Small Scale experiments for fundamental physics

ICTP Summer School on Particle Physics, June 12-15

Part 4

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Syllabus

- Introduction
- New (scalar) forces
- Gravitational Waves and Ultralight Dark Matter
- New (spin-dependent) forces

(relation to axions, EDMS, Cosmic DM experiments)

Outline for Lectures

- Lecture 3 –

  New (spin-dependent) forces

  - Background
  - Torsion balance tests
  - Magnetometry
  - New techniques: (ARIADNE)
  - Relation to axions, EDM experiments, Cosmic DM experiments

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}

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

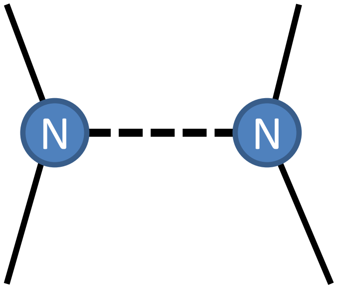
- Pseudoscalar coupling

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

In the non-relativistic limit:

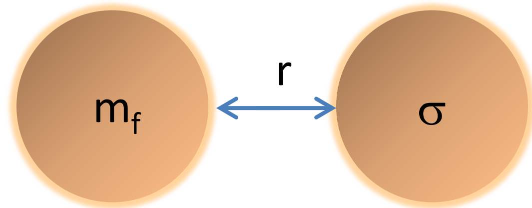
$$\mathcal{L} \supset \frac{\vec{\nabla} a}{f_a}\cdot\vec{\sigma}$$

Axion acts a force mediator between nucleons



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

Spin-dependent forces

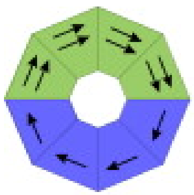


Monopole-Dipole axion exchange

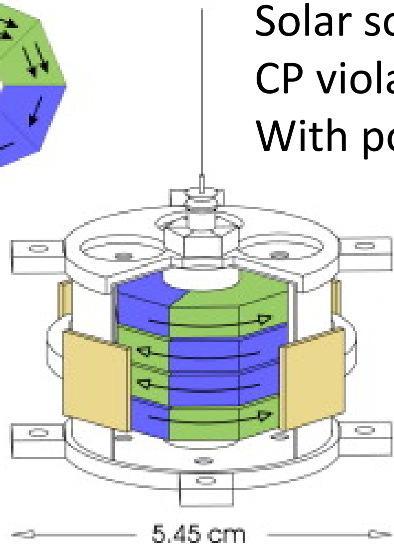
$$U(r) = \frac{\hbar^2 g_s^{N} g_p^{N}}{8\pi m_f}\left(\frac{1}{r\lambda_a} + \frac{1}{r^2}\right) e^{-r/\lambda_a} (\hat{\sigma}\cdot\hat{r}) \quad \equiv \mu \cdot B_{\mathrm{eff}}$$

Fictitious magnetic field

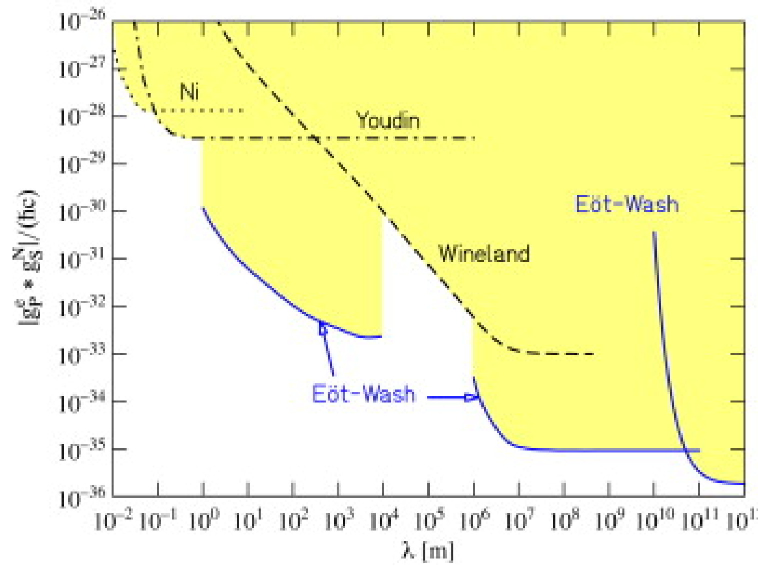
Spin-dependent forces- torsion balance



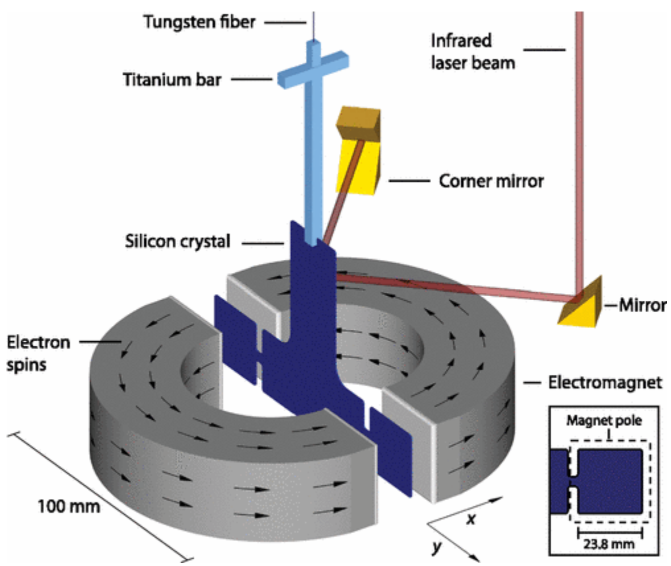
Lab-fixed,
Solar source
CP violation test
With polarized electrons

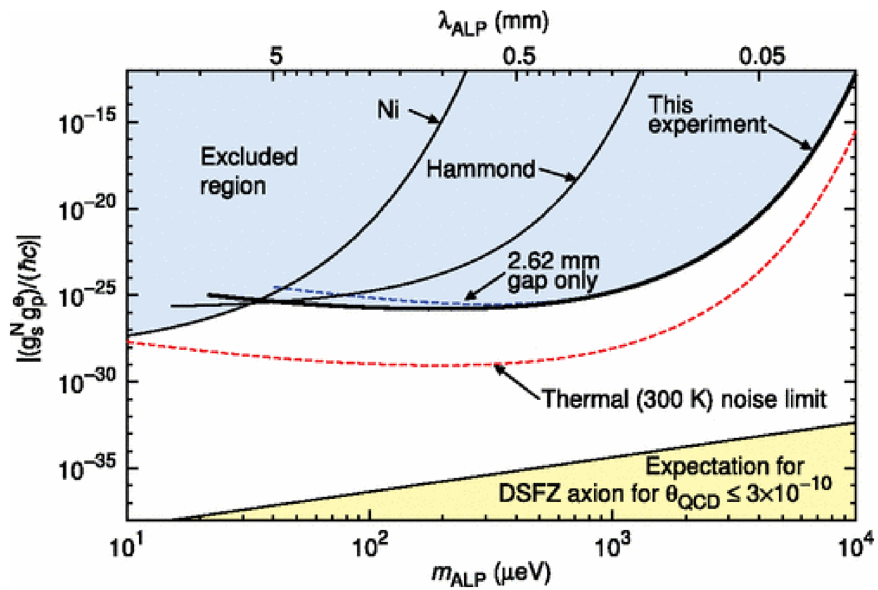


B. R. Heckel, E. G. Adelberger, C. E. Cramer, T. S. Cook, S. Schlamminger, and U. Schmidt Phys. Rev. D **78**, 092006 (2008)



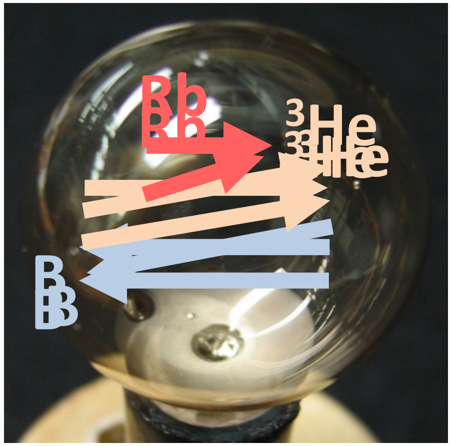
Axion-like particle (ALP) search:



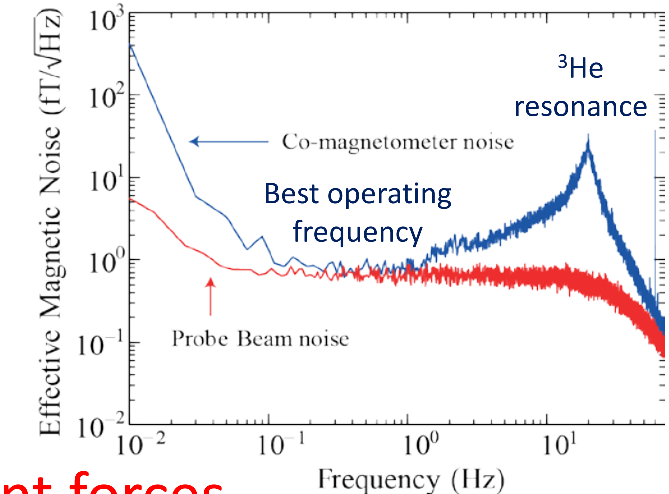


S. A. Hoedl, F. Fleischer, E. G. Adelberger, and B. R. Heckel Phys. Rev. Lett. **106**, 041801 (2011).

Noble gas alkali-metal co-magnetometer



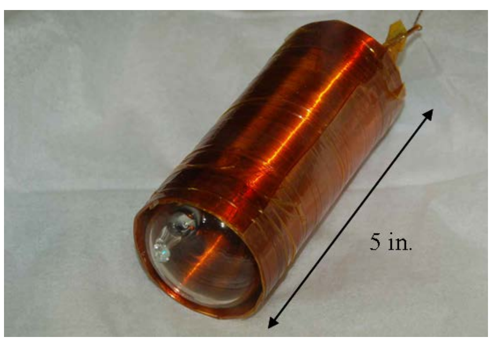
Polarize Rb
Interactions with
electrons with
^{3}He cause Rb tilt
Polarize ^{3}He by
laser
spin-exchange
Magnetic field
tilt cancels



Search for spin-dependent forces

Neutron non-magnetic spin-spin force

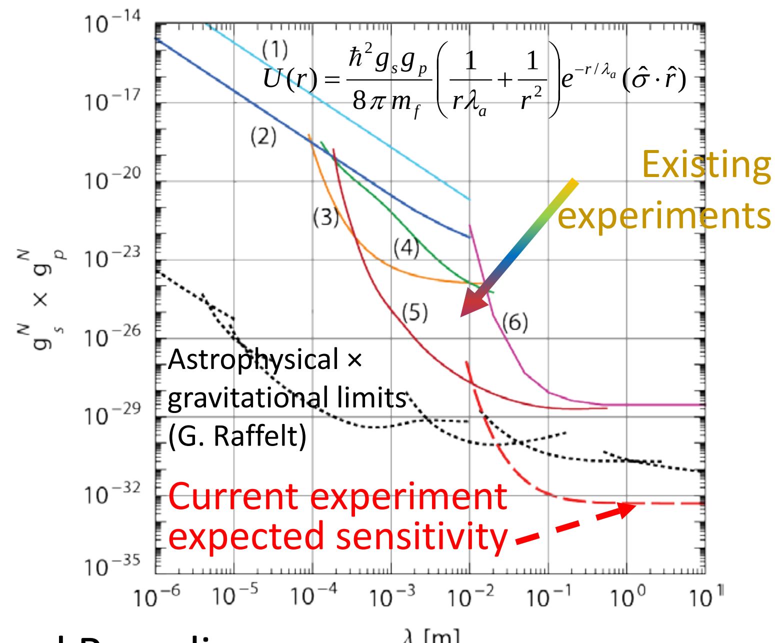
10^{22} polarized ^{3}He spins, direction reversed every 3 sec by NMR



Sensitivity (1σ) = 18 pHz = $4.3 \cdot 10^{-35}$ GeV
Smallest frequency shift ever measured

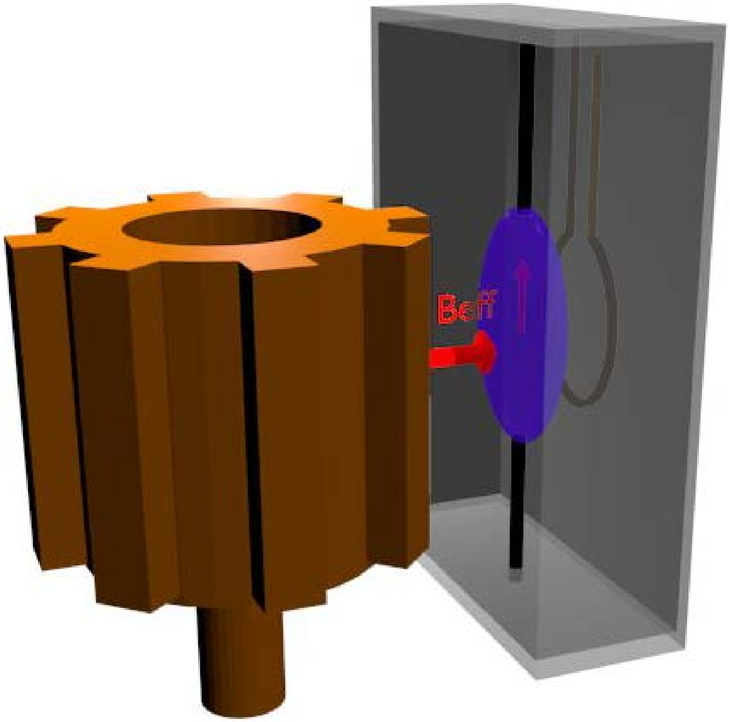
G. Vasilakis, J. M. Brown, T. W. Kornack, MVR, Phys. Rev. Lett. **103**, 261801 (2009)

Spin-mass CP-odd force



Slide from : Michael Romalis

The Axion Resonant InterAction Detection Experiment (ARIADNE)



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

Mark Cunningham (UNR)
Mindy Harkness (UNR)
Jordan Dargert (UNR)
Chloe Lohmeyer (UNR)
Asimina Arvanitaki (Perimeter)
Aharon Kapitulnik (Stanford)
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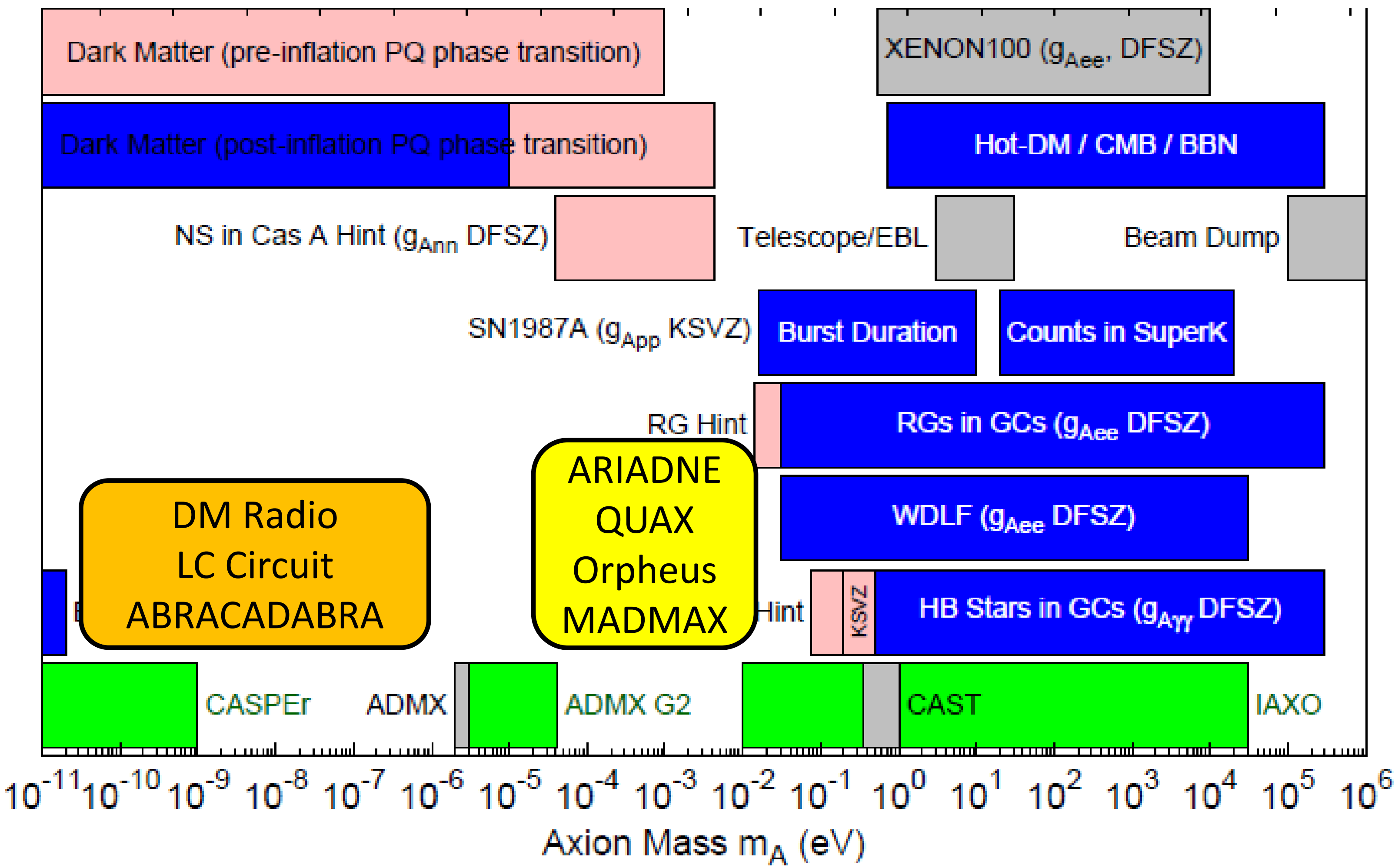
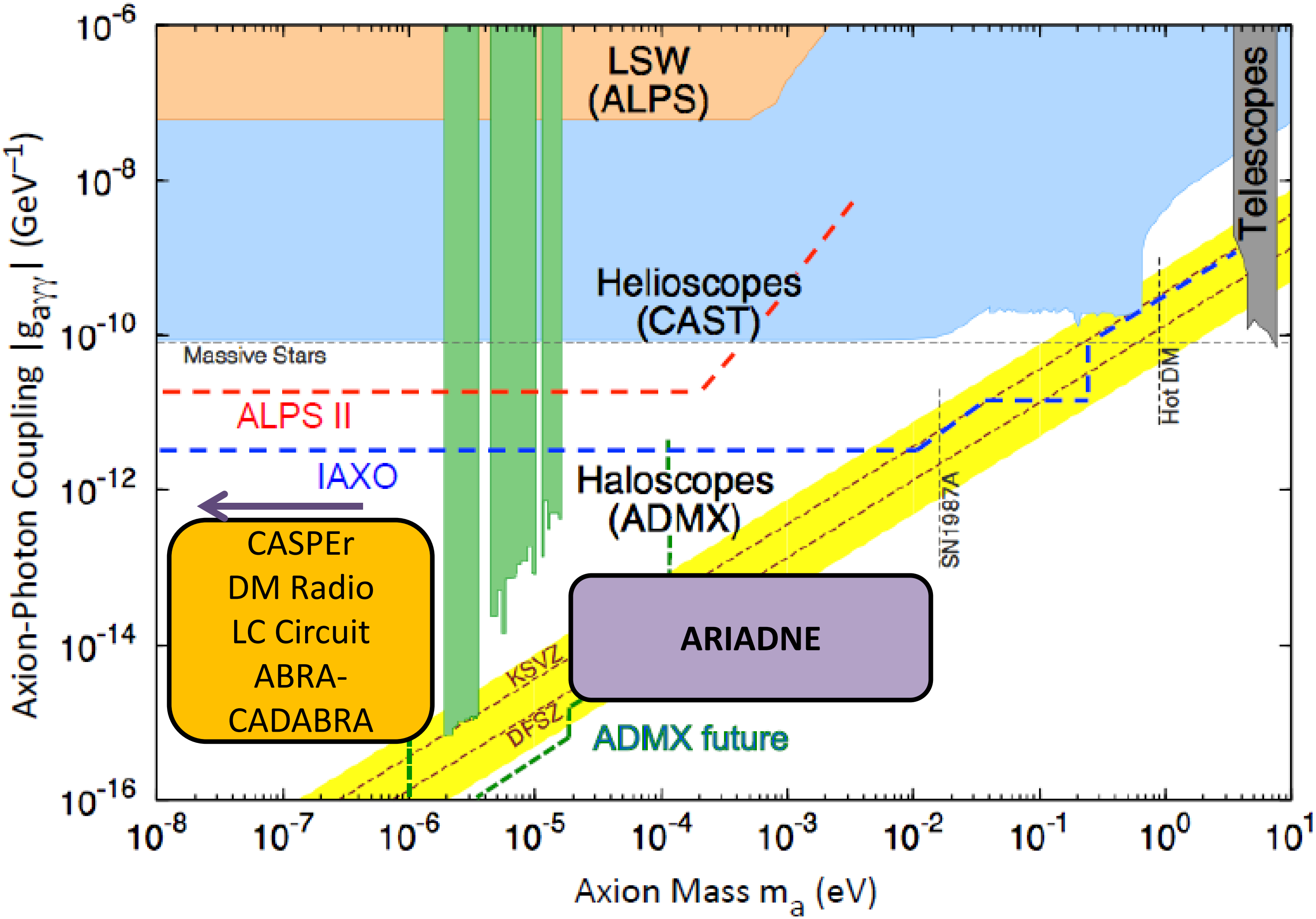
Erick Smith (IU)
Justin Shortino (IU)
Mofan Zhang (IU)
Andrew Rusch (IU)
Yannis Semertzidis (CAPP)
Yun Shin (CAPP)
Yong-Ho Lee (KRISS)

QCD Axion parameter space



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

Axion Parameter space



Adapted from Graham, arxiv: 1602.00039

Axion and ALP searches

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

Axion-exchange between nucleons

- Scalar coupling $\propto \theta_{QCD}$

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

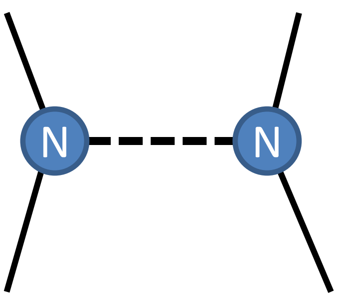
- Pseudoscalar coupling

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

In the non-relativistic limit:

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

Axion acts a force mediator between nucleons

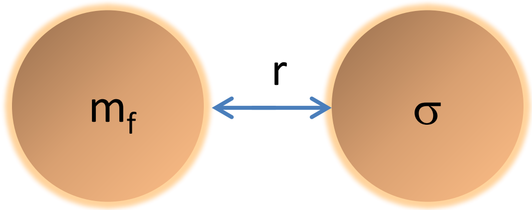


$(g_s^N)^2$ Monopole-monopole

$g_s^N g_P^N$ Monopole-dipole

$(g_p^N)^2$ dipole-dipole

Spin-dependent forces



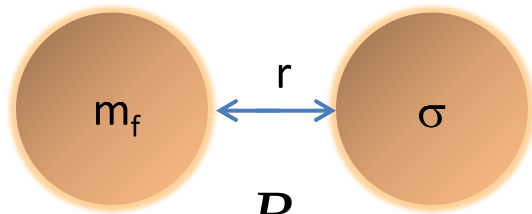
Monopole-Dipole axion exchange

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

Fictitious magnetic field

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

Using NMR for detection



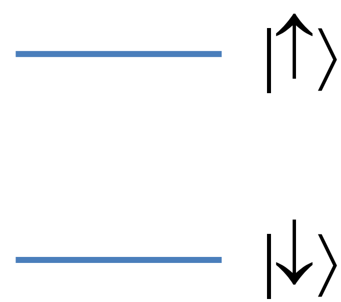
Spin ½ ^{3}He Nucleus

$$B_{\text{eff}}$$

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

Bloch Equations

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

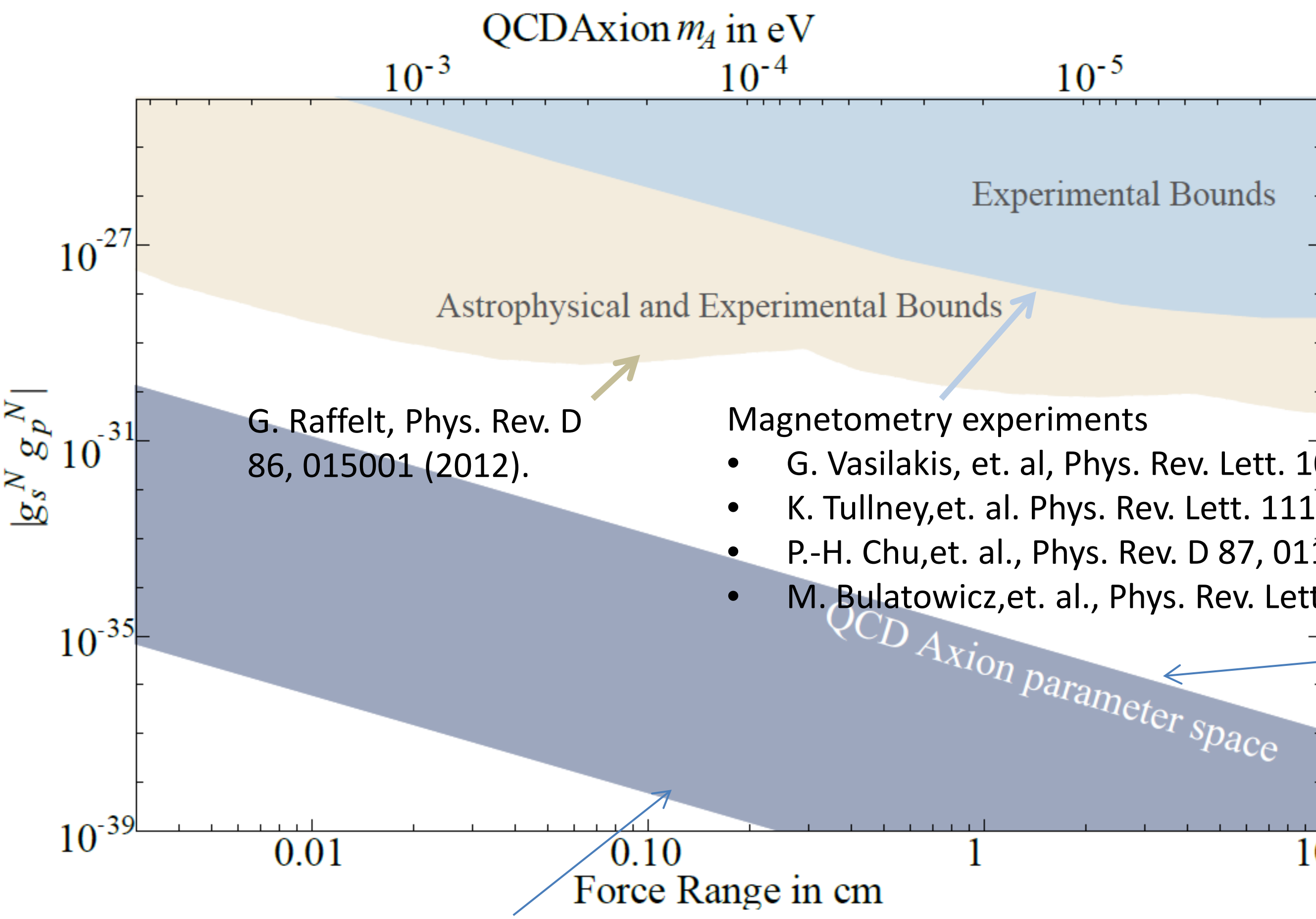


$$\omega = \frac{2\mu_N \cdot B_{\text{ext}}}{\hbar}$$

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).

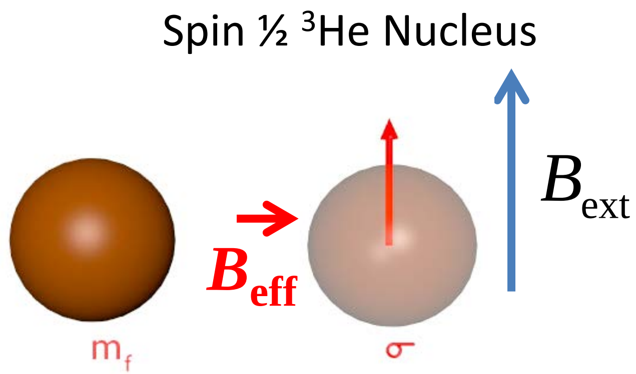
nEDM bound

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

Standard Model lower bound

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

ARIADNE: uses resonant enhancement



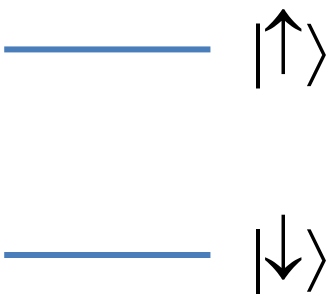
Oscillate the mass at Larmor frequency

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

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

Bloch Equations

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



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

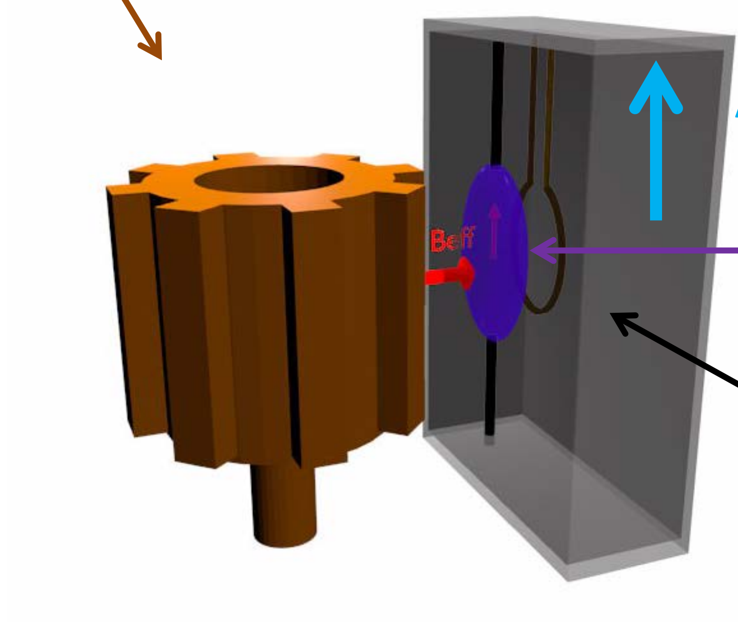
Time varying Axion B_{eff} drives spin precession
→ produces transverse magnetization

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}



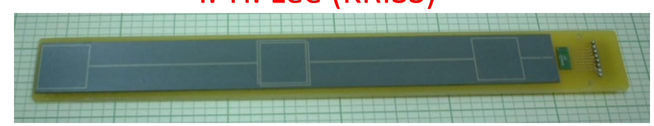
Applied Bias field B_{ext}

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

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

squid pickup loop

Y.-H. Lee (KRISS)



Limit: Transverse spin projection noise

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

Superconducting shielding (Stanford)

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

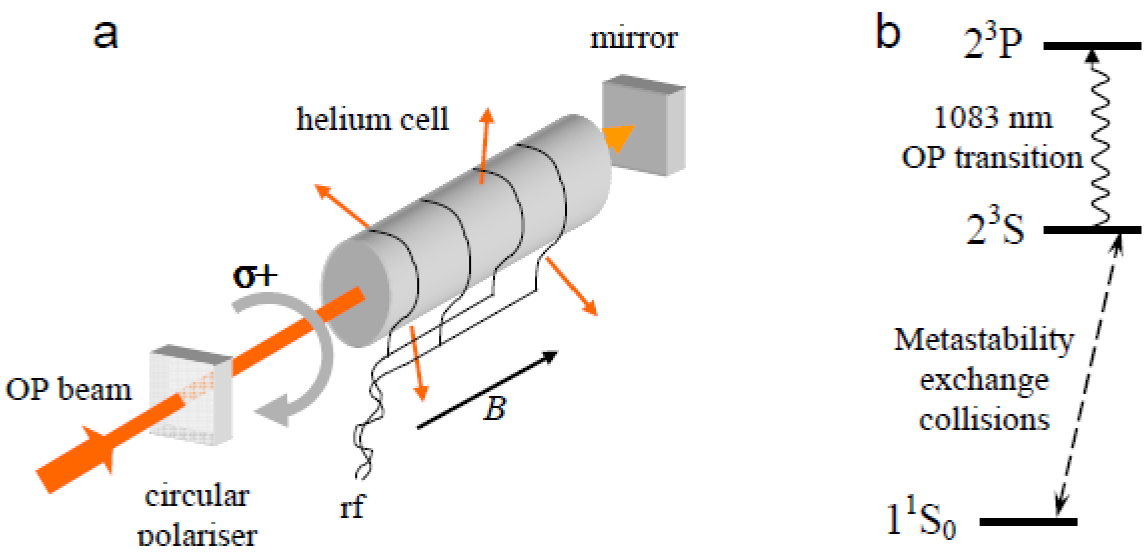
Hyperpolarized ^{3}He

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

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

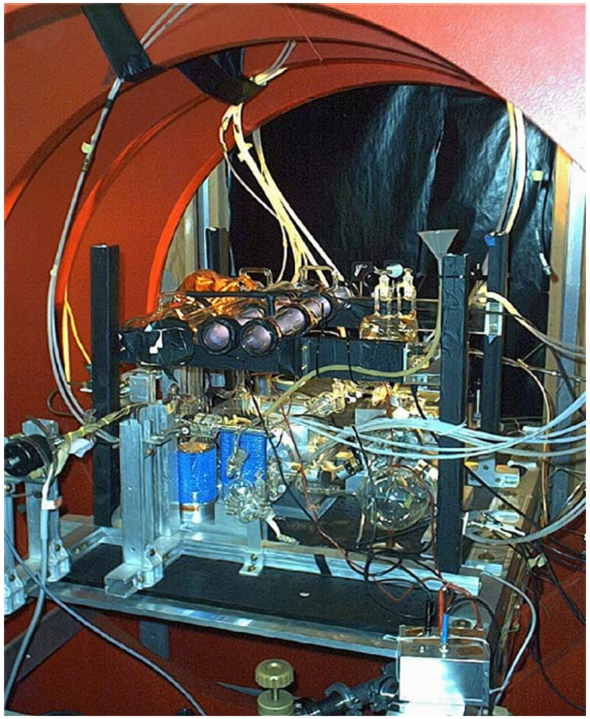
Optical pumping techniques

- Metastability exchange optical pumping



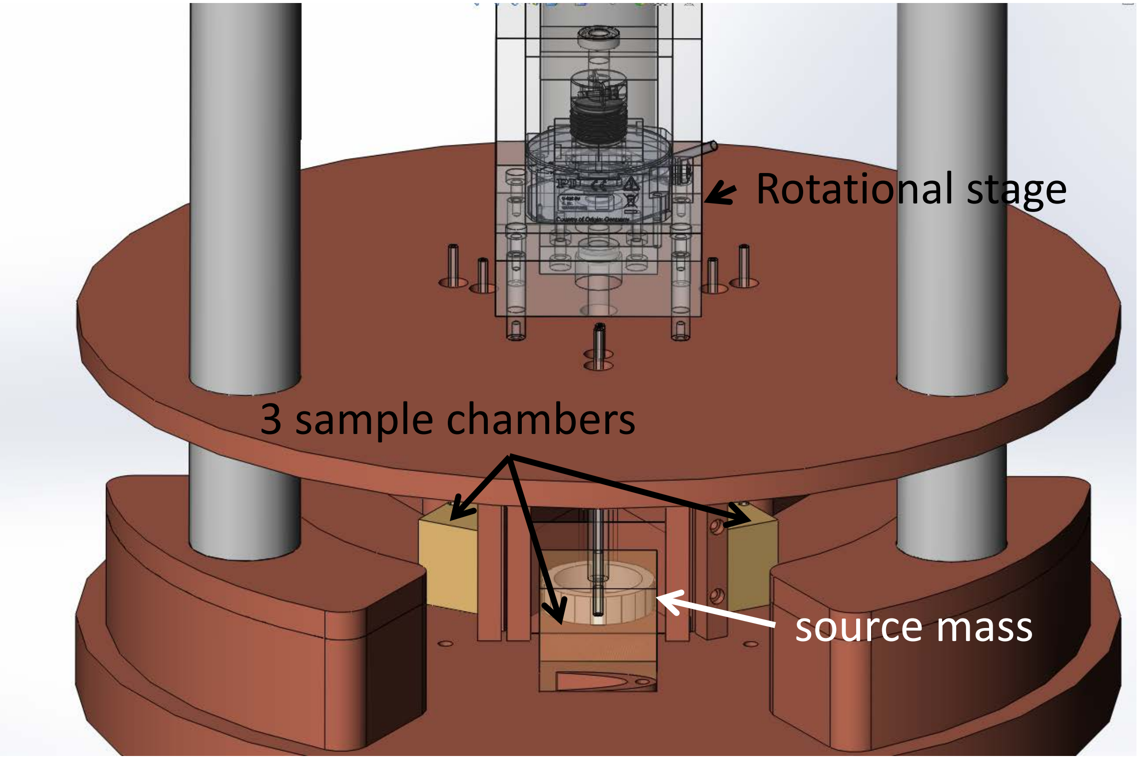
M Batz, P-J Nacher and G Tastevin, Journal of Physics: Conference Series **294** (2011) 012002

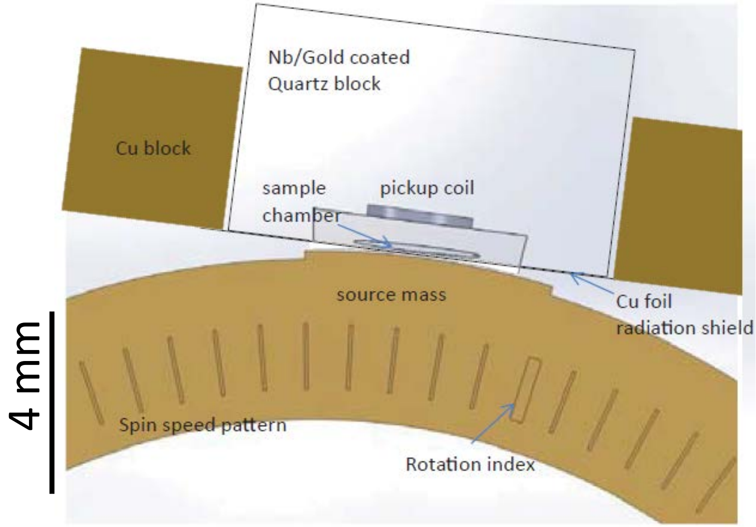
Indiana U. MEOP apparatus



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

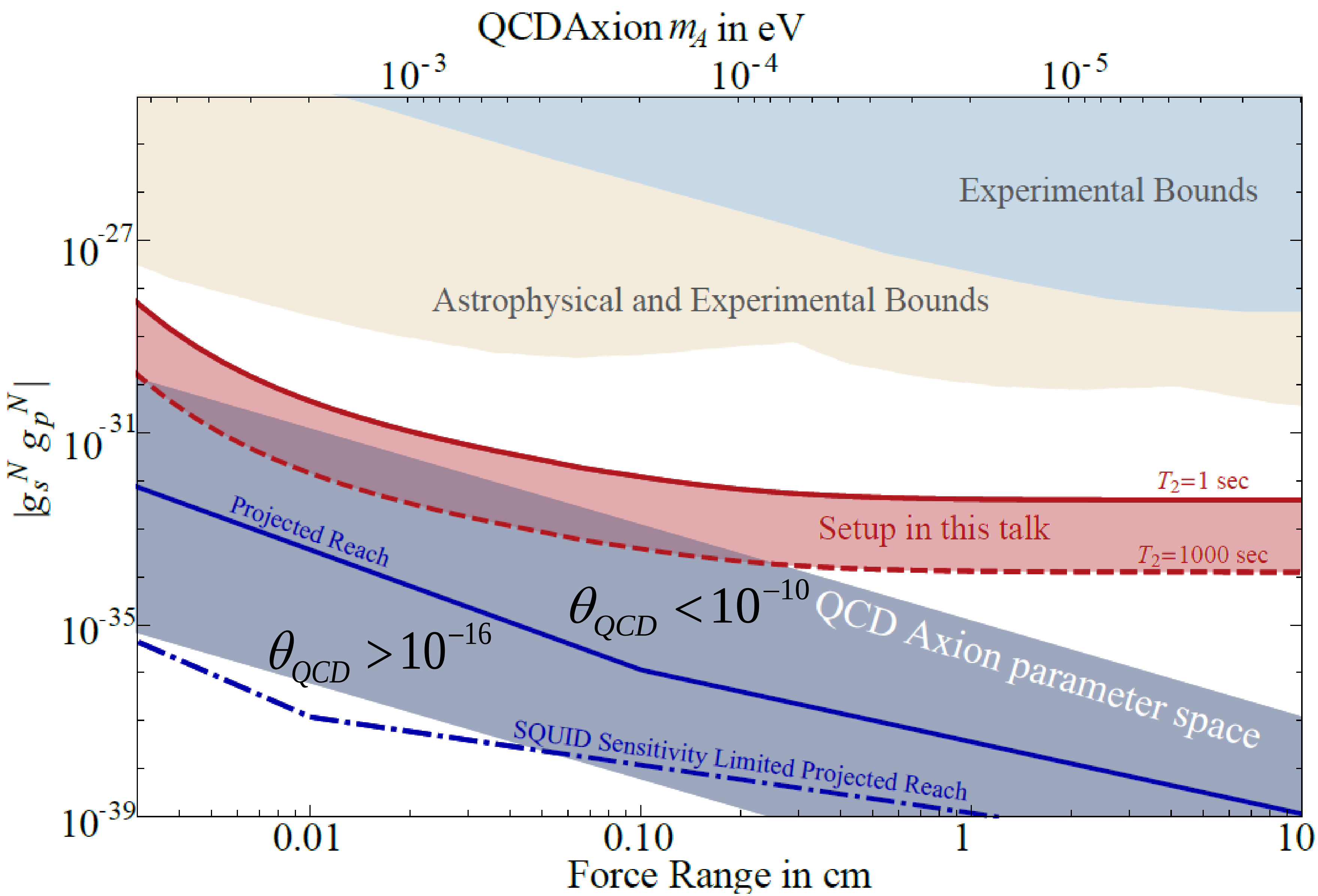
Experimental parameters





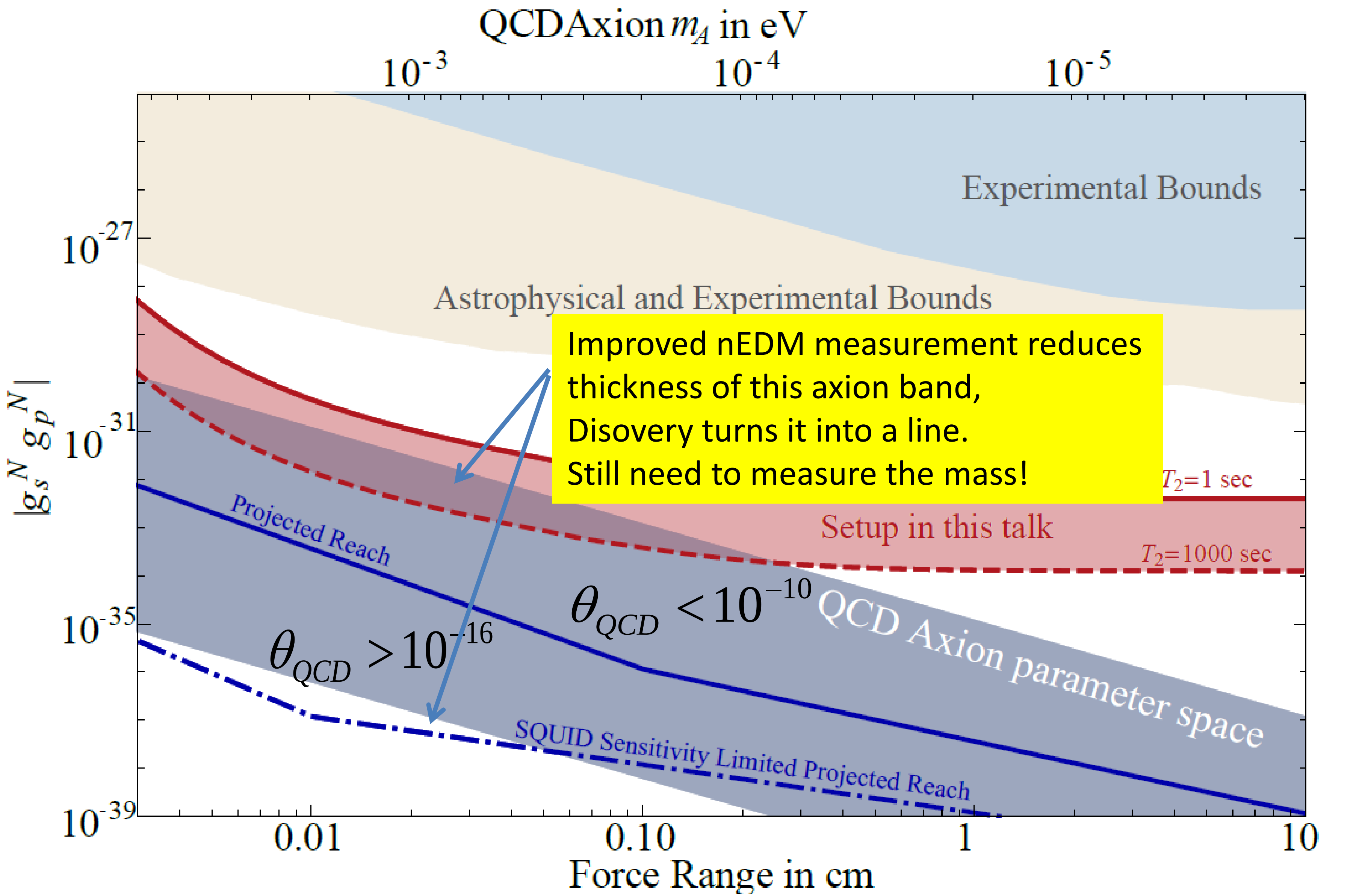
11 segments
100 Hz nuclear spin precession frequency
2 x 10^{21} / cc ^{3}He density
10 mm x 3 mm x 150 µm volume
Separation 200 µm
Tungsten source mass (high nucleon density)

Sensitivity



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

Complementarity with nEDM experiments



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

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

Superconducting Magnetic Shielding

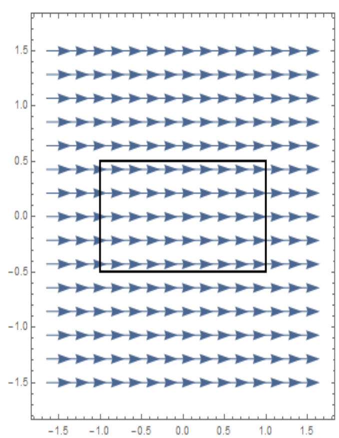
→ Essential to avoid Johnson noise

Meissner Effect

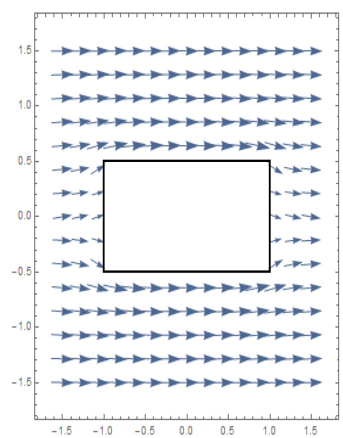
- No magnetic flux across superconducting boundary

Method of Images

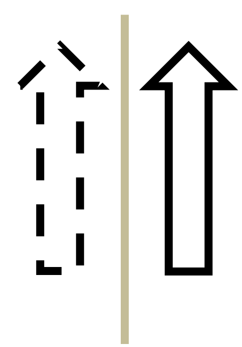
- Make “image currents” mirrored across the superconducting boundary



$T > T_c$



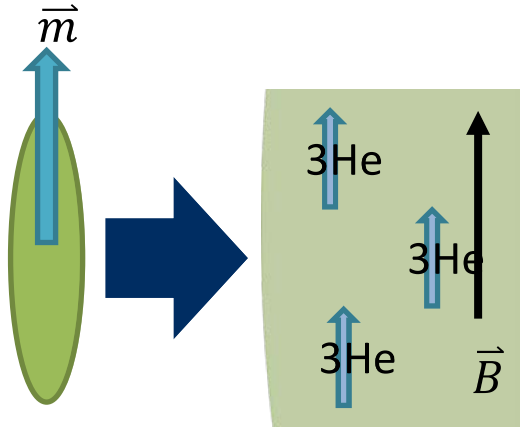
$T < T_c$



Dipole with image

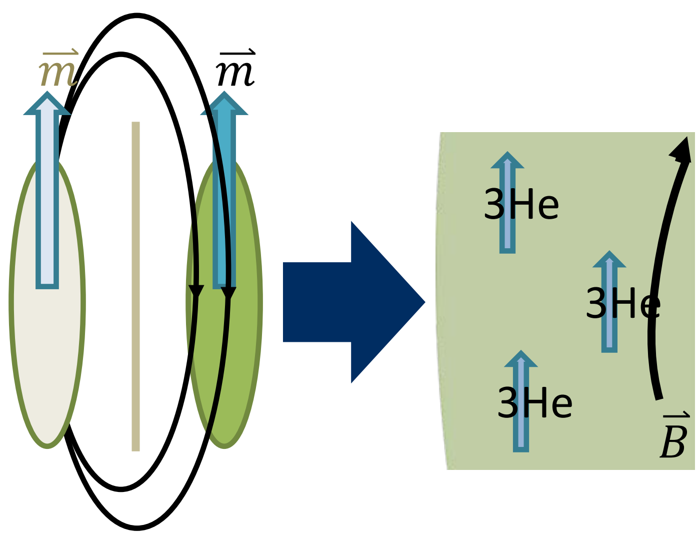
The Problem of Unwanted Images

- 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



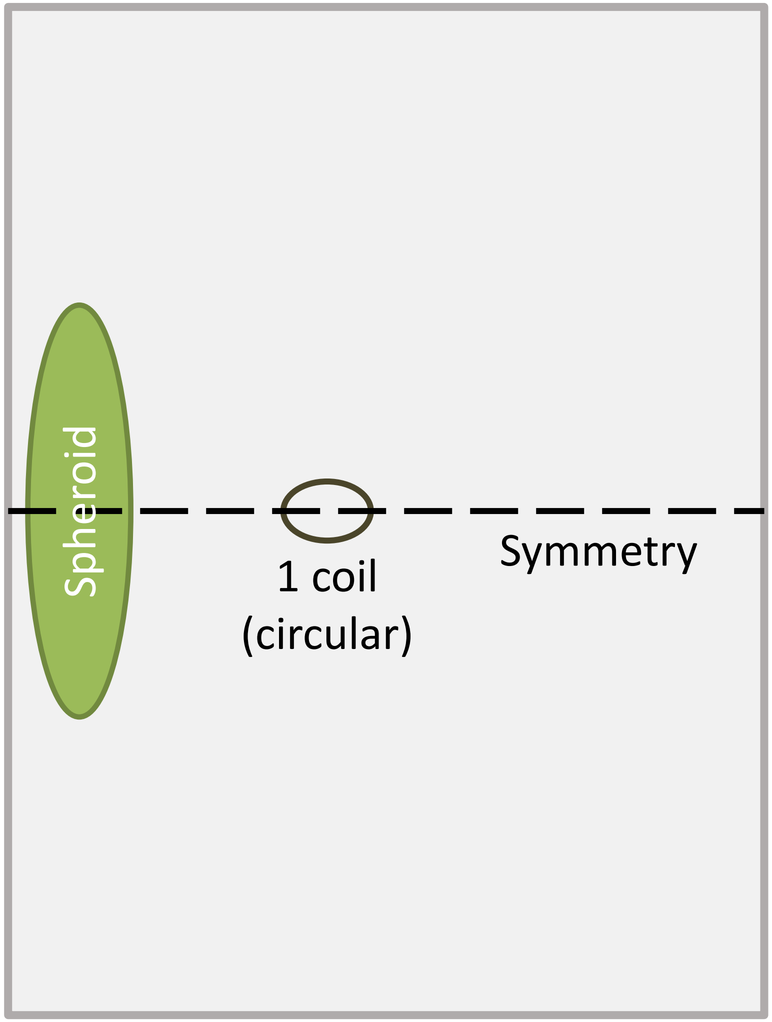
- $B_{in} \neq \text{const.}$
- $\overrightarrow{B_{in}} \nparallel \overrightarrow{m_i}$

→ variations in nuclear Larmor frequency!

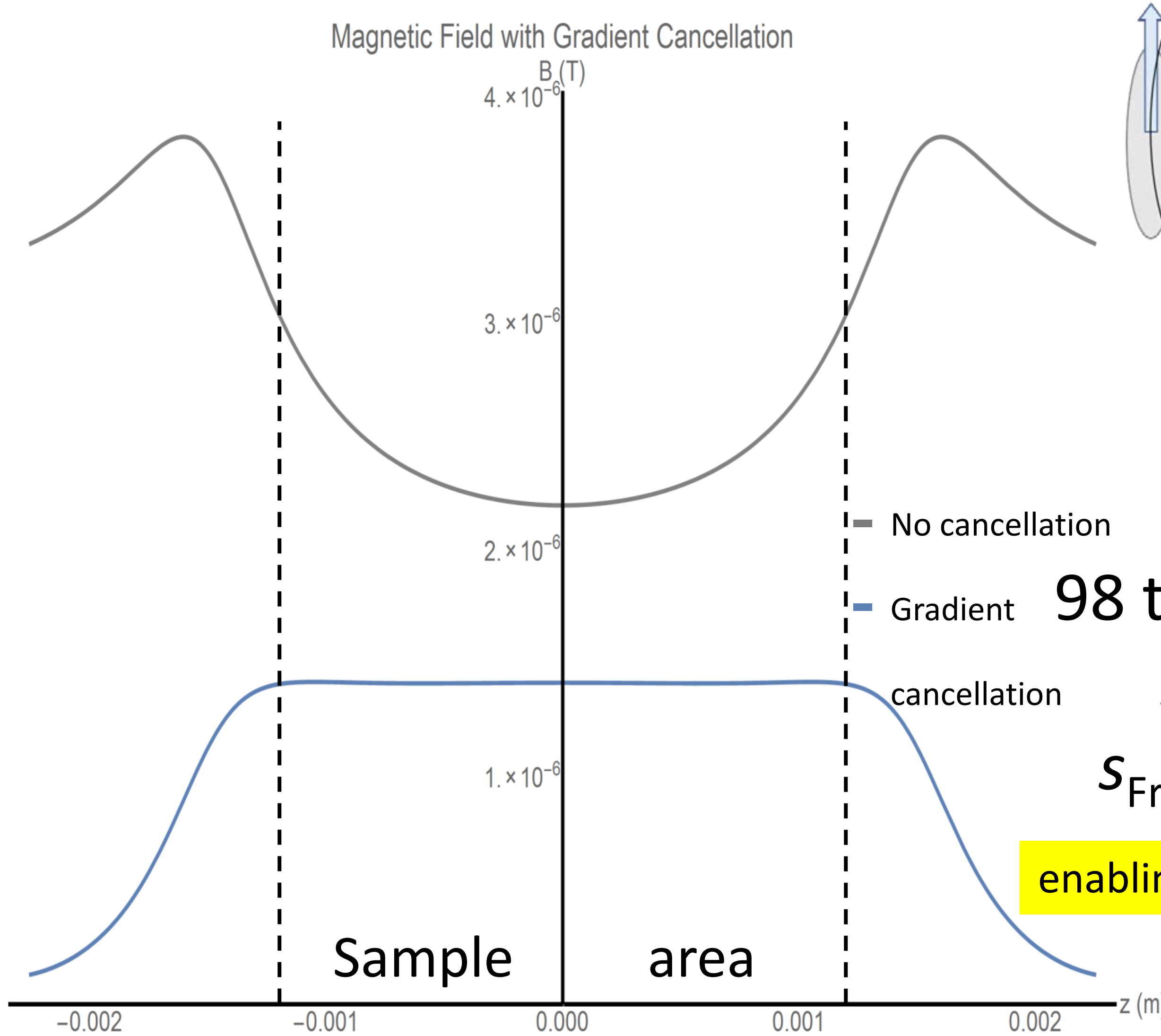
But want to drive entire sample on resonance

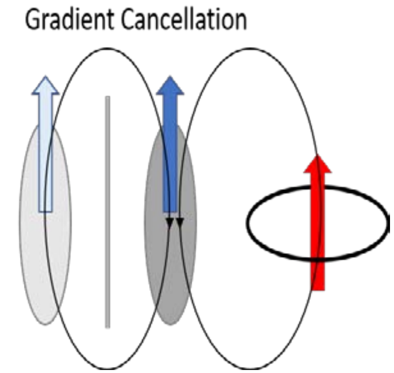
Flattening Solution

- 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%

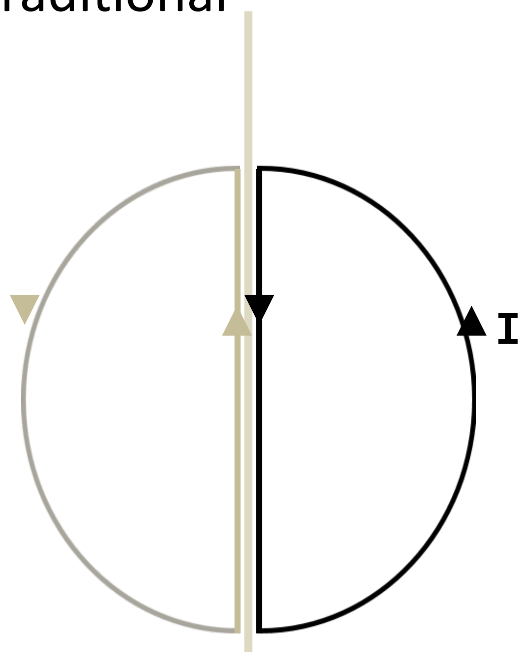
enabling T_2 of ~100 s

Tuning Solution – “D” Coils

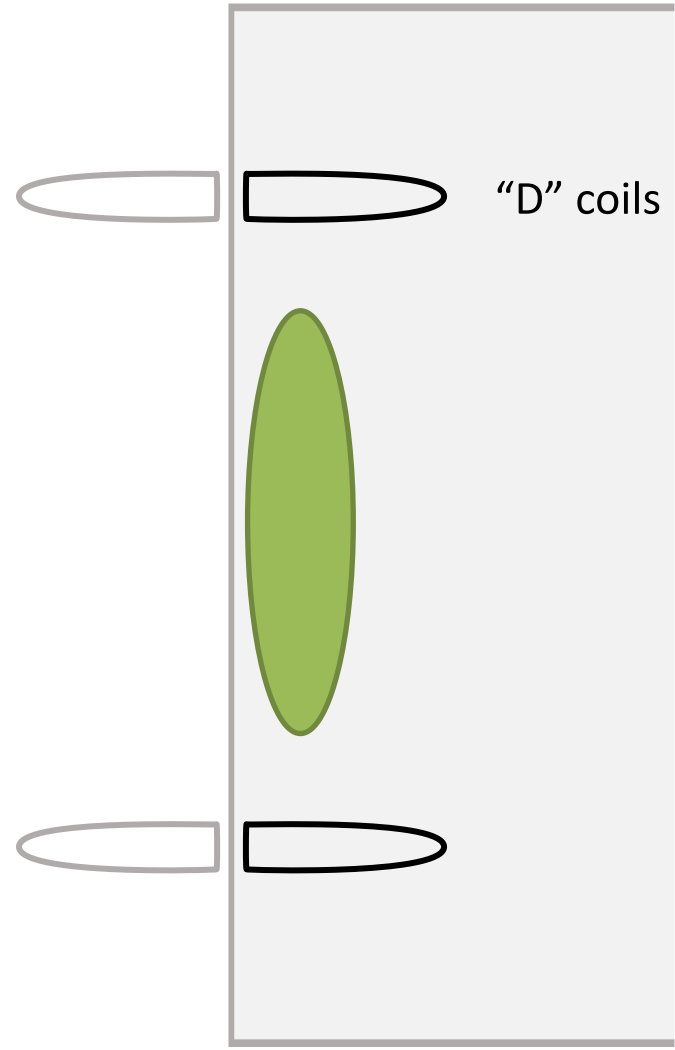
- Tune field with Helmholtz coils
  - Helmholtz field only flat near the center
  - Geometry restrictions prevent the spheroid from being centered in traditional Helmholtz coils

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

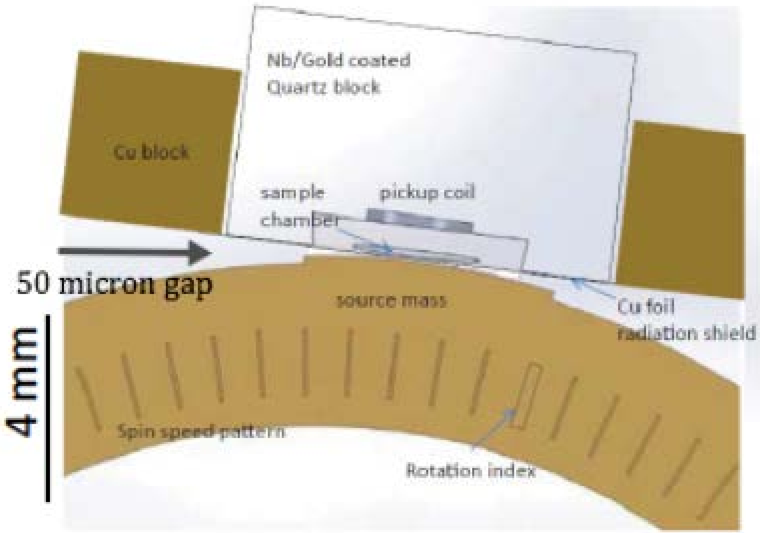
- Inner straight-line currents cancel
- Outer currents do not

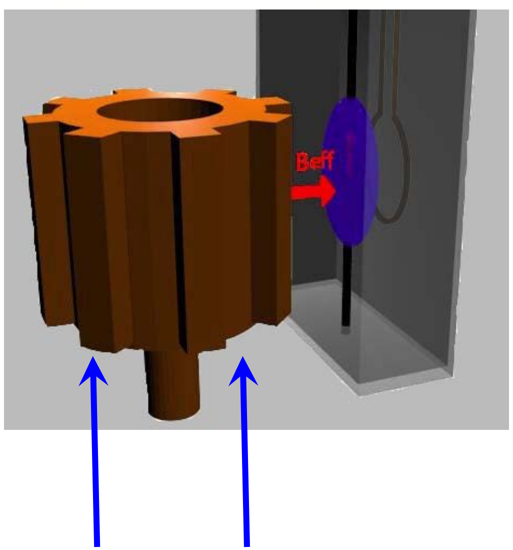


One “D” coil and image (bird’s eye view)

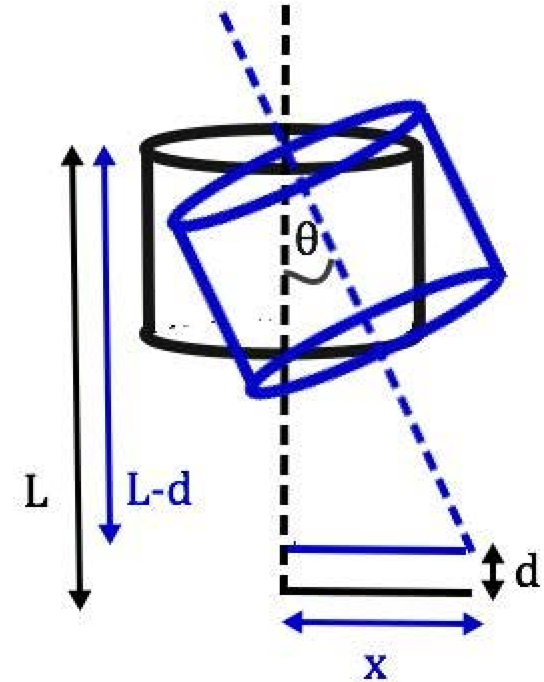


Rotary stage vibration and tilt

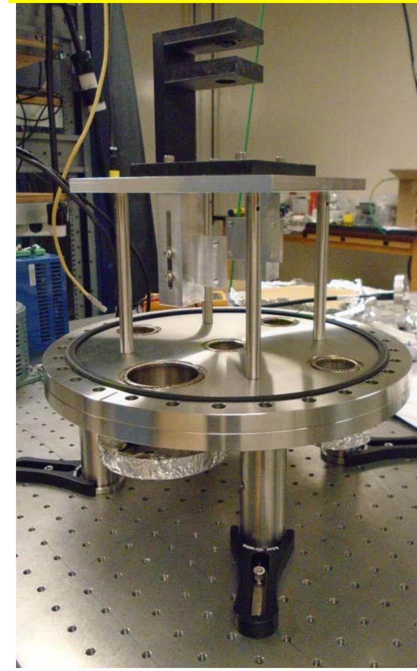




Interferometers

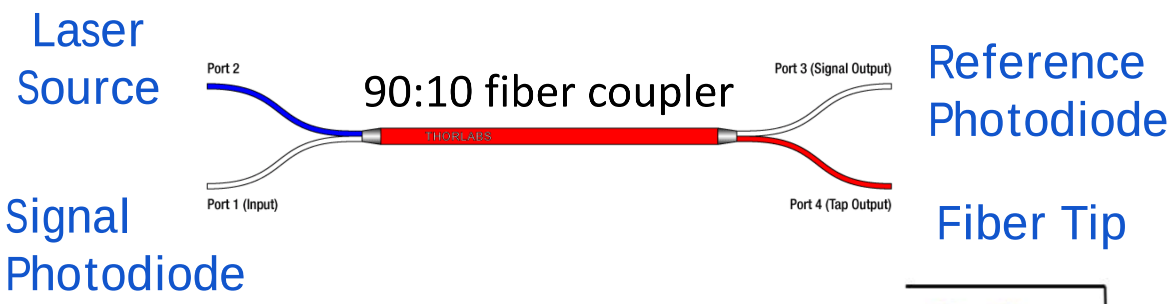


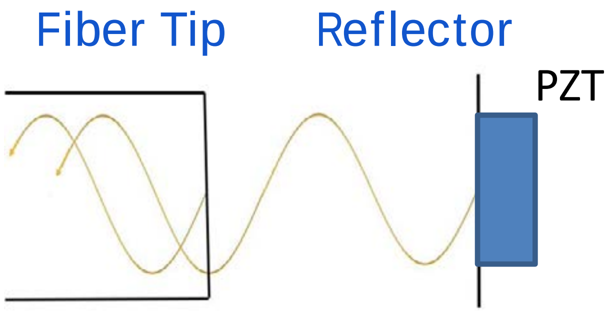
Rotary test chamber

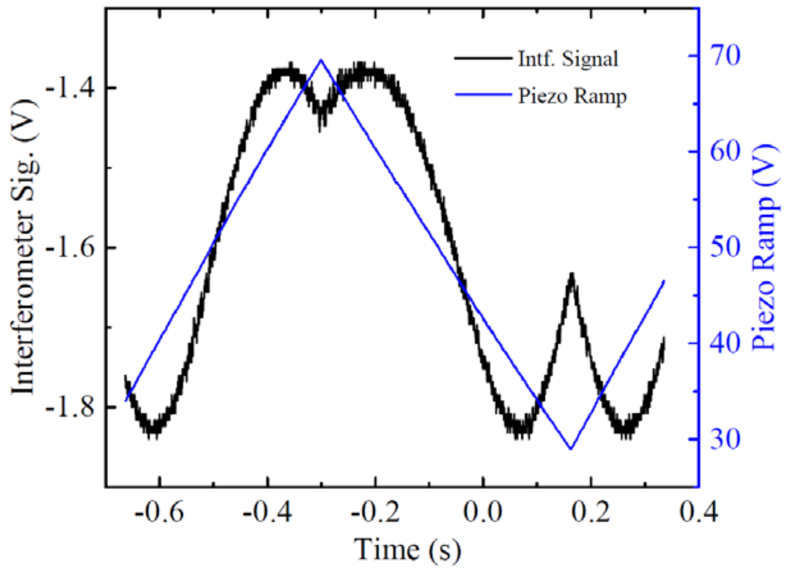


- Build an interferometer to measure the change in distance (d).
- We can find theta (ϴ) from:
  $$\Theta = \cos^{-1}((L-d)/L)$$
- We can solve for the wobble distance (X) by:
  $$X = L\sin(\Theta)$$

Fiber-coupled laser interferometers



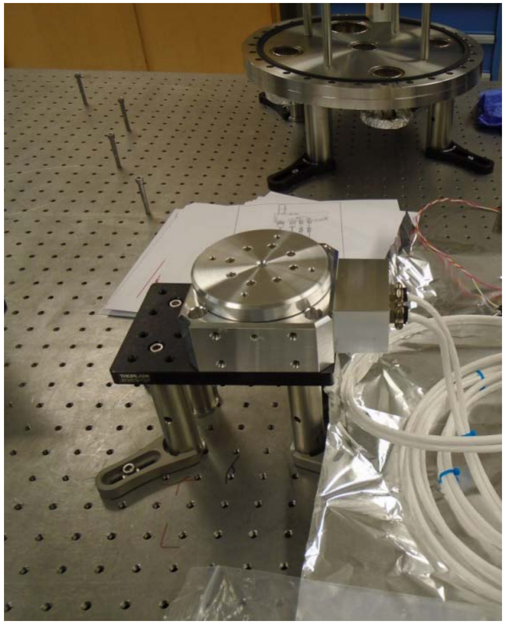




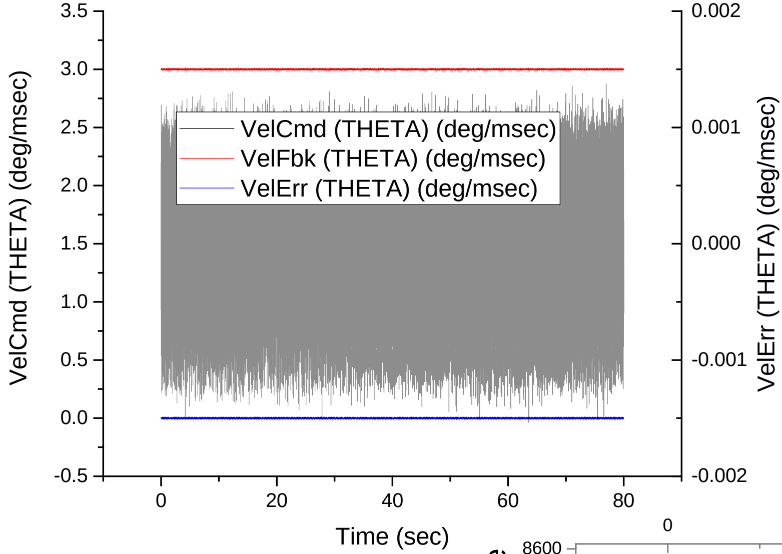
Fringe visibility
~0.13
Sensitivity
~160 nm/V
Shot noise limit
~20 pm/Hz$^{1/2}$

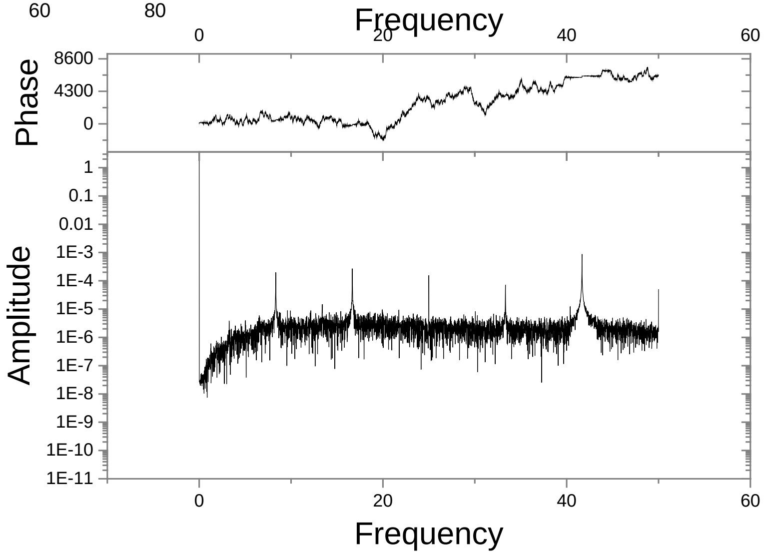
Speed stability test - direct drive stage

- Optical encoder
- Current feedback control



Stage speed stability error – unloaded, in air

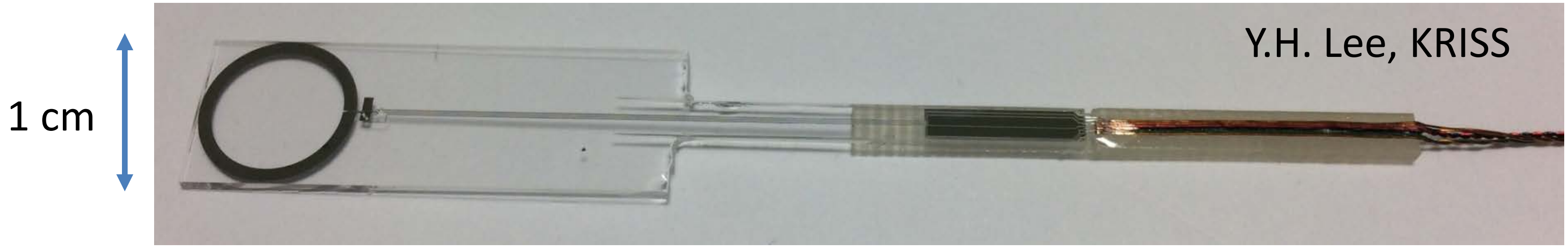


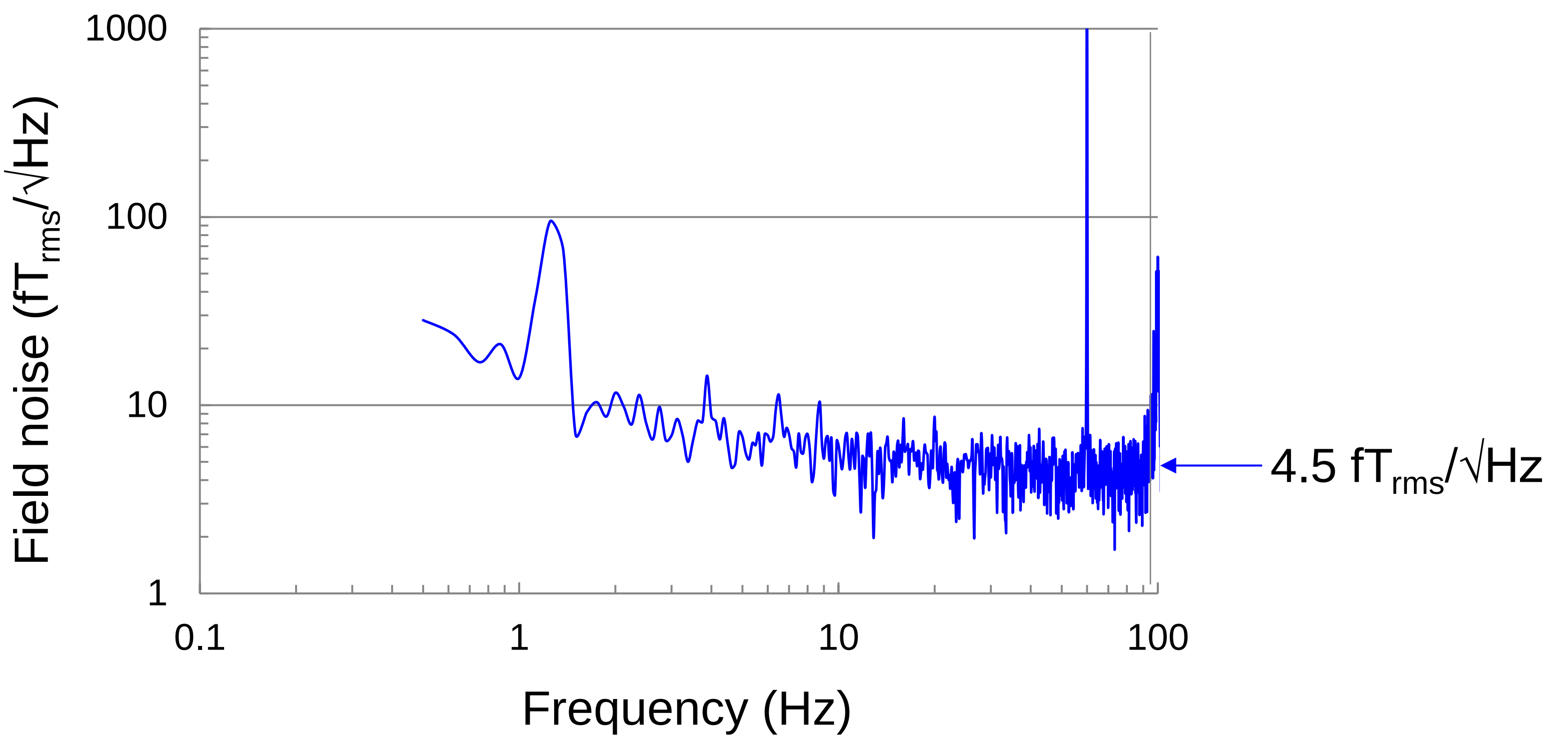


Rotation speed control
8.3 Hz ~ 1 part in 10000
RMS ~ 1 part in 3000

Allows utilization of T2 > 100s

SQUID Magnetometers



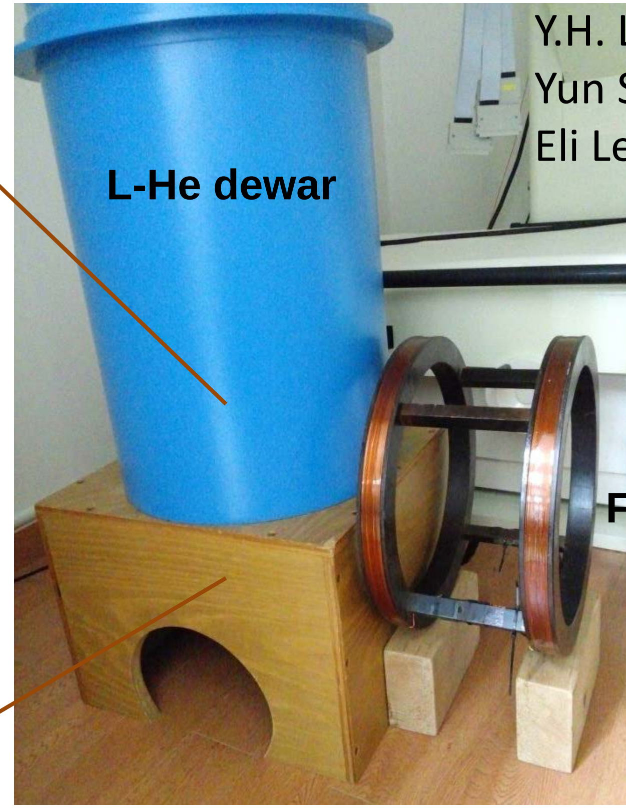


Measured inside a magnetically shielded room (without Nb tube)

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 planned Apr 2017

Summary for ARIADNE

ARIADNE → New resonant NMR method

- Gap in experimental QCD axion searches

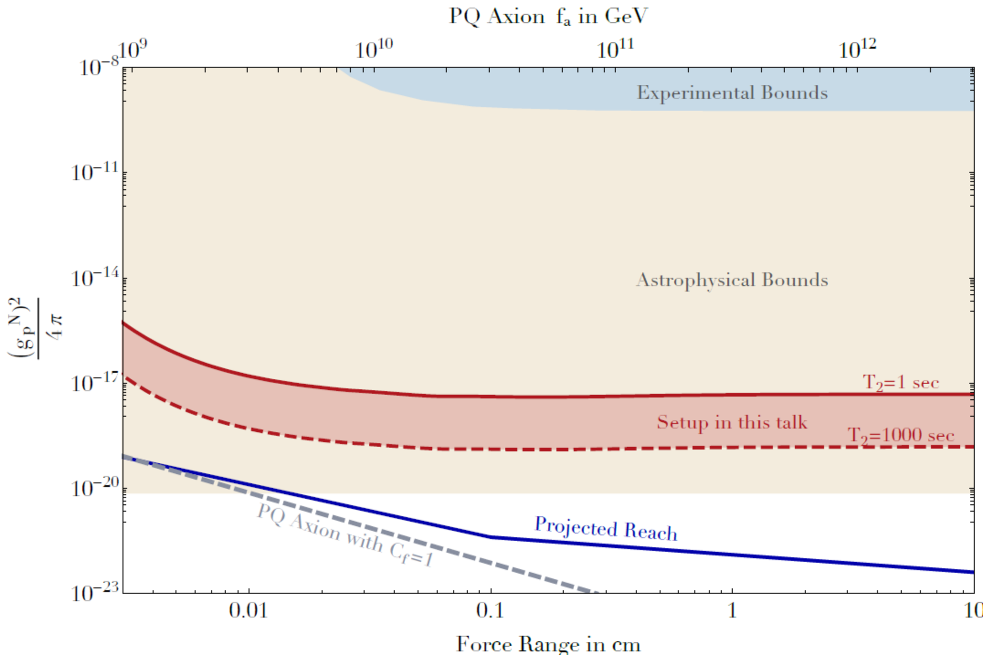
  $$0.1 \text{ meV} < m_a < 10 \text{ meV}$$

- 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), ^3He system (Indiana)

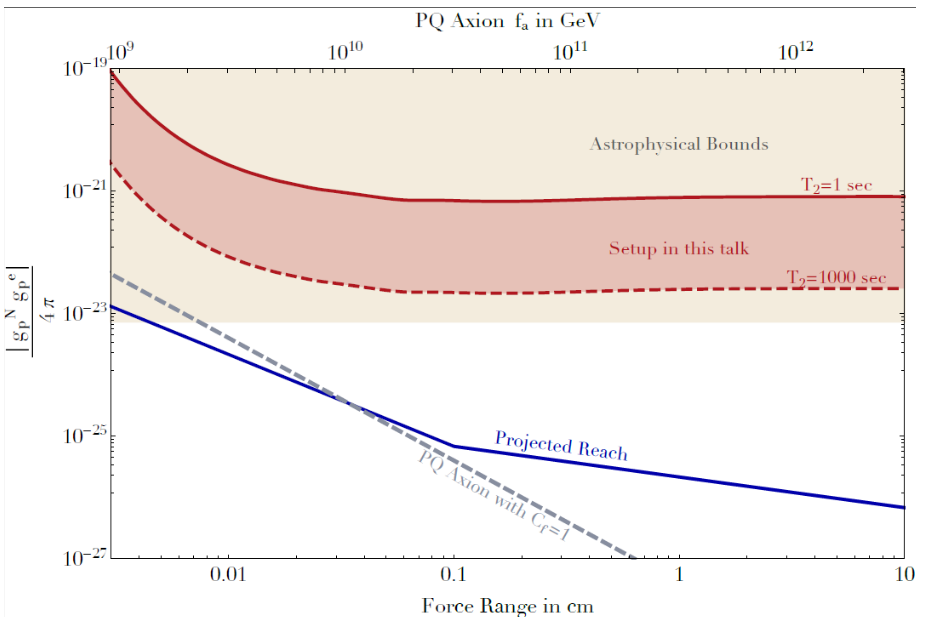
Dipole-Dipole axion forces

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

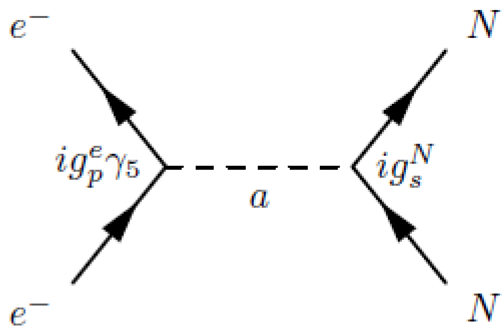
Nuclear spin

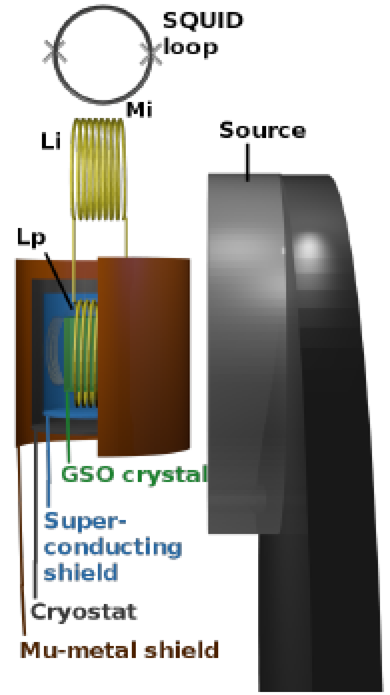


Electron spin



QUAX-gpgs





The experiment (see Ref.[16] for more details) is performed by measuring the magnetization of a cubic sample of gadolinium oxyorthosilicate Gd_2SiO_5 crystal (GSO) with 1 cm edge length, induced by $N_s = 4$ disk shaped lead masses (sources). The distance between the center of mass of each B_{eff} source and the GSO crystal is modulated in time by mounting the masses on a rotating aluminum wheel as illustrated in Fig.(3). Each mass is fixed on the aluminum

N. Cresini et.al., Arxiv: 1705.06044

New limits from QUAX gsgp (May 2017)

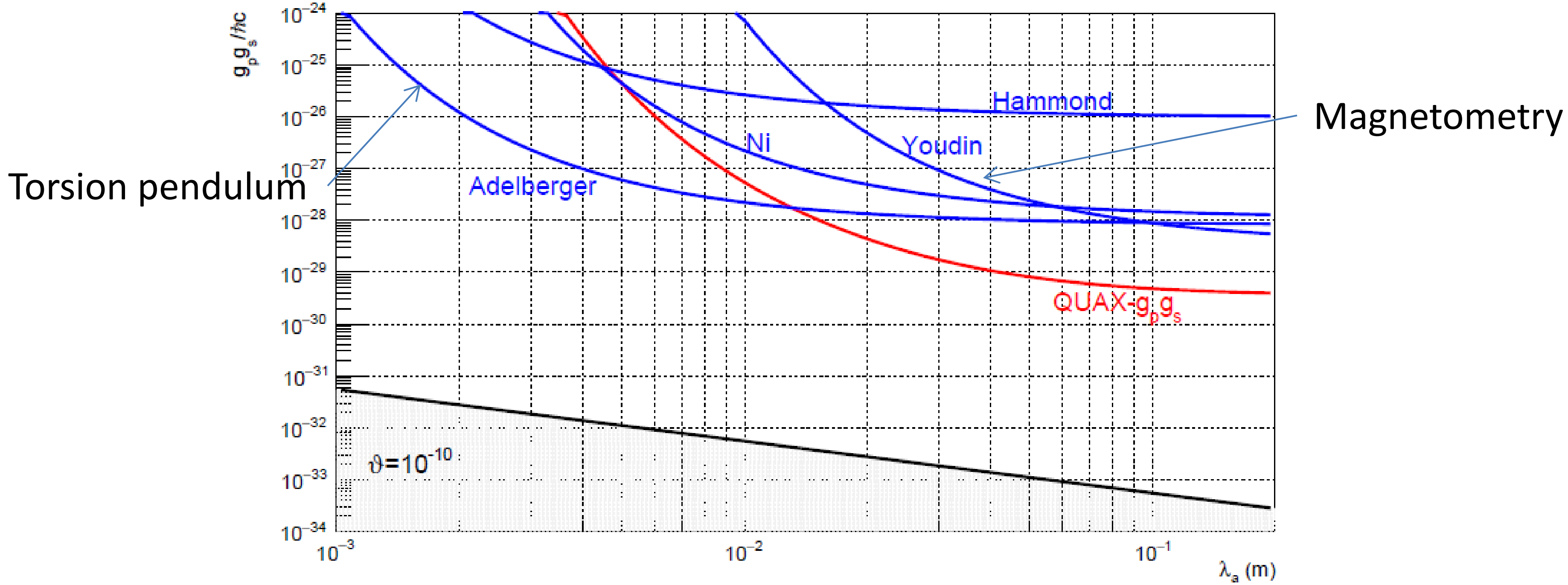


Figure 6: Exclusion plots of monopole-dipole coupling vs. λ_a. The limit on the $g_p^e g_s^N$ coupling is lowered of more than one order of magnitude in respect to the previous measurements for $\lambda \sim 10\,\text{cm}$ (red line). We also show the expected $g_p^e g_s^N$ magnitude in Eq.(2) for $\vartheta \sim 10^{-10}$ in transparent grey and upper limits already reported in literature: Hammond [7], Youdin [9], Ni [8] and Adelberger [18].

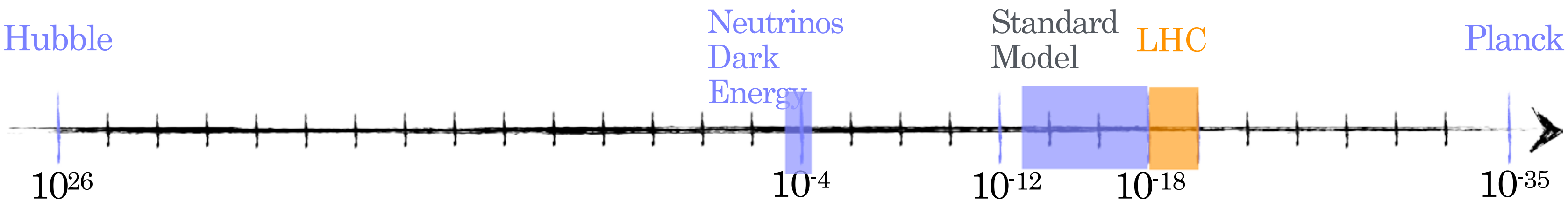
N. Cresini et.al., Arxiv: 1705.06044

Lots of opportunities to probe low energy fundamental physics!

- Short distance gravity tests
- Equivalence principle tests
- EDMs
- Axions
- Ultralight DM (scalars, axions, ALPS)
- Gravitational waves

…several others

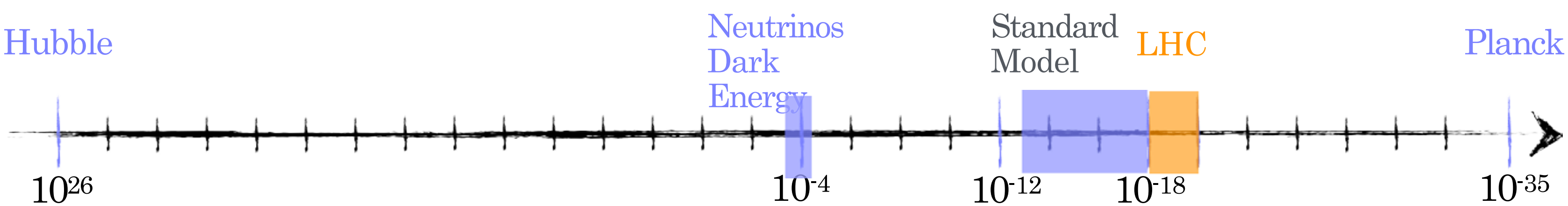
The Length Scales in the Universe



Scale in meters

80% of the energy scale left to explore

The Length Scales in the Universe



Scale in meters

There are more things in heaven and earth, Horatio,
Than are dreamt of in your philosophy.
- Hamlet

80% of the energy scale left to explore

From M. Arvanitaki