CAPP
Center for Axion and Precision Physics Research

Axion Resonant InterAction DetectioN Experiment

(Recent Progress in ARIADNE)

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On behalf of the ARIADNE Collaboration

Northwestern University, Stanford University, Indiana University, Perimeter Institute, PTB, UIUC and CAPP/IBS

The Axion Quest Conference
August 7th 2024

Outline

- New spin-dependent interactions
- ARIADNE experiment
- SQUID development at CAPP/IBS
- Other activities in ARIADNE collaboration

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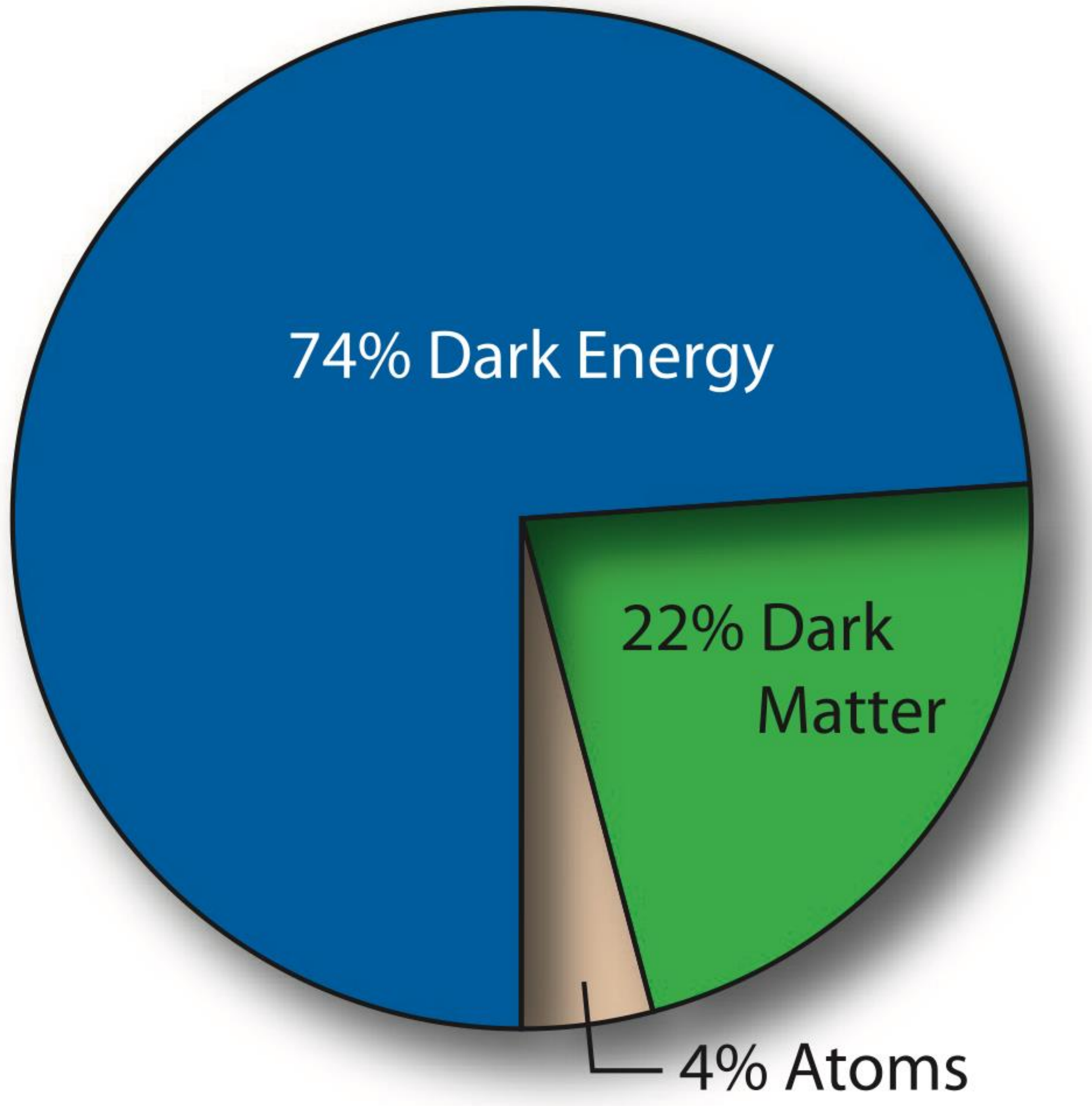
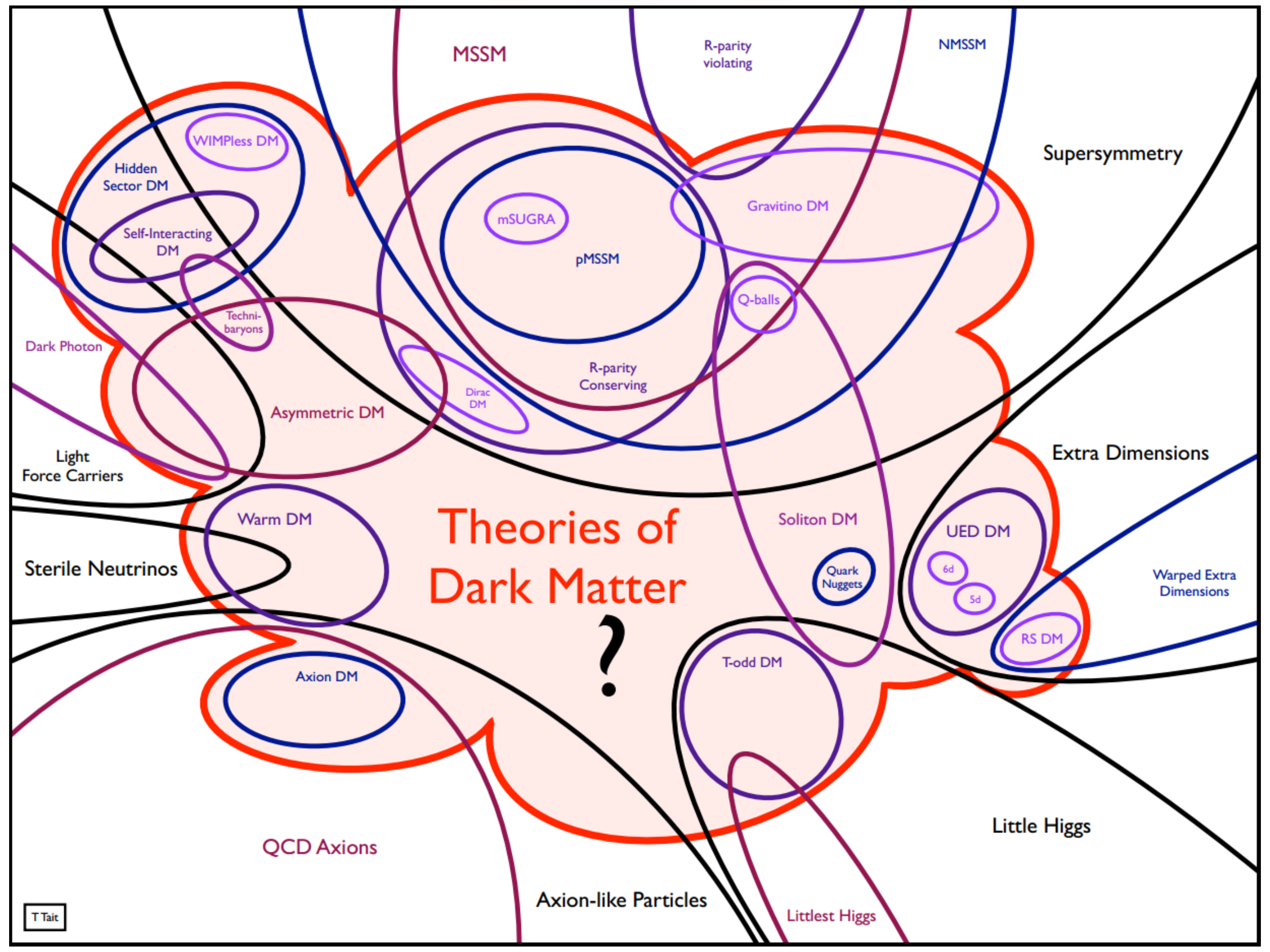
KAIST
KOREA ADVANCED INSTITUTE OF SCIENCE AND TECHNOLOGY
1971

Dark Matter and New Interactions

- About 96% of the Universe is filled with non-baryonic components; dark energy and dark matter
- Dark matter is not associated with Standard Model → New theory
- Theories beyond Standard Model predict weakly-coupled scalar, pseuo-scalar bosons as dark matter candidate
- Some light mass bosons may be an answer for dark matter and other fundamental physics questions: ex) axions
- Could it be associated with another, as of yet, unobserved interactions?





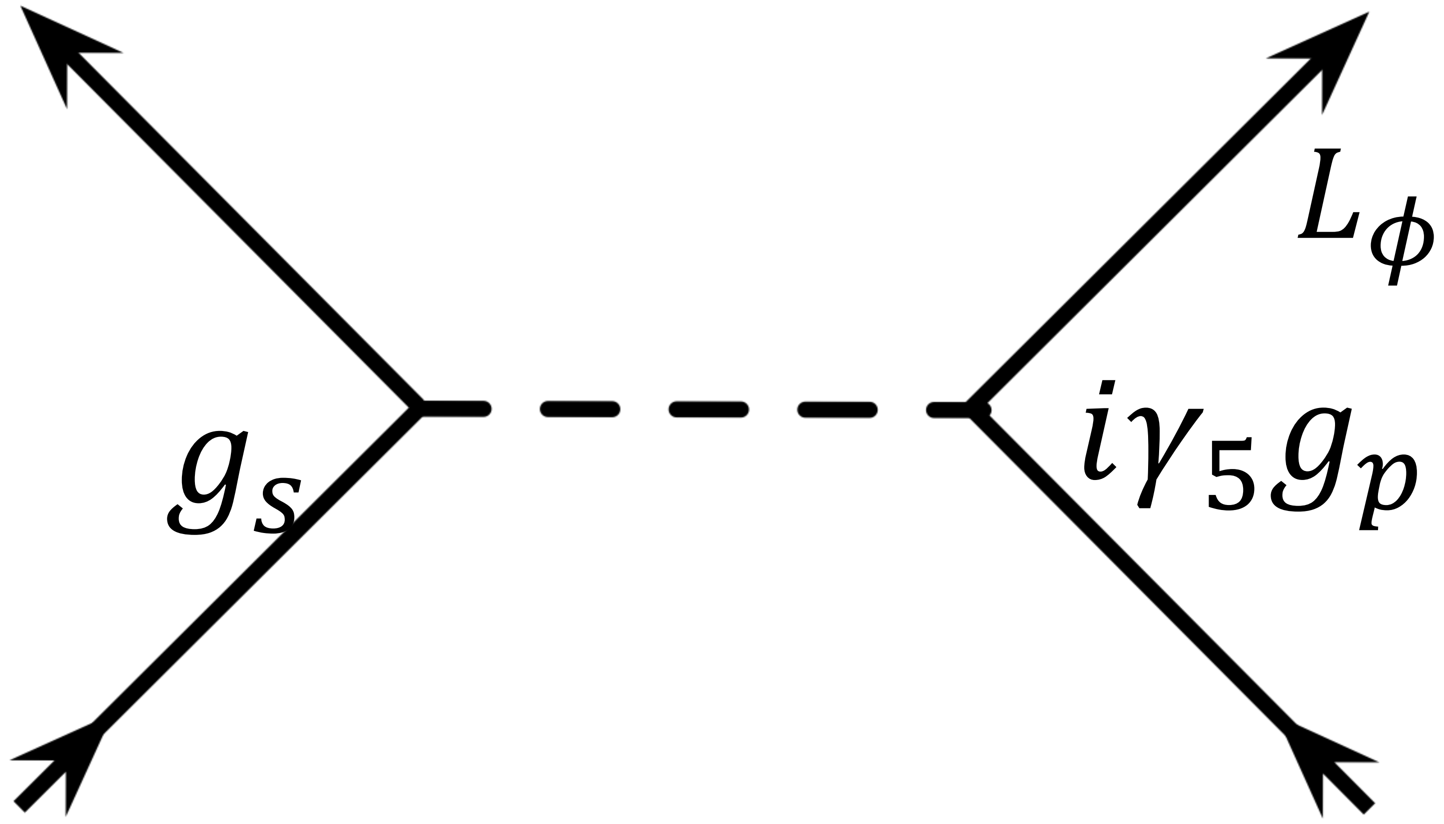
https://physics.aps.org/articles/v11/48

New spin-dependent interactions?

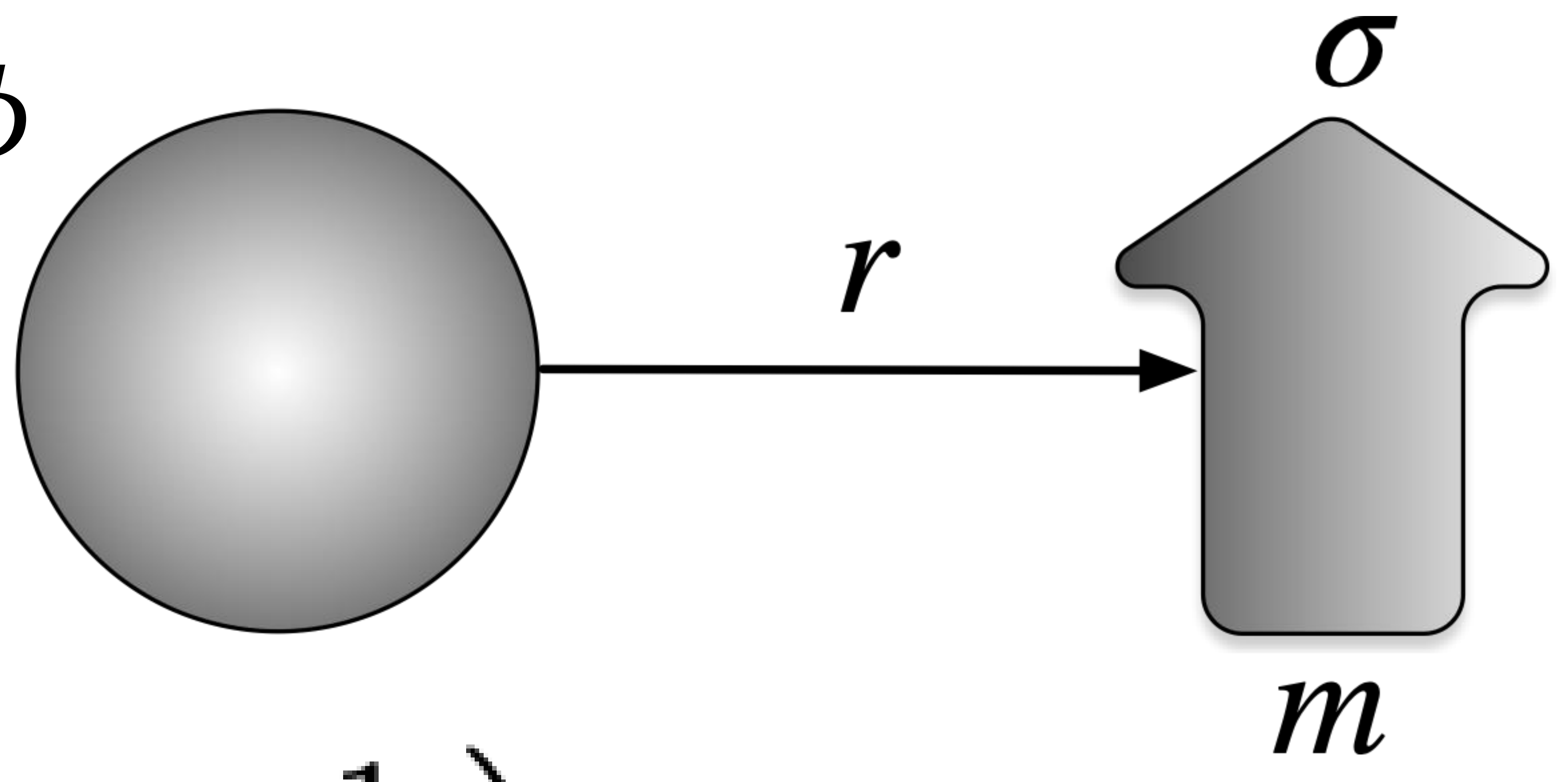
- Weakly-coupled, long-range interactions are a generic consequence of spontaneously broken continuous symmetries (Goldstone theorem)
  - Such boson with small enough mass have macroscopic Compton wavelength → possible to mediate new interactions in longer range.
- Specific theories (axions, extra dimensions) imply new interactions at sub-mm scales
  - Dark energy density of $\sim (1\mathrm{meV})^4$ order $\rightarrow \sim 100\mu\mathrm{m}$ scale
- Experimental tests for new spin-dependent interactions
  - Laboratory constraints in "mesoscopic" range is less common

An example of non-standard spin-dependent interaction with spin 0 boson exchange

Monopole-dipole interaction mediated by axions



$$L_\phi = \overline{\psi}(g_s + i\gamma_5 g_p)\psi\phi$$



$$V_{ps}(r) = \frac{\hbar}{8\pi m c} g_s g_p \left(\vec{\sigma}\cdot\hat{r}\right)\left(\frac{1}{\lambda r} + \frac{1}{r^2}\right) e^{-\frac{r}{\lambda}}$$

- **Originated from** $L_\phi = \overline{\psi}(g_s + i\gamma_5 g_p)\psi\phi$
- **Axion mediated interaction between polarized and unpolarized objects**
- **Violates both P and T symmetry**
- **Investigated by searching for frequency shifts correlated with position of unpolarized mass**
- **Not very well constrained over "mesoscopic" range (** $\mu m \sim mm$ **)**

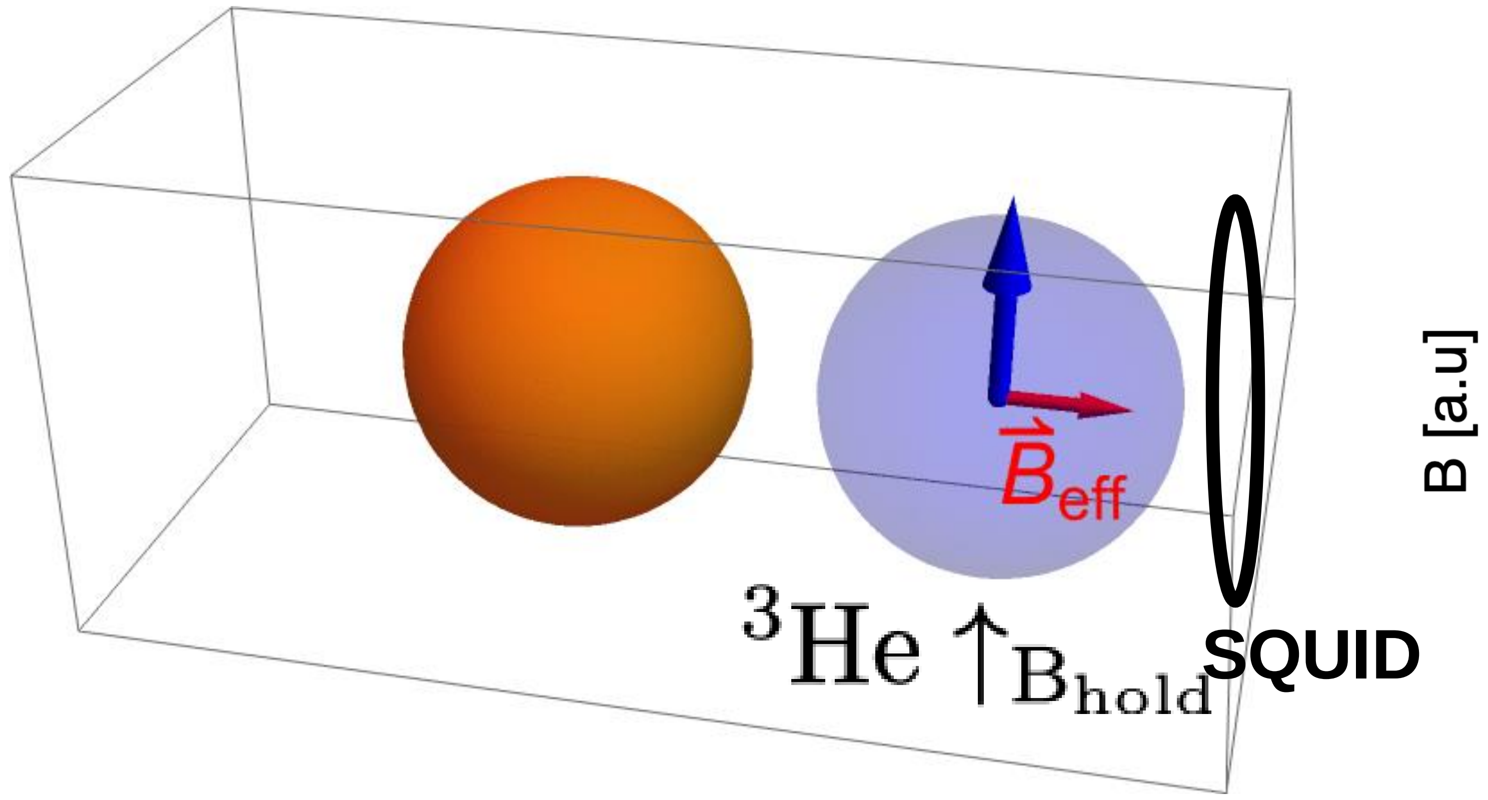
J. E. Moody and F. Wilczek, Phys. Rev. D 30, 130, 1984

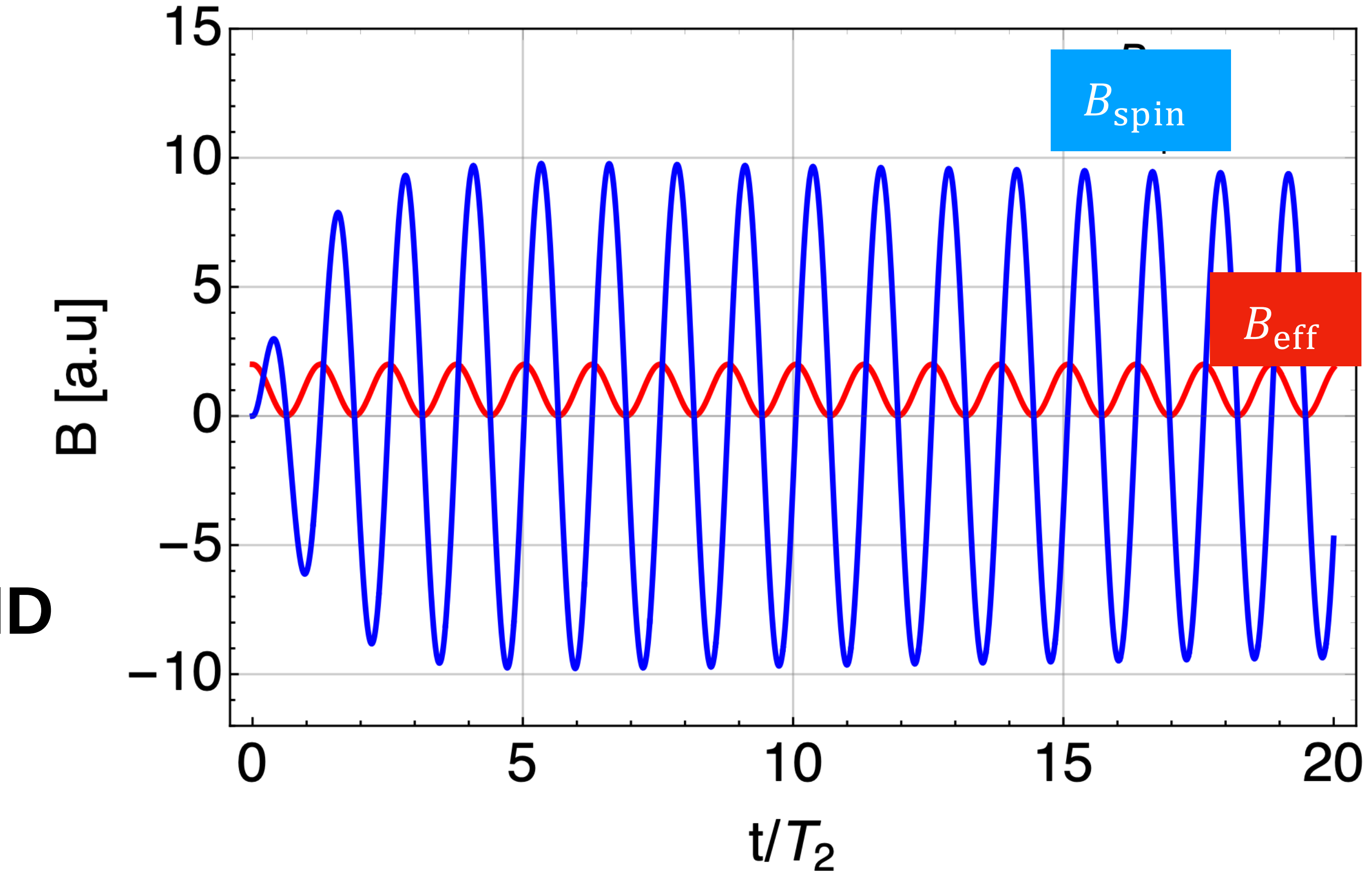
Axion Resonant InterAction DetectioN Experiment (ARIADNE)

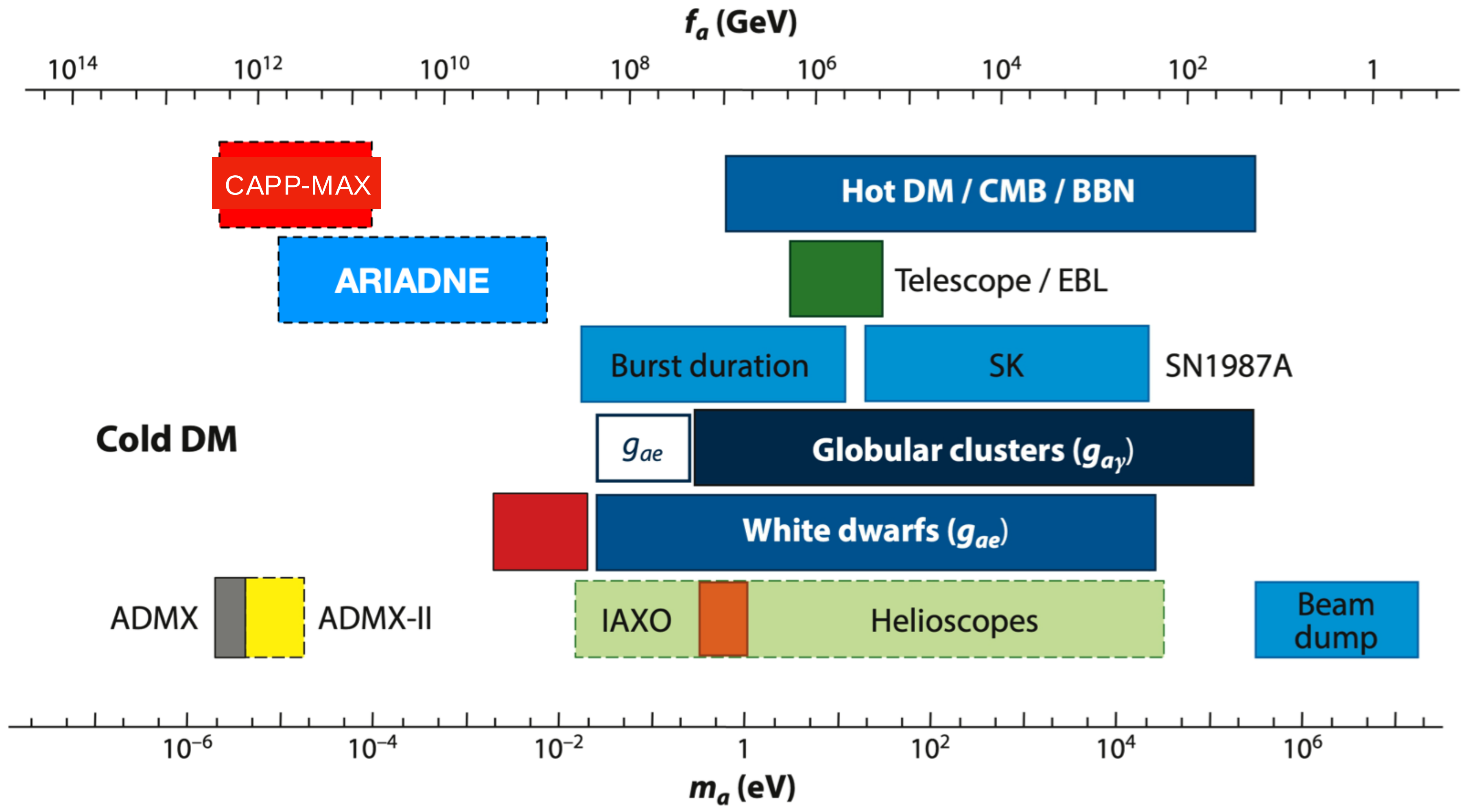
- **Search for QCD axion from monopole-dipole interaction between Tungsten mass and polarized 3He**
- **Effective magnetic field from** $U = -\vec{\mu} \cdot \vec{B}_{\text{eff}}$

$$\vec{B}_{\text{eff}} = -\frac{\hbar g_s g_p}{4\gamma\pi M}\left(\frac{1}{\lambda_\phi r} + \frac{1}{r^2}\right) e^{-r/\lambda_\phi}\ \hat{r}$$

  - Independent from fermion's magnetic moment,
  - not couple to the angular moment or charge
  - No Maxwell equation ➜ can't be screened by magnetic shielding
  - B_{eff} drive spin precession in a laser-polarized 3He: B_{spin}
  - $\vec{B}_{\text{eff}} \sim 10^{-22}\text{T} \rightarrow \vec{B}_{\text{spin}} \sim 10^{-18}$
- **Detect NMR signal with SQUID**
  - Resonant enhancement of signal with $Q \sim \omega T_2$
- **Source the axion field from local mass**: no dark matter axion required
- **Potential to probe broad axion mass range**: $0.1\text{meV} \leq m_a \leq 10\text{meV}$







J. Jaeckel and A. Ringward, Ann. Rev. Nucl. Part. Sci. 60, 405, 2010
A. Arvanitaki and A. A. Geraci, Phys. Rev. Lett. 113, 161801, 2014

ARIADNE Physics Reach

- The limit of $g_s g_p$ with the given experimental condition from

$$B_{\text{eff}} \leq B_{\text{min}},$$

- The fundamental noise limit from transverse magnetization of ^{3}He as

$$\sqrt{M_N^2} = \sqrt{\frac{\hbar \gamma \mu_{^3\text{He}} n_s T_2}{2V}}$$

- The minimum magnetic field from the noise becomes

$$B_{\text{min}} \simeq \frac{1}{p}\sqrt{\frac{2\hbar b}{n_s \mu_{^3\text{He}} T_2 V}}$$

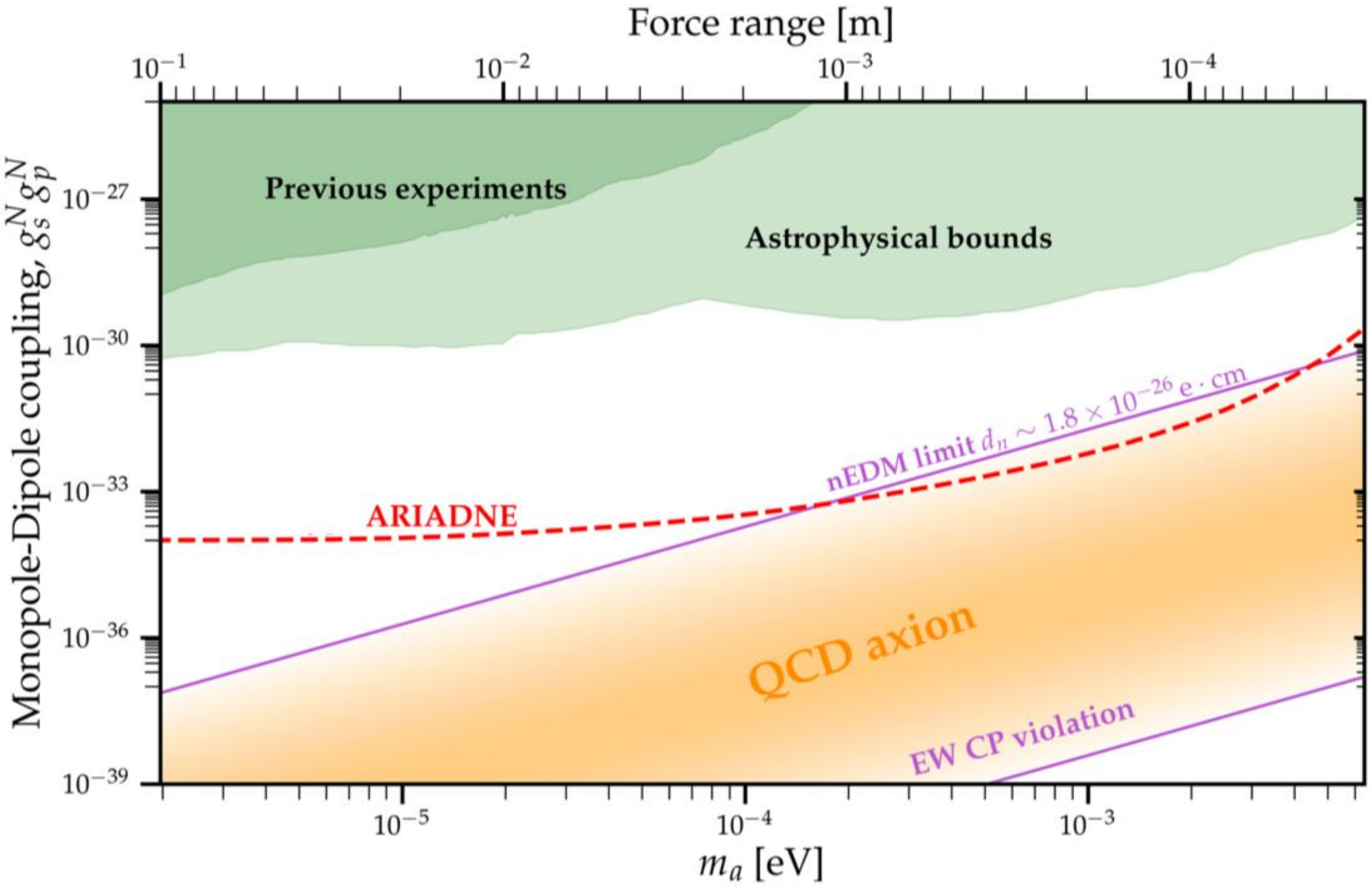
$$= \mathbf{3 \times 10^{-19}}\text{T} \times \left(\frac{1}{p}\right)\sqrt{\left(\frac{b}{1\text{Hz}}\right)\left(\frac{1\text{mm}^3}{V}\right)\left(\frac{10^{21}\text{cm}^{-3}}{n_s}\right)\left(\frac{1000s}{T_2}\right)}$$

- SNR in a measurement τ can be

$$\text{SNR} = \frac{B_{\text{eff}}\sqrt{\tau}}{B_{\text{min}}}$$

- The minimum coupling constant $g_s g_p$ becomes

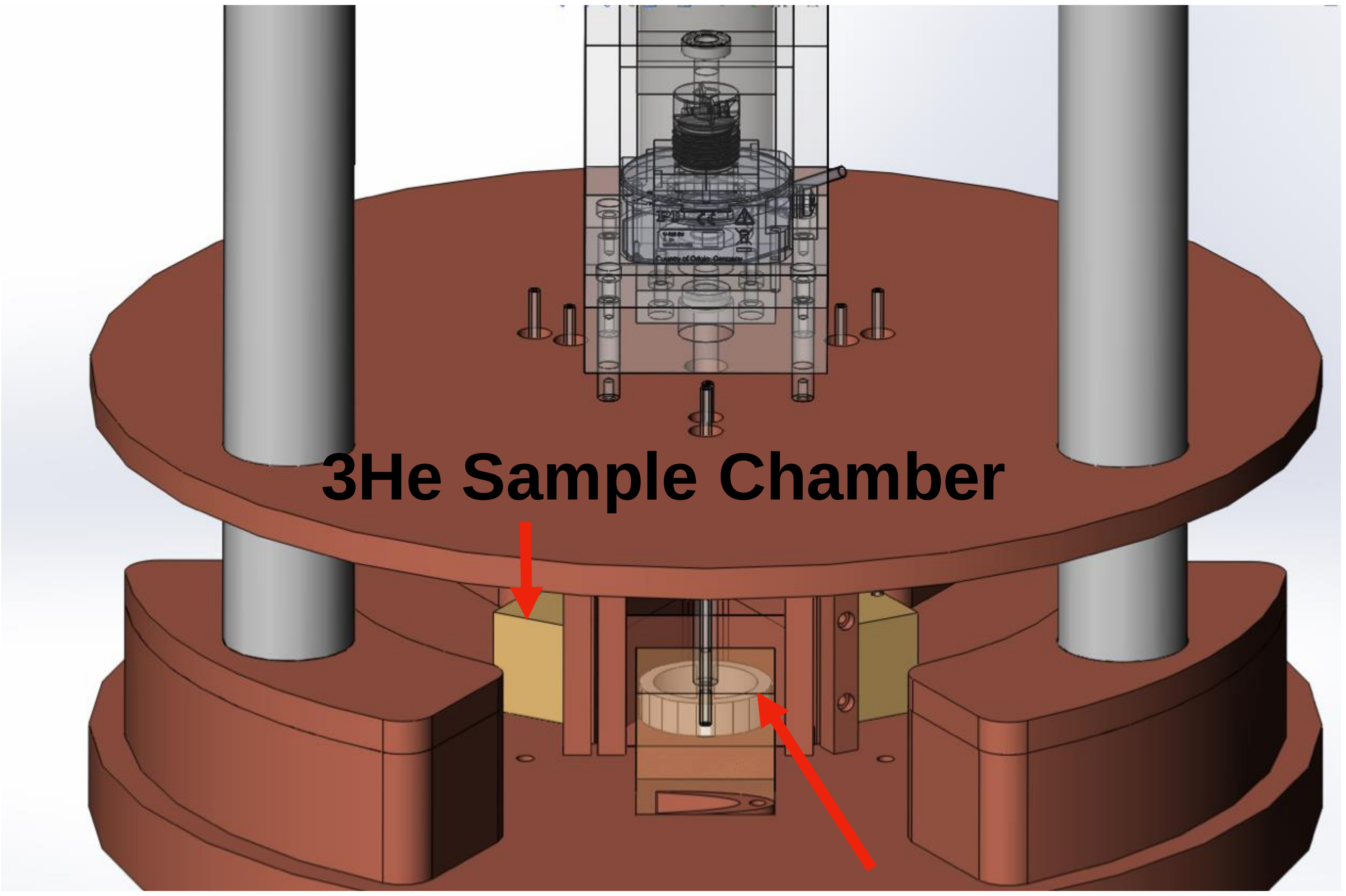
$$g_s g_p \leq \frac{\text{SNR} \times B_{\text{min}}}{\sqrt{\tau}} \frac{4\pi M \gamma_f}{\hbar n_s} \frac{1}{\int \left(\frac{1}{\lambda r} + \frac{1}{r^2}\right) e^{-r/\lambda} \hat{r} \cdot \hat{x} dV}$$

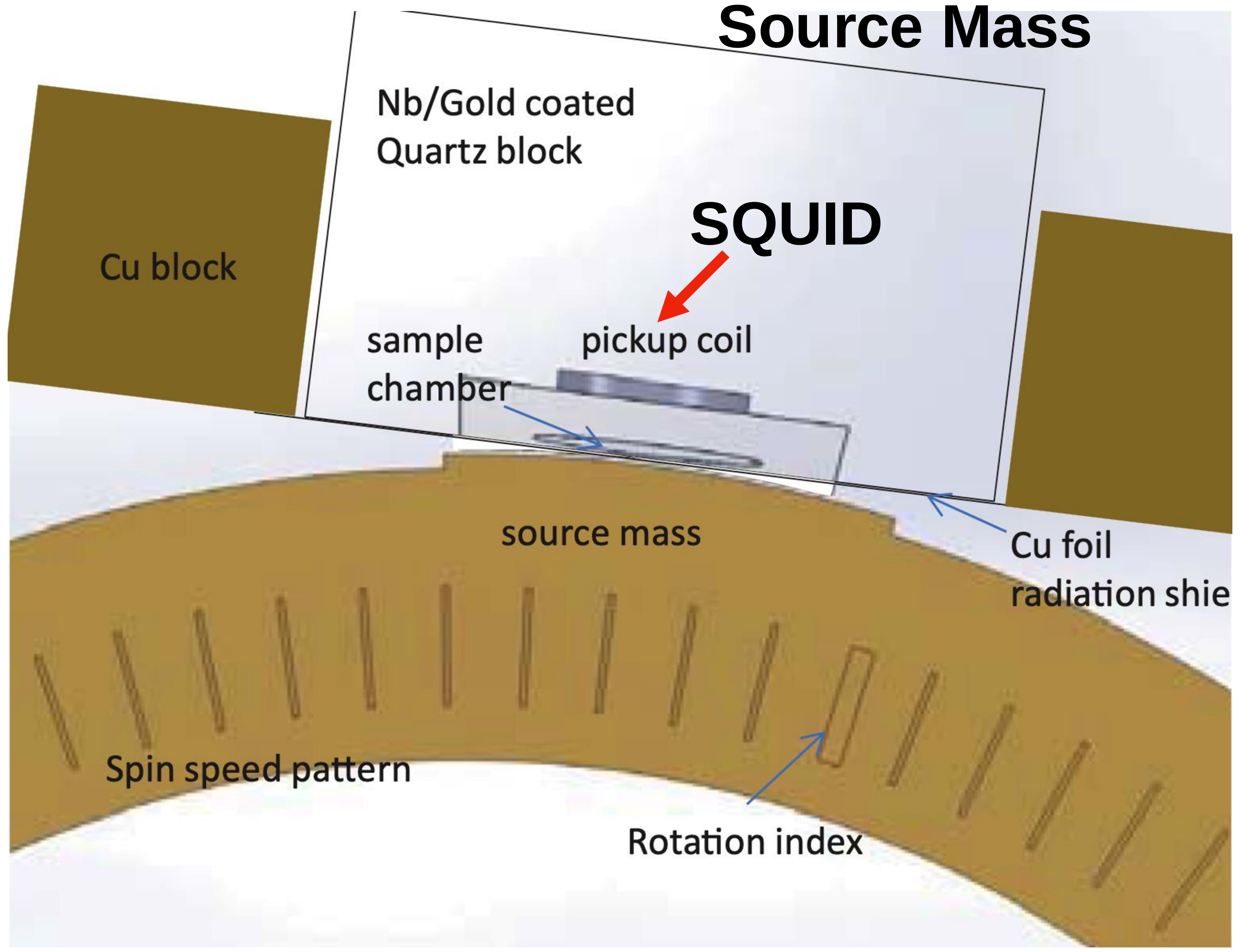


A. Arvanitaki and A. A. Geraci, Phys. Rev. Lett. 113, 161801, 2014

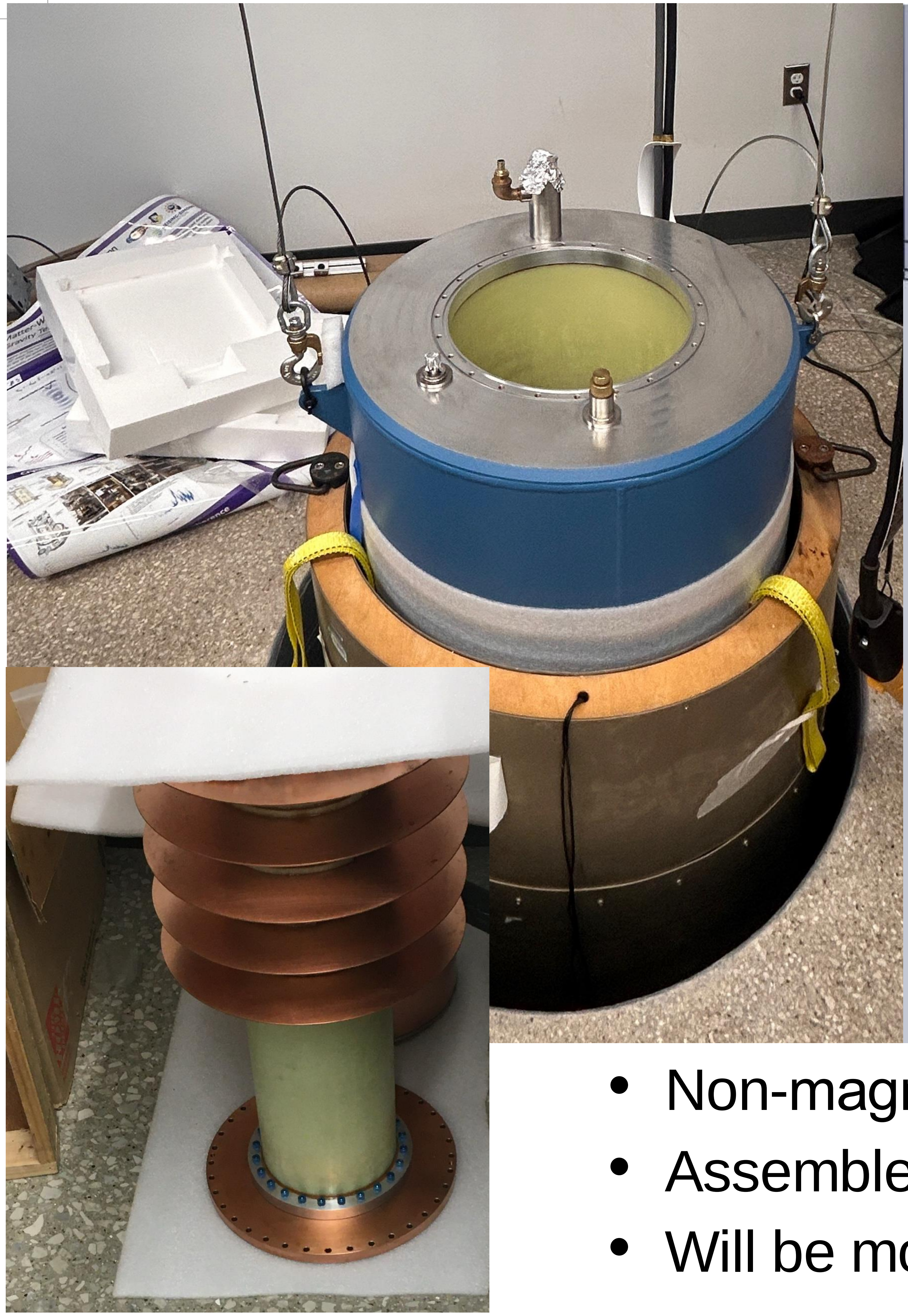
Experimental Design of ARIADNE

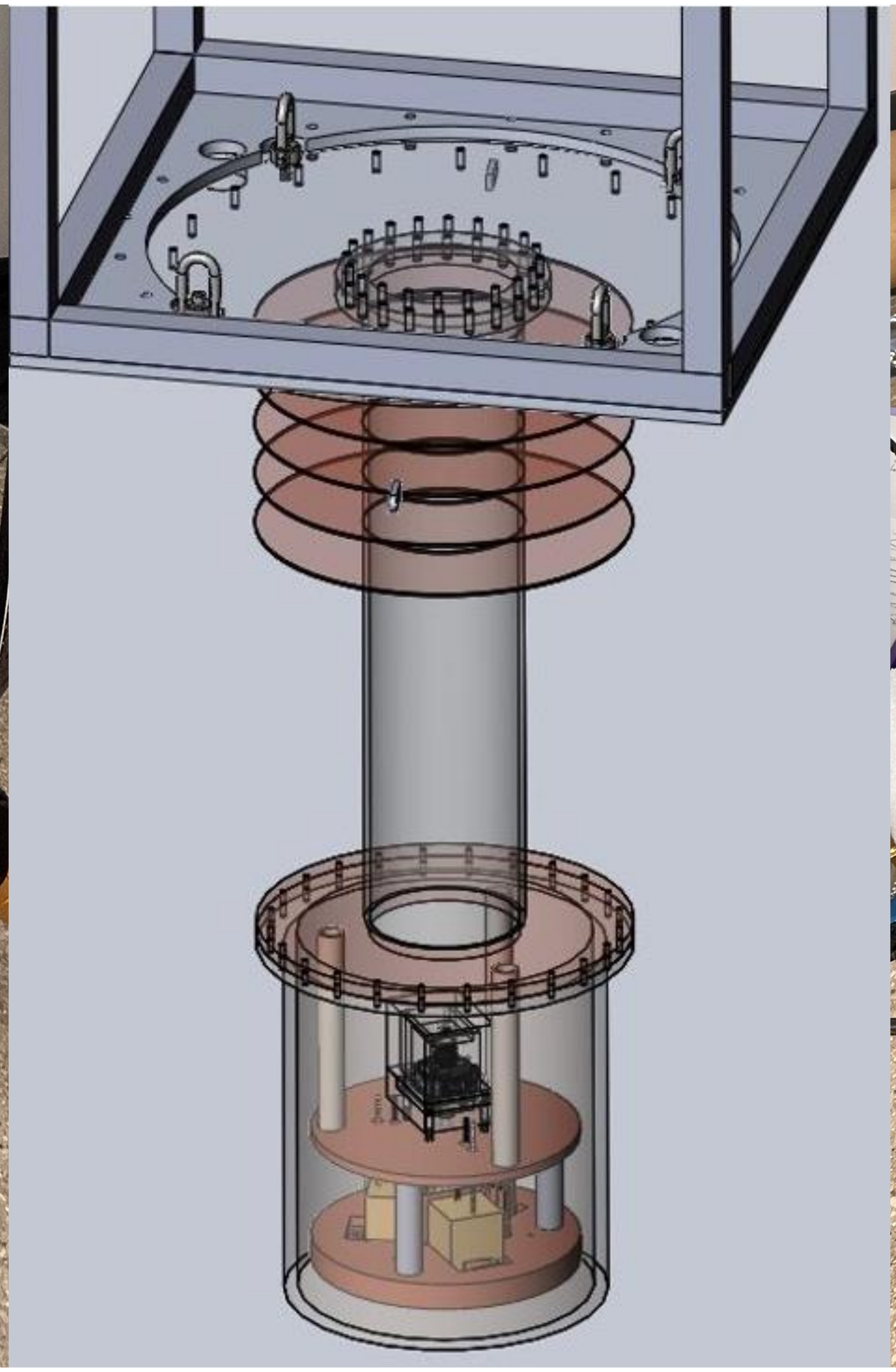
- **Detector part**
  - Polarized 3He gas (**Indiana**): $\sim 2 \times 10^{21}/\mathrm{cc}$ density
  - Quartz block (**Northwestern**/**Stanford**) with 3He chamber of $\sim 10\mathrm{mm} \times 3\mathrm{mm} \times 150\mu\mathrm{m}$
  - Superconducting magnetic shield (**CAPP**/**Northwestern**/**Stanford**): $\sim 10^{8}\mathrm{S.F}$
  - SQUID (**CAPP**): $\sim 4\mathrm{fT}/\sqrt{\mathrm{Hz}}$
- **Source Mass part**
  - Rotating Stage (**Northwestern**): 11 segments, 10Hz, $\omega = 10\omega_{\mathrm{rot}}$
  - Rotational Source Mass (**UIUC**): Tungsten (high nuclear density)

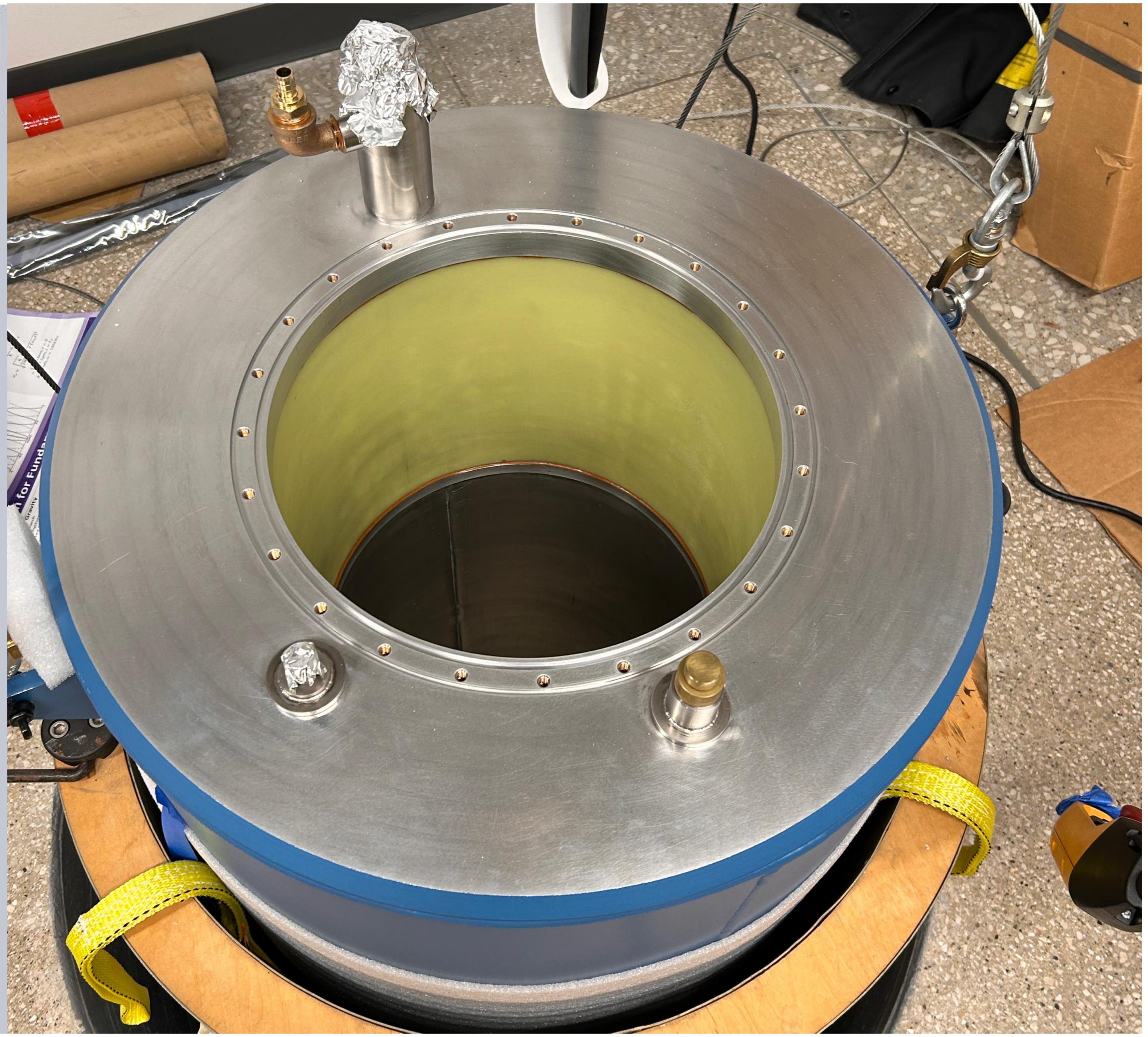




Non-magnetic LHe Dewar

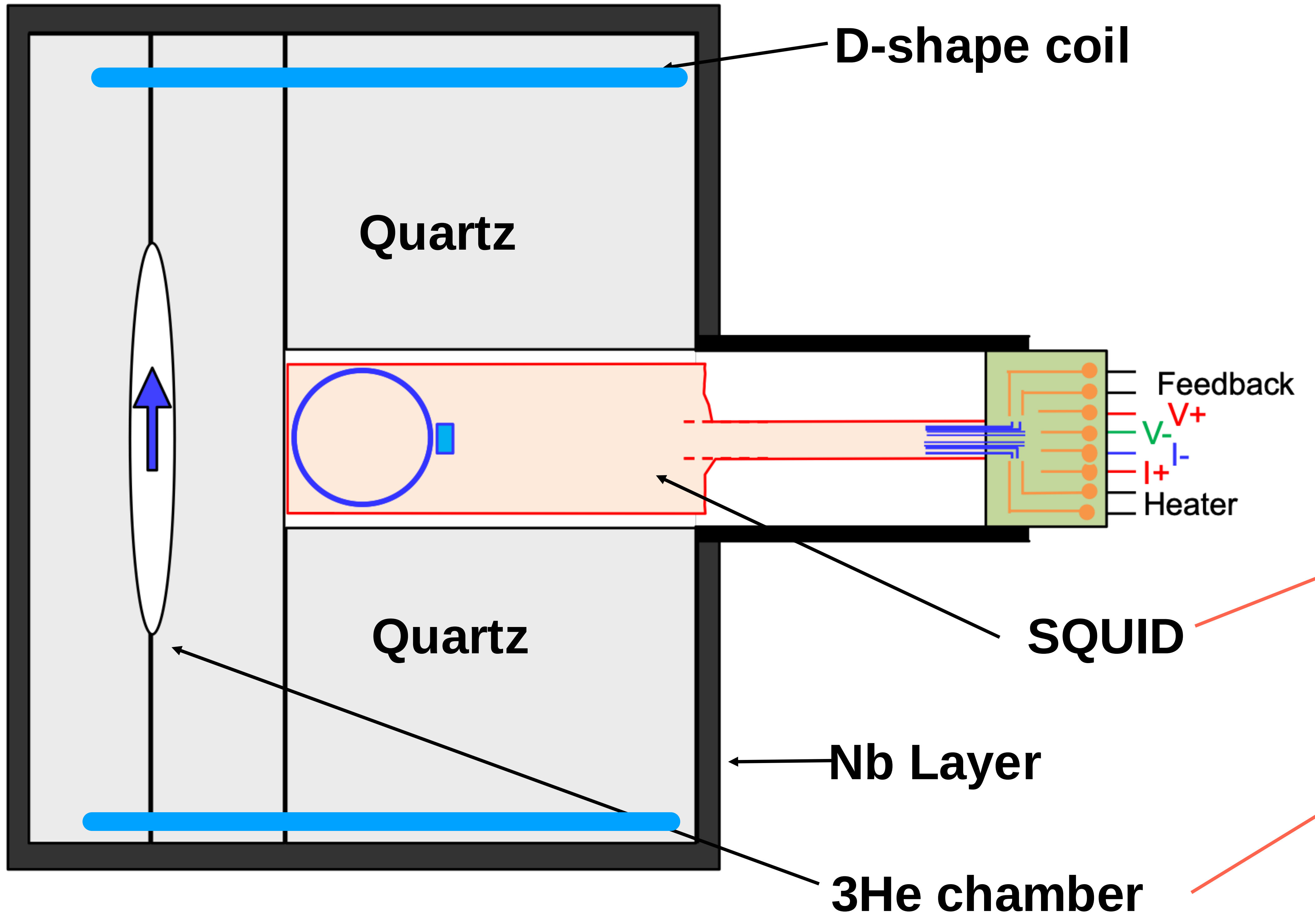


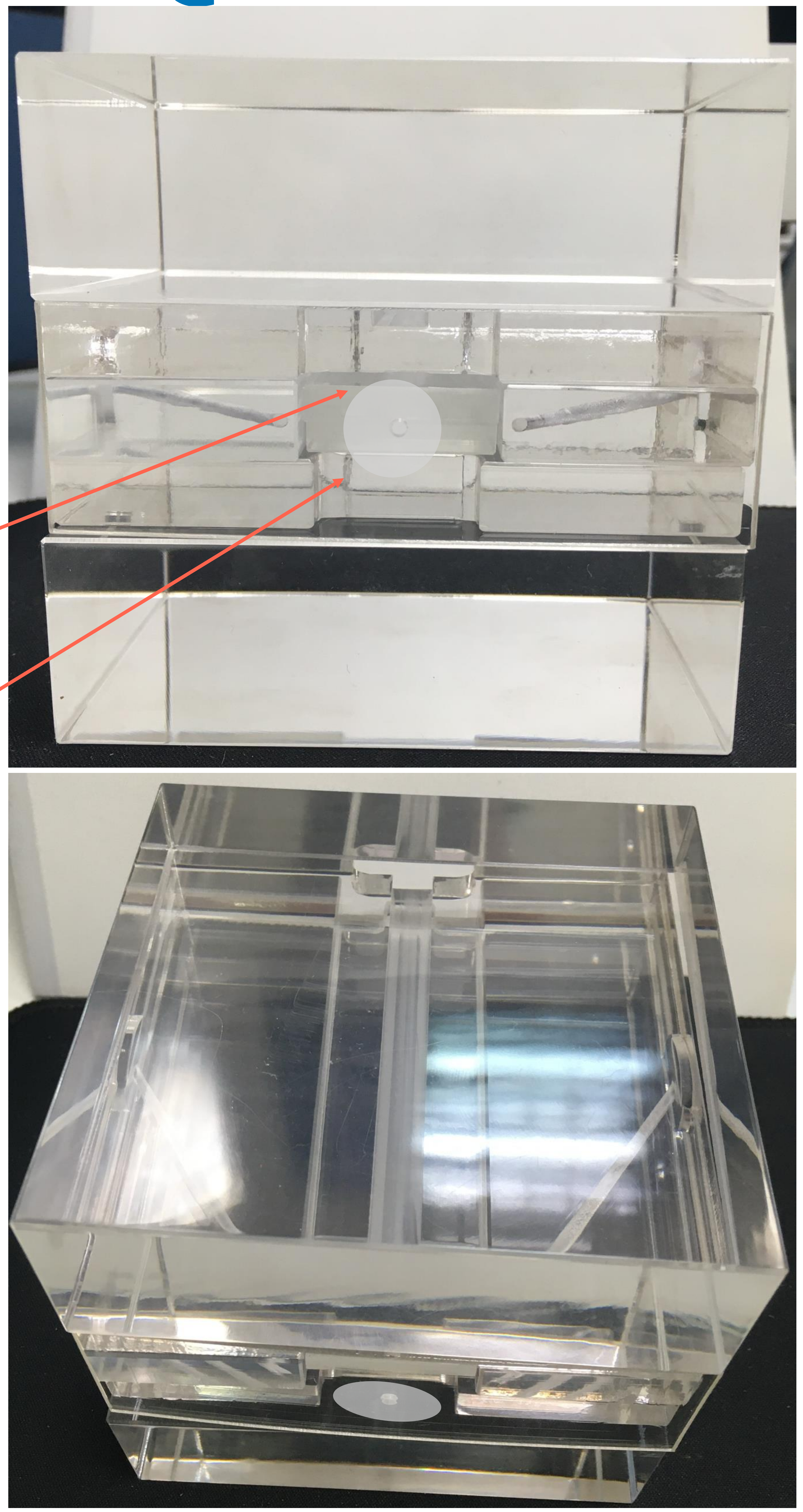




- Non-magnetic LHe Dewar made with G10 and Al, μ-metal Shielding
- Assembled at Northwestern University: Now in vacuum and cooling test
- Will be moved to Indianan University for installation of main components inside

Quartz block for 3He/SQUID





- Assembly of multiple quartz blocks: maintained at ~4.2K
- A spheroidal chamber for 3He sample with $10\mathrm{mm} \times 3\mathrm{mm} \times 150\mu\mathrm{m}$
- Wall thickness on a side to the source mass $\sim 75\mu\mathrm{m}$
- A sets of D coil for generating magnetic holding fields
- Nb layer with shielding factor of$\sim 10^8$

H Fosbinder-Elkins *et al* 2022 *Quantum Sci. Technol.* **7** 014002

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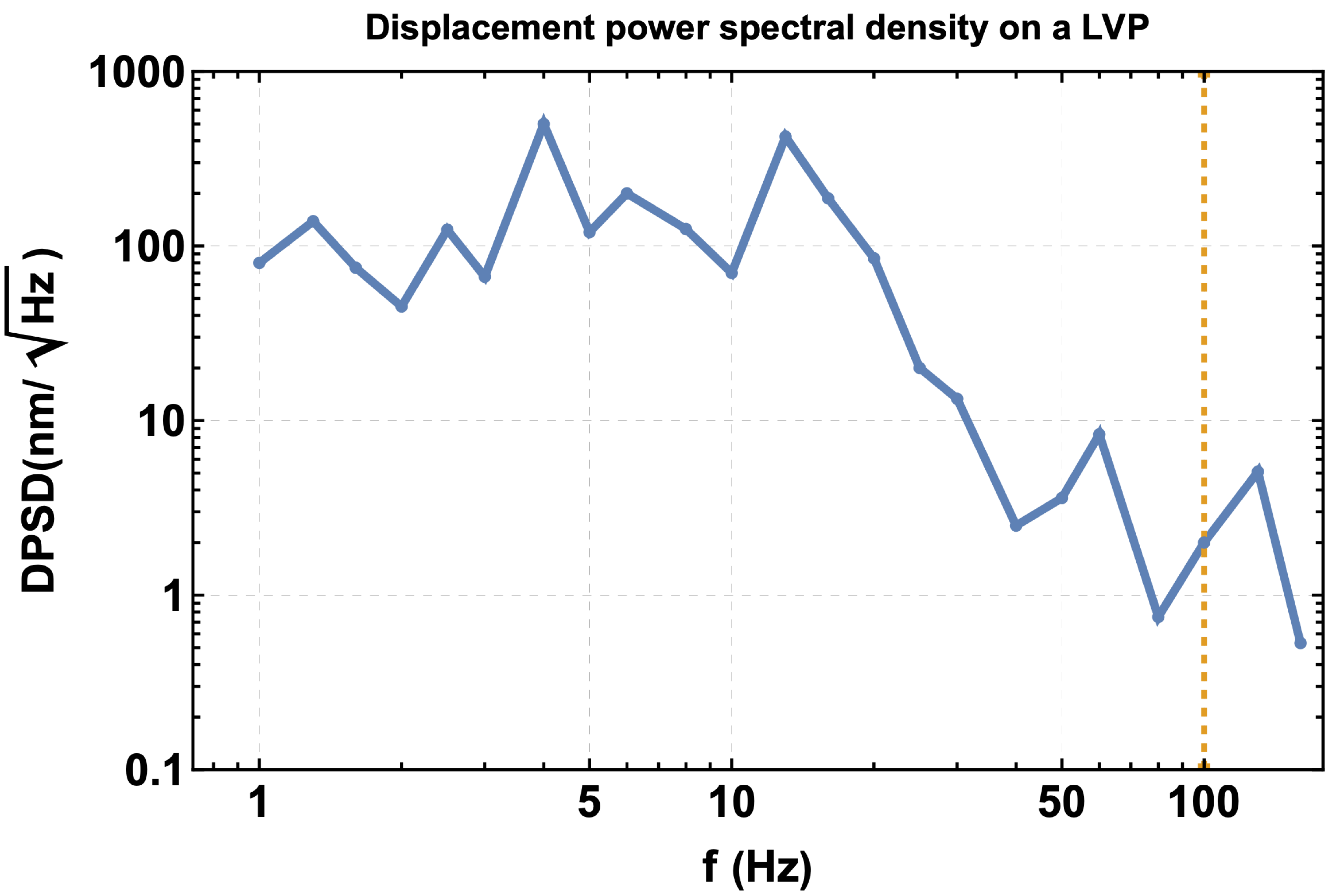
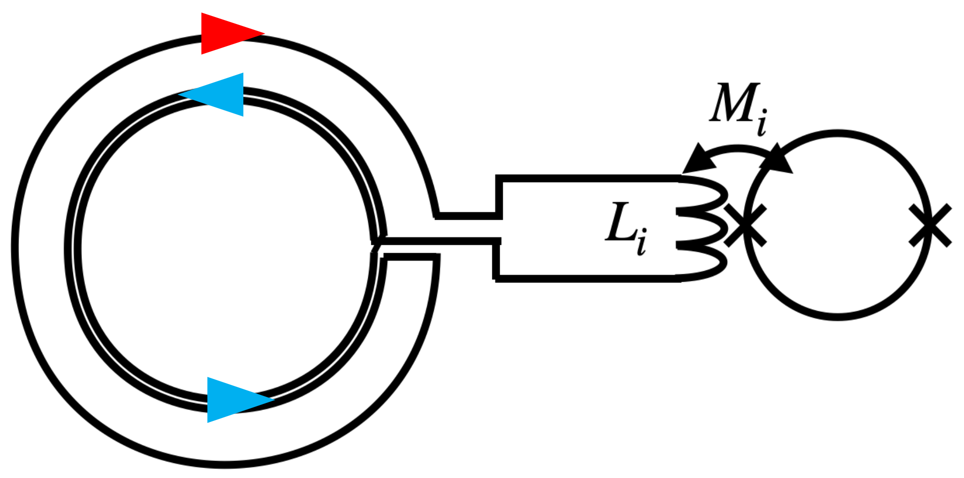
SQUID Development at CAPP/IBS

- The SQUID needs to be placed in the 30mG of holding field
  - Ambient noise ➔ Magnetometer vs Gradiometer
- The SQUID needs to be sensitive enough to detect dipole field
  - Magnetic noise level of SQUID: $\sim 4\mathrm{fT}/\sqrt{\mathrm{Hz}}$,
- The SQUID needs to be fully thermalized at 4.2K
  - Thermalization/operation of SQUID without direct contact with LHe

SQUID under the Magnetic Field



- Measured Displacement power spectral density with accelerometer on a low vibrational pad (LVP) at CAPP
- There exists a vibration with a level of $\sim 2\mathrm{nm}/\sqrt{\mathrm{Hz}}$ at 100Hz
- With a size of $d = 3mm$ in SQUID pickup coil under the 30mG of holding field
  - Magnetic noise level: $\delta B \approx 2\mathrm{pT}/\sqrt{\mathrm{Hz}}$
- Second order planer coaxial planner gradiometer



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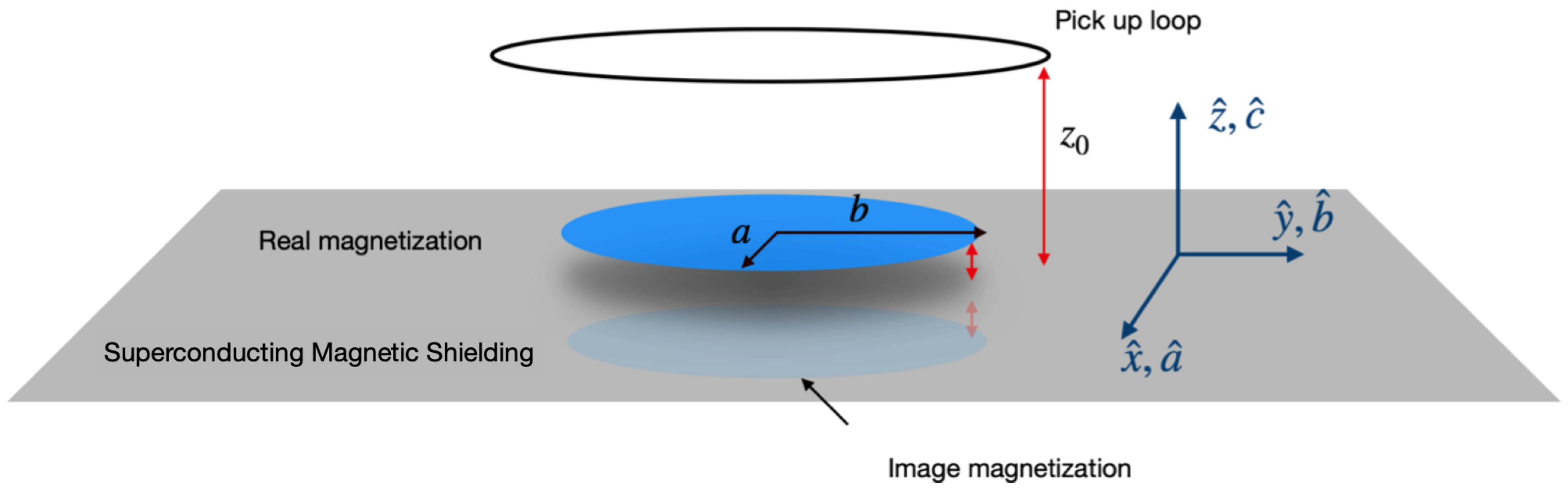
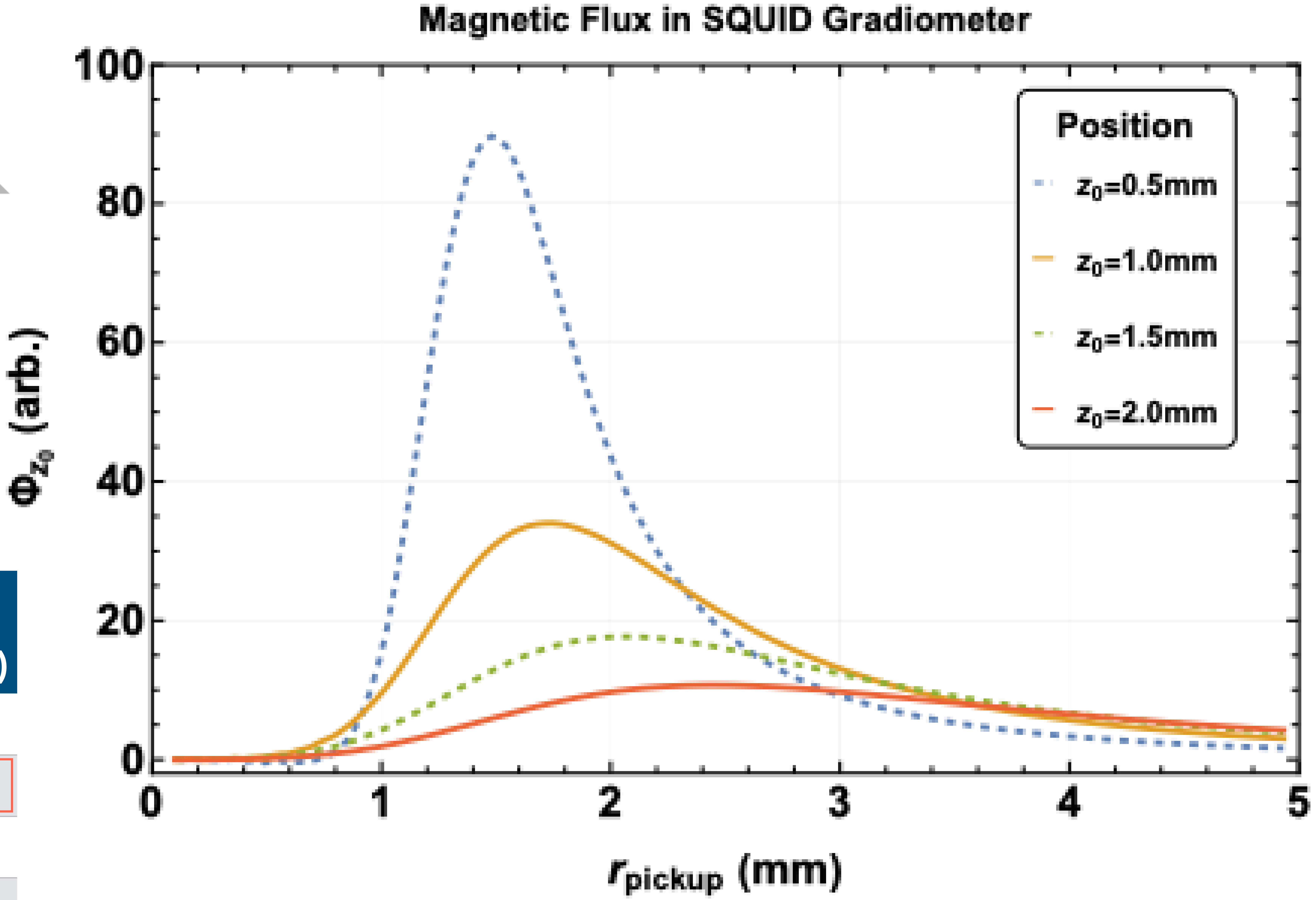
Transduced Magnetic Flux



- Magnetic flux passing through the pickup loop : Φ_{z_0}
- The compensation coil for gradiometer : $r_{\text{com}} = \sqrt{2} r_{\text{pickup}}$

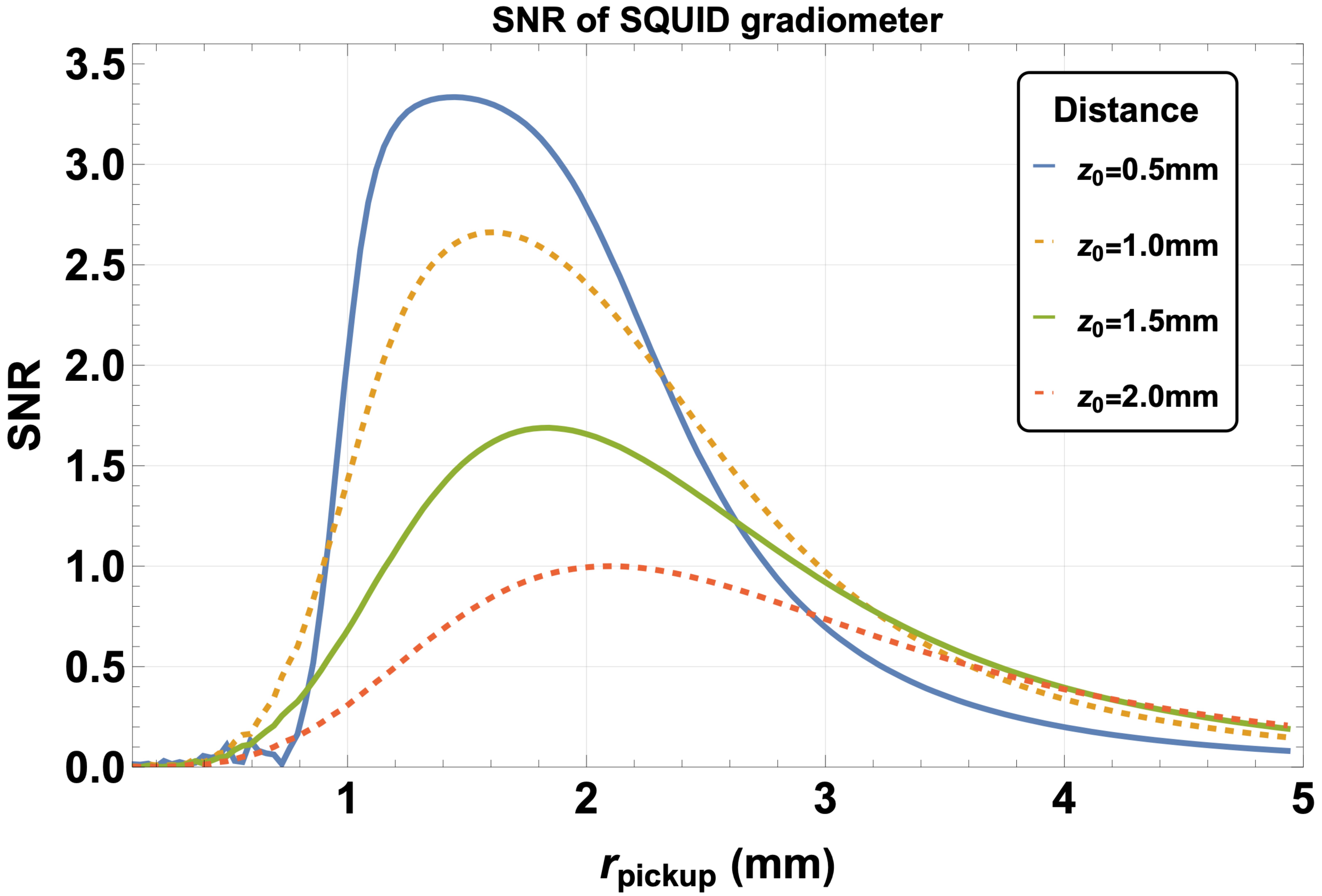
	Magnetometer		Gradiometer	
z0(mm)	r	ϕ (zWb)	r	ϕ (zWb)
0.5	1.42	56.3	1.48	89.7
1.0	1.55	24.8	1.74	34.0
1.5	1.78	13.6	2.04	17.7
2.0	2.07	8.47	2.43	10.7



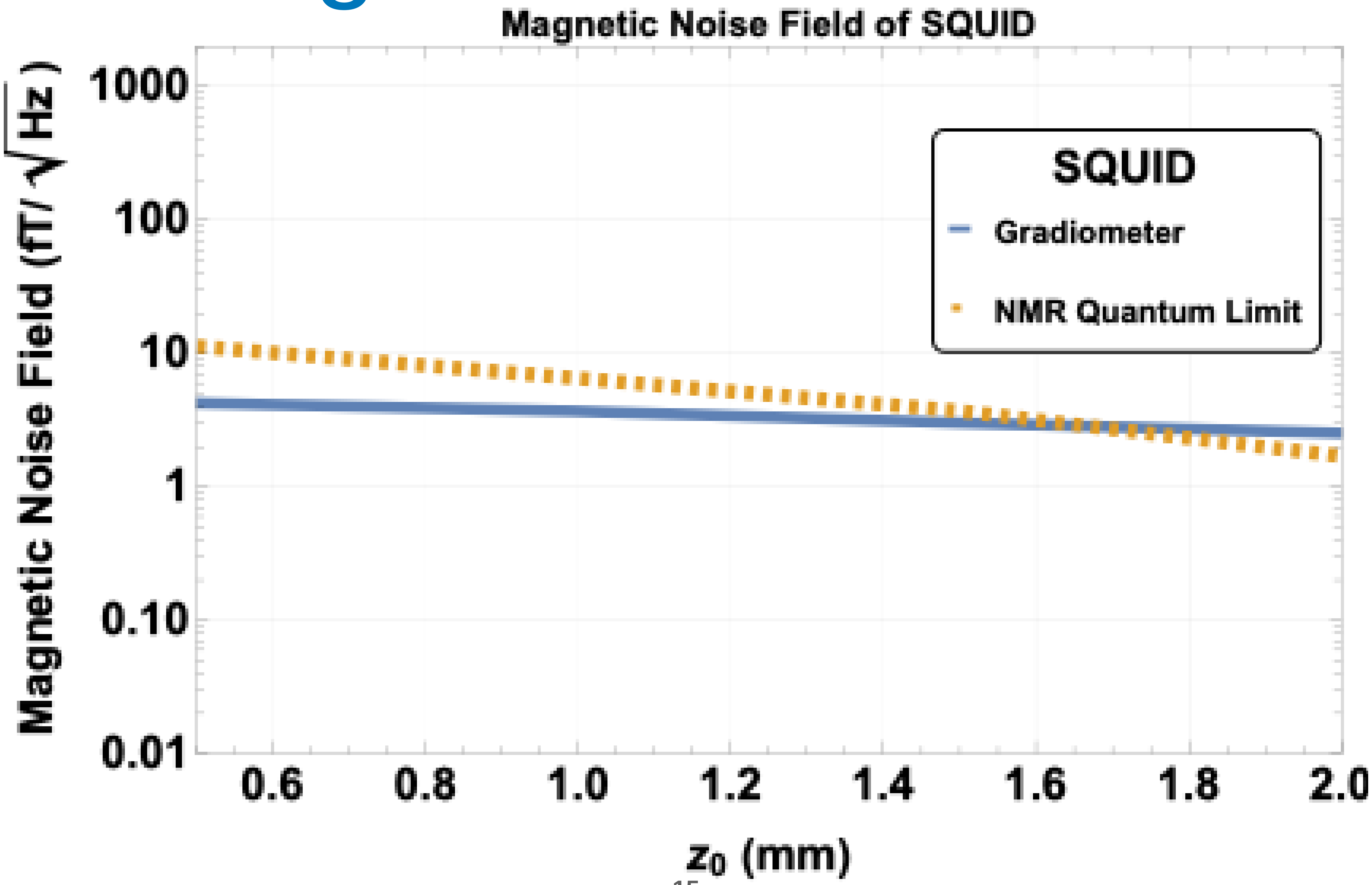
Optimization of SQUID Gradiometer

- $\mathrm{SNR} = \frac{\phi_g}{\sqrt{\delta\phi_n^2+\delta\phi_v^2+\delta\phi_q^2}}$
- Intrinsic noise $\delta\phi_n = 1\mu\phi_0/\sqrt{\mathrm{Hz}}$
- Vibrational noise $\delta\phi_v = 1\mathrm{nm}/\sqrt{\mathrm{Hz}}$
- Quantum noise $\delta\phi_q = \frac{\hbar\gamma}{2}\sqrt{\frac{n_{^3\mathrm{He}} T_2}{V}}$
- Relative SNR to SNR(z0=2mm, r=2.17mm)

	Gradiometer		
z_0(mm)	r	SNR_{max}	ϕ (zWb)
0.5	1.45	3.3	89.1
1.0	1.61	2.7	33.3
1.5	1.88	1.7	17.2
2.0	2.17	1.0	10.3

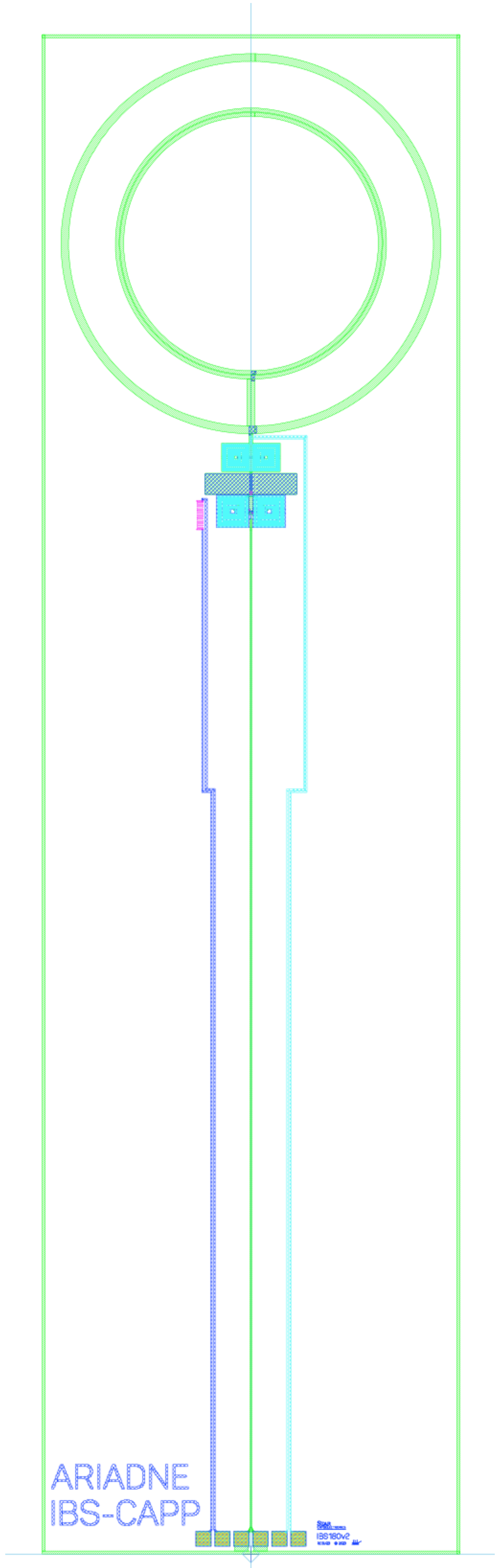


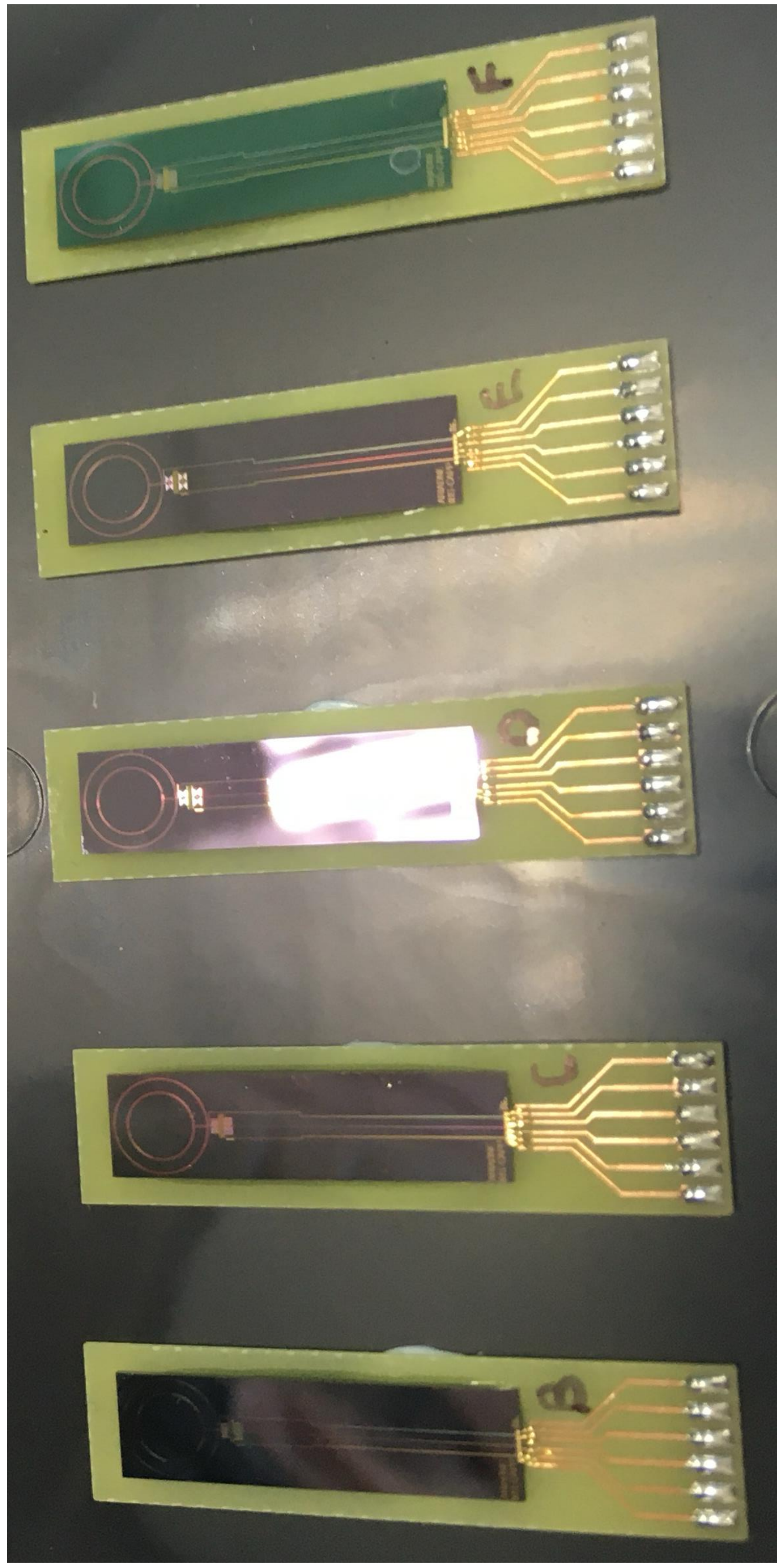
Magnetic Field Noise



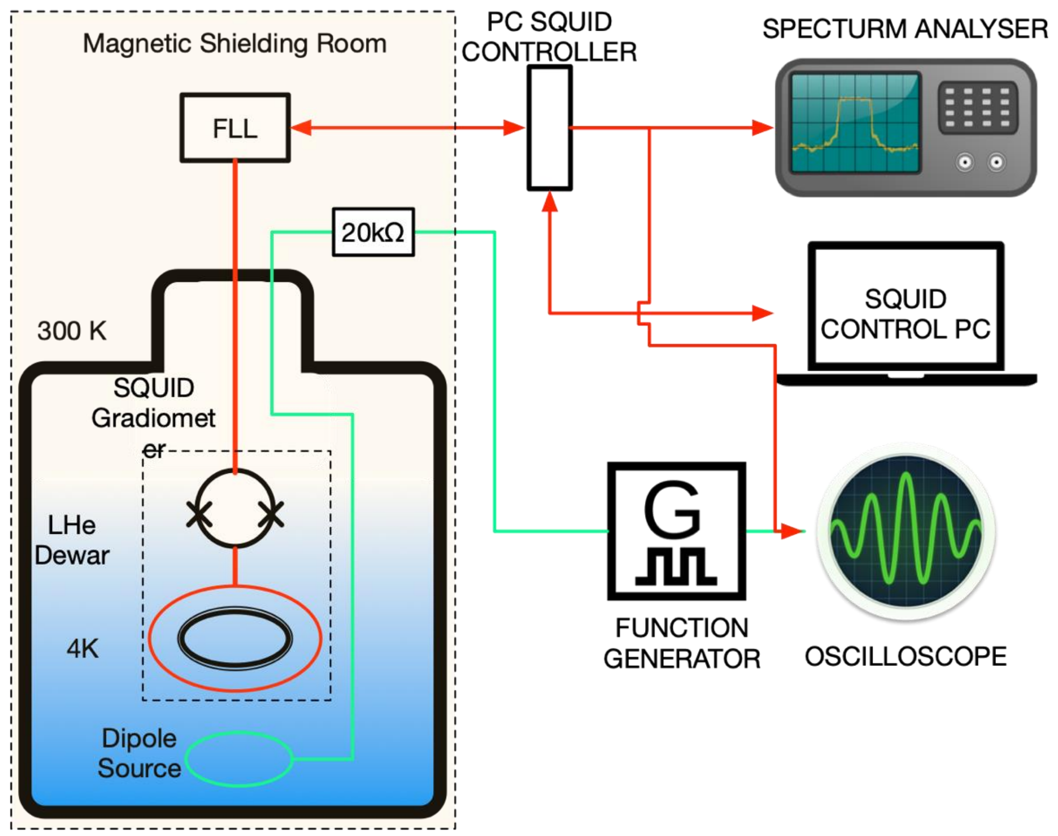
Thin-film SQUID Gradiometer

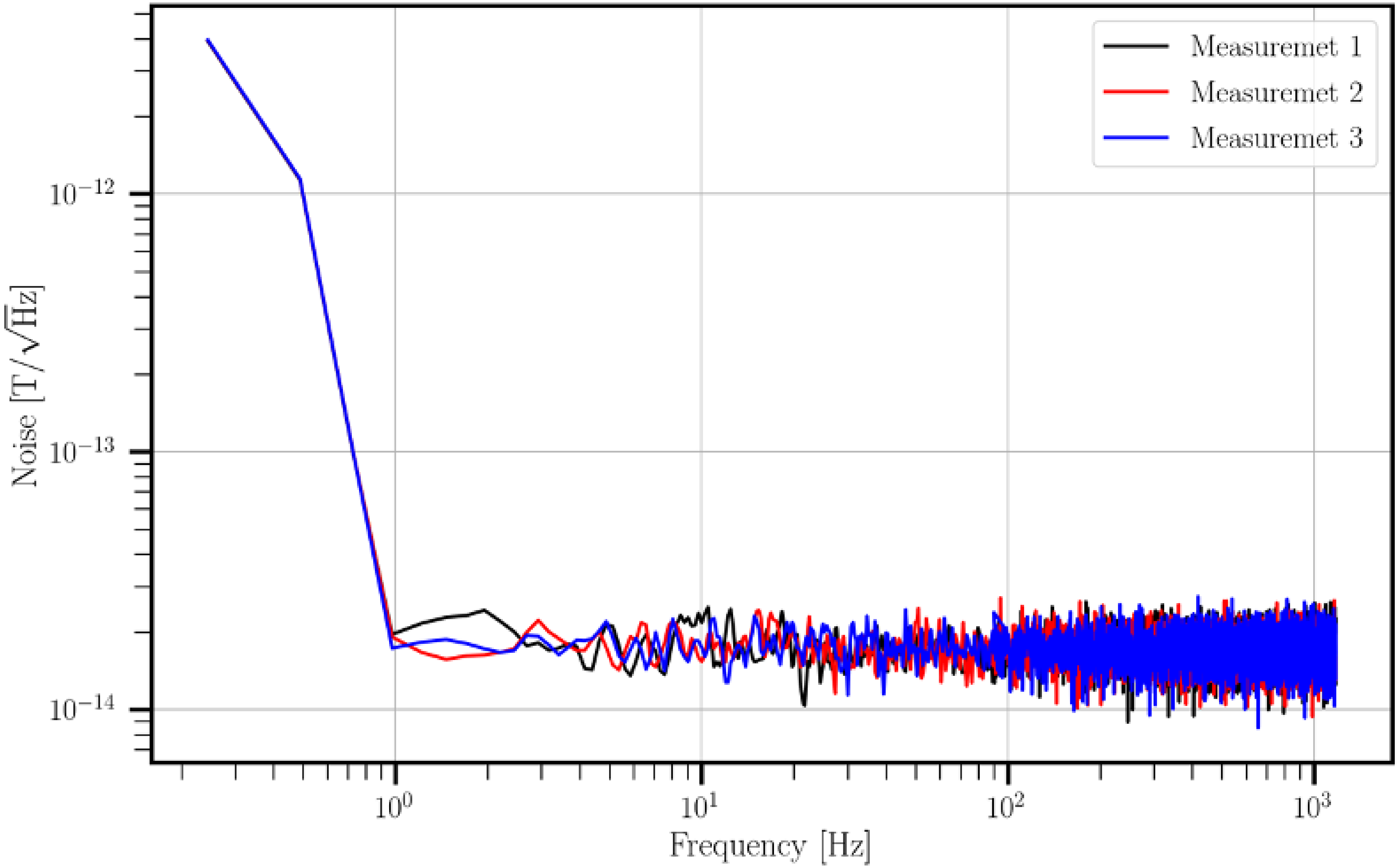
- Prototype for test purpose
- Fabricated by Star Cryo. LLC based on CAPP design values
- Inner coil 1: d=3.45mm, t=0.05mm
- Inner coil 2 : d=3.57mm, t=0.05mm
- Outer coil : d=5mm, t=0.1mm
- Estimated SQUID intrinsic noise: $\sim 4\mathrm{fT}/\sqrt{\mathrm{Hz}}$
  - Spin induced noise: $\sim 10\mathrm{fT}/\sqrt{\mathrm{Hz}}$





SQUID Noise spectrum

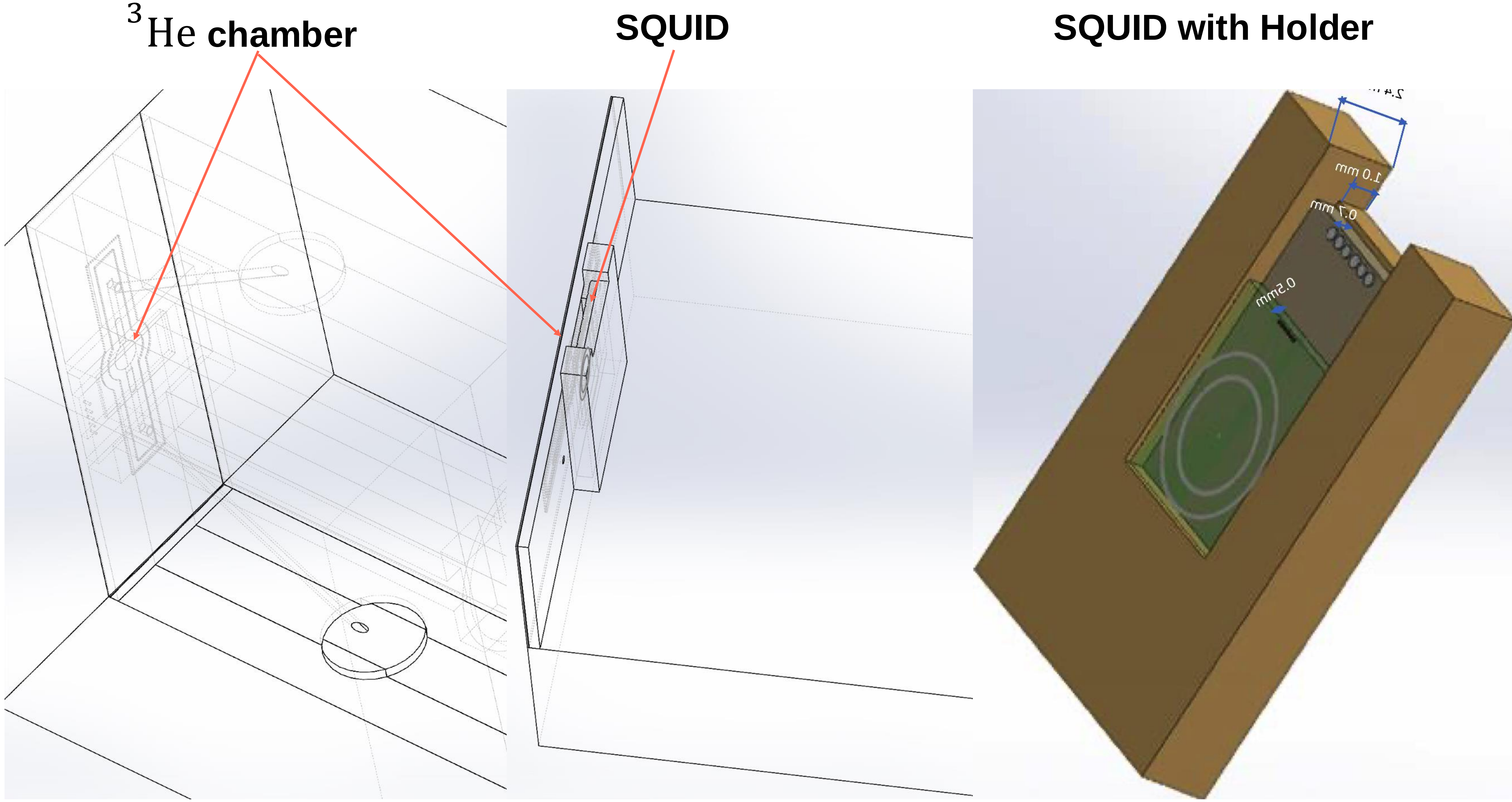




- Measured in a Magnetic Shielding Room (MSR)
- Cooled SQUID with LHe
- Measured magnetic field noise level:$\sim 14\mathrm{fT}/\sqrt{\mathrm{Hz}}$ at 100Hz

SQUID in the Quartz Container

- Need to cool down SQUID through contact with Quartz block
- Need to install SQUID in a very specific position
- Need to be able to swap SQUID
- SQUID holder with a material of good thermal conductivity (also non-magnetic)



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Thermal properties of materials

	T (K)	Copper	Aluminum	Stainless steel 304	Niobium	G10 A	Nylon	Pyrex B	Teflon	Al_2O_3
Young's modulus (GPa)	300	128	70.0	194	102	38	2.9	62.6	0.38	–
	80	140	76.8	208	–	41	7.6	–	5.4	–
	4	143	79.1	204	–	–	–	–	–	–
Stress at 0.2% strain (MPa)	300	350	110	1.1×10^3	–	1.2×10^3	59	–	7.5	–
	80	420	150	1.5×10^3	–	1.7×10^3	21	–	83	–
	4	–	–	–	–	–	–	–	–	–
Thermal conductivity ($Wm^{-1}K^{-1}$)	300	397	236	15.2	53.7	0.80 C	0.30	1.13	0.25	40
	80	571	415	8.33	57.9	0.50 C	0.22	0.52	0.22	900 D
	4	11370 E	1576	0.252	99.7	0.18 C	0.012	0.11	0.04	110 D

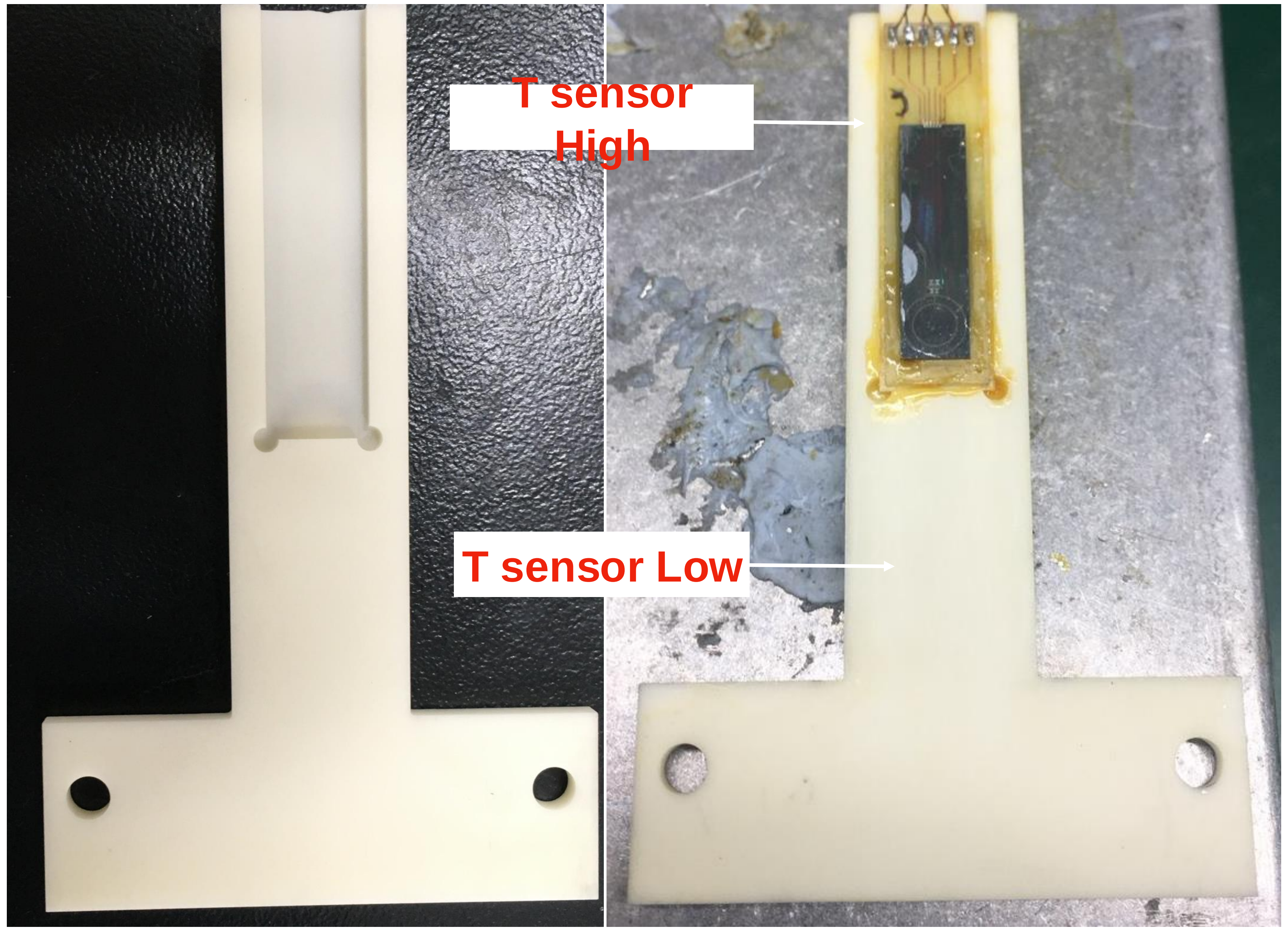
- Quartz (single crystal) : $\sim 200 \mathrm{W/mK}$ or higher
- G10 and Pyrex : $\sim 0.1 \mathrm{W/mK}$
- Polycrystalline Ceramic (MACOR) : $\sim 1 \mathrm{W/mK}$ at 4K

D: Single-crystal; polycrystalline 80K: 120 $Wm^{-1}K^{-1}$; 4K: ~1 $Wm^{-1}K^{-1}$
E: High-purity copper (better than 99.9 %), lower purity: value down to 300 $Wm^{-1}K^{-1}$
F: Warp direction (normal direction: 0.66 % @ 80 K; 0.72 % @ 4 K)
G: Value at 100 K

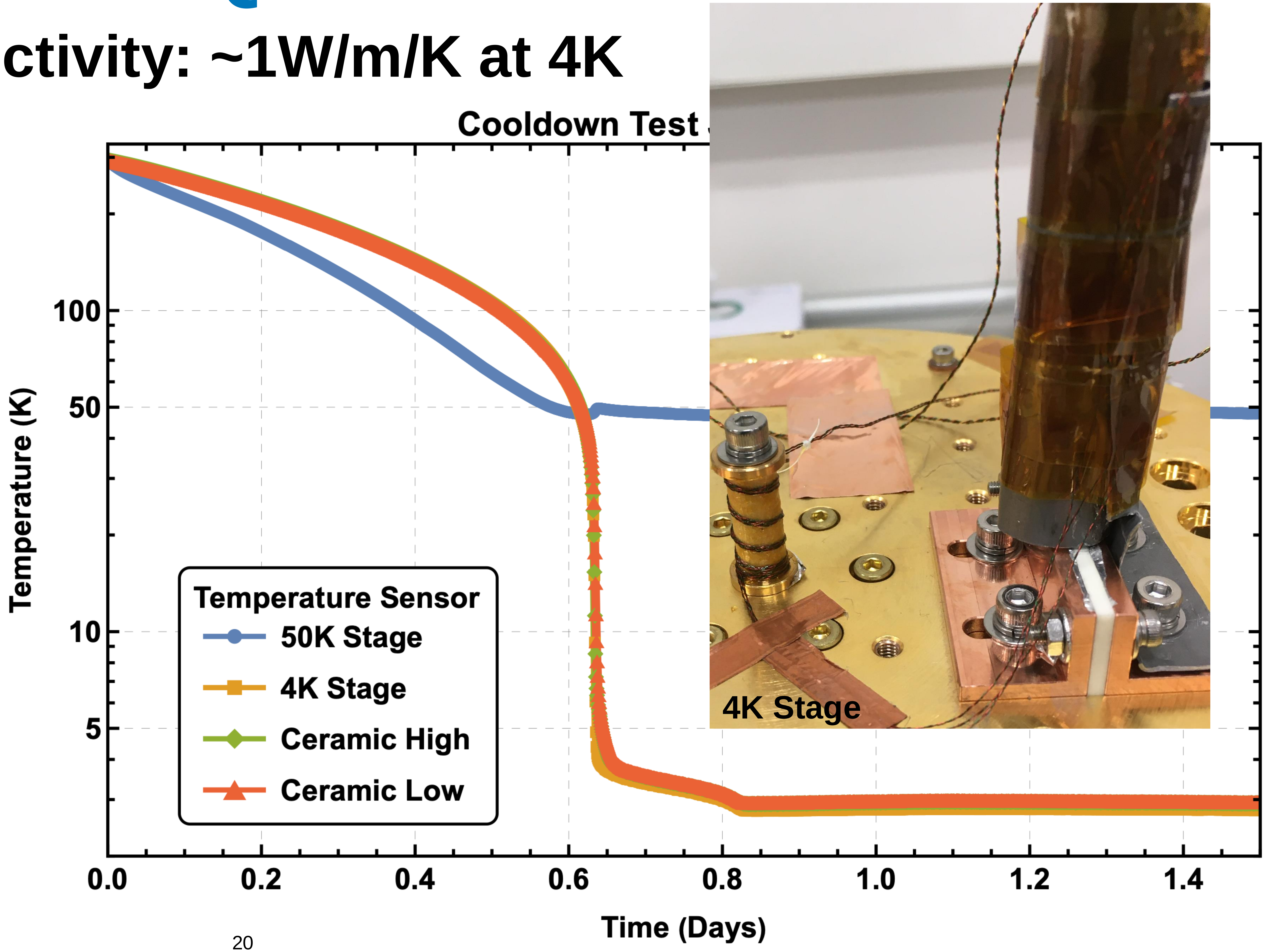
[1] J. Clarke and I. A. Braginski. The SQUID Handbook, Wiley VCH, 2004.

Ceramic SQUID Holder

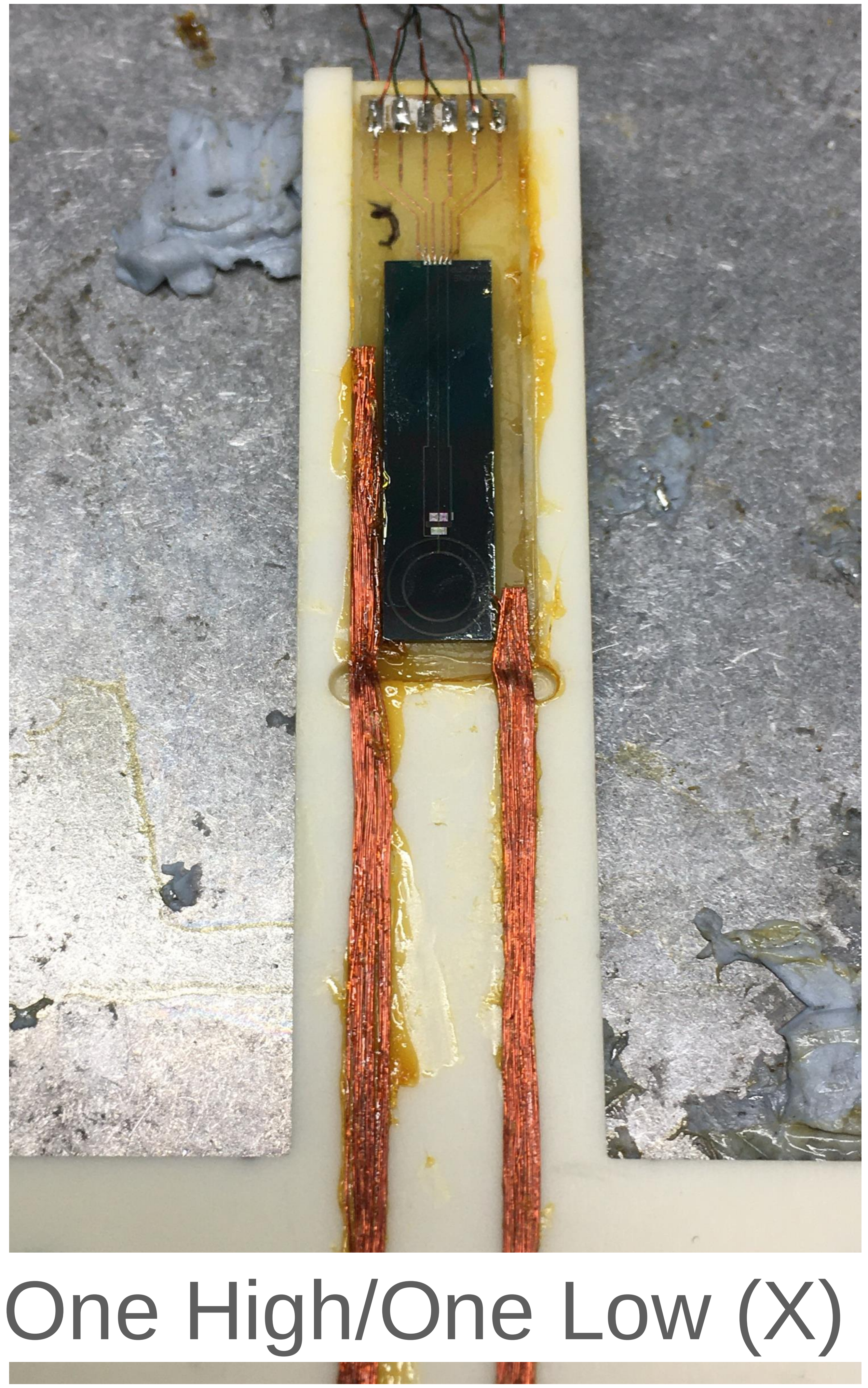
Expected thermal conductivity: ~1W/m/K at 4K

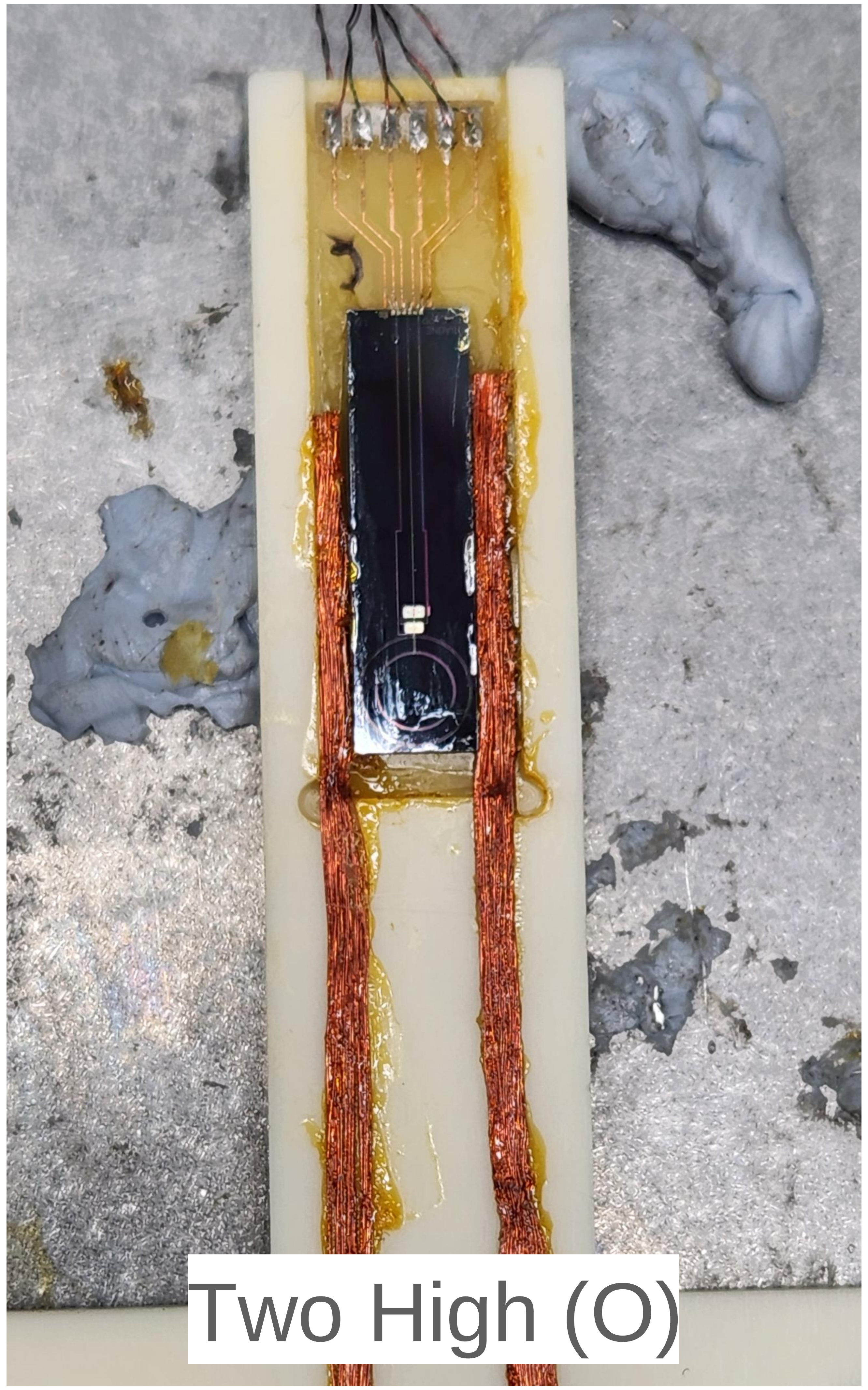


Ceramic Holder　　Ceramic Holder with SQUID



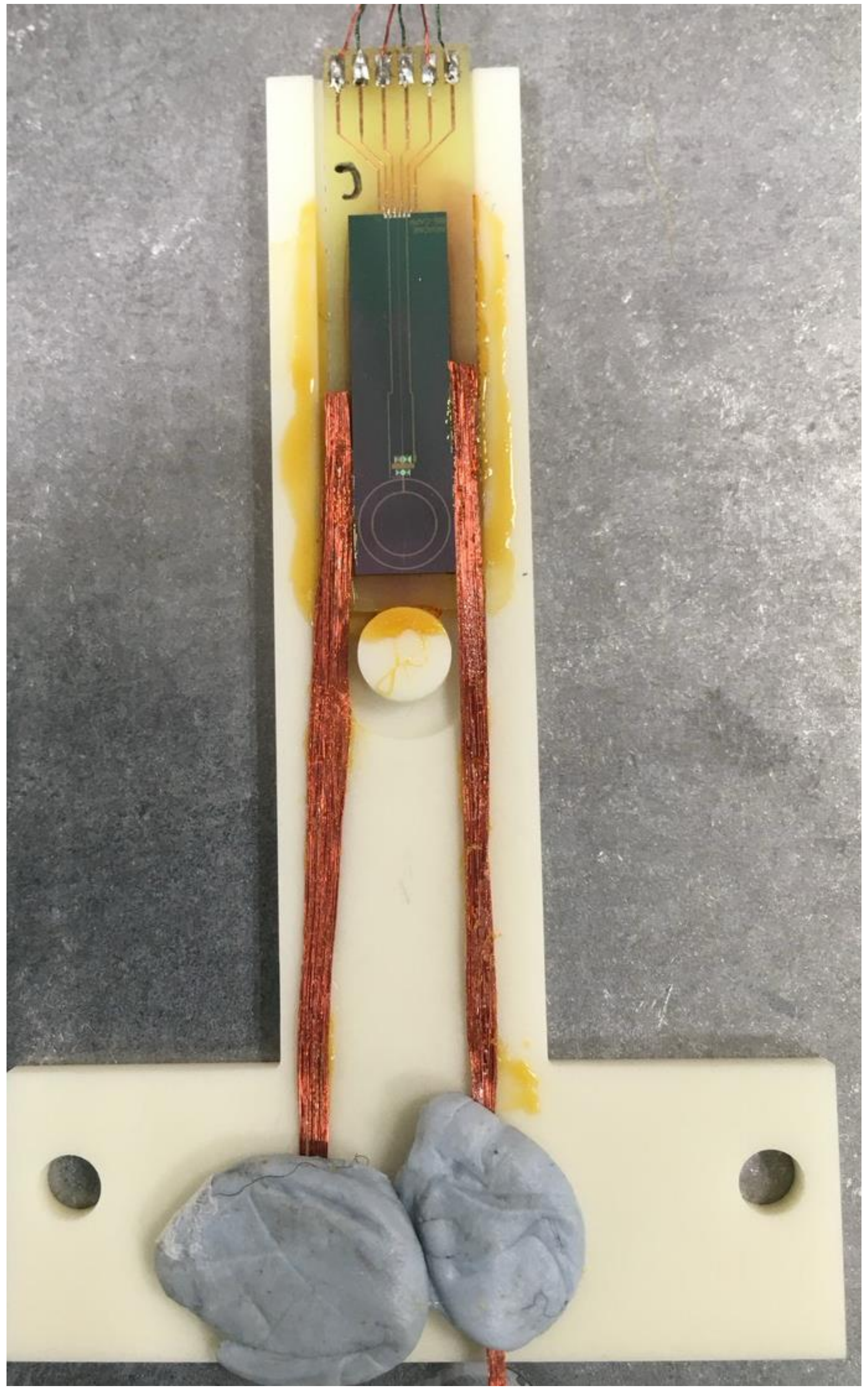
SQUID Thermalization at 4K

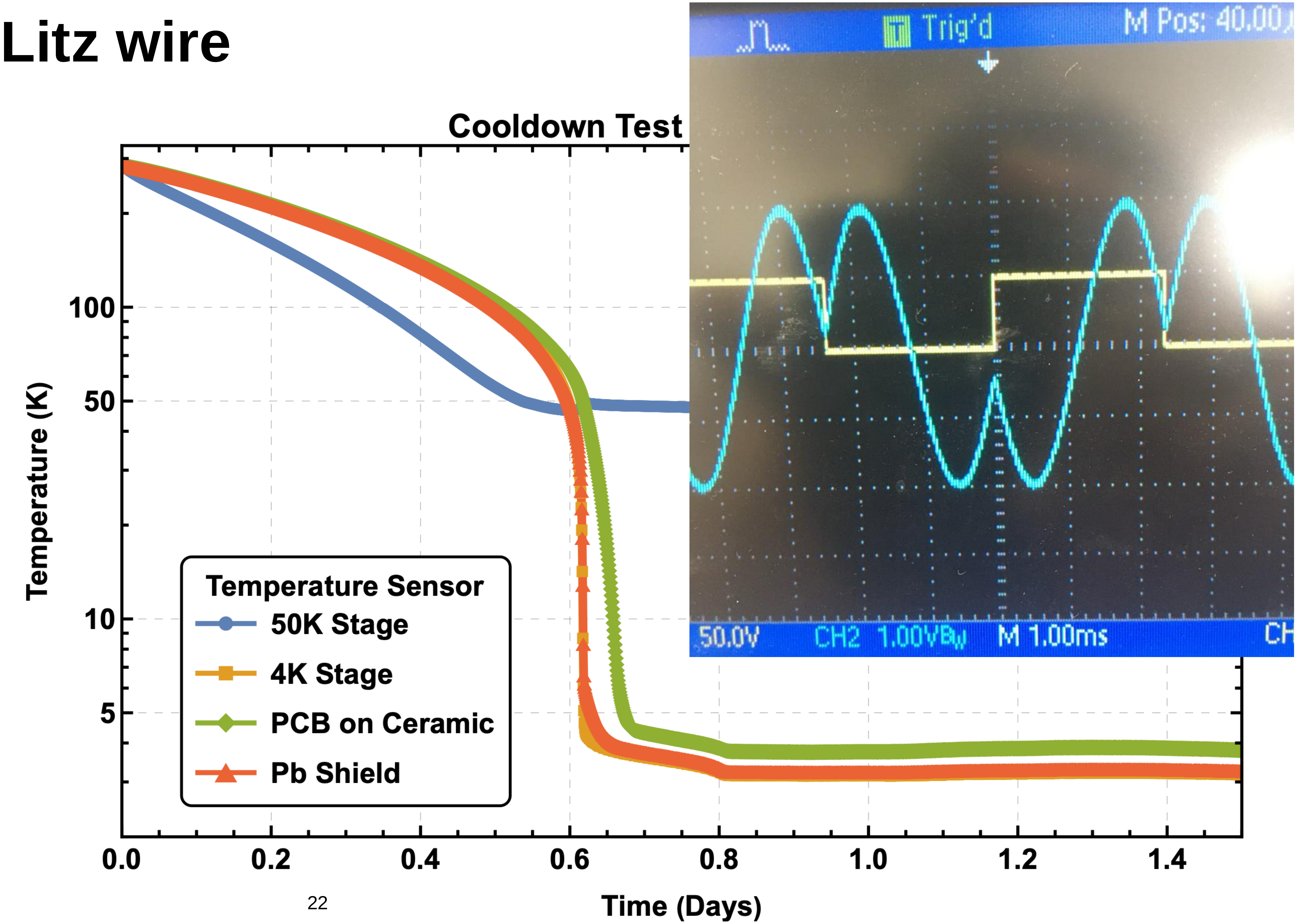




Thermal contact of SQUID

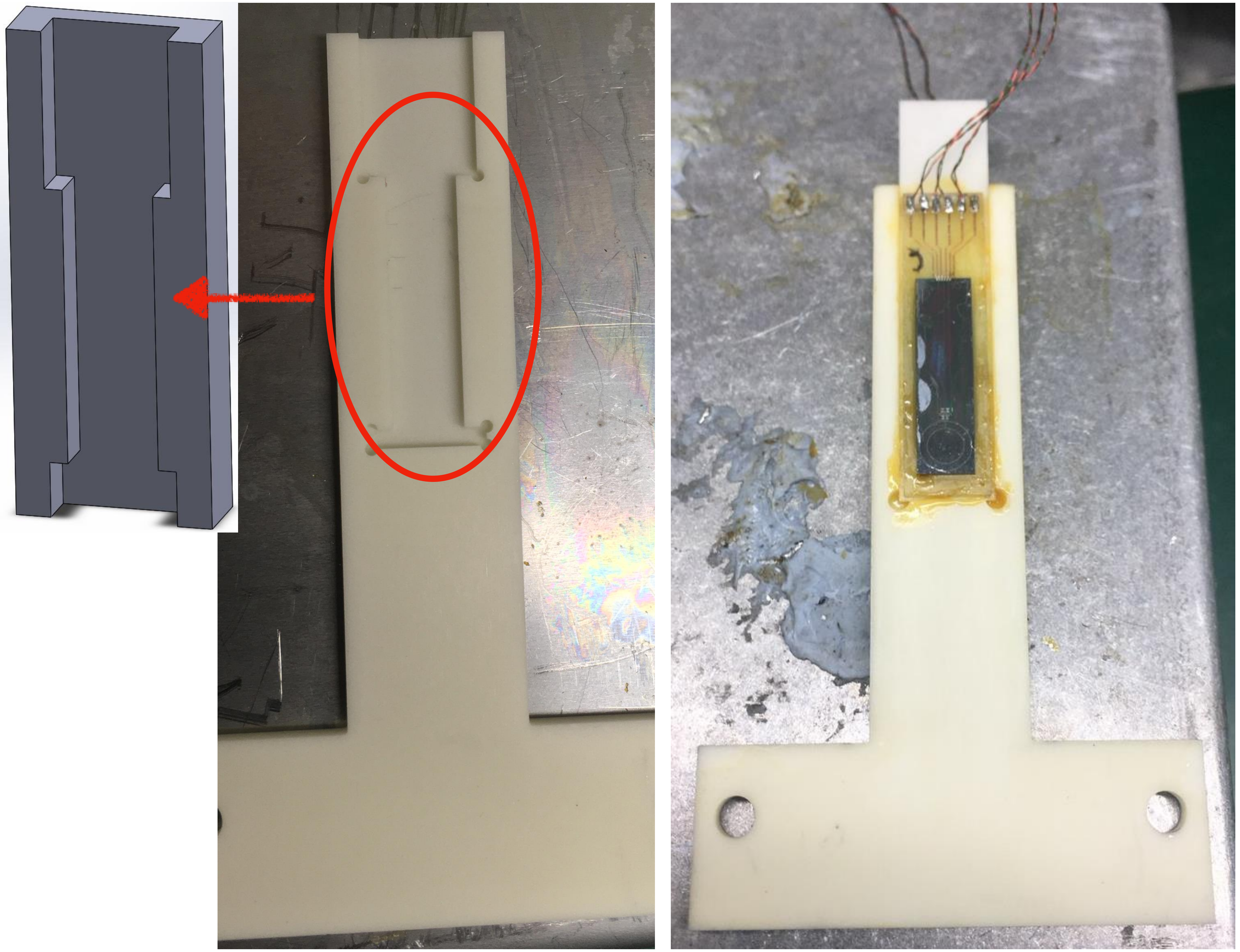
Added two stripes of Litz wire





Front Ceramic Holder

- Realize the effect of cooling without Litz wire
- Design front ceramic plate with narrow opening near SQUID chip
- Direct contact with Si wafer
- Improve thermalization of SQUID without any Litz strip
- Also protect SQUID bonding



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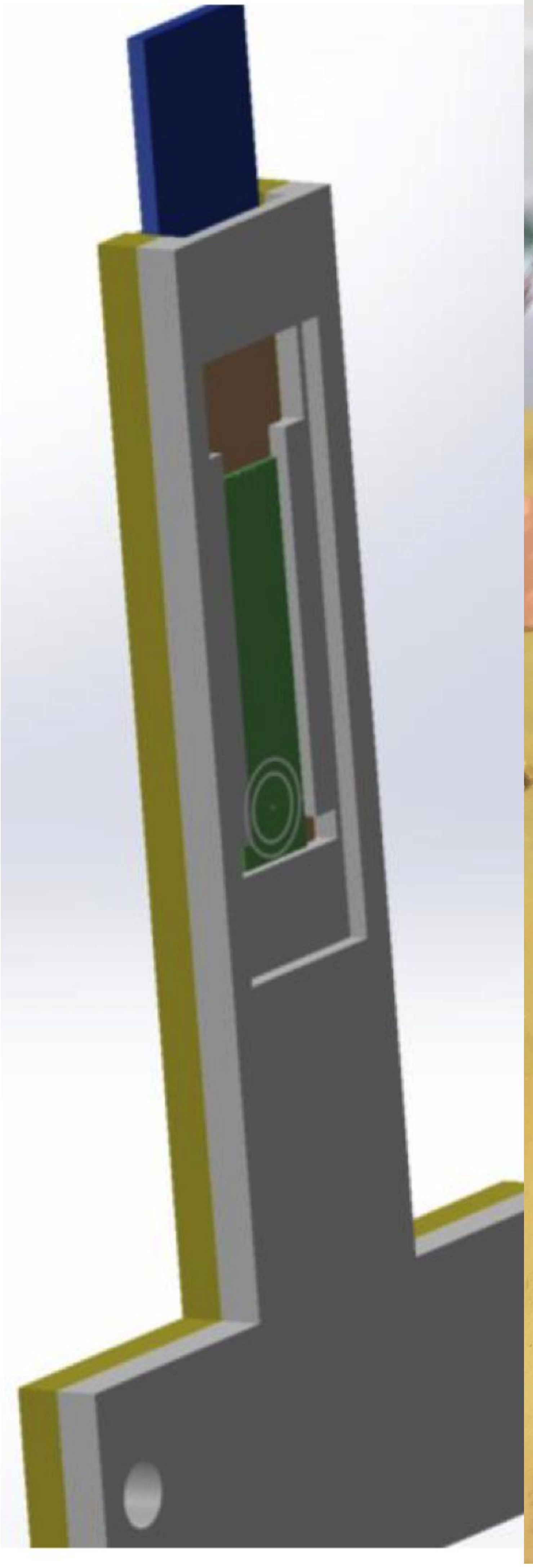
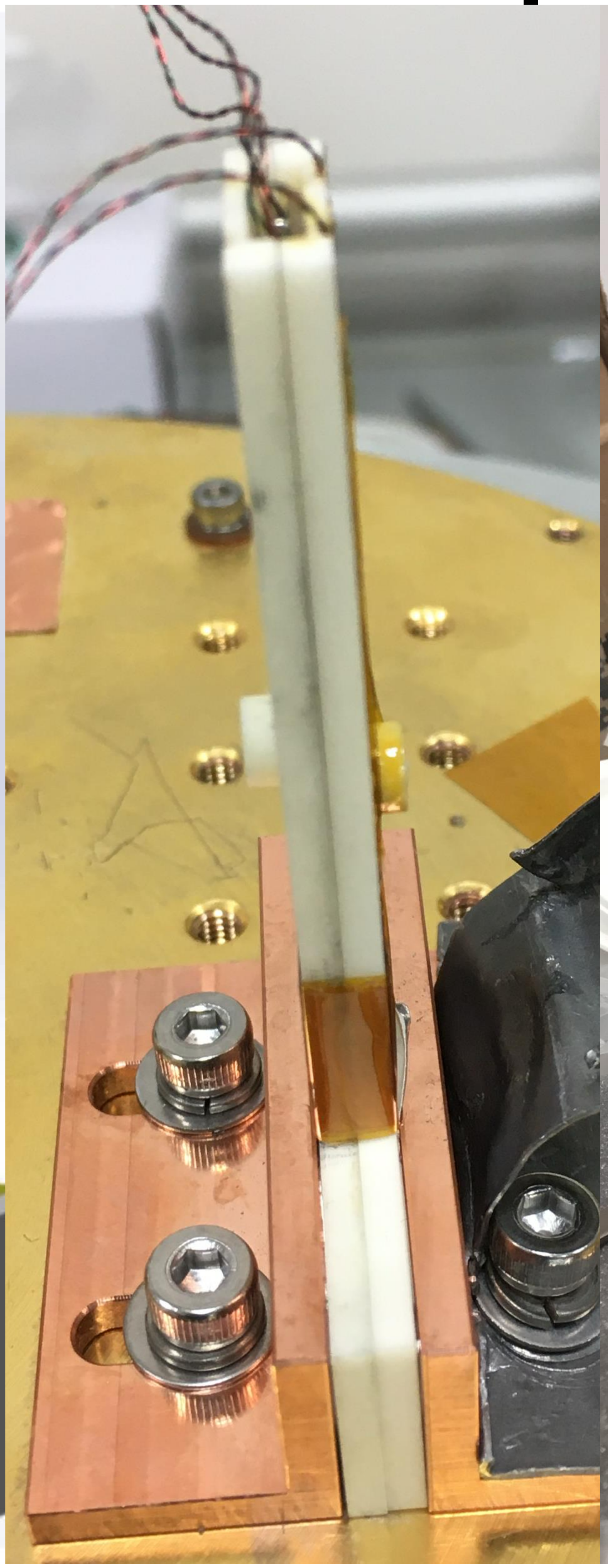
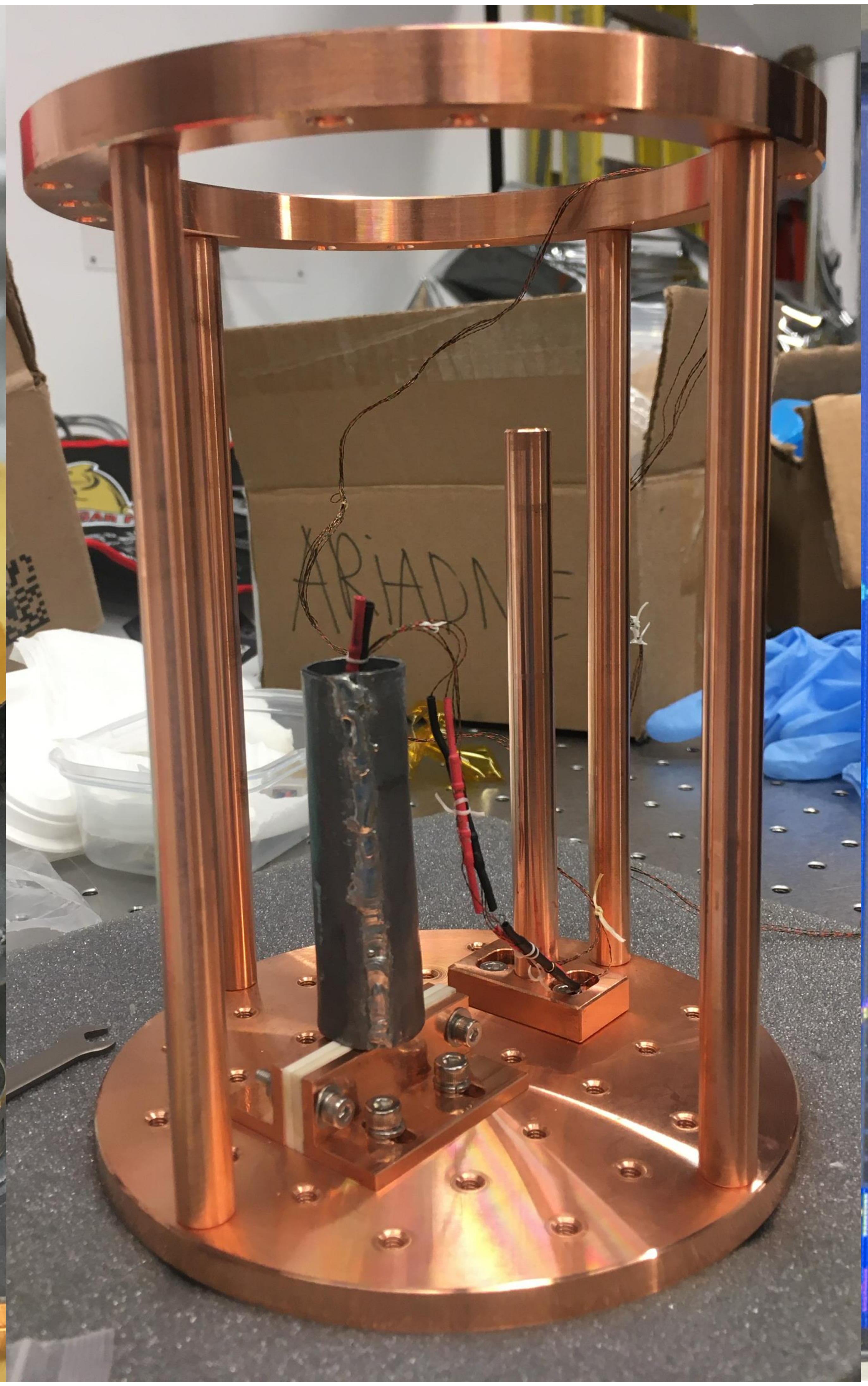
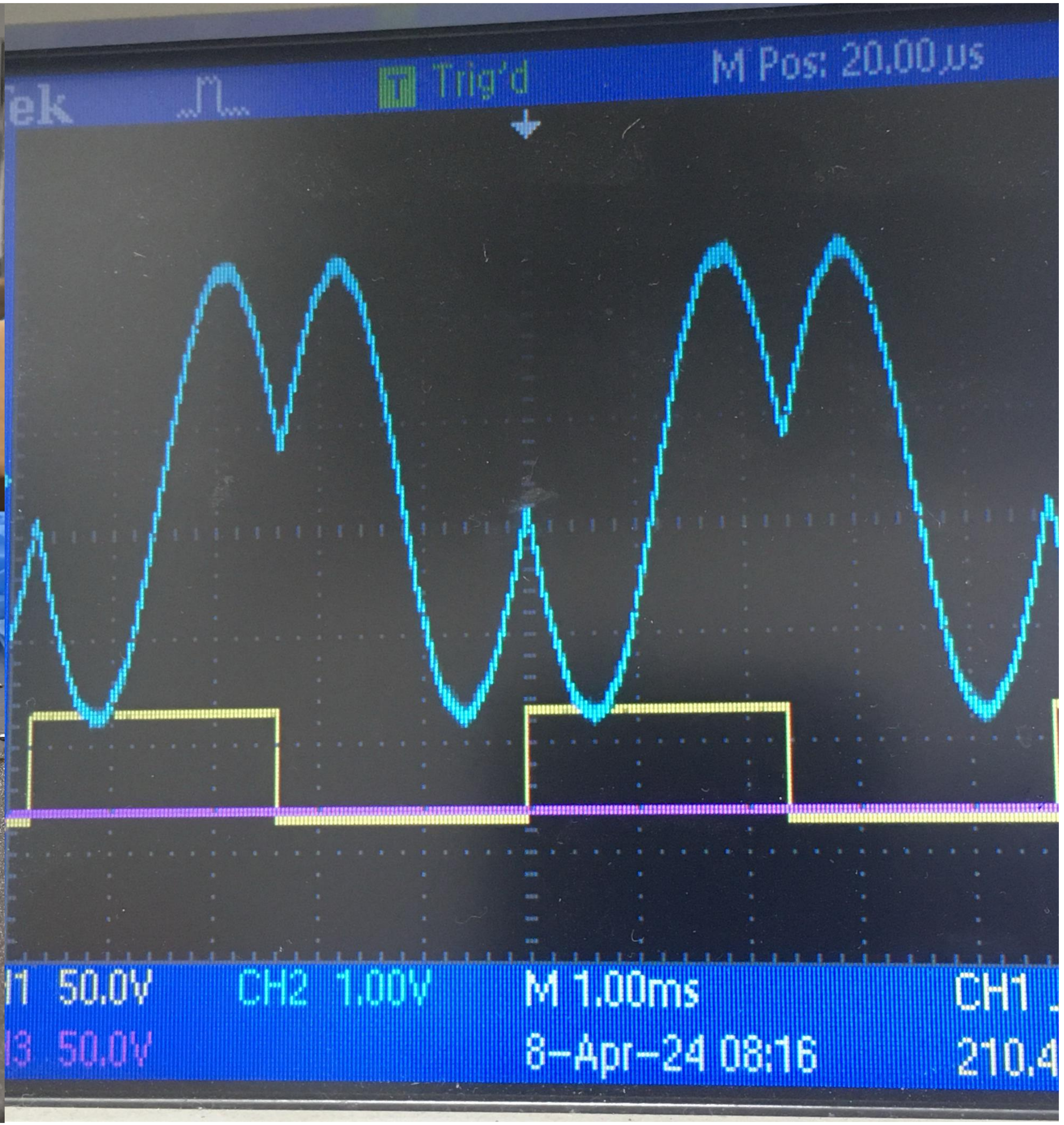
SQUID operation at 4K

with front ceramic plate





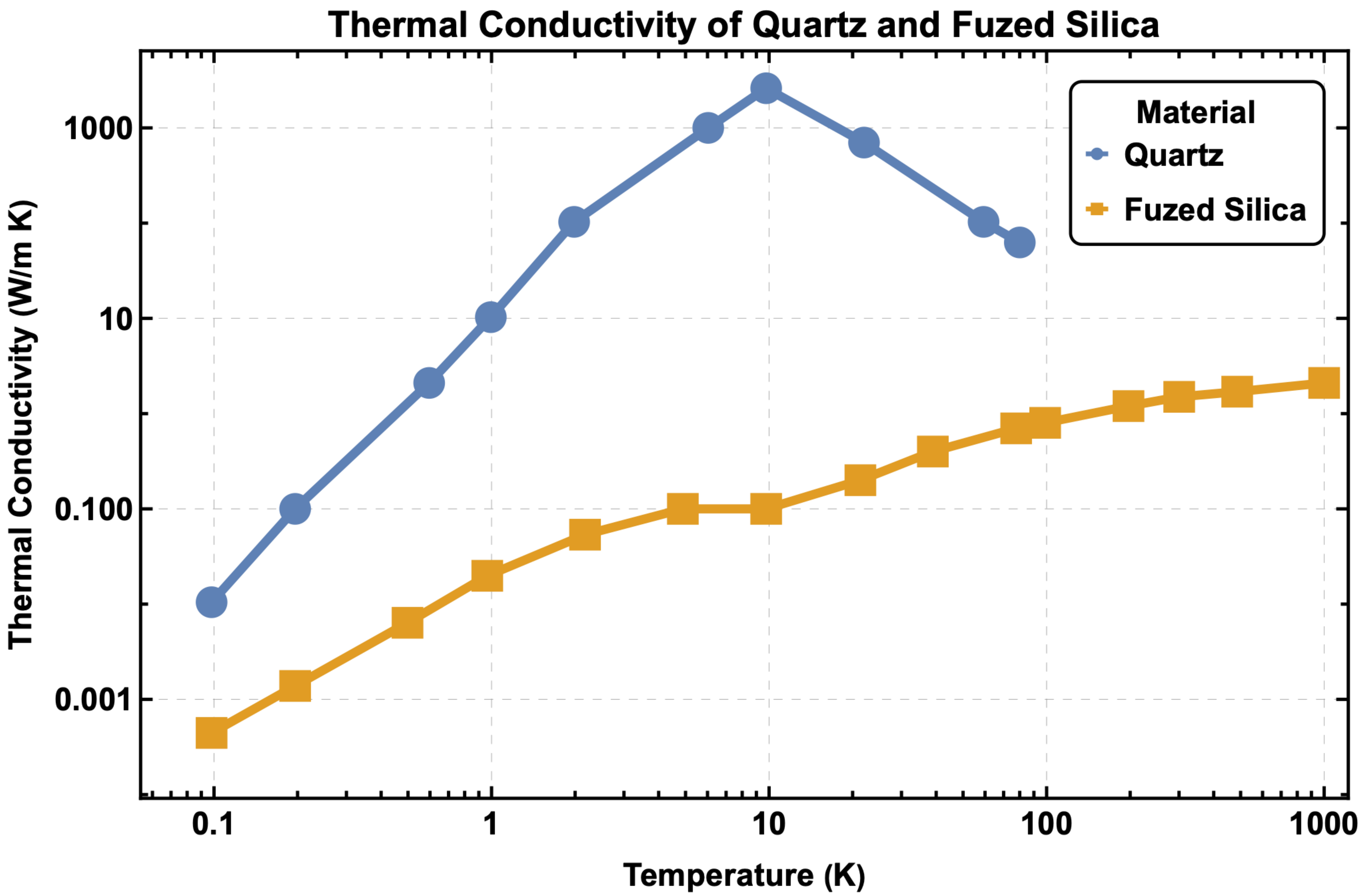


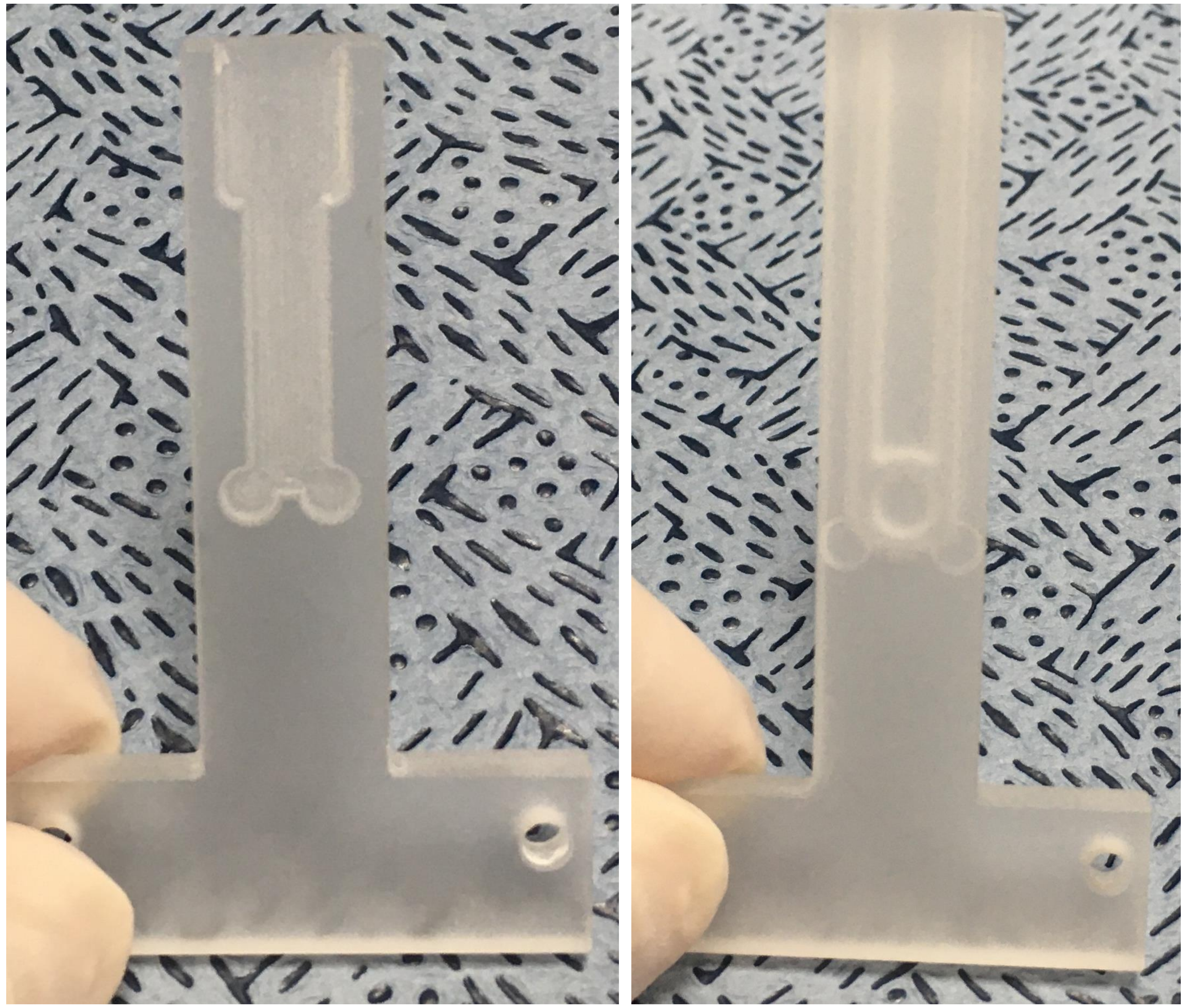


SQUID Noise Level

	$S_{\phi}^{1/2}(\phi_0/\sqrt{\mathrm{Hz}})$	$S_{B}^{1/2}(\mathrm{T}/\sqrt{\mathrm{Hz}})$
Pulse Tube Cryocooler	$\sim 35 \times 10^{-6}$	$\sim 10^{-12}$
Low-vibration Cryostat	$\sim 10 \times 10^{-6}$	$\sim 10^{-13}$
LHe Dewar (in MSR)	$\sim 5.0 \times 10^{-6}$	$\sim 1.4 \times 10^{-14}$

SQUID with Quartz Holder





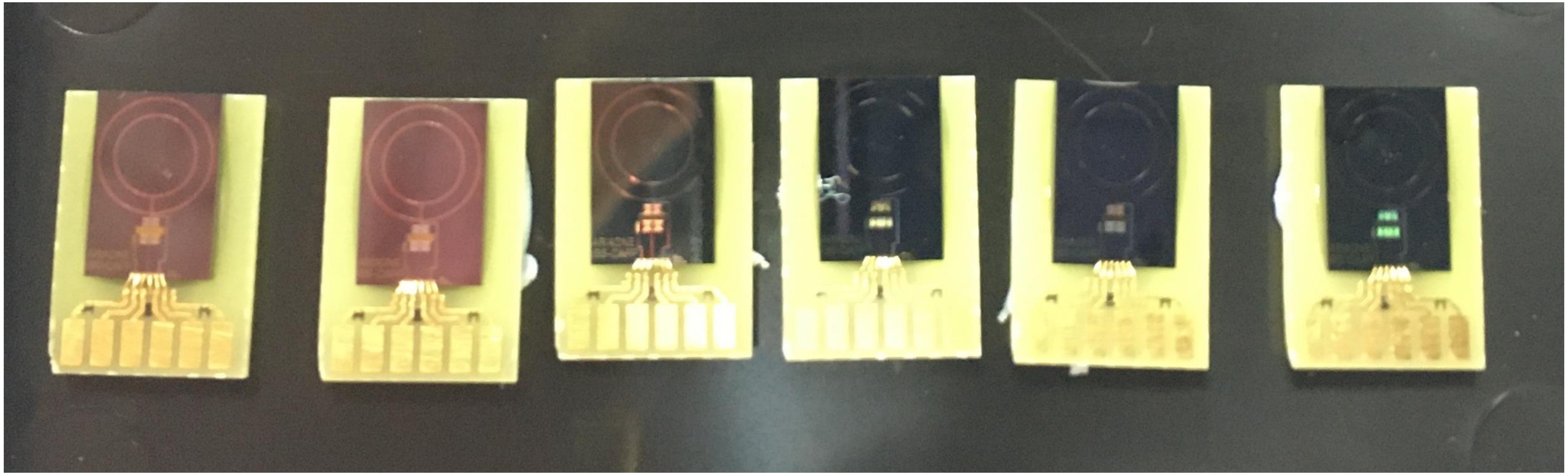
Front Holder

Rear Holder

- Fabrication of SQUID holders with polycrystalline Quartz
- Expected thermal conductivity : $\sim 1\mathrm{W/mK}$ at 4K
- Thermalization (and operation) of SQUID with new Quartz holder will be tested soon

M. Omini and A. Sparavigna, Physical Review B, 61, 6677 (2000)

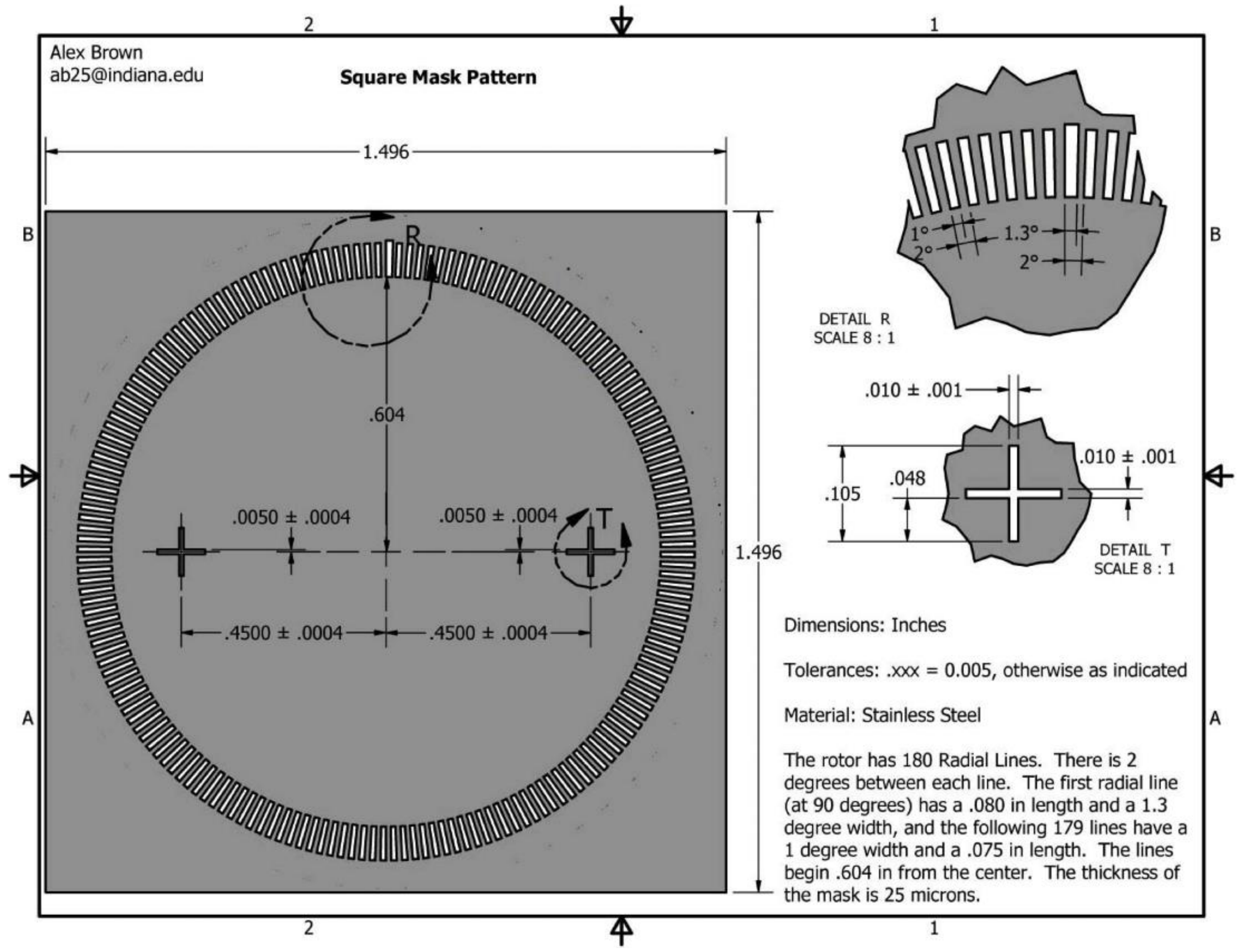
Second batch of SQUID

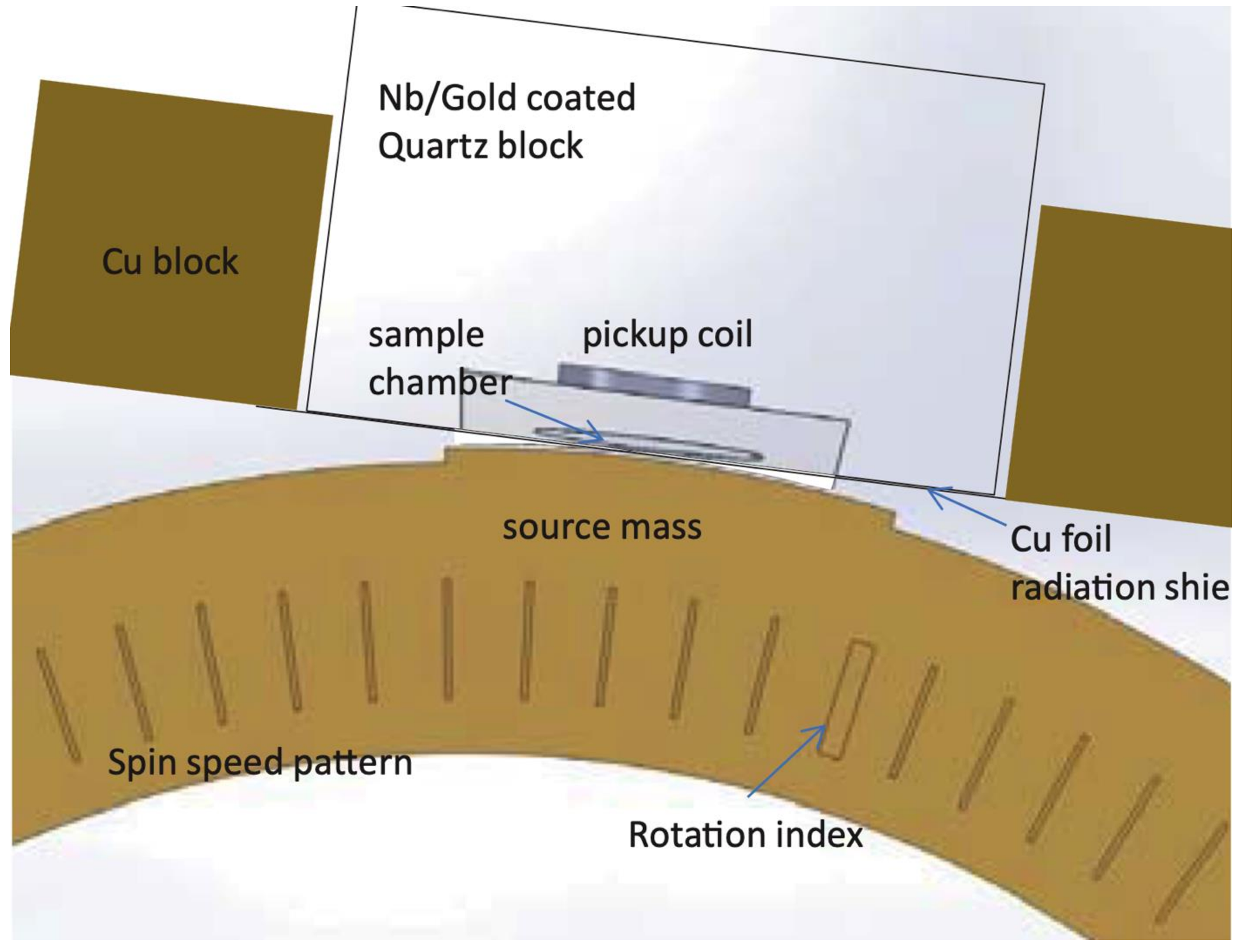


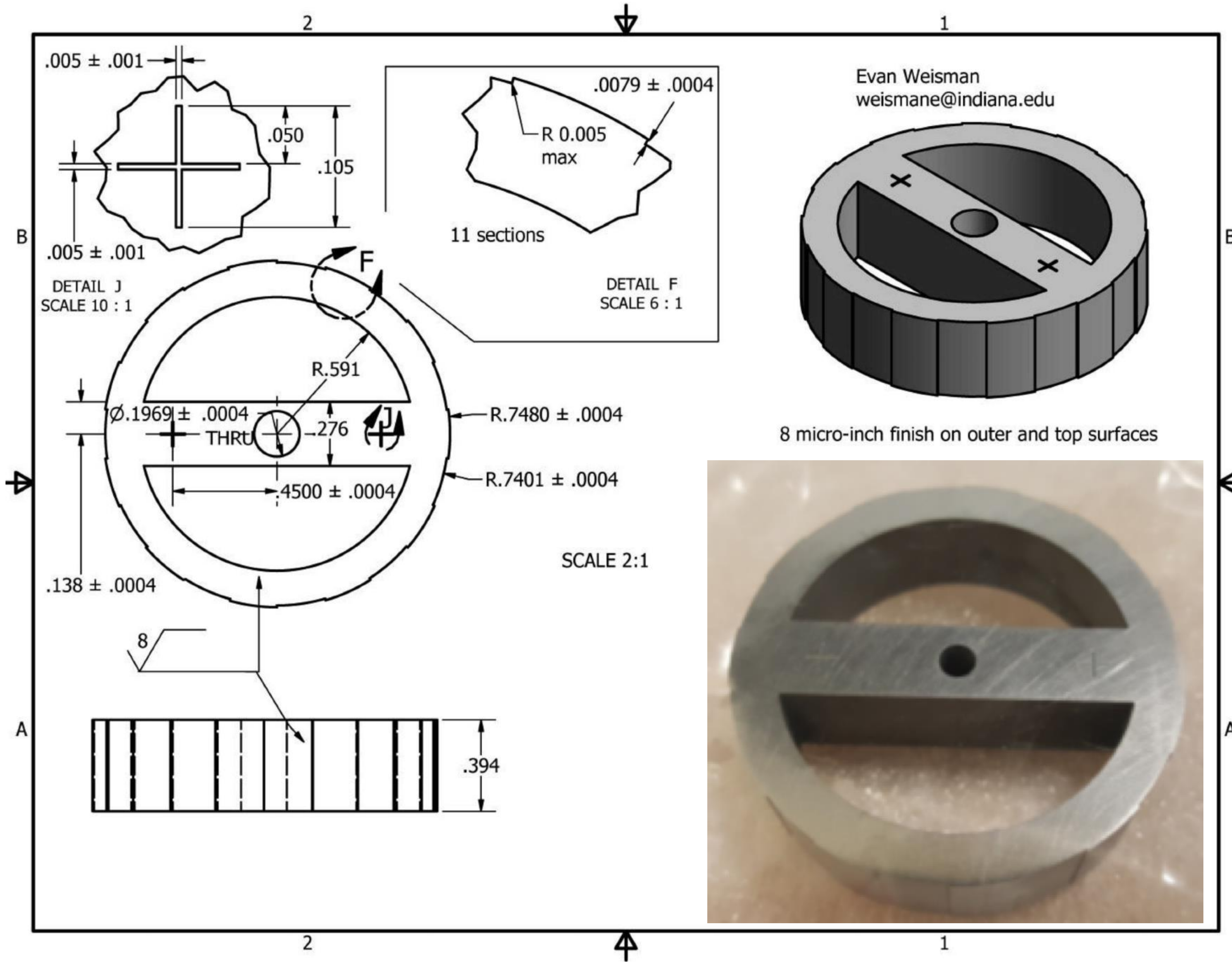
- Same pickup coil size
- Low profile design with shorter length

CAPP
Center for Axion and Precision Physics Research

Rotating Source Mass

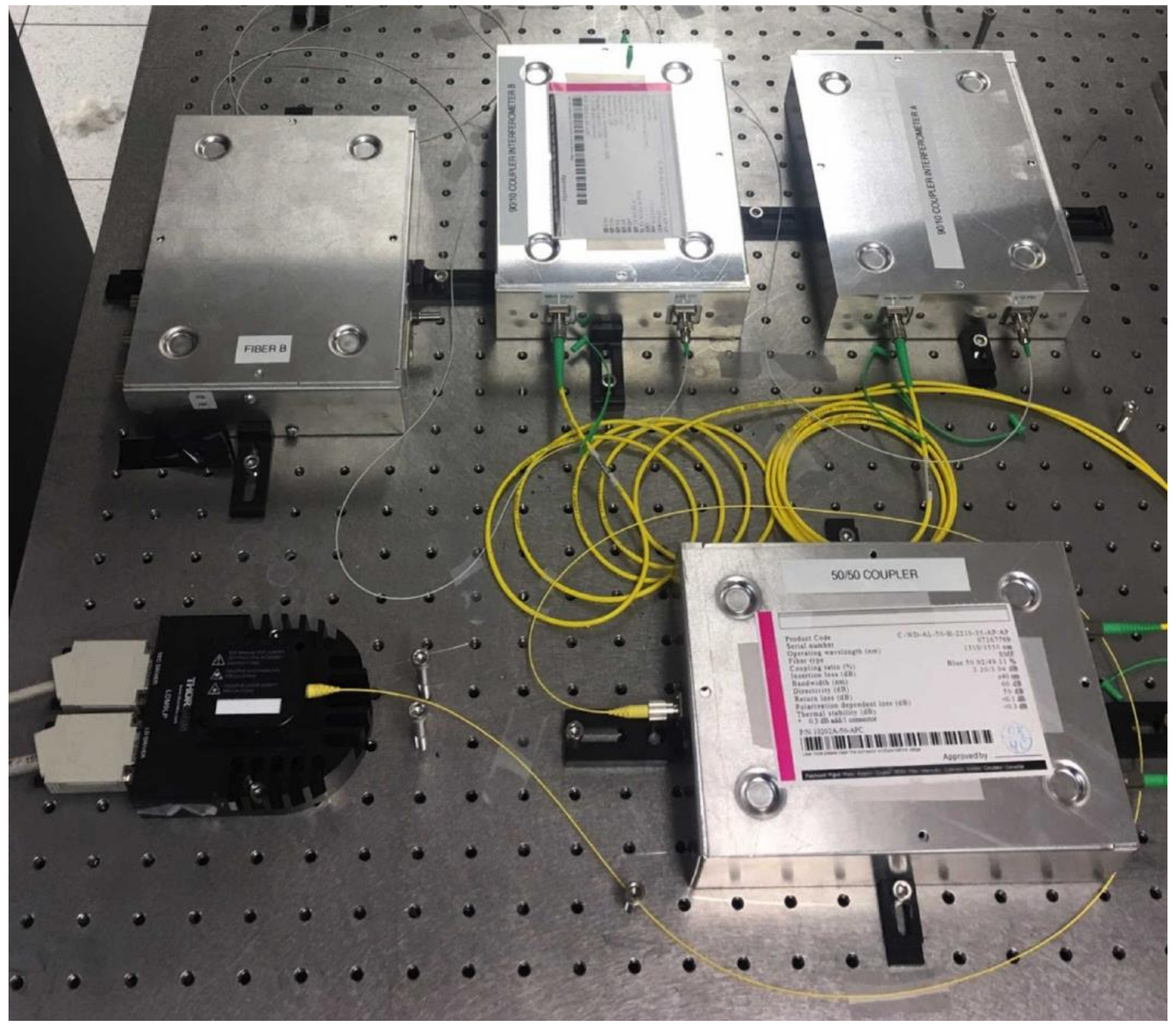


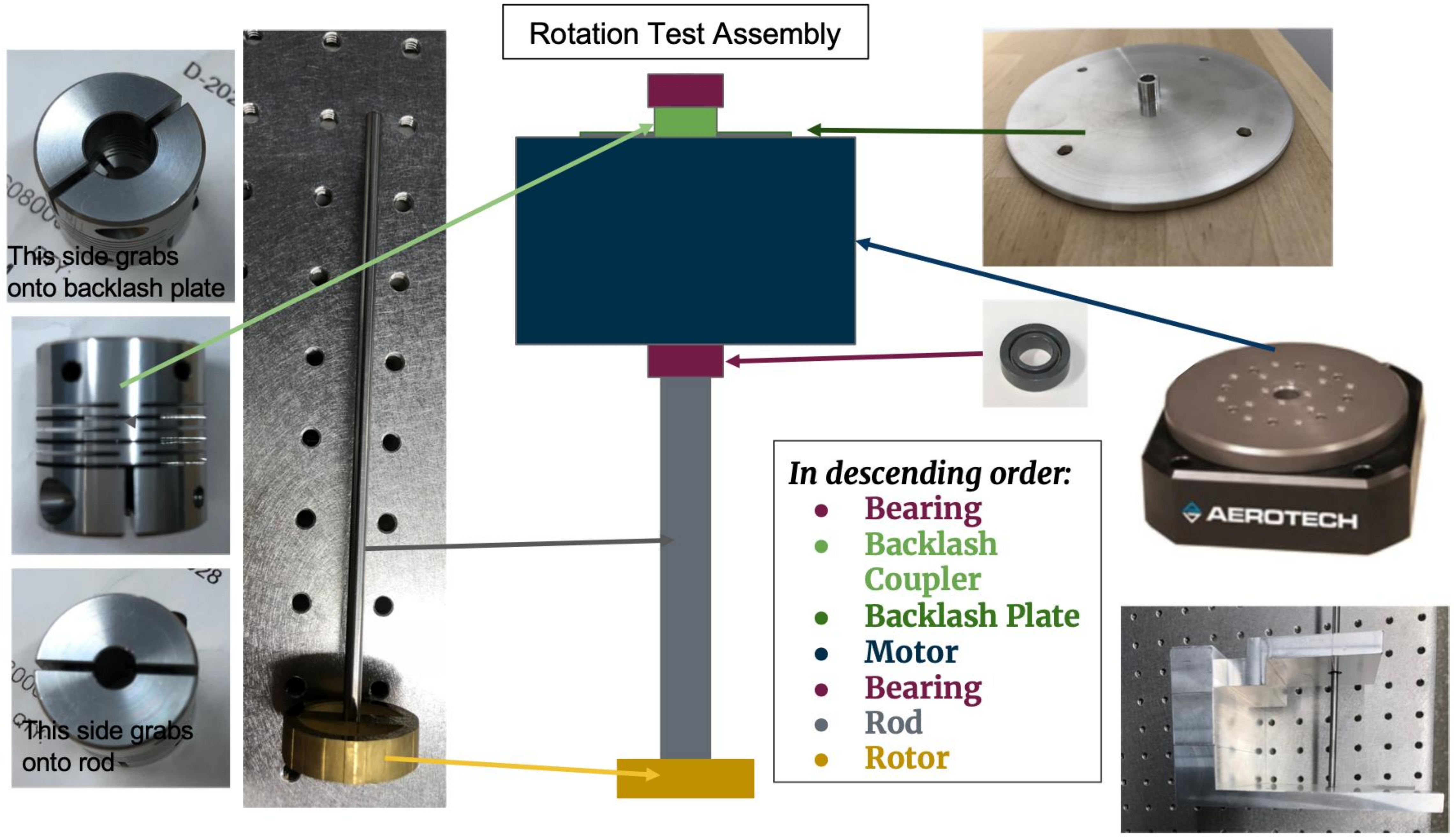


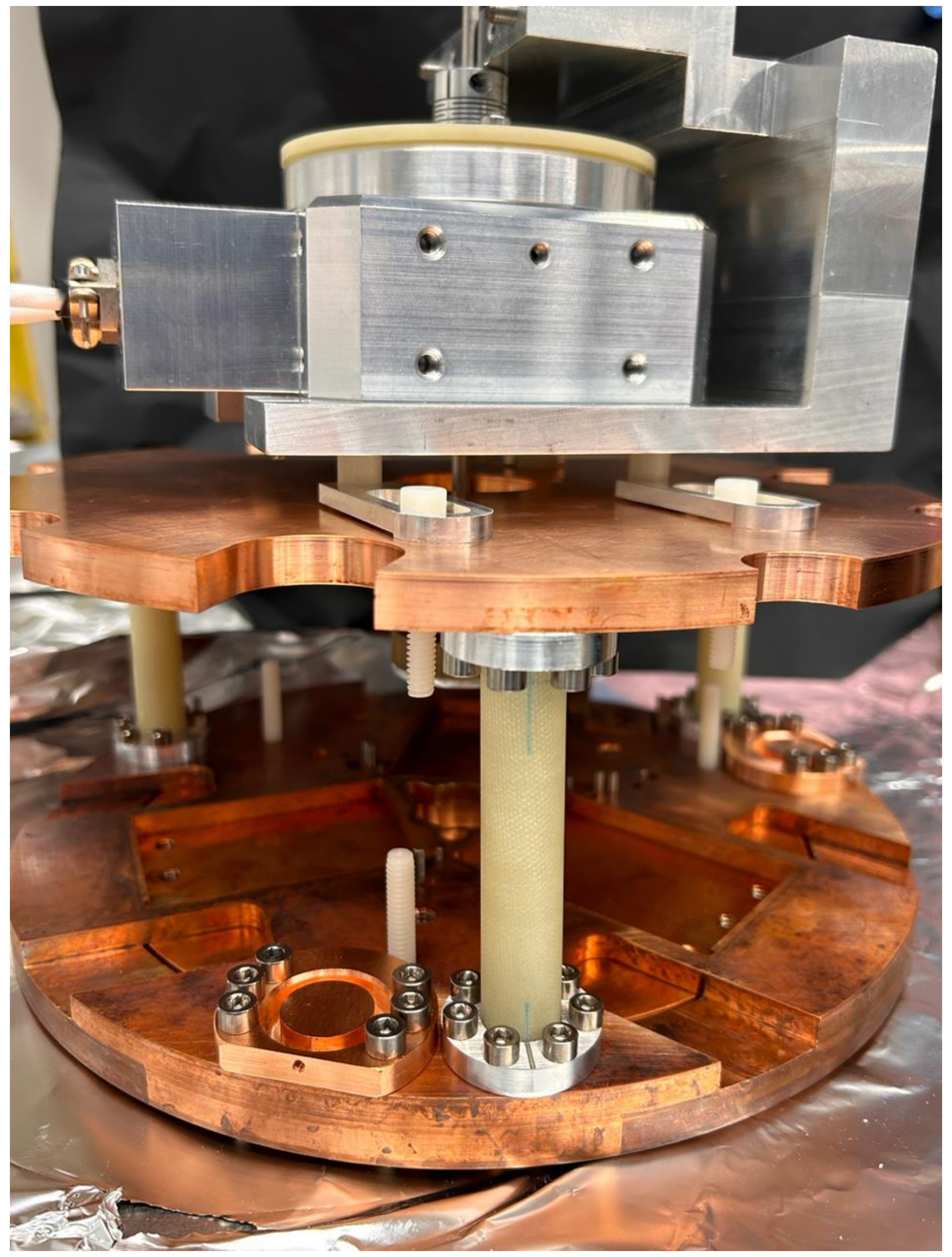


- Made with high purity Tungsten (~99.95%), magnetic impurity <0.4ppm
- 3.8cm outer diameter, 4mm thick Tungsten block,
- 11 segments, and 200μm modulation depth,
- Need to maintain the wobble below $\sim 10\mu m$ ➔ Position monitoring with two channels interferometer+Reflective index mark

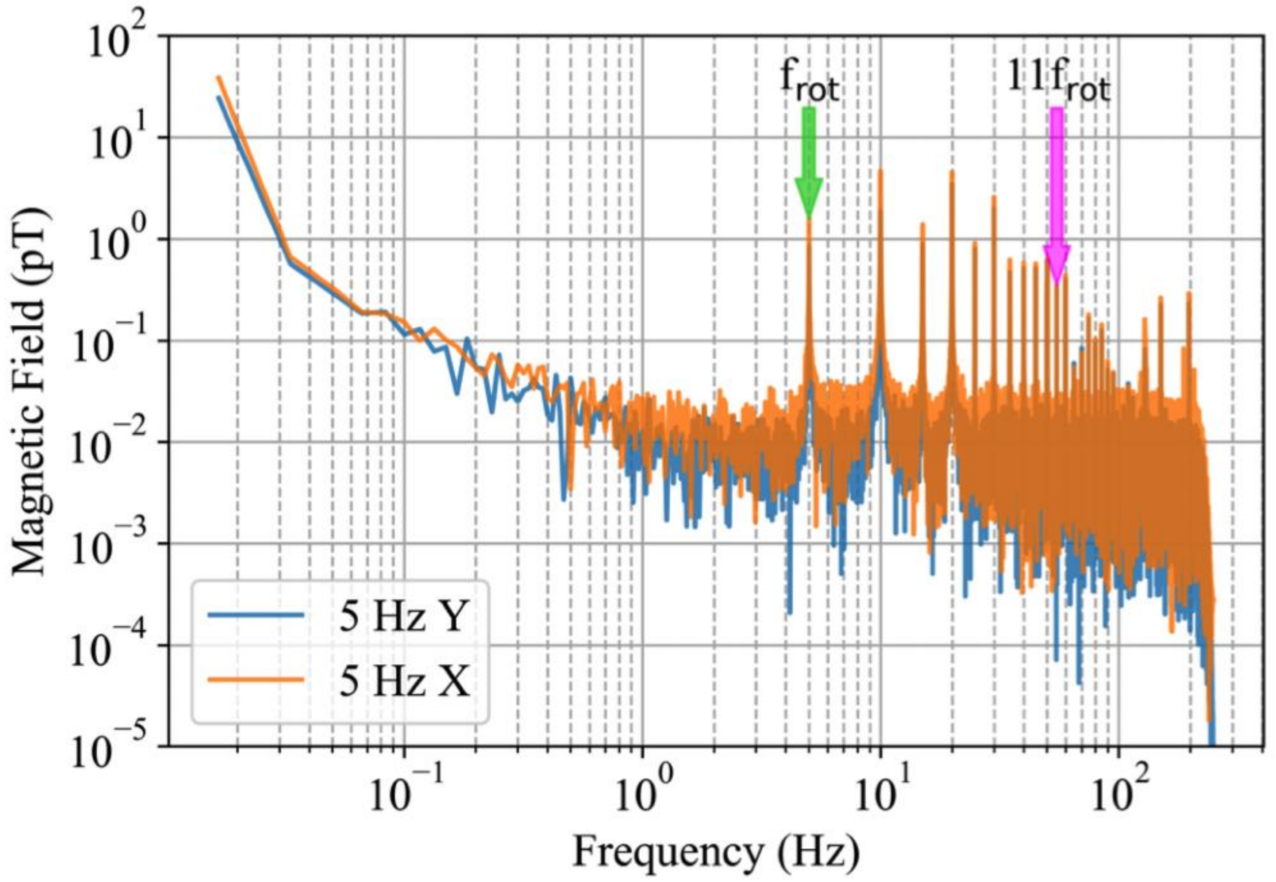
Rotating Drive Stage







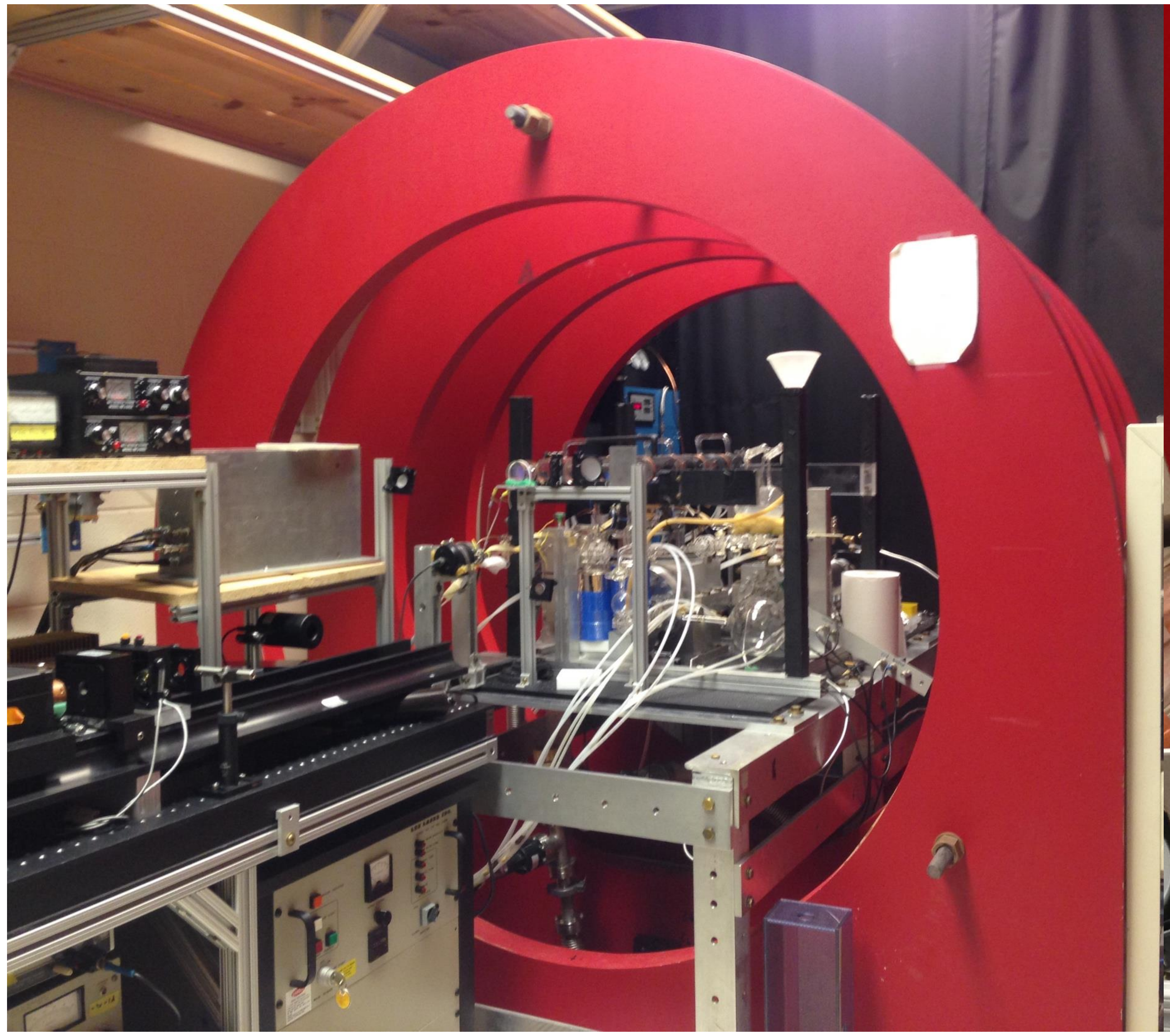
- Rotating stage remains at higher temperature (170K)
  - located inside layers of μ-metal shielding
- Source mass must be kept at a distance of 100μm from the Quartz block
  - Stability is monitored with interferometers (with reflective index on the mass)
- Characterization of magnetic field noise
  - 10μm wobble at 10Hz produce magnetic field noise of $5 \times 10^{-19} \mathrm{T}/\sqrt{\mathrm{Hz}}$

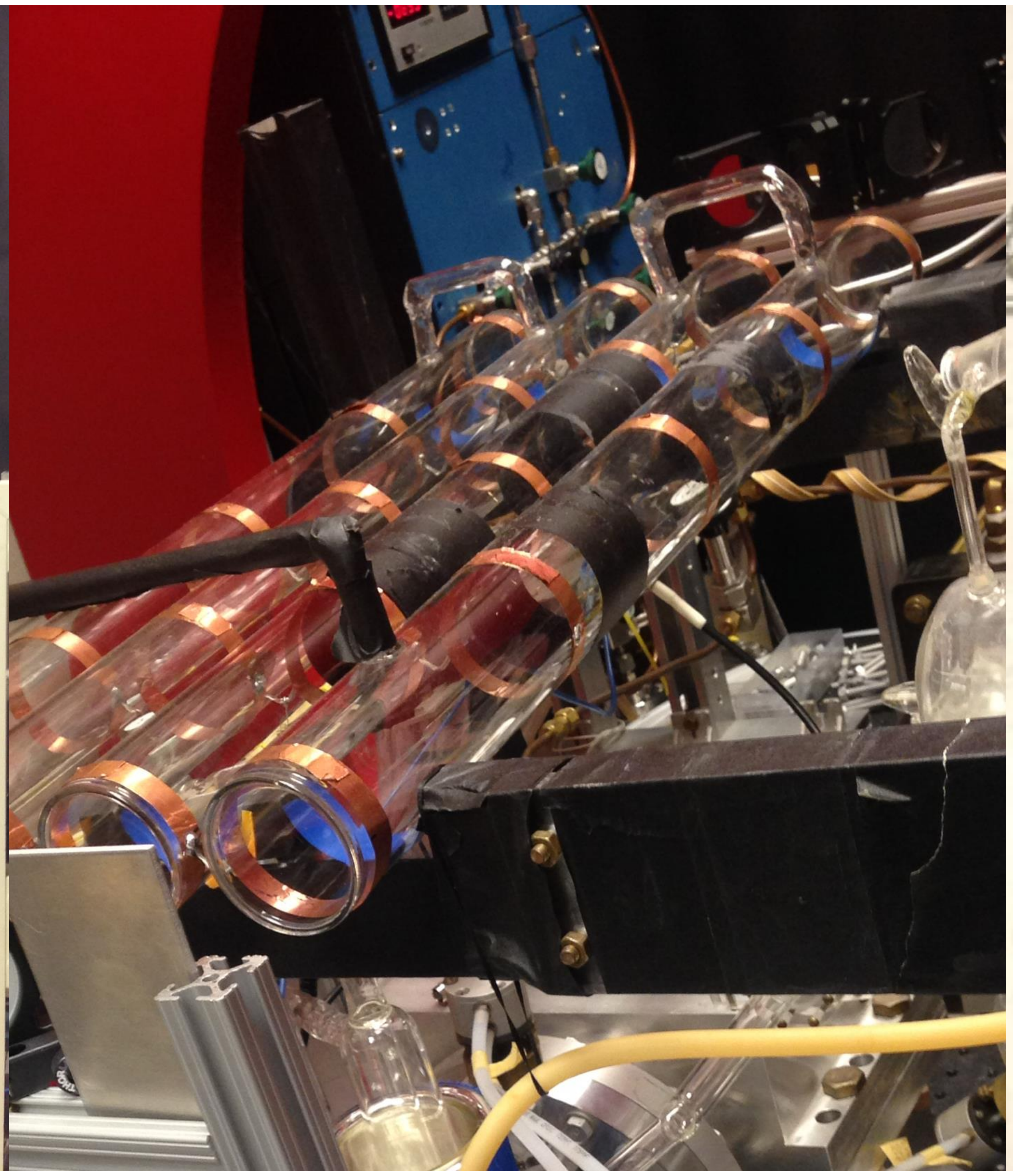


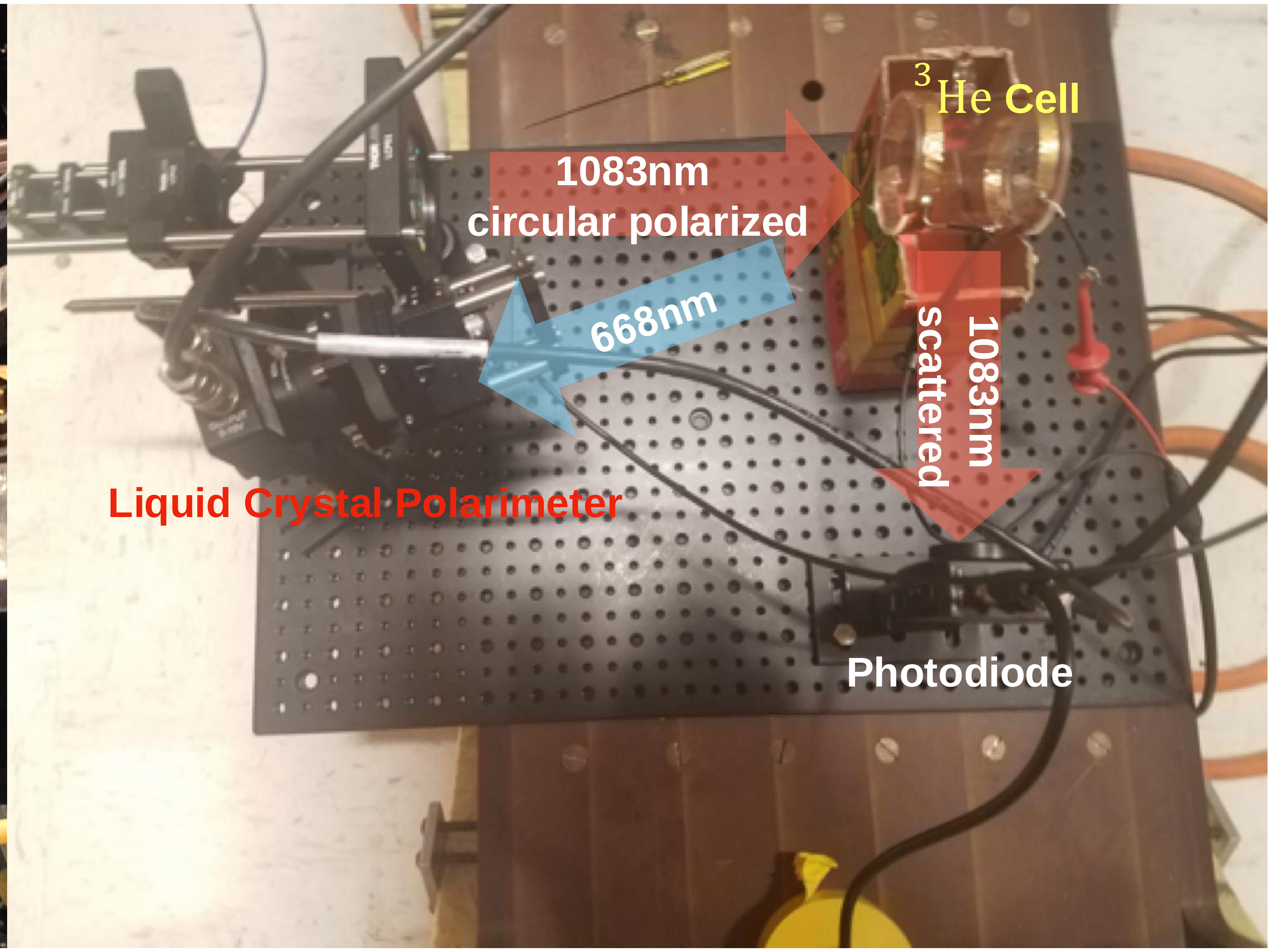
N. Aggarwal et. al. Phys. Rev. Res. 4, 013090, (2022)

MEOP 3He Polarization Setup at Indiana Univ.

- Four $1\mathrm{m}$ long pumping cells with polarization rate up to $P_{\mathrm{max}} \approx 0.7$ for $1\mathrm{mbar}$ of gas
- Pressurize up to $\approx 1\mathrm{bar}$ in a storage volume with non-magnetic compressor
- Final polarization up to $P_{\mathrm{storage}} \approx 0.55$ at the storage volume
- Upgrade with modern parts





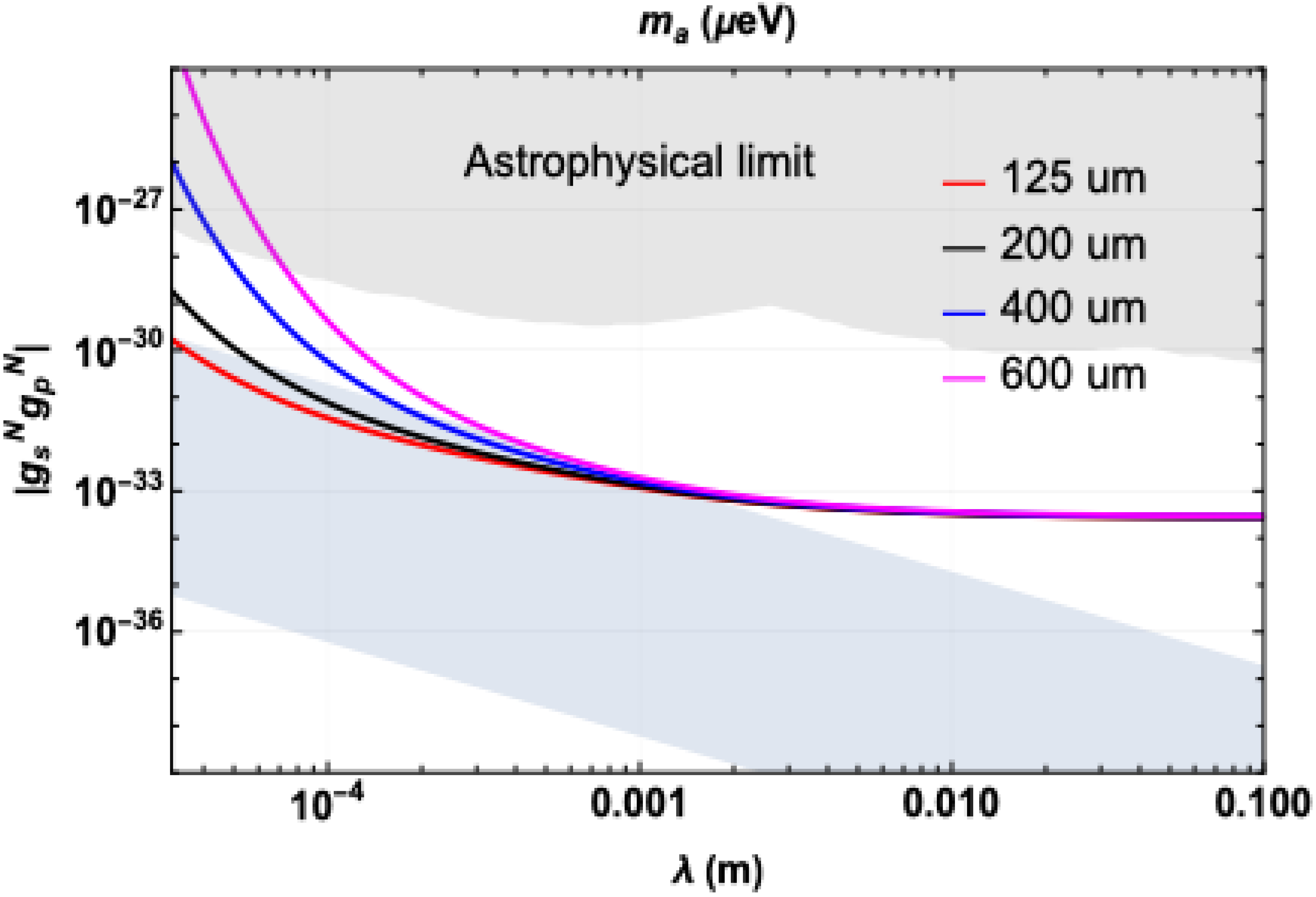


D. S. Hussey, et. al, Rev. of Sci Inst, 76(5), 053503, 2005

Summary

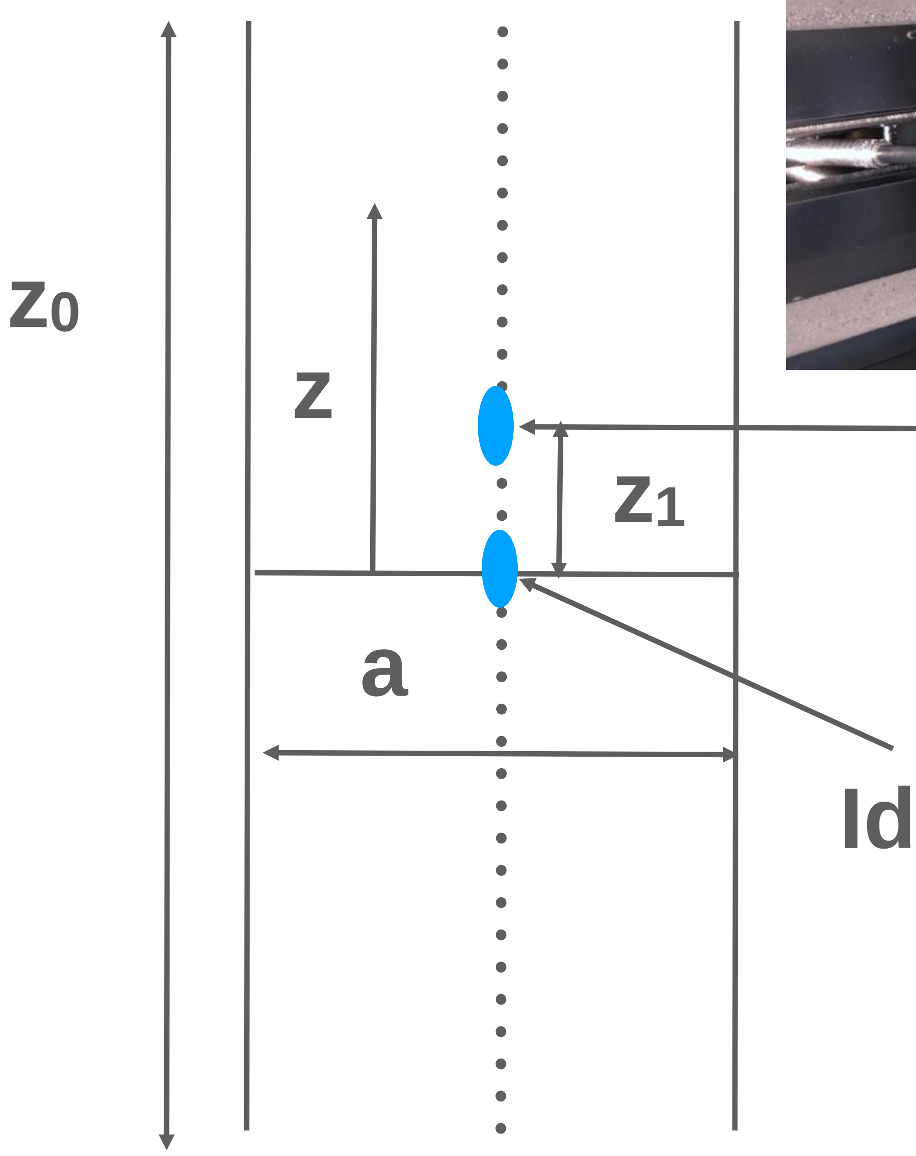
- Theories beyond Standard Model predict long-range, spin-dependent interactions that could be medicated by light bosons
- ARIADNE is a new experiment looking for axion mediated interaction with a resonant NMR method.
- ARIADNE could reach some of the interesting regime of parameter space corresponding to dark matter axions.
- ARIADNE plans to conduct first prototype measurement in 2025
- CAPP is actively working on the SQUID R&D for ARIADNE

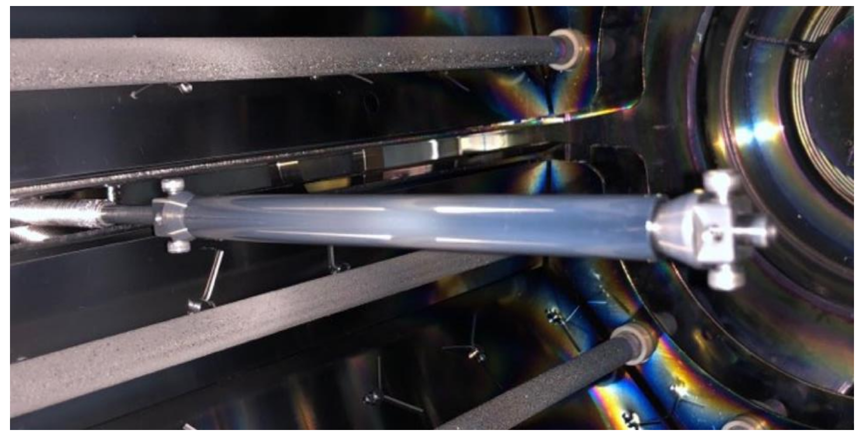
“Thank you!”



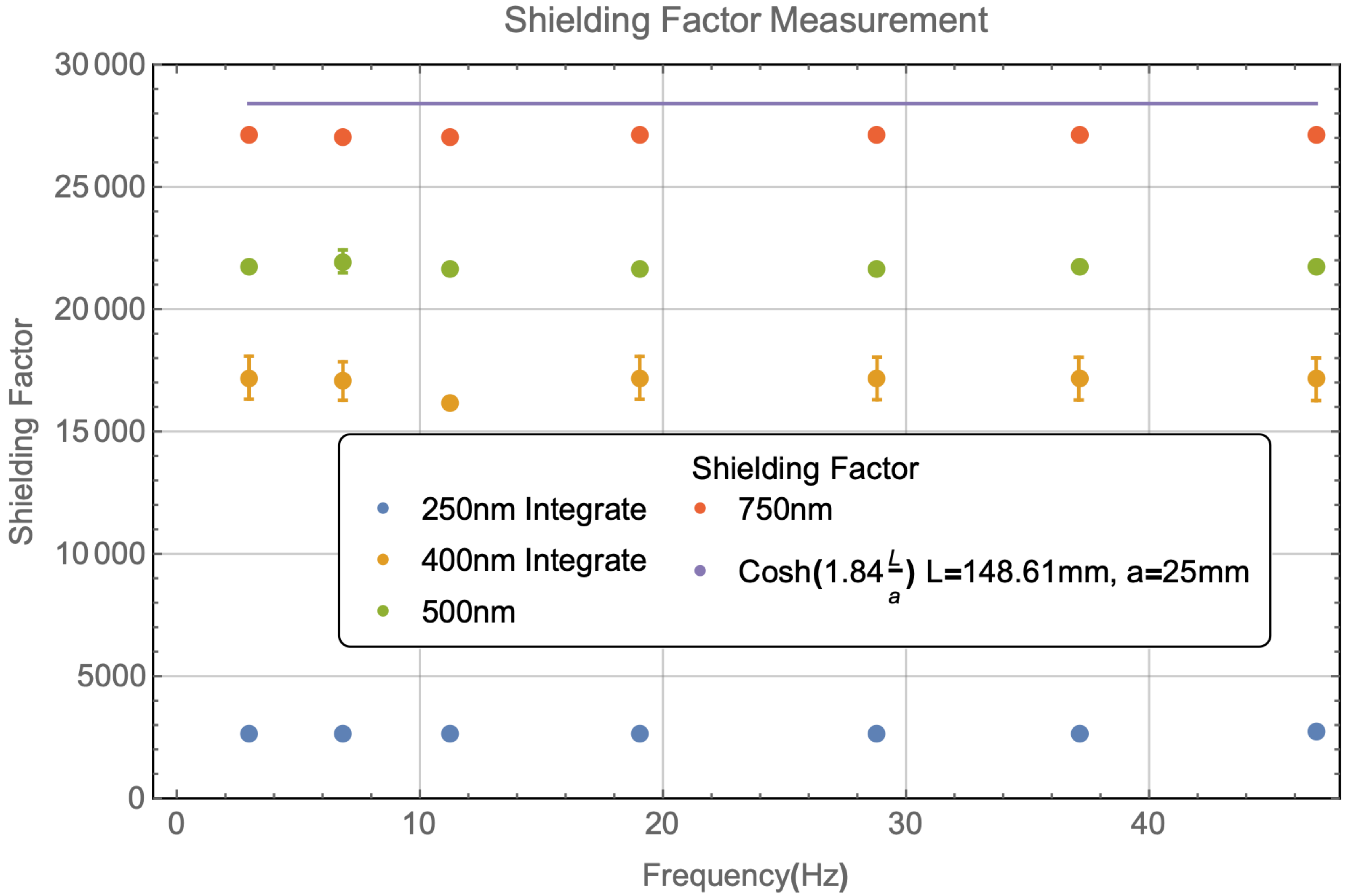
m_a (μeV)
Astrophysical limit
125 um
200 um
400 um
600 um
10^{-27}
10^{-30}
10^{-33}
10^{-36}
$|g_s{}^N g_p{}^N|$
10^{-4}
0.001
0.010
0.100
λ (m)

Superconducting Shielding





$$S.F_m = \frac{H_t(z=z_0)}{H_t(z=z_1)} = \frac{\cosh(1.84\frac{z_0}{a})}{\cosh(1.84\frac{z_1}{a})} = \frac{S.F_{id}}{\cosh(1.84\frac{z_1}{a})}$$



- Measured shielding factor of quartz tube with 250~750nm thicken of Nb sputtered layers,
- Compared with ideal shielding factor for Nb tube: $\mathrm{S}\cdot\mathrm{F}_{\mathrm{tube}} = \cosh(1.84\frac{z_0}{a})$ for $a = 25\mathrm{mm}$, $z_0 =\sim 150\mathrm{mm}$
- 10^8 S.F when $a \sim 14\mathrm{mm}$

H Fosbinder-Elkins *et al* 2022 *Quantum Sci. Technol.* **7** 014002