Results from ^{3}He/ ^{129}Xe clock comparison experiments for testing Lorentz invariance on the bound neutron

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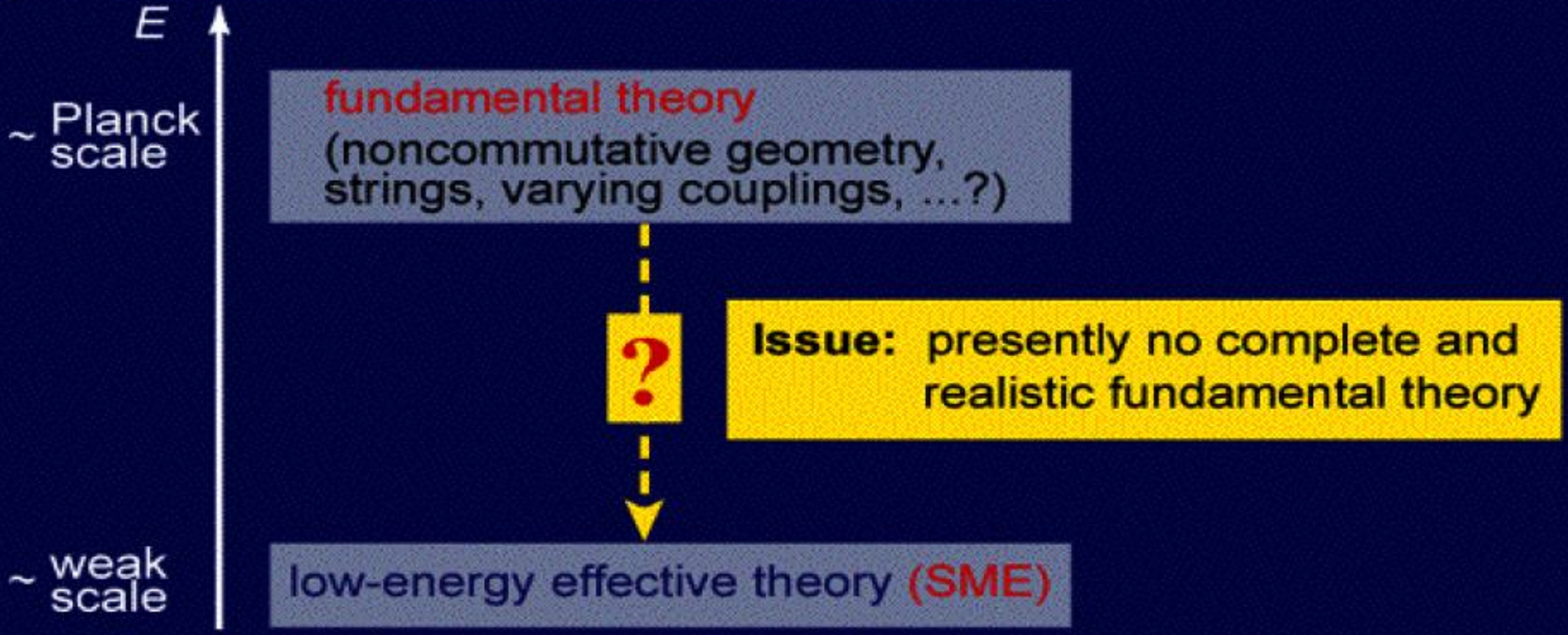
Outline:

- Standard Model Extension (Kostelecky)
- ^{3}He, ^{129}Xe clock based on free nuclear spin precession
- New limits on LV from clock comparison experiments
- Conclusion and Outlook

How to obtain low-energy effective theory?



fundamental theory
(noncommutative geometry, strings, varying couplings, ...?)

Issue: presently no complete and realistic fundamental theory

low-energy effective theory (SME)

Idea:
- examine manifestations of Lorentz/CPT violating vacuum
- construct all possible modifications to SM (previous sec.)

Advantage:
- independent of underlying theory
- describes all low-energy effects of Lorentz violation

Standard-Model Extension

A. Kostelecky and C. Lane: **Phys. Rev. D 60, 116010 (1999)**

Modified Dirac equation for a free spin ½ particle (w=e,p,n)

$$\left(\underbrace{i\gamma^{\mu}\partial_{\mu} - m_{w}}_{\text{standard DE}} \underbrace{\underbrace{- a^{w}_{\mu}\gamma^{\mu} - b^{w}_{\mu}\gamma_{5}\gamma^{\mu} + ie^{w}_{\nu}\partial^{\nu} - f^{w}_{\nu}\gamma_{5}\partial^{\nu} + i\frac{1}{2}g^{w}_{\lambda\mu\upsilon}\sigma^{\lambda\mu}\partial^{\nu}}_{\text{CPT violating}} \underbrace{- \frac{1}{2}H^{w}_{\mu\nu}\sigma^{\mu\nu} + ic^{w}_{\mu\nu}\gamma^{\mu}\partial^{\nu} + id^{w}_{\mu\nu}\gamma_{5}\gamma^{\mu}\partial^{\nu}}_{\text{CPT preserving terms}}}_{\text{Lorentz violating terms}} \right)\Psi = 0$$

Experimental access:

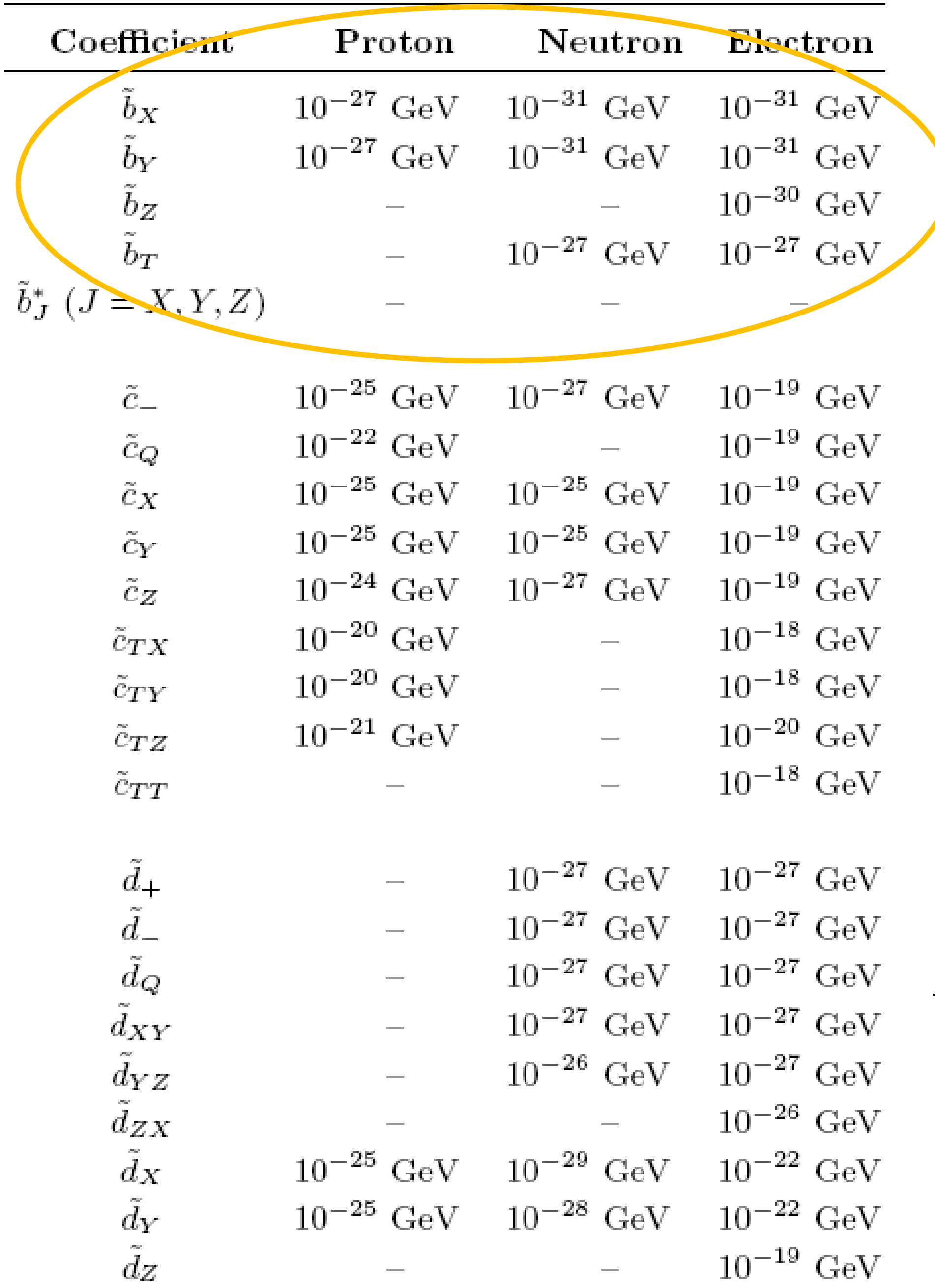
$$a^{w}_{\mu}, b^{w}_{\mu}, \ldots. \approx \eta_{w} \cdot \left(\frac{m_{w}}{M_{Planck}} \right)^{n}$$

coupling strength

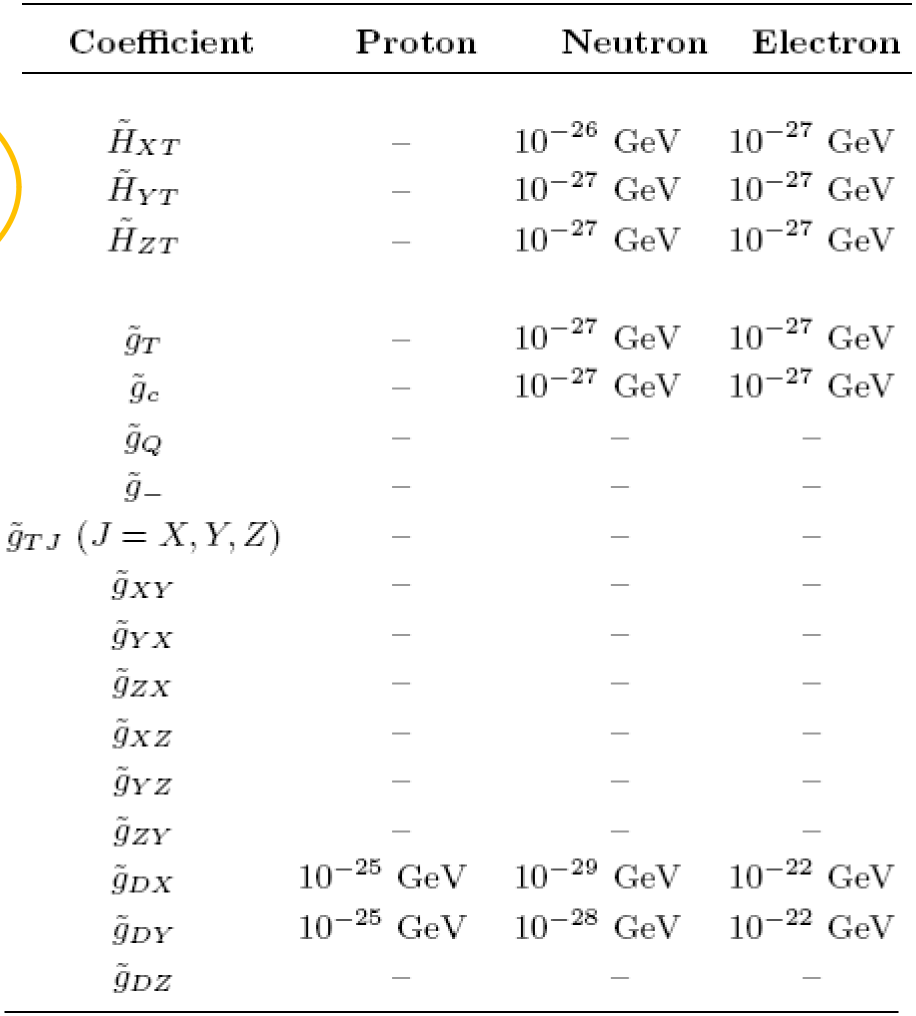
Doppler-shift
Cs- fountain
Torsion pendulum
Antihydrogen spectroscopy
Astrophysics
Hg/Cs comparison
He/Xe maser
UCN/Hg comparison
….

clock comparison experiments

Kostelecky et al., arXiv:0801.0287v2



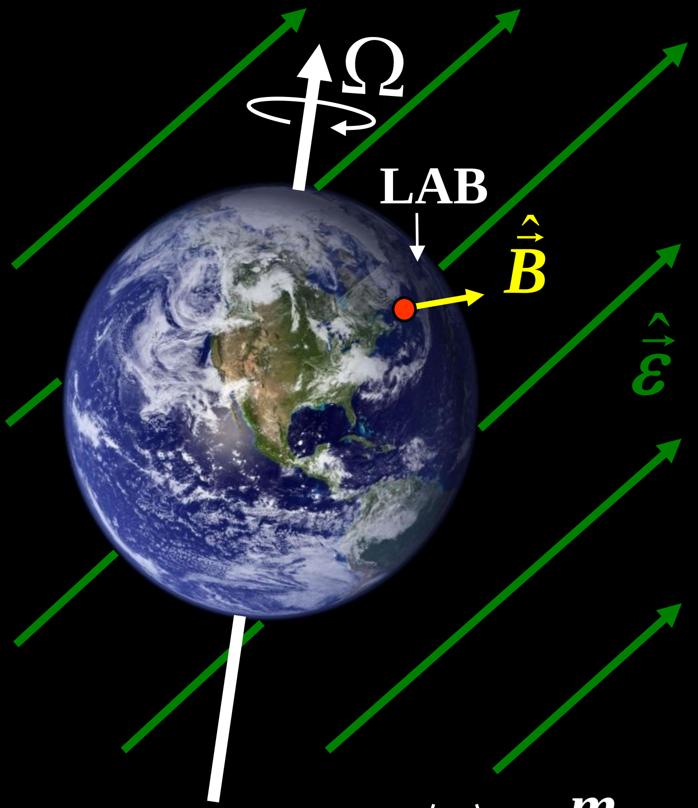
Coefficient	Proton	Neutron	Electron
$\tilde{b}_X$	10^{-27} GeV	10^{-31} GeV	10^{-31} GeV
$\tilde{b}_Y$	10^{-27} GeV	10^{-31} GeV	10^{-31} GeV
$\tilde{b}_Z$	–	–	10^{-30} GeV
$\tilde{b}_T$	–	10^{-27} GeV	10^{-27} GeV
$\tilde{b}^*_J$ $(J = X, Y, Z)$	–	–	–
$\tilde{c}_-$	10^{-25} GeV	10^{-27} GeV	10^{-19} GeV
$\tilde{c}_Q$	10^{-22} GeV	–	10^{-19} GeV
$\tilde{c}_X$	10^{-25} GeV	10^{-25} GeV	10^{-19} GeV
$\tilde{c}_Y$	10^{-25} GeV	10^{-25} GeV	10^{-19} GeV
$\tilde{c}_Z$	10^{-24} GeV	10^{-27} GeV	10^{-19} GeV
$\tilde{c}_{TX}$	10^{-20} GeV	–	10^{-18} GeV
$\tilde{c}_{TY}$	10^{-20} GeV	–	10^{-18} GeV
$\tilde{c}_{TZ}$	10^{-21} GeV	–	10^{-20} GeV
$\tilde{c}_{TT}$	–	–	10^{-18} GeV
$\tilde{d}_+$	–	10^{-27} GeV	10^{-27} GeV
$\tilde{d}_-$	–	10^{-27} GeV	10^{-27} GeV
$\tilde{d}_Q$	–	10^{-27} GeV	10^{-27} GeV
$\tilde{d}_{XY}$	–	10^{-27} GeV	10^{-27} GeV
$\tilde{d}_{YZ}$	–	10^{-26} GeV	10^{-27} GeV
$\tilde{d}_{ZX}$	–	–	10^{-26} GeV
$\tilde{d}_X$	10^{-25} GeV	10^{-29} GeV	10^{-22} GeV
$\tilde{d}_Y$	10^{-25} GeV	10^{-28} GeV	10^{-22} GeV
$\tilde{d}_Z$	–	–	10^{-19} GeV



Coefficient	Proton	Neutron	Electron
$\tilde{H}_{XT}$	–	10^{-26} GeV	10^{-27} GeV
$\tilde{H}_{YT}$	–	10^{-27} GeV	10^{-27} GeV
$\tilde{H}_{ZT}$	–	10^{-27} GeV	10^{-27} GeV
$\tilde{g}_T$	–	10^{-27} GeV	10^{-27} GeV
$\tilde{g}_c$	–	10^{-27} GeV	10^{-27} GeV
$\tilde{g}_Q$	–	–	–
$\tilde{g}_-$	–	–	–
$\tilde{g}_{TJ}$ $(J = X, Y, Z)$	–	–	–
$\tilde{g}_{XY}$	–	–	–
$\tilde{g}_{YX}$	–	–	–
$\tilde{g}_{ZX}$	–	–	–
$\tilde{g}_{XZ}$	–	–	–
$\tilde{g}_{YZ}$	–	–	–
$\tilde{g}_{ZY}$	–	–	–
$\tilde{g}_{DX}$	10^{-25} GeV	10^{-29} GeV	10^{-22} GeV
$\tilde{g}_{DY}$	10^{-25} GeV	10^{-28} GeV	10^{-22} GeV
$\tilde{g}_{DZ}$	–	–	–

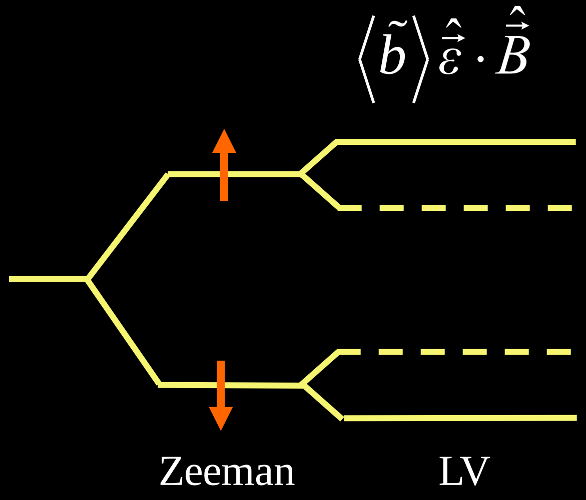
Clock-comparison experiments

coupling of spin $\vec{\sigma}$ to background field: $V = -\vec{\tilde{b}} \cdot \vec{\sigma}$



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

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



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

Clock-comparison:
Zeeman term drops out

$$\Delta\omega = \omega_A - \frac{\gamma_A}{\gamma_B}\omega_B = \left(1 - \frac{\gamma_A}{\gamma_B}\right) \cdot \omega_{LV}$$

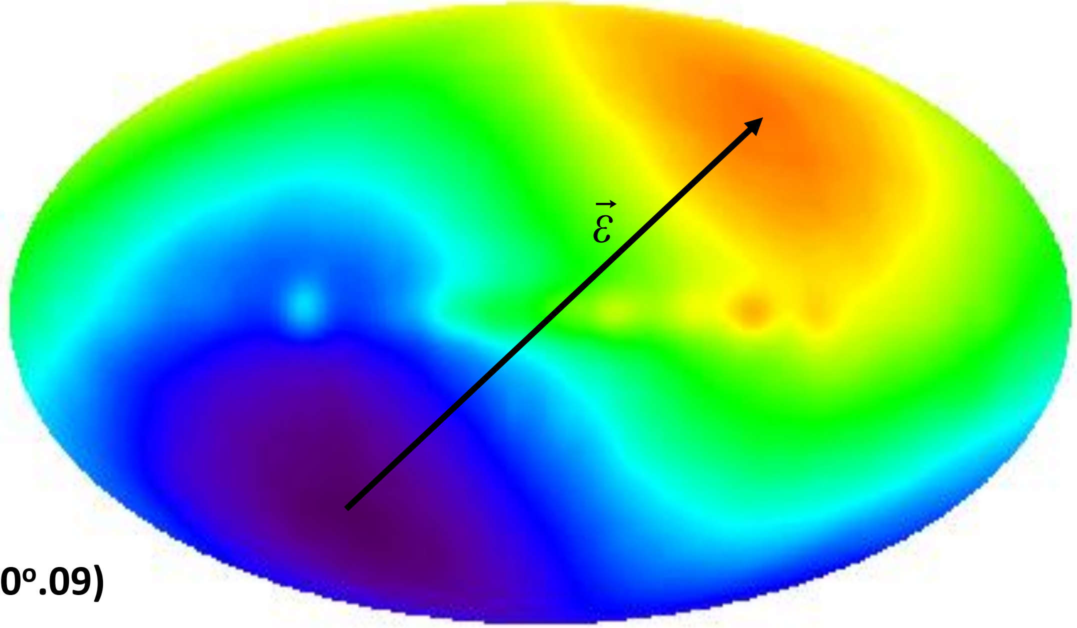
CMB dipole

$v = 368$ km/s

$\Delta T_{dip} \approx 3.3$ mK

galactic coordinate system

(*l*, *b*) = (264°.31±0°.04±0°.16, +48°.05±0°.02±0°.09)

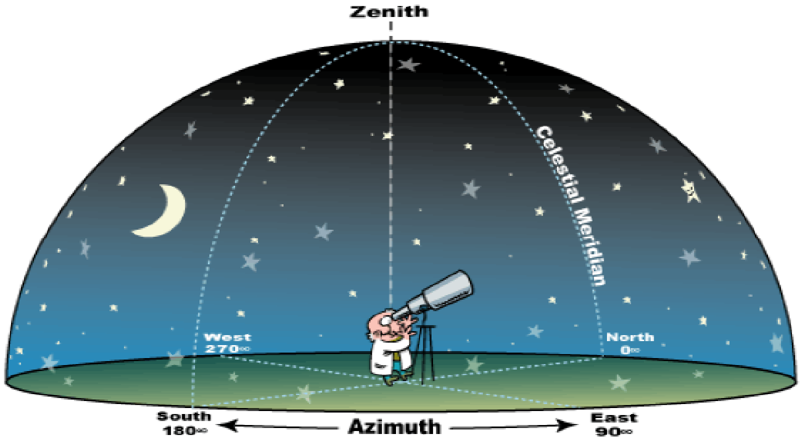


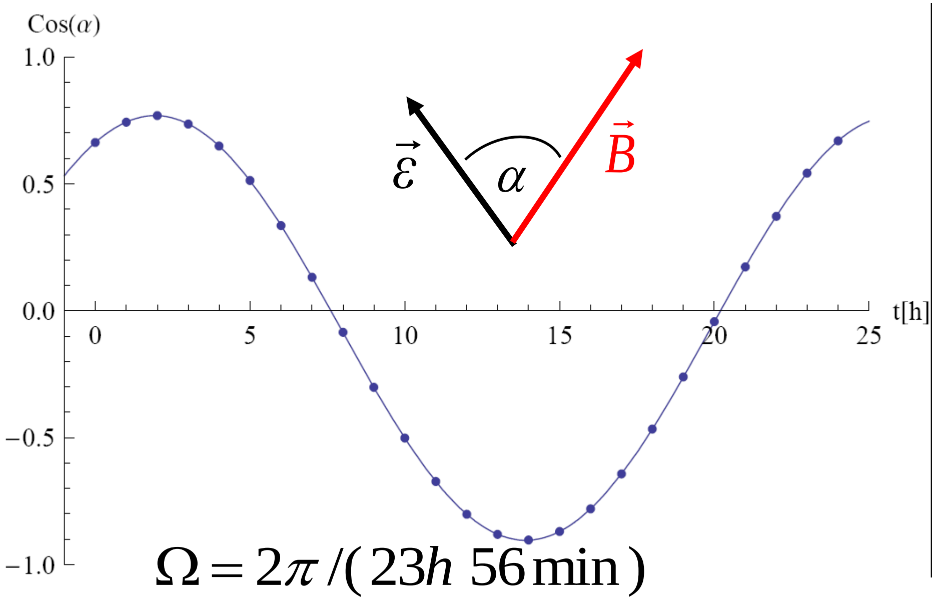
measurement on 01.10.2007 at

PTB-Berlin (52° 31´ north, 13° 25´ east)

horizon coordinate system

(observer's local horizon)

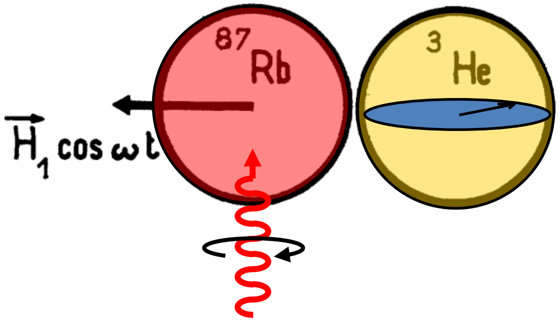


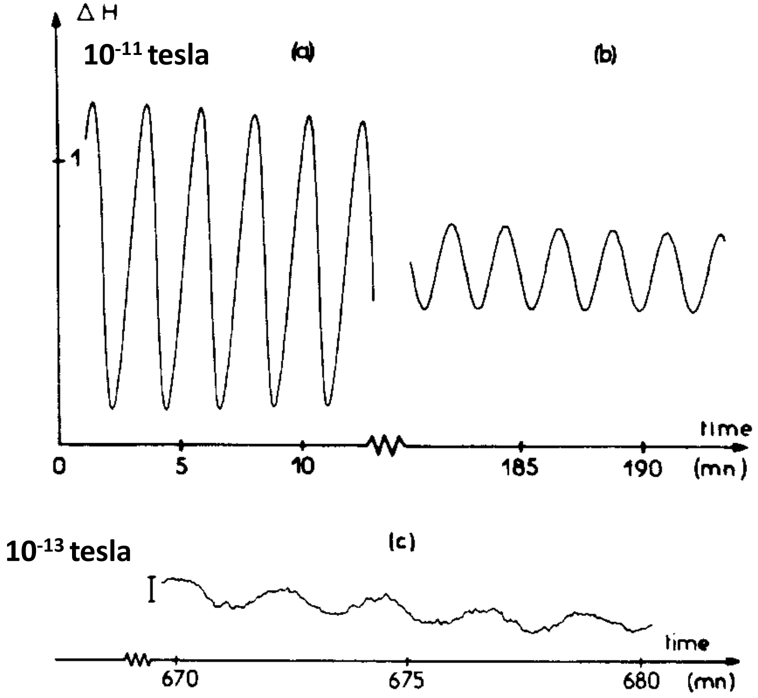


$$\Omega = 2\pi/(23h\ 56\min)$$

Detection of magnetic field produced by oriented nuclei

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





Results:

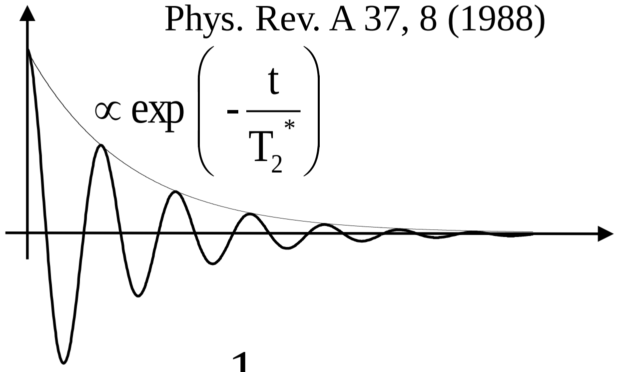
- ^{3}He spin precession: $T_2^* = 2\text{h}\ 20\text{min}$
- sensitivity of Rb-magnetometer:
  100fT@ BW 0.3 Hz
- $P_{He} \approx$ 5% @ 4 mbar

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)



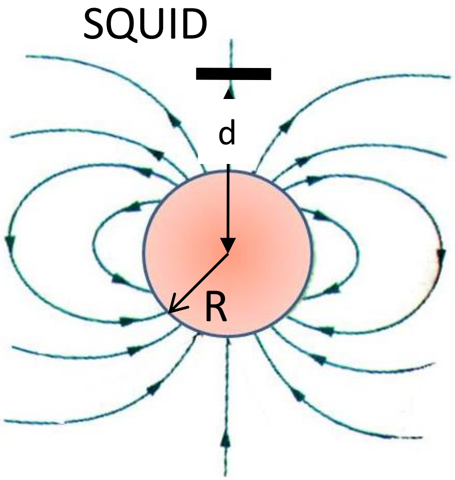
size: R
=> 3cm

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

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

longitudinal
relaxation time
T_1(He) > 100 h

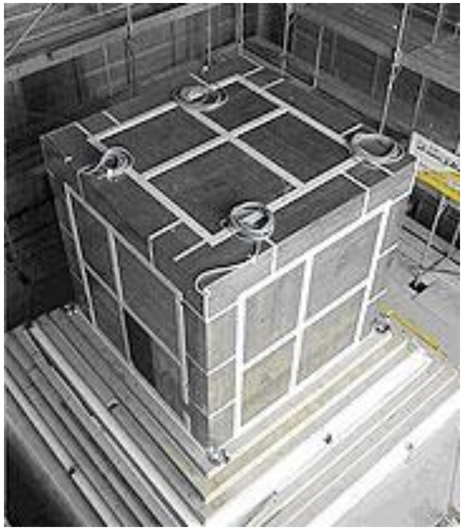
diffusion const. D ~ 1/p
→ low pressure
(p ~ mbar)



Signal:

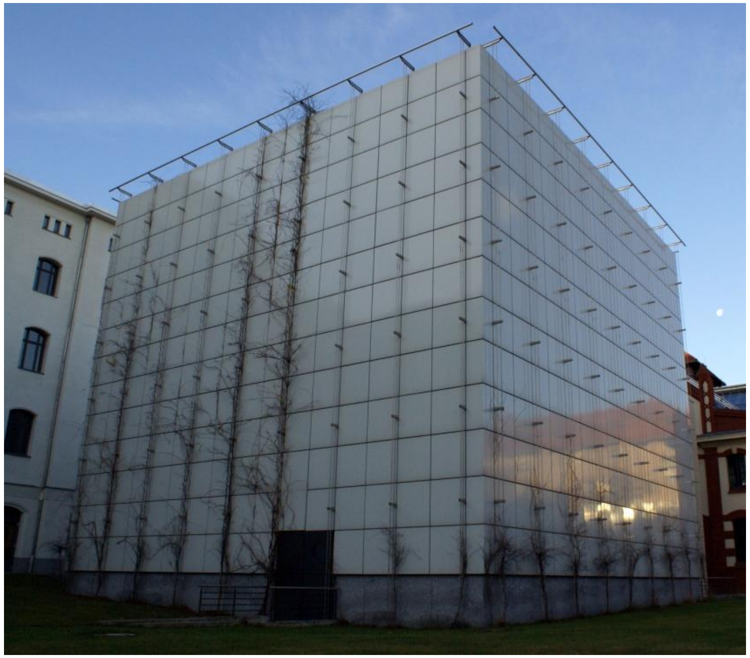
$$\Delta B[pT] \approx 220\cdot p[mbar]\cdot P\cdot\left(\frac{R}{d}\right)^3$$

BMSR 2, PTB Berlin

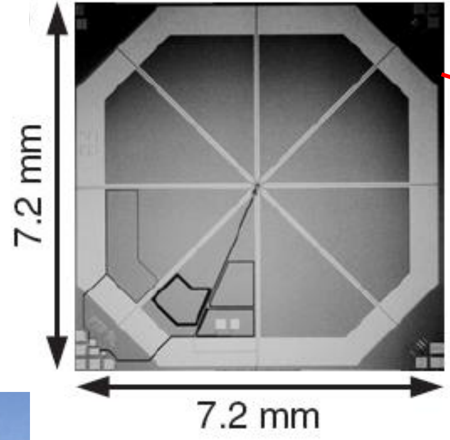


The 7-layered magnetically shielded room (residual field < 2 nT)

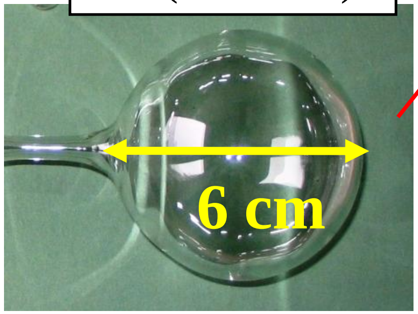
J. Bork, et al., Proc. Biomag 2000, 970 (2000).

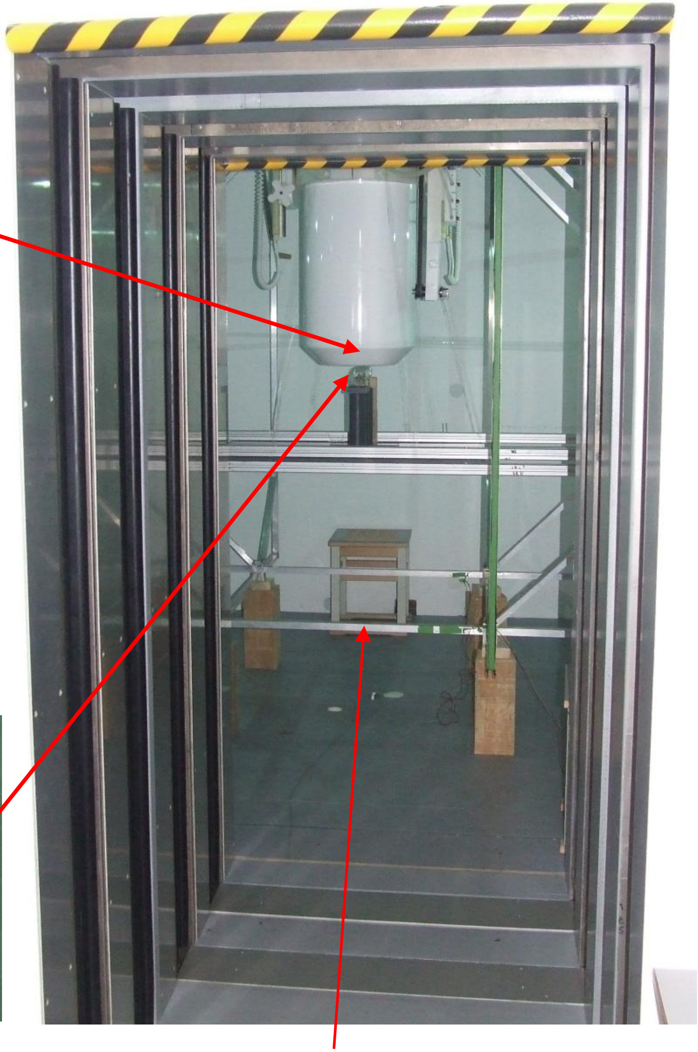


LT$_c$- SQUID



^{3}He (4.5 mbar)

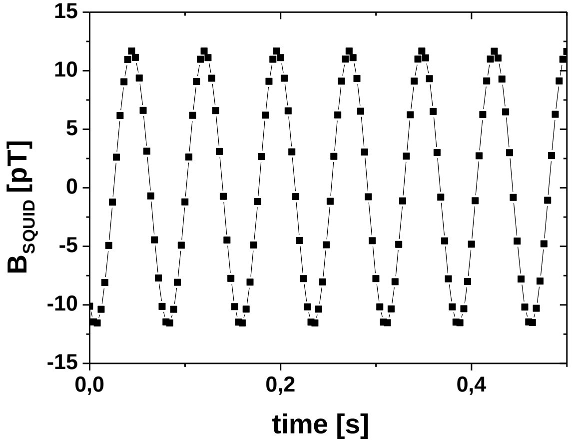


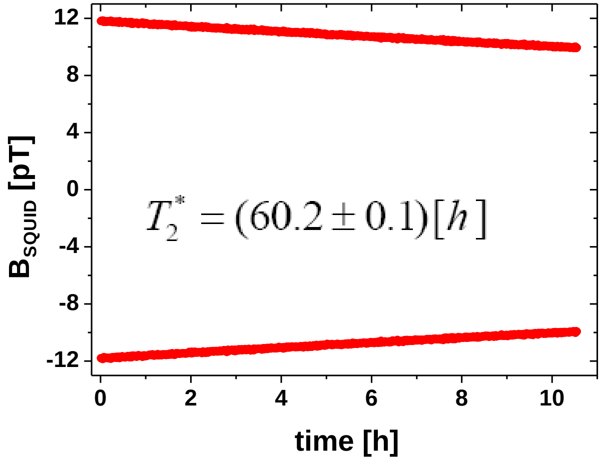


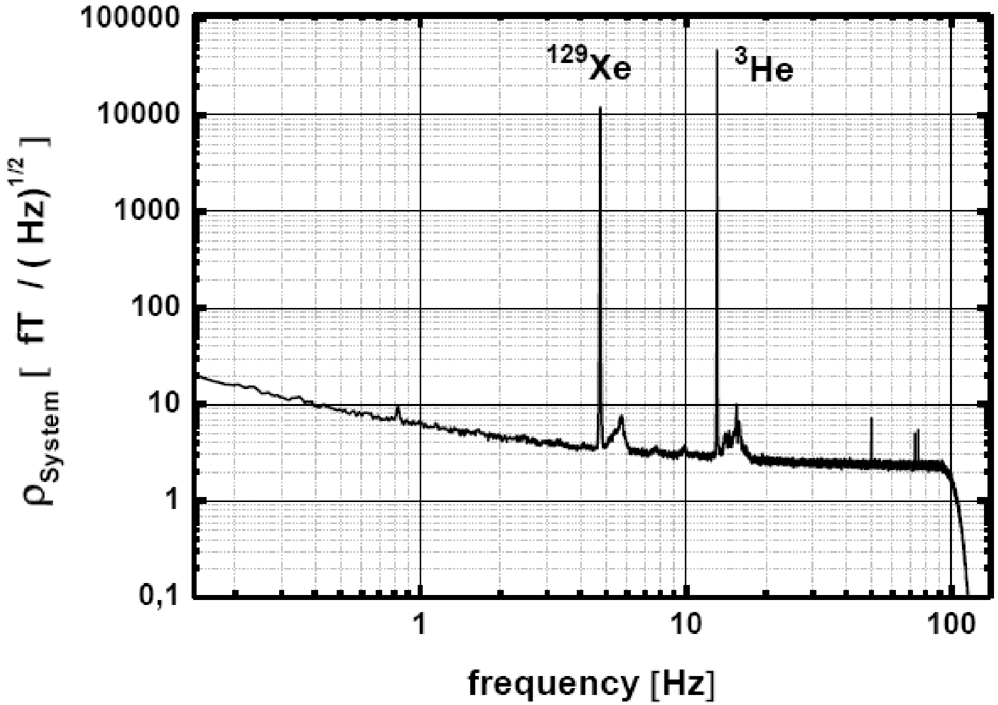
magnetic guiding field ≈ 0.4 μT (Helmholtz-coils)

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

Sensitivity of a free spin-precession ^{3}He clock







Cramer-Rao Lower Bound (CRLB)

$$s[n] = A \cdot \cos(2\pi \cdot f \cdot \Delta t \cdot n + \Phi) \cdot \exp(-\beta \cdot n) + w[n] \qquad n = 0,1,2,3,\ldots, N-1$$

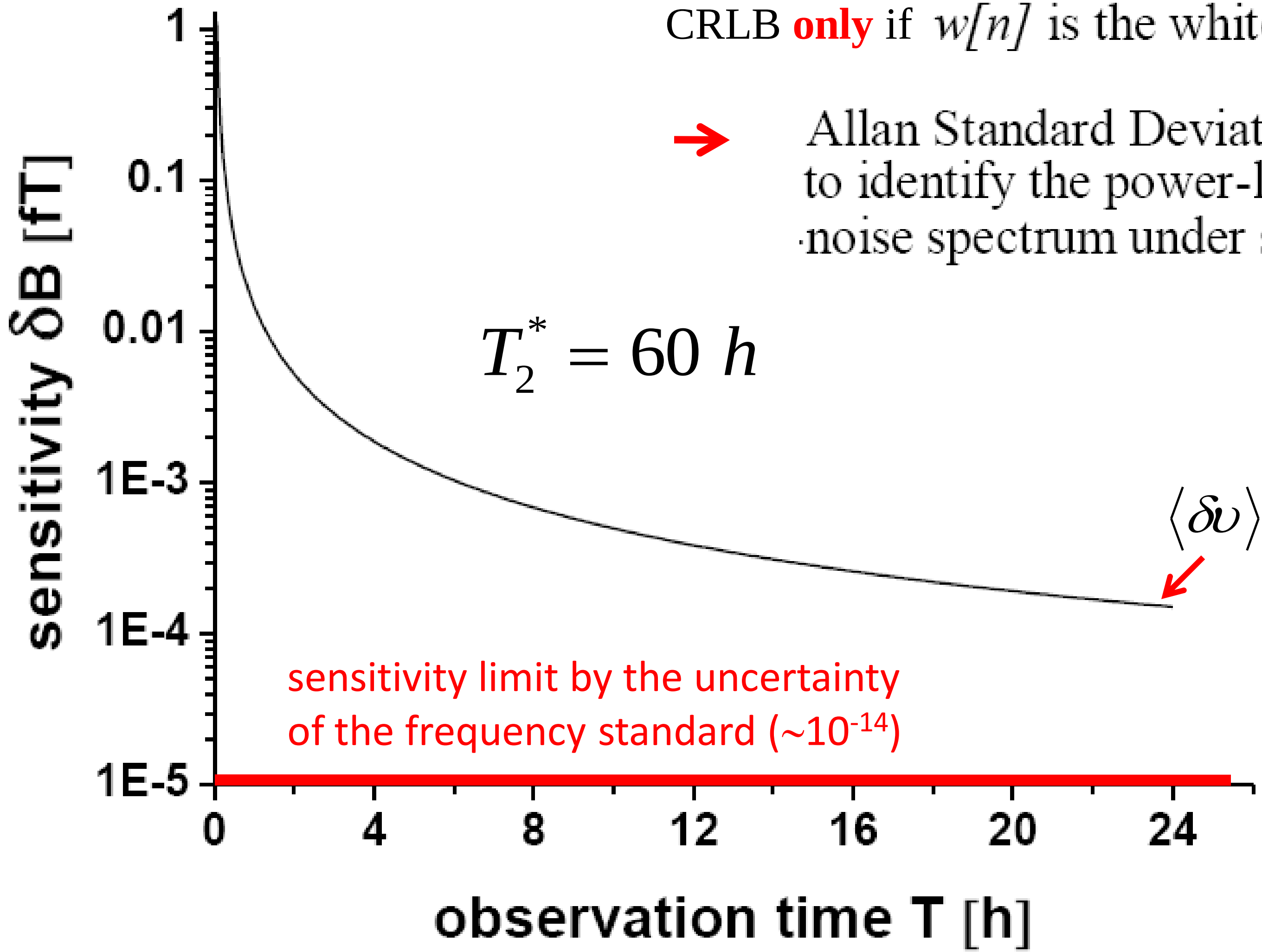
$$\boxed{\sigma_f^2 \geq \frac{12}{(2\pi)^2 (A / \rho_\alpha)^2 \cdot T^3} \cdot \mathrm{C}}$$

using

$$f = \gamma / (2\pi) \cdot B_0 \Rightarrow \delta B[fT] \approx 3150 \cdot \frac{\sqrt{C}}{T^{3/2}}$$

CRLB **only** if $w[n]$ is the white Gaussian noise

→ Allan Standard Deviation (ASD) to identify the power-law model for the noise spectrum under study



$T_2^* = 60\ h$

$\langle \delta\upsilon \rangle_{day} \approx 5\ pHz$

sensitivity limit by the uncertainty of the frequency standard (~10^{-14})

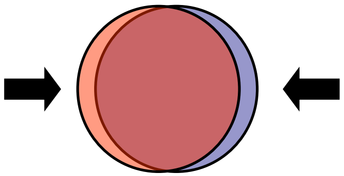
Advantage of long spin-coherence times:

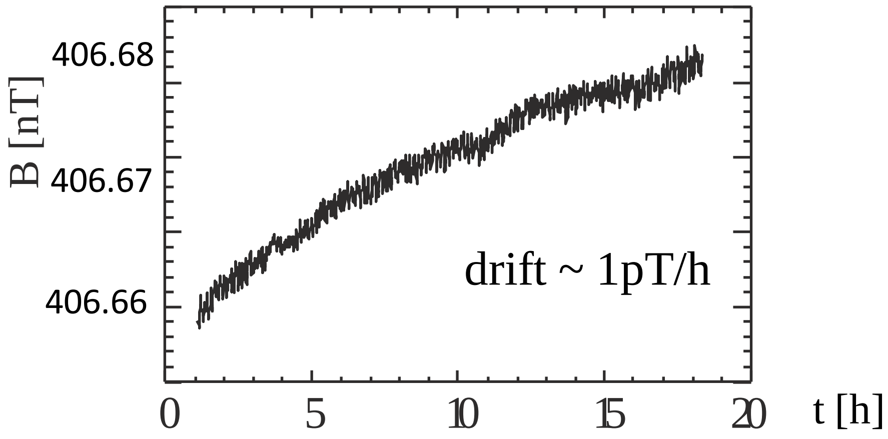
$\delta\upsilon \propto 1/T^{3/2}$ vs. series of short (ΔT) measurements $\delta\upsilon = \left(1/\Delta T^{3/2}\right) \cdot / \sqrt{T/\Delta T} = \left(1/T^{3/2}\right) \cdot \frac{T}{\Delta T}$

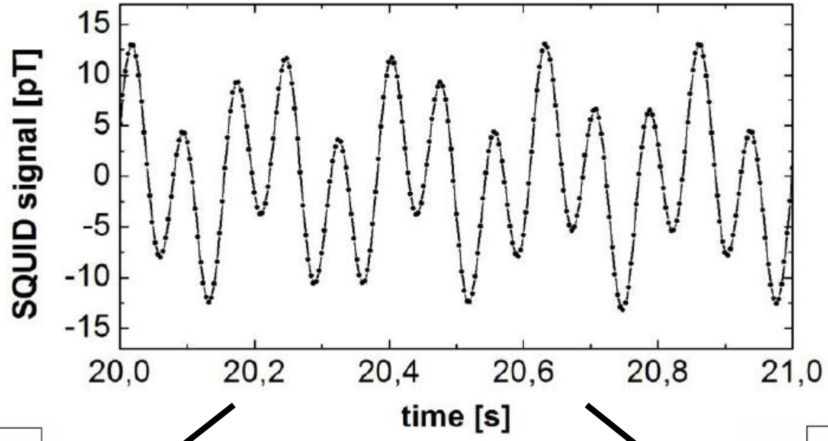
^{3}He / ^{129}Xe co-magnetometer

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

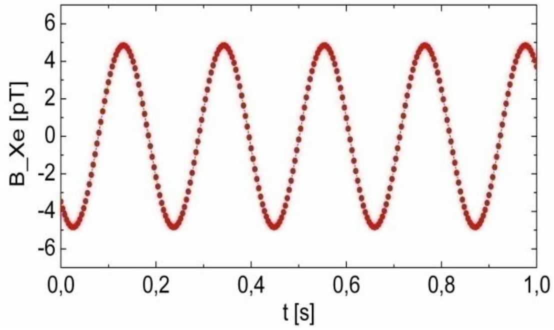
^{3}He / ^{129}Xe







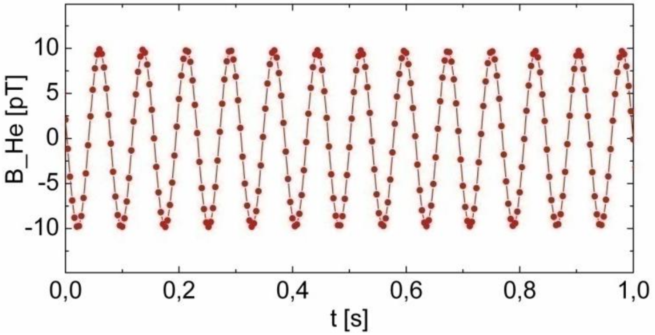
^{129}Xe



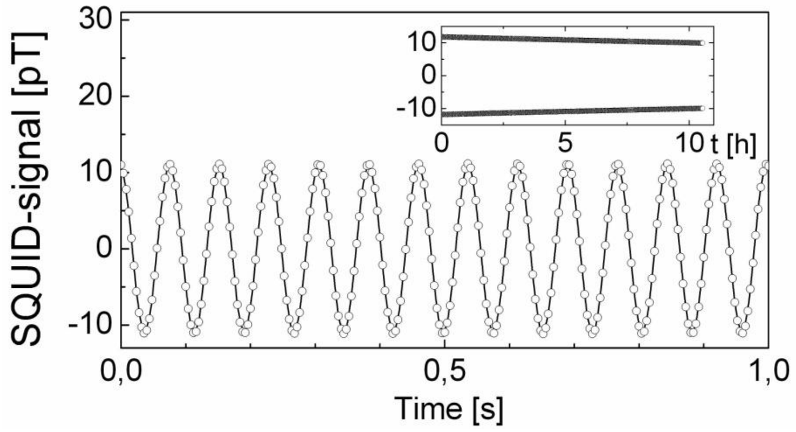
filtering:
4,7 Hz

filtering:
13 Hz

^{3}He



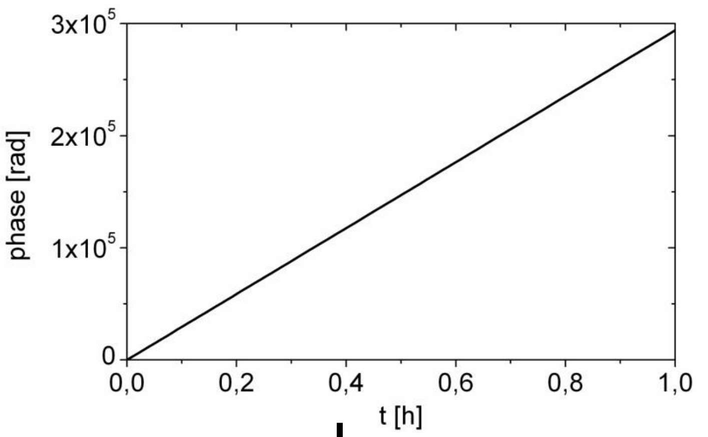
Analysis of phases



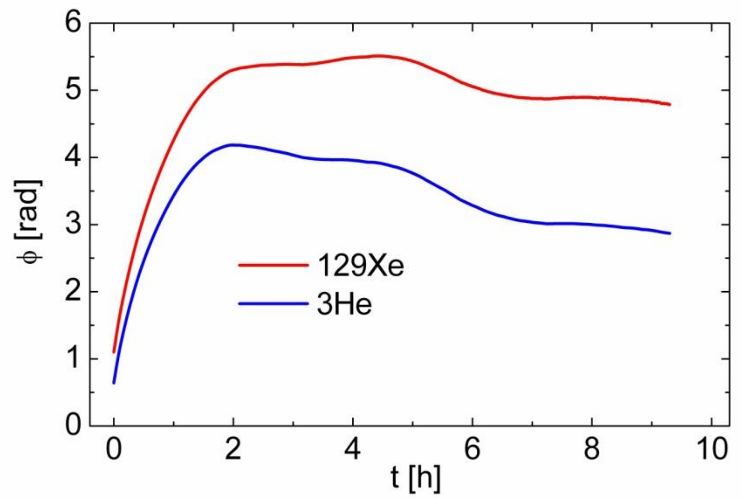
$$\Phi(t) = \int_0^t \omega(t')dt'$$

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

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



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

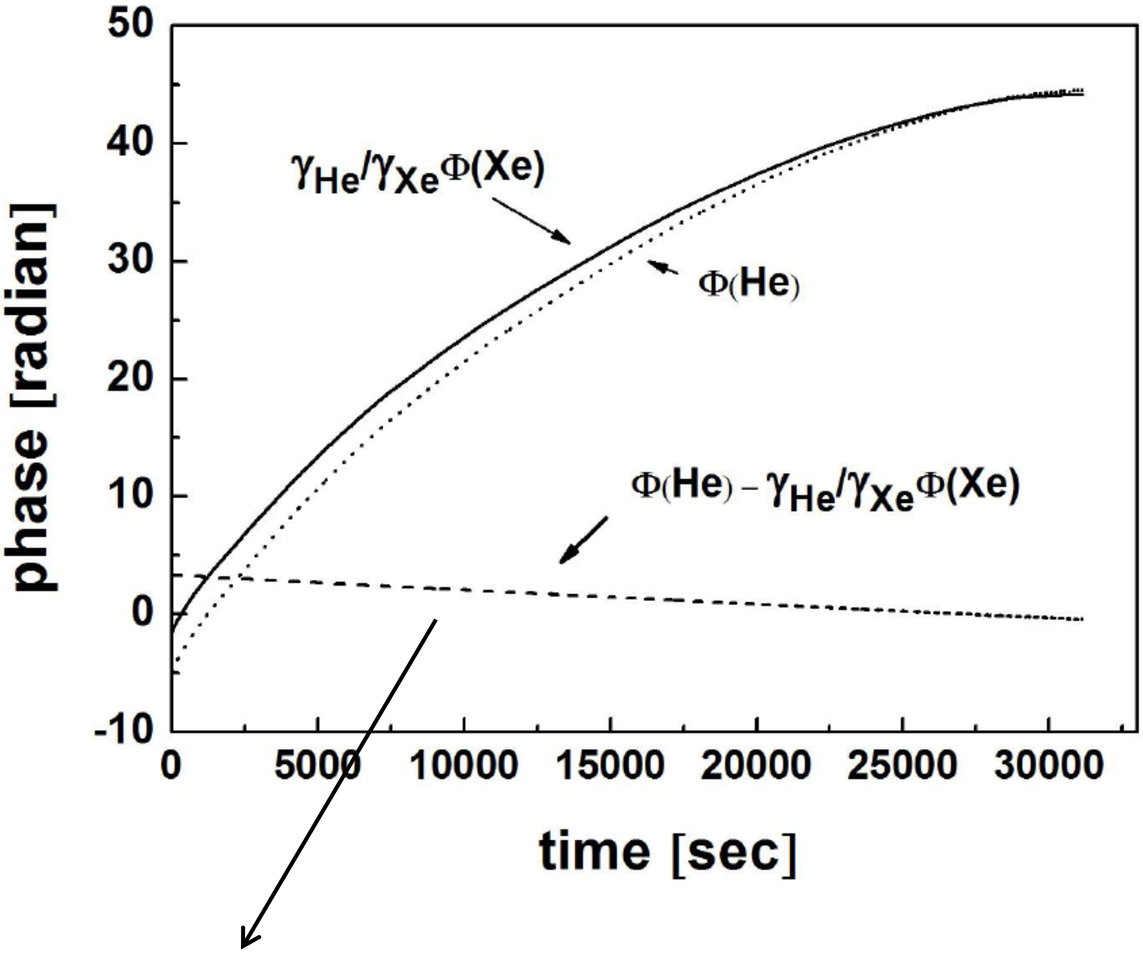


$$\gamma_{He} / \gamma_{Xe} = 2.75408159(20)$$

<u>expected:</u>

$$\Delta\Phi(t) = \Phi'_{He}(t) - {}^{\gamma_{He}}\!/_{\gamma_{Xe}} \cdot \Phi'_{Xe}(t)$$

$$= \Phi_0 + 2\pi / \Omega_s \cdot \left(\delta\upsilon_x \cdot \sin(\Omega_s t) - \delta\upsilon_y \cdot \cos(\Omega_s t)\right)$$



$$\Delta\Phi = \Phi_0 + \Omega_L \cdot t + \Phi_1 \cdot \exp\left(-t/T_x\right) + \Delta\Phi_{LV}(t)$$

Contribution to linear term:

- Earth‘s rotation

$$\left(1-\gamma_{He}/\gamma_{Xe}\right)\cdot\frac{2\pi}{T_s}\cdot 0.544 \approx 0.069\ mrad/s$$

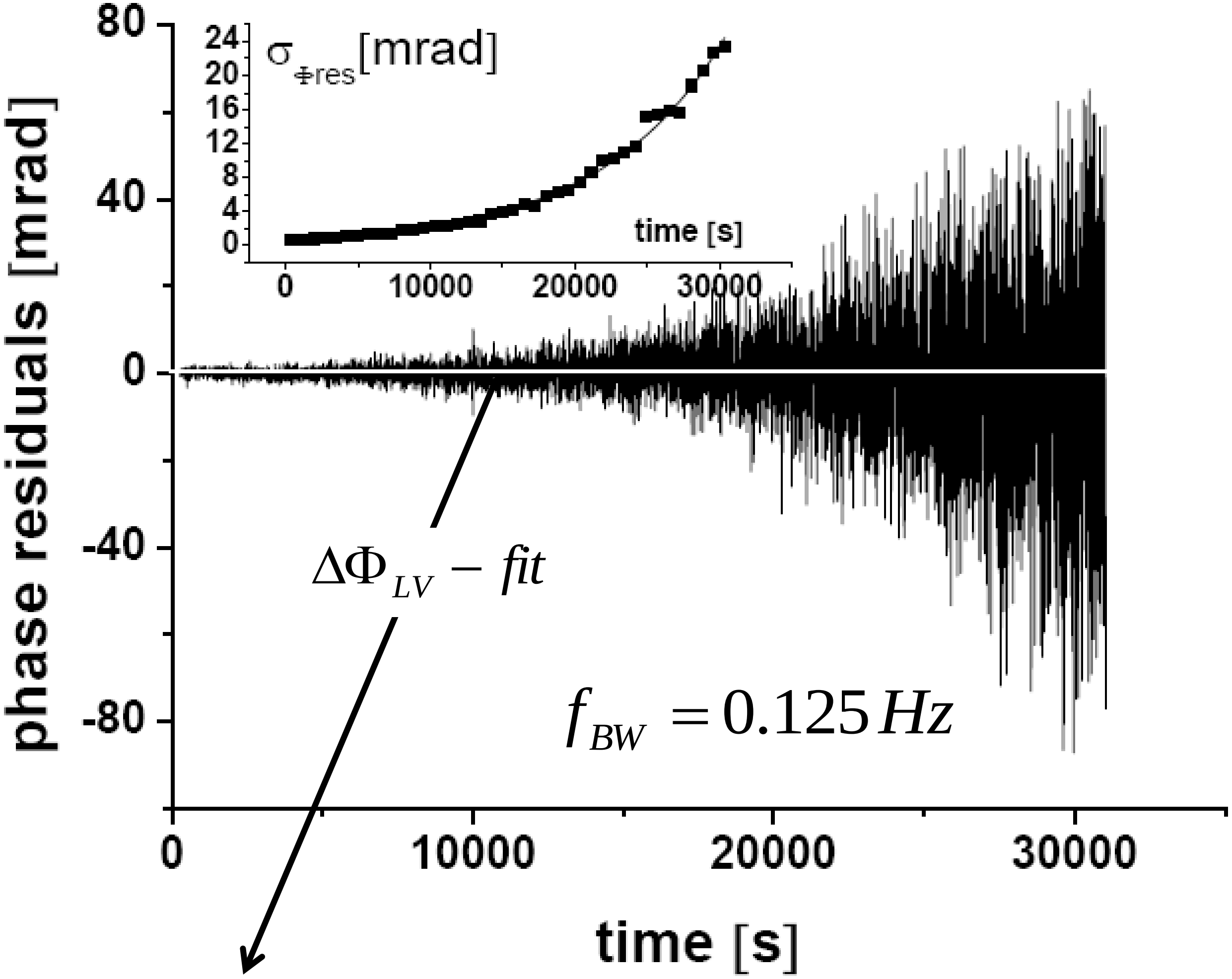
- chemical shift

$$\left(\gamma_{He}/\gamma_{Xe}\right)_{c.s.} \neq \left(\gamma_{He}/\gamma_{Xe}\right)_{literature}$$

- .....

Exponential term:

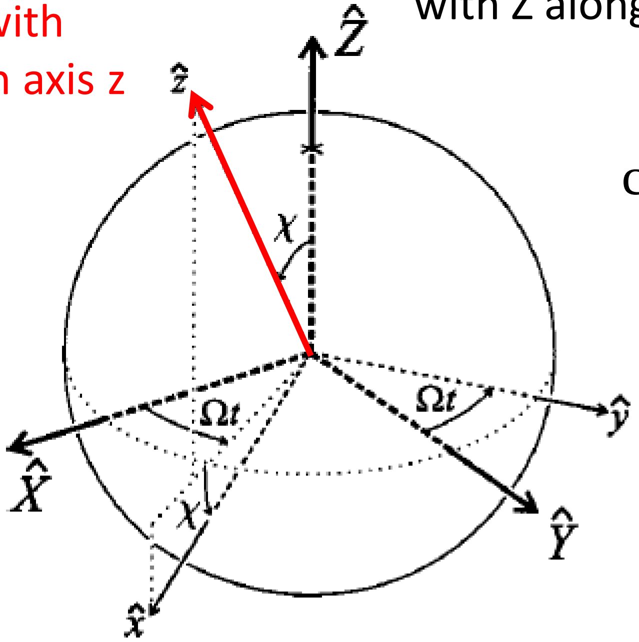
$$20\ h < T_x < 70\,h \qquad \textbf{?}$$



$$\delta\upsilon_x = (0.35 \pm 2.95)\cdot 10^{-9}\, Hz \text{ and } \delta\upsilon_y = (0.77 \pm 3.70)\cdot 10^{-9}\, Hz$$

$$\boxed{\Delta\upsilon_{\perp} = \sqrt{\delta\upsilon_x^2 + \delta\upsilon_y^2} = (0.8 \pm 4.7)\, nHz \ \text{(67\% C.L.)}}$$

Phys. Rev. D 60, 116010 (1999)



(X,Y,Z) non-rotating frame
with Z along Earth‘s rotation axis

Lab-frame with
quantization axis z

free neutron:

n : μ = -1.913 μ_K

Schmidt-Model

^{3}He: μ = -2.1276 μ_K

^{129}Xe: μ = -0.7779 μ_K

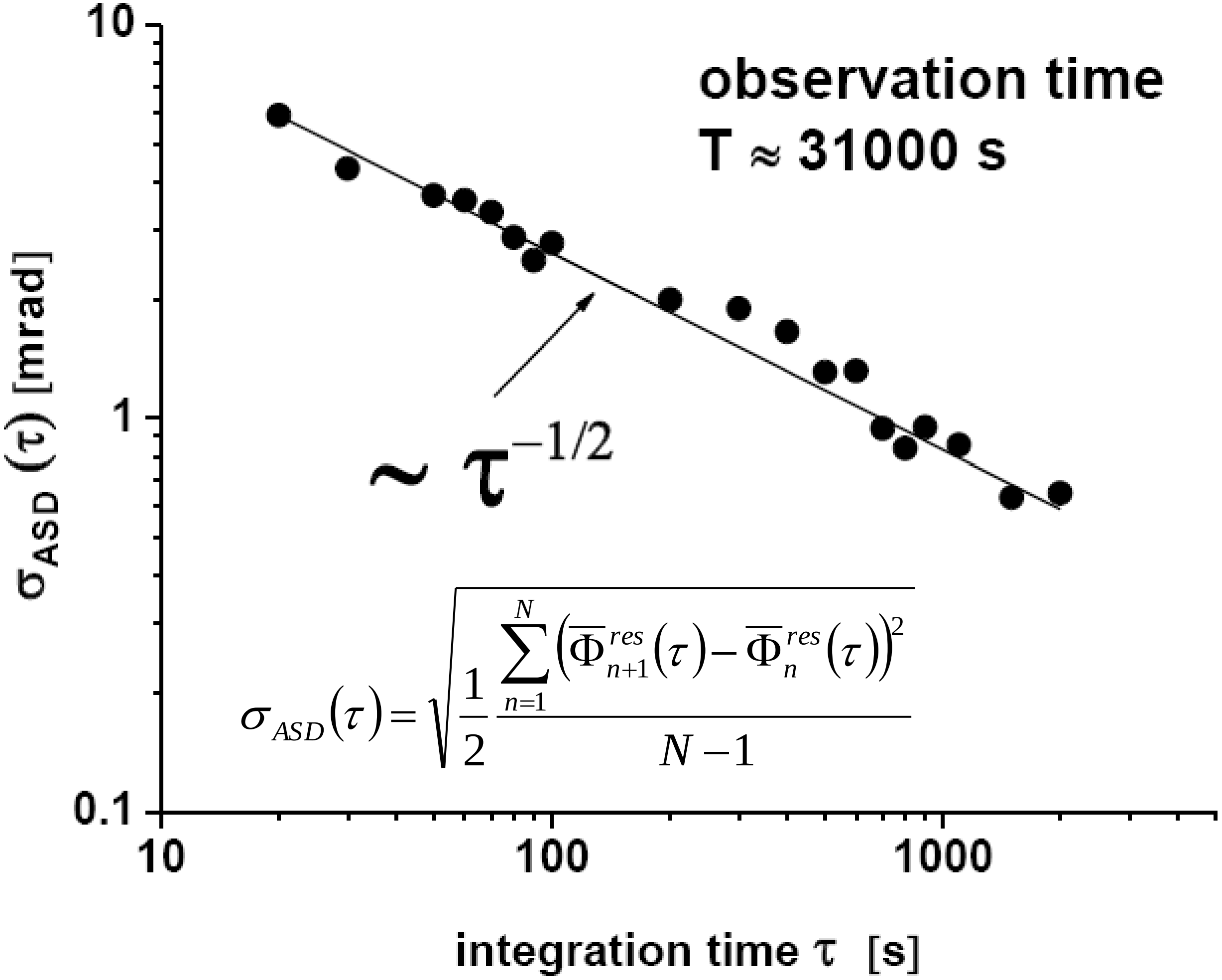
$$\cos\chi = \cos\theta \cdot \cos\rho$$
$$= 0.543$$

$$\theta = 52^0 31'$$
$$\rho = 28^0$$

$$\sin\chi \cdot \left| -3.5 \cdot \tilde{b}_J^n + 0.012 \cdot \tilde{d}_J^n + 0.012 \cdot \tilde{g}_{D,J}^n \right| \leq 2\pi \cdot \delta\upsilon_J \cdot \hbar \qquad J = X, Y$$

$$\tilde{b}_\perp^n = \sqrt{(\tilde{b}_X^n)^2 + (\tilde{b}_Y^n)^2} \leq 7 \cdot 10^{-33}\ GeV$$

ASD of residual phase noise



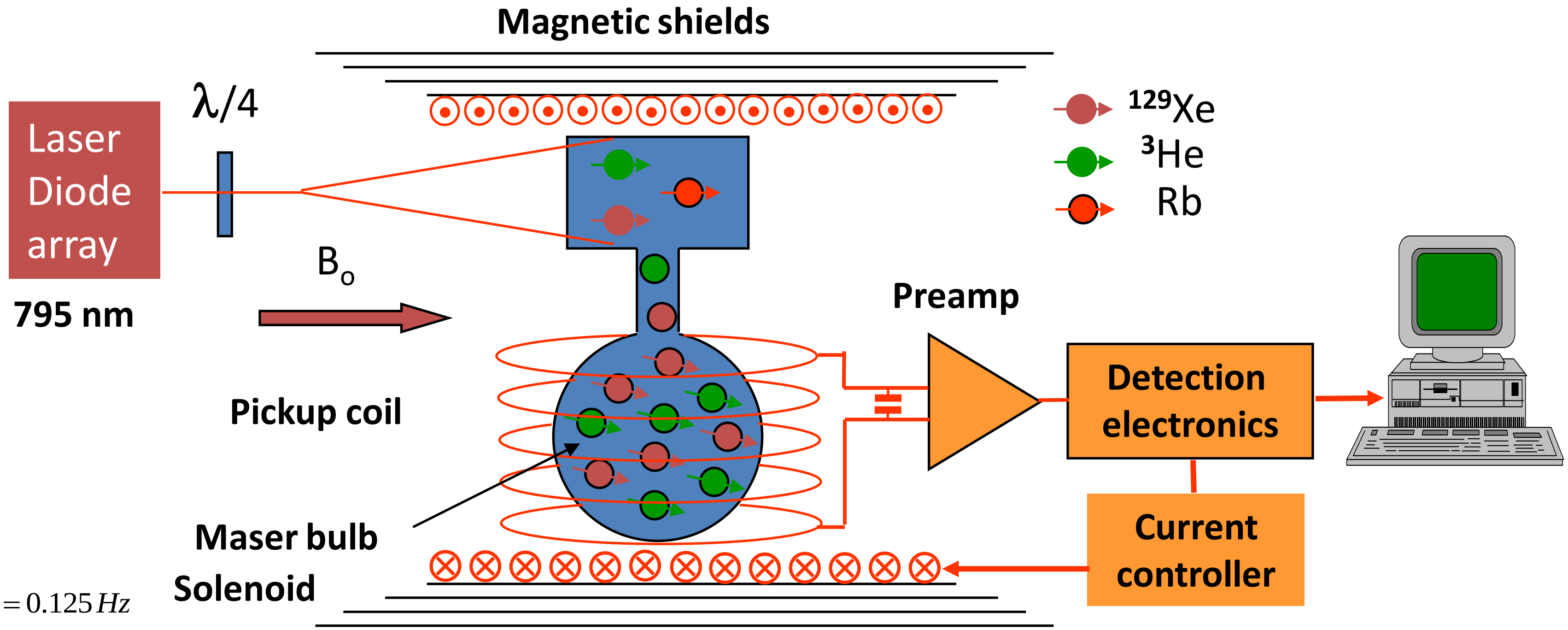
$$\sigma_{ASD}(\tau) = \sqrt{\frac{1}{2} \frac{\sum_{n=1}^{N} \left(\overline{\Phi}_{n+1}^{res}(\tau) - \overline{\Phi}_{n}^{res}(\tau) \right)^2}{N-1}}$$

observed fluctuations decrease as $\tau^{-1/2}$ indicating the presence of a white phase noise

CRLB power law ✓

Spin maser experiments with ^{3}He and ^{129}Xe set the best limit on LV effects for the neutron

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



Magnetic shields

Laser Diode array

795 nm

λ/4

B_o

^{129}Xe

^{3}He

Rb

Preamp

Detection electronics

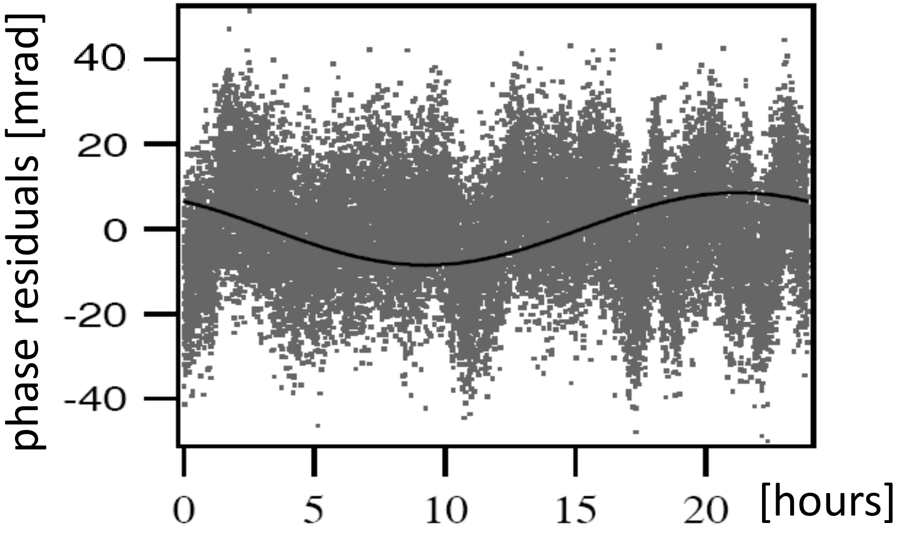
Current controller

Pickup coil

Maser bulb

Solenoid

$f_{BW} = 0.125\,Hz$



Fit to their data

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

➡ $$2\pi\left|\delta\upsilon_J\right|\geq\frac{1}{\hbar}\cdot\left|-3.5\,\tilde{b}_J^{n}\right|$$

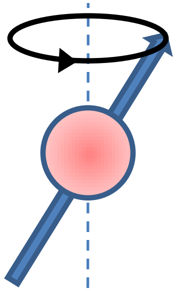
➡ $$\boxed{\left|\tilde{b}_{X,Y}^{n}\right|<10^{-31}\ GeV}$$

Conclusion and Outlook

- ^{3}He , ^{129}Xe clocks based on free spin precession
  → long spin coherence times

  $T^{*}_{2,He} > \; 60\,hours$

  $T^{*}_{2,Xe} = 3-6\ hours$ (so far limited by $T_{1,wall}$)



- Magnetometry

  $\langle \delta B \rangle \approx 1\,fT\ @\ 200\ s$ $\longrightarrow$ magnetometer for nEDM experiments

  $\langle \delta B \rangle \approx 10^{-4}\ fT\ @\,1\ day$

- clock comparison

  SME (Kostelecky): $V = -\vec{\tilde{b}} \cdot \vec{\sigma}$

Coefficient	Proton	Neutron	Electron
$\tilde{b}_X$	10^{-27} GeV	10^{-31} GeV	10^{-31} GeV
$\tilde{b}_Y$	10^{-27} GeV	10^{-31} GeV	10^{-31} GeV
$\tilde{b}_Z$	–	–	10^{-30} GeV
$\tilde{b}_T$	–	10^{-27} GeV	10^{-27} GeV

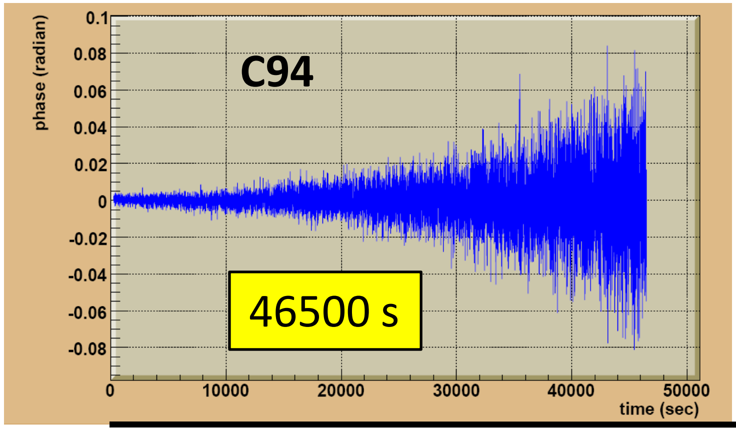
new limits on the bound neutron

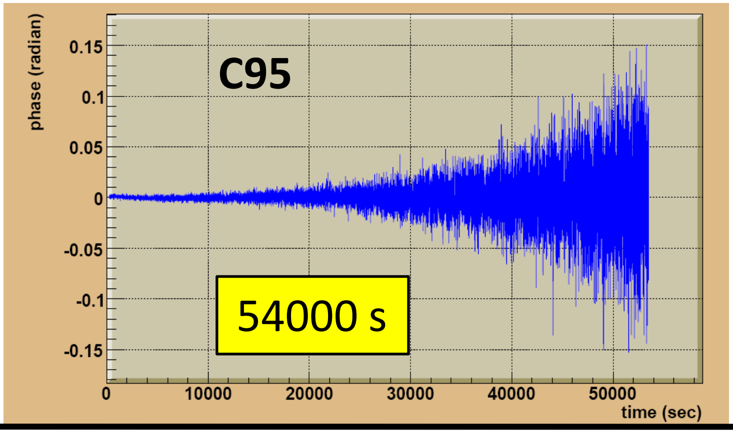
$$\left|\tilde{b}^{n}_{X}\right| \leq \; 4\cdot 10^{-33}\ GeV$$

$$\left|\tilde{b}^{n}_{Y}\right| \leq \; 5\cdot 10^{-33}\ GeV$$

C.Gemmel et al., arXiv:0905.3677
submitted to EPJ D

improved sensitivity: March 2009 run

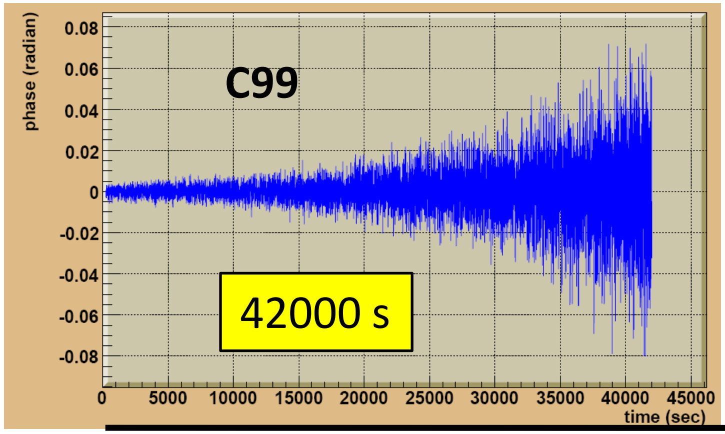


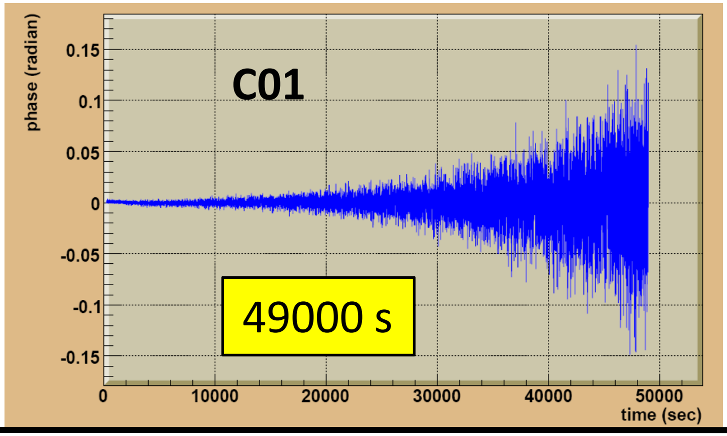


[h]

0

13:35

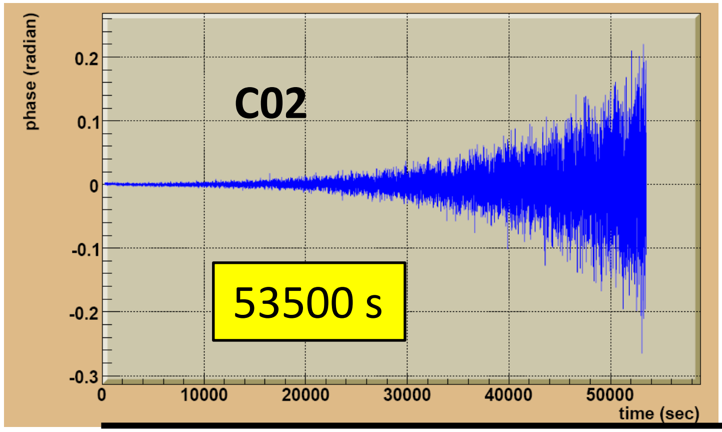


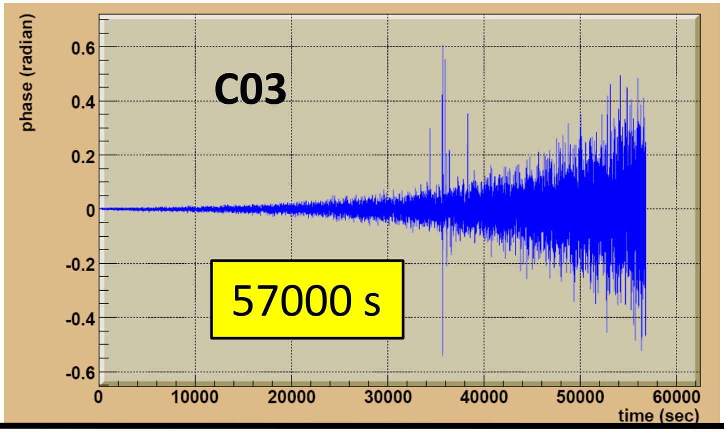


[h]

29:30

46:00





[h]

60:10

77:50

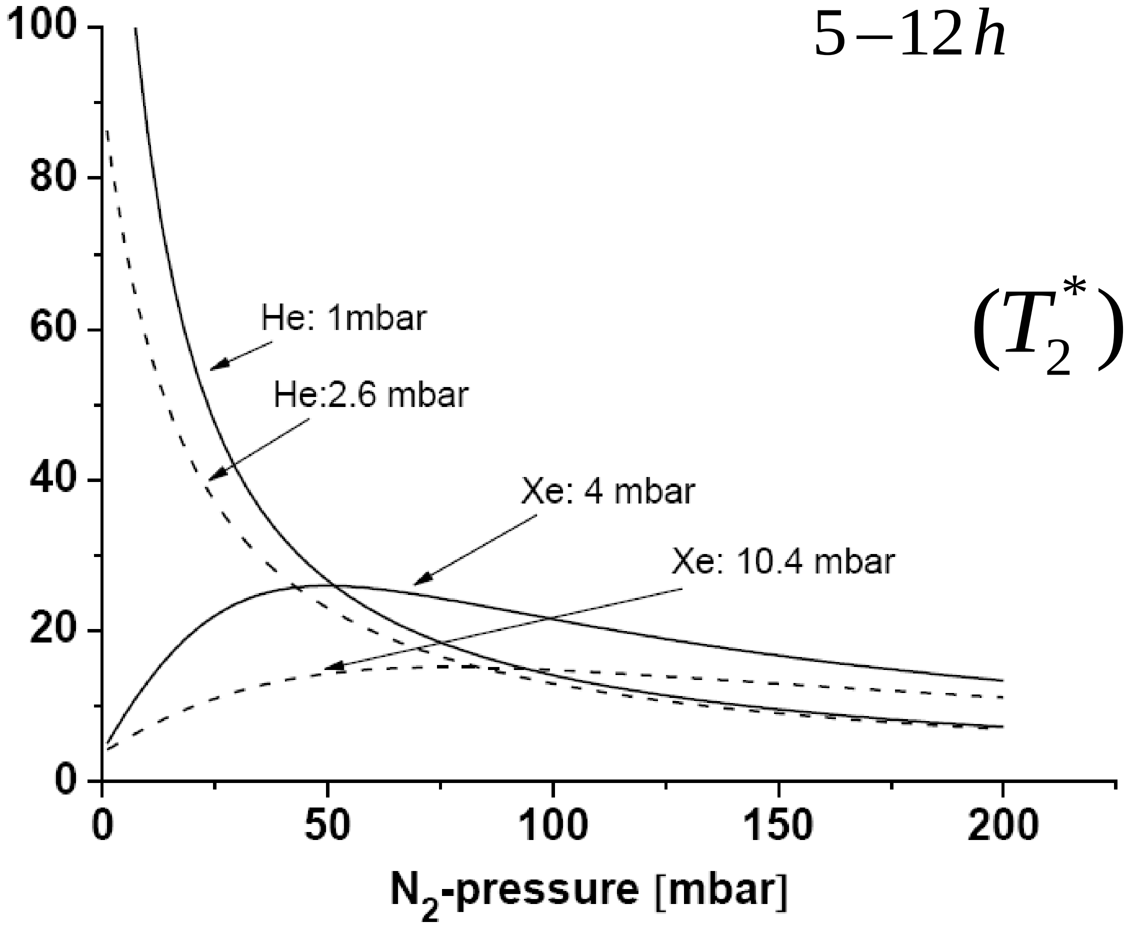
Relaxation of ^{129}Xe

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

$$\frac{1}{T_{1,wall}} \swarrow \; 5-12\,h$$

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

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



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

(measured)