Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin
Nationales Metrologieinstitut

Nuclear spin precession in ultra low fields
- a probe for new physics

Lutz Trahms
Physikalisch-Technische Bundesanstalt
Berlin

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Experimental Setup

Ultra-low magnetic fields

Magnetic sensors

Co-magnetometry

Search for exotic interactions

Nuclear magnetic moments

Axion wind

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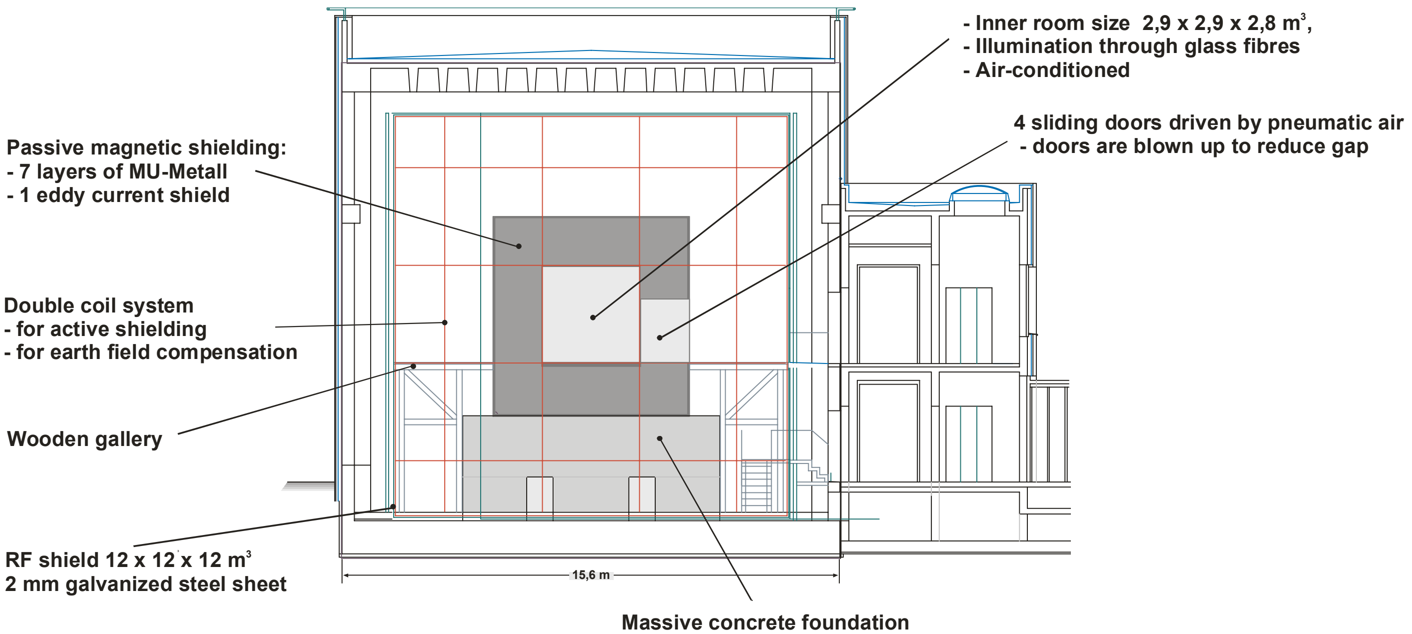
Ultra-low magnetic fields



Berlin Magnetically Shielded Room - 2

Ultra-low magnetic fields

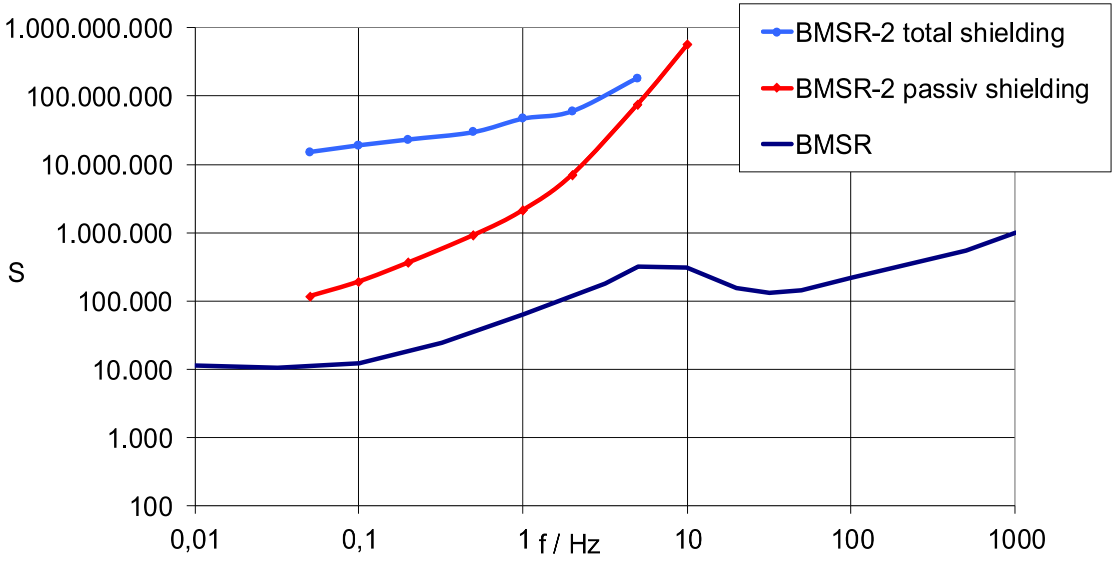
Berlin Magnetically Shielded Room - 2

- Passive magnetic shielding
  7-layers of mu-metal
- One eddy-current layer
- Active shielding coil system
  (feedback control)
- Shielding performance @ 0.1Hz

  Passive shielding: $2 \cdot 10^5$
  With active shielding: $2 \cdot 10^7$

2016

Ultra-low magnetic fields



	Residual Field	Homogeneity	Stability
2017	500 pT	0.2 pT/mm	2 pT/h
2018	100 pT	0.02 pT/mm	0.2 pT/h

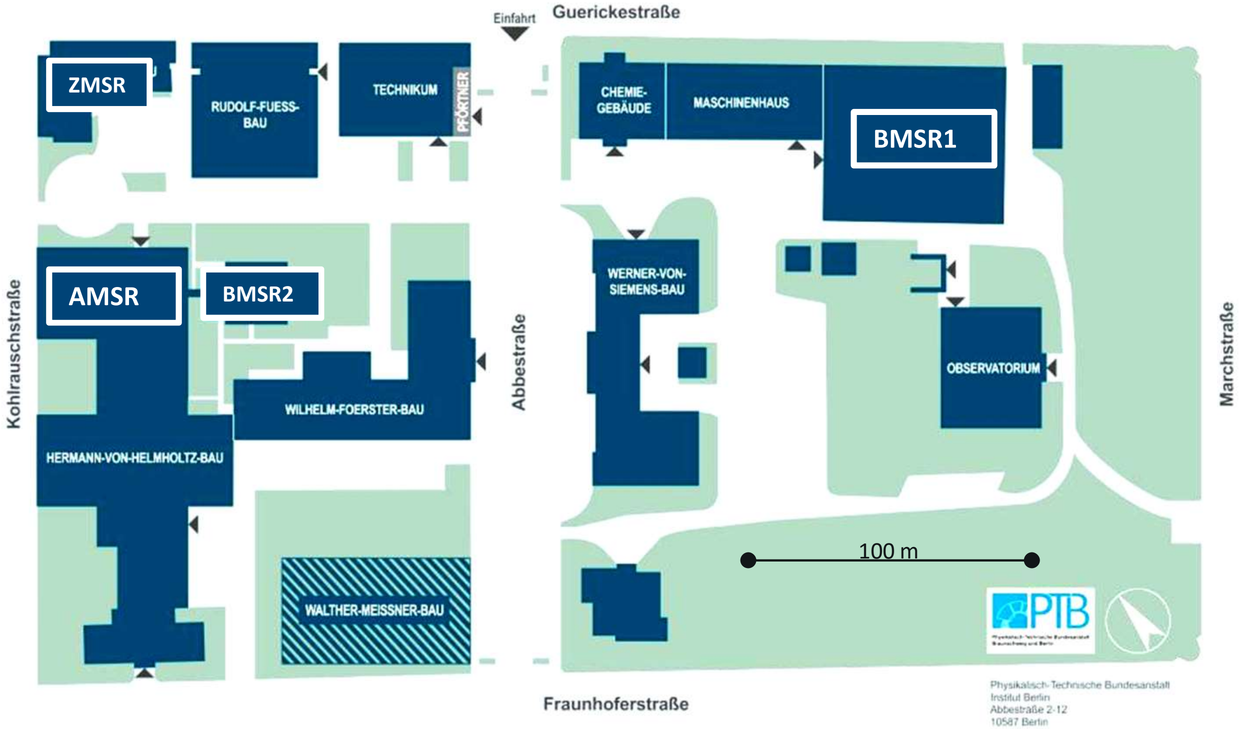
Upgrade 2018:

Add another mu-metal layer

Upgrade the temperature control

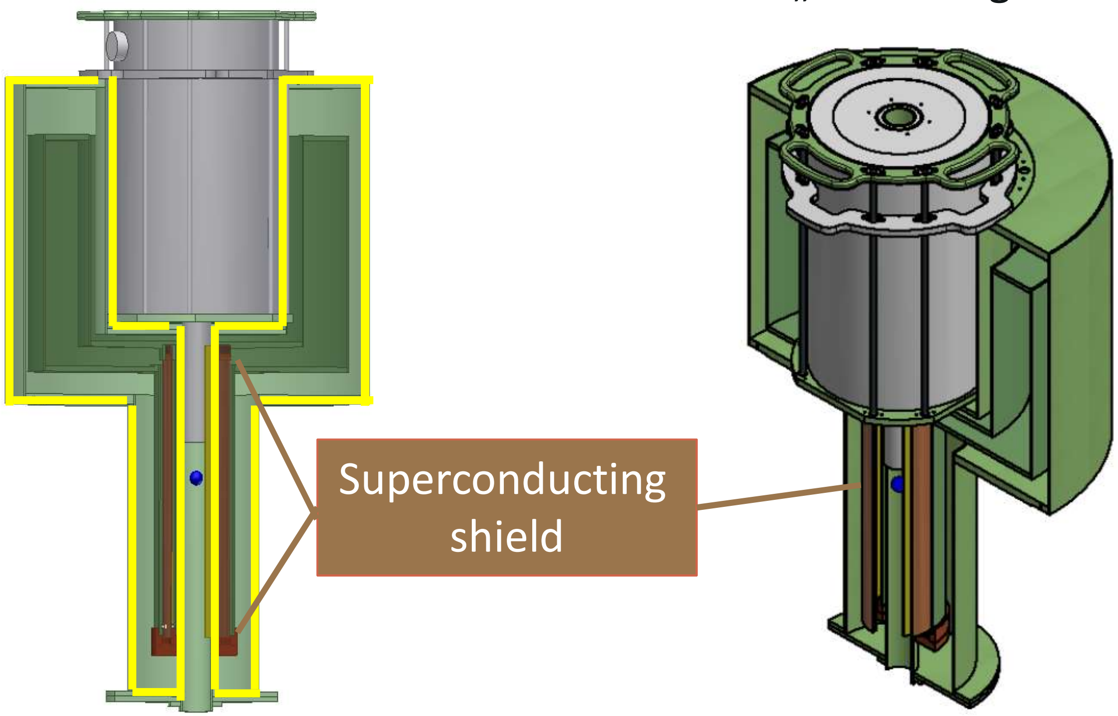
Ultra-low magnetic fields

PTB Campus Berlin



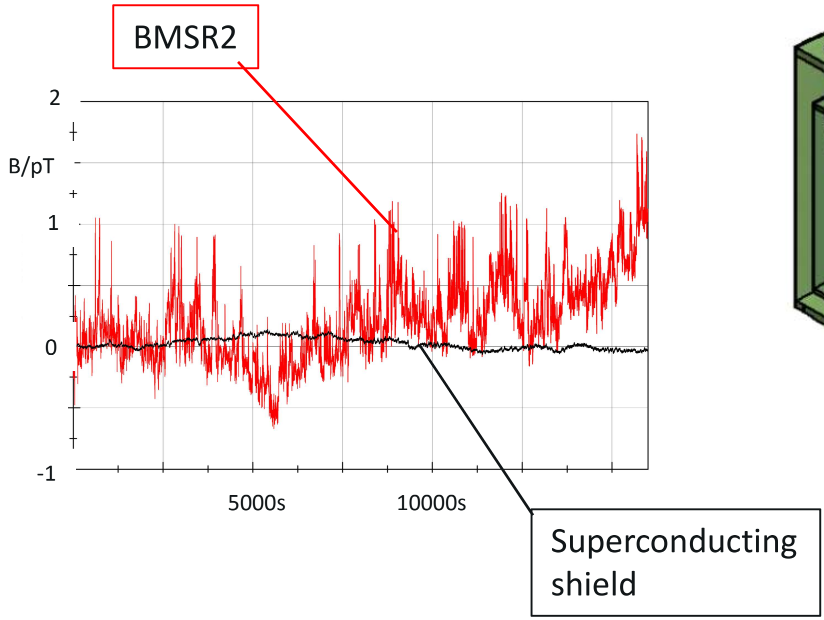
Ultra-low magnetic fields

The „Micromagnet“

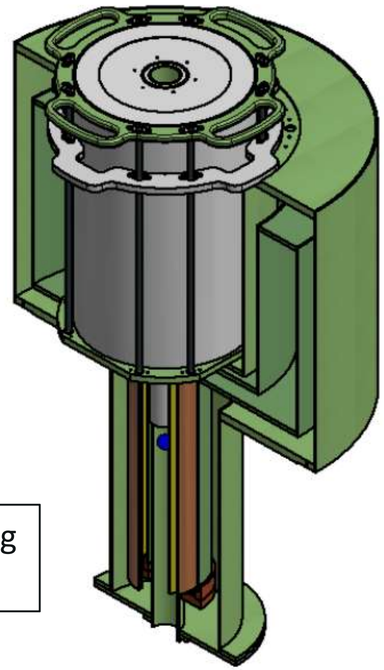


2018

Ultra-low magnetic fields

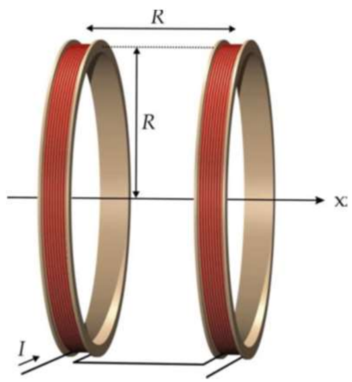


The „Micromagnet“



Ultra-low magnetic fields

Helmholtz-Coils inside BMSR-2

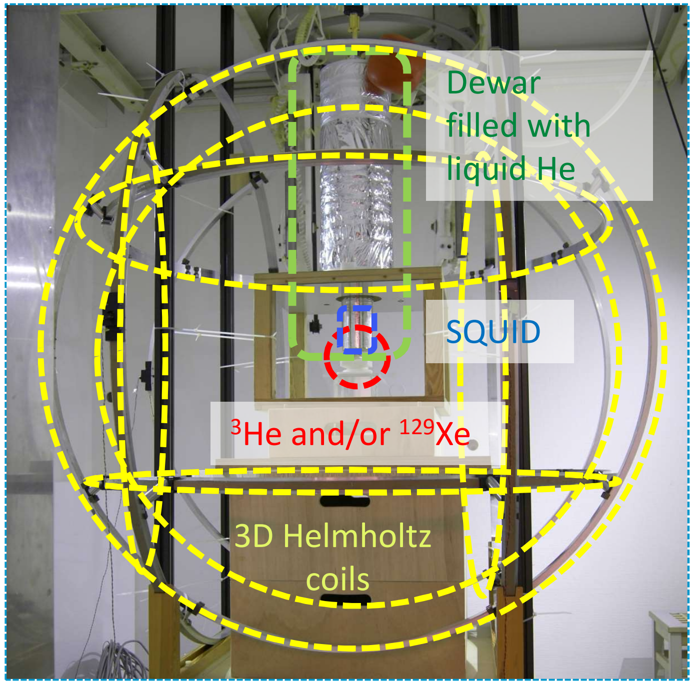


+

$\sim 1\mu T$

$< 0.5nT$

Ultra-low magnetic fields



Magnetic sensors

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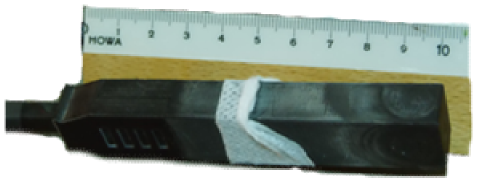
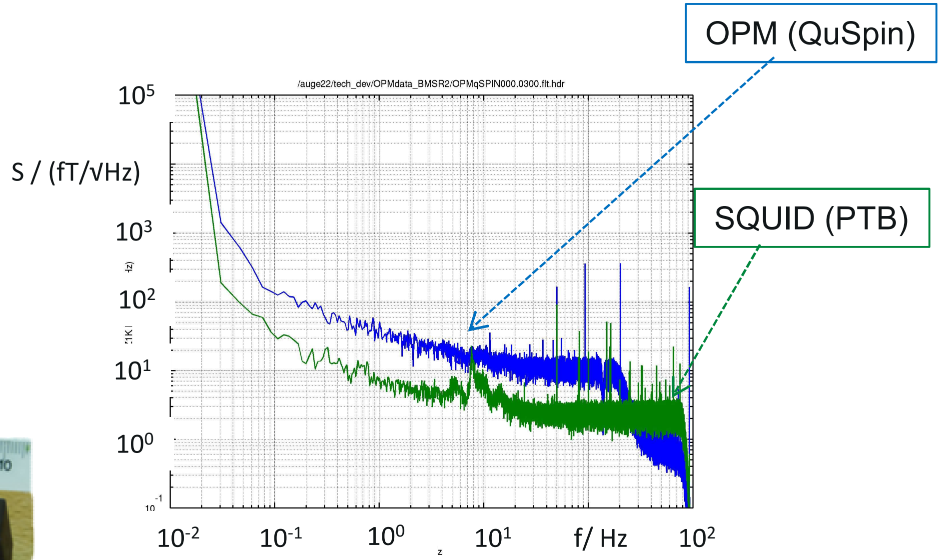
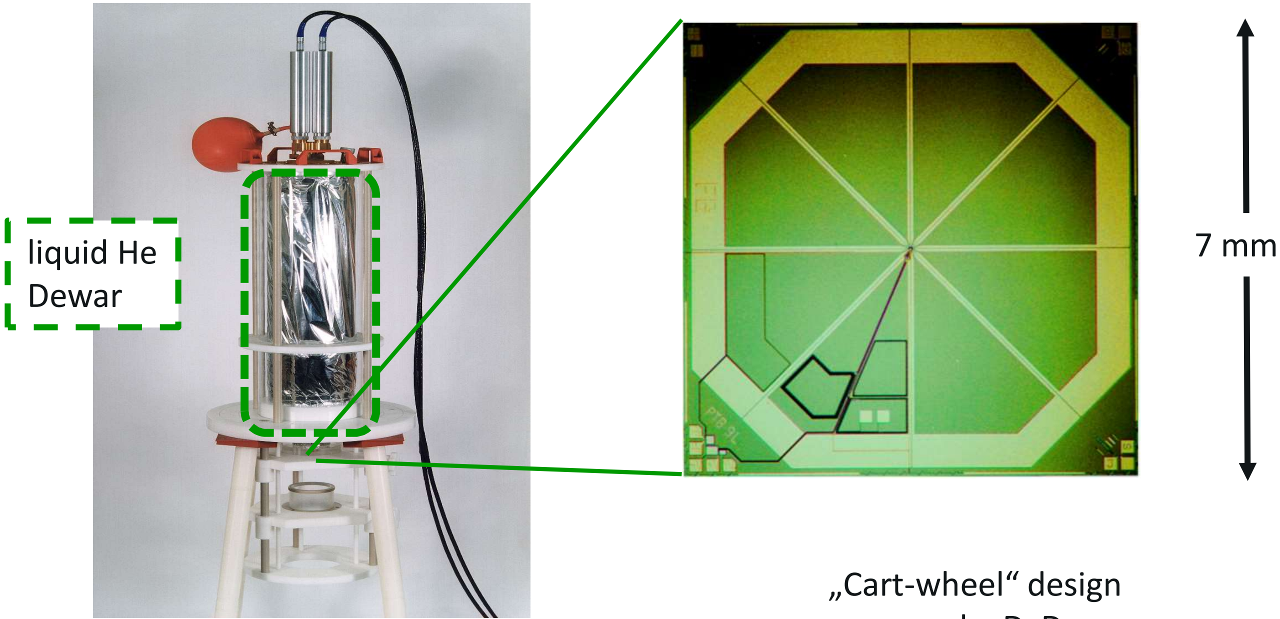
Magnetic sensors

Optically Pumped Magnetometer (OPM)





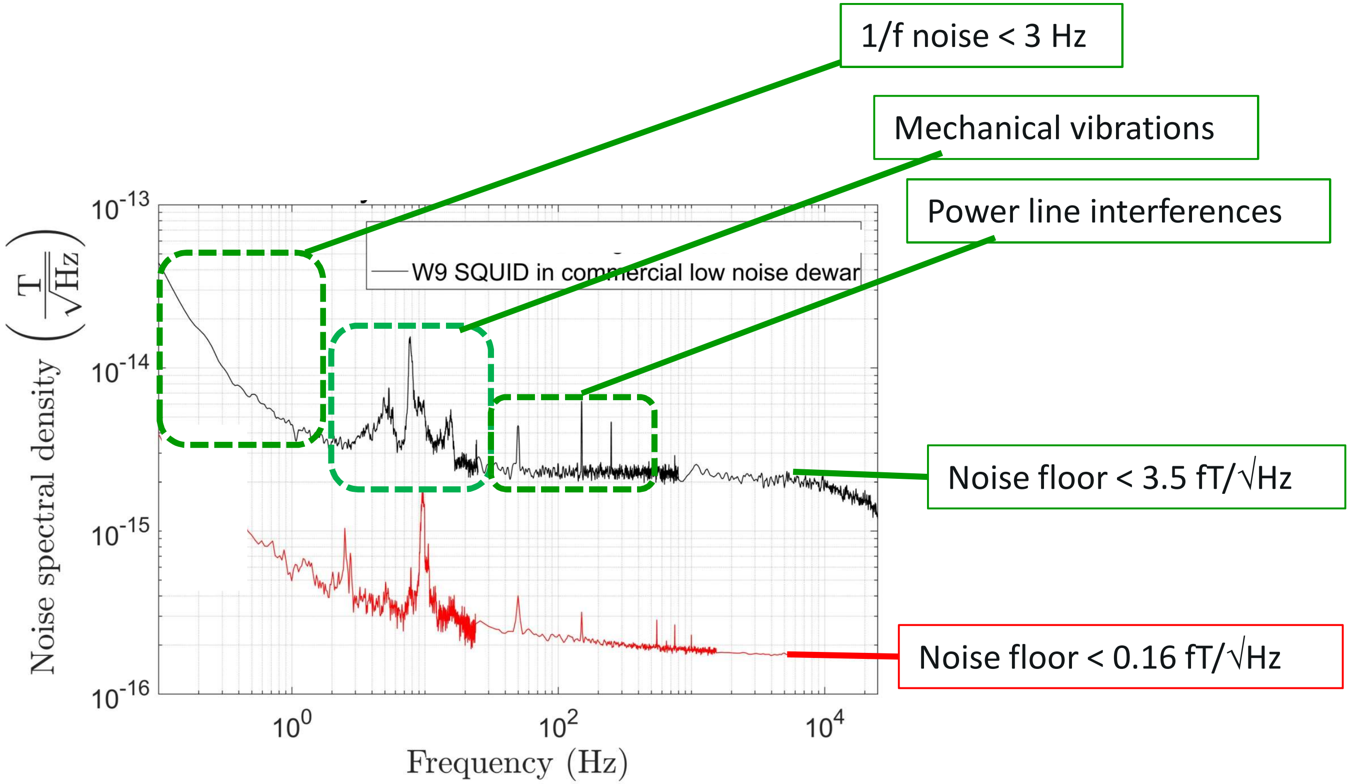
Superconducting Quantum Interference Device (SQUID)



„Cart-wheel“ design
by D. Drung

Magnetic sensors

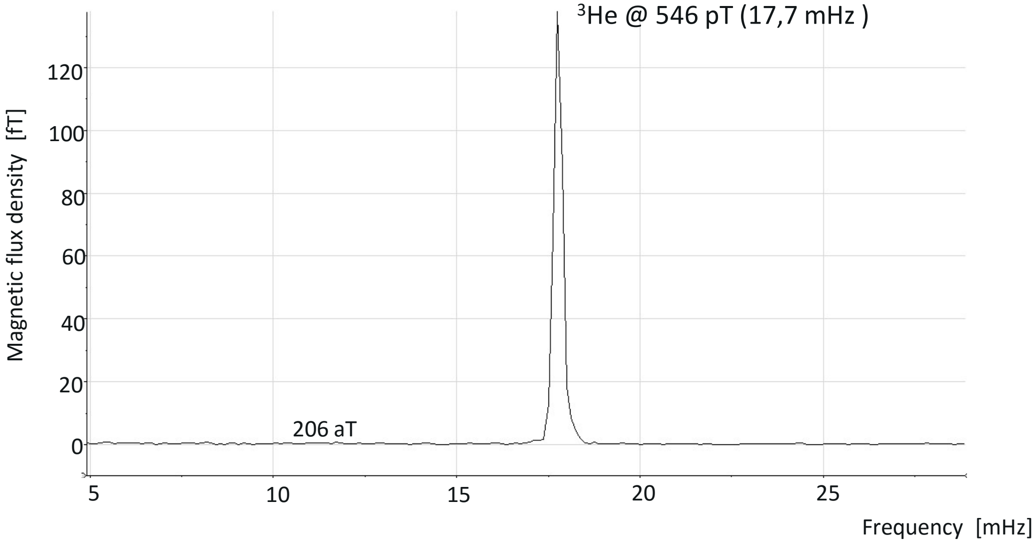
2017



Storm et al. APL, 2017

Magnetic sensors

^{3}He precession measured over 7000s



Core Facility „Metrology of ultra-low magnetic fields“

Since May 1st :

Core Facility offers access to external users


Divisions
Institutes at PTB
Institute for Experimental Quantum Metrology (QUEST)
Fundamental Physics for Metrology
Metrology for Functional Nanosystems
Core Facility "Metrology of Ultra-Low Magnetic Fields" of PTB
PTB Management
Conformity Assessment Body
Advisory Board ("Kuratorium")

Core Facility "Metrology of Ultra-Low Magnetic Fields" of PTB

Welcome to the Core facility "Measurement of Ultra-Low Magnetic Fields" of PTB

Since 1 May 2017, the Physikalisch-Technische Bundesanstalt operates a new Core Facility called "Metrology for Ultra-Low Magnetic Fields" on its site in Berlin-Charlottenburg. Funded by the Deutsche Forschungsgemeinschaft (DFG), PTB grants external scientists from universities, from international metrology institutes and from companies access to its know-how and to its equipment with instruments for the measurement of ultra-low magnetic fields – equipment which is unique in the world.

CONTACT

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Address
Physikalisch-Technische Bundesanstalt
Abbestraße 2–12
10587 Berlin

CO-WORKERS

Core Facility „Metrology of ultra-low magnetic fields“

Scientist 1: Development of magnetic metrology (Jens Voigt)

Scientist 2: Scientific support of external users

Engineer : Management and technical support of external users

DFG-funded

Open positions!

Experimental Setup

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- Co-magnetometry

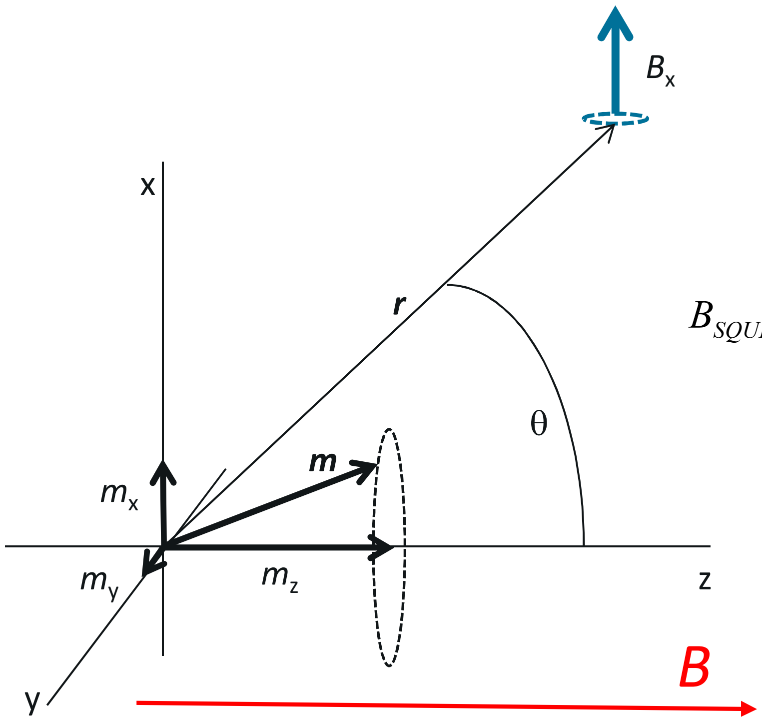
Search for exotic interactions

- Nuclear magnetic moments
- Axion wind

Co-magnetometry

Polarizing ^{3}He and ^{129}Xe

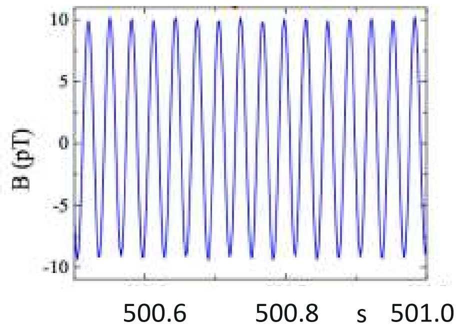
Co-magnetometry



$$m_x(t) = m_\perp^0 e^{-t/T_2^*} \cos \omega t$$
$$m_y(t) = m_\perp^0 e^{-t/T_2^*} \sin \omega t$$
$$m_z(t) = m_z^0 e^{-t/T_1}$$

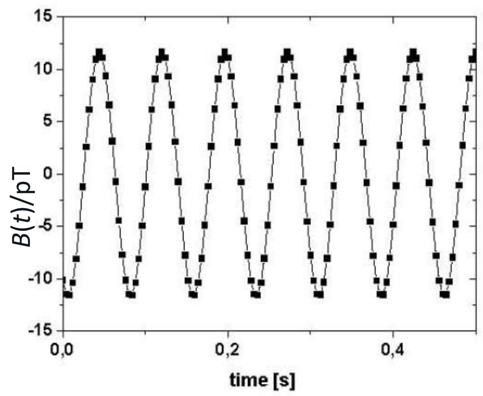
Signal seen by SQUID:

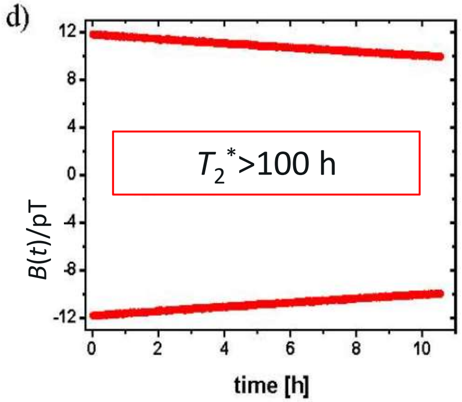
$$B_{SQUID} = B_X(t) = \frac{\mu_0}{4\pi \cdot |\vec{r}|^3} \cdot \left(\frac{3x^3 m_X(t) \vec{e}_X}{|\vec{r}|^2} - m_X(t) \vec{e}_X \right)$$



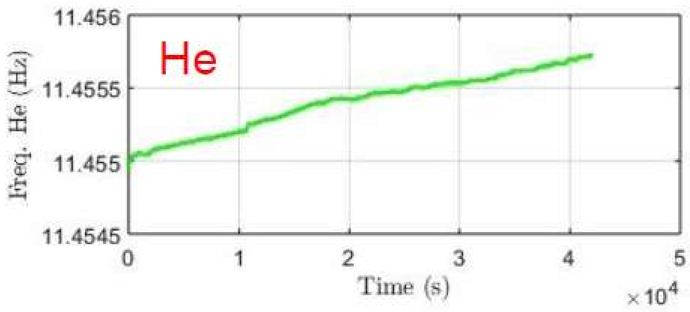
Co-magnetometry-

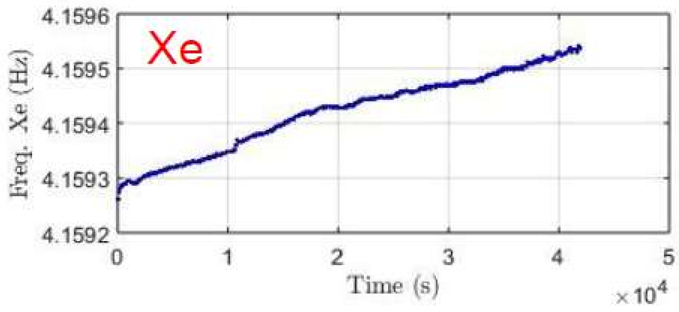
Nuclear precession as measured by a SQUID





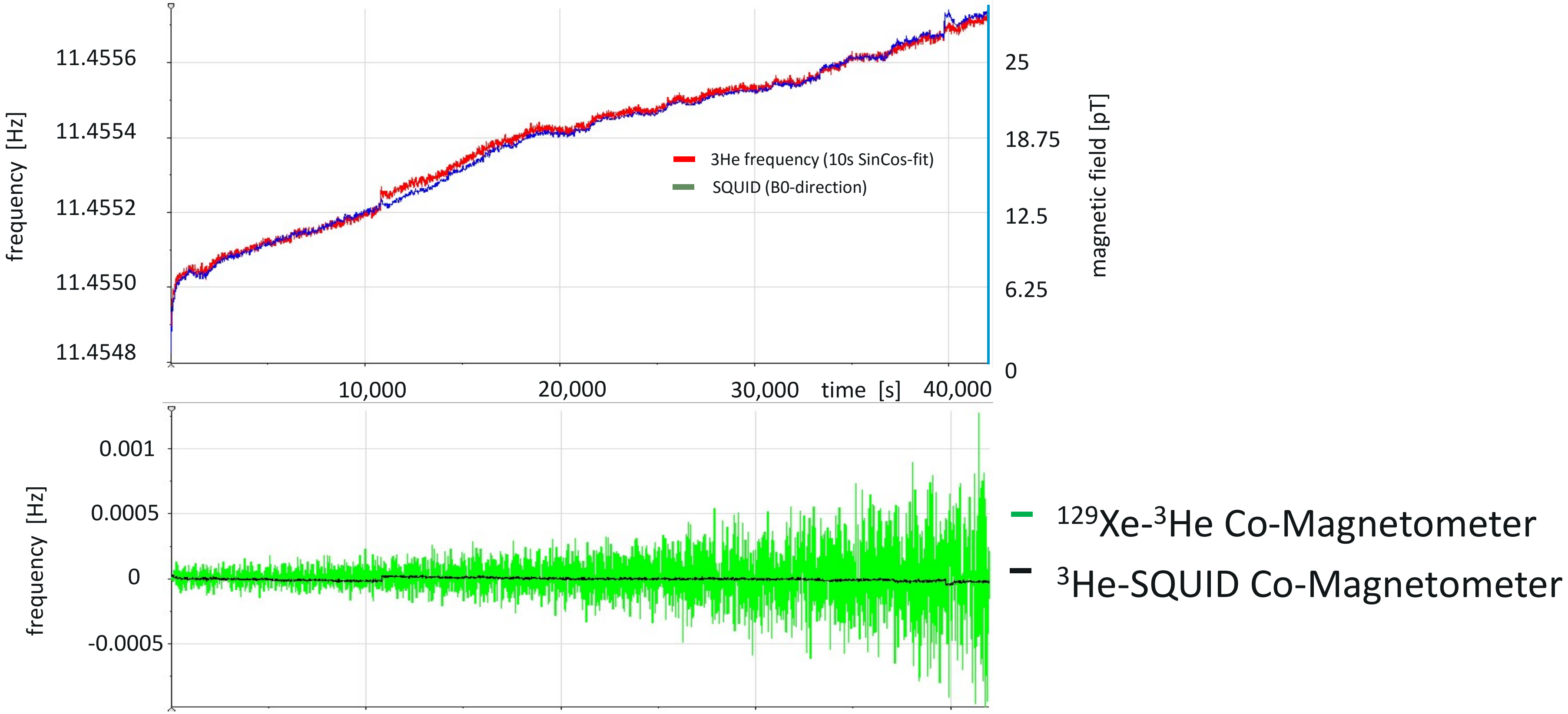
^{3}He





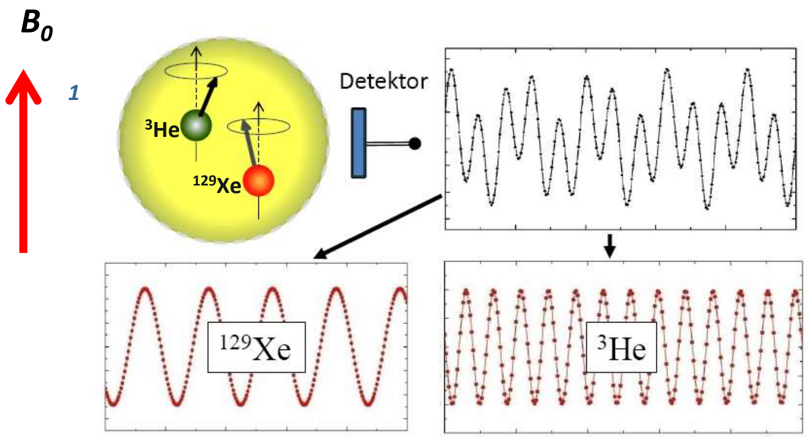
Co-magnetometry

Stabilizing the field by using the SQUID

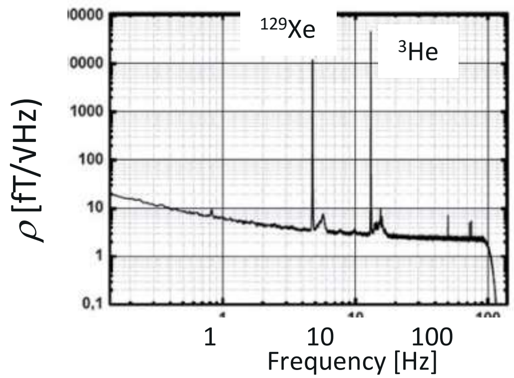


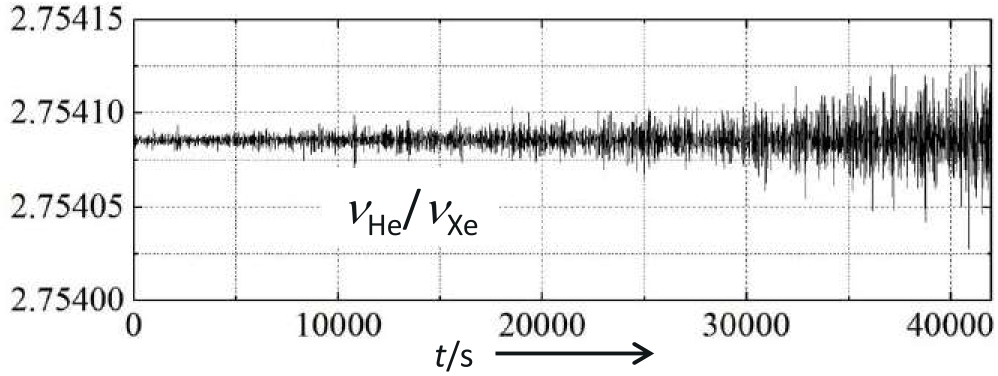
Co-magnetometry

NN-Co-magnetometry :
Observing two spin species (^{3}He and ^{129}Xe)in one cell

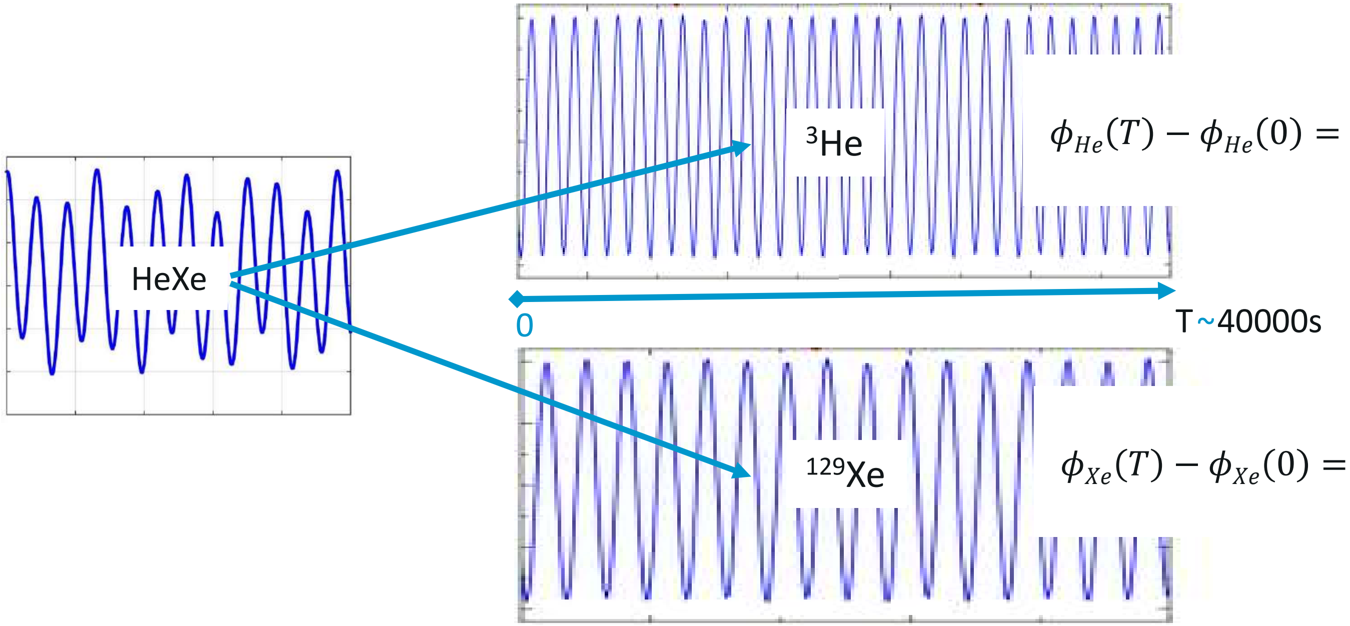


- Superposition of two frequencies
- Blockwise calculation of ν_{He}/ν_{Xe} eliminates the drifts
- The faster decay limits frequency resolution





Co-magnetometry



$$\phi_{He}(T) - \phi_{He}(0) = \gamma_{He} \int_0^T B(t)dt = T\bar{B}$$

$$\phi_{Xe}(T) - \phi_{Xe}(0) = \gamma_{Xe} \int_0^T B(t)dt = T\bar{B}$$

Even in the presence of magnetic field drifts,
its average value can be determined by an utmost precision !

Nuclear magnetic moments

Experimental Setup

- Ultra-low magnetic fields
- Magnetic sensors
- Co-magnetometry

Search for exotic interactions

- Nuclear magnetic moments
- Axion wind

Nuclear magnetic moments

Temporal variation of nuclear magnetic moments ?

Flambaum VV, Tedesco AF 2006 Phys Rev C 73, 055501

$$\frac{\gamma^{He}}{\gamma^{Xe}} = 2.75408160(31)$$

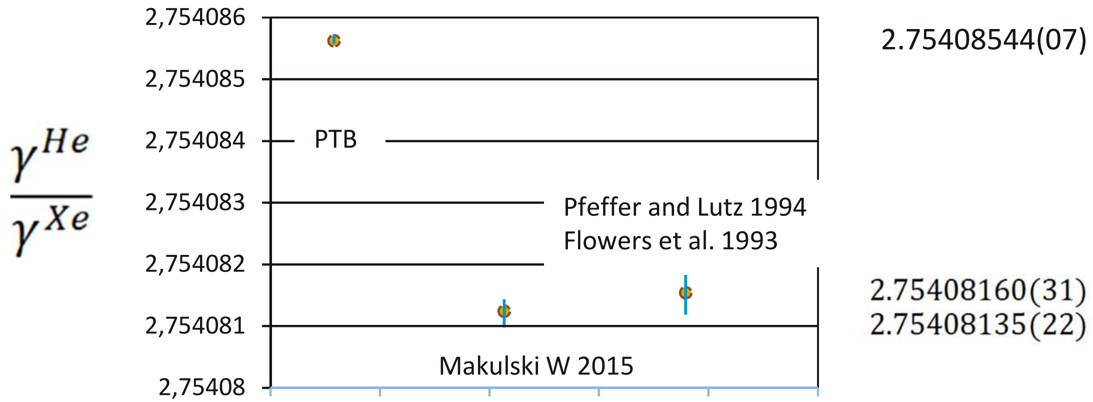
Pfeffer M and Lutz O 1994 J. Magn. Reson. 108 106
Flowers J L, Petley B W, and Richards M G 1993 Metrologia 30 75

$$\frac{\gamma^{He}}{\gamma^{Xe}} = 2.75408135(22)$$

Makulski W 2015 Magn. Reson. Chem. 53 273

→ up to now no instability observed

Nuclear magnetic moments



The PTB value is 1.5 ppm above the literature value

Instability ?

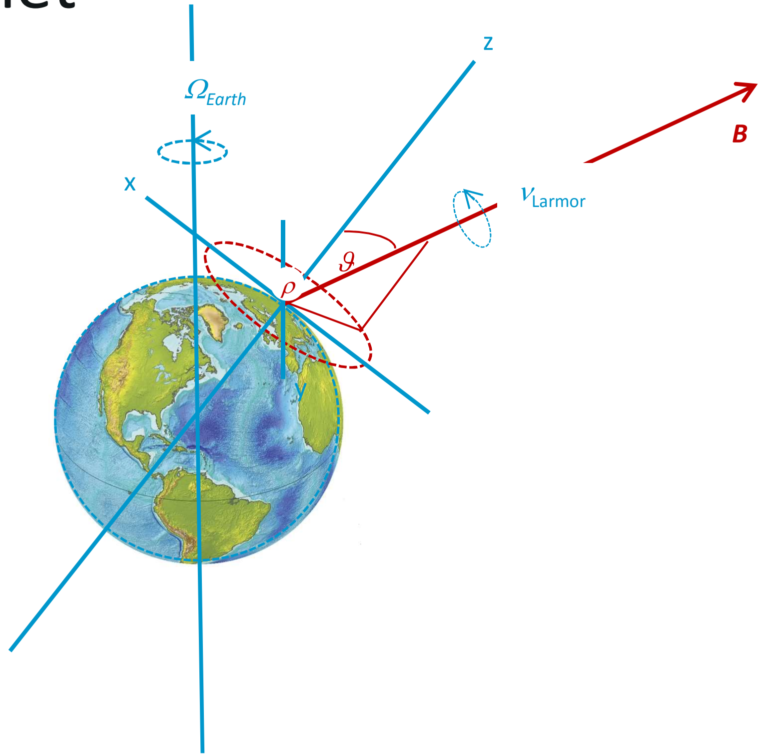
Ultra-low field effect ?

What about systematic errors ?

Nuclear magnetic moments

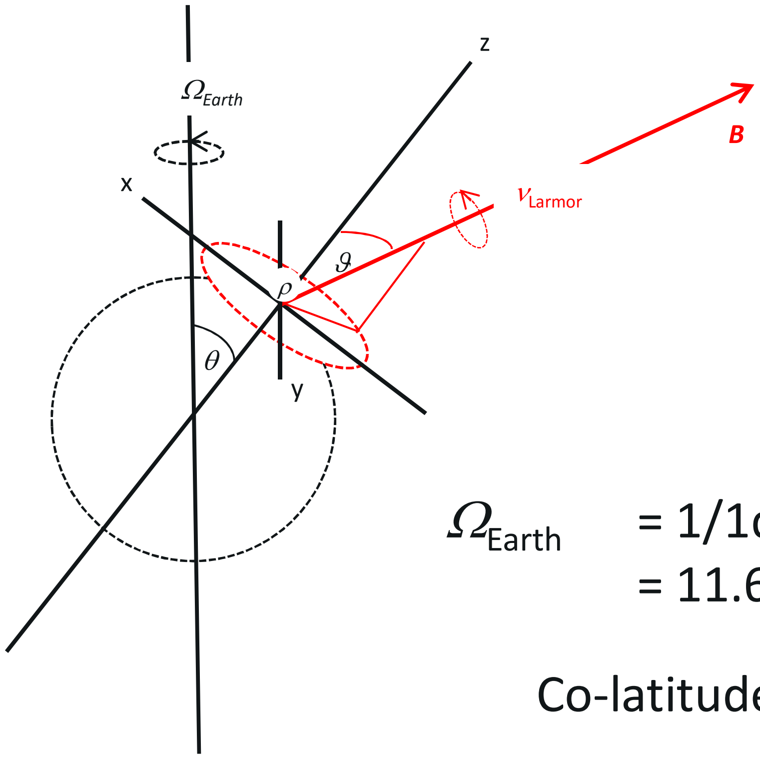
Our lab is on a spinning planet

1. The observer is spinning
2. The lab is in a rotating frame



1. The observer is spinning

We have to add
the observer's rotation
to the Larmor precession



$$\Delta\nu_{Obs} = \frac{\boldsymbol{\nu_{Larmor}}}{|\nu_{Larmor}|} \cdot \boldsymbol{\Omega}_{\mathbf{Earth}}$$

$$= \Omega_{Earth} \begin{pmatrix} \cos\rho\sin\vartheta \\ \sin\rho\sin\vartheta \\ \cos\vartheta \end{pmatrix} \cdot \begin{pmatrix} \sin\theta \\ 0 \\ \cos\theta \end{pmatrix}$$

$$= \Omega_{Earth}(\cos\rho\sin\vartheta\sin\theta + \cos\vartheta\cos\theta)$$

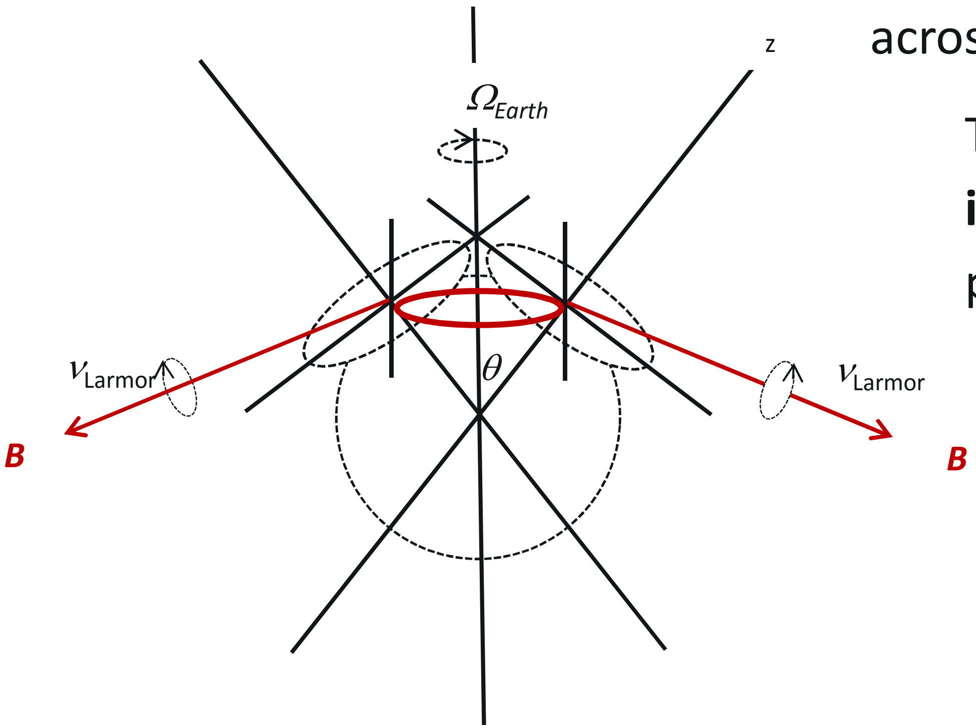
Ω_{Earth} = 1/1day
= 11.6057617(4) μHz

Co-latitude of Berlin:

θ = 90°- 52.5164°
= 37.4836(30)°

Nuclear magnetic moments

2. The lab is rotating



The daily motion of the lab on the surface of the spinning Earth along the latitude line moves **the applied magnetic field** across a curved surface.

This adds a **continuously increasing phase** to the Larmor precession frequency [Berry 1984]

Within one sidereal day the motion completes a full circle, which is the perimeter of a cone forming the solid angle $2\pi(1 - cos\ \theta)$ with its apex at the center of the Earth.

This adds an offset of $\Delta\nu_{\text{Berry}} = (1 - cos\theta)\ \Omega_{\text{Earth}}$ to ν_{Larmor},

which only depends on the geographical latitude of the lab.

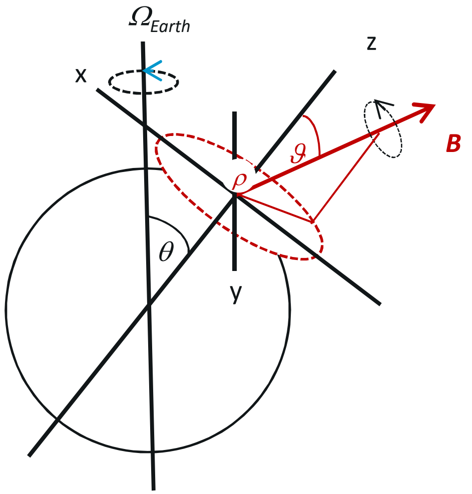
Nuclear magnetic moments

The precession frequency in the lab is shifted by a constant amount

$$\nu_{\mathrm{lab}} = \nu_{\mathrm{Larmor}} + \Delta\nu_{\mathrm{obs}} + \Delta\nu_{\mathrm{Berry.}}$$

$$= \nu_{\mathrm{Larmor}} - \Omega_{\mathrm{Earth}}(\cos\rho\sin\vartheta\sin\theta + \cos\vartheta\cos\theta + 1 - \cos\theta)$$

$$= \nu_{\mathrm{Larmor}} - \Omega_{\mathrm{Earth}}(\cos\rho\sin\theta + 1 - \cos\theta), \text{ if } \vartheta = 90°$$



Weighted phase difference:

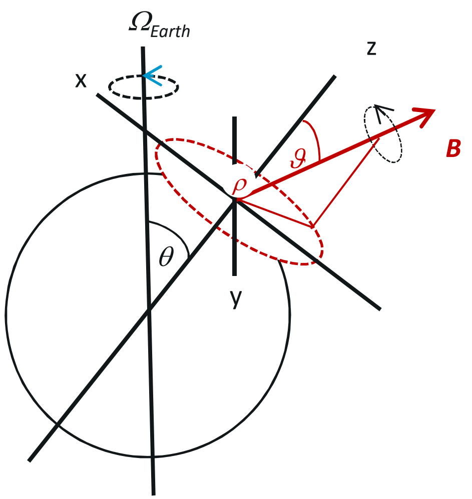
$$\nu_{\mathrm{Larmor}}^{\mathrm{He}} - \frac{\gamma^{\mathrm{He}}}{\gamma^{\mathrm{Xe}}}\nu_{\mathrm{Larmor}}^{\mathrm{Xe}} = 0$$

$$\nu_{\mathrm{Lab}}^{\mathrm{He}} - \frac{\gamma^{\mathrm{He}}}{\gamma^{\mathrm{Xe}}}\nu_{\mathrm{Lab}}^{\mathrm{Xe}} = \Omega_{\mathrm{Earth}}\left(\frac{\gamma^{\mathrm{He}}}{\gamma^{\mathrm{Xe}}} - 1\right)(\cos\rho\sin\theta + 1 - \cos\theta)$$

Nuclear magnetic moments

$$\nu_{Lab}^{He} - \frac{\gamma^{He}}{\gamma^{Xe}}\nu_{Lab}^{Xe} = \left(\frac{\gamma^{He}}{\gamma^{Xe}} - 1\right)\left[\underbrace{\Omega_{\mathrm{Earth}} \sin\theta\cos\rho}_{a} + \underbrace{\Omega_{\mathrm{Earth}}(1-\cos\theta)}_{b}\right]$$

a = 12.3882(14) μHz b = 4.2033(4) μHz



$$\left(\frac{\gamma^{He}}{\gamma^{Xe}}\right)_{LIT} = 2.75408135(22)$$

$$\Omega_{\mathrm{Earth}} = 11.6057617(4)\ \mu\mathrm{Hz}$$

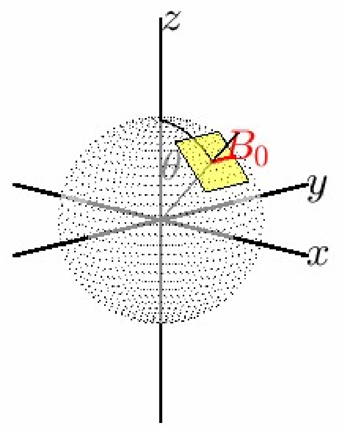
$$\theta = 37.4836(30)^\circ$$

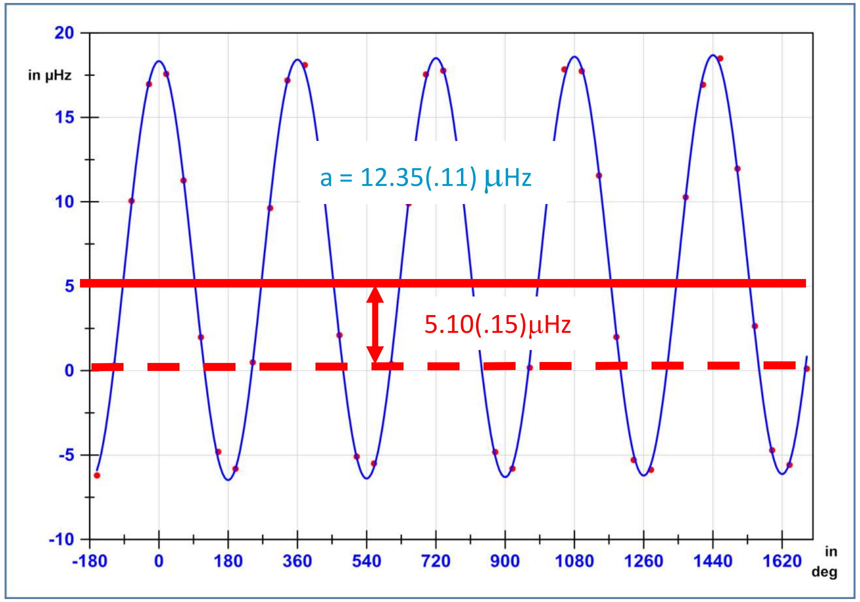
Nuclear magnetic moments

$$\nu_{Lab}^{He} - \frac{\gamma^{He}}{\gamma^{Xe}}\nu_{Lab}^{Xe} = \left(\frac{\gamma^{He}}{\gamma^{Xe}} - 1\right)[\underbrace{\Omega_{\text{Earth}}\sin\theta\cos\rho}_{a} + \underbrace{\Omega_{\text{Earth}}(1-\cos\theta)}_{b}]$$

a = 12.3882(14) μHz   *b* = 4.2033(4) μHz

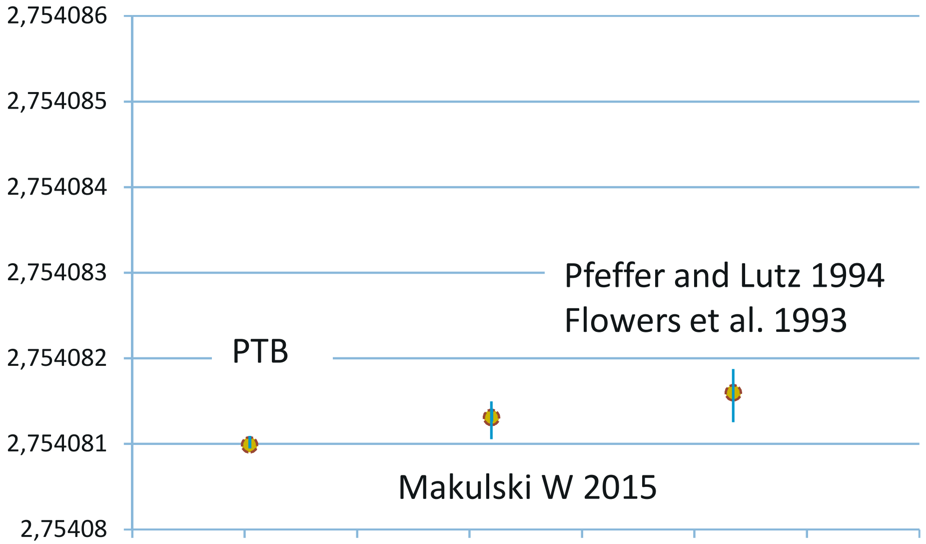
Let ρ vary in steps of 45°:





Nuclear magnetic moments

$$\frac{\gamma^{He}}{\gamma^{Xe}}$$



2.75408544(07)

2.75408160(31)

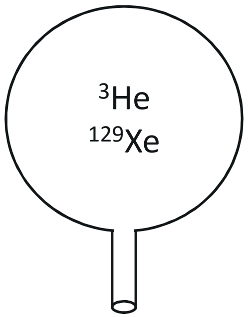
2.75408135(22)

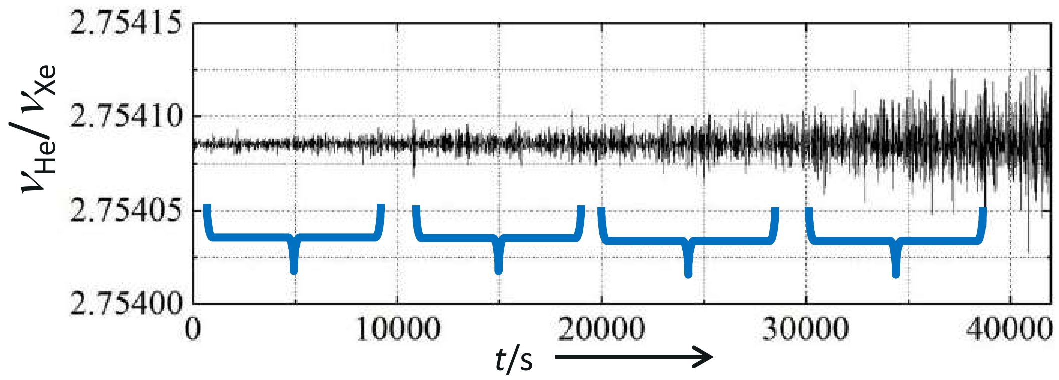
2.75408100(07)

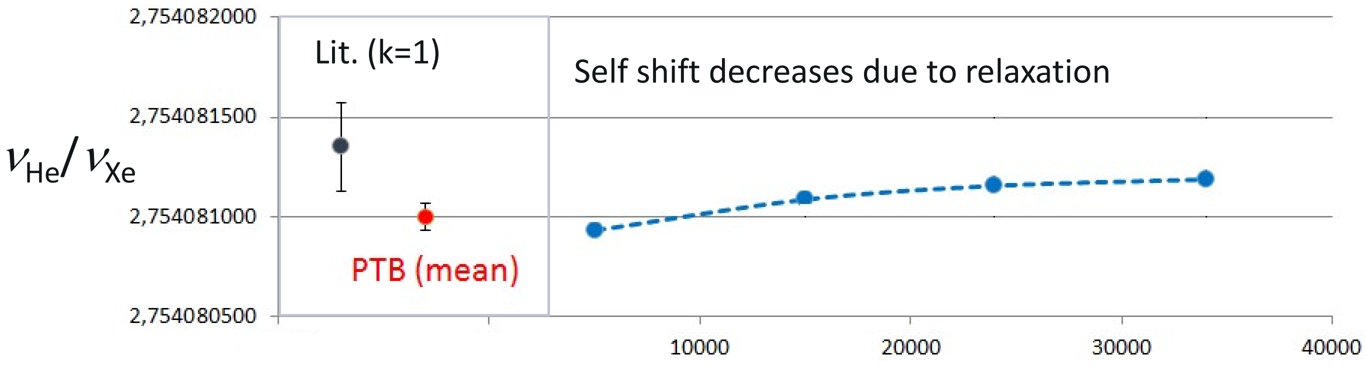
Nuclear magnetic moments

Additional systematics:

Self shift due to non-spherical symmetry







Nuclear magnetic moments

Statistical uncertainties:

- Thermally induced B_0 drift
- DAQ clock drift
- Current source drift

} removed by comagnetometer

Systematic errors :

- $\Delta\nu_{Earth}$ Earth rotation
- $\Delta\nu_{RBS}(t)$ self shift
- $\Delta\nu_{Chem}$ chemical shift

Axion wind

Experimental Setup

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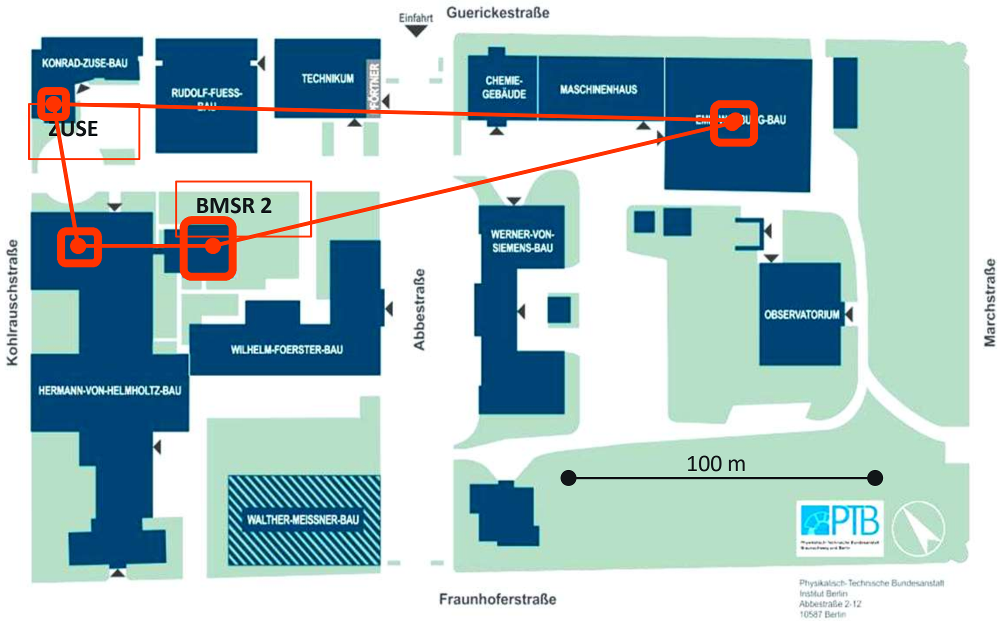
Search for exotic interactions

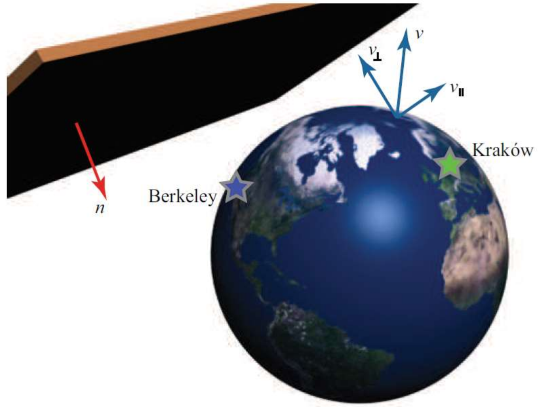
- Nuclear magnetic moments
- Axion wind

Axion wind

Global Network of Optical Magnetometers for Exotic Physics (GNOME)

Micro-GNOME





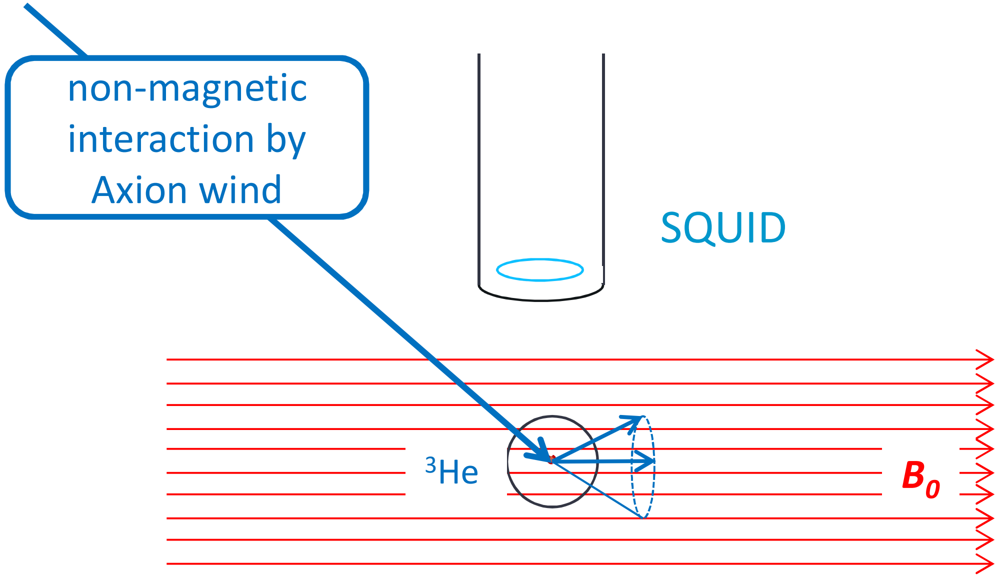
Expected time shift:

$$\Delta t = \Delta s / v_{\text{Earth}}$$
$$\approx 100\text{ m}/300\text{ (km/s)}$$
$$\approx 300\ \mu\text{s}$$

Pustelny et al. Ann Phys 2013

Axion wind

Cosmic **A**xion **S**pin **P**recession **E**xperiment (CASPEr)



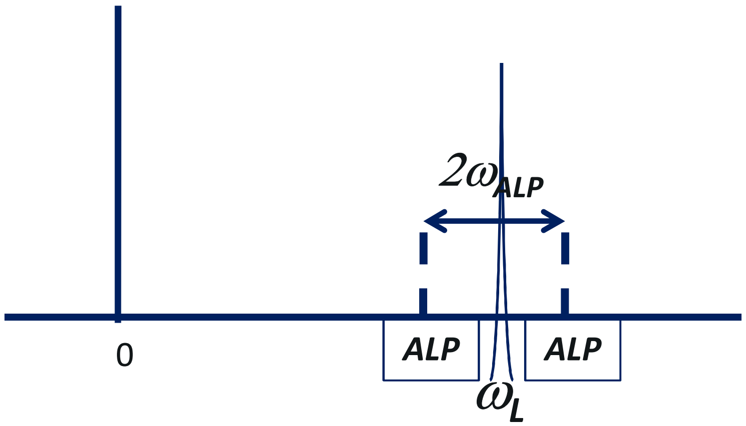
Axion interaction acts like a tickle pulse of NMR, when in resonance with the Larmor frequency

\+ high sensitivity
\- finding the resonance frequency

Budker et al. PRX (2014)
Graham and Rajendran PRD (2011, 2013))

Axion wind

Sidebands **i**n **L**armor **F**requency **I**nduced by **A**xions



+ they are at well defined positions
+ we cannot miss them

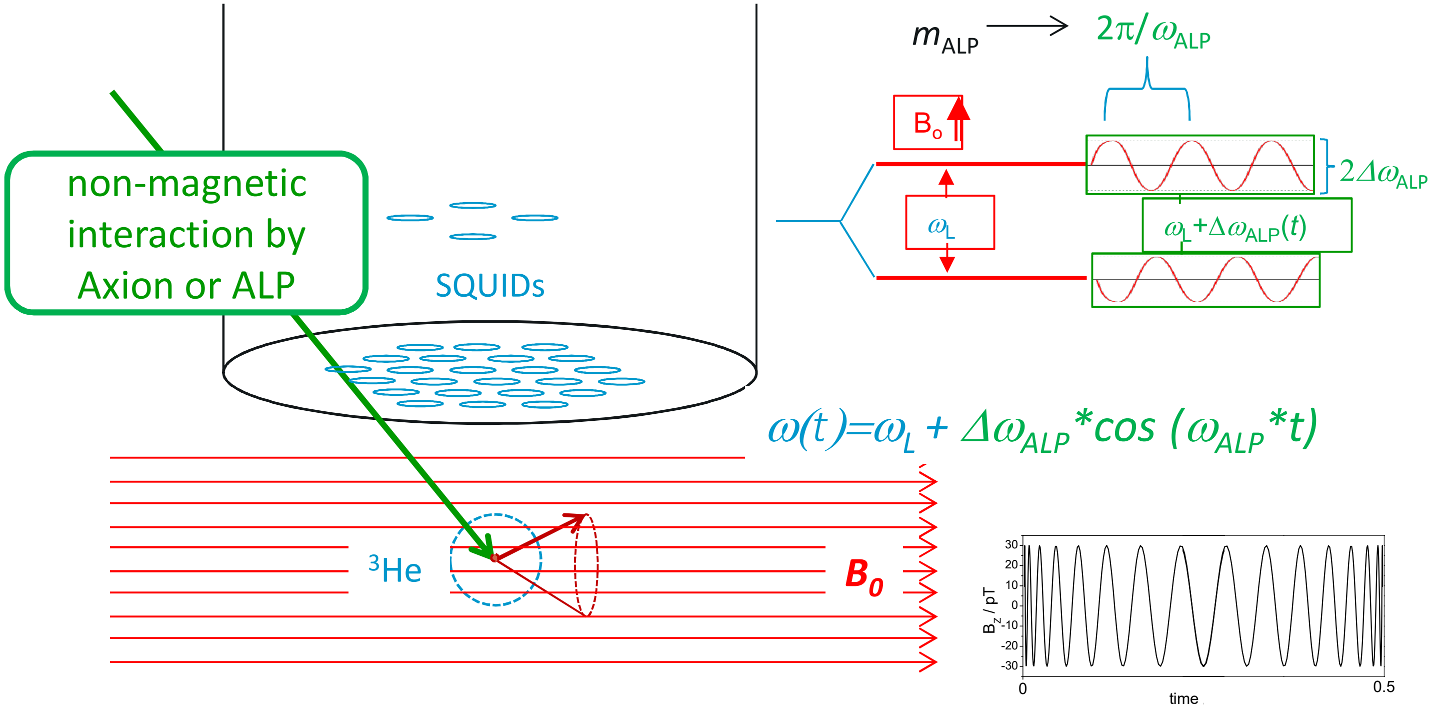
SILFIA Concept:

Frequency modulation of ω_L results in sidebands at $\omega_L \pm \omega_{ALP}$

Axion wind

Axion interaction acts like an oscillating magnetic field

$$B_{"ALP"} = \frac{\Delta\omega_{ALP}}{\gamma_{He}}$$



P. Graham and S. Rajendran, PRD 2011, 2013

Axion wind

Signal recorded by SQUID: $S(t) = A_{\mathrm{He}} \cos \phi(t)$

$$\phi(t) = \int \omega(t) dt$$

Frequency modulation :

$$\omega(t) = \omega_{\mathrm{L}} + \Delta\omega_{\mathrm{ALP}} \cos(\omega_{\mathrm{ALP}} t)$$

g_{aNN} m_{ALP}

$$= \int [\omega_{\mathrm{L}} + \Delta\omega_{\mathrm{ALP}} \cos(\omega_{\mathrm{ALP}} t)] dt$$

$$= \omega_{\mathrm{L}} t + \frac{\Delta\omega_{\mathrm{ALP}}}{\omega_{\mathrm{ALP}}} \sin(\omega_{\mathrm{ALP}} t)$$

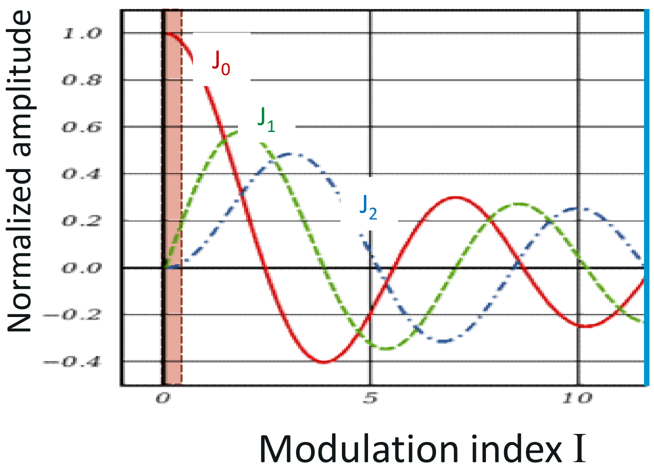
Modulation index ***I***

$$S(t) = A_{\mathrm{He}} \cos\left[\omega_{\mathrm{L}} t + \boxed{\frac{\Delta\omega_{\mathrm{ALP}}}{\omega_{\mathrm{ALP}}}} \sin(\omega_{\mathrm{ALP}} t)\right]$$

Axion wind

The amplitude of the side bands is given by the Bessel functions

$$A_n = A_{He} J_n(I)$$
$$= A_{He}\left[\frac{I^n}{2^n n!} - \frac{I^{n+2}}{2^{n+2}(n+1)!} + \cdots\right]$$



Modulation index : $I = \frac{\Delta\omega_{\text{ALP}}}{\omega_{\text{ALP}}} \ll 1$

$$A_1 = \frac{A_0}{2}\frac{\Delta\omega_{\text{ALP}}}{\omega_{\text{ALP}}}$$

with $A_0 \approx A_{\text{He}}$

Axion wind

Generating a fake axion signal:

Signal recorded by SQUID: $S(t) = A_{\mathrm{He}} \cos \phi(t)$

$$\phi(t) = \int \omega(t) dt$$

Frequency modulation :

$$\omega(t) = \omega_{\mathrm{L}} + \Delta\omega_{\mathrm{ALP}} \cos(\omega_{\mathrm{ALP}} t)$$

$$= \int [\omega_{\mathrm{L}} + \Delta\omega_{\mathrm{ALP}} \cos(\omega_{\mathrm{ALP}} t)] dt$$

$\Delta\omega_{\mathrm{ALP}}$ → $\gamma B_{\text{“ALP“}}$

$$= \omega_{\mathrm{L}} t + \frac{\Delta\omega_{\mathrm{ALP}}}{\omega_{\mathrm{ALP}}} \sin(\omega_{\mathrm{ALP}} t)$$

$$S(t) = A_{\mathrm{He}} \cos\left[\omega_{\mathrm{L}} t + \frac{\Delta\omega_{\mathrm{ALP}}}{\omega_{\mathrm{ALP}}} \sin(\omega_{\mathrm{ALP}} t)\right]$$

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Frequency modulation :

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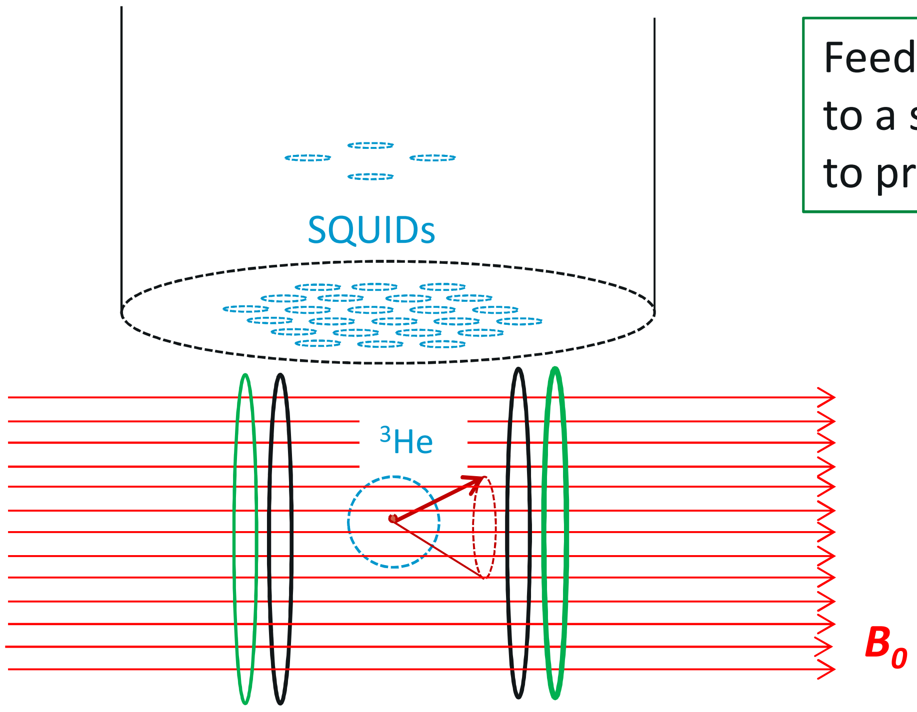
$\Delta\omega_{\text{ALP}} \rightarrow \gamma\, B_{\text{“ALP“}}$

$$\omega_{\text{L}} t + \frac{\gamma_{He} B_{"ALP"}}{\omega_{\text{ALP}}} \sin(\omega_{\text{ALP}} t)$$

$$S(t) = A_{\text{He}} \cos\left[\omega_{\text{L}} t + \frac{\gamma_{He} B_{"ALP"}}{\omega_{\text{ALP}}} \sin(\omega_{\text{ALP}} t)\right]$$

Generating a fake axion signal:



Feed a sinusodial current
to a second Helmholz coil
to produce a modulation field

B_0 = 1 μT
$B_{\text{“ALP“}}$ = 1 nT
$\nu_{\text{“ALP“}}$ = 1.5 Hz
A_0 = 12.6 fT

Axion wind

$B_0 + B_{\text{"ALP"}} * \sin(\omega_{ALP} * t)$

Feed a sinusodial current
to a second Helmholz coil
to produce a modulation field

B_0	= 1 µT
$B_{\text{"ALP"}}$	= 1 nT
$\nu_{\text{"ALP"}}$	= 1.5 Hz
A_0	= 12.6 fT

$\nu_{He} = \gamma_{He} B_0 = 32.4$ Hz

$\Delta\nu_{ALP} = \gamma_{He} B_{\text{"ALP"}} = 32.4$ mHz ± 3 mHz

$$I = \frac{\gamma_{He} B_{\text{"ALP"}}}{\gamma_{He} B_0}$$

$$= \frac{32.4\ \text{mHz}}{1.5\ \text{Hz}} = 21.6 \times 10^{-3}$$

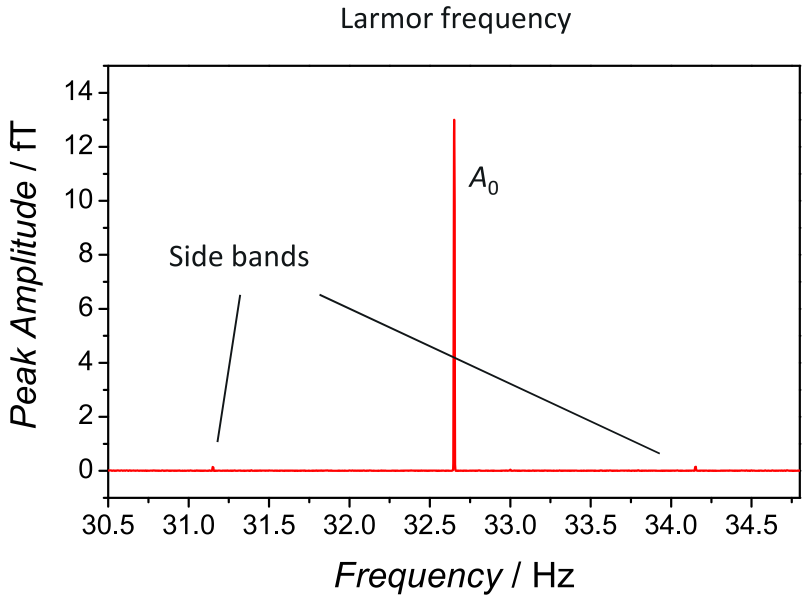
$$A_1 = \frac{A_0}{2} I$$

= 136 aT ± 15 aT

Axion wind

Measured amplitude spectrum

B_0 = 1 μT
$B_{\text{“ALP“}}$ = 1 nT
$\nu_{\text{“ALP“}}$ = 1.5 Hz
A_0 = 12.6 fT



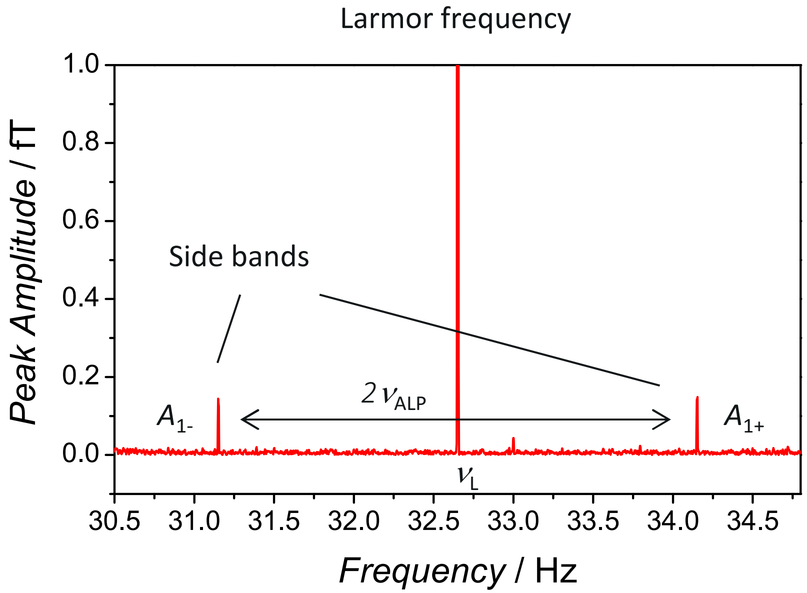
Axion wind

Measured amplitude spectrum
agrees with calculation

A_1 = 136 aT ± 15 aT

B_0	= 1 μT
$B_{“ALP“}$	= 1 nT ± 0.1 nT
$\nu_{“ALP“}$	= 1.5 Hz
A_0	= 12.6 fT

A_1 = 145 aT± 10 aT
ν_{ALP} = 1.5 Hz

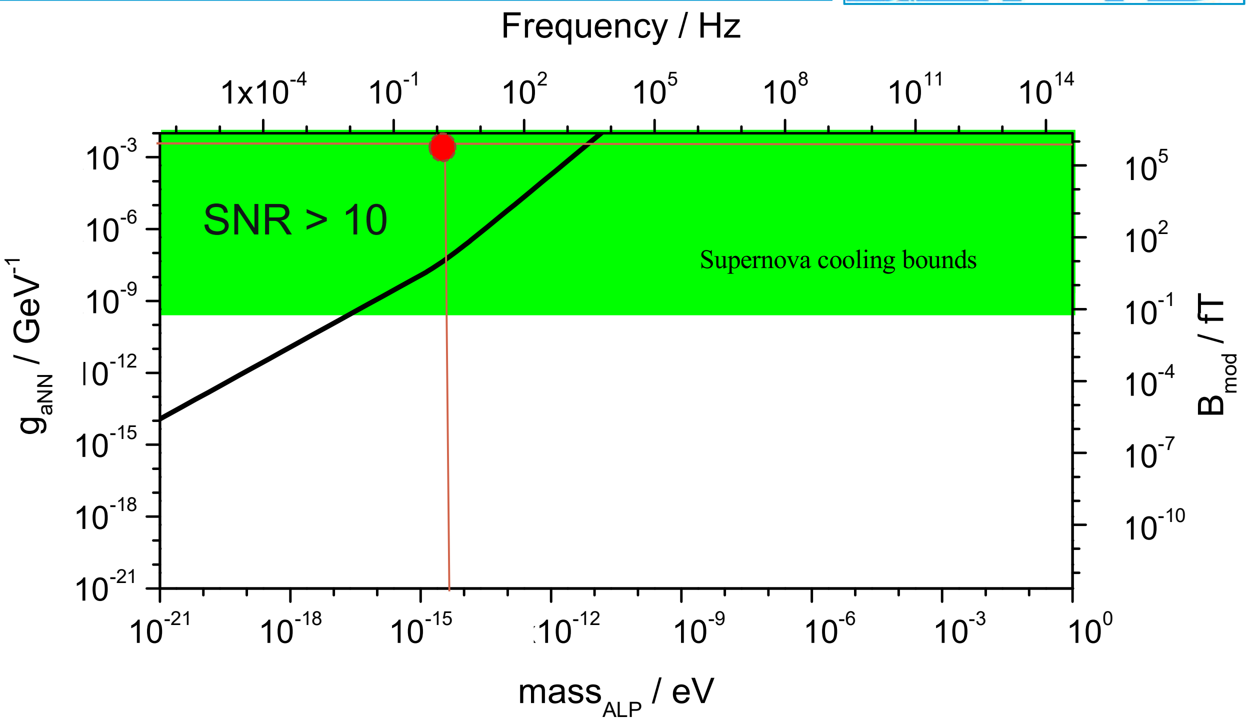


The side bands are at well defined frequencies !

Axion wind

Detection limits of SILFIA

$B_{\text{"ALP"}}$ = 1 nT
$\nu_{\text{"ALP"}}$ = 1.5 Hz

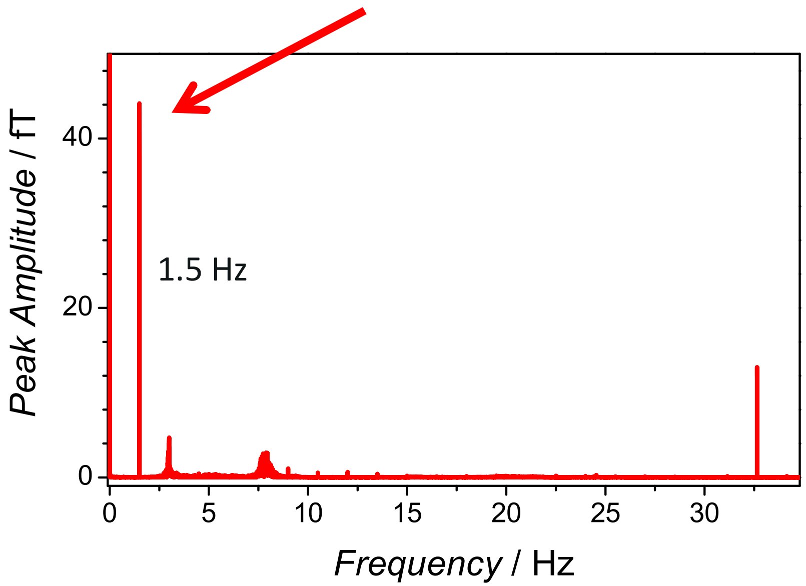


	Demo	Limits
Initial amplitude:	12.6 fT	100 pT
SQUID System noise:	3.5 fT/√Hz	160 aT/√Hz
Life time of precession T_2^*	600 s	100 hours
Axion Coherence time τ	-	$10^6/\nu_{ALP}$

Axion wind

How can we identify a magnetic artefact ?

In a SQUID magnetic artifacts generate a signal of their own !!



Summary

- SQUIDs reach a system noise level down to 160 $\mathrm{aT}/\sqrt{\mathrm{Hz}}$
- Larmor frequencies down to a few millihertz are available
- Co-magnetometry at ultra-low fields enables the determination of nuclear magnetic moments with small statistical errors
- Earth rotation has a significant systematic impact at ultra-low frequencies
- Axions of ultra-low masses down to 10^{-21}eV are detectable
- Artefacts are identified by the presence of an additional peak at the modulation frequency „ν_{ALP}“

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