Test of Lorentz Invariance with a ^{3}He/ ^{129}Xe co-magnetometer

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Outline:

- Motivation: Search for Lorentz violation
- Spin precession and relaxation
- Experiment and results
- Outlook

A. Kostelecky and C. Lane: Constraints on Lorentz Violation from Clock-Comparison Experiments, **Phys. Rev. D 60, 116010 (1999)):**

Lagrangian density for free spin ½ particle: $$L_{SME} = \frac{1}{2} i \bar{\Psi} \Gamma_{\upsilon} \overleftrightarrow{\partial}^{\upsilon} \Psi - \bar{\Psi} M \Psi$$

$$\Gamma_{\upsilon} = \gamma_{\upsilon} + c_{\mu\nu}\gamma^{\mu} + d_{\mu\upsilon}\gamma_5\gamma^{\mu} + e_{\upsilon} + if_{\upsilon}\gamma_5 + \frac{1}{2} g_{\lambda\mu\upsilon}\sigma^{\lambda\mu} \quad (\sigma^{\lambda\mu} = \gamma^{\lambda}\gamma^{\mu} - \gamma^{\mu}\gamma^{\lambda})$$

$$M = m + a_{\mu}\gamma^{\mu} + b_{\mu}\gamma_5\gamma^{\mu} + \frac{1}{2} H_{\mu\upsilon}\sigma^{\mu\upsilon}$$

- All additional terms violate Lorentz invariance,

  terms with $a_{\mu}, b_{\mu}, e_{\mu}, f_{\mu}, g_{\lambda\mu\upsilon}$ also violate CPT

SME: Hamiltonian

$$L_{SME} \rightarrow h_{rel} \xrightarrow{\text{F-W-Trafo}} h = h_{SM} + \delta h_{SME}$$

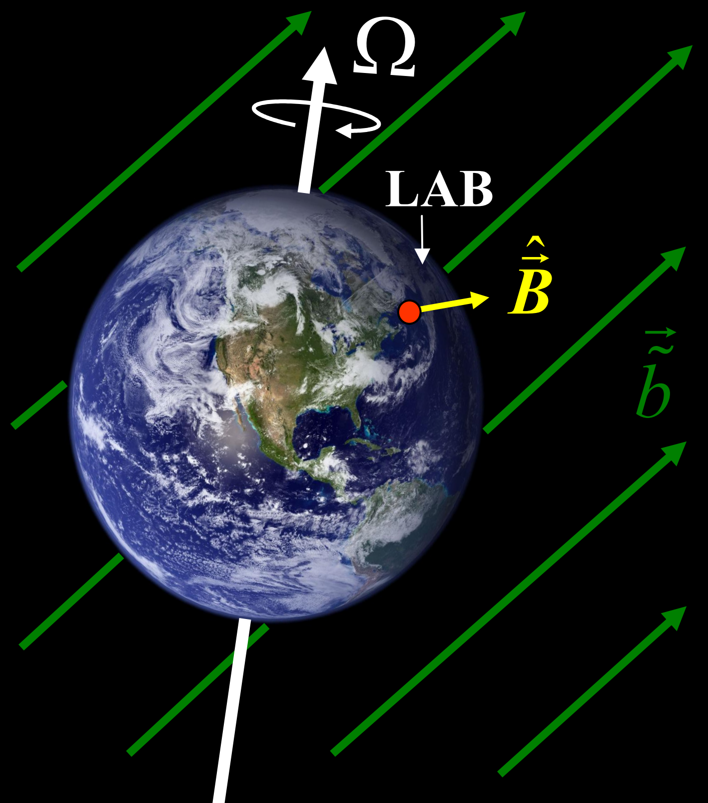
$$= \tilde{b}_j \cdot \sigma^j$$

Clock comparison experiments, e.g. He/Xe comagnetometer

$$\delta h_{SME} = \left(a_0 - mc_{00} - me_0\right) + \left(-b_j + md_{j0} - \frac{1}{2} m\varepsilon_{jkl} g_{kl0} + \frac{1}{2}\varepsilon_{jkl} H_{kl}\right)\sigma^j + \left[-a_j + m\left(c_{0j} + c_{j0}\right) + me_j\right]\frac{p_j}{m}$$
$$+ \left[b_0\delta_{jk} - m\left(d_{kj} + d_{00}\delta_{jk}\right) - m\varepsilon_{klm}\left(\frac{1}{2} g_{mlj} + g_{m00}\delta_{jl}\right) - \varepsilon_{jkl} H_{l0}\right]\frac{p_j}{m}\sigma^k + m\left(-c_{jk} - \frac{1}{2} c_{00}\delta_{jk}\right)\frac{p_j p_k}{m^2}$$
$$+ \left\{\left[m\left(d_{0j} + d_{j0}\right) - \frac{1}{2}\left(b_j + md_{j0} + \frac{1}{2} m\varepsilon_{jmn} g_{mn0} + \frac{1}{2}\varepsilon_{jmn} H_{mn}\right)\right]\delta_{kl} + \frac{1}{2}\left(b_j + \frac{1}{2} m\varepsilon_{lmn} g_{mn0}\right)\delta_{jk} - m\varepsilon_{jlm}\left(g_{m0k} + g_{mk0}\right)\right\}\frac{p_j p_k}{m^2}\sigma^l$$

Test of relativistic time dilation (Reinhardt et al., Nature Physics 3, 861 – 864, 2007)

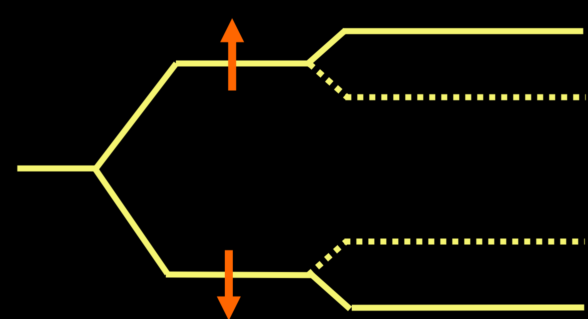
Coupling of spin $\vec{\sigma}$ to background field



$$H = -\vec{\mu}\cdot\vec{B} - \vec{\tilde{b}}\cdot\vec{\sigma}$$

$$\rightarrow \quad \nu = \underbrace{\frac{2}{h}\mu B}_{\nu_{\text{Zeeman}}} + \underbrace{\frac{2}{h}\langle\tilde{b}\rangle\cos(\angle\,\vec{\tilde{b}},\hat{\vec{B}})}_{\nu_{LV}}$$

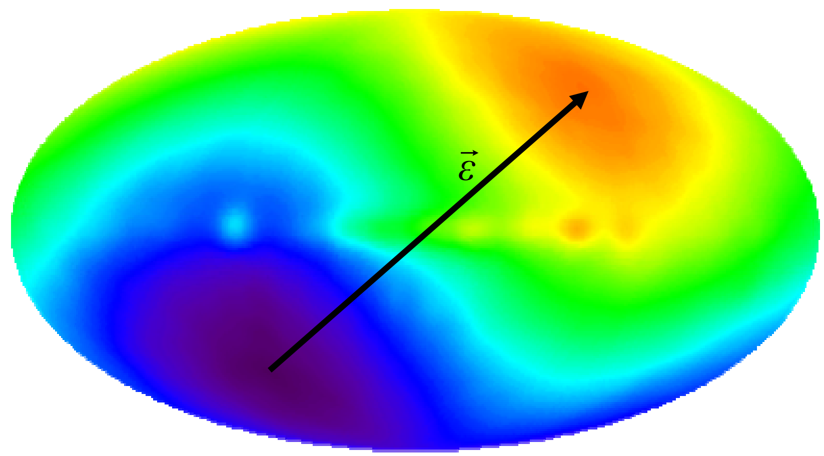
$$\vec{\tilde{b}}\cdot\vec{\sigma}$$



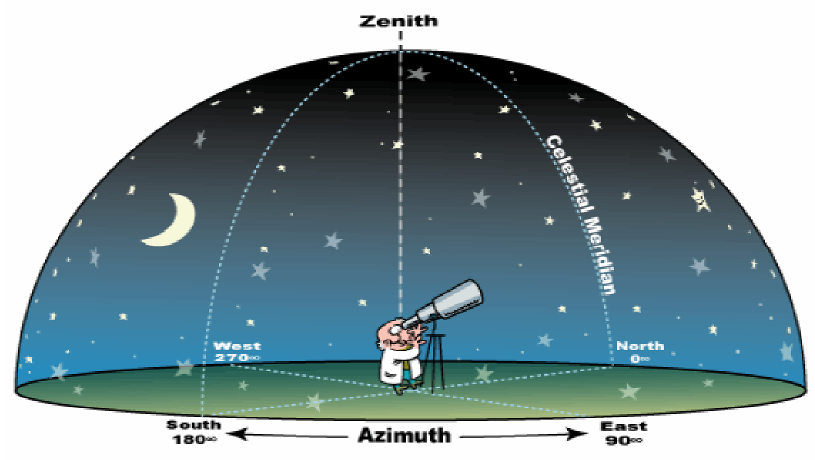
natural scale: $\langle\tilde{b}\rangle \leq \frac{m_n}{M_P}\times m_n = 10^{-19}\ GeV$

CMB dipole

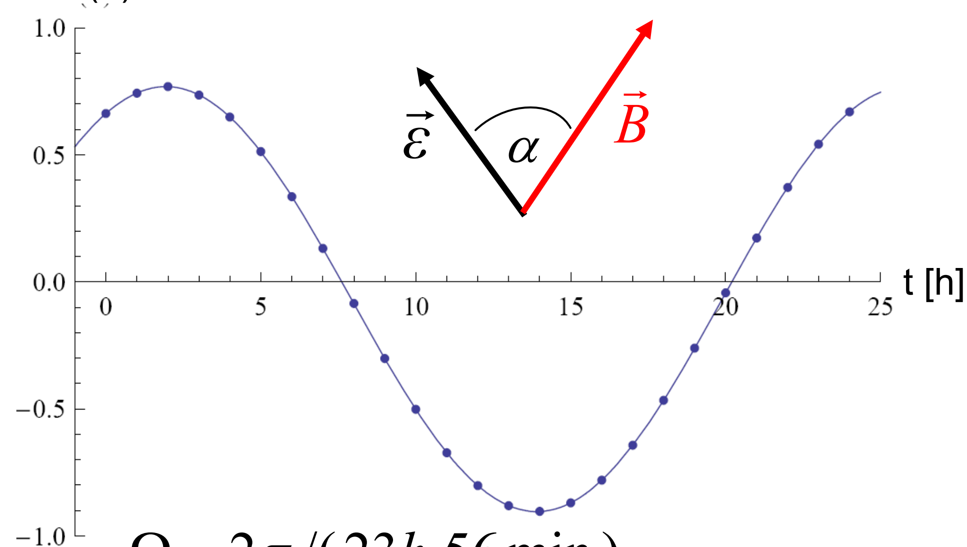
- solar system moves relative to CMB
  → temperature is distributed dipole-like



horizon coordinate system
(observer's local horizon)



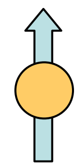
Angle between CMB dipole and magnetic field, 01.10.2007 at PTB-Berlin (52° 31´ north, 13° 25´ east)



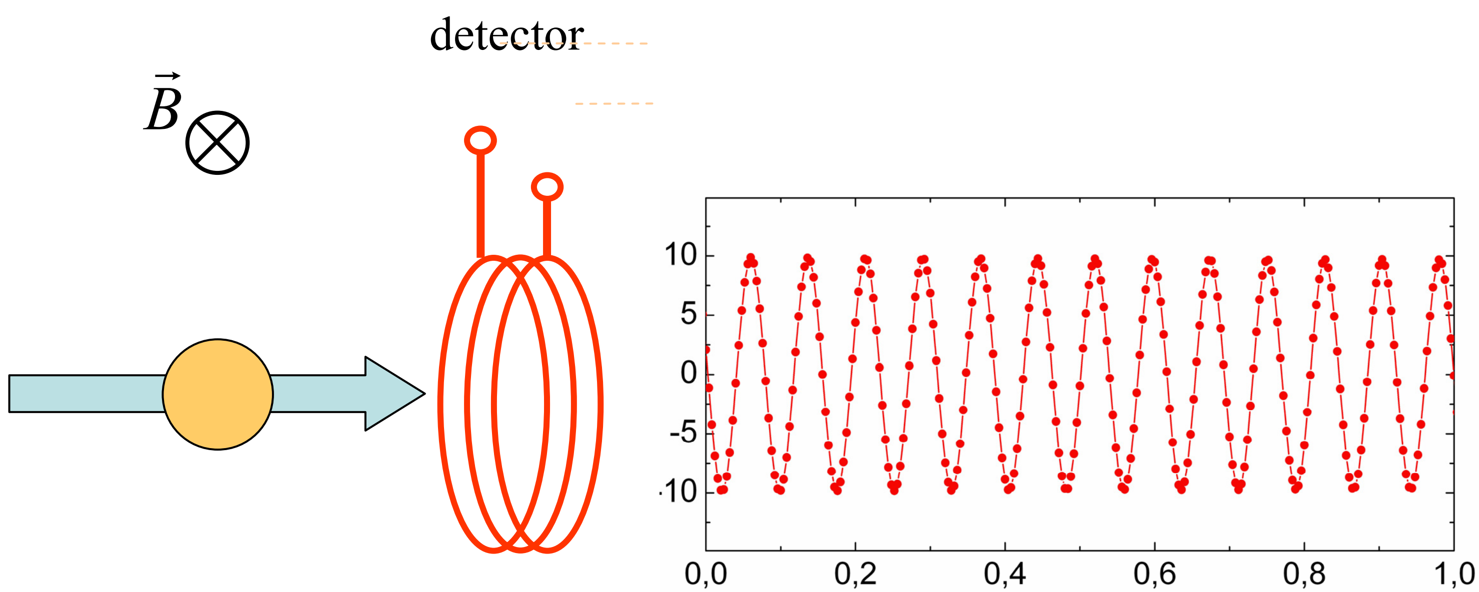
$$\Omega = 2\pi / (23h\ 56\,\text{min})$$

Principle of ^{3}He/ ^{129}Xe magnetometer

- Atoms with spin (e.g. ^{3}He and ^{129}Xe, I=1/2)
- Alignment of spins by optical pumping →



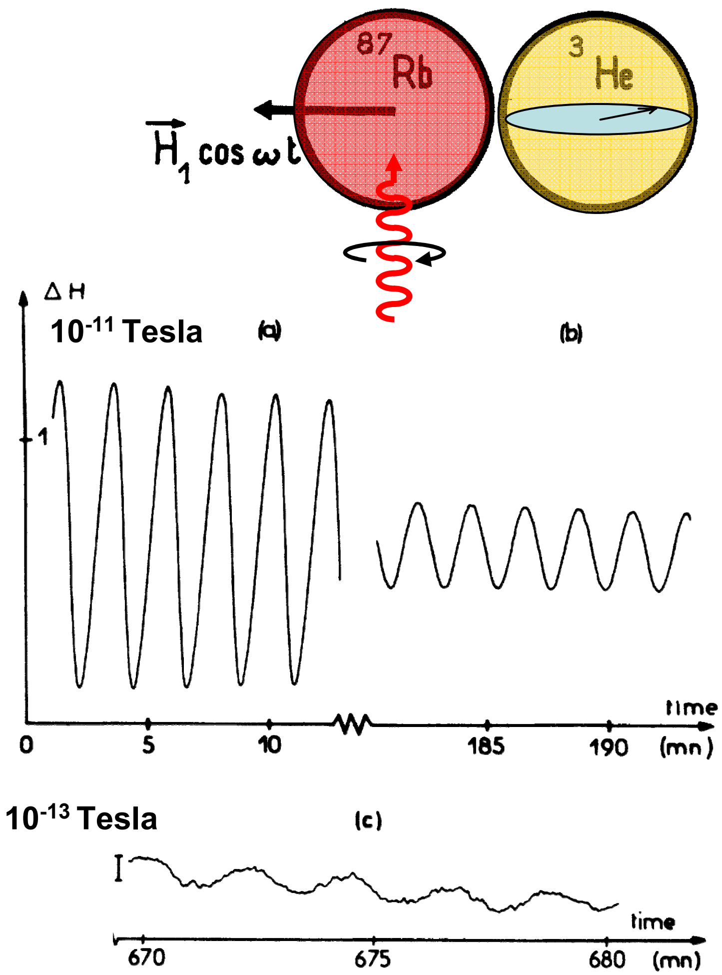
- $\pi/2$-flip → spin precession around magnetic field



$$2\pi\nu=\omega=\gamma B$$

Earlier measurement of spin precession

Detection of magnetic field produced by oriented nuclei
(Cohen-Tannoudji et al., PRL 22 (1969),758):



Results:

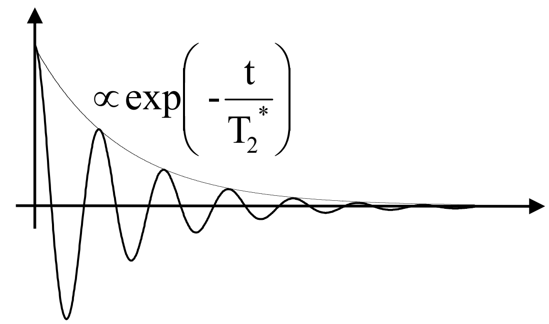
- p ≈ 4 mbar, P_{He} ≈ 5%
- sensitivity of Rb-magnetometer: 100 fT@ BW 0.3 Hz
- ^{3}He spin precession: T_2^* = 2h 20min

Improvement of measurement sensitivity:

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

Transverse Relaxation: T_2^*

- Transverse relaxation time T_2^*
  - dephasing of spins caused by field gradients
    → signal decay



radius (3cm)

absolute gradient
→ low magn. field
($B_0 \approx 400$ nT)

$$\frac{1}{T_2^*} \approx \frac{1}{T_1} + \frac{8\gamma^2 R^4}{175D}\left|\nabla B_z\right|^2 + D\cdot\frac{\left|\nabla B_x\right|^2+\left|\nabla B_y\right|^2}{B_0{}^2}\cdot\frac{1}{2\cdot(1+19\cdot D^2/(\gamma^2 B_0{}^2 R^4))}$$

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

longitudinal relaxation time

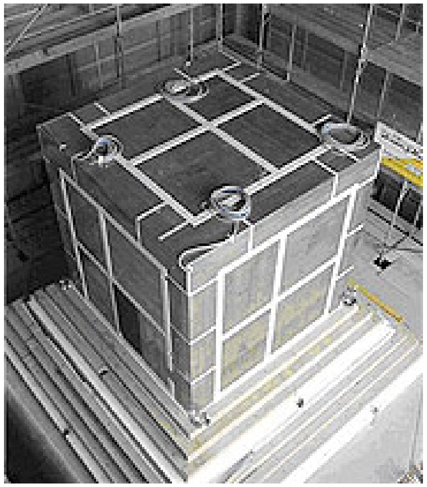
diffusion const. D ~ 1/p
→ low pressure
(p ~ mbar)

<u>Limiting mechanisms for T_1 time</u>

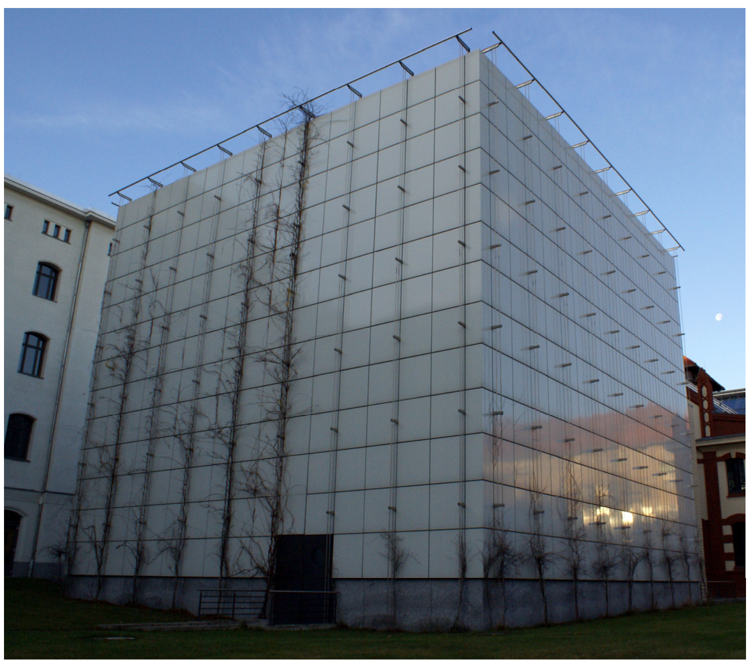
- ^{3}He: wall relaxation, T_1 (^{3}He) > 80 h measured
- ^{129}Xe: wall and van der Waals relaxation, T_1 (^{129}Xe) ≈ 12 h measured (with N_2 as buffer gas)

Experimental setup at BMSR 2, PTB Berlin

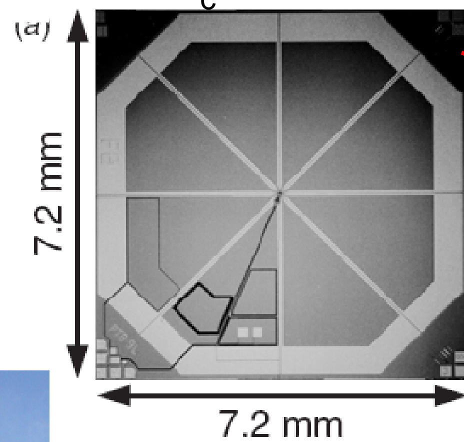
The 7-layered magnetically shielded room (residual field < 2 nT)



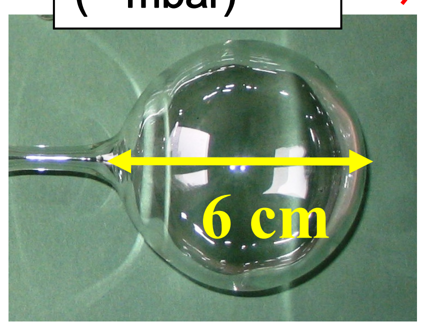
J. Bork, et al., Proc. Biomag 2000, 970 (2000).



LT_c- SQUID

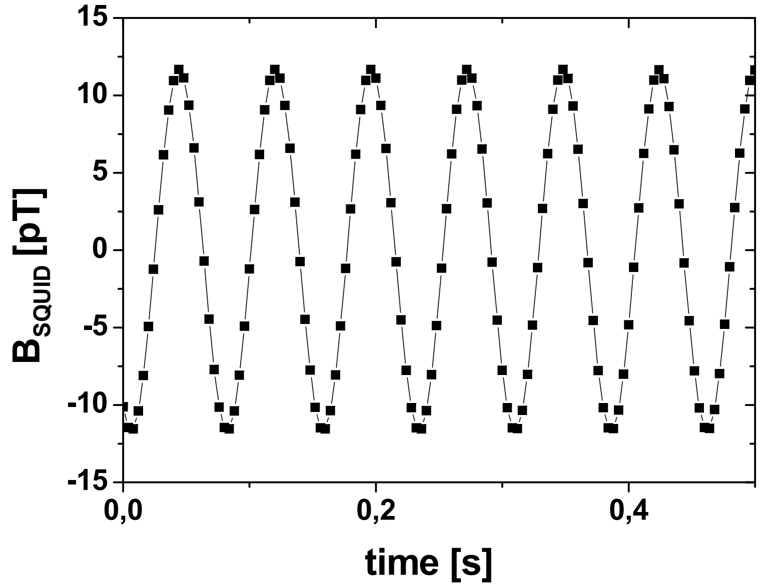


^3He, ^{129}Xe
(~ mbar)



magnetic guiding field ≈ 0.4 μT
(Helmholtz-coils)

^{3}He spin precession: results

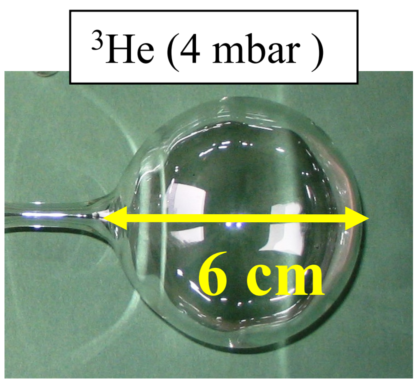


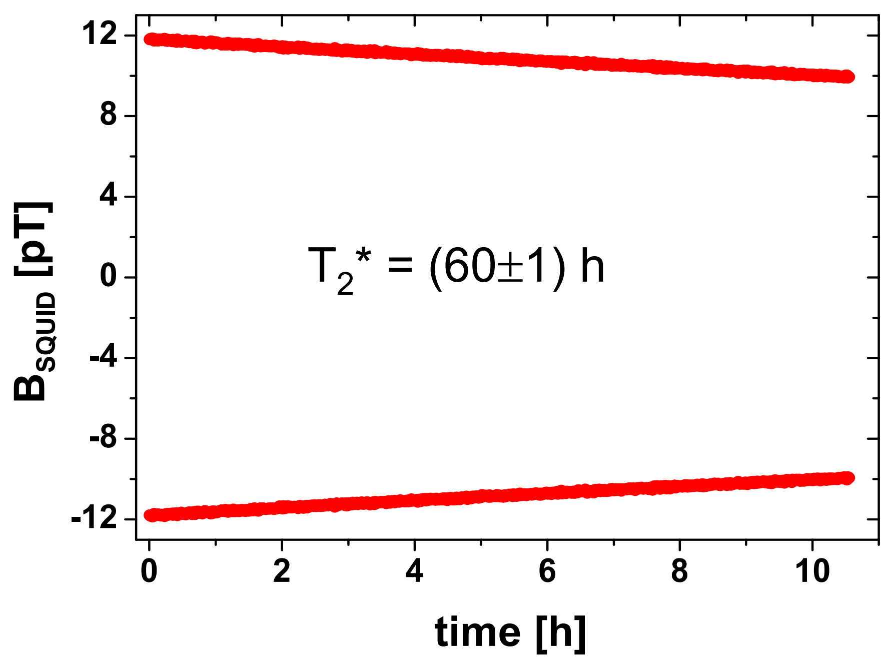
pressure: 4 mbar

$\nu \approx 13\ Hz\ \ (B \approx 400\ nT)$

$P \approx 12\%$

SNR ≈ 3000:1

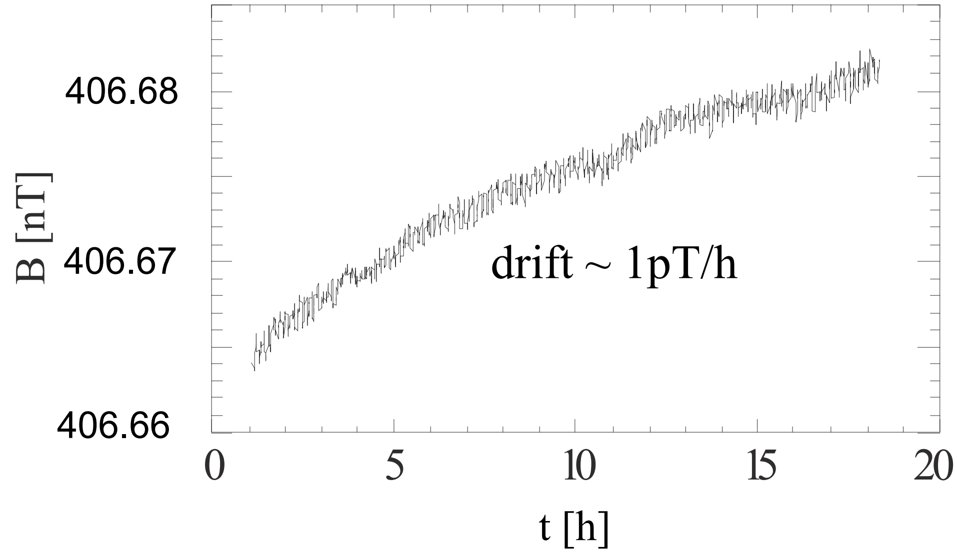




$^{3}He/^{129}Xe$ co-magnetometer

<u>Precession frequency:</u>

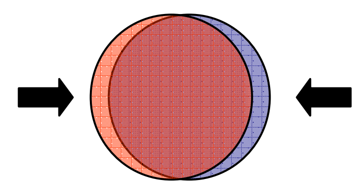
$$\omega = \omega_{Zeeman} + \omega_{LV} + \ldots$$



! variation of ω_{Zeeman} (**field drifts**) much bigger than ω_{LV}

<u>Elimination of Zeeman-term :</u>

^{3}He / ^{129}Xe

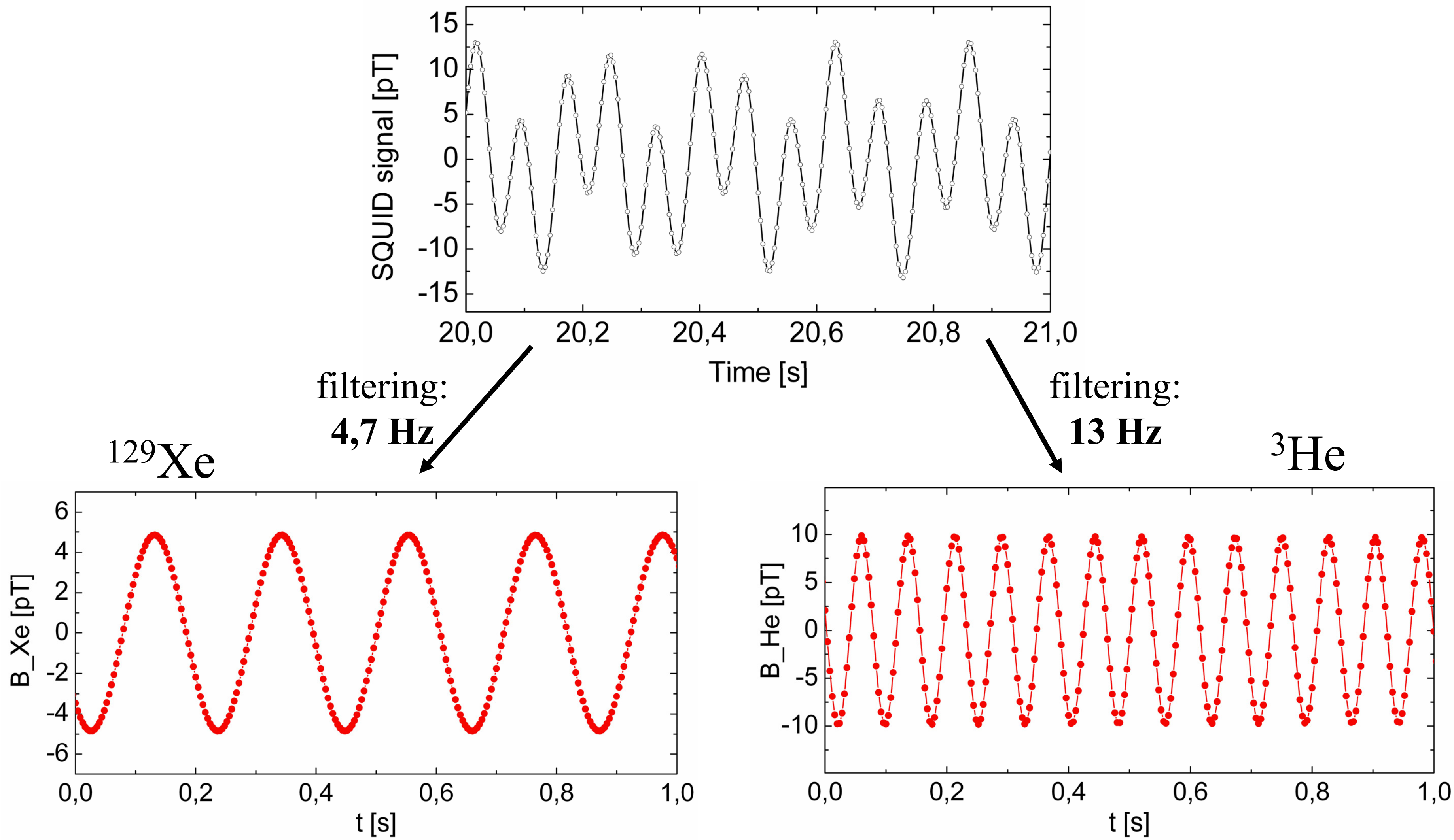


$$\omega_i(t) = \gamma_i B(t) + \omega_{LV}(t) + \ldots \quad , \ \omega_{LV}(He) \approx \omega_{LV}(Xe)$$

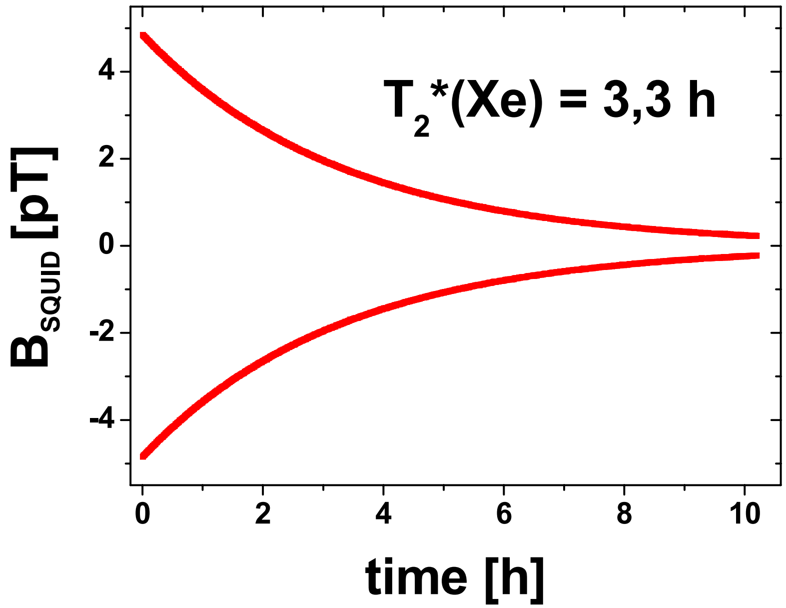
$$\Delta\omega = \omega_{He} - \frac{\gamma_{He}}{\gamma_{Xe}}\omega_{Xe}$$

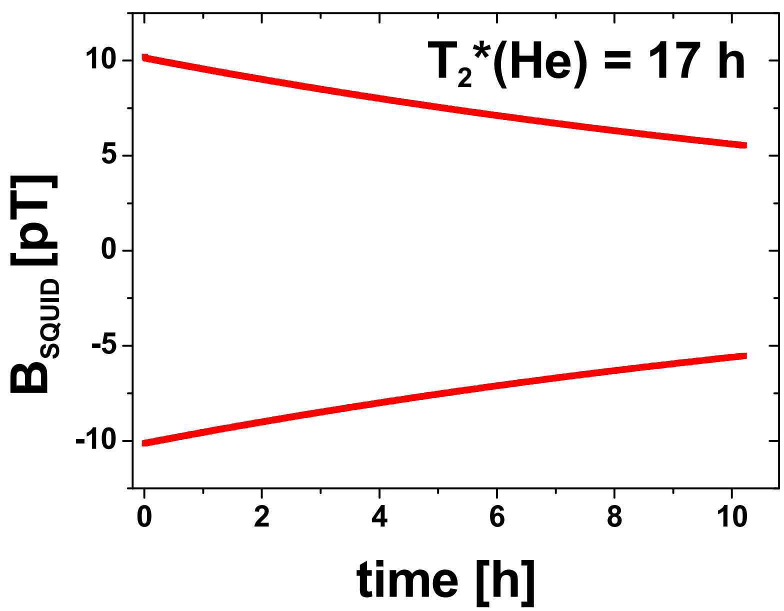
$$= \underbrace{\left(\gamma_{He} - \frac{\gamma_{He}}{\gamma_{Xe}} \cdot \gamma_{Xe}\right)}_{\equiv 0\ !} \cdot B(t) + \left(1 - \underbrace{\frac{\gamma_{He}}{\gamma_{Xe}}}_{= 2.75}\right) \cdot \omega_{LV}(t) + \ldots \approx -1.75 \cdot \omega_{LV}(\mathrm{t}) + \ldots$$

$^{3}He/^{129}Xe$ spin precession signal



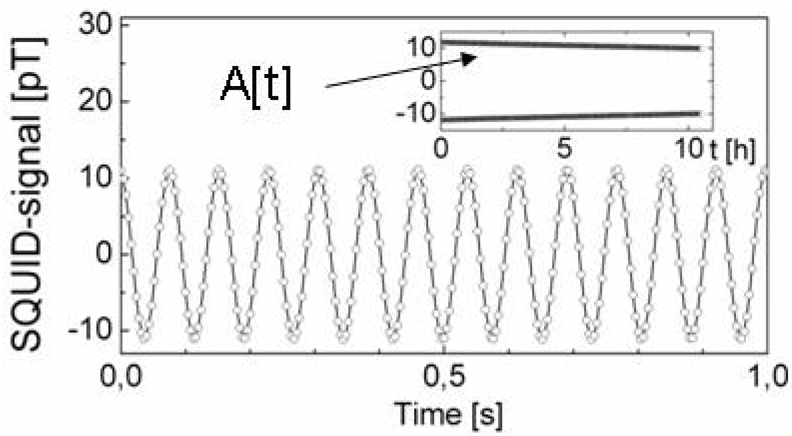
T_2^* relaxation times





- Exponential fit to envelopes of precession signal → T_2^* time
- gas mixture: ^{3}He, ^{129}Xe, N_2 (total pressure 80 mbar)

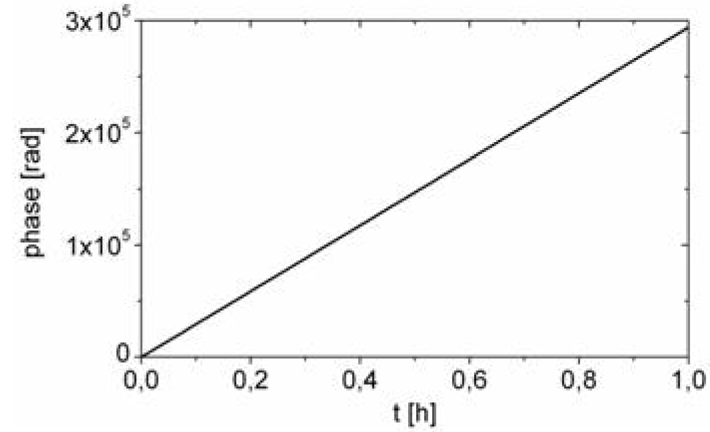
Analysis of phases



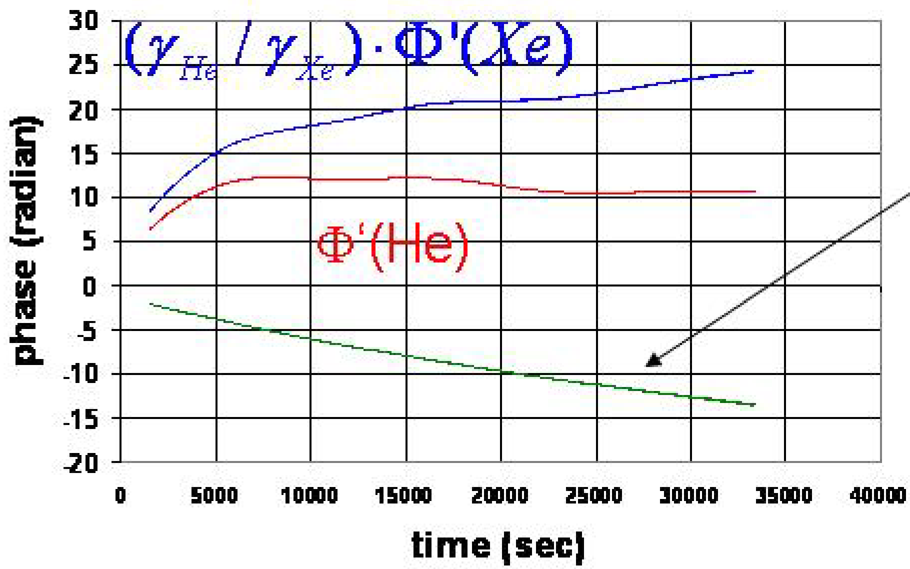
$$\Phi(t) = \int_0^t \omega(t')dt'$$

$$\omega(t) = \overline{\omega} + \Delta\omega(t)$$

$$(\Delta\omega << \overline{\omega})$$



subtract mean frequency: $\Phi'(t) = \int_0^t (\omega(t')-\overline{\omega})\,dt'$



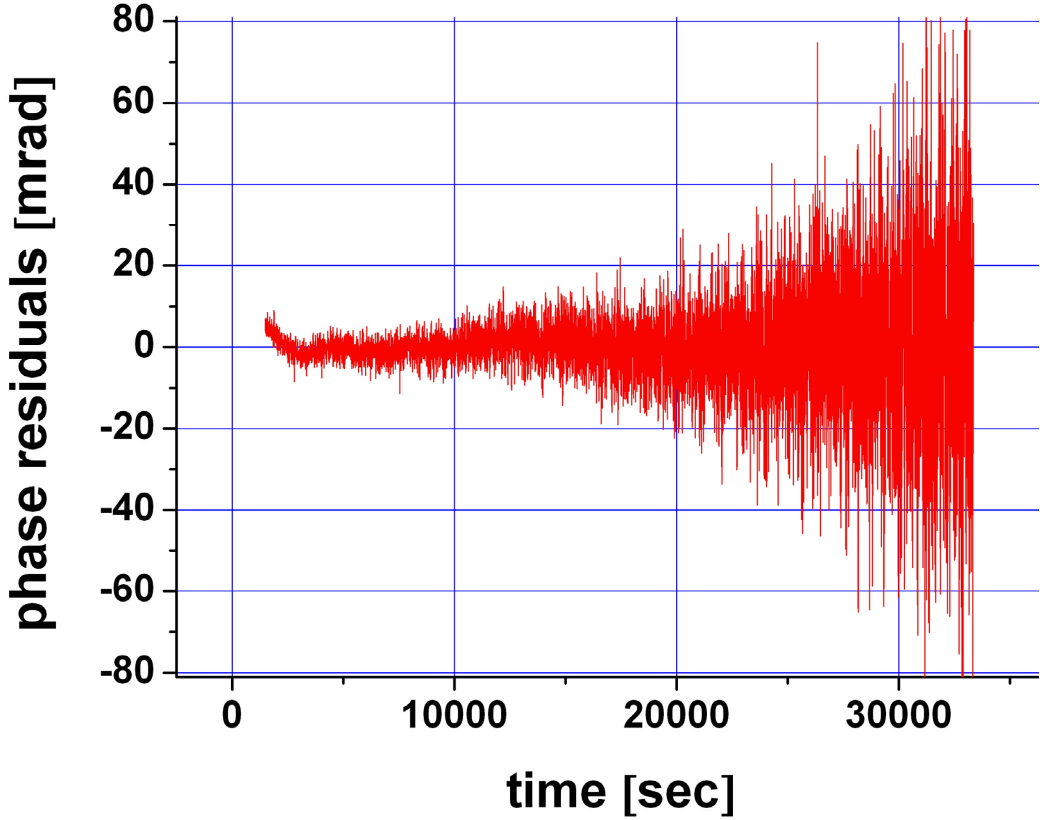
$$\Delta\Phi = \Phi_{He} - \frac{\gamma_{He}}{\gamma_{Xe}} \Phi_{Xe}$$

Fit: $a_0 + a_1 \cdot t + a_2 \cdot A_{He}(t) + a_3 \cdot A_{Xe}(t)$

linear term

Amplitudes of precession signals

Results of $^{3}He/^{129}Xe$ precession



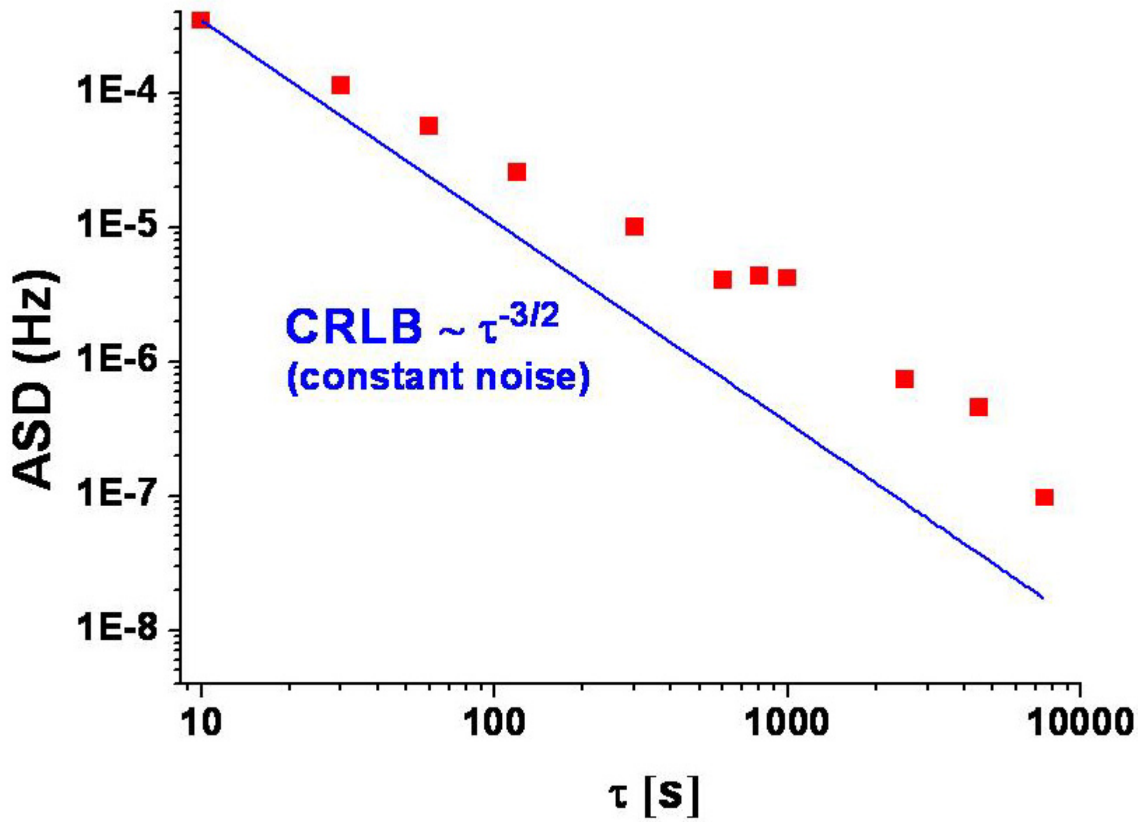
Typical phase residuals after subtraction of fit (bandwidth: 125 mHz);

Noise increases due to limited Xe precession time

Allan deviation

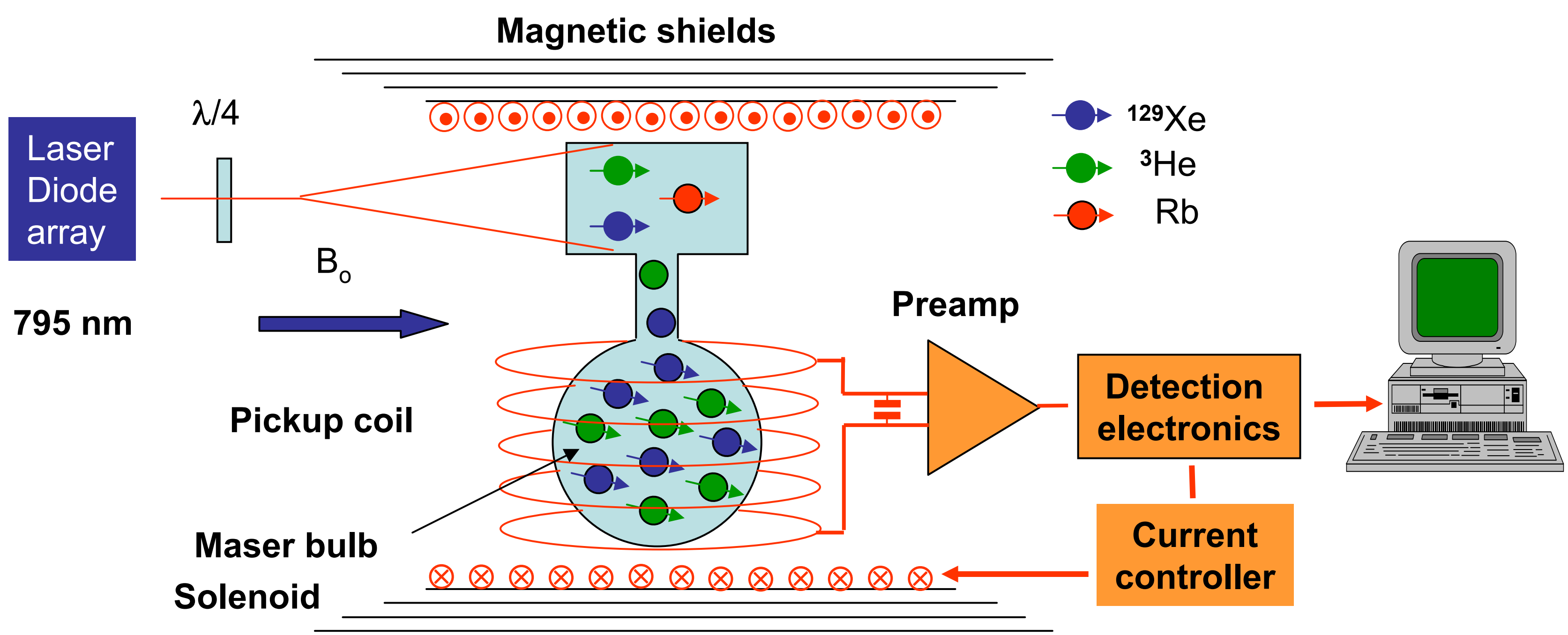
Allan deviation:

$$ASD(Hz) = \frac{1}{\tau}\sqrt{\frac{1}{2}\frac{\sum_{n=1}^{N}\left(\bar{\Phi}_{n+1}^{res}(\tau) - \bar{\Phi}_{n}^{res}(\tau)\right)^2}{N-1}}$$



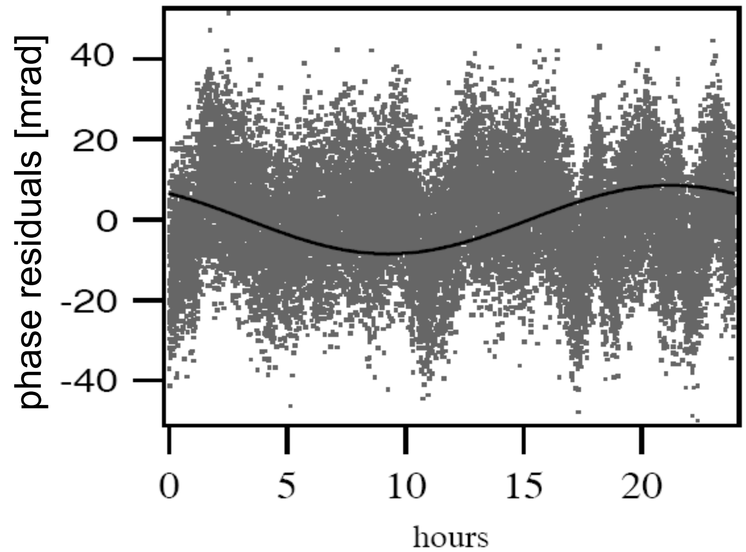
$^{3}He/^{129}Xe$ maser experiment

D.Bear et al., PRL 85 (2000) 5038 :



Problems: temperature variations, drifts of laser frequency, polarization fluctuations lead to frequency and phase noise

Comparison of both experiments



Fit to their data:

$$\delta\phi = 2\pi \cdot \Omega_s^{-1}\left[\delta\upsilon_X \cdot \sin(\Omega_s t) - \delta\upsilon_Y \cdot \cos(\Omega_s t)\right]$$

$$\Rightarrow \quad 2\pi\left|\delta\nu_J\right| \square \frac{1}{\hbar}\cdot\left|-3.5\,\tilde{b}_J^n\right|$$

$$\Rightarrow \quad \left|\tilde{b}_{X,Y}^n\right| < 10^{-31}\ \mathrm{GeV} \approx h \cdot 90\,\mathrm{nHz}$$

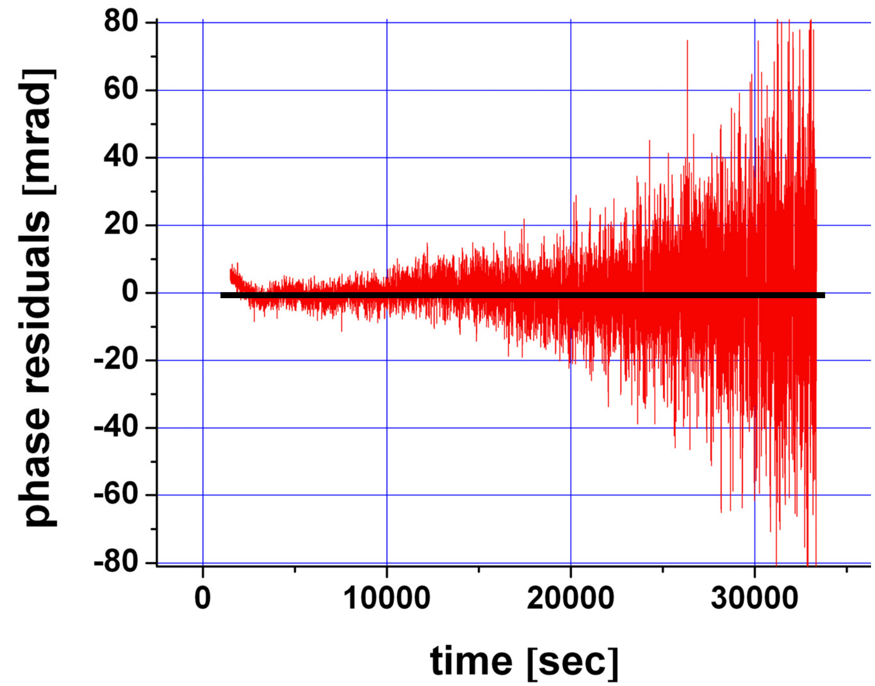
(D.Bear et al., PRL 85 (2000) 5038) :

Fit to our data:

$$\delta\phi = 2\pi \cdot \Omega_s^{-1}\left[\delta\upsilon_X \cdot \sin(\Omega_s t) - \delta\upsilon_Y \cdot \cos(\Omega_s t)\right]$$

→ upper limit in sensitivity:

$$\left|\delta\upsilon_{X,Y}\right| \leq\ 6\ nHz$$



Problem : linear term $a_1 \cdot t$ can mask possible LV effects due to limited free spin precession time

Conclusion and outlook

Results of $^{3}He/^{129}Xe$ co-magnetometer experiment:

- T_2^* times reached (total pressure 80 mbar):
  for He: 17 h; for Xe: 3.3 h
- upper limit in sensitivity: 6 nHz
- Problem: linear term masks possible Lorentz violation effects if measurement time to short

Improvements:

- increase T_1 relaxation time of Xenon (e.g. better demagnetization of cells)
- change direction of magnetic guiding field during spin-precession cycle (adiabatic rotation)