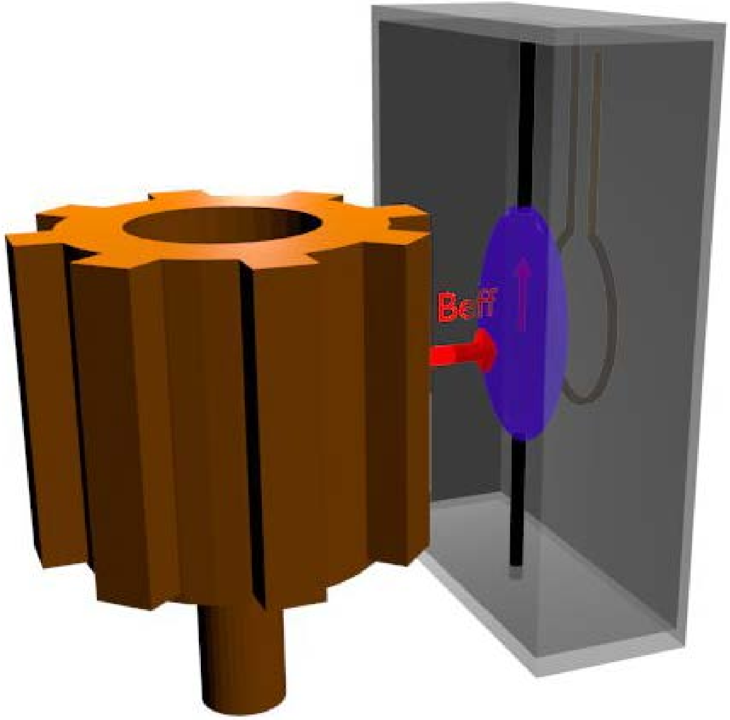
The Axion Resonant InterAction Detection Experiment (ARIADNE)



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Justin Shortino (IU)
Inbum Lee (IU)
Evan Weisman (IU)
Yannis Semertzidis (CAPP)
Yun Shin (CAPP)
Yong-Ho Lee (KRISS)

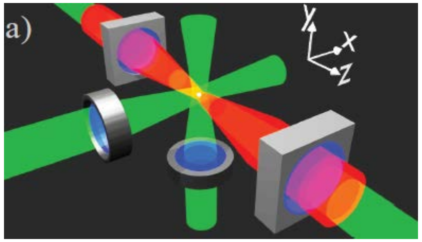
A. Geraci, University of Nevada, Reno

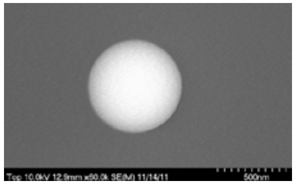
Tabletop experiments with skyscraper reach
Aug 9, 2017

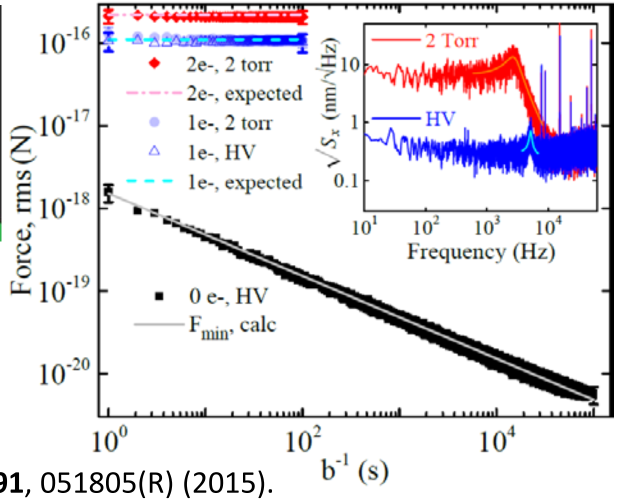
Our lab: Fundamental physics with resonant sensors

Techniques

Mechanical Resonance:
Optically levitated nanospheres



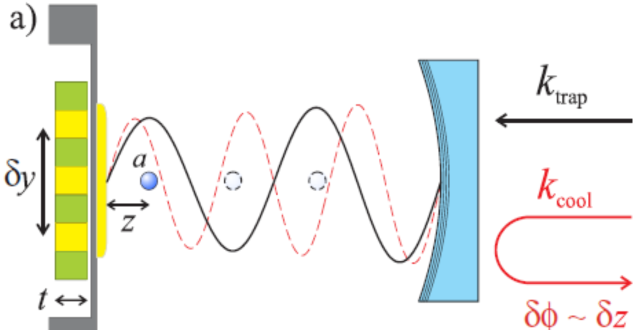




G. Ranjit et.al., *Phys. Rev. A* **91**, 051805(R) (2015).
G. Ranjit, M. Cunningham, K. Casey, and AG, *Phys. Rev. A*, **93**, 053801 (2016).

New Physics

Gravity at micron scales

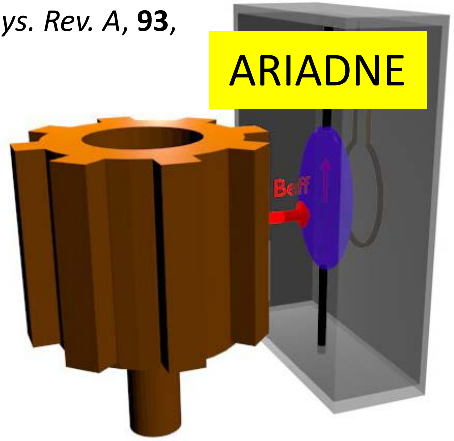


AG., S. Papp, and J. Kitching, *Phys. Rev. Lett.* **105**, 101101 (2010).

Gravitational Waves

A. Arvanitaki and AG., *Phys. Rev. Lett.* **110**, 071105 (2013).

Spin Resonance:
NMR –Laser polarized gases or liquids



Spin-dependent forces

- QCD Axion

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

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, 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).

Axion couplings

$$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

←

Coupling to electromagnetic field

ADMX, DM Radio, LC Circuit (DM)

CAST, IAXO (solar)

ALPS, ALPS-II (light thru walls)

$$\frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

Coupling to gluon field

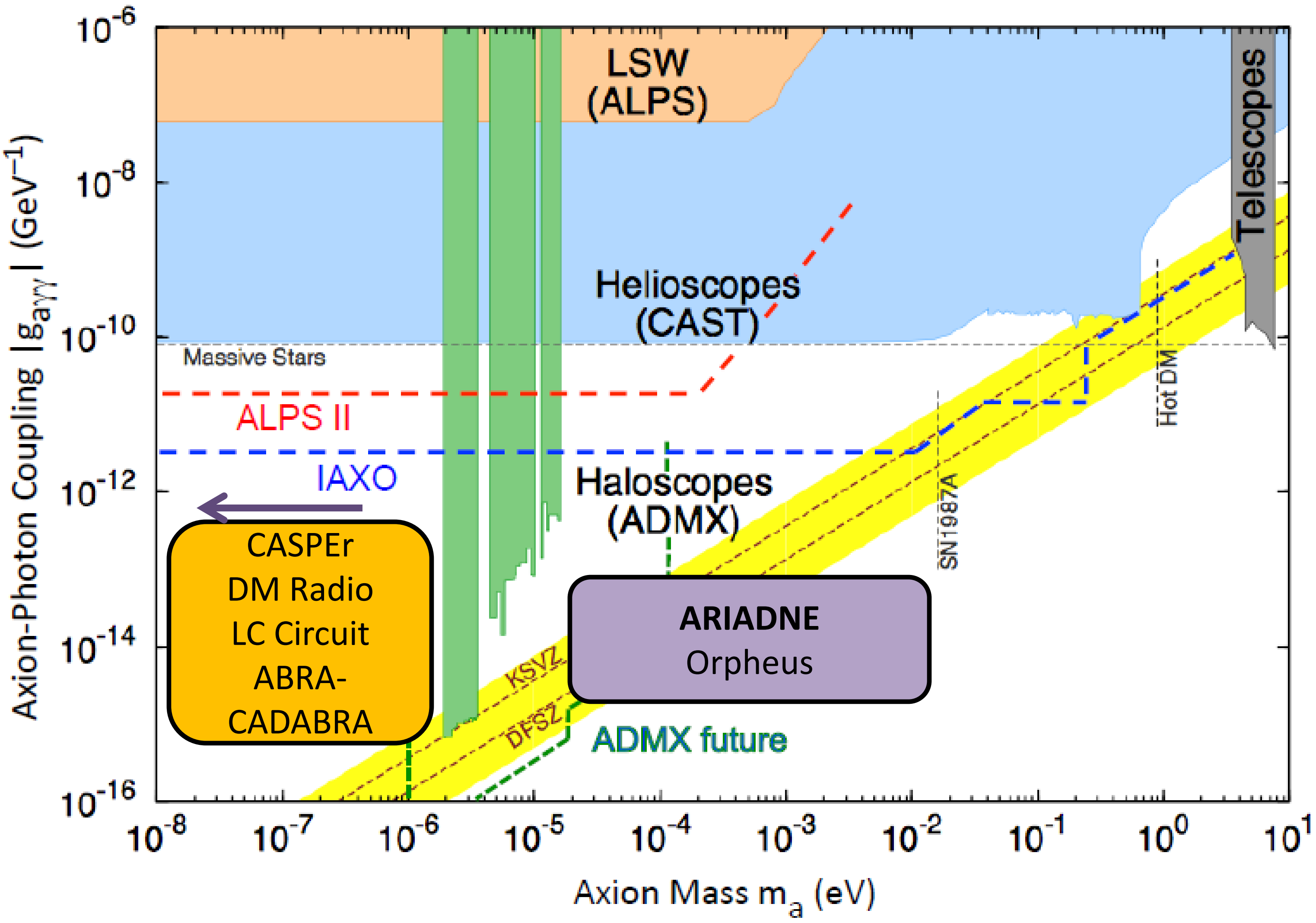
e.g. CASPEr-electric (DM)

$$\frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$

Coupling to fermions

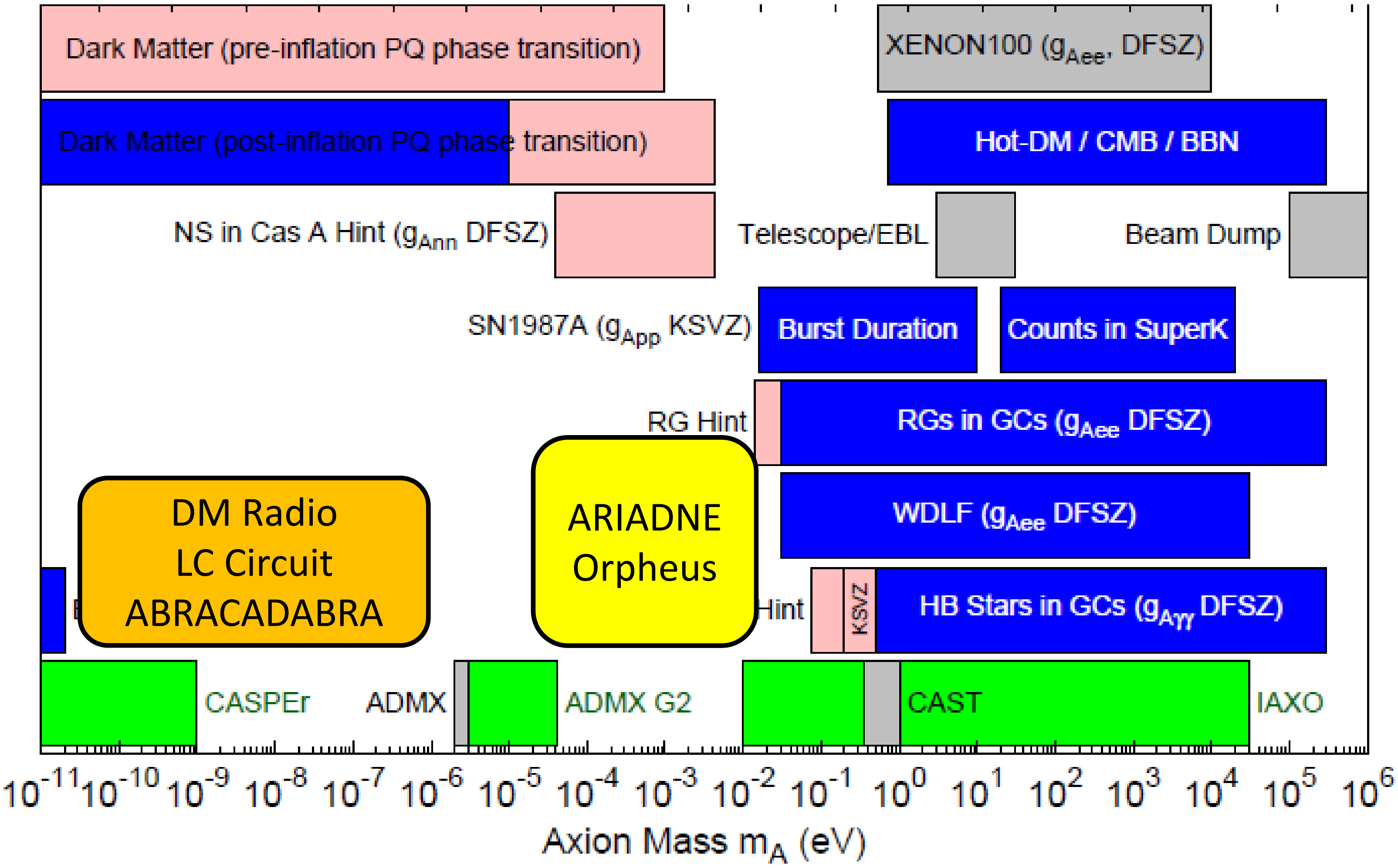
e.g.CASPEr-wind, QUAX (DM)

Axion Parameter space



Adapted from Graham, arxiv: 1602.00039

QCD Axion parameter space



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

Axion and ALP searches

Source	**Coupling**	
	Photons	**Nucleons**
Dark Matter (Cosmic) axions	**ADMX, ADMX-HF DM Radio, ABRA-CADABRA, LC Circuit, Orpheus**	**CASPEr-Electric CASPEr-Wind**
Solar axions	CAST IAXO	
Lab-produced axions	Light-shining-thru-walls (ALPS, ALPS-II)	ARIADNE

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, CAST, LC circuit, Casper

- Also mediates spin-dependent forces between matter objects at short range (down to 30 μm)

→ 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).

Axion-exchange between nucleons

- Scalar coupling ∝ θ_{QCD}

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

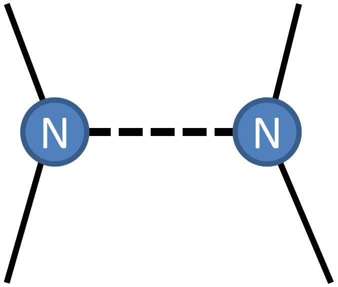
- Pseudoscalar coupling

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

In the non-relativistic limit:

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

Axion acts a force mediator between nucleons



$$(g_s^N)^2$$

Monopole-monopole

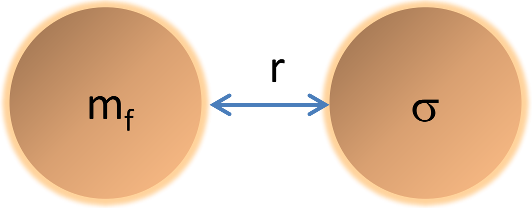
$$g_s^N g_P^N$$

Monopole-dipole

$$(g_p^N)^2$$

dipole-dipole

Spin-dependent forces



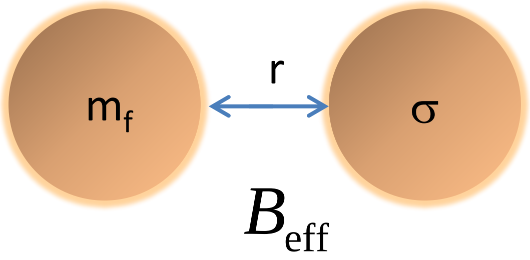
Monopole-Dipole axion exchange

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

Fictitious magnetic field

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

Using NMR for detection

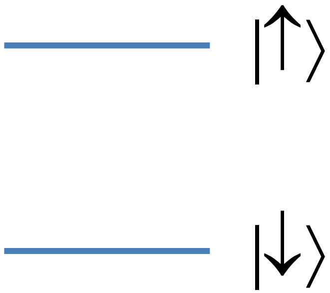


Spin ½ ^{3}He Nucleus

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

Bloch Equations

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

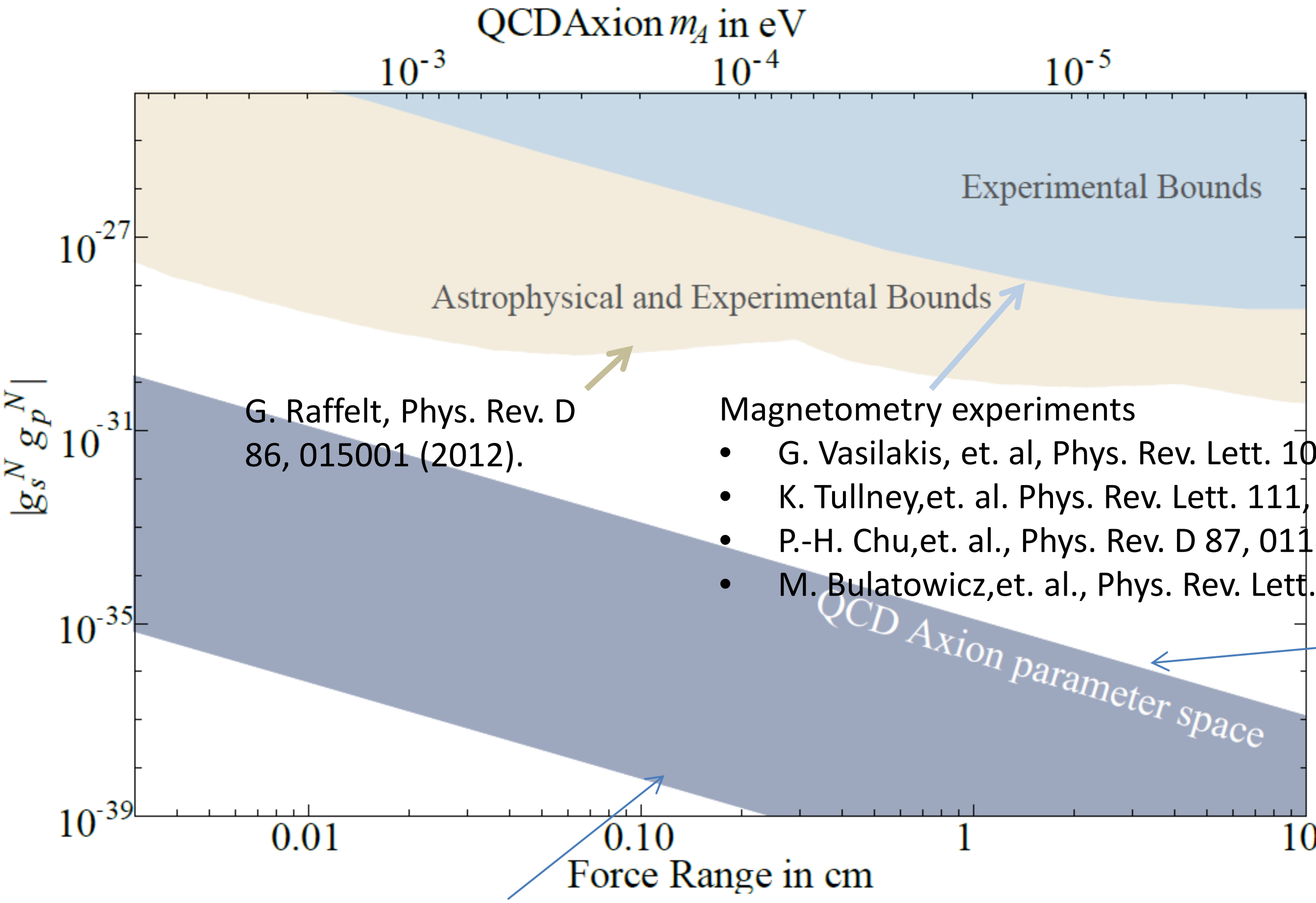


$$\omega = \frac{2\mu_N \cdot B_{\text{ext}}}{\hbar}$$

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

Axion B_{eff} modifies measured Larmor frequency

Constraints on spin dependent forces



G. Raffelt, Phys. Rev. D 86, 015001 (2012).

Magnetometry experiments

- G. Vasilakis, et. al, Phys. Rev. Lett. 103, 261801 (2009).
- K. Tullney,et. al. Phys. Rev. Lett. 111, 100801 (2013)
- P.-H. Chu,et. al., Phys. Rev. D 87, 011105(R) (2013).
- M. Bulatowicz,et. al., Phys. Rev. Lett. 111, 102001 (2013).

nEDM bound

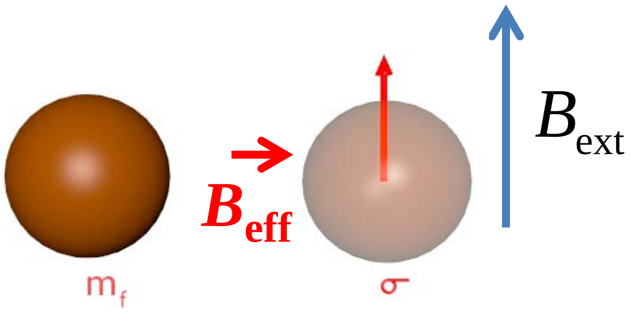
$$\theta_{QCD} < 10^{-10}$$

Standard Model lower bound

$$\theta_{QCD} > 10^{-16}$$

ARIADNE: uses resonant enhancement

Spin ½ ^{3}He Nucleus



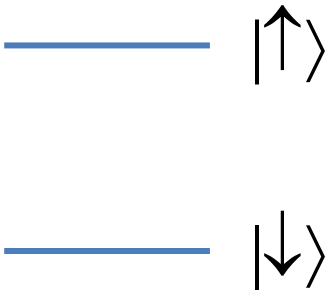
Oscillate the mass at Larmor frequency

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

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

Bloch Equations

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



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

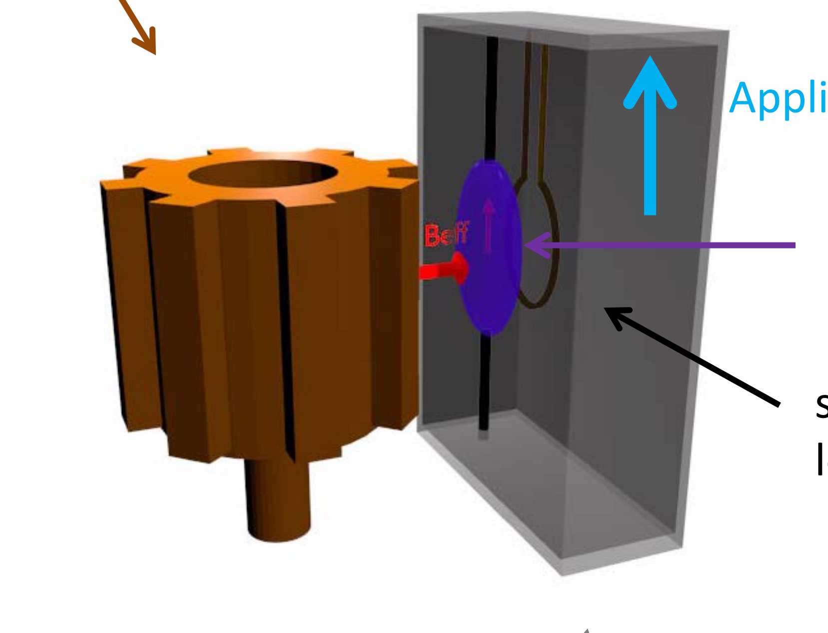
Time varying Axion B_{eff} drives spin precession
→ produces transverse magnetization

Amplitude is resonantly enhanced by Q factor ~ ωT_2.

Can be detected with a SQUID

Concept for ARIADNE

Unpolarized (tungsten) segmented cylinder sources B_{eff}



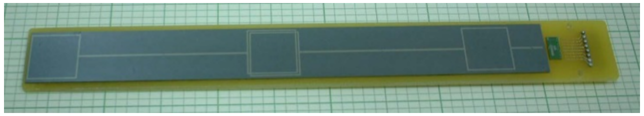
Applied Bias field B_{ext}

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

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

squid pickup loop

Y.-H. Lee (KRISS)



Superconducting shielding (Stanford)

Limit: Transverse spin projection noise

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

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

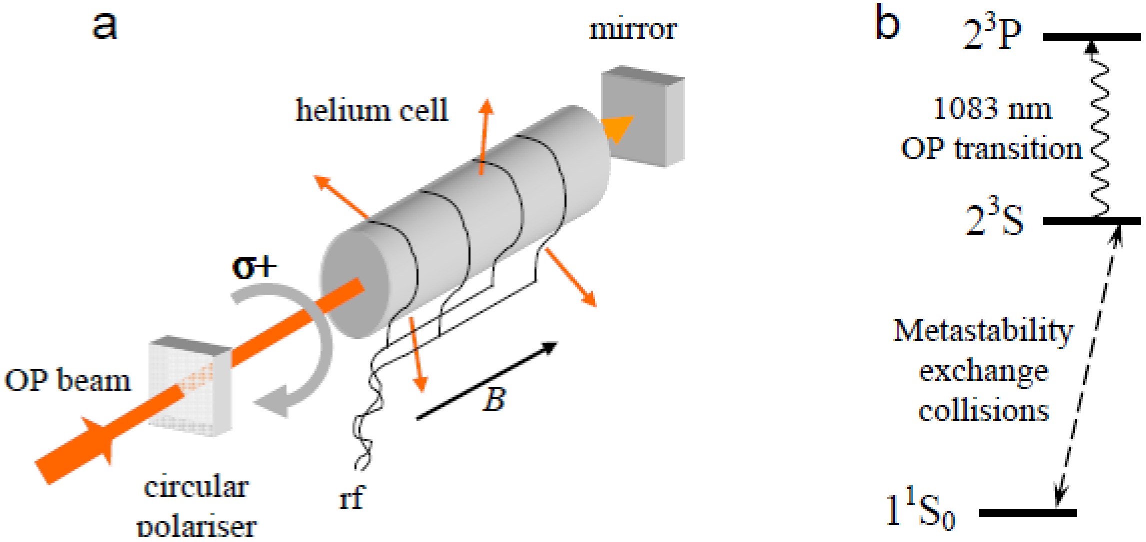
Hyperpolarized ^{3}He

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

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

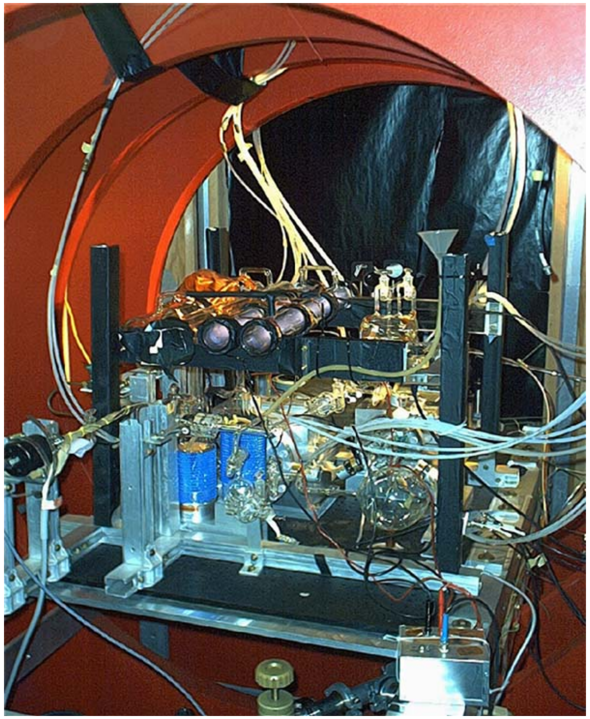
Optical pumping techniques

- Metastability exchange optical pumping



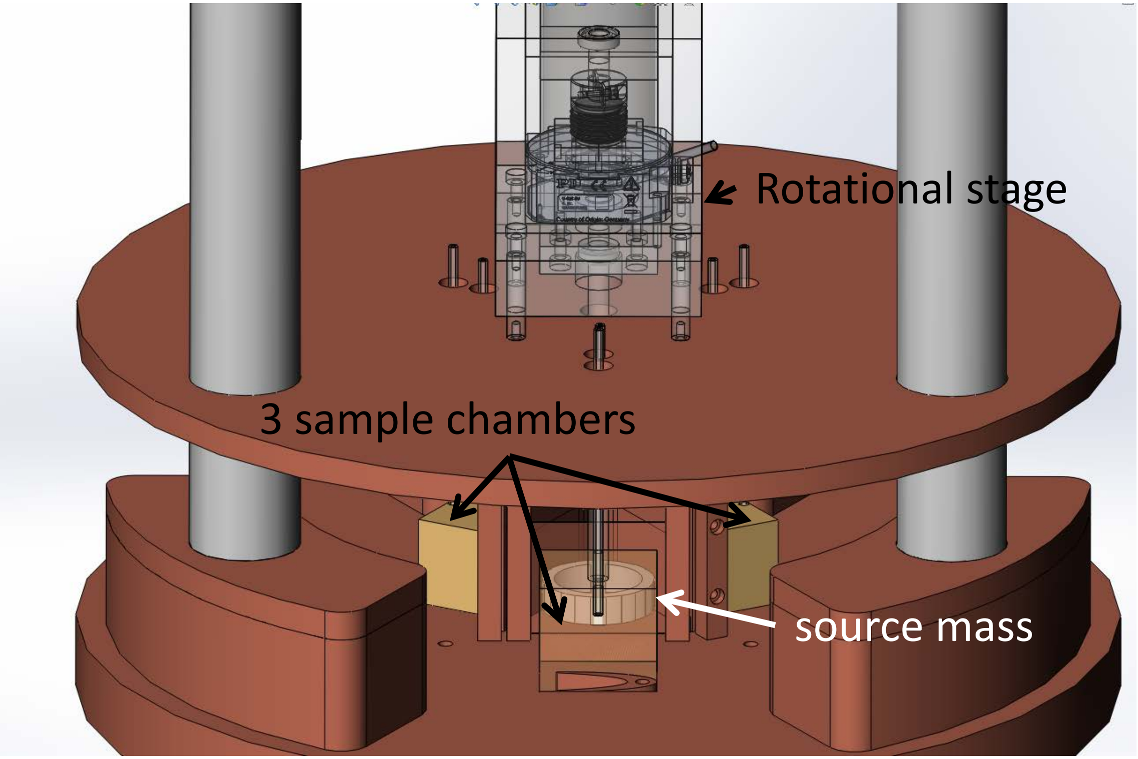
M Batz, P-J Nacher and G Tastevin, Journal of Physics: Conference Series **294** (2011) 012002

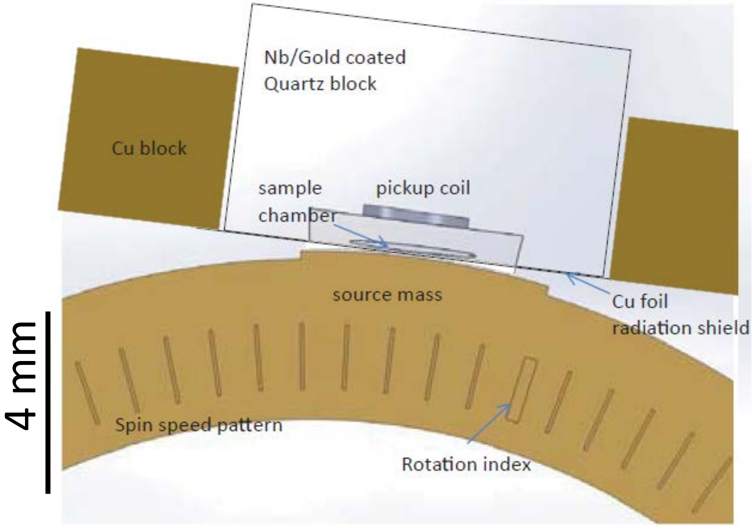
Indiana U. MEOP apparatus



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

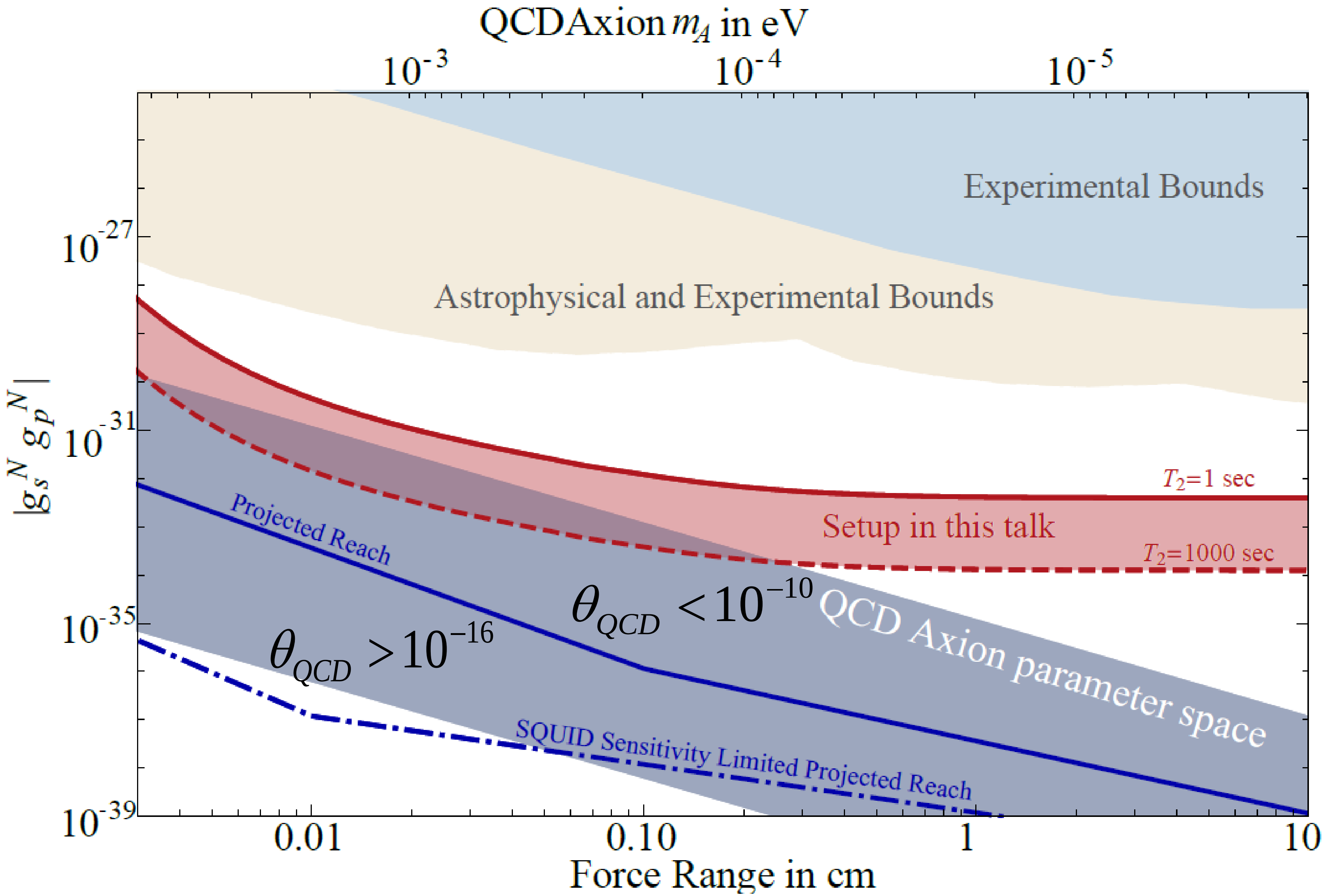
Experimental parameters





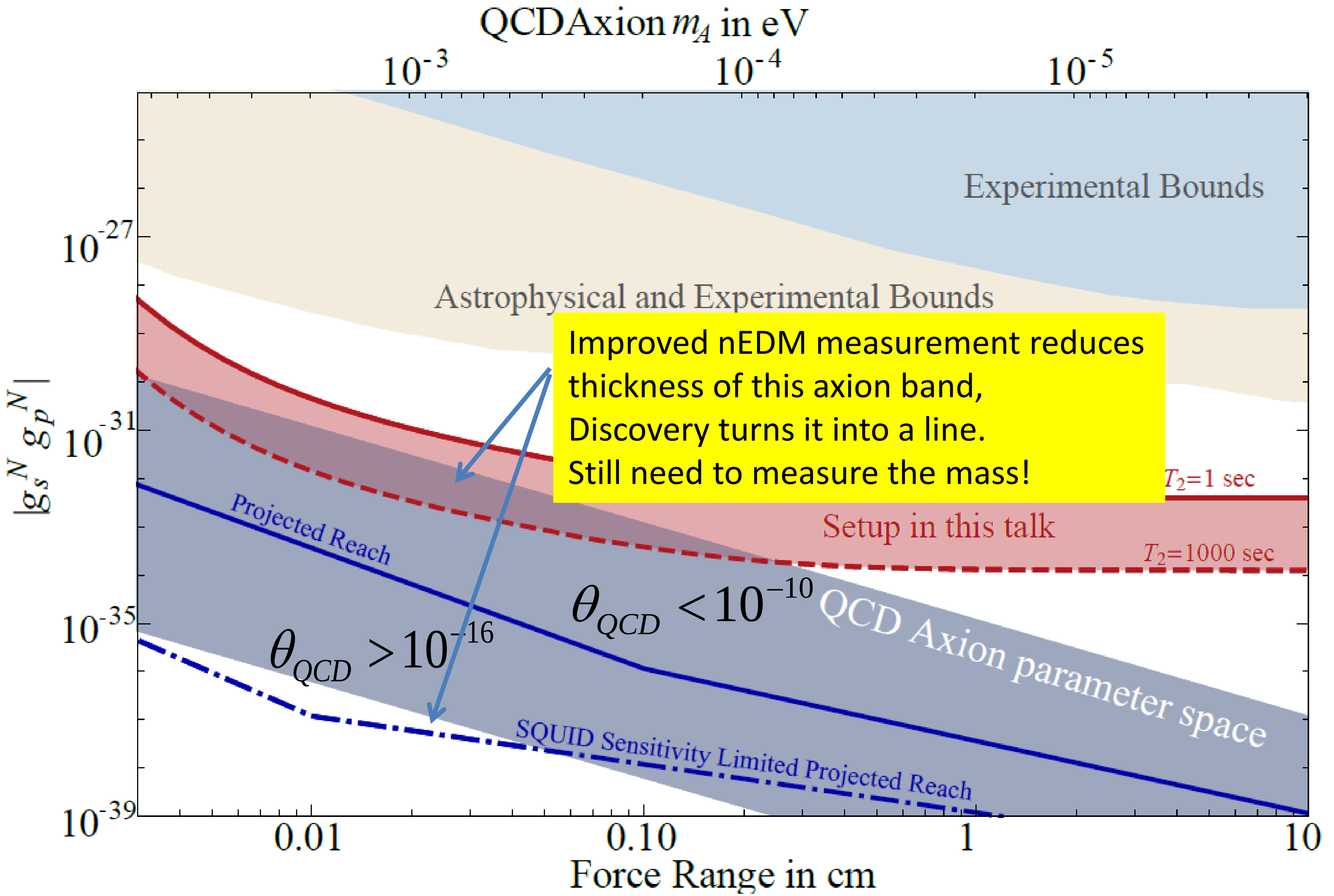
11 segments
100 Hz nuclear spin precession frequency
2 x 10^{21} / cc ^{3}He density
10 mm x 3 mm x 150 µm volume
Separation 200 µm
Tungsten source mass (high nucleon density)

Sensitivity



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

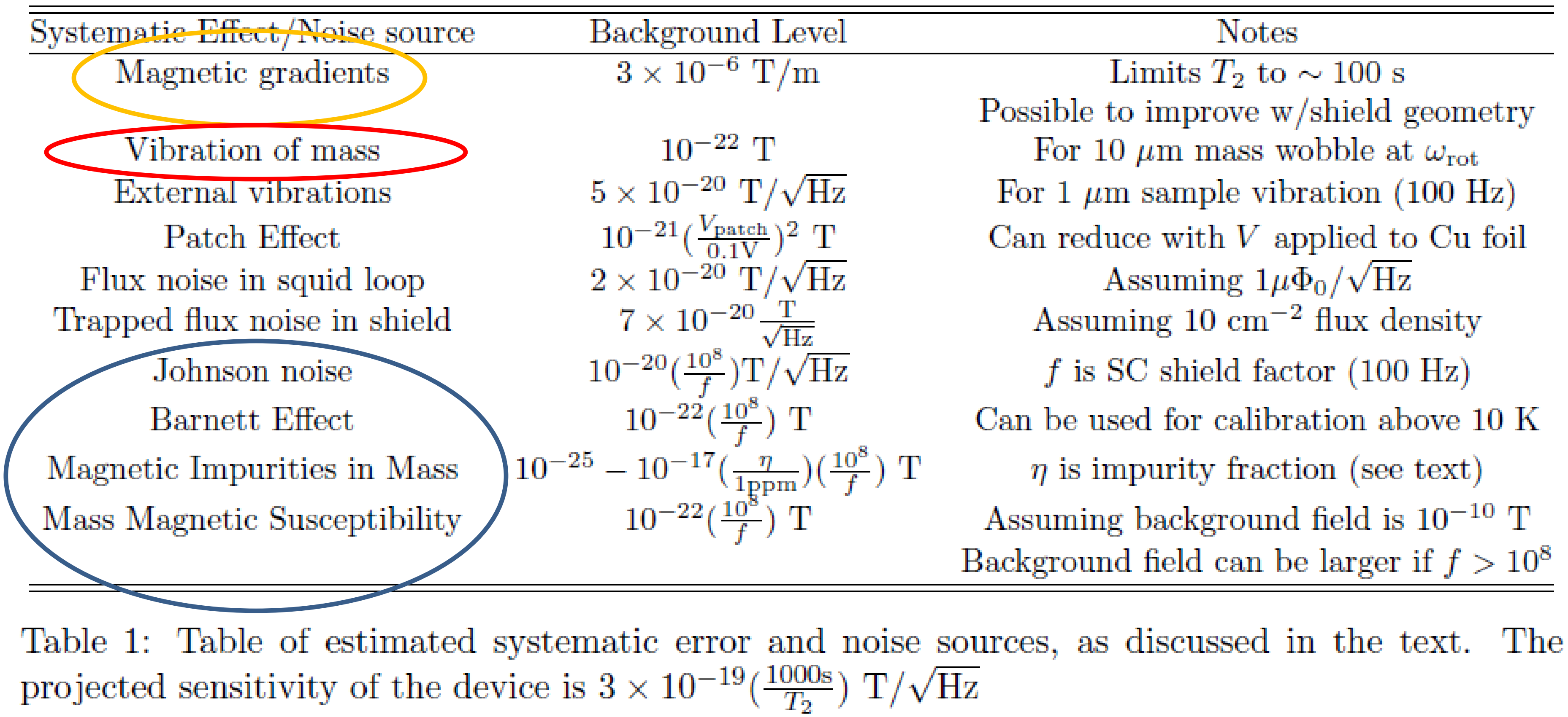
Complementarity with nEDM experiments



Improved nEDM measurement reduces thickness of this axion band,
Discovery turns it into a line.
Still need to measure the mass!

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

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 $3 \times 10^{-19}(\frac{1000\mathrm{s}}{T_2})$ T/$\sqrt{\mathrm{Hz}}$

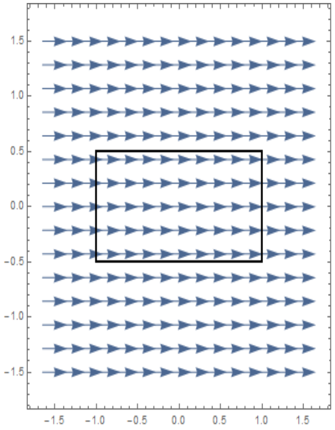
- Design/Simulation Work: Magnetic gradient reduction strategy
- Experimental testing in progress: Vibration tests, Shielding factor *f* test thin-film SC

Superconducting Magnetic Shielding

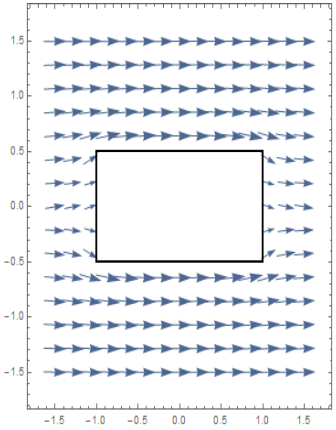
→ Essential to avoid Johnson noise

Meissner Effect

- No magnetic flux across superconducting boundary



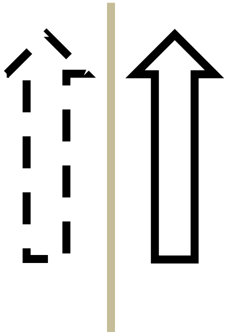
T > T_c



T < T_c

Method of Images

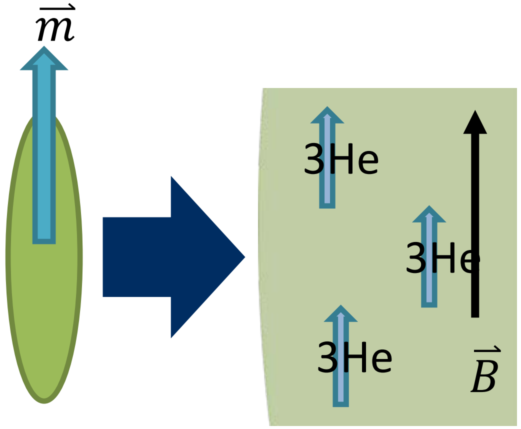
- Make “image currents” mirrored across the superconducting boundary



Dipole with image

The Problem of Unwanted Images

- ARIADNE uses magnetized spheroid
  - Constant interior field

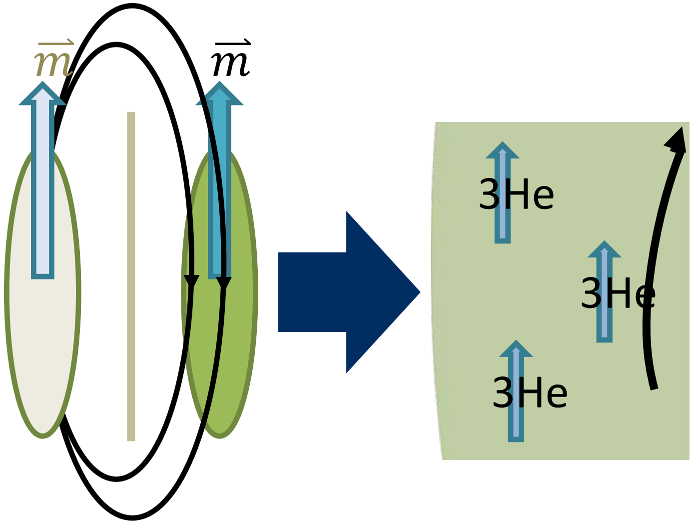


- $B_{in} = \text{const.}$
- $\overrightarrow{B_{in}} \parallel \overrightarrow{m_i}$

- Magnetic shielding introduces “image spheroid”

  Interior field varies

→ variations in nuclear Larmor frequency

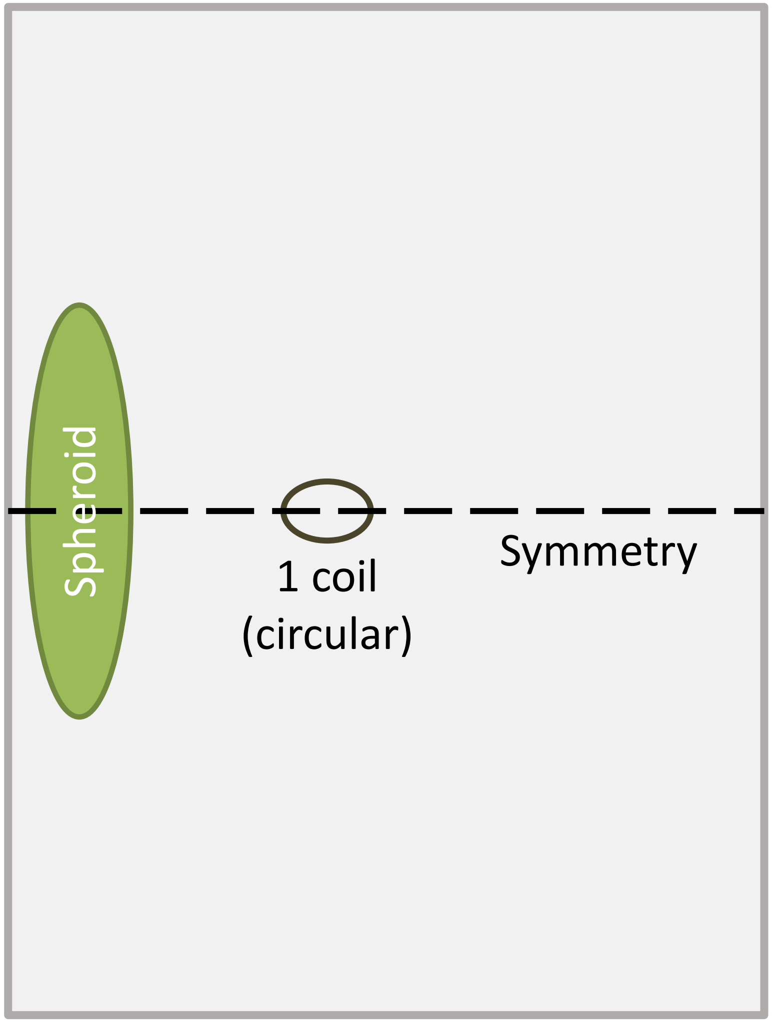


- $B_{in} \neq \text{const.}$
- $\overrightarrow{B_{in}} \nparallel \overrightarrow{m_i}$

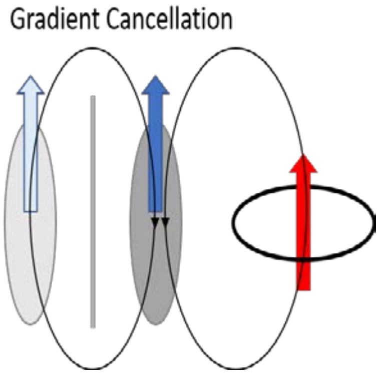
But want to drive entire sample on resonance

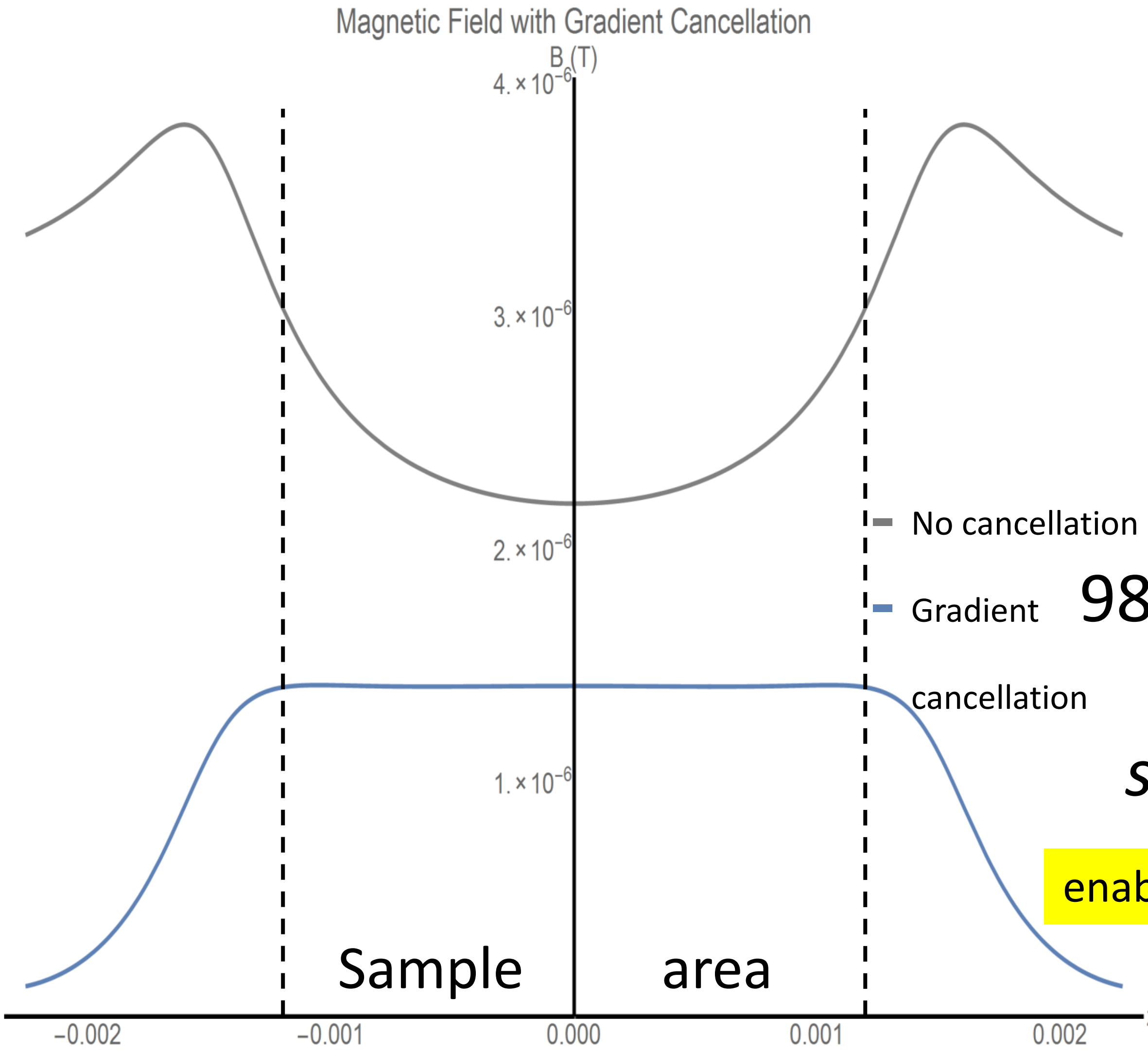
Flattening Solution

- 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%

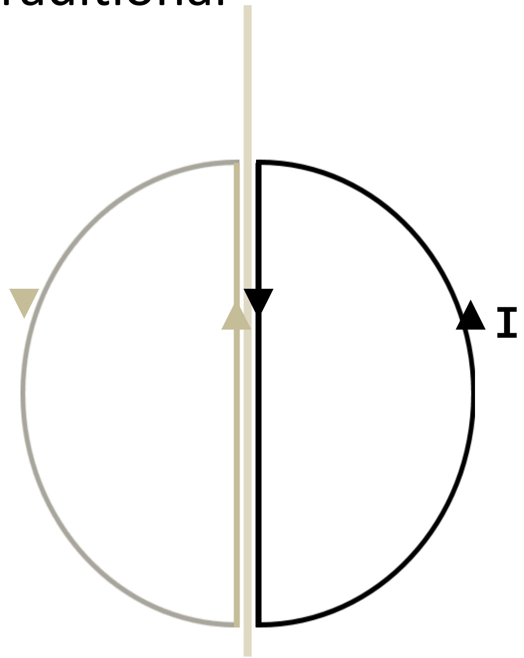
enabling T_2 of ~100 s

Tuning Solution – “D” Coils

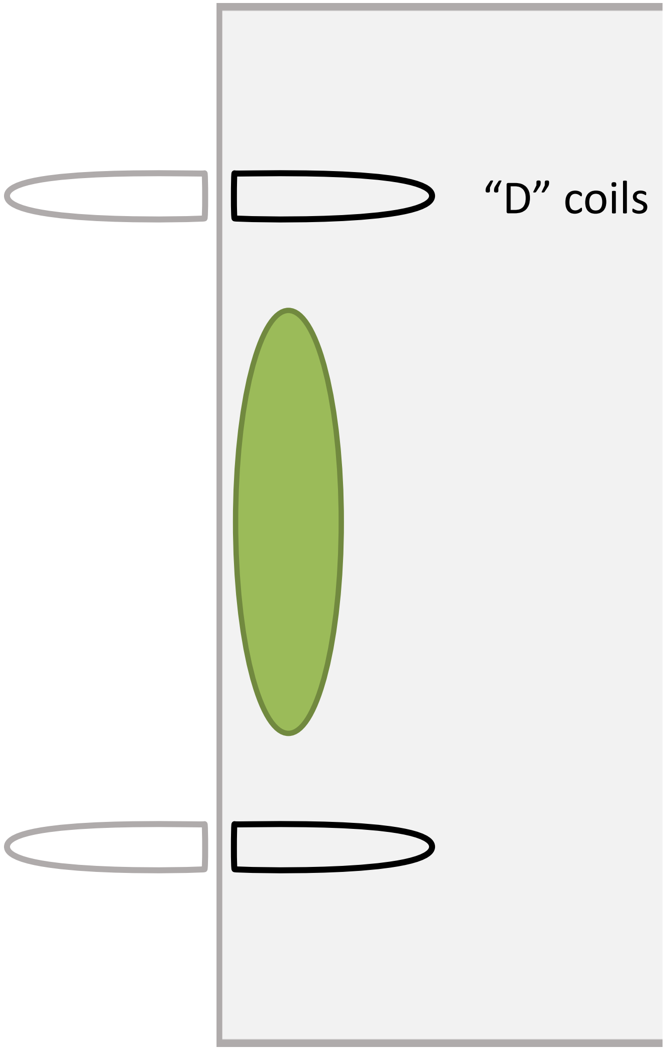
- Tune field with Helmholtz coils
  - Helmholtz field only flat near the center
  - Geometry restrictions prevent the spheroid from being centered in traditional Helmholtz coils

- “D” coils look like Helmholtz coils when their images are included

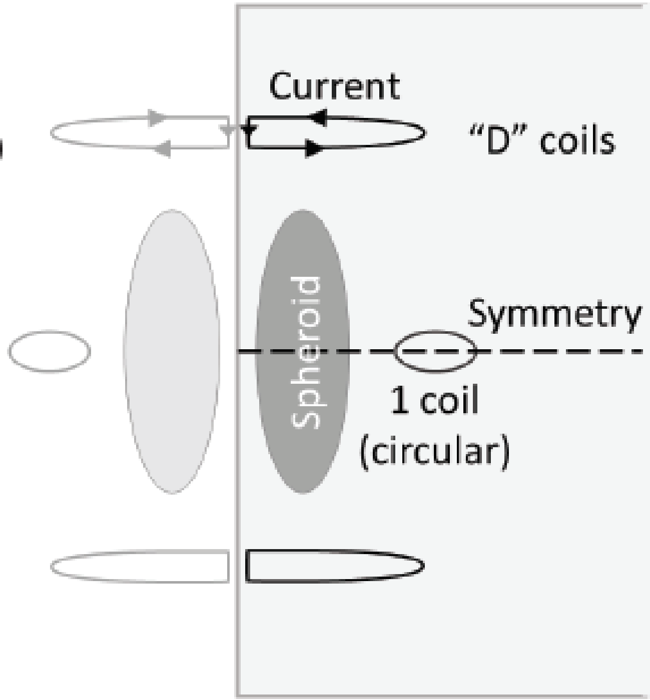
- Inner straight-line currents cancel
- Outer currents do not

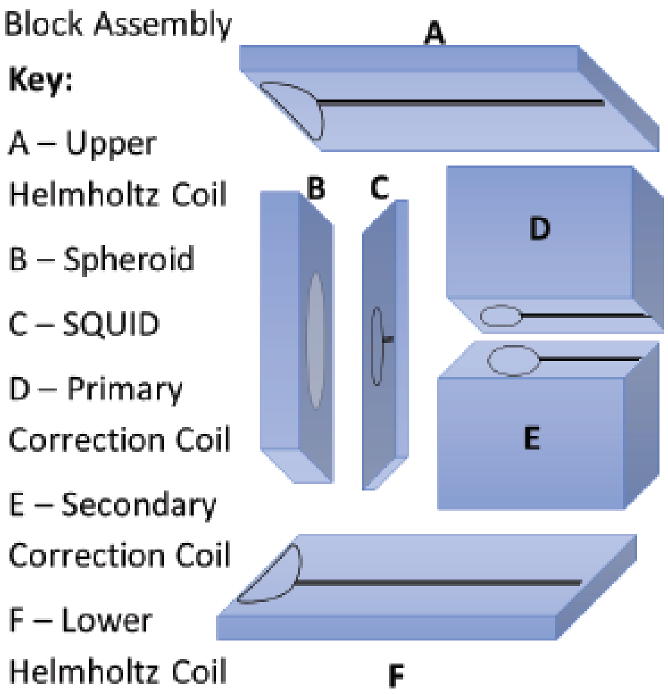


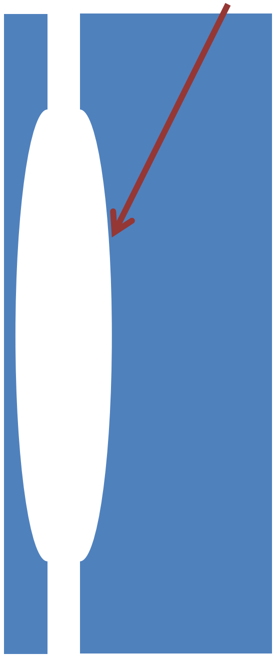
One “D” coil and image (bird’s eye view)

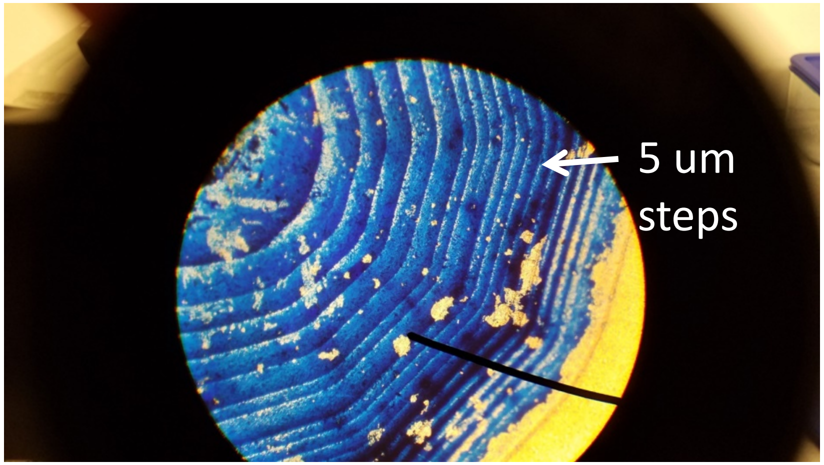


Quartz block assembly






Spheriodal pocket



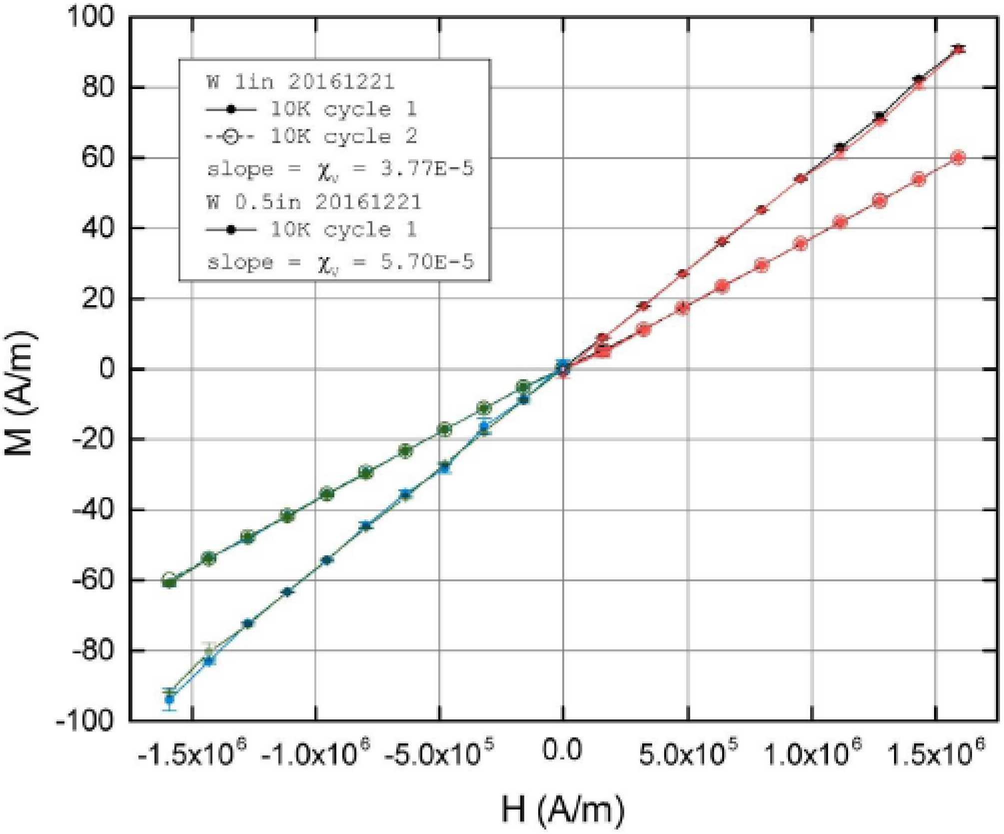
Milled spheriodal pocket in quartz

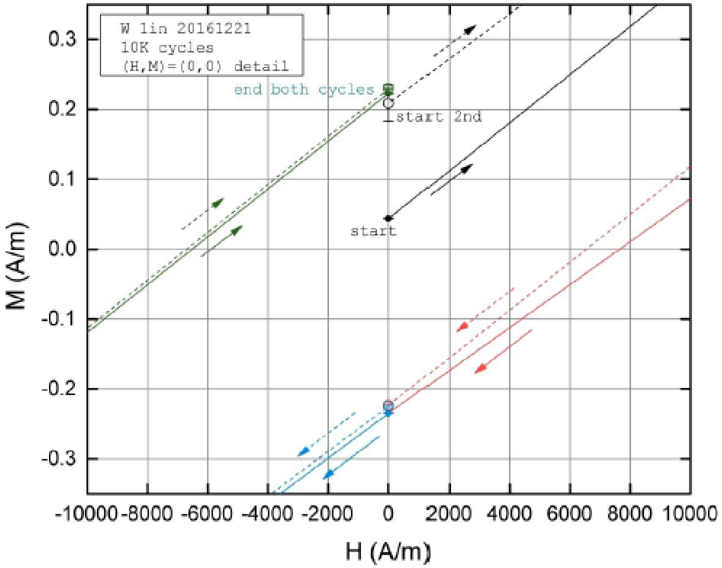
Fabrication/polishing tests is process – Aug 2017

Tungsten Source Mass Prototype

11 segments, 3.8 cm diameter Tungsten Sprocket prototype, Wire EDM

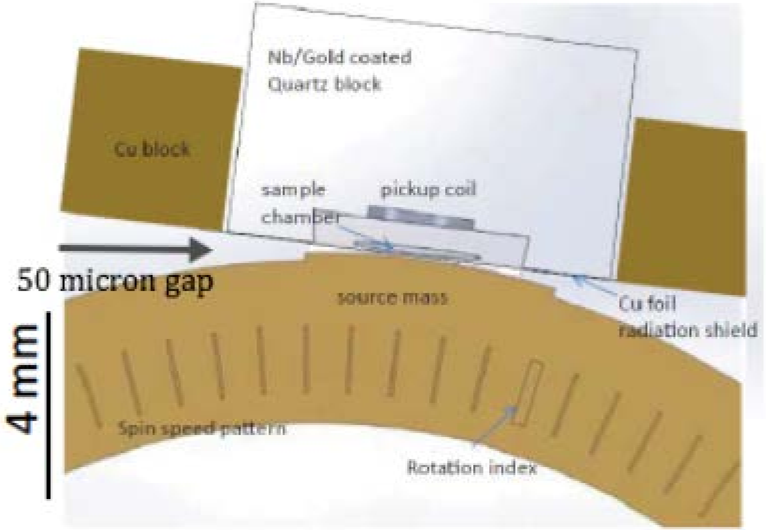
Magnetic impurity testing in machined Tungsten using commercial SQUID magnetometer -- Indiana

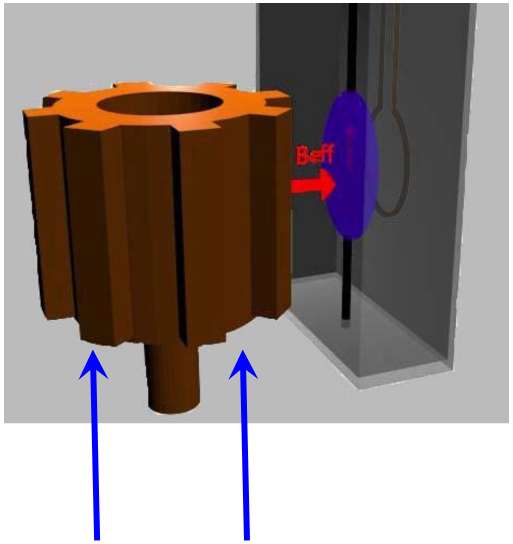




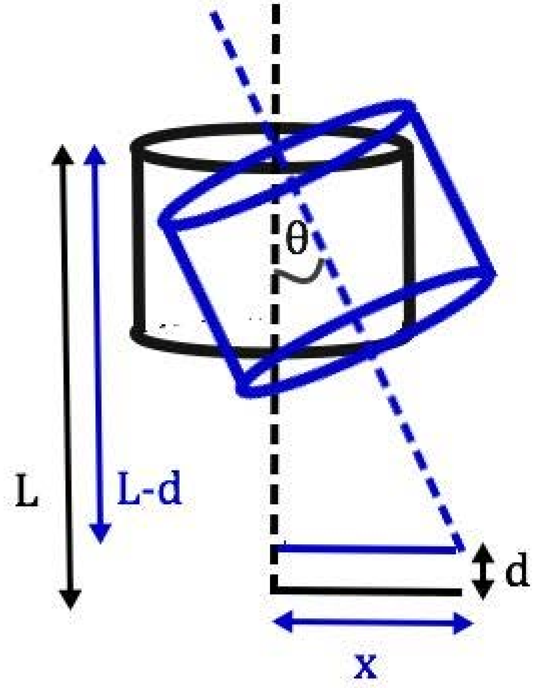
Magnetic impurities below 0.4 ppm

Rotary stage vibration and tilt

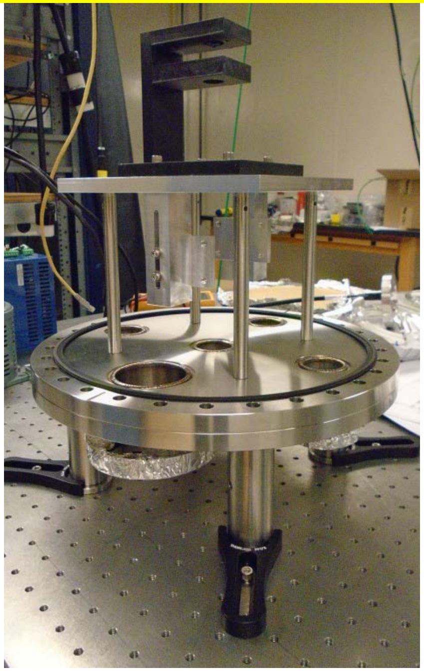




Interferometers



Rotary test chamber



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

Fiber-coupled laser interferometers

Laser Source

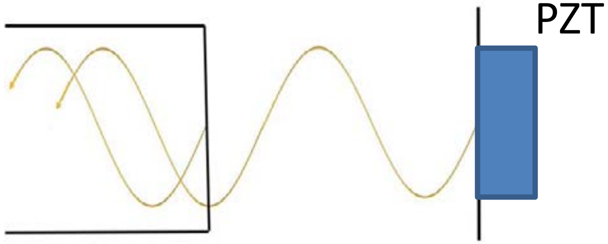
90:10 fiber coupler

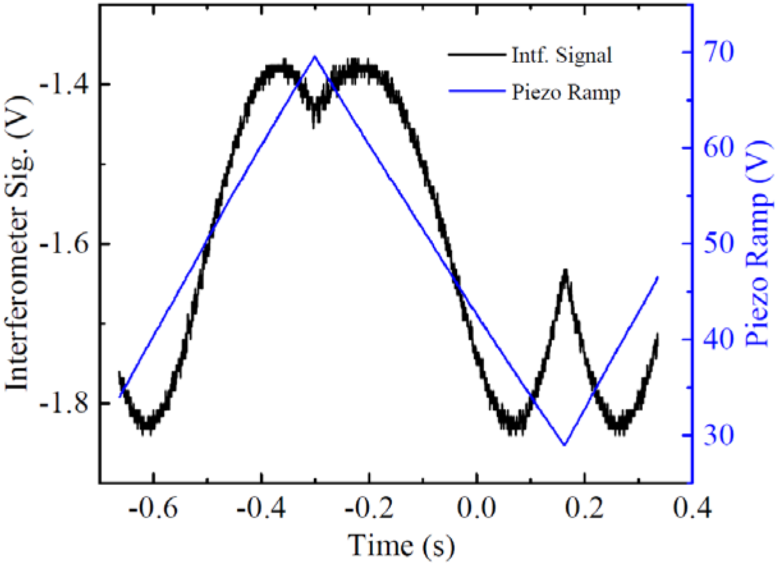
Reference Photodiode

Signal Photodiode

Fiber Tip

Reflector

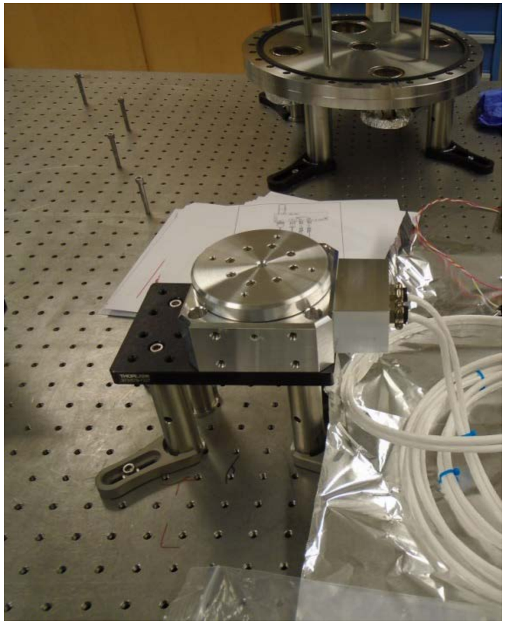




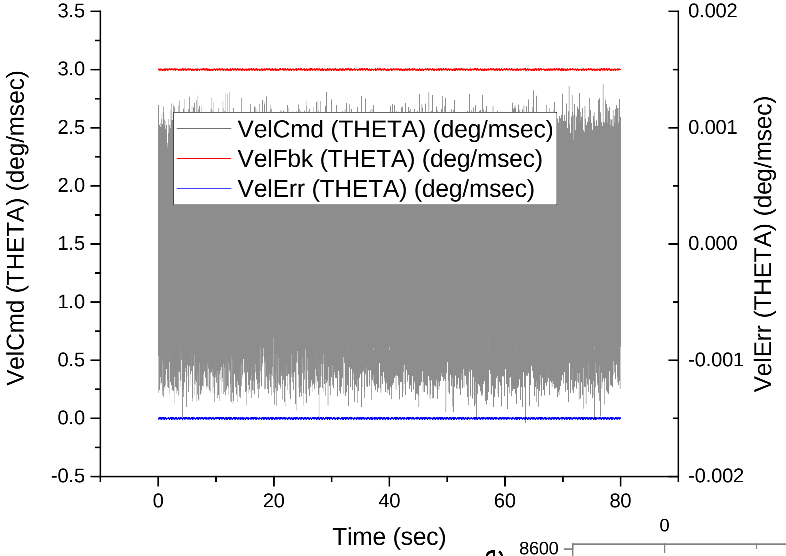
Fringe visibility
~0.13
Sensitivity
~160 nm/V
Shot noise limit
~20 pm/Hz$^{1/2}$

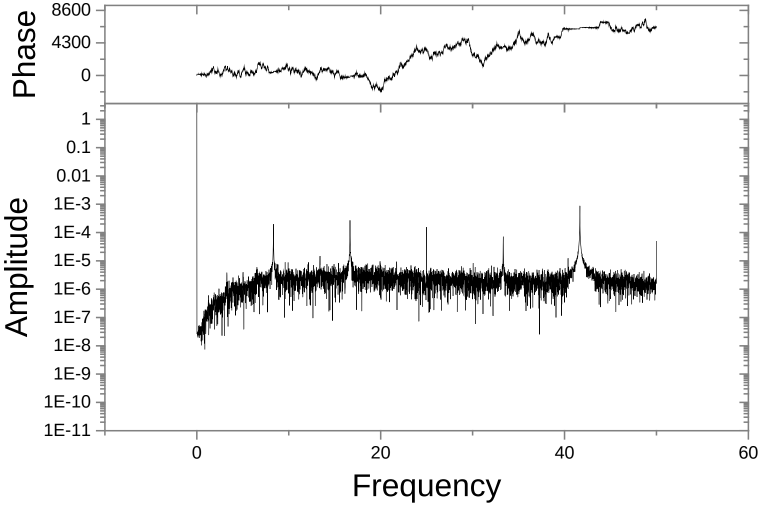
Speed stability test - direct drive stage

- Optical encoder
- Current feedback control



Stage speed stability error – unloaded, in air

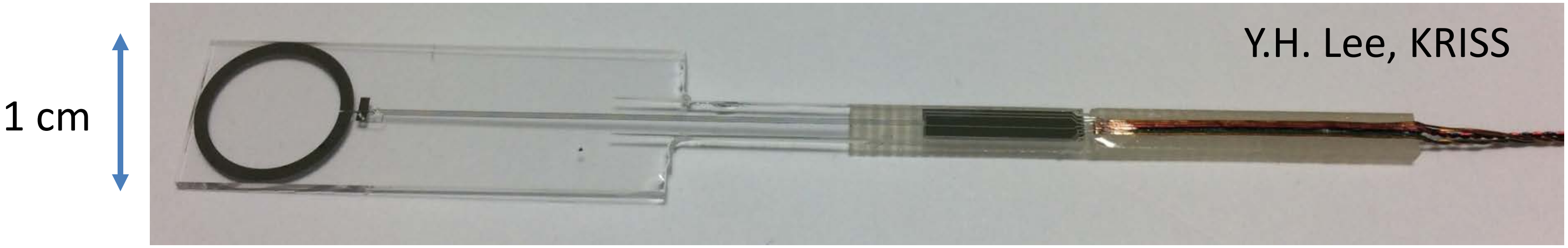




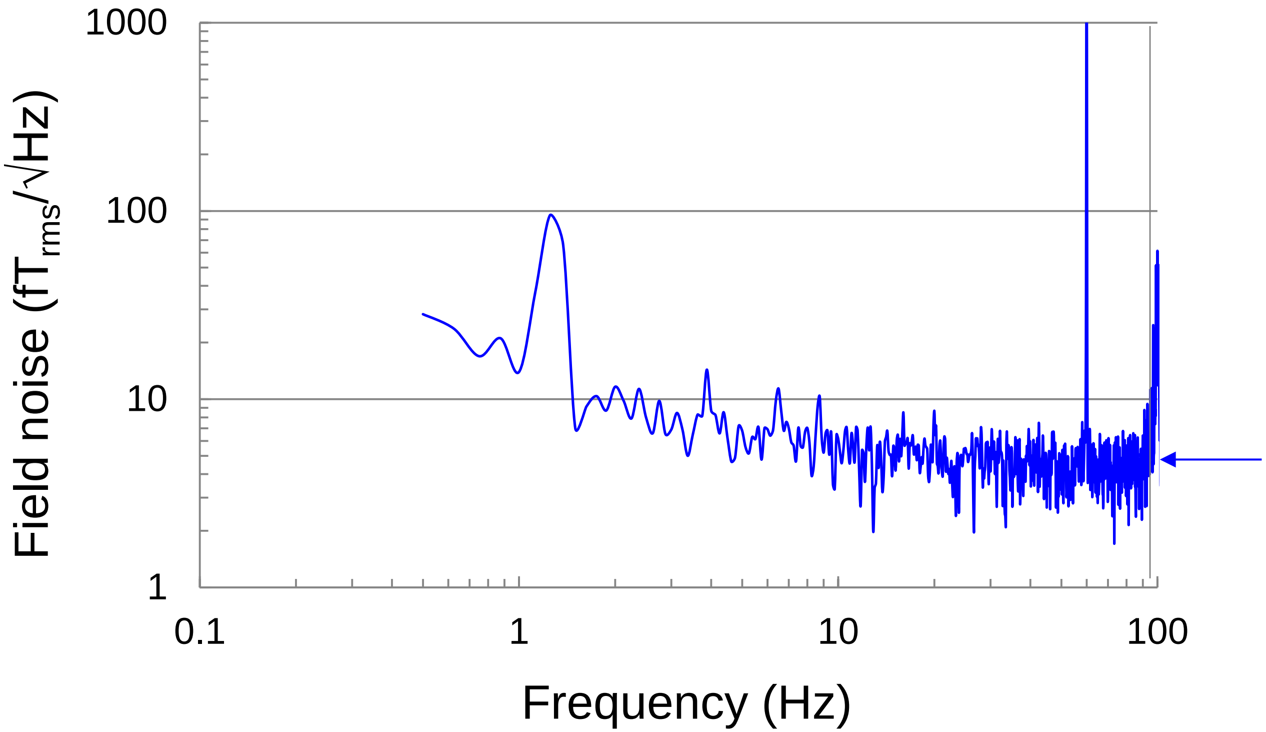
Rotation speed control
8.3 Hz ~ 1 part in 10000
RMS ~ 1 part in 3000

Allows utilization of T2 > 100s

SQUID Magnetometers



Y.H. Lee, KRISS



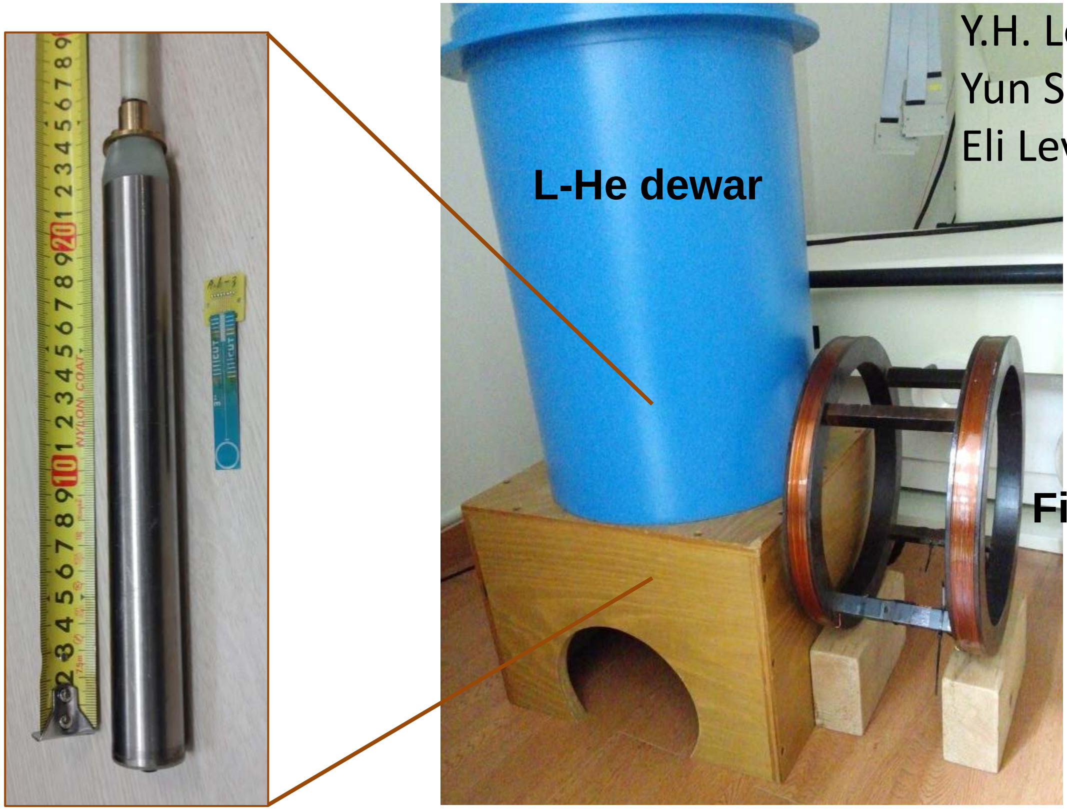
$4.5\ fT_{rms}/\sqrt{Hz}$

Measured inside a magnetically shielded room (without Nb tube)

Preliminary test of superconductive shielding

Y.H. Lee, KRISS,
Yun Shin (CAPP)
Eli Levenson-Falk (Stanford)

Nb tube:
23 mm ID
1 mm thick
Length 200 mm



Applied field: 10-100 μT_{pp} range (at 8 Hz)

SQUID magnetometer: Near the center of Nb tube
Shielding factor: ≒(0.5-3) x10^9 for transverse field

Goal: 10^8 with thin film Nb SC shield – tests underway Summer 2017

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
- Complementary to nEDM experiments
- Next tests – shielding (Stanford/Korea), vibration (UNR), ^{3}He system (Indiana)

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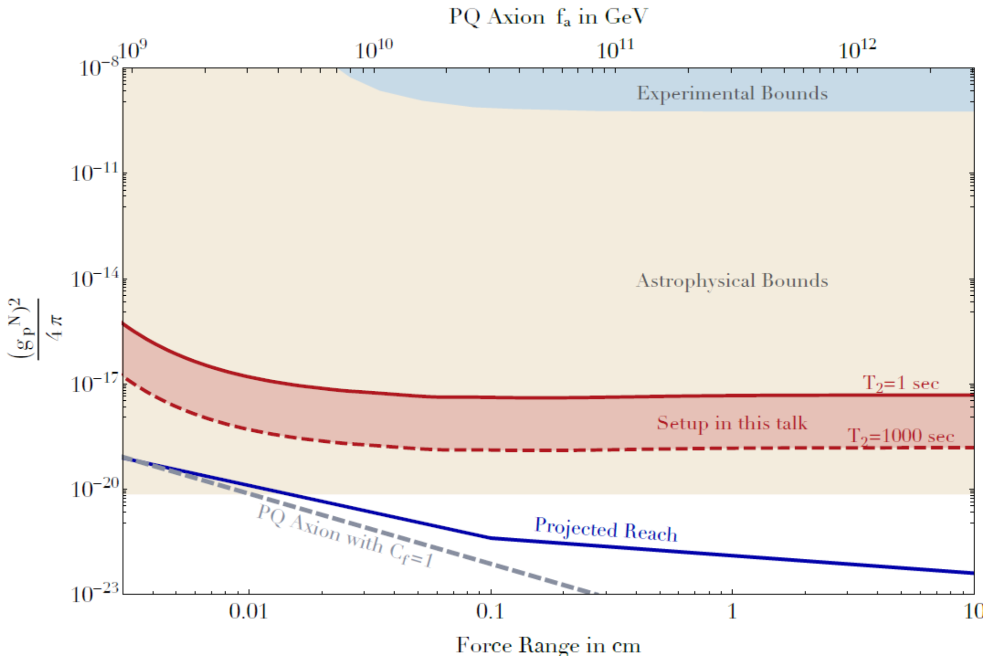
Not pictured: Apryl Witherspoon (UG), Ohidul Mojumder (UG), Hannah Mason (UG)

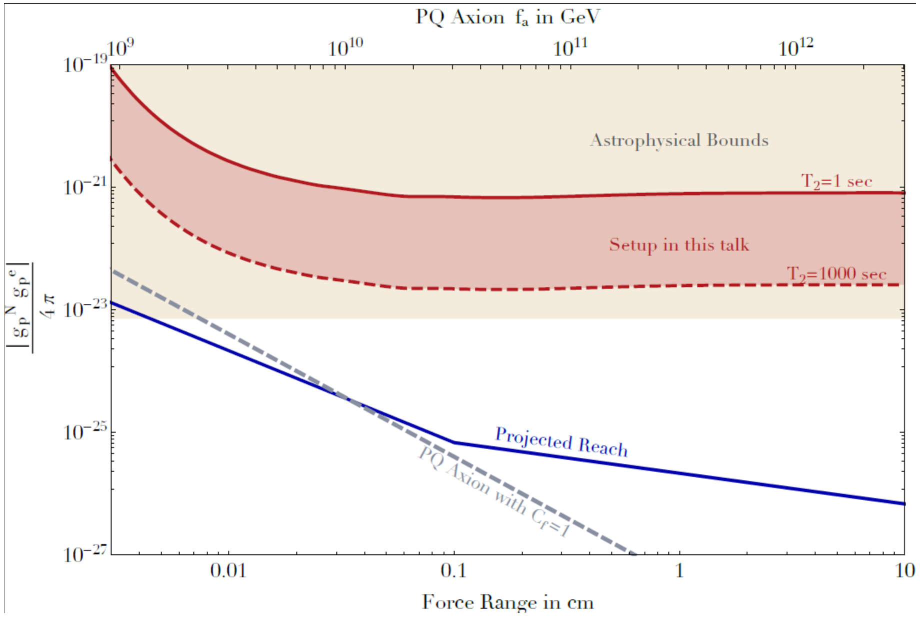
Dipole-Dipole axion forces

- Spin-polarized source mass
- May be competitive with astrophysical bounds
- Magnetic shielding requirements more stringent

Nuclear spin



Electron spin



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