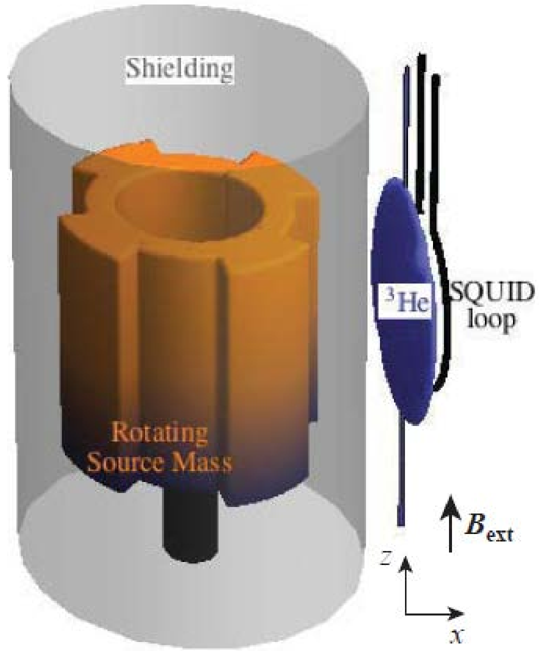
Axion NMR Experiment

The Axion Resonant InterAction DetectioN Experiment (ARIADNE)



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

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Jordan Dargert (UNR)

PATRAS Axion-WIMP 2015
A.Geraci, U. Nevada Reno

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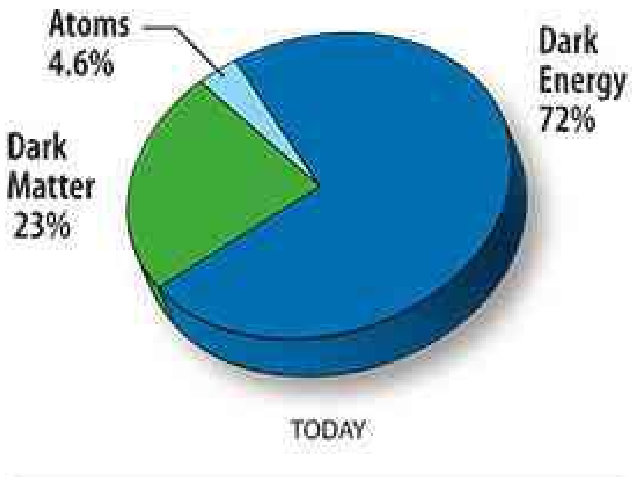
Axions

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

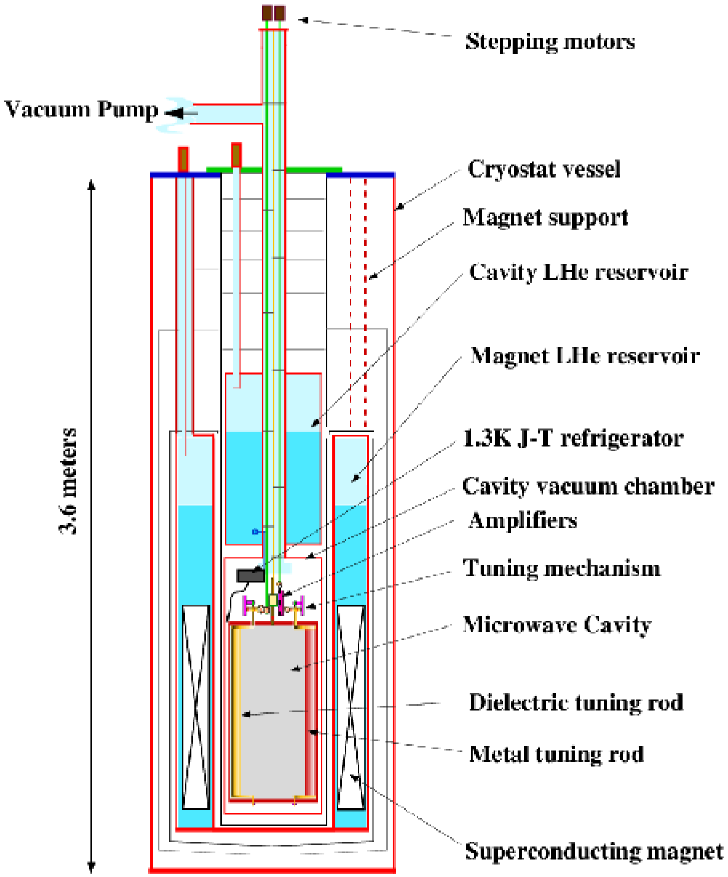


http://map.gsfc.nasa.gov/media/080998/index.html

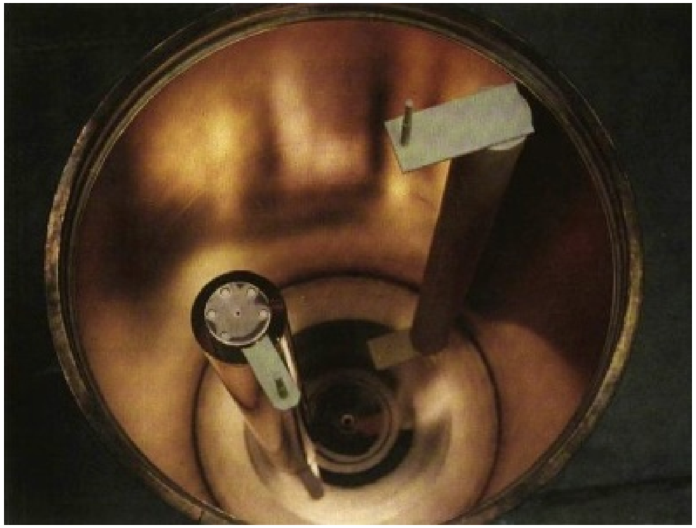
- R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. 38, 1440 (1977);
- S. Weinberg, Phys. Rev. Lett. 40, 223 (1978);
- F. Wilczek, Phys. Rev. Lett. 40, 279 (1978).
- J. E. Moody and F. Wilczek, Phys. Rev. D 30, 130 (1984).

ADMX experiment

Axion couples to 2 photons $g_{a\gamma\gamma}$ → Resonant axion to photon conversion in Microwave cavity in background magnetic field



Cavity resonance tuned to match oscillation frequency of cosmic axion field



http://www.phys.washington.edu/groups/admx/home.html

Another experiment planned in Korea with similar concept! [https://capp.ibs.re.kr]

CAST experiment

Conversion of solar axions to x-rays in background B field

Axions

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

- 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);
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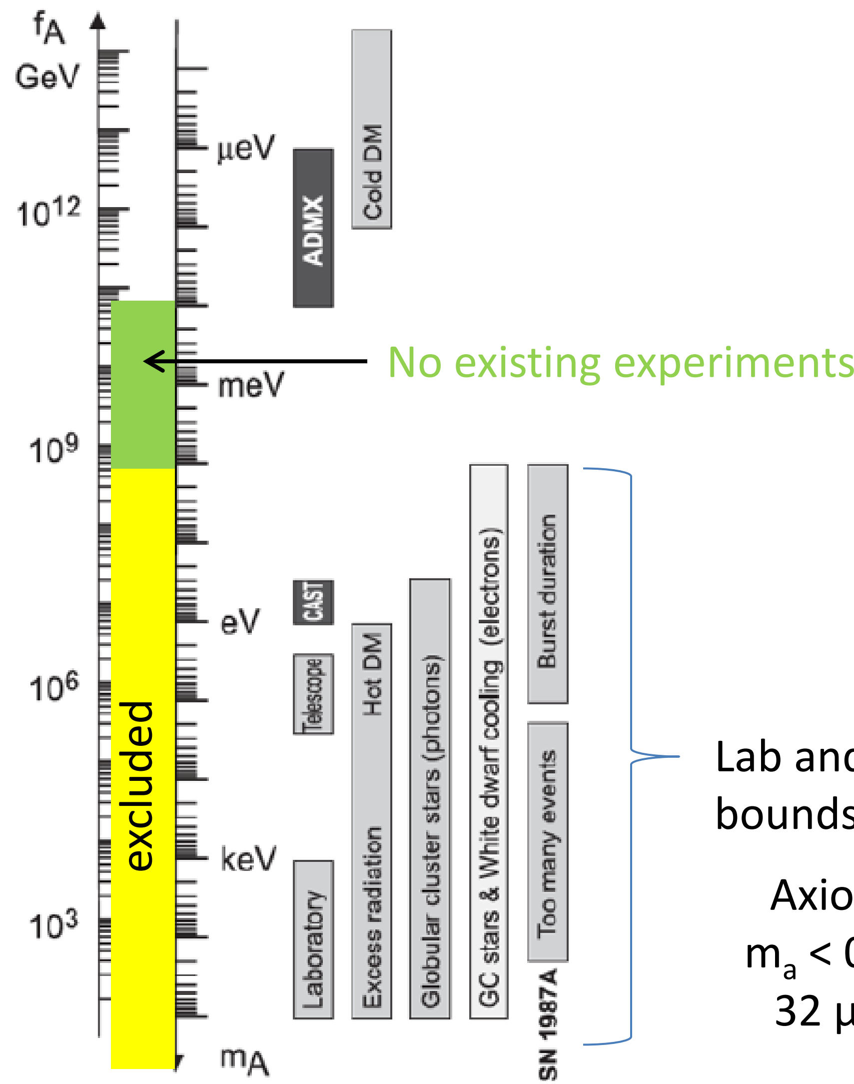
- J. E. Moody and F. Wilczek, Phys. Rev. D 30, 130 (1984).

QCD Axion parameter space

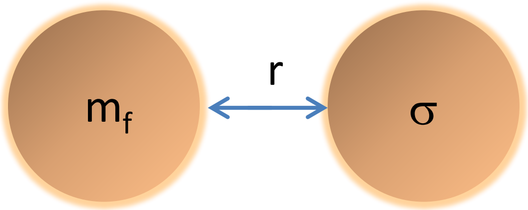
$$m_a = 6\times10^{-3}\,\mathrm{eV}\left(\frac{10^9\,\mathrm{GeV}}{f_a}\right)$$



Lab and Astrophysical bounds

Axion mass
$m_a < 0.006$ eV
$32\ \mu\mathrm{m} < \lambda_a$

Spin-dependent forces



Monopole-Dipole axion exchange

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

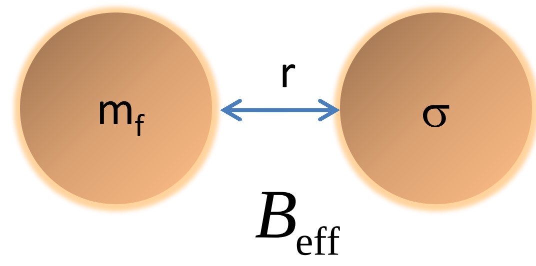
- Different than ordinary B field
- Does not couple to angular momentum
- Unaffected by magnetic shielding

Coupling constants

$$6\times10^{-27}\left(\frac{10^9\,\text{GeV}}{f_a}\right) < g_s < 10^{-21}\left(\frac{10^9\,\text{GeV}}{f_a}\right)$$

$$g_p = \frac{C_f m_f}{f_a} = C_f 10^{-9}\left(\frac{m_f}{1\text{GeV}}\right)\left(\frac{10^9\,\text{GeV}}{f_a}\right)$$

Using NMR for detection



Spin ½ ^{3}He Nucleus

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

Bloch Equations

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

$$|\uparrow\rangle$$

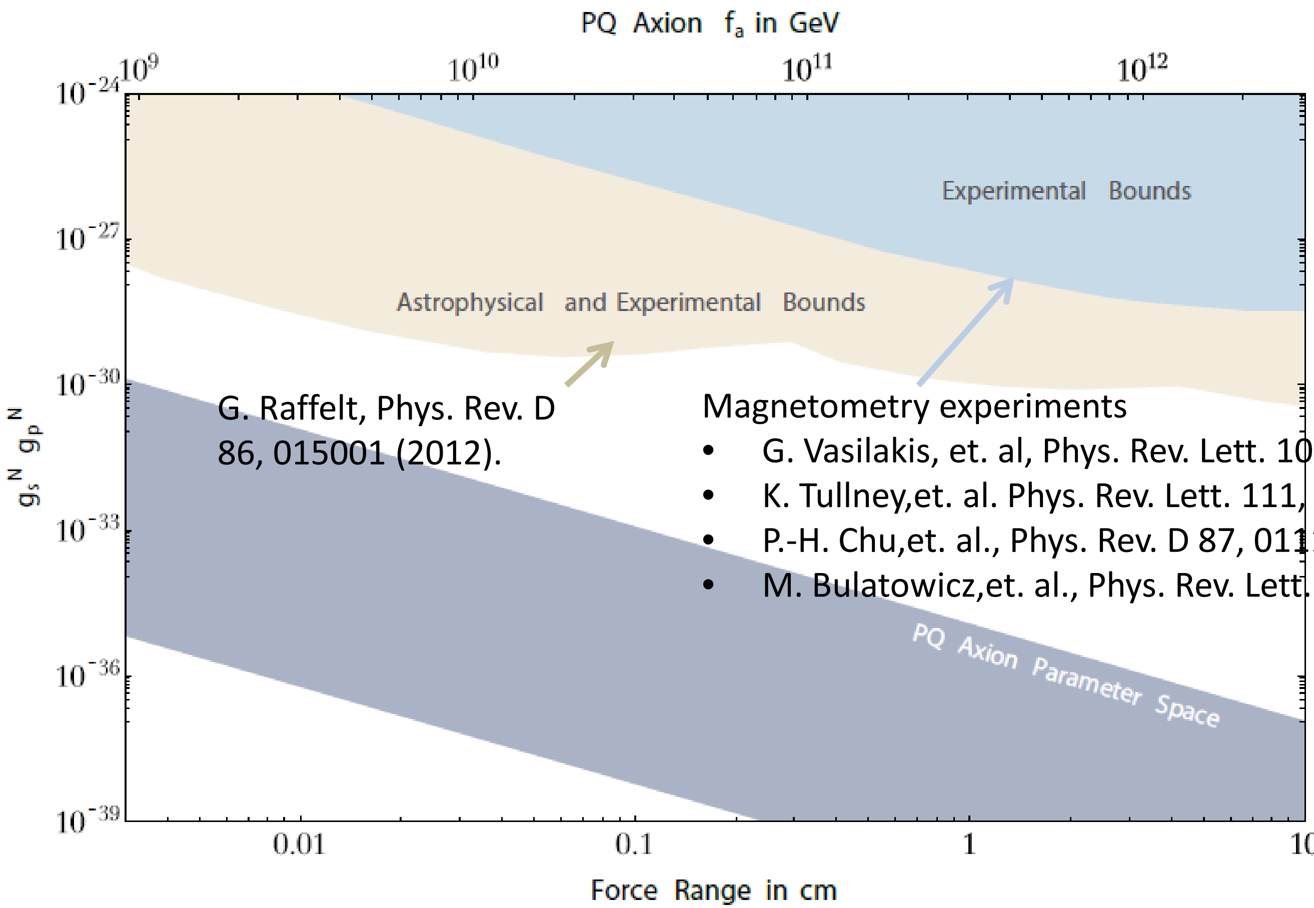
$$\omega = \frac{2\mu_N \cdot B_{\text{ext}}}{\hbar}$$

$$|\downarrow\rangle$$

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

Axion B_{eff} modifies measured Larmor frequency

Constraints on spin dependent forces



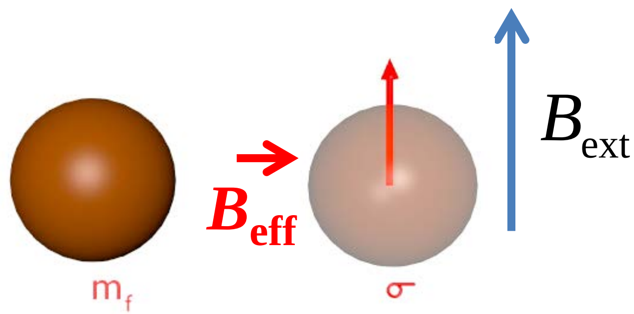
G. Raffelt, Phys. Rev. D 86, 015001 (2012).

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).

Resonant enhancement method

Spin ½ ^{3}He Nucleus



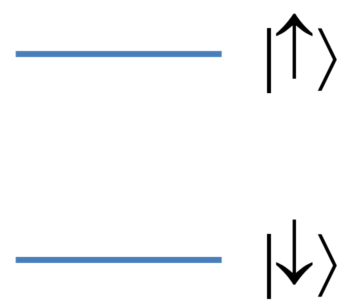
Oscillate the mass at Larmor frequency

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

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

Bloch Equations

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



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

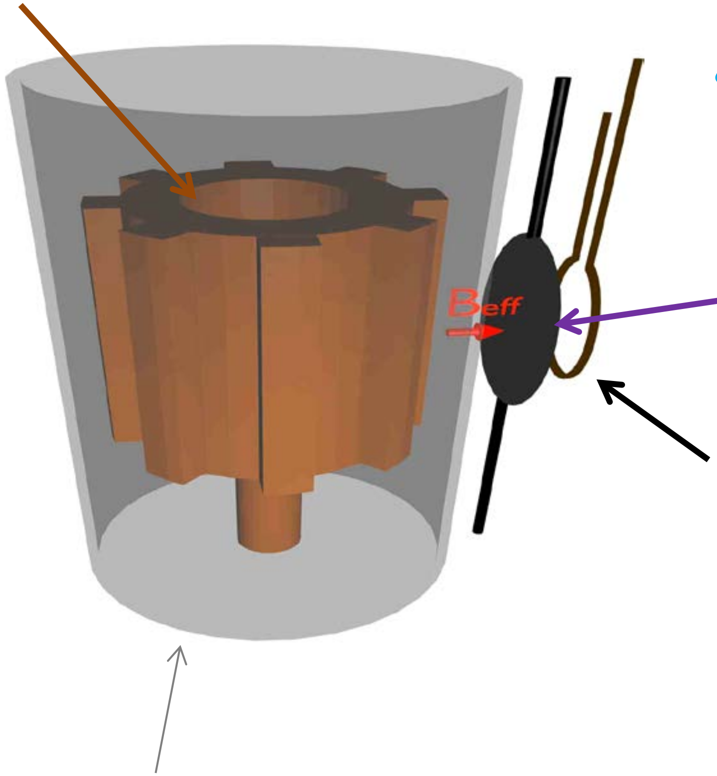
Time varying Axion B_{eff} drives spin precession → produces transverse magnetization

Amplitude is resonantly enhanced by Q factor ~ ωT_2.

Can be detected with a SQUID

Concept for new experiment

Rotating segmented cylinder sources B_{eff}



Applied Bias field B_{ext}

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

Polarized 3He gas senses B_{eff}

See upcoming talk by Yun Shin

squid pickup loop

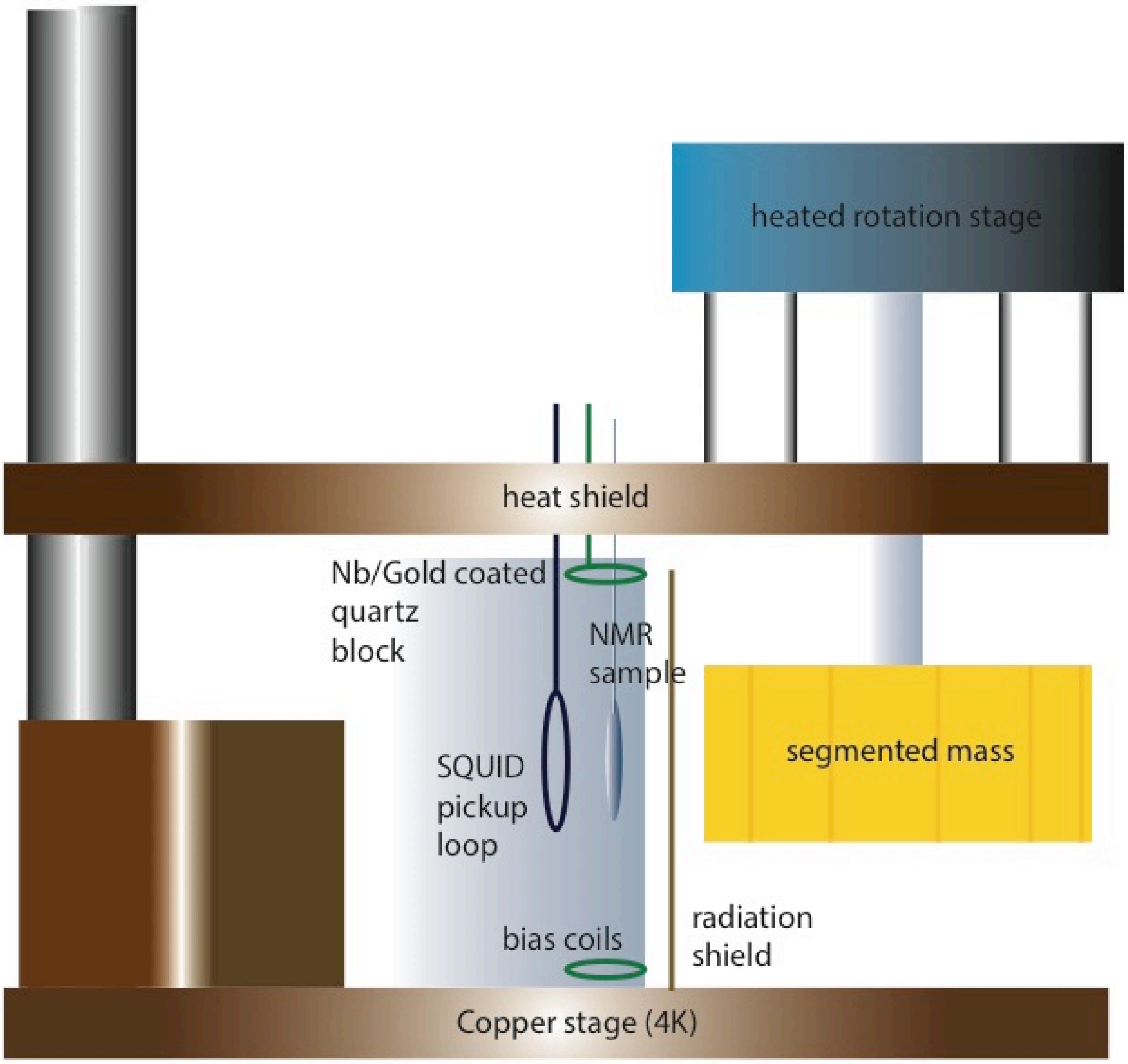
Superconducting shielding

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).

Cryostat Conceptual Design



Use polarized
3He gas at 4K
Precession ω

Rotating tungsten
mass
oscillates force
in resonance at nω

Superconducting
B shield

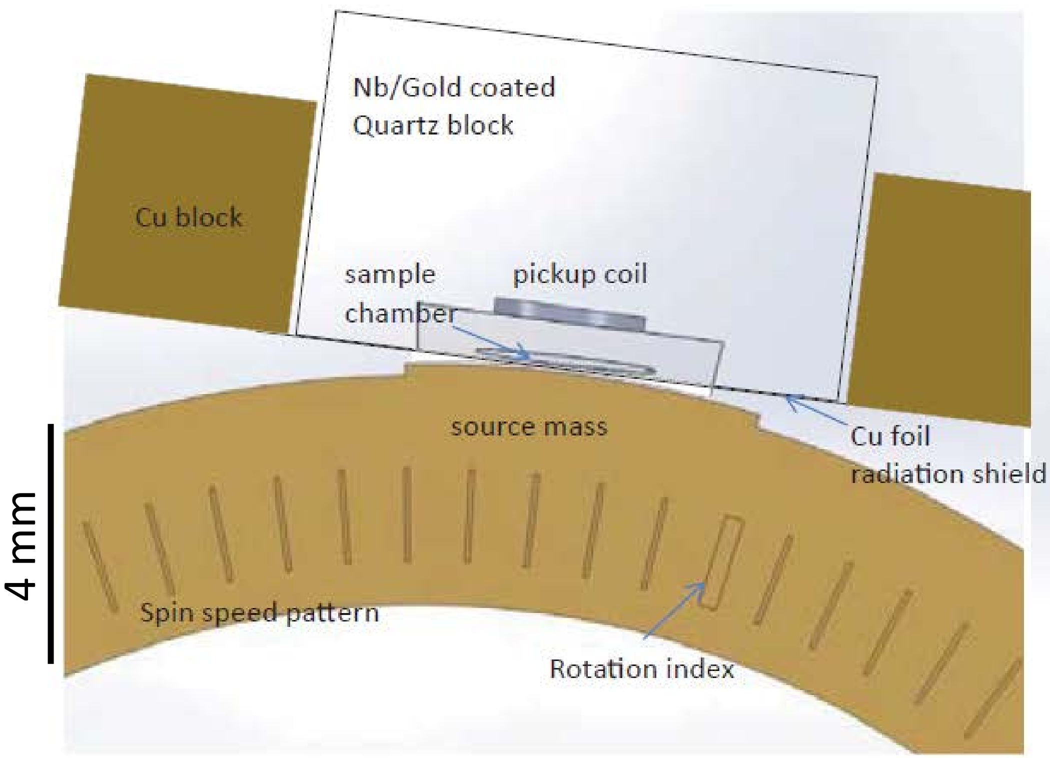
Ellipsoidal sample

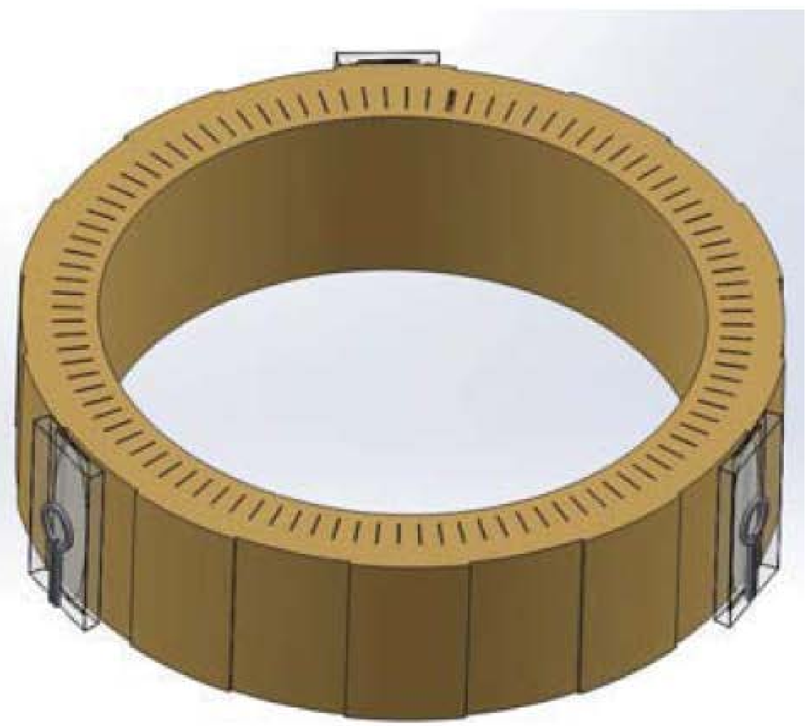
SQUID
magnetometry

Laser polarized
3He

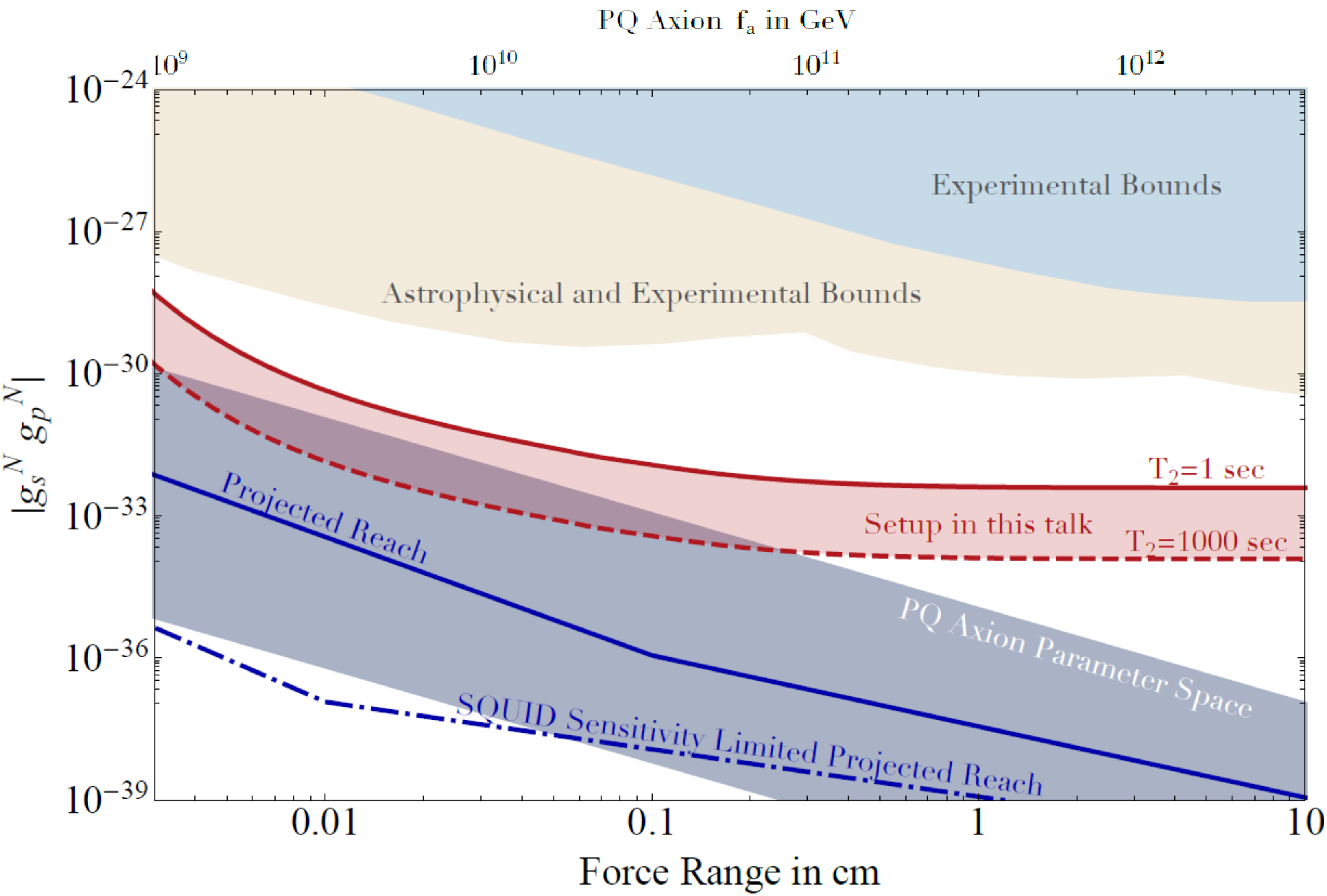
Experimental parameters

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)

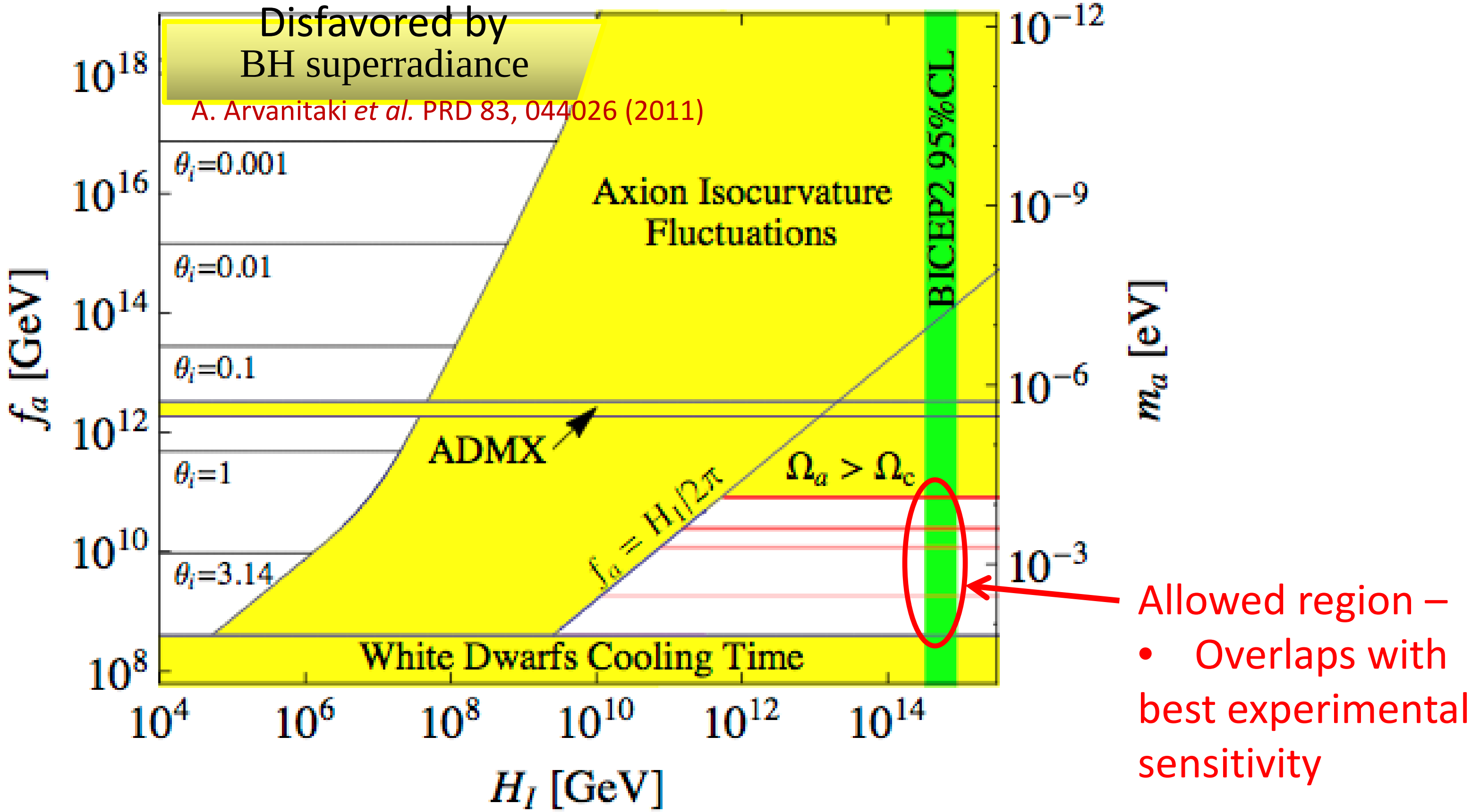




Sensitivity

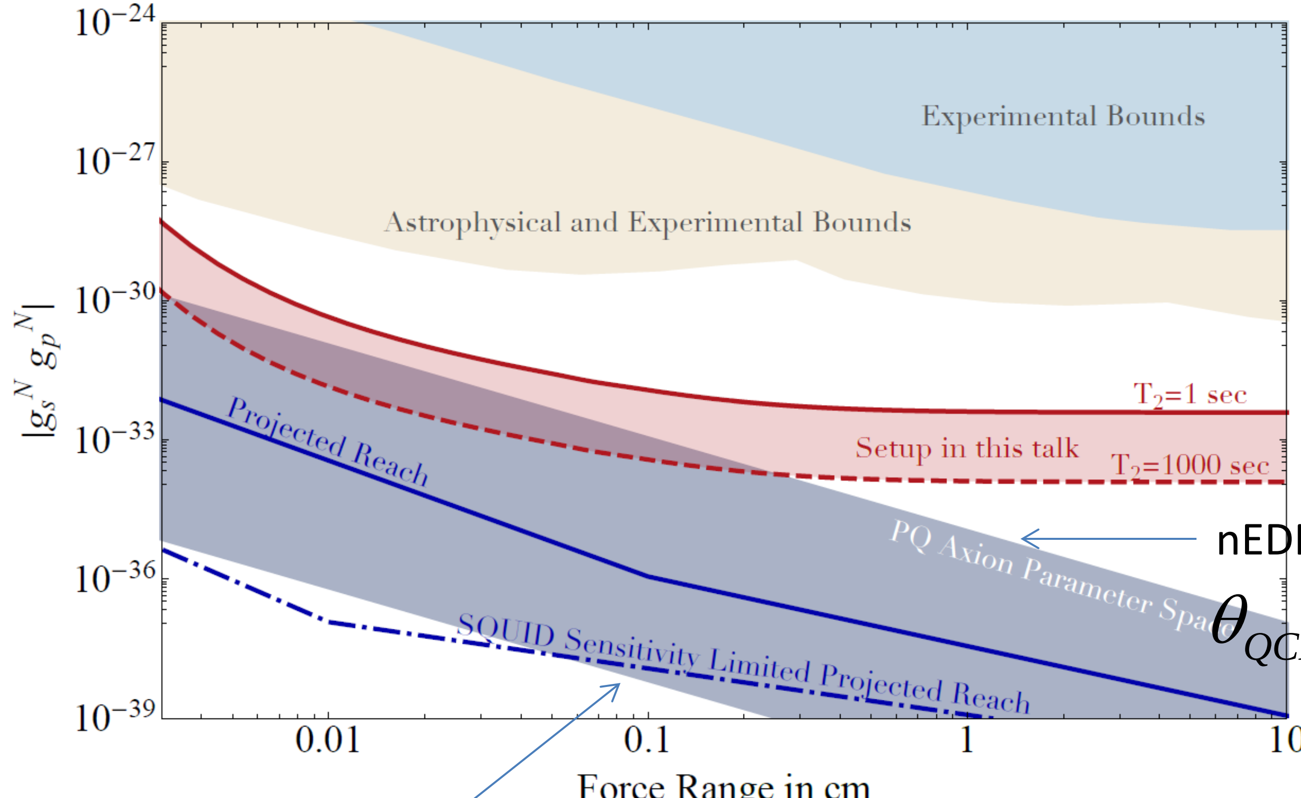


Axion Cosmology in light of Inflationary scale



Adapted from: Luca Visinelli and Paolo Gondolo, Phys. Rev. Lett. 113, 011802

Complementarity with EDM experiments



nEDM bound

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

Standard Model lower bound

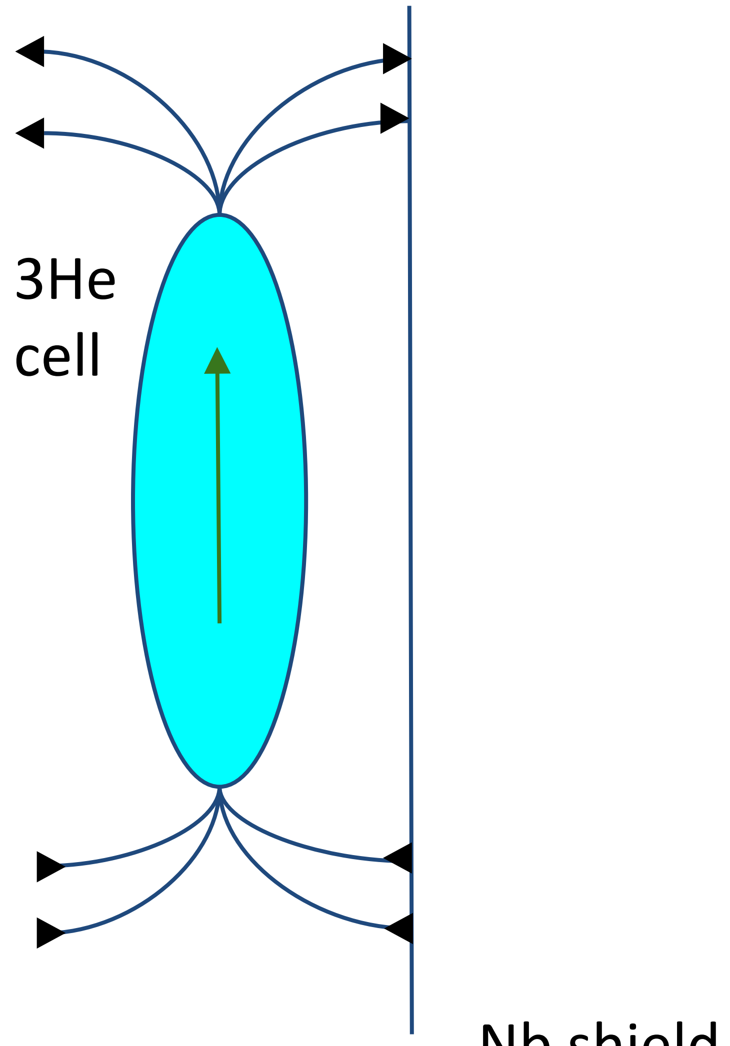
$$\theta_{QCD} > 10^{-16}$$

Experimental challenges

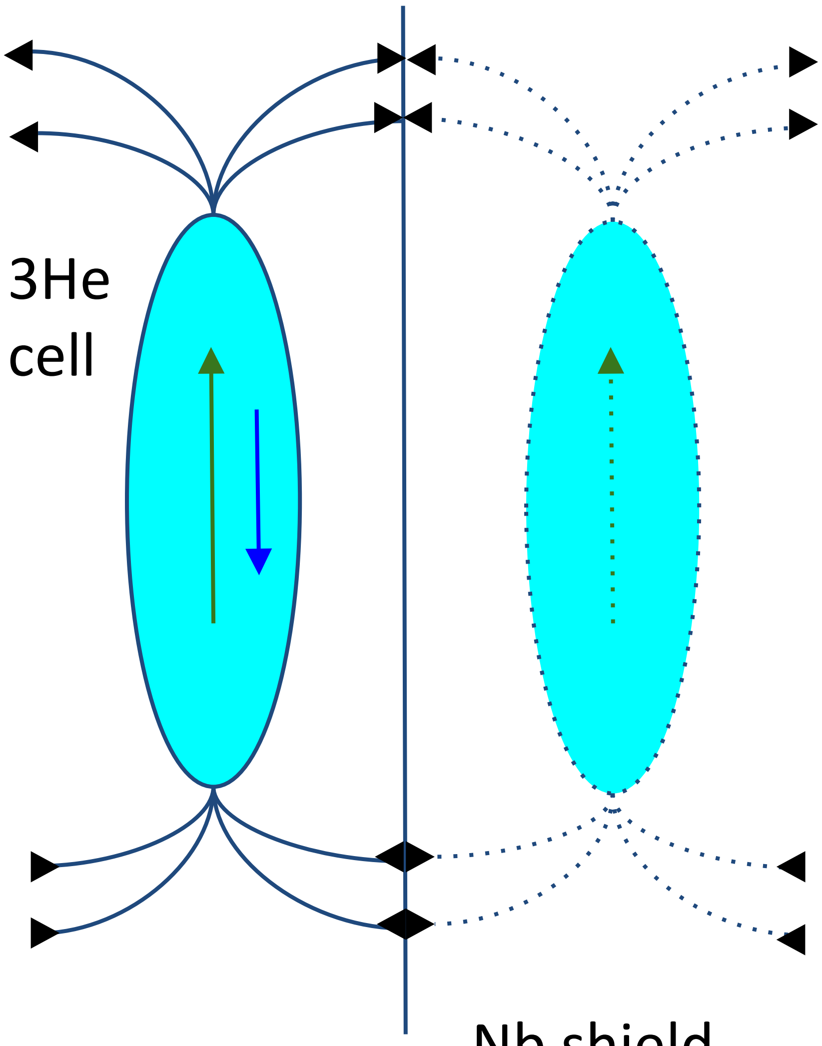
Systematic Effect/Noise source	Background Level	Notes
Magnetic gradients	3×10^{-6} T/m	Limits T_2 to ~ 100 s
		Possible to improve w/shield geometry
Vibration of mass	10^{-22} T	For 10 μm mass wobble at $\omega_{\rm rot}$
External vibrations	5×10^{-20} T/$\sqrt{\rm Hz}$	For 1 μm sample vibration (100 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/$\sqrt{\rm Hz}$

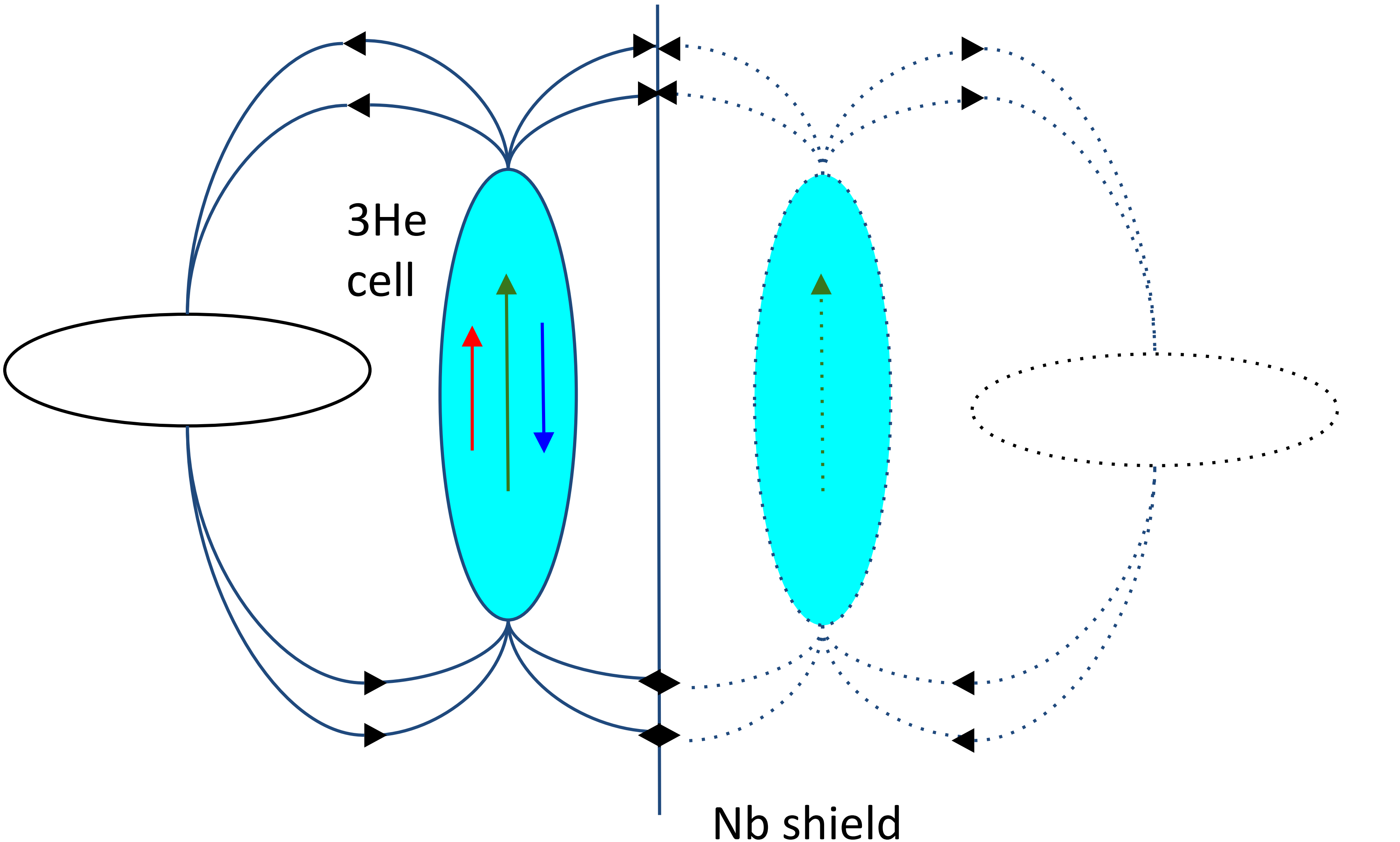
Magnetic Gradients



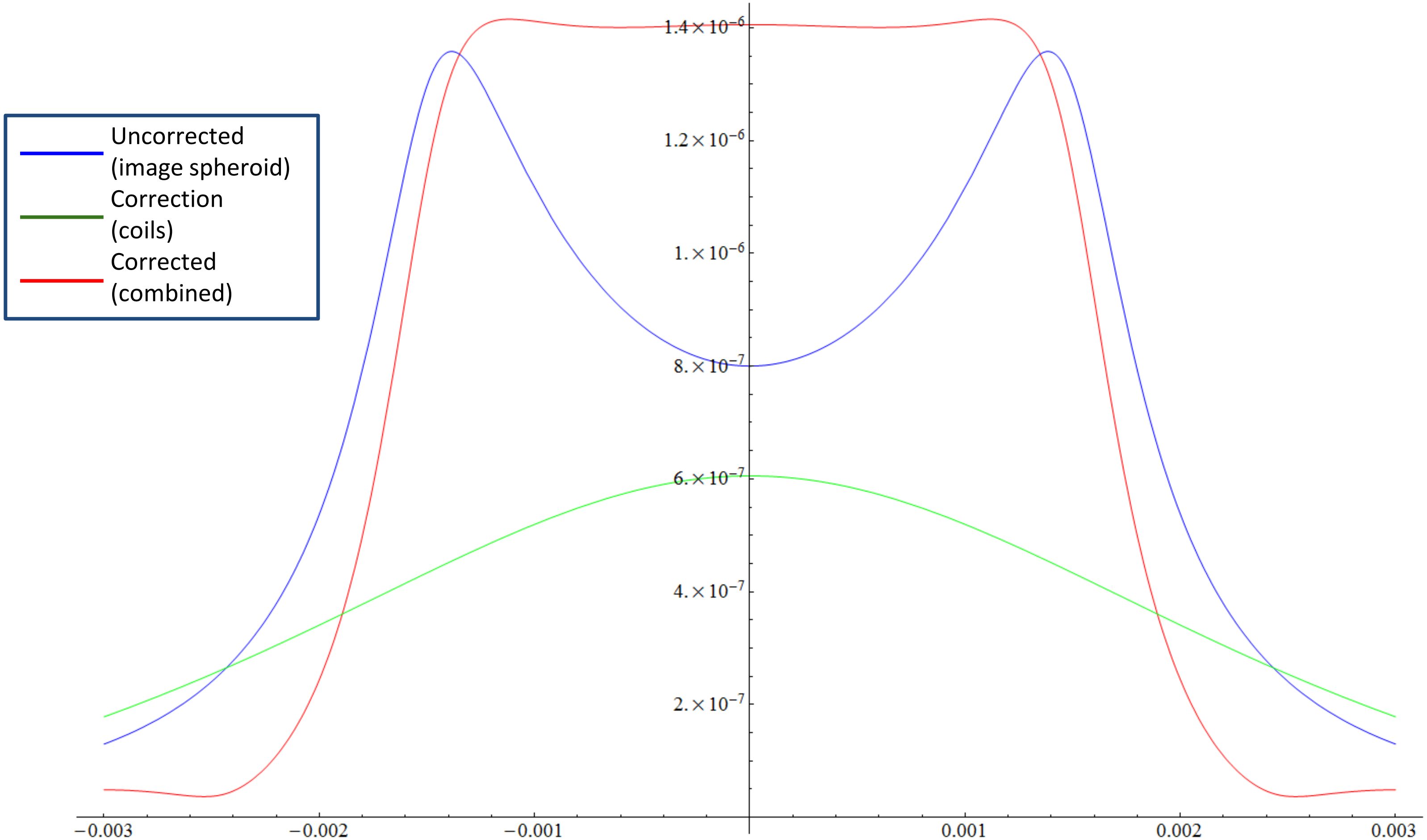
Magnetic Gradients



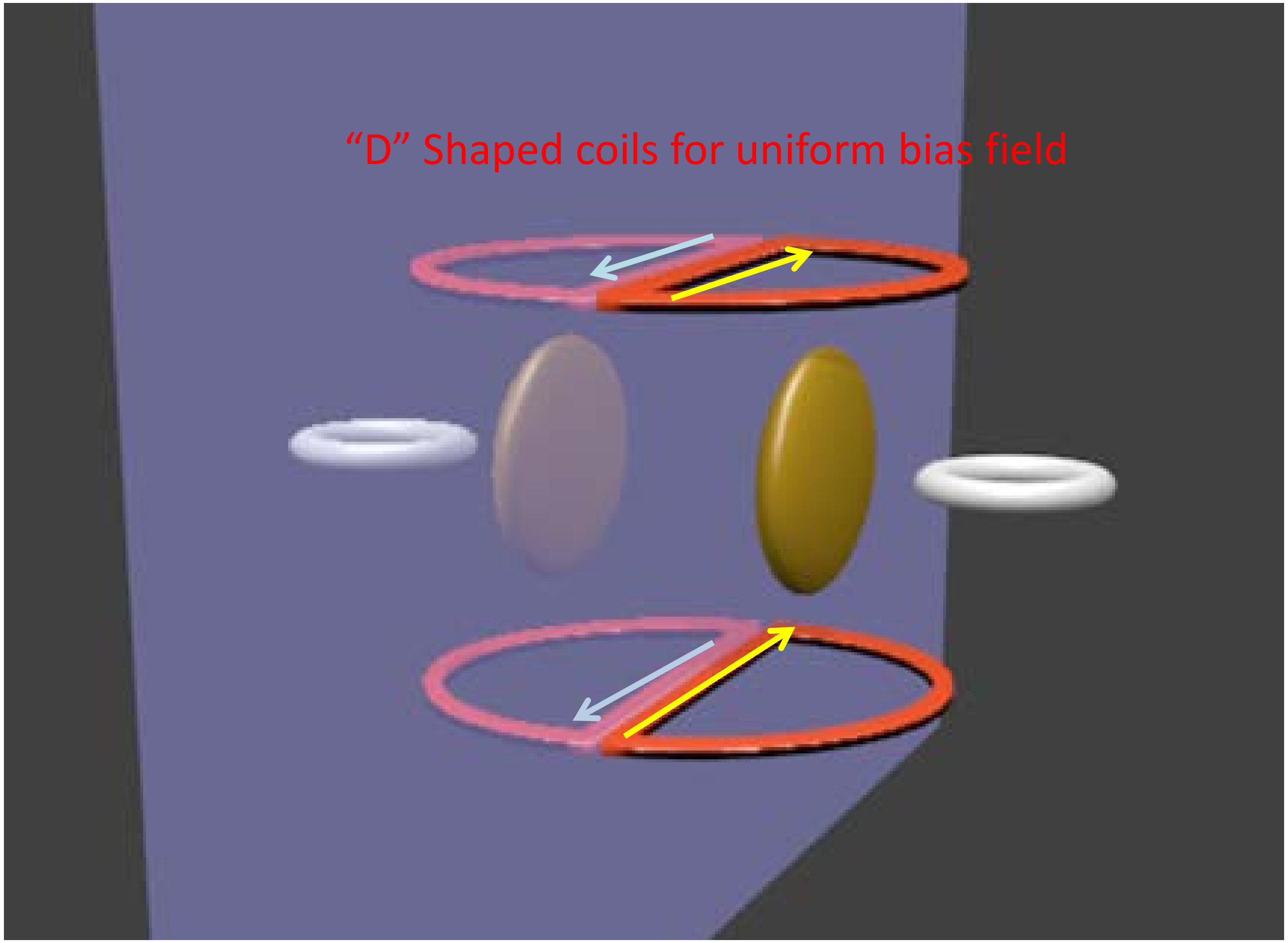
Magnetic Gradients



Gradient suppression



Magnetic Gradients



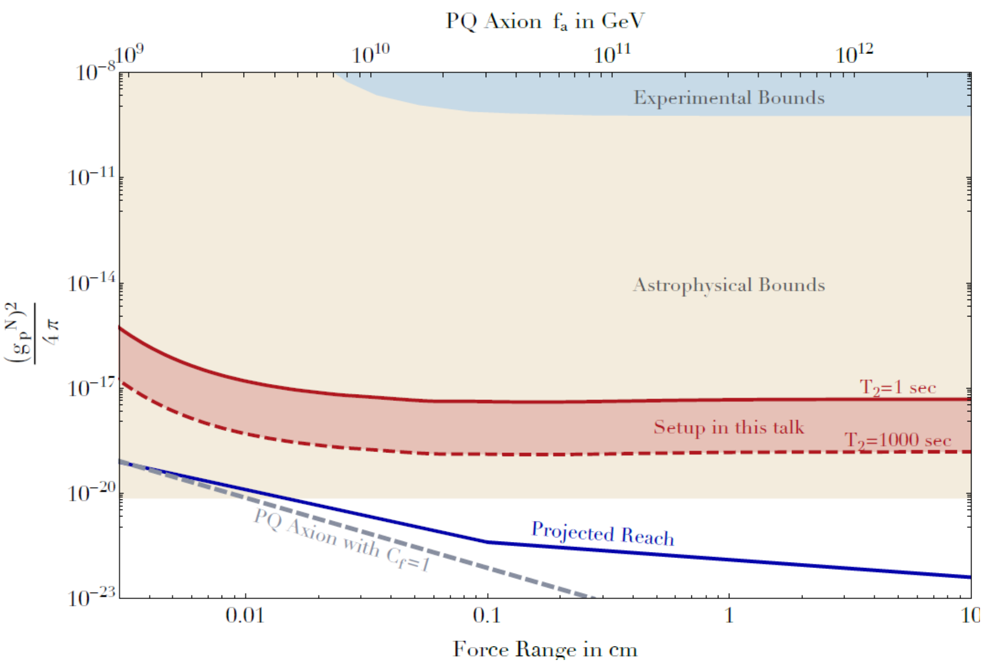
Gradient cancellation at the ~ 98 percent level looks feasible

T_2 in excess of 100s possible

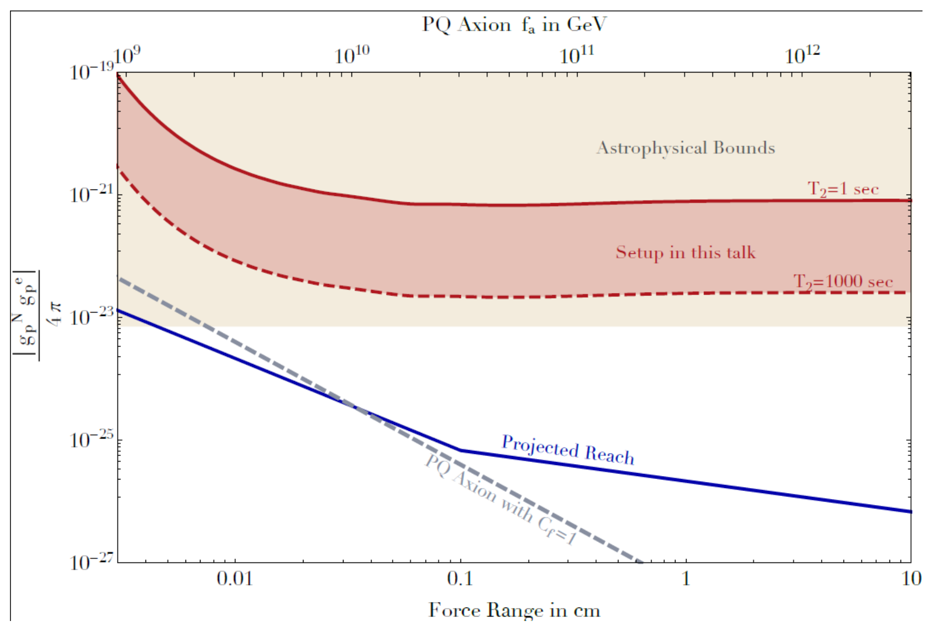
Dipole-Dipole axion forces

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

Nuclear spin



Electron spin



Summary

- Gap in experimental PQ axion searches 10^9 GeV < $f_a < 10^{11}$ GeV
- ARIADNE -- New resonant NMR method to probe into PQ axion parameter space
- Complementary to CAST, ADMX-type experiments
- Complementary to n-EDM searches

See also upcoming talks by Yannis Semertzidis and Yun Shin !!

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