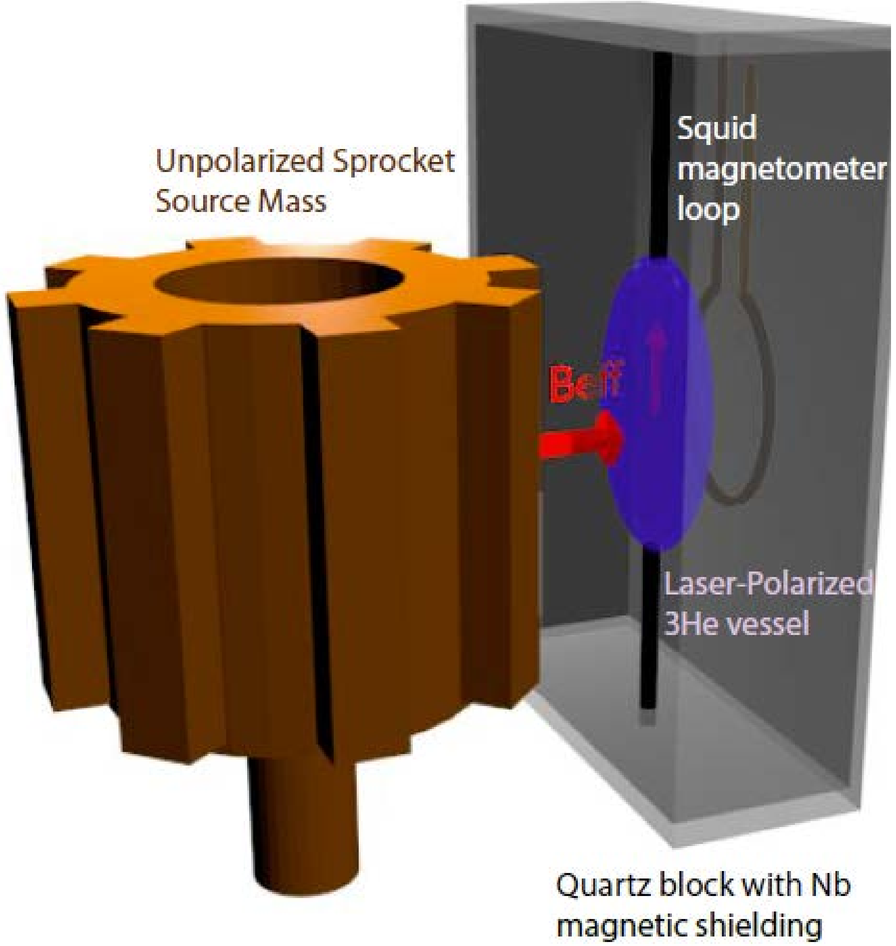
Axion **R**esonant **I**nter**A**ction **D**etectio**N** **E**xperiment (ARIADNE)



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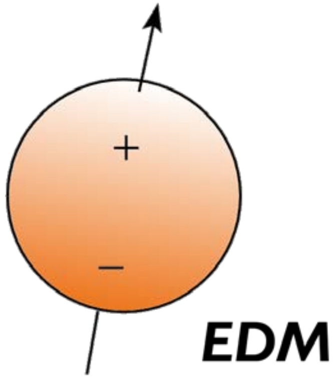
A. Geraci for the ARIADNE collaboration

PATRAS 2022, Mainz, Germany, Aug 8-12

Axions

- Light pseudoscalar particles in many theories Beyond Standard model
- Peccei-Quinn Axion (QCD) solves strong CP problem

$\theta_{QCD} < 10^{-10}$



- Dark matter candidate

- Also mediates spin-dependent “fifth-forces” at short range (down to 30 μm)

→ Can be sourced locally
No cosmological assumptions!

- R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. 38, 1440 (1977);
- S. Weinberg, Phys. Rev. Lett. 40, 223 (1978);
- F. Wilczek, Phys. Rev. Lett. 40, 279 (1978).
- J. E. Moody and F. Wilczek, Phys. Rev. D 30, 130 (1984).

Axion and ALP Searches

Source

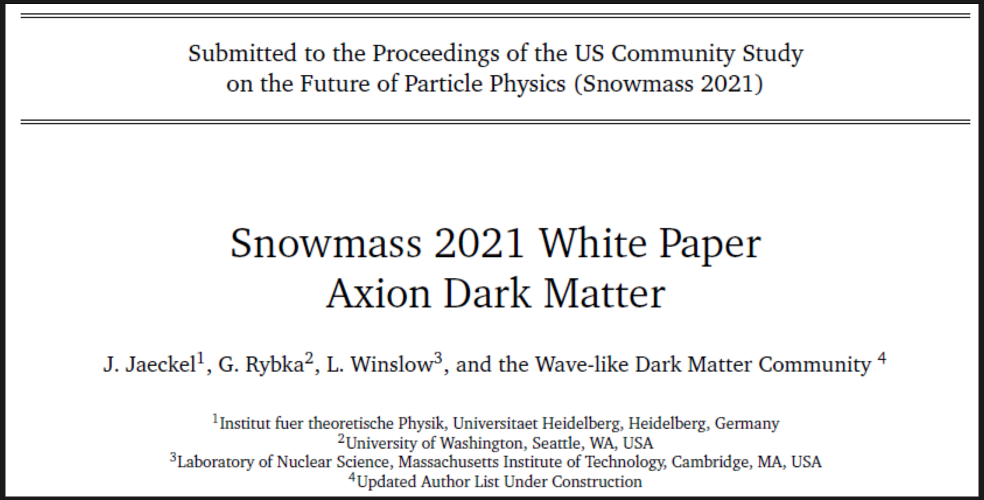
Coupling

	Photons	Nucleons	Electrons
Dark Matter (Cosmic) axions	ADMX, HAYSTAC, CAPP, ORGAN, DM Radio, LC Circuit, MADMAX	CASPEr	QUAX
Solar axions	CAST IAXO		
Lab-produced axions	Light-shining-thru-walls (ALPS, ALPS-II)	**ARIADNE**	

QCD axion parameter space

$$m_a \sim \Lambda_{QCD}^2 / f_a$$

Possible couplings: Gluons, photons, fermions



Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Snowmass 2021 White Paper
Axion Dark Matter

J. Jaeckel[1], G. Rybka[2], L. Winslow[3], and the Wave-like Dark Matter Community [4]

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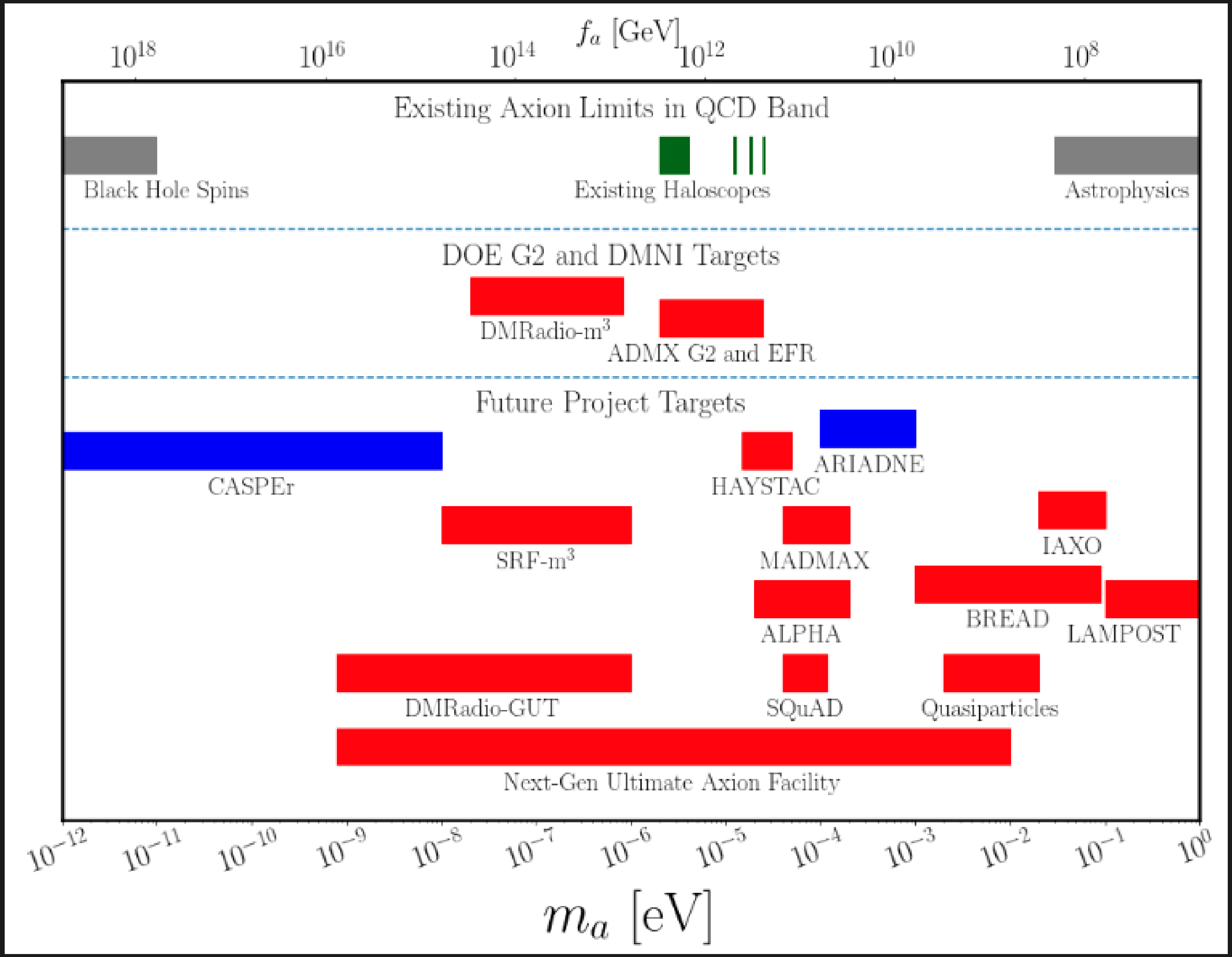
[4]Updated Author List Under Construction



Axion-exchange between nucleons

- Scalar coupling ∝ θ_{QCD}

$$\mathcal{L} \supset \frac{\theta_{QCD}}{f_a}\mu\ a\bar{\psi}\psi$$

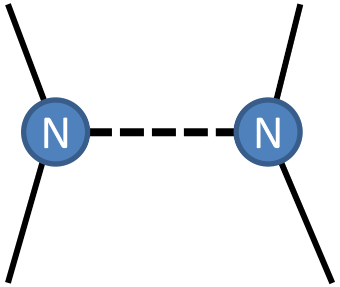
- Pseudoscalar coupling

$$\mathcal{L} \supset \frac{\partial_\mu a}{f_a}\bar{\psi}\gamma_\mu\gamma_5\psi$$

In the non-relativistic limit:

$$\mathcal{L} \supset \frac{\vec{\nabla} a}{f_a}\cdot\vec{\sigma}$$

Axion acts a force mediator between nucleons

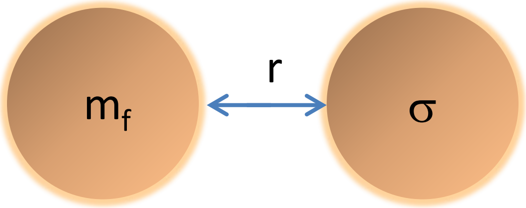


$$(g_s^N)^2 \qquad \boxed{g_s^N g_P^N} \qquad (g_p^N)^2$$

Monopole-monopole Monopole-dipole dipole-dipole

axion mass search range: 100 µeV < m_a < 10 meV

Spin-dependent forces



Monopole-Dipole axion exchange

$$U(r) = \frac{\hbar^2 g_s^{\,N} g_p^{\,N}}{8\pi m_f}\left(\frac{1}{r\lambda_a}+\frac{1}{r^2}\right)e^{-r/\lambda_a}(\hat{\sigma}\cdot\hat{r}) \qquad \equiv \mu\cdot B_{\text{eff}}$$

$m_a < 6$ meV → $\lambda_a > 30$ μm

Fictitious magnetic field

- Different than ordinary B field
- Does not couple to angular momentum
- Unaffected by magnetic shielding

Concept for ARIADNE

Unpolarized (tungsten)
segmented cylinder s

ed Bias field B_{ext}

$$\omega = \frac{2\mu_N \cdot B_{\text{ext}}}{\hbar}$$

Laser Polarized ^{3}He gas senses B_{eff} (Indiana U)

SQUID pickup loop measures resulting
precessing nuclear magnetization
(CAPP)

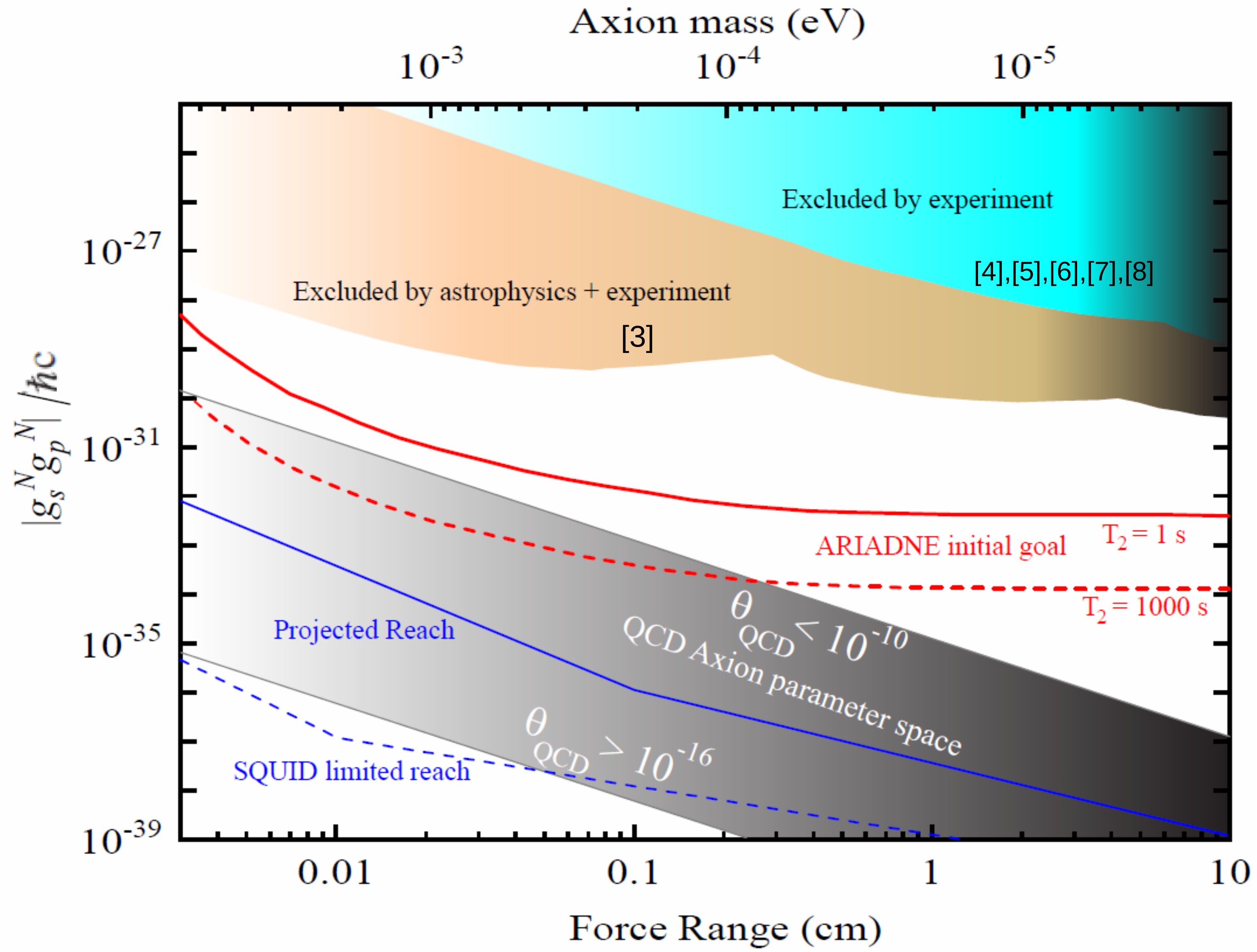
Superconducting shielding to screen
magnetic backgrounds (Stanford)

Limit: Transverse spin projection noise

$$B_{\text{min}} \approx p^{-1}\sqrt{\frac{2\hbar}{n_s \mu_{^3\text{He}} \gamma V T_2}} = 10^{-20}\frac{T}{\sqrt{Hz}} \times \left(\frac{1}{p}\right)\left(\frac{1\ \text{cm}^3}{V}\right)^{1/2}\left(\frac{10^{21}\ \text{cm}^{-3}}{n_s}\right)^{1/2}\left(\frac{1000\ \text{sec}}{T_2}\right)^{1/2}$$

A. Arvanitaki and A. Geraci., *Phys. Rev. Lett*. **113**, 161801 (2014)
A. Geraci et.al, arxiv: 1710.05413 (2017),

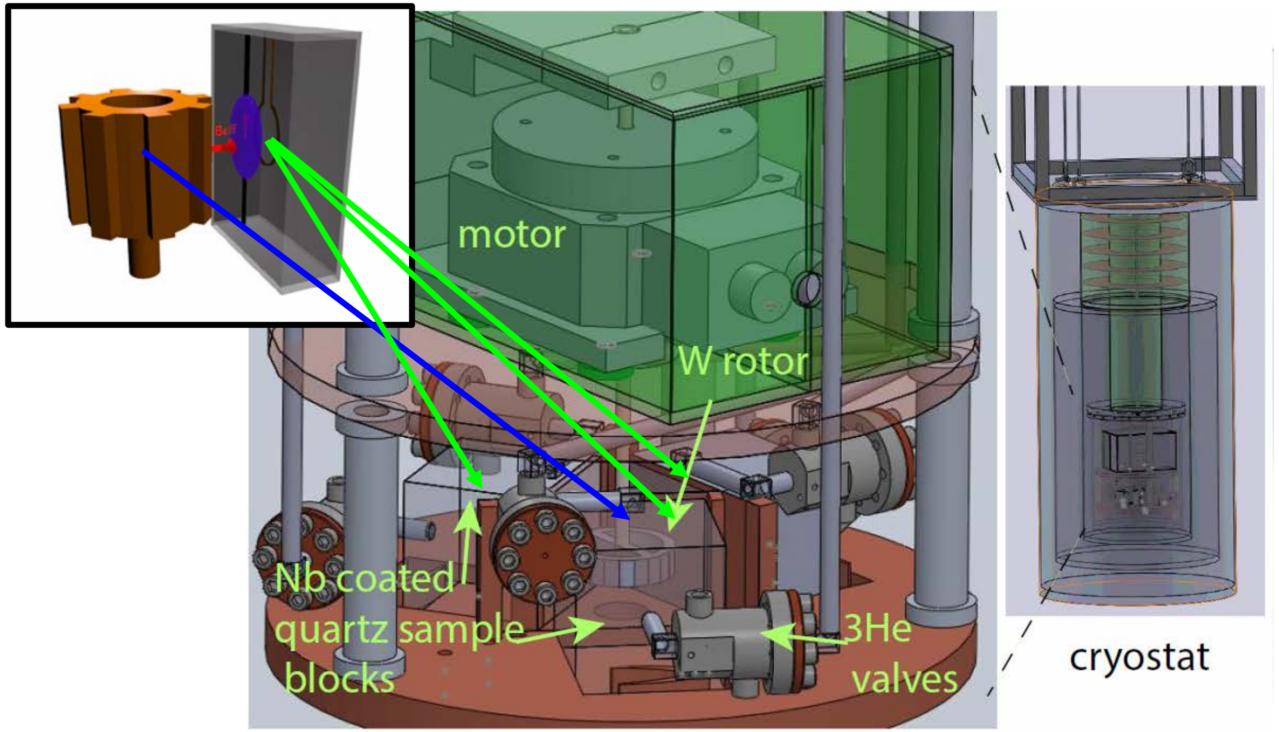
Projected Sensitivity



A. Arvanitaki and AG., *Phys. Rev. Lett*. 113,161801 (2014).

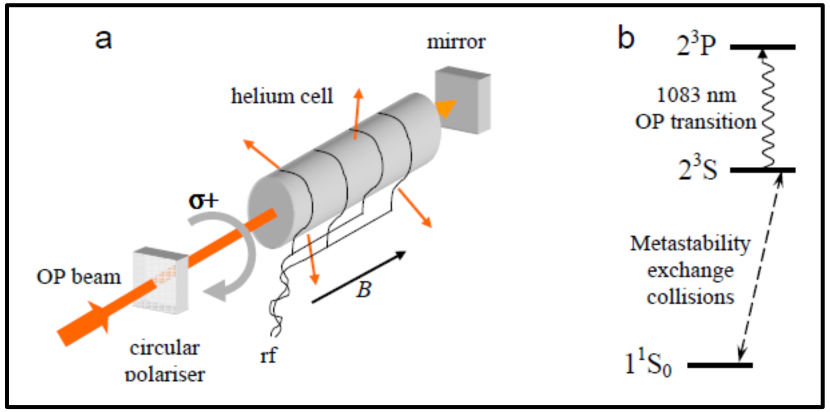
[3] G. Raffelt, Phys. Rev. D 86, 015001 (2012)] [4] G. Vasilakis, et. al, Phys. Rev. Lett. 103, 261801 (2009).
[5] K. Tullney,et. al. Phys. Rev. Lett. 111, 100801 (2013) **[6]** P.-H. Chu,et. al., Phys. Rev. D 87, 011105(R) (2013).
[7] M. Bulatowicz, et. al., Phys. Rev. Lett. 111, 102001 (2013), [8] Lee, et.al. Phys. Rev.Lett. 120, 161801 (2018).

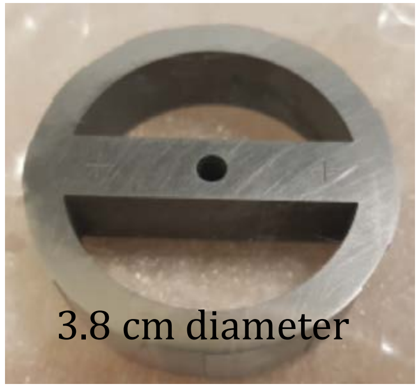
Experimental setup



Laser-polarized ^{3}He sensor

- Metastability exchange optical pumping





Tungsten source mass rotor

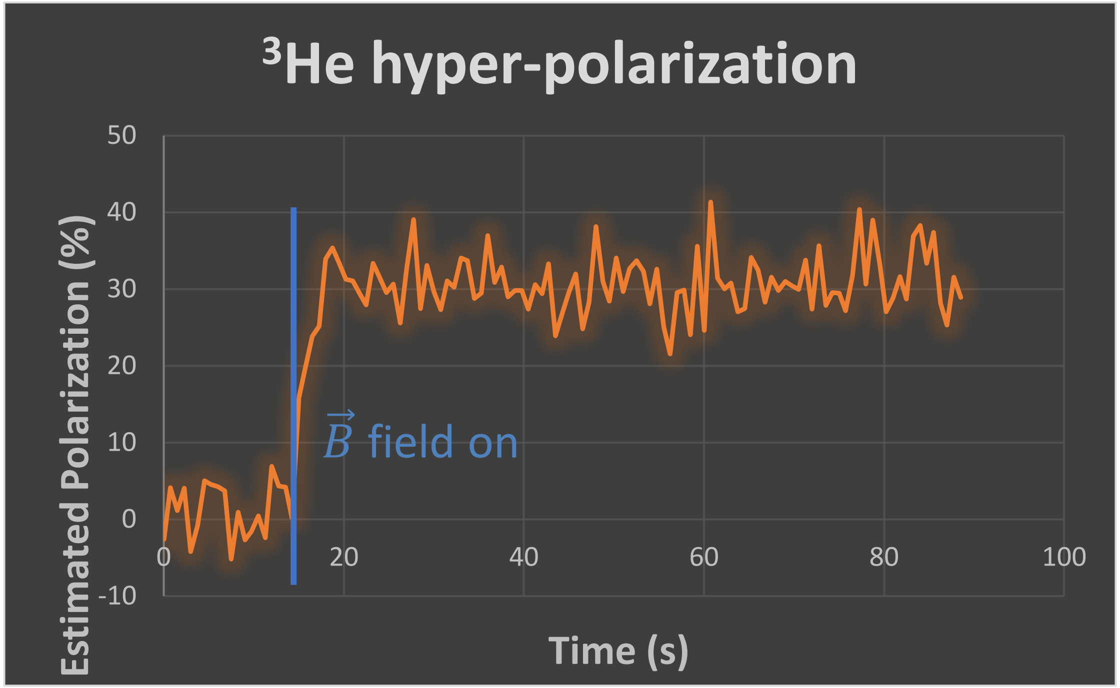
11 segments

100 Hz nuclear spin precession frequency

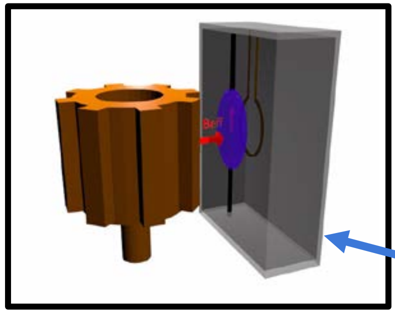
2 x 10^{21} / cc ^{3}He density

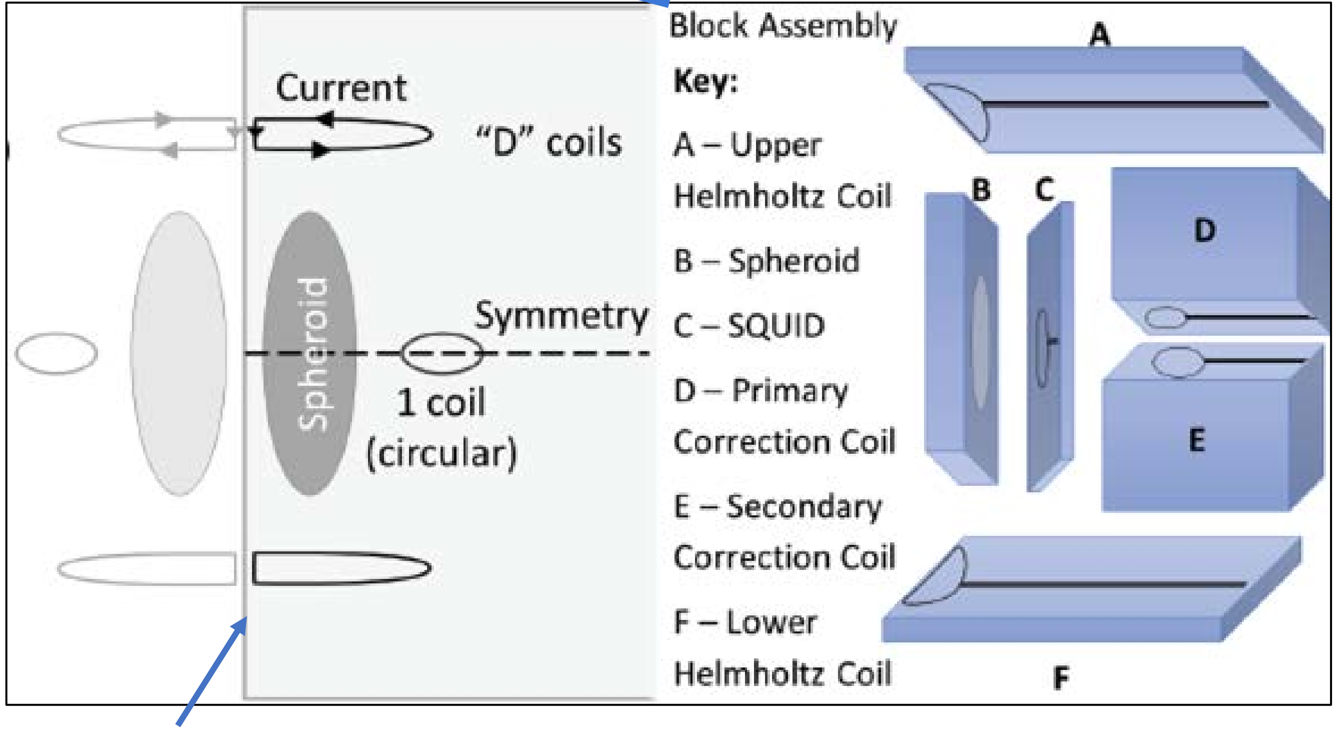
3 mm x 3 mm x 150 µm volume

Separation ~200 µm

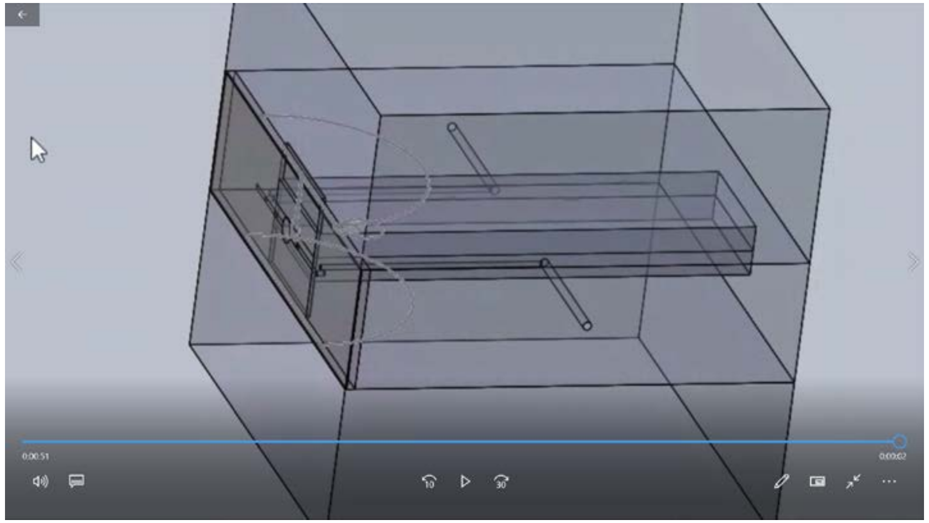


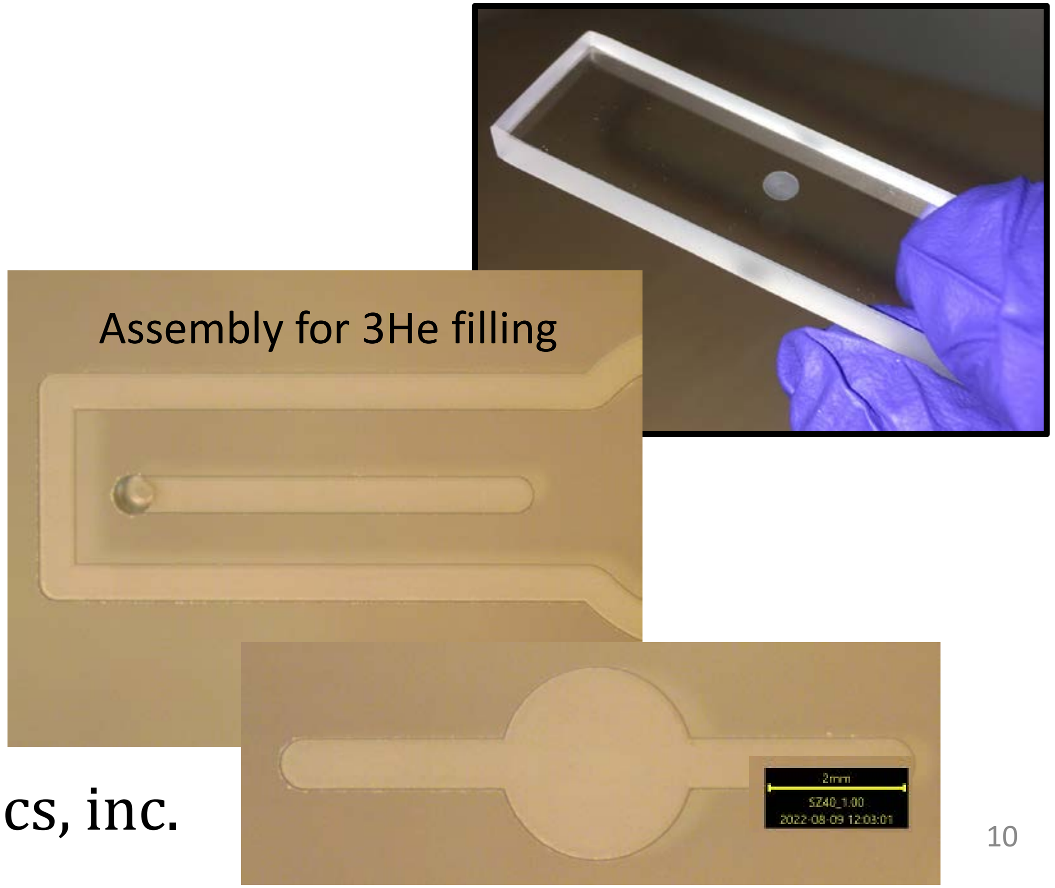
Quartz Sample Block Assembly





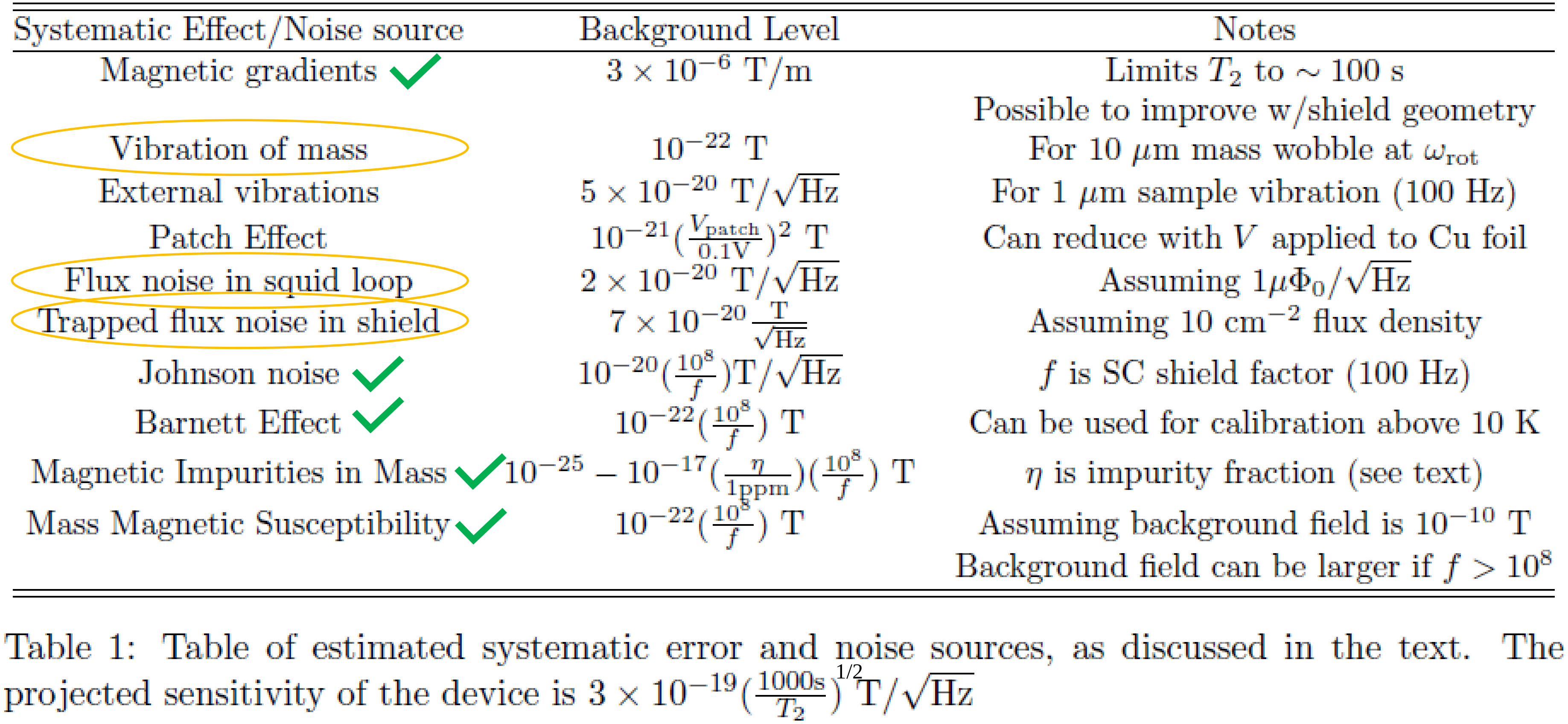
Nb shield




Assembly for 3He filling

Fabrication in process- Sierra optics, inc.

Experimental challenges



Systematic Effect/Noise source	Background Level	Notes
Magnetic gradients ✓	3×10^{-6} T/m	Limits T_2 to ~ 100 s Possible to improve w/shield geometry
Vibration of mass	10^{-22} T	For 10 μm mass wobble at ω_{rot}
External vibrations	5×10^{-20} T/$\sqrt{\mathrm{Hz}}$	For 1 μm sample vibration (100 Hz)
Patch Effect	$10^{-21}(\frac{V_{\mathrm{patch}}}{0.1\mathrm{V}})^2$ T	Can reduce with V applied to Cu foil
Flux noise in squid loop	2×10^{-20} T/$\sqrt{\mathrm{Hz}}$	Assuming $1\mu\Phi_0/\sqrt{\mathrm{Hz}}$
Trapped flux noise in shield	$7 \times 10^{-20} \frac{\mathrm{T}}{\sqrt{\mathrm{Hz}}}$	Assuming 10 cm^{-2} flux density
Johnson noise ✓	$10^{-20}(\frac{10^8}{f})$T/$\sqrt{\mathrm{Hz}}$	f is SC shield factor (100 Hz)
Barnett Effect ✓	$10^{-22}(\frac{10^8}{f})$ T	Can be used for calibration above 10 K
Magnetic Impurities in Mass ✓	$10^{-25} - 10^{-17}(\frac{\eta}{1\mathrm{ppm}})(\frac{10^8}{f})$ T	η is impurity fraction (see text)
Mass Magnetic Susceptibility ✓	$10^{-22}(\frac{10^8}{f})$ T	Assuming background field is 10^{-10} T Background field can be larger if $f > 10^8$

Table 1: Table of estimated systematic error and noise sources, as discussed in the text. The projected sensitivity of the device is $3 \times 10^{-19}(\frac{1000\mathrm{s}}{T_2})^{1/2}$T/$\sqrt{\mathrm{Hz}}$

Testing completed
or in process:

- Spin-speed stability of rotary stage ✓
- Wobble/vibration of source mass (in progress)
- Magnetic shielding factor tests for thin film Niobium ✓
- Tests for Magnetic impurities in Source mass ✓
- Trapped flux noise in Nb films, noise in squid loops (in progress)
- Design/Simulation Work: Magnetic gradient reduction strategy ✓

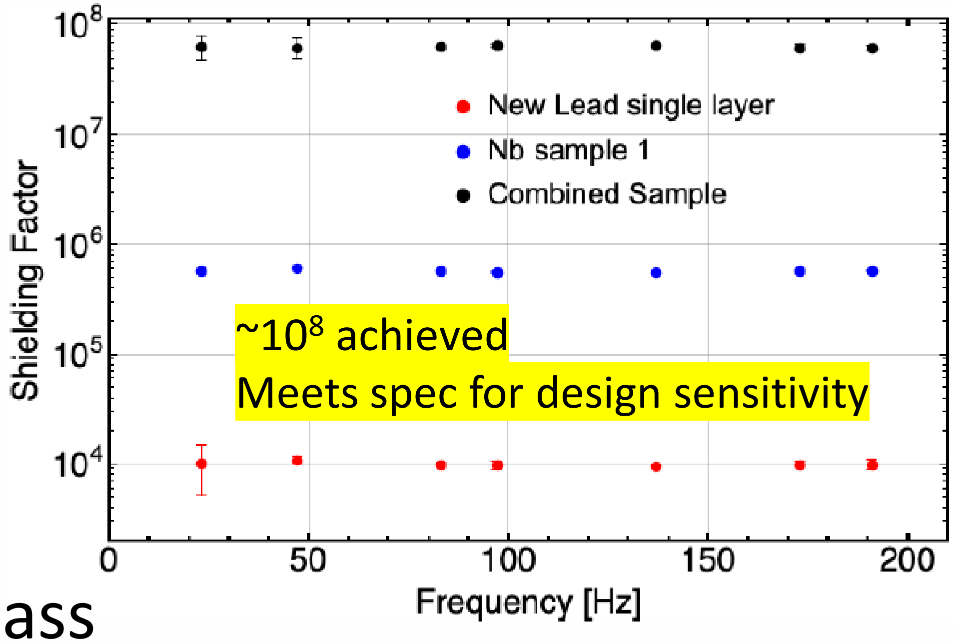
Backgrounds and noise tests

H. Fosbinder-Elkins, Y. Kim, J. Dargert *et.al.* Quantum Sci. Technol. 7 014002 (2022).

- Superconducting shielding test

→Essential for eliminating magnetic backgrounds
(Johnson noise, magnetic susceptibility, impurities, Barnett effect)

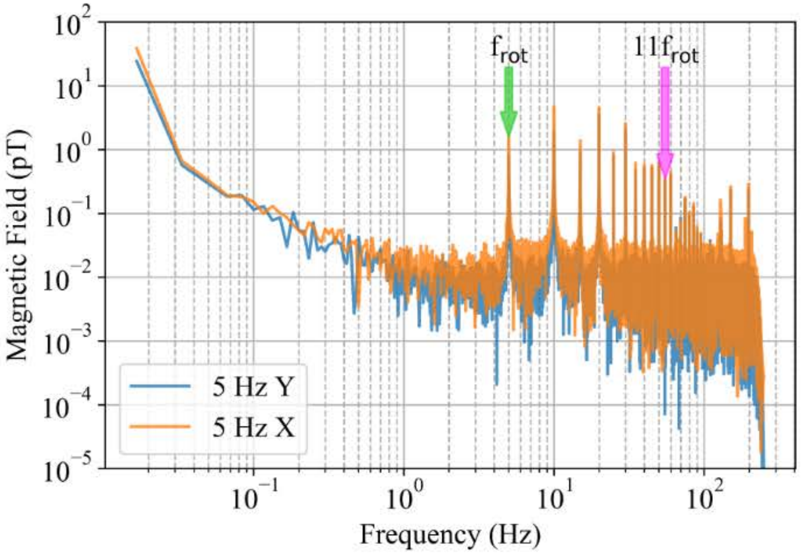
Testing: sputtered Nb on quartz tubes w/supplemental Pb foils



~10^8 achieved
Meets spec for design sensitivity

- Magnetic impurities test - tungsten source mass

Low-field, high-resolution optical magnetometry



N. Aggarwal, *et.al.*, Phys Rev Research (2021)

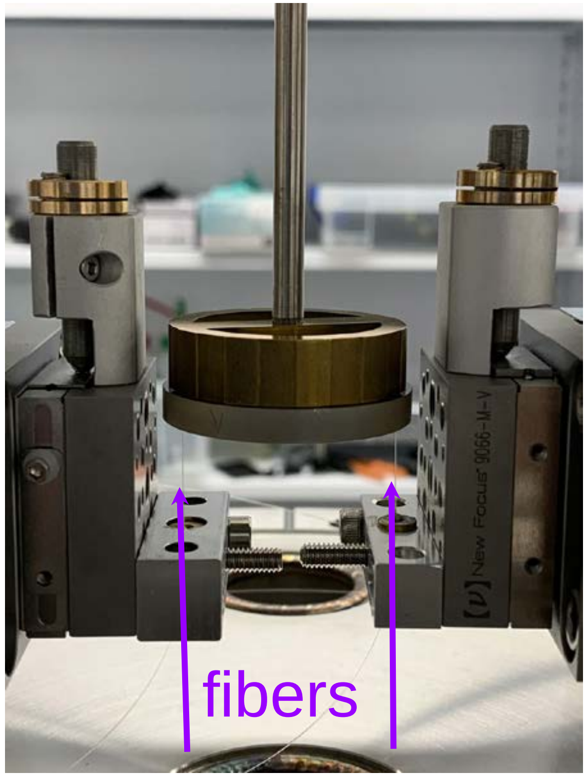
Magnetic field noise at 11 ω is less than 1pT

Consistent with Johnson noise plus a few (3) isolated surface magnetic domains

Meets spec for design sensitivity

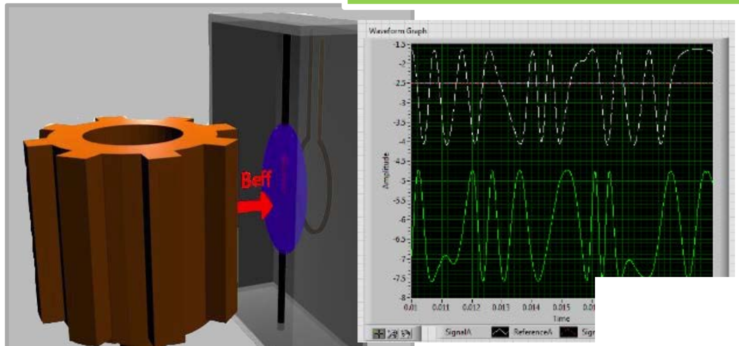
Backgrounds and noise tests

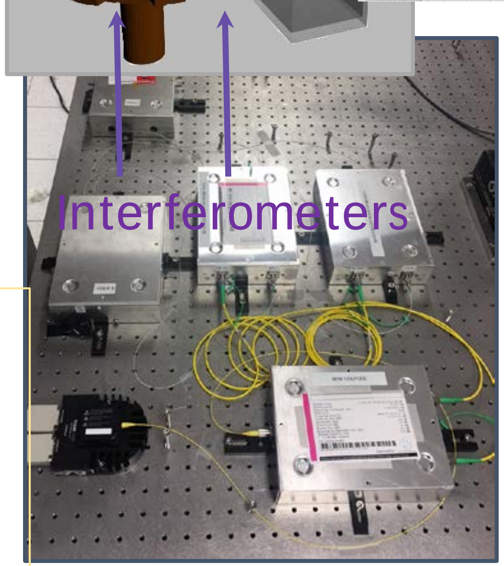
- Rotary stage stability test



Design spec: rotation “wobble” < 50 um

Monitored *in-situ* with fiber optic interferometers



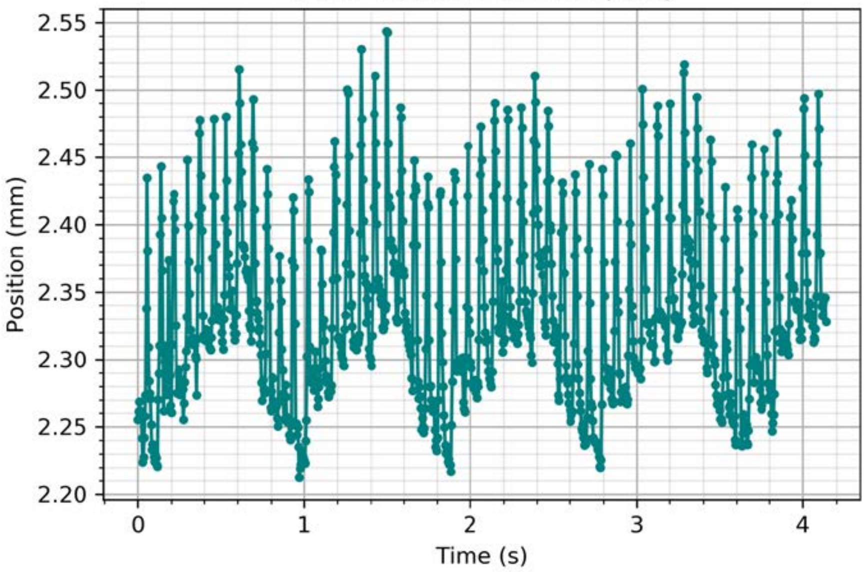


Rotation speed control
8.3 Hz ~ 1 part in 10000
RMS ~ 1 part in 3000

Allows utilization of T_2 > 100s

Preliminary benchtop optical test wobble ~ +/- 40um

Within factor of 2 of spec for design sensitivity
Balancing/wobble improvements in process



Conclusion

ARIADNE experiment: Fifth-force NMR search for QCD axion

→ lab-sourced search sensitive to QCD axion in under-explored mass range

$$100\ \mu\text{eV} < m_a < 10\ \text{meV}$$

→ No need to scan mass, independent of local DM density

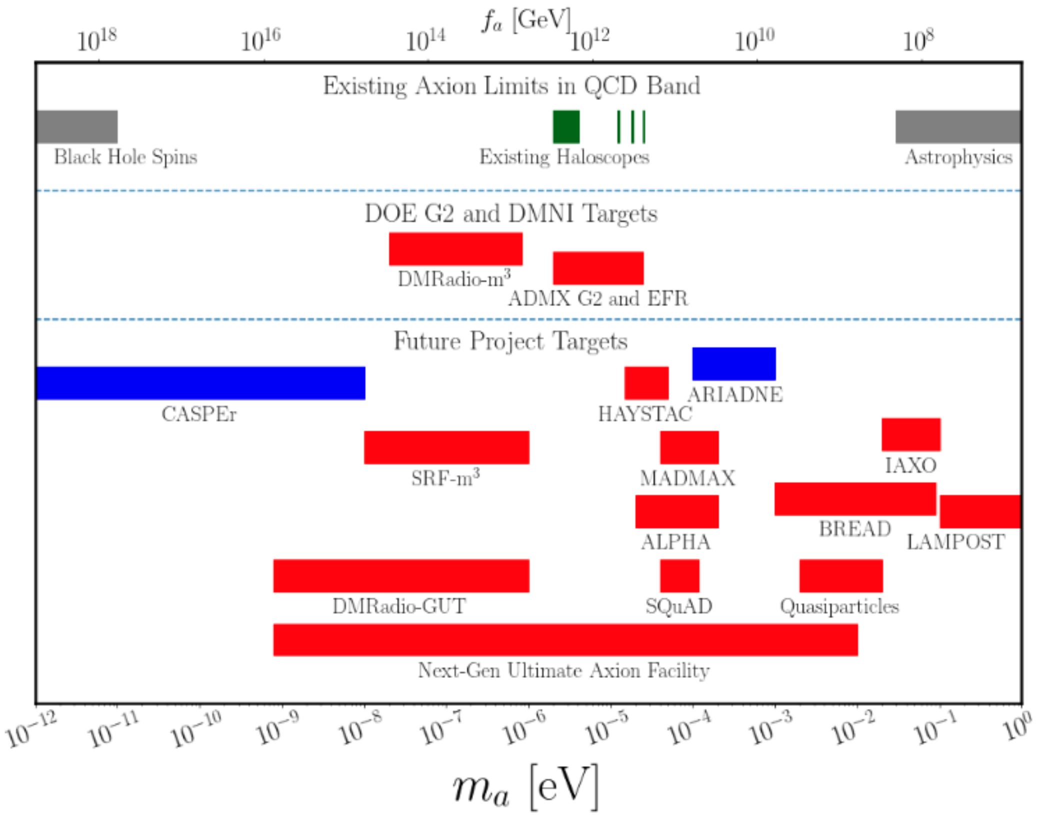
→ Complementary to neutron, proton EDM searches

→ Covers entire QCD axion parameter space when combined with haloscope and helioscope experiments

Estimated Timeline:

Cryostat completion: Fall 2022

Commissioning/
early data taking: 2023



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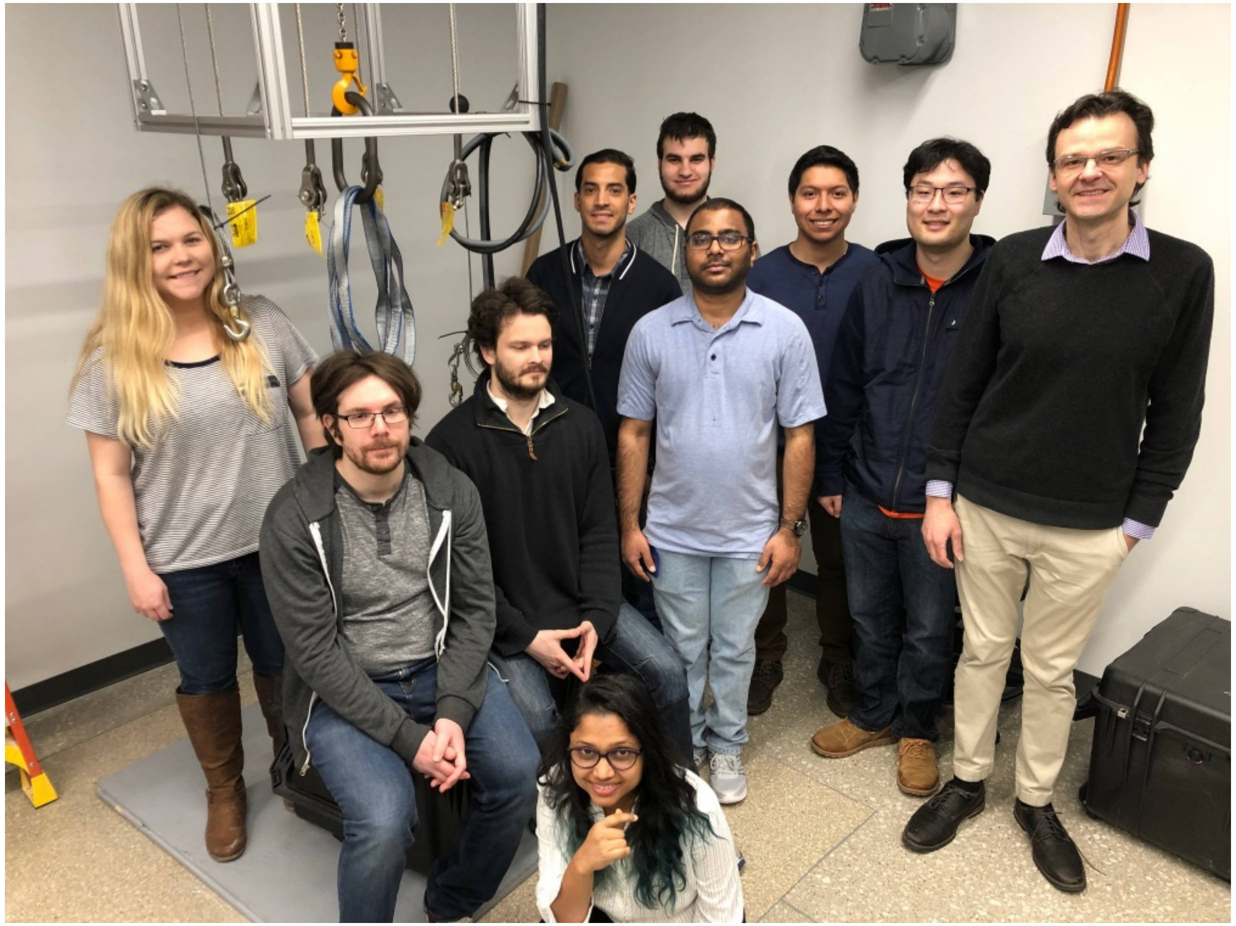

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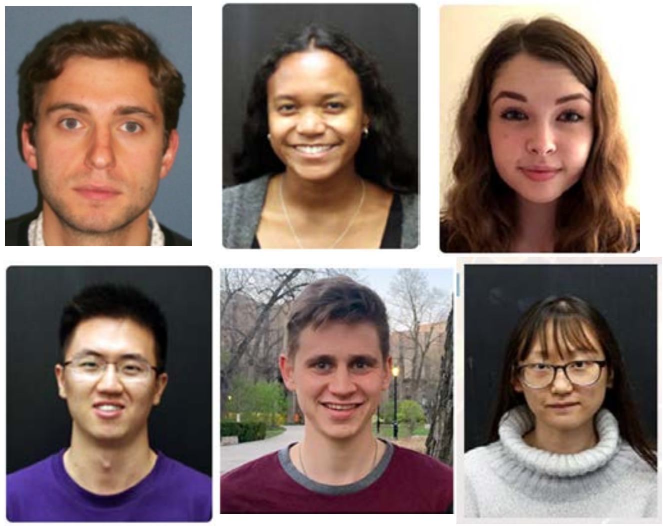

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