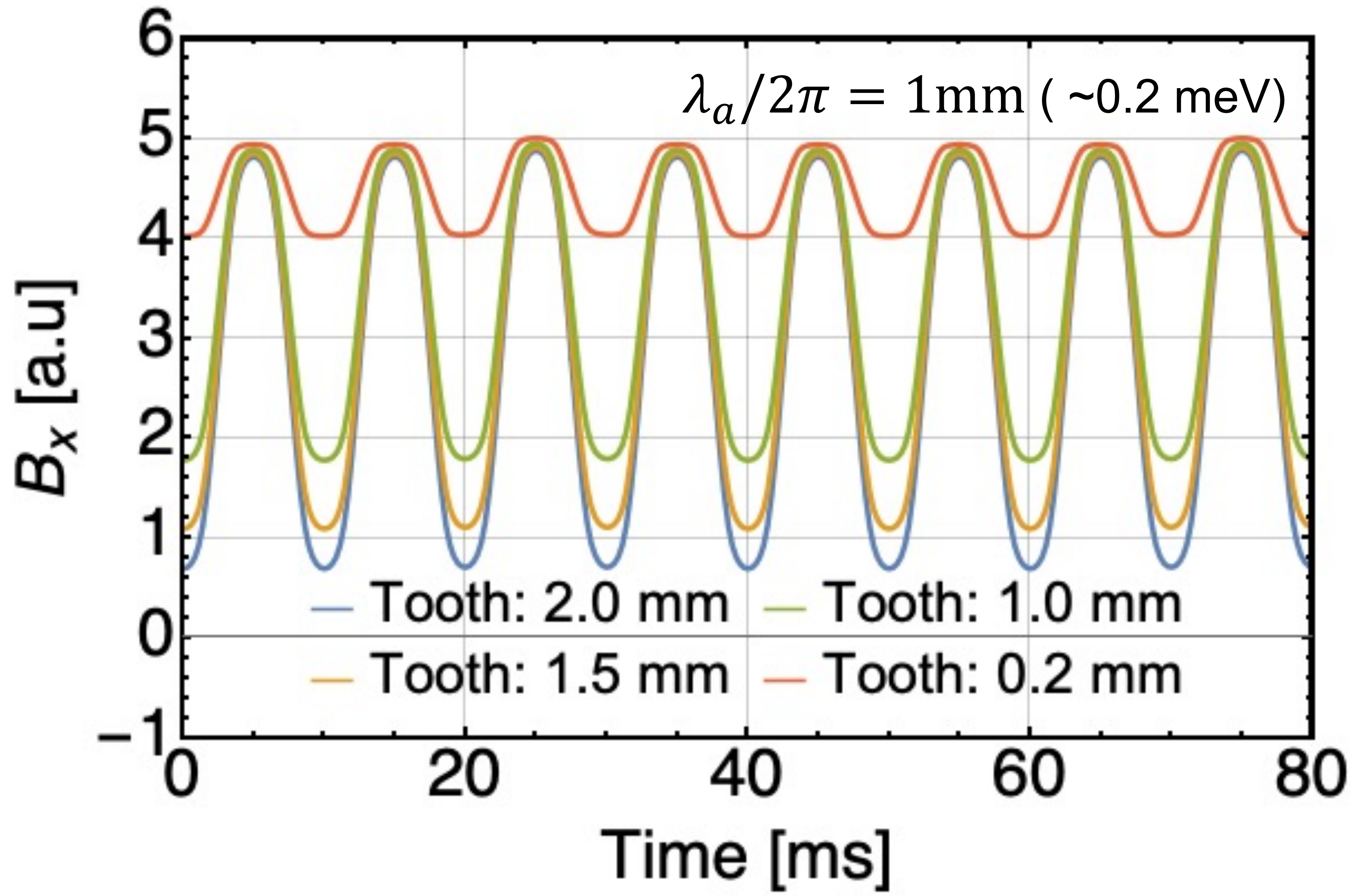
Thin film superconducting magnetic shield

Source mass optimization

Axion field modulation vs. sprocket tooth depth

- Current tooth depth (Δr): 200 μm
  - Axion induced field strength suppress as ($B_a \sim e^{-2\pi r/\lambda_a}$, $\lambda_a = h/m_a c$)
  - Modulation decrease $\Delta r < \lambda_a$
- Evaluate B_a with different depths
  - 2mm depth would provide 4.2 times stronger modulation
  - **4~6 times signal enhancement ~ 0.1meV axion**





Sprocket inner radius: 15mm, Outer radius: 19mm, Height: 1mm

Improved sensitivity with optimized design

Estimated noise with Gradiometer

	Noise source	Noise level (Wb)	Reduction method	After reduction (Wb)
Johnson noise	Source mass	$\sim 10^{-16}$	Superconducting shield (Shielding factor: 5×10^{7})	$\sim 10^{-24}$
Background noise*	Source mass rotation	$\sim 10^{-21}$ radial $\sim 10^{-18}$ vertical	Superconducting shield (Shielding factor: 5×10^{7})	$\sim 10^{-29}$ $\sim 10^{-25}$
Vibration noise	Acoustic vibration ($1nm/\sqrt{Hz}$)	$\sim 10^{-20}$	Planar gradiometer** (Balance level ~ 10^{-6})	$\sim 10^{-26}$

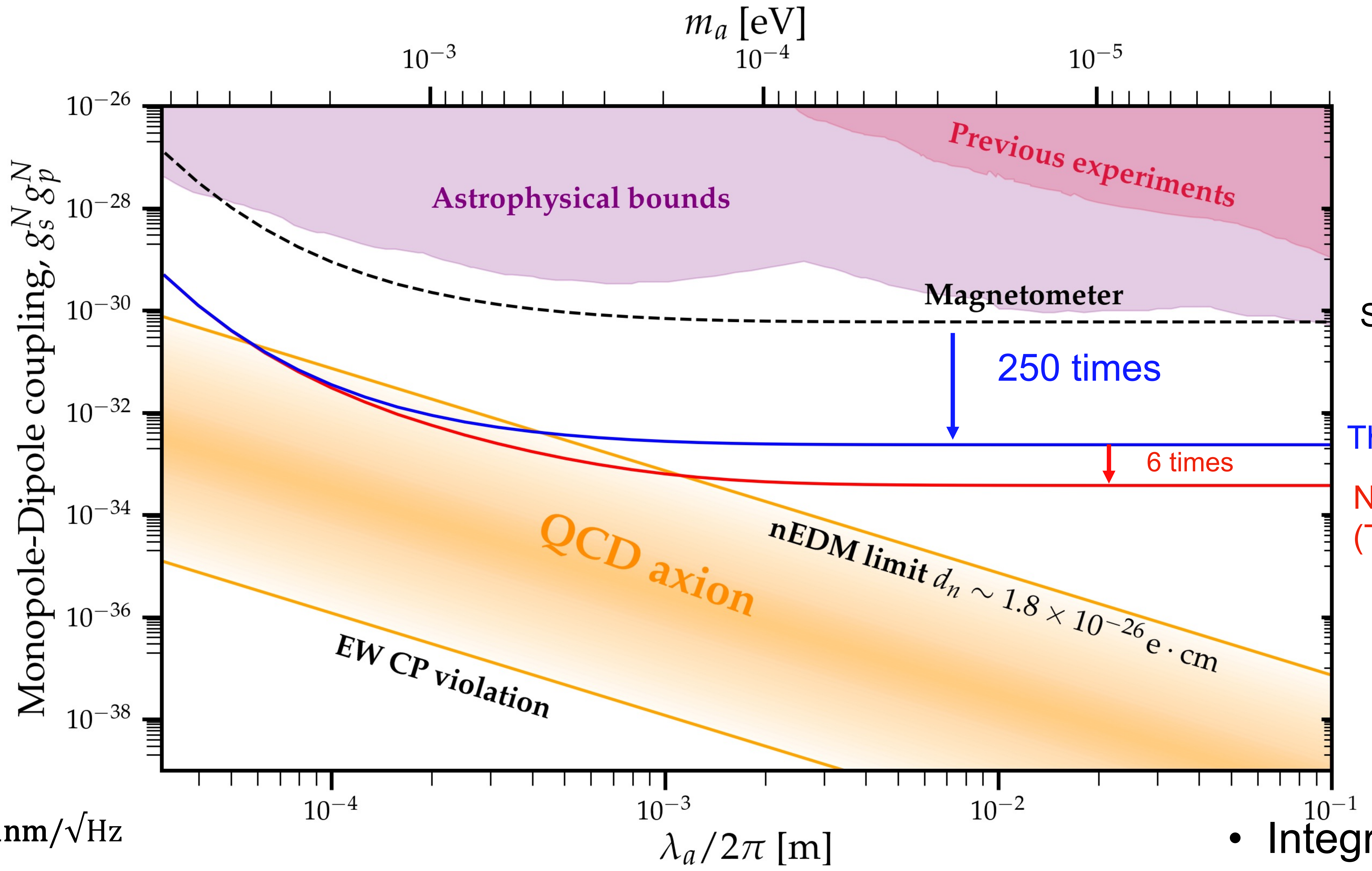
Dominant noise: Spin system quantum fluctuation induced noise ~ 10^{-22} Wb

*: Background noise: Oscillates with Larmor precession frequency (Barnett effect …)

**: Planar gradiometer intrinsic noise: $\sim 10^{-23}$ Wb

Integration time: 1 month

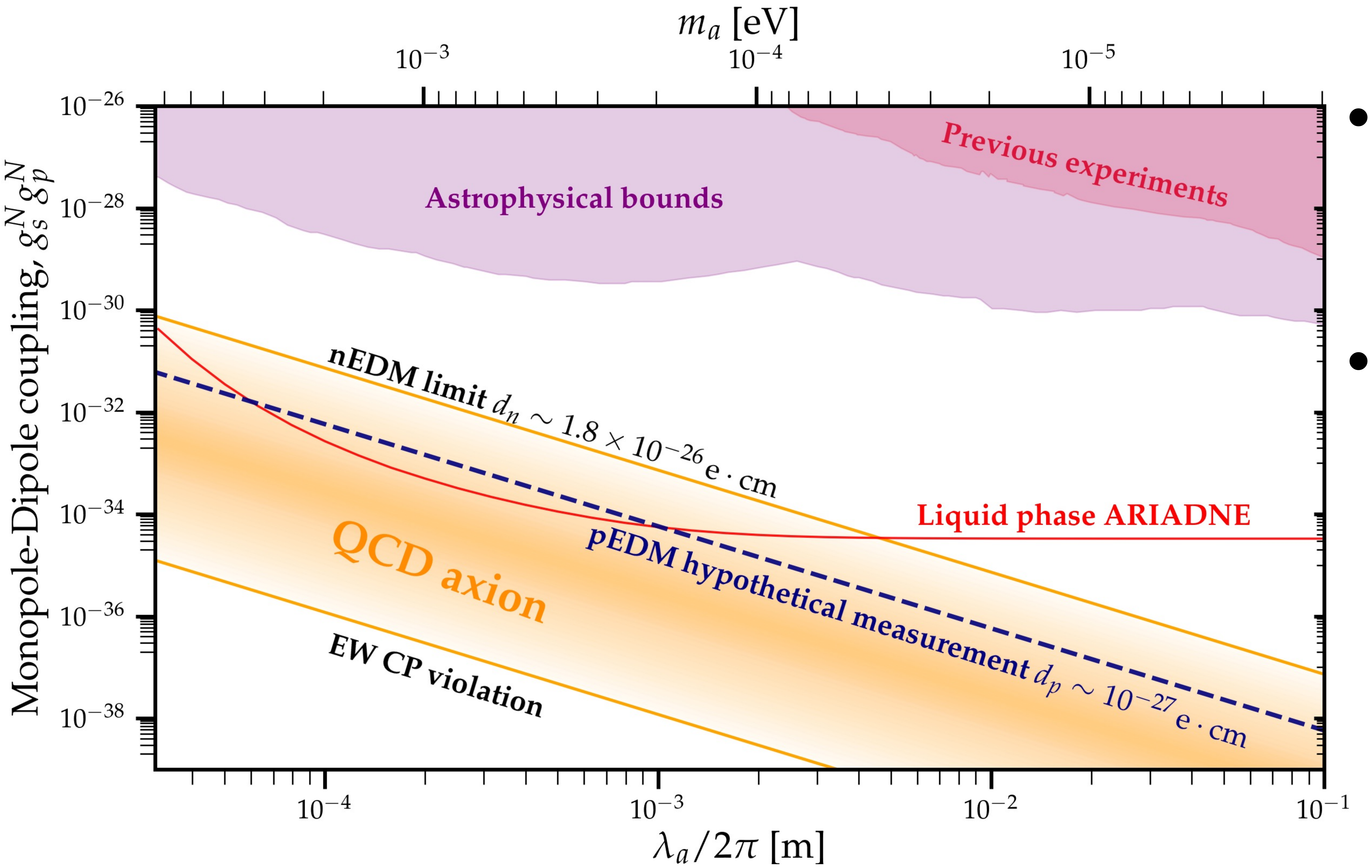
Projected sensitivity estimation



Vibration level: $1\text{nm}/\sqrt{\text{Hz}}$

- Integration time: 1month

ARIADNE and nucleon EDMs



Y. K. Semertzidis and S. Youn. , 2104.14831

- Combine with ARIADNE and nucleon EDM provides decisive information
- Scenario:
  - ARIADNE: Null axion
  - pEDM measure: $d_p \sim 10^{-27}\mathrm{e} \cdot \mathrm{cm}$
  - Exclude QCD axion independent of axion DM:

$$0.2\ \mathrm{meV} \lesssim m_a \lesssim 3\mathrm{meV}$$

Summary

- Axion mediated monopole-dipole interaction would be a strong indication of nonzero θ_{CP}
- ARIADNE is an experiments to detect axion mediated monopole-dipole interaction in sub-millimeter range
- Superconducting thin film, second order coaxial planar gradiometer attenuates noise to explore axion mass 0.1meV – 4 meV.
- Combine with ARIADNE and nucleon EDM provides decisive information for axion search

Axion Resonant InterAction DetectioN Experiment

ARIADNE

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Stanford University: Aharon Kapitulnik , Alan Fang, Sam Mumford
Indiana University: Josh Long, Chen-Yu Liu, Mike Snow, Inbum Lee, Justin Shortino
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