Kathlynne Tullney

Limits for Spin-Dependent Short-Range Interaction of Axion-Like Particles

PRiSMA JG|U

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PANIC 2014, Hamburg

Outline

- Motivation
- Principle of measurements
- Experimental setup
- Results
- Summary

Motivation

The strong CP-Problem

The non-trivial vacuum structure of QCD predicts violation of CP-symmetry:

$$L_\theta = \bar{\theta} \frac{g^2}{32\pi^2} G^b_{\mu\nu} \tilde{G}^{\mu\nu}_b$$

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$$|d_n| \approx \bar{\theta} \cdot 10^{-16} \text{ ecm} < 3 \cdot 10^{-26} \text{ ecm}$$

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Original proposal for Axion *(R. Peccei, H.Quinn PRL 38(1977),1440)* as possible solution to the „strong CP-Problem“ that cancels the CP violating term in the QCD.

$$L_a = \zeta\,\frac{a}{f_a}\,\frac{g^2}{32\pi^2}\,G^b_{\mu\nu}\tilde{G}^{\mu\nu}_b$$

$$\langle a\rangle = -f_a\,\frac{\bar{\theta}}{\zeta}$$

with: $m_a \propto \dfrac{1}{f_a}$

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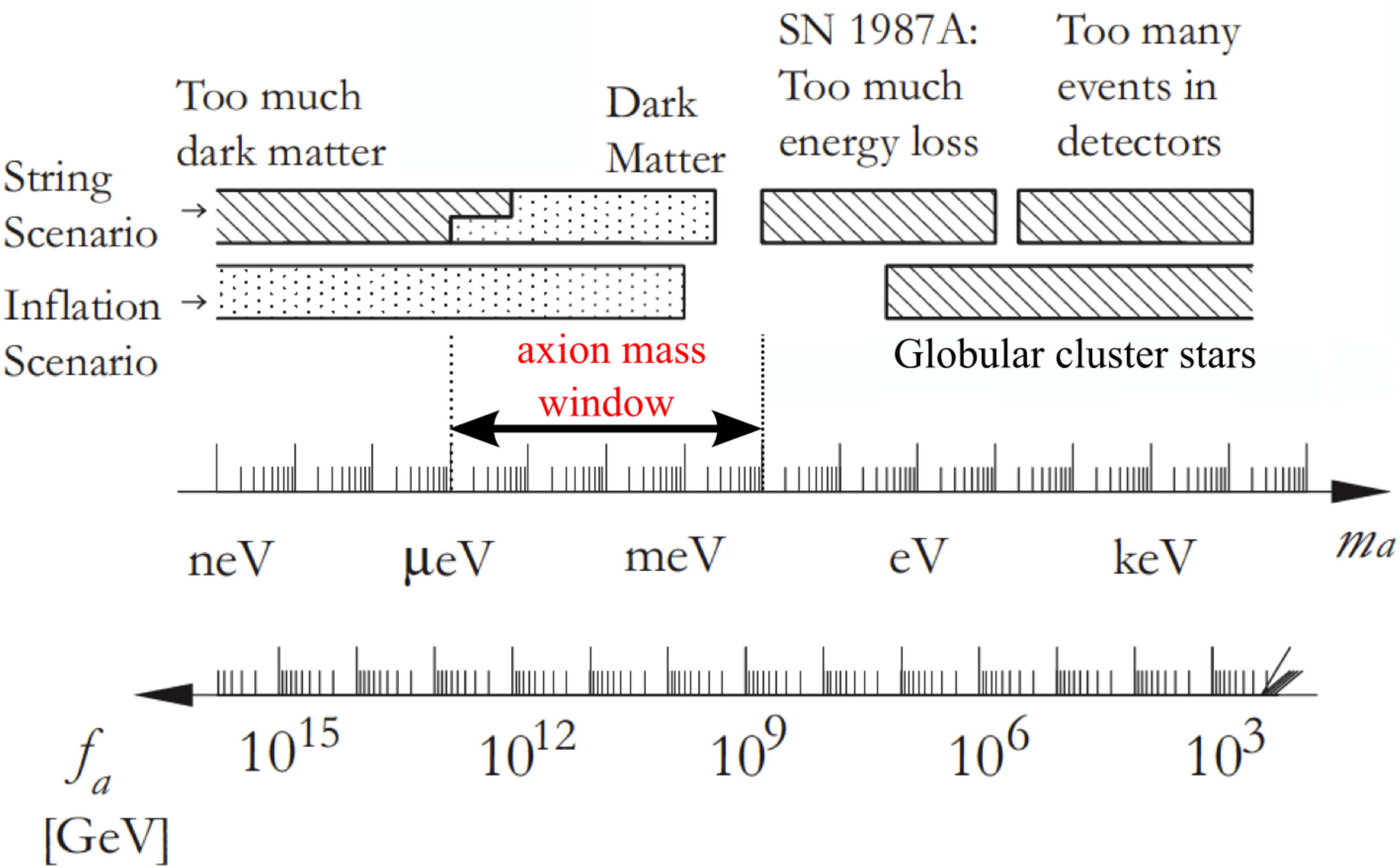
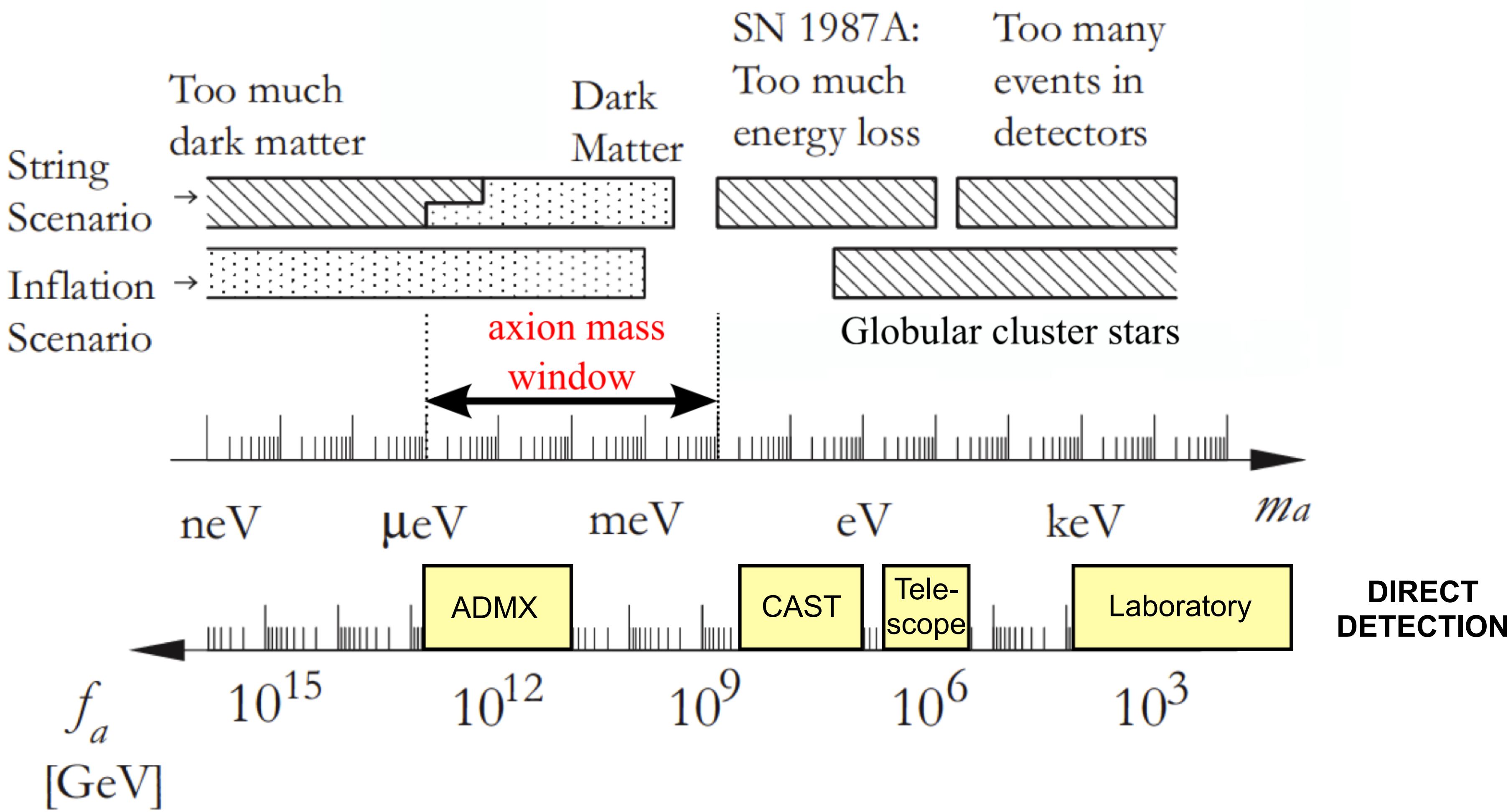
AXIONs: Light and weak interacting particles.
Modern Interest: Dark Matter candidate.

Axion Mass



Too much dark matter
Dark Matter
SN 1987A: Too much energy loss
Too many events in detectors
String Scenario
Inflation Scenario
axion mass window
Globular cluster stars
neV
μeV
meV
eV
keV
m_a
f_a [GeV]
10^{15}
10^{12}
10^{9}
10^{6}
10^{3}

Axion Mass



Too much
dark matter
Dark
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String
Scenario
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axion mass
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ma
ADMX
CAST
Tele-
scope
Laboratory
DIRECT
DETECTION
fa
[GeV]
10^15
10^12
10^9
10^6
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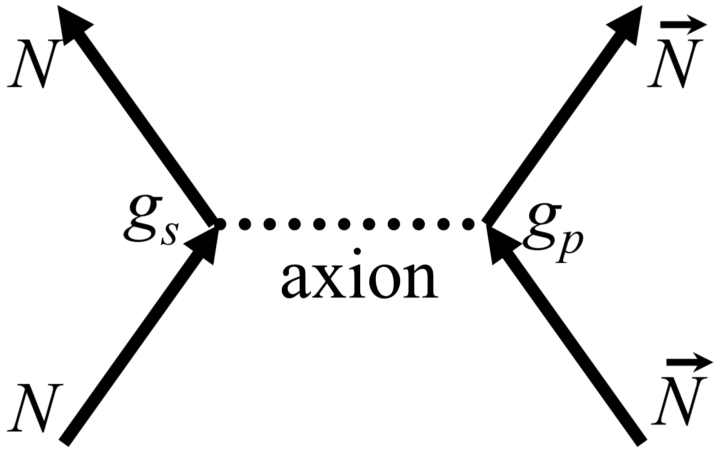
Motivation

Axion Potential:

Yukawa type potential with monopole-dipole coupling [1]

$$V(r) = \kappa \hat{n} \cdot \vec{\sigma} \left(\frac{1}{\lambda r} + \frac{1}{r^2} \right) e^{-r/\lambda}$$



[1] J.E. Moody and F. Wilczek. Phys. Rev. D, 30, 130 (1984).

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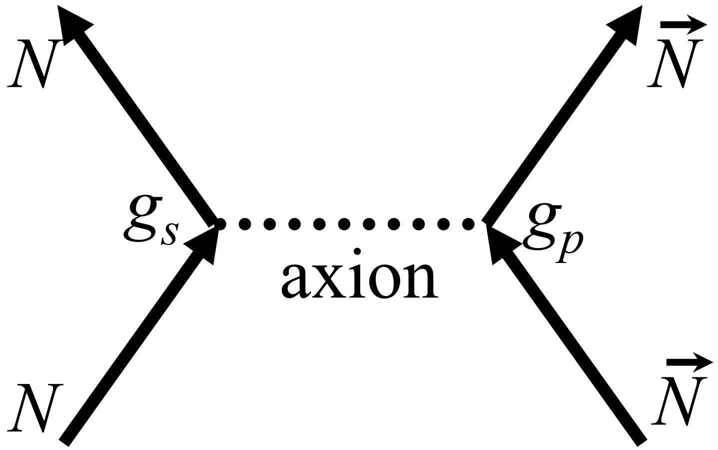

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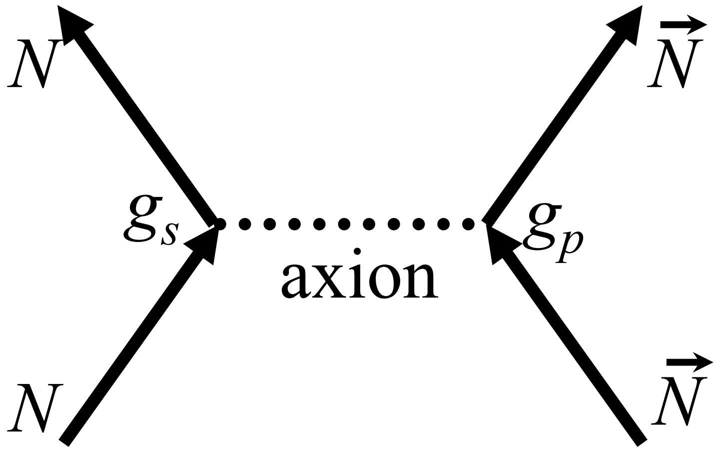


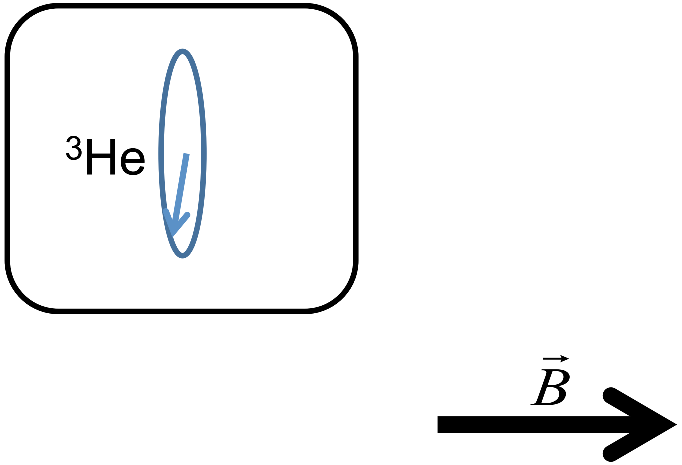
$\Rightarrow$ Indirect search of the axion via the axion potential in the range of the „axion mass window“:

10^{-6} eV $< m_a < 10^{-2}$ eV

10^{-5} m $< \lambda < 10^{-1}$ m

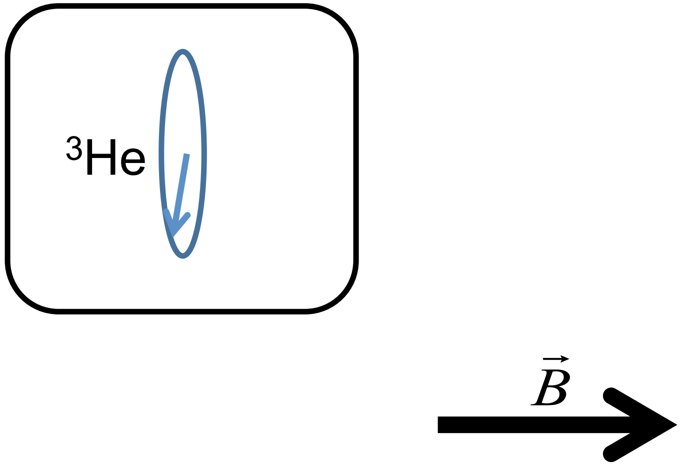
[1] J.E. Moody and F. Wilczek. Phys. Rev. D, 30, 130 (1984).

How to measure?



Principle of measurements

How to measure?



$$\omega_{\mathrm{L,He}}(t) = \gamma_{\mathrm{He}} \cdot B(t)$$

Principle of measurements

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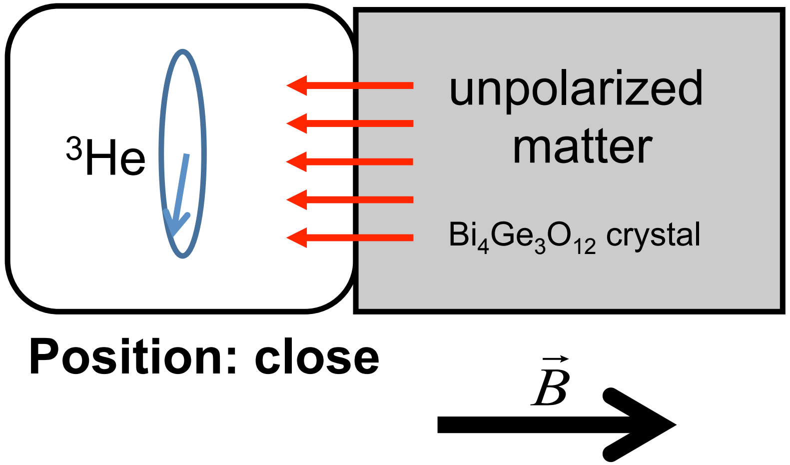

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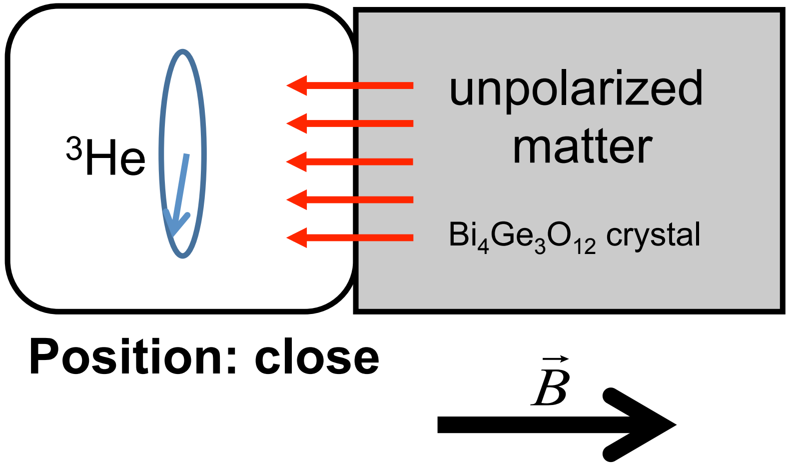

$$\omega_{close}(t) = \omega_{L,He}(t) + \omega_{sp}$$

with: $\omega_{L,He}(t) = \gamma_{He} \cdot B(t)$

$$\omega_{sp} = 2\pi \cdot \nu_{sp} = 2 \cdot \bar{V} / \hbar$$

Principle of measurements

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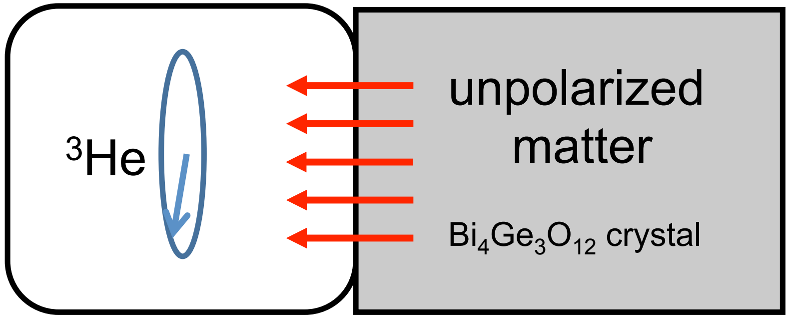

Position: close

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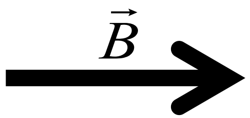
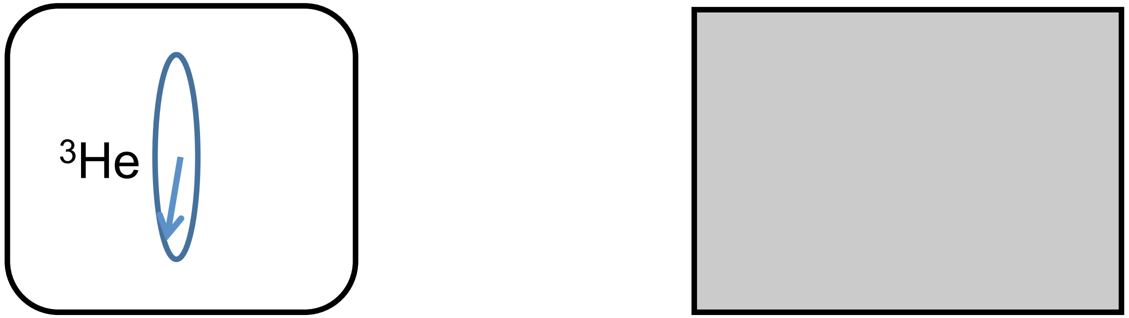


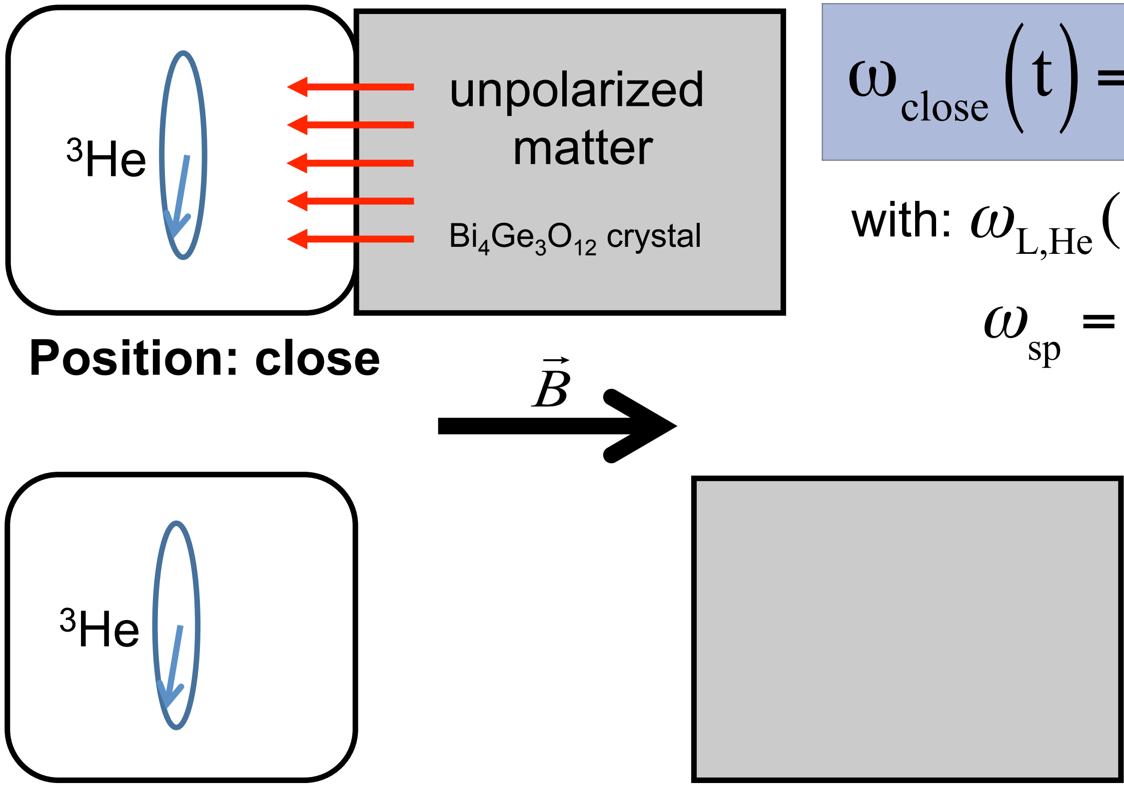


Position: distant

$$\omega_{distant}(t) = \omega_{L,He}(t)$$

Principle of measurements

How to measure?



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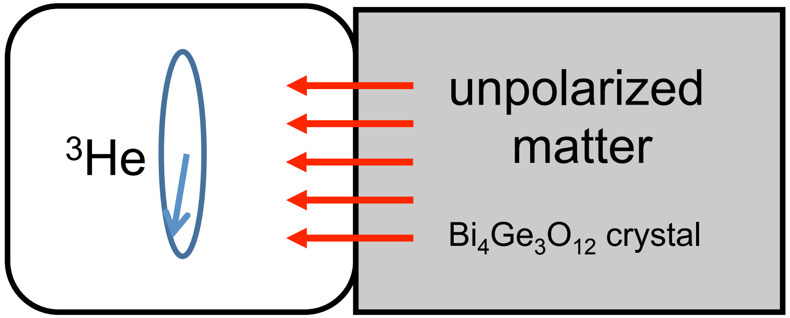
$$\omega_{distant}(t) = \omega_{L,He}(t)$$

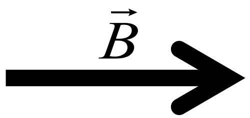
$$\Rightarrow \quad \omega_{sp} = \omega_{close}(t) - \omega_{distant}(t)$$

Principle of measurements

How to measure?



Position: close



$$\omega_{close}(t) = \omega_{L,He}(t) + \omega_{sp}$$

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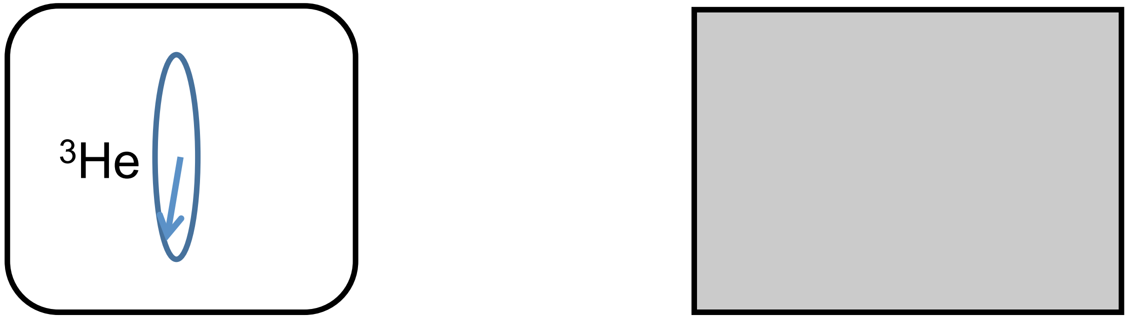


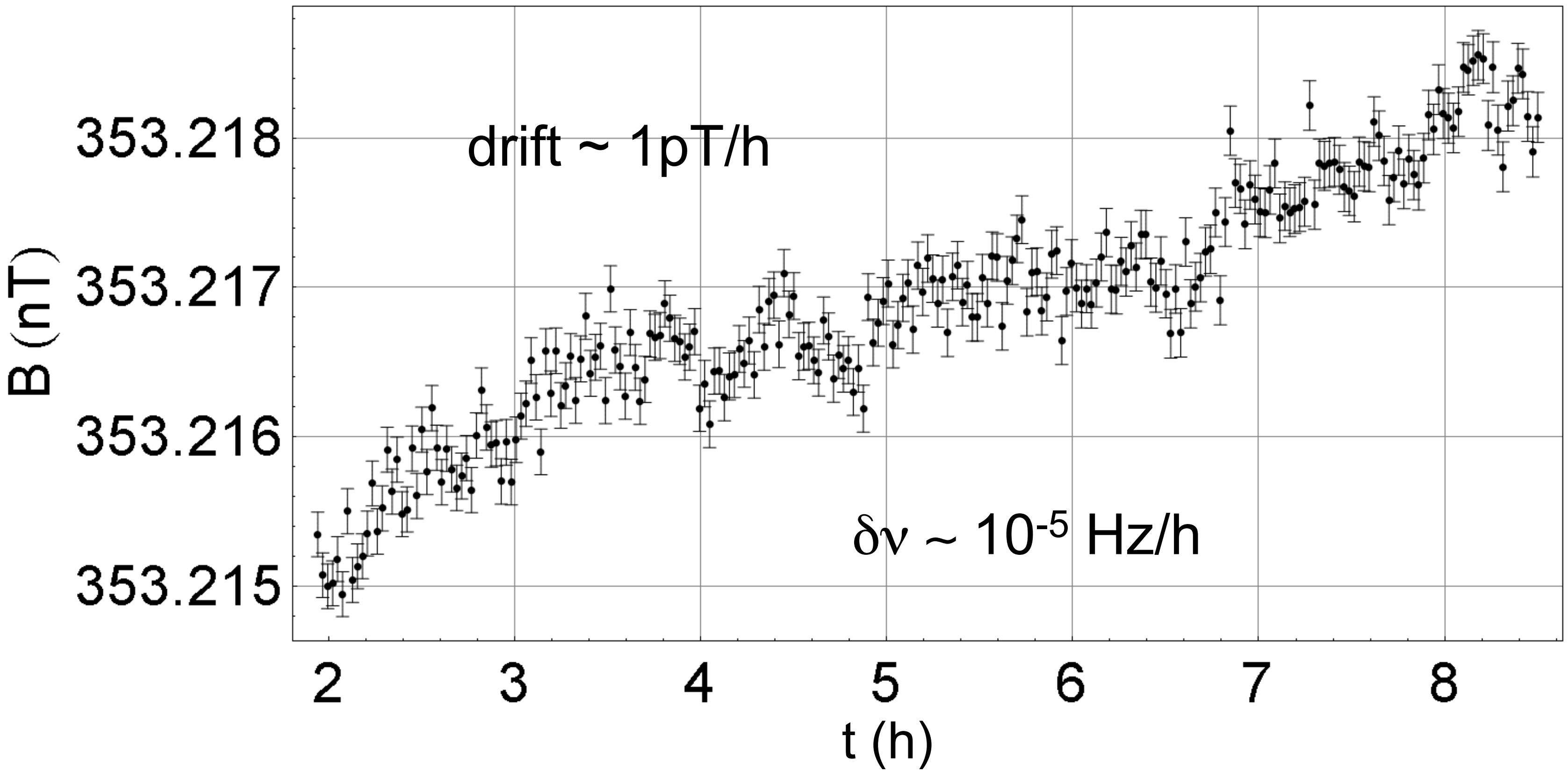
Position: distant

$$\omega_{distant}(t) = \omega_{L,He}(t)$$

$$\Rightarrow \omega_{sp} = \omega_{close}(t) - \omega_{distant}(t)$$

<u>Requirement:</u> $\omega_{L,He}(t) = const.$

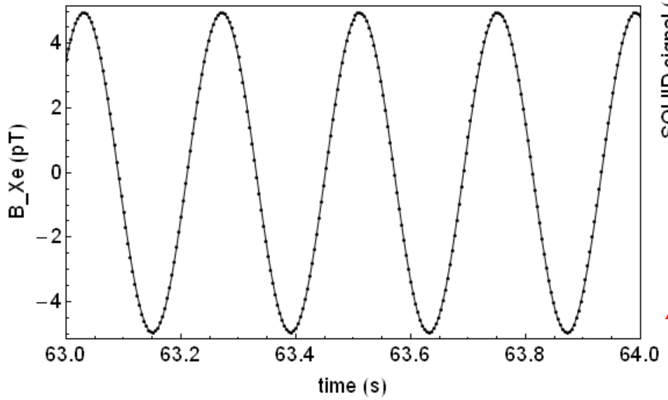
Principle of measurements

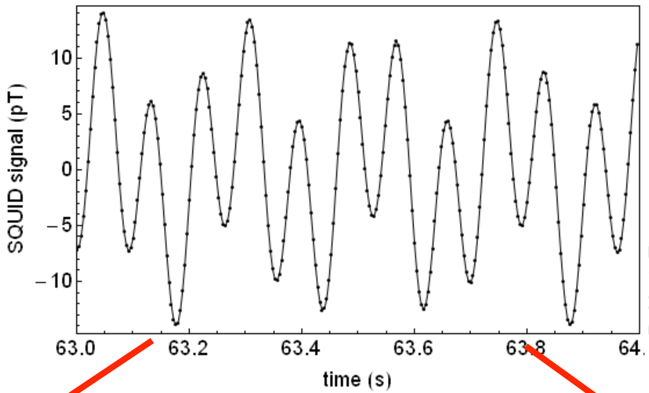


Principle of measurements

^{3}He/^{129}Xe Co-magnetometer

$$\omega_{Xe}(t) = \gamma_{Xe} \cdot B(t)$$





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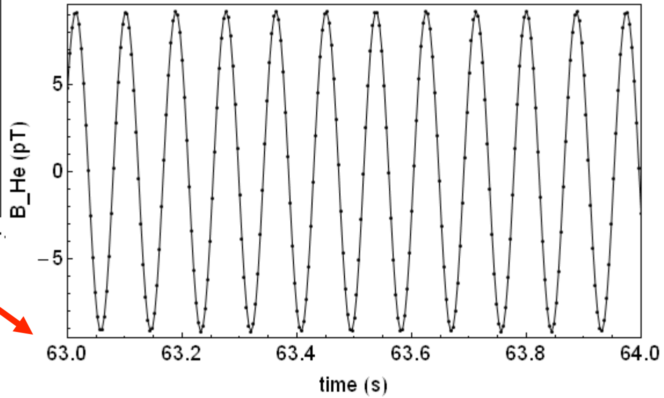

Elimination of magnetic field drifts (Zeeman-Term):

Frequency difference: $$\Delta\omega = \omega_{He} - \frac{\gamma_{He}}{\gamma_{Xe}}\omega_{Xe} = \left(\gamma_{He} - \frac{\gamma_{He}}{\gamma_{Xe}} \cdot \gamma_{Xe}\right) \cdot B(t) \overset{!}{=} 0$$

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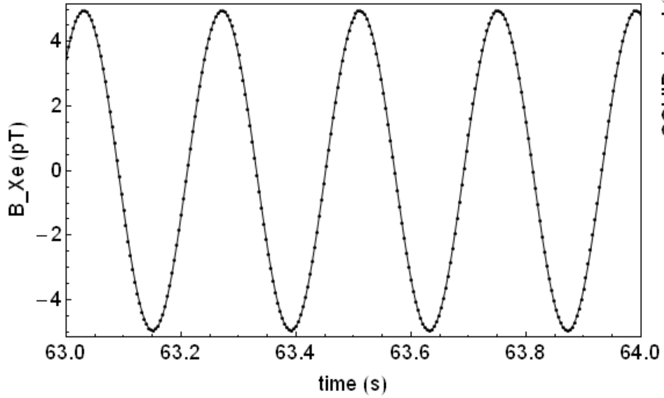

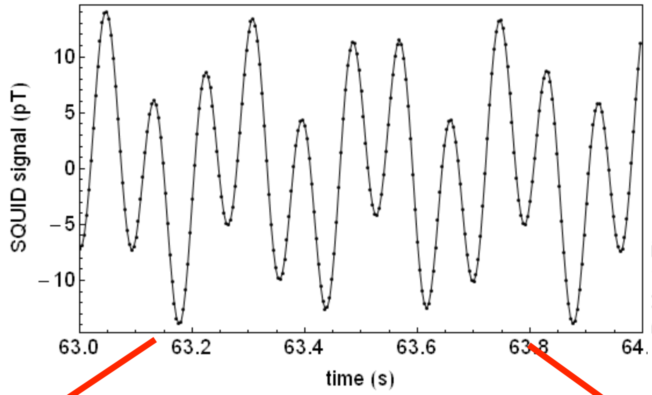

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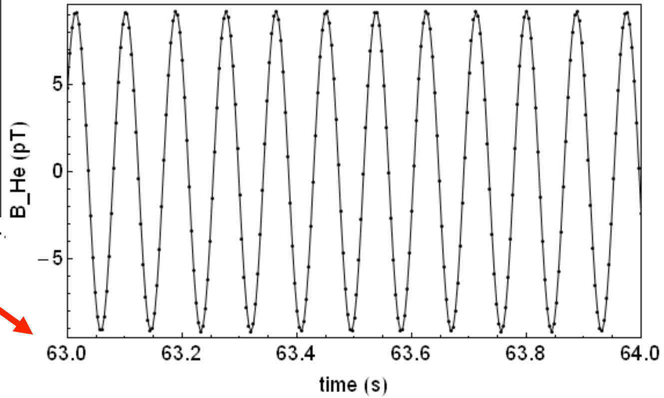

Elimination of magnetic field drifts (Zeeman-Term):

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$$\Phi(t) = \int_0^t \omega(t')dt'$$

Phase difference: $$\Delta\Phi(t) = \Phi_{He}(t) - \frac{\gamma_{He}}{\gamma_{Xe}} \cdot \Phi_{Xe}(t) = \Phi_0 \overset{!}{=} const.$$

$^{3}He/^{129}Xe$ Co-magnetometer

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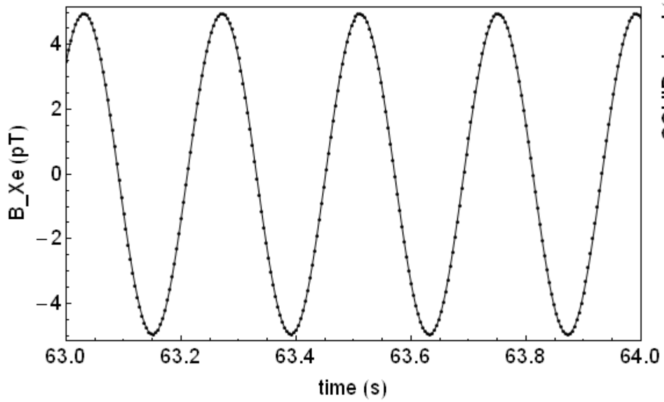

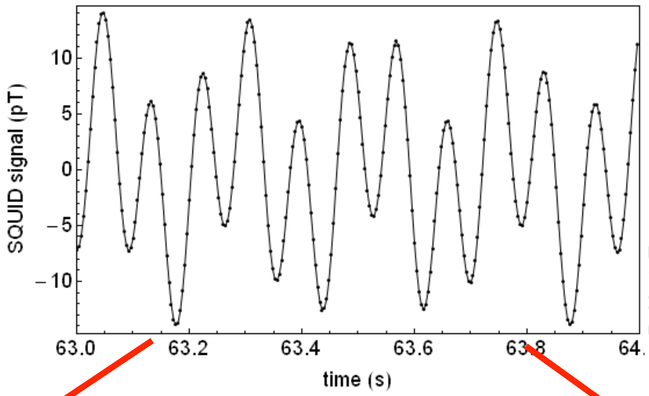

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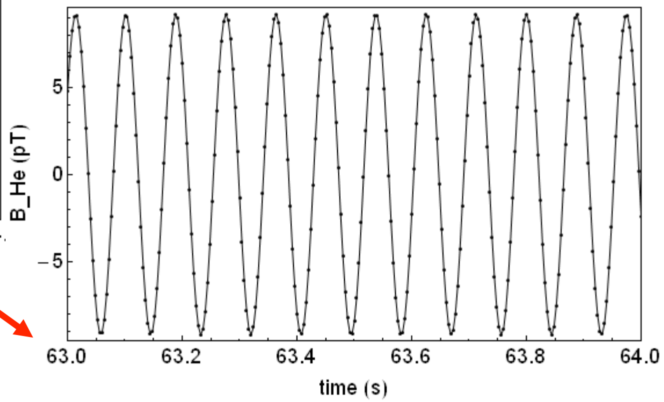

Elimination of magnetic field drifts (Zeeman-Term):

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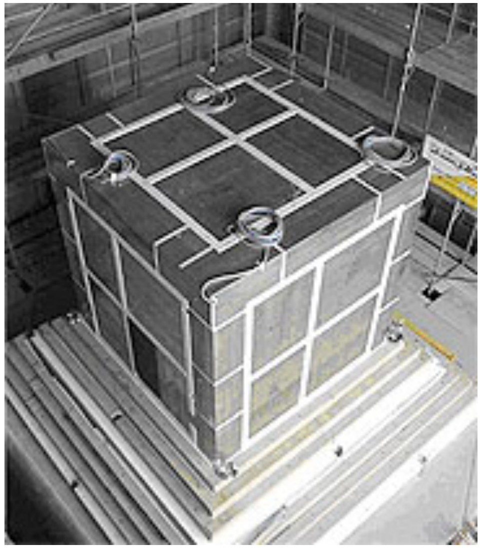
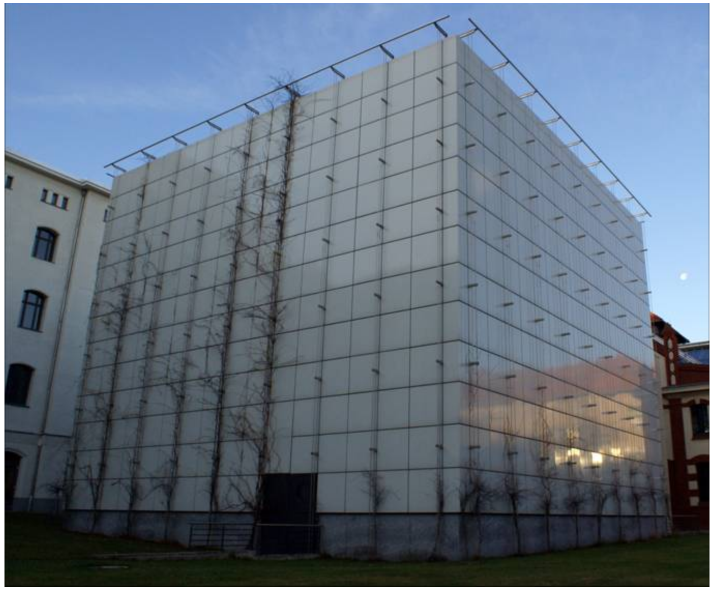
Experimental Setup

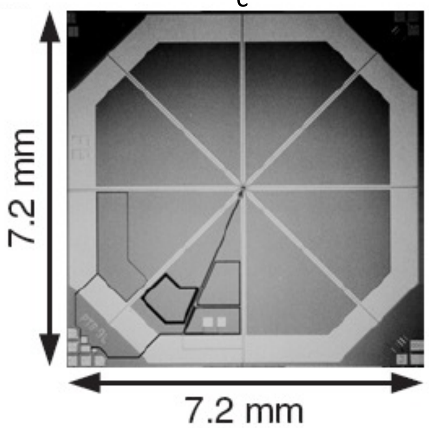


7 layered magnetically shielded room (residual field < 1 nT)

J. Bork, et al., Proc. Biomag 2000, 970 (2000).



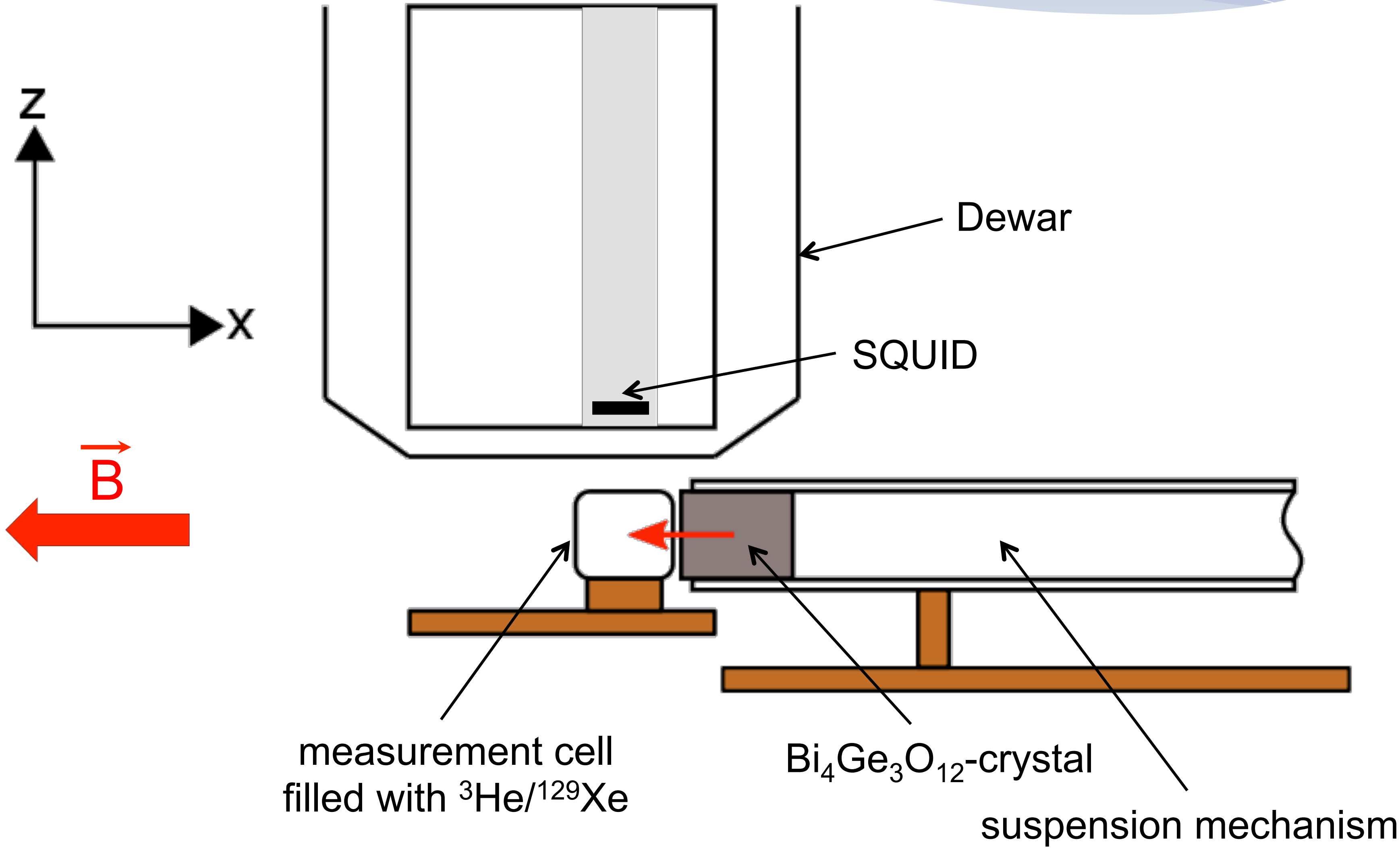
LT$_c$- SQUID



magn. guiding field $\approx$ 350 nT (Helmholtz-coils)

$$\left|\vec{\nabla} B_{\mathrm{x,y,z}}\right| \approx 20\,\mathrm{pT/cm}$$

Experimental Setup



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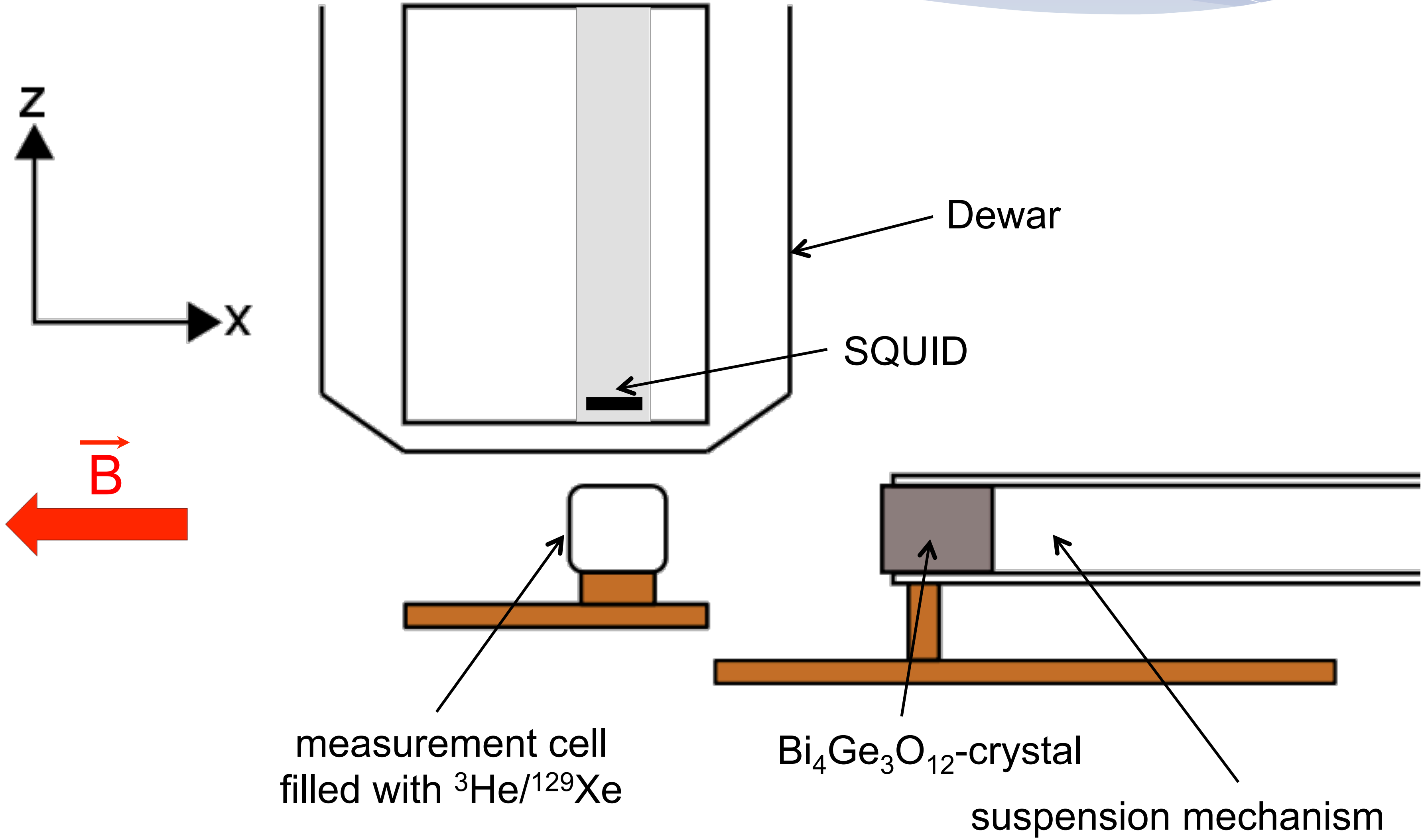
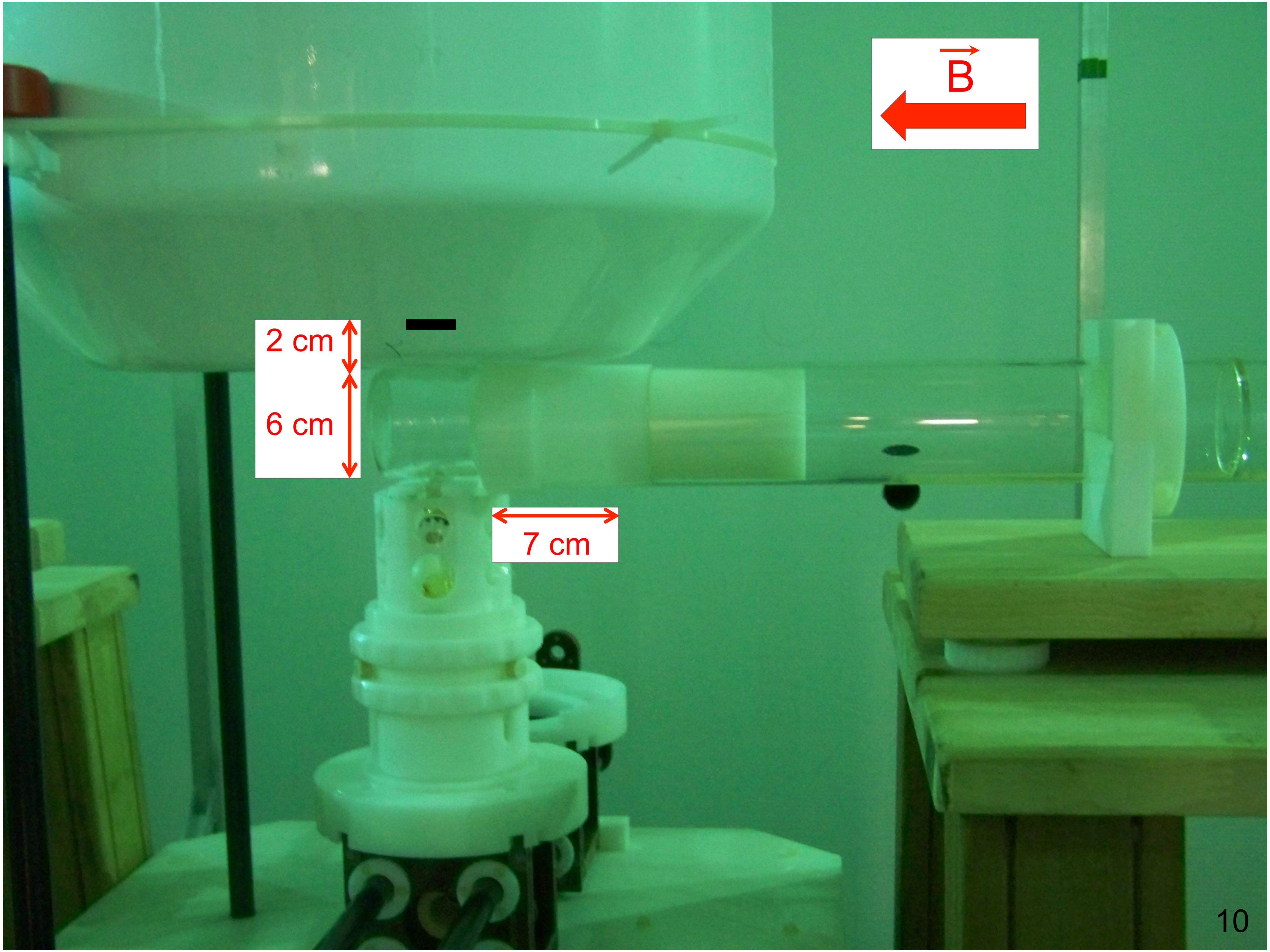
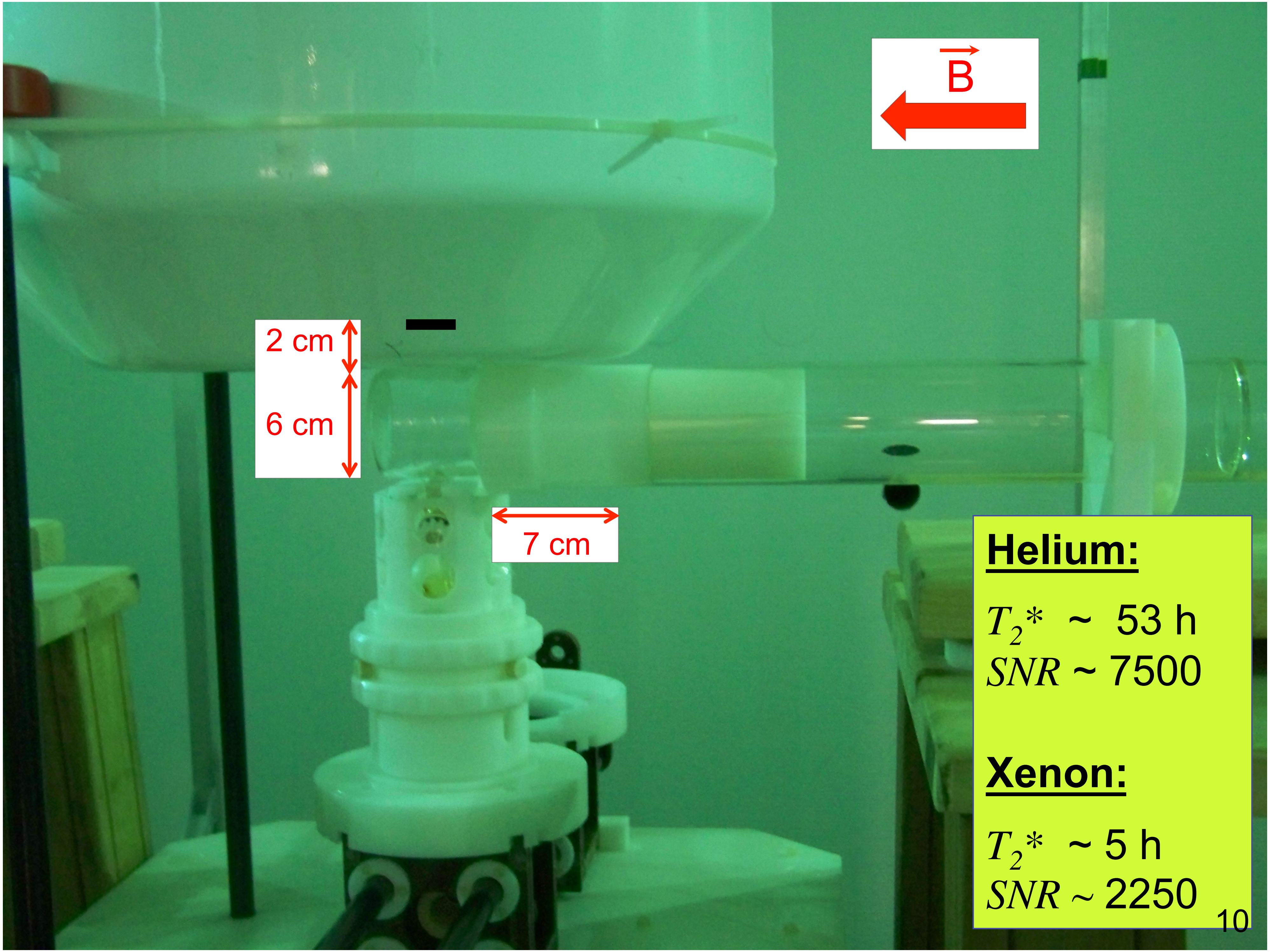


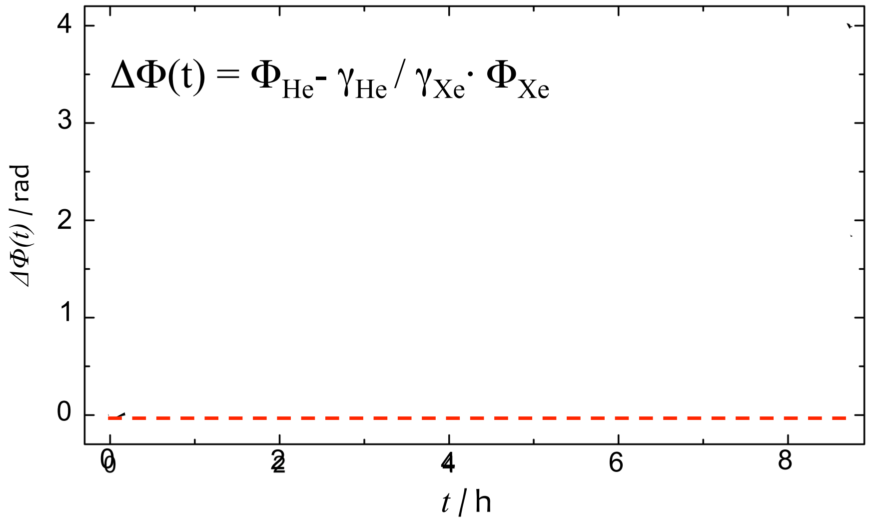

B
2 cm
6 cm
7 cm


B
2 cm
6 cm
7 cm
Helium:
T2* ~ 53 h
SNR ~ 7500
Xenon:
T2* ~ 5 h
SNR ~ 2250

Data Analysis

1. To cancel magnetic field influence we calculate the weighted phase difference:

$$\Delta\Phi(t) = \Phi_{He} - \frac{\gamma_{He}}{\gamma_{Xe}} \cdot \Phi_{Xe}$$



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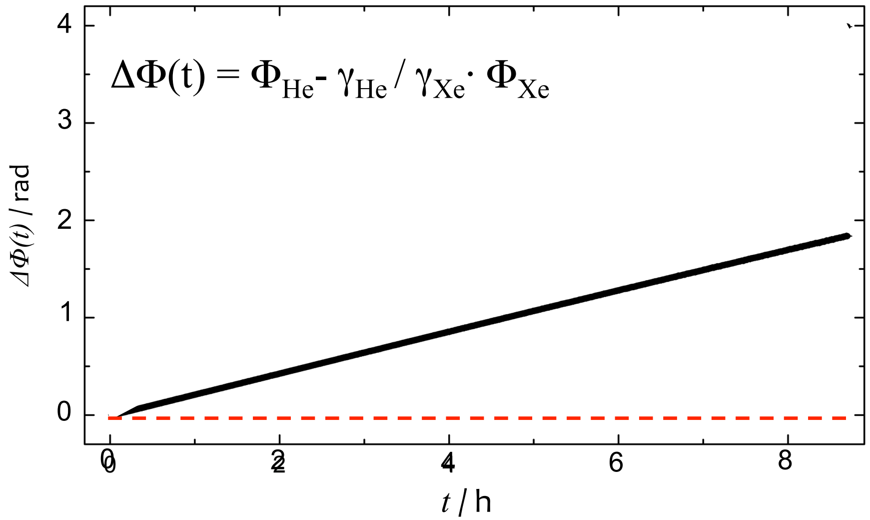

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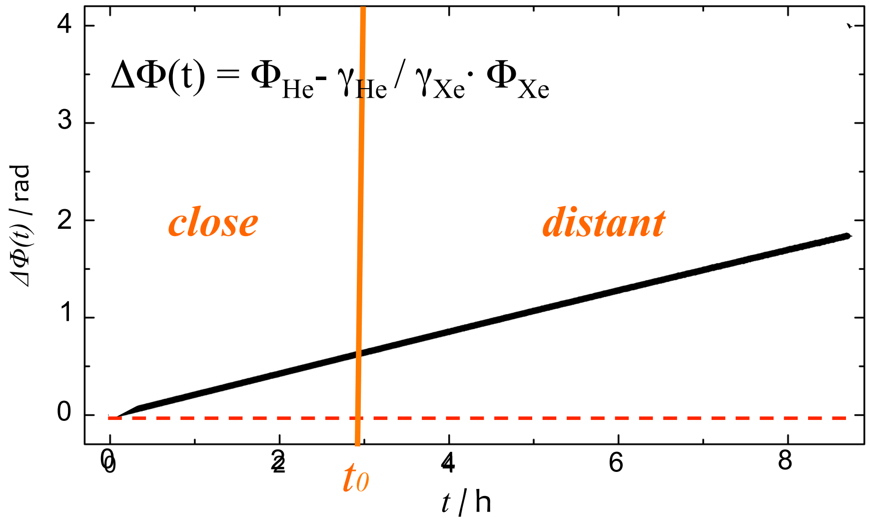
2. Temporal dependence can be described by:

$$f(t) = c + a_{lin} \cdot t + a_{He} \cdot e^{-t/T^{*}_{2,He}} + a_{Xe} \cdot e^{-t/T^{*}_{2,Xe}} + \Delta\omega_{sp} \cdot t \cdot H(t - t_0)$$



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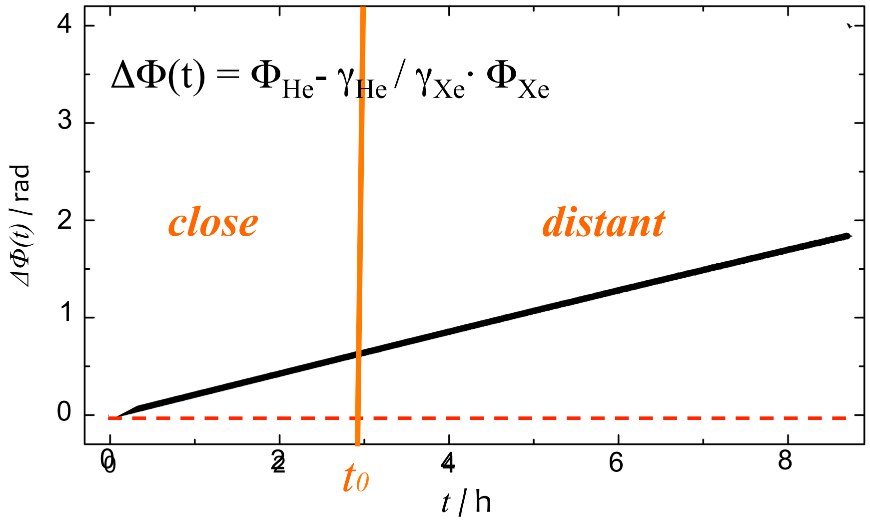
$$\Rightarrow \Delta\nu_{sp} = \frac{\Delta\omega_{sp}}{2\pi(1-\gamma_{He}/\gamma_{Xe})}$$



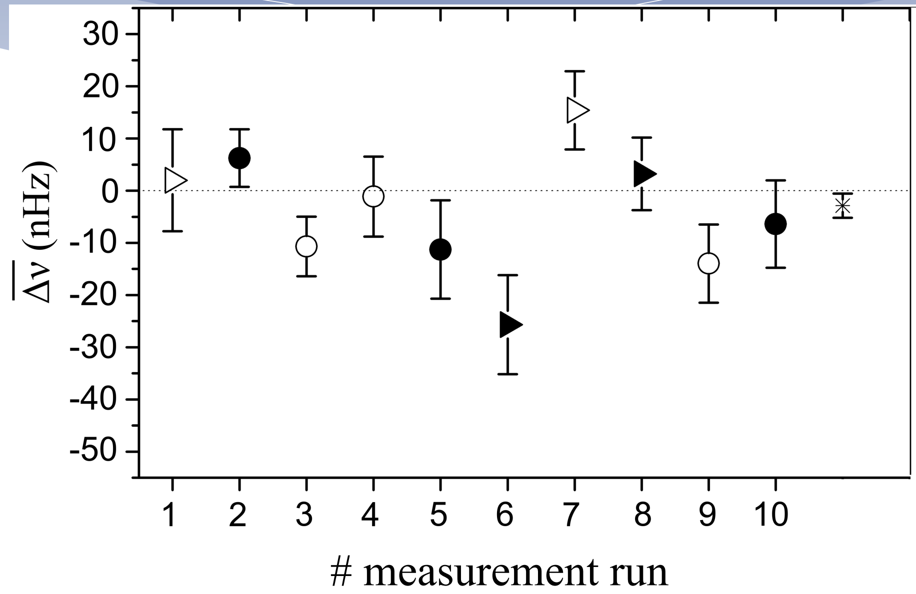
Summary Results

<u>September 2010:</u>

10 measurements (~9 hours)

gap = 2.2 mm

sample: $Bi_4Ge_3O_{12}$ with: ρ = 7.13 g/cm³



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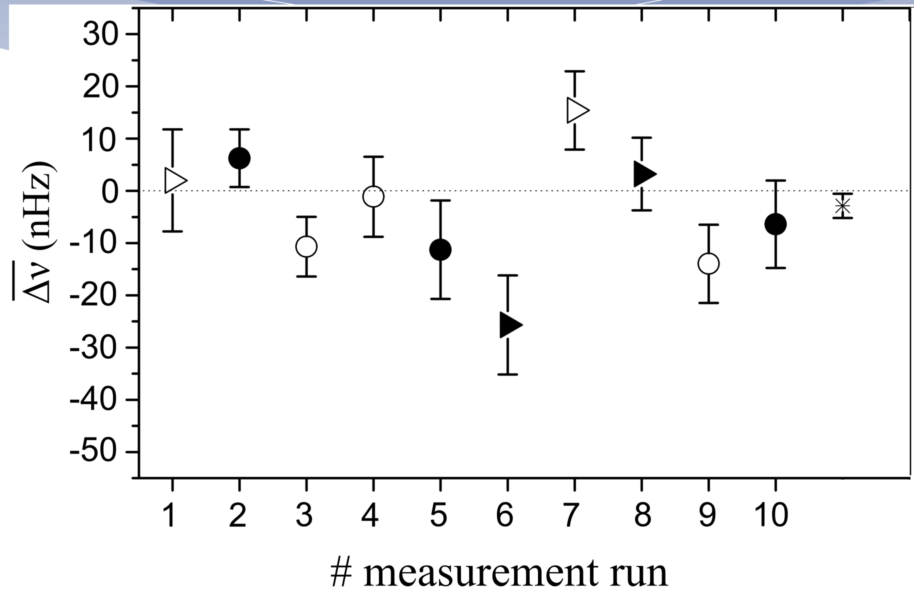

⇒ $\Delta\nu_{sp}$ = (-2.9 ± 3.5) nHz ⟶ $\delta(\Delta\nu_{sp})_{corr}$ = 7.1 nHz *(95% CL)*

K. Tullney et al. PRL 111, 100801 (2013)

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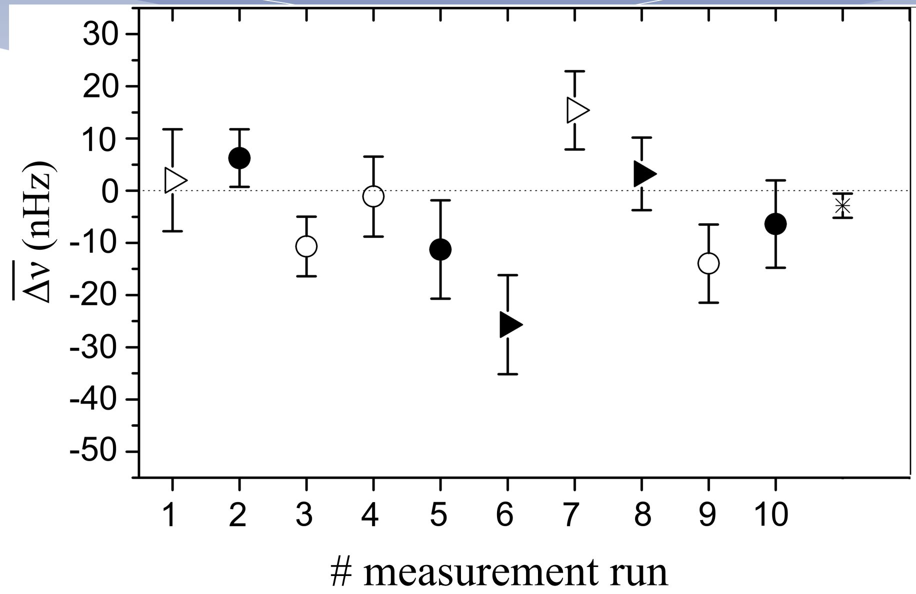

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K. Tullney et al.
PRL 111, 100801 (2013)

$$\delta\left(\Delta\nu_{sp}\right) > 2\left\langle V_{sp}\right\rangle / h$$

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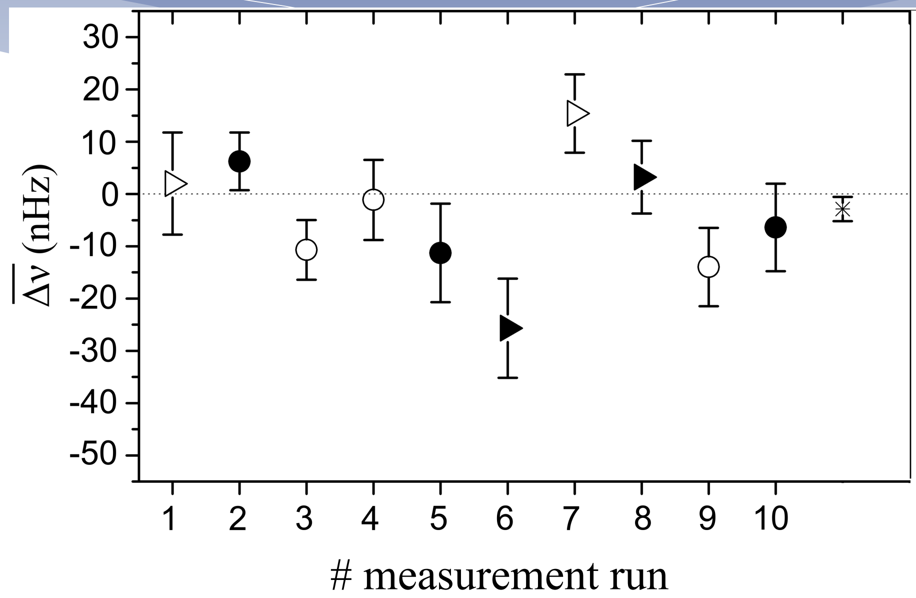

⇒ $\Delta\nu_{sp}$ = (-2.9 ± 3.5) nHz ⟶ $\delta(\Delta\nu_{sp})_{corr}$ = 7.1 nHz *(95% CL)*

K. Tullney et al.
PRL 111, 100801 (2013)

$$\delta\left(\Delta\nu_{sp}\right) > 2\left\langle V_{sp}\right\rangle / h$$

Potential: $$V_{sp}\left(\vec{r}\right) = \frac{\hbar^2 g_s g_p}{8\pi m_n}\left(\frac{\vec{r}}{r}\cdot\vec{\sigma}\right)\left(\frac{1}{r\lambda}+\frac{1}{r^2}\right)\cdot e^{-r/\lambda}$$

Summary Results

September 2010:

10 measurements (~9 hours)

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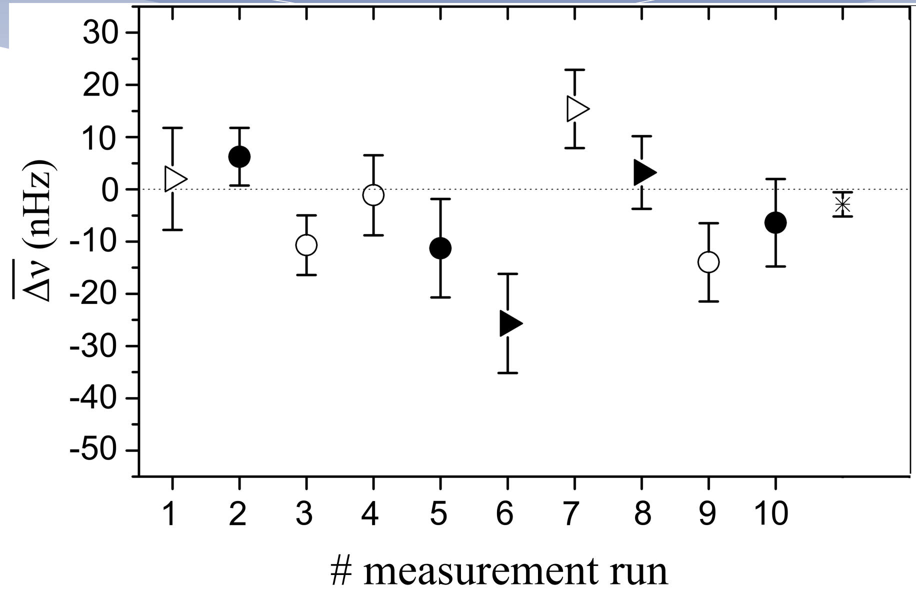

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$$\delta\left(\Delta\nu_{sp}\right) > 2\left\langle V_{sp}\right\rangle / h \quad \Rightarrow \quad g_s g_p(\lambda) < \frac{8\pi^2 \cdot m_n \cdot V_{cell} \cdot \delta\left(\Delta\nu_{sp}\right)}{\hbar \cdot N \cdot \left\langle V^*(\lambda)\right\rangle}$$

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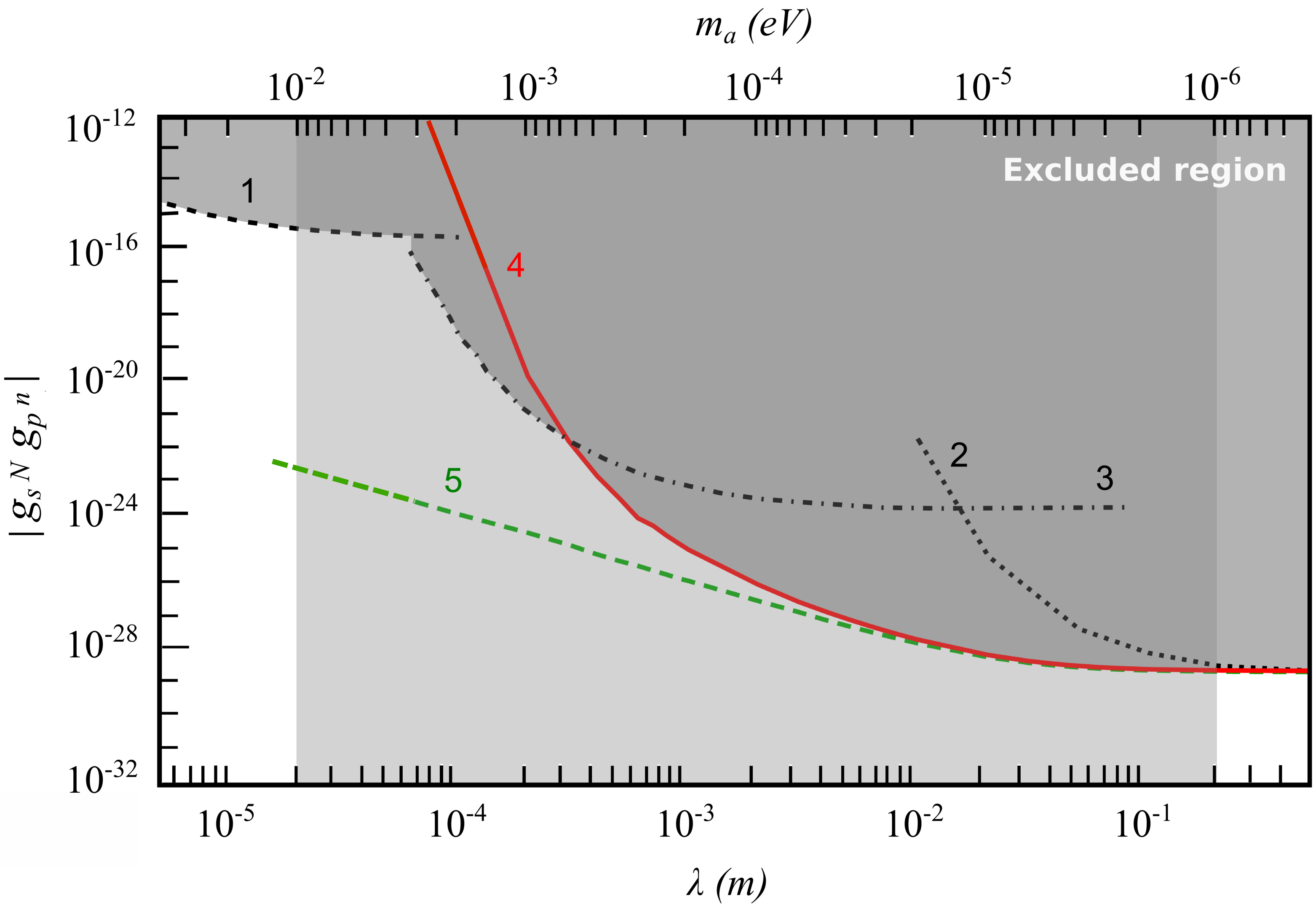
Exclusion Plot



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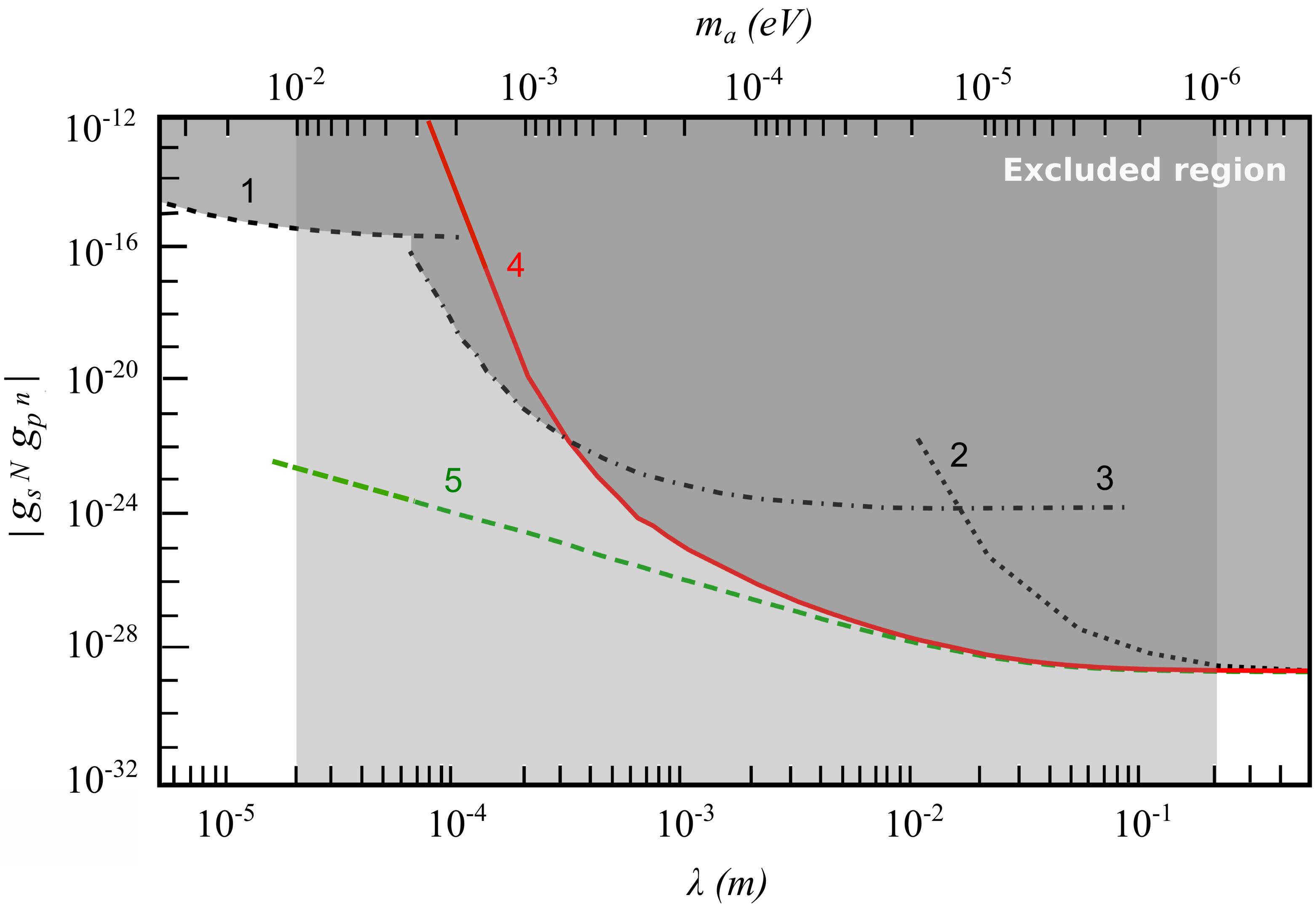

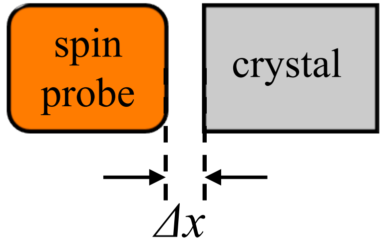

$$\langle V^*(\lambda) \rangle \propto e^{-\Delta x/\lambda}$$

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