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# Search for spin-dependent short range interaction of the bound neutron in $^{3}He/^{129}Xe$ clock comparison experiments

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# Outline:

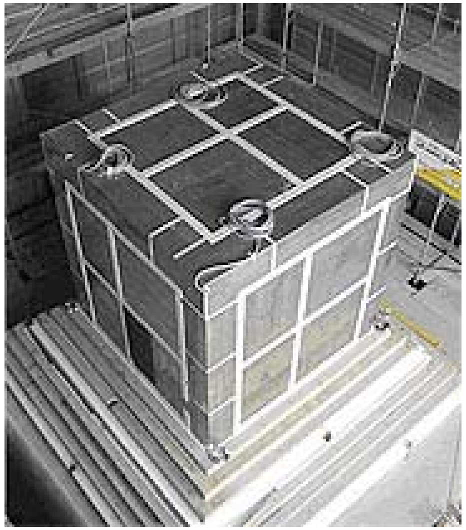
- motivation
- description of experiment
- measurement results
- conclusion and outlook

# Motivation

- New development:
  low-field magnetometer based on the detection of free spin-precession of gaseous, nuclear spin-polarized $^{3}He$ or $^{129}Xe$ samples with a SQUID as magnetic flux detector.
- Unique parameters:
  Very long relaxation of both gases ( $T_{2,He}$ ~ 60h, $T_{2,Xe}$ ~ 5h )
  High obtainable nuclear polarization (initial $P_{He} \leq 80\%$, $P_{Xe} \leq 40\%$ )
  - due to this high signal-to- noise ratio and long coherence time reachable in one measurement → very high accuracy of measurement of precession frequency << nHz (CRLB ~ $1/T^{3/2}$) [arXiv:0905.3677v1]
- Possibility to make $^{3}He$ - $^{129}Xe$ co-magnetometer:
  in this case in combination of weighted precession frequencies
  $\omega_{He} - \gamma_{He} / \gamma_{Xe}\, \omega_{Xe}$ fluctuations of ambient magnetic field compensated and it will be ideal for detection of non-magnetic spin-interaction.

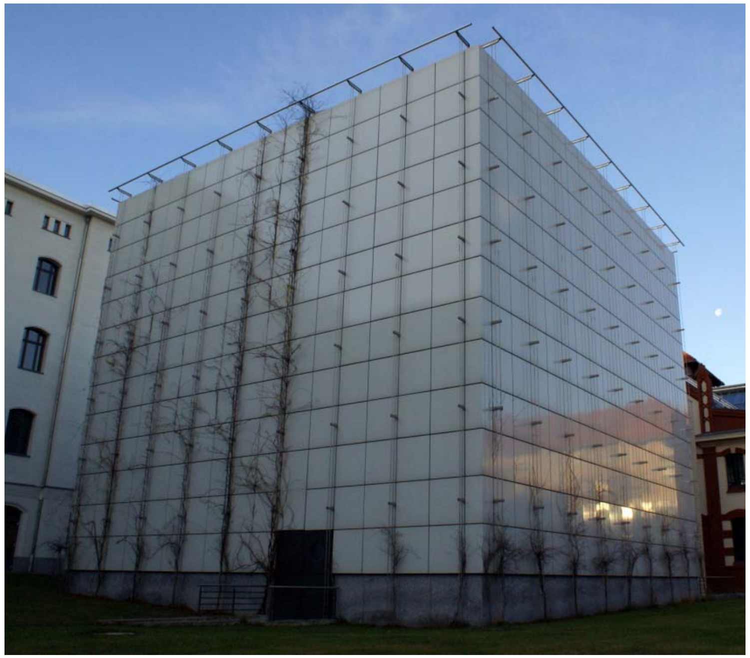
Several experiments looked for exotic pseudo-scalar interaction*. Most strong constraints in range 1 – 1000 cm were obtained in experiment with Cs(Hg) magnetometer [A.N.Youdin et al., PRL 77 (1996) 2170].
Performance of our $^{3}He$ – $^{129}Xe$ co-magnetometer exceed Cs(Hg) which enable us to search with higher sensitivity!
*[J.E. Moody and Frank Wilczek, Phys. Rev. D **30** (1984) 130 ]

# BMSR 2, PTB Berlin

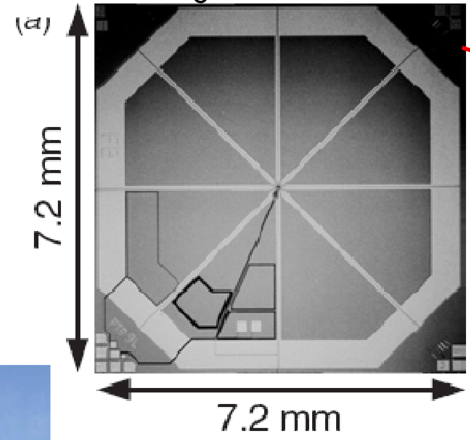


**The 7-layered magnetically shielded room (residual field < 1 nT)**

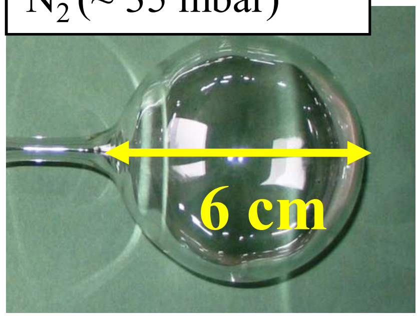
**J. Bork, et al., Proc. Biomag 2000, 970 (2000).**

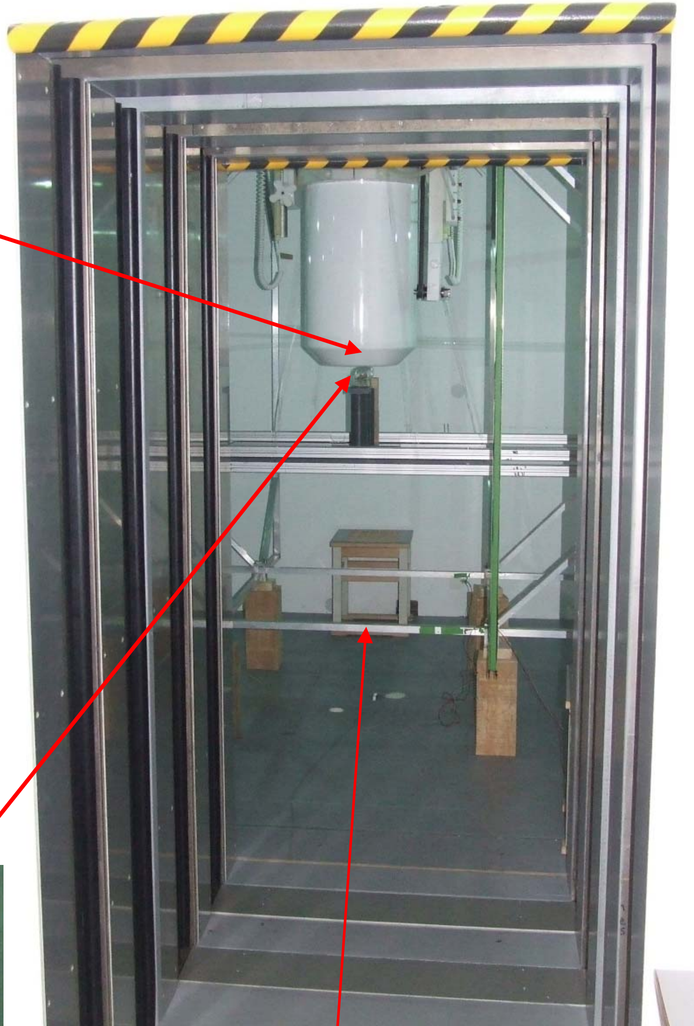


LT$_c$- SQUID



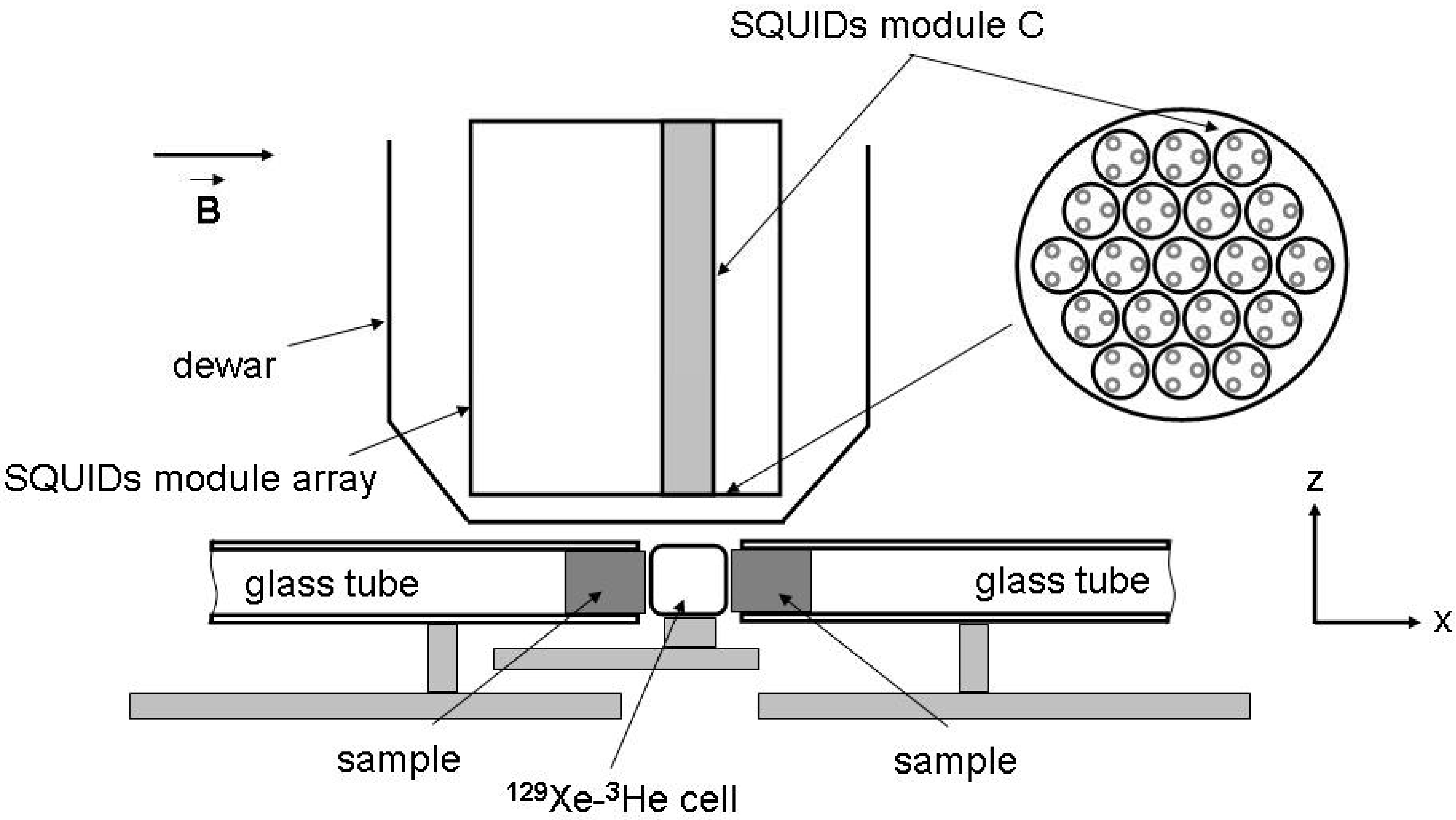

$^3$He (~2 mbar )
$^{129}$Xe (~ 12 mbar)
$N_2$ (~ 35 mbar)

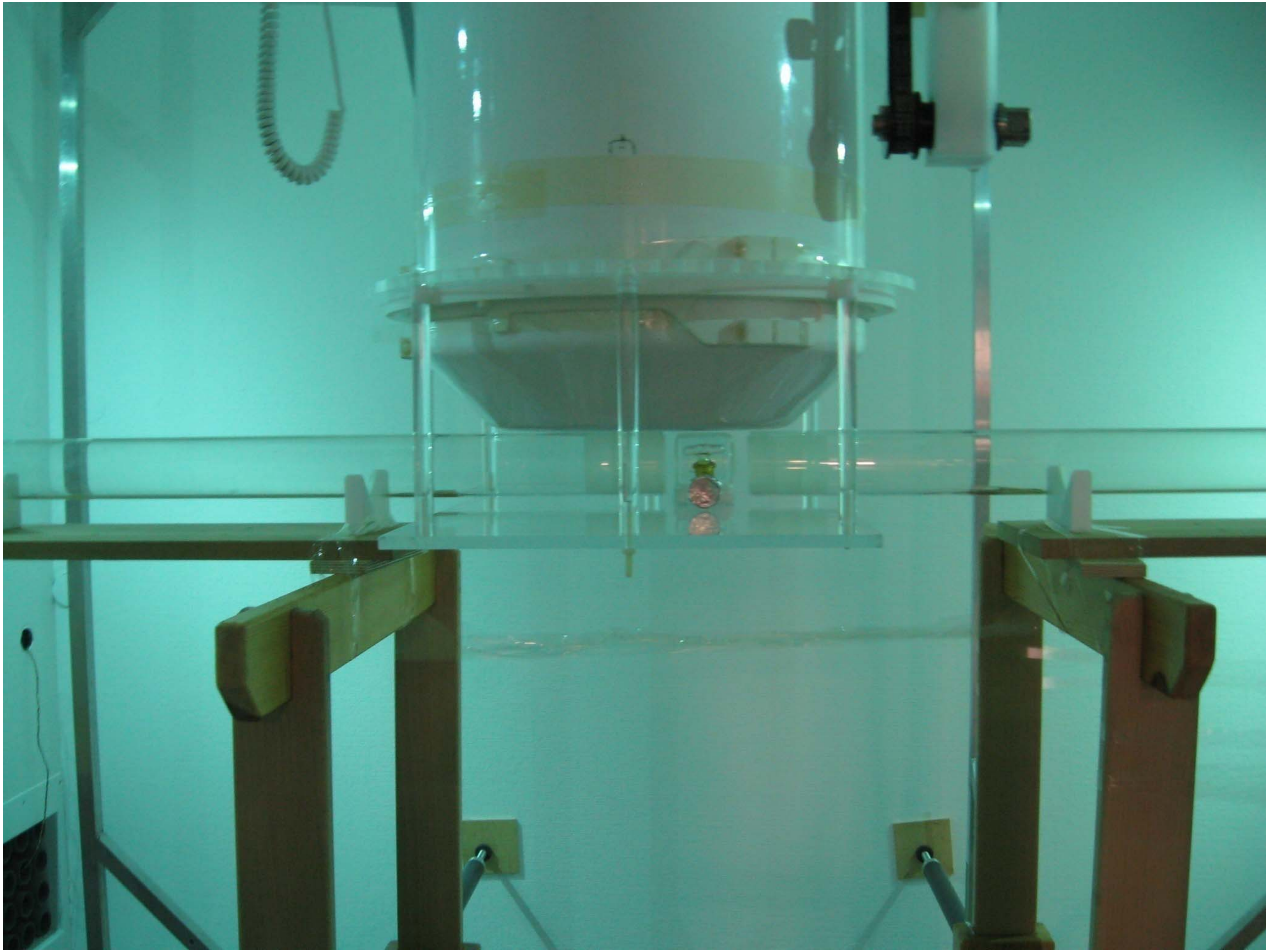


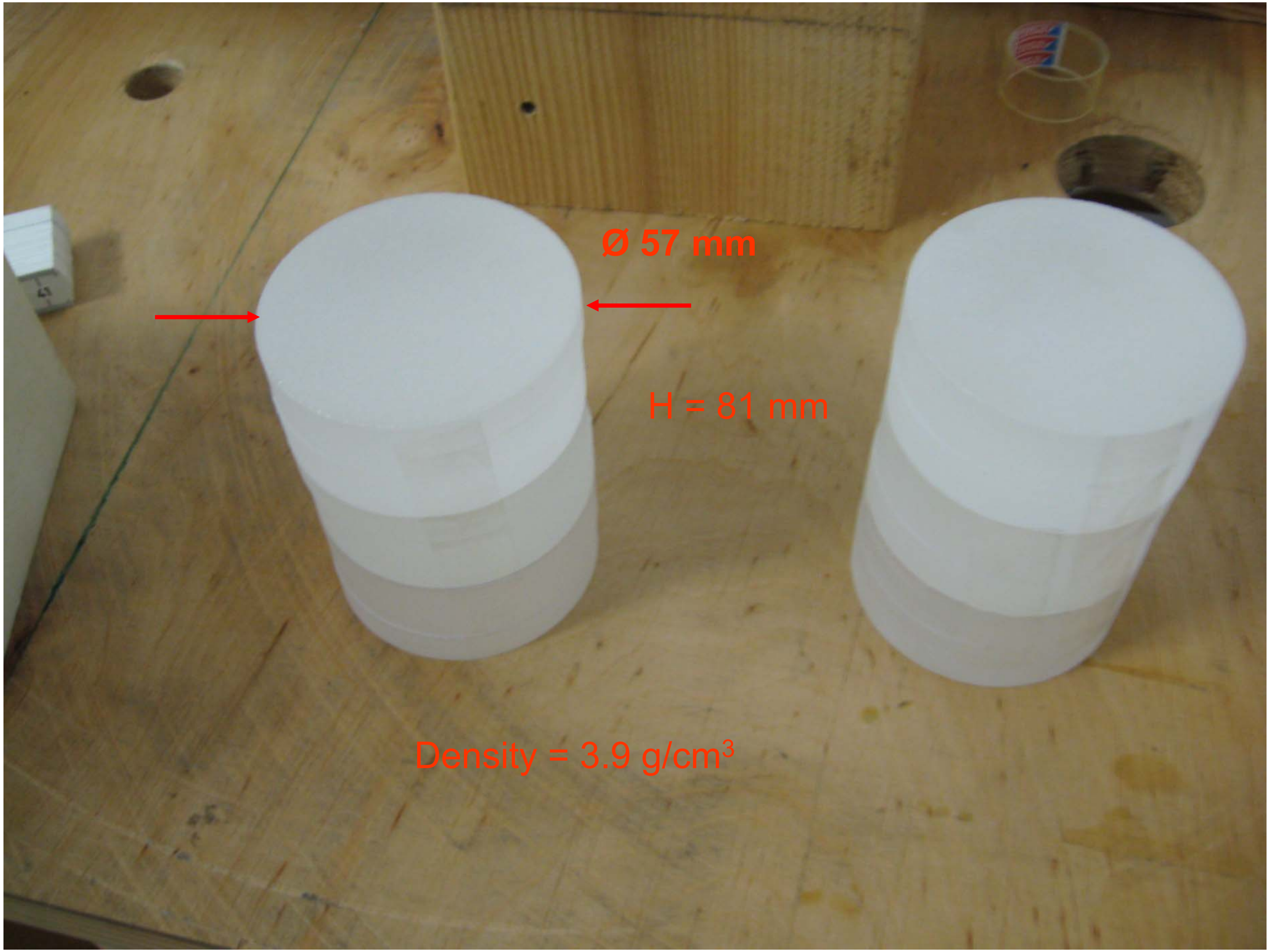



magnetic guiding field ≈ 0.4 μT
(Helmholtz-coils)

# Lay-out of experimental setup

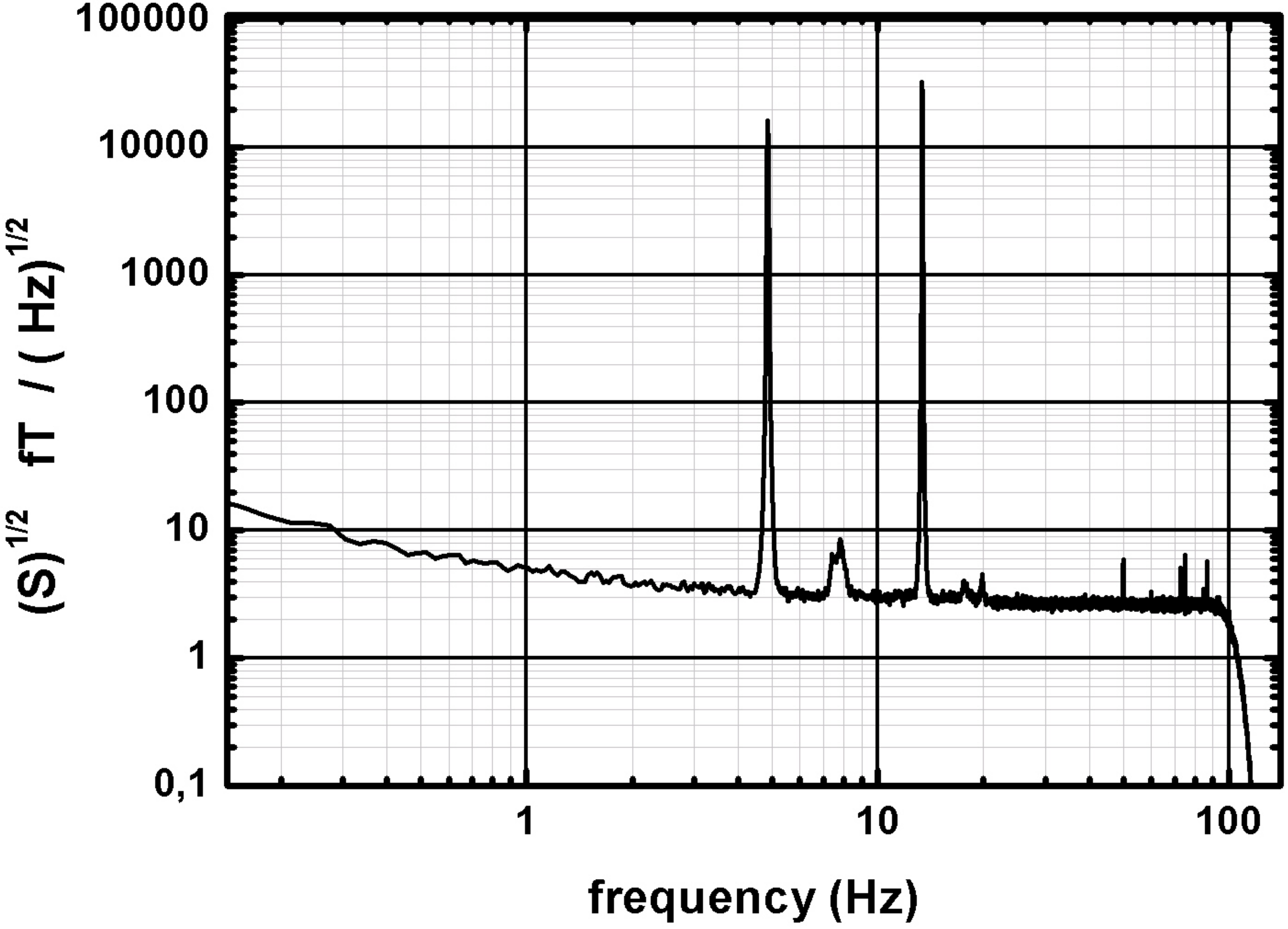






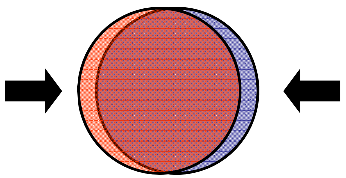

**Lead glass samples**

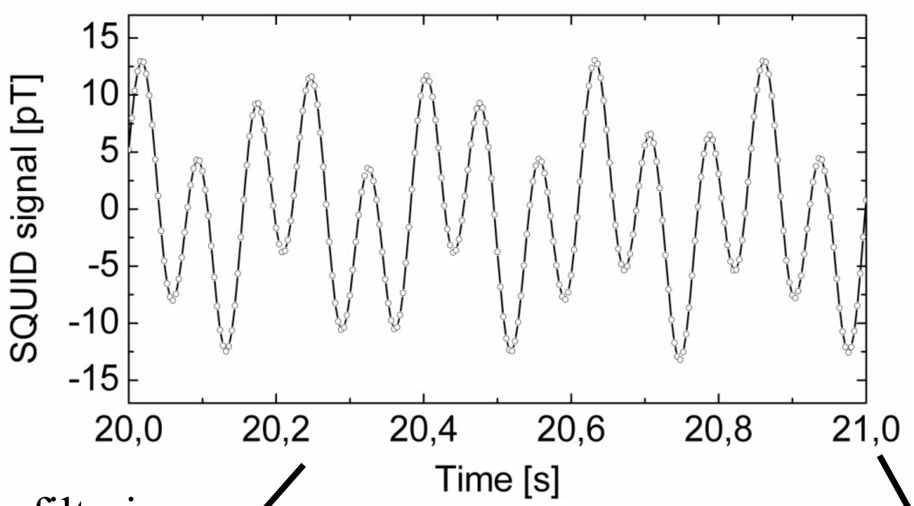
Power spectrum density of $^{3}He$-$^{129}Xe$ co-precession differential signals between SQUIDs Z1C and Z9C.



# Results of He/Xe co-magnetometry

$^3$He / $^{129}$Xe






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

$$= \left(\gamma_{He} - \frac{\gamma_{He}}{\gamma_{Xe}}\cdot\gamma_{Xe}\right)\cdot B(t) +$$

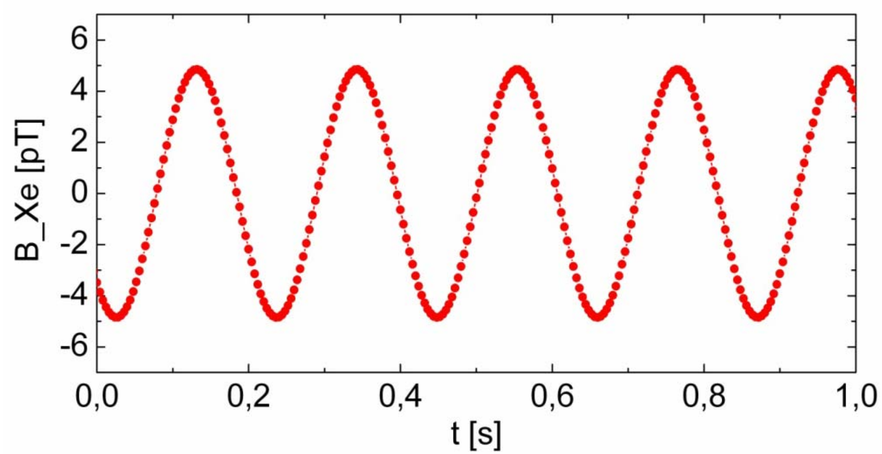
**≡ 0 !**

$$+ \left(1 - \frac{\gamma_{He}}{\gamma_{Xe}}\right)\cdot\omega_{LV}(t)$$

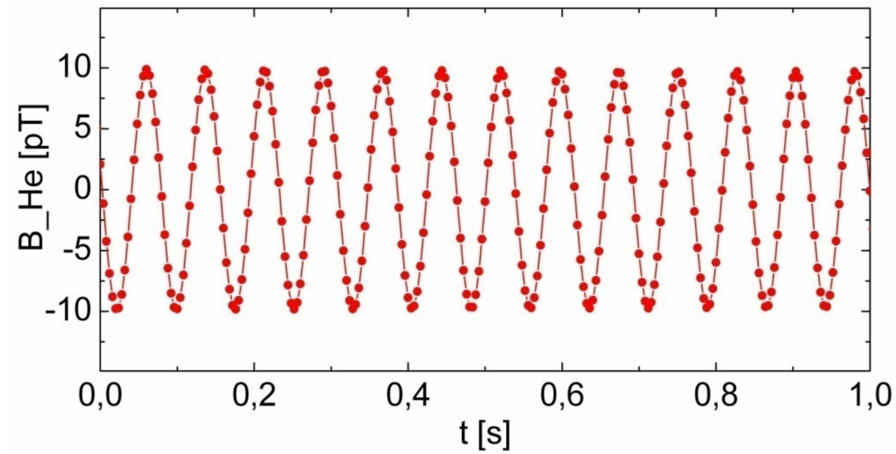
filtering:
**4,7 Hz**

filtering:
**13 Hz**

$^{129}$Xe




$^3$He



# Method for extraction of amplitude and phase of the signal

„Digital lockin“ method:

• First, the measured SQUID signal $s(t)$ is mixed numerically with a reference frequency ~ $\langle\omega_{He(Xe)}\rangle$ according to $s(t) \cdot exp(-i \langle\omega_{He(Xe)}\rangle t)$ and is then transformed into the frequency domain via direct Fourier transformation (FFT).

• After that, an exponential filter ~ $exp(-\omega^2/\omega_{cut}^2)$ is applied. Its cut-off frequency determines the bandwidth of our output data.

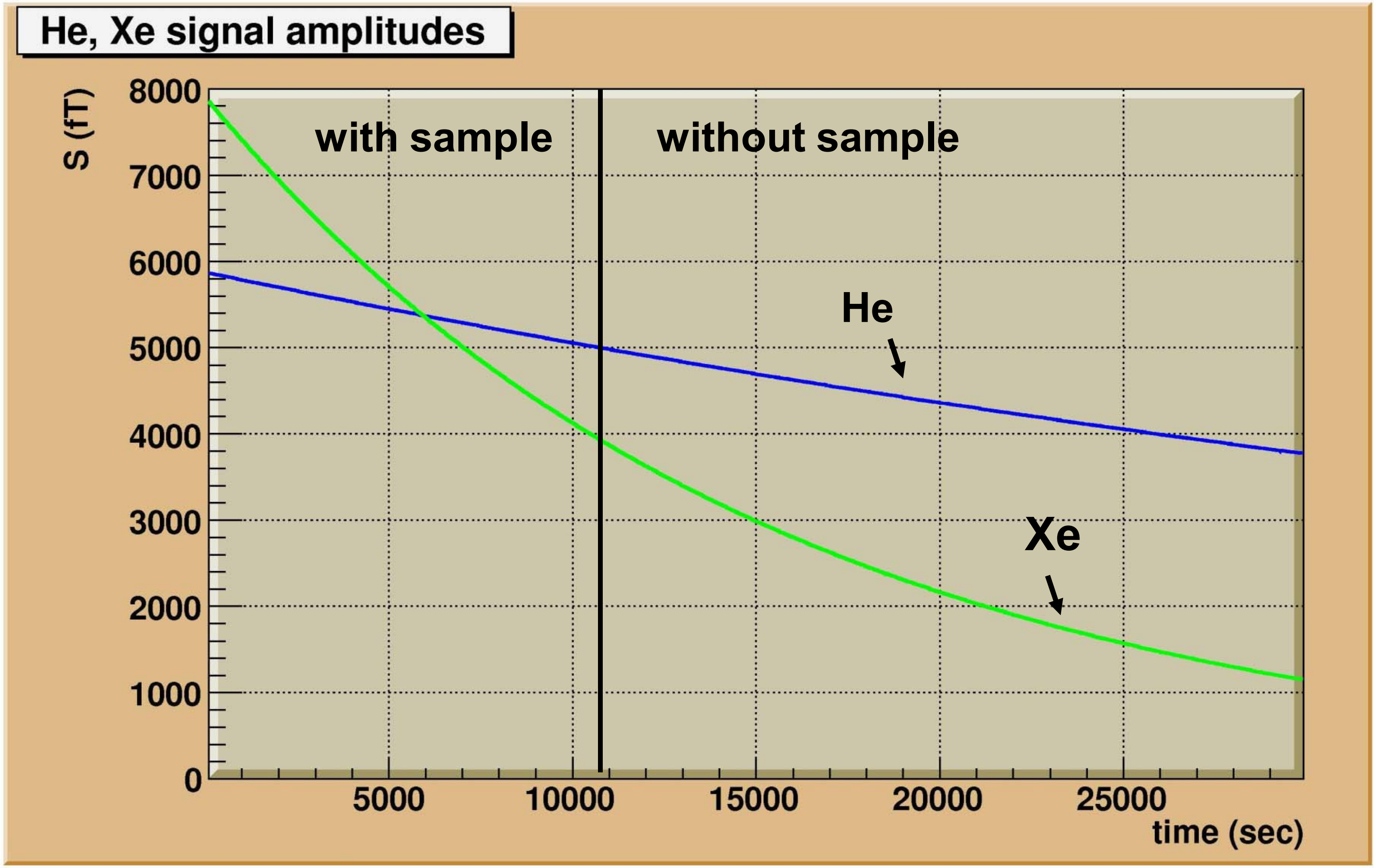
• The filtered data are then transformed back into the time domain using inverse FFT.

• The result is $\mathcal{F}_{He(Xe)}(t)$. The phase $\Phi_{He(Xe)}(t)$ is found as $atan(Im[\mathcal{F}_{He(Xe)}(t)]/Re[\mathcal{F}_{He(Xe)}(t)])$ and the amplitude is $2|\mathcal{F}_{He(Xe)}(t)|$.

Consecuently errors of phase fit should be scaled with factor:

$r = \sqrt{(\sqrt{\pi} \cdot \text{sample\_rate} / \omega_{cut})}$

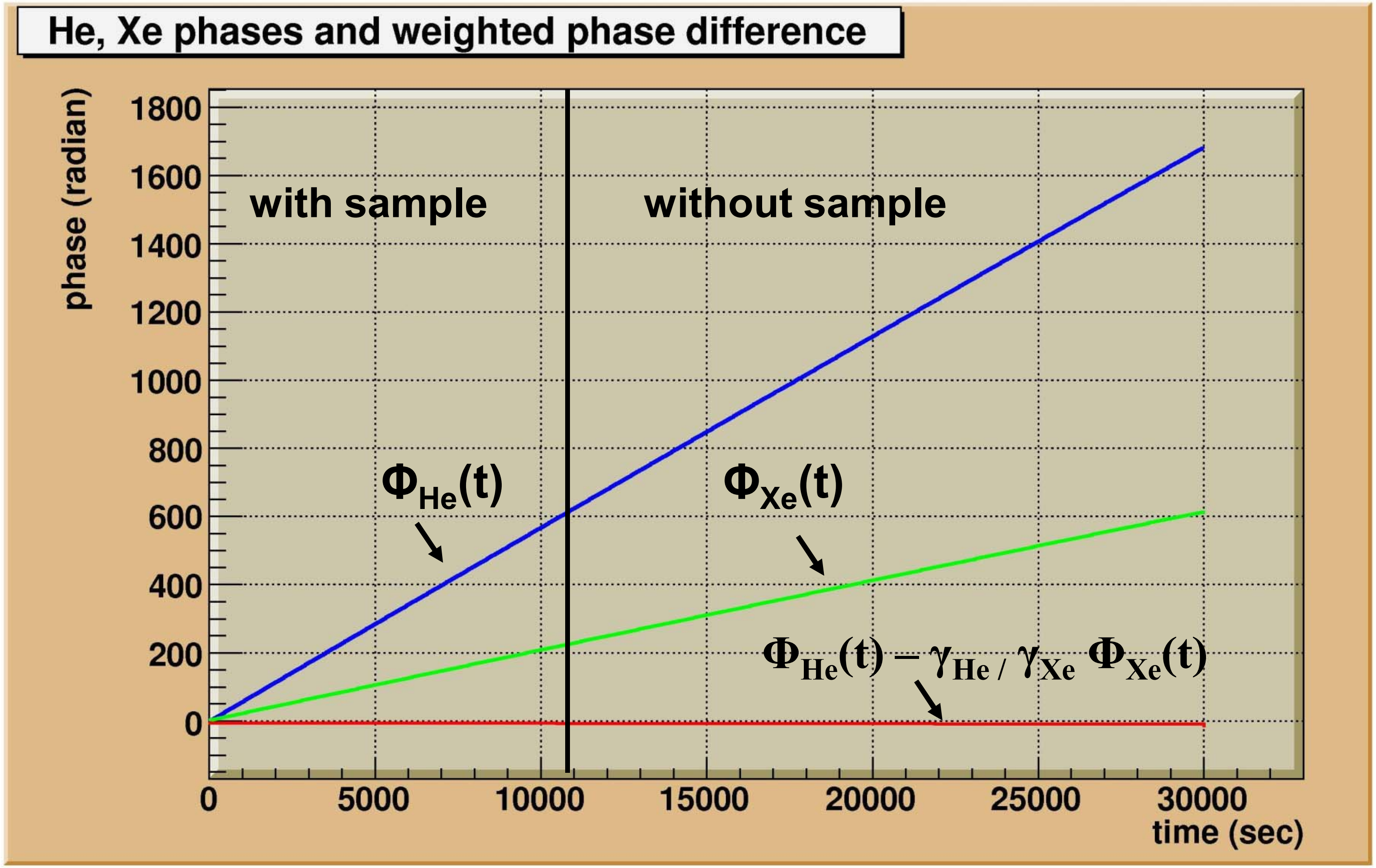
# Extracted signal amplitudes:



# Results for transverse relaxation time:

| Measurement: sample(s) | Mass sample(s) removal time / measurement time without sample (sec) | Gas mixture $^{3}He$ : $^{129}Xe$ : $N_2$ (mbar) | $^{3}He$ / $^{129}Xe$ initial amplitude (pT) | Relaxation time $T^*_2$ $^{3}He$ / $^{129}Xe$ before // after sample (s) removal (hours) |
|---|---|---|---|---|
| Two samples | 7200 / 10600 | 1 : 8.9 : 37 | 2.4 / 3.3 | 22.83 / 5.66 // 23.77 / 5.75 |
| Right sample | 10800 / 42700 | 2.3 : 9.6 : 36.1 | 10.7 / 5.6 | 17.87 / 4.70 // 18.26 / 4.76 |
| Left sample | 10800 / 25800 | 2.4 : 12 : 34.6 | 6.16 / 8.26 | 18.51 / 4.27 // 18.82 / 4.30 |

# Extracted phases:



# Results of measurement of change in the weighted precession frequencies difference caused by mass sample removal:

Two samples $\Delta\nu = -7.8 \pm 11.5$ nHz $\propto \Delta B = -0.24 \pm 0.35$ fT

Right sample $\Delta\nu = -60.8 \pm 7.8$ nHz $\propto \Delta B = -1.88 \pm 0.24$ fT

Left sample $\Delta\nu = -74.2 \pm 6.2$ nHz $\propto \Delta B = -2.29 \pm 0.19$ fT

=> $\delta\nu = \frac{1}{2}(\Delta\nu_{\text{right sample}} - \Delta\nu_{\text{left sample}}) = -6.7 \pm 5.0$ nHz

# Results of measurement of change in the magnetic field (from He phase alone):

Two samples $\Delta\nu \approx 6.4 \cdot 10^{-5}$ Hz $\propto \Delta B \approx 2$ pT

Right sample $\Delta\nu \approx 7.6 \cdot 10^{-5}$ Hz $\propto \Delta B \approx 2.3$ pT

Left sample $\Delta\nu \approx -0.85 \cdot 10^{-6}$ Hz $\propto \Delta B \approx -0.4$ pT

# Limitation on short range spin-dependent interaction:

The effective PT violating potential of interaction between spin of one fermion with another fermion is given by

$$V_{SP}(\mathbf{r}) = \frac{\hbar^2 g_S g_P}{8\pi m}\left(\frac{\mathbf{r}}{r}\cdot\boldsymbol{\sigma}\right)\left(\frac{1}{r\lambda}+\frac{1}{r^2}\right)e^{-r/\lambda}$$

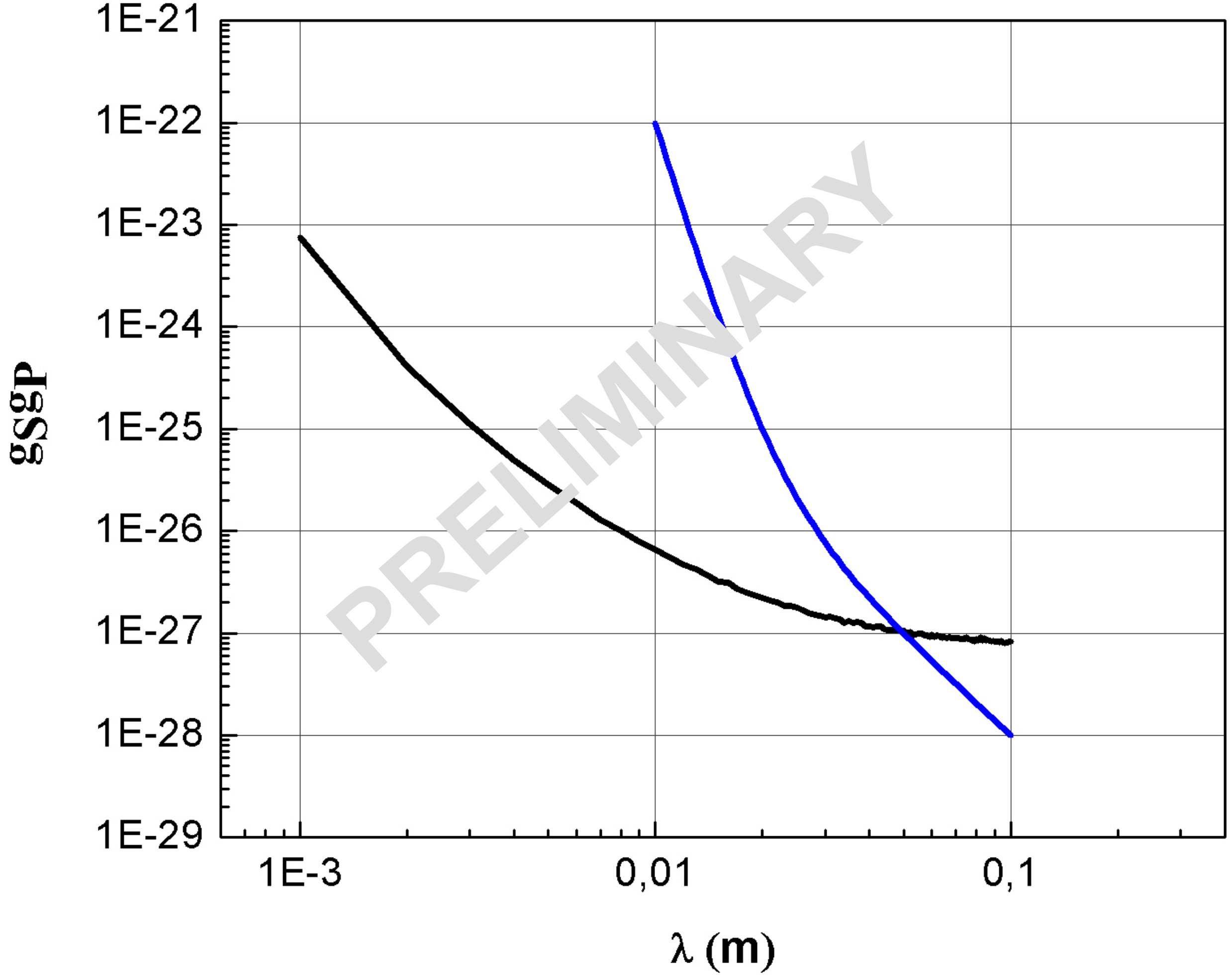
It follows that in case of limitation on weighted precession frequency difference change $\delta\nu$:

**$g_S g_P < 4\,(2\pi)^2\, m_{3He}\, \delta\nu\, /\, (NV\,\hbar\, \langle V^*(r)\rangle)$,**

where $V = 2.07 \cdot 10^{-4}\ m^{-3}$ is volume of lead glass sample,
$N = 2.3\cdot 10^{30}$ is its number density,
$V^*(r)$ is coordinate dependent part of $V(r)$.

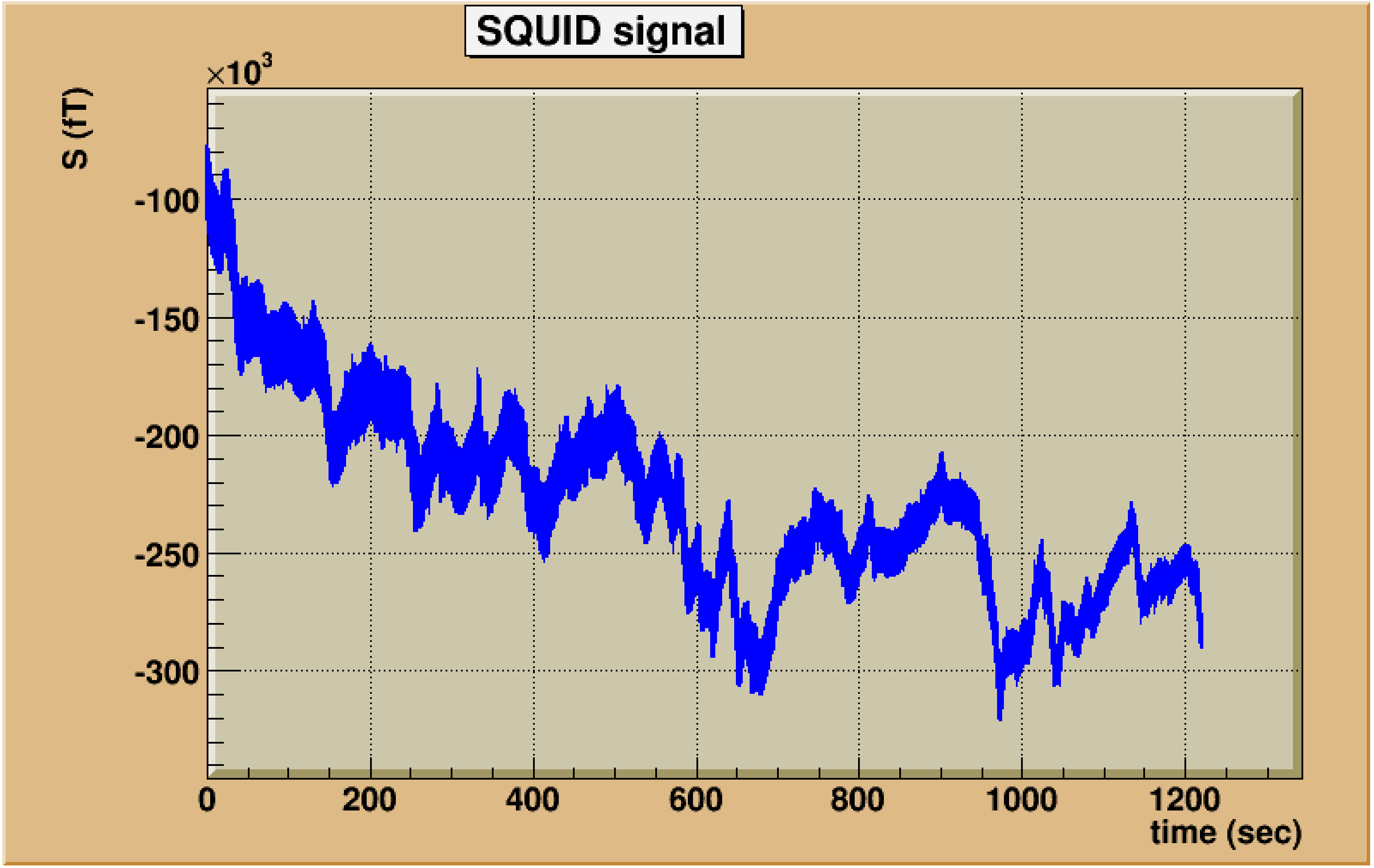
Average potential $\langle V^*(r)\rangle$ was calculated numerically for cell sizes diameter 6 cm x length 6 cm, gap 3 mm between cell inner volume and lead glass diameter 57 mm x length 81 mm.
Result for $\delta\nu \approx 12$ nHz (65% CL) is presented in next transparency.

# Constraints for the coupling constant product $g_S g_P$, as a function of range of the macroscopic force.



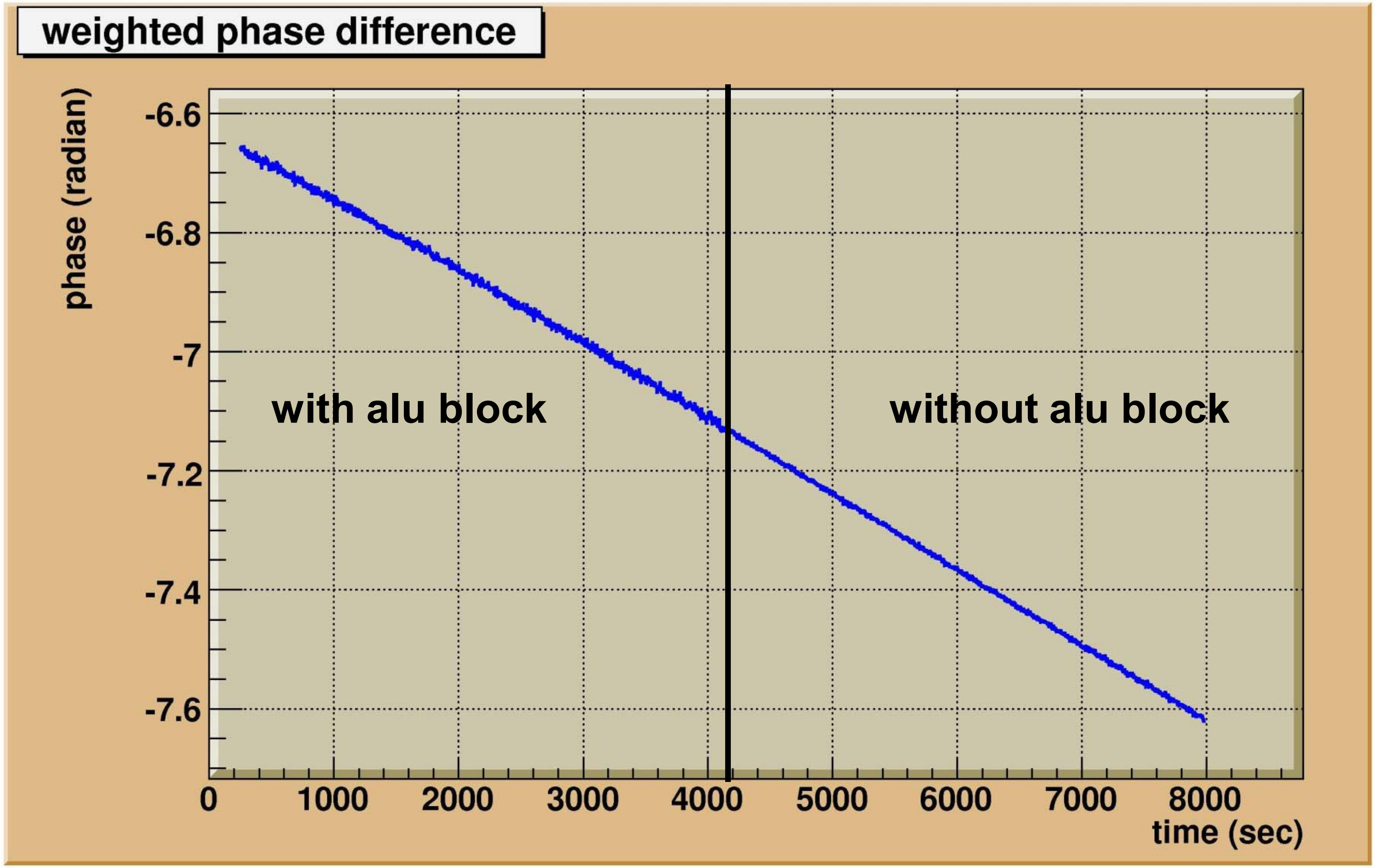

The blue solid line represents constraint obtained in [A.N.Youdin et al., PRL **77** (1996) 2170] and black solid line is limitation from the current experiment

# SQUID signal near block of bismuth*




*Goodfellow, ferromagnetic admixtures < 1 ppm. The alleged source of low frequency noise is thermoelectric currents coupled with heterogeneity of material.

# Result of measurement with block of aluminium




Result from fit for change in $^3$He precession frequency:

$\Delta\nu = (-6.2 \pm 0.4) \cdot 10^{-5}$ Hz $\propto$ $\Delta B = -1.9 \pm 0.1$ pT

# Conclusion and Outlook

• A novel $^3He/^{129}Xe$ co-magnetometer was used to probe macroscopic short range spin-dependent interactions (pseudo-scalar interaction)

• It was shown that high sensitivity of such co-magnetometer and immunity to the influence of magnetic field fluctuations allow us to reach a new constraints on pseudo-scalar interaction in range 0.2 – 10 cm.

• Further work on materials suitable for samples for such measurements can give an opportunity to improve significantly obtained constrains.