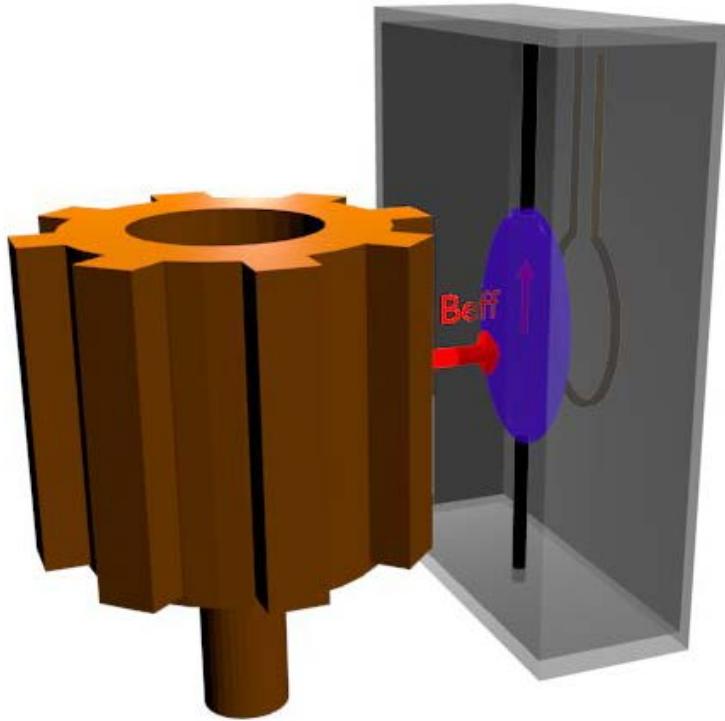


# Progress on the ARIADNE axion experiment



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

Mark Cunningham (UNR)  
Harry Fosbinder-Elkins (UNR)  
Jordan Dargert (UNR)  
Chloe Lohmeyer (UNR)  
**Asimina Arvanitaki** (Perimeter)  
**Aharon Kapitulnik** (Stanford)  
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Mofan Zhang (IU)  
Andrew Rusch (IU)  
**Yannis Semertzidis** (CAPP)  
Yun Shin (CAPP)  
Yong-Ho Lee (KRISS)

A. Geraci, University of Nevada Reno



**ibS** Institute for Basic Science

Axion Cavity and Detector Workshop, LLNL Jan 12, 2017



University of Nevada, Reno



PERIMETER INSTITUTE  
FOR THEORETICAL PHYSICS



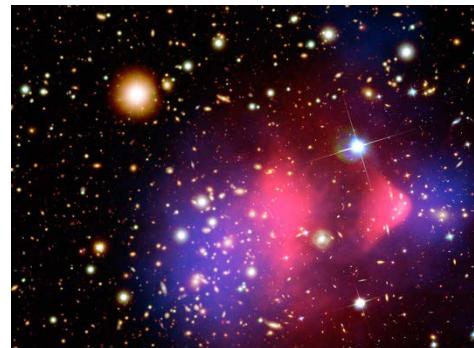
INDIANA UNIVERSITY



# Axions

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

Experiments: e.g. ADMX, CAST, LC circuit, Casper

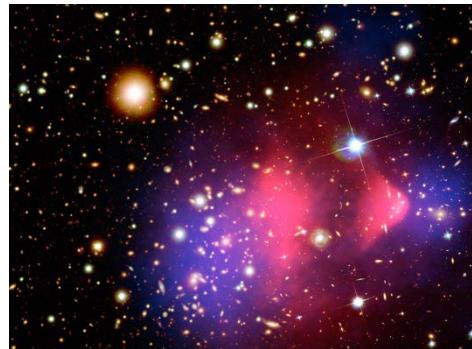


- R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. 38, 1440 (1977);
- S. Weinberg, Phys. Rev. Lett. 40, 223 (1978);
- F. Wilczek, Phys. Rev. Lett. 40, 279 (1978).
- J. E. Moody and F. Wilczek, Phys. Rev. D 30, 130 (1984).

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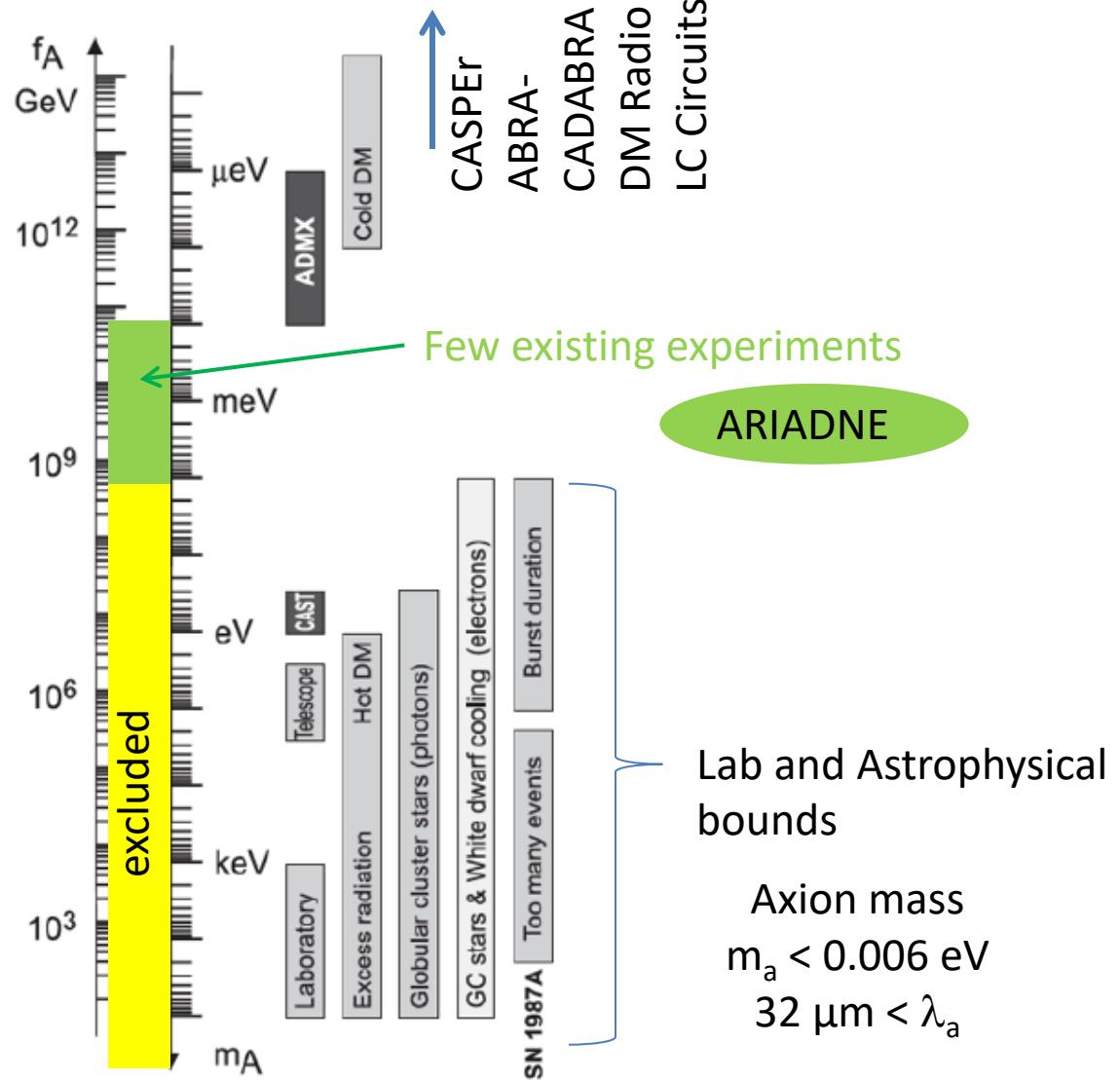


- Also mediates spin-dependent forces between matter objects at short range (down to 30  $\mu\text{m}$ )

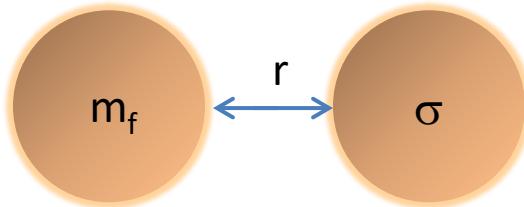
→ Can be sourced locally

- 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).

# QCD Axion parameter space



# Spin-dependent forces



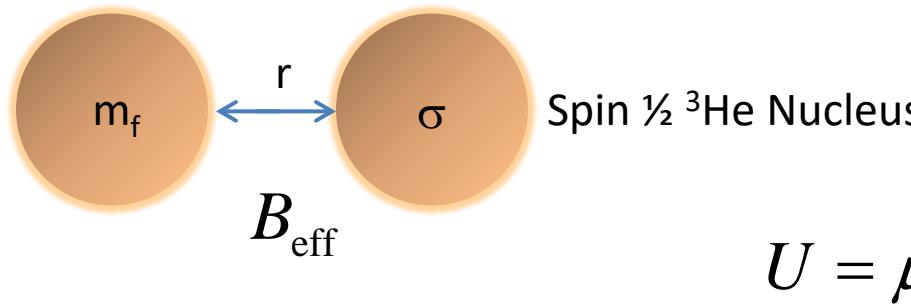
Monopole-Dipole axion exchange

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

Fictitious magnetic field

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

# Using NMR for detection



Bloch Equations

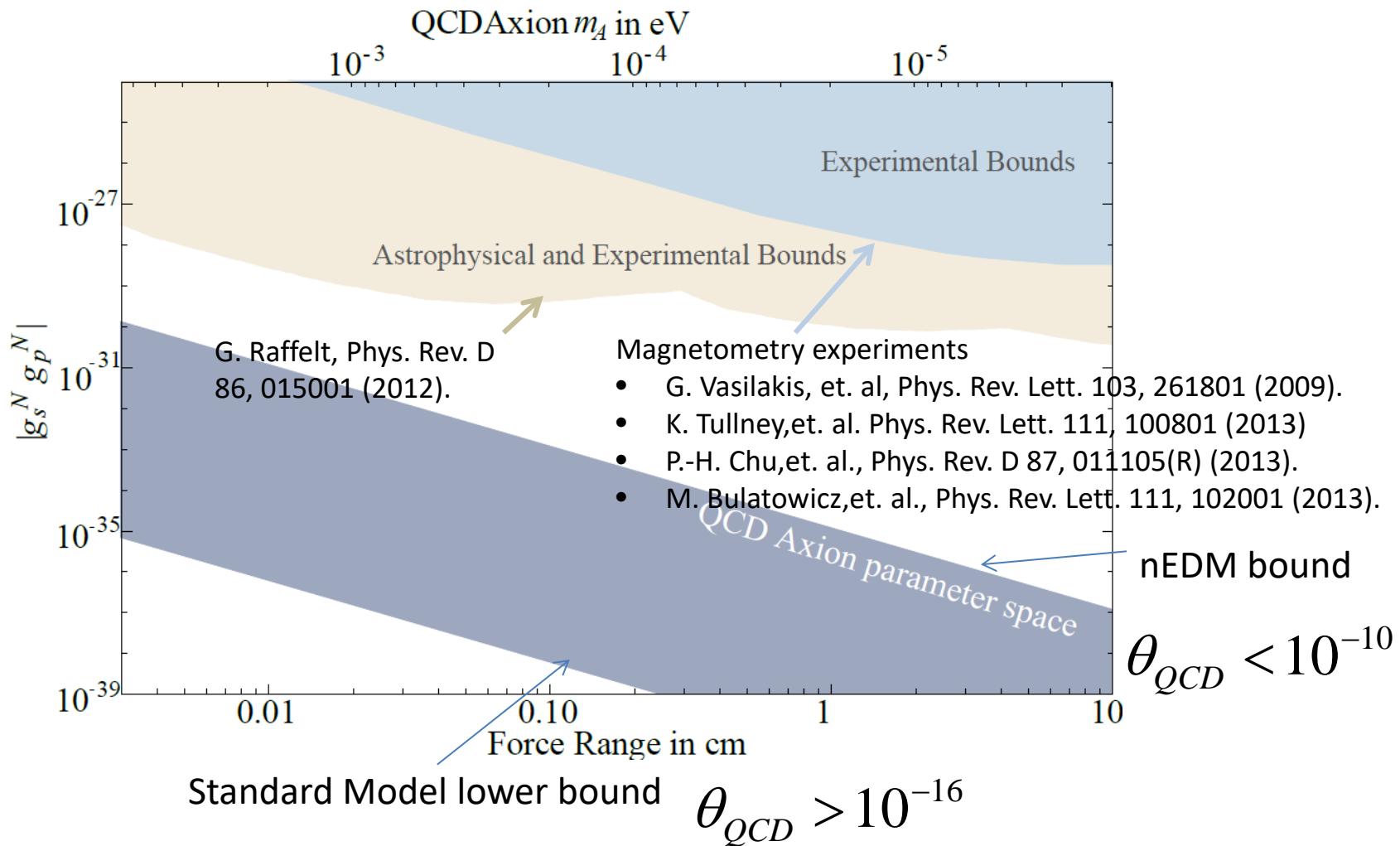
$$\frac{d\vec{M}}{dt} = \gamma \vec{M} \times \vec{B}$$

$$\begin{array}{c} \xrightarrow{\hspace{1cm}} | \uparrow \rangle \\ \xrightarrow{\hspace{1cm}} | \downarrow \rangle \end{array} \quad \omega = \frac{2\mu_N \cdot B_{\text{ext}}}{\hbar}$$

Spin precesses at nuclear spin Larmor frequency  $\omega = \gamma B$

Axion  $B_{\text{eff}}$  modifies measured Larmor frequency

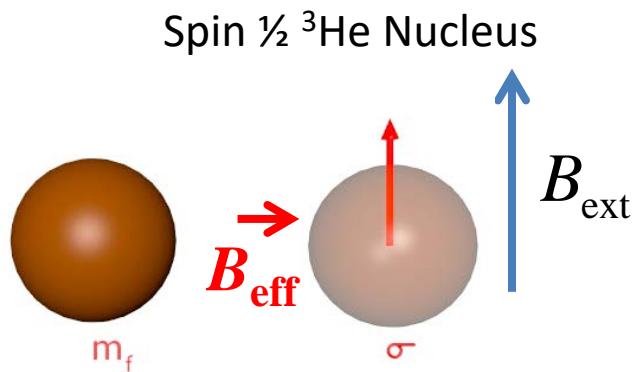
# Constraints on spin dependent forces



# ARIADNE: uses resonant enhancement

Oscillate the mass at Larmor frequency

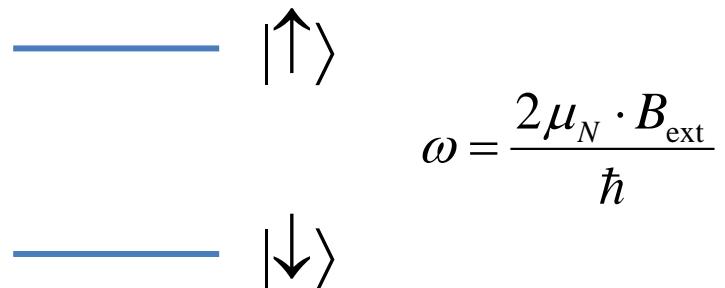
$$B_{\text{eff}} = B_{\perp} \cos(\omega t)$$



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

Bloch Equations

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



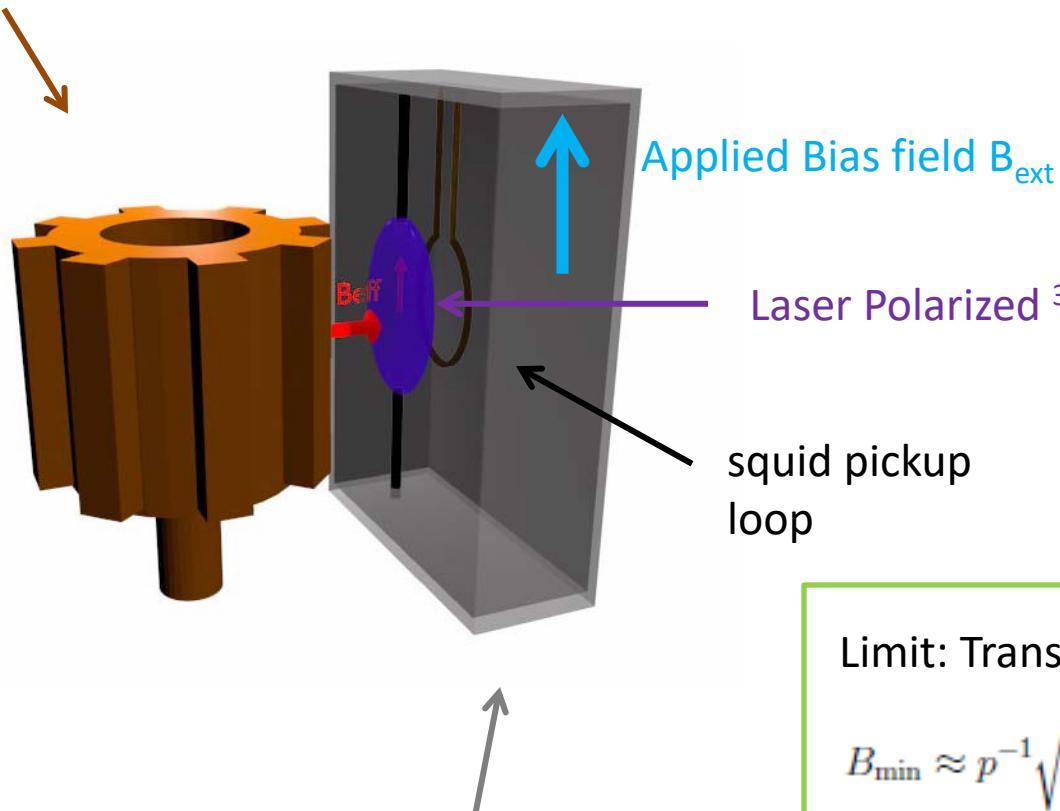
Time varying Axion  $B_{\text{eff}}$  drives spin precession  
→ produces transverse magnetization

Amplitude is resonantly enhanced by Q factor  $\sim \omega T_2$ .

Can be detected with a SQUID

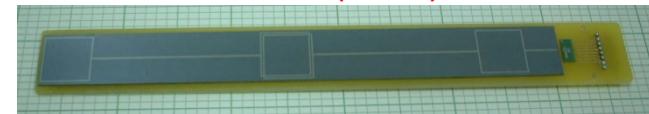
# Concept for ARIADNE

Unpolarized (tungsten) segmented cylinder sources  $B_{\text{eff}}$



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

Y.-H. Lee (KRISS)



Limit: Transverse spin projection noise

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

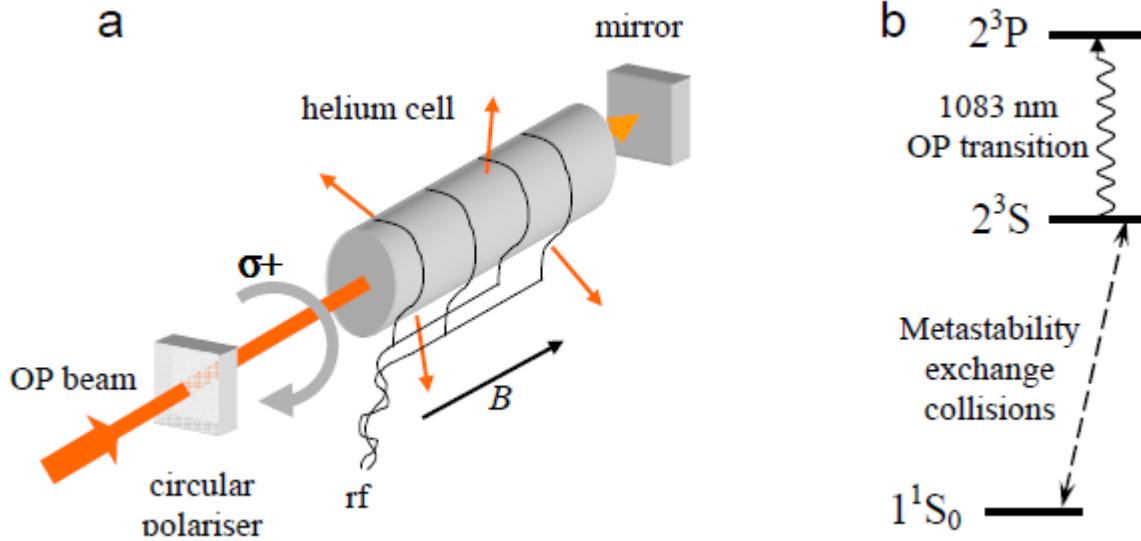
# Hyperpolarized $^3\text{He}$

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

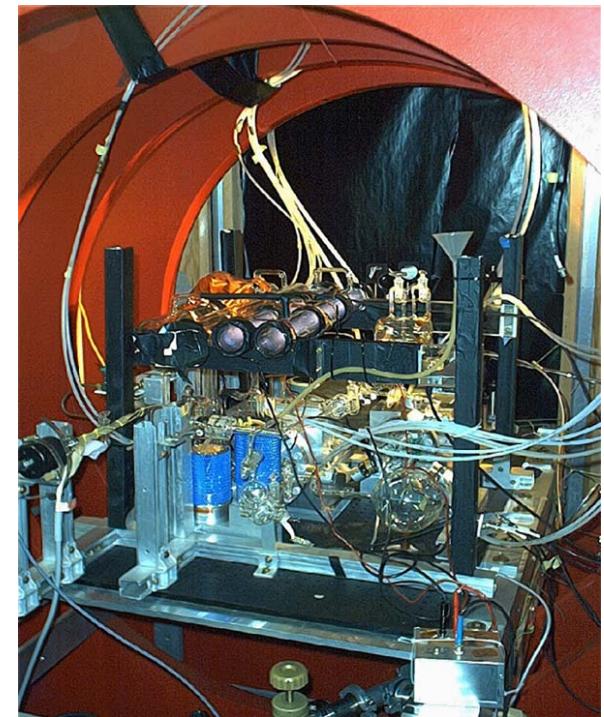
$$\exp[-\mu_N B / k_B T]$$

Optical pumping techniques

- Metastability exchange optical pumping

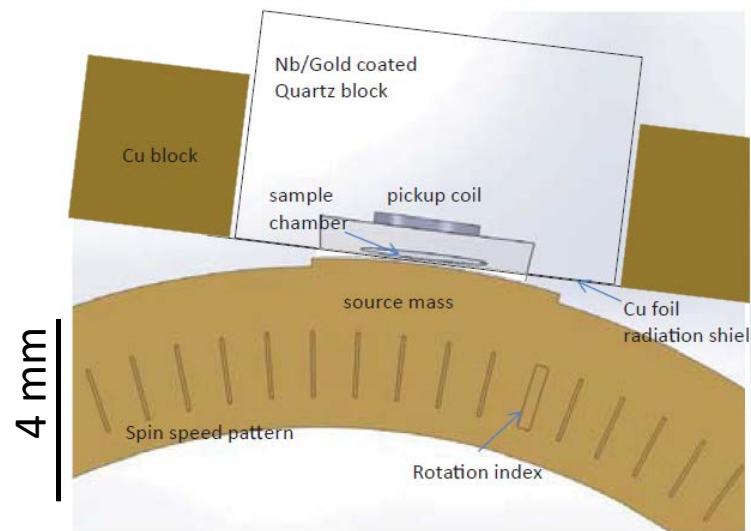
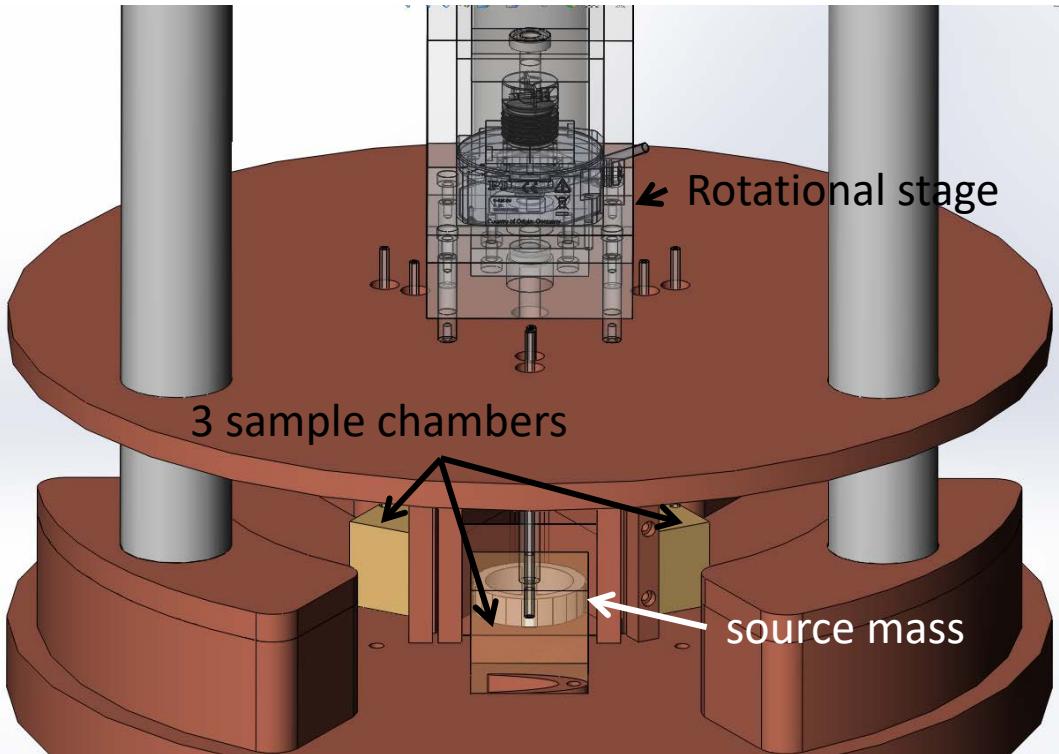


Indiana U. MEOP apparatus



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

# Experimental parameters



11 segments

100 Hz nuclear spin precession frequency

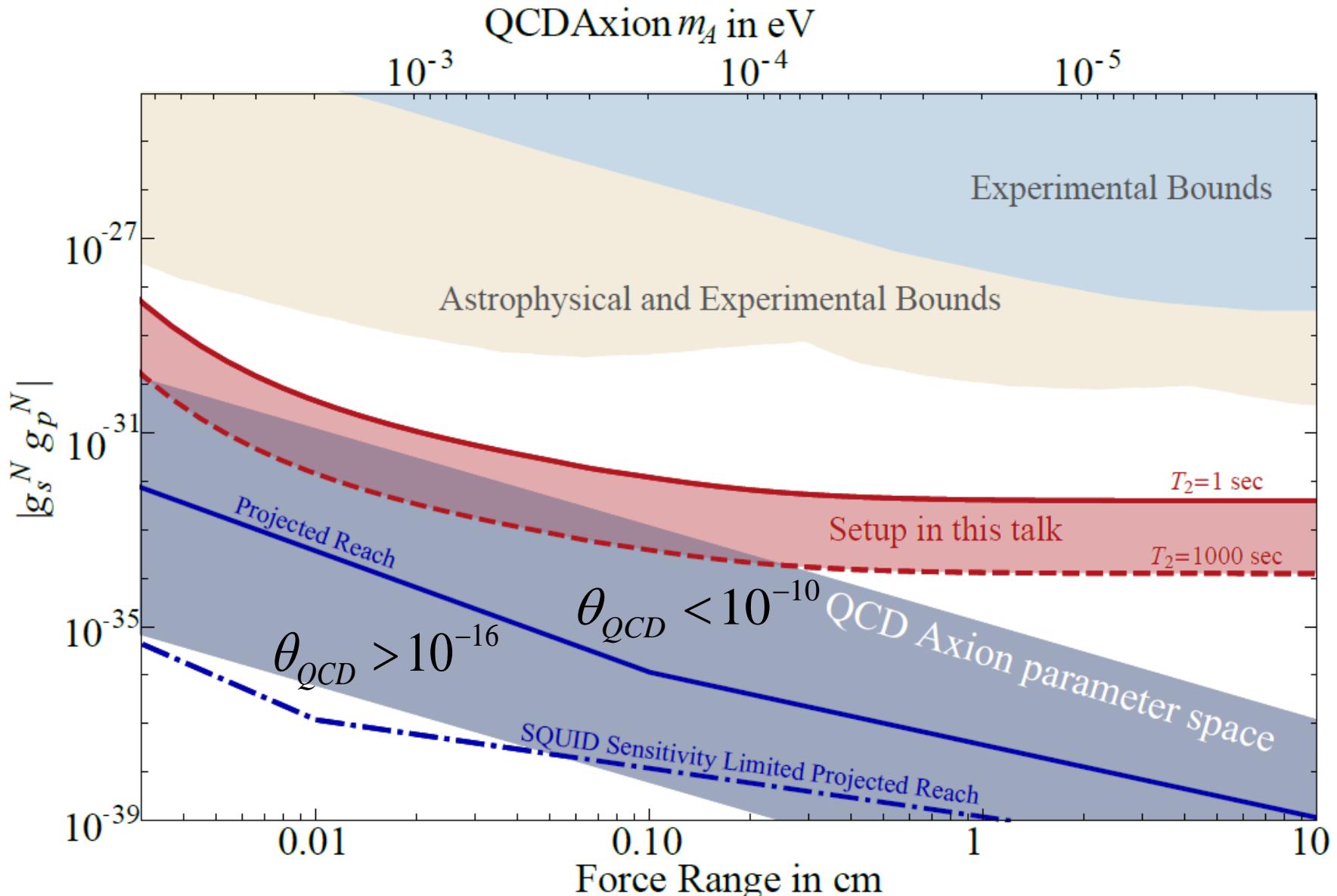
$2 \times 10^{21} / \text{cc}$   $^3\text{He}$  density

10 mm x 3 mm x 150  $\mu\text{m}$  volume

Separation 200  $\mu\text{m}$

Tungsten source mass (high nucleon density)

# Sensitivity



# Experimental challenges

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

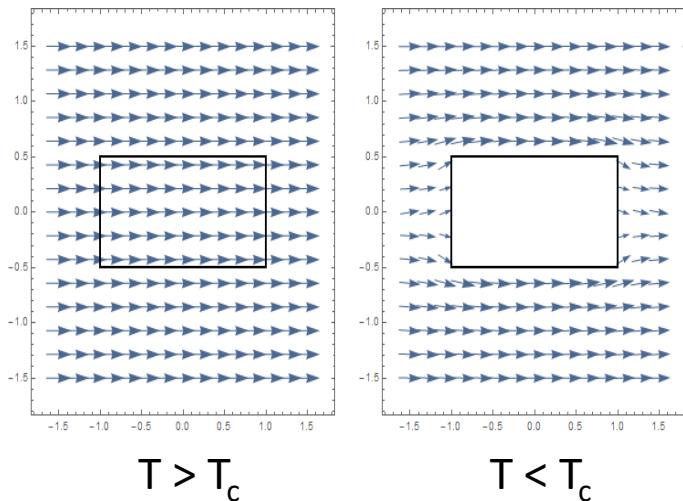
Table 1: Table of estimated systematic error and noise sources, as discussed in the text. The projected sensitivity of the device is  $3 \times 10^{-19} \left( \frac{1000\text{s}}{T_2} \right)$  T/ $\sqrt{\text{Hz}}$

# Superconducting Magnetic Shielding

→ Essential to avoid Johnson noise

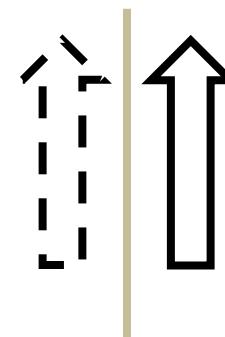
## Meissner Effect

- No magnetic flux across superconducting boundary



## Method of Images

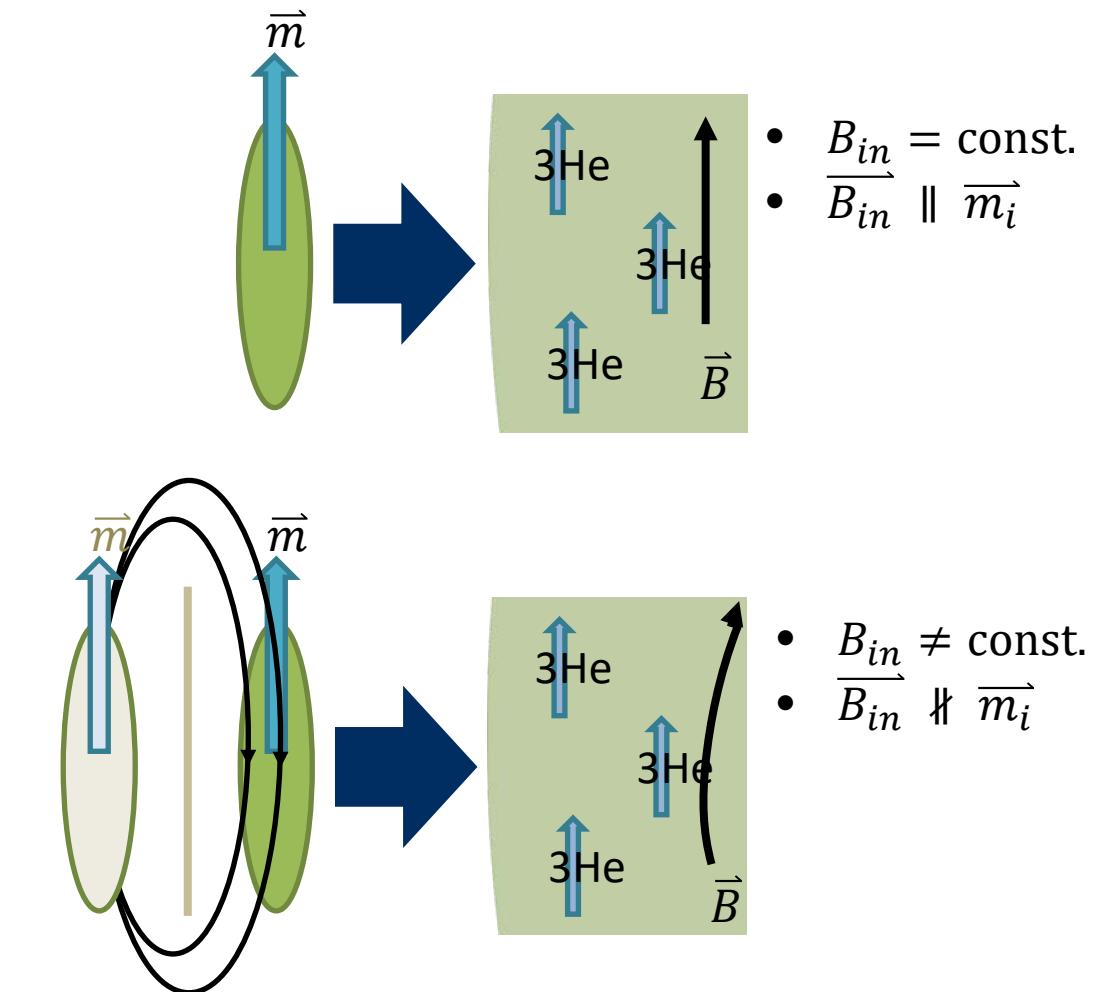
- Make “image currents” mirrored across the superconducting boundary



Dipole with image

# The Problem of Unwanted Images

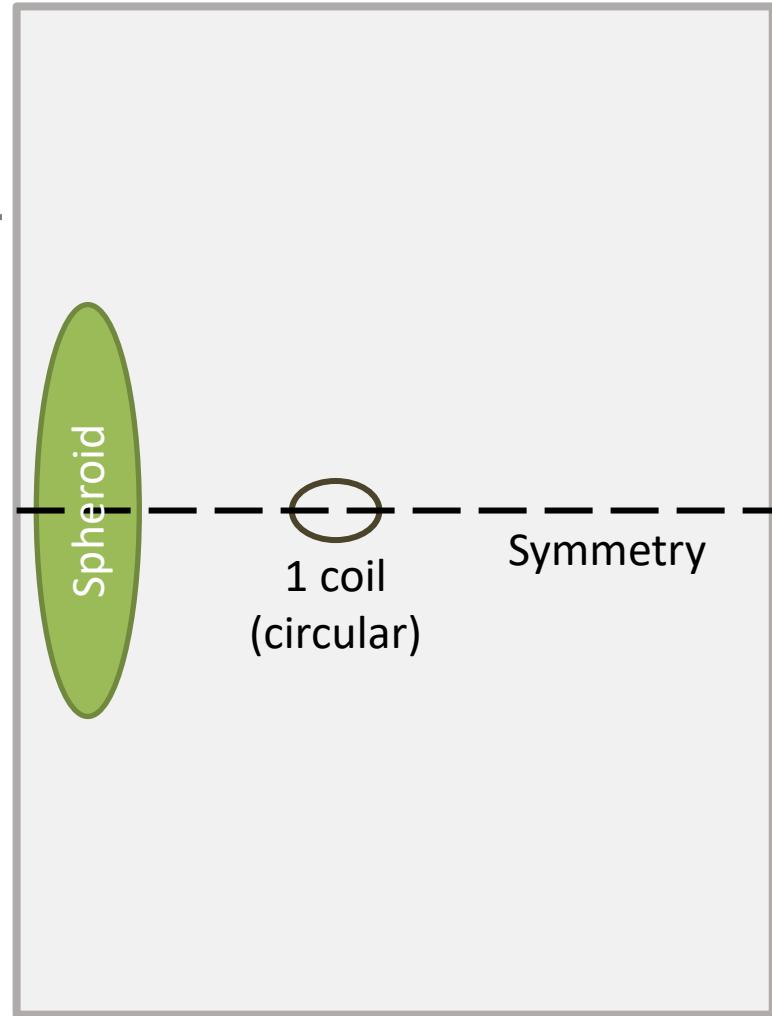
- ARIADNE uses magnetized spheroid
    - Constant interior field
  - Magnetic shielding introduces “image spheroid”
    - Interior field varies
- variations in nuclear Larmor frequency!



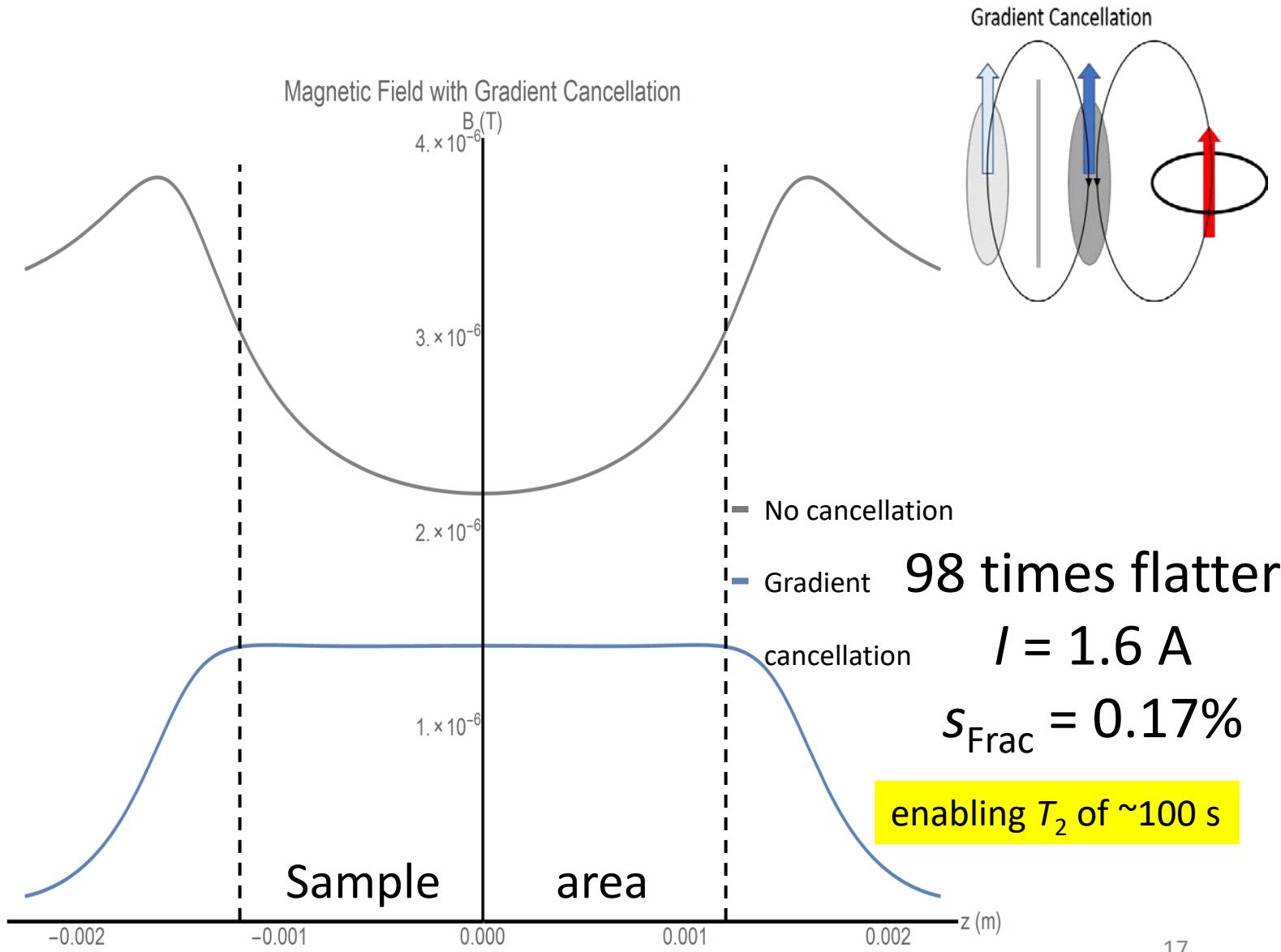
But want to drive entire sample on resonance

# Flattening Solution

- 1 coil – simple configuration
- Expected field from spheroid  $\sim 1 \mu\text{T}$ 
  - I on the 0.1 – 1 A range

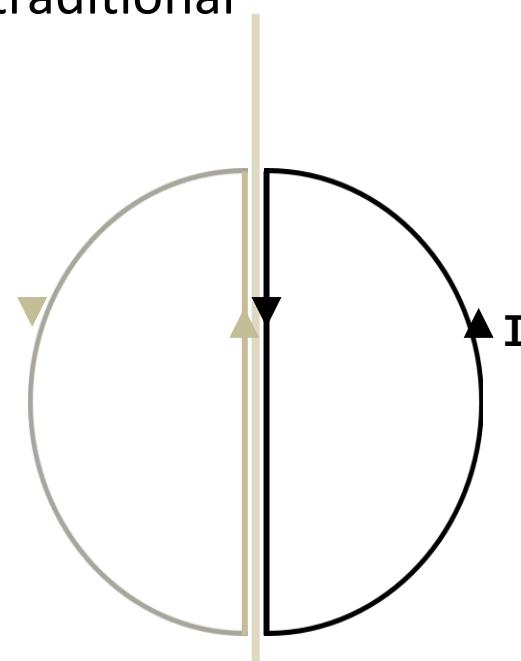


# Gradient Cancellation

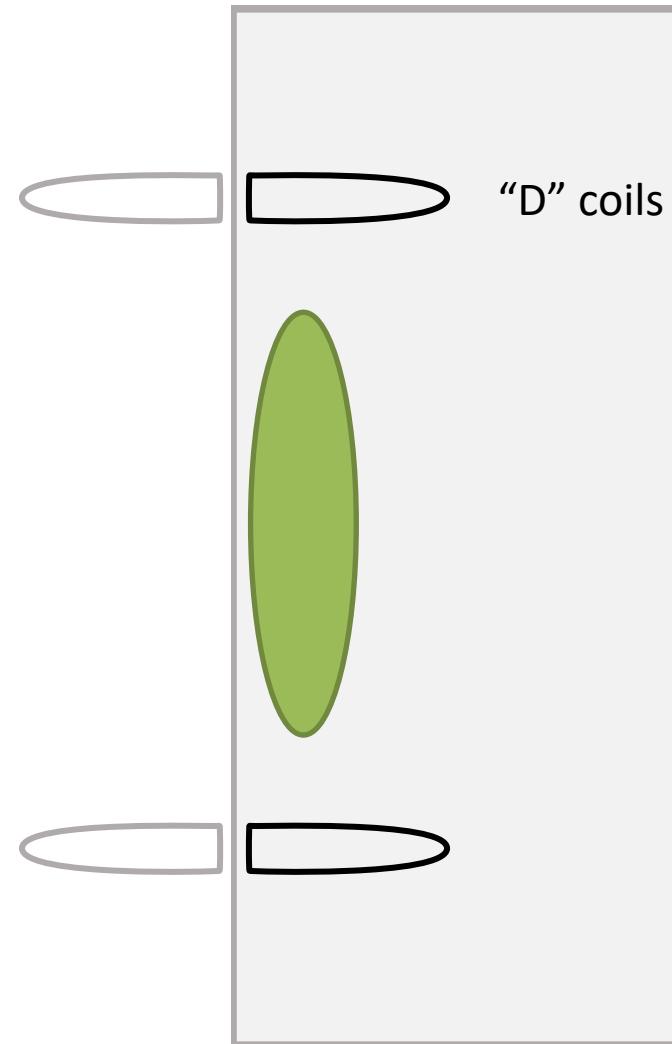


# Tuning Solution – “D” Coils

- 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



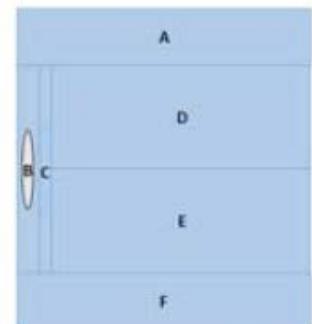
One “D” coil and image (bird’s eye view)



# Nb-coated quartz block design

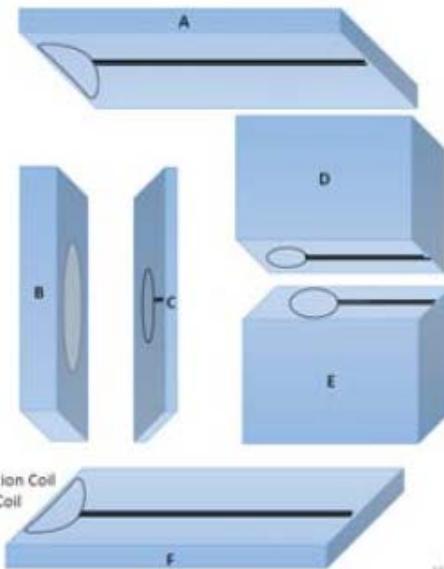
d)

## Block Production



Key:  
A – Upper Helmholtz Coil  
B – Spheroid  
C – SQUID  
D – Primary Correction Coil

E – Secondary Correction Coil  
F – Lower Helmholtz Coil



- Segmented design
- Nb film coating on exterior

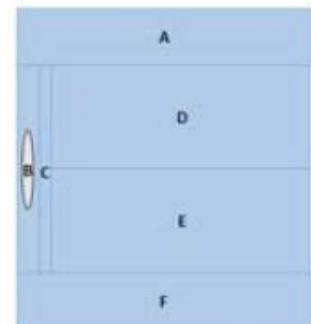
SQUID on Quartz (Y.H. Lee, KRISS)



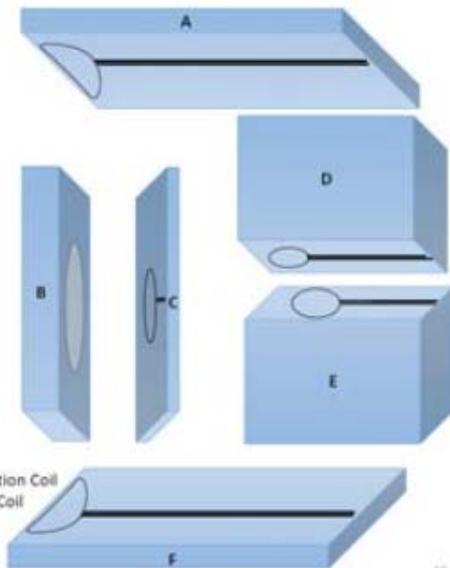
# Nb-coated quartz block design

d)

## Block Production

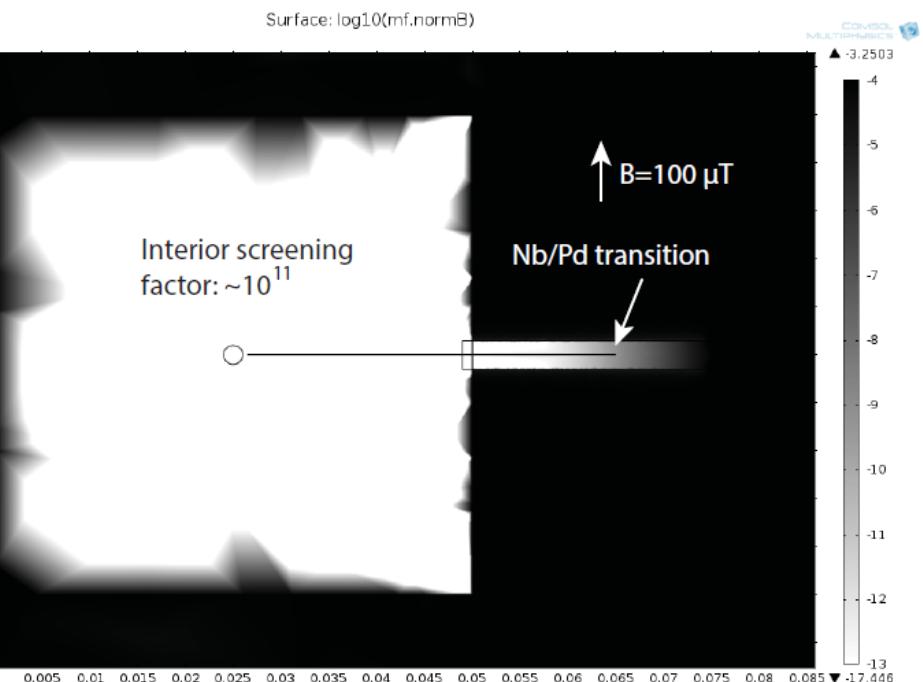


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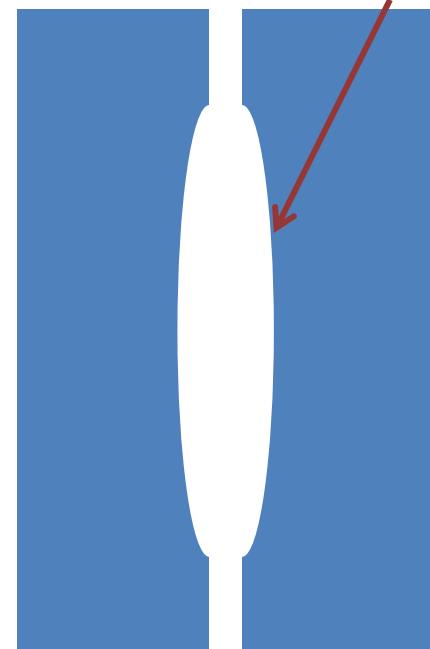


## Shielding requirements

- Shielding factor required for full sensitivity  $\sim 10^8$
- Openings required for wires
- Shielding factor tests soon!!

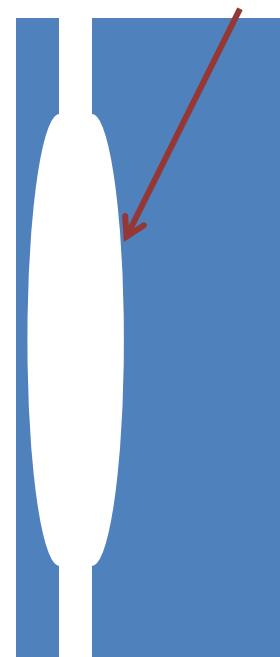
# Spheroidal cavity fabrication

Spheriodal pocket



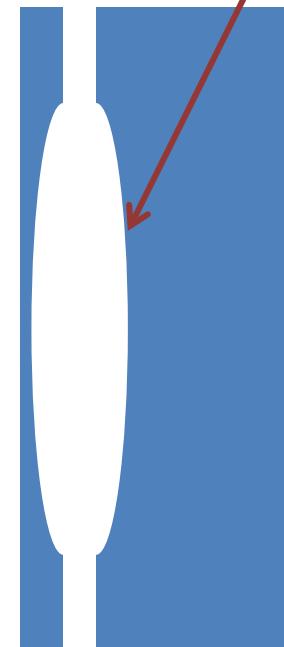
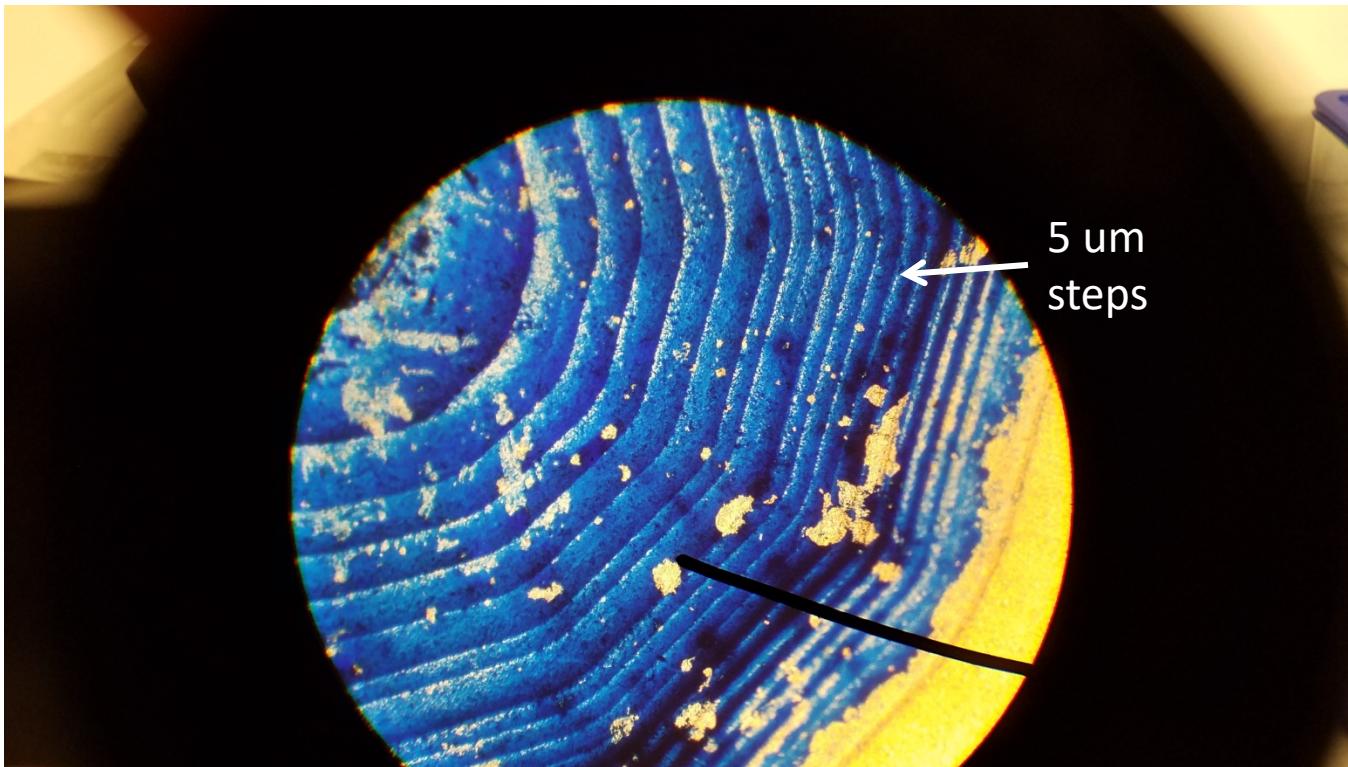
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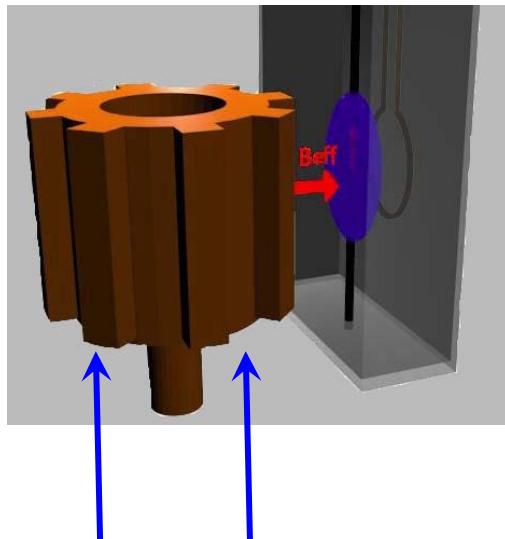
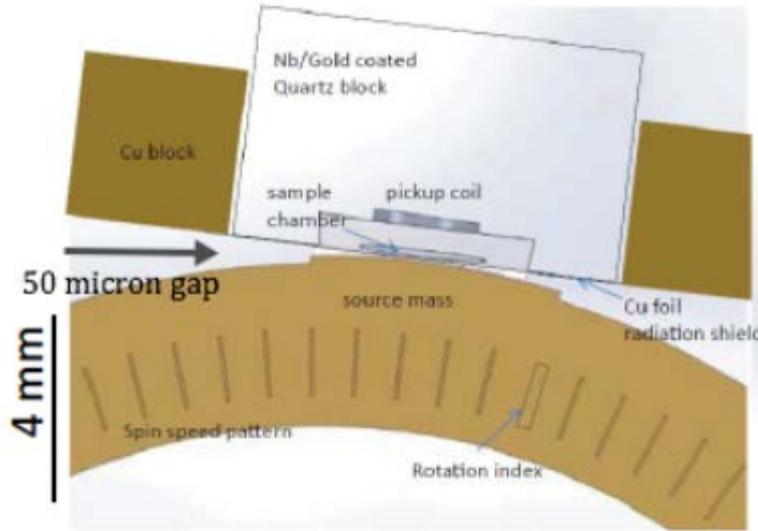
# Spheroidal cavity fabrication

- In progress..

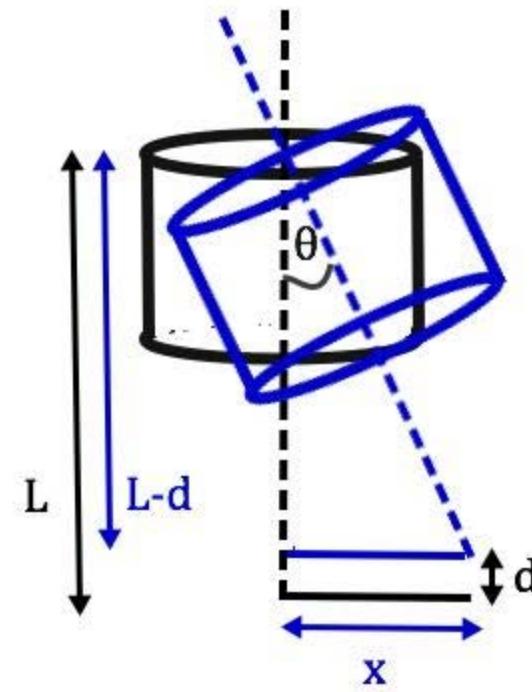


Finite-element  
simulations in process

# Rotary stage vibration and tilt

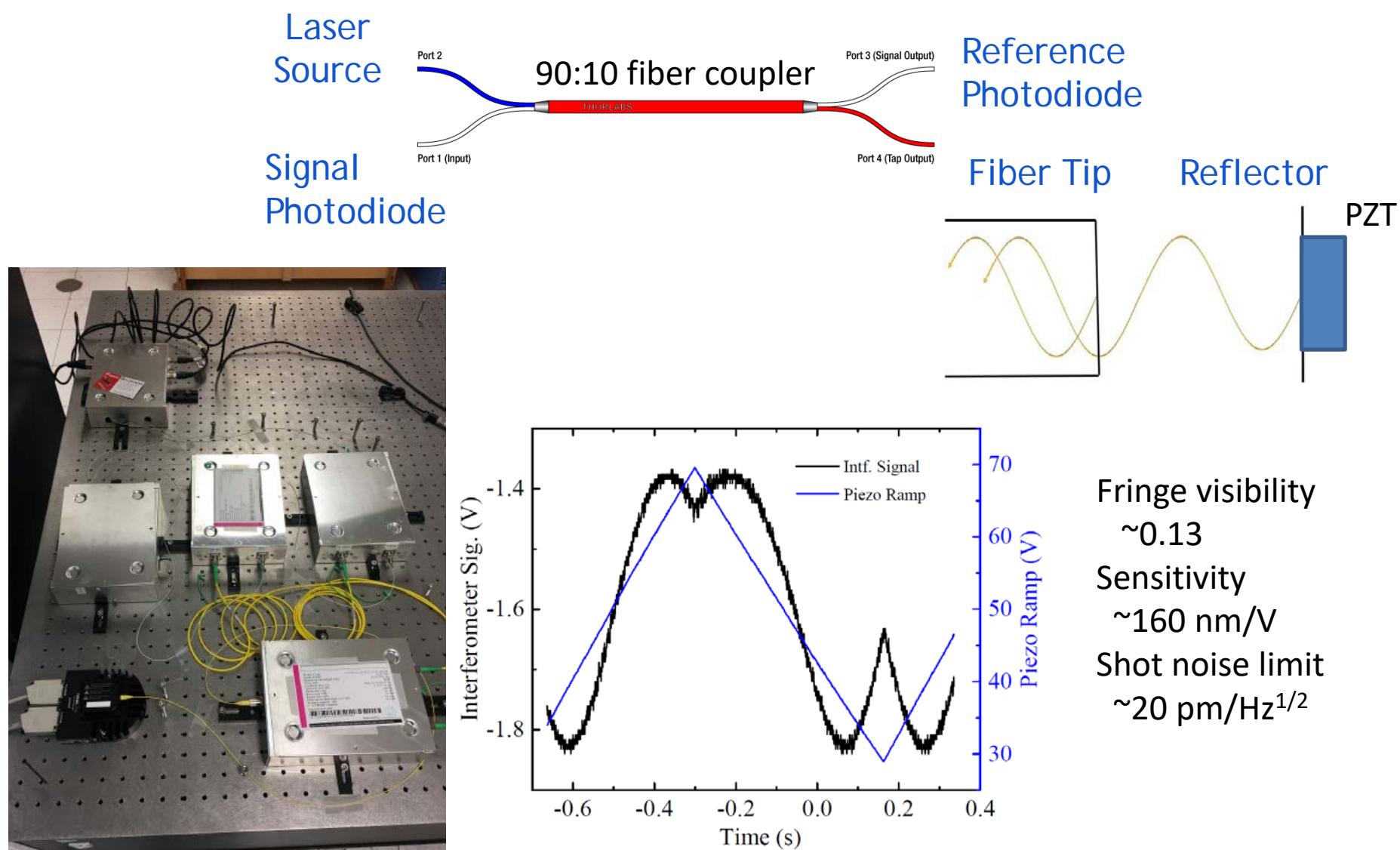


Interferometers



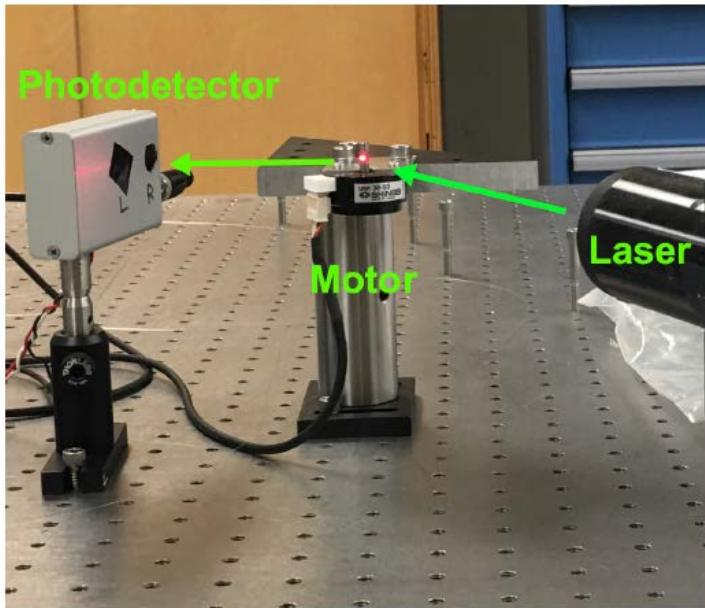
- Build an interferometer to measure the change in distance ( $d$ ).
- We can find theta ( $\Theta$ ) from:  
$$\Theta = \cos^{-1}((L-d)/L)$$
- We can solve for the wobble distance ( $X$ ) by:  
$$X = L \sin(\Theta)$$

# Fiber-coupled laser interferometers

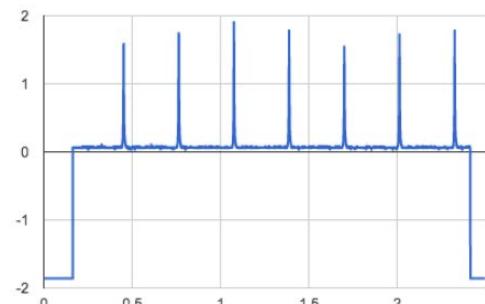
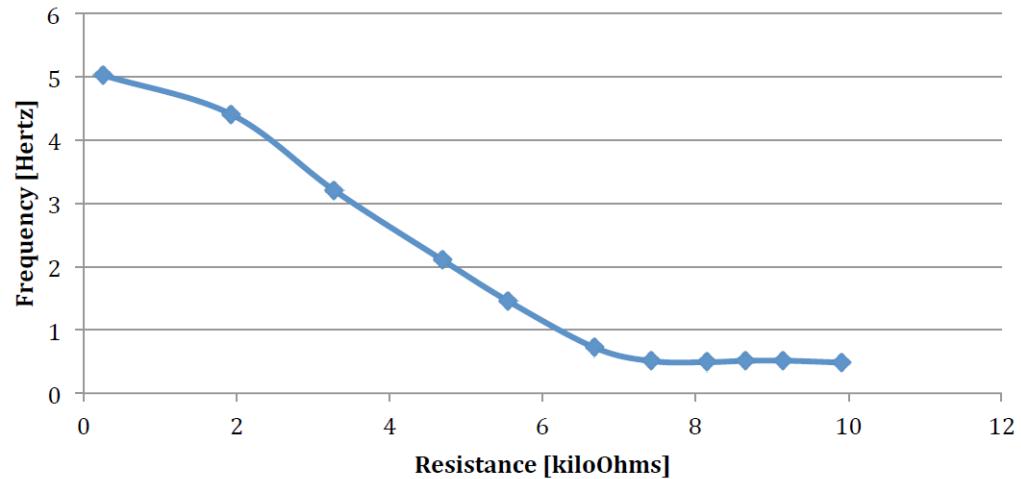


# Motor Characterization

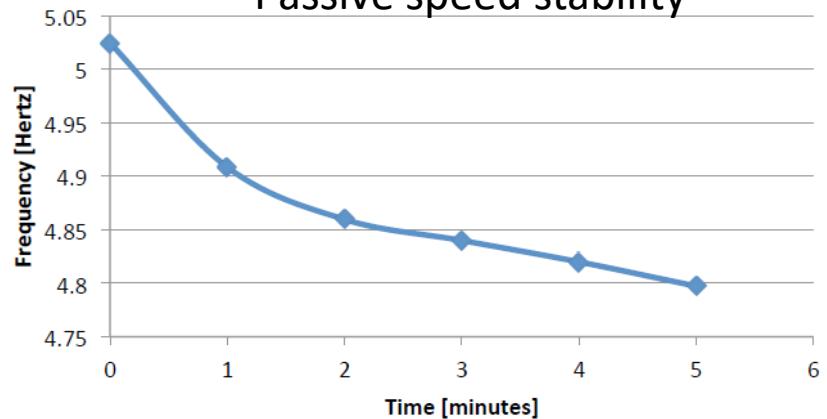
Fukoku-Shinsei 300 rpm ultrasonic motor



Frequency vs. Resistance

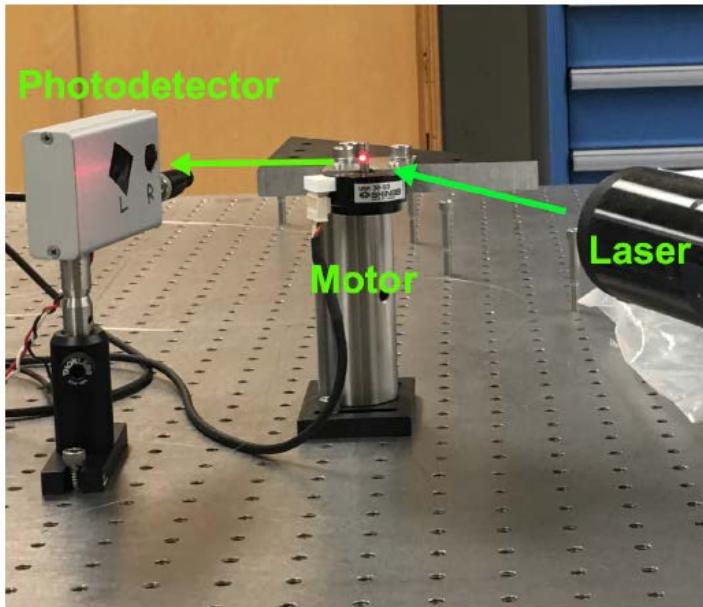


Passive speed stability

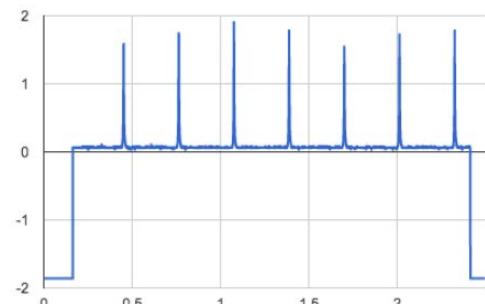
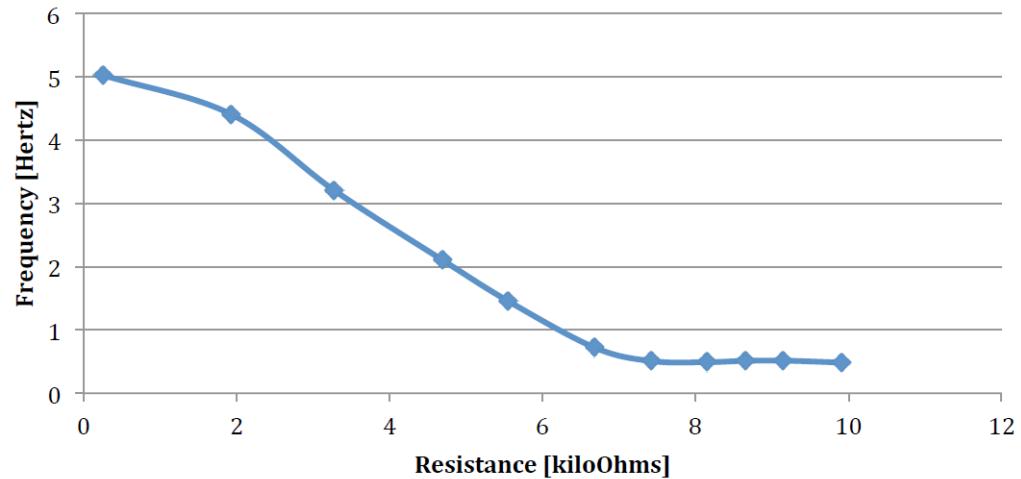


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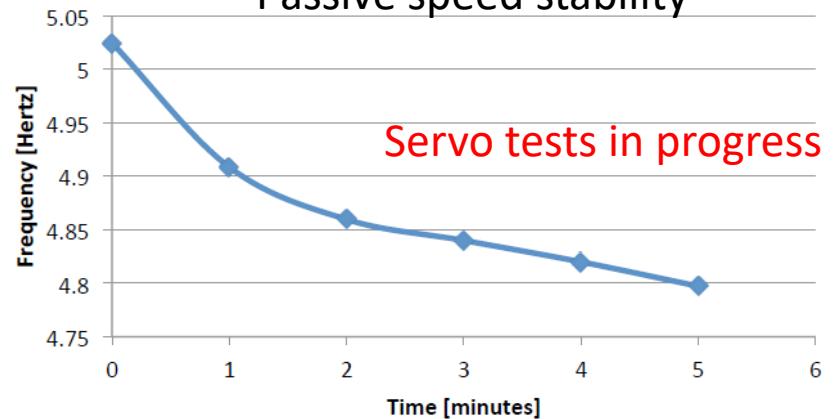
Fukoku-Shinsei 300 rpm ultrasonic motor



Frequency vs. Resistance



Passive speed stability



# Summary

- ARIADNE → New resonant NMR method
- Gap in experimental QCD axion searches  
$$0.1 \text{ meV} < m_a < 10 \text{ meV}$$
- Complementary to cavity-type (e.g. ADMX) experiments
- No need to scan mass, indep. of local DM density
- Next tests – shielding, vibration,  $^3\text{He}$  system



# Acknowledgements



PHY-1205994  
PHY-1506431  
PHY-1509176

University of Nevada, Reno

Jose Valencia(UG)      Mark Cunningham (G)      Andrew Geraci (PI)      Cris Montoya (G)      Jordan Dargert (G)



Apryl Witherspoon (UG)

Gambhir Ranjit (PD)

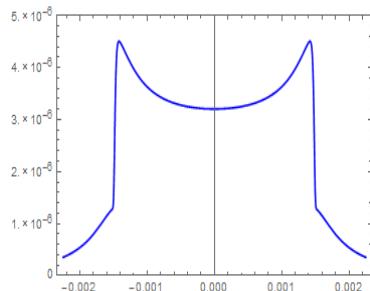
Chloe Lohmeyer(UG)

Kirsten Casey (UG)

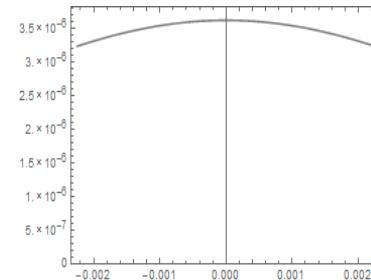
Postdoc and student positions available!

# Approaches and Results

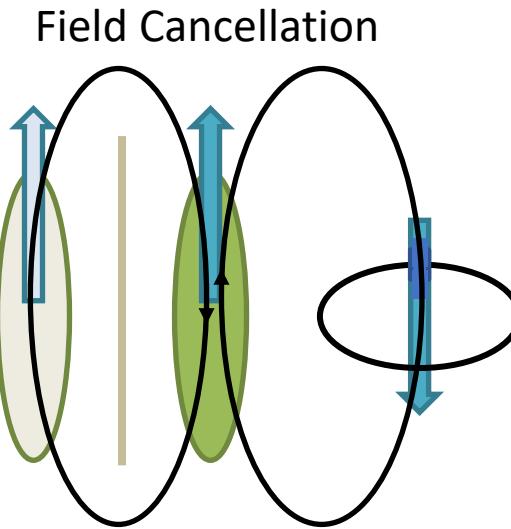
- Field cancellation
  - Cancel field from image spheroid
  - Tunable to arbitrary value
  - $B_{\text{total}}$  parallel to  $\vec{m}$
- Gradient cancellation
  - Flatten field by “filling in” central gap
  - Field not tunable (from  $|\vec{a} + \vec{b}|^2 = a^2 + b^2 + 2\vec{a} \cdot \vec{b}$  cross-correlation)
  - $B_{\text{total}}$  antiparallel to  $\vec{m}$  → restricts measurement times to  $T_1$
- Both in final design



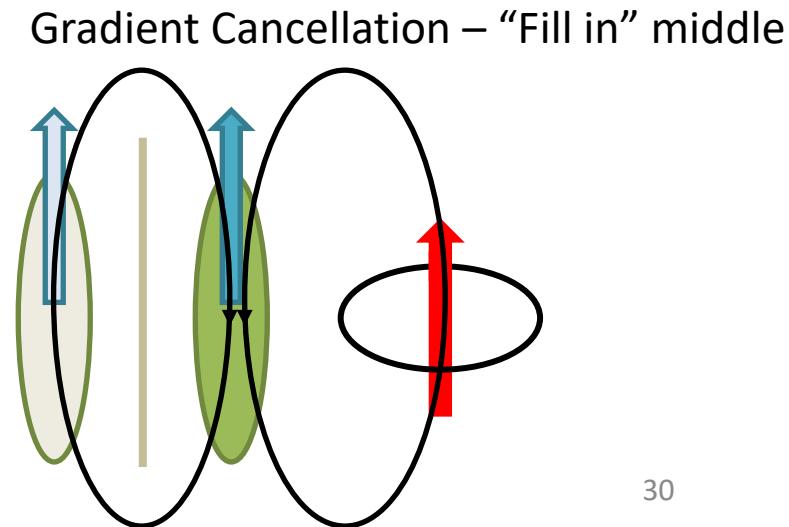
Perturbed  
spheroid field



Coil field



Field Cancellation



Gradient Cancellation – “Fill in” middle

# 1. Field Cancellation

