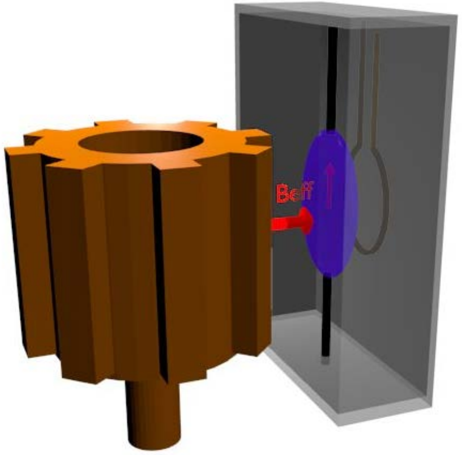
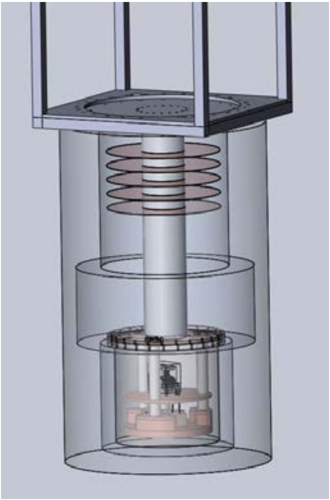
Searching for the QCD axion with ARIADNE



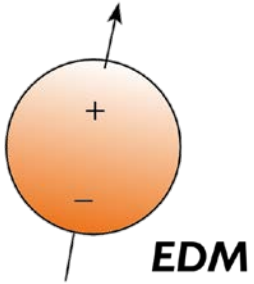


A. Geraci, Northwestern University
Center for Fundamental Physics (CFP)

Axions Beyond Gen2, Jan. 27, 2021

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

Experiments: e.g. ADMX, HAYSTAC, LC circuit, Casper, DM Radio, MADMAX, CAPP, ORGAN

- 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).

Axions

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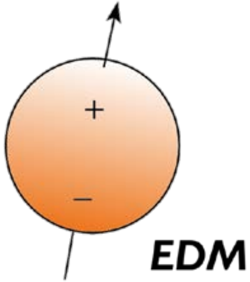


- Dark matter candidate
- Also mediates spin-dependent "fifth-forces" at short range (down to 30 μm)

→ 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 Resonant InterAction DetectioN Experiment

Grant No. PHY-1509176, 1510484, 1506508, 1806671, 1806395, 1806757

Collaborators

Northwestern: AG, Chloe Lohmeyer, Nancy Aggarwal

Perimeter Institute: Asimina Arvanitaki

Stanford University: Aharon Kapitulnik , Alan Fang, Sam Mumford

Indiana University: Josh Long, Chen-Yu Liu, Mike Snow, Inbum Lee, Justin Shortino

CAPP: Yannis Semertzidis, Yun Shin, Dongok Kim, Youngeun Kim

KRISS: Yong-Ho Lee

PTB: Lutz Trahms, Wolfgang Kilian, Allard Schnabel, Jens Voigt

Northwestern

Center for Fundamental Physics (CFP)

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Stanford University

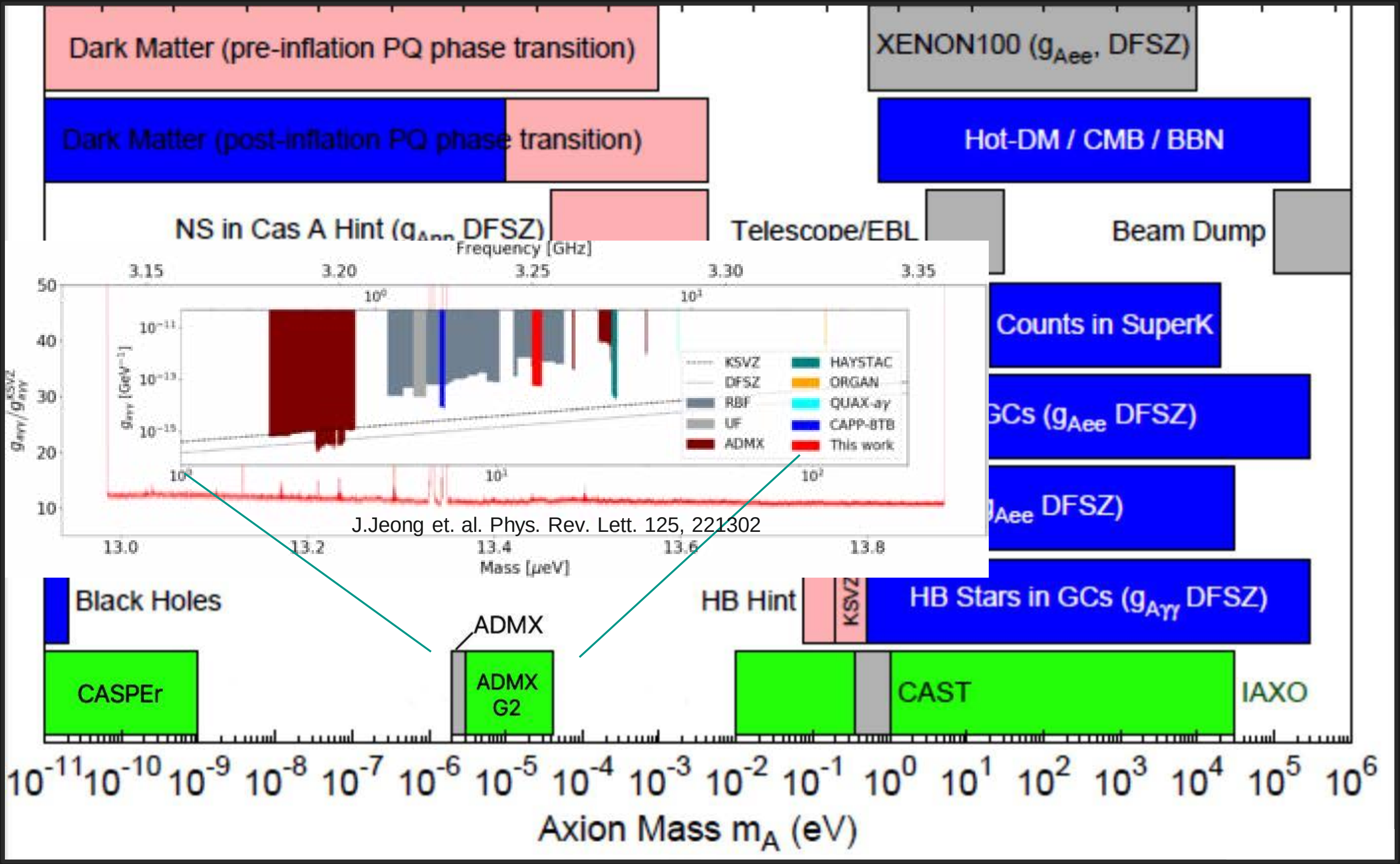
INDIANA UNIVERSITY

PTB Physikalisch-Technische Bundesanstalt Braunschweig und Berlin

Institute for Basic Science

QCD Axion Parameter Space

- Astrophysical Bounds
- Hints
- Experimental Bounds
- Current Experiments



Adapted from http://pdg.lbl.gov/2015/reviews/rpp2015-rev-axions.pdf

QCD Axion Parameter Space

- Astrophysical Bounds
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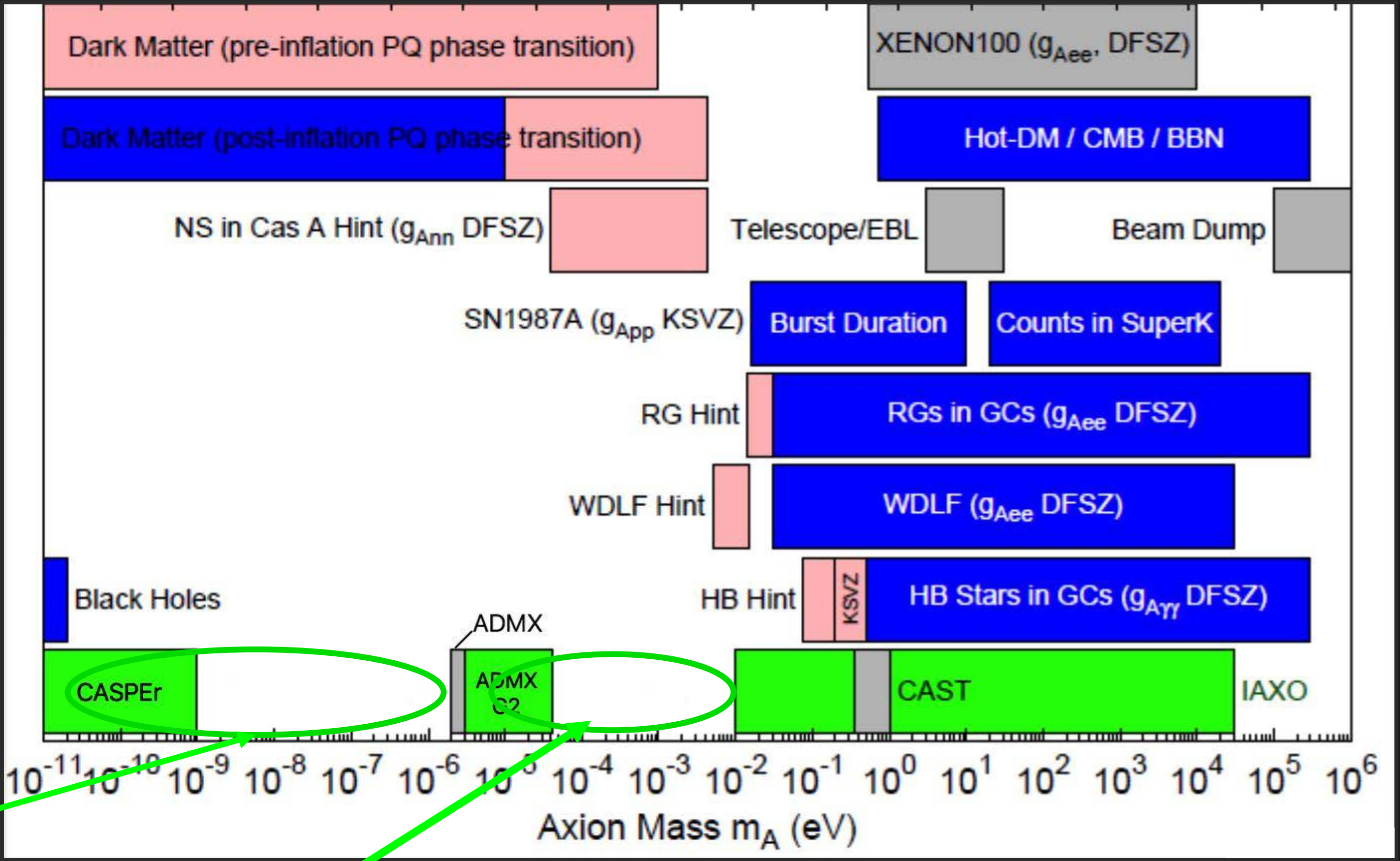
- Experimental Bounds
- Current Experiments



DM Radio
LC Circuit
ABRACADABRA

ARIADNE
MADMAX

Adapted from http://pdg.lbl.gov/2015/reviews/rpp2015-rev-axions.pdf

Axion and ALP Searches

Source | **Coupling**

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

Axion-exchange between nucleons

- Scalar coupling ∝ θ_{QCD}

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

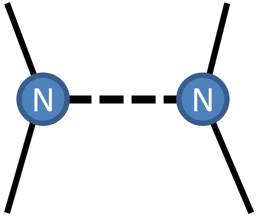
- Pseudoscalar coupling

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

In the non-relativistic limit:

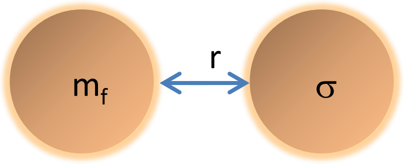
$$\mathcal{L} \supset \frac{\vec{\nabla} a}{f_a}\cdot\vec{\sigma}$$

Axion acts a force mediator between nucleons



$(g_s^N)^2$	$g_s^N g_P^N$	$(g_p^N)^2$
Monopole-monopole	Monopole-dipole	dipole-dipole

Spin-dependent forces



Monopole-Dipole axion exchange

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

$m_a < 6$ meV ➡ $\lambda_a > 30\ \mu$m

Fictitious magnetic field

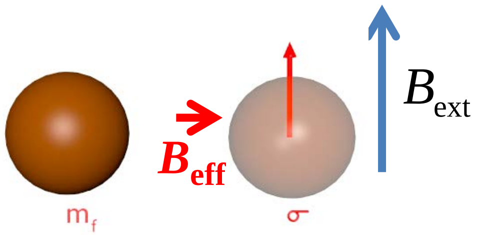
- Different than ordinary B field
- Does not couple to angular momentum
- Unaffected by magnetic shielding

NMR for detection

Spin ½ ^{3}He Nucleus

Oscillate the mass at Larmor frequency

$$B_{\text{eff}} = B_{\perp} \cos(\omega t)$$



$$U = \mu \cdot B_{\text{ext}}$$

Bloch Equations

$$\frac{d\vec{M}}{dt} = \gamma \vec{M} \times \vec{B}$$

$|\uparrow\rangle$

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

$|\downarrow\rangle$

Time varying Axion B_{eff} drives spin precession
→ produces transverse magnetization

Amplitude is resonantly enhanced by Q factor ~ ωT_2.

Can be detected with a SQUID

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

Concept for ARIADNE

Unpolarized (tungsten) segmented cylinder sources B_{eff}

ied Bias field B_{ext}

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

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

squid pickup
Loop (CAPP)

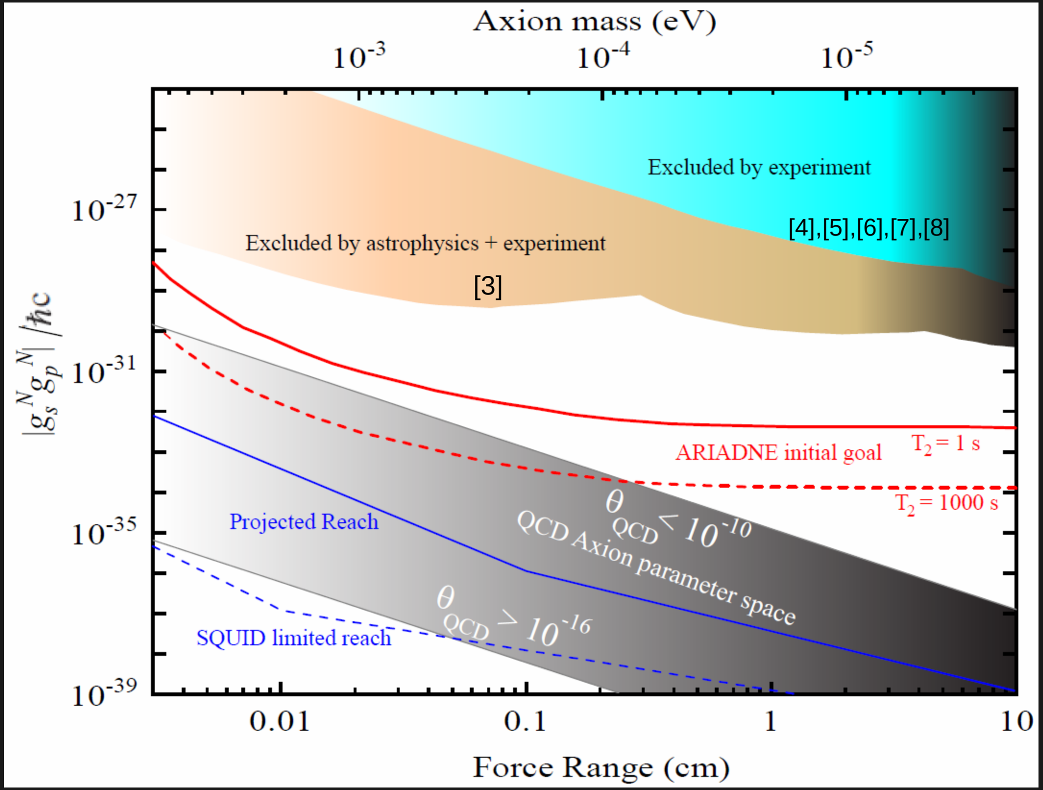
Superconducting shielding (Stanford)

Limit: Transverse spin projection noise

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

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

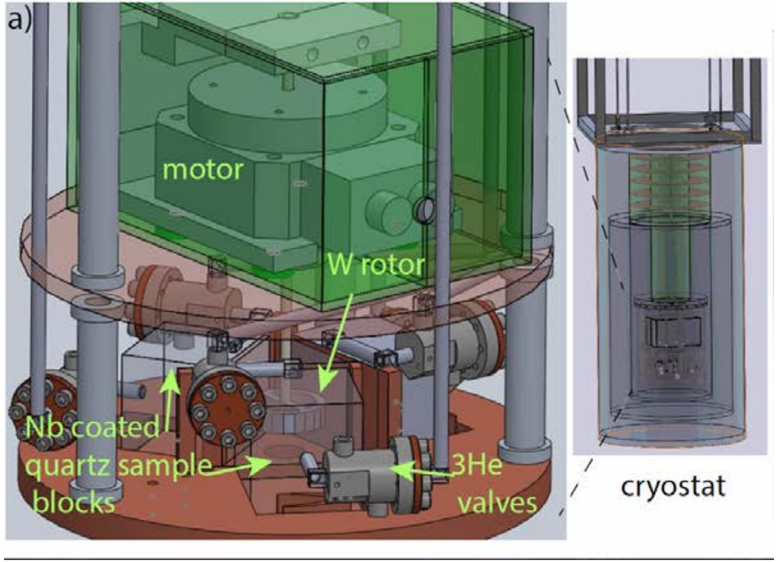
Constraints and Sensitivity

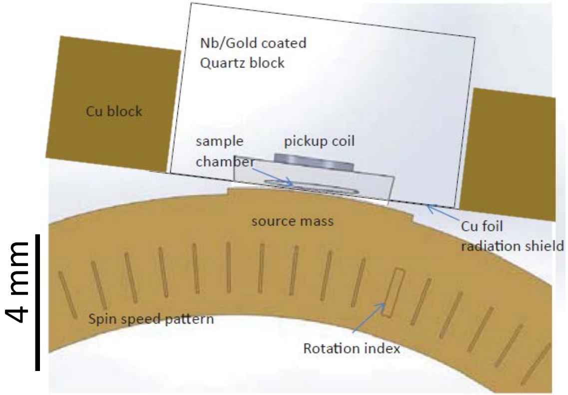


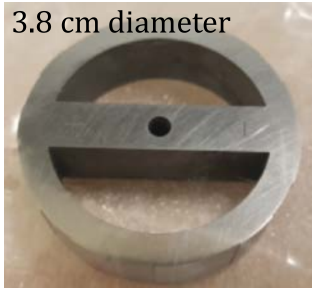
A. Arvanitaki and AG., *Phys. Rev. Lett*. 113,161801 (2014).

[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 parameters







Tungsten source mass (high nucleon density)
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

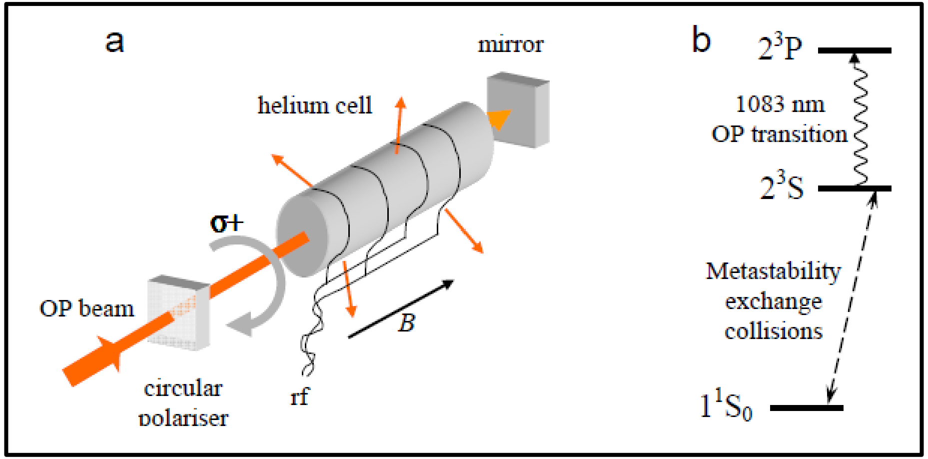
Hyperpolarized ^{3}He

- Ordinary magnetic fields cannot be used to reach near unity polarization

$$\exp[-\mu_N B / k_B T]$$

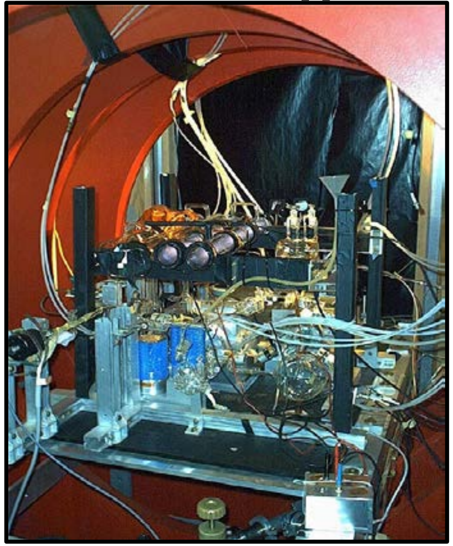
Optical pumping techniques

- Metastability exchange optical pumping



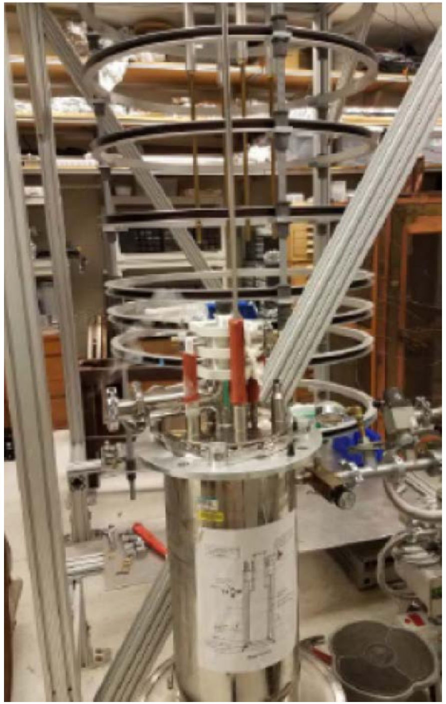
M Batz, P-J Nacher and G Tastevin, Journal of Physics: Conference Series **294** (2011) 012002

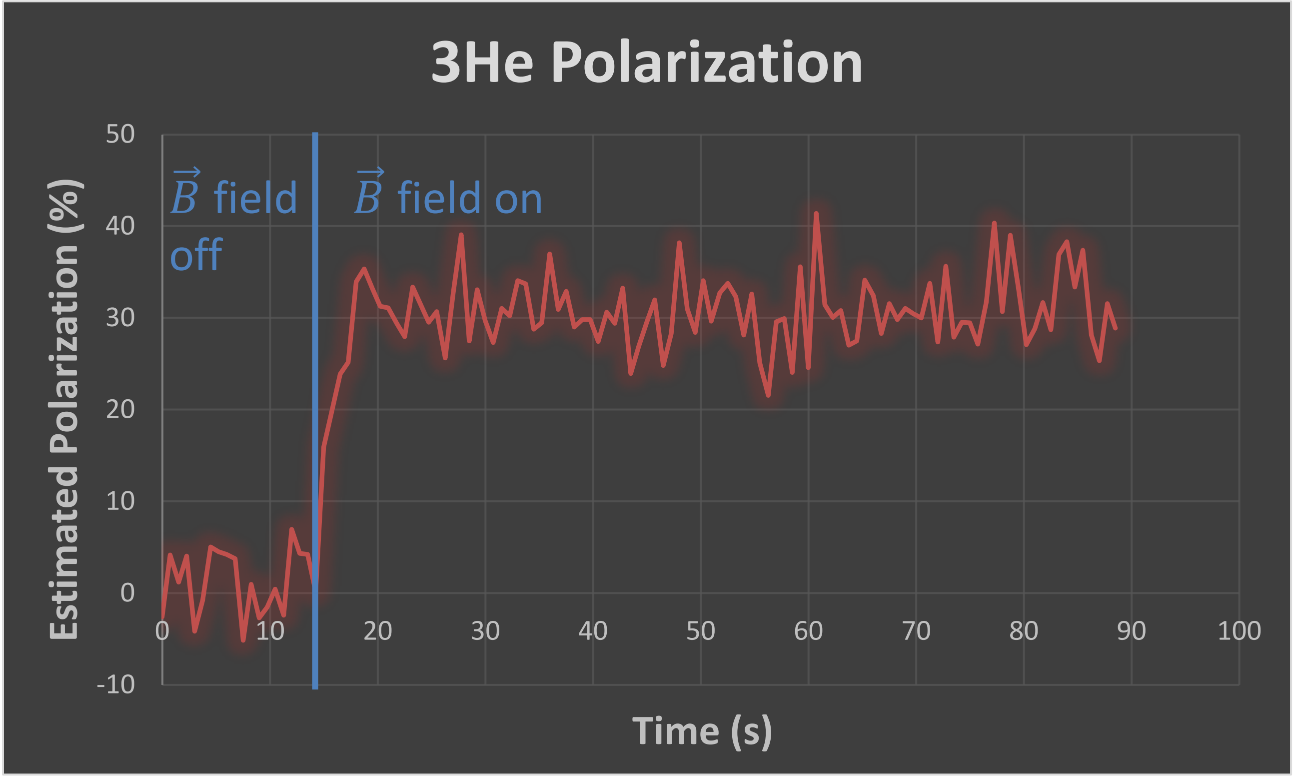
Indiana U. MEOP apparatus



Rev. Sci. Instrum. 76, 053503 (2005)

Hyperpolarized 3He at cryostat (MEOP)





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/$\sqrt{\text{Hz}}$	For 1 μm sample vibration (100 Hz)
Patch Effect	$10^{-21}(\frac{V_{patch}}{0.1V})^2$ T	Can reduce with V applied to Cu foil
Flux noise in squid loop	2×10^{-20} T/$\sqrt{\text{Hz}}$	Assuming $1\mu\Phi_0/\sqrt{\text{Hz}}$
Trapped flux noise in shield	$7 \times 10^{-20} \frac{\text{T}}{\sqrt{\text{Hz}}}$	Assuming 10 cm^{-2} flux density
Johnson noise	$10^{-20}(\frac{10^8}{f})$T/$\sqrt{\text{Hz}}$	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	$10^{-25} - 10^{-17}(\frac{\eta}{1\text{ppm}})(\frac{10^8}{f})$ 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 $3 \times 10^{-19}(\frac{1000\text{s}}{T_2})^{1/2}$T/$\sqrt{\text{Hz}}$

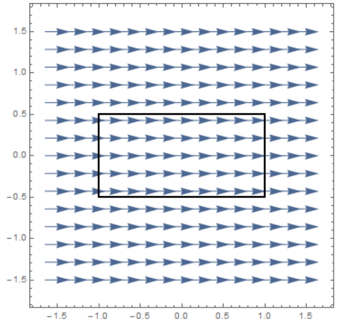
- Design/Simulation Work: Magnetic gradient reduction strategy
- Experimental testing in progress: Vibration tests, Shielding factor *f* test thin-film SC, Magnetic impurity tests

Superconducting Magnetic Shielding

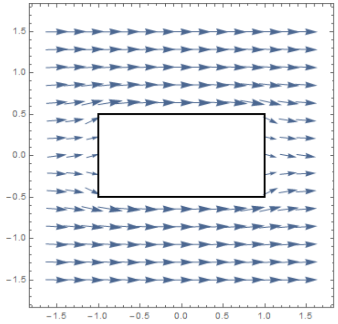
→ Essential to avoid Johnson noise

Meissner Effect

- No magnetic flux across superconducting boundary



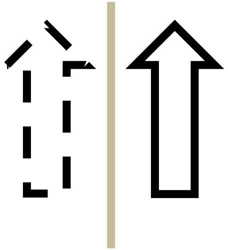
$T > T_c$



$T < T_c$

Method of Images

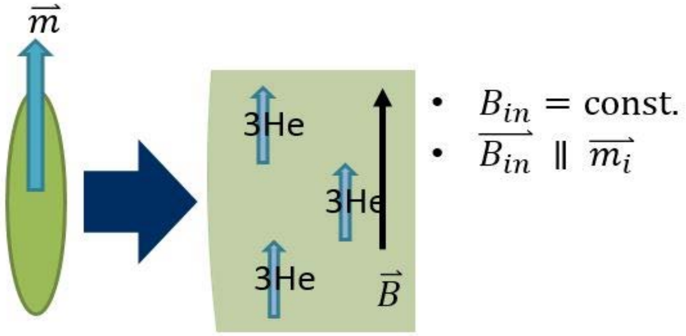
- Make “image currents” mirrored across the superconducting boundary



Dipole with image

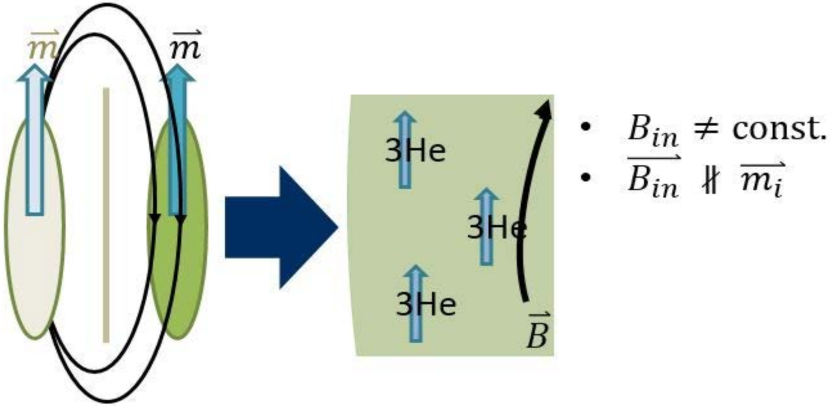
The Problem of Unwanted Images

- ARIADNE uses magnetized spheroid
  - Constant interior field



- Magnetic shielding introduces "image spheroid" Interior field varies

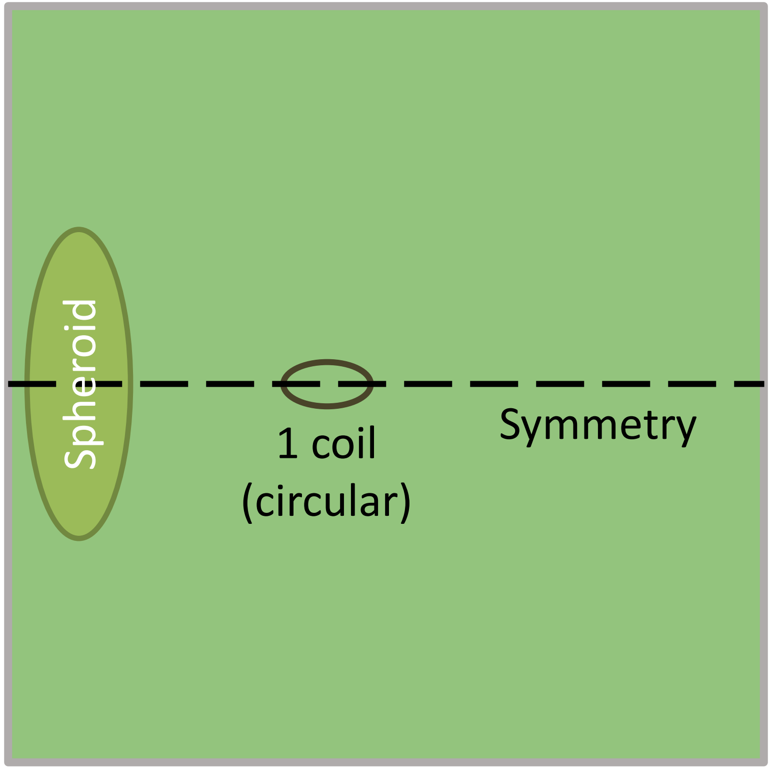
→ variations in nuclear Larmor frequency



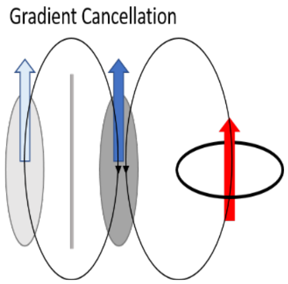
But want to drive entire sample on resonance

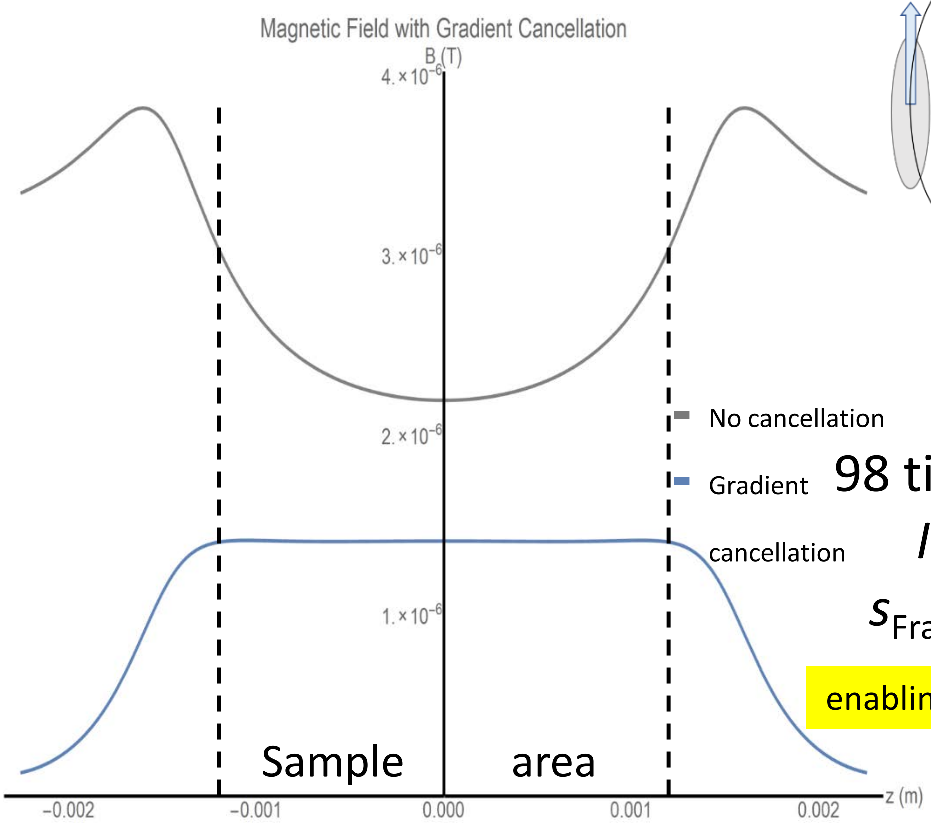
Flattening Solution

- 1 coil – simple configuration
- Expected field from spheroid ~1 μT
  - I on the 0.1 – 1 A range



Gradient Cancellation





98 times flatter

I = 1.6 A

s_{Frac} = 0.17%

enabling T_2 of ~100 s

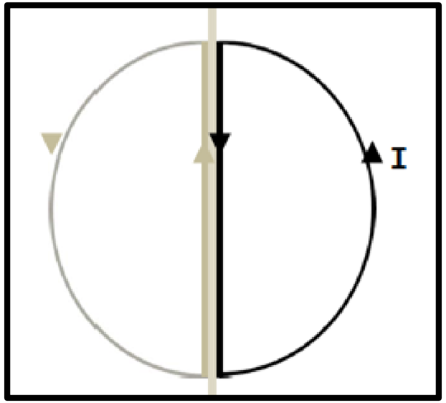
H. Fosbinder-Elkins, *et.al.*, arxiv:1710.08102 (2017).

Tuning Solution – "D" Coils

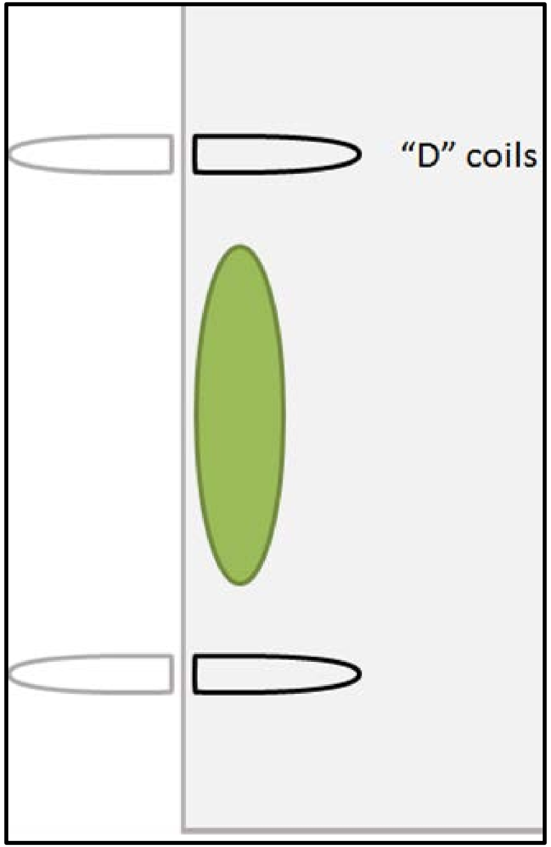
- Tune field with Helmholtz coils
  - Helmholtz field only flat near the center
  - Geometry restrictions prevent the spheroid from being centered in traditional Helmholtz coils

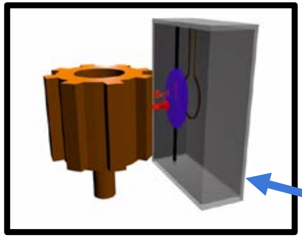
- "D" coils look like Helmholtz coils when their images are included

- Inner straight-line currents cancel
- Outer currents do not

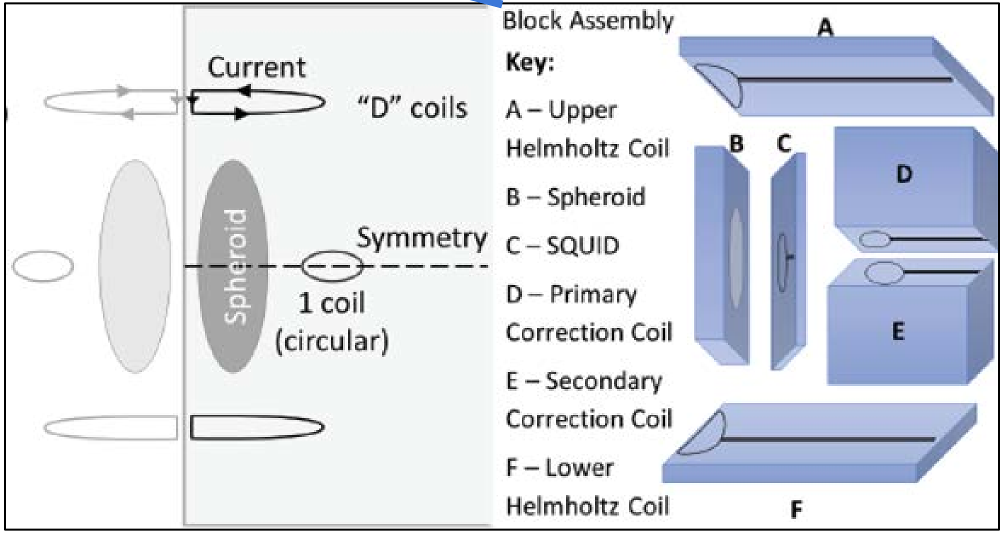


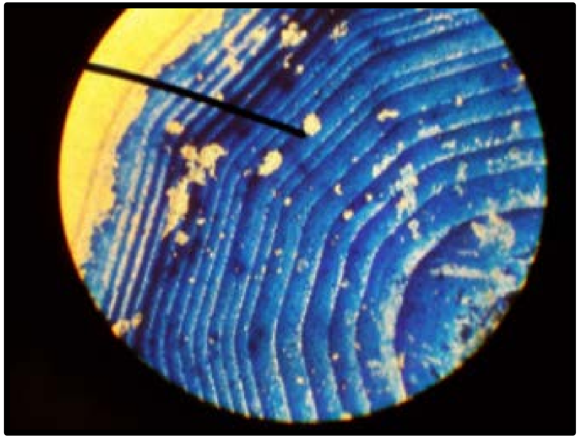
One "D" coil and image (bird's eye view)

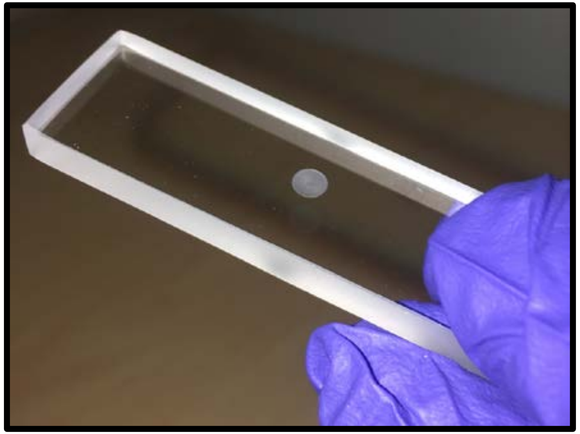




Quartz Block Sensor module



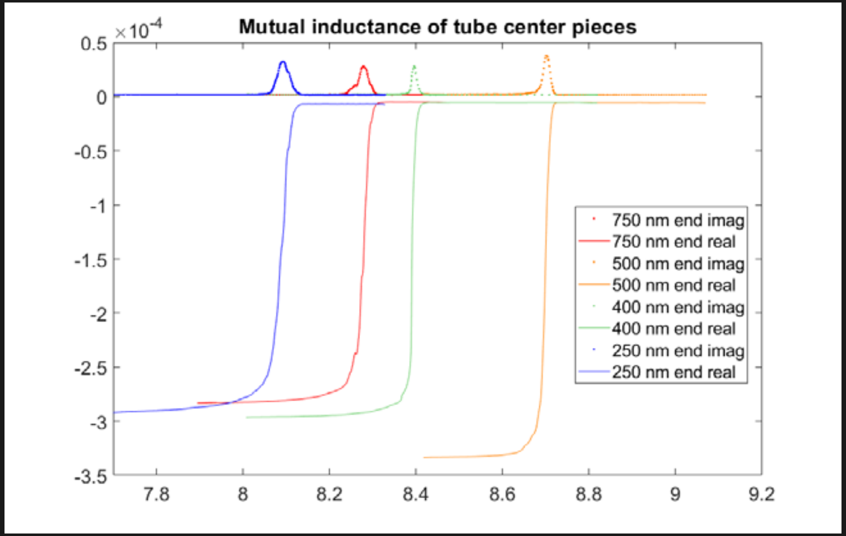




Fabrication/polishing tests in process
Latest batch just delivered Dec 2020

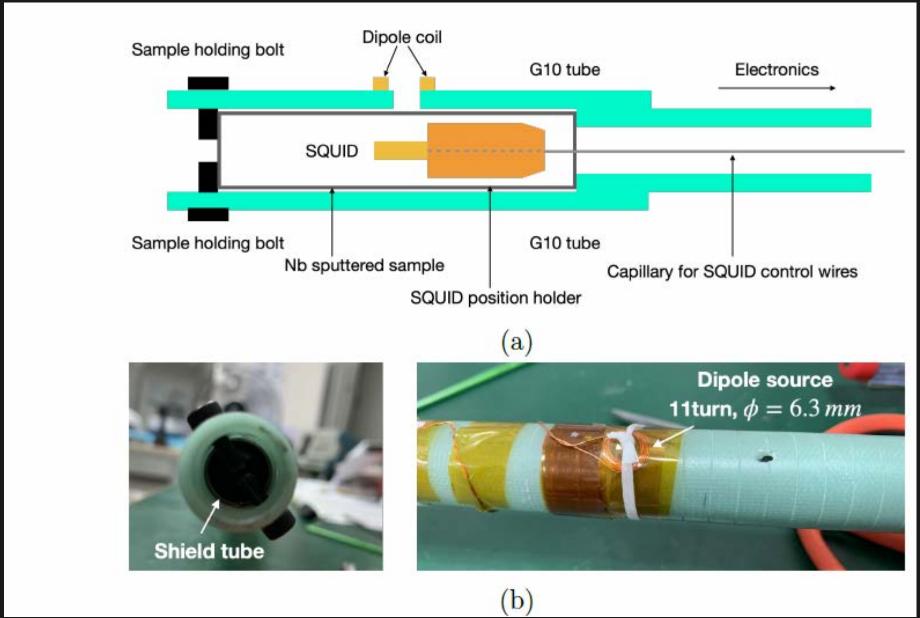
Thin Film Superconducting Shielding

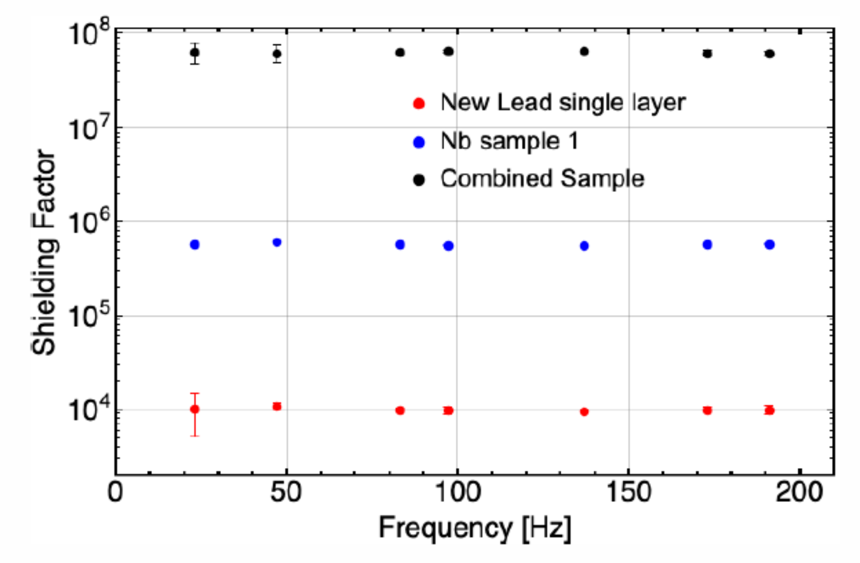
- Shield out ordinary magnetic noise
- Sputtered Niobium on quartz tubes/different geometries for tests
- Tests of adhesion, Tc, shielding factor



Younggeun Kim, Dongok Kim, Yun Chang Shin, Andrei Matlashov CAPP/IBS, A. Fang (Stanford)

Thin Film Superconducting Shielding Test





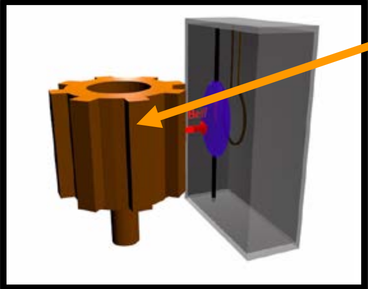
- Shielding Factor test setup Nb film 750nm thickness

- ~10^6 achieved so far (10^8 goal)
- Sputter deposition being optimized
- Using supplemental lead foil achieves theoretical value ~10^8

Younggeun Kim, Dongok Kim, Yun Chang Shin, Andrei Matlashov CAPP/IBS

Source Mass Prototype

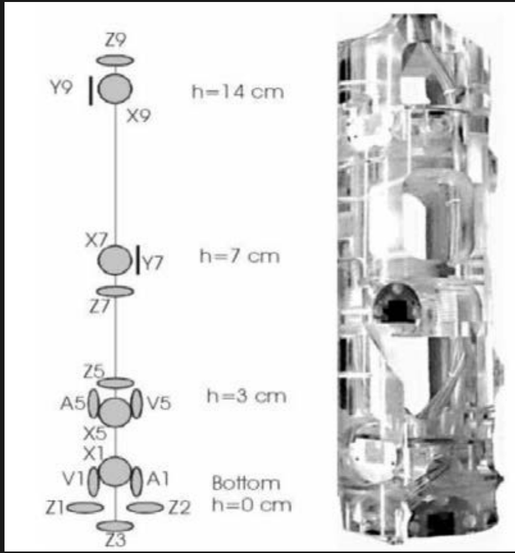
- Material: tungsten
- 11 segments
- 3.8 cm in diameter

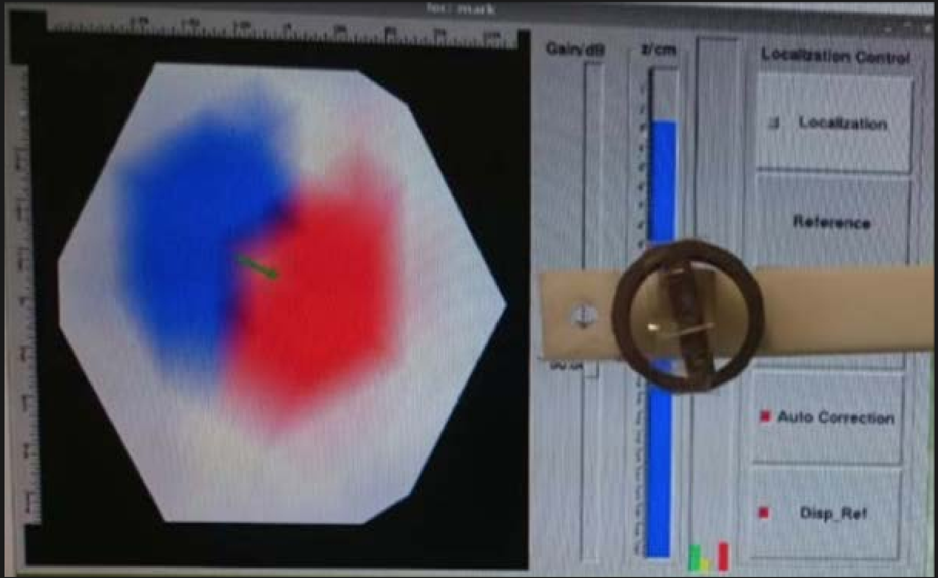


Source Mass Characterization

- Magnetized the wheel with a 30 mT magnet

- Wheel was brought under multichannel SQUID device in shielded room

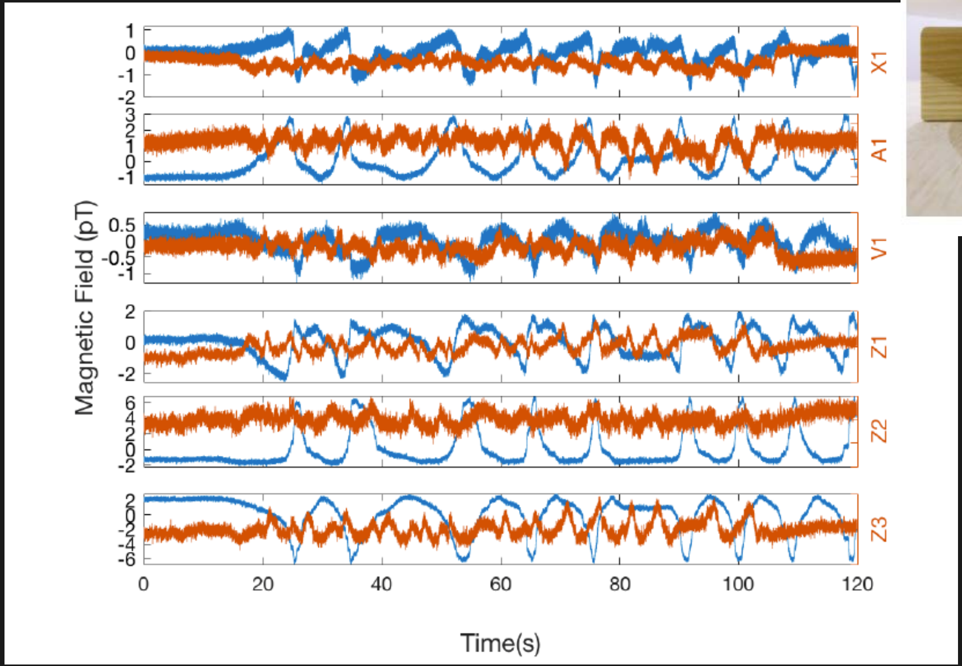


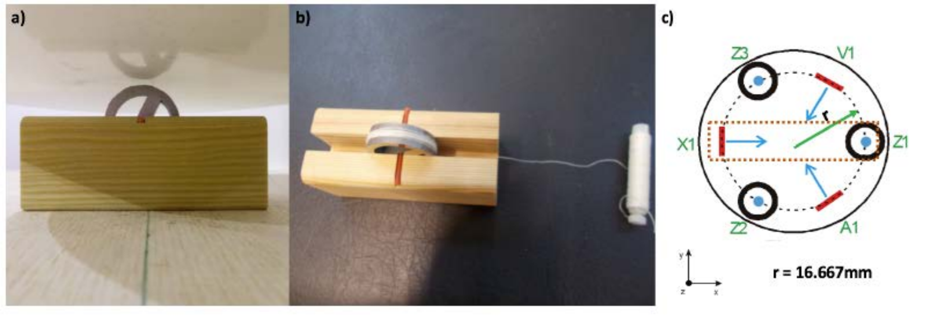


(PTB)

Source Mass Characterization

Before and after degaussing





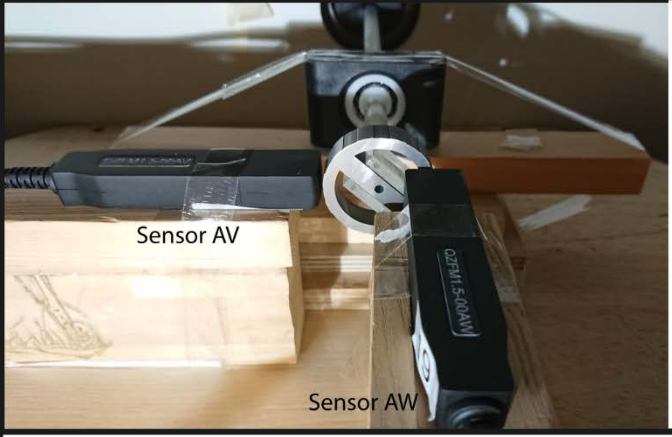
De-gaussing reduces residual field
To approx ~pT level near surface

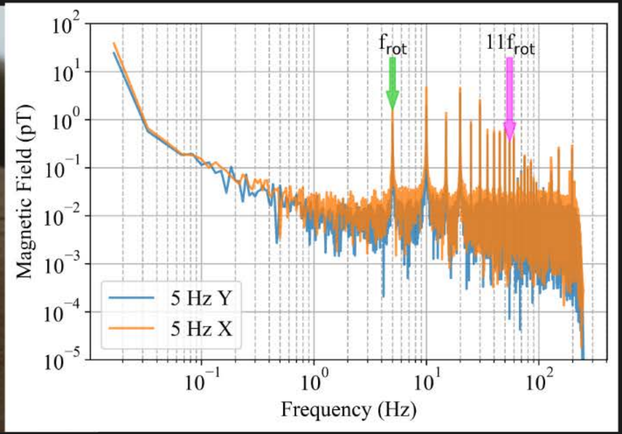
Consistent with expected Johnson noise

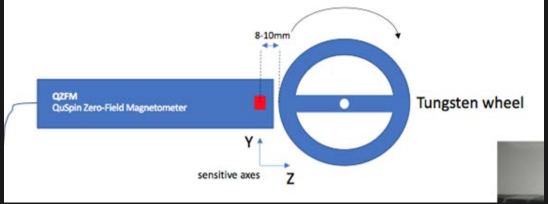
(PTB)

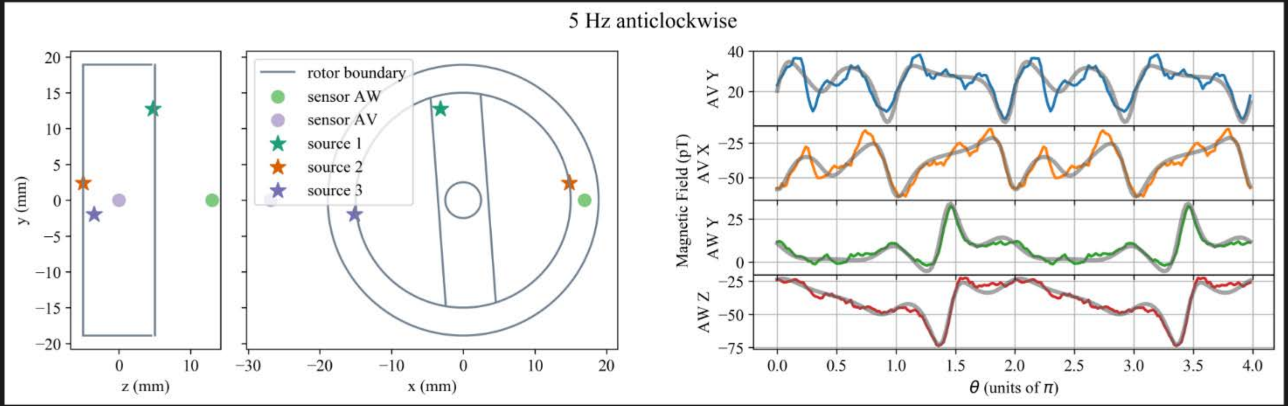
Magnetic Impurities mapping

Low-field, high-resolution optical magnetometry: QuSpin optical magnetometers





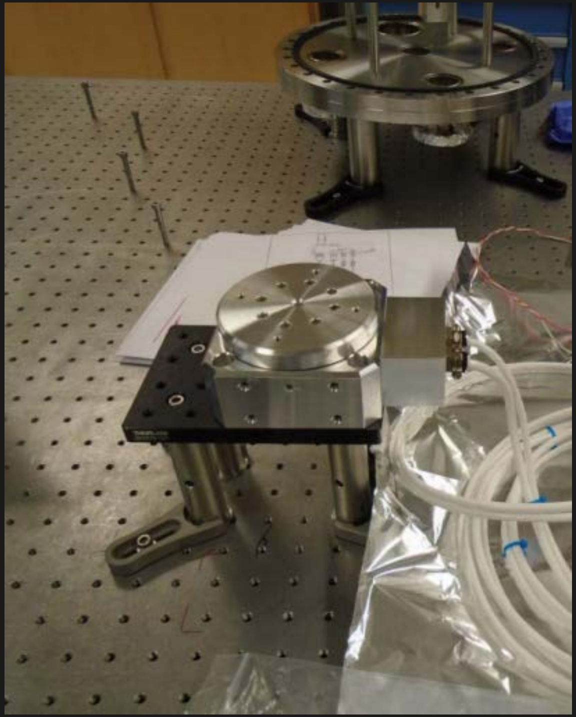




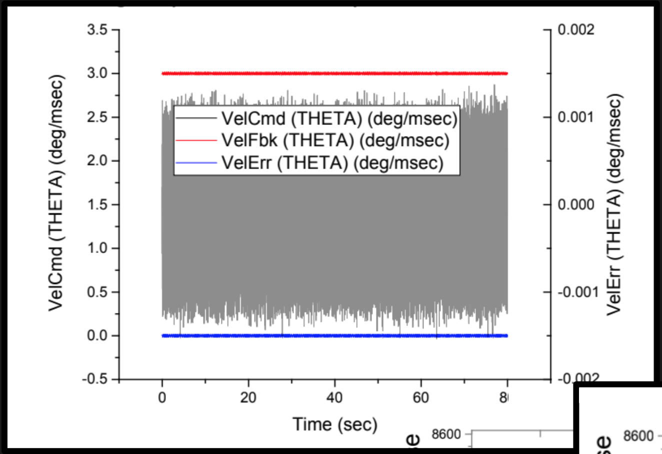
N. Aggarwal, *et.al.*, arXiv:2011.12617 (2020)

Speed Stability -Direct Drive Stage

- Optical encoder
- Current feedback control

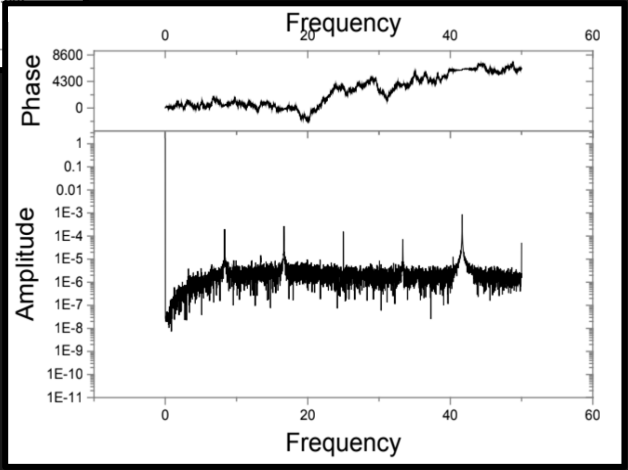


Stage speed stability error – unloaded, in air

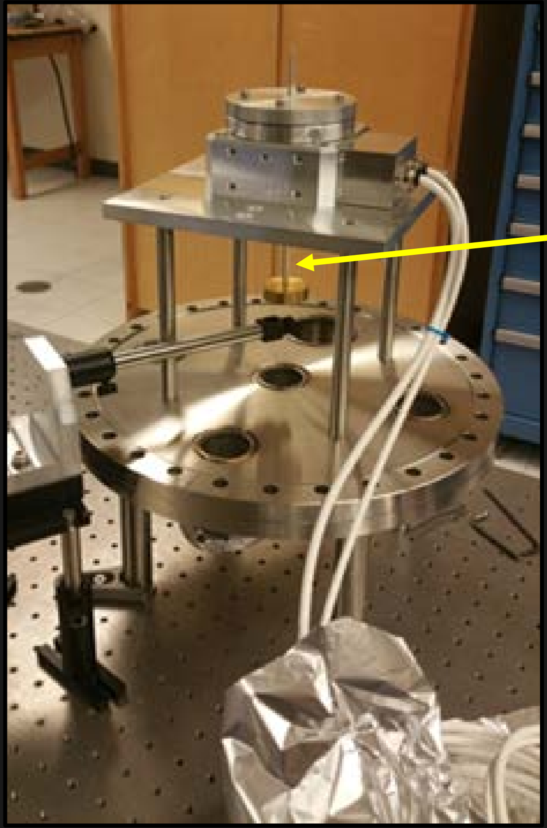


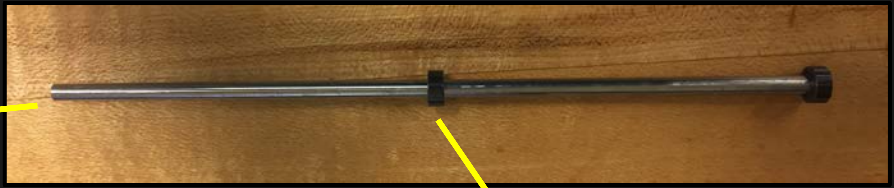
Rotation speed control
8.3 Hz ~ 1 part in 10000
RMS ~ 1 part in 3000

Allows utilization of T_2 > 100s



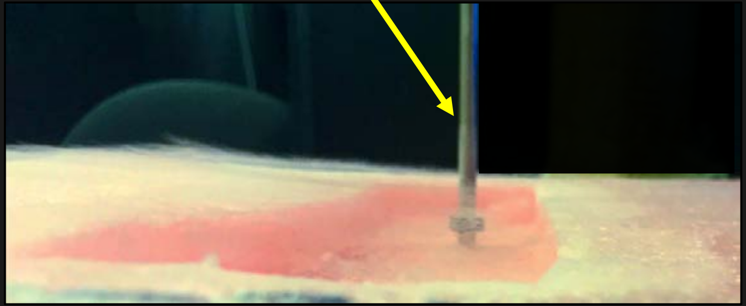
Rotary test Assembly





Rod details

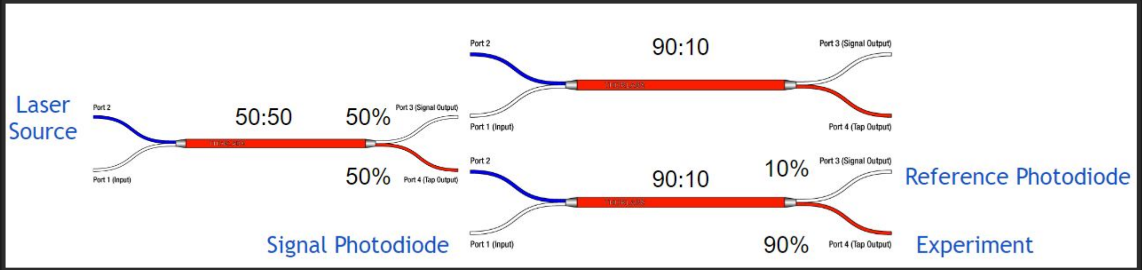
Material: Ti6Al4V
Diameter: 5 ± .01mm
Length: 7.5 ± .1”
Ovality: < .0004"
Runout: < .0005"

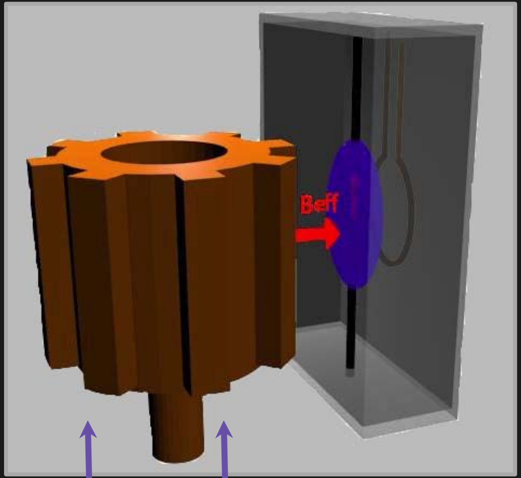


Original runout .0005" reduced to .0003" after bearing attachment

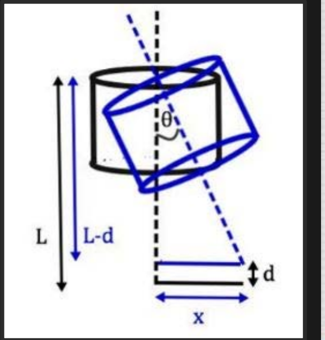
Rotational Stability

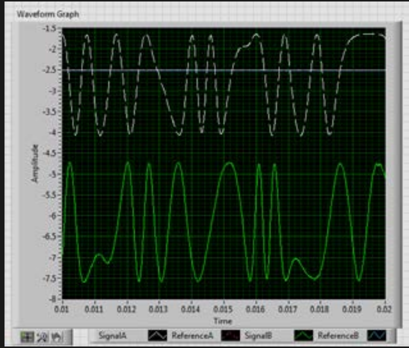
- Two interferometers pointed at bottom of sprocket
- Distance “d” is found
- Thus, wobble distance “x” can be found using geometry, calibrated with laser beam bounce
- Distance Sensitivity 19 pm/√Hz





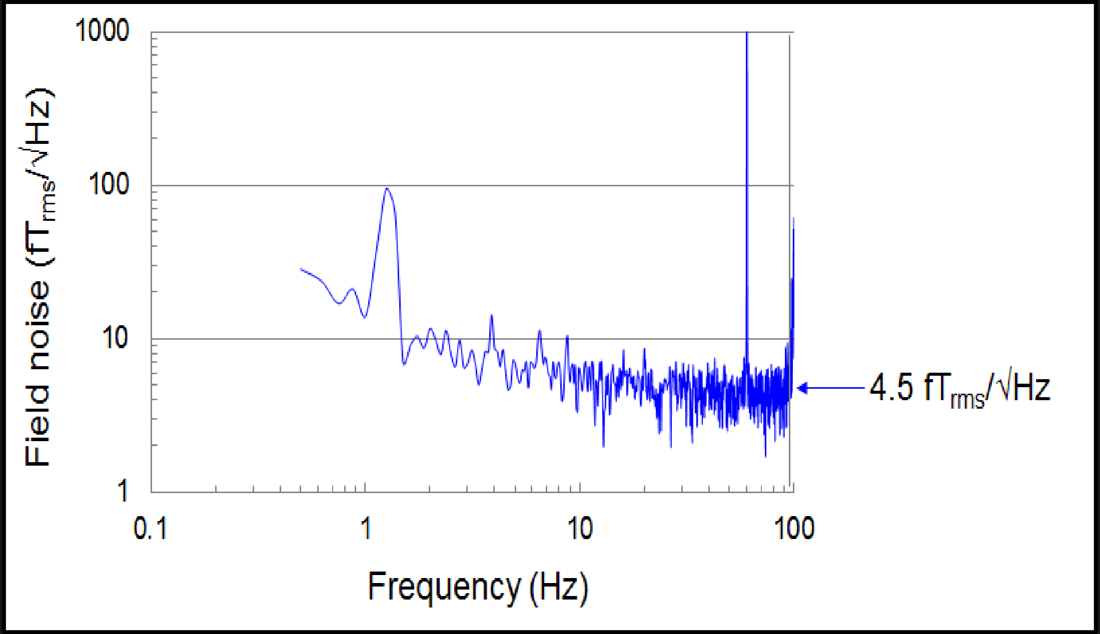
Interferometers





SQUID Development

Custom fabricated SQUID on quartz

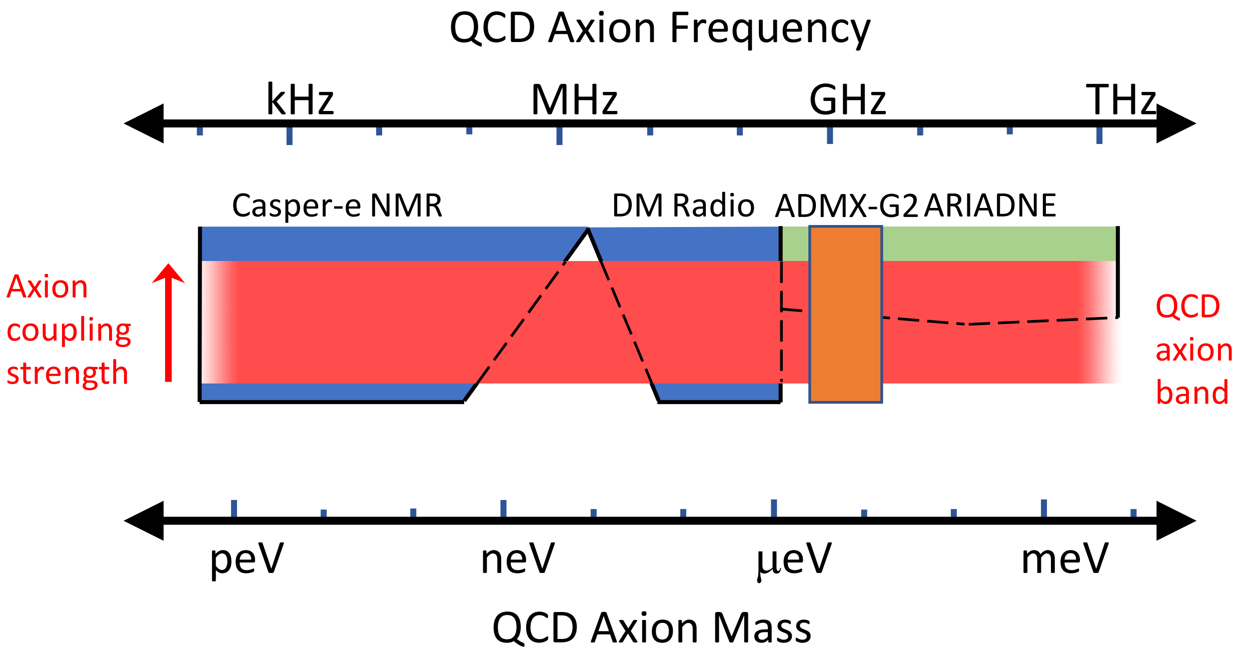


Field Noise from SQUID measured inside a magnetically shielded room

- Low-noise gradiometer design under investigation (CAPP/KRISS)

Yong-Ho Lee (KRISS)

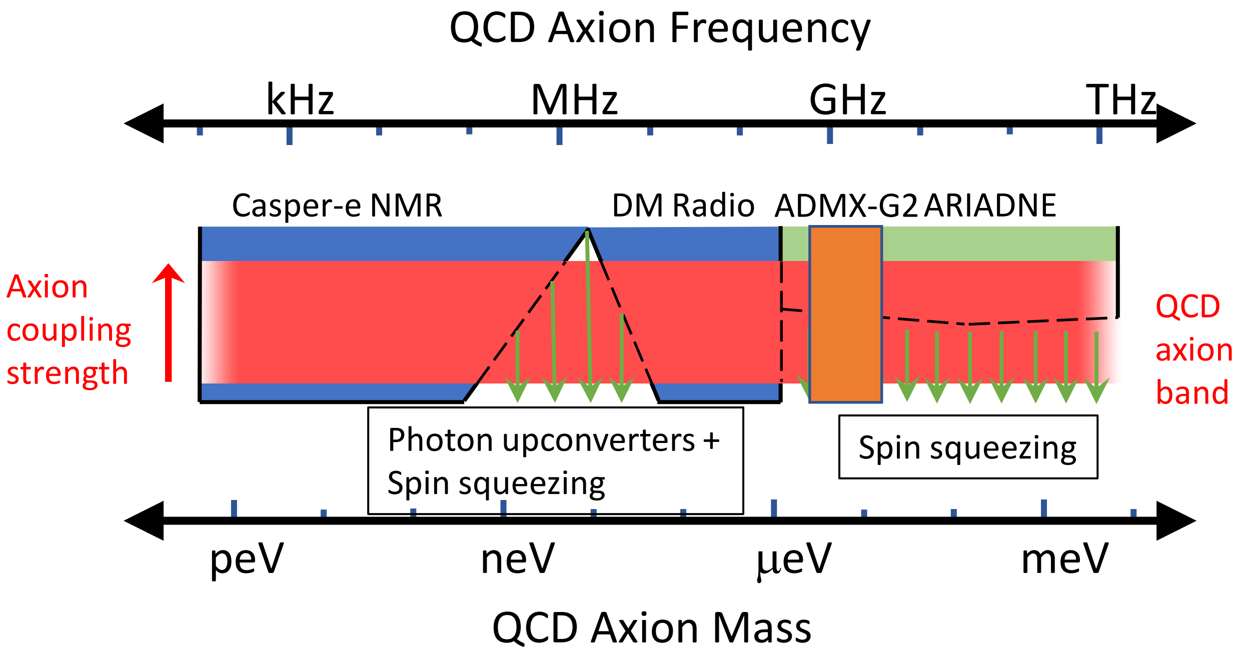
Future projections: axion searches at the Standard quantum limit



Adapted from K. Irwin

Axion searches at the Standard quantum limit

Green arrows: searches beyond the SQL



Adapted from K. Irwin

Conclusion

- ARIADNE → Fifth-force axion search using NMR method

  → Gap in experimental QCD axion searches

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

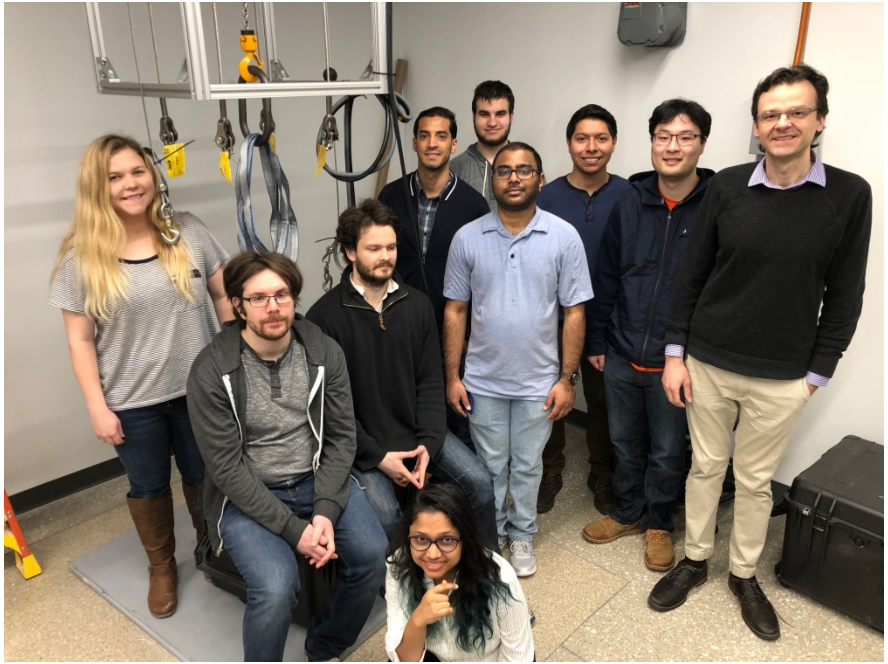
  → No need to scan mass, indep. of local DM density

  → Cryostat completion planned Summer 2021

  → Covers entire QCD axion parameter space when combined with haloscope and helioscope experiments (ADMX, HAYSTAC, Orpheus, DM Radio, LC Circuit, CAPP, CASPEr, MADMAX, IAXO)!

Acknowledgements

Center for Fundamental Physics (CFP)



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