ARIADNE: a laboratory search for the QCD axion with hyperpolarized 3He spins

Chloe Lohmeyer
CPAD Workshop
Thursday March 18th, 2021

Axion Resonant InterAction DetectioN Experiment

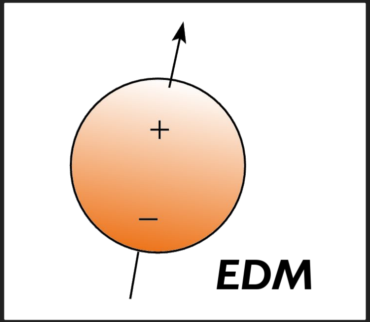
Grant No. PHY-1509176, 1510484, 1506508, 1806671, 1806395, 1806757

Collaborators

Northwestern: Andrew Geraci, 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, Allard Schnabel, Jens Voigt

Center for Fundamental Physics (CFP)

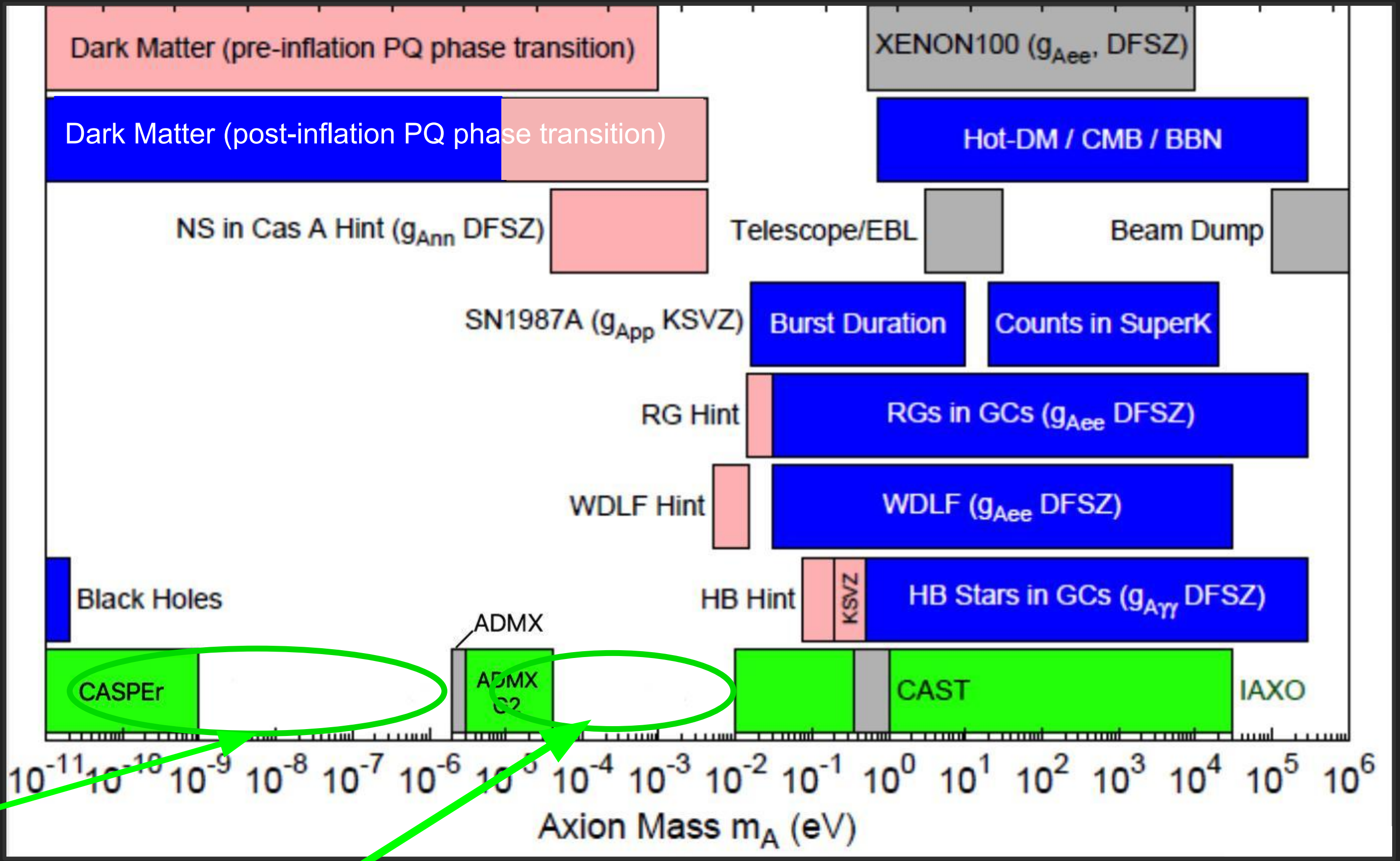
Axions



- Light pseudoscalar particles
- Peccei-Quinn (QCD) Axion to solve the strong CP Problem
- Dark matter candidate
- Current experiments depend on cosmological assumptions
- Mediate spin-dependent forces between matter objects at short range
- Can be sourced locally

R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. 38, 1440 (1977)

QCD Axion Parameter Space



- Astrophysical Bounds
- Hints
- Experimental Bounds
- Current Experiments

DM Radio
LC Circuit
ABRACADABRA

ARIADNE

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

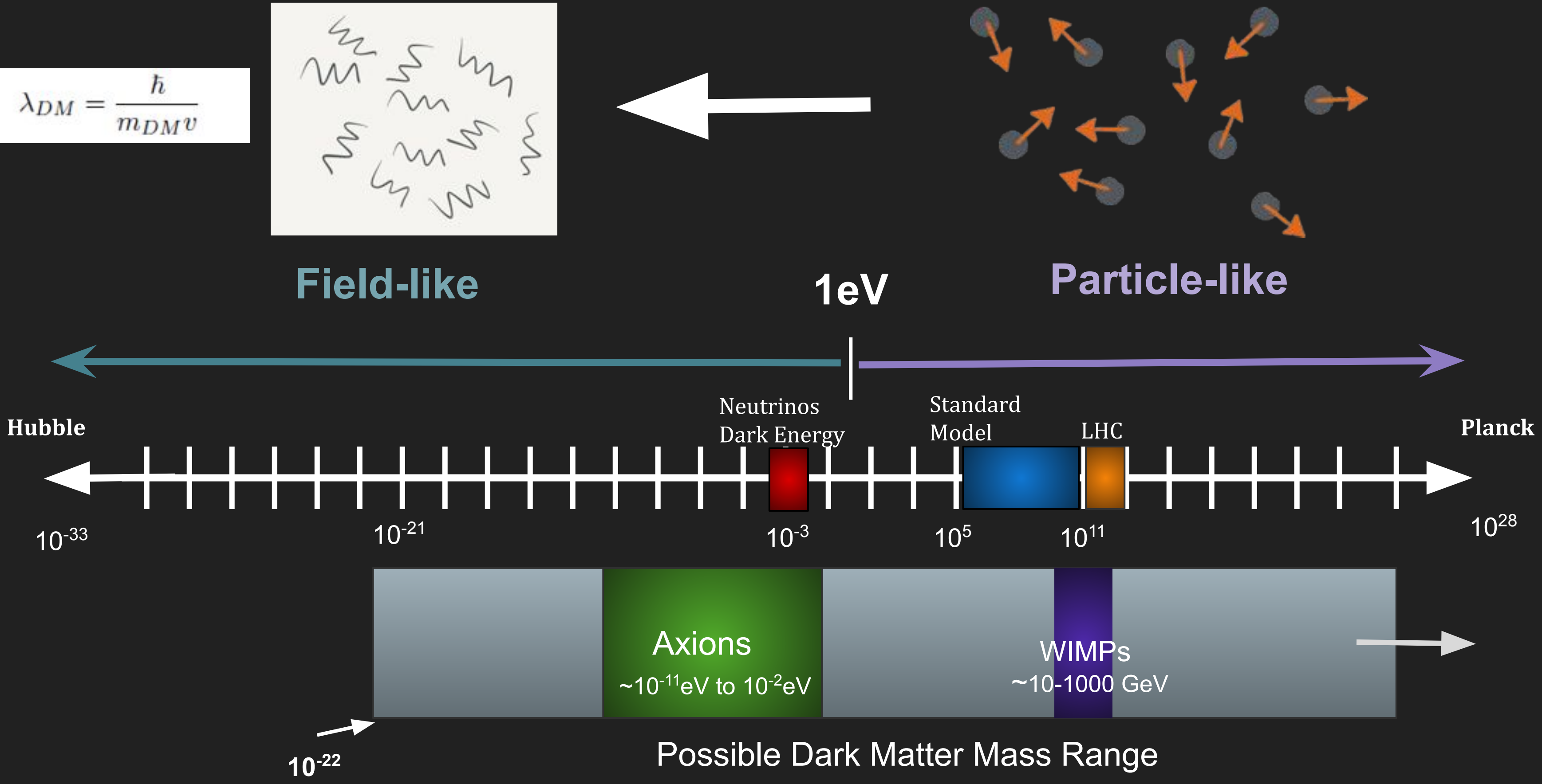
Axion and ALP Searches

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	

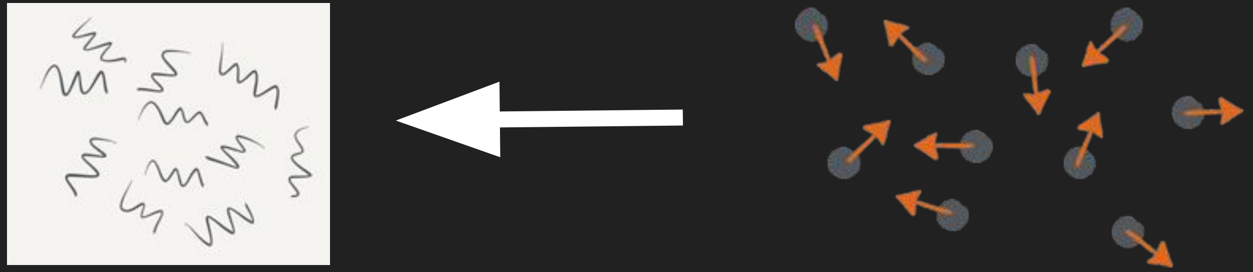
The energy scales of the Universe

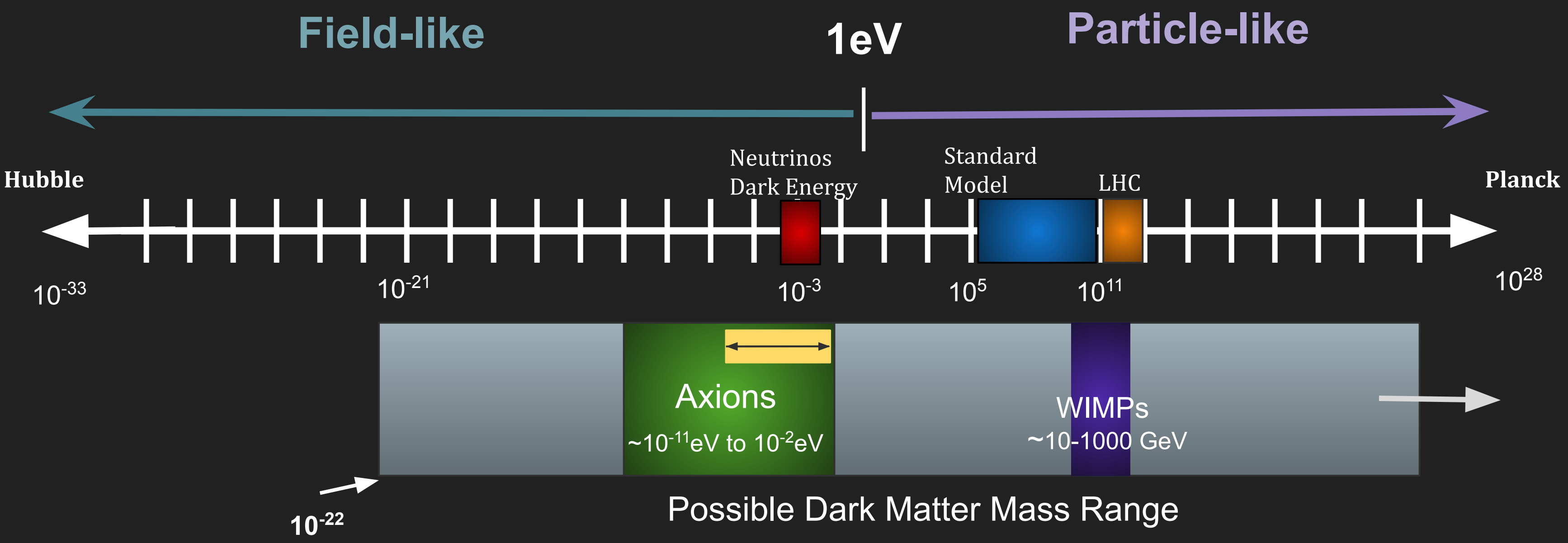
$$\lambda_{DM} = \frac{\hbar}{m_{DM} v}$$



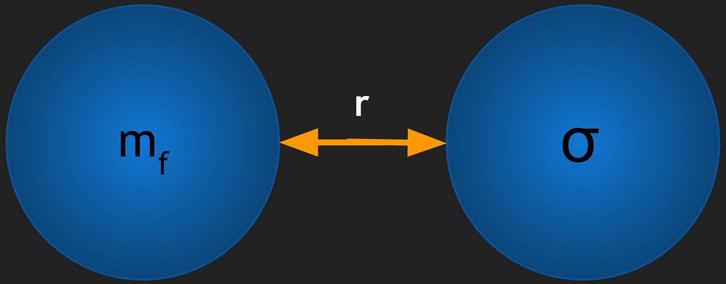
The energy scales of the Universe

$$\lambda_{DM} = \frac{\hbar}{m_{DM} v}$$





Spin-Dependent Forces



Monopole-Dipole Axion Exchange

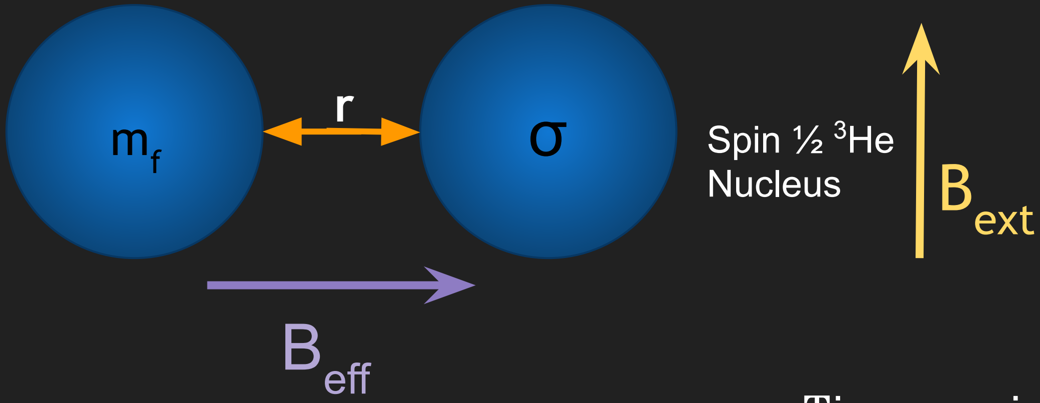
Fictitious magnetic field

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

- Different from an ordinary magnetic field
- Does not couple to angular momentum
- Does not obey Maxwell's Equations
- Unaffected by magnetic shielding

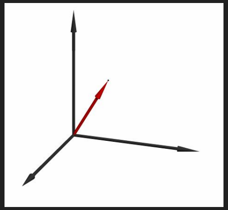
A. Arvanitaki and A. Geraci, Phys. Rev. Lett. 113, 161801 (2014)

NMR for detection



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

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



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

- Time varying B_{eff} drives spin precession
- This produces a transverse magnetization
- Magnetization can be detected using a SQUID

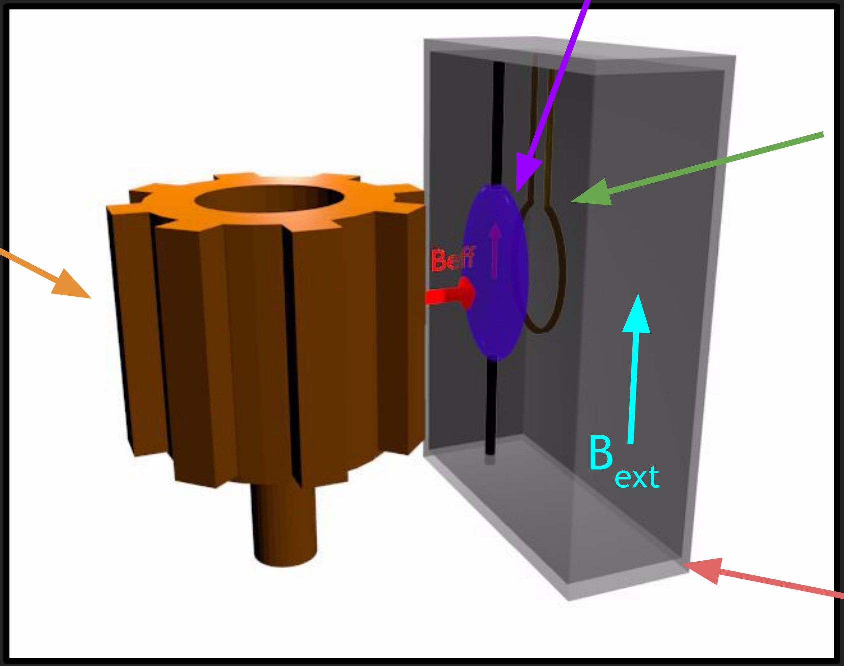
A. Arvanitaki and A. Geraci, Phys. Rev. Lett. 113, 161801 (2014)

Experimental Setup

Laser Polarized ^{3}He gas

Unpolarized tungsten source mass

SQUID pickup loop



Superconducting Shielding

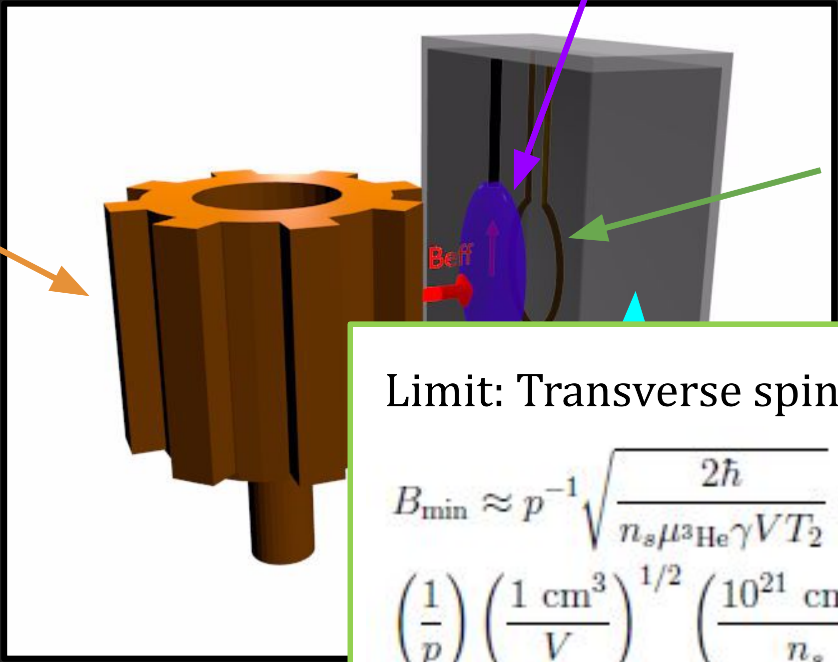
$$\omega = \frac{2\mu_N \cdot B_{ext}}{\hbar}$$

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

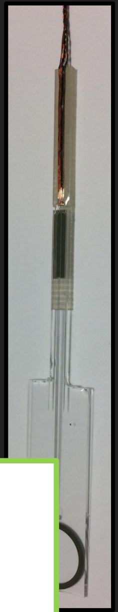
Experimental Setup

Unpolarized tungsten source mass

Laser Polarized ^{3}He gas



SQUID pickup loop



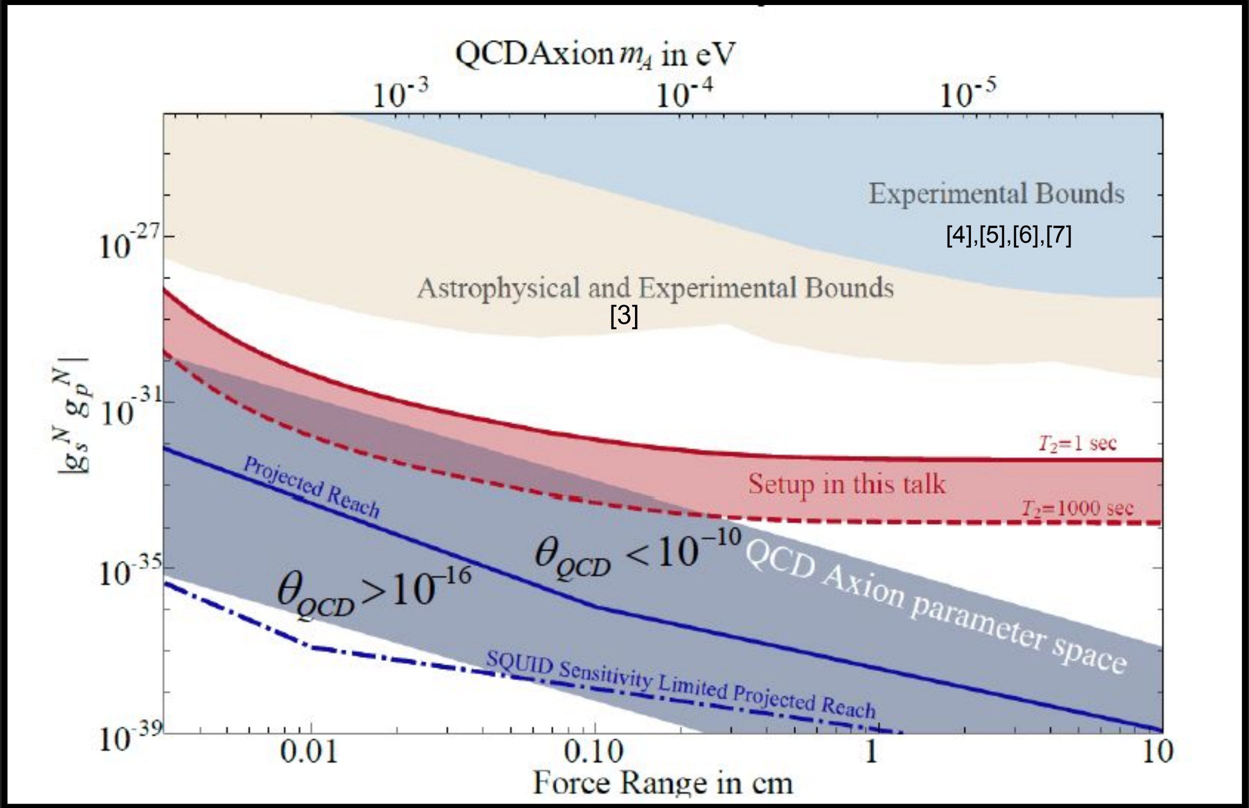
$$\omega = \frac{2\mu_N \cdot B_{ext}}{\hbar}$$

Limit: Transverse spin projection noise

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

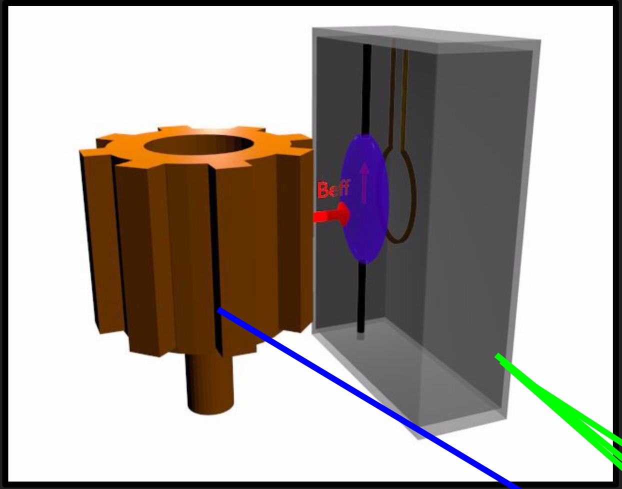
A. Arvanitaki and A. Geraci, Phys. Rev. Lett. 113, 161801 (2014)

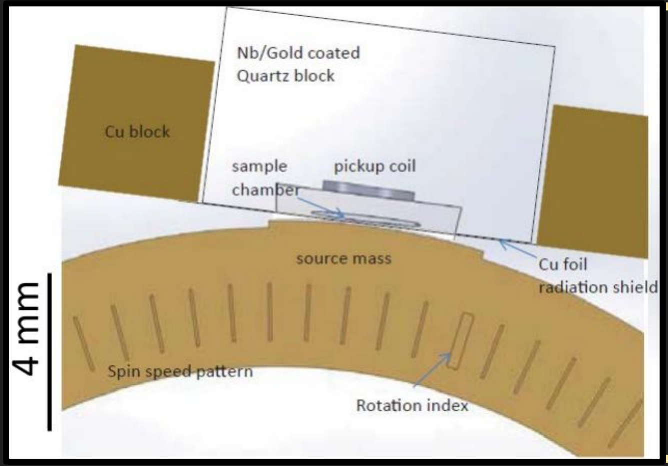
Constraints and Sensitivity



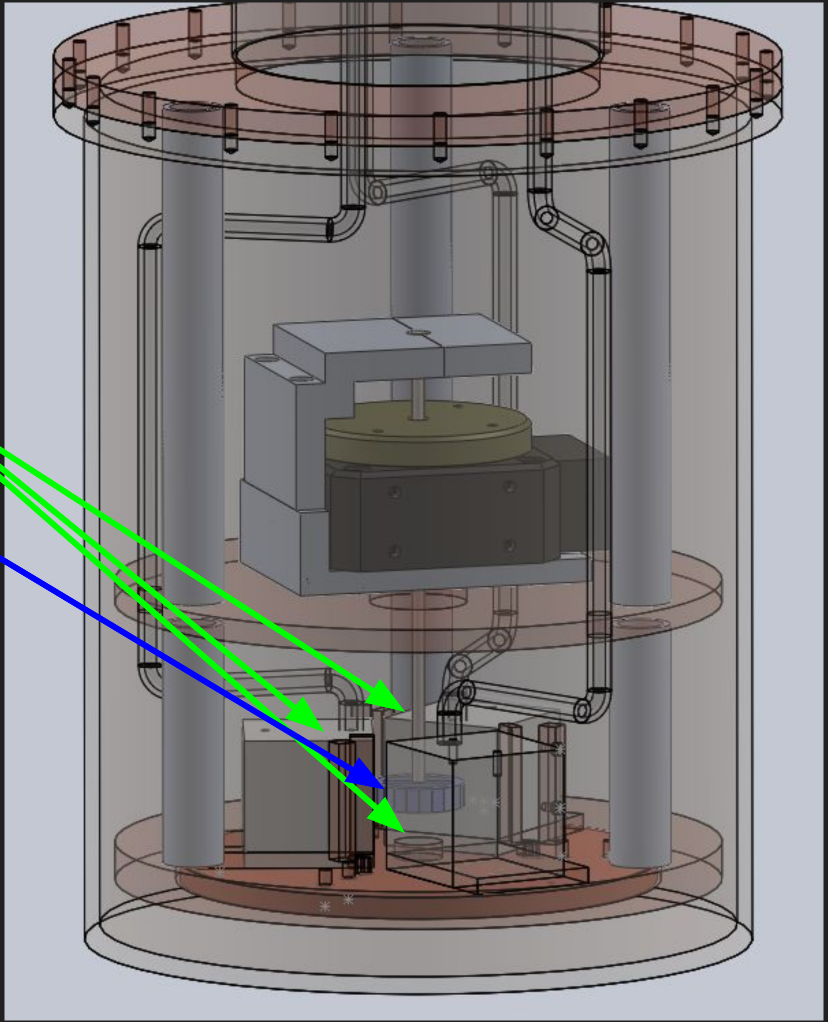
[3] G. Raffelt, Phys. Rev. D 86, 015001 (2012)] [4] G. Vasilakis, et. al, Phys. Rev. Lett. 103, 261801 (2009).
[5] K. Tullney,et. al. Phys. Rev. Lett. 111, 100801 (2013) **[6]** P.-H. Chu,et. al., Phys. Rev. D 87, 011105(R) (2013).
[7] M. Bulatowicz, et. al., Phys. Rev. Lett. 111, 102001 (2013).

Experimental Setup





- 11 segments
- 100 Hz nuclear spin precession frequency
- 2×10^{21} / cc ^{3}He density
- 10 mm x 3 mm x 150 µm volume
- Separation 200 µm
- Tungsten source mass (high nucleon density)



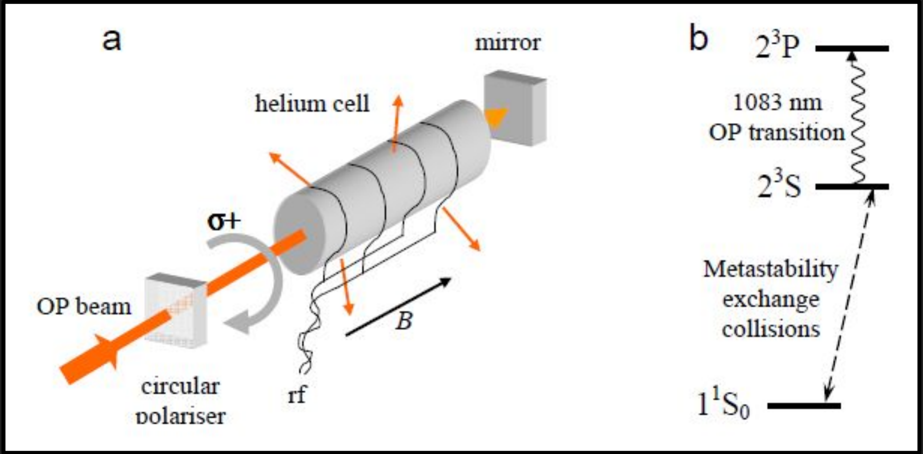
Hyperpolarized ^{3}He

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

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

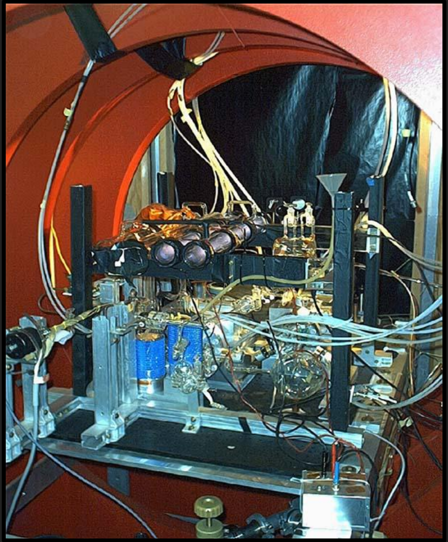
Optical pumping techniques

- 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)

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 $\omega_{\rm rot}$
External vibrations	5×10^{-20} T/$\sqrt{\rm Hz}$	For 1 μm sample vibration (100 Hz)
Patch Effect	$10^{-21}(\frac{V_{\rm patch}}{0.1{\rm V}})^2$ T	Can reduce with V applied to Cu foil
Flux noise in squid loop	2×10^{-20} T/$\sqrt{\rm Hz}$	Assuming $1\mu\Phi_0/\sqrt{\rm Hz}$
Trapped flux noise in shield	$7 \times 10^{-20} \frac{\rm T}{\sqrt{\rm Hz}}$	Assuming 10 cm^{-2} flux density
Johnson noise	$10^{-20}(\frac{10^8}{f})$T/$\sqrt{\rm Hz}$	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	$10^{-25} - 10^{-17}(\frac{\eta}{1{\rm ppm}})(\frac{10^8}{f})$ 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 $3 \times 10^{-19}(\frac{1000{\rm s}}{T_2})^{1/2}$ T/$\sqrt{\rm Hz}$

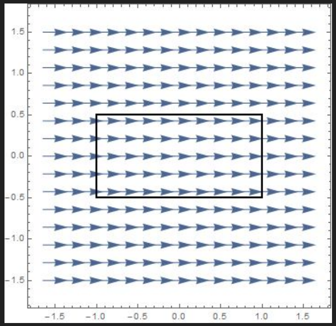
A. Geraci et al., arXiv.1710.05413. Submitted to Proceedings of the 2nd Axion Cavity and Detector Workshop (2017).

Superconducting Magnetic Shielding

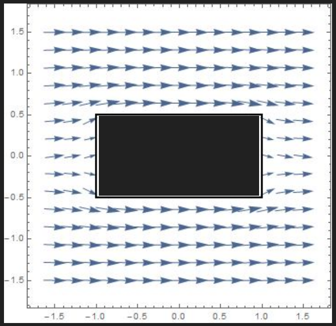
→ Essential to avoid Johnson noise

Meissner Effect

- No magnetic flux across superconducting boundary



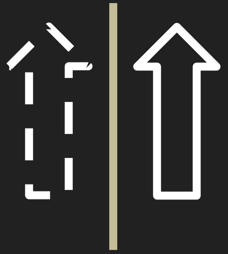
$T > T_c$



$T < T_c$

Method of Images

- Make "image currents" mirrored across the superconducting boundary



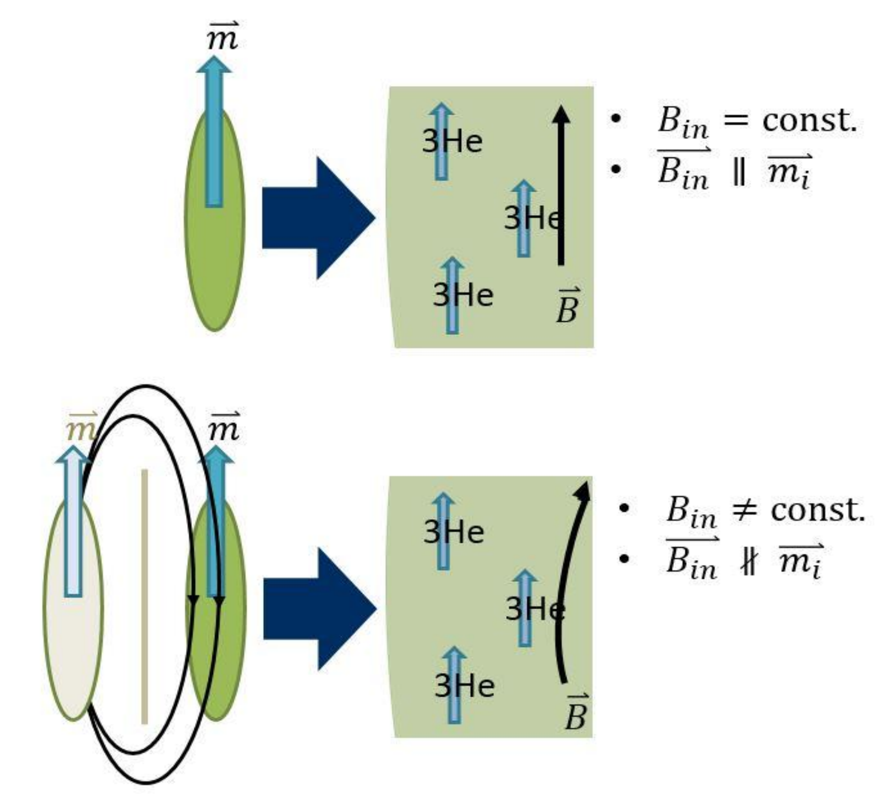
Dipole with image

The Problem of Unwanted Images

- ARIADNE uses magnetized spheroid
  - Constant interior field

- Magnetic shielding introduces “image spheroid”
  Interior field varies

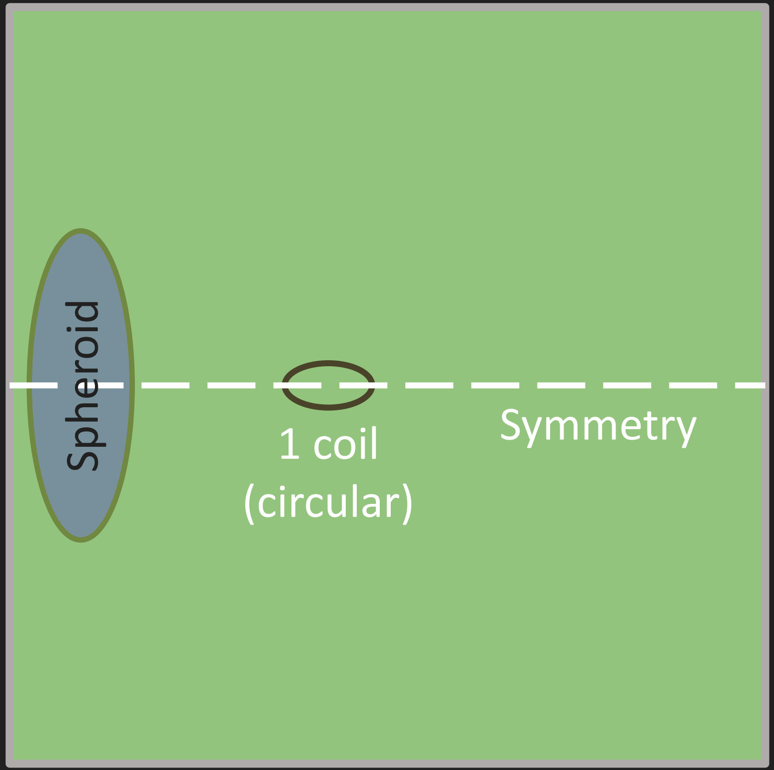
$\longrightarrow$ variations in nuclear Larmor frequency



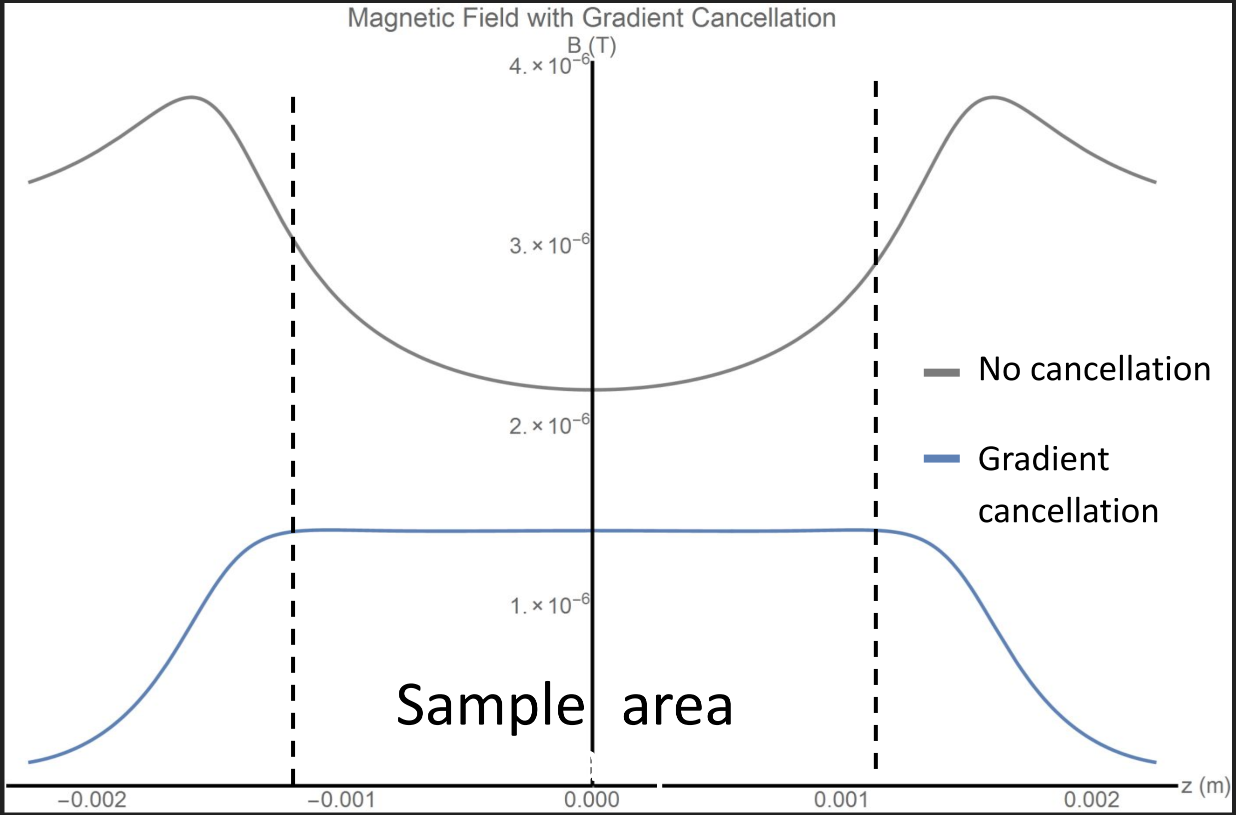
But want to drive entire sample on resonance

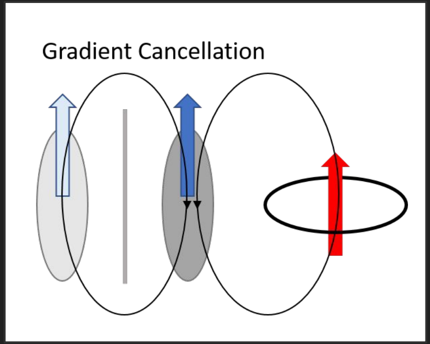
Flattening Solution

- 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

$s_{Frac} = 0.17\%$

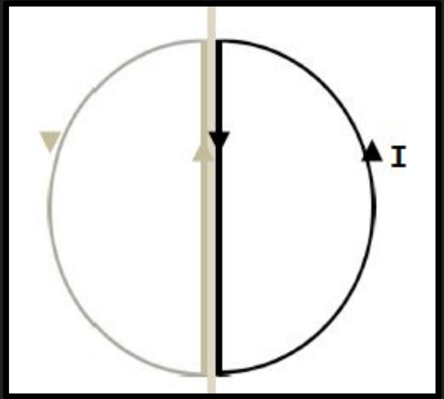
enabling T_2 of ~100 s

Tuning Solution – "D" Coils

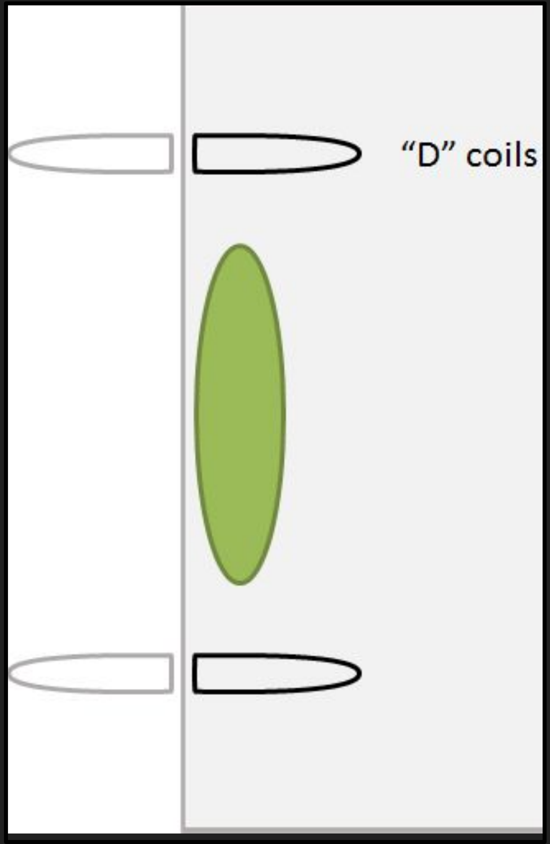
- Tune field with Helmholtz coils
  - Helmholtz field only flat near the center
  - Geometry restrictions prevent the spheroid from being centered in traditional Helmholtz coils

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

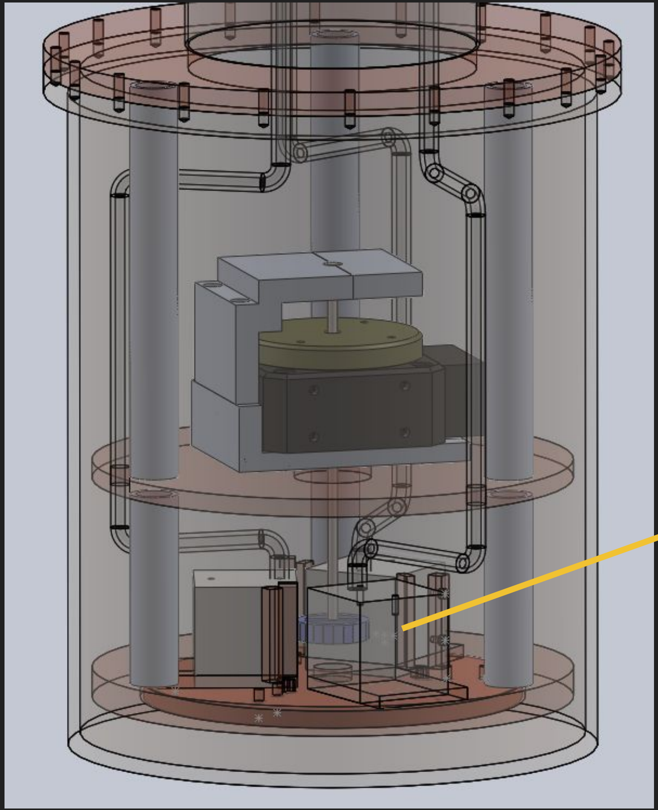
- Inner straight-line currents cancel
- Outer currents do not

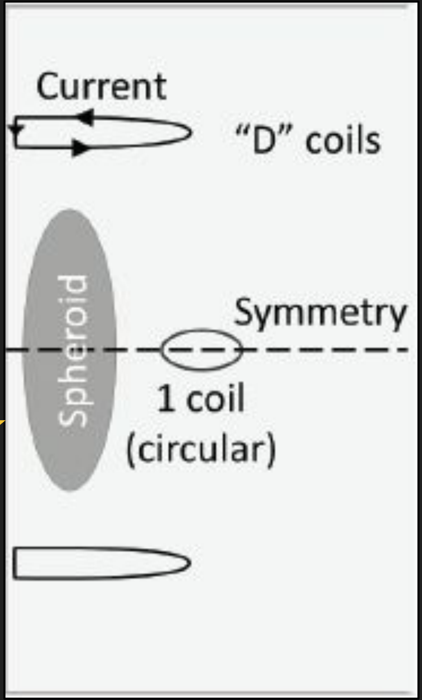


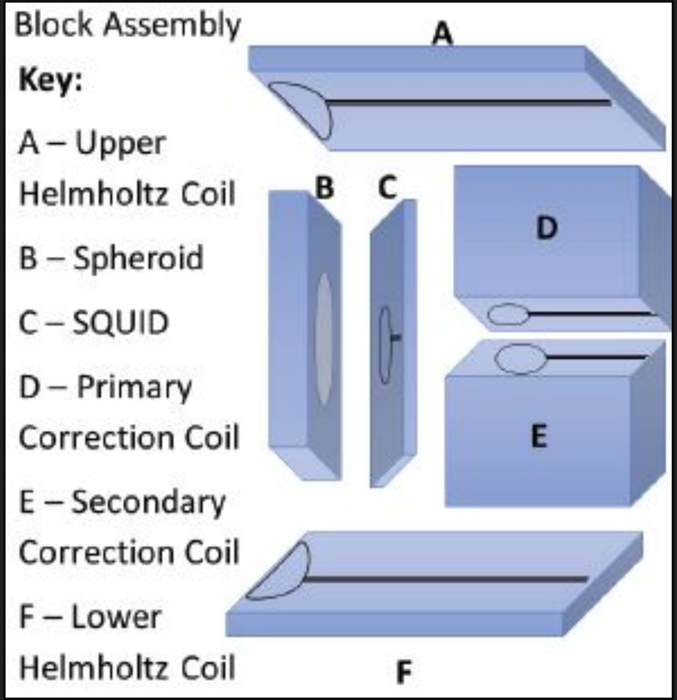
One "D" coil and image (bird's eye view)



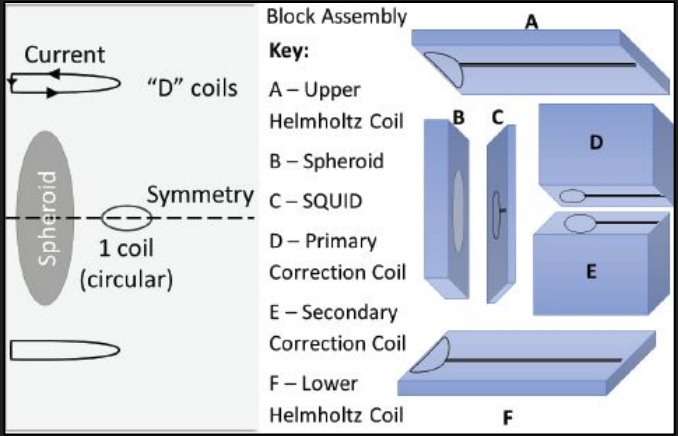
Sample Block Assembly

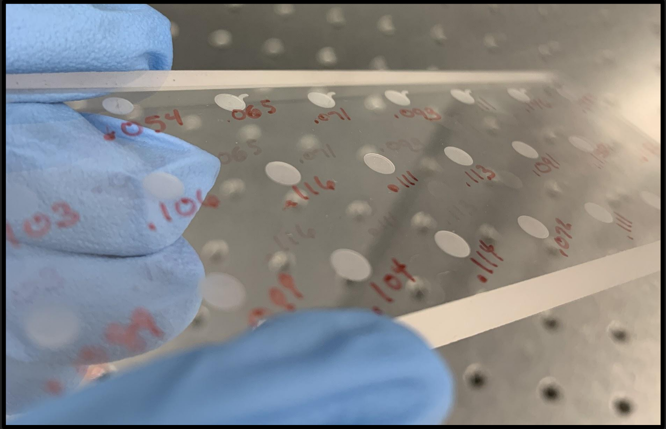


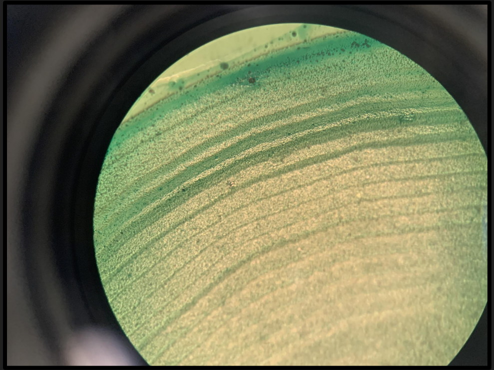




Sample Field Uniformity and Shape Manufacturing

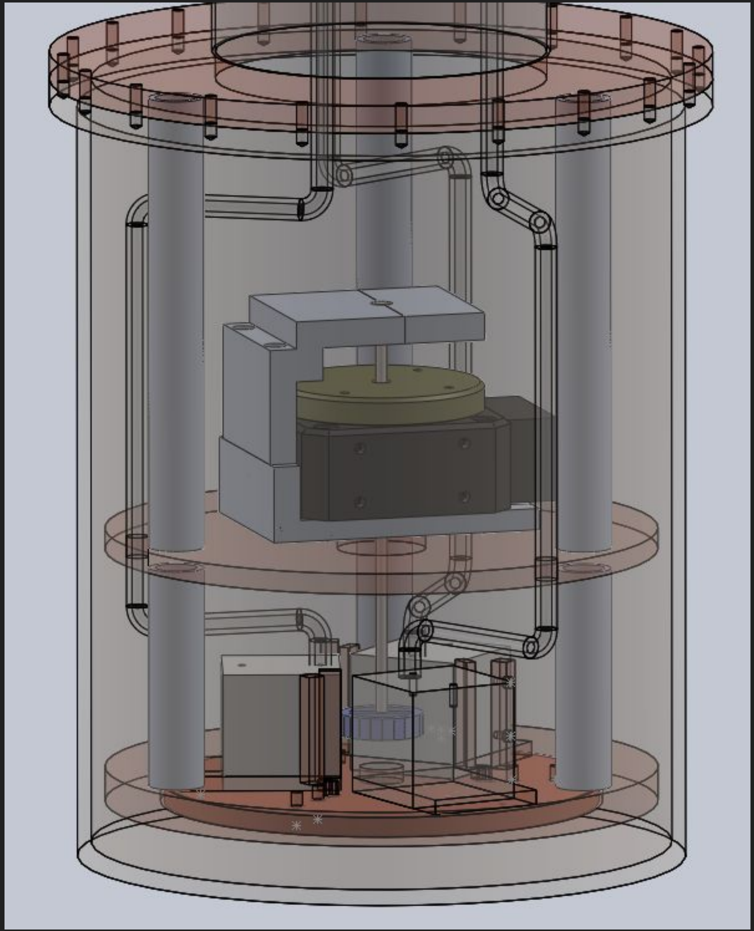


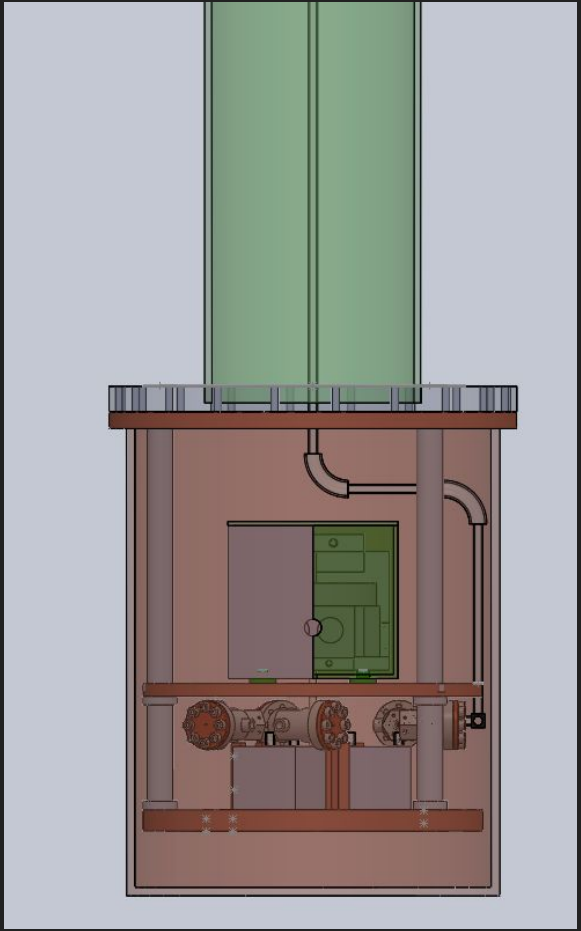




- Need uniform field to drive on resonance
- Machining perfect ellipsoid is non-trivial
- Performing Tests and simulations of "elliptical" and "spherical" cross-sections

He-3 Delivery System





Helium-3 Transport

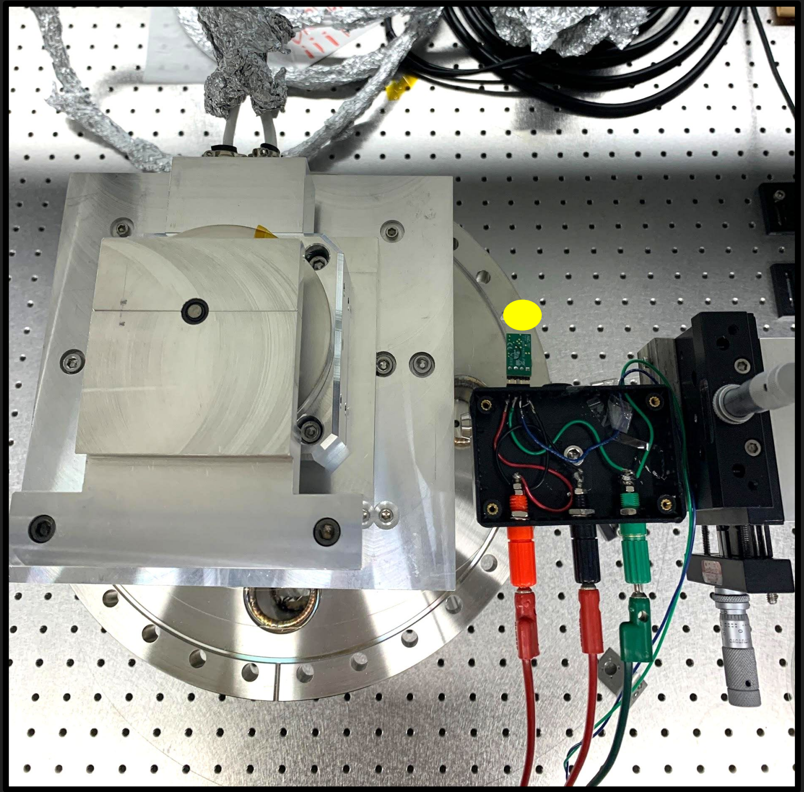
- Transverse magnetic gradients can couple to momentum eigenstates in diffusing 3He -> depolarization
- Gradient induced relaxation is the leading contributor to T1 less than 20 min.

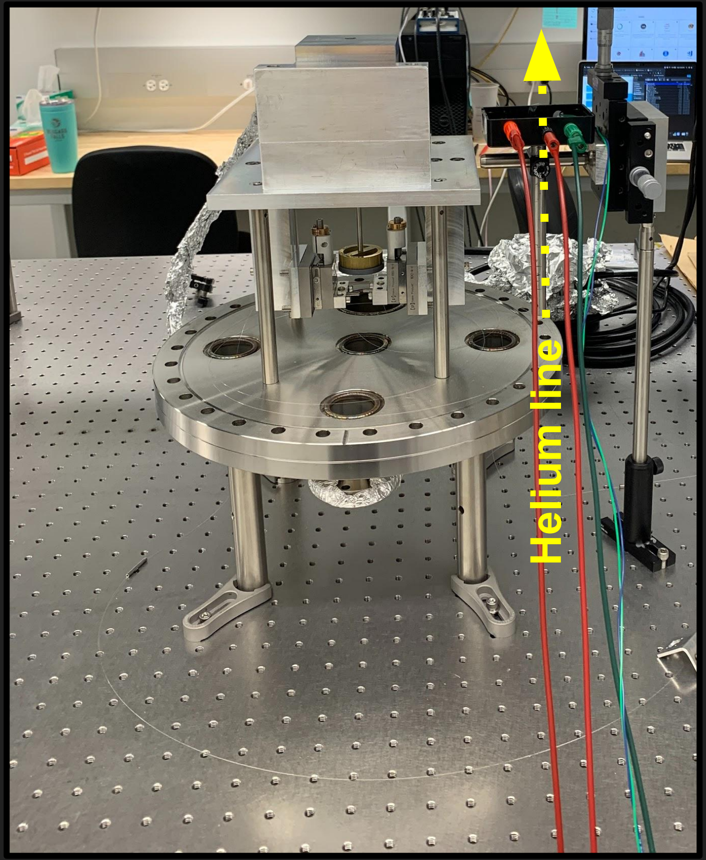
$$\frac{1}{T_1} = \frac{6700}{p}\left(\frac{|\nabla B_x|^2}{B_0^2} + \frac{|\nabla B_y|^2}{B_0^2}\right) \quad \mathrm{h}^{-1}$$

- T1 relaxation time on the order of 30 minutes gives a maximum allowable gradient of 3.6*10^-7 cm^-2

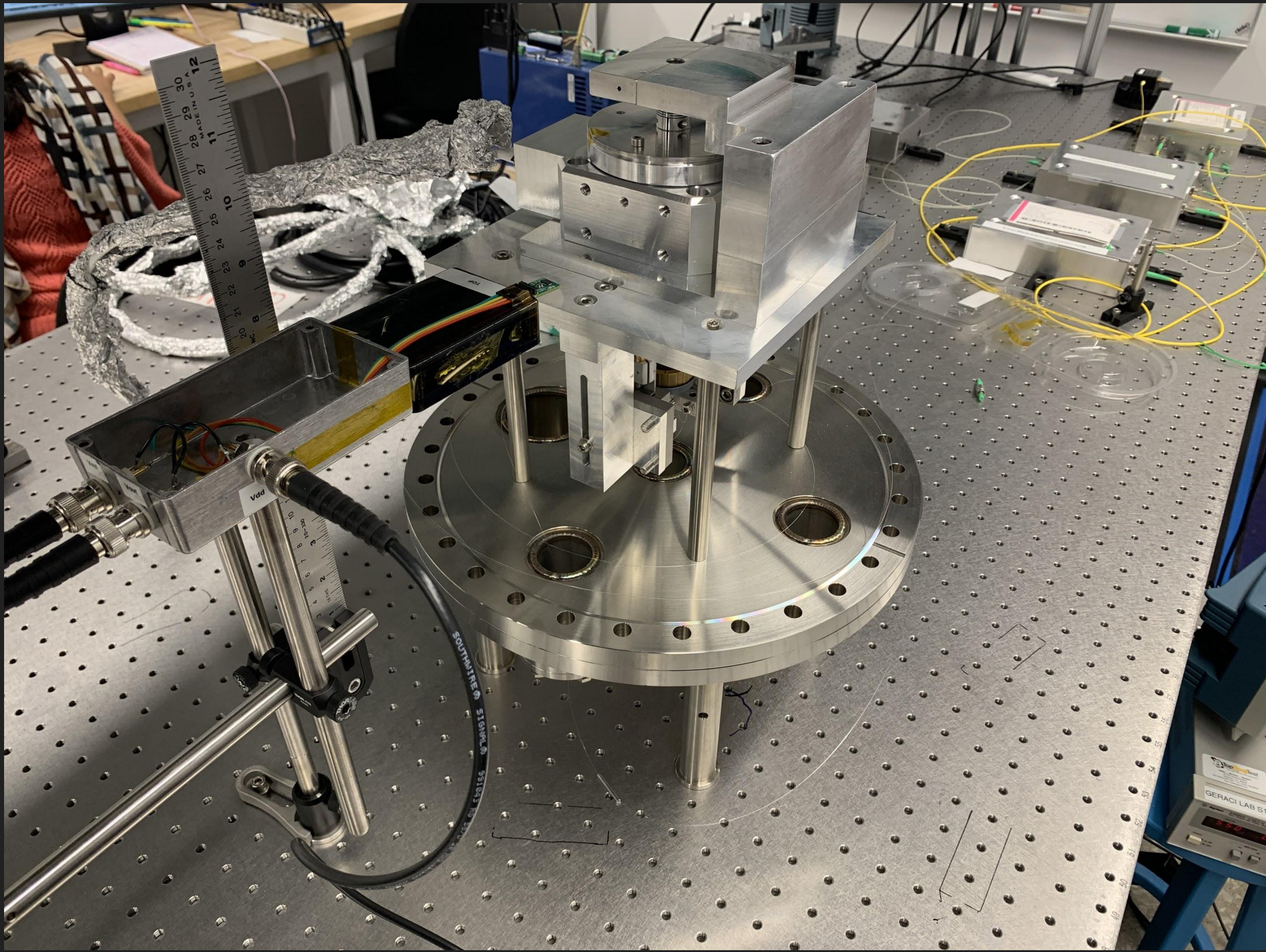
Magnetometry on Motor

Fluxgate magnetometer

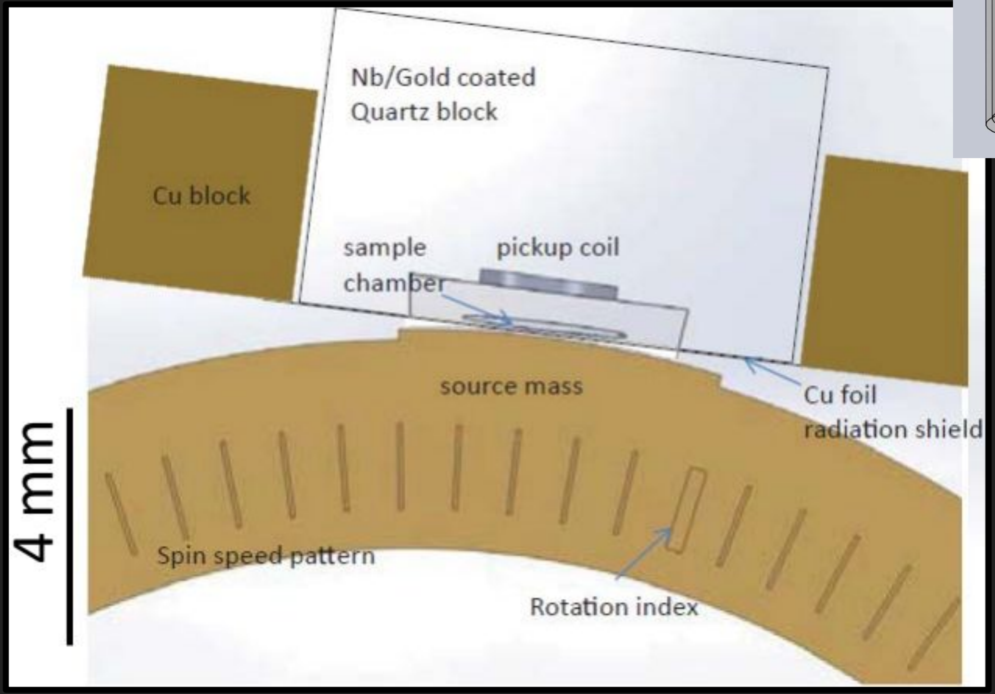


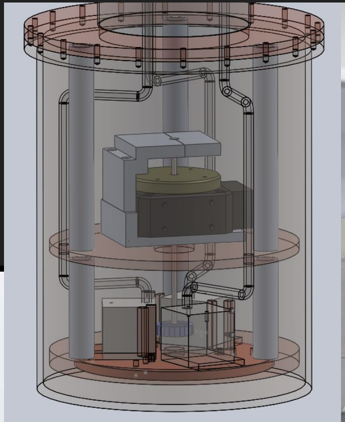


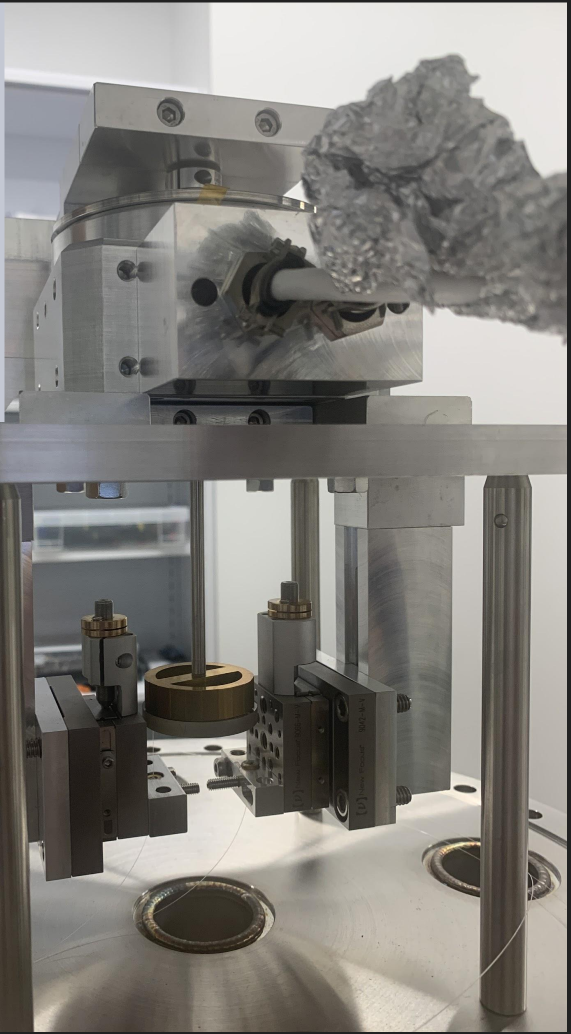
Magnetometry on Motor



Rotational Stability System

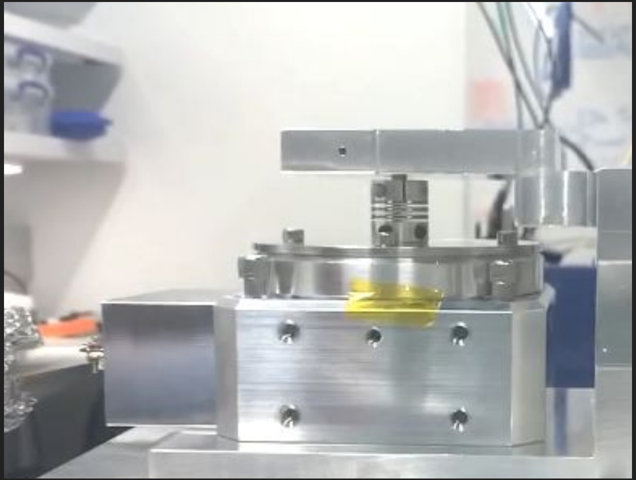




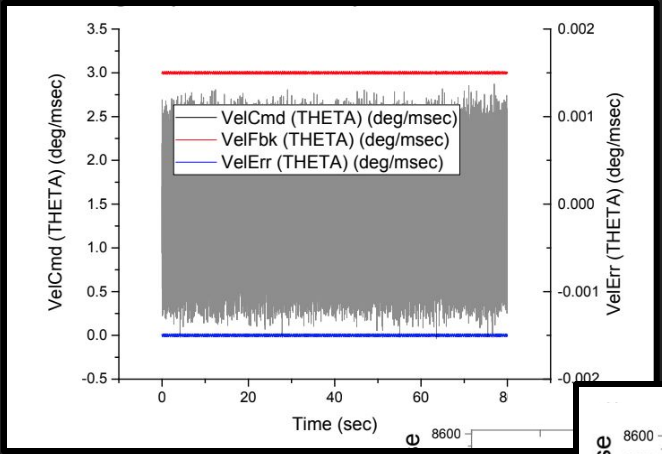


Speed Stability -Direct Drive Stage

- Optical encoder
- Current feedback control

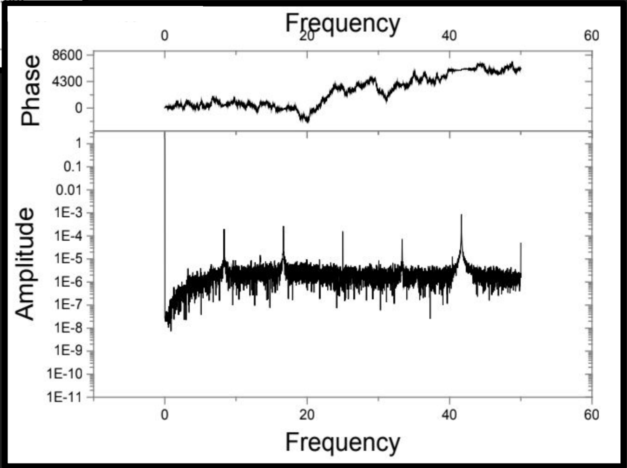


Stage speed stability error – unloaded, in air



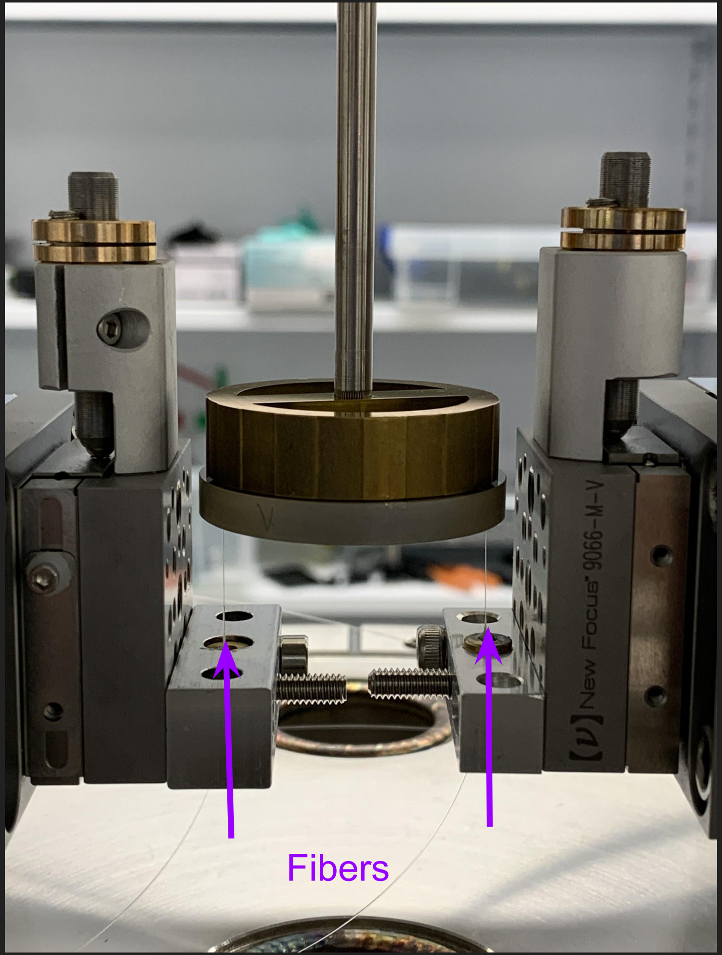
Rotation speed control
8.3 Hz ~ 1 part in 10000
RMS ~ 1 part in 3000

Allows utilization of T_2 > 100s



Rotational Stability Characterization

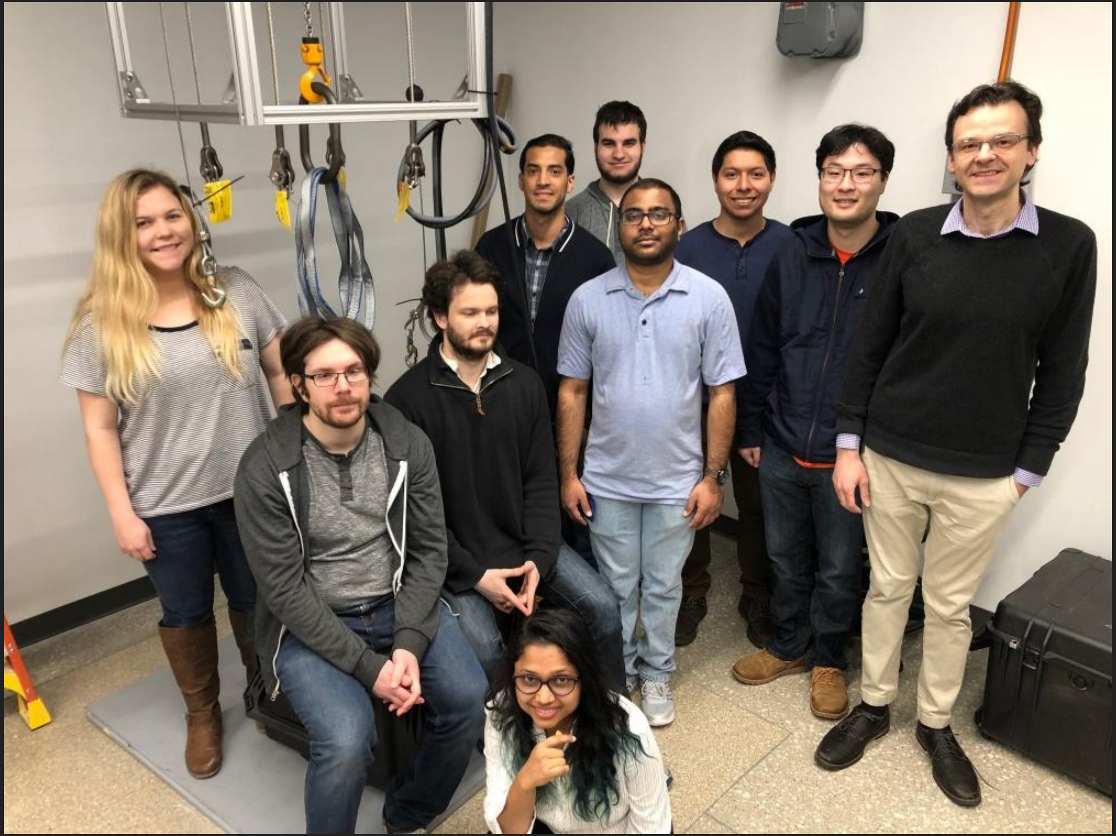
- Fiber Optic Interferometers



Summary

- ARIADNE: Fifth-force axion search using NMR method
  - Gap in experimental QCD axion searches
    - $1\ \mathrm{ueV} < m_a < 10\ \mathrm{meV}$
- Experiment requires highly polarized helium-3 spins as the sensor
- Experiment requires a superconducting shielding and a stable rotational system

Acknowledgements



This research is supported by the National Science Foundation (Grant No. PHY-1509176, 1510484, 1506508, 1806671, 1806395, 1806757

Group Members (left to right): Chloe Lohmeyer (G), Evan Weisman (PD), George Winstone (PD), Nancy Aggarwal (PD), Cris Montoya (PD), Daniel Grass (UG), Chethn Galla (G), Eduardo Allejandro (G), William Eom (G), Andy Geraci (PI)

Questions