Kathlynne Tullney

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

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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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From neutron EDM we get:

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

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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: $m_a \propto \frac{1}{f_a}$

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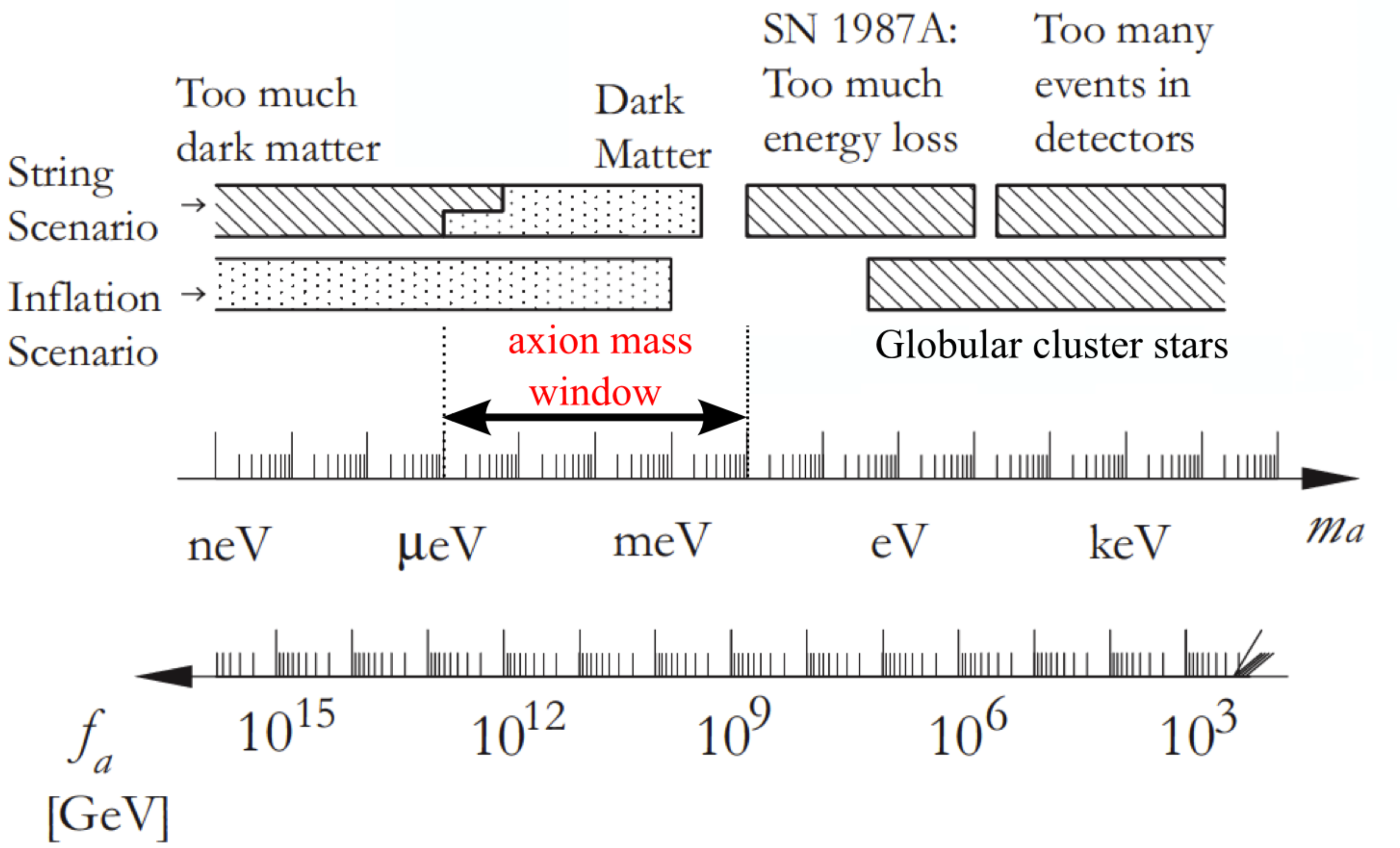
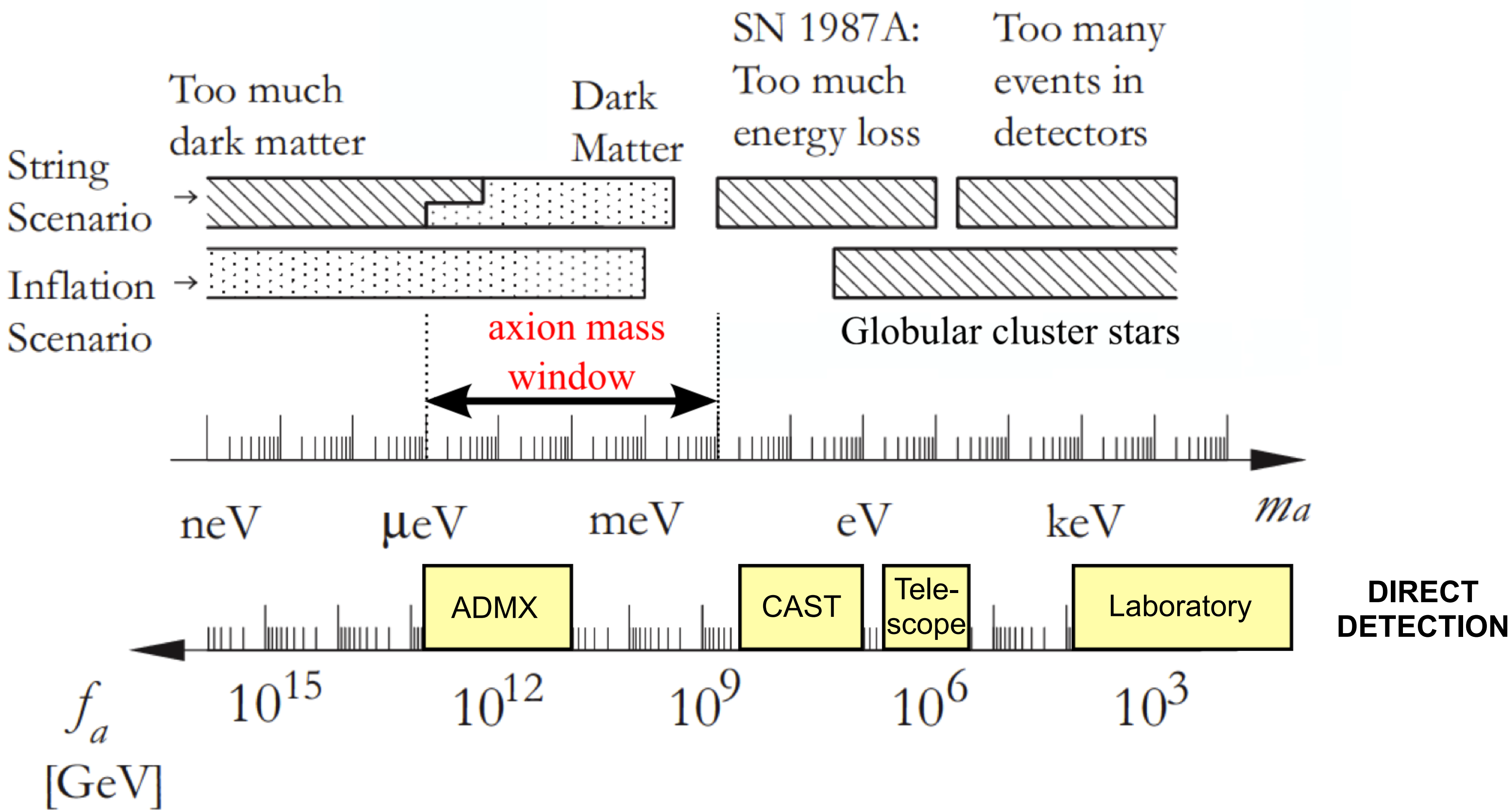
AXIONs: Light and weak interacting particles.
Modern Interest: Dark Matter candidate.

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
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axion mass
window
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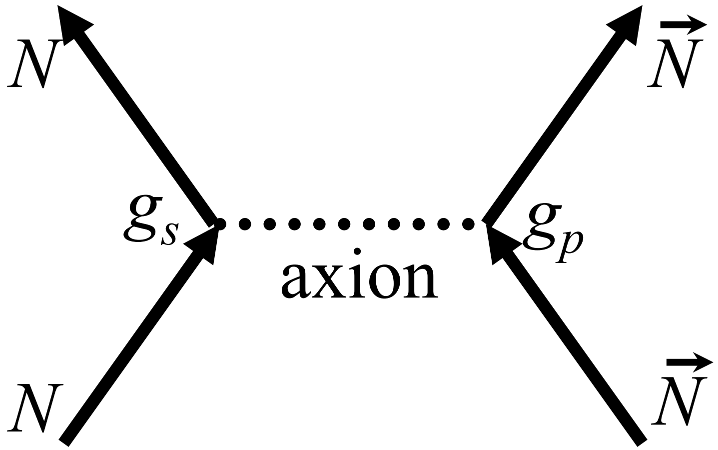
μeV
meV
eV
keV
ma
ADMX
CAST
Tele-
scope
Laboratory
DIRECT
DETECTION
fa
[GeV]
10^15
10^12
10^9
10^6
10^3

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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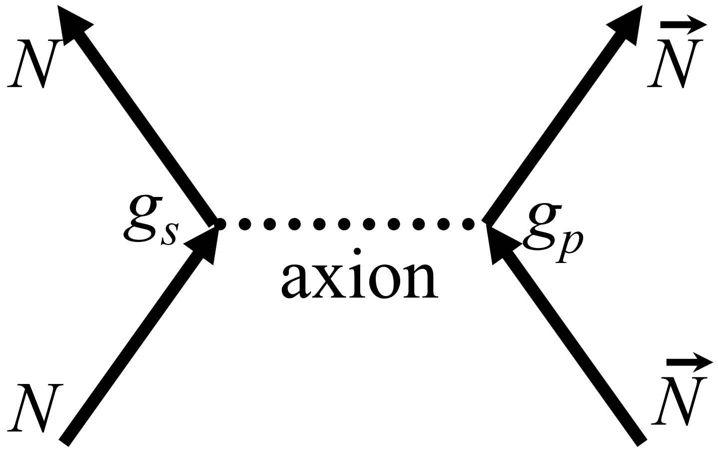

with: $\kappa = \frac{\hbar^2 g_s g_p}{8\pi m_n}$, $\lambda = \frac{\hbar}{m_a c}$

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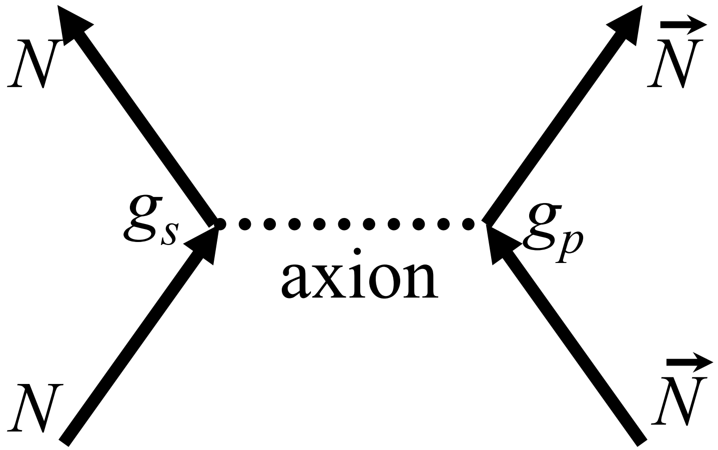

⇒ Indirect search of the axion via the axion potential in the range of the „axion mass window“:

$$10^{-6}\text{ eV} < m_a < 10^{-2}\text{ eV}$$
$$10^{-5}\text{ m} < \lambda < 10^{-1}\text{ m}$$

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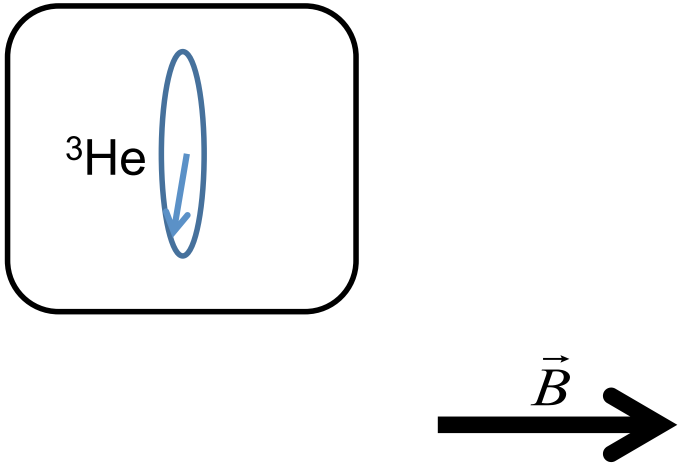
Principle of measurements

How to measure?



Principle of measurements

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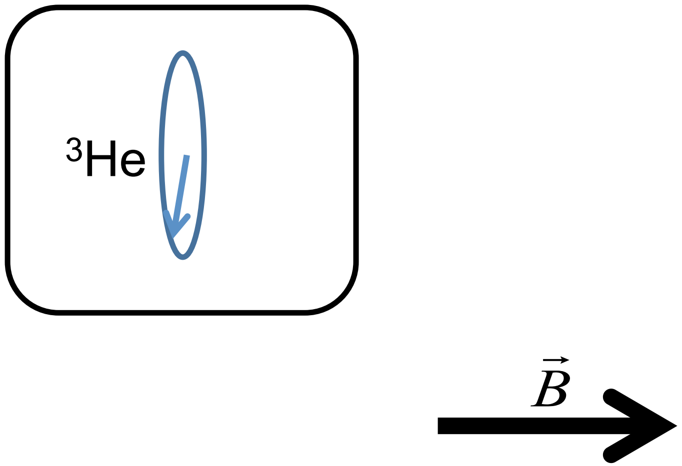
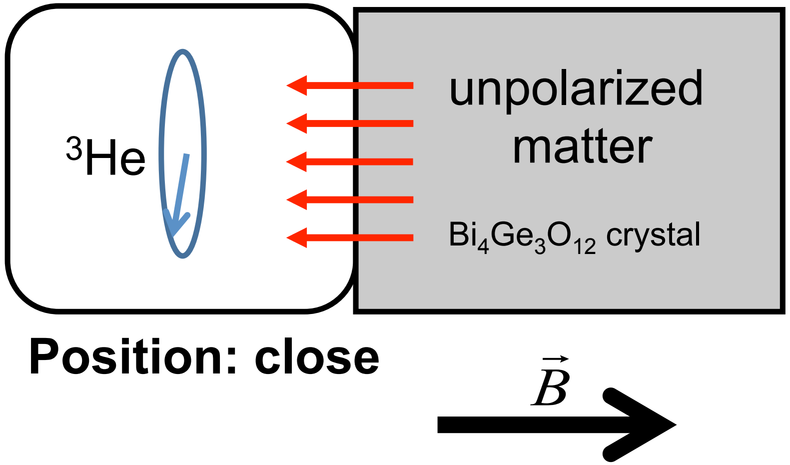


$$\omega_{\mathrm{L,He}}(t) = \gamma_{\mathrm{He}} \cdot B(t)$$

How to measure?



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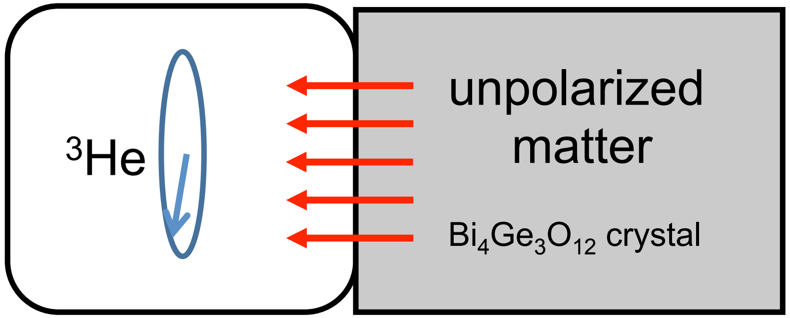
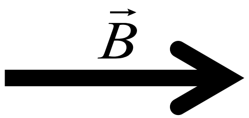


Position: close



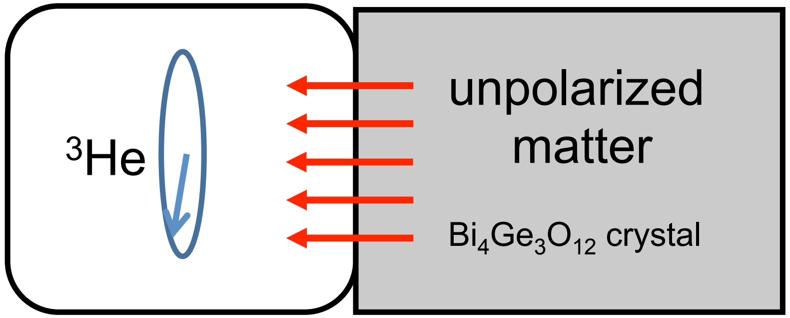
$$\omega_{close}(t) = \omega_{L,He}(t) + \omega_{sp}$$

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

How to measure?



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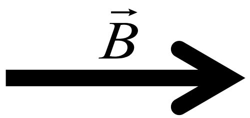

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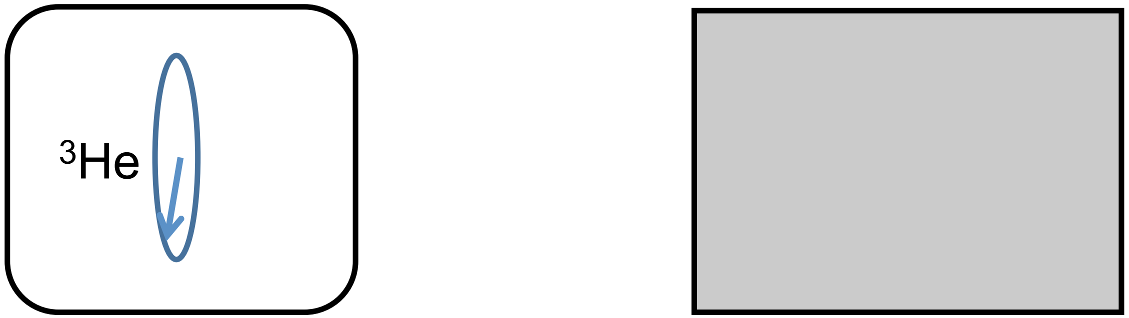
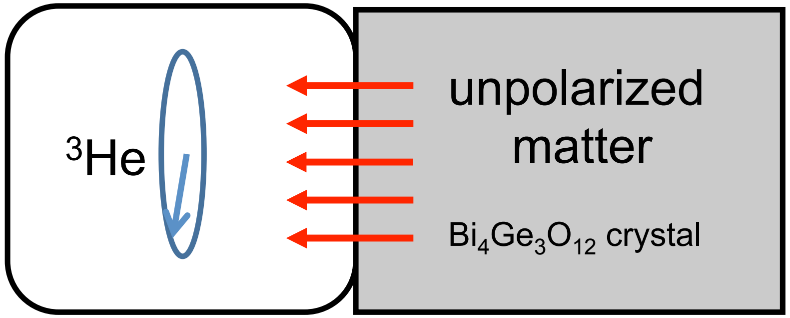


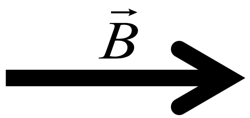
Position: distant

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

How to measure?



Position: close



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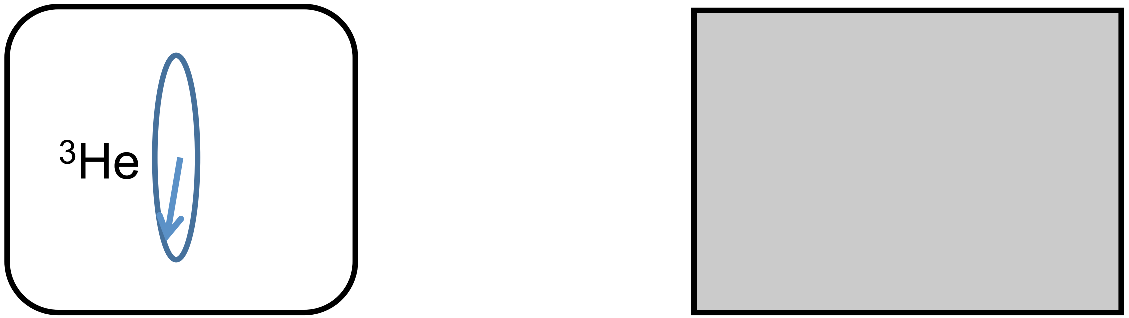


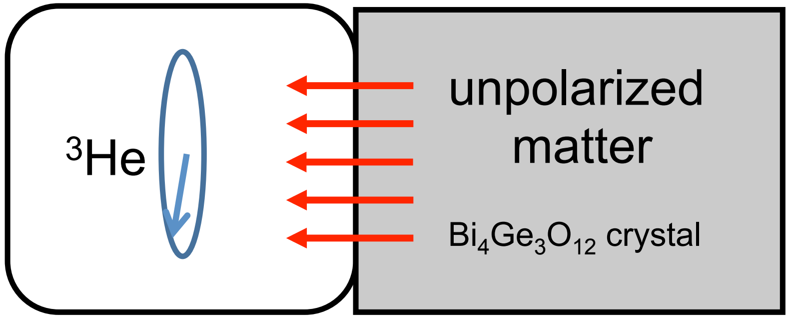
Position: distant

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

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

Principle of measurements

How to measure?



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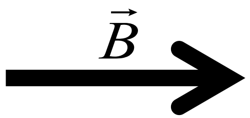
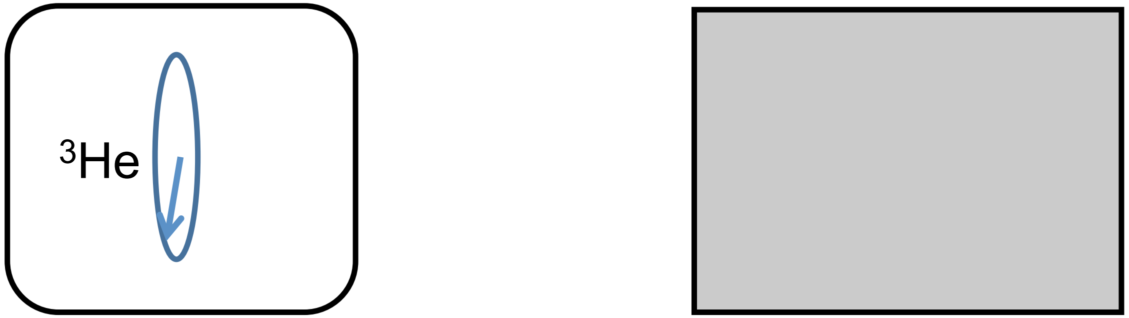




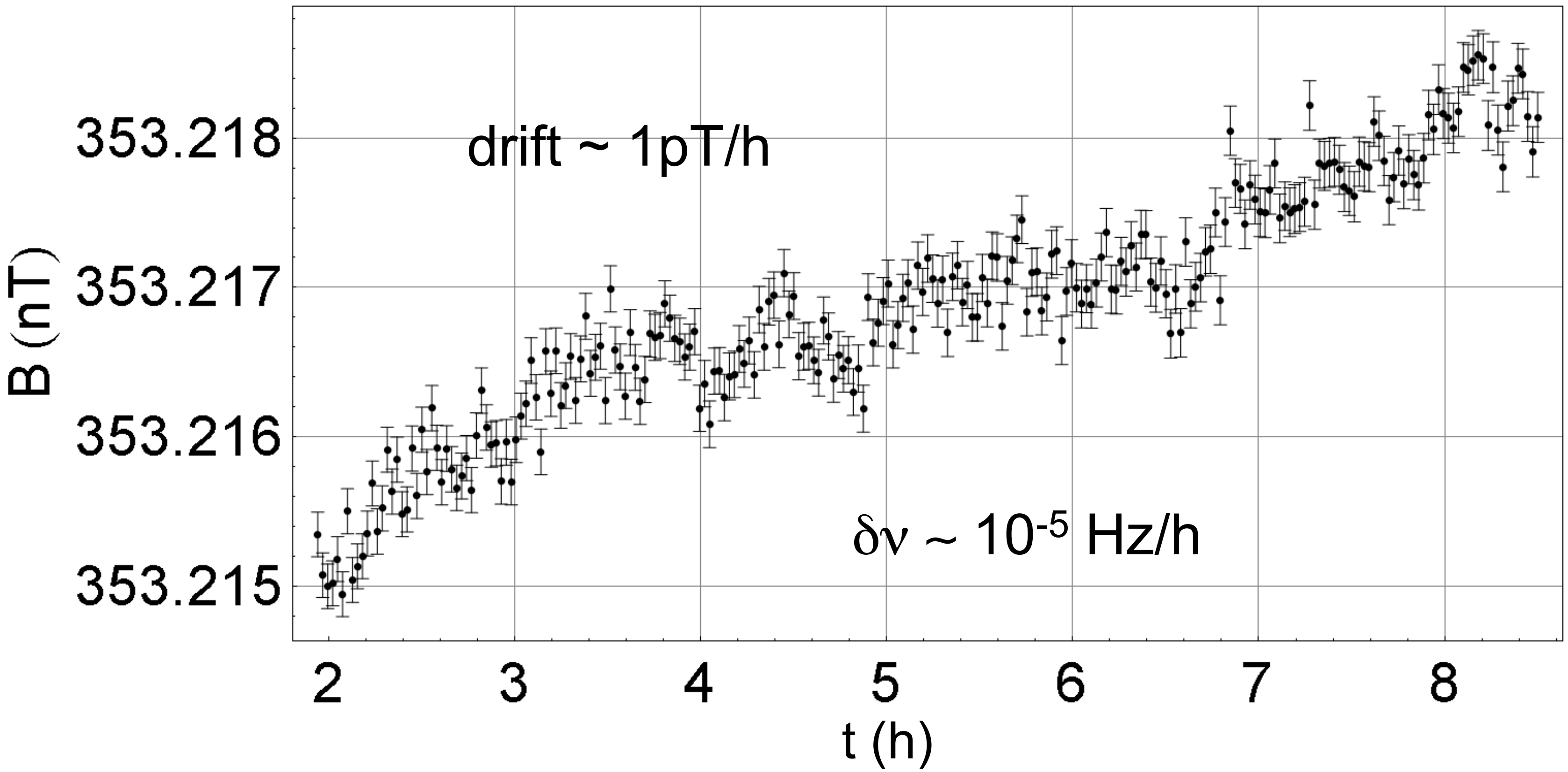
$$\omega_{distant}(t) = \omega_{L,He}(t)$$

Position: distant

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

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

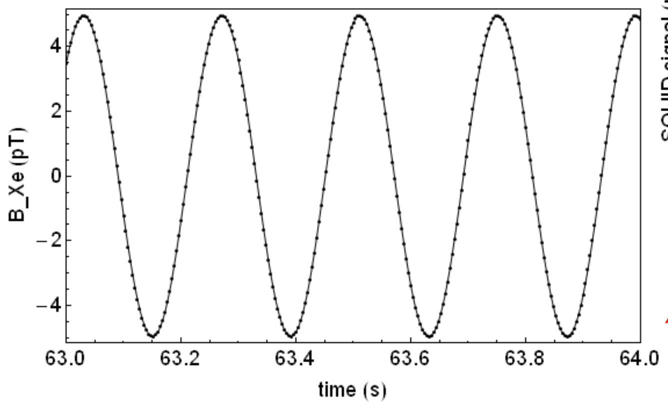
Principle of measurements

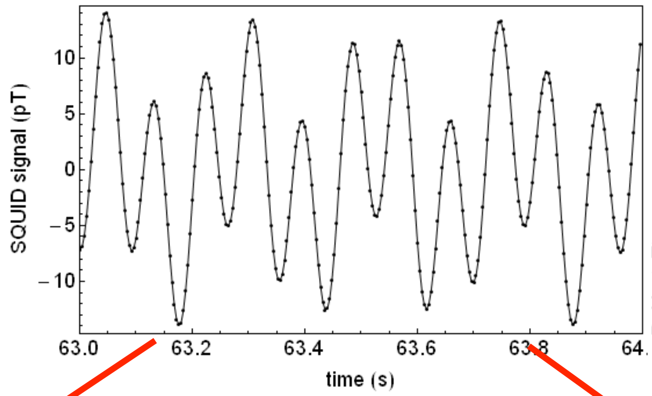


Principle of measurements

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

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





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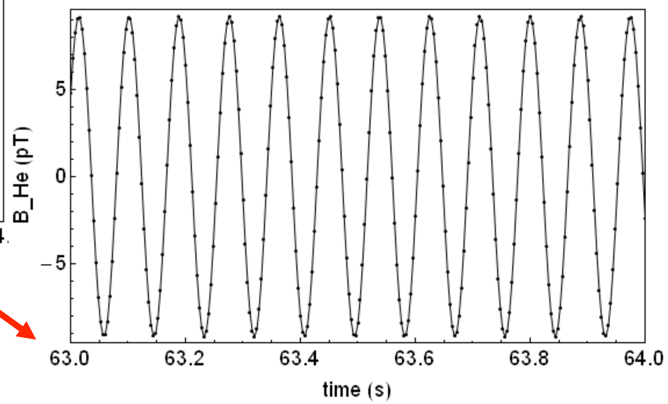

Elimination of magnetic field drifts (Zeeman-Term):

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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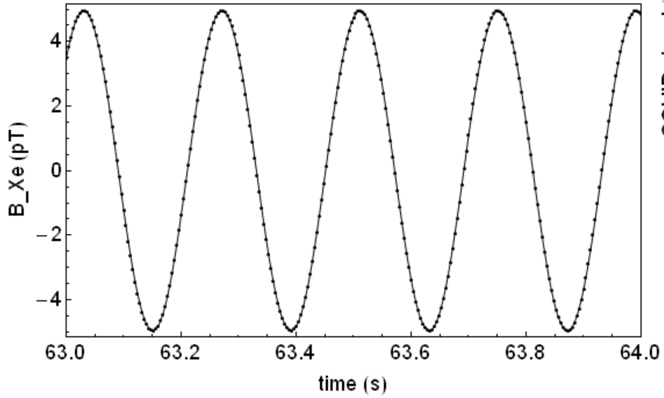

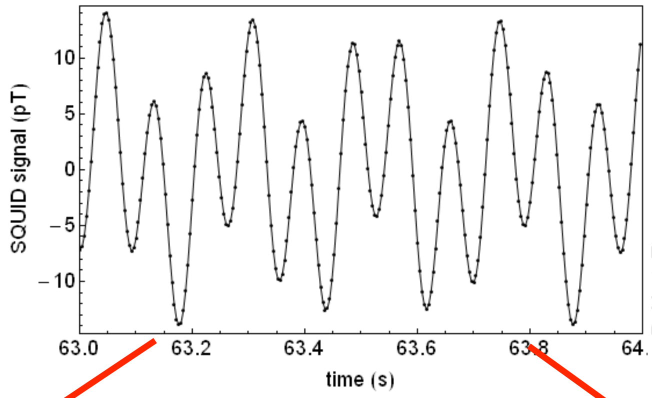

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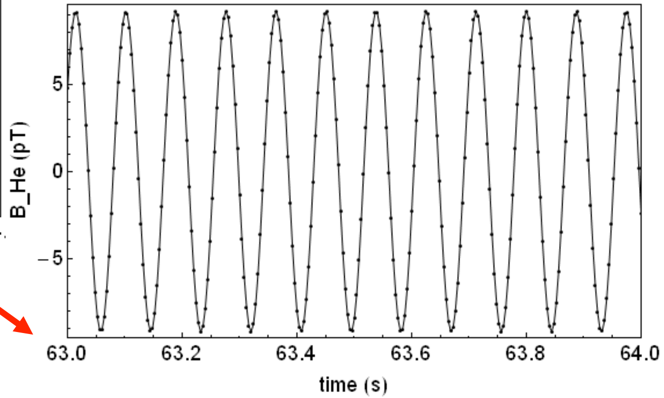

Elimination of magnetic field drifts (Zeeman-Term):

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

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

Principle of measurements

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

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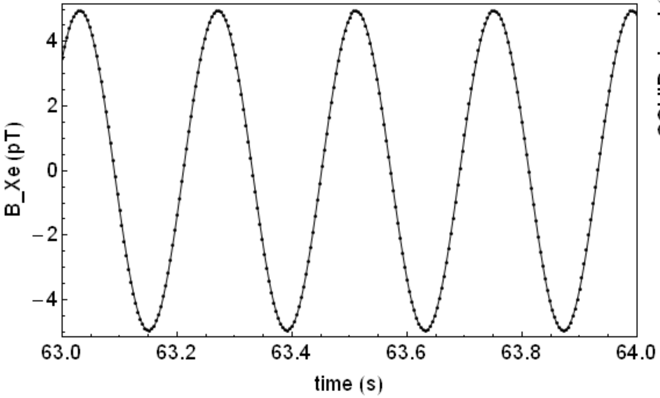

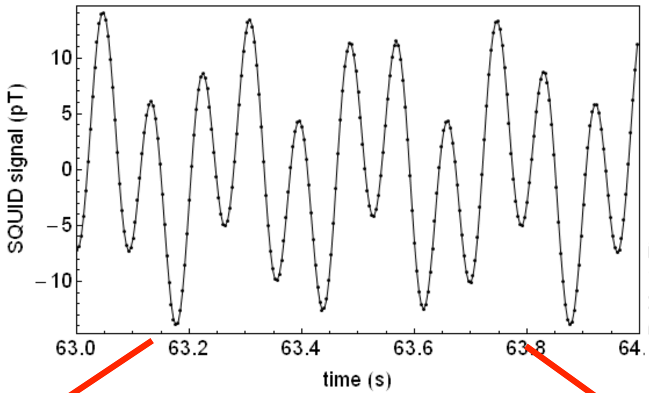

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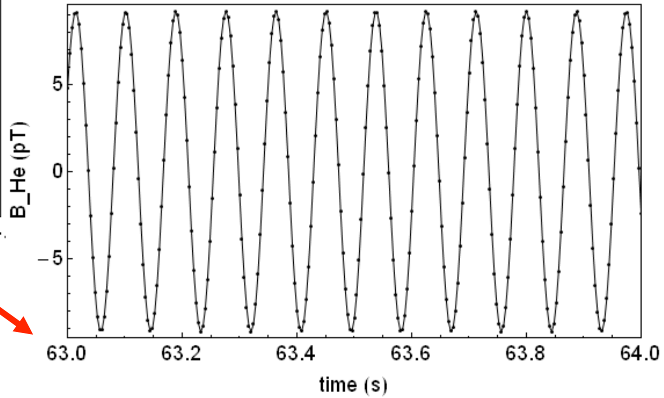

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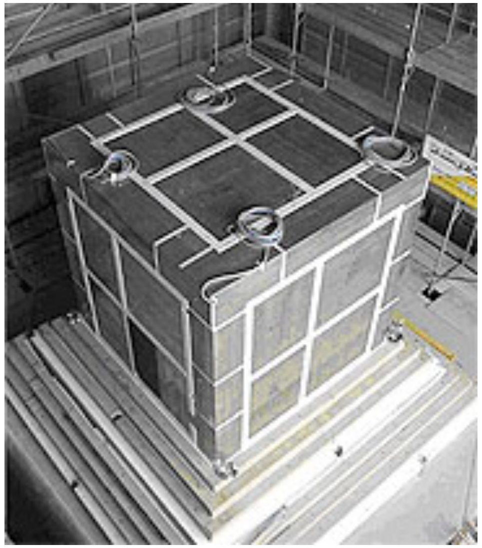
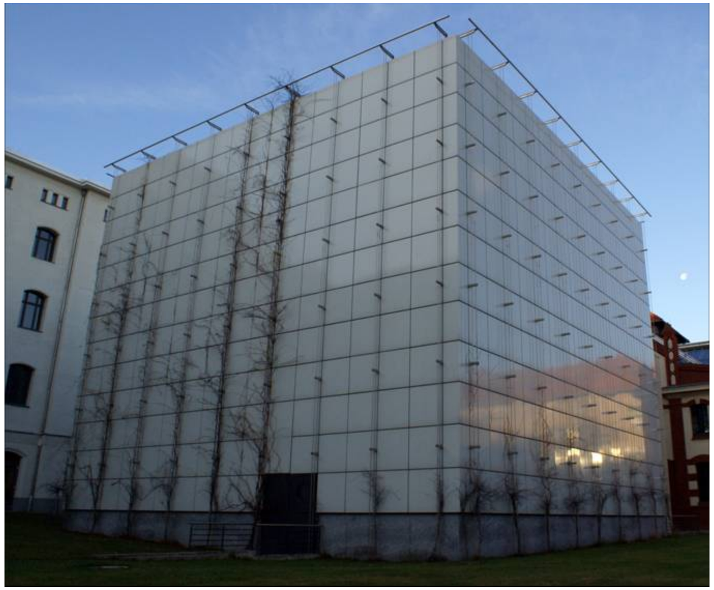
Experimental Setup

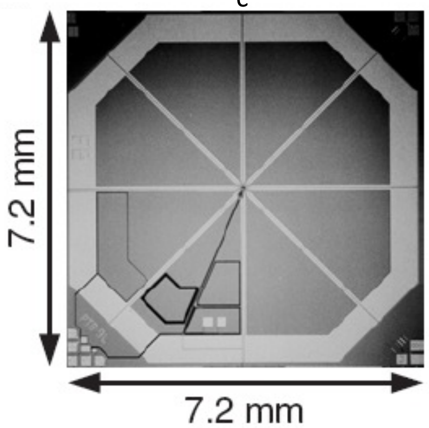


7 layered magnetically shielded room (residual field < 1 nT)

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



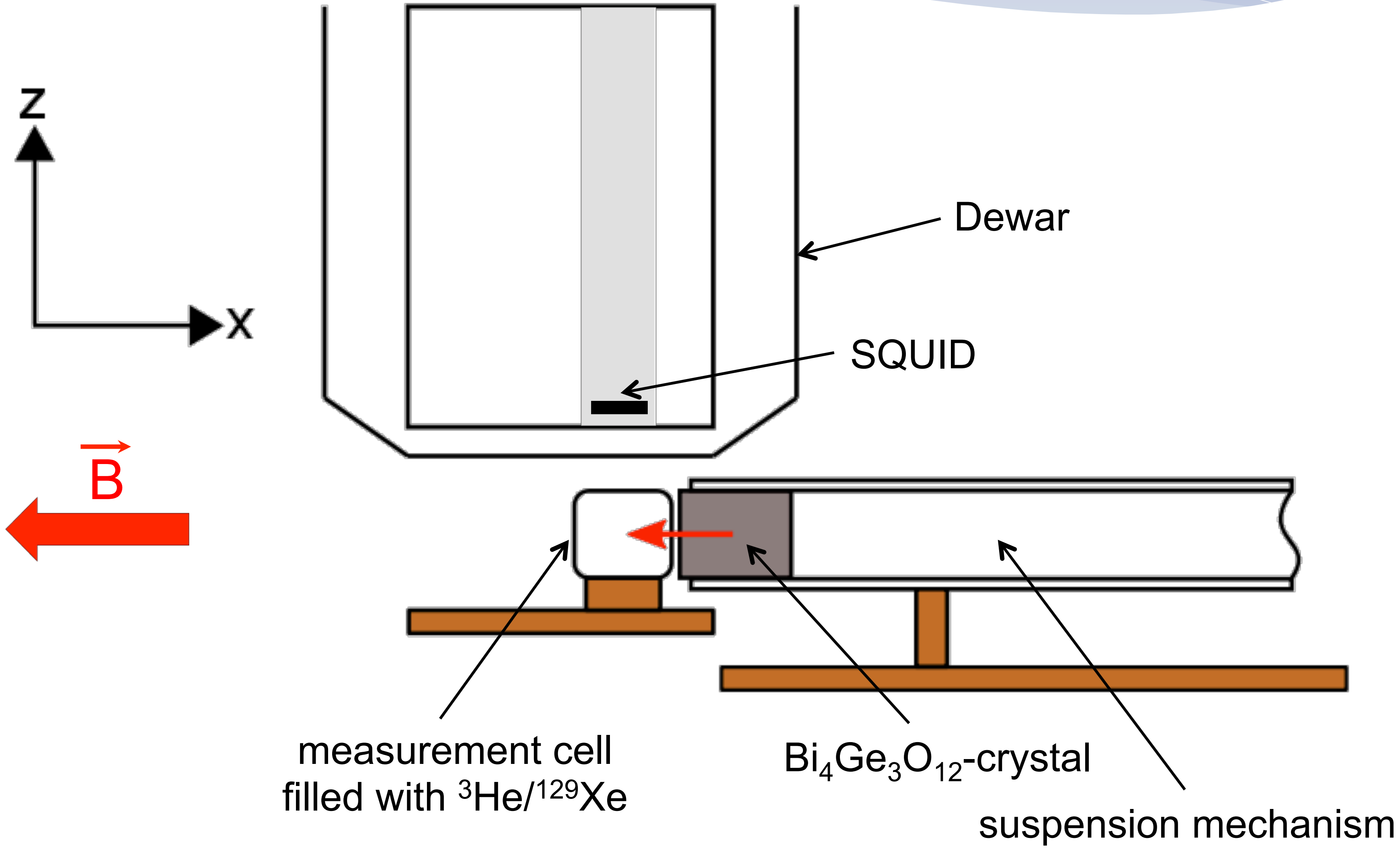
LT_c- SQUID



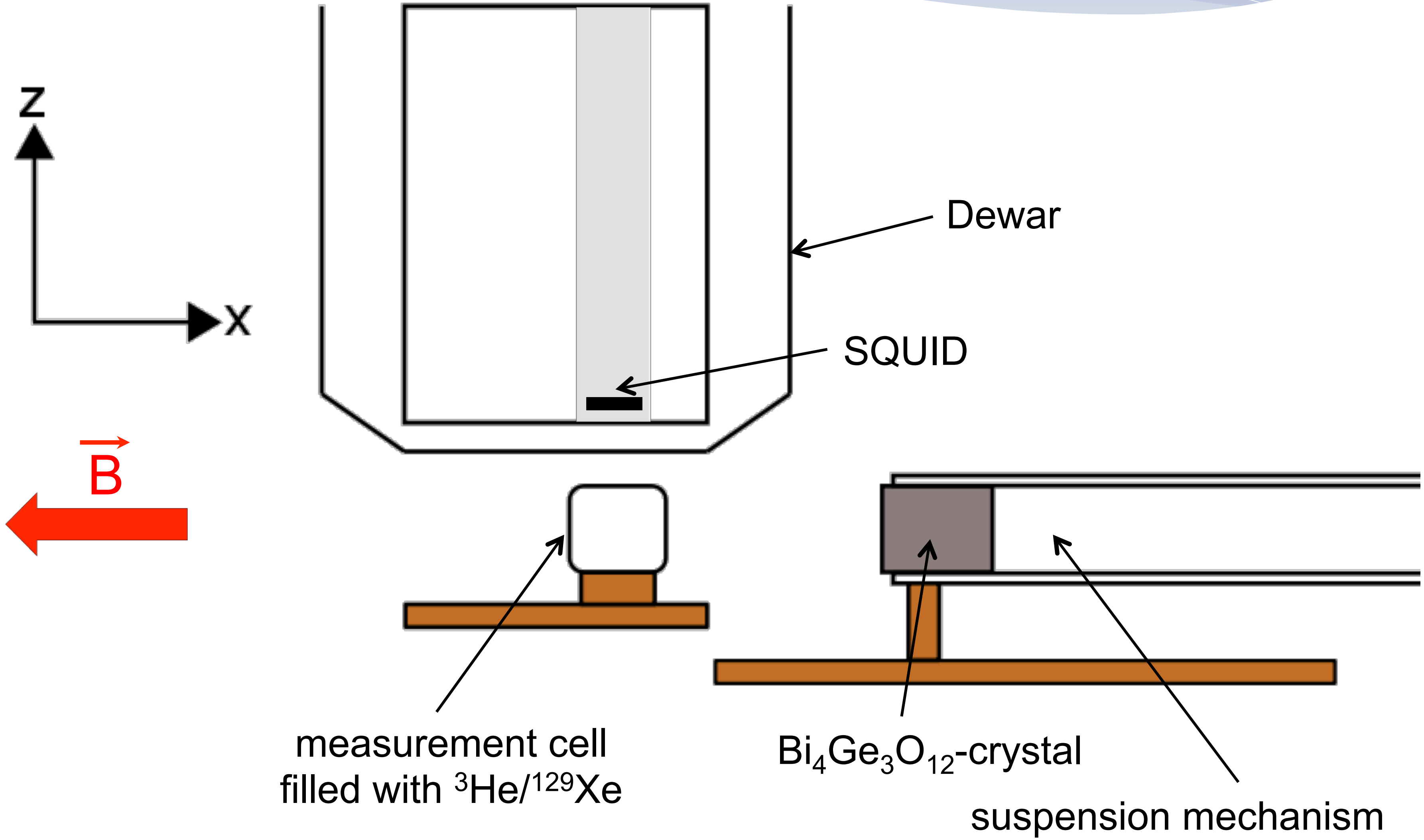
magn. guiding field $\approx$ 350 nT (Helmholtz-coils)

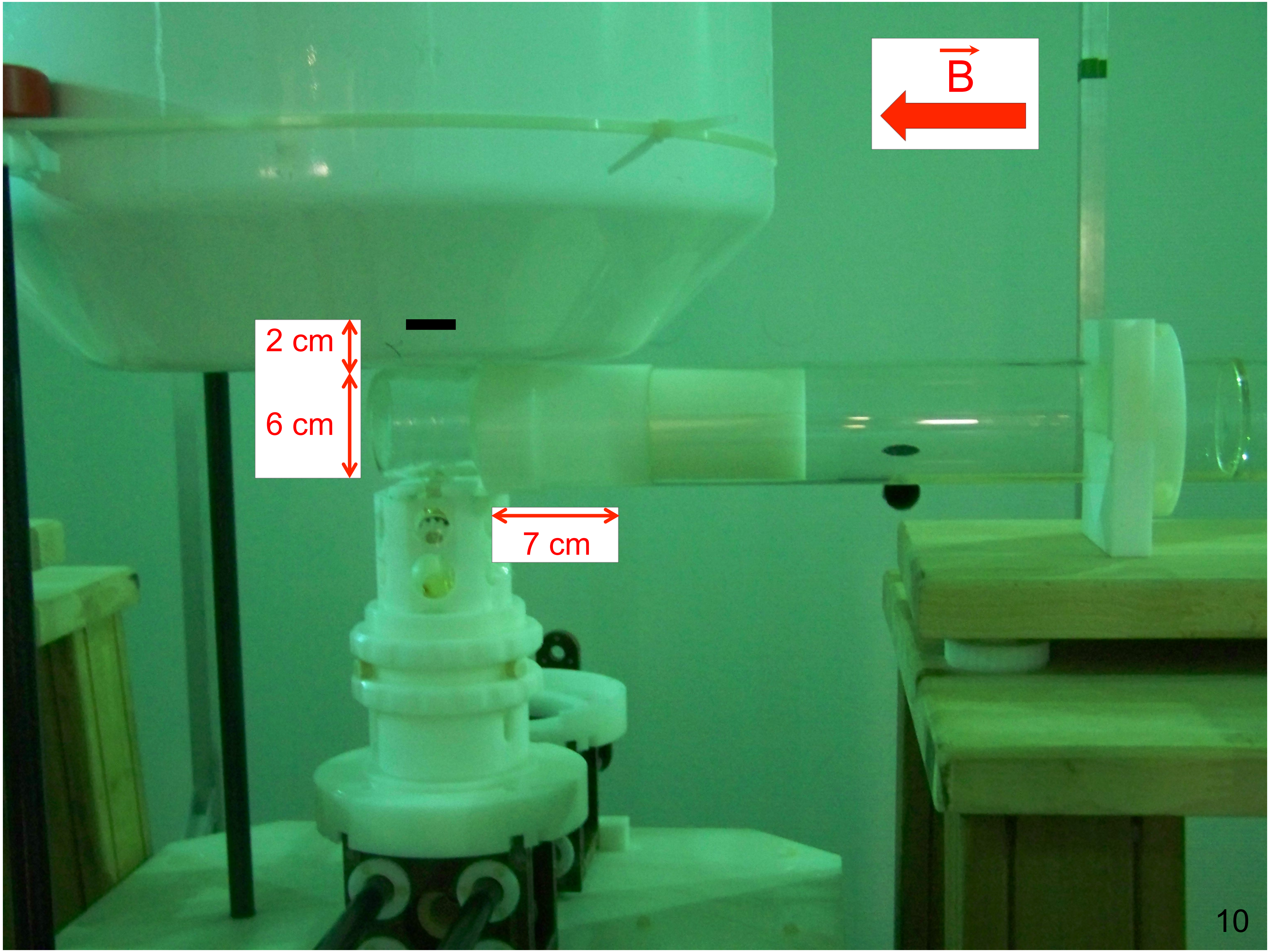
$$\left|\vec{\nabla} B_{x,y,z}\right| \approx 20\,\mathrm{pT/cm}$$

Experimental Setup

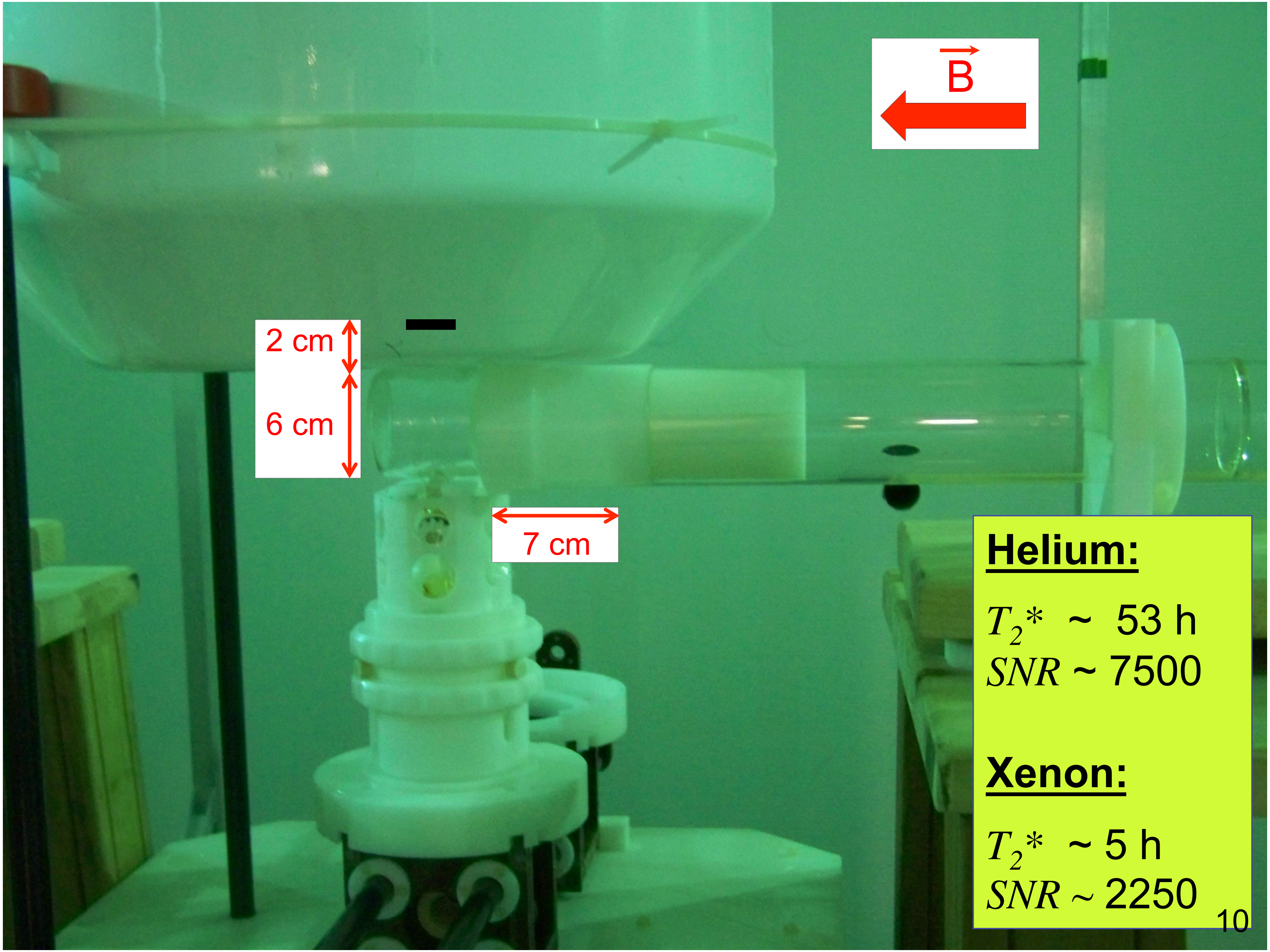


Experimental Setup





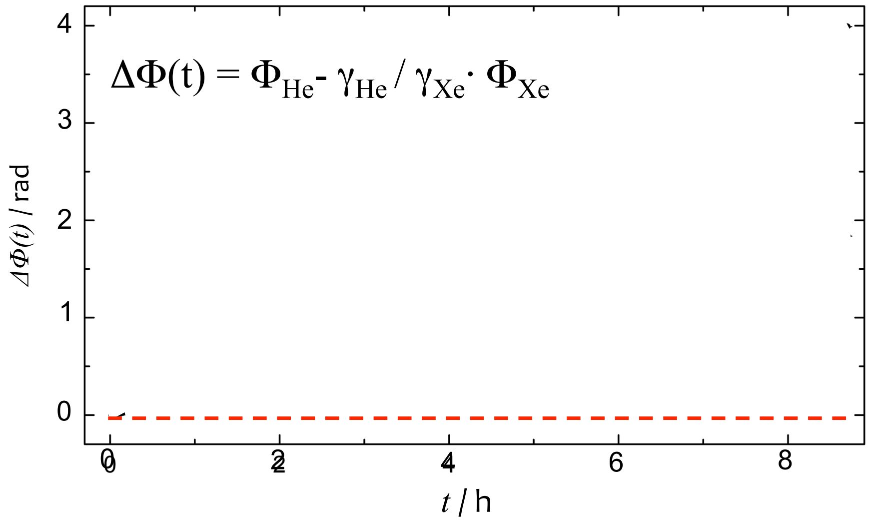
$\vec{B}$
2 cm
6 cm
7 cm


$\vec{B}$
2 cm
6 cm
7 cm
Helium:
T_2^* ~ 53 h
SNR ~ 7500
Xenon:
T_2^* ~ 5 h
SNR ~ 2250

Data Analysis

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

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



Data Analysis

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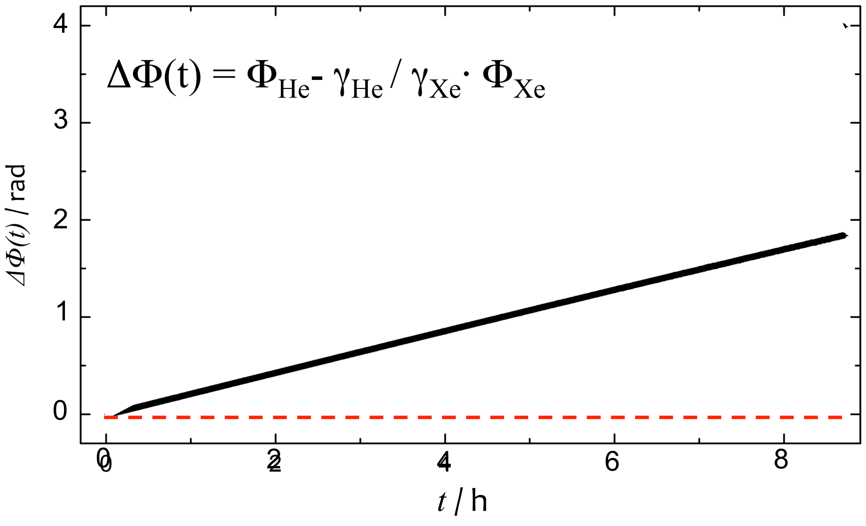
$$\Delta\Phi\left(t\right) = \Phi_{He} - \frac{\gamma_{He}}{\gamma_{Xe}} \cdot \Phi_{Xe} \neq \text{const}$$



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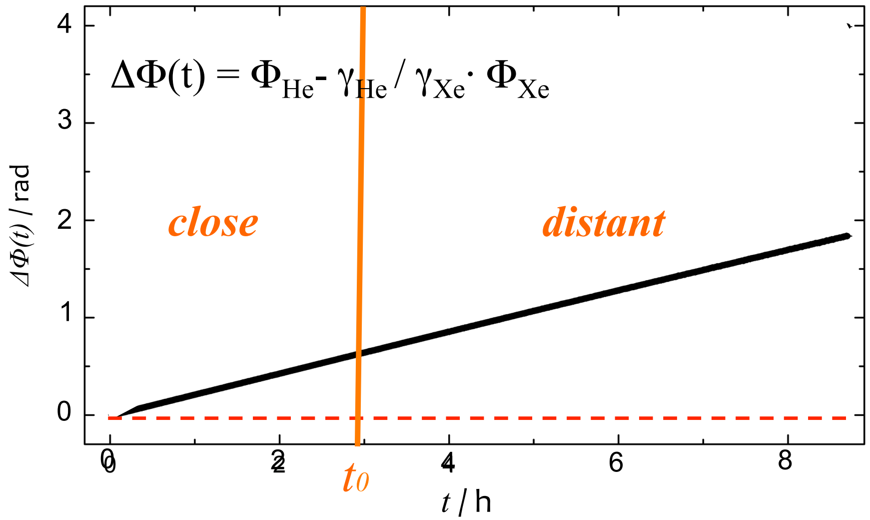
2. Temporal dependence can be described by:

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



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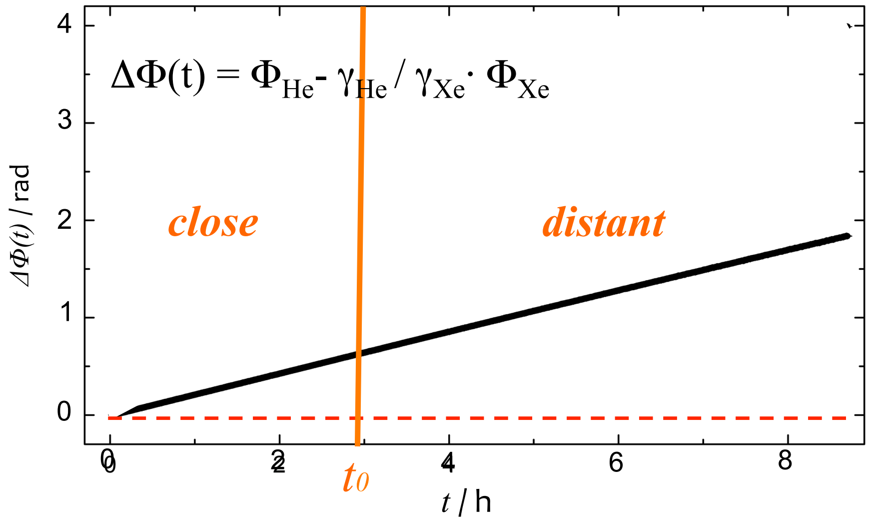
$$\Rightarrow \Delta\nu_{sp} = \frac{\Delta\omega_{sp}}{2\pi(1-\gamma_{He}/\gamma_{Xe})}$$



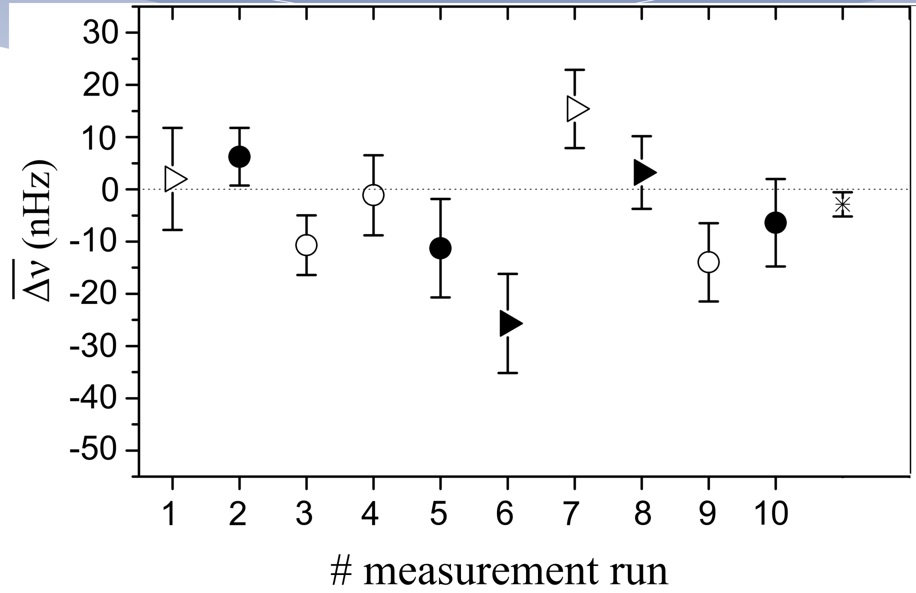
Summary Results

September 2010:

10 measurements (~9 hours)

gap = 2.2 mm

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



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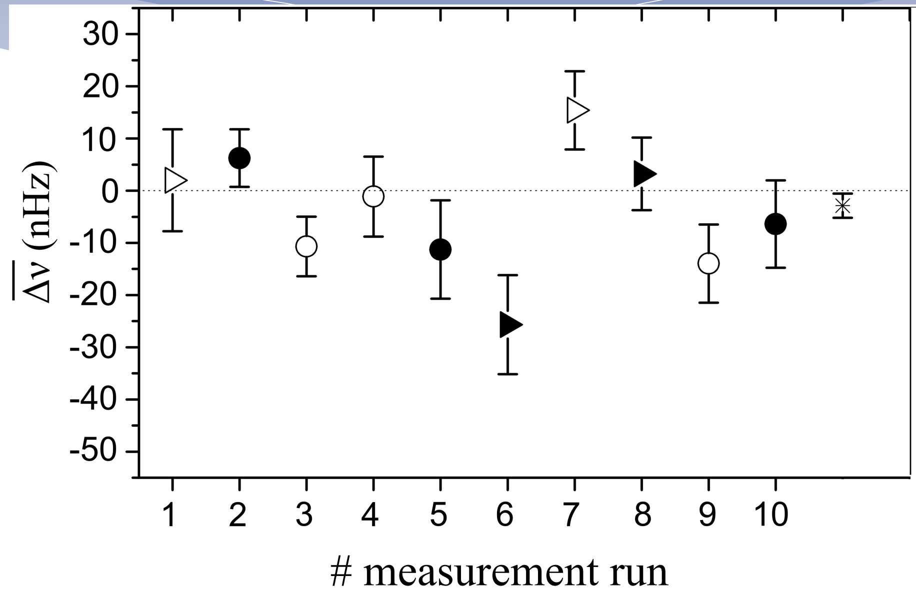

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K. Tullney et al.
PRL 111, 100801 (2013)

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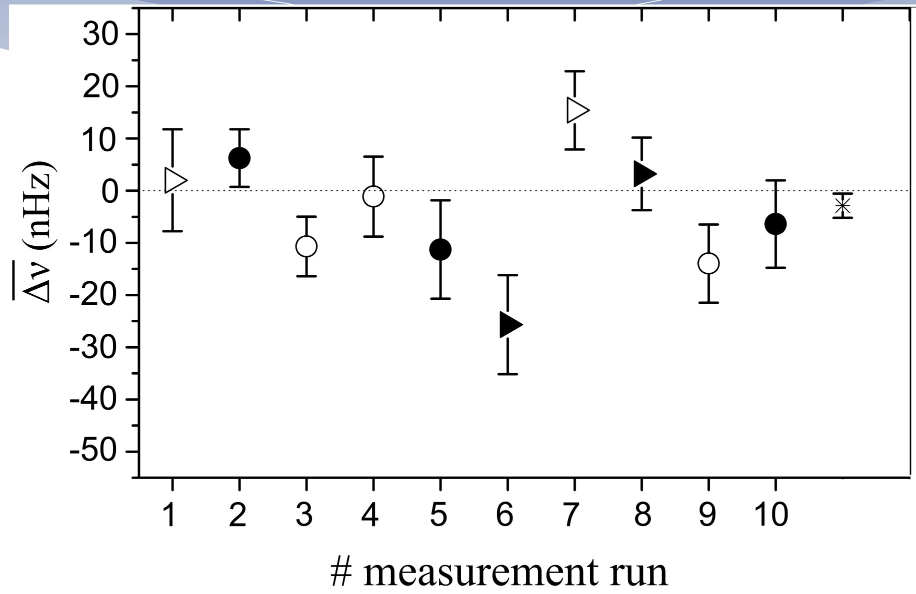

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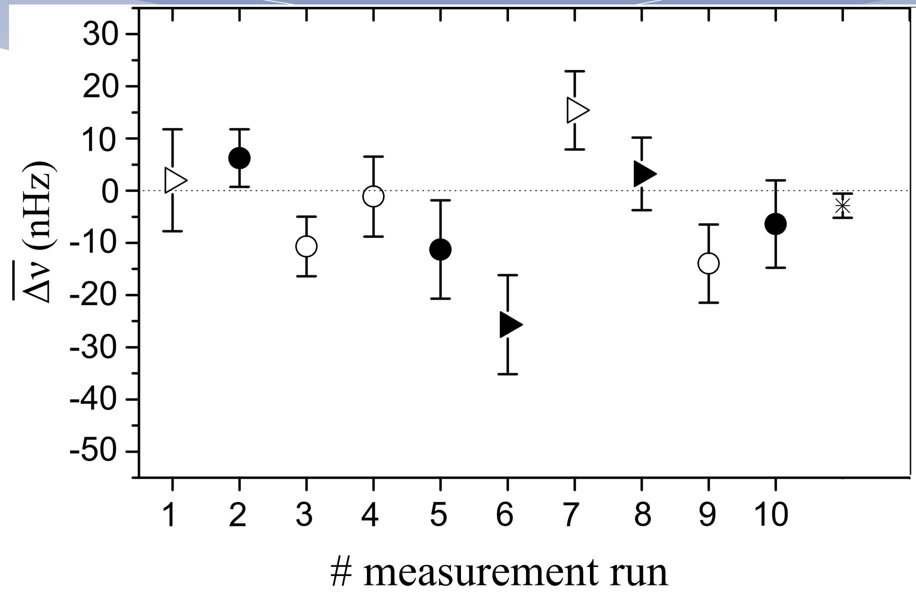

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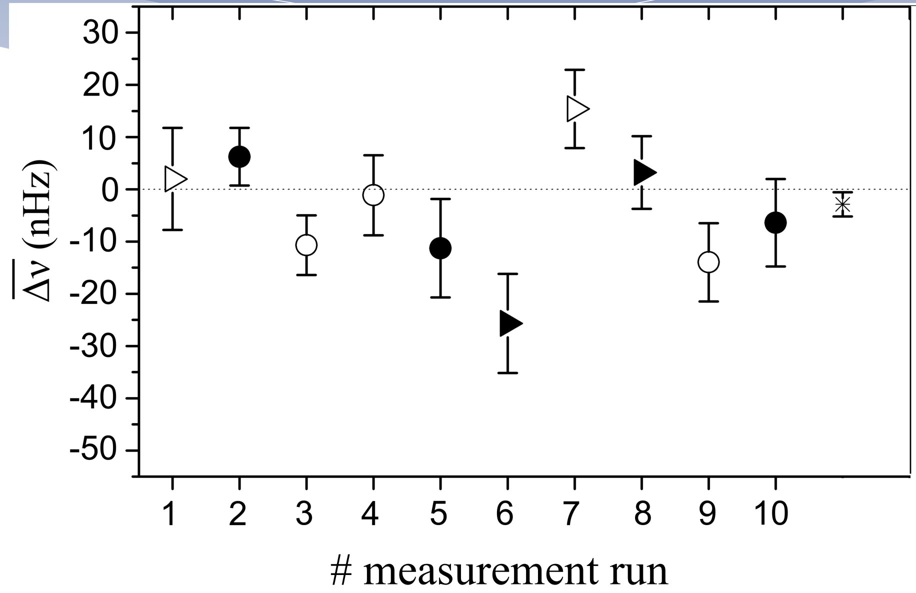

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$$\delta\left(\Delta\nu_{sp}\right) > 2\left\langle V_{sp}\right\rangle / h \quad \Rightarrow \quad g_s g_p\left(\lambda\right) < \frac{8\pi^2 \cdot m_n \cdot V_{cell} \cdot \delta\left(\Delta\nu_{sp}\right)}{\hbar \cdot N \cdot \left\langle V^*\left(\lambda\right)\right\rangle}$$

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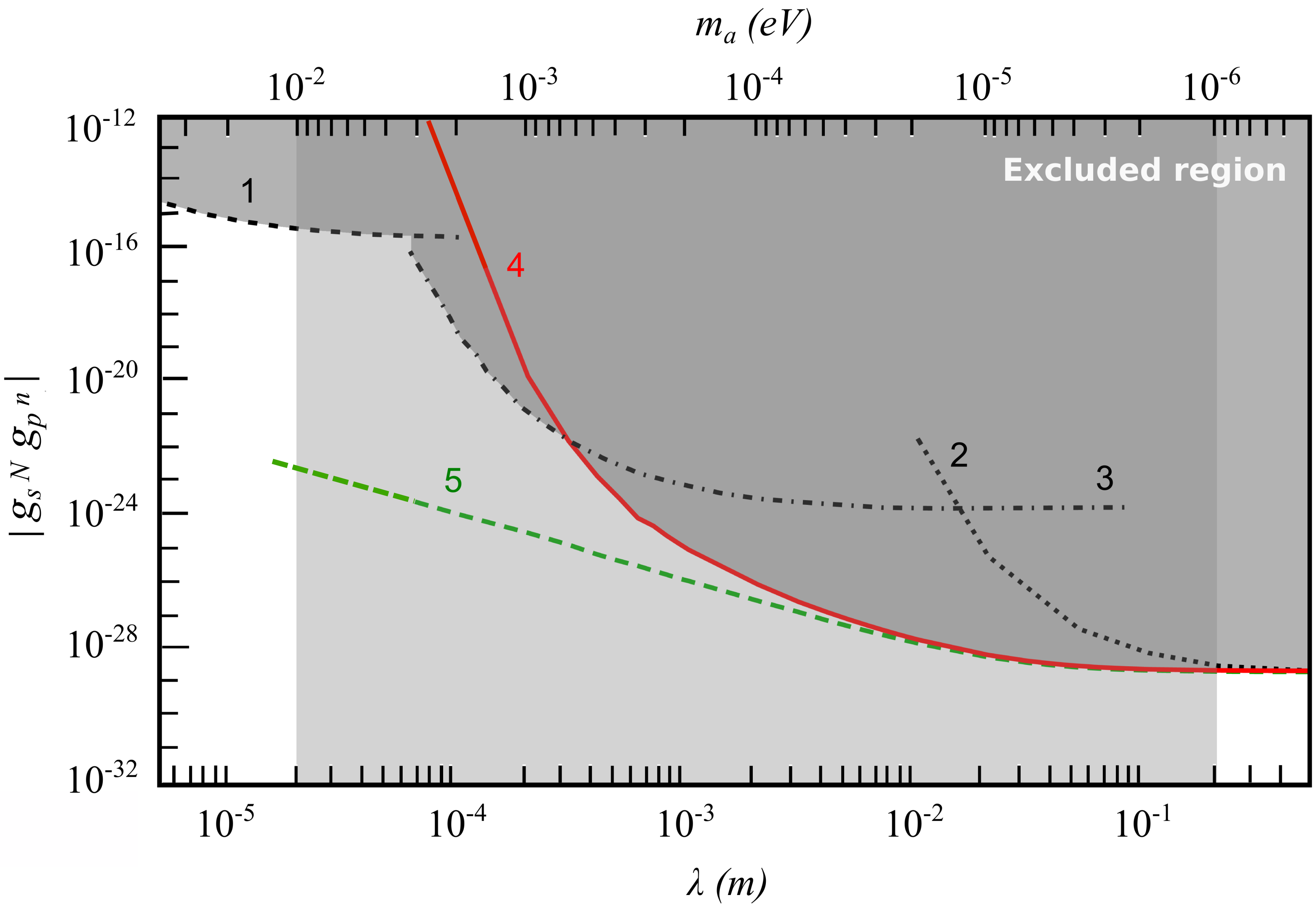
Exclusion Plot



1: T. Jenke (2012)
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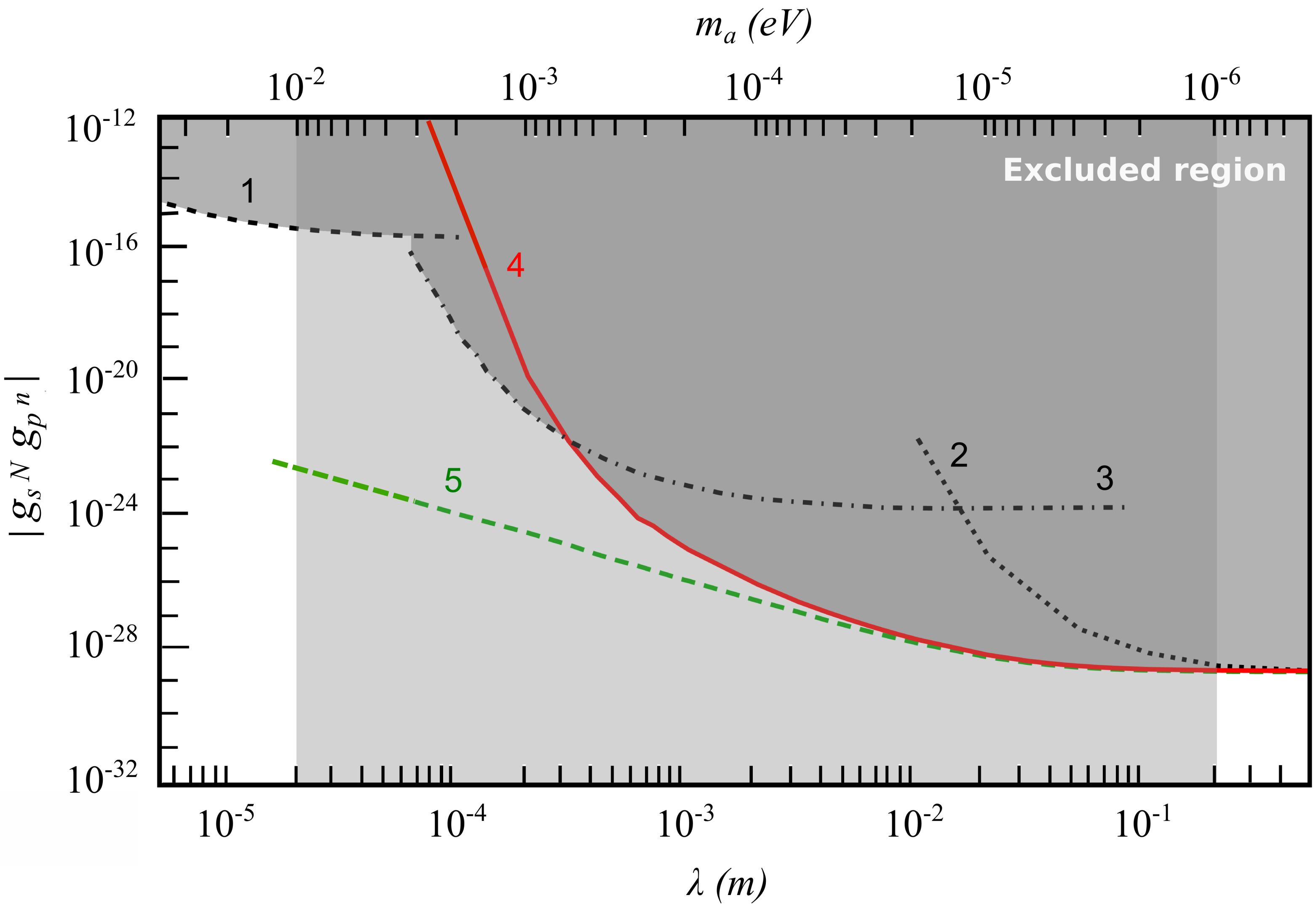

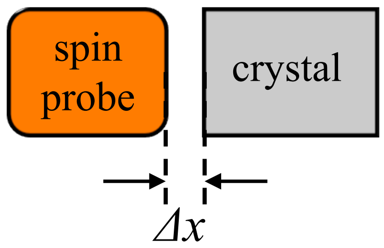

$$\langle V^*(\lambda) \rangle \propto e^{-\Delta x/\lambda}$$

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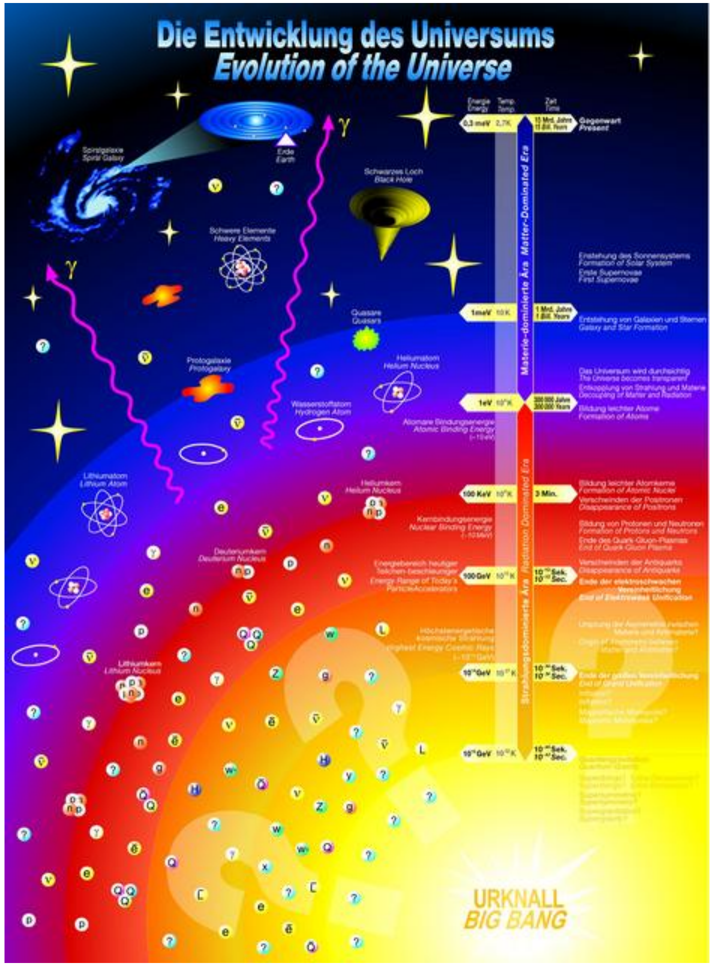
THANK YOU!

Motivation

Baryon/Anti-Baryon Puzzle

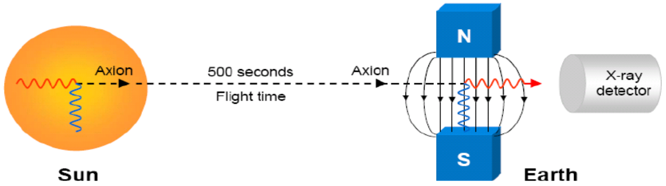


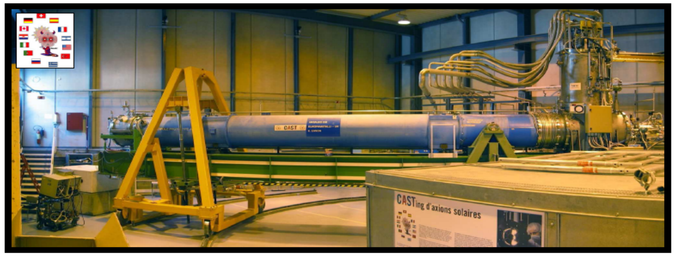
- Baryon/Anti-Baryon Asymmetry developed after 10^{-10} s after the Big Bang
- Observed Asymmetry: $n_B/n_\gamma=10^{-10}$
- Sacharow criteria:
  - ✓ Violation of baryon number
  - ✓ Thermal disequilibrium
  - ✓ CP-/C-Violation
- Calculated Asymmetry: $n_B/n_\gamma=10^{-18}$

Motivation

Solar axions

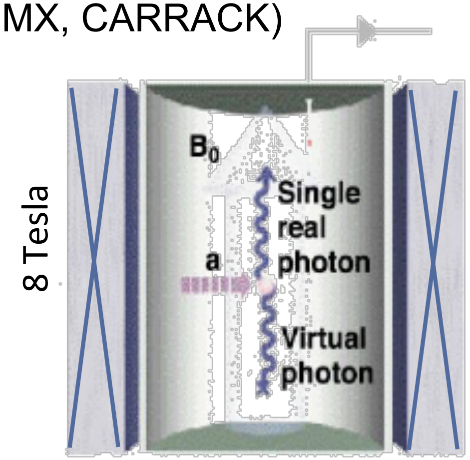
Helioscope experiment (CAST)





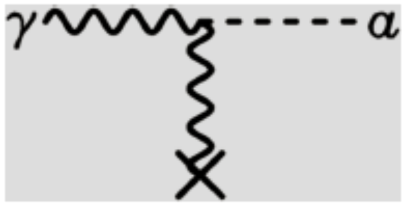
Galactic axions

microwave cavity experiment (ADMX, CARRACK)



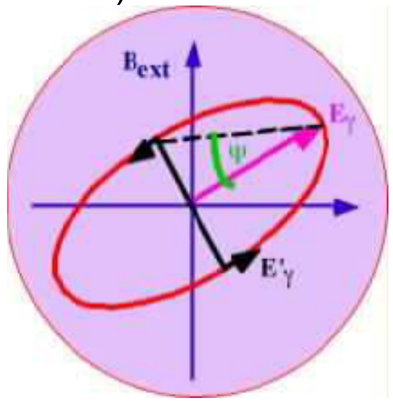
DIRECT search of the axion via the Primakoff effect

Primakoff effect
Conversion of an axion into a photon

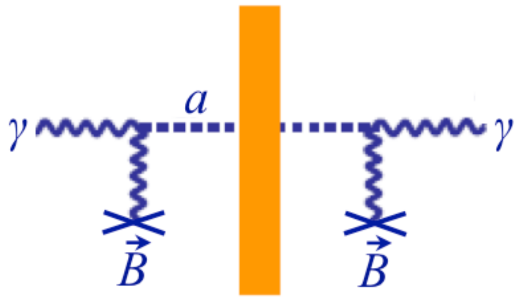


Labor axions

- Polarization experiments (PVLAS)



- „Light shinning through a wall“ experiment (BFRT, OSQAR, ALPS, LIPPS, GammaeV



Motivation

Axion Potential:

Yukawa type potential with monopole-dipole coupling [1]

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

with: $$\kappa = \frac{\hbar^2 g_s g_p}{8\pi m_n} \quad , \quad \lambda = \frac{\hbar}{m_a c}$$

polar vector ↑ $\hat{n}$, axial vector ↗ $\vec{\sigma}$

$$\hat{n}\cdot\vec{\sigma} \Rightarrow \begin{matrix} P\left(\hat{n}\cdot\vec{\sigma}\right) = -\left(\hat{n}\cdot\vec{\sigma}\right) \\ T\left(\hat{n}\cdot\vec{\sigma}\right) = -\left(\hat{n}\cdot\vec{\sigma}\right) \end{matrix} \Rightarrow$$

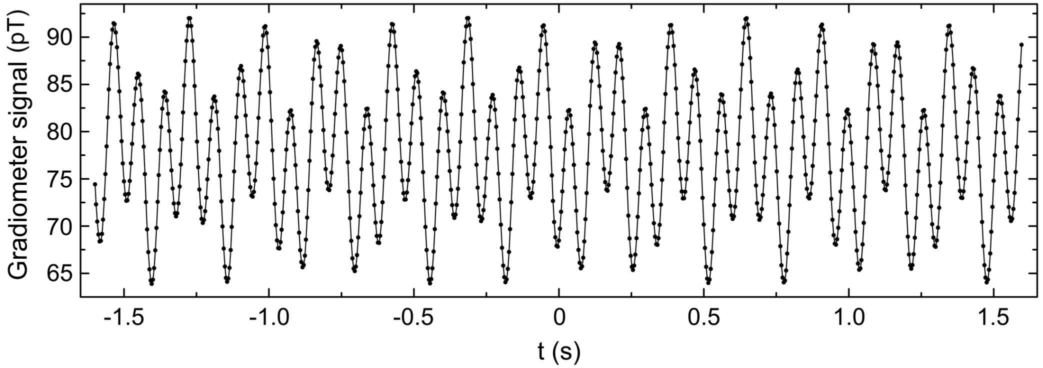
P-, T-violation
CP-violation

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

Data Analysis

Fit to raw data:

$$
\begin{aligned}
f^{i}(t) = \; & a^{i}_{s,He} \sin\left(\omega^{i}_{He} \cdot t\right) + a^{i}_{c,He} \cos\left(\omega^{i}_{He} \cdot t\right) \\
& + a^{i}_{s,Xe} \sin\left(\omega^{i}_{Xe} \cdot t\right) + a^{i}_{c,Xe} \cos\left(\omega^{i}_{Xe} \cdot t\right) \\
& + (c^{i}_{0} + c^{i}_{lin} \cdot t)
\end{aligned}
$$



↓ ^{3}He, ^{129}Xe phase

$$
\Phi^{i}_{He/Xe} = \arctan\left(\frac{a^{i}_{s,He/Xe}}{a^{i}_{cHe/Xe}}\right) + n^{i}_{He/Xe} \cdot 2\pi, \quad n^{i}_{He/Xe} \approx \bar{\omega}_{He/Xe} \cdot t
$$

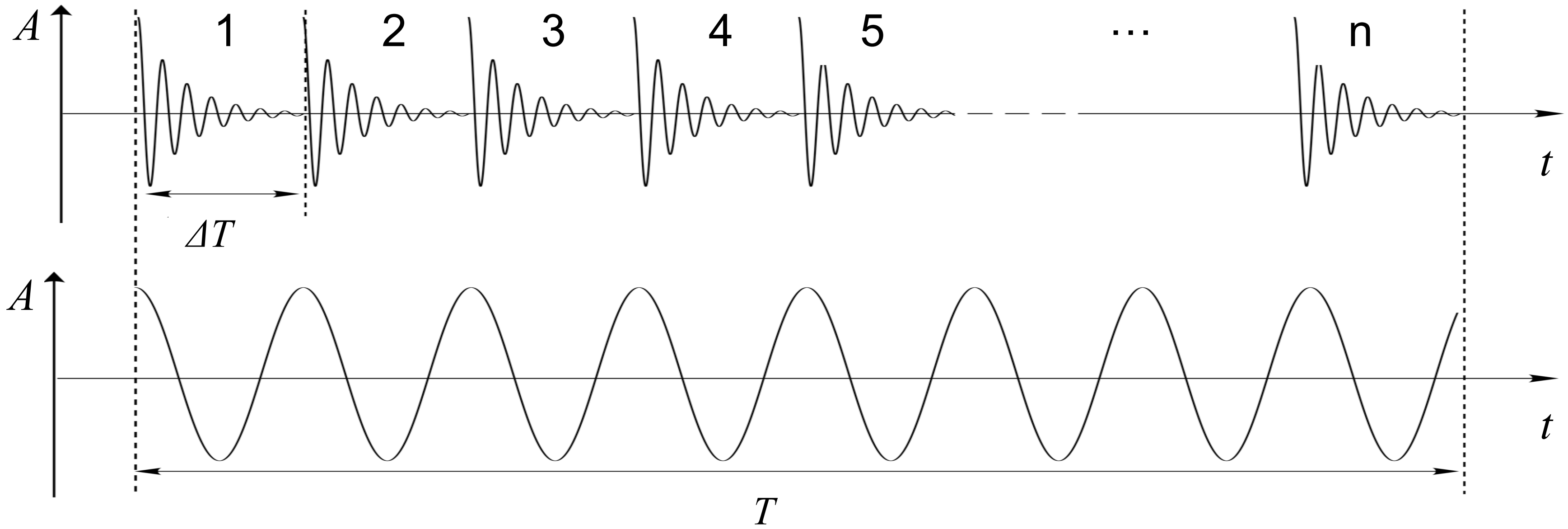
(number of periods since begin of measurement)

↓ weighted phase difference

$$
\Delta\Phi = \Phi_{He} - \frac{\gamma_{He}}{\gamma_{Xe}} \cdot \Phi_{Xe} \overset{!}{=} \Phi_{0}
$$

Sensitivity

Spin coherence time: long (T) vs. short (ΔT)



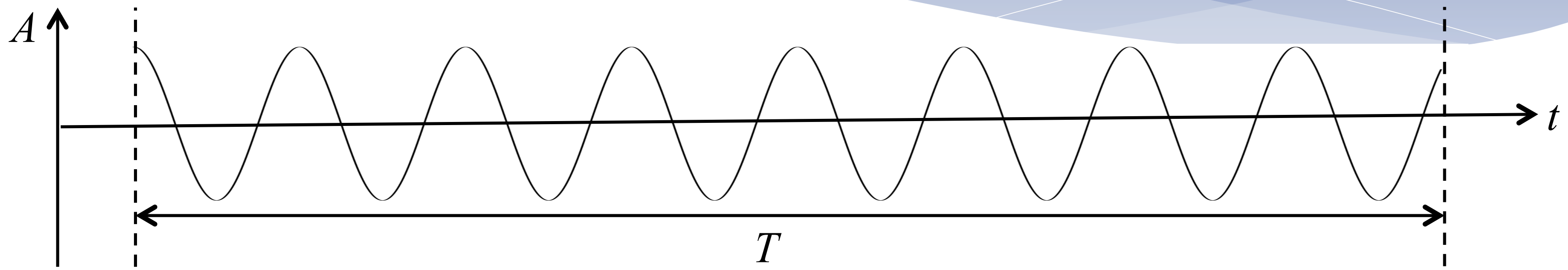
$$\sigma_{\nu,\,\mathrm{long}} \propto \frac{1}{T^{3/2}}$$

$$\sigma_{\nu,\,\mathrm{short},n} \propto \frac{1}{\sqrt{n}}\,\frac{1}{\Delta T^{3/2}} = \left(\frac{1}{T^{3/2}}\right)\cdot\frac{T}{\Delta T}$$

$$T = n \cdot \Delta T$$

<u>Example</u>: SNR = 10000:1 , f_{BW}= 1 Hz , T = 24 h, ΔT = 5 min $\rightarrow \sigma_{\nu,\,\mathrm{short}} = 300 \cdot \sigma_{\nu,\,\mathrm{long}}$

Precision of measurement



If the noise $w[n]$ is **Gaussian distributed**, the “Cramer-Rao-Lower Bound (CRLB)” sets the lower limit on the variance σ_ν:

$$\sigma_\nu \geq \frac{\sqrt{12}}{2\pi \cdot SNR \cdot \sqrt{\nu_{BW}} \cdot T^{3/2}} \cdot \sqrt{C\left(T_2^*\right)}$$

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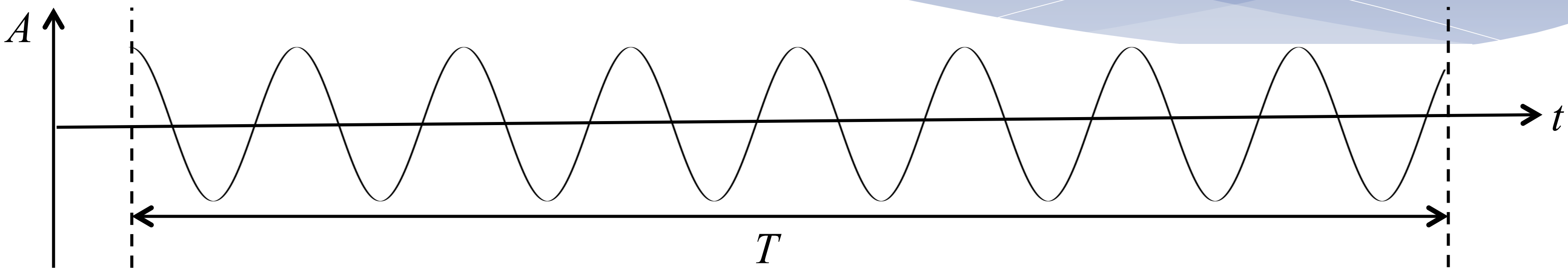

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Example:

SNR = 2300, ν_{BW} = 1 Hz, T= 9 h

$$\Rightarrow \sigma_\nu \approx 10^{-10}\,\mathrm{Hz}$$

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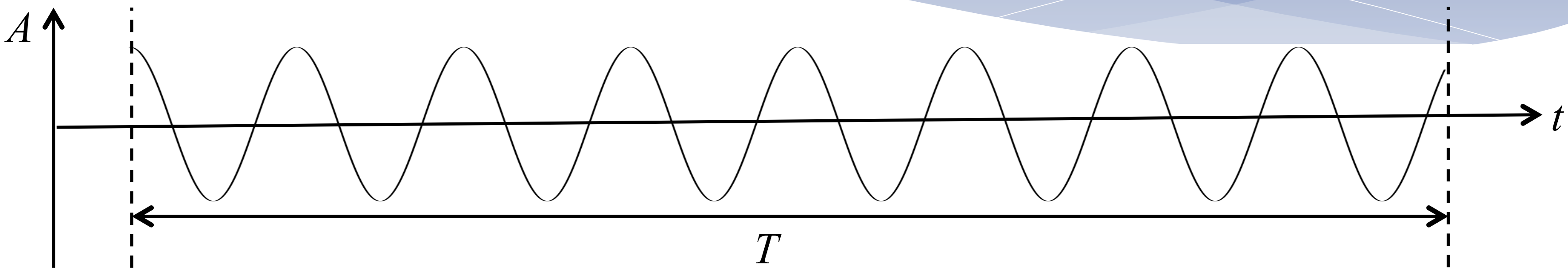

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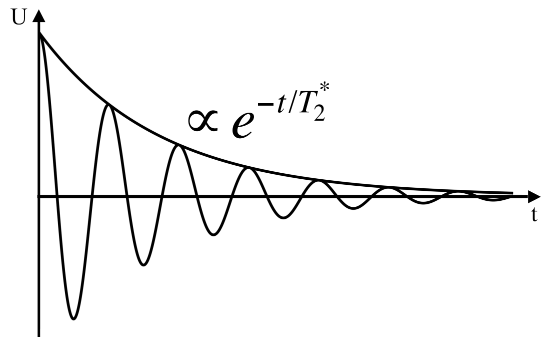
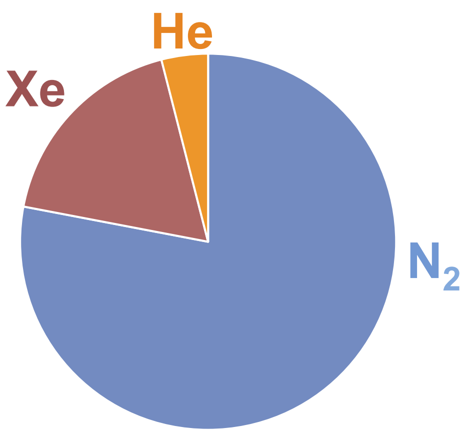


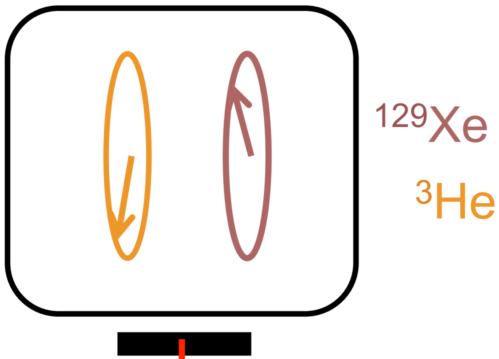
$\left(T_2^*\right)^{-1} \propto V^{4/3} p \left|\vec{\nabla} B_1\right|^2$ vs. $\mathrm{SNR} \propto pV$

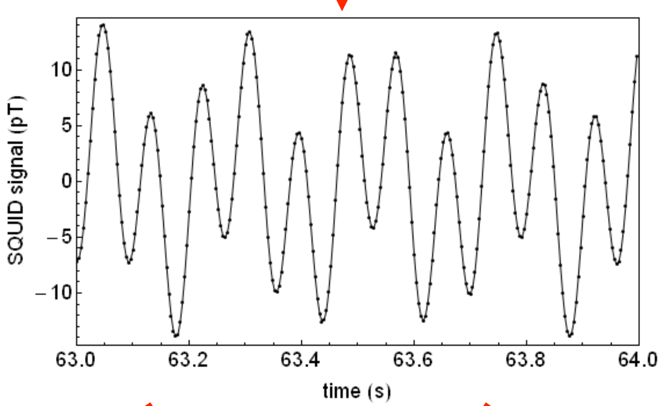
$p \approx \mathrm{mbar},\ V \approx 200\ \mathrm{cm}^3,\ B_1 \approx \mu T,\ \left|\vec{\nabla} B_1\right|^2 \approx \frac{pT}{cm}$

Data Acquisition

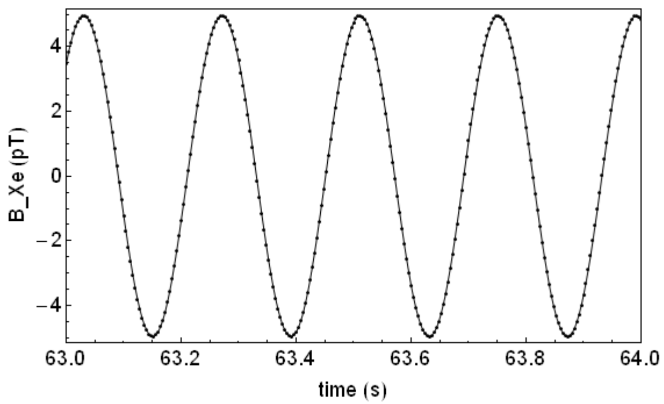
^3He, $^{129}Xe + N_2$ (buffer gas)
@ p_{tot} = 31…37 mbar



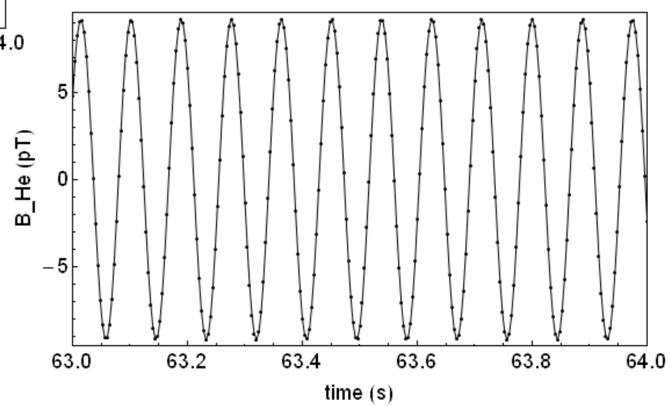




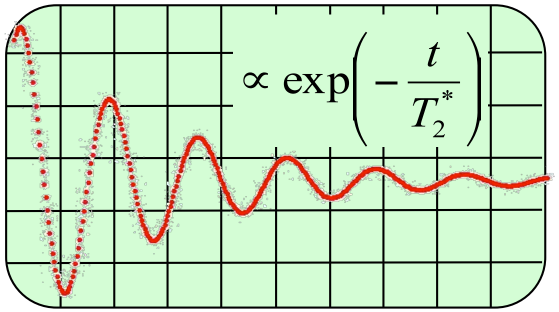
$$\omega_{Xe}(t) = \gamma_{Xe} \cdot B(t)$$



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



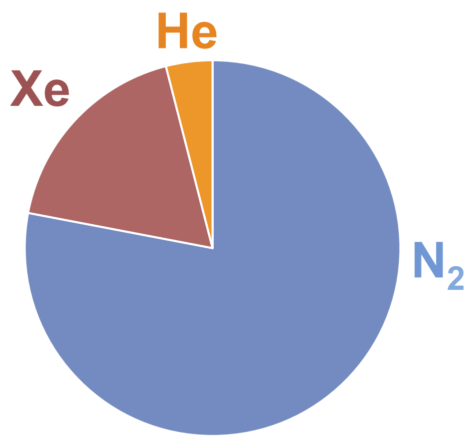
Transversal Relaxationtime



Free spin precession:

$$\text{signal} \propto \exp\left(-t/T_2^*\right)$$

T_2^*: ms → h



$$\frac{1}{T_2^*} = \frac{1}{T_{1,\text{wand}}} + \frac{1}{T_{1,\text{ vdW}}} + \frac{1}{T_{2,\text{ grad}}}$$

wall collisions [1]

$$T_{1,\text{wand}} \approx 8\text{ h} - 100\text{ h}$$

van der Waals molecules [2]

$$T_{1,\text{vdW}}^{\text{Xe}} \approx 13\text{ h}$$

field gradients [3]

$$T_{2,\text{ grad}} \propto \frac{1}{V^{4/3}\, p \left|\vec{\nabla} B_1\right|^2}$$

CRLB: $\sigma_\nu \propto \dfrac{1}{\text{SNR} \cdot \text{T}^{3/2}}$

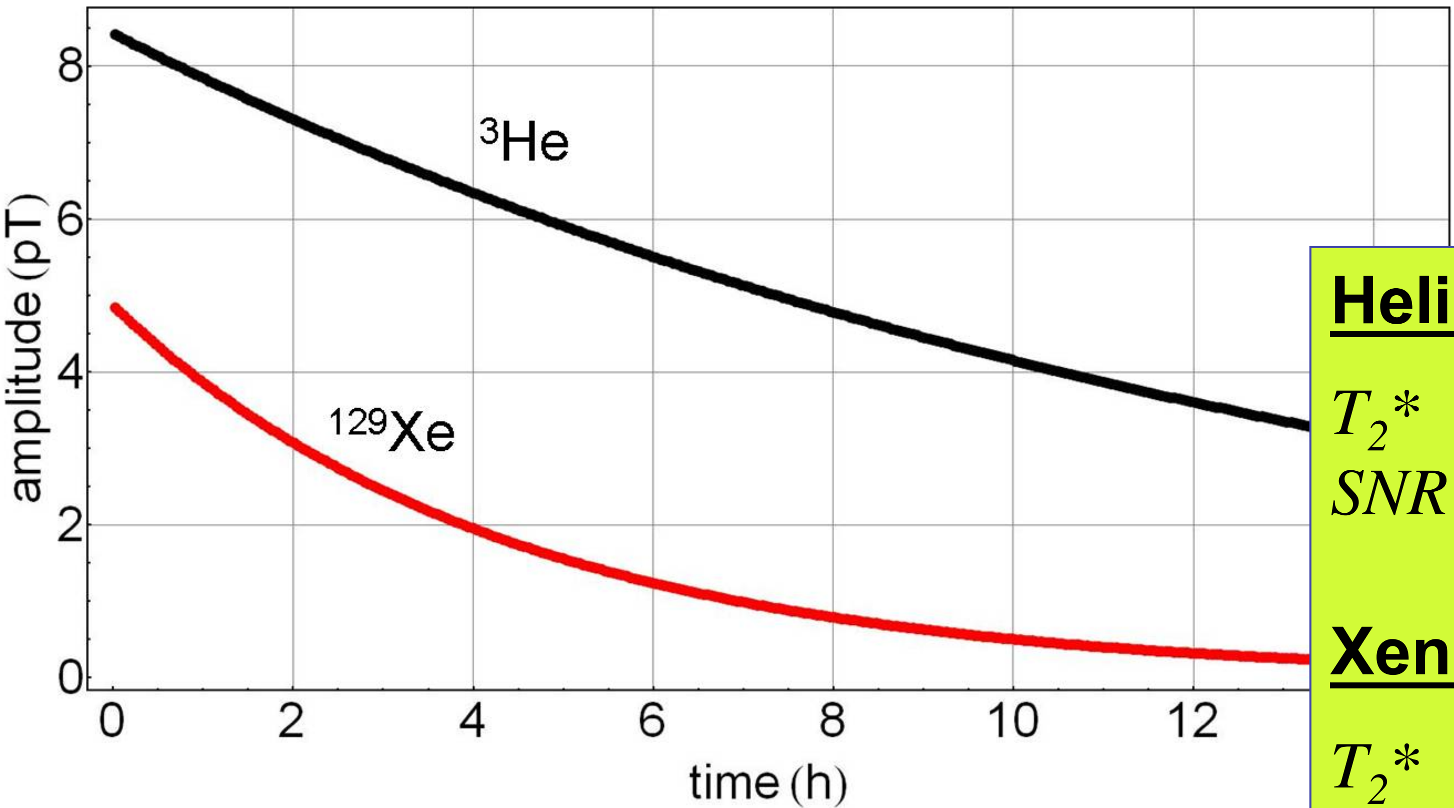
$$\text{signal} \propto p \cdot V \quad \Rightarrow \quad p\text{~mbar, V~100 cm}^3,\ B_1\text{~}\mu\text{T}$$ [4]

[1] J. Schmiedeskamp et al., Eur. Phys. J. D 38, 2006.
[2] B. Chann et al., PRL. 88(11), 2002.
[3] G. D. Cates, S. R. Schaefer, W. Happer, Phys. Rev. A 37, 1988.
[4] C. Gemmel et al., Eur. Phys. J. D 57, 2010.

Transversal Relaxationtime

R ≈ 3 cm

p_{He}≈ 2 mbar, p_{Xe}≈ 8 mbar, p_{N2} ≈ 35 mbar



Helium:

T_2* ~ 53 h
SNR ~ 7500

Xenon:

T_2* ~ 5 h
SNR ~ 2250

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PRL 111, 100801 (2013)

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

Analysis:

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

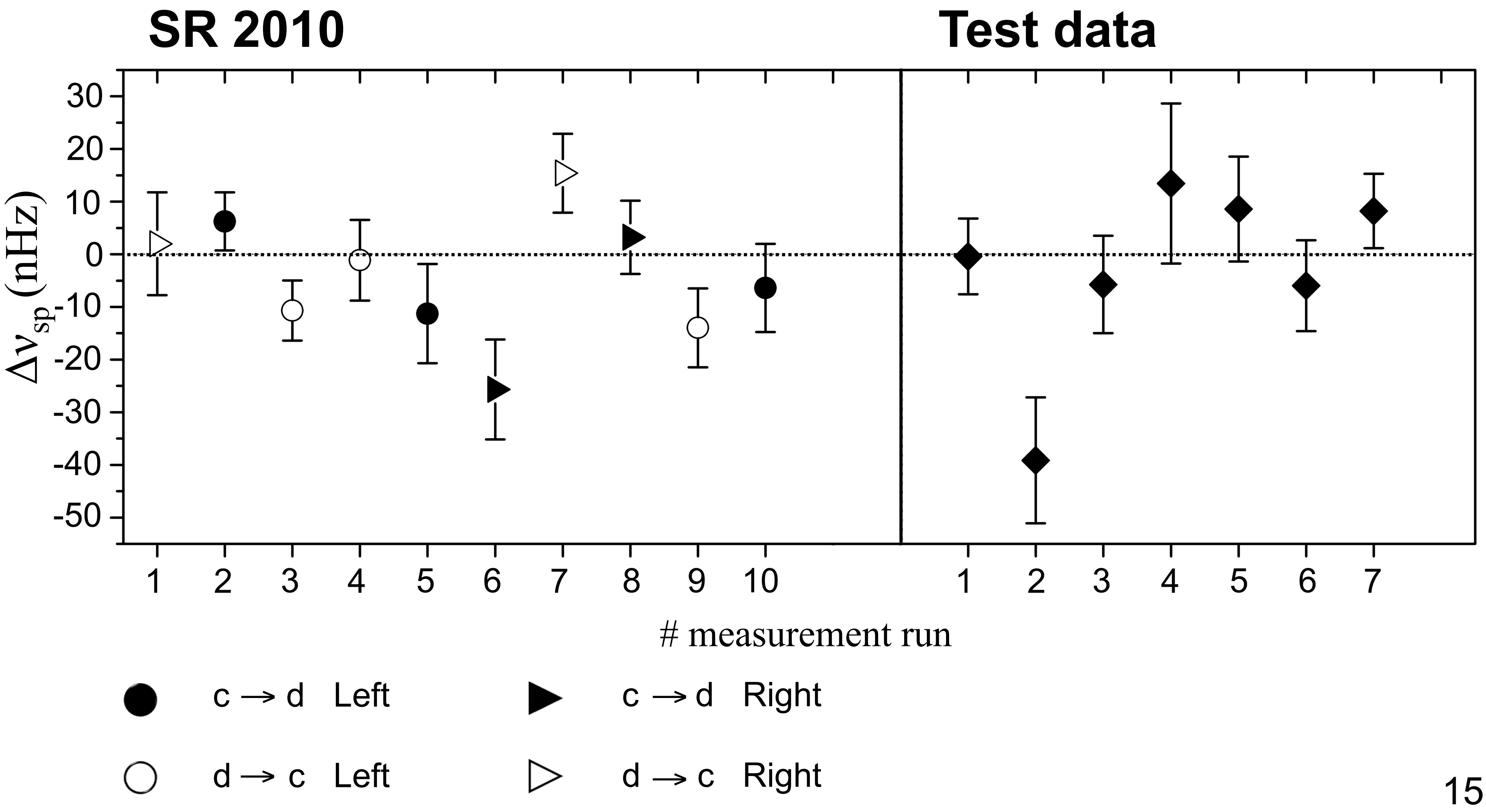
$$\langle V_{sp}\rangle = \frac{\hbar^2 g_s g_p}{8\pi m_n}\int_{VBGO}\int_{Vcell}\left(\frac{\vec{r}}{r}\cdot\vec{\sigma}\right)\left(\frac{1}{r\lambda}+\frac{1}{r^2}\right)\cdot e^{-r/\lambda}\, dV_{cell}\, dV_{BGO} = \frac{\hbar^2 g_s g_p}{8\pi m_n}\langle V^*(\lambda)\rangle$$

The mean potential $\langle V_{sp}\rangle$ was calculated numerically for our measurement cells (Ø= 58 mm, *l* = 58 mm). The gap between the inner volume of the measurement cell and the $Bi_4Ge_3O_{12}$ crystal (Ø= 60 mm, *l* = 70 mm) was 2.2 mm.

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

Results

$$\Delta\nu_{sp} = \frac{\Delta\omega_{sp}^{w}}{2\pi\cdot\left(1-\gamma_{He}/\gamma_{Xe}\right)}$$



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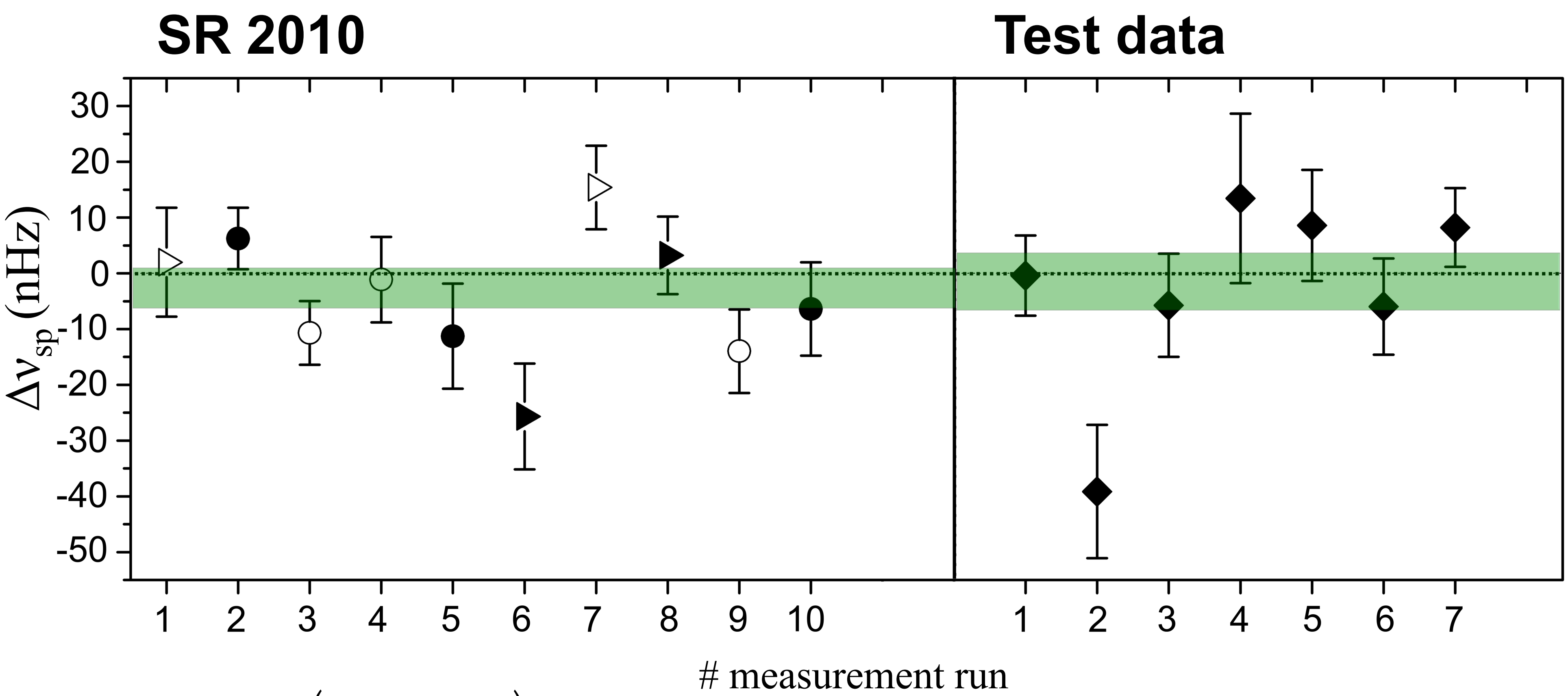
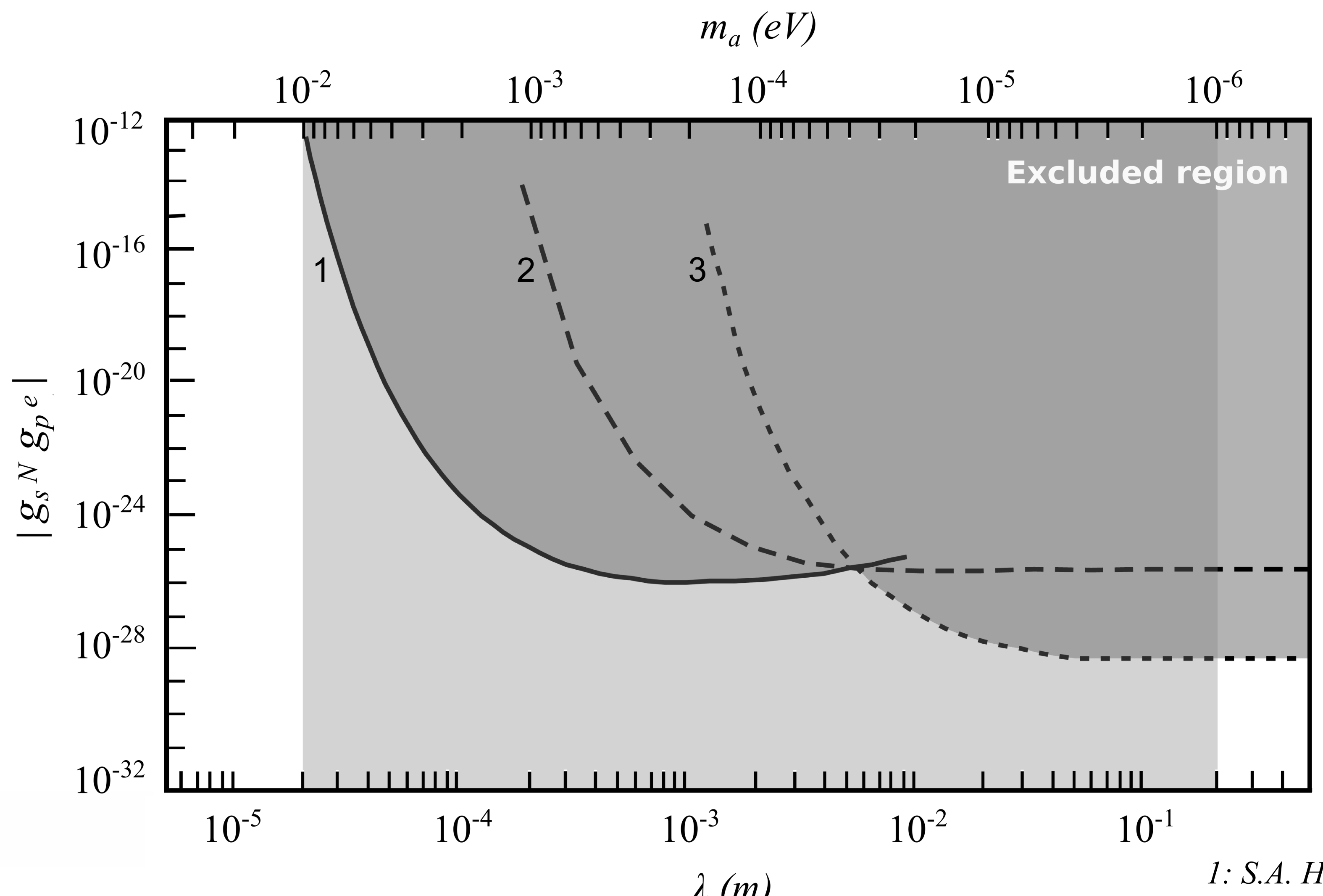


$$\Delta\nu_{Test} = \left(-1.4 \pm 5.2\right)\text{nHz}$$

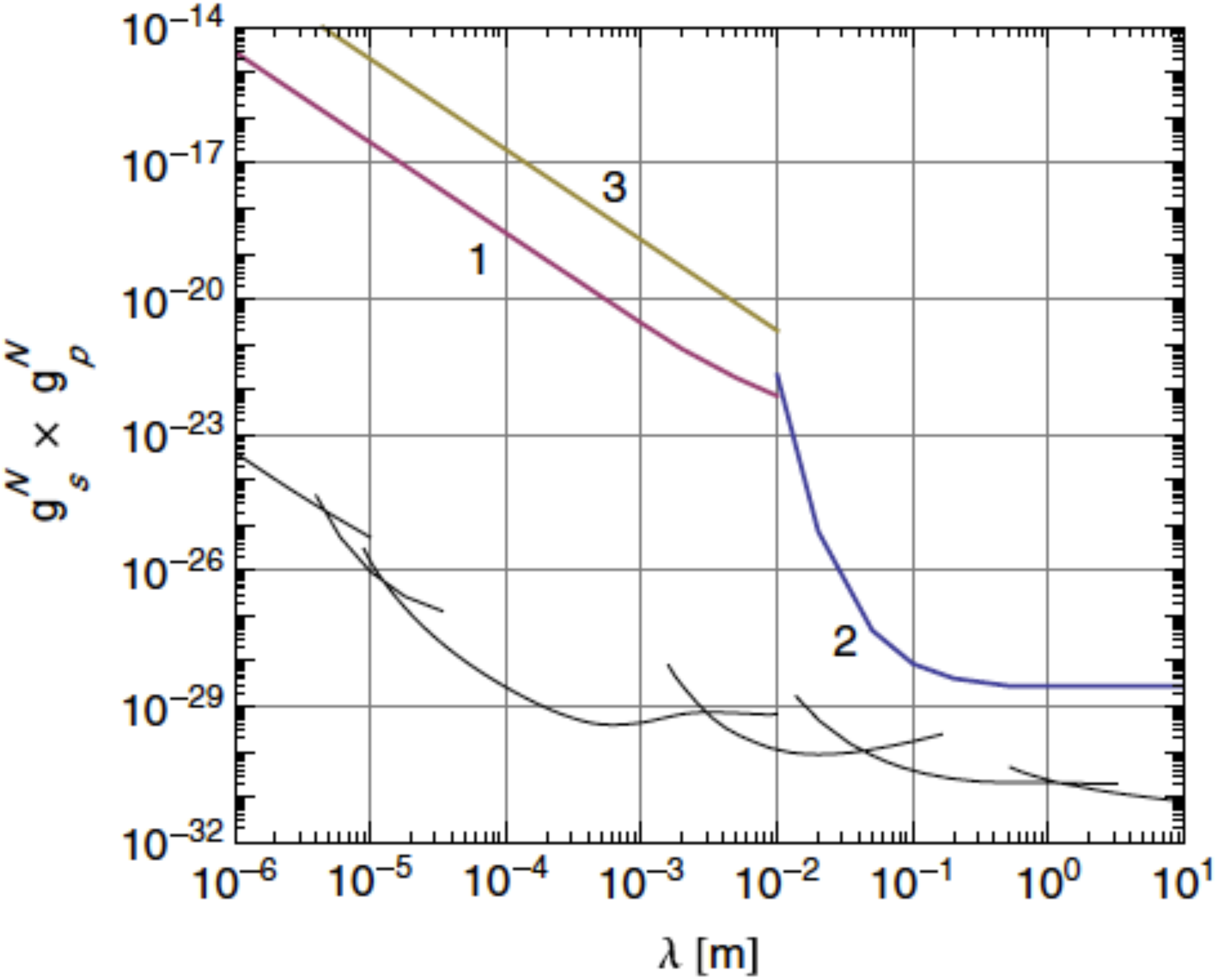
$$\Delta\nu_{sp} = \left(-2.9 \pm 3.5\right)\text{nHz}$$

Exclusion Plot



1: S.A. Hoedel (2011)
2: G.D. Hammond (2007)
3: W.-T. Ni (1998)

Exclusion Plot



1: A.K. Petukhov (2010)
2: A.N. Youdin (1996)
3: A.P. Serebrov (2010)

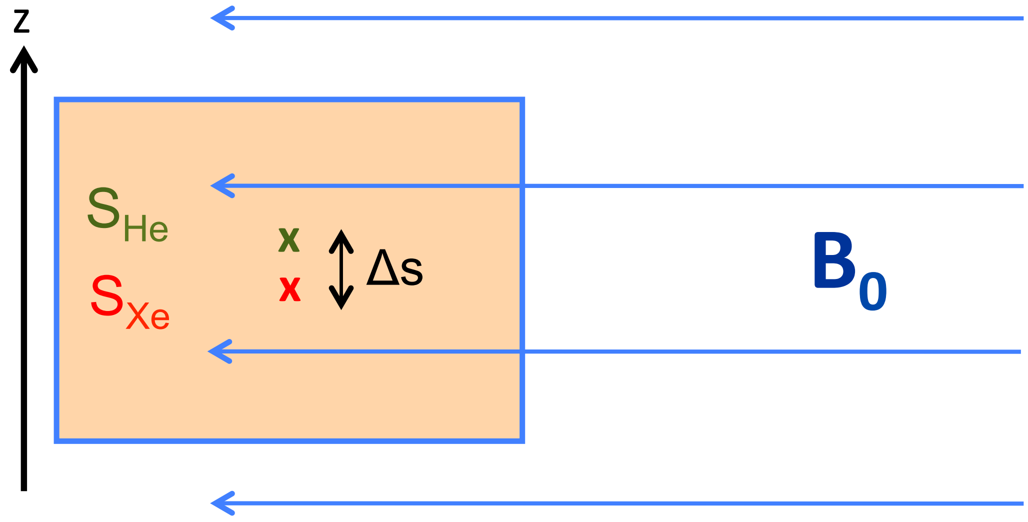
Plot taken from: *G. Raffelt, Phys. Rev. D 86, 015001 (2012)*

Influence of the $Bi_4Ge_3O_{12}$ crystal on T_2^*

Systematic errors

Transversal field gradients

$$\Delta\omega = \omega_{He} - \frac{\gamma_{He}}{\gamma_{Xe}}\omega_{Xe}$$



Systematic errors

Transversal field gradients

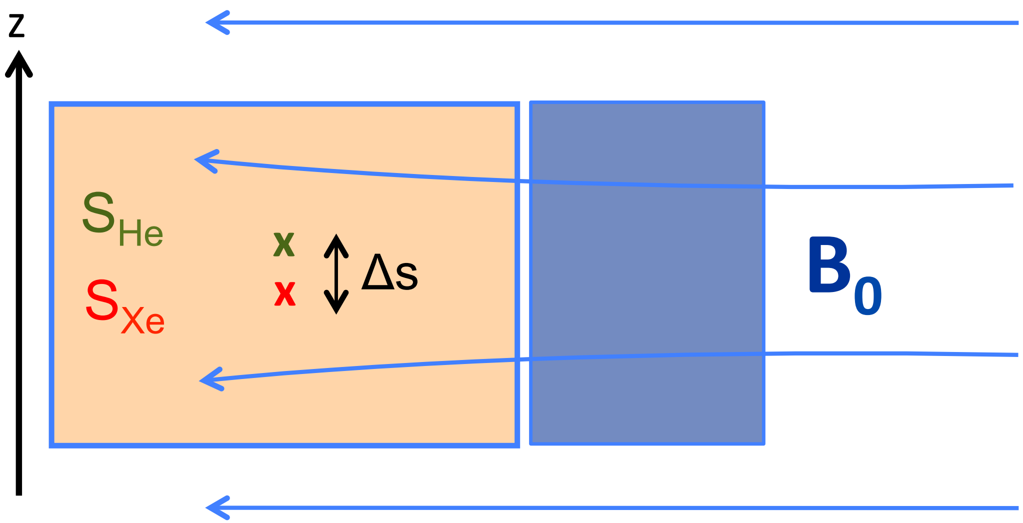
$$\Delta\omega = \omega_{He} - \frac{\gamma_{He}}{\gamma_{Xe}}\omega_{Xe} \quad \Rightarrow \quad \Delta\omega^{CM} = \gamma_{He}\cdot\left(B_{Xe}+\Delta B\right) - \gamma_{He}\cdot B_{Xe} = \gamma_{He}\cdot\Delta B \cdot H(t\text{-}t_0)$$

simulated: $\frac{\Delta B}{\Delta s} = \overline{\frac{\partial}{\partial z}B_{BGO}\left(z\right)} \leq 0.08\,\frac{pT}{cm}$

Barometric formula:

$$p\left(z\right) = p_0 \cdot exp\left(-\frac{Mg_0}{R_G T}z\right)$$

$$\Rightarrow \Delta s = S_{He} - S_{Xe} \approx 1.2\cdot 10^{-7}\ m$$



BGO magn. susceptibility $\chi \approx -19\cdot 10^{-6}$ @ B=1.5 T

S. Yamamoto, IEEE, Transationsactions on Nuclear Sience, Vol. 50, No. 5, 2003

$$\Rightarrow \boxed{\Delta\nu^{CM}_{sys} = \Delta s \cdot \overline{\frac{\partial}{\partial z}B_{BGO}\left(z\right)} \cdot \frac{\gamma_{He}}{2\pi\left(1-\gamma_{He}/\gamma_{Xe}\right)} \leq 0.03\ nHz}$$

Systematic errors

Field gradients (general)

$$\frac{1}{T_2^*} = \frac{1}{T_1} + \frac{1}{T_{2,\,field}}$$

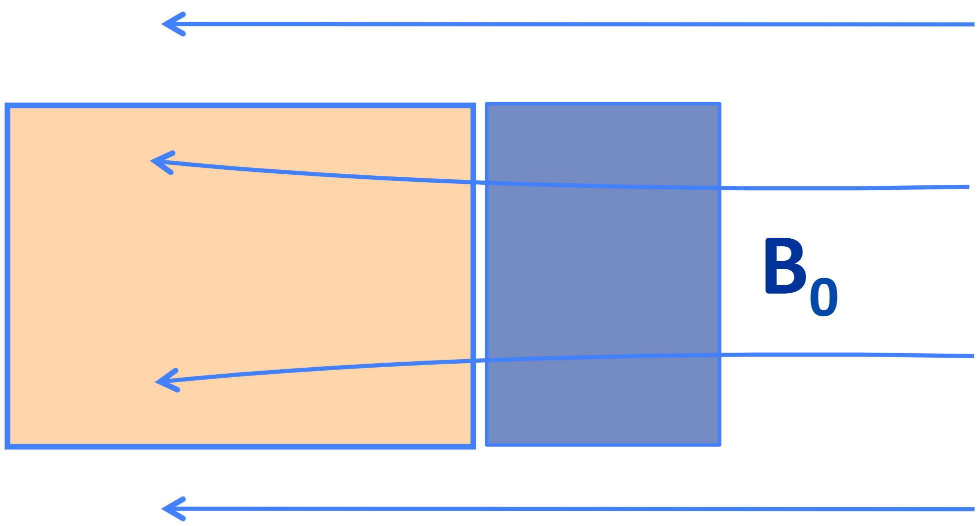
***T*$_{2,field}$ in low magnetic fields** *(G. D. Cates, et al., Phys. Rev. A 37, 2877)*

$$\frac{1}{T_{2,\,field}} \approx \frac{4R^4\gamma^2}{175D}\left(\left|\vec{\nabla}B_{1,\,z}\right|^2 + \left|\vec{\nabla}B_{1,\,y}\right|^2 + 2\left|\vec{\nabla}B_{1,\,x}\right|^2\right) \propto R^4 \cdot p \cdot \left|\vec{\nabla}B\right|^2$$

BGO magn. susceptibility $\chi \approx -19 \cdot 10^{-6}$ @ B=1.5 T

S. Yamamoto, IEEE, Transationsactions on Nuclear Sience, Vol. 50, No. 5, 2003

⇒ additional field gradients



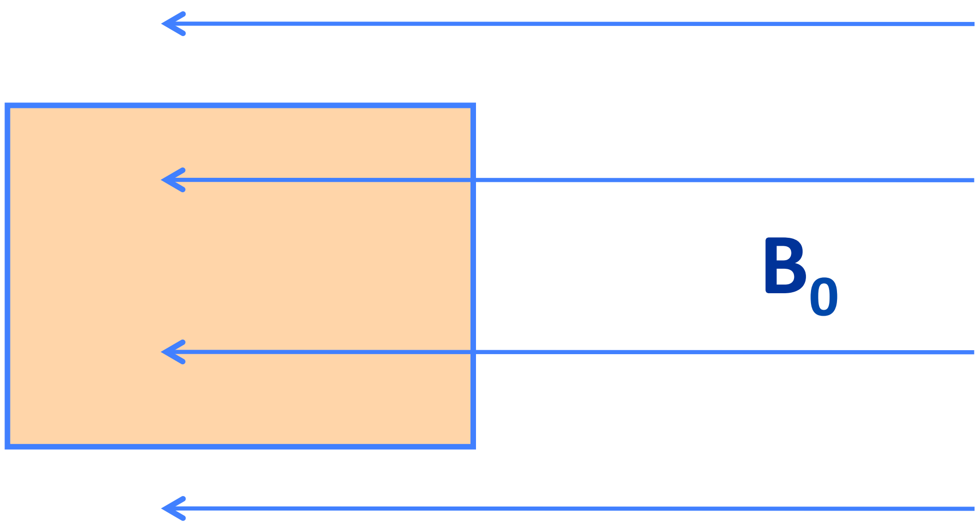
Systematic errors

Field gradients (general)

$$\frac{1}{T_2^*} = \frac{1}{T_1} + \frac{1}{T_{2,\,\mathrm{field}}} \qquad \frac{1}{T_{2,\,\mathrm{field}}} \approx \frac{4R^4\gamma^2}{175D}\left(\left|\vec{\nabla}B_{1,\,z}\right|^2 + \left|\vec{\nabla}B_{1,\,y}\right|^2 + 2\left|\vec{\nabla}B_{1,\,x}\right|^2\right) \propto R^4 \cdot p \cdot \left|\vec{\nabla}B\right|^2$$

BGO magn. susceptibility $\chi \approx -19 \cdot 10^{-6}$ @ B=1.5 T

$\Rightarrow$ additional field gradients



Error due to changes of T_2^*:

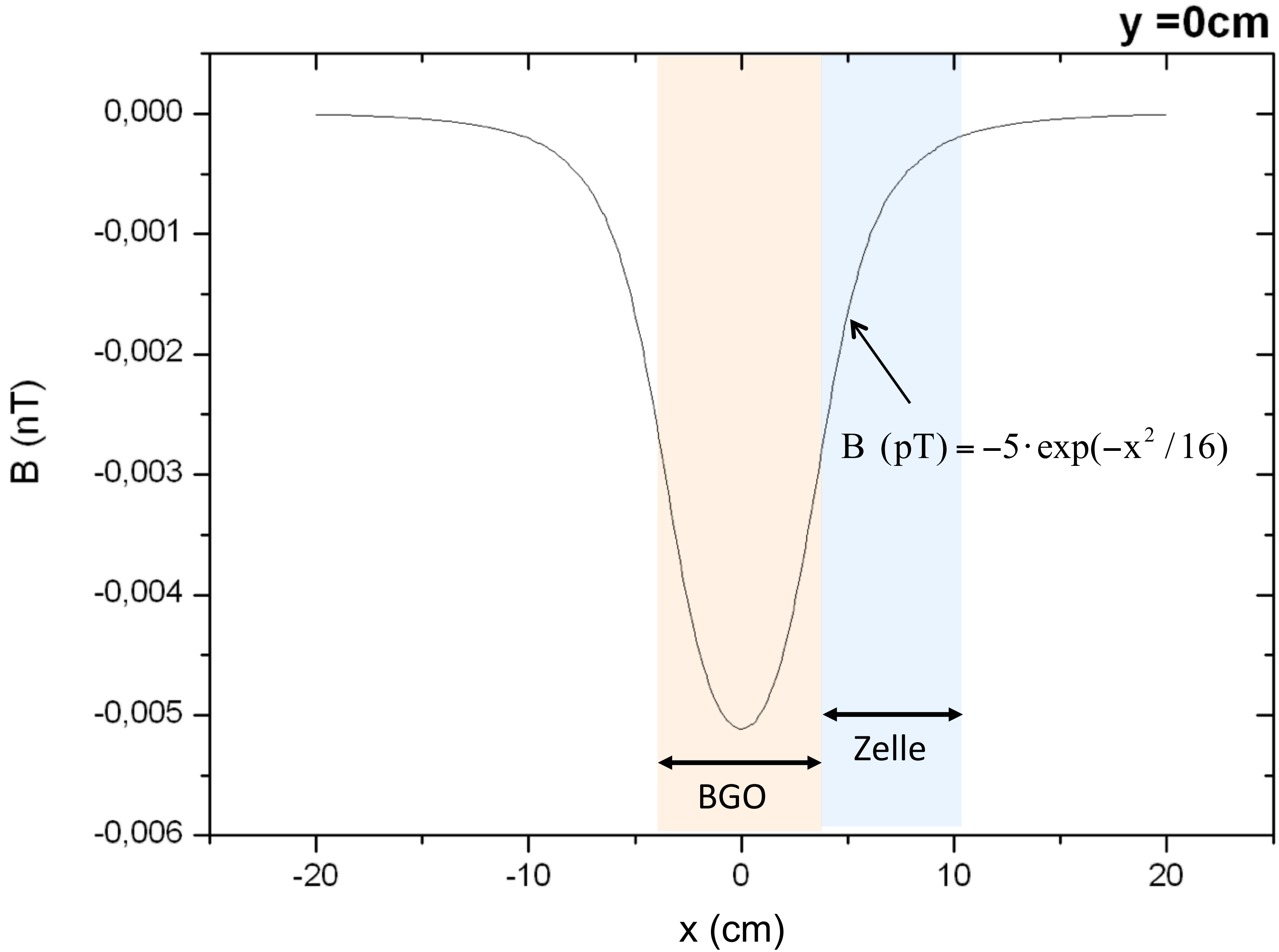
$$\left|\Delta\nu_{sys}^{T_2}\right| \le \frac{\dfrac{\Delta T_{2,He}^*}{\left(T_{2,He}^*\right)^2} \cdot \left(\dfrac{a_{He}}{T_{2,He}^*} - \dfrac{1}{2}\dfrac{a_{Xe}}{T_{2,Xe}^*}\right) \cdot \dfrac{t_0}{2}}{2\pi\left(1 - \gamma_{He}/\gamma_{Xe}\right)}$$

with: $\langle a_{He}\rangle \approx 11.5\ \mathrm{rad},\ \langle a_{Xe}\rangle \approx 0.1\ \mathrm{rad},\ t_0 = 3\ \mathrm{h},$

$T_{2,He}^* = 53\ \mathrm{h},\ T_{2,Xe}^* = 5\ \mathrm{h},\ \left|\Delta T_{2,He}^*\right| \le 160\ \mathrm{s}$

$$\Rightarrow \quad \boxed{\left|\Delta\nu_{sys}^{T_2}\right| \le 0.1\ \mathrm{nHz}}$$

Comsol Simulation



Comsol Simulation

Assumption:

$$B_{BGO}(pT) = -5 \cdot \exp(-x^2/16) \Rightarrow \partial B_{BGO}/\partial x\ (pT/cm) = +10/16 \cdot x \cdot \exp(-x^2/16)$$

Comsol Simulation

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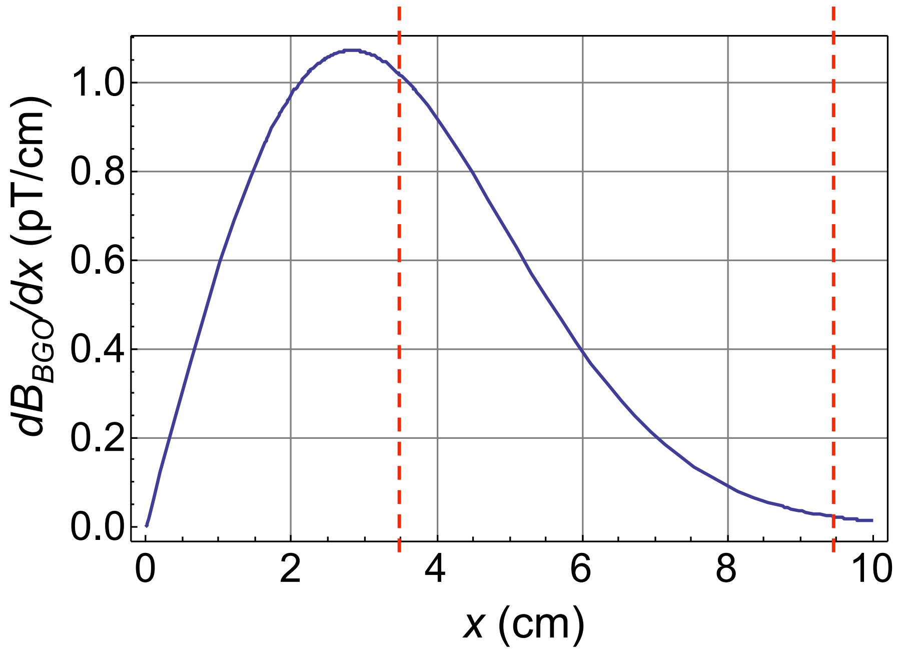
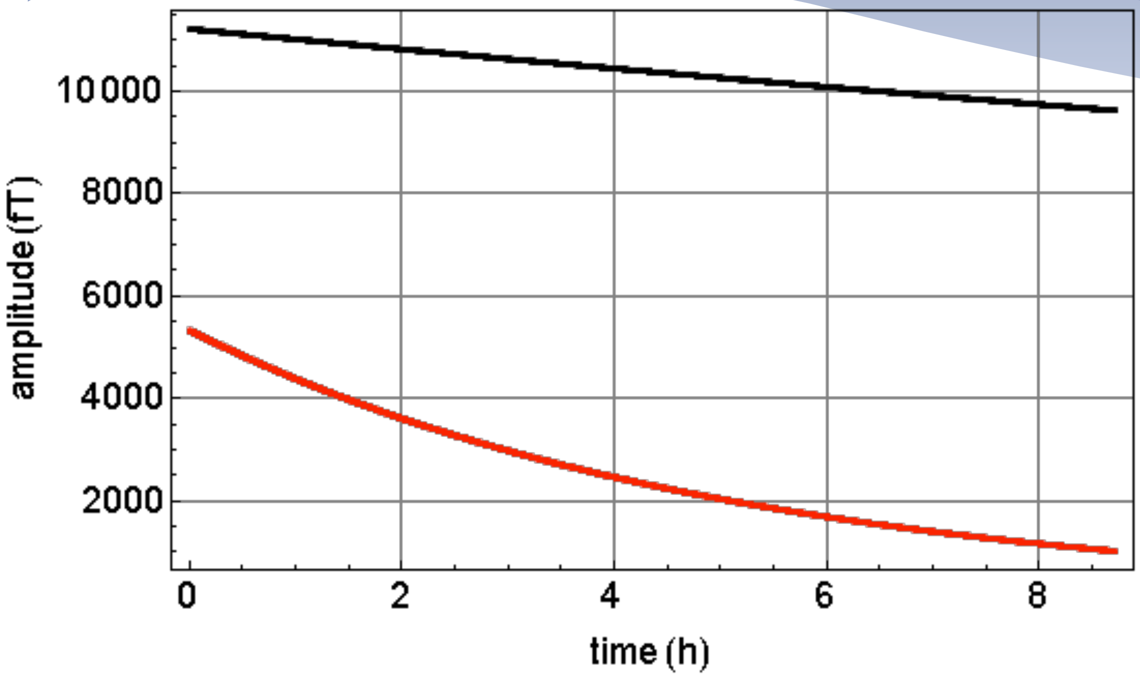


$$\overline{\partial B_{BGO}/\partial x} \approx 0.47\, pT/cm$$

$$\partial B_{BGO}/\partial y,\; \partial B_{BGO}/\partial z \;<<\; \partial B_{BGO}/\partial x$$

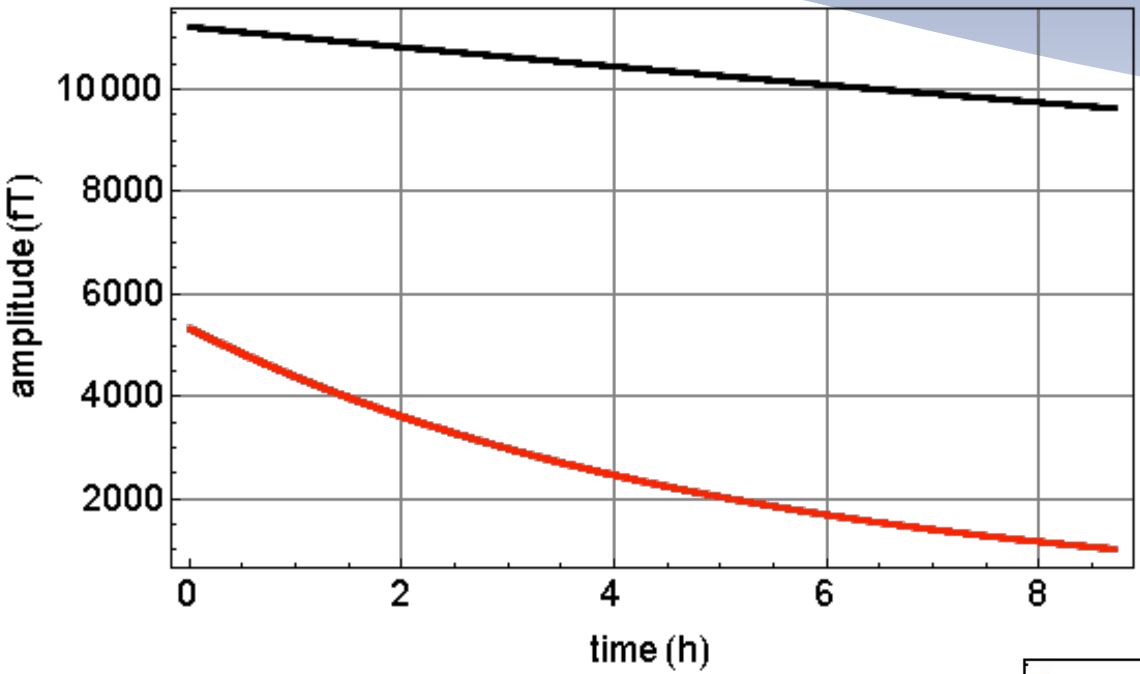
Determination of T_2^*



Exponential fit of amplitudes:

$$fit(t) = a_0 \cdot e^{-t/T_2}$$

Determination of T_2^*

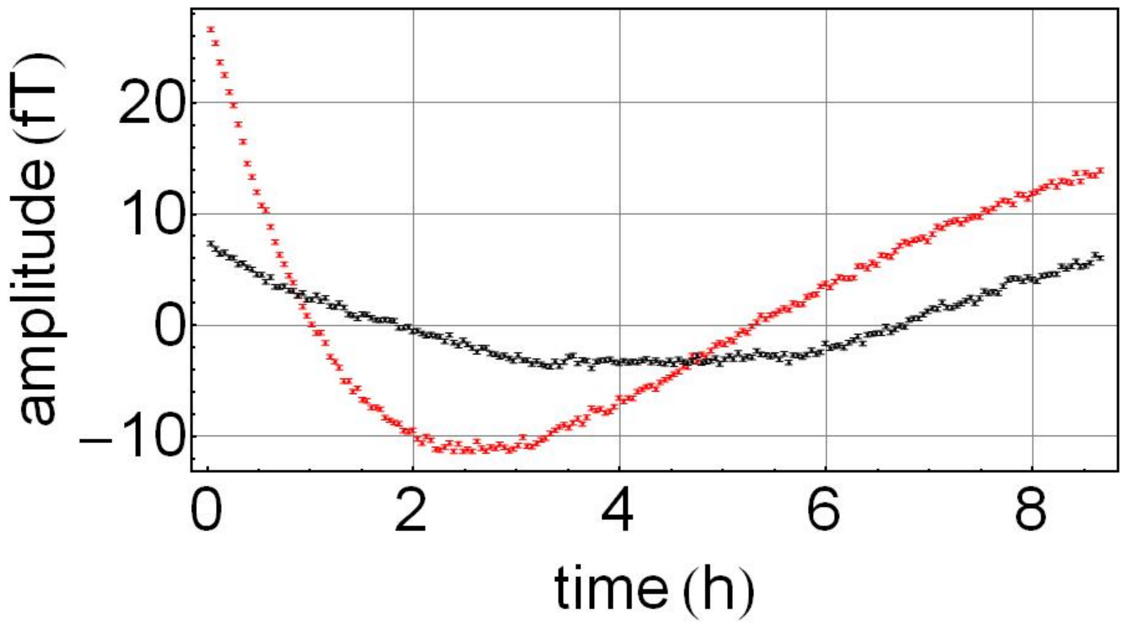


Exponential fit of amplitudes:

$$fit(t) = a_0 \cdot e^{-t/T_2}$$

Residuals:

$$residuals(t) = a(t) - fit(t)$$



Decay of Amplitudes

$$A(t) = f_a(t) \cdot f_b(t) \cdot f_c(t) \cdot \ldots \cdot A_0 \cdot e^{-t/T_2}$$

a.) Drift of SQUIDs and motion of SQUIDs in the magnetic field $f_a(t)$

b.) Changes of the field gradients

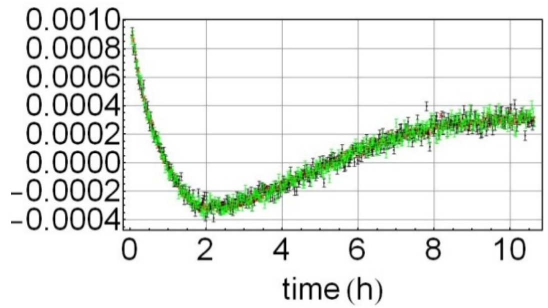
$$Ratio(t) = \frac{f_{b,Xe}(t)}{f_{b,He}(t)} \cdot \frac{f_{c,Xe}(t)}{f_{c,He}(t)} \cdot \frac{A_{0,Xe}}{A_{0,He}} \cdot e^{-t/T}$$

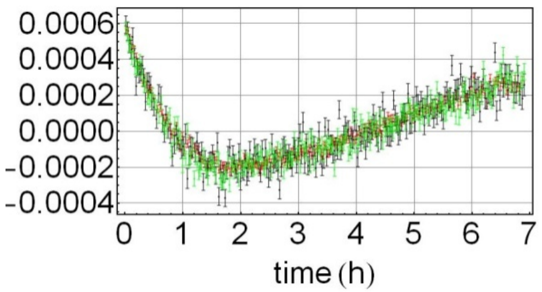
mit: $\frac{1}{T} = \frac{1}{T^{*}_{2,Xe}} - \frac{1}{T^{2}_{2,He}}$

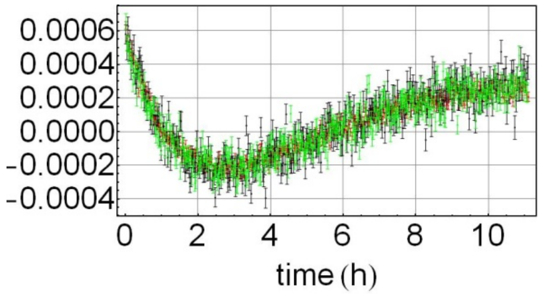
$\Longrightarrow$ Drift $f_a(t)$ due to SQUIDs and motion of SQUIDs in the magnetic drops out.

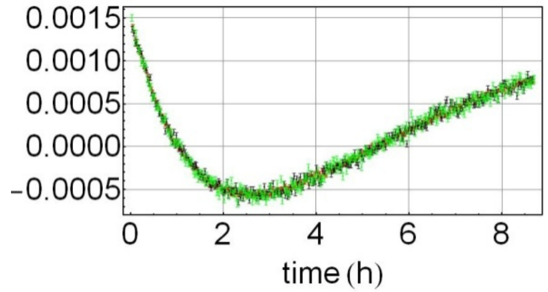
SR Measurements september 2010

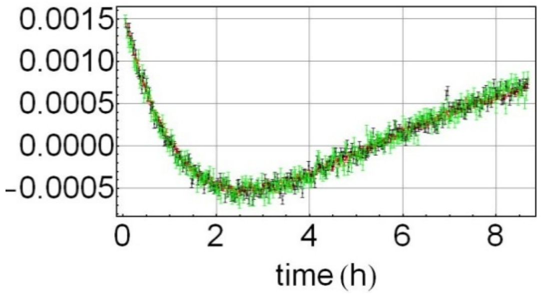
green: Z2E+Z5S, red: Z3D-Z2S, black: Z3I-Z1S

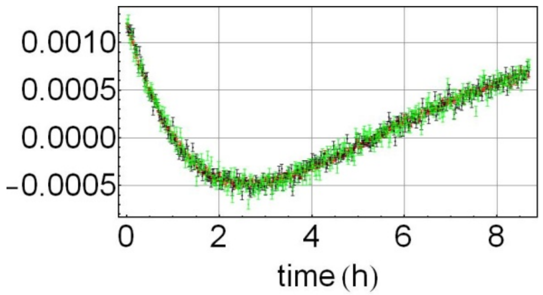


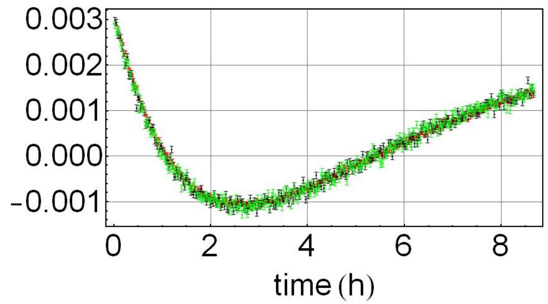


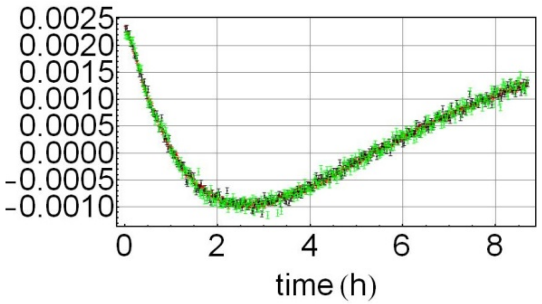


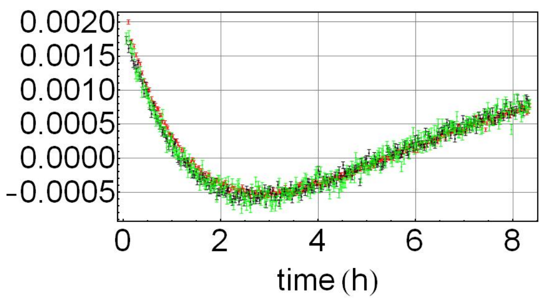


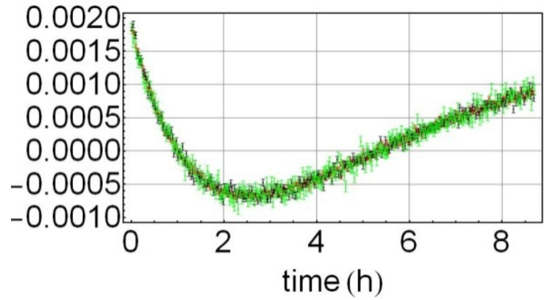












LV Measurements march 2009