Kathlynne Tullney

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

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SPIN 2014, Beijing

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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$$|d_n| \approx \bar{\theta} \cdot 10^{-16} \ \text{ecm} < 2.9 \cdot 10^{-26} \ \text{ecm}$$

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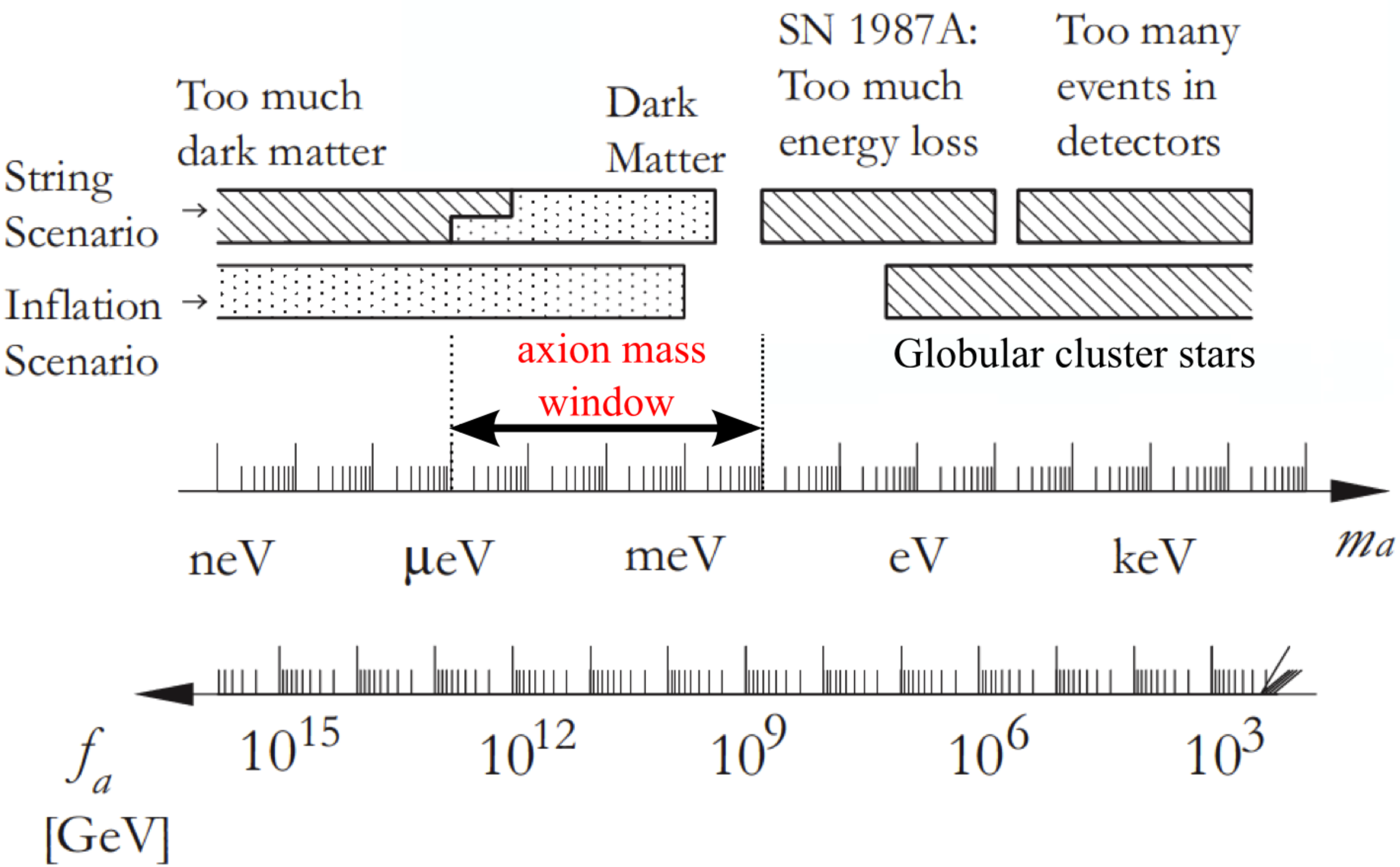
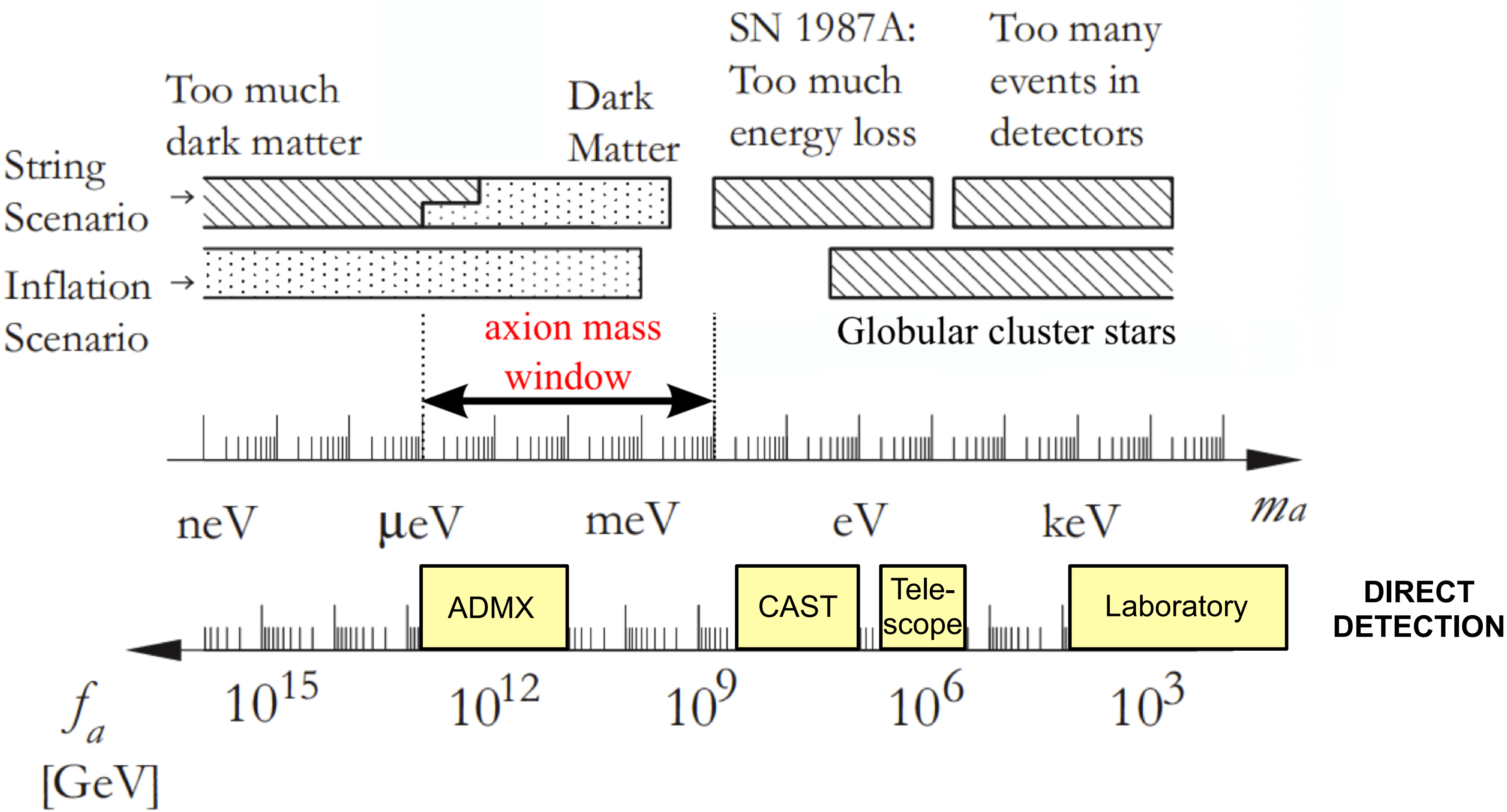
AXIONs: Light and weak interacting particles.
Modern Interest: Dark Matter candidate.

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



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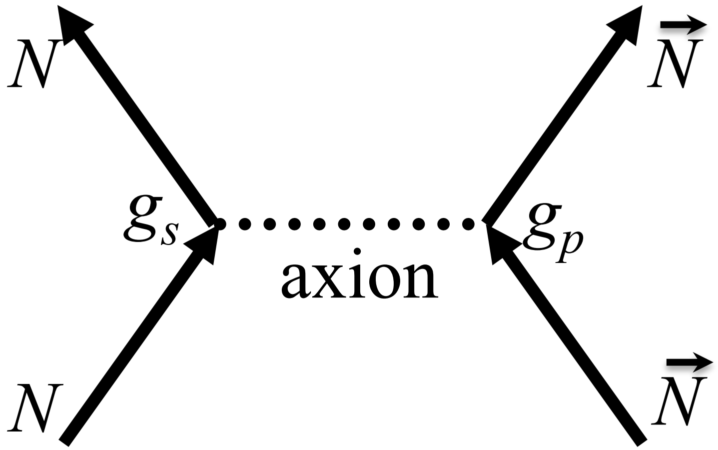
Axion Potential:

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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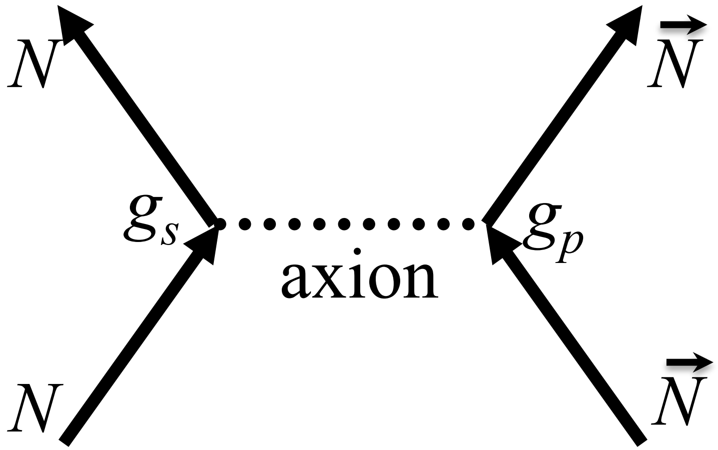

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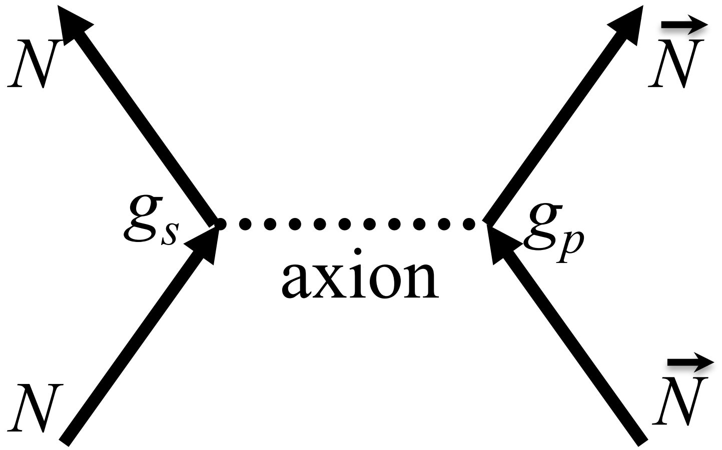

with: $$\kappa = \frac{\hbar^2 g_s g_p}{8\pi m_n} \quad , \quad \lambda = \frac{\hbar}{m_a c}$$

$\Rightarrow$ 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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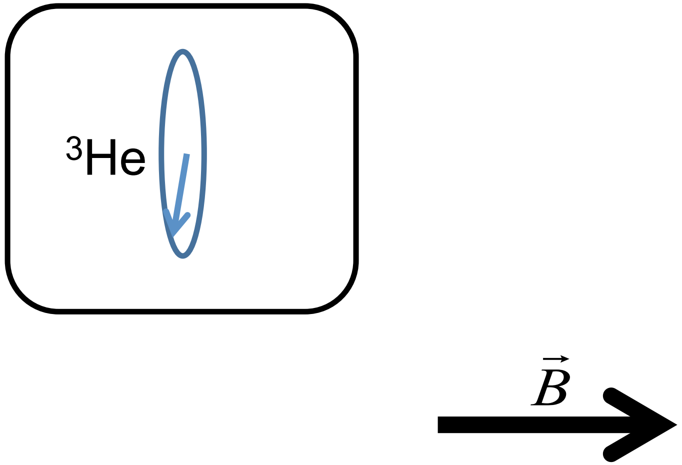
Principle of measurements

How to measure?



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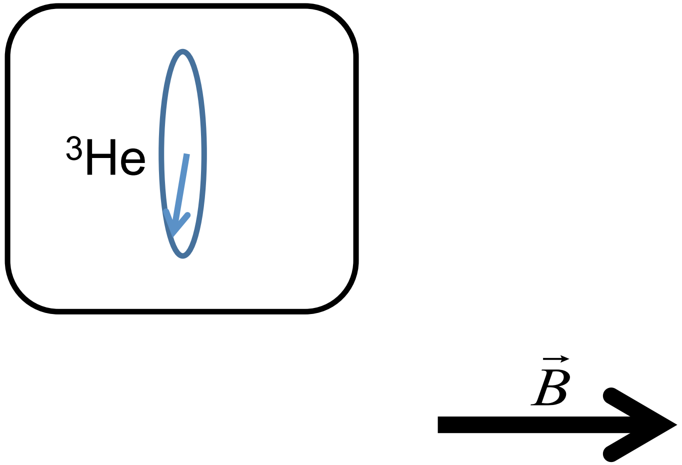

$$\omega_{\mathrm{L,He}}(t) = \gamma_{\mathrm{He}} \cdot B(t)$$

Principle of measurements

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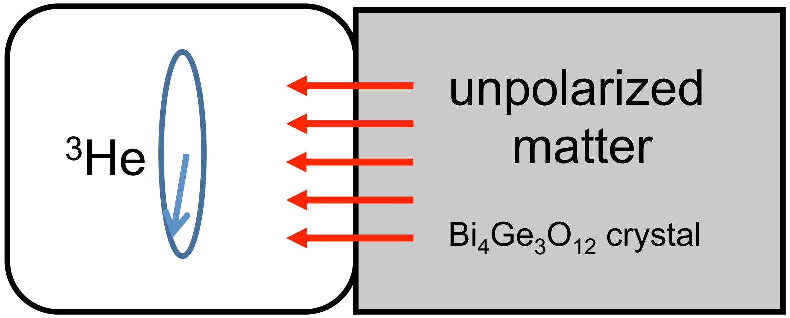
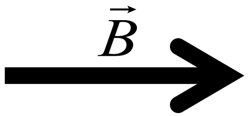


Position: close



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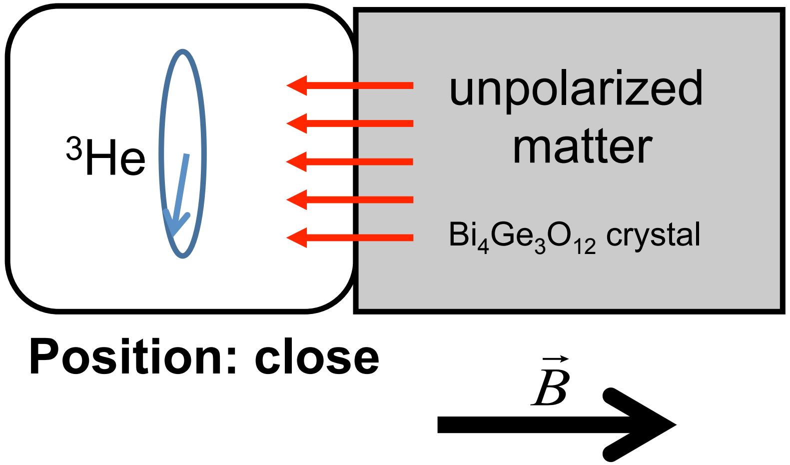

$$\omega_{close}(t) = \omega_{L,He}(t) + \omega_{sp}$$

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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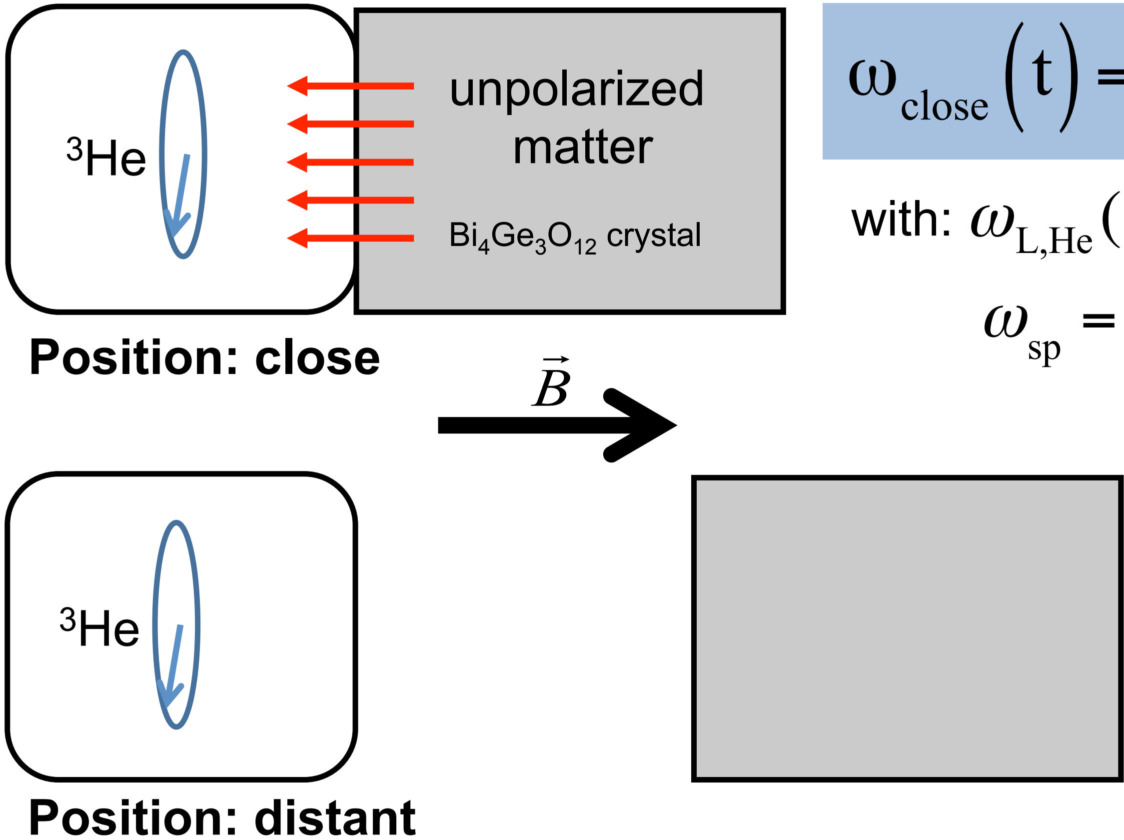

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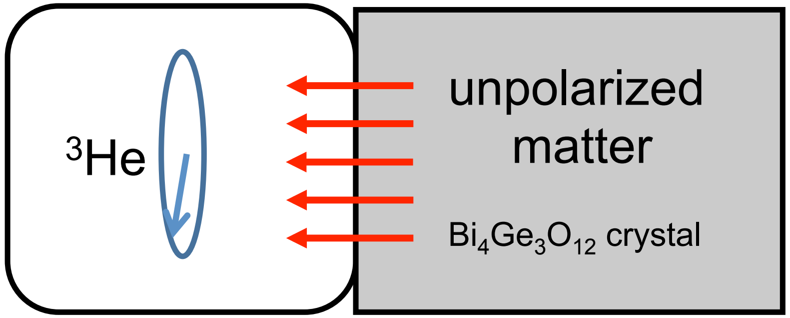
$$\omega_{distant}(t) = \omega_{L,He}(t)$$

How to measure?



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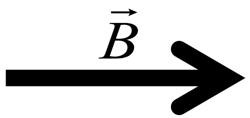
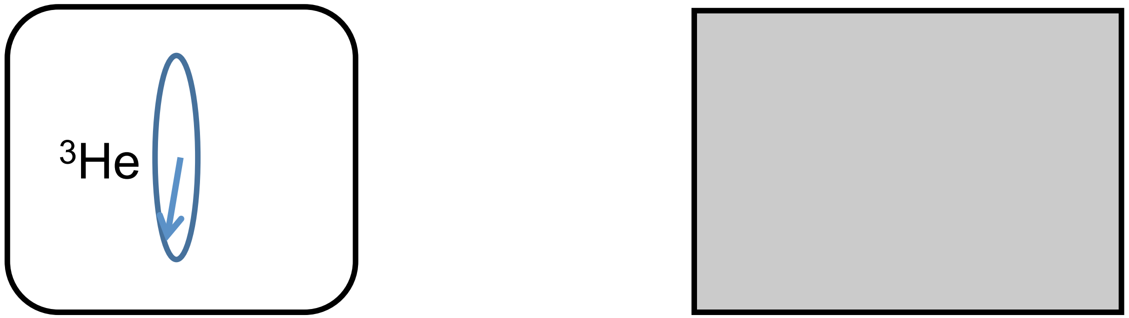




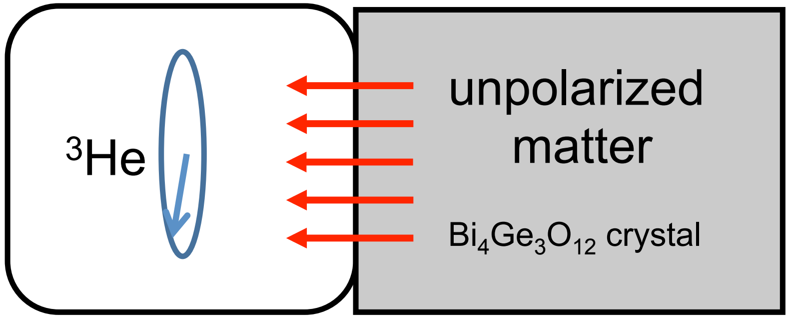
$$\omega_{distant}(t) = \omega_{L,He}(t)$$

Position: distant

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

Principle of measurements

How to measure?



Position: close

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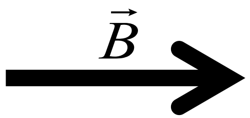
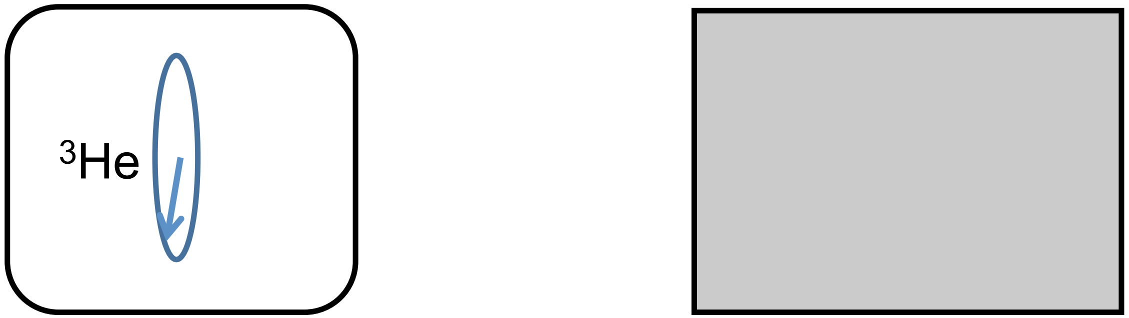




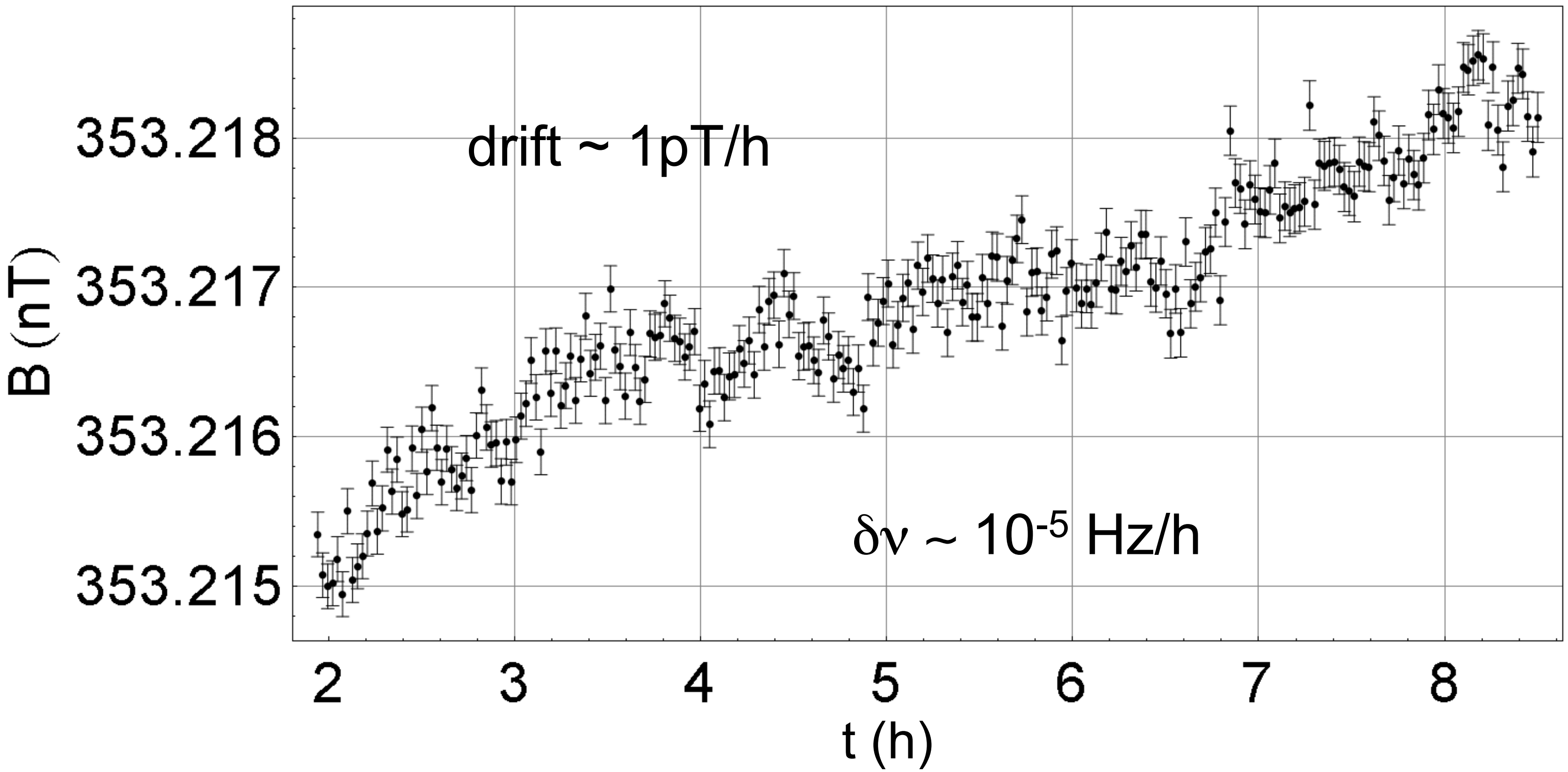
$$\omega_{distant}(t) = \omega_{L,He}(t)$$

Position: distant

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

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

Principle of measurements

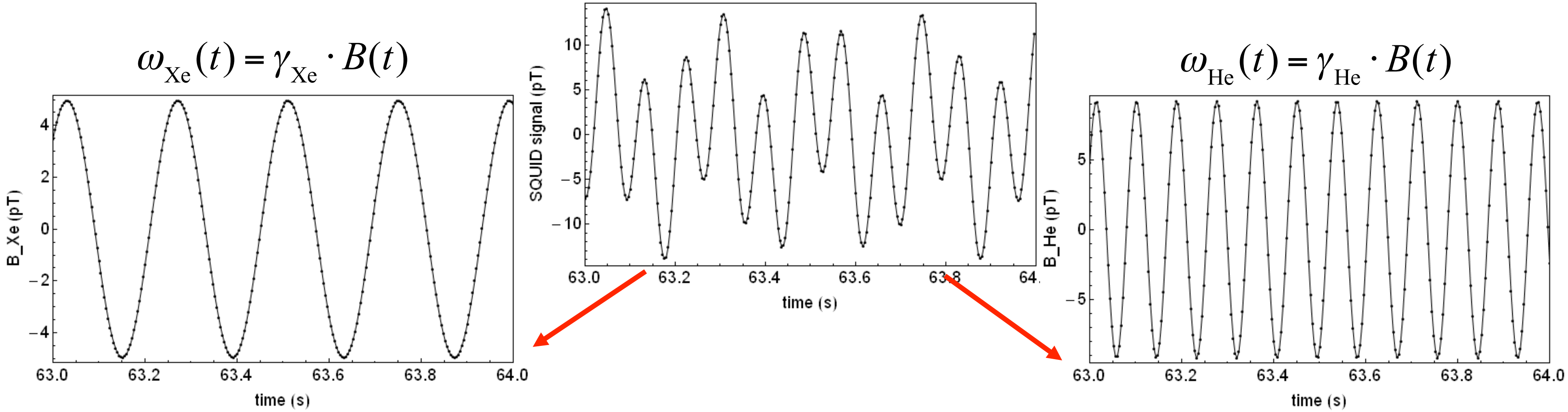


Principle of measurements

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

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

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



Elimination of magnetic field drifts (Zeeman term):

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

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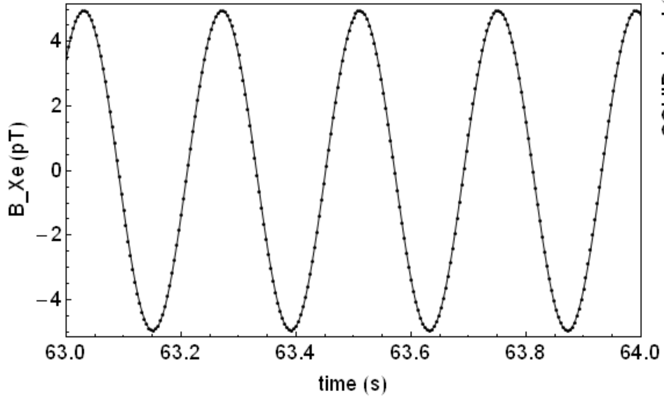
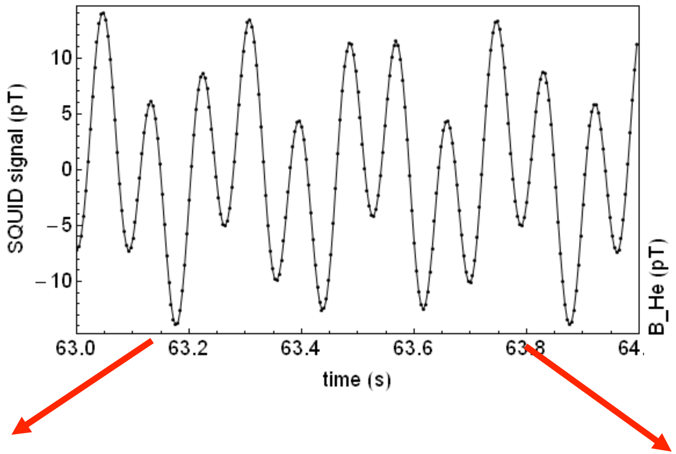
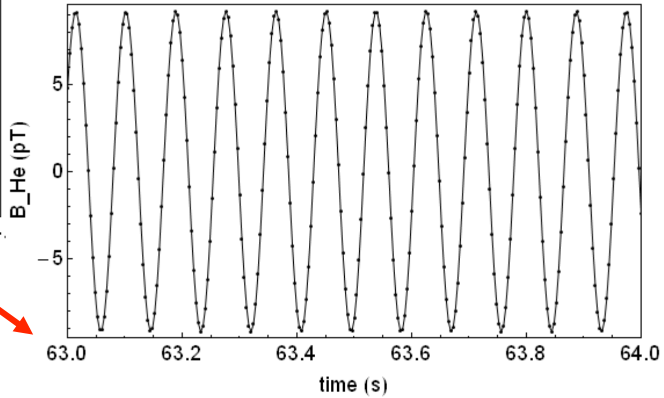




$$\omega_{\mathrm{He}}(t) = \gamma_{\mathrm{He}} \cdot B(t)$$



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

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

Principle of measurements

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

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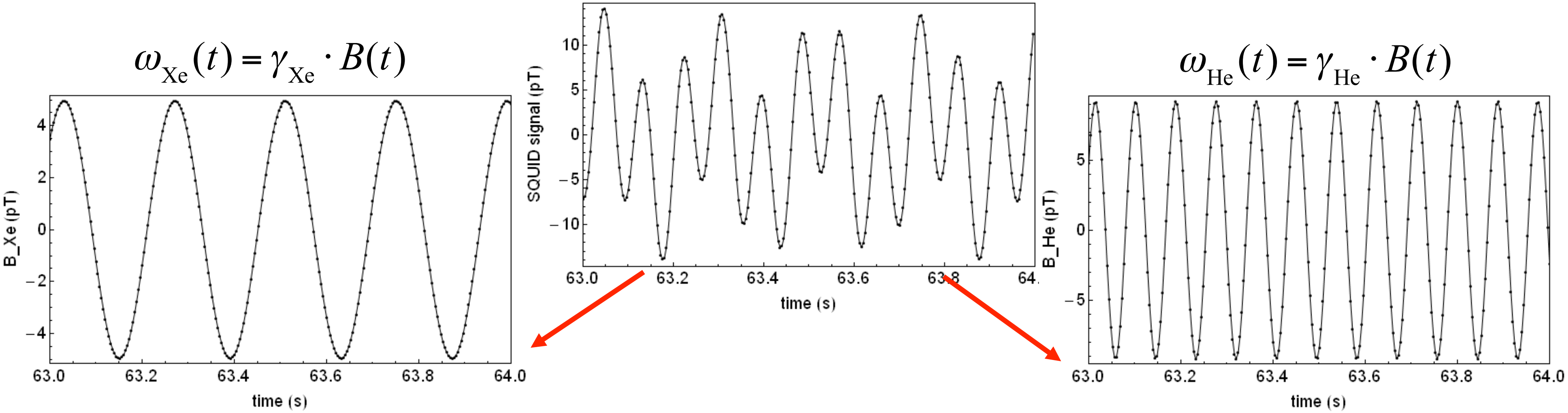

Elimination of magnetic field drifts (Zeeman term):

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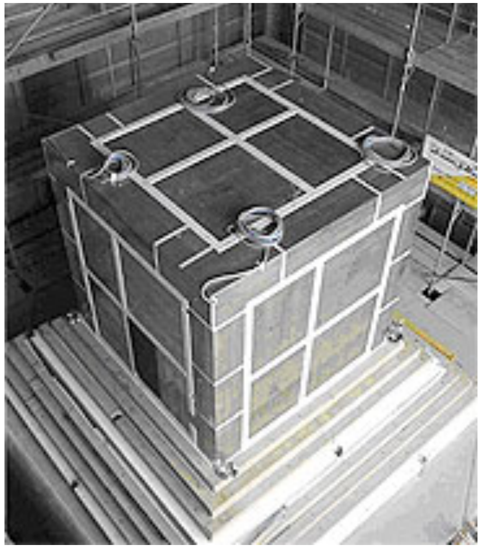
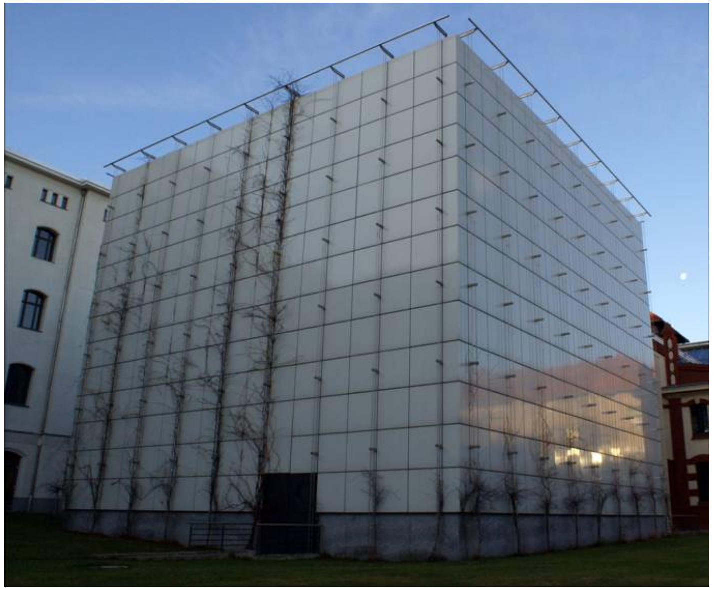
Experimental Setup

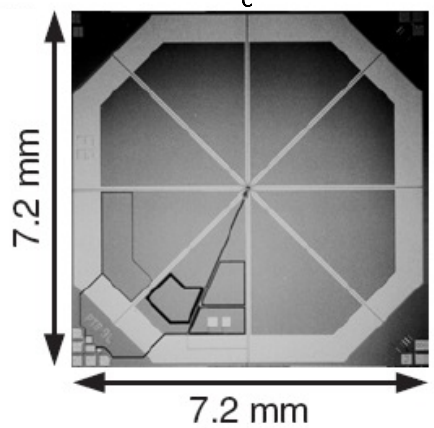


7 layered magnetically shielded room (residual field < 1 nT)

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



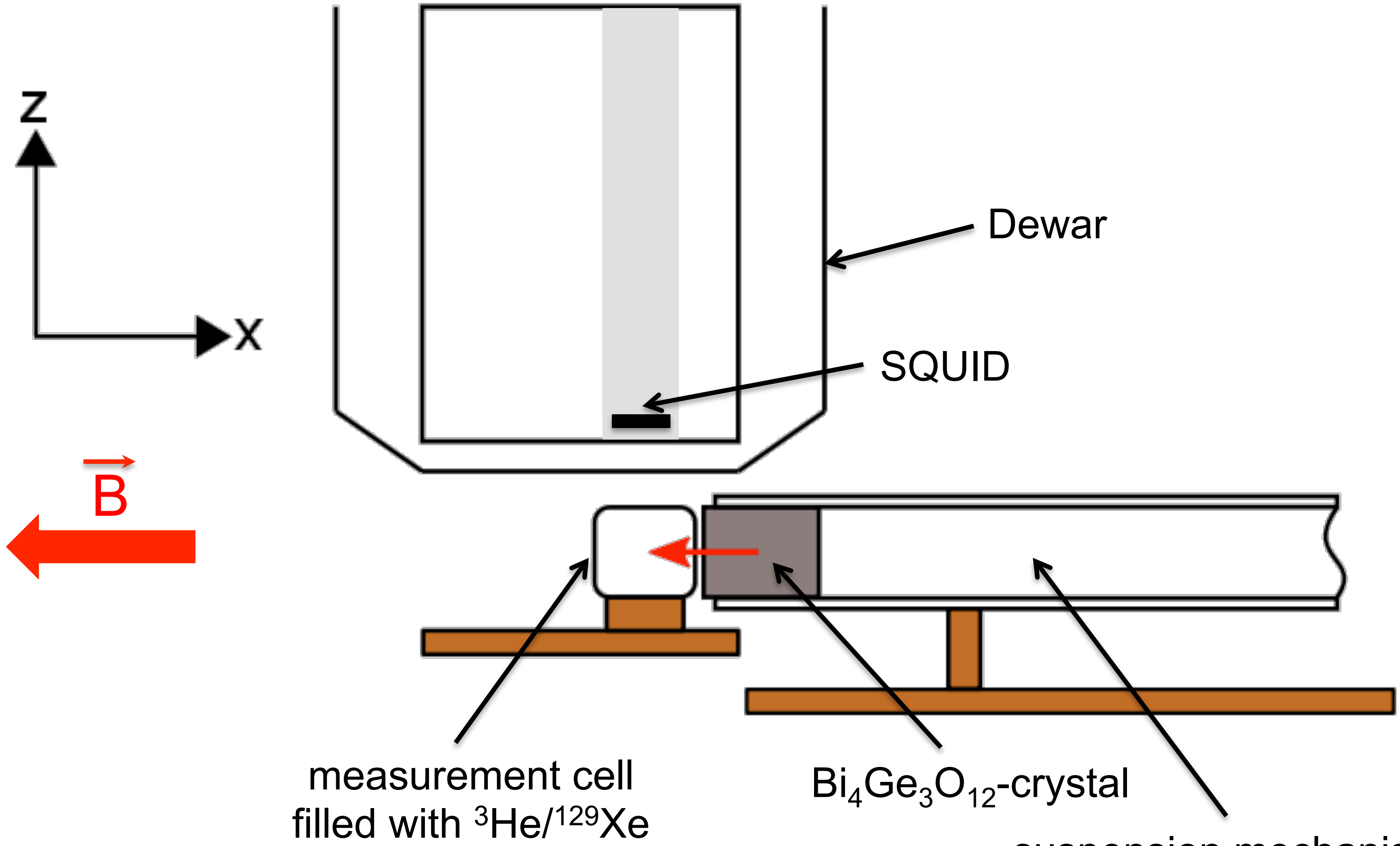
LT_c- SQUID



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

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

Experimental Setup



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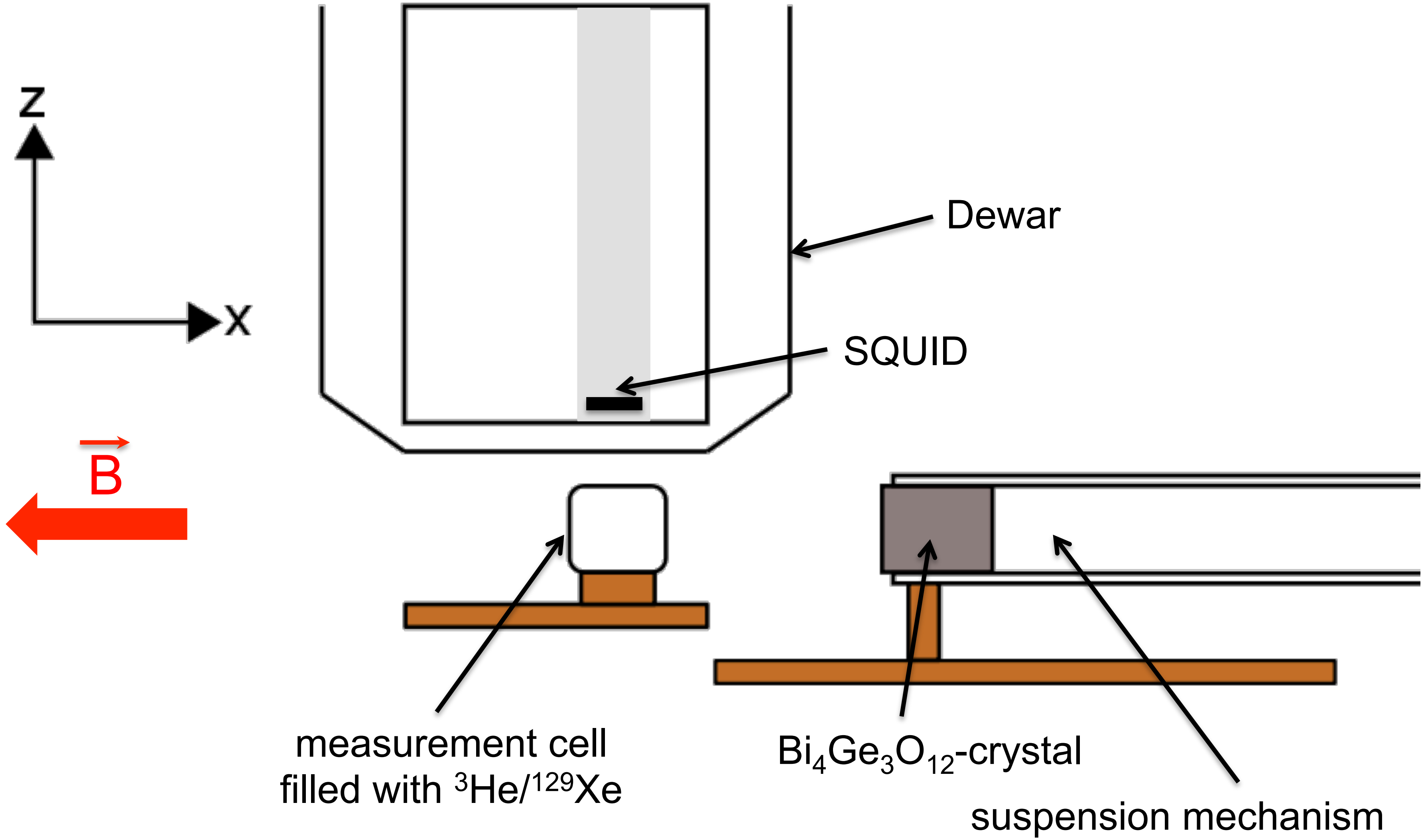
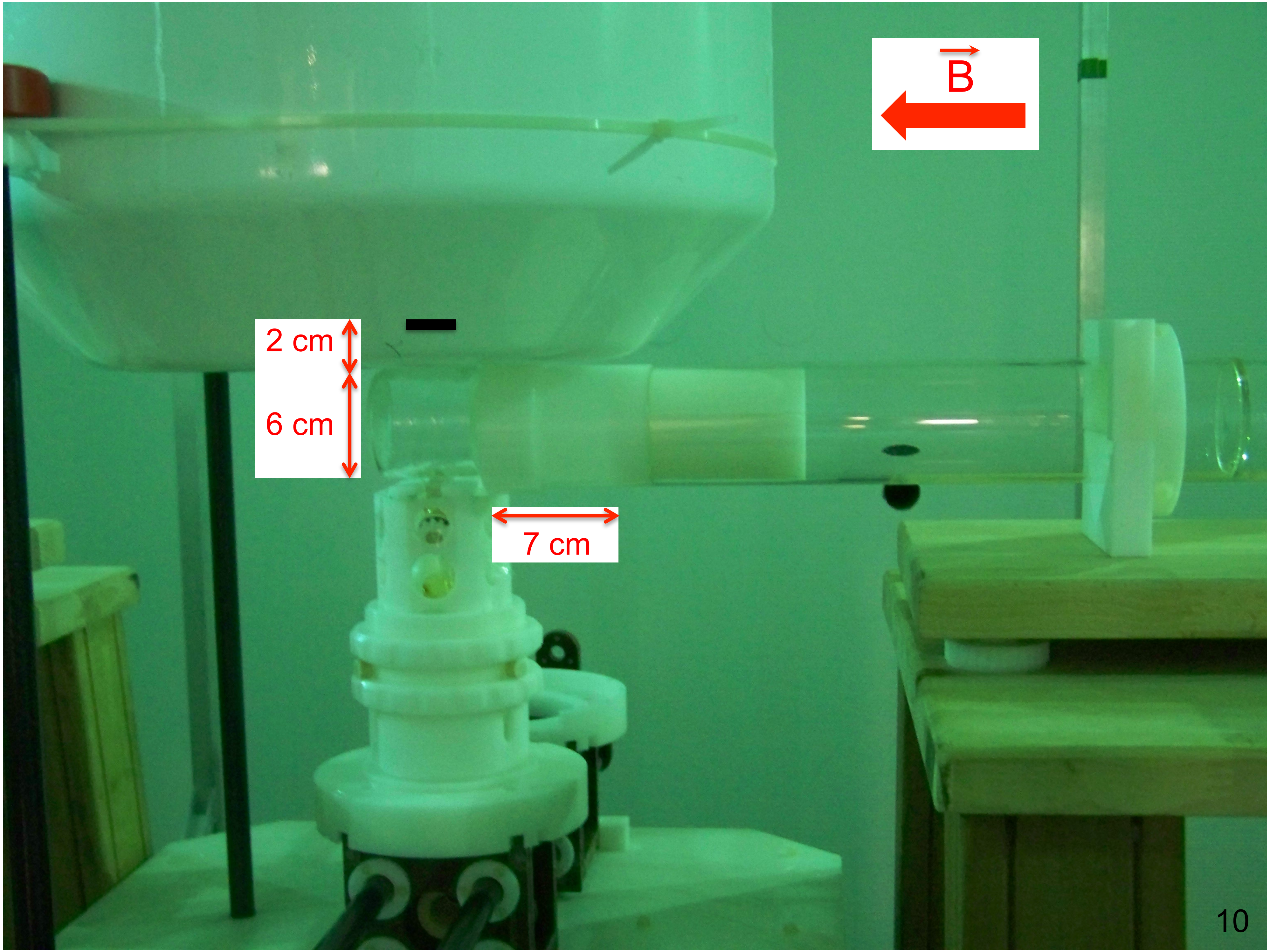
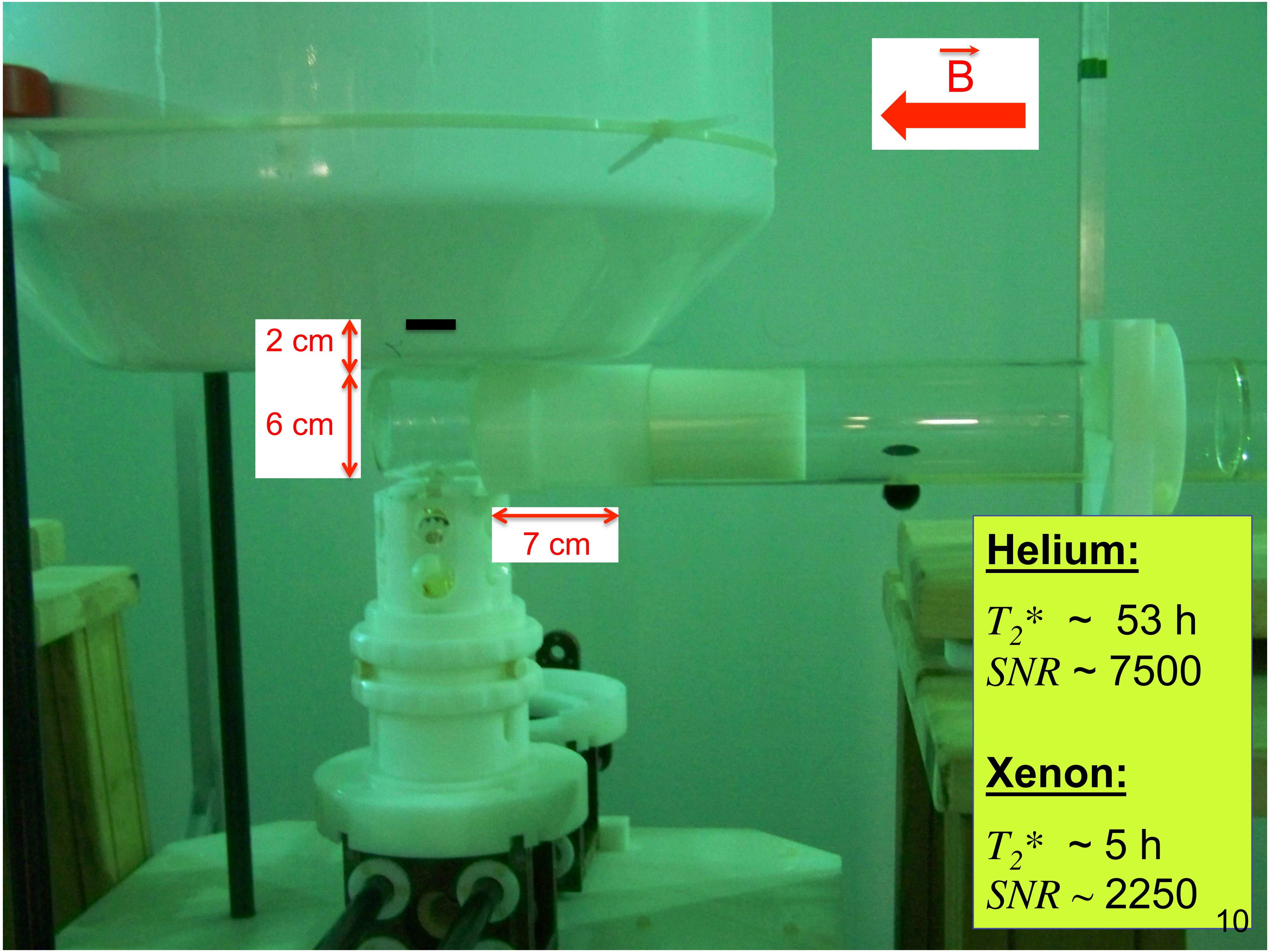


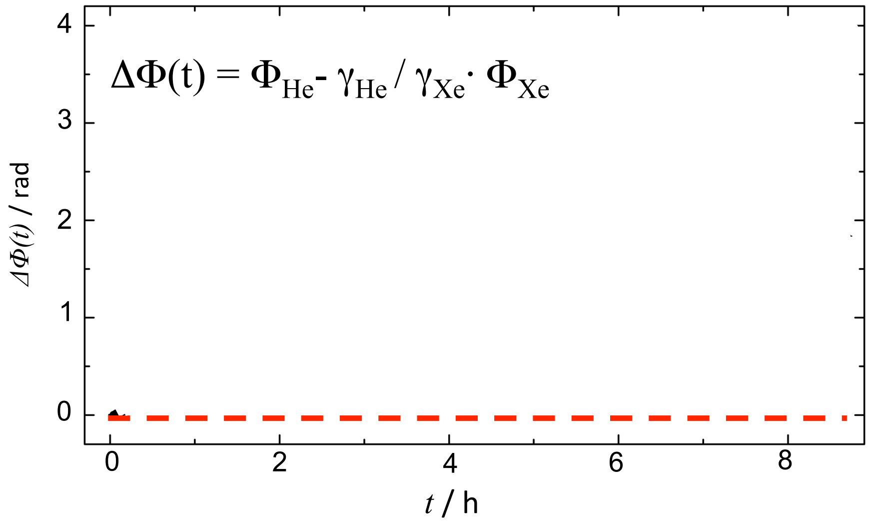

B
2 cm
6 cm
7 cm


B
2 cm
6 cm
7 cm
Helium:
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:

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



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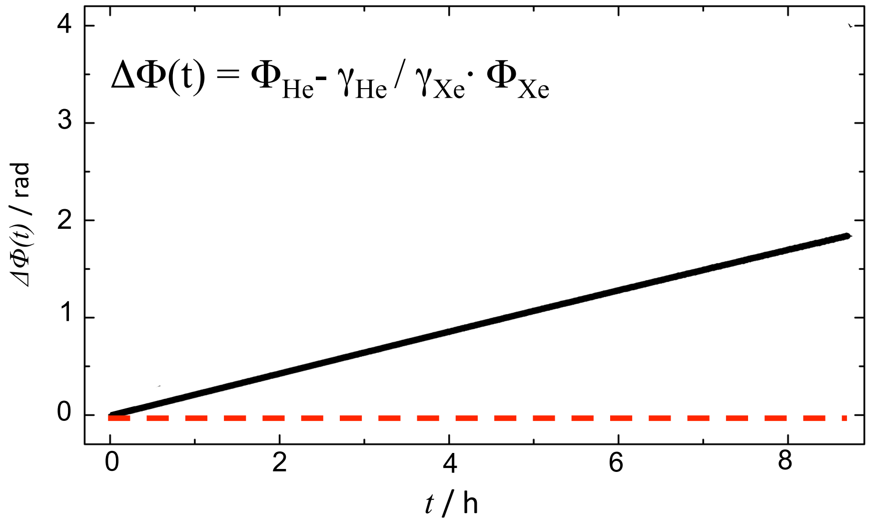

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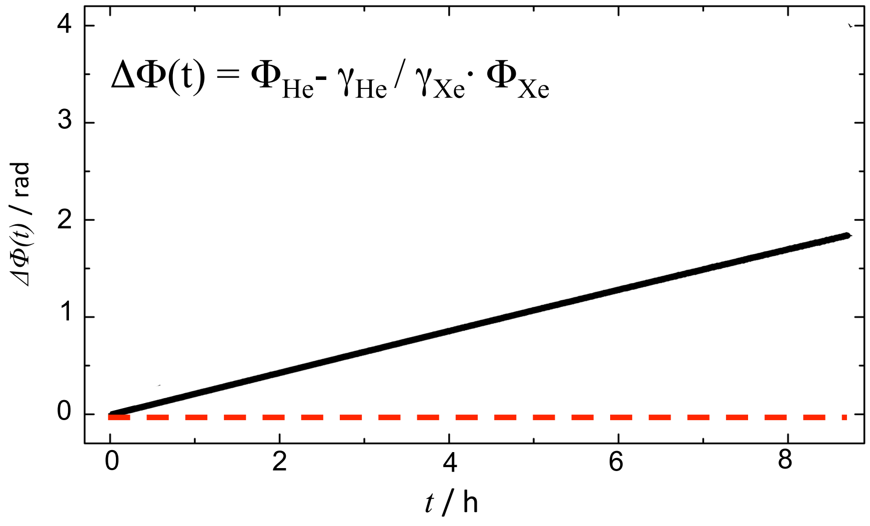
2. Temporal dependence can be described by:

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



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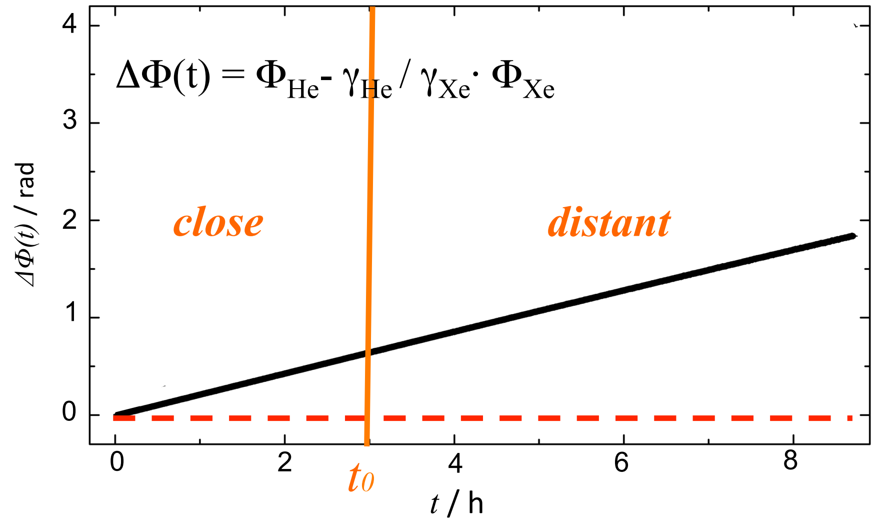

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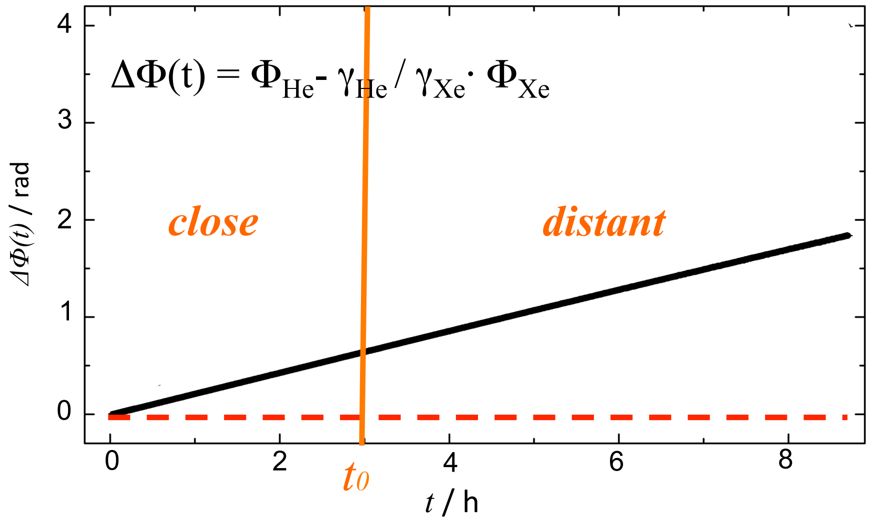
$$\Rightarrow \Delta\nu_{sp} = \frac{\Delta\omega_{sp}}{2\pi(1 - \gamma_{He} / \gamma_{Xe})}$$



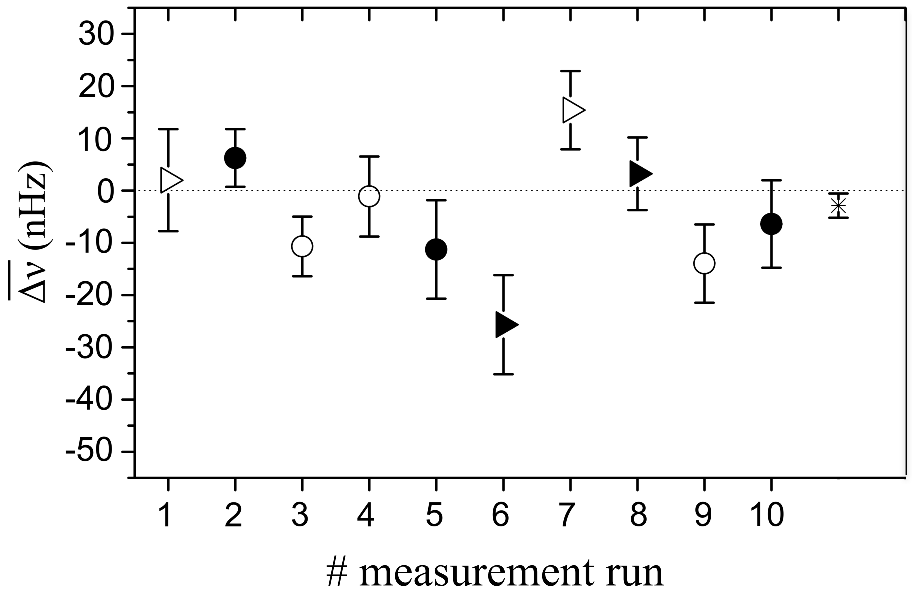
Summary Results

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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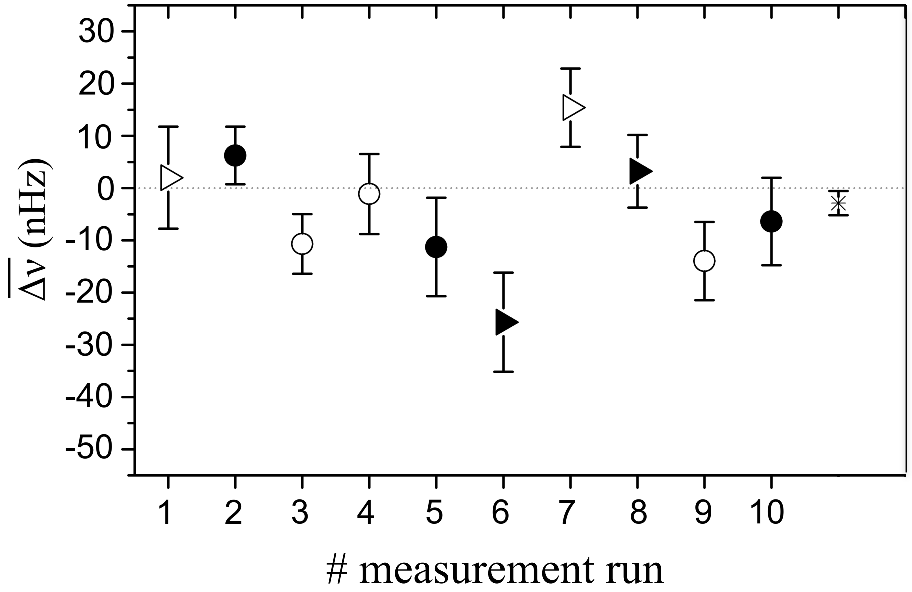

⇒ $\Delta\nu_{sp}$ = (-2.9 ± 3.5) nHz ⟶ $\delta(\Delta\nu_{sp})_{corr}$ = 7.1 nHz *(95% CL)*

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

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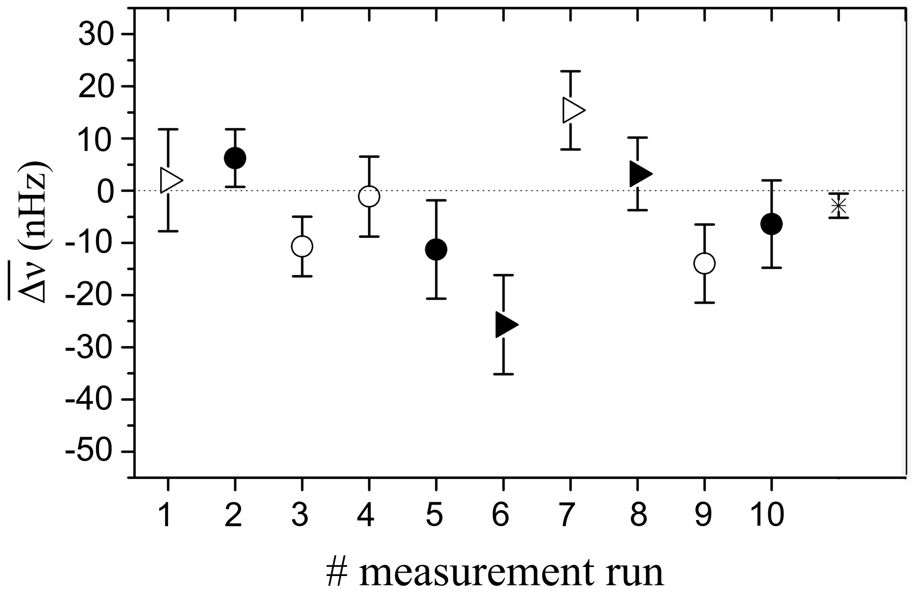

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$$\delta\left(\Delta\nu_{sp}\right) > 2\left\langle V_{sp}\right\rangle / h$$

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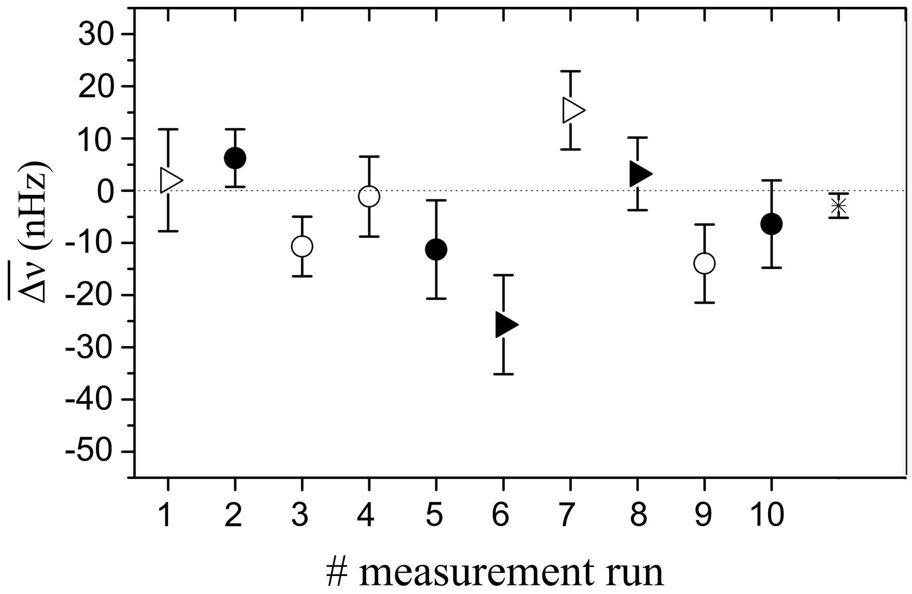

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K. Tullney et al.
PRL 111, 100801 (2013)

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

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

Summary Results

September 2010:

10 measurements (~9 hours)

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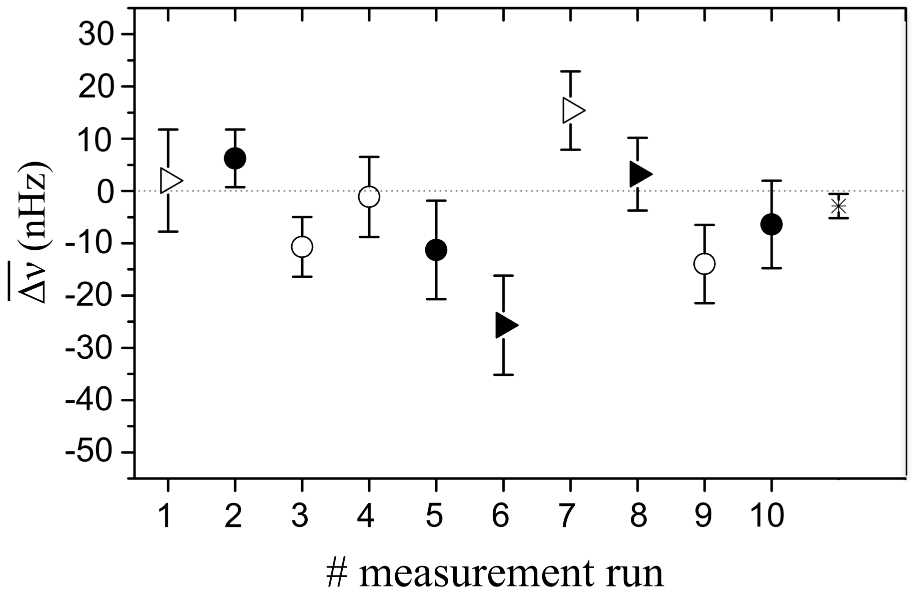

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$$\delta\left(\Delta\nu_{sp}\right) > 2\left\langle V_{sp}\right\rangle / h \quad \Rightarrow \quad g_s g_p\left(\lambda\right) < \frac{8\pi^2 \cdot m_n \cdot V_{cell} \cdot \delta\left(\Delta\nu_{sp}\right)}{\hbar \cdot N \cdot \left\langle V^*\left(\lambda\right)\right\rangle}$$

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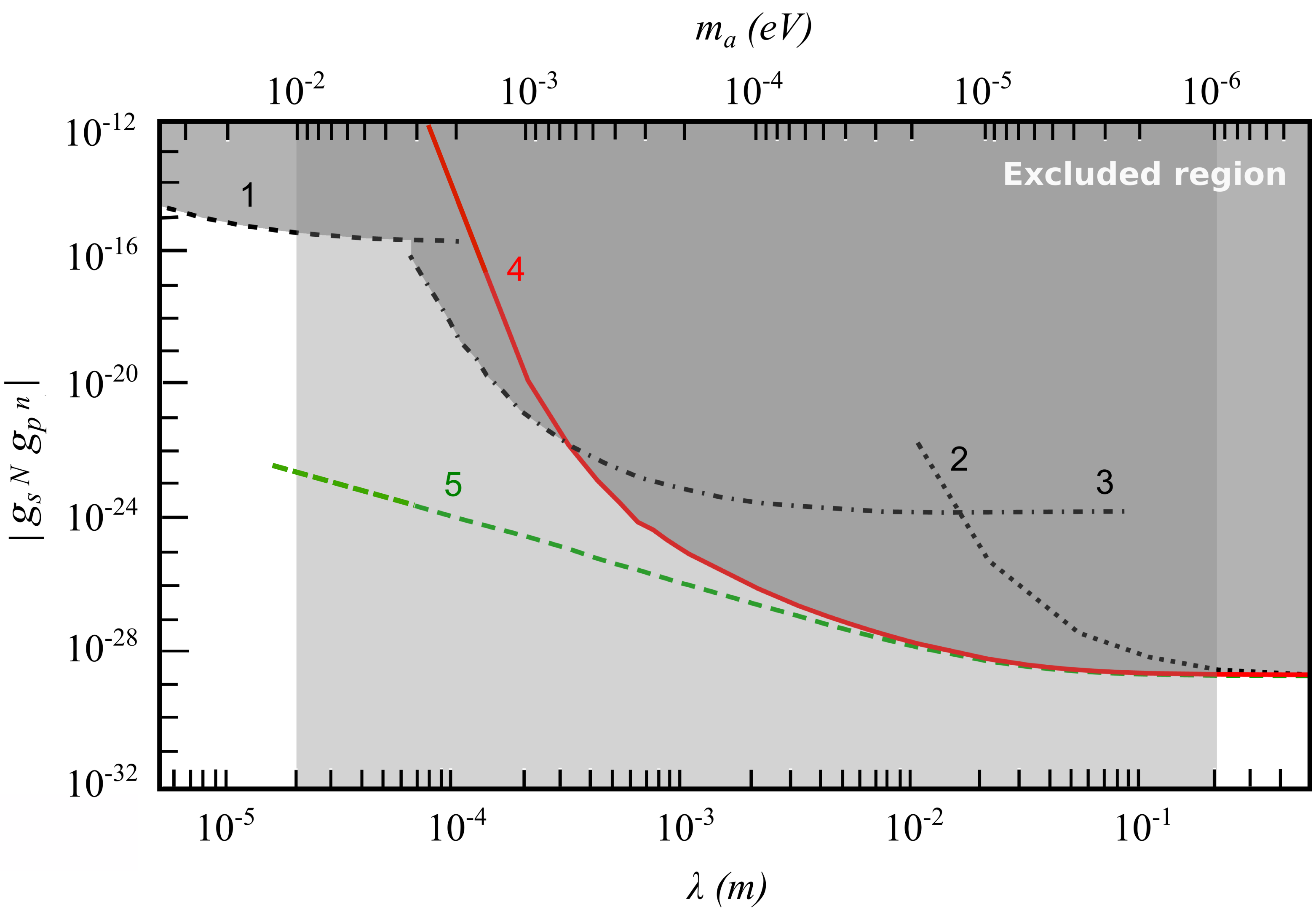
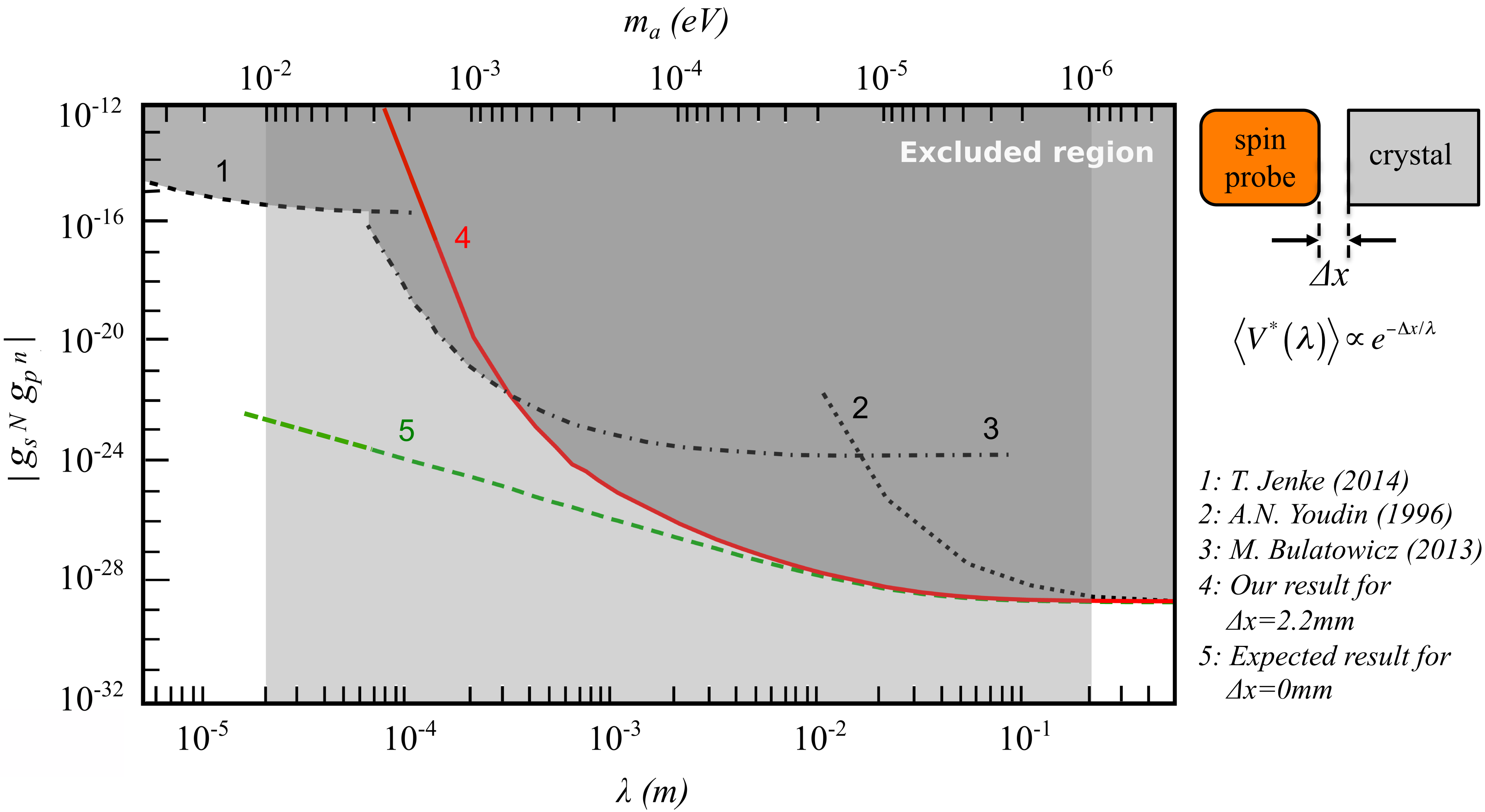
Exclusion Plot



1: T. Jenke (2014)
2: A.N. Youdin (1996)
3: M. Bulatowicz (2013)
4: Our result for Δx=2.2mm
5: Expected result for Δx=0mm

Exclusion Plot



Summary

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  Spin-dependent short-range interaction:

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J.E.Moody, F.Wilczek PRD 30 (1984), 130

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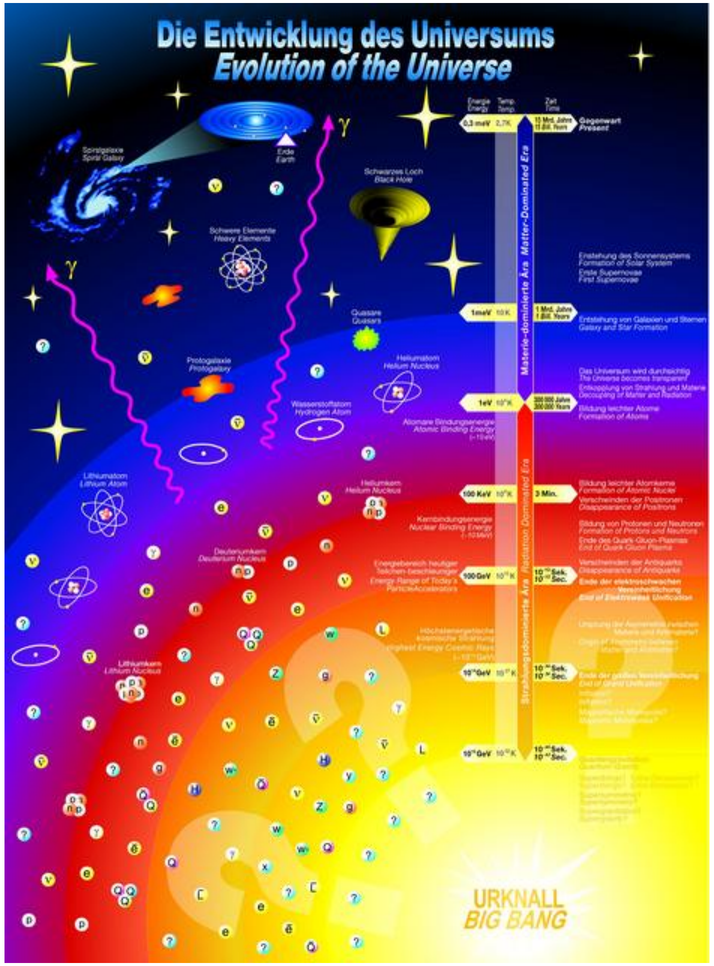
THANK YOU!

Motivation

Baryon/Anti-Baryon Puzzle

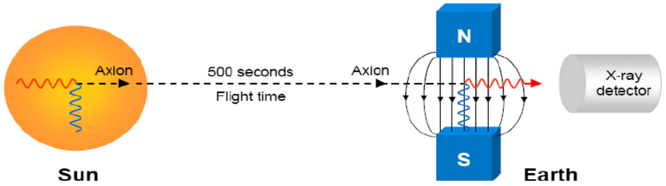


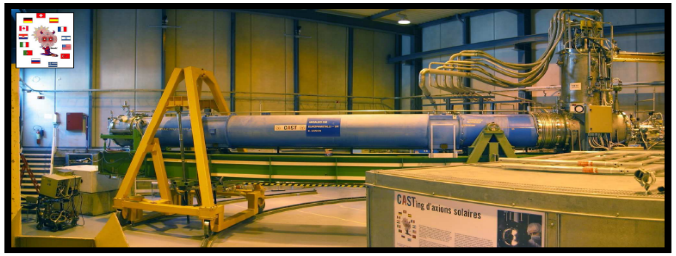
- Baryon/Anti-Baryon Asymmetry developed after 10^{-10} s after the Big Bang
- Observed Asymmetry: $n_B/n_\gamma=10^{-10}$
- Sacharow criteria:
  - ✓ Violation of baryon number
  - ✓ Thermal disequilibrium
  - ✓ CP-/C-Violation
- Calculated Asymmetry: $n_B/n_\gamma=10^{-18}$

Motivation

Solar axions

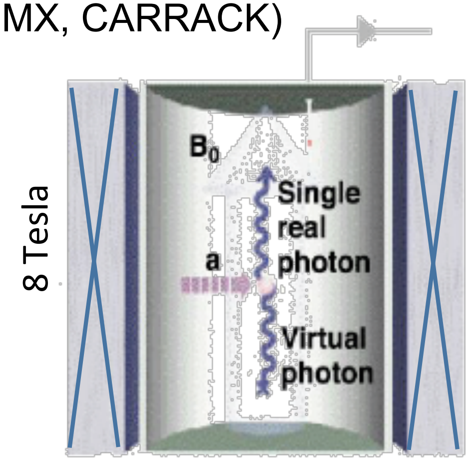
Helioscope experiment (CAST)





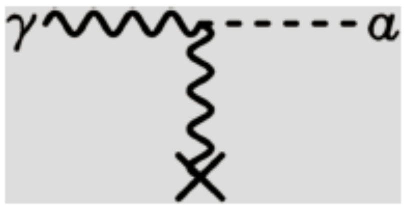
Galactic axions

microwave cavity experiment (ADMX, CARRACK)



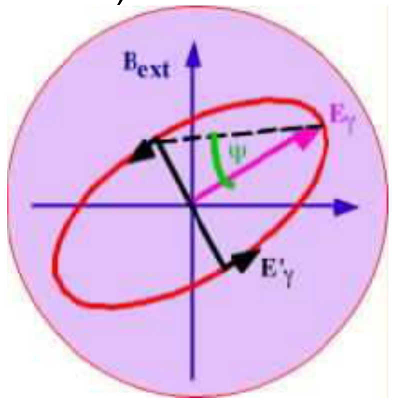
DIRECT search of the axion via the Primakoff effect

Primakoff effect
Conversion of an axion into a photon

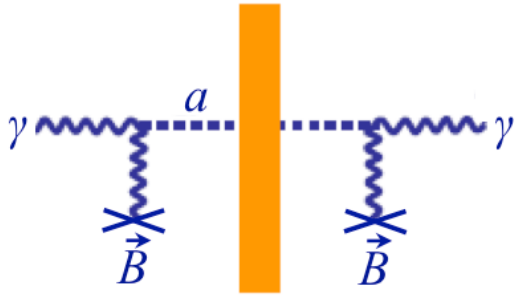


Labor axions

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

polar vector ↑ axial vector ↗

$$\hat{n} \cdot \vec{\sigma} \Rightarrow \begin{array}{l} P(\hat{n} \cdot \vec{\sigma}) = -(\hat{n} \cdot \vec{\sigma}) \\ T(\hat{n} \cdot \vec{\sigma}) = -(\hat{n} \cdot \vec{\sigma}) \end{array} \Rightarrow$$

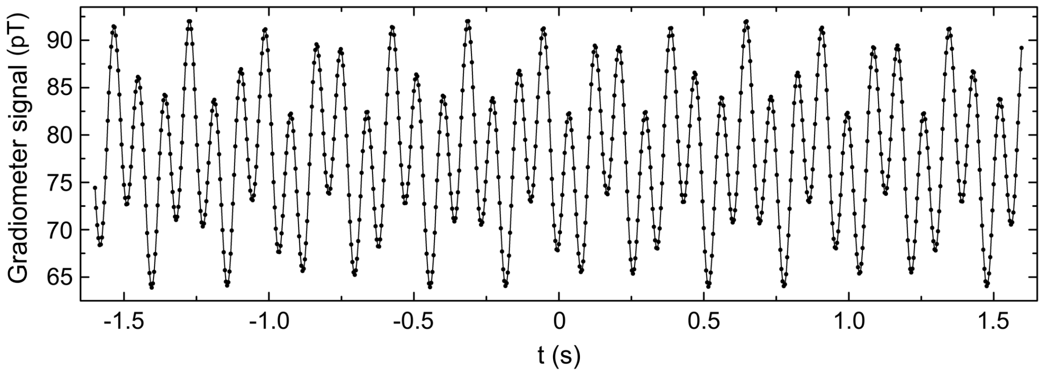
P-, T-violation
CP-violation

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

Data Analysis

Fit to raw data:

$$
\begin{aligned}
f^i(t) = \; & a^i_{s,\mathrm{He}} \sin\left(\omega^i_{\mathrm{He}} \cdot t\right) + a^i_{c,\mathrm{He}} \cos\left(\omega^i_{\mathrm{He}} \cdot t\right) \\
& + a^i_{s,\mathrm{Xe}} \sin\left(\omega^i_{\mathrm{Xe}} \cdot t\right) + a^i_{c,\mathrm{Xe}} \cos\left(\omega^i_{\mathrm{Xe}} \cdot t\right) \\
& + (c^i_0 + c^i_{\mathrm{lin}} \cdot t)
\end{aligned}
$$



↓ ^{3}He, ^{129}Xe phase

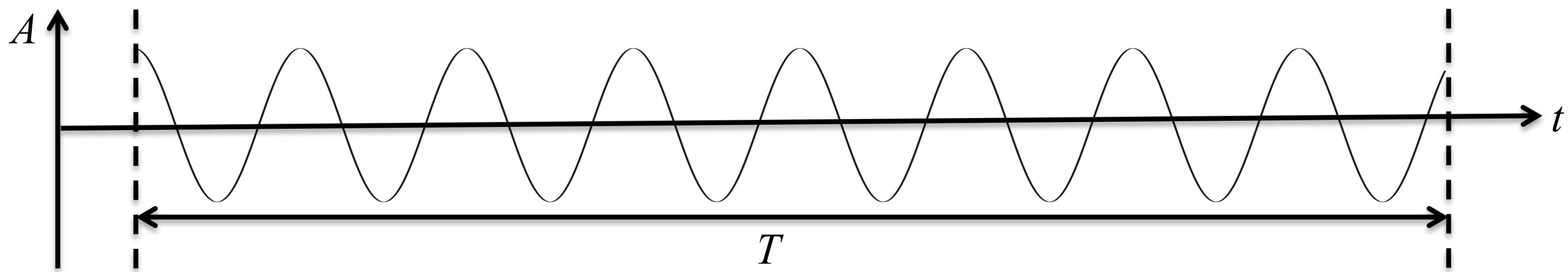
$$
\Phi^i_{\mathrm{He/Xe}} = \arctan\left(\frac{a^i_{s,\mathrm{He/Xe}}}{a^i_{c\mathrm{He/Xe}}}\right) + n^i_{\mathrm{He/Xe}} \cdot 2\pi, \quad n^i_{\mathrm{He/Xe}} \approx \bar{\omega}_{\mathrm{He/Xe}} \cdot t
$$

(number of periods since begin of measurement)

↓ weighted phase difference

$$
\Delta\Phi = \Phi_{\mathrm{He}} - \frac{\gamma_{\mathrm{He}}}{\gamma_{\mathrm{Xe}}} \cdot \Phi_{\mathrm{Xe}} \overset{!}{=} \Phi_0
$$

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:

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

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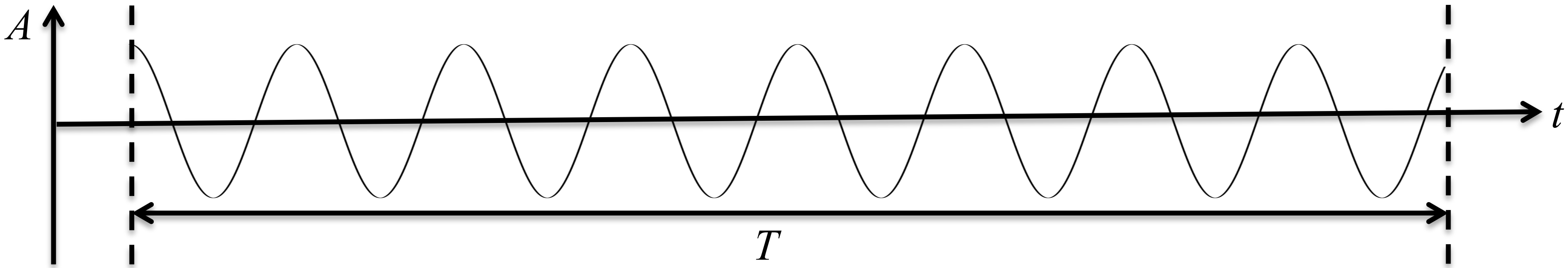

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Example:

SNR = 2300, ν_{BW} = 1 Hz, T= 9 h

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

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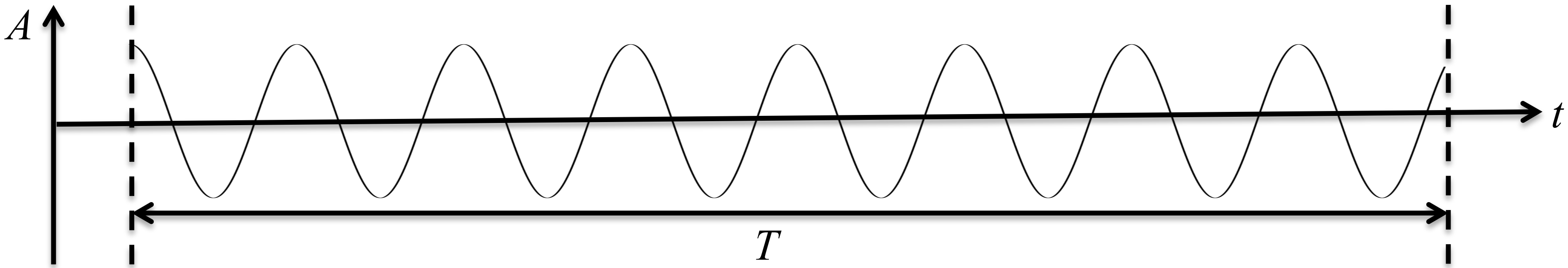

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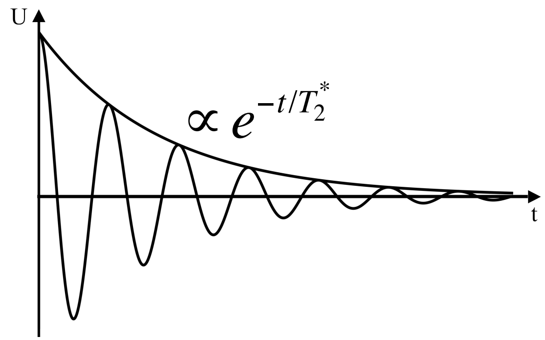
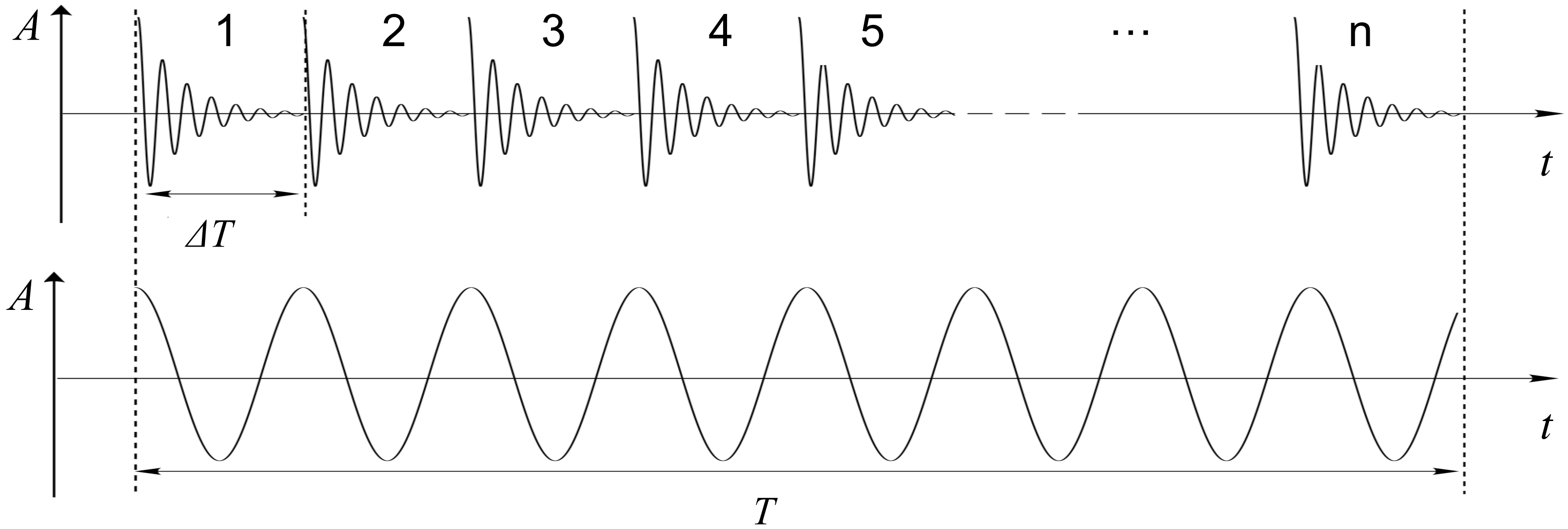


$$\left(T_2^*\right)^{-1} \propto V^{4/3} p \left|\vec{\nabla} B_1\right|^2 \quad \text{vs.} \quad \mathrm{SNR} \propto pV$$

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

Sensitivity

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



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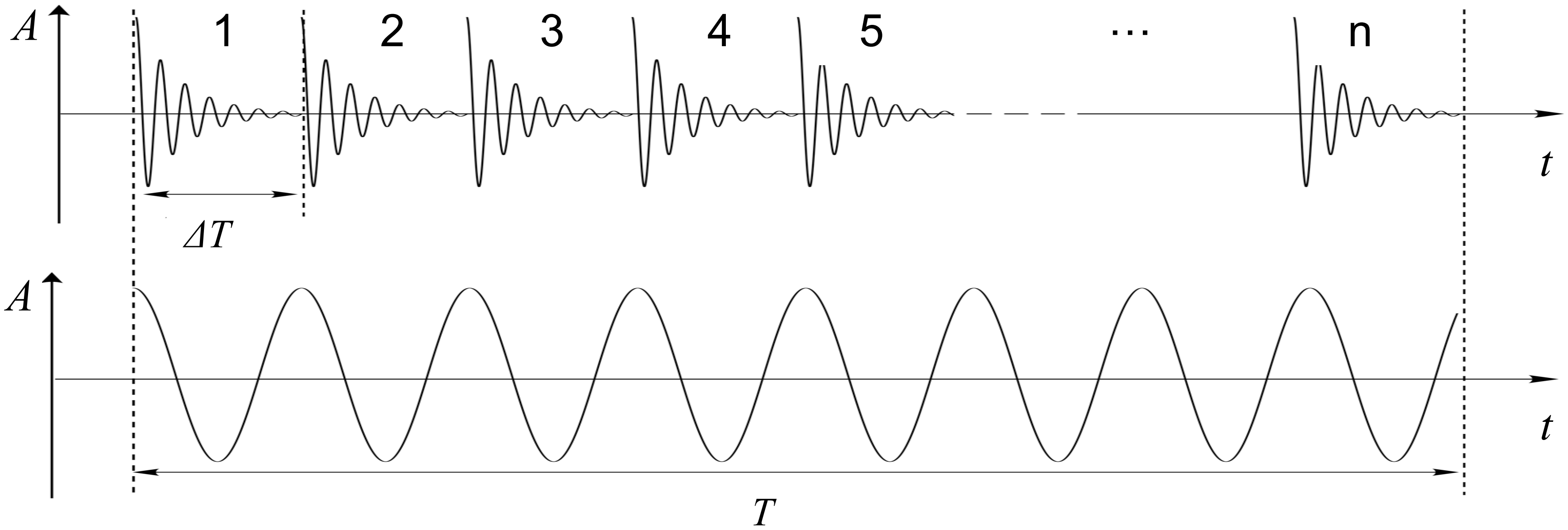

$$\sigma_{\nu,\,\mathrm{long}} \propto \frac{1}{T^{3/2}}$$

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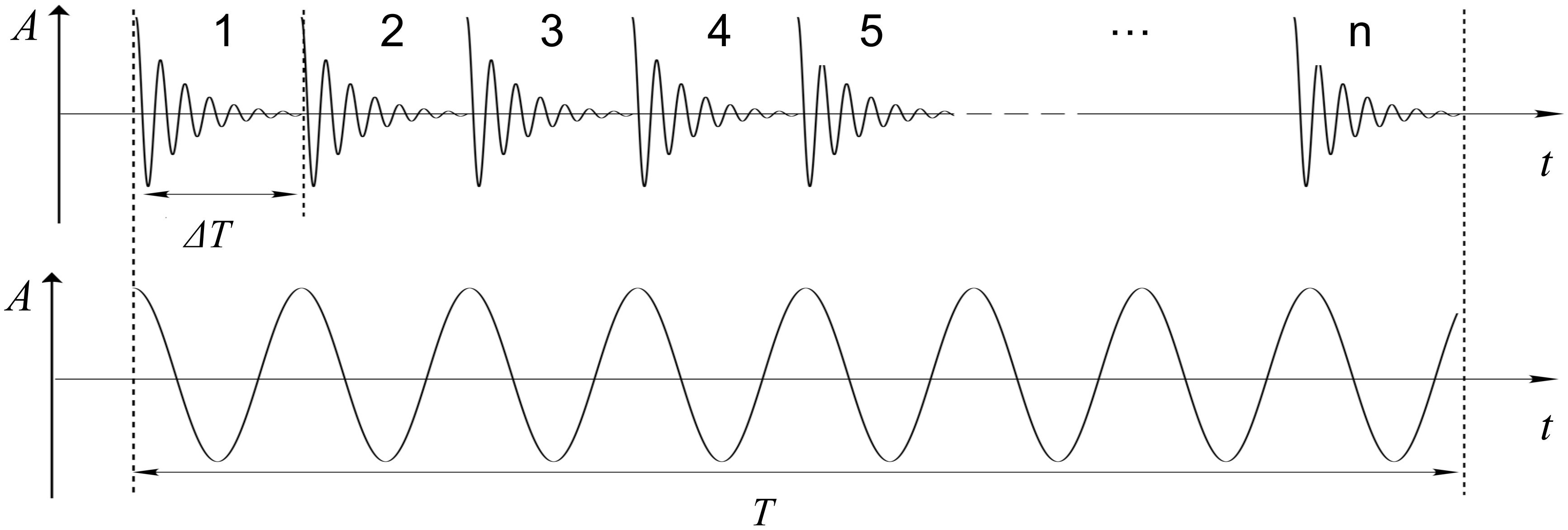

$$\sigma_{\nu,\,\mathrm{long}} \propto \frac{1}{T^{3/2}}$$

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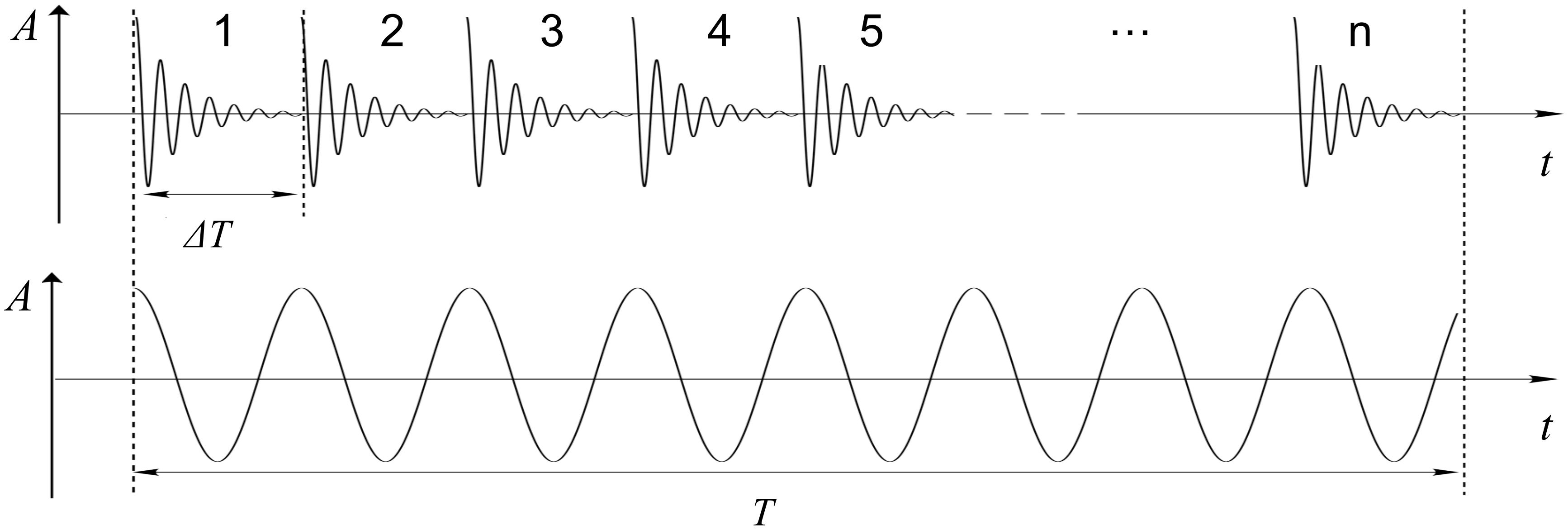

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$$T = n \cdot \Delta T$$

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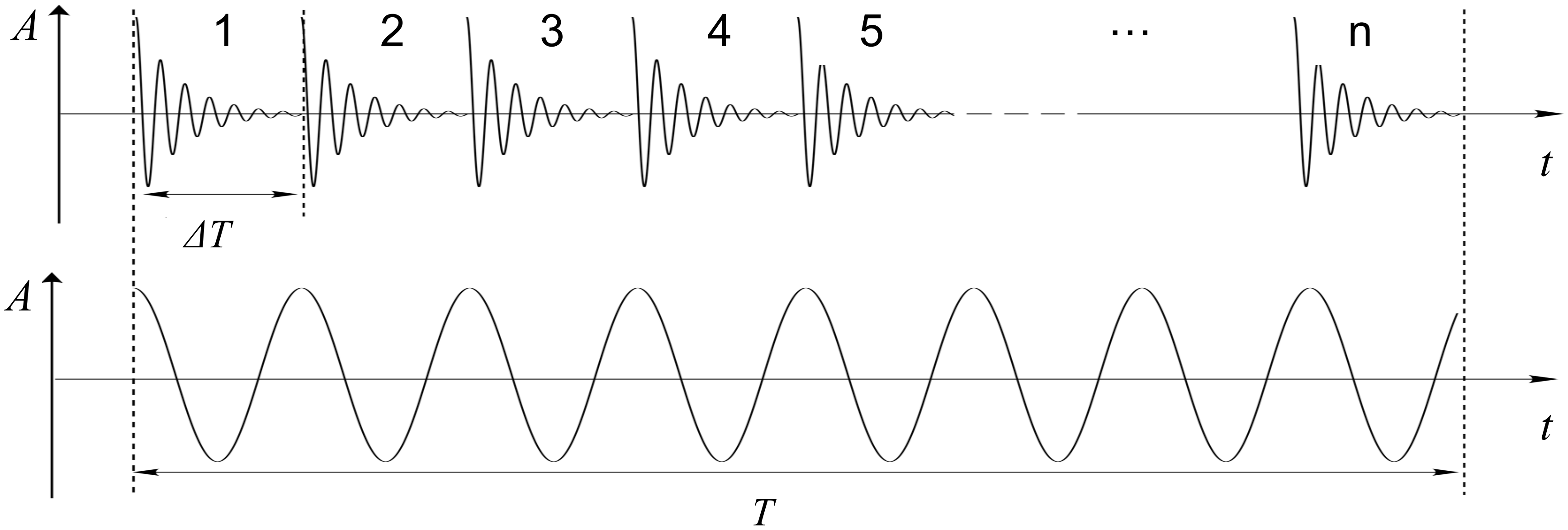

$$\sigma_{\nu,\,\text{long}} \propto \frac{1}{T^{3/2}}$$

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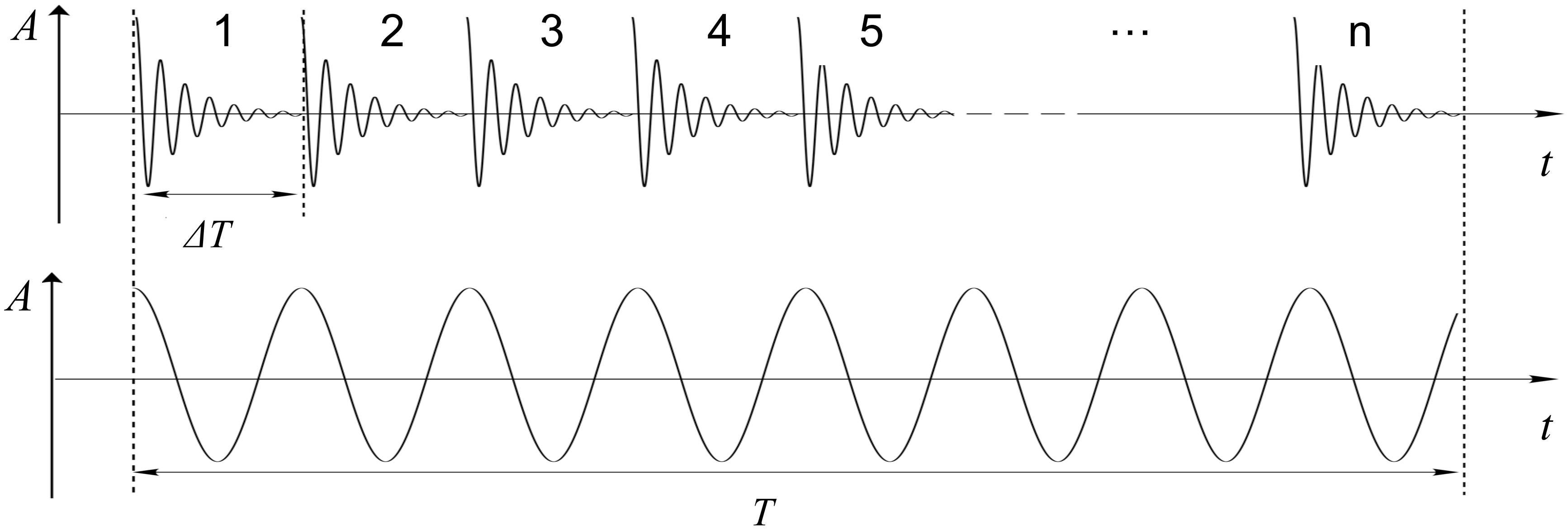

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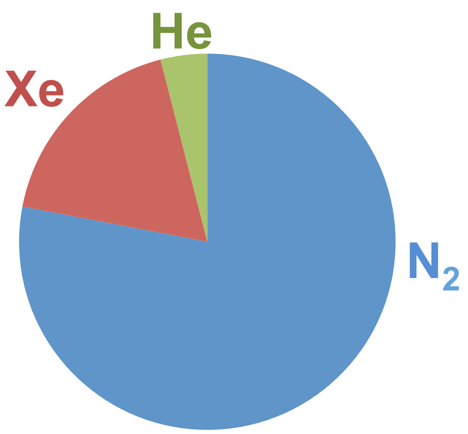
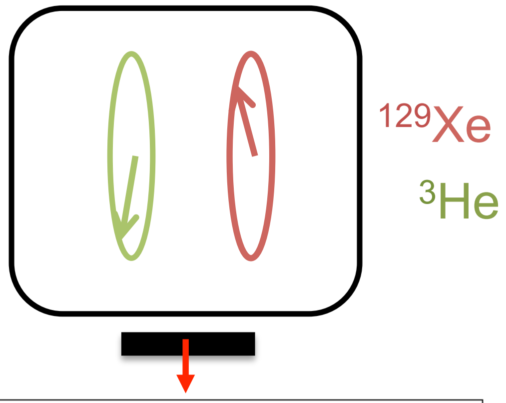
$$T = n \cdot \Delta T$$

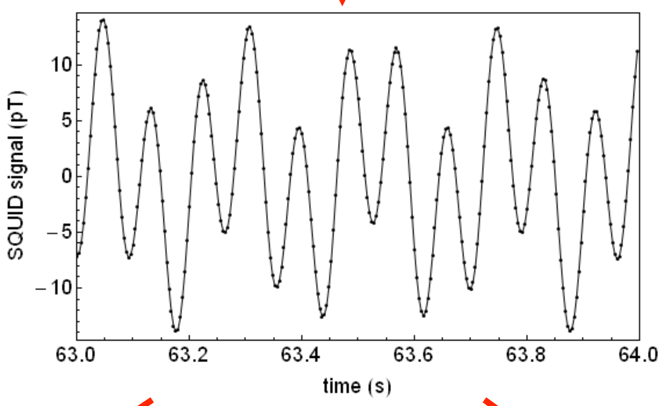
<u>Example</u>: SNR = 10000:1 , f_{BW}= 1 Hz , T = 24 h, ΔT = 5 min $\rightarrow \sigma_{\nu,\,short} = 300 \cdot \sigma_{\nu,\,long}$

Data Acquisition

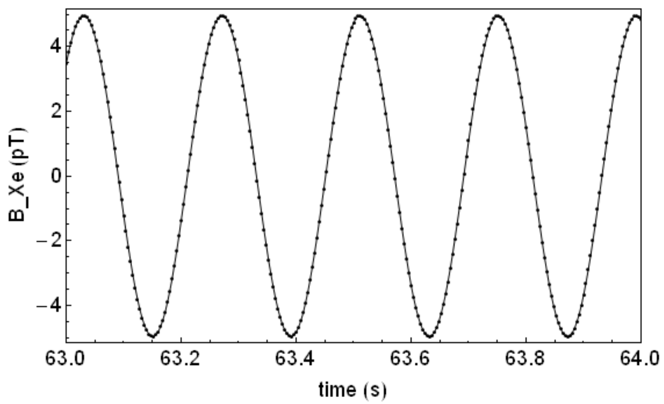
^{3}He, ^{129}Xe + N_2 (buffer gas)
@ p_{tot} = 31…37 mbar



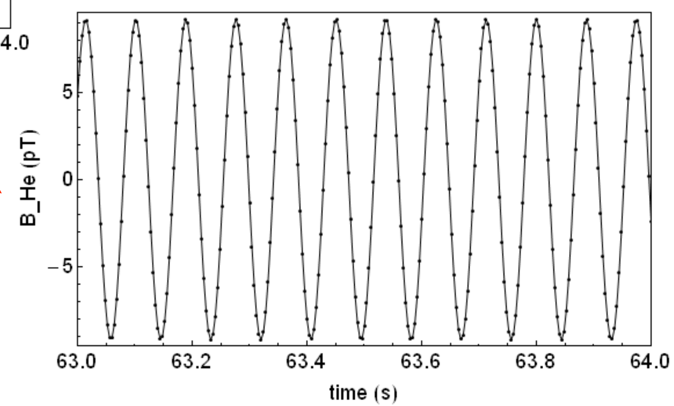




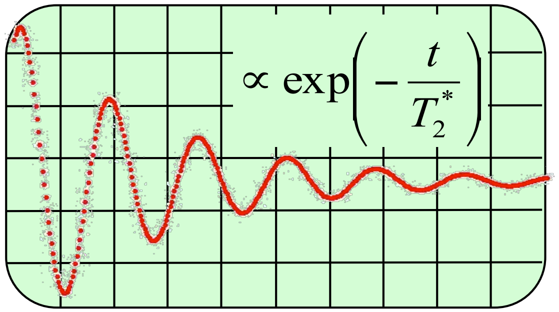
$$\omega_{Xe}(t) = \gamma_{Xe} \cdot B(t)$$



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



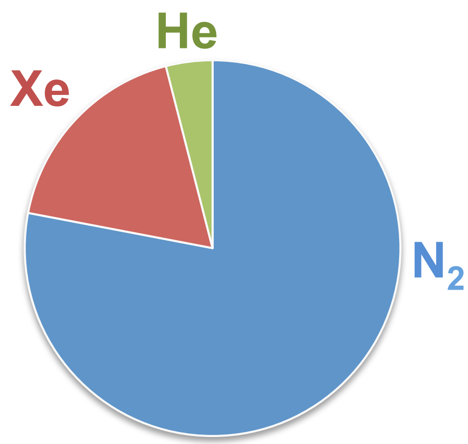
Transversal Relaxationtime



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

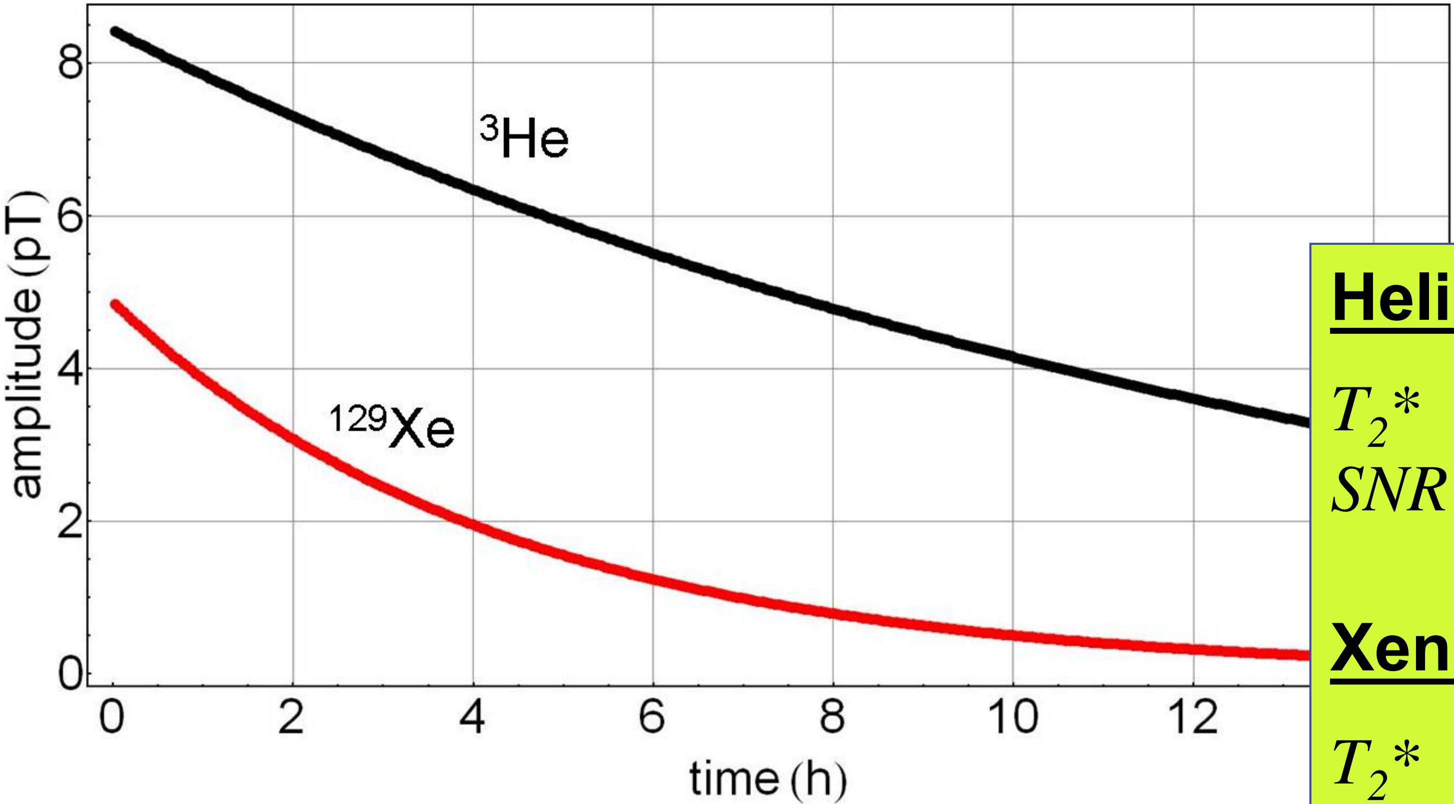
$$\text{signal} \propto p \cdot V \Rightarrow p\sim\text{mbar, V}\sim 100\text{ cm}^3\text{, } B_1 \sim \mu\text{T}$$ [4]

[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

Summary Results

September 2010:

10 measurements (~9 hours)

gap = 2.2 mm

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

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

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

Analysis:

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

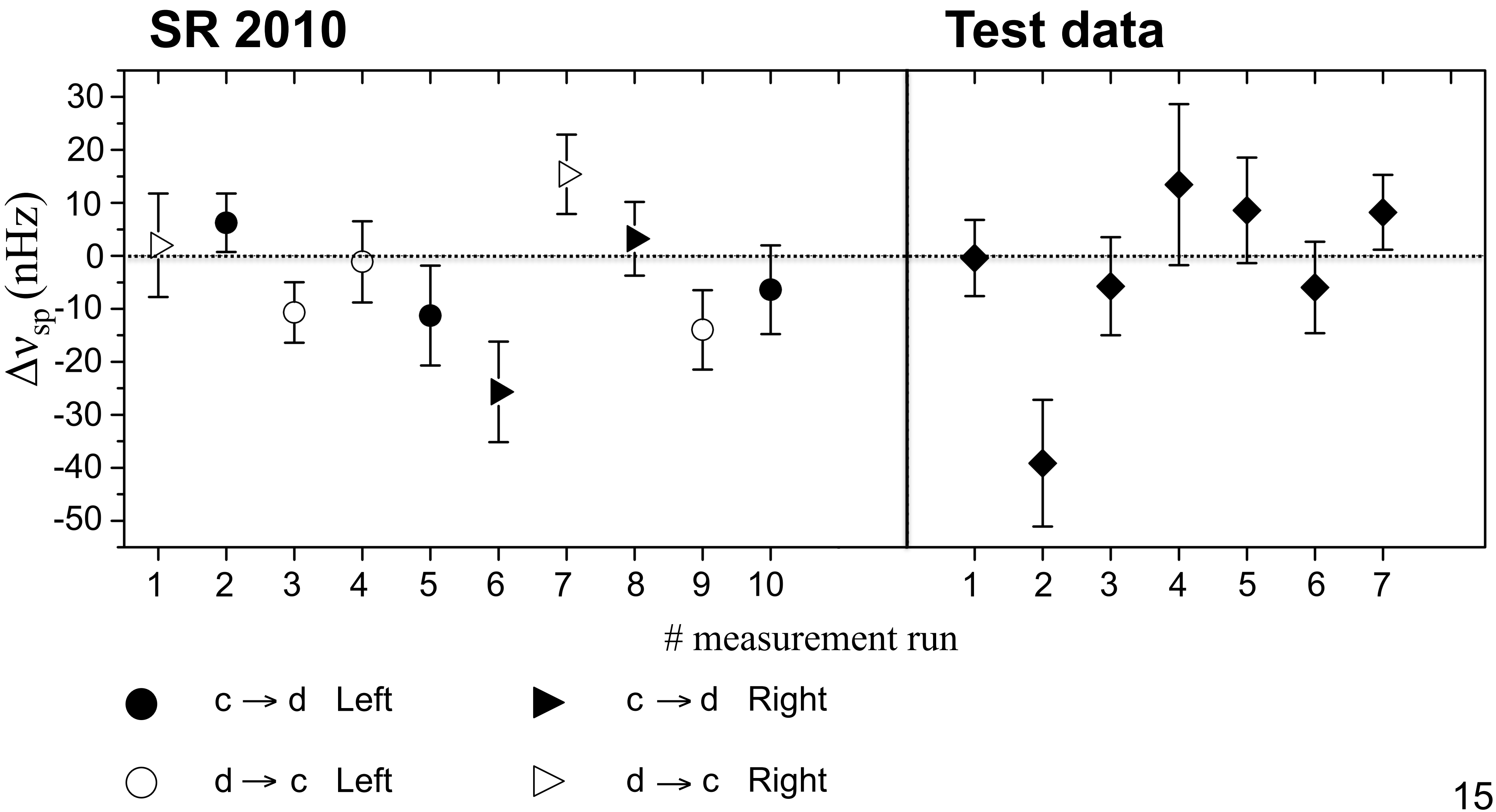
$$\langle V_{sp}\rangle = \frac{\hbar^2 g_s g_p}{8\pi m_n}\int_{VBGO}\int_{Vcell}\left(\frac{\vec{r}}{r}\cdot\vec{\sigma}\right)\left(\frac{1}{r\lambda}+\frac{1}{r^2}\right)\cdot e^{-r/\lambda}\, dV_{cell}\, dV_{BGO} = \frac{\hbar^2 g_s g_p}{8\pi m_n}\langle V^*(\lambda)\rangle$$

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

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



Results

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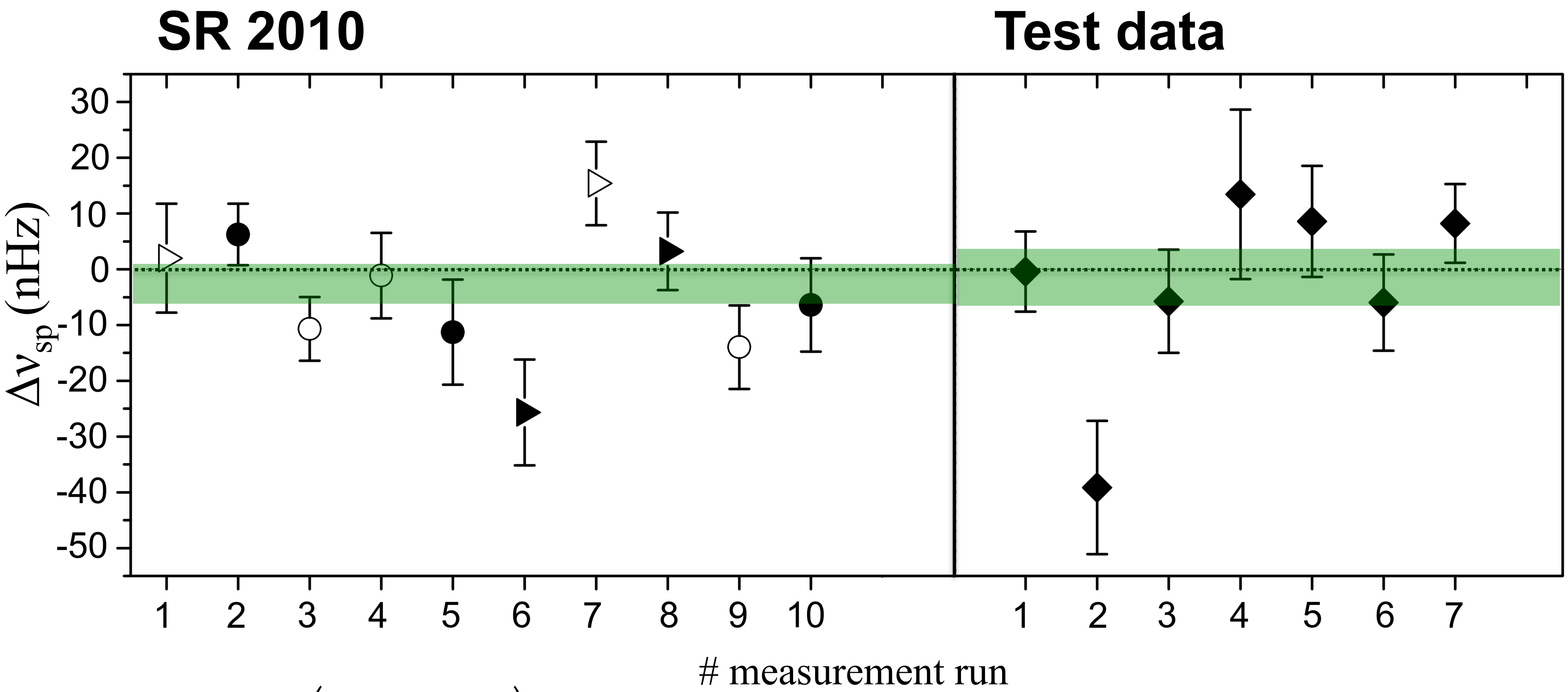
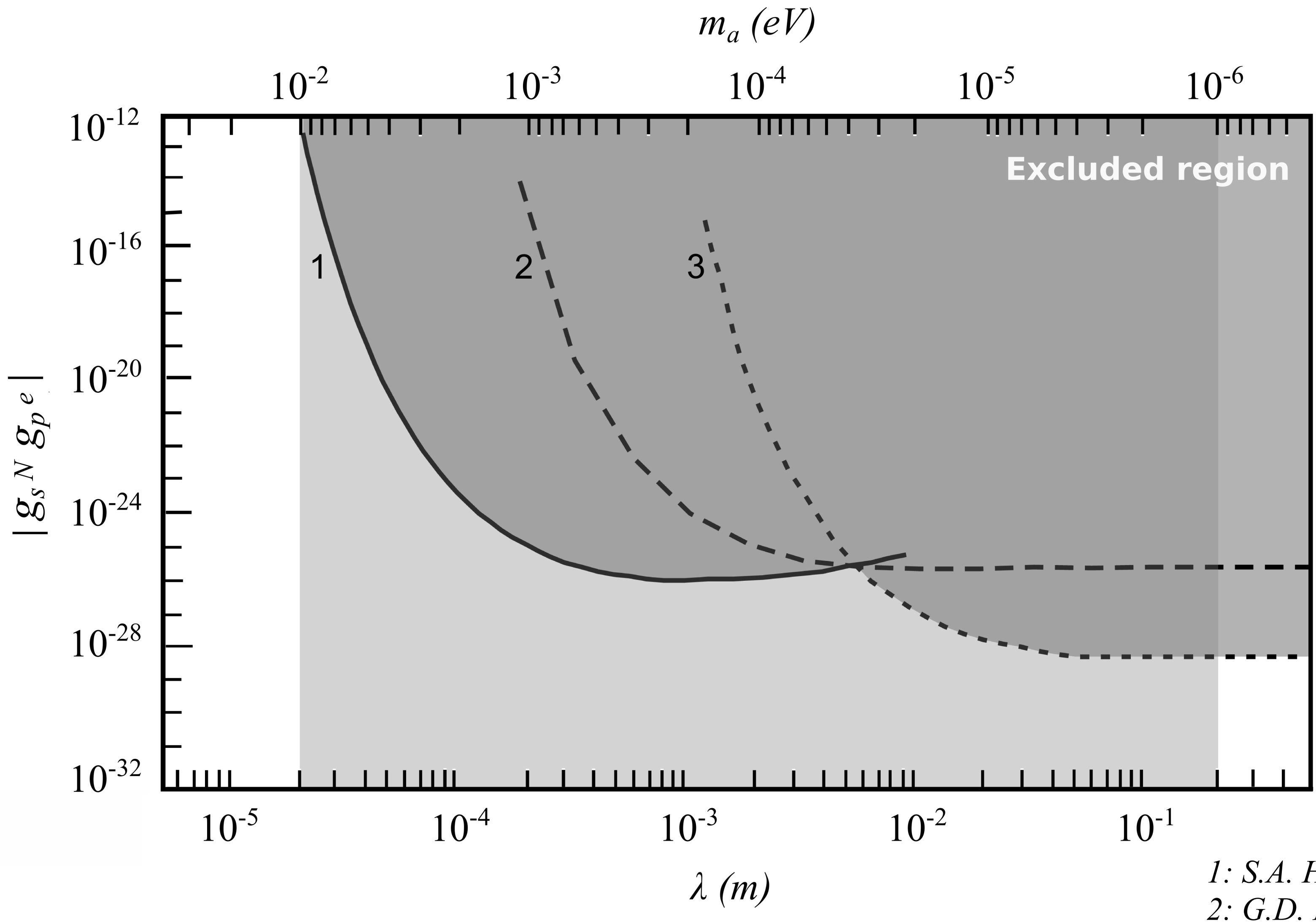


$$\Delta\nu_{Test} = \left(-1.4 \pm 5.2\right)\text{nHz}$$

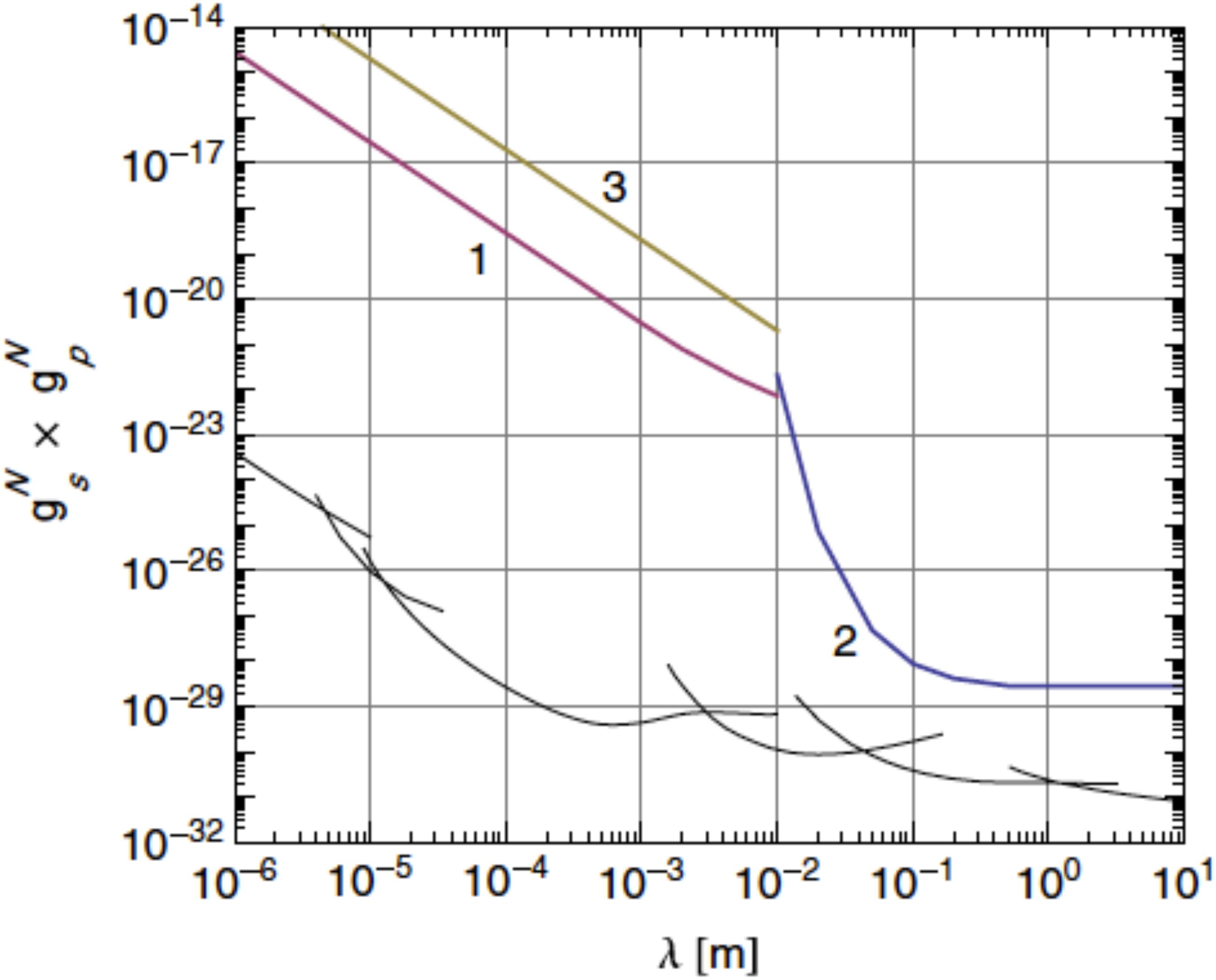
$$\Delta\nu_{sp} = \left(-2.9 \pm 3.5\right)\text{nHz}$$

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)

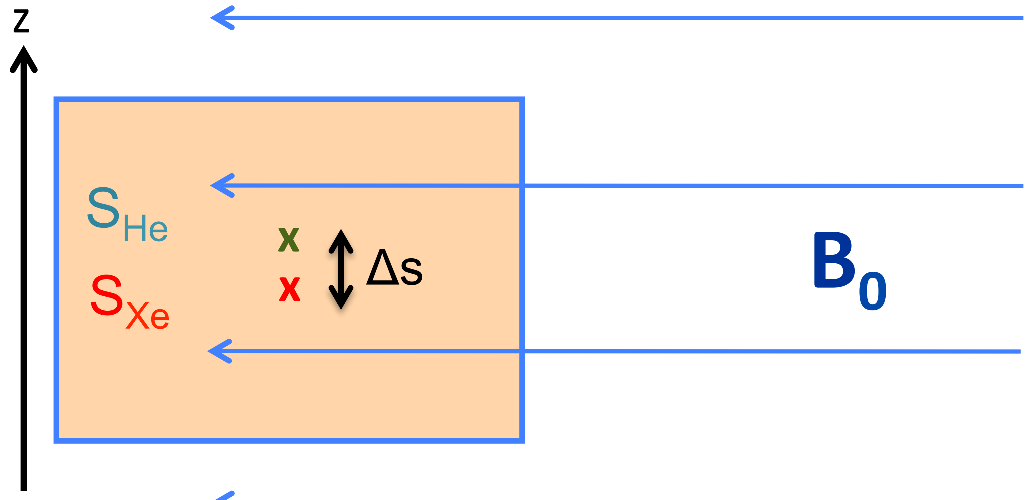
Plot taken from: *G. Raffelt, Phys. Rev. D 86, 015001 (2012)*

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

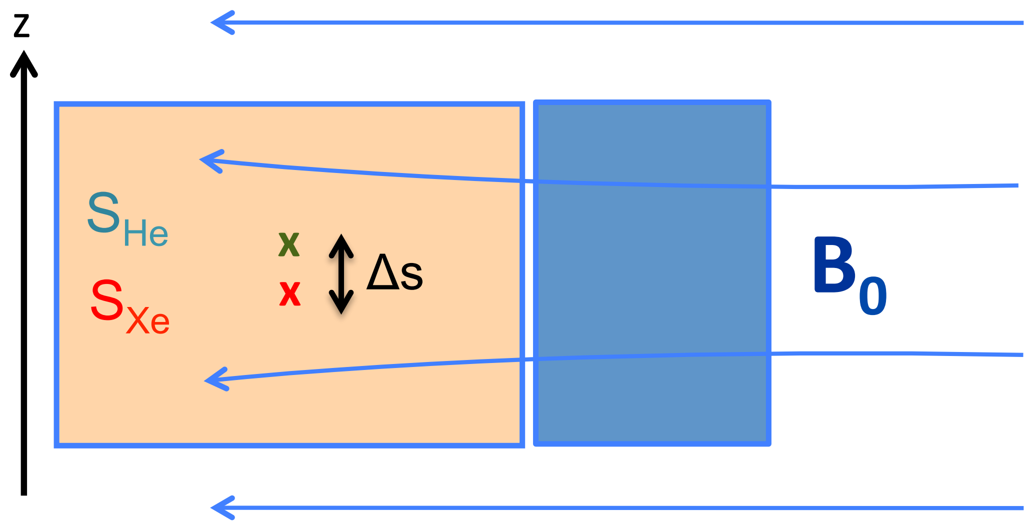
$$\Delta\omega = \omega_{He} - \frac{\gamma_{He}}{\gamma_{Xe}}\omega_{Xe} \Rightarrow \Delta\omega^{CM} = \gamma_{He}\cdot(B_{Xe}+\Delta B) - \gamma_{He}\cdot B_{Xe} = \gamma_{He}\cdot\Delta B \cdot H(t-t_0)$$

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

Barometric formula:

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

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



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

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

Systematic errors

Field gradients (general)

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

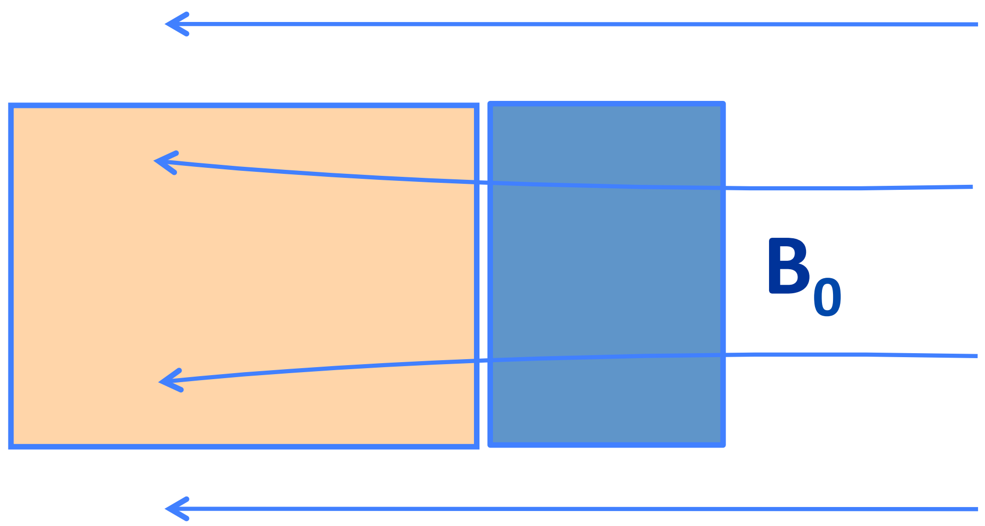
***$T_{2,field}$* in low magnetic fields** *(G. D. Cates, et al., Phys. Rev. A 37, 2877)*

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

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

$\Rightarrow$ additional field gradients



Systematic errors

Field gradients (general)

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

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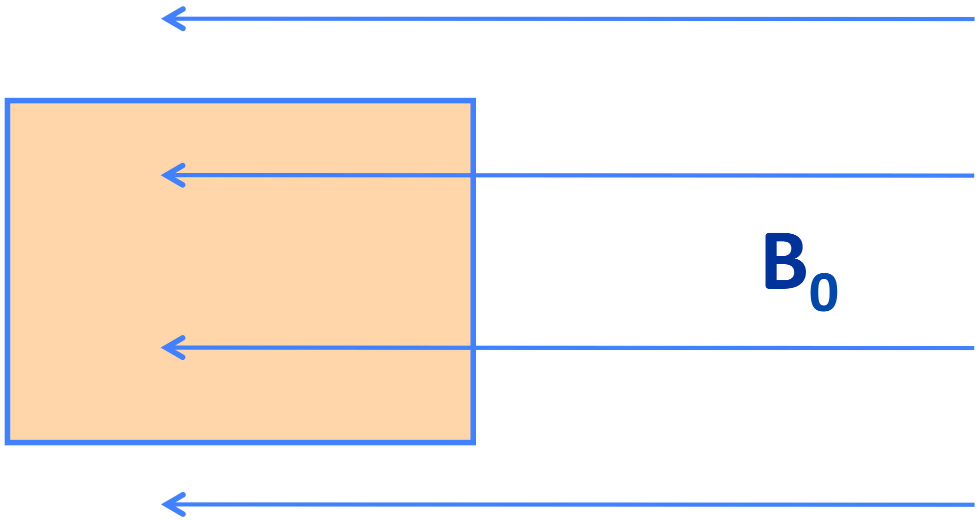


Error due to changes of T_2^*:

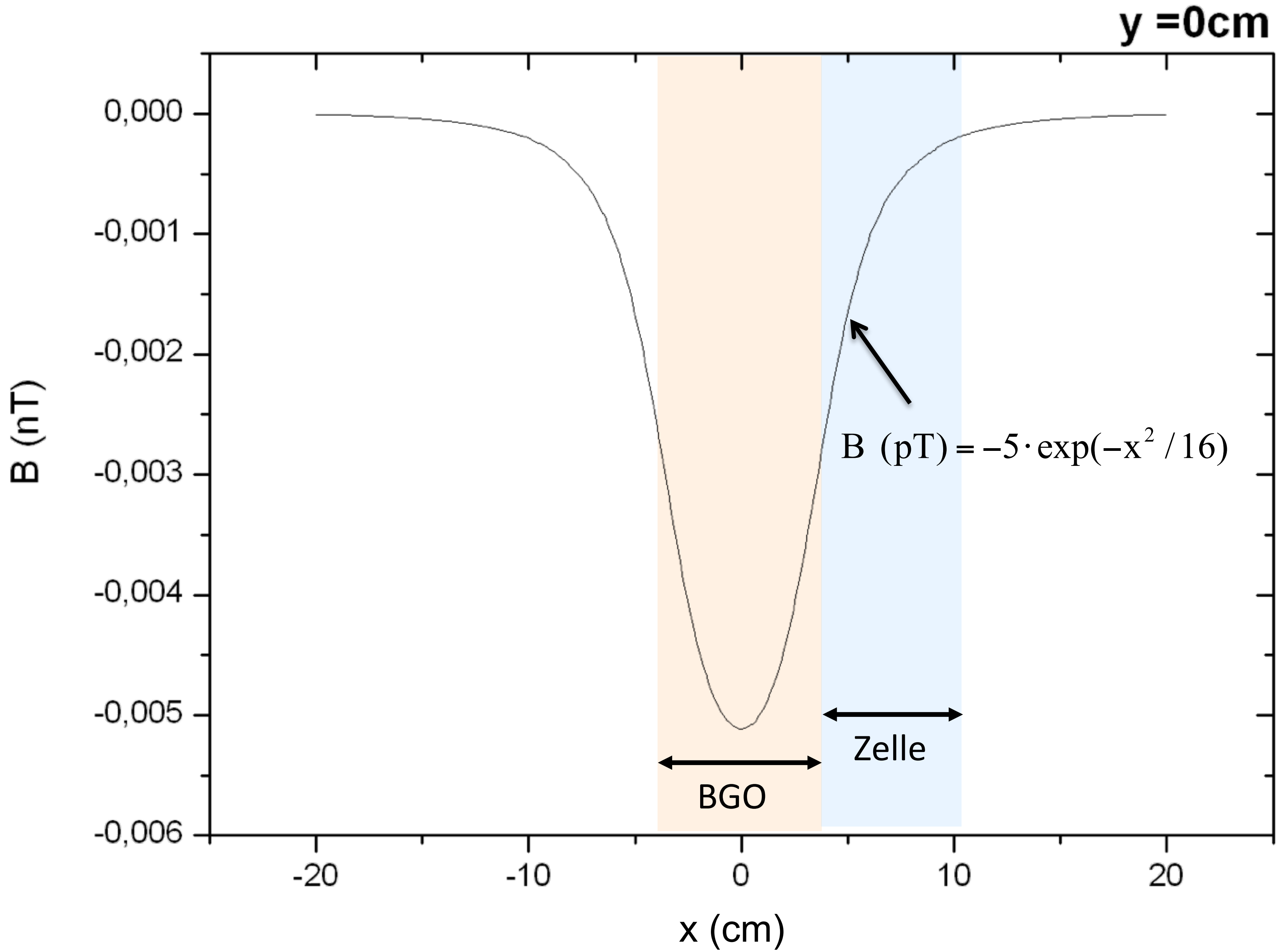
$$\left|\Delta\nu_{\mathrm{sys}}^{T_2}\right| \le \frac{\dfrac{\Delta T_{2,\mathrm{He}}^*}{\left(T_{2,\mathrm{He}}^*\right)^2} \cdot \left(\dfrac{a_{\mathrm{He}}}{T_{2,\mathrm{He}}^*} - \dfrac{1}{2}\dfrac{a_{\mathrm{Xe}}}{T_{2,\mathrm{Xe}}^*}\right) \cdot \dfrac{t_0}{2}}{2\pi\left(1 - \gamma_{\mathrm{He}}/\gamma_{\mathrm{Xe}}\right)}$$

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

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

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

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

Assumption:

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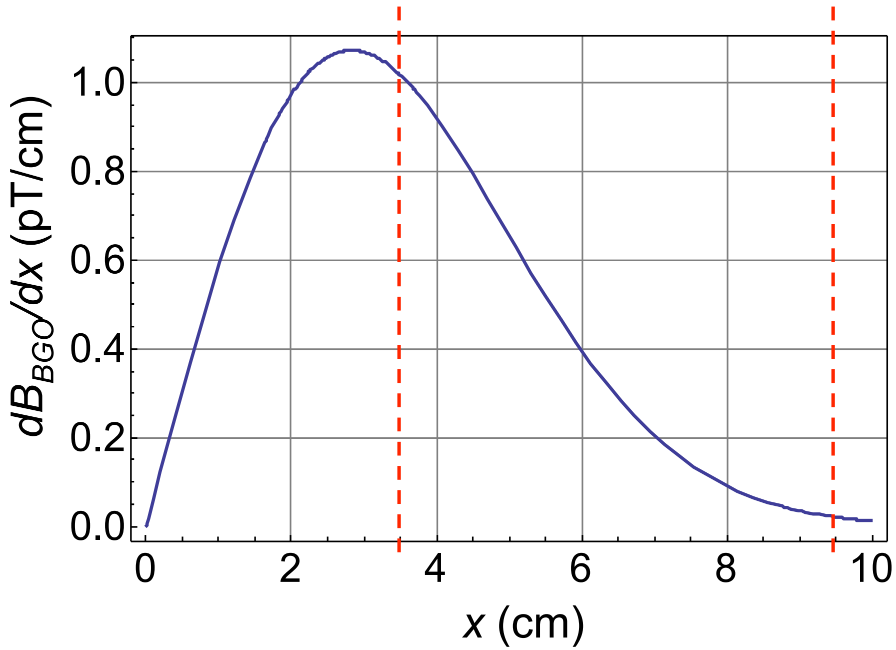
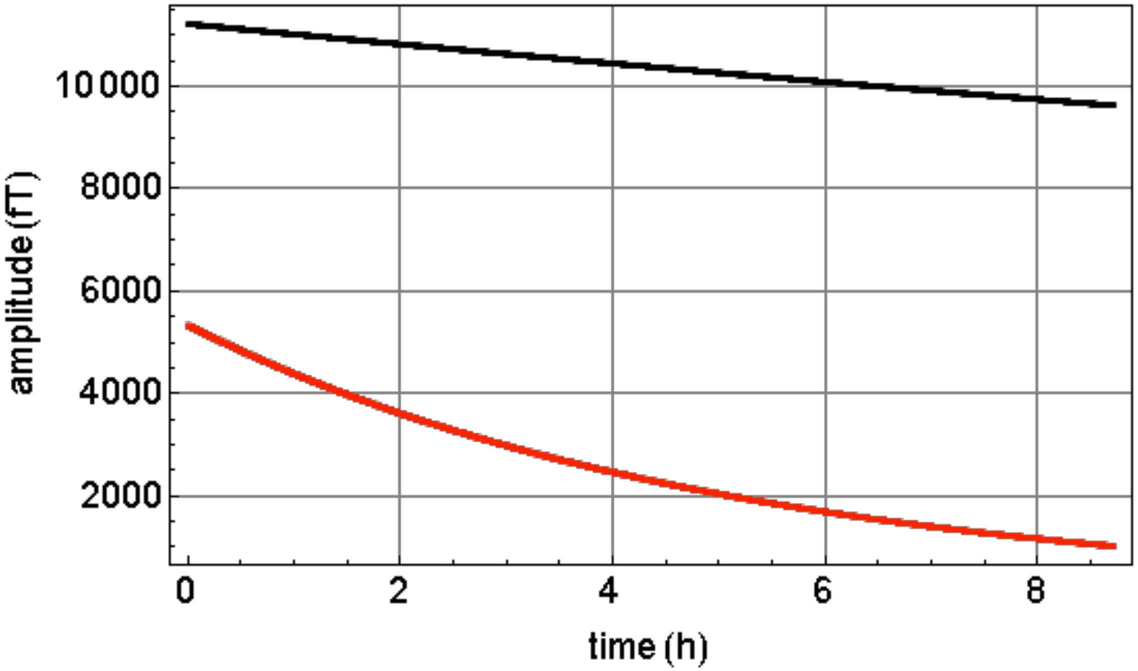


$$\overline{\partial B_{BGO}/\partial x} \approx 0.47\, pT/cm$$

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

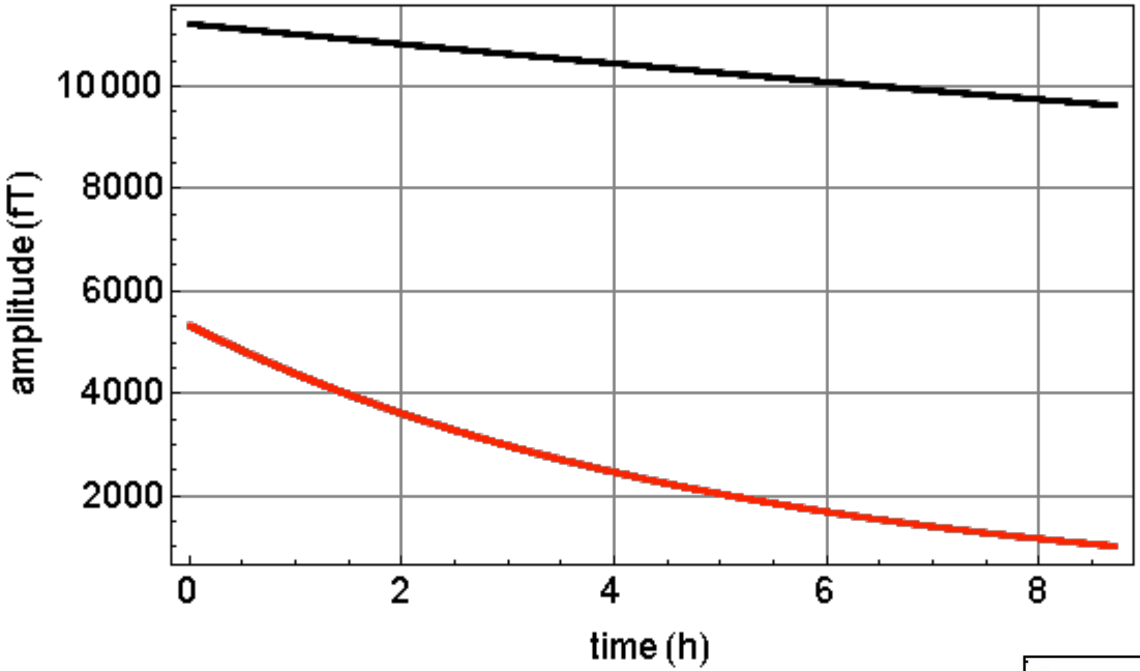
Determination of T_2^*



Exponential fit of amplitudes:

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

Determination of T_2^*

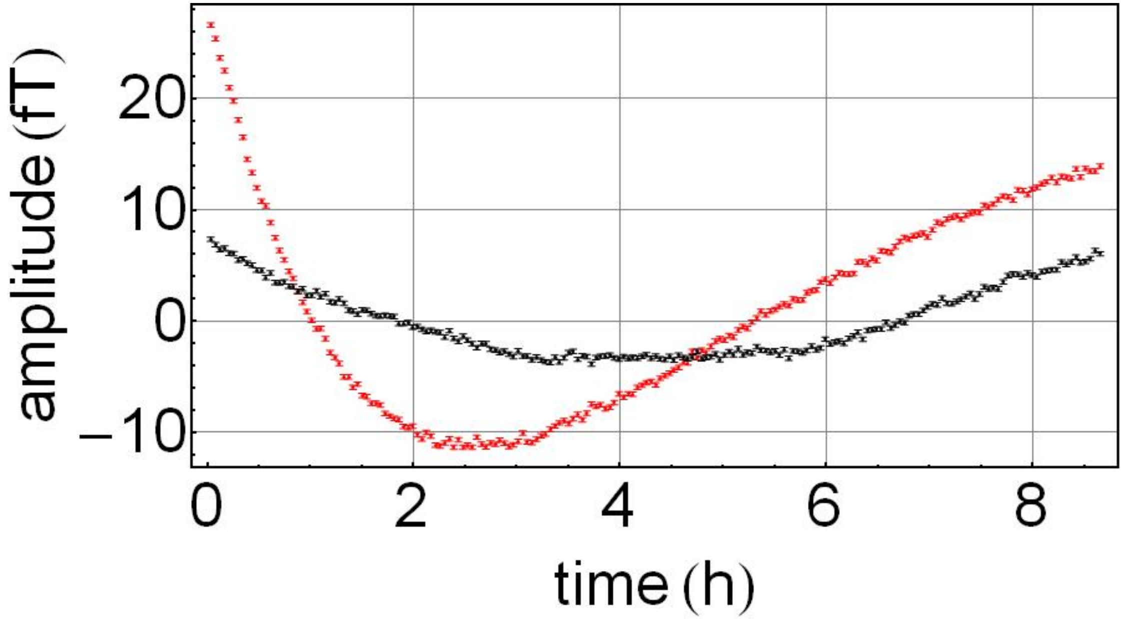


Exponential fit of amplitudes:

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

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 $f_a(t)$

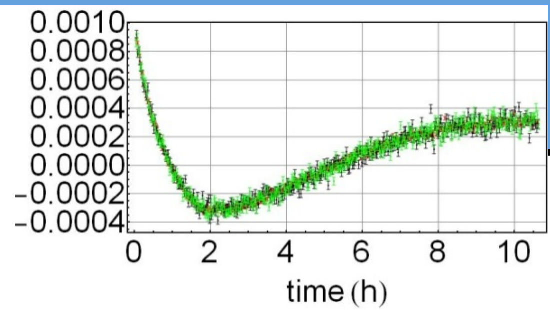
b.) Changes of the field gradients

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

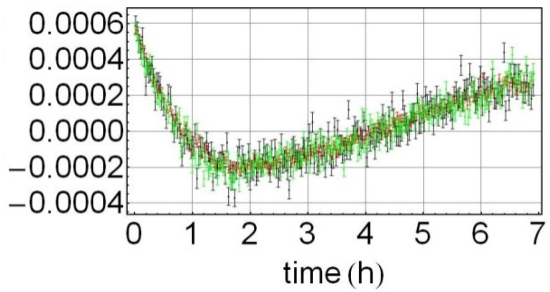
mit: $\frac{1}{T} = \frac{1}{T^*_{2,Xe}} - \frac{1}{T^2_{2,He}}$

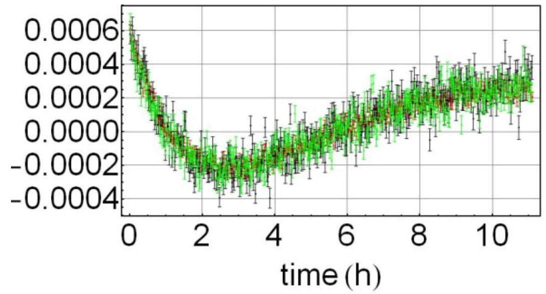
$\Longrightarrow$ Drift $f_a(t)$ due to SQUIDs and motion of SQUIDs in the magnetic drops out.

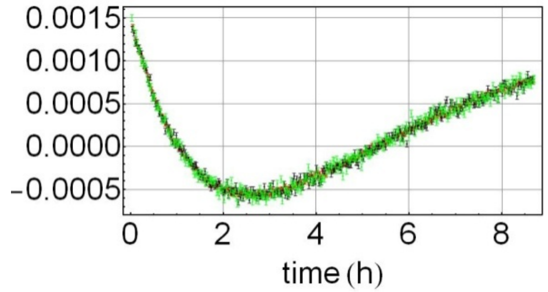
SR Measurements september 2010

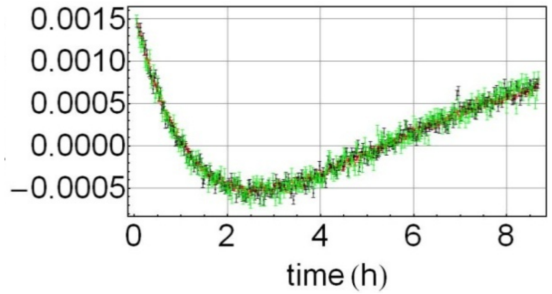


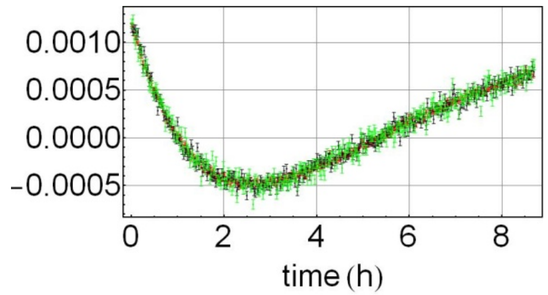
green: Z2E+Z5S, red: Z3D-Z2S, black: Z3I-Z1S

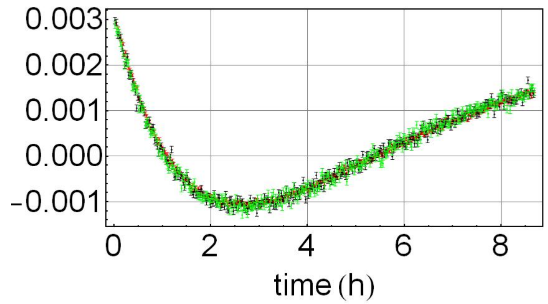


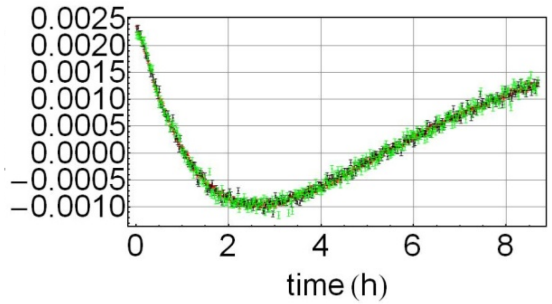


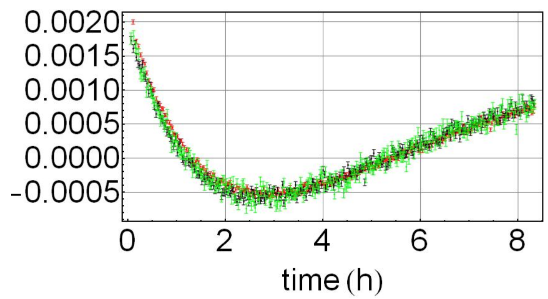


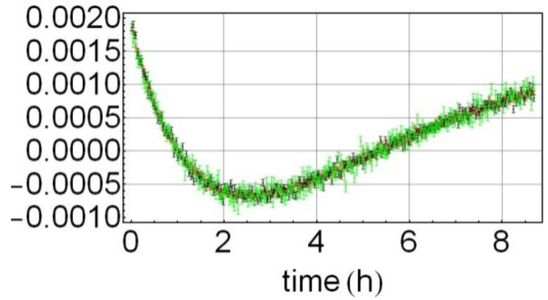












LV Measurements march 2009