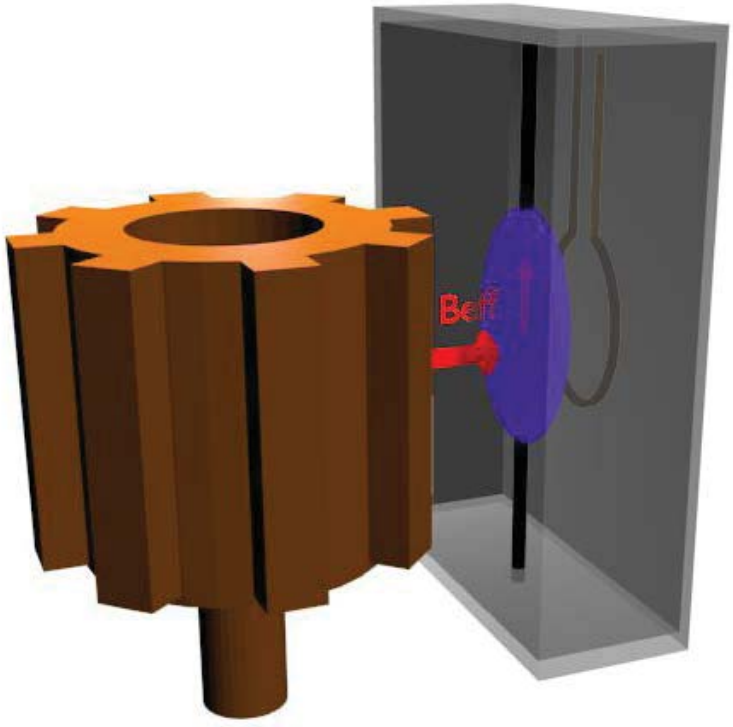
The Axion Resonant InterAction Detection Experiment (ARIADNE)



Mark Cunningham (UNR)
Mindy Harkness (UNR)
Jordan Dargert (UNR)
Chloe Lohmeyer (UNR)
Harry Fosbinder-Elkins (UNR)
Asimina Arvanitaki (Perimeter)
Aharon Kapitulnik (Stanford)
Eli Levenson-Falk (Stanford)
Sam Mumford (Stanford)
Josh Long (IU)
Chen-Yu Liu (IU)
Mike Snow (IU)
Erick Smith (IU)
Justin Shortino (IU)
Inbum Lee (IU)
Evan Weisman (IU)
Yannis Semertzidis (CAPP)
Yun Shin (CAPP)
Yong-Ho Lee (KRISS)

A. Geraci, UN-Reno

Light Dark World 2017, Pittsburgh

HEISING-SIMONS FOUNDATION
NSF
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University of Nevada, Reno
PERIMETER INSTITUTE FOR THEORETICAL PHYSICS
INDIANA UNIVERSITY
LELAND STANFORD JUNIOR UNIVERSITY 1891

Geraci Lab moving January 2018

Northwestern University

The Center for Fundamental Physics at Low Energy (CFP)

Department of Physics and Astronomy

Core Research Groups in the CFP:

Board of Trustees Professor Gerald Gabrielse, one of the world's leading practitioners of fundamental, low energy physics and an active member of the National Academy of Sciences, is relocating from Harvard to Northwestern to be the founding director of the CFP. An award-winning researcher and teacher, Gabrielse has chaired both the Harvard Physics Department and the Division of Atomic, Molecular and Optical Physics (DAMOP) of the American Physical Society, and he leads the international ATRAP Collaboration at CERN. The **Gabrielse research group** tested the most precise prediction of the Standard Model of Particle Physics using the most precisely measured property of an elementary particle, tested the Standard Model's most fundamental symmetry to an exquisite precision, made one of the most stringent tests of Supersymmetry and other proposed improvements to the Standard Model, and started low energy antiproton and antihydrogen physics.

Associate Professor Brian Odom is joining the CFP. His fundamental physics accomplishments include a Harvard measurement of the electron magnetic moment (for which he received the DAMOP PhD thesis prize), and dark matter research done while a Kavli postdoctoral fellow at the University of Chicago. The **Odom research group** at Northwestern is successfully developing methods to trap, cool and probe molecular ions. One motivation is to use these for fundamental physics measurements, including new searches for time variations of some of the fundamental constants of nature.

Two new faculty members will shortly be hired to lead additional core research groups of the CFP.

Opportunities for postdocs, students!
New faculty search underway Fall 2017!

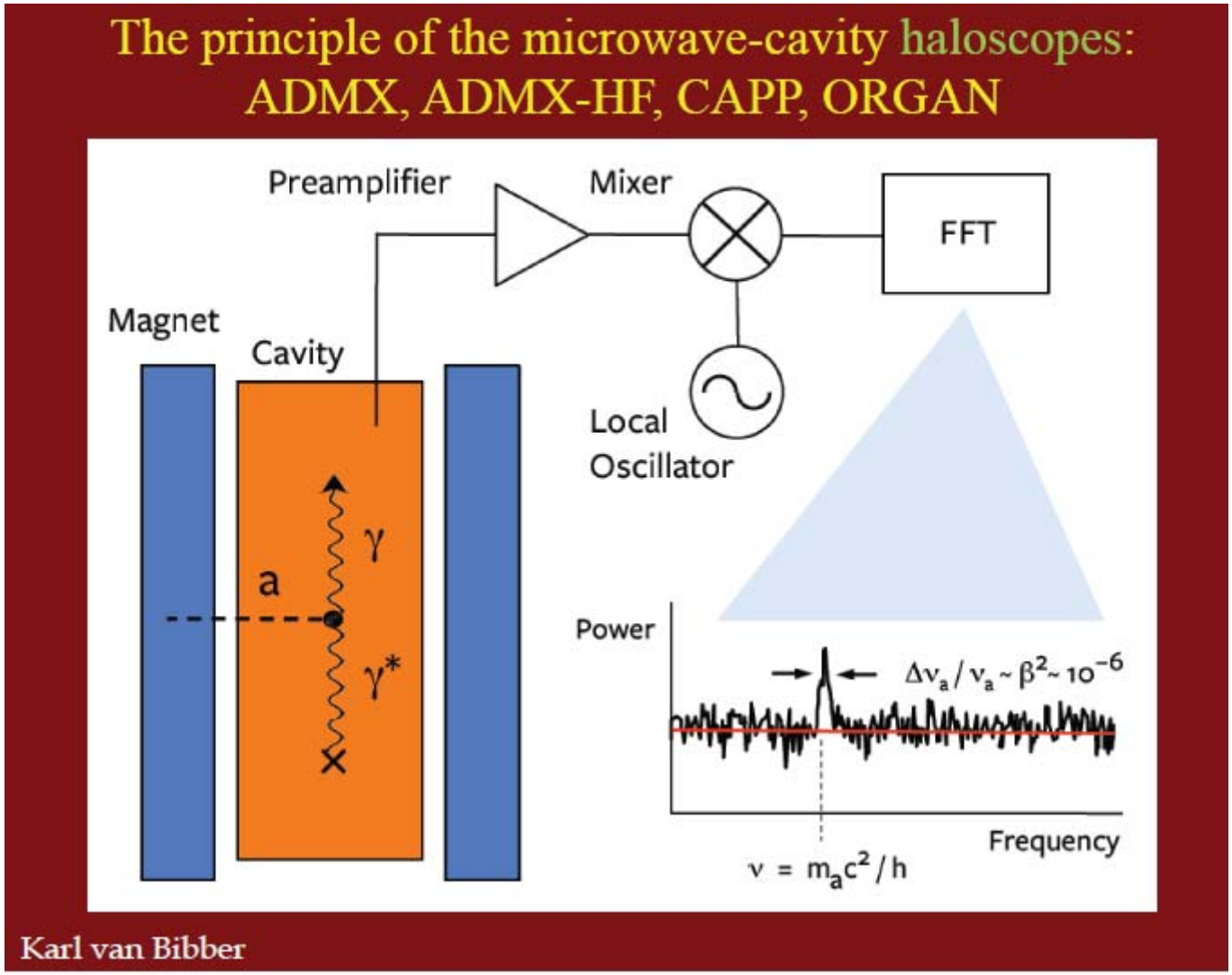
Axions

- Light pseudoscalar particles in many theories Beyond Standard model
- Peccei-Quinn Axion (QCD) solves strong CP problem $\theta_{QCD} < 10^{-10}$
- Dark matter candidate

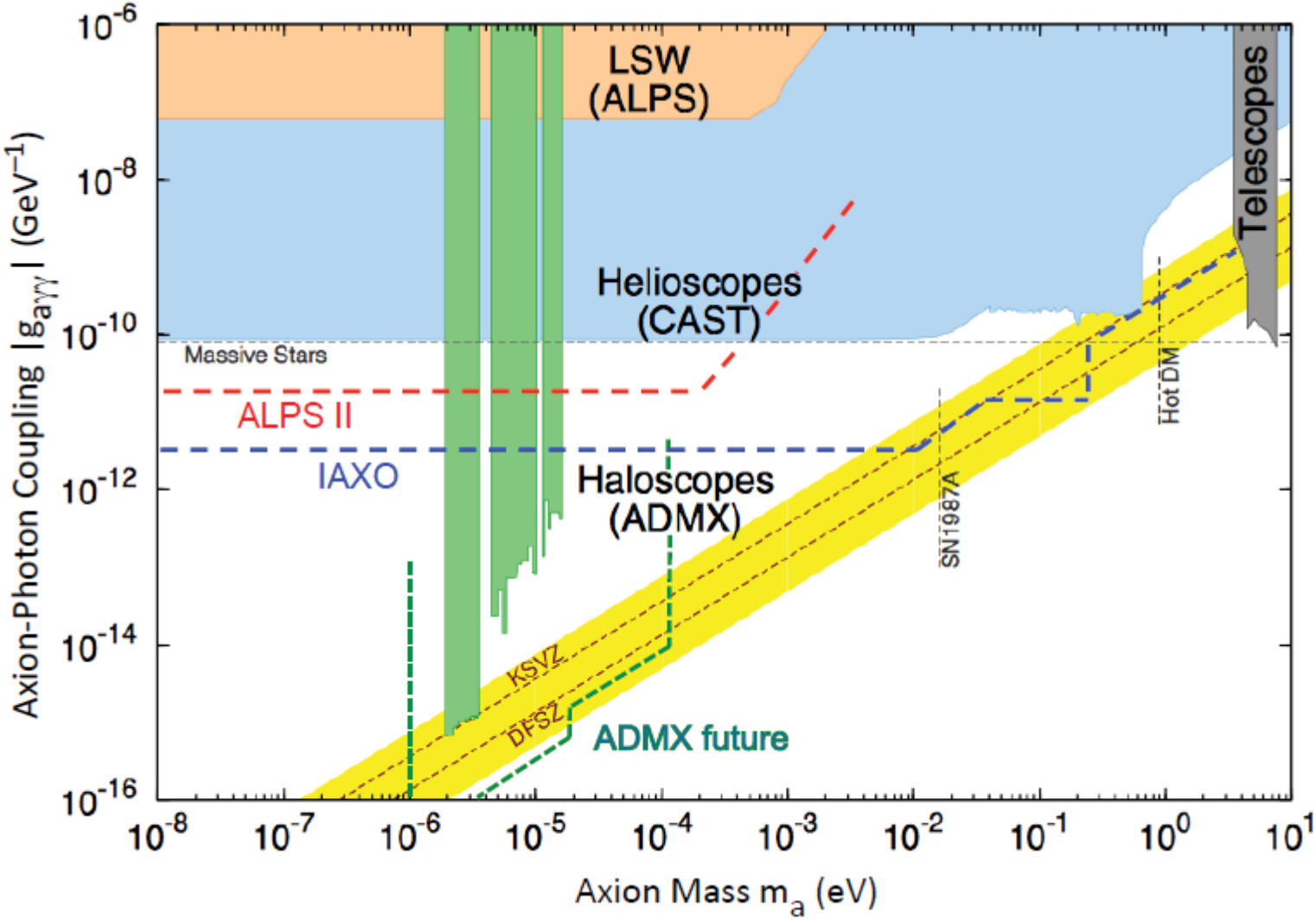
Experiments: e.g. ADMX, HAYSTACK, LC-circuit, Casper

- 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).

Haloscopes


The principle of the microwave-cavity haloscopes:
ADMX, ADMX-HF, CAPP, ORGAN
Preamplifier
Mixer
FFT
Magnet
Cavity
Local
Oscillator
a
γ
γ*
Power
$\Delta\nu_a / \nu_a \sim \beta^2 \sim 10^{-6}$
Frequency
$\nu = m_a c^2 / h$
Karl van Bibber

Axion Parameter space



Adapted from Graham, arxiv: 1602.00039

Axion couplings

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

Coupling to electromagnetic field

ADMX, DM Radio, LC Circuit

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

Coupling to gluon field

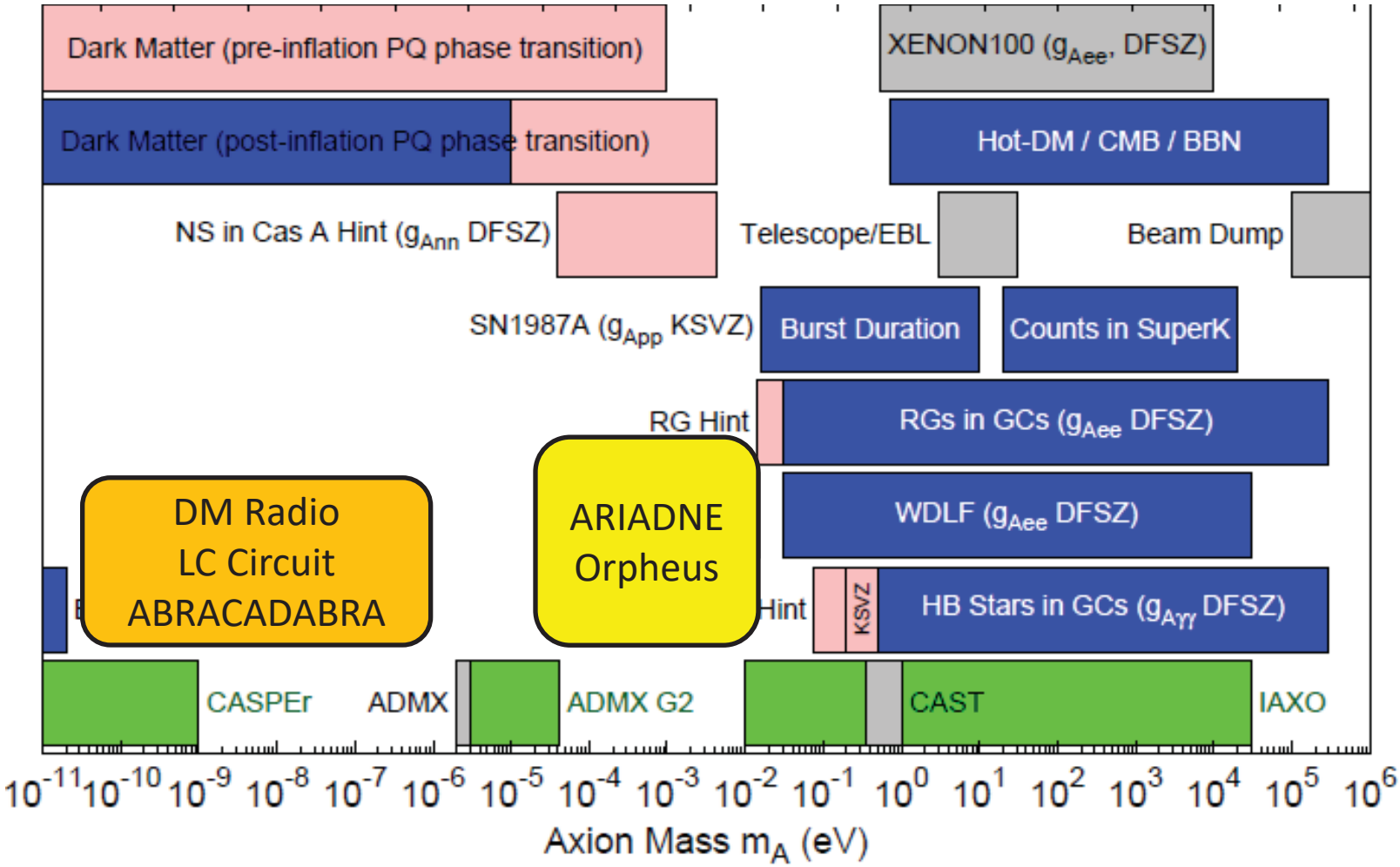
e.g. CASPEr-electric

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

Coupling to fermions

e.g.CASPEr-wind, QUAX

QCD Axion parameter space



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

Axion and ALP searches

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

Axion-exchange between nucleons

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

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

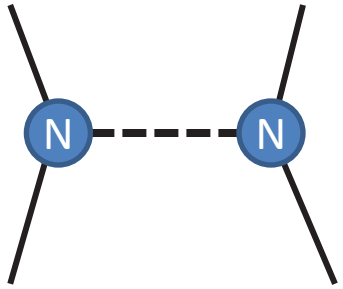
- Pseudoscalar coupling

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

In the non-relativistic limit:

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

Axion acts a force mediator between nucleons

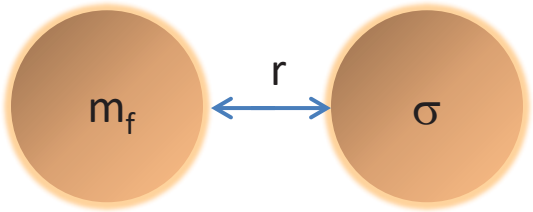


$(g_s^N)^2$ Monopole-monopole

$g_s^N g_P^N$ Monopole-dipole

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

Spin-dependent forces



Monopole-Dipole axion exchange

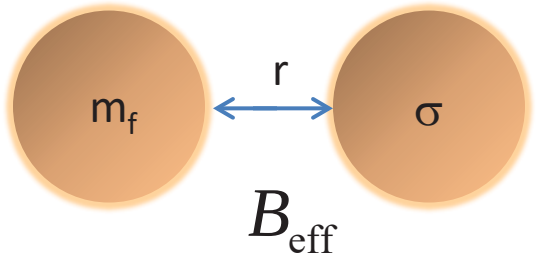
$$U(r) = \frac{\hbar^2 g_s^N g_p^N}{8\pi m_f}\left(\frac{1}{r\lambda_a} + \frac{1}{r^2}\right)e^{-r/\lambda_a}(\hat{\sigma}\cdot\hat{r}) \quad \equiv \mu \cdot B_{\text{eff}}$$

$m_a < 6$ meV ⟹ $\lambda_a > 30$ μm

Fictitious magnetic field

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

Using NMR for detection

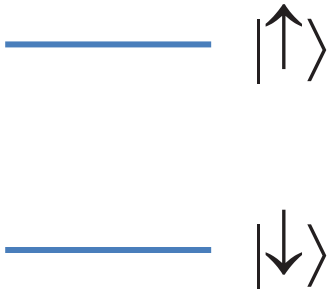


Spin ½ ^{3}He Nucleus

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

Bloch Equations

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

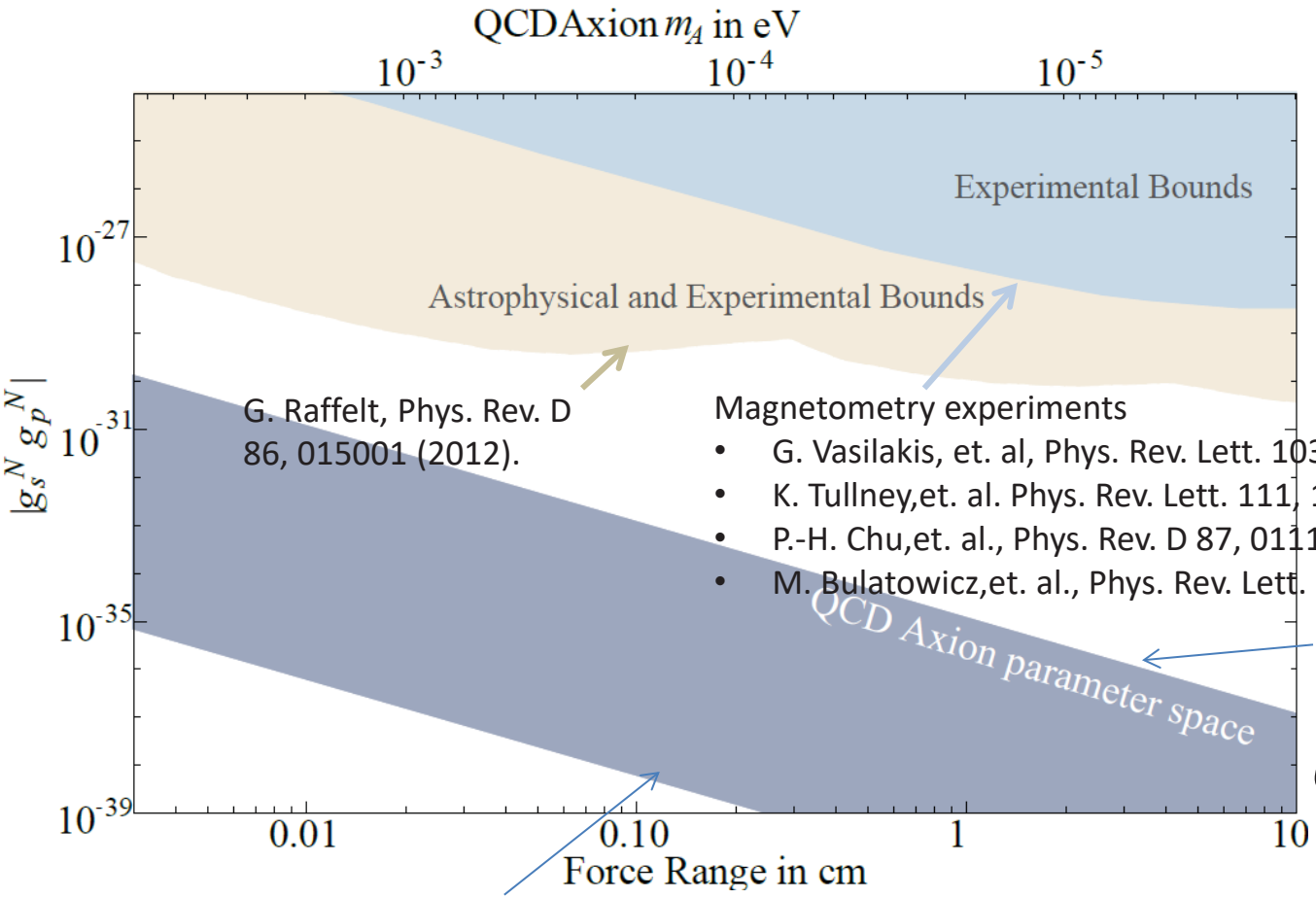


$$\omega = \frac{2\mu_N \cdot B_{\text{ext}}}{\hbar}$$

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

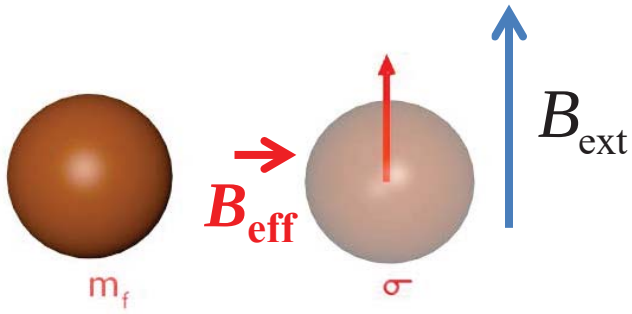
$\theta_{QCD} > 10^{-16}$

ARIADNE: uses resonant enhancement

Spin ½ ^{3}He Nucleus

Oscillate the mass at Larmor frequency

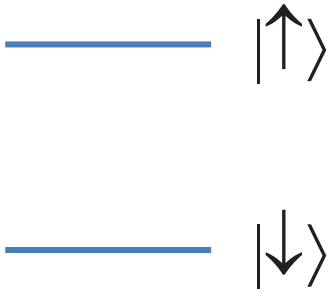
$$B_{\text{eff}} = B_{\perp}\cos(\omega t)$$



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

Bloch Equations

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



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

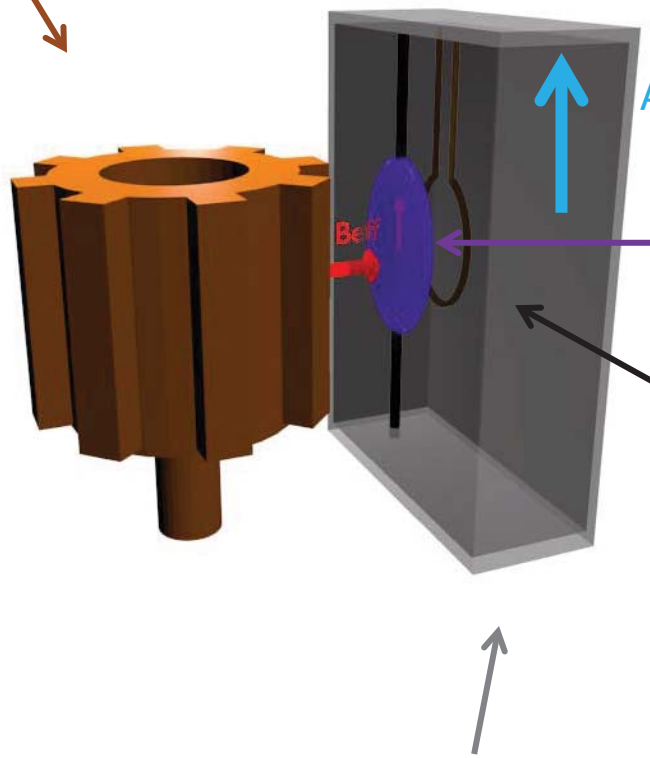
Time varying Axion B_{eff} drives spin precession → produces transverse magnetization

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}



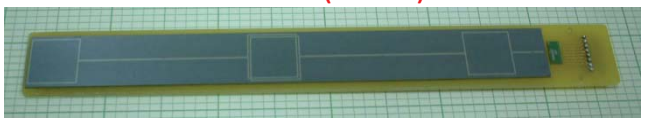
Applied Bias field B_{ext}

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

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).

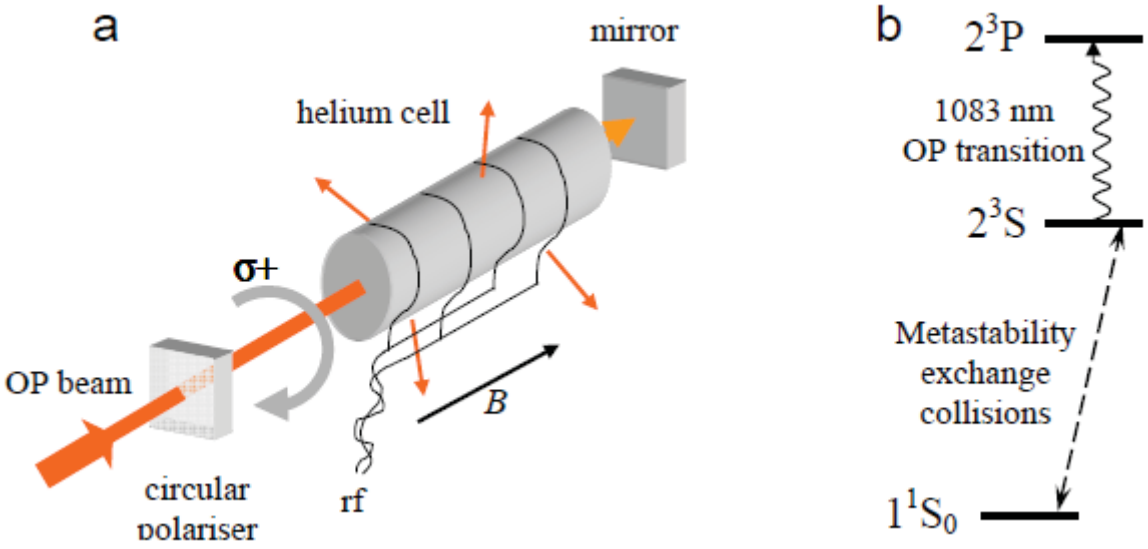
Hyperpolarized ^{3}He

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

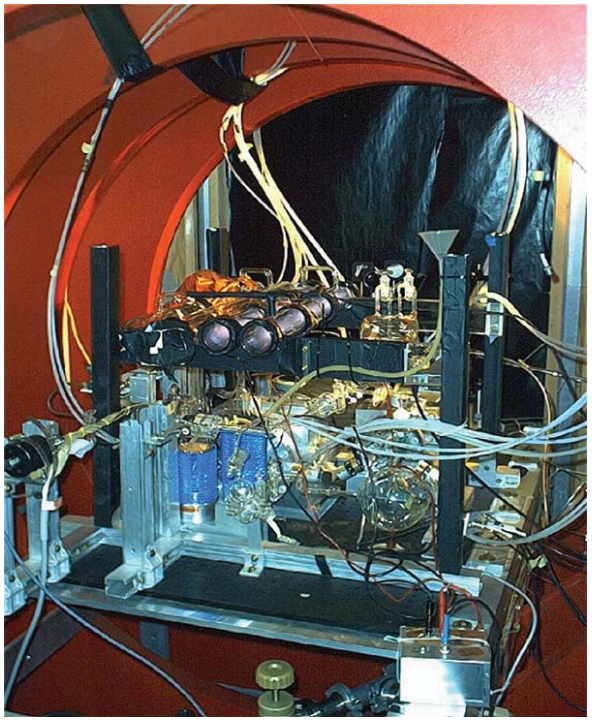
$$\exp[-\mu_N B / k_B T]$$

Optical pumping techniques

- Metastability exchange optical pumping



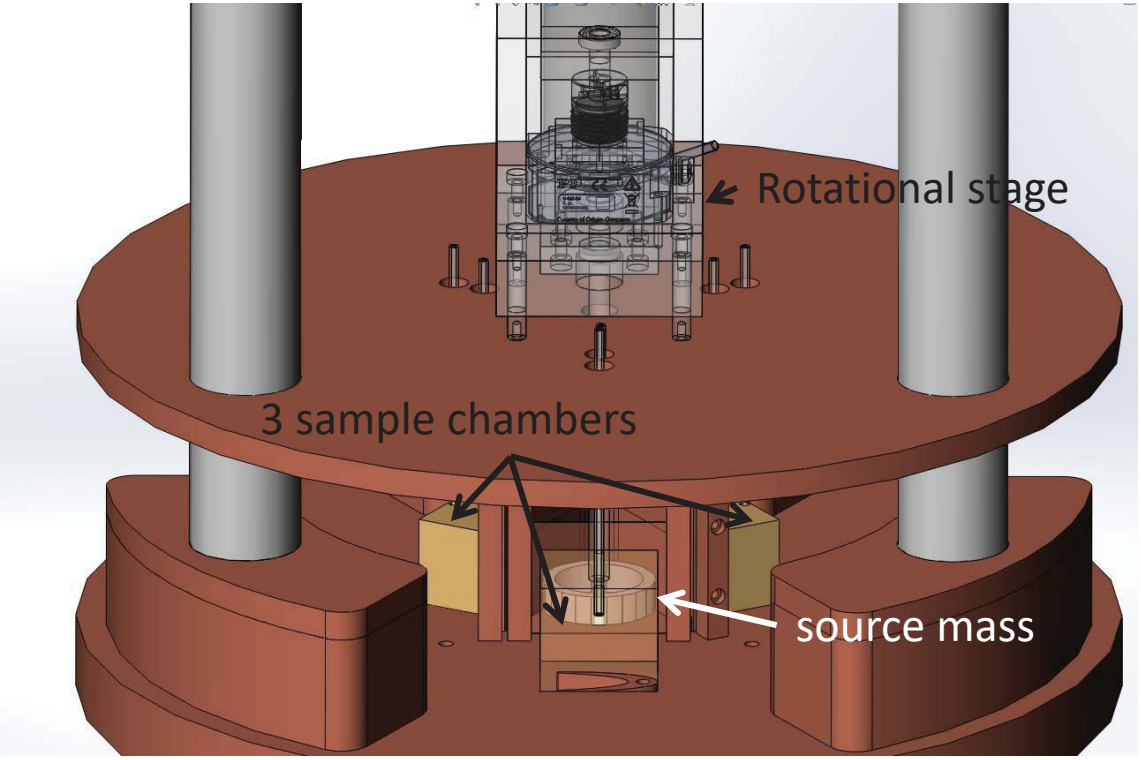
Indiana U. MEOP apparatus

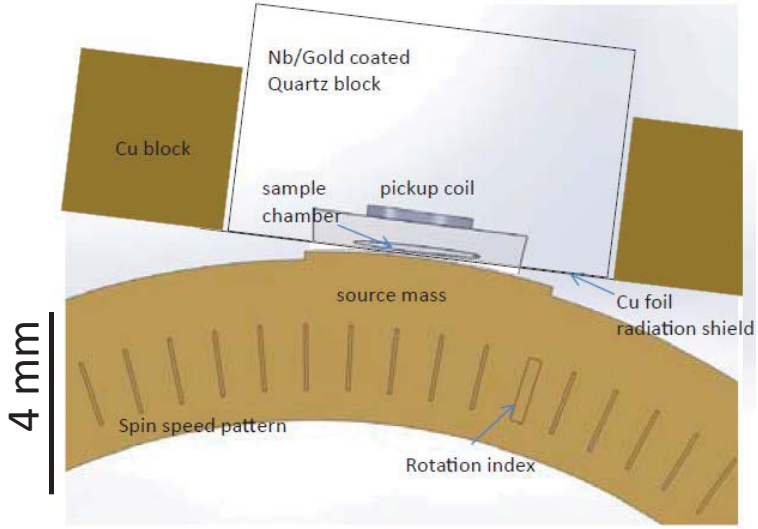


Rev. Sci. Instrum. 76, 053503 (2005)

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

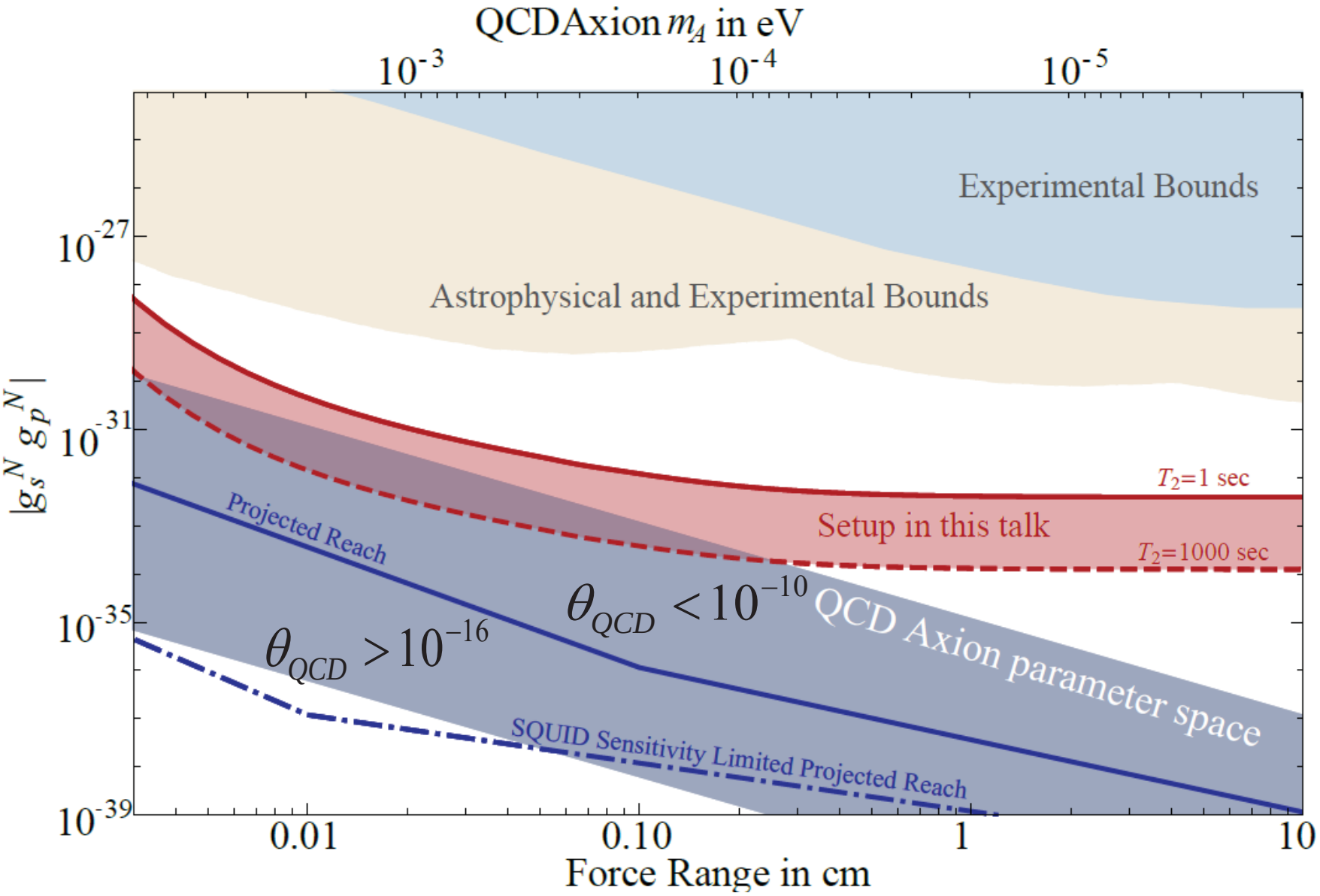
Experimental parameters





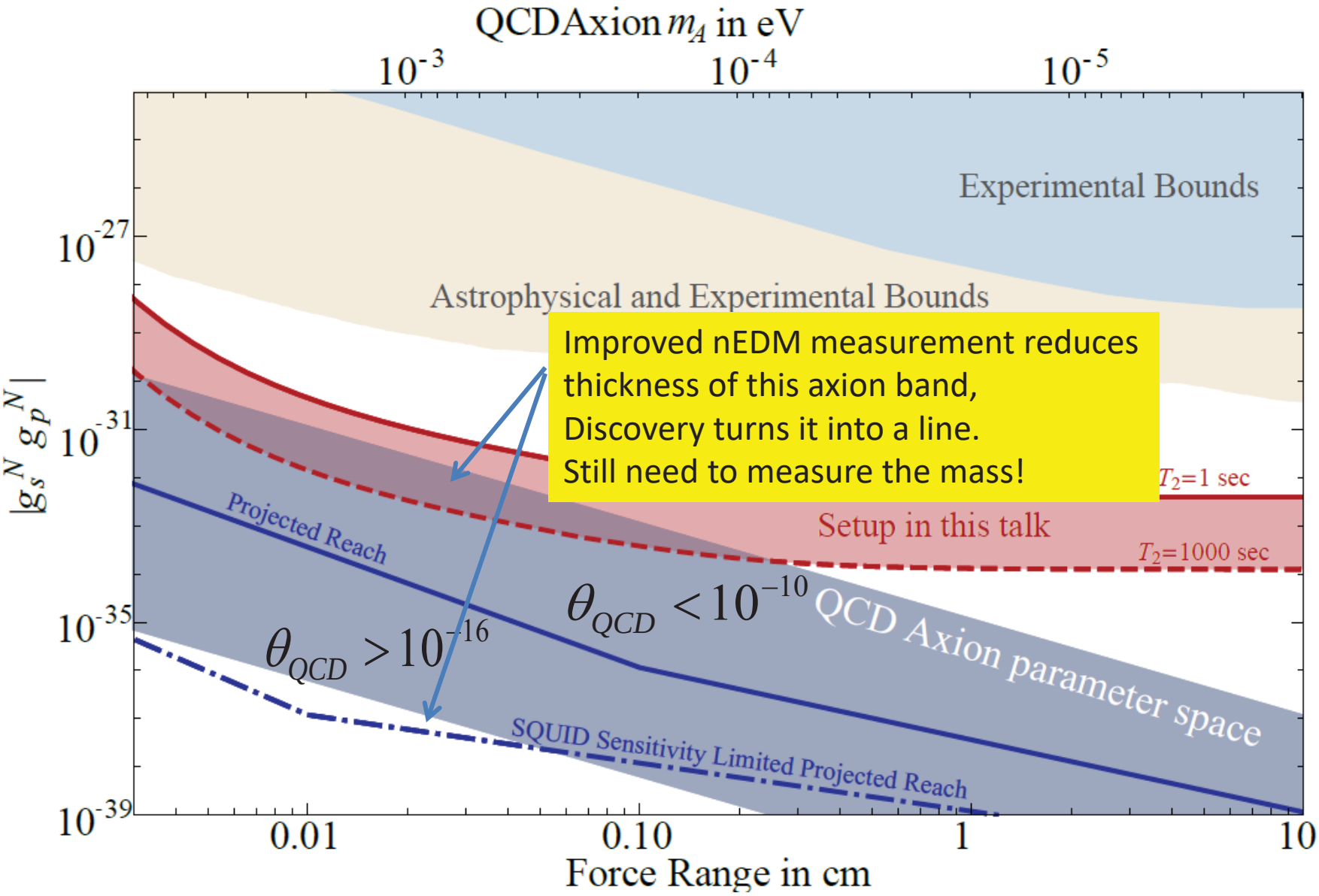
11 segments
100 Hz nuclear spin precession frequency
2 x 10^{21} / cc ^{3}He density
10 mm x 3 mm x 150 µm volume
Separation 200 µm
Tungsten source mass (high nucleon density)

Sensitivity



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

Complementarity with nEDM experiments



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 $\omega_{\rm rot}$
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

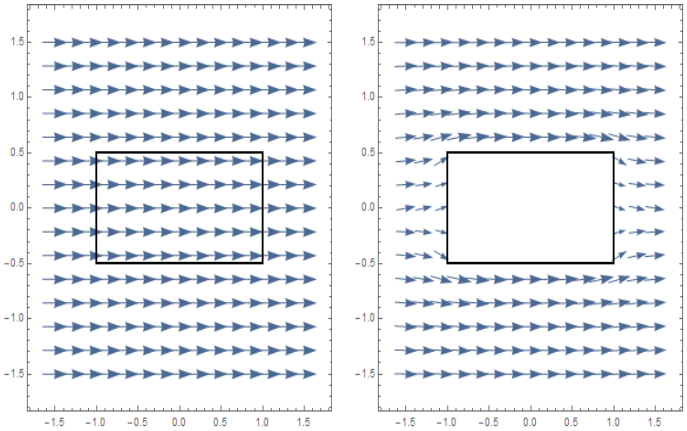
→ Essential to avoid Johnson noise

Meissner Effect

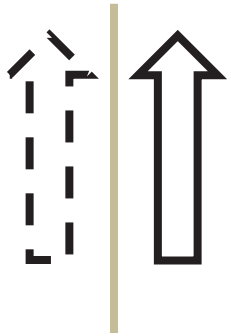
- No magnetic flux across superconducting boundary

Method of Images

- Make “image currents” mirrored across the superconducting boundary



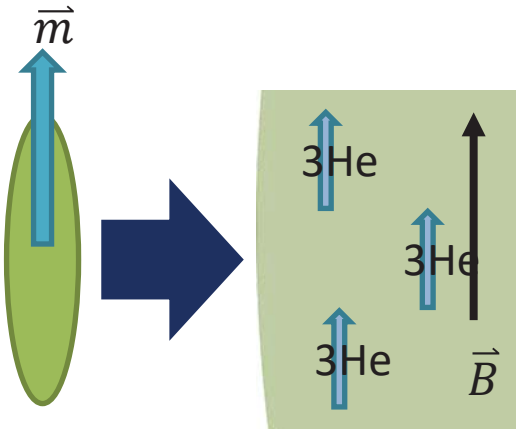
$T > T_c$ $T < T_c$



Dipole with image

The Problem of Unwanted Images

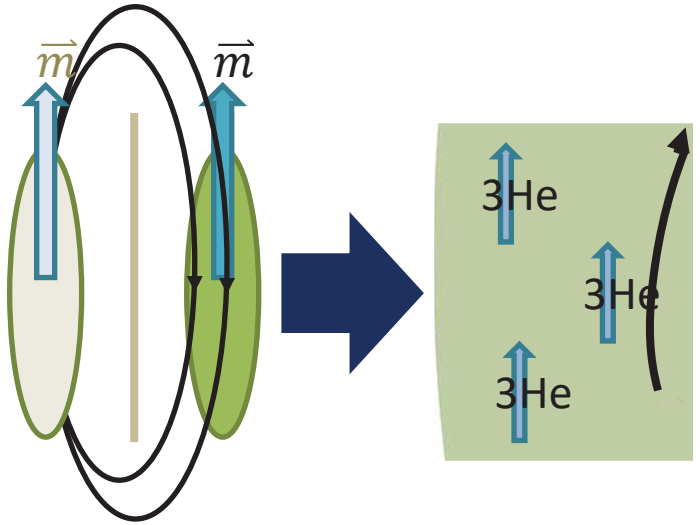
- ARIADNE uses magnetized spheroid
  - Constant interior field



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

- Magnetic shielding introduces “image spheroid”
  Interior field varies

→ variations in nuclear Larmor frequency

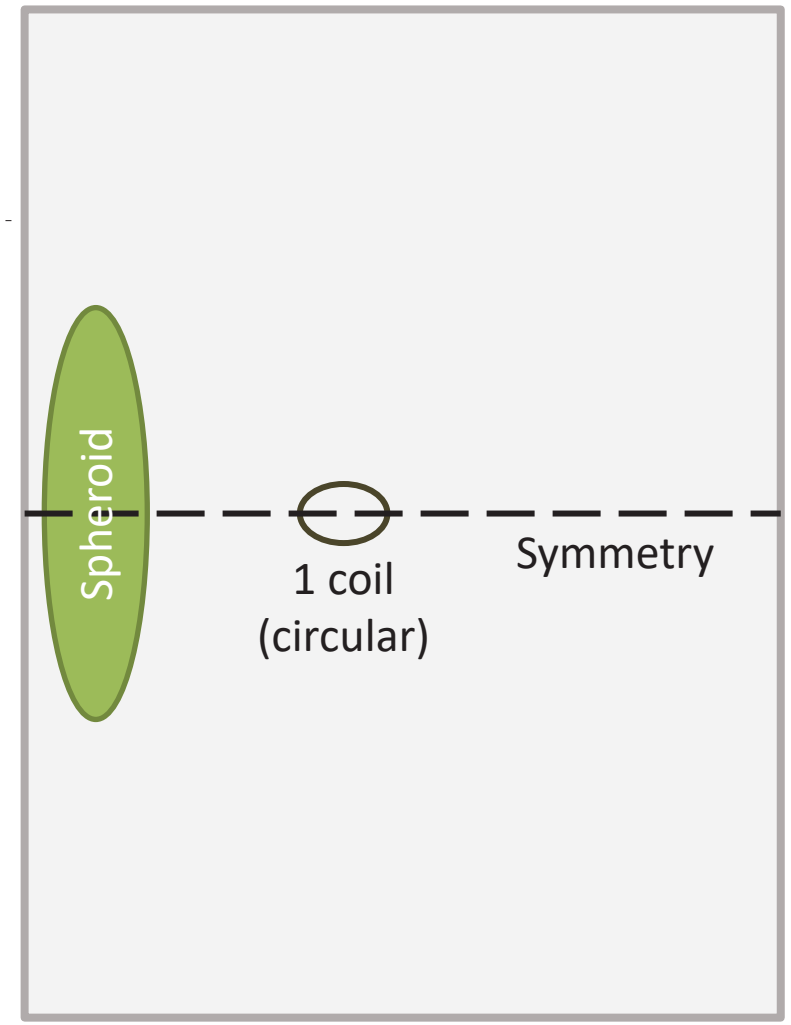


- $B_{in} \neq \text{const.}$
- $\overrightarrow{B_{in}} \nparallel \overrightarrow{m_i}$

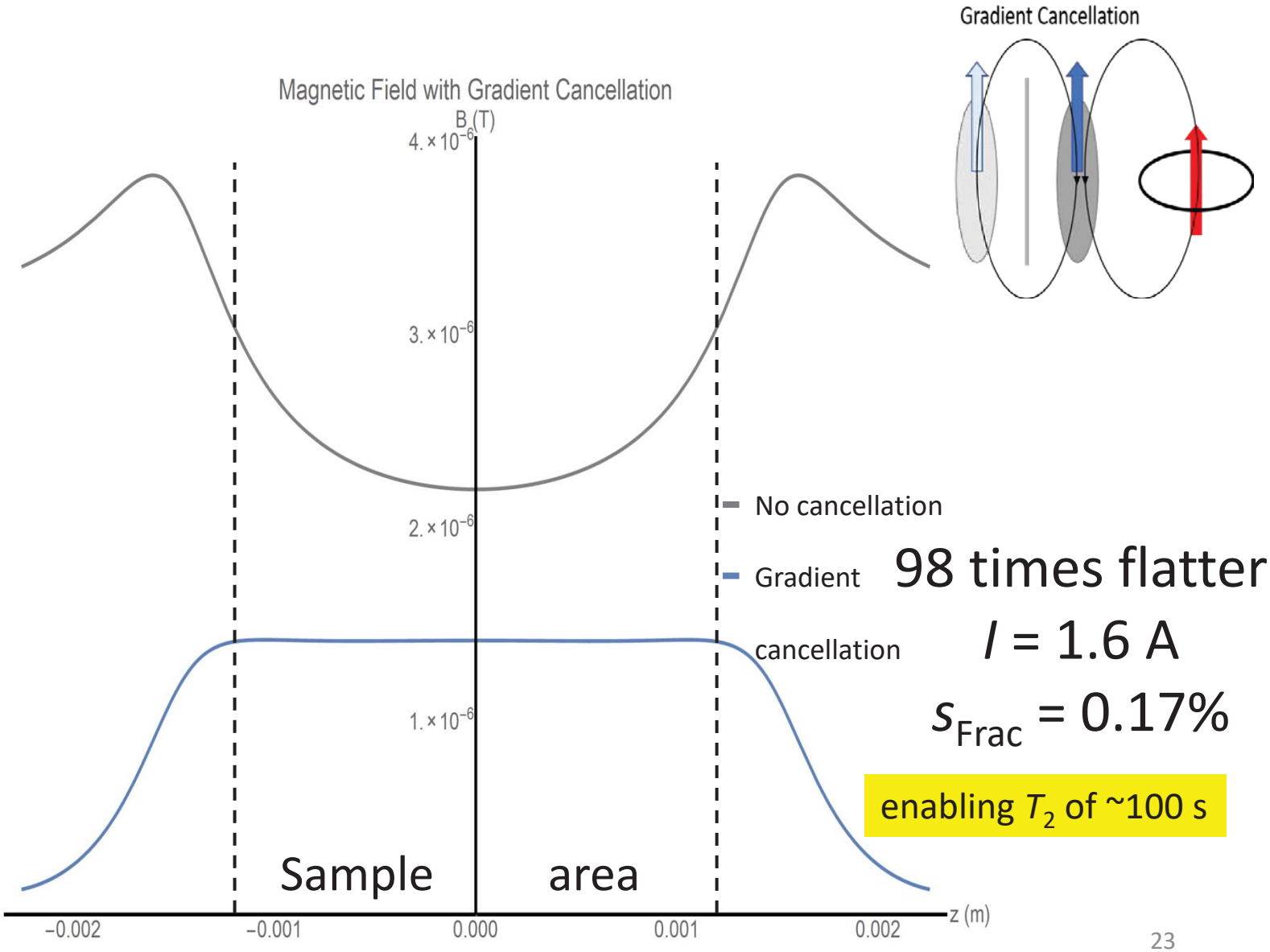
But want to drive entire sample on resonance

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

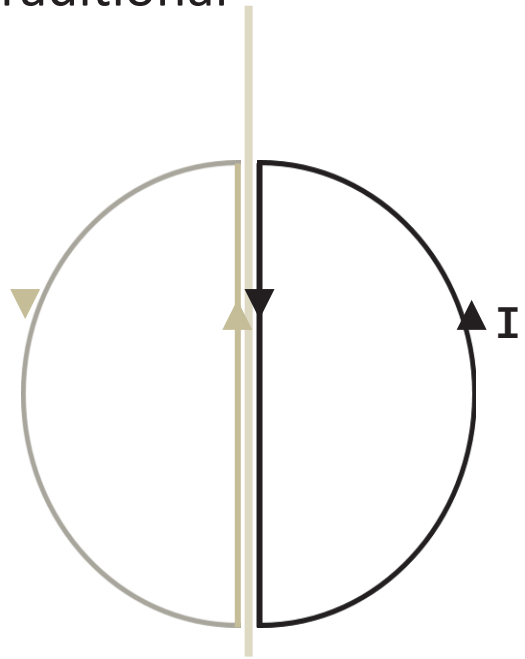
I = 1.6 A

s_{Frac} = 0.17%

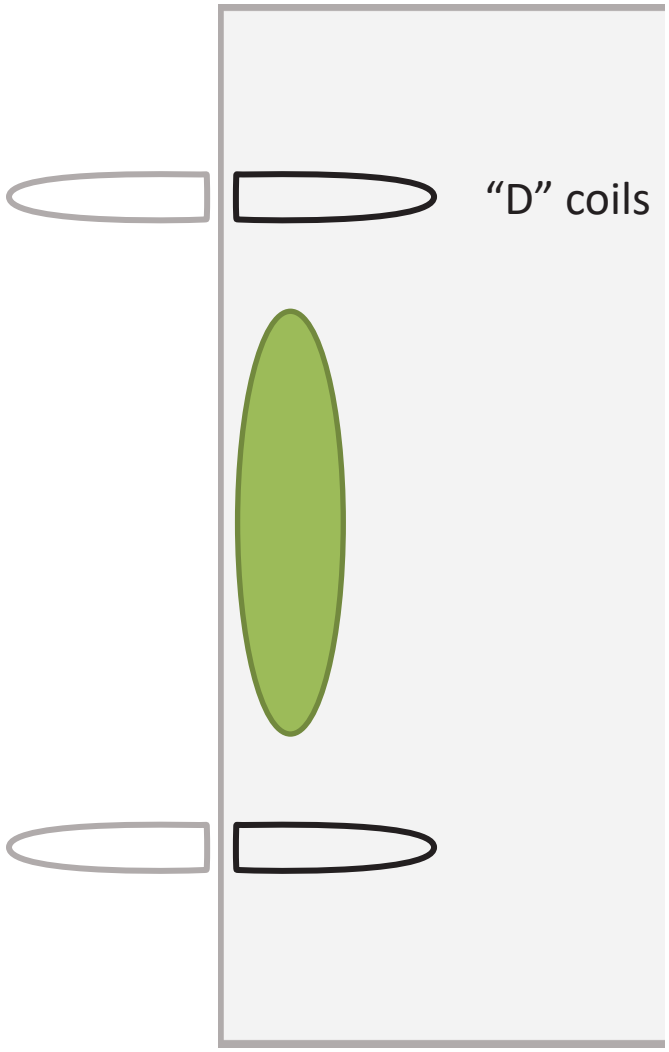
enabling T_2 of ~100 s

Tuning Solution – “D” Coils

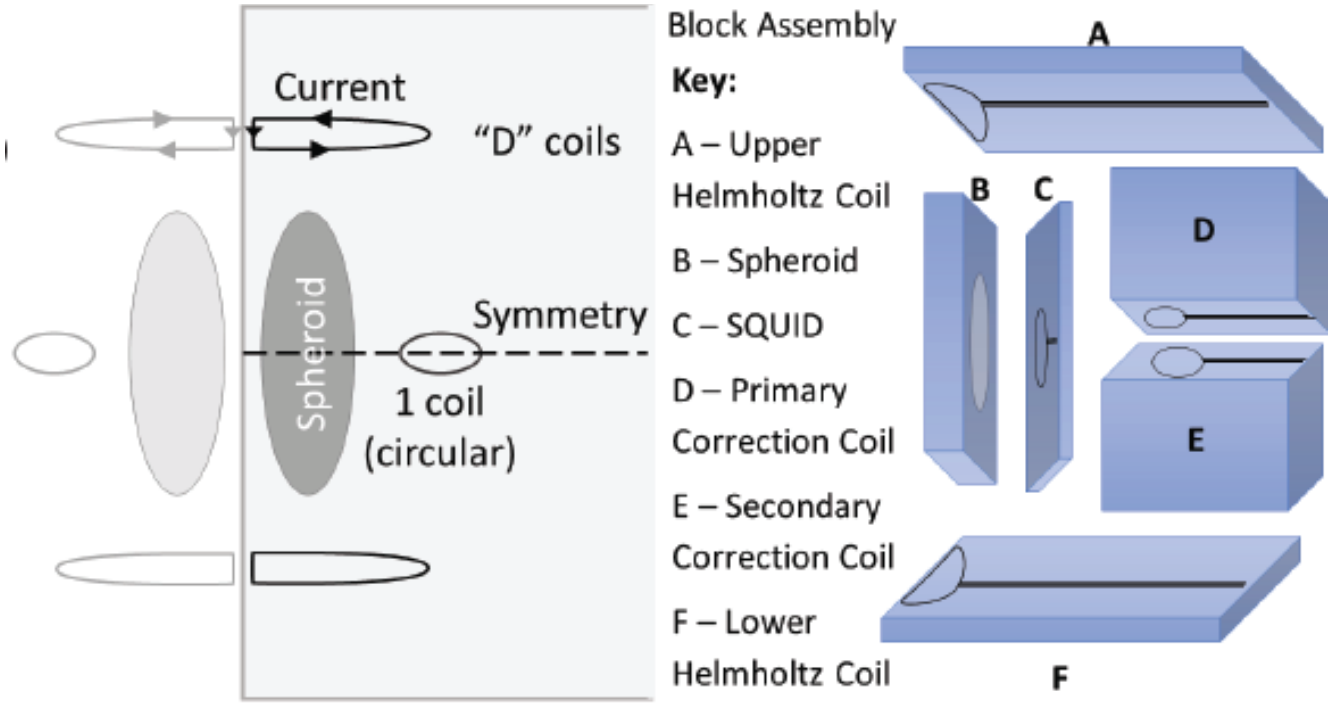
- Tune field with Helmholtz coils
  - Helmholtz field only flat near the center
  - Geometry restrictions prevent the spheroid from being centered in traditional Helmholtz coils
- “D” coils look like Helmholtz coils when their images are included
- Inner straight-line currents cancel
- Outer currents do not



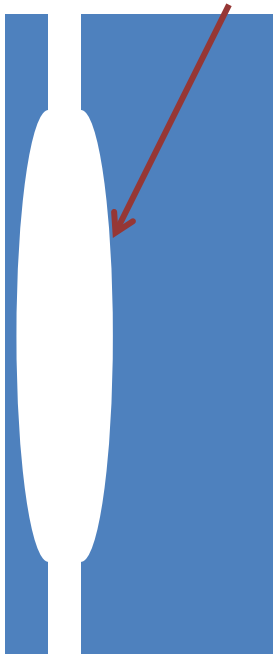
One “D” coil and image (bird’s eye view)



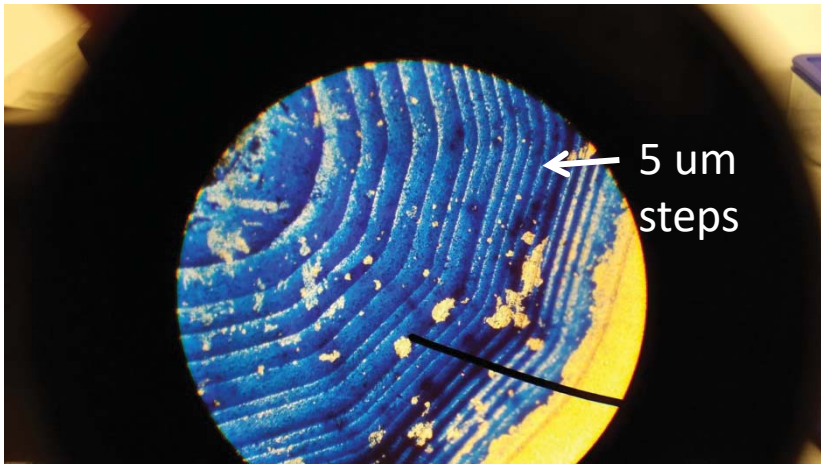
Quartz block assembly



Spheriodal pocket



Milled spheriodal pocket in quartz

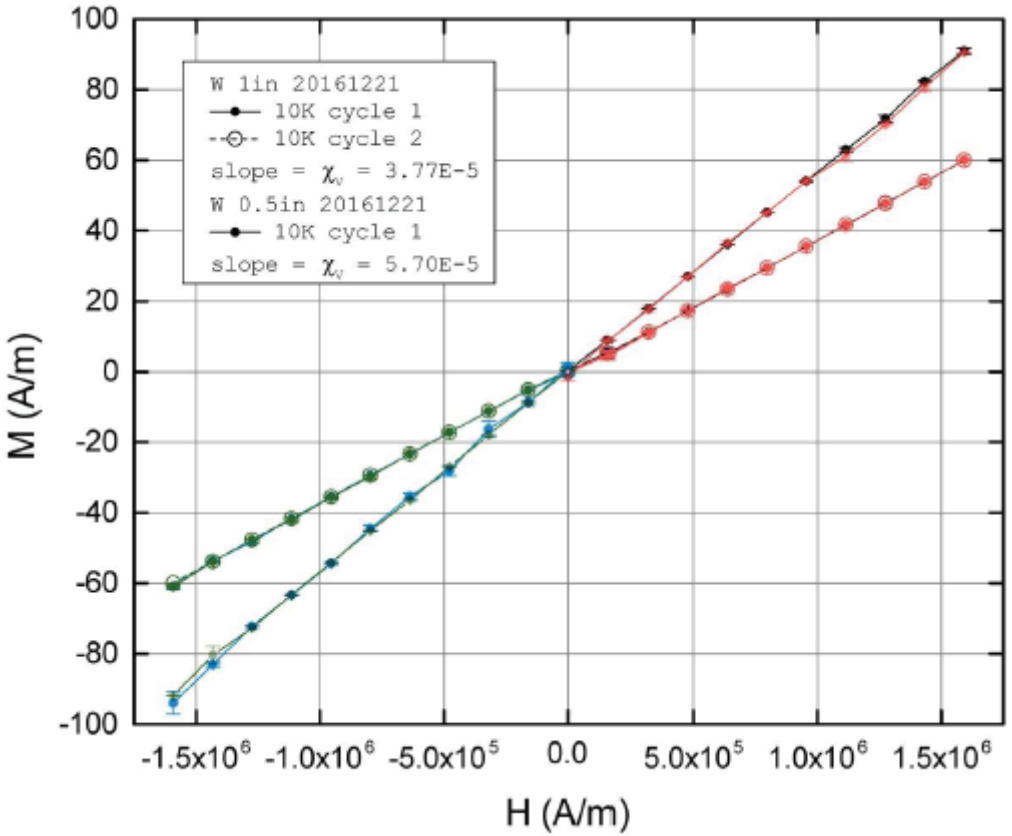


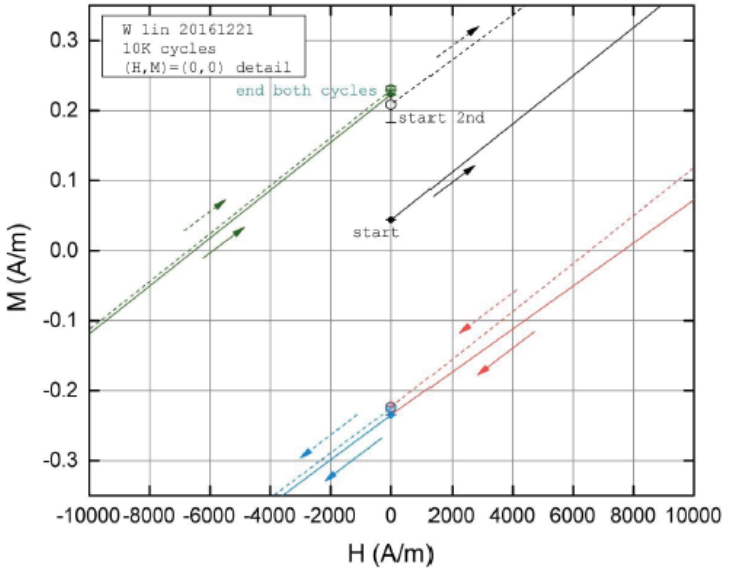
Fabrication/polishing tests is process – Oct 2017

Tungsten Source Mass Prototype

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

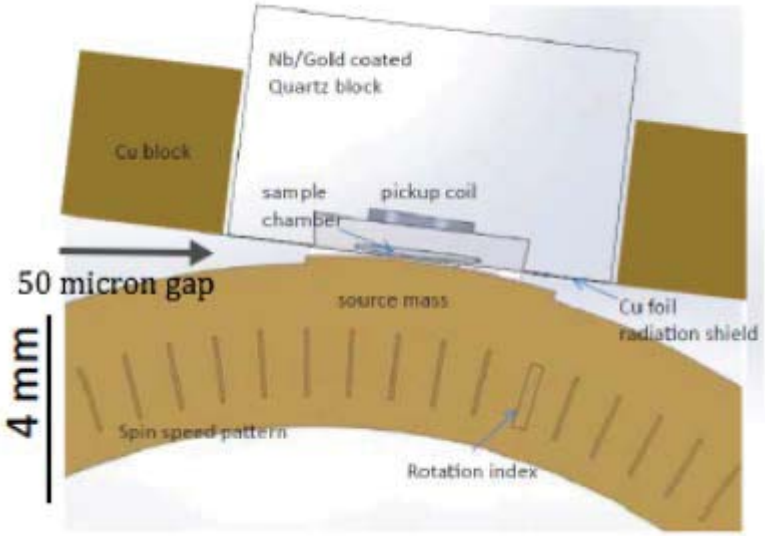
Magnetic impurity testing in Tungsten
using commercial SQUID magnetometer -- Indiana

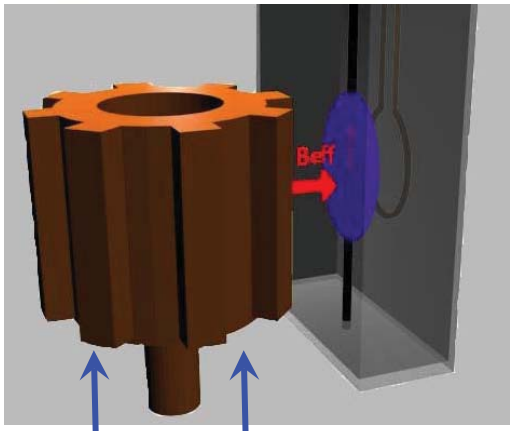




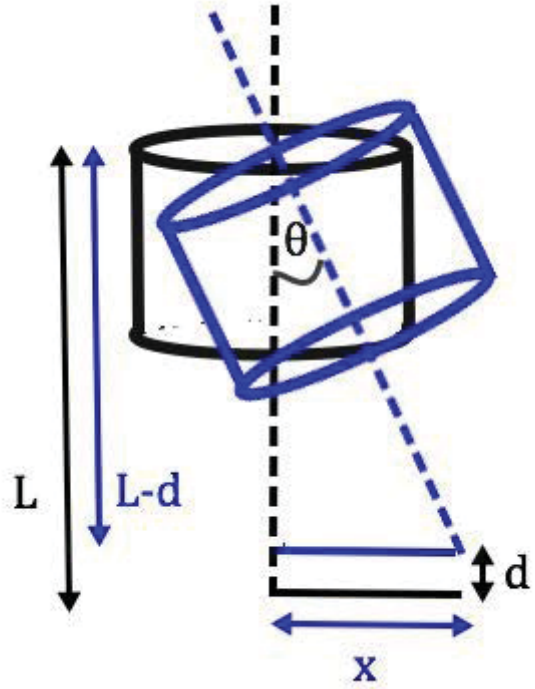
Magnetic impurities below 0.4 ppm

Rotary stage vibration and tilt

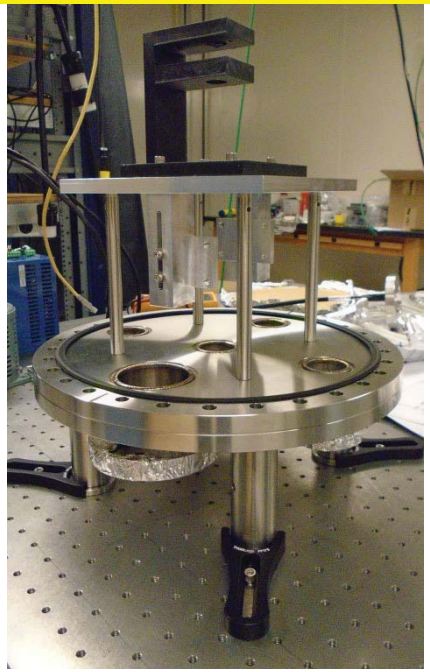




Interferometers



Rotary test chamber

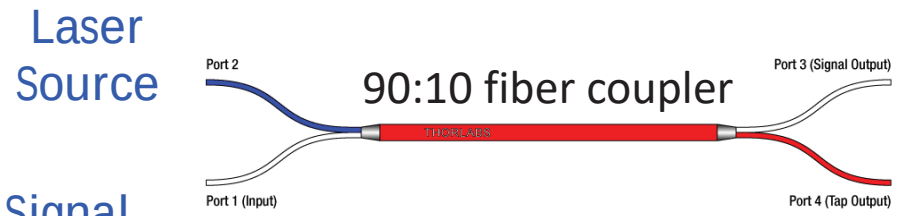


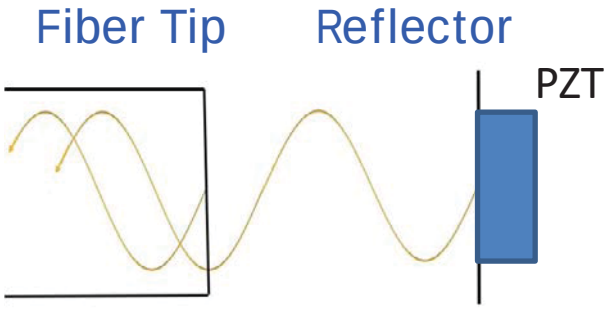
- Build an interferometer to measure the change in distance (d).
- We can find theta (Θ) from:

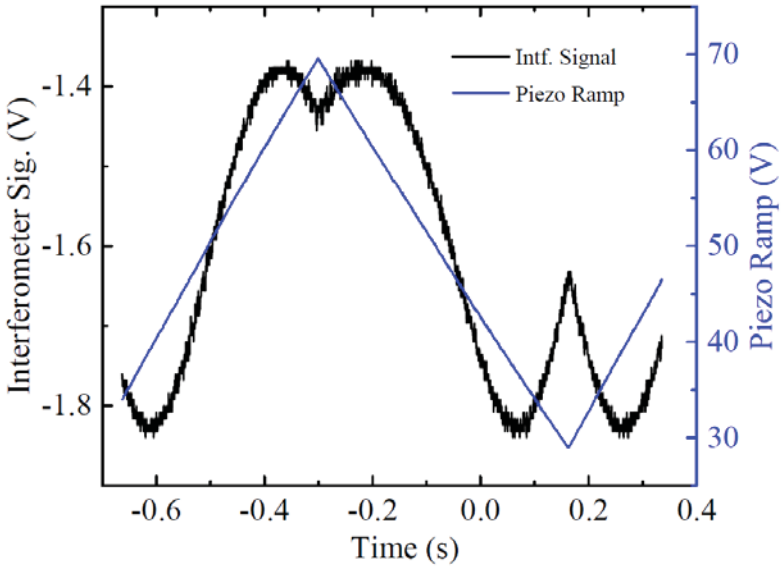
  $\Theta = \cos^{-1}((L-d)/L)$
- We can solve for the wobble distance (X) by:

  $X = L\sin(\Theta)$

Fiber-coupled laser interferometers



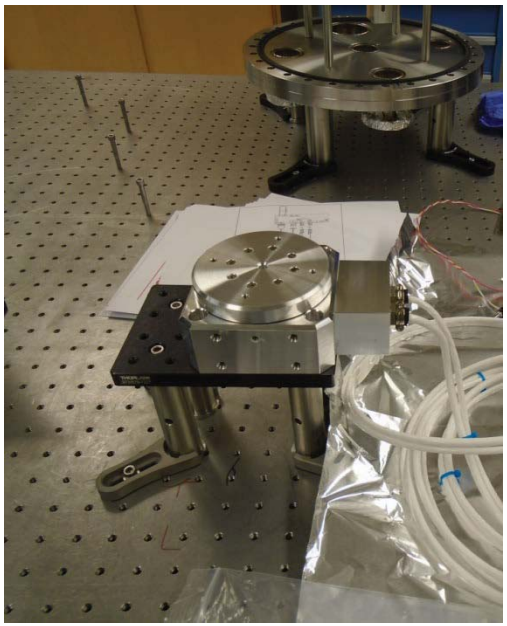




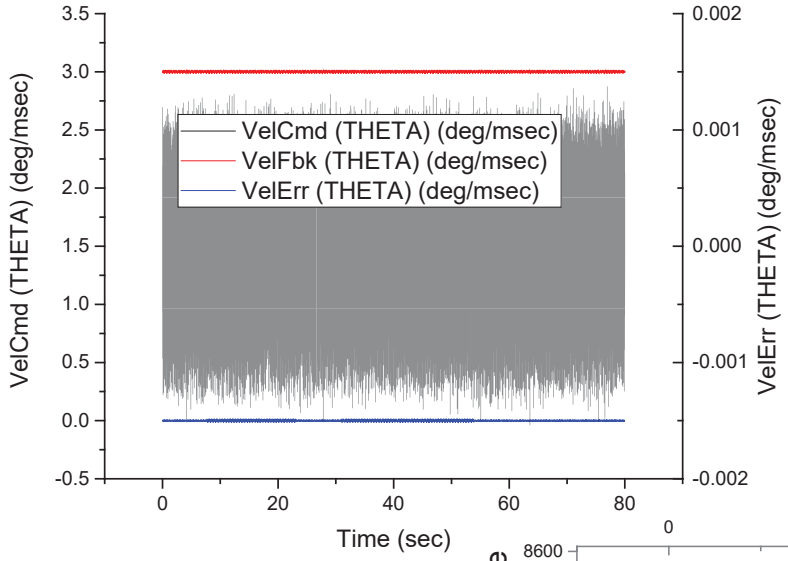
Fringe visibility
~0.13
Sensitivity
~160 nm/V
Shot noise limit
~20 pm/Hz$^{1/2}$

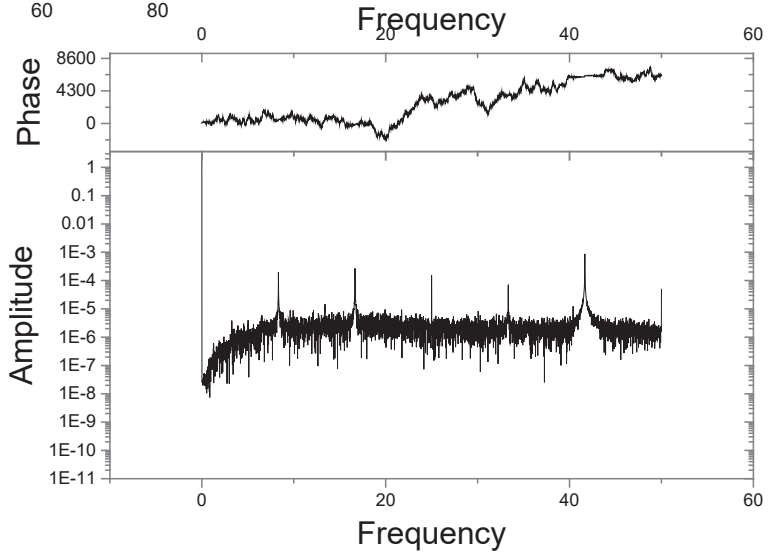
Speed stability test - direct drive stage

- 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

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 (Stanford/Korea), vibration (UNR), ^{3}He system (Indiana)

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