Yu.Sobolev

Search for spin-dependent short-range forces in $^{3}He/^{129}Xe$ clock comparison experiment

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Outline:

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

Search for a new pseudoscalar boson (Axion-like particle)

Original proposal for Axion (F.Wilczek, 1978 and others) : prediction as a consequence of a possible solution to the „Strong CP Problem“

$$d_n \propto \overline{\theta}\,\frac{1}{\Lambda_{QCD}} \approx 10^{-16}\,\overline{\theta} e\cdot cm$$

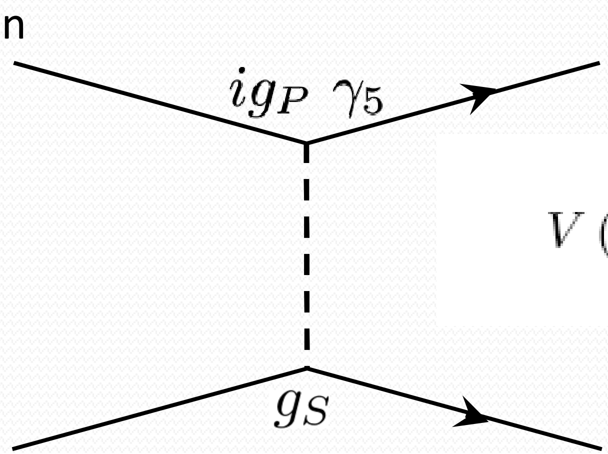
Modern interest: Dark Matter candidate. All couplings to matter are weak

Signature of a new pseudoscalar boson: New Short-Range Potential

Monopole-dipole: monopole-dipole interactions of range λ mediated by new light boson of mass M

$$\lambda = \frac{\hbar}{Mc}$$

Dipole (probe)



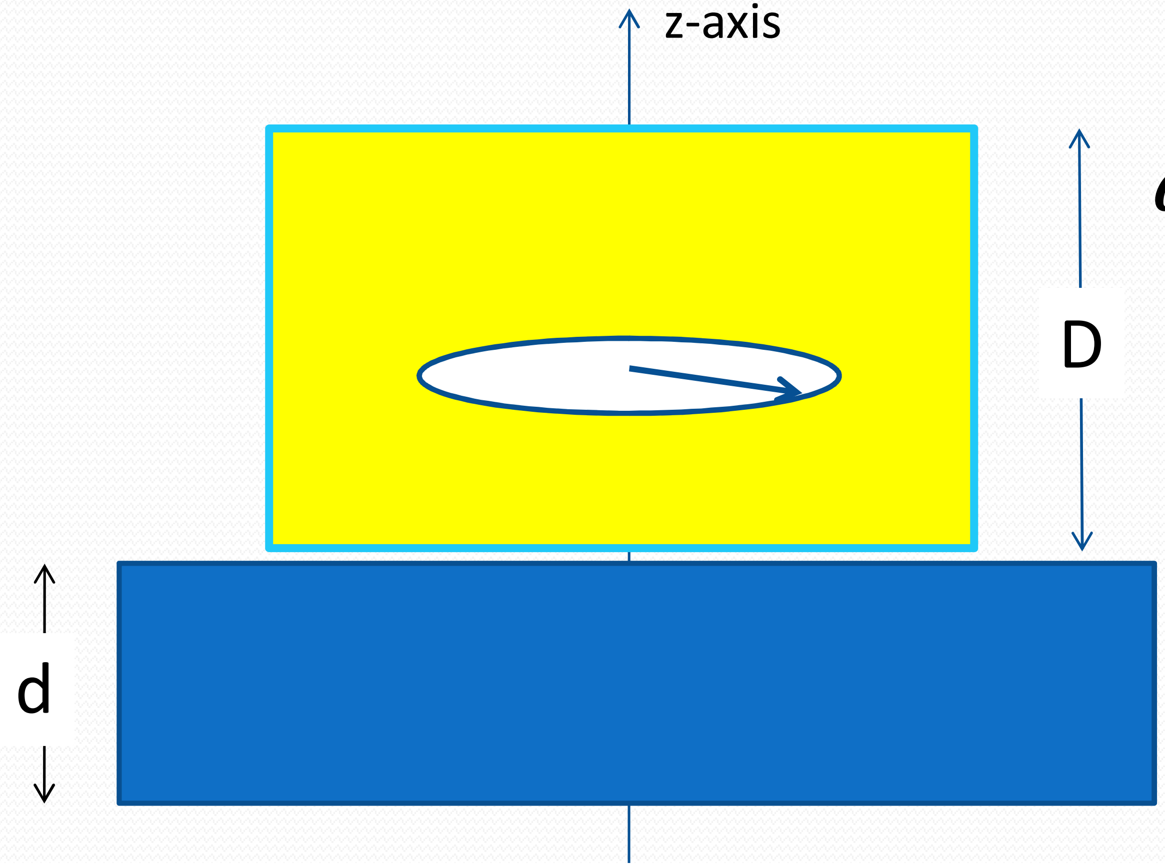
Monopole (source)

$\not P$ $\not C P$ Scalar-Pseudoscalar

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

$$\kappa = \frac{\hbar^2 g_S g_P}{8\pi m_n}$$

How to measure?



$$\omega = \omega_L + \Delta\omega$$

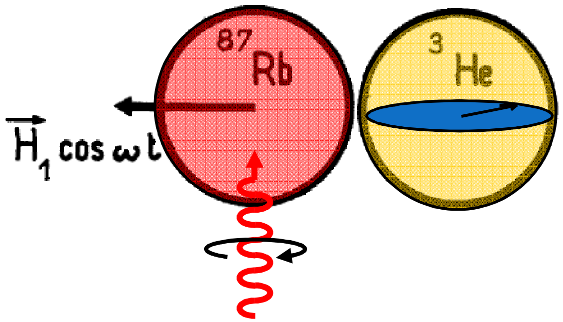
$$\Delta\omega = \overline{V} / \hbar$$

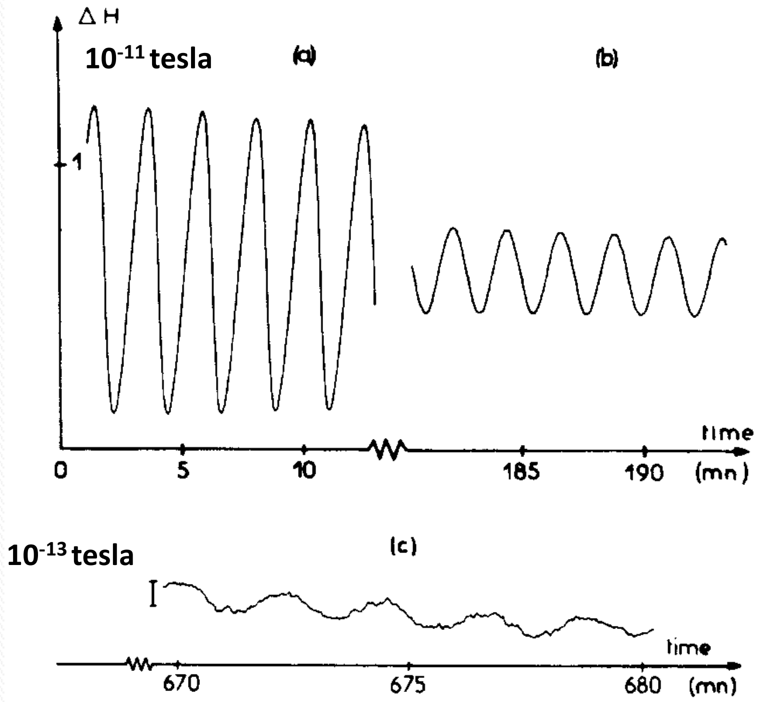
$$\overline{V} = \pm \frac{1}{D} \int_0^D V(z)\,\mathrm{d}z = \pm V(0)\,\frac{\lambda}{D}\left(1 - \mathrm{e}^{-D/\lambda}\right)\left(1 - \mathrm{e}^{-d/\lambda}\right),$$

$$V(0) = N \cdot \lambda \cdot \hbar^2 \cdot \frac{g_s \cdot g_p}{4 \cdot m_N}$$

Detection of magnetic field produced by oriented nuclei

(Cohen-Tannoudji et al., PRL 22 (1969),758)





Results:

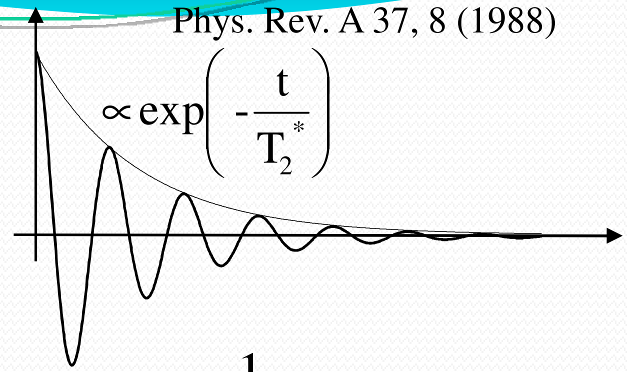
- ^{3}He spin precession: T_2^* = 2h 20min
- sensitivity of Rb-magnetometer:
  100fT@ BW 0.3 Hz
- $P_{He} \approx$ 5% @ 4 mbar

Improvement of measurement sensitivity:

- SQUID-detectors@2 fT/√Hz
- laser for OP of ^{3}He @ P> 70%
- longer T_2^*-times (needed !!!)

Transverse Relaxation: T_2^*

Cates; Schaefer; Happer:
Phys. Rev. A 37, 8 (1988)



$\propto \exp\left(-\frac{t}{T_2^*}\right)$

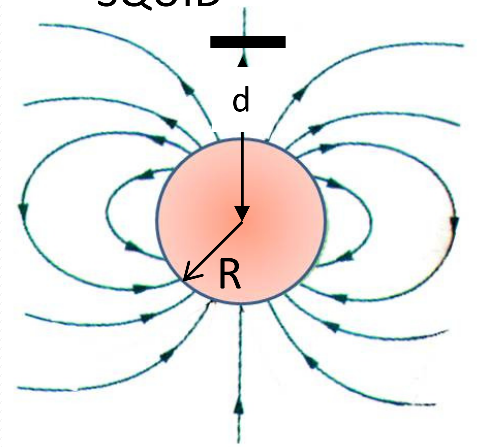
size: R
=> 3cm

absolute gradient
→ low magn. field
($B_0 \approx 1\ \mu T$)

$$\frac{1}{T_2*} = \frac{1}{T_1} + \frac{8R^4\gamma^2\left|\vec{\nabla}B_{1z}\right|^2}{175\,D} + D\frac{\left|\vec{\nabla}B_{1x}\right|^2 + \left|\vec{\nabla}B_{1y}\right|^2}{B_o^2} \cdot \sum_n \frac{1}{\left|x_{1n}^2 - 2\right|\left[1 + x_{1n}^4\left(\gamma B_o R^2 / D\right)^{-2}\right]}$$

longitudinal
relaxation time
T_1(He) > 100 h

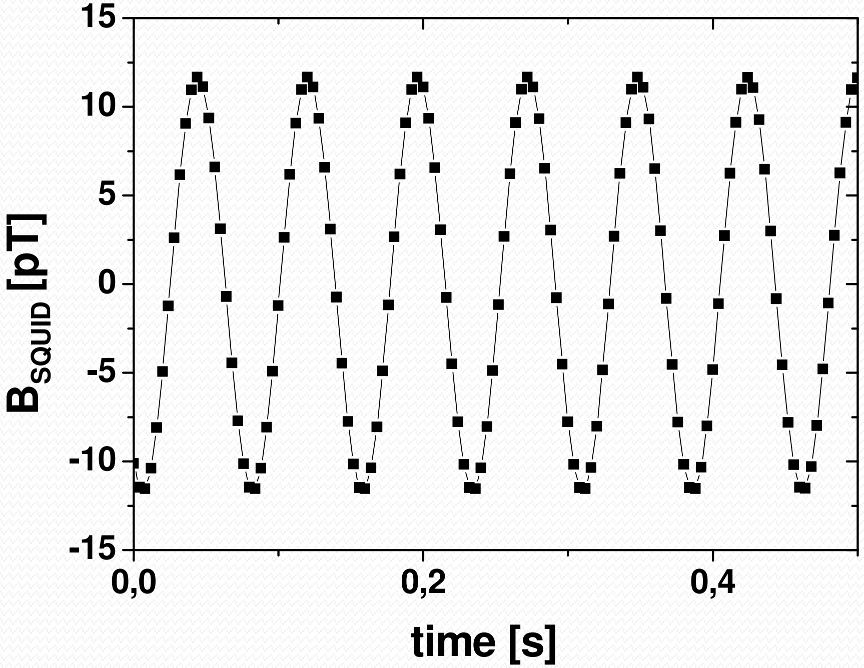
diffusion const. D ~ 1/p
→ low pressure
(p ~ mbar)

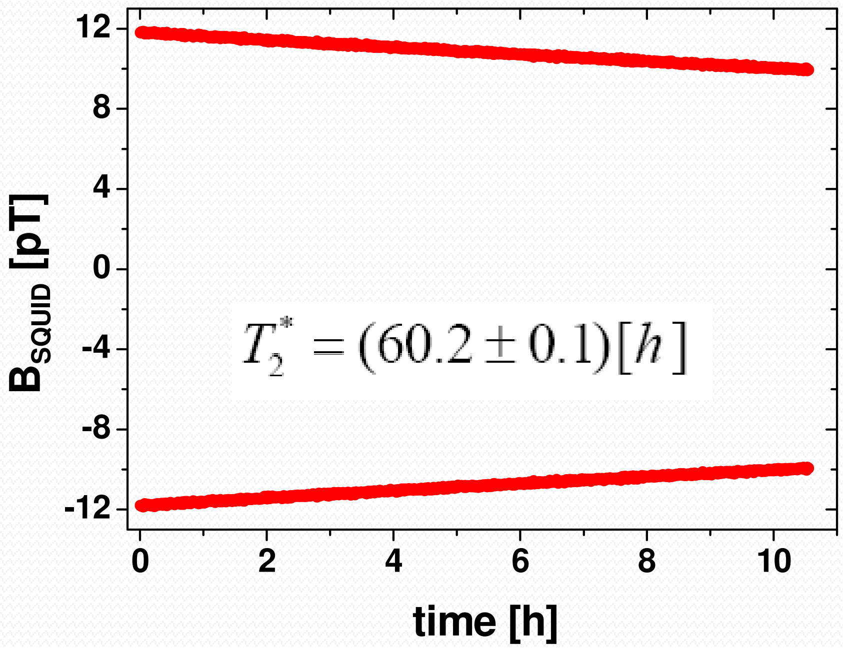


Signal:

$$\Delta B[pT] \approx 220 \cdot p[mbar] \cdot P \cdot \left(\frac{R}{d}\right)^3$$

^{3}He free spin-precession signal

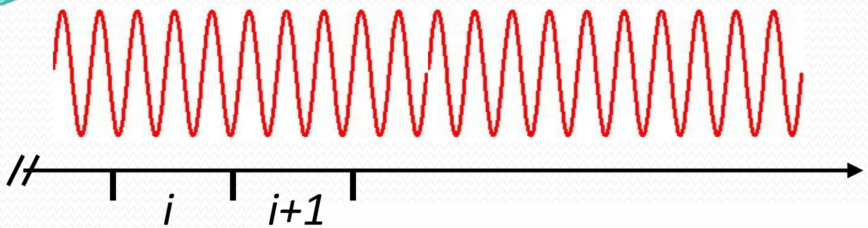




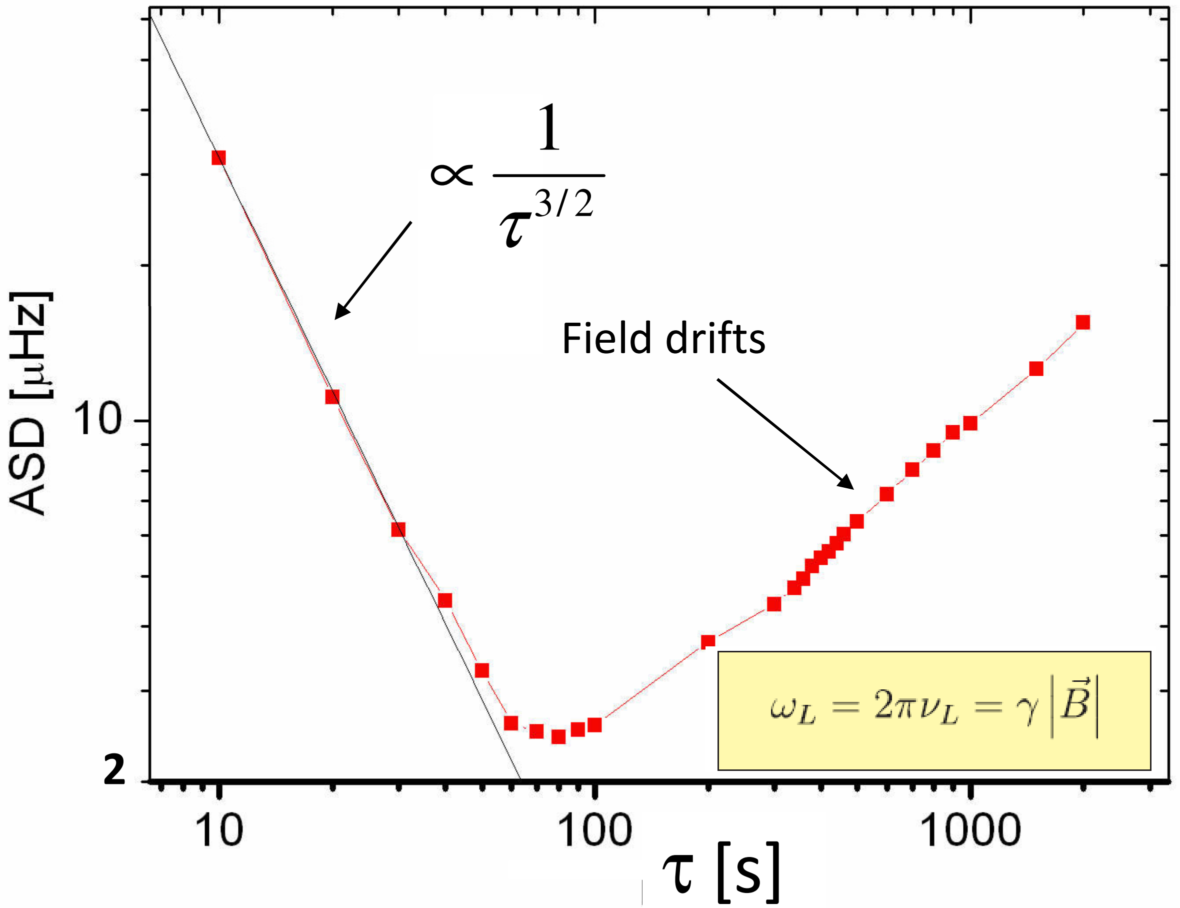
parameters: p_{He}= 4.5 mbar ; P_{He}= 15% ; R_{int}=2.9 cm; d = 6cm

expected $T^*_{2,\exp}$: $$\frac{1}{T^*_{2,\exp}} = \frac{1}{T_{1,wall}} + \frac{1}{T_{2,field}} = \frac{1}{(85 \pm 5)h} + \frac{1}{(370 \pm 64)h} \rightarrow T^*_{2,\exp} = (69 \pm 4)h$$

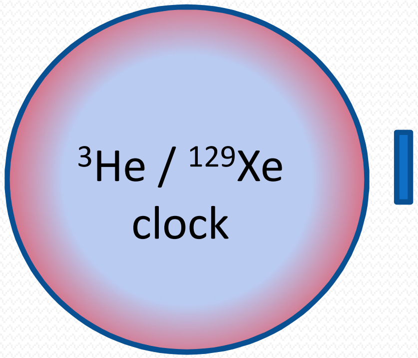
Allan Standard Deviation

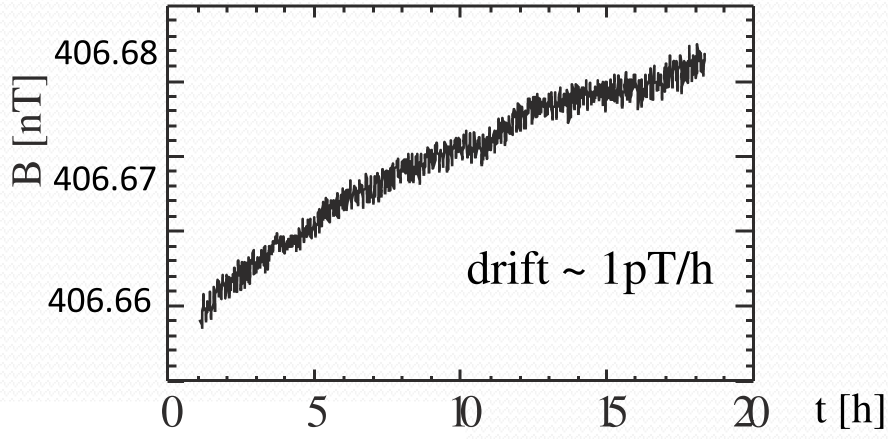


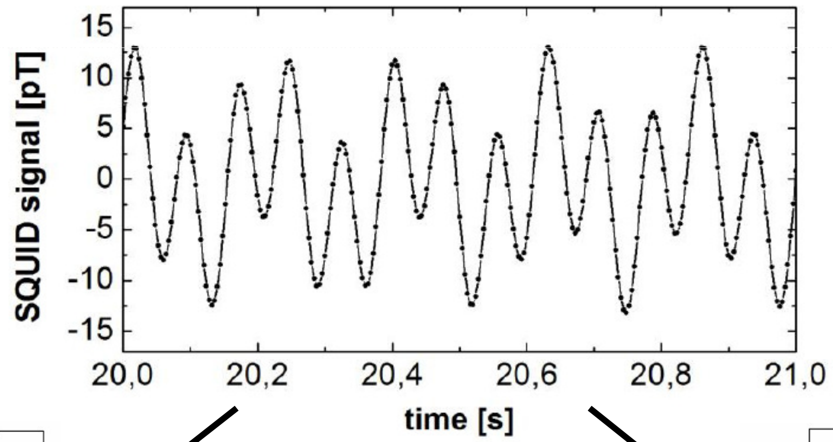
$$\sigma_v(\tau) = \sqrt{\frac{1}{2}\frac{\sum_{i=1}^{N-1}\left(\overline{v}_{i+1}(\tau) - \overline{v}_i(\tau)\right)^2}{N-1}}$$



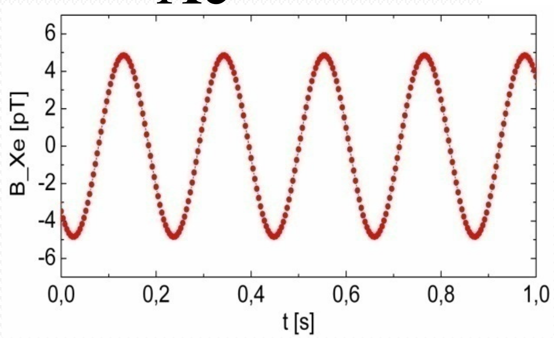
^{3}He / ^{129}Xe clock comparison







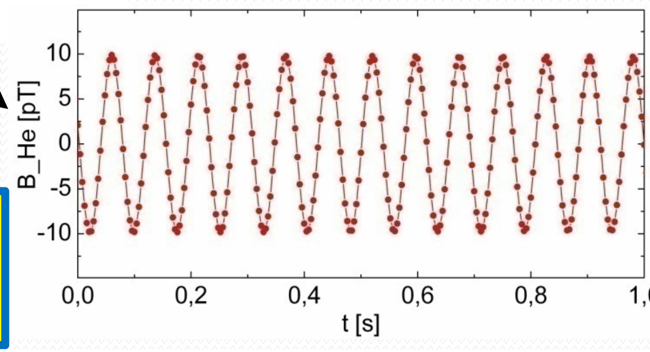
^{129}Xe



filtering: **4,7 Hz**

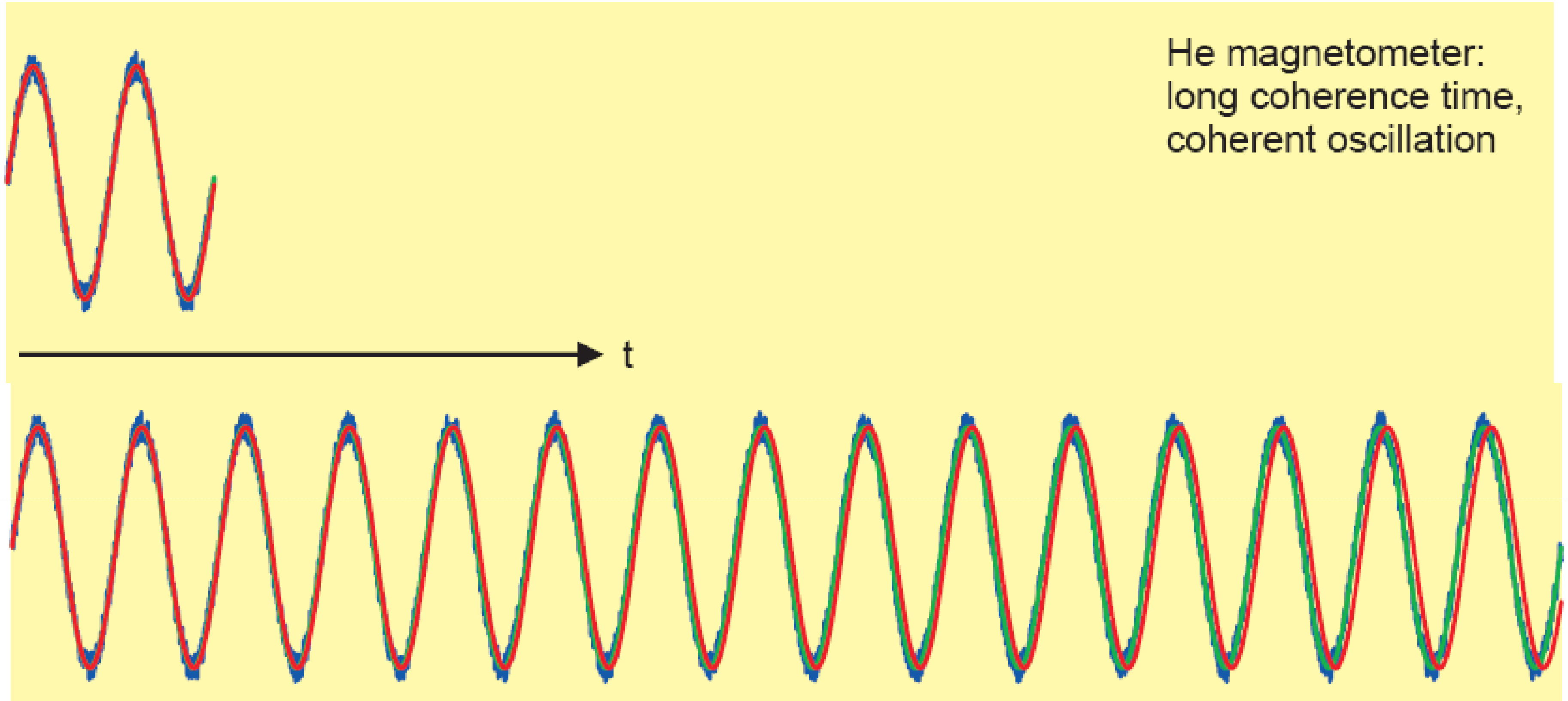
filtering: **13 Hz**

^{3}He



$$\Delta\omega = \omega_{L,He} - \frac{\gamma_{He}}{\gamma_{Xe}} \cdot \omega_{L,Xe} \overset{!}{=} 0$$

FREQUENCY ESTIMATION

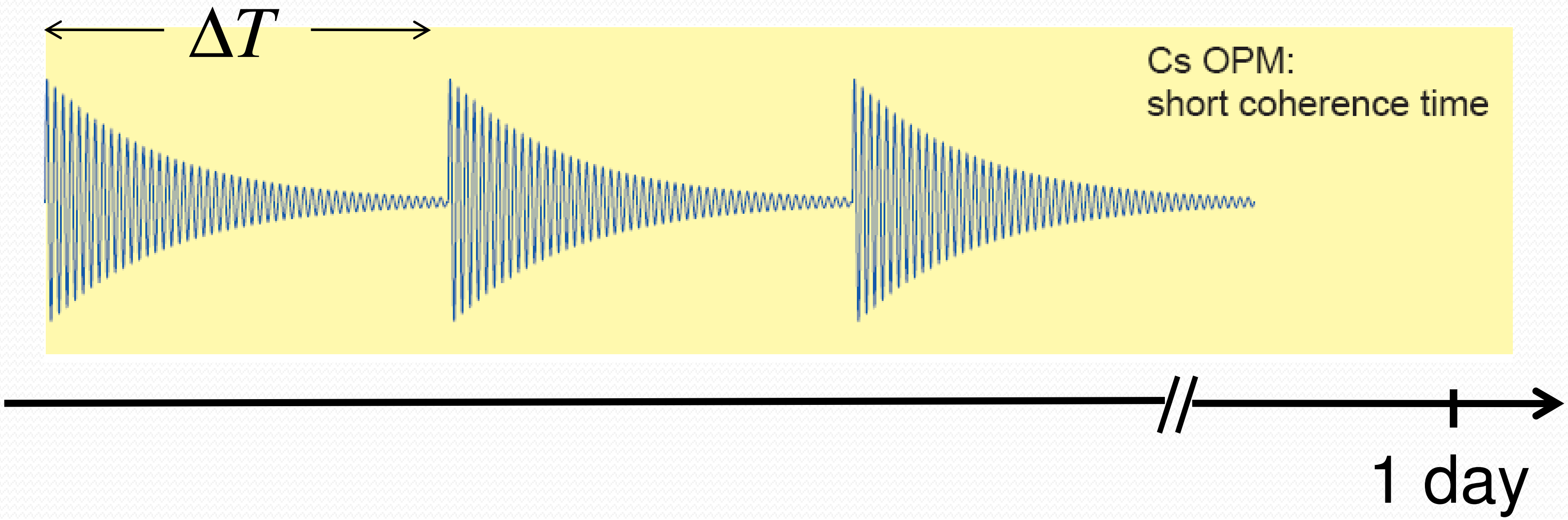


Accuracy of frequency determination:

$$\sigma_\nu \propto \left[\text{Fourier width } \frac{1}{\tau}\right] \times \frac{1}{\left[\#\text{ of data points } \tau\right]^{1/2}}$$

$$\propto \frac{1}{\tau^{3/2}}$$

Sensitivity of clocks with short coherence times:



$$\sqrt{\sigma_f^2} \propto \left(1 \big/ \Delta T^{3/2} \right) \cdot / \sqrt{T / \Delta T} = \left(1 \big/ T^{3/2} \right) \cdot \frac{T}{\Delta T}$$

example : $\Delta T = 5$ min $\rightarrow\ \approx 300 \times$ less sensitive !

The recorded signal S from the precessing spins can be written as:

$$S[n] = A \cdot \cos\left(2\pi \cdot f \cdot \Delta t \cdot n + \Phi\right) \cdot \exp(-\Delta t / T_2^* \cdot n) + w[n] \qquad n = 0,1,2,3,\ldots,N-1$$

If the noise w[n] is Gaussian distributed, initial phase is known, the Cramer-Rao Lower Bound (CRLB) sets the lower limit on the variance

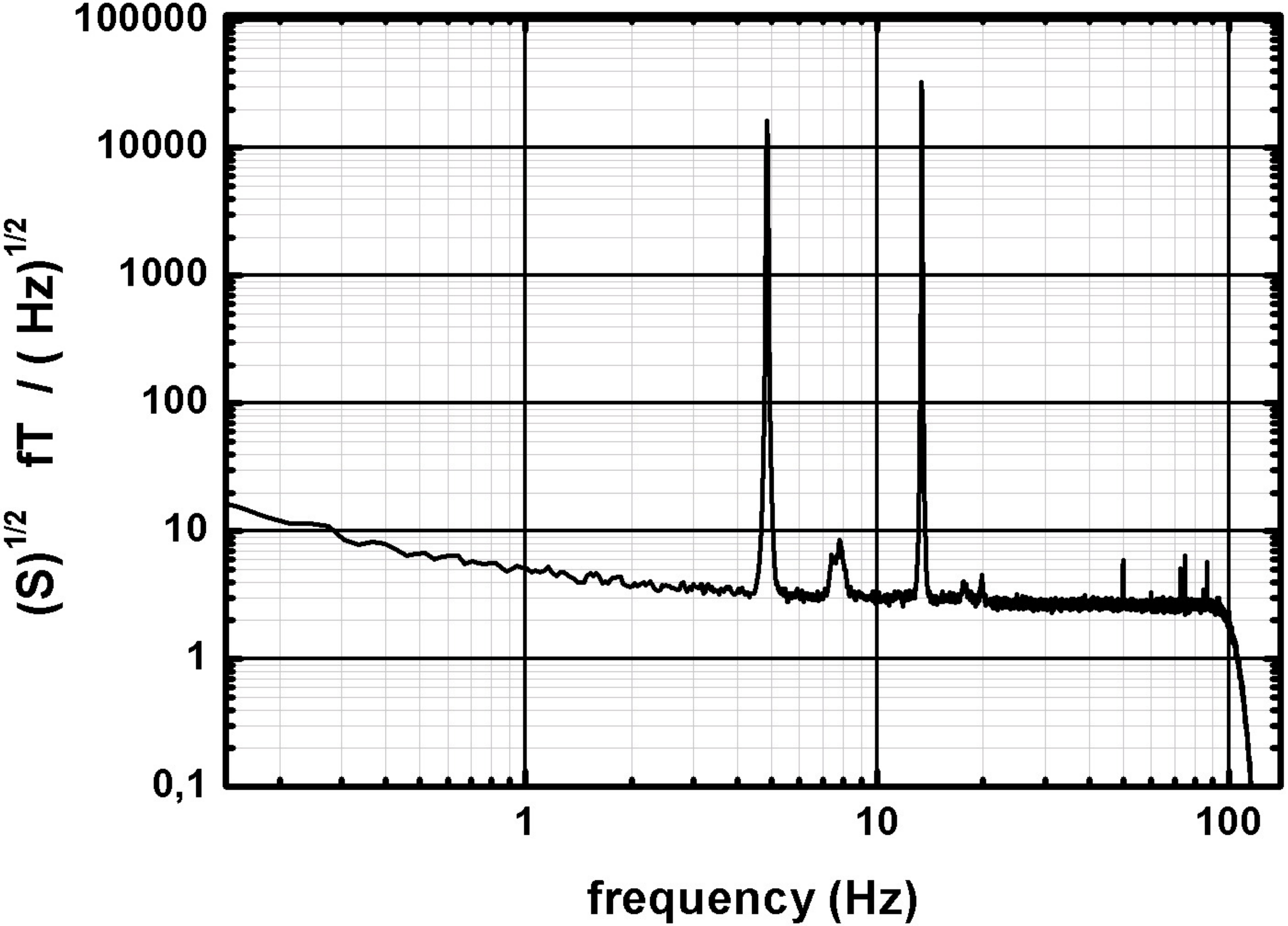
$$\sigma_f^2 \geq \frac{3}{(2\pi)^2 \cdot (SNR)^2 \cdot f_{BW} \cdot T^3} \times C(T_2^*)$$

example: SNR = 2000:1
f_{BW} = 1 Hz
T= 10000 s

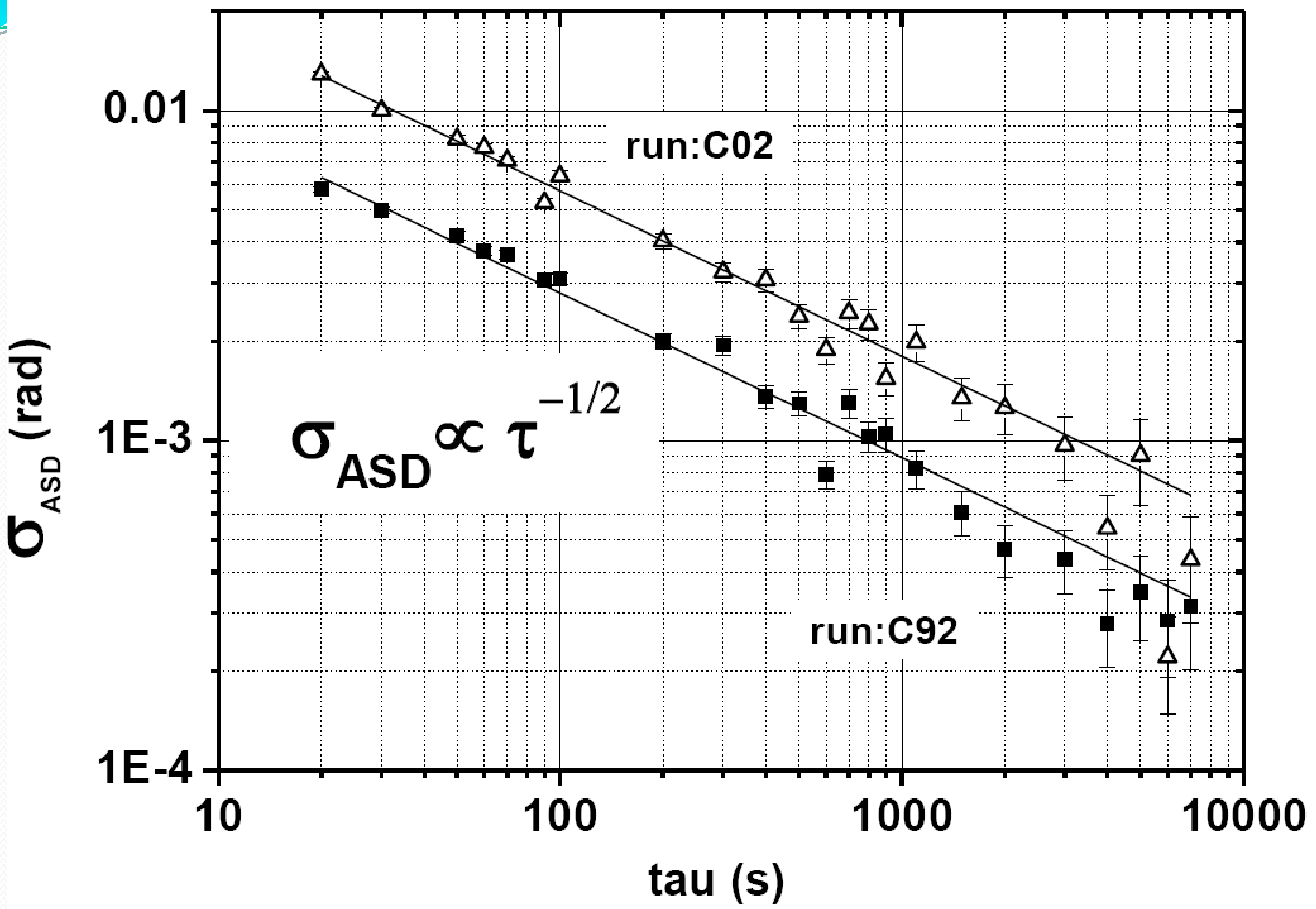
$$\sqrt{\sigma_f^2} \approx 0{,}15\ nHz$$

For more details look article: „Ultra-sensitive magnetometry based on free precession of nuclear spins“, accepted in EPJD

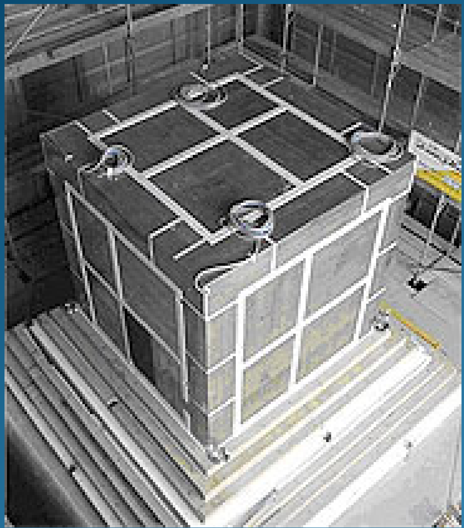
Power spectrum density of ^{3}He-^{129}Xe co-precession differential signals between SQUIDs Z1C and Z9C.



ASD of phase residuals

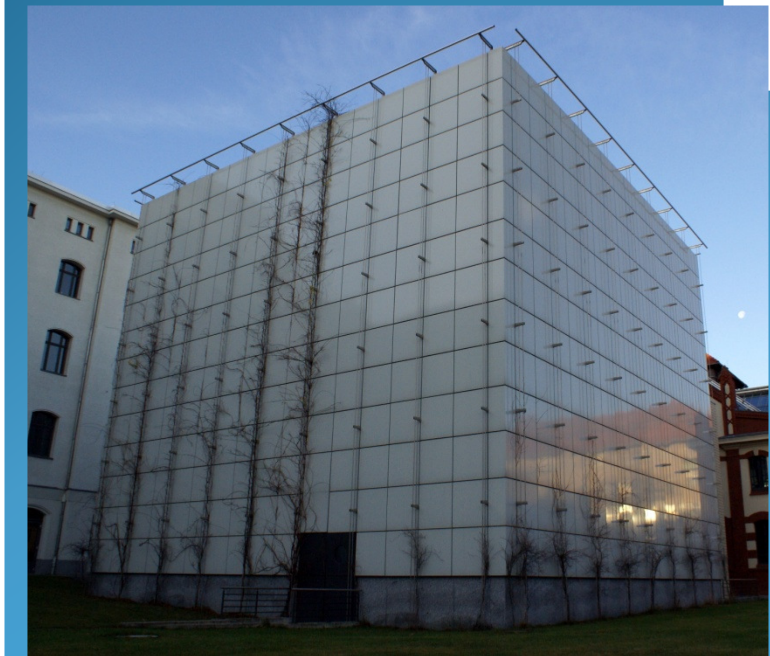


BMSR 2, PTB Berlin

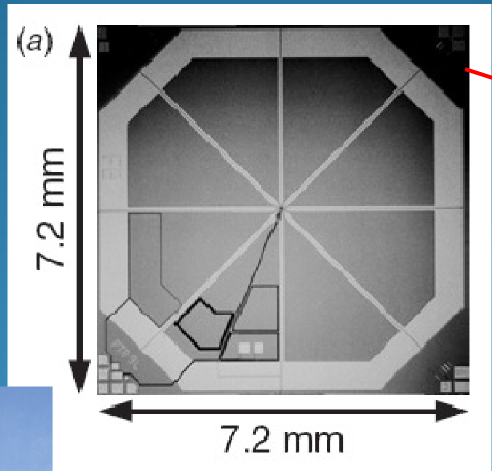


The 7-layered magnetically shielded room (residual field < 1 nT)

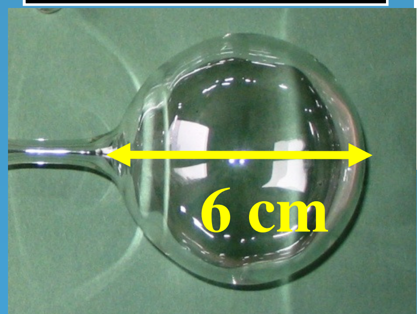
J. Bork, et al., Proc. Biomag 2000, 970 (2000).



LT_c- SQUID

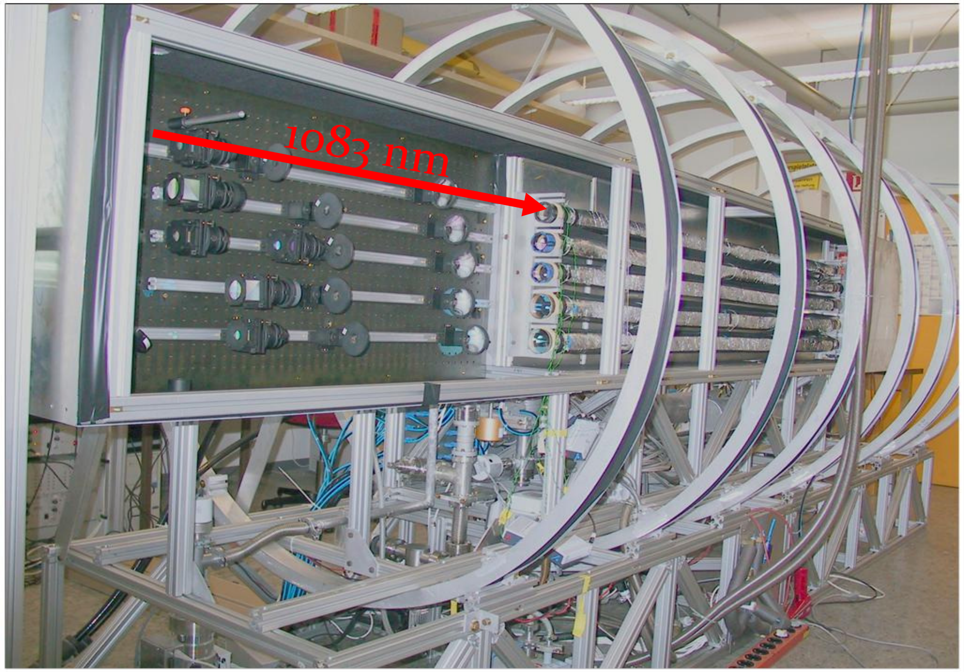


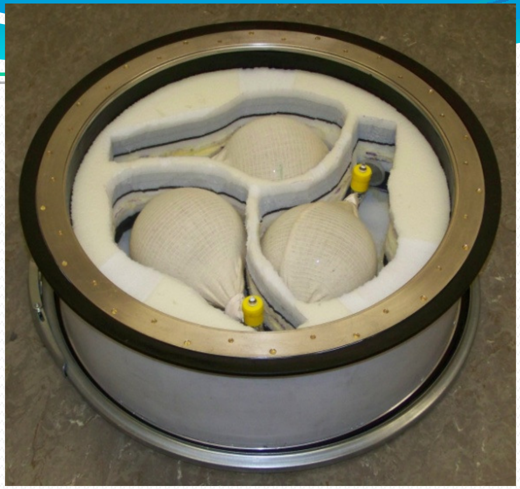
^3He (~2 mbar)
^{129}Xe (~ 12 mbar)
N_2 (~ 35 mbar)



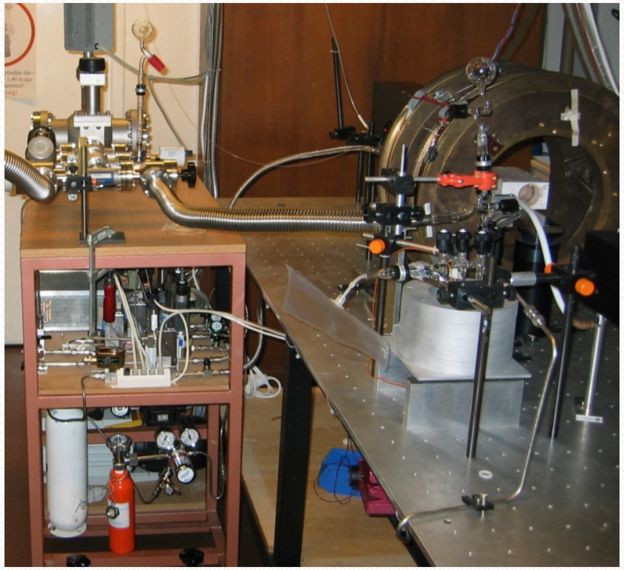
magnetic guiding field ≈ 0.4 µT
(Helmholtz-coils)

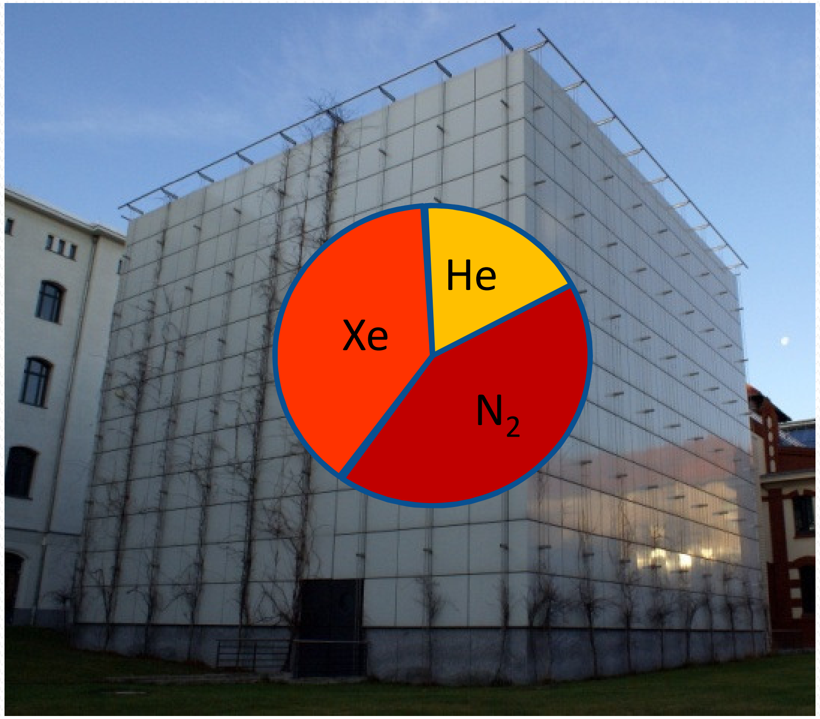
MEOP Polarizer Mainz: ^3He

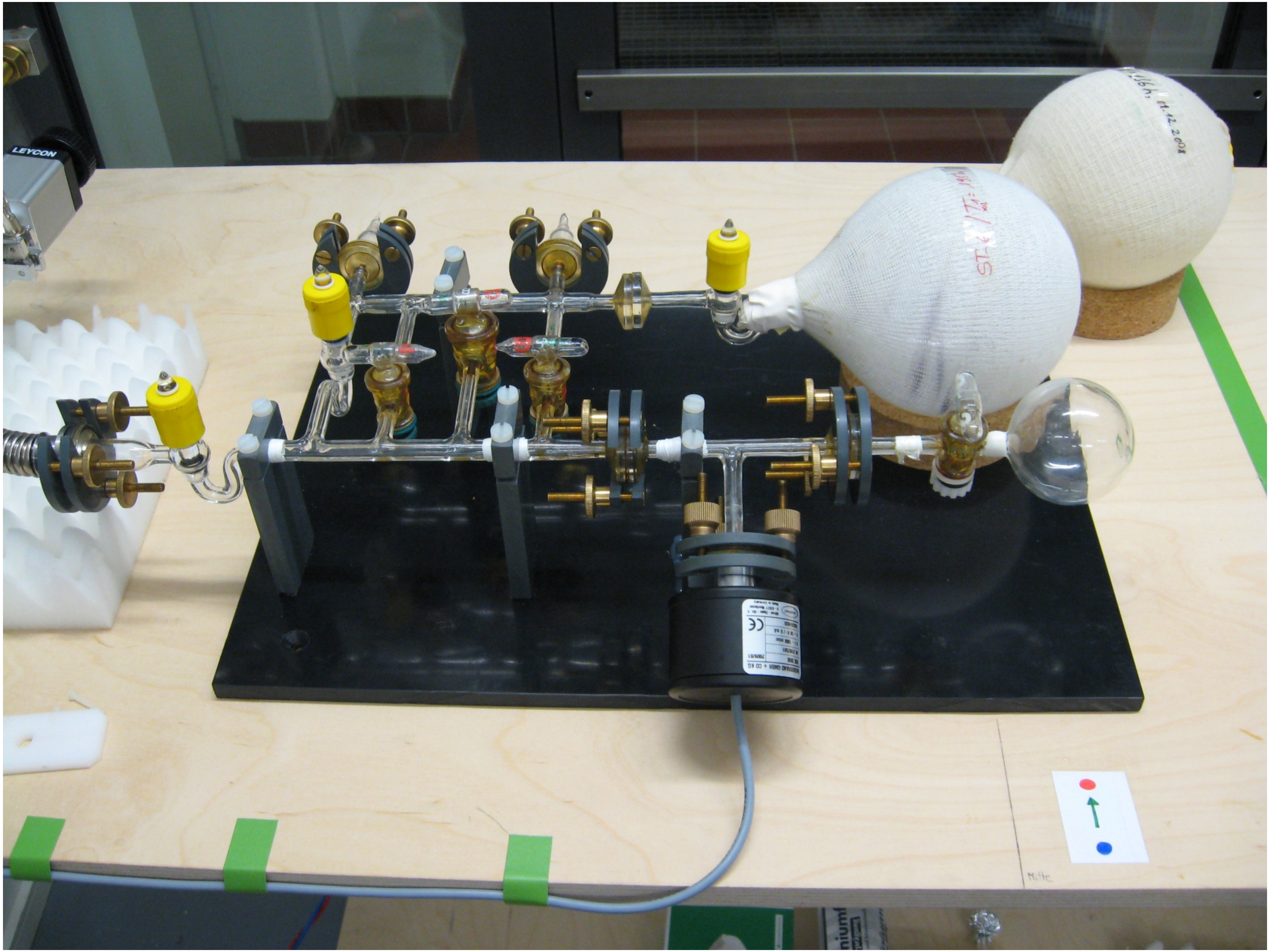




SEOP Polarizer PTB: Xe






LEYCON

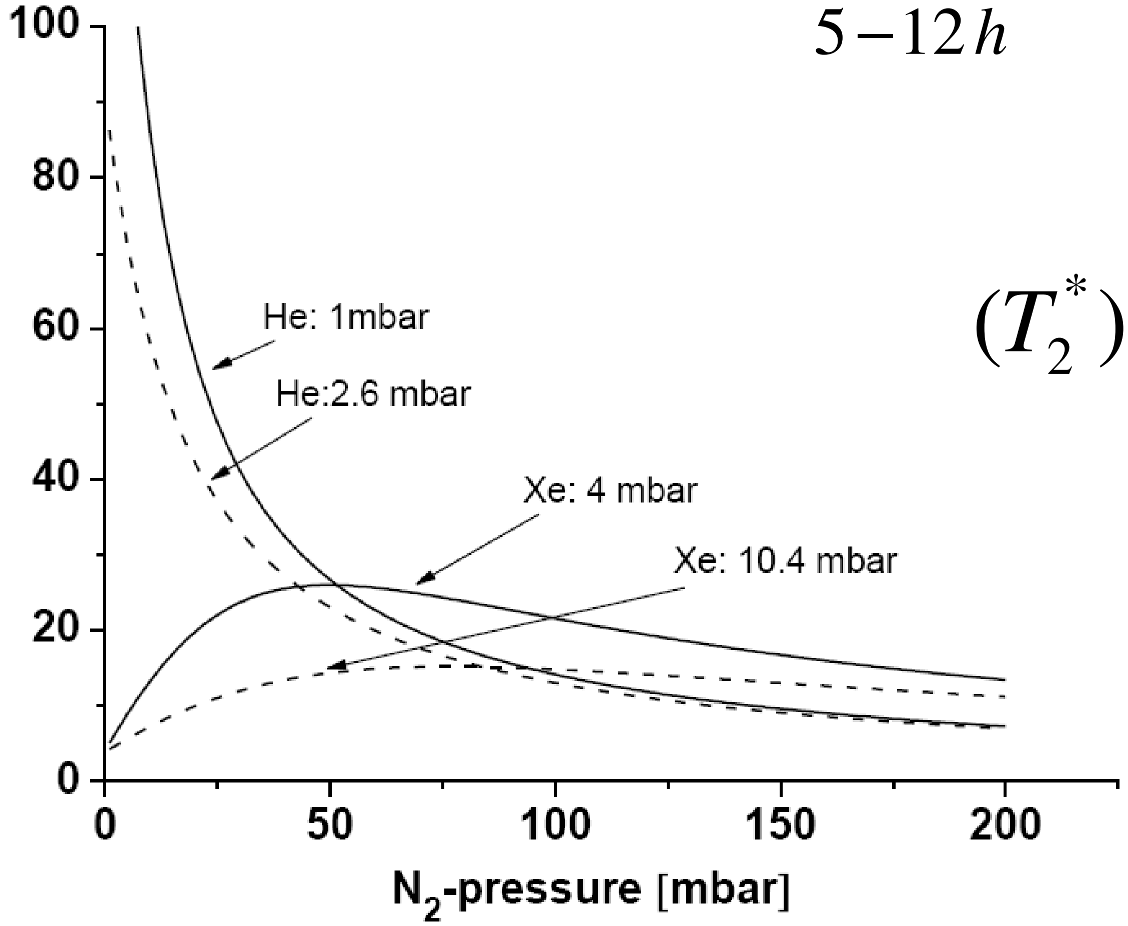
Relaxation of ^{129}Xe

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

$T_{1,wall}$: $5-12\,h$

$T_{1,vdW}$: $\frac{1}{4.1h} \cdot \frac{1}{(1+1.05\cdot[N_2]/[Xe])}$

$\left(1/T_{1,vdW} + 1/T_{2,field}\right)^{-1}[h]$



$$(T_2^*)_{Xe} \approx 3-6\,h$$

(measured)

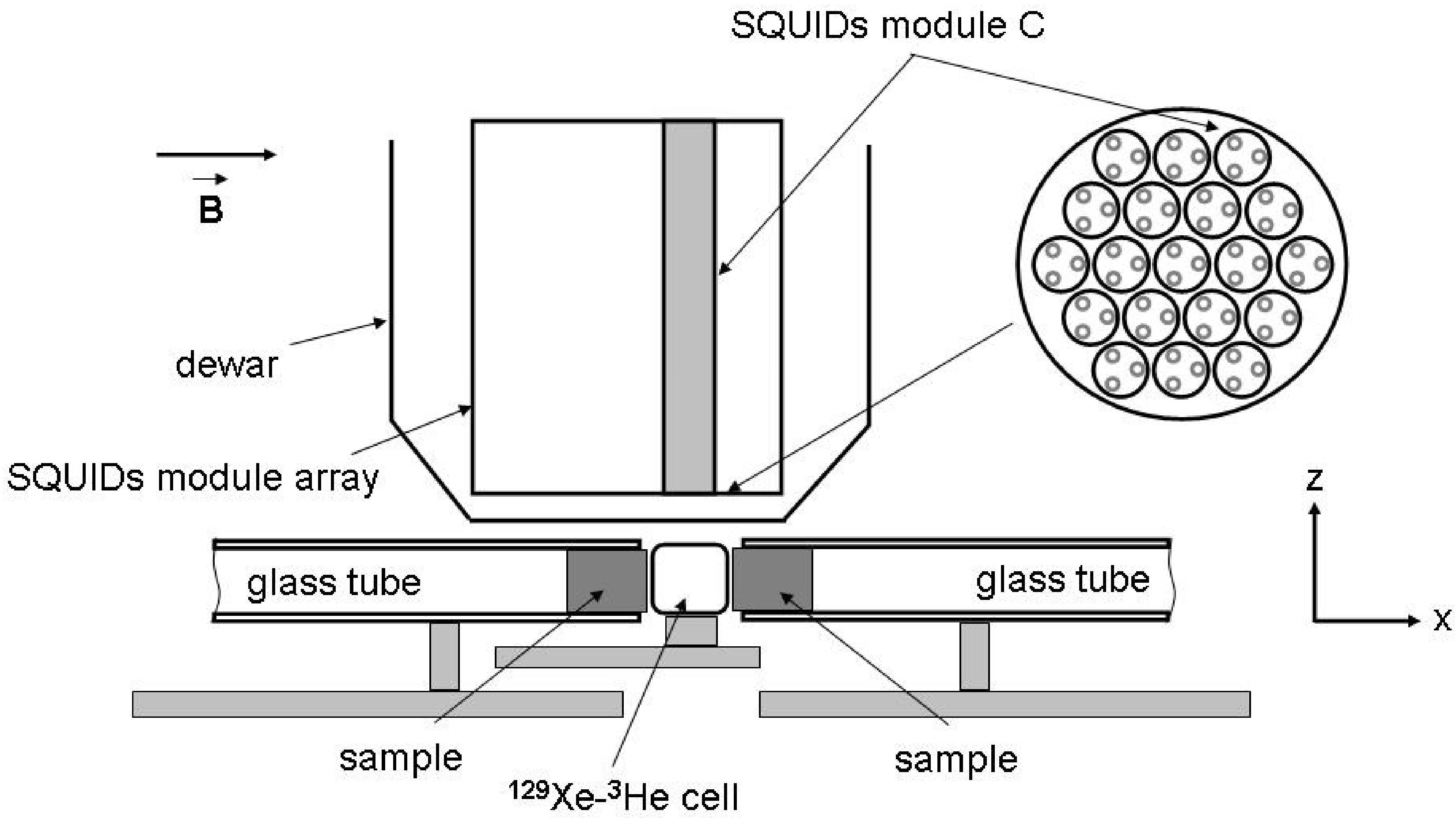
^{3}He/^{129}Xe clock-comparison experiments

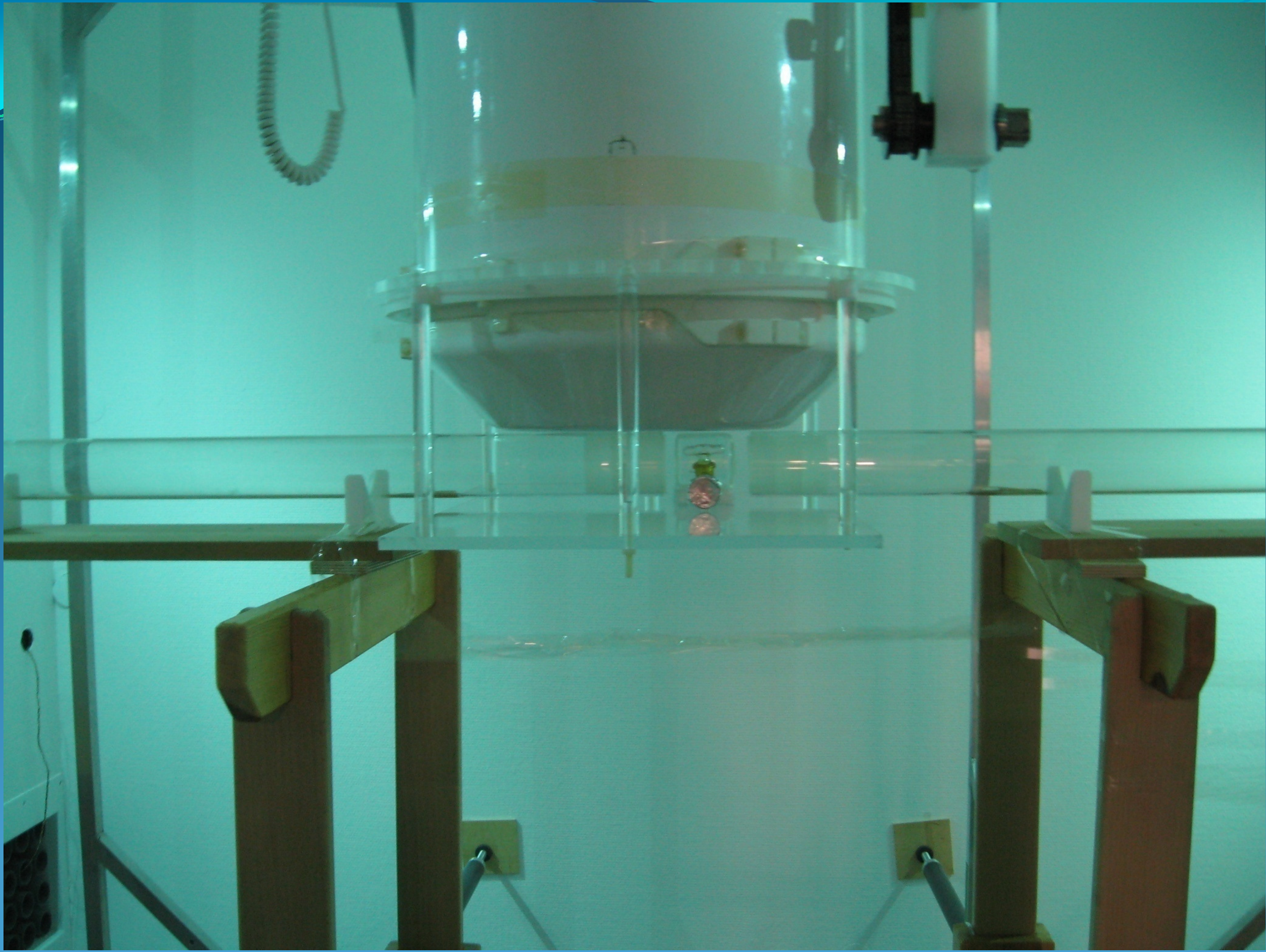
$$\Delta\omega = \omega_{L,He} - \frac{\gamma_{He}}{\gamma_{Xe}} \cdot \omega_{L,Xe} \neq 0$$

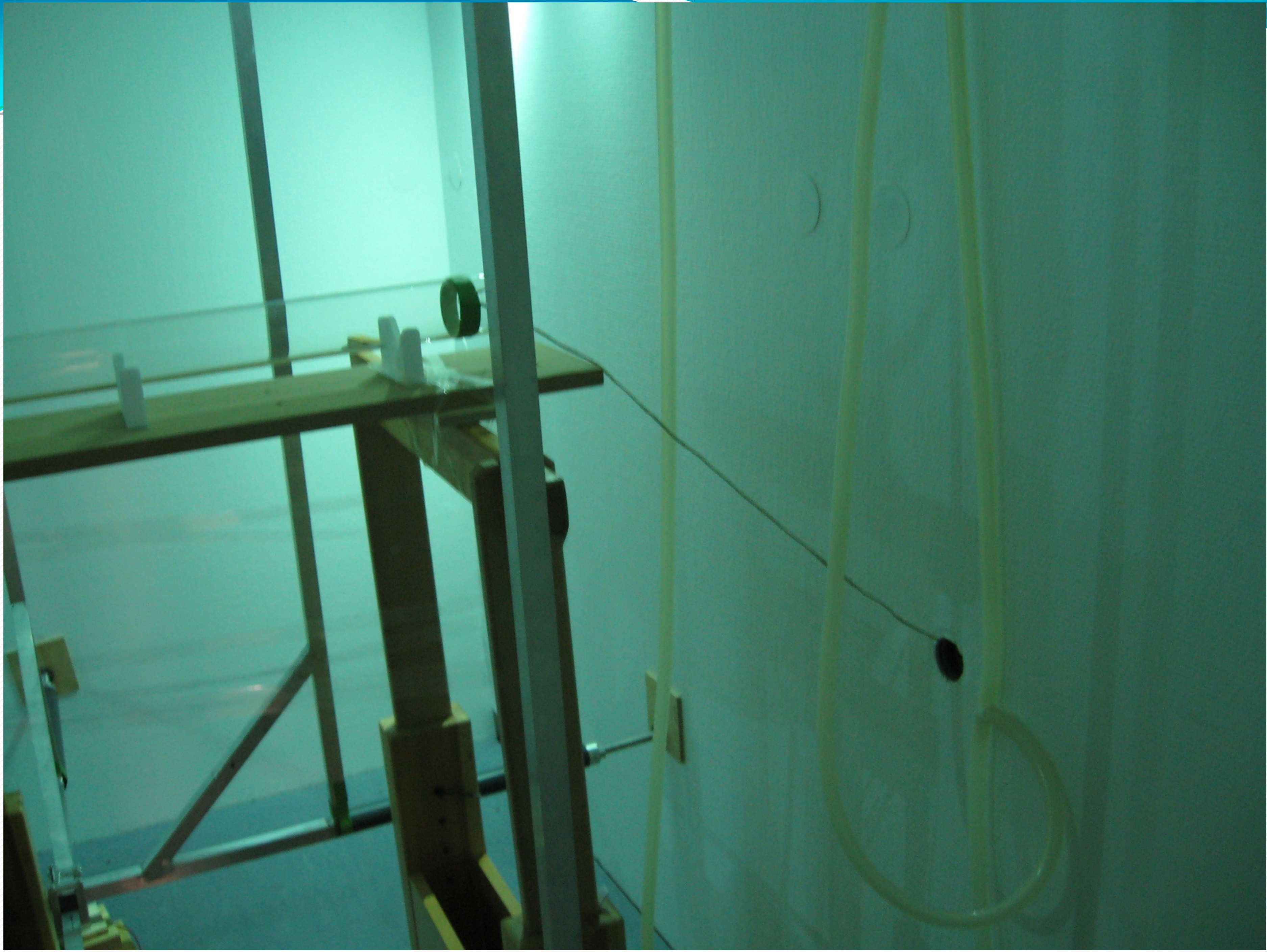
The detection of the free precession of co-located ^{3}He/^{129}Xe sample spins can be used as ultra-sensitive probe for
non-magnetic spin interactions

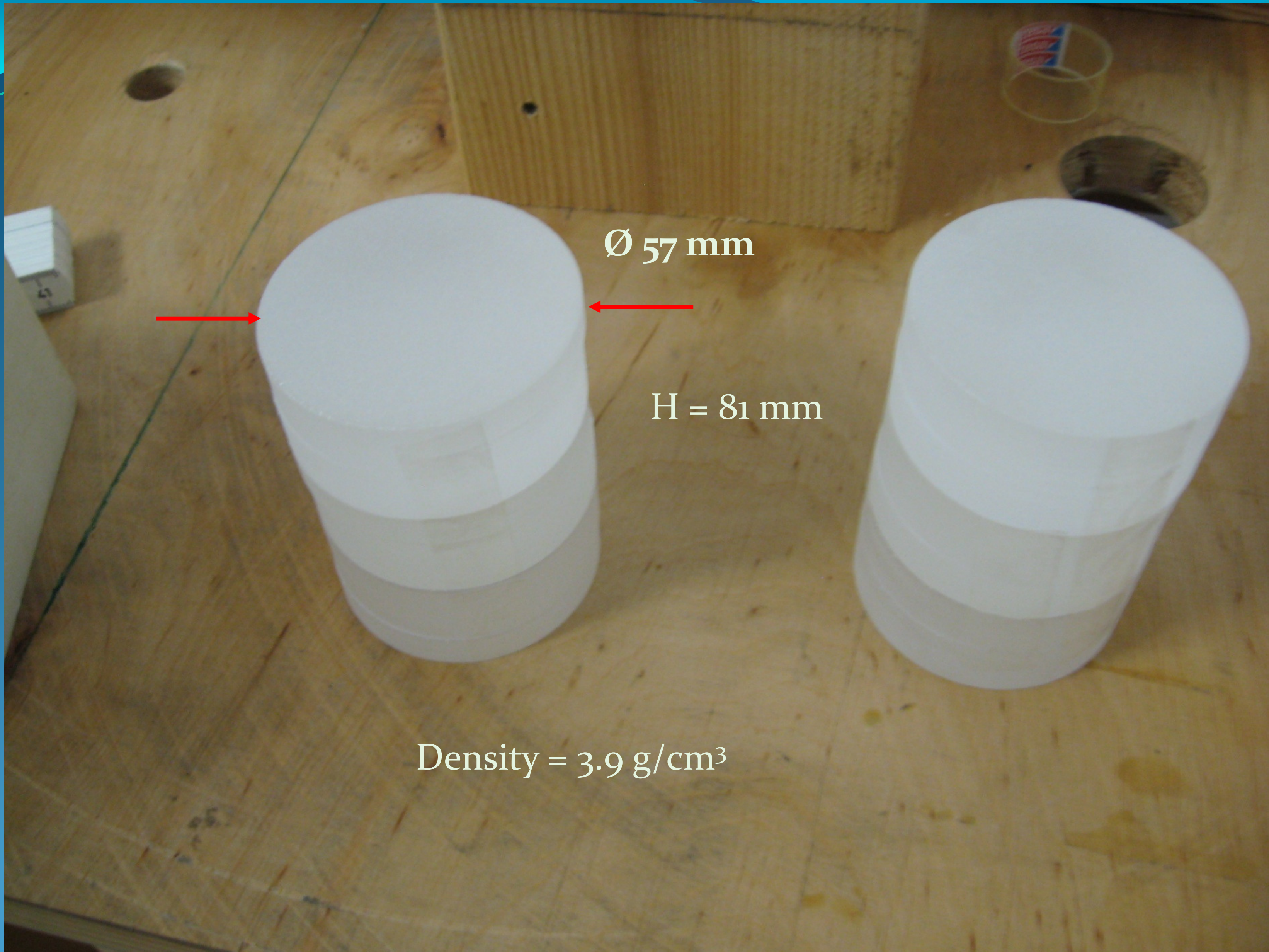
- Search for a Lorentz violating sidereal modulation of the Larmor frequency
- Search for spin-dependent short-range interactions
- Search for EDM of Xenon

Lay-out of experimental setup









Lead glass samples

Results for transverse relaxation time:

Measurement: sample(s)	Mass sample(s) removal time / measurement time without sample (sec)	Gas mixture ^3He : ^{129}Xe : N_2 (mbar)	^3He / ^{129}Xe initial amplitude (pT)	Relaxation time T^*_2 ^3He / ^{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

Two methods for extraction of amplitude and phase of the signal:

Direct fit of signal*

Minimization of sum of the squared residuals:

$$\sum_i \left[Y_i - F(t_i, \vec{a})\right]^2,$$

$$F(t_i, \vec{a}) = a_0 + a_1 \sin(a_2 t + \Phi_{He})$$
$$+ a_3 \sin(a_4 t + \Phi_{Xe})$$

a_i are assumed as constant parameters for given sample -> all measurement should be divided in short intervals. Then He,Xe signal phases vs. time can be found as simple sum:

$$\varphi_{He,Xe}(t_k) = \sum_{i=0}^{k} a_{2,4|i} \cdot \Delta t$$

while magnetic field magnitude for each time interval can be found as:

$$B_i = \gamma_{He,Xe} a_{2,4|i}$$

* Under development with help of U.Schmidt (Heidelberg)

„Digital lockin“ method:

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

- After that, a gaussian 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 $\boldsymbol{F}_{He(Xe)}(t)$. The phase $\Phi_{He(Xe)}(t)$ is found as

$$\varphi(t) = \arctan\left(\frac{\mathrm{Im}\left[F_{He(Xe)}(t)\right]}{\mathrm{Re}\left[F_{He(Xe)}(t)\right]}\right)$$

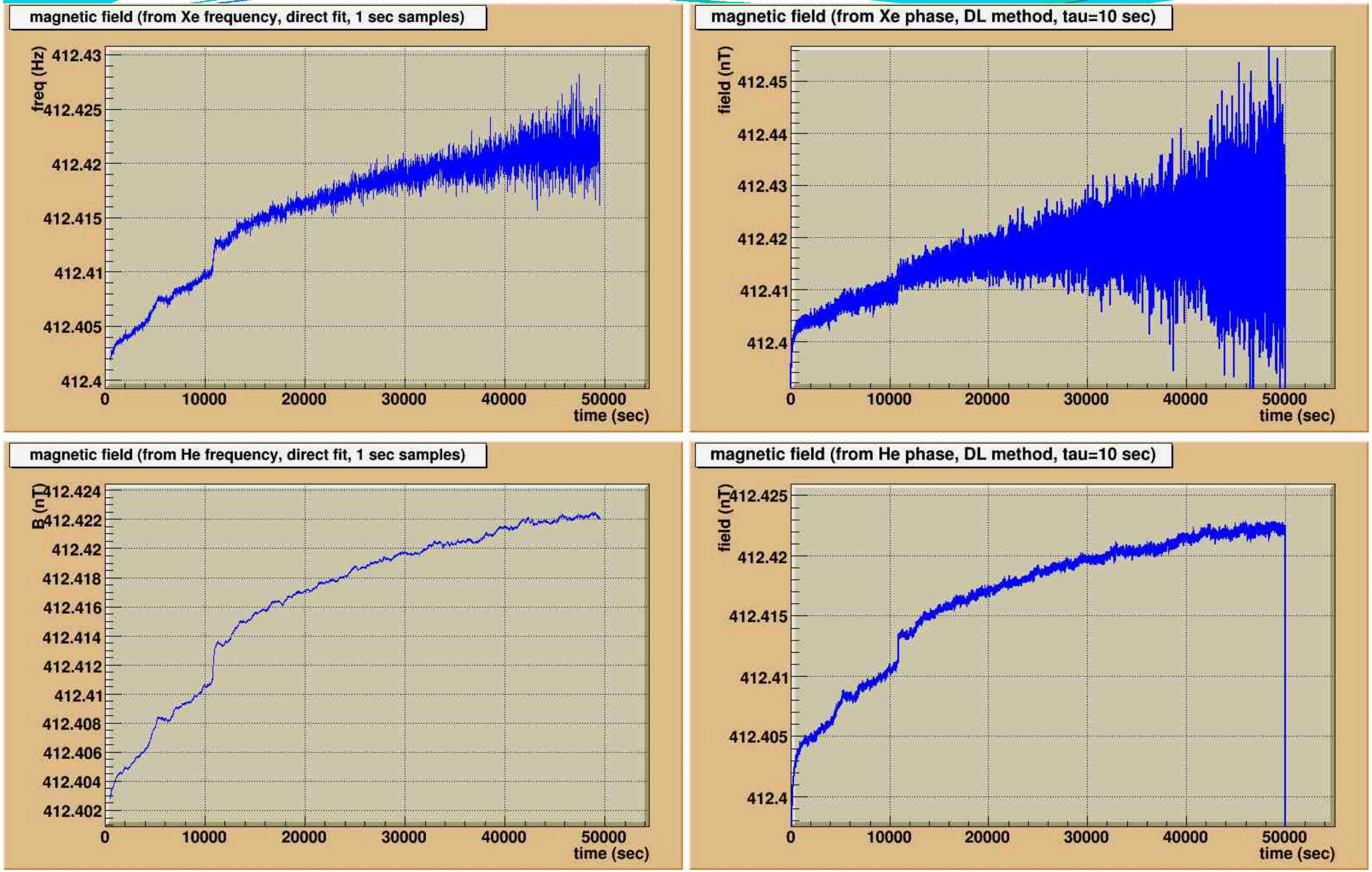
and the amplitude is $|\,\boldsymbol{F}_{He(Xe)}(t)\,|$

→ Consecuently errors of phase fit should be scaled with factor:

$$r = \sqrt{(2\sqrt{\pi} \cdot \text{sample\_rate} / \omega_{cut})}$$

→ Precession frequencies and magnetic field magnitude can be found via numerical time derivative from phases $\Phi_{He(Xe)}(t)$

Comparison of results of two methods for obtaining of magnetic field magnitude:



with direct fit

with digital lockin method

Further data processing for extraction of short-range interaction effect:

1. To cancel magnetic field influence we calculate from He,Xe phases the following weighted phase difference:

$$\Delta\varphi(t) = \varphi_{He} - \frac{\gamma_{He}}{\gamma_{Xe}} \cdot \varphi_{Xe}$$

2. Make polynomial fit $a_0 + a_1 t + a_2 t^2 + ..$ of $\Delta\varphi(t)$ for measurements with sample and without

3. Compare linear terms $\nu = a_1 / 2\pi$ of fit

Preliminary results for left and right samples (with direct fit method):

Right sample $\Delta\nu$ = 10.6 ± 1.7 nHz $\propto \Delta B$ = 0.33 ± 0.05 fT

Left sample $\Delta\nu$ = 9.7 ± 1.7 nHz $\propto \Delta B$ = 0.30 ± 0.05 fT

=> $\delta\nu = \frac{1}{2} (\Delta\nu_{\text{right sample}} - \Delta\nu_{\text{left sample}})$ = 0.9 ± 1.2 nHz

Possible false effects:

1. Effects due to paramagnetism or magnetization of samples (one sample shows 2 pT change in magnetic field after removal): distance between He and Xe mass centres Δz_{CM} ~ 0.1 µm is extremely small according to Maxwell-Boltzmann distribution:

$$\Delta z_{CM} \approx \int z \cdot e^{-\frac{m_{Xe} g z}{kT}} dV \;\; / \int e^{-\frac{m_{Xe} g z}{kT}} dV \; - \frac{1}{V} \int z dV$$

-> therefore expected effects should be << 1 fT

2. Effects due to temperature variations, rotation of residual magnetic field inside magnetically shielded room
-> so far we have no information –> should be investigated!

3. Effect from demagnetization field of polarized precessing He, Xe gases inside cylindrical cell: we observed that weighted phase difference is not constant in time and depends on He and Xe transverse polarization:

$$\Delta\varphi(t) \sim A e^{-t/T_{2He}} + B e^{-t/T_{2Xe}}$$

-> we used approximation by polynom-fit

Limitation on short range spin-dependent interaction:

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

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

V*(r) is coordinate dependent part of V(r).

Average potential <V*(r)> 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.

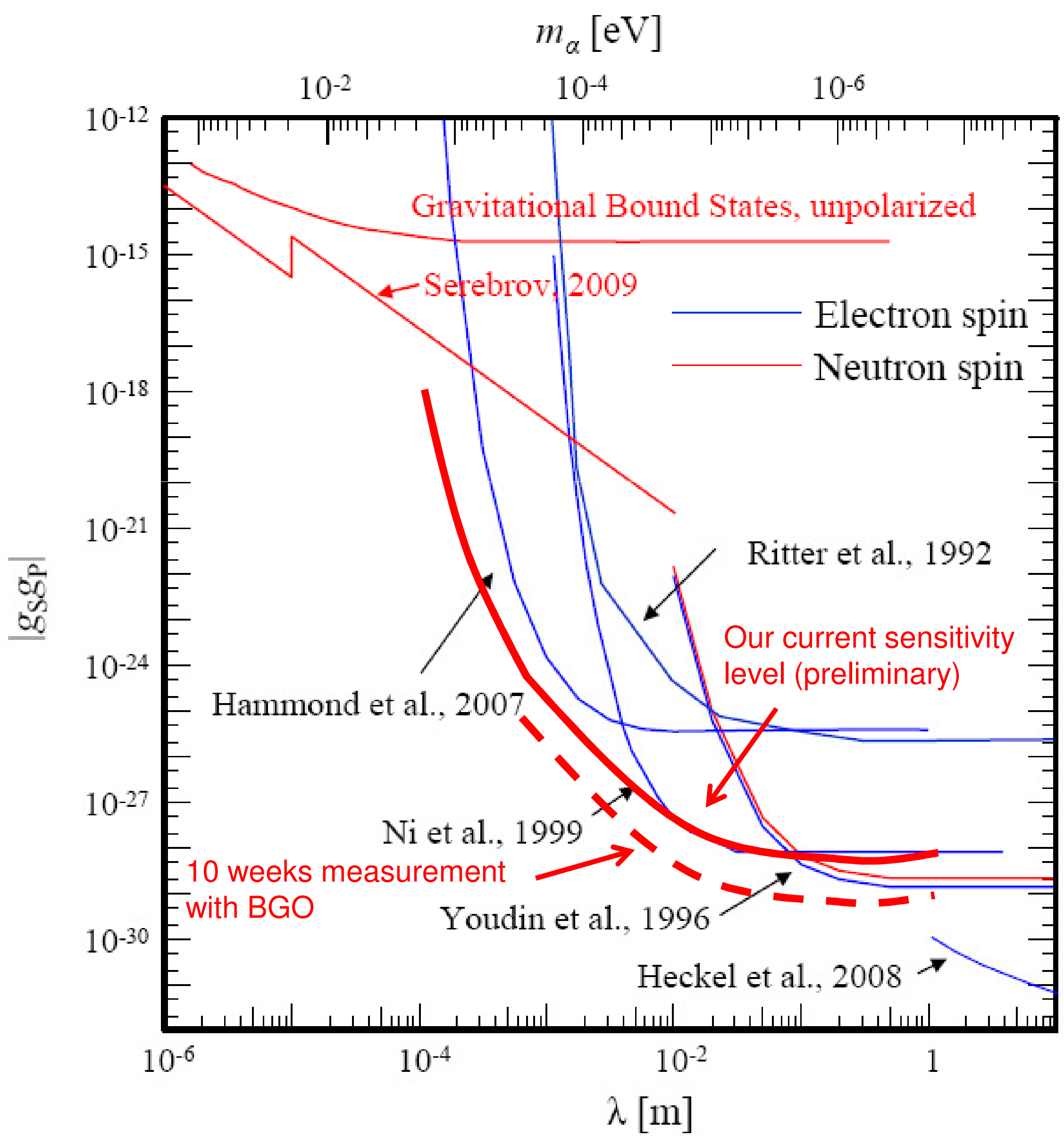
Next, from the measured value of δν we get

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

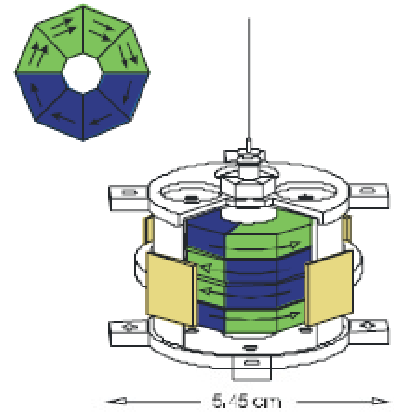
where $V = 2.07 \cdot 10^{-4}\ m^{-3}$ is volume of lead glass sample,
$N = 2.3 \cdot 10^{30}\ m^{-3}$ is its number density,

Result for sensitivity level δν ≈ 1.2 nHz is presented in next transparency.

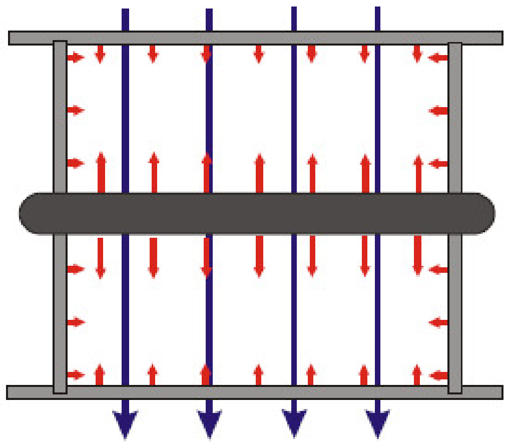
Exclusion Plot for new spin-dependent forces



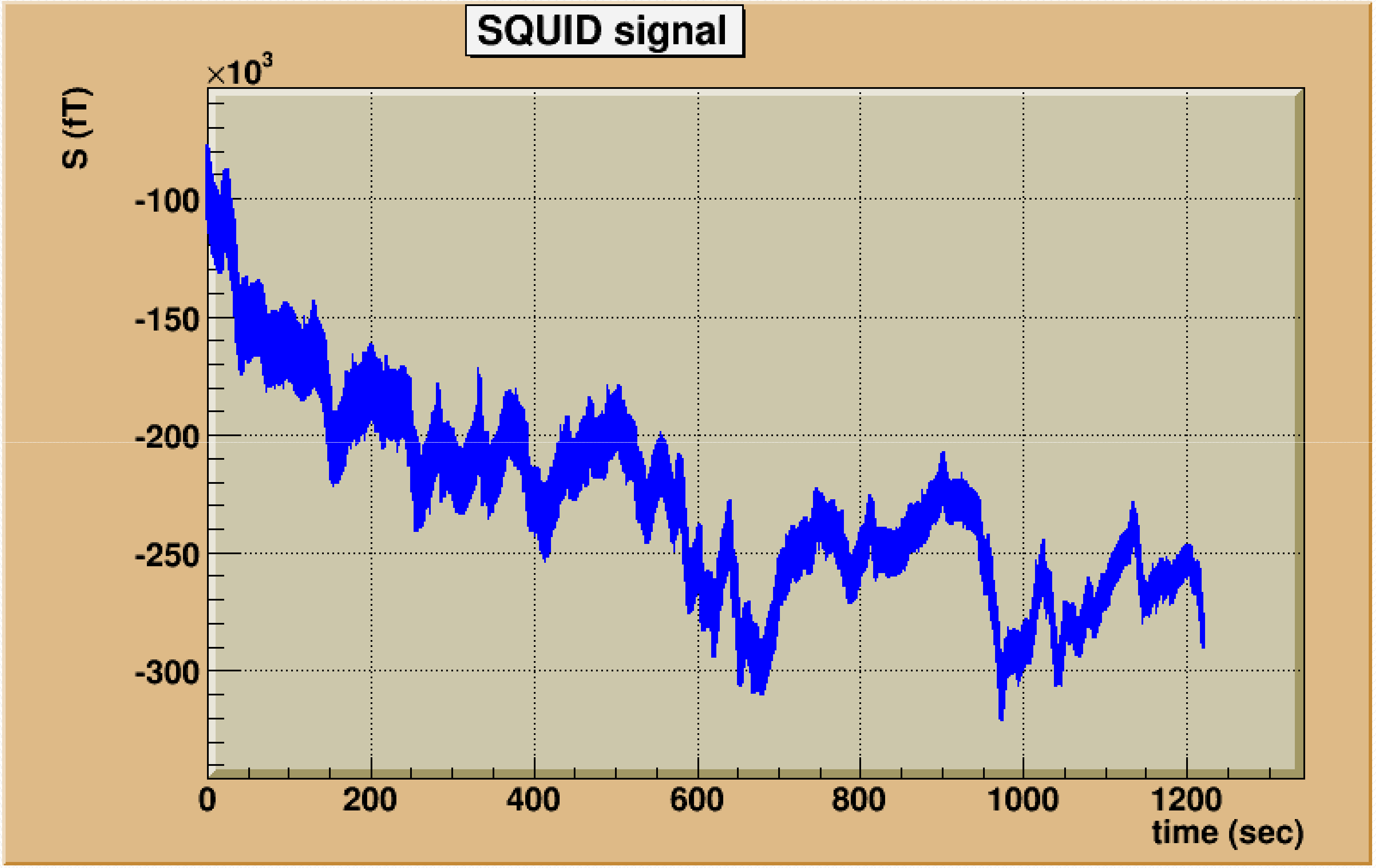
Heckel et al., 2008:



Serebrov 2009, Zimmer 2008:

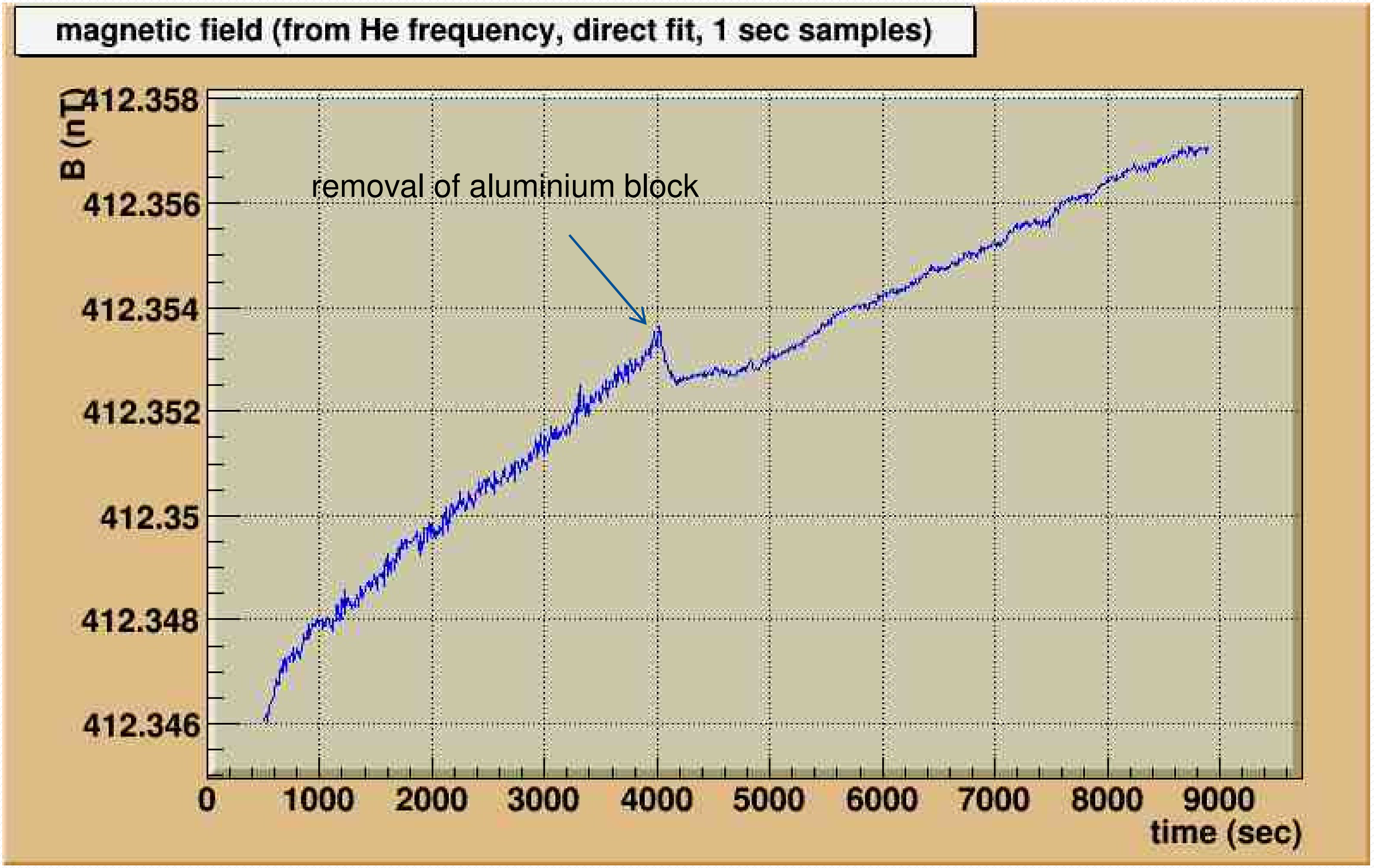


SQUID signal near block of bismuth*



*Goodfellow, ferromagnetic admixtures < 1 ppm.

Magnetic field measured by SQUID via He precession signal in presence of block of aluminium (diameter 56 mm length 70 mm)



Conclusion and Outlook

• A novel $^{3}He/^{129}Xe$ 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 investigation of possible systematic effects and on materials suitable for samples for such measurements can give an opportunity to improve significantly existed constrains.